Overview of BSM Activities

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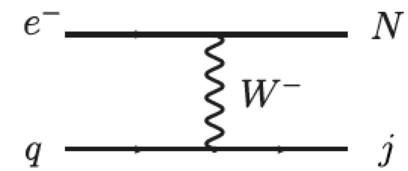
LHeC and FCC-eh Workshop

11-13 September 2017
CERN
Europe/Zurich timezone

BSM Physics

- Wiki page started: *https://twiki.cern.ch/twiki/bin/view/LHeC/LHeCFCCehBSM*
- exclude BSM Higgs, BSM top
- focus on understanding common features of leptons and quarks:
  - same generation weak isospin symmetry, electric charge quantization
    $\rightarrow$ compositeness? larger symmetry group?
    - Leptoquarks, excited/heavy fermions, new interactions
      ➔ *see talk by Oliver Fischer on sterile neutrinos*
    - EW interactions only $\rightarrow$ *see talks by EW group*

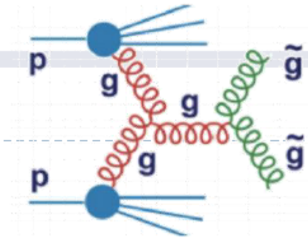


- Supersymmetry, RPC and RPV
  - strong constraints on minimal model, but not all phase space studied
    ➔ *see talks by Monica, Kechen, Sho and Jose*
- Composite Higgs (hierarchy problem)
  - new strong interaction $\rightarrow$ Higgs is a pseudoGoldstone boson
  - new phenomenology
    - Higgs properties $\rightarrow$ *see talks by Higgs group*
    - vector diboson resonances
      - constraints from LHC ~ TeV
      - in VBS, check unitarity, new resonances
    - new fermions: vector-like leptons and quarks
      - constraints on VLQ at LHC ~ TeV
- Dark, hidden Sector
  - dark matter candidates, long-lived particles
    ➔ *see talks later in this session*

ep vs pp colliders and added values

- Cannot compete on cm energy
  - LHeC (60 GeV x 7 TeV) → 1.3 TeV
  - FCC-eh (60 GeV x 50 TeV) → 3.5 TeV
    (60 GeV x 13.5 TeV) → 1.8 TeV
- But much improved PDF's
  → higher precision of measurements
  ➔ *see Jan's talk:*
  effect on m_W and $\sin\theta_W$ measurements
- Much less background and pileup than at pp colliders
  - *possibly >60-140 pileup events per beam crossing at HL-LHC*
    ~ 0.1 at LHeC
    - *forward jets in VBS difficult to identify at pp colliders*

Impact of PDF at High x

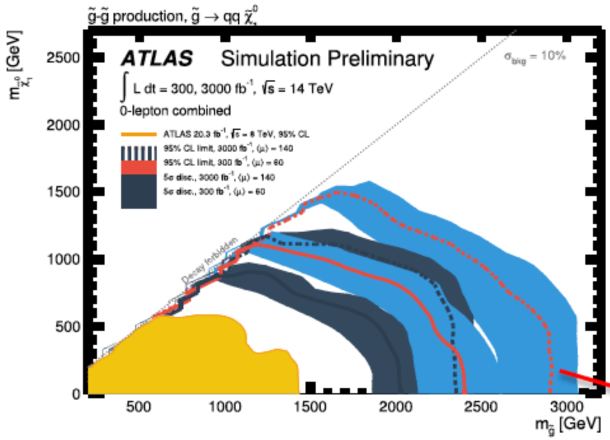


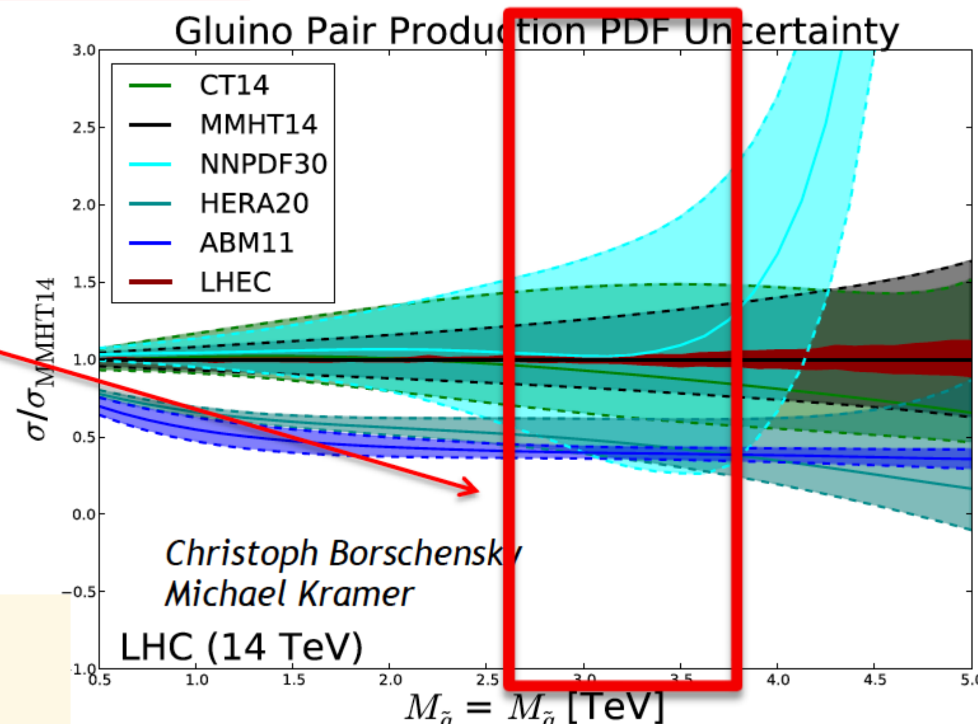
- large uncertainties in high x PDFs limit searches for NP

  many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production
- For HL-LHC → studied in detail impact of LHeC

< x > ~ 0.4

prescription from J. Rojo to avoid negative x-section at at high masses for NNPDF30nlo → x-section calculation unstable





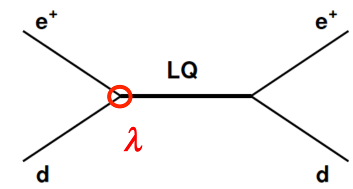
- Studies updated with modern PDF sets
  - M(squark)=M(gluino)=μ_R=μ_F
  - LHeC PDF uncertainties unchanged
  - Normalized to MMHT14

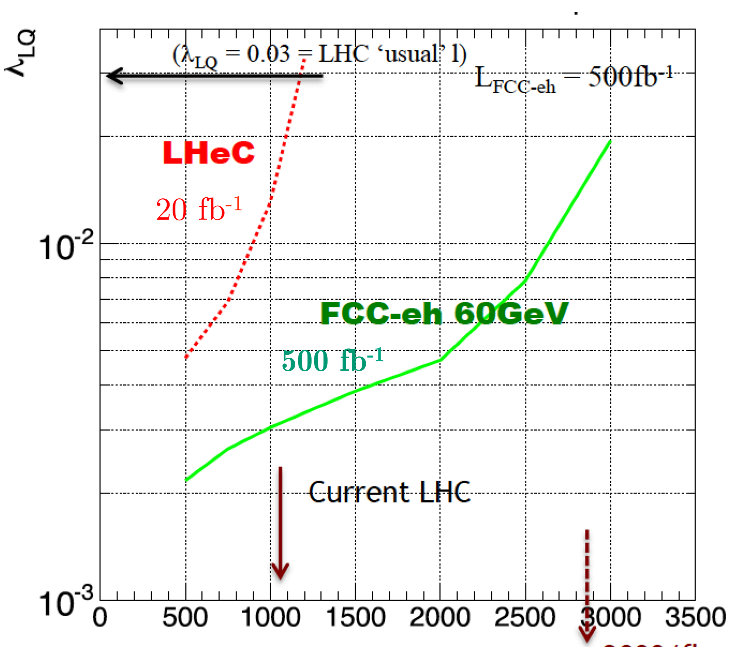
arXiv:1211.5102

Hopefully, we will update studies with LHeC PDF unc in performing studies for the HL-LHC Yellow Report

Leptoquarks

- LQ's carry baryon and lepton number
  - predicted in technicolor and Pati-Salam models
  - can be scalar or vector (Buchmuller classification)
  - possible family mixing → FCNC and LFV
  - s-channel production at ep colliders
    - sensitive to LQ-e-q coupling
    - mostly pair-production at LHC, insensitive to coupling
      - present limit: ~ 1.1 TeV for 1st generation LQ
      - estimated reach ~ 1.5 TeV (**A. Belyaev et al., arXiv:hep-ph/0502067**)
        ~ 2.8-2.9 TeV for HL-LHC (**use http://collider-reach.web.cern.ch**)





$$\textit{note}: \text{sensitive to } \lambda \ll e = \sqrt{4\pi\alpha} = 0.312$$

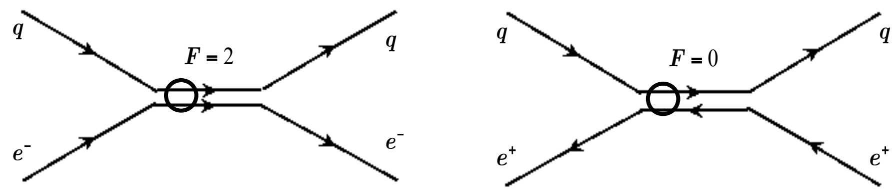
Sensitivity of HL-LHC could go to ~2.8 –2.9 TeV
→Close to the reach for FCC-eh
→Dependence on lambda

If deviations are found by the end of HL-LHC, FCC-hh will definitely see them, and FCC-eh can characterize those signals!

Measuring the LQ quantum numbers at ep colliders

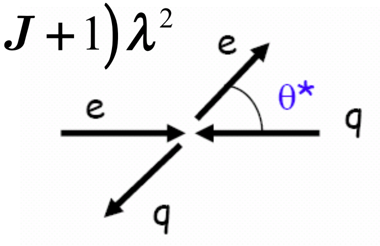
- Quantum numbers and couplings:
  - **Fermion number and LQ charge**
    - **can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$**
    - **at LHC: very poor asymmetry precision achievable in single LQ production**

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



  - **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**

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



    - **at LHeC, cos θ* distribution is sensitive to the spin**
    - **vector leptoquarks can have anomalous couplings**
  - **couple chirally (i.e. to L or R but not both) ?**
    - **could be probed by measuring sensitivity of cross sections to polarization of the electron beam**
  - **generation mixing ?**
    - **does LQ decay to 2nd generation?**
  - **BR to neutrino, good S/B in νj channel**

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

RPV SUSY

Squarks in RPV models could be an example of 'Leptoquarks'

L-number violating terms

$$W_{\not{R}_p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k^C + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k^C + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}_i^C\hat{D}_j^C\hat{D}_k^C$$

bilinear terms

B-number violating terms

ΔL =1, 9 λ couplings, 27 λ' couplings

Plethora of new couplings, only partially constraints (m/100 GeV)

Various strong constraints already from LHC on λ and λ'' *(from multilepton and multijet searches)*

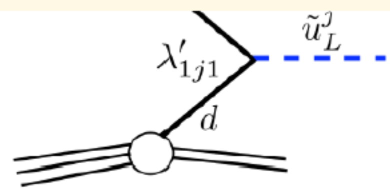
Very recently, H. Dreiner et al. released an extremely comprehensive review of the current constraints on LLE, LQD and UUD couplings https://arxiv.org/abs/1706.09418

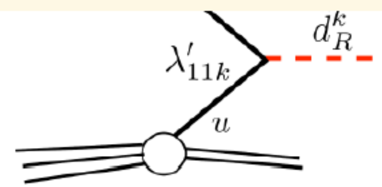
Couplings with third gen quarks

In e-p production rate depending on:

e-d-t: λ'_{131} (constraint: < 0.03)

e-u-b: λ'_{113} (constraint: < 0.02)





RPV SUSY

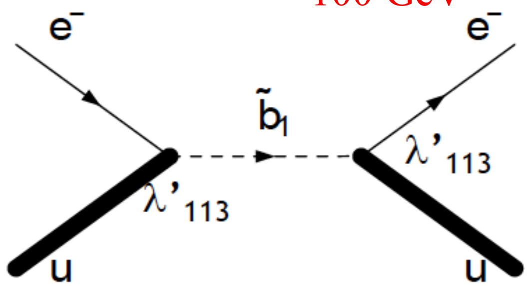
lepton-flavor-conserving process under single coupling dominance hypothesis

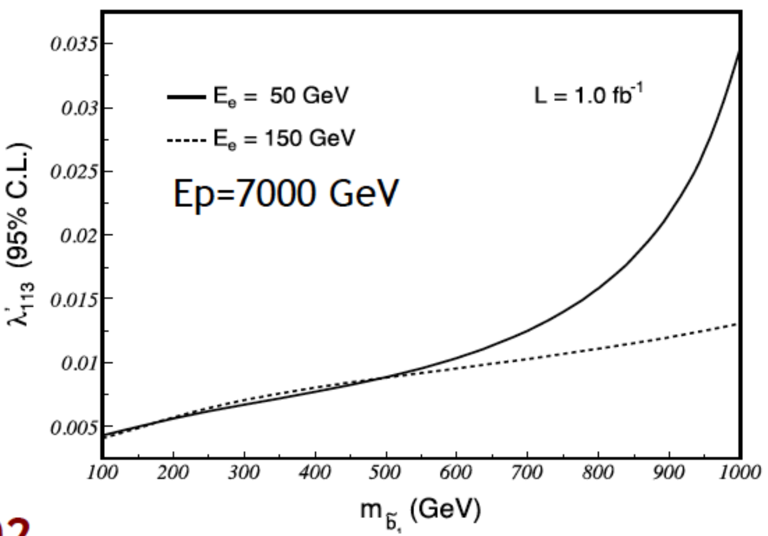
single sbottom/stop production (signal like leptoquarks, with generation mixing)

arXiV:1401.4266

< 100 fb-1 needed for 1 TeV RPV sbottom 5s discovery

sbottom $\lambda'_{113} < 0.02 \frac{m_{\tilde{b}_R}}{100\text{ GeV}}$



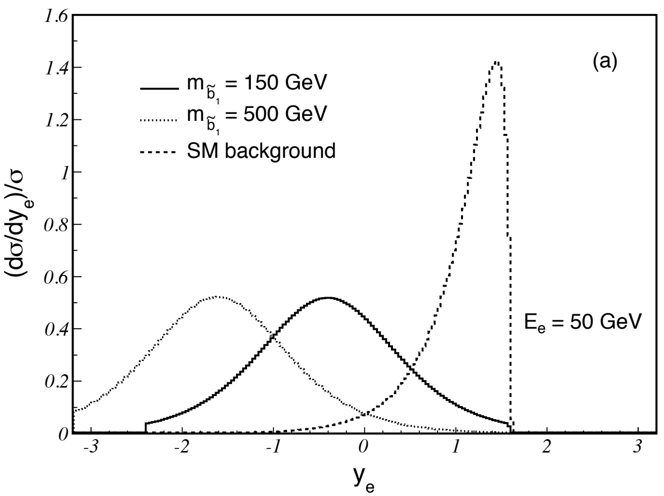


Probe RPV LQD terms: $(\lambda'_{113})^2$

@FCC-eh: same analysis as for LQ →

Sensitivity up to 2.5 TeV for $\lambda'_{113}<0.02$

also strong bounds from $\beta\beta0\nu$



λ'_{113} can be more strongly constrained under certain assumptions. At the LHC, current constraints on other sparticles are tight but yet 'reasonable' and not on sbottom

Contact Interactions

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

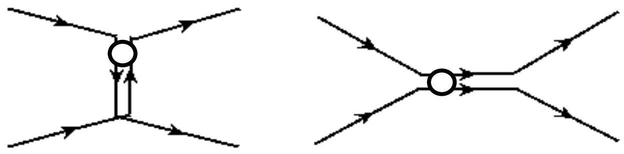
seen as an effective 4-fermion interaction

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

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

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

$$\Lambda \equiv \begin{cases} LQ \text{ in t-channel, mass } \gg \sqrt{s} \\ \text{Planck scale } (M_s) \text{ of extra-dimensional models} \\ \text{compositeness scale} \\ \ldots \end{cases}$$



Translate to limit on the quark radius

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

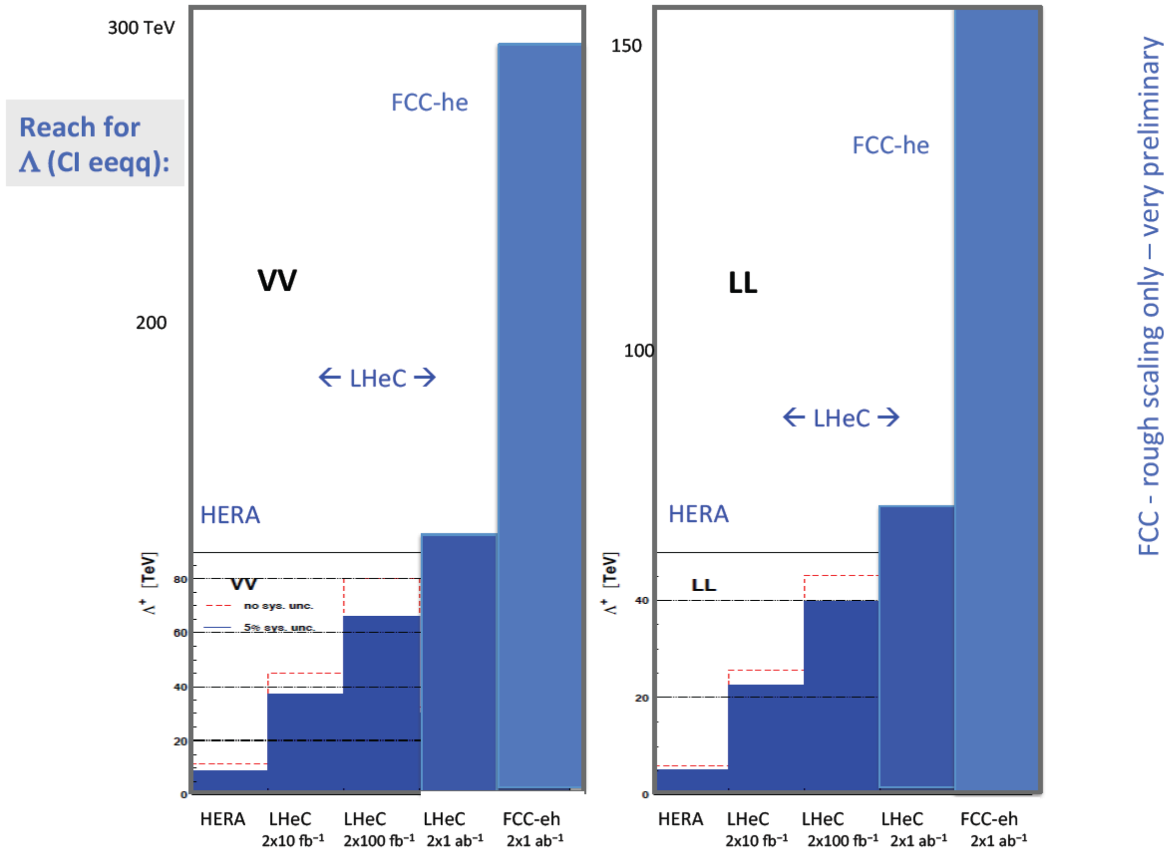
$$\frac{\hbar c}{1.3\ \text{TeV}} = 1.5 \times 10^{-4}\ \text{fm}$$

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

Zarnecki: arXiv:0809.2917

see also new limits from HERA: **Zeus Collaboration, 1604.01280 and Zarnecki, 1611.03825**

Scale of contact interaction at Future Colliders



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

95% exclusion limit on radius at LHeC ~ 10^{-19} m
Extrapolating to FCC-eh, estimate ~1.5-3.0 x 10^{-20} m limit on radius

Excited fermions

Excited fermions could be produced directly if their mass is below compositeness scale

Assume spin = ½, L, R doublets

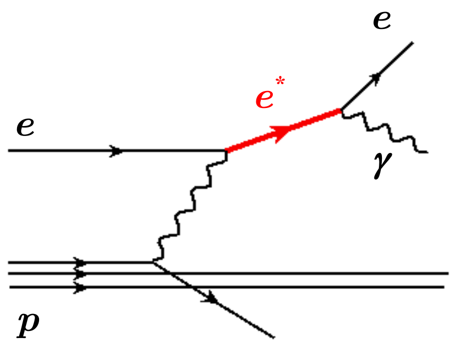
- gauge interaction Lagrangian

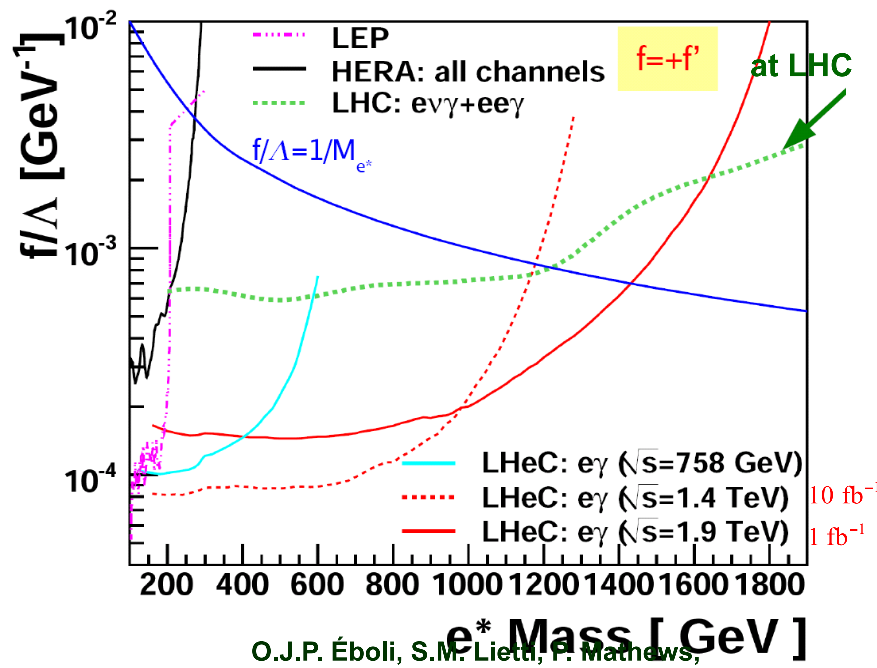
$$\mathcal{L} = \frac{1}{2\Lambda}\bar{f}^*_R\sigma_{\mu\nu}\left[gf\frac{\tau_a}{2}W^a_{\mu\nu} + g'f'B_{\mu\nu} + g_s f_s\frac{\lambda_a}{2}G^a_{\mu\nu}\right]f_L$$

- contact interaction Lagrangian

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

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





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

LHC could probe up to 1-2 TeV

for $f = f' = 1, \Lambda = m_{e^*}$ (or $f/\Lambda = 1/m_{e^*}$)

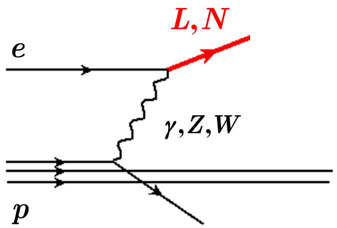
O. Cakir, A. Yilmaz, S. Sultansoy,
PR D70 (2004) 075011,
A. Belyaev, C. Leroy, R. Mehdiyev,
Eur Phys J C 41, s02, 1–10 (2005)

For lower masses (lower Λ), e-p colliders could extend sensitivity to f

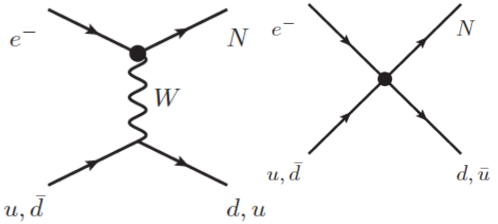
Heavy fermions/ colored bosons

heavy leptons:

- vector-like leptons: left and right chiralities have same transformation properties
    - predicted in GUT theories (E_6) or in Composite Higgs Models
    - couplings: $eEZ, \nu EW, eEH; \quad \nu NZ, eNW, \nu NH$



- Majorana Neutrino Production in an Effective Approach
  (L. Duarte et al. 1412.1433)
  SM background from $p\gamma \rightarrow \ell^{+} + 3j + \nu \quad pe^{-} \rightarrow e^{+} + 3j + 2\nu_e$
  able to discover Majorana neutrinos up to 700 GeV (for E_e = 50 GeV)

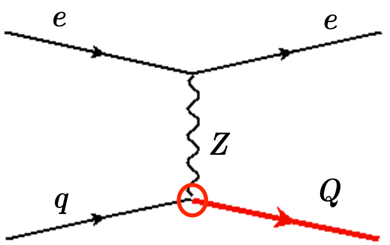


$N \rightarrow \ell^{+} +$ jets

- sterile neutrinos → see Oliver's talk

vector-like quarks? (LHC constraints ~ 800 GeV)

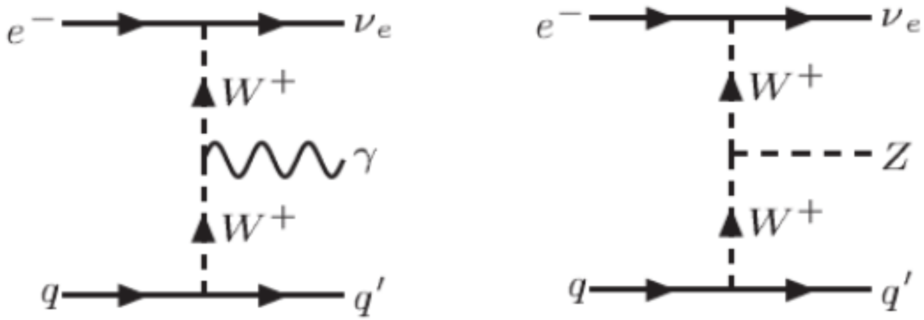
- single production of top partners,
  sensitive to couplings: $qQZ, qQW, qQH;$
  (coupling to light quarks)



anomalous triple gauge boson couplings

Turk Cakir, Senol, A, Tasci, A T, Cakir, O, https://cds.cern.ch/record/2209389/ , https://arxiv.org/abs/1406.7696

Sudhansu S. B, Monalisa P, Sreerup, https://arxiv.org/abs/1405.6056

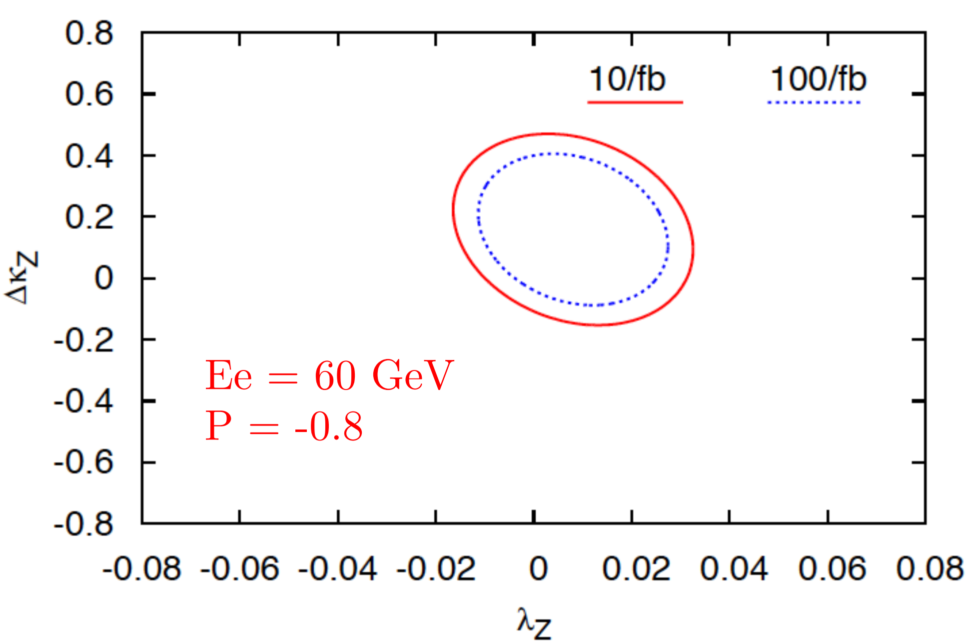


$$L = igw w_\gamma [g_1^\gamma (W_{\mu\nu}^\dagger W^\mu A^\nu - W^{\mu\nu} W_\mu^\dagger A_\nu) + \kappa_\gamma W_\mu^\dagger W_\nu A^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu A^{\nu\rho}] +$$

$$igw w_Z [g_1^Z (W_{\mu\nu}^\dagger W^\mu Z^\nu - W^{\mu\nu} W_\mu^\dagger Z_\nu) + \kappa_Z W_\mu^\dagger W_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu Z^{\nu\rho}] \quad (1)$$

→ *sensitivity comparable to LHC*
improves with polarized beam

aTGC



T Cakir et al.,
https://arxiv.org/abs/1406.7696

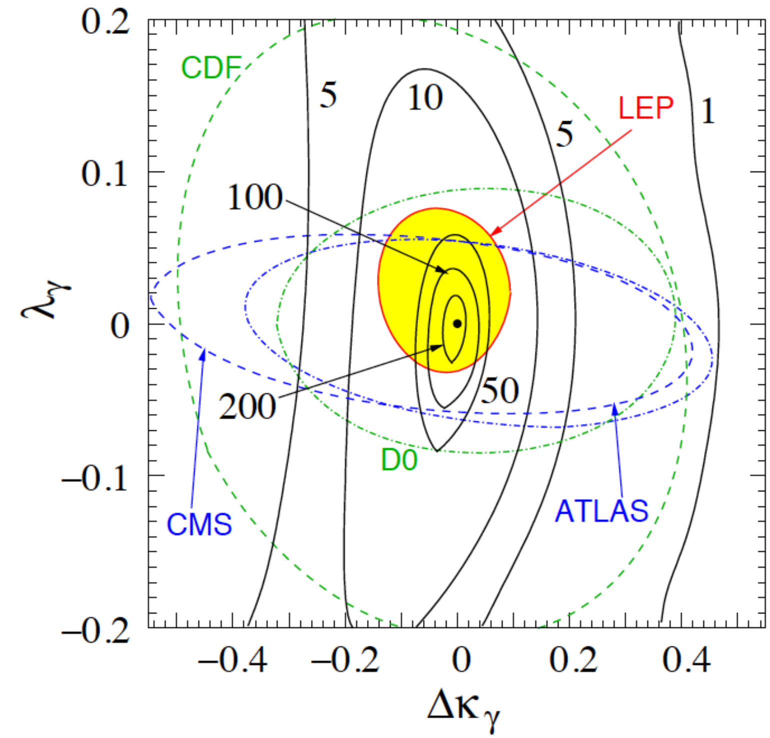


Figure 5: 95% C.L. discovery contours in the $\Delta\kappa_\gamma$–λ_γ plane corresponding to an electron beam energy of 140 GeV. The dot in the centre represents the Standard Model value. The region between this dot and each contour is *not* discoverable for the luminosity (in fb^{-1}) marked alongside the contour. The different experimental bounds at 95% C.L. are also exhibited.

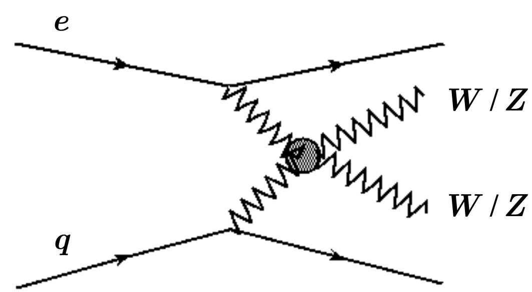
Sudhansu S. B et al., https://arxiv.org/abs/1405.6056

aQGC's

- Is unitarity restored only by Higgs? are there new resonances (CH model) ?
  - expect below ~ 2-3 TeV

    $$e^- q \rightarrow e^-(q)WZ, \quad (\nu q)WZ$$

    → *look for deviations from SM predictions:*



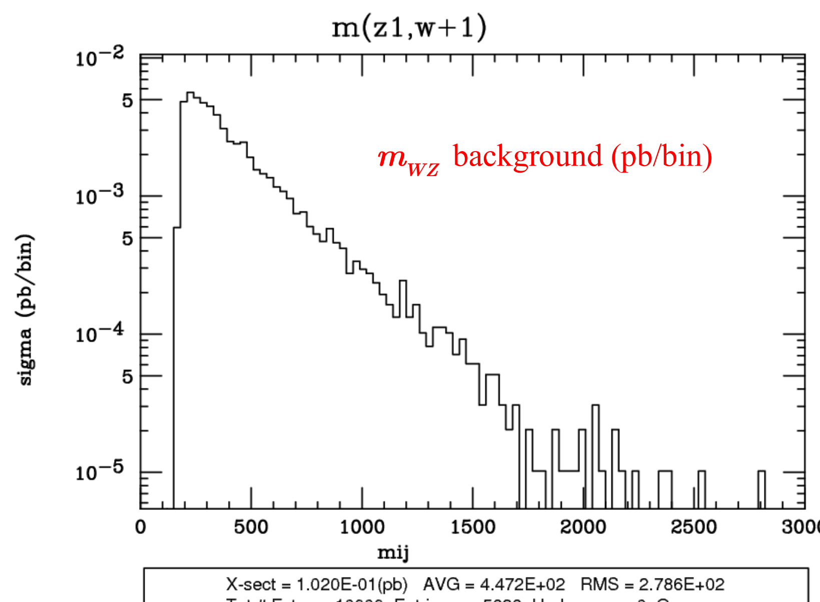
  - high background from QCD diagrams at LHC
    - gluon exchange, gluon initial state are absent at FCC-eh
  - anomalous QGC in effective field theory (dim. 6 operators)

highly dependent on acceptance and performance of detector)

- LHC14: B_{QCD} = 4200 fb B_{EW} = 300 fb
- FCC-eh B_{EW} = 100 fb

low cross section, but kinematics of signal distinct from background need v. good detector performance

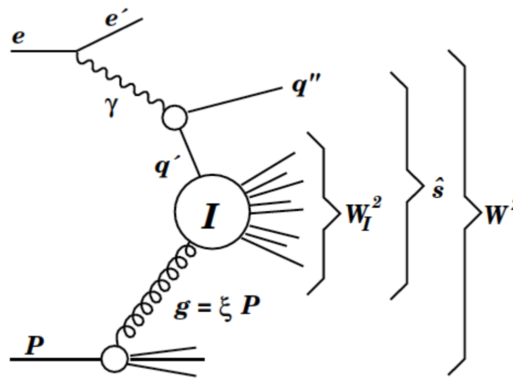
possibly use hadronic decay of W and Z (boosted, high mass object)?



instantons: QCD BSM?

Instantons → non-perturbative fluctuations of the gluon field

- in every instanton event, qqbar pairs of each of the **n**f flavours occur precisely once.
- Right-handed quarks are produced in instanton-induced processes, left-handed quarks are produced in anti-instanton processes.
- The quarks and gluons emerging from the instanton subprocess are distributed isotropically in the instanton rest system. Therefore one expects to find a pseudorapidity region with a width of typically 2 units in **η**, densely populated with particles of relatively high transverse momentum and isotropically distributed in azimuth, measured in the instanton rest frame. The large number of partons emitted in the instanton process leads to a high multiplicity of charged and neutral particles. Besides this band in pseudo-rapidity, the hadronic final state also contains a current jet emerging from the outgoing current quark **q″**.



NC DIS variables:

$s = (e + P)^2$

$Q^2 = -\gamma^2 = -(e - e')^2$

$x = Q^2 / (2P \cdot \gamma)$

$y = Q^2 / (s\ x)$

$W^2 = (\gamma + P)^2 = Q^2 (1 - x)/x$

$\hat{s} = (\gamma + g)^2$

$\xi = x\ (1 + \hat{s}/Q^2)$

Variables of the instanton subprocess:

$Q'^2 \equiv -q'^2 = -(\gamma - q'')^2$

$x' \equiv Q'^2\ /\ (2\ g \cdot q')$

$W_I^2 \equiv (q' + g)^2 = Q'^2\ (1 - x')/x'$

H1 Collaboration, arXiv:1603.05567

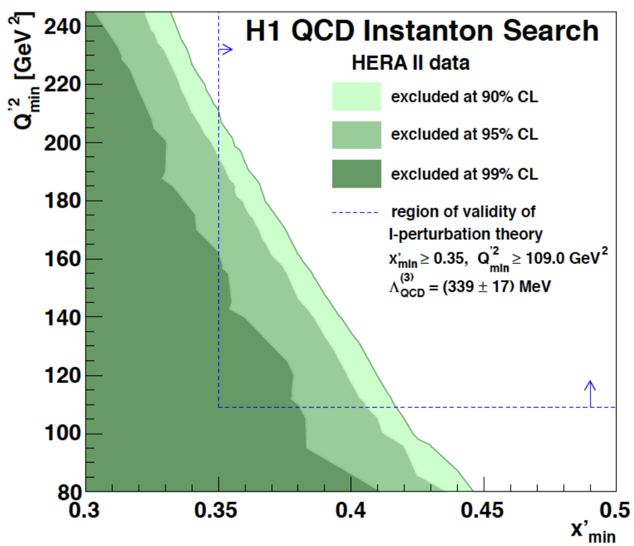


Figure 8: Instanton production exclusion limits as a function of $x'_{\rm min}$ and $Q'^2_{\rm min}$. The regions excluded at confidence levels of 90%, 95% and 99% are shown. The region of validity of instanton perturbation theory is indicated (dashed line).

code to generate it with new Herwig7 being tested (S. Amoroso)

Conclusions

- Given that the LHC has not yet found anything, we need to be as broad as possible in our searches for new physics.
- FCC-eh offers low background for precision BSM searches
  - important particularly for Vector boson scattering process
  - also for SUSY searches in difficult phase space regions
  - a lot going on in BSM Higgs, BSM top
- Improved pdf's at low and high x allow better precision in measurements and limit settings from LHC and FCC-hh
- focus on electron-quark couplings and common characteristics
  - Leptoquarks
  - contact interactions
  - heavy/excited leptons and quarks
- A lot more is in progress: RPV SUSY based on recent reviews, other SUSY scenarios and sterile neutrinos, → *see next talks in this session*

For better evaluation of the potential, use simple benchmark models and realistic detector simulation (Delphes model from Higgs group)

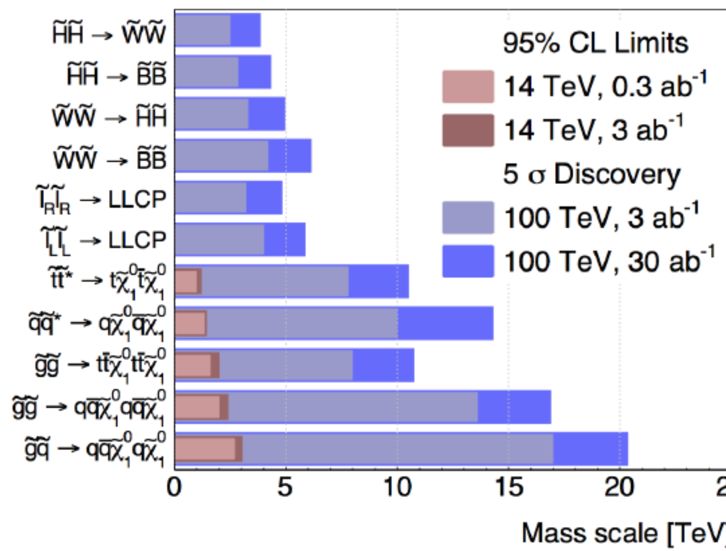
- must consider other energy scenarios
- ep process working with HERWIG7 as well as Pythia6, starting from LHE files

backup

Impact of PDF @ High x: FCC

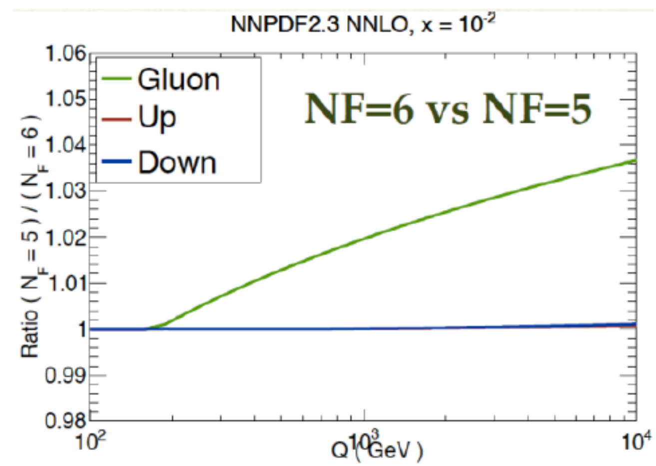
- FCC-hh reach up to **13(16) TeV for gluino pair production, 17(20) TeV for non-decoupled squark/gluino for 3(30)/ab^{-1}**

- Similar x range for the sensitive region (<x> ~ 0.4) → ~40-50% uncertainties on the prediction of gluon-gluon initiated processes
  - *Might be an issue also for central values*



Other aspects might play a non-negligible role:

Top PDF: at the very high Q2, top becomes small and will have to be included as 6F PDFs

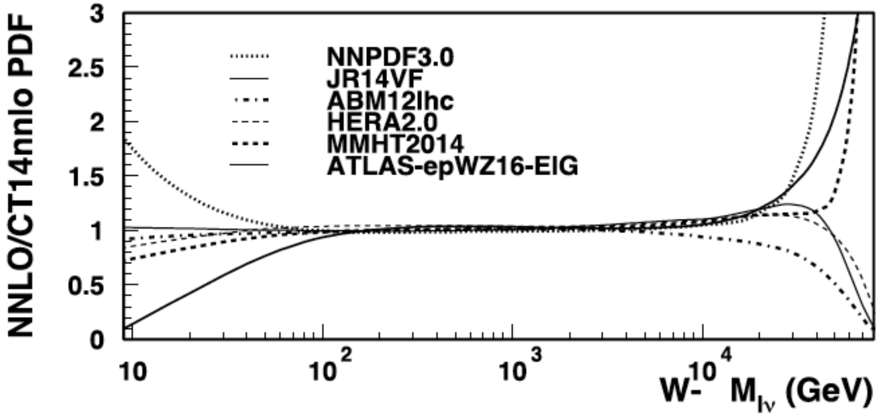


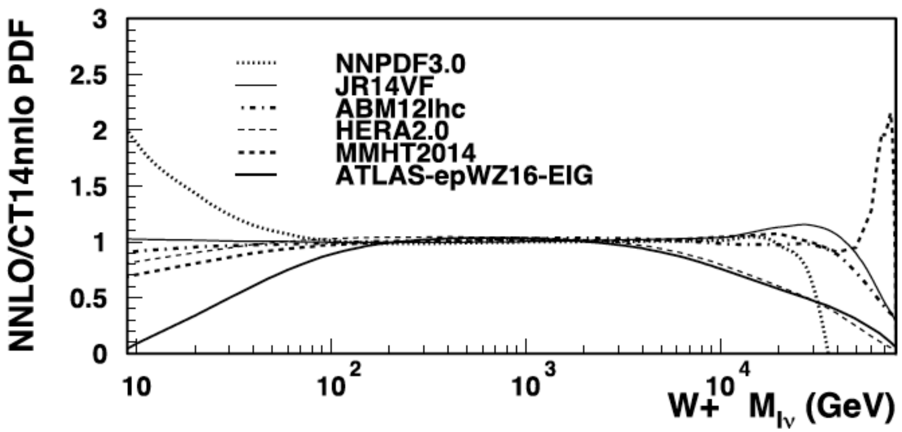
No doubts that having an e-p machine running in parallel with p-p will be very important

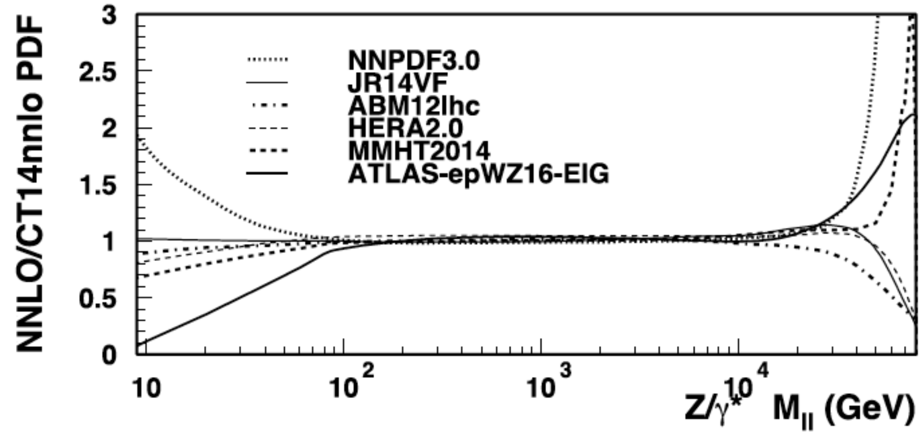
Impact of PDF: High mass Drell-Yan

- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar

Uta Klein
VRAP 0.9 for NNLO QCD







"Troubles" at low and high x

FCCeh (and before, LHeC) can improve low and high M(ll) and M(lv) precision for standard candle measurements and searches for new physics

Leptogluons

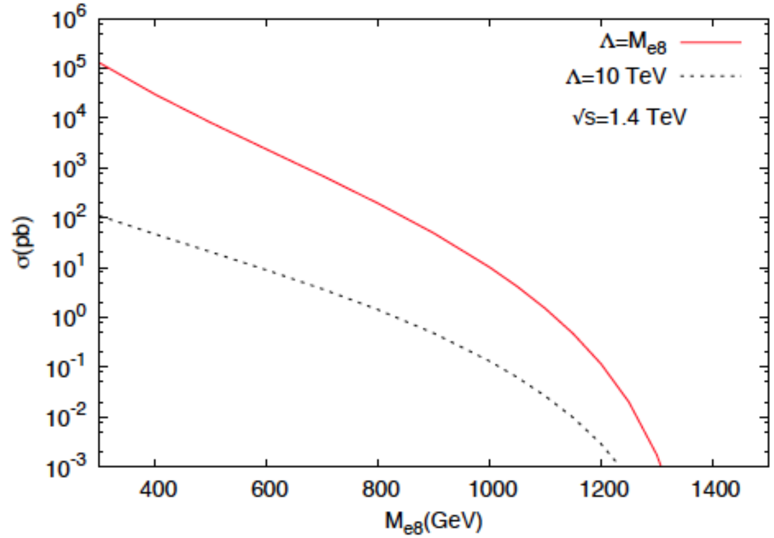
Leptogluons are color-octet partners of leptons

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)

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



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