Leptoquarks directly at the LHC

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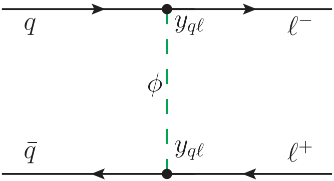
04.07.2017

Contents

What are leptoquarks

Drell-Yan process at tree level



arXiv:1610.03795

- Six scalar LQ and six vector LQ
- Two scalar LQ that don't violate Baryon number
  - R_2 $(\mathbf{3}, \mathbf{2}, 7/6)$ and $\tilde{R}_2$ $(\mathbf{3}, \mathbf{2}, 1/6)$
- Terminology: ElectroUp, MuoUp,...

- $\mathcal{L} = -y_{ij}\bar{u}_{R,i}R_2^a\epsilon^{ab}L_{L,j}^b + y'_{ij}\bar{e}_{R,i}R_2^{a*}Q_{L,j}^a +$ h.c.

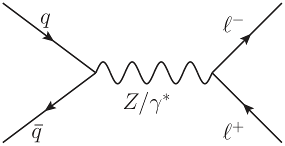
Reasons for research

- Grand unified theory
- Mediators of dark matter-SM interactions
- Feature in models beyond the SM like SUSY, technicolour and composite models
- Explanation for some anomalies in low-energy flavour experiments
- One possibility of NP particle that couples to SM fermions

- Indirect searches provide stronger limits
- Hints even if
  - Mass of LQ-pair higher than collision energy
  - Coupling strength of single production too low for direct detection

Reasons for dilepton measurements

Drell-Yan process at tree level



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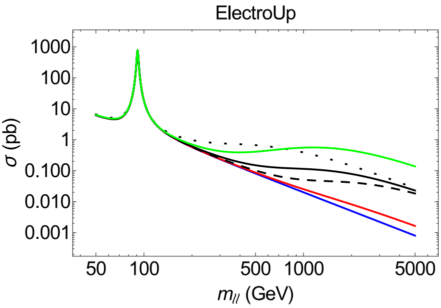
- More precisely reconstructed than most other final states
- Easily triggerable
- Background sources well known
- High rates

- LQ produce a peak in the invariant mass spectrum (m_{ll})
- LQ produce a left-right or forward-backward asymmetry in the angular spectrum

m_{ll} probe

- $d\sigma_{\text{tot}} \equiv \frac{d\sigma_{\text{tot}}}{d\cos\theta} = d\sigma_{\text{SM}} + d\sigma_{\text{int}} + d\sigma_{\text{LQ}}$



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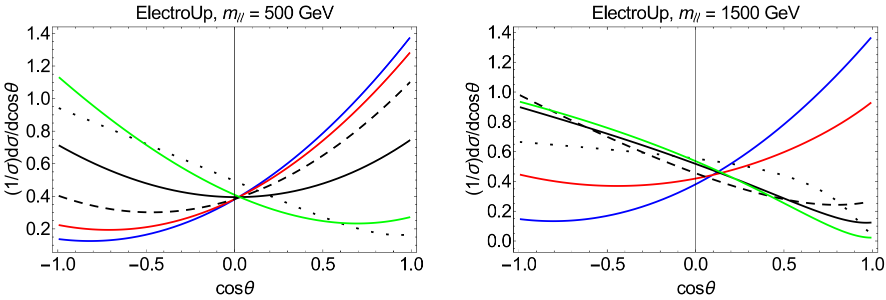
- Constructive interference increase the rate of dileptons
- LeptoUps interfere always constructive
- Destructive interference for small y_{de} and/or high m_{LQ}

- $m_{ll} \gg m_{LQ}$: $d\sigma_{\text{tot}} \approx d\sigma_{\text{SM}} + const.$

Dilepton angular distribution



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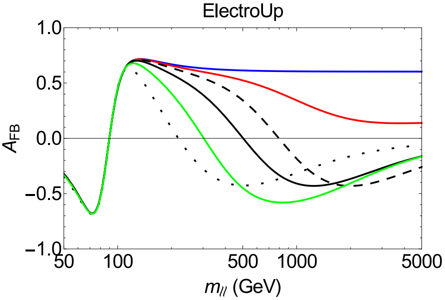
- Normalized cross-section for two different m_{ll}
- Huge difference between SM and LQ model

Definition forward-backward asymmetry

$$A_{FB} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] dc_\theta \frac{d^2\sigma}{dc_\theta dm_{ll}}}{\left[\int_0^1 + \int_{-1}^0\right] dc_\theta \frac{d^2\sigma}{dc_\theta dm_{ll}}} = \frac{N_F - N_B}{N_{tot}}$$



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Forward-backward asymmetry by Collins and Soper

- Boost every event along the beam axis to the dilepton centre-of-momentum frame
- Neglect the transverse momentum

$$\cos\theta_{CS} = \frac{p_z^{tot}}{|p_z^{tot}|} 2 \frac{p_+^{l^-} p_-^{l^+} - p_+^{l^+} p_-^{l^-}}{m_{ll}^2} \quad \text{with} \quad p_\pm^i \equiv \frac{(E^i \pm p_z^i)}{\sqrt{2}}$$

$$A_{FB}^{CS} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)} \quad \text{with} \quad \Delta|\eta| \equiv |\eta^-| - |\eta^+|$$

Problems with forward-backward asymmetry by Collins and Soper

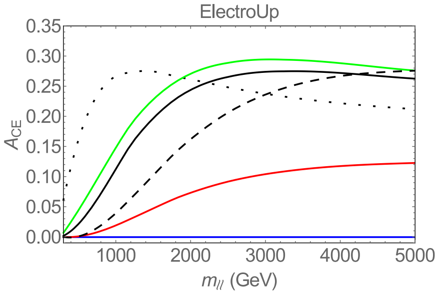
- $\Delta\,|\eta|$ isn't invariant under longitudinal Lorentz boosts
- Use not-so-evident analytical equations or use a Monte Carlo phase shift generator
- $A_{FB}(SM)$ vanishes for γ and is finite for Z mediated processes

The angular distribution should be

- frame-independent
- vanishing in SM

Centre-edge asymmetry

- Angular distribution depends on $|\Delta\eta|$
- There is always a well-fitting y_0 that fulfils $A_{CE}(SM) = 0$



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$$A_{CE}(m_{ll}) = \frac{N\left(0 < |\Delta\eta| < y_0\right) - N\left(y_0 < |\Delta\eta| < y_{max}\right)}{N\left(0 < |\Delta\eta| < y_0\right) + N\left(y_0 < |\Delta\eta| < y_{max}\right)}$$

Atomic parity violation

- Wood, et al measured 1997 the nuclear weak charge in caesium-133
- LQ change the value depending on the coupling $\left|y_{(u,d)e}\right|^2$

Muon anomalous magnetic moment

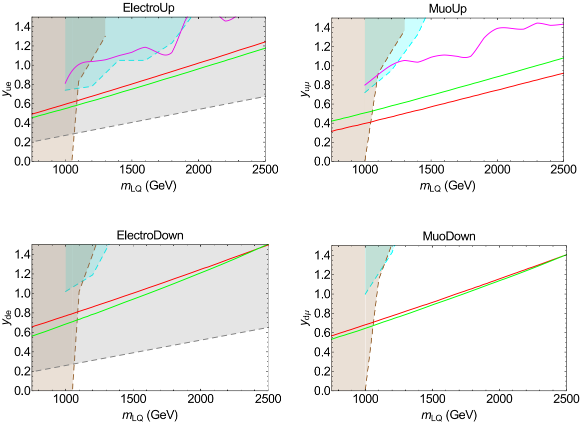
- 3σ discrepancy between experimental and theoretical value of $a_\mu = \frac{(g-2)_\mu}{2}$
- Constraining limits are weaker than limits from other probes

Single and pair production

- The final state of single produced LQ is l^+l^-j
- LQ change the amplitude of Drell-Yan processes
- Sensitive to coupling y_{LQ} and mass m_{LQ} of LQ

- Pair-produced LQ decaying to l^+l^-jj, $\nu\bar{\nu}jj$ and $\nu l^{\pm}jj$
- LQ change m_{ll} and transverse Energy E_T
- Pair-produced LQ are QCD-dominated and hence only sensitive to small y_{LQ}

Complete measurement results



- m_{ll} spectra from ATLAS
- m_{ll} from M. B. Wise and Y. Zhang
- A_{FB} from CMS
- Pair production from ATLAS
- Single production from CMS
- APV with 2σ from Wood, et al

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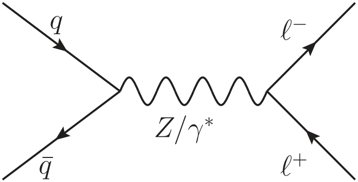
Summary



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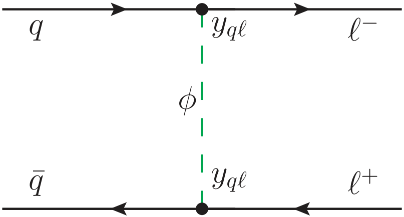

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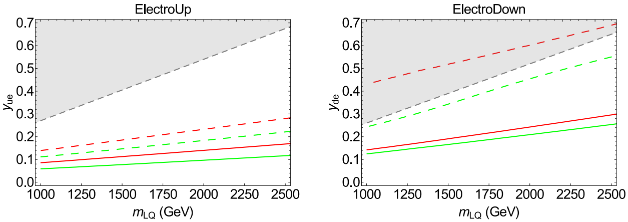
- $d\sigma_{\text{tot}} = d\sigma_{\text{SM}} + d\sigma_{\text{int}} + d\sigma_{\text{LQ}}$
- Differences between SM and LQ in angular distributions like forward-backward asymmetry
- Up to now only limits to the mass and coupling of LQ

Outlook



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- Atomic parity violation
- Forward-backward asymmetries
- m_{ll} spectra
- Dashed: integrated luminosity $\mathcal{L} = 300\,\text{fb}^{-1}$
- Solid: integrated luminosity $\mathcal{L} = 3000\,\text{fb}^{-1}$

Outlook

- More data with LHC run ii
- Probe with other quarks

Literature

- N. Raj; Anticipating Non-Resonant New Physics in Dilepton Angular Spectra at the LHC; 2016; (arXiv:1610.03795)
- I. Doršner, et al; Physics of leptoquarks in precision experiments and at particle colliders; 2016; (arXiv:1603.04993)
- J. C. Collins, D. E. Soper; Angular distribution of dileptons in high-energy hadron collisions; 1977; (DOI:10.1103/PhysRevD.16.2219)

Literature

- M. B. Wise, Y. Zhang; Effective Theory and Simple Completions for Neutrino Interactions; 2014; (arXiv:1404.4663)
- C. S. Wood, et al; Measurement of parity nonconservation and an anapole moment in cesium; 1997; (DOI:10.1126/science.275.5307.1759)
- G. W. Bennett et al. [Muon g-2 Collaboration]; Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL; 2006; (arXiv:hep-ex/0602035)

m_{ll} distribution

$$d\sigma_{\mathsf{SM}} = \frac{1}{32\pi m_{ll}^2 N_c} \sum_{\text{spins}} |\mathcal{M}_{SM}|^2$$

$$d\sigma_{\mathsf{int}} = -\frac{1}{32\pi m_{ll}^2 N_c} \sum_{\text{spins}} 2\Re\left(\mathcal{M}_{SM}\mathcal{M}_{LQ}^*\right)$$

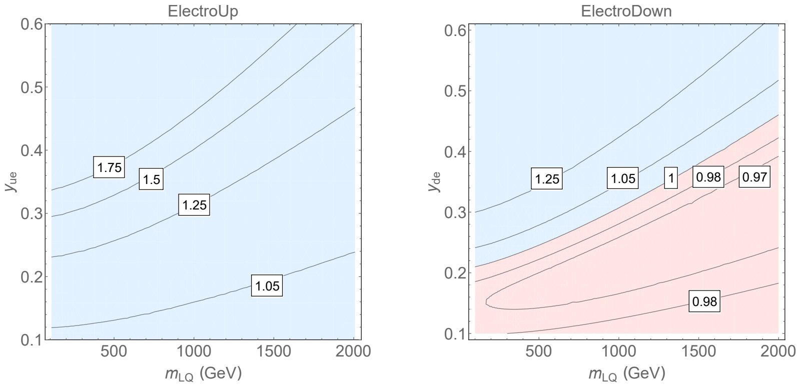
$$d\sigma_{\mathsf{LQ}} = \frac{1}{32\pi m_{ll}^2 N_c} \sum_{\text{spins}} |\mathcal{M}_{LQ}|^2$$

with the number of QCD colours $N_c = 3$, the SM amplitude $\mathcal{M}_{SM} = \mathcal{M}_\gamma + \mathcal{M}_Z$ and the amplitude for the LQ $\mathcal{M}_{LQ}$

m_{ll} distribution

$$
\begin{aligned}
\mathcal{M}_\gamma =& iQ_q e \left[\bar{v}(p_{\bar{q}})\gamma^\mu u(p_q)\right] \frac{-g_{\mu\nu}}{m_{ll}^2} \left[\bar{u}(p_{l-})\gamma^\nu v(p_{l+})\right] \\
\mathcal{M}_Z =& i \left[\bar{v}(p_{\bar{q}})\gamma^\mu \left(g_L^q P_L + g_R^q P_R\right) u(p_q)\right] \frac{-g_{\mu\nu}}{m_{ll}^2 - M_Z^2 - i\Gamma_Z M_Z} \\
& \left[\bar{u}(p_{l-})\gamma^\nu \left(g_L^q P_L + g_R^q P_R\right) v(p_{l+})\right] \\
\mathcal{M}_{LQ} =& i y_{ql}^2 \left[\bar{v}(p_{\bar{q}}) P_R v(p_{l+})\right] \frac{1}{\hat{t} - m_{LQ}^2} \left[\bar{u}(p_{l-}) P_L u(p_q)\right]
\end{aligned}
$$

Constructive and destructive interference



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Contours of the ratio $\frac{d\sigma_{\text{tot}}}{d\sigma_{\text{SM}}}$ at $m_{ll} = 1500 GeV$

Forward-backward asymmetry in the SM

Analytical solution for the SM forward-backward asymmetry for $m_{ll} \gg M_Z$:

$$A_{FB} = \frac{3}{4} \frac{\beta_e \Gamma_-^1 + \Gamma_-^2}{\beta_e^2 + \beta_e \Gamma_+^1 + \Gamma_+^2}$$

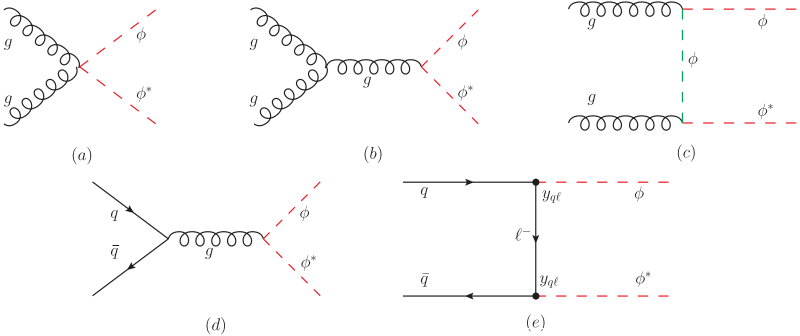
where

$$\beta_e = 2e^2 Q_q Q_l$$
$$\Gamma_\pm^n = \left[\left(g_L^q\right)^n \pm \left(g_R^q\right)^n\right] \left[\left(g_L^l\right)^n \pm \left(g_R^l\right)^n\right]$$

$A_{FB}(SM, q = u, l = e) = 0.6043$ and $A_{FB}(SM, q = d, l = e) = 0.6365$

Direct searches with pair production

Pair production Feynman diagrams



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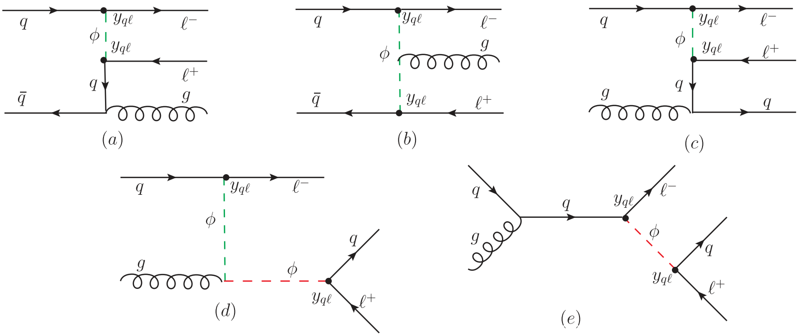
Direct searches with pair production

Single production Feynman diagrams



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