BSM Summary

Contributions from various authors

G. Azuelos, E. Perez, editors of BSM chapter of LHeC CDR

overview of chapter

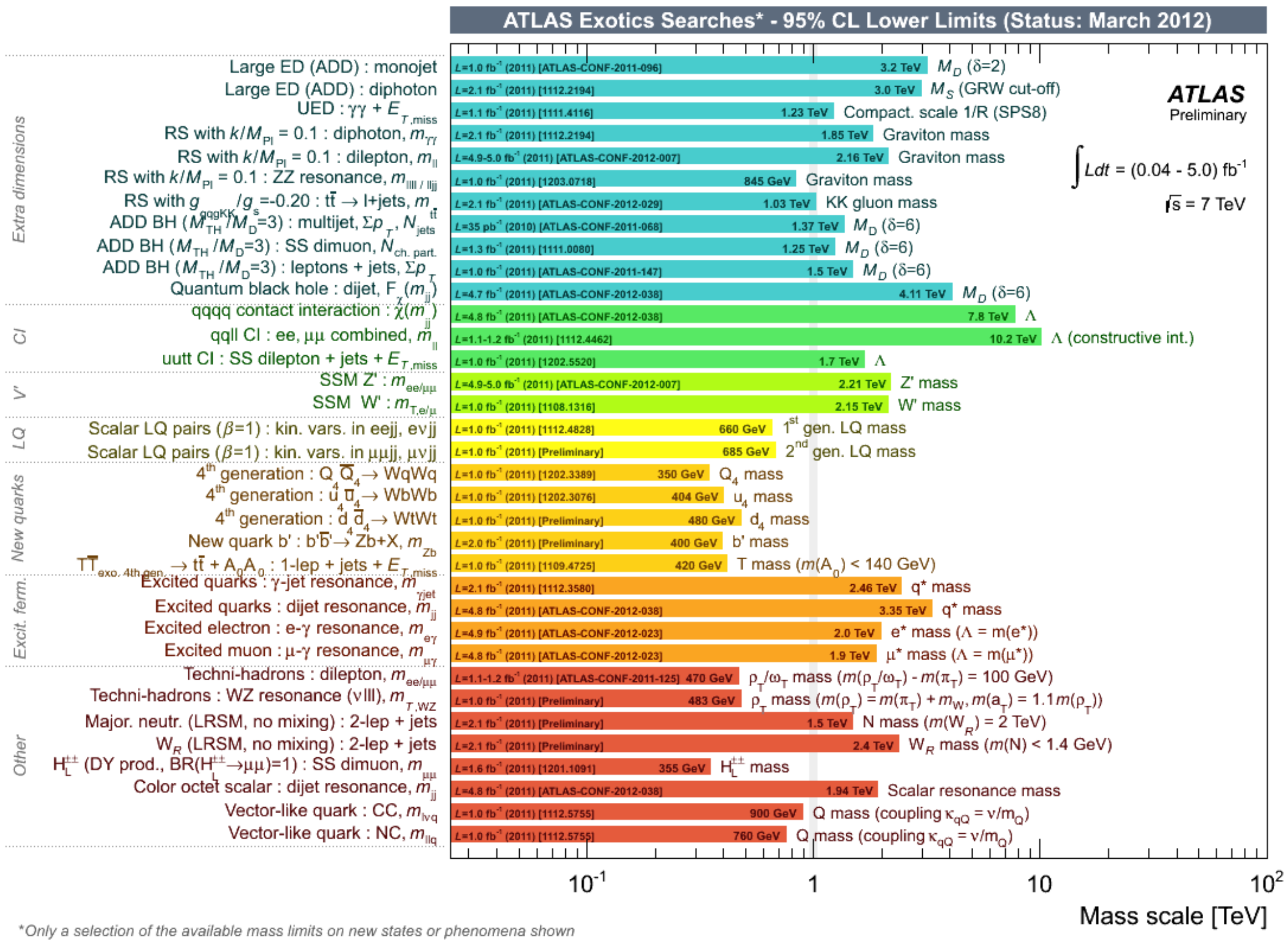
- Leptoquarks
- contact interactions
- heavy and excited fermions
- diquarks
- RPV SUSY
- Higgs by VBF → coupling to bbar
- ***WWH*** anomalous coupling

LHC is a "discovery machine"

➔ new bsm physics will likely be discovered there first

- for now, tension in MSSM scenario, bounds on new physics, hint of a Higgs-like signal at 125 GeV

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/CombinedSummaryPlots



Added value of LHeC

LHeC:

What could be the "added value" of LHeC for BSM physics ?

- new physics at high scale
  - specificity of LHeC :
    Why do leptons and quarks share (only) EW interactions?
  - New physics at very high energy scales:
    effective theory: contact interactions → deviations from SM
  - Intermediate, accessible scale:
    - new bosons: leptoquarks, leptogluons
    - excited states of fermions (q-e compositeness)
    - diquarks
    - anomalous q and e interactions → in particular with γq

    ➔ higher reach in single production for specific processes

    ➔ possibility to study properties of new particles & interactions
  - SUSY → *see talk by Monica D'Onofrio*
- Higgs couplings to bb, probing VVH coupling

  → *see talks by Masaki Ishitsuka, Bruce Mellado*
- cleaner environment, better S/N
- improved pdfs ➔ higher precision from measurements performed at LHC

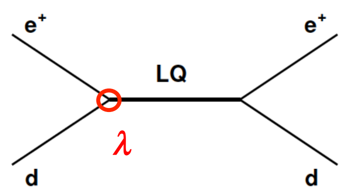
Leptoquarks

LQ's carry baryon and lepton number

- squarks decaying by R-parity violation $\mathcal{W}_{RPV} = \lambda'_{ijk} L_i Q_j \bar{D}_k \Rightarrow \begin{cases} e^- + \bar{d} \to \bar{\tilde{u}} \to e^- + \bar{d} \\ e^- + u \to \tilde{d} \to e^- + u \end{cases}$
- 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

LHeC is ideal for the study of leptoquarks

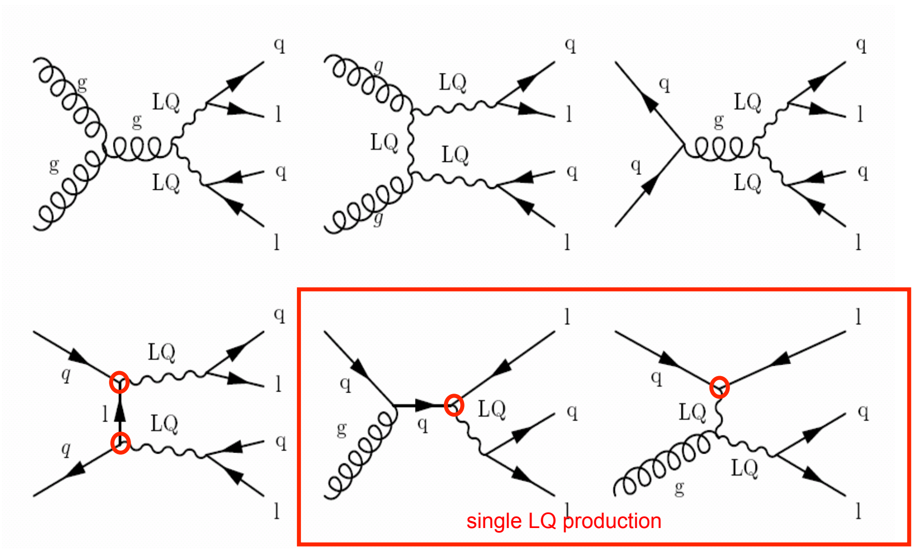
- s-channel production in $e^{\pm}p$ collisions



LQ's can be scalar or vector
➔ Buchmüller classification (many other conventions)

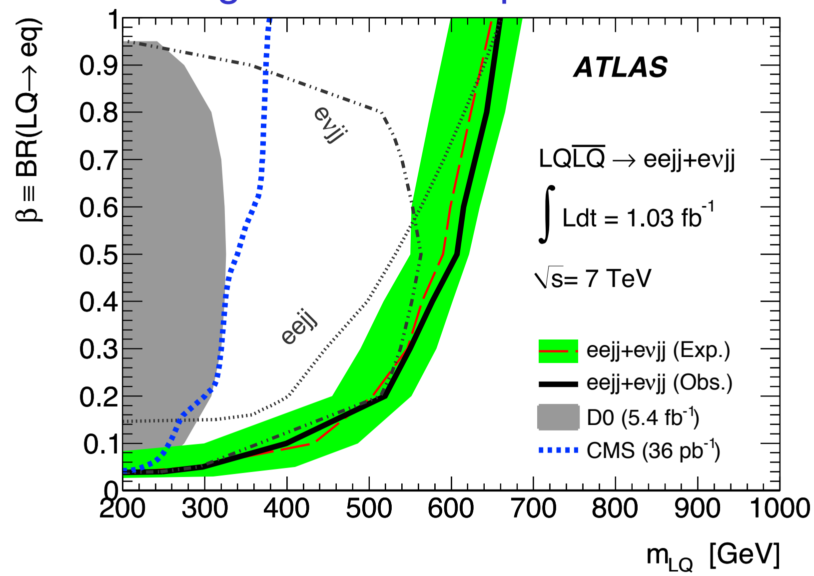
- family mixing $\rightarrow$ FCNC and LFV, lepton universality
- non-chiral ? (couple to L and to R quarks simultaneously?)

LQ's at the LHC



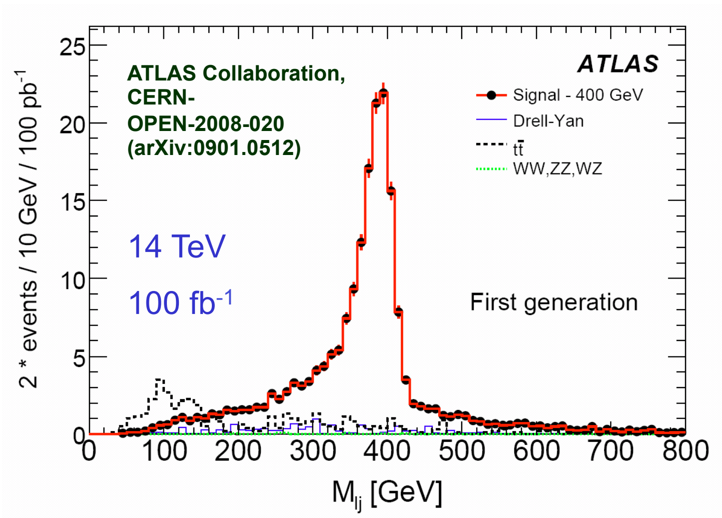
At the LHC, pair production is essentially independent of the LQ-q-e coupling λ $\rightarrow$ pair production abundant

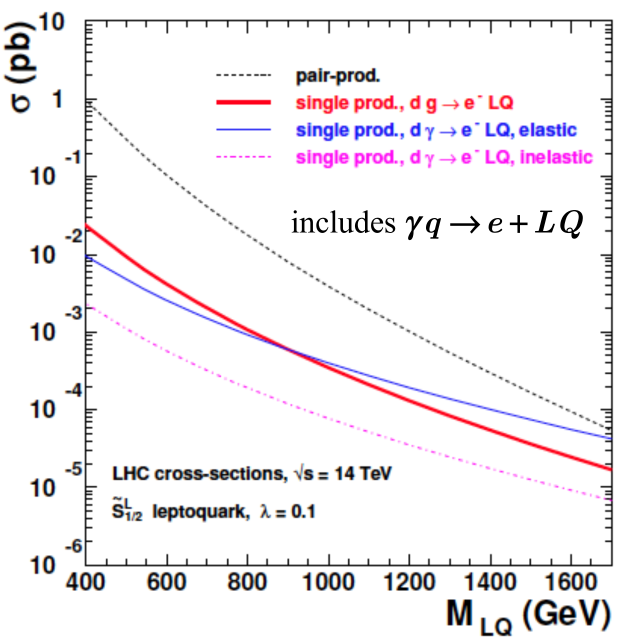
1st generation LQ pair



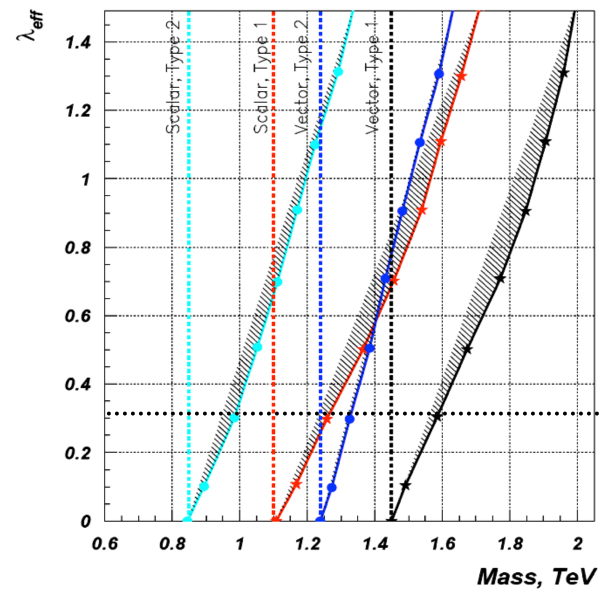
Phys. Lett. B709 (2012) pp 158-176

LQ's at the LHC at 14 TeV





single production suppressed by dependence on λ



LHC
300 fb^{-1}

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

combined single and pair production, eq and νq channels

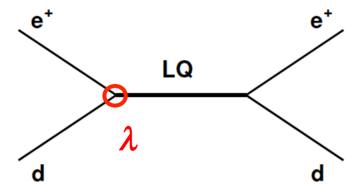
single + pair production
type 1 : $2\mathbf{l} + j$
type 2 : $\mathbf{l} + j + \not{E}_T$

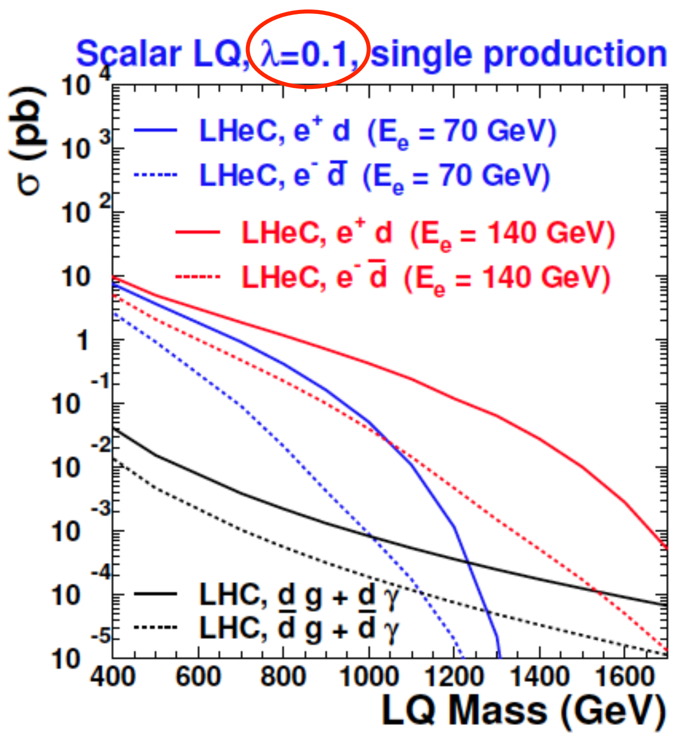
A. Belyaev et al., JHEP0509:005,2005 (arXiv:hep-ph/0502067)

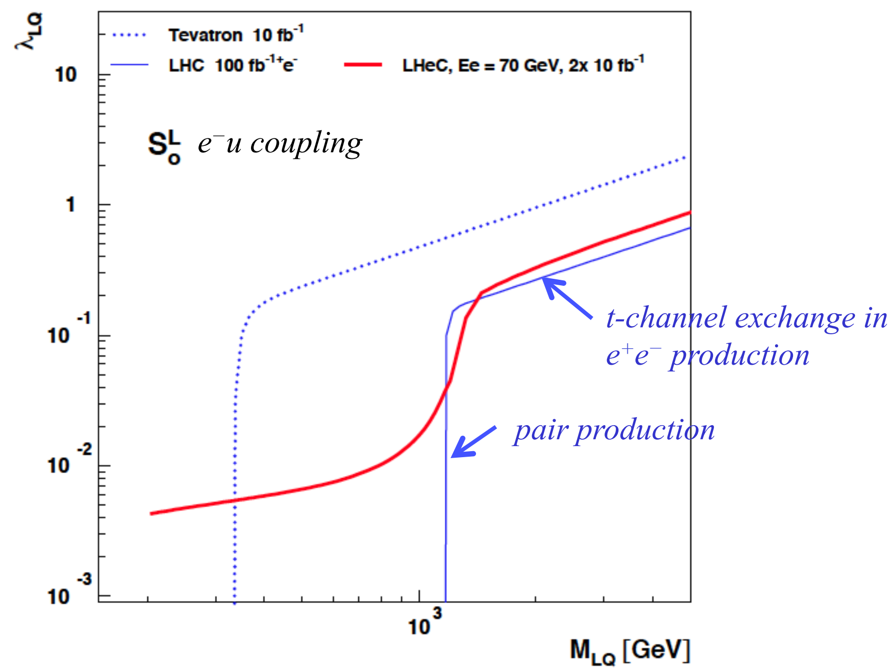
LQ cross section at the LHeC

H1 and ZEUS:

$\lambda < \sqrt{4\pi\alpha} \sim 0.3$ *for 1st generation LQ of mass < 300 GeV*







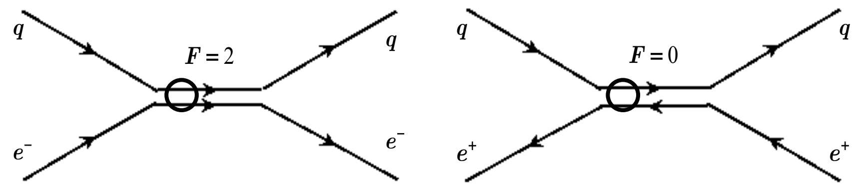
contact term for high mass LQ
➔ distortion of NC cross section

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

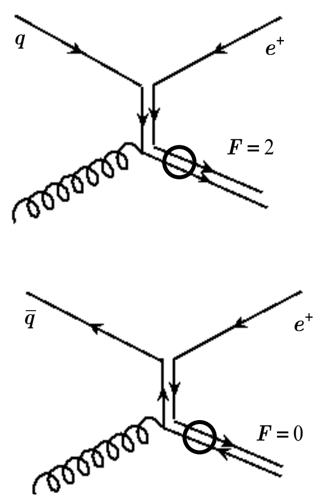
Simpler and more direct mode of production allows measure of quantum numbers and couplings:

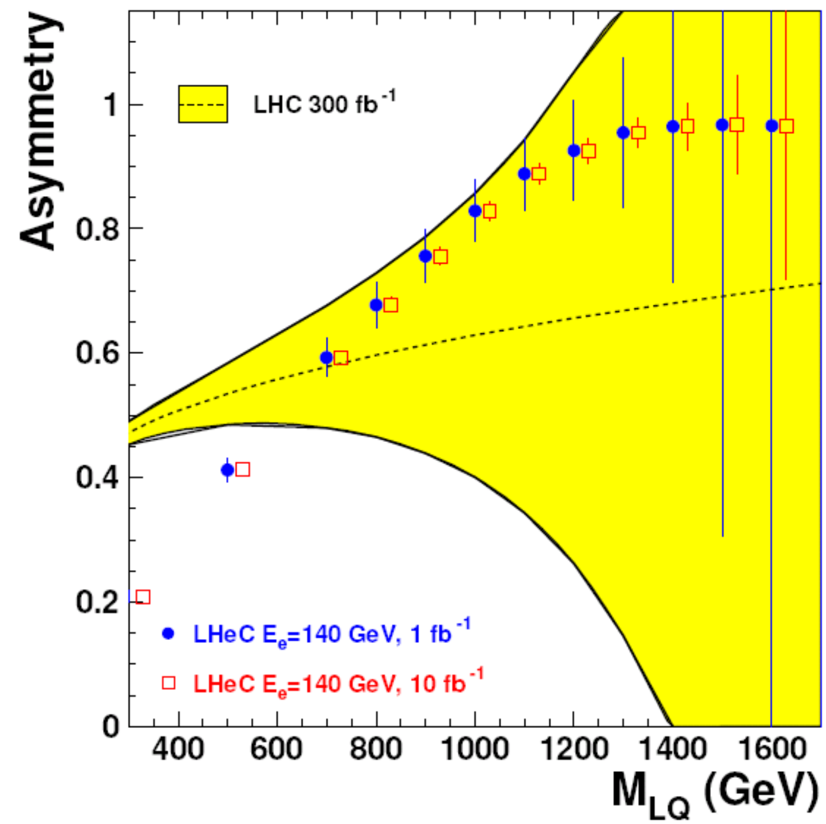
F: fermion number can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$

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



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



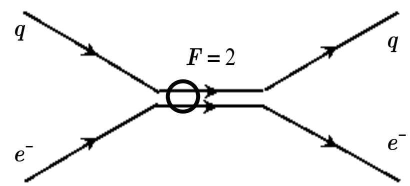


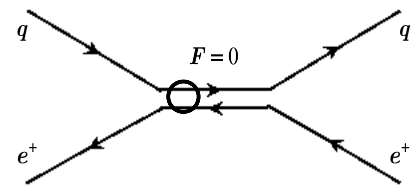
Fermion number determination

Simpler and more direct mode of production allows measure of quantum numbers and couplings:

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

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





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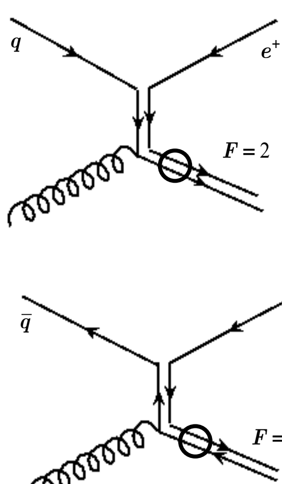
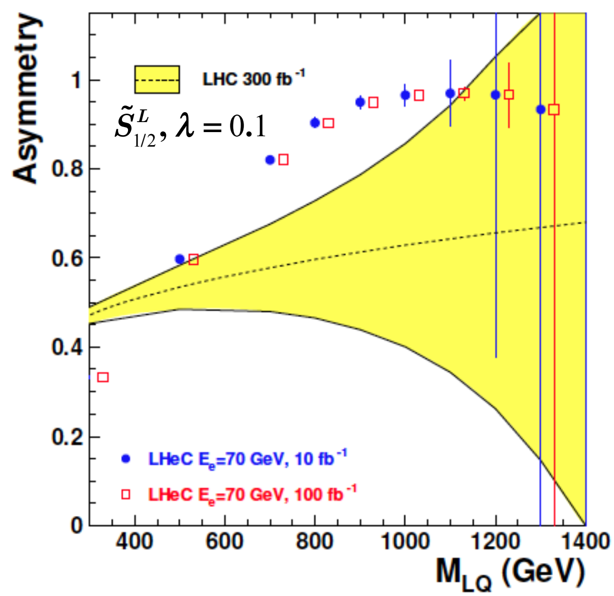
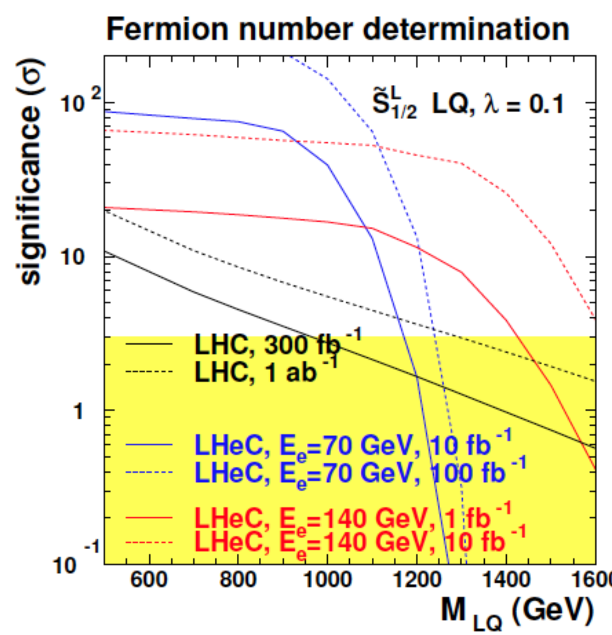


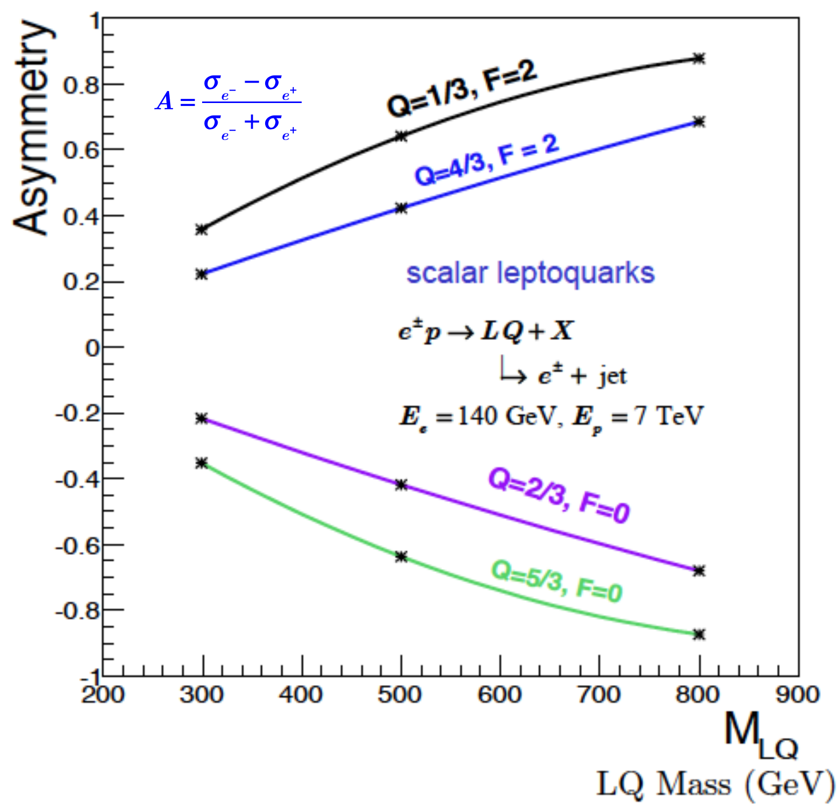




Preliminary results for LHC obtained with CalcHEP, new LQ model by A. Belyaev and A. Pukhov (private comm.)

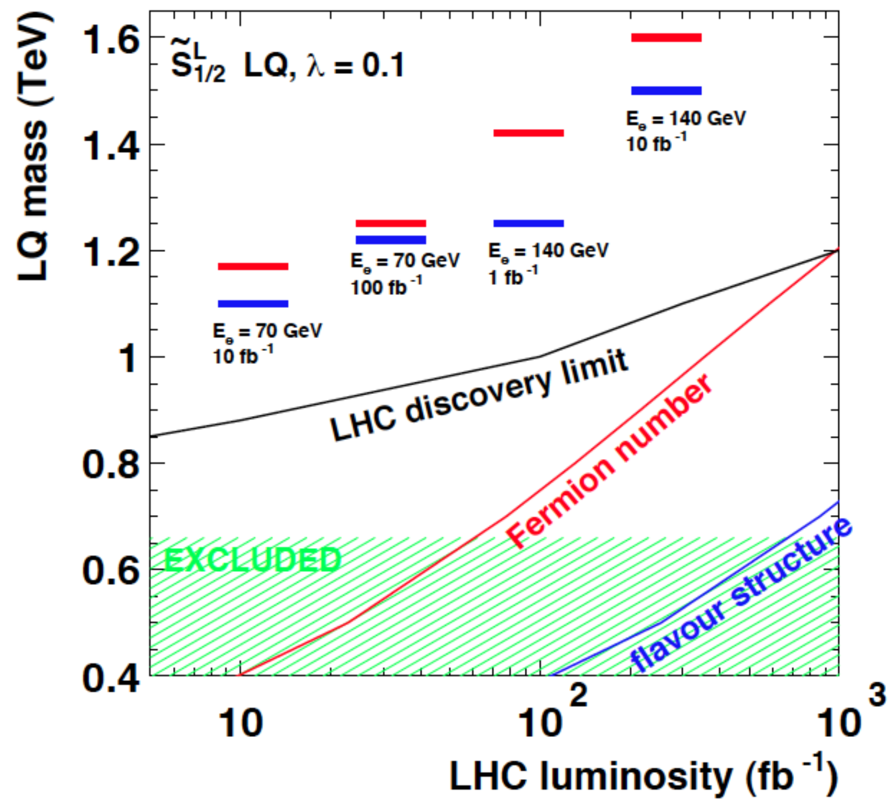
LQ charge and flavor structure

Asymmetry also probes the **LQ charge**



note: LQs belonging to an isodoublet might be degenerate

LHC vs LHeC



Other properties of LQ's

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 of LQ decay is sensitive to the spin

$$\text{scalar}: \quad \text{flat } d\sigma/dy$$

$$\text{vector}: \; d\sigma/dy \sim (1-y)^2 \qquad \left[y = \frac{1}{2}(1+\cos\theta^*) \right]$$

$$NC: \sim y^{-2}$$

- vector leptoquarks can have anomalous couplings

BR to neutrino

- good S/B in νj channel

λ = e-q-LQ coupling

- knowing the charge and spin, λ can be determined

$$\sigma_{prod} \sim (2J+1)\lambda^2$$

chiral structure?

- could be probed by measuring sensitivity of cross sections to polarization of the electron beam

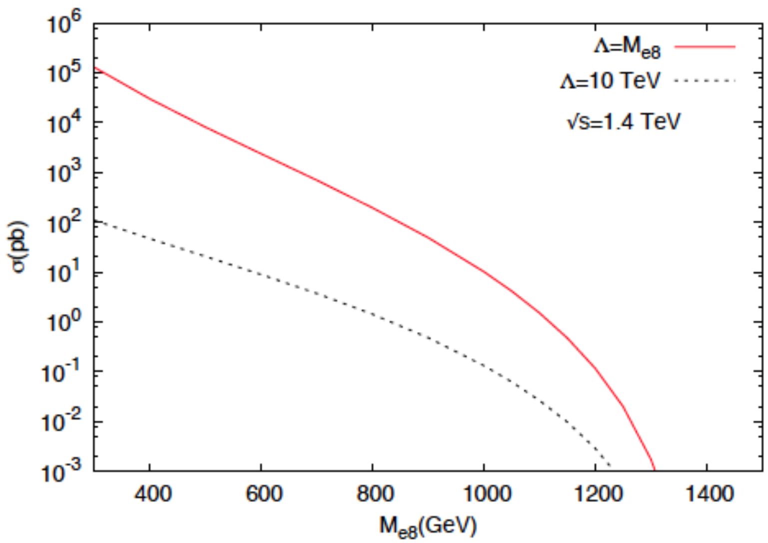
Leptogluons

Leptogluons are color-octet partners of leptons

In certain compositeness models, the lepton may be a bound state of 2 color triplet preons

They couple to a lepton and gluon, and the phenomenology is similar to that of LQ's (but different spins → different ang. distributions)

$$L = \frac{1}{2\Lambda}\sum_{l}\{\bar{l}_8^{\alpha} g_s G_{\mu\nu}^{\alpha}\sigma^{\mu\nu}(\eta_L l_L + \eta_R l_R) + h.c.\}$$



Typical cross section

140 GeV x 7 TeV

M_{e8}, GeV	$L_{int} = 1 fb^{-1}$	$L_{int} = 10 fb^{-1}$
500	245 (320)	440 (570)
750	150 (195)	275 (355)
1000	82 (110)	155 (205)
1250	41 (56)	81 (107)
1500	16 (23)	34 (46)

Achievable compositeness scale (in TeV) for 5σ (3σ) statistical significance

M. Sahin, S. Sultansoy and S. Turkoz

Contact Interactions

Substructure? GUT representation? exchange of a heavy particle (LQ, G*)?

New physics could be at a higher scale $\Lambda \gg \sqrt{s}$ **:**

4-fermion interaction $\Rightarrow M_{eq \to eq} \sim \Lambda^{-2}$

Λ **:** LQ mass >> √s,
M$_S$ of extra dimension models,
compositeness scale

$$\mathcal{L} = \frac{4\pi\,\varepsilon}{\Lambda^2}\, j_\mu^{(e)} j^{\mu(q)}; \quad q = u, d; \quad \varepsilon = \pm 1$$

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

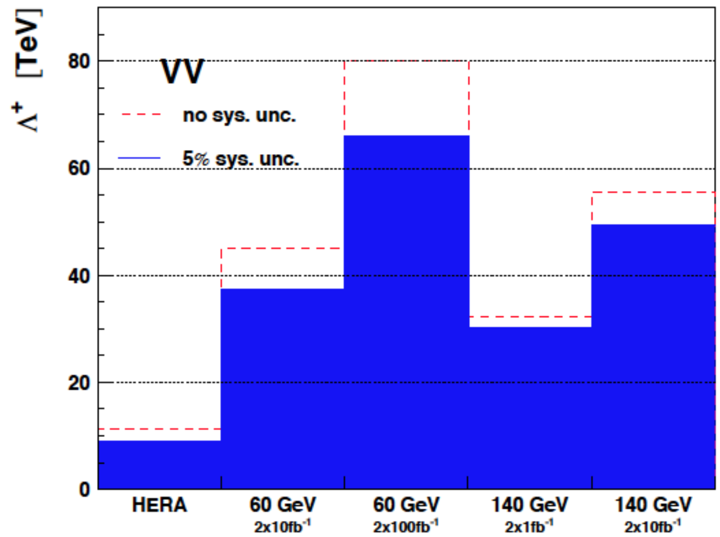
$$\Rightarrow \text{ all combinations of couplings } \eta_{ab} = 4\pi\,\varepsilon \frac{\eta_a^{(e)} \eta_b^{(q)}}{\Lambda_{ab}^2}$$

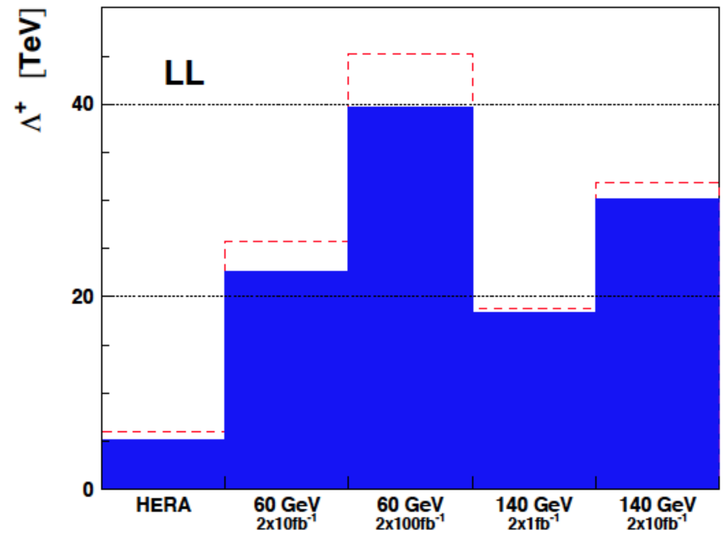
At the LHC,

- 4-quark contact interaction (dijet cross section and angular distribution):
  ➔ Λ < 7.8 TeV → extrapolate few 10's of TeV
- dilepton production
  - with 1 fb^{-1} at 7 TeV, $\Lambda \geq$ 7 TeV → extrapolate to ~ 30 TeV with 300 fb^{-1}, 14 TeV

Contact Interaction

Model	η_{LL}^{ed}	η_{LR}^{ed}	η_{RL}^{ed}	η_{RR}^{ed}	η_{LL}^{eu}	η_{LR}^{eu}	η_{RL}^{eu}	η_{RR}^{eu}
VV	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$	$+\eta$

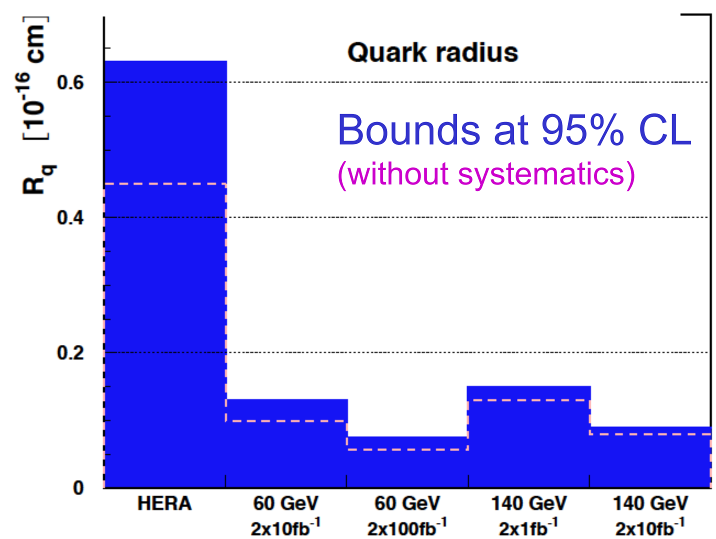




Quark radius from Q^2 dependence of DIS cross section

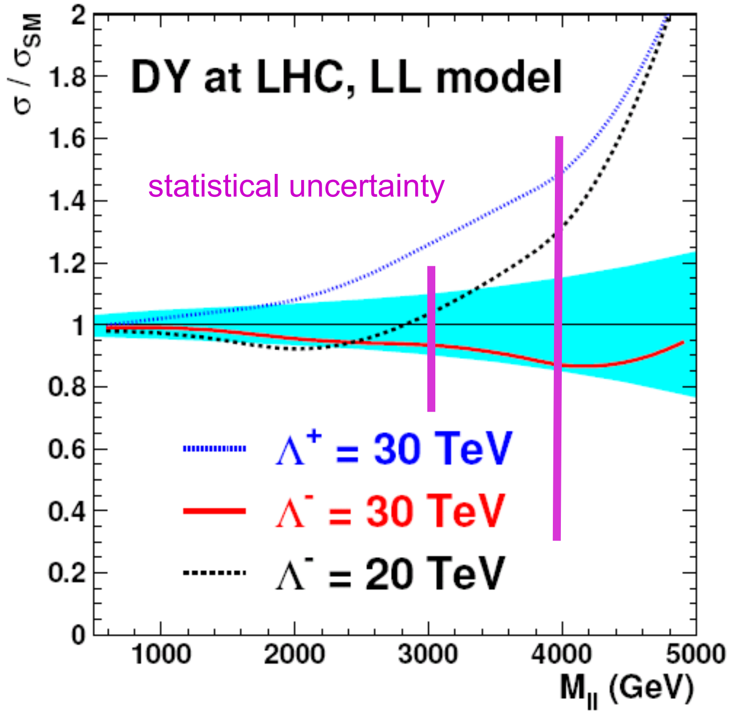
$$f(Q^2) = 1 - \frac{1}{6}\langle r^2 \rangle Q^2 ,$$

$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2} f_e^2(Q^2)\, f_q^2(Q^2)$$

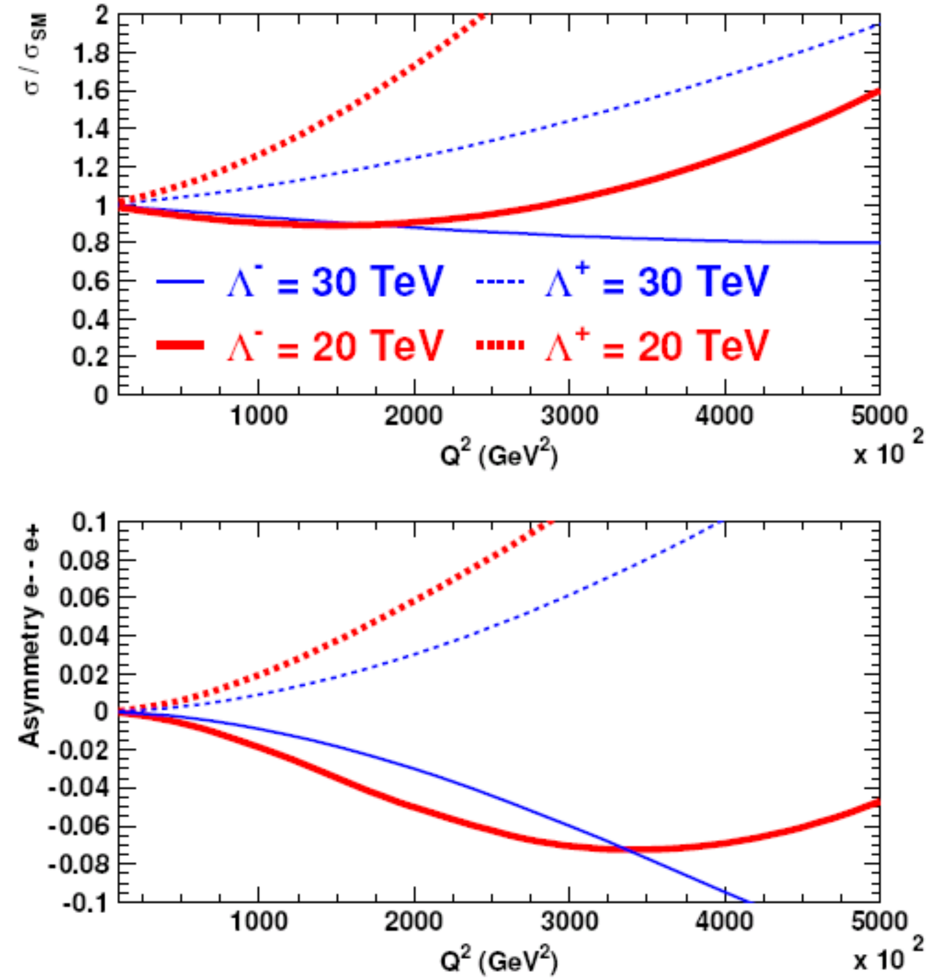


A. F. Zarnecki, arXiv:0809.2917

resolving ambiguities on scale of compositeness



LHeC



E. Perez

reach on compositeness scale comparable to LHC reach,
but LHeC resolves ambiguities:

- sign of interference determined from asymmetry $e^{\pm}$
- chiral nature of the interaction from polarization

Excited fermions

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

- gauge interaction Lagrangian

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

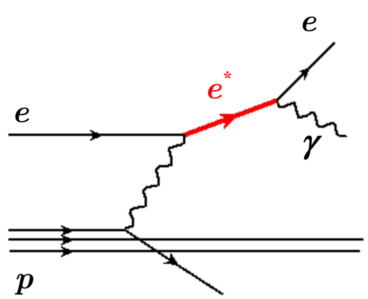
conventional reference point: $\frac{f}{\Lambda} = \frac{1}{m^*}$

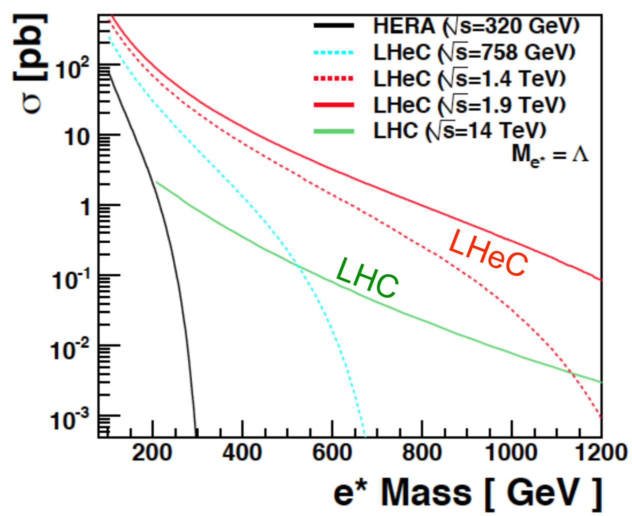
similar Lagrangian for 4th family lepton: replace couplings by anomalous couplings

- contact interaction Lagrangian

conventional reference point: $\Lambda = m^*, \quad \eta_L = +1, \quad \eta_R = 0$

$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu j^\mu; \quad j_\mu = \eta_L \bar{f}_L\gamma_\mu f_L + \eta'_L \bar{f}^*_L\gamma_\mu f^*_L + \eta''_L \bar{f}^*_L\gamma_\mu f_L + h.c. + (L \leftrightarrow R) \;\Rightarrow\; \sigma \sim \frac{\hat{s}|\eta|^2}{\Lambda^4}$$



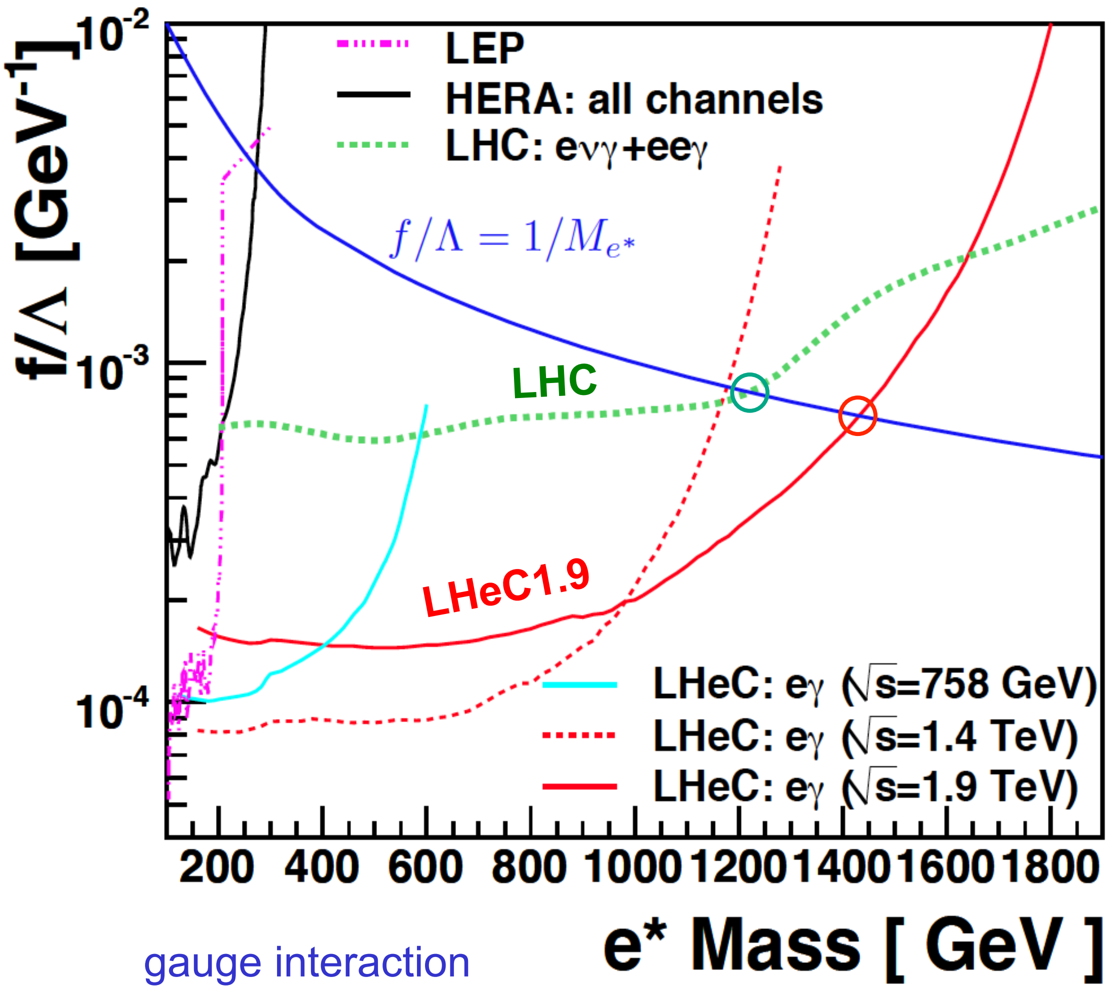


gauge interaction production cross section

LHC excludes up to ~ 1.8 TeV
for production by *contact* interaction

LHeC has higher cross section

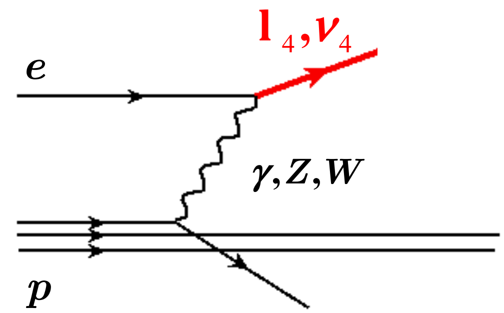
Sensitivity to excited electron search



gauge interaction

LHeC could probe smaller couplings f/Λ

equivalent description for heavy leptons



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

Production at LHeC by anomalous couplings

similarly for excited quarks (especially if qQg coupling suppressed)

Heavy quarks: anomalous couplings in γp collisions

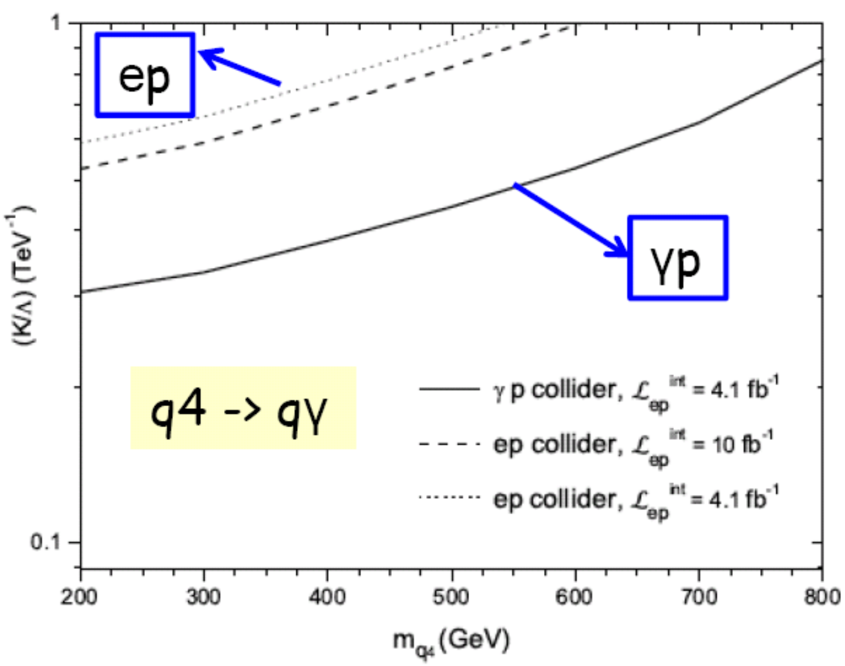
t quark (or q* or Q) – anomalous coupling in γp option
available using Compton back-scattering
pulsed superconducting linac + LHC ring

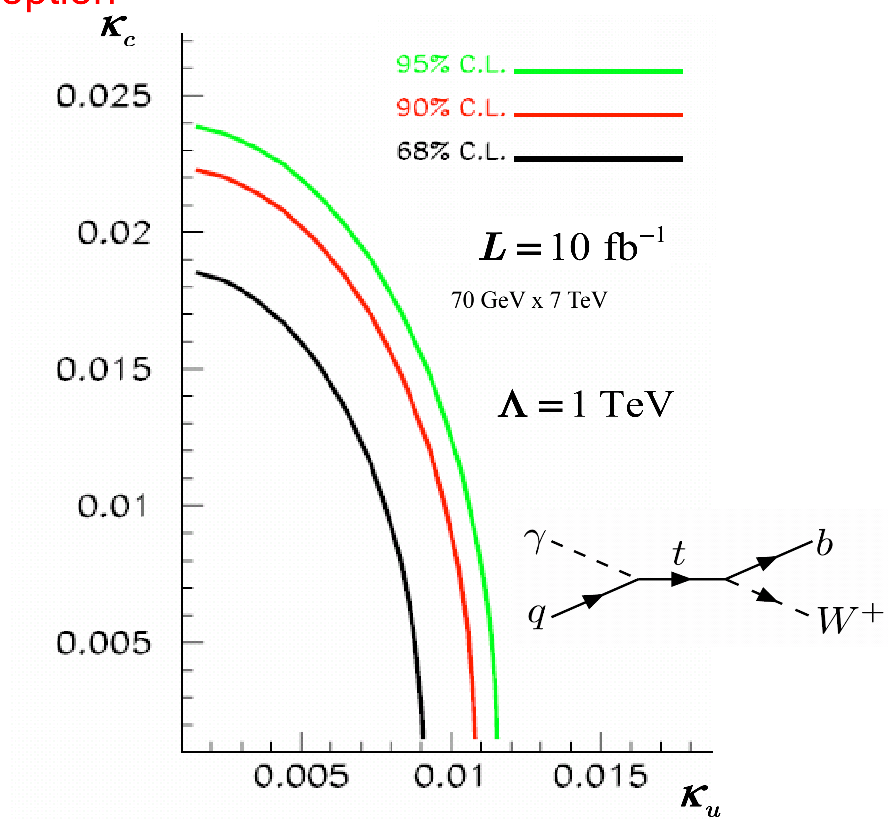
$t \to \gamma q$ also possible at LHC:

$$\mathcal{L} = -g_e \sum_{q=u,c} Q_q \frac{\kappa_q}{\Lambda} \bar{t} \sigma^{\mu\nu} (f_q + h_q \gamma_5)\, q\, A_{\mu\nu} + h.c.$$

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

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



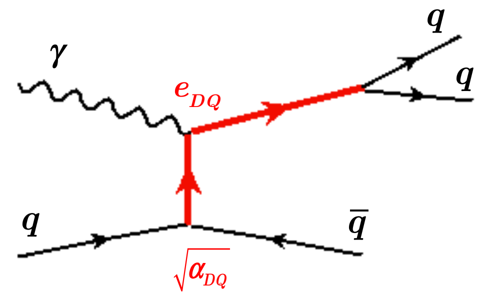


IT Cakir, O. Cakir and S. Sultansoy,
PL B685 (2010) 170

Diquarks

Diquarks predicted in superstring-inspired E6 and composite models

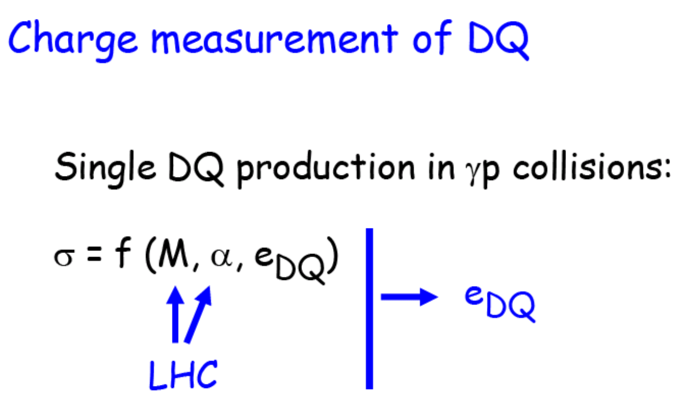
- more generically, diquarks could carry charge 1/3, 2/3, 4/3 and be scalar or vector
- γp production:



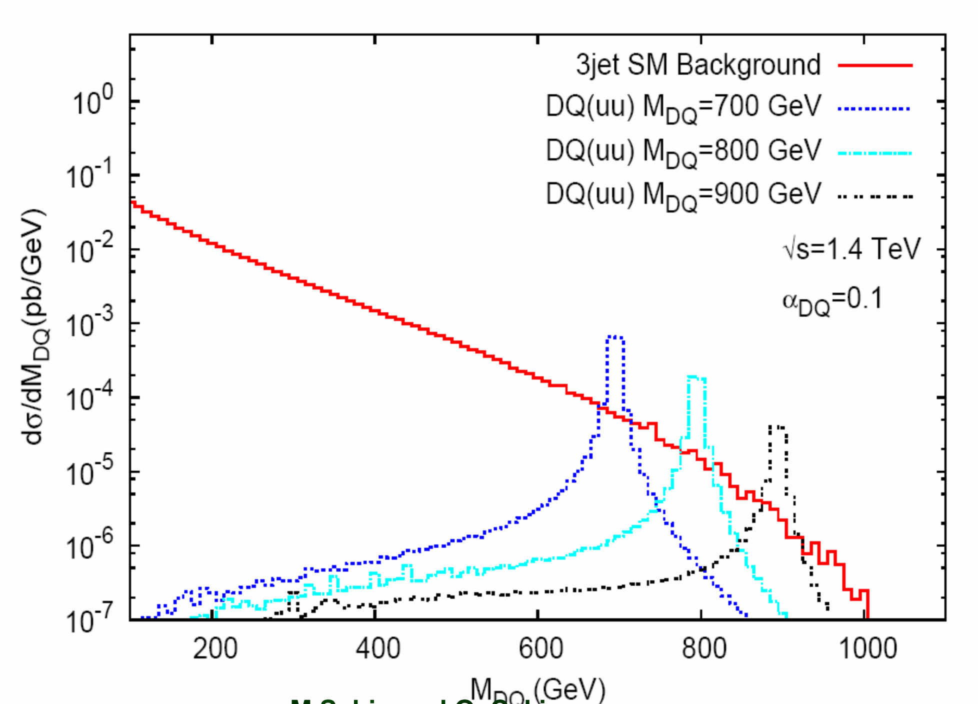
E_6 diquarks excluded by CDF in range
$290 < m_{DQ} < 630$ GeV

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

LHC can hardly measure the charge



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



M Şahin and O. Çakir, arXiv:0911.0496

RPV SUSY

LHC imposes very strong constraints on MSSM: what will be the focus in 2020?

→ Possibly RPV in strong production, stop pair, sleptons, Higgsinos

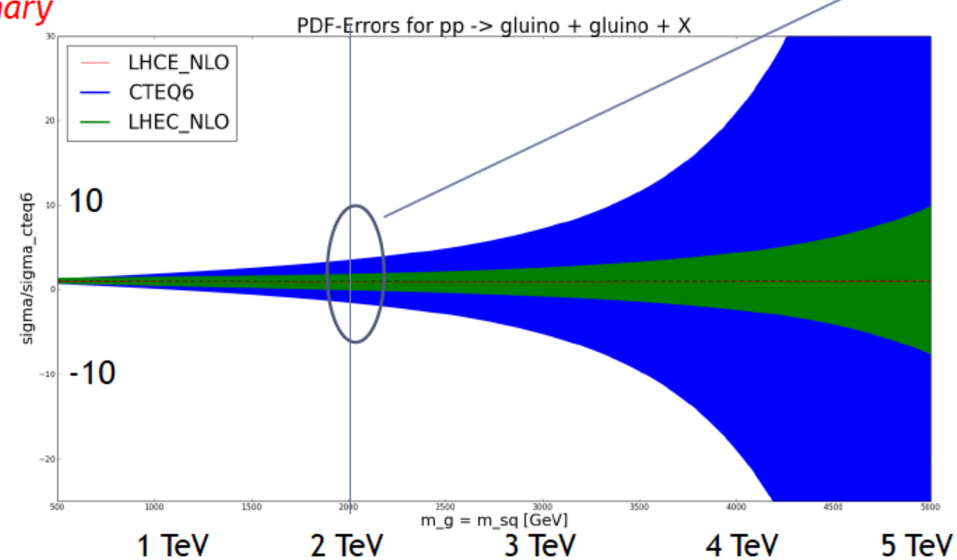
→ importance of pdf's to characterize the physics, if deviations are seen

What the LHeC can do

- M.Kramer and R.Klees working on impact of improved PDF fits on theoretical predictions for SUSY process:
  - Example: gl-gl production (assuming m_gl = m_sq)
  - without(blue, CTEQ6) and with (green) LHeC PDF

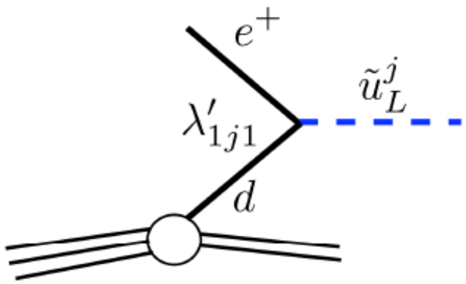
Improve of
factor of 2-3 @ 2 TeV
factor of 10 at 3.5 TeV

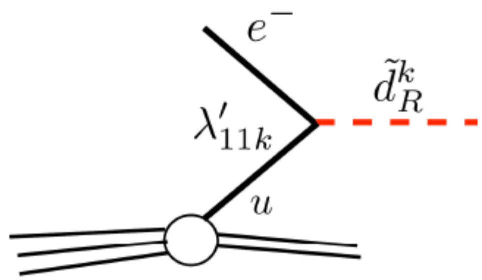
preliminary

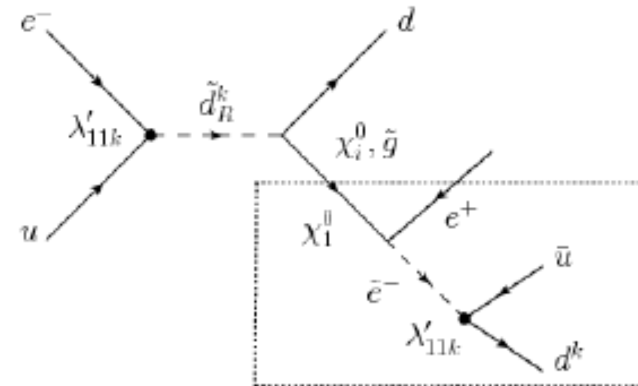


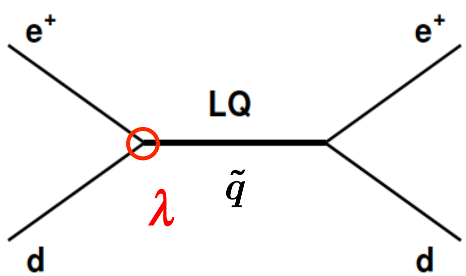
slide from M. D'Onofrio

RPV SUSY

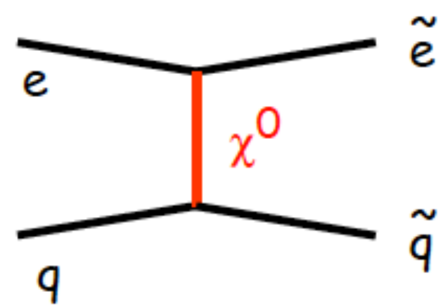








RPV violating squark have similar phenomenology as scalar Leptoquarks



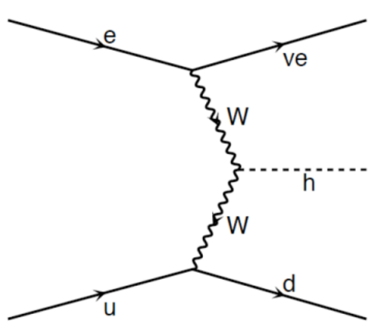
These cross sections are sizeable for lower mass sfermions, possibly already constrained

Higgs coupling to $b\bar{b}$

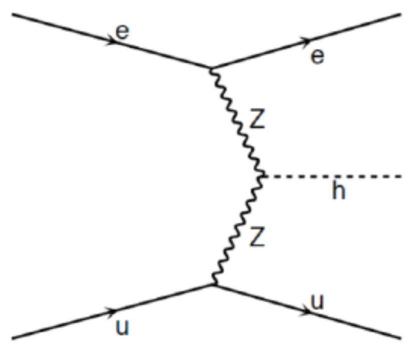
M. Ishitsuka, K. Kimura, U. Klein,M. Kuze, C. Hengler

- Higgs mass most likely in range ~125 GeV
- In this mass range, the principal decay is to $b\bar{b}$: ~ 60%
  large QCD background at LHC → Hbb coupling difficult to measure

➔ *LHeC can produce Higgs by Vector Boson scattering :*



CC, ~ 160 fb



NC, ~ 40 fb for 140 x 7000 GeV

$\sqrt{s} = 2.05\,TeV$

Challenging measurement, which imposes constraints on the detector:

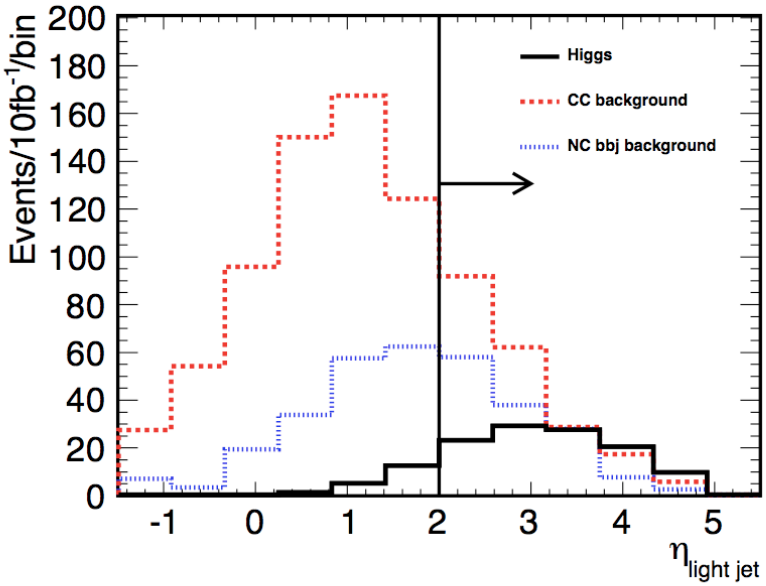
high backgrounds from single top and multijets

forward acceptance crucial

Need for a realistic detector simulation

PGS:

- em calorimeter resolution: $5\% \times \sqrt{E}$
- had. calorimeter resolution: $60\% \times \sqrt{E}$
- jet cone: 0.5
- b-tagging: 60% b, 10% c,
- calorimeter coverage up to $|\eta| < 5$



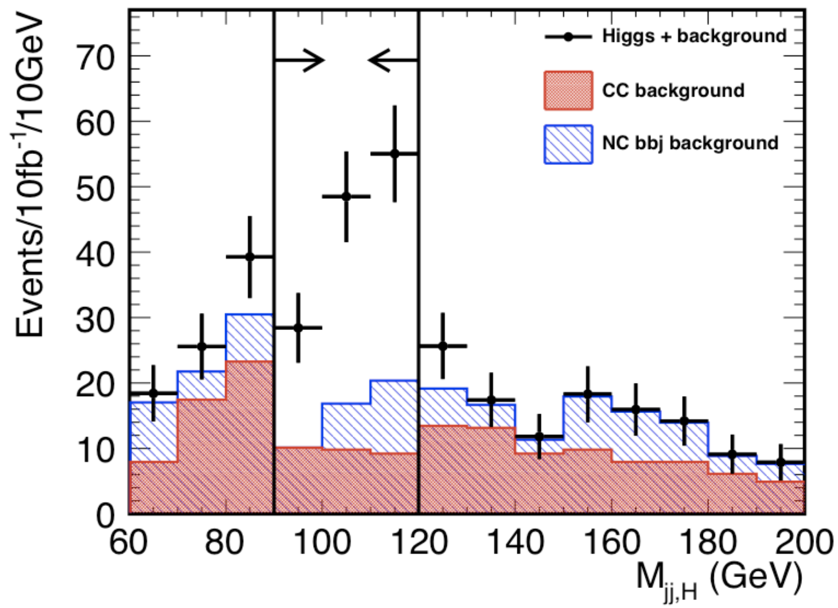
~ 15% statistical precision in Hbb coupling $g^2_{Hbb} \cdot g^2_{HWW} / \Gamma_H$

Summary of event selection

- CC only: Etmiss > 20 GeV, Q^2 > 400 GeV, y_{JB}<0.9
- 2 b jets
- single top veto
- forward jet tagging

$$y_{JB} = \sum (E - p_z) / 2E_e$$

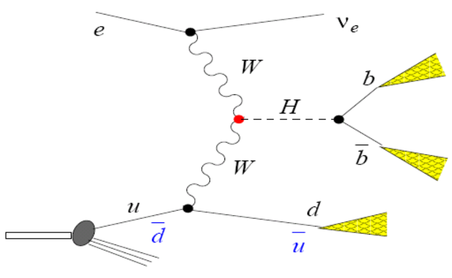
$$Q^2_{JB} = E^2_{T,miss} / (1 - y_{JB})$$



	E_e = 150 GeV (10 fb^{-1})	E_e = 60 GeV (100 fb^{-1})
$H \rightarrow bb$ signal	84.6	248
S/N	1.79	1.05
S/√N	12.3	16.1

Probing the HWW vertex

B. Mellado, R. Godbole



ep collider

Is the observed Higgs really the SM Higgs: $J^{PC} = 0^{++}$?
difficult to study at LHC (and e^+e^-),
except for H -> $ZZ^{(*)}$, but rates are low

$H(k) \bullet W_\mu^+(p) \bullet W_\nu^-(q)$ vertex:

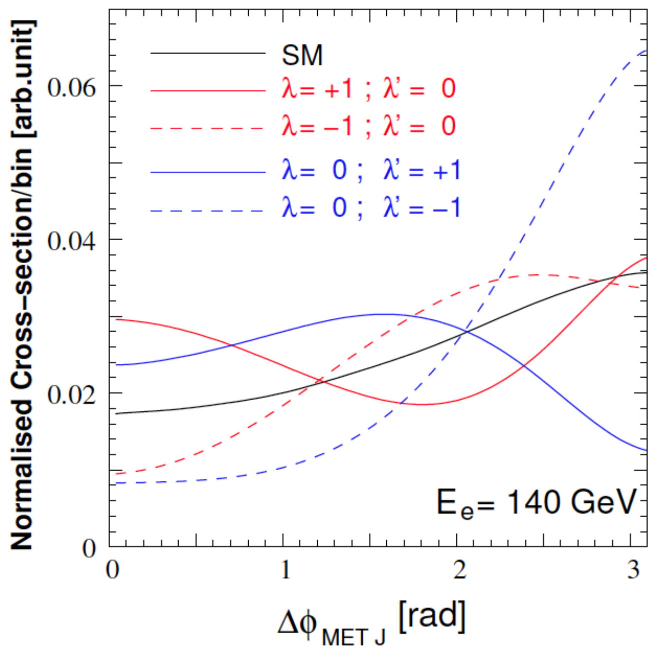
$$i\Gamma^{\mu\nu}(p,q)\,\varepsilon_\mu(p)\,\varepsilon_\nu^*(p)$$

$$\Gamma^{\mu\nu}(p,q) = -g\,M_W g^{\mu\nu} - \frac{g}{M_W}\left[\lambda\left(p\cdot q\, g_{\mu\nu}\right) + i\lambda'\varepsilon_{\mu\nu\rho\sigma}p^\rho q^\sigma\right]$$

At the LHeC:

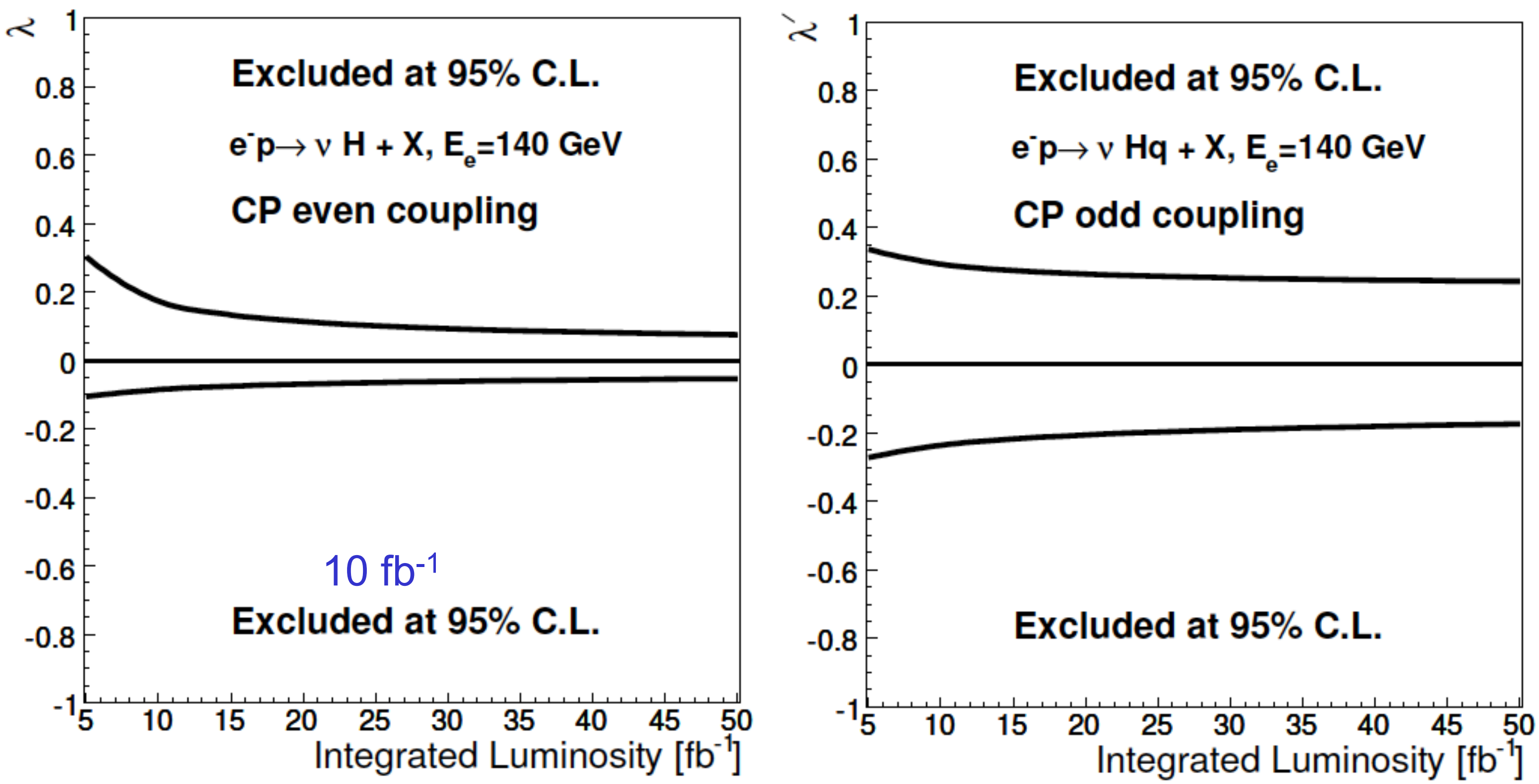
forward and backward directions well determined,
low background and low contamination
from other processes

Sensitive variable:
delta-phi between Etmiss and tag jet



Exclusion of anomalous HWW coupling

Following detailed simulation:

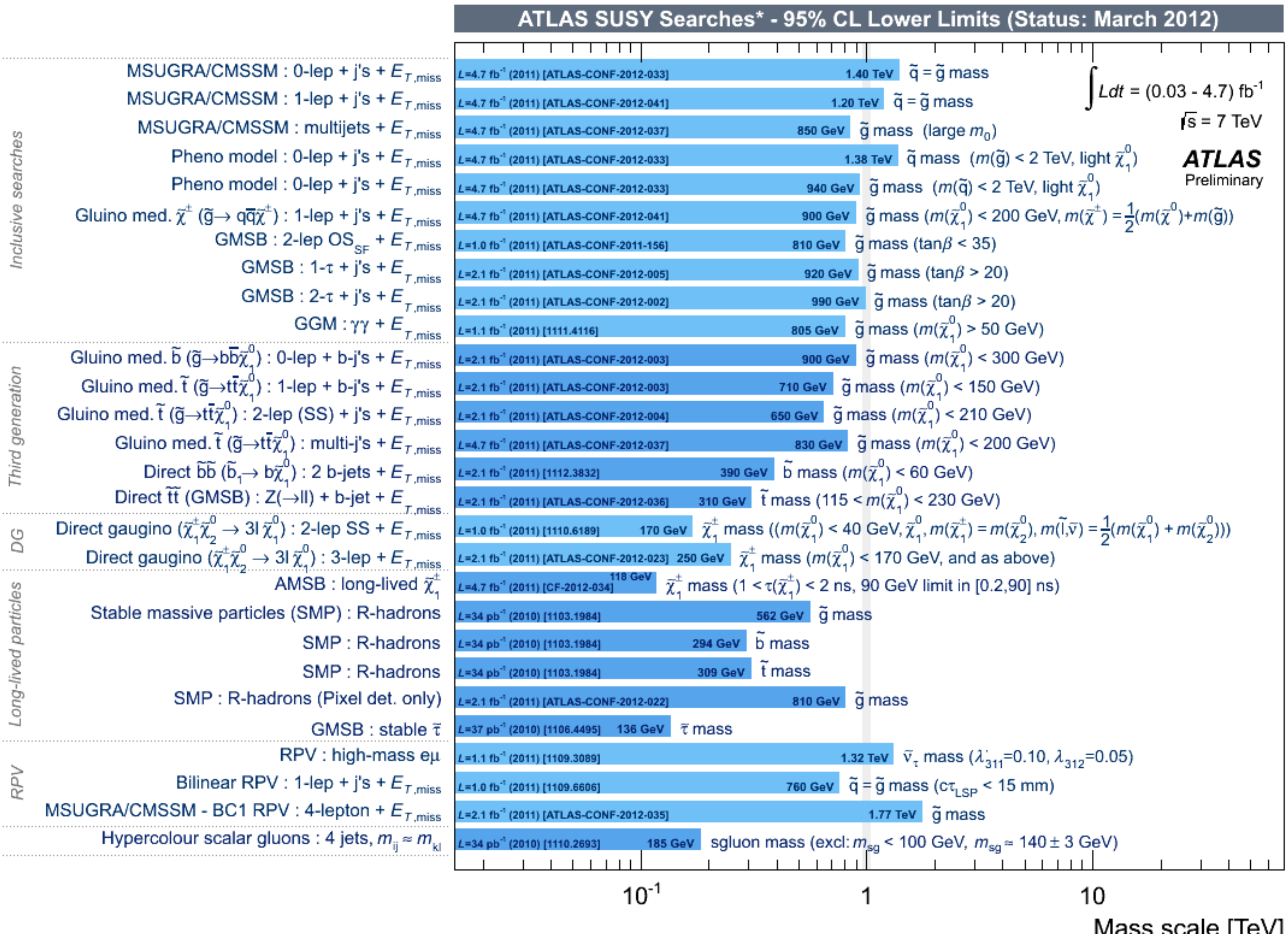


S. S. Biswal, R. M. Godbole, B. Mellado, S. Raychaudhuri

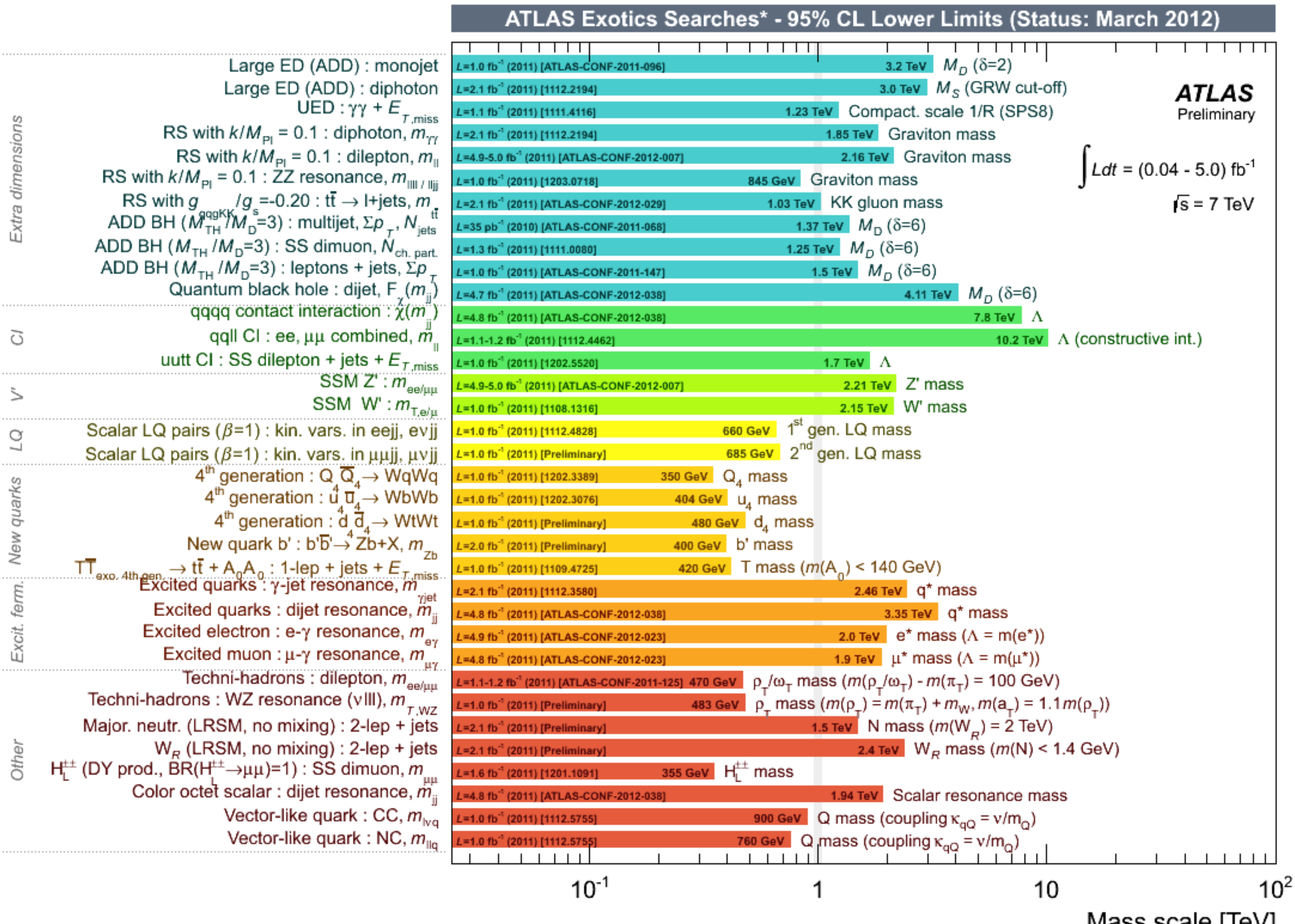
http://arxiv.org/abs/1203.6285

Summary

- **LHeC can complement LHC in understanding new physics phenomena**
  - contact interactions
  - Leptoquarks and RPV SUSY:
    - LHeC is ideal machine to study in detail all properties
  - excited and/or heavy fermions
  - anomalous couplings
- **Higgs parameters**
  - H-b-b coupling can be measured through VBF, H → bb
    - needs good detector performance
  - HWW coupling:
    - CP-odd component through phi correlations between tag jets



*Only a selection of the available mass limits on new states or phenomena shown

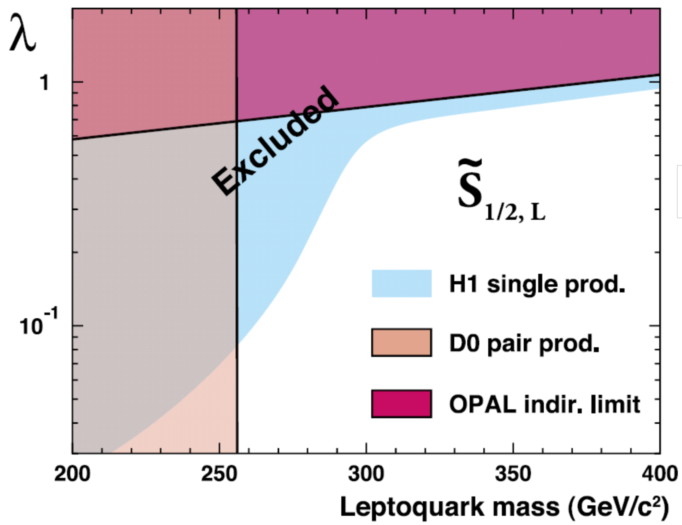


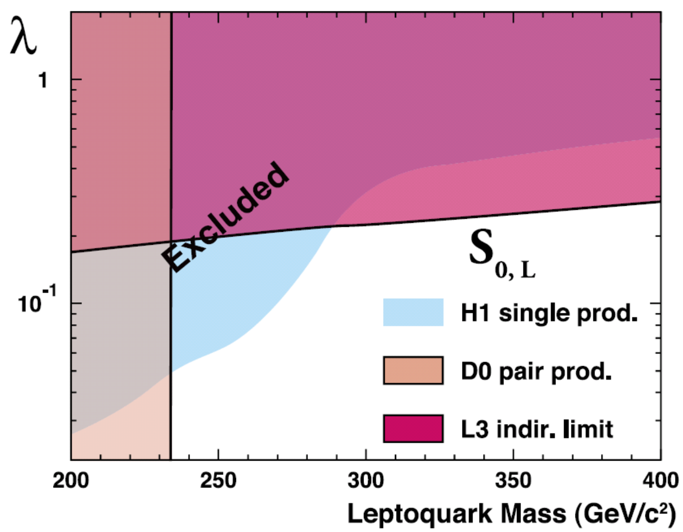
*Only a selection of the available mass limits on new states or phenomena shown

$F = 2$	Prod./Decay	β_e	$F = 0$	Prod./Decay	β_e
Scalar Leptoquarks					
$^{1/3}S_0$	$e_L^- u_L \to e^- u$	1/2	$^{5/3}S_{1/2}$	$e_L^- \bar{u}_L \to e^- \bar{u}$	1
	$e_R^- u_R \to e^- u$	1		$e_R^- \bar{u}_R \to e^- \bar{u}$	1
$^{4/3}\tilde{S}_0$	$e_R^- d_R \to e^- d$	1	$^{2/3}S_{1/2}$	$e_R^- \bar{d}_R \to e^- \bar{d}$	1
$^{4/3}S_1$	$e_L^- d_L \to e^- d$	1	$^{2/3}\tilde{S}_{1/2}$	$e_L^- \bar{d}_L \to e^- \bar{d}$	1
$^{1/3}S_1$	$e_L^- u_L \to e^- u$	1/2			
Vector Leptoquarks					
$^{4/3}V_{1/2}$	$e_R^- d_L \to e^- d$	1	$^{2/3}V_0$	$e_R^- \bar{d}_L \to e^- \bar{d}$	1
	$e_L^- d_R \to e^- d$	1		$e_L^- \bar{d}_R \to e^- \bar{d}$	1/2
$^{1/3}V_{1/2}$	$e_R^- u_L \to e^- u$	1	$^{5/3}\tilde{V}_0$	$e_R^- \bar{u}_L \to e^- \bar{u}$	1
$^{1/3}\tilde{V}_{1/2}$	$e_L^- u_R \to e^- u$	1	$^{5/3}V_1$	$e_L^- \bar{u}_R \to e^- \bar{u}$	1
			$^{2/3}V_1$	$e_L^- \bar{d}_R \to e^- \bar{d}$	1/2

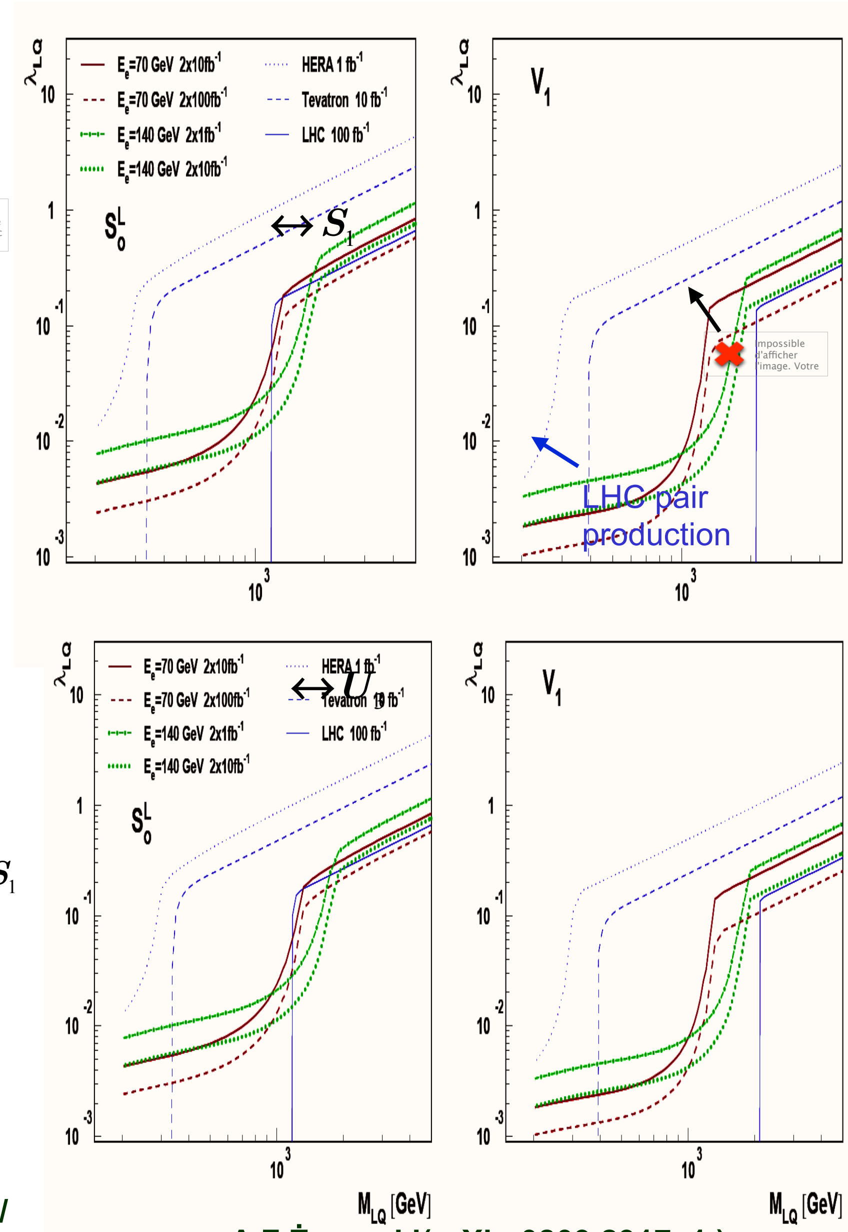
Table 6.1: Leptoquark isospin families in the Buchmüller-Rückl-Wyler model. For each leptoquark, the superscript corresponds to its electric charge, while the subscript denotes its weak isospin. β_e denotes the branching ratio of the LQ into $e + q$.

Present and expected bounds or discovery reach





$\leftrightarrow S_1$



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

A F Żarnecki(arXiv:0809.2917v1)