BSM physics at LHeC/FCCeh

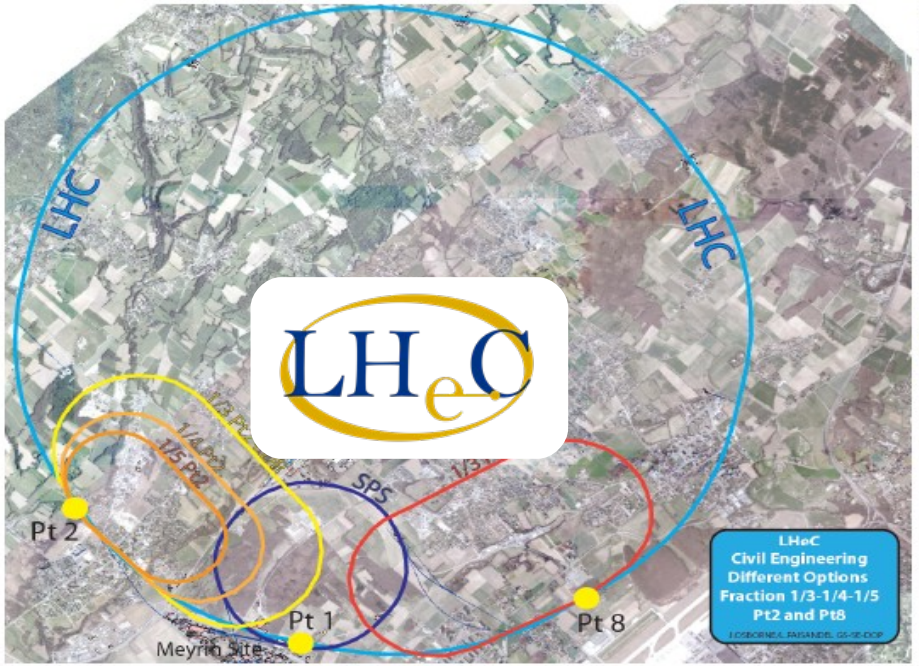
D. Britzger
O. Fischer,M. D'Onofrio,
and the LHeC/FCC-eh BSM group

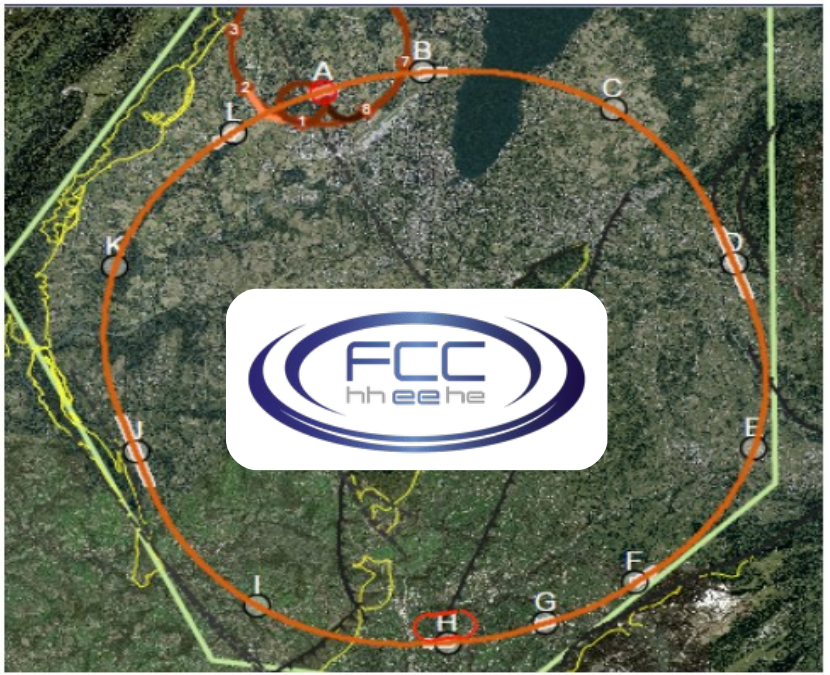
ICHEP2018, Seoul
06.07.2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MAX-PLANCK-GESELLSCHAFT

Future proposed ep-colliders: LHeC & FCC-eh





Electron ring

- Energy recovery linac: E_e = 60 GeV
- Polarisation up to P_e ~ 80%
- Similar concept for LHeC & FCC-eh

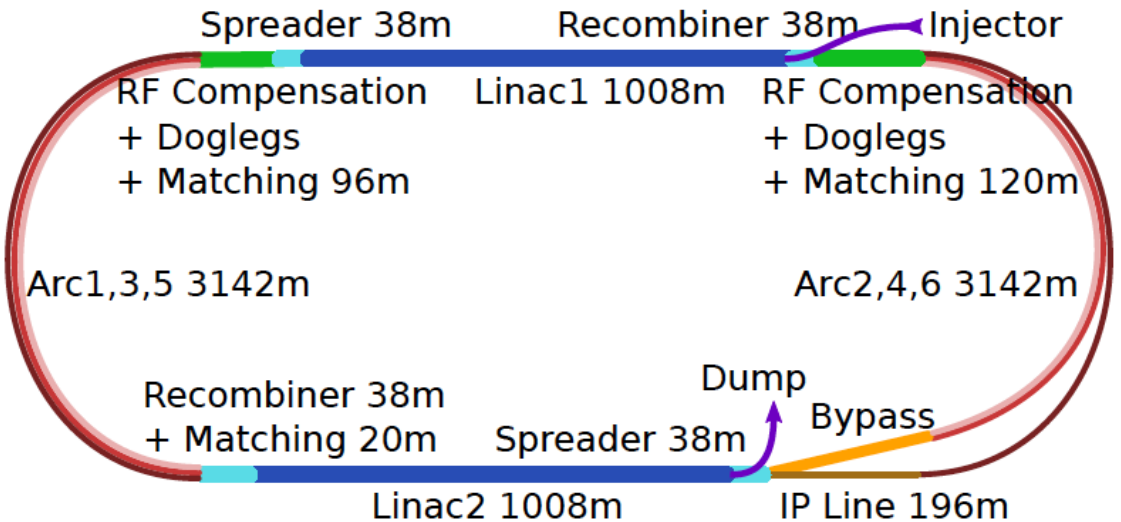
Center-of-mass energies

- LHeC: $\sqrt{s}$ ~ 1.3 TeV
- FCC-eh: $\sqrt{s}$ ~ 3.5 TeV
- Up to 1 ab^{-1} integrated luminosity

60 GeV Electron ERL

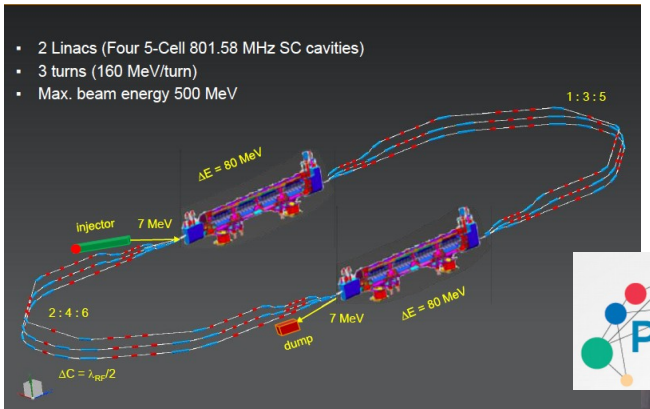
see talk by D. Schulte

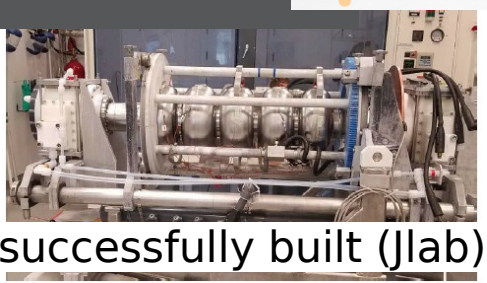
Electron beam
60GeV acceleration with Recirculating Linacs



A. Bogaz (JLab) @ ERL '15

Proof-of-concept under construction:
Powerful **ERL** for **E**xperiments **at Orsay**





First 802 MHz cavity successfully built (Jlab)

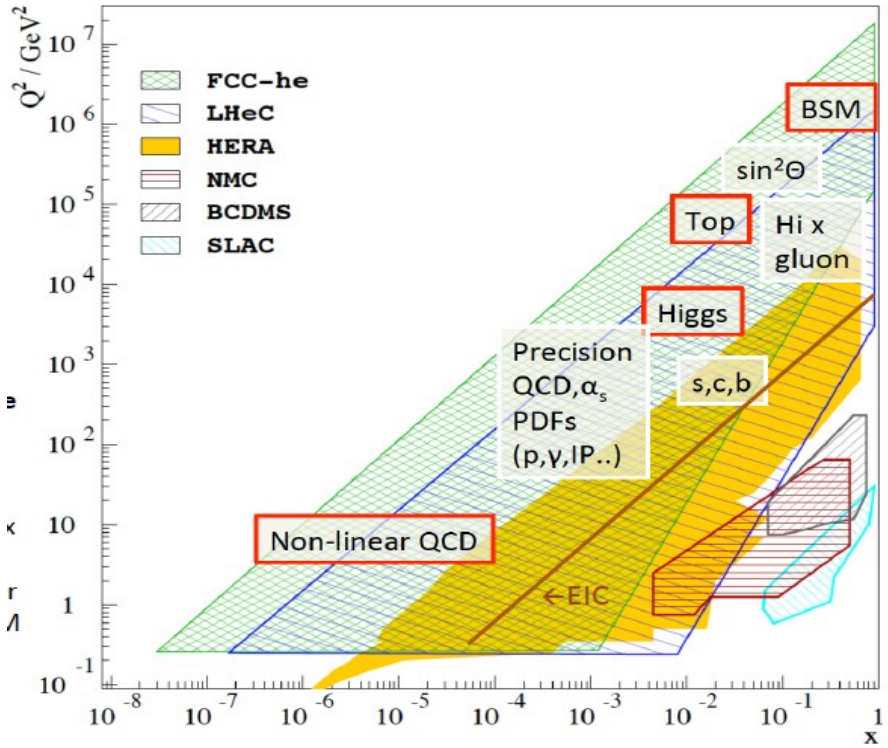
CDR 1705.08783 [J.Phys G] → TDR in 2019

Concurrent operation to pp. Power limit: 100 MW, 10^{34} cm^{-2} s^{-1} luminosity

- LHeC/FCCeh: 1000 times HERA luminosity. It therefore extends up to x~1.

LHeC & FCC-eh – kinematic range

e.g.: P. Newman [NPPS 191 (2009) 307]



Precise QCD constraints for pp

- PDFs
- Strong coupling
- Monte Carlo optimizations

Comprehensive physics programme

- Higgs physics
- Top-Quark (properties, top-PDFs)
- Heavy-quarks (s,c,b-quarks)
- low-x physics (non-linear QCD?),
- eA physics (see talk by Z. Zhang)

Searches for BSM

- Complementary to e+e- and pp

factor of 15/120 (LHeC/FCCeh) extension of Q^2, 1/x reach w.r.t. HERA
Four orders of magnitude extension in lepton-nucleus (ion) DIS

Outline

I will present a few highlights of on-going studies of BSM @ e-p

Selected list of topics ...

- Leptoquarks and R-parity violating SUSY
- R-parity conserving SUSY: prompt Higgsinos
- BSM Higgs: charged higgs….
- Long-lived particles
- anomalous couplings (VVV,VVVV), Contact-interactions, compositness, high-precision EW, sterile neutrinos….

BSM programme at e-p aims to

- Explore new and/or challenging scenarios
- Characterize hints for new physics if some deviations from the SM are found in pp

Indirect impact on search potential for FCC-hh (→ PDFs)

Plans for Yellow Report and FCC CDR

Outlook and summary

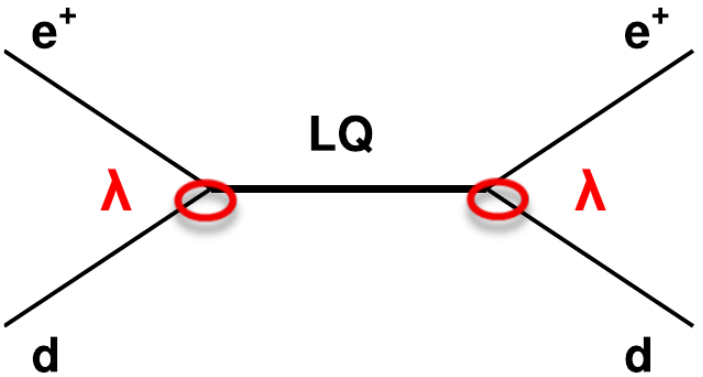
Aim of this talk:

→ Report on most recent studies and progress

→ Brief overview of previously finalized studies

→ Encourage future studies and synergies

Leptoquark searches



lately, LQs raised a lot of attention as possible motivation for LHCb anomalies

see e.g. JHEP 1711 (2017) 044

- (mostly involving 3rd generation LQ)

At pp: mostly pair production ***(single production possible)***

At ep: singly produced as s-channel resonance ***(or u-channel virtual exchange)***

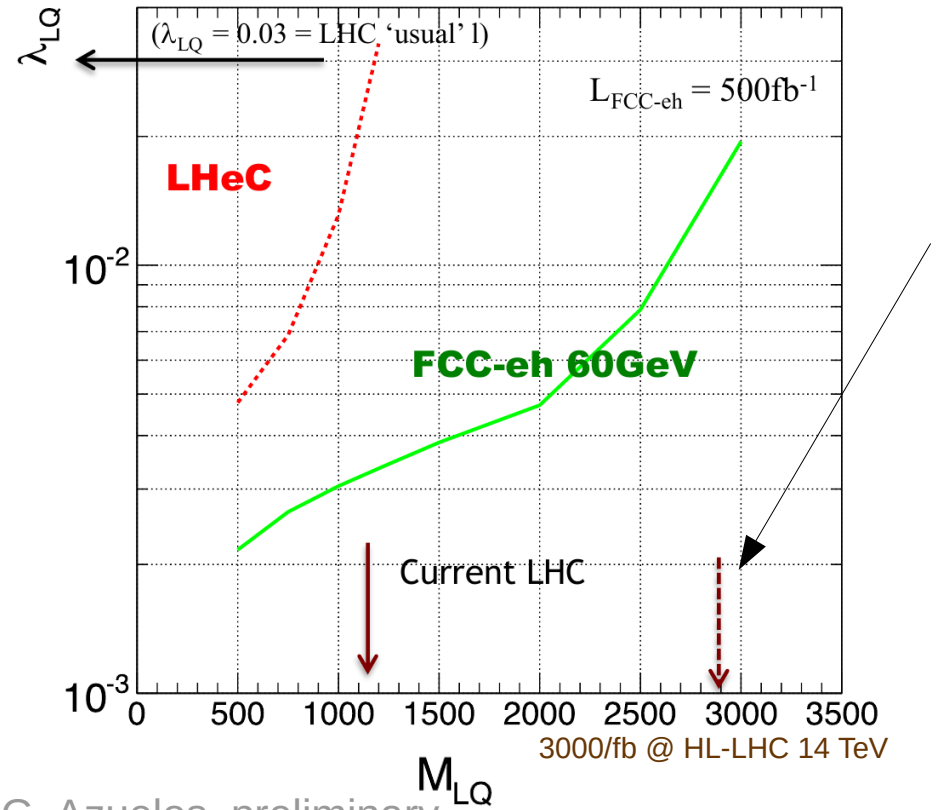
- Very sensitive to 1st generation, sensitive to λ

→ can measure ferminon number, flavor structure, spin, ...

LQ reach at LHC & FCC-eh

1st generation LQs

- Current LHC constraints for 1st, 2nd, 3rd gen. LQ ~ 1.0-1.1TeV



G. Azuelos, preliminary

e-p scenario: sensitive to λ < 0.03

Sensitivity of HL-LHC: ~ 2.9 TeV

- 3000/fb @ 14TeV
- FCC-eh and HL-LHC close in reach

If deviations are found by the end of HL-LHC…

- FCC-hh will definitely see them, and...
  FCC-eh can characterize those signals!

More ideas are explored:

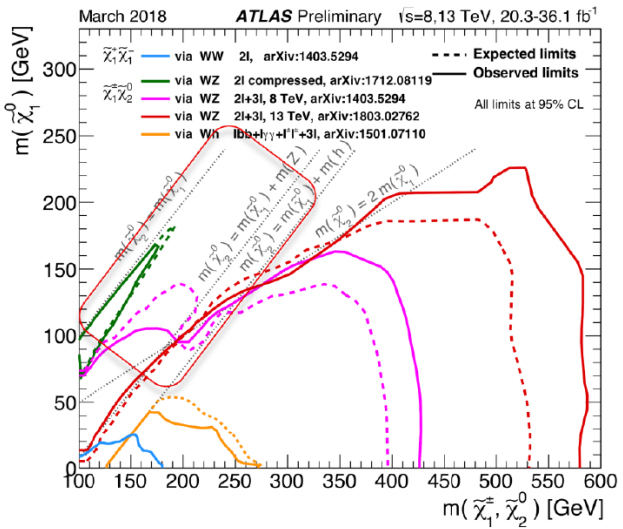
- Zhang, Yue, Liu, Mod.Phys.Lett. A33 (2018) 1850039
- 1st gen. scalar LQs in 2-simplified SLQ model
  → possible SLQs might be discovered a the LHeC

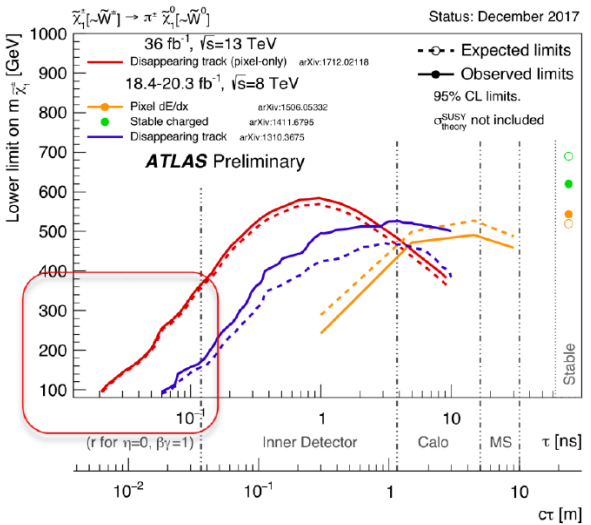
SUSY searches (EWK, RPV): Motivation

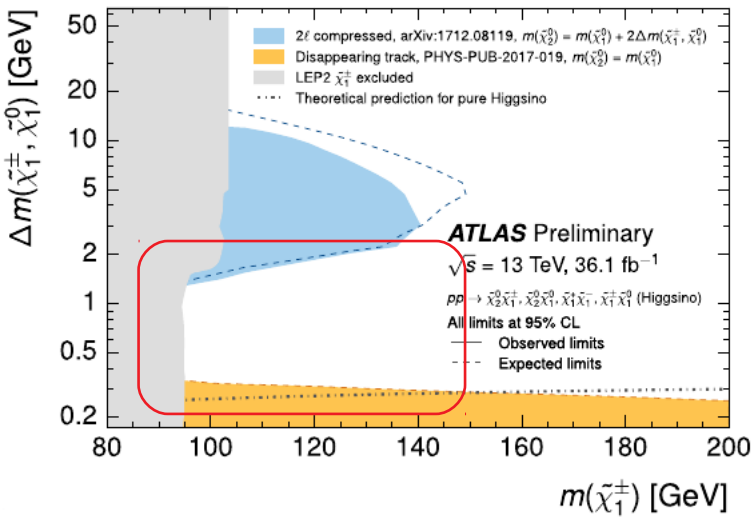
At pp: SUSY EWK sector (compressed scenarios) remain challenging in favored regions of the parameter space

- As seen: Higgsino scenarios (~ mass degenerate, low cross sections)
- Wino/bino compressed (sleptons heavier than chargino/neutralino)
- Promptly decaying or long-lived (exp. short lifetimes)

E.g. Higgsino-like LSP can be a good DM candidate





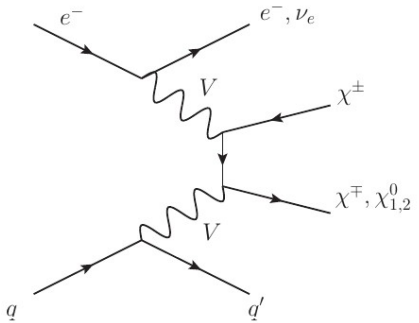


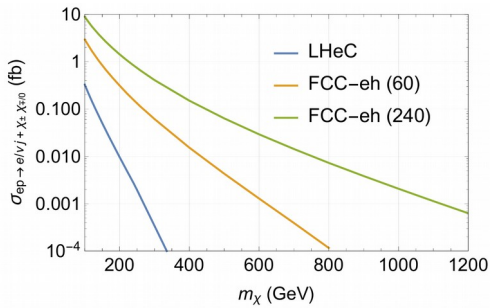
see e.g. ATLAS and/or CMS SUSY webpages for recent results

Long-lived particles (LLPs)

LLPs are very well motivated

- e.g. by approximate symmetries, sequestration of sectors. ...



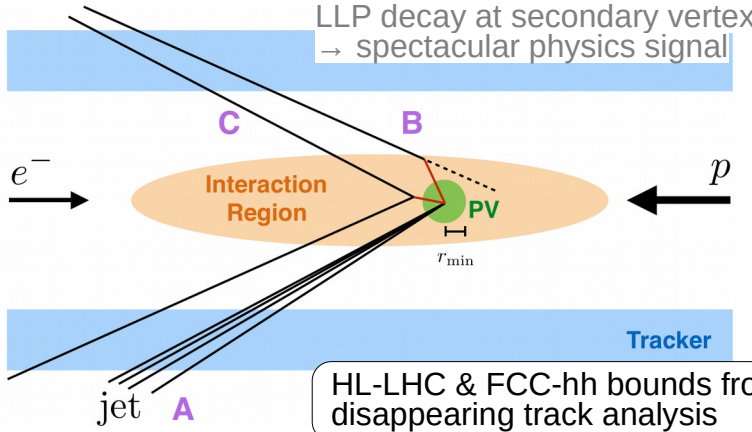


Curtin, Deshpande, Fischer, Zurita, arXiv:1712.07135

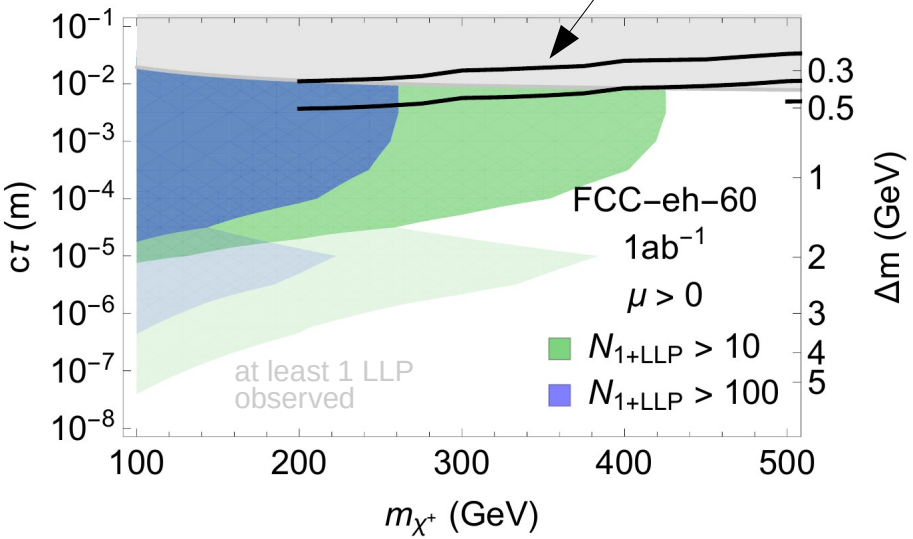
- Pure Higgsinos most challenging at pp colliders
  → soft decaying, short lifetime (cτ ~ μm)
- LLP decay at secondary vertex
- DIS-jet → triggering & primary vertex at O(10μm)
- Single soft displaced pion (for small Δm ~ 0.2-1GeV)

Looks like hadronic noise…

… but can be detected at ep colliders

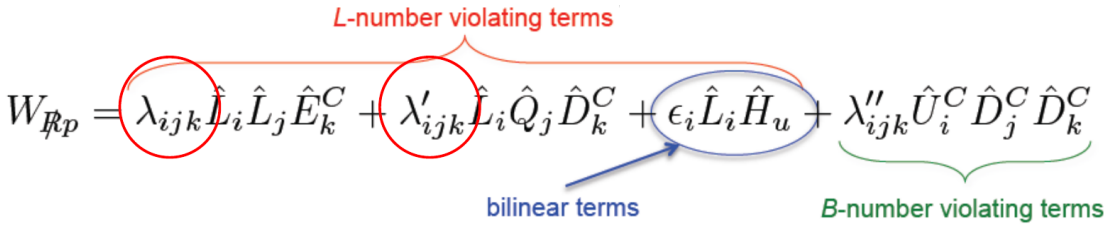


HL-LHC & FCC-hh bounds from disappearing track analysis



R-parity violating SUSY

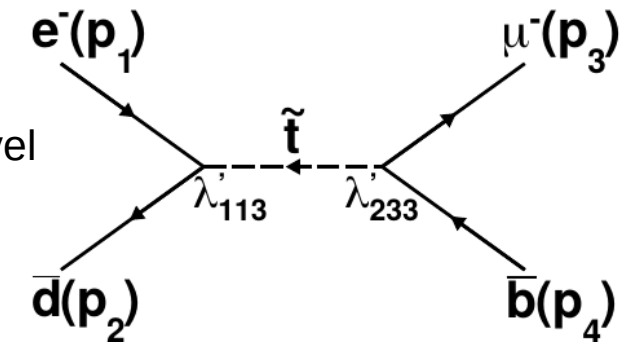
One of the most-often studied cases at ep up to now...



- *Various strong constraints from LHC on λ and λ"* (from multilepton and multijet searches)
  see e.g. Krauss, Dreiner et al., EPJ C77 (2017) 856

At ep colliders, studies made on stop and sbottom (phenomenology equivalent to LQ)

stop RPV parton-level Feynman diagram



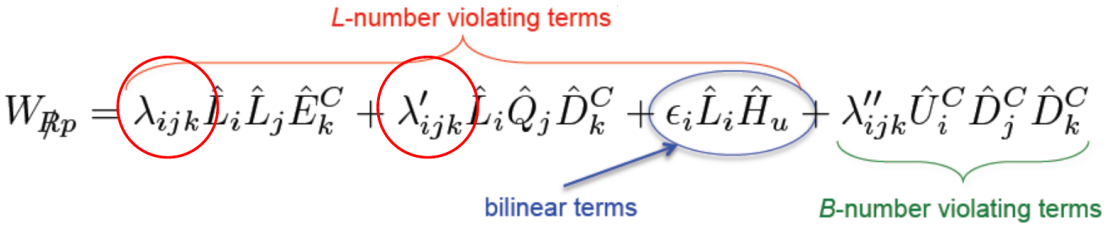
Couplings with third gen quarks
In e-p production rate depending on:
e-d-t: λ'_{131} (constraint: < 0.03)

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

Wei, Zhang, Guo, Han, Ma, Li, Wang, JHEP 1107 (2011) 003
see for sbottom e.g.:
Zhang, Wei, Han, Ma, Mod.Phys.Lett. A29 (2014) 1450029

R-parity violating SUSY

One of the most-often studied cases at ep up to now...



Upcoming updates for the CDR

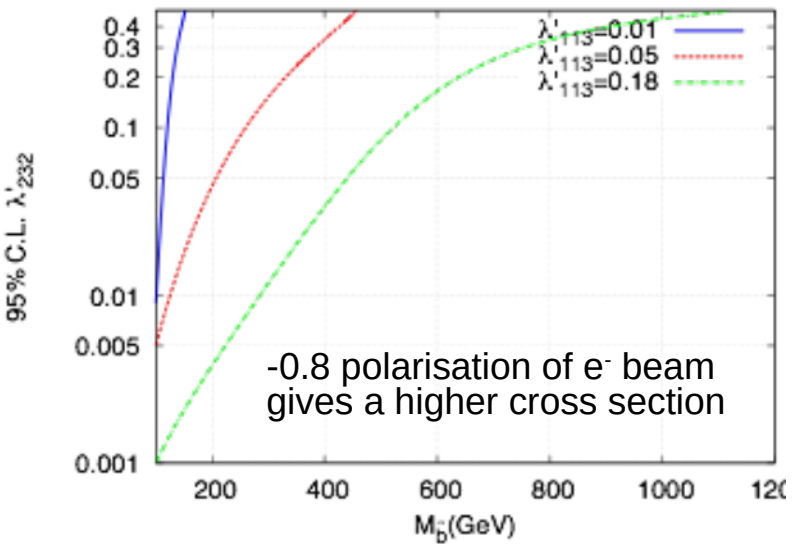
Ren-You Zhang, Liang Han, et al.

- LHeC & FCC-eh potential being re-evaluated

Sinan Kuday, in prep.:

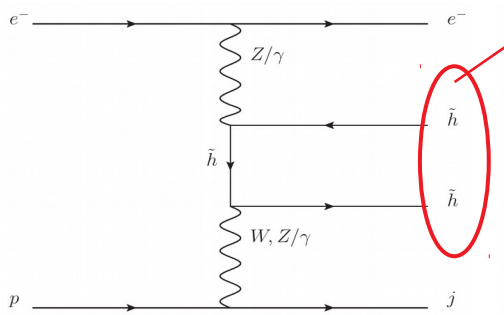
- Preliminary results on single RPV sbottom production
- LHeC (E_e= 60 GeV) can extend the limits of LQD couplings
- up to 10^{-3} with just 1 fb^{-1} int.lum. at the %95 C.L.
- FCC-eh: expect to have sensitivity up to 2.5 TeV for λ'_{113}<0.02

sbottom production, S. Kuday, in prep.



RPC SUSY: Prompt Higgsino searches @ LHeC

Han, Li, Pan, Wang, arXiv:1802.03679



Typical signal: electron + jet + missing energy

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

Interesting study of kinematic variables which could be helpful for signatures of this kind

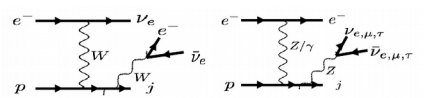
- Prompt Higgsino: very difficult in pp, small cross section
- Realistic cut-based analysis

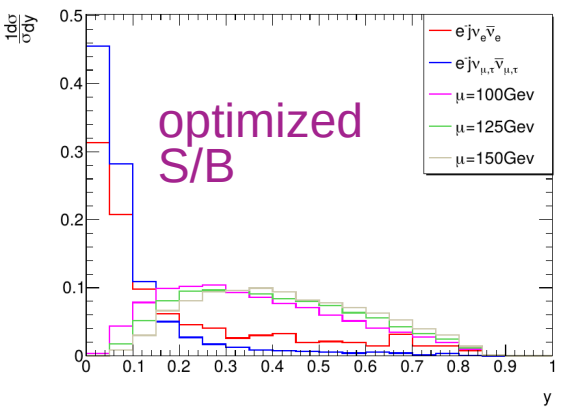
cutflow

cut	$e^-j\nu_e\bar{\nu}_e$	$e^-j\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$	$\mu = 100GeV$	$\mu = 125GeV$	$\mu = 150GeV$
basic cuts	243600	58110	1300	508.7	245.9
$\not{E}_T > 30$ GeV	212619	40351	1168	462.6	224
$p_T^e < 30$ GeV	46562	16836	579.2	222.7	106.2
$\eta_j < -2.0 \& \eta_e > 2.0$	1864	2595	267.8	96.15	43.19
$m_{ej} > 400$ GeV	1108	1631	205.7	72.4	32
$y > 2.0$	294.8	127.8	153	60	28.11

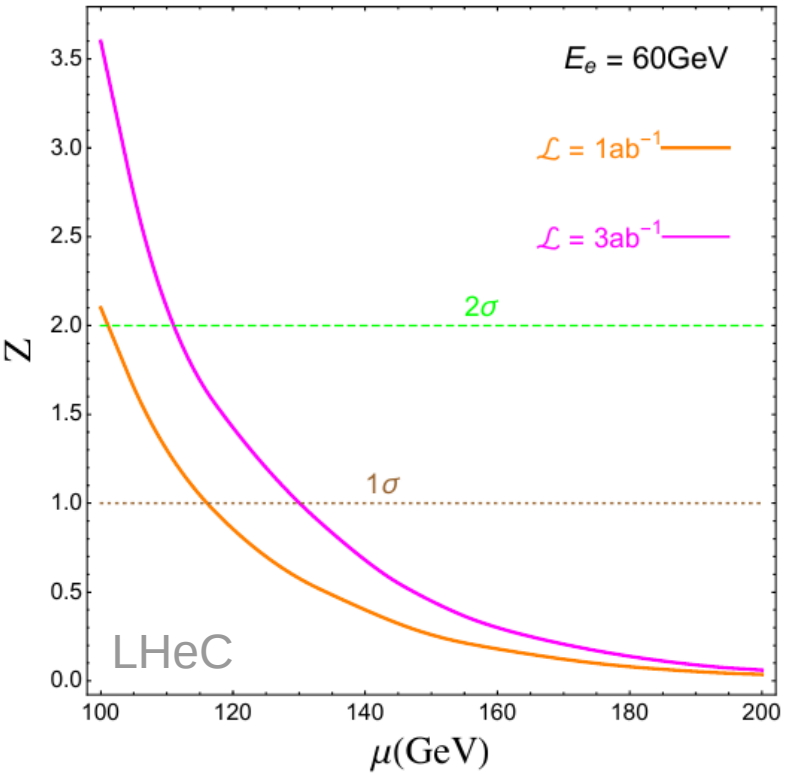
TABLE I: Cut flow of the signal and background events for μ= 100, 125, and 150 GeV at 140 GeV electron beam energy LHeC with $\mathcal{L} = 1$ ab^{-1}.

SM background





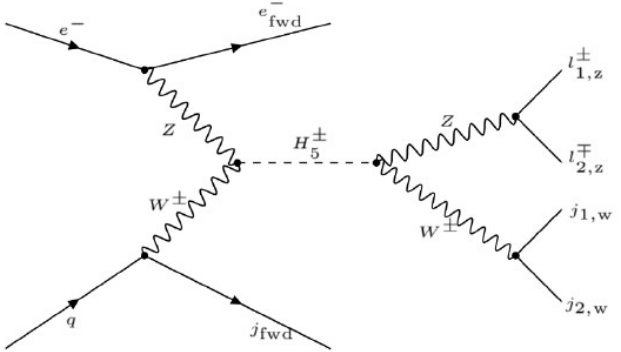
The significance *Z* varying with the Higgsino mass μ



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

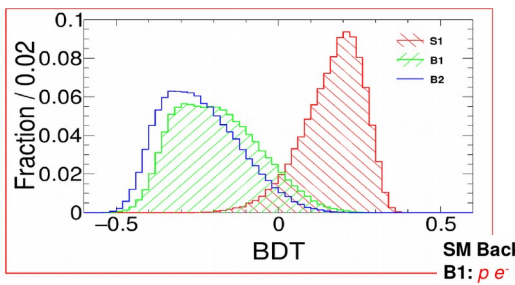
Georgi-Machacek Model: *Extended Higgs sector with higher isospin multiplets*

- 5-plet: H_5^{++}, H_5^{+},H_5^{0},H_5^{-},H_5^{--}
- Singly charged Higgs. Signal:



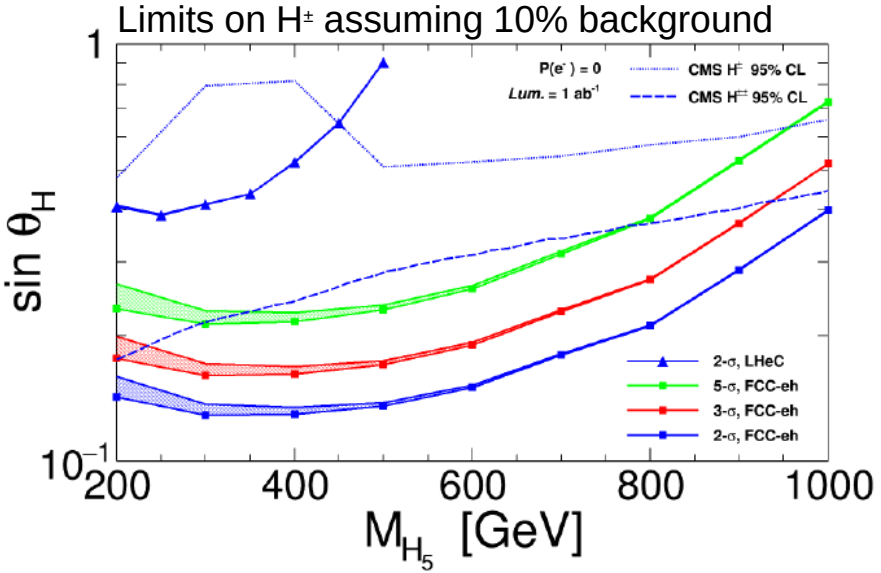
Azuelos, Sun, Wang, PR D 97 (2018) 116005

- MVA detector-level analysis



SM Background
B1: $p\,e^- > j\,e^-\,Z\,V,\ V \to jj$
B2: $p\,e^- > j\,e^-\,Z\,jj$, jets from QCD radiation

Limits on $H^{\pm}$ assuming 10% background



- $\sin\theta_H < 0.15$ @ 2-σ, for 600 GeV
- around 500GeV: limits stronger than existing ones

- $H^{\pm\pm}$ also studied: Sun, Luo, Wei, Liu, PR D96 (2017) 095003

Extended Higgs Sector at the LHeC & FCC-eh

See Chen Zhang's talk: SM & BSM Higgs physics

- today, 17:30, R202, Higgs physics track

Highlighted

- Exotic Higgs decays
- Higgs → invisible

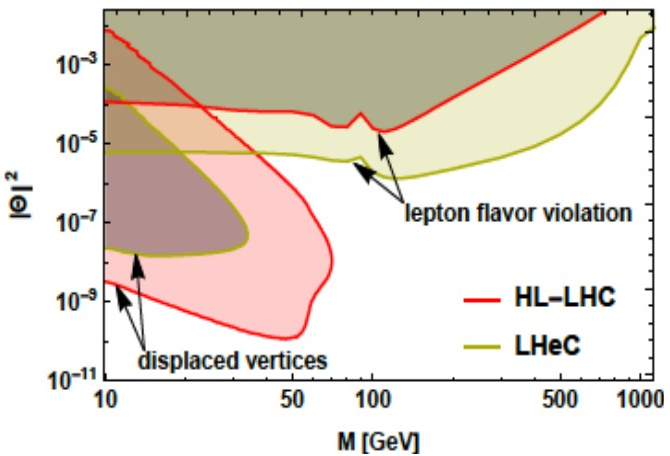
- NMSSM:
  - Light neutral CP-even Higgs @LHeC: e+2b+j or 2b+j+MET. (S. P. Das & M. Nowakowski, PRD 96, 055014(2017))
  - Light charged Higgs @FCC-eh: b+2j+MET. (S. P. Das, J. Hernández-Sánchez, S. Moretti & A. Rosado, 1806.08361)
- Two Higgs Doublet Model:
  - Type I CP-even Higgs @LHeC & FCC-eh. (C. Mosomane, M. Kumar, A. S. Cornell & B. Mellado, 1707.05997)
  - Type III Flavor-violating Higgs @LHeC: b+2j+MET. (S. P. Das, J. Hernández-Sánchez, S. Moretti, A. Rosado, R. Xoxocotzi, PRD 94, 055003 (2016))
- Georgi-Machacek Model:
  - Doubly charged Higgs @LHeC & FCC-eh: same-sign dimuon+j+MET. (H. Sun, X. Luo, W. Wei & T. Liu, PRD 96, 095003 (2017)).
  - Singly charged Higgs @LHeC & FCC-eh: 3l+3j. (G. Azuelos, H. Sun & K. Wang., PRD 97, 116005 (2018)).

New physics through high-precision

Masses

- **Charm**: HERA (40MeV) → LHeC (3MeV)
- **W**: LHeC 15MeV
  W-predictions to 2.8MeV
- **Top**: through EWK loops ~3GeV
  direct: to be studied
- **Higgs**: cross section to 0.3%. Mass dependent
- **Neutrinos**: Heavy 'sterile' neutrinos

Bruening, Klein, arXiv:1305.2090

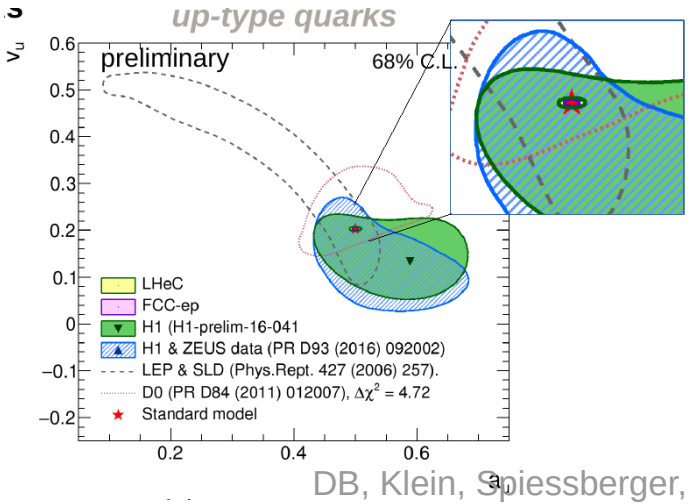


Antusch, Cazzato, Fischer, in prep.
Antusch, Cazzato, Fischer, Int.J.Mod.Phys. D26 (2017) 1750078

Precision EWK & QCD

- V_{tb}: to 0.01
- V_{cs}: to 0.02 [LHC+LHeC, like ATLAS+HERA]
- α_s to 0.1 – 0.3% → GUT, extra-dim., ...
- $\sin^2\theta_W(\mu)$: LHeC to 1TeV with 0.3%
  Perle @ 0.4GeV, LHC+LHeC better than LEP
- **EWK form factors**: 0.3% (O(LEP+SLD))
- **weak NC couplings of quarks**

arXiv:1211.5102



DB, Klein, Spiessberger, in prep.

Impact of PDFs @ high-x

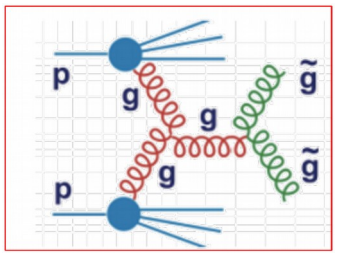
see also talk by C. Gwenlan on PDFs

Large uncertainties in high-x PDFs

- limit searches for new physics at high scales

Gluino pair-production in pp

- gluon-gluon initiated

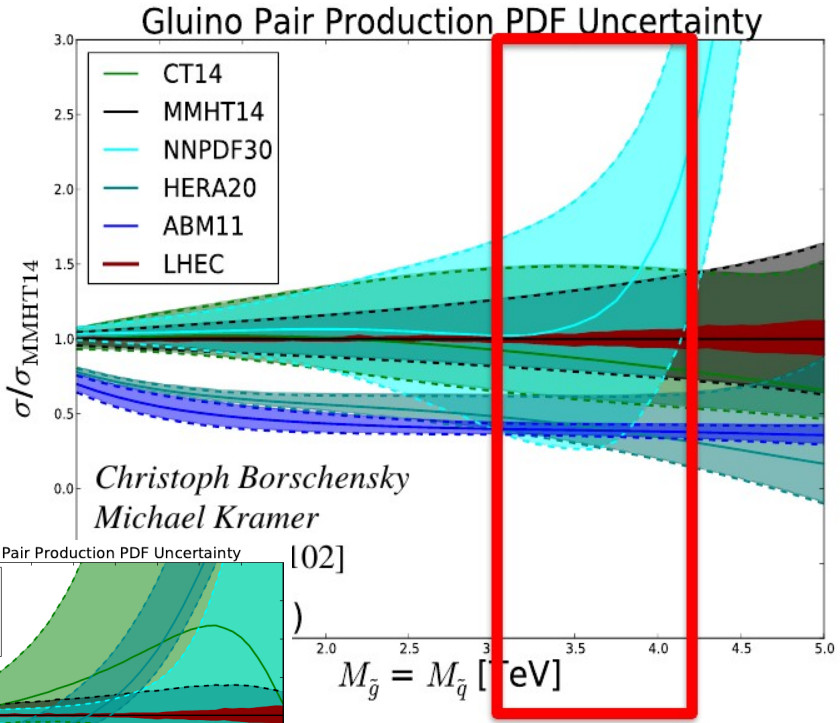


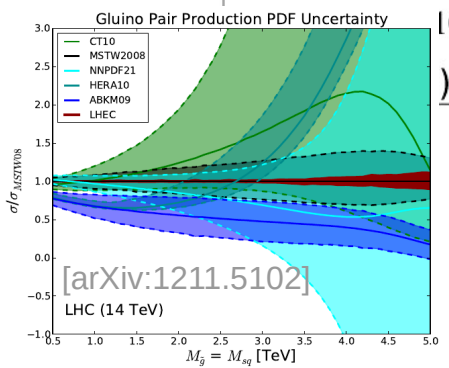
- HL-LHC
  ~50% uncertainty at ~3.5TeV

- @FCC-hh
  reducing PDF uncertainties will be crucial to improve *pp* BSM limits

High-x PDFs accessible only with high-lumi (ep) data

arXiv:1211.5102 and update for CDR



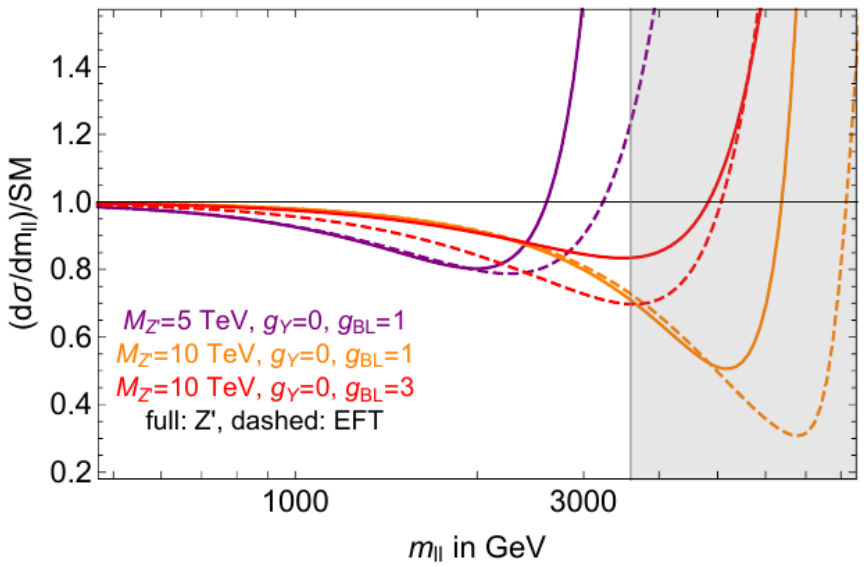


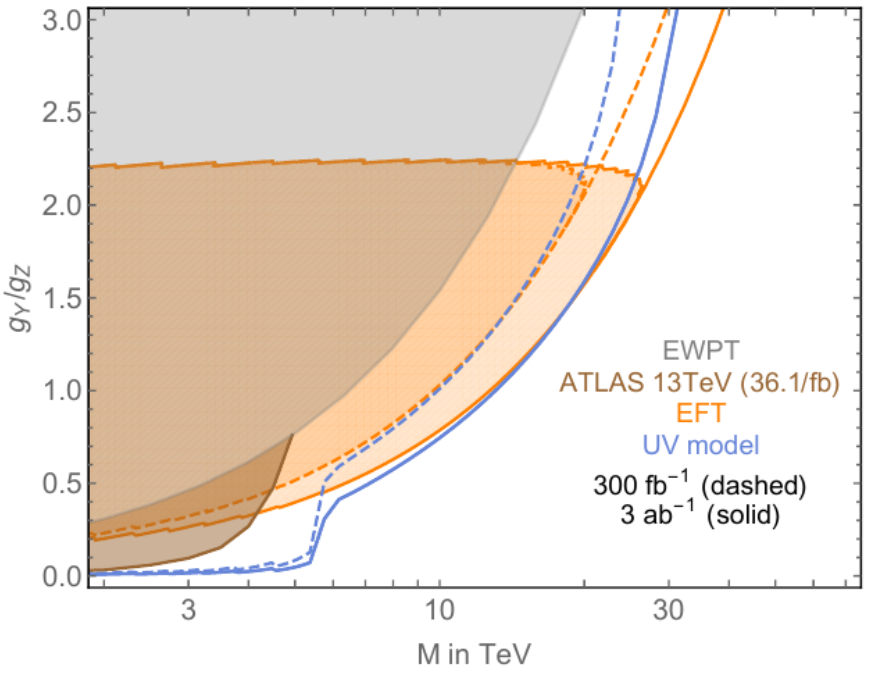
Relevance of PDF

Indirect constraints on Z'

- If $m_{Z'}$ >> 5TeV: main contributions from interference effects modifying Drell-Yan
- HL-LHC can do a lot → but need very precise predictions of SM DY (again PDF!)

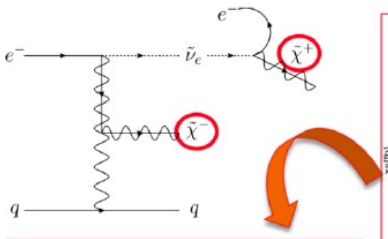
Alioli, Farina, Pappadopulo, Ruderman, PRL 120 (2018) 101801



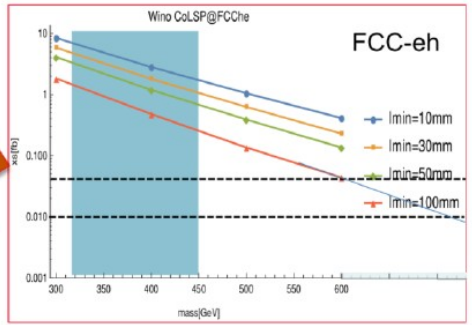


… many more studies

too many studies for 15'

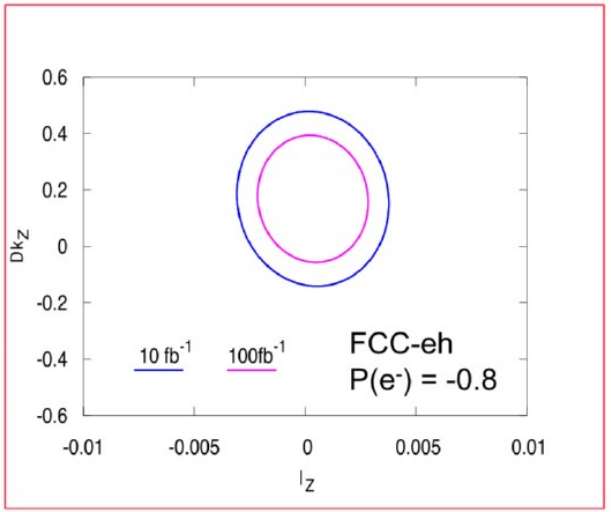


1 ab-1 @ FCC-eh:
$c\tau$ > 100 mm
~ 40 events for 600 GeV
~ 10 events for 750 GeV
excellent discovery potential



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

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



- Charged scalars in 2HDM models
- Light, long lived sleptons
- Anomalous gauge couplings
- Contact interactions
- …

2HDM	X	Y	Z	$m_H^{\pm}$ = 110 GeV	
				cb	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

slide by J. Zurita, DIS18

A wide programme of searches ongoing

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

Summary and Outlook

The LHeC & FCC-eh project

- LHeC: 60 GeV electron times 7TeV proton (√s=1.3TeV), synchronous with HL-LHC
- FCC-eh: 60 GeV electron times 50TeV proton (√s=3.5TeV), synchronous with FCC-hh

LHeC and FCC-eh offer a variety of opportunities for precision BSM searches

Ideal to study properties of new particles with couplings to electron-quark

Complementary and supportive for pp searches

Great opportunity (and time) for new ideas

- Currently: many updates with realistic conditions (detector, lumi, ...)

Documentation

- CDR: arXiv:1206.2913, lhec.web.cern.ch
- Update on CDR will be written in early 2019
- Submission of papers for the European strategy Dec. 2018

More on LHeC

Workshop: LHeC/FCCeh and PERLE
Last week at Orsay near Paris

New and Updates on

Physics: PDFs, QCD, H, t, BSM, eA + Relation eh-hh..
Accelerator: IR, Optics, Lattice, Cost-Energy, CE..
Detector: the GPD and its fwd and bwd detectors
PERLE: Source, Injector, Cavity, Cryomodule,.. Physics
Project Development towards the ES2020:
LHeC + FCCeh+ PERLE input 12/18. PERLE TDR in 2019.

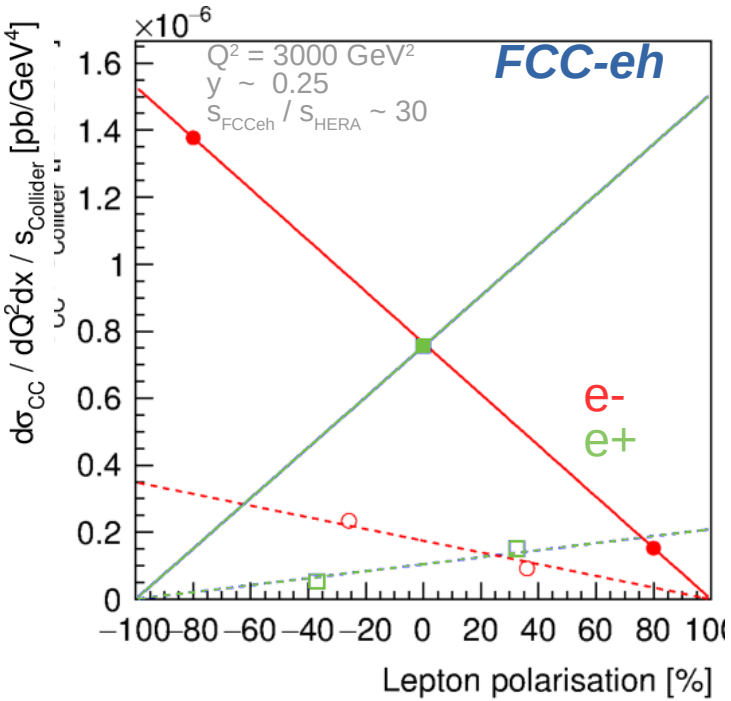
https://indico.cern.ch/event/698368/

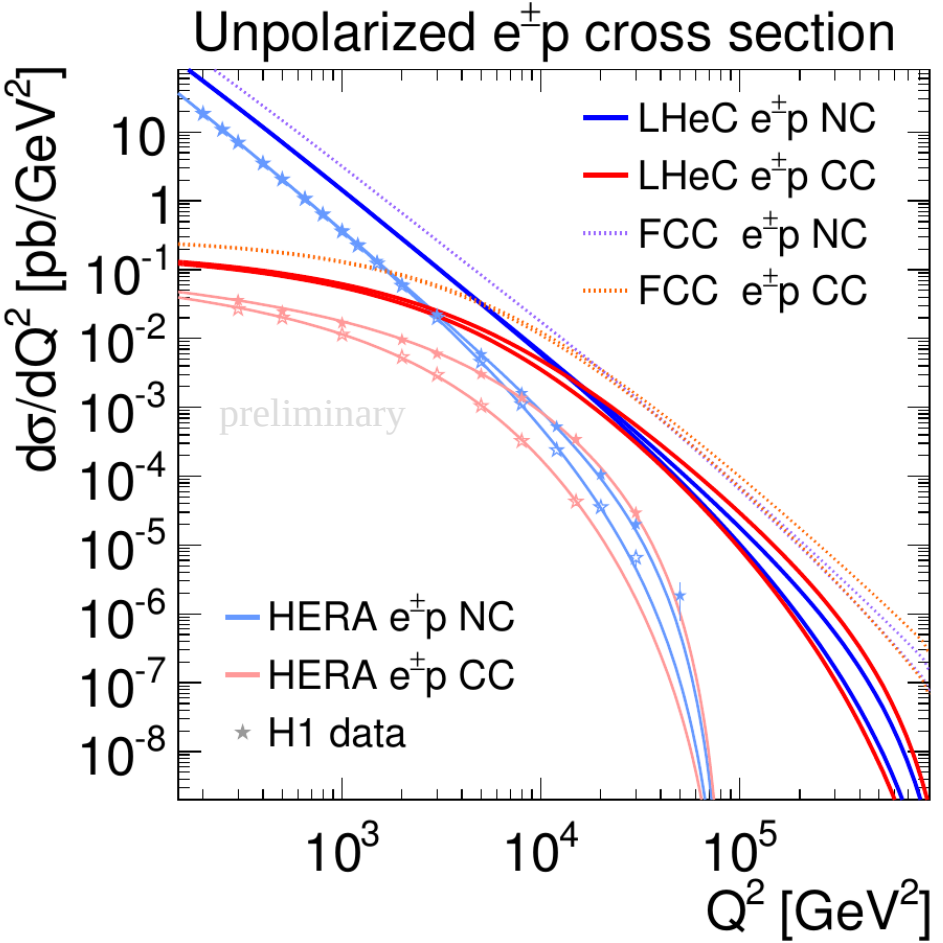
LHeC, FCC-eh: NC and CC cross sections

LHeC/FCCeh running scenario

- e- +80%, -80% (1ab^{-1})
- e+ unpolarised lepton beam (0.3ab^{-1})

CC: No right-handed weak currents





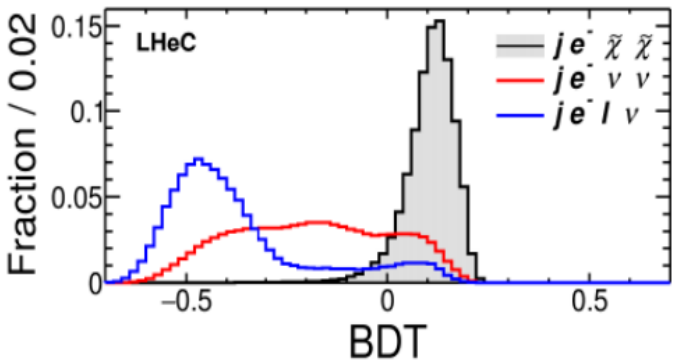
'light' sleptons (m>chargino,neutralino)

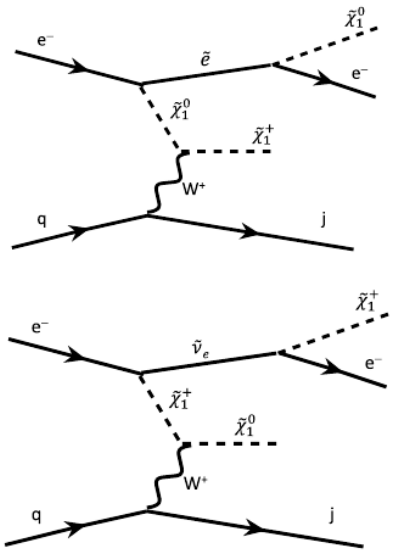
Sleptons might be a bit heavier than EWKinos but still light (Motivated by g-2 anomalies)

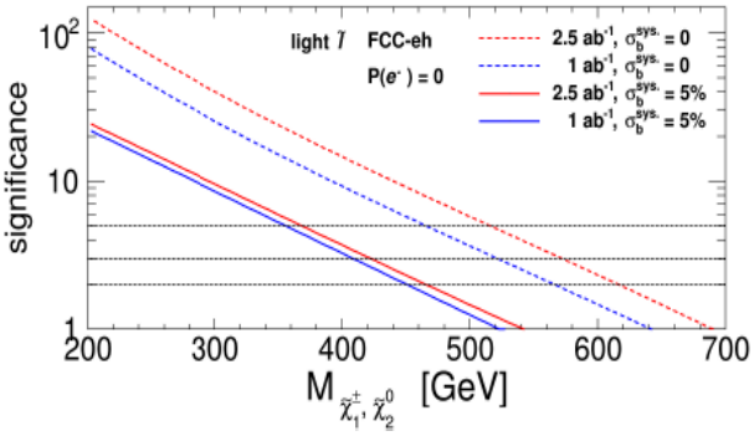
- Would play no role in the decay of charginos/neutralino2.
  At pp: very challenging

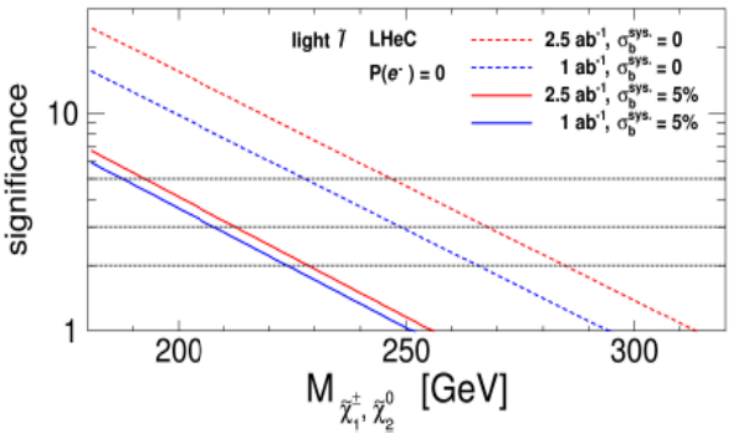
Wang, Azuelos, D'Onofrio, Iwamoto, preliminary

- Reasonable No. of events,
- low syst. expected
- MVA-BDT analysis:



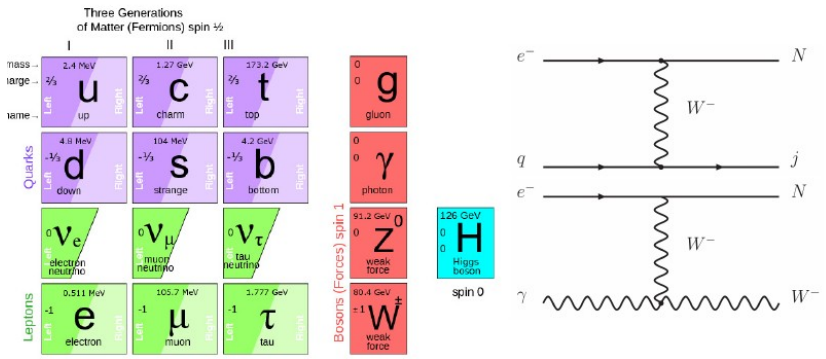


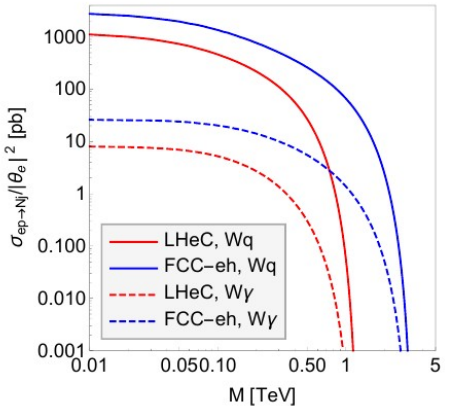




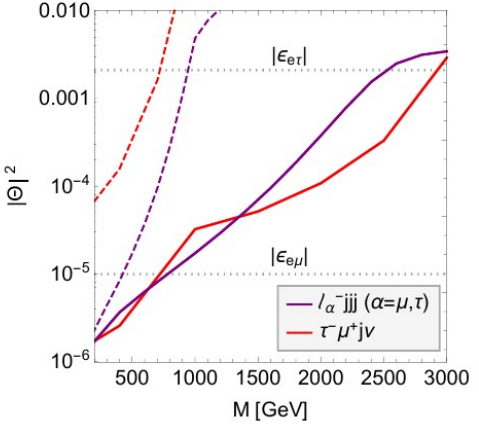
Sterile neutrinos

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





- Neutrino oscillations → type I seesaw
- Lowscale seesaw models allow large production xsections at colliders
- Present constraints: $|\theta_e| \leq 10^{-3}$
- Searches via lepton-flavor violating final states: μ +jets, $\mu\tau$ + jets



- Displaced vertex searches for heavy neutrino masses $< m_W$

ep collider is ideal to study common features of electrons and quarks with

- EW / VBF production, LQ, multi-jet final states, forward objects

BSM programme at e-p aims to

- Explore new and/or challenging scenarios
- Characterize 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 pile-up (good secondary vertex resolution)
  - Some difficult aspects:
    low production rate for NP processes due to small √s

Lately, good engagement from theory community working with experimentalists