BSM Physics @ ep Colliders

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on behalf of
the LHeC/FCC-eh BSM Physics Group

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Thank Monica D'Onofrio & Georges Azuelos for preparing the slides.

Introduction

★ ep collider is ideal to study common features of electrons and quarks with
→ EW / VBF production, LQ, multi-jet final states, forward objects

★ 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 difficulties:
low production rate for NP processes due to small $\sqrt{s}$

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

Outline

★ **Indirect impact from improved PDF**

★ **Direct Searches**

- BSM Higgs: invisible decay; H->4b, H->multi-j, H^+, H^{++}
- RPC SUSY: DM, sleptons
- Anomalous gauge couplings: VVV , VVVV
- Leptoquarks & RPV SUSY squarks: (limits, quantum # & couplings)
- Contact interactions: *eeqq* (very heavy LQ, compositeness)
- Vector boson scattering
- BSM in the top sector: see [Christian Schwanenberger's talk "*Top physics in ep*"]
- Sterile neutrinos & more long-lived particles: see [Oliver Fischer's talk "*Heavy neutrino discovery prospects at FCC*"]

★ **Outlook & Summary**

More details, see [https://twiki.cern.ch/twiki/bin/viewauth/LHeC/LHeCFCCehBSM]

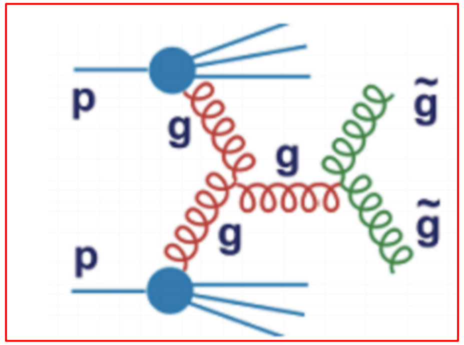
Indirect Impact on BSM from Improved PDF

see [Claire Gwenlan's talk "*PDFs at the FCC-eh*"]

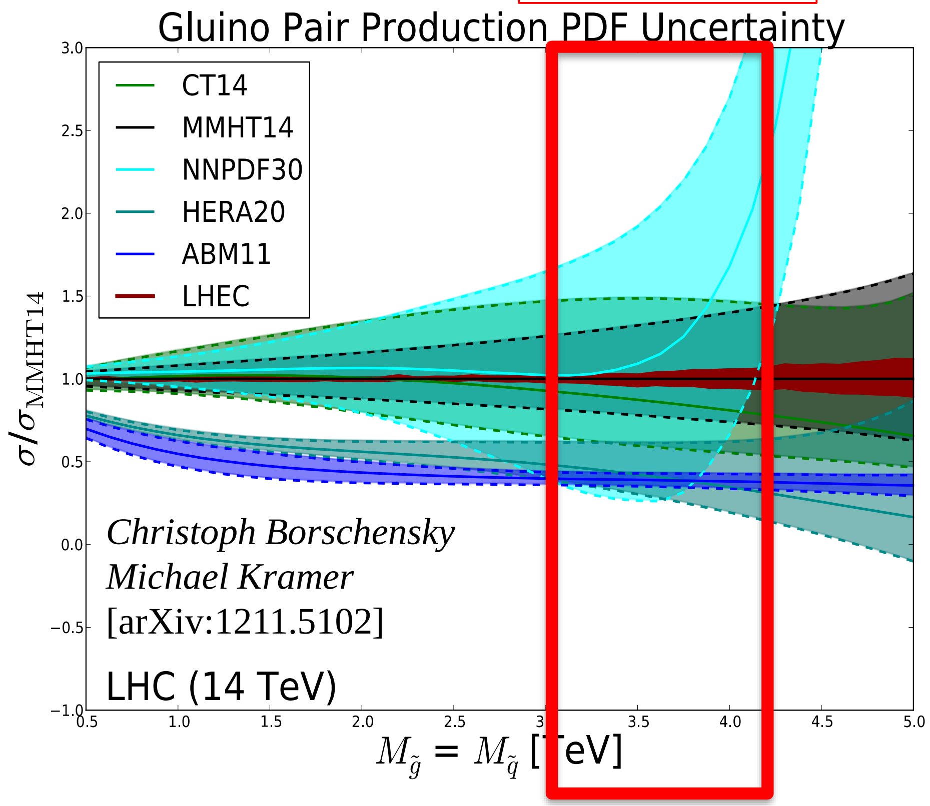
Example: gluon-gluon initiated processes

→ 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 can be crucial to improve the pp limits.

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

BSM Higgs

Higgs invisible decays

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

Higgs exotic decays

- $h \rightarrow 2\phi \rightarrow (b\bar{b})(b\bar{b})$ [S. Liu, Y. Tang, C. Zhang, S. Zhu, 1608.08458]
- $h \rightarrow \tilde{\chi}_1^0\,\tilde{\chi}_1^0 \rightarrow (3j)(3j)$ in RPV SUSY

Charged Higgs

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

  [H. Sun, X. Luo, W. Wei and T. Liu, Phys. Rev. D 96, 095003 (2017)]
- $H^{\pm}$, in Vector Boson Scattering

  [Georges Azuelos, Hao Sun, and Kechen Wang, 1712.07505]
- H^{+}, in 2HDM type III, $p\,e^{-} \rightarrow \nu j H^{+} \rightarrow \nu j\,(c\bar{b})$,

  [J. Hernández-Sánchez, etc. 1612.06316]

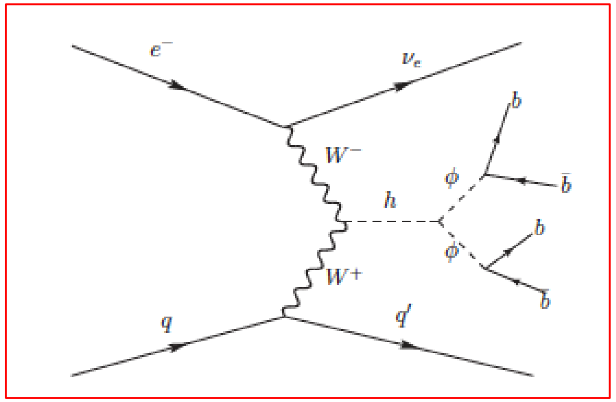
Higgs Exotic Decays

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

Introducing a new real scalar ϕ with effective interaction

$$\mathcal{L}_{eff} = \lambda_h v h \phi^2 + \lambda_b \phi \bar{b} b + \mathcal{L}_{\phi\,\mathrm{decay,other}}$$

Final state: 1 fwd j + 4 b + MET

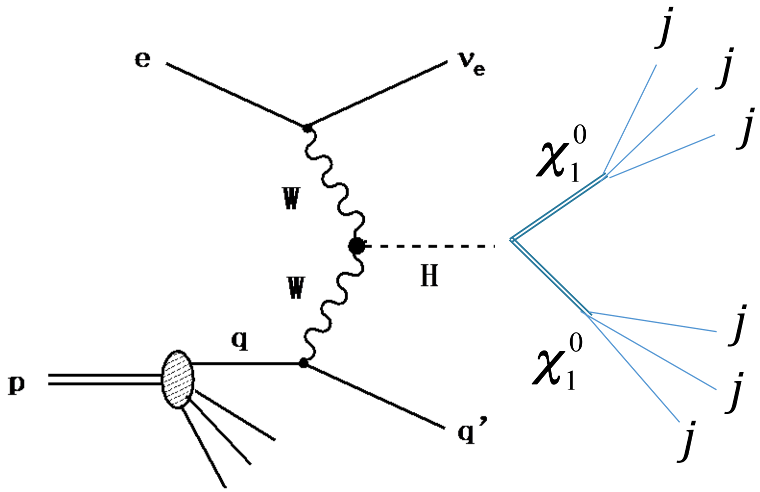


$h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to (3j)(3j)$ in RPV SUSY

- Neutralino might decay in 3 jets (UDD terms)

Some estimates:

N_{exp} = L × σ_h × BR($h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$) × [BR($\tilde{\chi}_1^0$ → jjj)]^2
In 1 ab^{-1}, σ_h=1008 fb (CC with P=-80%),
assuming BR($h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$) = 10%,
N_{exp} = 108000 × [BR($\tilde{\chi}_1^0$ → jjj)]^2 ~ 1000
→ if BR($\tilde{\chi}_1^0$ → jjj) ~ 10%, good potential at FCC-eh



Higgs Exotic Decays

$$\Phi \equiv \begin{pmatrix} 0 \\ \frac{\tilde{h}+v}{\sqrt{2}} \end{pmatrix}, \quad S \equiv \frac{h'+x}{\sqrt{2}}$$

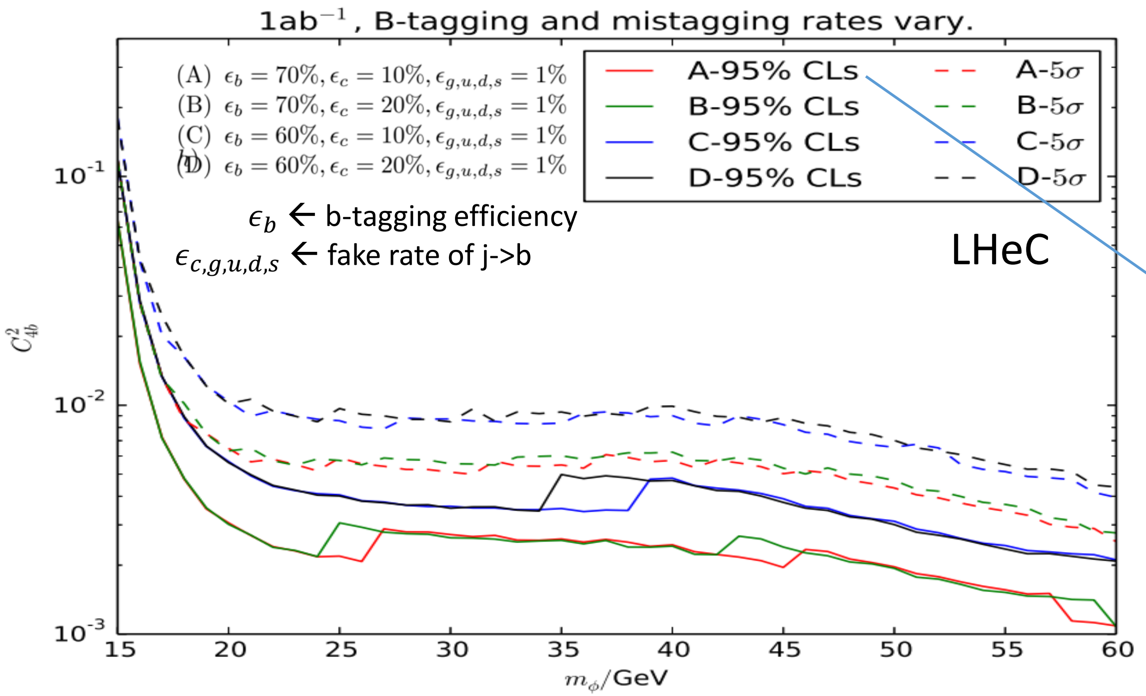
$$\begin{pmatrix} \phi \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \tilde{h} \\ h' \end{pmatrix}$$

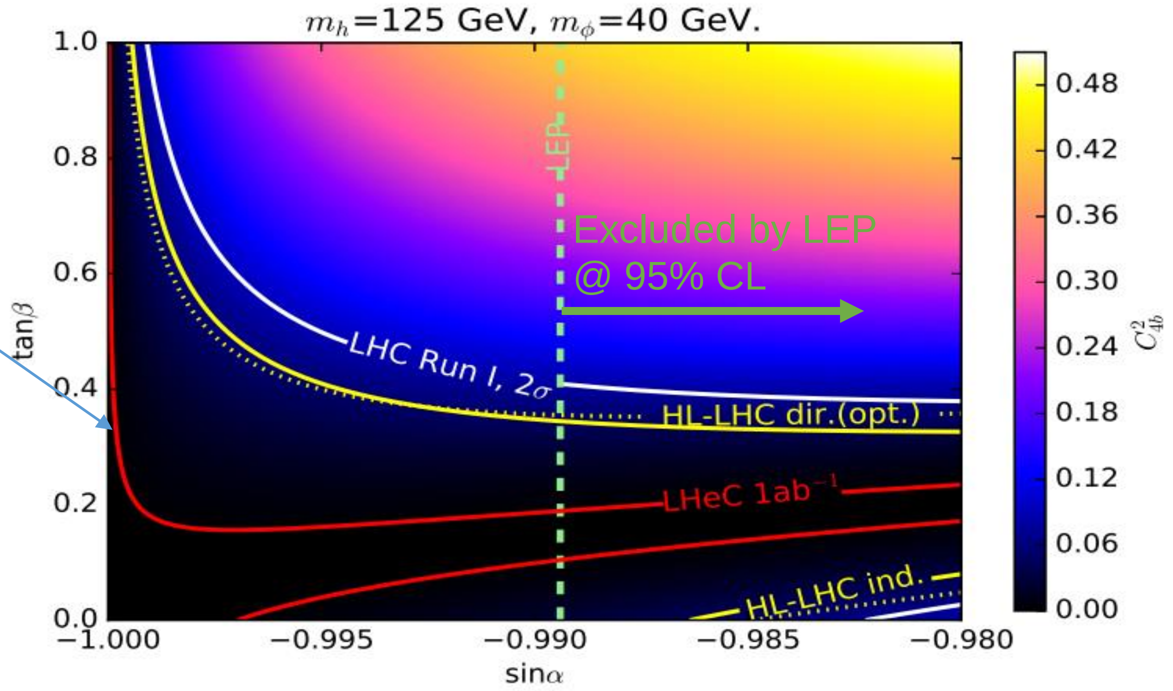
$$\tan\beta \equiv \frac{v}{x}$$

$h \to 2\phi \to (b\bar{b})(b\bar{b})$ [S. Liu, Y. Tang, C. Zhang, S. Zhu, 1608.08458]

Cut-based Analysis @ parton-level

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





LHeC, with 1 ab^{-1},
=> m_ϕ = 20 ~ 60 GeV, $C_{4b}^2 < 3 \times 10^{-3}$ @ 95% C.L.

→ Analysis @ FCC-eh in progress
→ Much better limits expected.

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

Theoretical Motivation of Georgi-Machacek Model:

→ No fundamental reason for a minimal Higgs sector => important to extending scalar sector with higher isospoin multiplets

→ Might generate a Majorana mass for neutrinos via the type-II seesaw mechanism

→ It preserves the custodial $SU(2)_C$ symmetry at tree level => keeping the EW ρ parameter ~ 1 => less constrained experimentally

Scalar sector of the GM model:

complex isospin doublet (ϕ^+, ϕ^0) with hypercharge Y=1;

real triplet $(\xi^+,\ \xi^0,\ \xi^-)$ with Y=0;

complex triplet $(\chi^{++},\ \chi^+,\ \chi^0)$ with Y = 2;

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

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

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

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

Δ

mixing : θ_H

Φ

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 : α → H, 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. $M(H_5)$, $\sin\theta_H$.

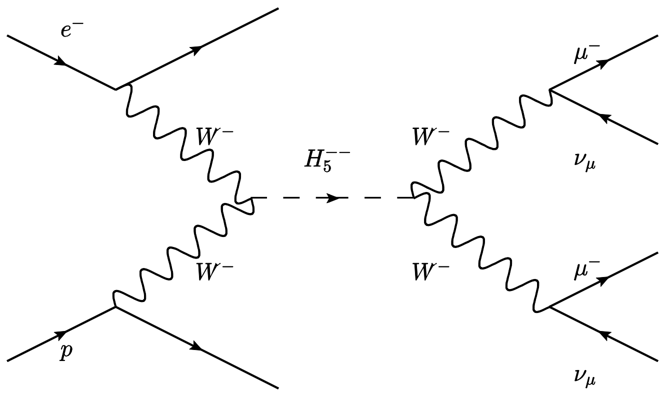
$H^{\pm\pm}$ in Vector Boson Scattering

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

Signal via WW-fusion in the GM model

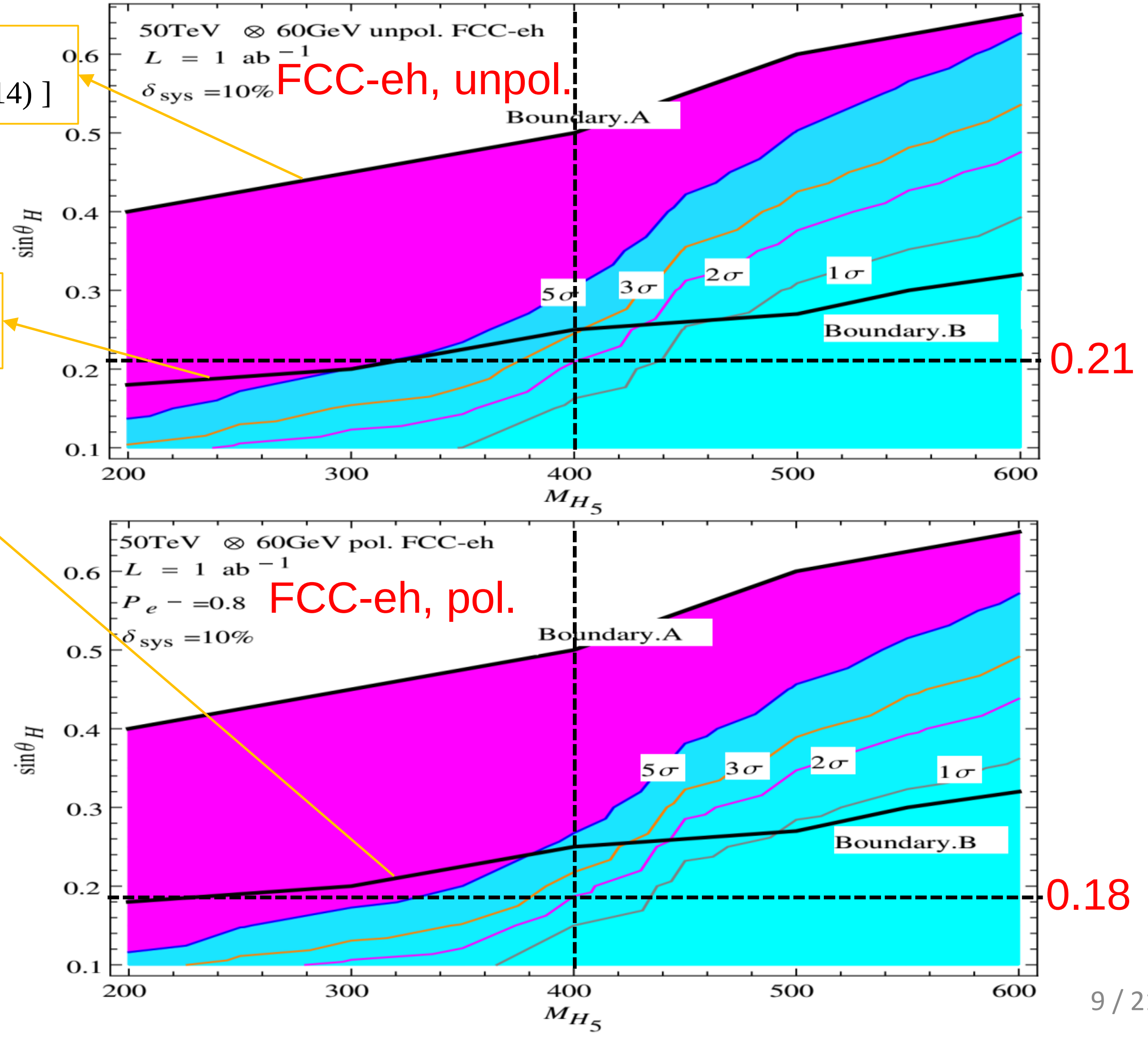
$p\, e^- \to j\, \nu_e\, (H_5^{--} \to W^- W^-) \to j\, \nu_e\, (\mu^-\nu_\mu)(\mu^-\nu_\mu)$

Final state: ≥ 1 j + 2 μ^- + MET



LHC limit from
[Phys. Rev. D 90, 115025 (2014)]

CMS $H^{\pm\pm}$ limit from
[CMS PAS SMP-17-004]



Cut-and-count analysis @ detector-level

Basic cut

$\not{E}_T \geq 10\text{GeV}$

$p^{j,l}_T \geq 10\text{GeV}$

$|\eta^j| \leq 5,\ |\eta^l| \leq 2.5,$

$\Delta R_{jj} \geq 0.4,\ \Delta R_{jl} \geq 0.4,\ \Delta R_{ll} \geq 0.4$

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

Optimized:

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

$\Delta R^{\mu\mu}$

$M^{\mu\mu}_{inv} > 75\text{GeV}$

$M^{\mu\mu}_T > 40\text{GeV}$

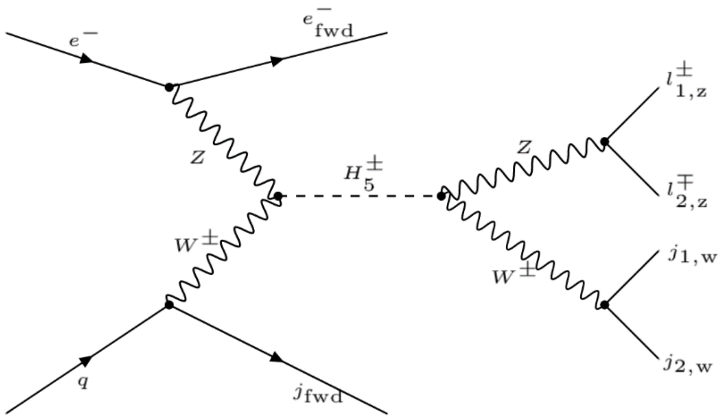
$H^{\pm}$ in Vector Boson Scattering

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

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, μ .



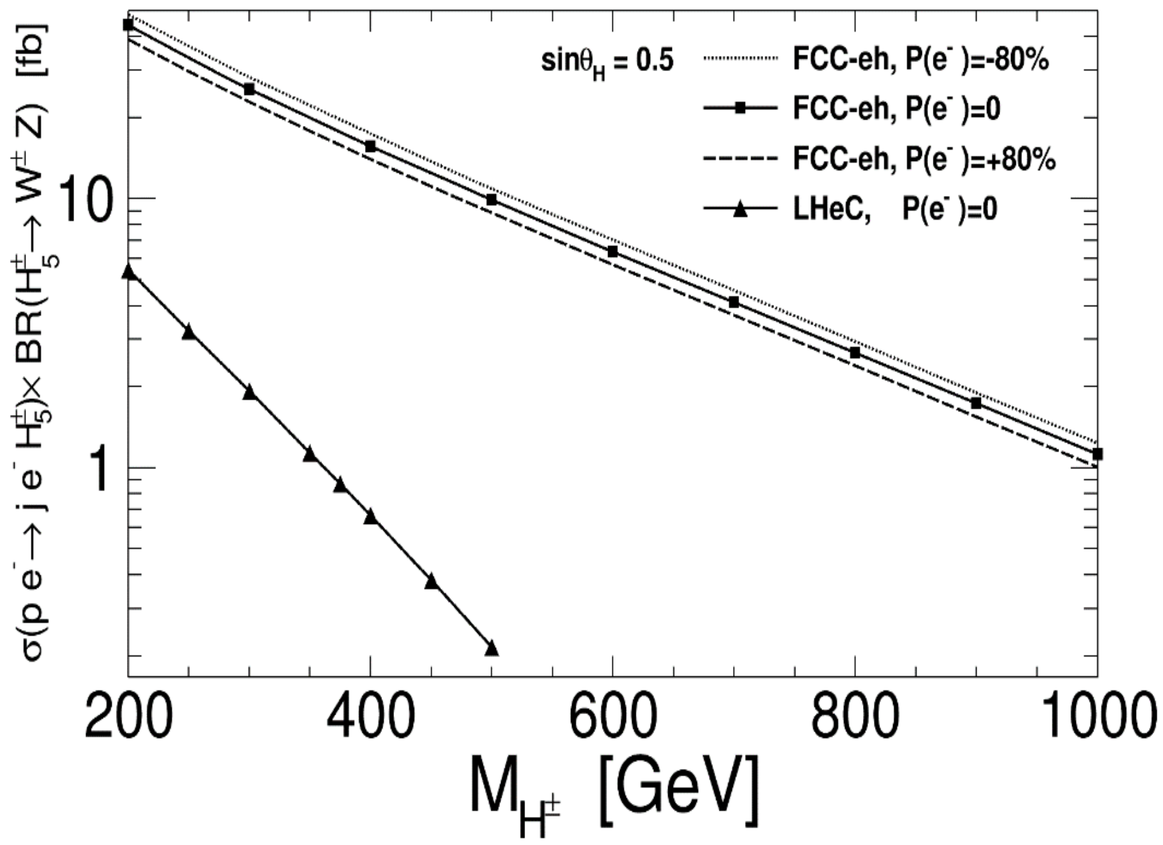
SM Background

B1: *p e^- > j e^- Z V, V → jj*

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

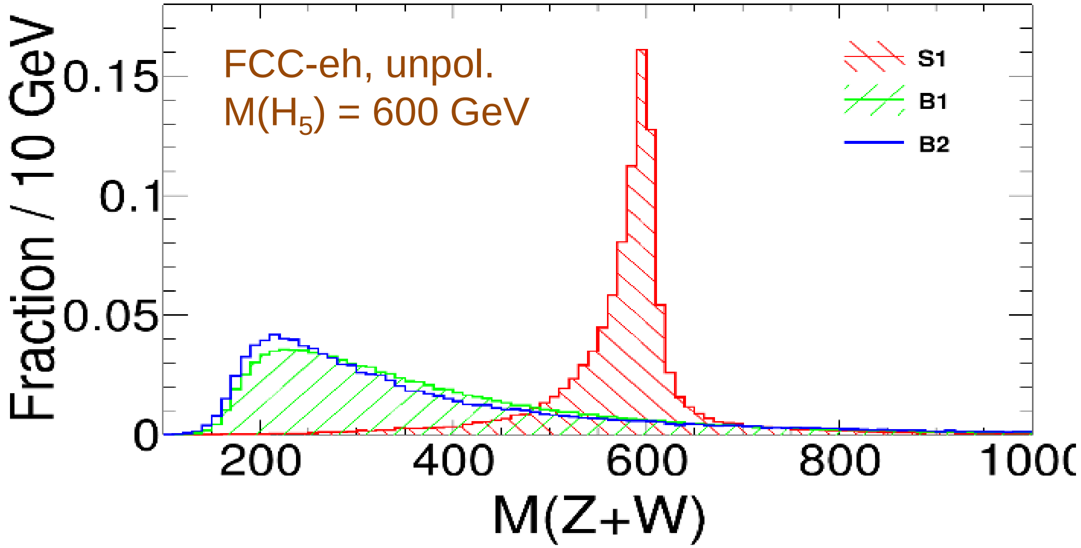
Signal production cross section

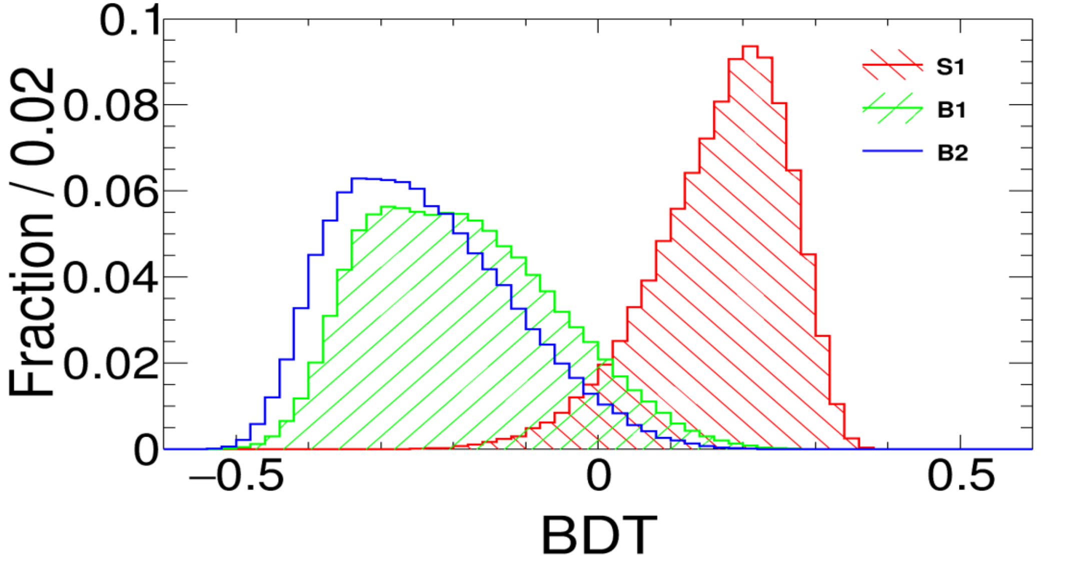
p e^- → j e^- $H_5^{\pm}$, ($H_5^{\pm}$ → Z $W^{\pm}$)



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

→ MVA-BDT analysis @ detector-level



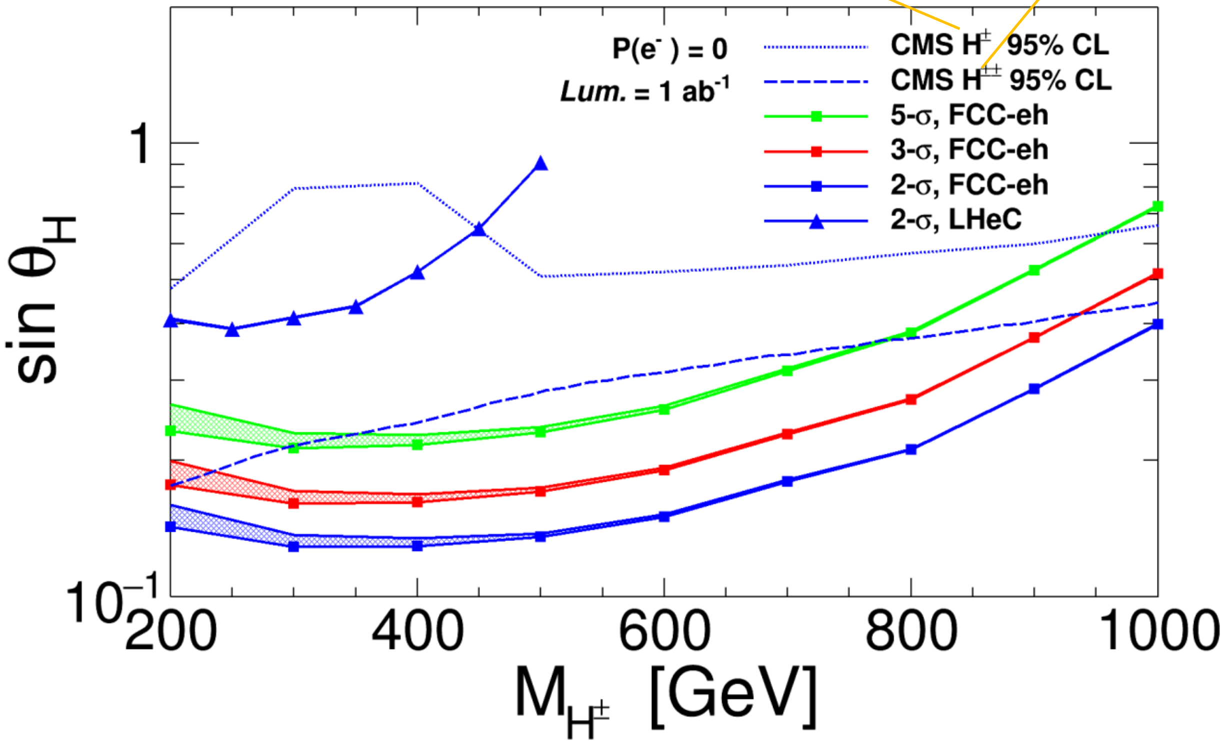


Limits for $H_5^{\pm}$ Search

→ 10% systematic uncertainty on background included

[Phys.Rev.Lett. 119 (2017)] 15.2 fb^{-1} @ 13 TeV

[arXiv:1709.05822] 35.9 fb^{-1} @ 13 TeV



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

→ Compared with present CMS limits, FCC-eh limits are much stronger around 500 GeV.

H^+ in 2HDM type III

[J. Hernández-Sánchez, etc. 1612.06316]

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

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	[fb]s $.cb$
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

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

(Here, $\epsilon_b = 0.50, \epsilon_c = 0.1$ and $\epsilon_j = 0.01$, where $j = u, d, s, g$)

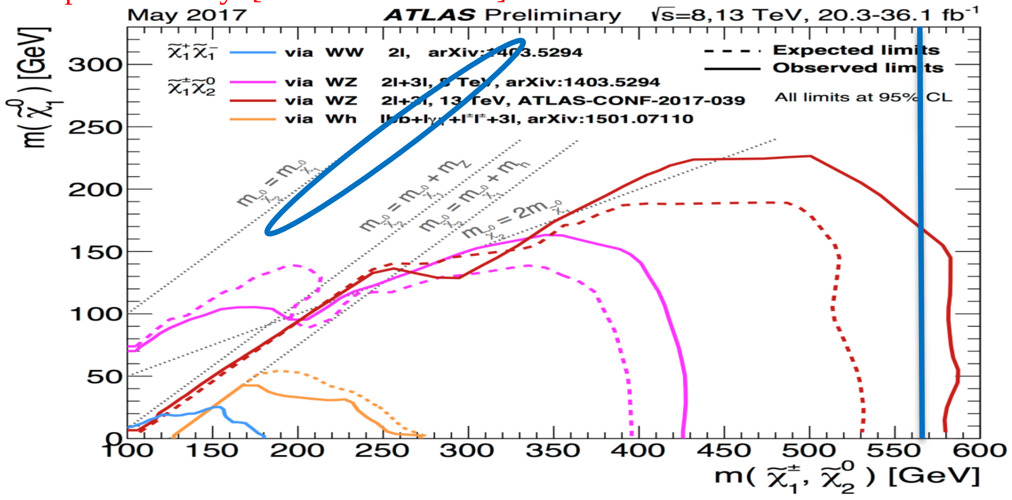
	S	B	$\mathcal{S} = S/B^{1/2}$
Ia ($X = 5, Y = 5$)	243.4	3835.1	3.9
Ib ($X = 5, Y = 5$)	249.5	3835.1	4.0
II ($X = 32, Y = 0.5$)	230	3835.1	3.7
Y ($X = 32, Y = 0.5$)	187.8	3835.1	3.0

→ H^+ of the 2HDM-III with mass 110 GeV would be observed with ~ 3–4 σ significance @ LHeC with 100 fb^{-1}
→ Challenging at pp due to large background for multi-jet final state
→ Good discovery potential at FCC-eh

R-Parity Conserving SUSY

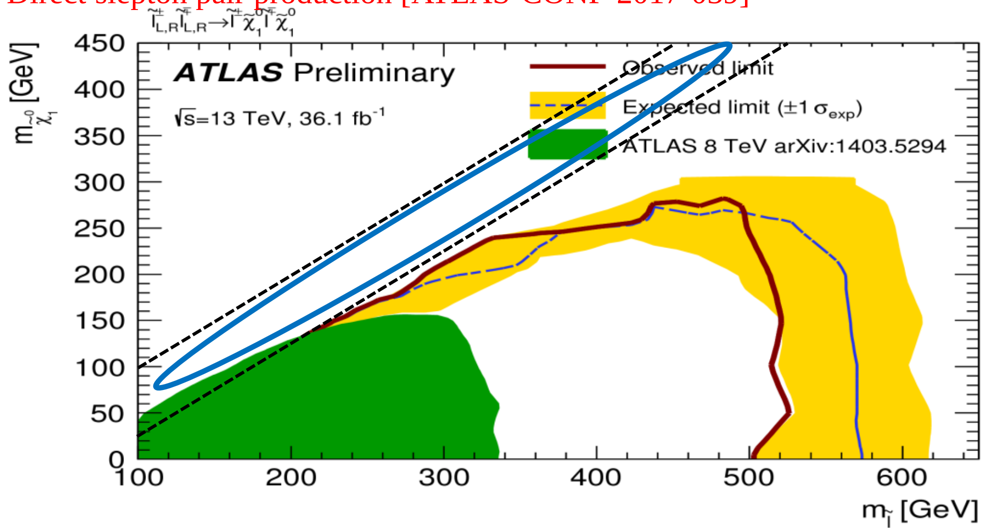
Current LHC limits on SUSY DM:

Slepton is heavy [arXiv:1509.07152]:



Current LHC limits on SUSY sleptons

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



Complementary at ep:

(a) Compressed Scenarios:

→ decay products are very soft, challenging @ pp

→ fwd *j/e*, low bkg, feasible @ ep

(b) Light sleptons:

→ can be motivited by the "muon g-2"

→ DM production can be enhanced by the slepton decays.

Signal scenarios:

Bino: $M_{\tilde{\chi}_1^0}$

Wino: $M_{\tilde{\chi}_1^\pm} \sim M_{\tilde{\chi}_2^0} = M_{\tilde{\chi}_1^0} + 1\text{ GeV}$

(1) Slepton slightly heavier (light slepton case)

Slepton: $M_{\tilde{l}_L} = M_{\tilde{\chi}_1^\pm}$ + 35 GeV

Sneutrino: $M_{\tilde{\nu}} \sim M_{\tilde{l}_L}$ – 9 GeV

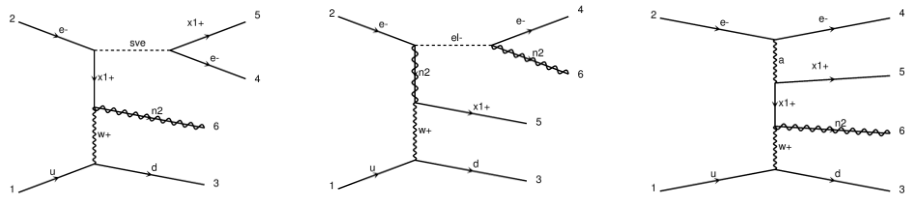
(2) Slepton & Sneutrino heavy and decoupled (Heavy slepton case)

R-Parity Conserving SUSY

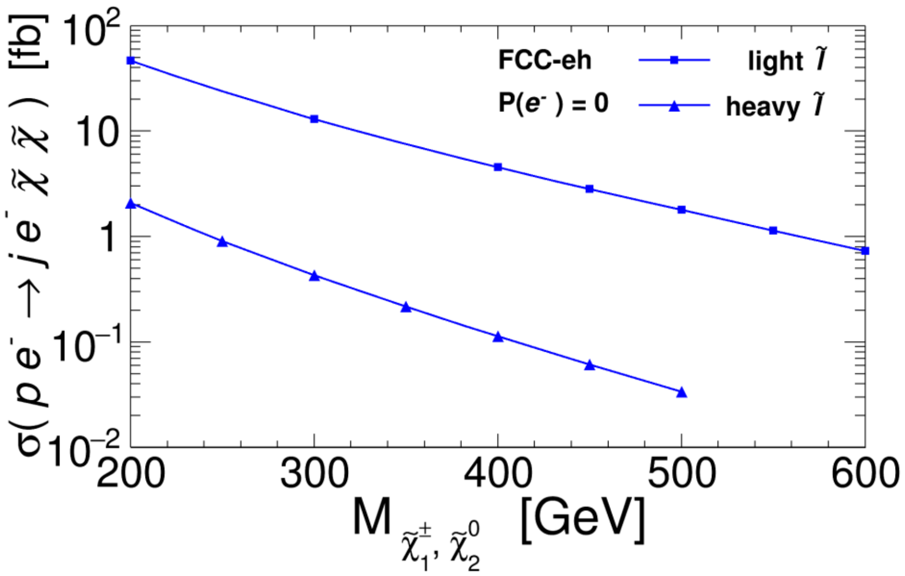
Dark matter via kinematical observables

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

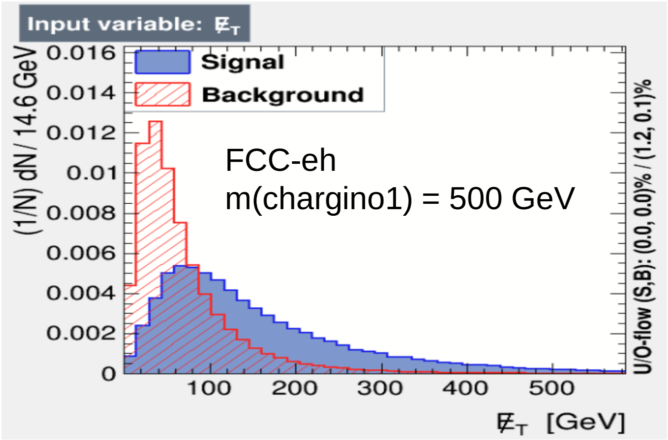
MVA-BDT analysis @ detector-level

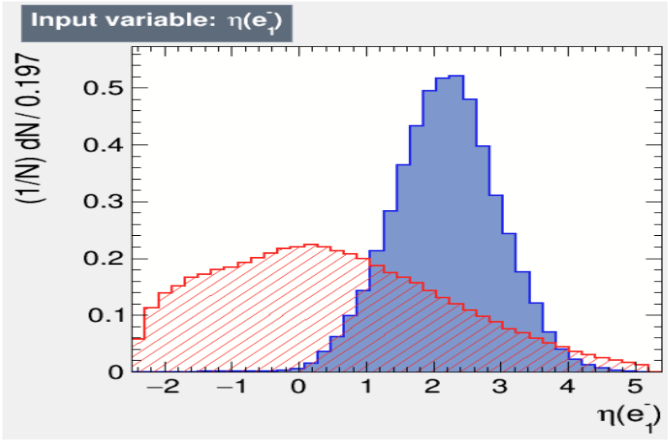


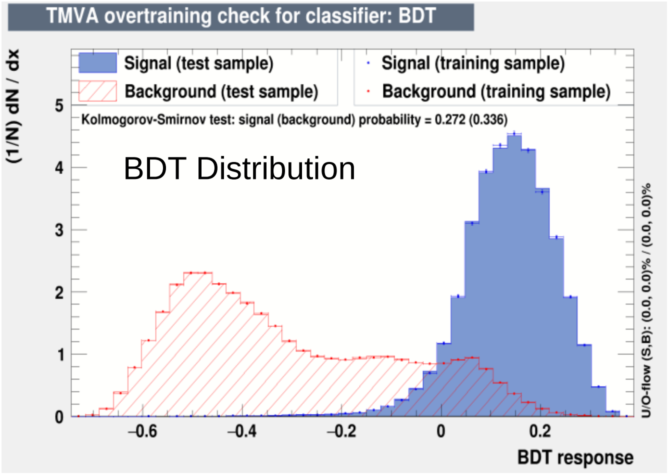
Production cross sections

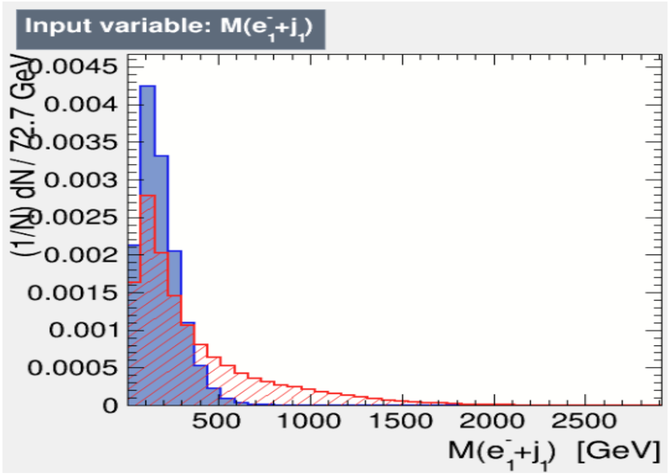


Example input observables







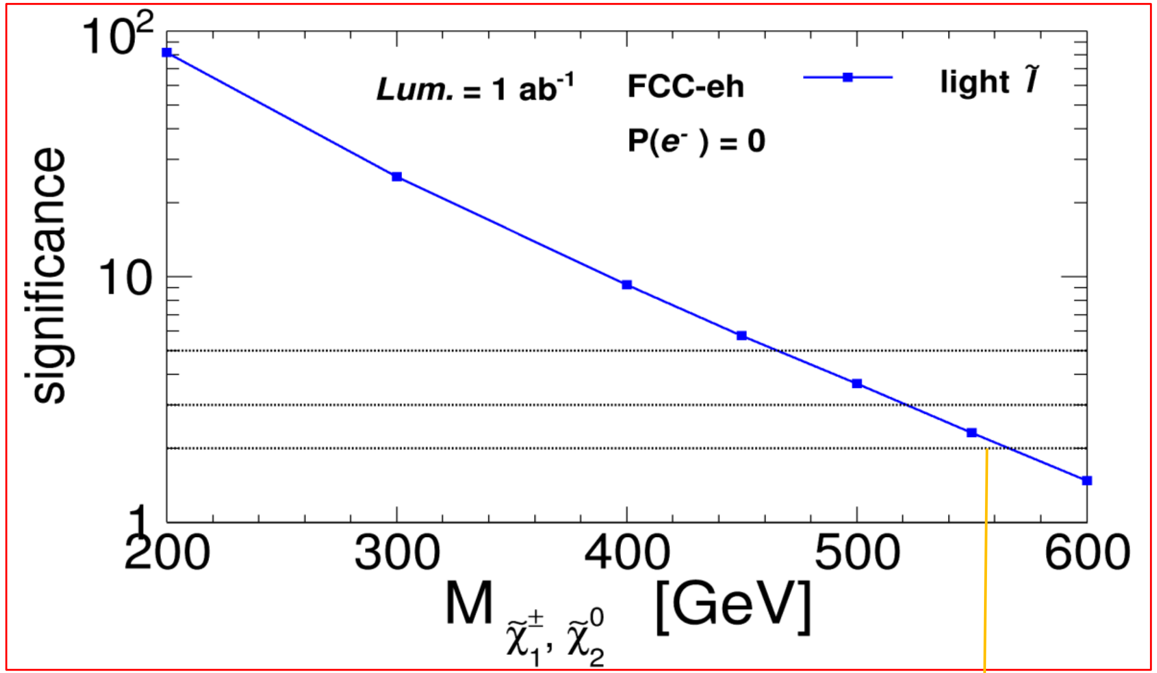


R-Parity Conserving SUSY

Dark matter via kinematical observables

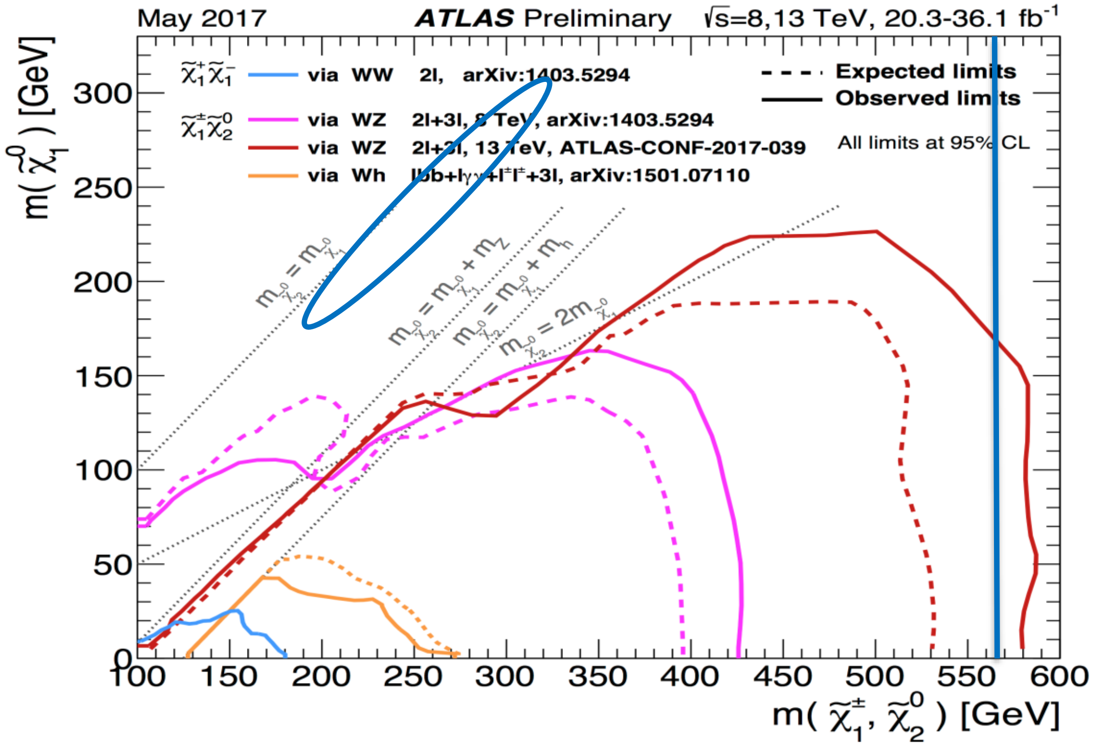
Preliminary results from [Kechen Wang, Sho Iwamoto, Monica D'Onofrio, Georges Azuelos]

Limits on DM mass



1 ab^{-1} @ FCC-eh:
> 560 GeV @ 2-σ

Complementary between ep and pp



R-Parity Conserving SUSY

DM & Sleptons via disappearing tracks

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

Higgsino:

disappearing tracks + soft pion (from chargino decay)

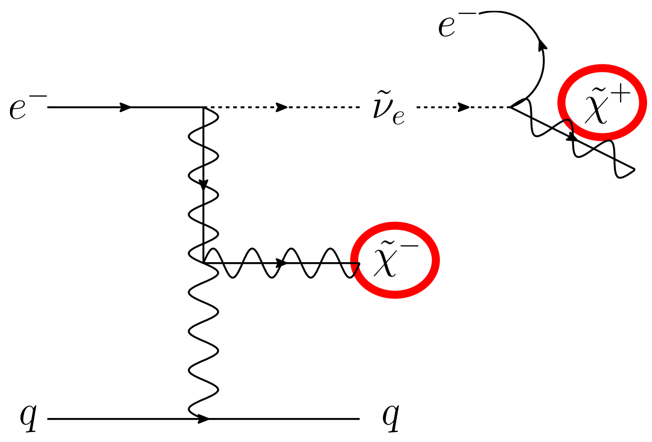
see [Kaustubh Deshpande's talk "*LLPs at FCC*"]

[David Curtin, Kaustubh Deshpande, Oliver Fischer, Jose Zurita, 1712.07135]

Other scenarios at FCC-eh:

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

→ Cross section enhanced with "3-body production"

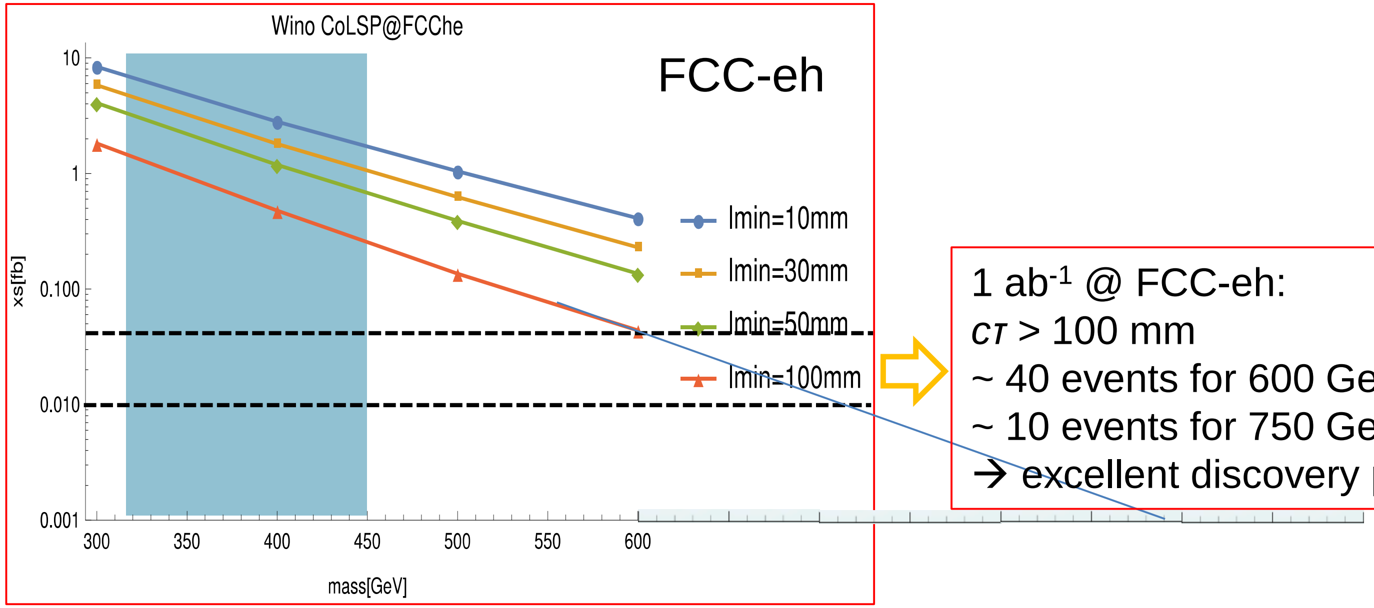


→ More scenarios are in progress.

Simple efficiency analysis

→ Requiring minimal detection length l_{min}

→ Charginos (Wino) with selectron



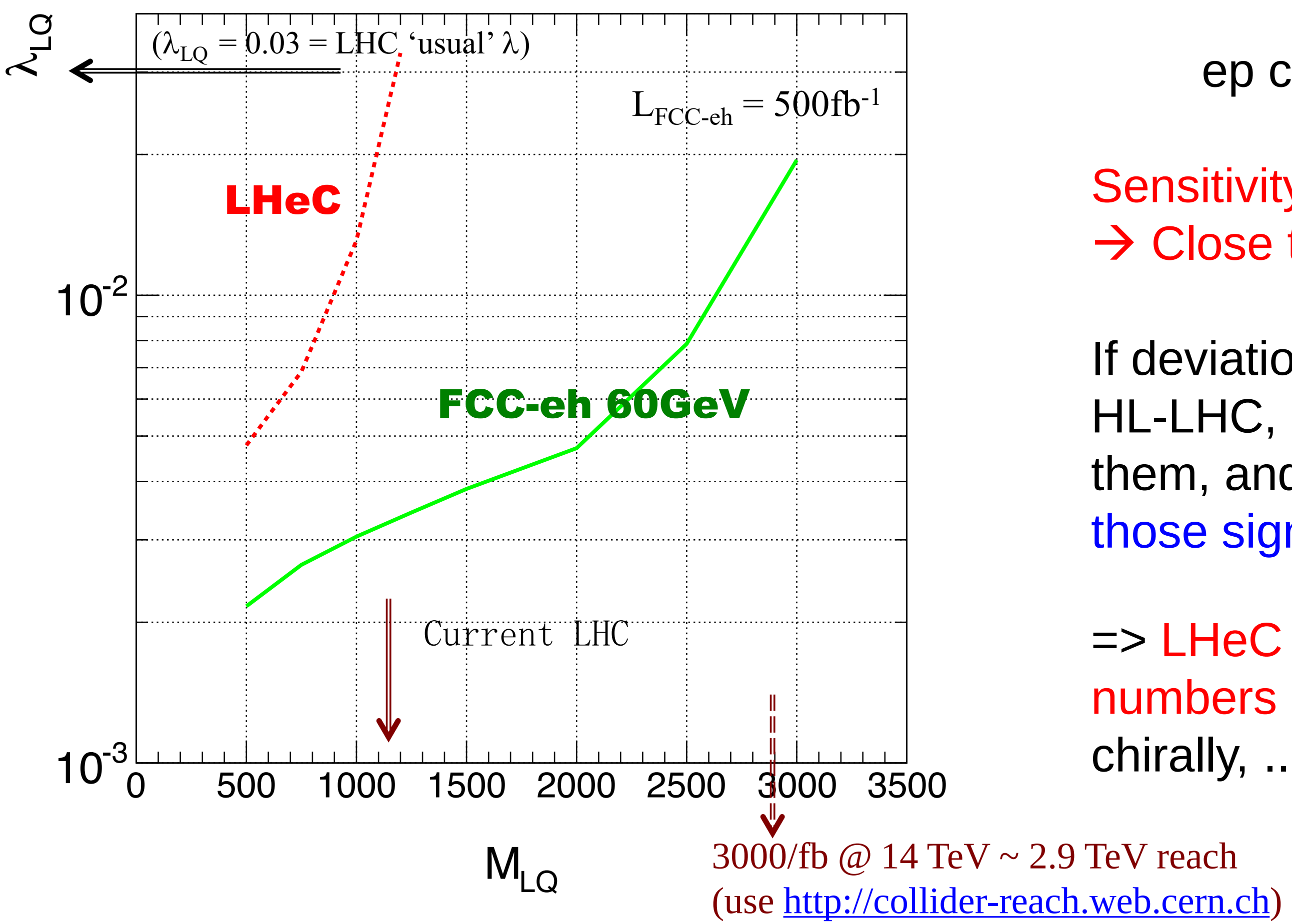
1 ab^{-1} @ FCC-eh:
$c\tau$ > 100 mm
~ 40 events for 600 GeV
~ 10 events for 750 GeV
→ excellent discovery potential

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

Leptoquarks

Limits of Leptoquarks

(increased interest in LQ due to recent B anomalies)



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 interaction *eeqq* (very heavy LQ, compositeness)
Reach for Λ @ FCC-eh with 2 ab^{-1} → VV: ~290 TeV; LL: ~160 TeV
[LHeC results: see CDR 2012]

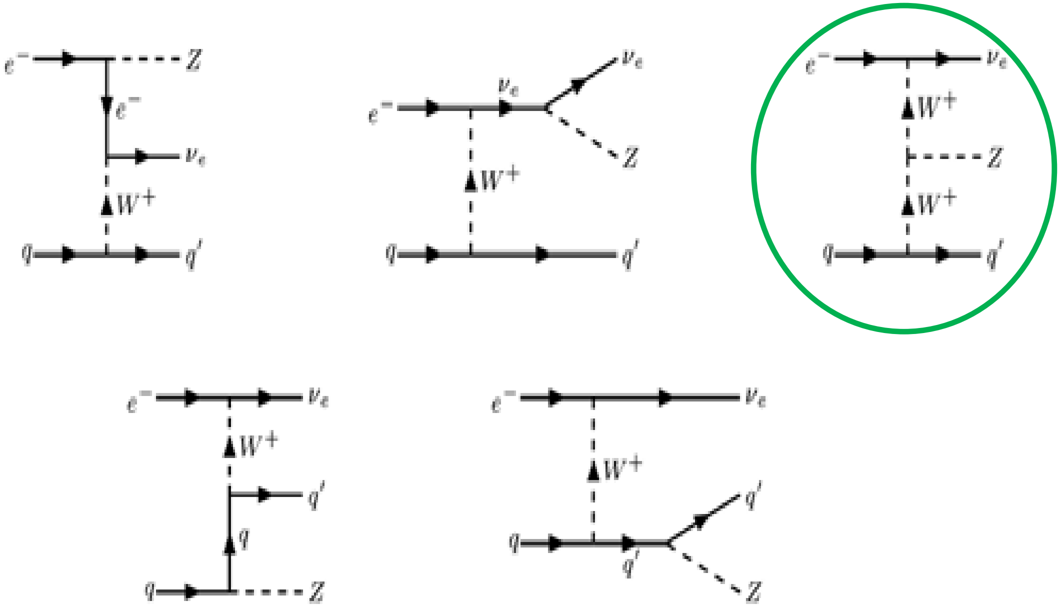
Anomalous Gauge Couplings

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

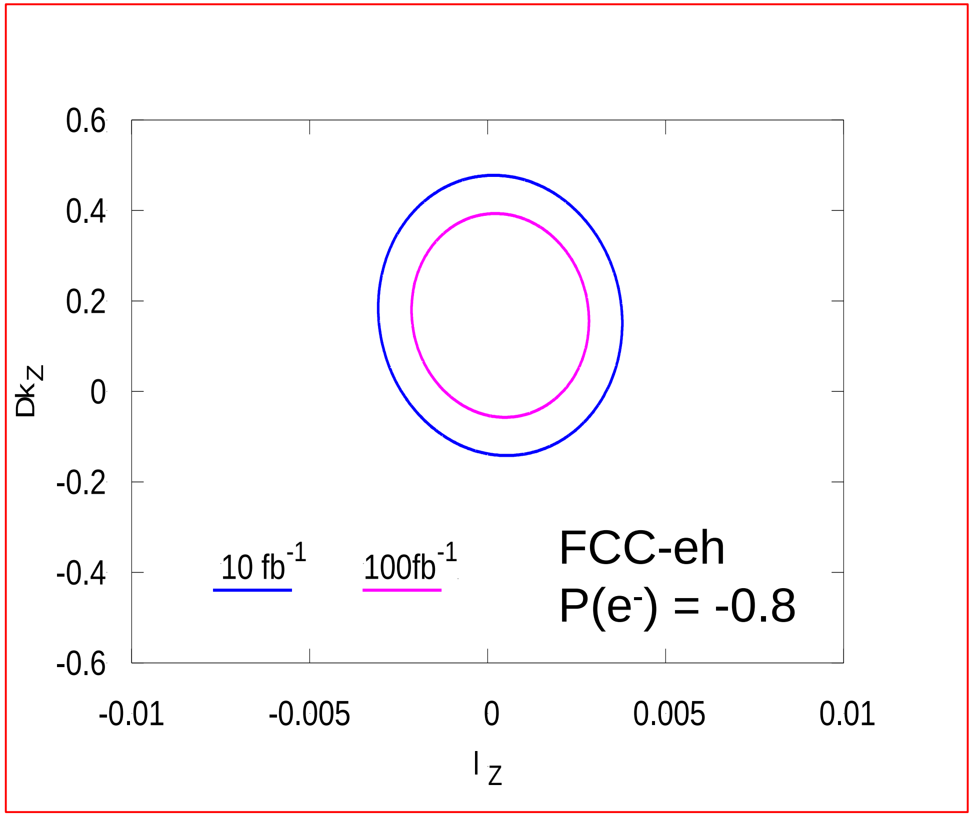
[A. Senol, O. Cakir, I. Turk Cakir]

$ep \rightarrow \nu_e qZX$ for *Z → ll (l = e, μ)*

Analysis of the signal & backgrounds



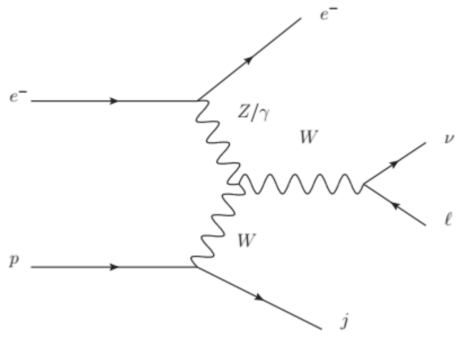
Sensitivities to anomalous couplings $\lambda_Z \sim 10^{-3}$



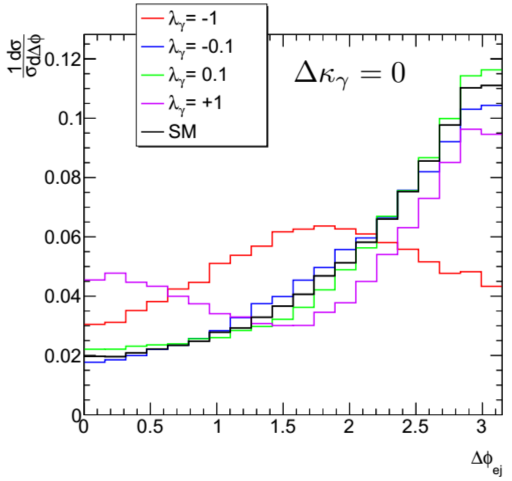
Anomalous Gauge Couplings

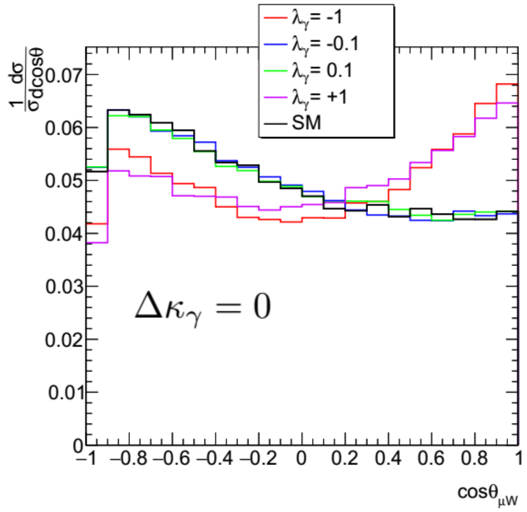
Triple Gauge Couplings (WWV, V = γ, Z)

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



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

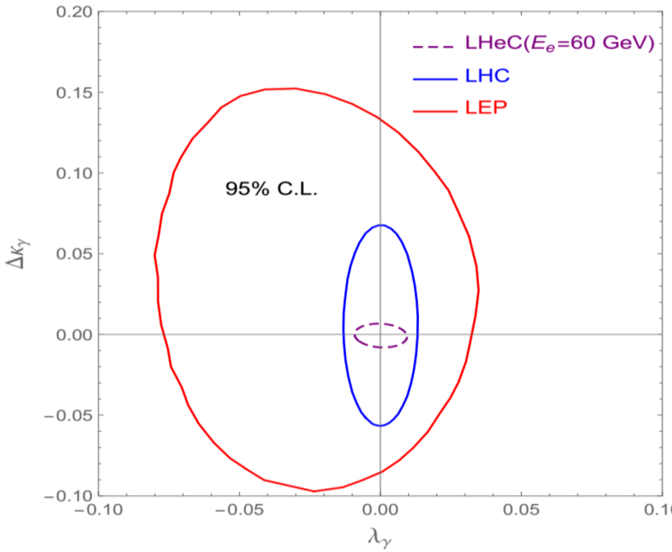




$\Delta\phi_{ej}$ -- azimuthal angle difference between scattered beam electron and jet

$\theta_{\mu W}$ -- 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 sensitivity @ FCC-eh, in progress

Summary and Complementary between ep and pp

From [Georges Azuelos and Monica D'Onofrio]

Compositeness	• *4-fermion EFT: Lepton-quark compositeness scale* • *Quark radius*
Leptoquarks and RPV squark decay	• *Accessible range largely excluded, but not completely* • *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* • *Extend sensitivity to eγ 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* • *Disppearing tracks*
Anomalous Quartic Gauge Couplings	• *Better control on background:* *no gluon exchange diagrams (mostly FCC?)*
Extended Higgs sector: higher isospin multiplet	• *Singly- and doubly- charged higgs by VBF (mostly FCC)*

Conclusion & Outlook

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

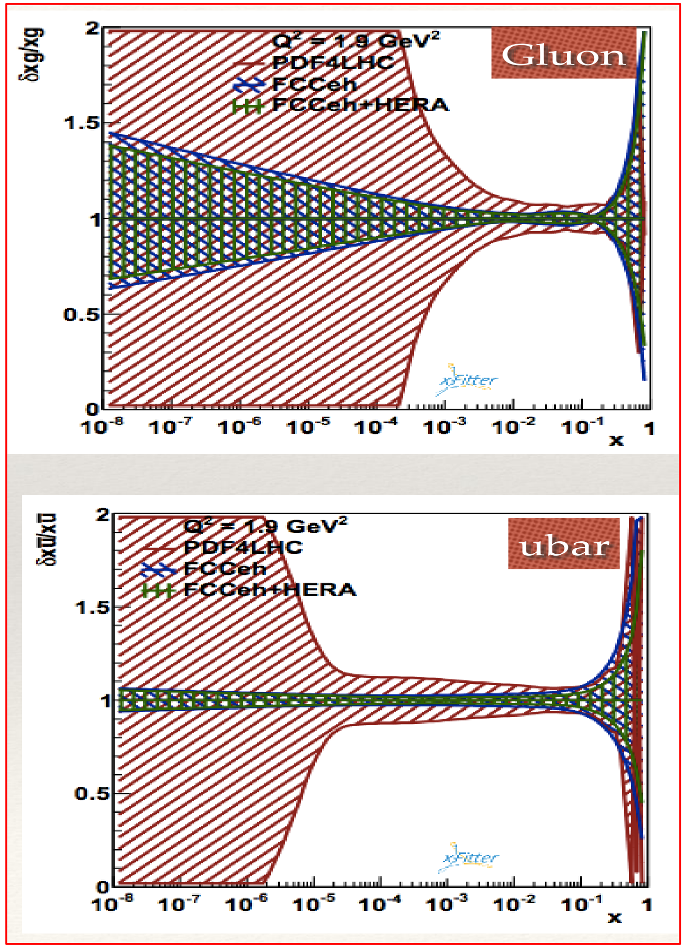
- ★ Improving pp limits indirectly by improved PDF (@ high and low x)

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

- ★ 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

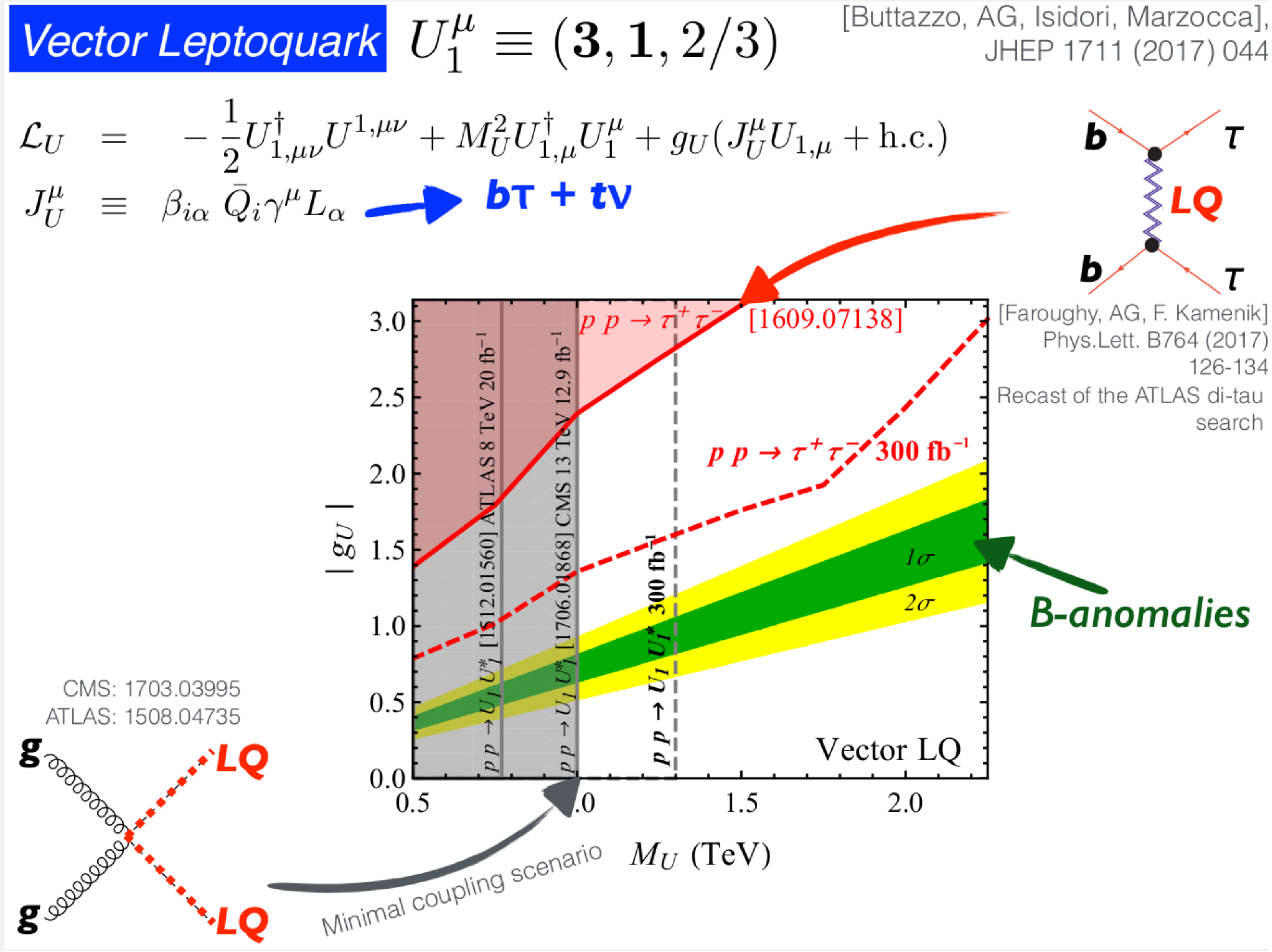
→ high-x: very poorly constrained;
limits searches for new, heavy particles

→ 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

Leptoquarks and B-anomalies

Slide from [Dec. 14, 2017, https://indico.desy.de/indico/event/18276/contribution/1/material/slides/0.pdf]

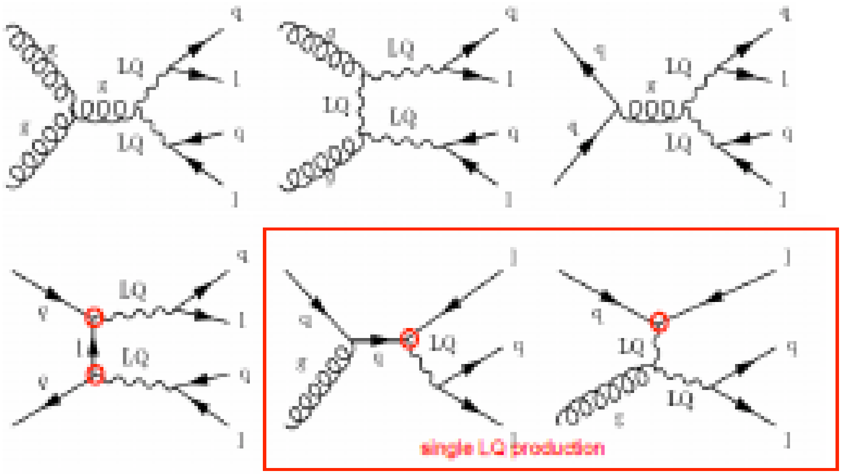


Leptoquarks

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)

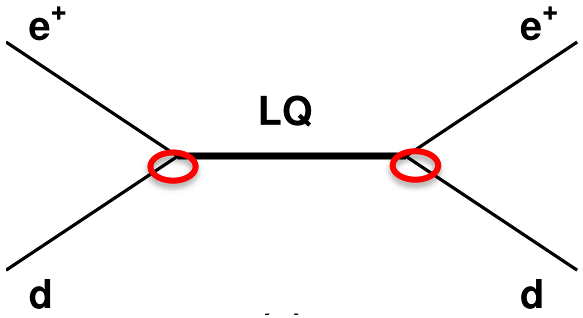
At the p-p



→ mostly pair production (from gg or qq)
→ not sensitive to the LQ-*q*-*l* coupling

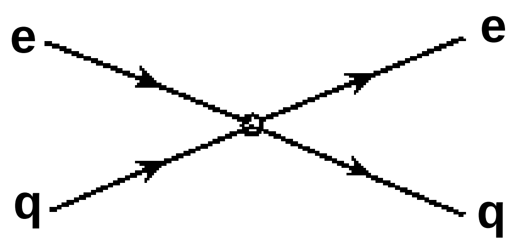
At the e-p

→ 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 LQ-*q*-*l* coupling

Contact Interactions



Contact interaction eeqq

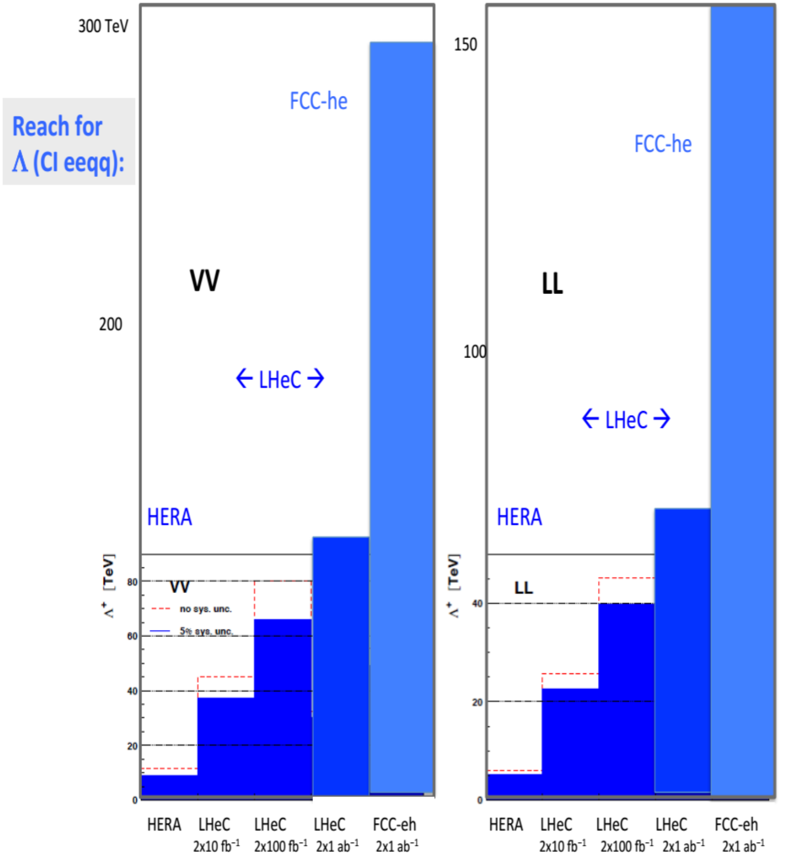
- if new physics enters at higher energy scales: Λ>> √s
- such indirect signatures can be seen as effective 4-fermion interaction

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]



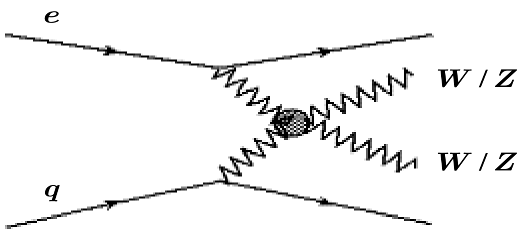
→ comparable to FCC-hh for some of the couplings
→ same as HL-LHC vs LHeC
→ need more calculations !

Vector Boson Scattering

New resonances possibly relevant for unitarity restoring

→ expect below ~ 2-3 TeV

→ look for deviations from SM predictions



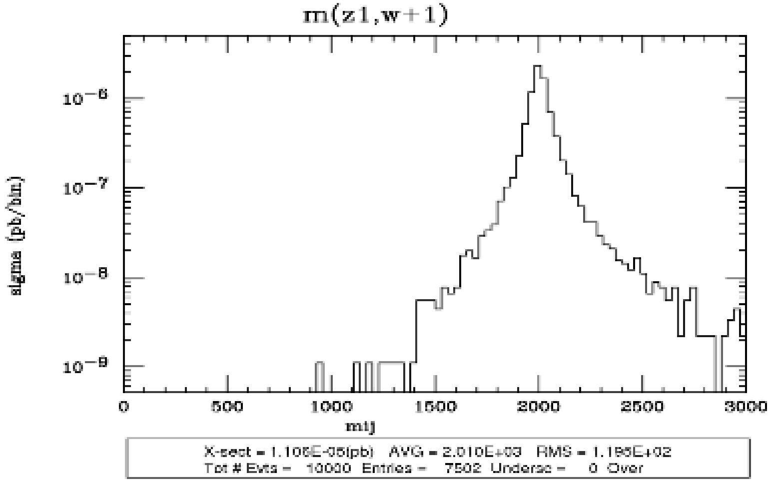
$$e^- q \rightarrow e^- (q) WZ, \quad (\nu q) WZ$$

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

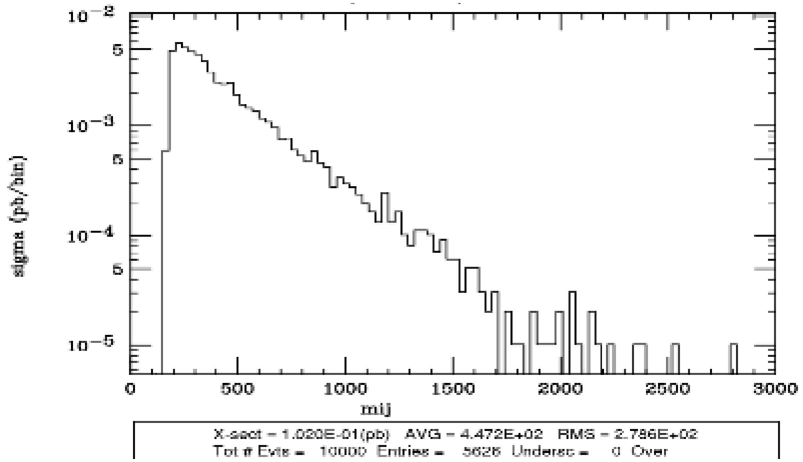
→ Cleaner at FCC-eh

Preliminary results from [Georges Azuelos's study]

For a 2 TeV resonance



m(WZ), background



→ 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

→ low pile-up

Anomalous Gauge Couplings

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

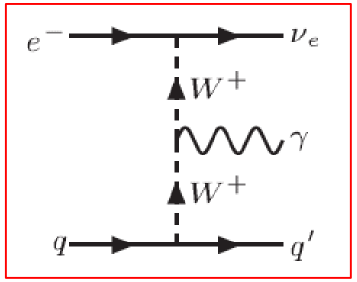
→ Precisely defined in SM

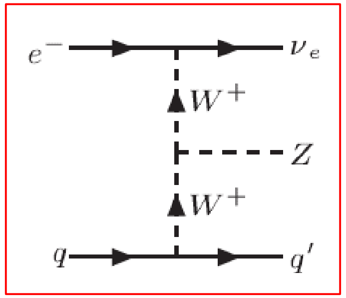
→ Parameterize possible new physics contributions to this vertex ($\Delta\kappa_\gamma, \lambda_\gamma$)

→ 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 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.





single γ production@LHeC: 1405.6056, 1406.7696, FCC-DRAFT-ACC-2016-017;

At the ep:

→ 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 !

Existing limits: *WW* pair production@LEP/LHC: 1302.3415, 1703.06095, 1706.01702;

aTGC	LEP	CMS, 8 TeV	ATLAS, 8 TeV	SM
$\Delta\kappa_\gamma$	[-0.099, 0.066]	[-0.044, 0.063]	[-0.061, 0.064]	0
λ_γ	[-0.059, 0.017]	[-0.011, 0.011]	[-0.013, 0.013]	0

Table 1: 95% C.L. limits on $\Delta\kappa_\gamma$ and λ_γ at LEP and LHC. These bounds are from single parameter fittings. LHC measurement of WW/WZ pair production in semi-leptonic decay channel with an integrated luminosity of 19 ab^{-1}(CMS) and 20.2 ab^{-1}(ALTAS) give the above abounds. arXiv:1302.3415, 1703.06095, 1706.01702

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

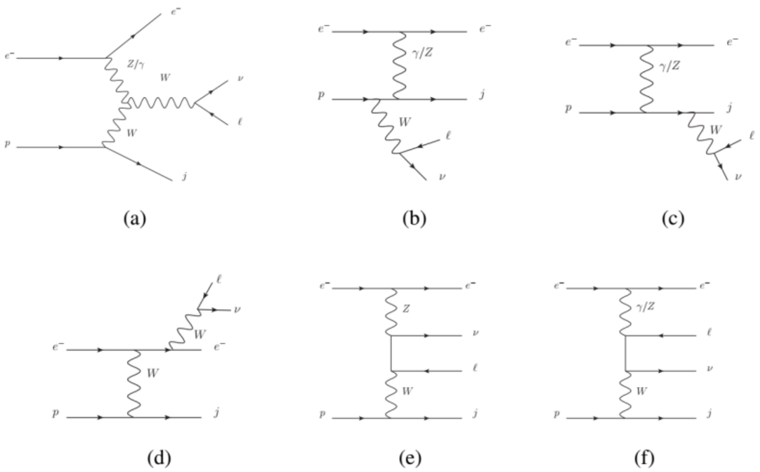


FIG. 1: Diagrams of $e^-p \to e^-\mu^+\nu_\mu j$ process.

parameter \ variable	μ^+ decay, $E_e = 60$ GeV		μ^+ decay, $E_e = 140$ GeV		
	$\cos\theta_{\mu^+W^+}$	$\Delta\phi_{ej}$	$\cos\theta_{\mu^+W^+}$	$\Delta\phi_{ej}$	SM
λ_γ	—	[-0.0074, 0.0062]	—	[-0.0038, 0.002]	0
$\Delta\kappa_\gamma$	[-0.005, 0.0058]	[-0.0057, 0.0061]	[-0.0032, 0.0029]	[-0.0023, 0.0026]	0

parameter \ variable	μ^- decay, $E_e = 60$ GeV		μ^- decay, $E_e = 140$ GeV		
	$\cos\theta_{\mu^-W^-}$	$\Delta\phi_{ej}$	$\cos\theta_{\mu^-W^-}$	$\Delta\phi_{ej}$	SM
λ_γ	—	[-0.011, 0.011]	—	[-0.0027, 0.0051]	0
$\Delta\kappa_\gamma$	[-0.0078, 0.0078]	[-0.0075, 0.008]	[-0.005, 0.0029]	[-0.0041, 0.0051]	0

TABLE II: The 95% C.L. bound on aTGC λ_γ and $\Delta\kappa_\gamma$, obtained from the kinematic observables $\cos\theta_{\mu^\pm W^\pm}$ and $\Delta\phi_{ej}$ at LHeC with $E_e = 60$ and 140 GeV. The results listed are from single-parameter fitting when the other one is fixed to its SM value. The "—" in the table means this bound is no better than the ones from LEP.

GM model

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

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