BSM searches at FCC-eh

Monica D'Onofrio
(University of Liverpool)
for the BSM ep team
[coord. MD, Oliver Fischer, Georges Azuelos]

FCC Week, Amsterdam, April 12th 2018

Introduction

- ep collider is ideal to study common features of electrons and quarks with
  - EW / VBF production, LQ,multi-jet final states, forward objects
- Broad BSM program at the FCC-eh in terms of
  - Exploration of new and/or challenging scenarios
  - Characterization of hints for new physics if some excess or deviations from the SM are found at pp colliders
- Differences and complementarities with *pp* colliders
  - Some promising aspects:
  - → small background due to absence of QCD interaction between *e* and *p*
  - → very low pileup
  - Some difficult aspects:
  - → low production rate for NP processes due to small s
- Lately, great engagement from theory community working with experimentalists

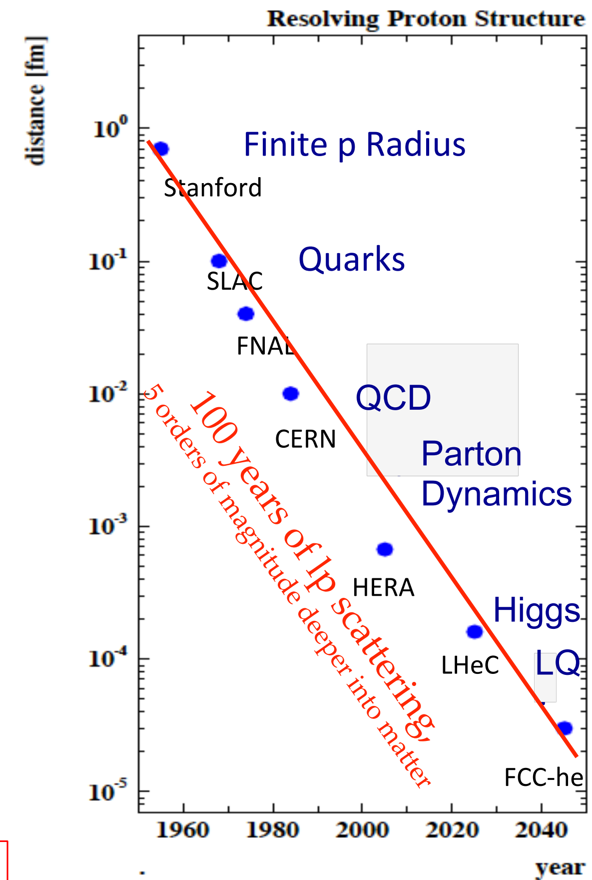
A wide programme of searches on going…

number	general
1	Acar, Y. C., Akay, A. N., Beser, S., Karadeniz, H., Kaya, U., Oner, B. B., & Sultansoy, S., FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics., http://arxiv.org/abs/1608.02190
	SUSY (general)
2	Han, C., Li, R., Pan, R.-Q., & Wang, K. , Searching for the light Higgsinos at the CERN LHeC., http://arxiv.org/abs/1802.03679
3	S. Kuday, Resonant Production of Sbottom via RPV Couplings at the LHeC https://arxiv.org/abs/1304.2124
4	Hong-Tang, W., Ren-You, Z., Lei, G., Liang, H., Wen-Gan, M., Xiao-Peng, L., & Ting-Ting, W., Probe R-parity violating stop resonance at the LHeC, http://lanl.arxiv.org/abs/1107.4461
	Long-lived particles - SUSY and beyond
5	Curtin, D., Deshpande, K., Fischer, O., & Zurita, J., New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders. http://arxiv.org/abs/1712.07135
	heavy/sterile neutrinos
6	Duarte, L., Zapata, G., & Sampayo, O. A., Angular and polarization trails from effective interactions of Majorana neutrinos at the LHeC., http://arxiv.org/abs/1802.07620
7	Antusch, S., Cazzato, E., & Fischer, O. Sterile ,neutrino searches at future e^-e^+, pp, and e^-p colliders,, http://arxiv.org/abs/1612.02728
8	Duarte, L., González-Sprinberg, G. A., & Sampayo, O. A., Majorana Neutrinos Production at LHeC in an Effective Approach, http://xxx.lanl.gov/abs/1412.1433
	anomalous couplings, Effective Lagrangian
9	Kuday, S., Saygin, H., Hos, I., & Cetin, F., Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider., http://arxiv.org/abs/1702.00185
10	Cakir, I. T., Cakir, O., Senol, A., & Tasci, A. T., Search for Anomalous WW\gamma and WWZ Couplings with Polarized e-Beam at the LHeC, Acta Physica Polonica B, 45(10), 1947 (2014) https://doi.org/10.55
	BSM Higgs:
11	Azuelos, G., Sun, H., & Wang, K., Search for Singly Charged Higgs in Vector Boson Scattering at the ep Colliders., http://arxiv.org/abs/1712.07505, see also K. Wang and H Sun: talk at Sept. 2017 workshop
12	Sun H, Luo X, Wei W, Liu T., Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the ep colliders, Phys. Rev. D 96, 095003
	compositeness, contact interactions, excited/heavy fermions,GUT
13	Zarnecki: arXiv:0809.2917, hep-ph/0104107
14	see also new limits from HERA: Zeus Collaboration, 1604.01280 and Zarnecki, 1611.03825
15	Liu, Y.-B., Search for single production of vector-like top partners at the Large Hadron Electron Collider., http://arxiv.org/abs/1704.02059
16	Lindner, M., Queiroz, F. S., Rodejohann, W., & Yaguna, C. E., Left-right symmetry and lepton number violation at the Large Hadron electron Collider., Journal of High Energy Physics, 2016(6), 140., https://doi.or
17	Mondal, S., & Rai, S. K., Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider, Physical Review D, 93(1), 11702. (2016) https://doi.org/10.1103/PhysRevD.9
	top quark FCNC and anomalous couplings (top group)
18	http://arxiv.org/abs/1701.06932, Denizli H, Senol A, Yilmaz A, Cakir IT, Karadeniz H, Cakir O., Top quark FCNC couplings at future circular hadron electron colliders
19	http://arxiv.org/abs/1703.02691, Wang X, Sun H, Luo X., Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC
20	http://arxiv.org/abs/1705.05419, Cakir IT, Yilmaz A, Denizli H, Senol A, Karadeniz H, Cakir O., Probing the Anomalous FCNC $tq\gamma$ Couplings at Large Hadron electron Collider
21	Sarmiento-Alvarado, I. A., Bouzas, A. O., & Larios, F., Analysis of the top-quark charged-current coupling at the LHeC, http://arxiv.org/abs/1412.6679
22	Dutta, S., Goyal, A., Kumar, M., & Mellado, B., Measuring anomalous Wtb couplings at e^-p collider, http://arxiv.org/abs/1307.1688
	exotic and miscellaneous
23	Acar, Y. C., Kaya, U., Oner, B. B., & Sultansoy, S., Color Octet Electron Search Potential of the FCC Based e-p Colliders, http://arxiv.org/abs/1605.08028
24	Hernandez-Sanchez, J., Das, S. P., Moretti, S., Rosado, A., & Xoxocotzi, R., Flavor violating signatures of neutral Higgs bosons at the LHeC, http://arxiv.org/abs/1509.05491
25	Das, S. P., Hernández-Sánchez, J., Rosado, A., & Xoxocotzi, R., Flavor signatures of lighter and heavier Higgs bosons within Two Higgs Doublet Model type III at the LHeC, http://arxiv.org/abs/1503.01464
26	Sahin, M., Resonant Production of Spin-3/2 Color Octet Electron at the LHeC. Acta Physica Polonica B, 45(9), 1811 (2014), https://doi.org/10.5506/APhysPolB.45.1811
27	Ren-You, Z., Hua, W., Liang, H., & Wen-Gan, M., Probing L-violating coupling via sbottom resonance production at the LHeC, http://lanl.arxiv.org/abs/1401.4266

Outline

- I will give an overview on on-going studies focusing on a selected list of topics
  - Direct searches for BSM
    - BSM Higgs (new charged higgses)
    - SUSY:
      - RPC (EWK, Higgsinos prompt and long-lived)
      - RPV (3rd generation squarks)
    - Leptoquarks
    - Sterile neutrinos
    - anomalous couplings (VVV)
  - [in back-up] Indirect impact on search potential for FCC-hh: **improved PDF**
  - Outlook and summary

HERA-LHeC-FCC-eh:
finest microscopes, resolution as 1/Q



Aim of this talk:
→ report on most recent studies and progress
→ brief overview of previously finalized studies
→ encourage future studies and synergies

BSM Higgs

- Higgs invisible decays
  - h → Chi0 Chi0 → *invisible*
- Higgs exotic decays
  - h → $2\phi \rightarrow bb\ (bb)$ [arXiV1608.08458]

Just seen in Uta's talk

- **Charged Higgs**
  - $H^{\pm}$, in Vector Boson Scattering

[Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505]

  - $H^{\pm\pm}$, in Vector Boson Scattering [in back-up]

[H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017)]

  - H^{+}, in 2HDM type III, $p\ e \rightarrow \nu j H \rightarrow \nu j\ cb$

[J. Hernández-Sánchez, etc. 1612.06316]

(see also talk by K. Wang at 2nd FCC Physics Week, Jan 2018)

$H\pm$, $H\pm\pm$ in Vector Boson Scattering

- **Georgi-Machacek Model:**
  - No fundamental reason for a minimal Higgs sector => extend scalar sector with higher isospin multiplets
  - Might generate Majorana mass for neutrinos via type-II seesaw mechanism

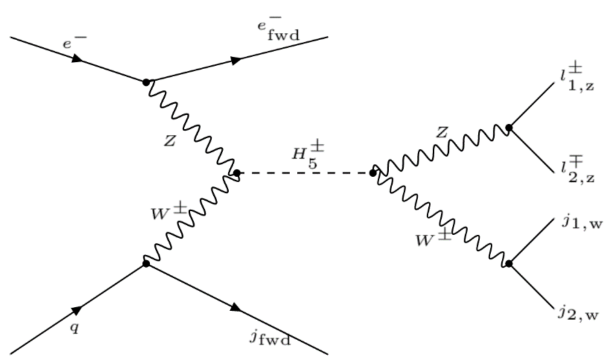
2 free pars. $M(H_5)$, $\sin\theta_H$

$$\text{5-plet } \; H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$$

$$BR(H_5^{\pm} \to W^{\pm}Z) \approx 100\ \%$$
$$BR(H_5^{\pm\pm} \to W^{\pm}W^{\pm}) \approx 100\ \%$$

$H\pm$

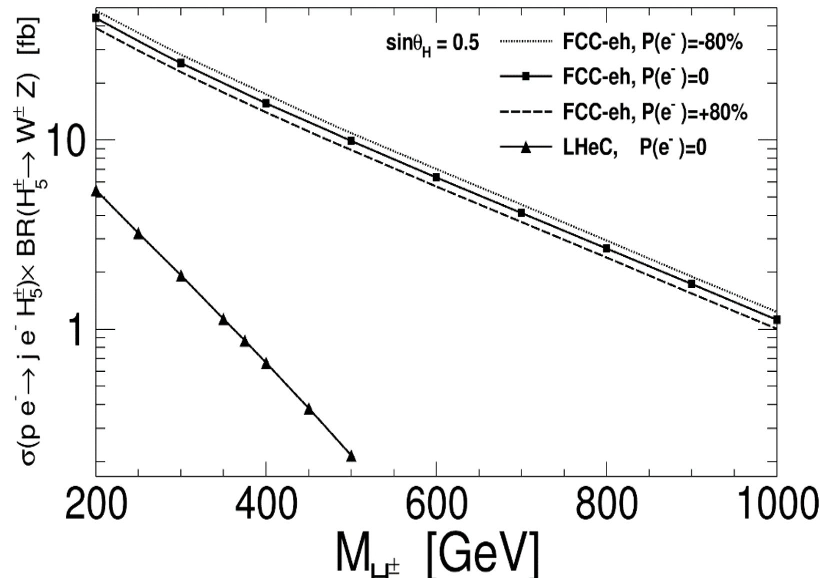
[Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505]



Final state: 1 e^- + 1 j + 1 Z(-> $l^+ l^-$) + 1 W(-> j j); l = e, μ

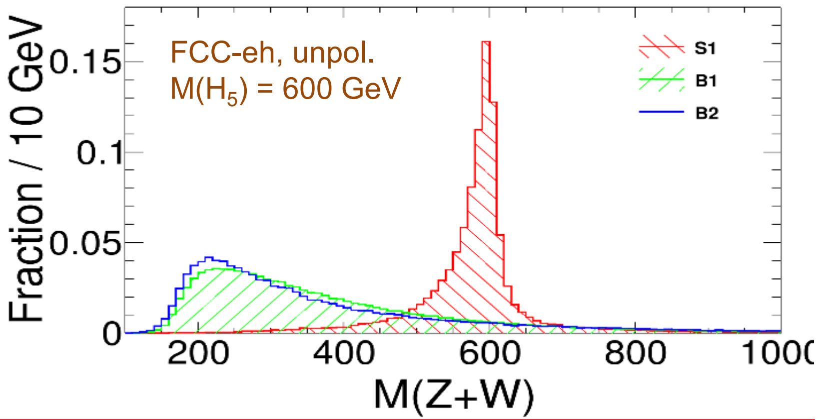
Signal production cross section

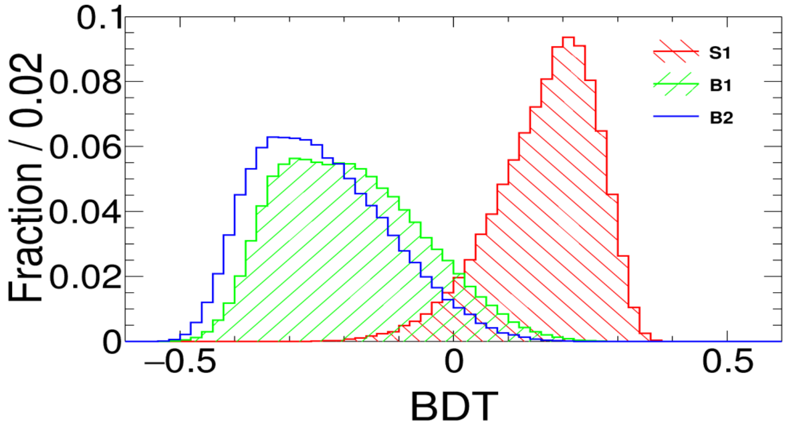
p e^- → j e^- $H_5^{\pm}$, ($H_5^{\pm}$ → Z $W^{\pm}$)



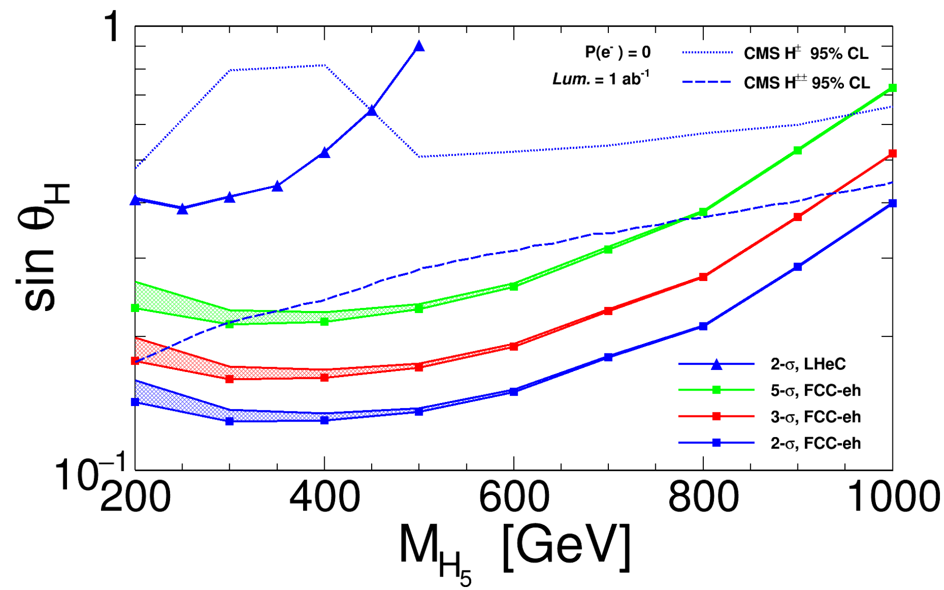
$H\pm$ in Vector Boson Scattering

- MVA BDT analysis @ detector-level





Limits for $H\pm$ assuming 10% systematic uncertainty on the background



$\sin\theta_H$ < 0.15 @ 2-σ, for 600 GeV

Around 500-600 GeV, strong constraints in comparison to the existing (CMS) ones

H+ in 2HDM type III models

[J. Hernández-Sánchez, etc. 1612.06316]

- CC production, various scenarios considered

$$p\, e^- \to \nu j H^+ \to \nu j\, (c\bar{b})$$

Parameters for a few optimistic benchmark points in the 2HDM-III as a 2HDM-I, -II and -Y configuration.

2HDM	X	Y	Z	$m_H^\pm = 110$ GeV cb	$\sigma.cb$
Ia	5	5	5	0.99	97.36
Ib	5	5	5	0.99	99.80
IIa	32	0.5	32	0.99	92.00
Ya	32	0.5	0.5	0.99	75.12

@ LHeC with 100/fb only

(Here, $\varepsilon_b = 0.50, \varepsilon_c = 0.1$ and $\varepsilon_j = 0.01$, where $j = u,d,s,g$)

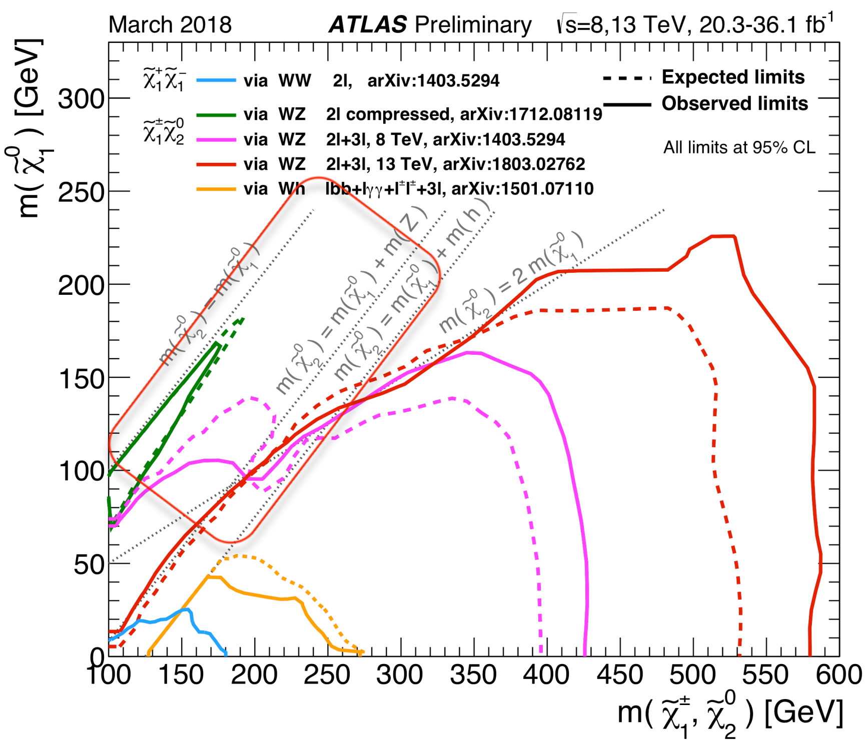
	S	B	$\mathscr{S} = S/B^{1/2}$
Ia ($X = 5, Y = 5$)	243.4	3835.1	3.9
Ib ($X = 5, Y = 5$)	249.5	3835.1	4.0
II ($X = 32, Y = 0.5$)	230	3835.1	3.7
Y ($X = 32, Y = 0.5$)	187.8	3835.1	3.0

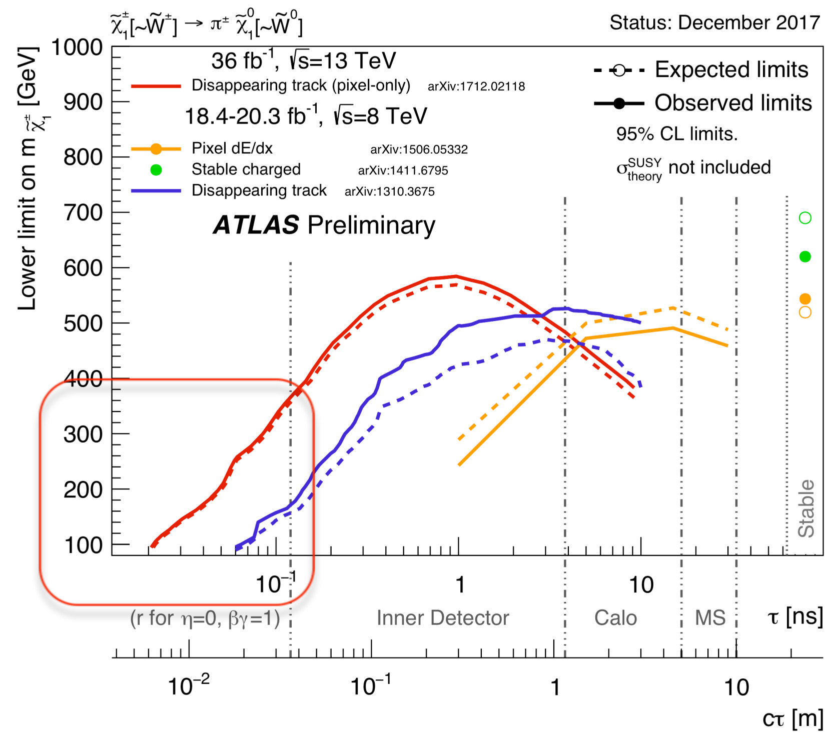
Masses O(100 GeV) are very challenging at p-p due to large bkg from multi-jet bkg

Good discovery potential at FCC-eh [work in progress]

EWK SUSY sector: higgsinos and more

- SUSY EWK sector remains the most challenging for pp colliders in favored regions of the parameter space
  - Higgsino scenarios (~ mass degenerate, low cross sections)
  - Wino/bino compressed (sleptons heavier than charg/neut)
  - Promptly decaying or long-lived (exp. short lifetimes)

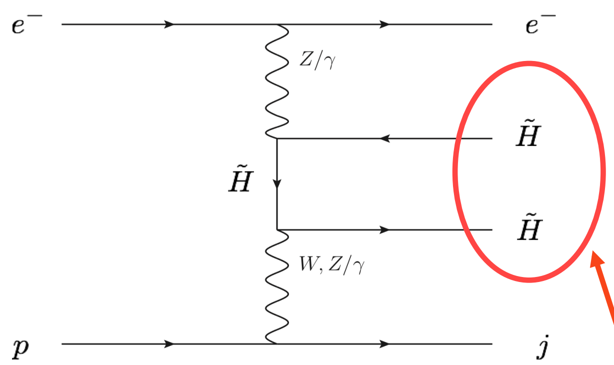


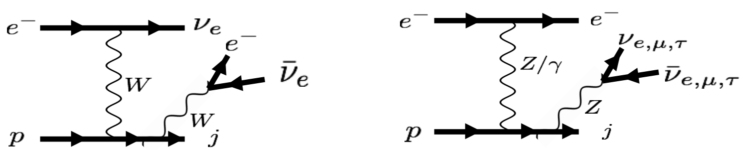


(prompt) Higgsino

C

- C. Han, R. Li, R. Pan, K. Wang arXiv:1802.03679
- Clearly a difficult scenario to probe at the LHC (JHEP 1402 (2014) 049)



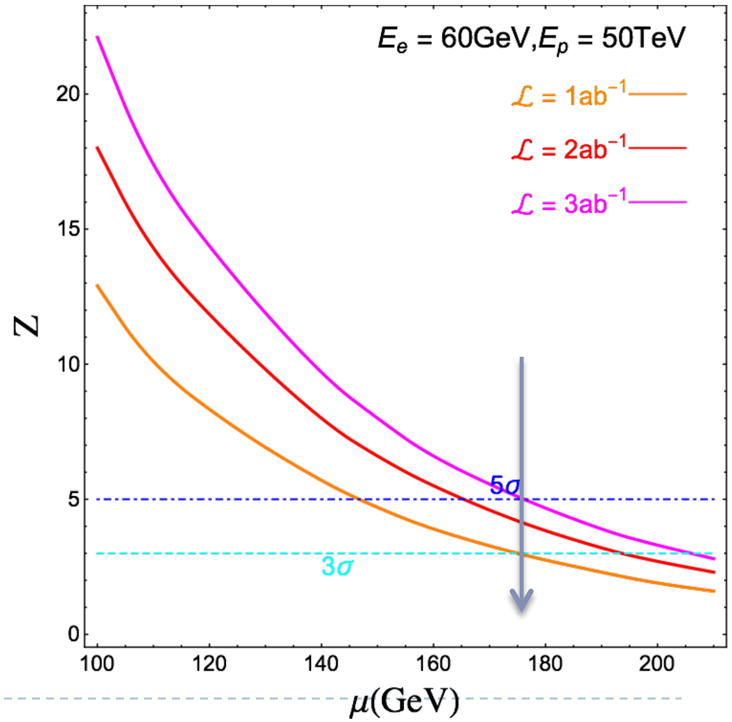


Standard model main backgrounds

Typical signal: electron + jet + missing energy

$$E_T^{miss} > 70 \text{ GeV}$$
$$5 \text{ GeV} < p_T^e < 25 \text{ GeV}, \ 1.0 < \eta^e < 5.0$$
$$p_T^j > 20 \text{ GeV}, \ -5.0 < \eta^j < -3.0$$
$$m_{ej} > 400 \text{ GeV}$$
$$y = \frac{k_p \cdot (k_e^{in} - k_e^{out})}{k_e^{in} \cdot k_p} > 0.2$$

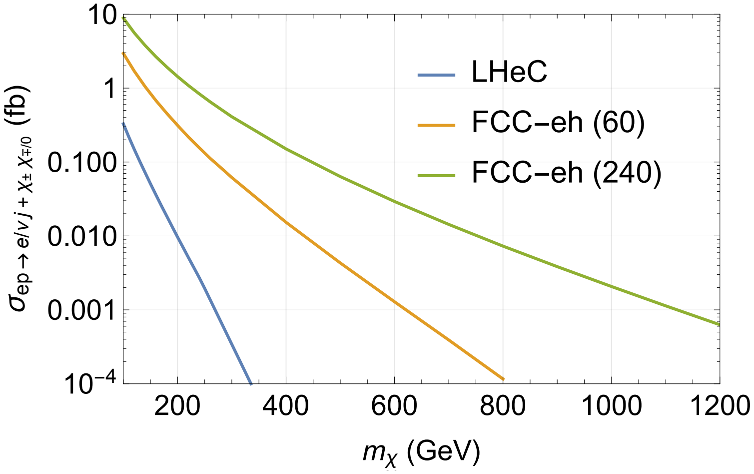
preliminary result

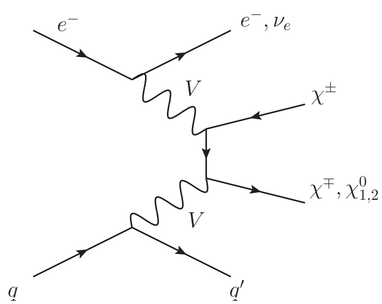


(long-lived) Higgsino

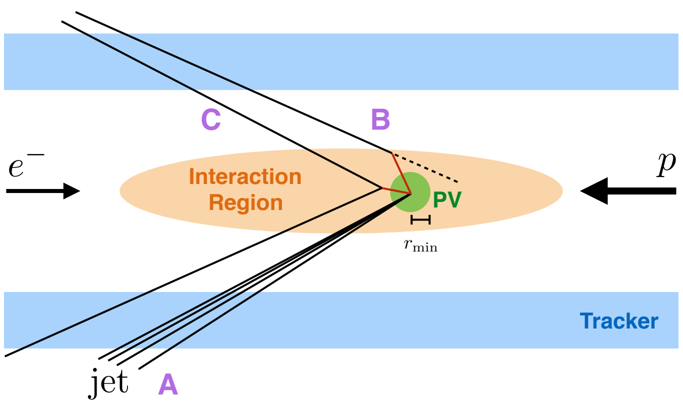
Curtin, Deshpande, Fischer, Zurita, arXiv:**1712.07135** (2017)

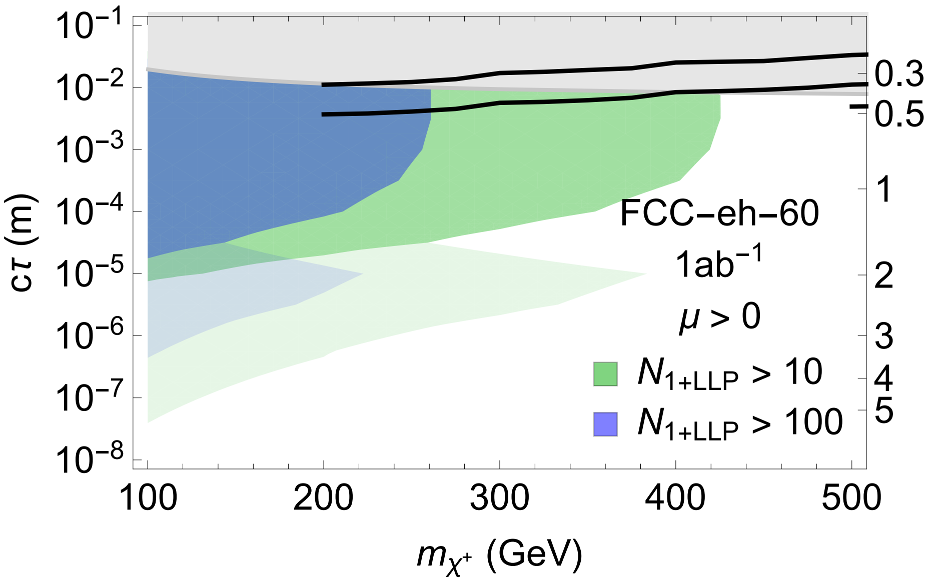
- Production at e-p via vector boson fusion





softly decaying, short-lived (~ μm) long-lived particles



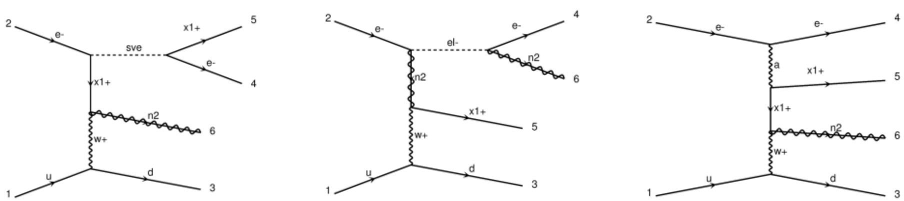


Signal: **single soft displaced pion**
Beam remnant jet ⇒ primary vertex with O(10) μm precision

~ 450 GeV higgsino (thermal relic DM) can be discovered with 1/ab

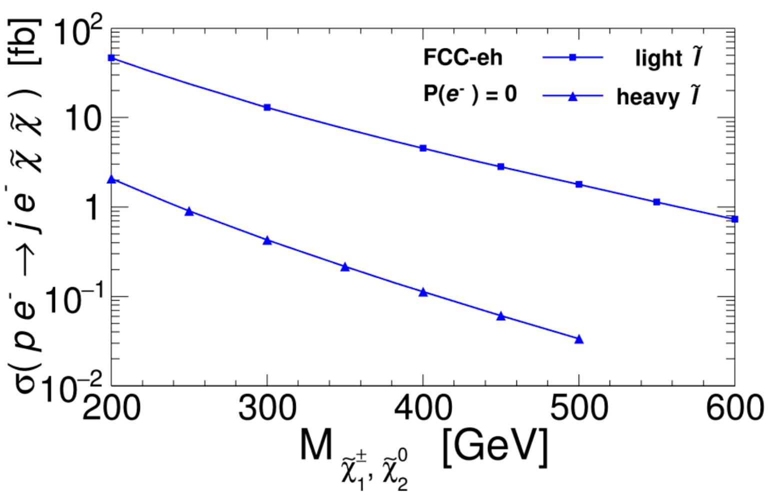
“light” sleptons (m > charg, neut)

- Sleptons might be a bit heavier than EWKinos
  - Motivated by g-2 anomalies
  - Would play no role in the decay of charginos and next-to-lightest neutralino – phenomenology unchanged at pp
  - At e-p, cross section is enhanced

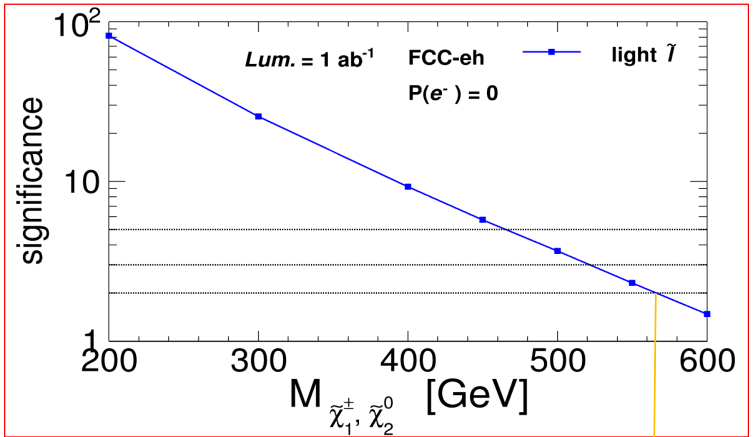


MVA-BDT analysis @ detector-level

Production cross sections



Limits on DM mass



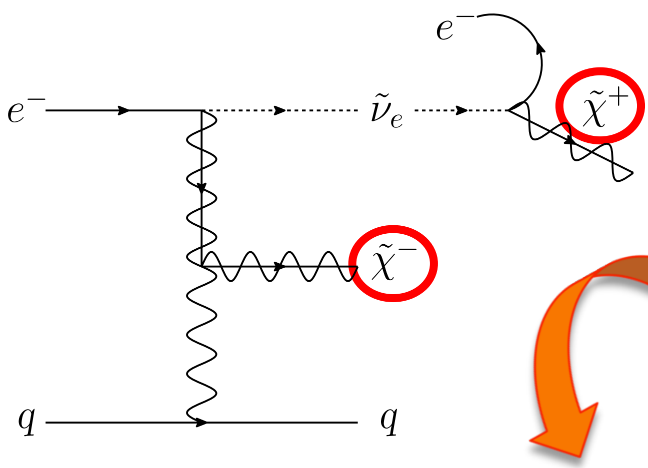
1 ab^{-1} @ FCC-eh:
> 560 GeV @ 2-σ

Preliminary results from [Kechen Wang, Sho Iwamoto, Monica D’Onofrio, Georges Azuelos]

“light” sleptons (m > charg, neut), long-lived

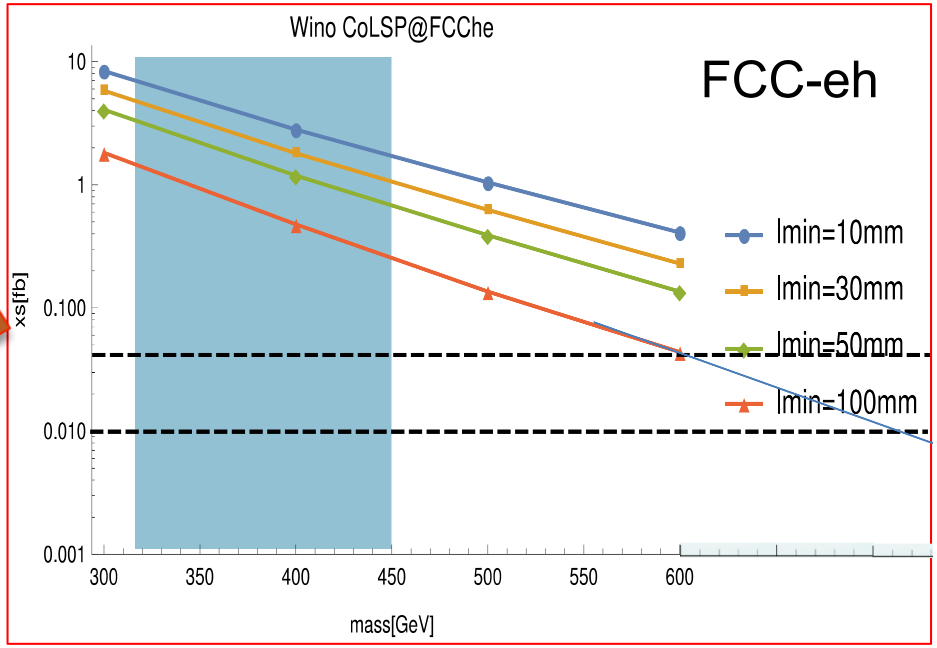
- If charginos are long-lived

→ Cross section enhanced with “3-body production”



Simple efficiency analysis

- Requiring minimal detection length l_{min}
- Charginos (Wino) with selectron



1 ab-1 @ FCC-eh:
$c\tau$ > 100 mm
~ 40 events for 600 GeV
~ 10 events for 750 GeV
excellent discovery potential

With no polarization;
$m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV

Preliminary results from [Kechen Wang, Sho Iwamoto, Monica D’Onofrio, Georges Azuelos]

R-parity violating SUSY

Most studied at e-p colliders

L-number violating terms

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

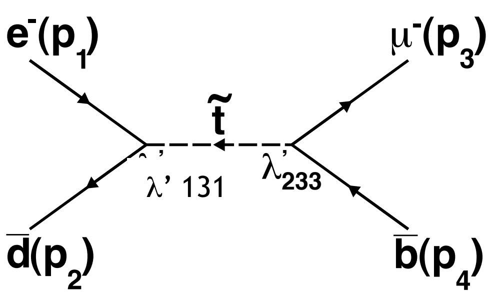
bilinear terms

B-number violating terms

Various strong constrains from LHC on λ and λ'' ***(from multilepton and multijet searches)*****. At e-p colliders, studies made on stop and sbottom:**

stop

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



Couplings with third gen quarks

In e-p production rate depending on:

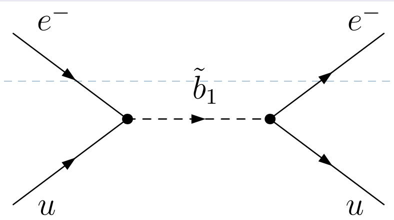
e-d-t: λ'_{131} (constraint: < 0.03)

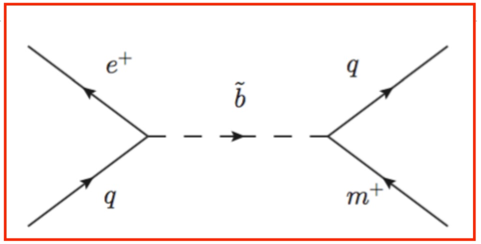
Probe RPV LQD terms:

In this case $\lambda'_{131} \times \lambda'_{233}$

FCC-eh potential being re-evaluated:
(Ren-You Zhang, Liang Han et al)

single RPV sbottom production

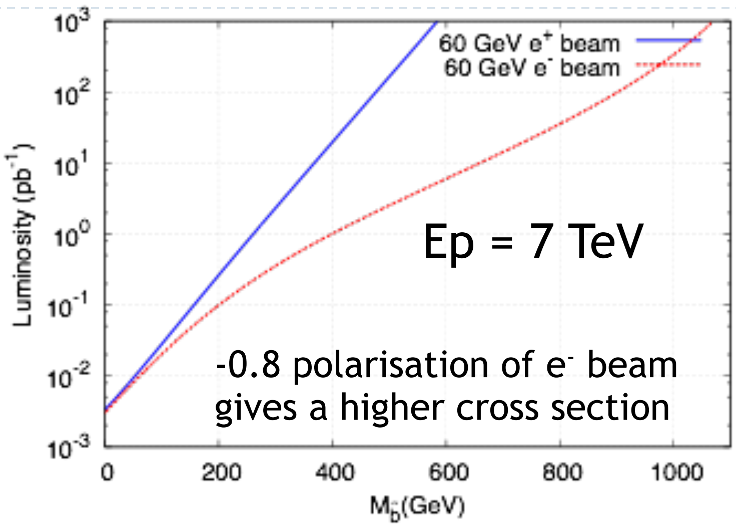


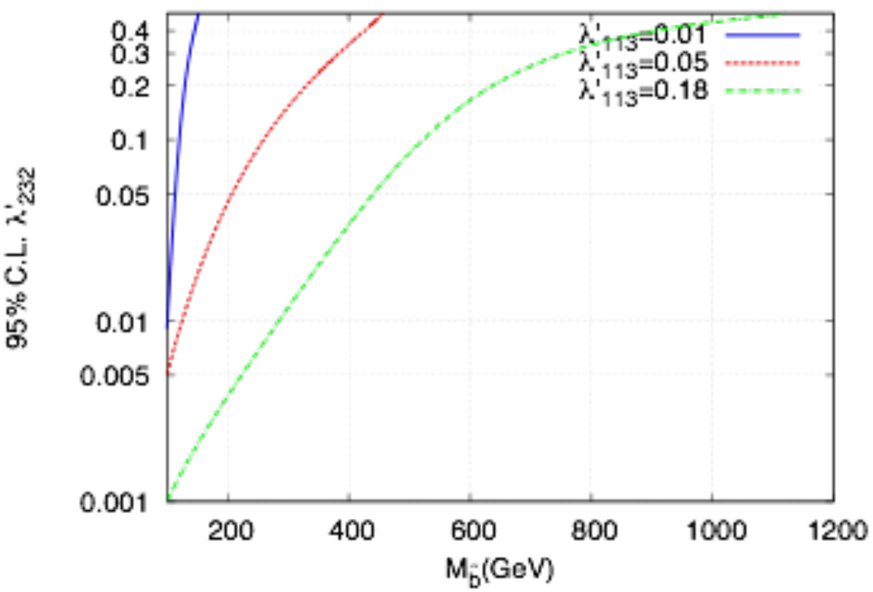


Recent coupling limits

$$\lambda'_{113} = \lambda'_{123} \leq 0.18\,, \qquad \lambda'_{231} = \lambda'_{232} \leq 0.45$$

Preliminary results (Sinan Kuday, in prep.)





- **LHeC can extend the limits of LQD couplings up to *10^{-3}* for just *1 fb^{-1}* integrated luminosity at the %95 C.L. with 60 GeV e^- beam option.**

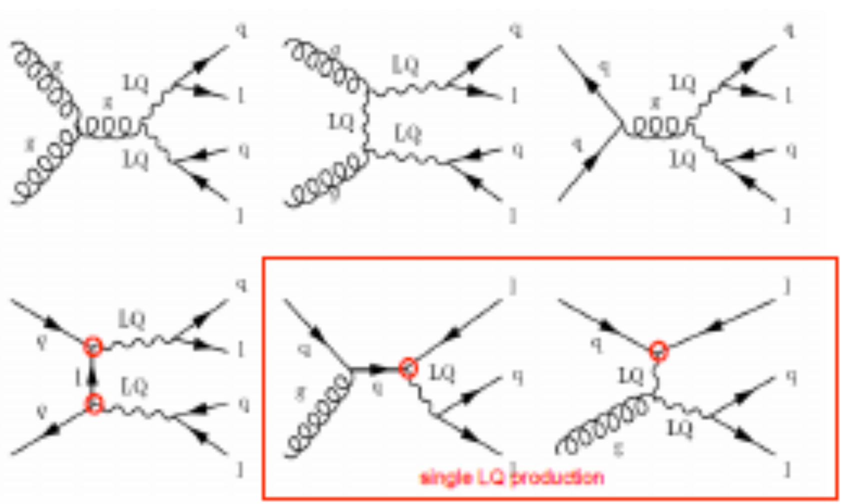
@FCC-eh: expect to have
Sensitivity up to 2.5 TeV for $\lambda'_{113}<0.02$
[work in progress for FCC CDR]

Lepto-quark production

→ lately, LQs raised a lot of attention as possible motivation for LHCb anomalies (mostly involving 3rd generation LQ)

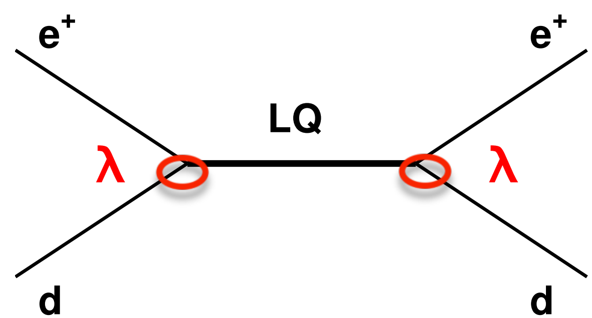
→ Phenomenology pretty equivalent to SUSY RPV

- **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:** ideally suited to search for and study properties of new particles coupling to both leptons and quarks



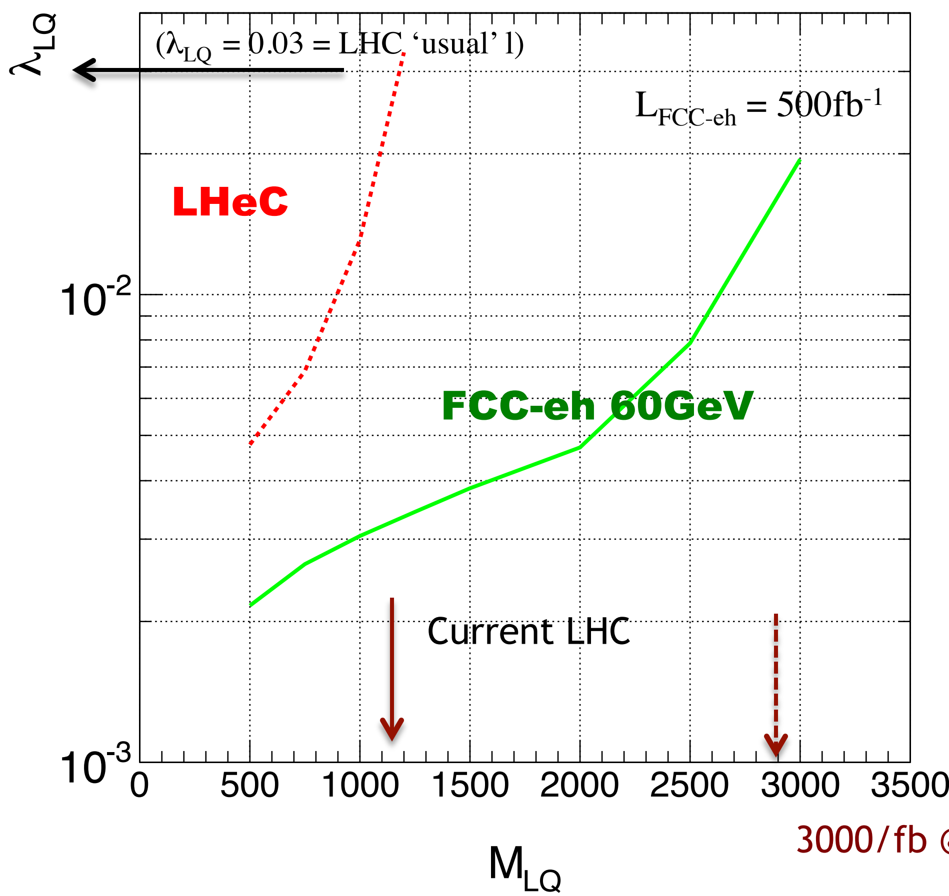
- single, resonant production; sensitive to λ

LQ reach at FCC -eh

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

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

(CMS also excluded single production 1^{st} gen LQ < 860 GeV)



e-p scenario:

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

Sensitivity of HL-LHC could go to ~2.8 – 2.9 TeV

→ Close to the reach for FCC-eh

→ Dependence on λ

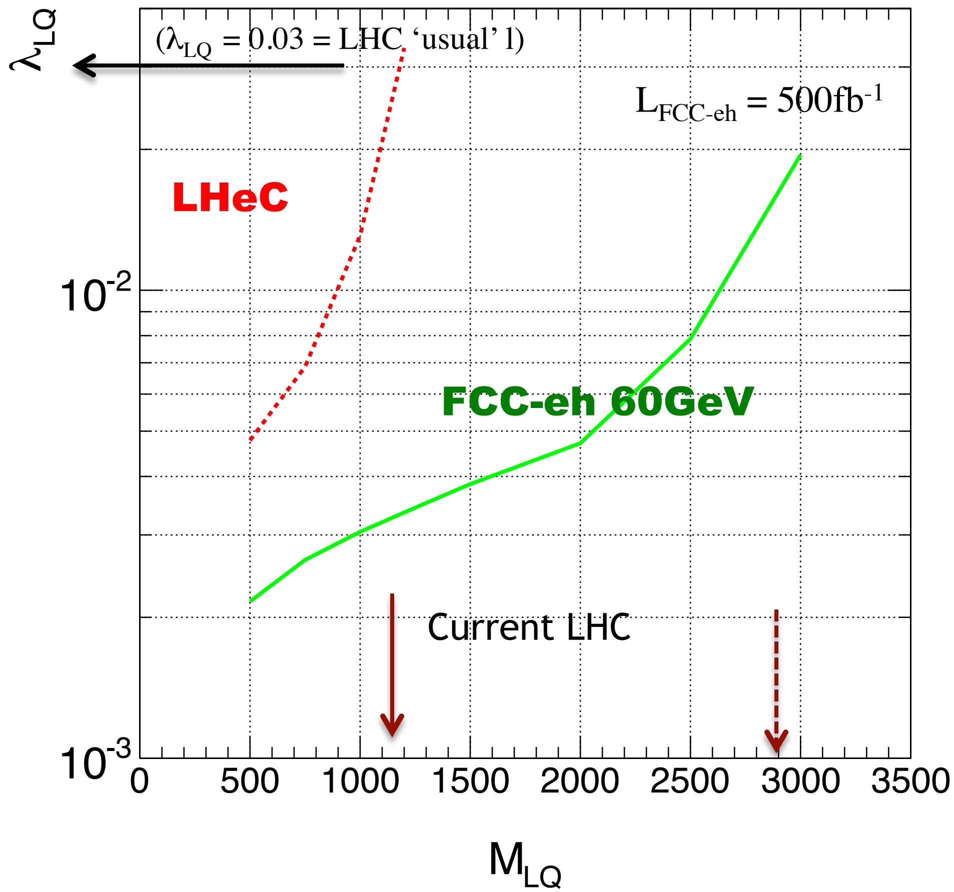
If deviations are found by the end of HL-LHC, FCC-hh will definitely see them, and FCC-eh can characterize those signals!

LQ 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	$\beta = 0$

(CMS also excluded single production 1st gen LQ < 860 GeV)

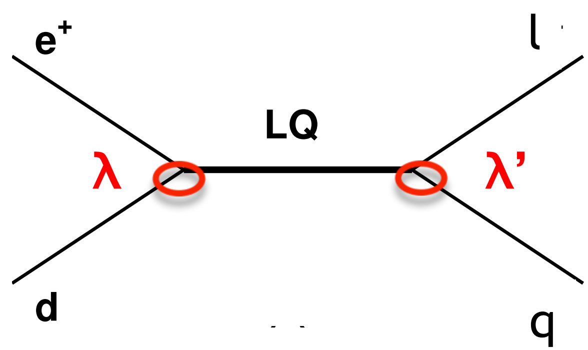


e-p scenario:

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

Results being revisited, see for example Mod.Phys.Lett. A33 (2018) no.06, 1850039

More ideas being explored about mixed generation LQ. E.g.:

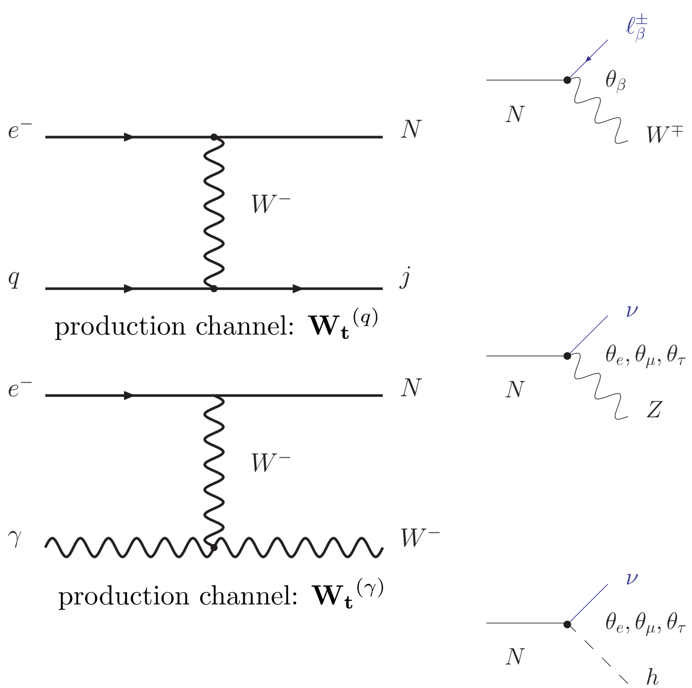


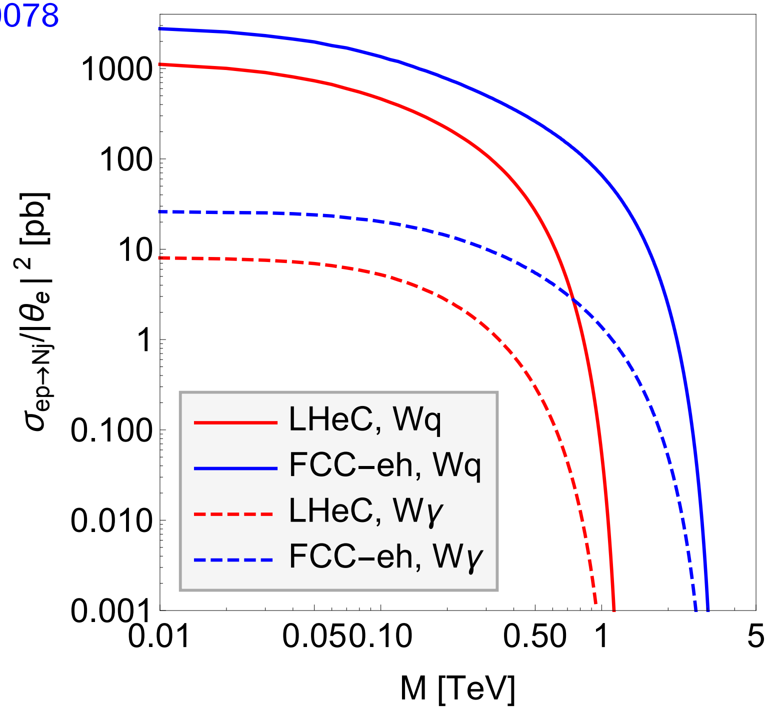
e.g. reach equivalent to RPV SUSY

Sterile neutrinos

- Neutrino oscillations are evidence for non-zero m_ν
- Low scale type I seesaw with sterile neutrinos
  → heavy neutrino mass eigenstates with $M \sim v_{EW}$
- Neutrino mixing $|\theta_\alpha|, \alpha = e,\mu,\tau \Rightarrow$ Weak current production. Antusch, Fischer; JHEP **1410** (2014) 094
- Present constraints: $|\theta_e| \leq 10^{-3} \Rightarrow$ sizable cross sections at ep.

Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078





σ divided by the square of the active-sterile mixing parameter $|\theta_e|^2$

Sterile neutrinos (II)

Leading order signatures

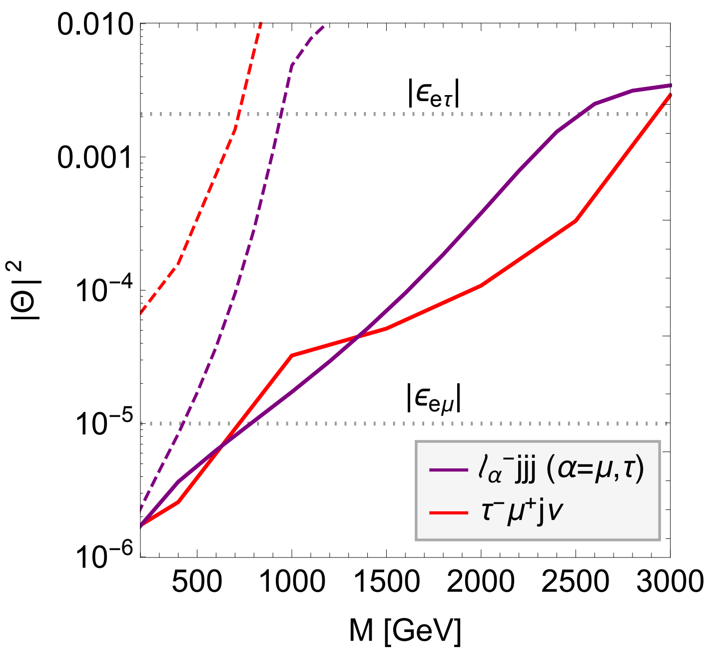
Name	Final State	Channel [production,decay]	$\|\theta_\alpha\|$ dependency	LNV/LFV
lepton-trijet	$jjj\ell_\alpha$	$[\mathbf{W_t}^{(q)}, W]$	$\frac{\|\theta_e\theta_\alpha\|^2}{\theta^2}$	✓/✓
jet-dilepton	$j\ell_\alpha^\pm\ell_\beta^\mp\nu$	$[\mathbf{W_t}^{(q)}, \{W, Z(h)\}]$	$\left\{\frac{\|\theta_e\theta_\alpha\|^{2\,(*)}}{\theta^2}, \|\theta_e\|^{2(*)}\right\}$	×/✓
trijet	$jjj\nu$	$[\mathbf{W_t}^{(q)}, Z(h)]$	$\|\theta_e\|^2$	×
monojet	$j\nu\nu\nu$	$[\mathbf{W_t}^{(q)}, Z]$	$\|\theta_e\|^2$	×

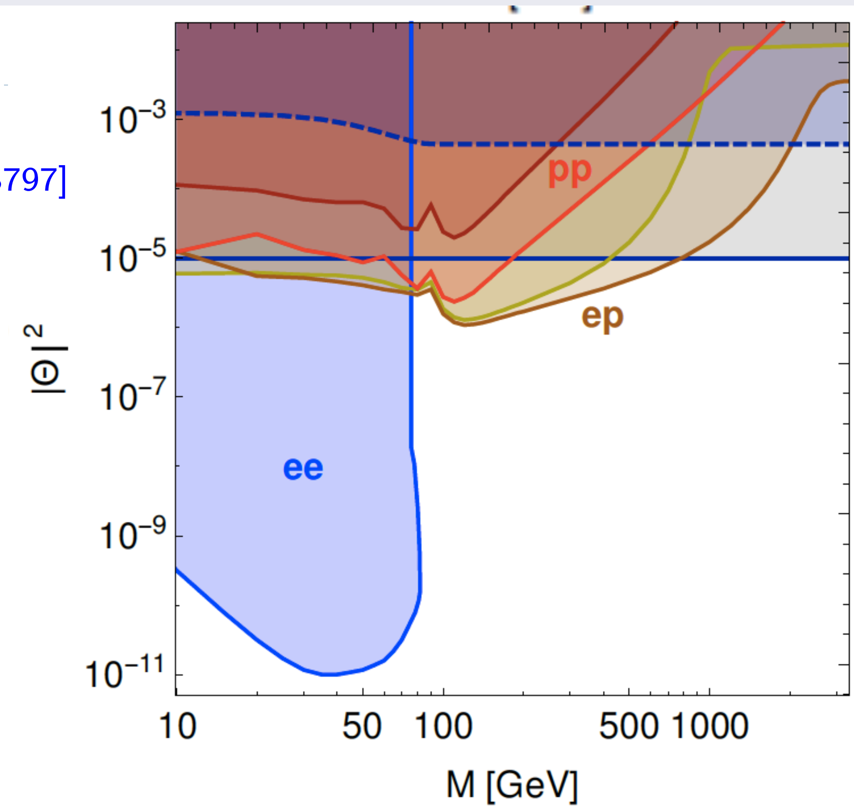
lepton-quadrijet	$jjjj\ell_\alpha$	$[\mathbf{W_t}^{(\gamma)}, W]$	$\frac{\|\theta_e\theta_\alpha\|^2}{\theta^2}$	✓/✓
dilepton-dijet	$\ell_\alpha\ell_\beta\nu jj$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\|\theta_e\theta_\alpha\|^{2\,(*)}}{\theta^2}, \|\theta_e\|^{2(*)}\right\}$	×/✓
trilepton	$\ell_\alpha^-\ell_\beta^-\ell_\gamma^+\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, \{W, Z(h)\}]$	$\left\{\frac{\|\theta_e\theta_\alpha\|^{2\,(*)}}{\theta^2}, \|\theta_e\|^{2(*)}\right\}$	×/✓
quadrijet	$jjjj\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\|\theta_e\|^2$	×
lepton-dijet	$\ell_\alpha^- jj\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z(h)]$	$\|\theta_e\|^2$	×
dijet	$jj\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\|\theta_e\|^2$	×
monolepton	$\ell_\alpha^-\nu\nu\nu\nu$	$[\mathbf{W_t}^{(\gamma)}, Z]$	$\|\theta_e\|^2$	×

- LNV/LFV indicates that an unambiguous signal (with no neutrinos in the final states) for LNV and/or LFV is possible
- Signatures can be prompt or long-lived (displaced vertex)

Sterile neutrinos (III)

- **Displaced vertices:**
  - Heavy neutrino-antineutrino oscillations
  - Oscillation from Δm^2_ν Antusch *et al.*; [1709.03797]
- **Lepton flavor violation:**
  - Unambiguous: μ+jets, τ+jets, $\mu\tau$ + jets
  - highest sensitivity to $|\theta_\varepsilon\theta_\alpha|^2$, $\alpha = \mu, \tau$





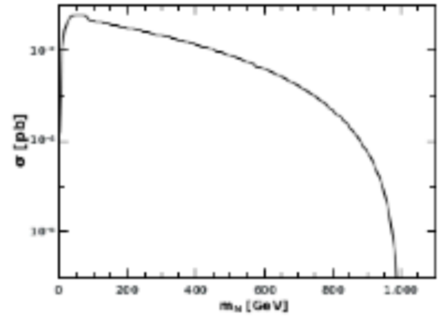
complementarities ee-pp-ep

Antusch *et al.*; Int. J. Mod. Phys. A **32** (2017) no.14, 1750078

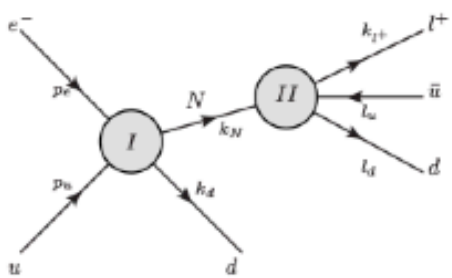
More: “Effective” majorana neutrinos

(Duarte, Zapata, Sampayo)

- *Model BSM Majorana neutrino N_R interactions with effective Lagrangian for $e^- p \to l^+ + 3jets$



*Goal: distinguish scalar and vectorial interactions.



Vectorial

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}\Big\{-\frac{m_W v}{\sqrt{2}}\alpha_W^{(i)} W^{\dagger\mu}\,\overline{N}_R\gamma_\mu e_{R,i} + \alpha_{V_0}^{(i,j)} \bar{d}_{R,i}\gamma^\mu u_{R,i}\overline{N}_R\gamma_\mu e_{R,j} + \alpha_{S_1}^{(i,j)}(\bar{u}_{L,i}u_{R,i}\overline{N}\nu_{L,j} + \bar{d}_{L,i}u_{R,i}\overline{N}e_{L,j}) + \alpha_{S_2}^{(i,j)}(\bar{\nu}_{L,i}N_R\bar{d}_{L,i}d_{R,j} - \bar{e}_{L,i}N_R\bar{u}_{L,i}d_{R,j}) + \alpha_{S_3}^{(i,j)}(\bar{u}_{L,i}N_R\bar{e}_{L,i}d_{R,j} - \bar{d}_{L,i}N_R\bar{\nu}_{L,i}d_{R,j}) + h.c.\Big\}$$

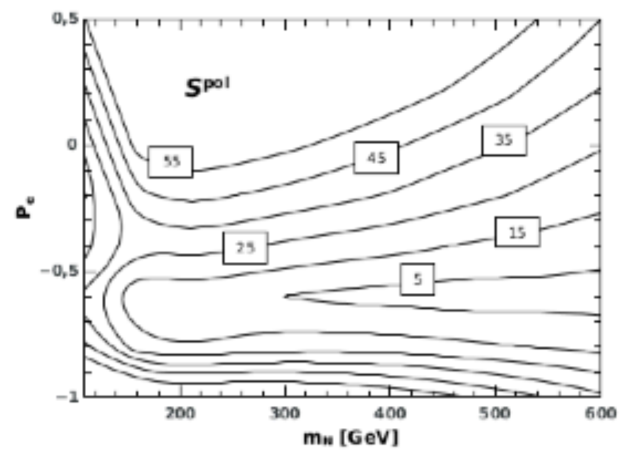
Scalar

FCC-eh POLARIZED BEAM:

* The number of events produced by scalar and vectorial interactions depends on initial electron polarization P_e.

S^{pol} contour plot: deviation between both contributions for L= 2 ab^{-1}

$$S^{pol} = \frac{N^{vec} - N^{sca}}{\sqrt{N^{vec}} + \sqrt{N^{sca}}}$$



* arXiv: 1802.07620, 1412.1433

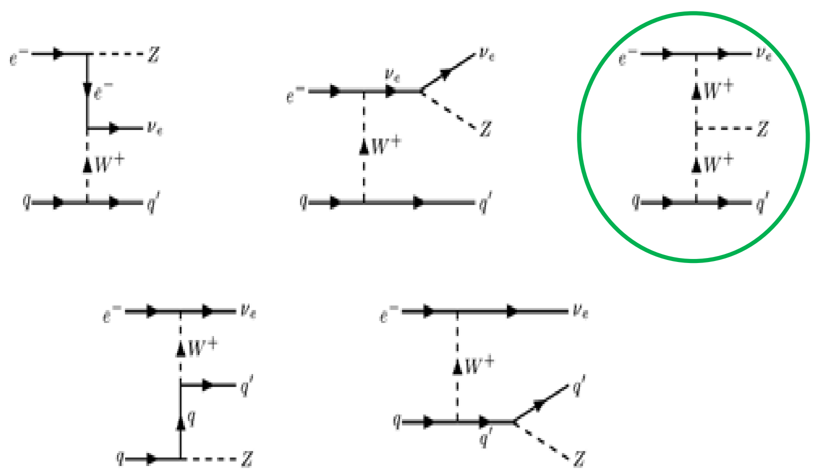
FCC-eh can give a hint on the kind of new physics behind Lepton Number Violation and N interactions!!

Anomalous gauge coupling

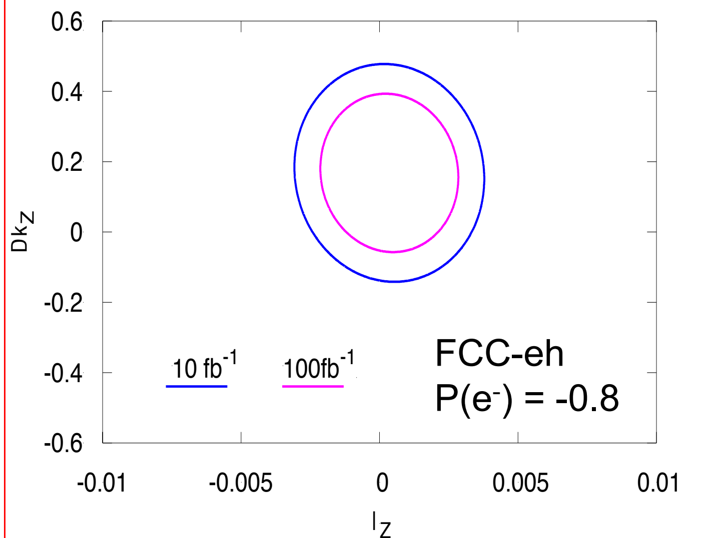
- Triple gauge boson vertices WWV, V=γ,Z
  - Precisely defined in SM
  - Parametrise possible new physics contributions to this vertex $(\Delta\kappa_\gamma, \lambda_\gamma)$
  - Current constraints (best from LEP) use various assumptions

[A. Senol, O. Cakir, I. Turk Cakir]

$ep \rightarrow \nu_e qZX$ for $Z \rightarrow ll$ ($l = e, \mu$)



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



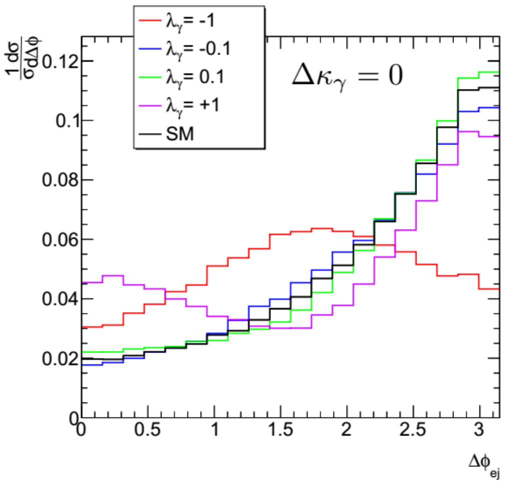
https://cds.cern.ch/record/2209389/?ln=en

Anomalous gauge coupling (II)

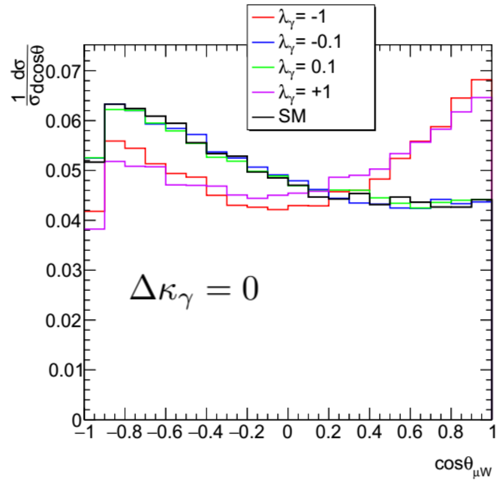
- Triple gauge boson vertices WWV, V=γ,Z

[R. Li, X. Shen, K. Wang, T. Xu, L. Zhang and G. Zhu, 1711.05607]

Process $p\, e^- \to j\, e^- \mu^+ \nu$

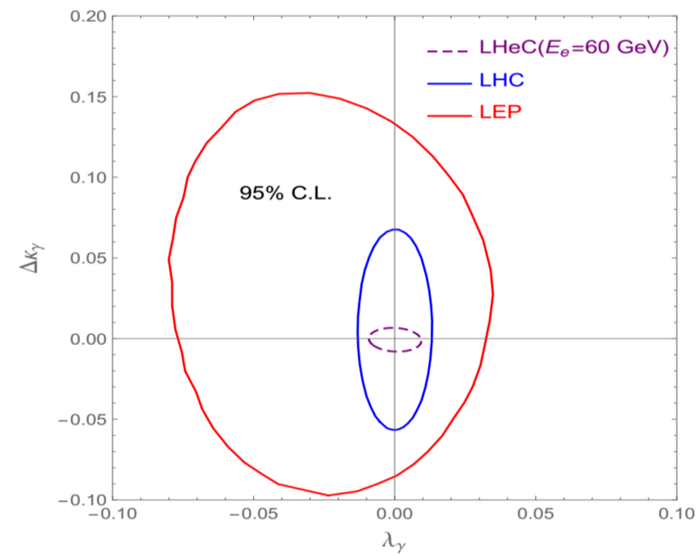


$\Delta\phi_{ej}$: azimuthal angle between scattered beam electron and jet



$\theta_{\mu W}$ angle between decay product μ+ in the W+ rest frame and the W+ direction in the collision rest frame

Limits via shape analysis by constructing χ^2 from all bins



Sensitivity ~ 10-3 @ LHeC with 2-3 ab^{-1} → Better @ FCC-eh! Work in progress

Summary and outlook

- FCC-eh offers a variety of opportunities for BSM searches in a lot of expected and maybe unexpected scenarios
  - LQ and RPV SUSY but also
  - EWK SUSY and DM
  - BSM Higgs
  - Sterile neutrinos
- Prompt and non-prompt signatures are being explored
  - Potential for LLP is huge thanks to the low expectation of bkg
- Ideal to study properties of new particles with couplings to electron-quark
- Ideal to improve precision of measurements and searches thanks to PDF improvements (see other talks this conference and in back-up)

Great opportunity for new ideas - all being documented in the CDR !

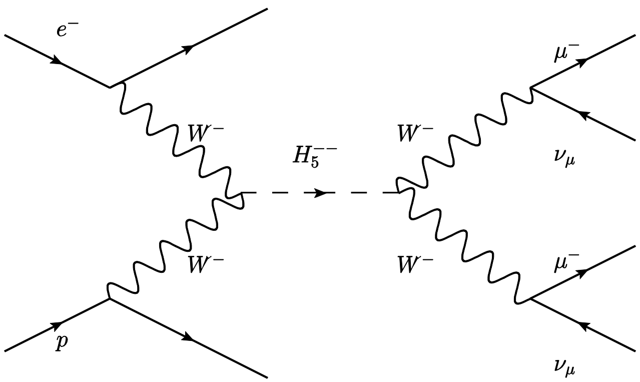
Back-up

$H^{\pm\pm}$ in Vector Boson Scattering

Signal via WW-fusion

[H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017)]

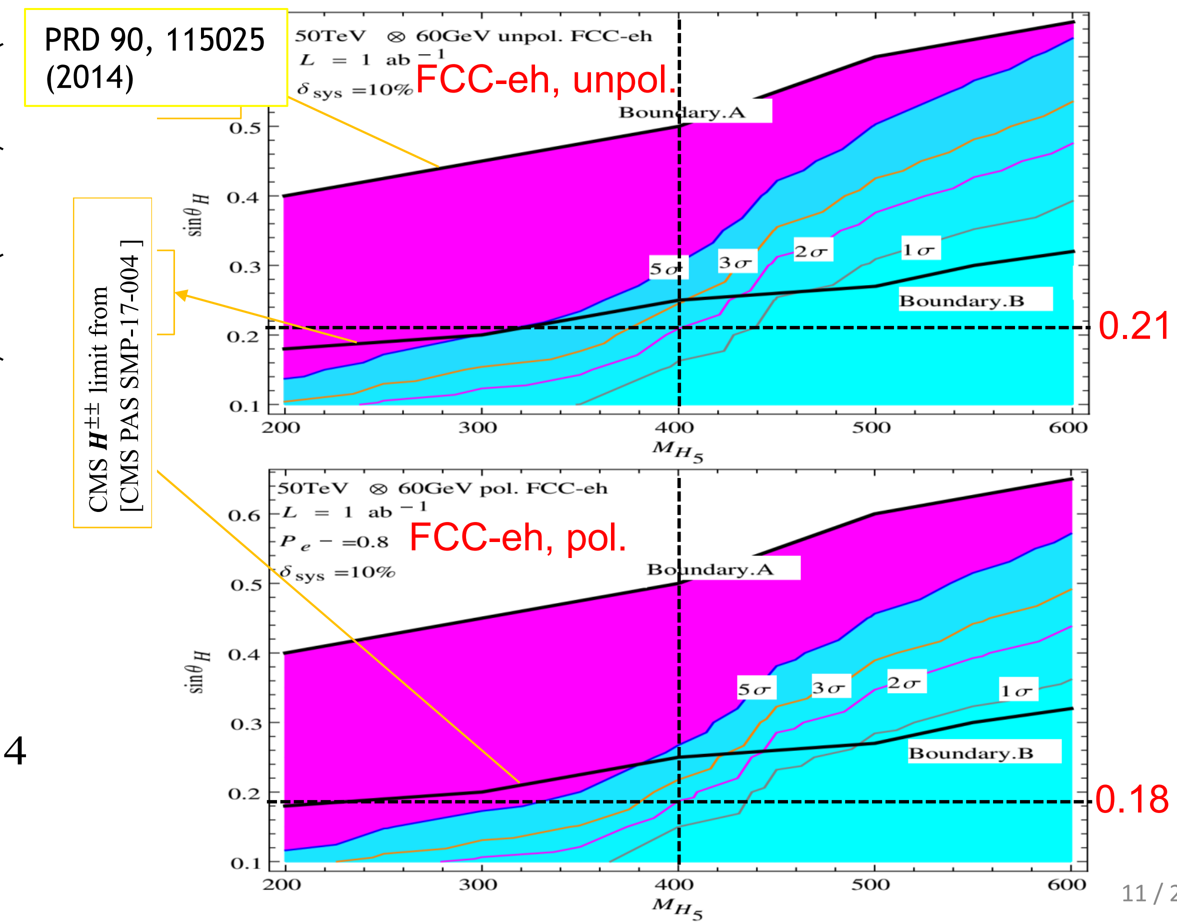
Final state: ≥ 1 j + 2 μ^- + MET



Cut-and-count analysis @ detector-level

$$\not{E}_T \geq 10\text{GeV}$$
$$p^{j,l}_T \geq 10\text{GeV}$$
$$|\eta^j| \leq 5,\ |\eta^l| \leq 2.5,$$
$$\Delta R_{jj} \geq 0.4,\ \Delta R_{jl} \geq 0.4,\ \Delta R_{ll} \geq 0.4$$

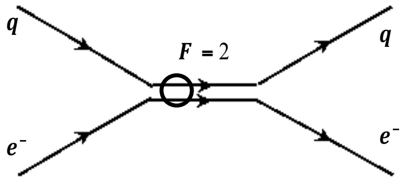
$$\Delta\Phi^{\mu\mu} \in (-\pi,-1.28) \text{ or } (1.36,\pi)$$
$$\Delta R^{\mu\mu} \quad M^{\mu\mu}_{inv} > 75\text{GeV}$$
$$M^{\mu\mu}_T > 40\text{GeV}$$

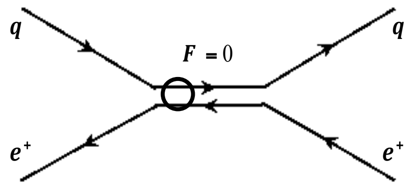


Measuring the LQ quantum numbers in e-p

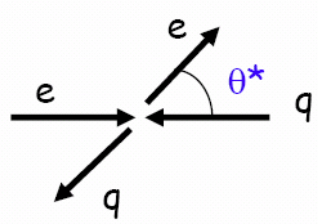
- Quantum numbers and couplings:
  - Fermion number:
    - can be obtained from asymmetry in single LQ production, since q have higher x than $\bar{q}$
    - At pp: very poor asymmetry precision achievable in single LQ production

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





  - 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

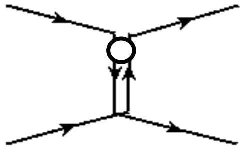
- if new physics enters at higher scales: Λ>> √s
- such indirect signatures can be seen as effective 4-fermion interaction

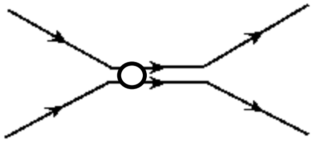
$$\mathcal{L} = \frac{4\pi}{2\Lambda^2} j_\mu^{(e)} j^{\mu(q)}; \quad j_\mu^{(f=e,q)} = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_R \bar{f}_R \gamma_\mu f_R + h.c.$$

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

- 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

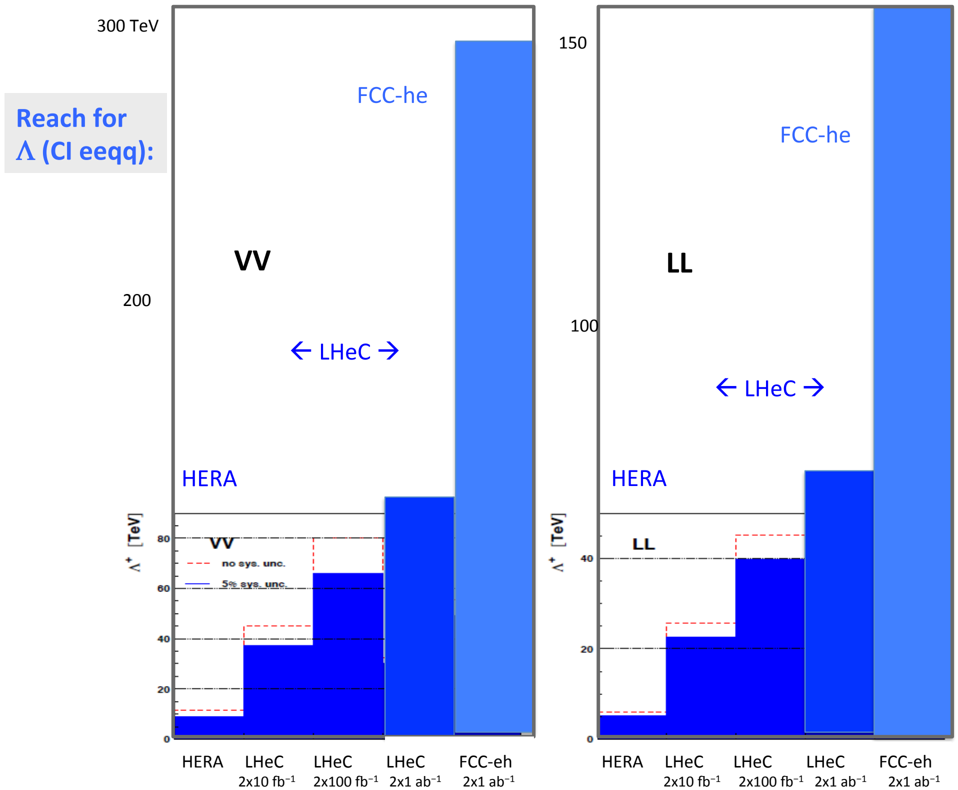
R → 3(1.5) x 10^{-20}m
pessimistic(optimistic) calculations

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



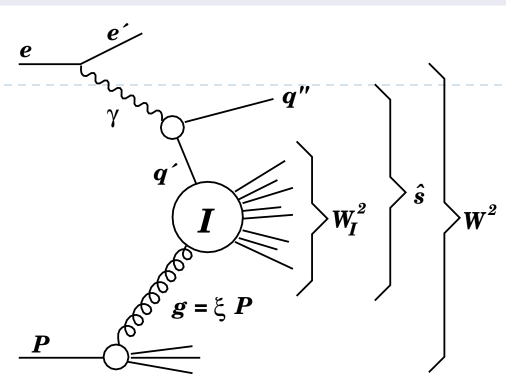
VV: all couplings with +ve sign

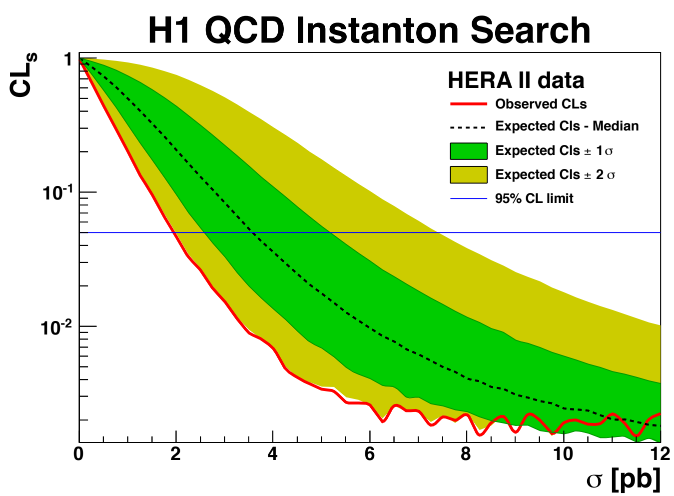
LL: only LL couplings between q and e

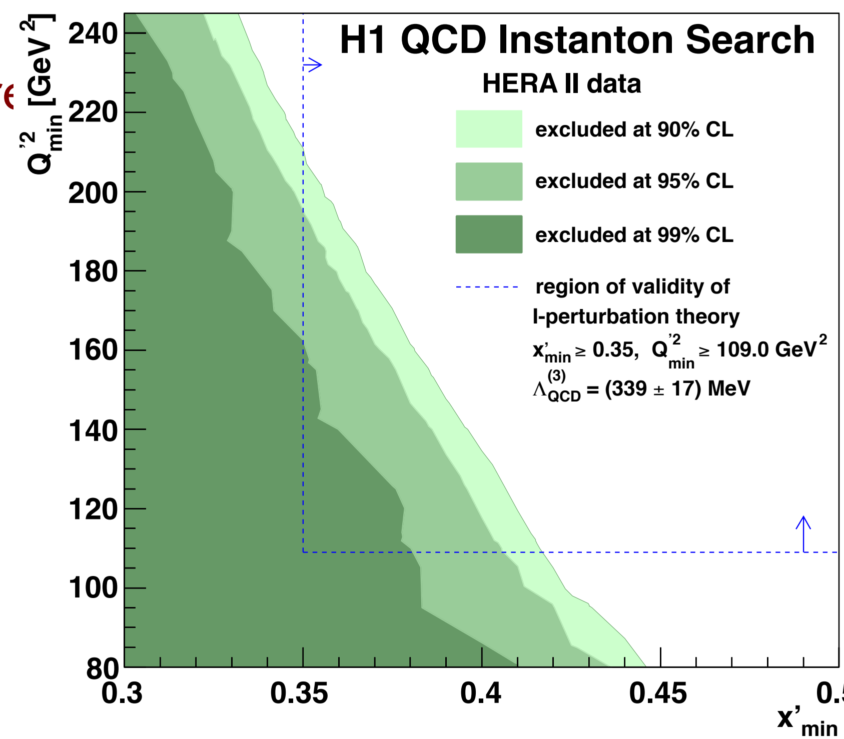
~ equivalent sensitivity at the FCC-hh at least for some of the couplings (same as HL-LHC vs LHeC) but need more calculations!

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







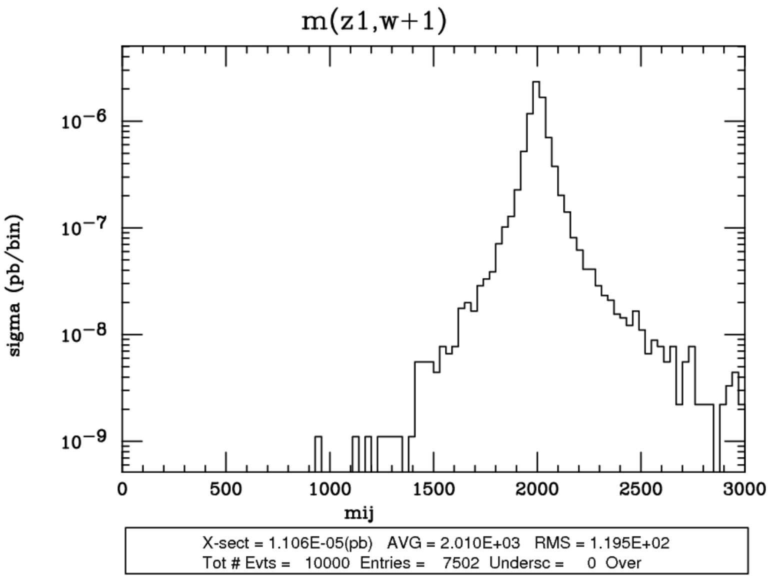
Eur.Phys.J. C76 (2016) no.7, 381

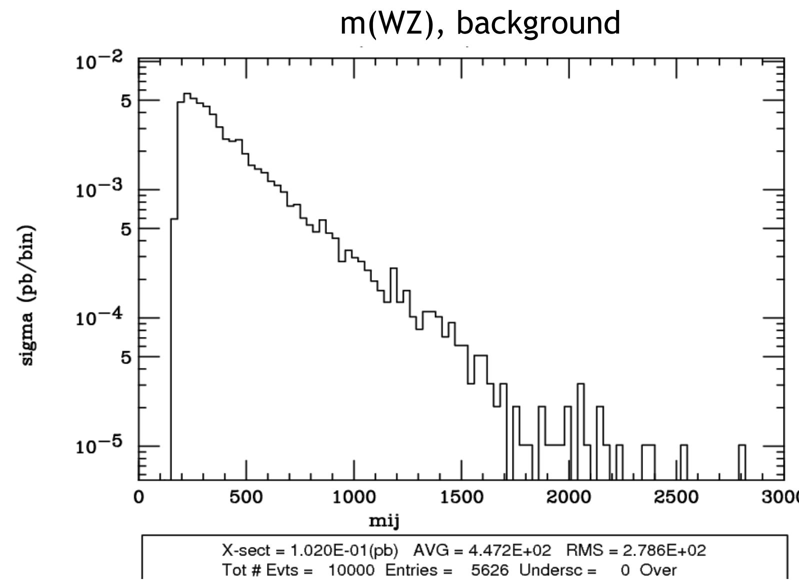
Vector Boson Scattering

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

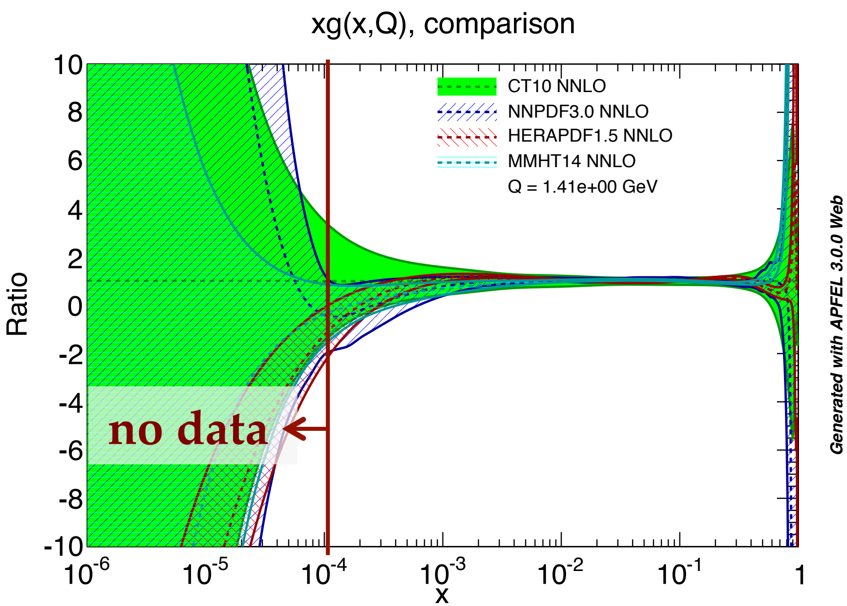
- highly dependent on acceptance and performance of detector
- FCC-eh (2 TeV resonance): S = 0.01 fb, B_{EW} = 100 fb

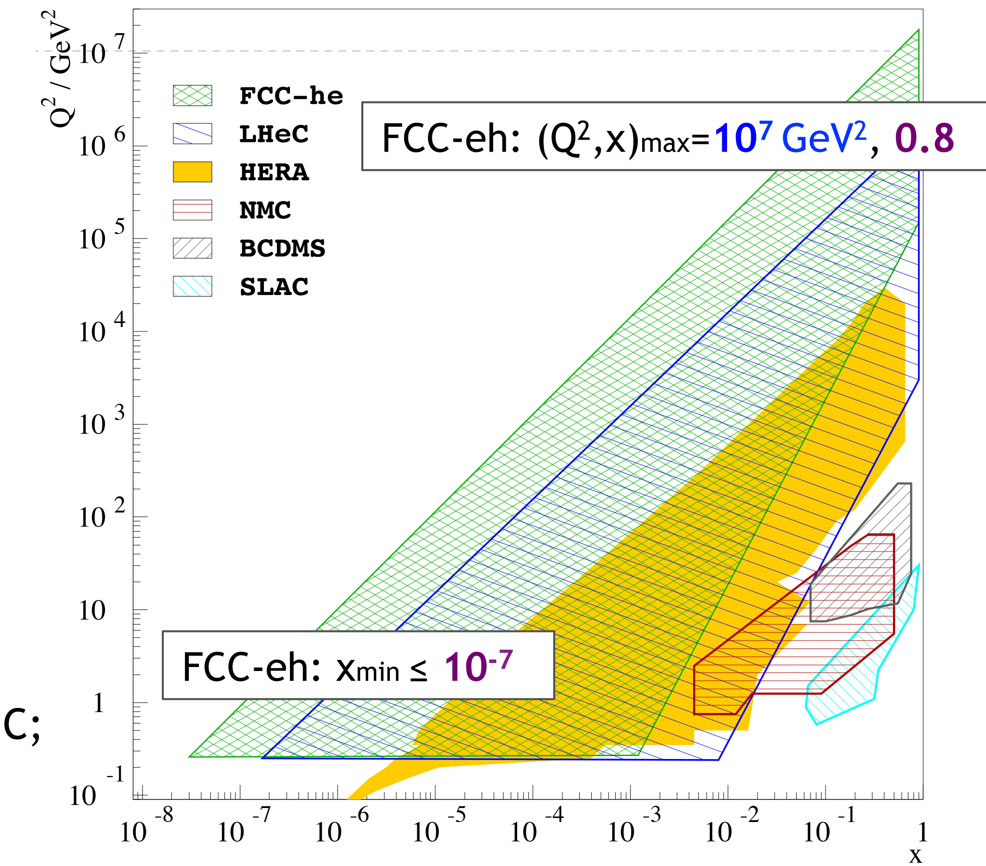
(for comparison, LHC14: S = 0.12 fb B_{QCD} = 4.2 pb B_{EW} = 300 fb)

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**

Improving PDFs with the LHeC





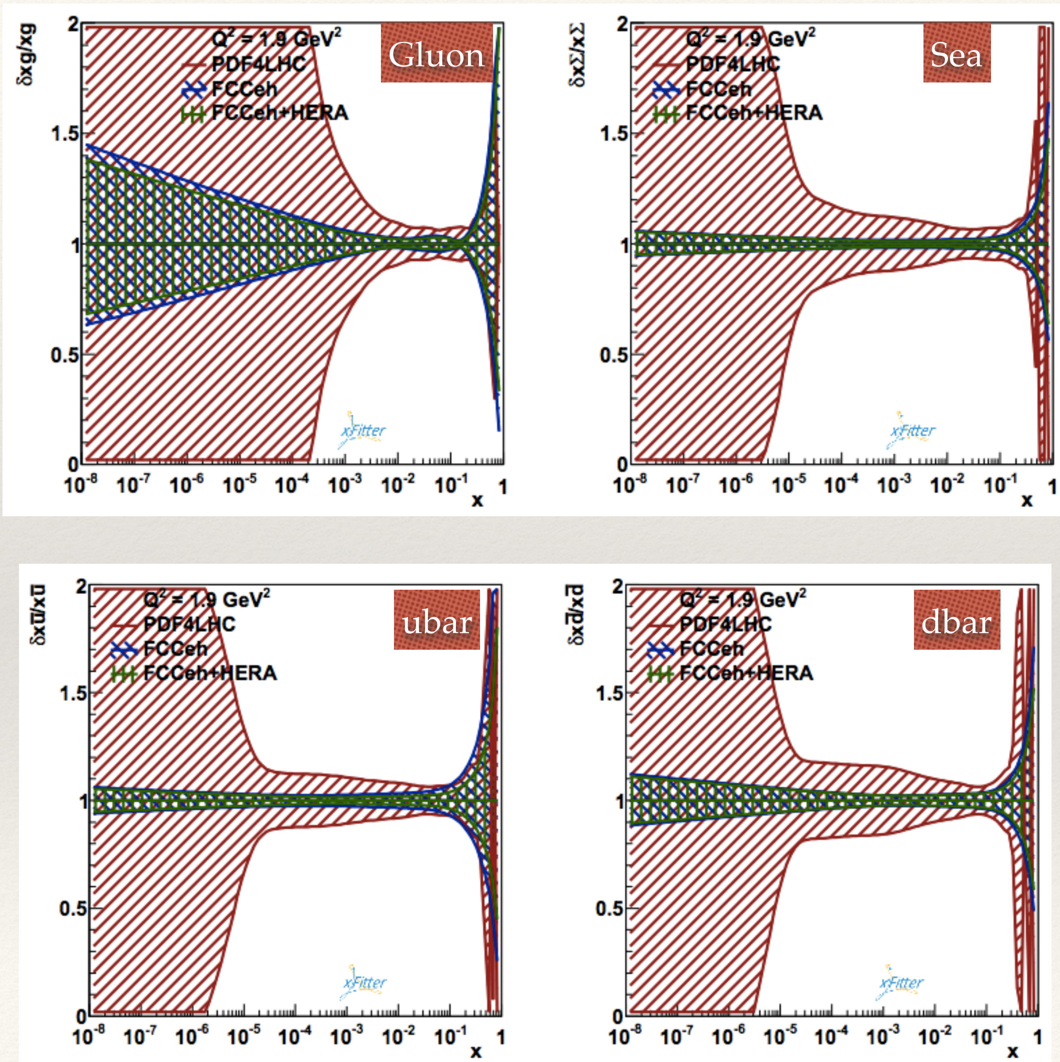
- **low-x:** no current data to constrain $x \leq 10^{-4}$; better but not much after HL-LHC; rely purely on extrapolation non-linear equations, gluon saturation?
- **mid-x:** need higher precision for Higgs
- **high-x:** very poorly constrained – limits searches for new, heavy particles

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

FCC week 2017| CERN

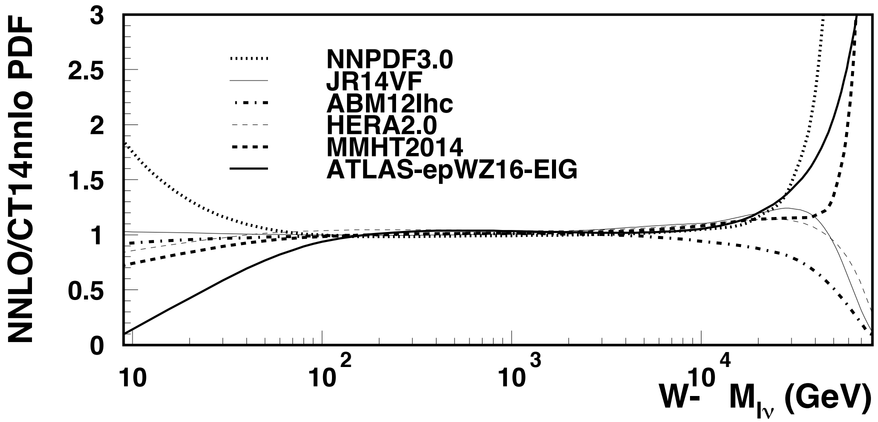
17

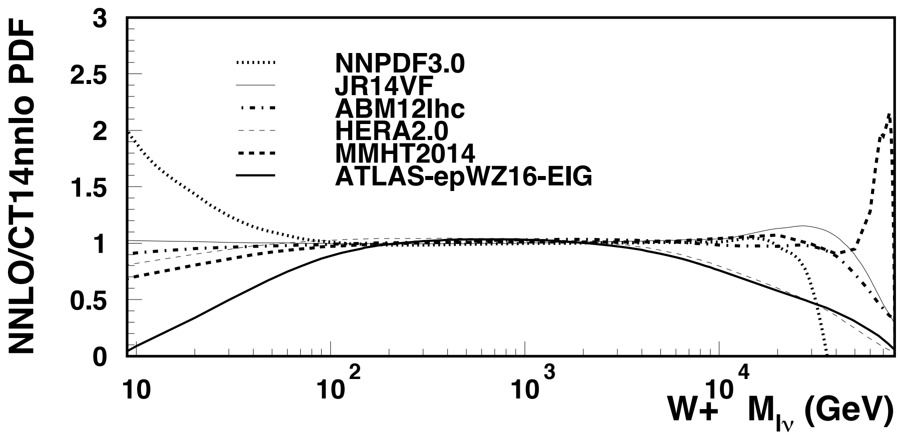
Impact of PDF: High mass Drell-Yan

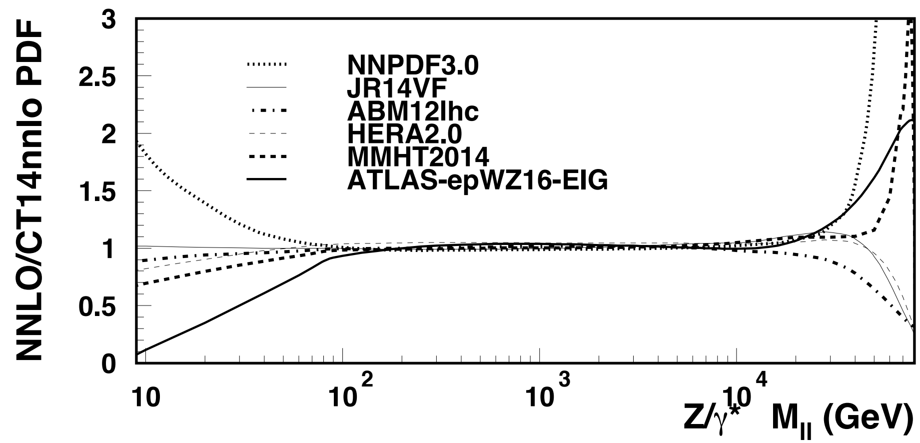
- Non resonant searches for ED (interference) sensitive to tails of DY distributions thus to PDF. Predominantly q-qbar

Uta Klein

VRAP 0.9 for NNLO QCD







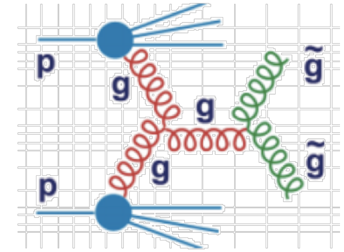
"Troubles" at low and high x

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

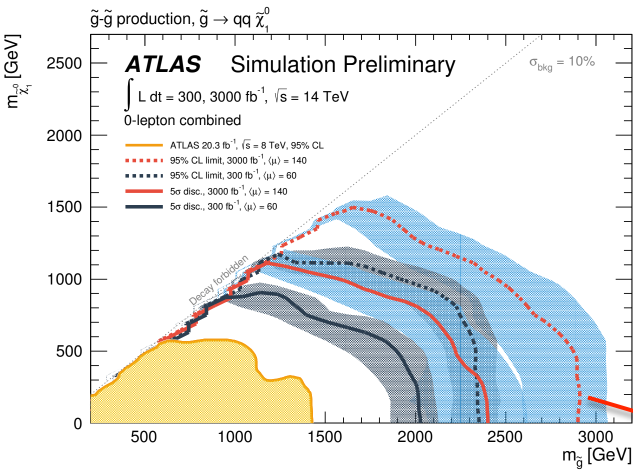
Impact of PDF @ High x

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

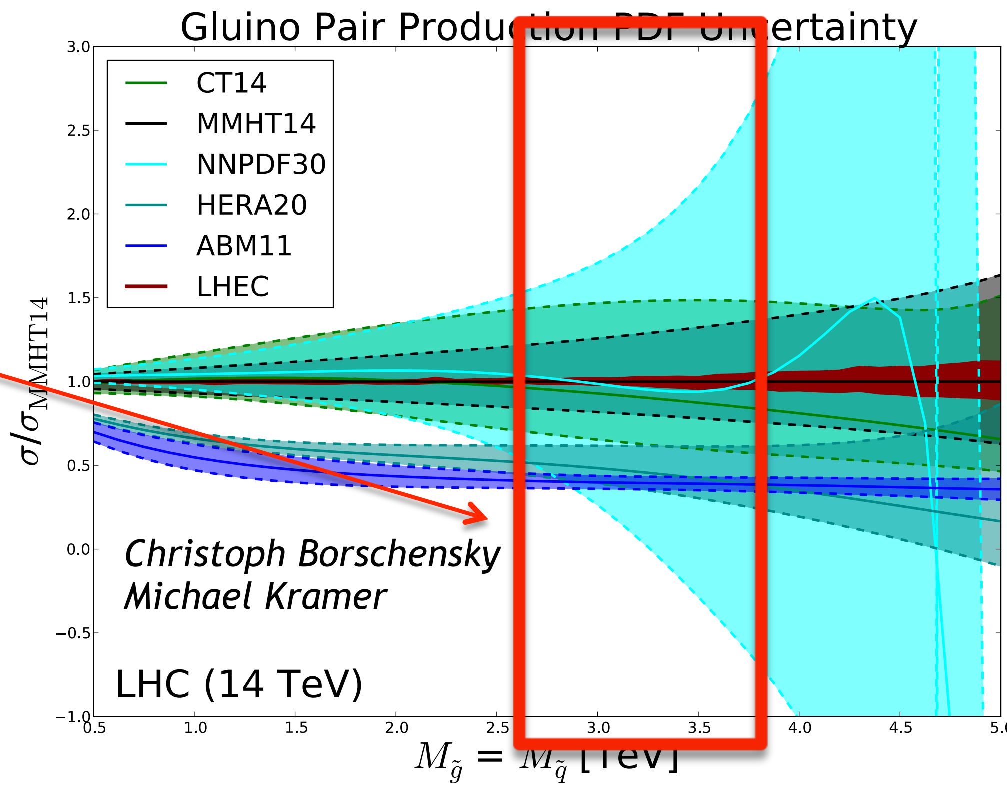
  many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production



- 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

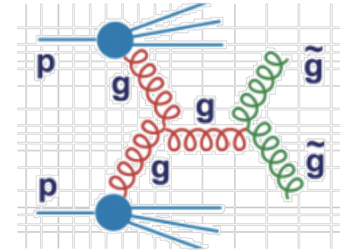
NNPDF30nlo become negative at high masses despite positive constraints applied to the fitting procedure

arXiv:1211.5102

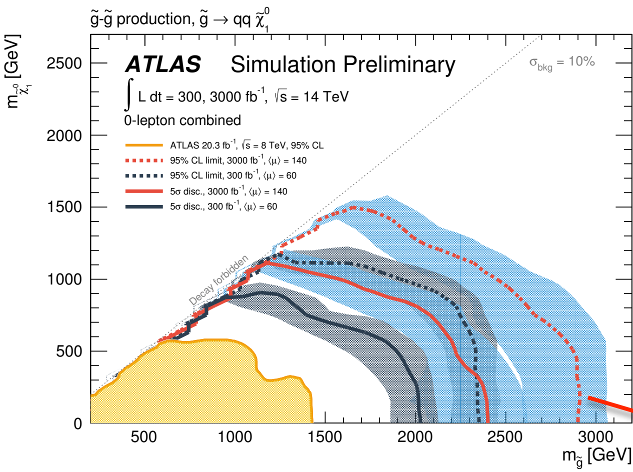
Impact of PDF @ High x

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

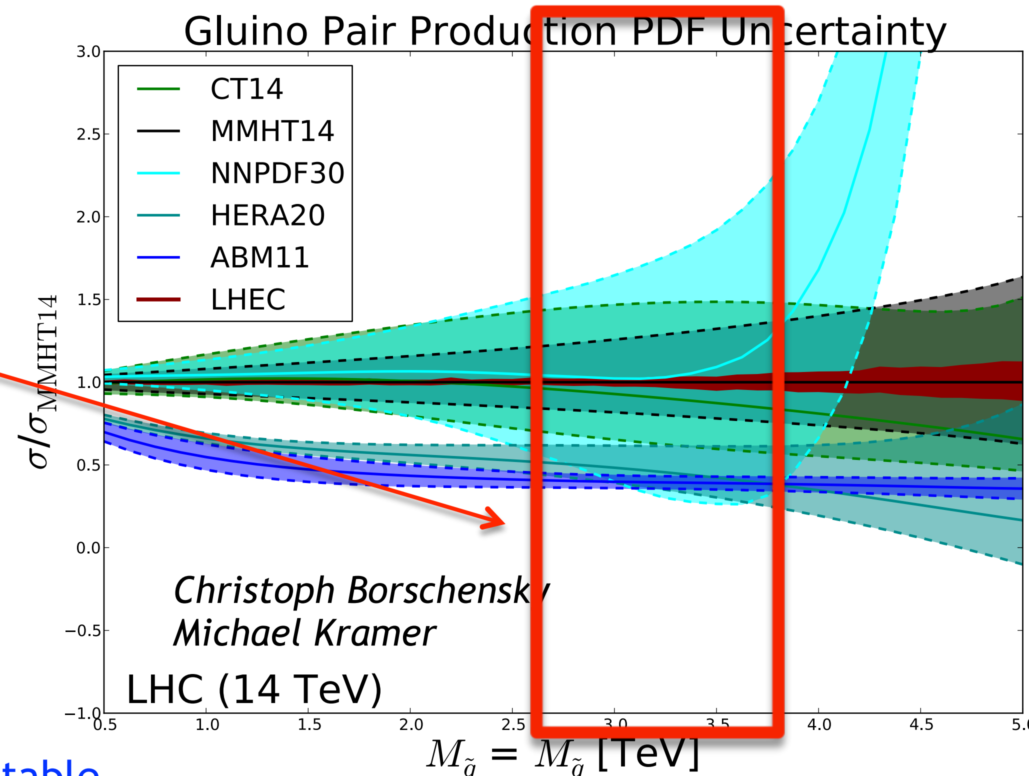
  many interesting processes at LHC are gluon-gluon initiated: top, Higgs, … and BSM processes, such as gluino pair production



- 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

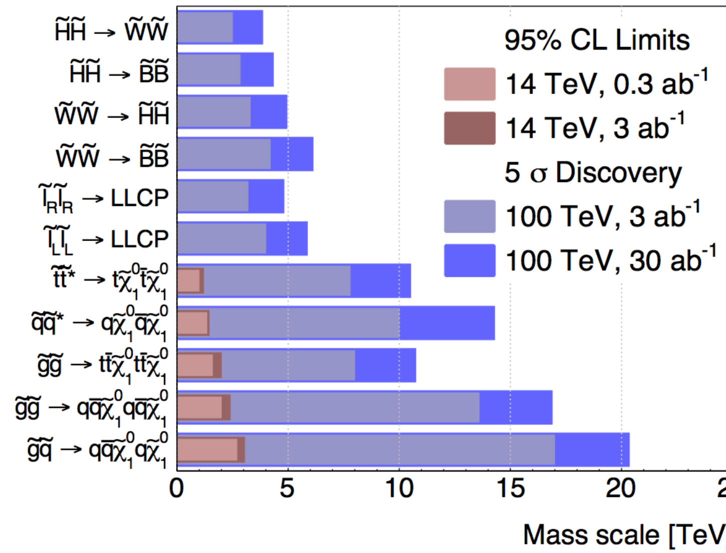
Use prescription from J. Rojo to avoid negative x-section at at high masses for NNPDF30nlo → x-section calculation unstable

arXiv:1211.5102

Impact of PDF @ High x: FCC

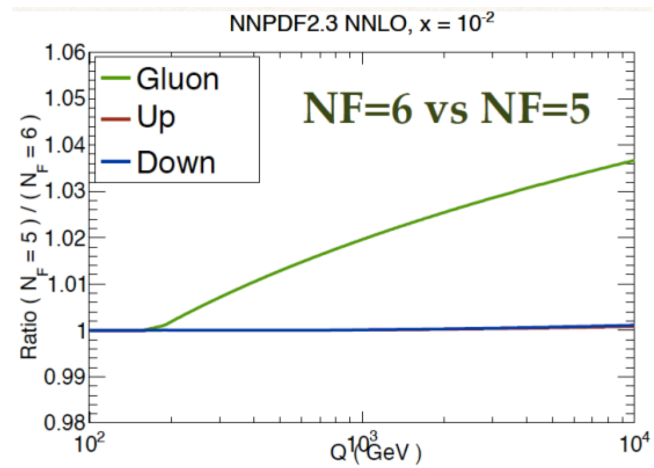
- FCC-hh reach up to **13(16) TeV for gluino pair production, 17(20) TeV for non-decoupled squark/gluino for 3(30)/ab^{-1}**

- 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:

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