Overview of BSM physics at LHeC and FCC-eh

Monica D'Onc
(University of Liv

Georges Azuelos
(University of Montreal)

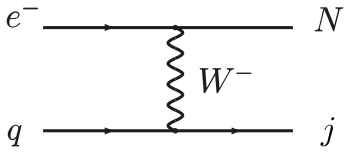
LHeC/FCCeh workshop
September 11th 2017

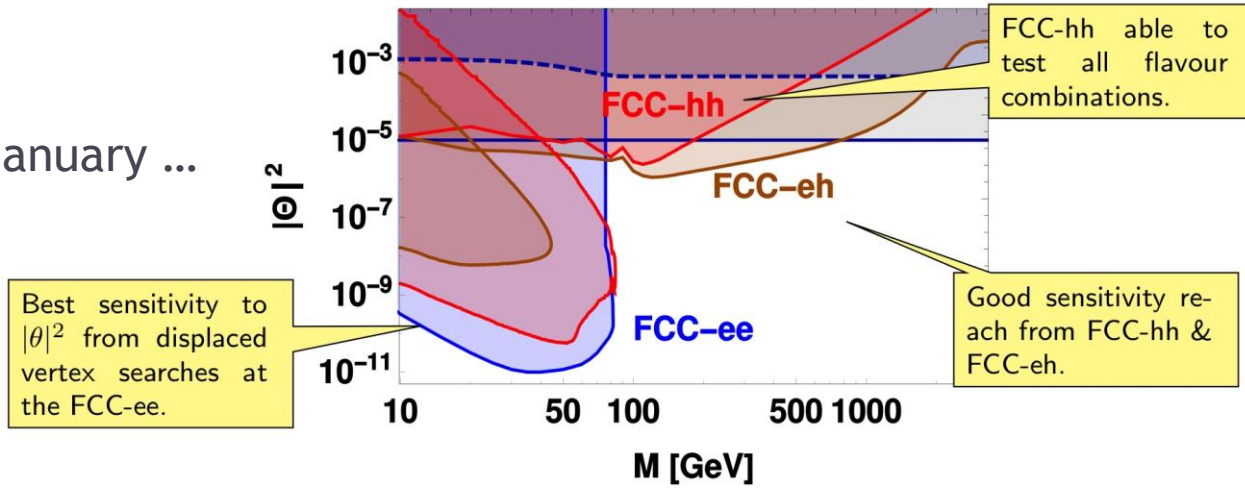
Introduction

- BSM physics is a broad topic!
- We have already seen a lot in this workshop
  - BSM Higgs physics, intended as new decays of the SM higgs boson or as production of new (usually heavy) additional higgs bosons
  - BSM Top physics, e.g. FCNC in the top sector
- In this session, we will see more on what LHeC and FCC-eh can do in the hunt for new physics
  - Indirect complementarities with HL-LHC and FCC-hh
  - Direct searches
    - The “classic”: leptoquarks, contact interactions, RPV SUSY
    - Anomalous couplings, instantons and more…
    - New fronts: long-lived particles, EWK SUSY searches

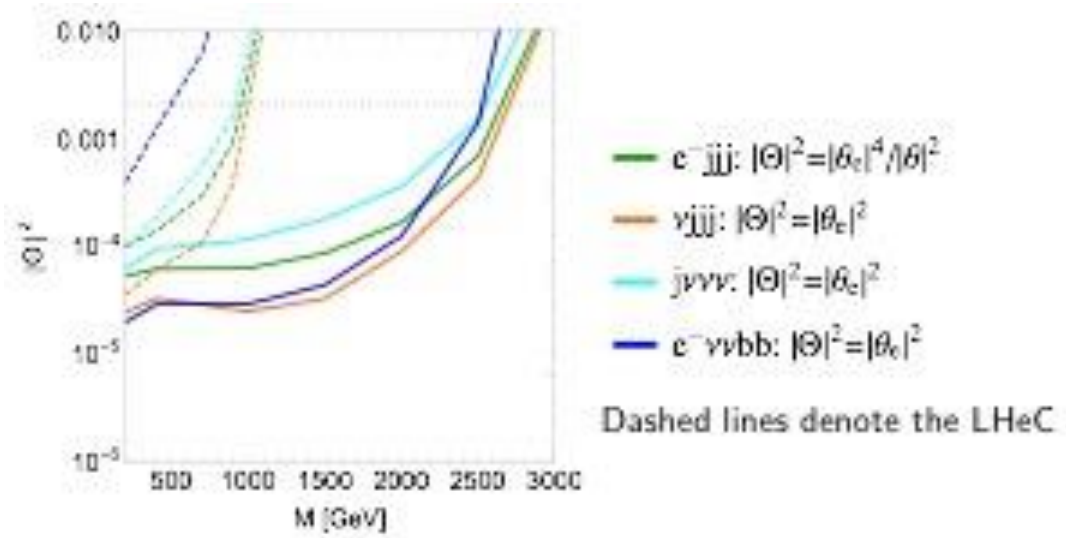
Some examples at this meeting

- Heavy and sterile neutrinos (see Oliver Fischer's talk today)
  - @ LFV signatures and displaced vertex search
    → this is how it was in January …

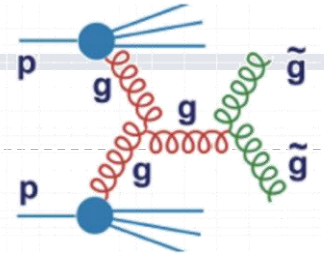




- lepton-flavor-conserving signatures



Impact of PDF @ High x

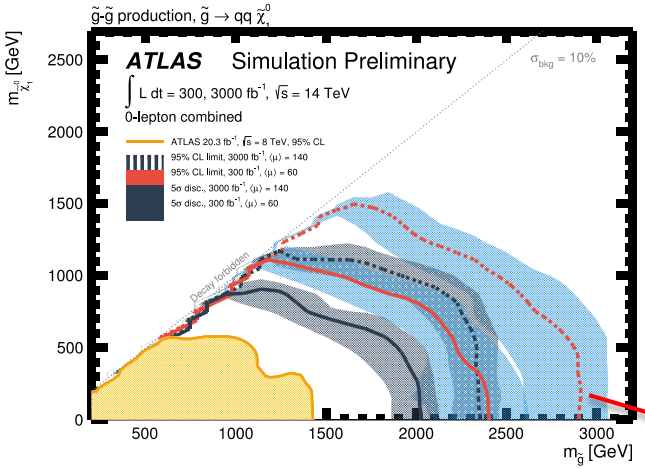


- large uncertainties in high x PDFs limit searches for NP

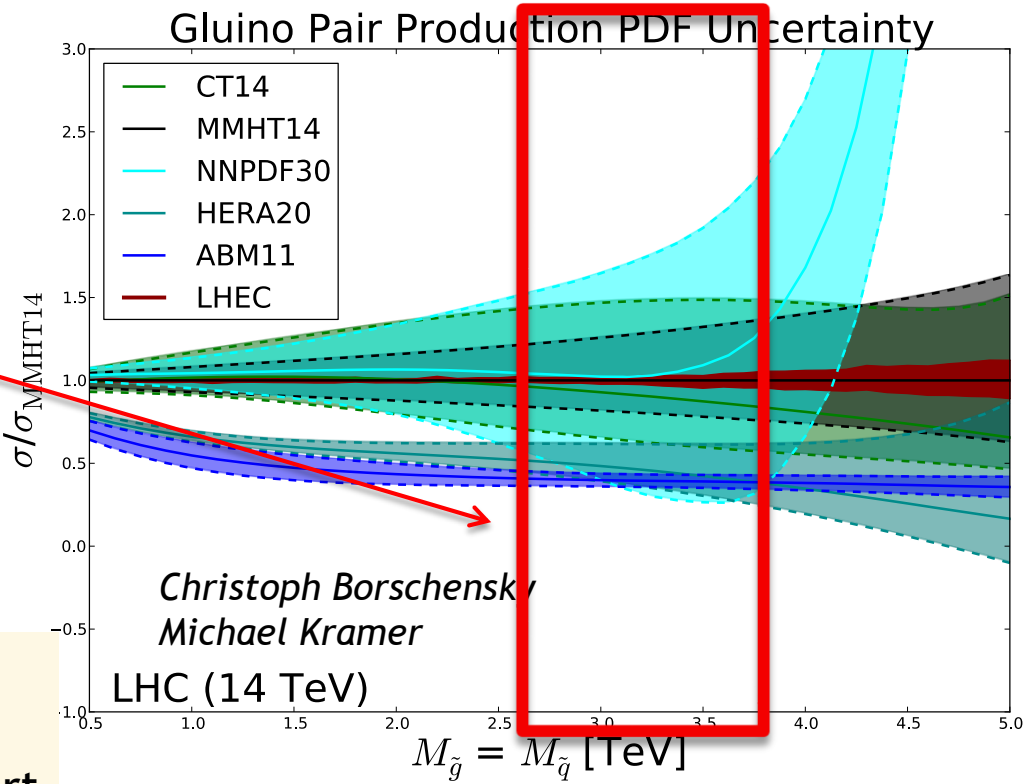
  many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production

- For HL-LHC → studied in detail impact of LHeC

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



< x > ~ 0.4



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

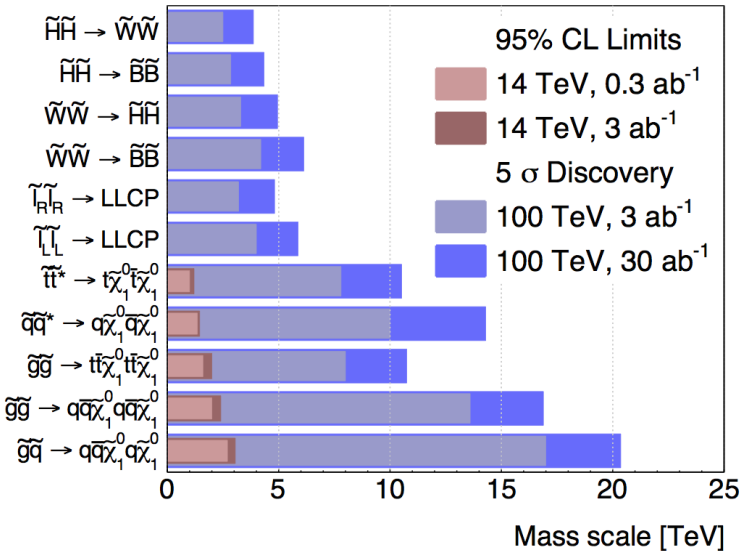
Hopefully, we will update studies with LHeC PDF unc in performing studies for the HL-LHC Yellow Report

arXiv:1211.5102

Impact of PDF @ High x: FCC

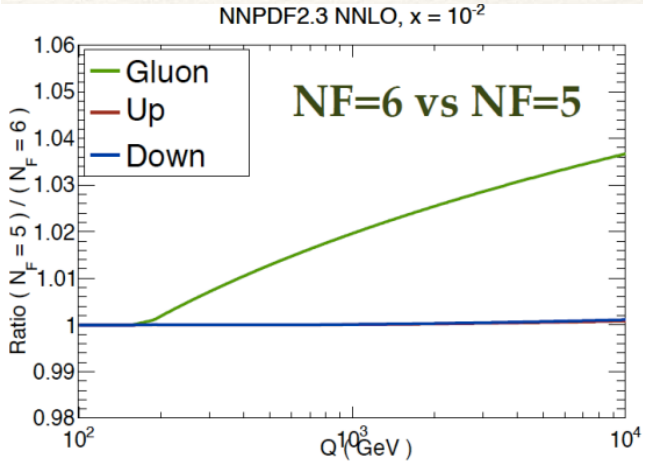
- FCC-hh reach up to **13(16) TeV for gluino pair production, 17(20) TeV for non-decoupled squark/gluino for 3(30)/ab^{-1}**

- 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:

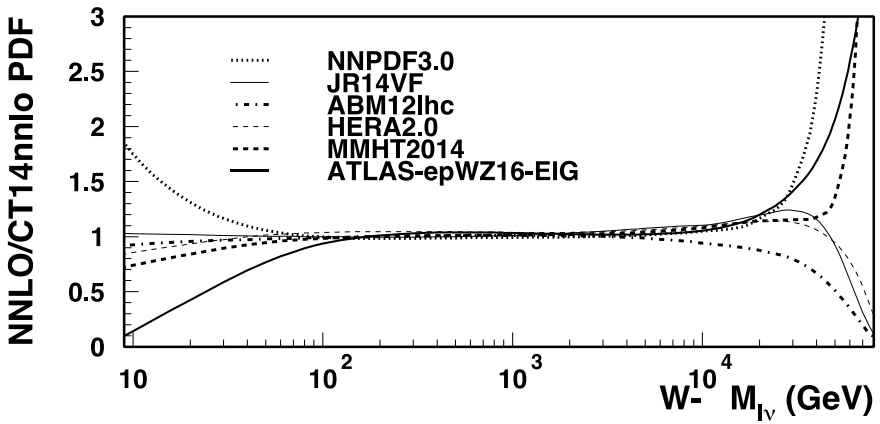
Top PDF: at the very high Q2, top becomes small and will have to be included as 6F PDFs

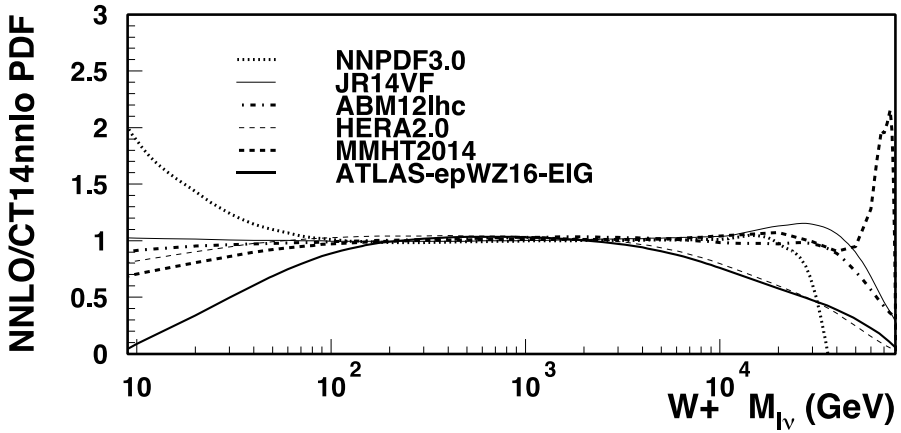


No doubts that having an e-p machine running in parallel with p-p will be very important

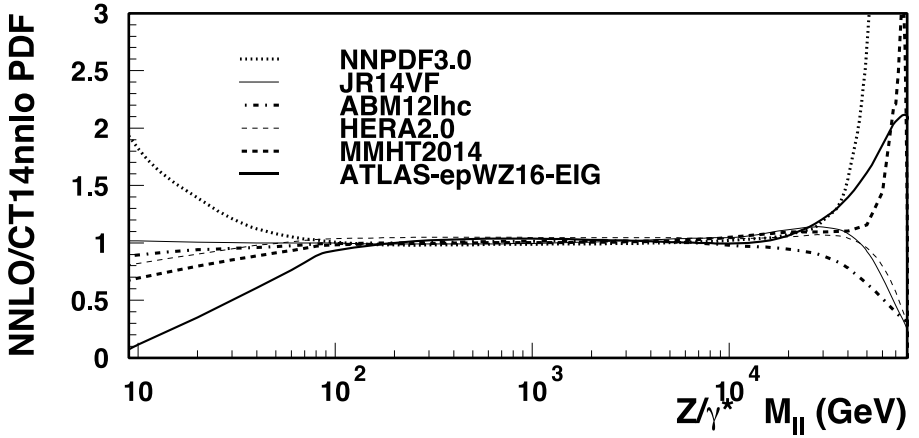
Impact of PDF: High mass Drell-Yan

- 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

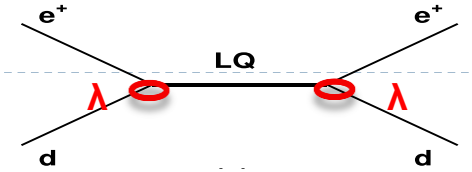


"Troubles" at low and high x

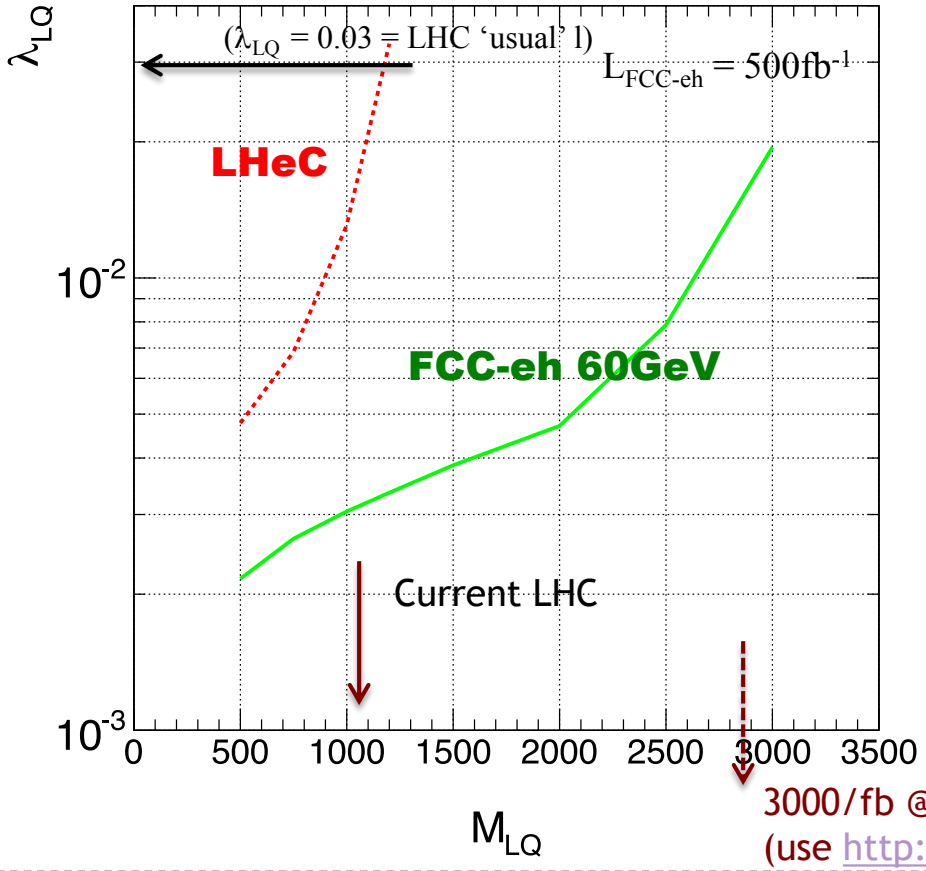
FCCeh (and before, LHeC) can improve low and high M(ll) and M(lv) precision for standard candle measurements and searches for new physics

Direct searches: Lepto-quarks

1st generation LQs → Current constraints almost there with 3.2/fb @ 13 TeV



LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$



ep scenario:

sensitive to λ << e=√4πα=0.03

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!

3000/fb @ 14 TeV ~ 2.9 TeV reach
(use http://collider-reach.web.cern.ch)

Contact interactions

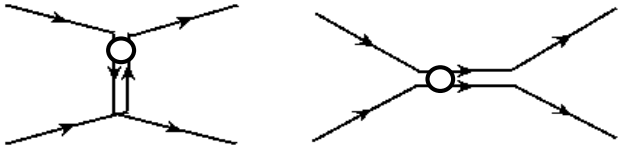
- **if new physics enters at higher scales: Λ>> √s**
- such indirect signatures can be seen as effective 4-fermion interaction

$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)}; \quad j_\mu^{(f=e,q)} = \eta_L \, \bar{f}_L \gamma_\mu f_L + \eta_R \, \bar{f}_R \gamma_\mu f_R + h.c.$$

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

- may be applied very generally to new phenomena

Λ
- LQ mass >> √s
- Planck scale (Ms) of extra dimensional models
- compositeness scale
- …



Sensitivity to fermion radius recalculated with current expectations at the FCC-eh

R → 3(1.5) x 10^{-20}m

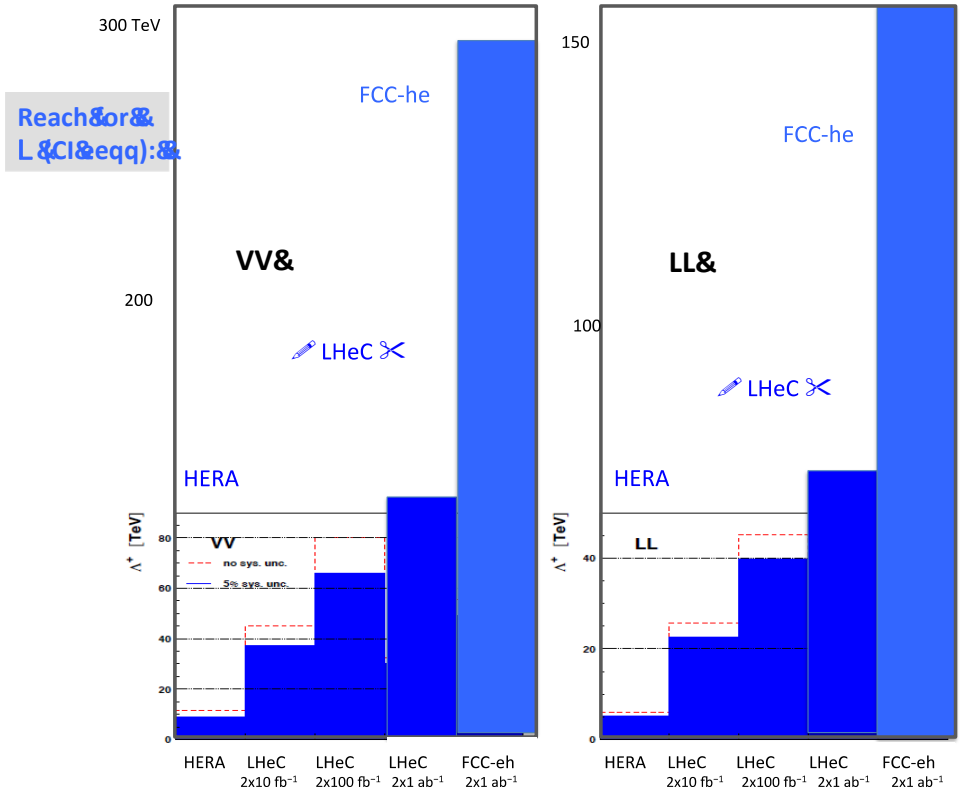
pessimistic(optimistic) calculations

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

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

Contact interactions (eeqq)

- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.
- Reach for Λ (CI eeqq): VV: ~290 TeV; LL: ~160 TeV



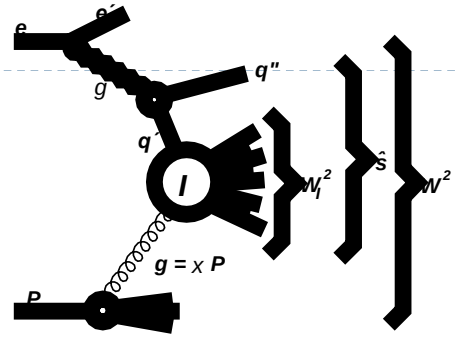
VV: all couplings with +ve sign

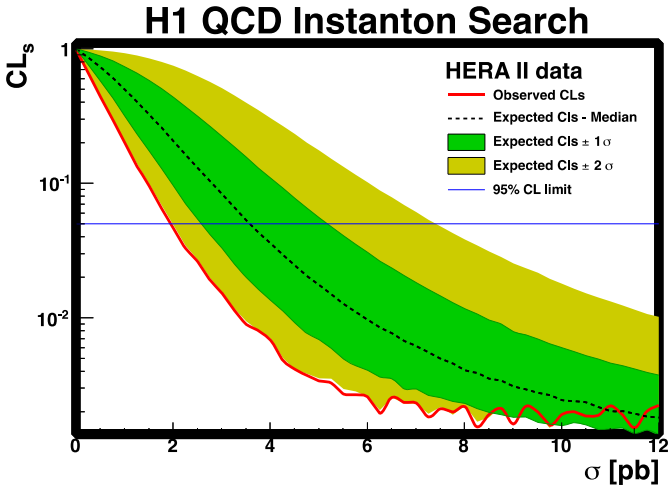
LL: only LL couplings between q and e

~ equivalent sensitivity at the FCC-hh at least for some of the couplings (same as HL-LHC vs LHeC) but need more calculations!

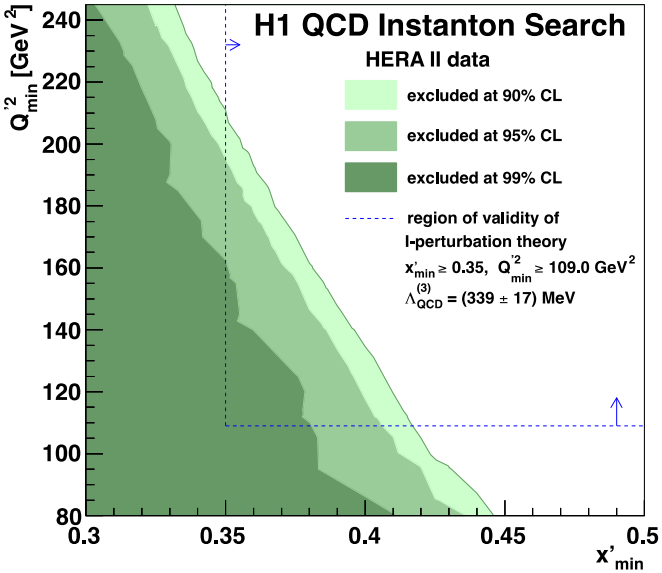
E-p "specific" searches: Instantons

- New physics as non-perturbative QCD effect at high energies
  - Instantons → non-perturbative fluctuations of the gluon field
- Photon-gluon fusion process
- HERA recent results start probing interesting theoretical scenarios





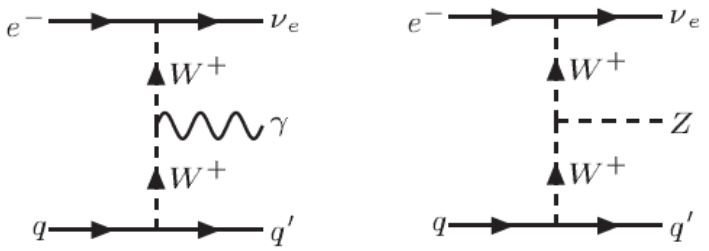
Eur.Phys.J. C76 (2016) no.7, 381



Feasibility is now been considered → code to generate it with new Herwig7 being tested but still issues in compiling it (S. Amoroso)

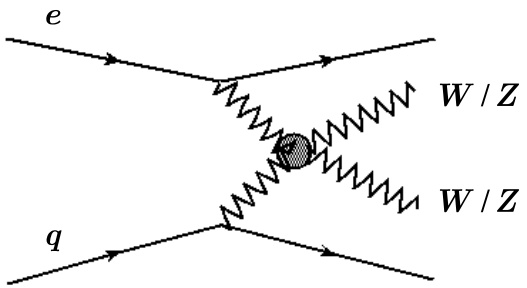
BSM in Vector Boson (VB) scattering

- VB scattering at high mass:
  - anomalous TGC, QGC couplings in VVV, VVVV ?



  - New resonances possibly relevant for unitarity restoring
    - expect below ~ 2-3 TeV → *look for deviations from SM predictions:*

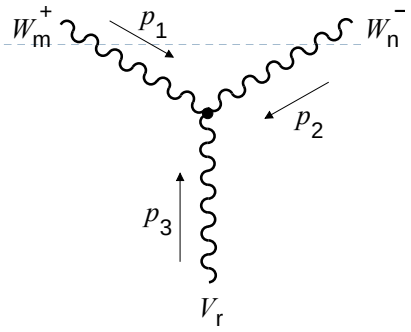
$$e^- q \to e^-(q)WZ, \quad (\nu q)WZ$$



Challenging at p-p (high QCD bkg, pile-up), cleaner at FCC-eh

Anomalous couplings WWV

- Triple gauge boson vertices WWV, V=γ,Z:
  - Precisely defined in SM
  - Parametrise possible new physics contributions to this vertex $(\Delta\kappa_\gamma, \lambda_\gamma)$
  - Current constraints (best from LEP) use various assumptions



	LEP [9]	CDF [12]	D0 [13]	ATLAS [10]	CMS [11]
$\Delta\kappa_\gamma$	[-0.099, 0.066]	[-0.460, 0.390]	[-0.158, 0.255]	[-0.135, 0.190]	[-0.210, 0.220]
λ_γ	[-0.059, 0.017]	[-0.180, 0.170]	[-0.036, 0.044]	[-0.065, 0.061]	[-0.048, 0.037]

Table 1: Allowed ranges, at 95% C.L., on the anomalous WWγ couplings from the data collected at the LEP, Tevatron and LHC experiments. In each case, the most restrictive of the reported measurements is taken.

http://arxiv.org/pdf/1405.6056v1.pdf

https://arxiv.org/abs/1406.7696

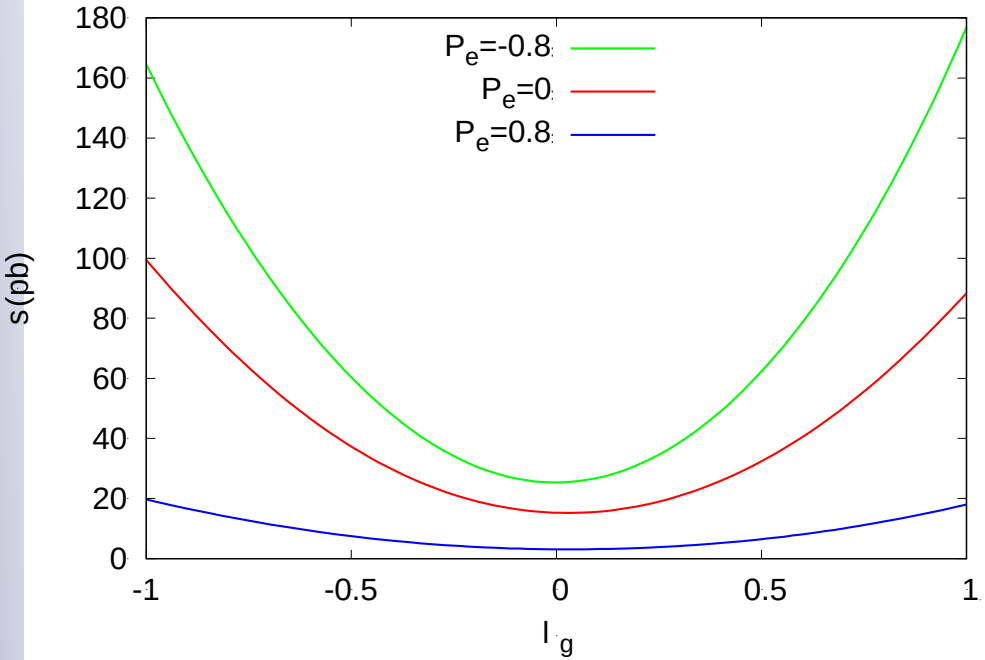
At the e-p:

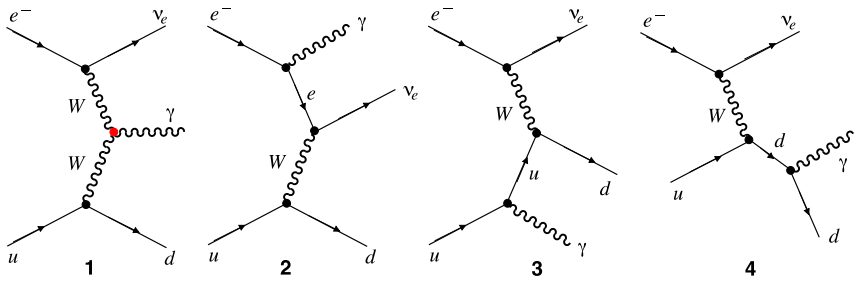
- can clearly distinguish between CC events e + p → ve + jet (W-exchange) and NC events e + p → e + jet (photon or Z boson exchange)
- triggering on a final state photon, can provide very clean bounds on the anomalous TGV's!

FCC-eh Anomalous WW γ and WWZ Couplings

- Study for FCC-eh
- https://cds.cern.ch/record/2209389/?ln=en
  - Report studies for Ee = 80 GeV
  - Update here for Ee = 60 GeV

A. Senol, O. Cakir, I. Turk Cakirç



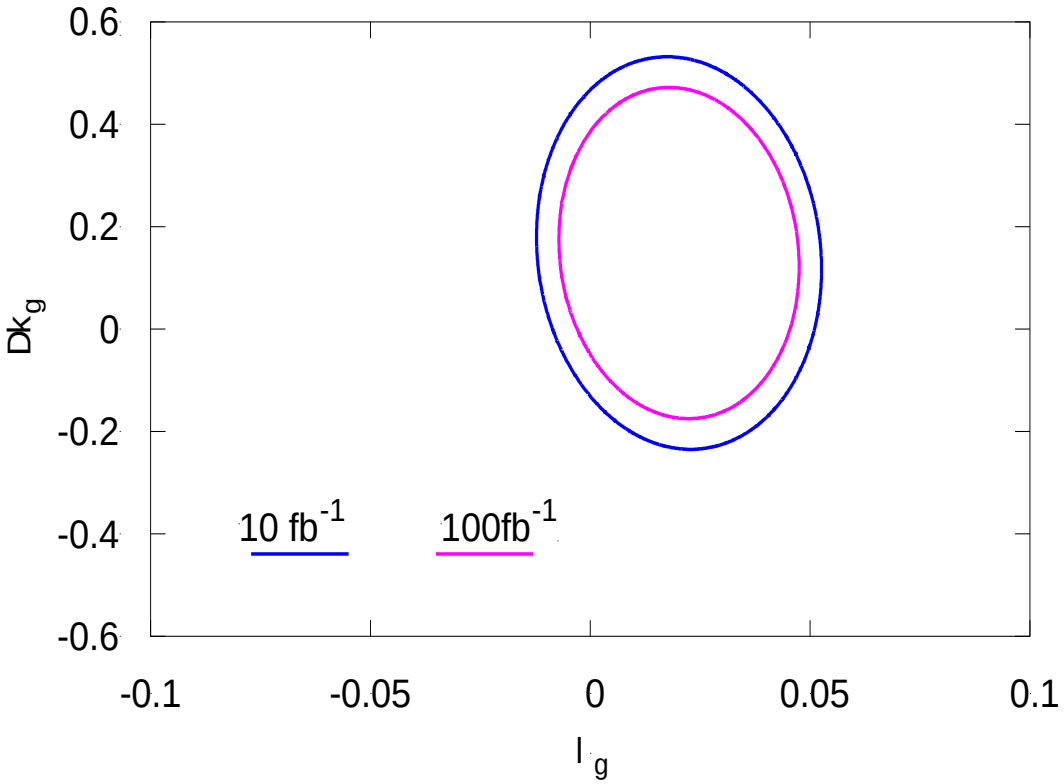


Cross section depending on anomalous λ_γ coupling of the process $ep \rightarrow \nu\, q\gamma X$ for E_e = 60 GeV and E_p=50 TeV at FCC-ep.

Anomalous WWγ Couplings

$\delta\Delta\kappa_V = \Delta\kappa_V^{upper} - \Delta\kappa_V^{lower}, \delta\lambda_V = \lambda_V^{upper} - \lambda_V^{lower}$

A. Senol, O. Cakir, I. Turk Cakirç



Sensitivities to anomalous couplings $\lambda_\gamma \sim 10^{-2}$

For comparison:

TABLE I
THE AVAILABLE 95% C.L. TWO-PARAMETER BOUNDS ON ANOMALOUS COUPLINGS ($\Delta\kappa\gamma$, $\lambda\gamma$) AND (ΔKz, λZ) FROM THE ATLAS AND CMS EXPERIMENTS

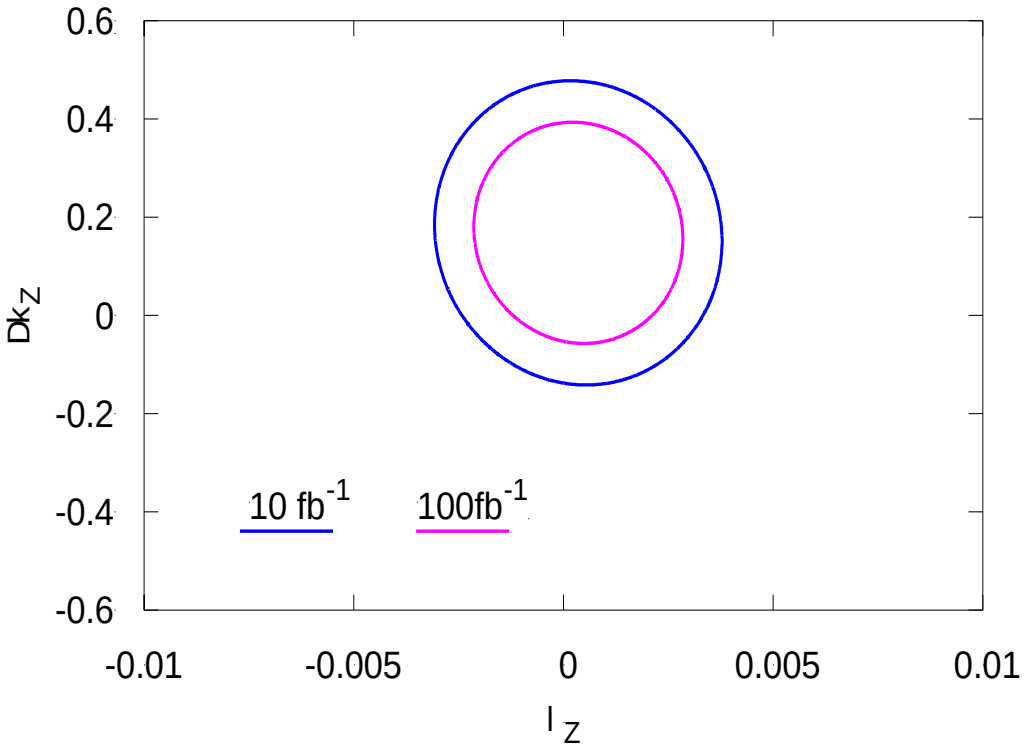
	ATLAS	CMS	ATLAS (upper-lower)	CMS (upper-lower)
$\Delta\kappa\gamma$	-0.420,0.480	-0.250, 0.250	0.900	0.500
$\lambda\gamma$	-0.068,0.062	-0.050, 0.042	0.130	0.092
$\Delta\kappa z$	-0.045,0.045	-0.160, 0.180	0.090	0.340
λz	-0.063,0.063	-0.055, 0.055	0.126	0.110

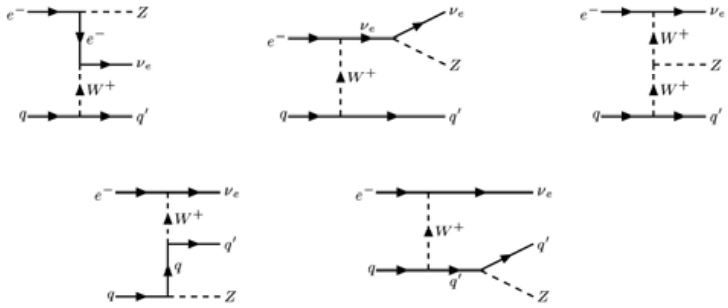
Two dimensional 95% C.L contour plot anomalous couplings in the $\lambda_\gamma - \Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb-1 and 100 fb-1 at FCC-ep with electron beam energy E_e =60 GeV with polarization P =−0.8 .

Anomalous WWZ Couplings

analysis of the signal and backgrounds
for $Z \rightarrow ll'(l = e, \mu)$

A. Senol, O. Cakir, I. Turk Cakirç





Sensitivities to anomalous couplings $\lambda_Z \sim 10^{-3}$

For comparison:

TABLE I
THE AVAILABLE 95% C.L. TWO-PARAMETER BOUNDS ON ANOMALOUS COUPLINGS ($\Delta\kappa\gamma$, $\lambda\gamma$) AND (ΔKZ, λZ) FROM THE ATLAS AND CMS EXPERIMENTS

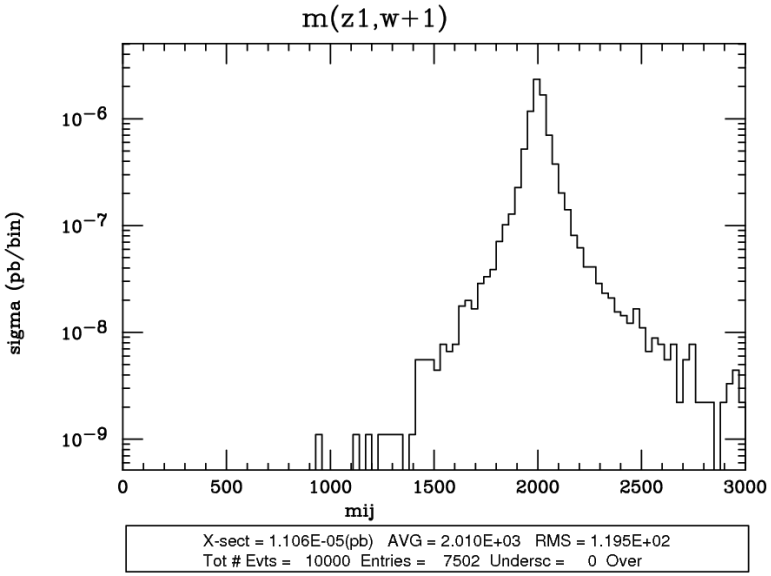
	ATLAS	CMS	ATLAS (upper-lower)	CMS (upper-lower)
$\Delta\kappa\gamma$	-0.420,0.480	-0.250, 0.250	0.900	0.500
$\lambda\gamma$	-0.068,0.062	-0.050, 0.042	0.130	0.092
$\Delta\kappa z$	-0.045,0.045	-0.160, 0.180	0.090	0.340
λz	-0.063,0.063	-0.055, 0.055	0.126	0.110

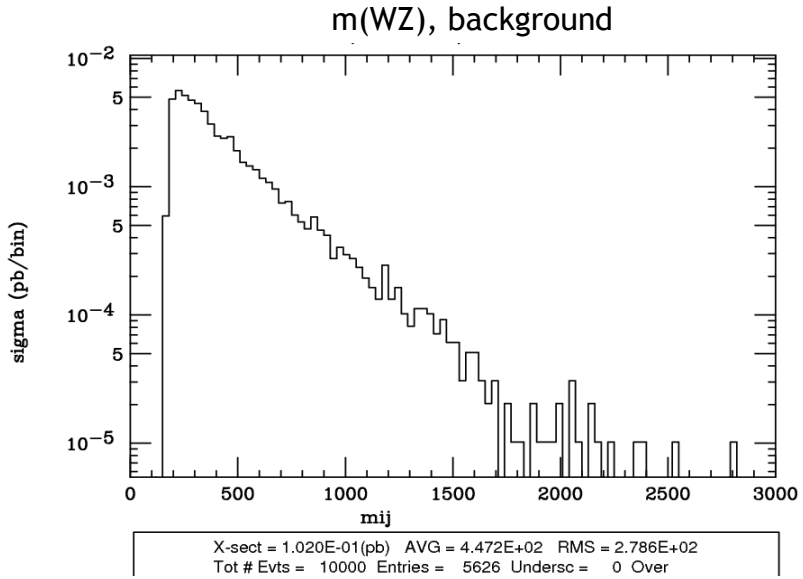
Two-dimensional 95% C.L contour plot of anomalous couplings in the λ_Z $-\Delta\kappa_Z$ plane for the integrated luminosity of 10fb-1 and 100 fb^{-1} at FCC-ep with electron beam energy *Ee*=60 GeV with polarization *P=-0.8*.

Vector Boson Scattering

Georges Azuelos

2 TeV resonance $e^- q \to e^-(q)WZ, \quad (\nu q)WZ$





Typical cross sections for 2 TeV resonance (c_F=0, c_H=1, g_V=3, 60 GeV x 50 TeV)

Heavy Vector Triplet model, D. Pappadopoulo et al., JHEP 1409 (2014) 060, 1402.4431

- highly dependent on acceptance and performance of detector
- FCC-eh (2 TeV resonance): S = 0.01 fb, B_{EW} = 100 fb

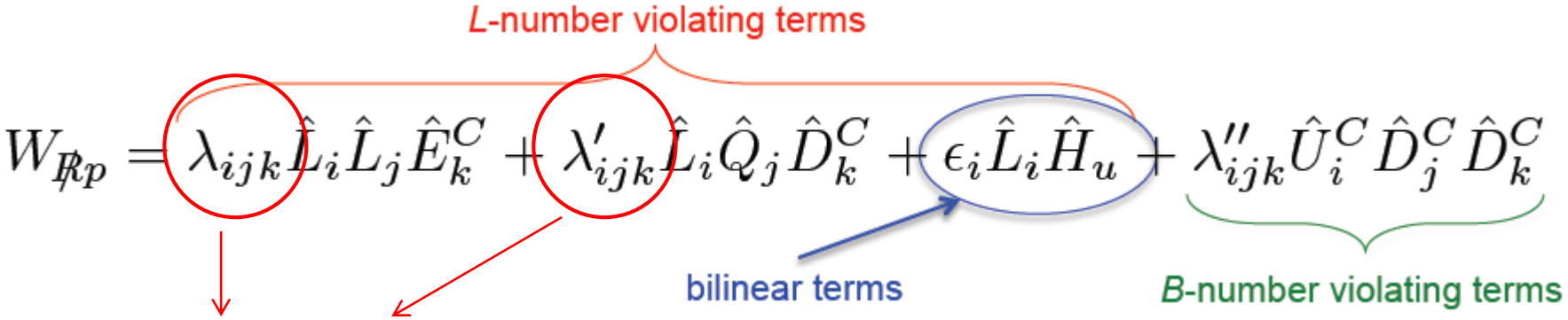
(for comparison, LHC14: S = 0.12 fb B_{QCD} = 4.2 pb B_{EW} = 300 fb)

low cross section, but kinematics of signal distinct from background
(invariant mass, rapidity of the objects, can use W/Z boosted hadronic decays)

→ **Need very good detector performance**

R-parity violating SUSY

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



$\Delta L = 1$, 9 λ couplings, 27 λ' couplings

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

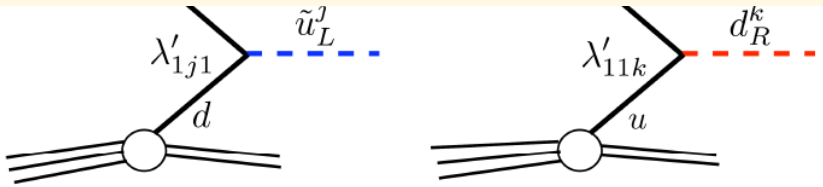
Various strong constraints already from LHC on λ and λ'' ***(from multilepton and multijet searches)***

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)

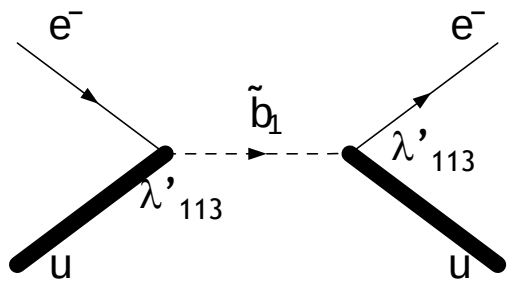


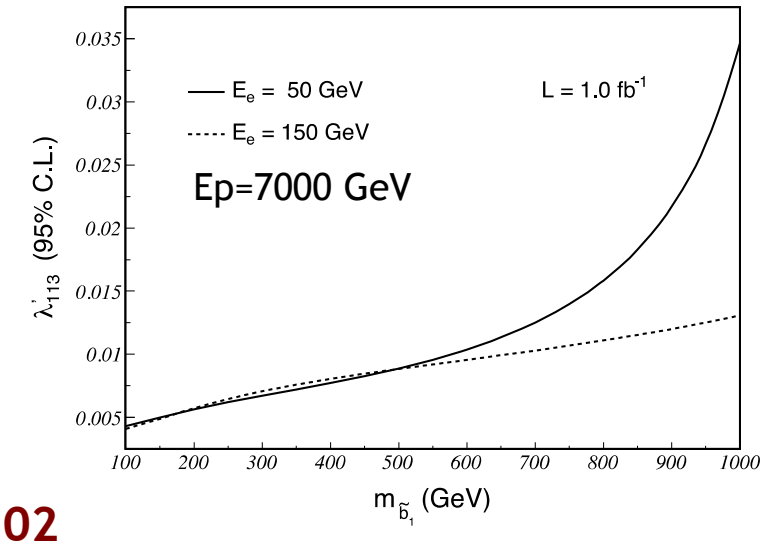
SUSY - R-parity violating

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

http://xxx.tau.ac.il/abs/1401.4266

sbottom





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

@FCC-eh: same analysis as for LQ → **Sensitivity up to 2.5 TeV for λ'_{113}<0.02**

Couplings	λ_{ijk}	λ'_{1jk}	λ'_{2jk}	λ'_{3jk}	λ''_{ijk}
Bound	0.49^a	0.09^a	0.59	1.1	0.5^b

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

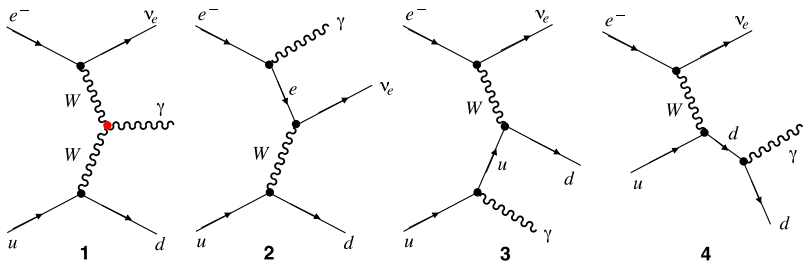
	$\tilde{\chi}_1^0$ LSP region					$\tilde{\tau}_1$ LSP region					
Coupling	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}_{1st/2nd}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{q}_{1st/2nd}}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\tau}_1}$
λ'_{113}	1410	780	1440	240	480	1580	1070	1430	290	560	220

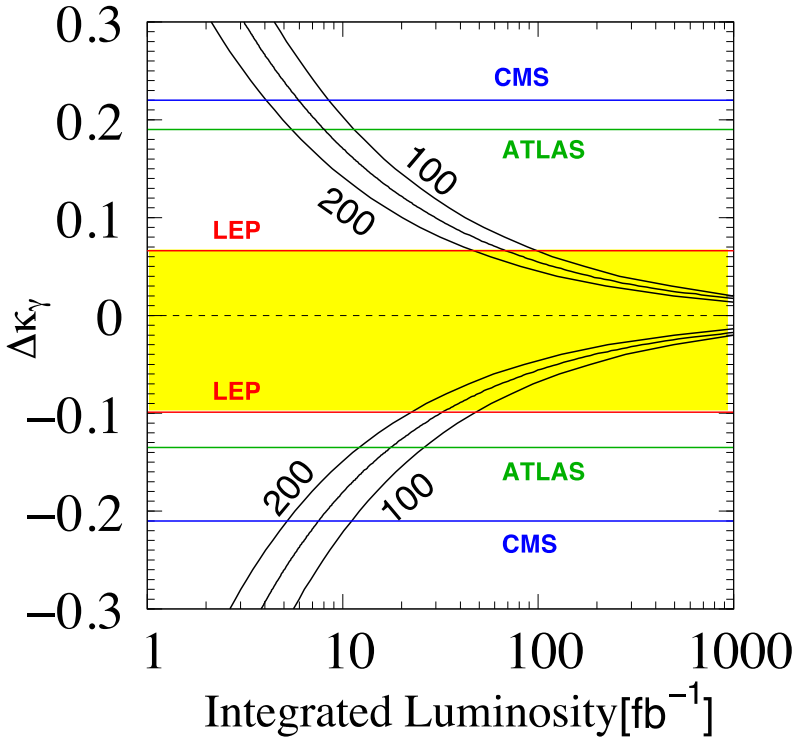
Back-up

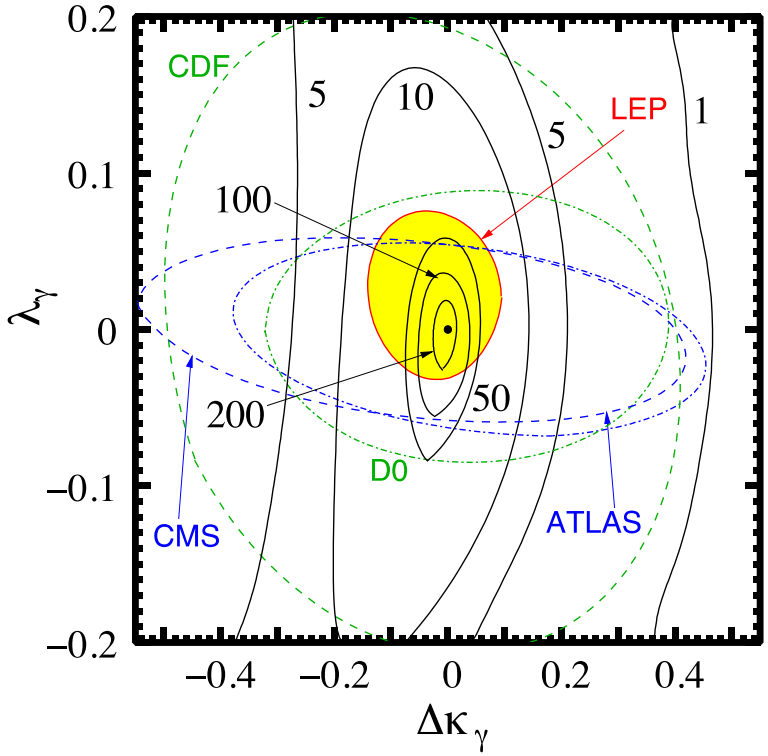
LHeC Prospects for WWγ

http://arxiv.org/pdf/1405.6056v1.pdf

- Select on p_T of γ and jet
- Sensitivity to Δφ (γ-jet)







Competitive constraints at LHeC already for ~ 100 fb^{-1}

Can access a space inaccessible for LEP

(Note: E(e)=100 GeV → expect slightly worse for 60 GeV, but not much)

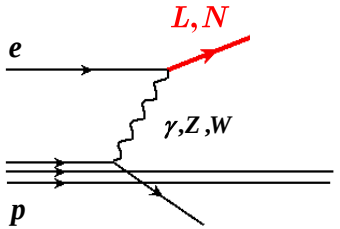
Heavy fermions/ colored bosons: covered in other talks

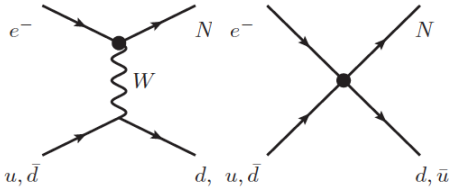
heavy leptons:

- vector-like leptons: left and right chiralities have same transform 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 $p\gamma \to \ell^+ + 3j + \nu \quad pe^- \to e^+ + 3j + 2\nu_e$

  able to discover Majorana neutrinos up to 700 GeV (for E_e = 50 GeV)

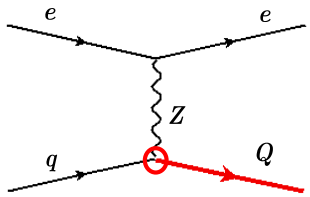




$N \to \ell^+ +$ jets

vector-like quarks

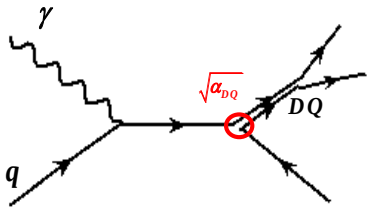
- single production of top partners, sensitive to couplings: qQZ, qQW, qQH
  (coupling to light quarks)



REMOVE ???

diquarks M Şahin and O. Çakir, arXiv:0911.0496

- predicted in superstring inspired E6 and composite models
- could carry charge 1/3, 2/3, 4/3 and be scalar or vector
- in gp production $\mathcal{L}_{|B|=2/3} = \left(g_{1L}\bar{Q}_L^c i\tau_2 Q_L + g_{1R}\bar{u}_R^c d_R\right) D Q_1^c + \text{h.c.}$

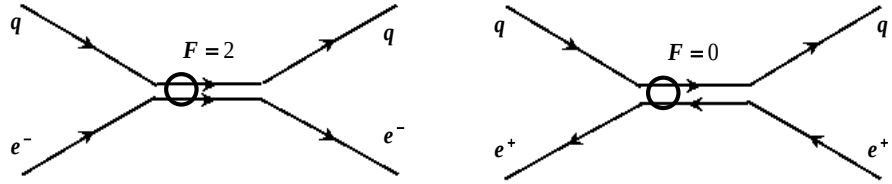


LHeC reach excluded
vector and scalar diquarks can be distinguished by the angular distribution of their decays

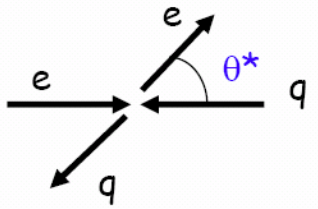
Measuring the LQ quantum numbers in e-p

- Quantum numbers and couplings:
  - Fermion number:
    - can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$
    - At pp: 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 p-p, 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 e-p, 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? $e_L^- u_L \rightarrow S_3 \rightarrow \nu_e d_L$
  - BR to neutrino, good S/B in νj channel