## *From EWK and Higgs physics to BSM searches:*  **the electron-proton case**

**deliveries of ep/eA at the** 



### **Monica D'Onofrio University of Liverpool** • **empowering the LHC/FCC search**

*(on behalf and thanks to the work of many people in past years, in particular Max Klein, Uta Klein, Oliver Fischer, Jose Zurita, Daniel Britzger, Christian Schwanenberger...*) • **improve SM measurements**

> **ES UK Strategy 23/09/2024**

**The Universität** 

![](_page_0_Picture_5.jpeg)

### $F_1$ DIS and pp colliders: an historical synergy

![](_page_1_Figure_1.jpeg)

Idea and details already presented and discussed by Paul

**LHeC e-p:**  $E_e = 60$ <sup>(\*)</sup> GeV,  $E_p = 7$  TeV  $\sqrt{s} = 1.3$  TeV à For **FCC-eh**: 50 TeV protons, **√s = 3.5 TeV**

**LHeC e-Ion: Ee=60 (\*) GeV, EIon=2.76 TeV** → For **FCC-eh**: increase up to ~20 TeV

![](_page_1_Figure_5.jpeg)

2 Monica D'Onofrio, ES UK 2024

*Q*<sup>2</sup> = !(*k* ! *k* ')

 $\blacksquare$ 

 $\blacksquare$ 

 $\mathbf{v}^2$ 

24/9/24

#### **Collision energy above the threshold for EW/Higgs/Top Collision energy above the threshold for EW/Higgs/Top Collision energy above the threshold for EW/Higgs/Top** tion  $\overline{4}$ **The real game change between HERA**<br> **The real game change between HERA** Log(ep→HX)  $\overline{3}$ and the LHeC/FCC-eh  $H = \frac{H}{L}$  $\overline{2}$ **DIS Higgs Production Cross Section** tion  $\overline{4}$  $\overline{C}$  **Figure 2 Figure 2 Figure 2 Figure 2 P**  $\mathbf{1}$ Log(ep→HX)  $\overline{3}$ *1000 fb*  $\overline{\phantom{0}}$  $\Omega$ *200 fb* FCC-eh  $\frac{1}{2}$ -eh *200,000 H's*  $\overline{2}$ *200 fb*  $W$ *200,000 H's*  $-1$  $-- H$  $T<sub>1</sub>$  $\mathbf{1}$  $-2$ **HERA**  $\mathbf 0$ *200 fb 200,000 H's*  $\overline{Z}$  $W$  $-3$  $q$  $-1$  $\cdots$   $H$ Ч  $-q$  $-4$  $-2$ compared to protect the protection of the second state are reasonably the second state are reasonably the second state and  $-3$  $-5$ con  $q \rightarrow q'$  are  $q' \rightarrow q'$  in **com**  $\frac{q}{q}$   $\frac{q}{q}$   $\frac{q}{q}$   $\frac{q}{q}$  $\frac{1}{2}$  contained to  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  are events with much  $-4$ reasonably clean Higgs events with much  $-6$ reasonably clean miggs events with much less backgrounds compared to proton compared to provide the proton contains the reasonably collected to provide the reasonable  $-5$ less backgrounds  $-7$   $\perp$ *at these energies and luminosities, interactions*  css backgrounds  $-6$ HERA, versus polarized (P=-0.8) at LHeC and FCC-eh *at these energies and luminosities, interactions with all SM particles can be measured precisely* 0 1 2 3 4 *at these energies and luminosities, interactions*  HERA, versus polarized (P=-0.8) at LHeC and FCC-eh assuming unpolarized electron beams at EIC and the cms energy /TeV gy /TeV *with all SM particles can be measured precisely with all SM particles can be measured precisely* 0 1 2 3 4

3 Monica D'Onofrio, ES UK 2024 24/9/24

## **Outline**

The *eh* programmes of LHC and FCC are designed to operate **synchronously** with *hh* **Interesting physics programme on its own and synergic:** 

- PDFs, strong coupling constant, low-x measurements
- W mass, top mass, on other precision measurements in EWK and Top sectors
- $\blacktriangleright$  **Higgs measurements with additional sensitivity**  $\rightarrow$  **precision higgs facility together with LHC**
- Searches for new physics, including prompt and long-lived new scalars from Higgs, SUSY **particles, neavy neutrinos, dark photons and axions**
- $\blacktriangleright$  High-energy and high-density measurements of heavy ion collisions

à *the LHeC(FCC-eh) will contribute to the main objectives of the HL-LHC(FCC-hh), empowering its programme and bringing in more variety* 

### Some key examples in the following

much mor[e in CDR https://arxiv.org/abs/200](https://arxiv.org/abs/2007.14491)7.14491, [https://cds.cern.ch/record/2729018/files/ECFA-Newsl](https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf)etter-5- [Summer2](https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf)[020.pdf, Eur. Phys. J. C \(202](https://link.springer.com/content/pdf/10.1140/epjc/s10052-021-09967-z)2) 82:40, FCC CDR: EPJC 79, no. 6, 474 (2019) , Phys Eur. Phys. J. ST 228, no. 4, 755 (2019)

4 Monica D'Onofrio, ES UK 2024 24/9/24

## **DIS and EWK measurements**

 $\Box$  LHeC/FCC-eh are excellent facilities for testing FW theory

![](_page_4_Figure_2.jpeg)

### **Key observables:**

- W mass
- Effective EWK mixing angle

Measurements as standalone and in combination with HL-LHC

## **DIS and EWK measurements: W mass**

### ´ **@ HL-LHC W mass** precision measurement uses dedicated dataset at low <mu>

- $\rightarrow$  exploit the extended leptonic coverage
- $\rightarrow$  LHeC will provide additional precision through PDF

 $\Delta m_W$  =  $\pm$ 6 MeV (with reduced PDF unc from HL LHC)  $\begin{bmatrix} 1 & 0 & 0 \ 0 & 1 & 0 \end{bmatrix}$  $\Delta m_{\rm W}$  =  $\pm 2$  MeV (with improved PDF from LHeC)  $\frac{8}{6}$  **of the SM shallow error ellipse and a precise test of the SM shallow error ellipse and a precise test of the SM shallow error ellipse and a precise test of** 

´ MW and MZ (as well as mTop) will be measurable energy parameters ↵ and *G*<sup>F</sup> as input (plus values for masses like *M<sup>t</sup>* and *M<sup>H</sup>* needed for loop at unprecedent precision independently at the LHeC

*Z*-boson masses at the LHeC for di⊄erent scenarios in comparison with today's measurements [331–333]

![](_page_5_Figure_6.jpeg)

![](_page_5_Figure_7.jpeg)

### **DIS** and EWK measurements:  $\sin^2\theta_{\text{eff}}$ 0.1 % and better than 1 % over a wide kinematic range of about 25 *<* p*Q*<sup>2</sup> *<* 700 GeV.

LHeC will contribute to the ffective EWK mixing angle sin<sup>2</sup> $\theta_{\text{eff}}$  precision measurements  $\text{cost}$  and indiractly, alluminosity and indirectly and indirectly weak mixing and sinal angle single sing

■ **Direct** measurements using higher-order loop corrections

$$
\sin^2 \theta_W^{\text{eff},\ell}(\mu^2) = \kappa_{\text{NC},\ell}(\mu^2) \sin^2 \theta_W
$$

- Scale dependence of  $sin^2\theta_{eff}$  not negligible
- **Example 3 Simultaneous fits made with PDFs** 
	- $\blacksquare$  Indirect: improving precision of HI-I HC studies • Indirect: improving precision of HL-LHC studies
	- 12Since in the Linds and NCsince in the Linds and NCsin<br>■ Use F-B Asymmetry measurements

![](_page_6_Figure_8.jpeg)

![](_page_6_Figure_9.jpeg)

**Precisions**  $\rightarrow$  **1 ⋅ 10<sup>-5</sup> if 0.23153 ± 0.00018**  $rac{0.23153 \pm 0.00018}{0.23153 \pm 0.00018}$  **PDF uncertainties are** and a combination combination improved with LHeC and a combined separate measurements (not shown a combination o <sup>Z</sup>) from LHeC inclusive DIS data with

24/9/24

### **DIS and EWK measurements: sin<sup>2</sup>** $\theta$ 0.1 % and better than 1 % over a wide kinematic range of about 25 *<* p*Q*<sup>2</sup> *<* 700 GeV.

LHeC will contribute to the effective EWK mixing and the contribute to the effective EWK mixing centremente directly and indirectly **n** measurements directly and indirectly measurements directly

■ **Direct** measurements using higher-order loop corrections PDF uncert. 10<sup>5</sup> *<sup>±</sup>* <sup>24</sup> *<sup>±</sup>* <sup>16</sup> *<sup>±</sup>* <sup>13</sup> *<sup>±</sup>* <sup>3</sup>

$$
\sin^2 \theta_W^{\text{eff},\ell}(\mu^2) = \kappa_{\text{NC},\ell}(\mu^2) \sin^2 \theta_W
$$

- Scale dependence of  $sin^2\theta_{eff}$  not negligible
- **Example 3 Simultaneous fits made with PDFs** 
	- $\blacksquare$  Indirect: improving precision of HI-I HC studies • Indirect: improving precision of HL-LHC studies
	- 12Since in the Linds and NCsince in the Linds and NCsin<br>■ Use F-B Asymmetry measurements

![](_page_7_Figure_8.jpeg)

![](_page_7_Figure_9.jpeg)

It may be further of interest, to determine the value of the election of the e $4$ ective weak mixing angle of the e $4$ 

<sup>24/9/24</sup>

## **Higgs physics at ep**

### ■ Production of Higgs boson via Vector-Boson-Scattering

### Total cross section  $(m_H=125 \text{ GeV})$

![](_page_8_Figure_3.jpeg)

*b*-comparisons and  $\frac{1}{2}$  be measured the measured of  $\frac{2}{2}$  be measured.

*cc* 0.029 60 000 9 000

24/9/24

## **Higgs to bbar and ccbar**

- Higgs to bb or cc signal, -0.8 polarization considered
- Detector level analysis with realistic tagger
	- Efficiency 60-75% for b-tagged jets
	- $\blacktriangleright$  ~ 10% efficiency for charm jets [conservative]<sub>2, expresive</sub>

![](_page_9_Figure_5.jpeg)

**Example 1.1** Signal strength µ constraints to  $\frac{20}{1}$ electron polarisation polarisation at LHEC. The *S<sub>/B</sub>* is about 2*.9 for the events in the Higgs mass range of 100 to 100 t* **130 GeV. Events are generated with Madel with Madel with Madel with**  $\frac{80 - 90}{90}$ 

![](_page_9_Figure_7.jpeg)

![](_page_9_Figure_8.jpeg)

![](_page_9_Figure_9.jpeg)

![](_page_9_Figure_10.jpeg)

 $\blacksquare$  modified with a minimum difference mass cut of 60  $\blacksquare$ 

## **Prospects for Higgs in ep**

**• Prospects for signal strength measurements of Higgs decays** 

![](_page_10_Figure_2.jpeg)

![](_page_11_Figure_0.jpeg)

*µV <sup>X</sup>* <sup>=</sup> <sup>2</sup> *<sup>V</sup> ·* <sup>2</sup>

*<sup>X</sup> ·* <sup>1</sup>

*,* (4.1)

## **Combinations of LHeC + HL-LHC**

**Determination of SM Higgs couplings jointly from pp + ep** 

![](_page_12_Figure_2.jpeg)

#### **Indirect Impact of ep on pp Higgs** In Ref. [600], ↵s-related uncertainties are propagated assuming ↵<sup>s</sup> = 0*.*118 *±* 0*.*0015, and the  $\blacksquare$  Indirect Impact of an op pp  $\blacksquare$ **Fugue Communished and** *LH* uncertainties in Tab. 7.4 are calculated using MCFM calculated using MCFM interfaced to PDFs determined from t For *gg* ! *<sup>H</sup>*, the LL resummation of the matrix elements matched to fixed order at N3LO was done in Refs.  $\alpha$  and the results are shown in Figs. 9.13 and 9.13 shown in Figs. 9.14. Fig. 9.13 shown in Figs. 9.13 shown in Figs. 9.14. Figs. 9.1 increasing impact of resummation on the cross section with increasing energy. It also illustrates

- $\blacksquare$  ► Calculation of all production modes improved by  $\alpha_{\sf s}$  and PDF:  $\blacksquare$  chapter 3, and with the exception of with the corresponding under  $\blacksquare$  $\mathbf{p}$  and  $\mathbf{D}\mathbf{D}\mathbf{F}$  extrapolation, not the modification, not the modification of the matrix elements elements elements of the matrix elements of the matrix elements of the matrix elements of the matrix element  $div \cdot \mathbf{v}$ .
- **Exence are reasonally determined at N3LO in pQCD**

![](_page_13_Figure_3.jpeg)

fraction is small (large rapidities) the e $\frac{1}{2}$ 

## **Top physics: Wtb coupling measurements**

### Dominated by single top production

- ~ 1.9 pb e.g. Vtb vertex studies
- $\blacksquare$  In addition, photoproduction of top-pairs
- $\blacktriangleright$  Can do precision measurements and measurements of rare processes

![](_page_14_Figure_5.jpeg)

![](_page_14_Figure_6.jpeg)

particular their electroweak interaction. Selected highlights in top quark physics are summarised

15 Monica D'Onofrio, ES UK 2024

![](_page_15_Figure_0.jpeg)

## **Searches for new physics**

- ep collider is ideal to study common features of electrons and quarks with
	- ´ EW / VBF production, LQ, forward objects, **long-lived particles,** DM
- ´ Differences and complementarities with *pp* colliders
	- Some promising aspects:
	- $\rightarrow$  small background due to absence of QCD interaction between *e* and *p*
	- $\rightarrow$  very low pileup
	- Some difficult aspects:
	- $\rightarrow$  low production rate for NP processes due to small s

#### 7.5 Measuring the Top-quark–Higgs Yukawa Coupling . . . . . . . . . . . . . . . . . 182 <u>[https://arxiv.org/abs/2007.](https://arxiv.org/abs/2007.14491)14491</u>

![](_page_16_Picture_270.jpeg)

+others published afterwords [leptophi](https://arxiv.org/abs/2207.01656)l[ic DM, non-resonan](https://arxiv.org/abs/2102.12507)t BSM [di](https://arxiv.org/abs/2102.12507)-[Higgs, heavy majorana ne](https://arxiv.org/abs/2201.12997)utrino, [exotics](https://arxiv.org/abs/2008.09614) higgs …

**Only a few specific examples given here**

17 Monica D'Onofrio, ES UK 2024

#### **Hidden, dark sectors** entirety for further analysis, as doing so would saturate the experiment data-acquisition and 101 reprofit corriders. It is orient the ease meeting somme caying to minimal compariments, once indicate on the minimal temporary framework in the minimal temporary framework in the minimal temporary framework in the mann 44.0 references above. In the FIPs above. In the FIPs and the FIPs and the FIPs, interactions, the FIPs, interactions, interactions. The SM gauge groups, interactions, interactions, including the SM gauge groups, interacti  $\frac{1}{2}$  with the SM through portals that can be considered by the mediator of the mediator. Since it is generally not possible to record all events in their

- New physics models predicting long-lived particles gained to of attention in the past tew years requires the employment of specific data-taking and analysis techniques [489] (see also Chapter 11).  $\overline{1}$   $\overline{1}$  trigger system
	- Hidden, dark sector
	- **•** populated by feebly interacting particles invisible particles example interacting particles and particles and indicated  $P_{\mu\nu}^{2}$  be number to populated by feebly interacting particles compare collider results to d invisible particles constitute the cosmological dark matter; fourthat, it would be necessary to Scalar (Dark Higgs, *S*) (*µS* + *AHS*<sup>2</sup>)<br>
	Scalar (Dark Higgs, *S*) (*µS* + *AHS*<sup>2</sup>)*H*<sub>2</sub>
- $\blacksquare$  Might be difficult in certain regions at hin  $\alpha$ bservations (e.g. the dark matter relic density). The comparison of the sensitivity of experiments at future colliders and direct/indirect detection experiments searching for dark matter for
	- $\blacktriangleright$  Large backgrounds and high pileup
	- detector dimensions and geometrical acceptance feebly-interacting particles **Frontiers 14**
		- [e.g. short-distances are hard to cover for hh] wn particles or interactions are needed to explain a number of observed phenomena and outstanding questions in particle physics, astrophysics and cosmology. While there is a vast

the models in this section can be found in Chapter 9.

Fermion (Sterile Neutrino, *N*) *y<sup>N</sup> LHN*

 $\blacktriangleright$  At LHeC (and FCC-eh), one can reconstructed on the search for new particles with sizeable couplings displaced vertices and as such be sensitivet om particles and masses above the EW scale. An alternative possibility, largely unexplored, non-promptly decaying, light new particless that particles responsible for the still unexplained phenomena are below the EW scale and landscape of theoretical models that try to address these puzzles, on the experimental side most

> benchmark value is  $r_{min} = 40 \mu m$  ( $\sim$  5 nominal detector resolutions);  $p_T$  threshold for reconstruction of a single charged particle is chosen as 100 MeV

![](_page_17_Picture_10.jpeg)

revealing evidence for invisible particle production, even  $\frac{m}{n}$ 

Searches at high-energy hadron colliders have  $\frac{1}{2}$  the best reach for the visible detection limits at 98% CL, direct detection limits at 98% CL. The visible detection limits at 98% CL. The visible detection limits at

The discovery of inpisible particles at a collider gexperiment does not imply that those

*x*, the dark matter renc density <u>a</u><sub>1</sub> *a*<sub>1</sub> *F*<sub>1</sub> *G*<sub>1</sub> meaning *a<sub>µ</sub>y*<sub>1</sub> *a*<sub>*z*</sub> *a*<sub>*x*</sub> *a*<sub>*x*</sub> *a*<sub>*x*</sub> *a*<sub>*x*</sub> *a*<sup>*x*</sup> *a*<sup></sup>

in the mass region between  $10 \text{ GeV}$  and  $\frac{1}{2} \Re\epsilon \text{V}$  is a still possible with ran increased dataset at he sto

Direct searches, Scalar DM<br> $\frac{10^{-48}}{5}$  Collider limits at 95% CL, direct

and DD experiments exclude the areas above the curves.

decays <u>of the</u> Higgs boson) with constraints from current and future direct detection ex on the spin-independent WIMP–nucleon scattering cross section for a simplified n the Higgs Bosth decaying to Hivisible (DM) particles, entitle Majorana (t6p) or scalar  $\mathfrak k$ ollider limits bre-shown at 9 $\mathfrak k$ % (Ch and direct detection limits at 90% Ch  $_0$ Collide

multi-TeV mediator particles. Going beyond the HL-LHC reach for those same reso

 $\frac{43.1}{1000}$  and  $\frac{43.1}{1000}$  and  $\frac{43.1}{1000}$  and  $\frac{43.1}{1000}$   $\frac{43.1}{1000}$   $\frac{43.1}{1000}$  becouraged bashings boson) with constraints from current and thus contrained the strong of the strong of the stro  $\frac{4}{3}$  varior corriders (see Sect. 6.0 and e.g. Ref.  $\frac{430}{90}$ ,  $\frac{430}{90}$ ,  $\frac{431}{90}$  and  $\frac{431}{90}$  and

 $\begin{bmatrix} \text{C}_{1} & \text{C}_{2} & \text{C}_{3} & \text{C}_{4} & \text{C}_{5} & \text{C}_{6} & \text{C}_{7} & \text{C}_{8} \end{bmatrix}$   $\begin{bmatrix} \text{C}_{1} & \text{C}_{2} & \text{C}_{3} & \text{C}_{4} & \text{C}_{5} & \text{C}_{6} & \text{C}_{6} & \text{C}_{7} & \text{C}_{7} & \text{C}_{8} \end{bmatrix}$ 

 $\frac{364}{100}$  Searches at migh-energy madion completes have the ocst leader for  $\frac{10^6}{10^6}$  visitorly  $\frac{10^6}{10^6}$  europen strategy

hadron colliders (see Sect. 8.6 and e.g. Rep. 1488), bein it in indetently more challenging than for lepton colliders. It is often the case that subatures of sub- $\frac{1}{100}$  resonances that hadron to  $\frac{1}{100}$ liders are indistinguishable from those of their inigh-rate backgrounds, especially respectations the rh the impact of simultaneous *pp* interactions on searches for hadronically decaying resonances at high-luminosity hadron colliders. Since it is generally not possible to record all events in their

24/9/24

### **Complementarity of e-p: Dark photons**  $17$  invariant (but not not necessarily Lorentz-invariant) combinations of SM fields. Following combinations of  $\mathbb{R}$ **18 Source Execute in the set of the September 1854** of **C-p.** Datk protons

 $\blacksquare$  have masses around the GeV scale and their **Interaction Region** interactions are QED-like, scaled with the 134 *CHAPTER 8. BEYOND THE STANDARD MODEL*  $\blacksquare$  small mixing parameter  $\varepsilon$ .  $F'_{\mu\nu}B^{\mu\nu}$  $-\frac{\varepsilon}{2\cos\theta_w}$  $\mu$  10<sup>-1</sup> Figure 3: Sketch of the signal signature of a displaced dark photon decay. The proton (electron) beam is denoted by the larger Scalar (Dark Higgs, *<sup>S</sup>*) (*µS*+l*HSS*<sup>2</sup> )*H*†  $\sim$  smaller arrow from  $\sim$  10<sup>-2</sup>  $\equiv$  coropanic from the primary vertex is inferred from the hadronic final states in the hadronic *H*  $\gamma'$ *e e* **X and the scattered electron inside the primary vertex (labeled "PV" ) inside the primary vertex (labeled "PV" ) inside the interaction region**  $\mathcal{L}$  **inside the dark photon of the dark photon of the dark photon of the d** *e e*  $\alpha$  and decays after some finite distance into the two charged particles  $f_{\alpha}$  and Fermion (Sterile Neutrino, *N*) *yNLHN*  $\gamma$  $\gamma'$  $p \longrightarrow \sum_{x} x \longrightarrow p \longrightarrow \sum_{x} x$ *p p X X* Excluded region: *Gi,µ*n*G*˜ *<sup>µ</sup>*<sup>n</sup> y<br>500 million particular and services an  $10^{-4}$ Pseudo-scalar (Axion, *a*) *<sup>a</sup>* NA62-dump, 2024++ *<sup>i</sup>* , y SeaQuest. 2021++ Figure 1: Feynman diagrams for the dark photon production processes in electron-proton collisions. Here *p* and *X* denotes a parton SHiP. 2026++ *fa*  $\begin{bmatrix} 1 & 0.001 \end{bmatrix}$  proton before and after the scattering process, respectively. Belle II - 50 ab LHCb upgrade - 50 fb<sup>-</sup> *Present* exclusion  $10^{-5}$ LHCb upgrade II - 300 fb<sup>1</sup> **MATHUSLA-200 - 3 ab**  $5 \times 10^{-7}$ **FASER - 150 fb** FASER2 - 3 ab HL-LHC - 3 ab **My** W  $10^{-6}$ FCC-hh - 3 ab *µ*  $\sqrt{2}$  is  $\sqrt{2}$  $CEPC - 5.6$  ab  $FCC-ee<sub>z pole</sub> - 150 ab$ FCC-ee<sub>240</sub> - 5 ab<br>ILC<sub>con</sub> - 6 ab<sup>-1</sup> LHeC - 1 ab FCC-eh - 3 ab' 22 is the *day* is the couple of the *day of data* singlet that couples to the SM Higgs of data couples to the SM Higgs of data couples to the SM Higgs of data couples to the SM Higgs of the SM Higgs of data couples to the  $CLIC<sub>max</sub> - 1$  ab<sup>-1</sup>  $_{0}$  - 2.5 at  $\overline{1}$  $23$  and  $24$  is a  $\frac{1}{2}$  is a  $\frac{1}{2}$  is a  $\frac{1}{2}$  is a  $\frac{1}{2}$  couples the SM left-handed leptons. The SM left-handed leptons. The SM left -  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $\frac{1}{2}$  and  $10<sup>3</sup>$  $10<sup>2</sup>$ 10  $m_{\mu}$  (GeV)  $\bigcup_{1 \times 10^{-5}} \bigcup_{\substack{11 \times 10^{-5} \text{ LHCB}}} \text{Prob}(p_T(\text{X}) = 5 \text{ GeV})$   $\bigcup_{\substack{24 \times 10^{-5} \text{ LHCB}}} \text{Covering important regions between pp and ee}$  $F_1 \times 10^{-5}$  **e**  $F_2 \times 10^{-5}$  **e**  $F_3 \times 10^{-5}$  **e**  $F_4 \times 10^{-5}$  **e**  $F_5 \times 10^{-5}$  **e**  $F_6 \times 10^{-5}$  **e**  $F_7 \times 10^{-5}$  **e**  $F_8 \times 10^{-5}$  **e**  $F_9 \$ *X*, with *X* denoting a number of hadrons. The  $\sqrt{\frac{60.601 \text{ m}}{1000 \text{ m}} \cdot \frac{60.601 \text{ m}}{1000 \text{ m}} \cdot \frac{60.601 \text{ m}}{1000 \text{ m}}}}$  $\frac{1}{2}$  / low-energy experiments  $25$  be  $m_{V}$  [GeV] Monica D'Onofrio, ES UK 2024 19  $m_y$ <sup>[GeV]</sup> Monica D'Onofrio, ES UK 2024 24/9/24  $\mathcal{L}_{\text{H}}$  and  $\mathcal{L}_{\text{H}}$  on  $\mathcal{L}_{\text{H}}$  and  $\mathcal{L$ comparable (larger) cross section and results in larger (smaller) angles for the <sup>0</sup> emission. We expect that FIG. 6. Projected sensitivity of dark photon searches at the LHeC and FCC-he via displaced dark photon decays. The sensitivity <sup>26</sup> *axion* (or axion-like) particle *a* that couples to gauge and fermion fields at dimension five. are expressed as 90% CL exclusion limits. The sensitivity of future colliders, mostly covers the control are at the 90% consider and consider a transverse momentum cut on the final-state hadrons of 5 GeV. The blue and consider and consider a transverse momentum cut on the final-state hadrons of 5 GeV. The blue and co large-mass, large-coupling range, and is fully complementary to the the low-mass, very lowred areas denote the assumption of zero and 100 background events, respectively; the solid and dashed lines correspond to coupling regime where beam-dump and fixed-target experiments are most sensitive. reconstruction efficiencies of 100% and 20%, respectively. The shaded gray area labeled with "LHCb" is currently being tested by the

we do not expect the momentum threshold of  $\mathcal{N}$ 

[PhysRevD.101.0](https://mmm.cern.ch/owa/redir.aspx?C=ef6Q1WB5D1HHp2o1t9iUS6OBsYxyNsZsl2_ZEaqC6UayfbHtYPfXCA..&URL=https%3a%2f%2fjournals.aps.org%2fprd%2fabstract%2f10.1103%2fPhysRevD.101.015020)15020

#### **Complementarity of e-p: new scalars** correspond to the bounds on the Higgs/dark-Higgs quartic coupling l*HS* and on *m*  $\blacksquare$ **the scheme used in the Scheme used in the Physics Beam**

- Interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by the scalar mixing angle. a spectric model, where thermie and production rate or the LLF are
- $\blacksquare$  The contours are for 3 events and consider displacements larger than 50  $\mu$ m to be free of  $\blacksquare$   $\blacksquare$  The contours background.  $10^{-1}$

![](_page_19_Figure_3.jpeg)

 $\gtrsim$  mc schsitivity for sub-TeV resonances at hadron colliders requires data-taking and analysis techniques  $[489]$  (see also Chapter 11).

direct and individual detection experiment, as well as to astrophysical matter relic density) the comparison of the sensitivity of experie the cosmological dark matter; for that, it would be necessary to aircraft to a streamhysical d direct/indirect detection ex inauch i Gimitarty to the case of the Higgs exotics decays, sterfle helf Production Decay Sensitivity of the LFV lepton-trijet Sterile neutrinos - III Antusch *et al.*; arXiv:1908.02852 [hep-ph] *e* isible particles at a collider experiment does not imply that those an be found in Chapter <sup>6</sup>.<sup>*HN*</sup>  $\alpha$ <sup>1</sup> (*x*) (*n*)  $\alpha$ <sup>*H*</sup><sup>*H*</sup> $\alpha$ <sup>*H*</sup> $\alpha$ <sup>*H*</sup> $\alpha$ <sup>*H*<sub> $\alpha$ </sub><sup>*H*<sub> $$ matter reached (ACA) and the comparison of the set and **a**<br>d direct/indirect detection experiments searching

![](_page_20_Figure_2.jpeg)

collider types.

21 Monica D'Onofrio, ES UK 2024

*N*

 $\ell_{\alpha}^ \alpha$ 

## **Conclusions**

´ In a snapshot: great potential for a **compelling and competitive physics programme Some physics highlights of the LHeC (ep/eA@LHC)**

![](_page_21_Figure_2.jpeg)

![](_page_21_Figure_3.jpeg)

- + BSM physics searches (direct, but also indirectly)
- An electron-proton facility represents a seminal opportunity on its own and in combination of pp with ep: here presented some of the studies carried out in the past, more could be done
- DIS can sustain HL-LHC and bridge to CERN's long-term future, empowering the HL-LHC **programme** (as, in the future, an FCC-eh would do for FCC-hh)

![](_page_22_Picture_0.jpeg)

50 years Max's fest (December 2022)

https://indico.ph.liv.ac.uk/ev [ent/743/timetable/#20](https://indico.ph.liv.ac.uk/event/743/timetable/)221209

23 Monica D'Onofrio, ES UK 2024 24/9/24

# Back up

![](_page_24_Figure_0.jpeg)

#### BDT *>* 0*.*262 149 600 86 sea siet Compressed slepton scenarios: results ssed slepton scenarios: re cancertainty no systematic uncertainty of the statistic uncertainty of the statistical statistics. r 2[(*N<sup>s</sup>* <sup>+</sup> *<sup>N</sup>b*)ln(1 + *<sup>N</sup><sup>s</sup>* with unpolarized electron beam. The significances including  $\mathbf{r}$  $\mathbf{s}$ ; results on the background are presented as  $\mathbf{s}$

[PhysRevD.101.](https://journals.aps.org/prd/abstract/10.1103/PhysRevD.101.095015)095015

˜*±*

 $\overline{1}$   $\overline{1}$   $\overline{1}$   $\overline{2}$   $\overline{3}$   $\overline{2}$   $\overline{3}$   $\overline{4}$   $\overline{2}$   $\overline{$ 

![](_page_25_Figure_2.jpeg)

![](_page_25_Picture_1628.jpeg)

and the LHeC (lower) with the unpolarized electron beam  $\sim$  1.1  $\sim$ 

tially on SUSY signal *j* experiments in the main  $\frac{1}{2}$ 

- ˜*±* <sup>1</sup> *,*˜<sup>0</sup> 2 [GeV] <sup>250</sup> *j e* ⌫⌫ *j e* `⌫ • Of course, systematic uncertainties play a **i**nitial 1231 *CMS Phase 2 Simulation Pic*  $\begin{array}{cc} \text{CMS } & \text{Phases } 2 \text{ Simulation } \text{Pre} \ \text{Simulation } \text{Pre} \ \text{Sim} \ \text{Prox} \ \$ crucial role (0-5% here) *<sup>N</sup>*<sup>2</sup> *N*<sup>2</sup> *<sup>b</sup>* + (*N<sup>s</sup>* + *Nb*)<sup>2</sup> ase-2 S *<sup>b</sup>N<sup>s</sup>* Sc, systematic uncertainties pt
- $\overline{\mathbf{p}}$  **b**  $\mathbf{p}$  as  $\mathbf{p}$  **b**  $\mathbf{p}$  **LI**  $\mathbf{p}$  **LI**  $\mathbf{p}$  **c**  $\mathbf{p}$   $\blacktriangleright$  Comparisons with HL-LHC: **parisons with HL-LHC** 
	- The interpretation with a securities and  $\mathbb{F}$  sequen-sequence sequence sequence sequence sequence sequen-sequence sequen-sequence sequence sequence sequence sequence sequence sequence sequence sequence sequence sequen of differences in models but the compressed-slepton scenario, and for the SM background similar mass range three sets of the numbers of  $\mathbb{Z}$ • Not straightforward because ard because  $\overline{c}$  charged sleptons, here as summations, here as  $\overline{c}$

1+ 1 GeV, and prompt ˜*<sup>±</sup>*

![](_page_25_Figure_7.jpeg)

#### **SUSY EWK production: Phenomenology** ction: Phenomenology  $\mathbf{S}$   $\mathbf{S}$ √uon. 1 henomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross  $\frac{1}{2}$  and the ration, of the road model although the the end-gines, as well as then production of between Higgsino states: aqutralinos and  $20 \times 10^{12}$  $U = E / V$  , the following simplified relation  $\frac{1}{2}$  and  $\frac{1}{2}$  for the partial decay of th
	- EWK phenomenology broadly driven by the LSP and Next-LSP nature χ0 , χ<sup>0</sup> riven by the LSP and Next-LSP na
	- $\blacktriangleright$  Examples of classifications (c[f: arXiV: 13](https://arxiv.org/pdf/1309.5966.pdf)09.5966)

![](_page_26_Figure_4.jpeg)

#### $\Box$  directly down to the phase suppression comparing to the decay of  $\Box$ **Used as benchmarks:**

- $T_{\text{max}}$  is the usual scenario scenario, which is strongly motivated  $\chi$   $\chi$ **Bino LSP** (2)  $\chi^+{}_{1}\chi^-{}_{1}$  and  $\chi^{\pm}{}_{1}\chi^0{}_{2}$  processes  $: M_1 < M_2$ , |µ| • Bino LSP, wino-bino cross sections (1)  $\textsf{Mass}(\chi^{\pm}_1) = \textsf{Mass}(\chi^0_2)$
- Higgsino-LSP, higgsino-like cross sections<br>• Higgsino-LSP, higgsino-like cross sections  $(1)$  Small mass splitting  $\chi^0_{1}$ ,  $\chi^{\pm}$ <sub>1</sub>,  $\chi^0_{2}$ <sup>2</sup> Wino LSP (2) Consider triplets for cross sections (3) Role of high-multiplicity neutralinos and

 $\sigma_{\rm H}(\chi^{\pm}{}_{1}\chi^{0}{}_{2} + \chi^{+}{}_{1}\chi^{-}{}_{1} + \chi^{+}{}_{1}\chi^{0}{}_{1})$  $\text{Higgsino LSP}$  < or <<  $\sigma_{\text{W}}(\chi^{\pm}1\chi^{0})$ 

24/9/24

## What if the m(chargino)~m(neutralino1)?

 $\blacktriangleright$  The decay of chargino is **NOT** prompt  $\rightarrow$  long-lived particles (LLP)! **Searches for disappearing tracks: LLCP with** *cτ >~* **10mm** [long-lived charged particles]

### **Simplest models at FCC-he: four-body process and tiny cross section**

• Charginos (Wino or Higgsino)

![](_page_27_Figure_4.jpeg)

## **Comparisons with other facilities**

- **8.5. Thermal Higgsino/Wino dark matter mass <b>8.5. DARK MATTER** 1312 1313
- $\blacksquare$  Comparisons computed for the European strategy

![](_page_28_Figure_3.jpeg)

- FCC-eh not directly competitive with FCC-hh but still reasonable reach
- In all cases FCC-eh sensitivity to **short decay lengths**, possibly much less than a single micron, improves with respect to what the FCC-hh can accomplish with disappearing track searches th respect to what the rice hir can accomptism with disappearing track scarcites

## **Results for disappearing track analysis**

## $\triangleright$  contours of N<sub>1+LLP</sub> and N<sub>2 LLP</sub>

![](_page_29_Figure_2.jpeg)

green region: 2σ sensitivity estimate in the presence of τ backgrounds black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

### **Sensitive to very short lifetimes exceeds that of hh colliders**

![](_page_29_Figure_5.jpeg)

24/9/24

30 Monica D'Onofrio, ES UK 2024

## **Results for disappearing track analysis @ FCC**

## $\triangleright$  contours of N<sub>1+LLP</sub> and N<sub>2 LLP</sub>

![](_page_30_Figure_2.jpeg)

green region: 2σ sensitivity estimate in the presence of τ backgrounds black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic) and the FCC-hh

### **Sensitive to very short lifetimes exceeds that of hh colliders**

![](_page_30_Figure_5.jpeg)

24/9/24

31 Monica D'Onofrio, ES UK 2024

#### **Compressed slepton scenarios: results** number of signal and background events passing the BDT **Compressed slepton scenario** cance. Assuming no systematic uncertainty, the statistical significance, stat, of the potential signal is evaluated  $\mathbf{C}$ Compressed slopter seed in Complete  $\frac{1}{2}$  $\frac{1105}{7}$ <sup>1</sup> *,*˜<sup>0</sup>

 $\blacktriangleright$  Evaluate significance with statistical and systematic uncertainties cal significance, stat, of the potential signal is evaluated as stat = 2[(*N<sup>s</sup>* <sup>+</sup> *<sup>N</sup>b*)ln(1 + *<sup>N</sup><sup>s</sup> N I* and systematic uncertainties  $\blacksquare$   $\blacksquare$  Evaluate significance with statistical and systematic uncertai **m**<br>*d*<br>*d*<br>*d* id systematic uncertainties in the BDT-score distribution is reported in the BDT-score distribution in the set  $\frac{1}{\sqrt{1-\frac{1}{2}}\cos\theta}$  is given in Table II,  $\frac{1}{\sqrt{1-\frac{1}{2}}\cos\theta}$ 

$$
\sigma_{\text{stat}} = \sqrt{2[(N_s + N_b)\ln(1 + \frac{N_s}{N_b}) - N_s]}.
$$

$$
\sigma_{\text{stat+syst}} = \left[ 2\left( (N_s + N_b) \ln \frac{(N_s + N_b)(N_b + \sigma_b^2)}{N_b^2 + (N_s + N_b)\sigma_b^2} - \frac{N_b^2}{\sigma_b^2} \ln \left[ 1 + \frac{\sigma_b^2 N_s}{N_b (N_b + \sigma_b^2)} \right] \right) \right]^{1/2}.
$$

• Of course, systematic uncertainties play a crucial role, as in monojet searches at pp à **Here we consider 0-5%**  2 *b* matic drictit<br>n monoiet se certainties p  $\sigma$ *pet searc*  $\blacksquare$  a crucial role as in monoiet searches at **produce** (2) **processes** of *course*, systematic uncertainties play IV. COMPRESSED-SLEPTON SCENARIO  $T_{\text{max}}$   $\sim$  consider  $\Omega$  F $\alpha$ three sets consider  $0.5\%$  $\blacksquare$   $\blacksquare$  Or course, systematic uncertainties a diudiai rud, as in munujed searches on  $\blacksquare$ in the last row.

> → Projections for HL-LHC consider 1-3%  $\frac{1}{2}$  (3)

![](_page_31_Picture_1105.jpeg)

![](_page_31_Figure_7.jpeg)

#### **Compressed slepton scenarios: the analysis** compressed siepton sechanos, the analysis *ep* colliders and the Delphes card files for the LHeC and Acssed sicpton seculatios. the al *ep* colliders and the Delphes card files for the LHeC and effice: the analysis Due to the presence of large missing transverse mo-

- $\blacktriangleright$  **Final state**: 1 e- + 1 j + MET (*E<sup>T</sup> , j*1), (*E<sup>T</sup> , e*1), (*E<sup>T</sup> , j*<sup>1</sup> + *e*1);  $\mathbf{L}$  $\alpha$  in the final state, production of  $\alpha$  is the final state of  $\alpha$  in the state of  $\alpha$
- Analysis at detector-level using a simple Boost Decision Tree. **2**<br>**2** *Pecision Tree* is at detector-level using a simple Boost Decision Tree.  $\frac{1}{2}$ neutrinos  $\frac{1}{2}$ separate the background into two categories in the 2-4-5-5 categories: the 2-2-5 categorie
- $\blacktriangleright$  Backgrounds: all processes with one or two neutrinos (to also take into account mis-identified leptons):  $p\, e^- \rightarrow j\, e^- \, \nu \nu$  , mis-identified leptons):  $pe^- \rightarrow je^- \nu \nu$ ,  $pe^- \rightarrow je^- \ell \nu$ **L L 1** +  $\frac{1}{2}$  +  $\frac{$ ounds: all processes with one or two neutrinos (to also take into account
- Pre-selections:  $\blacksquare$   $\blacksquare$  Dre selections: **FIG. Exercise from the SM background. The BDT thresh-BDT thresh-BDT**
- **Example 20** At least one jet with  $p_T > 20$  GeV,  $|\eta| \le 6.0$ ; FIG. 2. Production cross sections (*pe* ! *je*˜˜) for both
- the compressed- and decoupled-slepton scenarios at the FCC- $10^{10}$ 2.
- **Example 3** No b-jet with  $p_T > 20$  GeV; eh and for the compressed-slepton scenario at the LHeC with
	- $\blacksquare$  No muon or tau with  $p_T > 10$  GeV;  $\frac{1}{\sqrt{2}}$  signal and background events passing the BDT  $\frac{1}{\sqrt{2}}$  $\blacksquare$  No muon or tau with  $p_T > 10$  GeV; <sup>1</sup> and ˜<sup>0</sup> <sup>1</sup> is Bino while ˜*<sup>±</sup>*  $\epsilon$  No muon or tau with  $p_T > 10$  GeV,
	- <sup>2</sup> are Wino with almost degen-**Example 3.4.3.3.** Missing transverse momentum  $E^{miss}$ <sub>T</sub> > 50 GeV
- $\blacksquare$  Use BDT with simple kinematic variables and angular correlations as input<br>  $\frac{d}{dt}$  $\Box$   $\Box$  Us MadGraph5 aMC@NLO version 2.4.3. For the compressed-<sup>1</sup> *,*˜<sup>0</sup>  $T_{\text{tot}}$  simple kinematic variables  $0$   $\frac{1}{-0.5}$  ( ↑ Use BDT with simple kinematic ar  $\frac{1}{3}$  and angular correlations as input tons and decoupled and decoupled to the set of the set o

![](_page_32_Figure_11.jpeg)

˜*±*

#### **Long-lived EWKinos: disappearing tracks**  While these cosmological bounds continued bounds continued bounds continued bounds continued bounds complement searches, they are much more more more more in the search model-dependent of the more can be a search of the can be a imagine a Higgsino-like inert doublet scenario which does not  $\alpha$  discrete ogning the matrix mine the position of the primary vertex (PV) as  $\alpha$

 $\blacksquare$   $\blacksquare$  long lived charginos are typically significantly boosted along the proton beam direction, **EXECUTE:** which increases their lifetime in the laboratory frame.  $b_{\rm com} \approx \frac{1}{2} \sqrt{E_e}$ the Higgsino production process. ignificantly boosted along the proton beam direction,  $\frac{1}{2}\sqrt{E_e/E_p}\approx 5.5$ **Physics of disappearing tracks**  y signific<br>C

![](_page_33_Figure_2.jpeg)

 $8.8$  It is also possible to have an accidental  $\sim$ *Analysis strategy* 3-4 hits only in the inner-most tracker amissing (disappearing track) (or a "kink" if the harder daughter **d1** is charged)

Monica D'Onofrio, ES UK 2024  $\overline{34}$  and  $\overline{34}$  will not consider the so called blind-spots  $\overline{34}$ 

## **Analysis strategy**

- One or two charginos are produced at the PV, which is identified by the triggering jet (A).
- A chargino decaying to a single charged particle (B)

If the impact parameter with respect to the PV is greater than a given  $r_{min}$  we can tag this track as originating from an LLP decay

- heavily relies on backgrounds due to pile-up being either absent or controllable.
	- $\triangleright$  benchmark value is r<sub>min</sub> = 40µm (~ 5 nominal detector resolutions);  $p_T$  threshold for reconstruction of a single charged particle is chosen as 100 MeV
	- $\blacktriangleright$  Assume 100% efficiency
- Estimate probability of detecting 1 or 2 LLP 35

Monica D'Onofrio, ES UK 2024

![](_page_34_Figure_9.jpeg)

### **Backgrounds:**

- Taus: proper lifetime of ∼ 0.1mm and beta-decay into the same range of final states as the charginos.
- suppressed considerably with simple kinematic cuts as it is central in eta
- **rejection of 10-4(10−5) for 1(2)**t

24/9/24

![](_page_35_Figure_0.jpeg)

heavy quark e $\pm$ ects have to be considered in addition. In addition. In addition. In addition, the fit is rep

### gluon fusion and *ttH*¯ , below 2 % for *W H* and *ZH*, and 0.4% for weak boson fusion. The LHeC uncertainties in Tab. 7.4 are calculated using MCFM calculated using MCFM interfaced to PDFs determined from t

**42**

 $\Box$ ,  $\blacksquare$  Improvement in the calculation of pp $\rightarrow$ HX  $\vert \vert$  calculated at N<sup>3</sup>LO in pQCD thanks to PDF  $\mathcal{I}^{\perp}$  in  $\mathcal{I}^{\perp}$  and we will be calculation of pp  $\mathcal{I}^{\perp}$  in  $\mathcal{I}^{\perp}$ 

![](_page_35_Picture_915.jpeg)

**arbitrary**

**0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1**

#### EWK cross section EIC, LHeC, FCC-eh ross section  $\text{FIC}$  I  $\text{H}_{\text{e}}\text{C}$   $\text{FCC}_{\text{e}}\text{ch}$  $t_{\rm c}$ , to the LH

**Fig. 1** Single differential inclusive DIS cross sections for neutral- and charged-current  $e^- p$  DIS with longitudinally polarized electrons ( $P_e$  = −0*.*8) at LHeC, EIC, FCC-*eh*, and HERA. For HERA, unpolarized cross sections are displayed together with data from the H1 experiment

![](_page_36_Figure_2.jpeg)

![](_page_36_Figure_3.jpeg)

37 Monica D'Onofrio, ES UK 2024 charged-current *e*<sup>−</sup> *p* DIS with longitudinally polarized electrons (*Pe* = proton scattering as a function of *Q*<sup>2</sup> comparing the future parameters.

 $\frac{1}{24}$  S<sub>1</sub>  $\frac{1}{9}$   $\frac{1}{24}$  $p$  are different determinations of the electroweak physics of the electroweak physics of the electroweak physics  $\mu$