BSM Physics at Energy-frontier Lepton-hadron Colliders

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on behalf of
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Outline

★ **Indirect impact from improved PDF**

★ Direct Searches

- Leptoquarks: limits, quantum # & couplings
- Contact interactions: eeqq
- Anomalous gauge couplings: VVV
- Vector boson scattering
- BSM in the top sector
- RPC SUSY: DM, sleptons
- RPV SUSY: neutralinos, squarks
- BSM Higgs: exotic (invisible) decay; H^+, H^{++}
- Sterile neutrinos

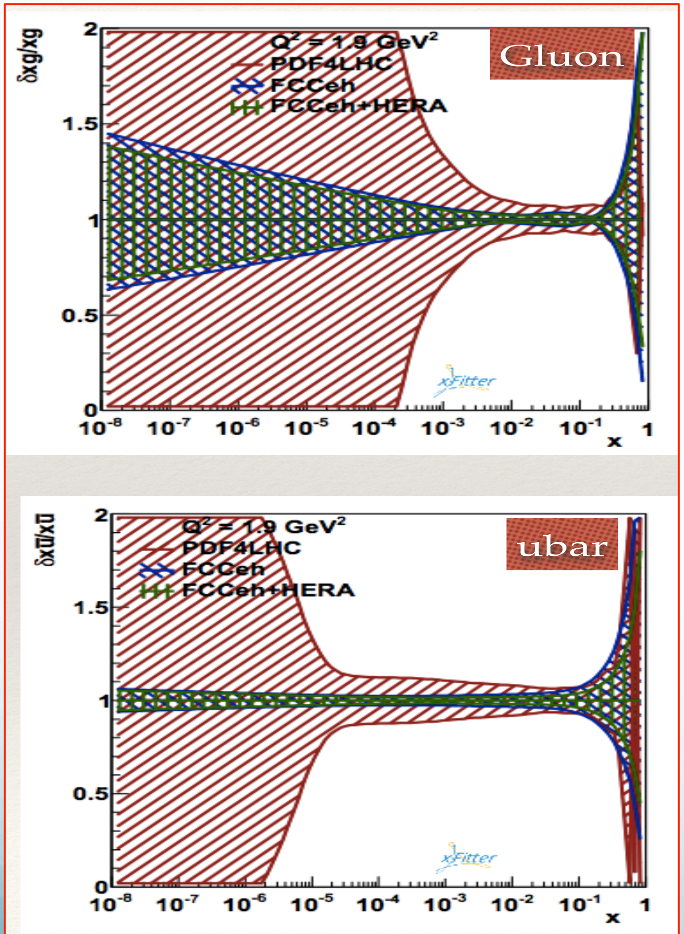
★ Outlook & Summary

Aim of this talk:
→ Review BSM studies @ ep;
→ Encourage more future studies @ ep colliders.

More details,
see [Monica D'Onofrio's talk "BSM searches at FCC-eh *(selected topics)*" in the 1st FCC Physics week, https://indico.cern.ch/event/550509/contributions/2413829/attachments/1398547/2133088/FCCPhysics_BSMJan2017.pdf]

Improved PDF Measurements @ LHeC & FCC-eh

See also [Max Klein's talk "FCC-eh – Status and CDR Plan" in FCC week]



→ low-x: no current data to constrain $x \leq 10^{-4}$; better but not much after HL-LHC;

→ 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

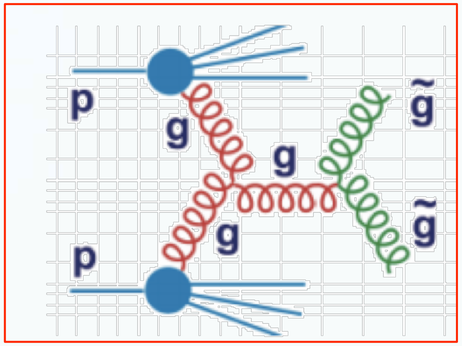
→ important for the FCC-hh as it will probe much lower x regions for standard processes

Indirect Impact on BSM from Improved PDF

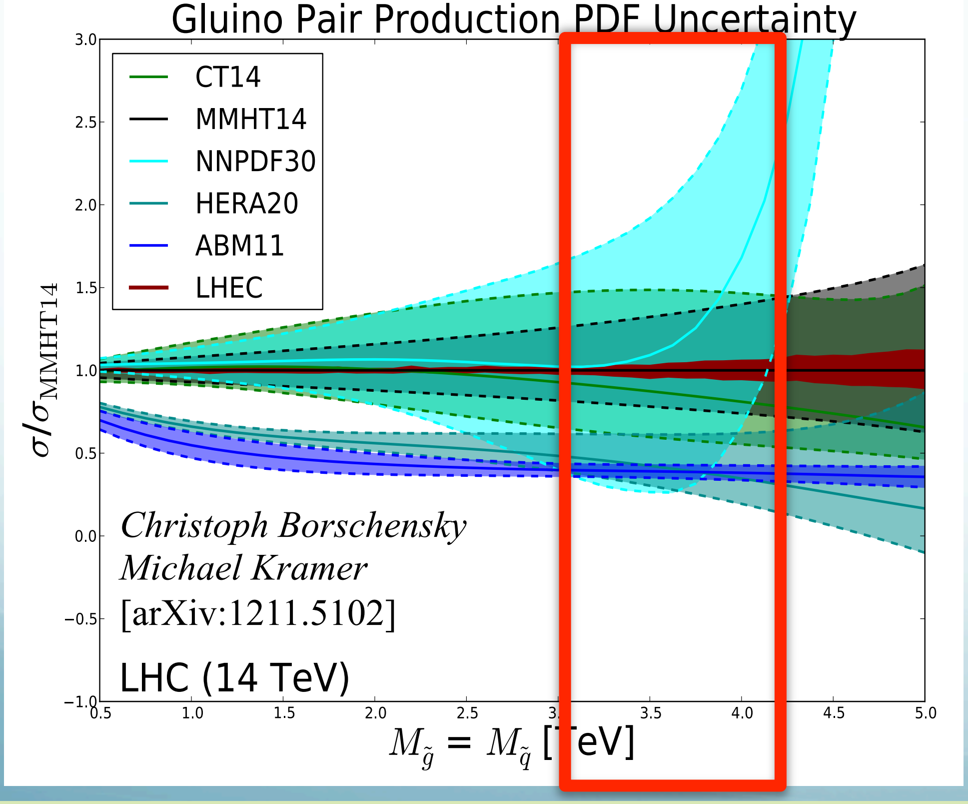
Example: gluon-gluon initiated processes

→ 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



< x > ~ 0.4



At HL-LHC,

~ 40-50% uncertainties on the gluon-gluon initiated gluino production cross section in high x region .

At FCC-hh,

Similar x range for sensitive region

=> reducing PDF uncertainties by ep might be crucial to improve the pp limits.

Outline

★ Indirect impact from improved PDF

★ **Direct Searches**

- Leptoquarks: limits, quantum # & couplings
- Contact interactions: eeqq
- Anomalous gauge couplings: VVV
- Vector boson scattering
- BSM in the top sector: see [Orhan Cakir's talk "Top Physics"]
- RPC SUSY: DM, sleptons
- RPV SUSY: neutralinos, squarks
- BSM Higgs: exotic (invisible) decay; H^{+}, H^{++}
- Sterile neutrinos

★ Outlook & Summary

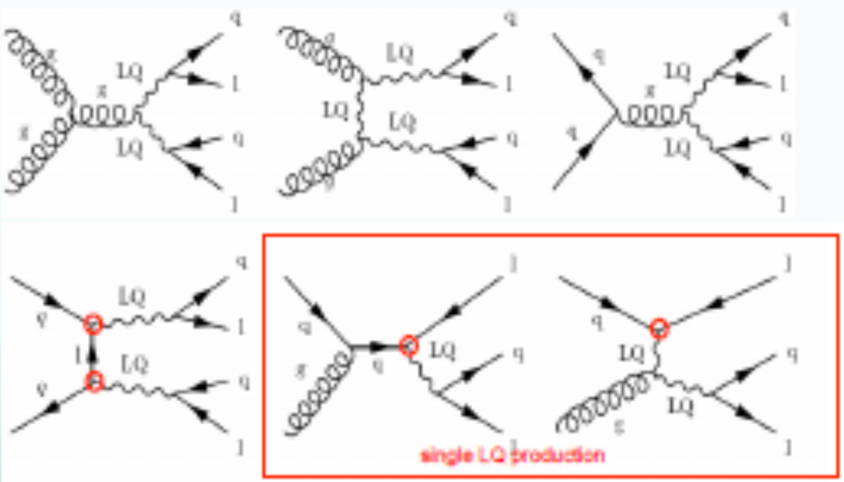
Leptoquarks

Leptoquarks (LQs)

→ appear in several extensions to SM: production s ~ $\lambda^2 q(x)$

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

At the p-p



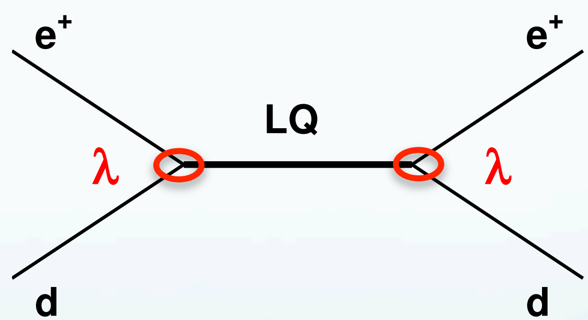
→ mostly pair production (from gg or qq)

→ not sensitive to the LQ-*q*-*l* coupling λ

At the e-p

→ both baryon & lepton quantum numbers

→ ideally suited to search for and study properties of new particles coupling to both leptons and quarks

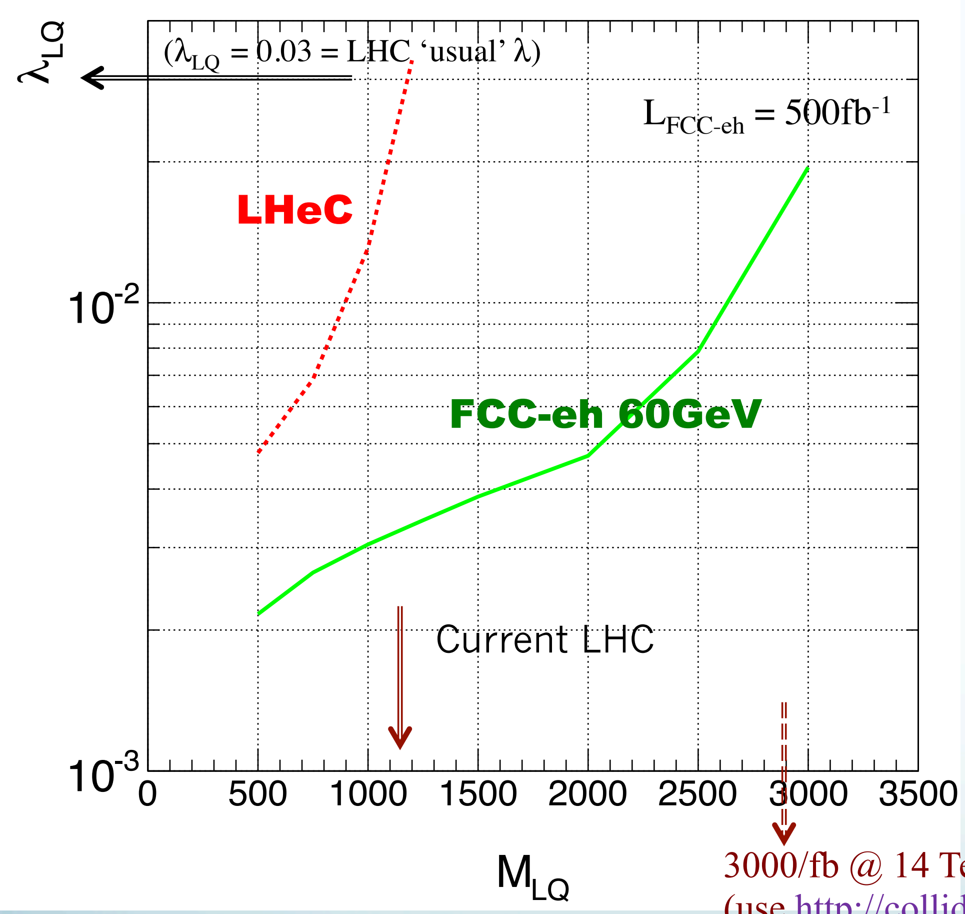


→ single, resonant production

→ sensitive to λ

Leptoquarks

Limits of Leptoquarks



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

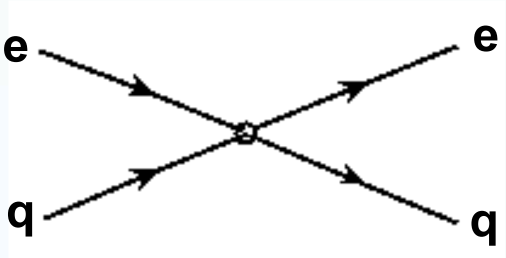
ep collider:
sensitive to $\lambda << e = \sqrt{4\pi\alpha} = 0.03$

Sensitivity @ HL-LHC ~ 2.9 TeV
→ Close to the reach for FCC-eh

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

=> LHeC / FCC-eh offer opportunity to evaluate quantum numbers & couplings
(fermion number, spin, couple chirally, ...)

Contact Interactions



Contact interaction eeqq

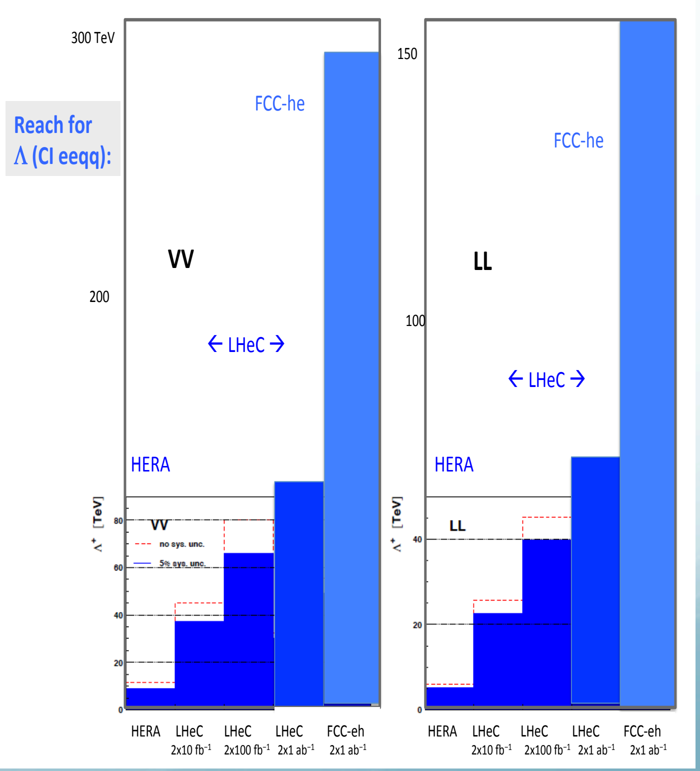
- if new physics enters at higher energy scales: $\Lambda >> \sqrt{s}$
- such indirect signatures can be seen as effective 4-fermion interaction

VV: all couplings with +ve sign
LL: only LL couplings between q and e

- New currents or heavy bosons may produce indirect effect via new particle exchange interfering with γ/Z fields.

- Reach for Λ

  → VV: ~290 TeV; LL: ~160 TeV
  [LHeC results: see CDR 2012]



→ comparable to FCC-hh for some of the couplings
→ same as HL-LHC vs LHeC
→ need more calculations !

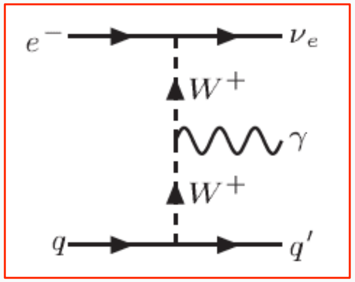
Anomalous Gauge Couplings

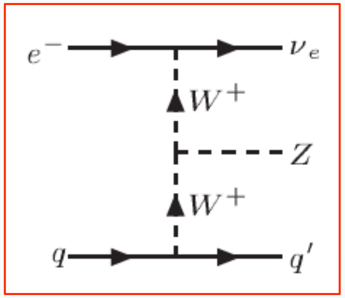
Triple Gauge Couplings (WWV, V = γ, Z)

→ Precisely defined in SM

→ Parameterize 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 → ν_e + jet (W-exchange) and NC events e + p → e + jet (photon or Z boson exchange)

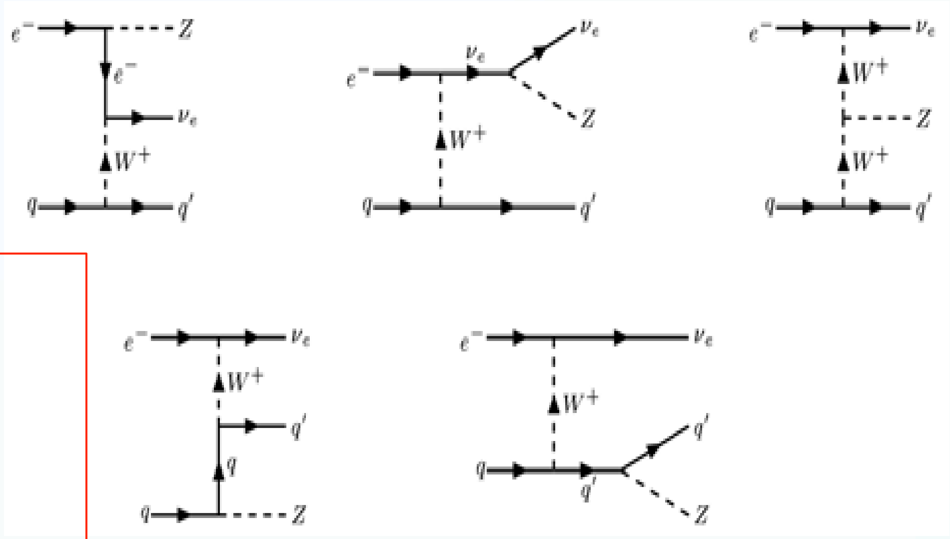
→ triggering on a final state photon, can provide very clean bounds on the anomalous TGC's !

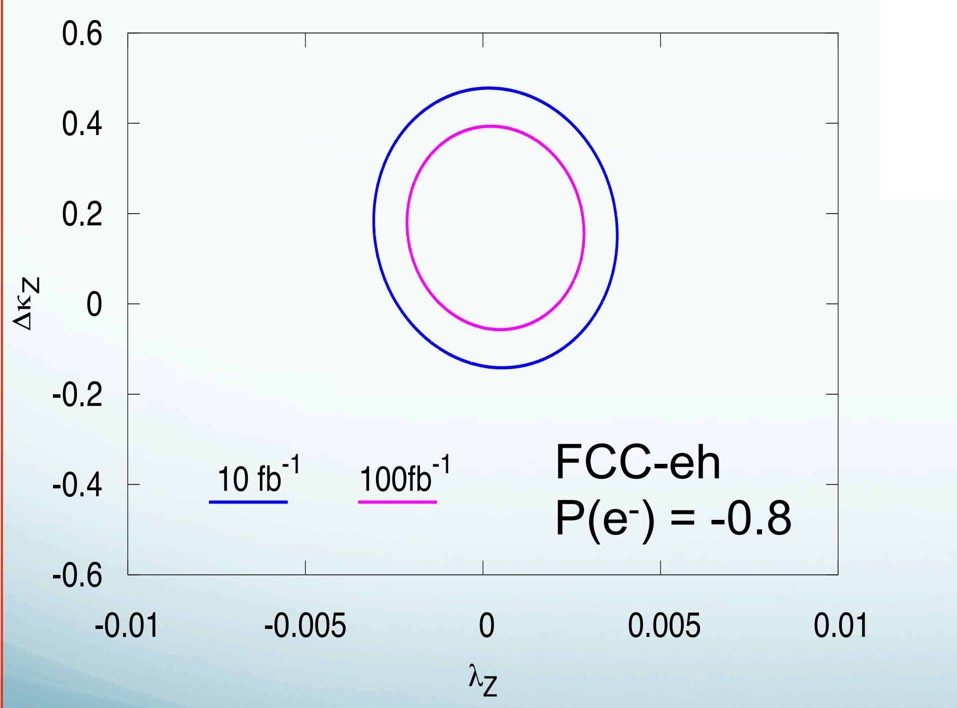
Anomalous Gauge Couplings

Triple Gauge Couplings (WWV, V = γ, Z)

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

Analysis of the signal & backgrounds for $Z \to ll'(l = e, \mu)$





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

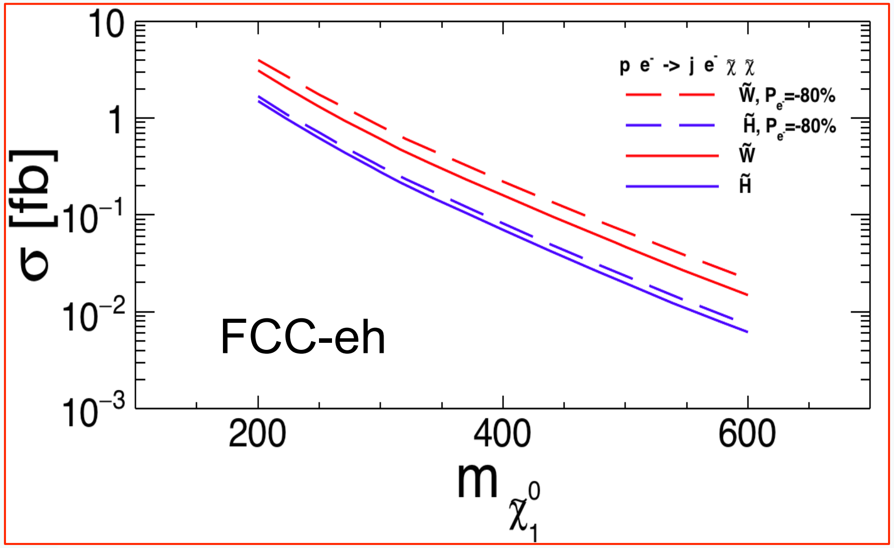
	ATLAS	CMS	ATLAS (upper-lower)	CMS (upper-lower)
$\Delta\kappa\gamma$	-0.420,0.480	-0.250, 0.250	0.900	0.500
$\lambda\gamma$	-0.068,0.062	-0.050, 0.042	0.130	0.092
$\Delta\kappa$Z	-0.045,0.045	-0.160, 0.180	0.090	0.340
λZ	-0.063,0.063	-0.055, 0.055	0.126	0.110

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

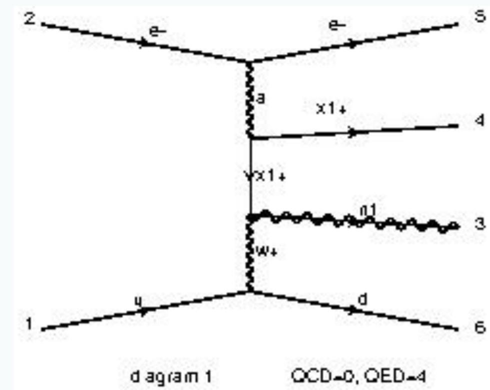
R-Parity Conserving SUSY

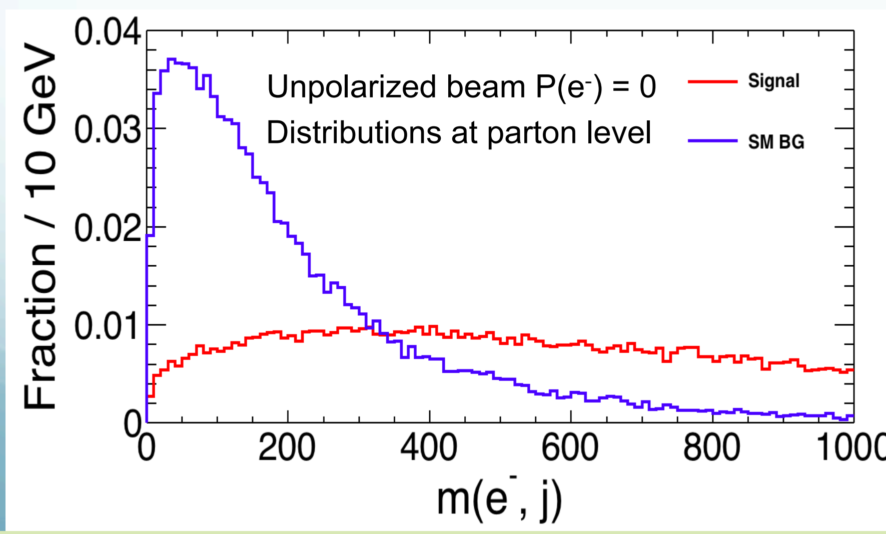
Dark matter via kinematical observables

Preliminary results from [K. Wang, S. Iwamoto, M. D'Onofrio, G. Azuelos]



If DM ~ Wino, Higgsino,
challenging @ pp via kinematical obs.
← decay products are too soft





Simple Cut-based analysis at parton-level leads to a signal significance >= 1 with 1000/fb

MVA analyses would be beneficial

→ Possible to discover / exclude Wino/ Higgsino DM in certain mass range

→ preliminary, worth more investigating

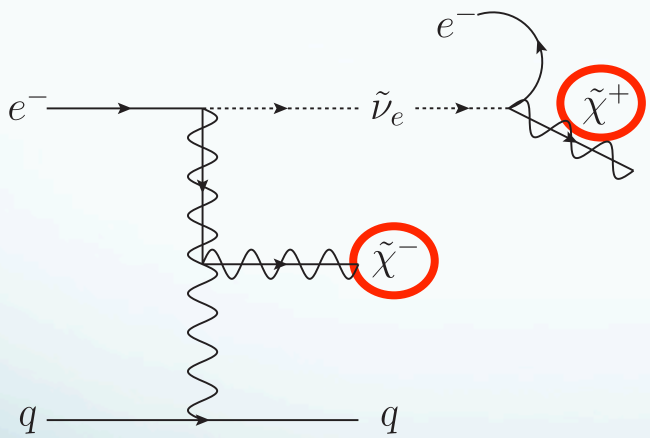
R-Parity Conserving SUSY

DM & Sleptons via disappearing tracks
Long-lived charged particles with *cτ* >~ 10mm

based on [slide from Sho Iwamoto]

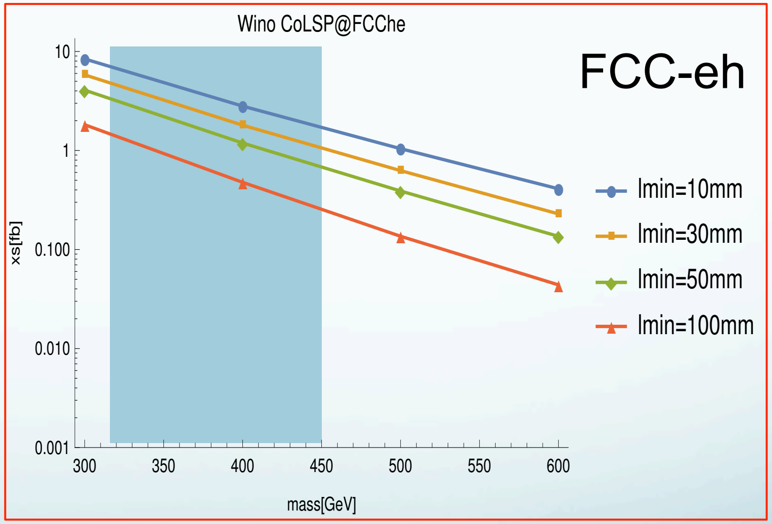
Simplest models at FCC-eh:

→ Cross section enhanced with "3-body production"



Simple efficiency analysis

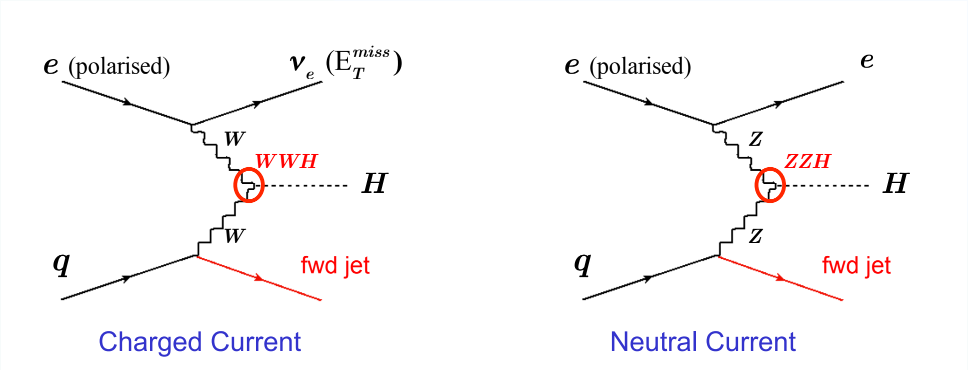
→ Requiring minimal detection length l_{min}
→ Charginos (Wino) with selectron

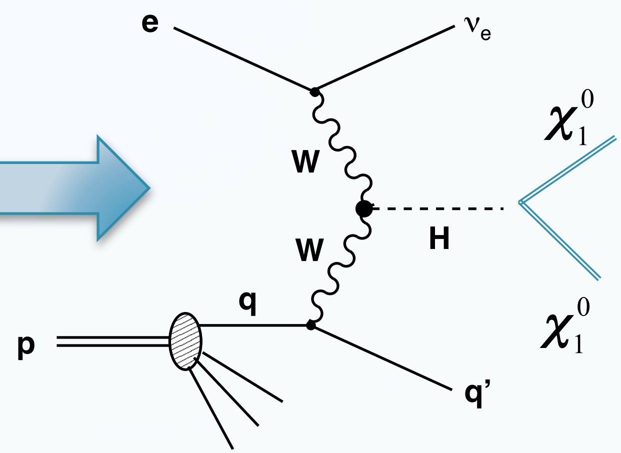


With no polarization;
$m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV

R-Parity Violating SUSY

Neutralinos





- In addition to the higgs to invisible and higgs to 4b, there are several other RPV cases to be considered. E.g.
  - Neutralino might decay in 3 jets (UDD terms)

$$h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow 3j\,3j \text{ (resonances)}$$

Some statistics: N_{exp} = L × s(h) × BR($h \rightarrow \chi_1^0 \chi_1^0$) × [BR($\chi_1^0 \rightarrow jjj$)]^2

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

N exp = 85000 × [BR($\chi_1^0 \rightarrow jjj$)]^2

→ sizable dataset if BR($\chi_1^0 \rightarrow jjj$) not too small

Single Sbottom/Stop production (signal like leptoquarks, with generation mixing)

BSM Higgs

- **Higgs exotic production & decays**
  - See [Kechen Wang, “Higgs Physics at the LHeC and FCC-eh”]
  - exotic decays
    → invisible decay: h -> invisible
    → h -> 2 Φ -> (bb)(bb)
    → Anomalous HVV couplings

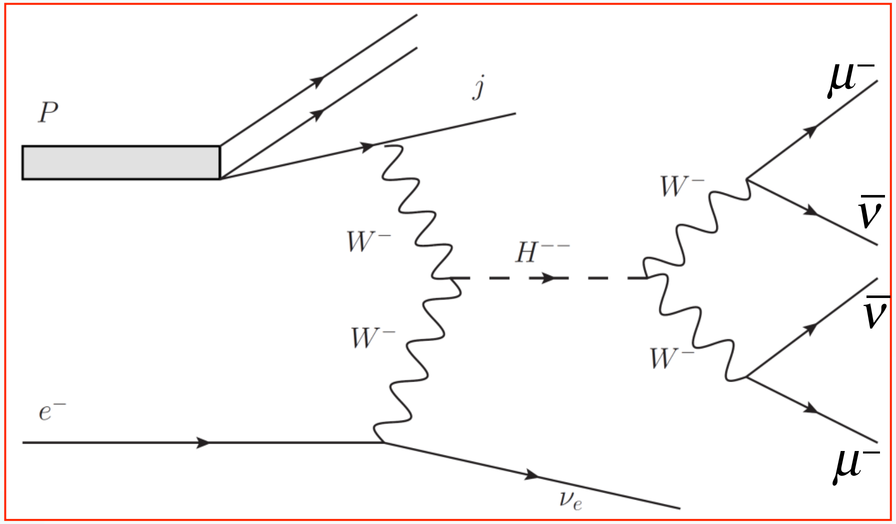
  - **BSM higgs**
    → H^{--},
    → H+, [J. Hernández-Sánchez, etc. 1612.06316]

BSM Higgs

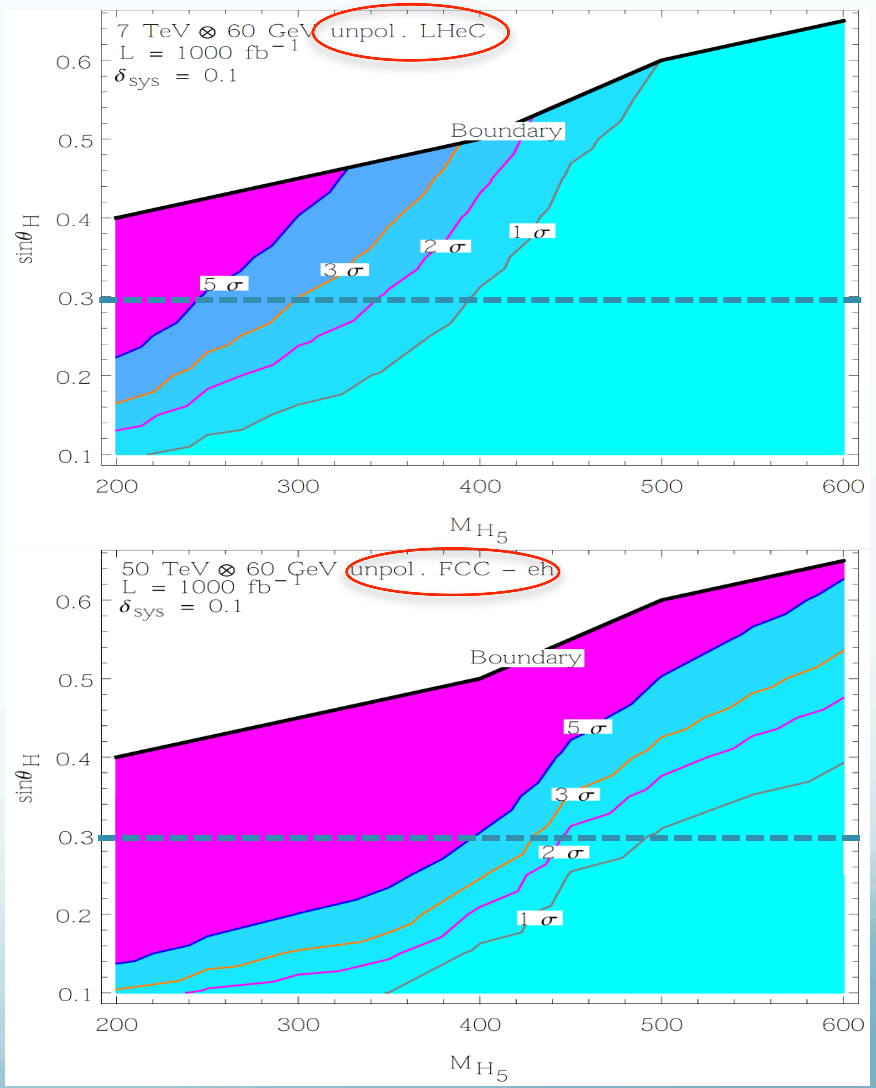
Double charged Higgs H⁻⁻

from [Hao Sun & Xuan Luo's study]

Signal in the Georgi-Machacek model via WW-fusion



Discovery significance



$$S:\ e^-p \rightarrow \nu_e (H_5^{--} \rightarrow W^- W^-) j$$
$$\rightarrow \nu_e \bar{\nu}_\mu \bar{\nu}_\mu \mu^- \mu^- j$$

$$B:\ e^-p \rightarrow \nu_e \bar{\nu}_\mu \bar{\nu}_\mu \mu^- \mu^- j$$

Sterile Neutrinos

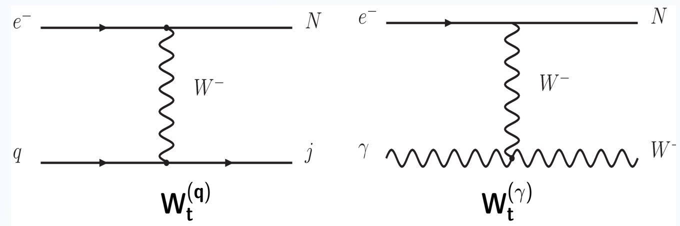
Slide from [Oliver Fischer]

Related articles considering electron-proton colliders

["Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider", S. Mondal, S. K. Rai, Phys. Rev. D 93 (2016) no.1, 011702]

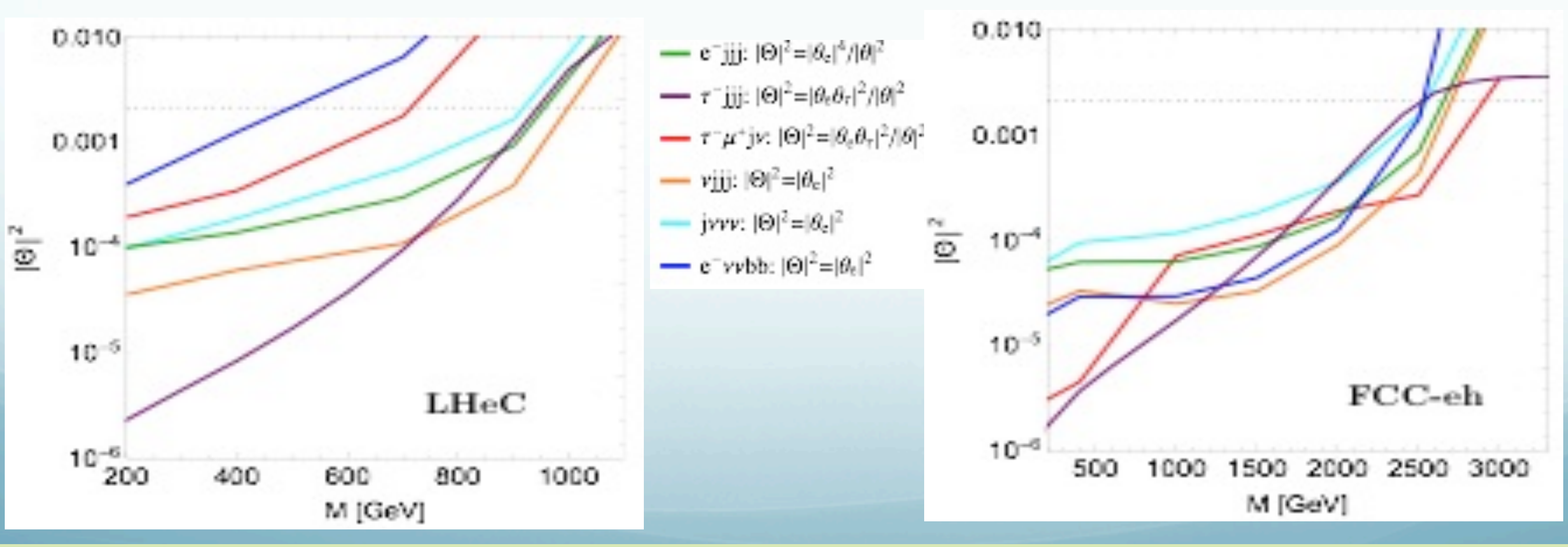
["Probing the Heavy Neutrinos of Inverse Seesaw Model at the LHeC", S. Mondal, S. K. Rai; Phys. Rev. D 94 (2016) no.3, 033008]

["Left-Right Symmetry and Lepton Number Violation at the Large Hadron Electron Collider", M. Lindner, F. S. Queiroz, W. Rodejohann, C. E. Yaguna; JHEP 1606 (2016) 140]



- Leading order production of heavy neutrino mass eigenstate.
- $W_t^{(q)}$: dominant at lower center-of-mass energies.
- $W_t^{(\gamma)}$: relevant for larger masses.

limits for LNC signatures [S. Antusch, E. Cazzato, O. Fischer, 1612.02728]



Summary & Outlook

- ★ ep offers a variety of opportunities for BSM searches
  → precision measurements, complementary searches;
  distinguishing & characterization new physics theories;

- ★ Improving pp limits indirectly by improved PDF (@ high and low x)

- ★ Fruitful BSM physics scenarios:
  → Leptoquarks, Contact interactions, Anomalous gauge couplings, Vector boson scattering, BSM top physics, SUSY (RPV & RPC), BSM Higgs, Sterile neutrinos...

- ★ Ideal to search and study properties of new particles with
  → couplings to electron-quark, EW production, multi-jets final states

- ★ Compare with pp colliders
  → Some promising: clean environment (samller bkg), forward objects
  → Some difficult: small production due to small sqrt(s)

- ★ Physics potential yet to be fully exploited
  → Detector-level studies crucial for next phase
  → You are welcome to join our team !!!

Backup Slides

Related previous talks at FCC week 2017

General introduction & accelerators,
see [Frank Zimmermann's talk "HE-LHC and FCC-eh CDR plan and status"]

General introduction, physics, detector, CDR,
see [Max Klein's talk "FCC-eh – Status and CDR Plan"]

[Daniel Britzger, "Hard QCD, PDFs and EW"]

[Uta Klein, "SM and BSM Higgs"]

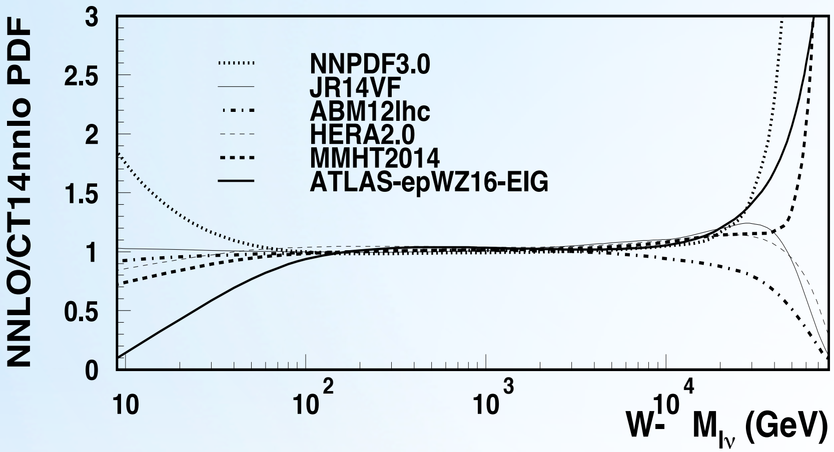
[Orhan Cakir, "Top Physics"]

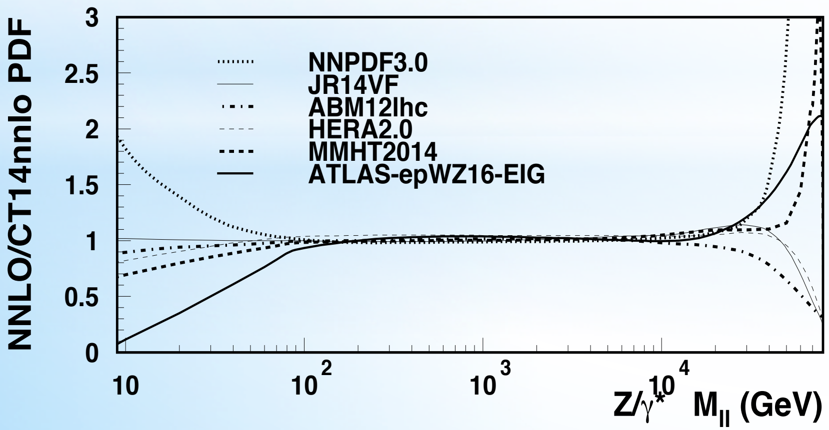
Sterile neutrinos,
see [Oliver Fischer's talk "An example of synergy in BSM physics:
Right-handed neutrinos"]

Indirect Impact on BSM from Improved PDF

Example: High mass Drell-Yan

from [Uta Klein, VRAP 0.9 for NNLO QCD]





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

→ "Troubles" at low and high x

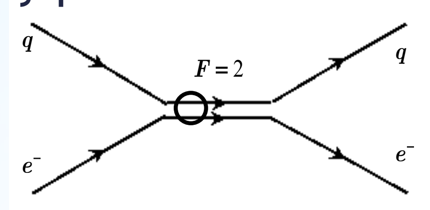
→ FCCeh (and before, LHeC) can improve low and high M(*ll*) and M(*lv*) precision for standard candle measurements and searches for new physics

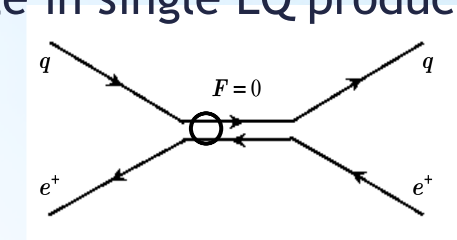
Leptoquarks

Quantum # & 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

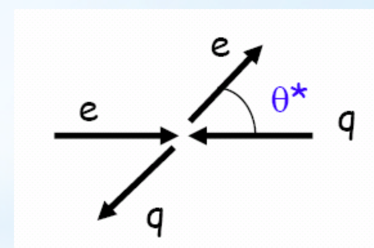
$$A=\frac{\sigma_{e^-}-\sigma_{e^+}}{\sigma_{e^-}+\sigma_{e^+}}\begin{cases}>0 \text{ for F=2}\\ <0 \text{ for F=0}\end{cases}$$





- spin
  - At p-p, pair production of LQ-LQ leads to angular distributions which depend on the g-LQ-LQ coupling

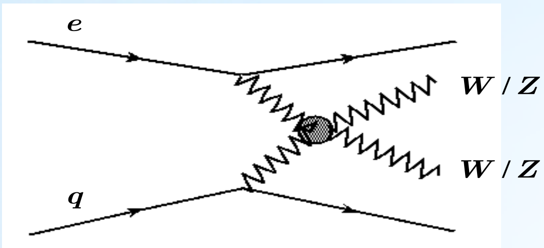
    -> may need to look for spin correlations
  - At e-p, cos q* distribution is sensitive to the spin
  - vector leptoquarks can have anomalous couplings



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

Vector Boson Scattering

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

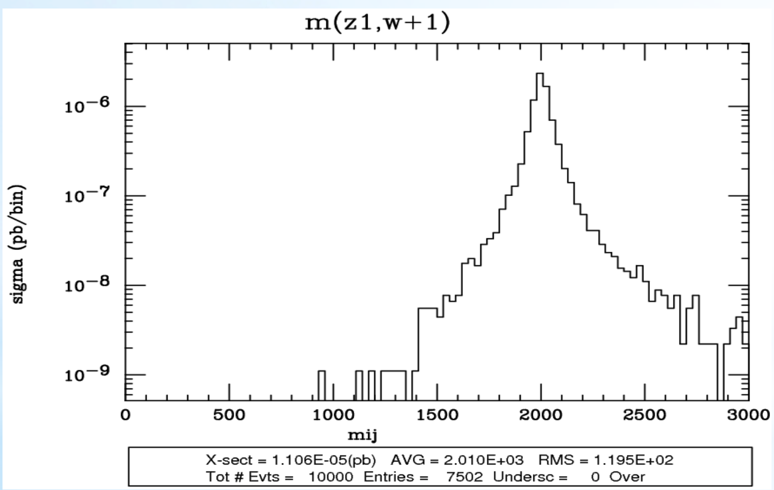


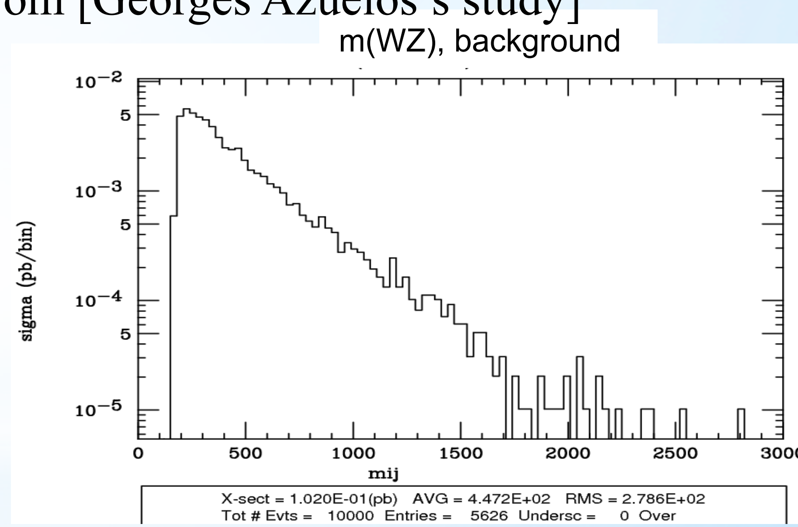
$$e^- q \rightarrow e^-(q)WZ, \quad (\nu q)WZ$$

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

Preliminary results from [Georges Azuelos's study]

For a 2 TeV resonance





→ low cross section [1402.4431]
→ there is some potential to study VBS at high mass

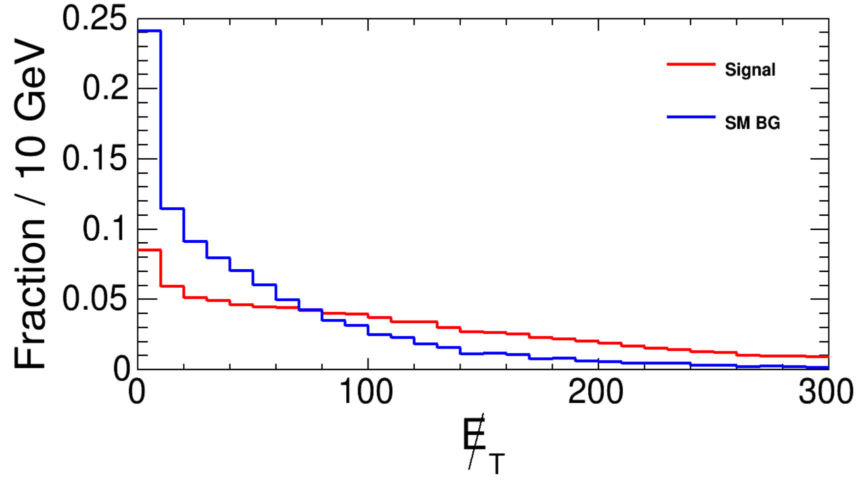
→ kinematics distinct between signal & background
→ cleaner, small background for masses ~ 2TeV

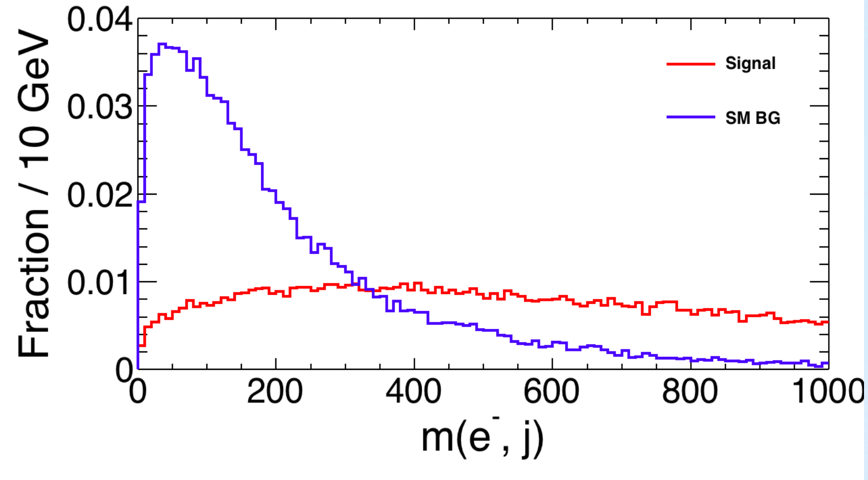
R-Parity Conserving SUSY

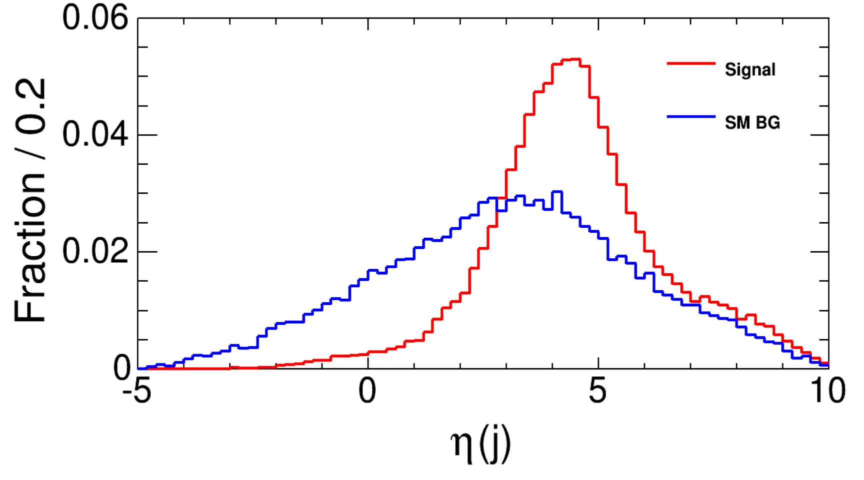
Dark matter via kinematical observables

Distributions at parton level

Unpolarized beam P(e-) = 0







Benchmark point:
pure Wino DM:
M_2 ~ 200 GeV; M_1, μ >> M2;
m(neutrino1) ~ m(chargino1) ~ 200 GeV.
chargino1: Wino with 0.3% Higgsino

Backgrounds

→ Similar to Higgs->invisible
→ Generating inclusively
→ Including "W j v", "Z j e",
"e- j v v (via ZZ/WZ/WA fusion)"
→ Missing "W j e-", single top

R-Parity Conserving SUSY

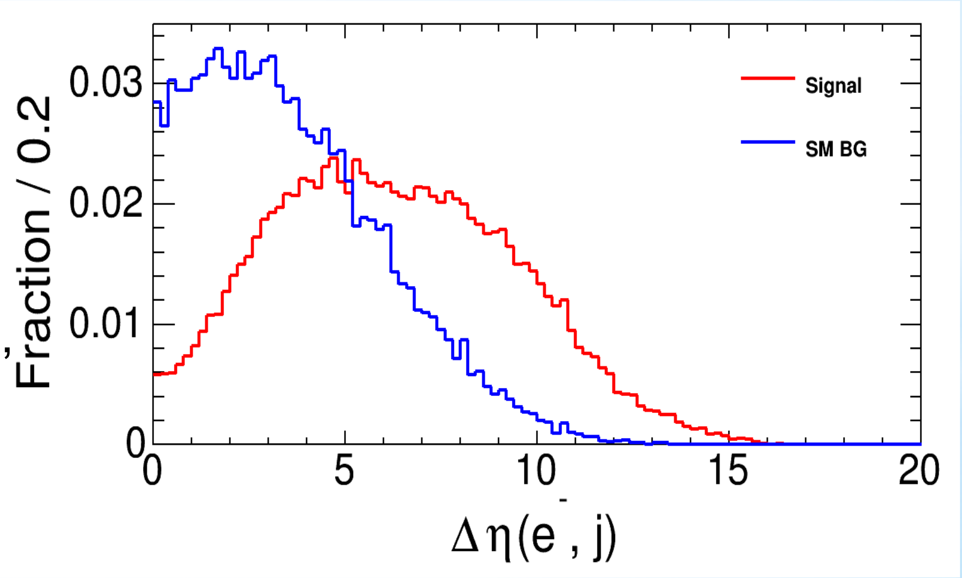
Dark matter via kinematical observables

Signal MadGraph generating:
import model mssm
define dm = n1 n2 x1+ x1-
generate p e- > j e- dm dm

Background MadGraph generating:
“import model sm-full
define dm = ve vm vt ve~ vm~ vt~
generate p e- > j e- dm dm ”

Basic selections on pT jets, electron, eta range: signal and background ‘efficiency’
→ **eff_S = 28%, eff_B = 4.7%**

MET>100 GeV, M_T(met, j)>150 GeV , Δφ(MET,j)> 3.0, Δφ(e,j)<2.0, Δη(e,j)>5.0, M(j+e)>350 GeV, M_T(MET, j+e) > 500 GeV
→ **eff_S = 4%, eff_B = 0.05%**



R-Parity Conserving SUSY

DM & Sleptons via disappearing tracks

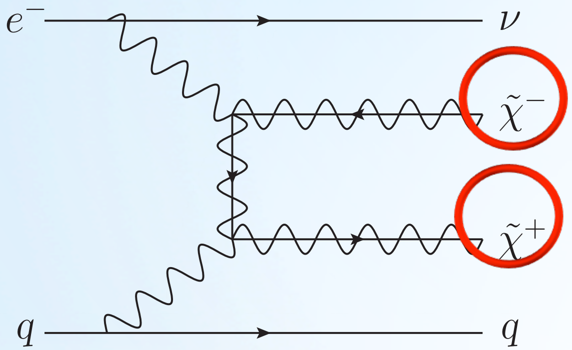
Long-lived charged particles with $c\tau$ >~ 10mm

based on [slide from Sho Iwamoto]

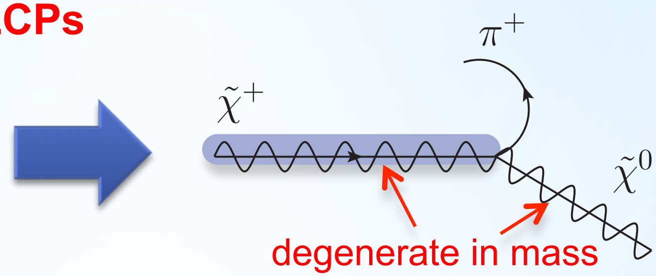
Simplest models at FCC-eh:

→ Small cross section with "4-body production"

Charginos (Wino or Higgsino)

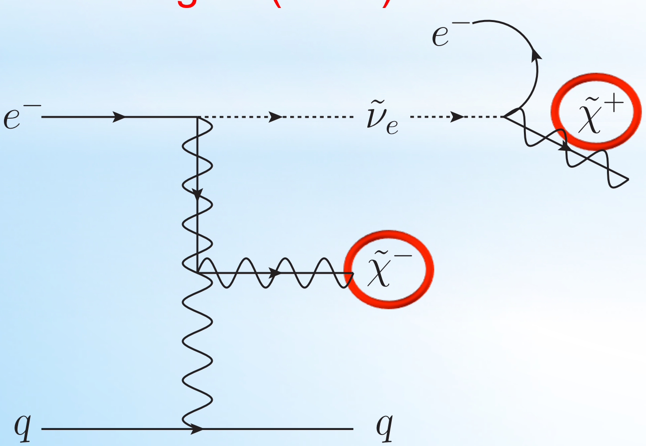


disappearing track

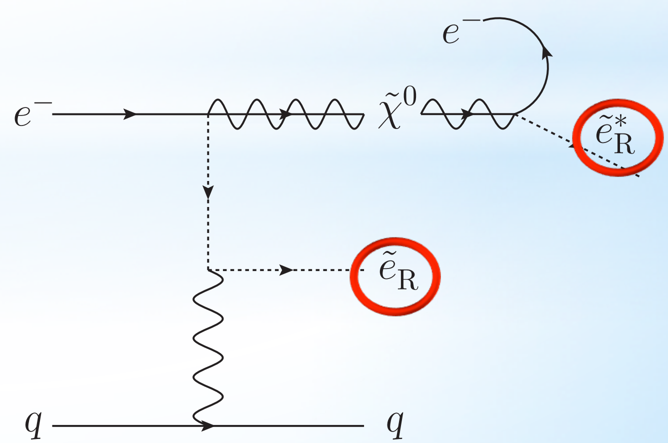


→ Cross section enhanced with "3-body production"

- Chargino (Wino) with selectron



- Selectrons with neutralino



R-Parity Conserving SUSY

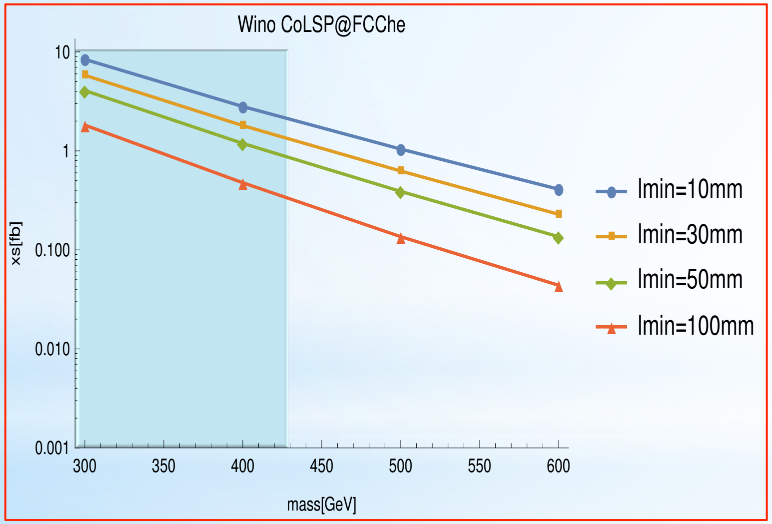
DM & Sleptons via disappearing tracks
Long-lived charged particles with $c\tau$ >~ 10mm

based on [slide from Sho Iwamoto]

Simple efficiency analysis

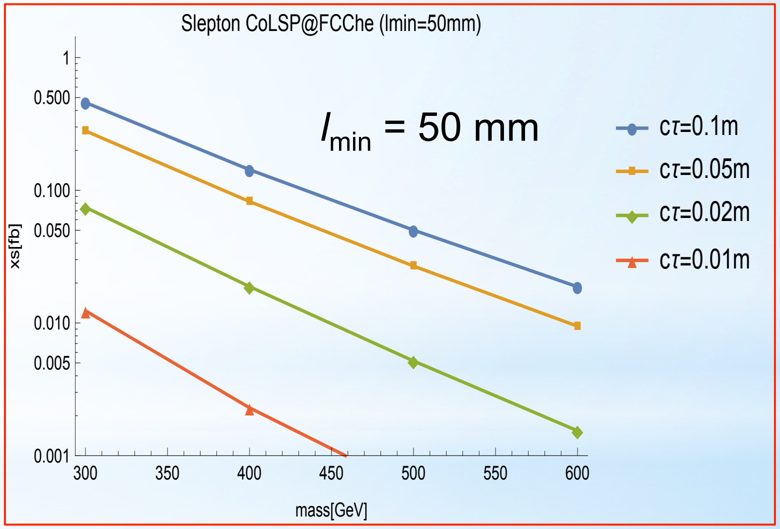
Requiring minimal detection length l_{min} @ FCC-eh

Charginos (Wino) w/ selectron
("3-body production")



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

Sleptons w/ neutralino (Bino)
("3-body production")



With no polarization;
$m_{\tilde{\chi}_1^0} = m_{\tilde{e}} + 1\,\mathrm{GeV}$

R-Parity Conserving SUSY

DM & Sleptons via disappearing tracks

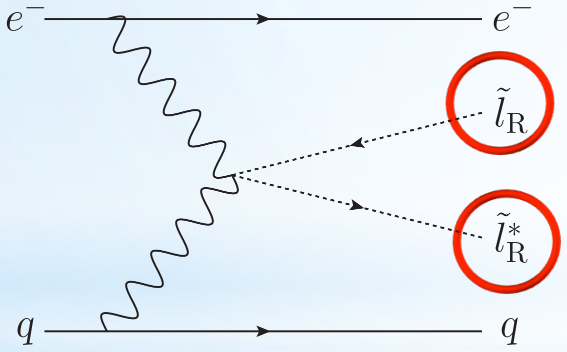
Long-lived charged particles with *cτ* >~ 10mm

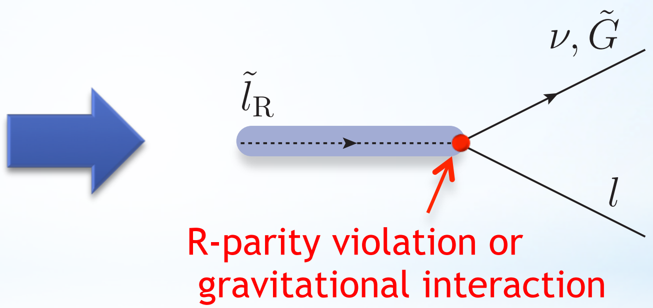
[slide from Sho Iwamoto]

Simplest models at FCC-he

- Sleptons decaying via
  - gravitational interaction
  - R-parity violation

disappearing track (or “kink”)





R-Parity Conserving SUSY

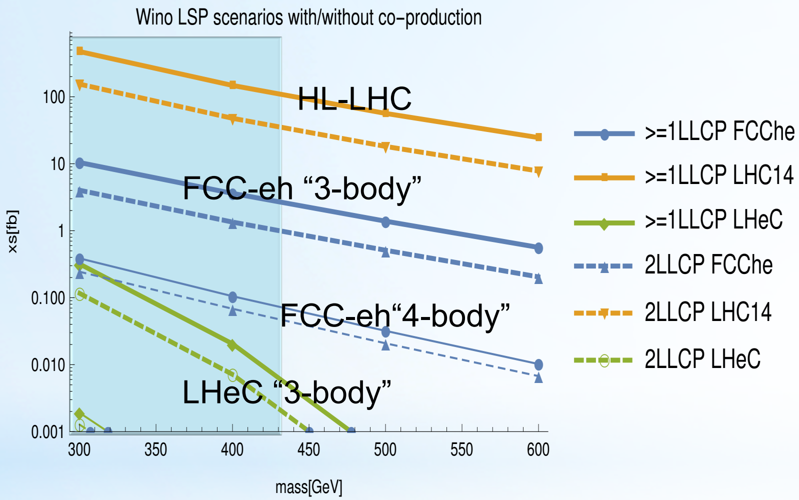
DM & Sleptons via disappearing tracks

Long-lived charged particles with *cτ* >~ 10mm

[slide from Sho Iwamoto]

Nominal cross section without acceptance / efficiency

Charginos (Wino LSP)



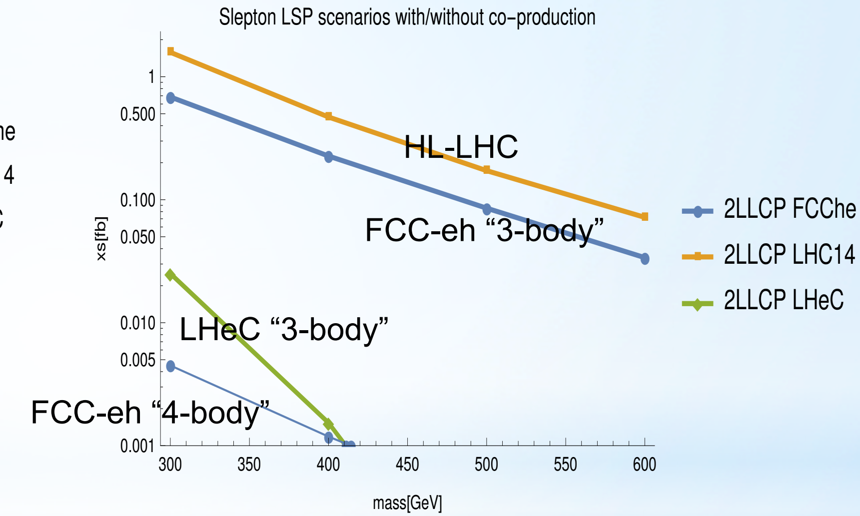
With no polarization.

Shaded region is excluded by ATLAS (13TeV, 36/fb)

FCC-he “3-body” process assumes

$m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV

Sleptons



With no polarization.

FCC-he “3-body” process assumes

$m_{\tilde{\chi}_1^0} = m_{\tilde{e}} + 1\,\mathrm{GeV}$

R-Parity Violating SUSY

Squarks ← an example of "Leptoquarks"

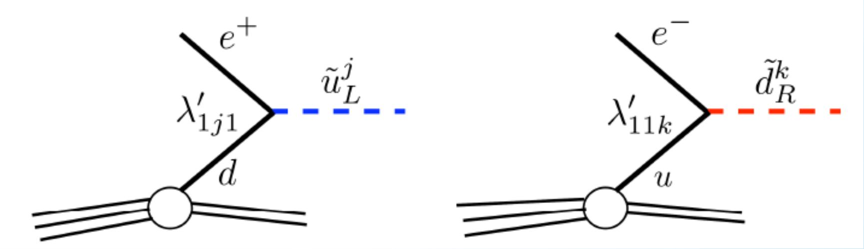
$$W_{\not R_p} = \overbrace{\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k + \underbrace{\epsilon_i\hat{L}_i\hat{H}_u}_{\text{bilinear terms}}}^{L\text{-number violating terms}} + \underbrace{\lambda''_{ijk}\hat{U}^C_i\hat{D}^C_j\hat{D}^C_k}_{B\text{-number violating terms}}$$

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)*

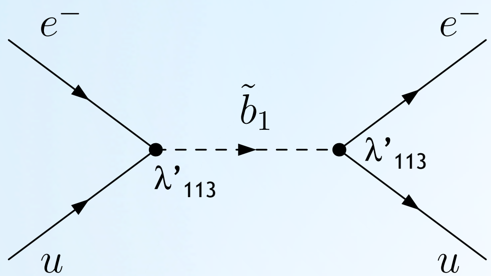


R-Parity Violating SUSY

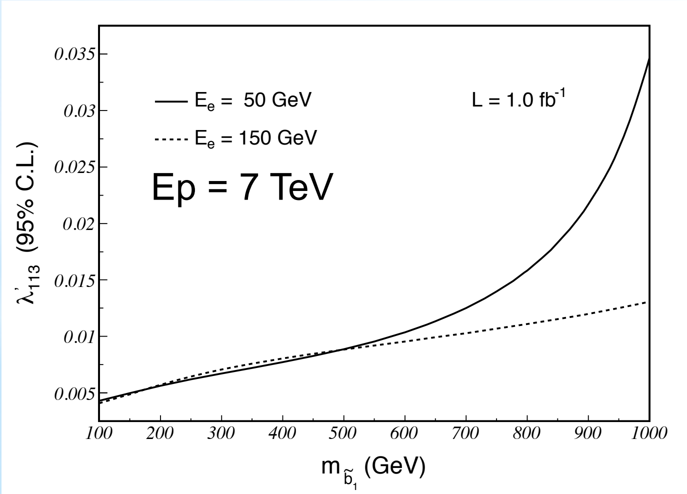
Single Sbottom/Stop production (signal like leptoquarks, with generation mixing)

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

sbottom



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

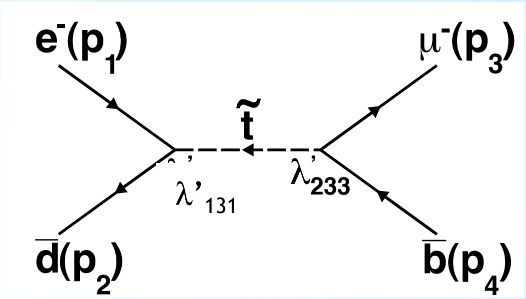


@FCC-eh: same analysis as for LQ → Sensitivity up to 2.5 TeV for λ'_{113}<0.02

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

stop

λ'_{131}< 0.03
also stronger bounds from ββ0ν



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

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

BSM Higgs

Single charged Higgs H^+ @ LHeC

2HDM type III from [J. Hernández-Sánchez, etc. 1612.06316]

charge current production processes

$e^- p \to \nu_e q H^+$, with $H^+ \to c\bar{b} + c.c.$

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	$\sigma.cb$ [fb]
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

Significances with 100 fb^{-1} @ parton level

(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

→ A charged Higgs boson of the 2HDM-III would be observed with approximately a 3–4 σ significance.

→ At the end of the LHeC era, with 1000 fb^{-1} of data, the detection of such a charged Higgs boson would be certain.