Precision physics and searches

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The ep/eA study at the LHC and FCC – new impactful goals for the community

WG2

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

ep-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics programme

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

developing a sustainable LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

- typically 2-3 conveners per theme
- annual ep/eA workshops (WS)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (TWS)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

Introduction: eh-eA precision and search programme

Rich e-p physics programme developed in the past decade; highlights include:

- PDFs, strong coupling constant, low-x measurements *(see previous talk)*
- W mass, top mass, on other precision measurements in EWK and Top sectors *this talk*
- Higgs measurements – very rich programme to determine couplings at <% precision
- Searches for new physics, including prompt and long-lived new scalars from Higgs, SUSY particles, heavy sterile neutrinos, dark photons and more
- High-energy and high-density measurements of heavy ion collisions

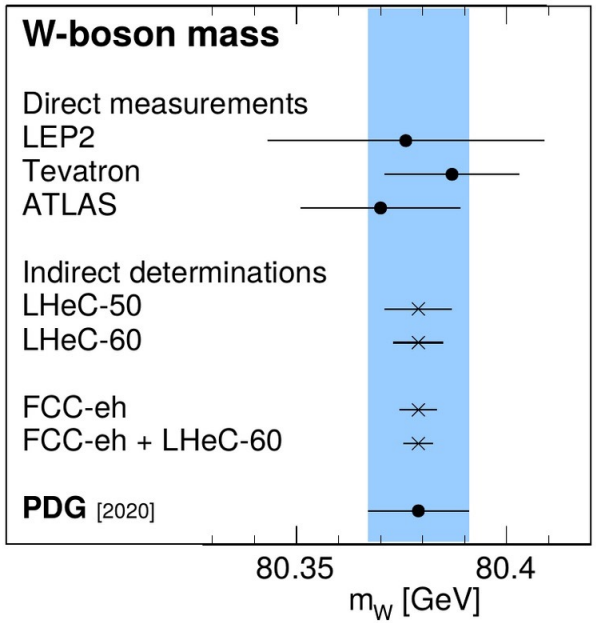
Lot done and published, but much more can be done to exploit the e-p opportunity!

- CDR updated: https://arxiv.org/abs/2007.14491 → 300+ pages document, ~300 authors among experimentalists and theorists, + documents submitted for the **European Strategy of PP 2020** and **Snowmass 2021**

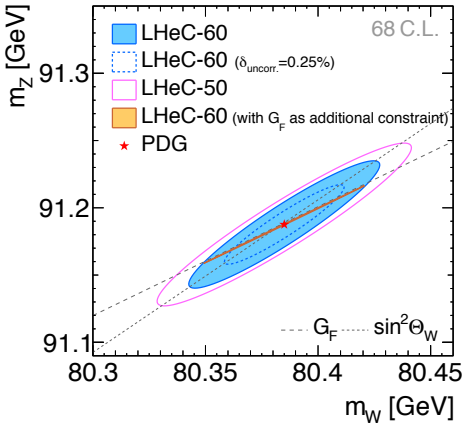
The *eh* programmes of LHC and FCC are designed to operate **synchronously** with *hh,* offering the best way to exploit the expensive hadron beams we (will) have (see also WP3)

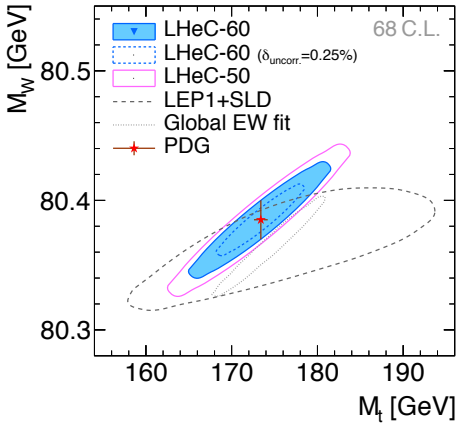
EWK Precision physics at e-p: highlights

- M_W and M_Z will be measurable at unprecedent precision **at the LHeC and FCC-eh**
  - very relevant, as well as the top mass, for new physics constraints



Smallest uncertainties (0.5%) from a single experiment





- Complementary to HL-LHC W mass precision measurement uses dedicated dataset at low <mu>

LHeC will provide ultimate PDF for additional precision for pp

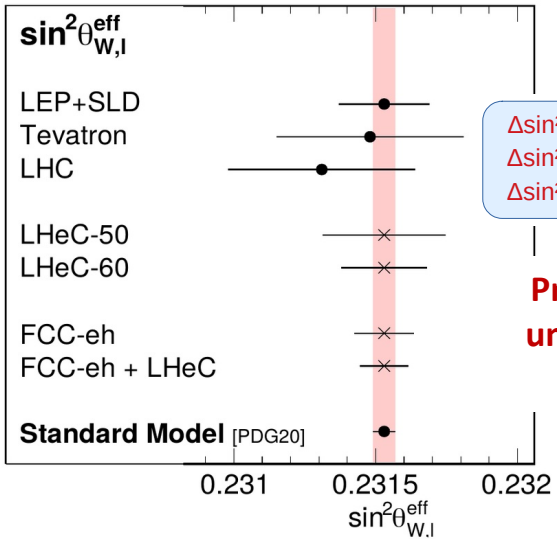
ATL-PHYS-PUB-2018-026

EWK Precision physics at e-p: highlights (2)

- LHeC/FCC-eh will contribute to $\sin^2\theta_{\text{eff}}$ precision measurements directly and indirectly
  - **Direct** measurements using higher-order loop corrections

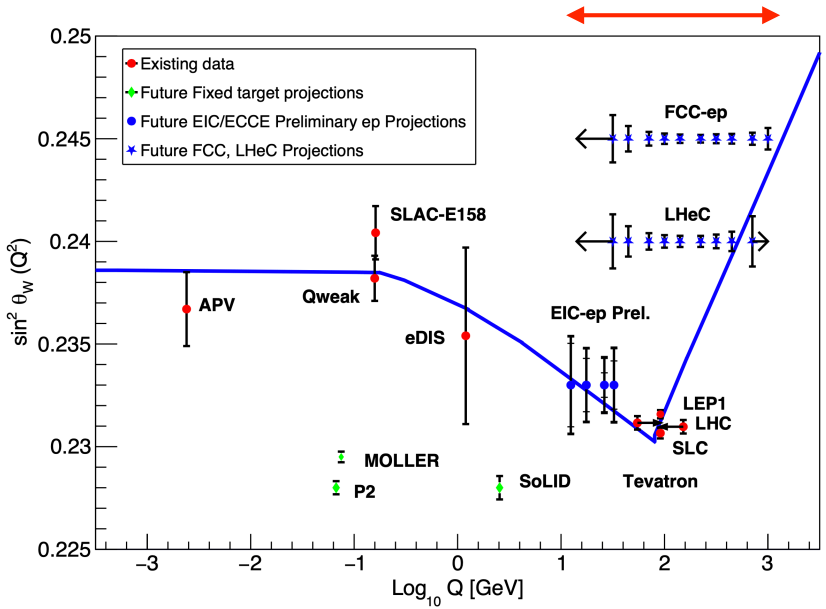
$$\sin^2\theta_{\mathrm{W}}^{\mathrm{eff},\ell}(\mu^2) = \kappa_{\mathrm{NC},\ell}(\mu^2)\sin^2\theta_{\mathrm{W}}$$

    - simultaneous fits made with PDFs
  - **Indirect:** improving precision of HL-LHC studies
    - Use F-B Asymmetry measurements



$\Delta\sin^2\theta_w$ (LHeC-50)	= ±0.00021
$\Delta\sin^2\theta_w$ (LHeC-60)	= ±0.00015
$\Delta\sin^2\theta_w$ (FCC-eh+LHeC)	= ±0.000086

Precisions: < 1 · 10^{-5} if PDF uncertainties are improved already with LHeC

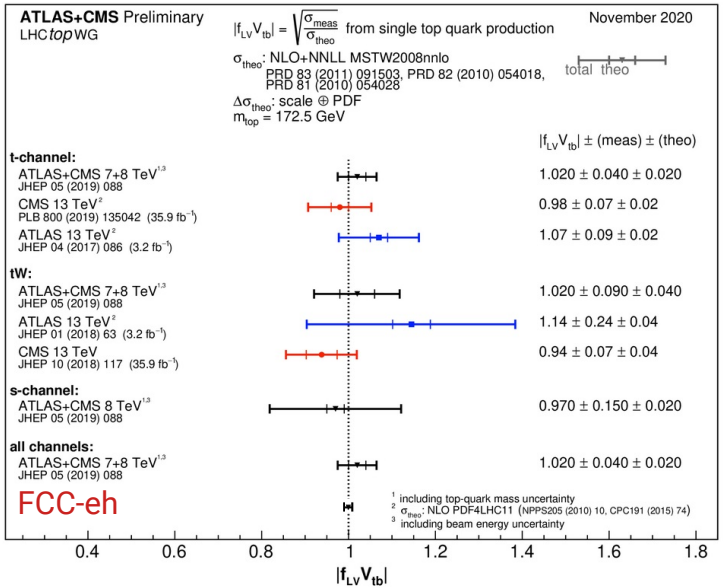


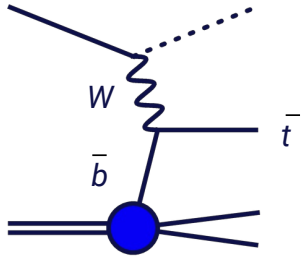
→ **probe large range of scale dependence**

This and more in arXiv:2203.06237

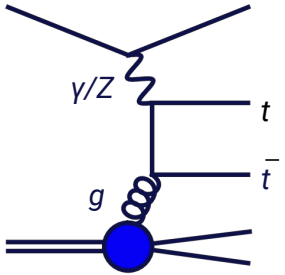
Top precision physics at e-p: highlights

- Production dominated by single top processes
  - In addition, photoproduction of top-pairs
- Can do precision measurements and measurements of rare processes





LHeC σ~ 1.9pb
FCC-eh σ~15.3pb

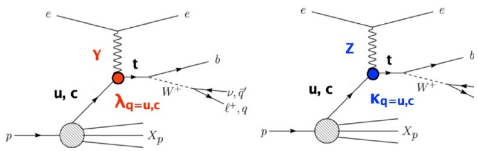


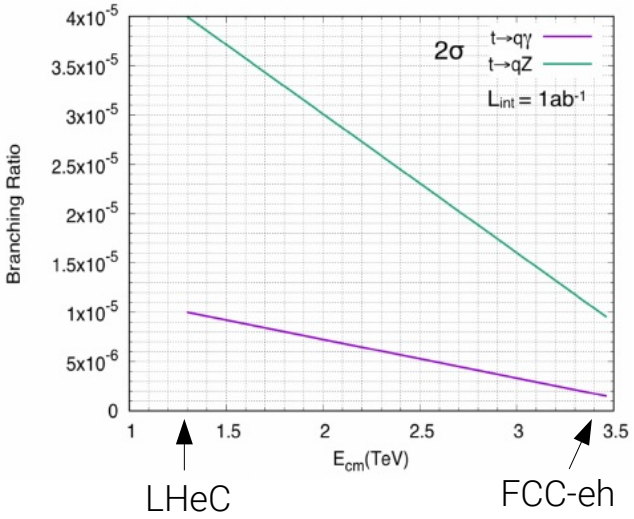
LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

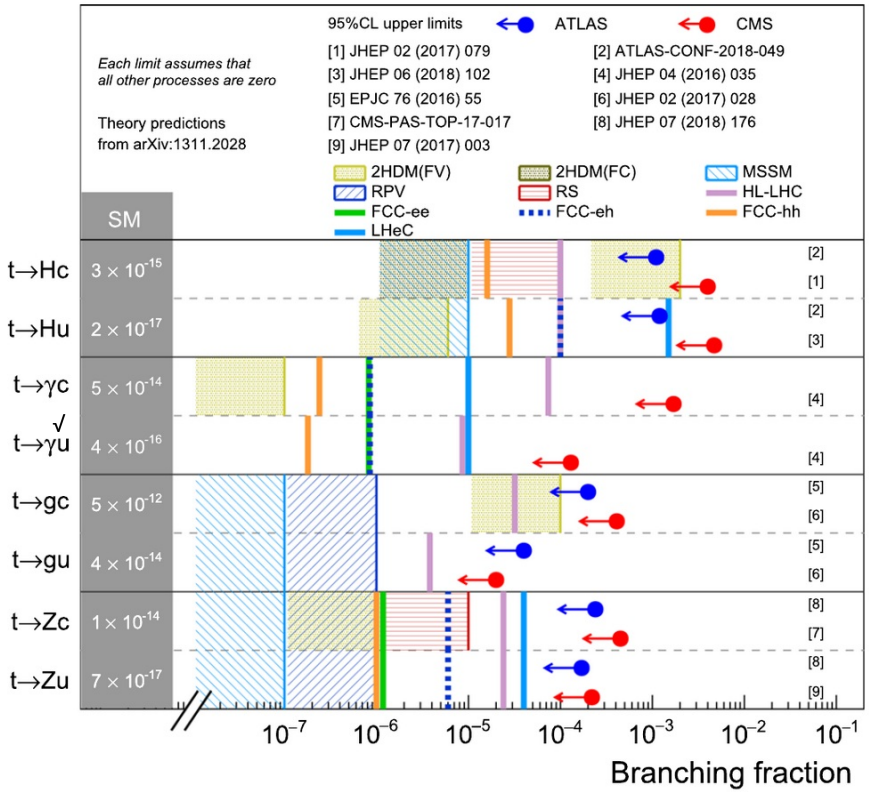
Direct measurements of V_{tb}
Precision below **1%**
Limits on anomalous *Wtb* couplings: **< 0.01**

New physics in the Top sector at e-p: highlights

- Measurements of rare processes: FCNC
- Excellent complementarities with ee and pp colliders, i.e. t→q γ/Z

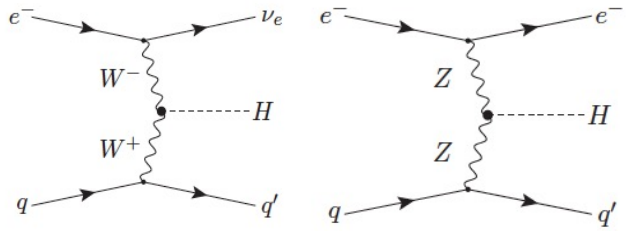






Higgs precision physics at e-p: highlights

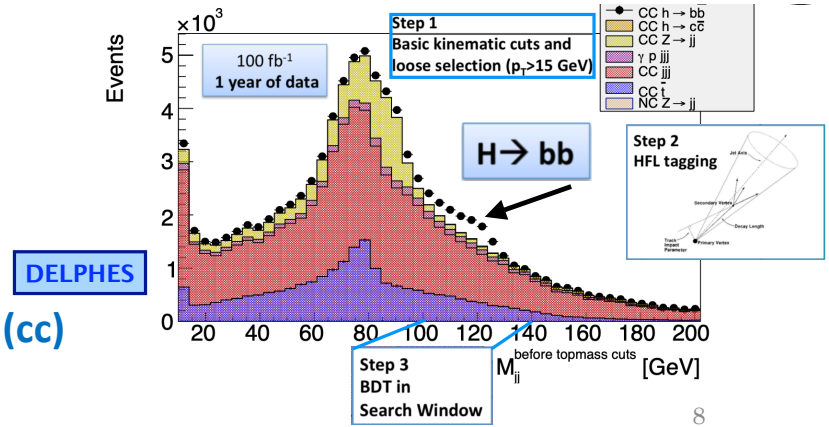
- Production of Higgs boson via Vector-Boson-Scattering, considerably large cross section



Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P=-0.8)$	fb	197	372	516	1038
σ_{NC} $(P=-0.8)$	fb	24	48	70	149
σ_{CC} $(P=0)$	fb	110	206	289	577
σ_{NC} $(P=0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

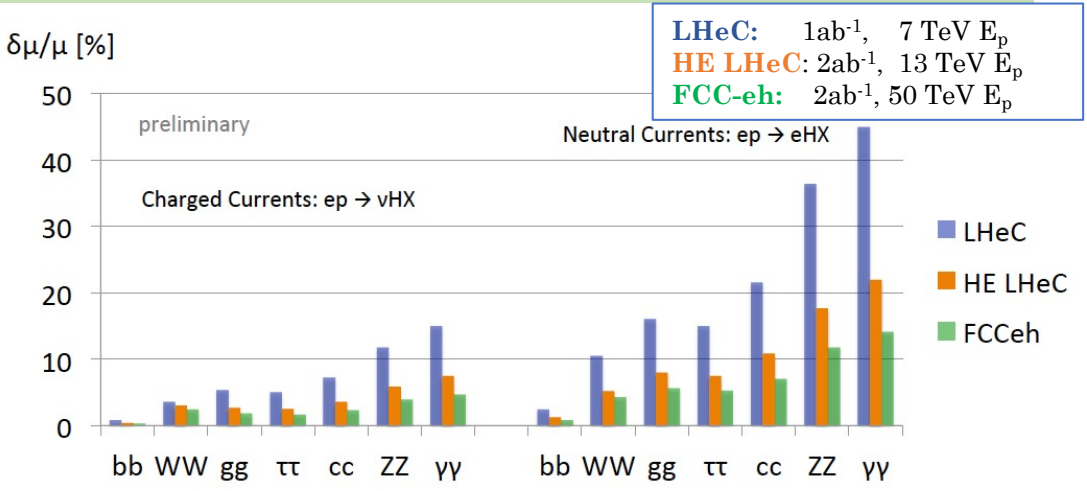
A large dataset of Higgs events for precision measurements (+100k events for h→bbbar and +5k for h→ccbar)

- Precision measurements of Higgs couplings:
  - Profit of clean environment (pile-up free)
  - Characterized by low background rates
  - Small systematic uncertainties achievable
- For b and c (e.g. at the LHeC):
  - Signal strength μ constraints to **0.8% (bb)** and **7.4% (cc)**



Higgs precision physics at e-p: highlights (2)

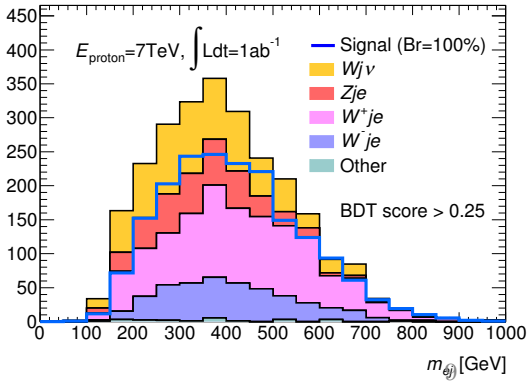
- Very promising prospects in most channels
  - HL-LHC and LHeC competitive with e+e- colliders as well
- Sensitivity to charm-, W- and gluon-couplings could be re-evaluated with new tools i.e. developed at ATLAS/CMS (e.g. b/c-tagging, jet-taggers etc).



- Processes of interests with high potential include:
  - Couplings with potential **DM candidates (pp+ep)**
    - Use electron-jet invariant mass and BDT techniques

$$\mathrm{Br}(h \rightarrow \mathrm{invisible}) = 6\,\%\ \mathrm{at}\ 2\sigma\ \mathrm{level}$$

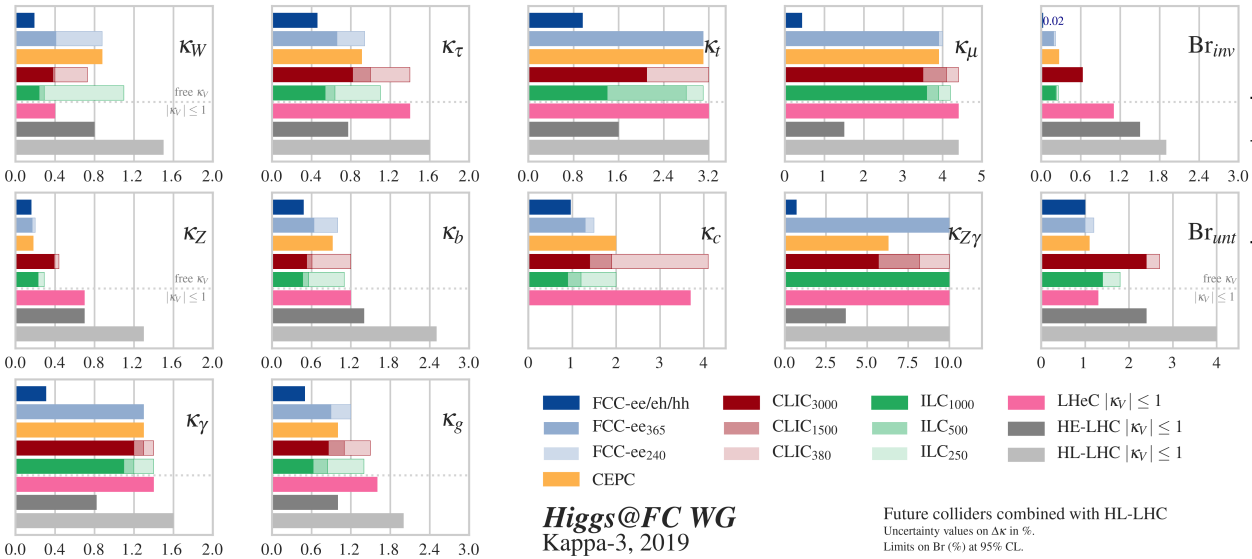
  - **di-higgs and higgs self-coupling:**
    - Promising studies in the past to be updated!



Higgs precision physics at e-p: highlights (3)

- More generally, the ESPPU studies have shown the potential of the Higgs precision measurements at the LHeC and FCC-eh in the searches for new physics
- Employing Kappa framework (coupling strength modified parameters) to parameterise possible deviations from SM couplings

From the ES Briefing Book: uncertainties on κ_i



Better quantified: arXiv:2007.14491

Setup	$b\bar{b}$	WW	gg	$\tau\tau$	cc	ZZ	$\gamma\gamma$
LHeC	1.9	0.70	3.5	3.1	3.8	1.2	6.8
HE-LHeC	1.0	0.38	1.8	1.6	1.9	0.6	3.5
FCC-eh	0.60	0.22	1.1	0.93	1.2	0.35	2.1

Very high precision thanks to clean environment in luminous region and to the combination of CC and NC DIS

Combinations with HL-LHC/pp to be further evaluated!

Searches for new physics at e-p: highlights

- ep collider is ideal to study common features of electrons and quarks with **EW / VBF production, LQ, forward objects, long-lived particles**. Aims:
  - 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
  - **promising aspects**: small background due to absence of QCD interaction between *e* and *p,* very low pileup
  - **difficult aspects**: low production rate for NP processes

- Several models target in recent years, but **more to be considered** → further involvement of theory community to test their models systematically for e-p (LHeC and FCC-eh)

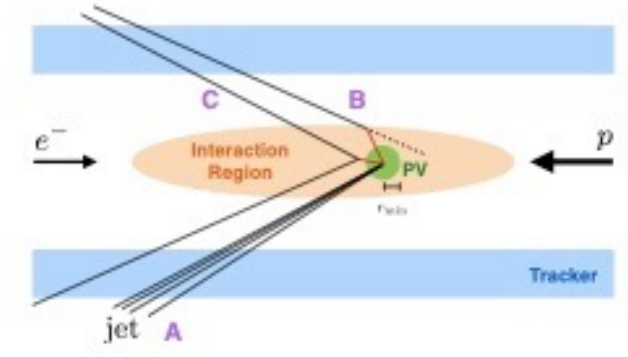
https://arxiv.org/abs/2007.14491

+ FCC CDR: Eur. Phys. J. C 79, no. 6, 474 - Physics Eur. Phys. J. ST 228, no. 4, 755 - FCC-hh/eh and several dedicated publications

Searches for new physics at e-p: highlights (2)

- Hidden, dark sectors at e-p: populated by feebly interacting (and long-lived) particles
- At LHeC and FCC-eh, one can reconstruct displaced vertices and as such be sensitive to non-promptly decaying, light new particles
  - **Benchmarks** agreed by the community

Portal	Coupling
Vector (Dark Vector, A_μ)	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Scalar (Dark Higgs, S)	$(\mu S + \lambda_{HS}S^2)H^\dagger H$
Pseudo-scalar (Axion, a)	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Fermion (Sterile Neutrino, N)	$y_N LHN$



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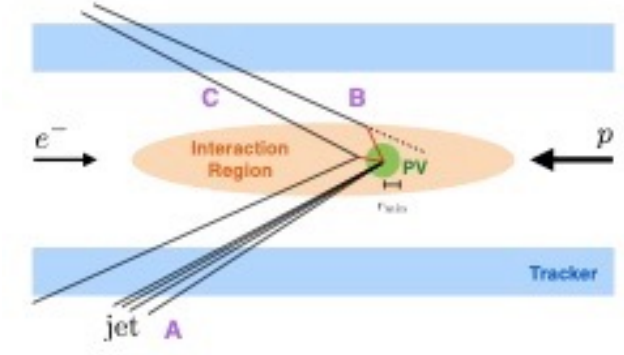
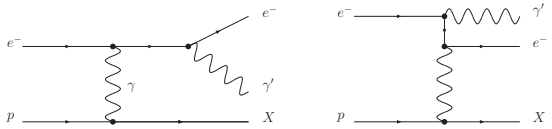
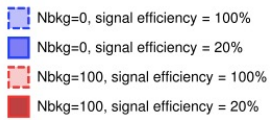
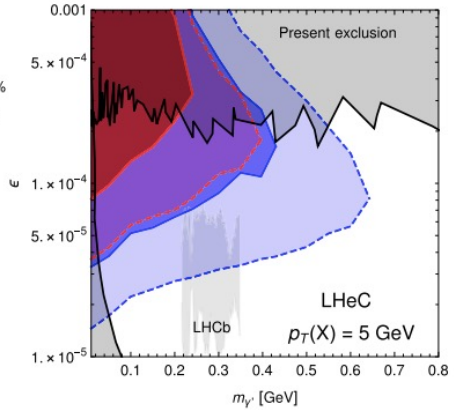
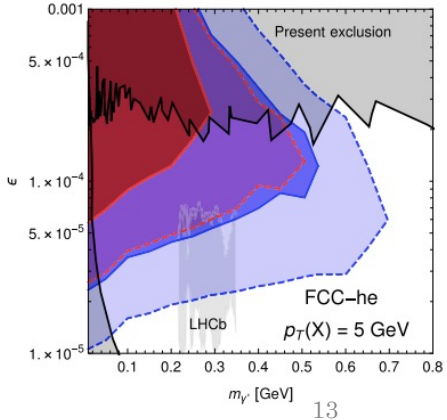


- E.g. **dark photons**









Covering regions complementary to pp and ee / low-energy experiments

Searches for new physics at e-p: highlights (4)

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- At LHeC and FCC-eh, one can reconstruct displaced vertices and as such be sensitive to non-promptly decaying, light new particles
  - **Benchmarks** agreed by the community

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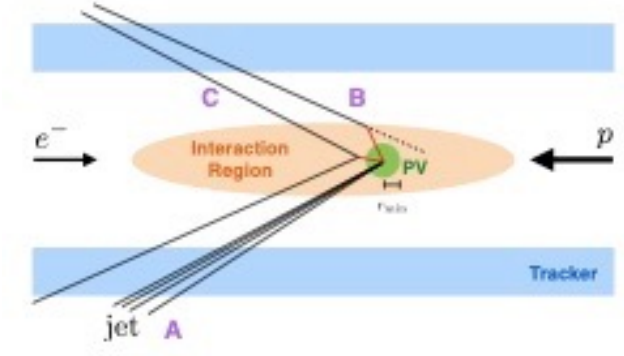
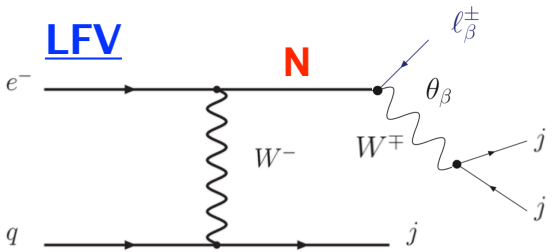
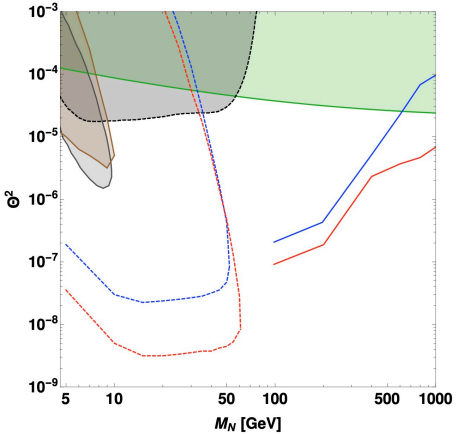


- E.g. **heavy sterile neutrinos**



MEG: $\Theta^2=|\theta_e\theta_\mu|$
DELPHI: $\Theta^2=|\theta|^2$
ATLAS: $\Theta^2=|\theta_\mu|^2$
LHCb: $\Theta^2=|\theta_\mu|^2$
LHeC (LFV): $\Theta^2=|\theta_e\theta_\mu|$
FCC-he (LFV): $\Theta^2=|\theta_e\theta_\mu|$
LHeC (displaced): $\Theta^2=|\theta_e|^2$
FCC-he (displaced): $\Theta^2=|\theta_e|^2$

Different analyses depending on m(N) and m(W) relations



+more recent results e.g. in 2201.12997 [hep-ph]

eh-eA precision and search programme – Objectives and Challenges

CDR and dedicated studies have shown that the ep precision and search programme at LHeC and FCC-eh can be complementary to that of LHC and FCC:

- High precision measurements of specific parameters (EWK, top, Higgs)
- Searches in complementary phase space regions

Concrete objectives beyond the CDR should include studies on (few examples provided):

- Precision and top measurements: EWK fundamental parameters, Vts couplings
- Higgs: use modern tools and ID techniques from ATLAS/CMS to (re-)evaluate couplings with heavy flavour quarks, W bosons and gluons, top-Higgs couplings, exotics Higgs couplings (e.g. invisible decays); **must-do:** di-higgs and higgs self-coupling re-evaluation!
- BSM: short and medium lifetime for feebly interacting particles from hidden sectors, lepton-quark interactions, LFV processes

Most important challenges to be addressed: engage with the community to systematically consider ep in evaluation of sensitivity for NP models, Higgs measurements etc

eh-eA precision and search programme – Methodology and Deliverables

Methodology:

- Regular meetings (once a month), topical (precision, higgs, BSM)
- Participation and discussion at main future colliders meetings, eg:
  - FCC-PED, FCC-LLP groups etc (currently mostly focused on ee and bit of pp)
  - Higgs and BSM workshops
- Promotion of projects for students to perform feasibility studies
  - In this, provide initial settings, central repository with software and MC samples

Potential collaborators:

- ATLAS/CMS/LHCb/ALICE as well as Physics beyond collider experiments (could focus on complementarities for a start – phase space, lifetime etc. -, but also get inputs on tools that can be common – ID of b- and c-jet, tau reconstruction etc)
- Theory community

Expected deliverables:

- document for European Strategy
- Topical papers (group could help in reviews, journal paper writing etc)

eh-eA precision and search programme – Organisation and Practical aspects

Mailing list: ep-eA-WG2-precision-and-searches@cern.ch

Anyone with a CERN account or a light account can register to this email list (as well as sign out).
Subscribe/unsubscribe to the list via: https://e-groups.cern.ch/ (use the search option, and search for "ep-eA-WG" in all e-groups).

Expected meetings: once a month, first meeting Jan-Feb 2024

Indico page: https://indico.cern.ch/category/17308/

Several opportunities for conference talks on the topics of precision, Higgs and BSM at major conferences

Get in touch: Monica D'Onofrio, Uta Klein, Christian Schwanenberger