Supermodels: Early new physics at the LHC?

Zoltan Ligeti

PLB 690 (2010) 280 [arXiv:0909.5213]

with Christian Bauer, Martin Schmaltz, Jesse Thaler, Devin Walker

- Introduction
- Resonance scenarios
  ... parton luminosities, couplings, rates
- Supermodel building
  ... Z's, diquarks, promising final states
- Conclusions

Disclaimers

Main Entry: **su·per·mod·el**

Pronunciation: \ˈsü-pər-ˌmä-dᵊl\

Function: *noun*

Date: 1977

: a famous and successful fashion model

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“Unfortunately, the defining property of supermodels is that they are unattainable”

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  I'll argue that — with our definition — this may not be the case...

"... 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"

- What is the minimal LHC data that probes new physics, beyond existing bounds?

The (ever changing) LHC timeline

- Since March: 7 TeV collisions with $\mathcal{L}$ exceeding $10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by now
- At machine startups, significant uncertainty in “delivered” / “useful” luminosity

  So far, it looks great!
- LHC luminosity will depend on the behavior of the machine as the run progresses

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- The Tevatron is running well: $\sim 60\,\mathrm{pb}^{-1}$ / week, and should reach $10\,\mathrm{fb}^{-1}$ in 2010
- CDF and DØ are well-understood detectors (jet energy scale, missing E_T, ...)

- We considered $10\,\mathrm{pb}^{-1} - 100\,\mathrm{pb}^{-1}$ (and explored varying center of mass energy)

Q: Can the LHC with few $\times 10\,\mathrm{pb}^{-1}$ discover new physics?

A_0: No way...

- Looking at practically any of the pre-2009 studies:

  $\lesssim 50\,\mathrm{pb}^{-1}$ = "engineering run"

- Other possible answers:

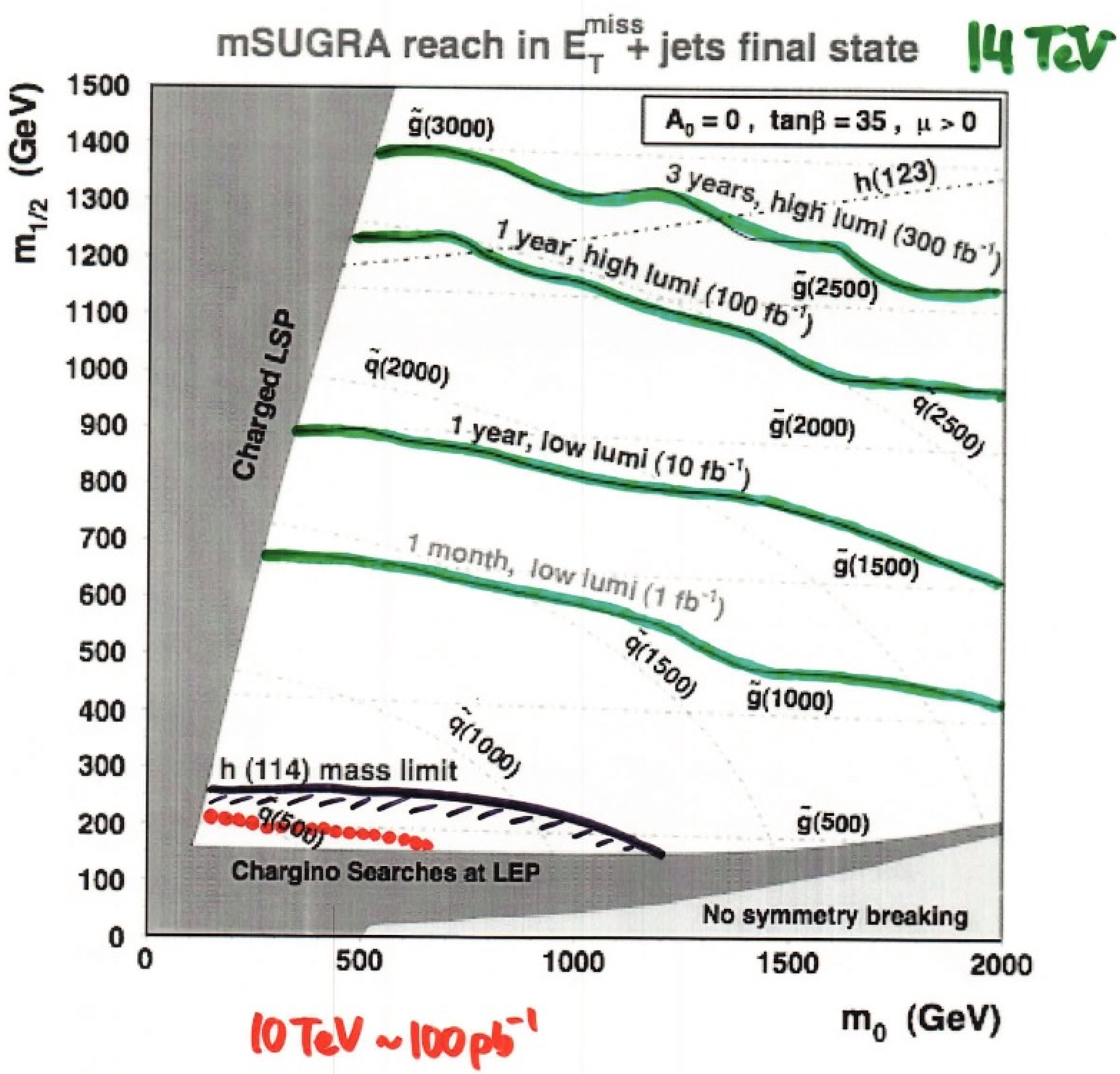
  Good search at $10\,\mathrm{fb}^{-1}$

  = Good search at $10\,\mathrm{pb}^{-1}$

  Probes an actual Lagrangian?

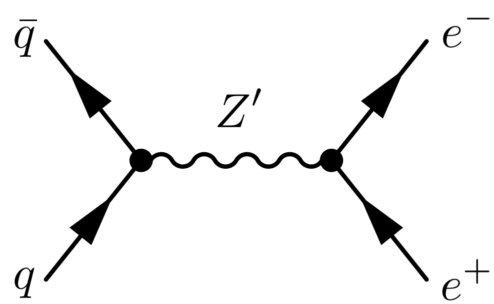
- Lots of searches have not been done before

  Better to do at well-understood Tevatron detectors?

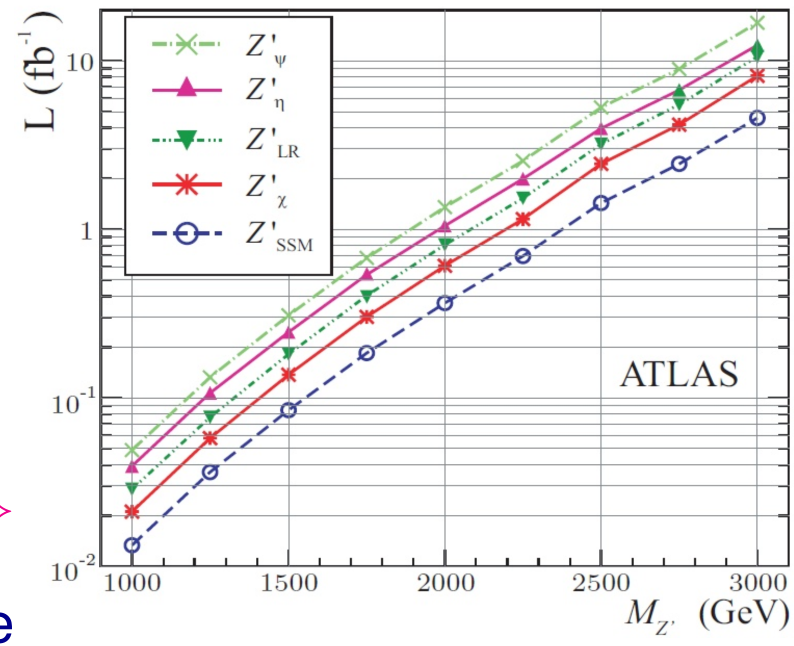


A_1: Yes — can find Z' bosons

- Can clearly superseed the Tevatron sensitivity



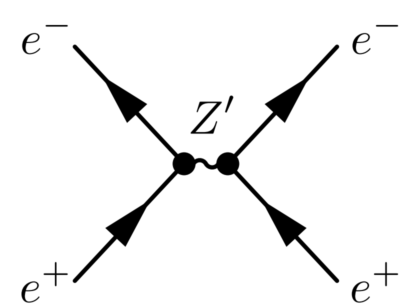
Integrated luminosity needed for 5σ discovery $\Rightarrow$



[Aad *et al.*, ATLAS Collaboration, 0901.0512]

Initial $q\bar{q}$ state is not optimal for LHC's advantage

- Does early LHC search go beyond existing bounds?



The LEP bound, in simplest models: $m_{Z'} \gtrsim 3\,\mathrm{TeV}$

Model building gymnastics needed to construct models that can be discovered with early LHC data [E.g., Salvioni, Villadoro, Zwirner, 0909.1320]

A_2: Supermodels

- Could new physics be first discovered in early LHC? (beyond Tevatron, LEP, etc.)
- Want to identify actual Lagrangians that:

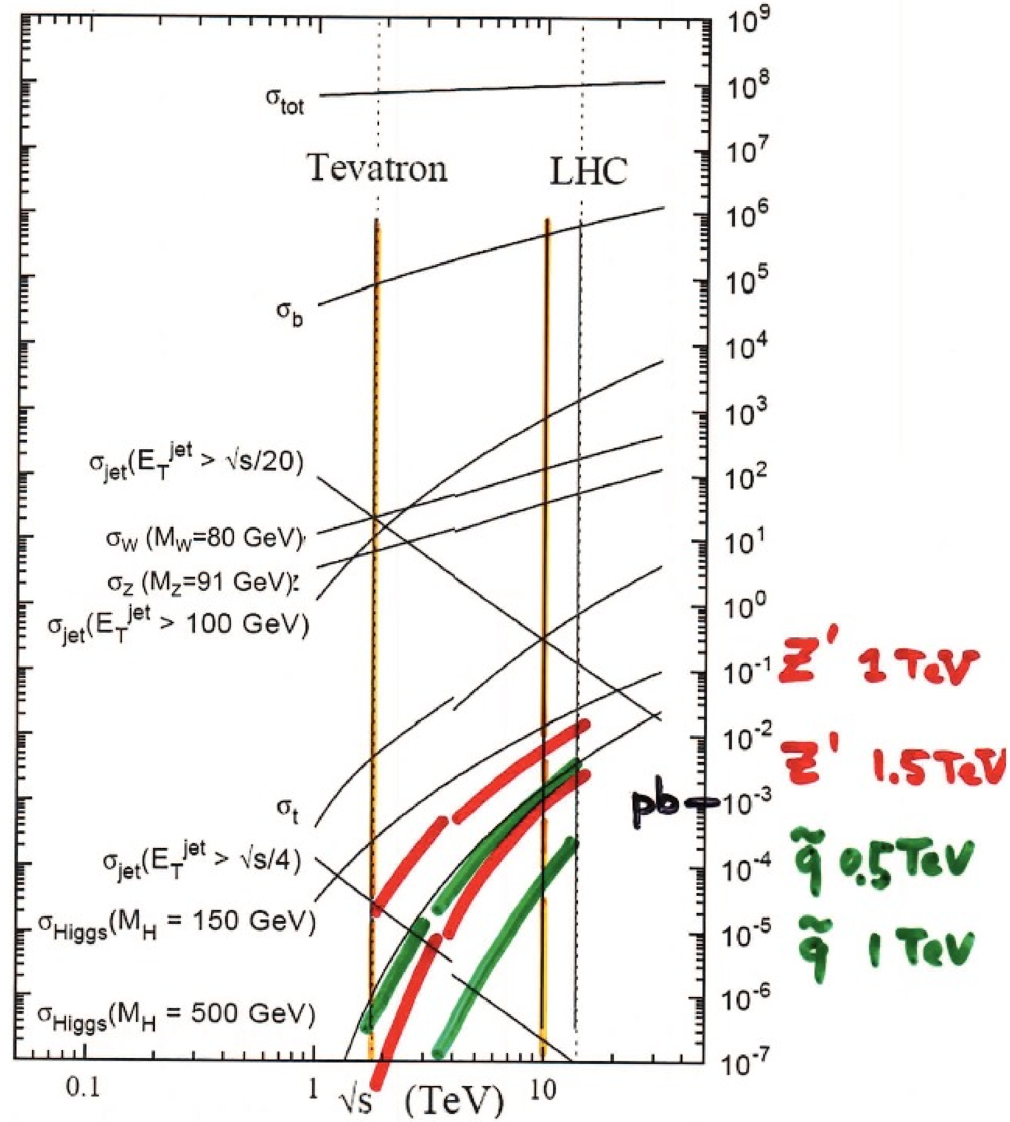
1. Can be seen with $10\,\mathrm{pb}^{-1}$ LHC data — demand: > 10 events
2. Cannot be seen with $10\,\mathrm{fb}^{-1}$ Tevatron data — demand: < 10 events
3. Yield clean, virtually background-free signatures — demand: some e, μ
4. Consistent with other existing bounds

- Need to compare rates at LHC vs. Tevatron: for $N_{\mathrm{LHC}} \gtrsim N_{\mathrm{TEV}}$, roughly

$$\frac{(\mathcal{L} \times \sigma \times \mathrm{Br} \times \mathrm{Eff})_{\mathrm{LHC}}}{(\mathcal{L} \times \sigma \times \mathrm{Br} \times \mathrm{Eff})_{\mathrm{TEV}}} \sim \frac{(\mathcal{L} \times \sigma)_{\mathrm{LHC}}}{(\mathcal{L} \times \sigma)_{\mathrm{TEV}}} \Rightarrow \text{ need: } \frac{\sigma_{\mathrm{LHC}}}{\sigma_{\mathrm{TEV}}} \gtrsim \frac{\mathcal{L}_{\mathrm{TEV}}}{\mathcal{L}_{\mathrm{LHC}}}$$

Cross sections at LHC vs. Tevatron

$$N_{\rm events} = \mathcal{L} \times \sigma \times {\rm Br} \times {\rm Eff}$$



- Early LHC discovery: (with $10\,{\rm pb}^{-1}$)

$$N_{\rm events}^{\rm LHC} \geq 10$$

$\sigma > 1\,{\rm pb}$ — mostly SM processes

$10\,{\rm pb}^{-1}$ is a lot of data!

- Early first LHC discovery:

$$N_{\rm events}^{\rm TEV} \leq 10$$

$10000\,{\rm pb}^{-1}$ is really a lot of data!

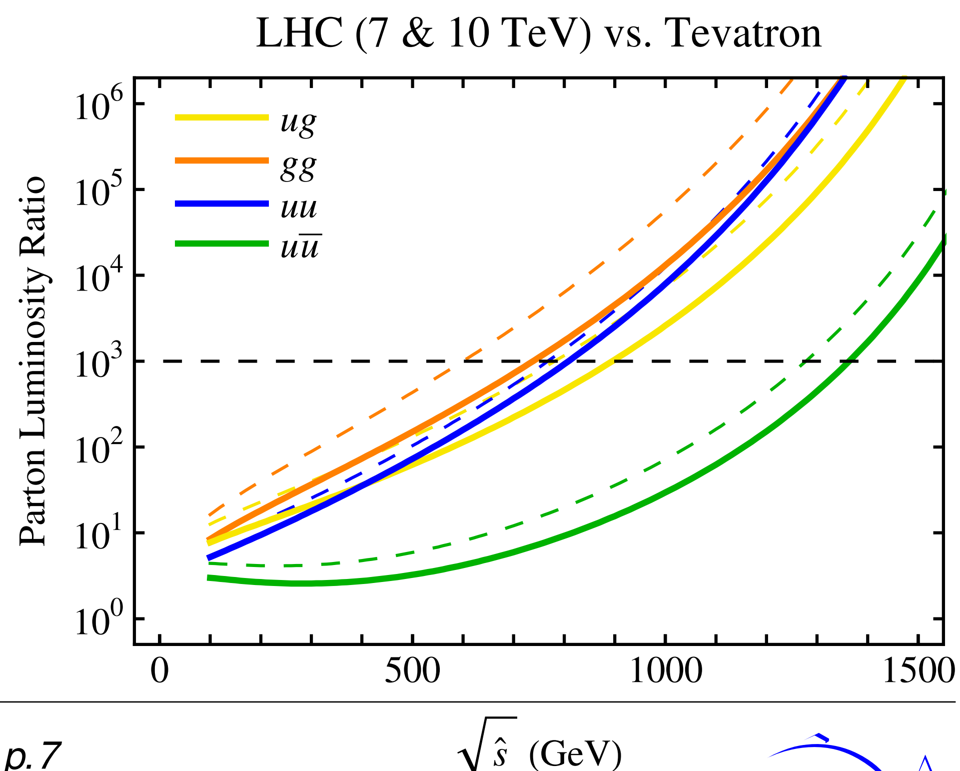
- Three orders of magnitude increase from $2 \rightarrow 10\,{\rm TeV}$ is actually possible

Parton luminosities at LHC vs. Tevatron

- Recall: $$\frac{d\sigma}{d\hat{s}} = \sum_{ij} \underbrace{\hat{\sigma}_{ij}(\hat{s})}_{\text{collider indep.}} \times \underbrace{\int_0^1 dx_i\, dx_j\, f_i(x_i)\, f_j(x_j)\, \delta(\hat{s} - x_i x_j s)}_{\text{process independent}}$$
  "parton luminosity" $\equiv \mathcal{F}_{ij}(s, \hat{s})$
- If one partonic ij channel and narrow $\hat{s}$ range dominate: $\frac{\sigma_{\text{LHC}}}{\sigma_{\text{TEV}}} \simeq \frac{\mathcal{F}_{ij}(s_{\text{LHC}}, \hat{s})}{\mathcal{F}_{ij}(2\,\text{TeV}, \hat{s})}$
- LHC wins for sufficiently large $\hat{s}$ (partonic center-of-mass energy)

  In gg, gq, qq channels above ~ 800 GeV, but in $q\bar{q}$ only above ~ 1.3 TeV

  (Plots use CTEQ-5L parton distributions; MSTW 2008 gives compatible results at this level)

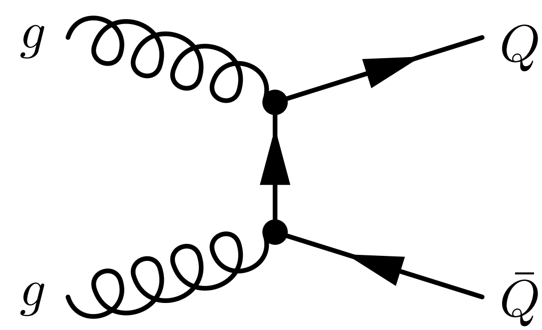


New physics scenarios

First attempt: QCD pair production

- “Well-known”: LHC $=$ gluon collider $\Rightarrow$ QCD pair production (large gg channel)

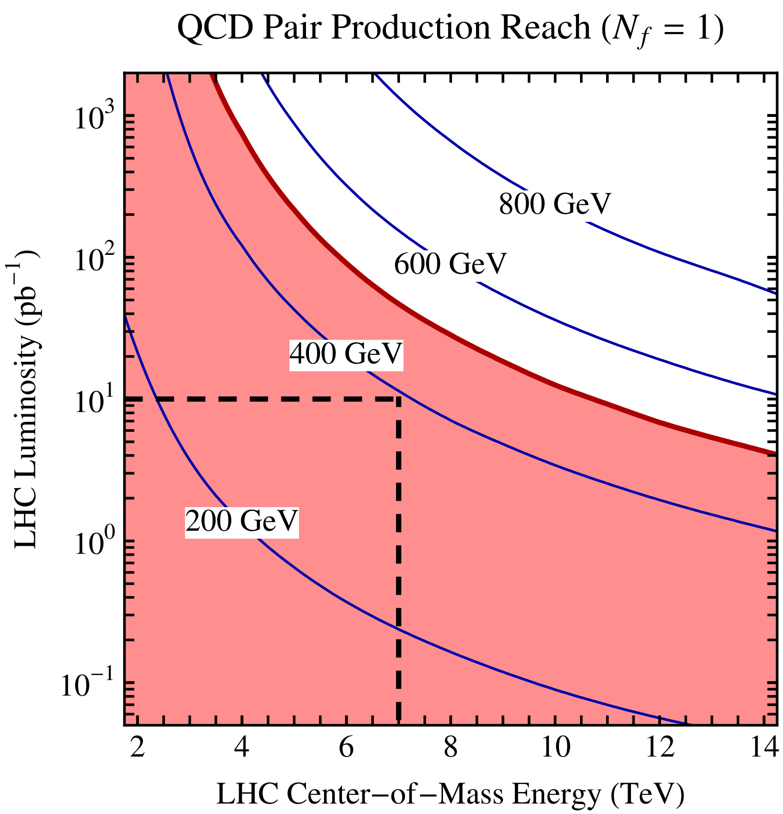
1. $N_{\rm LHC} > 10$
   Yes! $1\,\rm pb$ @ $10\,\rm TeV$ for $500\,\rm GeV$ pairs
2. $N_{\rm TEV} < 10$
   Need to check (next slide)
3. Highly visible final state?
   Need model building (in two slides)
4. Satisfies other bounds
   Can be arranged, believe me...

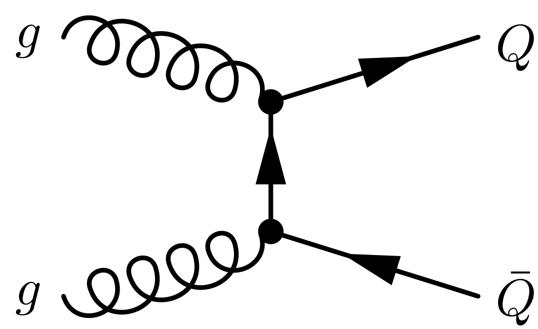


First attempt: QCD pair production

- "Well-known": LHC $=$ gluon collider $\Rightarrow$ QCD pair production (large gg channel)

  1. $N_{\rm LHC} > 10$, 2. $N_{\rm TEV} < 10$





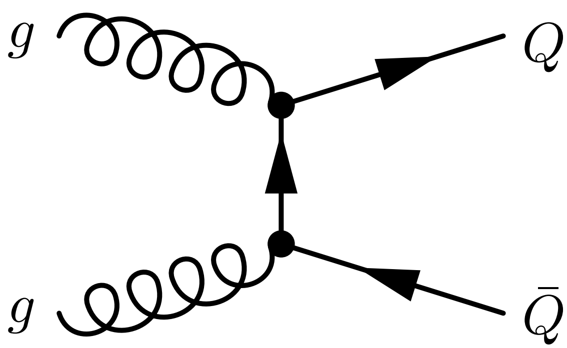
- Not a supermodel for $7\,{\rm TeV}$ LHC with $10\,{\rm pb}^{-1}$, but it may be for $100\,{\rm pb}^{-1}$

First attempt: QCD pair production

- “Well-known”: LHC $=$ gluon collider $\Rightarrow$ QCD pair production (large gg channel)

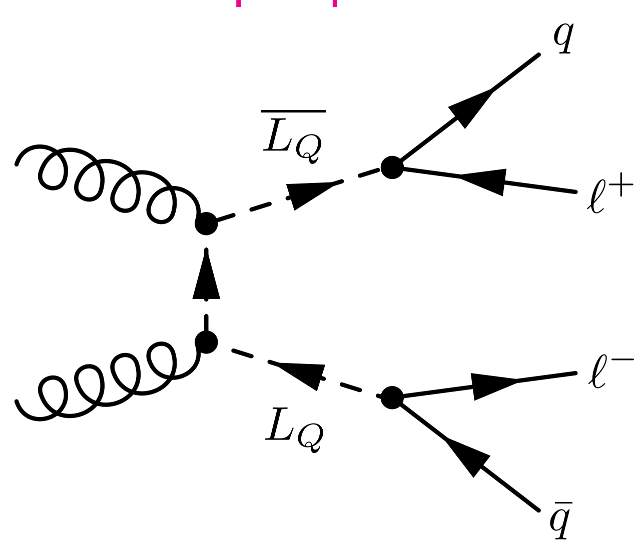
  3. Highly visible final state? Background free?

Stable “quarks”



several variants, R-hadrons

Leptoquarks



2 jets $+2$ leptons w/ QCD cross section

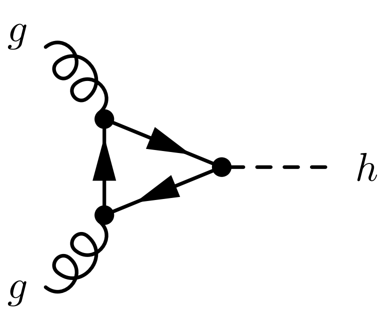
- These can occur with near 100% branching ratios

Do better: resonances and couplings

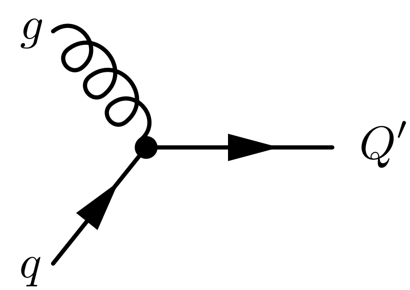
- Phase space factor for final state particles: $\prod_{i=1}^{n} \frac{\mathrm{d}^3 p_i}{(2\pi)^3\, 2E_i} \;\Rightarrow\; \left(\frac{1}{16\pi^2}\right)^n$
- Focus on single resonance production (like Z at LEP)

Our “notation”:

$q\bar{q}$	“Z'”	qq	“Diquark”	$\leftarrow$ renormalizable couplings
gg	“Higgs”	qg	“Excited quark”	$\leftarrow$ nonrenormalizable couplings



Loop $\Rightarrow \frac{1}{16\pi^2}\,\frac{1}{M}$

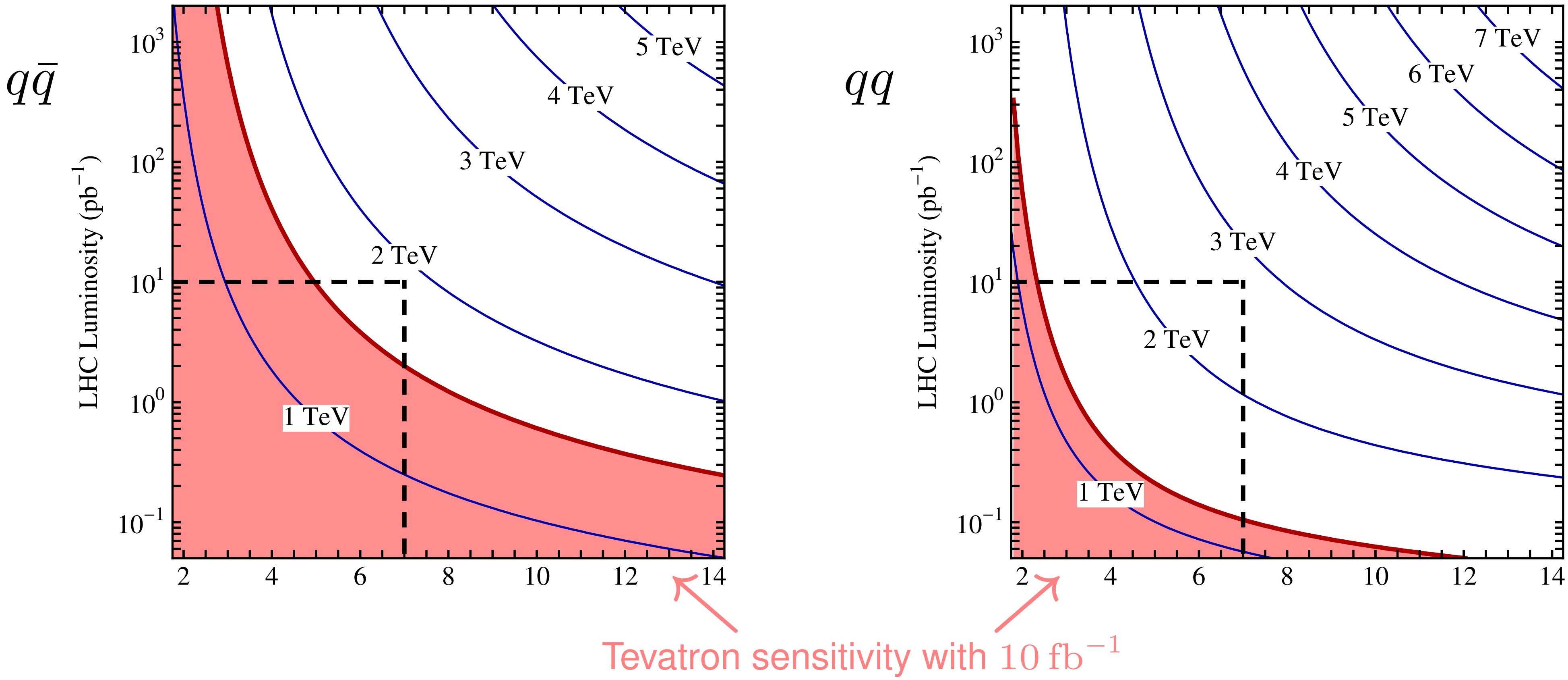


$\overline{Q'} i \not{D} q$ not gauge invariant $\Rightarrow \frac{1}{\Lambda}\, \overline{Q'}\, \sigma_{\mu\nu} G^{\mu\nu} q$

if weakly coupled: $\Lambda \sim 16\pi^2 M$

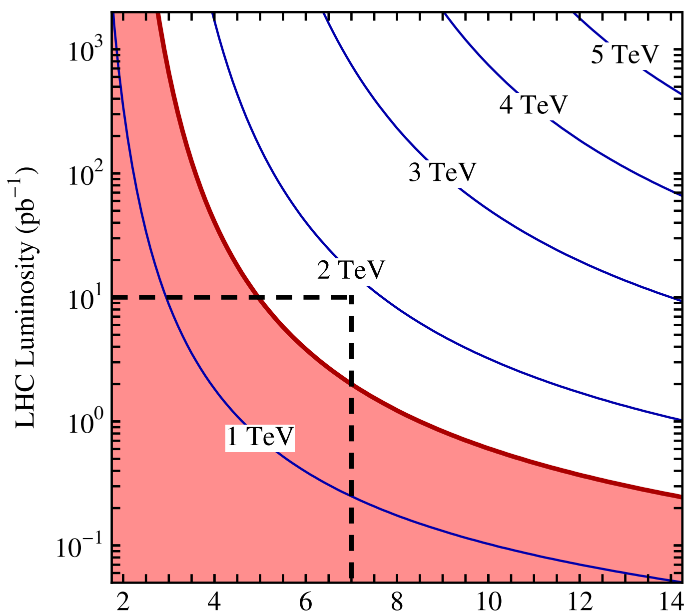
- Both gg and qg: some suppressions of couplings — weaken LHC’s advantage

LHC vs Tevatron reach



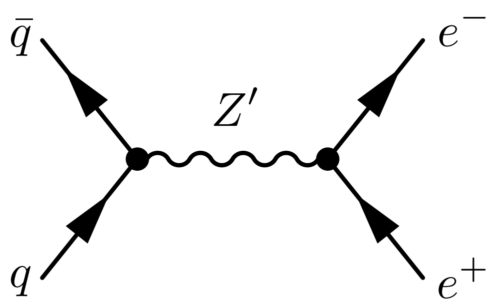
- LHC's advantage is the greatest in the qq resonance channel

$q\bar{q}$ resonances

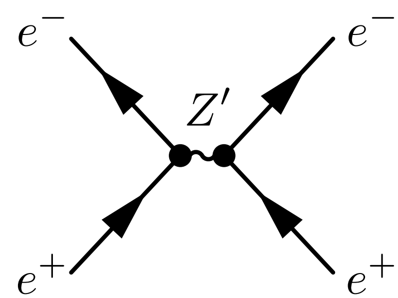


Z' bosons (recall from before)

- LHC production:

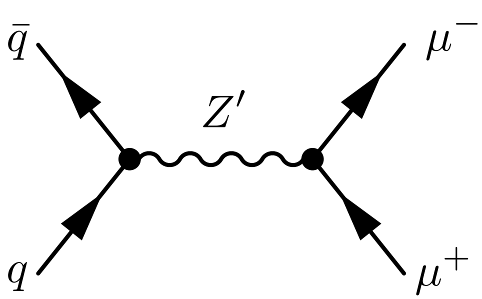


LEP bound:



To avoid LEP bounds, no flavor-universal $g_{q,\ell}$ values allow Z' to be a supermodel production: $\sigma(q\bar{q} \to Z') \propto g_q^2$, decay: $\mathcal{B}(Z' \to \ell^+\ell^-) \propto g_\ell^2/(\alpha g_\ell^2 + 6g_q^2)$

- Imagine an electrophobic Z' to suppress $\mathcal{B}(Z' \to e^+e^-)$, e.g., $B - 3L_\mu$ boson:

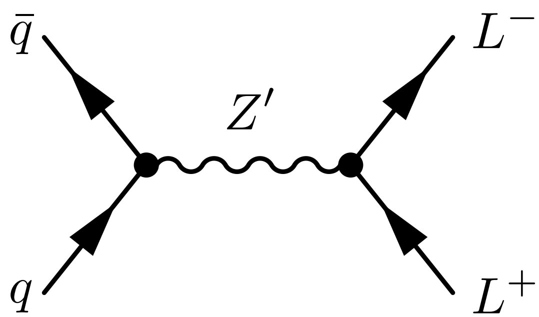


A supermodel, but it ain't pretty...

[Salvioni, Strumia, Villadoro, Zwirner, 0911.1450]

Z' decays to exotic stuff

- Simplest idea: the Z' decays to two new stable leptons

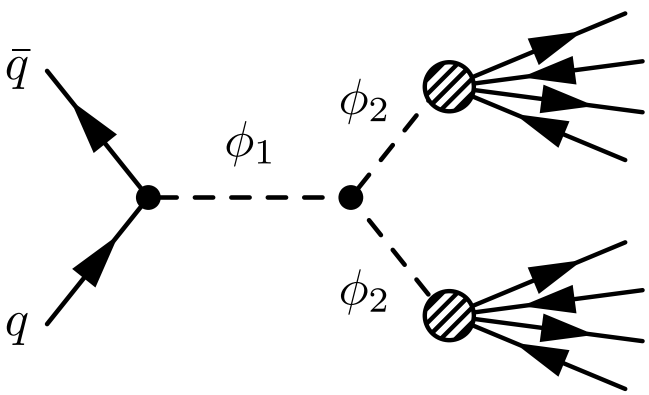


Can have large branching fraction

No FCNC bounds

Cosmologically safe if late decay

- Could encounter Hidden Valley type topologies at $10\,\mathrm{pb}^{-1}$

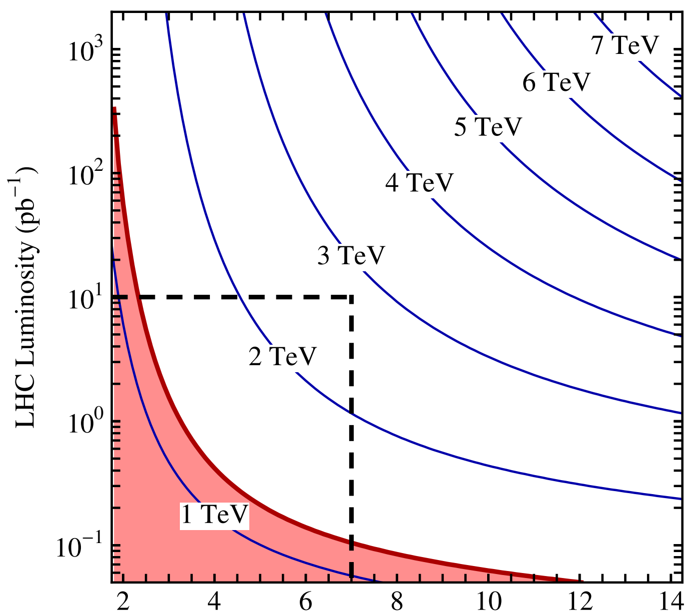


Large $\phi_1\phi_2\phi_2$ coupling for large branching fraction

Small couplings at ϕ_2 decay, so it hasn't been discovered yet

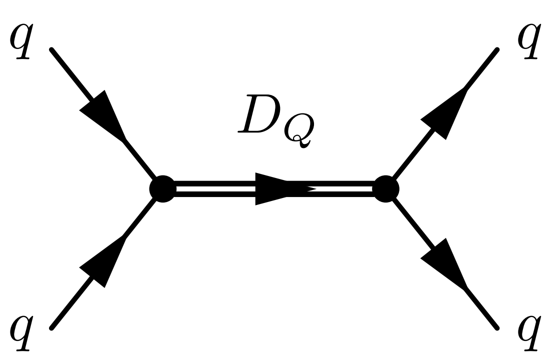
Unlikely to be easily reconstructible

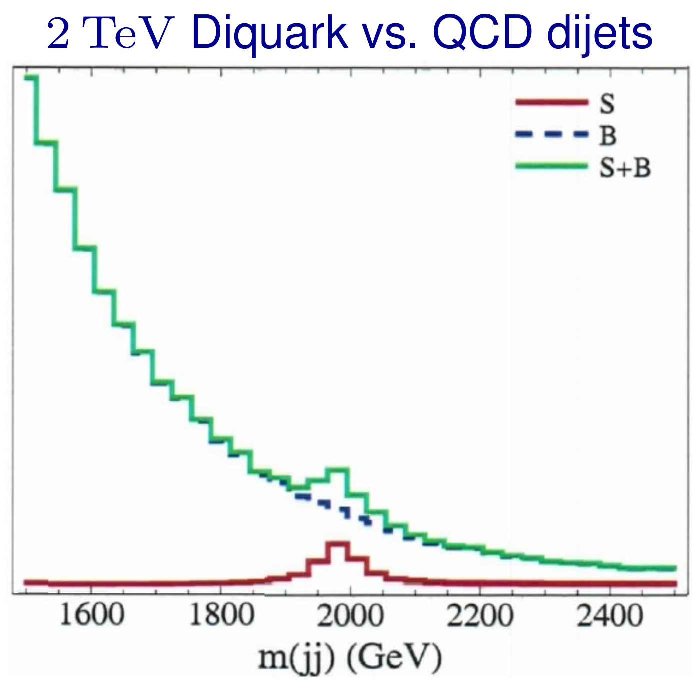
qq resonances — “diquarks”



Diquark resonances

- Enormous cross sections possible — simplest decay is back to a pair of jets:





- The dijet final state might be difficult in the early data [Next two talks]

E.g., superstring inspired E_6 GUTs contain/predict diquarks [Angelopoulos et al., NPB 292 (1987) 59]

Flavor bounds can be satisfied

- Can impose MFV to satisfy flavor bounds

V – XIV are various diquark states

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$	Couples to
I	1	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R \ Q_L$
II	8	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R \ Q_L$
III	1	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R \ Q_L$
IV	8	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R \ Q_L$
V	3	1	-4/3	$(3,1,1)$	$u_R \ u_R$
VI	$\bar{6}$	1	-4/3	$(\bar{6},1,1)$	$u_R \ u_R$
VII	3	1	2/3	$(1,3,1)$	$d_R \ d_R$
VIII	$\bar{6}$	1	2/3	$(1,\bar{6},1)$	$d_R \ d_R$
IX	3	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R \ u_R$
X	$\bar{6}$	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R \ u_R$
XI	3	1	-1/3	$(1,1,\bar{6})$	$Q_L \ Q_L$
XII	$\bar{6}$	1	-1/3	$(1,1,3)$	$Q_L \ Q_L$
XIII	3	3	-1/3	$(1,1,3)$	$Q_L \ Q_L$
XIV	$\bar{6}$	3	-1/3	$(1,1,\bar{6})$	$Q_L \ Q_L$

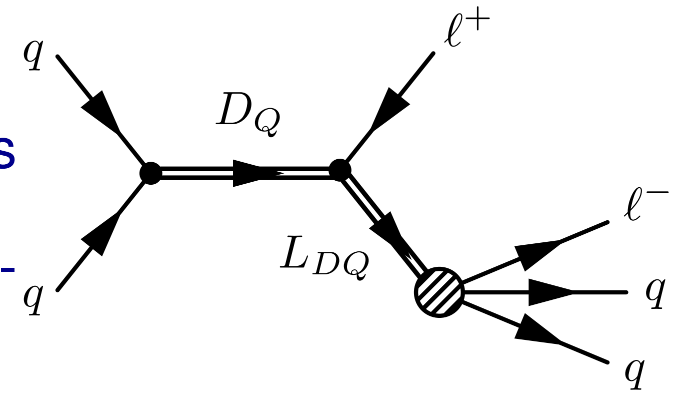
[Arnold, Pospelov, Trott, Wise, 0911.2225]

A Diquark Supermodel

- Squeezing leptons from diquarks...

  Dilepton edge, corresponding to D_Q and L_{DQ} masses

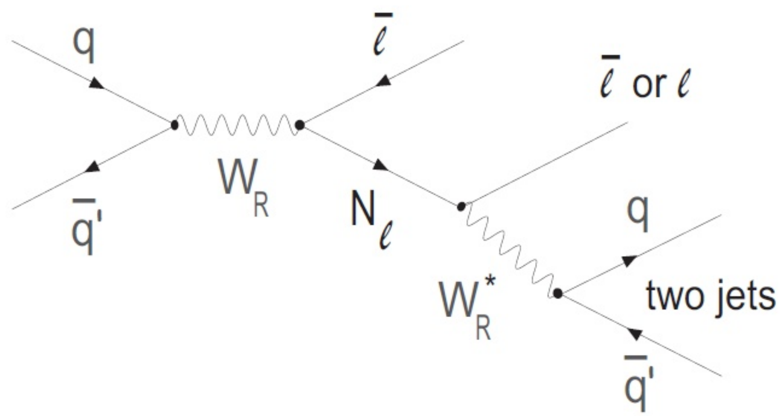
  In simplest scenario, L_{DQ} decays via production diagram (off-shell D_Q)



- Signature: $\ell^+\ell^-$ with a high mass edge + 2 jets (color cons.)

- The identical $2j + \ell^+\ell^-$ channel is well-studied for "more motivated" searches
- The same final state is the classic signature of left-right symmetric models

  Discovering a W_R @ $2\,\mathrm{TeV}$ requires $\gtrsim 1\,\mathrm{fb}^{-1}$



[Aad *et al.*, ATLAS Collaboration, 0901.0512]

- With diquarks, interesting search at $10\,\mathrm{pb}^{-1}$

Ways to get around our conclusions

- Possibilities we did not consider:

  (i) Nonperturbative couplings

  (ii) Pair production enhanced by high particle multiplicities

  (iii) Comparing to published Tevatron bounds (some of which only use $\sim 100\,\mathrm{pb}^{-1}$)

  (iv) The early LHC data used for analysis approaches / goes beyond $100\,\mathrm{pb}^{-1}$

- E.g.: CMSSM regions recently discussed with discovery potential with $< 100\,\mathrm{pb}^{-1}$ contain particles right at their exclusion limits

  (ii) color factors help; (iii) Tevatron bounds can be improved

  Agree that QCD pair production w/ $50\,\mathrm{pb}^{-1}$ is promising in optimal circumstances

With $\mathcal{O}(10\,\mathrm{pb}^{-1})$ of early LHC data...

...can we really expect to probe new physics?

Yes! Supermodels!

Conclusions

- Big difference in discovery potential of 10s and 100s of pb^{-1} data
- Limited reach for SUSY (except if right at exclusion limits), Higgs, little Higgs, ...
- Substantial reach for Supermodels — two representative examples:

$10\,\mathrm{pb}^{-1}$: Diquark $\to 2j$ or $2j + \ell^+\ell^-$, etc. — true supermodels

(high mass lepton edge, extra hard jets, no missing energy)

$100\,\mathrm{pb}^{-1}$: $Z' \to L^+L^-$

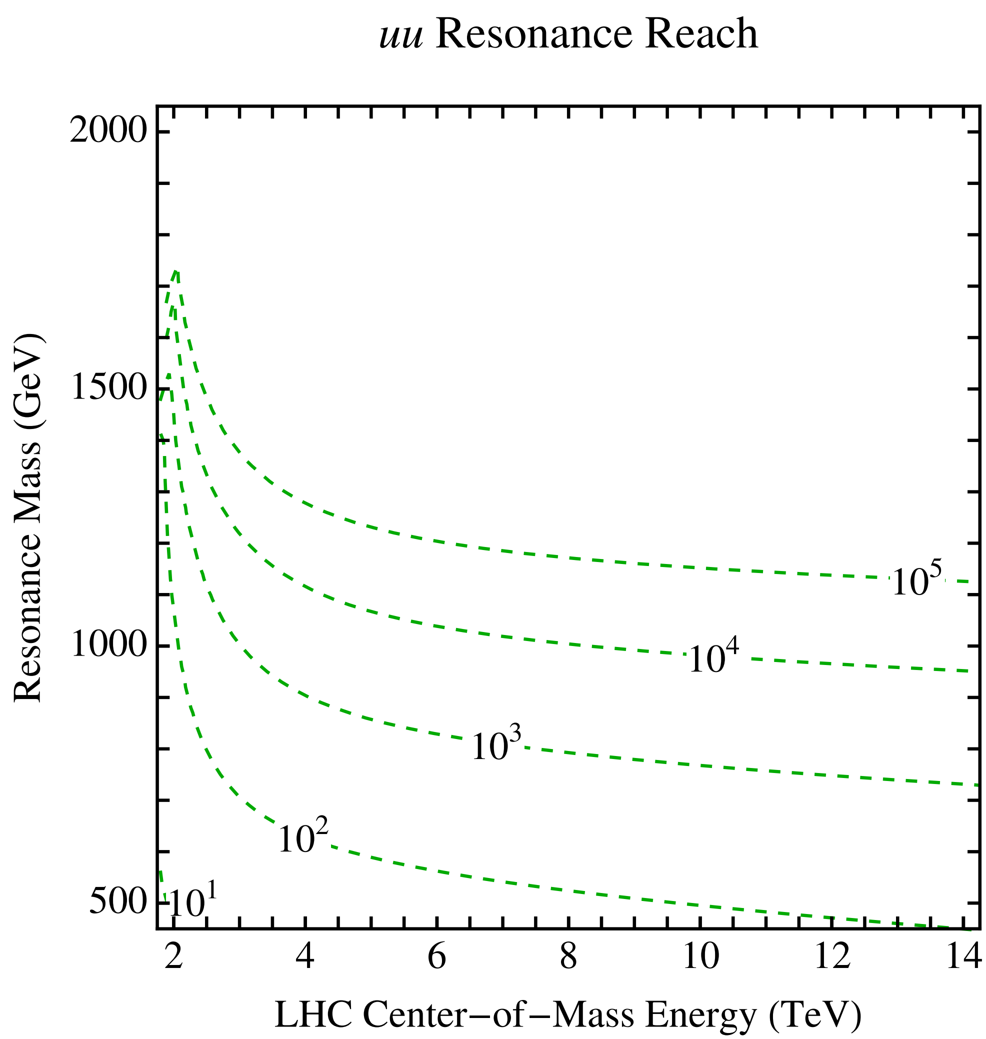
(stable charged particles, not necessarily slow)

- Good benchmarks for later searches — generic new physics signatures, plus actual Lagrangians to make it interesting in early data
- With $\gtrsim 100\,\mathrm{pb}^{-1}$ good data, significant discovery reach for "motivated" models

Backup Slides

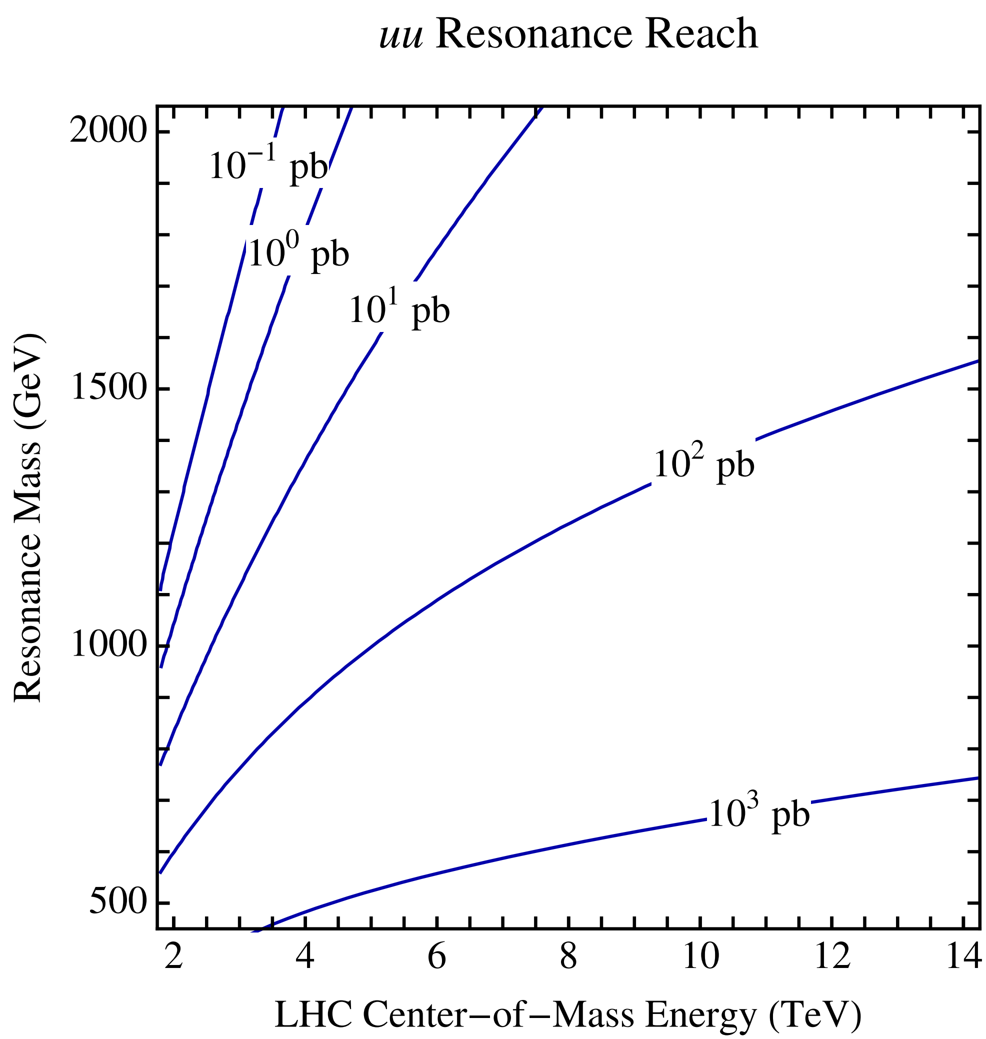
Supermodel parameter space

- Cross section ratio: $\sigma_{\rm LHC}/\sigma_{\rm TEV} > 10^3\ [10^2]$ for LHC with $10\,{\rm pb}^{-1}\ [100\,{\rm pb}^{-1}]$



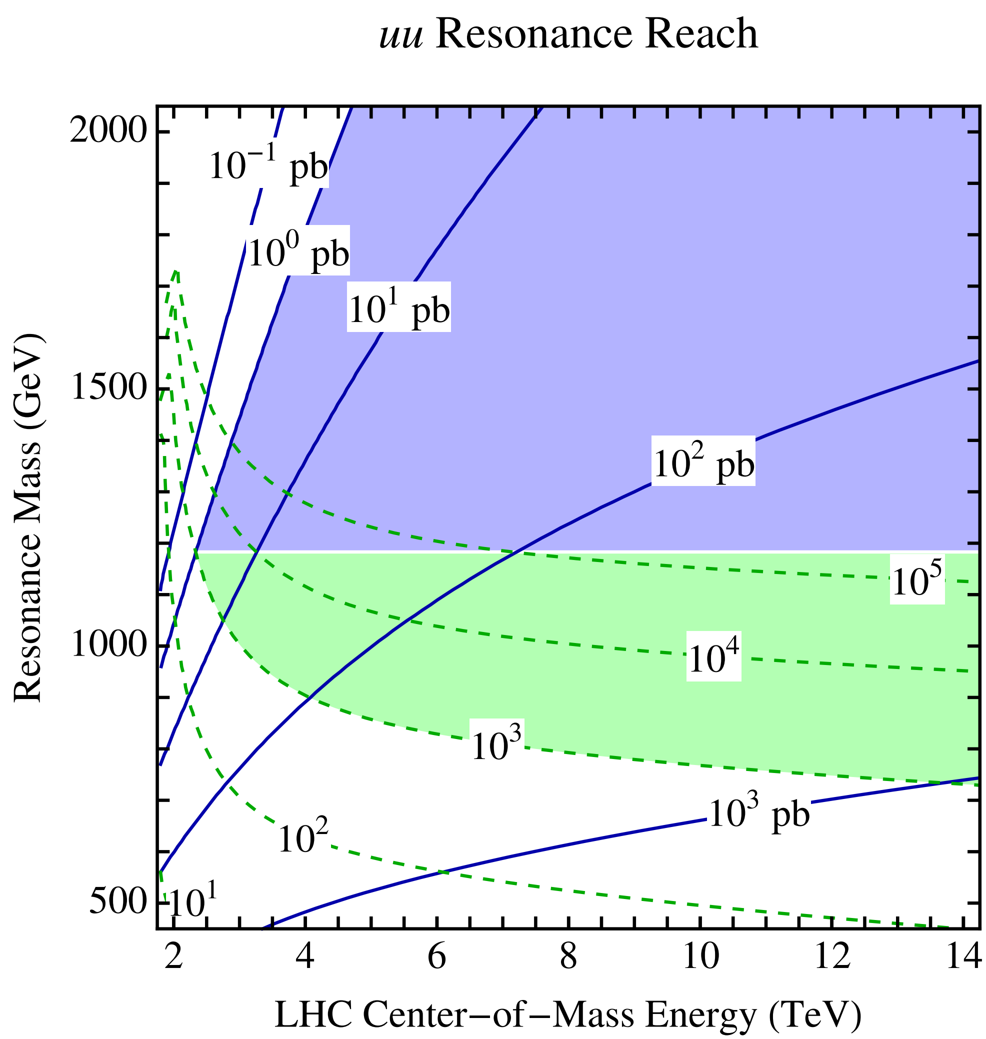
Supermodel parameter space

- At least 10 events: $\sigma_{\rm LHC} > 10^0\,{\rm pb}$ for $10\,{\rm pb}^{-1}$ (can scale w/ ${\rm Br} \times {\rm Eff}$ in a model)



Supermodel parameter space

- Combining both conditions:



Sanity check: sequential Z'

- In this case $g^2_{\rm eff} \times {\rm Br} \times {\rm Eff} \sim 0.01$, "predicts" a $1\,{\rm fb}^{-1}$ Tevatron bound about $1\,{\rm TeV}$