The Search for Leptoquark Pair Production With the CMS Detector at the LHC

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For the CMS Collaboration

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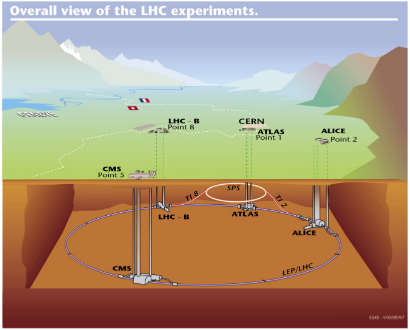
The Large Hadron Collider

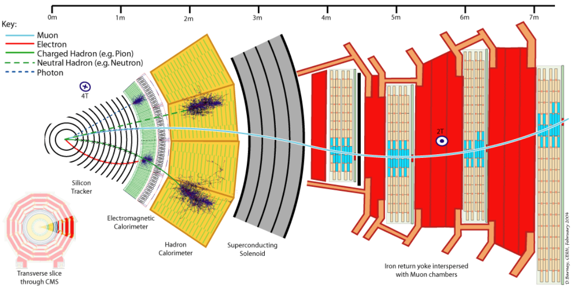
- Is located 175 meters beneath Switzerland and France in 27km of tunnel.
- Is built and operated by a collaboration of over 10,000 scientists and engineers, and hundreds of universities.
- Contains 1232 dipole superconducting magnets for beam circulation and 392 quadrupoles for beam focusing.
- Operates at 1.9^o Kelvin using almost 100 tonnes of liquid He.



- Beam intersects at 4 detectors for proton or heavy ion collisions.
- Is designed for 14TeV pp collisions with bunches colliding at 40MHz.

The Compact Muon Solenoid (CMS) Detector

- It is 15 meters tall, weight over 12 tons, and is designed to take data with 1000 particle tracks streaming through it every 25 ns.
- Inner silicon tracker to determines the tracks and vertices.
- $PbWO_4$ ECAL and brass-scintillator HCAL to measure the energies of photons, electrons, and hadrons.
- Muon subsystem with DTs, RPCs, and CSCs to measure muons with p_T up to 1 TeV in p_T with resolution of 1-5%.



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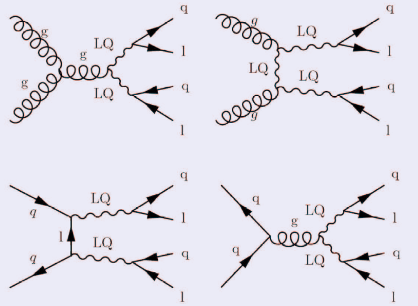
Leptoquark Basics

- LQ's are hypothetical particles carrying both baryon and lepton number.
- Predicted by GUTs, Superstring-inspired E_6 models, Technicolor Schemes, Composite Models, R-Parity violating SUSY
- According to the minimal Buchmüller-Rückl-Wyler (mBRW) general effective Lagrangian, LQs couple to a **single generation**

Leading Order Diagrams



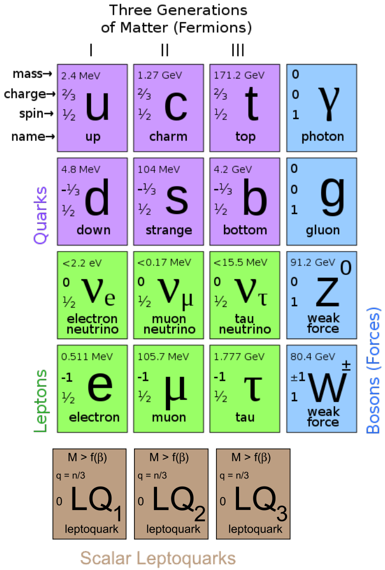
Model Parameters

Model parameters	
M_{LQ}	LQ mass
β	BR(LQ→$l^{+/-}$ + q)
$\lambda_{l\text{-}q\text{-}LQ}$	l-q-LQ coupling
LQs can be scalar* or vector	

(*) In this study

More LQ Theory

- Bosons with both lepton and baryon number and dimensionless coupling to SM fermions.
- Have fractional electric charge.
- Typically considered to couple to single generation to avoid flavor-changing neutral current.
- Direct limits from collider experiments on Mass and β
- Indirect limits at low-energy experiments from LQ-induced four-fermion interactions.
- $\sigma_{\text{LO}} \left[q\overline{q} \vee gg \to \text{LQ} + \overline{\text{LQ}} \right] = f(\alpha_s, M, \hat{s})$
  - Coupling strength λ has no first-order contribution.



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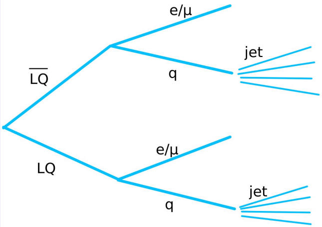
DiLepton DiJet Channel

$LQ + \overline{LQ} \rightarrow lljj$ Final State



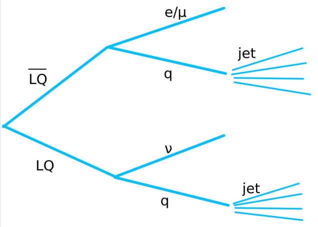
Backgrounds

- Z + 2 or more Jets
- $t\bar{t}$ + jets
  - Both Ws decay leptonically
- Diboson (WW/WZ/ZZ)
- W + Jets
- With a jet faking a lepton
- Multijet Processes
  - With a jet faking lepton

CMS EXO-11-027 and CMS EXO-11-028

Lepton $+\not\!\!E_T$ + DiJet Channel

$\text{LQ} + \overline{\text{LQ}} \rightarrow l\nu jj$ Final State



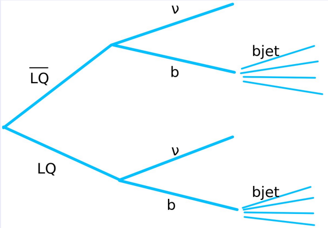
Backgrounds

- W + 2 or more Jets
- $t\bar{t}$ + jets
  - One W decays leptonically
  - One W decays hadronically
- Diboson (WW/WZ/ZZ)
- Z + Jets
  - One lepton fails ID
- Multijet Processes
  - With a jet faking lepton

CMS EXO-11-027 and CMS EXO-11-028

$bb\nu_\tau\nu_\tau$ Channel

LQ + $\overline{\text{LQ}} \rightarrow bb\nu\nu$ Final State



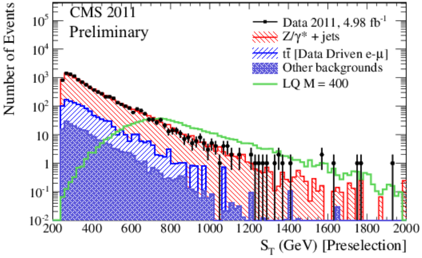
Backgrounds

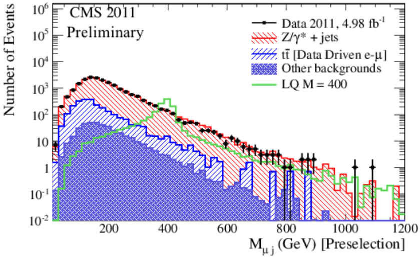
- Heavy Flavor Multijets
- W + HF Jets
- Z + HF Jets
- $t\bar{t}$ + jets
- Diboson

CMS EXO-11-030

Discriminating Variables for *lljj*

- Optimized cuts on M_{ll}, $S_T^{lljj} \equiv p_T(l_1) + p_T(l_2) + p_T(j_1) + p_T(j_2)$, and the LQ ($l$+jet) invariant Mass

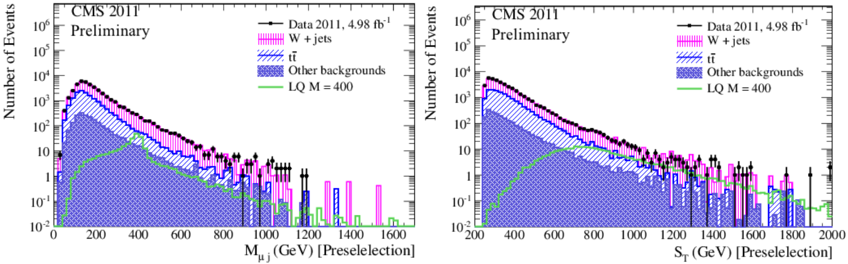




M_{LQ} (GeV)	250	350	400	450	500	550	600	650	750	850
$S_T^{ll} >$ (GeV)	330	450	530	610	690	720	770	810	880	900
$M_{ll} >$ (GeV)	100	110	120	130	130	130	130	130	140	150
$min M(l,\text{jet}) >$ (GeV)	60	160	200	250	300	340	370	400	470	500

Discriminating Variables for $l\nu jj$

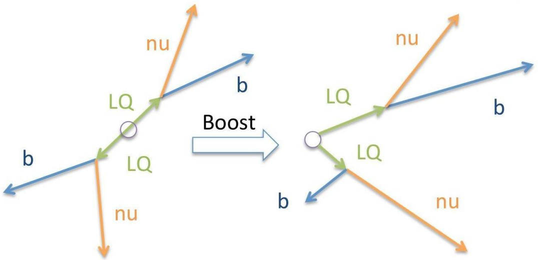
- Demand $M_T^{(l,\not{E}_T)} > 120$ GeV
- Optimized cuts on $\not{E}_T$, $S_T^{l\nu jj} \equiv p_T(l_1) + \not{E}_T + p_T(j_1) + p_T(j_2)$, and the LQ (l+jet) invariant Mass



M_{LQ} (GeV)	250	350	400	450	500	550	600	650	750	850
$S_T^{l\nu} >$ (GeV)	450	570	650	700	800	850	890	970	1000	1000
$E_T^{miss} >$ (GeV)	100	120	120	140	160	160	180	180	220	240
$M(l,\text{jet}) >$ (GeV)	150	300	360	360	360	480	480	540	540	540

Discriminating Variables for $bb\nu\nu$

- Select events with two high p_T b-tagged jets, using track-counting high-efficiency
  - Two good tracks in the jet with high significance of the impact parameter.
- Using a Razor analysis by grouping event products into two "mega-jets"
- Event is viewed in the Razor Frame, a longitudinally boosted frame in which jet energies are equal.
  - $\beta_L^{R^*} \equiv (p_z^{j1} + p_z^{j2})/(E^{j1} + E^{j2})$



- Discrimination performed with the Razor Mass and the Razor Transverse Mass.
  - $M_R \equiv \sqrt{(E^{j1} + E^{j2})^2 - (p_z^{j1} + p_z^{j2})^2}$
  - $M_R^T \equiv \frac{1}{4}\sqrt{\not{E}_T(p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p_T}^{j1} + \vec{p_T}^{j2})}$
  - $R \equiv M_R^T / M_R$

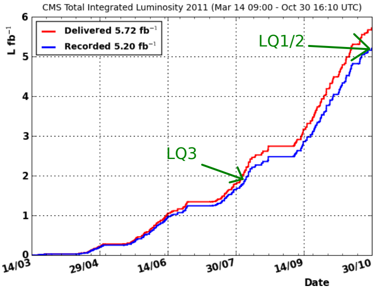
Outline

MC Samples For Signal And Background

- PYTHIA Samples with $\approx 50k$ events at each M_{LQ}; $250 < M_{LQ} < 850$ GeV

m_{LQ}[GeV]	μ/m_{LQ}	σ(NLO)[pb]	PDF uncertainty
250	1	3.47	0.372
400	1	0.205	0.0357
550	1	0.0236	0.00558
700	1	0.00377	0.00114
850	1	0.000732	0.000276

- $t\bar{t}$ events, generated with MADGRAPH;
- W and Z events ($N_{Jets} \leq 5$), with SHERPA in binned by N_{Jets}. [LQ1/2]
- W and Z with MADGRAPH [LQ3]
- DiBoson WW,WZ,ZZ generated with MADGRAPH;



Background Estimation

$LQ + \overline{LQ} \rightarrow lljj$ Final State

- Z MC scale factor derived in the control region $80 < M_{ll} < 100 GeV$
- $t\bar{t}$ determined from data with orthogonal $e - \mu$ sample.
- Multijet with fake-rate method.

$LQ + \overline{LQ} \rightarrow l\nu jj$ Final State

- W MC scale factor derived in the control region $50 < M^T_{l\nu} < 110 GeV$
- $t\bar{t}$ MC scaled to data in the $N_{jet} \geq 4$ control region.
- Multijet with fake-rate method.

$LQ + \overline{LQ} \rightarrow bb\nu\nu$ Final State

- Backgrounds are determined as the shape of the M_R variable.
  - Empirically, M_R fits well to two exponentials of differing slopes.
  - Shapes can be derived in orthogonal control regions containing leptons.
  - For various cuts on R
- W/Z shapes from simulation.
- $t\bar{t}$ from control region with tight μ.
- HF Multijets from control region with loose μ.
- Normalizations from side band of search region (high H_T)

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Systematic Uncertainties

LQ1/2 Uncertainties

Uncertainty	Magnitude
Jet Energy Scale	4%
Background modeling	Varies
e Energy Scale	1(3)%
e Trigger/Reco/ID/Iso	3%
μ Momentum Scale	1%
μ Reco/ID/Iso	1%
Jet Resolution	$(5-14)\%$
Electron Resolution	1(3)%
Muon Resolution	4%
Pileup	8%
Integrated Luminosity	2.2%

LQ3 Uncertainties

Uncertainty	Magnitude
Jet Energy Scale	3%
B-Tagging Efficiency	10%
M_R Shape	9%
Lepton Trigger	3%
Razor Trigger	2%
Integrated Luminosity	4.5%

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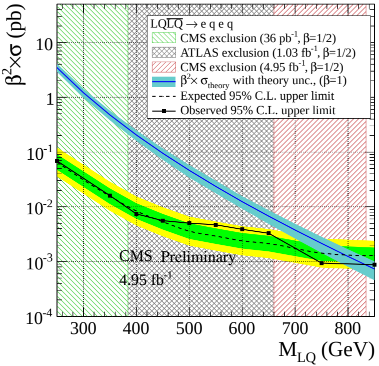
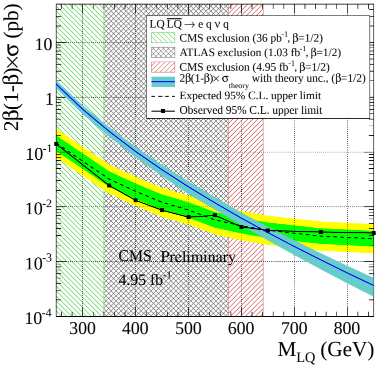
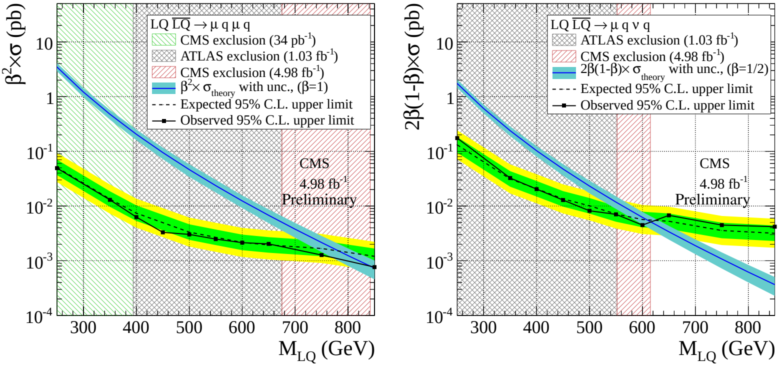
LQ1 Limits





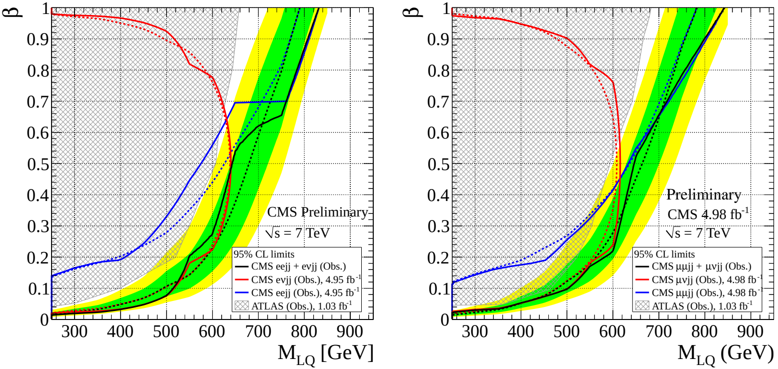
Using the CL_S frequentist method, first generation scalar LQs are excluded with masses less than 834 (641) GeV with the assumption that $\beta = 1(0.5)$. The median expected limit is 792 (640) GeV.

LQ2 Limits



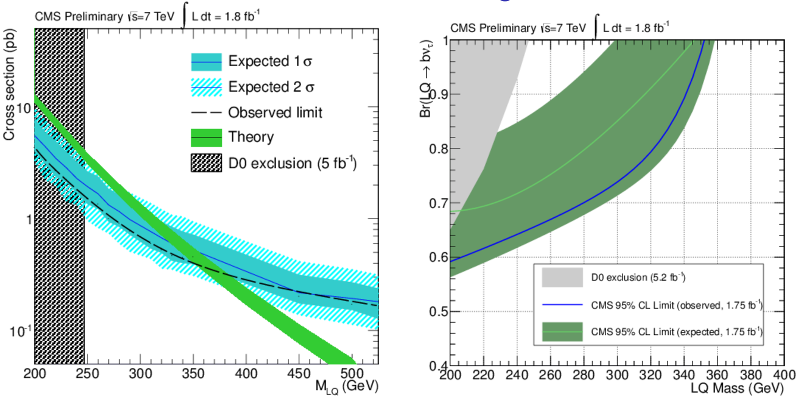
Using the CL_S frequentist method, second generation scalar LQs are excluded with masses less than 842 (615) GeV with the assumption that $\beta = 1(0.5)$. The median expected limit is 785 (609) GeV.

Combination of *lljj* and *lνjj* channels.



Combining the *lljj* and *lνjj* channels, the observed and expected limits on β vs M_{LQ} can be further improved. For $\beta = 1/2$, the observed limits on mass becomes 642 and 646 GeV for first and second generation LQ's, respectively.

LQ3 Results For Unit and Variable Branching



Third generation scalar LQs with masses less than 350 GeV with the assumption that $\beta = 0$. The median expected limit is 340 GeV. Limits are also shown for variable branching ration $\mathrm{BR}(\mathrm{LQ} \to b\nu) = (1 - \beta)$.

Outline

Conclusions and looking forward.

- Using the most recent 7TeV Data from the CMS Detector, we've made huge improvements on the known limits of leptoquark pair production.
- Results include scalar leptoquarks in three generations.
- Efforts are underway to continue with increased energy and integrated luminosity in 2012.
- We'd like to thank our collaborators at CMS and the LHC for their tremendous efforts and success in keep the collider and detectors productive and operational.