Szupermodellek: Korai új fizika az LHC-nél?

Ligeti Zoltán

arXiv:0909.5213

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

- Introduction

  ... early LHC plans and expectations

- Resonance scenarios

  ... parton luminosities, couplings, rates

- Some model building

  ... Z's, diquarks, promising final states

- Conclusions

Disclaimers

Main Entry: **su·per·mod·el**

Pronunciation: \'sü-pər-ˌmä-dᵊl\

Function: *noun*

Date: 1977

: a famous and successful fashion model

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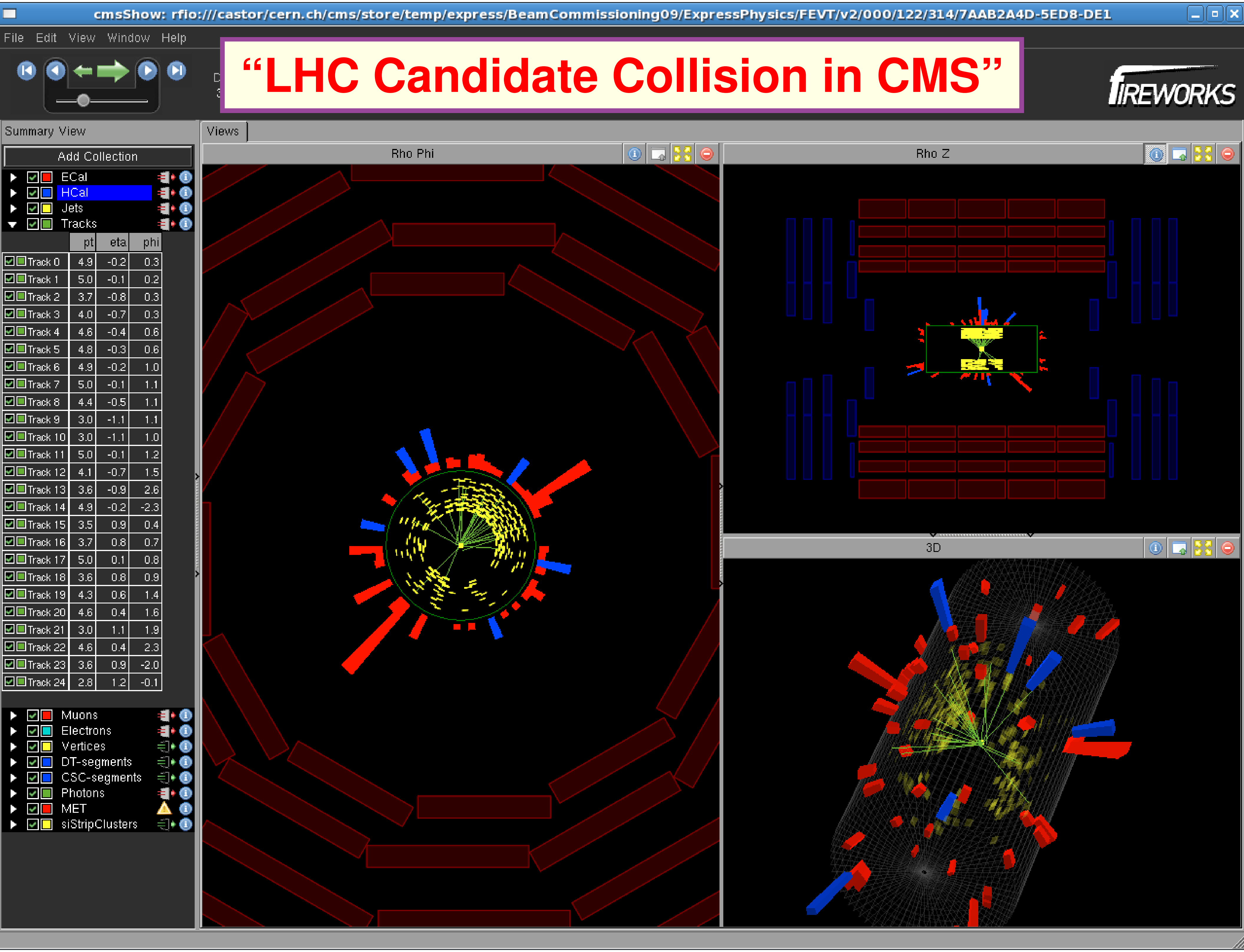
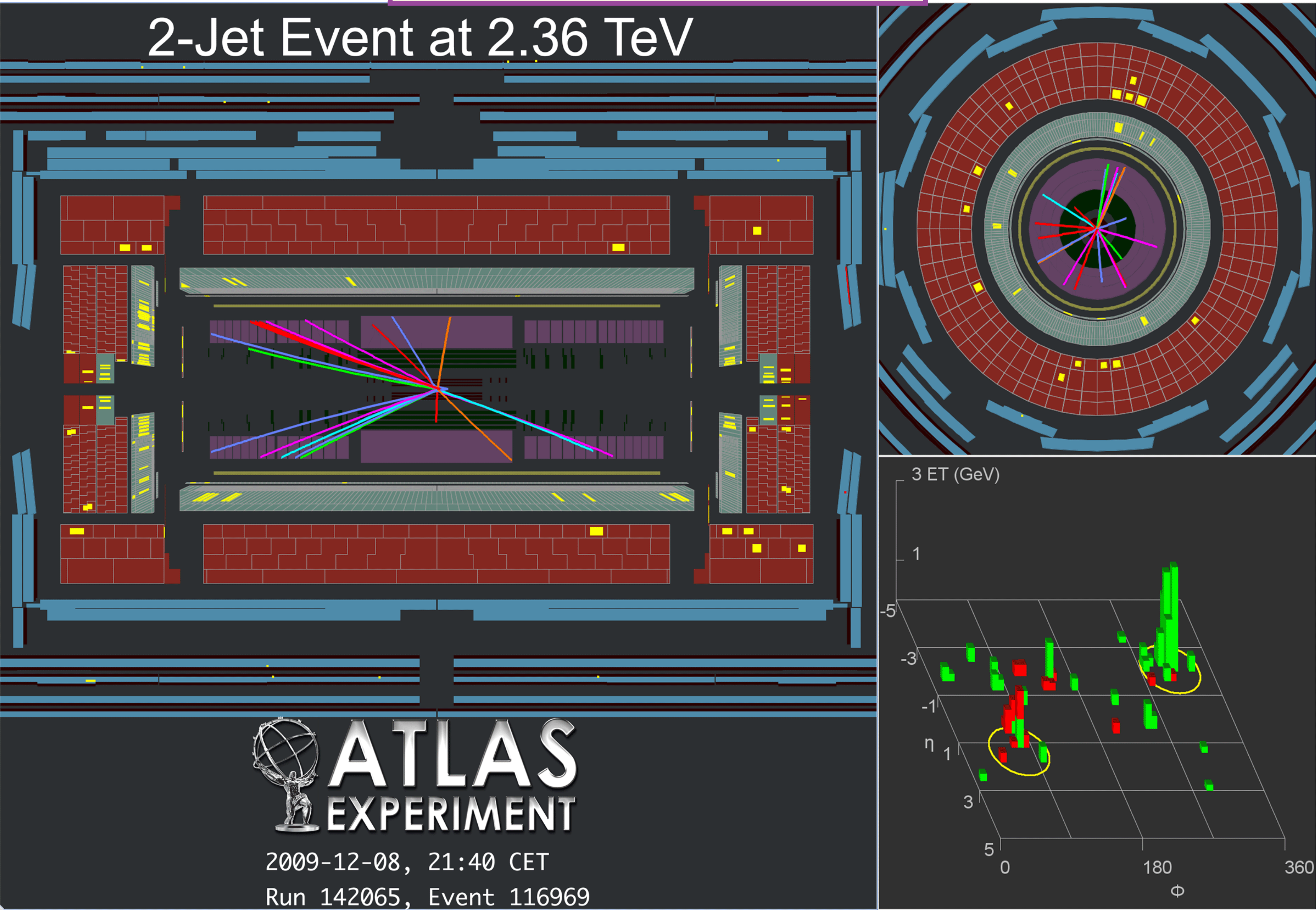
"... allow ourselves to contemplate new physics which is not motivated by model building goals such as unification, weak scale dark matter, or solving the hierarchy problem"

⇒ "I do not see how the course of physics could be affected by the existence of this paper"

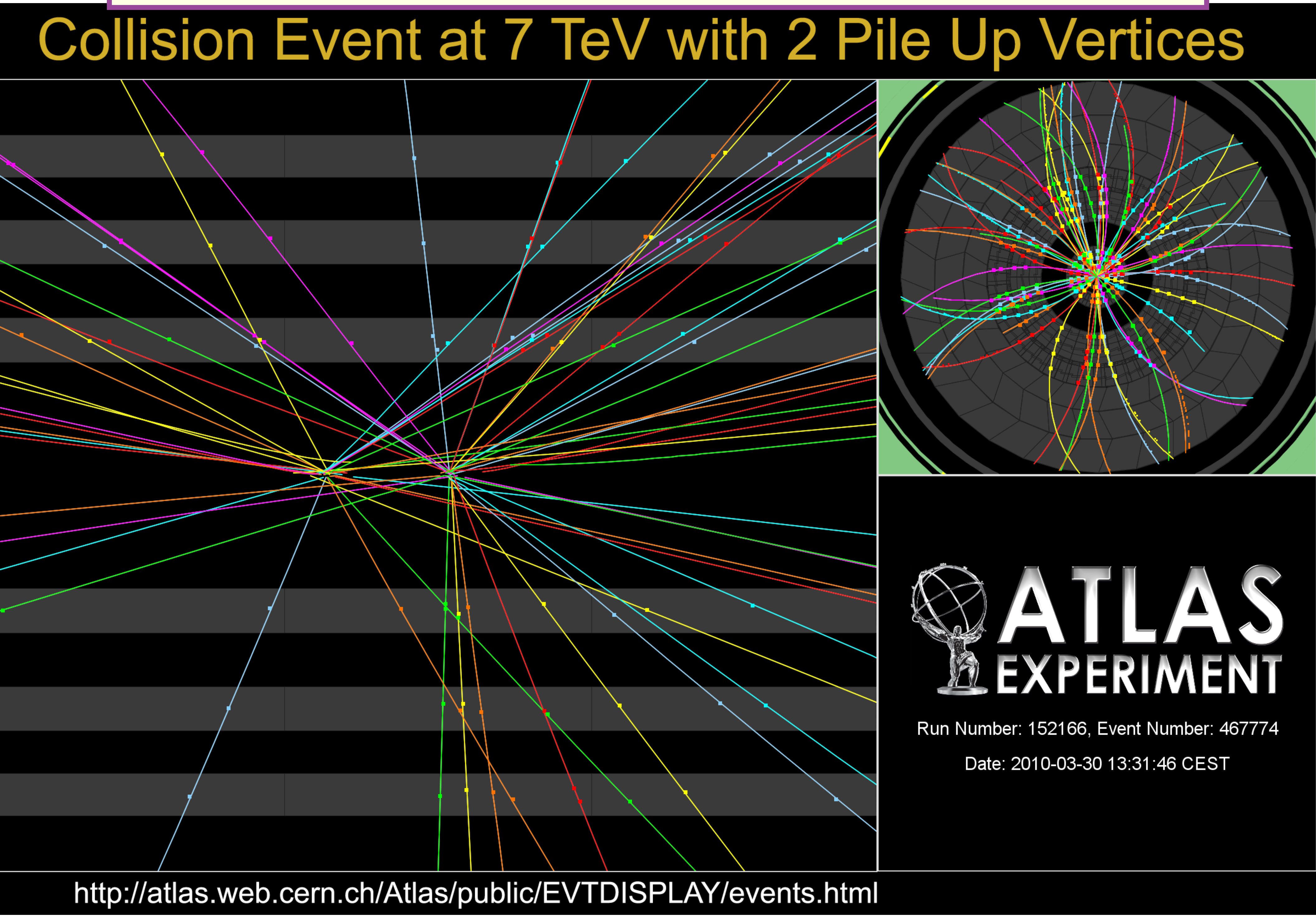
“LHC Candidate Collision in CMS”



An ATLAS dijet event

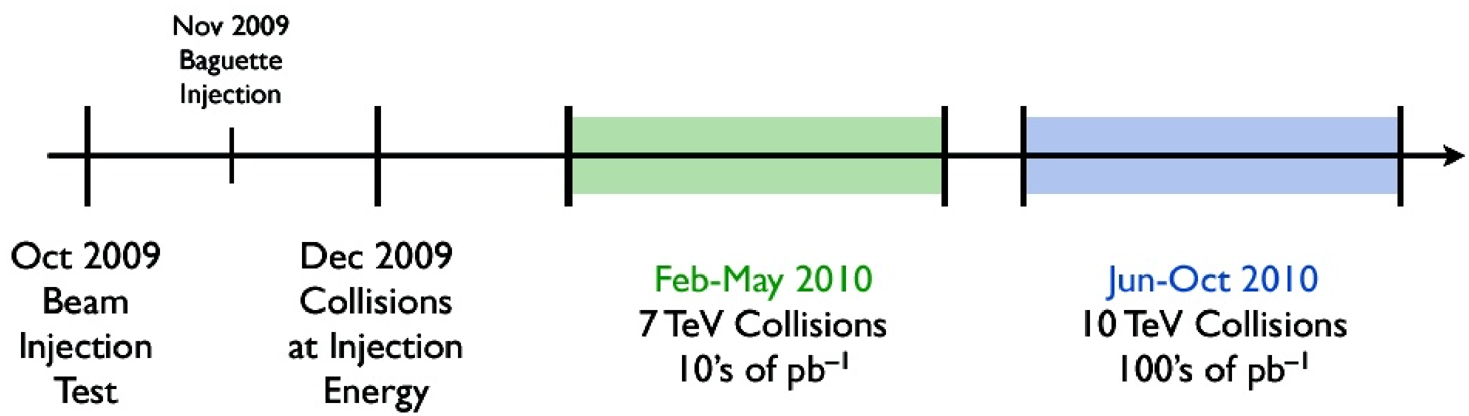


Yesterday: 7 TeV collisions, $\mathcal{L} < 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Early LHC timeline

- I stopped updating this slide...



- Usable luminosity $\stackrel{?}{\neq}$ delivered luminosity

$\Downarrow$

- Assume, pessimistically: $7-10\,\mathrm{TeV},\ 10\,\mathrm{pb}^{-1}$ (“low”)

  $100\,\mathrm{pb}^{-1}$ (“high”)

- The LHC luminosity and energy will depend on the behavior of the accelerator as the run progresses — substantial uncertainty in predictions

Q: Can the LHC with $< 100\,\mathrm{pb}^{-1}$ discover new physics?

A_0: No way...

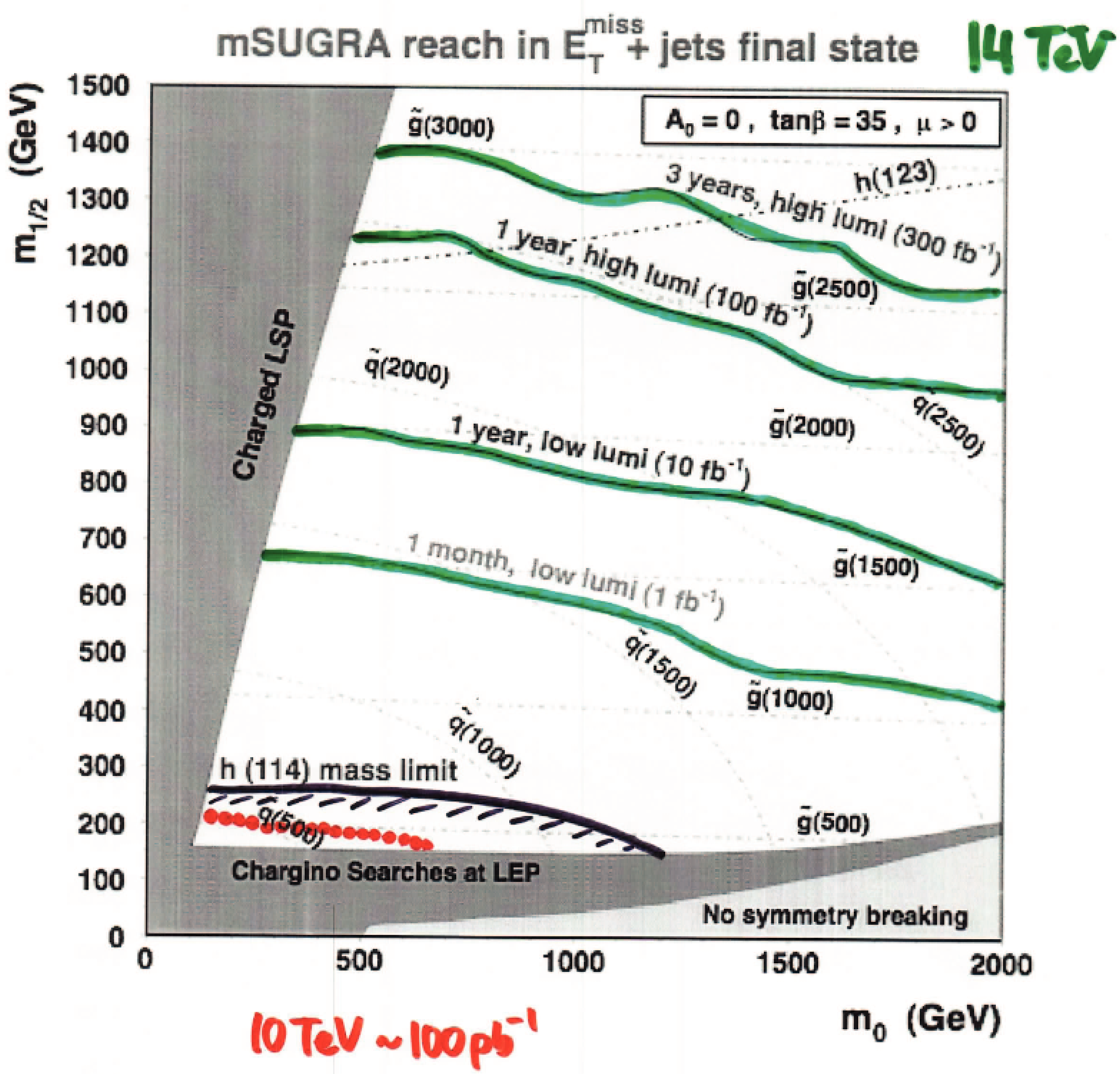
- Looking at practically any of the existing SUSY studies:

  Early LHC = "Engineering Run"

- Other possible answers:
- Good search at $10\,\mathrm{fb}^{-1}$ = Good search at $10\,\mathrm{pb}^{-1}$

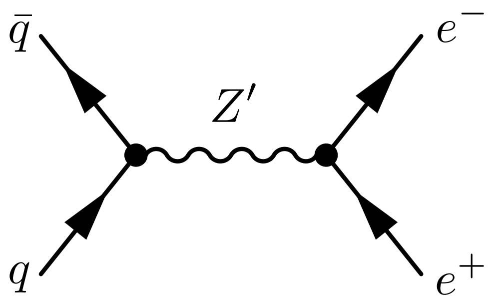
  Probes an actual Lagrangian?
- Lots of searches have not been done before

  Better to do at well-understood Tevatron detectors?

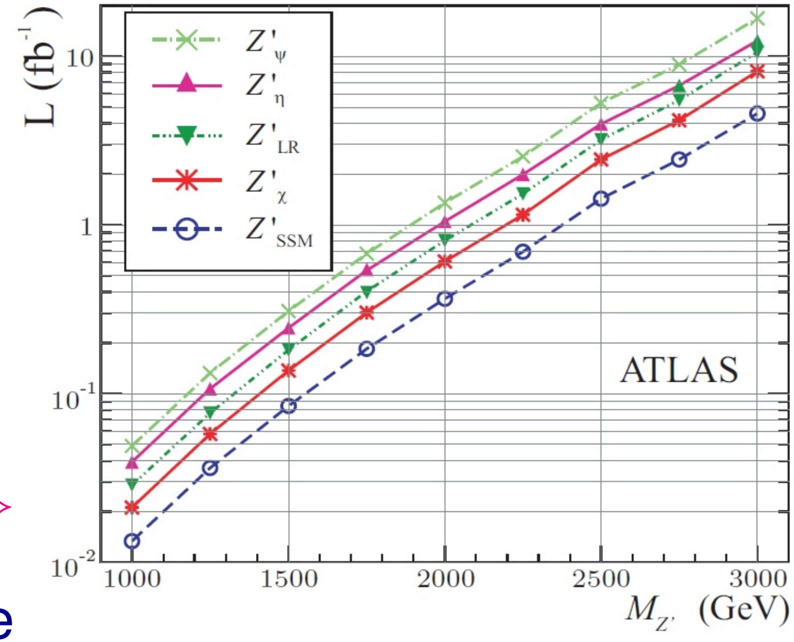


A$_1$: Yes – can find Z' bosons

- Can clearly superseed the Tevatron sensitivity



Integrated luminosity needed for 5σ discovery $\Rightarrow$

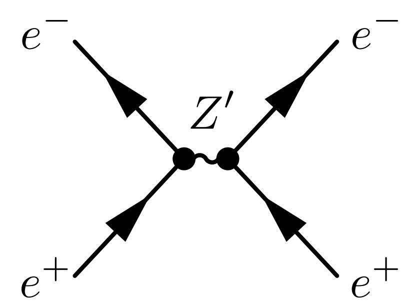


[Aad *et al.*, ATLAS Collaboration, 0901.0512]

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

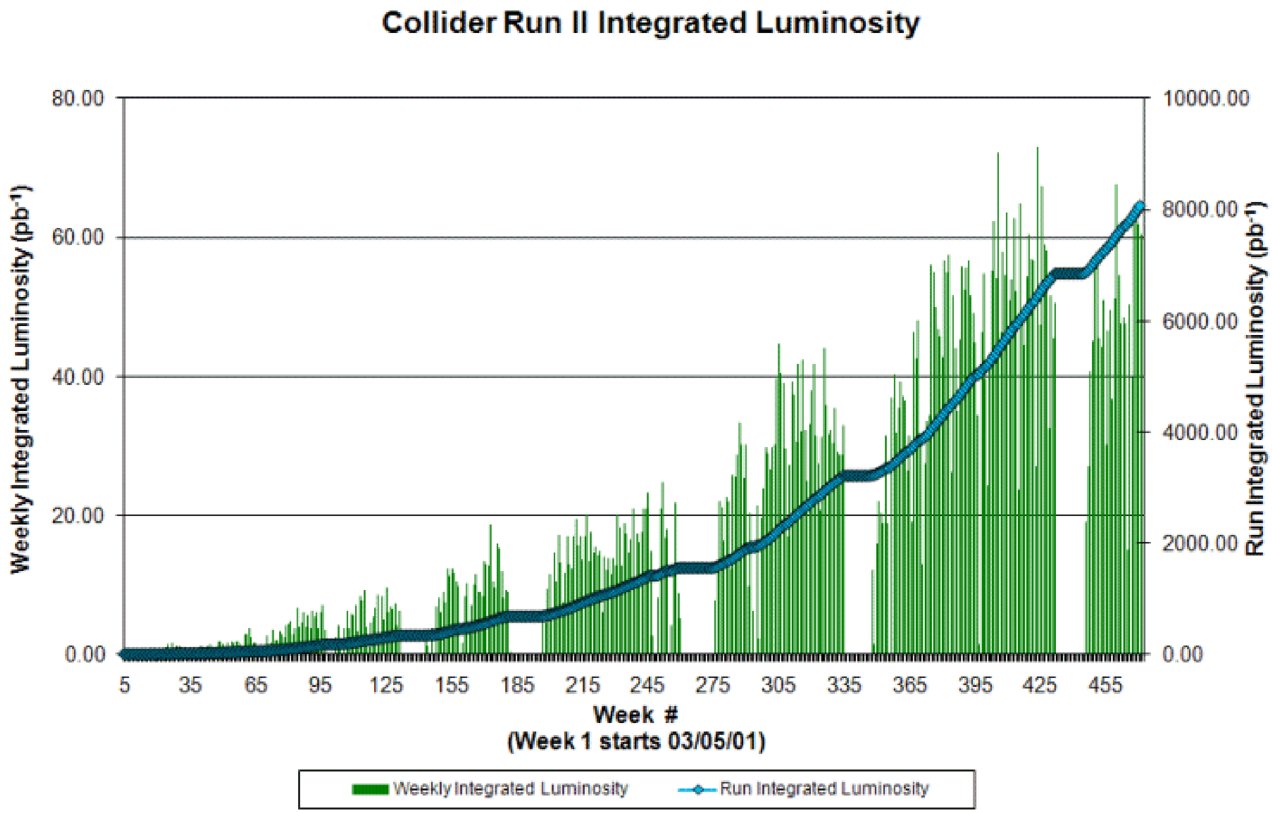
- Could new physics be first discovered in early LHC? (beyond Tevatron, LEP, etc.)
- Want to identify actual Lagrangians that:

1. Can be seen with $10\,\mathrm{pb}^{-1}$ LHC data
2. Cannot be seen with $10\,\mathrm{fb}^{-1}$ Tevatron data
3. Yield clean, virtually background-free signatures
4. Consistent with other existing bounds

$\Rightarrow$ Need to compare production rates at the LHC and the Tevatron

The Tevatron is running well

- The Tevatron collects about $60\,\mathrm{pb}^{-1}$ / week, and can reach $10\,\mathrm{fb}^{-1}$ in 2010



- And CDF and DØ are well-understood detectors (jet energy scale, missing E_T, ...)

Cross sections

- Early LHC discovery:

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

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

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

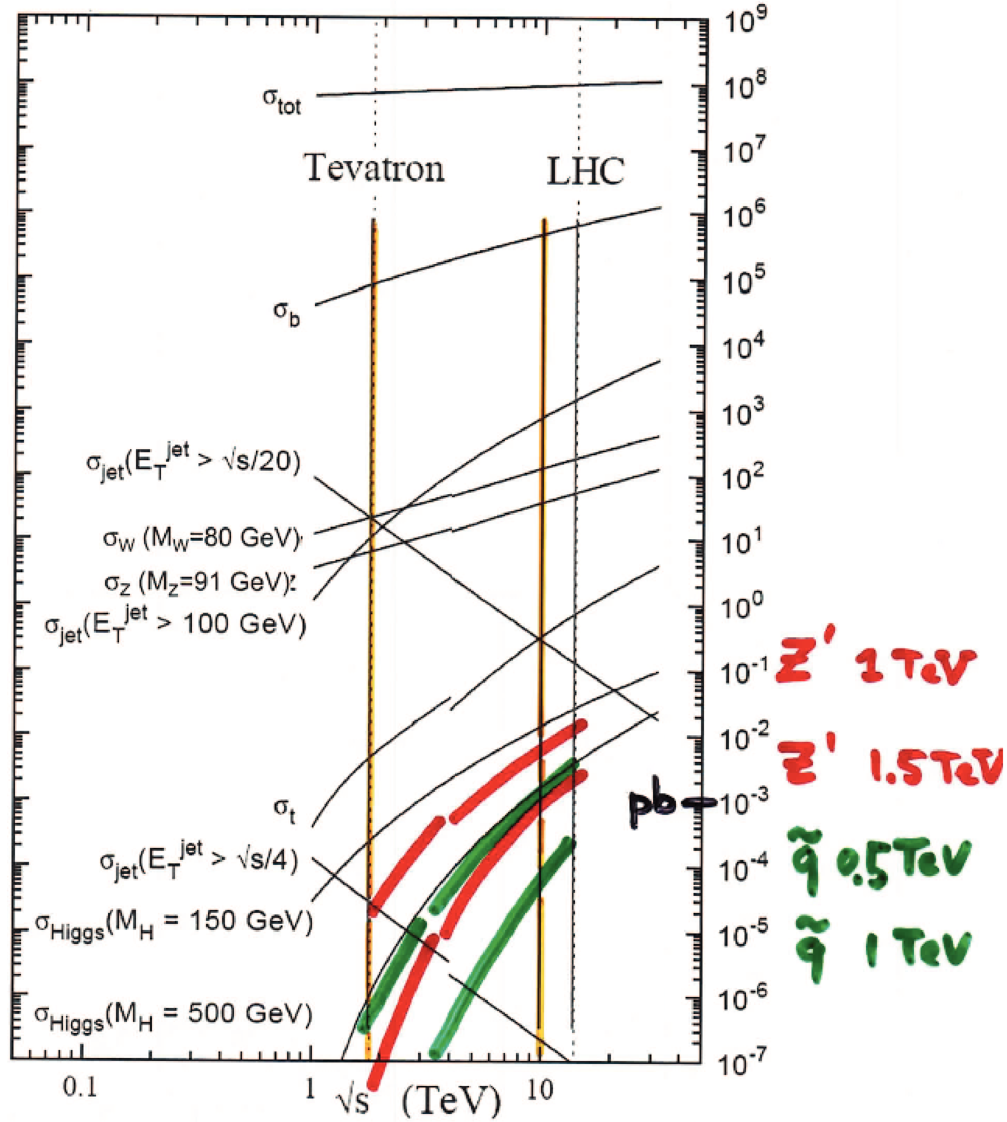
- Early first LHC discovery:

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

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

- Three orders of magnitude change from $2 \rightarrow 10\,\text{TeV}$ is indeed possible

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



How to beat the Tevatron

- "Easy" signature: leptons (detectors won't be very well understood early on)

$$N_{\rm LHC} \gtrsim 10 \quad \Rightarrow \quad \sigma \times {\rm Br} \gtrsim \begin{cases} 1\,{\rm pb} & \text{“low”} \\ 0.1\,{\rm pb} & \text{“high”} \end{cases}$$

- Better sensitivity at LHC than at Tevatron, LEP, etc., $N_{\rm LHC} \gtrsim N_{\rm TEV}$

$$\frac{(\mathcal{L} \times \sigma \times {\rm Br} \times {\rm Eff})_{\rm LHC}}{(\mathcal{L} \times \sigma \times {\rm Br} \times {\rm Eff})_{\rm TEV}} \sim \frac{(\mathcal{L} \times \sigma)_{\rm LHC}}{(\mathcal{L} \times \sigma)_{\rm TEV}} \quad \Rightarrow \quad \frac{\sigma_{\rm LHC}}{\sigma_{\rm TEV}} \gtrsim \frac{\mathcal{L}_{\rm TEV}}{\mathcal{L}_{\rm LHC}} = \begin{cases} 10^3 & \text{“low”} \\ 10^2 & \text{“high”} \end{cases}$$

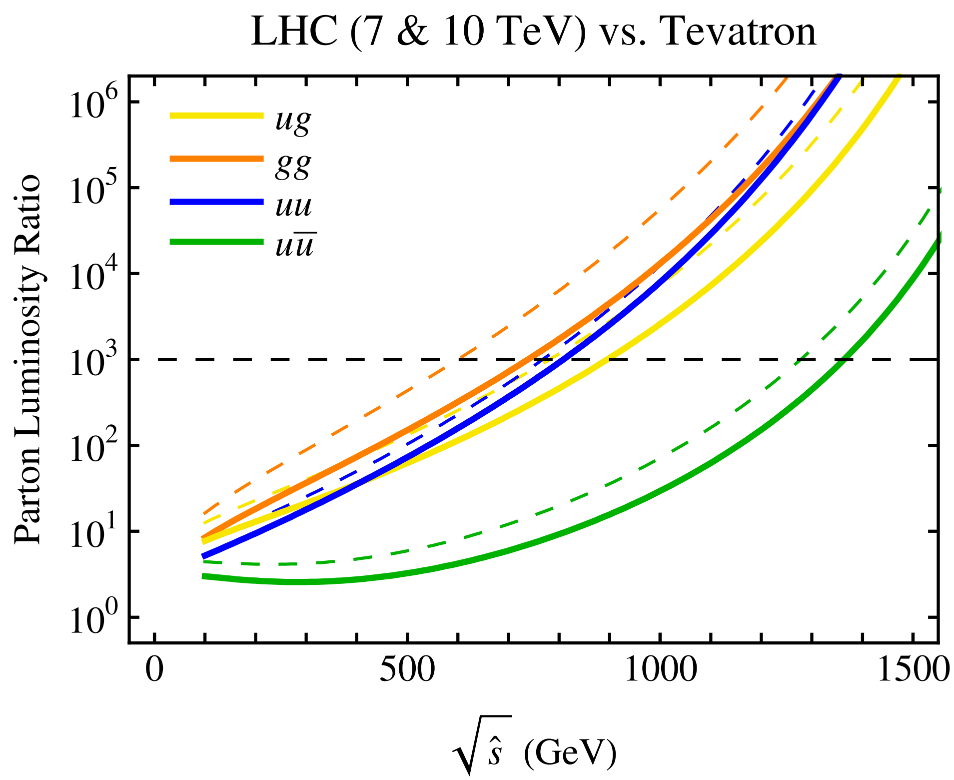
- Recall:

$$\frac{{\rm d}\sigma}{{\rm d}\hat{s}} = \sum_{ij} \underbrace{\hat{\sigma}_{ij}(\hat{s})}_{\rm collider\ indep.} \times \underbrace{\int_0^1 {\rm d}x_i\, {\rm d}x_j\, f_i(x_i)\, f_j(x_j)\, \delta(\hat{s} - x_i x_j s)}_{\rm process\ independent}$$

"parton luminosity" $\equiv \mathcal{F}_{ij}(s, \hat{s})$

- If one partonic ij channel and narrow $\hat{s}$ range dominate: $\displaystyle \frac{\sigma_{\rm LHC}}{\sigma_{\rm TEV}} \simeq \frac{\mathcal{F}_{ij}(s_{\rm LHC}, \hat{s})}{\mathcal{F}_{ij}(2\,{\rm TeV}, \hat{s})}$

Ratio of LHC / Tevatron parton luminosities



- LHC wins for sufficiently large $\hat{s}$ (partonic center-of-mass energy)

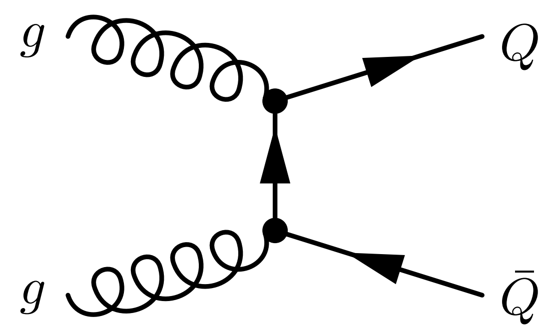
  In gg, gq, qq channels above $\sim 800\,\mathrm{GeV}$, in $q\bar{q}$ only above $\sim 1.3\,\mathrm{TeV}$

Resonance scenarios

First supermodel attempt

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

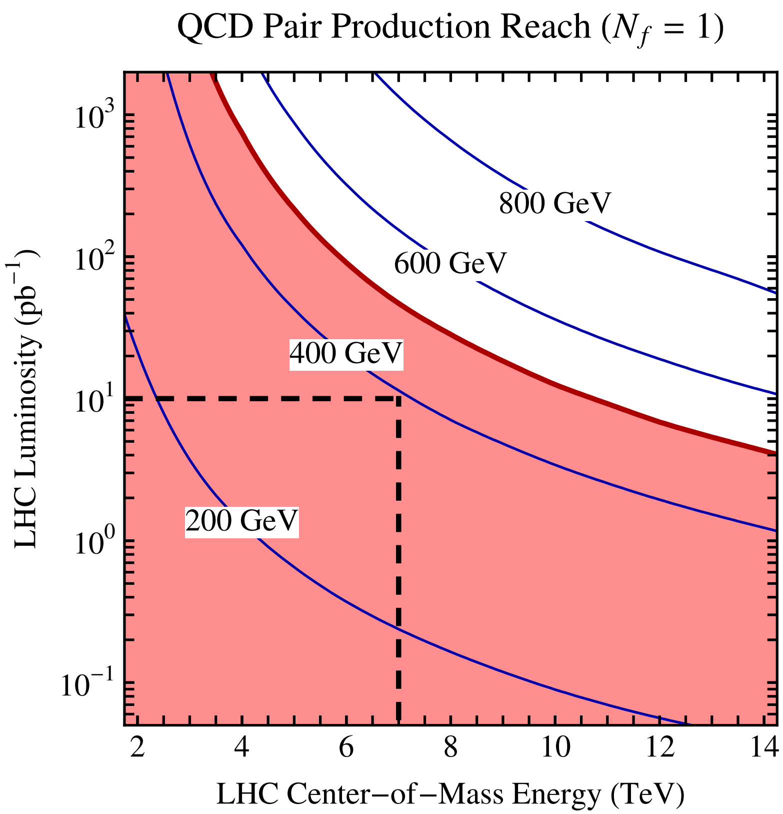
1. $N_{\mathrm{LHC}} > 10$
   Yes! $1\,\mathrm{pb}$ **@** $10\,\mathrm{TeV}$ for $500\,\mathrm{GeV}$ pairs
2. $N_{\mathrm{TEV}} < 10$
   Need to check (next slide)
3. Highly visible final state?
   Need model building (in two slides)
4. Satisfies other bounds
   Can be arranged, believe me...

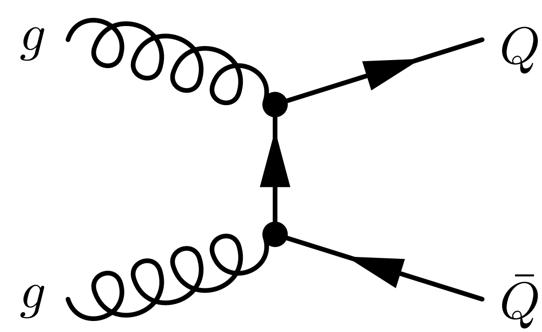


First supermodel attempt

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

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





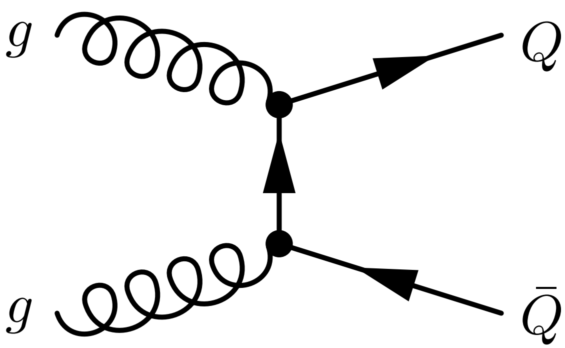
- Supermodel at $10\,\mathrm{TeV}$ LHC with $100\,\mathrm{pb}^{-1}$ but not at $7\,\mathrm{TeV}$ with $10\,\mathrm{pb}^{-1}$

First supermodel attempt

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

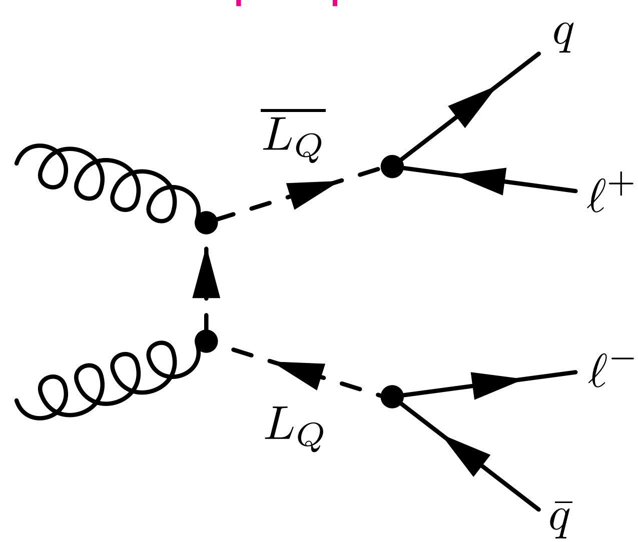
  3. Highly visible final state? Background free?

Stable "quarks"



several variants, R-hadrons

Leptoquarks



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

- These can happen with 100% branching ratios

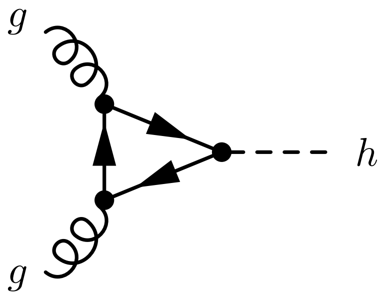
Possible to do better!

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

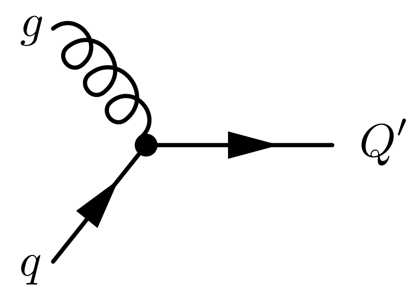
Our "notation":

gg^* "Higgs"	qg^* "Excited quark"
$q\bar{q}$ "Z'"	qq "Diquark"

* = loop factors



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

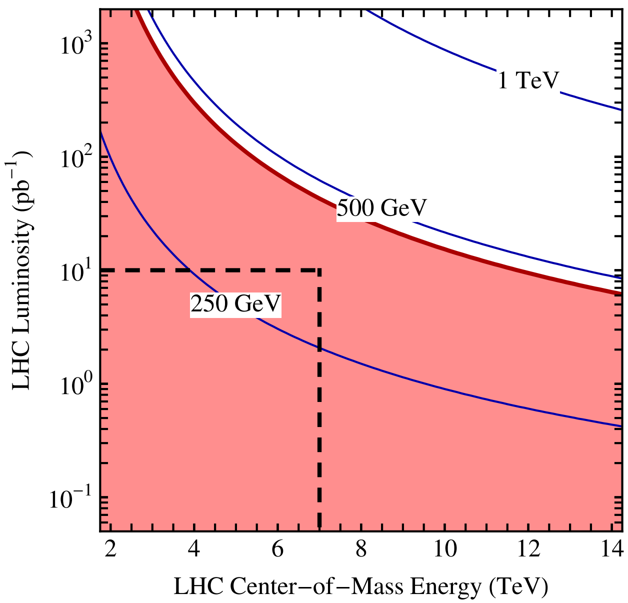


$\overline{Q'}\, i \not{D} q$ not gauge invariant $\Rightarrow \frac{1}{\Lambda}\, \overline{Q'}\, \sigma_{\mu\nu} G^{\mu\nu} q$

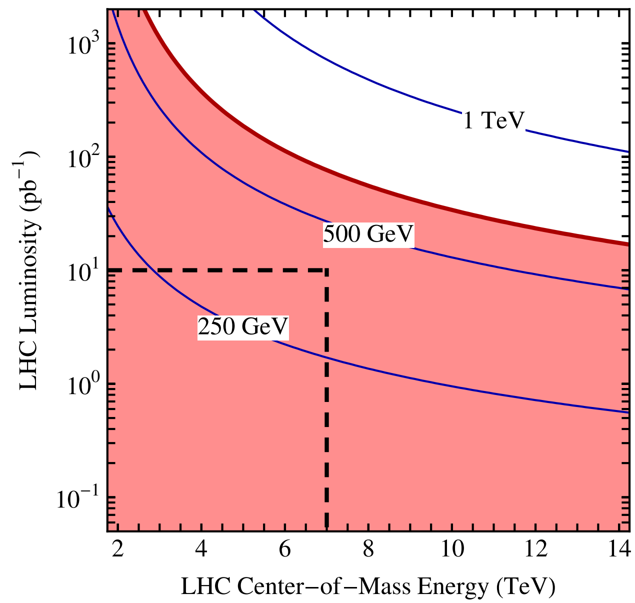
- Both gg and qg: substantial suppressions — if weakly coupled: $\Lambda \sim 16\pi^2\, M$

LHC vs Tevatron reach

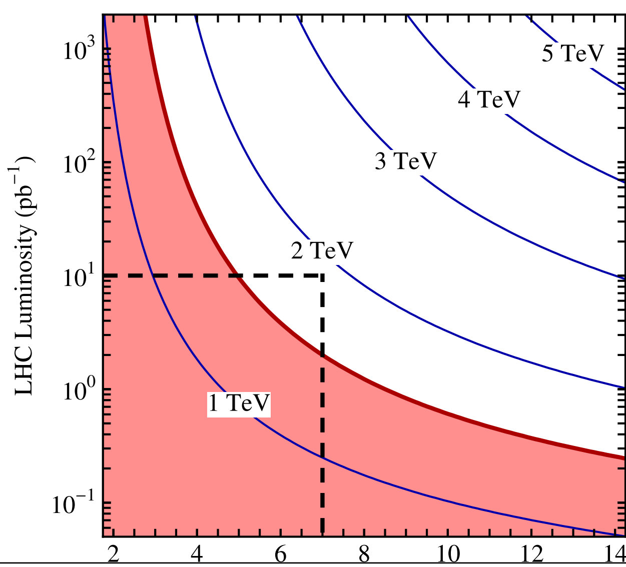
gg^*



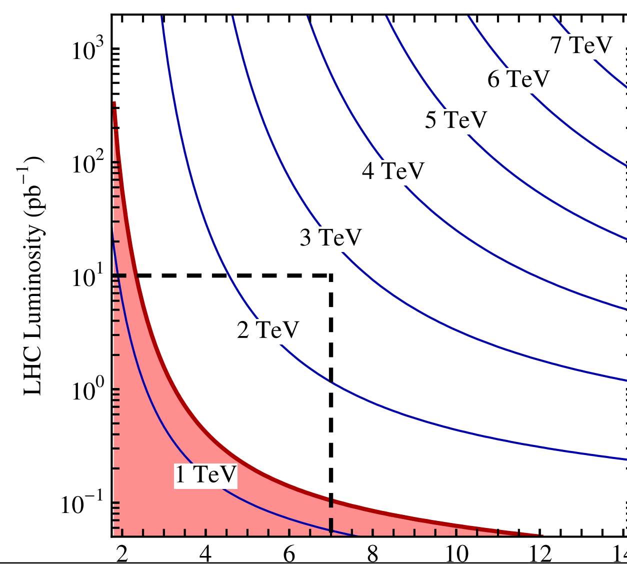
qg^*



$q\bar{q}\,!$

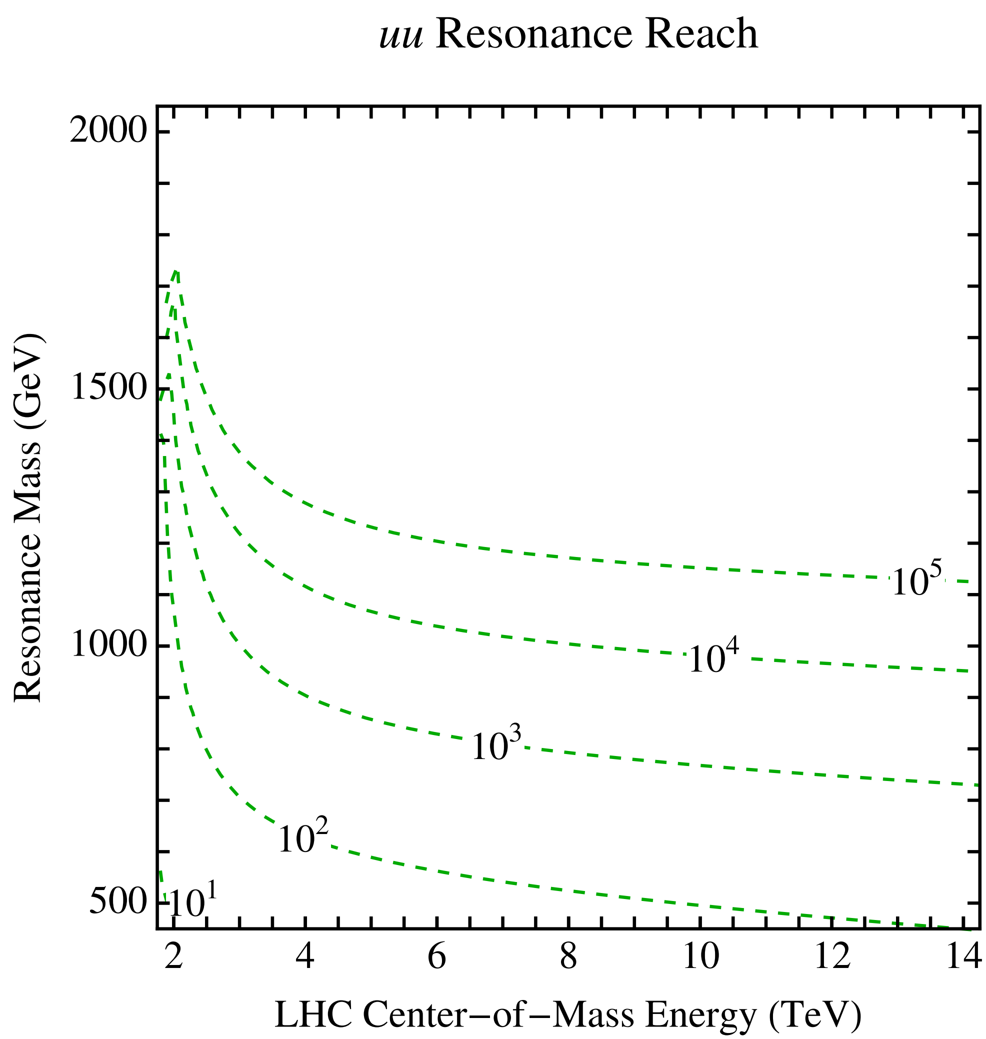


$qq\,!!$



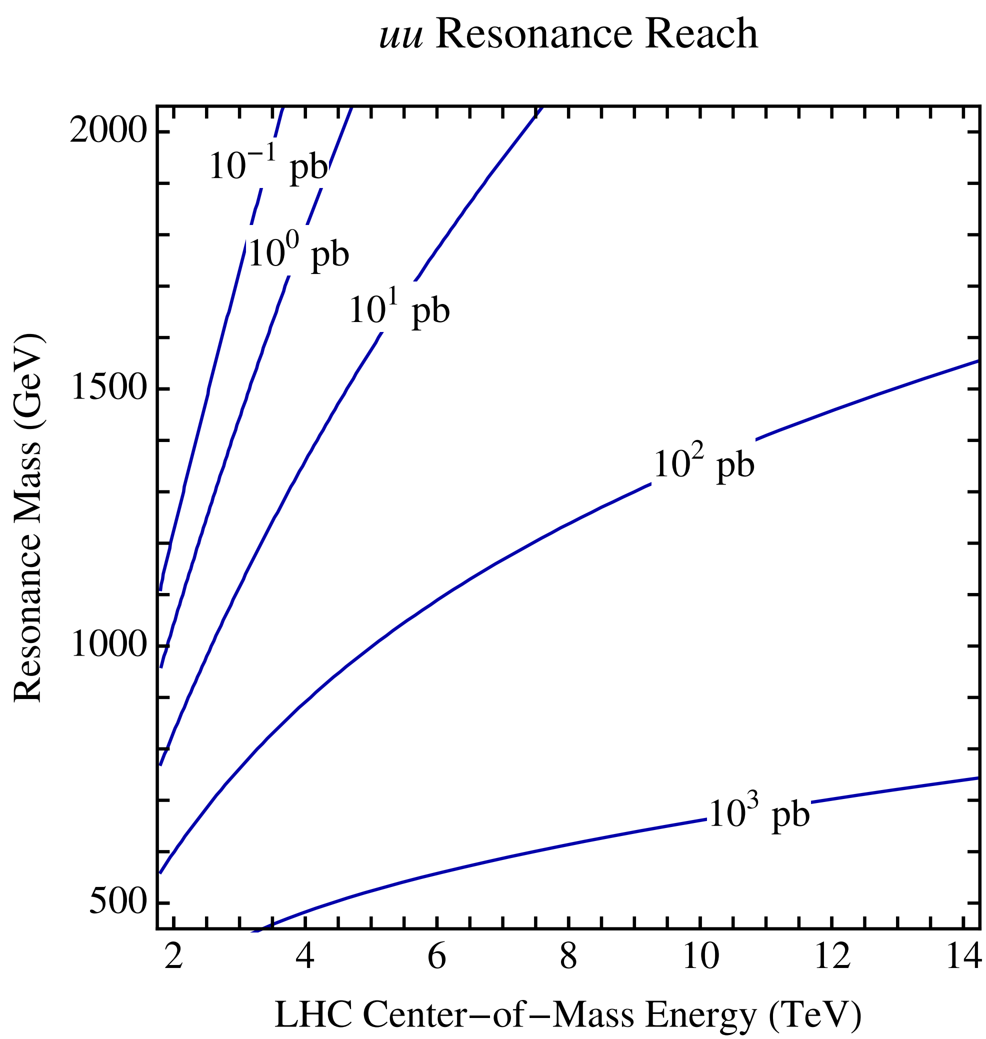
Supermodel parameter space

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



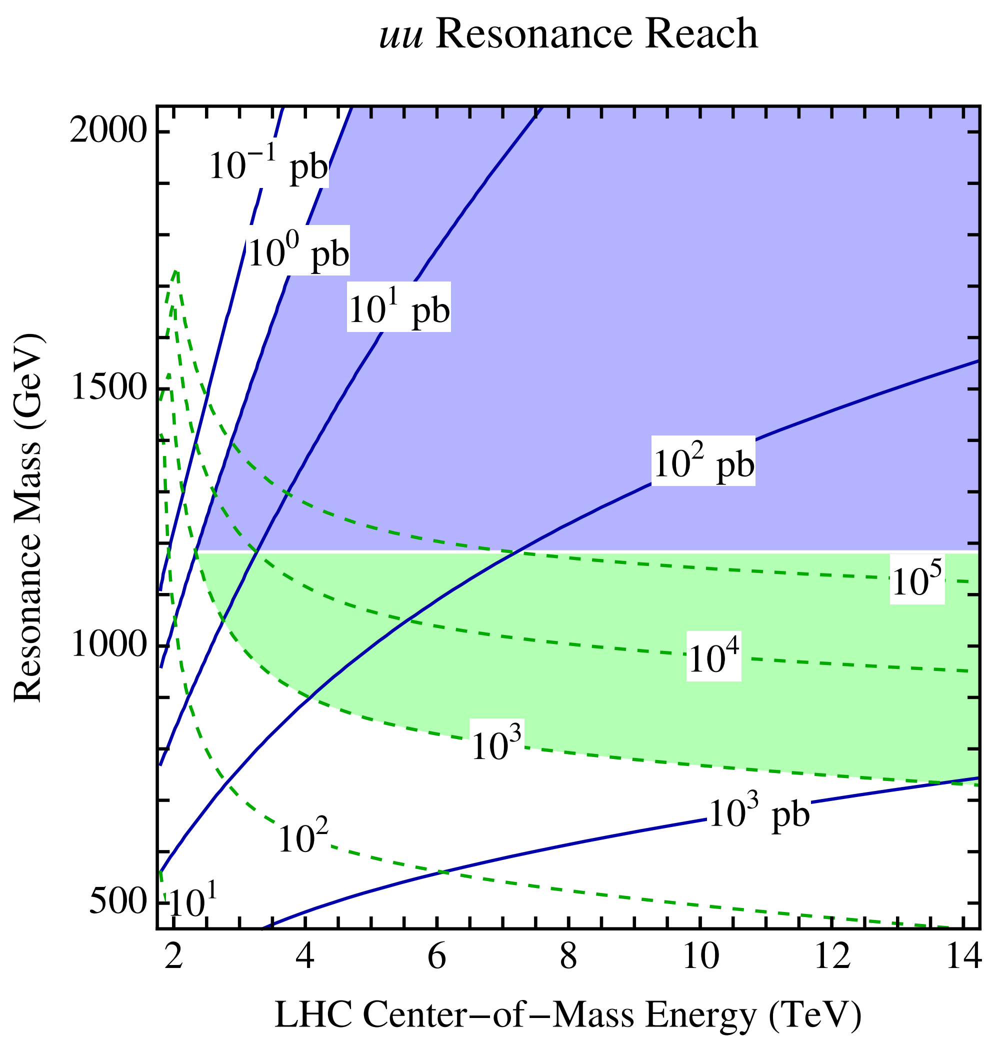
Supermodel parameter space

- 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)



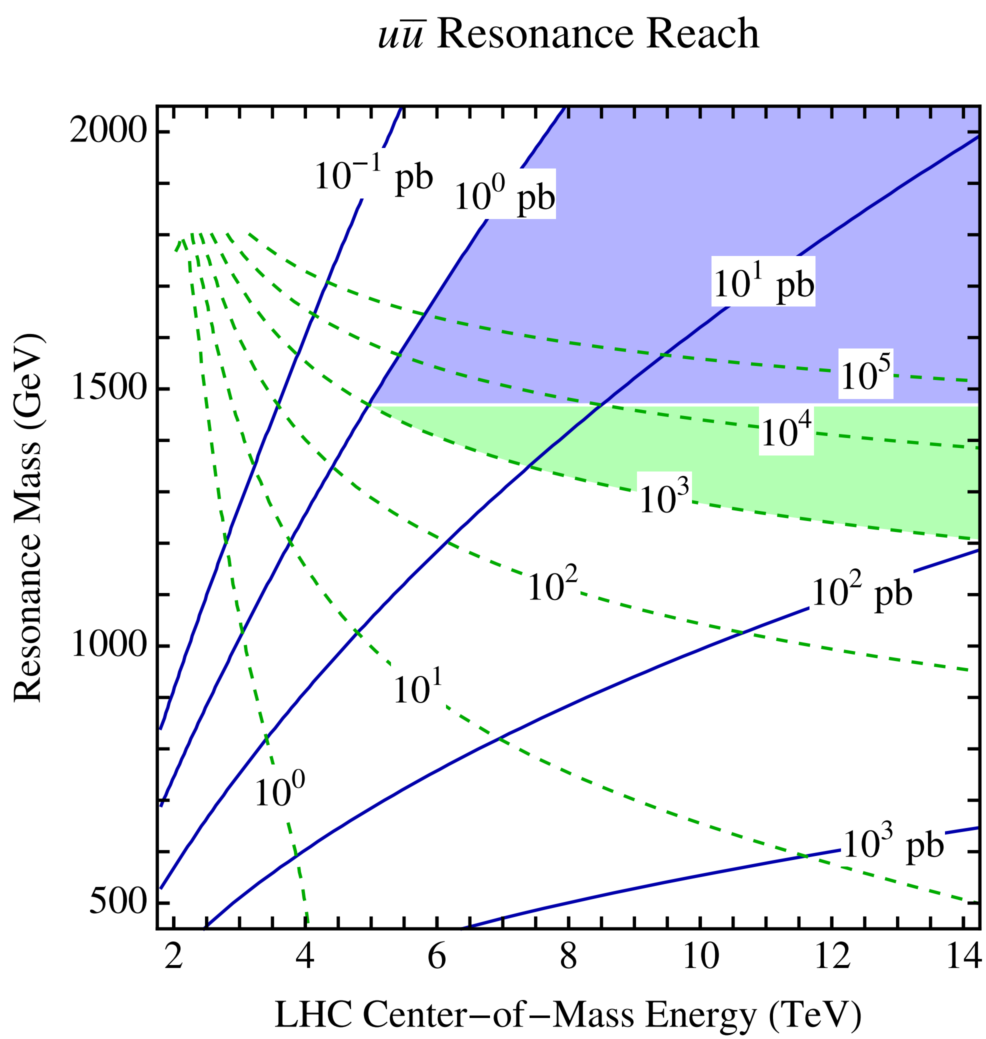
Supermodel parameter space

- Combining both conditions:



Sanity check: sequential Z'

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



Sampling Supermodels

Supermodel Building

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

$\}$

$10\,{\rm TeV}$ LHC with $100\,{\rm pb}^{-1}$

gg: QCD pair production

qg: Excited quarks

$7\,{\rm TeV}$ LHC with $10\,{\rm pb}^{-1}$

$q\bar{q}$: Z' & qq: Diquarks

3. Highly visible final state?

Next part of the talk

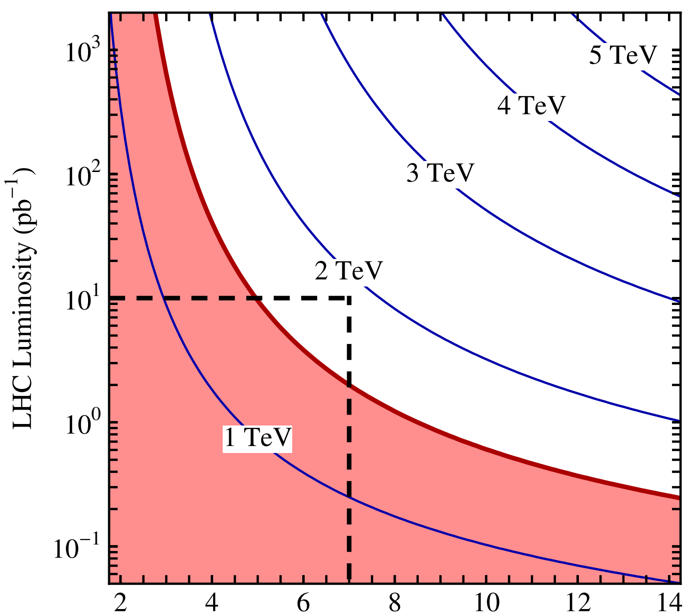
(need to avoid decay back to the initial state)

4. Satisfies other bounds

Can be arranged...

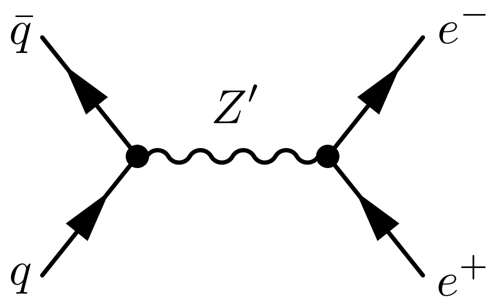
$q\bar{q}$ resonances

$q\bar{q}\,!$

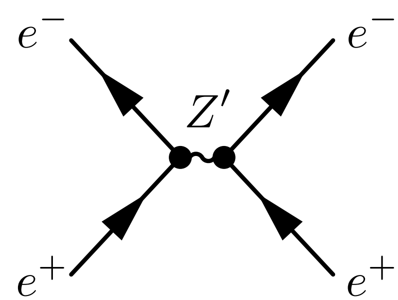


Z' bosons (recall from before)

- LHC production:



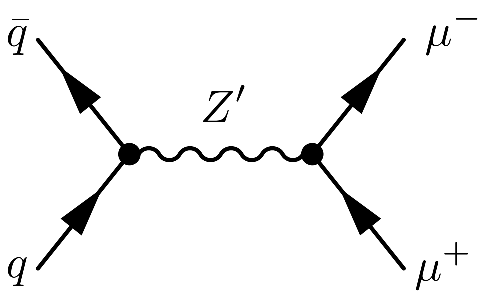
LEP bound:



To avoid LEP bounds, no flavor-universal $g_{q,\ell}$ values allow Z' to be a supermodel

$\sigma(q\bar{q} \to Z') \propto g_q^2$, $\mathcal{B}(Z' \to \ell^+\ell^-) \propto g_\ell^2/(\alpha g_\ell^2 + 6g_q^2)$

- Can imagine an electrophobic Z' to suppress $\mathcal{B}(Z' \to e^+e^-)$, a $B - L_\mu$ boson...

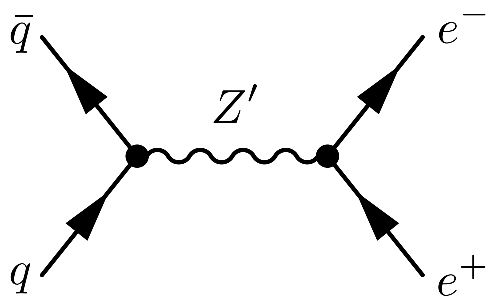


Works, but would it be your favorite?

[Salvioni, Strumia, Villadoro, Zwirner, 0911.1450]

Z' bosons (recall from before)

- LHC production:



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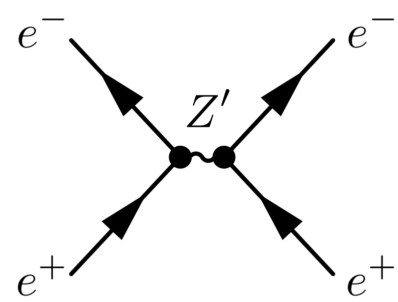

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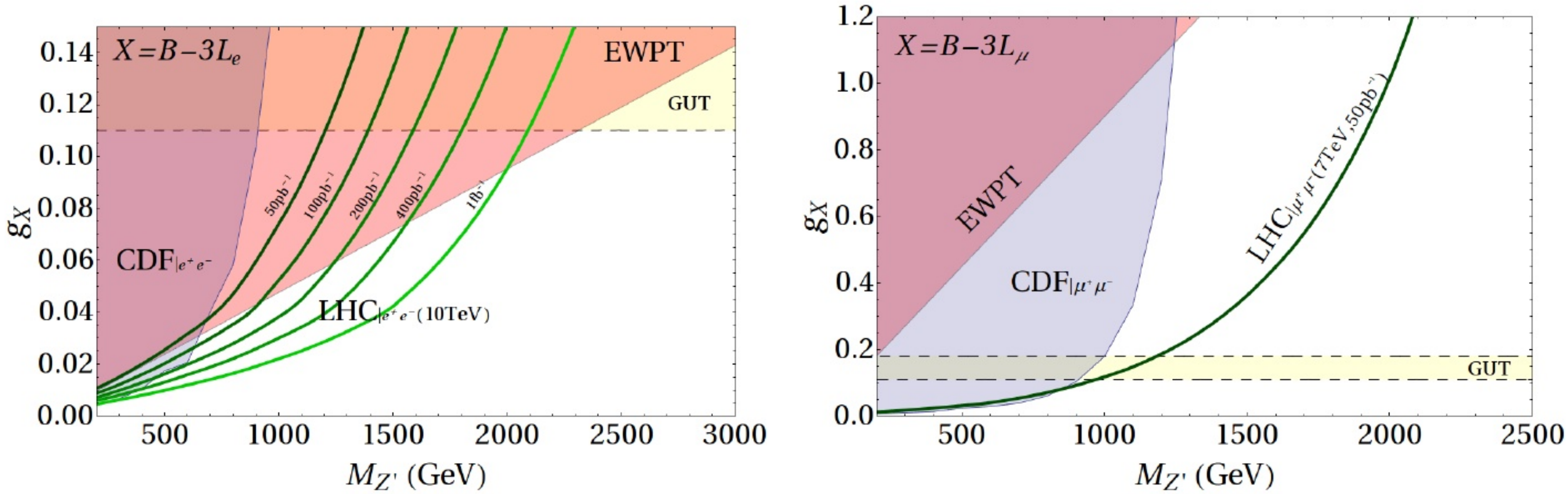
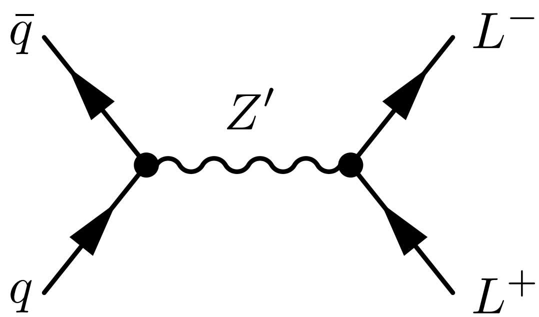


[0911.1450]

Z' decays to exotic stuff

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

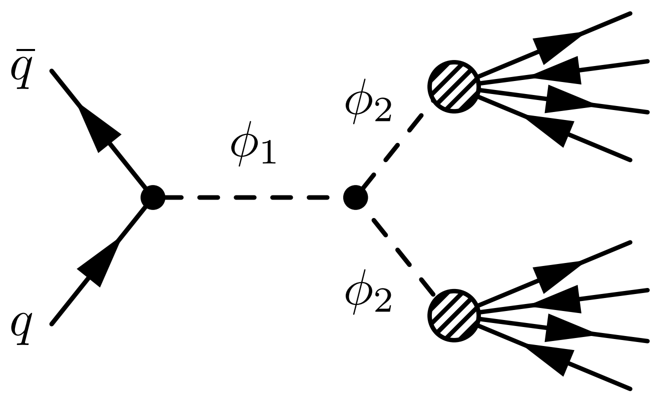


Can have large branching fraction

No FCNC bounds

Cosmologically safe if late decay

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



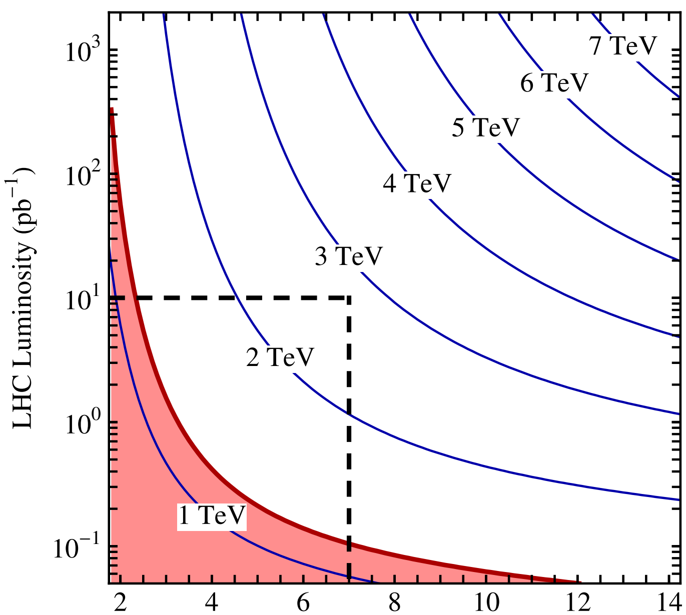
Large $\phi_1\phi_2\phi_2$ coupling for large branching fraction

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

Unlikely to be easily reconstructable

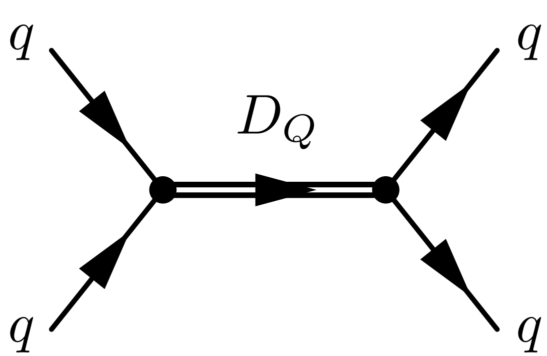
qq resonances

qq !!

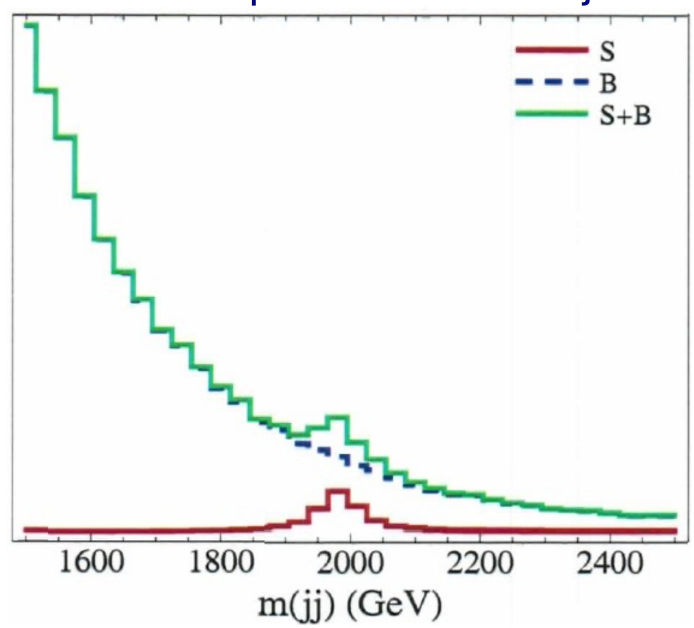


Diquark resonances

- Enormous cross sections possible:



Large luminosity
$2\,\mathrm{TeV}$ Diquark vs. QCD dijets



- However, the dijet final state might be problematic in the early data

[E.g., superstring inspired E_6 GUTs contain/predict diquarks]

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	$(\bar{3},1,1)$	$u_R\ u_R$
VI	$\bar{6}$	1	-4/3	$(\bar{6},1,1)$	$u_R\ u_R$
VII	3	1	2/3	$(1,\bar{3},1)$	$d_R\ d_R$
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	$(1,1,\bar{3})$	$Q_L\ Q_L$
XIII	3	3	-1/3	$(1,1,\bar{3})$	$Q_L\ Q_L$
XIV	$\bar{6}$	3	-1/3	$(1,1,\bar{6})$	$Q_L\ Q_L$

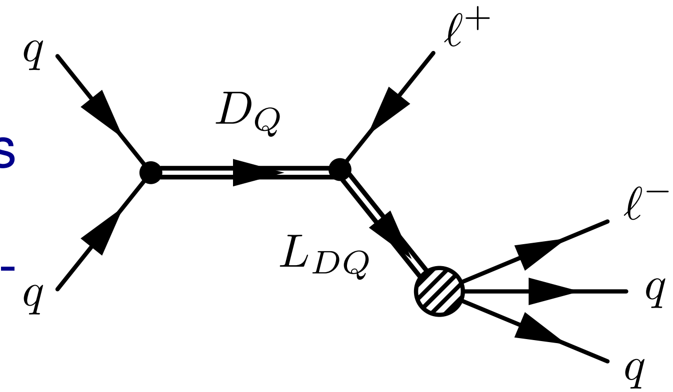
[Arnold, Pospelov, Trott, Wise, 0911.2225]

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)

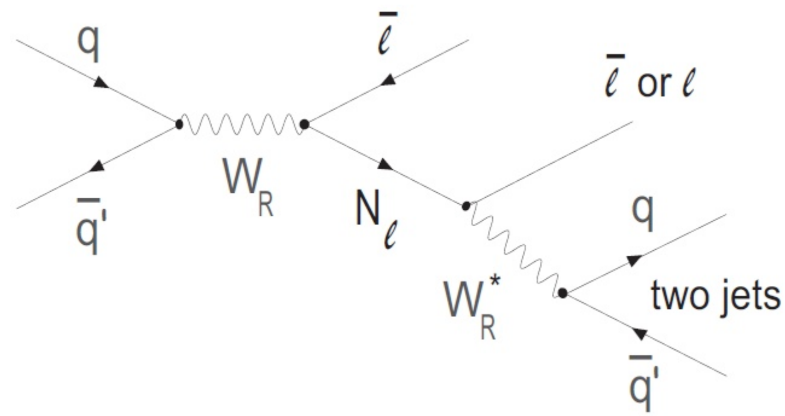


- The most Z'-like signature: $\ell^+\ell^-$ with a high mass edge $+\ 2$ jets (color cons.)

- 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 $\gtrsim 1\,\mathrm{fb}^{-1}$

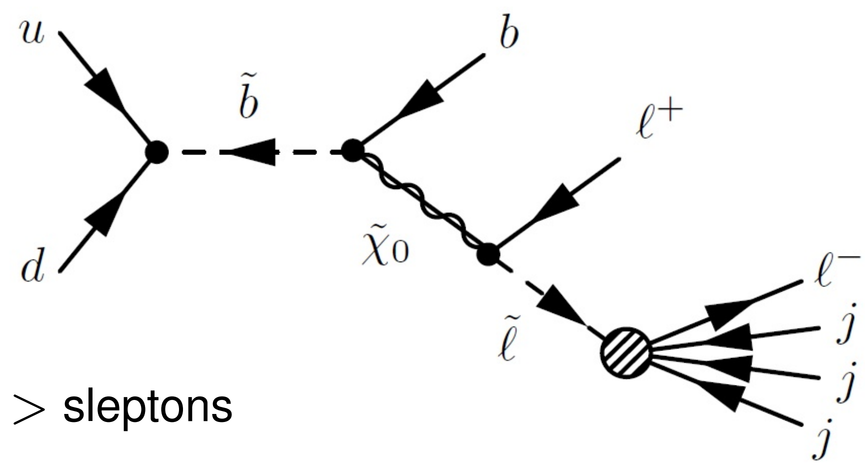


- With diquarks, interesting search at $10\,\mathrm{pb}^{-1}$

[Figure from: Aad *et al.*, ATLAS Collaboration, 0901.0512]

Squarks as Diquarks

- MSSM with R-parity violation and slepton LSP
- $W = \lambda_{113} U^c D^c D^c$ allowed with $\mathcal{O}(1)$ coupling for squark masses $> 1\,\mathrm{TeV}$



Decay chains very sensitive to spectrum

E.g., if: gluinos $>$ squarks $>$ $SU(2)$ gauginos $>$ bino $>$ sleptons

- If mass ordering is: squarks $>$ gluinos $>$ $SU(2)$ gauginos $>$ sleptons $>$ bino

$$
\begin{aligned}
&\tilde{b}^c \to b\,\tilde{g} \\
&\quad \hookrightarrow 2j\,\chi_2 \\
&\qquad \hookrightarrow \ell\,\tilde{\ell} \\
&\qquad\quad \hookrightarrow \ell\,\chi_1 \\
&\qquad\qquad \hookrightarrow 3j\ ,
\end{aligned}
$$

Many ways to get copious leptons...

Let alone if left- and right-handed sleptons alternate with neutralinos...

With less than 100 pb^{-1} of early LHC data...

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

Yes! Supermodels!

Conclusions

- Huge difference between $10\,\mathrm{pb}^{-1}$ & $100\,\mathrm{pb}^{-1}$ (and $7\,\mathrm{TeV}$ vs. $10\,\mathrm{TeV}$)
- Marginal reach for SUSY, Higgs, little Higgs
- Substantially extended reach for Supermodels — two representative examples:

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

(stable charged particles, not necessarily slow)

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

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

- Good benchmarks for later searches — generic new physics signatures, plus actual Lagrangians to make it interesting in early data
- When ATLAS & CMS get near $1\,\mathrm{fb}^{-1}$ of good data, even at $7\,\mathrm{TeV}$, there is clearly significant discovery reach for many “more motivated” models