Uncertain Risk, Science Experiments, and the Courts

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ABSTRACT

Legal scholarship has looked at problems of uncertainty—
"unknown unknowns"—in a variety of contexts, from financial
regulation to national security. This Article, however, focuses on
uncertain risk in what may be its most challenging arena: experimental
scientific research. Notably, this context imposes a key conceptual
hurdle. In other arenas, law and regulation can work to lessen
uncertainty. But with science-experiment risk, uncertainty cannot be
sidestepped, since going beyond the current state of human knowledge
is the whole point of experimental research. Moreover, science-
experiment risk involves the highest possible stakes, since future
experiments could plausibly lead to global catastrophe, even human
extinction.

As a case study, this Article explores an extreme science-gone-wrong
scenario: a particle-collider-spawned black hole that grows to devour
our planet. No credible source considers such a disaster likely, but
scientific uncertainty has made the possibility of such a mishap
frustratingly difficult to exclude. Thus, the black hole case provides a
sharp example of how the classical mode of quantitative risk
assessment breaks down under the weight of unknown unknowns.
Proceeding from this example, this Article attempts to answer questions
such as: How can the courts make good decisions about the
reasonableness of risk where safety depends on understanding laws of

nature the experiment itself is designed to uncover? And how can the courts keep the masses safe from science while keeping science safe from the masses?

The answers revolve around the insight that courts can conduct a qualitative meta-analysis, looking at such factors as the existence of conflicts of interest, the influence of institutional pressures, and the extent to which safety rationales rely on untested assumptions. With this test suite, courts can guard the rule of law while leaving the scientific frontier open for exploration.

INTRODUCTION

If the Earth is ever destroyed by a science experiment, it will not be a failure of science. It will be a failure of law. In particular, it will result from the law's inability to deal with issues of uncertain risk[1] —commonly called "unknown unknowns."[2] This Article explains what this problem is, why it deserves to be taken seriously, and how the law can cope with it.

Leading-edge science experiments raise the specter of huge, bizarre catastrophe scenarios: a plutonium-laden spacecraft causing millions of cancers by burning up in the atmosphere;[3] a microbiology lab unleashing a pandemic with the escape of an exotic pathogen;[4] a particle accelerator collapsing the Earth into an ultradense ball of "strange matter" or destroying it with a black hole.[5] None of these

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1. *See* Barry R. Furrow, *Governing Science: Public Risks and Private Remedies,* 131 U. PA. L. REV. 1403, 1404 (1983) ("Risks generated by research activities are in a special category. Unlike the usual environmental harms, where the damage-creating instrumentality is already producing a by-product that poses some level of long term health impact, harms . . . include problems of feared catastrophe, with uncertainty as the dominant feature.").

2. The phrase "unknown unknowns" describes the risk of things going wrong in a way that cannot be anticipated. *See, e.g.,* Richard A. Epstein, *In Defense of the Contract at Will,* 51 U. CHI. L. REV. 947, 969 (1984) (defending at-will employment contracts on the basis that they allow employers and employees to plan for "known unknowns," being distinguishable from "unknown unknowns"). The most famous use of the phrase "unknown unknowns," however, is probably that of defense secretary Donald Rumsfeld in the context of his discussion of the possibility that Iraq might supply weapons of mass destruction to terrorists. *See* Donald Rumsfeld, U.S. Sec'y of Def., DoD News Briefing, DOD (Feb. 12, 2002, 11:30 AM), http://archive.defense.gov/transcripts/transcript.aspx?transcriptid=2636 [https://perma.cc/27EA-PEC8]. In response to a question regarding reports of a lack of evidence for a direct link between the Iraqi government and terrorists organizations seeking weapons of mass destruction, Rumsfeld said, "Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns—the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones." *Id.*

3. *See* Haw. Cty. Green Party v. Clinton, 980 F. Supp. 1160, 1168-69 (D. Haw. 1997); Karl Grossman, *The Risk of Cassini Probe Plutonium,* CHRISTIAN SCI. MONITOR (Oct. 10, 1997), http://www.csmonitor.com/1997/1010/101097.opin.opin.1.html [https://perma.cc/QH79-ZGPN]; *Cassini Roars into Space,* CNN (Oct. 15, 1997), http://www.cnn.com/TECH/9710/15/cassini.launch/ [https://perma.cc/4DD8-NV5A]; Najmedin Meshkati, *Probability, Plutonium Don't Mix,* L.A. TIMES (Oct. 10, 1997), http://articles.latimes.com/print/1997/oct/10/local/me-41149 [https://perma.cc/T3DR-N784].

4. *See* Michael Baram, *Biotechnological Research on the Most Dangerous Pathogens: Challenges for Risk Governance and Safety Management,* 47 SAFETY SCI. 890, 891-82 (2009). In a somewhat related vein are uncertain astrobiology risks associated with hypothetical extraterrestrial microbes—so-called "backward contamination"—from a Mars sample return mission. *See generally* Molly K. Macauley, *Flying in the Face of Uncertainty: Human Risk in Space Activities,* 6 CHI. J. INT'L. L. 131, 144-45 (2005).

5. *See* Eric E. Johnson, *Agencies and Science-Experiment Risk,* 2016 U. ILL. L. REV. 527, 542-53 (2016) [hereinafter Johnson, *Agencies*] (regarding strange matter); Samuel J. Adams, *"Honey I Blew Up the World!": One Small Step Towards Filling the Regulatory "Black Hole" at the Intersection of High-Energy Particle Colliders and International Law,* 38 GA. J.

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disaster scenarios is likely, yet all are theoretically plausible. And as questions of the acceptability of such risks arise, it necessarily falls to the legal system to provide answers. Why is this the law's job? While it is the role of scientists to expand our understanding of the natural world and probe the unknown, it is the role of courts to balance the rights and interests of people and institutions. Thus, for better or worse, analyzing whether an experiment is unreasonably dangerous is ultimately a question for the law and legal analysis—and not something that can be foisted off on science.[6]

How the law should carry off this kind of analysis, however, is a tricky business. While courts routinely deal with conflicting rights, duties, freedoms, and obligations, this is usually done against a background of established facts and knowable risks. In other words, uncertainty tends not to be a problem when it comes to ordinary cases, such as liability for a barrel dropping out of a warehouse or a railroad employee jostling a bundle of fireworks.[7] In these and other everyday cases, questions of cause and effect are dealt with using common sense. Jurors and judges make determinations about due care and undue risk based on their accumulated experience of living in the world. This is tolerably fair, reasonably efficient, and helpfully encouraging of safe behavior.

Subject matter that is more science-intensive requires going beyond common sense—but not necessarily confronting uncertainty. Indeed, over the past several decades, courts have embraced a classical quantitative paradigm of risk assessment that assumes away uncertainty.[8] In this classical quantitative mode, risk is represented by hard numbers, including quantified probabilities of injury. These numbers can be plugged into a cost-benefit analysis,[9] yielding a mathematical result. In this way, classical quantitative risk assessment is premised on the idea that risk can be reduced entirely to *known unknowns*. For instance, what is the risk that a drug

INT'L & COMP. L. 131, 139-44 (2009) (regarding strange matter and black holes); Eric E. Johnson, *The Black Hole Case: The Injunction Against the End of the World*, 76 TENN. L. REV. 819, 829-32 (2009) [hereinafter Johnson, *Black Hole Case*] (regarding black holes).

6. *See generally* Eric E. Johnson, *CERN on Trial: Could a Lawsuit Shut the LHC Down?*, NEW SCIENTIST (February 17, 2010), https://www.newscientist.com/article/mg20527485-700-cern-on-trial-could-a-lawsuit-shut-the-lhc-down/ [https://perma.cc/D44J-VQ36] (arguing that questions of real-world risk from science experiments cannot justly be resolved in a purely academic fashion by scientists).

7. Byrne v. Boadle, 159 Eng. Rep. 299, 299-300 (Ex. 1863) (barrel falling out of warehouse onto pedestrian); Palsgraf v. Long Island R.R., 162 N.E. 99, 99 (N.Y. 1928) (railroad employee jostling package of fireworks loose from a passenger causing explosion).

8. *See, e.g.,* Ind. Harbor Belt R.R. Co. v. Am. Cyanamid Co., 916 F.2d 1174, 1179-82 (7th Cir. 1990) (using a classical way of thinking about risk—something in the vein of cost-benefit analysis—to decide what liability rule to apply to the shipment of volatile, toxic chemicals by rail).

9. *See* Molly J. Walker Wilson, *Cultural Understandings of Risk and the Tyranny of the Experts*, 90 OR. L. REV. 113, 117 (2011).

treatment will cause a particular debilitating side effect? With classical risk assessment, we gather empirical data and quantify the probabilities. At that point, a spreadsheet provides the answer.[10]

The classical quantitative approach assumes that all necessary information is available, all potential problems have been identified, and the optimal solution can be found with reasoned thinking.[11] This approach works well most of the time. In essence, the classical approach aims to take the risk out of risk. Courts, in adhering to this sort of risk analysis, have become avid consumers of expert-crafted quantitative analysis.[12] And in the process, courts have come to regard even the most complex questions of risk as tamable by science.[13] But reliance on experts begs a disquieting question: What is the risk that the experts themselves have made a mistake?

Unfortunately, this meta-risk—that is, the risk that a risk assessment is flawed—is unquantifiable. The expert's analysis might depend on faulty data, might rest on unwarranted assumptions, or might fail to identify all the ways in which things could go wrong. Crucially, our inability to quantify danger does not mean that we are safe.[14] As physicist Lisa Randall has written, "Many people take away the wrong lesson and conclude that the absence of reliable predictions implies an absence of risk. In fact, quite the opposite applies."[15]

So here is the conundrum: If courts are to think about questions of risk in an honest and complete way, they cannot ignore such unknown unknowns. Yet it would seem to be an impossible task for the courts to make fair, well-reasoned decisions on the basis of things that they cannot know.

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10. *See generally* Melissa Marie Bean, *Fatal Flaws in the Food and Drug Administration's Drug-Approval Formula*, 2003 UTAH L. REV. 881, 882-88 (2003) (describing the FDA drug-approval process); J. Warren Rissier, *The FDA's Proposed Labeling Rules for Over-the-Counter Drugs and Preemption of State Tort Law*, 71 S. CAL. L. REV. 1387, 1391-93 (1998) (same).

11. *See* Saiña Hassanzadeh, Analysis of the Causes of Delay in Collaborative Decision-Making Under Uncertainty in Pharmaceutical R&D Projects, (Dec. 3, 2012) (unpublished Ph.D. dissertation, University of Toulouse) (on file with University of Toulouse) at 26.

12. *See, e.g.*, Gen. Elec. Co. v. Joiner, 522 U.S. 136, 149 (1997) (Breyer, J., concurring) ("[A]s cases presenting significant science-related issues have increased in number, judges have increasingly found in the Rules of Evidence and Civil Procedure ways to help them overcome the inherent difficulty of making determinations about complicated scientific, or otherwise technical, evidence.").

13. *See* Wilson, *supra* note 9, at 123.

14. *Cf.* Wendy E. Wagner, *Trans-Science in Torts*, 96 YALE L.J. 428, 429 n.11 (1986) ("[T]he legal system ignores hazards and other man-made risks which have not yet been studied thoroughly or analyzed statistically. The high improbability that the effects of an unsafe product will be quantified, in turn, considerably impedes deterrence.").

15. LISA RANDALL, KNOCKING ON HEAVEN'S DOOR: HOW PHYSICS AND SCIENTIFIC THINKING ILLUMINATE THE UNIVERSE AND THE MODERN WORLD 192 (2011) (discussion in the context of risks including macroeconomic risk posed by financial markets).

Recently, legal scholars have begun to work in earnest on problems of law and uncertain risk.[16] Legal scholarship has looked at how to cope with uncertainty in areas such as pharmaceuticals, financial markets, engineering, and national security.[17] The first line of defense against catastrophe, in all these contexts, is to avoid uncertainty as much as possible. And here, the financiers, drug companies, engineers, and security professionals are aligned with the lawyers, judges, and regulators. Everyone wants to keep the unknown unknowns at bay and avoid surprises.

Scientists engaged in pure, leading-edge research, however, are different. They run toward the unknown unknowns.[18] They crave surprises.[19] This is why it is so compelling to consider risks posed by scientific research done for the sake of exploration and discovery: Uncertainty is the essence of the endeavor. And as difficult as it is to confront uncertainty, refusing to confront it in the context of leading-edge science is even worse. If courts decide that no injunction can be based on uncertain risk or that experimenters' safety assessments are immune from challenge by those with lesser scientific credentials, then the rule of law capitulates when it may be needed the most. On the other hand, if courts decide that no uncertain risk is worth taking, then our pursuit of fundamental knowledge about the universe and our place in it may wither and die.

The urgency of figuring out how to think clearly about these issues will not lessen with time. To the contrary, uncertain risks in experimental science are bound to proliferate. Physicists will seek to

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16. *See, e.g.,* Kathryn Judge, *Information Gaps and Shadow Banking,* 103 VA. L. REV. 411, 447-68 (2017) (exploring unknown unknowns in banking and capital markets regulation); Jennifer Nou, *Intra-Agency Coordination,* 129 HARV. L. REV. 421, 463-64 (2015) (discussing agency means of dealing with uncertain risks); Thomas O. McGarity, *Science and Policy in Setting National Ambient Air Quality Standards: Resolving the Ozone Enigma,* 93 TEX. L. REV. 1783, 1809 (2015) (discussing risk uncertainty in the context of EPA standard setting); Albert C. Lin, *Myths of Environmental Law,* 2015 UTAH L. REV. 45, 56-57 (2015) (arguing that misconceptions about uncertain risks are part of a damaging set of myths about environmental law); Gregory N. Mandel & Gary E. Marchant, *The Living Regulatory Challenges of Synthetic Biology,* 100 IOWA L. REV. 155, 168 (2014) (discussing uncertainty in risk from synthetic biological organisms); *see also* Christian Chessman, *A "Source" of Error: Computer Code, Criminal Defendants, and the Constitution,* 105 CALIF. L. REV. 179, 196-99 (2017) (unknown unknowns in source code for technologies used in criminal prosecutions).

17. *See, e.g.,* Daniel A. Farber, *Uncertainty,* 99 GEO. L.J. 901, 946-58 (2011) (discussing risks in the contexts of applied nanotechnology, nuclear waste storage, and financial-market regulation); Ryan Bubb & Prasad Krishnamurthy, *Regulating Against Bubbles: How Mortgage Regulation Can Keep Main Street and Wall Street Safe—from Themselves,* 163 U. PA. L. REV. 1539, 1575-76 (2015) (discussing unknown unknowns in financial markets).

18. *See, e.g.,* DON LINCOLN, THE QUANTUM FRONTIER: THE LARGE HADRON COLLIDER 62 (2009) [hereinafter LINCOLN, QUANTUM FRONTIER] ("[T]here can always be surprises. This is the research frontier, after all.").

19. *See, e.g.,* SEAN CARROLL, THE PARTICLE AT THE END OF THE UNIVERSE: HOW THE HUNT FOR THE HIGGS BOSON LEADS US TO THE EDGE OF A NEW WORLD 48 (2012) (speaking of the hopes of "discovering something completely unanticipated, and being sent back to the theoretical drawing board as a result").

build ever more energetic particle accelerators.[20] More and more labs will conduct genetic experiments with viruses.[21] And researchers will soon enter new areas of potential hazards, including nanotechnology and artificial intelligence.[22] Courts dealing with challenges to allegedly risky science experiments must therefore learn how to go beyond the classical paradigm and find new ways of coping with such questions. That is where this Article comes in: figuring out how courts can do this rationally, efficiently, and fairly.

Critics might see this project as ultimately futile, arguing that courts are not institutionally qualified to deal with scientifically complex subject matter.[23] This Article will show, however, that not only can generalist judges handle the science, they can achieve better decision-making than scientists and specialist experts in areas where uncertainty dominates. This is because in cases dominated by scientific or statistical uncertainty, classical quantitative assessment is impossible to do in a rigorous way. This means that courts must, out of necessity, deal with risk in qualitative terms.

The remaining question is how to do this well. This Article provides a path: Where there is an alleged low-probability risk of catastrophe posed by a novel science experiment—which is to say a situation in which uncertainty dominates—the courts should conduct a meta-analysis targeted to the knowable human and institutional factors that surround the uncertainty. By scrutinizing the risk-assessment process and the risk assessors themselves, courts can form a meaningful opinion on the risk that the experimenters' own risk as-sessments are untrustworthy. This Article explains how to do this in detail, discussing five categories of qualitative meta-analysis, each of which becomes a factor to be considered by the courts in dealing with issues of uncertain science-experiment risk.[24] Those five categories are: (1) the potential for defective theoretical groundings in a risk assessment; (2) the potential for faulty scientific work; (3) the potential for credulity and neglect; (4) a lack of independence and the existence

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20. *See* George Musser, *Next-Gen Particle Accelerators to Surpass Large Hadron Collider*, SCI. AM.: CRITICAL OPALESCENCE (June 9, 2014), https://blogs.scientificameri-can.com/critical-opalescence/next-gen-particle-accelerators-to-surpass-large-hadron-col-lider/ [https://perma.cc/A7DY-ECBU].

21. *See generally* Baram, *supra* note 4.

22. *See, e.g.*, Nick Bostrom, *Existential Risks: Analyzing Human Extinction Scenarios and Related Hazards*, 9 J. EVOLUTION & TECH. 1, 1 (2002) (discussing nanotechnology and artificial intelligence); Lisa Marie Segarra, *Elon Musk: AI Poses 'Vastly More Risk Than North Korea'*, FORTUNE (Aug 12, 2017, 9:34 AM), http://fortune.com/2017/08/12/elon-musk-ai-poses-vastly-more-risk-than-north-korea/ [https://perma.cc/J4AC-4TUJ] (quoting Elon Musk, "If you're not concerned about AI safety, you should be. Vastly more risk than North Korea," and AI is a "fundamental existential risk for human civilization").

23. *See* Furrow, *supra* note 1, at 1458 (reviewing arguments that courts lack the institutional competence to grapple effectively with complex modern hazards).

24. *See infra* Section IV.B.

of conflicts of interest infecting a risk assessment; and (5) the potential for fraud, lies, and faked results.

Working through these factors provides courts a way to award plaintiffs appropriate relief from unreasonable experiment risk. At the same time, this analysis leaves room for experimenters to push the frontiers of scientific knowledge. Bottom line, the analytical tools offered in this Article allow the striking of the right balance: protecting the public from unreasonable risks while protecting scientific inquiry from being suffocated by unreasonable fears.

A discussion of risk, science, and uncertainty involves a heavy dose of abstraction and a great deal of abstruse subject matter. Thus, it is helpful to use a case study to ground the analysis. This Article uses as a case study the question of whether Europe's Large Hadron Collider (LHC)[25] might precipitate a black-hole catastrophe. The LHC/black-hole question is an excellent vehicle for thinking about risk and judicial decisionmaking for multiple reasons. First, there is a rich documentary record that tracks the controversy. Second, with the existence of the planet allegedly on the line, it is a question with the highest possible stakes. Finally, perched at the leading edge of particle physics, it involves the most unknowable of unknowns.

Part I of this Article sets out the LHC/black-hole case study. Part II discusses conceptual and practical problems for the courts in confronting issues of science-research risk. Part III explores issues of rhetoric and the framing of questions of risk and uncertainty. Part IV details a proposed multi-factor test for using qualitative meta-analysis to judge the acceptability of risk in the science-experiment context.

I. A CASE OF UNKNOWN UNKNOWNS: THE BLACK HOLE QUESTION

In this Part, I set out the case study that provides the concrete set of facts this Article uses both to build up and shakedown the abstract analytical tools it advances. In particular, this Part contains background on the LHC particle accelerator, the laboratory organization that operates it, and the black-hole risk critics say the experiment might pose.[26] Thanks to the available published sources about the black-hole question, which I summarize here, there is an abundance of grist for the mill of uncertain-risk analysis.

To be clear, there is no suggestion—at least not from a credible source—that the chance of the destruction of the planet by this or any

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25. *See generally Faq LHC the Guide,* CERN, http://cds.cern.ch/record/2255762/files /CERN-Brochure-2017-002-Eng.pdf [https://perma.cc/GSA9-3N86] [hereinafter CERN 2017 faq].

26. In prior work, I provided an explication of the LHC/black-hole question with considerably more detail than I provide here. *See generally* Johnson, *Black Hole Case, supra* note 5, at 838-60.

other current science experiment is anything other than small. But even a small chance may be very significant given the magnitude of the harm. That, along with the extreme features of the controversy, make it a good model for uncertain-risk analysis.

A. CERN and the LHC

Founded in 1954, CERN is the world's pre-eminent laboratory for particle physics, a discipline studying the most fundamental aspects of matter and energy.[27] Located just outside of Geneva, CERN's campus spans the border of Switzerland and France.[28] As an intergovernmental organization comprising 23 member states, CERN is a mammoth institution.[29] Its 2019 budget was 1.292 billion CHF ($1.46 billion USD).[30] A recent count indicated that over 17,500 people are involved with CERN in some capacity.[31]

CERN's current program is centered around the LHC, a superconducting synchrotron particle collider (also known as a "particle accelerator") along with the various experiments using the collider.[32] The LHC's development began in the 1980s, and construction was approved in 1994.[33] Following many delays and setbacks, the operational phase of the LHC program became the subject of extreme anticipation in the physics community.

The LHC's capacity to manipulate matter at the most basic levels is unprecedented. For instance, the particle collisions produce the hottest temperatures ever achieved by humans—100,000 times hotter

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27. *See CERN European Organization for Nuclear Research,* CERN 1 (2010), http://cds.cern.ch/record/1278456/files/CERN-Brochure-2010-005-Eng.pdf [https://perma.cc/9MHU-HMVF].

28. *Id.*

29. *Our Member States,* CERN, https://home.cern/about/who-we-are/our-governance/member-states [https://perma.cc/S7L9-BK92] (last visited March 30, 2021).

30. *See Final Budget of the Organization of the Organization for the Sixty-Fifth Financial Year 2019,* CERN, https://cds.cern.ch/record/2652956/files/English.pdf [https://perma.cc/2J9L-YRWV] [hereinafter CERN 2019 budget].

31. *Our People,* CERN, https://home.cern/about/who-we-are/our-people [https://perma.cc/DH4U-BE62] (last visited March 30, 2021).

32. *See* CERN 2019 budget, *supra* note 30, at 16 (evidencing primacy of LHC in terms of CERN expenses); CERN, 2019 ANNUAL REPORT 4-5 (2019), https://cds.cern.ch/record/2723123/files/AnnualReport2019EN.pdf [https://perma.cc/4L86-TZXR] (evidencing centrality of LHC program to CERN); *id.* at 14 ("The Large Hadron Collider (LHC) is the Laboratory's flagship machine . . . ."); CERN 2017 faq, *supra* note 25, at 12 (describing CERN's accelerator complex as a chain of machines, each accelerating the beam to successively higher energies, with the LHC being the last part of this chain, but noting that some lower-energy accelerators in the series have "their own experimental halls, where their beams are used for experiments at lower energies"); *id.* at 15-47 (describing the collider and its component experiments).

33. CERN 2017 faq, *supra* note 25, at 16.

than the center of the sun.[34] The aim of the endeavor is to advance understanding of the fundamental particles and forces that make up the physical universe.[35] It is hoped the LHC may shed light on some of the most compelling topics in particle physics,[36] including the existence of hidden dimensions[37] and evidence of what constitutes dark matter.[38] Indeed, the LHC already achieved a triumphant discovery by finding the celebrated Higgs boson—a fundamental particle that is understood to impart mass to matter.[39]

The size of the LHC matches its scientific ambitions. CERN hails the LHC as "the largest machine in the world."[40] The beam tunnel is 17 miles around.[41] The magnets used to accelerate the particles through that tunnel are cooled with about 90 metric tons of superfluid helium,[42] achieving a temperature colder than outer space. The accelerated particles form an ion beam "powerful enough to melt a small car almost instantaneously."[43] And as a whole, the apparatus consumes enough power for a medium-sized city.[44]

The LHC was designed to collide protons at an energy of 14 trillion electron volts (TeV),[45] 14 times the energy of any previous collider.[46] Scientists have dubbed this new energy range the "Terascale."[47] The

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34. DON LINCOLN, THE LARGE HADRON COLLIDER 25 (2014) [hereinafter LINCOLN, COLLIDER] (highest human-achieved temperatures); CERN 2017 faq, *supra* note 25, at 25 (temperature comparison to sun).

35. *See About CERN*, CERN, https://home.cern/about [https://perma.cc/2R49-4NDL] (last visited March 30, 2021).

36. *See* CERN 2017 faq, *supra* note 25, at 22-23.

37. *See Extra Dimensions, Gravitations, and Tiny Black Holes*, CERN, https://home.cern/science/physics/extra-dimensions-gravitons-and-tiny-black-holes [https://perma.cc/5X2Z-M6F6] (last visited March 30, 2021).

38. *See id.*

39. *See* Jacob Aron, *Elusive Higgs Wins Physics Nobel, Shared with Englert*, NEWSCIENTIST (Oct. 8, 2013), http://www.newscientist.com/article/dn24365-elusive-higgs-wins-physics-nobel-shared-with-englert.html [https://perma.cc/6WXU-4LAF].

40. *The Large Hadron Collider*, CERN, https://timeline.web.cern.ch/taxonomy/term/93 [https://perma.cc/63ZQ-CCGR] (last visited March 30, 2021).

41. *See* CERN 2017 faq, *supra* note 25, at 15.

42. *Id.* at 33.

43. Travis Lupick, *B.C. Scientists Aim to Unlock Secrets of the Universe*, STRAIGHT (May 15, 2008, 10:01 AM), http://www.straight.com/article-145556/end-world [https://perma.cc/7HP8-MJ2W].

44. *See id.* (noting LHC "will consume as much power as a medium-sized city"); *see also Powering CERN*, CERN, http://home.web.cern.ch/about/engineering/powering-cern [https://perma.cc/E757-K9GV] [hereinafter Powering CERN] (last visited March 30, 2021) ("At peak consumption, usually from May to mid-December, CERN uses about 200 mega-watts of power, which is about a third of the amount of energy used to feed the nearby city of Geneva in Switzerland.").

45. CERN 2017 faq, *supra* note 25, at 3.

46. *See Tevatron Accelerator*, FERMILAB, http://www.fnal.gov/pub/science/accelerator/ [https://perma.cc/KBT2-R76W] (last visited March 30, 2021).

47. Particle Physics Project Prioritization Panel, *US Particle Physics: Scientific Opportunities, A Strategic Plan for the Next Ten Years*, OSTI 2 (May 29, 2008),

LHC, however, has yet to achieve the 14 TeV energy level. Instead, a number of setbacks have made for some rough going. Early on, the LHC suffered a couple of unanticipated mishaps that caused parts of the machine to blow up.

During a test in 2007, a design defect caused one of the magnet units to explode.[48] In explaining the error that led to the accident, a laboratory director said, "[W]e are dumbfounded that we missed some very simple balance of forces. Not only was it missed in the engineering design but also in the four engineering reviews carried out between 1998 and 2002 before launching the construction of the magnets."[49]

Then in 2008, shortly after the LHC's launch, a faulty electrical connection caused a mishap that damaged 53 of the LHC's magnet units.[50] Although CERN's initial reports characterized the event as a "leak," Cal Tech physicist Sean Carroll wrote that "'explosion' is a more accurate description."[51] Magnets were ripped out of their floor bolts and six tons of helium spewed into the tunnel in a matter of minutes.[52]

With repairs, CERN was able to get the LHC working again in November 2009, and within a few months it was up to operating at half its design energy, producing collisions at 7 TeV.[53] In 2012, even with the LHC still running far below its designed energy level, experimenters announced that the discovery of a new boson particle believed to be the long-sought Higgs boson.[54]

Then, in February 2013, the LHC ended its initial three-year run and began a long shutdown period during which the interconnections between magnets could be rebuilt such that the machine would

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https://science.osti.gov/-/media/hep/pdf/files/pdfs/p5_report_06022008.pdf [https://perma.cc/MX5J-GEHU].

48. Pier Oddone, *The World Stage*, FERMILAB TODAY (Apr. 3, 2007), http://www.fnal.gov/pub/today/archive/archive_2007/today07-04-03.html [https://perma.cc/PTN2-BZAR].

49. *Id.*

50. *Large Hadron Collider Ready to Restart,* BOSTON.COM (Nov. 20, 2009), http://www.boston.com/bigpicture/2009/11/large_hadron_collider_ready_to.html [https://perma.cc/7S3E-5G48].

51. CARROLL, *supra* note 19, at 76.

52. *Id.* at 76-77.

53. CERN, 2009 ANNUAL REPORT 21 (2009), https://cds.cern.ch/record/1516877/files/Annual%20report%202009.pdf [https://perma.cc/BK5N-6NH4] (discussing repairs); CERN, 2010 ANNUAL REPORT 7 (2010), https://cds.cern.ch/record/1516878/files/Annual%20report%202010.pdf [https://perma.cc/VN4C-RWJ5] (discussing 7 TeV operation)

54. CERN, 2012 ANNUAL REPORT 5-6, 13 (2012), https://cds.cern.ch/record/1563863/files/Annual%20Report.pdf [https://perma.cc/TDP4-2PFS].

eventually be able to reach its design energy.[55] In 2015, the LHC was relaunched, achieving collisions at a record 13 TeV.[56]

B.   A Quick Primer on Experimental Particle Physics

Particle physics—also known as high-energy physics—is complex. But the basics of particle-accelerator experimentation are not difficult to understand.[57]

Particle-collider experimentation revolves around Einstein's famous insight that matter and energy are two versions of the same thing, expressed in the equation $E = mc^2$ (energy is equivalent to mass multiplied by the square of the speed of light).[58] If you think through the implications of this equation, you can grasp the fundamentals of how experiments are done in particle physics.

First, you need to take note of the fact that the speed of light is a very large quantity: 670 million miles per hour, or 3×10^8 meters per second.[59] Squaring it makes it all the larger. To equate mass to energy, you must multiply this immense number by the amount of mass.[60] So, $E = mc^2$ means that an extremely small amount of matter corresponds to an extremely large quantity of energy.[61]

The most famous application of the $E = mc^2$ principle is nuclear reactors and nuclear bombs. Those devices convert matter into energy—destroying tiny amounts of matter to release prodigious amounts of energy.[62]

Particle colliders work the same principle in reverse.[63] $E = mc^2$ rearranged algebraically is $E/c^2 = m$. That means it takes an enormous amount of energy to create a very tiny amount of matter.[64] This is not an analogy. Particle colliders *literally* turn energy into matter in the

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55.   James Gillies, *First Three-Year LHC Running Period Reaches a Conclusion*, CERN (Feb. 14, 2013), https://home.cern/news/news/accelerators/first-three-year-lhc-running-period-reaches-conclusion [https://perma.cc/M5CB-9V68].

56.   *See LHC Experiments Back in Business at Record Energy,* CERN (Jun. 5, 2015), https://home.cern/news/news/accelerators/lhc-experiments-back-business-record-energy-0 [https://perma.cc/KKA6-RH3L]; *see also* Caroline Duc, *Long Shutdown 1: Exciting Times Ahead*, CERN (Feb. 8, 2013), http://home.web.cern.ch/about/updates/2013/02/long-shutdown-1-exciting-times-ahead [https://perma.cc/WR9Z-8DZ8]; Jonathon Webb, *LHC Smashes Energy Record with Test Collisions* , BBC (May 21, 2015), http://www.bbc.com/news/science-environment-32809636 [https://perma.cc/27Z4-7TDA].

57.   An excellent readable introduction to the field is KENNETH W. FORD, THE QUANTUM WORLD (2004).

58.   *See* FRANK CLOSE, PARTICLE PHYSICS: A VERY SHORT INTRODUCTION 17 (2004).

59.   FORD, *supra* note 57, at 251.

60.   *See id.* at 19.

61.   *Id.*

62.   *See* RICHARD P. FEYNMAN, SIX NOT-SO-EASY PIECES 70 (1997).

63.   *See* FORD, *supra* note 57, at 21.

64.   *See* DAVID GRIFFITHS, INTRODUCTION TO ELEMENTARY PARTICLES 5 (2d ed. 2008).

proportion dictated by Einstein's equation.[65] The LHC, as a specific example, takes electricity from the Geneva-area power grid and turns that energy into ultra-microscopic amounts of newly formed matter.[66]

Working the uphill-side of Einstein's equation takes money, ingenuity, and a lot of power.[67] The LHC uses enough electricity to power 300,000 homes.[68] To turn this energy into mass, the LHC creates powerful oscillating magnetic fields that propel batches of particles around its 17-mile circumference.[69] The LHC's magnets are designed to add more and more energy into the particles until they are pushed up to 99.9999991% of the speed of light.[70] In this way, electrical energy from the power grid is turned into kinetic energy, the energy of motion.[71] Then, with one set of particles going clockwise and another set going counter-clockwise, the batches of particles are steered so that they collide with one another, converting the accumulated kinetic energy into a splatter of newly formed matter.[72] Thus, the general goal is not—as one might intuitively believe—to break the particles apart and see what is inside them. The goal, instead, is to create new particles, especially bizarre and novel forms of matter that would not otherwise be humanly accessible.[73]

That leaves just one thing left to explain—how it is that particle accelerators manage to create exotic, scientifically interesting forms of matter, as opposed to the boring, everyday-variety of matter that can be found anywhere on Earth. The answer is that, most of the time,

65. *See* FORD, *supra* note 57, at 19-21.

66. *See* Lupick, *supra* note 43; Powering CERN, *supra* note 44; GRIFFITHS, *supra* note 64, at 5.

67. *See, e.g.,* LINCOLN, COLLIDER, *supra* note 34, at 55-56 (discussing how detectors work and listing price and energies for the LHC detectors).

68. Powering CERN *supra* note 44. The other reason the LHC uses so much power is to provide the refrigeration needed for 17 miles worth of superconducting magnets cooled to a couple of degrees above absolute zero. *Id.*

69. *See* LINCOLN, COLLIDER, *supra* note 34, at 28-32 (describing how electric and magnetic fields are used to accelerate and guide particles in a synchrotron accelerator).

70. *See* CERN 2017 faq, *supra* note 25, at 4, 12.

71. *See* GRIFFITHS, *supra* note 64, at 96-102 (discussing energy, momentum, and particle collisions); Powering CERN, *supra* note 44 (describing use of power from grid); *see also* FEYNMAN, SIX EASY PIECES 80-85 (1995) (discussing kinetic energy and the conservation of energy).

72. *See* FORD, *supra* note 57, at 21 ("A major purpose of modern accelerators is to change kinetic energy into mass . . . ."); GRIFFITHS, *supra* note 64, at 4-6.

73. *See* FORD, *supra* note 57, at 21 ("When a proton, with a kinetic energy that is perhaps a thousand times its rest energy, slams into another proton, a great deal of that kinetic energy is available to make new mass. Dozens or hundreds of particles may fly away from the point of collision."); Particle Physics Project Prioritization Panel, *supra* note 47, at 21 ("Making particles collide at the highest possible energies is an essential pathway to discoveries in particle physics. These collisions convert energy into new particles, including particles that were prominent in the early universe but are no longer present on Earth. . . . Higher energies enable the production of heavier particles . . . .").

particle collisions don't produce anything interesting.[74] Interesting particles tend to be rare birds.[75] Because of this, big particle colliders like the LHC are designed to collide a great quantity of particles each second and to run for many years. Every once in a while, a collision yields something unusual—something unstable and short-lived, such as the particles that existed around the time of the Big Bang. It is a feature of quantum mechanics: If the laws of physics do not prohibit a thing from being created, then, given enough repeated tries, that thing will be created.[76] Every collision is a pull of the quantum-mechanics slot machine. If you are patient enough—and if you have enough quarters—you will see every combination of the reels.

The only effective limit to what particle collisions can produce is the amount of energy involved in the collisions.[77] Suppose a much-sought particle has a mass greater than 1 TeV. That means an accelerator capable of a maximum energy of 1 TeV will never make one, no matter how many billions of collisions are undertaken. This is why physicists get so excited when a new accelerator is constructed that is capable of record-breaking energies.[78] It means never-before-seen particles can be produced.

In this way, uncertainty is at the essence of particle-physics experiments. Colliders like the LHC are not just about trying to confirm hypotheses. The desire to build them is fueled, in substantial part, by the prospect of finding something entirely new, something that doesn't correspond to any current theory.[79]

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74. *See* Chad Orzel, *Eight Things to Know as the Large Hadron Collider Breaks Energy Records*, FORBES (May 21, 2015, 3:32 PM), https://www.forbes.com/sites/chadorzel/2015/05/21/things-to-know-as-the-large-hadron-collider-breaks-energy-records/#20a5f98873ce [https://perma.cc/2BAE-VQ5R] ("Most of the time, the collisions at the LHC produce ordinary, boring particles. A tiny fraction of the collisions, though, will produce more exotic things, and those collisions are the ones physicists are most interested in.").

75. *See* CLOSE, *supra* note 58 (discussing the need to separate out interesting collision products from the mundane).

76. *See* BRIAN COX & JEFF FORSHAW, THE QUANTUM UNIVERSE: EVERYTHING THAT CAN HAPPEN DOES HAPPEN 45-74 (2011).

77. *See* GRIFFITHS, *supra* note 64, at 4-6.

78. *See* CARROLL, *supra* note 19, at 61 ("Reaching unprecedented energies is literally like visiting a place nobody has ever seen.").

79. *See id.* at 48.

Dan Tovey, a University of Sheffield physicist on the team for the LHC's Atlas experiment, explained the excitement around the LHC this way:

> Individually, we all have the things that we're particularly interested in; there's a variety of new physics models that could show up. But to be honest, we can't say for certain what—if anything—will show up. And the best thing that could possibly happen is that we find something that nobody has predicted at all. Something completely new and unexpected, which would set off a fresh programme of research for years to come.[80]

In other words, the LHC is a machine designed specifically to encounter unknown unknowns. "What we really want is to be wrong," particle physicist Sean Carroll has written. "It's a great triumph to discover the Higgs, but things get really exciting when we are surprised by something new."[81]

C. Black Holes and Safety

Now we come to the question of whether the LHC could spawn a planet-destroying black hole.[82] Explaining the thinking about an artificial black-hole disaster is best done in a chronological manner. This is because the safety argument has not been static; instead, it has changed over time. As one set of safety rationales has been undermined by evolving understandings in theoretical physics, experimenters have abandoned old arguments and adopted new ones.

Questions circulating in the media about whether particle colliders might produce black holes date back at least to 1999, around the time of the start-up of an earlier experiment—the Relativistic Heavy Ion Collider (RHIC, pronounced "rick"), located on Long Island about 60 miles east of New York City.[83]

The dust-up about the RHIC led physicists in 1999 to issue an assurance that, for the foreseeable future, no particle collider would be

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80. Webb, *supra* note 56 (quoting Tovey) (internal paragraph break omitted).

81. CARROLL, *supra* note 19, at 54.

82. Beyond dangerous black holes, there are other catastrophic risk scenarios that have been discussed. *See generally* Johnson, *Black Hole Case*, *supra* note 5, at 829-34. Of particular note is the question of whether the LHC could produce a dangerous strangelet. *See id.* at 829-31. For an update on the LHC/strangelet question, see LHC Safety Assessment Group, *Implications of LHC Heavy Ion Data for Multi-Strange Baryon Production*, CERN 1 (2011), https://public-archive.web.cern.ch/downloads/LSAG/LHCaddALICE2011.pdf [https://perma.cc/TLP2-WXPE].

83. The controversy over the RHIC principally involves not black holes, but a disaster scenario involving the creation of a "strangelet," which theoretically could physically collapse the planet into a small hyperdense ball by converting all normal matter on Earth into strange matter. I discuss the RHIC more in my prior work. *See* Johnson, *Black Hole Case*, *supra* note 5, at 829-31.

capable of generating the energies necessary to form a black hole.[84] Media interest in the question then subsided.

But it turned out that the physicists' safety pronouncements in 1999 were substantially mistaken. In what is a superb example of the emergence of an unknown unknown, two separate teams of theorists in 2001 demonstrated that, under certain assumptions, it actually was possible to produce black holes with a present-day accelerator—the LHC, which was then under construction.[85]

CERN subsequently acknowledged a need for further safety assessment work.[86] The ensuing report, issued by a CERN group in 2003, concluded that accelerator-produced black holes would pose no threat since they would rapidly evaporate via a process called "Hawking radiation,"[87] the namesake of theoretical physicist Stephen Hawking.

In the work that made him famous, Hawking provided a mathematical argument from quantum mechanics and the theory of relativity that black holes must emit radiation in some form.[88] And since mass and energy are two different manifestations of the same thing—$E = mc^2$ again—then if a black hole emits radiation, it must lose mass.[89] According to Hawking's theory, the smaller a black hole is, the faster it must radiate. And since any accelerator-produced black hole would be extremely tiny, it would, according to Hawking's theory, radiate into nothingness almost instantly.[90] Hawking radiation has never been observed, but the theory is nonetheless "often considered one of the most secure" in its subfield of physics.[91]

While some felt that the possibility of stable, non-radiating black holes should be taken seriously,[92] the particle physics community, as a whole, did not. But along came another unknown unknown. A very well-regarded scientist, William Unruh, called the black-hole-

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84. *See* W. BUSZA ET. AL., REVIEW OF SPECULATIVE "DISASTER SCENARIOS" AT RHIC 2 & 7 (1999), http://www.bnl.gov/rhic/docs/rhicreport.pdf [https://perma.cc/KM2Y-VA8E].

85. Steven B. Giddings & Scott Thomas, *High Energy Colliders as Black Hole Factories: The End of Short Distance Physics,* 65 PHYSICAL REV. D 056010-1, 056010-1 (2002); Savas Dimopoulos & Greg Landsberg, *Black Holes at the Large Hadron Collider,* 87 PHYSICAL REV. LETTERS 161602-1, 161602-1 (2001).

86. *See* J.-P. BLAIZOT ET AL. ("LHC Safety Study Group" or "LSSG"), STUDY OF POTEN-TIALLY DANGEROUS EVENTS DURING HEAVY-ION COLLISIONS AT THE LHC: REPORT OF THE LHC SAFETY STUDY GROUP 1 (2003), https://cds.cern.ch/record/613175/files/CERN-2003-001.pdf [https://perma.cc/K62R-T4DH].

87. Johnson, *Black Hole Case, supra* note 5, at 840-41.

88. *See* Stephen W. Hawking, *Particle Creation by Black Holes,* 43 COMMS. IN MATHEMATICAL PHYSICS 199 (1975); Stephen W. Hawking, *Black Hole Explosions?,* 248 NATURE 30, 30 (1974) [hereinafter Hawking, *Black Hole*].

89. *See* Hawking, *Black Hole, supra* note 88, at 30.

90. *See* BLAIZOT ET AL., *supra* note 86, at 12.

91. *See* Adam D. Helfer, *Do Black Holes Radiate?,* 66 REPS. ON PROGRESS IN PHYSICS 943, 943 (2003).

92. *See id.*

radiation theory into question.[93] Since Unruh was himself one of the pioneers of the theory of radiating black holes, his opinion was potentially influential.

CERN subsequently stopped relying on Hawking radiation as a safety rationale, and a new round of theoretical work was done on the issue.[94] The result was a highly complex paper, released in 2008, which rested its assurance of safety on a multi-faceted approach.[95] Authored by particle physicists Steven B. Giddings and Michelangelo L. Mangano, the paper used theoretical astrophysics to conclude that, under some scenarios, synthetic black holes would be able to harmlessly coexist with Earth, since they would grow too slowly to be dangerous. Under other scenarios, the paper concluded, telescope observations of certain white dwarf stars could be counted upon to rule out the dangers on an empirical basis.[96] On the basis of this work, CERN issued reports concluding that the safety question had been put to rest.[97]

After the public release of Giddings and Mangano's paper, Rainer Plaga, an astrophysicist, emerged with a critique. Plaga argued that the black-hole scenario could not be ruled out.[98] In the days leading up to the anticipated start-up of LHC collisions, Giddings and Mangano responded to some, but not all, of Plaga's arguments.[99]

That is where the back-and-forth with CERN over safety, black holes, and the LHC ends. Once the LHC started up—albeit at reduced power—the media interest in the black-hole question went away, and CERN appears to have done no additional work on the issue.[100]

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93. *See* William G. Unruh & Ralf Schützhold, *Universality of the Hawking Effect*, 71 PHYSICAL REV. D 024028-1, 024028-1, 024028-11 (2005); Johnson, *Black Hole Case, supra* note 5, at 842.

94. *See* Johnson, *Black Hole Case, supra* note 5, at 850.

95. *See* Steven B. Giddings & Michelangelo L. Mangano, *Astrophysical Implications of Hypothetical Stable TeV-Scale Black Holes,* 78 PHYSICAL REV. D 035009-1 (2008).

96. *Id.* at 1-2; Johnson, *Black Hole Case, supra* note 5, at 845-49.

97. JOHN ELLIS ET AL. ("LHC SAFETY ASSESSMENT GROUP"), REVIEW OF THE SAFETY OF LHC COLLISIONS 1-3 (2008), http://arxiv.org/abs/0806.3414v2 [https://perma.cc/BC9K-EY3Q]; CERN SCIENTIFIC POLICY COMMITTEE, SPC REPORT ON LSAG DOCUMENTS 1, 4 (2008), https://indico.cern.ch/event/35065/contributions/1757729/at-tachments/693082/951703/SPC_on_LSAG_report.pdf [https://perma.cc/JYW3-XBTK].

98. *See* R. Plaga, *On the Potential Catastrophic Risk from Metastable Quantum-Black Holes Produced at Particle Colliders,* ARXIV (Sept. 26, 2008), https://arxiv.org/pdf/0808.1415v2.pdf [https://perma.cc/QHR7-PQPS].

99. *See* Steven B. Giddings and Michelangelo L. Mangano, *Comments on Claimed Risk from Metastable Black Holes,* ARXIV (Aug. 29, 2008), https://arxiv.org/pdf/0808.4087v1.pdf [https://perma.cc/V74Z-LPDW] (Giddings & Mangano response to Plaga's paper); Plaga, *supra* note 98, at 11 (noting lack of response to some argumentation); Johnson, *Black Hole Case, supra* note 5, at 854-56 (discussing the Giddings & Mangano response to Plaga's paper).

100. For a discussion of some later-released scientific papers relevant to the black-holes issue, see Adams, *supra* note 5, at 143-44.

The chronology of the safety debate, viewed as a whole, exhibits a pattern of confident conclusions, new revelations, and refortification with different theoretical tacks. That is, risk questions are initially answered as if all issues are fully known. Then unknown unknowns emerge. But these are swept aside with a fresh reappraisal of alleged risk as being fully understood and entirely benign.

This pattern could be seen as evidence of a results-oriented research approach, one lacking academic detachedness. Indeed, in 2010, John Ellis, a top theoretical physicist for CERN who worked on one of the lab's safety reports, seemed to confirm this view. Ellis told Physics World magazine that there had been no scientific motivation for the safety reviews, calling them a "foregone conclusion."[101]

When everything is taken into consideration, the question of whether the LHC presents a significant risk of ultimate catastrophe seems not to have been adequately put to rest. That being said, to the extent there are continuing questions about risks, that does not mean the LHC itself is dangerous. Just as danger might lurk in the unknown, so might safety, and perhaps even some unanticipated bounty for humankind. Clearly, however, the question of black-hole risk is more complex—and more uncertain—than it might at first seem.

II. CONCEPTUAL AND PRACTICAL PROBLEMS

In this Part, I will look at three particular problems for traditional risk assessment in the context of leading-edge scientific experimentation. Those three problems are: (1) It is difficult to rely on experts for conducting traditional risk analysis, since those experts tend to have personal connections to the experimental work being analyzed; (2) a classical quantitative risk assessment may require the application of uncertain science that the experiment itself is designed to illuminate; and (3) if the probability of disaster is calculated to be very low, then that probability number is rendered virtually meaningless, since the probability of error in the derivation dwarfs the derived probability of catastrophe. I will explain each in turn.

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101.   Edwin Cartlidge, *Law and the End of the World,* PHYSICS WORLD, Feb. 2, 2010, at 12-13, https://physicsworld.com/a/law-and-the-end-of-the-world/ [https://perma.cc/2HT8-VLKU] (quoting Ellis: "'Every time someone comes up with a new theoretical speculation about accelerator safety, it is interesting to see why that speculation does not constitute risk, but it always comes back to the cosmic-ray argument,' he says. So does that mean these safety reviews are nothing more than a curiosity? 'Correct. There is no scientific motivation for these reviews. They are a foregone conclusion, even though the community has the right to expect CERN to demonstrate the validity of the safety arguments.'").

A. The Lack of Disinterested Experts

Traditional risk analysis is "distinctly expert-centered."[102] But when it comes to science-experiment risk, there may be a scarcity of disinterested experts. With leading-edge science experiments, the leading experts tend to be the exact same people who are involved in the experiment—either directly or indirectly.

The LHC/black-holes question illustrates this. Around half the particle physicists in the world are involved with CERN research.[103] Meanwhile, the other half form an extended network of friends and acquaintances. Sharon Traweek, an anthropologist who did a particle-physics ethnography, describes particle physicists as forming a restrictive, cohesive community.[104] Relationships among particle physicists are highly important, according to Traweek,[105] and those particle physicists who do not know each other well want to.[106] Thus, if one wanted to find particle physicists not part of the broader circle of friends of an allegedly dangerous experiment, doing so might prove impossible.

In the case of the LHC, however, the primary risk assessment work was not done by people with mere indirect relations. Instead, the work was done by persons employed by or having direct ties to CERN. In 2007, CERN management set up the LHC Safety Assessment Group (LSAG),[107] and each of the five members was a physicist from CERN's Theory Division.[108] One of the members, Mangano, co-authored the

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102. *See* Wilson, *supra* note 9, at 123.

103. *See* Press Release, CERN, CERN launches 50th anniversary celebrations (Mar. 1, 2004) https://home.cern/news/press-release/cern/cern-launches-50th-anniversary-celebrations [https://perma.cc/LM4A-C6EG] (CERN's "unique facilities play host to around half the world's particle physicists."); *see also* Elizabeth Kolbert, *Crash Course*, NEW YORKER (May 14, 2007), https://www.newyorker.com/magazine/2007/05/14/crash-course [https://perma.cc/NW8L-V8EG] ("Once the collider begins operating at full power . . . nearly half the particle physicists in the world will be involved in analyzing its four-million-mega-byte-per-hour stream of data.").

104. SHARON TRAWEEK, BEAMTIMES AND LIFETIMES: THE WORLD OF HIGH ENERGY PHYSICISTS 4, 78, 93 (1992).

105. *Id.* at xi, 106-07.

106. *Id.* at 3.

107. Jonathan R. Ellis, *The LHC Is Safe*, CERN (Aug. 14, 2008), http://cdsweb.cern.ch/record/1120625 [https://perma.cc/S47Y-3H2G] [hereinafter Ellis Video] (beginning at 6 minutes).

108. *See* John Ellis, Gian Giudice, Michelangelo Mangano, Igor Tkachev, and Urs Wiedemann, *Review of the Safety LHC Collisions*, CERN (2008), https://arxiv.org/vc/arxiv/pa-pers/0806/0806.3414v1.pdf [https://perma.cc/V2WL-4C7J] [hereinafter LSAG] (original version of the report that reviews and confirms the conclusions of 2003 LHC Safety Study Group). Note that "v2" of the report, dated September 18, 2008, removed reference to Igor Tkachev's CERN affiliation. *See* John Ellis, Gian Giudice, Michelangelo Mangano, Igor Tkachev, and Urs Wiedemann, *LSAG Review of the Safety of LHC Collisions*, CERN 1 (2008), https://arxiv.org/pdf/0806.3414v2.pdf [https://perma.cc/DLG7-FNPC] [hereinafter LSAG Version 2]. *But cf.* Gary Felder and Igor Tkachev, *LATTICEEASY: A Program for Lattice Simulations of Scalar Fields in an Expanding Universe,* 178 COMPUTER PHYSICS COMMS. 929, 929 (2008) (listing Tkachev's institution as CERN Theory Division).

paper that served as the foundation for LSAG's final report.[109] The other author of that key paper, Giddings, was not employed by CERN while he was working on the paper, but he was at that time anticipating a visiting position with CERN that had been previously approved.[110]

It should be pointed out that even though the formal risk assessment was done by CERN affiliated individuals, the assessment was nonetheless subject to peer-review by the particle physics community beyond CERN. The Giddings and Mangano paper, for instance, was subject to formal peer review by being published in *Physical Review D*. And pre-prints were subject to peer review in the substantive sense of being made publicly available in a forum where they could be read and commented upon.[111]

The experimental particle physics community seems to have publicly voiced little or no objection to LSAG's conclusions. It might be argued that this lack of objection is evidence that the safety assessment, despite its conflict-of-interest issues, is nonetheless trustworthy. But, as discussed above,[112] particle physicists form a close, interdependent community, with half of them tied to CERN. In a tight-knit group such as this, on a question that affects the group as a whole, all the experts have a stake in the matter. None are disinterested. This observation is, of course, not an indictment of particle physicists. Nor is it, indirectly, an indictment of any other scientific community. The point, instead, is that trustworthy traditional risk assessments in such contexts are not easily had.

B.   The Need for Uncertain Scientific Principles Under Investigation

A second problem that may occur in trying to resolve questions regarding the safety of novel science experiments is that a thorough traditional risk assessment might require knowledge that the experiment itself is designed to supply.

Again, the LHC/black-holes question provides examples. The theorized phenomenon of Hawking radiation—used at one point as a safety rationale for particle collisions[113]—has not been experimentally

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109.   *See* Giddings & Mangano, *supra* note 95, at 1.

110.   Johnson, *Black Hole Case*, *supra* note 5, at 846.

111.   That forum is the arXiv (pronounced "archive"), a depository of papers in physics, mathematics, and other subjects. *See generally* Dov Greenbaum, *Is It Really Possible to Do the Kessel Run in Less Than Twelve Parsecs and Should It Matter? Science and Film and Its Policy Implications,* 11 VAND. J. ENT. & TECH. L. 249, 310 n.340 (2009) (describing the arXiv); Jeremy M. Grushcow, *Measuring Secrecy: A Cost of the Patent System Revealed,* 33 J. LEG. STUD. 59, 81 (2004) (same).

112.   *See supra* Section II.A.; TRAWEEK, *supra* note 104 and accompanying text.

113.   *See supra* Section I.C.

validated.[114] The LHC experiment itself, however, could provide evidence of Hawking radiation.[115] And if Hawking radiation were shown empirically, CERN's safety argument would be easily made. Thus, leading-edge science experiments can be vulnerable to a kind of catch-22: Advances in fundamental knowledge could demonstrate the safety of a given experimental activity. But that same experimental activity is the readiest means to make the needed advances in fundamental knowledge.

Another unanswered question from physics, which the LHC could help answer, is whether there are hidden, extra dimensions to our universe.[116] The LHC can create black holes, the theory goes, only if there are one or more extra dimensions.[117]

A bit of background on extra dimensions: As we experience reality, there are four dimensions, three dimensions of space and one dimension of time. According to some theories of fundamental physics, however, there could be extra dimensions of space, dimensions that are a part of reality, but that are generally inaccessible to us.[118] Like cartoon characters trapped on a 2-D page, we might be trapped in a 3-D slice of a broader universe to which we are oblivious. Hidden extra dimensions are particularly important to string theory, which some physicists advocate as a way to explain all fundamental particles and forces within a single theoretical framework.[119] According to string theory, there might be 11 dimensions altogether.[120]

The number of extra dimensions is important to the black-hole safety analysis—because how fast a stable black hole could grow inside the Earth is understood to depend on the number of hidden dimensions. The Giddings and Mangano paper estimated, for instance, that if there are eight or more spacetime dimensions, it would take many billions of years for any black hole to grow large enough to be threatening to the Earth.[121] But if we live in a 5-D reality—that is, with

114. *See, e.g.,* RANDALL, *supra* note 15, at 172. Notably, a laboratory analog to a black hole, in which sound is a stand-in for light, has produced results analogous to Hawking radiation. *See* Davide Castelvecchi, *Artificial Black Hole Creates Its Own Version of Hawking Radiation,* 536 NATURE 258, 258 (2016) (describing experiment and results). The results, however, are not considered a confirmation of true Hawking radiation. *See id.* at 259 ("[P]hysicists are impressed, but they caution that the results are not clear-cut. And some doubt whether laboratory analogues can reveal much about real black holes." Quoting physicist Silke Weinfurtner, "This experiment, if all statements hold, is really amazing," but "[i]t doesn't prove that Hawking radiation exists around astrophysical black holes.").

115. *See* Giddings & Thomas, *supra* note 85, at 1-2.

116. *See generally Extra Dimensions,* CERN retrieved from http://press.cern/backgrounders/extra-dimensions [https://perma.cc/GL8Y-YHKW] [hereinafter CERN Extra Dimensions].

117. *See supra* note 85.

118. *See, e.g.,* CERN Extra Dimensions, *supra* note 116.

119. *See, e.g.,* DAVID MCMAHON, STRING THEORY DEMYSTIFIED xi (2009).

120. *See* CERN Extra Dimensions, *supra* note 116.

121. *See* Giddings & Mangano, *supra* note 95, at 14.

just one extra dimension—then under Giddings and Mangano's analysis it might only take 300,000 years for a black hole to mature and devour the Earth.[122] Once again, the ultimate level of risk of black holes appears to rest on unknown science that the LHC may or may not shed light on.

C. The Effect of Uncertainty in Low-Probability Risk Assessments

The third problem with traditional risk assessment for leading-edge science experiments is something we can call the uncertainty-swamping problem, which is that low-probability risk assessments tend to be meaningless. This is a woeful effect of the uncertainty that stubbornly clings to assessments of long odds: Where the probability of disaster is determined to be very low, then the probability number lacks robustness, since the chance of disaster described by the probability will be much lower than the chance that the probability assessment itself is wrong.[123]

Philosophers Toby Ord, Rafaela Hillerbrand, and Anders Sandberg put it this way: "When an expert provides a calculation of the probability of an outcome, they are really providing the probability of the outcome occurring, given that their argument is watertight."[124] This becomes a problem for a very low stated probability of disaster, since the likelihood that the stated probability is wrong will be much greater than the stated probability of disaster.

The problem is easy to see with an example: Suppose a person is given the task of determining the risk that a dam will break. After data is gathered about water pressures, the strength of the concrete and steel, and so forth, a series of calculations is done, and the result indicates that the probability of a catastrophic dam break is no greater than one in a billion. That seems reassuring. But what is the chance that the person doing these calculations has used faulty data or has made a mistake with the math? The chance of that happening is much, much greater than one in a billion. Thus, the true ceiling on the riskiness of the proposition is almost entirely described by the chance that the person doing the assessment has erred in the assessment work itself. As particle physicist Lisa Randall said in discussing risk

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122. *Id.* at 13.

123. This problem was pointed out by a team of researchers from Oxford's Future of Humanity Institute. *See* Toby Ord, Rafaela Hillerbrand, & Anders Sandberg, *Probing the Improbable: Methodological Challenges for Risks with Low Probabilities and High Stakes*, 13 J. RISK RES. 191, 191 (2010); *see also* Johnson, *Black Hole Case*, *supra* note 5, at 890-92. The label "uncertainty-swamping problem" is a label I have picked for convenience in referring to the concept.

124. *See* Ord, Hillerbrand, & Sandberg, *supra* note 123.

generally, "A prediction of low risk is meaningless if the uncertainties associated with the underlying assumptions are much greater."[125]

The black-hole/LHC safety question is a prime example of the uncertainty-swamping problem. Physicists have not published any quantification of the odds of a black-hole disaster at the LHC. But in spoken remarks at Oxford's Future of Humanity Institute, CERN physicist Mangano spoke of probabilities below 10^{-40}.[126] It is helpful to translate this number out of scientific notation: less than 10^{-40} means less than one in 10 thousand trillion trillion trillion. Or, if you are partial to obscure number names, less than one in 10 duodecillion. That is a small number indeed. And even when the alleged harm is the annihilation of Earth, it seems—at least to me—perfectly fine to ignore such an infinitesimal chance. But the chance that this probability assessment is wrong is much, much greater than 10^{-40}. The assessment could be faulty for any of a number of reasons, including mathematical miscalculations, faulty data, and uncertain or unwarranted assumptions.

Unfortunately, we cannot directly measure the uncertainty of the LHC safety assessment work. Doing so would require us to have unavailable knowledge. But to get at least a gross idea of the likelihood that error could have crept into LHC risk-assessment work, we might borrow error rates that have been empirically determined for other forms of scientific work. In the life sciences, one study found that as many as one in 100 articles may contain errors warranting retraction.[127] Other research found that as many as one in 10 articles in elite journals have flawed statistical results.[128] Using these statistics as a stand-in implies that a truer view of the maximum probability of disaster at the LHC must take into account something like a one-in-10 or one-in-100 chance that the safety assessment is wrong.[129]

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125. RANDALL, *supra* note 15, at 181.

126. *See* Michelangelo L. Mangano, Physics Department Theory Group, CERN, Address at University of Oxford Future of Humanity Institute: Expected and Unexpected in the Exploration of the Fundamental Laws of Nature, VIMEO (2008), http://vimeo.com/4704040 [https://perma.cc/7Y9B-6HHZ] (beginning at 47 minutes) (explaining that the probability that a particular white dwarf of certain characteristics would have persisted despite the laws of physics being such that they would allow dangerous black-hole formation to take place at the LHC to be less than 10^{-40}, and further noting that this would be the probability for the survival of one such star, and there are multiple such stars).

127. *See* Ord, Hillerbrand, & Sandberg, *supra* note 123, at 193-94.

128. *See id.* at 196. The journals studied were *Nature* and the *British Medical Journal*. See also Johnson, *Black Hole Case*, *supra* note 5, at 892 and surrounding text discussing this research.

129. This number is a plausible stand-in for purposes of illustrating the concept, but there are good reasons to think that LHC risk assessment work might be considerably more error prone than life-sciences work. The physics involved is arguably more complex. And particle-physics risk assessment would also seem to require more in the way of atypically used assumptions.

Of course, the safety assessment could be wrong without the LHC itself being dangerous. Nonetheless, the total ceiling on risk of operating the LHC must mostly be described by the chance that the safety assessment is wrong. And that probability, even if small, is significant.

The uncertainty-swamping problem creates quite a conundrum. It cannot follow from this line of reasoning that we must judge the LHC to be unacceptably risky simply because we can't be sure that that the probability of disaster is less than one in 10. By that line of reasoning, we would have to abandon all leading-edge science experiments—and maybe never leave the house again. Clearly, such a sweeping concept of unacceptable risk is not tenable.

What are needed are principled and sensible ways to deal with these problems, such that we neither need to prohibit all leading-edge science experiments nor give them all a free pass. Providing these principled and sensible ways of dealing with uncertain risk is the ultimate aim of this Article, and I delineate those methods in Part IV, below. But before diving into those methods, it is useful first to explore how uncertainty plays into the rhetoric of risk.

III. RHETORICAL ISSUES

In addition to the above-described problems, there is an additional wrinkle for risk assessment in the science-experiment context: Knowledge asymmetries and opportunities for selective assertions of uncertainty can be used to reframe questions of risk. This reframing can permit experiment proponents to gain a substantial rhetorical advantage, steering public discourse in a way that is a boon to experiment proponents and detrimental to the safety debate.

At the heart of this issue is something quite counterintuitive: Considering that traditional risk analysis involves cost-benefit scrutiny and relies on calculations and statistics,[130] one might think that this mathematically based way of evaluating risk would be embraced by scientists. Yet this is not necessarily the case. In a twist, when it came to the black-hole issue, particle physicists moved away from expressing risk in quantitative terms. Instead, they moved to speaking of risk in qualitative terms.

A. Using Pricelessness to Avoid Quantitative Analysis of Benefits

Traditional risk assessment is not just about producing quantified probabilities of harm. It also needs a quantification of benefits to use as a point of comparison. This is the sine qua non of cost-benefit analysis: Put the costs on one side of the scale, benefits on the other,

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130. Wilson, *supra* note 9, at 123.

and see which way the balance tilts. Thus, within the traditional-risk-analysis mode, one way proponents of science experiments can avoid a negative assessment is to frustrate the quantification of the benefits of the experiment. Doing so makes an experimental program incomprehensible to a cost-benefit formula.

Particle physicists learned to resist providing a quantified assessment of the benefits of their experimental programs well before the LHC/black-holes controversy. Such a tack grows out of necessity in lobbying for the funding to build multi-billion-dollar particle colliders. In general, proponents of particle experiments will concede that, viewed as an investment, particle physics generates "no return."[131] At first glance, this appears to be an admission against self-interest. But, as judge and legal scholar Richard A. Posner pointed out, this seeming weakness is actually a source of strength: "[I]t stumps people who want to argue that the costs exceed the benefits."[132]

In truth, particle physics can yield practical benefits. The World Wide Web was a spinoff invention from the planning phase of the LHC.[133] And medical proton therapy is a spinoff of particle accelerator technology.[134] But practical dividends of this significance are rare. Worse, they appear idiosyncratic, making it difficult to put on a convincing case that particle experimentation reliably yields quantifiable benefits.

So, if proponents of particle physics experiments do not attempt to quantify benefits, how do they argue in favor of their expensive experiments? The answer is that they provide qualitative statements. Often these statements are emotionally charged. For instance, physicist Stephen Hawking characterized the LHC as "vital if the human race is not to stultify and eventually die out."[135]

A recurrent theme in the non-quantified argument for particle colliders is to make a special claim of importance for particle physics over other scientific fields. An example is what Nobel laureate Steven Weinberg had to say in his book *Dreams of a Final Theory*: "The reason we give the impression that we think that elementary particle physics is more fundamental than other branches of physics is because it is,"

131. *See, e.g.*, Mangano, *supra* note 126 (beginning at 41 minutes).

132. RICHARD A. POSNER, CATASTROPHE: RISK AND RESPONSE 147-48 (2004). Posner discussed the RHIC/strange-matter scenario.

133. *See Facts About W3C*, W3C, http://www.w3.org/Consortium/facts#history [https://perma.cc/4HDE-MR3G] (last visited March 30, 2021); Tim Berners-Lee, *Information Management: A Proposal,* W3C, http://www.w3.org/History/1989/proposal.html [https://perma.cc/FF3X-2H7Z] (last visited March 30, 2021).

134. Jeremy N. A. Matthews, *Accelerators Shrink to Meet Growing Demand for Proton Therapy,* 62 PHYSICS TODAY 22 (Mar. 1, 2009), https://physicstoday.scita-tion.org/doi/abs/10.1063/1.3099570 [https://perma.cc/PTJ3-KFFG].

135. Jon Swaine, *Stephen Hawking: Large Hadron Collider Vital for Humanity,* TELEGRAPH (Sep. 8, 2008), http://www.telegraph.co.uk/news/2710348/Stephen-Hawking-Large-Hadron-Collider-vital-for-humanity.html [https://perma.cc/DB9P-86AM].

he wrote.[136] "I do not know how to defend the amounts being spent on particle physics without being frank about this."[137] Thus, particle physics experimentation is a project for which no practical benefit is anticipated or sought.[138] The upside is philosophic. And, when framed in language such as "unmask[ing] the cosmos" and "our species . . . finally reaching childhood's end,"[139] it is sublime.

This allows experiment proponents to beat cost-benefit scrutiny. Once the benefit has been taken out of the realm of numbers, classical cost-benefit analysis is a moot issue. And at that point, quantitative risk assessments can be brushed off as irrelevant.

B. *Moving Away from the "Probability Mode"*

Scientists advocating large-scale leading-edge science experiments can also repel criticism by dequantifying the discussion of risk on the other end of the cost-benefit formula—by refusing to use numerical values to discuss the chance of disaster.

Following the safety controversy over the RHIC project in the late 1990s,[140] the particle-physics lobby apparently learned to keep quantified probabilities out of the LHC safety debate.[141] By doing so, physicists could avoid uncomfortable questions of what constitutes an acceptable level of risk of planetary destruction. Instead, the disaster question was cast as binary—either the experiment entailed a risk, or it did not.

A window into how physicists plan the public-relations side of risk assessment comes from the video of a presentation given by CERN theorist John Ellis to his colleagues at the laboratory.[142] In the discussion following the presentation, an audience member said to

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136. STEVEN WEINBERG, DREAMS OF A FINAL THEORY 55 (1992).

137. *Id.*

138. *See* TRAWEEK, *supra* note 104, at 2-3 ("The physicists' calling is awesome: memoirs and biographies often present this corps d'elite as unique, Promethean heroes of the search for truth . . . . The extraordinary scale and costliness of much physics research if anything reinforces its cultural value. The great accelerators, for example, are like medieval cathedrals: free from the constraints of cost-benefit analysis.").

139. *See* BRIAN GREENE, THE FABRIC OF THE COSMOS 22 (2004) ("[A]s we've continued to unmask the cosmos, we've gained the intimacy that comes only from closing in on the clarity of truth. The explorations have far to go, but to many it feels as though our species is finally reaching childhood's end.").

140. Regarding the RHIC safety debate, see W. BUSZA ET. AL, *supra* note 84 and accompanying text; *infra* notes 241-242 and accompanying text.

141. *See* Ellis Video, *supra* note 107 (beginning at 64 minutes). But note A.V. Sokolov & M.S. Pshirkov, *Future 100 TeV Colliders' Safety in the Context of Stable Micro Black Holes Production*, 14 ARXIV (Nov. 15, 2016), https://arxiv.org/pdf/1611.04949v1.pdf [https://perma.cc/MQ78-2MLG], in which physicists, apparently unaffiliated with CERN, provide analysis regarding a proposed future 100 TeV collider at CERN, concluding "the probability that at least one black hole will be trapped inside the Earth during the whole time of the exploitation of the collider is less than 16%."

142. *See* Ellis Video, *supra* note 107.

Ellis, "I've noticed that, very wisely, you haven't pronounced the word 'probability.'" [143]

"Absolutely," Ellis said.[144]

The audience member noted that when probability comes into the debate, critics can easily make an argument that the LHC is not worthwhile.[145] That is because, no matter how small the likelihood of destruction, since the harm is so enormous, operating the LHC may be painted as a poor choice.

The audience member explained that:

> [P]robability played an important role in the hands of [experiment critics] because what they did is they took whatever probability you computed, and multiplied it by a bigger number, which is the number of casualties, or else the number of people now, [and] the number of people in the future. If that is not enough ... you multiply it by the number of bacteria.[146]

For experiment proponents, probability rhetoric creates another challenge. When scientists provide a quantitative assessment in the form of a probability bound—that is, a worst-case limit on how likely a disaster could be—this ceiling on risk may be consumed by the public as if it were an estimate of the actual probability of disaster. To take a hypothetical example, a probability bound of one in a billion does not mean that an event is likely to occur once in a billion trials. It means that the risk is not more than one in a billion—even though in reality it might be far less.

Probability bounds are not actual probabilities, and thus it is fallacious to equate the two. But it is not necessarily fallacious to view probability bounds as reasonable stand-ins for probabilities. In thinking through the ultimate question of whether an experiment should be given a green light, it may be a sensible analytical step to weigh a worst-case scenario against an endeavor with only a nebulous, philosophic benefit.

Sensible or not, however, such worst-case-scenario analysis only works against the interests of experimenters. Thus, the disincentive to produce quantified probability bounds remains.

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143. *See id.* (beginning at 64 minutes).
144. *Id.*
145. *See id.* (beginning at 65 minutes).
146. *Id.* (beginning at 64 minutes).

When it came to talking about LHC/black-hole risk, instead of assigning probabilities for LHC/black-hole risk, CERN issued unquantified statements disclaiming all risk. The Giddings and Mangano paper, for instance, provided no quantified odds. Its conclusion was a qualitative one:

> In short, this study finds no basis for concerns that TeV-scale black holes from the LHC could pose a risk to Earth on time scales shorter than the Earth's natural lifetime. Indeed, conservative arguments based on detailed calculations and the best-available scientific knowledge, including solid astronomical data, conclude, from multiple perspectives, that there is no risk of any significance whatsoever from such black holes.[147]

Note that this statement allows that some possibility of danger exists, but whatever quantitative extent that risk might have is veiled behind the value judgment that the risk is of "no . . . significance whatsoever."[148]

One problem with such qualitative statements is that they are susceptible to recharacterization. For instance, the LSAG's report on the black-hole issue, while relying on the Giddings and Mangano paper to provide its rationale, framed its conclusion with a rosier qualitative statement, saying that LHC-generated black holes "present no conceivable danger."[149] Upon receipt of the LSAG report, CERN's permanently constituted Scientific Policy Committee went even further, saying that LSAG's report provided a "proof" that the LHC was safe.[150]

There can also be coordination of rhetoric among particle physicists in an effort to help shape public debate. As reported in a 2007 *New Yorker* magazine article, CERN's chief science officer Jos Engelen explained that when it comes to LHC disaster scenarios, CERN officials are instructed "not to say that the probability is very small but that the probability is *zero*."[151]

Another example along these lines comes from Ellis's account of his interactions with Cambridge University's Martin Rees—Britain's Astronomer Royal and a CERN outsider. When Rees stated that the risk of the LHC causing disaster was no more than one in 50 million,[152] Ellis reached out to him.

"I . . . extracted from him a statement that he'd never done an estimate, and he doesn't believe there's any risk. So he's also gone over to the not-talking-about-probability mode," Ellis said. "But I'm

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147. *See* Giddings & Mangano, *supra* note 95, at 27.
148. *Id.*
149. LSAG Version 2, *supra* note 108, at 1-2.
150. CERN SCIENTIFIC POLICY COMMITTEE, *supra* note 97, at 1.
151. *See* Kolbert, *supra* note 103.
152. Ellis Video, *supra* note 107 (beginning at 65 minutes).

keeping his statement in my mail until such time as this issue raises its head."[153]

Ellis said in 2008 that, since the LSAG report came out, he had seen no discussion of risk in the probability mode.[154]

C.   Constructing the Quantum Straw Man

Another way in which LHC proponents re-framed the debate to their advantage was to make use of a particular kind of uncertainty—quantum uncertainty—as a way to paint the black-hole question as silly.

Nima Arkani-Hamed, a particle physicist at Princeton, proffered the argument in perhaps its most colorful and memorable form to *The New York Times* when he explained that there was a minuscule probability "the Large Hadron Collider might make dragons that might eat us up."[155]

CERN's Engelen offered an expanded version of the argument to the *New Yorker*:

> In quantum mechanics, there is a probability that this pen will fall
> through the table . . . All of a sudden, it will be on the floor. Because it
> can behave as a wave, it can go through; we call that the "tunnel effect."
> If you calculate the probability that this happens, it is not identical to
> zero. It is a very small probability. But it never happens. I've never seen
> it happen. You have never seen it happen. But to the general public you
> make a casual remark, "It is not identical to zero, it is very small,"
> and...[156]

The reporter indicates Engelen then shrugged.[157]

This quantum-chance-of-anything argument was embraced by the press and the blogosphere, constituting a clear public-relations victory.[158] But the argument is fallacious.

Logically speaking, the quantum dragon is a straw man. Note that no critic of the LHC argued that the collider should be shut down because of a generic quantum-mechanics-type chance that the collider

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153. *Id.* (beginning at 66 minutes).

154. *Id.* (beginning at 65 minutes).

155. Dennis Overbye, *Asking a Judge to Save the World, and Maybe a Whole Lot More,* N.Y. TIMES (Mar. 29, 2008), http://www.nytimes.com/2008/03/29/science/29collider.html [https://perma.cc/B64Q-TYK7].

156. Kolbert, *supra* note 103 (quoting Jos Engelen, last ellipsis original).

157. *Id.*

158. *See, e.g.,* Sharon Weinberger, *Collider May End World! (Or Spit out Man Eating Dragons),* WIRED (Apr. 16, 2008, 11:00 AM), http://blog.wired.com/defense/2008/04/collider-may-en.html [https://perma.cc/8JVU-N9Z8]; Dennis Overbye, *Gauging a Collider's Odds of Creating a Black Hole,* N.Y. TIMES (Apr. 15, 2008), http://www.nytimes.com/2008/04/15/science/15risk.html [https://perma.cc/UL9C-V9W5] ("Besides, the random nature of quantum physics means that there is always a minuscule, but nonzero, chance of anything occurring, including that the new collider could spit out man-eating dragons."). Bloggers and blog commenters citing this argument are too numerous to cite.

would produce a planet-eating black hole. Instead, the argument was first, that the LHC, owing to its novel characteristics, might, according to current theory, produce black holes, and second, that there is no good way to rule out that such a black hole would destroy the planet.

What is especially slippery about the quantum-dragons argument is that it is clothed in the language of particle physics. By incanting "quantum mechanics," the argument seems to claim some particular relevance to particle accelerators. But that is not the case.

Since there is a quantum-mechanical chance of anything happening,[159] the quantum-dragons-type of straw man can be applied to any debate. For instance, a person arguing for the safety of tobacco could make the same argument in response to the allegation that cigarettes cause cancer. Such a person could point out that there is, quantum mechanically speaking, a chance that cigarettes will turn into little sticks of dynamite and explode. The argument is just as irrelevant to a debate about tobacco as it is to the LHC.

In the end, the quantum-dragons argument is a potent example of how self-interested experts can use knowledge asymmetries to insulate experimental programs from criticism.

D.   The Relation of Rhetoric to Legal Process

In rounding out this discussion of rhetoric in the context of science-experiment risk uncertainty, it makes sense to discuss why rhetoric matters. The rhetoric discussed above was aired in the course of public debate and offered to shape public opinion—not in the courtroom context where it was meant to persuade a judge. Yet, there are good reasons to believe that debates about the safety of science that take place in the media are likely to have an effect on litigation outcomes.

Courts are, of course, meant to be instruments of the rule of law, and thus public opinion arguably has no direct relevance to deciding issues such as whether a court should use its equitable powers to halt a scientific experiment. Yet it would be naïve to say that public opinion does not carry a great deal of weight inside a courtroom. As U.S. Chief Justice William H. Rehnquist observed, "Judges, so long as they are relatively normal human beings, can no more escape being influenced by public opinion in the long run than can people working at other jobs."[160] Thus, a victory won through the media in the court of public opinion is likely to become a hurdle to obtaining an injunction, should one be merited.

Additionally, the public debate will affect the likelihood that private plaintiffs will step forward to pursue litigation that would put the

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159. That is, anything that is not prohibited by the physical laws. For a discussion of this aspect of quantum mechanics, see COX & FORSHAW, *supra* note 76.

160. William H. Rehnquist, *Constitutional Law and Public Opinion*, 20 SUFFOLK U. L. REV. 751, 768 (1986).

purported riskiness of a science research program before a judge. For private litigation to be an effective legal instrument to protect against public risks, there must be plaintiffs who are willing to invest time and financial resources far out of proportion to their individual share of any risk that inures to the public as a whole.[161] The asymmetrical burden that falls on private plaintiffs to litigate public-risk issues has led Barry R. Furrow to suggest a public funding mechanism to compensate lawyers—particularly in lawsuits that only pursue an injunction and do not seek damages remedies.[162]

Another reason that public-debate rhetoric is important is that the dynamics of the debate outside the litigation context are likely to mirror debate that would take place in court. The same ways of framing questions of risk and asserting uncertainty that are persuasive to the public are likely to be persuasive to a judge. That being the case, it becomes all that much more important that judges have analytical tools to allow them to analyze the appropriateness for halting potentially dangerous activities where the risk calculus is dominated by uncertainty. Providing those analytical tools is the purpose of the next Part.

IV. WAYS FOR COURTS TO NAVIGATE UNCERTAINTY

Up to this point, I have sought to show how uncertainty in the context of science-experiment risk poses special problems for the legal resolution of questions about whether science research programs are unacceptably risky. I have argued that uncertainty makes science-experiment risk inapt for traditional risk assessment and that traditional modes of thinking about risk allow adroit proponents of scientific experiments to reframe questions of risk in a way that is favorable for the experimenters. It follows that the courts cannot abdicate their decision-making and analytical responsibilities to expert scientists who are proponents of an experiment.

That being the case, what is a court to do? In the absence of meaningful quantitative data about probabilities, how can a court judge the acceptability of the risk? In this Part, my goal is to show that, despite the difficulties, there is a way for the courts to meaningfully cope with the unknown unknowns, such that a court could enjoin leading-edge scientific research under appropriate circumstances.

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161. *See* Furrow, *supra* note 1, at 1458-59 (noting that critics argue "prospective lawsuits for relief . . . are too dependent upon the willingness and financial ability of private groups to sue, leading to spotty, incomplete regulation").

162. *Id.* at 1463.

A. *The Need to Evaluate Uncertain Risks in Qualitative Terms*

The first and most important point for courts dealing with uncertain quantitative risk is that courts must deal with this risk in qualitative terms—not withstanding courts' past preference for looking at risk in quantitative terms.[163] The reason why is simple: There is no other choice. In other words, the courts must deal in qualitative terms out of necessity. As discussed above, when it comes to catastrophe scenarios with very low quantified probabilities, the uncertainty of the probability will always eclipse the probability figure.[164] Thus, very low probability numbers are essentially meaningless, and the apparent precision of the numbers is illusory. Accordingly, courts must deal in qualitative terms to decide whether an experiment poses unacceptable risk.

In making sure this conclusion is right, it is helpful to explore some hypothetical alternatives.

One alternative could be for courts to dismiss claims as *de minimis* where computed probabilities are so low that they are eclipsed by uncertainty. This is not a frivolous idea. Indeed, this would seem to be an equitable solution where a low probability is coupled with a correspondingly small harm.

In other words, we would ask *what is the worst that could go wrong?* The death of a single person, for instance, may be a small enough harm that a claim is dismissible when it is accompanied with a quantified low probability of harm. In such a case, even if the chance that the probability is wrong is greater than the probability itself, the total ceiling on the likelihood that something will go wrong may still be small enough to ignore in a case in which the worst that could happen is a single death.

Mass catastrophe scenarios, however, cannot be ignored in the same way. Where the alleged harm is large—such as the death of millions—then even very low probabilities of calamity make for equitably significant claims. Thus, it is not defensible to dismiss claims on a *de minimis* basis where uncertainty eclipses the quantified probability of harm in high-harm scenarios.

Another alternative proposal would be for courts to abstain from deciding matters where risks cannot be made reasonably certain. Courts might claim that if they cannot make a decision based on reasonably certain quantitative analysis, then the courts should not

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163. *See, e.g.*, Haw. Cty. Green Party v. Clinton, 980 F. Supp. 1160, 1168-69 (D. Haw. 1997) (using quantified costs and probabilities in denying an application for injunction to halt launch of the Cassini space probe carrying 32.8 kg of plutonium as a power source, which plaintiffs alleged caused a cancer risk in the event of a launch accident or navigation error).

164. *See supra* Section II.C.

make any decision at all. This path, however, is wrong for at least two reasons.

First, courts have long made decisions without quantitative analysis. In fact, that is what the courts have done for hundreds of years. And outside of dealing with certain technical subjects, working without quantitative analysis continues to be the everyday occupation of the courts. Slip-and-fall accidents, negligently caused automobile collisions, and a thousand other harm/injury scenarios are dealt with in a tolerably fair way with qualitative reasoning about what constitutes reasonable care.[165] So for the courts to throw up their hands when dealing with science-experiment risk cases would be arbitrary and unjustified.

The second reason that courts must not abstain from adjudicating research-risk disputes without reasonably certain quantitative analysis is more fundamental: It is the job of the courts to balance the rights and interests of the persons before it. It should be seen as intolerable for courts to walk away from the job just because it is difficult—even if it is extremely difficult.

There are, of course, circumstances in which courts abstain from deciding matters, but the rationale cannot merely be because deciding the matter is hard. Federal courts, for instance, make use of various abstention doctrines that allow them to avoid deciding questions better left to state courts.[166] But in such situations, state courts typically can hear the dispute—meaning there is only abstention by certain courts, not a true instance of abstention by the judiciary as a whole.[167]

Another situation in which courts abstain from adjudication is under the political-question doctrine. Indeed, one dominant consideration in favor of the invocation of the political-question doctrine is "the lack of satisfactory criteria for a judicial determination."[168] But political-question doctrine does not point to the propriety of abstaining from deciding quantitatively uncertain research-risk cases. The invocation of political-question doctrine

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165. *See, e.g.*, Ramirez v. Plough, Inc., 863 P.2d 167, 171 (Cal. 1993) ("In most cases, courts have fixed no standard for care for tort liability more precise than that of a reasonably prudent person under like circumstances.").

166. *See, e.g.*, Colo. River Water Conservation Dist. v. United States, 424 U.S. 800, 813-18 (1976) (abstention by a federal court in exceptional circumstances when there is parallel state court litigation); Younger v. Harris, 401 U.S. 37, 48-53 (1971) (limiting the ability of federal courts to interfere with proceedings in the state courts); R.R. Comm'n of Tex. v. Pullman Co., 312 U.S. 496, 500-01 (1941) (discretionary abstention by federal courts on the constitutionality of state law where the state law is ambiguous or uncertain and where future state court decisions might make federal court resolution of federal constitutional questions unnecessary).

167. *See Colo. River Water Conservation Dist.*, 424 U.S. at 813-18.

168. Baker v. Carr, 369 U.S. 186, 210 (1962) (quoting Coleman v. Miller, 307 U.S. 433, 454-55 (1939)).

requires a determination that the matter is appropriately decided by political branches of the government.[169] There is, of course, no necessity that leading-edge science experiments be undertaken by the government itself. And for many reasons, the political system is ill-suited to decision-making with regard to low-probability catastrophic risks presented by science experiments.[170] These reasons include cognitive biases that lead to undervaluing potential risks, which in turn lead to citizen non-engagement in the political process.[171]

Beyond the inappropriateness of *de minimis* dismissals and abstention to avoid dealing in qualitative terms with uncertain risk, there is an additional compelling reason for why qualitative risk evaluation is appropriate in cases of uncertain experiment risk: Scientists themselves—even in the most math-intensive disciplines—habitually reason qualitatively and judge the strength of arguments in qualitative terms.

With specific regard to the LHC, physicists moved away from quantitative "probability mode" rhetoric in favor of discussing possible catastrophe risks in qualitative terms.[172] In doing this, LHC supporters may have been mindful of the political and public-relations ramifications of quantified probabilities. Yet there is an important sense in which particle physicists would not be able to get away from qualitative reasoning even if they wanted to: All quantitative models depend on assumptions, the plausibility of which involves the rough exercise of professional judgment. And that undertaking is quintessentially qualitative.

A simple example will show how qualitative reasoning is, of necessity, fundamental to physicists' risk assessments of their own experiments. Consider the issue of whether previously observed naturally occurring cosmic rays are good stand-ins for collisions in a particle accelerator when considering safety issues. If they are, then cosmic-ray data can be used in models that produce quantified probability ceilings. But are they? The threshold determination of the appropriateness of underlying models and assumptions is, frustratingly, unsusceptible to empirical, quantitative treatment.

In the end, courts are compelled by logic and practical necessity to use qualitative reasoning in evaluating quantitatively uncertain low-probability catastrophic risks from research. In the next subpart, I describe how the courts can do this fairly and meaningfully.

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169. *Id.* at 210.
170. *See* Johnson, *Agencies, supra* note 5, at 582-83.
171. *See id.*
172. *See supra* Section III.B.

B.   General Methods of Evaluating
Uncertain Risks in Qualitative Terms

In cases of alleged low-probability catastrophic risk posed by science experiments—where uncertainty dominates—courts should conduct a kind of meta-analysis that gets above the level affected by uncertainty.[173] The object of the meta-analysis is to judge the reliability or dubiousness of scientists' assessments that their own experiments are safe. In other words, we must get a handle on the risk that the risk assessment is wrong. We can do this by looking at the risk assessors and the risk assessment process.[174]

Two concerns here are paramount. The meta-analysis should render science-experiment risk amenable to a determination of unacceptable risk and injunction in some cases. That is, it should be possible for plaintiffs to win sometimes. But the meta-analysis should not be so skeptical of scientists' own judgments, and so deferential to critics, that the analysis always leads to the conclusion that the challenged experiment should be halted. That is, it should be possible for defendants to win sometimes.

At the end of the day, the law should be capable of sheltering complainants from unreasonable risks imposed by others, and simultaneously the law ought to ensure room for scientific progress at the frontiers of knowledge.

So how can we have a principled, meaningful method of analyzing uncertain risk that appropriately safeguards society without halting the broader project of scientific discovery? The answer is that courts must look at the human aspects. Science, after all, is a human project, and scientists are human. Looking at the potential for human failure—something the courts are used to doing in innumerable other contexts—provides the potential for meaningful qualitative assessment of quantitatively uncertain risks.

Prior human failures in analyzing risk are pathmarking. Consider, for example, the space shuttle *Challenger* and *Columbia* disasters. NASA management made judgments in each case that risks were acceptable—even when they really were not.[175]

The *Challenger* exploded 73 seconds after liftoff.[176] As the shuttle began to ascend, an incompletely sealed O-ring in a joint between segments of a solid rocket booster allowed a flame of hot rocket exhaust

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173. What I am suggesting here is an adaptation of an approach I suggested previously for the related problem of courts dealing with scientific questions of extraordinary complexity that are opaque to laypersons. *See* Johnson, *Black Hole Case, supra* note 5, at 883-907.

174. *See id.*

175. *See* 1 COLUMBIA ACCIDENT INVESTIGATION BOARD, COLUMBIA ACCIDENT INVESTIGATION BOARD REPORT 200 (2003), https://www.nasa.gov/columbia/home/CAIB_Vol1.html [https://perma.cc/X6VG-MDXH] [hereinafter CAIB].

176. *See Challenger Explosion*, NASA, http://er.jsc.nasa.gov/seh/explode.html [https://perma.cc/66FS-J6GV] (last visited March 30, 2021).

to erupt from the booster's side.[177] The growing eruption of super-heated gases breached the neighboring liquid-fuel-carrying external tank and destroyed the tank's lower attachment to the booster.[178] Freed from its lower attachment strut, the booster twisted away, shattering the external tank, which instantly released its load of liquid oxygen and hydrogen—with the resulting mixture then exploding directly underneath the shuttle.[179]

Before the *Challenger* launched on the morning of January 28, 1986, engineers with an aerospace contractor argued that data indicated the crucial O-rings would not seal in the cold temperatures then prevailing at the Kennedy Space Center.[180] An engineer recalled 30 years later, "They had their mind set on going up and proving to the world they were right and they knew what they were doing. But they didn't."[181]

The *Columbia* accident of February 2003 was caused by a similar blindness to risk. During launch, a piece of insulation foam from the outside of the external tank separated and punctured a heat-shield panel on *Columbia*'s left wing.[182] After more than two weeks in orbit, *Columbia* re-entered the Earth's atmosphere.[183] As *Columbia* streaked toward the ground, air was turned to plasma by the friction of re-entry, and this air entered the hole in the heat shield.[184] Like a blowtorch, the super-heated air tore into the structural elements of the wing, causing structural failure that led to the break-up of the shuttle.[185]

As with *Challenger*, *Columbia* exemplified a pattern of institutional failures to recognize hazards. NASA managers ignored engineers' concerns as well as a number of near-misses on previous missions.[186] The *Columbia* investigation board said in its final report, "In our view, the NASA organizational culture had as much to do with this accident as the foam."[187]

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177. *Id.*

178. *Id.*

179. *Id.*

180. *See* Howard Berkes, *30 Years After Disaster, Challenger Engineer Still Blames Himself*, NPR (Jan. 28, 2016, 6:25 PM), http://www.npr.org/sections/thetwoway/2016/01/28/464744781/30-years-after-disaster-challenger-engineer-still-blames-himself [https://perma.cc/QCT7-GF75].

181. *Id.* (quoting Bob Ebeling).

182. MARCIA S. SMITH, NASA's SPACE SHUTTLE COLUMBIA: SYNOPSIS OF THE REPORT OF THE COLUMBIA ACCIDENT INVESTIGATION BOARD 1-2 (2003), http://history.nasa.gov/columbia/Troxell/Columbia%20Web%20Site/Documents/Congress/CRS%20Summary%20of%20CAIB%20Report.pdf [https://perma.cc/TD4R-M58K].

183. *Id.* at 1.

184. *Id.* at 2.

185. *Id.*

186. *Id.* at 3-4.

187. CAIB, *supra* note 175, at 97.

Considering these and other examples, there is no question that it is possible for an organization of people with surpassing intelligence to blunder into disaster. The meta-analysis I propose here revolves around trying to perceive the potential for such failures in a particular case brought before a court.

For analytical purposes it is helpful to divide this qualitative meta-analysis into categories, which translate into factors for courts to use in deciding questions of risk acceptability. These five factors are: (1) the potential for defective theoretical groundings; (2) the potential for faulty scientific work; (3) the potential for credulity and neglect; (4) a lack of independence and the existence of conflicts of interest; and (5) the potential for fraud, lies, and faked results.[188]

1. Defective Theoretical Groundings

All risk assessments of science research depend on theoretical understanding, and there is an ever-present risk that the theory upon which the risk-assessment is based is not sound. Science, after all, is an activity, not a static body of knowledge. And scientific theory changes over time. Thus, despite the best efforts of scientists, theory sometimes turns out to be wrong.[189] As such, mistaken theory is a classic unknown unknown.

In and of itself, there is nothing bad about the fact that scientists make mistakes about theory. Being wrong, and then realizing this wrongness at some later point, is part of scientific progress. At least as long as theory is only bandied about as an academic matter, this kind of mistaken understanding is not dangerous. When theory is used as the foundation for a real-world safety analysis, however, defective theory can lead to catastrophe.

The generic possibility that all our understanding in a particular field of science might turn out to be naïvely mistaken is not of much help to a court in trying to analyze uncertain science experiment risk. For instance, the fact that it was once thought that all the stars were points of light on an enormous sphere around the Earth does not justify the conclusion that a contemporary science experiment is unsusceptible to being judged safe. Such general doubt would not allow us to distinguish research endeavors appropriate for an injunction from all the rest of the experimental scientific work that is necessary for fundamental scientific progress.

A principled way for a court to distinguish less reliable theoretical underpinnings is to consider the newness of the theory and how

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188. The first through fourth categories generally track those I set out in previous work. *See* Johnson, *Black Hole Case, supra* note 5, at 886.

189. *See, e.g.,* STEPHEN HAWKING & LEONARD MLODINOW, A BRIEFER HISTORY OF TIME 5 (2005) (discussing the potential for theory to be fundamentally upended over the long term).

quickly evolving the field is. When theory is newer and subject to active, back-and-forth discussion among theorists, then a court should place correspondingly less confidence in the risk analysis built on top of it.

The LHC/black-hole issue provides a good example of quickly-shifting theory that might cause one to doubt the reliability of safety assurances: In 1999, the argument for accelerator safety rested on the conclusion that, under prevailing theory, accelerators for the foreseeable future lacked the power to create black holes.[190] Not long afterward, theorists showed that if new theory about the existence of hidden dimensions in the universe turned out to be correct, black holes "will be produced."[191] A new safety case was fashioned on the basis that black holes would evaporate because of Hawking radiation.[192] Then a few years later, that argument was abandoned after a respected theorist called black-hole evaporation into question.[193] With CERN's safety rationale eroded, a new safety case was fashioned for the LHC in 2008, on the eve of the collider's launch. This new safety rationale followed a branching logic to conclude that black holes were not a danger since under some assumptions black holes could be ruled out based on empirical observations of certain white-dwarf stars, and under other assumptions, black holes would grow too slowly to constitute a threat.[194]

This chronology suggests a lack of stability in theoretical groundings. In fact, CERN theoretical physicist John Ellis even characterized the theory of micro black holes as "a fast moving subject."[195]

All in all, it seems plausible to decide on the basis of the quick pace of theory that reliance upon current theoretical understandings for safety assurances may be premature. And it calls into question CERN's representation that LHC safety claims are rooted in "firmly established theory."[196]

It is also worth noting in this respect that Steven Giddings, co-author of the primary paper concluding that the LHC does not pose a black hole danger, has been noted by a fellow scientist as having exhibited a "stubborn attachment to wrongheaded ideas" in the past—specifically concerning theory about black holes.[197] Of course, such an allegation, even if true, would not mean Giddings was mistaken in his

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190. *See supra* Section I.C; *see also* Johnson, *Black Hole Case, supra* note 5, at 838, 889.

191. *See* BLAIZOT ET AL., *supra* note 86, at 11-12; *see also supra* note 85.

192. *See supra* Section I.C; Johnson, *Black Hole Case, supra* note 5, at 840-41, 889.

193. *See* Unruh & Schützhold, *supra* note 93, at 1-2, 11; *see also supra* Section I.C; Johnson, *Black Hole Case, supra* note 5, at 841-42, 889.

194. *See generally* Giddings & Mangano, *supra* note 95.

195. Ellis Video, *supra* note 107 (beginning at 10 minutes).

196. *See* CERN SCIENTIFIC POLICY COMMITTEE, *supra* note 97, at 4.

197. LEONARD SUSSKIND, THE BLACK HOLE WAR 235 (2008).

analysis about LHC safety. But the statement does suggest that it is not inconceivable that any given scientist might be operating from mistaken theoretical ideas.

Bottom line, the lack of stability for relied-upon theory in this area would be of legitimate concern to a court undertaking a meta-analysis of risk-assessment reliability.

2. Faulty Scientific Work

Even where the theory is solid, scientific analysis can go awry in other ways, including through observational errors, mistranscribed data, calculation mistakes, inaccurate assumptions, or other types of faulty scientific work. Any of these kinds of errors might lead to unsound conclusions about safety.

Errors in physics work can, for instance, result from carelessness. Indeed, CERN's Nobel-winning experimenter Carlo Rubbia is known to have reported inaccurate numbers from his experiments.[198] Apparently this often happened because Rubbia lacked the patience to take adequate care with his work.[199] And those close to him suggested that the inaccuracies did not seem to bother him.[200]

Even when care is taken, however, errors can creep up. In their discussion of LHC risk, philosophers Ord, Hillerbrand, and Sandberg noted that mistakes in calculations at hospitals cause drug-dosage mistakes around one to two percent of the time.[201] The error rate in such a context ought to be particularly concerning since in a hospital everyone is aware that a failure to take care may result in the immediate loss of life.

In the academic context, Ord and colleagues point to studies showing that 6.3 in 100,000 papers in the life sciences are retracted.[202] Yet not all flaws in academic science work lead to retraction. Ord's team also notes a study of the prestigious journals *Nature* and the *British Medical Journal*, which found flawed statistical results about 11% of the time.[203]

While errors in the area of biology and medical sciences seem to be better studied, there are examples of notable errors in physics work as well.

The 1954 Castle Bravo thermonuclear "H-bomb" test conducted by the United States in the South Pacific Ocean is a historically

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198. GARY TAUBES, NOBEL DREAMS: POWER, DECEIT, AND THE ULTIMATE EXPERIMENT 6 (1986).

199. *Id.*

200. *Id.* (quoting a colleague of Rubbia: "His numbers are what they are. They are usually wrong—but if they suit his purpose, nothing is wrong.").

201. *See* Ord et al., *supra* note 123, at 7.

202. *Id.* at 4.

203. *Id.* at 7.

documented case of faulty physics work. Castle Bravo surprised civilian and military workers with a runaway explosion that yielded three times the force predicted.[204] The device used an untried fusion fuel, an isotope of lithium called lithium-6.[205] The unanticipated problem came from the fact that the bomb also contained a large portion of lithium-7, which scientists assumed was essentially inert in terms of the fusion reaction.[206] Based on these beliefs, in constructing a model to predict the size of the explosion, physicists assumed that only lithium-6 would contribute to the fusion reaction; thus, they computed no contribution from lithium-7.[207]

Yet as would be understood later, the impact of one neutron on a lithium-7 nucleus causes it to release two neutrons, adding to the burgeoning chain reaction.[208] Even more crucially, the net loss of a neutron transforms the lithium-7 nucleus into lithium-6.[209] Thus the "inert" ingredient was, in an instant, converted into potent fuel for the nuclear reaction.[210]

Given their problematic assumption, physicists' modeling of Castle Bravo deviated substantially from the real-world results. Instead of yielding a five-megaton explosion, the detonation ended up producing 15 megatons.[211] Ships that were stationed at what was believed to be a safe distance away found themselves too close to the explosion's supersized fireball and mushroom cloud.[212] The mistake turned out to be lethal. A crewmember of a Japanese fishing vessel—operating in waters outside the U.S. Navy's safety perimeter—was killed by radioactive fallout.[213]

One might think that bomb-scientists would not make such a mistake twice. But a following test, Castle Romeo, was also three times the predicted yield because of the same erroneous assumptions in modeling.[214]

The Castle Bravo and Castle Romeo disasters are powerful examples of unknown unknowns. Working at the leading edge of physics, scientists were able to construct a quantitative model for the behavior of chain-reacting nuclei undergoing fusion. But there was no way they could have meaningfully quantified the risk that their model

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204. *See id.* at 9.

205. *See* RICHARD RHODES, DARK SUN: THE MAKING OF THE HYDROGEN BOMB 541 (1995).

206. *Id.*

207. *Id.*

208. *See* DAVID M. BLADES & JOSEPH M. SIRACUSA, A HISTORY OF U.S. NUCLEAR TESTING AND ITS INFLUENCE ON NUCLEAR THOUGHT, 1945-1963 at 60 (2014).

209. *See id.*

210. RHODES, *supra* note 205 at 541.

211. *Id.*

212. *See id.*

213. *Id.* at 542.

214. *Id.*

itself was wrong. Yet it was. These episodes are a powerful reminder that uncertain risk is real risk.

Constructively, the Castle Bravo and Castle Romeo examples point to how a court can conduct a meta-analysis of risk uncertainty in the context of leading-edge science experiments with alleged catastrophic potential. A court should look at how novel the modeling is, how many layers of assumption it uses, the complexity of its calculations, and the sources of its data.

3. Credulity and Neglect

Another category for evaluating, in a qualitative way, the acceptability of uncertain risk concerns to what extent there is a possibility for scientists to be too ready to believe a rosy view of potential dangers (credulity) and to not properly pay attention to signals that safety has not been adequately assured (neglect).

In general, people are irrational in making judgments about risk—something increasingly delineated by the study of behavioral economics.[215] Cognitive biases that result in patterns of irrationality include *myopia bias*, which is the overvaluing of the here-and-now and undervaluing of the future;[216] *probability neglect*, which comprises focusing unduly on sure losses and having less-than-warranted concern with unsure losses;[217] and *optimism bias*, in which people tend to think that the future will reveal some costless way to undo or avoid hazards.[218] Particularly relevant to leading-edge science-experiment catastrophes scenarios is *availability bias*, which causes people to undervalue the likelihood of things coming to pass that are hard to imagine and for which instances cannot be easily brought to mind.[219] Indeed, a catastrophe caused by a synthetic black hole taxes the imagination like few things can.

There is an irony here. The observation that people are irrational about risk has often been used to justify relying on scientific experts for judging risk. That is, as opposed to letting generalist judges or lay juries reckon the risk for themselves. But the idea that scientific experts are somehow immune to cognitive biases is unfortunately wrong. Experts are indeed vulnerable to biasing influences.[220] As Dan Kahan and co-authors have written, "Like members of the general

215. *See, e.g.*, CASS R. SUNSTEIN, RISK AND REASON: SAFETY, LAW, AND THE ENVIRONMENT 28-52 (2002) (discussing irrationality in valuing risk).

216. *See* David A. Dana, *A Behavioral Economic Defense of the Precautionary Principle*, 97 NW. U. L. REV. 1315, 1324-25 (2003).

217. *See* Dan M. Kahan et al., *Fear of Democracy: A Cultural Evaluation of Sunstein on Risk*, 119 HARV. L. REV. 1071, 1077-78 (2006).

218. *See* Dana, *supra* note 216, at 1325.

219. *See* Wilson, *supra* note 9, at 134; Amos Tversky & Daniel Kahneman, *Judgment Under Uncertainty: Heuristics and Biases*, 185 SCIENCE 1124, 1127 (1974).

220. *See* Kahan, et al., *supra* note 217, at 1081-82, 1093-94.

public, experts are inclined to form attitudes toward risk that best express their cultural vision."[221]

To form a qualitative assessment of the extent to which cultural vision could affect safety assessments about the risk of experiments, courts should look at the scientists' organizational culture, as well as their community norms, group politics, and power dynamics. These human elements may provide reasons to be confident in or skeptical of the scientists' judgments about the risk of their own experimental programs.

As a complement to looking at the cultural context, it will likely be of use to a court to look at the safety argument itself. This is because certain aspects of the scientists' argument may be relevant in evaluating susceptibility to bias and cultural filtering.

Simple arguments for safety will, for instance, be more resistant to such biases and filters. No amount of bias or cultural filtering would, for example, cause someone to believe $2 + 2 = 5$. But the more complex the chain of reasoning involved, the more opportunity there is for judgment calls regarding what assumptions to make and what data to reference. That, in turn, means there is more room for bias and cultural influence that may undermine scientists' own judgment about the riskiness of their experiments.

One can imagine readily applying this sort of analysis to the LHC/black-holes case. Some factors counseling skepticism of the risk assessment offered by CERN include the involvement of people with career stakes in the outcome of the assessment, the complexity of the safety case, and the fact that the assumptions and models used in the risk analysis require the exercise of discretionary judgment.

4. Lack of Independence; Conflicts of Interest

An additional category for courts to consider in a meta-analysis of uncertain risk is the potential for bias and influence in the risk assessment process that is brought about by a lack of independence and the existence of conflicts of interest. The relevant questions here revolve around to what extent the risk assessors are independent of the organizations and scientific communities whose risk is being assessed.

This kind of inquiry is indubitably within the competence of the judiciary. In fact, it is the bread-and-butter of trial courts. Showing bias or influence is a key means of impeaching the credibility of witnesses, which is an important consideration for factfinders trying

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221. *See id.* at 1094.

to decide among conflicting views of reality offered by opposing sides in a litigation.[222]

Taking the LHC/black-hole question as an example, a reviewing court would want to look at whether risk assessment work was done by persons unaffiliated with CERN or other institutions with a stake in the matter. And courts would want to weigh the potential that risk assessors, regardless of institutional affiliation, might have a personal interest in whether the experiment were judged too risky to proceed.

Applying this perspective to the LHC suggests a court might deem the LHC risk assessment, in its current state, to be unpersuasive. The scientific work relied upon by CERN for demonstrating the LHC's safety was not independent.[223] As discussed, the work was done by employees of CERN or persons with close ties to the organization.[224]

Indeed, in discussing questions of catastrophic risk from particle accelerator experiments, Cambridge University theoretical physicist Adrian Kent has raised concerns about safety analysts' lack of independence,[225] as has University of Roma–La Sapienza theoretical physicist Francesco Calogero.[226]

5. *Fraud, Lies, and Faked Results*

While hopefully rare, there is in science the potential for out-and-out fraud and lying. It is hard to gauge how widespread deliberate deception may be in the experimental sciences. Fraud and lies are—by

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222. *Cf.* Pennsylvania v. Ritchie, 480 U.S. 39, 62 (1987) (Blackmun, J., concurring) ("[O]ne of the primary purposes of cross-examination is to call into question a witness' credibility. This purpose is often met when defense counsel can demonstrate that the witness is biased . . . .").

223. *See supra* notes 107-110 and accompanying text.

224. *See supra* Section III.A.

225. *See* Adrian Kent, *A Critical Look at Risk Assessment for Global Catastrophes*, 24 RISK ANALYSIS 157, 157 (2004) ("Future policy on catastrophe risks would be more rational, and more deserving of public trust, if acceptable risk bounds were generally agreed upon ahead of time and if serious research on whether those bounds could indeed be guaranteed was carried out well in advance of any hypothetically risky experiment, with the relevant debates involving experts with no stake in the experiments under consideration."). It should be noted that Kent was focusing on the killer-strangelet planetary-collapse scenario, not black holes.

226. *See* Francesco Calogero, *Might a Laboratory Experiment Destroy Planet Earth?*, 25 INTERDISCIPLINARY SCI. REVS. 191, 198 (2000) (writing with regard to strangelet-disaster risk scenarios, "[I]t is of course appropriate that, to the maximum extent possible, those who are assigned the task of making such evaluations should not be affected by any conflict of interest."). As with Kent (*supra* note 225), Calogero was addressing the strangelet disaster scenario, not black holes. *See also* Marshall Chance Peterson, *The* Sancho *Effect: Why the Large Hadron Collider Won't Destroy the World, and How It Could Improve Science in the Courts,* 54 JURIMETRICS 303, 316 (2014) (noting that with regard to the LHC "much of the safety review was performed by CERN employees, creating a significant risk of bias in the reviews"); Grant Wilson, *Minimizing Global Catastrophic and Existential Risks from Emerging Technologies Through International Law,* 31 VA. ENVTL. L.J. 307, 338 (2013) (stating that the LHC risk issue "demonstrates that self-assessments of safety by scientists intimately involved with a project should be given additional review").

their very nature—purposefully concealed. But at least some information on unethical conduct in particle-physics came to light through a book written by physics-trained journalist Gary Taubes[227] concerning CERN physicist Carlo Rubbia, winner of the 1984 Nobel Prize in physics for leading the experimental program that discovered the W and Z bosons.[228]

In the 1960s at CERN, Rubbia undertook an experiment to find a particle called the psi hyperon.[229] The experiment failed.[230] Yet Rubbia, undaunted, faked the results and reported concocted data at a CERN seminar.[231] Taubes documented that Rubbia actually advised fellow physicists never to admit that an experiment had failed, as doing so could be detrimental to one's career.[232]

It is hard to know how common such instances of fakery are in particle physics, but when Taubes was working to confirm the account of Rubbia's presentation of fake data, one famed physicist, Georges Charpak, told Taubes the Rubbia story was too trivial to mention, since the high-energy physics field is filled with similar stories.[233]

Rubbia was also not above lying in order to be able to carry out an experiment in the first place. After management rejected his experiment proposals, Taubes documented that Rubbia would attach his apparatuses to test beams in order to carry out the unauthorized experiments he wanted to pursue.[234] When questioned about his set-ups, Rubbia would explain that he was just checking his equipment.[235] Taubes reports that colleague Charpak had a rosy gloss for this behavior as well, characterizing it as "proof of [Rubbia's] love for the subject."[236]

If a scientist would fake results and lie in order to go forward with an experiment, it seems plausible that scientists could do the same to allay public fears and move ahead with an experimental project that has been in the works for decades and represents an investment of billions of dollars. To be very clear, when it comes to CERN and the LHC, there is not the slightest suggestion that anyone involved in the safety assessment work engaged in dishonesty. Moreover, institutions change over time, and CERN today is presumably quite different than CERN was in Rubbia's day. But Rubbia's chicanery, and the apparent

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227.   *See* TAUBES, *supra* note 198. Taubes studied physics at Harvard University. *See id.* at 263.

228.   *Id.* at xiii-xv.

229.   *Id.* at 6-7.

230.   *Id.* at 7.

231.   *Id.*

232.   *Id.*

233.   *Id.*

234.   *Id.* at 6.

235.   *Id.*

236.   *Id.*

wide-spread tolerance of it, is a stark reminder that leading-edge science experimentation is not somehow immune from the sorts of ambition-fueled moral failings that occur throughout society.

C. Taking Account of Differing Values and Stakes for Scientists and Nonscientists

In tandem with the methods I discussed immediately above for dealing with uncertainty,[237] courts also need to take account of the differing values and stakes between scientists and nonscientists.

We must first begin with the observation, which is straightforward once one thinks about it, that scientists have different interests than nonscientists. Both scientists and nonscientists, of course, value their lives and the existence of the planet. And both place a value on scientific discovery. Nonetheless, their priorities are very different. Particle physicists get a great deal of value out of high-energy accelerator experiments. The general public, by contrast, gets very little. As a result, and assuming everyone is well informed, it is to be expected that scientists will tolerate a larger level of catastrophic risk from the scientific enterprise than nonscientists would be comfortable with.

It is difficult to overstate the extent to which particle physicists desire the experimental exploration of the particle world. The careers and intellectual lives of particle physicists revolve around the big experiment of their generation. Theoretical particle physicist Sean Carroll has written emotively of how a vast number of scientists have devoted their entire working lives to small pieces of the mammoth effort to design, build, operate, and learn from particle accelerators.[238] In discussing the particular need for the LHC, he wrote, "An entire generation of particle physicists has risen up the academic ladder from students to senior professors, all without having a single new phenomenon that they could discover or explain. The anticipation has been close to unbearable."[239]

By contrast, the average person gets little out of particle-physics experimentation. Collider experiments are not aimed at discovering anything practical, and their technological spinoffs are serendipitous.[240] Moreover, the field is esoteric and substantially incomprehensible to nearly everyone. Thus, notwithstanding the best efforts of science popularizers, non-physicist bystanders get relatively few benefits in terms of the joy of discovery—at least in comparison with the physicists themselves.

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237. *See supra* Section IV.B.
238. *See* CARROLL, *supra* note 19, at 1-2.
239. *See id.* at 8.
240. *See, e.g.*, TAUBES, *supra* note 198, at ix-x.

As a result of the wildly different interests at stake, particle physicists can be expected to tolerate a much higher level of catastrophic risk from particle experiments than everyone else. This, of course, is a matter of logic and common sense. Yet there is actually a way to illuminate the issue quantitatively.

In 1999, a group of four elite physicists—including one Nobel Prize winner to-be—did a report on the question of the risk of strangelet catastrophe at the Brookhaven National Laboratory's RHIC accelerator.[241] Following the issuance of the report, the Brookhaven lab commenced operation of the RHIC. In the report, the scientists on the panel revealed that they would be comfortable with at least as much as a one-in-10,000 risk of destroying the Earth in order to have the experiment go forward. Specifically, they wrote that a one-in-10,000 risk of destroying the Earth—a probability ceiling indicated by one of their models—left "a comfortable margin of error."[242]

In fact, one imagines that this statement, had it been understood at the time, might have caused something of a media firestorm. Yet the numbers were stated in complicated mathematical terms that were undoubtedly opaque for most readers. Moreover, the "comfortable margin" statement was in a highly technical section of the report. Contemporaneous media reports in 1999 were oblivious to this, and instead focused on the panel's bottom-line conclusory statement that the RHIC was not dangerous, in essence reporting the controversy to be over.[243] The fact that the RHIC report opined a one-in-10,000 probability bound on the total destruction of Earth was "comfortable" was only deciphered a few years later by Cambridge physicist Adrian Kent.[244] And at that point it seemed the news media had moved on.

What is clear is that the RHIC report authors' ideas of acceptable risk were deeply out of step with the remainder of society. As a quantitative point of comparison, consider that government agencies dealing with environmental contamination or regulation of carcinogens frequently find risk to be on the border of acceptable and unacceptable when it is within a range of between a one-in-10,000 to

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241. *See* W. BUSZA ET AL., *supra* note 84.

242. *See id.*; Kent, *supra* note 225, at 161. *See also* Johnson, *Agencies, supra* note 5, at 548-49 n.134 (discussing this number, including previously published erroneous statements of the number, my communications with Dr. Kent regarding the number, and Dr. Kent's subsequent correction). Note that the Busza report also offers non-quantified reasons for why the strangelet disaster scenario should be excluded from consideration.

243. *See, e.g.*, Curt Suplee, *Scare Stories and Mysteries of Quarky Behavior*, WASH. POST (Sept. 13, 1999), http://nuclear.ucdavis.edu/rhic/washpost.html [https://perma.cc/3UT7-GWDH] ("No, the scientists keep repeating, with weary resignation, the experiment will not tear our region of space to subatomic shreds.").

244. That scientist was Adrian Kent. *See* Kent, *supra* note 225, at 161; *see also* Johnson, *Agencies, supra* note 5, at 548-49.

a one-in-a-million chance of causing the death of just one person.[245] A risk greater than one in 10,000—again, for a single fatality—has been considered generally unacceptable.[246] By these standards, a maximum probability of one in 10,000 of killing every person on Earth should be manifestly unacceptable.

Another point of comparison for levels of acceptable risk comes from the particle physics field itself. When the risk is not environmental catastrophe, but rather the risk is being premature in declaring the discovery of a new particle, the statistical standard insisted upon is five-sigma.[247] Translated into regular numbers, this means particle physicists will not deem it safe to announce the discovery of a new particle until there is less than a chance of about one in 3.5 million that they are wrong. Or more precisely, five sigma means there is less than about a one-in-3.5-million chance that their results were obtained because of randomness rather than underlying physical reality.[248]

Suffice it to say that scientists and nonscientists assign very different valuations to science-experiment risk. And this is not merely true in the abstract—it is true even in hard, quantitative terms, as the RHIC report and the five-sigma standard show.

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245. *See, e.g.,* Adam Babich, *Too Much Science in Environmental Law*, 28 COLUM. J. ENVTL. L. 119, 152-53 (2003) (explaining that the Environmental Protection Agency (EPA) has used an acceptable risk range from a one-in-a-million to one-in-10,000 chance of an individual death); Matthew D. Adler, *Against "Individual Risk": A Sympathetic Critique of Risk Assessment*, 153 U. PA. L. REV. 1121, 1122-23 (2005) (discussing the use of a one-in-a-million threshold in the EPA regulatory context of air pollution; noting the EPA's acceptable risk range for Superfund cleanup is between one in 10,000 and one in 1 million for lifetime fatality risk for individuals with maximal exposure; and noting that the Food and Drug Administration (FDA) has traditionally used a one-in-1-million threshold for carcinogenic food constituents); Listing of D&C Orange No. 17 for Use in Externally Applied Drugs and Cosmetics, 51 Fed. Reg. 28,331, 28,345 (Aug. 7, 1986) (FDA stating that the "1 in 1 million level has become a benchmark in the evaluation of the safety of carcinogenic compounds administered to food-producing animals"). It should be pointed out, however, that agencies may find considerably higher levels of risk to be acceptable in certain contexts, such as where the benefits are seen to outweigh the risk. *See, e.g.,* Frank B. Cross, *Beyond Benzene: Establishing Principles for a Significance Threshold on Regulatable Risks of Cancer*, 35 EMORY L. J. 1, 43 (1986) (describing how the Nuclear Regulatory Commission considered an increased chance of cancer from plant accidents of about 1.3 in 10,000 to be acceptable given the benefits of nuclear power).

246. *See supra* note 245.

247. *See, e.g.,* LINCOLN, COLLIDER, *supra* note 34, at 150 (discussing a "semi-rigid set of rules" according to which, "[i]n order to say 'we observed something,' you must have 5 sigma evidence—this is an extremely high standard"); JIM BAGGOTT, HIGGS: THE INVENTION & DIS-COVERY OF THE 'GOD PARTICLE' 193 (2012) (reporting that "to warrant declaration of a 'discovery', particle physicists actually demand five-sigma data, or confidence levels of 99.9999%").

248. *See* Evelyn Lamb, *5 Sigma What's That?*, SCI. AM.: OBSERVATIONS (Jul. 17, 2012), https://blogs.scientificamerican.com/observations/five-sigmawhats-that/ [https://perma.cc/4W77-PSM6] ("In short, five-sigma corresponds to a p-value, or probability, of 3×10^{-7}, or about 1 in 3.5 million. This is not the probability that the Higgs boson does or doesn't exist; rather, it is the probability that *if* the particle does not exist, the data that CERN scientists collected in Geneva, Switzerland, would be at least as extreme as what they observed.").

D.   Testing Opinions Analogically

One particular technique that courts can use to undertake a probing qualitative analysis—a shortcut to evaluating the trustworthiness of scientists' assurances—is to compare assessments physicists have made of the safety of their own experiments with their assessments in areas outside their own sphere of self-interest.

A simple example comes from Stephen Hawking, who opined that the LHC is "absolutely safe."[249] Yet speaking outside of the context of LHC safety, he wrote that it is plausible that current physics theory may someday be regarded "as ridiculous as a tower of turtles."[250] Given Hawking's understanding that today's physics theory might not endure, one might find some reason to doubt his ironclad conclusion about LHC safety.

A better example of conflicting views on risk, one with richer detail, is the writing that well-known particle physicist Lisa Randall has done about risk issues with regard to the LHC and with regard to the economic impact of financial derivatives trading.

Randall is a proponent of the LHC, saying that the risk of the accelerator generating dangerous black holes is "essentially nonexistent."[251] Notably, she does admit that some uncertainties are involved when it comes to the question of accelerator-created black holes.[252] Yet Randall's bottom-line assessment is that uncertainties in the LHC/black-hole risk question can be safely ignored:

> Luckily for our search for understanding, we are extremely certain that the probability of producing dangerous black holes is minuscule. We don't know the precise numerical probability for a catastrophic outcome, but we don't need to because it's so negligible. Any event that won't happen even once in the lifetime of the universe can be safely ignored.[253]

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249.   Swaine, *supra* note 135.

250.   HAWKING & MLODINOW, *supra* note 189, at 5.

251.   *See* RANDALL, *supra* note 15, at 179.

252.   *See id.* at 172 ("No one really knows how to solve systems in which both quantum mechanics and gravity play an essential role. String theory is physicists' best attempt, but we don't yet understand all its implications. This means that in principle there could be a loophole. Extremely tiny black holes, which we will understand only with a theory of quantum gravity, are unlikely to behave the same way as the big black holes we derive using classical gravity. Perhaps such very tiny black holes don't decay at the rates we expect. Even this isn't a serious loophole however.") (internal paragraph break omitted).

253.   *Id.* at 186-87.

It is interesting to compare Randall's thinking about the LHC/black-hole question to how she views risk in the financial system. Randall advocates additional regulation for the financial system. Why? She urges that attention should be paid even to unlikely outcomes if the harm would be very large. With insight that could easily be applied to the black hole case, she writes:

> The financial crisis happened because of events that were outside the range of what the experts had taken into account . . . Virtually no one paid attention to the "unlikely" events that precipitated the crisis. Risks that might otherwise have been apparent therefore never came up for consideration. But even unlikely events need to be considered when they can have significant enough impact. . . .
>
> On top of the calculational problems and hidden prejudices buried in . . . underlying assumptions, many practical policy decisions involve unknown unknowns . . . . This can make any prediction attempts—that will inevitably fail to factor in these unknowns—completely moot.[254]

Similarly, Randall explains why we cannot rely on experts in the realm of finance and economics:

> After all, "experts" told us that derivatives were a way of minimizing risk, not creating potential crises. "Expert" economists told us that deregulation was essential to the competitiveness of American business, not to the potential downfall of the American economy. . . .
>
> Clearly experts can be shortsighted. And experts can have conflicts of interest.[255]

Yet Randall exempts particle physicists from such fallibility—despite the fact that physicists can be notably shortsighted. Recall that in 1999 physicists prematurely declared that present-day accelerators could not have enough energy to create black holes—only to be undermined by evolving theory a couple years later. And physicists, of course, can have conflicts of interest. Recall that CERN's safety assessment was done by people employed by or connected with CERN.[256]

Randall seems to appreciate the tension in her views. She writes, "Yet despite my confidence that it was okay to rely on experts when evaluating potential risks from the LHC, I recognize the potential limitations of this strategy and don't know quite how to address them."[257]

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254. *Id.* at 186.
255. *Id.* at 195.
256. *See supra* Section II.A.
257. RANDALL, *supra* note 15, at 195.

CONCLUSION

This Article has sought to demonstrate that courts can deal sensibly and constructively with unknown unknowns—even in the intensely challenging context of leading-edge science experiment risk. To be analytically rigorous in the face of quantitative uncertainty, courts must embrace a qualitative way of looking at risk—a rough figuring of factors—which corresponds with the kind of qualitative reasoning that courts apply in the more prosaic kinds of cases they encounter every day. Such a qualitative way of dealing with risk is vastly preferable to the alternative, which is to plug uncertain numbers into a cost-benefit formula, a practice that has the unfortunate effect of multiplying uncertainty to produce meaningless results that take on an aura of quantitative precision.

Such a conclusion may be surprising and counterintuitive. After all, we live in an era of big data and massive computational power. Increasingly, quantitative sophistication is thought of as the go-to solution for intractable problems. Thus, it might seem to be a step backward to embrace qualitative reasoning in lieu of quantitative analysis. But when the inputs are uncertain—as they are with catastrophe risks posed by leading-edge science research—we really have no choice. Quantitative sophistication offers an illusory allure. Qualitative analysis, though less neat, offers a principled, honest way forward.

To be rigorous, qualitative analysis of uncertain risks should, as discussed in this Article, look to considerations such as the pace of progress in the relevant scientific field, the social context in which scientists operate, the existence of conflicts of interest, and the potential for cognitive biases that could affect the conclusions of scientists with regard to the safety of their own experiments.

The prescriptions set out in this Article for dealing with uncertainty in the science-experiment context may have considerable relevance elsewhere. It may be useful, for instance, to apply the qualitative meta-analysis advanced in this Article to questions of risk in financial-market regulation, pharmaceutical regulation, and other areas bedeviled by unknown unknowns. Wherever uncertain inputs meet long odds, quantitative meaninglessness can result, making principled qualitative meta-analysis a potentially useful tool. This Article has sought to contribute to the broader conversation about uncertain risk across all areas of the law by taking leading-edge experimental science as the hard case.

Yet the fact that science experimentation is a hard case is not the only or even the primary reason to focus on it in the context of uncertain risk. The most compelling reason for concentrating attention in this area has to do with how scientists go about exploring and advancing our knowledge of the natural world: They poke and prod.

And to explore the most fundamental aspects of nature, scientists manipulate nature in fundamental ways. It follows that low-probability/high-harm catastrophe scenarios wind up as a recurrent feature of leading-edge research.

In years to come, scientists will be pushing into many areas where no one will have a complete handle on what might go wrong—including, for instance, artificial intelligence research, nanotechnology, and the genetic manipulation of pathogens. Many areas of research will raise the prospect of potential cataclysmic harm. We can expect that scientists will only push ahead where the likelihood of catastrophe from any given experiment seems small. But the law must consider the long view: With many scientists from many fields working over the course of many years, the occurrence of some planet-wide disaster is not at all far-fetched. Thus, the law and the courts should take it as their duty to face head on the conundrums of science-experiment risk.

In sum, we must accept the fact that it is in our nature as humans to push the frontiers of our understanding. And we must accept as well that we can be mistake-prone and shortsighted in doing so. Acknowledging our inability to turn uncertainty into certainty is the first step toward being prudent and rational when it comes to uncertain risks of leading-edge science research. Taking up intelligent means of handling such uncertainty must be the next step.