Beyond Standard Model Physics at LHeC and FCC-eh

G. Azuelos on behalf of LHeC/BSM team

26 July– 6 Aug. 2020, Prague (Virtual Conference)
http://ichep2020.org/

Introduction

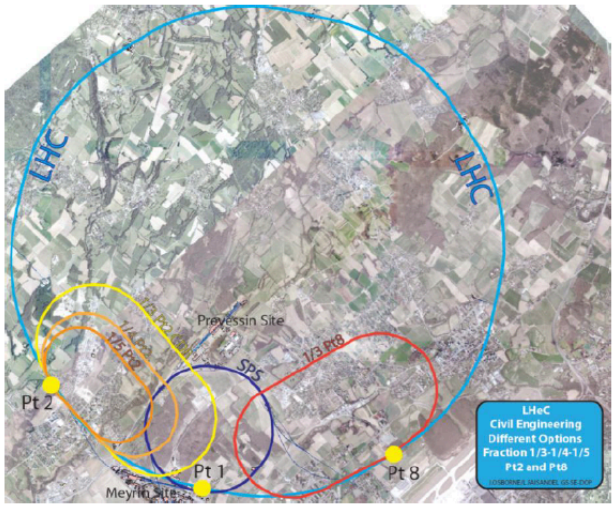
Future ep colliders:

LHeC: 60 GeV x 7 TeV, $\sqrt{s} = 1.35$ TeV
FCCeh: 60 GeV x 50 TeV, $\sqrt{s} = 3.5$ TeV
~ 1 ab^{-1}

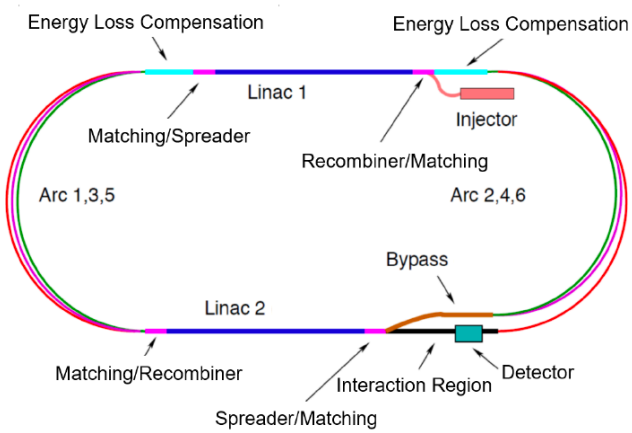
concurrent running periods with LHC (arXiv:1810.13022)
Energy recovery LINAC

D. Pellegrini et al., Phys. Rev. ST Accel. Beams 18, 121004

LHeC detector → see Yuji Yamazaki, #737



BSM Physics limited by cm energy, but
- **low background**
- **very low pileup**
- **much improved pdf** → see C. Gwenlan, #731
- **polarized e⁻ beam**
  - → precision measurements,
  - → new regions of challenging phase space unexplored by *pp* colliders



LHeC CDR, 2012: J.Phys.G 39 (2012) 075001, (1206.2913)
new updated version (white paper) just submitted

Outline, selected topics

Leptoquarks

- **unexplored phase space at pp colliders, high mass at FCC-eh**

BSM Higgs

- **heavy scalar**
  - neutral scalars, 2HDM-III, FV $b\,\bar{s}$, NMSSM
- **charged Higgs,**
  - **Georgi-Machacek model**
  - $e^-p \to \nu\, H^+ q,\, H^+ \to c\bar{b}$, 2HDM, $H^+ \to s\,c, s\,u$, NMSSM
- **H → Long-lived light particles**
- Higgs self-coupling, H→ invisible → see U. Klein, #734
- top-Higgs interaction → see D. Britzger, #733

SUSY

- **electroweakinos in compressed scenario, displaced vertex and Long-lived particles**

Heavy fermions

- **heavy neutrinos**
- Heavy fermions: excited fermions, Vector-like fermions
- colour-octet leptons

Dark photons

Axion-Like Particles

Anomalous Triple Gauge Couplings → see D. Britzger, #733

Quark substructure (quark radius $< 10^{-19}$ m at LHeC, 100 fb^{-1})

Lepton-quark compositeness

Charged Lepton-flavour violation (via Z': ep → τ j, μ j))

Leptoquarks

- Long history:
  - Pati-Salam model, technicolor, Grand Unified Theories, compositeness models
- B decay anomalies

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\Bigg|_{l\in\{e,\mu\}}$$

3.8 sigma excess with respect to the SM values

$$R_{J/\psi} = \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu})}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu})} = 0.71 \pm 0.25$$

2 sigma excess

$$R_{K^{(*)}}^{[q_1^2,q_2^2]} = \frac{\mathcal{B}'(B \to K^{(*)}\mu\mu)}{\mathcal{B}'(B \to K^{(*)}ee)},$$

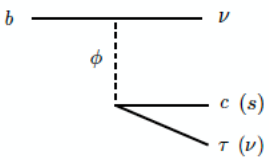
2.5 sigma deficiency

  - lepton non-universality?
  - S_3, $(\tilde{R}_2)$ sensitive to $R_K^{(*)}$
  - S_1, R_2 sensitive to $R_D^{(*)}$
  - vector LQ's
- $\tilde{R}_2$ allows for the possibility of RH neutrinos (3 generations)

S. Mandal, N. Sinha and M. Mitra, Phys.Rev.D 98 (2018) 9, 095004 (arXiv:1807.06455)

I. Doršner et al., 1603.04993

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^L)$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\overline{R}})$	0



Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
S_1	✗*	✓	✗*
R_2	✗*	✓	✗
$\widetilde{R}_2$	✗	✗	✗
S_3	✓	✗	✗
U_1	✓	✓	✓
U_3	✓	✗	✗

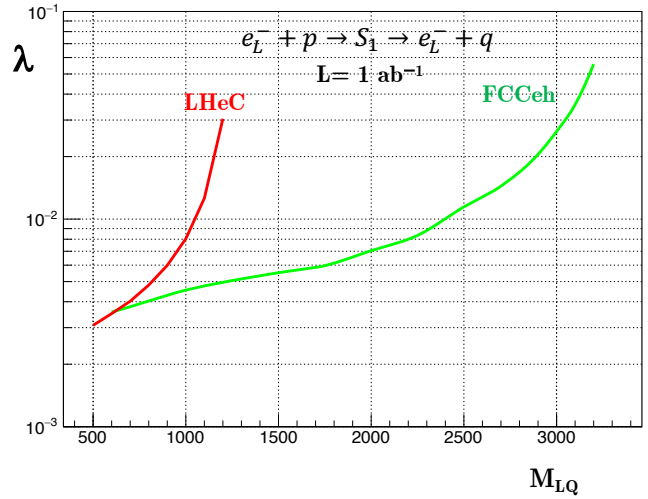
A. Angelescu et al., JHEP 10 (2018) 183, (1808.08179)

Leptoquarks: direct s-channel production at ep colliders

- very sensitive to LQ-e-q coupling, up to 2 orders of magnitude below e.m. strength ($\sqrt{4\pi\alpha} \sim 0.3$)
- ... and to LQ properties, if discovered
  - fermion number, charge, *much more sensitive than at LHC, from sign and size of asymmetry (need both e^+ and e^-, coupling to q or $\bar{q}$)*

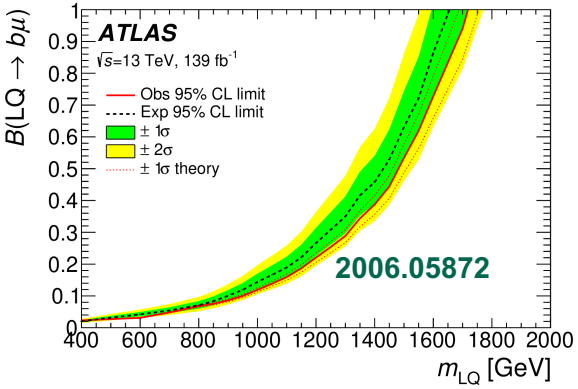
$$\mathcal{A}_{ep} = \frac{\sigma_{prod}(e^+p) - \sigma_{prod}(e^-p)}{\sigma_{prod}(e^+p) + \sigma_{prod}(e^-p)}$$

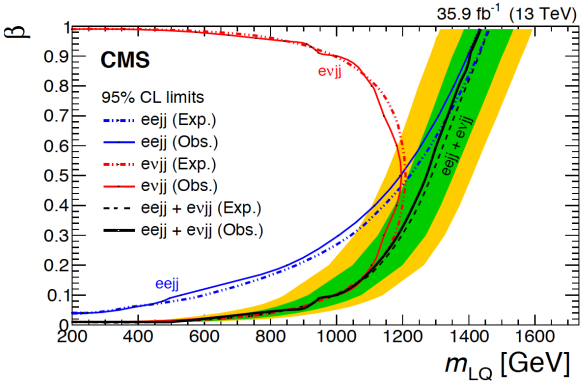
  - spin, *(scalar of vector) from angular distribution*
  - chiral structure, *with polarized beams ($e_L^- p$ vs $e_R^- p$)*
- scalar LQ possible interpretation as R-parity violating squark decay
- contact term for high mass (mass scale of contact interaction ~ 65 TeV at LHeC)

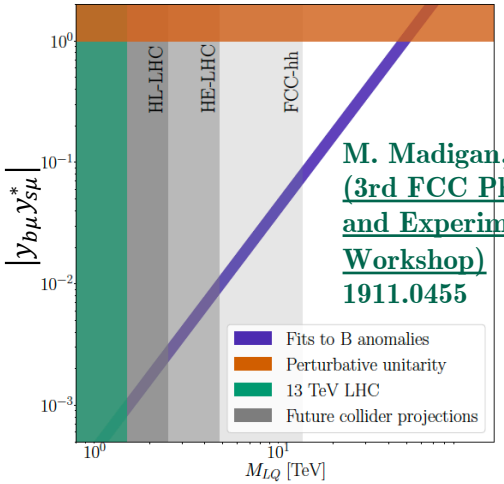


At pp colliders, scalar LQ pair production ($g \to LQ\ LQ$) is independent of *LQ-l-q* coupling

- *upper limits on LQ mass, as a function of BR to charged lepton channel*
- *less stringent constraints when β is small*



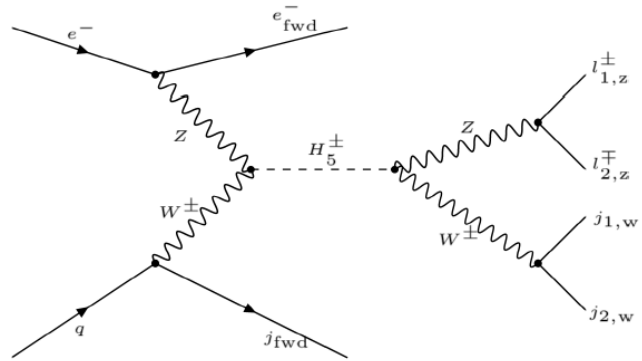




Charged Higgs, Georgi-Machacek model

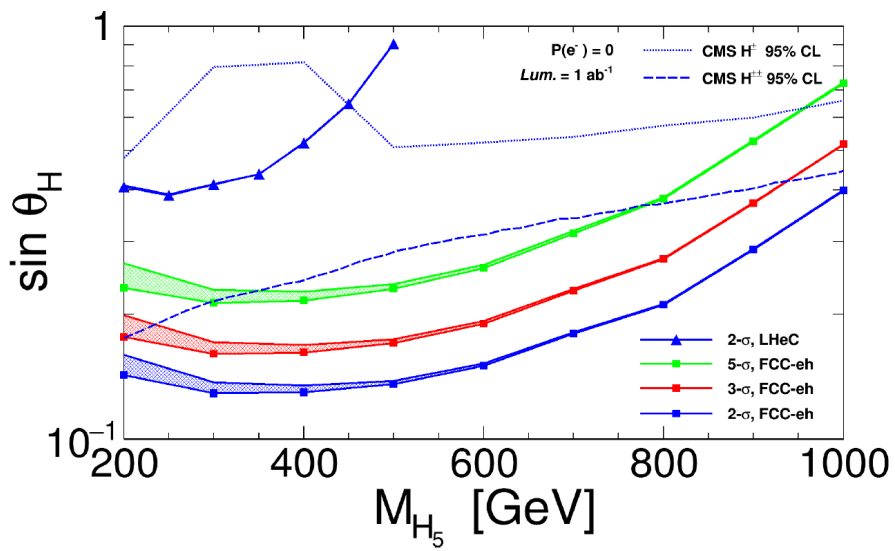
G.A., H. Sun and K. Wang, Phys.Rev.D 97 (2018) 11, 116005 (1712.07505)

(see U. Klein, #734, for Higgs physics studies)



- Extended Higgs sector, with isospin triplets, satisfying custodial symmetry
  - ➔ $\rho = \frac{M_W^2}{M_Z^2 \cos\theta_W} = 1$ at tree level
- Higgs bidoublet and two triplets (one real and one complex) arranged as a bitriplet
- physical spectrum includes fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$ which does not couple to fermions
  - ➔ only produced by VBS
- parameters:
  - mass of H_5
  - mixing angle $s_H = \sin\theta_H$

Analysis based on Delphes detector simulation and BDT signal optimization

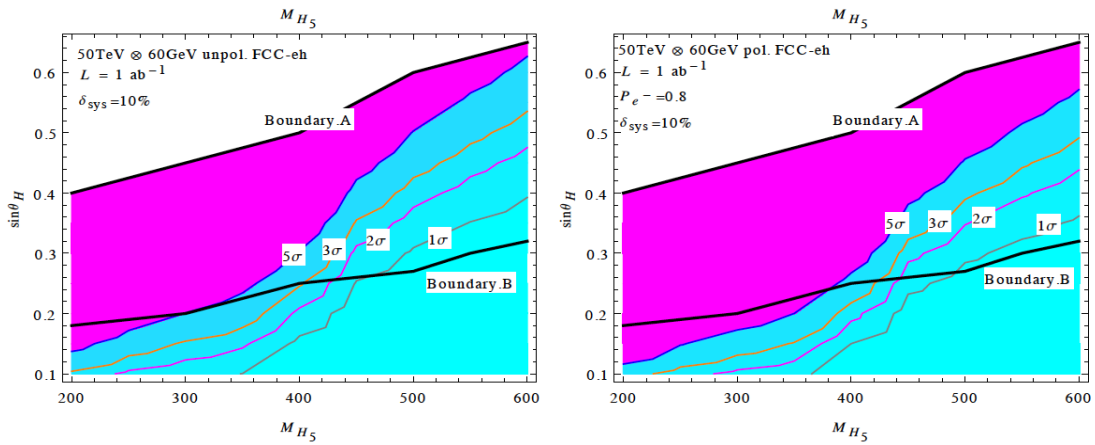


Charged Higgs

- $e^-p \to \nu H^{\pm\pm} q,\ H^{\pm\pm} \to W^\pm W^\pm$ in GM model

  H. Sun, et al., Phys.Rev.D 96 (2017) 9, 095003, (1710.06284)

  - LHeC: 2−3σ at LHeC for $M_{H_5} < 300$ GeV and $\sin\theta_H < 0.2$
  - more sensitivity for small $\sin\theta_H$ at FCC−eh, unpolarized and polarized beams



CMS limit

- $e^-p \to \nu H^+ q,\ \ H^+ \to c\bar{b}$ in 2HDM, type III

  J. Hernandez-Sanchez et al., Proceedings, CHARGED2016, (1612.06316)

  - flavour-violating decays, with FCNC's controlled in Yukawa Lagrangian
  - 3σ with 100 fb^{-1} for mass 100-200 GeV
    (at LHC, strong limit on $B(t \to H^+ b)$, assuming $B(H^+ \to cb)$=1, or $B(H^+ \to cs)$ =1)

- $e^-b \to \nu H^+ b,\ \ H^\pm \to sc + su$ in NMSSM at FCC-eh

  A.P. Das et al., arXiv:1806.08361

  - additional singlet S, looking for *light* charged Higgs
  - 4.4(2.2)σ with 1 ab^{-1} for mass of 114(121) GeV

Heavy neutrinos

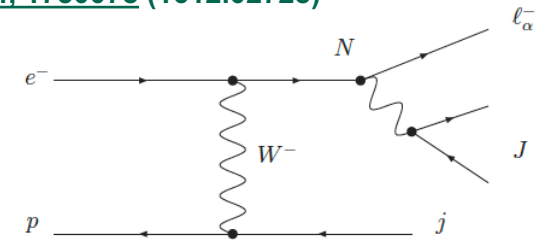
S. Antusch, E. Cazzato and O. Fischer, Int.J.Mod.Phys.A 32 (2017) 14, 1750078 (1612.02728)

- $e^- p \to \ell^- + 3j$
  - LFV final states (Majorana neutrinos): $e^- p \to \mu^- + 3j$
  - in low-scale see-saw models with 2 sterile neutrinos with weak mixing with SM neutrinos
    $\to$ long lifetime

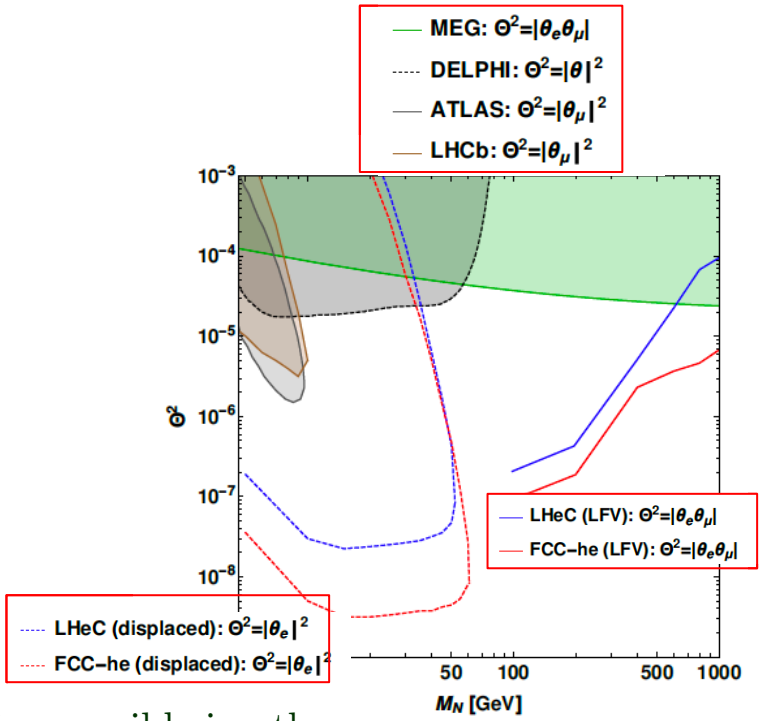
    S. Antusch, O. Fischer and A. Hammad, JHEP 03 (2020) 110, (1908.02852)
    S. Mondal and S. K. Rai, Phys.Rev.D 94 (2016) 3, 033008 (1605.04508)
    - displaced vertex
      - BDT analysis
      - tracking resolution: 8 μm
      - displacement ~ 40 μm
  - effective Lagrangian parametrization

    L. Duarte, G. A. Gonzalez-Sprinberg and O. A. Sampayo, Phys.Rev.D 91 (2015) 5, 053007 (1412.1433)
    - sizable lepton number violating effects for effective couplings of order 1
  - discriminate between scalar and vector effective interaction using polarized electrons

    L. Duarte, G. Zapata and O. A. Sampayo, Eur.Phys.J.C 78 (2018) 5, 352, (1802.07620)
  - Left-Right Symmetric model: $e^- p \to e^+ + 3j$
    M. Lindner, et al., JHEP 06 (2016) 140 (1604.08596)
    - depends on charge misID, can cover regions inaccessible in other searches



$(e^- p \to N + j;\ N \to \mu^- W;\ W \to 2j)$



Electroweakinos in compressed scenarios

- compressed scenario (small $\Delta m(\tilde{\chi}_1^{\pm}/\chi_2^0,\ \chi_1^0)$)
  - assume ~ degenerate $\tilde{\chi}_1^{\pm}/\chi_2^0$ (Wino)
  - difficult to investigate at LHC because of soft decay products and large background
  - sleptons, $\tilde{\ell}$, could be also NLSP

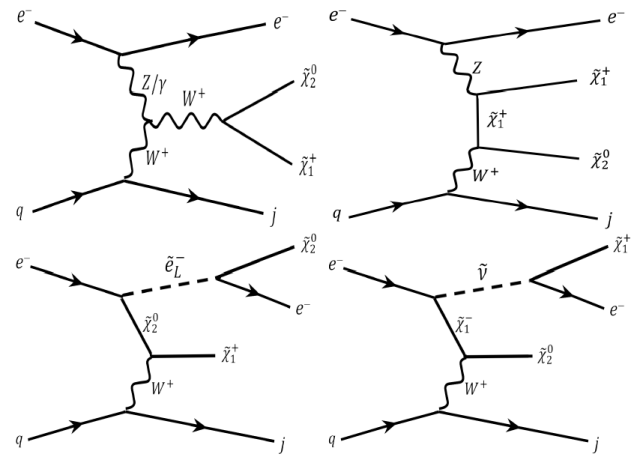
G. A., M. D'Onofrio, S. Iwamoto and K. Wang, Phys.Rev.D 101 (2020) 9, 095015 (1912.03823)

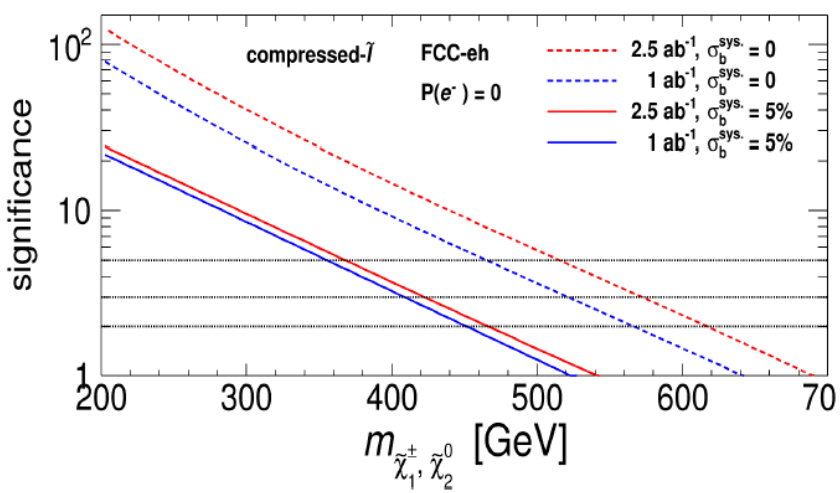
- study based on BDT
  - benchmark: $\Delta m = m_{\tilde{\ell}} - m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} = 35$ GeV

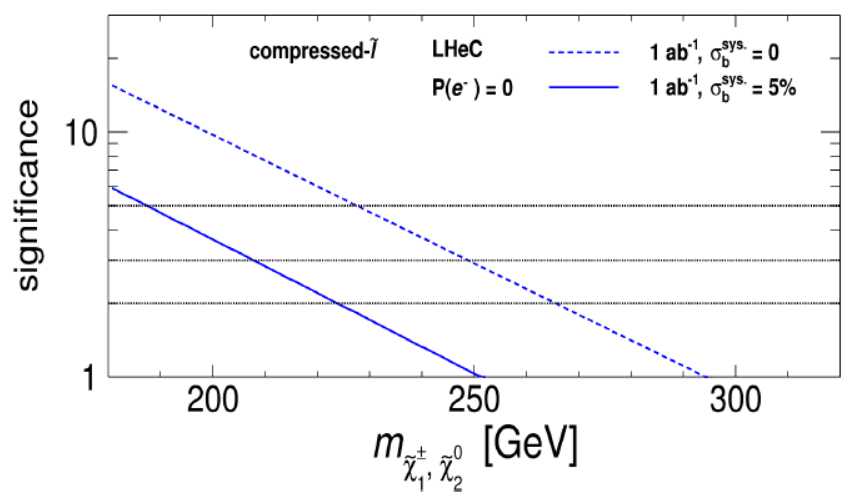
    $m_{\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 1$ GeV

    $\tilde{\chi}_1^0$ is Bino, $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ are Wino
  - limits on $\tilde{\chi}$ mass, 1 ab^{-1}
    - LHeC: ~ 220 GeV, with 5% syst. uncertainty

      $\gtrsim$ LHC limit
    - FCCeh: ~ 450 GeV, with 5% syst. uncertainty
    - HL-LHC: ~ 400 GeV







more SUSY

- Light Higgsinos in compressed spectrum

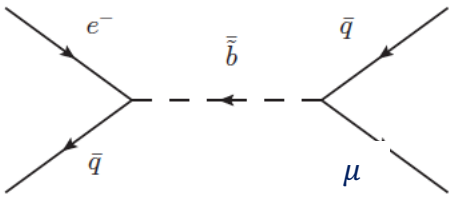
  C. Han et al., Phys.Rev.D 98 (2018) 11, 115003 (1802.03679)

  - decoupled scenario (heavy slepton)
  - LHeC: 2σ for mass=115 GeV, 1 ab^{-1}

- RPV, resonant production of $\tilde{b}$

  S. Kuday, Korean Phys.Soc. 64 (2014) 1783, (1304.2124)

  (also R. Zhang et al., with 150 GeV e- beam)



$e^- p \to \tilde{b} \to \mu q$

  - constraints on $\hat{L}\hat{Q}\hat{D}$ couplings λ'_{113} , λ'_{123} , λ'_{231} , λ'_{232}
    - present bounds:
      $\lambda'_{113} = \lambda'_{123} < 0.18$, $\lambda'_{231} = \lambda'_{232} < 0.45$(Barbier et al.)
    - couplings can be considerably extended with 1 fb^{-1} for low $\tilde{b}$ mass

- prompt decay of low mass gluinos: 50-70 GeV

  D. Curtin, K. Deshpande, O. Fischer and J. Zurita, Phys.Rev.D 99 (2019) 5, 055011, (1812.01568)

  - RPV or "stealth" SUSY, multiple soft jets ➔ hadronic noise at LHC
  - 95% exclusion with simple cuts, at LHeC, 1 ab^{-1}, with 1% syst. error

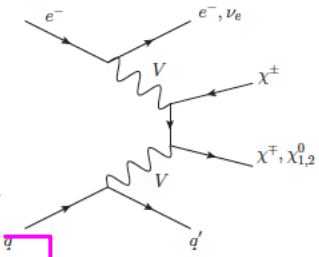
- improved interpretation of LHC mass limit for gluinos, given very low pdf uncertainty. (1211.5102)

Long-lived particles

D. Curtin, K. Deshpande, O. Fischer and J. Zurita, JHEP 07 (2018) 024, (1712.07135)

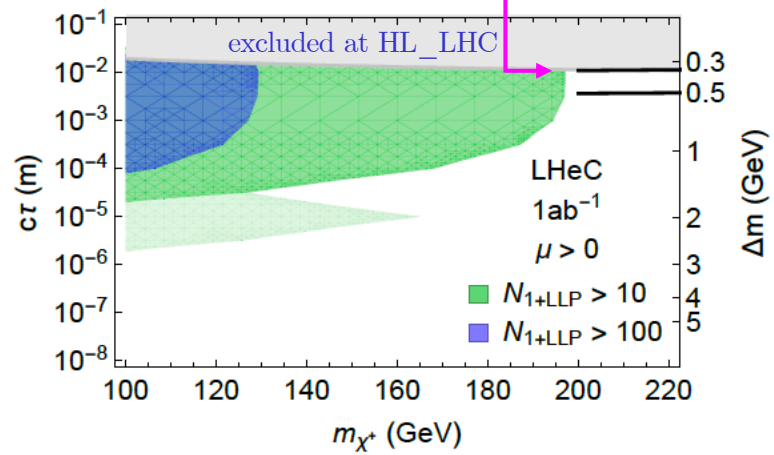
LLP: predicted in hidden sector models

Very clean enviroment allows for reconstruction of soft displaced final states

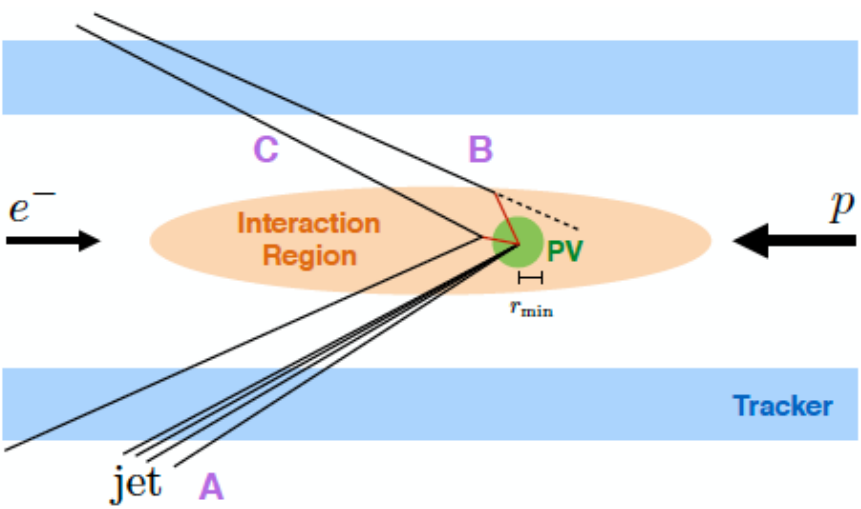


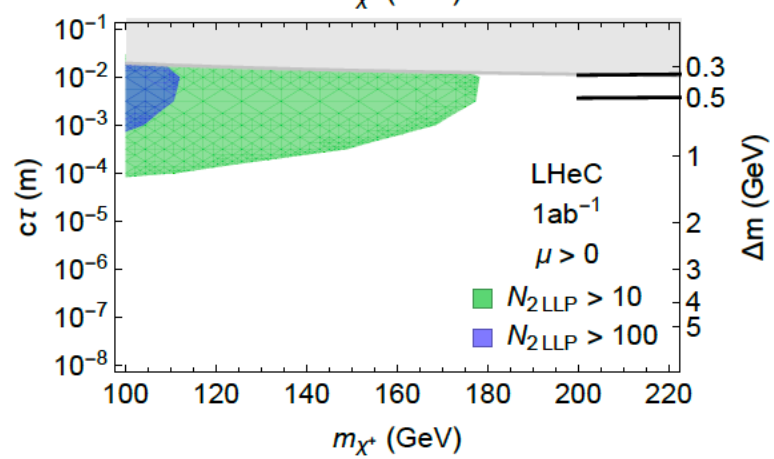
- long-lived Higgsinos
  - compressed scenario: small mixing, small mass splitting
    - long lifetime of chargino/neutralino
    - look for displaced vertex
      ($\tilde{\chi}^\pm \to e^\pm/\mu^\pm/\pi^\pm + \tilde{\chi}^0$)
      or large impact parameter
      ($\tilde{\chi}^0 \to$ 1 charged particle)

limits from disappearing track searches at HL-LHC



Assume 5-16 μm tracking resolution, 50-400 MeV single track reconstruction

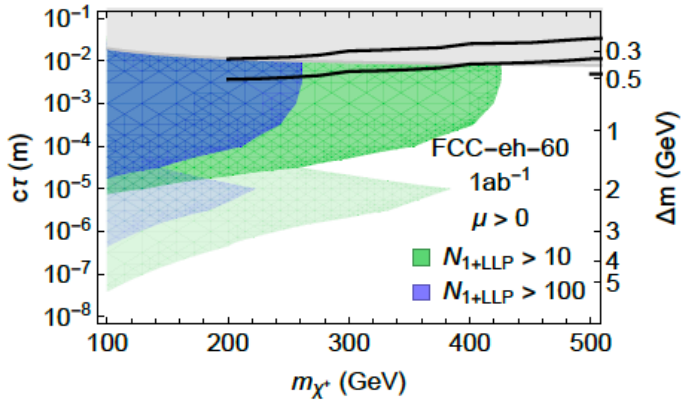


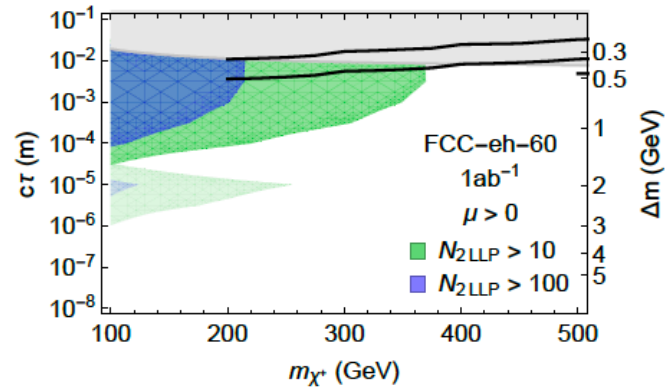


Long-lived particles

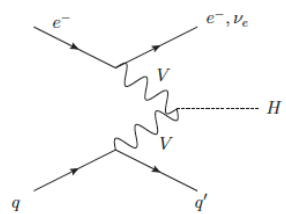
D. Curtin, K. Deshpande, O. Fischer and J. Zurita, JHEP 07 (2018) 024, (1712.07135)

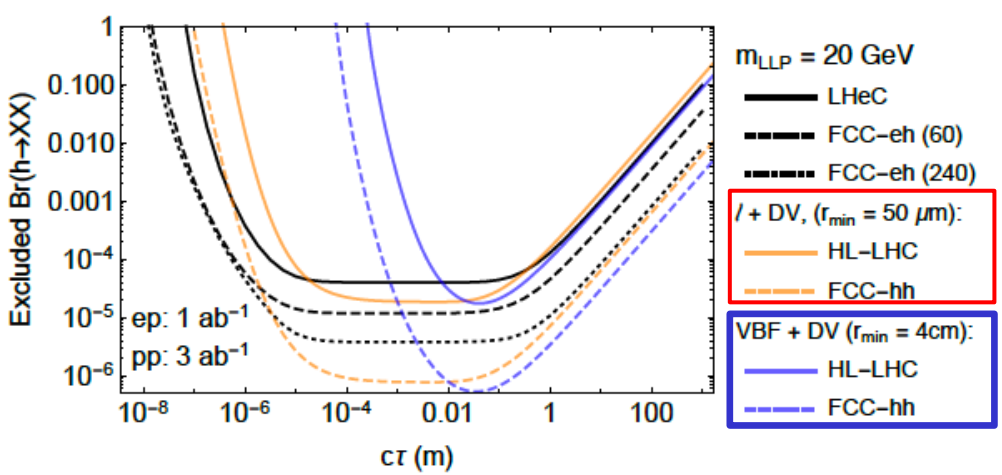
At FCC-eh:

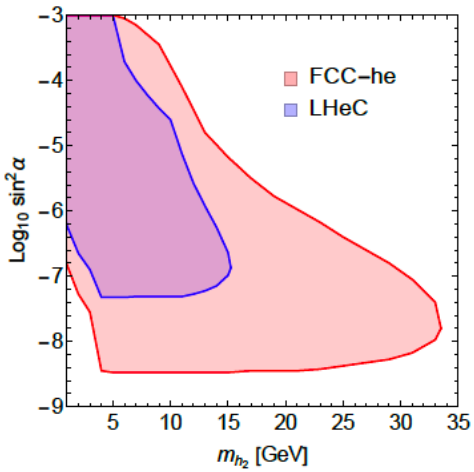




- Higgs to LLP: $H \to XX$
  - *light* X mixing with h
  - $X \to b\bar{b}$







Dark sector

Dark photons

Additional $U(1)_X$, with weak kinematic mixing of $U(1)_Y$

- SM photon couples to dark fermions
- dark photon couples to electric charge of SM fermions
  - expect very low mass: decays to e/μ/q pairs
  - weak mixing → long lifetime → displaced vertex

Axion-like particles (ALP)

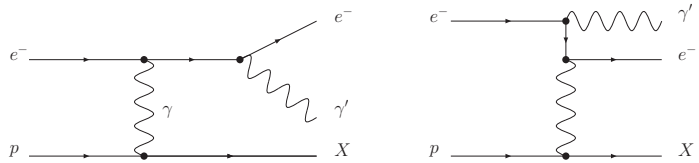
pseudoscalar particles, (low) mass

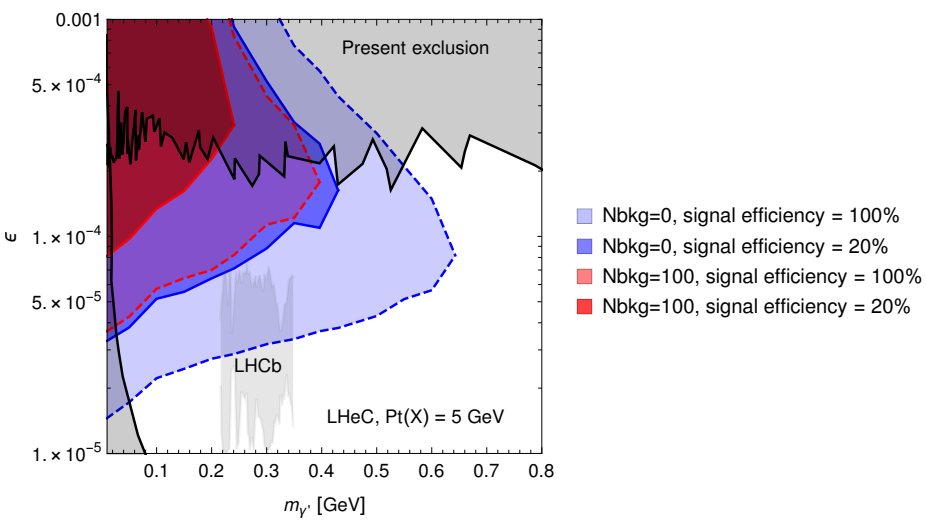
motivated by QCD axion,

possible dark matter mediator to dark sector

pNBG in composite models

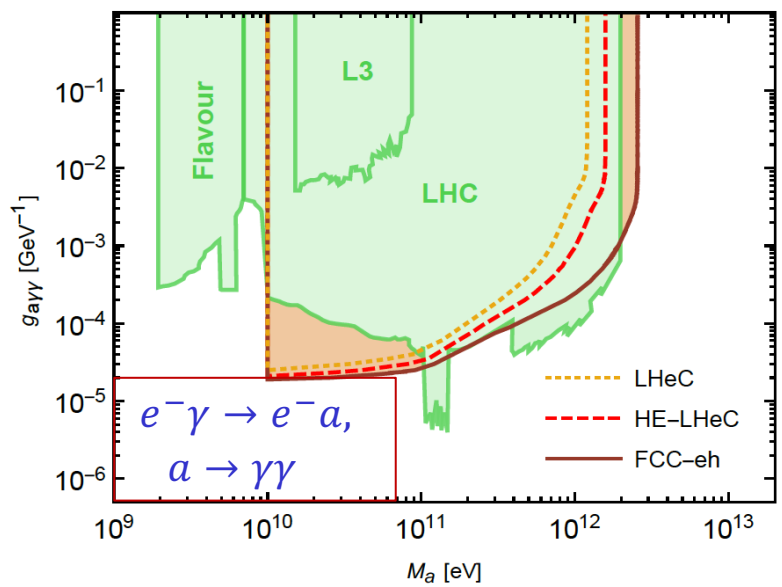
→ decay into photons, leptons, hadrons





M. D'Onofrio, O. Fischer and Z. S. Wang, Phys.Rev.D 101 (2020) 1, 01502 (1909.02312)

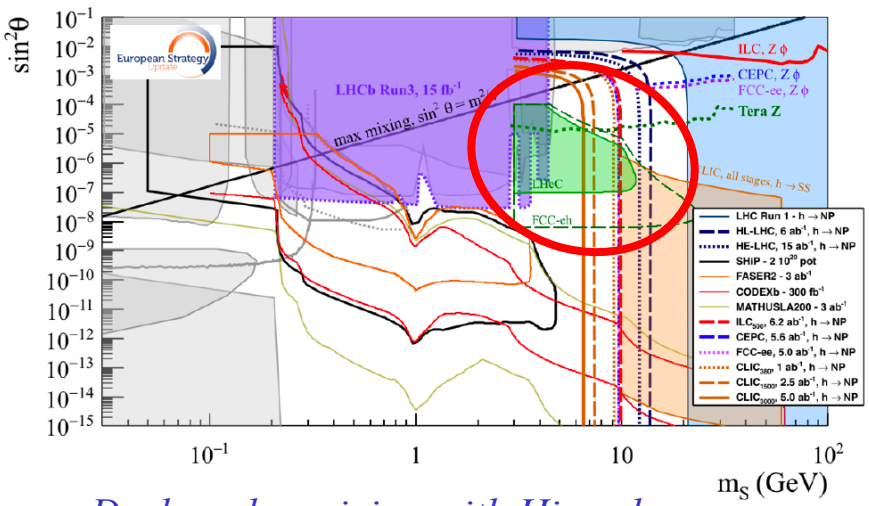
exclude 10 GeV – 1(3) TeV at LHeC(FCC-eh)



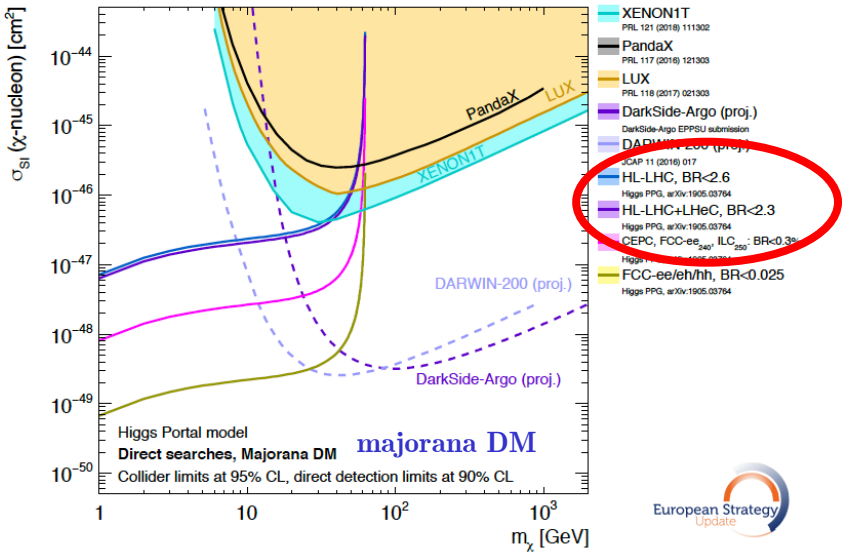
C-X Yue, M-Z liu and Y-C Guo, Phys.Rev.D 100 (2019) 1, 015020 (1904.10657)

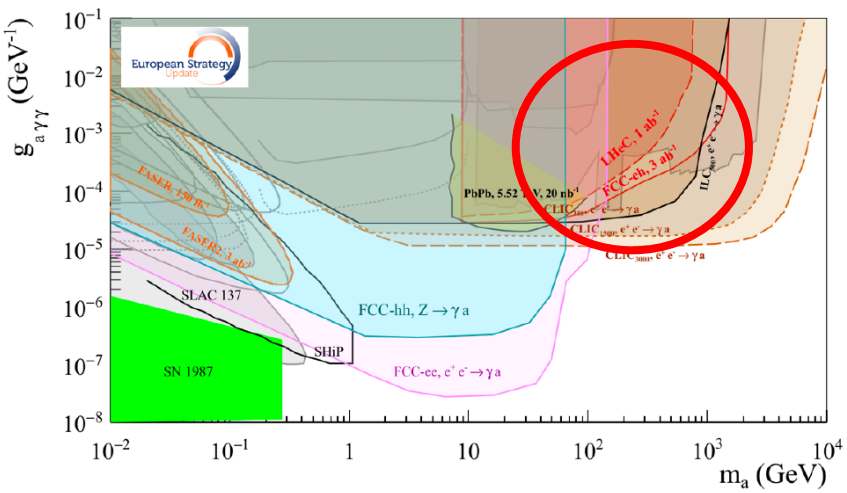
Complementarity of ep colliders for dark sector

Physics Briefing book, ESU, 1910.11755

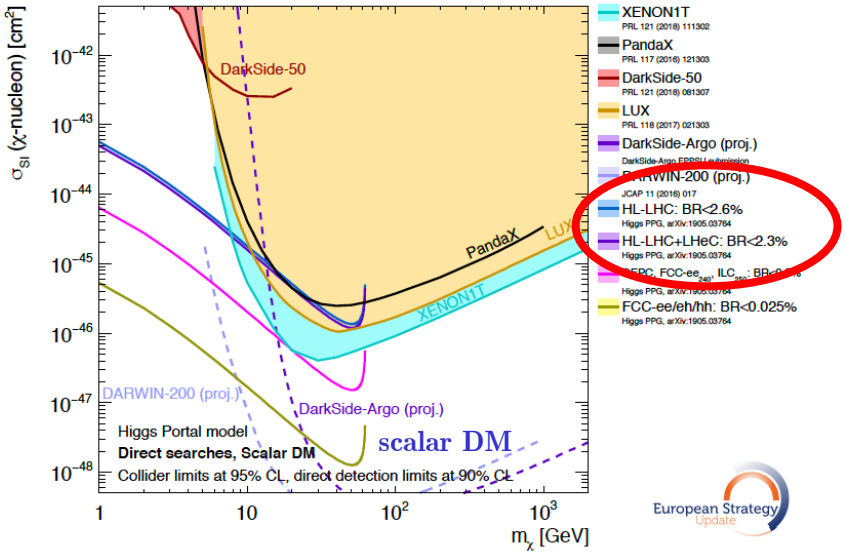


Dark scalar mixing with Higgs boson





ALPs coupled to photons



Higgs portal for SI wimp-nucleon coupling

Conclusion

Thanks to clean environment, low pileup,
ep colliders offer a rich program of BSM physics, mostly based on precision measurements

The LHeC can probe sensitive regions of phase space difficult of access at LHC and complement results from LHC

FCC-eh opens higher energy regime

Thank you

backup

Vector-like quarks

- VLQ's predicted in composite-Higgs models
  - cancel quadratic divergences in Higgs mass (hierarchy problem)
  - third generation coupling most important
  - produced in pair at LHC ➔ independent of coupling
- At LHeC/FCC-eh
  - $e^-p \to T(\to tZ)\nu_e;\quad t \to Wb \to jjb,\ Z \to \ell^+\ell^-$

    Y-J Zhang, L. Han & Y-B Liu, Physics Letters B 768 (2017) 241
  - $e^-p \to T(\to bW^+)\nu_e;\quad W^+ \to \ell^+\bar{\nu}_\ell$

    L. Han, Y-J Zhang & Y-B Liu, Physics Letters B 771 (2017) 106
  - $e^-p \to T(\to th)\nu_e;\quad t \to Wb \to jjb,\ h \to bb$ (also $T \to bW^+$)

    Y-B Liu, arXiv:1704.02059

LHeC: (140 GeV polarized e- beam)
- *generation mixing enhances cross section*
- *with 1/ab, 3σ sensitivity to coupling:*
  g~ 0.1 even with no generation mixing*