BSM searches at FCC-eh
(selected topics)

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for the BSM ep team
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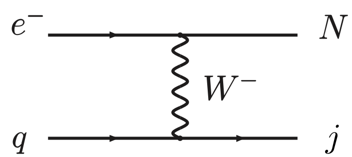
1st FCC Physics Week
January 19th 2017

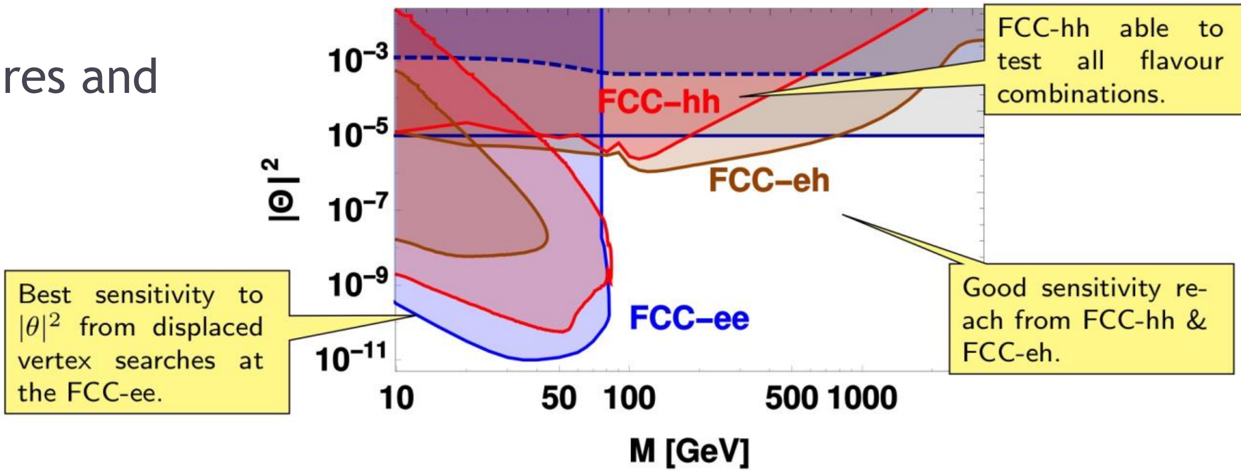
Prelude

- The HL-LHC results will be crucial to re-focus the BSM program at the FCC in terms of
  - Characterization of hints for new physics if some excess or deviations from the SM are found
  - Constraints of new physics models and complementary searches wrt the hh/ee cases
  - Exploration of new scenarios
- Not an easy task at the moment
- Wish: engage the theory community!

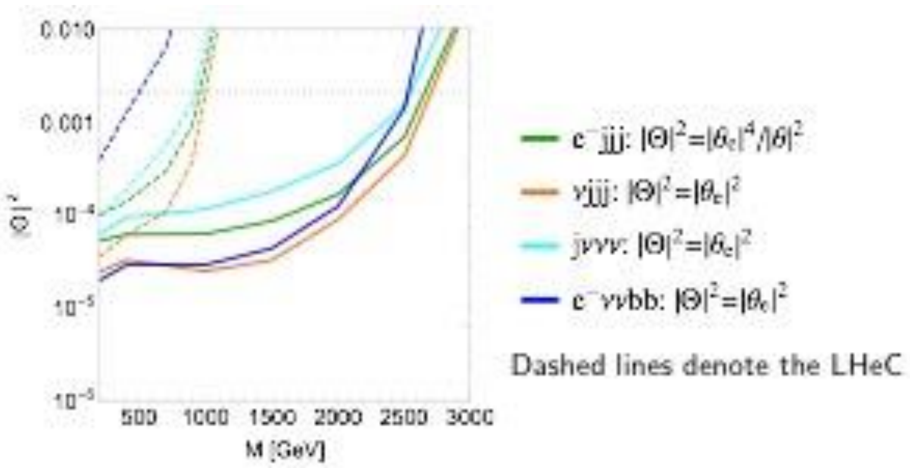
Some examples at this meeting

- Heavy neutrinos (see Eros Cazzato's and Oliver Fischer's talks yesterday)
  - @ FCC-eh: LFV signatures and displaced vertex search





- lepton-flavor-conserving signatures



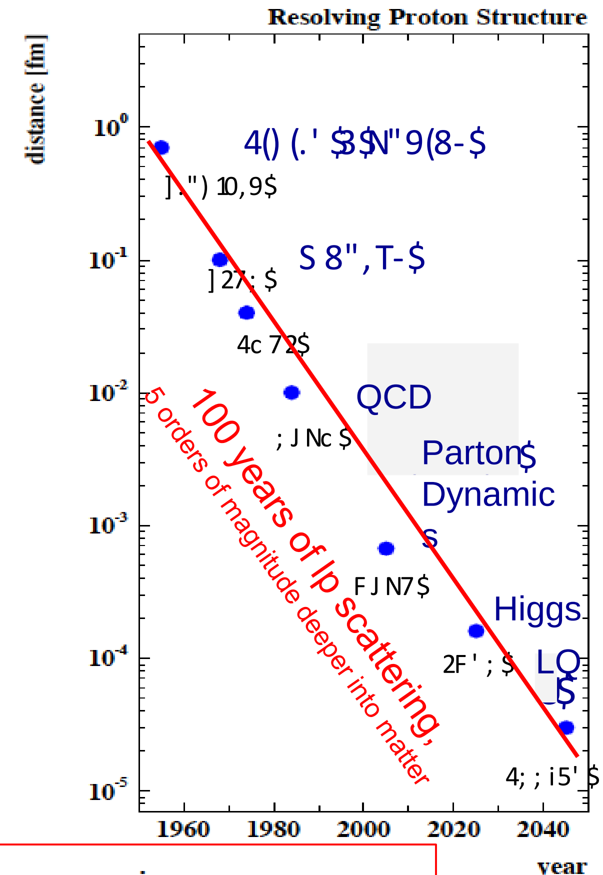
- Top physics and FCNC
  - See later this afternoon (Orhan Cakir's talk)
  - Poster on FCNC couplings of Higgs-top by B. Hacisahinoglu
- Anomalous HVV couplings
  - (see poster M. Altinli et al.)
- Preonic models
  - Saleh Sultansoy's talk after this

Outline

- Interesting BSM-eh cases made at this workshop
- In this talk I will hint a few more topics
  - Indirect impact on search potential for FCC-hh: **improved PDF**
  - Direct searches for BSM
    - Leptoquark
    - contact interactions
    - anomalous couplings (VVV)
    - Vector Boson scattering
    - SUSY: RPV and RPC
  - Outlook and summary

HERA-LHeC-FCC-eh:

finest microscopes, resolution as 1/Q



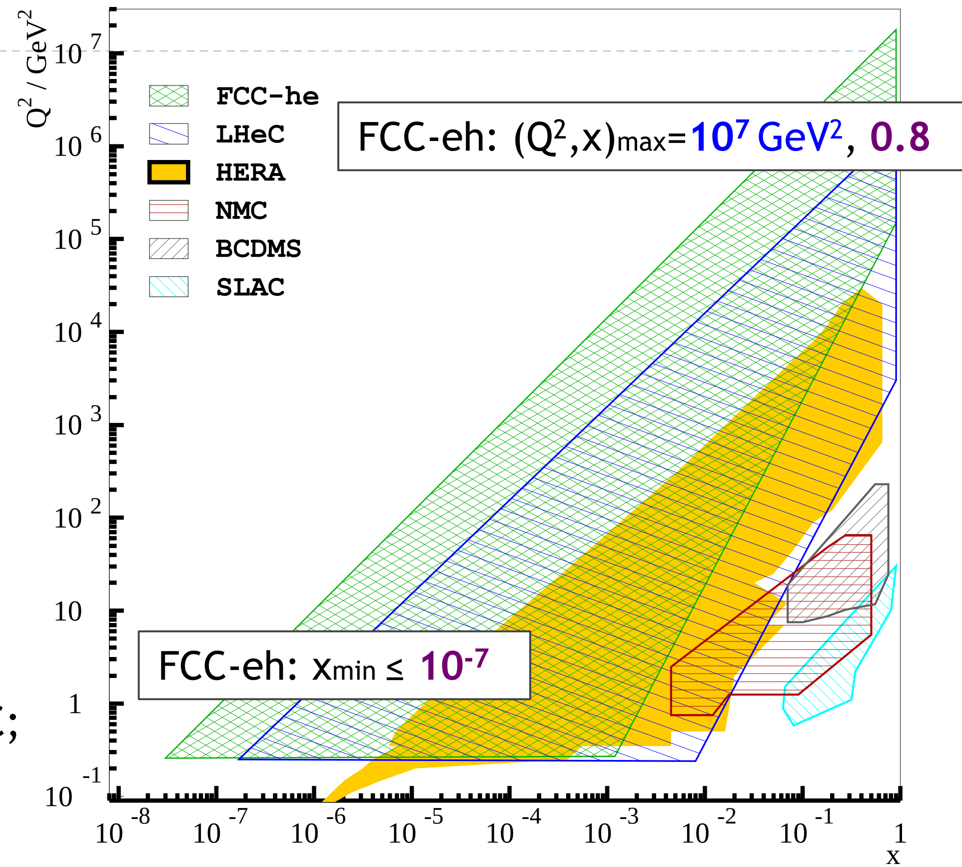
continuing studies to get better precision on potential discoveries and constraints on BSM models
Detector performance simulation in progress

Indirect impact on search potential for FCC-hh: improved PDF

Improving PDFs with the LHeC

no data

- **low-x:** no current data to constrain $x \leq 10^{-4}$; better but not much after HL-LHC; rely purely on extrapolation non-linear equations, gluon saturation?
- **mid-x:** need higher precision for Higgs
- **high-x:** very poorly constrained – limits searches for new, heavy particles

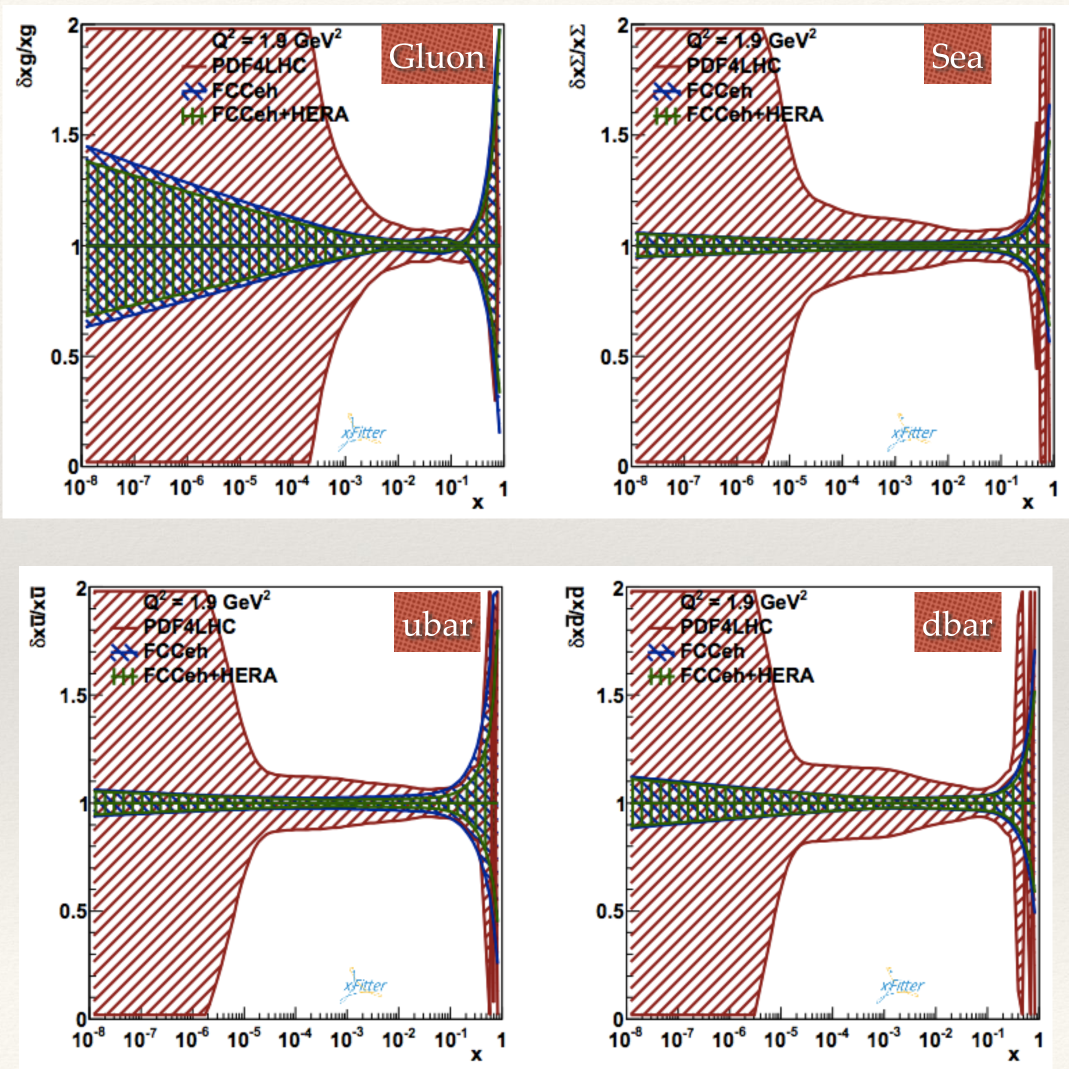


FCC-eh: access to much smaller x, larger Q^2

Impact on PDF → also depends on whether LHeC is realized or not

Potential of FCCeh on PDFs

See Stefano and Voica's presentation



PDF4LHC set

vs

FCCeh (+HERA)

at starting scale

FCCeh brings substantial impact at low x

important for the FCCpp as it will probe much lower x regions for standard processes

17

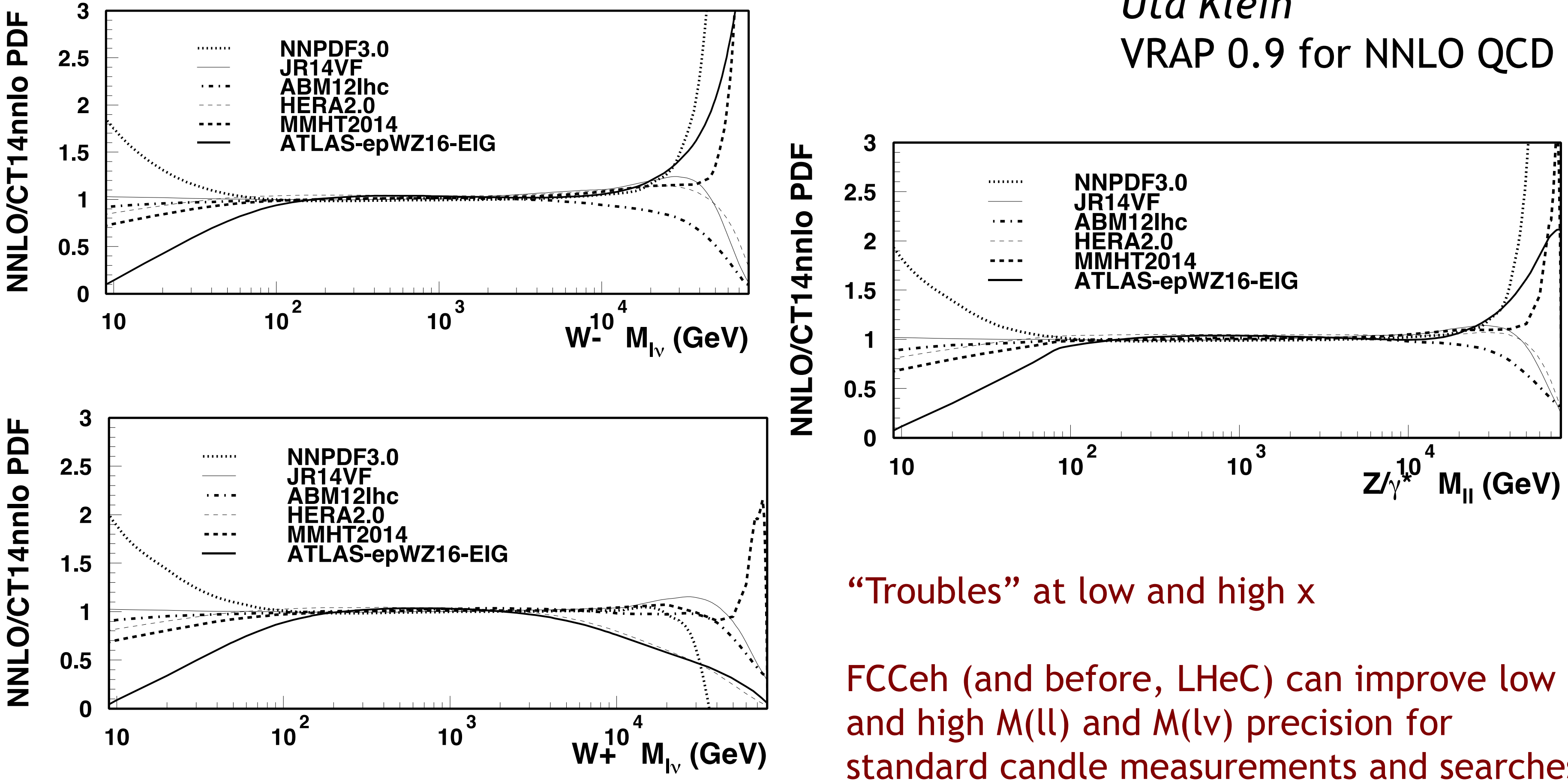
FCC week 2017| CERN

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



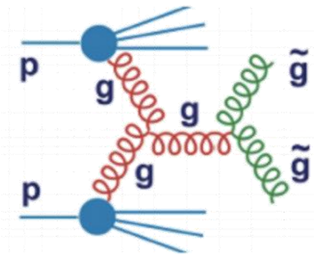
"Troubles" at low and high x

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

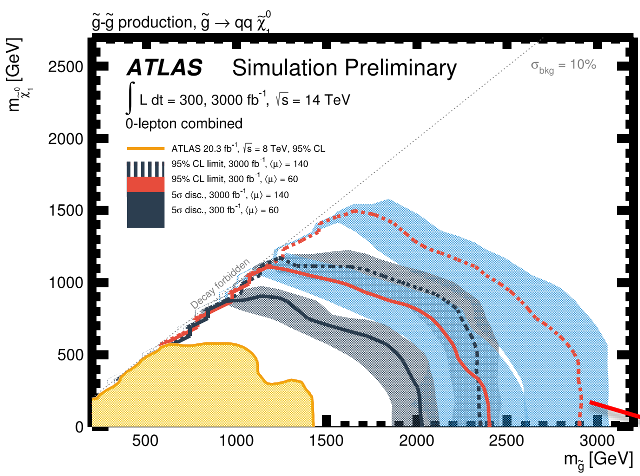
Impact of PDF @ High x

- large uncertainties in high x PDFs limit searches for new physics at high scales

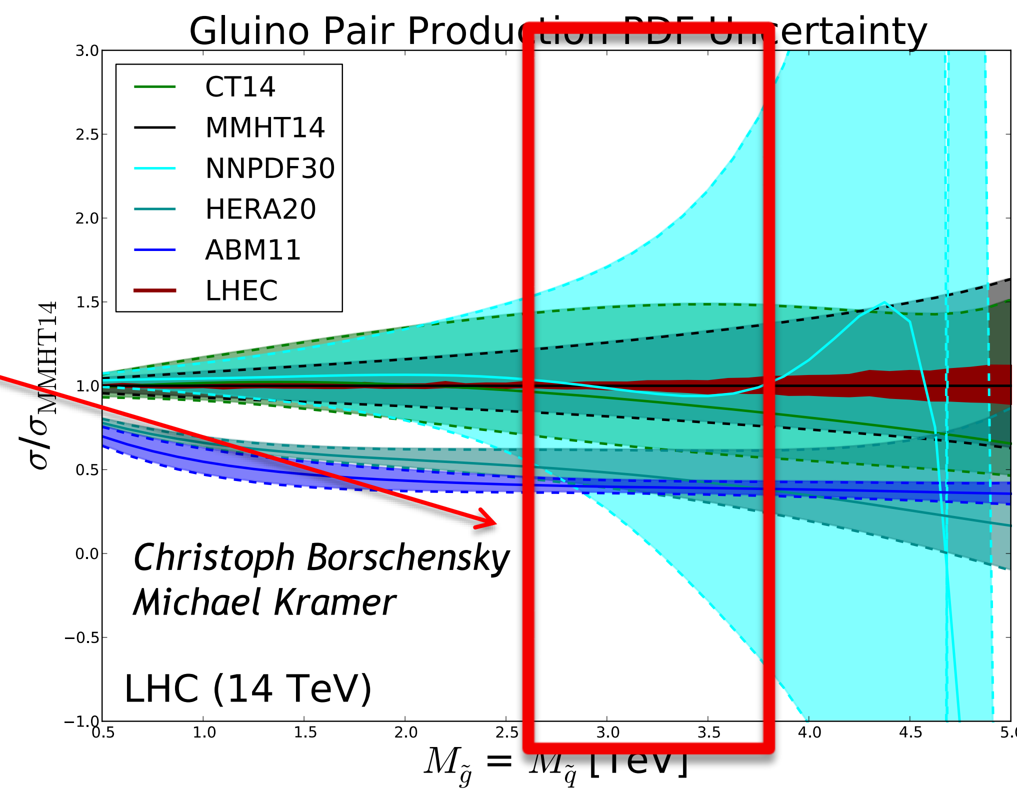
  many interesting processes at LHC are gluon-gluon initiated:
  top, Higgs, … and BSM processes, such as gluino pair production



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



< x > ~ 0.4



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

NNPDF30nlo become negative at high masses despite positive constraints applied to the fitting procedure

arXiv:1211.5102

Impact of PDF @ High x

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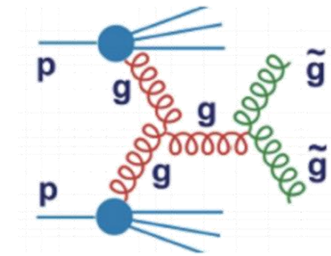

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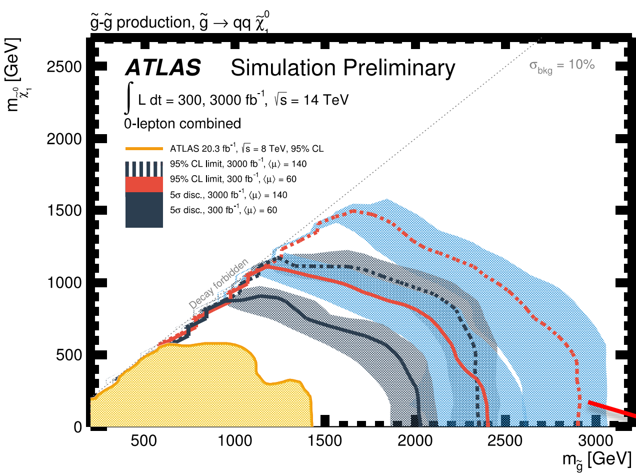

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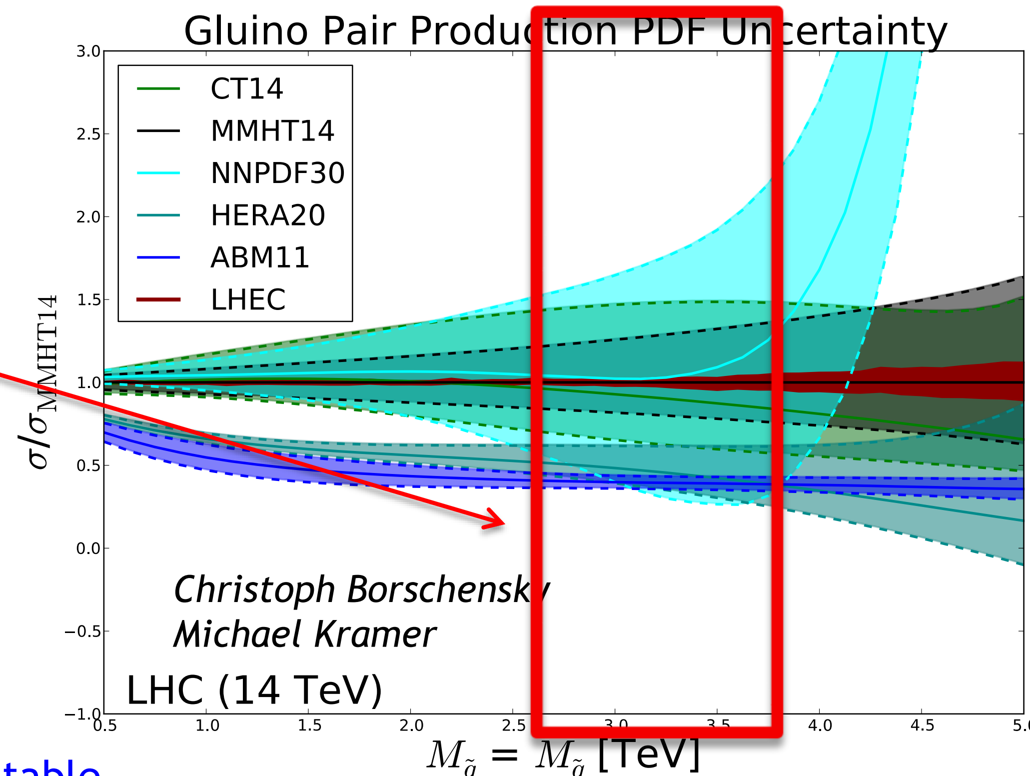

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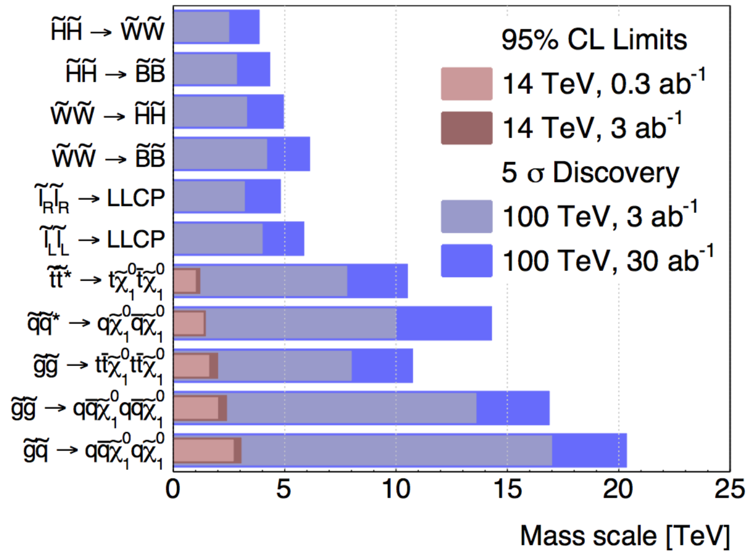
Use prescription from J. Rojo to avoid negative x-section at at high masses for NNPDF30nlo → x-section calculation unstable

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}**

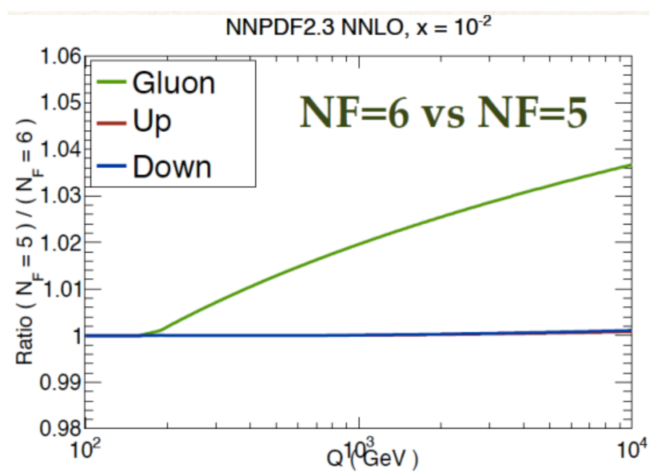


- Similar x range for the sensitive region (<x> ~ 0.4) → ~40-50% uncertainties on the prediction of gluon-gluon initiated processes
  - *Might be an issue also for central values*

Other aspects might play a non-negligible role:

See also Stefano's talk

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

Direct searches at FCC-eh

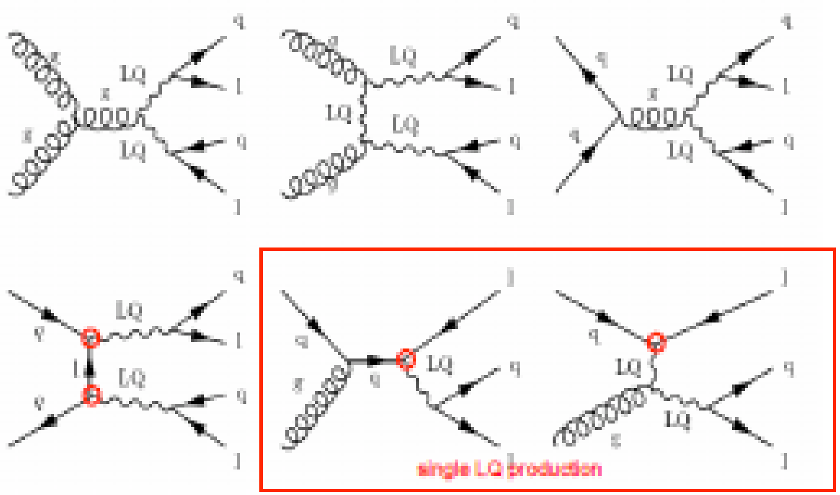
LQ production

Leptoquarks (LQs) appear in several extensions to SM: production $\sigma \sim \lambda^2 q(x)$

can be **scalar** or **vector**, with fermion number 0 (e^-qbar) or 2 (e^-q)

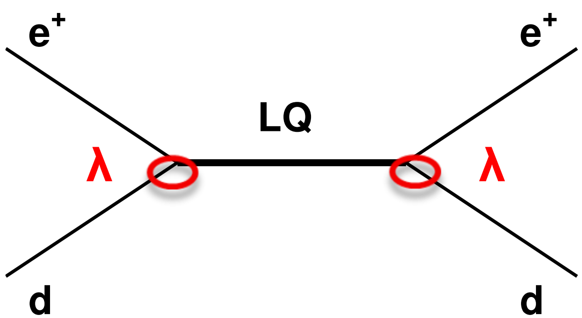
- **At the p-p,** mostly pair production (from gg or qq)
  - if λ not too strong (0.3 or lower)

  cross section independent on λ



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

- **At the e-p**: both baryon and lepton quantum numbers – ideally suited to search for and study properties of new particles coupling to both leptons and quarks

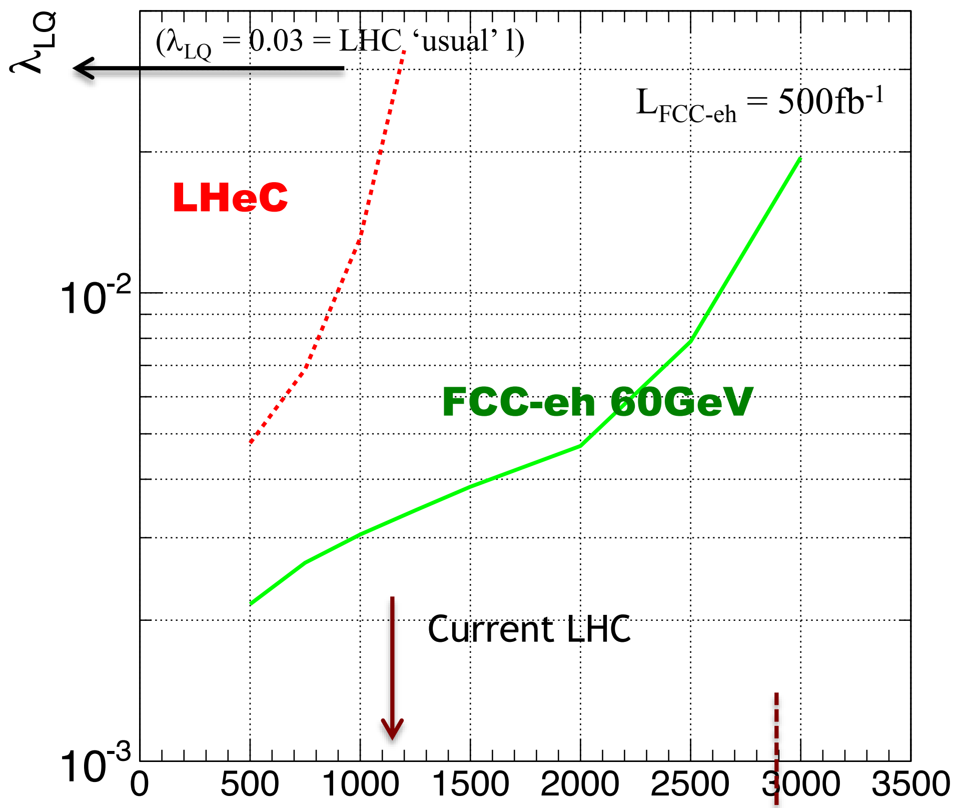


- single, resonant production; sensitive to λ

LQ status and reach at FCC -eh

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	$\beta = 0$



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

ep scenario:

sensitive to $\lambda << e=\sqrt{4\pi\alpha}=0.03$

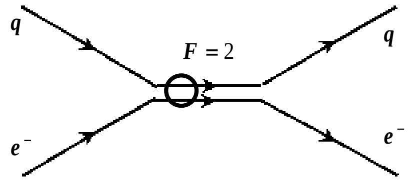
Sensitivity of HL-LHC could go to ~2.8 – 2.9 TeV
→ Close to the reach for FCC-eh
→ Dependence on lambda

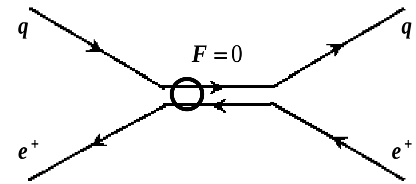
If deviations are found by the end of HL-LHC, FCC-hh will definitely see them, and FCC-eh can characterize those signals!

Measuring the LQ quantum numbers in e-p

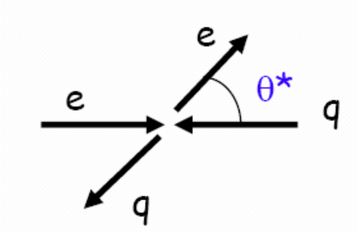
- Quantum numbers and couplings:
  - Fermion number:
    - can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$
    - At pp: very poor asymmetry precision achievable in single LQ production

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





  - 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



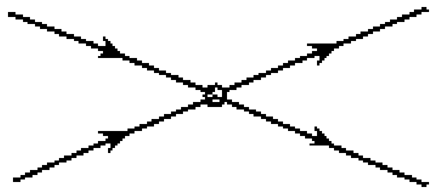
  - couple chirally (i.e. to L or R but not both) ?
    - could be probed by measuring sensitivity of cross sections to polarization of the electron beam
  - generation mixing ?
    - does LQ decay to 2nd generation? $e_L^- u_L \rightarrow S_3 \rightarrow \nu_e d_L$
  - BR to neutrino, good S/B in νj channel

Contact interactions

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

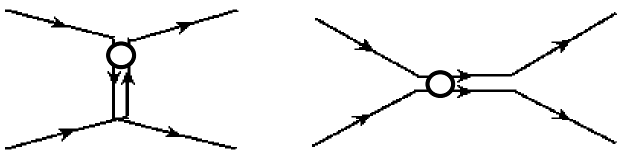
$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)}; \quad j_\mu^{(f=e,q)} = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_R \bar{f}_R \gamma_\mu f_R + h.c.$$

$\Rightarrow$ 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

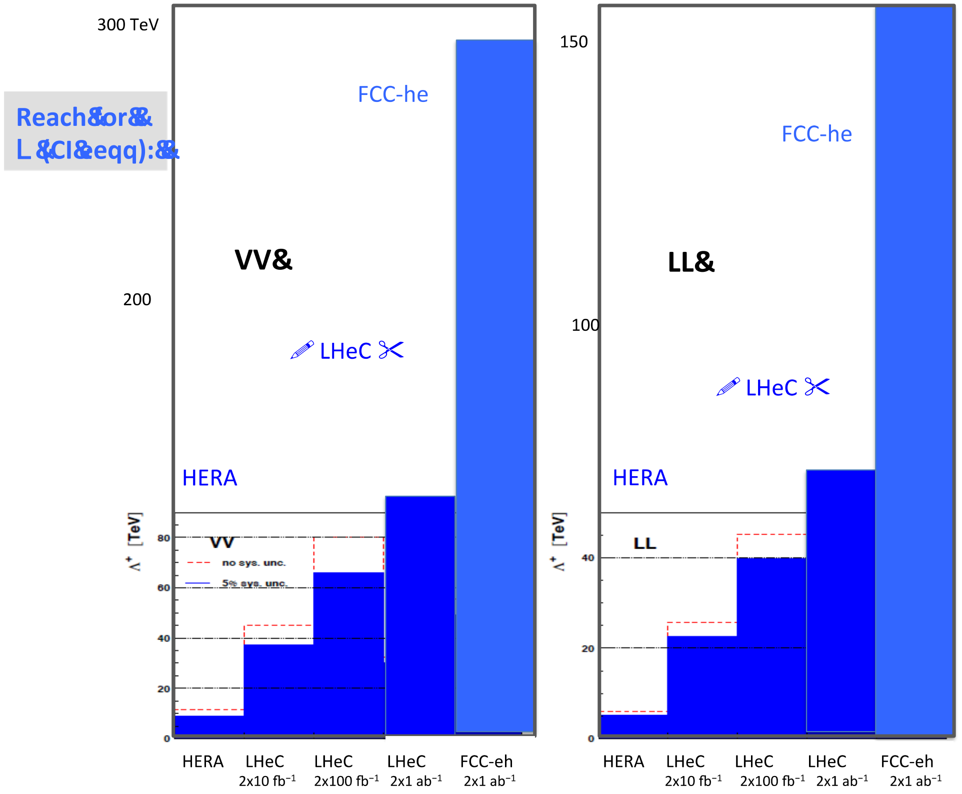
R → 3(1.5) x 10^{-20}m
pessimistic(optimistic) calculations

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



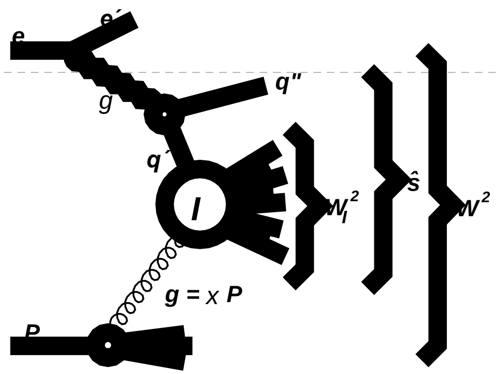
VV: all couplings with +ve sign

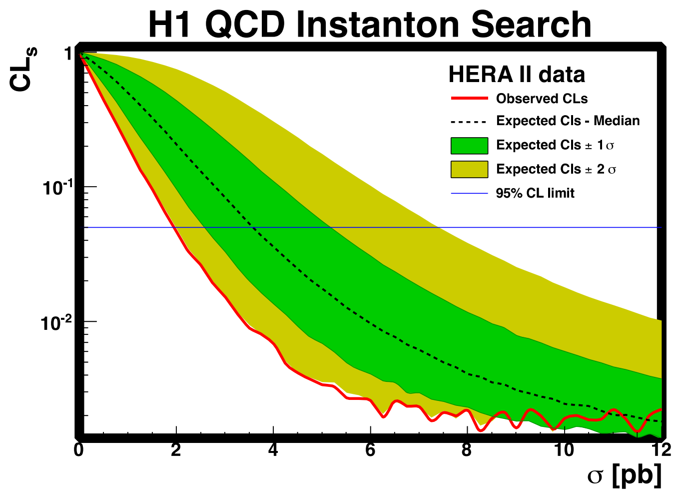
LL: only LL couplings between q and e

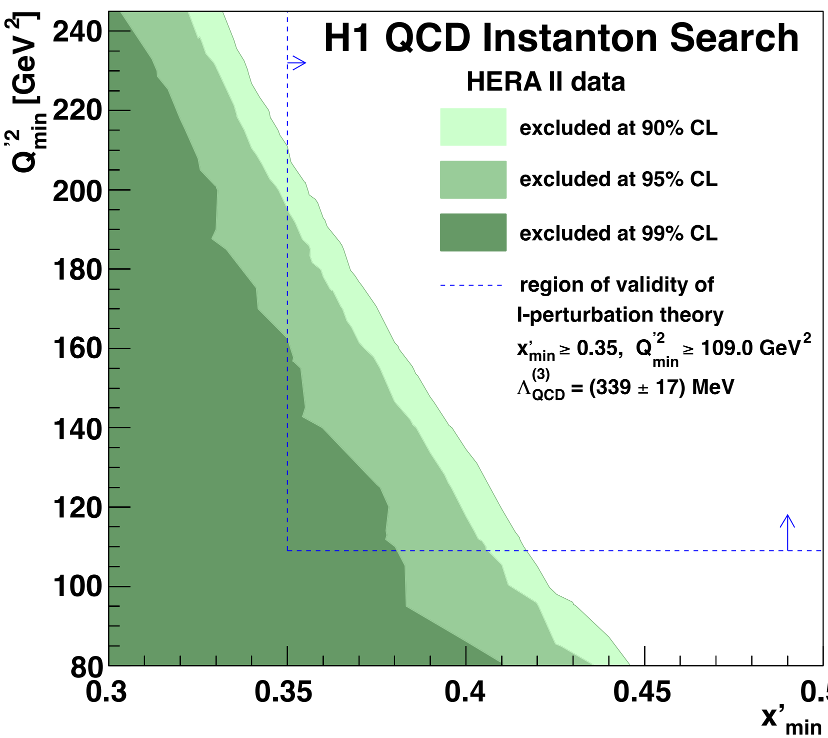
~ equivalent sensitivity at the FCC-hh at least for some of the couplings (same as HL-LHC vs LHeC) but need more calculations!

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
- Feasibility could / should be considered for the future



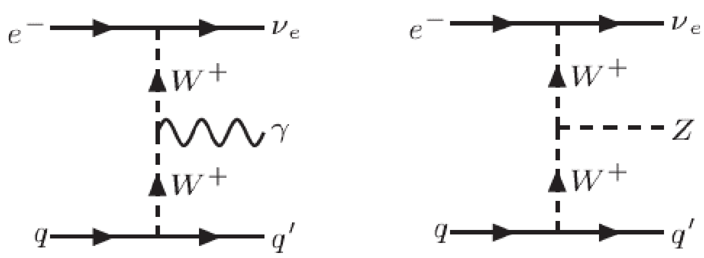




Eur.Phys.J. C76 (2016) no.7, 381

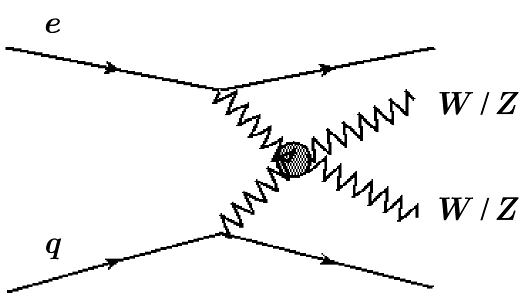
BSM in Vector Boson (VB) scattering

- 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:*

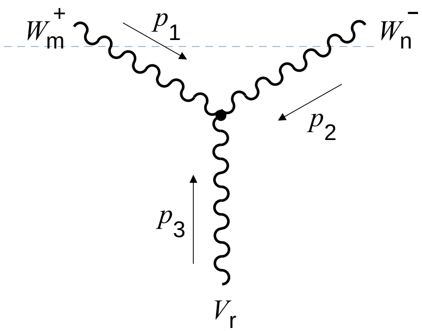
$$e^- q \rightarrow e^- (q) WZ, \quad (\nu q) WZ$$



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 $WW\gamma$ 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

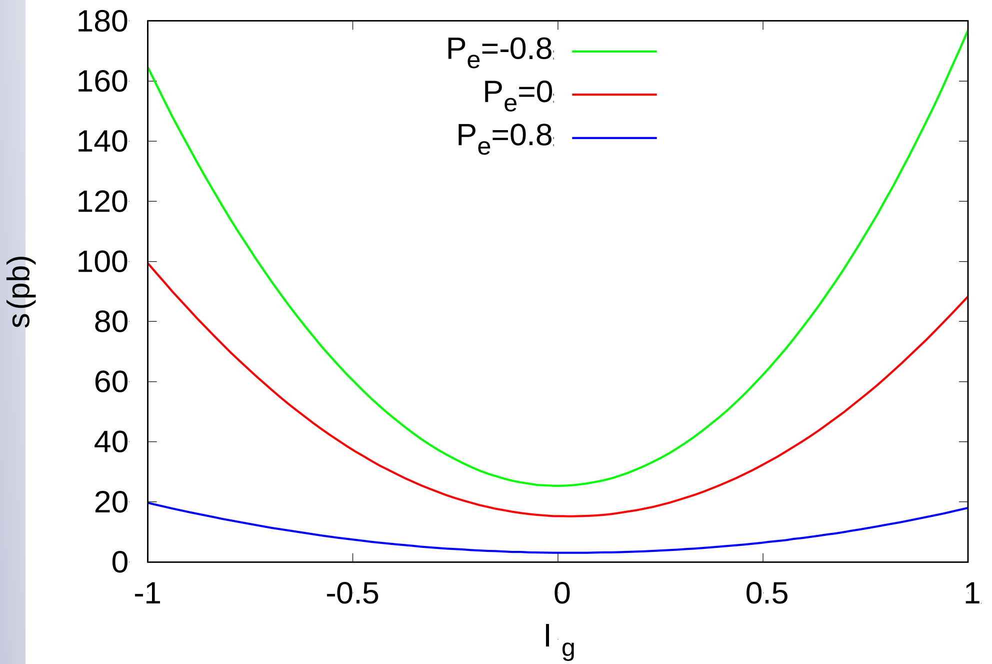
At the e-p:

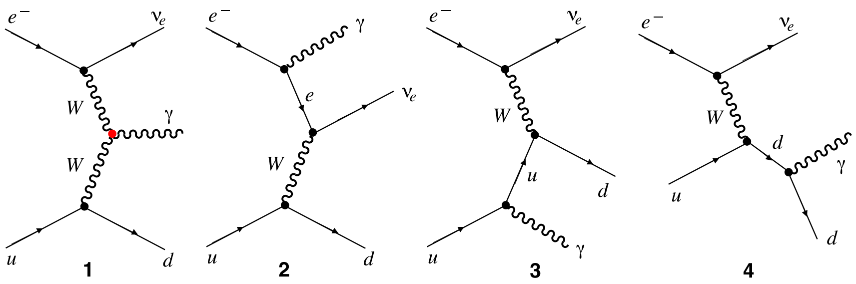
- can clearly distinguish between CC events e + p → νe + jet (W-exchange) and NC events e + p → e + jet (photon or Z boson exchange)
- triggering on a final state photon, can provide very clean bounds on the anomalous TGV's!

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



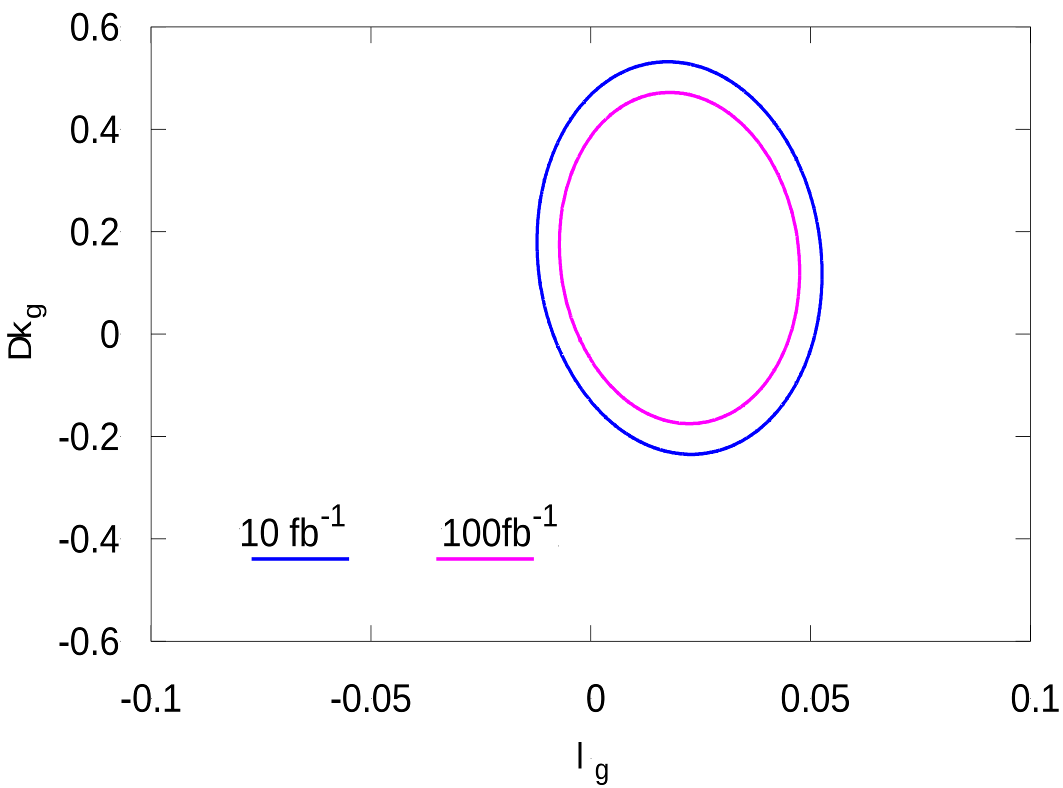


Cross section depending on anomalous λ_γ coupling of the process $ep \rightarrow \nu q \gamma X$ for E_e = 60 GeV and E_p=50 TeV at FCC-ep.

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 (Δκγ, λγ) AND (ΔKz, λZ) FROM THE ATLAS AND CMS EXPERIMENTS

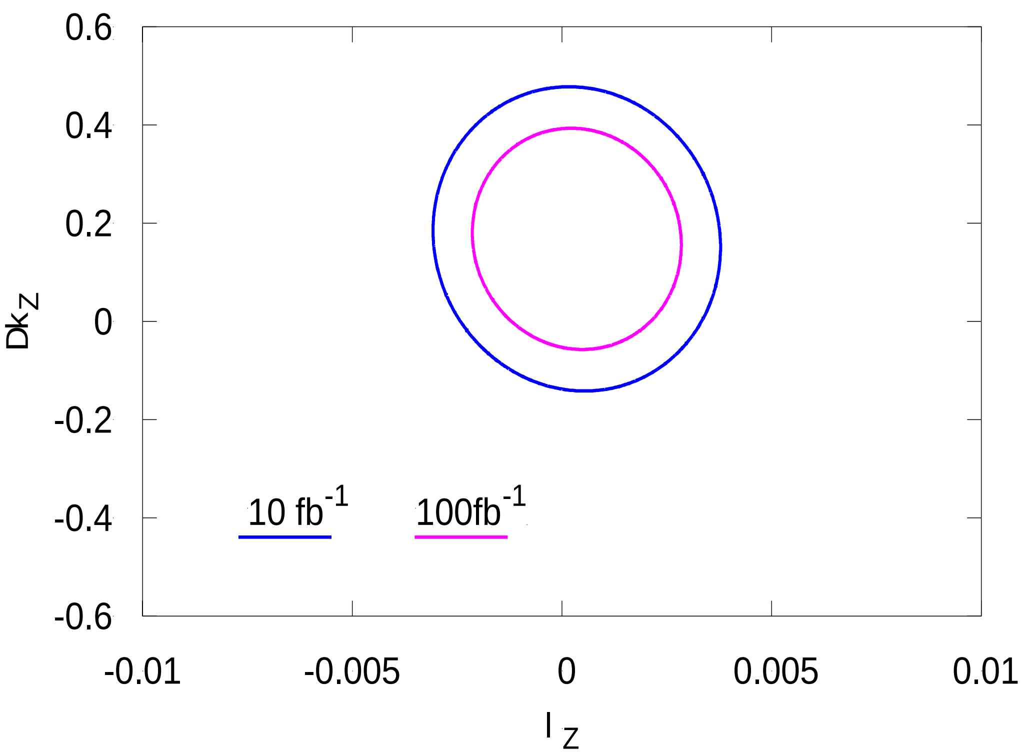
	ATLAS	CMS	ATLAS (upper-lower)	CMS (upper-lower)
$\Delta\kappa\gamma$	-0.420,0.480	-0.250, 0.250	0.900	0.500
$\lambda\gamma$	-0.068,0.062	-0.050, 0.042	0.130	0.092
$\Delta\kappa z$	-0.045,0.045	-0.160, 0.180	0.090	0.340
λz	-0.063,0.063	-0.055, 0.055	0.126	0.110

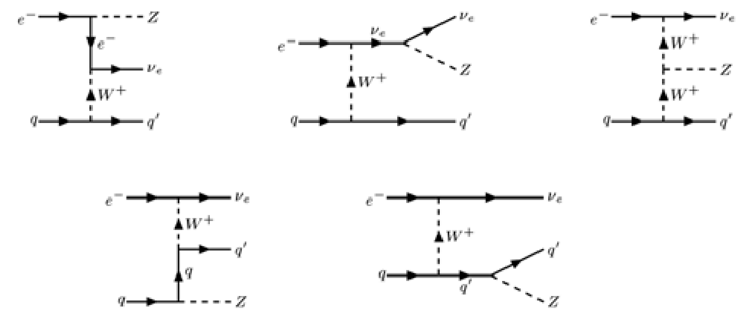
Two dimensional 95% C.L contour plot anomalous couplings in the $\lambda_\gamma - \Delta\kappa_\gamma$ plane for the integrated luminosity of 10 fb-1 and 100 fb-1 at FCC-ep with electron beam energy E_e =60 GeV with polarization P =−0.8 .

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 $\lambda_Z \sim 10^{-3}$

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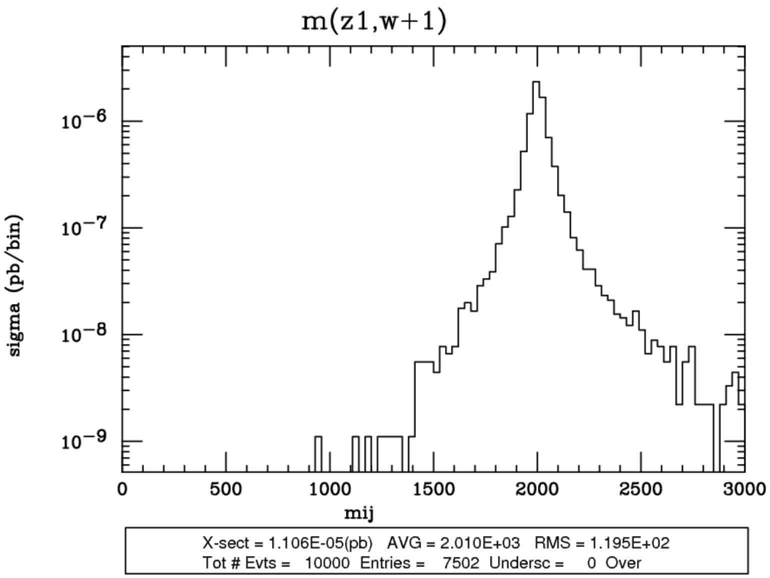
Two-dimensional 95% C.L contour plot of anomalous couplings in the $\lambda_Z - \Delta\kappa_Z$ plane for the integrated luminosity of 10fb-1 and 100 fb^{-1} at FCC-ep with electron beam energy *Ee*=60 GeV with polarization *P=-0.8*.

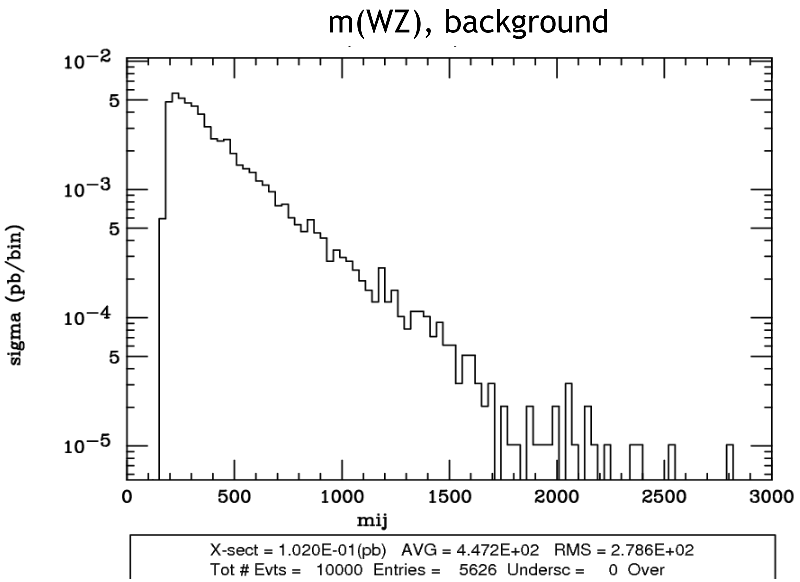
Vector Boson Scattering

Georges Azuelos

2 TeV resonance

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





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'

L-number violating terms

$$W_{\not R p} = \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k$$

bilinear terms

B-number violating terms

ΔL =1, 9 λ couplings, 27 λ' couplings

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

	$\lambda_{ijk}L_iL_j\bar{E}_k$	$\lambda'_{1jk}L_1Q_j\bar{D}_k$	$\lambda'_{2jk}L_2Q_j\bar{D}_k$	$\lambda'_{3jk}L_3Q_j\bar{D}_k$
weakest	0.07	0.28	0.56	0.52
strongest	0.05	$5.\cdot 10^{-4}$	0.06	0.11

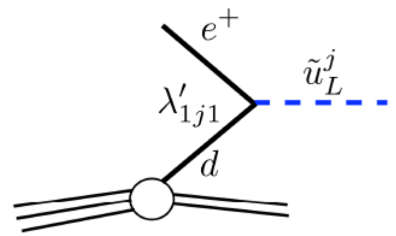
Various strong constraints already from LHC on λ and λ'' ***(from multilepton and multijet searches)***

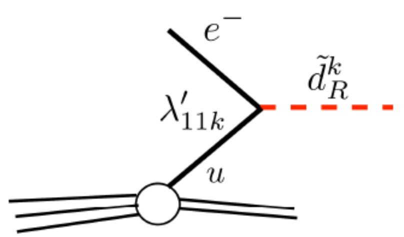
Couplings with third gen quarks

In e-p production rate depending on:

e-d-t: λ'_{131} (constraint: < 0.03)

e-u-b: λ'_{113} (constraint: < 0.02)



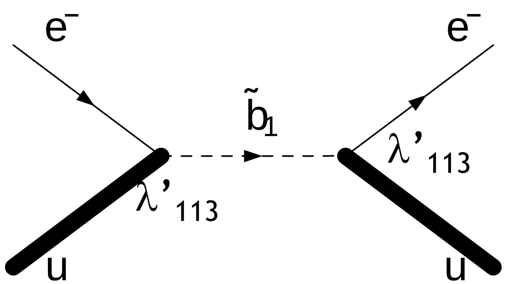


SUSY – R-parity violating

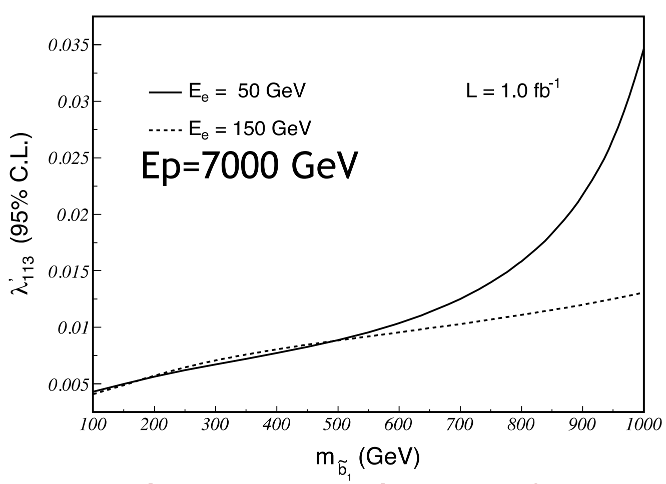
single sbottom/stop production (signal like leptoquarks, with generation mixing)

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

sbottom



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



@FCC-eh: same analysis as for LQ →

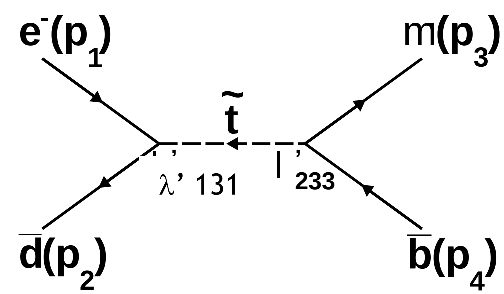
Sensitivity up to 2.5 TeV for $\lambda'_{113}<0.02$

http://arxiv.org/pdf/1107.4461v2.pdf

stop

$\Lambda'_{131} < 0.03$

also stronger bounds from ββ0ν



Probe RPV LQD terms:
In this case $\lambda'_{131} \times \lambda'_{233}$

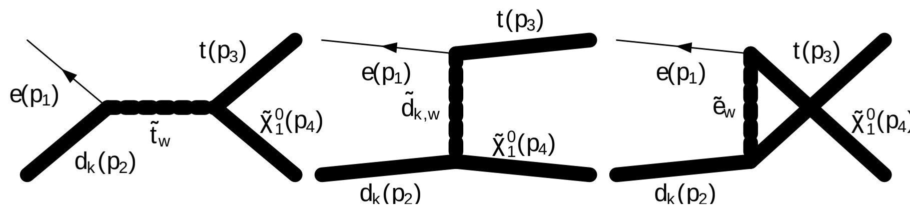
- requires good b-tagging
- $\lambda'_{223} < 0.45$ (constraints not sensitive to it down to ~ 0.05)
- Dependency on λ'_{131} :
  - LHeC (1/fb): 300 GeV, $\lambda'_{131} = 0.005$
  - FCC-eh potential to be evaluated

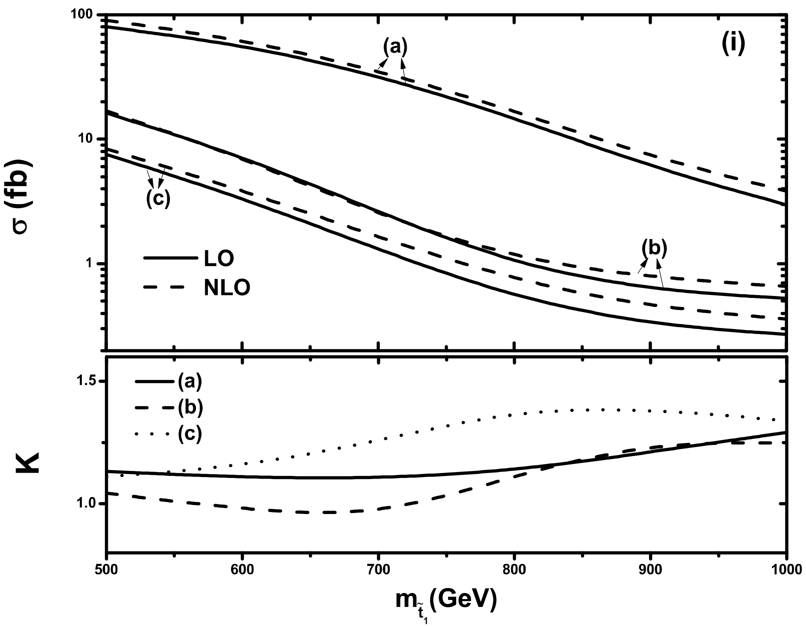
A "different" SUSY RPV: Single-top + neutralino

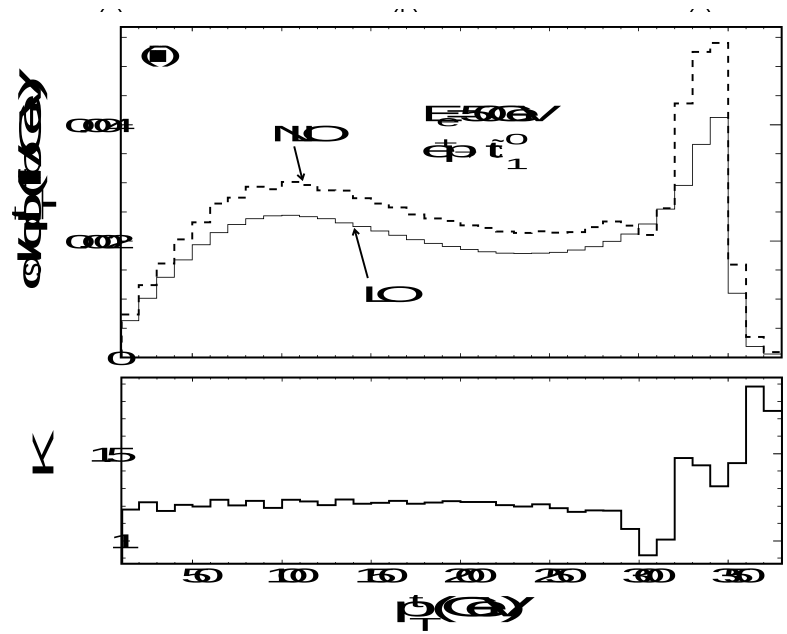
- Studies carried out in the past (for LHeC) shows potentially interesting signatures → resonant / non-resonant top+neutralino production

  http://arxiv.org/pdf/1307.2308v2.pdf

- Could lead to interesting discovery e.g. **neutralinos decays in RPV scenarios**

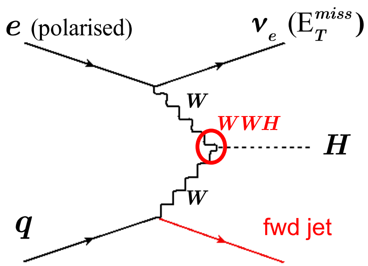




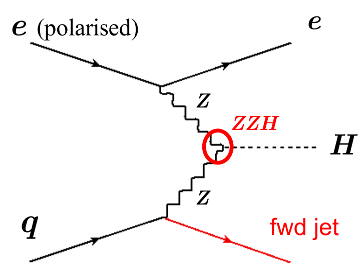


SUSY RPV in Higgs Sector

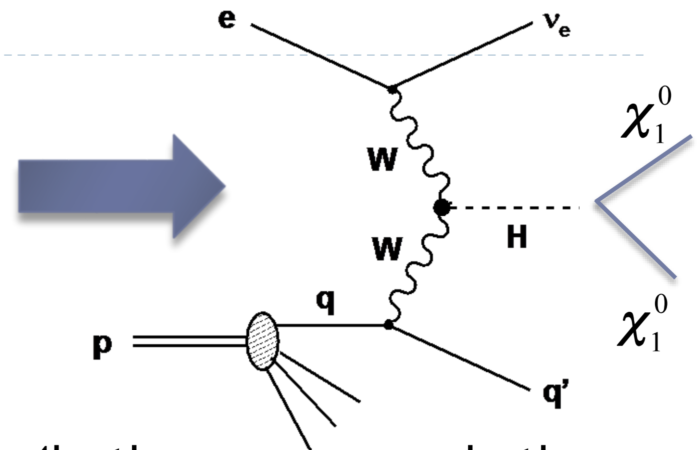
See also Uta Klein's talk yesterday



Charged Current



Neutral Current



- In addition to the higgs to invisible and higgs to 4b, there are several other RPV cases to be considered. E.g.

$$h \to \chi_1^0 \chi_1^0 \to 3j\,3j \text{ (resonances)}$$

  - Neut1 might decay in 3 jets (UDD terms)

$$h \to \chi_1^0 \chi_1^0 \to jjjj\nu\nu \text{ (non-resonant, with MET)}$$

  - Neut1 might decay also in lepton+neutrinos (LLE terms)
    - Prompt or delayed: displaced vertex doable but not yet explored

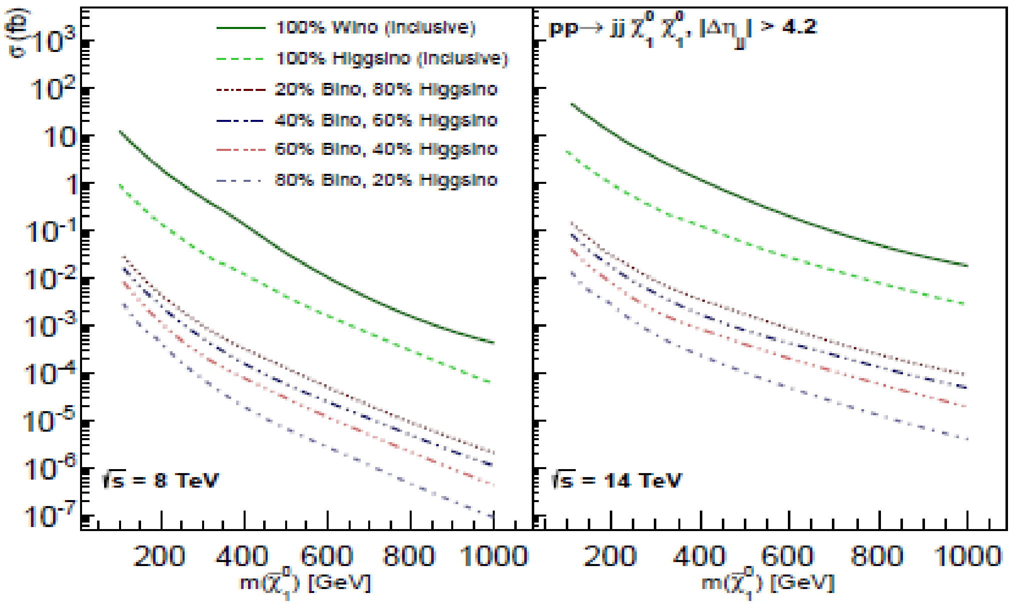
Some statistics: N_exp = L × σ(h) × BR($h \to \chi_1^0 \chi_1^0$) × [BR($\chi_1^0 \to X$)]^2

In 1/ab, **σ(h)=850 fb (CC)**, assuming BR($h \to \chi_1^0 \chi_1^0$) = 10%

N exp = 85000 × [BR($\chi_1^0 \to X$)]^2 → **sizable dataset if BR not too small**

Hopes for RPC SUSY? EWK RPC

- Charginos (C) and Neutralinos (N) fundamental for SUSY
  - Expected to be light in most scenarios (C1, N1, N2 in particular)
  - N1 is often the LSP and one of the preferred DM candidate
- One of the most difficult scenarios for the p-p: medium-compressed N1, C1, N2 (DM few GeV)
  - Not visible in direct searches, mono-photon and mono-jet searches possibly not sensitive because of systematic uncertatinties VS tiny xsect.
  - VBF scenarios investigated for 14 TeV LHC



$$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj,\ \tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} jj,\ \tilde{\chi}_1^{\pm} \tilde{\chi}_1^0 jj$$

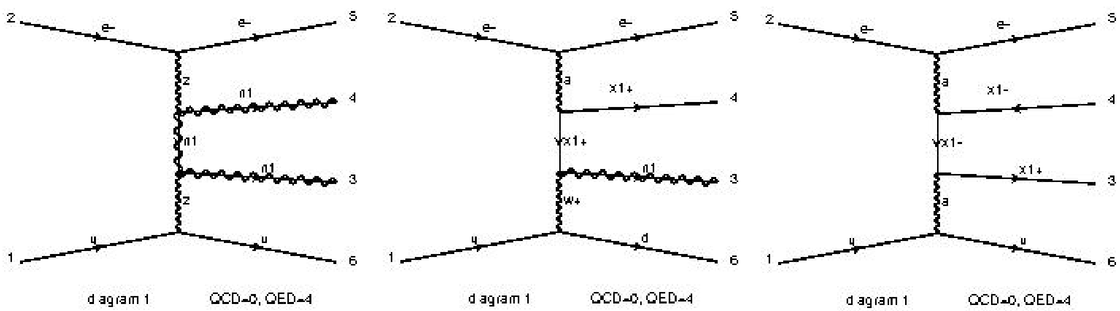
50 fb xsection for pure Wino-like N1

Promising for low N1, but possibly large bkg from SM (ie Z,higgs production)

EWK RPC-SUSY production

Kechen Wang (and MD)

- Question: can anything be done at the FCC-eh ?
- Production of monojet-like signatures → not feasible
- Production of the kind e+j+MET → possible
- First look, using Madgraph:



- Example of diagram for C1C1. Production of N1N1 and C1N2 equivalent for almost degenerate masses
- Coupling strenghts depend on the Wino-Higgsino mixture

FCC-eh (Ep = 50 TeV, Ee = 60 GeV with no polarization).

Benchmark point:
pure Wino DM: M2 ~ 200 GeV; M1, \mu >> M2;
m(neutrino1) ~ m(chargino1) ~ 200 GeV.

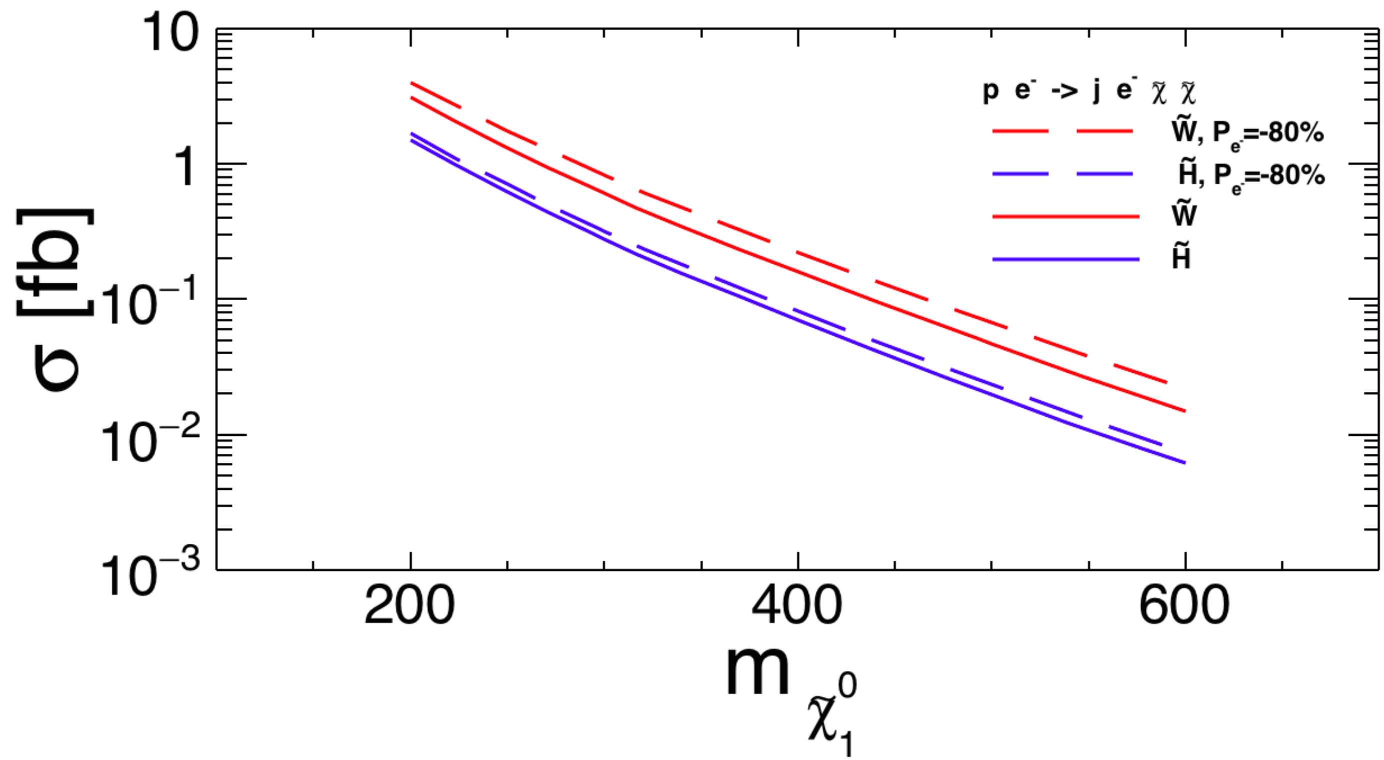
MadGraph generating:
“import model mssm-full
define dm = n1 n2 x1+ x1-
generate p e- > dm dm e- j / go ul cl t1 ur cr t2 dl sl b1 dr sr b2 ul\
~ cl~ t1~ ur~ cr~ t2~ dl~ sl~ b1~ dr~ sr~ b2~ h2 h3 h+ h- sve svm svt\
el- mul- ta1- er- mur- ta2- sve~ svm~ svt~ el+ mul+ ta1+ er+ mur+ ta2\
+ n3 n4 x2+ x2- QCD=0 QED=4 ”

will use P=-0.8 for next round

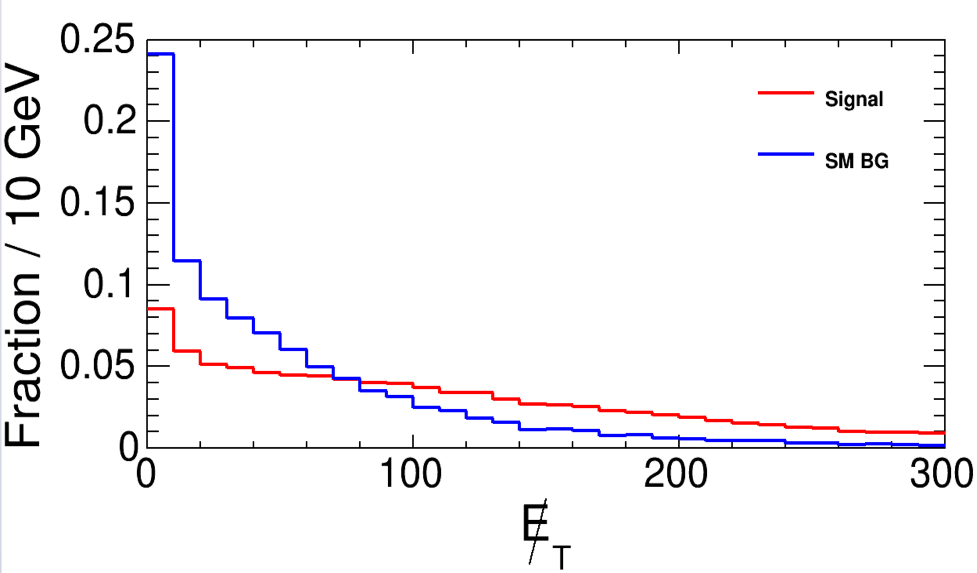
EWK RPC-SUSY production

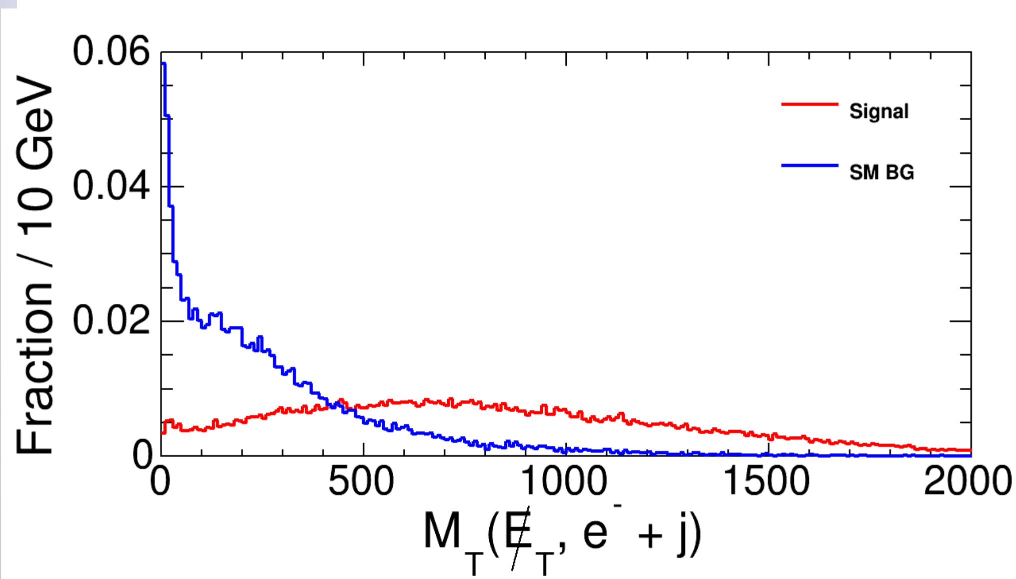
- Question: can anything be done at the FCC-eh ?
- Production of monojet-like signatures → not feasible
- Production of the kind e+j+MET → possible
- Polarization -0.8 lead to a 30% increase in x-sections, which are anyway small:

Kechen Wang



SUSY EWK production





σ(Wino 200 GeV, P=0.0) = 3 fb

Bkg: j e MET including W/Z processes

Basic selections on pT jets, electron, eta range: signal and background 'efficiency'
→ **eff_S = 25%, eff_B = 0.04%**

MET>100 GeV, MT(met, j)>150 GeV , Dphi(MET,jet)> 3, Dphi (e,j)<2, MT(MET, j+e) → **eff_S = 15%, eff_B = 0.02%**

Simple cut-and-count analysis based on 'TRUTH' studies lead to a signal significance >= 1 with 1000/fb (fake-MET bkg also missing)

MVA analyses would be beneficial (as in h→Inv case, see Uta's talk)

Just started but worth investigating

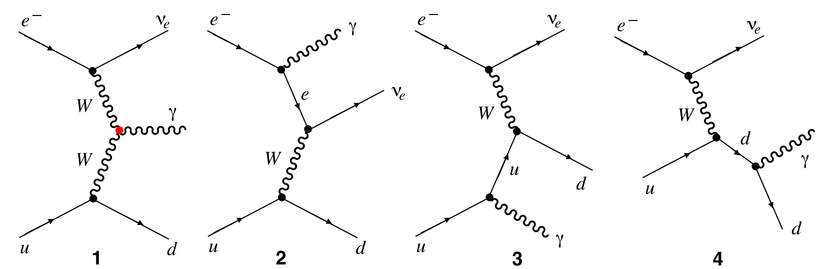
Summary and outlook

- FCC-eh offers a variety of opportunities for BSM searches
- Crucial interplay in the context of PDF sets (@ high and low x)
- Ideal to search and study properties of new particles with couplings to electron-quark
- Nice prospects for "classic" searches on leptoquarks, contact interactions, anomalous couplings and RPV/RPC SUSY
  - Some promising, some difficult
- Physics potential yet to be fully exploited
  - Engagement from theory community is really important → leading to very interesting results where it started!
  - Detector-level studies crucial for next phase

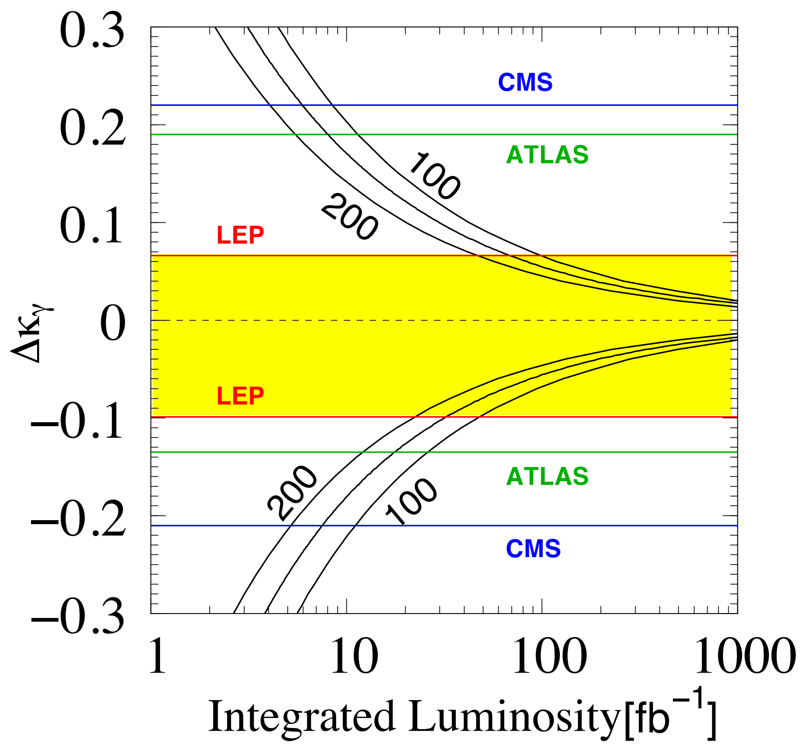
Back-up

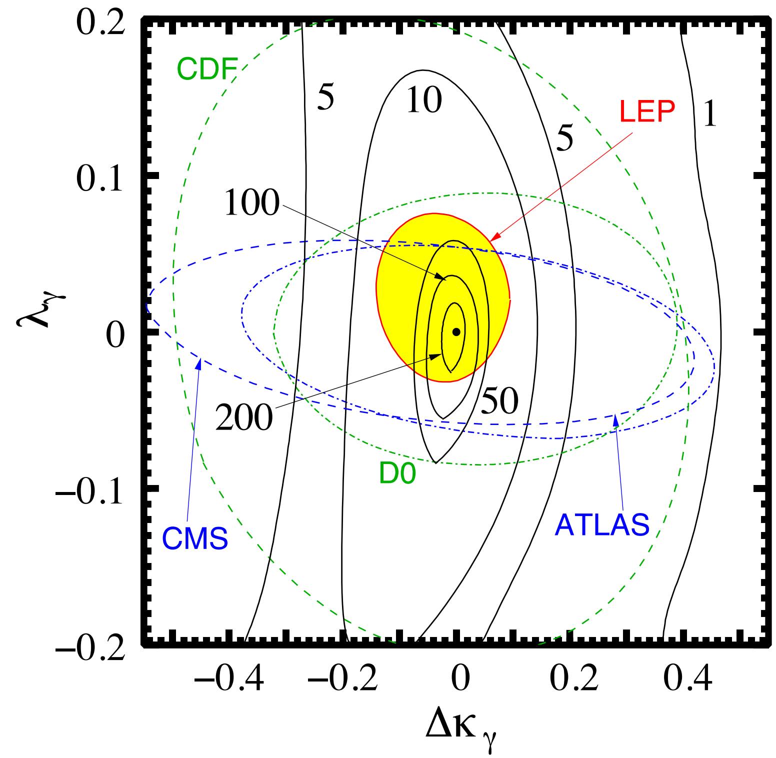
LHeC Prospects for WWγ

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



- Select on p_T of γ and jet
- Sensitivity to $\Delta\phi$ (γ-jet)





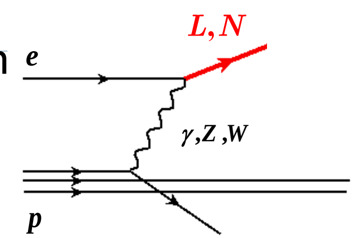
Competitive constraints at LHeC already for ~ 100 fb^{-1}

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:

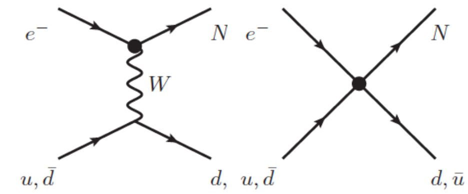


- vector-like leptons: left and right chiralities have same transform properties
  - predicted in GUT theories (E_6) or in Composite Higgs Models
  - couplings: $eEZ, \nu EW, eEH; \quad \nu NZ, eNW, \nu NH$
- Majorana Neutrino Production in an Effective Approach

  (L. Duarte et al. 1412.1433)

  SM background from $p\gamma \rightarrow \ell^+ + 3j + \nu \quad pe^- \rightarrow e^+ + 3j + 2\nu_e$

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

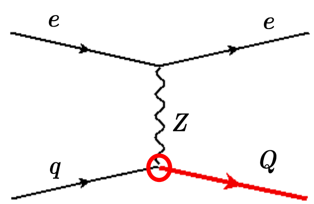


$N \rightarrow \ell^+ +$ jets

vector-like quarks

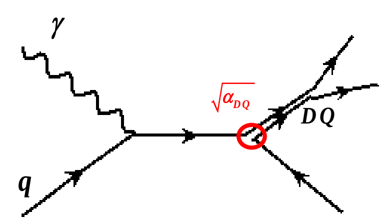
- single production of top partners, sensitive to couplings: qQZ, qQW, qQH

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

LHeC reach excluded

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