BSM Chapter for the LHeC CDR

G. Azuelos, E. Perez, editors

Contributions from various authors

overview of chapter

- Leptoquarks
- contact interactions
- heavy and excited fermions
- diquarks
- Higgs by VBF -> coupling to bbar
- WWH coupling

Introduction

- **LHC is a "discovery machine"**
  ➔ new bsm physics will likely be discovered there first
- **LHeC:**
  What could be the "added value" of LHeC for BSM physics ?
  - new physics at high scale → ***see talk by E. Perez***
    - specificity of LHeC :
      is there any new unknown lepton-quark interaction beyond EW ?
    - New physics at very high 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

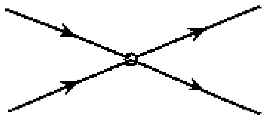
      ➔ higher reach in single production for specific processes

      ➔ possibility to study properties of new particles & interactions
  - Higgs couplings to bb → ***see talk by U. Klein***
  - Probing VVH coupling → ***see talk by R. Godbole***
  - cleaner environment, better S/N
  - improved pdfs ➔ higher precision from measurements performed at LHC

Contact Interactions

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

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



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

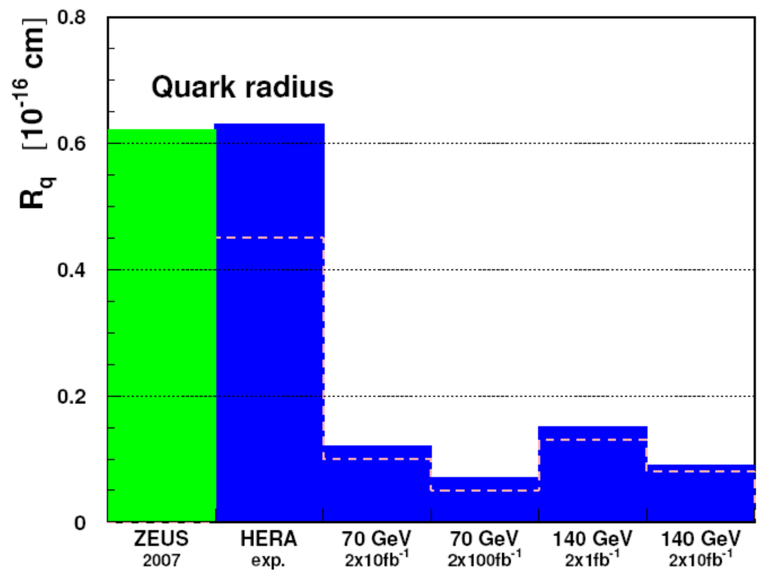
$$j_\mu^{(f=e,q)} = \eta_{LL}\, \bar{f}_L \gamma_\mu f_L + \eta_{RR}\, \bar{f}_R \gamma_\mu f_R + h.c.$$

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

Quark radius from Q^2 dependence of DIS cross section

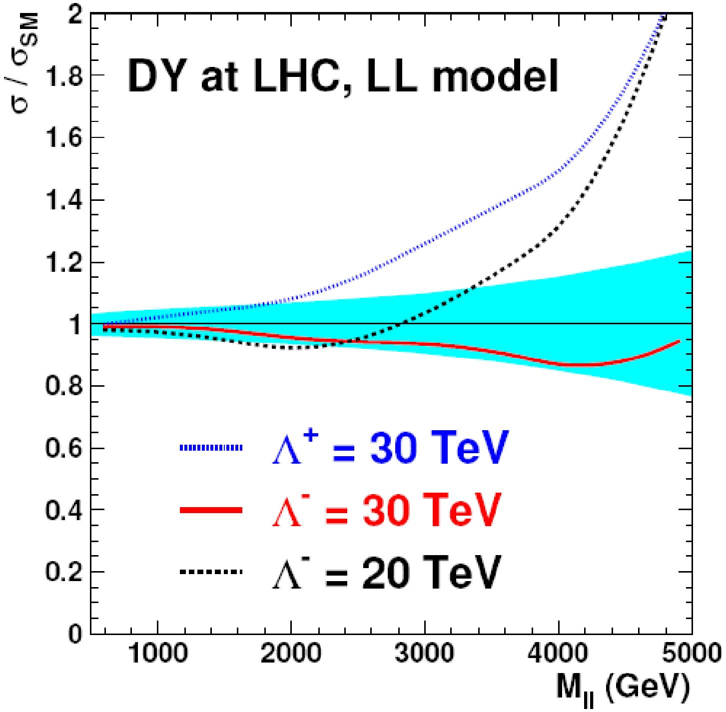
$$f(Q^2) = 1 - \frac{1}{6} \langle r^2 \rangle Q^2 \; ,$$

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

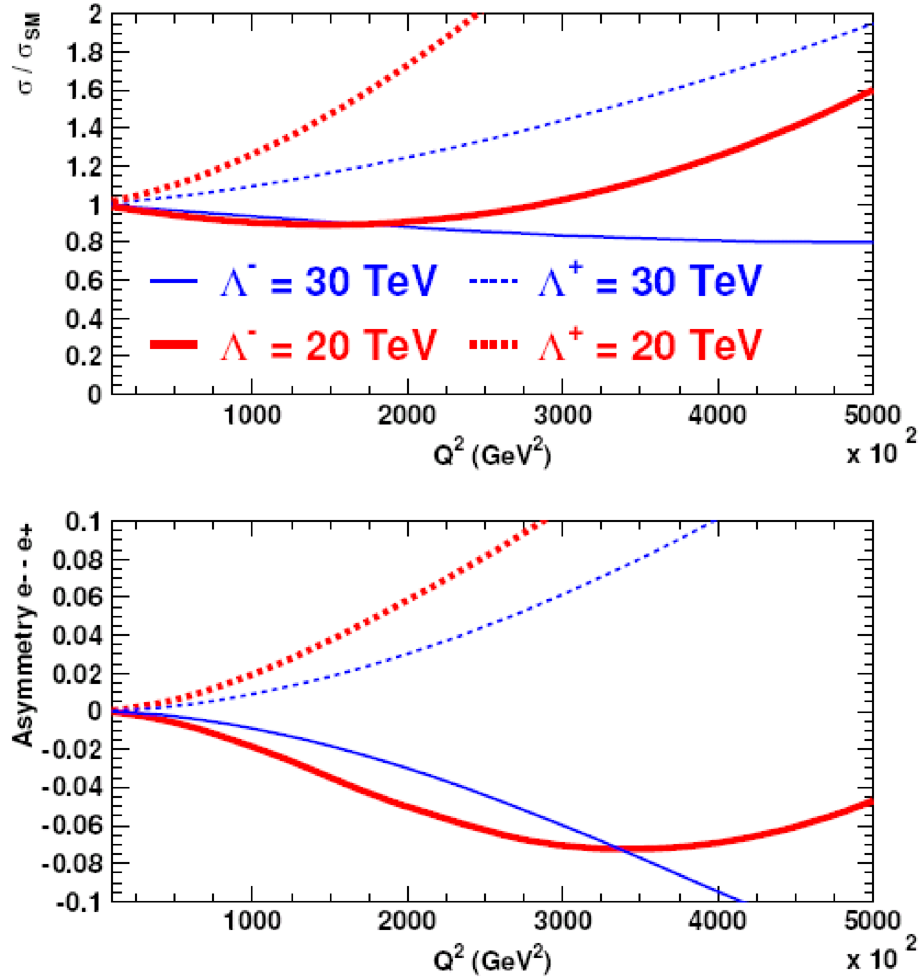


A. F. Zarnecki, arXiv:0809.2917

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

Leptoquarks

Leptoquarks are predicted in extensions of the SM

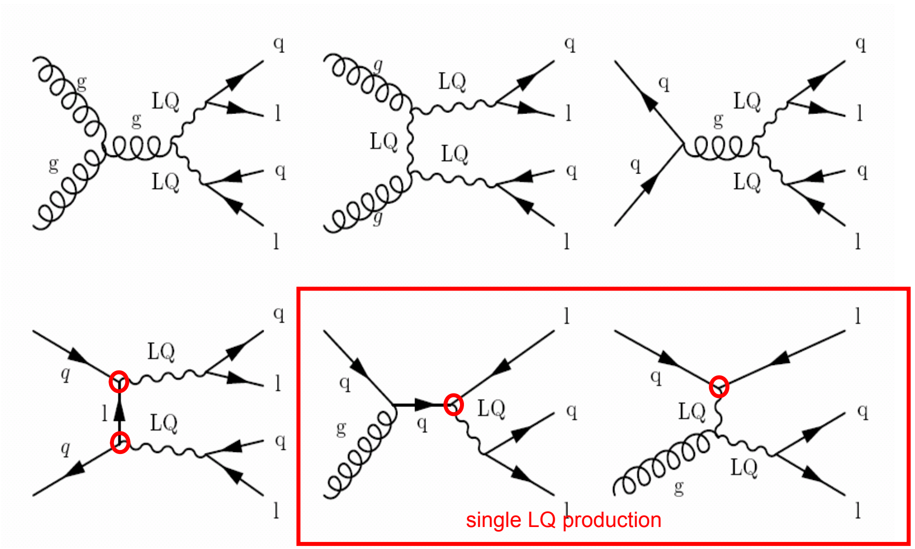
- E_6: new fields possibly having both B and L quantum numbers
- technicolor: bound states of technifermions
- Pati-Salam: lepton is a 4^{th} quark color
- squarks decaying by R-parity violation

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

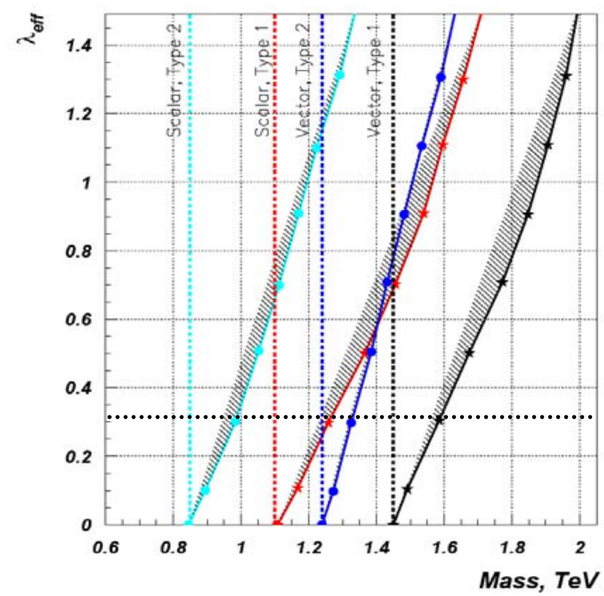
LQ's carry baryon and lepton number; can be scalar or vector
➔ Buchmüller classification (many other conventions)

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

at the LHC



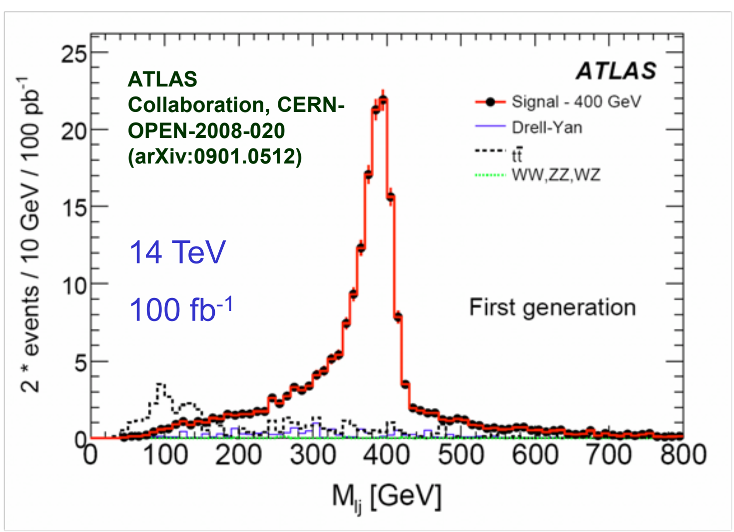
single production suppressed by dependence on λ



LHC
300 fb^{-1}

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

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

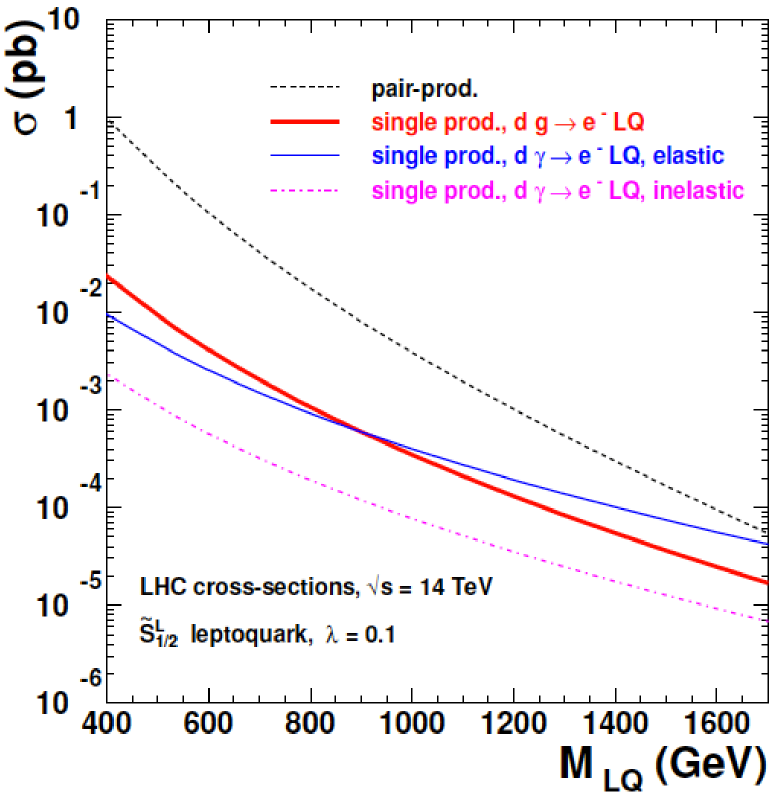


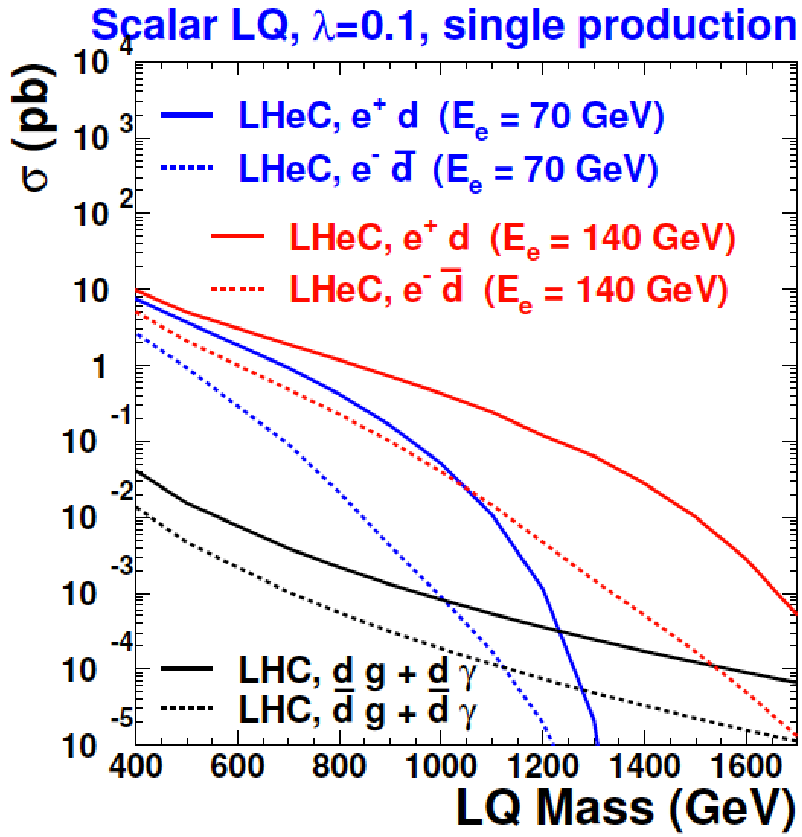
combined single and pair production, eq and νq channels

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

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

Single LQ production



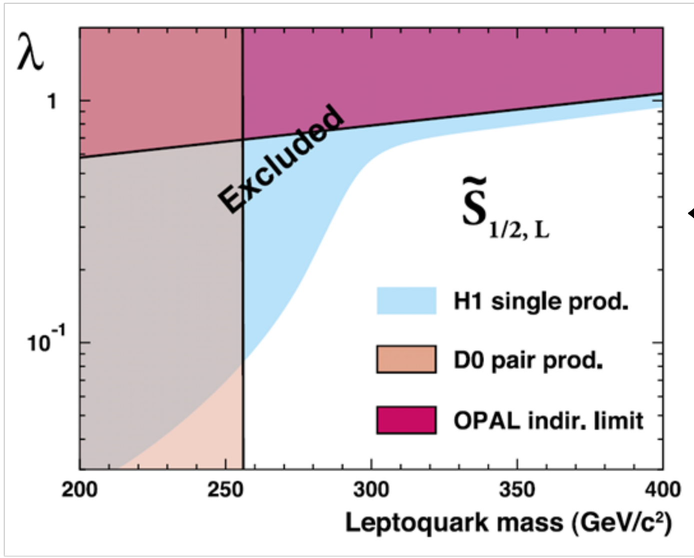


γq process increases the x-section for single LQ production at the LHC. But it is still much lower (O(100)) than the x-section in ep.

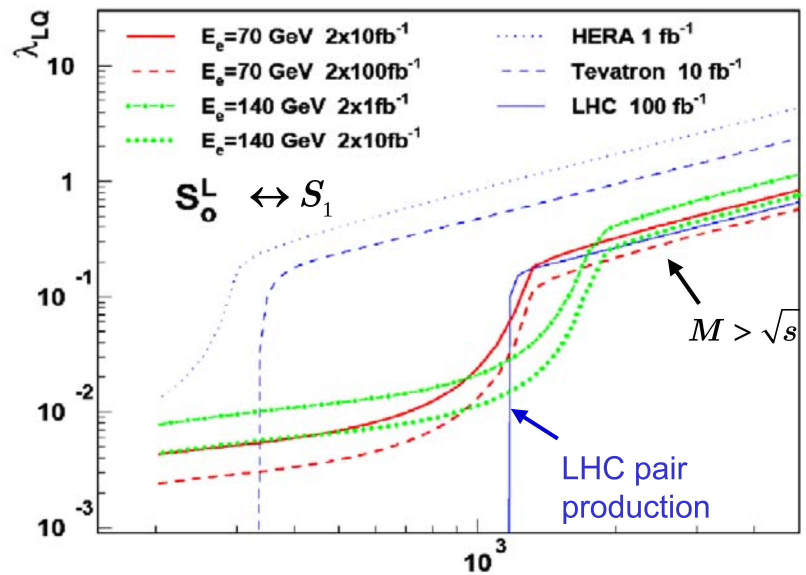
Can we still use single LQ production at the HLC to determine the LQ properties ?

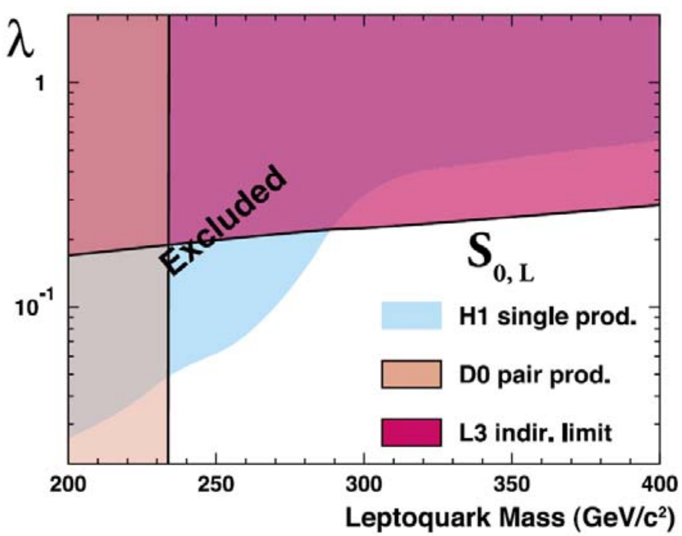
Slide from Emmanuelle

Present and expected bounds or discovery reach



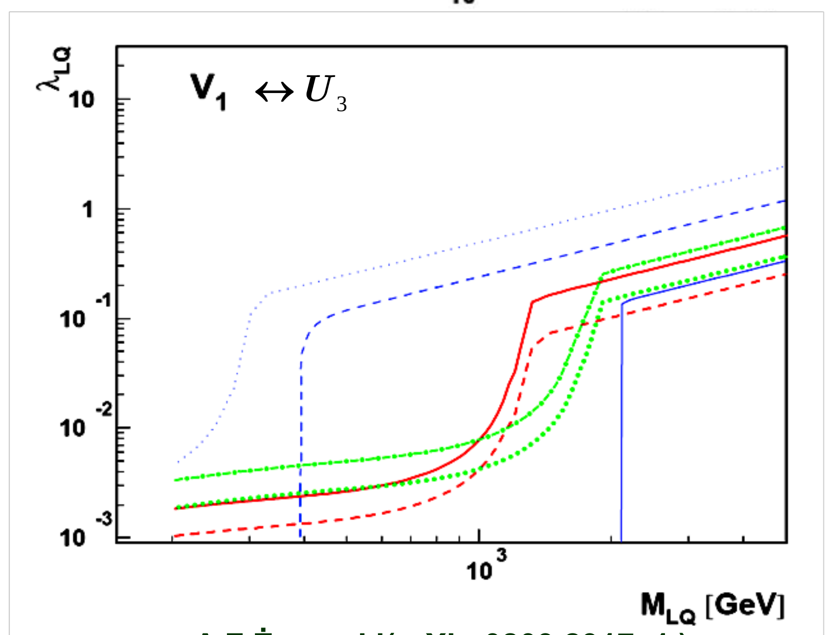
$\leftrightarrow \tilde{R}_2$





$\leftrightarrow S_1$

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

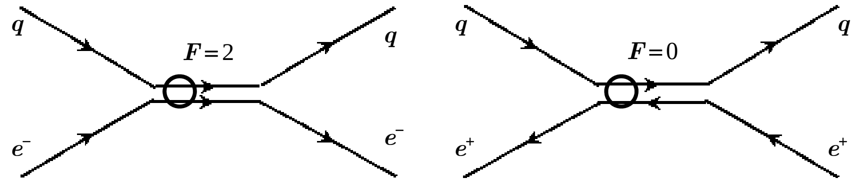


A F Żarnecki(arXiv:0809.2917v1)

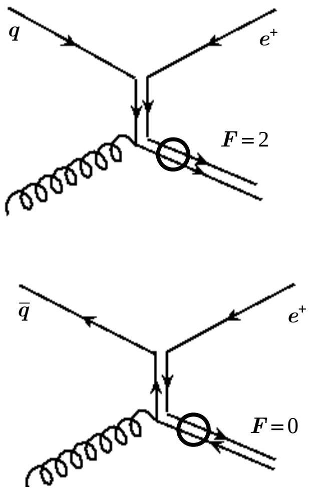
If LQs are discovered, what can we learn at the LHeC?

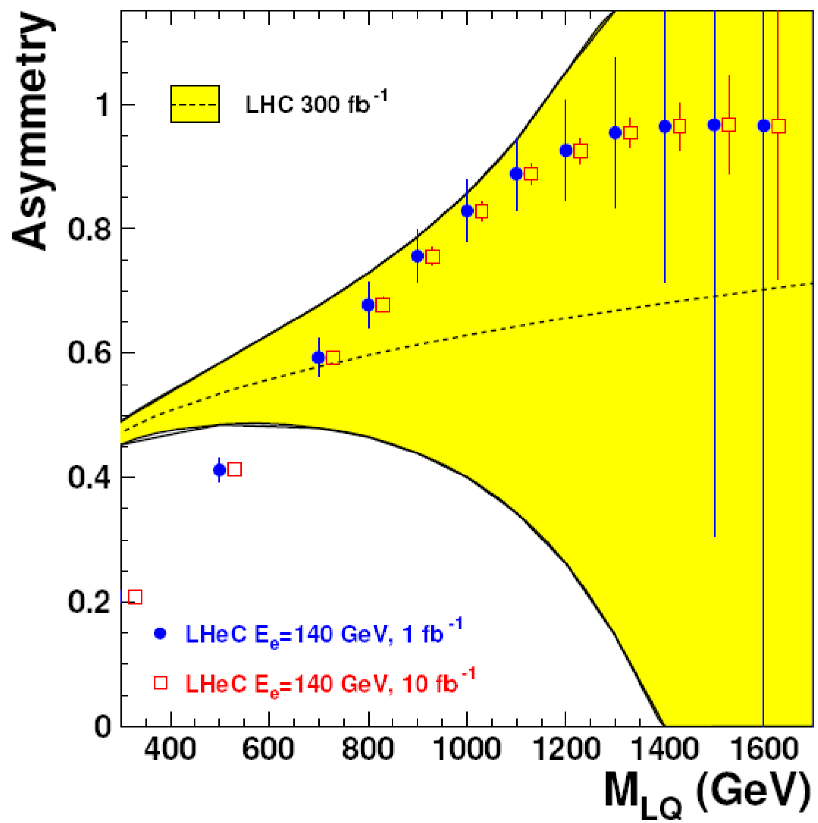
- Quantum numbers and couplings:
  - **F: fermion number can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$**

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



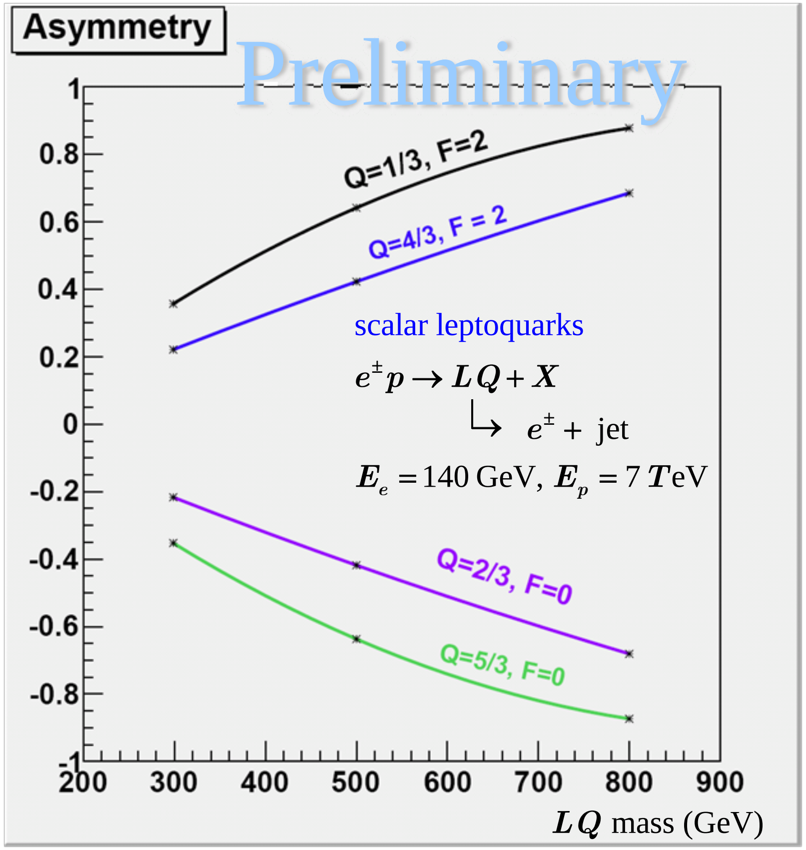
- **can also be probed in single LQ production at the LHC, but cross section is low**





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

Asymmetry also probes the **LQ charge**



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.)

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**

BR to neutrino

- **good S/B in νj channel**

e-q-LQ coupling

- **knowing the charge and spin, λ can be determined**

Leptogluons

Leptogluons are color-octet partners of leptons

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

It couples to a lepton and gluon, and the phenomenolgy is similar to that of LQ's

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

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)

Table 2.22: Achievable compositeness scale Λ in TeV units at LHeC2 for 5σ (3σ) statistical significance.

140 GeV x 7 TeV

M. Sahin, S. Sultansoy and S. Turkoz

Excited fermions

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

  - gauge interaction Lagrangian

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

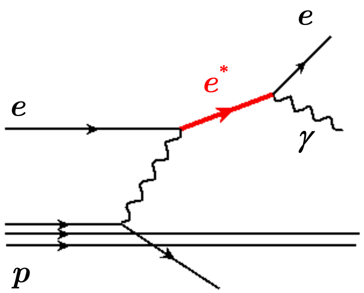
conventional reference point: $\frac{f}{\Lambda} = \frac{1}{m^*}$

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

  - contact interaction Lagrangian

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

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



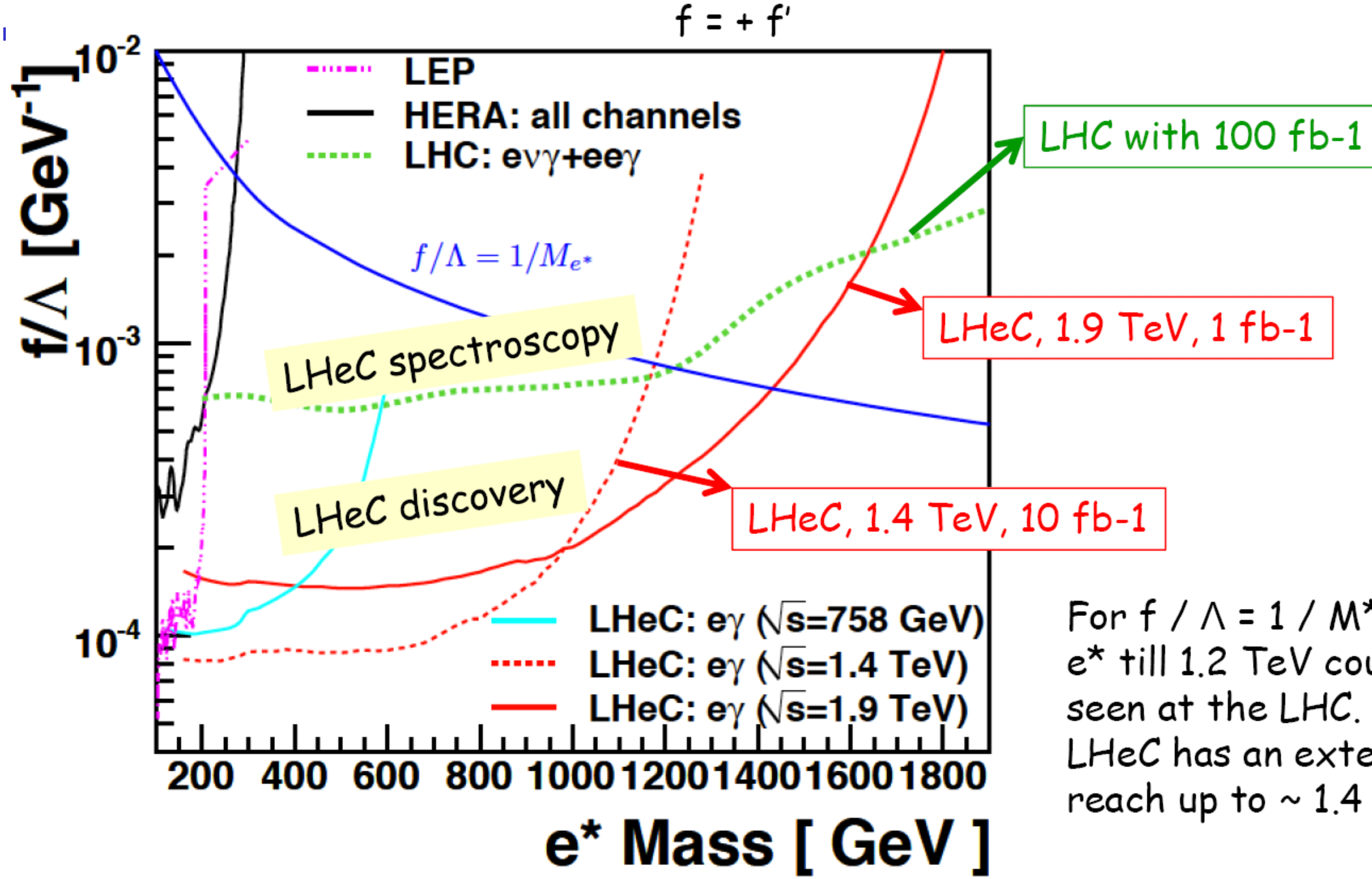
LHC could probe up to 1-2 TeV for $f = f' = 1, \Lambda = m_{e^*}$

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)

LHeC has higher cross section

Excited leptons



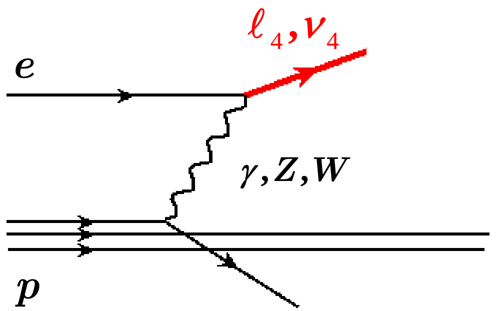
For f / Λ = 1 / M* :
e* till 1.2 TeV could be seen at the LHC.
LHeC has an extended reach up to ~ 1.4 TeV.

If LHC observes the single-production of e*: its properties could be studied at LHeC (larger single cross-section).

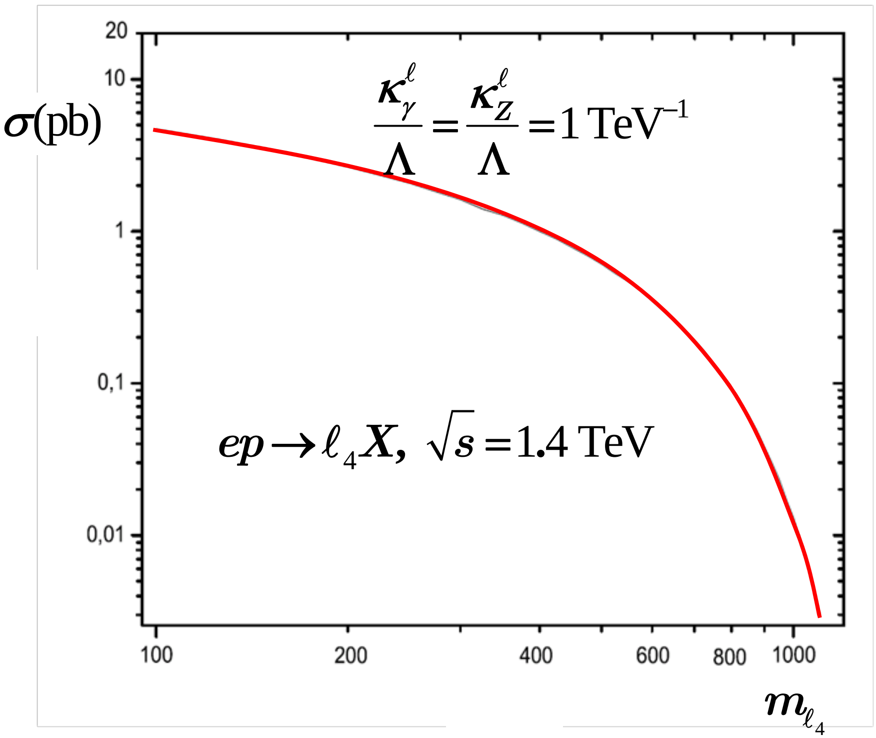
heavy leptons (4th family or other)

Heavy fermions predicted in many BSM theories

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



Production at LHeC by anomalous couplings:



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

Charged leptons:

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

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

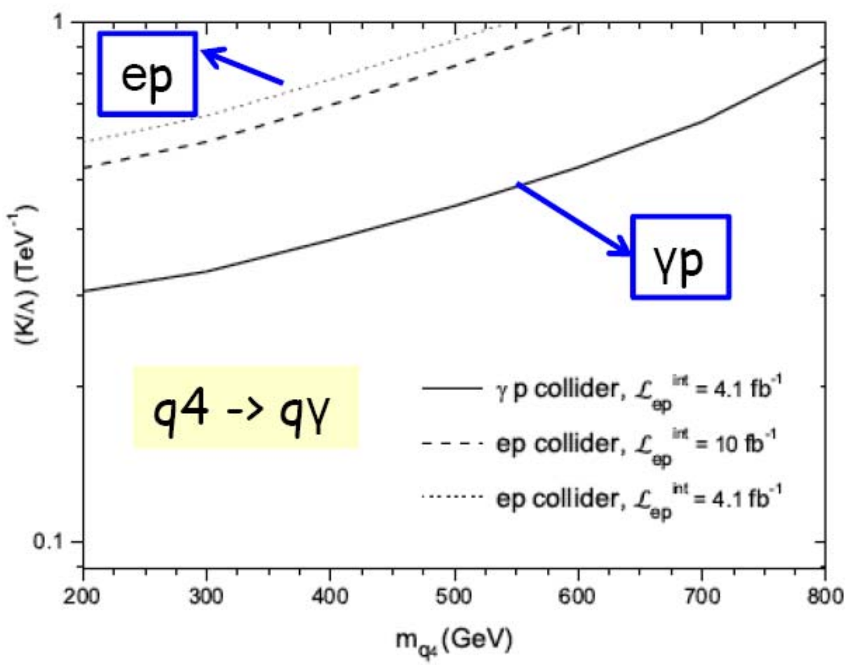
heavy quarks: anomalous couplings in γp collisions

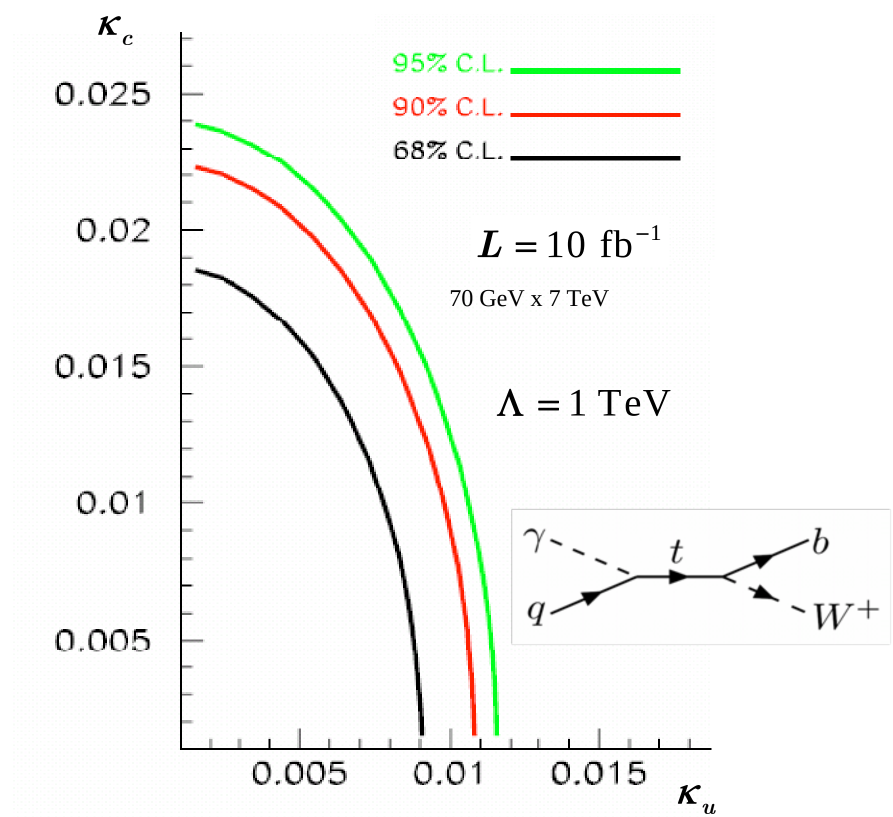
t quark – anomalous coupling in γp option
available using Compton back-scattering
pulsed superconducting linac + LHC ring

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





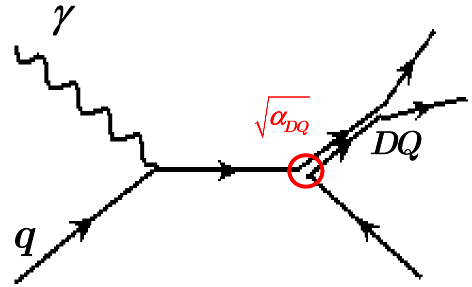
IT Cakir, O. Cakir and S. Sultansoy, PL B685 (2010) 170

added value of LHeC if gQq coupling small

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

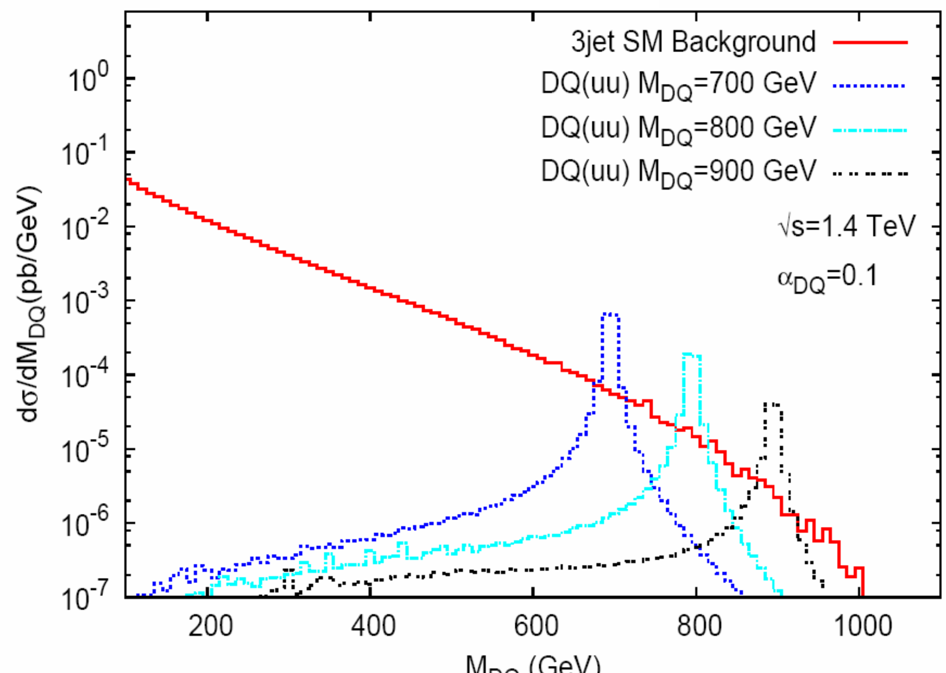
Charge measurement of DQ

Single DQ production in γp collisions:

$\sigma = f(M, \alpha, e_{DQ})$ → e_{DQ}

LHC

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



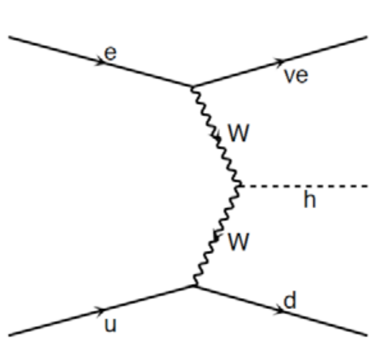
M Şahin and O. Çakir, arXiv:0911.0496

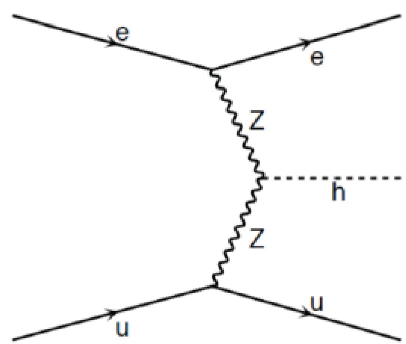
Higgs coupling to $b\bar{b}$

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

- Higgs mass most likely in range ~115-150 GeV
- In this mass range, the principal decay is to $b\bar{b}$
  huge QCD background at LHC → Hbb coupling difficult to measure

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





CC, ~ 200 fb NC, ~ 50 fb for 150 x 7000 GeV

$\sqrt{s} = 2.05\ TeV$

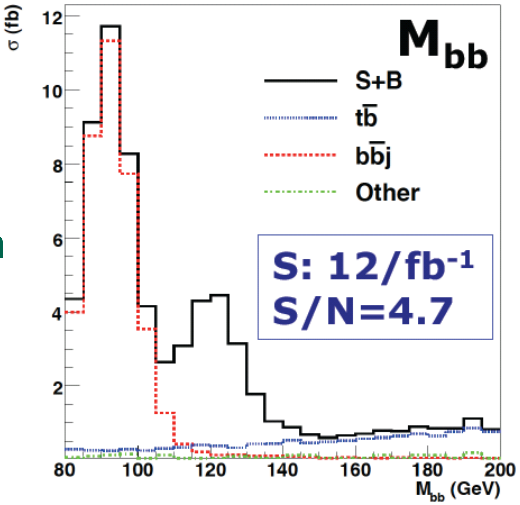
Challenging measurement, which imposes constraints on the detector:
forward acceptance crucial

Higgs coupling to $b\bar{b}$

Previous generator-level study gave encouraging results

(B. Mellado, T. Han arXiv:0909.2460)

- needs good b-tag efficiency: 60%
- forward jet tagging: $1<\eta<5$ and $p_T>30$ GeV



Need for a more realistic evaluation using detector simulation

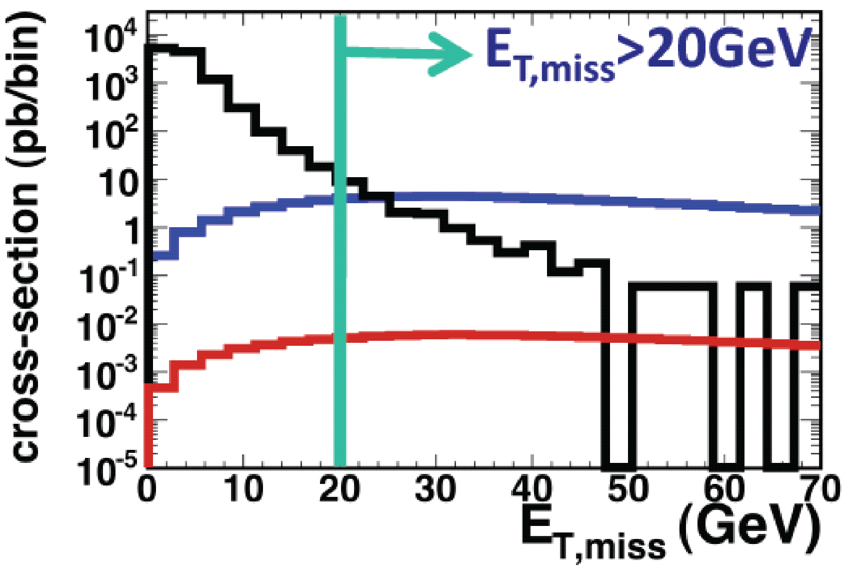
- signals and backgrounds generated with MadGraph
  - → need to modify pythia-pgs interface to run for DIS
- allow Higgs decay in MadGraph
- PGS:
  - em calorimeter resolution: $5\% \times \sqrt{E}$
  - had. calorimeter resolution: $60\% \times \sqrt{E}$
  - jet cone: 0.5
  - b-tagging: 60% b, 10% c, 1% usdg flat in range $|\eta| < 3$
  - calorimeter coverage up to $|\eta| < 5$

Higgs coupling to $b\bar{b}$

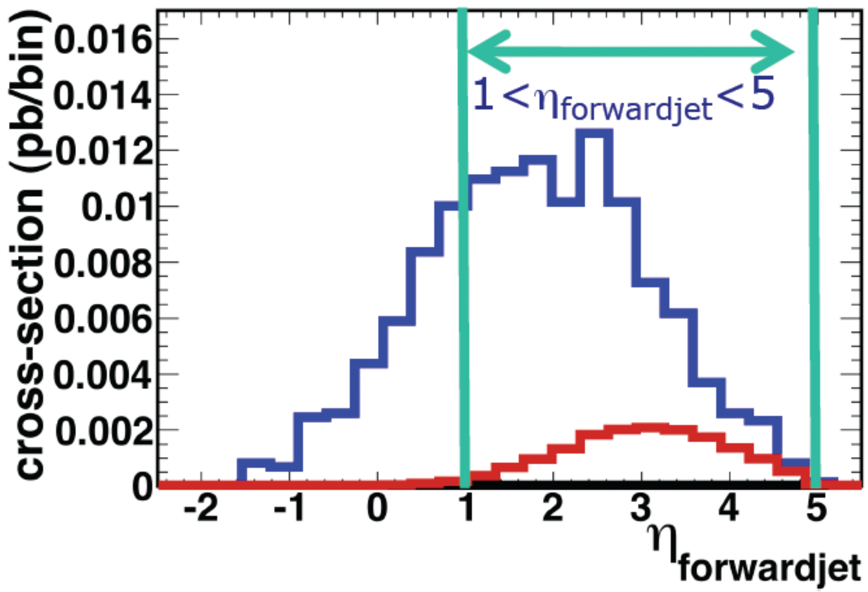
Summary of event selection

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

$E_{T,miss}$



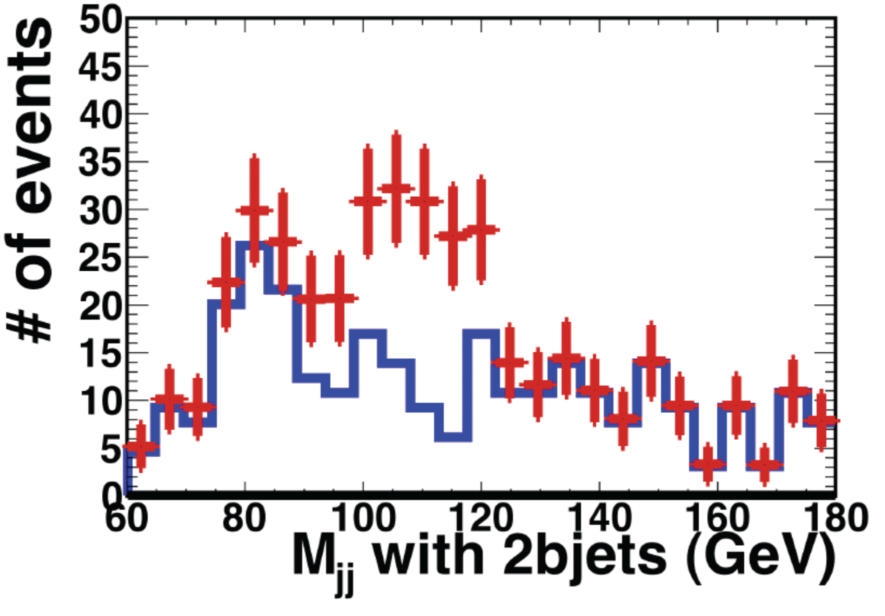
Fwd Jet Tag



Number of events after ALL cuts.

	Higgs event	CC 3jets bg	NC 3jets bg	S/N	S/√N
# of events	104	86.4	0	1.2	11

- **Efficiency of Higgs event selection is 6.5%** (104/1600)
- **We could identify H→bb events within 11σ.**



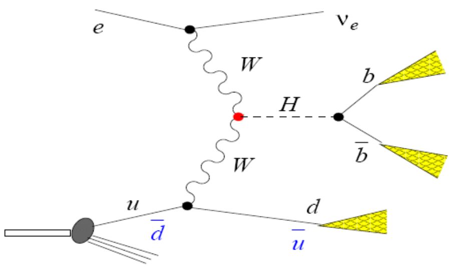
E_e = 150 GeV,

m_H = 120 GeV

10 fb^{-1}

Probing the HWW vertex

R. Godbole



ep collider

- Is the observed Higgs really the SM Higgs: $J^{PC} = 0^{++}$?

HVV:

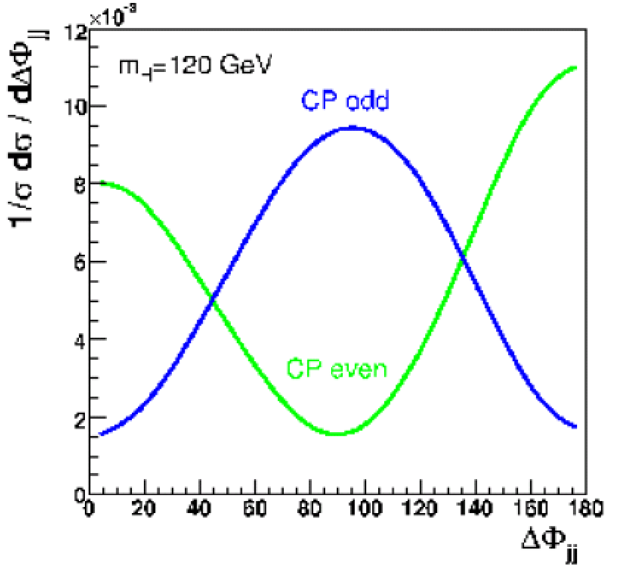
$$V^{\mu\nu}_{HVV} = -ig\left[f_1\, g_{\mu\nu} + f_2\,(g_{\mu\nu}k1.k2 - k1_\nu k2_\mu) + f_3\, i\epsilon_{\mu\nu\alpha\beta}\, k_1^\alpha k_2^\beta \right]$$

$$f3 = \lambda'/m_W$$

dimension-5 vertex for coupling of CP-odd component

Sensitive variable:
delta-phi between tag jets

need ~ 30 fb^{-1} at LHC for 3s exclusion of CP-odd state

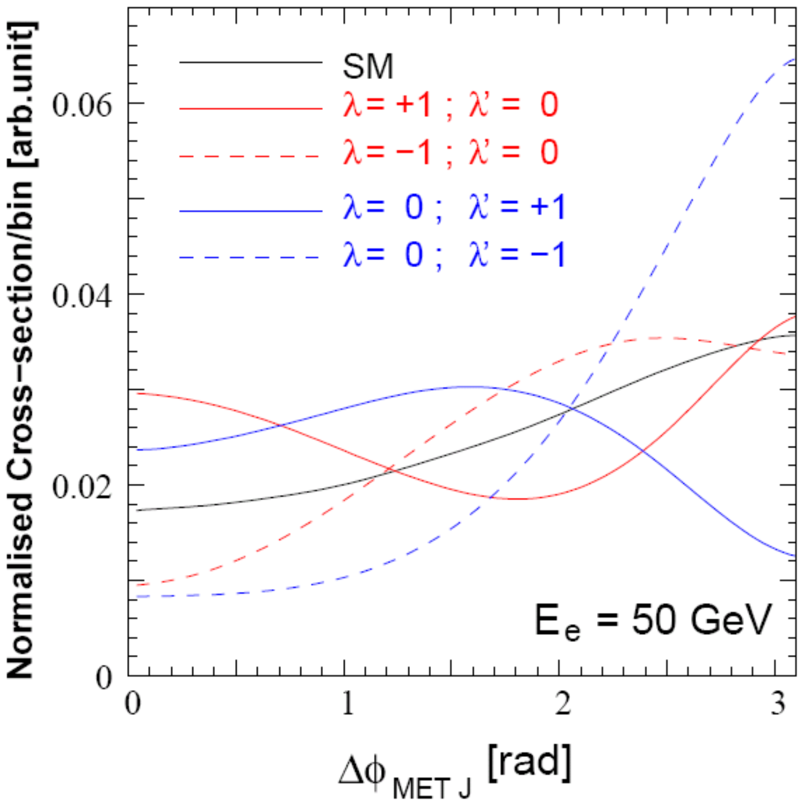


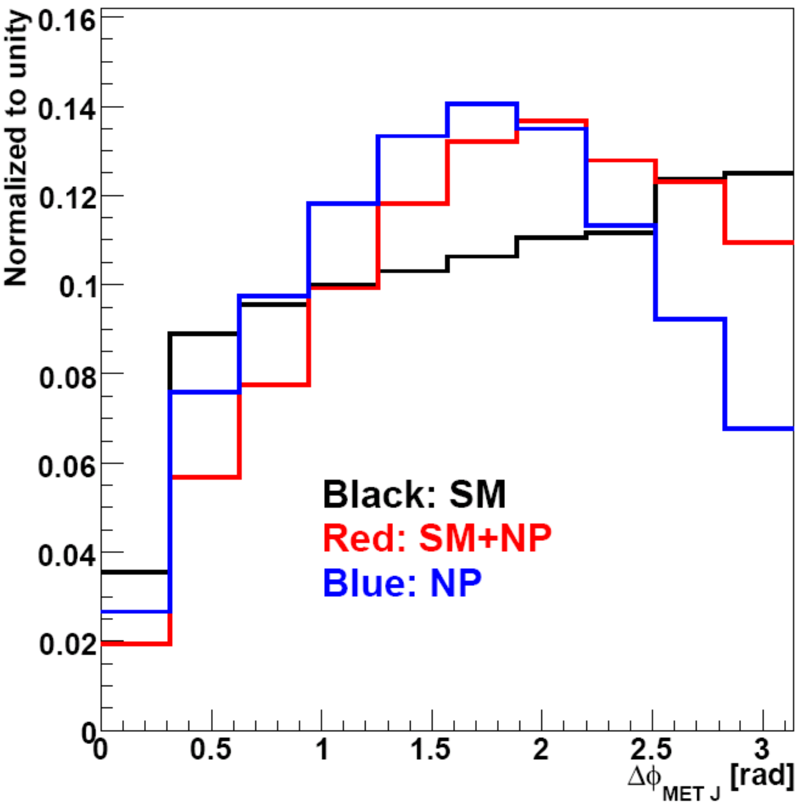
C. Ruwiedel et al, EPJC 51 (2007) 385

For CP-odd Higgs, H → WW has very small BR ➔ would like to use bb decay

→ proven to be possible at LHeC !

→ can also separate HWW and HZZ couplings at LHeC





using parton level results from B. Mellado and T. Han

Summary

- **LHeC can complement LHC in understanding new physics phenomena**
  - contact interactions
  - Leptoquarks:
    - 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, $H \rightarrow bb$
    - needs good detector performance
  - HWW coupling:
    - CP-odd component through phi correlations between tag jets