Leptoquarks

Simona Rolli
US Department of Energy
Office of High Energy Physics
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Leptoquarks Mini Review - M. Tanabashi, S. Rolli

Outline

- Current Review
  - Theory Introduction
  - Experimental Results
    - Direct production: HERA (new results), Tevatron (obsolete), LHC (new result)
    - Indirect production: listings?
- Plans for updated review
  - More theory info on LFV and LQ connection
    - Upcoming experiment at the Intensity Frontier
    - Remove some obsolete collider results?

Leptoquarks

- **Leptoquarks (LQ)** are hypothetical particles which appear in many SM extensions to explain **symmetry between leptons and quarks**
  - SU(5) GUT model
  - superstring-inspired models
  - 'colour' SU(4) Pati-Salam model
  - composite models
  - Technicolor
  - RPV SUSY

•LQs are **coupled to both leptons and quarks** and carry SU(3) color, fractional electric charge, baryon (B) and lepton (L) numbers

•LQ are assumed to couple to same-generation fermions (FCNC and lepton-family number violation constraints)

•LQs can have:

–spin 0 (scalar)

•couplings fixed, i.e., no free parameters

•Isotropic decay

–spin 1 (vector)

•anomalous magnetic (k_G) and electric quadrupole (λ_G) model-dependent couplings

–Yang-Mills coupling: $k_G = \lambda_G = 0$

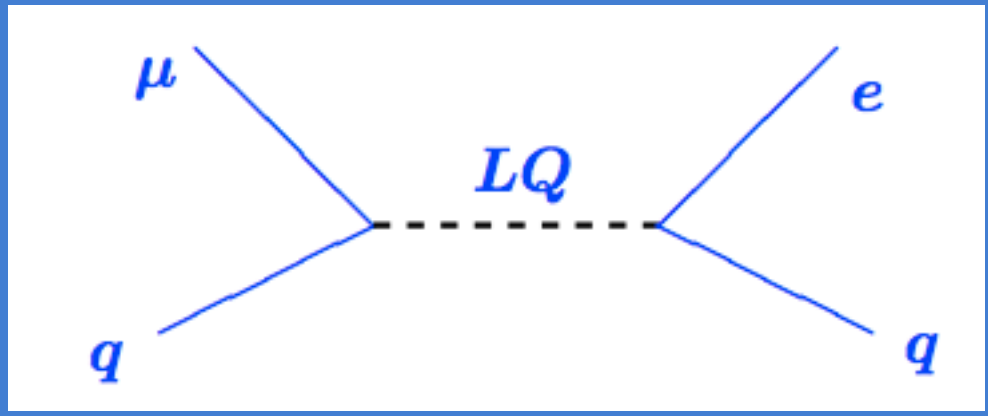
–Minimal coupling: $K_G = 1$, $\lambda_G = 0$

–Decay amplitude proportional to $(1 + \cos\theta^*)^2$

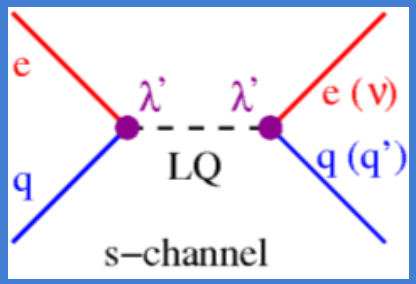
- **Experimental evidence searched:**
  - indirectly: LQ-induced 4-fermion interactions; rare processes; LVF experiments
  - directly: production cross sections at collider experiments

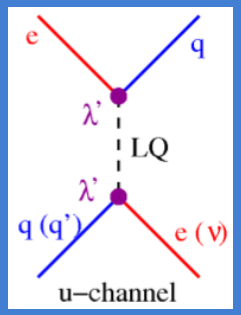
Renewed interest on LFV LQ-induced processes

- The origin of quark and lepton masses (arising from physics at some high scale) is likely to induce flavor processes involving mesons, muons, ...
- Leptoquarks which couple to both eq and μq induce μN → eN conversion:



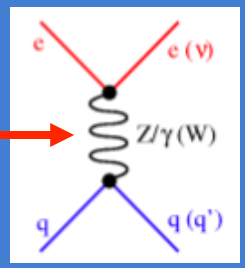
LQ at HERA: 1st generation

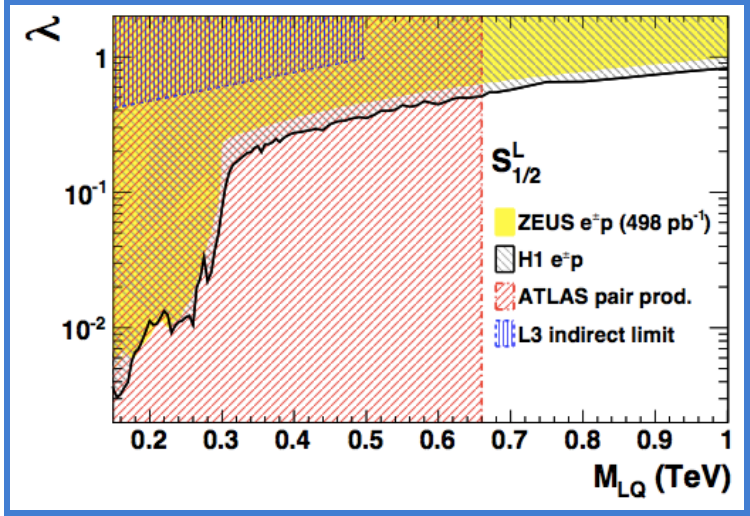




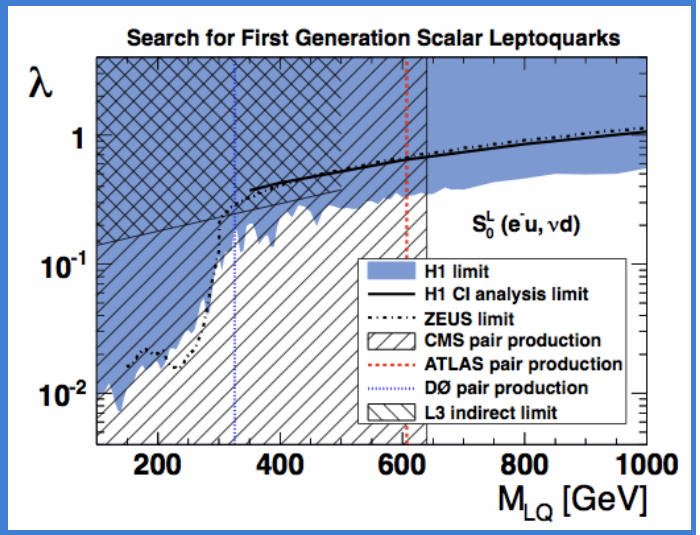
Search for a resonant structure in the LQ mass distribution

Spectra dominated by SM DIS
No excess observed





Cross-section is dependent on the Leptoquarks Yukawa coupling λ-mass exclusion plots



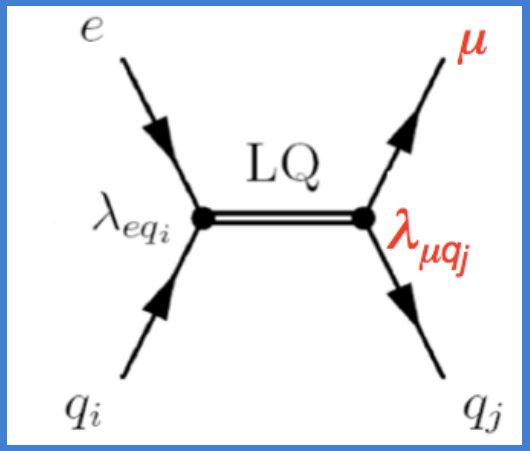
R-parity violating SUSY
u-type squark, decaying into ed

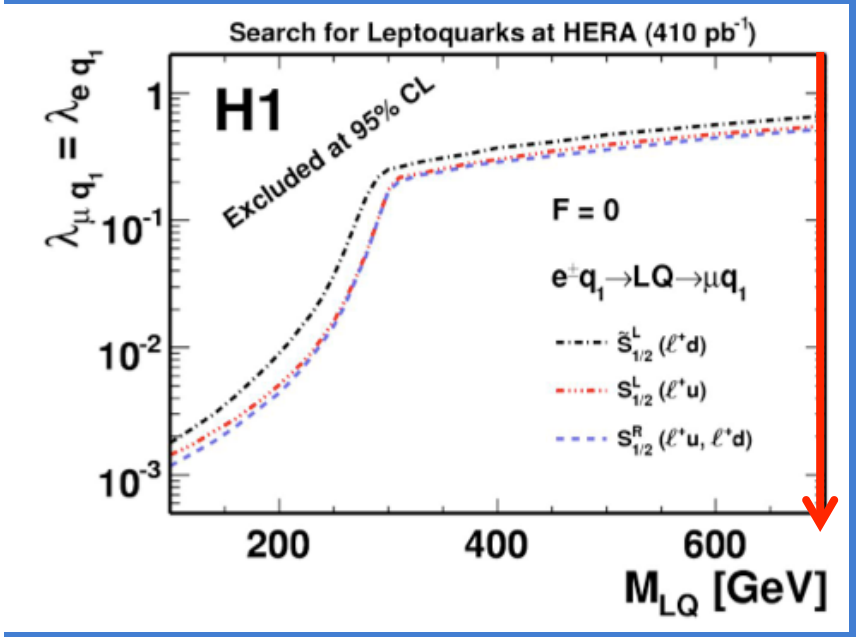
R-parity violating SUSY
d-type squark, decaying into eu, dv

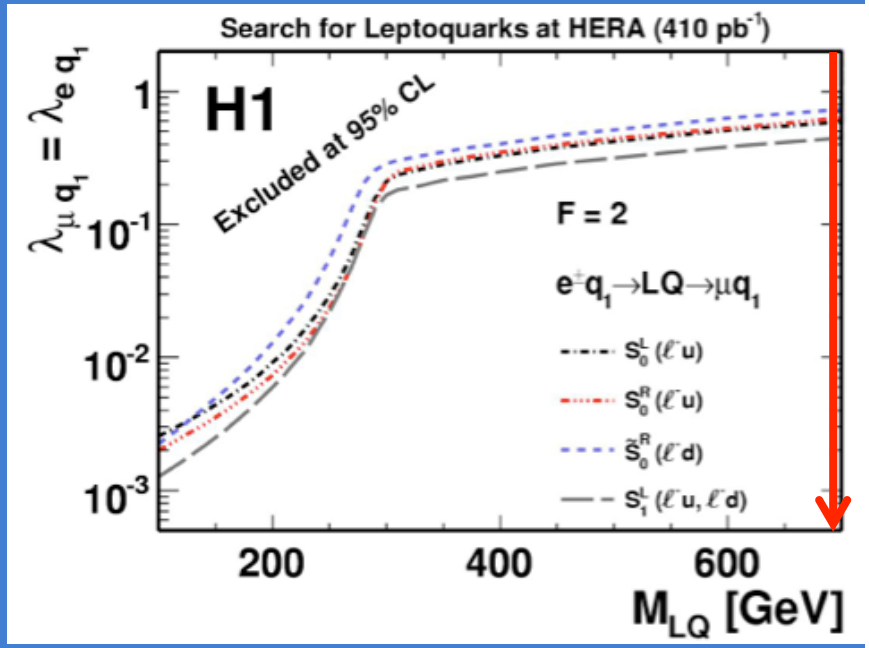
Leptoquarks at HERA: LFV

- Lepton flavor violating LQ
- Study of the LQ decay to μ-jet and τ-jet

CMS Limit on β=1 1070 GeV;
β=0.5 785 (8 TeV data)

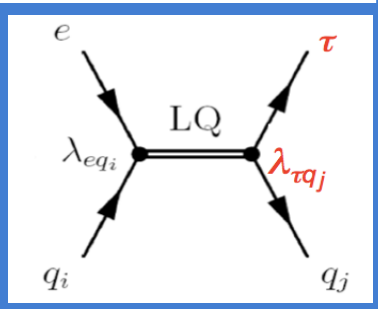




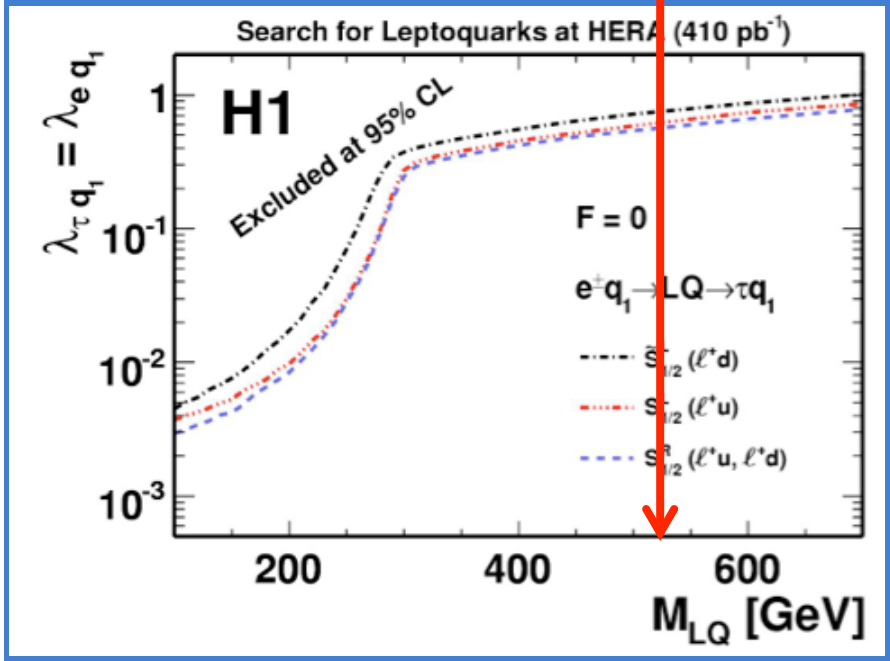


Leptoquarks at HERA: LFV

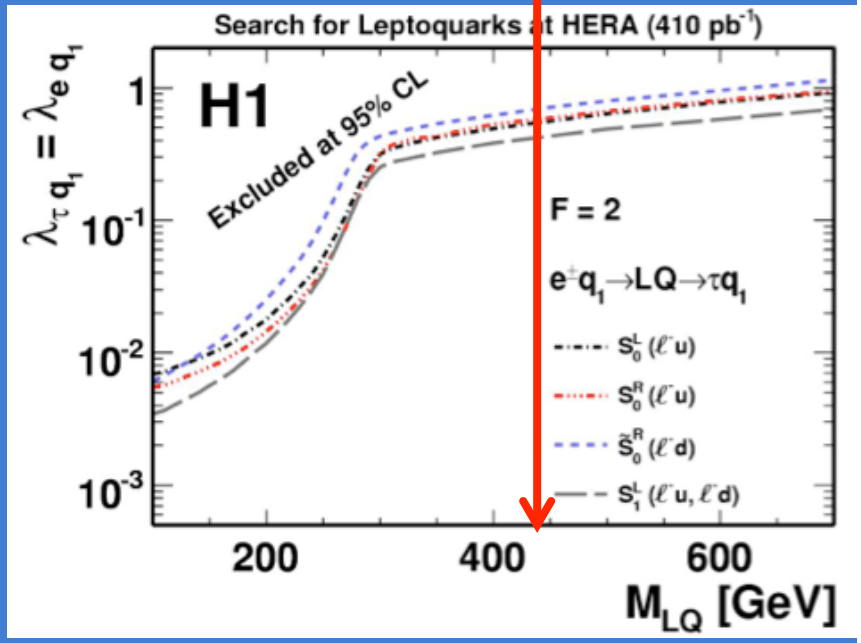
- Lepton flavor violating LQ
- Study of the LQ decay to τ-jet



ATLAS Limit on β=1 534 GeV



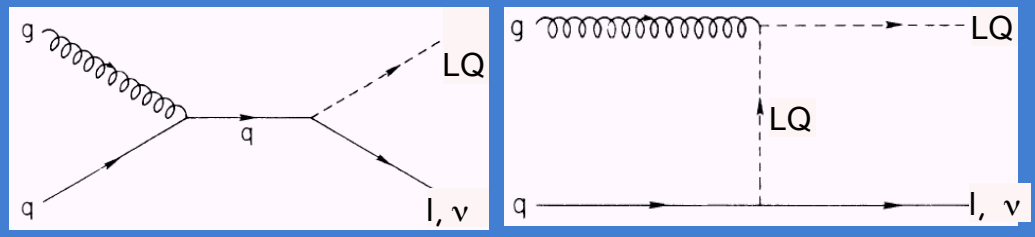
CMS Limit on β=0.5 450



LQ at Hadron Colliders: Production

- **Single production**
  - strongly depends on λ
  - possible signatures:
    - l^+l^- + jet
    - $l\nu$ + jet
    - $\nu\nu$ + jet
  - Main background: Zjet & tt

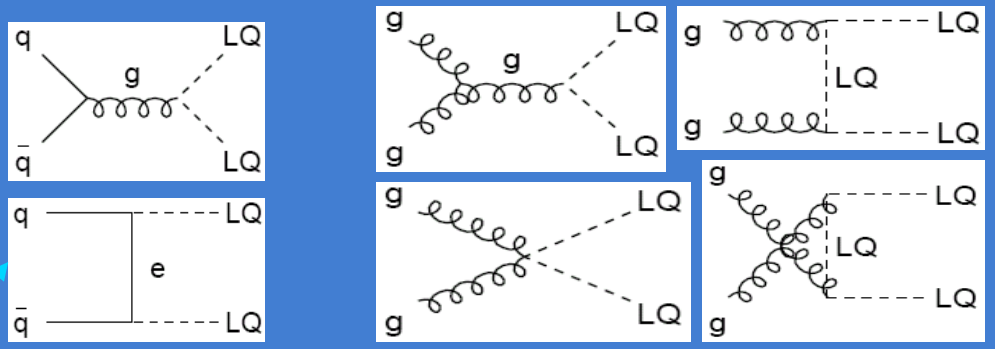
$qg \rightarrow \ell LQ$, $qg \rightarrow \nu LQ$



Generally negligible for m(LQ) < 1 TeV

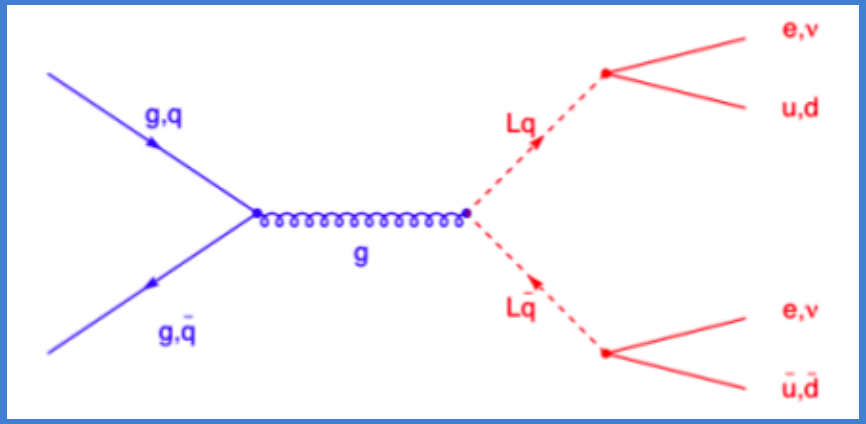
- **Pair production**
  - Practically independent of Yukawa coupling λ (only g-LQ-LQ vertex)
  - Depends mainly on LQ mass

$q\bar{q} \rightarrow LQ\ LQ$ $gg \rightarrow LQ\ LQ$



- λ dependent process
- does not contribute significantly to 2nd & 3rd generation

LQ at Hadron Colliders: Decay



Decay

- Each generation can decay into 3 final states:

β = Br (LQ→lq)

β = 1

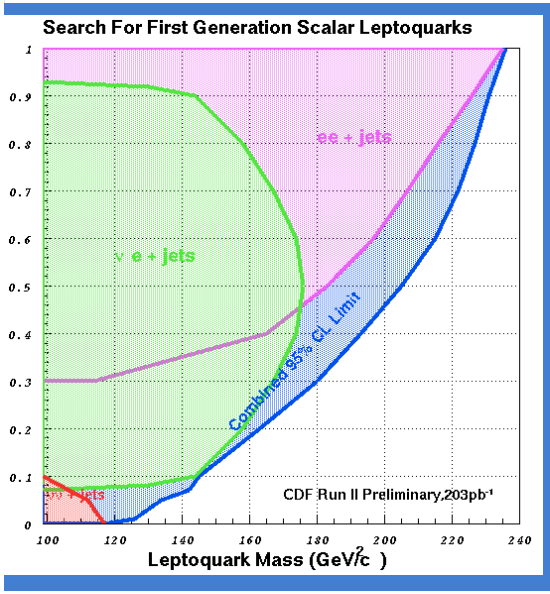
β = 0.5

β = 0

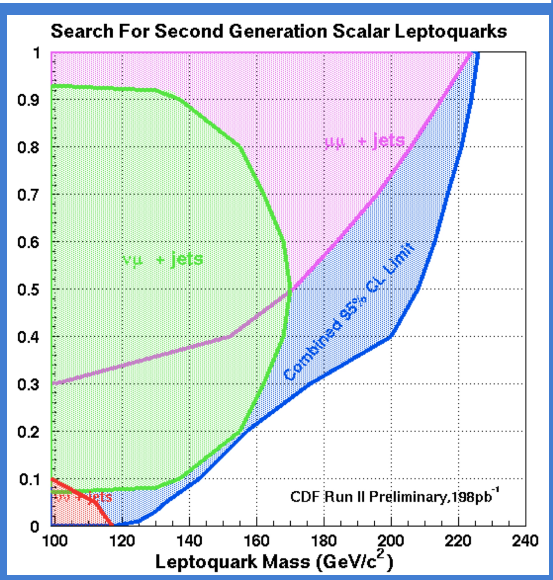
Exclusive to hadron colliders

1st Generation	2nd Generation	3rd Generation
$LQ\,\overline{LQ} \to e^- e^+ q\bar{q}$	$LQ\,\overline{LQ} \to \mu^+ \mu^- q\bar{q}$	$LQ\,\overline{LQ} \to \tau^+ \tau^- q\bar{q}$
$LQ\,\overline{LQ} \to e^{\pm} \nu_e q_i q_j$	$LQ\,\overline{LQ} \to \mu^{\pm} \nu_\mu q_i q_j$	$LQ\,\overline{LQ} \to \tau^{\pm} \nu q_i q_j$
$LQ\,\overline{LQ} \to \nu_e \nu_e q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\mu \nu_\mu q\bar{q}$	$LQ\,\overline{LQ} \to \nu_\tau \nu_\tau q\bar{q}$

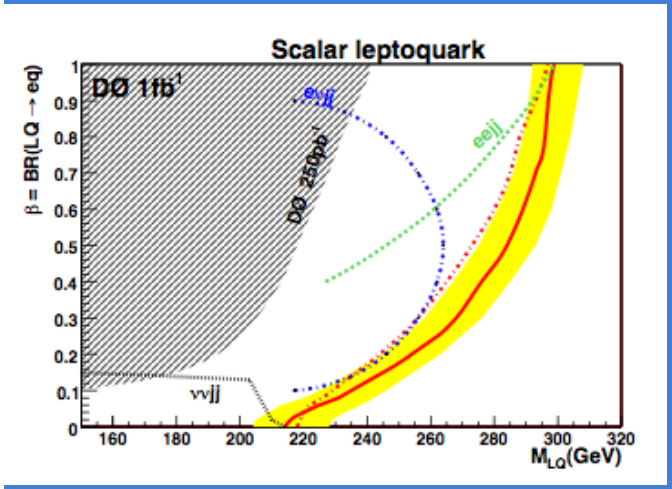
LQ at the Tevatron



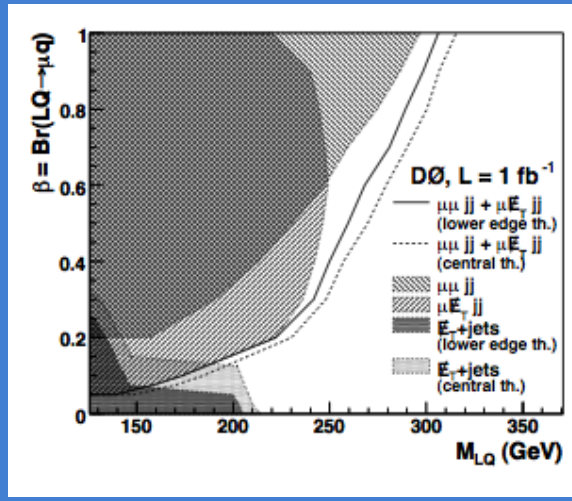
Phys Rev D 72, 2005



Phys Rev D 73, 2006

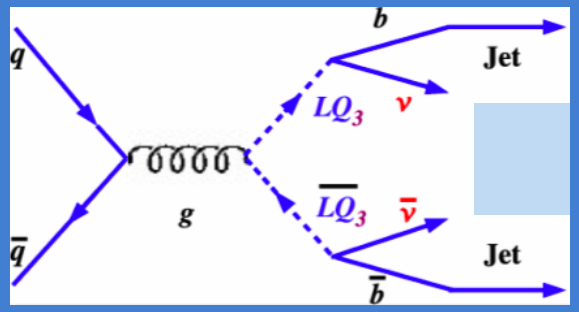


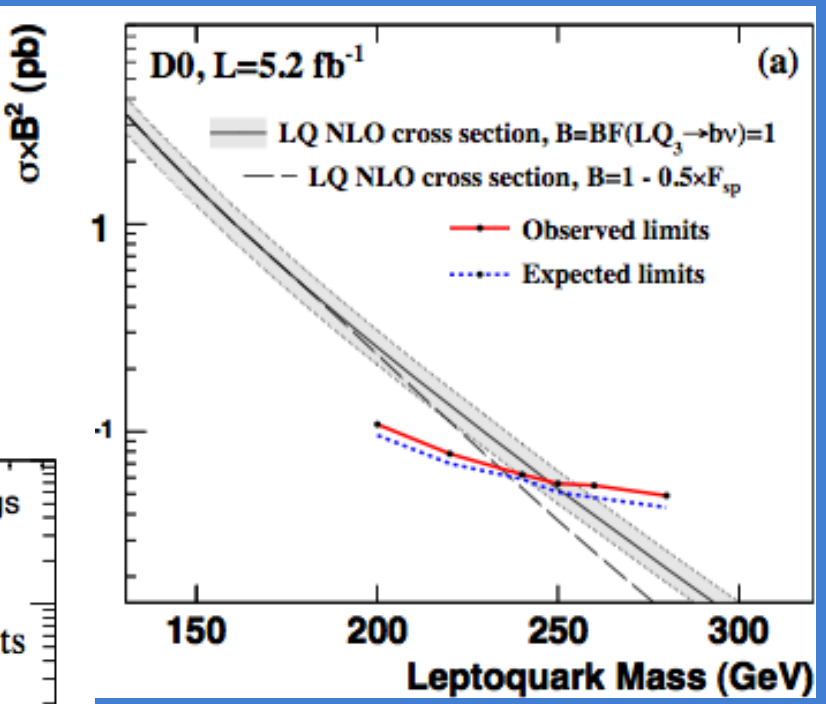
Phys. Lett. B **681**, 224 (2009)

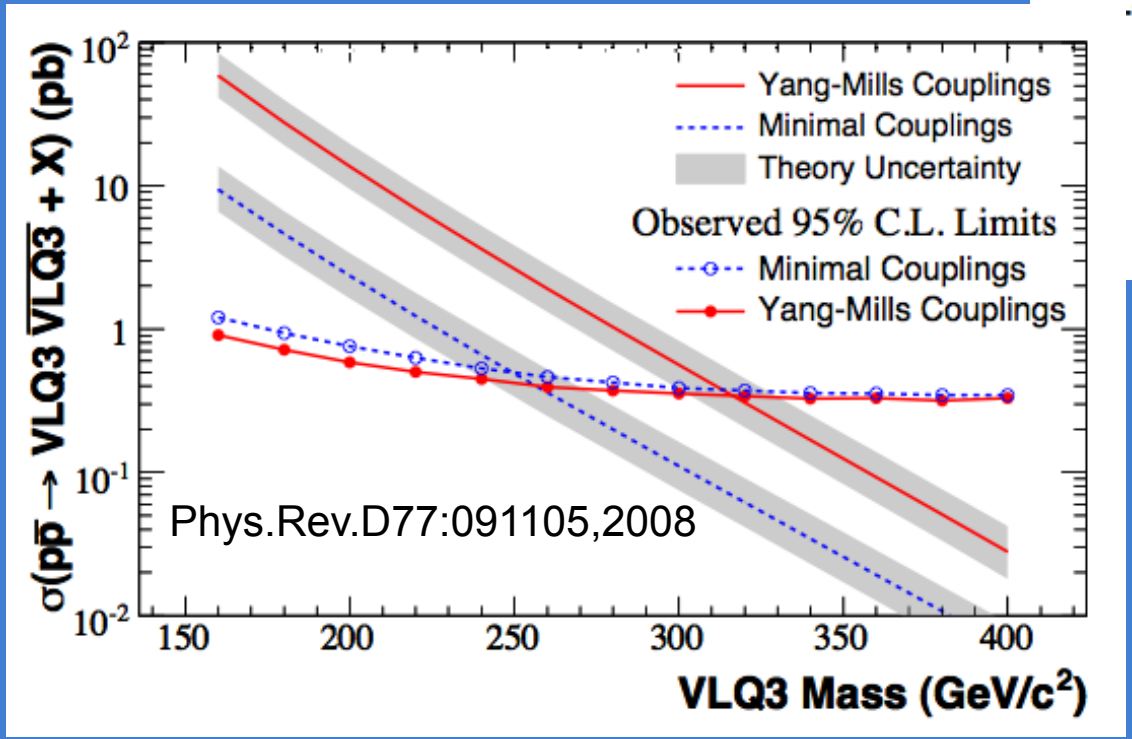


Phys. Lett. B **671**, 224 (2009)

LQ at the Tevatron: 3rd Gen

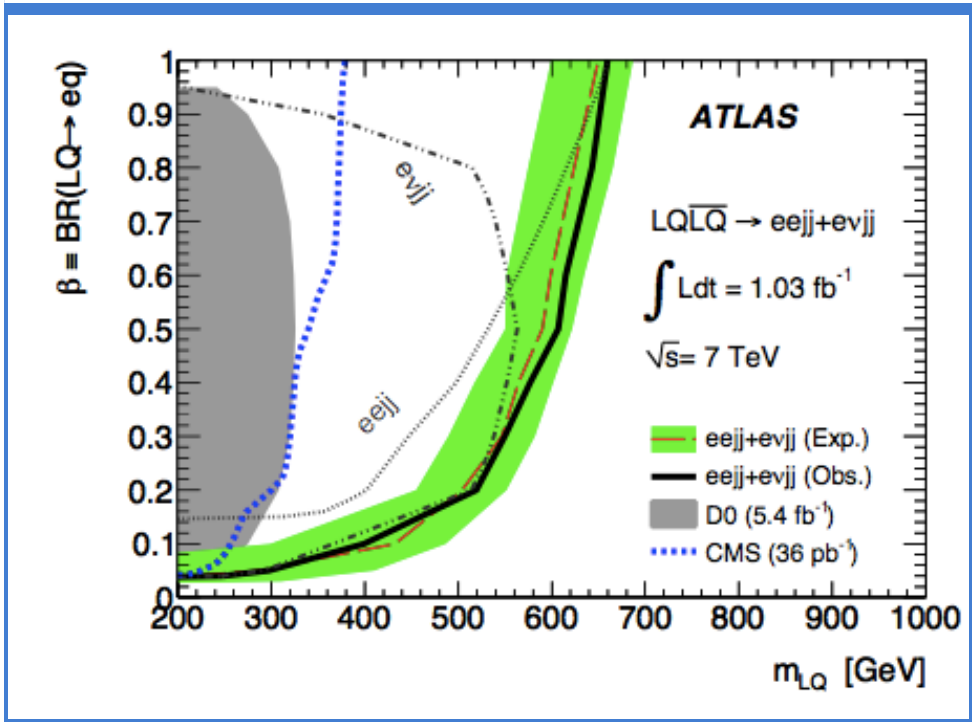




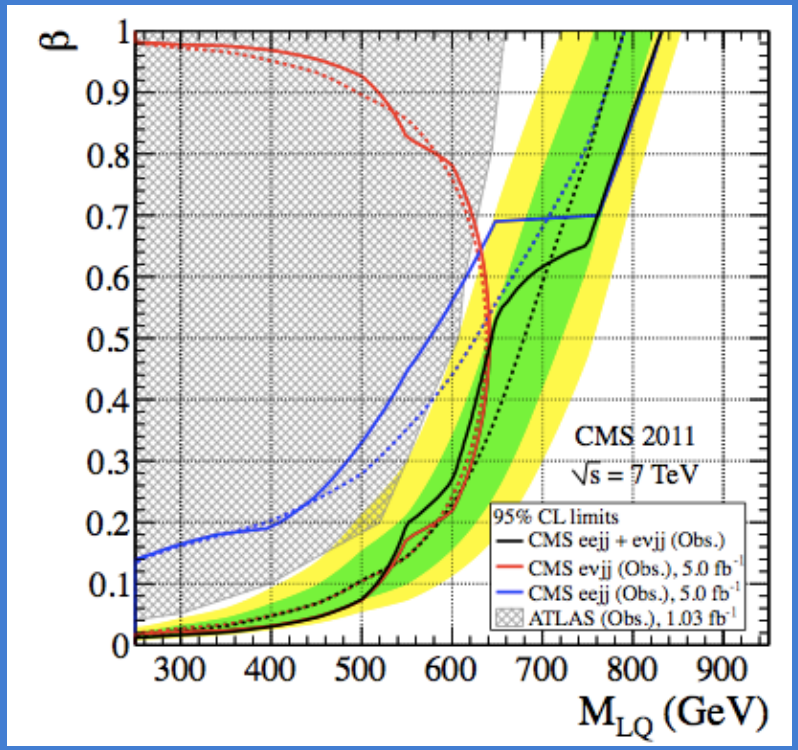


Phys. Lett. B **693**, 95 (2010)

LHC Results (7 TeV run): 1st Gen

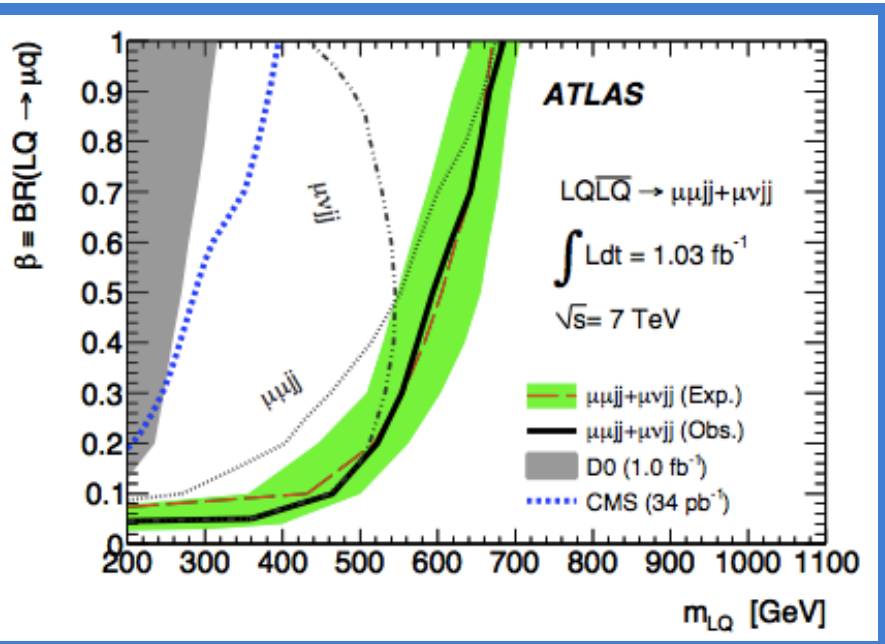


ATLAS
M(LQ) > 660 GeV/c^2 (β=1)
M(LQ) > 607 GeV/c^2 (β=05)
Already in mini-review

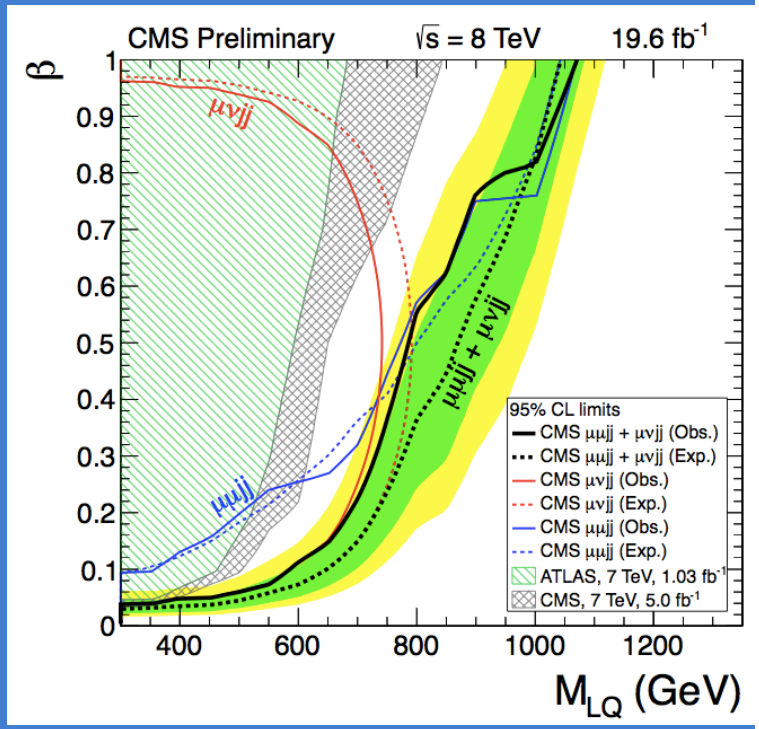


CMS
M(LQ) > 830 GeV/c^2 (β=1)
M(LQ) > 640 GeV/c^2 (β=05)
-mini-review update!

LHC Results (7/8 TeV run): 2nd Gen

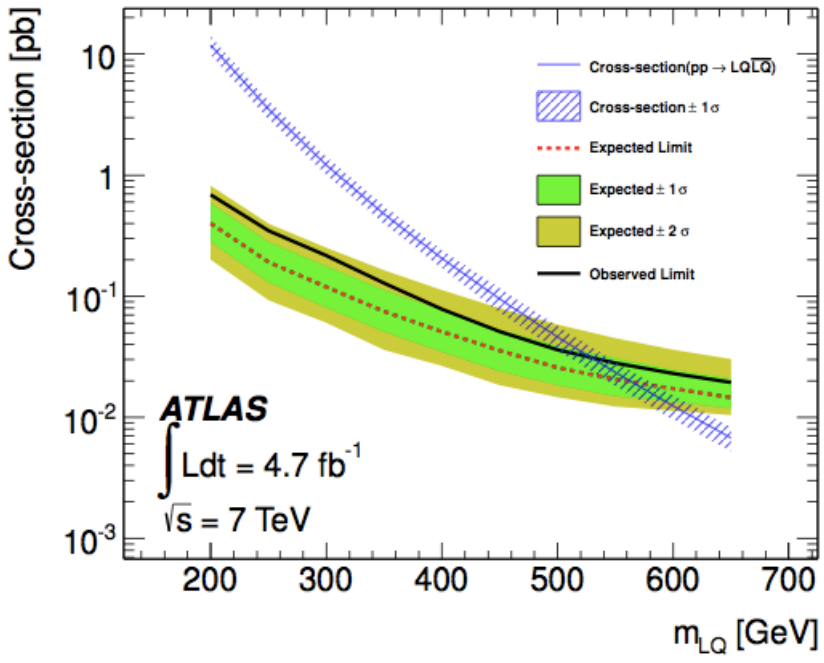


ATLAS (7 TeV)
M(LQ) > 685 GeV/c^2 (β=1)
M(LQ) > 594 GeV/c^2 (β=0.5)
Update in mini-review !

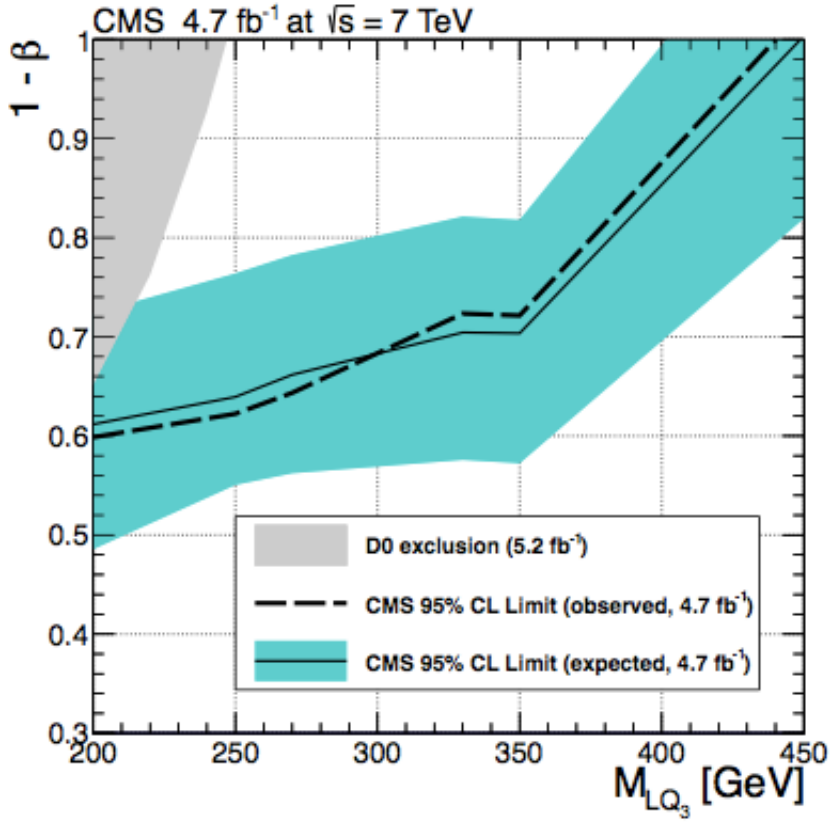


CMS (8 TeV)
M(LQ) > 1070 GeV/c^2 (β=1)
M(LQ) > 785 GeV/c^2 (β=05)
-mini-review update!

LHC Results: 3rd Generation



ATLAS (7 TeV)
M(LQ) > 534 GeV/c^2 (β=1)
Update in mini-review !



CMS (7 TeV)
M(LQ) > 525 GeV/c^2 (β=1)
M(LQ) > 450 GeV/c^2 (β=05)
-mini-review update!

Conclusions and Plans

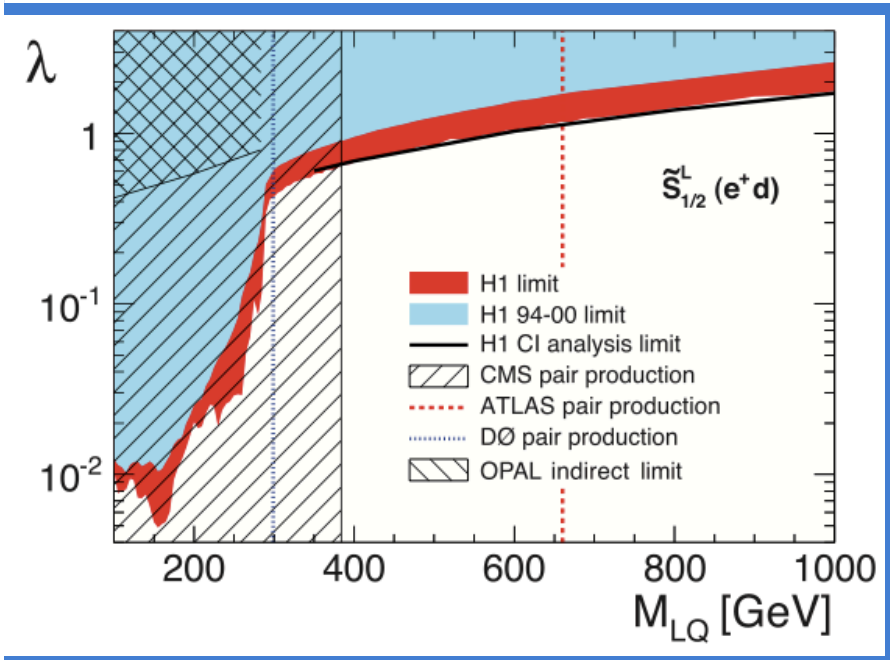
LQ are interesting and a sensible choice for new physics particles;

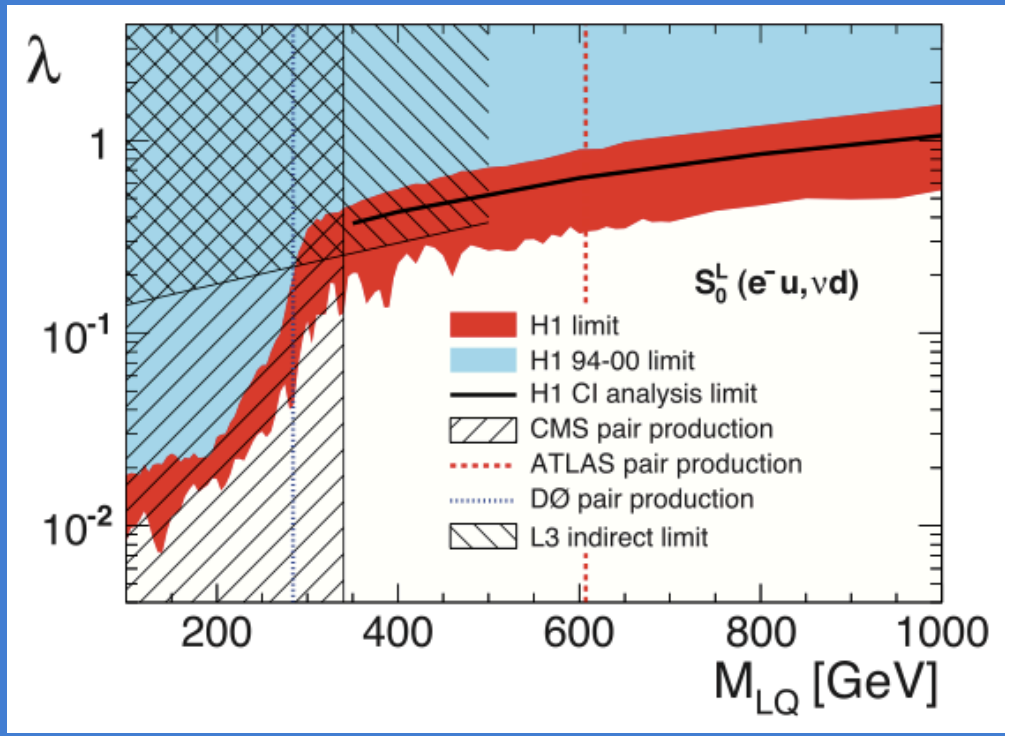
However, so far there is no sign of BSM physics at colliders;
The strongest evidence for BSM physics comes from the neutrino sector and the cosmic frontier (DM and DE)
The neutrino sector is pointing to some form of LFV, which is getting renewed experimental attention at the Intensity Frontier, where much higher scales could be probed;

The PDG LQ mini-review has dutifully reported on HERA, Tevatron and LHC increasing limits

- most stringent up-to-date limits (will make another yearly revision for the 2013 printed version); should remove Tevatron results?
- not much on LFV so far – new HERA results and new theoretical hypotheses driven by renewed experimental efforts at the Intensity Frontier (Mu2E conversion, neutrino sector etc) – plans to expand on this
- Rare decays constraints (encoded in the listing)

Current PDG Summary





Backup

TABLE 1 Leptoquark classification according to electroweak quantum numbers

Type	Q	Coupling	β	F
S_0^L	$-1/3$	$\lambda_L(e_L u)$, $-\lambda_L(\nu_e d)$	1/2	2
S_0^R	$-1/3$	$\lambda_R(e_R u)$	1	2
$\tilde{S}_0^R$	$-4/3$	$\lambda_R(e_R d)$	1	2
S_1^L	$-4/3$	$-\sqrt{2}\lambda_L(e_L d)$	1	2
	$-1/3$	$-\lambda_L(e_L u)$, $-\lambda_L(\nu_e d)$	1/2	2
	$+2/3$	$\sqrt{2}\lambda_L(\nu_e u)$	0	2
$V_{1/2}^L$	$-4/3$	$\lambda_L(e_L \bar{d})$	1	2
	$-1/3$	$\lambda_L(\nu_e \bar{d})$	0	2
$V_{1/2}^R$	$-4/3$	$\lambda_R(e_R \bar{d})$	1	2
	$-1/3$	$\lambda_R(e_R u)$	1	2
$\tilde{V}_{1/2}^L$	$-1/3$	$\lambda_L(e_L u)$	1	2
	$+2/3$	$\lambda_L(\nu_e u)$	0	2
$S_{1/2}^L$	$-5/3$	$\lambda_L(e_L \bar{u})$	1	0
	$-2/3$	$\lambda_L(\nu_e \bar{u})$	0	0
$S_{1/2}^R$	$-5/3$	$\lambda_R(e_R \bar{u})$	1	0
	$-2/3$	$-\lambda_R(e_R \bar{d})$	1	0
$\tilde{S}_{1/2}^L$	$-2/3$	$\lambda_L(e_L \bar{d})$	1	0
	$+1/3$	$\lambda_L(\nu_e \bar{d})$	0	0
V_0^L	$-2/3$	$\lambda_L(e_L \bar{d})$, $\lambda_L(\nu_e \bar{u})$	1/2	0
V_0^R	$-2/3$	$\lambda_R(e_R \bar{d})$	1	0
$\tilde{V}_0^R$	$-5/3$	$\lambda_R(e_R \bar{u})$	1	0
V_1^L	$-5/3$	$\sqrt{2}\lambda_L(e_L \bar{u})$	1	0
	$-2/3$	$-\lambda_L(e_L \bar{d})$, $\lambda_L(\nu_e \bar{u})$	1/2	0
	$+1/3$	$\sqrt{2}\lambda_L(\nu_e \bar{d})$	0	0

Leptoquarks classification
(Buchmuller-Ruckl-Wyler)

F = L + 3B

β = Br (LQ $\rightarrow$ lq)

V/S: vector or scalar

Subscript : weak isospin

Superscript: coupling to left-handed or right-handed fermions

At the Tevatron/LHC LQ production does not depend explicitly on EW quantum numbers