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New Physics with earliest LHC data

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Summary. — We investigate which new physics models could be discovered in the first year of the LHC. Such a "Supermodel" is a new physics scenario for which the LHC sensitivity with only $10\,\mathrm{pb}^{-1}$ useful luminosity is greater than that of the Tevatron with $10\,\mathrm{fb}^{-1}$. The simplest supermodels involve s-channel resonances in the quark-antiquark and especially in the quark-quark channels. We concentrate on easily visible final states with small standard model backgrounds, and suggest simple searches, besides those for Z' states, which could discover new physics in early LHC data.

PACS `12.90.+b` – Miscellaneous theoretical ideas and models.

1. – Introduction

In this paper, we explore the new physics discovery potential of the first LHC run. A more detailed description of this work can be found in [1]. The latest LHC schedule calls for collisions at 7 TeV throughout much of 2010 and 2011, with the hope of delivering about $100\,\mathrm{pb}^{-1}$ integrated luminosity in 2010 and $1\,\mathrm{fb}^{-1}$ by the end of 2011 [2,3]. Given the inherent uncertainties in this schedule, we take a look at the new physics capabilities of a $10\,\mathrm{pb}^{-1}$ low-luminosity data set. We allow ourselves to contemplate new physics which is not motivated by model building goals such as unification, weak scale dark matter, or solving the hierarchy problem.

We find that there is a set of interesting new physics scenarios that could give a clean, observable signal in early LHC data, while not being detected with $10\,\mathrm{fb}^{-1}$ of Tevatron data (the projected integrated luminosity at the end of 2010). These models are also consistent with previous experiments such as LEP II, precision electroweak constraints, and flavor physics. Moreover, some of these scenarios have similar signatures to "well-motivated" new physics models that require higher luminosity for discovery.

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To set the stage, recall that the production cross sections for new hypothetical particles can be quite large. For example, QCD pair production of 500 GeV colored particles have cross sections in the pb range, such that tens of such particles could be produced in early LHC. Of course, in order for the new particles to be observable, they must have sufficiently large branching fractions to final states with distinctive signatures and controllable standard model backgrounds. Also, the new particles should not be ruled out by current or future Tevatron searches, implying that the cross section times integrated luminosity at the LHC should be larger than the corresponding quantity at the Tevatron.

Thus, the four criteria for a new physics scenario to be discovered in early LHC with low luminosity are:

1) Large enough LHC cross section for at least 10 signal events with $10\,\mathrm{pb}^{-1}$ of data.

2) Small enough cross section to evade detection by 2010 at the Tevatron with $10\,\mathrm{fb}^{-1}$.

3) Large branching fraction to an "easy" final state with essentially no backgrounds.

4) Consistency with other existing bounds.

We call a new physics scenario satisfying these conditions a *supermodel*.

The classic example for a candidate supermodel is a TeV-scale Z' boson [4]. Assuming the Z' mass exceeds the Tevatron reach, but is light enough and has large enough couplings so that it can be produced copiously at the LHC, it can be discovered through its decay to electron and muon pairs. Such leptonic finals states are "easy" to reconstruct with a peak in the invariant mass distribution, which reduces the already low standard model backgrounds.

However, a typical leptonically decaying Z' is not a supermodel. First, since the Z' is produced via the quark-antiquark initial state, the Tevatron is quite competitive with the LHC. Second, the leptonic branching fraction is severely bounded by LEP II data, which restricts the couplings of the Z' to leptons. It is therefore nontrivial to find supermodels that are as discoverable as a standard Z' but consistent with known bounds on new physics.

2. – Production modes

In this section, we discuss which production modes have the potential to be supermodels, deferring detailed model building to sect. **3**. Since the expected integrated luminosity at the Tevatron ($\sim 10\,\mathrm{fb}^{-1}$) is orders of magnitude larger than our $10\,\mathrm{pb}^{-1}$ benchmark luminosity for early LHC analysis, and since $p\bar{p}$ parton luminosities are not so different from pp parton luminosities, one must consider sufficiently heavy new particles to evade the Tevatron reach. We will find that the most promising perturbative scenarios accessible with $10\,\mathrm{pb}^{-1}$ of LHC data are qq and $q\bar{q}$ resonances.

In fig. 1 we plot the LHC parton luminosities, defined as

$$\mathcal{F}_{ij}(\hat{s}, s) = \int_{\hat{s}/s}^{1} \mathrm{d}x_i \, \frac{\hat{s}}{x_i s} \, f_i(x_i) \, f_j[\hat{s}/(x_i s)], \tag{1}$$

and the ratios of parton luminosities at the LHC and Tevatron. Here $\sqrt{s}$ is the center-of-mass energy of the collider, $\sqrt{\hat{s}}$ is the invariant mass of the two interacting partons, and $f_i(x_i)$ are parton distribution functions [5] at momentum fraction x_i and scale $\sqrt{\hat{s}}$.

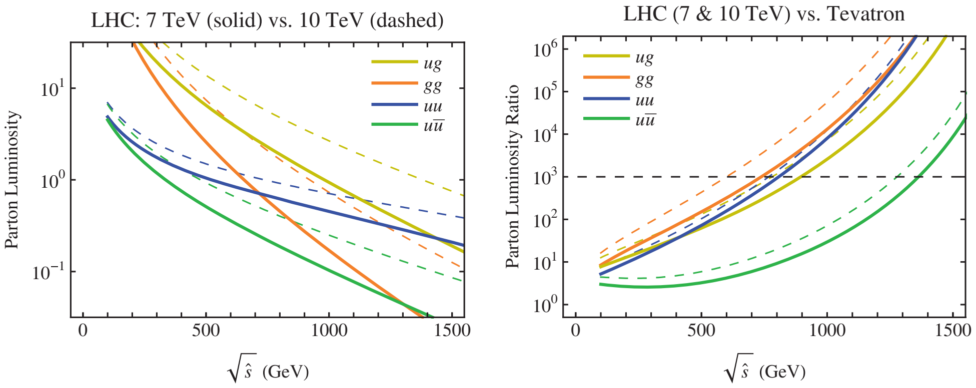

Fig. 1. – Left panel: LHC parton luminosities as defined in eqs. (1), as functions of the partonic invariant mass. The solid (dashed) curves are for the 7 TeV (10 TeV) LHC. The up quark has been chosen as a representative quark, and each curve includes the contribution from the CP conjugate initial partons. Right panel: ratios of the parton luminosities for 7 TeV (solid) and 10 TeV (dashed) LHC compared to the 1.96 TeV Tevatron, as functions of the partonic invariant mass. When this ratio is above the 10^3 horizontal dashed line, the LHC with $10\,\mathrm{pb}^{-1}$ will have greater sensitivity than the Tevatron with $10\,\mathrm{fb}^{-1}$.

Figure 1 shows that the gg parton luminosity only dominates for small invariant mass, where the initial LHC data set cannot compete with the Tevatron. At large invariant masses the LHC parton luminosities become sufficiently enhanced compared to the Tevatron. Thus supermodels will always involve high invariant masses in order to beat the Tevatron. We will emphasize this point in the next subsection by showing why QCD pair production is not a supermodel, and then go on to consider supermodels constructed from s-channel resonances.

2˙1. *QCD pair production?* – A simple process initiated by gluons is QCD pair production of new colored particles. For not too heavy states, it can have a cross section above a pb, yielding $\mathcal{O}(10)$ events with $10\,\mathrm{pb}^{-1}$ of LHC data. However, such processes are generically not supermodels. For concreteness, we study the production of a color-triplet quark Q. Assuming decays to a highly visible final state and perfect reconstruction efficiencies one can use standard QCD to calculate the largest value of m_Q for which the Tevatron would observe 10 $Q\overline{Q}$ pair production events with $10\,\mathrm{fb}^{-1}$ of data. In this idealized example, the hypothetical Tevatron bound is $m_Q > 500\,\mathrm{GeV}$. The same exercise can be repeated for the LHC as a function of the center-of-mass energy and integrated luminosity, and the result is shown in fig. 2.

To reach the Tevatron sensitivity for QCD pair production at a 7 TeV LHC, the required luminosity is about $50\,\mathrm{pb}^{-1}$. While this is likely within the reach of an early LHC run, the LHC will not easily surpass Tevatron bounds in this channel, and it is unlikely that a 5σ LHC discovery is possible without the Tevatron already having seen some events. The situation is improved if there is a large multiplicity of near-degenerate new colored states or if the new states are color octets (like gluinos in supersymmetry). Then the total cross sections are larger by a multiplicity factor and the LHC reach can surpass that of the Tevatron by going to higher masses.

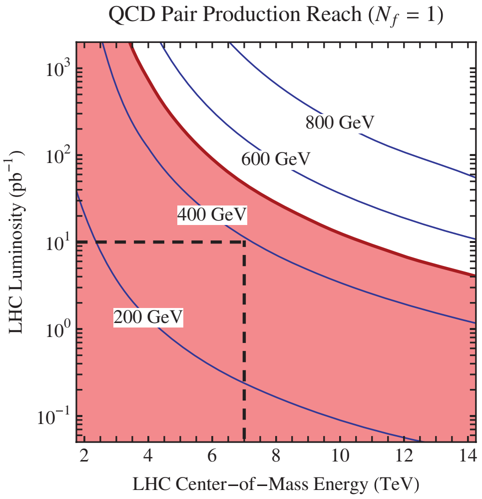

Fig. 2. – LHC reach for pair production of a single flavor of heavy quark as a function of energy and luminosity. Each contour corresponds to the production of 10 events at the LHC for the indicated quark mass. The shaded region corresponds to the would-be Tevatron bound (see text). The intersection of the straight dashed lines corresponds to the maximum quark mass ($\sim 400\,\text{GeV}$) probed by the 7 TeV LHC with $10\,\text{pb}^{-1}$ of data.

2·2. *Resonance production.* – While pair production of new colored particles is not a supermodel, production of an s-channel resonance has the potential to be a supermodel, as long as the resonance has renormalizable couplings to the partonic initial states. Recall that parametrically the production cross section for a single resonance is enhanced over pair production by a phase space factor of $16\pi^2$.

In the narrow width approximation, we parametrize single resonance production by

$$\sigma(p_i p_j \to X) = [g^2_{\text{eff}}]_{ij}\, \delta(\hat{s} - m_X^2), \tag{2}$$

where $p_{i,j}$ denote the two partons which participate in the hard scattering, m_X is the mass of the resonance, and $[g^2_{\text{eff}}]_{ij}$ encodes all information about the production of resonance X from the two partons, including couplings, polarization, and color factors. Using the parton luminosities defined in eq. (1), the hadronic cross section is

$$\sigma(pp \to X) = \frac{1}{m_X^2} \sum_{ij} [g^2_{\text{eff}}]_{ij}\, \mathcal{F}_{ij}(m_X^2, s). \tag{3}$$

For the resonances considered in this paper, one production channel dominates, allowing us to drop the ij label from g^2_{eff}. For reasonably narrow resonances with dimension-four couplings, g^2_{eff} can be order 1, which is the case for the $q\bar{q}$ and qq initial states. However, for the qg or gg initial states $SU(3)$ gauge invariance forbids renormalizable couplings to a single resonance. Thus the effective coupling of such a resonance either includes a loop factor, or it is suppressed by a high scale. Either way this suppresses cross sections for gg and qg resonances, and we will not consider them further.

In fig. 3, we show our estimate of the generic early LHC reach in m_X, as a function of the energy and luminosity, for the two promising resonance channels $\bar{q}q$ and qq using

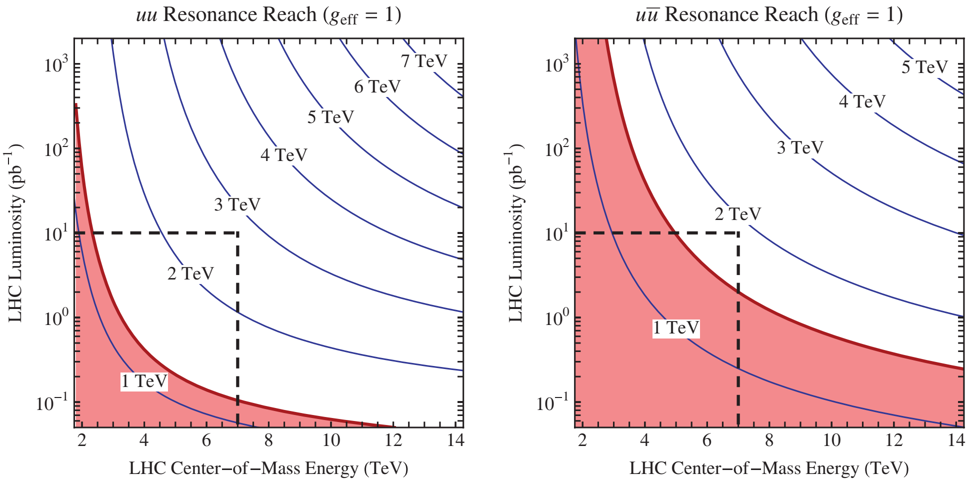

Fig. 3. – (Colour on-line) LHC reach for single resonance production as a function of energy and luminosity. As in fig. 2, the contours show the production of 10 events for a given resonance mass, the red regions show the Tevatron sensitivity with $10\,\mathrm{fb}^{-1}$, and the intersection of the dashed lines shows the maximum resonance mass which can be probed by the 7 TeV LHC with $10\,\mathrm{pb}^{-1}$ data. One sees that the early LHC can exceed the Tevatron sensitivity for $q\bar{q}$ and especially for qq resonances.

the effective coupling $g^2_{\mathrm{eff}} \sim 1$. As in fig. 2, we assume 100% branching fraction of X to highly visible final states and assume perfect detector efficiency, though we will relax these assumptions below.

In the $u\bar{u}$ and especially in the uu channels the first LHC run even with modest energy and luminosity will supersede the Tevatron. Thus, qq and $q\bar{q}$ resonances are good starting points for constructing supermodels, examples will appear in sect. **3**.

2˙3. *Production of qq and $q\bar{q}$ resonances.* – The plots in fig. 3 give a rough idea of the LHC discovery potential for s-channel resonances. They are valid for a particular value of the effective coupling, g^2_{eff}, and assume that the X resonance is observed with 100% efficiency. For qq and $q\bar{q}$ resonances, we are interested in the dependence of the reach on g^2_{eff} and on branching fractions/efficiencies. Here, we introduce a new kind of plot which is convenient for reading off cross sections at the LHC and comparing them to the Tevatron for variable couplings and detection efficiencies. In fig. 4, we plot in the LHC energy *vs.* resonance mass plane the contours of constant production cross section and contours of constant ratio of LHC *vs.* Tevatron cross section.

The solid curves in fig. 4 show contours of constant LHC cross sections for $g^2_{\mathrm{eff}} = 1$. From these, one can read off how many events are produced for a given LHC luminosity as a function of the resonance mass and the LHC energy. For example, assuming 100% visible decay rate and detection efficiency, the region to the right of the curve labeled "10^0 pb" will yield at least 10 events with $10\,\mathrm{pb}^{-1}$ of LHC data. The dashed curves in fig. 4 show contours of constant ratio of LHC *vs.* Tevatron cross sections. From these, one can read off the advantage of the LHC compared to the Tevatron for a given model.

Thus the region in which the LHC has better sensitivity than the Tevatron and yields at least a certain number of events is a "wedge" bounded by a solid and a dashed curve.

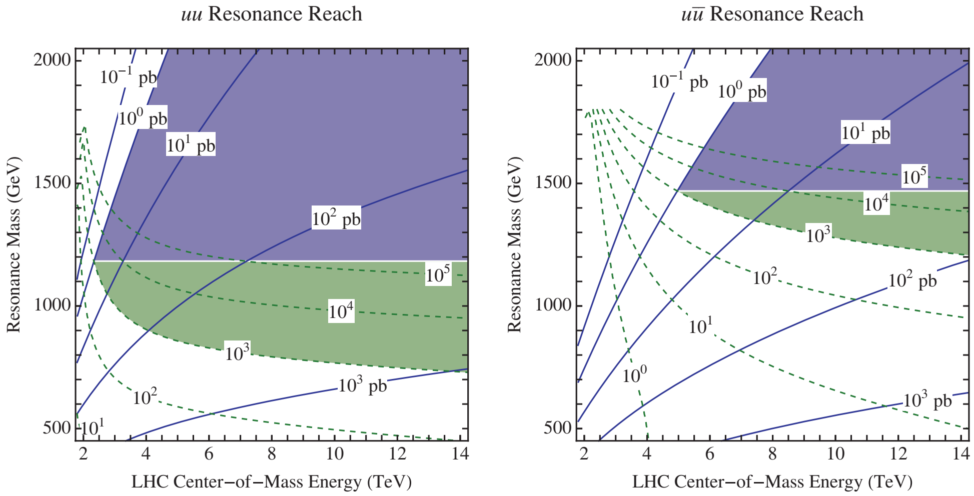

Fig. 4. – (Colour on-line) The LHC reach for uu and $u\bar{u}$ resonances in the LHC energy *vs.* resonance mass plane. The solid lines are contours of constant LHC production cross sections for $g^2_{\text{eff}} = 1$, and the dashed green lines are contours of constant LHC to Tevatron cross section ratios. The blue shaded regions show where the discovery reach of a $10\,\text{pb}^{-1}$ LHC run is beyond that of the $10\,\text{fb}^{-1}$ Tevatron. The green regions show where the LHC sensitivity is greater than that of the Tevatron, but the Tevatron can also see at least 10 events.

For example, the wedge to the right of the intersection of the "10^0 pb" and the "10^3" curves gives the region for which at least 10 events are produced with $10\,\text{pb}^{-1}$ of LHC data and the number of events at the LHC is greater than that at the Tevatron. Everywhere in the shaded wedge in fig. 4 the LHC sensitivity is better than that of the Tevatron. However, in the lower region, the sensitivity of the Tevatron is still sufficient to rule out the new physics. Thus only the upper region is the true LHC discovery region.

Using these plots, one can also estimate the minimum value of m_X and $g^2_{\text{eff}}\,\mathcal{B}\,\text{Eff}_{\text{LHC}}$ for a scenario to be a supermodel. Take a $q\bar{q}$ resonance as an example. A 7 TeV and $10\,\text{pb}^{-1}$ early LHC run supersedes the Tevatron sensitivity for a $m_X > 1.4\,\text{TeV}$ (the value of the "10^3" dashed curve at 7 TeV). We can then read off that $g^2_{\text{eff}}\,\mathcal{B}\,\text{Eff}_{\text{LHC}} > 0.1$ is required to observe at least 10 events.

3. – Example supermodels

Considering production cross sections alone, $q\bar{q}$ and qq resonances emerged as the best starting points for constructing supermodels. In this section, we consider some concrete supermodel examples to demonstrate what kind of final states can be obtained from the decay of these resonances. Since we are interested in final states that involve the cleanest signatures and least background contamination, we concentrate on decay chains yielding at least two charged leptons or two other stable charged particles in the final state.

3˙1. *The case against a standard* Z'. – For a $q\bar{q}$ resonance to be supermodel, it must have a large branching fraction to visible final states. In particular, since a $q\bar{q}$ resonance can have zero electric charge, it is natural for such a resonance to decay to pairs of oppositely charged leptons, in particular e^+e^- and $\mu^+\mu^-$. However, the same resonance also induces a low energy effective four-lepton vertex, and such operators are severely constrained by LEP II. As recently emphasized in ref. [6], once the LEP II bound is imposed, the branching fraction of the $q\bar{q}$ resonance to $\ell^+\ell^-$ has to be too small to realize a supermodel. There are ways to evade this conclusion. Since the LEP II bound only applies for the electron coupling, one could imagine coupling the Z' only to muons. However, such flavor non-universal couplings typically require significant fine-tuning to avoid constraints from flavor changing neutral currents.

3˙2. *Decays to quasi-stable particles.* – While the decay of a Z' to standard model charged leptons does not give a viable supermodel example of topology A, one could imagine a $q\bar{q}$ resonance that instead decayed with a large branching fraction to new quasi-stable charged particles. Since ATLAS and CMS trigger on penetrating charged particles as if they were muons [7], such scenarios are as visible in the early LHC data as a Z' decaying to muons. Alternatively, one could consider a Z' that decayed to quasi-stable colored particles that then form R-hadron-like bound states with QCD partons. Such R-hadron final states could potentially be visible in early LHC data, though charge flipping interactions [7] complicate both triggering and momentum reconstruction.

3˙3. *Fun with diquarks.* – From fig. 4, one sees that qq resonances can yield an impressive early LHC reach. Such resonances are known as diquarks, and they have spin zero or one, carry baryon number 2/3, and electric charge 4/3, 1/3 or −2/3. They may transform as a **6** or $\overline{\mathbf{3}}$ of color. Their couplings are necessarily non-trivial in flavor space because the initial quarks carry flavor. Flavor changing neutral currents impose constraints on couplings of new states with masses of order TeV and large couplings to first generation quarks. We chose diquarks with the same flavor quantum numbers as the quarks which produce them, allowing the couplings of the diquark to quarks to be flavor invariant.

To be concrete, we consider a spin-zero and color-six diquark D, with couplings to the $SU(2)$ singlet up-type quarks only and symmetric in flavor indices. The production operator can be written as $\mathcal{O}_D = \frac{\kappa_D}{2} D\, u^c u^c$, where u^c are the up-type singlet quarks and D is the diquark. Then the partonic cross section is

$$\sigma(uu \to D) = \frac{\pi}{6}\, \kappa_D^2\, \delta(\hat{s} - m_D^2). \tag{4}$$

If $\mathcal{O}_D$ were the only coupling of the diquark, then any produced diquark would simply decay back to the initial state with a partial width given by $\Gamma = \kappa_D^2 m_D/(16\pi)$. To be a supermodel, the diquark has to have a large branching fraction to a visible final state. By color conservation, diquark decays must yield at least two jets in the final state, so the most Z'-like decay possible for a diquark yields two oppositely charged leptons in addition to two jets in the final state.

For example, we can introduce a vector-like fermion L and L^c, with the quantum numbers $L = (6, 1, 7/3)$ under $SU(3)_C \times SU(2)_L \times U(1)_Y$. Given its quantum numbers, L/L^c would be called a "leptodiquark". The diquark can decay via the operator $\bar{\kappa}_D\, D\, L^c e^c$ with a decay width of $\Gamma = \bar{\kappa}_D^2 m_D/(16\pi)$. Thus, as long as $\bar{\kappa}_D > \kappa_D$, the diquark preferentially decays to the leptodiquark and a lepton. The L^c will finally decay via its two couplings given above leading to the full decay chain:

$$uu \to D \to \ell^- L \to \ell^- \ell^+\, 2j. \tag{5}$$

While this diquark-leptodiquark system may strike the reader as baroque, the identical decay topology appears in the case of a W'_R gauge boson [8,9], where the diquark plays the role of the W'_R and the leptodiquark plays the role of a right-handed neutrino. However, discovering a left-right symmetric model through this channel typically requires $1\,\mathrm{fb}^{-1}$ of LHC data, whereas the diquark-leptodiquark example motivates a search for the $2j+\ell^+\ell^-$ final state in early LHC data.

3˙4. *Resurrecting pair production.* – In subsect. **2**˙1, we argued that QCD pair production of new colored resonances was not a supermodel. However, one could still get pair production of new particles via decay of a supermodel resonance.

For example, using either a $q\bar{q}$ or a qq resonance, one can produce vector-like up-type quarks U and U^c with quantum numbers $U = (3, 1, 2/3)$. They can be produced via the Z' through $Z' \to \overline{U}U$ or via the diquark through $D \to U^c U^c$. If these new colored particles were exactly stable, they would form R-hadron-like bound states as mentioned above. However, the heavy U/U^c quarks could also decay via small CKM-like mixings with the standard model quarks, leading to $U \to Z{+}u/c/t$ and $U \to W{+}d/s/b$. However, such decays are not ideal for making a supermodel, since the W (Z) boson only has 22% (7%) branching fraction to electrons and muons.

Another option to force leptons to appear in the final state is to have a resonance decay to pairs of colored particles that also carry lepton number such as leptoquarks.

Finally, a neutral $q\bar{q}$ resonance can dominantly decay to two secondary resonances that carry no standard model charges. These secondary resonances have a huge range of possible final states. Such scenarios will be supermodels as long as the secondary resonances have an $\mathcal{O}(1)$ branching fraction to highly visible final states.

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