Aspects of BSM Physics at LHeC

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for the LHeC Collaboration

overview of some recent and ongoing preliminary work on exotic physics at LHeC

- Brief introduction to LHeC
- BSM processes
  - Leptoquarks
  - heavy and excited fermions
  - contact interactions
  - diquarks

LHeC

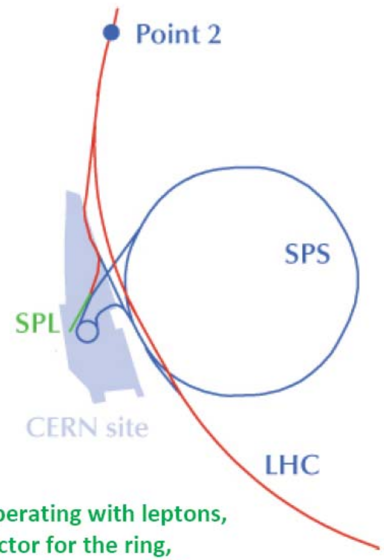
Assume 7 TeV LHC proton or nucleus beam

- Ring-Ring option
  - E_e = 10… 80 GeV
    Luminosity ~ 10^{33} cm^{-2}s^{-1}

Ring-Linac option

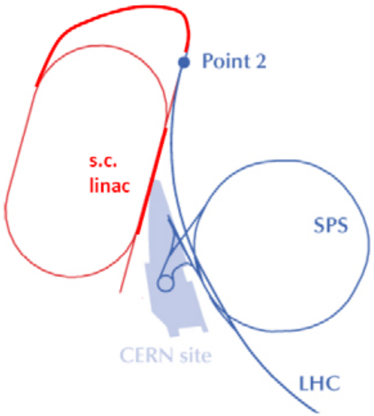
- E_e = 60 GeV, pulsed or CW ➔ $\sqrt{s} = 1.3$ TeV
- Ee = 140 GeV, pulsed ➔ $\sqrt{s} = 2.0$ TeV

Luminosity: ~ 10^{32} cm^{-2}s^{-1} at high energy



SPL, operating with leptons, as injector for the ring, possibly with recirculation

- polarization difficult



up to 70 GeV: option for cw operation and recirculation with energy recovery; > 70 GeV: pulsed operation at higher gradient ; γ-hadron option

- γ-p option
- e^+ luminosity low
- polarization possible

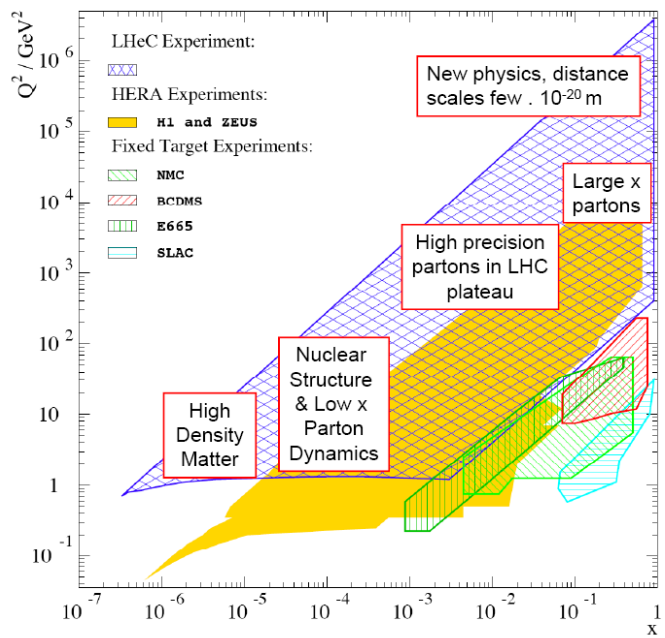
- Detector design under study → *see talk by P. Kostka [297]*

F. Zimmermann at PAC09, Vancouver
http://www.ep.ph.bham.ac.uk/exp/LHeC//talks/zimmermann.PAC09.pdf
→ see also talk by J. Jowett [290]

Introduction

We project into the future:

- LHC is a "discovery machine"
  ➔ new bsm physics will likely be discovered there first
  - we will assume E_{CM} = 14 TeV and $\int \mathcal{L}\, dt$ = 100 fb^{-1} achieved at LHC
- LHeC:
  - rich physics program in QCD and pdf
    → see previous talks, this morning in Future of DIS session: O. Behnke, K. Kutak, J. Rojo, N Armesto Perez
  - BSM: What could be the "added value" of LHeC ?
    - improved pdfs
      ➔ higher precision from measurements performed at LHC
    - cleaner environment, better S/N
    - new observables in specific processes
      - Higgs couplings to bb
        → see next talk, U. Klein
      - Leptoquarks
      - heavy and excited fermions, diquarks



Leptoquarks

Leptoquarks are predicted in extensions of the SM

- E_6: new fields possibly having both B and L quantum numbers
- technicolor: bound states of technifermions
- Pati-Salam: lepton is a 4th quark color
- squarks decaying by R-parity violation $\mathcal{W}_{RPV} = \lambda'_{ijk} L_i Q_j \bar{D}_k \Rightarrow \begin{cases} e^- + \bar{d} \to \bar{\tilde{u}} \to e^- + \bar{d} \\ e^- + u \to \tilde{d} \to e^- + u \end{cases}$

LQ's carry baryon and lepton number; can be scalar or vector
➔ Buchmüller classification

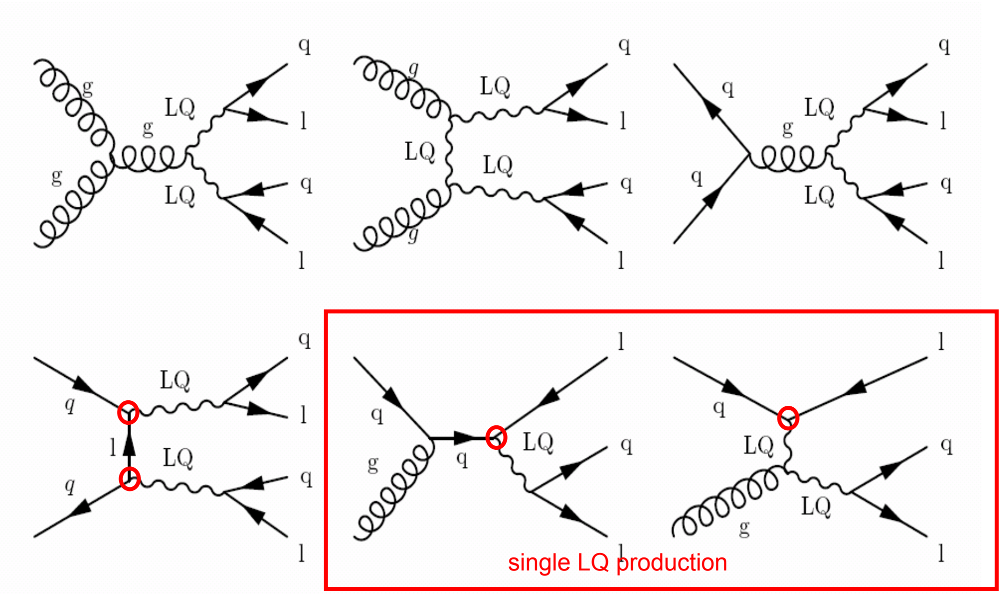
Quantum numbers of scalar and vector leptoquarks with $SU(3)\times SU(2)\times U(1)$ invariant couplings to quark–lepton pairs ($Y=Q_{em}-T_3$).

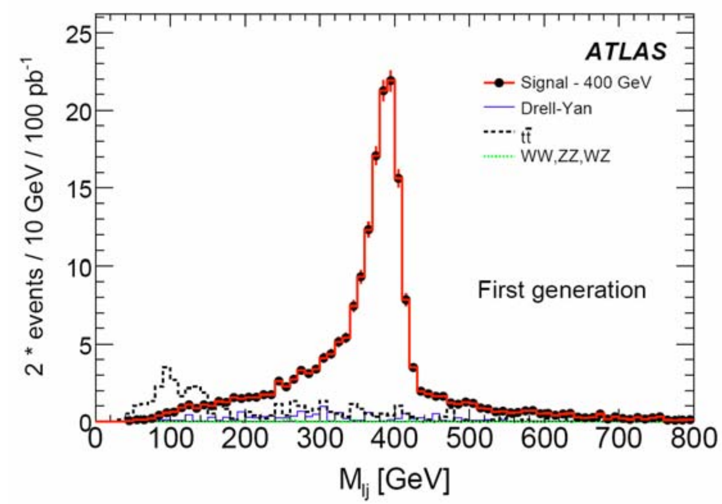
	Spin	$F=3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
S_1	0	−2	3*	1	$\frac{1}{3}$
$\tilde{S}_1$	0	−2	3*	1	$\frac{4}{3}$
S_3	0	−2	3*	3	$\frac{1}{3}$
V_2	1	−2	3*	2	$\frac{5}{6}$
$\tilde{V}_2$	1	−2	3*	2	$-\frac{1}{6}$
R_2	0	0	3	2	$\frac{7}{6}$
$\tilde{R}_2$	0	0	3	2	$\frac{1}{6}$
U_1	1	0	3	1	$\frac{2}{3}$
$\tilde{U}_1$	1	0	3	1	$\frac{5}{3}$
U_3	1	0	3	3	$\frac{2}{3}$

- family mixing
  → FCNC and LFV

- non-chiral ? (couple to L and to R quarks simultaneously)
  → lepton universality

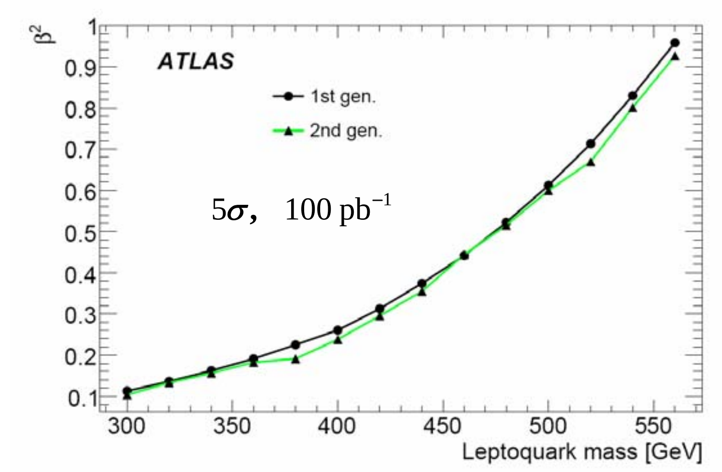
at the LHC





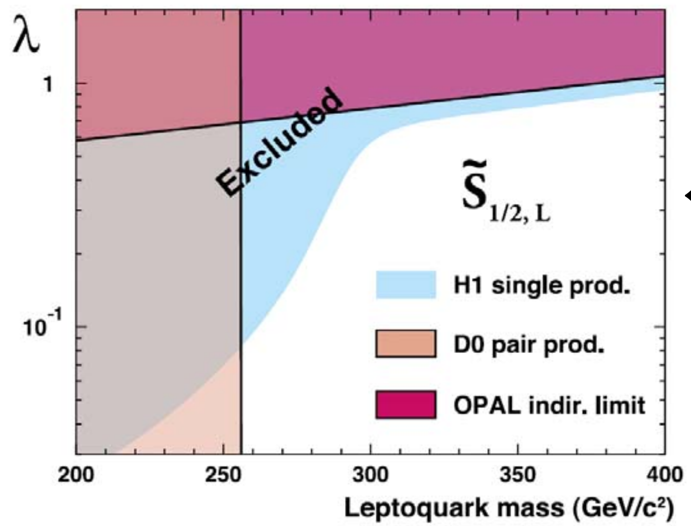
At the LHC, pair production is essentially independent of the LQ-q-e coupling λ

single production suppressed by dependence on λ

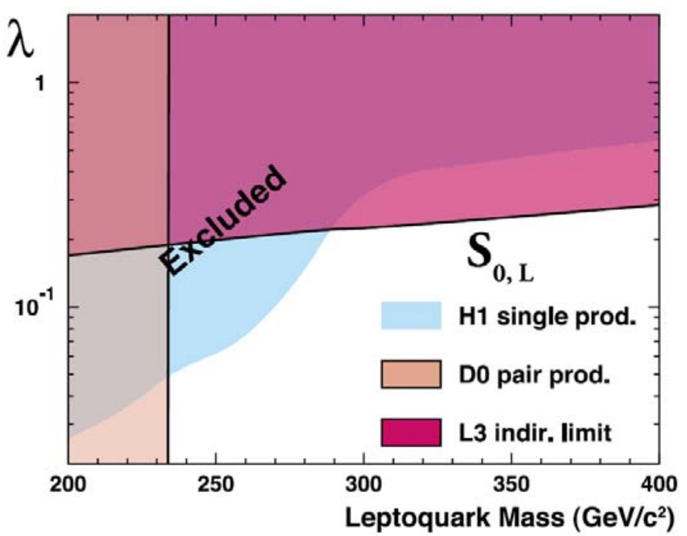


ATLAS Collaboration, CERN-OPEN-2008-020 (arXiv:0901.0512)

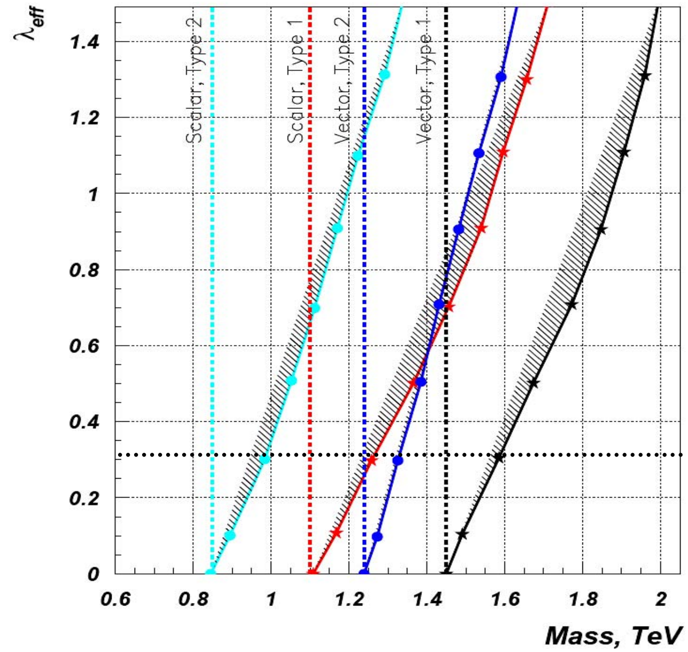
Present and expected bounds or discovery reach



$\leftrightarrow \tilde{R}_2$



$\leftrightarrow S_1$



LHC
300 fb^{-1}

$\lambda_{\mathrm{eff}} = e = \sqrt{4\pi\alpha} = 0.312$

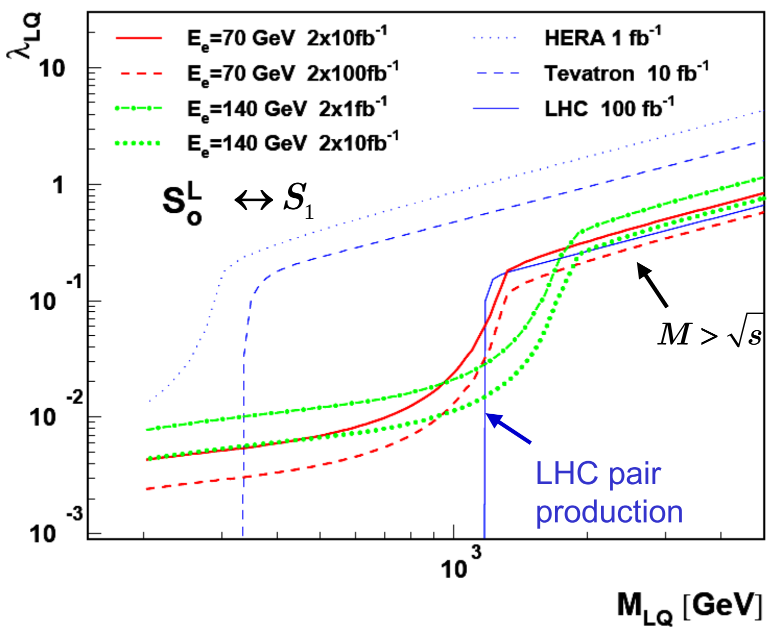
combined single and pair production, eq and νq channels

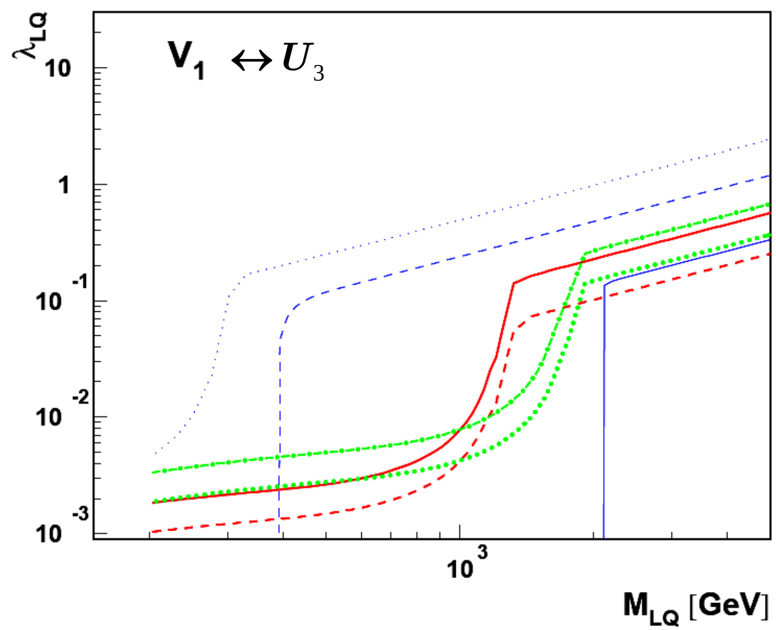
single + pair production
type 1 : $2\ell + j$
type 2 : $\ell + j + \not{E}_T$

Particle Data Group, http://www-pdg.lbl.gov/

A. Belyaev et al., JHEP0509:005,2005 (arXiv:hep-ph/0502067)

LQ at LHeC





DIS background suppressed by cut on $y = \frac{1}{2}(1 - \cos\theta^*)$

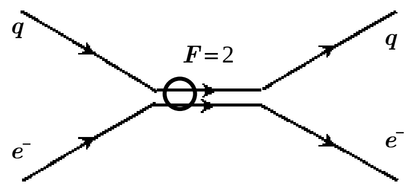
A F Żarnecki(arXiv:0809.2917v1)

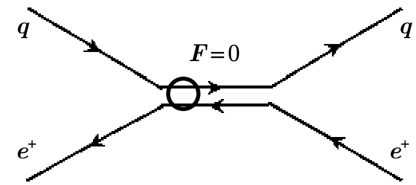
If LQs are discovered, what can we learn at the LHeC?

Quantum numbers and couplings:

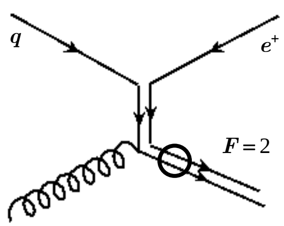
- **F: fermion number can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$**

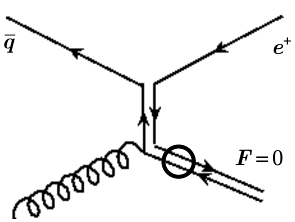
$$A = \frac{\sigma_{e^-} - \sigma_{e^+}}{\sigma_{e^-} + \sigma_{e^+}} \begin{cases} > 0 \text{ for F=2} \\ < 0 \text{ for F=0} \end{cases}$$

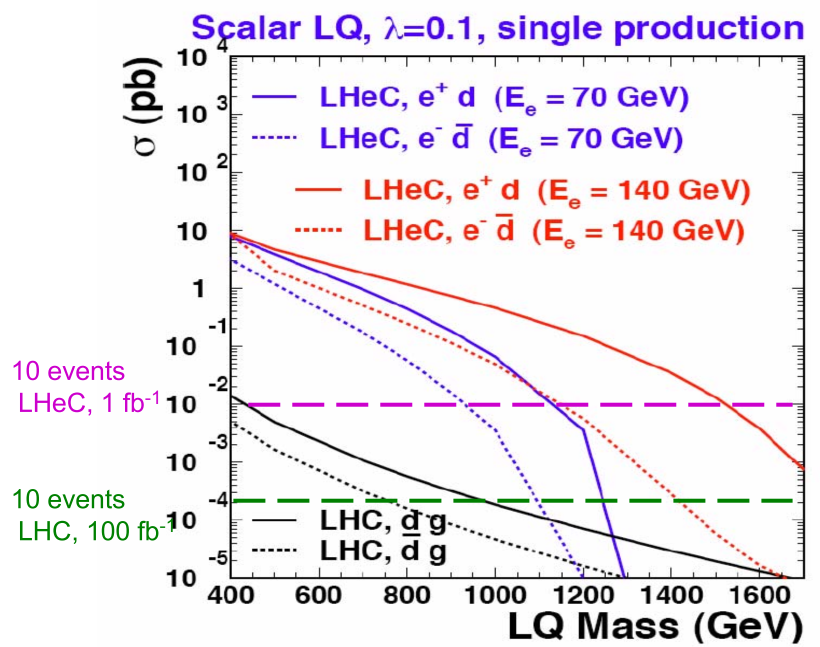




- **can also be probed in single LQ production at the LHC, but cross section is low**

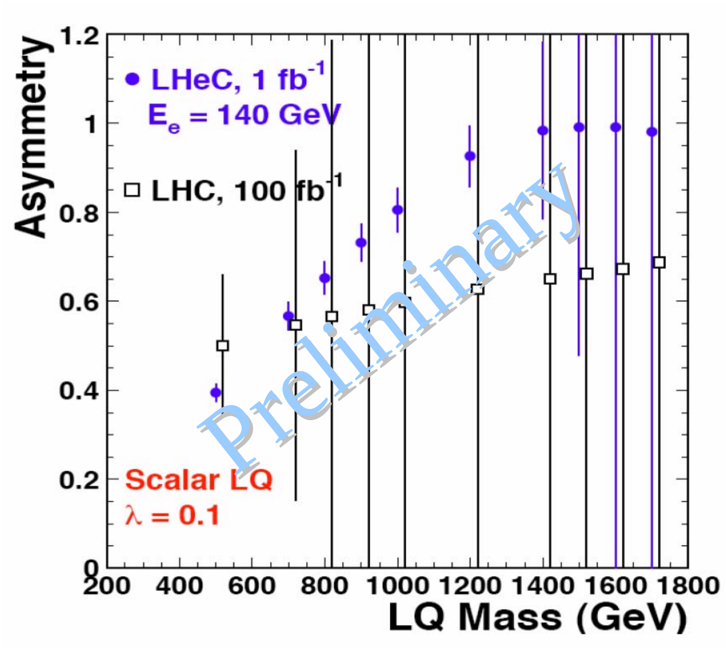




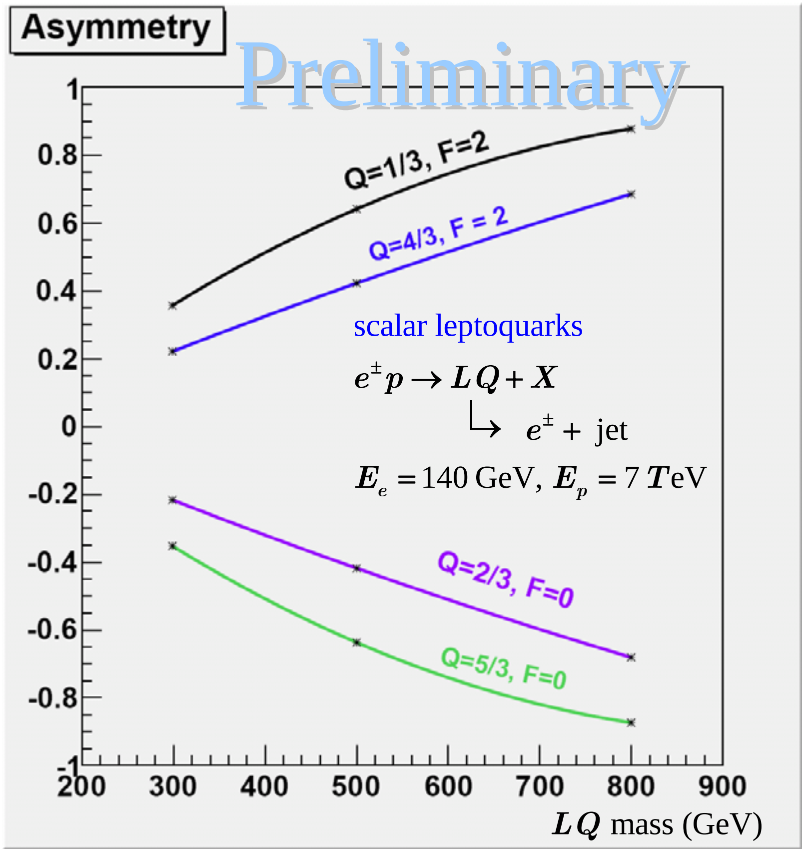


Note: $\gamma \to ee$ followed by $ep \to LQ$ not yet considered

If LQs are discovered, what can we learn at the LHeC?



Asymmetry also probes the **LQ charge**:



At LHC, we have poorer precision on the asymmetry

main backgrounds:

$Z +$ jets, fake electrons

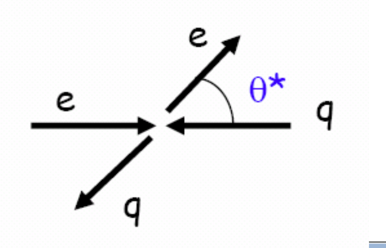
note: LQs belonging to an isodoublet might be degenerate

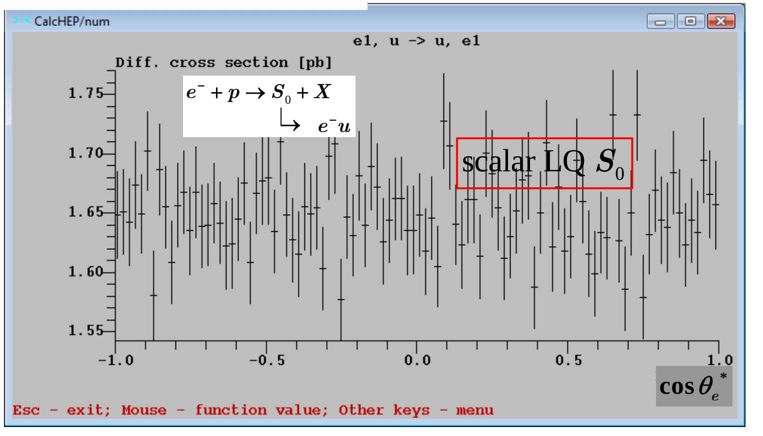
Preliminary results obtained with CalcHEP, new LQ model by A. Belyaev and A. Pukhov (private comm.)

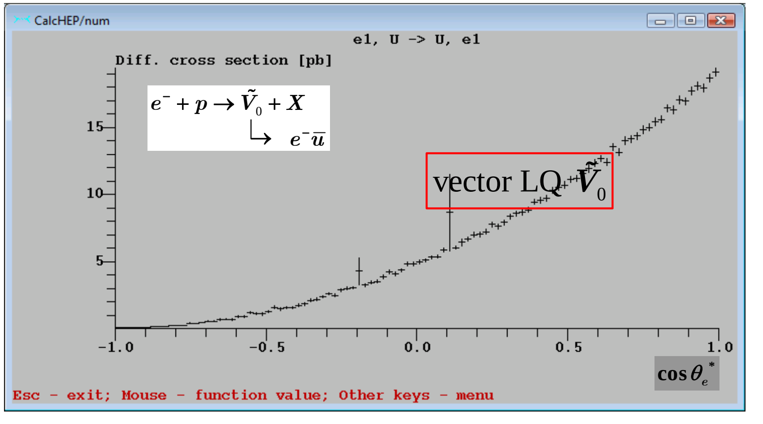
If LQs are discovered, what can we learn at the LHeC?

- Quantum numbers and couplings:
  - spin
    - at LHC, pair production of LQ-LQ leads to angular distributions which depend on the g-LQ-LQ coupling
      ➔ may need to look for spin correlations
    - at LHeC, cos θ* distribution is sensitive to the spin
    - vector leptoquarks can have anomalous couplings
  - chiral ?
    - could be probed by measuring sensitivity of cross sections to polarization of the electron beam
  - generation mixing ?
    - does LQ decay to 2nd generation?
      H1 Coll., Eur. Phys. J. C 11, 447 (1999)
  - RPV in squark decays
    - measure of R-parity violation in production and decay
  - BR to neutrino
    - good S/B in νj channel

$$e_L^- u_L \rightarrow S_3 \rightarrow \nu_e d_L$$





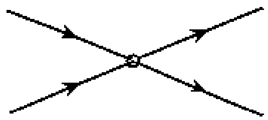


Preliminary results obtained with CalcHEP,
new LQ model by A. Belyaev and A. Pukhov (private comm.)

Contact Interactions

New physics could be at a higher scale $\Lambda \gg \sqrt{s}$ **:** $\Rightarrow M_{eq\to eq} \sim \Lambda^{-2}$

$\Lambda =$ LQ mass >> √s,
M_S of extra dimension models,
compositeness scale

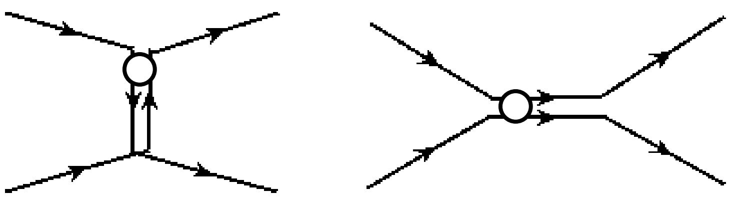


$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)};$$

$$j_\mu^{(f=e,q)} = \eta_L \, \bar{f}_L \gamma_\mu f_L + \eta_R \, \bar{f}_R \gamma_\mu f_R + h.c.$$

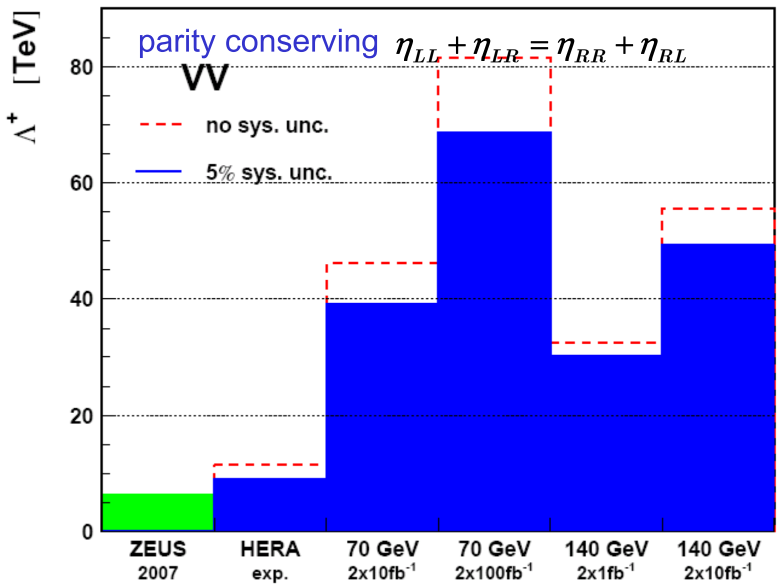
$\Rightarrow$ all combinations of couplings $\eta_{ij} = \eta_i^{(e)} \eta_j^{(q)}; \quad q = u, d$

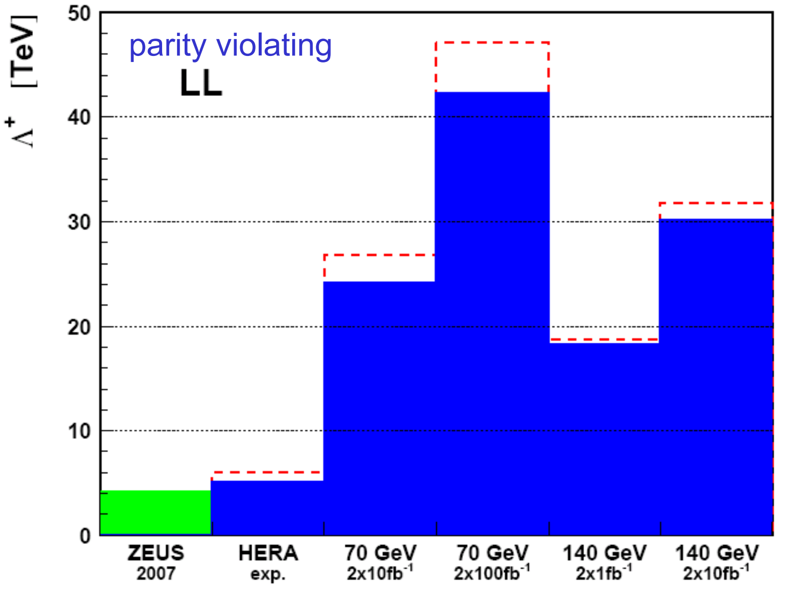
for comparable scale,
s, u **channels must be treated separately**
(e.g. graviton exchange, LQ exchange)



A.F. Zarnecki, arXiv:0809.2917

95% exclusion limits

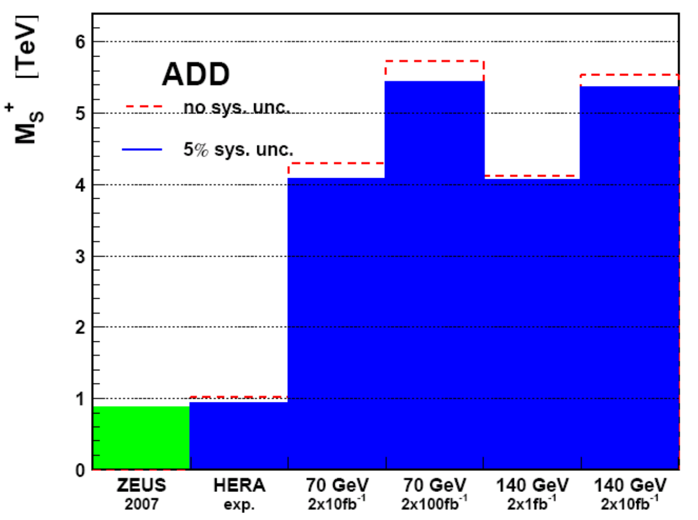




Large extra dimensions model

$$\eta_{LL}=\eta_{RR}=\frac{\mp\pi}{2M_S^4}(4t+s)$$

$$\eta_{LR}=\eta_{RL}=\frac{\mp\pi}{2M_S^4}(4t+3s)$$



A. F. Zarnecki, arXiv:0809.291

Excited fermions

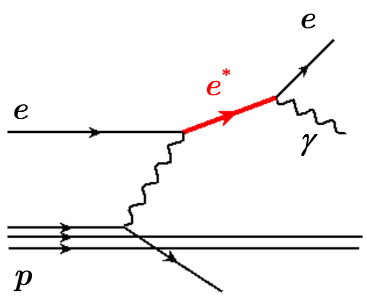
- Excited fermions could be produced directly if their mass is below compositeness scale
  Assume spin = ½, L, R doublets
  - gauge interaction Lagrangian

$$\mathcal{L} = \frac{1}{2\Lambda}\bar{f}^*_R \sigma_{\mu\nu}\left[g f \frac{\tau_a}{2} W^a_{\mu\nu} + g' f' B_{\mu\nu} + g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu}\right] f_L$$

  - contact interaction Lagrangian

$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu j^\mu;$$

$$j_\mu = \eta_L \bar{f}_L\gamma_\mu f_L + \eta'_L \bar{f}^*_L \gamma_\mu f^*_L + \eta''_L \bar{f}^*_L\gamma_\mu f_L + h.c. + (L\leftrightarrow R)$$



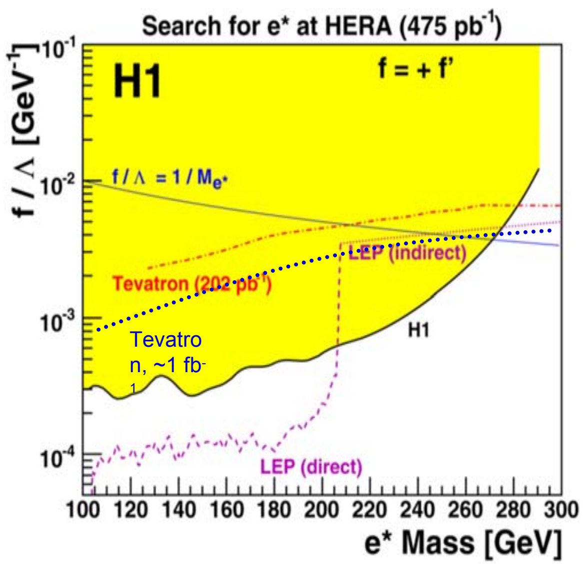
present limits

LHC could probe up to 1-2 TeV

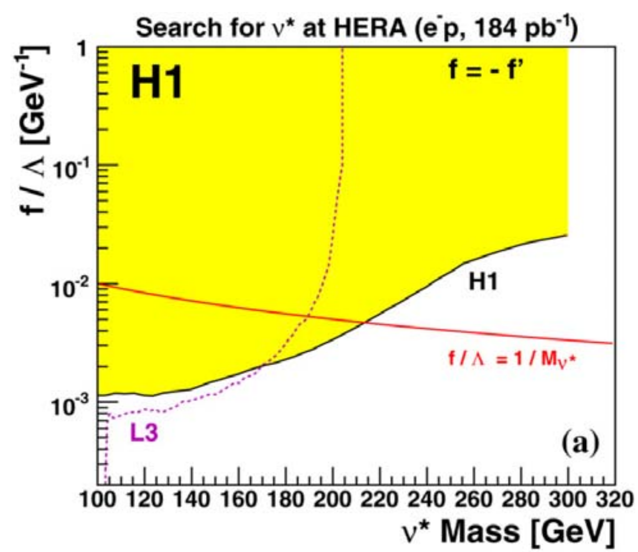
for $f = f' = 1, \Lambda = m_{e^*}$

O. Cakir, A. Yilmaz, S. Sultansoy, PR D70 (2004) 075011,

A. Belyaev, C. Leroy, R. Mehdiyev, Eur Phys J C 41, s02, 1–10 (2005)



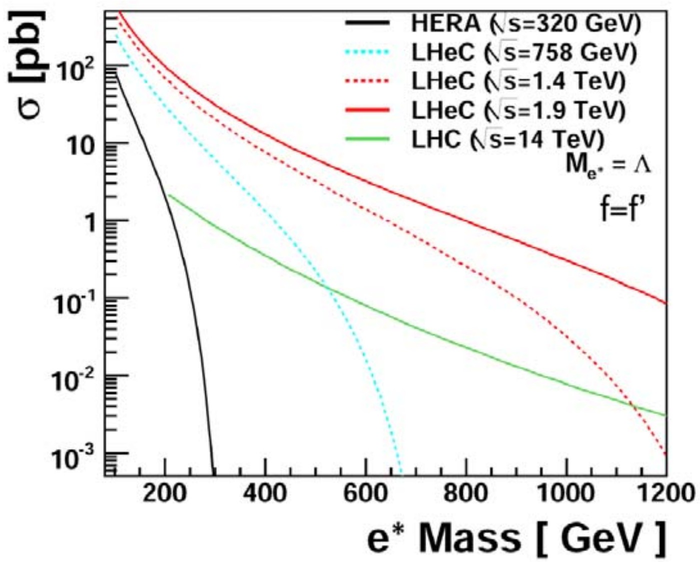
PL B666 (2008)131



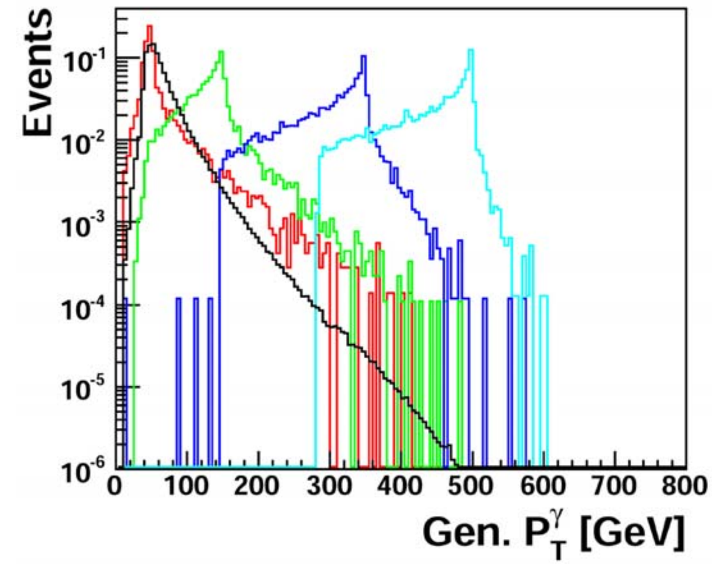
PL B663 (2008)382

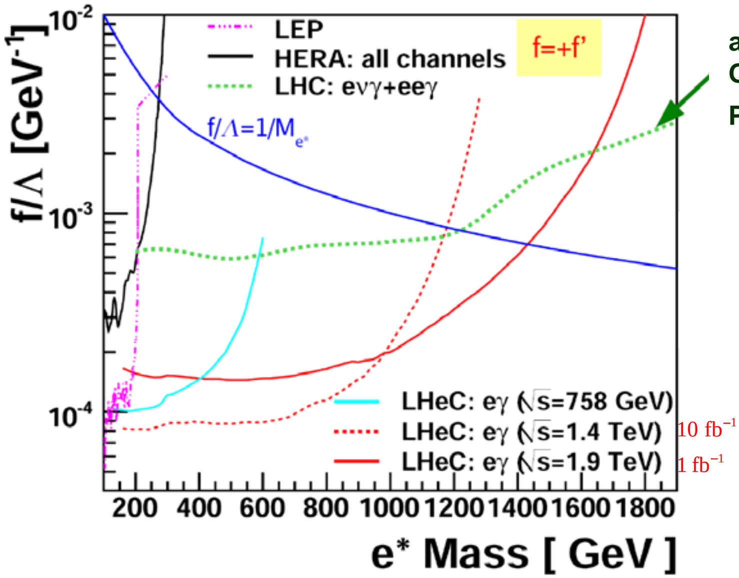
exemple: ep → e* → eγ

single production cross section



kinematic distribution





at LHC
O.J.P. Éboli, S.M. Lietti, P. Mathews,
Phys. Rev. D 65, 075003 (2002)

LHeC could extend the reach for excited electrons, in the e-γ mode

contact interaction cross section ~ $\frac{1}{\Lambda^4}$
→ not very significant at high mass

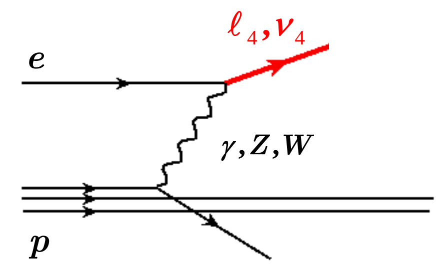
T. Nguyet Trinh and E. Sauvan,
1st ECFA-CERN LHeC workshop (Divonne, 2008)
http://indico.cern.ch/conferenceDisplay.py?confId=31463

heavy leptons (4^{th} family)

Heavy fermions predicted in many BSM theories

- 4^{th} family: not excluded by EW precision measurements
- GUT theories: E_6
- mirror fermions,
- vector-like fermions

➔ will be copiously produced in pair at LHC,
but anomalous coupling measurement more difficult



Production by anomalous couplings:

- charged current for production of ν_4 :

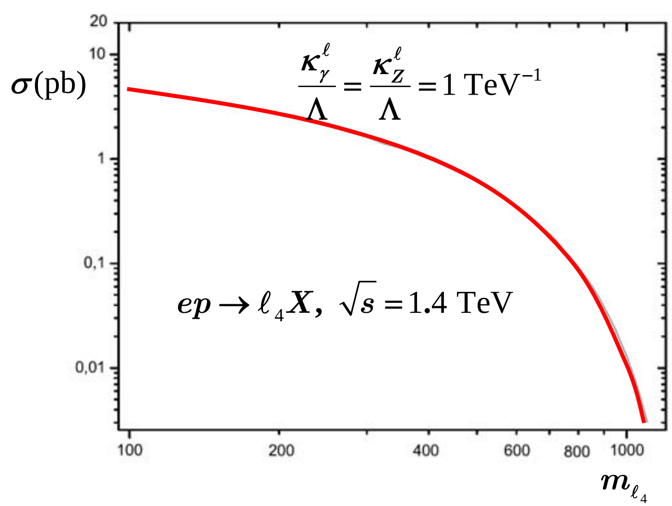
$$\mathcal{L} = \left(\frac{g_W}{\sqrt{2}}\right) \bar{\ell}_i \left[\left| V_{\nu_4 \ell_i} \right| \gamma_\mu + \frac{i}{2} \frac{\kappa_W^{\nu_4 \ell_i}}{\Lambda} \sigma_{\mu\nu} q^\nu \right] P_L \, \nu_4 W^\mu$$

$$\left(V_{\nu_4 \ell} < 10^{-3} - 10^{-5} \right)$$

- neutral current for production of e_4 or ν_4 :

$$\mathcal{L}_{NC}^{\nu_4} = \left(\frac{g_Z}{2}\right) \bar{\nu}_i \left[\frac{i}{2} \frac{\kappa_Z^{\nu_4 \nu_i}}{\Lambda} \sigma_{\mu\nu} q^\nu \right] P_L \nu_4 Z^\mu$$

$$\mathcal{L}_{NC}^{\ell_4} = g_e \frac{\kappa_\gamma^{\ell_i}}{\Lambda} \bar{\ell}_4 \, \sigma_{\mu\nu} \, \ell_i F^{\mu\nu} + g_Z \frac{\kappa_Z^{\ell_i}}{2\Lambda} \bar{\ell}_4 \, \sigma_{\mu\nu} \, \ell_i Z^{\mu\nu} + \text{h. c.}$$



A.K. Çiftçi et al.,
Mod Phys Lett A23 (2008) 1047

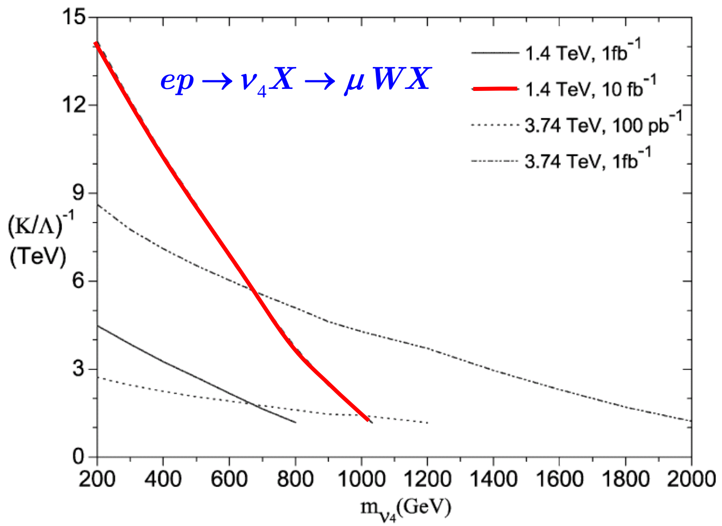
heavy leptons (4th family)

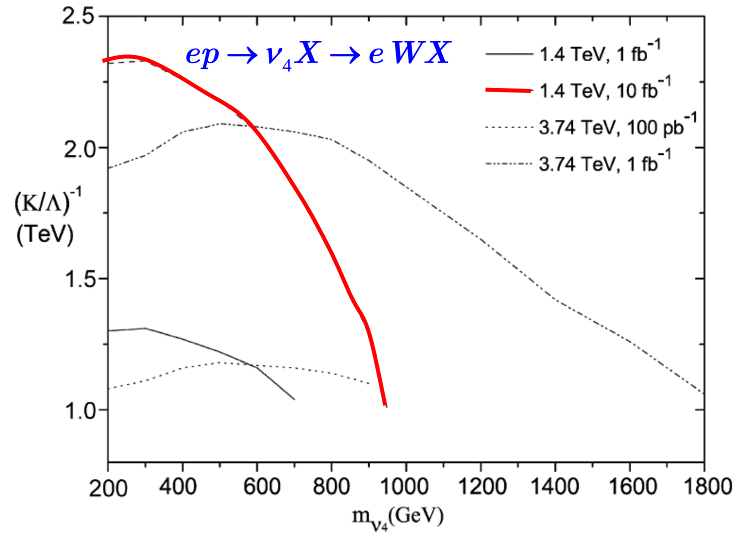
Charged leptons:

➔ can achieve 5 σ discovery up to mass of 800 GeV, for $\sqrt{s} = 1.4$ TeV and 1 fb^{-1}

$$\left(\frac{\kappa_\gamma^\ell}{\Lambda} = \frac{\kappa_Z^\ell}{\Lambda} = 1\ \mathrm{TeV}^{-1} \right)$$

4th family neutrinos:





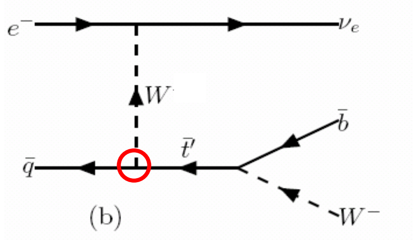
A.K. Çiftçi et al.,
Mod Phys Lett A23 (2008) 1047
Phys Lett B660 (2008) 534

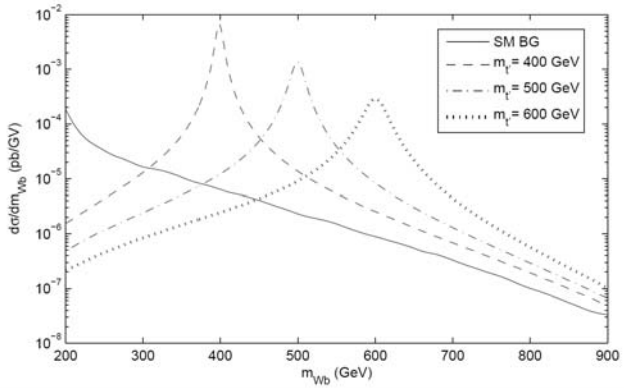
4th family up-type and down-type quarks

t' quark

- Also possible at LHC, but possibly higher background
- Single production sensitive to new matrix elements in CKM matrix
  - assume: t' → W+q
    with $V_{t'd}=0.063$, $V_{t's}=0.46$, $V_{t'b}=0.47$

    ➔ 5σ significance up to ~ 800 GeV with 10 fb^{-1}

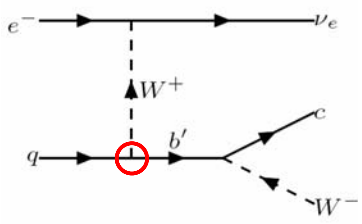


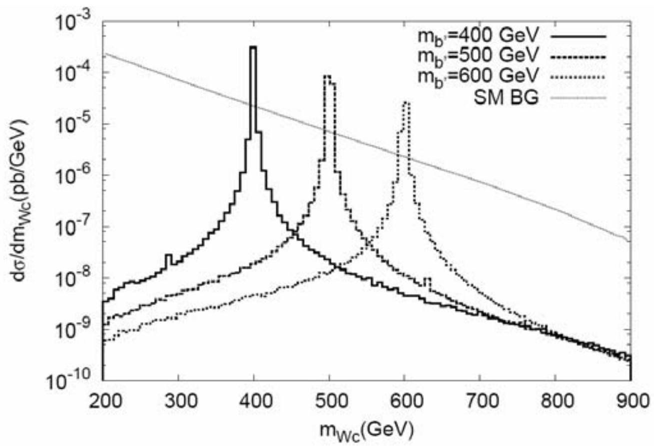


b' quark

- assume: $m_{b'} < m_{t'}$
  and $V_{ub'}=0.028$, $V_{cb'}=0.116$, $V_{t'b'}=0.99$

  ➔ 5σ significance up to ~ 500 GeV with 10 fb^{-1}





O. Cakir et al., arXiv:0905.4347 and arXiv:0912.2041

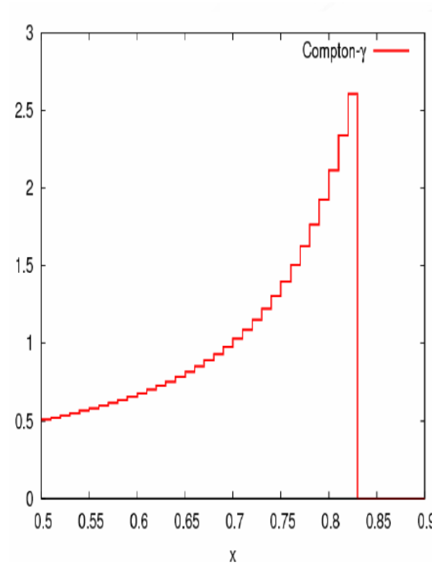
heavy quarks: anomalous couplings in γp collisions

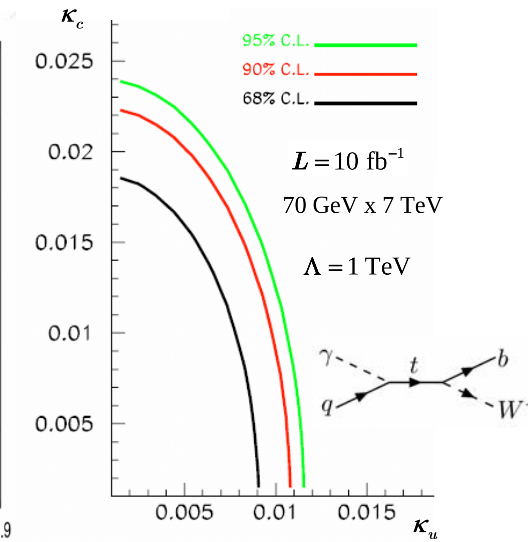
t quark – anomalous coupling

- pulsed superconducting linac + LHC ring
  ➔ γp option available using Compton back-scattering
  - with simple cuts on p_T of jet and m_{Wb}
- $t \to \gamma q$ also possible at LHC:

$$BR(t \to \gamma q) < \sim 2\times10^{-4} \text{ with } 100 \text{ fb}^{-1} \text{ (CMS)}$$
$$< 7\times10^{-4} \text{ with } 1 \text{ fb}^{-1} \text{ (ATLAS)}$$

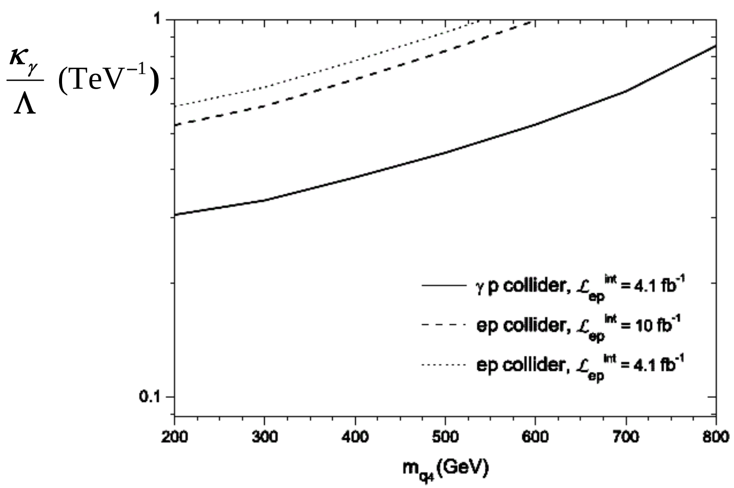
note: $\kappa/\Lambda = 0.01 \Rightarrow BR(t \to u\gamma) \sim 2\times10^{-6}$

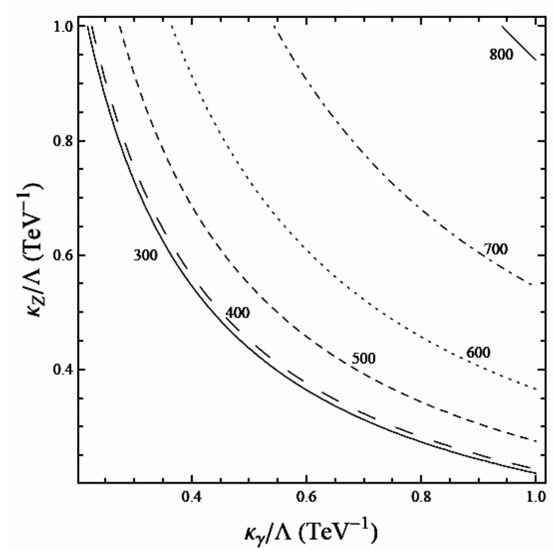




IT Cakir, O. Cakir and S. Sultansoy, PL B685 (2010) 170

t' quark – anomalous production





$$\gamma p \to t'(b') + X$$
$$\hookrightarrow q\gamma$$

R. Çiftçi and A.K. Çiftçi, arXiv:0904.4489

assuming only anomalous couplings to lighter generations, and $\kappa_g = 0$

Diquarks

Diquarks predicted in superstring-inspired E6 and composite models

$$W = \lambda_9 h Q Q; \quad \begin{cases} h = \text{diquark (B=2/3, L=0, Q=1/3)} \\ Q = \begin{pmatrix} u \\ d \end{pmatrix}_L \end{cases}$$

- more generally, diquarks could carry charge 1/3, 2/3, 4/3 and be scalar or vector

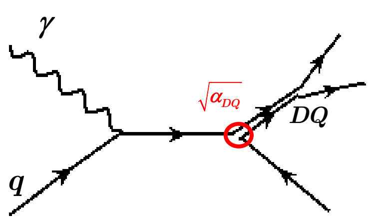
$$\mathcal{L}_{|B|=2/3} = \left(g_{1L} \bar{Q}_L^c i \tau_2 Q_L + g_{1R} \bar{u}_R^c d_R \right) DQ_1^c + \text{h.c.}$$

where DQ_1 is a scalar isosinglet diquark
(similar terms for other types of diquarks)

E_6 diquarks excluded by CDF in range $290 < m_{DQ} < 630$ GeV

Phys.Rev.D79:112002,2009 (2009)

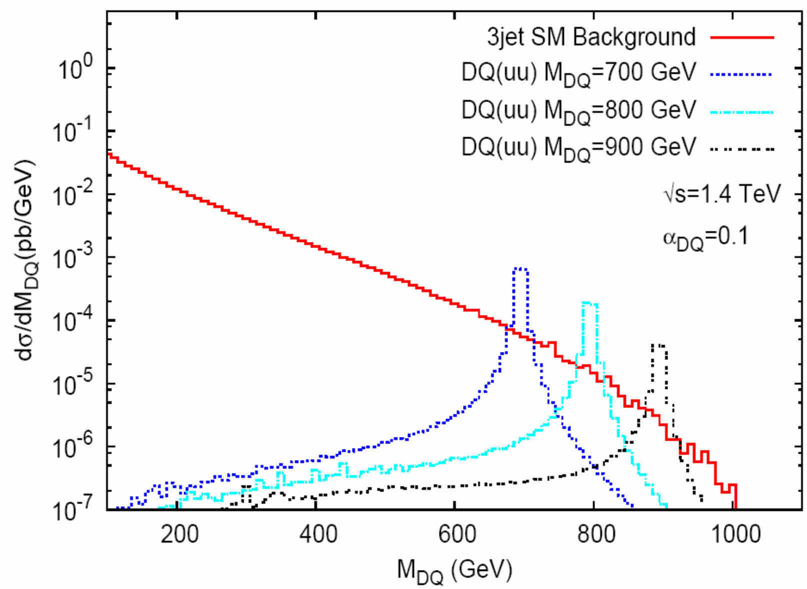
- γp production:



- *with a cut on* p_T(jet) > 50 GeV *and on di-jet invariant mass, 5σ significance is obtained up to*

m < 700 GeV for 70 x 7000 GeV²
900 GeV 140 x 7000 GeV²

- vector and scalar quarks can be distinguished by the angular distribution of their decays



M Şahin and O. Çakir, arXiv:0911.0496

Other examples of new physics

- **improved pdf's**

  → better info from LHC measurements of cross sections in SM and BSM physics

  → contact interactions:

  - excess/reduction in dijet cross section due to poor knowledge of pdfs?
  - make use of asymmetry in cross section in e^+ and e^- to determine sign of interference
  - in Drell-Yan: comparing $qq \to ll$ and $eq \to eq$ constrains Λ

  E. Perez, at LHC2FC

- **R-parity conserved SUSY** $eq \to \tilde{e}\tilde{q}$ via t-exchange of $\tilde{\chi}$
  - masses predicted ~ (700,150) GeV in CMSSM and NUHM1 models

    (O. Buchmueller et al., JHEP 0809:117,2008)

    have sizeable cross sections at LHeC:

    → could extend discovery over LHC and possibly yield improved information on masses and couplings?

- **Z' couplings**
  - polarization and charge asymmetries can help distinguish between Z' models (E_6, LRSM, ALRSM, little Higgs, SSM, …)

    T. Rizzo, PR D77 (2008) 115016

Summary

- LHeC can complement LHC in understanding new physics phenomena
- more precision and more complete interpretation of LHC discoveries
- TeV ep collisions:
  - since there is no strong interaction, one can probe interraltion between leptons and quarks in a fundamental theory: leptoquarks, compositeness, contact interactions…

Many thanks to E. Perez, M. Klein, et al.