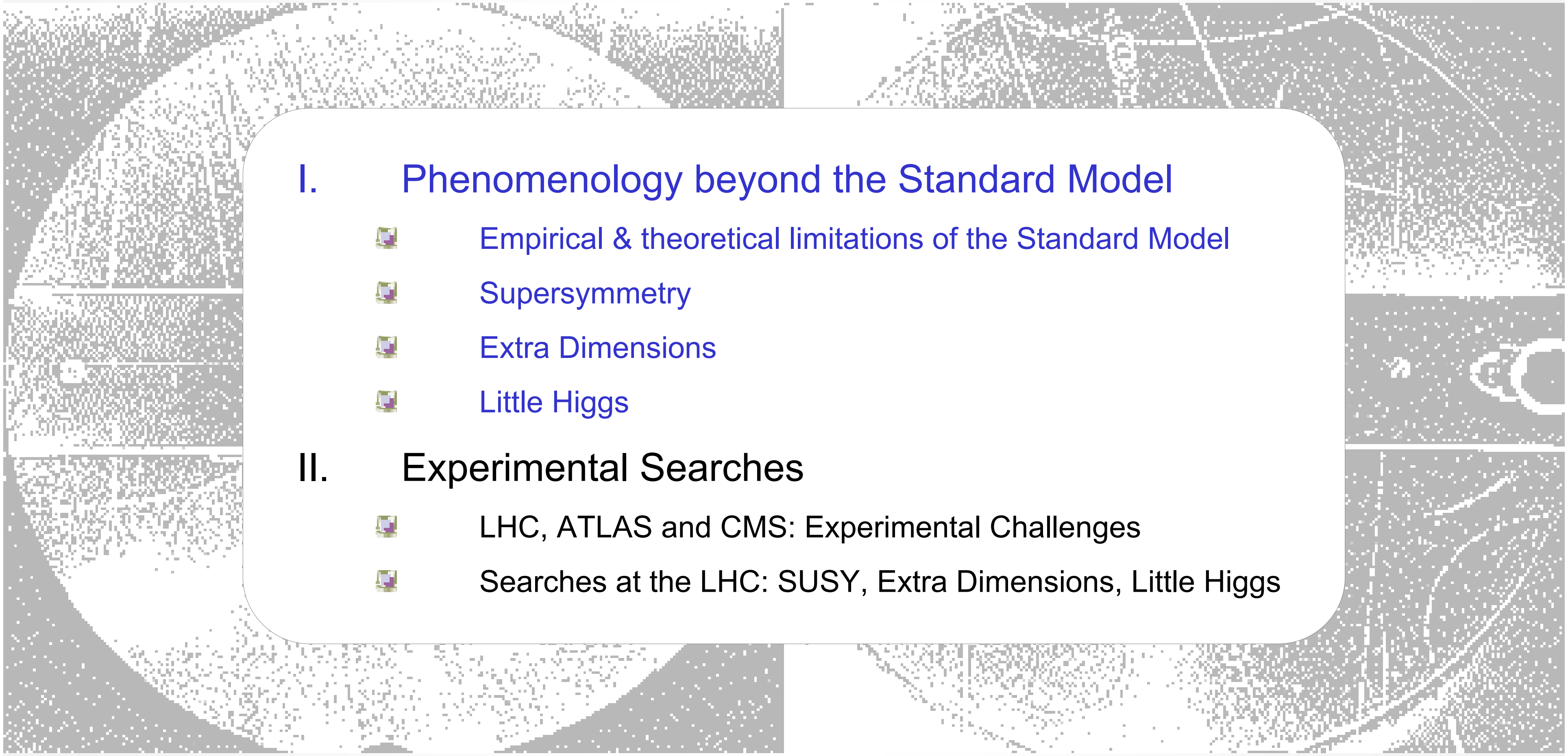

Part 1 – Phenomenology

Discovery Physics at the LHC

Andreas Hoecker, CERN

XI Mexican Workshop on Particles and Fields, Nov 7-12, 2007, Tuxtla Gutiérrez, Mexico

Lecture Themes



I. Phenomenology beyond the Standard Model

- Empirical & theoretical limitations of the Standard Model
- Supersymmetry
- Extra Dimensions
- Little Higgs

II. Experimental Searches

- LHC, ATLAS and CMS: Experimental Challenges
- Searches at the LHC: SUSY, Extra Dimensions, Little Higgs

Lectures based on many, many sources… please contact me for a authorship questions

Empirical and Theoretical

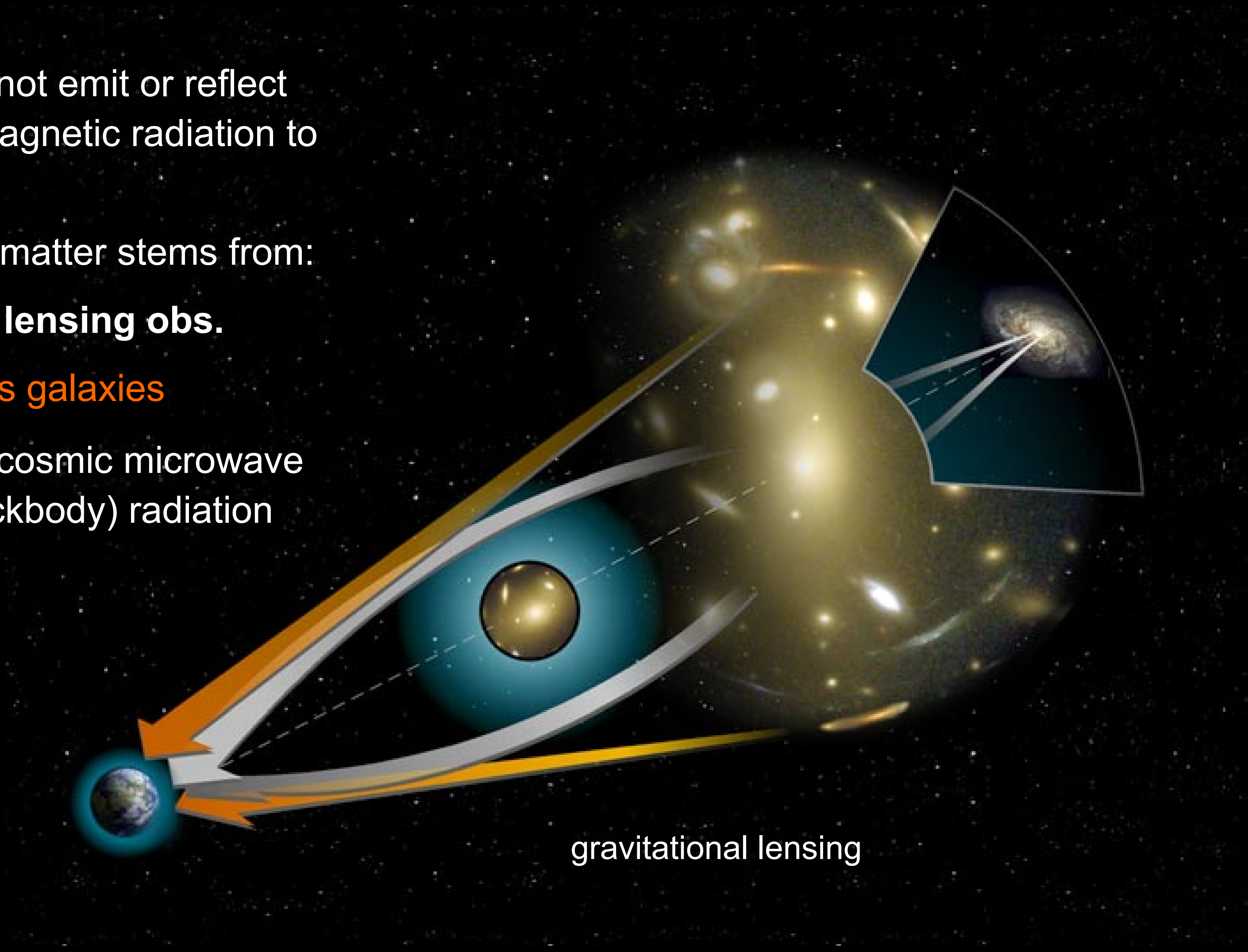
Limitations of the Standard Model

- Dark matter (and, perhaps, dark energy)
- Baryogenesis and Leptogenesis
- Grand Unification of the gauge couplings
- The gauge hierarchy Problem
- The strong *CP* Problem (why is $\theta \sim 0$?)
- Neutrino masses
- Gravitation
- (New Physics: why not ? [D.E. Kaplan])

Neutrino masses and inclusion of **gravity** in the SM require new physics at the scales ~10^{14} GeV and ~10^{19} GeV, respectively.

Dark Matter

- *Dark matter* does not emit or reflect sufficient electromagnetic radiation to be detected
- Evidence for dark matter stems from:
  - **gravitational lensing obs.**
  - rotation curves galaxies
  - anisotropy of cosmic microwave background (blackbody) radiation



gravitational lensing

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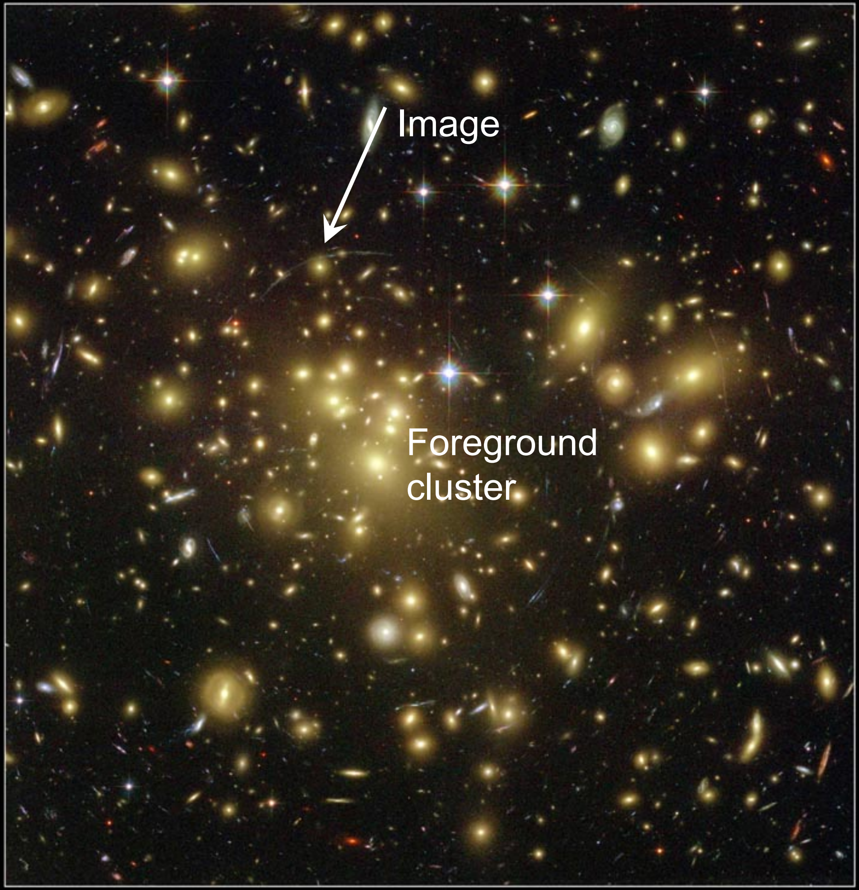

Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

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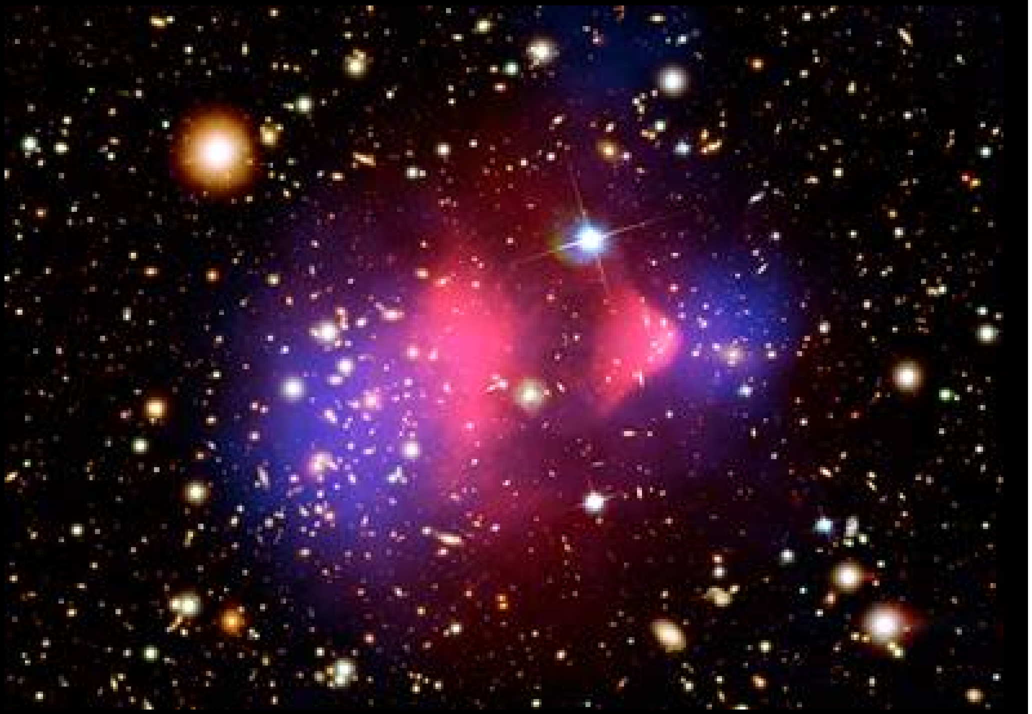
Bullet cluster: Collision of galaxy clusters: baryonic matter, stars – weakly affected by collisions – and strongly affected gas (pink in picture), and collisionless dark matter (blue)



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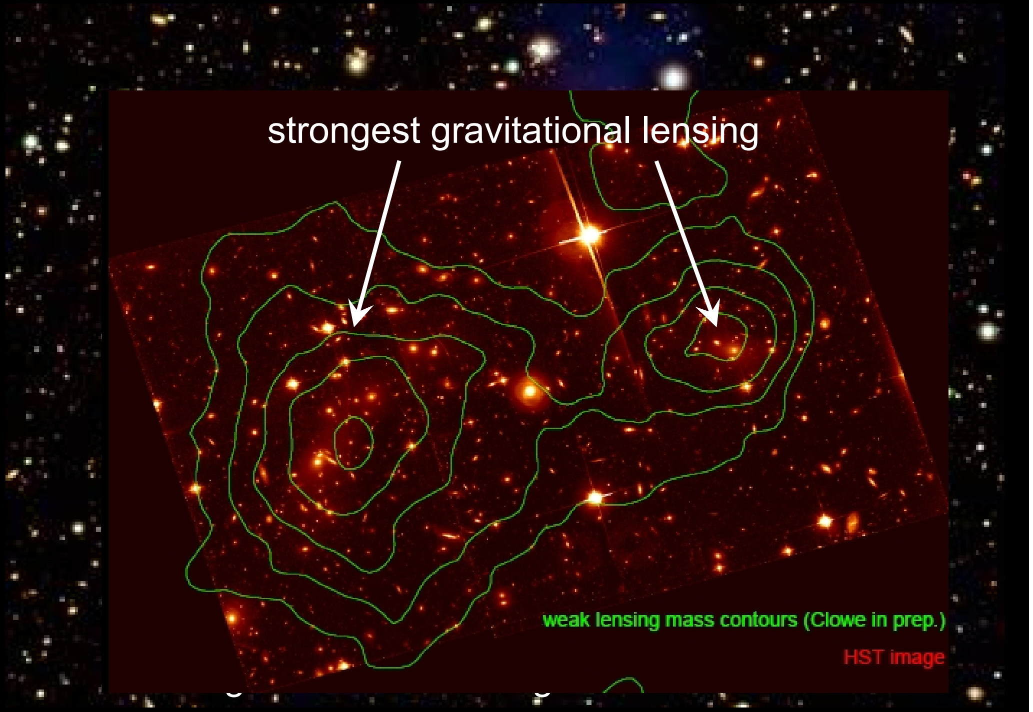
Interesting side effect: the observed pattern allows to derive limits on cross sections of self-interacting dark matter !

Bullet cluster: Collision of galaxy clusters: baryonic matter, stars – weakly affected by collisions – and strongly affected gas (pink in picture), and collisionless dark matter (blue)



Mass density contours superimposed over photograph taken with Hubble Space Telescope

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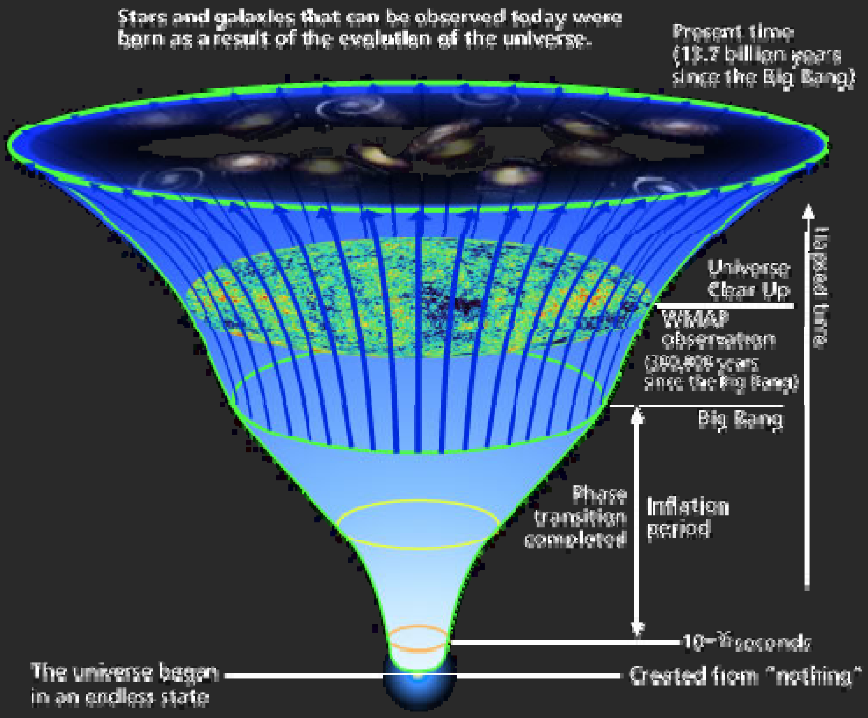
→ 2006 Nobel Price in Physics:
John C. Mather, and George F. Smoot
(COBE satellite)



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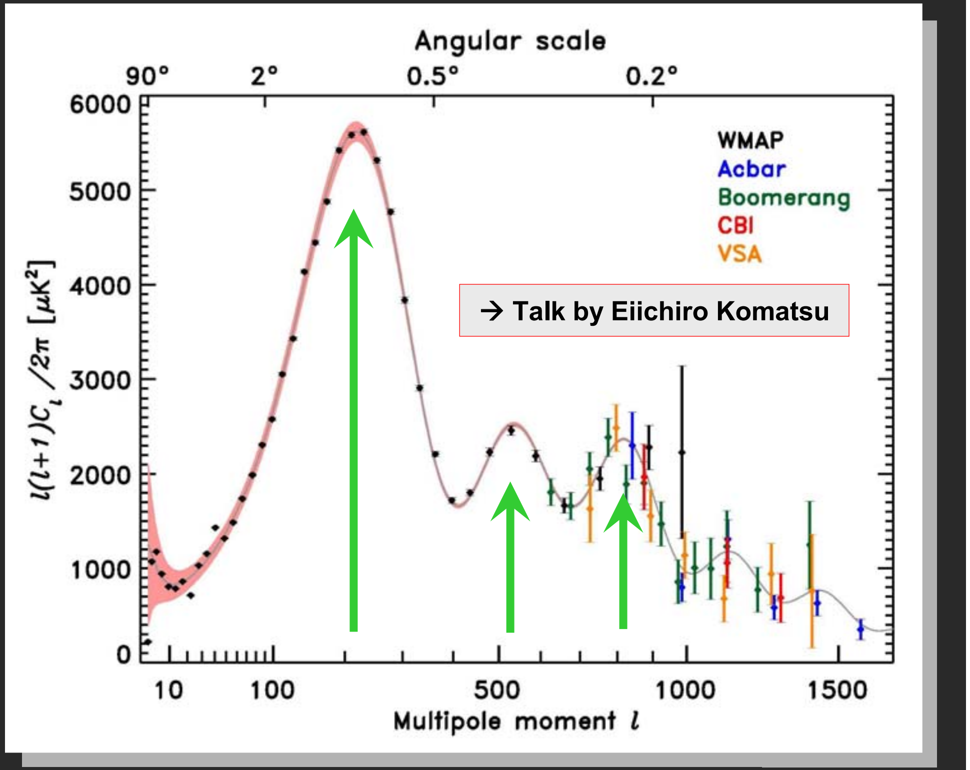
arXiv:astro-ph/0603451



→ **Talk by Eiichiro Komatsu**

- First peak determines curvature of universe
- Second peak (ratio of odd-to-even peaks) determines reduced baryon density
- Third peak is related to dark matter density !
- **Data analysis reveals a flat universe and lots of unknown matter and energy !**

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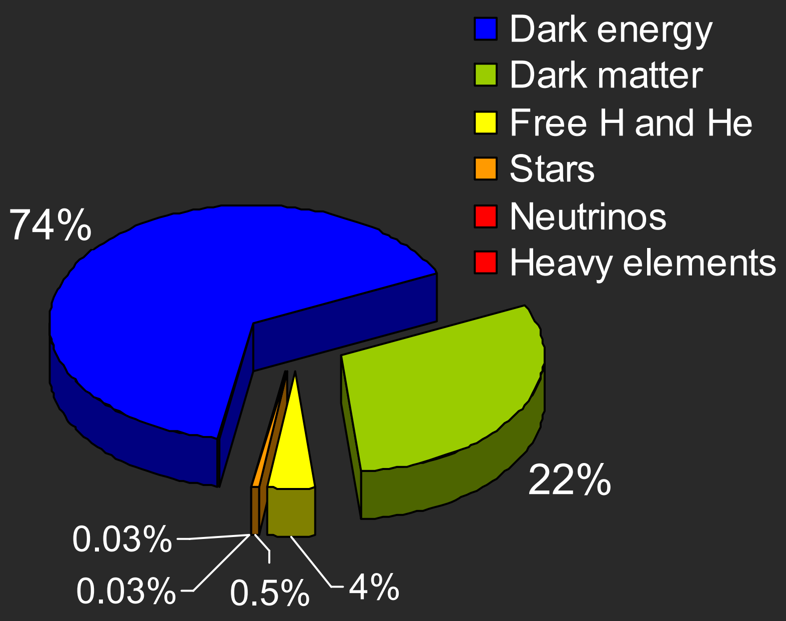


→ Talk by Francisco Guzmán

Dwarf galaxies need dark matter too ?

- First peak determines curvature of universe
- Second peak (ratio of odd-to-even peaks) determines reduced baryon density
- Third peak is related to dark matter density !

➧ **Data analysis reveals a flat universe and lots of unknown matter and energy !**

Dark Matter: The “WIMP Miracle”

- Consider Some new particle χ
- During an early *soup*, its annihilation reaction is in thermal equilibrium

$$\chi\chi \leftrightarrow f\bar{f}$$

- As the *soup* expands it cools down, so that (assuming here: $m(\chi) \gg m(f)$, still remaining in thermal equilibrium)

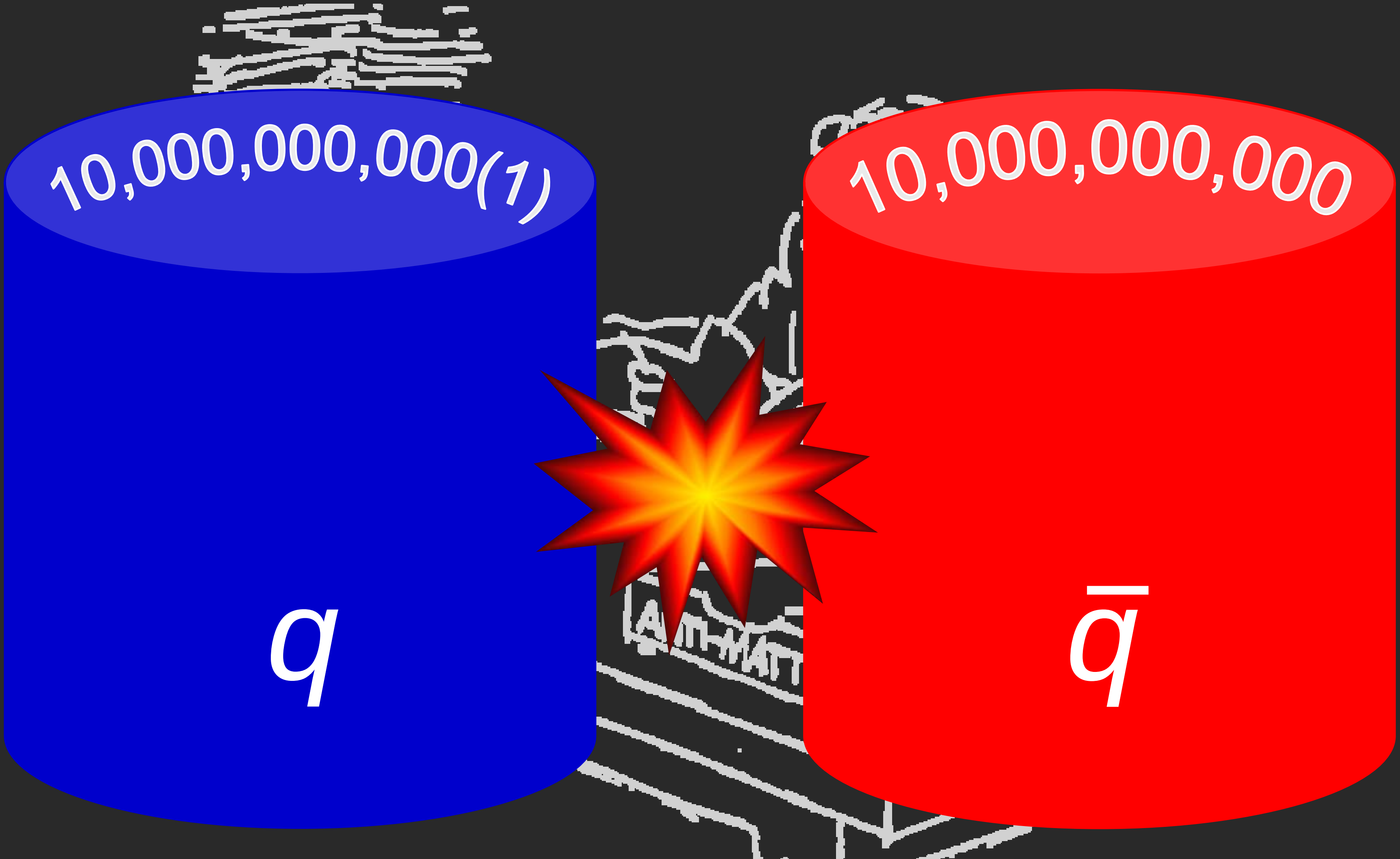
$$\chi\chi \rightarrow f\bar{f}$$

- When $\sigma_A \ll H(T)$, some χ freeze out and create weakly interacting **dark matter** Ω_{DM}
- The abundance of the dark matter inverse proportional to the annihilation cross section

$$\Omega_{\mathrm{DM}} \propto \frac{1}{\langle \upsilon\sigma_A \rangle} \propto m_\chi^2 \quad \Rightarrow \quad \Omega_{\mathrm{DM}} \approx 0.1 \;\; \rightarrow \;\; m_\chi \sim 0.1 - 1\,\mathrm{TeV}$$

COINCIDENCE ?

Matter-Antimatter Asymmetry



10,000,000,000(1)

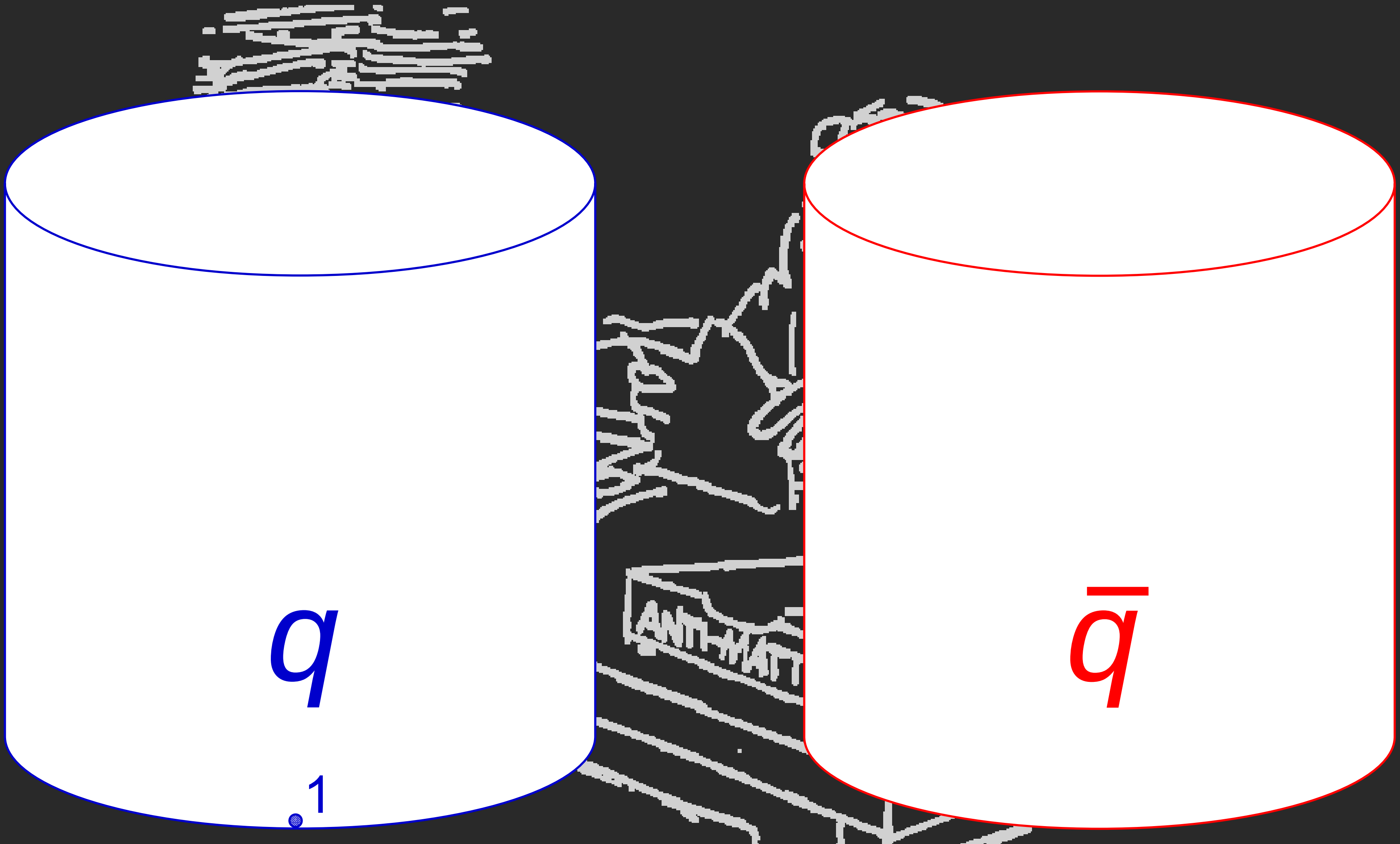
10,000,000,000

q

$\bar{q}$

Early universe ?

Matter-Antimatter Asymmetry



Current universe

Sakharov Conditions

- Is baryon asymmetry initial condition ? Possible ?
- Dynamically generated ?

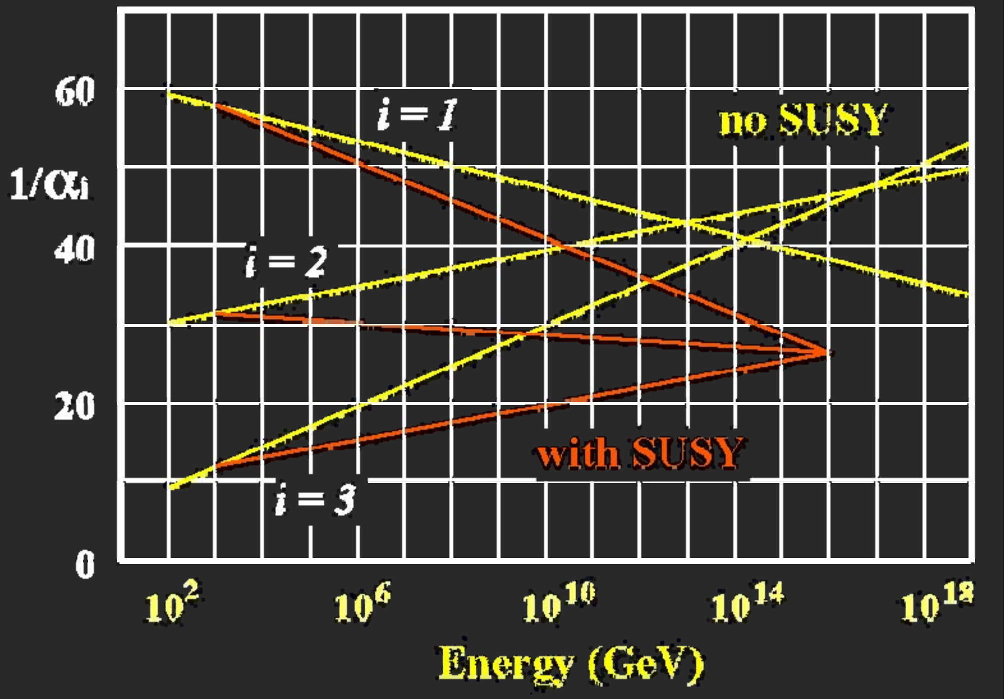
Sakharov conditions (1967) for Baryogenesis

1. Baryon number violation → new physics !
2. *C* and *CP* violation → (probably) new physics !
3. Departure from thermodynamic equilibrium (non-stationary system)

Grand Unification of the Gauge Couplings (GUT)

- Electromagnetic and weak couplings unify at *E* ~100 GeV
- When computing the renormalization group equations (=running) for the unified SU(3)×SU(2)×U(1) couplings α_1 (EM/hypercharge) α_2 (weak), and α_3 (strong), one finds that all three almost meet at *E* ~10^{15} GeV, but not quite !
- SM extensions such as Supersymmetry (SUSY) with a characteristic mass scale of ~1 TeV can have the right properties to adjust the RGEs and allow for GUT at *E* ~10^{16} GeV

T. Kondo (KEK)



➧ **Exact unification does not need to occur, but wouldn't it be very appealing if it did ?**

It would be consistent with the speculation that the three couplings (forces) are in effect different manifestations of a single overarching gauge symmetry

A Light Higgs ?

- If a Higgs boson with mass < 1 TeV is discovered, the Standard Model is complete !
- However, when computing radiative corrections to the bare Higgs mass a problem occurs:

Higgs
radiative
corrections

$$m_H^2 = m_0^2 + \delta m_H^2 \quad \text{where:} \quad \delta m_H^2 \propto \underbrace{\int_0^\infty d^4k \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2}}_{\text{Integral quadratically divergent}} + \ldots$$

- The cut-off sets the scale where new particles and physical laws must come in
- Above the EW scale we only know of two scales: GUT (~10^{16} GeV) and Planck (~10^{19} GeV)
- Such a cut-off would require an incredible amount of finetuning to keep m_H light and stable

$$m_H^2 \overset{?}{\overbrace{=}} (120\text{ GeV})^2 = m_0^2 + C \cdot \Lambda^2_{\text{cut-off}}$$

The natural Higgs mass seems to be M_{Pl} rather than the experimentally favoured value…

A Light Higgs ?

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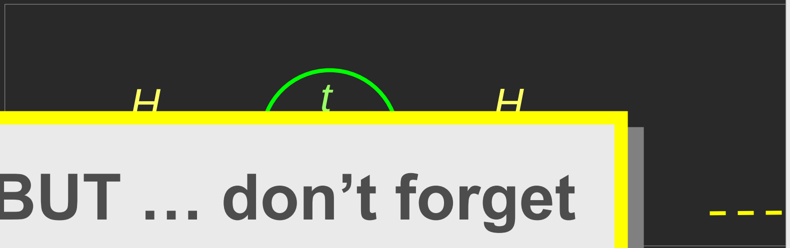
- However, when computing radiative corrections ccurs:

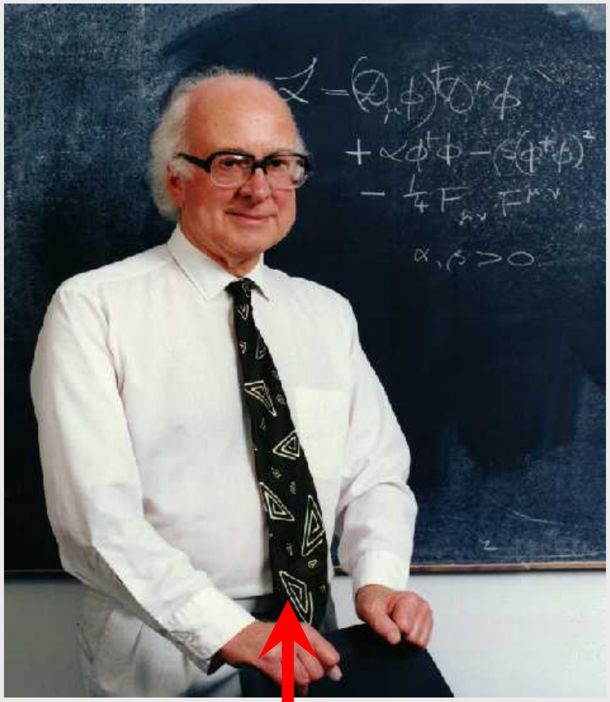


BUT … don't forget … the Higgs is not yet discovered !

$$\int d^4k \, \frac{k^2}{\left(k^2\right.}$$

Integral quadra

P.W. Higgs, Phys. Lett. 12 (1964) 132



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$$m_H^2 \overset{?}{=} (120\ \text{GeV})^2 =$$

Only unambiguous example of observed Higgs

[Old joke, plagiarized from D. Froidevaux, CERN]

experimentally favoured value…

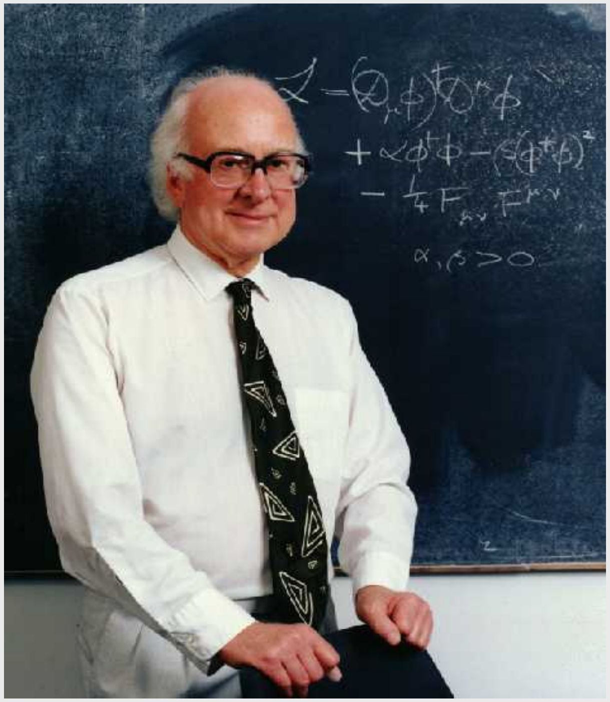
The Higgs

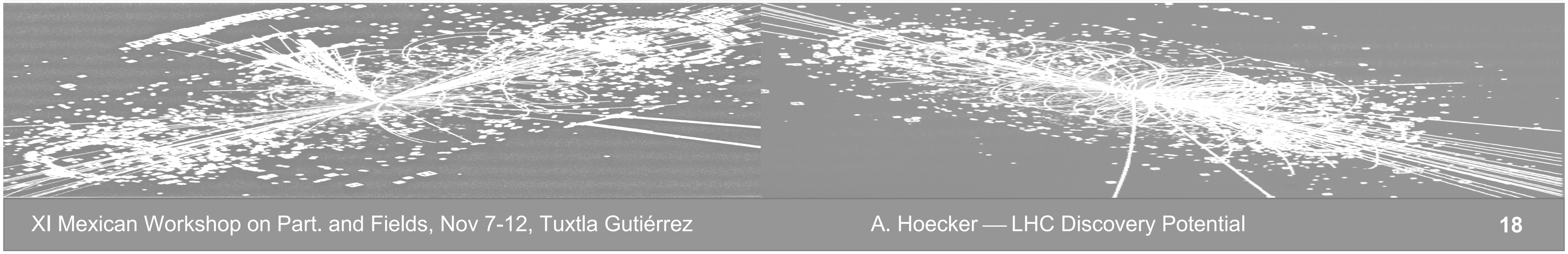
Let’s follow Daniel Froidevaux some more:

The Higgs has been with us for four decades as:

- a theoretical concept
- self-interacting scalar fields with non-zero vacuum expectation values
- an incarnation of the “Communist Party since it controls the *Masses*”
  [L. Alvarez-Gaumé at CERN summer school in Alushta]
- a painful part of the first chapter in our PhD thesis …

P.W. Higgs, Phys. Lett. 12 (1964) 132



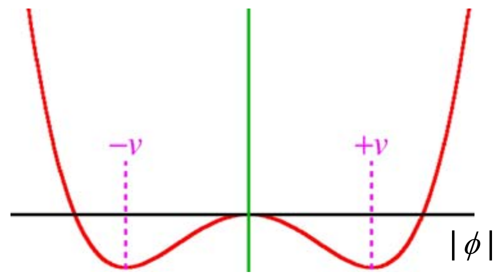


A single Slide on … the Higgs Mechanism

- The fermion and gauge-boson masses of the SM are dynamically generated via the **Higgs mechanism** when spontaneously breaking electroweak symmetry
- Recall the **Higgs "Mexican hat" potential at $T \approx 0$**:

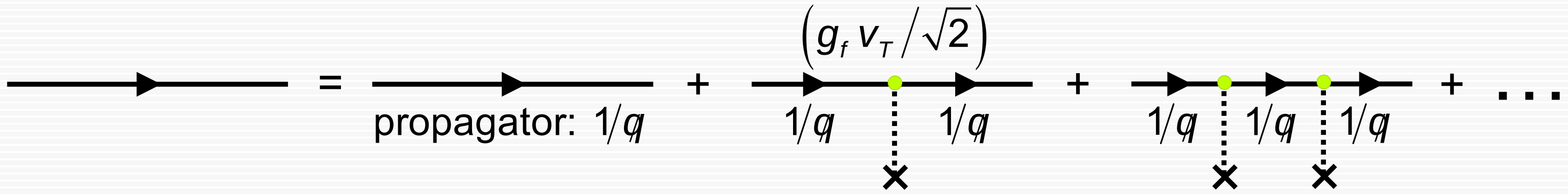
$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 \quad , \quad \mu^2 < 0$$

with vacuum expectation value: $\langle 0|\phi|0\rangle_{T=0} = \upsilon_{T=0}/\sqrt{2}$



$$\upsilon_{T=0} = \sqrt{-\frac{\mu^2}{2\lambda}} = \frac{1}{\sqrt{\sqrt{2}G_F}} = 246 \text{ GeV}$$

- At $T < T_{\text{EW}}$, the massless fermion fields interact with the non-vanishing Higgs "condensates":



- Geometric series yields massive propagator creating effective mass for fermion:

$$\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q} + \ldots = \frac{1}{q}\sum_{n=0}^{\infty}\left(\left(\frac{g_f v_T}{\sqrt{2}}\right)\frac{1}{q}\right)^n = \frac{1}{q - \left(g_f v_T/\sqrt{2}\right)}$$

similar for gauge bosons

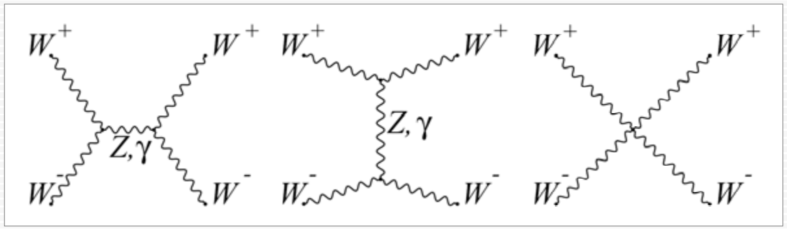
Theoretical Arguments for a light (but not too light) Higgs

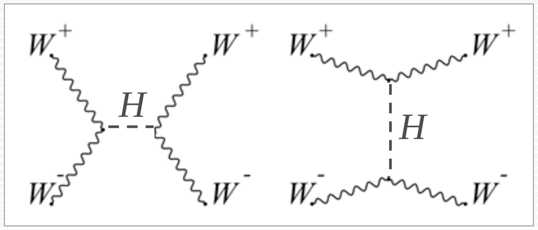
- **Unitarity**: if only Z and γ are exchanged, the amplitude of (longitudinal) W^+W^- scattering is:

$$A_{Z,\gamma}\left(W^+W^- \to W^+W^-\right) \propto \frac{1}{\upsilon^2}(s+t)$$

violating unitarity. The Higgs contributes with:

$$A_H\left(W^+W^- \to W^+W^-\right) \propto -\frac{m_H^2}{\upsilon^2}\left(\frac{s}{s-m_H^2}+\frac{t}{t-m_H^2}\right)$$





Higgs regularises total amplitude, if m_H not too large !

- **Landau Pole**: Higgs self-coupling in potential is UV divergent (→ only good solution is "trivial": $\lambda(M_W) \to 0$):

Coupling λ increases with mass μ: $\frac{d\lambda(\mu)}{d\ln\mu^2} \propto \lambda^2 \;\Rightarrow\; \lambda(\mu) = \frac{\lambda(\mu_0)}{\underline{1 - C\lambda(\mu_0)\ln(\mu/\mu_0)}}$

denominator can be =0
→ Landau pole!

Landau pole leads to upper limit: $m_H^2 \propto \lambda(\upsilon) < 53 \cdot \upsilon^2 \ln^{-1}(\Lambda/\upsilon) \approx 300\ (1500)\ \text{GeV}\ \left\{\Lambda = 10^{19}\ (10^3)\ \text{GeV}\right\}$

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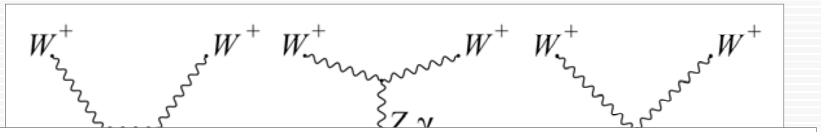
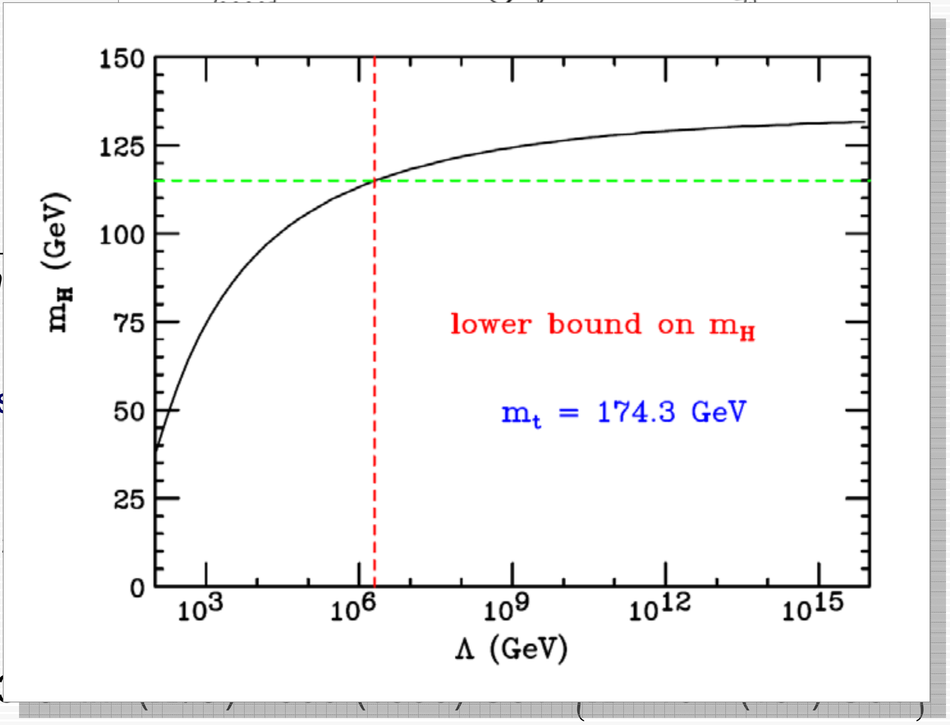


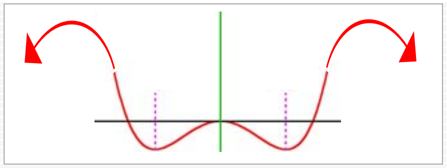


- **Landau Pole**: Higgs self-coupling in potential i divergent (→ only good solution is "trivial": $\lambda(M_W)$

Coupling λ increases with mass μ: $\frac{d\lambda(\mu)}{d\ln\mu^2} \propto \lambda$

Landau pole leads to upper limit: $m_H^2 \propto \lambda(\upsilon) < 5$

- **Stability**: for light Higgs (small λ), top quark contributions can decrease λ and make it negative; stability requirement leads to lower limit on m_H

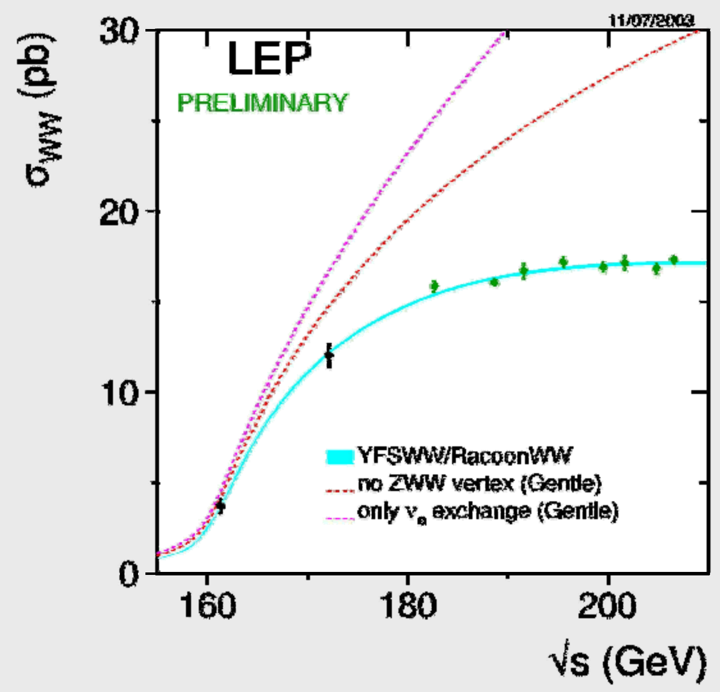


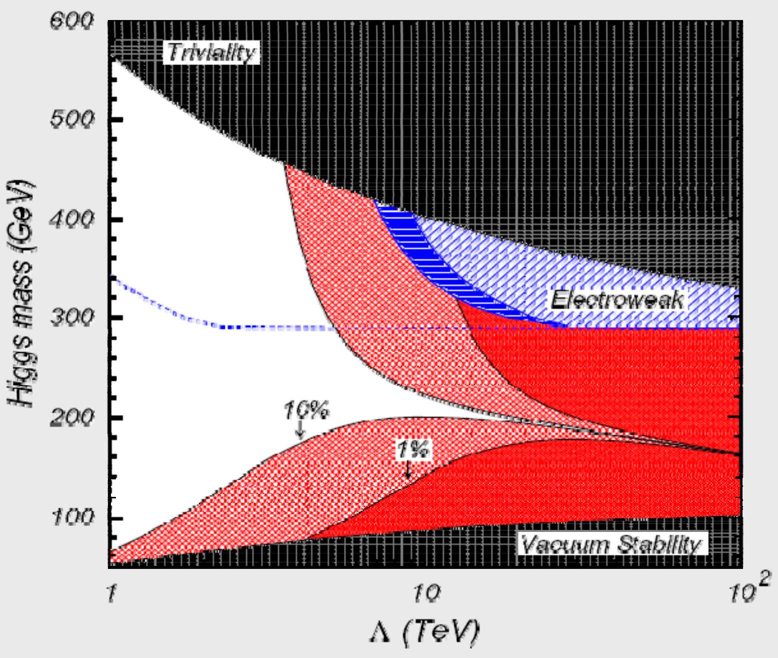
Stability criterion:

$\lambda(\mu) > 0,\ \forall \mu < \Lambda_{\text{cut-off}}$

A Light Standard Model Higgs Boson

- If indeed the mass of the Higgs is light it will be produced at the LHC
  → see Lorenzo Diaz' lecture





Experimental result: $e^+e^- \to W^+W^-$ cross section measured at LEP2. Contribution which grows like $s \cdot m_e^2$ is cancelled by Higgs amplitude

Higgs mass as a function of cut-off scale Λ

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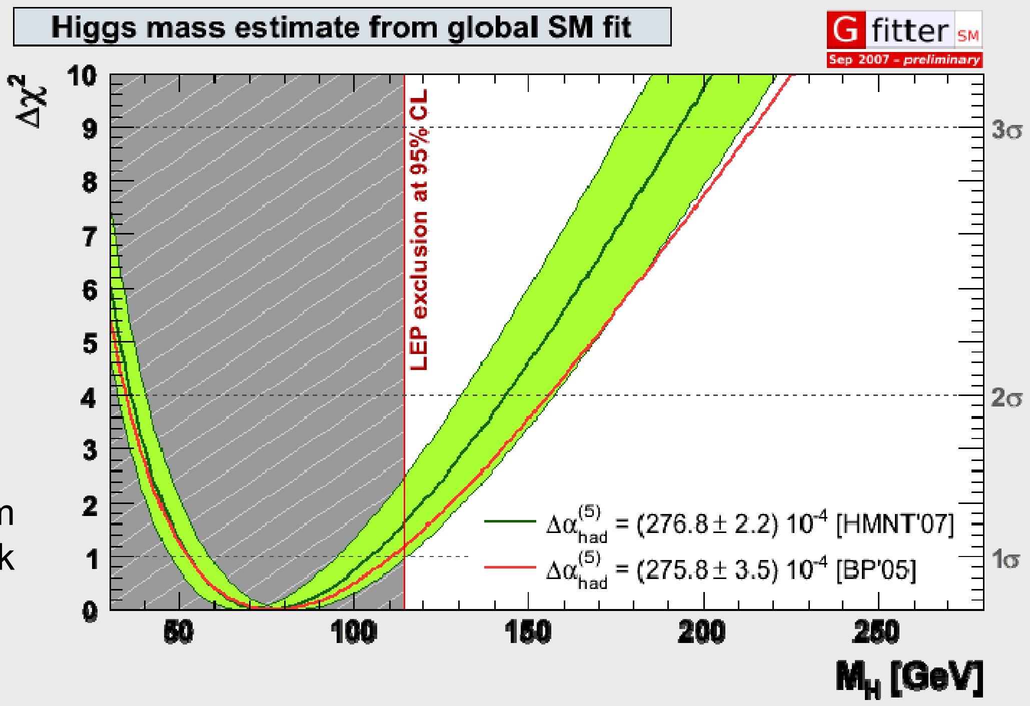


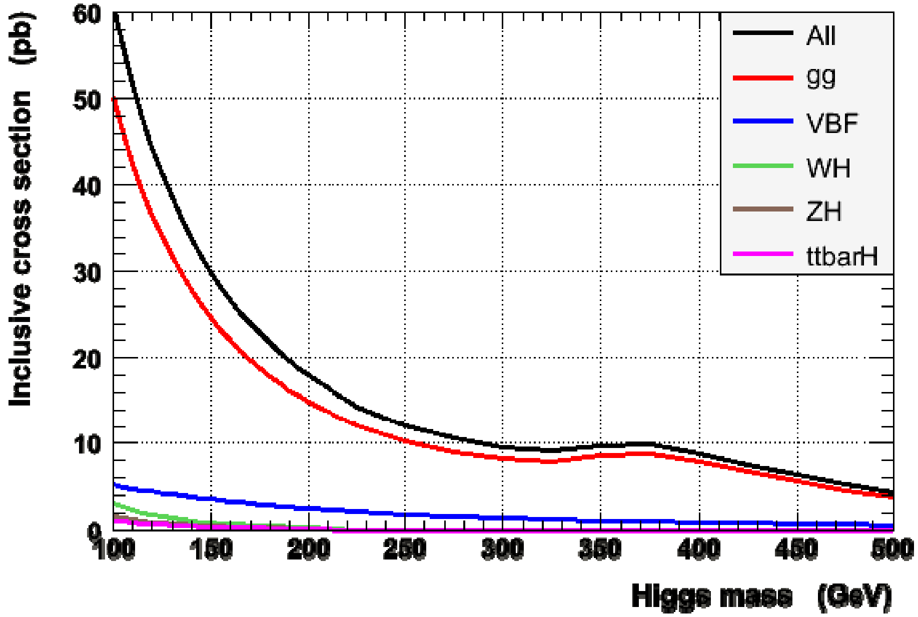
Higgs mass from fit to electroweak data

$$\Delta\rho_{(\mathrm{Higgs})} = \frac{11 G_F m_Z^2 \cos^2\theta_W}{24\sqrt{2}\pi^2} \log\left(\frac{m_H^2}{m_W^2}\right)$$

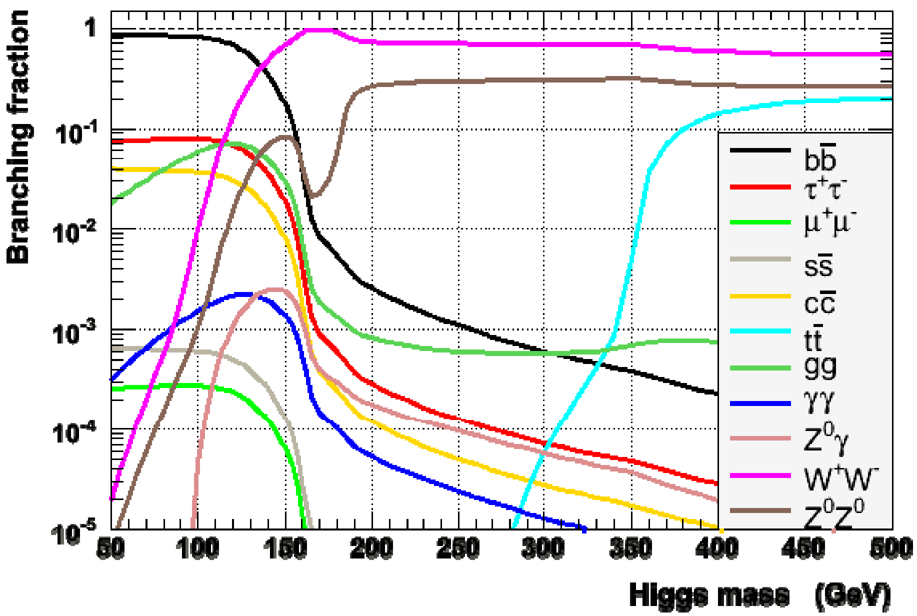
Standard Model Higgs @ LHC

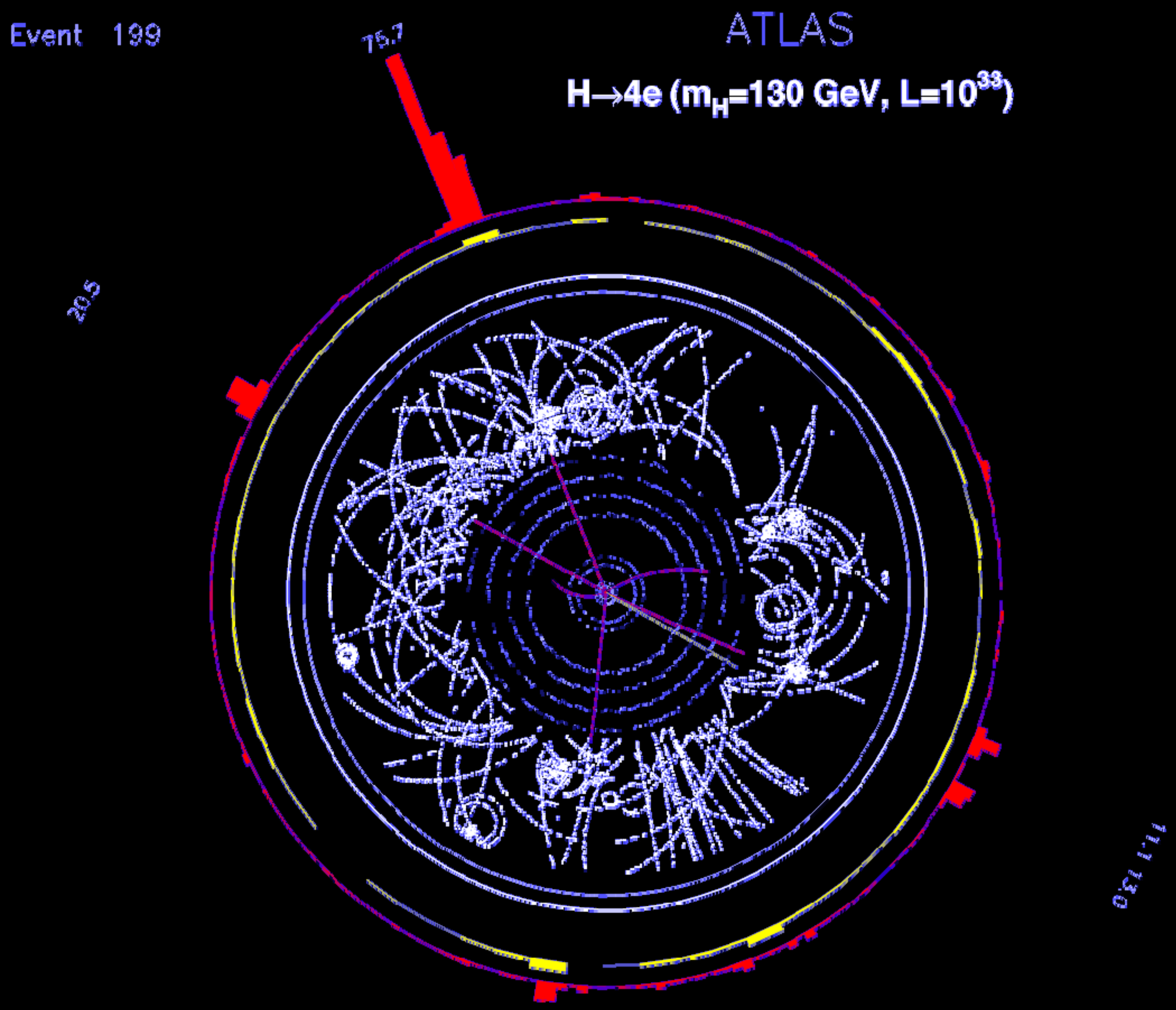
- Inclusive SM Higgs production cross section (left) and branching fractions (right)

SM Higgs inclusive NLO cross section (COM-PHYS-2007-024)



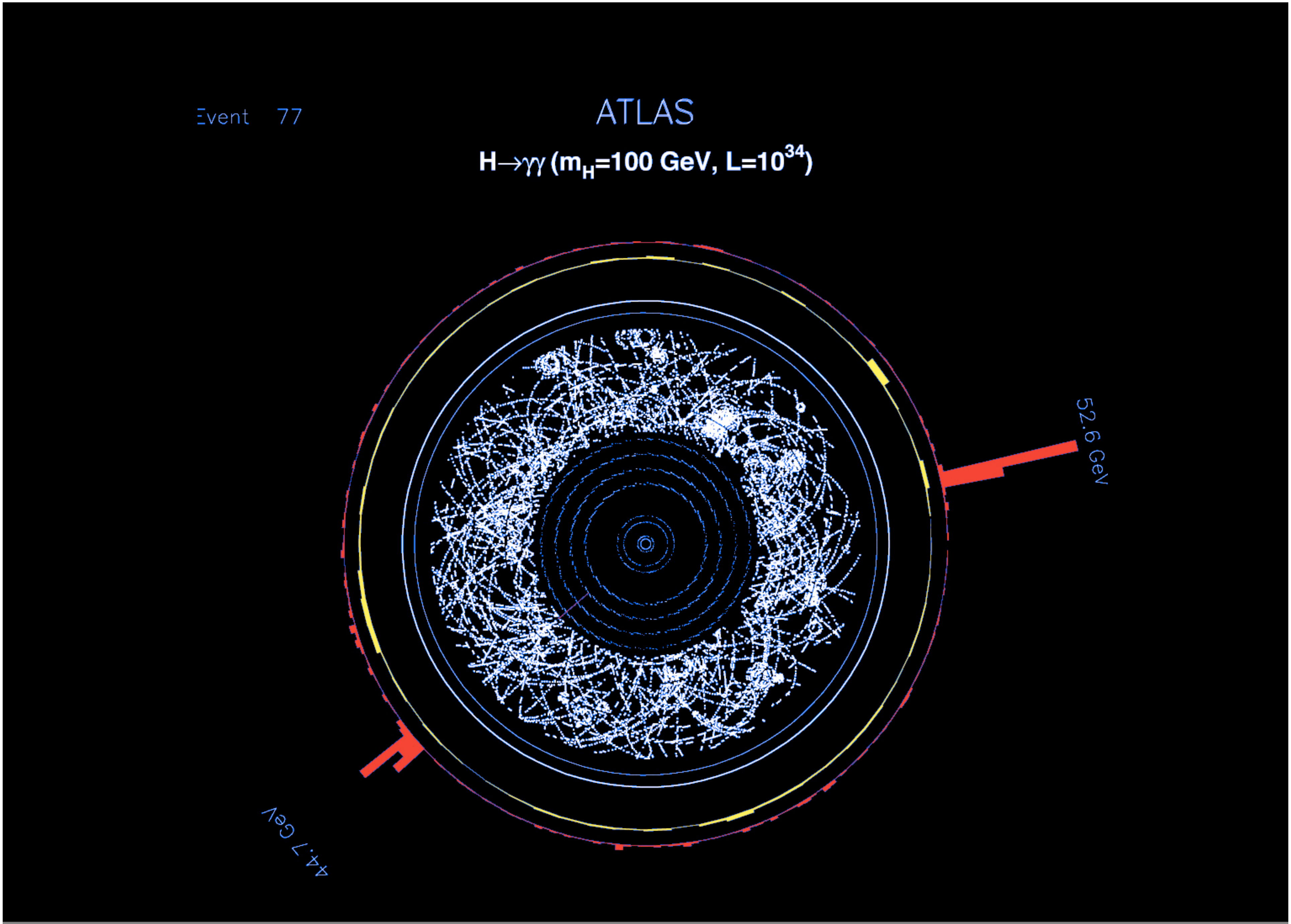
SM Higgs Branching Fractions (HDECAY 2.0)

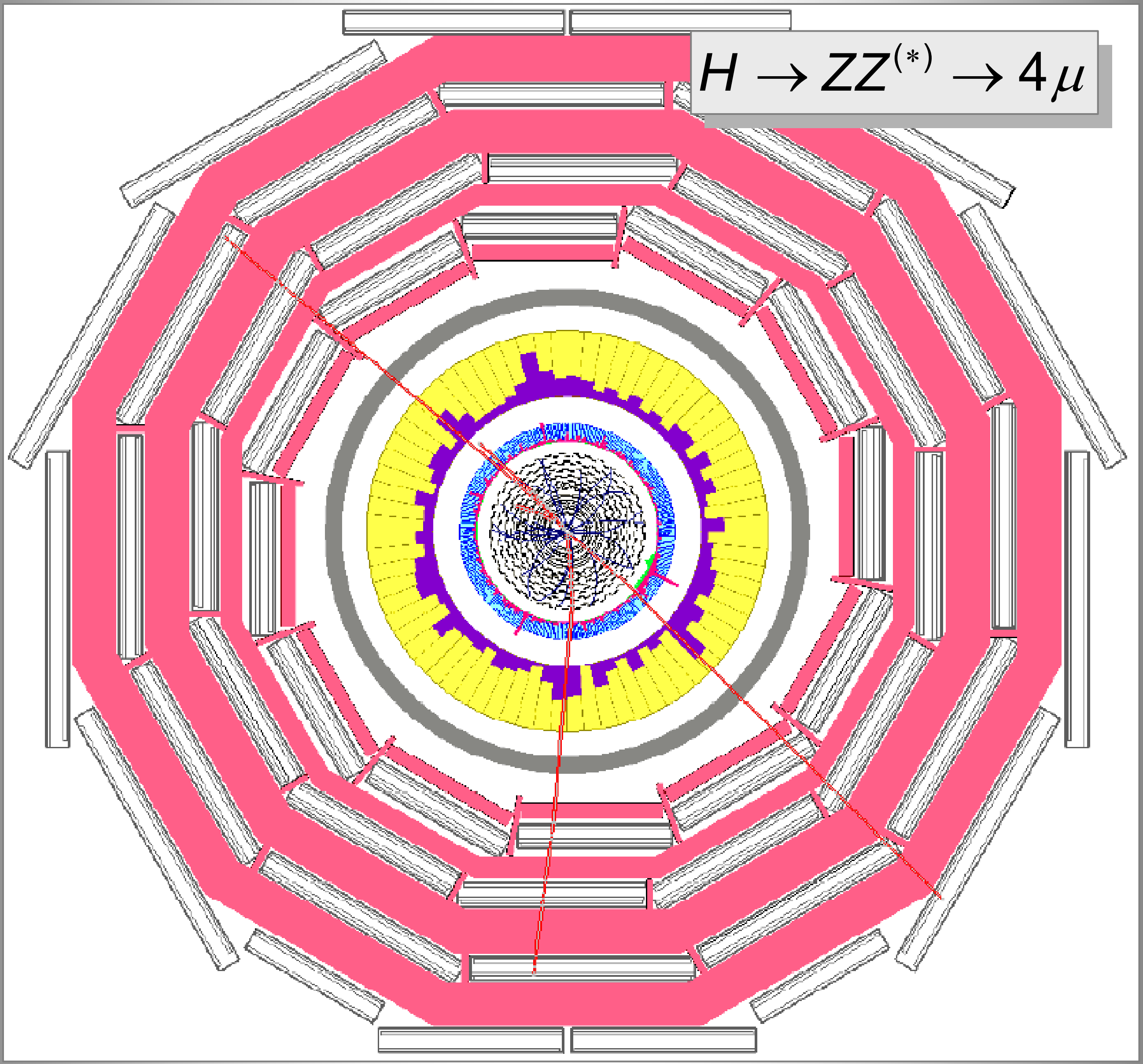




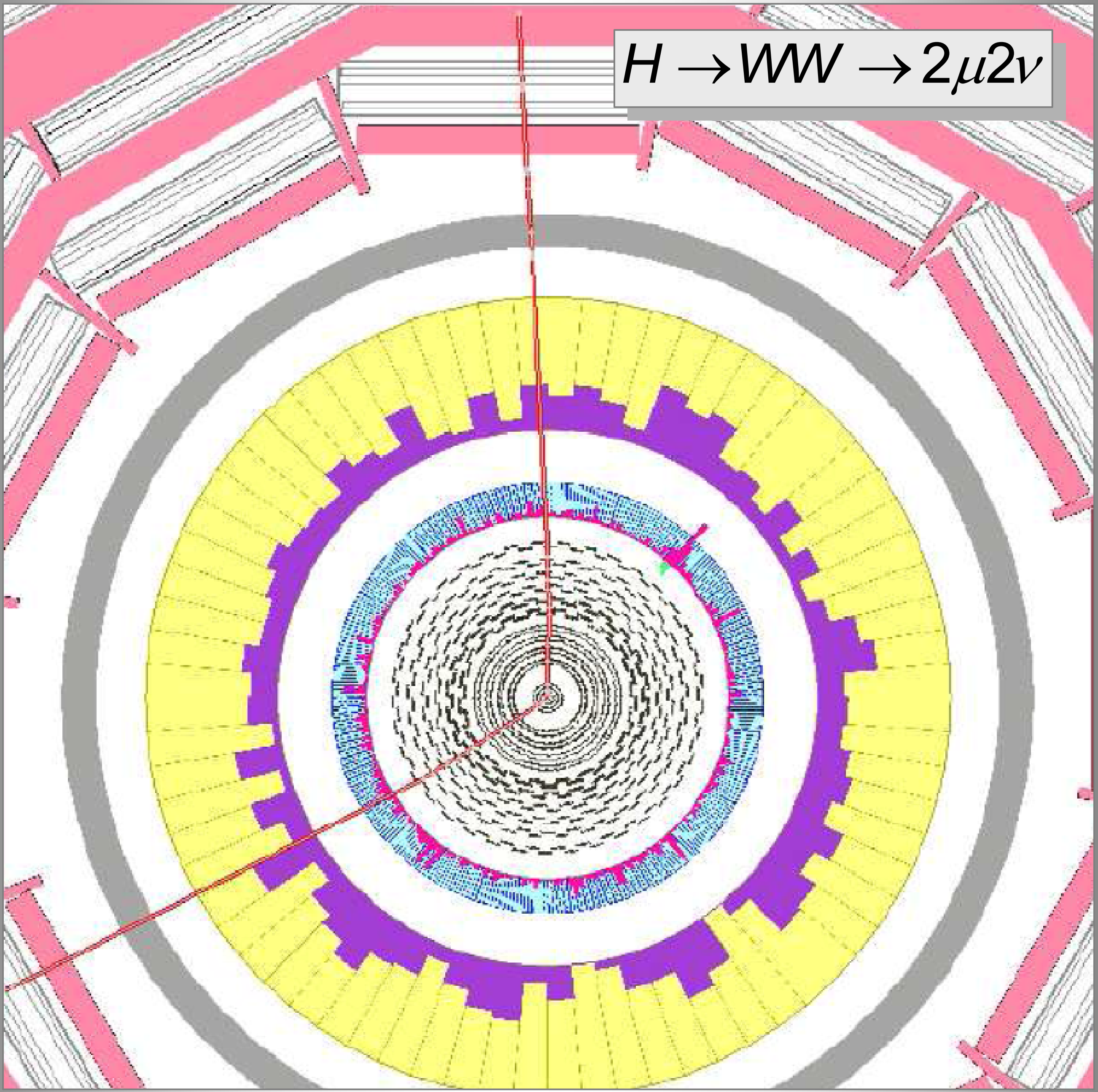
H→4e (m_H=130 GeV, L=10^{33})

$H \rightarrow \gamma\gamma$ (m_H=100 GeV, L=10^{34})

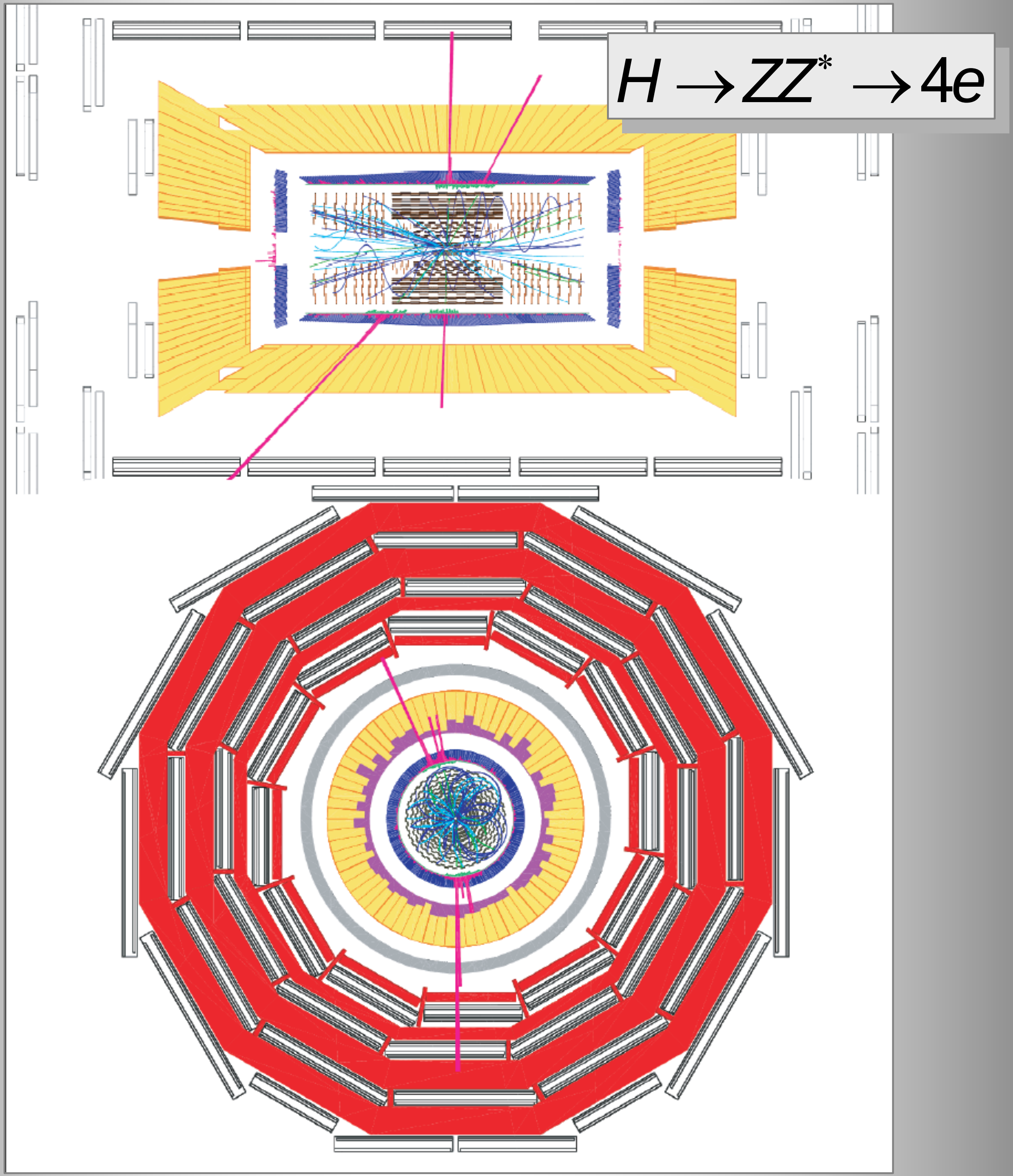




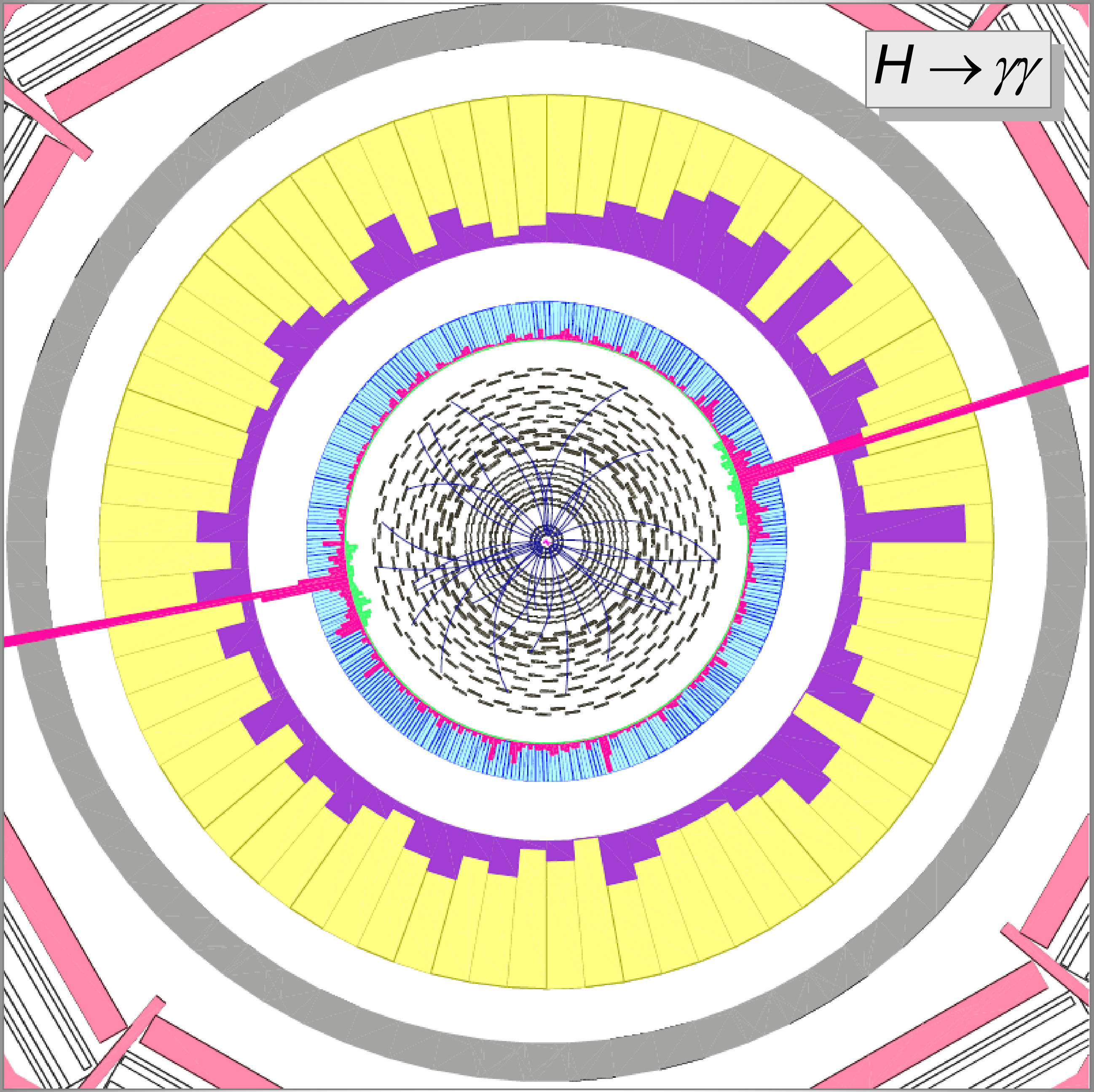
$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$



$H \rightarrow WW \rightarrow 2\mu 2\nu$



$H \to ZZ^* \to 4e$


$H \to \gamma\gamma$

The Hierarchy Problem

The Gauge Hierarchy Problem…

- …denotes this finetuning of parameters, and the strong dependence of physics at the weak scale on the physics at (presumably) much higher scale.
- If the loops are cut off at the scale of gravity, why is the scale of electroweak symmetry breaking so different from the scale of gravity? Why is $m_W \ll M_{\rm Pl}$?
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}m_W^2} \gg G_N = \frac{1}{M_{\rm Pl}^2}$

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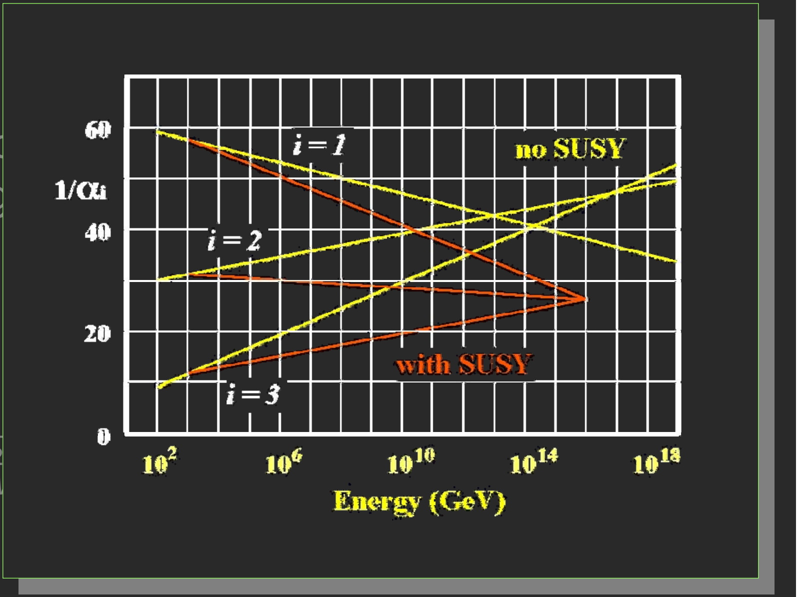

Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences. The “desert” between the EW and GUT/Planck scales is not empty!

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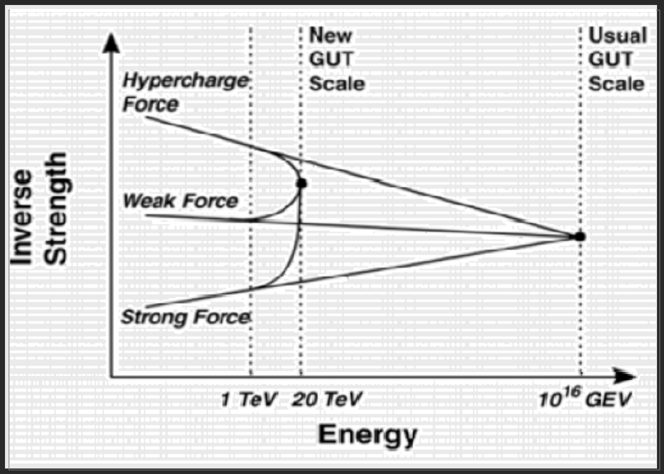

Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences. The “desert” between the EW and GUT/Planck scales is not empty!
- New physics modifies the running of the couplings, approaching GUT to the EW scale.

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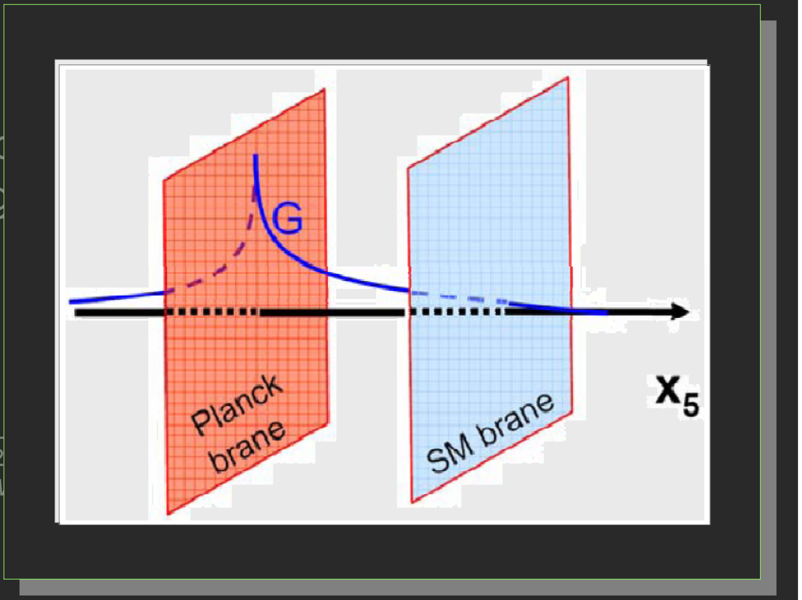
- If the loops are cut off at the scale of gravity, why is breaking so different from the scale of gravity? Why
- Equivalently, why is gravity so weak? $G_F = \frac{g^2}{4\sqrt{2}m_W^2}$



Possible solutions to the hierarchy problem:

- New physics appears not much above the EW scale and regularises the quadratic divergences. The “desert” between the EW and GUT/Planck scales is not empty!
- New physics modifies the running of the couplings, approaching GUT to the EW scale.
- Gravity is not as weak as we think, it’s only diluted in our 4D world but it is as strong as EW interactions in, *e.g.*, 5 or more dimensions, $(M_{Pl})^{5D} \sim O(\text{TeV})$

The Hierarchy Problem

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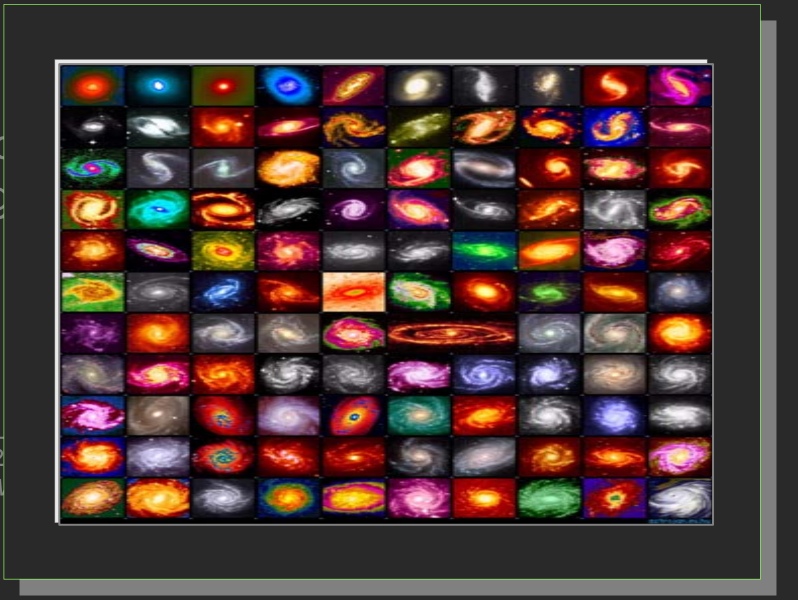

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- Gravity is not as weak as we think, it’s only diluted in our 4D world but it is as strong as EW interactions in, *e.g.*, 5 or more dimensions, $(M_{\rm Pl})^{5D} \sim O(\text{TeV})$
- Anthropic principle: the theory is finetuned. Explanation for parameter determination is statistical rather than dynamic.

New Physics: Why Not ?

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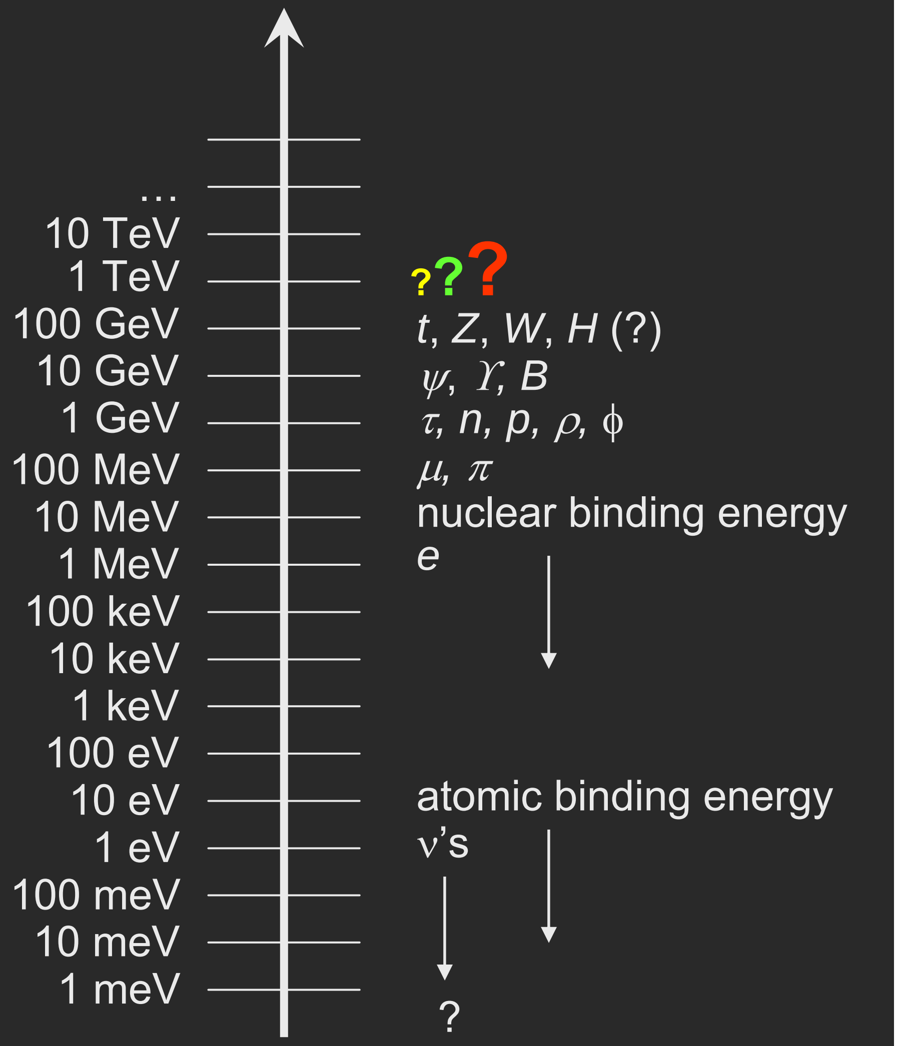
Summer School, CERN 2007

Why should there be a desert in the logarithmic energy scale ?



…	
10 TeV	
1 TeV	???
100 GeV	*t*, *Z*, *W*, *H* (?)
10 GeV	ψ, Υ, *B*
1 GeV	τ, *n*, *p*, ρ, ϕ
100 MeV	μ, π
10 MeV	nuclear binding energy
1 MeV	*e*
100 keV	
10 keV	
1 keV	
100 eV	
10 eV	atomic binding energy
1 eV	ν's
100 meV	
10 meV	
1 meV	?

What the New Physics Should Be …

Three diagrams give the largest contributions to the Higgs radiative corrections…

Top loop	$-(3/8\pi^2)\lambda_t^2\Lambda^2$	$\sim (2\ \text{TeV})^2$
Gauge boson loop	$(9/64\pi^2)g^2\Lambda^2$	$\sim (700\ \text{GeV})^2$
Higgs loop	$-(1/16\pi^2)\lambda^2\Lambda^2$	$\sim (500\ \text{GeV})^2$

Contributions of diagrams, assuming $\Lambda_{\text{cut-off}} \sim 10$ TeV

- The total mass-squared of the Higgs is the sum of these contributions and the tree-level
- What would be the cut-off (= new physics) scales if only small (~10%) finetuning existed

  → $\Lambda_{\text{top}} < 2$ TeV, $\Lambda_{\text{gauge}} < 5$ TeV, $\Lambda_{\text{Higgs}} < 10$ TeV
- Hence… with a new physics sensitivity of ~3 TeV, the LHC could discover the new physics !
- To naturally cancel these divergences, the new physics should couple to the Higgs and should be related to the particles in the loop (top, gauge, Higgs) by some symmetry

Extending the Standard Model ?

There are arguments ***against*** New Physics at 1 TeV:

- Electroweak precision data
- Flavour changing neutral currents
- *CP* violation in flavour and non-flavour sector
- Baryon and lepton number violation

Some Observations Beforehand (II)

- The hierarchy problem (among others) of the SM Higgs sector can be turned into a prediction that **new physics** is expected at the TeV scale
- Since precision data do not give hints for new physics, we can use the data to constrain "**effective models**" that have the particle content of the SM, and where new physics is parameterized by loop operators suppressed by the new physics scale $\Lambda > O(\text{TeV})$.
- The operators can be categorized by the **symmetries they break**, for example:

Broken symmetry	Operators	$O(\Lambda)$
Baryon number	$(QQQL)/\Lambda^2$	10^{12} TeV
Flavour (1st,2nd family), *CP*	$(dsds)/\Lambda^2$	10^4 TeV
Flavour (1st,3rd family), *CP*	$(dbdb)/\Lambda^2$	10^3 TeV
Flavour (2nd,3rd family), *CP*	$m_b(s\sigma_{\mu\nu}F^{\mu\nu}b)/\Lambda^2$	50 TeV

example only… many more indirect constraints

- The question is: **how to stabilize the light Higgs without violating the above bounds ?**
- The answer to this is by no means trivial, and the SM extensions discussed in the following only partially succeed in doing so … some apparent finetuning seems to be always involved

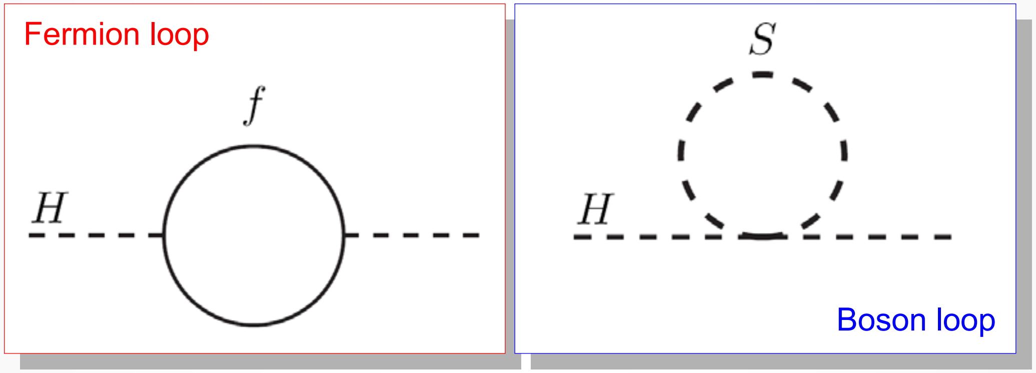
Extending the Standard Model

- **Supersymmetry**
- Extra dimensions
- Little Higgs

Supersymmetry (SUSY)

- We saw that the light scalar **Higgs** boson is **unprotected at GUT/ Planck scales**
- On the contrary, all the ***other*** light particles of the SM ***are* protected** against large scales:
  - Due to chiral symmetry, mass corrections to fermion are logarithmic in *E* (as opposed to quadratic)
  - Gauge symmetry protects the bosons (no correction to photon or gluon masses)

- **Fermion** and **boson** loops contribute with **different signs** to the Higgs radiative corrections: if there existed a **symmetry** relating these two, this could protect the masses of the scalar !



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- **Fermion** and **boson** loops contribute with **different signs** to the Higgs radiative corrections: if there existed a **symmetry** relating these two, this could protect the masses of the scalar !
- **Supersymmetry** realises this by transforming **bosons** ↔ **fermions**
  - SUSY transforms for example a scalar boson into a spin-½ fermion, whose mass is protected
  - Hence, the scalar mass is also protected (precisely through SUSY)
  - ➡ This solves the **naturalness** and the **hierarchy problems** of the SM (at least technically)
- Local gauge invariance of SUSY requires existence of spin-3/2 and spin-2 particles
  - This naturally introduces the spin-2 graviton, assumed to mediate the gravitational force

SM → SUSY

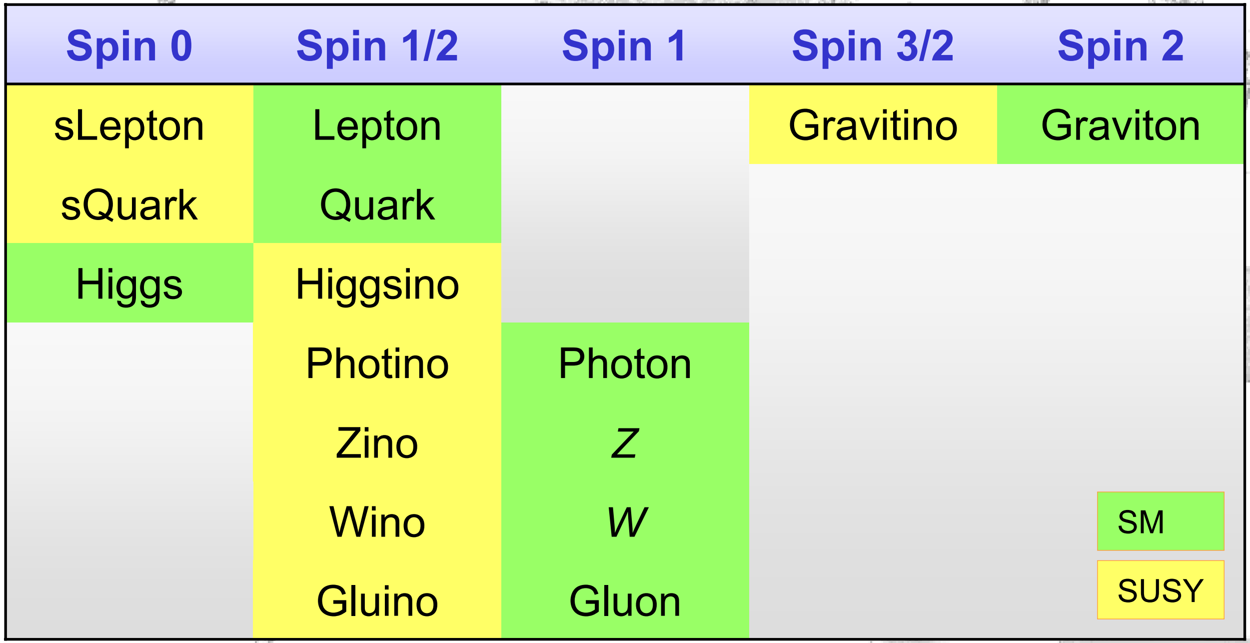
$$e_L \rightarrow \tilde{e}_L$$

$$\gamma \rightarrow \tilde{\gamma}$$

$$\ldots \rightarrow \tilde{\ldots}$$

Minimal Supersymmetric Standard Model – MSSM

- SUSY has: N_{dof} (bosons) = N_{dof} (fermions) [*cf*. SM: N_{dof}(bosons) $\ll$ N_{dof} (fermions)]
  - To create ***supermultiplets***, we need to add one ***superpartner*** to each SM particle
  - Superpartners have **opposite spin statistics** but otherwise **equal quantum numbers**
  - Need to introduce an **additional Higgs doublet** to the non-SUSY side



Spin 0	Spin 1/2	Spin 1	Spin 3/2	Spin 2
sLepton	Lepton		Gravitino	Graviton
sQuark	Quark			
Higgs	Higgsino			
	Photino	Photon		
	Zino	*Z*		
	Wino	*W*		
	Gluino	Gluon		

🟩 SM

🟨 SUSY

The MSSM Supermultiplets

Eigenstates of gauge

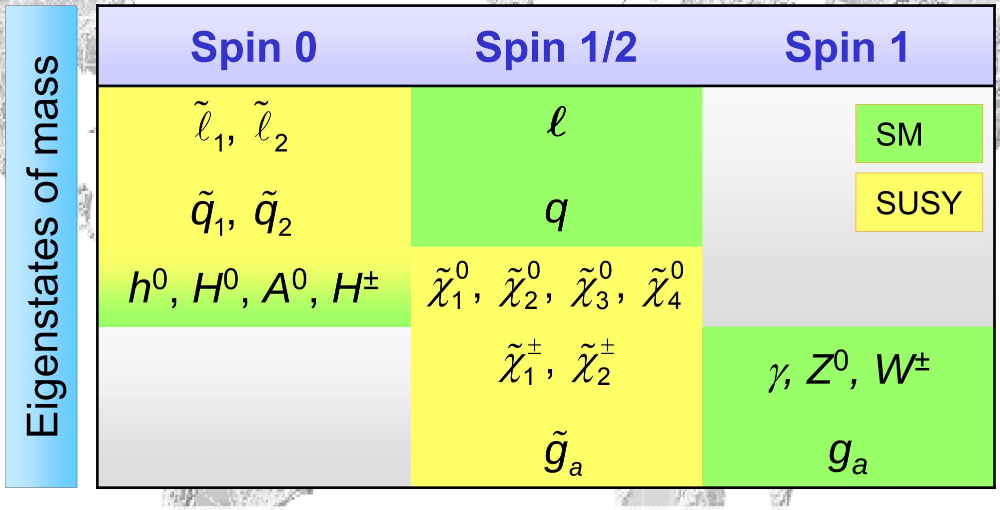
Superfield	Spin 0	Spin 1/2	Spin 1	SU(3)×SU(2)×U(1)
Q	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	–	$(3,2,\frac{1}{3})$
U^c	$\tilde{u}_R^*$	$\bar{u}_R$	–	$(\bar{3},1,-\frac{4}{3})$
D^c	$\tilde{d}_R^*$	$\bar{d}_R$	–	$(\bar{3},1,\frac{2}{3})$
L	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_L$	$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$	–	$(1,2,-1)$
E^c	$\tilde{e}_R^*$	e_R	–	$(1,1,2)$
H_1	$\begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}_L$	$\begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix}_L$	–	$(1,2,-1)$
H_2	$\begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}_L$	$\begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix}_L$	–	$(1,2,1)$
B	–	$\tilde{B}^0$	B^0	$(1,1,0)$
W	–	$\tilde{W}^{\pm,0}$	$W^{\pm,0}$	$(1,3,0)$
G	–	$\tilde{g}_a$	g_a	$(8,1,0)$

Chiral Super-multiplets

Gauge Super-multiplets

The full particle content of the MSSM: each SM helicity state has a corresponding "**s**partner" (the indices indicate the helicities of the SM partner)

The MSSM Supermultiplets



Eigenstates of mass

Spin 0	Spin 1/2	Spin 1
$\tilde{\ell}_1, \tilde{\ell}_2$	ℓ	
$\tilde{q}_1, \tilde{q}_2$	q	
$h^0, H^0, A^0, H^\pm$	$\tilde{\chi}^0_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3, \tilde{\chi}^0_4$	
	$\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2$	$\gamma, Z^0, W^\pm$
	$\tilde{g}_a$	g_a

🟩 SM

🟨 SUSY

The gauge-mixed physical states that propagate in space and time and that can be observed.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

Charginos : mass eigenstates of winos and charged higgsinos

The MSSM Supermultiplets

Note: all scalar particles with same *e*-charge, *R*-parity and colour quantum number can mix !

Eigenst

	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\gamma, Z^0, W^\pm$
	$\tilde{g}_a$	g_a

The gauge-mixed physical states that propagate in space and time and that can be observed.

Neutralinos: mass eigenstates of photinos, zinos, neutral higgsinos

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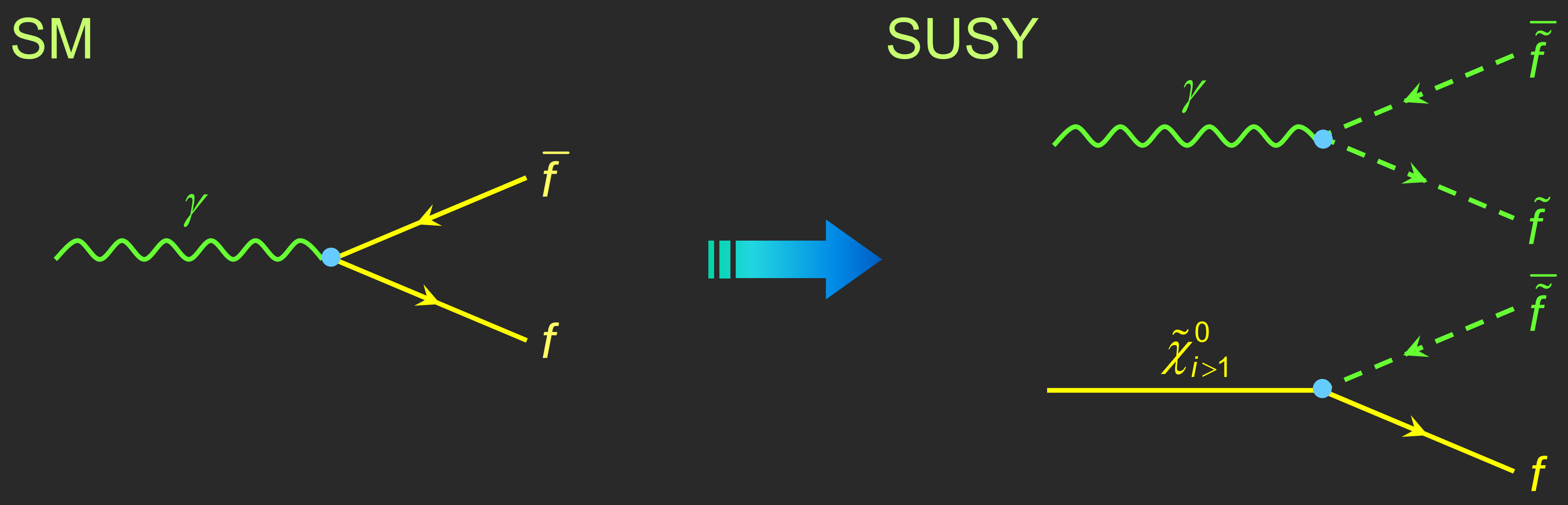
Interactions of SUSY Particles



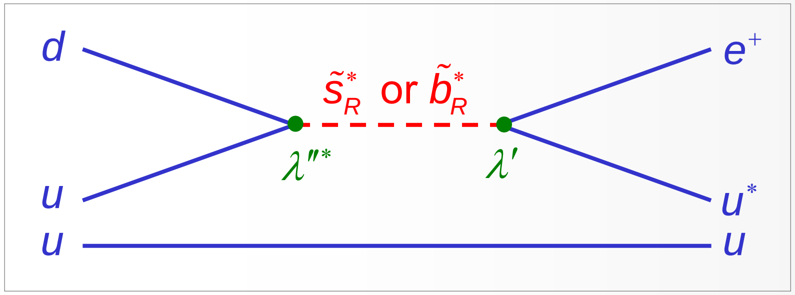
MSSM: take any SM diagram and switch the spin of two lines

R-Parity

- The *superpotential* contains new lepton- or baryon number violating couplings

$$\left[\frac{1}{2}\lambda\cdot LLE^c + \lambda'\cdot LQD^c + \mu'\cdot LH_2\right]_{\Delta L=1}$$

$$\left[\frac{1}{2}\lambda''\cdot U^cD^cD^c\right]_{\Delta B=1}$$



Proton decay
$p \rightarrow e^+\pi^0$

Unless couplings very small – or sfermions very heavy

- Avoid proton decay by introducing discrete *R*-parity (or matter-parity):

$$R = (-1)^{3B+L+2S} = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for SUSY partners} \end{cases}$$

  - All interactions with odd numbers of SUSY particles are forbidden (SUSY production in pairs !)
  - The lightest SUSY particle (LSP) is stable; if LSP neutral → missing energy in detector
  - SUSY naturally provides a dark matter candidate (should be neutral (WIMP) → $\tilde{\chi}_1^0$ LSP candidate)

- *R*-parity has important phenomenological and <u>experimental</u> consequences (see later)

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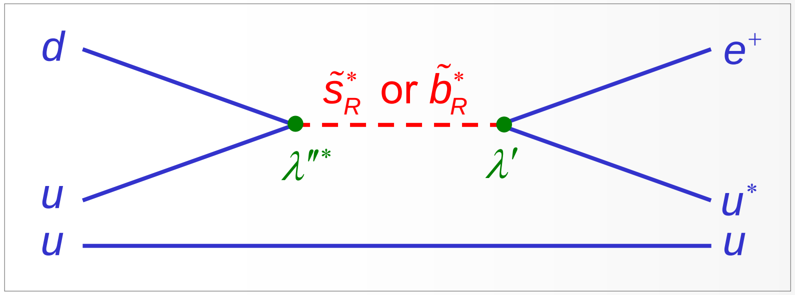

Proton decay
$p \to e^+\pi^0$

Unless couplings very small – or sfermions very heavy

- Throughout this lecture, we will assume that *R*-parity is conserved

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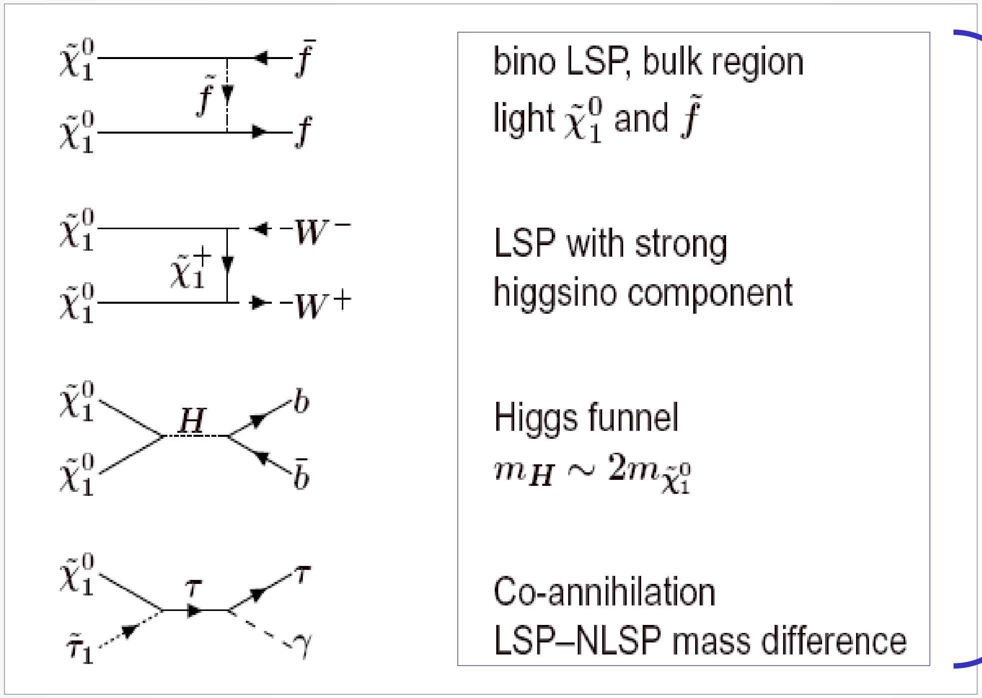
SUSY and Dark Matter

- *R*-parity provides **dark matter candiates**: sneutrino (ruled out?), gravitino and **neutralino**
- The **χ^0 LSP** as **thermal relic**: relic density computed as thermally avaraged cross section of all χ^0 annihilation channels → **Cold dark matter density: $\Omega_{DM}h^2 \sim \langle\sigma v\rangle^{-1} \sim 1\ \text{pb}^{-1}$**



bino LSP, bulk region
light $\tilde{\chi}_1^0$ and $\tilde{f}$

LSP with strong
higgsino component

Higgs funnel
$m_H \sim 2m_{\tilde{\chi}_1^0}$

Co-annihilation
LSP–NLSP mass difference

© Sabine Kraml

Denotes particular SUSY parameter settings (see later for mSUGRA)

- CMB measurement: $0.094 < \Omega_{DM}h^2 < 0.129$ strongly bounds SUSY parameter space

[However, bounds are model-dependent: MSSM parameters, *R*-parity, other DM candidates, ...]

Observations

- If SUSY is unbroken (and *R*-parity is conserved), the MSSM has only a single additional parameter arising from the new Higgs doublet
- This is however not realised in nature:
  - In a given multiplet, the masses of the (s)particles are identical, but no scalar electron is observed
  - EW symmetry breaking would be impossible (positive or zero Higgs potential)
- ➔ SUSY – if it exists – must be broken in the vacuum state chosen by *our* nature !

- Spontaneous SUSY breaking is much more complicated than the EWSB in the SM
- Masses are added by hand to the SUSY Lagrangian ("soft" symmetry beaking)
  - Unlike massive fermions, massive sfermions do not break gauge symmetry of the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}$$

Caution: doesn't SUSY breaking also break our all-order cancellation of the Higgs radiative corrections ?
→ yes, but only logarithmically: $\delta m_H^2 \sim \ln(\Lambda_{\text{cut-off}}/m_{\text{soft}})$

m_{soft} should not be too large because we don't want to finetune when stabilising the Higgs

Observations

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$\tilde{A}^{\dagger}\mathbf{m}_A^2\tilde{A}$, where: $\tilde{A}=\tilde{Q},\tilde{L},\tilde{U}^c,\tilde{D}^c,\tilde{E}^c$	Squark and slepton terms ($\mathbf{m}^2_A$: 3×3 matrix)
$m_{H_1}^2 H_1^* H_1 + m_{H_2}^2 H_2^* H_2 + \left(\mu B \cdot H_1 H_2 + \text{h.c.}\right)$	Higgs boson mass terms
$\tilde{U}^c\mathbf{A}_u\tilde{Q}H_2 + \tilde{D}^c\mathbf{A}_d\tilde{Q}H_1 + \tilde{E}^c\mathbf{A}_e\tilde{L}H_1 + \text{h.c.}$	Trilinear Yukawa couplings ($\mathbf{A}_i$: 3×3 matrices)
$M_1\tilde{B}\tilde{B} + M_2\tilde{W}\tilde{W} + M_3\tilde{g}_a\tilde{g}_a + \text{c.c.}$	Gaugino mass terms

MSSM Parameters

- The MSSM defined by these soft SSB terms has a many free parameters

Let’s first recall the free Standard Model parameters:

fermion masses:	9
quark-mixing matrix (CKM):	4
boson masses:	2
coupling constants:	3
strong *CP* parameter:	1
	$\sum = 19$ (included in the MSSM parameters)

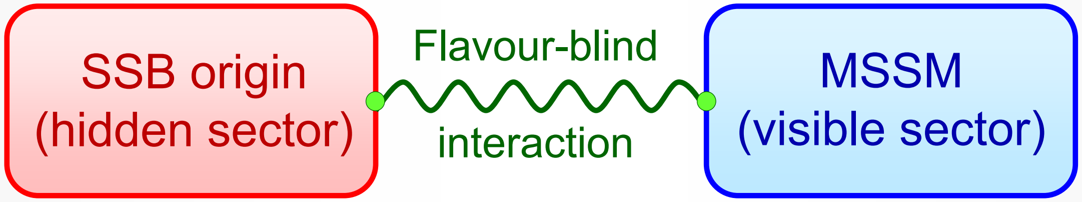
MSSM Parameters

- The MSSM defined by these soft SSB terms has a many free parameters
- The flavour-independent sector has:
  - 3 real gaugino couplings and 3 complex gaugino masses
  - Higgs sector has: complex μ (from superpotential) and B (soft-term multiplying $\mu H_1 H_2$), and m_{H1}, m_{H2}
  - ➨ Removing 2 unphysical phases (due to U(1) symmetries), leaves 13 free parameters
- The flavour sector has (not considering neutrino mass matrices here):
  - 6 complex 3×3 matrices: Y_u, Y_d, Y_f (Yukawa couplings) and $\mathbf{A}_u$, $\mathbf{A}_d$, $\mathbf{A}_e$ (trilinear couplings)
  - 5 mass matrices: $\mathbf{m}^2_{\tilde{Q}}$, $\mathbf{m}^2_{\tilde{L}}$, $\mathbf{m}^2_{\tilde{U}^c}$, $\mathbf{m}^2_{\tilde{D}^c}$, $\mathbf{m}^2_{\tilde{E}^c}$
  - ➨ This gives 153 parameters (84 moduli and 69 phases); removing unphysical phases, and using unitarity reduces this to 110 free parameters (69 moduli and 41 phases)
- Hence, the generic MSSM has **124 free parameters** (of which 44 are *CP*-violating phases!)
- Many of these parameters are already constrained from experiment:
  - Lepton sector: electric dipole moments (EDMs), magnetic moments, charged-lepton flavour violation
  - Quark sector: *n*-EDM, rare (radiative) *B* decays, flavour-changing neutral currents, *CP* violation

➨ **It is very difficult to introduce SSB without creating a conflict with experimental data**
On the other hand: if SUSY is discovered, we'd already know much about its flavours

C(onstrained)MSSMs: Modeling SUSY Breaking

- One can assume that SSB is hidden, and the various models then differ in how the SSB is transmitted through flavour-blind interactions to the observables



SSB origin (hidden sector)

Flavour-blind interaction

MSSM (visible sector)

- Through gravitational interaction (SUGRA): the minimum model mSUGRA has only 5 parameters:

At GUT scale →

$$m_0^2 = M_{\tilde Q}^2 = M_{\tilde U}^2 = M_{\tilde D}^2 = M_{\tilde L}^2 = M_{\tilde E}^2 = m_{H_1}^2 = m_{H_2}^2$$

$$m_{1/2} = M_1 = M_2 = M_3$$

$$A_0 = A_u = A_d = A_e$$

$$\tan\beta = v_2/v_1$$

$$\mathrm{sgn}(\mu)$$

$|\mu|$ is obtained from other mSUGRA parameters and m_Z after minimisation of Higgs potential

The renormalisation group equations govern the running to the EW scale

At one loop all M_i/α_i are equal, so that:

$m_{\tilde q} \gg m_{\tilde\ell_L} \approx m_{\tilde\nu} < m_{\tilde\ell_R}$

Lightest neutralino is LSP

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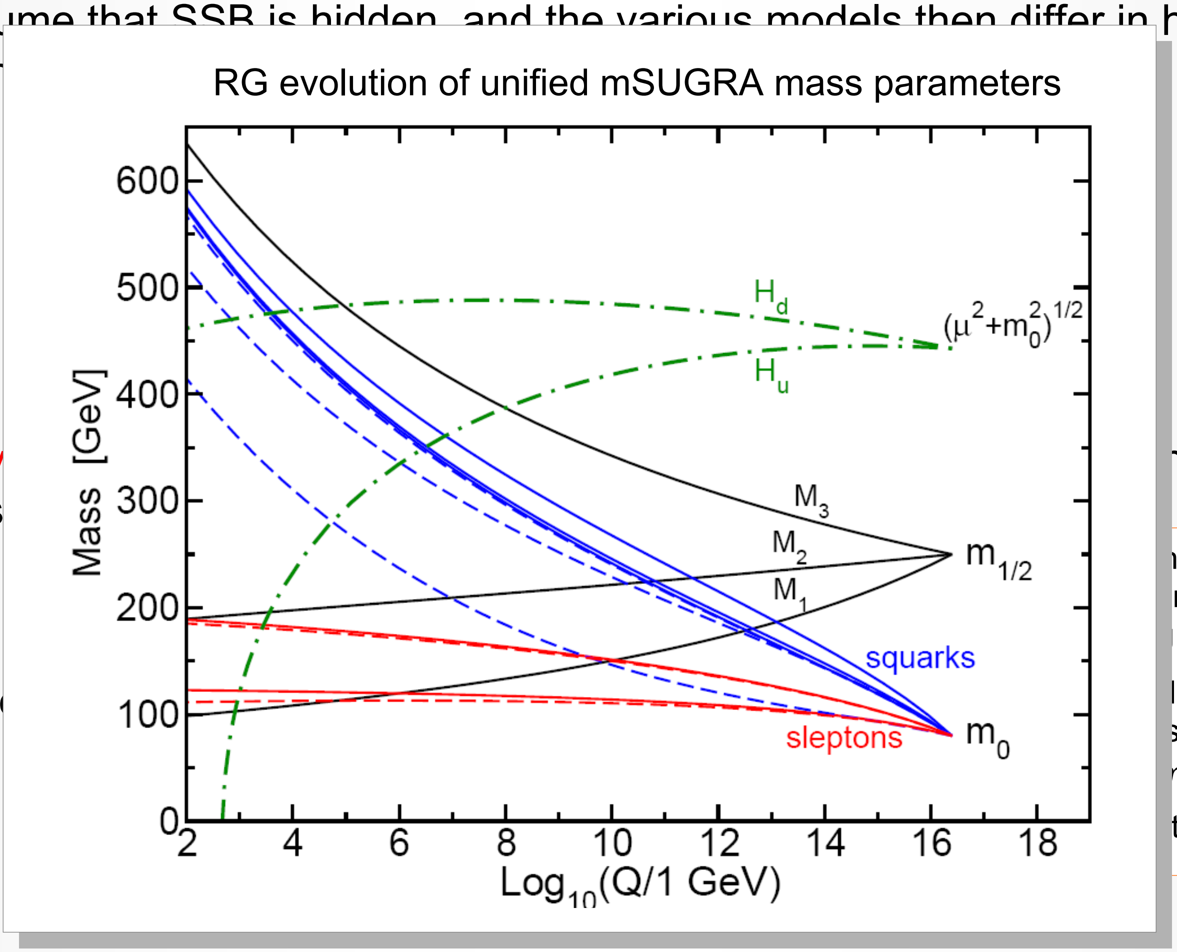

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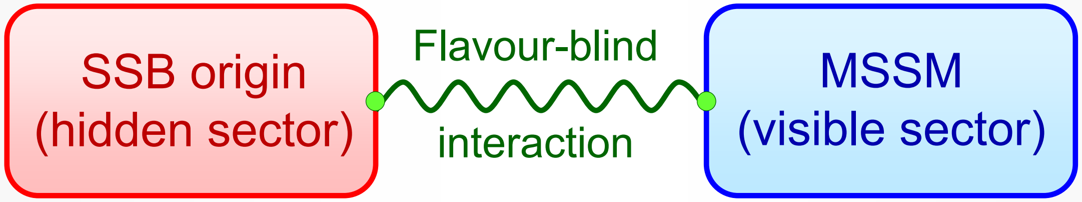
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Lightest neutralino is LSP

- Through gauge interaction (GMSB): “messenger fields” transmit the SSB to the MSSM
  - The SSB scale is much smaller than in SUGRA
  - Very light gravitino is LSP, different experimental signature than SUGRA (where $m_{3/2} \sim m_{\mathrm{soft}}$)

Gaugino Mass Hierarchies

Hierarchy	**Phenomenological Consequences**
$M_3 > M_2 > M_1$	mSUGRA – Jets, leptons & missing energy
$M_3 > M_1 > M_2$	Lepton cascades, lightest slepton charged
$M_2 > M_3 > M_1$	Only jets & missing energy
$M_1 > M_3 > M_2$	Jets & missing energy and/or lightest slepton charged
$M_2 > M_1 > M_3$	Gluino may be long lived, at least 4-body decay

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The Supersymmetric Higgs Sector

- At least 2 Higgs doublets with opposite hypercharge (Y_H) are necessary to realise EWSB

$$H_1^{Y_{H_1}=-1} = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2^{Y_{H_2}=+1} = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$$

Theoretical reasons:

1. Require $\Sigma_{f \in Gen..} Y_f = 0$ to cancel chiral anomalies
2. In SM, masses of weak isospin fermions created by ϕ and $i\tau_2\phi^*$, but conjugated superfields not allowed in superpotential

- Remember, the SM Higgs potential reads:

$$V_H = \mu^2 |H|^2 + \lambda |H|^4$$

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- The MSSM potential involving the Higgs fields reads $(m_{1(2)}^2 = m_{H_{1(2)}}^2 + |\mu|^2,\ m_{12}^2 = \mu B)$

$$V_H = \frac{1}{8}\left(g^2 + g'^2\right)\left(|H_1|^2 - |H_2|^2\right)^2 + \frac{1}{2} g^2 \left|H_1^\dagger H_2\right|^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_{12}^2 \varepsilon_{ij}\left(H_1^i H_2^j + H_1^{*i} H_2^{*j}\right)$$

SM: λ

- The only free parameters are the m_i. Quartic couplings of the Higgs are constrained by the gauge coupling constants, g, g', in SUSY, while they are free (parameterised by λ) in the SM

➨ Contrary to the SM, an upper bound on the lightest Higgs mass can be set in SUSY !

SUSY Higgs Doublet – Species & Masses

- The vacuum expectation values (VEV) of the neutral Higgs fields are:

$$\langle H_1^0 \rangle = v_1/\sqrt{2},\ \langle H_2^0 \rangle = v_2/\sqrt{2} \quad \text{with} \quad v_1^2 + v_2^2 = v^2 = (246\ \text{GeV})^2$$

  - $v_{1(2)}$ gives mass to fermions with weak isospin $I_z = -1/2$ $[d_i, e_i]$ ($+1/2$ $[u_i, \nu_l]$)
  - The ratio of VEVs determines the mixing parameter: $\tan\beta = v_2 / v_1$

- After EWSB, 5 out of 8 degrees of freedom (dof) become the physical Higgs fields

$$h_{CP\text{-even}}^{(\text{light})},\ H_{CP\text{-even}}^{(\text{heavy})},\ A_{CP\text{-odd}},\ H^+,\ H^-$$

  - As in the SM, the remaining 3 dof become the longitudinal modes of W^+, W^- and Z^0

- The 6 parameters of the MSSM Higgs sector reduce to 2. By convention use: **$\tan\beta$, m_A**

- Large **$\tan\beta$** values enhance MSSM Higgs couplings to down-type fermions, such as b and τ

MSSM Higgs Searches at LEP

- The masses of the physical fields are obtained by minimising the Higgs potential; at tree level:

$$m_h = \frac{1}{\sqrt{2}}\left(m_A^2 + m_Z^2 - \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos 2\beta}\right)^{1/2} < m_Z \qquad m_{H^\pm} = \sqrt{m_A^2 + m_W^2} > m_W$$

For $m_A \gg m_Z$ [“*decoupling*”] → $m_{H\pm} \approx m_A \approx m_H$ and $m_h \approx m_Z\,|\cos 2\beta|$

- If there weren’t higher order corrections (m_h< 128 GeV) it would have been excluded already !

Higgs radiative corrections

$$\delta m_h^2 = \frac{3G_F m_t^4}{\sqrt{2}\pi^2}\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \ldots$$

MSSM Higgs Searches at LEP

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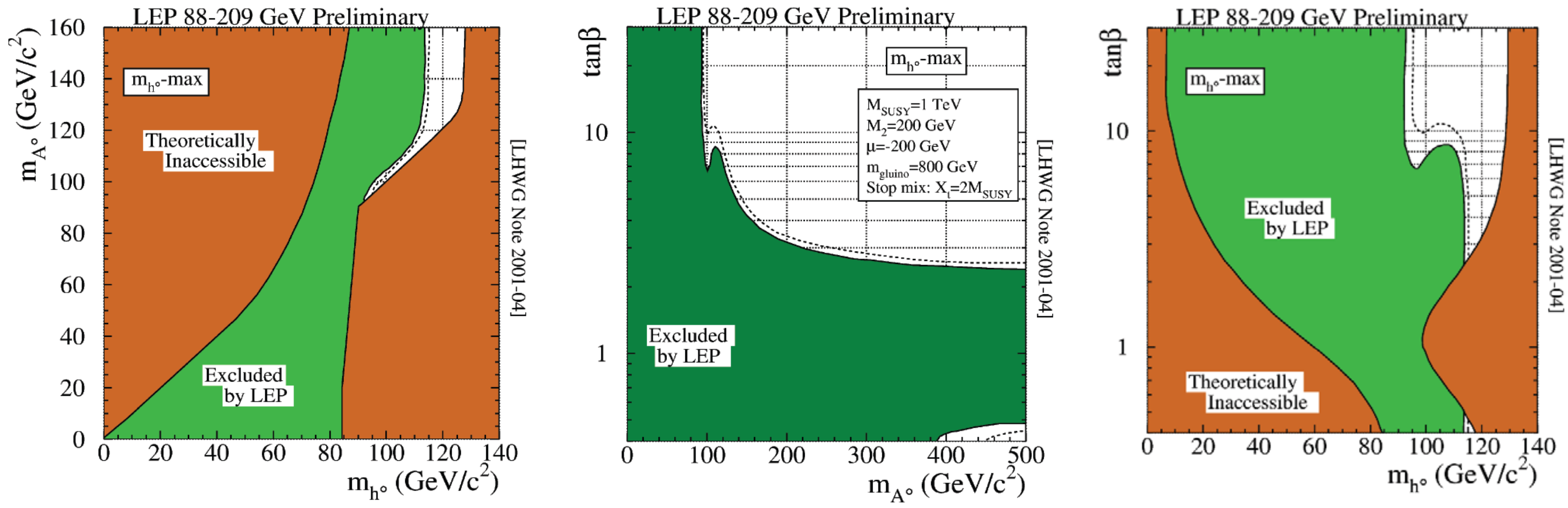
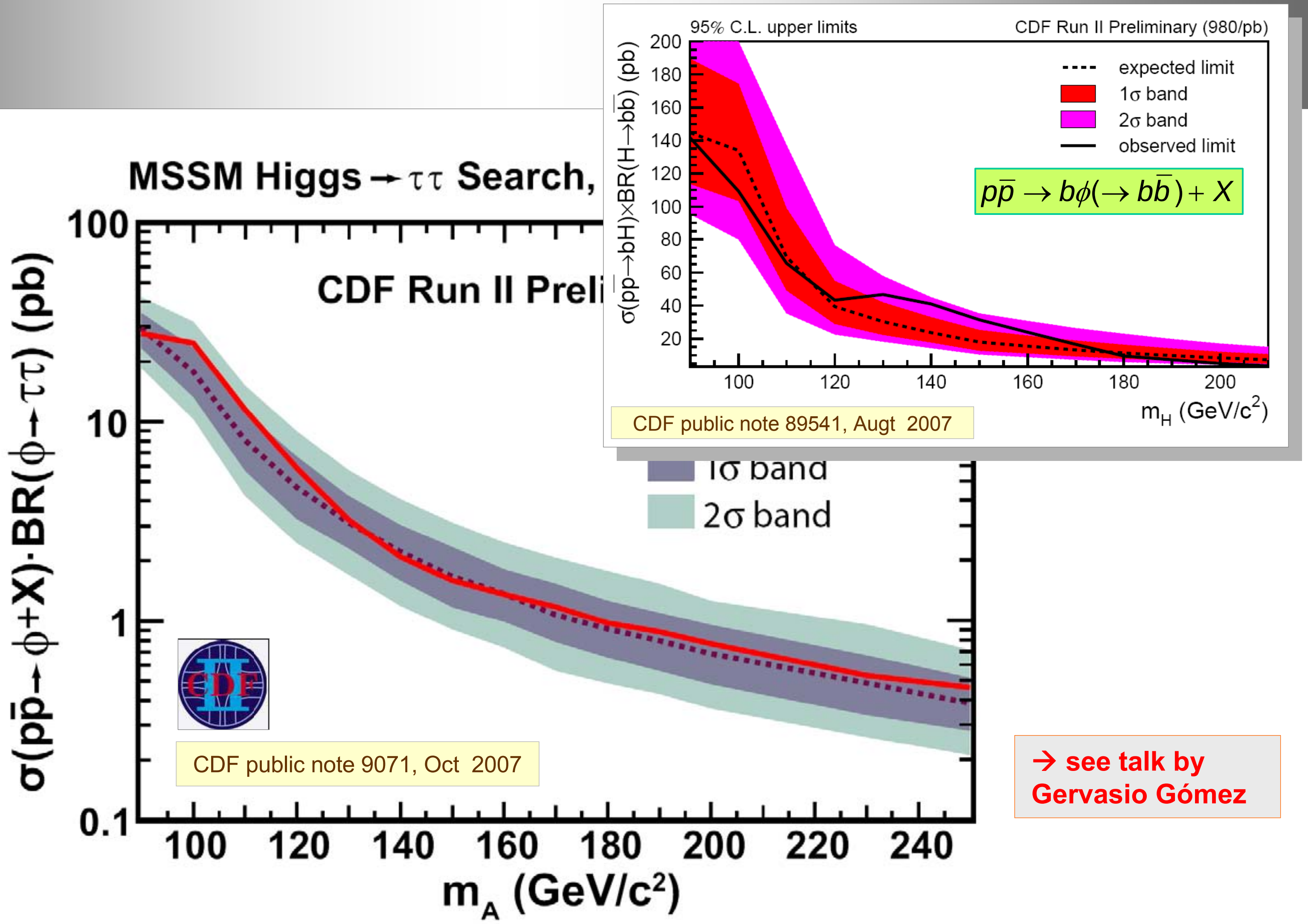
Limits from LEP...



Latest $\phi\,(H, A) \to \tau\tau$ Search from CDF



CDF public note 89541, Augt 2007

CDF public note 9071, Oct 2007

→ see talk by Gervasio Gómez

Digression: SUSY Higgs – Couplings

- SUSY Higgs couplings to gauge bosons:
  - Trilinear couplings $VVH_{i,}$ $V=W,Z$ (do not exist for $H^\pm$ (charge conservation) A (*CP* invariance)):

    $g(VVh) \propto \sin(\alpha-\beta)$ and $g(VVH) \propto m_V \cos(\alpha-\beta)$ → $g(VVh)^2 + g(VVH)^2 = g(VVH)_{\text{MS}}$

    Note: <u>no</u> $\gamma\gamma H$ or γZH couplings ($m_\gamma = 0$), <u>nor</u> γZH coupling (*CP* invariance)
  - Trilinear couplings $VH_iH_{j,}$:

    ZhA, ZHA, ZH^+H^-, γH^+H^-, and $WH^\pm h$, $WH^\pm H$, $WH^\pm A$

    Note: *Zhh, ZHh, ZHH, ZAA* forbidden (*CP* invariance)
  - Quartic couplings:

    ZZH_iH, $W^+W^-H_iH_j$, ($H_{i,j} = h, H, A, H^\pm$), $\gamma\gamma\, H^+H^-$, γZH^+H^-, $ZWH^\pm H_i$, $\gamma WH^\pm H_i$ ($H_{i,j} = h, H, A$),

- SUSY Higgs couplings to fermions:
  - Trilinear Yukawa couplings between Higgs and two fermions (dominated by heavy top, bottom quarks)

    $\lambda(H_ipp) \propto m_p \times f(\text{trig}(\alpha)/\text{trig}(\beta))$, where $p=u,d$-type, and $H_i = h, H, A$,

    $\lambda(H^\pm pq) \propto f(m_p,m_q) \times V_{\text{CKM}} \times f'(\text{trig}(\alpha), \text{trig}(\beta))$

    Note: A, $H^\pm$ couplings to down-type quarks increase with $\tan\beta$, while those to up-type quarks decrs.

    Couplings to τ also important for searches at LHC

SUSY – Résumé and Comments

- The MSSM naturally responds to a number of SM problems:
  - The quadratic divergence of the Higgs radiative corrections becomes logarithmic
  - SUSY “naturalises” the Higgs and cures the hierarchy problem by introducing new fields at *O*(TeV)
  - Grand unification of the forces at high scale is achieved
  - The existence of a spin-2 graviton (and a spin-3/2 gravitino) is naturally embedded in SUSY
  - SUSY provides a cold dark matter candidate → LSP
- **BUT: no experimental evidence for SUSY yet → SUSY has entered finetuning territory (“little hierarchy problem”)**
- Other SUSY models exist, for example the controversial *Split Supersymmetry*

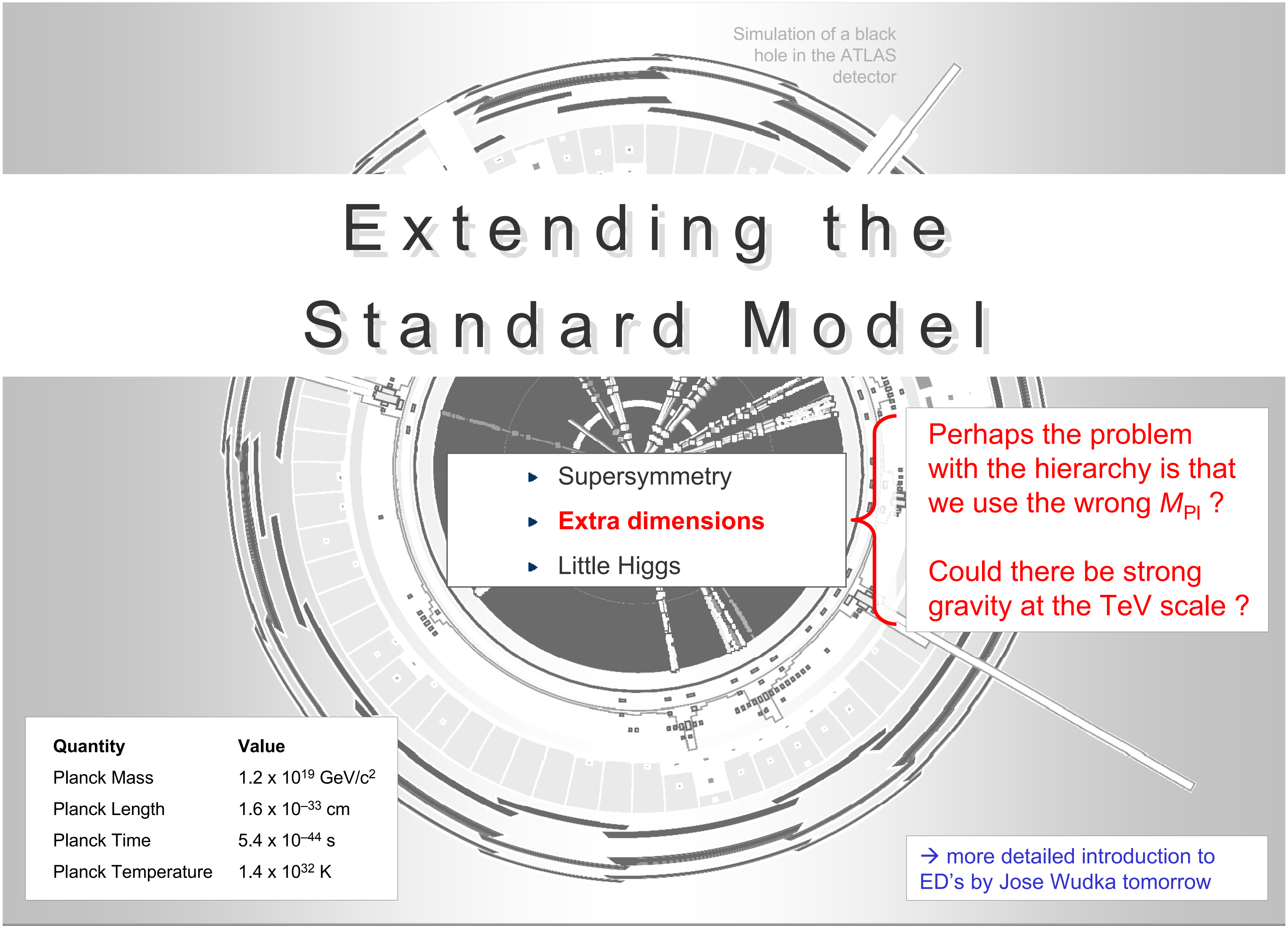
  Following the anthropic principle, it is suggested to **not cure the hierarchy problem with SUSY**

  - Lightest Higgs and gaugino sector light (keeps dark matter candidate and GUT)
  - Very heavy sfermions at M_{SUSY} scale $O(10^{10}\text{ GeV})$
  - Cures problem that no indirect SUSY hints have been observed
  - Very different phenomenology and experimental signature, in particular (very) long-lived gluinos !

$$\tau_{\tilde{g}} \approx 2\text{ sec.} \times \left(\frac{350\text{ GeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\text{SUSY}}}{10^6\text{ TeV}}\right)^4$$

gluinos must decay
through (heavy) squarks

and **tomorrow** …


Simulation of a black hole in the ATLAS detector

Extending the Standard Model

- Supersymmetry
- **Extra dimensions**
- Little Higgs

Perhaps the problem with the hierarchy is that we use the wrong M_{Pl} ?

Could there be strong gravity at the TeV scale ?

Quantity	**Value**
Planck Mass	1.2×10^{19} GeV/c^2
Planck Length	1.6×10^{-33} cm
Planck Time	5.4×10^{-44} s
Planck Temperature	1.4×10^{32} K

→ more detailed introduction to ED’s by Jose Wudka tomorrow

Extra Dimensions (EDs) ?

- Since the very end of the last century, an old theory (~1920), invented to unify gravitation and EM interaction was rediscovered to solve the hierarchy problem… the **Kaluza-Klein theory**

- ED theories associate “Kaluza-Klein towers” with the particles propagating in (compact) EDs

- String theory requires 10–11 space-time dimensions → **≤ 7 extra spatial dimensions (ED)** ?

- String theory acts at scale $M_{\text{string}} \sim M_{\text{Pl}} \sim 10^{19}$ GeV ~ **1.6 10^{-33} cm → not observable at LHC**

- Up to $M_{\text{EW}} \sim 10^{2}$ GeV ~ **1.6 10^{-16} cm [SM], and 10^{-2} cm [Gravitation] EDs can be excluded**

- Relatively large EDs in which gravitons propagate are thus not excluded; the SM particles could be confined in a smaller sub-space: a “***brane***”

- Gravity would allow us to probe the EDs

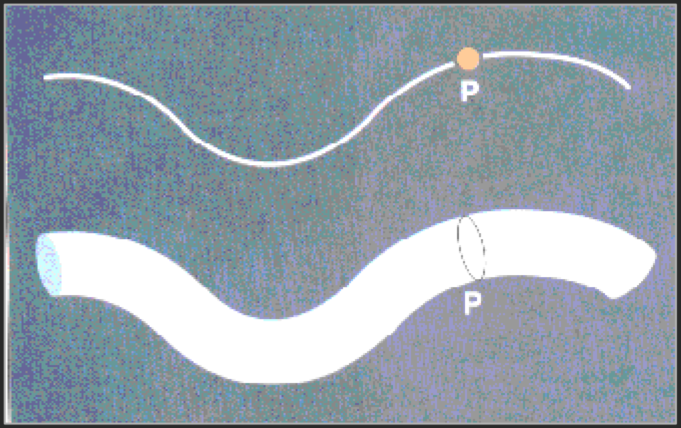
- Unfortunately, since gravity is a very weak force, and the EDs are small, we can hardly see the effects of them in a laboratory… **unless gravitation could be amplified making extra dimensions of up to a mm possible** ?

Extra Dimensions are Compactified …

If there are extra (spatial) dimensions …

…why did we only observe 3 spatial dimensions so far ?

Extra Dimensions are Compactified …



Extra space dimensions are hidden from view because they are "compactified“, *i.e.*, tightly rolled up. In this demonstration, a 2D surface is rolled up in a tube (bottom), becoming so tightly rolled that it looks like a 1D line (top). [Graphics by Mark McLellan].

If the size of the compact ED is much smaller than the wavelength of the particles we are observing, then the ED could remain hidden

Extra Dimensions and Newton's Gravitation

- Let us consider d EDs with some size R, the distance r_{12} between two masses m_1 and m_2
  - If $r_{12} \gg R$, we approximately live in a 4D world with gravitational force:

$$F^{(4)}(r_{12}) = \frac{G^{(4)} m_1 m_2}{r_{12}^2} = \frac{m_1 m_2}{\left(M_{\text{Pl}}^{(4)}\right)^2 \cdot r_{12}^2}$$

  - If $r_{12} \ll R$, we live in a (4+d)D world with the modified Newton force:

$$F^{(4+d)}(r_{12}) = \frac{G^{(4+d)} m_1 m_2}{r_{12}^{d+2}} = \frac{m_1 m_2}{\left(M_{\text{Pl}}^{(4+d)}\right)^{d+2} \cdot r_{12}^{d+2}}$$

  - From continuity at $r_{12} = R$, one finds:

$$\left(M_{\text{Pl}}^{(4)}\right)^2 = \left(M_{\text{Pl}}^{(4+d)}\right)^{d+2} \cdot R^d$$

4D gravity is diluted by the extra dimension !

The Planck scale is no longer fundamental !

- At the LHC scale of $M_D \equiv M_{\text{Pl}}^{(4+d)} \sim 1$ TeV, one finds:

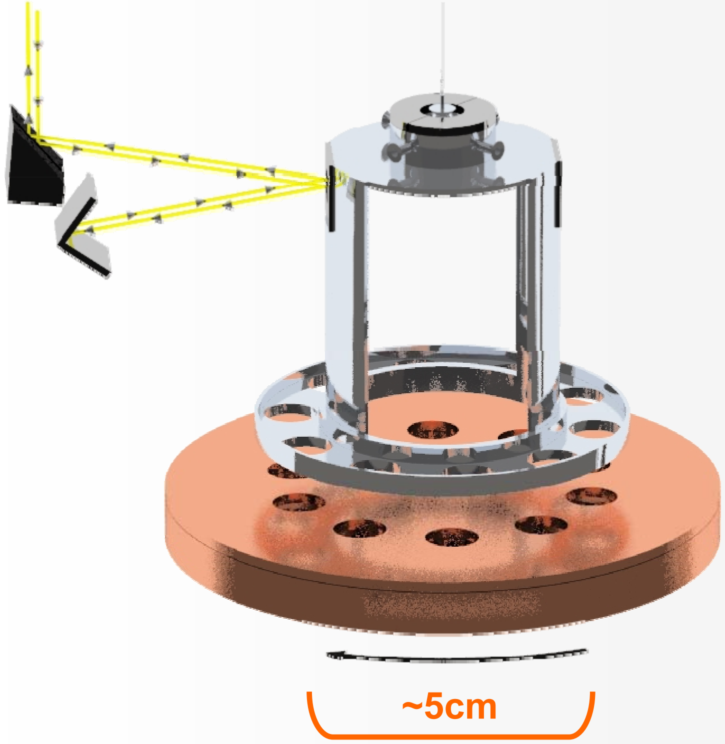
d=1: $R \sim 10^{14}$ cm (excluded from large scale gravitation tests, *e.g.*, planetary orbits)
d=2: $R \sim 10^{-2}$ cm (limit from gravitation tests) → only probes energy scale $R^{-1} \sim 2\ 10^{-3}$ eV !
d=3: $R \sim 10^{-7}$ cm (allowed)

Measuring Gravity at Short Distances

- Parametrise break-down of $1/r^2$ law by: $V(r_{12}) = \frac{Gm_1m_2}{r_{12}}\left[1+\alpha\cdot e^{-r_{12}/\lambda}\right]$

Hoyle *et al.*
hep-ph/0405262

- **Eöt-Wash Torsion pendulum experiments:**
  - *Missing* masses are 10 holes in Al ring
  - 2 Cu rotating attractor disks with 10 holes
  - Upper disk: holes as Al ring
  - Lower (thicker) disk: holes displaced
  - If G = Newton, twists from both disks cancel
  - Twist measured by reflecting laser light
  - Surfaces gold-coated to shield EM forces



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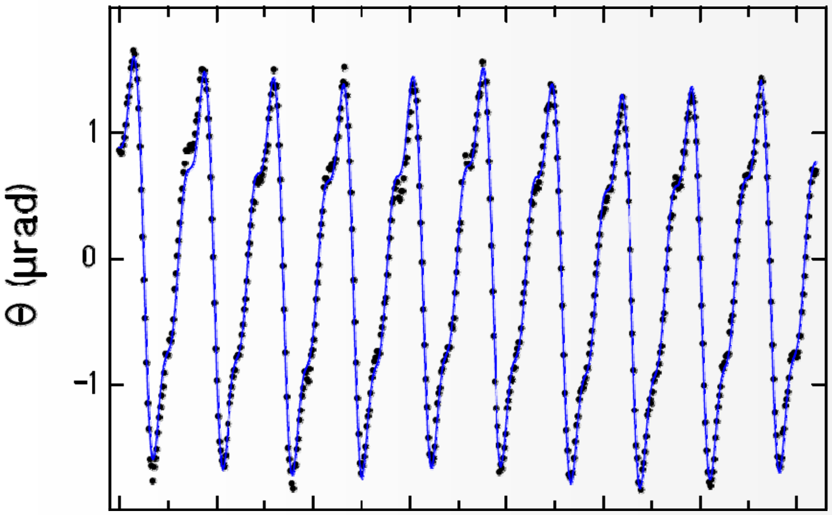

Data with fitted "gravitational signals"
No deviation from Newton law seen

- Newtonian fits agree with observed twist patterns (2006 results)
  - 1 dominant ED: $R < 44\ \mu\text{m}$
  - 2 equal sized EDs: $M_D > 3.2$ TeV

Measuring Gravity at Short Distances

Hoyle *et al.*
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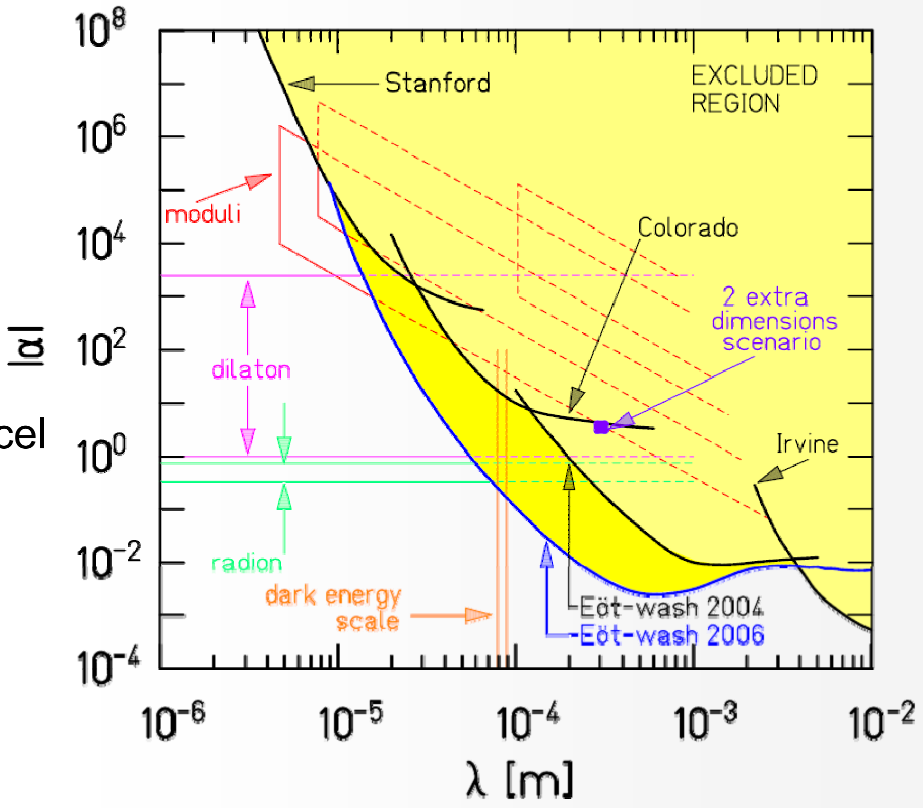
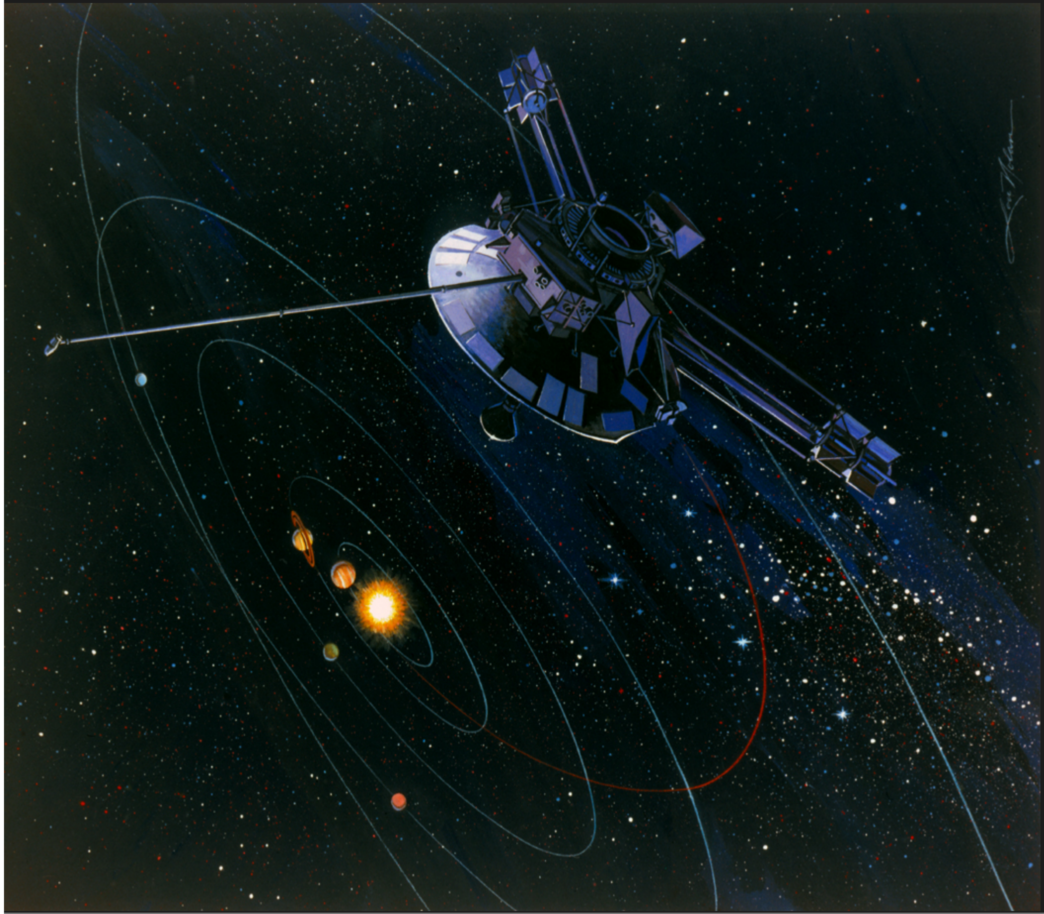


- Newtonian fits agree with observed twist patterns (2006 results)
  - 1 dominant ED: R < 44 μm
  - 2 equal sized EDs: M_D > 3.2 TeV

The Pioneer 10 /11 Anomaly

Pioneer 10: launched in March 2, 1972; it left the solar system 1983;
now heading towards Aldebaran (Taurus constellation)



- Anomaly consists of (blue-shifted) Doppler frequency drift, that can be interpreted as acceleration of ~10^{-9} g towards Sun

- Known systematic effects ~15% (incl. computation accuracy and internal and external spacecraft systems)
- Unknown systematics ?
  - Gas leaks [would be sufficient, but why both spacecrafts, and why directed]
  - Heat [much available from PI source; however, wouldn't be constant over all times]
- **Modified gravity ?**

see, *e.g.*, Anderson *et al.*
gr- qc/0104064

Kaluza-Klein Towers

Suppose a massless scalar ϕ in a 5D space. 1D, *y*, is compactified on a circle with radius *R*

- This requires periodic boundary conditions: $\phi\left(x^{(4)},y\right) = \phi\left(x^{(4)},y+n\cdot 2\pi R\right)\ ,\ n\in\mathbb{Z}$

  which translate into a quantification of the momentum in this dimension: $p = n/R$

- Developing ϕ into Fourier series of *y*,

$$\phi\left(x^{(4)},y\right) = \sum_n \phi_n = \sum_n \phi\left(x^{(4)}\right)e^{iny}$$

  one finds that the ensemble of ϕ_n represents a **Kaluza-Klein (KK) tower** of momentum eigenstates, **KK-modes**, and the mass-squared of the mode ϕ_n in 4D (solution of Klein-Gordon equation) is given by:

$$m_n^2 = m_0^2 + \left(\frac{n}{R}\right)^2 \quad \Rightarrow \quad \Delta m = \frac{1}{R} \overbrace{\sim}^{R\sim 2\times 10^{-17}\,\text{cm}} 1\ \text{TeV}$$

  (*n*th excitations of *ground* state)

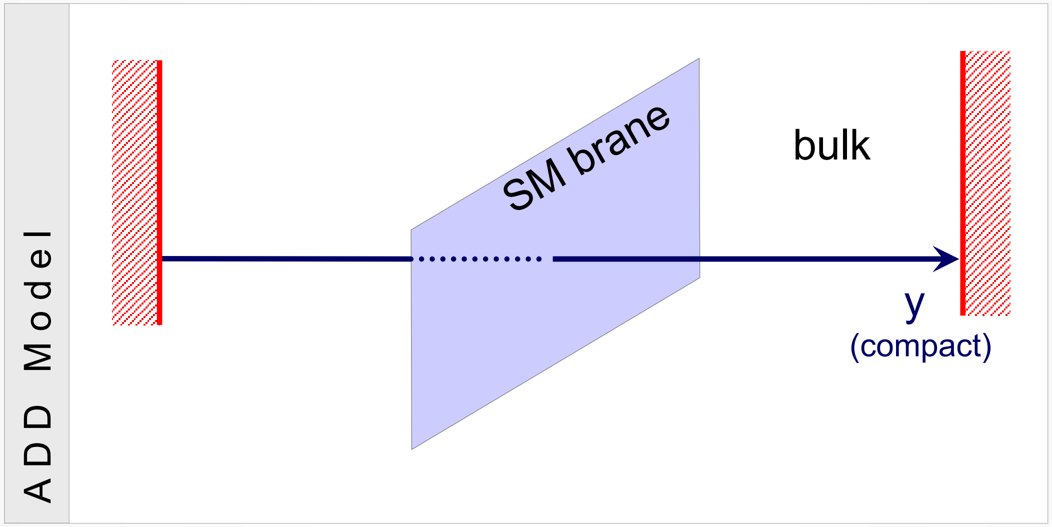
- KK attempted in 1920 to unify EM interactions and gravitation with their theory: they have developed the metric between space-time and the 5th D around small perturbations proportional to the photon field A_μ.

- Computing the effective action with this metric in 4D, one recovers the 4D gravitation by identifying:

$$G^{(4)} = \frac{1}{2\pi R} G^{(5)}$$

- In the KK theory, ***G*$^{(4)}$ is only a reflection of the *real* gravitational constant *G*$^{(5)}$**, reduced by the extra dimension !

The ADD Model



Arkani-Hamed, Dimopoulos, Dvali, hep-ph/9803315
3272 citations to date !

- The SM fields are trapped on 4D SM brane; only gravitons see the ED *y* and have KK states
  [would the SM fields propagate into the large ED, they would associate KK towers that we should have observed already]
- The small 4D coupling of the graviton to the SM particles is compensated at large enough energy by the large number of accessible KK states that is summed over
  [remember: the mass difference of a KK towers is given by the (small) energy scale (R^{-1}) of the large ED]
- No momentum conservation per ED, *i.e.*, gravitons are emitted into ED by SM fields
- Main ADD ED signatures at the LHC:
  1. *pp* → jet + missing energy (from undetected sum of accessible KK graviton towers)
  2. gravitons can modify SM cross sections through loops (here: all KK towers are virtually accessible)

The ADD Model

ADD Model

Universal Extra Dimensions

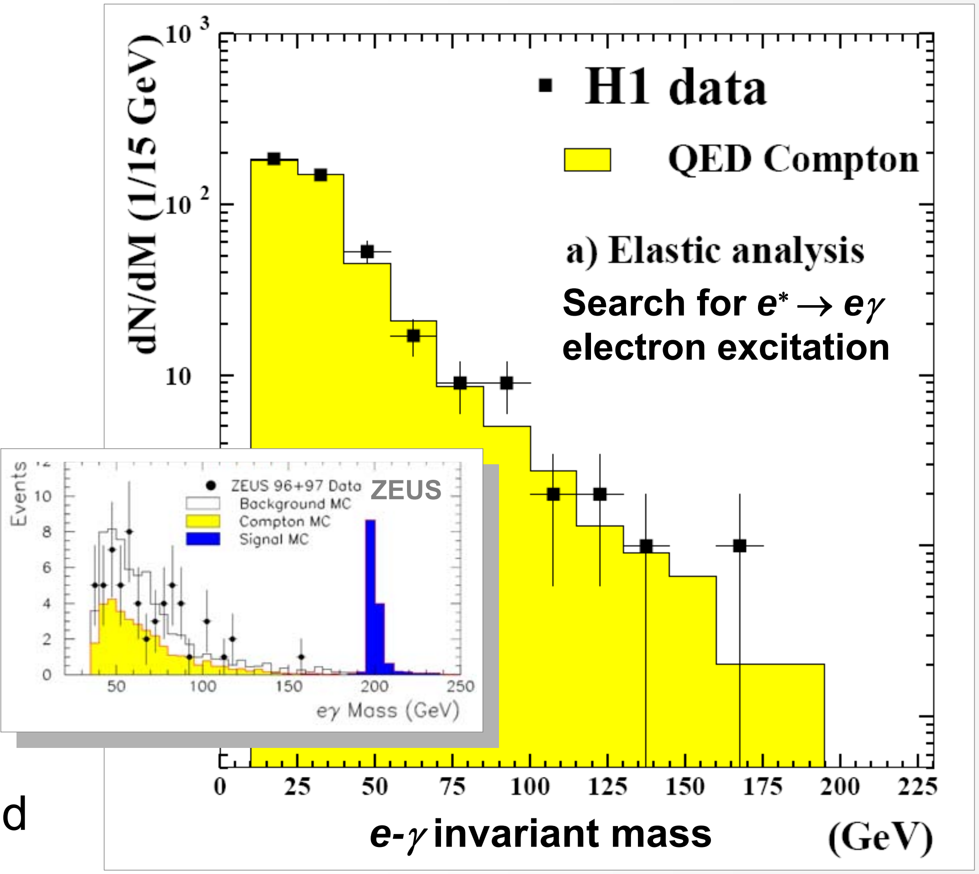
Variation of this model for **small EDs:** let SM propagate into the bulk. Translation invariance along ED provides conservation of KK number in 4D theory → “**LKP” for odd number of EDs** (“KK parity” $(-1)^{n}$). SUSY-like phenomenology.

[Appelquist-Cheng-Dobrescu , 2001]

© Scientific American

Gauge Forces in the Bulk ?

- Interactions between SM fields measured to very high accuracy ~ 10^{-16} cm
- If gauge forces acted in the bulk, deviations to SM should measurable
- Indeed, the boundary conditions in the compactified ED would create KK towers (→ Z', γ', … excitations) for SM fields
- For large EDs, the KK mass splitting would be small enough to be observable
- Lepton excitations also occur for compositness models parametrised by contact interaction terms



Search for $e^* \to e\gamma$ electron excitation

e-γ invariant mass

Unfortunately, there is a little secret in the ADD model.

The original purpose of it to eliminate the hierarchy problem is missed: although the true (4+*d*) Planck scale is indeed of *O*(EW), one finds that $R \cdot M_D = (M_{\mathrm{Pl}}/M_D)^{2/d}$ is a very large number (due to the large EDs).

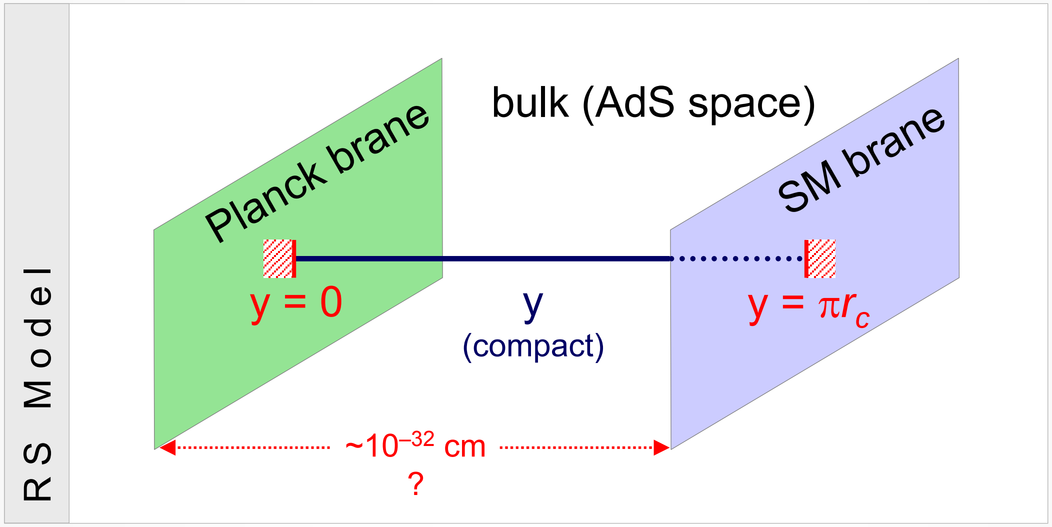
➔ ADD trades one hierarchy problem for another one !

Until now it was assumed that the extra dimensions are flat, or only weakly curved, and that they factorise with the other spatial dimensions

But the extra dimension could also be strongly curved (or "warped") by a large negative cosmological constant.

This has surprising consequences…

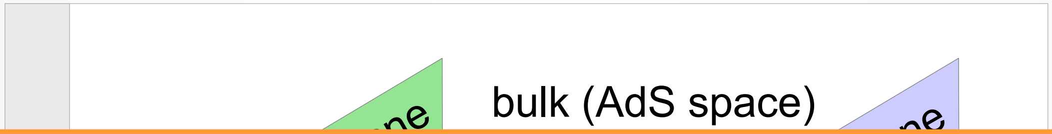
Warped Extra Dimensions



Randal-Sundrum,
hep-ph/9905221
3526 citations to date !

- As ADD, but special metric: $ds^2 = e^{-2k|y|}\,\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$ → 4D subspace depends on y
- Parameter k has dimension; basic assumption of RS: no mass hierarchies → $k \sim M_D \sim M_{Pl}$
- Solving Einstein's equations and integrating out y, one finds for 4D: $M_{Pl} = \frac{M_D^2}{k}\left(1 - \underbrace{e^{-2\pi k r_c}}_{\text{“warp factor”}}\right)$
- For a mass $m_0 \sim M_{Pl}$, we – on the SM brane – see the red-shifted: $m = m_0 e^{-\pi k r_c}$!
  $O(10^{-15})$ for $kr_c \sim 11$ → large hierarchy is naturally explained by exponential factor !
- RS ED signature at the LHC: the KK gravitons-to-SM couplings are enhanced by warp factor
  - Weak scale graviton KKs with weak scale couplings should produce universal spin-2 resonances !

Warped Extra Dimensions



Randal-Sundrum,
hep-ph/9905221
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If discovered, to truly identify these spin-2 resonances as gravitons, one needs to demonstrate:

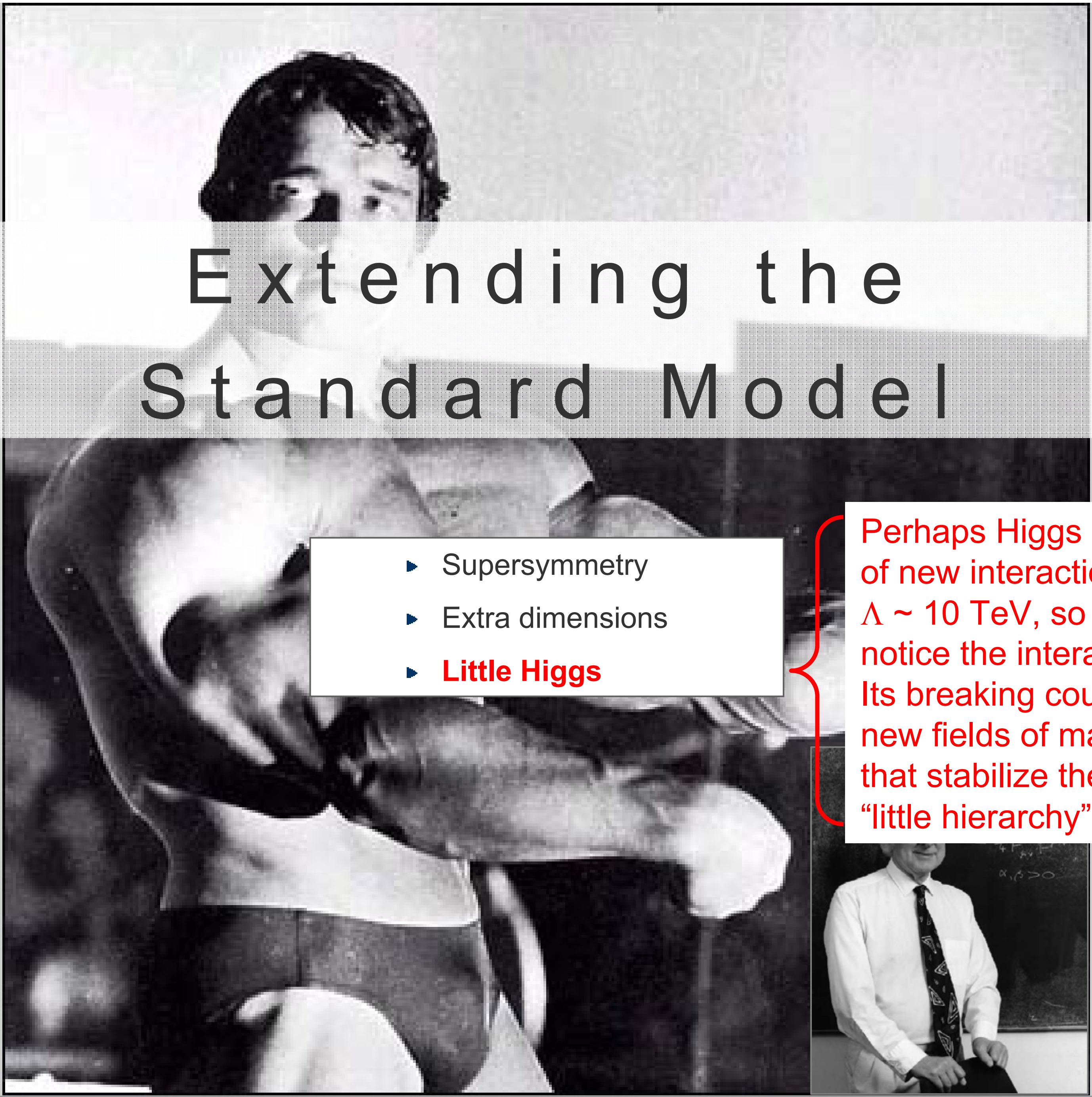
1. That it is indeed spin-2 (“easy” from angular distribution)
2. That couplings are universal (general relativity)
   → measure branching ratios

- Parameter *k* has dimension; basic assumption of RS: no mass hierarchies → $k \sim M_D \sim M_{Pl}$
- Solving Einstein’s equations and integrating out *y*, one finds for 4D: $M_{Pl} = \frac{M_D^2}{k}\left(1 - \underbrace{e^{-2\pi k r_c}}\right)$
- For a mass $m_0 \sim M_{Pl}$, we – on the SM brane – see the red-shifted: $m = m_0 e^{-\pi k r_c}$! “warp factor”
  $O(10^{-15})$ for $kr_c \sim 11$ → large hierarchy is naturally explained by exponential factor !
- RS ED signature at the LHC: the KK gravitons-to-SM couplings are enhanced by warp factor
  - Weak scale graviton KKs with weak scale couplings should produce universal spin-2 resonances !

EDs in Astrophysics and Cosmology

- Large EDs would act only after the inflation period; they could influence:
  - Primordial nucleosynthesis
  - Cosmic microwave background – if the gravitons decay into photons by interacting with the SM brane
- A priori, nothing is known about cosmology when we enter the domain of strong gravitation. For example: non-perturbative effects could occur
- EDs could modify the ν-nucleon scattering cross section of ultra-high energetic cosmic ν's
- EDs could modify deflection angle of gravitational lensing [limit: for d=2, M_D > 4 TeV]
- EDs could influence the maximum allowed mass for neutron stars, and contribute to cooling of stars: limit on ED scale from super nova (SN1987A) [d=2, M_D > 50 TeV, d=4, M_D > 1 TeV]

Extending the Standard Model



- Supersymmetry
- Extra dimensions
- **Little Higgs**

Perhaps Higgs is Goldstone of new interaction at scale $\Lambda \sim 10$ TeV, so we didn't notice the interaction yet ? Its breaking could lead to new fields of mass ~ 1 TeV that stabilize the SM for the "little hierarchy": $v \to \Lambda$

A “Little(st)” Higgs ?

- Seeks to solve the radiative instability of the SM Higgs sector (up to O(10 TeV))
- In the “Little Higgs” model, the massless Higgs is generated (in analogy of the pion in QCD) as a Goldstone via SSB of a new symmetry
- It’s mass is acquired during EWSB. The new symmetry being still approximately valid, the Higgs mass is protected (*at 1-loop order*) and stays small

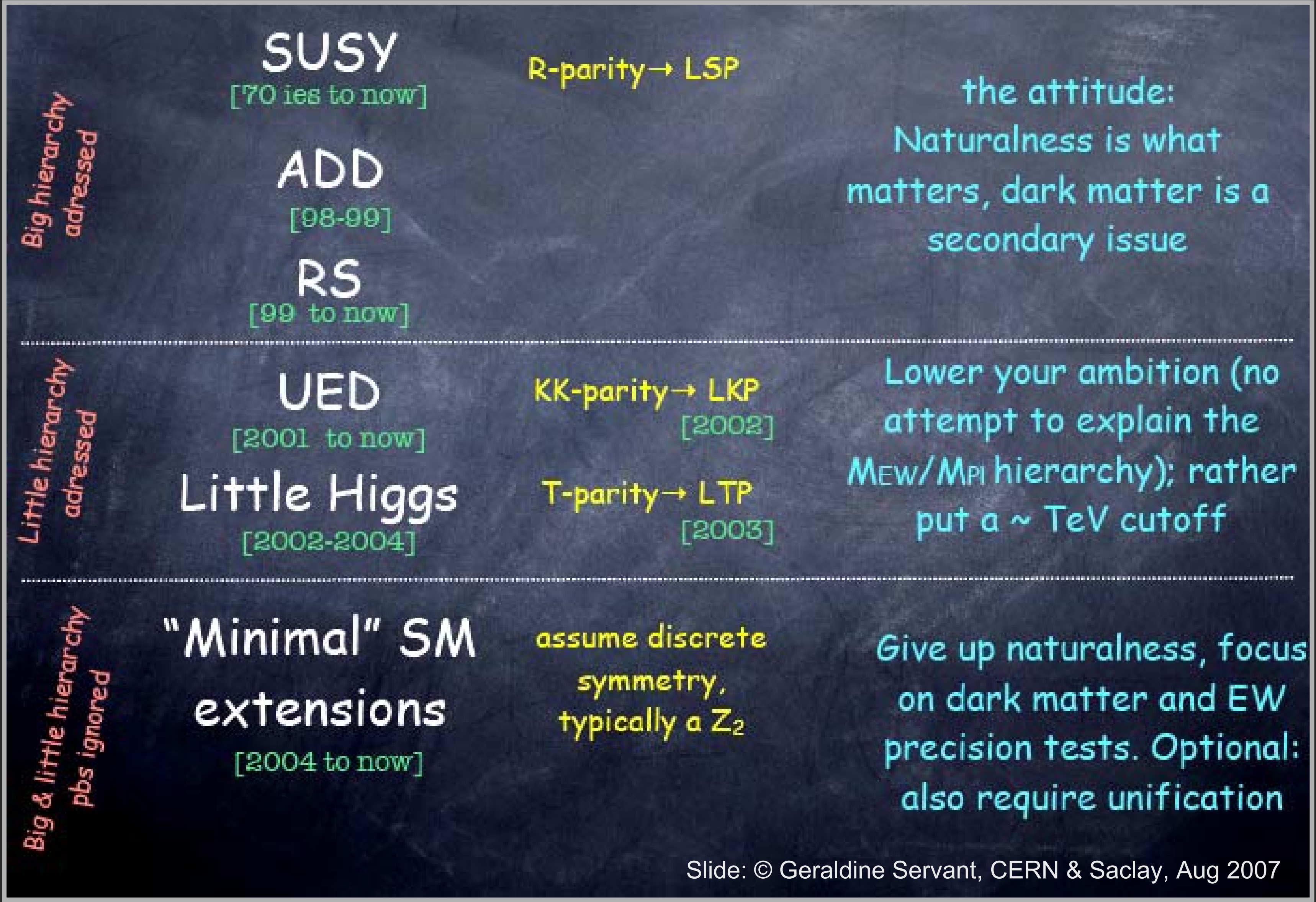
- As new symmetry one could use SU(5), embedding the unified gauge group $(SU(2)\times U(1))^2$
  - Breaking SU(5) by a VEV into SO(5) creates 14 “Goldstone” bosons
  - Then, the group $(SU(2)\times U(1))^2$ is broken into $SU(2)_L\times U(1)_Y$, where 4 of the 14 Goldstone bosons are used to create massive longitudinal SM gauge fields ($W^{\pm}_H$, Z_H, A_H) of the broken gauge group
  - Among the remaining Goldstone bosons one finds a complex scalar doublet (SM Higgs), and a scalar triplet with 5 Higgs bosons: ϕ^0 , $\phi^{\pm}$, $\phi^{\pm\pm}$

- Breaking SU(5) requires at least one heavy, O(TeV), new particle for each particle contributing to the radiative corrections of the Higgs, which cancel the SM corrections
  - By construction: the $W^{\pm}_H$, Z_H cancel the weak divergence, a new quark T cancels the top-quark divergence, the new Higgs triplet cancels the SM Higgs divergence
  - The new heavy top and gauge bosons decay into their SM partners through associated Higgs production. These and the new Higgs fields could be discovered at the LHC

Conclusions

of the phenomenological introduction

Model Building Beyond the SM: Historical Overview



Big hierarchy adressed	SUSY [70 ies to now] ADD [98-99] RS [99 to now]	R-parity→ LSP	the attitude: Naturalness is what matters, dark matter is a secondary issue
Little hierarchy adressed	UED [2001 to now] Little Higgs [2002-2004]	KK-parity→ LKP [2002] T-parity→ LTP [2003]	Lower your ambition (no attempt to explain the M_{EW}/M_{Pl} hierarchy); rather put a ~ TeV cutoff
Big & little hierarchy pbs ignored	"Minimal" SM extensions [2004 to now]	assume discrete symmetry, typically a Z_2	Give up naturalness, focus on dark matter and EW precision tests. Optional: also require unification

Slide: © Geraldine Servant, CERN & Saclay, Aug 2007

Part 2 – Experimental Searches

Discovery Physics at the LHC

Andreas Hoecker, CERN

XI Mexican Workshop on Particles and Fields, Nov 7-12, 2007, Tuxtla Gutiérrez, Mexico

Lecture Themes

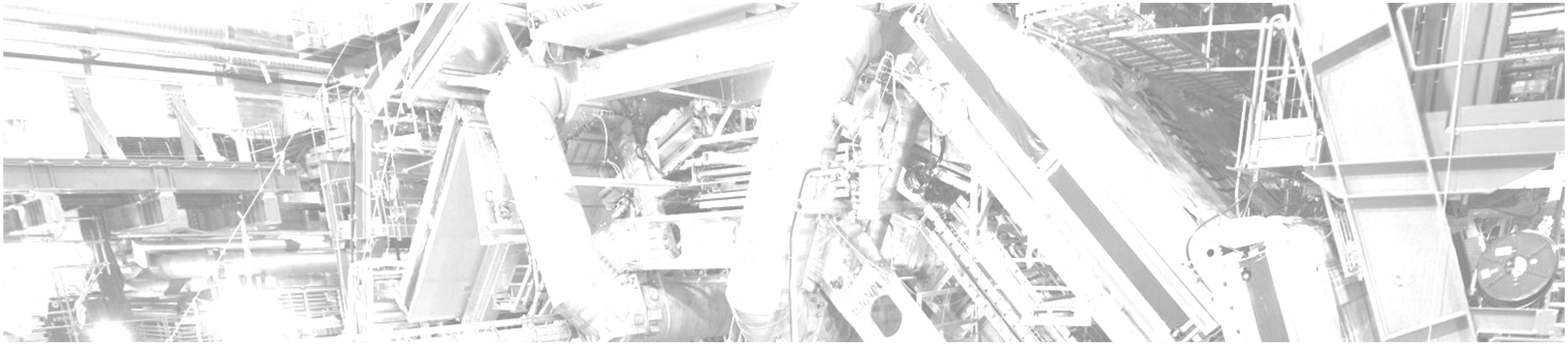
I. Phenomenology beyond the Standard Model

- Empirical & theoretical limitations of the Standard Model
- Supersymmetry
- Extra Dimensions
- Little Higgs

II. Experimental Searches

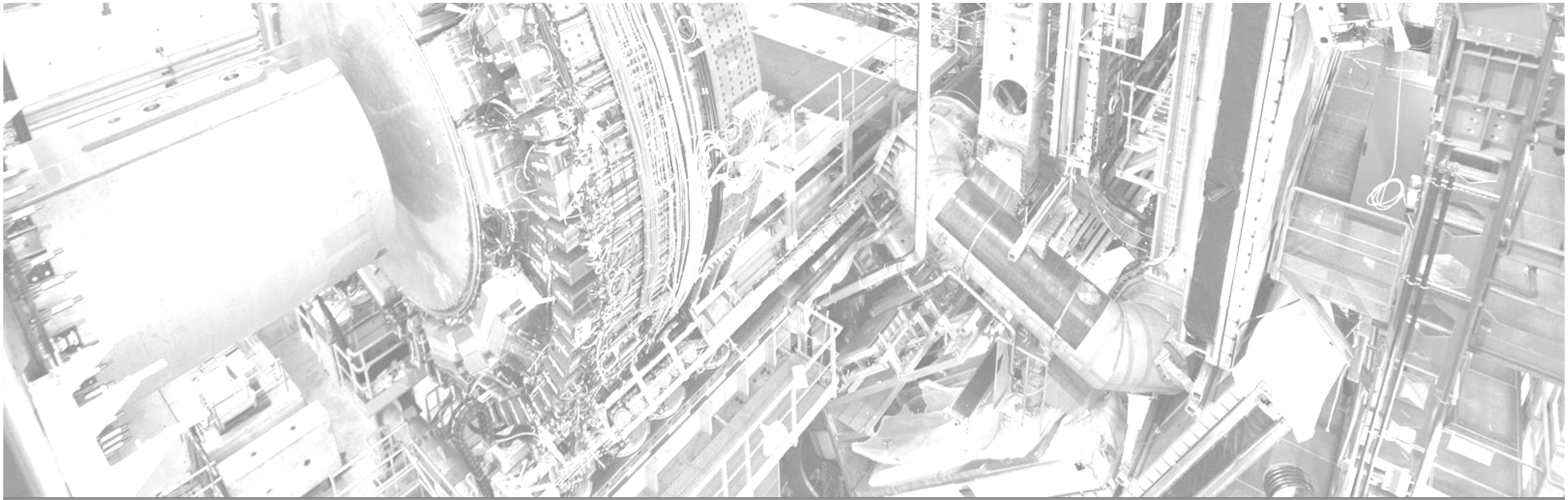
- LHC, ATLAS and CMS: Experimental Challenges
- Searches at the LHC: SUSY, Extra Dimensions, Little Higgs

Lectures based on many, many sources… please contact me for the list

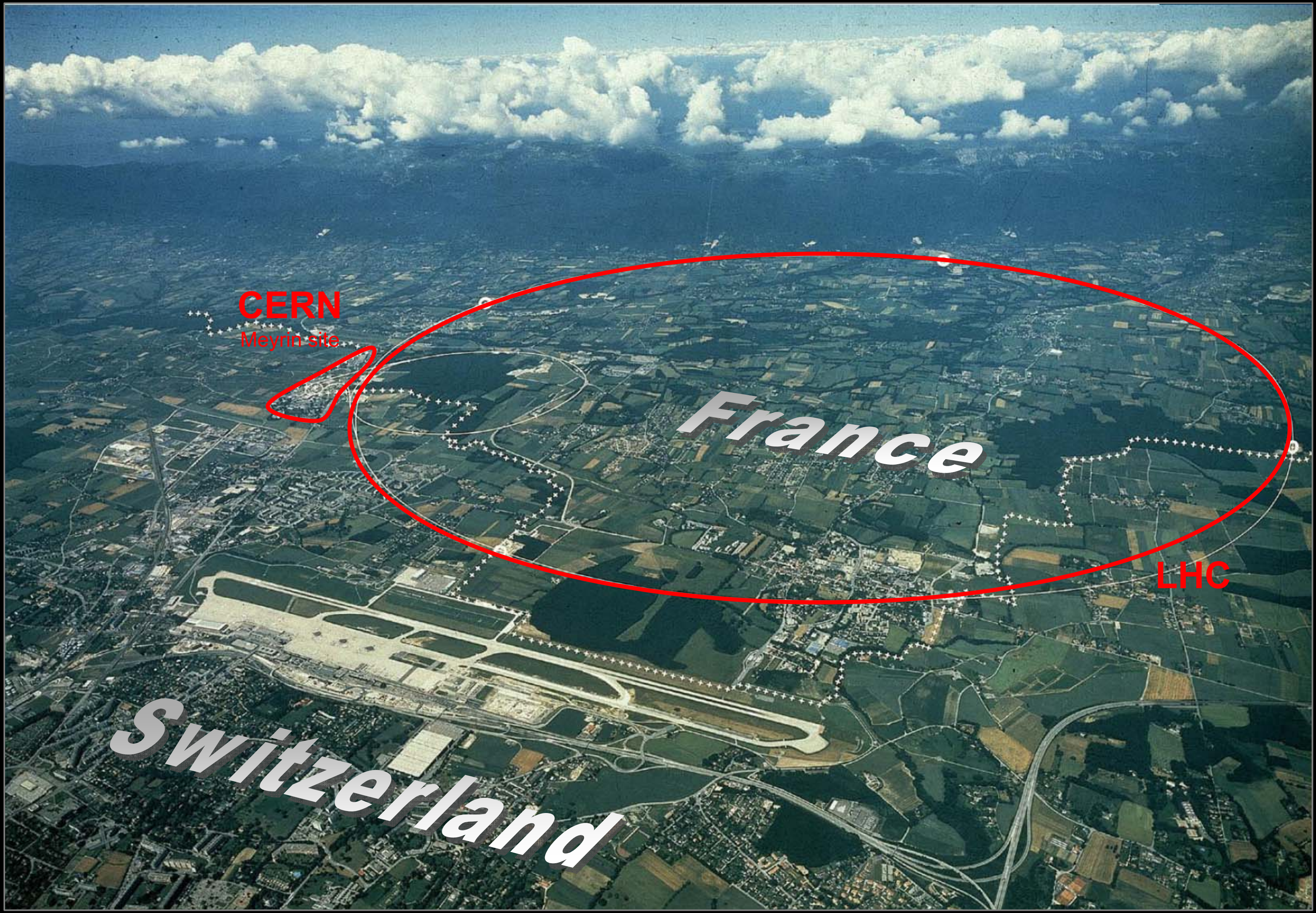


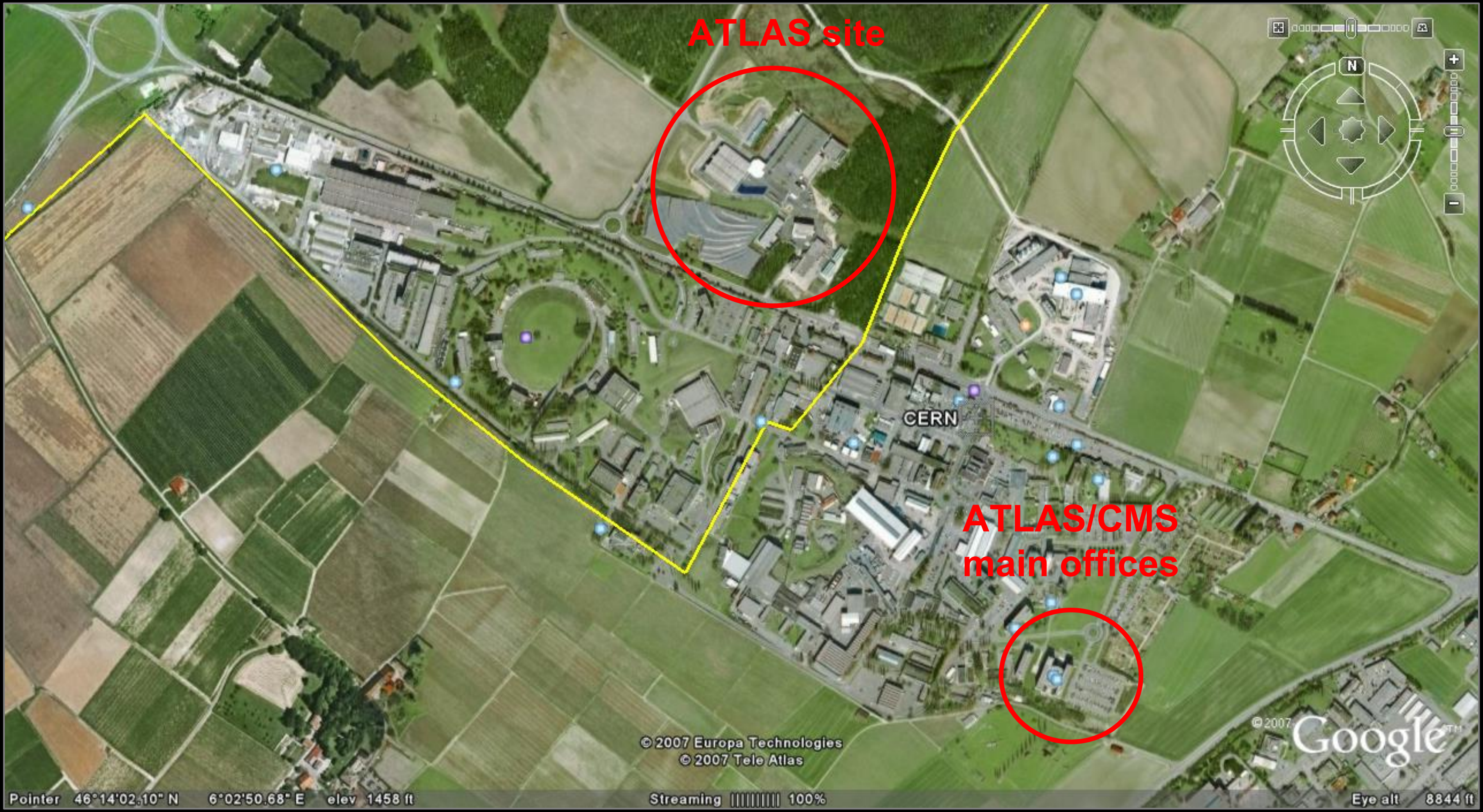
LHC, ATLAS and CMS

Experimental Challenges



CERN & THE LHC


CERN
Meyrin site
France
LHC
Switzerland


ATLAS site
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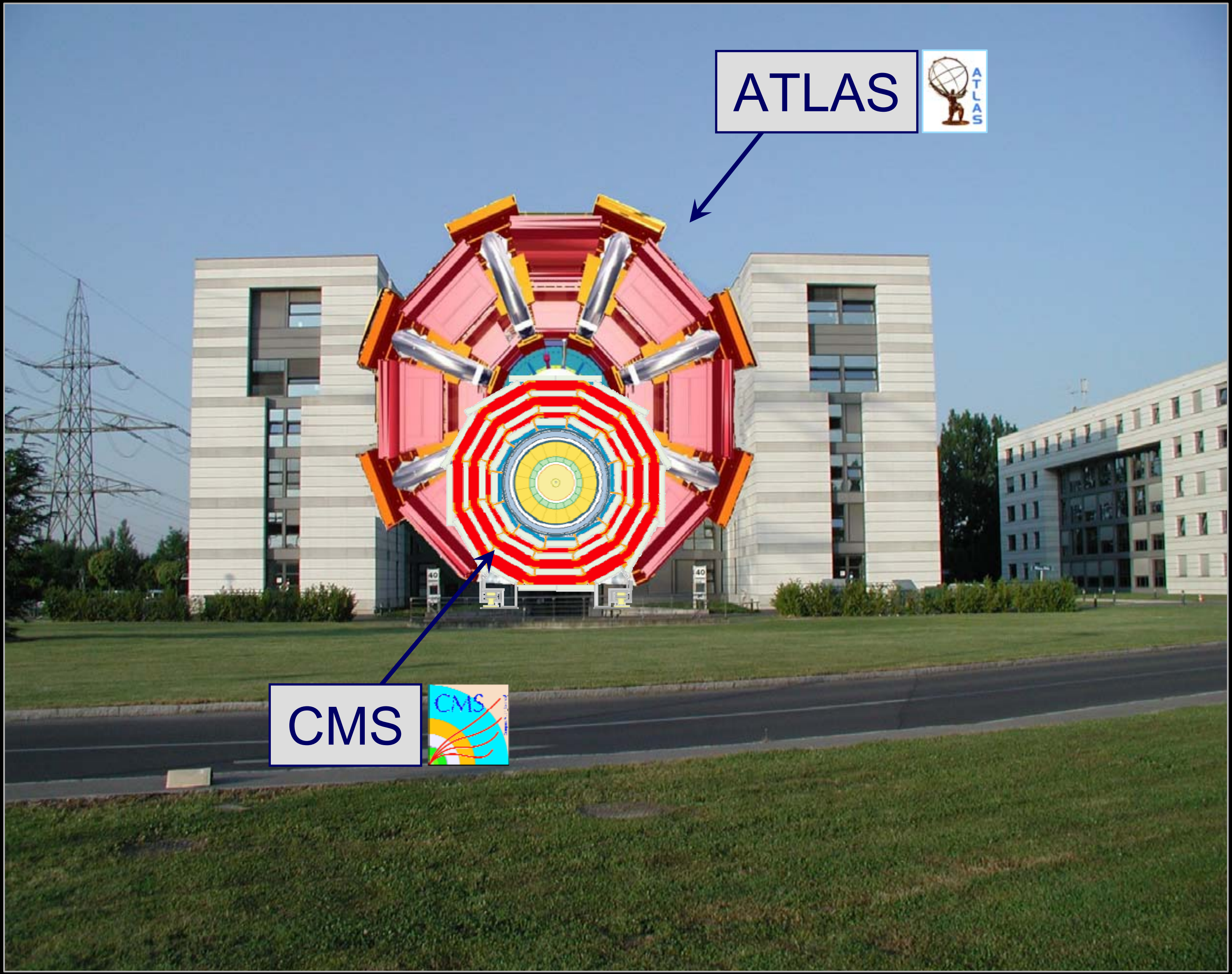
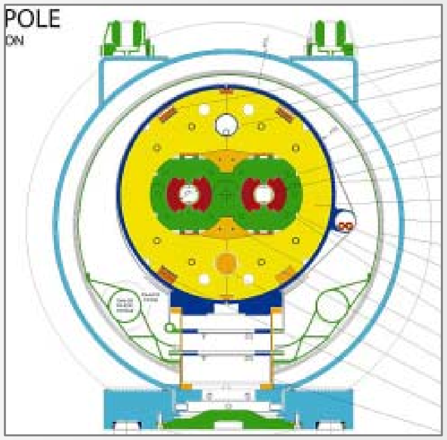

ATLAS
CMS

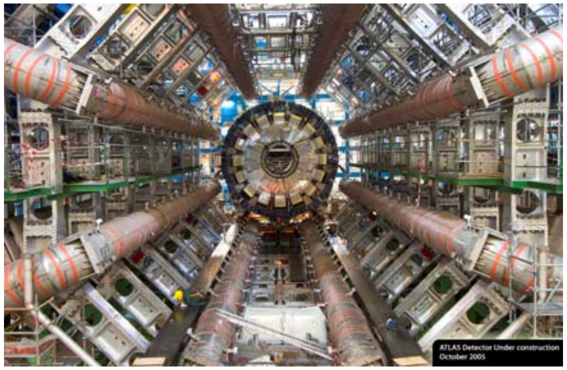
LHC: The Accelerator Challenge

- The search for new phenomena exploits smaller and smaller distances → larger and larger energies
- The LHC collides protons at E_{CM} = 14 TeV → probing a distance of 1.4 10^{-18} cm ? … not quite, since protons are composites
- Want to produce rare new particles → need high intensity beams
- Proton energy is limited by magnets that guide the circular beams
- $E_{proton} \sim 0.3 \cdot B \cdot r$: since radius is fixed, use as strong fields as possible (> 8 T), and fill all free LHC sections with magnets (~2/3)



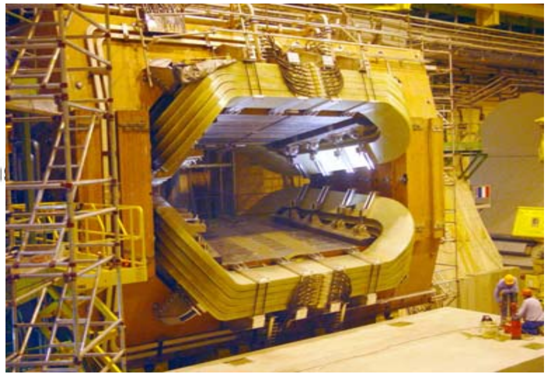
LHC dipole section. Proton-proton acceleration requires two beam pipes

ATLAS



CMS

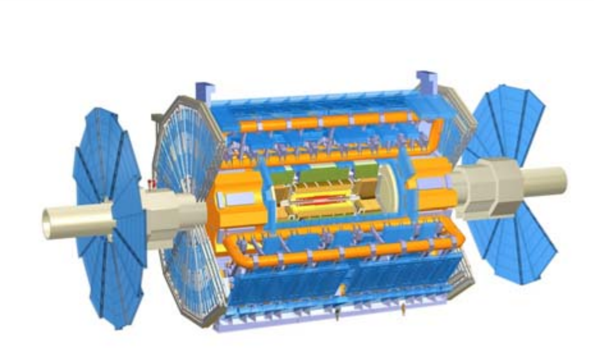
LHCb



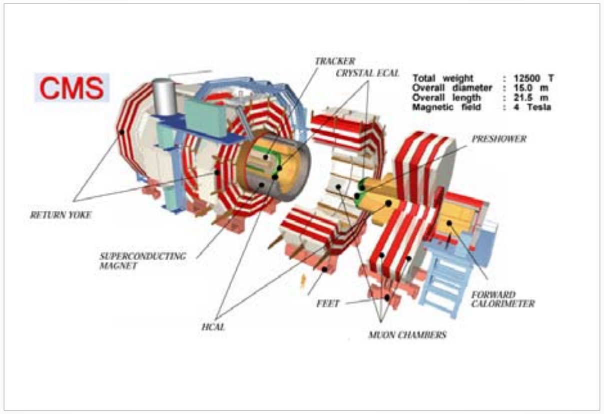
and also ALICE !

The LHC and its Experiments

ATLAS



CMS

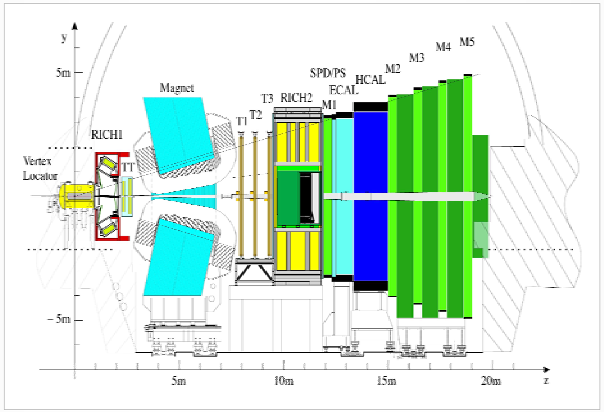


ALTAS and CMS have same physics goals: concentrate on "high-p_T" discovery physics

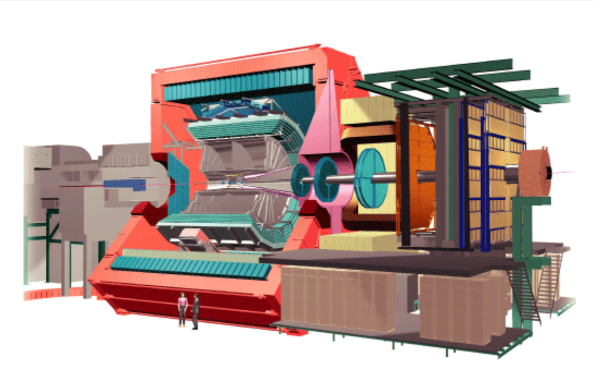
The detector concepts are however different: this provides necessary redundancy and fruitful competition

LHCb looks like a fixed-target experiment (though it is not!), because it concentrates on low-p_T *B* physics

LHCb



ALICE

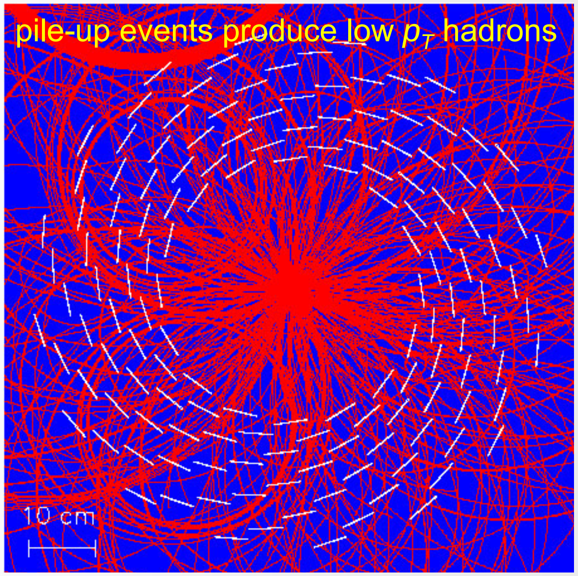


There are two more (much smaller) experiments at the LHC: TOTEM (measuring elastic and diffractive processes), and LHCf (testing cosmic shower models)

ALICE will exploit high-energetic nucleus-nucleus ("heavy-ion") collisions

The Experimental Challenges

- At high luminosity (10^{34} cm^{-2}s^{-1}), ~25 “pile-up” interactions will occur in one bunch crossing
  - Need extremely fast detector response within 25 ns “exposure time” (= 40 MHz bunch crossing rate)
  - Need fine granular detector to “reconstruct” and filter out interesting events
- Basic detector concepts:
  - Symmetric beams → symmetric detector, pointing geometry
  - Collision products move from the interaction point outwards
  - Trajectories of charged particles bending in *B* field are measured
  - Calorimeters measure electron, photon, hadron energy deposits
  - Tracks of remaining (unabsorbed) muons are measured



18 superimposed *pp* collisions in CMS tracker
(there are also 4 muons from Higgs decay…)

- Event reconstruction:
  - “Trigger” on (= flag) an interesting event, and read out detector
  - Reconstruction starts with detector signals:
    - space points from ionization by charged particles in tracking systems
    - energies from showers in calorimeter cells/crystals
    - signals from particle-identification detectors (sensitive to mass of particles)
  - “Fit” track helices to space points
  - “Cluster” adjacent calorimeter energy deposits

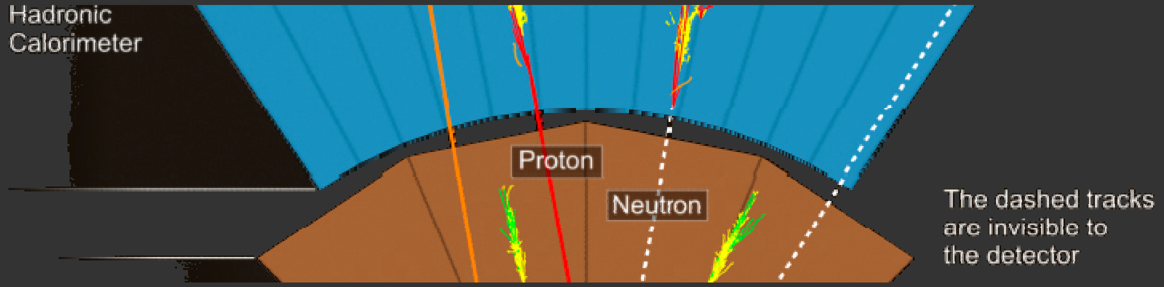
ATLAS & CMS: Performance Overview

	ATLAS	**CMS**
INNER TRACKER	• Silicon pixels + strips • TRT with particle identification • B = 2T • $\sigma(p_T) \sim 3.8\%$ (at 100 GeV, $\eta = 0$)	• Silicon pixels + strips • No dedicated particle identification • B = 4T • $\sigma(p_T) \sim 1.5\%$ (at 100 GeV, $\eta = 0$)
MAGNETS	• Solonoid + Air-core muon toroids • Calorimeters outside field • 4 magnets	• Solenoid • Calorimeters inside field • 1 magnet
EM CALORIMETER	• Pb / Liquid argon accordion • $\sigma(E) \sim 10\text{–}12\% / \sqrt{E} \oplus 0.2\text{–}0.35\%$ • Uniform longitudinal segmentation • Saturation at ~ 3 TeV	• $PbWO_4$ scintillation crystals • $\sigma(E) \sim 3\text{–}5.5\% / \sqrt{E} \oplus 0.5\%$ • No longitudinal segmentation • Saturation at 1.7 TeV
HAD CALORIMETER	• Fe / Scint. & Cu-liquid argon • $\sigma(E) \sim 45\% / \sqrt{E} \oplus 1.3\%$ (Barrel)	• Brass / scint. • $\sigma(E) \sim 100\% / \sqrt{E} \oplus 8\%$ (Barrel)
MUON	• Monitored drift tubes + CSC (fwd) • $\sigma(p_T) \sim 10.5 / 10.4\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)	• Drift tubes + CSC (fwd) • $\sigma(p_T) \sim 13 / 4.5\%$ (1 TeV, $\eta = 0$) (standalone / combined with tracker)

Source: Froidevaux-Sphicas, Ann Rev 56, 375 (2006)

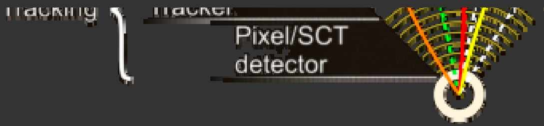
Electron, Photon and Muon Identification

- **Electrons and Photons (*e*, γ)** – combine information from calorimeters and tracking devices
  - e, γ provide narrow clusters in electromagnetic calorimeter, and deposit all their energy therein
  - *e* (γ) clusters must (*not*) match with incoming track
  - *e* can be separated from pions using transition radiation in TRT (ATLAS)
  - For many interesting physics processes *e*'s and γ's are isolated from other particles
  - However, not so for *e*'s from charm and beauty decays and γ's from π^0 decays
  - Backgrounds stem mostly from misidentified jets



The dashed tracks are invisible to the detector

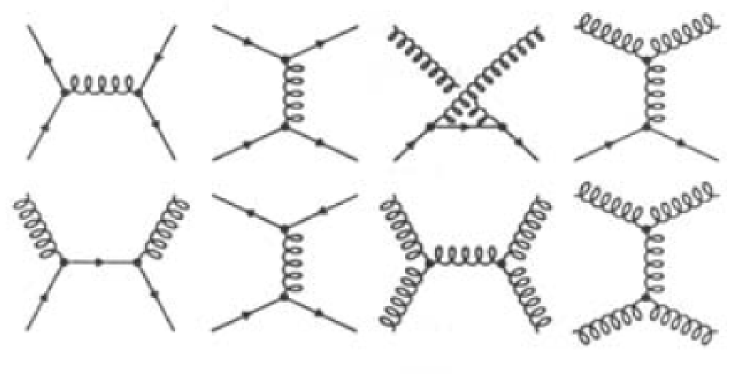
- **Muons (*μ*)** – identified using muon chambers at outer detector (other particles are absorbed)
  - *μ* momentum and charge can be determined from track bending in *B* field of muon chambers
  - Backgrounds stem mostly from charged π/*K* decays in flight



ATLAS

Jets and "Missing Transverse Energy"

- **Jets** – reconstruction in calorimeters (use of tracking devices can help)
  - Jets are QCD hard scattering processes
  - Because of QCD confinement, the outgoing quarks and gluons "hadronize" into colourless hadrons (and other particles)
  - Jets dominate high-p_T cross section at LHC
  - While jets are interesting in its own right
  - …they are dominant background for rare processes, like decays of Higgs particles
  - Reconstruction rather bold: take all clusters (and tracks) within cone around jet axis
  - Jet energy calibration is a major headache



Feynman graphs for quark-quark, quark-gluon and gluon-gluon scattering

Jets and "Missing Transverse Energy"

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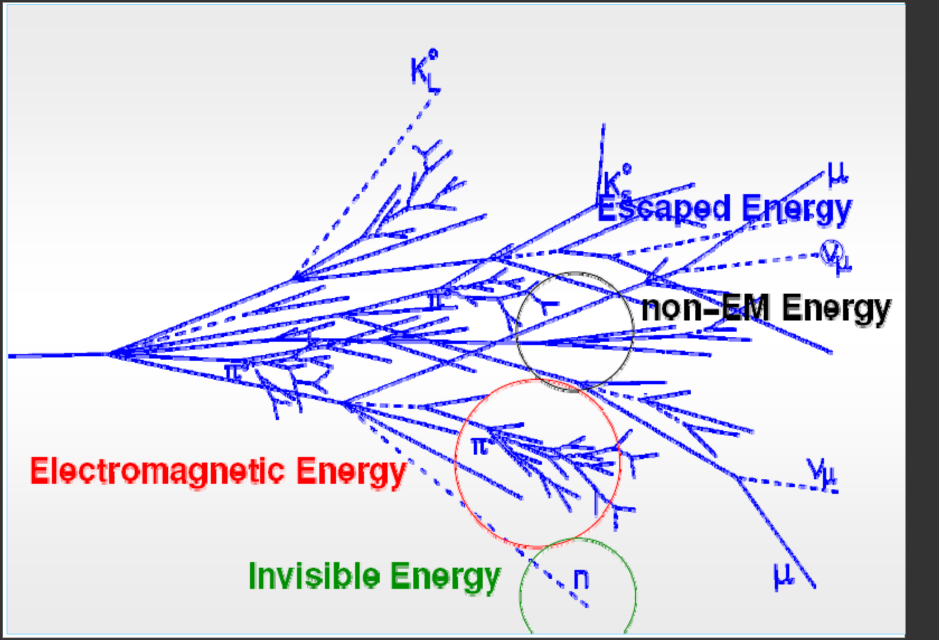

A hadronic shower consists of:

- EM energy (e.g., $\pi^0 \rightarrow \gamma\gamma$) O(50%)
- non-EM energy (*e.g.*, dE/dx from $\pi^\pm,\mu^\pm,K^\pm$) O(25%)
- invisible energy (nuclear fission/excitation) O(25%)
- escaped energy (*e.g.* neutrinos) O(2%)

Jets and "Missing Transverse Energy"

- **Jets** – reconstruction in calorimeters (use of tracking devices can help)
  - Jets are QCD hard scattering processes
  - Because of QCD confinement, the outgoing quarks and gluons "hadronize" into colourless hadrons (and other particles)
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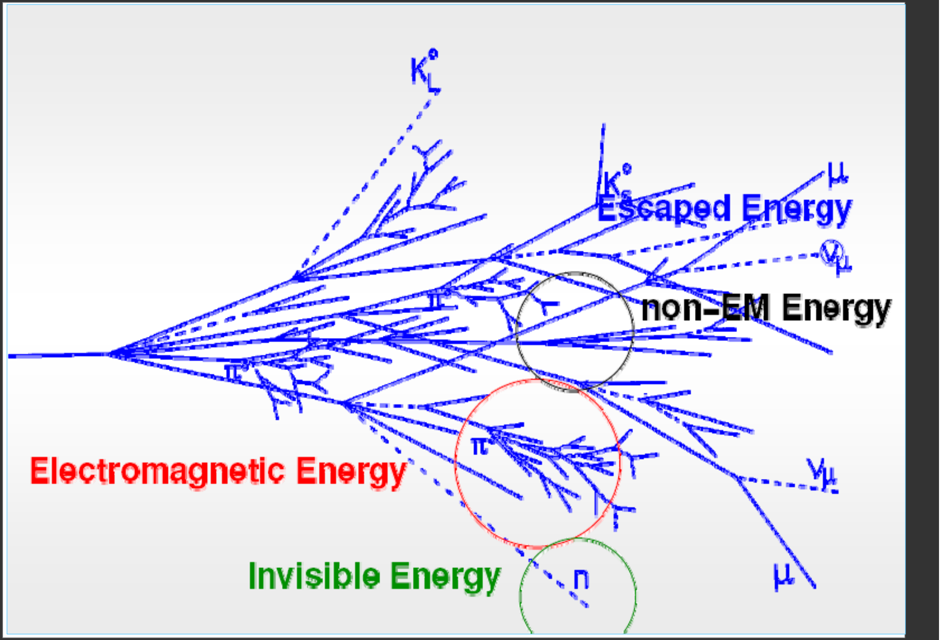
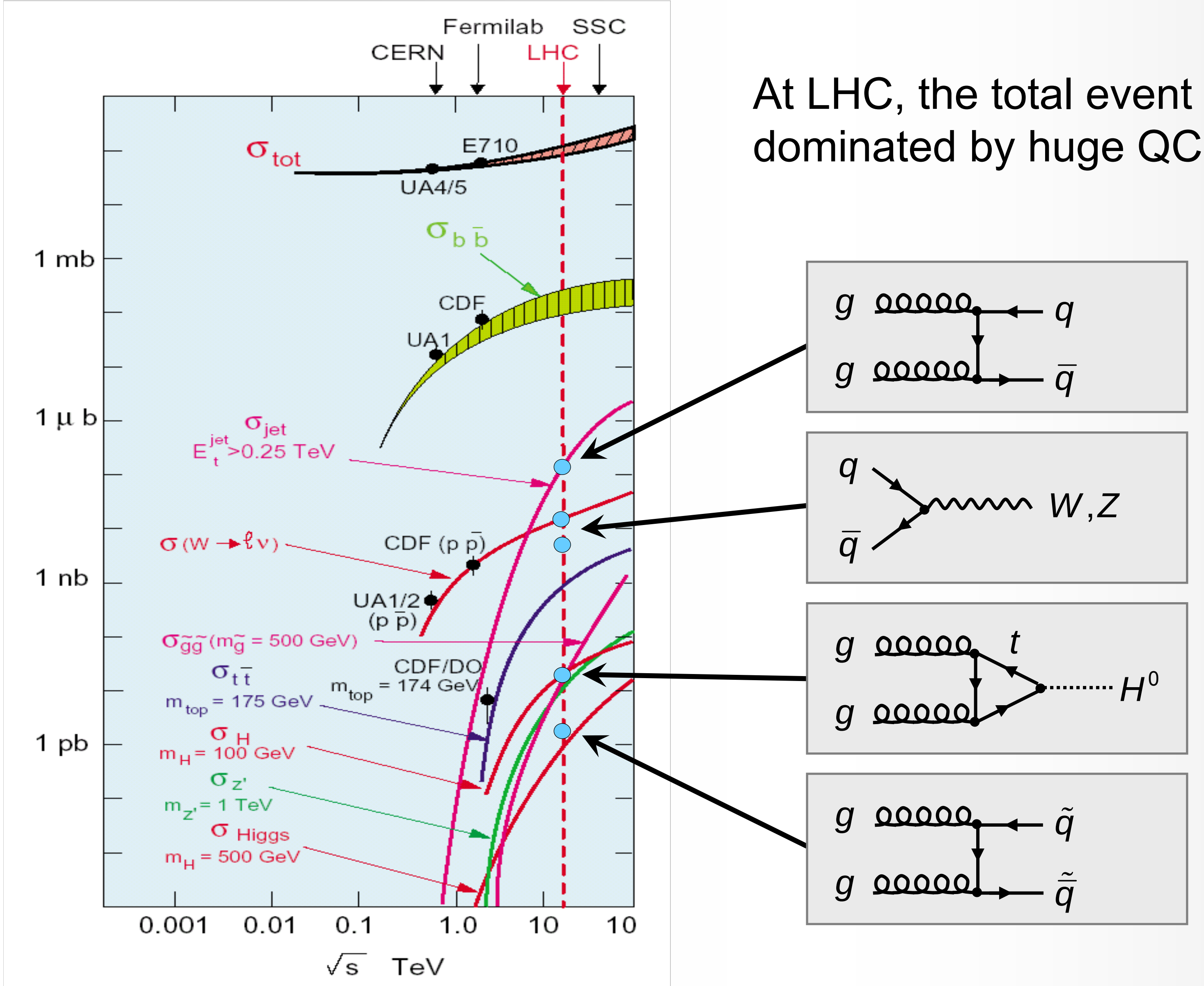


- **Missing Transverse Energy**
  - In principle: $E_{T,\text{miss}} = \sum_{I,j} E_{T,i} E_{T,j} \cos(\phi_I - \phi_j) = 0$ at LHC
  - If $E_{T,\text{mis}} \neq 0$, particles may have escaped detection (*e.g.*, neutrinos, or New Physics)
  - Fake $E_{T,\text{mis}}$ can be easily created by acceptance effects, miscalibration, instrumental failures

Cross Sections

At LHC, the total event rate is dominated by huge QCD cross section



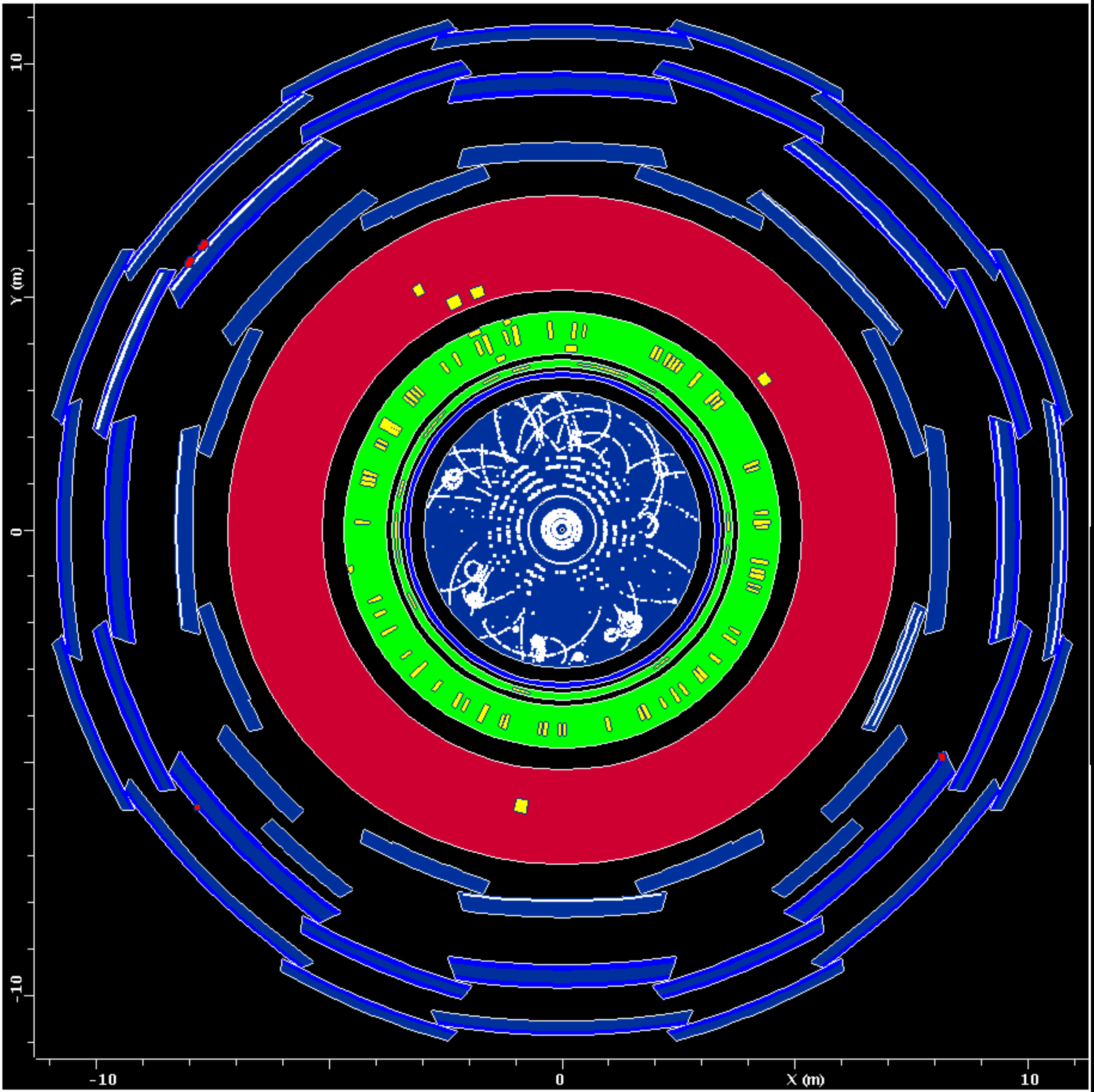
High-p_T QCD jets

W, *Z* production

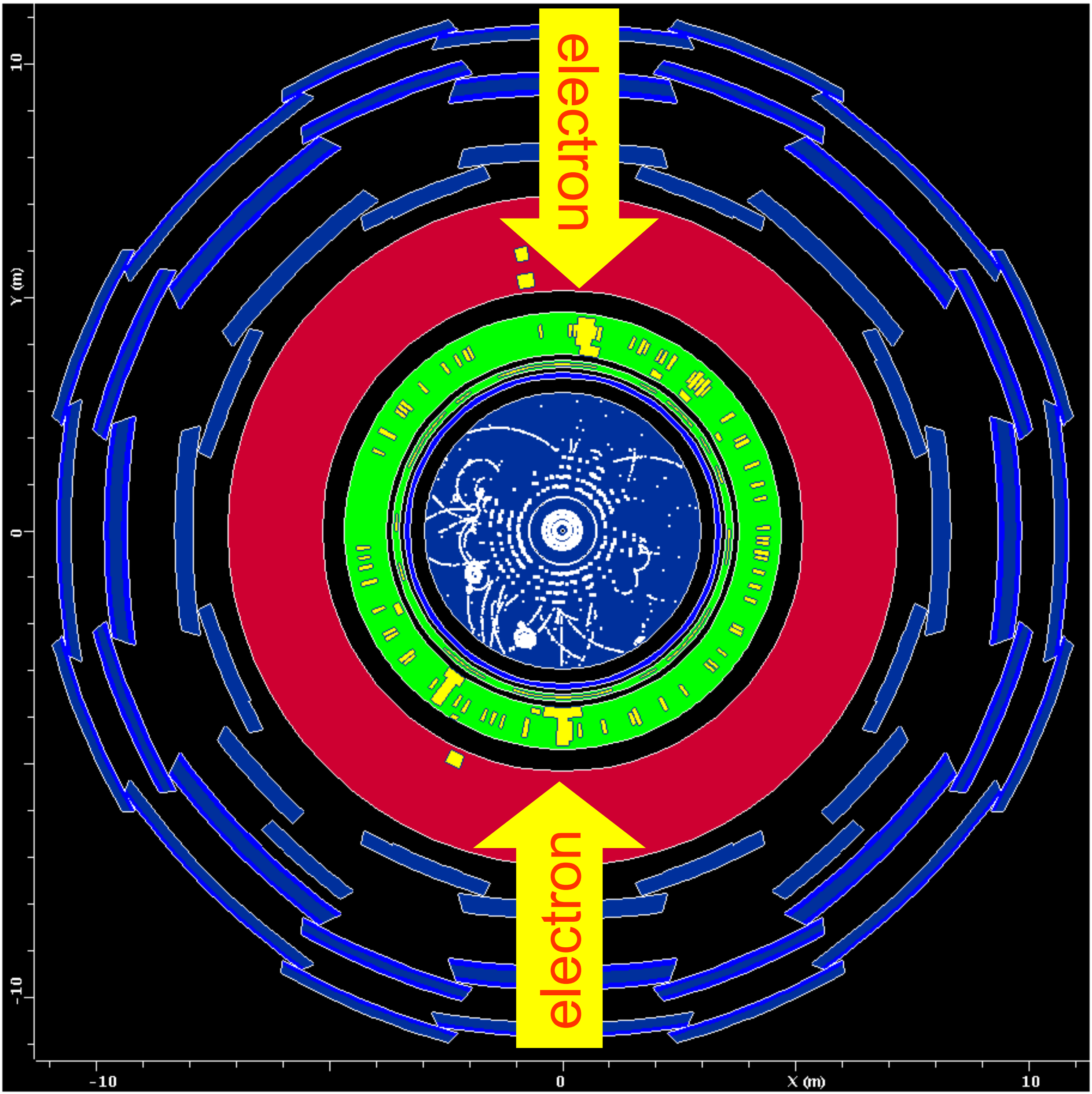
gluon-to-Higgs fusion

squarks, gluinos
(*m* ~ 1 TeV)

Simulating Characteristic Events with ATLAS

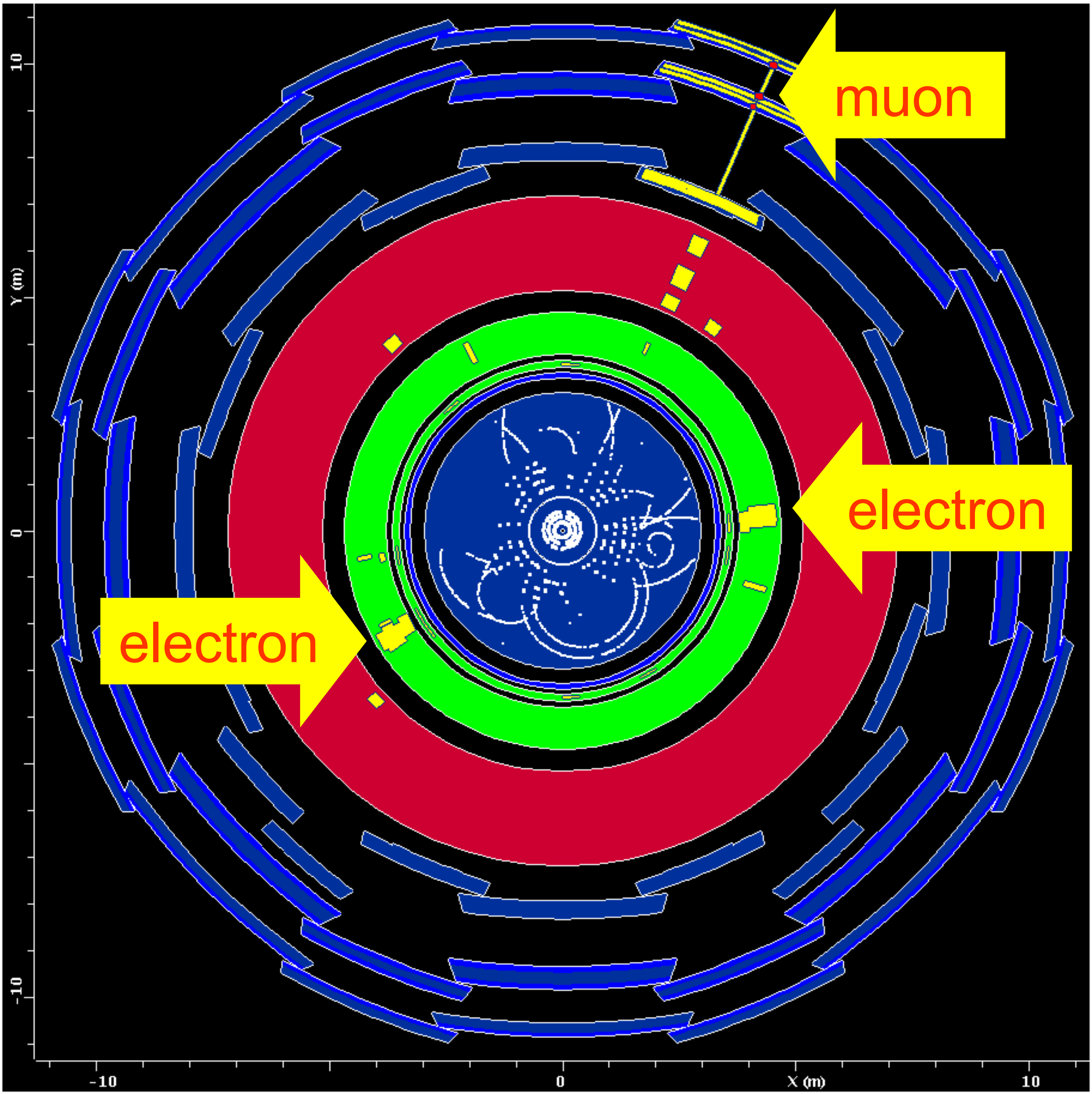


Minimum bias event
rejected by Trigger



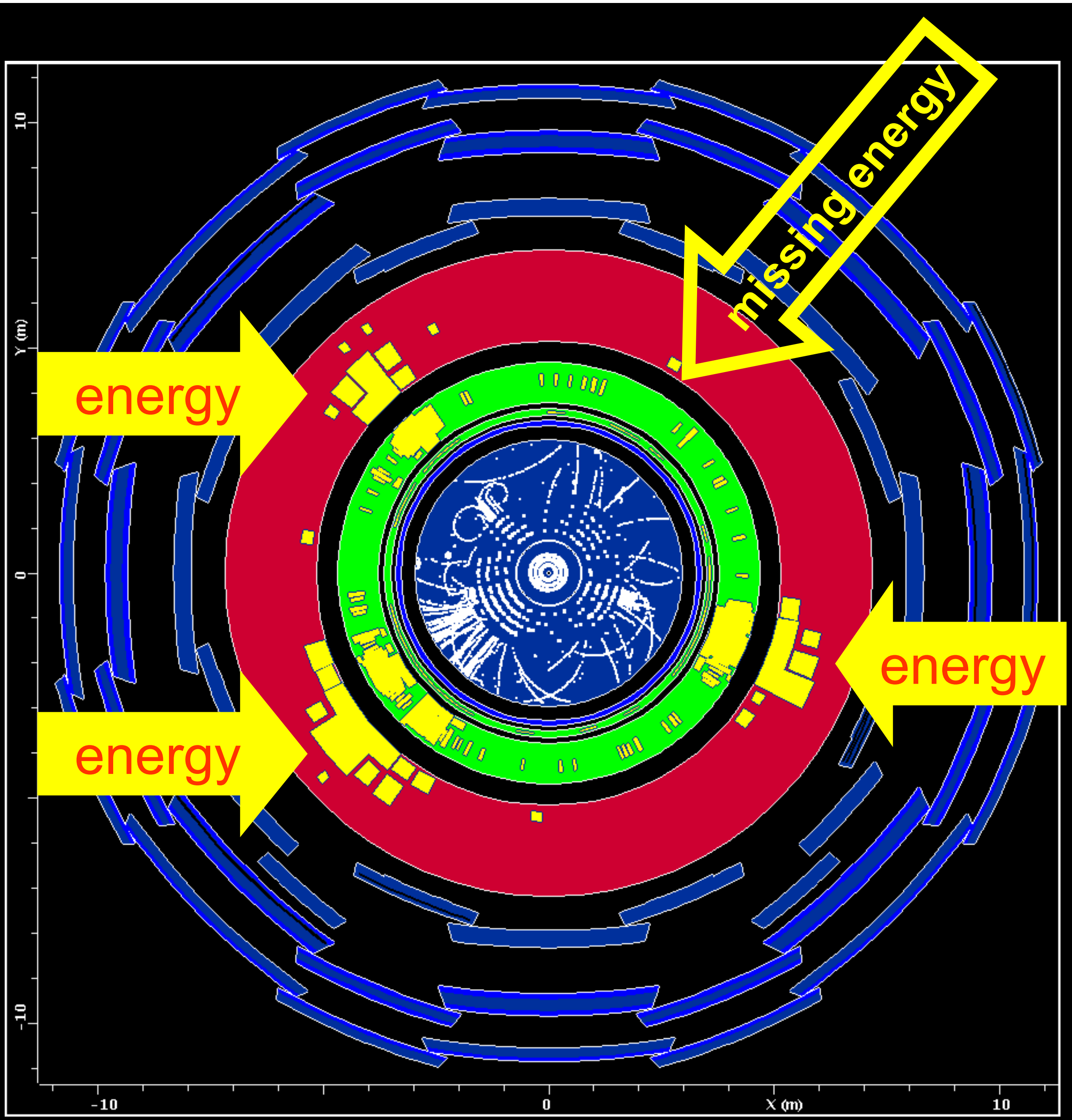
$Z \rightarrow e^{+}e^{-}$

accepted by Trigger



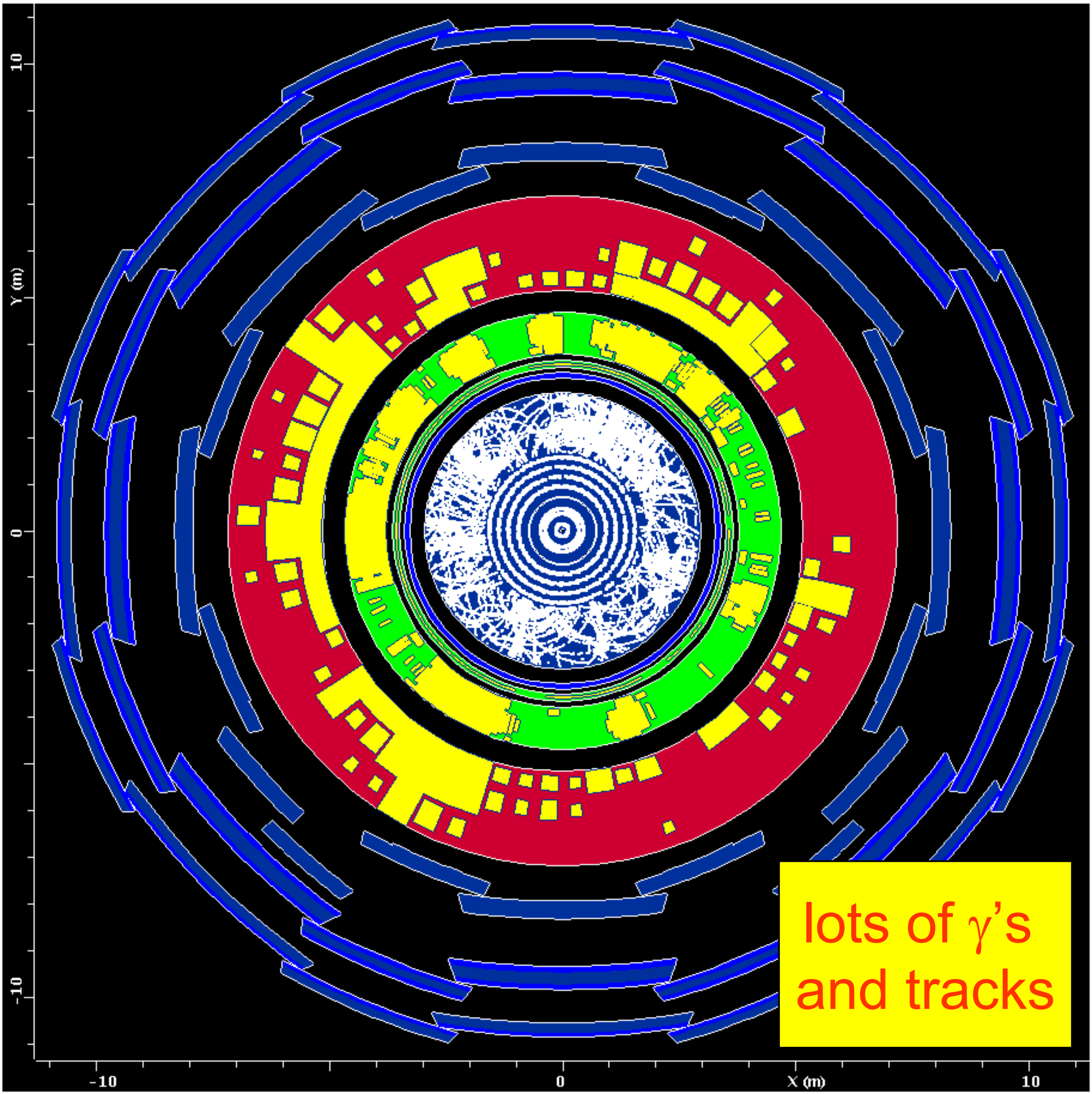
$Z \rightarrow e^+e^-$

accepted by Trigger



SUSY event
accepted by Trigger

Micro Black Hole accepted by Trigger



lots of γ's and tracks

Searches at the LHC

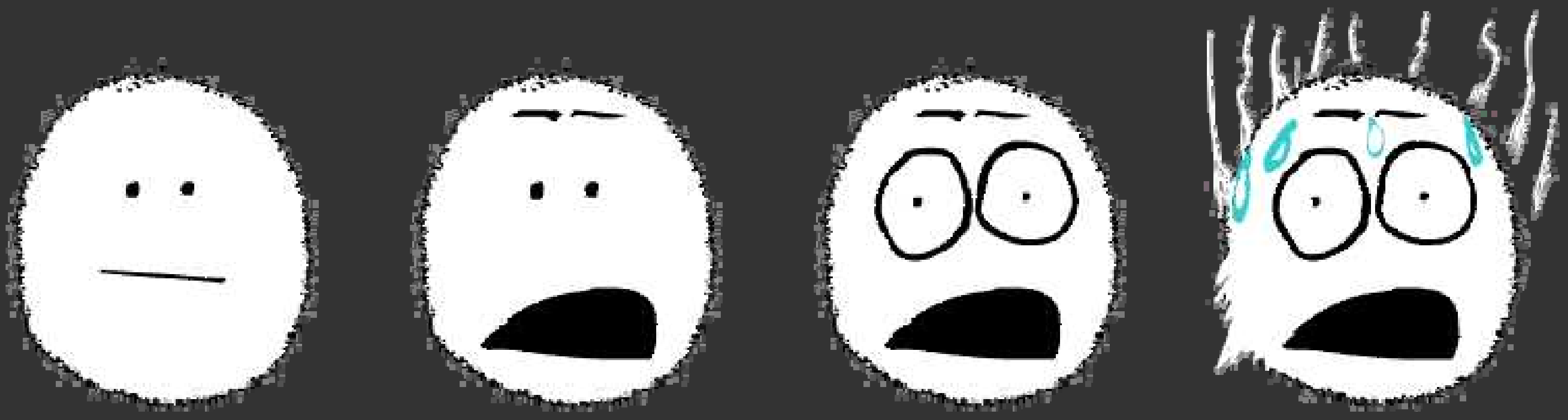
— LHC Startup —

Recall: 1 $\mathrm{pb}^{-1} = 10^{36}\ \mathrm{cm}^{-2}$

1 second at $L = 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow \int L dt = 10^{-5}\ \mathrm{pb}^{-1}$

1 non-stop running day at $L = 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow \int L dt = 0.86\ \mathrm{pb}^{-1}$

Help !



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… 4 text-only slides ahead ☹

Many Searches do NOT Require High Lumi

- Even with several 100 pb^{-1} many New Physics signals visible over large part of parameter space. Extend current Tevatron limits after few pb^{-1} of 14 TeV data …
  - SUSY: 500 GeV sparticles produced with *O*(pb) cross sections, spectacular signature
  - Significant reach for excited quarks, *Z*’ and RS gravitons (over DY background), …
  - Quickly reach multi-TeV sensitivity to SUSY and resonances
  - Can even exclude Higgs mass ranges (in particular for MSSM Higgses)

- Discovery claim requires the understanding of the Standard Model backgrounds
  - QCD jets and underlying event
  - *b*-quark production
  - top-quark production
  - *W*, *Z,* Drell-Yan production with jets
  - [Cavern background and pileup less important during low-luminosity phase]

Start-up Detector Commissioning (I)

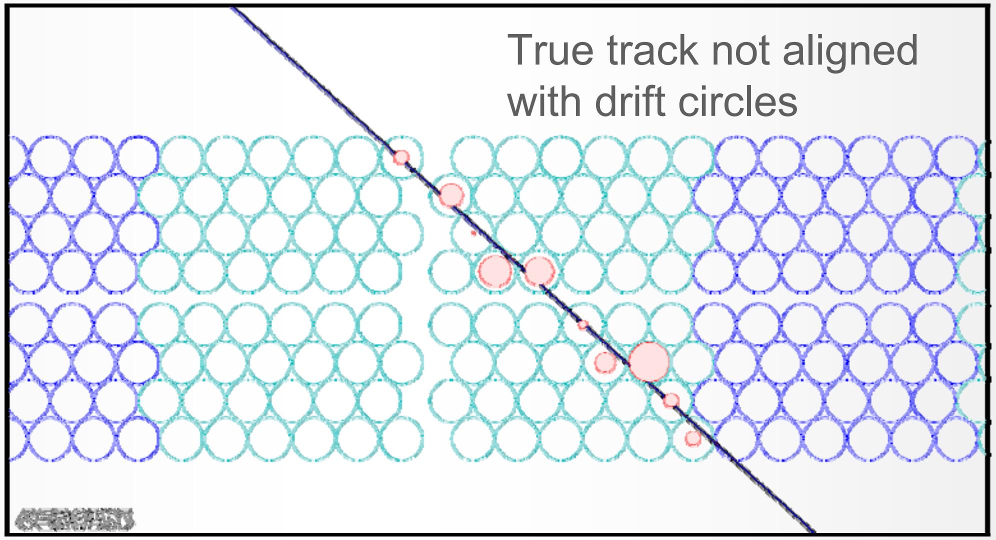
Need to early and fully commission the experiments to reach performance goals

Before LHC collisions:

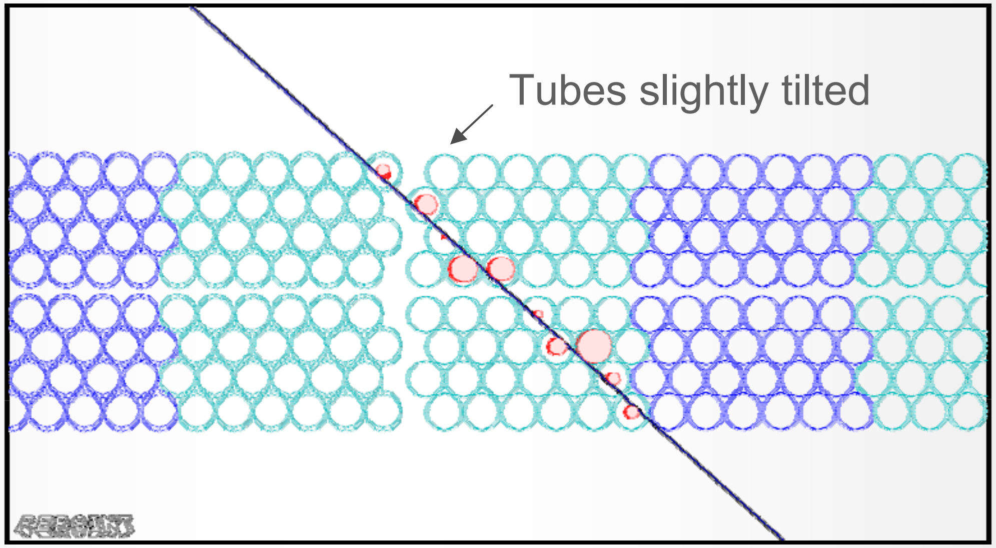
- Perform and maximally exploit test-beam measurements to understand detector components and tune simulation
- Perform realistic dress rehearsals to test acquisition, streaming and distribution of data
- Test calibration and alignment procedures with “as-installed” simulation samples
- Precisely map *B*-fields with survey data from magnetic probes
- Electronics channels are calibrated and mapped as dead or noisy with charge and/or external source injections
- Collect large cosmic ray muon samples for initial detector alignment (barrel)
- Use beam halo events for initial end-cap alignment

ATLAS Muon Spectrometer Alignment

Muon from simulated tt_{bar} event using tilted & egg-shape geometry


True track not aligned with drift circles

Reconstruction with ideal geometry


Tubes slightly tilted

Reconstruction with correct geometry

Start-up Detector Commissioning (II)

With LHC collisions:

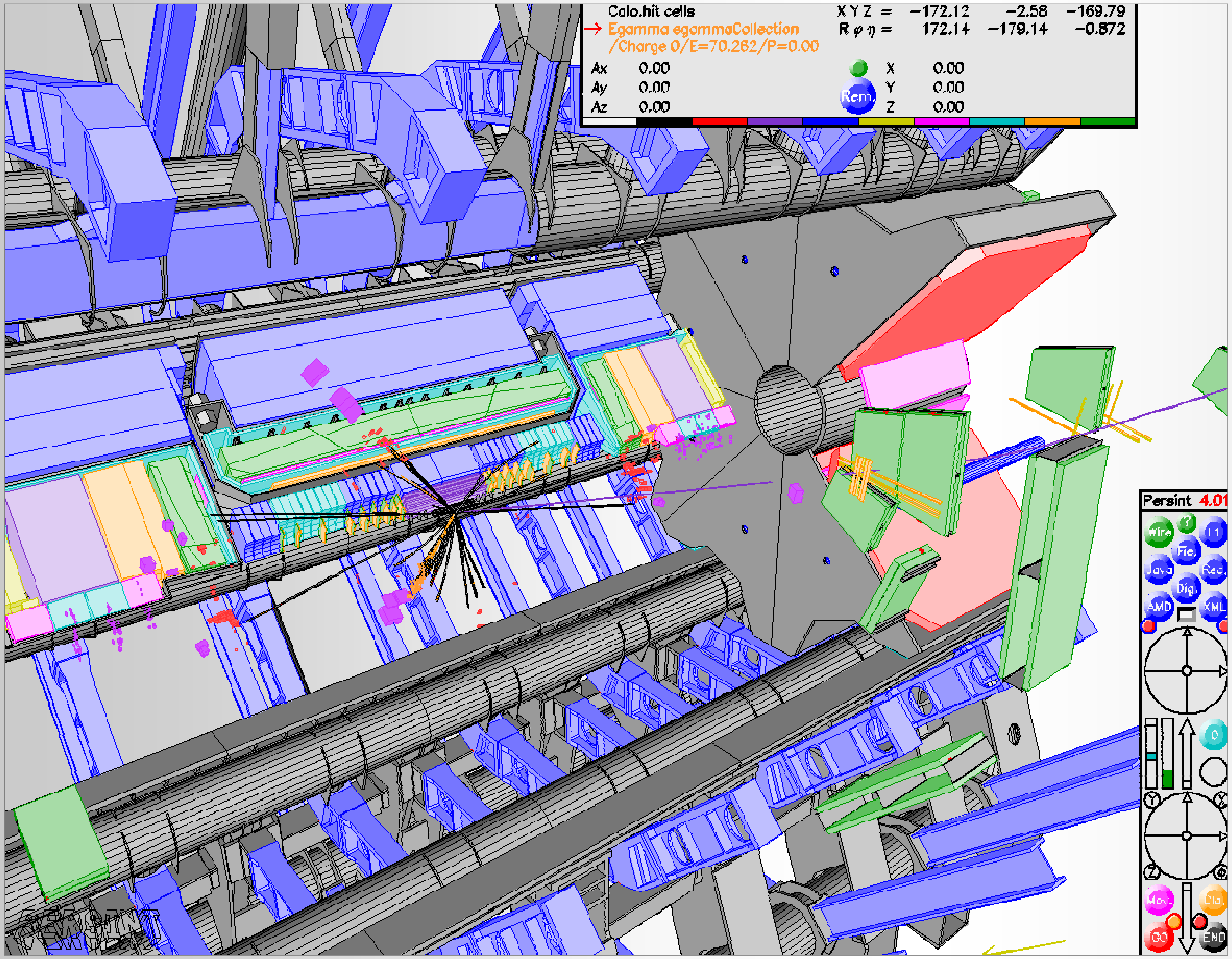
- Quickly time-in detector components with LHC bunches and trigger signal
- Subsequently operate hardware and software triggers with min. bias events; first commission single-object triggers, followed by topological signatures, isolation and $E_{T,\mathrm{miss}}$
- Copious isolated tracks used to improve inner tracker alignment; use additional information from E/p of tracks with opposite charge, and K^0, Λ_b mass and lifetimes
- Initial monitor of uniformity (azimuthally and $\pm\eta$) of calorimeter response
- Initial checks of calorimeter simulation by comparing track E/p and jet shower shapes
- Collect low-p_T leptons from c, b and J/ψ, $\Upsilon \rightarrow \mu\mu$ decays (>100k registered J/ψ /pb^{-1})
- Collect high-p_T leptons from W and Z decays (~7k/pb^{-1} and ~2k/pb^{-1})
- Quickly map pre-calorimeter material to $O(1\%)$ with photon conversions, also use momentum dependence of invariant mass reconstruction of light resonances

Start-up Detector Commissioning (III)

With LHC collisions:

- EM inter-calibration with inclusive electrons, later with $Z \to ee$ (~100 pb^{-1} for 0.7% EM uniformity (ATLAS)), also for global EM energy scale (similar: μ scale with $Z \to \mu\mu$)
- Hadronic track and jet inter-calibration with E/p, E_T balancing in di-jet, γ-jet, Z-jet events; global jet energy scale to < 5% after few months (ATLAS)
- Jet calibration with tt_{bar} events, with $W \to jj$ & $W \to e/\mu\nu$ (~250/pb^{-1}); calibrate *b*-tagging
- $E_{T,\mathrm{miss}}$ reconstruction requires event cleaning from beam halo, beam-gas collisions, cavern bkg, cosmics, and accurate mapping of instrumental deficiencies
- Study of $E_{T,\mathrm{miss}}$ tails with min. bias ($E_{T,\mathrm{miss}}$ vs ΣE_T), Z, W events → ~5% scale accuracy with 100 pb^{-1}
- Measure *e* and μ efficiencies and fake rates from $Z \to ee,\mu\mu$ “tag-and-probe” method
- Measure first differential and total cross sections for SM processes, study underlying event, verify PDFs, search for extraordinary physics, …

A tt_{bar} event with ATLAS

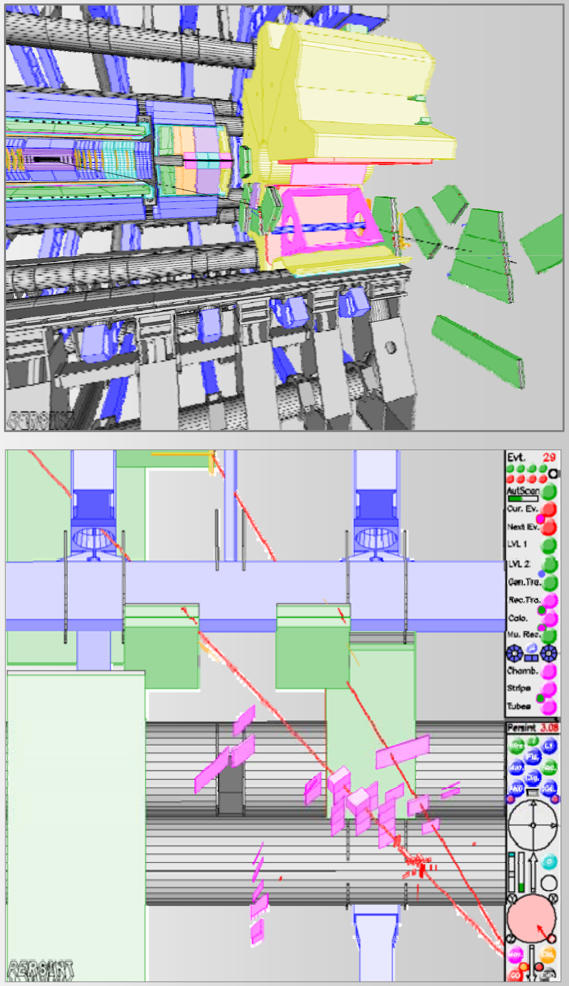


Calo.hit cells
→ Egamma egammaCollection
/Charge 0/E=70.262/P=0.00

XYZ = −172.12 −2.58 −169.79
R φ η = 172.14 −179.14 −0.872

Ax 0.00
Ay 0.00
Az 0.00

X 0.00
Y 0.00
Z 0.00



Muons through calorimeter

Start-up Detector Commissioning: top Signal

Can we observe an early top signal with limited detector performance (no *b*-tag) ?

Can we use it to understand detector **and** physics ?

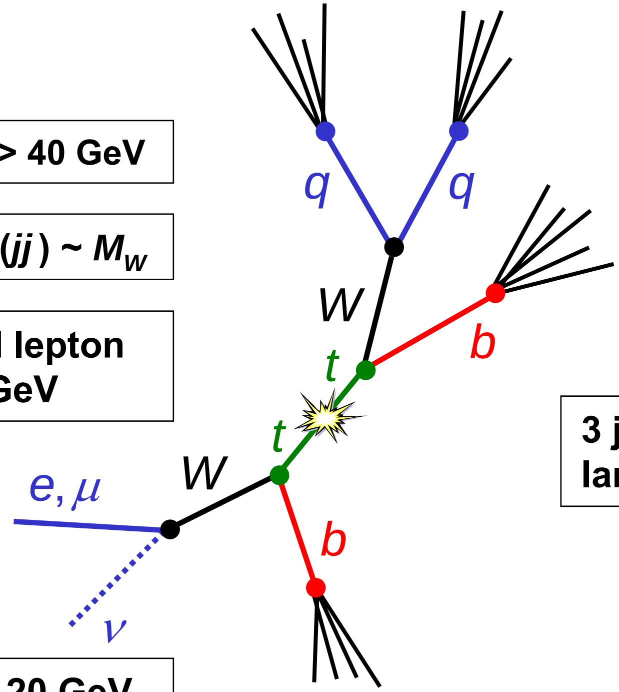
$\sigma_{tt} \approx 250$ pb for $tt \rightarrow bW\,bW \rightarrow b\ell\nu\,bjj$

4 jets p_T> 40 GeV

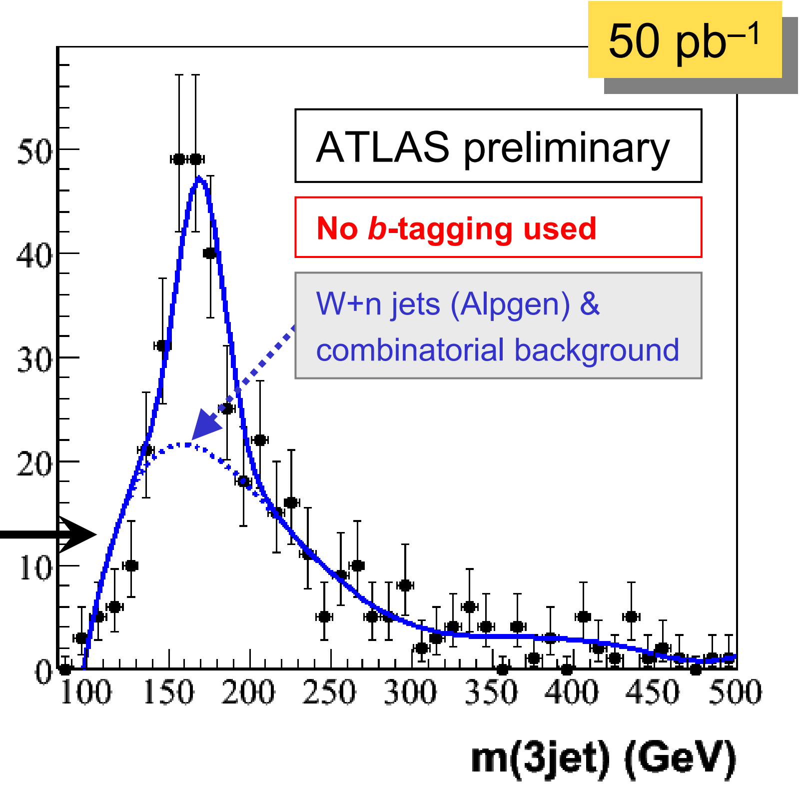
2 jets $M(jj) \sim M_W$

Isolated lepton p_T> 20 GeV

$E_{T,miss}$ > 20 GeV



3 jets with largest $\sum p_T$



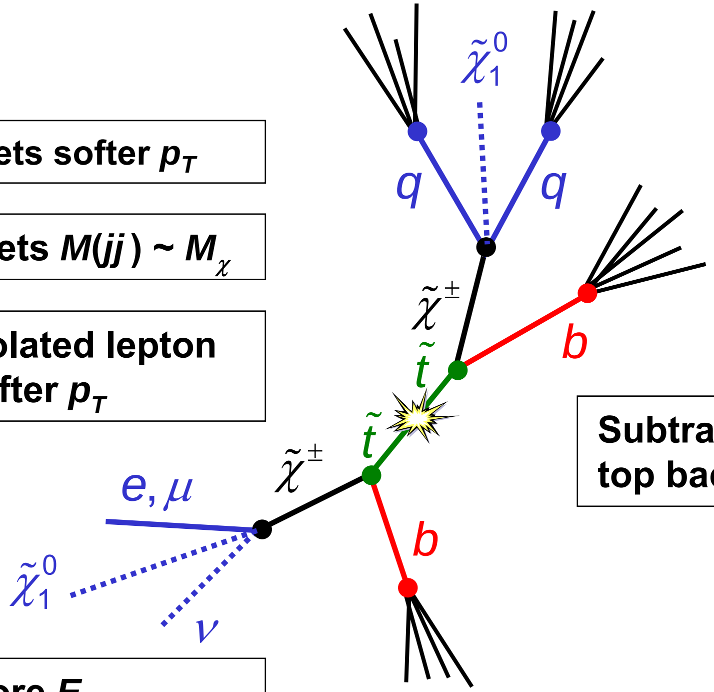
Be Ready for Surprises

Example: SUSY with **very light stop** (m_{stop} ~ 137 GeV < m_{top})

(Conflict with m_h lower limit ☹)

Final state similar to t-pair production, but more $E_{T,miss}$ and softer lepton, jets

$\sigma_{st\,st} \approx$ 412 pb for $st\,st \rightarrow b\chi\, b\chi \rightarrow b\chi^0 \ell\nu\, b\chi^0 jj$



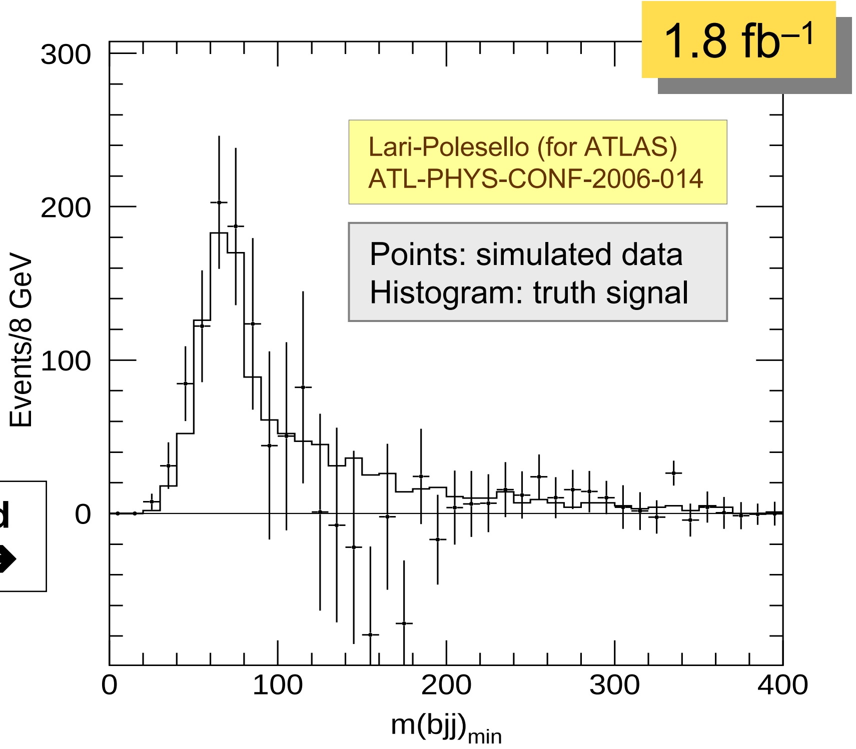
4 jets softer p_T

2 jets $M(jj)$ ~ M_χ

Isolated lepton softer p_T

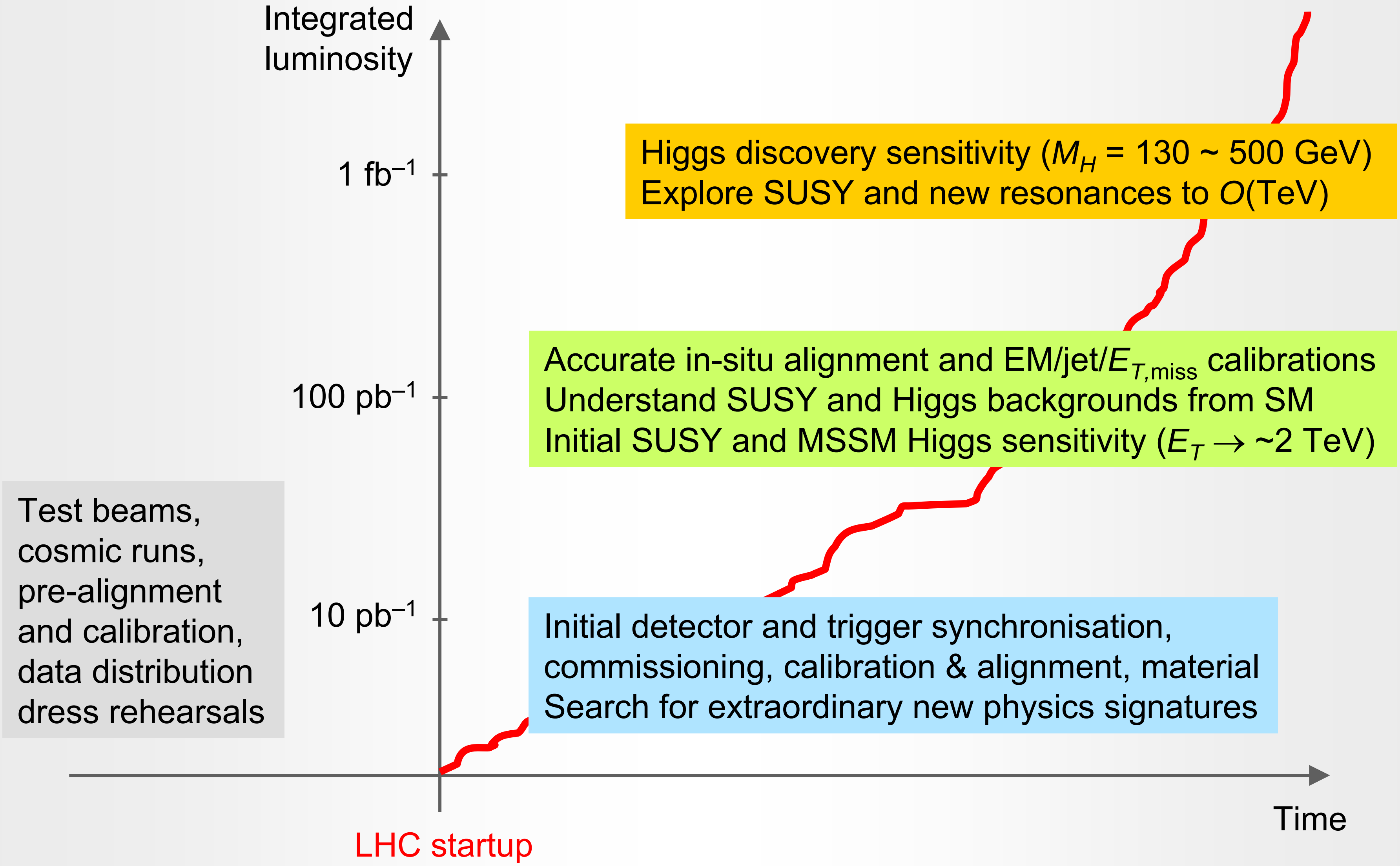
more $E_{T,miss}$

Subtract expected top background ➔



Lari-Polesello (for ATLAS)
ATL-PHYS-CONF-2006-014

Start-up Programme in a Nutshell



Higgs discovery sensitivity (M_H = 130 ~ 500 GeV)
Explore SUSY and new resonances to O(TeV)

Accurate in-situ alignment and EM/jet/$E_{T,\text{miss}}$ calibrations
Understand SUSY and Higgs backgrounds from SM
Initial SUSY and MSSM Higgs sensitivity ($E_T \to$ ~2 TeV)

Initial detector and trigger synchronisation, commissioning, calibration & alignment, material
Search for extraordinary new physics signatures

Test beams, cosmic runs, pre-alignment and calibration, data distribution dress rehearsals

and **tomorrow** …

Searches at the LHC

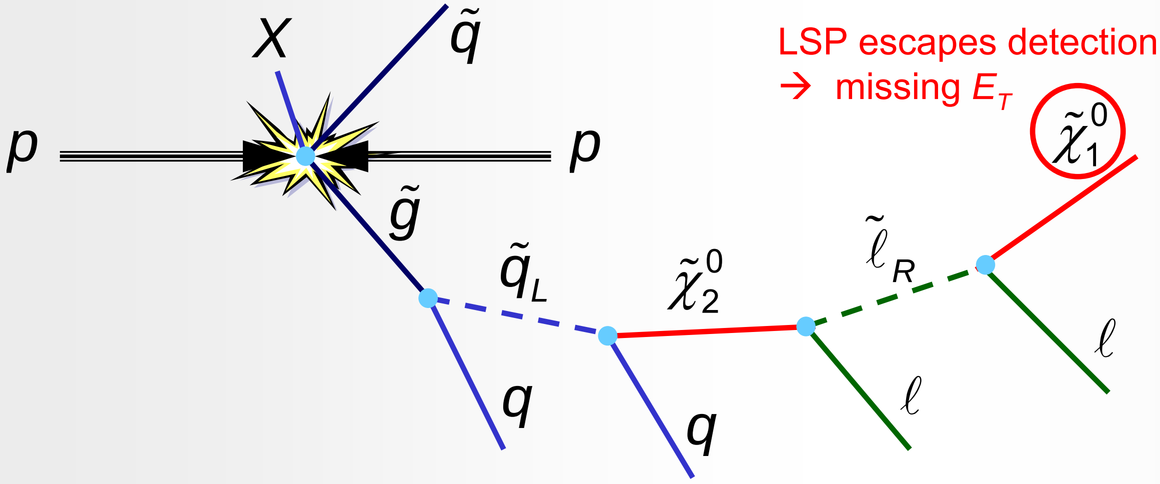
— Supersymmetry —

Search strategy:

1. Inclusive searches. Discovery and determination of SUSY mass scale
2. If signal, exclusive searches and reconstruction of decay cascades. Also, interpretation within specific models
3. Attempt for less model-dependent interpretation

Characteristic SUSY “Cascades” at the LHC

- Conserved ***R*-parity** requires existence of a **lightest stable SUSY particle (LSP)**. Since no exotic strong or EM bound states (isotopes) have been observed, the LSP should be neutral and colourless → **WIMP** ! LSP signature just as heavy neutrino
- The LSP is typically found to be a spin-½ **neutralino**, a linear combination of gauginos (in much of the SUSY parameter space the neutralino is a mixture of photino and zino)
- With *R*-parity: **SUSY** production in **pairs** only → **requires energy 2×SUSY mass** !



LSP escapes detection → missing E_T

“Typical” SUSY decay chain at the LHC

But why the “*T*” in missing E_T ?

The hard-scattering processes are not longitudinally balanced

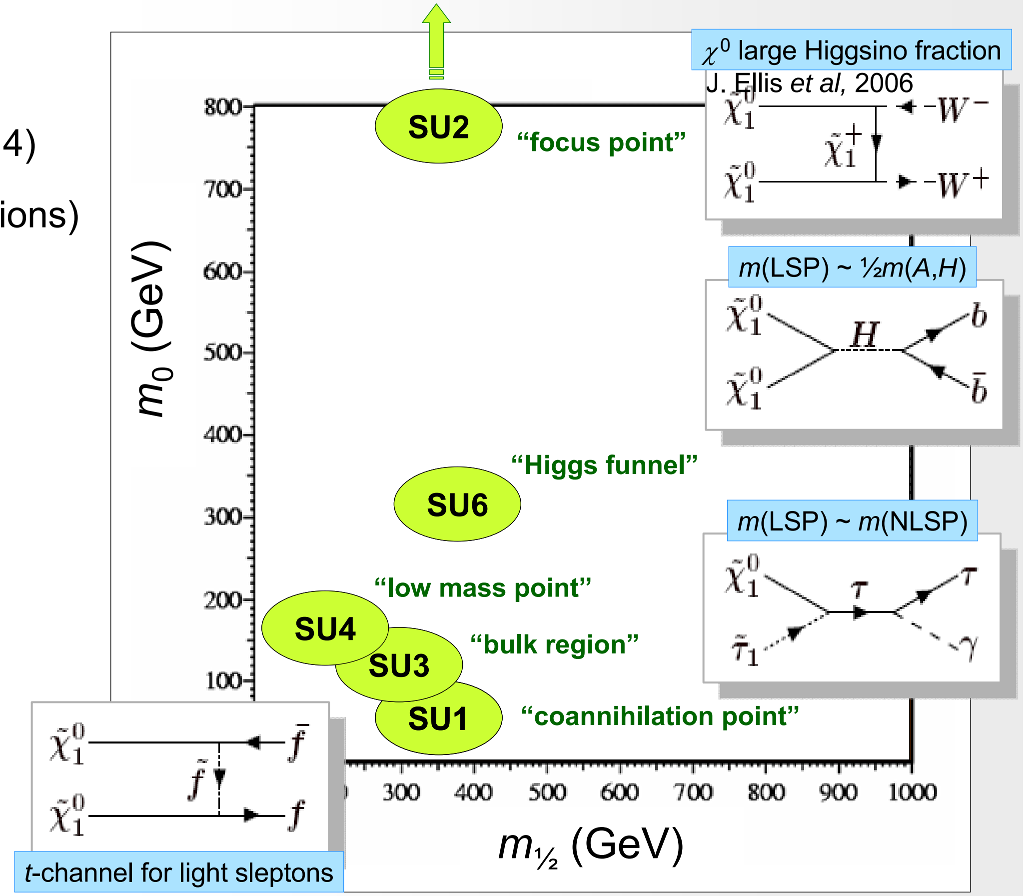
Hence, we do not know what longitudinal energy to expect

Fortunately, the events are transversely balanced !

Inclusive SUSY Searches

- Prepare SUSY searches with Monte Carlo: since SUSY parameters unknown, choose "representative" scenarios (*e.g.*, mSUGRA) → points need to respect $\Omega_{DM} \sim 0.1$

- Choose a few "characteristic" points
  - At the limit of experimental exclusion (SU4)
  - "Typical" point (SU3, light LSP and sfermions)
  - Special-feature points (SU1, SU2, SU6)



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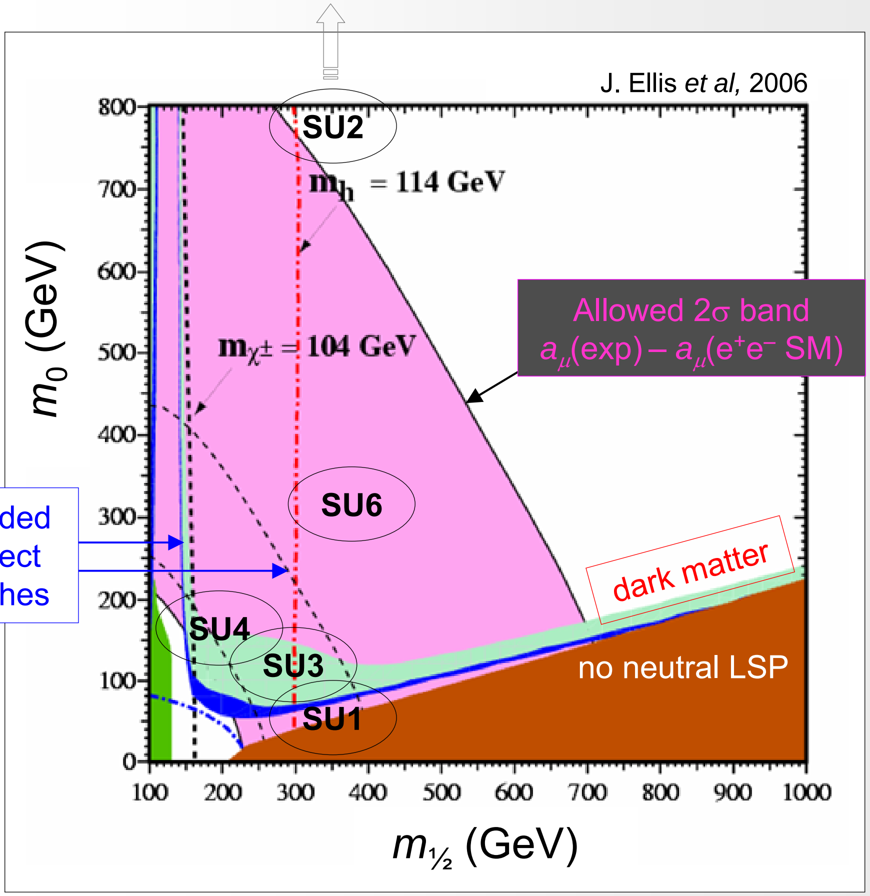
  - Special-feature points (SU1, SU2, SU6)

- Since mSUGRA has only 5 parameters, it is highly constraining …and can be already well constrained from data !
  - From direct accelerator searches
  - From indirect accelerator searches
  - From cosmology



Excluded by direct searches

Inclusive SUSY Searches

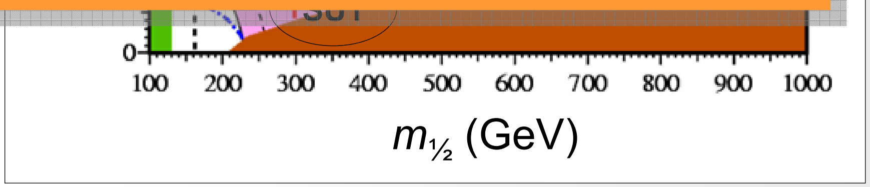
- Prepare SUSY searches with Monte Carlo: since SUSY parameters unknown, choose “representative” scenarios (*e.g.*, mSUGRA) → points need to respect Ω_{DM} ~ 0.1

An example for the interplay between particle physics and cosmology

But: cannot trust Ω_{DM} constraints !

- what if gravity is modified ?
- what if *R*-parity is violated ?
- what if SUSY breaking is gauge-mediated ?
- …

  - From cosmology

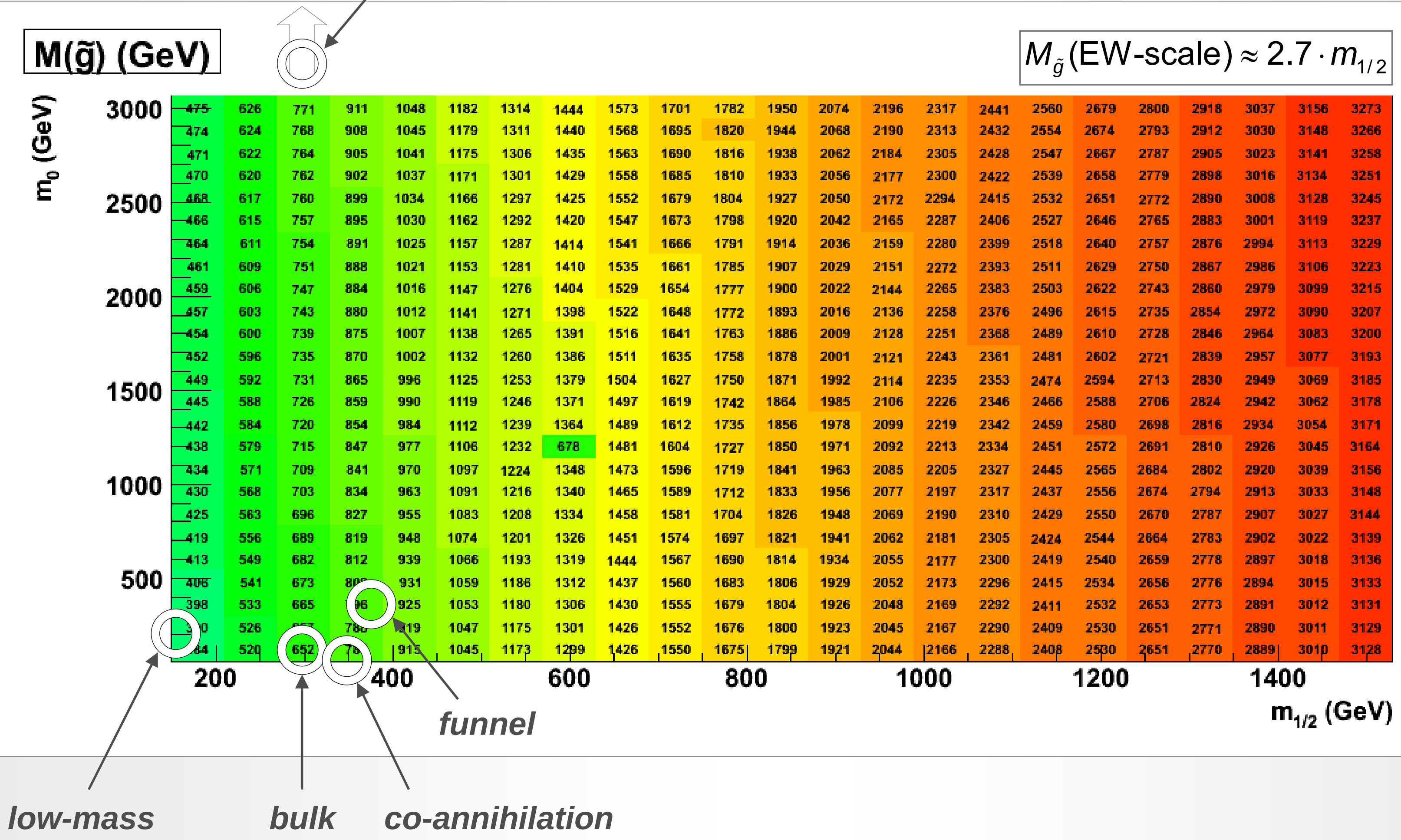


Probing mSUGRA

C. Clement (CERN) 2007

Fixed input parameters: $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$

$M_{\tilde{g}}\,(\text{EW-scale}) \approx 2.7 \cdot m_{1/2}$



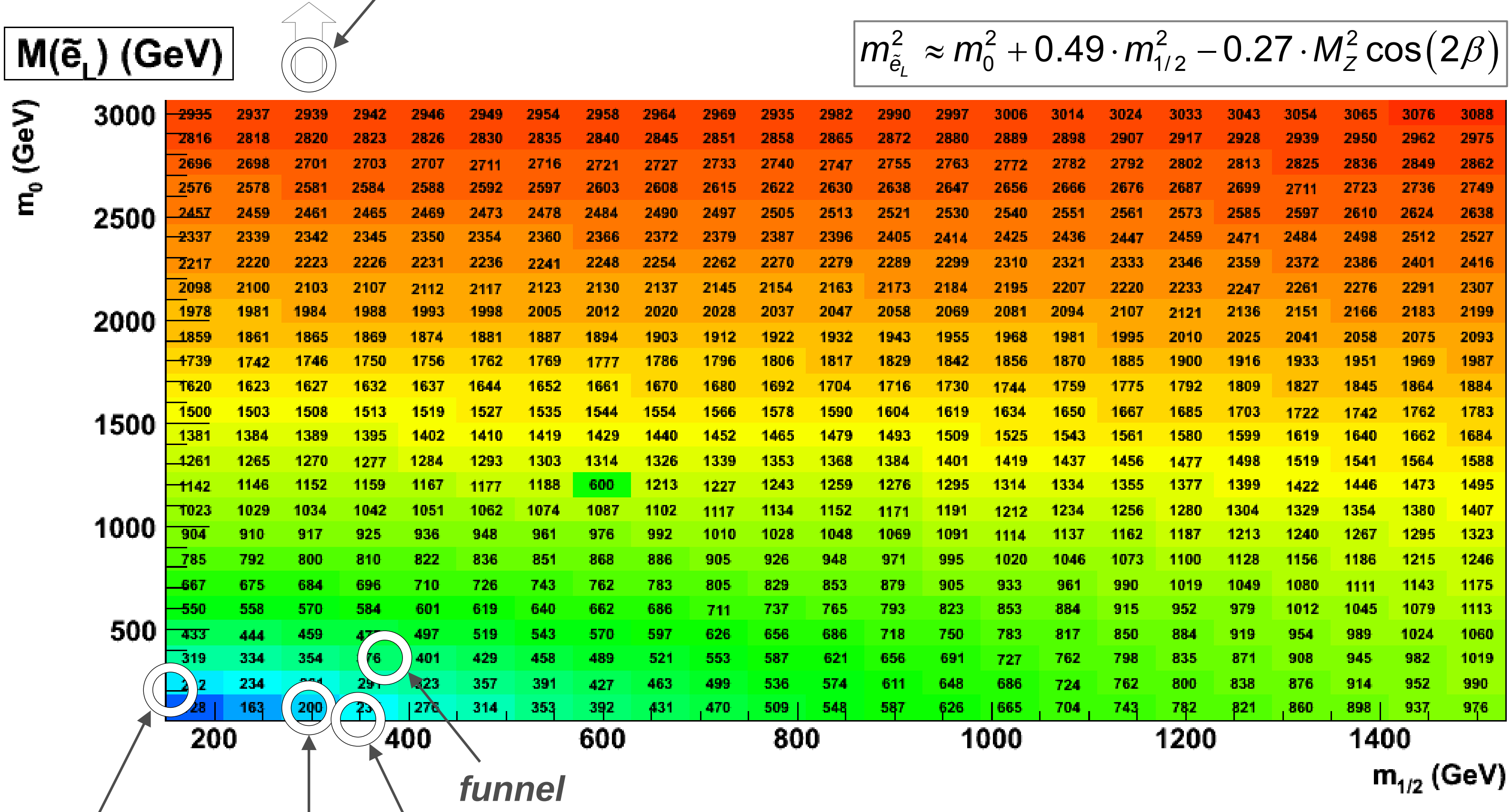
475	626	771	911	1048	1182	1314	1444	1573	1701	1782	1950	2074	2196	2317	2441	2560	2679	2800	2918	3037	3156	3273
474	624	768	908	1045	1179	1311	1440	1568	1695	1820	1944	2068	2190	2313	2432	2554	2674	2793	2912	3030	3148	3266
471	622	764	905	1041	1175	1306	1435	1563	1690	1816	1938	2062	2184	2305	2428	2547	2667	2787	2905	3023	3141	3258
470	620	762	902	1037	1171	1301	1429	1558	1685	1810	1933	2056	2177	2300	2422	2539	2658	2779	2898	3016	3134	3251
468	617	760	899	1034	1166	1297	1425	1552	1679	1804	1927	2050	2172	2294	2415	2532	2651	2772	2890	3008	3128	3245
466	615	757	895	1030	1162	1292	1420	1547	1673	1798	1920	2042	2165	2287	2406	2527	2646	2765	2883	3001	3119	3237
464	611	754	891	1025	1157	1287	1414	1541	1666	1791	1914	2036	2159	2280	2399	2518	2640	2757	2876	2994	3113	3229
461	609	751	888	1021	1153	1281	1410	1535	1661	1785	1907	2029	2151	2272	2393	2511	2629	2750	2867	2986	3106	3223
459	606	747	884	1016	1147	1276	1404	1529	1654	1777	1900	2022	2144	2265	2383	2503	2622	2743	2860	2979	3099	3215
457	603	743	880	1012	1141	1271	1398	1522	1648	1772	1893	2016	2136	2258	2376	2496	2615	2735	2854	2972	3090	3207
454	600	739	875	1007	1138	1265	1391	1516	1641	1763	1886	2009	2128	2251	2368	2489	2610	2728	2846	2964	3083	3200
452	596	735	870	1002	1132	1260	1386	1511	1635	1758	1878	2001	2121	2243	2361	2481	2602	2721	2839	2957	3077	3193
449	592	731	865	996	1125	1253	1379	1504	1627	1750	1871	1992	2114	2235	2353	2474	2594	2713	2830	2949	3069	3185
445	588	726	859	990	1119	1246	1371	1497	1619	1742	1864	1985	2106	2226	2346	2466	2588	2706	2824	2942	3062	3178
442	584	720	854	984	1112	1239	1364	1489	1612	1735	1856	1978	2099	2219	2342	2459	2580	2698	2816	2934	3054	3171
438	579	715	847	977	1106	1232	678	1481	1604	1727	1850	1971	2092	2213	2334	2451	2572	2691	2810	2926	3045	3164
434	571	709	841	970	1097	1224	1348	1473	1596	1719	1841	1963	2085	2205	2327	2445	2565	2684	2802	2920	3039	3156
430	568	703	834	963	1091	1216	1340	1465	1589	1712	1833	1956	2077	2197	2317	2437	2556	2674	2794	2913	3033	3148
425	563	696	827	955	1083	1208	1334	1458	1581	1704	1826	1948	2069	2190	2310	2429	2550	2670	2787	2907	3027	3144
419	556	689	819	948	1074	1201	1326	1451	1574	1697	1821	1941	2062	2181	2305	2424	2544	2664	2783	2902	3022	3139
413	549	682	812	939	1066	1193	1319	1444	1567	1690	1814	1934	2055	2177	2300	2419	2540	2659	2778	2897	3018	3136
406	541	673	[illegible]	931	1059	1186	1312	1437	1560	1683	1806	1929	2052	2173	2296	2415	2534	2656	2776	2894	3015	3133
398	533	665	[illegible]	925	1053	1180	1306	1430	1555	1679	1804	1926	2048	2169	2292	2411	2532	2653	2773	2891	3012	3131
[illegible]	526	[illegible]	[illegible]	[illegible]	1047	1175	1301	1426	1552	1676	1800	1923	2045	2167	2290	2409	2530	2651	2771	2890	3011	3129
[illegible]	520	652	[illegible]	915	1045	1173	1299	1426	1550	1675	1799	1921	2044	2166	2288	2408	2530	2651	2770	2889	3010	3128

Probing mSUGRA

C. Clement (CERN) 2007

Fixed input parameters: tanβ = 10 , μ > 0, A_0 = 0

$$m^2_{\tilde{e}_L} \approx m_0^2 + 0.49 \cdot m^2_{1/2} - 0.27 \cdot M_Z^2 \cos(2\beta)$$



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2816	2818	2820	2823	2826	2830	2835	2840	2845	2851	2858	2865	2872	2880	2889	2898	2907	2917	2928	2939	2950	2962	2975
2696	2698	2701	2703	2707	2711	2716	2721	2727	2733	2740	2747	2755	2763	2772	2782	2792	2802	2813	2825	2836	2849	2862
2576	2578	2581	2584	2588	2592	2597	2603	2608	2615	2622	2630	2638	2647	2656	2666	2676	2687	2699	2711	2723	2736	2749
2457	2459	2461	2465	2469	2473	2478	2484	2490	2497	2505	2513	2521	2530	2540	2551	2561	2573	2585	2597	2610	2624	2638
2337	2339	2342	2345	2350	2354	2360	2366	2372	2379	2387	2396	2405	2414	2425	2436	2447	2459	2471	2484	2498	2512	2527
2217	2220	2223	2226	2231	2236	2241	2248	2254	2262	2270	2279	2289	2299	2310	2321	2333	2346	2359	2372	2386	2401	2416
2098	2100	2103	2107	2112	2117	2123	2130	2137	2145	2154	2163	2173	2184	2195	2207	2220	2233	2247	2261	2276	2291	2307
1978	1981	1984	1988	1993	1998	2005	2012	2020	2028	2037	2047	2058	2069	2081	2094	2107	2121	2136	2151	2166	2183	2199
1859	1861	1865	1869	1874	1881	1887	1894	1903	1912	1922	1932	1943	1955	1968	1981	1995	2010	2025	2041	2058	2075	2093
1739	1742	1746	1750	1756	1762	1769	1777	1786	1796	1806	1817	1829	1842	1856	1870	1885	1900	1916	1933	1951	1969	1987
1620	1623	1627	1632	1637	1644	1652	1661	1670	1680	1692	1704	1716	1730	1744	1759	1775	1792	1809	1827	1845	1864	1884
1500	1503	1508	1513	1519	1527	1535	1544	1554	1566	1578	1590	1604	1619	1634	1650	1667	1685	1703	1722	1742	1762	1783
1381	1384	1389	1395	1402	1410	1419	1429	1440	1452	1465	1479	1493	1509	1525	1543	1561	1580	1599	1619	1640	1662	1684
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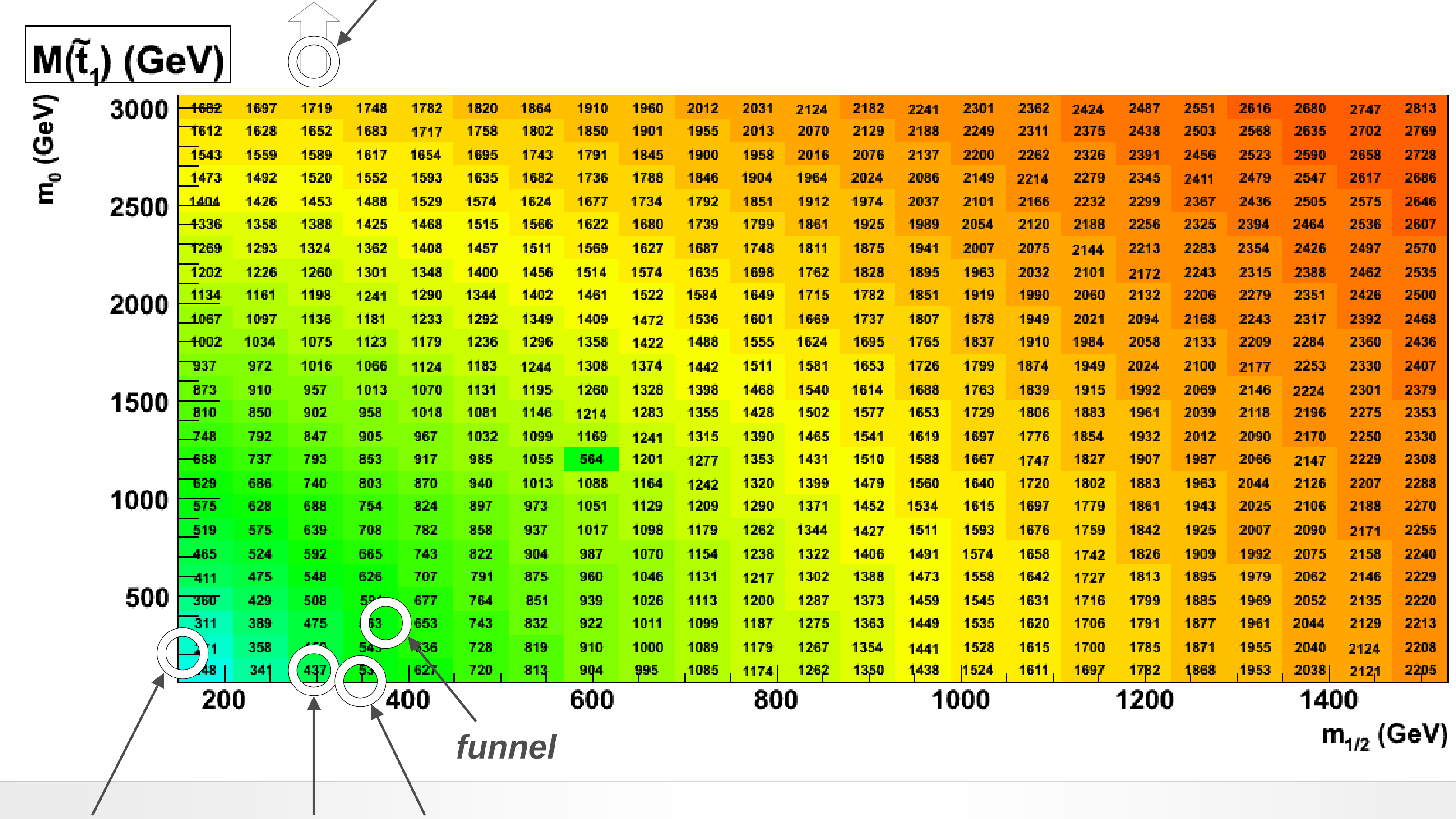
1142	1146	1152	1159	1167	1177	1188	600	1213	1227	1243	1259	1276	1295	1314	1334	1355	1377	1399	1422	1446	1473	1495
1023	1029	1034	1042	1051	1062	1074	1087	1102	1117	1134	1152	1171	1191	1212	1234	1256	1280	1304	1329	1354	1380	1407
904	910	917	925	936	948	961	976	992	1010	1028	1048	1069	1091	1114	1137	1162	1187	1213	1240	1267	1295	1323
785	792	800	810	822	836	851	868	886	905	926	948	971	995	1020	1046	1073	1100	1128	1156	1186	1215	1246
667	675	684	696	710	726	743	762	783	805	829	853	879	905	933	961	990	1019	1049	1080	1111	1143	1175
550	558	570	584	601	619	640	662	686	711	737	765	793	823	853	884	915	952	979	1012	1045	1079	1113
433	444	459	[illegible]	497	519	543	570	597	626	656	686	718	750	783	817	850	884	919	954	989	1024	1060
319	334	354	[illegible]	401	429	458	489	521	553	587	621	656	691	727	762	798	835	871	908	945	982	1019
[illegible]	234	[illegible]	[illegible]	[illegible]	357	391	427	463	499	536	574	611	648	686	724	762	800	838	876	914	952	990
[illegible]	163	200	[illegible]	276	314	353	392	431	470	509	548	587	626	665	704	743	782	821	860	898	937	976

low-mass *bulk* *co-annihilation*

Probing mSUGRA

C. Clement (CERN) 2007

Fixed input parameters: tanβ = 10 , μ > 0, A_0 = 0



focus

funnel

low-mass

bulk

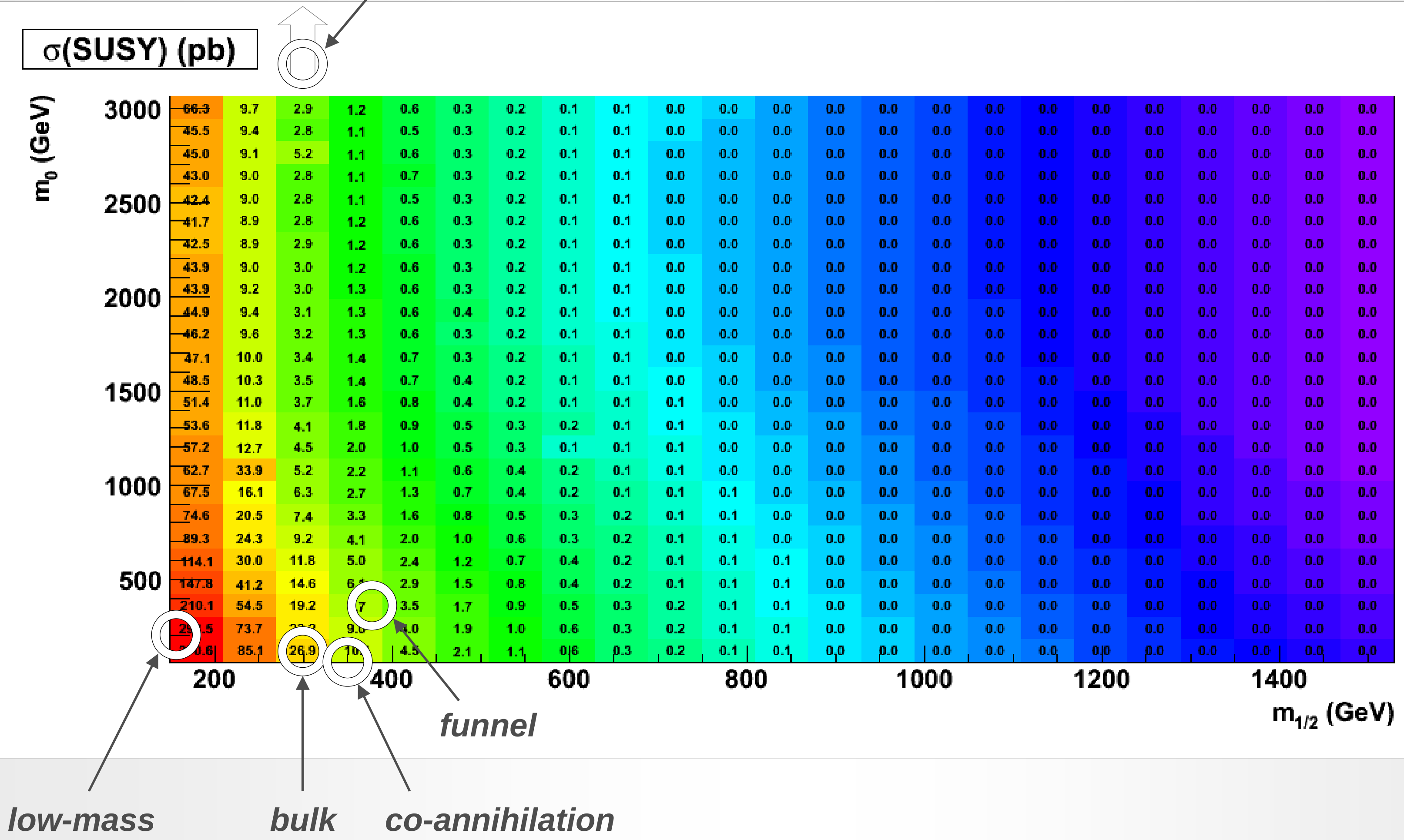
co-annihilation

1682	1697	1719	1748	1782	1820	1864	1910	1960	2012	2031	2124	2182	2241	2301	2362	2424	2487	2551	2616	2680	2747	2813
1612	1628	1652	1683	1717	1758	1802	1850	1901	1955	2013	2070	2129	2188	2249	2311	2375	2438	2503	2568	2635	2702	2769
1543	1559	1589	1617	1654	1695	1743	1791	1845	1900	1958	2016	2076	2137	2200	2262	2326	2391	2456	2523	2590	2658	2728
1473	1492	1520	1552	1593	1635	1682	1736	1788	1846	1904	1964	2024	2086	2149	2214	2279	2345	2411	2479	2547	2617	2686
1404	1426	1453	1488	1529	1574	1624	1677	1734	1792	1851	1912	1974	2037	2101	2166	2232	2299	2367	2436	2505	2575	2646
1336	1358	1388	1425	1468	1515	1566	1622	1680	1739	1799	1861	1925	1989	2054	2120	2188	2256	2325	2394	2464	2536	2607
1269	1293	1324	1362	1408	1457	1511	1569	1627	1687	1748	1811	1875	1941	2007	2075	2144	2213	2283	2354	2426	2497	2570
1202	1226	1260	1301	1348	1400	1456	1514	1574	1635	1698	1762	1828	1895	1963	2032	2101	2172	2243	2315	2388	2462	2535
1134	1161	1198	1241	1290	1344	1402	1461	1522	1584	1649	1715	1782	1851	1919	1990	2060	2132	2206	2279	2351	2426	2500
1067	1097	1136	1181	1233	1292	1349	1409	1472	1536	1601	1669	1737	1807	1878	1949	2021	2094	2168	2243	2317	2392	2468
1002	1034	1075	1123	1179	1236	1296	1358	1422	1488	1555	1624	1695	1765	1837	1910	1984	2058	2133	2209	2284	2360	2436
937	972	1016	1066	1124	1183	1244	1308	1374	1442	1511	1581	1653	1726	1799	1874	1949	2024	2100	2177	2253	2330	2407
873	910	957	1013	1070	1131	1195	1260	1328	1398	1468	1540	1614	1688	1763	1839	1915	1992	2069	2146	2224	2301	2379
810	850	902	958	1018	1081	1146	1214	1283	1355	1428	1502	1577	1653	1729	1806	1883	1961	2039	2118	2196	2275	2353
748	792	847	905	967	1032	1099	1169	1241	1315	1390	1465	1541	1619	1697	1776	1854	1932	2012	2090	2170	2250	2330
688	737	793	853	917	985	1055	564	1201	1277	1353	1431	1510	1588	1667	1747	1827	1907	1987	2066	2147	2229	2308
629	686	740	803	870	940	1013	1088	1164	1242	1320	1399	1479	1560	1640	1720	1802	1883	1963	2044	2126	2207	2288
575	628	688	754	824	897	973	1051	1129	1209	1290	1371	1452	1534	1615	1697	1779	1861	1943	2025	2106	2188	2270
519	575	639	708	782	858	937	1017	1098	1179	1262	1344	1427	1511	1593	1676	1759	1842	1925	2007	2090	2171	2255
465	524	592	665	743	822	904	987	1070	1154	1238	1322	1406	1491	1574	1658	1742	1826	1909	1992	2075	2158	2240
411	475	548	626	707	791	875	960	1046	1131	1217	1302	1388	1473	1558	1642	1727	1813	1895	1979	2062	2146	2229
360	429	508	[illegible]	677	764	851	939	1026	1113	1200	1287	1373	1459	1545	1631	1716	1799	1885	1969	2052	2135	2220
311	389	475	[illegible]	653	743	832	922	1011	1099	1187	1275	1363	1449	1535	1620	1706	1791	1877	1961	2044	2129	2213
271	358	[illegible]	[illegible]	636	728	819	910	1000	1089	1179	1267	1354	1441	1528	1615	1700	1785	1871	1955	2040	2124	2208
248	341	437	[illegible]	627	720	813	904	995	1085	1174	1262	1350	1438	1524	1611	1697	1782	1868	1953	2038	2121	2205

Probing mSUGRA

C. Clement (CERN) 2007

Fixed input parameters: $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$



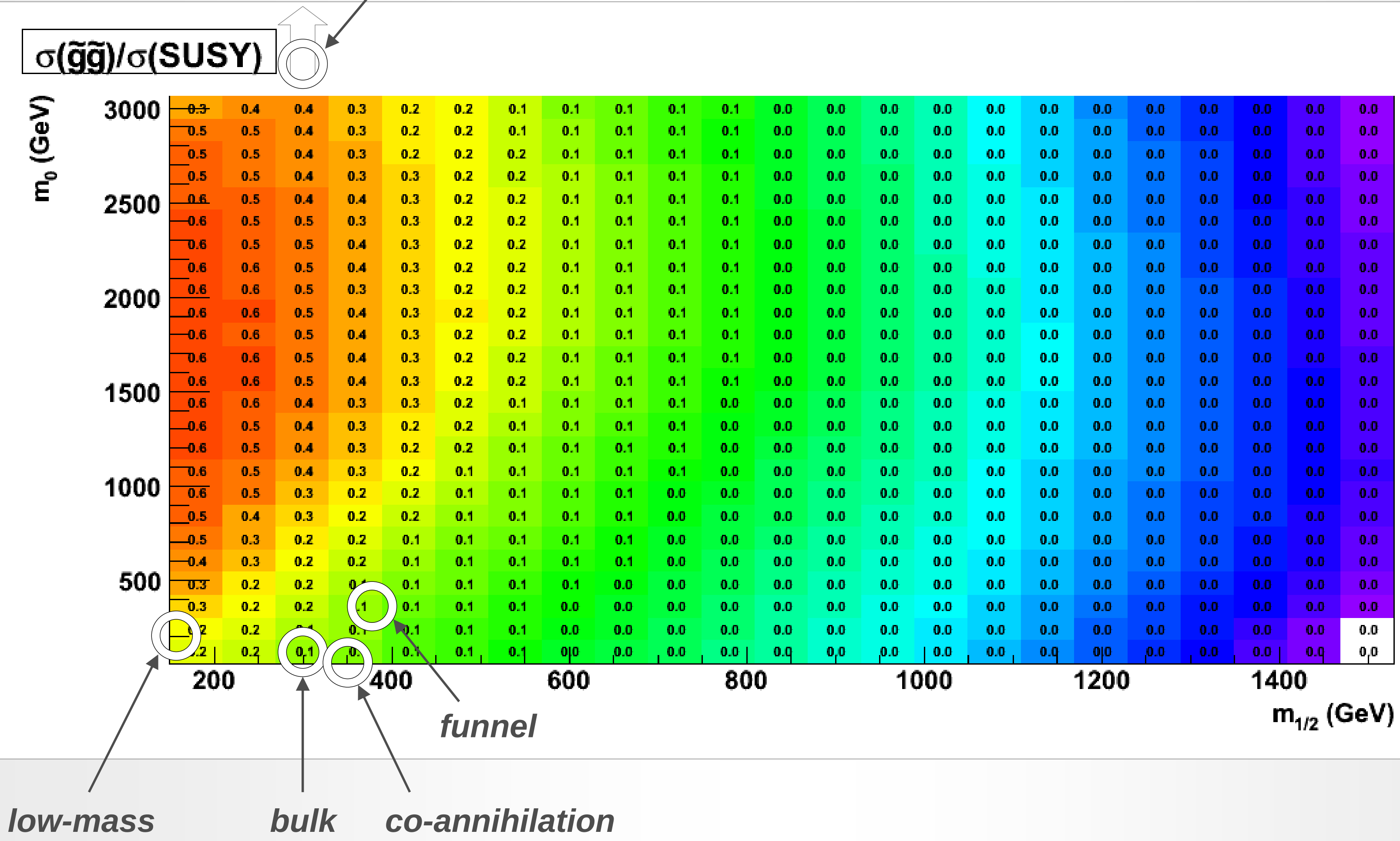
66.3	9.7	2.9	1.2	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45.5	9.4	2.8	1.1	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45.0	9.1	5.2	1.1	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43.0	9.0	2.8	1.1	0.7	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42.4	9.0	2.8	1.1	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
41.7	8.9	2.8	1.2	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
42.5	8.9	2.9	1.2	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43.9	9.0	3.0	1.2	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43.9	9.2	3.0	1.3	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44.9	9.4	3.1	1.3	0.6	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
46.2	9.6	3.2	1.3	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
47.1	10.0	3.4	1.4	0.7	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
48.5	10.3	3.5	1.4	0.7	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
51.4	11.0	3.7	1.6	0.8	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
53.6	11.8	4.1	1.8	0.9	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
57.2	12.7	4.5	2.0	1.0	0.5	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
62.7	33.9	5.2	2.2	1.1	0.6	0.4	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
67.5	16.1	6.3	2.7	1.3	0.7	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
74.6	20.5	7.4	3.3	1.6	0.8	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
89.3	24.3	9.2	4.1	2.0	1.0	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114.1	30.0	11.8	5.0	2.4	1.2	0.7	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
147.8	41.2	14.6	[illegible]	2.9	1.5	0.8	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210.1	54.5	19.2	[illegible]	3.5	1.7	0.9	0.5	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[illegible]	73.7	[illegible]	9.0	[illegible]	1.9	1.0	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
[illegible]	85.1	26.9	[illegible]	4.5	2.1	1.1	0.6	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Probing mSUGRA

C. Clement (CERN) 2007

focus

Fixed input parameters: $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$



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0.5	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	0.5	0.4	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	0.5	0.4	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.4	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.5	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.3	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.6	0.4	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.6	0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.3	0.2	0.2	.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.2	0.2	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.2	0.2	0.1	0.	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

funnel

low-mass

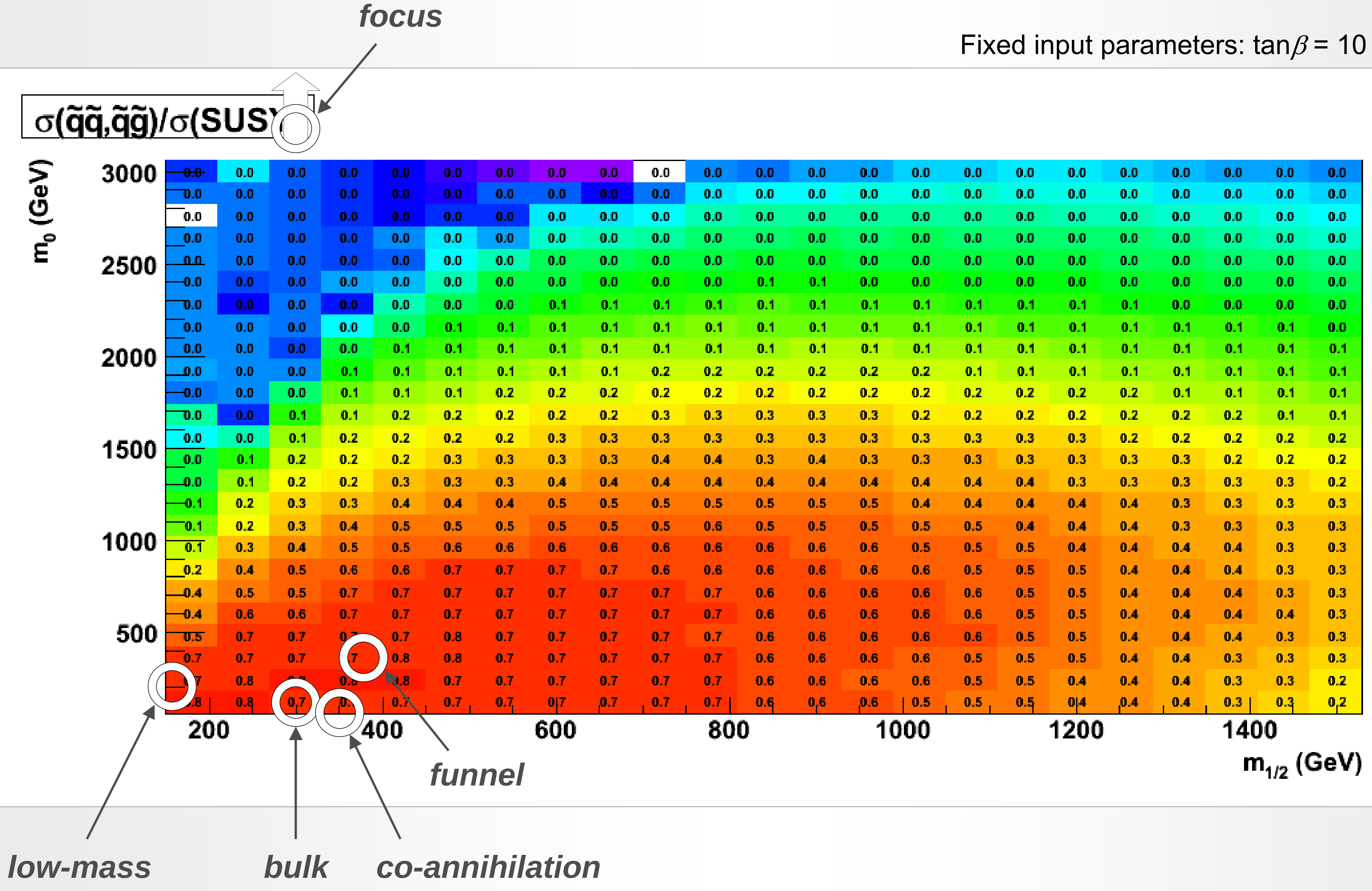
bulk

co-annihilation

Probing mSUGRA

C. Clement (CERN) 2007

Fixed input parameters: $\tan\beta = 10$, $\mu > 0$, $A_0 = 0$



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0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
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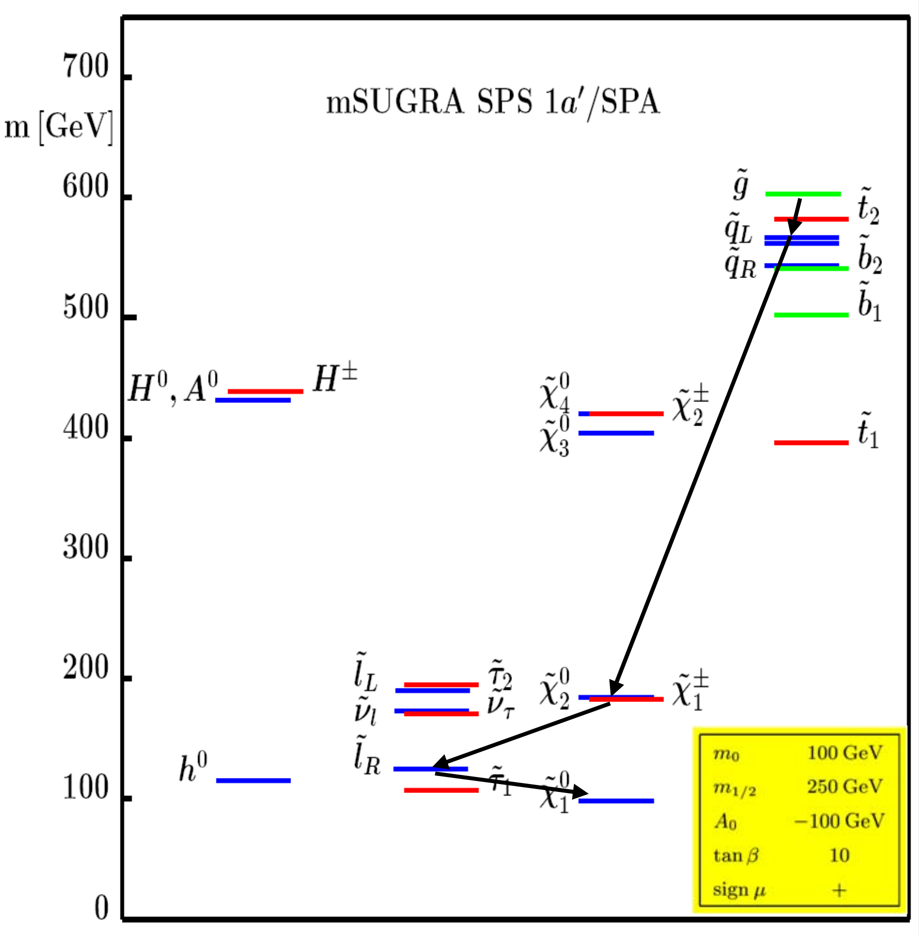
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.0
0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
0.0	0.0	0.1	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
0.0	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.3	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2
0.0	0.1	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2
0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3
0.1	0.2	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.3	0.3
0.1	0.3	0.4	0.5	0.5	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3
0.2	0.4	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3
0.4	0.5	0.5	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3
0.4	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.3
0.5	0.7	0.7	0.7	0.7	0.8	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3
0.7	0.7	0.7	[illegible]	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.3	0.3	0.3
[illegible]	0.8	[illegible]	[illegible]	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.2
[illegible]	0.8	0.7	[illegible]	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.4	0.4	0.4	0.3	0.3	0.2

Inclusive SUSY Searches … continued

- The precise signatures of the SUSY “cascades” are driven by the masses of the SUSY particles

- To good generality we can expect:
  - High-p_T jets from squark & gluino decays
  - Leptons from gaugino & slepton decays
  - Missing energy from LSPs



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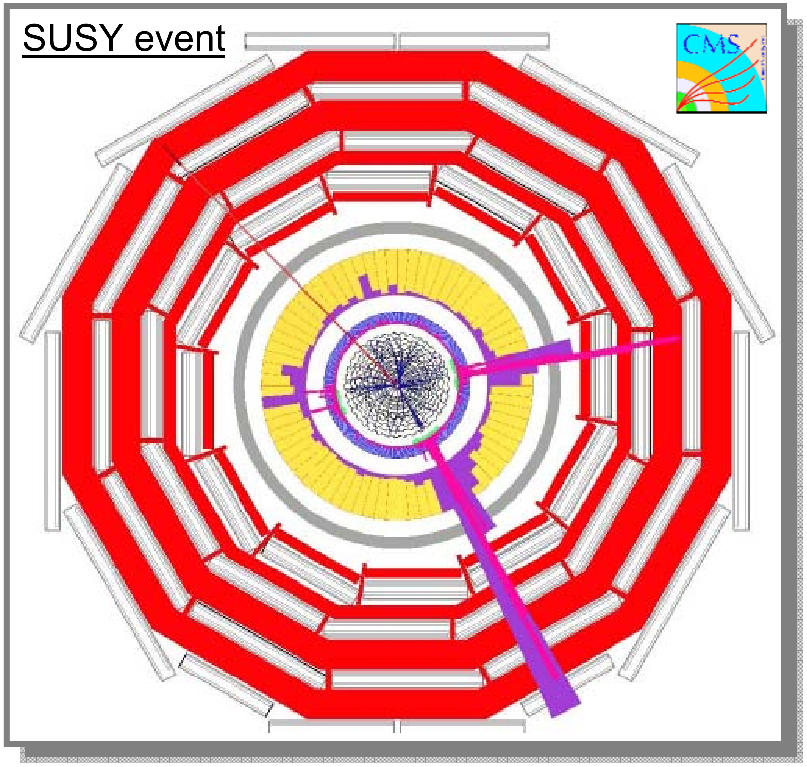
- This lays out an **inclusive** search strategy
- Detector requirements:
  - Excellent EM & jet-energy measurement
  - Excellent lepton identification
  - Hermeticity (good acceptance)



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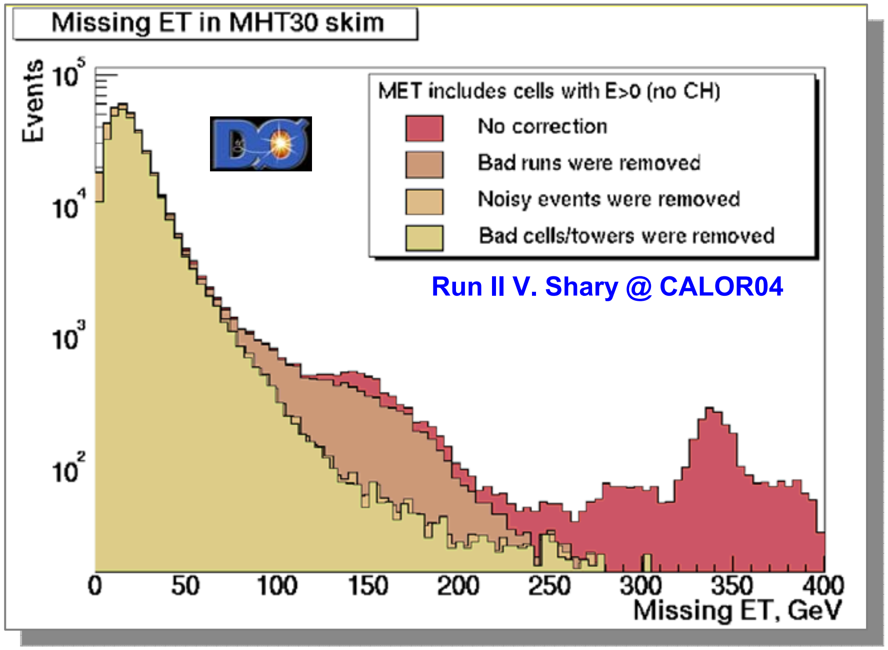
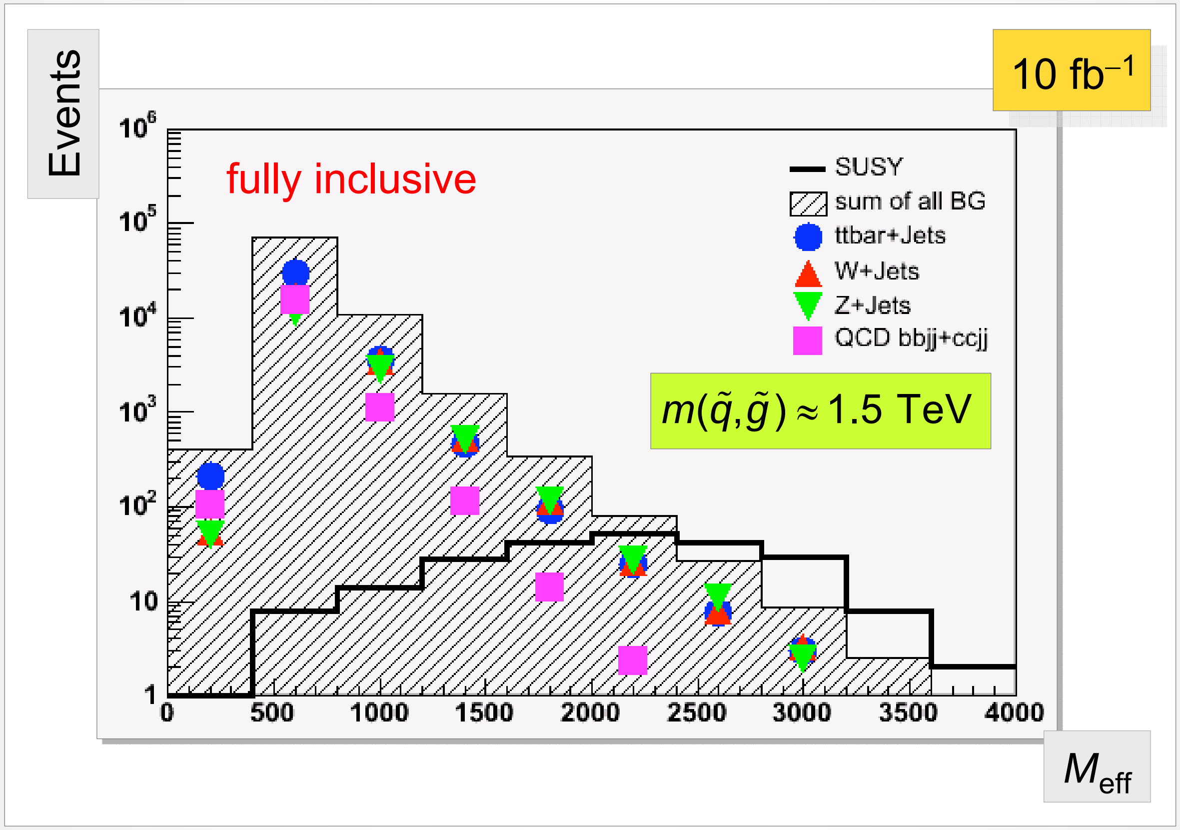
Measuring missing energy is a tough task !



Run II V. Shary @ CALOR04

Inclusive SUSY Searches ... continued

- A sensitive variable to detect SUSY decays is the “**effective mass**”: $M_{\text{eff}} = E_{T,\text{miss}} + \sum_{\text{jets, leptons}} p_T$



Inclusive SUSY Searches ... continued

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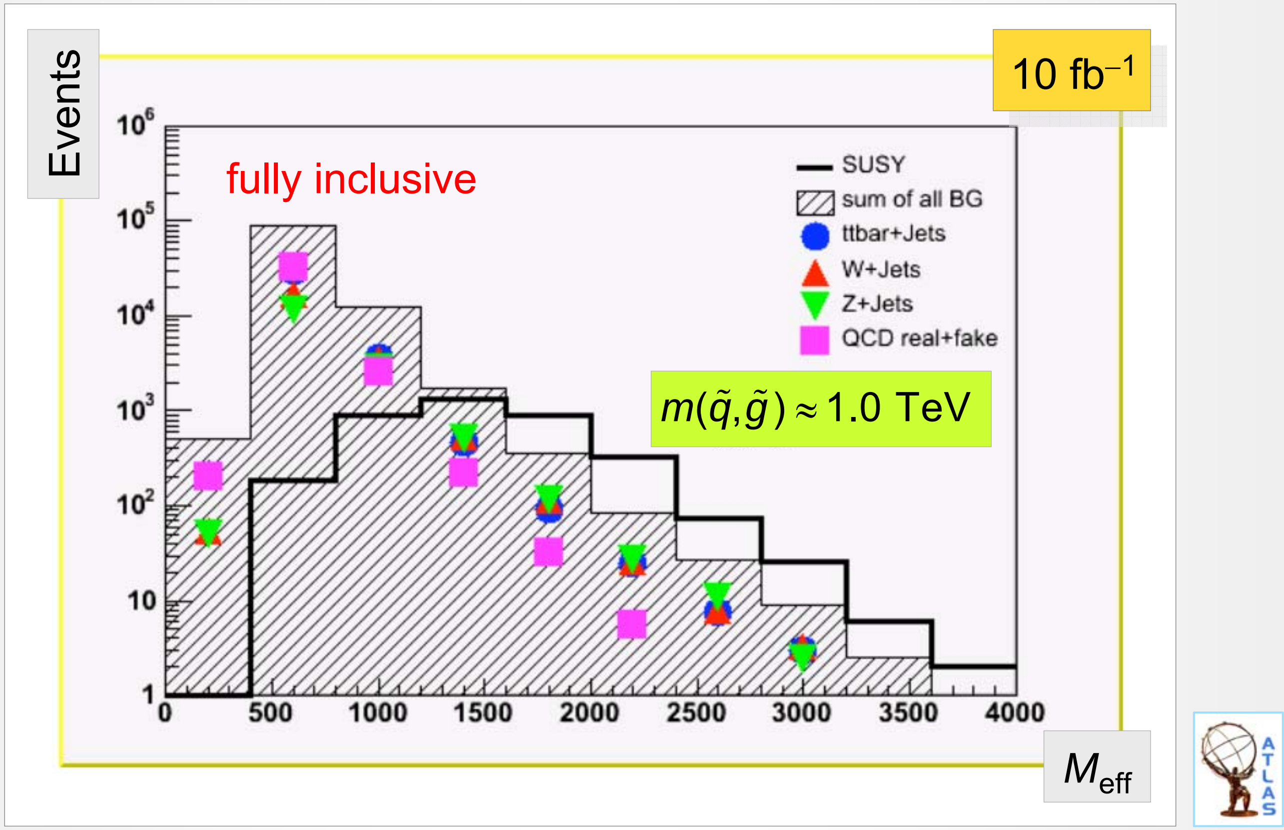
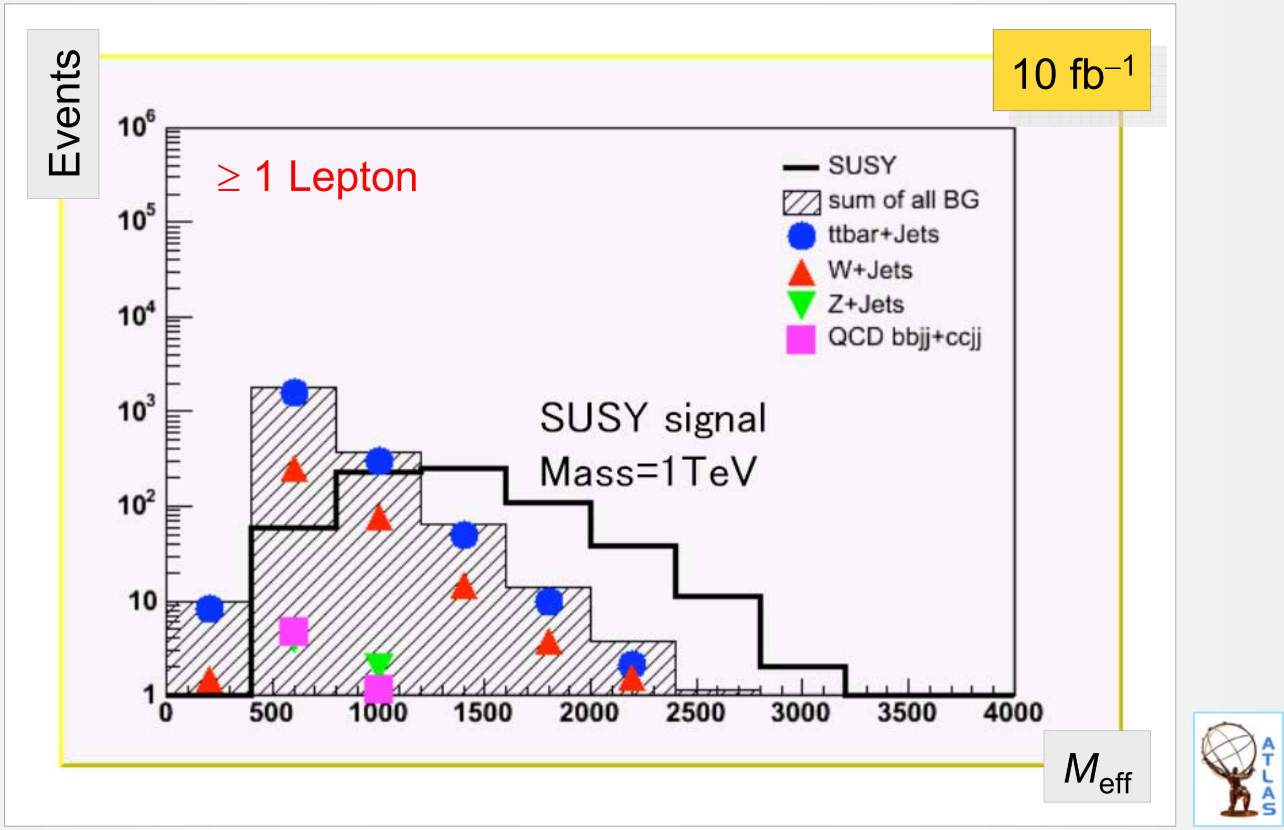


Inclusive SUSY Searches ... continued

- A sensitive variable to detect SUSY decays is the "**effective mass**": $M_{\text{eff}} = E_{T,\text{miss}} + \sum_{\text{jets, leptons}} p_T$

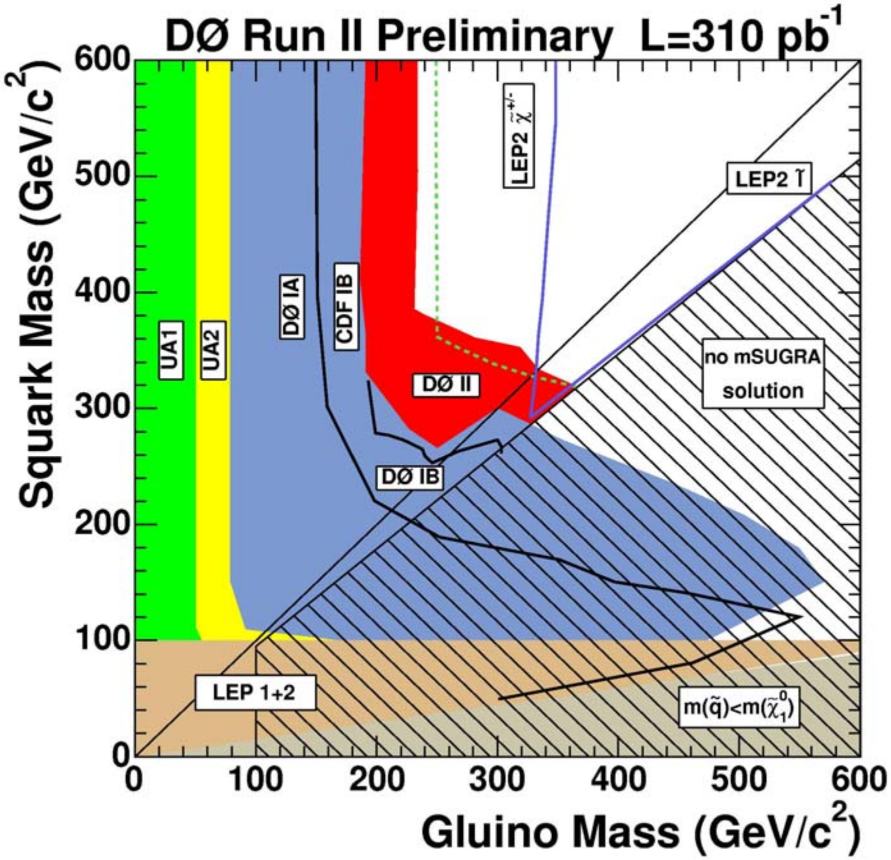


- Requiring ≥1 lepton reduces QCD background by factor of 20–30, with signal loss of only factor of ~3 (production through weak interaction) → better S/B than fully inclusive analysis

Squarks and Gluinos: Reach of the LHC

- mSUGRA limits on squark and gluino masses from D0 (Tevatron)

Note: newer results than shown available → see talk by R. van Kooten

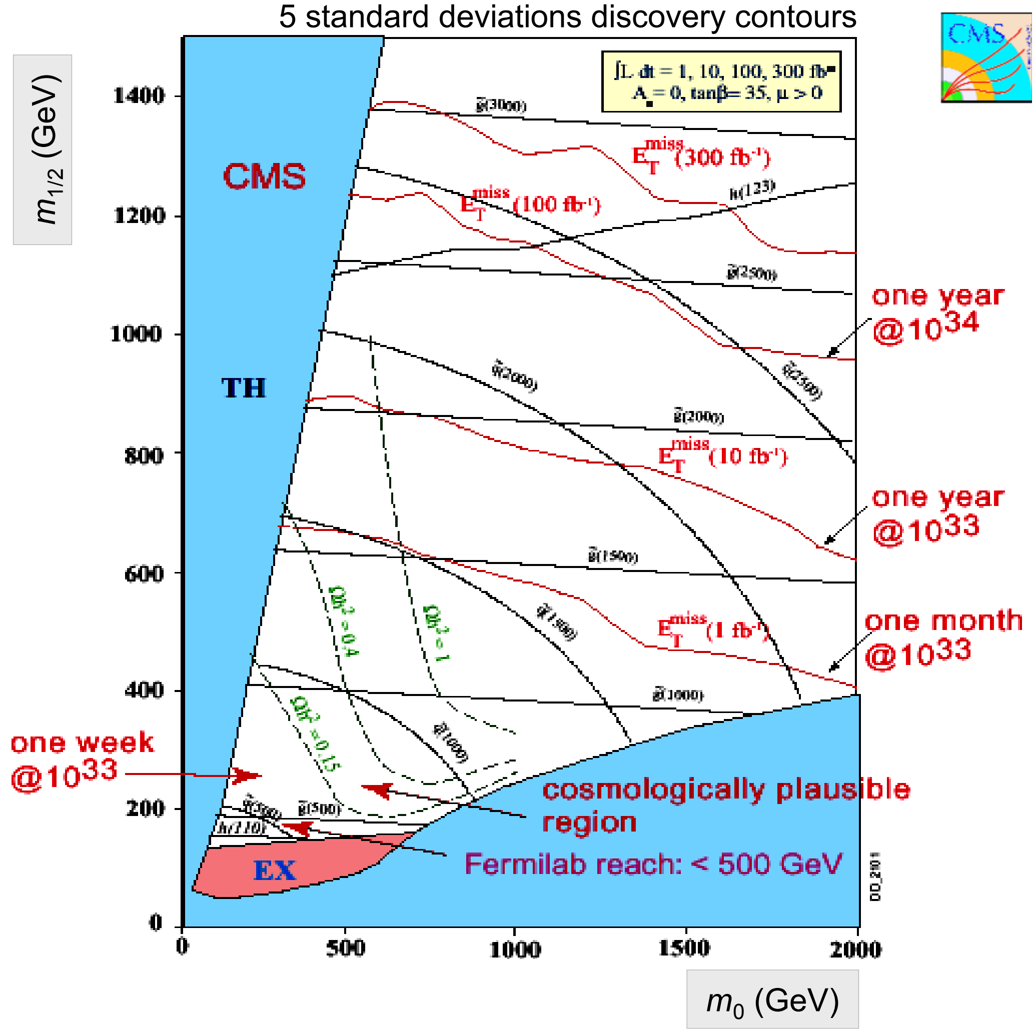


Squarks and Gluinos: Reach of the LHC

- Experiments evaluate their SUSY discovery potential using some “standard” mSUGRA setup

5σ discovery reach for SUSY:

Time period	Luminosity [cm^{-2}s^{-1}]	squark/gluino masses
1 month	10^{33}	~1.3 TeV
1 year	10^{33}	~1.8 TeV
1 year	10^{34}	~2.5 TeV
Ultimate	$\int$ = 300 fb^{-1}	~2.5–3 TeV
D0 & CDF	$\int$ = 0.3 fb^{-1}	$>_{(2\sigma)}$ 0.35 TeV



5 standard deviations discovery contours

one year @10^{34}

one year @10^{33}

one month @10^{33}

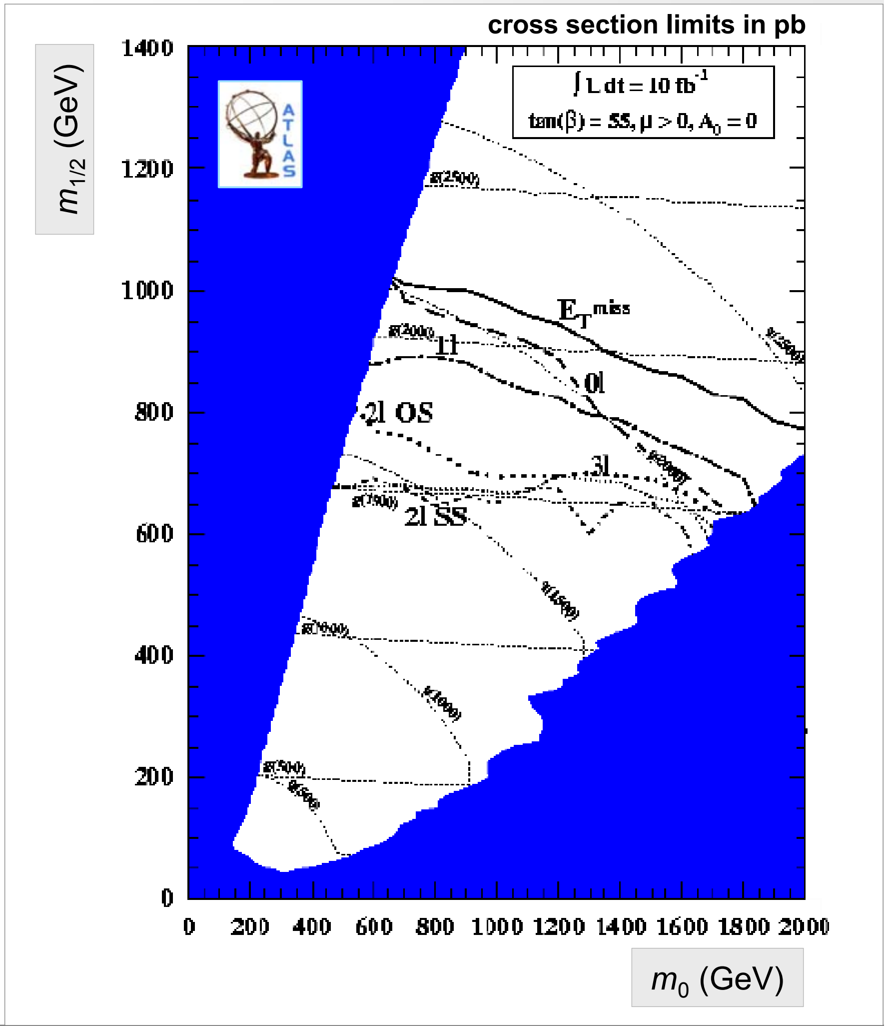
one week @10^{33}

cosmologically plausible region

Fermilab reach: < 500 GeV

Comparison with Direct Dark Matter Searches

- There also exist direct searches for WIMP's through elastic scattering between cosmic WIMP (*e.g.*, a neutralino) and nucleus, generating a recoil energy spectrum of the nucleus
- Complementary sensitivity to mSUGRA masses, in particular for large tanβ values



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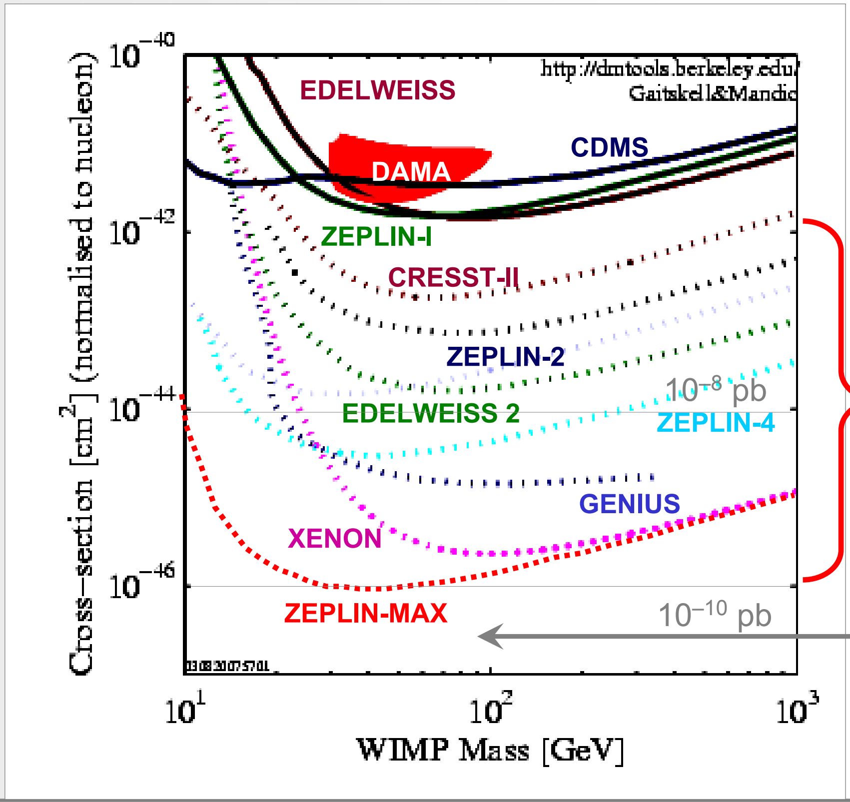
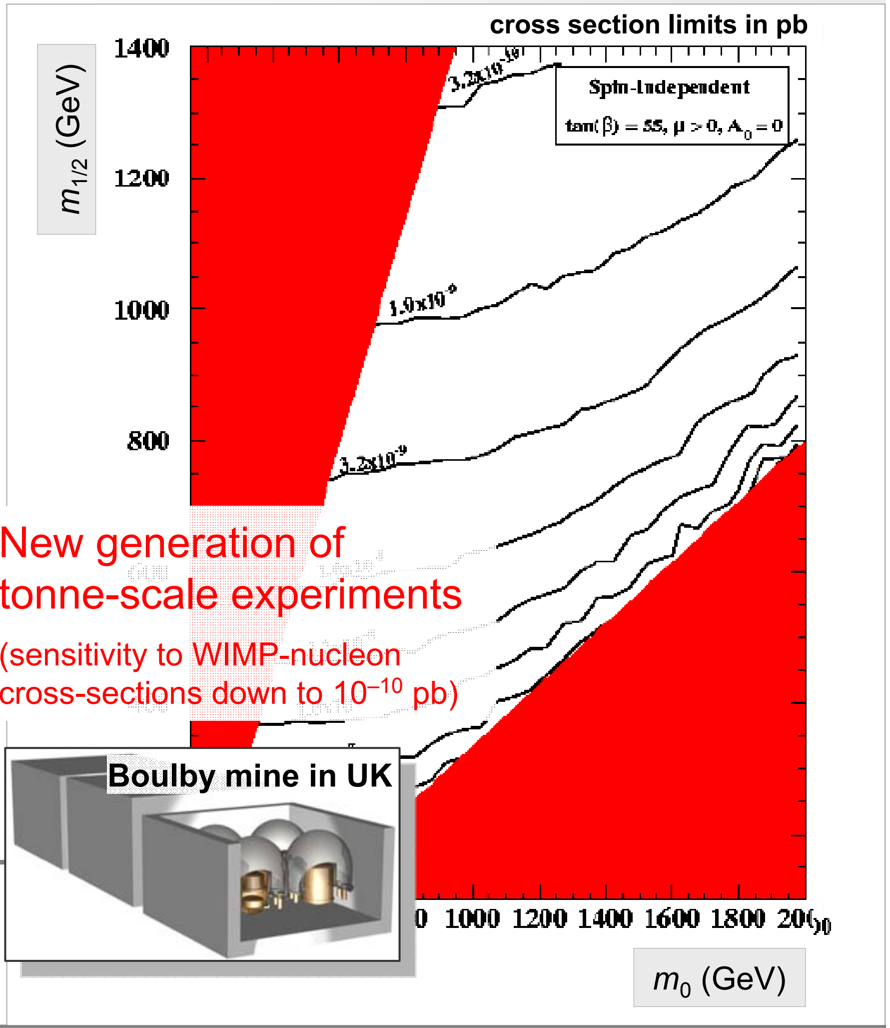




New generation of tonne-scale experiments

(sensitivity to WIMP-nucleon cross-sections down to 10^{-10} pb)

Once SUSY has been Discovered … Measure it !

- **Inclusive SUSY discovery** will provide indications about underlying scenario:
  - SUSY mass scale and cross section
  - *R*-parity ($E_{T,\text{miss}}$ spectrum), Gauge-mediated SB (hard γ's, NLSP's, long-lived gluinos), large tanβ (τ's)

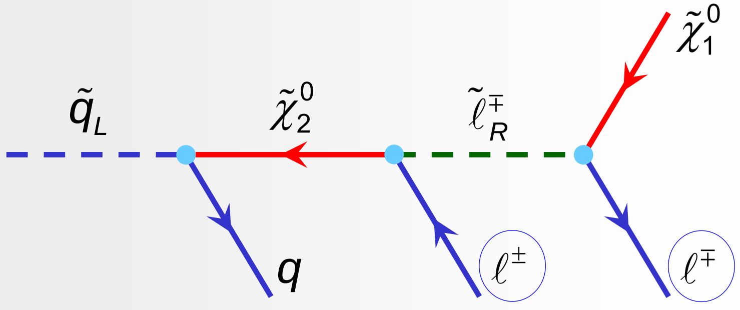
- However, fundamental SUSY parameters (**masses**, **couplings**, **spins**, …) can only be inferred from direct measurements of **sparticle properties**

- **Exclusive reconstruction** of SUSY final states is possible:
  - Select final state signatures that identify exclusive decay chains (*e.g.*, 2 or 3 final state leptons)
  - Apply kinematic constraints to eliminate escaped particles (*e.g.*, LSP)
  - Fit, *e.g.*, masses of particles in decay chain

- Remarks:
  - *R*-parity conservation: at least two LSP's in event → no direct mass peaks, but kinematic "endpoints"
  - These endpoints depend on the masses of the involved particles
  - When cascade of at least 3 consecutive two-body decays occurred → full kinematics accessible

Exclusive Reconstruction: An Example

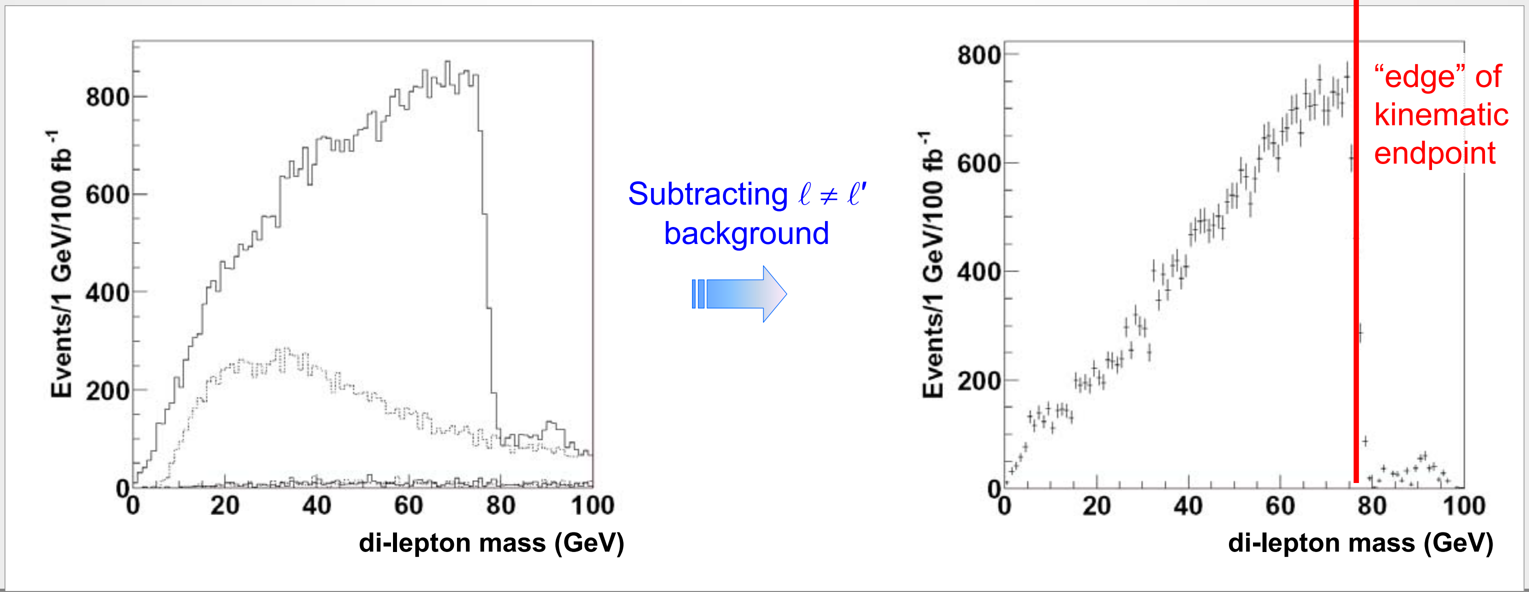
- Let’s look again at the process: $pp \to X + \tilde{g} + \tilde{g}\left(\to q + \underbrace{\tilde{q}_L\left(\to q + \tilde{\chi}_2^0\left(\to \ell^\pm + \tilde{\ell}_R^\mp\left(\to \ell^\mp + \tilde{\chi}_1^0\big|_{LSP}\right)\right)\right)}_{\text{3 two-body decays ! } (m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0})}\right)$



leptons have same flavour !
(use for background fighting)

Di-lepton kinematic endpoint:

$$m_{\ell\ell}^{\max} = \frac{1}{m_{\tilde{\ell}_R}}\sqrt{\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}_R}^2\right)\left(m_{\tilde{\ell}_R}^2 - m_{\tilde{\chi}_1^0}^2\right)}$$



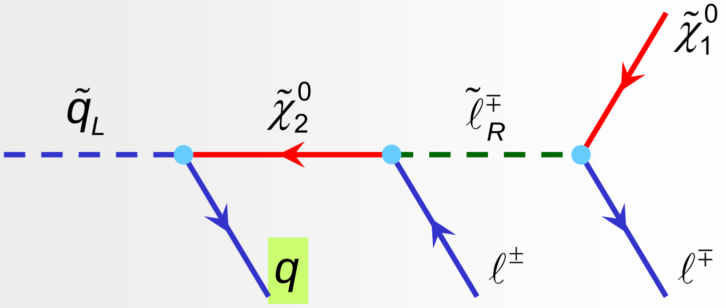
Subtracting $\ell \neq \ell'$ background

“edge” of kinematic endpoint

… Also Reconstructing the Jet

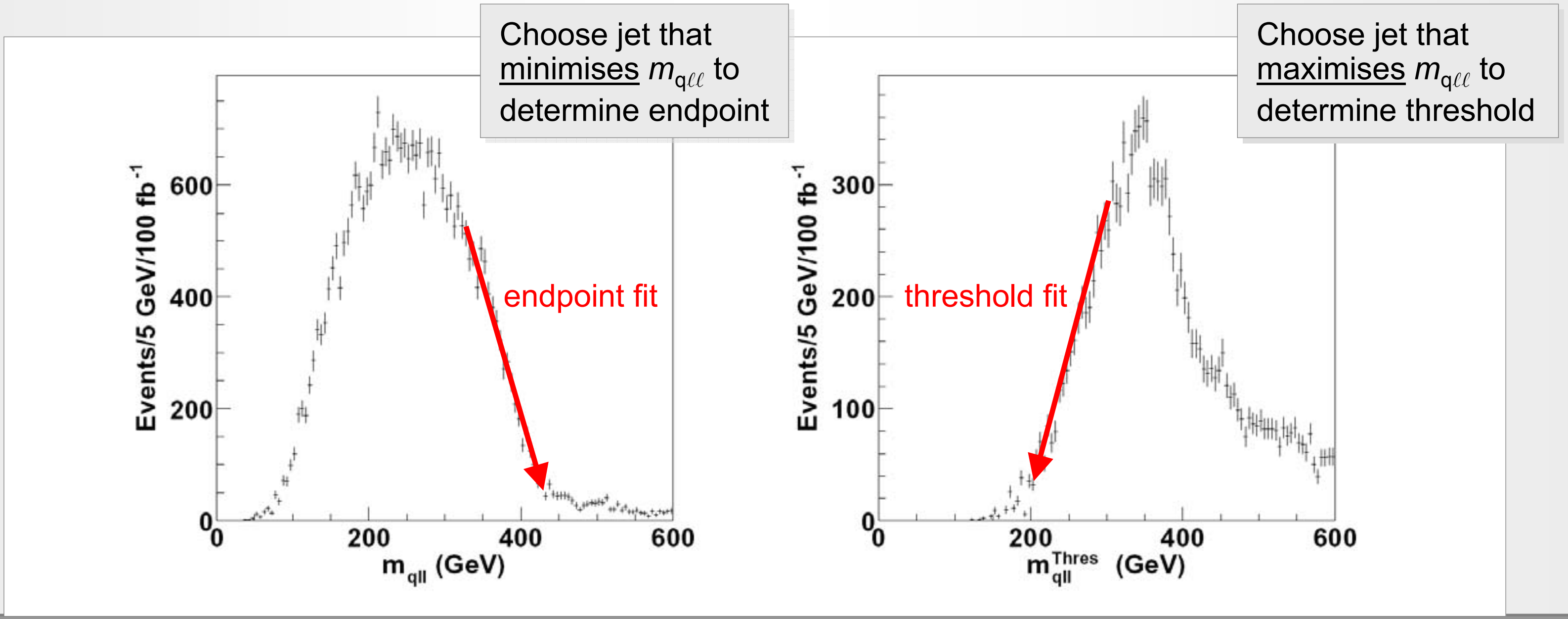
- We can also use jets from:

$$pp \to X + \tilde{g} + \tilde{g}\left(\to q + \underbrace{\tilde{q}_L\left(\to q + \tilde{\chi}_2^0\left(\to \ell^\pm + \tilde{\ell}_R^\mp\left(\to \ell^\mp + \tilde{\chi}_1^0\big|_{LSP}\right)\right)\right)}_{\text{3 two-body decays ! } (m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0})}\right)$$



Theoretical kinematic endpoint of the $q\ell^+\ell^-$ system:

$$m_{q\ell\ell}^{\max} = \frac{1}{m_{\tilde{\chi}_2^0}}\sqrt{\left(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2\right)\left(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2\right)}$$



Choose jet that <u>minimises</u> $m_{q\ell\ell}$ to determine endpoint

Choose jet that <u>maximises</u> $m_{q\ell\ell}$ to determine threshold

… Also Reconstructing the Jet

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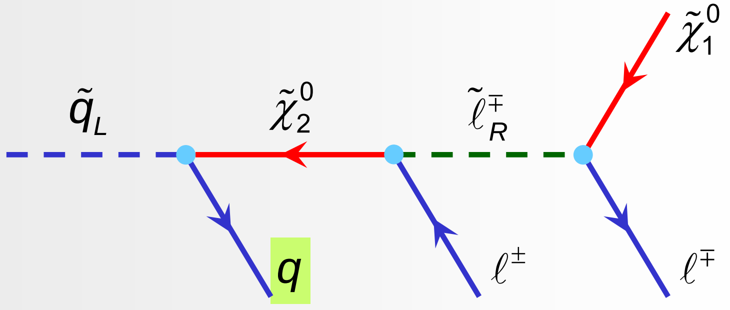

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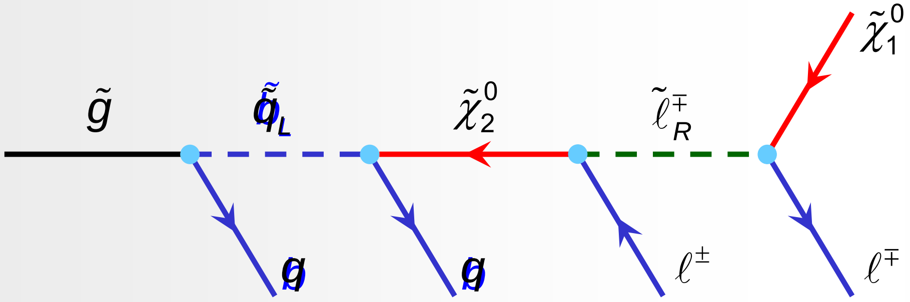
- One can also look into the corresponding ***qℓ* endpoints and thresholds**
- In total **6 distributions can be fit** to determine the corresponding sparticle masses
  - An ATLAS study for 100 fb^{-1} finds mass precisions of 12% (χ_1), 6% (χ_2), 9% (ℓ_R~), 3% (q_R~)
- Thorough experimental and theoretical work will be necessary to **control the backgrounds** from other jet-lepton(-lepton) combinations in the event and initial state radiation of jets

… Reconstructing sbottom and gluino Masses

- Let’s look again at the full decay chain:



To reject combinatorial background, use only *b* jets

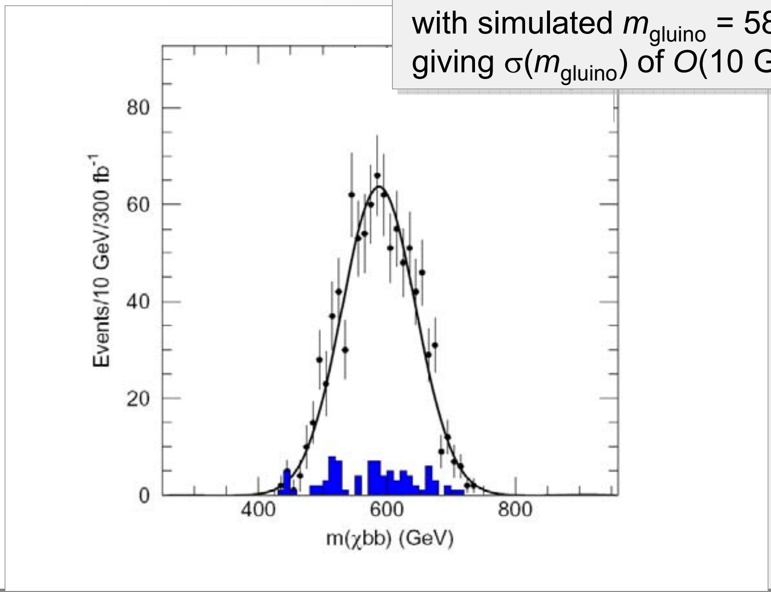
Close to the $\ell^+\ell^-$ endpoint, the χ_2 (~in rest) has residual momentum:

$$\vec{p}\left(\tilde{\chi}_2^0\right) \approx \left(1+\frac{m_{\tilde{\chi}_1^0}}{m_{\ell\ell}}\right)\cdot \vec{p}\left(\ell^+\ell^-\right)$$

The neutralino masses are known from the preceding analysis

→ **χ_2 4-vector is known**

- The gluino and sbottom masses are then obtained from the $bb\chi_2$ and $b\chi_2$ invariant masses, respectively



ATLAS estimate for 300 fb^{-1}, with simulated m_{gluino} = 588 GeV, giving $\sigma(m_{\text{gluino}})$ of O(10 GeV)

… Reconstructing sbottom and gluino Masses

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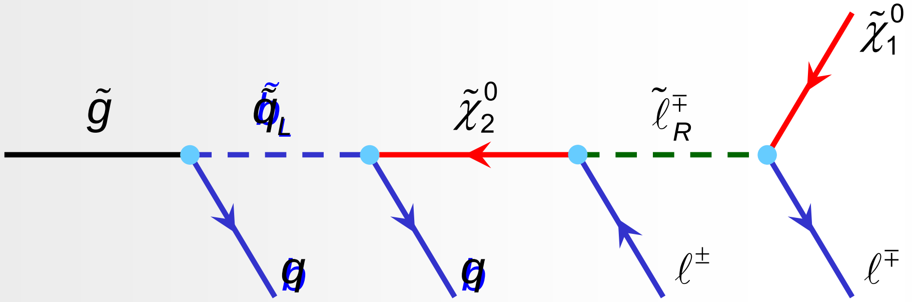

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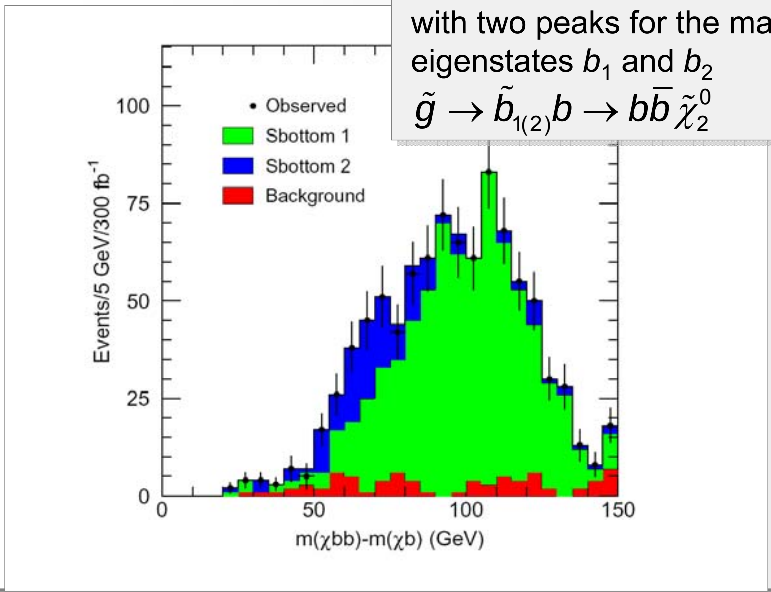
- The gluino and sbottom masses are then obtained from the $bb\chi_2$ and $b\chi_2$ invariant masses, respectively
- The sbottom mass is then best obtained from mass difference (reduces errors)
- One can do better by using all events (not only those at $\ell^+\ell^-$ endpoint) together with a global fit to full decay kinematics

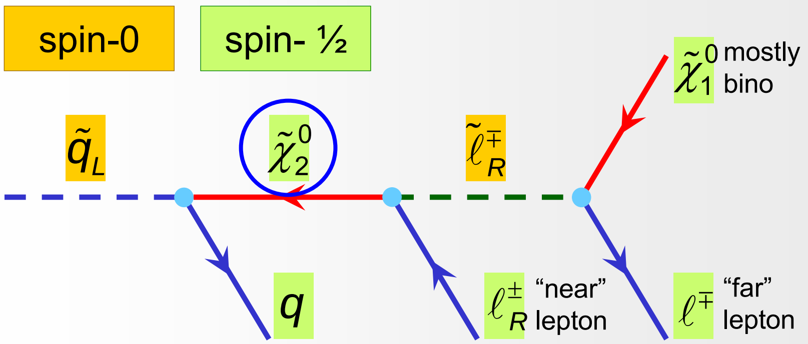


ATLAS estimate for 300 fb^{-1}, with two peaks for the mass eigenstates b_1 and b_2

$\tilde{g} \to \tilde{b}_{1(2)} b \to b\bar{b}\,\tilde{\chi}_2^0$

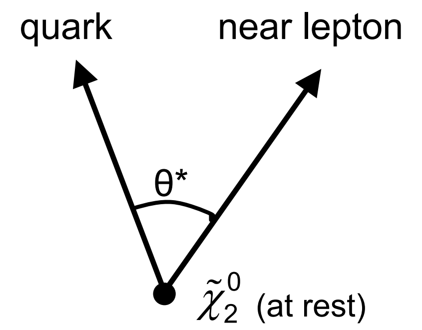
If we Discovered Something… is it SUSY ? $^{(*)}$

- If observed, the signatures discussed so far provide **strong hints for SUSY**
- To verify that the new fields are indeed the SM Superpartners → **measure their spins**
- Not easy at LHC, but (hopefully) possible



Decay chain sensitive to fermionic character of χ_2

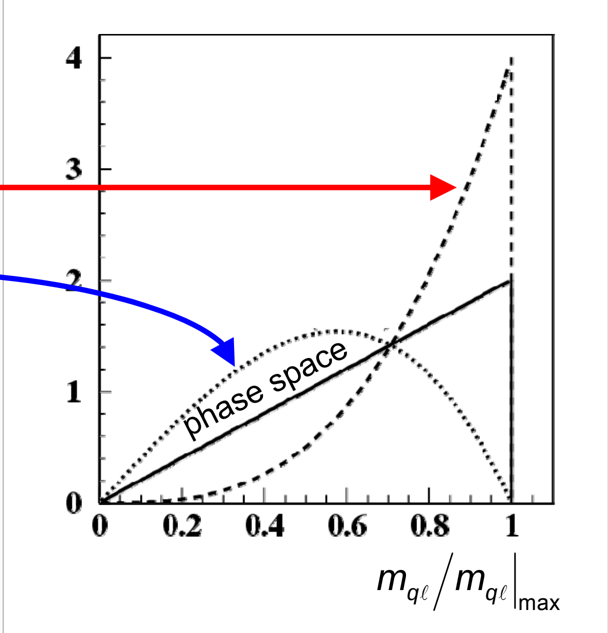
- Invariant mass of quark-lepton system depends on the polarization of neutralino



Invariant mass of $q\ell$ system strongly charge-dependent

$$m^2_{q\ell^+} = m^2_{q\ell^+}\Big|_{\max} \cdot \sin^2\left(\theta^*/2\right)$$

$$m^2_{q\ell^-} = m^2_{q\ell^-}\Big|_{\max} \cdot \cos^2\left(\theta^*/2\right)$$



- Problem: this effect is <u>inverted</u> for anti-squark decay !

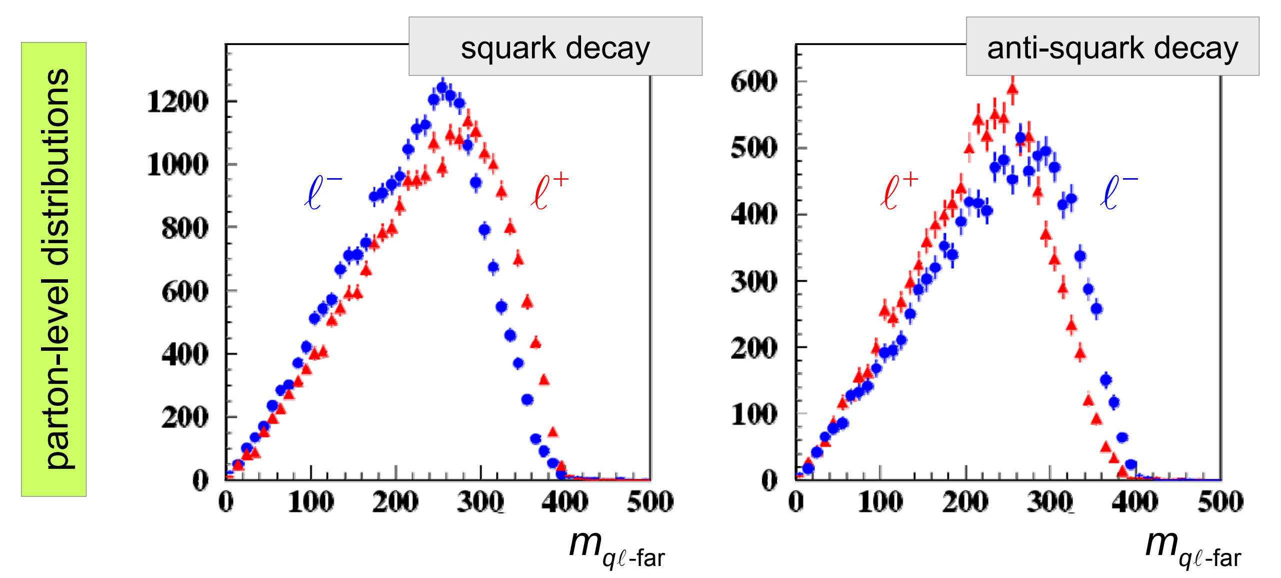
$^{(*)}$ For example, UED KK signals with WIMP LKPs could fool us !

Measuring the χ_2 Spin

- Experimental Problems:
  1) Cannot distinguish "near" from "far" lepton ➡ Plot $m_{q\ell}$ for both leptons
  2) Cannot distinguish quark from anti-quark jet ➡ Fortunately: LHC produces ~2x more squarks than anti-squarks

- To 1) : Some residual asymmetry left from boost of slepton in the χ_2 rest frame

  → see quark-lepton(far) invariant mass (parton-level):



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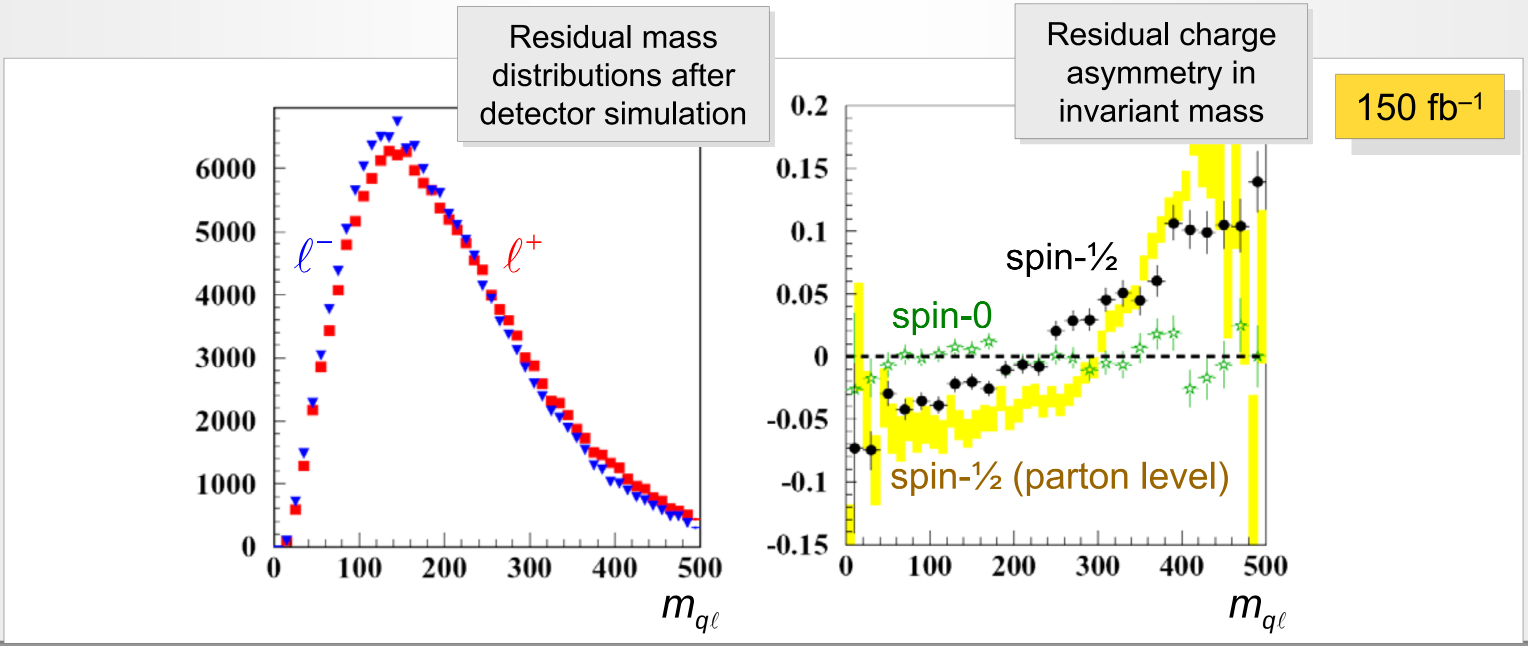
  1) Cannot distinguish “near” from “far” lepton ➧ Plot $m_{q\ell}$ for both leptons
  2) Cannot distinguish quark from anti-quark jet ➧ Fortunately: LHC produces ~2x more squarks than anti-squarks

- Measure the asymmetry: $A^{+-}\left(\sin(\theta^*/2)\right) = \dfrac{dN/dm_{q\ell^+} - dN/dm_{q\ell^-}}{dN/dm_{q\ell^+} + dN/dm_{q\ell^-}} = \begin{cases} A^{\tilde{q}\bar{\tilde{q}}}\left(2\sin(\theta^*/2)-1\right), & \text{if } |s_{\tilde{\chi}_2^0}| = 1/2 \\ 0, & \text{if } |s_{\tilde{\chi}_2^0}| = 0 \end{cases}$


Residual mass distributions after detector simulation

Residual charge asymmetry in invariant mass

150 fb^{-1}

Constraining the MSSM Parameter Space

- SUSY fits to observables usually work in particular scenario (mSUGRA, GMSB, …)
- Mass differences (edges), sbottom & gluino masses can be measured, LSP less accurate
- **But: there are ambiguities on decay chain in the kinematic edge results**
- Cross sections versus mass scale can be used as additional information
- Relative abundance of OSSF, OSOF, SSSF, SSOF lepton pairs model dependent
- But: decay chains with leptons may simply not exist

In general:

- Use statistical tricks to solve multi-parameter problem (Markov chains)
- One can try to “inverse” the map of (1808) LHC signatures to (15 dim.) theory parameter space

Lester-Parker-White
hep-ph/0508143

Arkani-Hamed *et al.*
hep-ph/0512190

Gauge Mediated SUSY Breaking

- Messenger scale $M_m \ll M_{\mathrm{Pl}}$, SUSY breaking scale $F_m \ll (10^{10}\ \mathrm{GeV})^2$
- Very light gravitino ($\ll$ 1 GeV) is LSP
- Signatures determined by NLSP: either neutralino or slepton … and by C_{grav} parameter determining lifetime of NLSP

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma \quad \text{or} \quad \tilde{\ell}_R \rightarrow \tilde{G}\ell$$

Distinguish 4 cases:

Cases	Phenomenology and signature	Observables	Results
$C_{\mathrm{grav}} = 1$ (fast decay) **NLSP = neutralino**	2 high-E_T γ's & jets & leptons & $E_{T,\mathrm{miss}}$	Lepton-γ edges: $M_{\ell\ell,\mathrm{max}}$, $M_{\ell\ell\gamma,\mathrm{max}}$, $M_{\ell(1,2)\gamma,\mathrm{max}}$	$M_{\tilde{\ell}_R}$, $M_{\tilde{\chi}_1^0}$, $M_{\tilde{\chi}_2^0}$ also: $M_{\tilde{g}}$, $M_{\tilde{q}}$
$C_{\mathrm{grav}} \gg 1$ (slow decay) **NLSP = neutralino**	$c\tau(\chi^0)$ ~ 1 km, ≈SUGRA, more $E_{T,\mathrm{miss}}$ & non-pointing high-E_T γ's	ATLAS can measure γ angle with long. EM calo layers	For 30 fb^{-1}, can exclude $C_{\mathrm{grav}} \rightarrow 10^8$, *i.e.*, $F_m/M_m > 10^4$ GeV
$C_{\mathrm{grav}} = 1$ (fast decay) **NLSP = slepton**	If $N_5 > 5$, NLSP RH sleptons, large X-section → 25 pb, leptons & $E_{T,\mathrm{miss}}$	Several lepton edges, large measurement potential	Various SUSY masses (see above)
$C_{\mathrm{grav}} \gg 1$ (slow decay) **NLSP = slepton**	stau NLSP, $c\tau$ ~ 1 km, new heavy quasi-stable lepton	Detect in muon system by time-of-flight (late arrival compared to μ's)	stau and all neutralino masses

SUSY Higgs Discovery Potential

- The neutral and charged bosons from the two SUSY Higgs doublets are produced via:

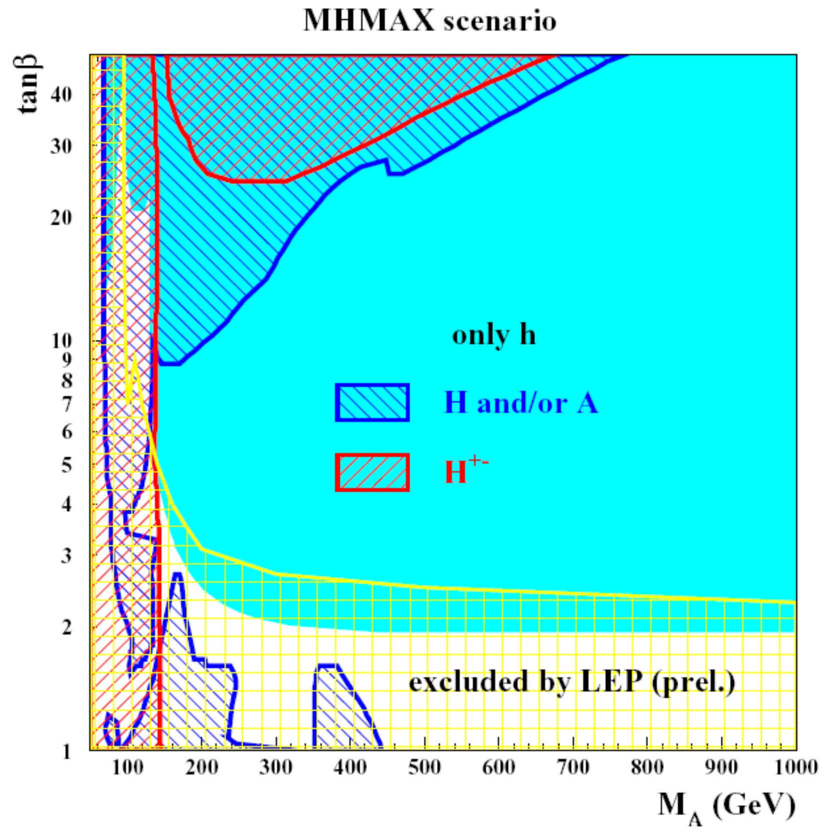
  h, H, A: gluon-gluon- or vector-boson fusion, qq scattering with associated vector boson or heavy quark

  $H^{\pm}$: top decay, gluon-bottom fusion, light qq' annihilation

SUSY Higgs Discovery Potential

- Search strategies for lightest SUSY and SM Higgs are similar
- Since the Higgs couples to masses, interactions with heavy particles (t, τ) are preferred

5σ contours



30 fb^{-1}

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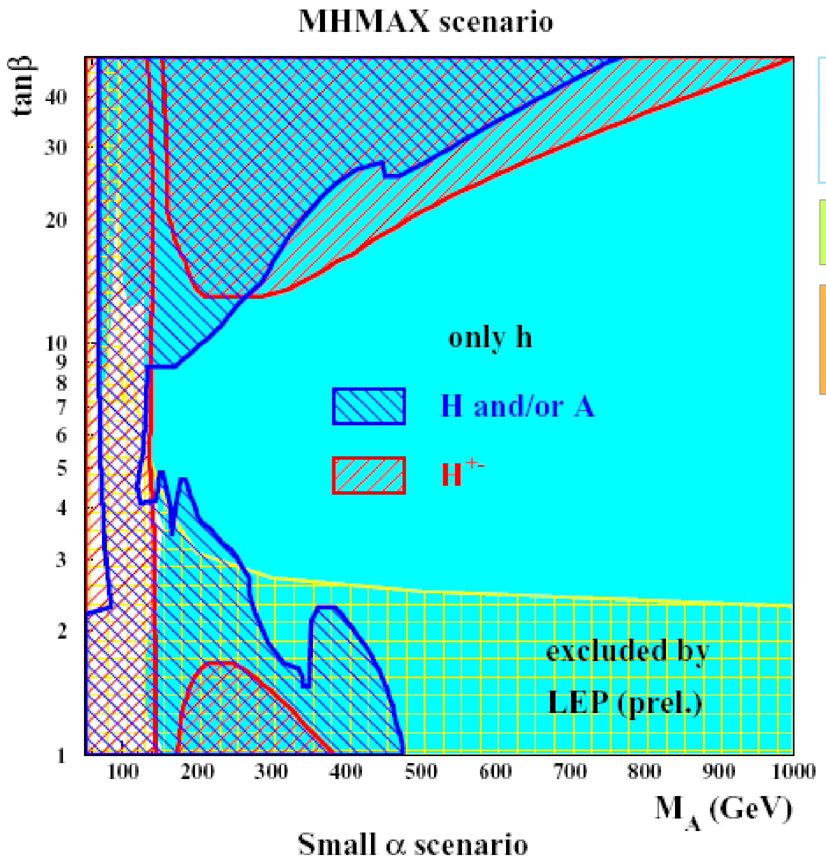


300 fb^{-1}

The *h* can be excluded in all parameter scenarios

SUSY – Final Remarks…

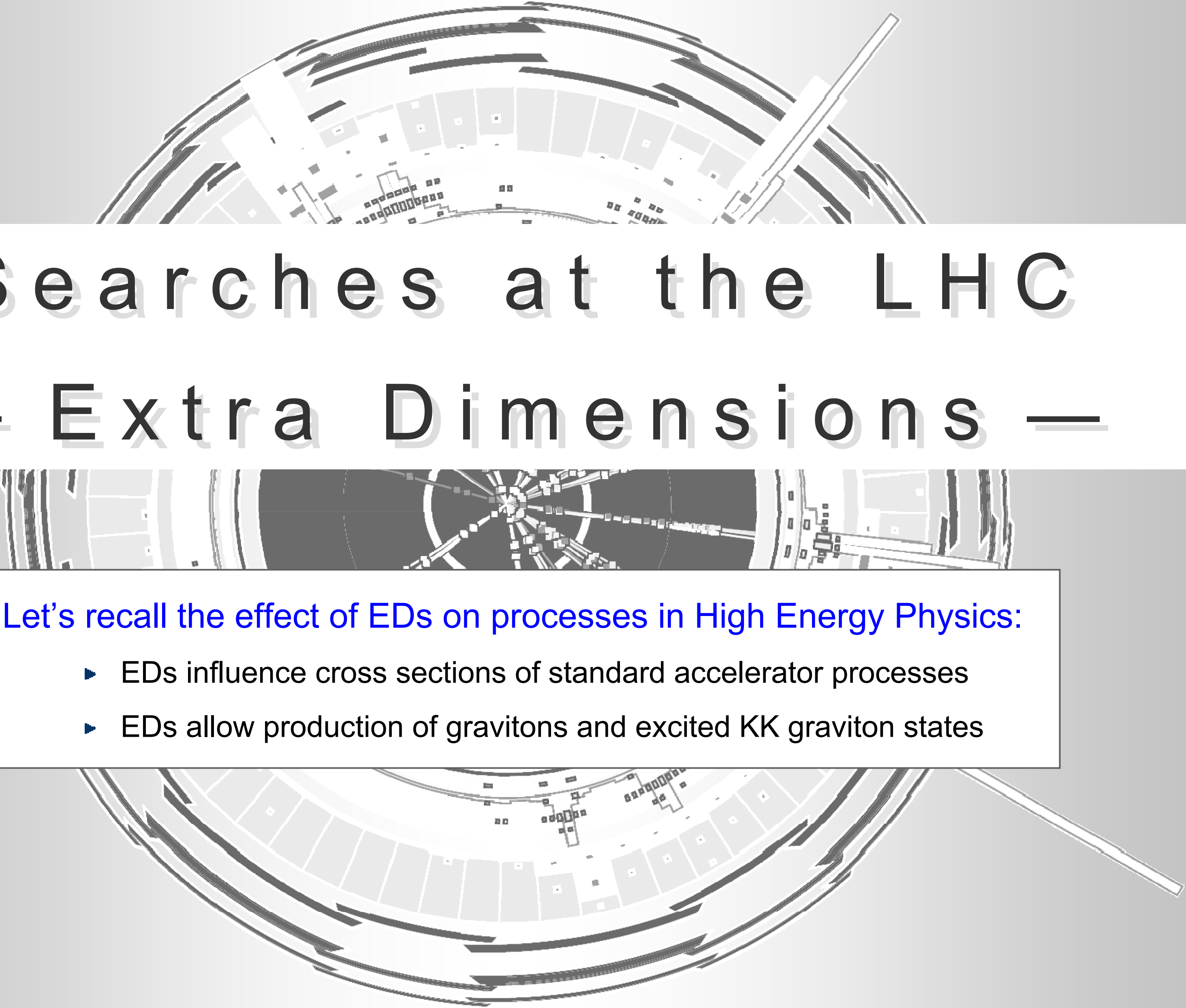
SUSY could also break *R*-parity

(The signature could be τ's in final state from $\tilde{\chi}^0 \rightarrow \tilde{\tau}\tau$ decays)

Signals due to other phenomena could look like SUSY

Proceed SUSY search as model-independently as possible

Check for anomalies: γ's, τ's, strange *t*'s



Searches at the LHC

— Extra Dimensions —

Let’s recall the effect of EDs on processes in High Energy Physics:

- EDs influence cross sections of standard accelerator processes
- EDs allow production of gravitons and excited KK graviton states

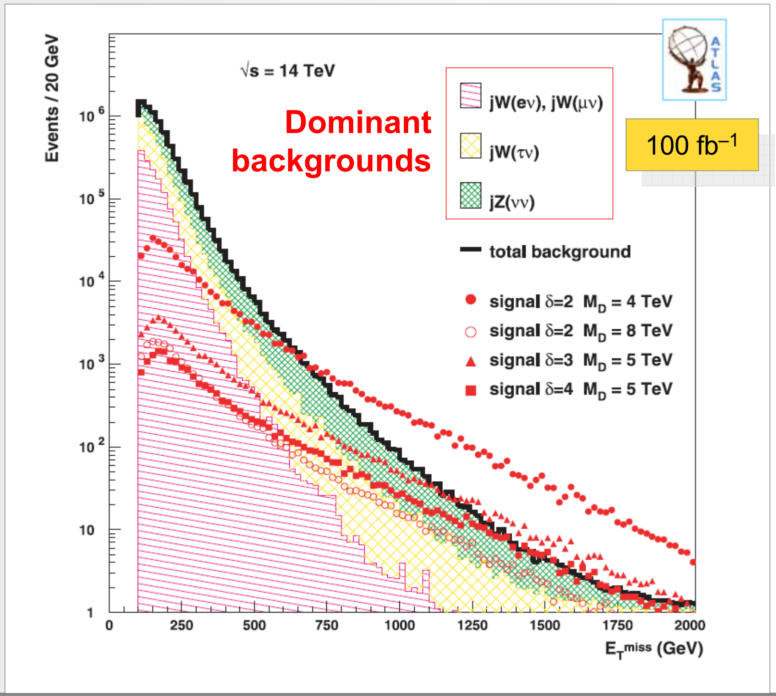
Large Extra Dimensions (ADD)

- The most direct manifestation of EDs would be the presence of **KK gravitons: G_{KK}**
- Tiny graviton coupling: ~1/M_{Pl} compensated by large G_{KK} multiplicity: ~$(R\sqrt{s})^d$ (in E interval $\sqrt{s}$)
- ➡ (partonic) **cross section**: $\sigma \sim (\sqrt{s} / M_D^2)^d$ **can be macroscopic**

- The produced **gravitons do not interact in detector**
- Signature: **mono-jet or high-E_T γ + $E_{T,\mathrm{miss}}$, no lepton** (→ veto)

Typical processes are:

$$q\bar{q} \to (g,\gamma) + G_{KK}$$
$$qg \to q + G_{KK}$$
$$gg \to g + G_{KK}$$



- $E_{T,\mathrm{miss}}$ distribution for signal for varying M_D and d, and for the dominant background
- ➡ For example: M_D ~ 9 (6) TeV and d = 2 (4) EDs yields compactification radius of $10^{-6}\mu$m;
- ➡ No sensitivity to larger scales or EDs at LHC
- ➡ In case of a discovery, it will be difficult to extract both M_D and d

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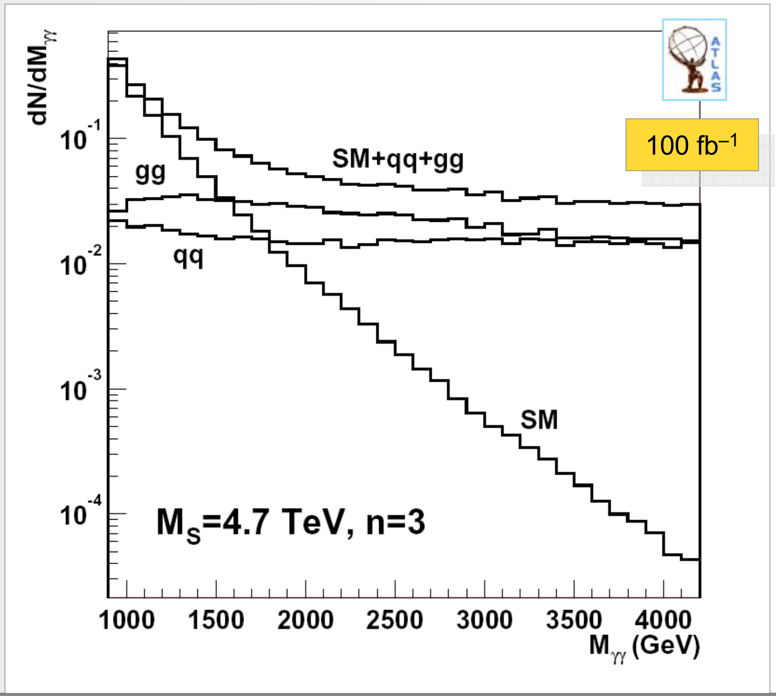

- Virtual gravitons can change the Drell-Yan cross section: $pp \rightarrow X + \ell^+\ell^-, \gamma\gamma$ leading to large $\ell^+\ell^-, \gamma\gamma$ invariant mass tails
- Figure shows $m(\gamma\gamma)$ for d=3 and divergence cut-off M_s=4.7 TeV

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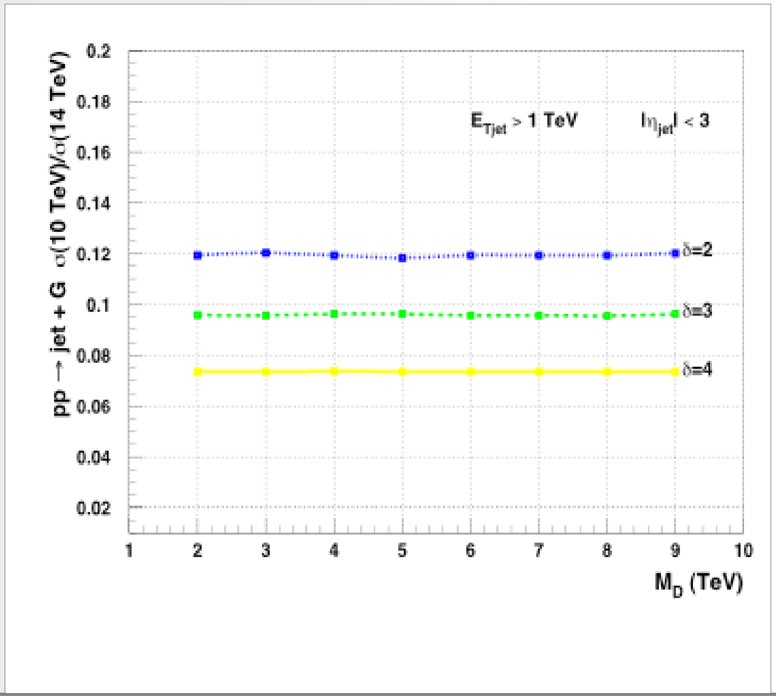
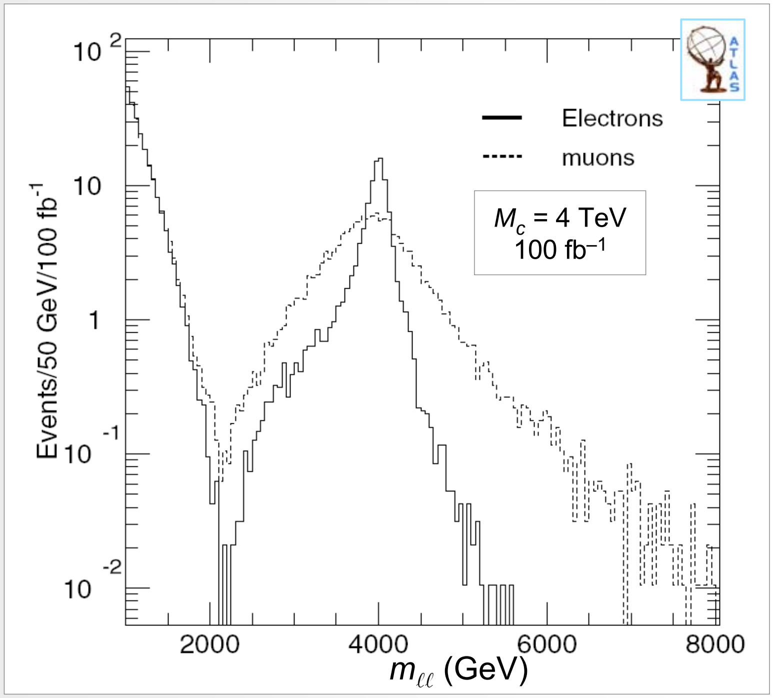


Disentangle M_D and d via $\sigma(\sqrt{s})$ dependence:

- Use ratio: σ(10 TeV) /σ(14 TeV)
- Requires 5% accuracy (incl. knowledge of luminosity) to distinguish d = 2,3
- Requires O(10) more luminosity at 10 TeV

Small Extra Dimensions

- In the previous example, the SM particles were confined within the SM brane; if gauge fields propagated into the bulk, KK excitations of γ or Z should be observed, if EDs not too small
- The characteristic size of the compact dimensions is then $R \sim 1/M_c \sim 1\ \text{TeV}^{-1}$
- Considering only 1 ED, the EW precision measurements give a lower limit $M_c > 4$ TeV
- The masses of the KK excitations of the gauge bosons are given by: $m_{Vn}^2 = m_V^2 + (n \cdot M_c)^2$



- The peak corresponds to the first KK excitation of Z: Z^1 (Z^1 and γ^1 are ~ degenerated)
- For ATLAS: the excellent resolution of the calorimeter at high p_T, allows to measure the width of the excitation in the mode e^+e^-
- Not as good for the muons

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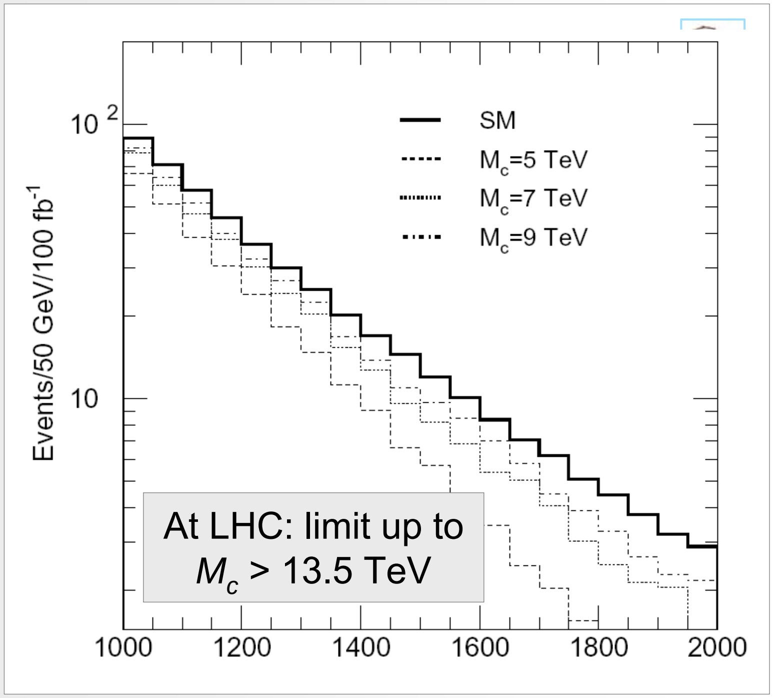

At LHC: limit up to $M_c > 13.5$ TeV

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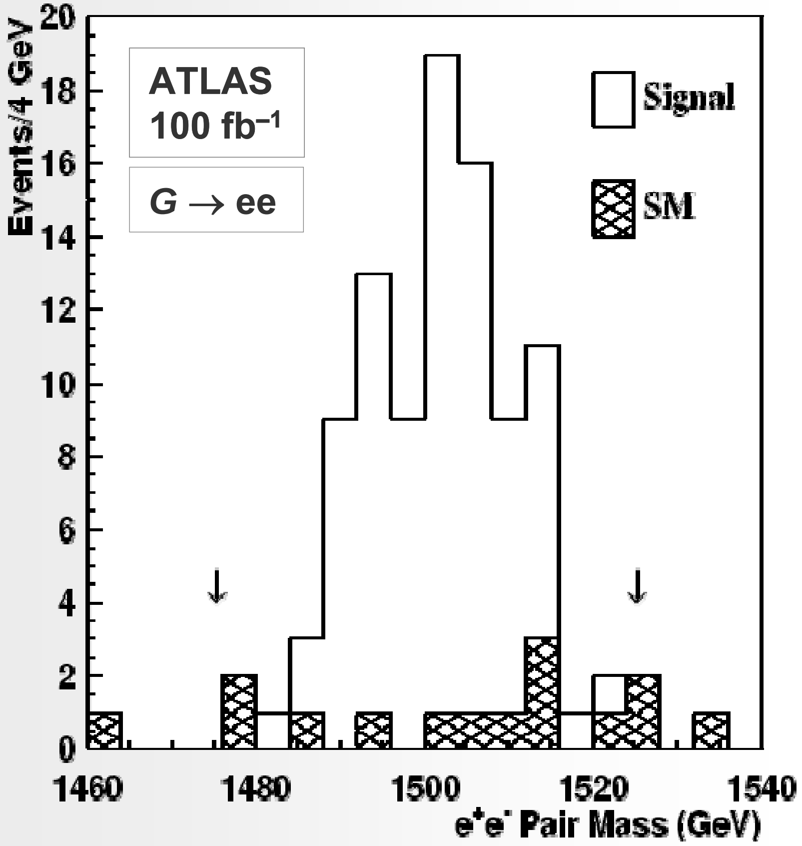
- For ATLAS: the excellent resolution of the calorimeter at high p_T, allows to measure the width of the excitation in the mode e^+e^-
- Not as good for the muons

➧ Larger masses than 4 TeV are accessible through interference of the SM di-lepton amplitude with the KK excitations

Randall-Sundrum Graviton decays to e^+e^- (I)

- 1500 TeV G_{KK} resonance over small Drell-Yan SM background



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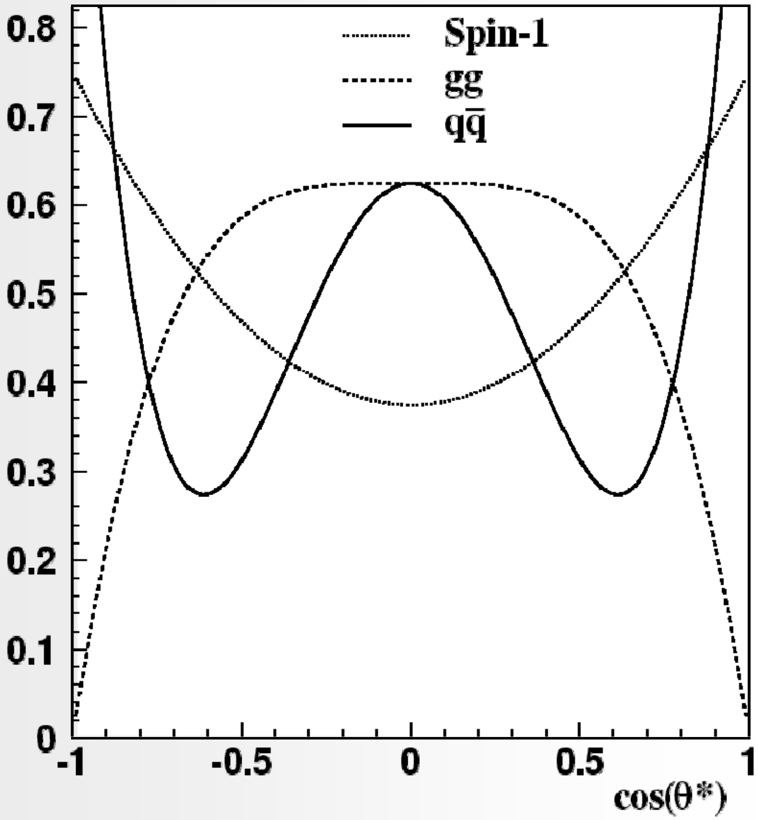
- Angular distribution of e+ in G_{KK} rest frame sensitive to G_{KK} spin and production



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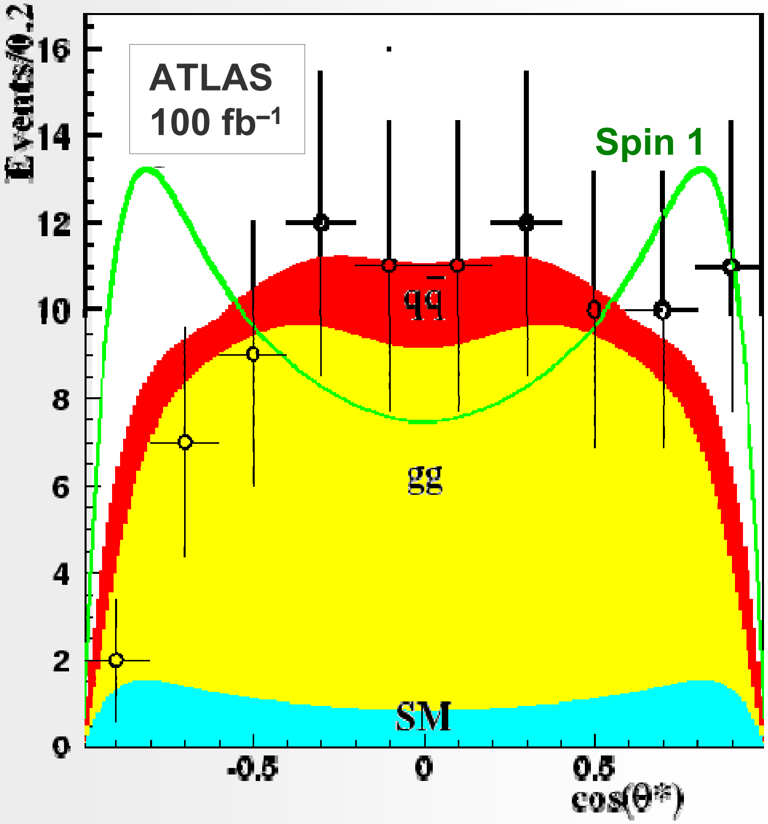
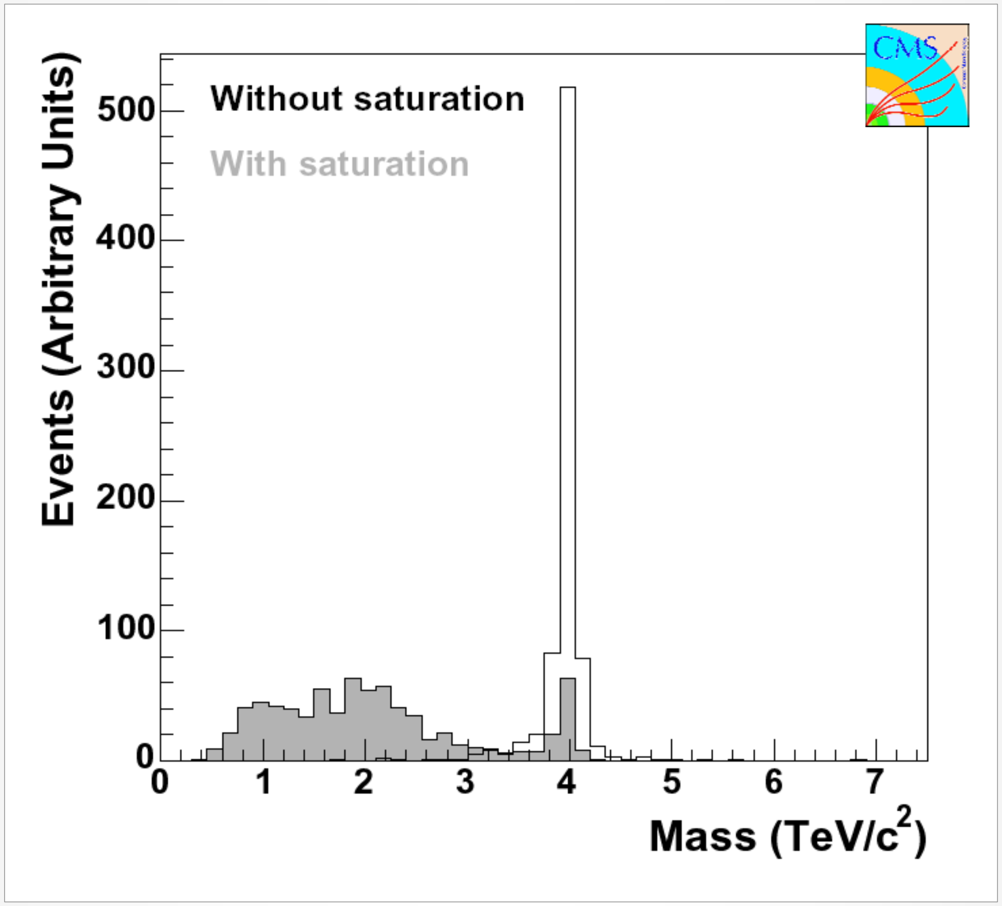


- G_{KK} production dominantly via gluon fusion
- Acceptance discards events at $|\cos\theta^*| \to 1$

Randall-Sundrum Graviton decays to e^+e^- (II)

- At very high p_T, di-electrons have better intrinsic mass resolution than di-muons
- However: the EM calorimeters suffers from saturation of dynamic range (CMS > ATLAS)

Note: width of KK gravitons smaller than experimental resolution



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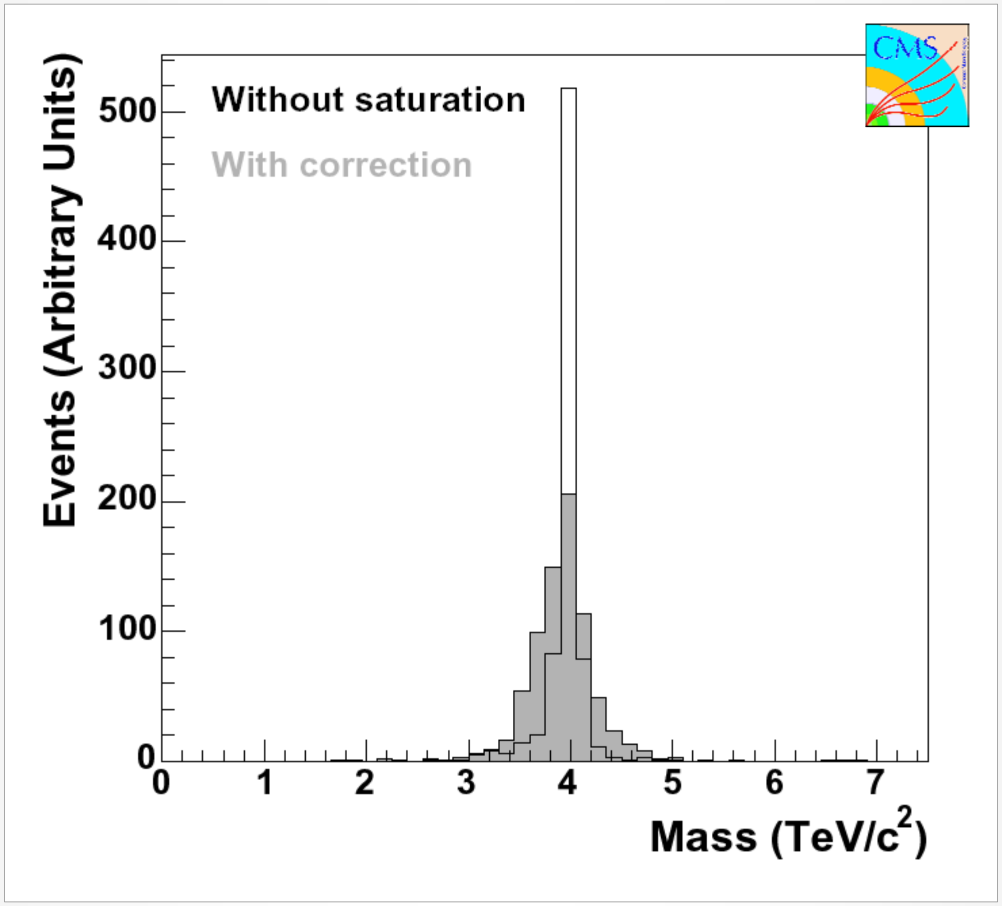


Randall-Sundrum Graviton Exploration

- Once discovered, verify that the coupling of G_{KK} is universal
  - Measure branching fractions of $G_{KK} \rightarrow ee, \mu\mu, jj, bb, WW, ZZ$
  - Use angular distributions to separate *gg* from *qq* couplings

- Estimate model parameters r_c and k from G_{KK} mass and $\sigma \times$ BR
- In our example of $m(G_{KK})$ = 1.5 TeV, measure mass to O(1 GeV) precision, and $\sigma \times$ BR to 14% from *ee* channel alone (stat. limited)

Recall warp factor:
$e^{-kr_c\pi}$

- With this measure:

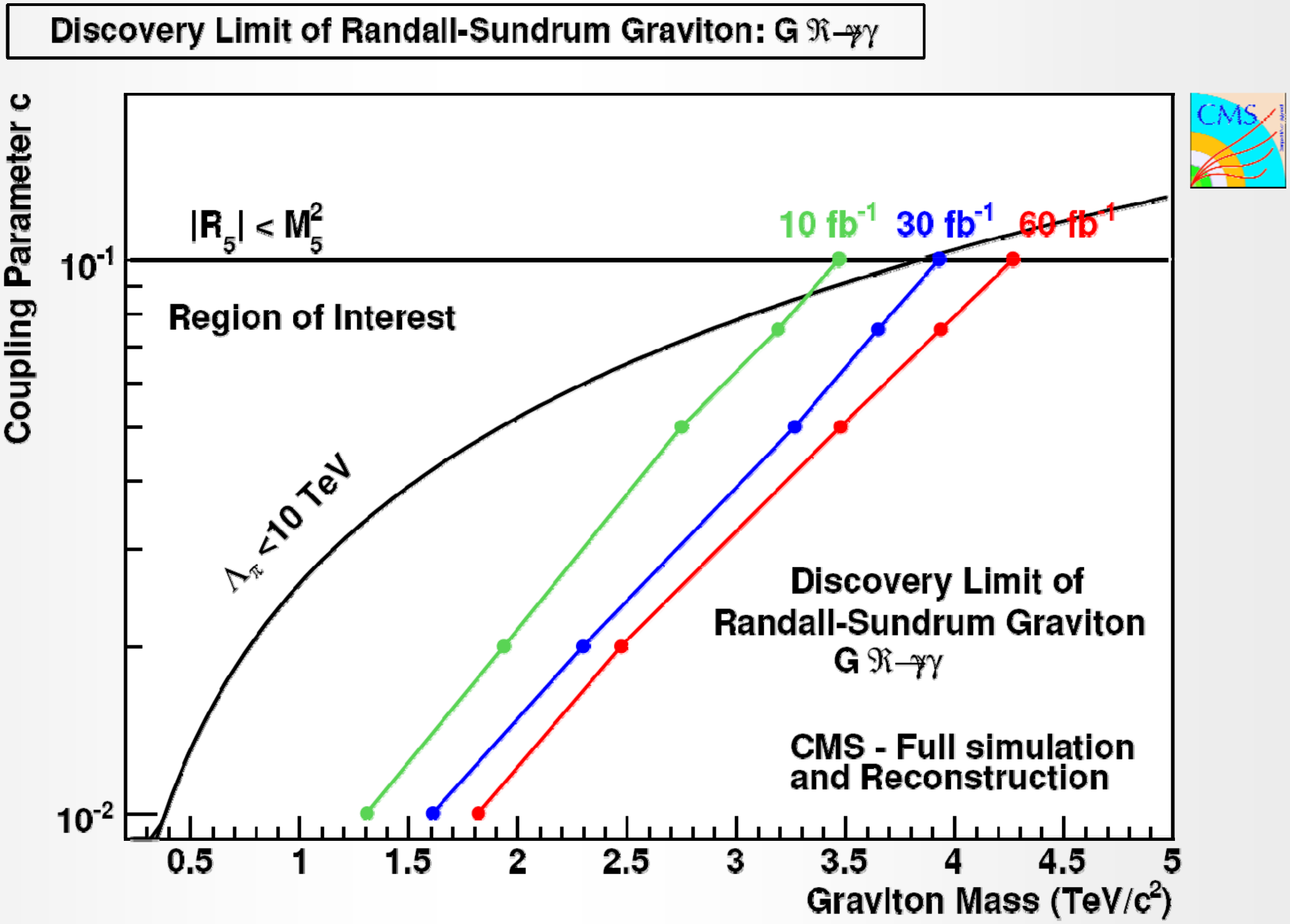
$$\left.\begin{aligned} r_c &= (8.2 \pm 0.6) \cdot 10^{-32}\ \text{m} \\ k &= (2.4 \pm 0.2) \cdot 10^{16}\ \text{GeV} \end{aligned}\right\} kr_c = (9.8 \pm 1.1)$$

Randall-Sundrum Graviton Search Reach

$c = k / M_{Pl}$

Recall: *k* is curvature of AdS$_5$ space

Note: theory only valid for *c* < 0.1 and only useful to solve hierarchy problem for $\Lambda_\pi = M_{Pl}\exp(-kr_c\pi) = M_G/(3.8\cdot c) \sim 10$ TeV



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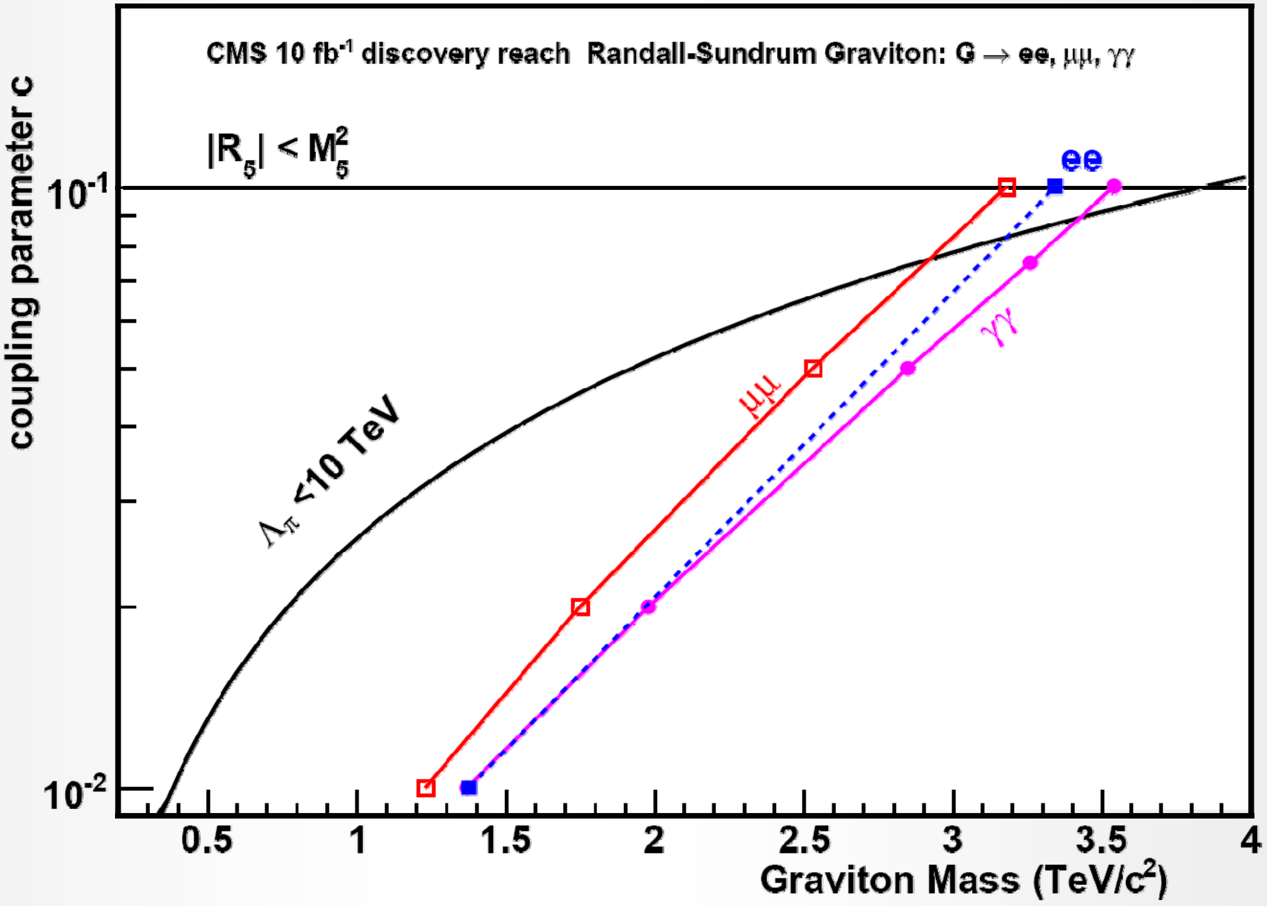
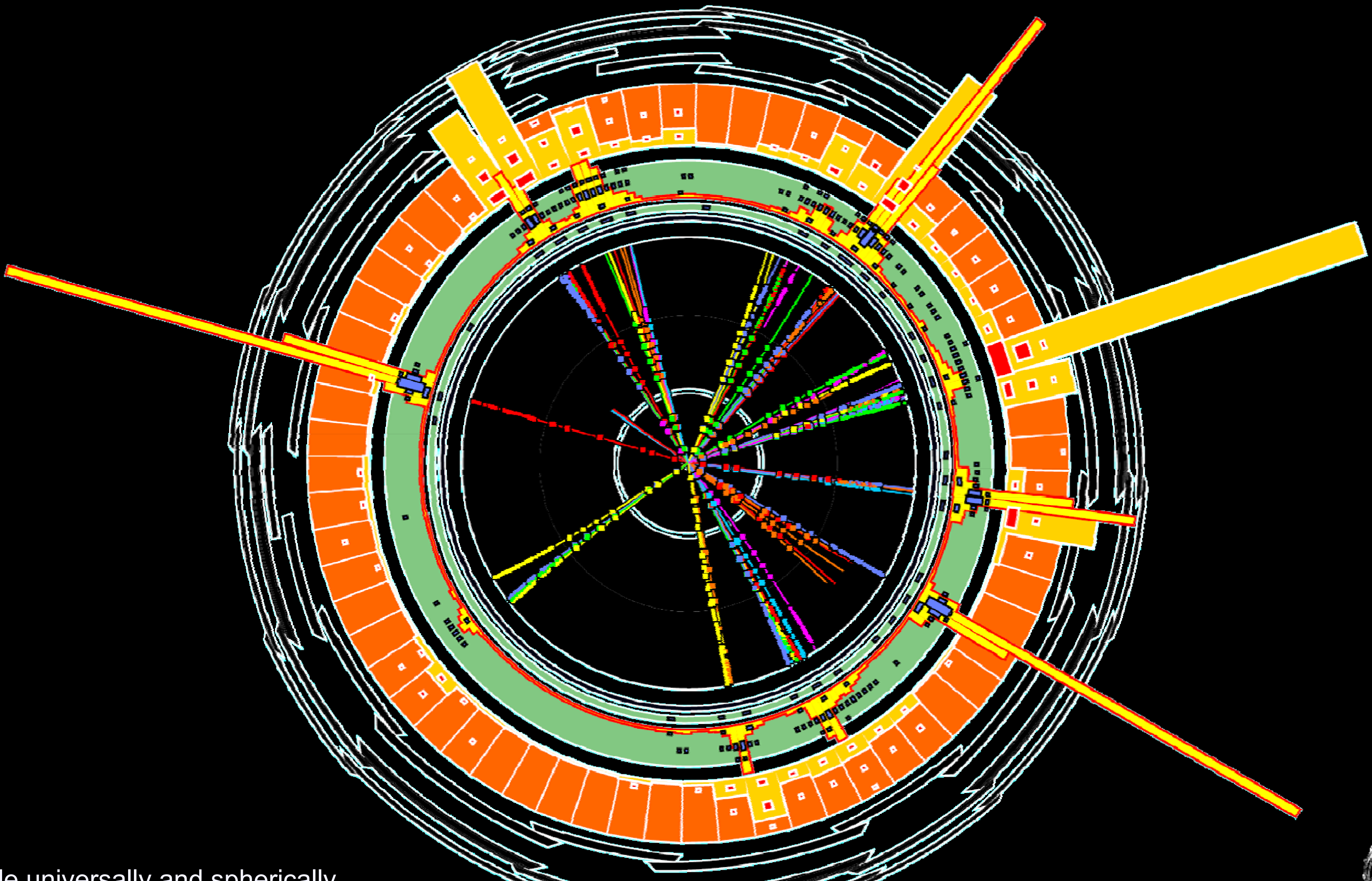


All of the interesting parameter space for 1 ED can be probed with 30 fb^{-1}

Entering Trans-Planck Scales: **Black Holes**



Black hole universally and spherically evaporating into leptons, photons and jets in ATLAS. Final state multiplicity increases with M_{BH}

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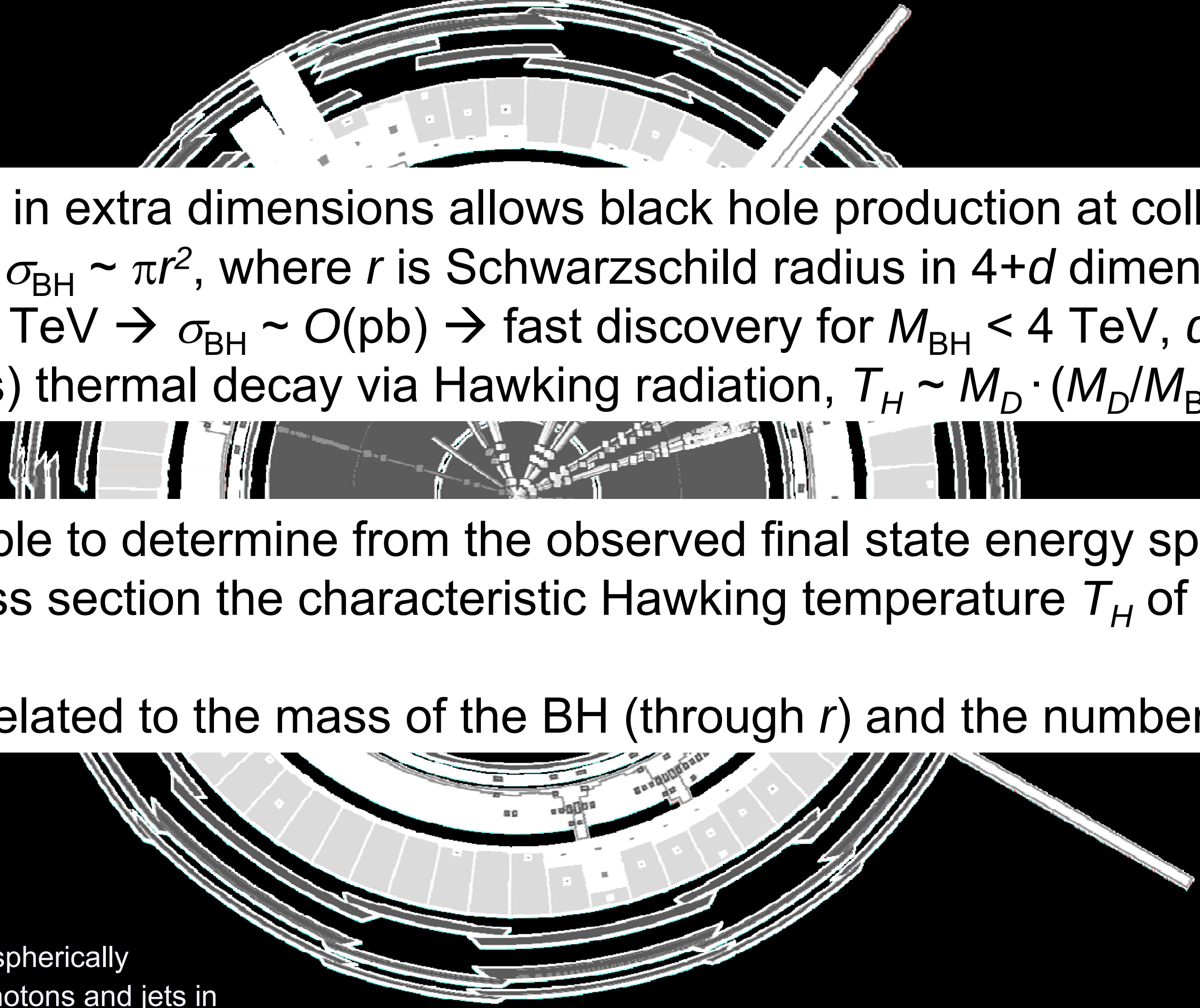


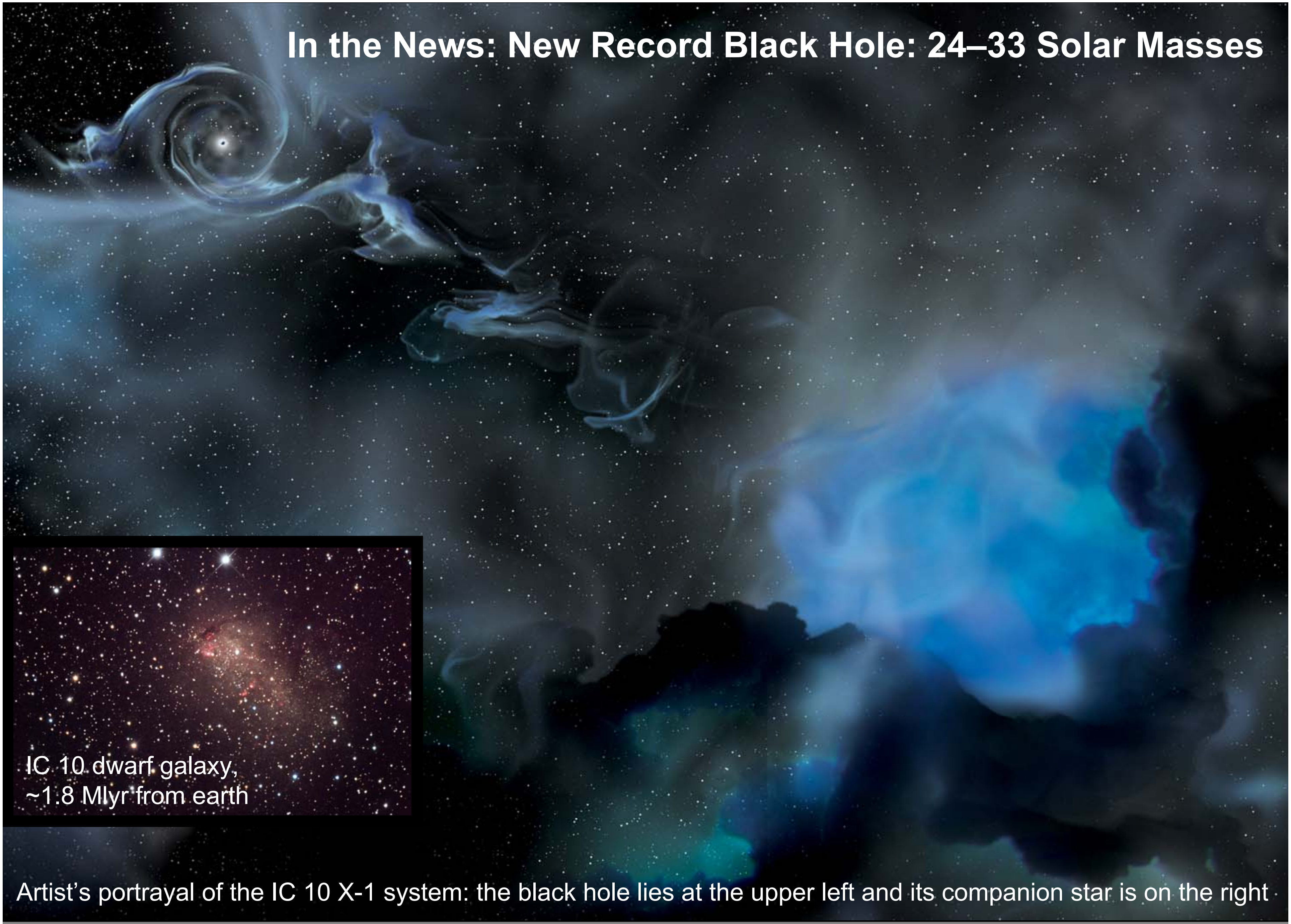
Strong gravity in extra dimensions allows black hole production at colliders
Cross section $\sigma_{\mathrm{BH}} \sim \pi r^2$, where r is Schwarzschild radius in $4+d$ dimensions
With $M_D \sim 2$–3 TeV → $\sigma_{\mathrm{BH}} \sim O(\mathrm{pb})$ → fast discovery for $M_{\mathrm{BH}} < 4$ TeV, $d = 2$-6
Fast ($\tau \sim 10^{-27}$ s) thermal decay via Hawking radiation, $T_H \sim M_D \cdot (M_D/M_{\mathrm{BH}})^{1/(d+1)}$

It may be possible to determine from the observed final state energy spectrum and the BH cross section the characteristic Hawking temperature T_H of the BH

T_H can then be related to the mass of the BH (through r) and the number of EDs

Black hole universally and spherically evaporating into leptons, photons and jets in ATLAS. Final state multiplicity increases with M_{BH}

In the News: New Record Black Hole: 24–33 Solar Masses

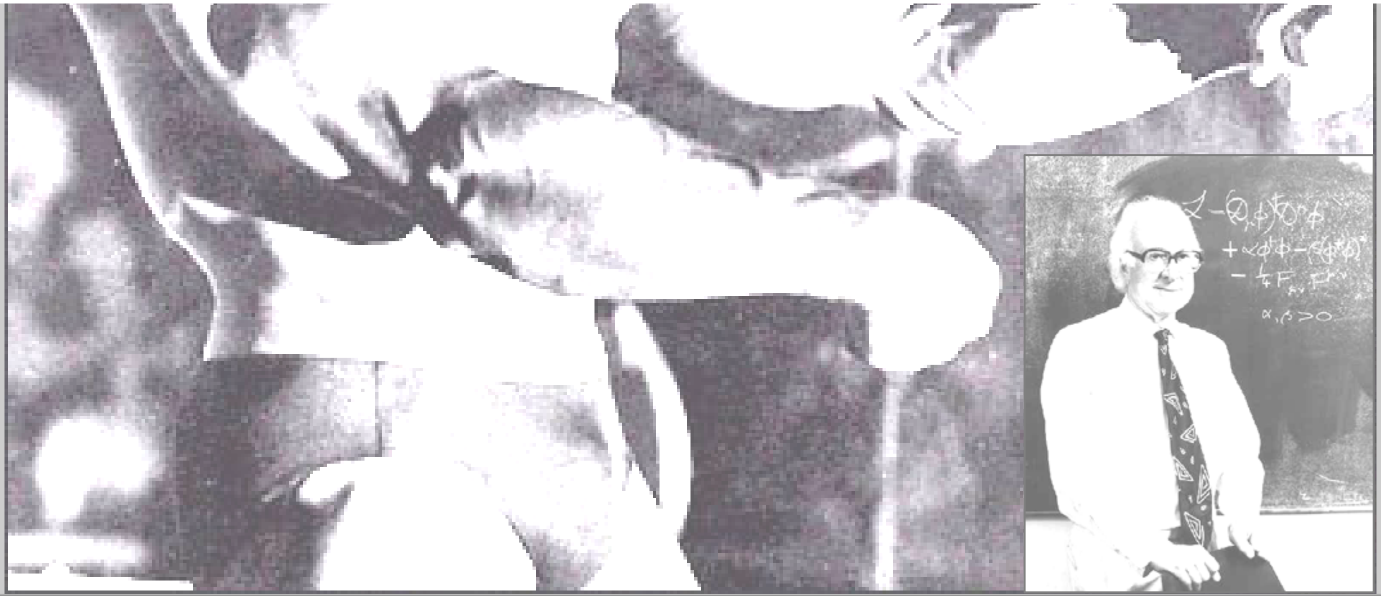


IC 10 dwarf galaxy,
~1.8 Mlyr from earth

Artist’s portrayal of the IC 10 X-1 system: the black hole lies at the upper left and its companion star is on the right

Searches at the LHC

— Little Higgs —



Little Higgs (I)

- The breaking of a new SU(5) symmetry leads to new *O*(TeV) particles, among which are **a new top quark (*T*)**, **new gauge fields $W^{\pm}_H$, Z_H, A_H**, and **5 new Higgs bosons**

- Example:

  T signature at the LHC:

T production at LHC:

$$gg, q\bar{q} \rightarrow T\bar{T}$$

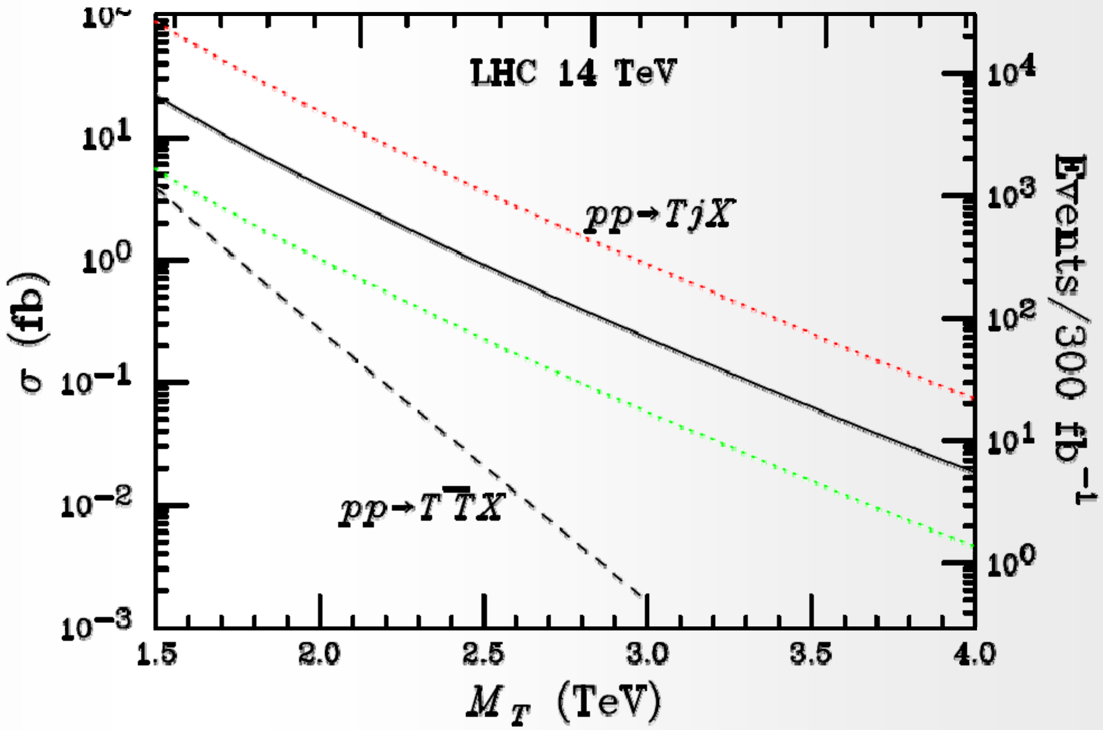
$$qb \rightarrow q'T$$

dominant if *m*(*T*) > 0.7 TeV

Dominant *T* decays:

$$T \rightarrow tZ, bW$$

$$T \rightarrow tH$$



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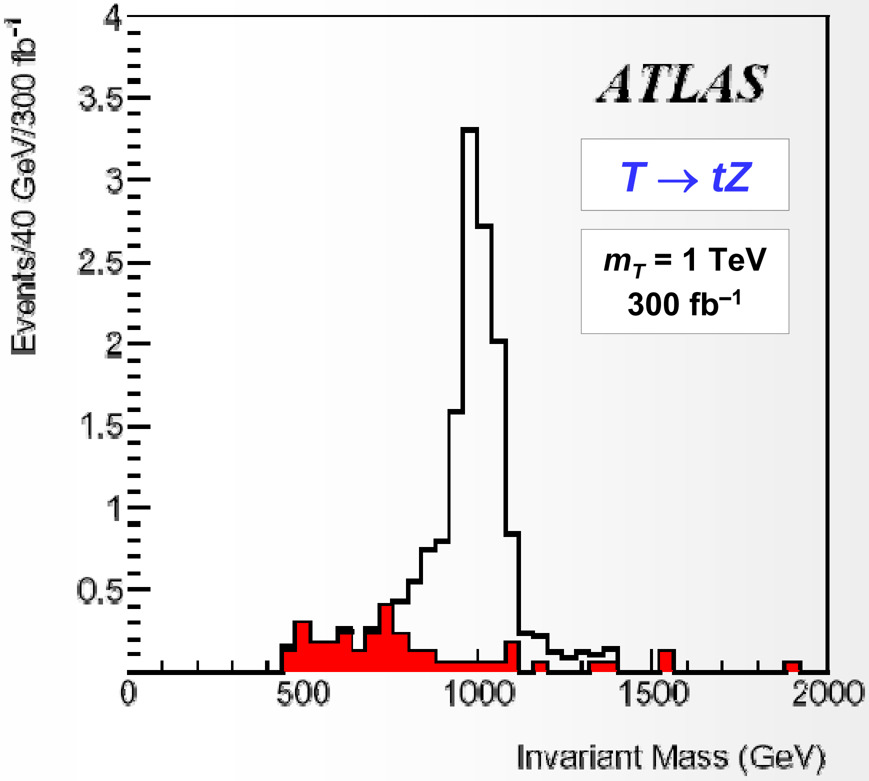

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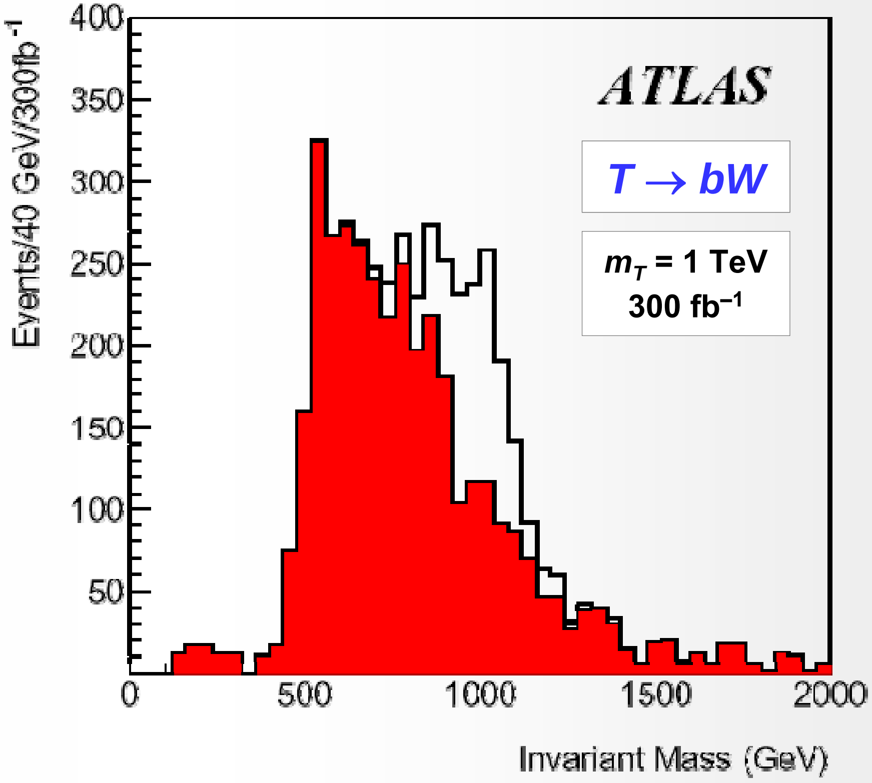


Little Higgs (II)

- Example:
  new Higgs boson: ϕ^{++}

ϕ^{++} production at LHC:

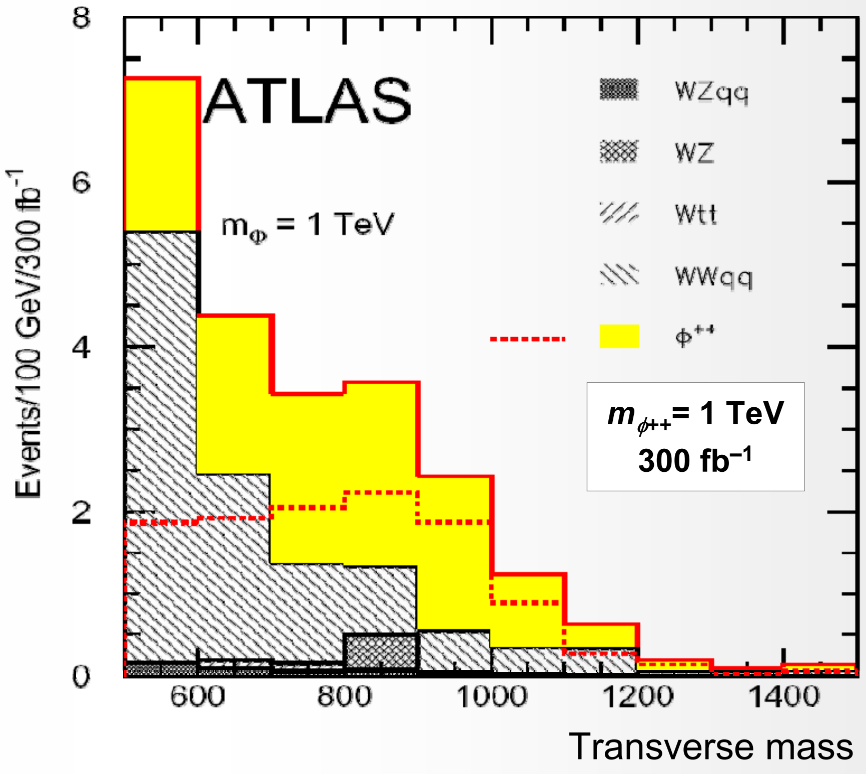
$$q\bar{q} \to \phi^{++}\phi^{--} \to 4\ell$$

too small cross section
for discovery

Vector-boson fusion:

$$uu \to dd\phi^{++} \to ddW^{+}W^{+}$$

signature is 2 leptons
with same charge



Conclusions

A **large number of interesting SM extensions** exists of which only a few have been mentioned in this short lecture. Among those left out are:

Next-to-MSSM extension:

- Additional singlet solving the m_h problem (however, may sacrifice unification of gauge couplings)
- Extends Higgs sector by *CP*-even and odd fields, drastically changing Higgs phenomenology

Generic Z' and other heavy resonances:

- Occur, *e*.*g*., in GUT models
- Signature is heavy di-lepton invariant mass peaks

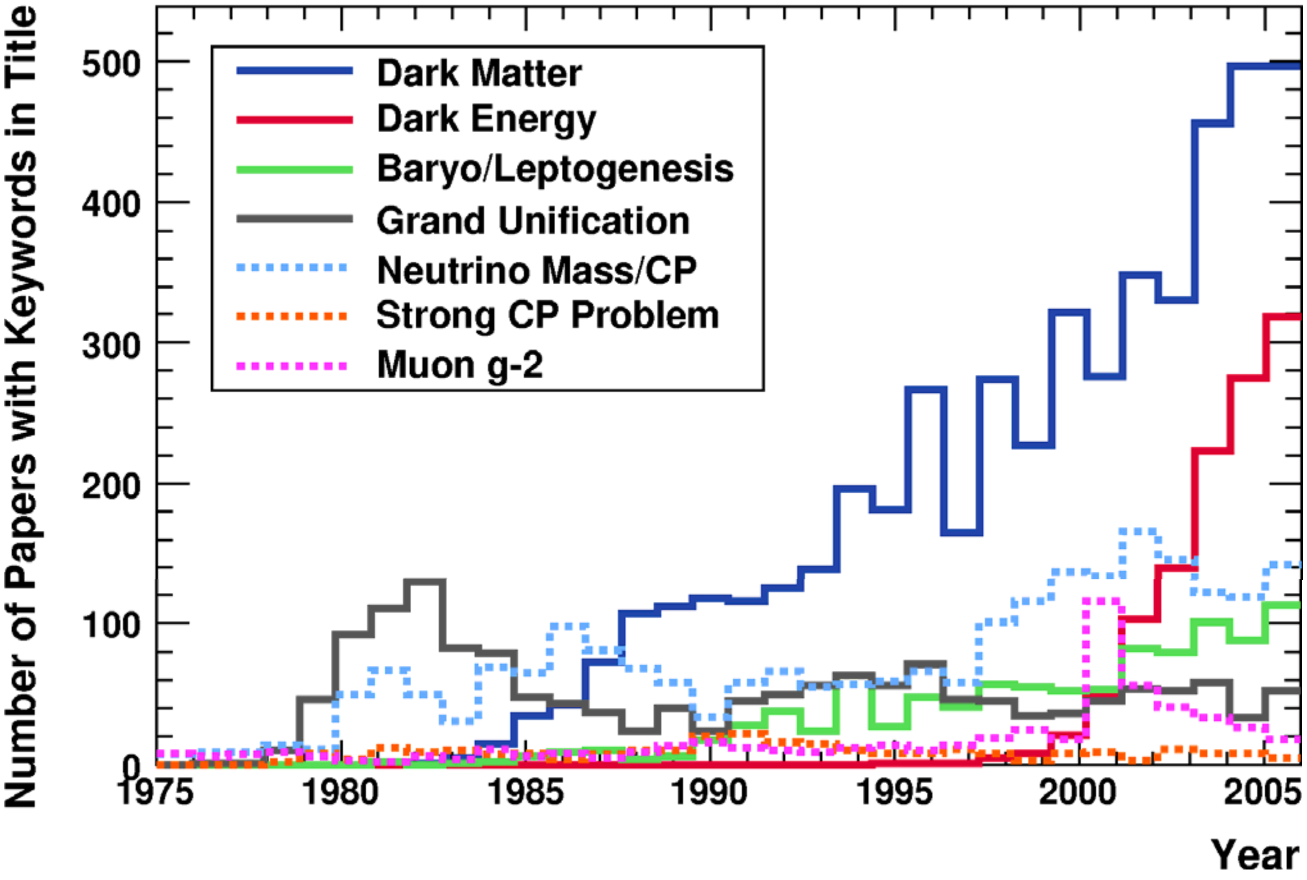
Curved extra dimensions:

- Radions

Many more: Technicolor, (Higgs) Compositness & Contact interactions, Leptoquarks, …

Which path should I follow for my analysis ?

What SPIRES Finds Important



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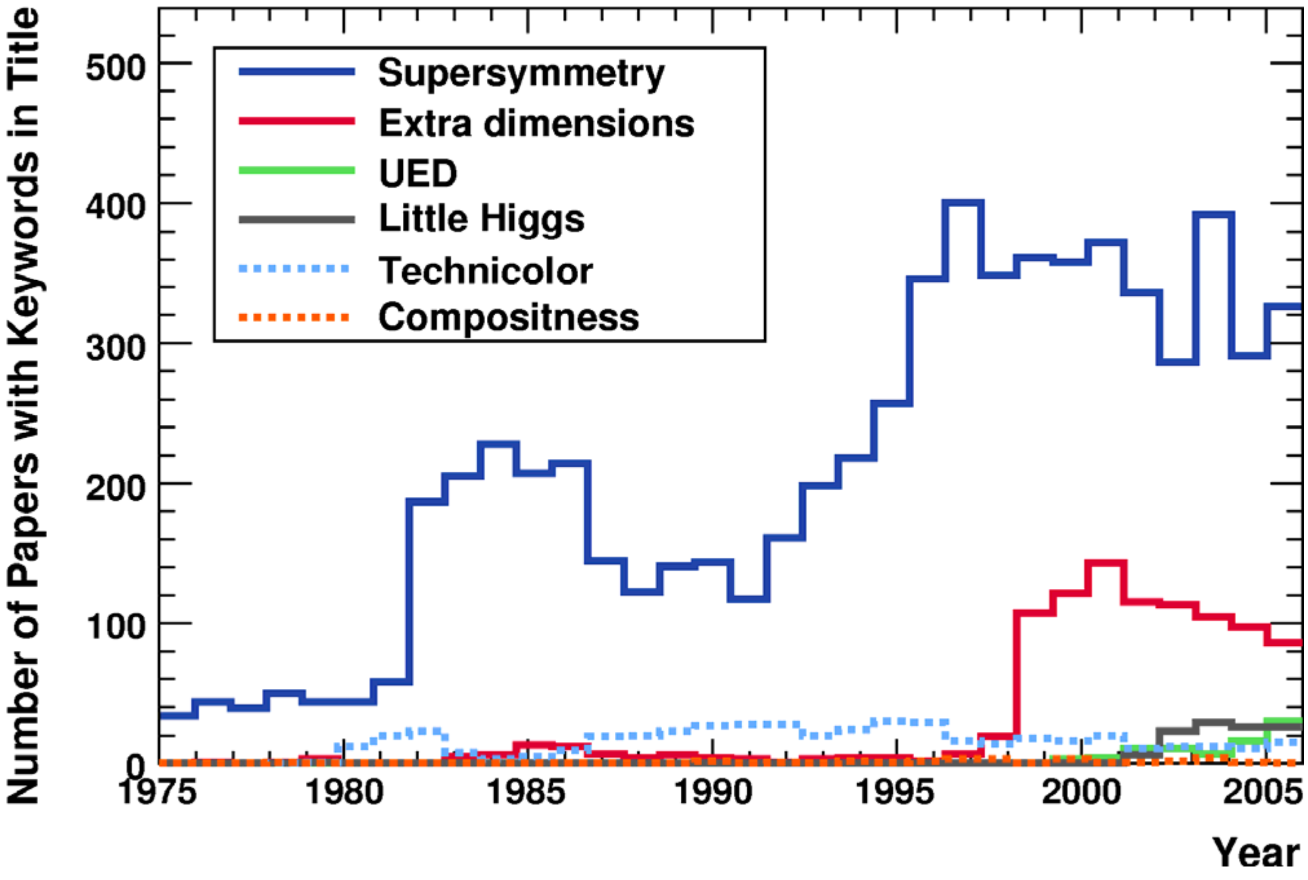

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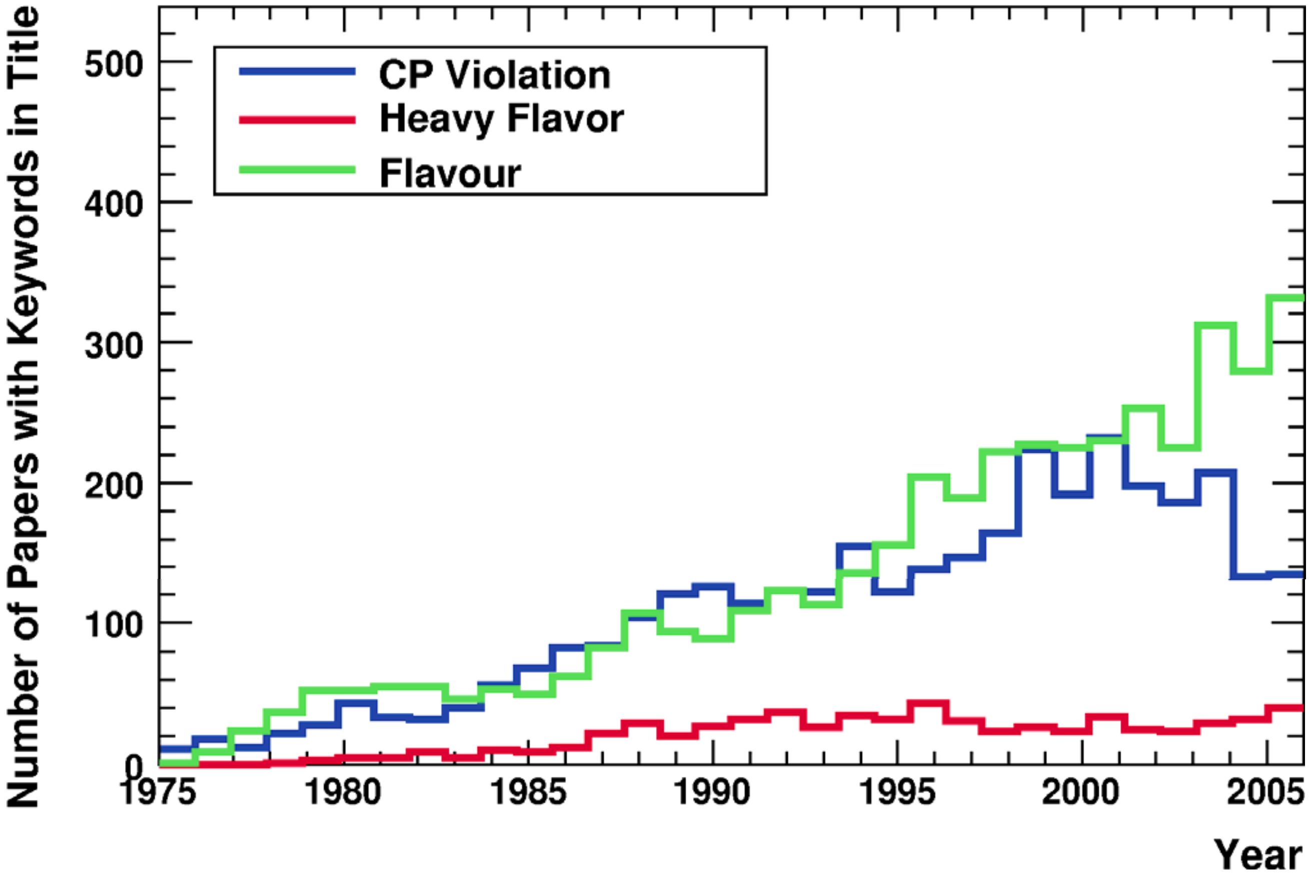

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Experimentalists cannot afford to have theoretical prejudice.

We must follow all paths!

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