# BSM Physics @ ep Colliders

Co-author: Monica D'Onofrio & Georges Azuelos
Presenter: Kechen Wang (DESY)
on behalf of
the LHeC/FCC-eh BSM Physics Group

2nd FCC Physics Workshop, CERN
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# Outline

Aim of this talk:
→ List promising topics
→ show progress of BSM studies @ ep;
focus on just updated one's / recent studies;
→ Encourage more future studies

★ **Indirect impact from improved PDF**

★ Direct Searches

- BSM Higgs: invisible decay; H->4b, H->multi-j, $H^+$, $H^{++}$
- SUSY: DM, sleptons
- Anomalous gauge couplings: VVV, ~~VVVV~~ updated
- Leptoquarks: RPV SUSY squarks, limits, quantum # & couplings; B anomaly (LHCb); 1-page
- Contact interactions: eeqq (very heavy LQ, compositeness)

- ~~Vector boson scattering~~
- ~~BSM in the top sector~~
- ~~Sterile neutrinos~~

★ Outlook & Summary

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 ]
& [Kechen Wang's talk "BSM Physics at Energy-frontier Lepton-hadron Colliders" in the EPS-HEP Conference 2017,
https://indico.cern.ch/event/466934/contributions/2583549/attachments/1489690/2314998/EPS-HEP_BSM_at_ep_colliders_2.pdf ]

# Outline

★ **Indirect impact from improved PDF**

★ Direct Searches

- BSM Higgs: exotic (invisible) decay; H->4b, $H^+$, $H^{++}$
- RPC SUSY: DM, sleptons
- RPV SUSY: neutralinos, squarks
- Anomalous gauge couplings: VVV, ~~VVVV~~ updated
- Leptoquarks: limits, quantum # & couplings;
- Contact interactions: eeqq (very heavy LQ, compositeness)

- ~~Vector boson scattering~~
- ~~BSM in the top sector~~ [Christian Schwanenberger, "Top physics in ep" ]

- ~~Sterile neutrinos~~ [Oliver Fischer's talk "Heavy neutrino discovery prospects at FCC"]

★ Outlook & Summary

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

★ Compared with *pp* colliders
→ Some promising:
clean environment (samller bkg, low pileup), forward objects
→ Some difficult:
small production due to small $\sqrt{s}$

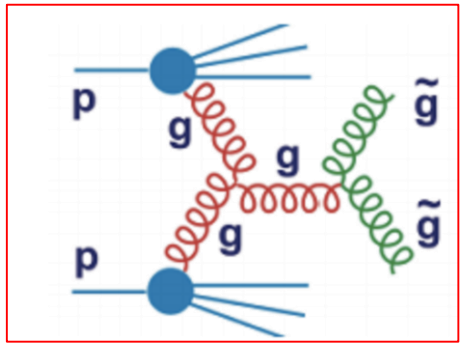
# Indirect Impact on BSM from Improved PDF

comment on [Claire Gwenlan's talk "PDFs at the FCC-eh" ], before

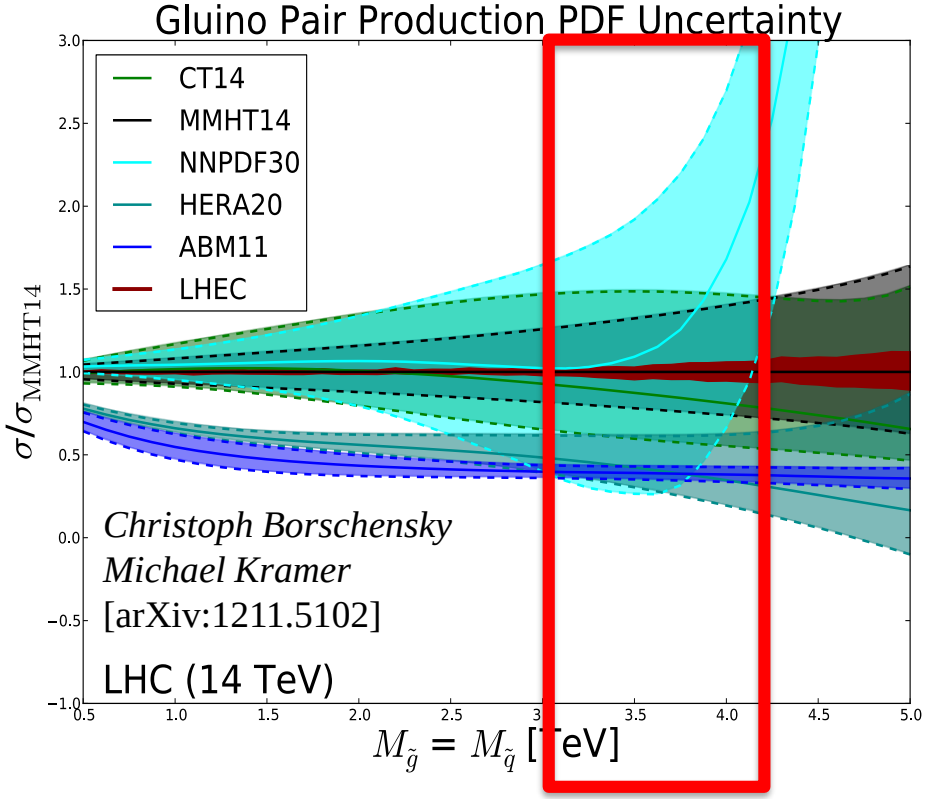
**Example: gluon-gluon initiated processes**

→ 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.

# BSM Higgs

- **Higgs invisible decays**
  - $h \to invisible$, [Uta Klein's talk "*Higgs SM Couplings at FCC-ep*" ]

- **Higgs exotic decays**
  - $h \to 2\phi \to (b\bar{b})(b\bar{b})$
  - $h \to \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \to (3j)(3j)$ in RPV SUSY

- **Charged Higgs**
  - $H^+$, in 2HDM type III, $p\, e^- \to \nu j H^+ \to \nu j\, (c\bar{b})$,

    [J. Hernández-Sánchez, etc. 1612.06316]
  - $H^{\pm\pm}$, $H^{\pm}$ in Vector Boson Scattering

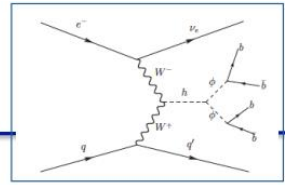
# BSM Higgs

$h \to 2\phi \to (b\bar{b})(b\bar{b})$

[ Slide from Uta Klein ]

## Exotic Higgs at LHeC@1ab$^{-1}$

[arXiv:1608.08458]



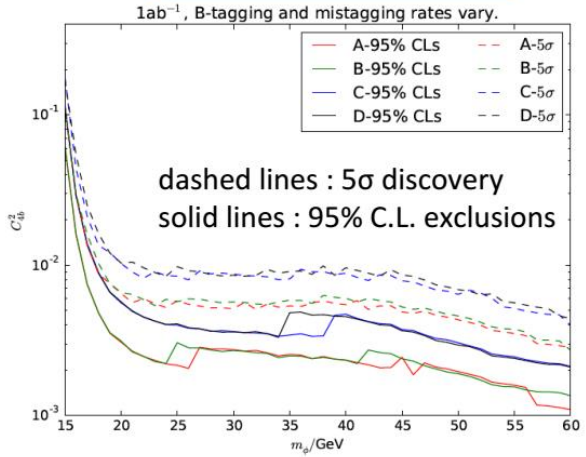
Btag scenarios

(A) $\epsilon_b = 70\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(B) $\epsilon_b = 70\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

(C) $\epsilon_b = 60\%, \epsilon_c = 10\%, \epsilon_{g,u,d,s} = 1\%$

(D) $\epsilon_b = 60\%, \epsilon_c = 20\%, \epsilon_{g,u,d,s} = 1\%$

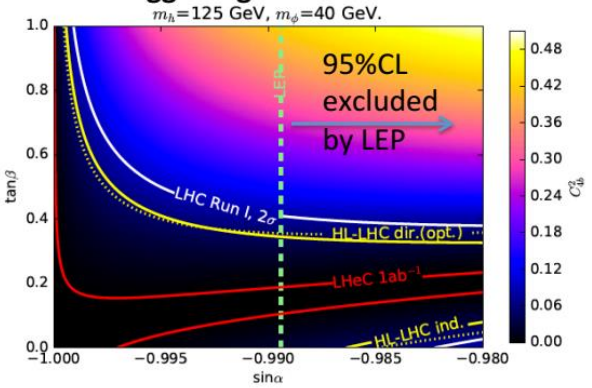



95% C.L. for $m_\phi$ of 20, 40, 60 GeV for

$C_{4b}^2 = \kappa_V^2 \times \mathrm{Br}(h \to \phi\phi) \times \mathrm{Br}^2(\phi \to b\bar{b})$

is 0.3%, 0.2% and 0.1%

**Sensitivity comparison in Higgs Singlet Model**




$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}, S \equiv \frac{h'+x}{\sqrt{2}} \qquad (12)$$

Here $v = 246$ GeV ensures the correct mass generation for $W, Z$ bosons and SM fermions. The gauge eigenstates $\tilde{h}, h'$ can be related to mass eigenstates $\phi, h$ via an orthogonal rotation

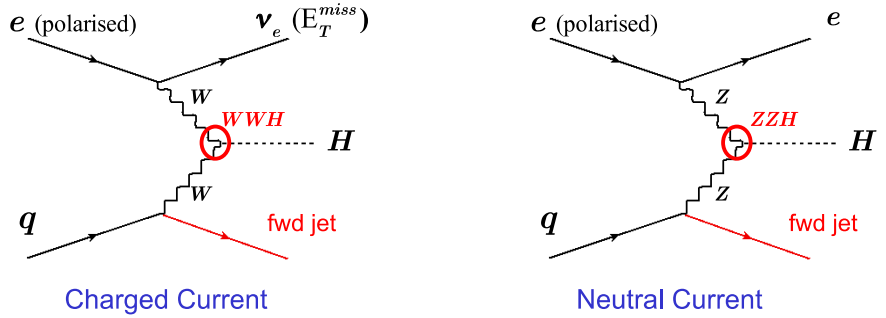
$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix} \qquad (13)$$

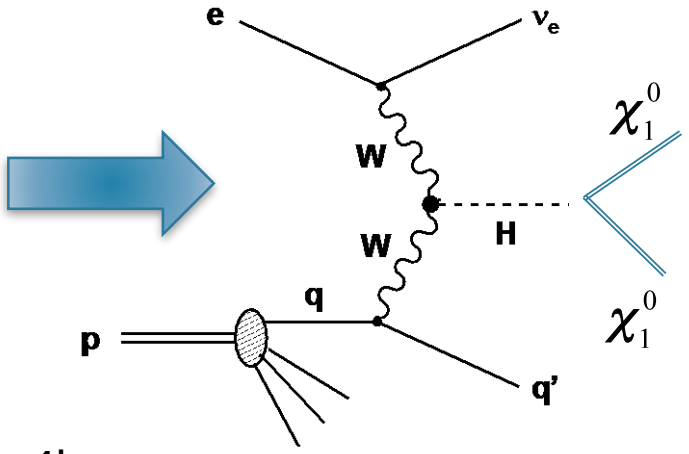
Now it is convenient to parameterize the model in terms of five more physical quantities: ($m_\phi, m_h$ are masses of $\phi$ and $h$ respectively)

$$m_\phi, m_h, \alpha, v, \tan\beta \equiv \frac{v}{x} \qquad (14)$$

# BSM Higgs

$h \to \tilde{\chi}_1^0\, \tilde{\chi}_1^0 \to (3j)(3j)$ in RPV SUSY




- 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)

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

**Some statistics:** $N_{exp} = L \times \sigma_h \times BR(h \to \tilde{\chi}_1^0\, \tilde{\chi}_1^0) \times [BR(\tilde{\chi}_1^0 \to jjj)]^2$

In 1 ab$^{-1}$, $\sigma_h$**=850 fb (CC)**, assuming $BR(h \to \tilde{\chi}_1^0\, \tilde{\chi}_1^0) = 10\%$

$N_{exp} = 85000 \times [BR(\tilde{\chi}_1^0 \to jjj)]^2$

→ sizable dataset if $BR(\tilde{\chi}_1^0 \to jjj)$ not too small

# BSM Higgs
# Georgi – Machacek (GM) Model

**Scalar sector of the GM model:**
complex isospin doublet $(\phi^+, \phi^0)$ with hypercharge Y=1 ;
real triplet $(\xi^+, \ \xi^0, \ \xi^-)$ with Y=0;
complex triplet $(\chi^{++}, \ \chi^+, \ \chi^0)$ with Y = 2;

→ Scalar potential is chosen to preserve a global $SU(2)_L \times SU(2)_R$ symmetry

Using $SU(2)_L \times SU(2)_R$ covariant forms of the fields:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \qquad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

**Signatures of the five-plet in GM model:**
[H. Logan, M. Zaro, LHCHXSWG-2015-001]

$$v^2 = v_\Phi^2 + 8v_\Delta^2$$

$$\sin\theta_H = \frac{2\sqrt{2}\, v_\Delta}{v}$$

$$\cos\theta_H = \frac{v_\Phi}{v}$$

$\Delta$

**mixing :** $\theta_H$

$\Phi$

**Physical fields under the custodial SU(2) symmetry**

**5 - plet** $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

**3 - plet** $H_3^+, H_3^0, H_3^-$

**singlet** $H_1^{'0}$

**mixing :** $\alpha$ → H

**singlet** $H_1^0$ → h → **125GeV Higgs**

- Have a common mass $M(H_5)$;
- Do not couple to fermions;
- Tree-level $H_5VV$ interaction;
- Production via VBF;
- $g(H_5VV) \propto \sin\theta_H$
  => $\sigma(VBF \to H_5) \propto \sin^2\theta_H$;
- $BR(H_5^\pm \to W^\pm Z) \approx 100\ \%$ ;
  $BR(H_5^{\pm\pm} \to W^\pm W^\pm) \approx 100\ \%$ ;
- 2 free pars. $M(H_5)$, $\sin\theta_H$ .

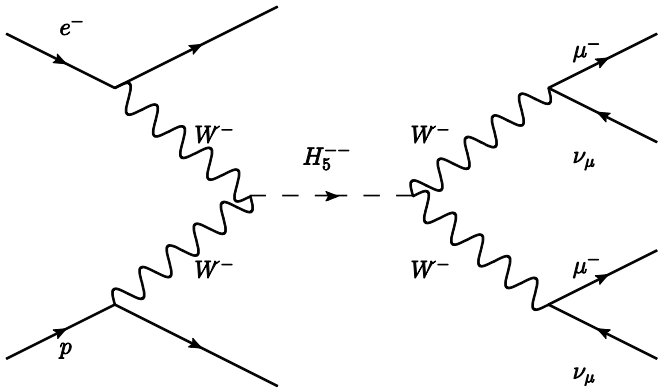
# BSM Higgs

## Double charged Higgs $H^{\pm\pm}$

Signal via WW-fusion in the Georgi-Machacek model

$p\ e^- \to j\ \nu_e\ (\mathrm{H_5^{--}} \to \mathrm{W^-\ W^-}) \to \mathrm{j}\ \nu_e\ (\mu^-\ \nu_\mu)(\mu^-\ \nu_\mu)$

Final state: ≥ 1 j + 2 $\mu^-$ + MET




Simulation by "MadGraph + PYTHIA + Delphes".

## Event selection:

Basic cut

$$\not{E}_T \geq 10\mathrm{GeV}$$
$$p^{j,\ell}{}_T \geq 10\mathrm{GeV}$$
$$|\eta^j| \leq 5,\ |\eta^\ell| \leq 2.5,$$
$$\Delta R_{jj} \geq 0.4,\ \Delta R_{j\ell} \geq 0.4,\ \Delta R_{\ell\ell} \geq 0.4$$

Basic selection: $\not{E}_T + 2\mu^- + \geq 1\mathrm{jet(s)}$

Optimized:

$\Delta\Phi^{\mu\mu} \in (-\pi,-1.28)$ or $(1.36,\pi)$

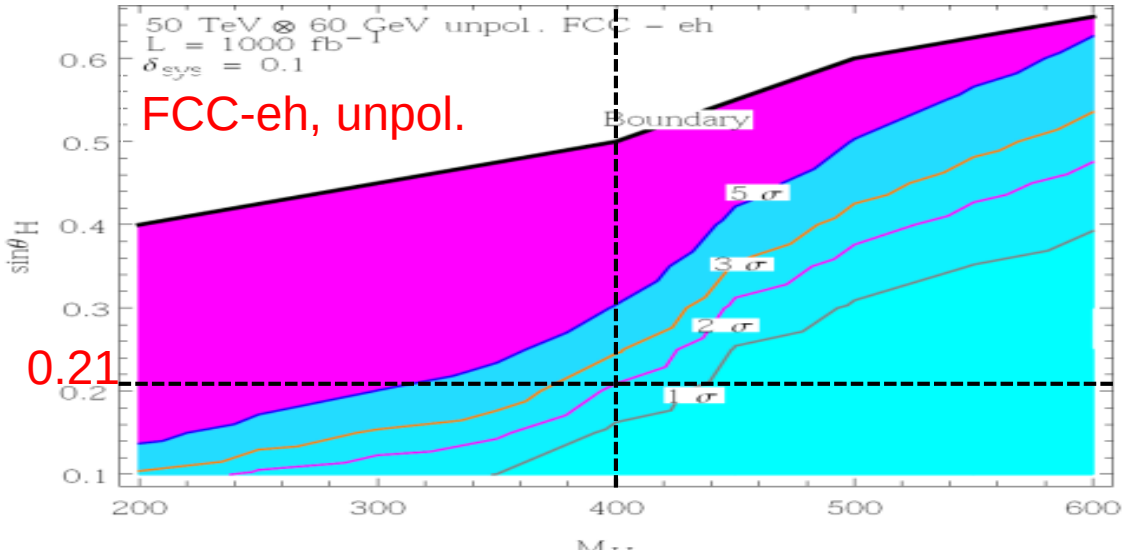
$\Delta R^{\mu\mu}$ $\quad M^{\mu\mu}_{inv} > 75\mathrm{GeV}$

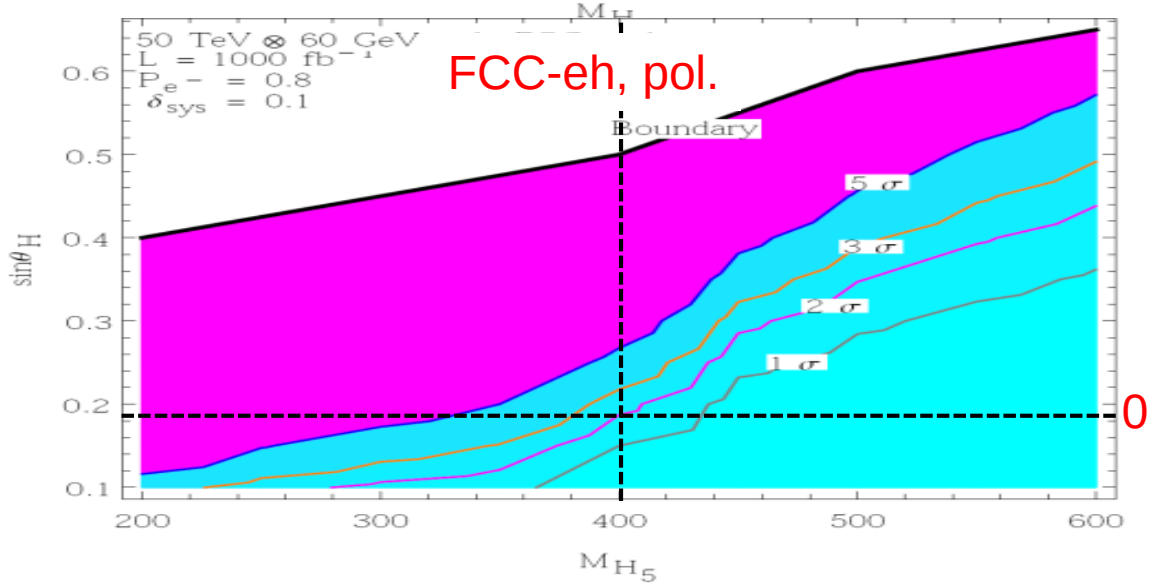
$\quad M^{\mu\mu}_{T} > 40\mathrm{GeV}$

[study by H. Sun, X. Luo, W. Wei and T. Liu ]

**Significances** in $\sin\theta_H$ vs. $M_{H_5}$ Plain

→ *Lum* = 1 ab$^{-1}$, systematic uncertainty $\sigma_{sys}$ = 10%



# BSM Higgs

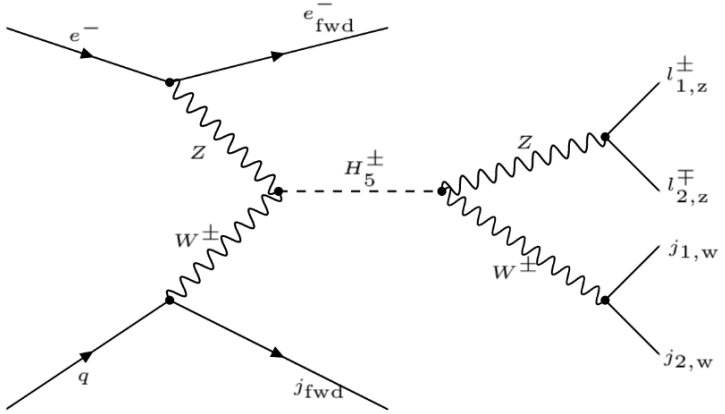
## Signal Scenarios for $H_5^{\pm}$ Search [Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505 ]

**Collider:** FCC-eh & LHeC

**Signal:**

Production of $H_5^+$ & $H_5^-$ in the Georgi – Machacek Model

→ Final state: 1 $e^-$ + 1 j + 1 Z(-> $l^+ l^-$) + 1 W(-> j j); $l$ = e,$\mu$.



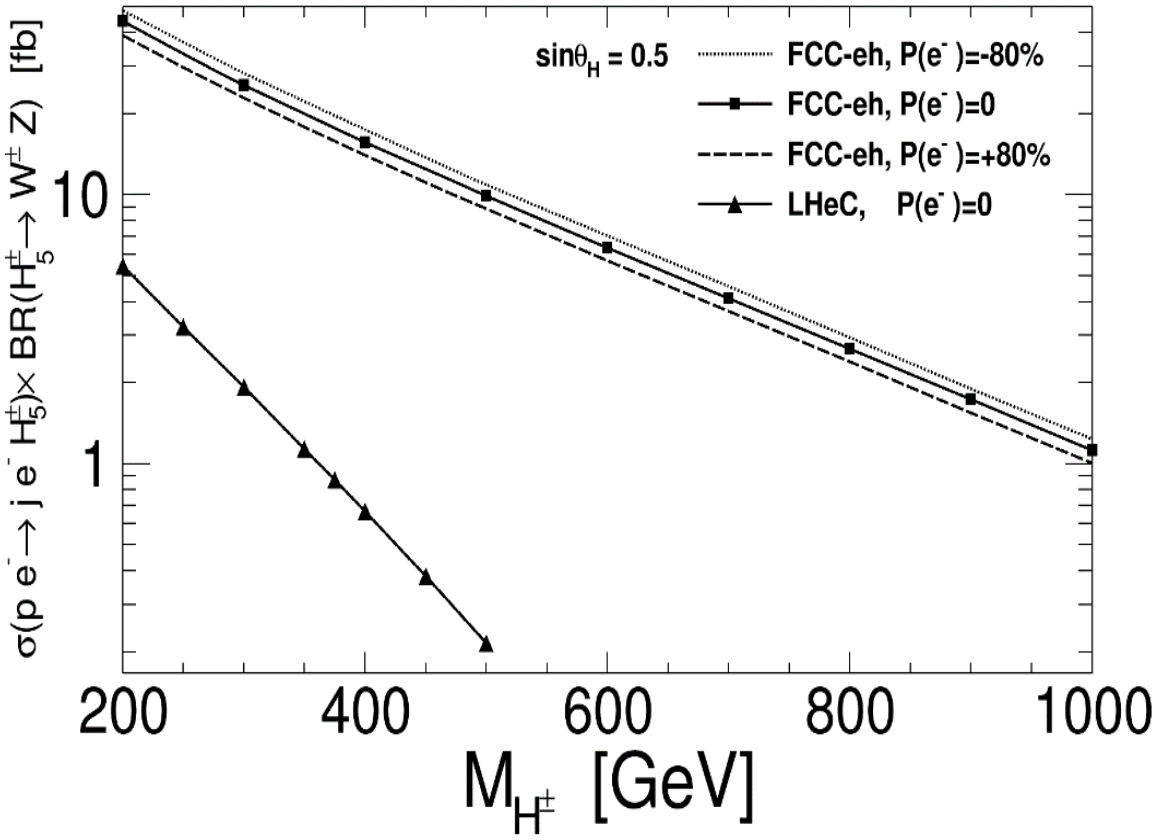

**SM Background**

**B1:** *p $e^-$ > j $e^-$ Z V, V → jj*

**B2:** *p $e^-$ > j $e^-$ Z jj*, jets from QCD radiation

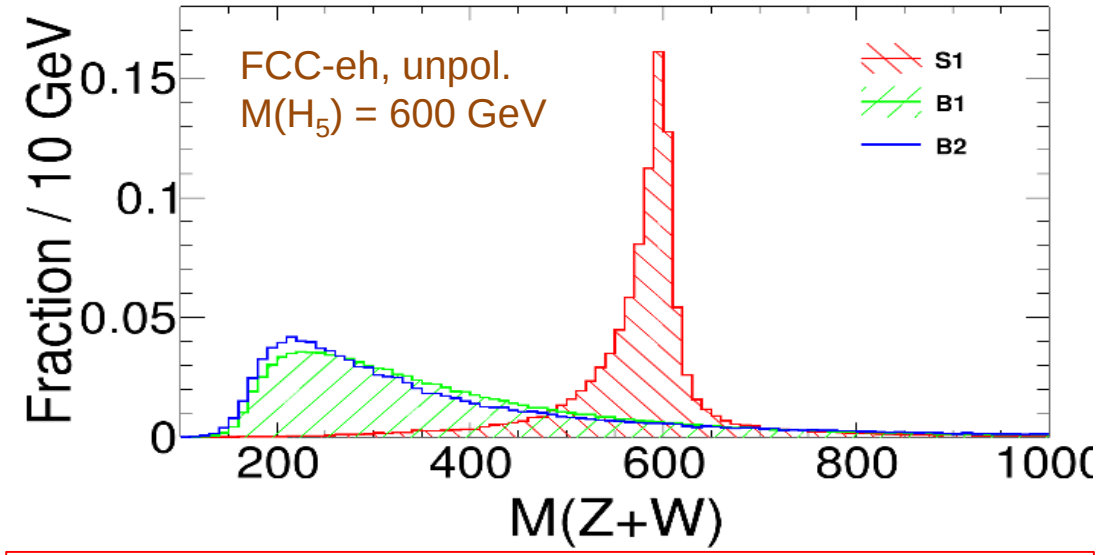
**Signal production cross section**

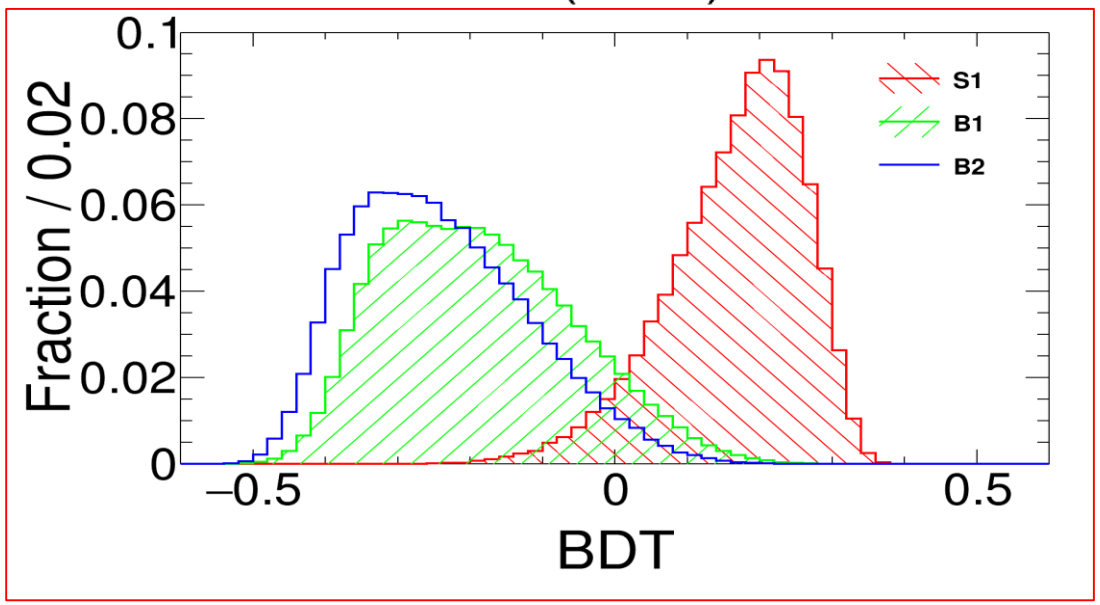
p $e^-$ → j $e^-$ $H_5^{\pm}$, ($H_5^{\pm}$ → Z $W^{\pm}$)



# BSM Higgs

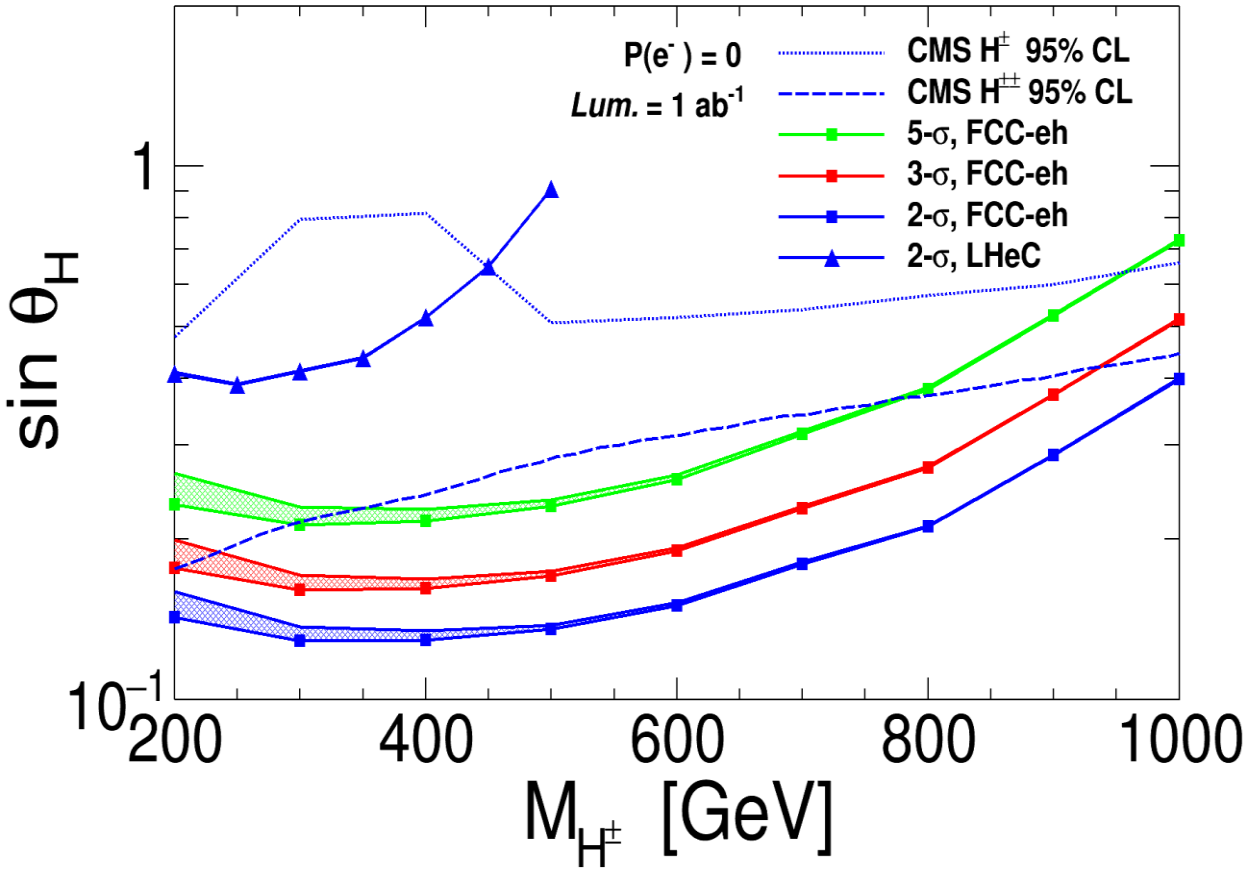
→ MVA-BDT analysis @ detector-level




## Limits for $H_5^{\pm}$ Search

→ 10% systematic uncertainty on background included



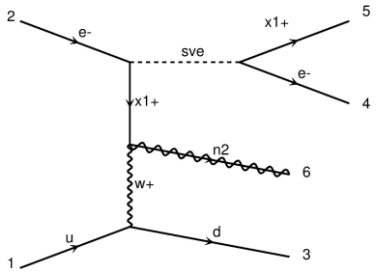
# R-Parity Conserving SUSY

**Dark matter via kinematical observables**

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

**Collider:**

FCC-eh ( Ep = 50 TeV, Ee = 60 GeV ).




**Motivations:**

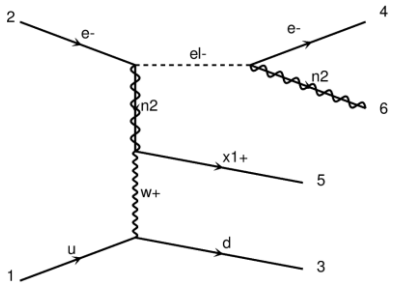
(a) Compressed Scenarios:

decay products are very soft, challenging at pp colliders.

(b) Light sleptons:

Can be motivited by the "muon g-2"

DM production can be enhanced by the slepton decays.




**Signal scenarios:**

Bino: m_{neutralino1};

Wino: m_{chargino1} = m_{neutralino2} = m_{neutralino1} + 1 GeV;

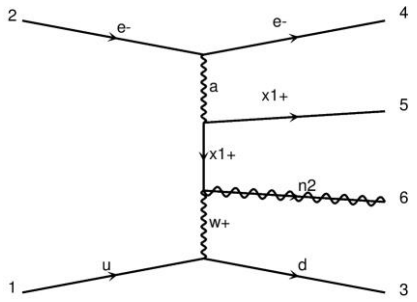
**(1) Light slepton scenario**

Slepton: m_{slepton_L} = m_{chargino1} + 35 GeV;

Sneutrino: m_{sneutrino} ~ m{slepton_L} - 9 GeV (tanβ = 30)

BR( slepton -> neutralino2,1 e-): 40%

BR(sneutrino -> chargino1 e-): 60%




**(2) Heavy slepton scenario**

Slepton & Sneutrino: Heavy and decoupled.

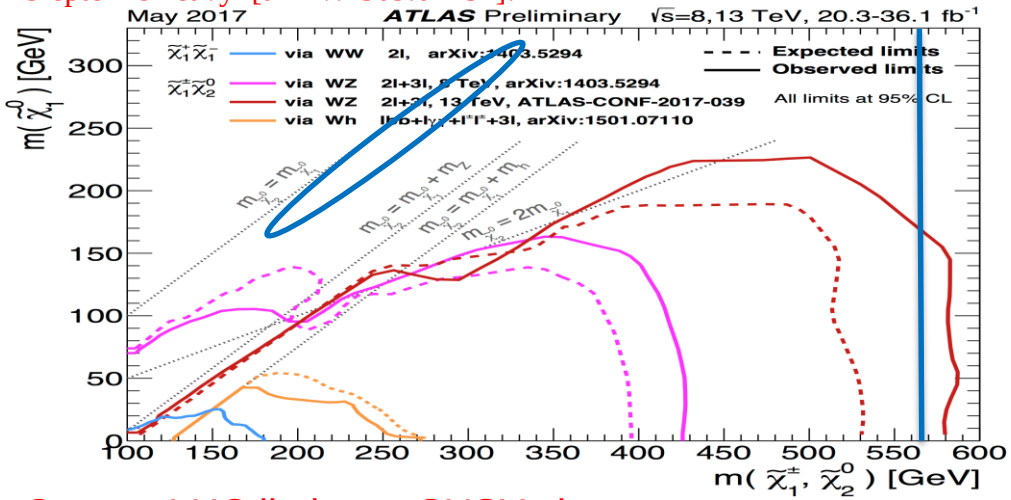
# R-Parity Conserving SUSY

## Dark matter via kinematical observables

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

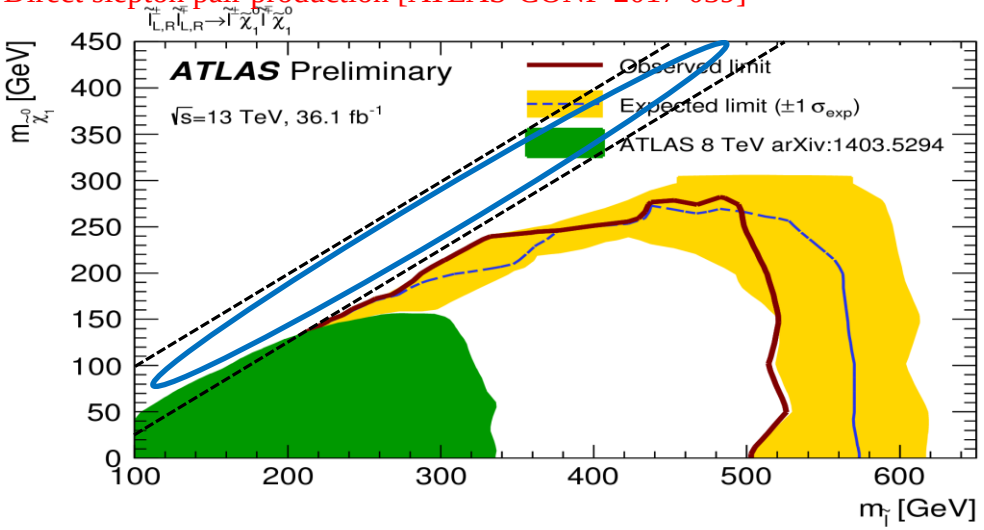
Current LHC limits on SUSY DM:

Slepton is heavy [arXiv:1509.07152]:

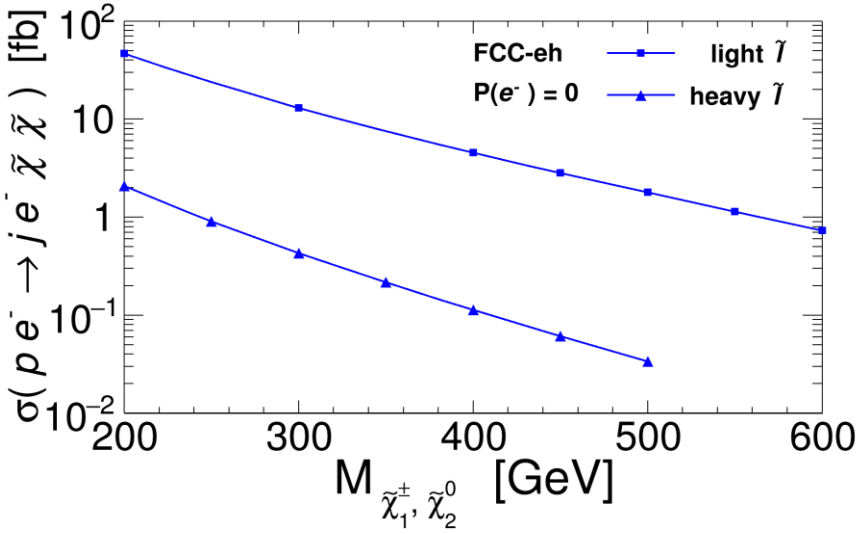



Current LHC limits on SUSY sleptons

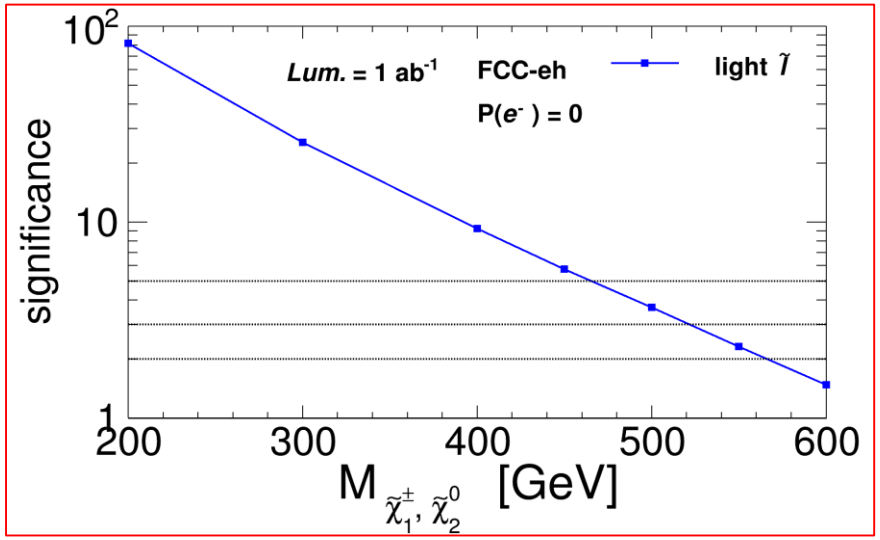
Direct slepton pair production [ATLAS-CONF-2017-039]




Production cross sections




Limits via MVA-BDT analysis @ detector-level



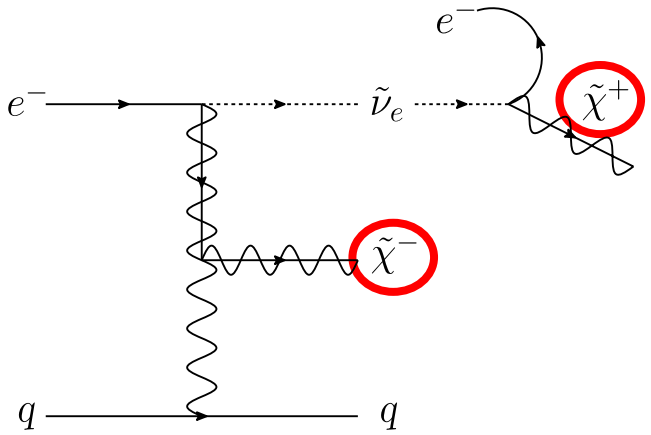
# R-Parity Conserving SUSY

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

comment on [Kaustubh Deshpande's talk "LLPs at FCC" ], before based on [slide from Sho Iwamoto]

**Simplest models at FCC-eh:**

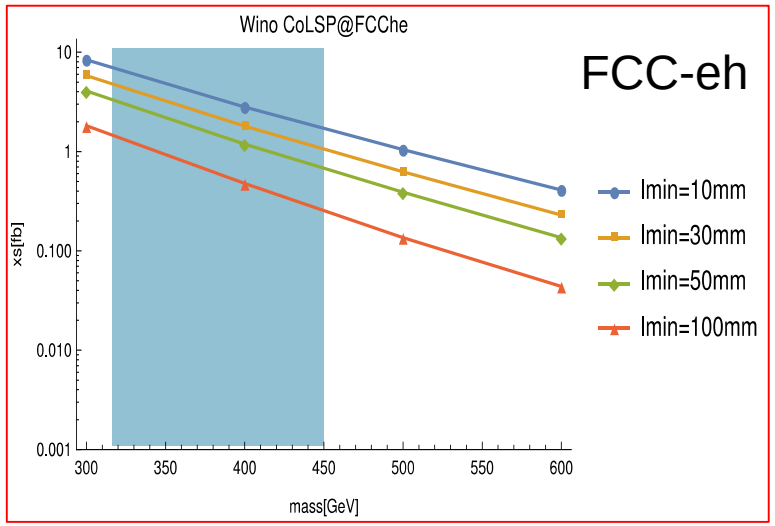
→ Cross section enhanced with "3-body production"




→ More scenarios are in progress.

**Simple efficiency analysis**

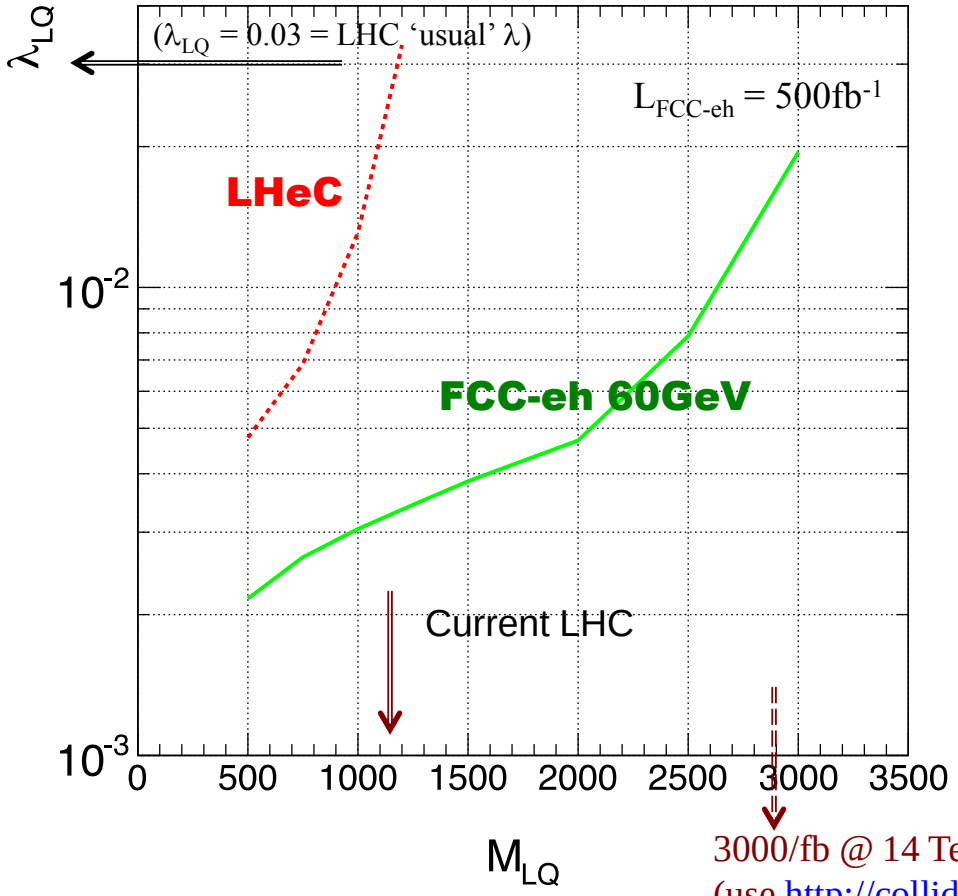
→ Requiring minimal detection length $l_{min}$
→ Charginos (Wino) with selectron




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

# Leptoquarks

**Limits of Leptoquarks**




**B anomaly (LHCb); 1-page**

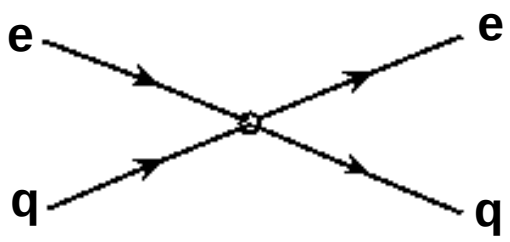
ep collider: sensitive to $\lambda < 0.03$

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, ... )

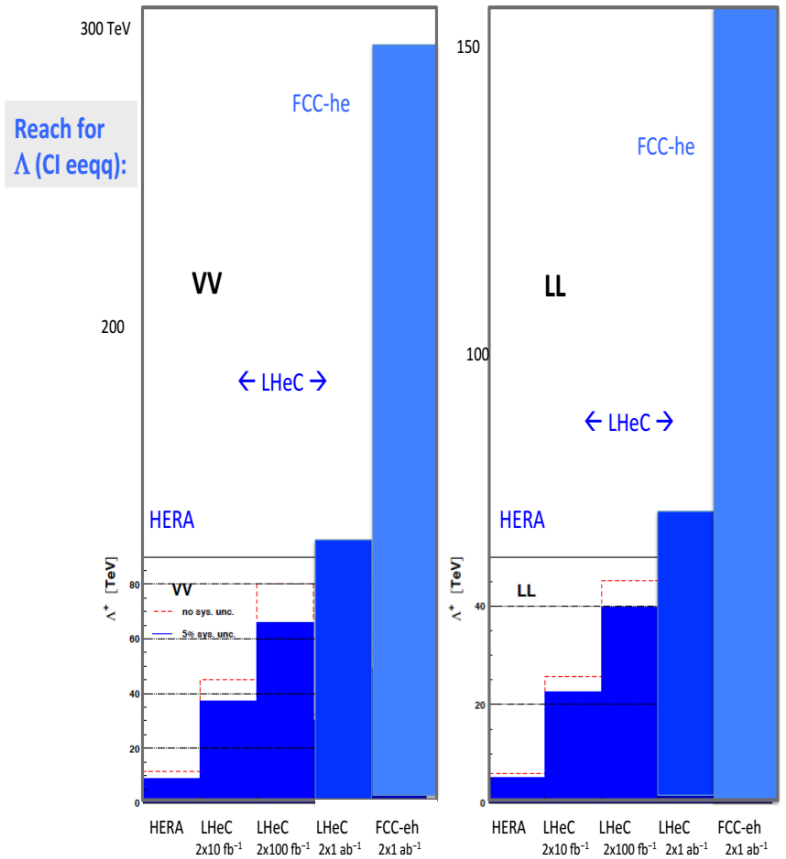
# Contact Interactions




**Contact interaction eeqq**

- if new physics enters at higher energy scales: Λ>> √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

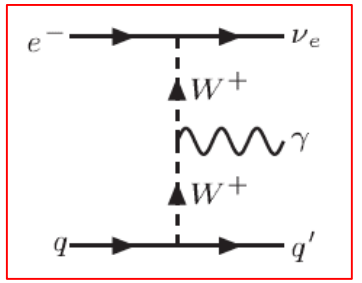
Comment on [Daniel Britzger's talk "EW measurements in ep" ], before

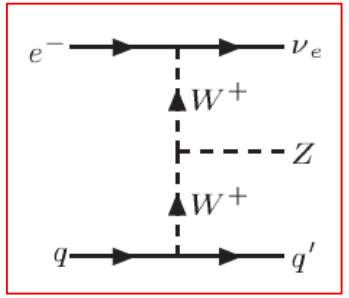
**Triple Gauge Couplings** (WWV, V = γ, Z)

→ 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] |
| $\lambda_\gamma$ | [-0.059, 0.017] | [-0.180, 0.170] | [-0.036, 0.044] | [-0.065, 0.061] | [-0.048, 0.037] |

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

[http://arxiv.org/pdf/1405.6056v1.pdf ]
[https://arxiv.org/abs/1406.7696 ]

At the e-p:

→ can clearly distinguish between CC events e + p → $\nu_e$ + jet (W-exchange) and NC events e + p → e + jet (photon or Z boson exchange)

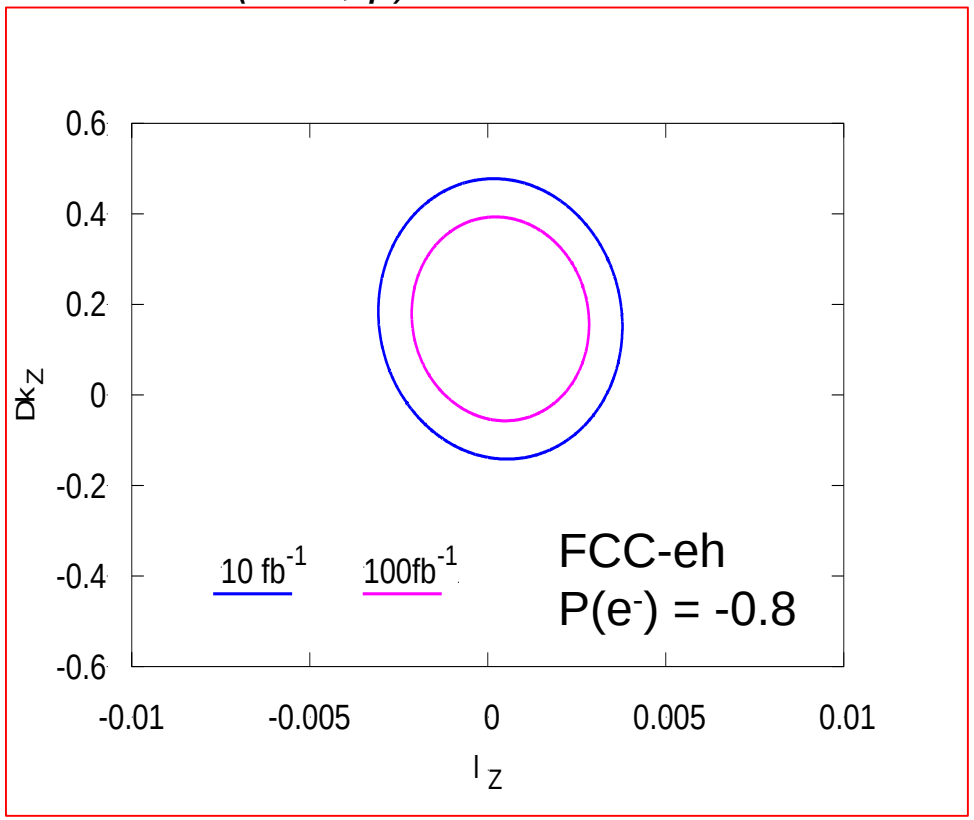
→ triggering on a final state photon, can provide very clean bounds on the anomalous TGC's !

# Anomalous Gauge Couplings

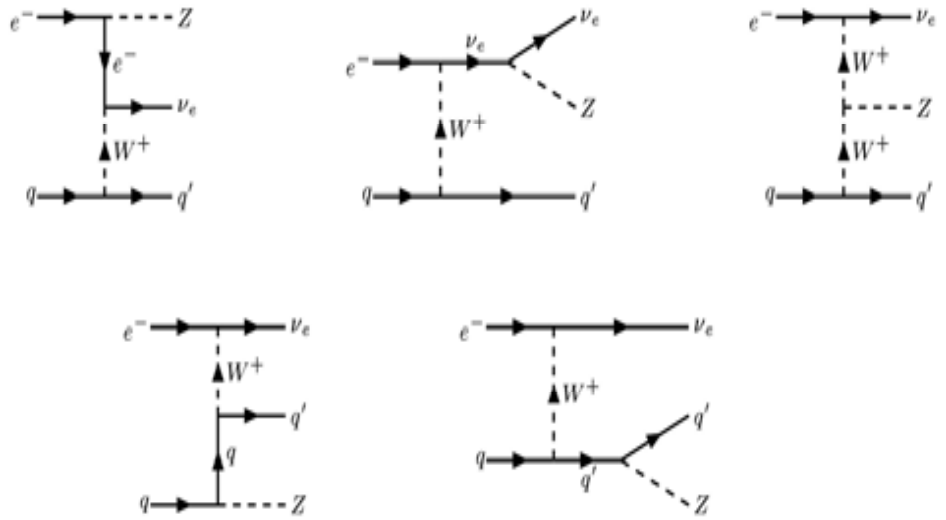
**Triple Gauge Couplings** (WWV, V = γ, Z)

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

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




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



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) |
|---|---|---|---|---|
| Δκγ | -0.420,0.480 | -0.250, 0.250 | 0.900 | 0.500 |
| λγ | -0.068,0.062 | -0.050, 0.042 | 0.130 | 0.092 |
| ΔκZ | -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 |

# Complementary between ep and pp

From [Georges Azuelos and Monica D'Onofrio ]

| | |
|---|---|
| Compositeness | • *4-fermion EFT: Lepton-quark compositeness scale*<br>• *Quark radius* |
| Leptoquarks and RPV squark decay | • *Accessible range largely excluded, but not completely*<br>• *Better measure of LQ characteristics, if they exist* |
| Anomalous Triple Gauge Couplings | • *Comparable to LHC* |
| Top FCNC couplings | • $tu\gamma, tc\gamma, tuH$ *couplings* |
| Vector-like leptons, heavy/excited leptons, bileptons, higher isospin lepton multiplets | • *No constraints on VLL, so far, at LHC*<br>• *Extend sensitivity to* $e\gamma$ *for lower masses* |
| Heavy neutrinos, Majorana neutrinos, sterile neutrinos | • *Symmetry-protected see-saw model* |
| SUSY EW: compressed scenario, Higgsino, (dark sector) | • *Long-lived neutral particles*<br>• *Disppearing tracks* |
| Anomalous Quartic Gauge Couplings | • *Better control on background:*<br>*no gluon exchange diagrams (mostly FCC?)* |
| Extended Higgs sector: higher isospin multiplet | • *Singly- and doubly- charged higgs by VBF (mostly FCC)* |

# 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...

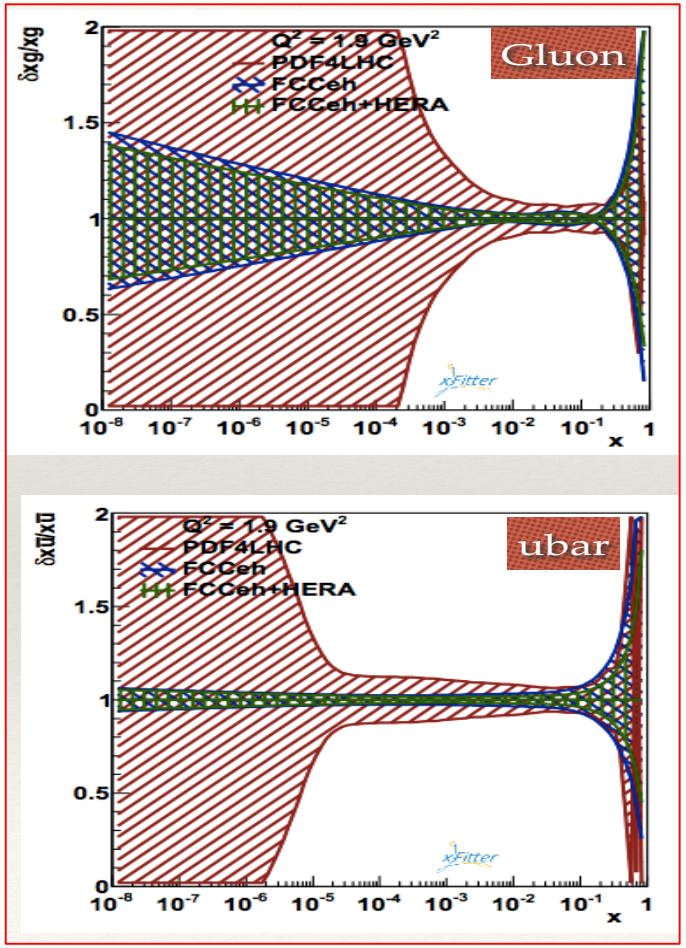
- ★ Ideal to search and study properties of new particles with
  → couplings to electron-quark, EW production, multi-jets final states

- ★ 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

# Improved PDF Measurements @ LHeC & FCC-eh




→ 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

# Searches to be followed in a nutshell

From [Georges Azuelos and Monica D'Onofrio ]

| Analysis + Target | People | Status | Overlap |
|---|---|---|---|
| Contact Interaction and quark radius (LHeC/FCC) | To be defined, looking for people who did this for HERA | Must redo previous studies | - |
| Leptoquarks (LHeC/FCC) | GA did initial studies | Ready at particle level, more needed ? | - |
| SUSY EWK prompt (LHeC/FCC) | Kechen, Sho, MD, GA | In progress - paper in preparation | - |
| SUSY EWK LLP (LHeC/FCC) | Kechen, Sho, MD, GA | In progress - paper in preparation | - |
| SUSY EWK higgsino - LLP (LHeC/FCC) disappearing tracks | Oliver Fischer, Jose Zurita, David Curtin | In progress - paper in preparation | - |
| Heavy neutrinos (FCC only?) | Oliver Fischer, Jose Zurita, David Curtin | In progress - paper in preparation | - |
| Vector-like leptons/ doubly-charged leptons (LHeC/FCC) | O. Cakir et al. | starting | - |
| Anomalous couplings EWK aTGC(LHeC+FCC) and aQGC(FCC) | Orhan Cakir et collaborators | In progress - update of the paper in preparation | Maybe SM EWK ? |
| (2) Top Anomalous couplings / FCNC (LHeC/FCC) | O Cakir et al. and Hao Sun | In progress / 2 different studies | Top&Higgs group |
| (2) BSM Higgs - H+ and H++ (FCC mostly) | GA, Kechen, Hao Sun (BSM) + James H, Hao (Higgs) | In progress (2 kind of studies - targeting different models) | Top&Higgs group |
| Instantons (LHeC/FCC) | Simone Amoroso | starting | QCD/SM |

# Leptoquarks

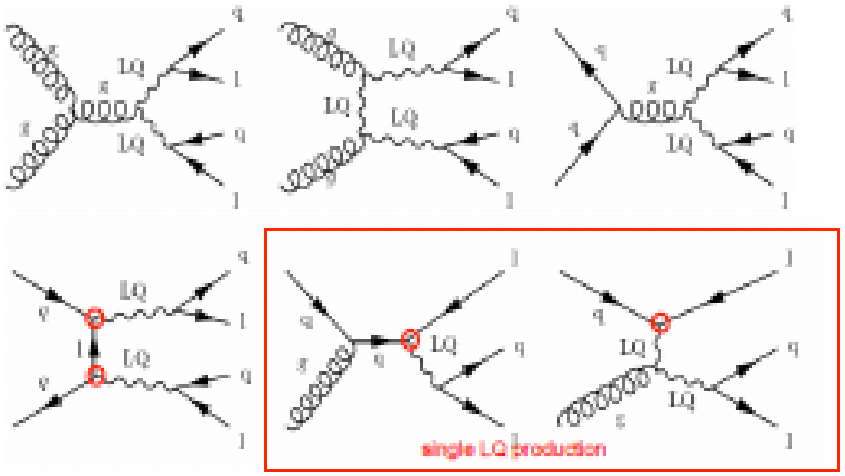
**Leptoquarks (LQs)**

→ 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**



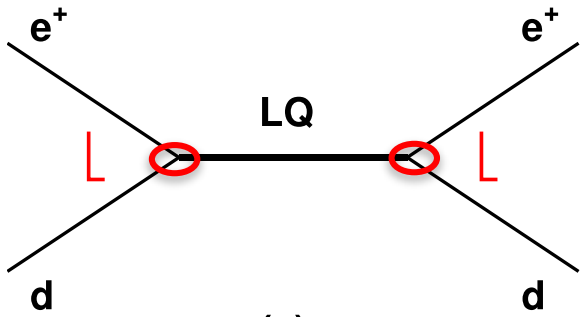

→ mostly pair production (from gg or qq)

→ not sensitive to the LQ-*q*-*l* coupling $\lambda$

**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

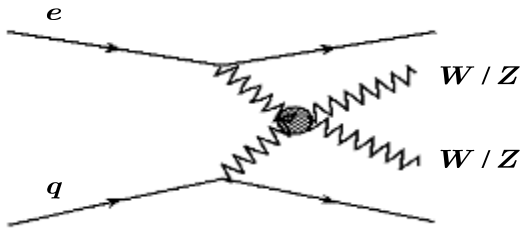



→ single, resonant production

→ sensitive to $\lambda$

# Vector Boson Scattering

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

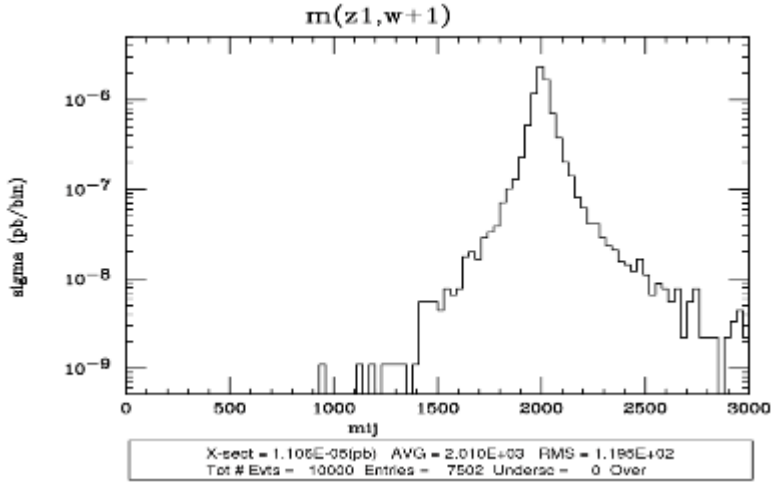



$$e^- q \to e^-(q)WZ, \quad (\nu q)WZ$$

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

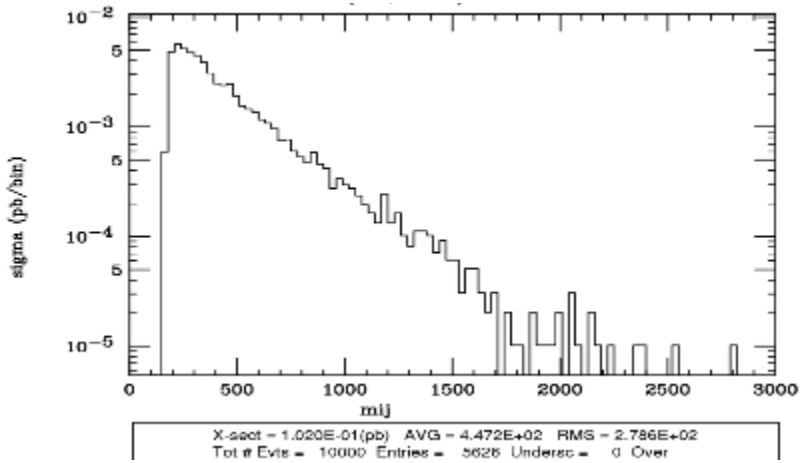
Preliminary results from [Georges Azuelos's study]

For a 2 TeV resonance




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

m(WZ), background




→ kinematics distinct between signal & background
→ cleaner, small background for masses ~ 2TeV
→ low pile-up

# Sterile Neutrinos

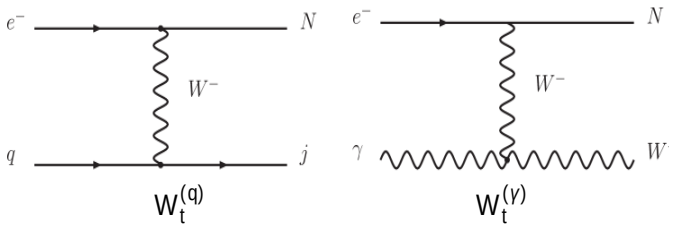
Slide from [Oliver Fischer ]

## 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 ]

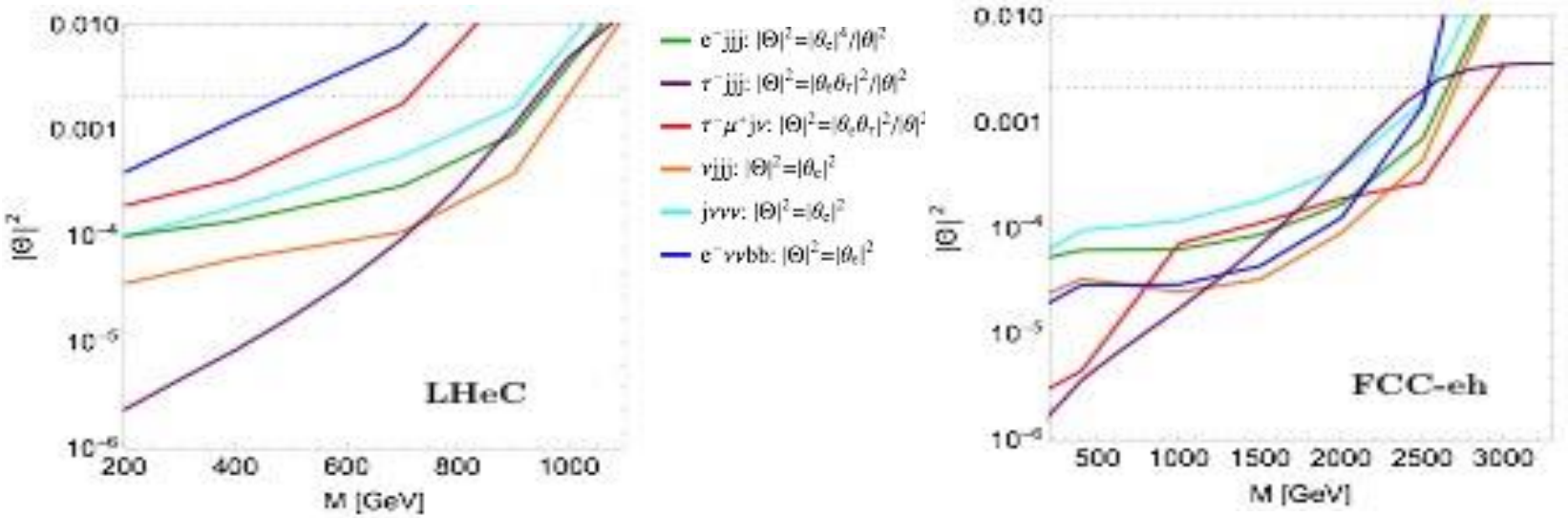
["Probing the Heavy Neutrinos of Inverse Seesaw Model at the LHeC", S. Mondal, S. K. Rai; Phys. Rev. D 94 (2016) no.3, 033008 ]

["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 ]



# Related previous talks at FCC week 2018

General introduction, physics, detector, CDR,
~~see [Claire Gwenlan's talk "PDFs at the FCC-eh" ], before~~
~~see [Uta Klein's talk "Higgs SM Couplings at FCC-ep" ],~~ before

Sterile neutrinos,
~~see [Oliver Fischer's talk "Heavy neutrino discovery prospects at FCC"]~~, before

[Daniel Britzger, "EW measurements in ep" ], before

~~[Kaustubh Deshpande, "LLPs at FCC" ], before~~

After:
~~[Christian Schwanenberger, "Top physics in ep" ]~~