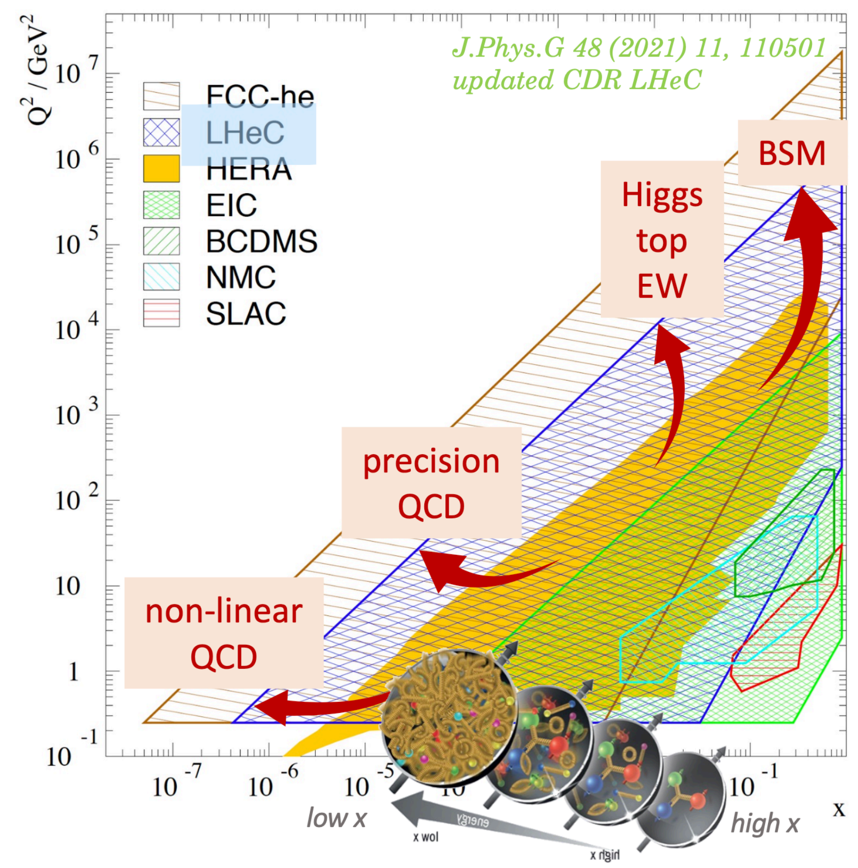
From EWK and Higgs physics to BSM searches: the electron-proton case



Monica D'Onofrio

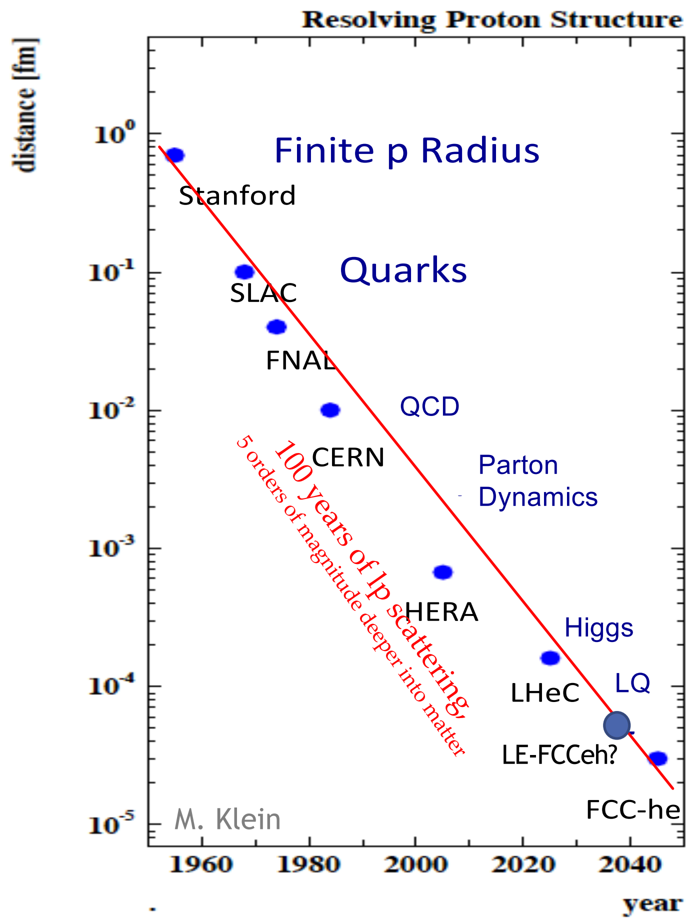
University of Liverpool

(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…)

ES UK Strategy

23/09/2024

DIS and pp colliders: an historical synergy



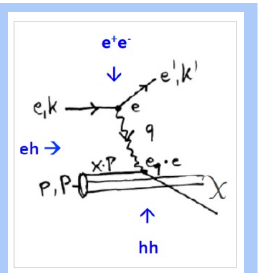
Idea and details already presented and discussed by Paul

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

LHeC e-Ion: E_e=60 (*) GeV, E_{Ion}=2.76 TeV
→ For **FCC-eh**: increase up to ~20 TeV

the synergy pattern

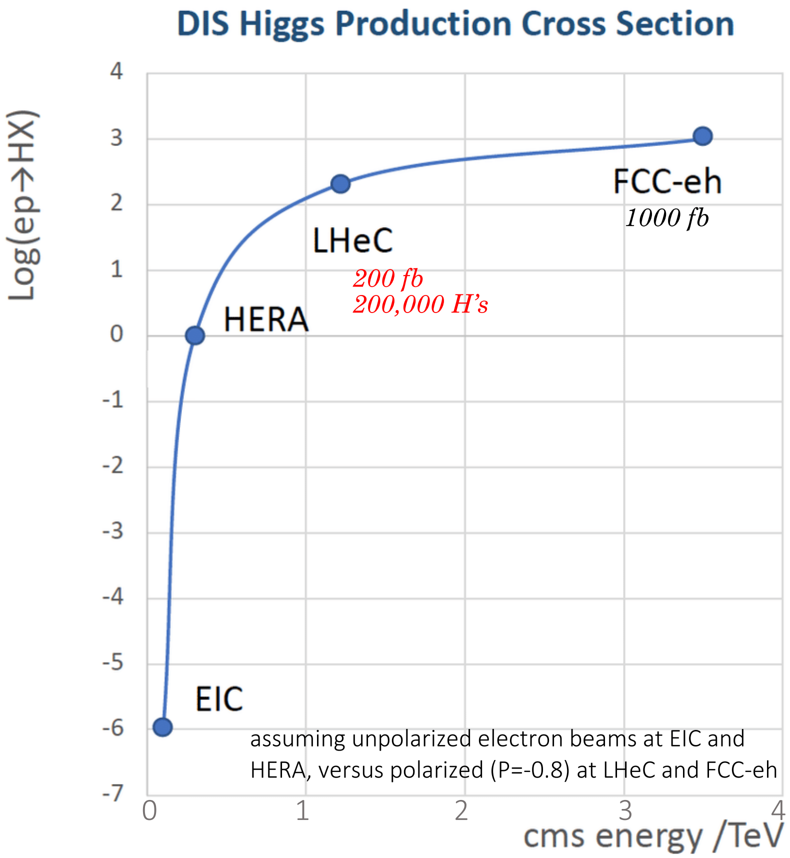
Tevatron/HERA/LEP
(Fermiscale)
↓
HL-LHC/LHeC
(Terascale)
↓
FCC-hh/FCC-eh
(Terascale)



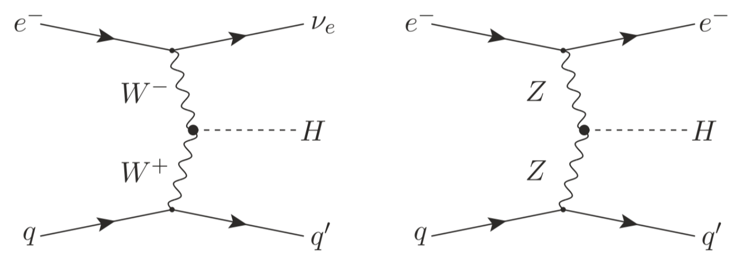
e^+e^-
CepC, ILC
FCC-ee,
CLIC, C^3
$\mu^+\mu^-$

The future Particle Physics at colliders?

Collision energy above the threshold for EW/Higgs/Top



= the real game change between HERA and the LHeC/FCC-eh



compared to proton collisions, these are reasonably clean Higgs events with much less backgrounds

at these energies and luminosities, interactions with all SM particles can be measured precisely

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**
- **Higgs measurements with additional sensitivity → 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**
- High-energy and high-density measurements of heavy ion collisions

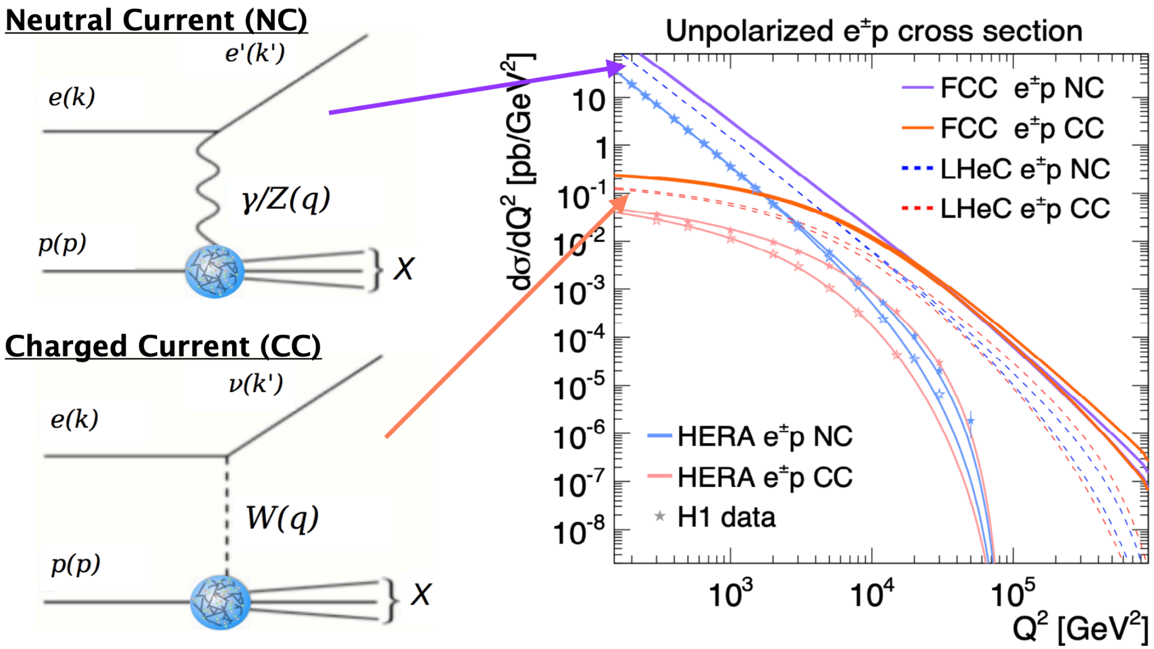
→ the LHeC(FCC-eh) will contribute to the main objectives of the HL-LHC(FCC-hh), empowering its programme and bringing in more variety

Some key examples in the following

much more in CDR https://arxiv.org/abs/2007.14491, https://cds.cern.ch/record/2729018/files/ECFA-Newsletter-5-Summer2020.pdf, Eur. Phys. J. C (2022) 82:40, FCC CDR: EPJC 79, no. 6, 474 (2019) , Phys Eur. Phys. J. ST 228, no. 4, 755 (2019)

DIS and EWK measurements

- LHeC/FCC-eh are excellent facilities for testing EW theory
  - Polarized e- electron beams also possible (+-80%)



Key observables:

- W mass
- Effective EWK mixing angle

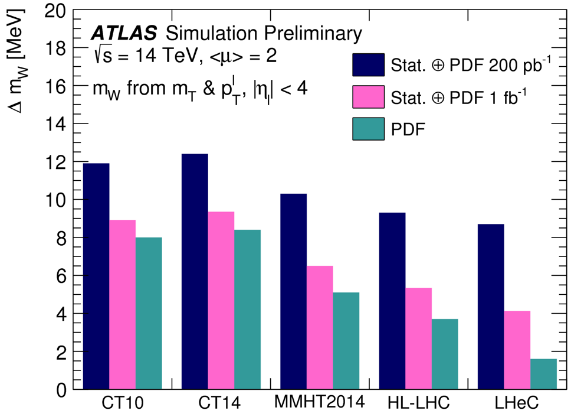
Measurements as standalone and in combination with HL-LHC

https://link.springer.com/content/pdf/10.1140/epjc/s10052-020-8367-y

DIS and EWK measurements: W mass

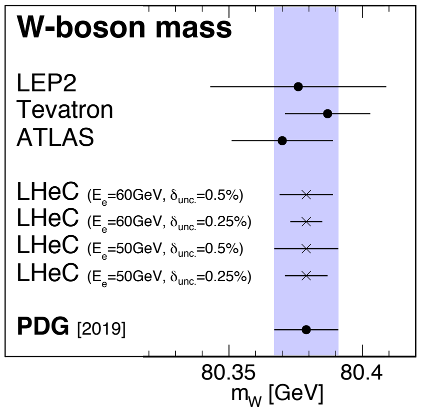
- **@ HL-LHC W mass** precision measurement uses dedicated dataset at low <mu>
  - → exploit the extended leptonic coverage
  - → LHeC will provide additional precision through PDF

Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)
Δm_W = ±2 MeV (with improved PDF from LHeC)

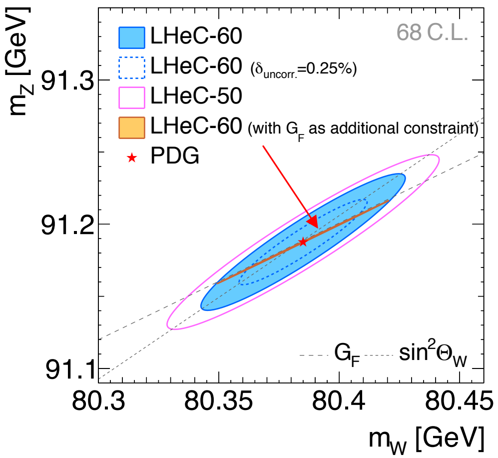


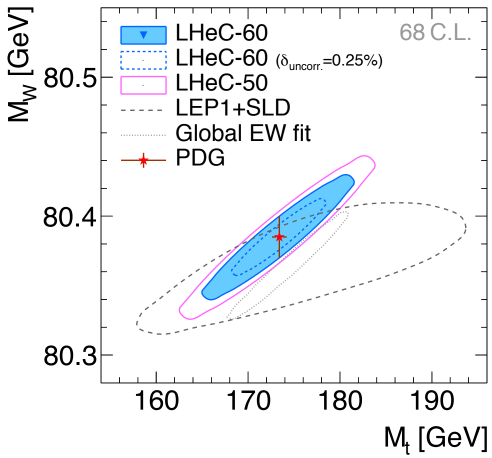
ATL-PHYS-PUB-2018-026

- M_W and M_Z (as well as m_{Top}) will be measurable
at unprecedent precision independently at the LHeC



Even more relevant after recent CDF results and claimed 9 MeV precision!





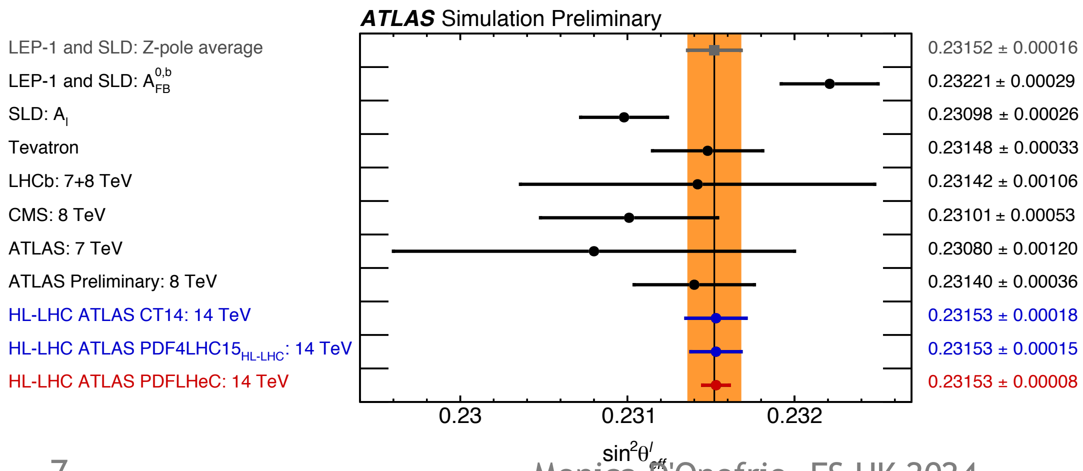
DIS and EWK measurements: $\sin^2\theta_{eff}$

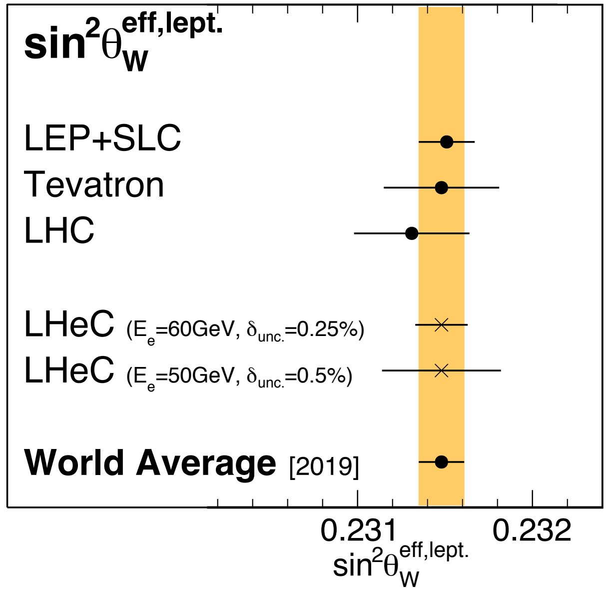
LHeC will contribute to the ffective EWK mixing angle $\sin^2\theta_{eff}$ precision measurements directly and indirectly

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

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

- Scale dependence of $\sin^2\theta_{eff}$ not negligible
  - simultaneous fits made with PDFs
- **Indirect:** improving precision of HL-LHC studies
  - Use F-B Asymmetry measurements





Precisions → $1 \cdot 10^{-5}$ if PDF uncertainties are improved with LHeC

DIS and EWK measurements: $\sin^2\theta_{eff}$

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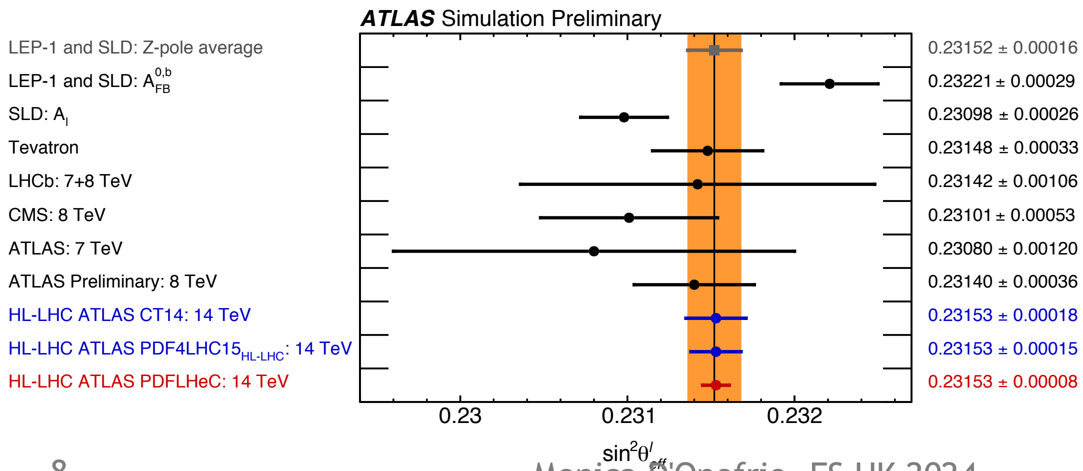
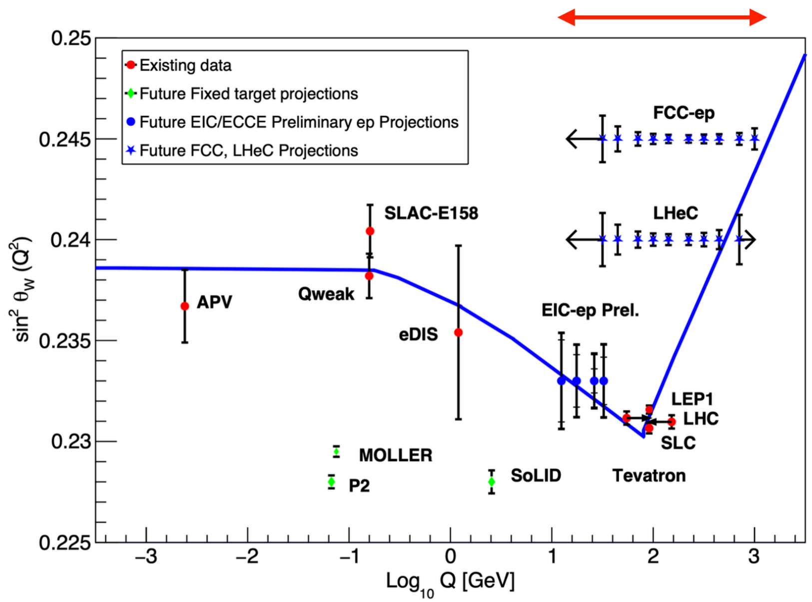


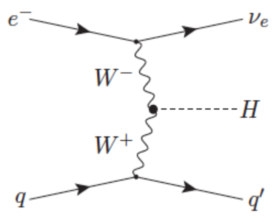


→ **probe large range of scale dependence**

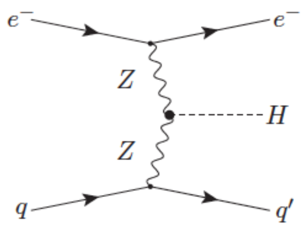
Higgs physics at ep

- Production of Higgs boson via **Vector-Boson-Scattering**

Charged Currents

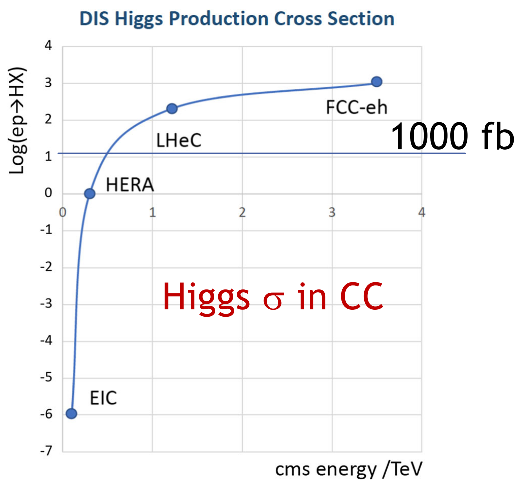


Neutral Currents



Total cross section (m_H=125 GeV)

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



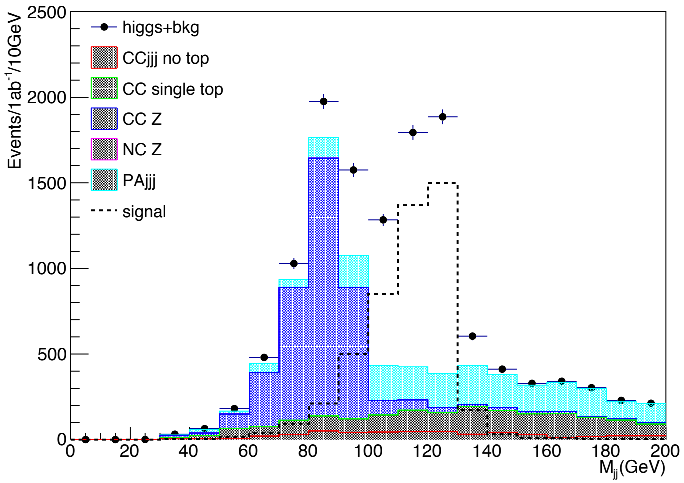
A large dataset of Higgs events for precision measurements

LHeC Higgs		CC (e^-p)	NC (e^-p)	CC (e^+p)
Polarisation		-0.8	-0.8	0
Luminosity [ab^{-1}]		1	1	0.1
Cross Section [fb]		196	25	58
Decay	BrFraction	N^H_{CC} e^-p	N^H_{NC} e^-p	N^H_{CC} e^+p
$H \to b\bar{b}$	0.577	113 100	13 900	3 350
$H \to c\bar{c}$	0.029	5 700	700	170
$H \to \tau^+\tau^-$	0.063	12 350	1 600	370
$H \to \mu\mu$	0.00022	50	5	–
$H \to 4l$	0.00013	30	3	–
$H \to 2l2\nu$	0.0106	2 080	250	60
$H \to gg$	0.086	16 850	2 050	500
$H \to WW$	0.215	42 100	5 150	1 250
$H \to ZZ$	0.0264	5 200	600	150
$H \to \gamma\gamma$	0.00228	450	60	15
$H \to Z\gamma$	0.00154	300	40	10

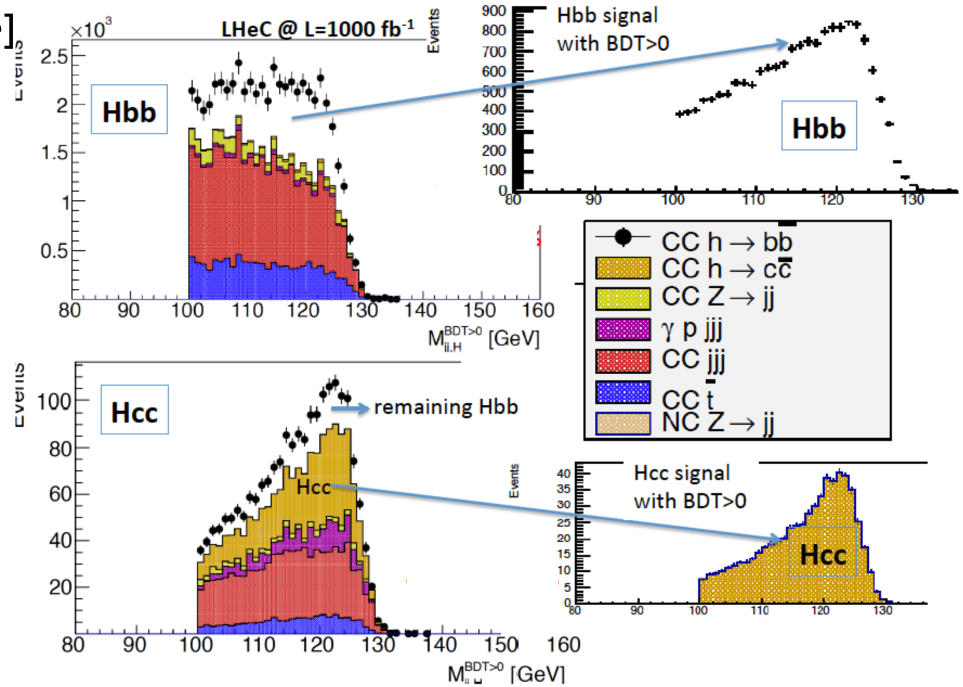
Higgs to bbar and ccbar

- Higgs to bb or cc signal, -0.8 polarization considered
- Detector level analysis with realistic tagger
  - Efficiency 60-75% for b-tagged jets
  - ~ 10% efficiency for charm jets [conservative]

Can effectively separate bb and cc final states



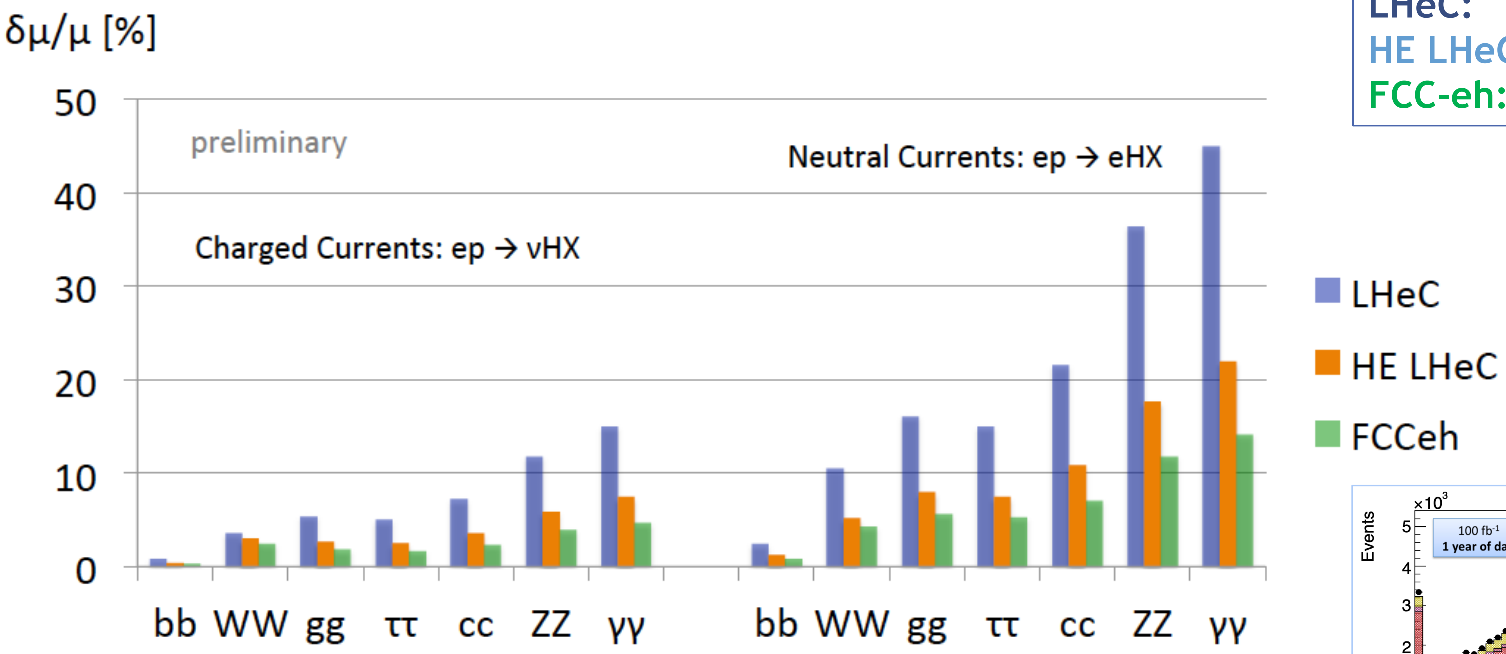
Signal strength μ constraints to 0.8% (bb) and 7.4% (cc)

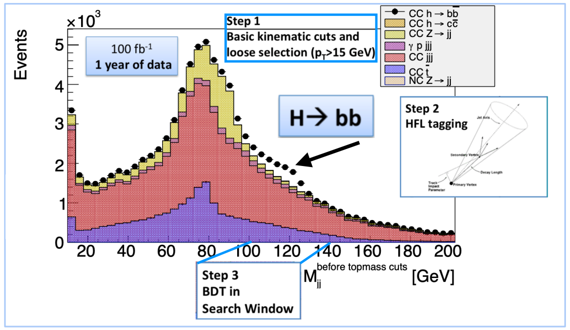


Prospects for Higgs in ep

- Prospects for signal strength measurements of Higgs decays

LHeC: 1ab^{-1}, 7 TeV E_p
HE LHeC: 2ab^{-1}, 13 TeV E_p
FCC-eh: 2ab^{-1}, 50 TeV E_p

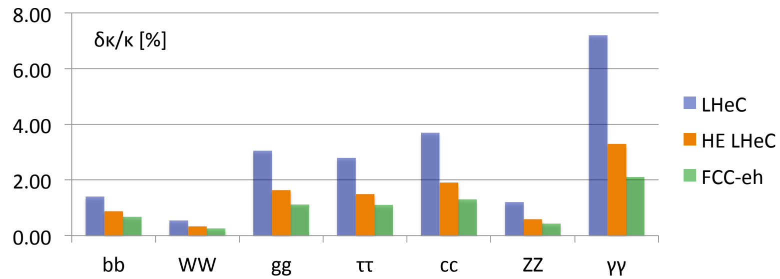




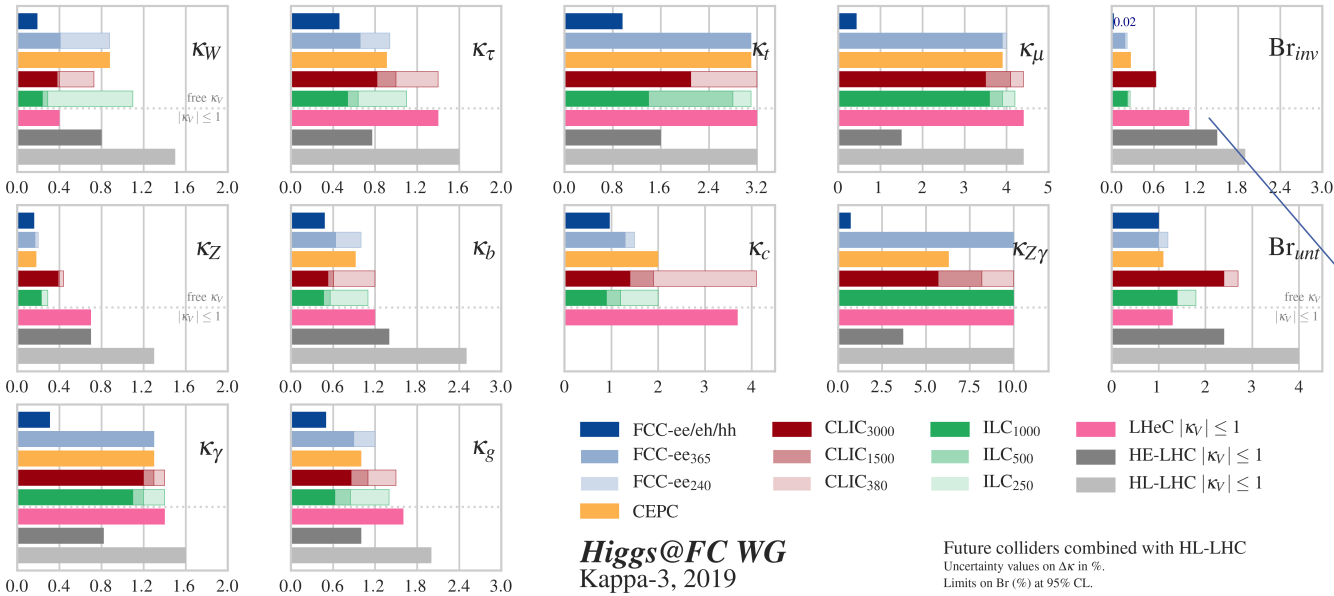
Signal strength μ constraints to 0.8% (bb) and 7.4% (cc)

Kappa factor framework

- κ_i : coupling strength modified parameters
- powerful method to parameterise possible deviations from SM couplings



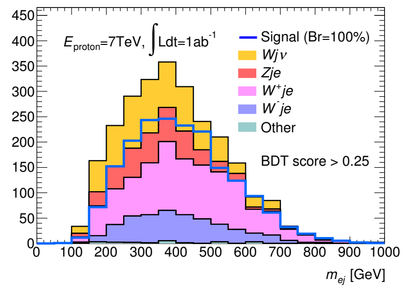
From the ES Briefing Book: uncertainties on κ_i



Note: good potential for improving on **Higgs invisible** with HL+LHeC but more refined analyses needed

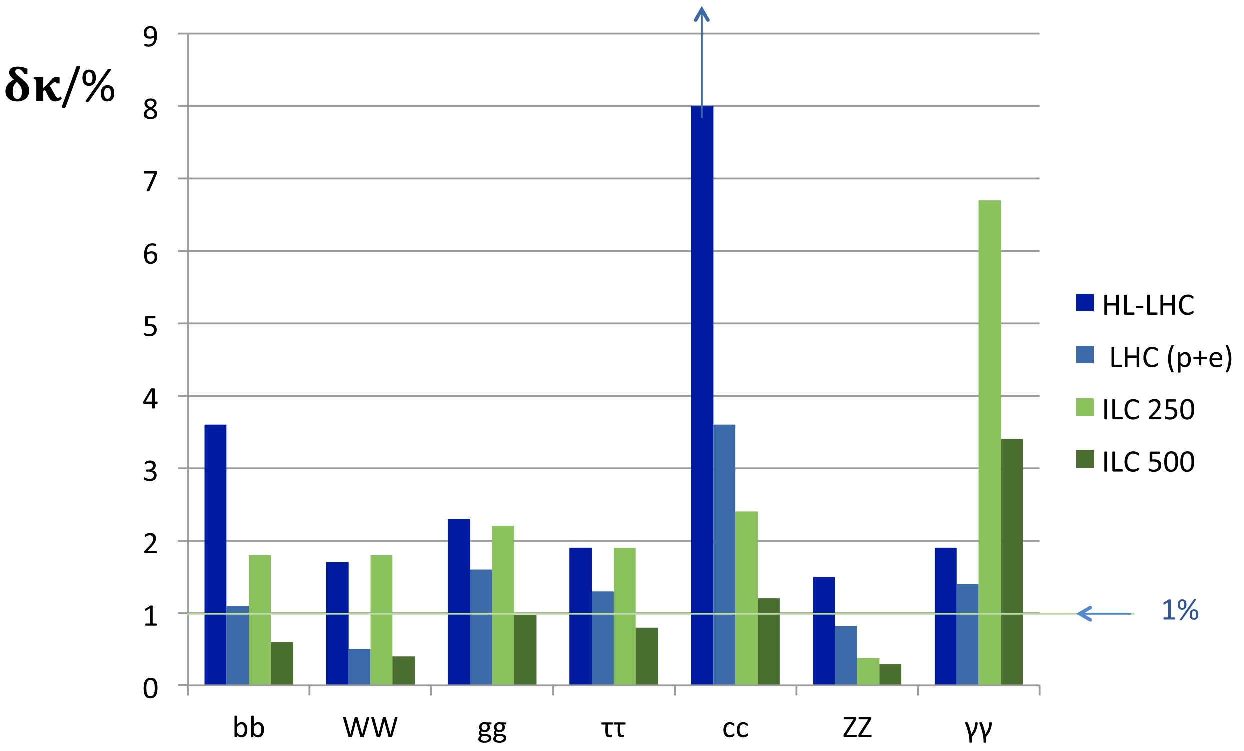
$\mathrm{Br}(h \rightarrow \mathrm{invisible}) = 6\,\%$ at 2σ level

Electron-jet invariant mass



Combinations of LHeC + HL-LHC

Determination of SM Higgs couplings jointly from pp + ep



The combined ep+pp at LHC reaches below 1% for dominant channels

LHeC adds charm decays.

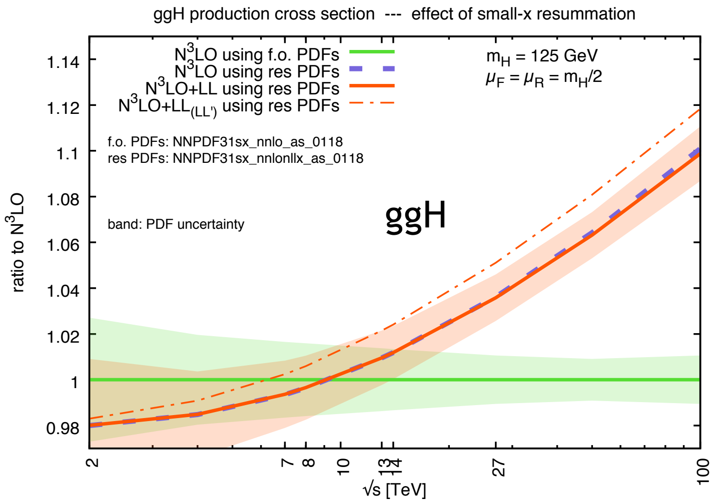
Overall, adding electrons makes the LHC a Higgs precision facility

More in progress: e.g. joint ep-pp simulation analysis of the prospects for **di-Higgs production**

Indirect Impact of ep on pp Higgs

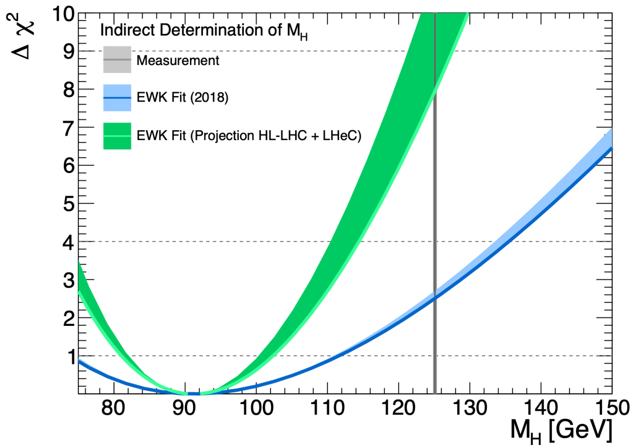
- Calculation of all production modes improved by α_S and PDF:
  - Even clearer for pp→HX calculated at N^3LO in pQCD

Process	σ_H [pb]	$\Delta\sigma_{\rm scales}$	$\Delta\sigma_{\rm PDF+\alpha_s}$	
			HL-LHC PDF	LHeC PDF
Gluon-fusion	54.7	5.4 %	3.1 %	0.4 %
Vector-boson-fusion	4.3	2.1 %	0.4 %	0.3 %
$pp \to WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \to ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \to t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %



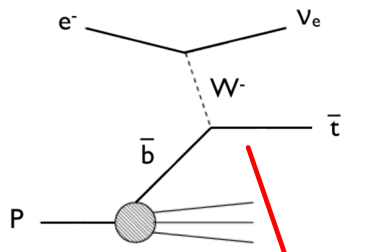
increasing impact of resummation on the cross section with increasing energy → main effect comes through the modification of the extraction of parton densities and their extrapolation

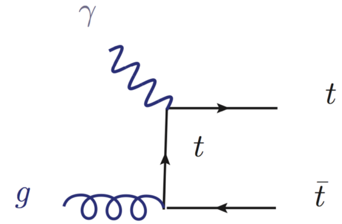
- Indirect determination of Higgs mass



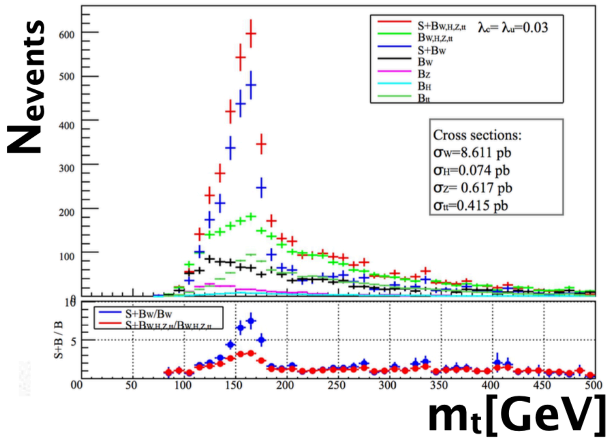
Top physics: Wtb coupling measurements

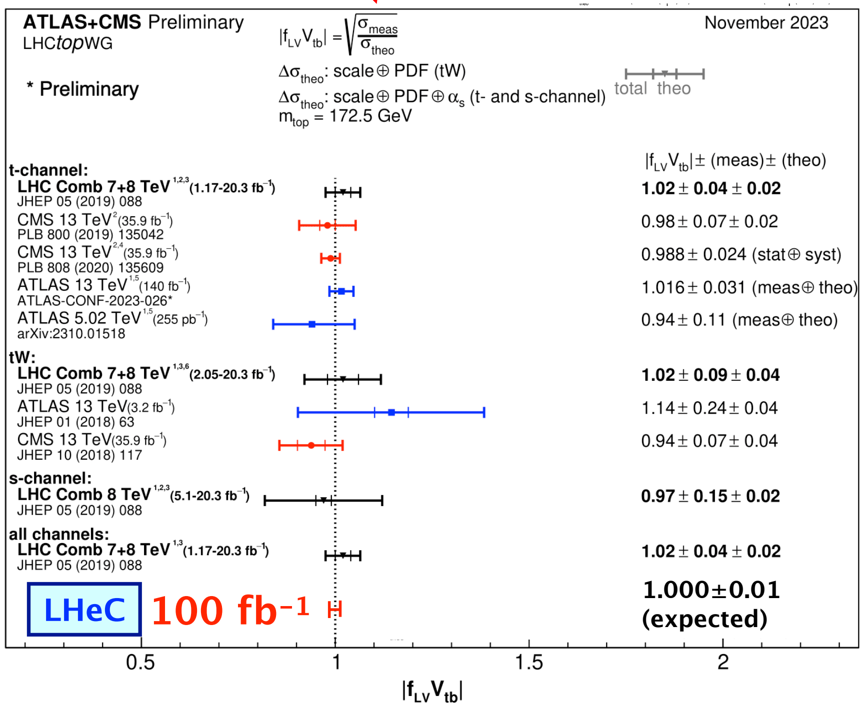
- Dominated by single top production
  - ~ 1.9 pb – e.g. **Vtb** vertex studies
  - In addition, photoproduction of top-pairs



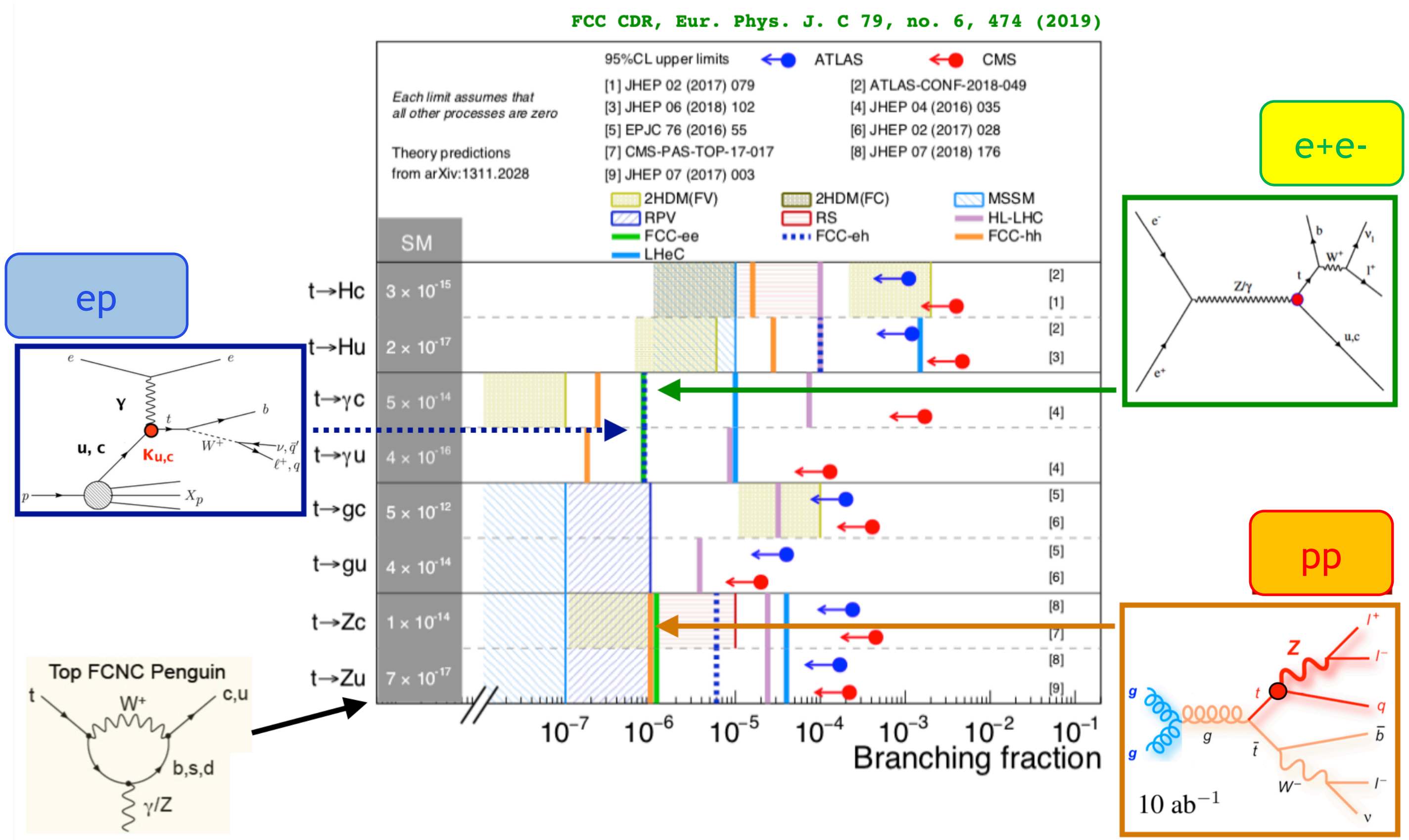


- Can do precision measurements and measurements of rare processes





Top physics: Flavour Changing Neutral Current



Excellent complementarities with ee and pp colliders

Shown:
HL-LHC and ILC 250 GeV

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:

  → small background due to absence of QCD interaction between *e* and *p*

  → very low pileup

  - Some difficult aspects:

  → low production rate for NP processes due to small s

https://arxiv.org/abs/2007.14491

8 **Searches for Physics Beyond the Standard Model**

+others published afterwords leptophilic DM, non-resonant BSM di-Higgs, heavy majorana neutrino, exotics higgs …

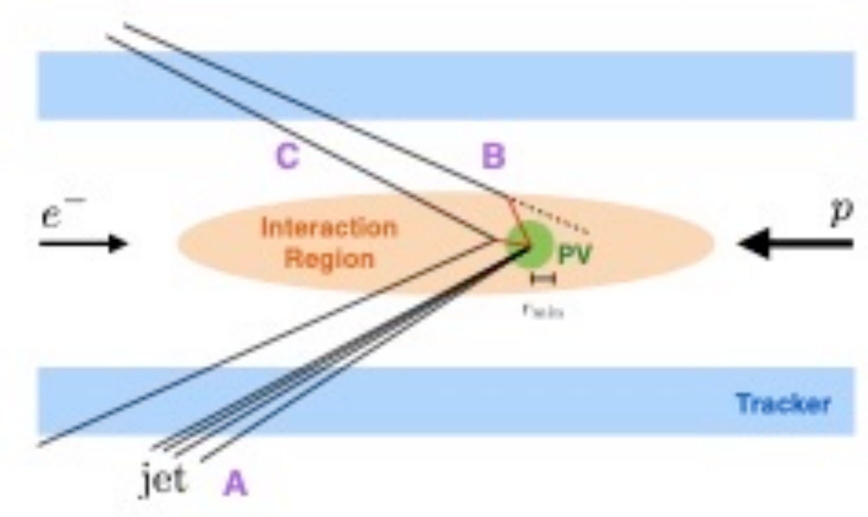
Only a few specific examples given here

Hidden, dark sectors at e-p

- New physics models predicting long-lived particles gained lot of attention in the past few years
  - Hidden, dark sector
  - populated by feebly interacting particles
- Might be difficult in certain regions at hh
  - Large backgrounds and high pileup
  - detector dimensions and geometrical acceptance
    - [e.g. short-distances are hard to cover for hh]

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)	$y_N L H N$

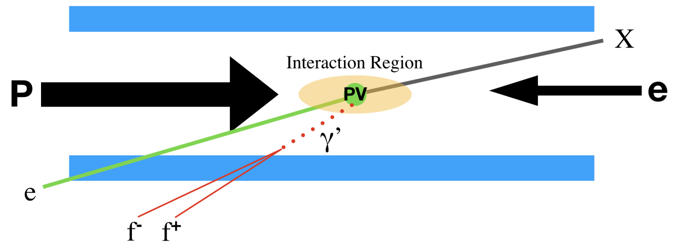
- At LHeC (and FCC-eh), one can reconstruct displaced vertices and as such be sensitive to non-promptly decaying, light new particles



benchmark value is r_{min} = 40μm (~ 5 nominal detector resolutions); p_T threshold for reconstruction of a single charged particle is chosen as 100 MeV

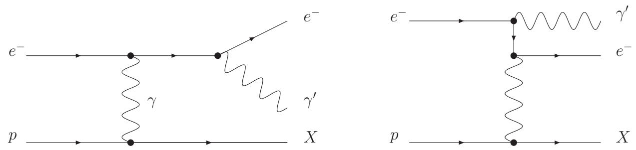
Complementarity of e-p: Dark photons

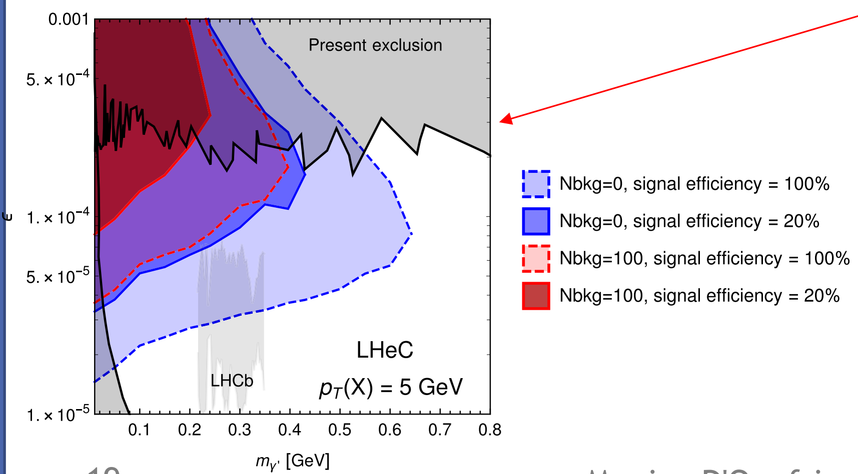
PhysRevD.101.015020

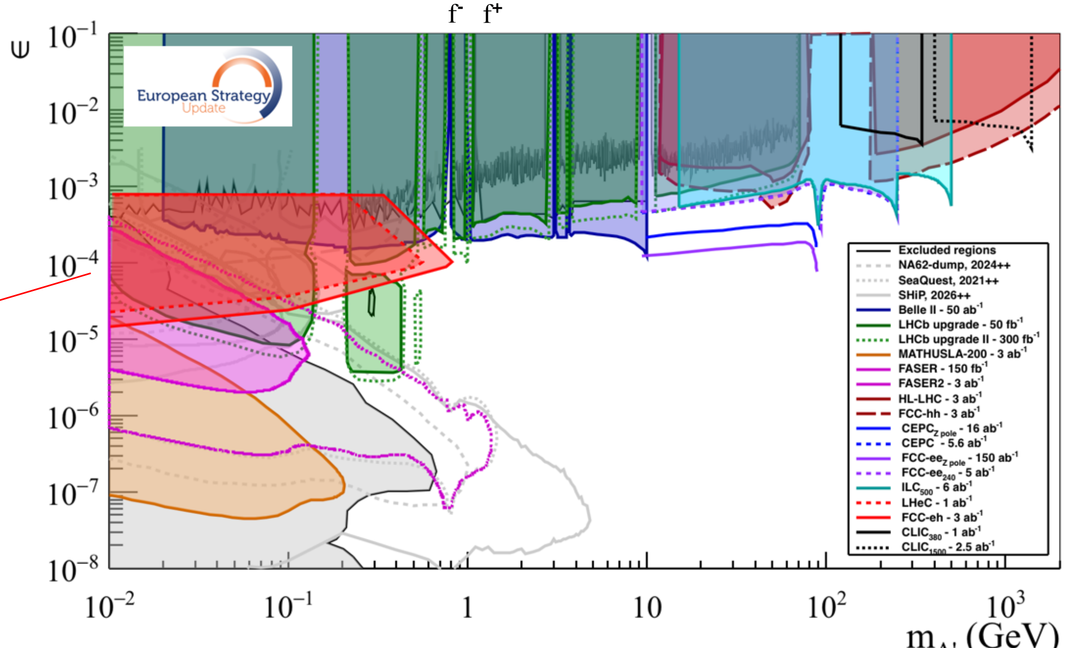


- have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.

$$-\frac{\varepsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$





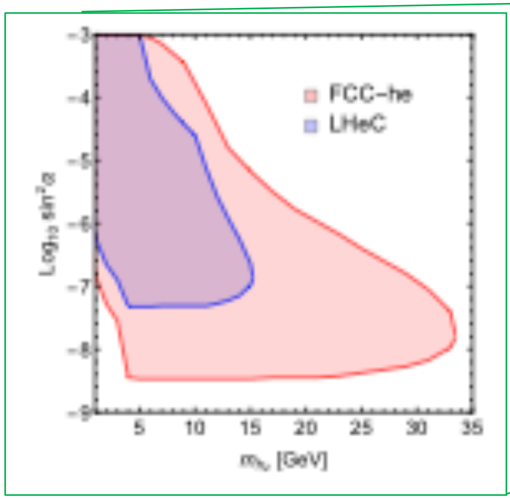


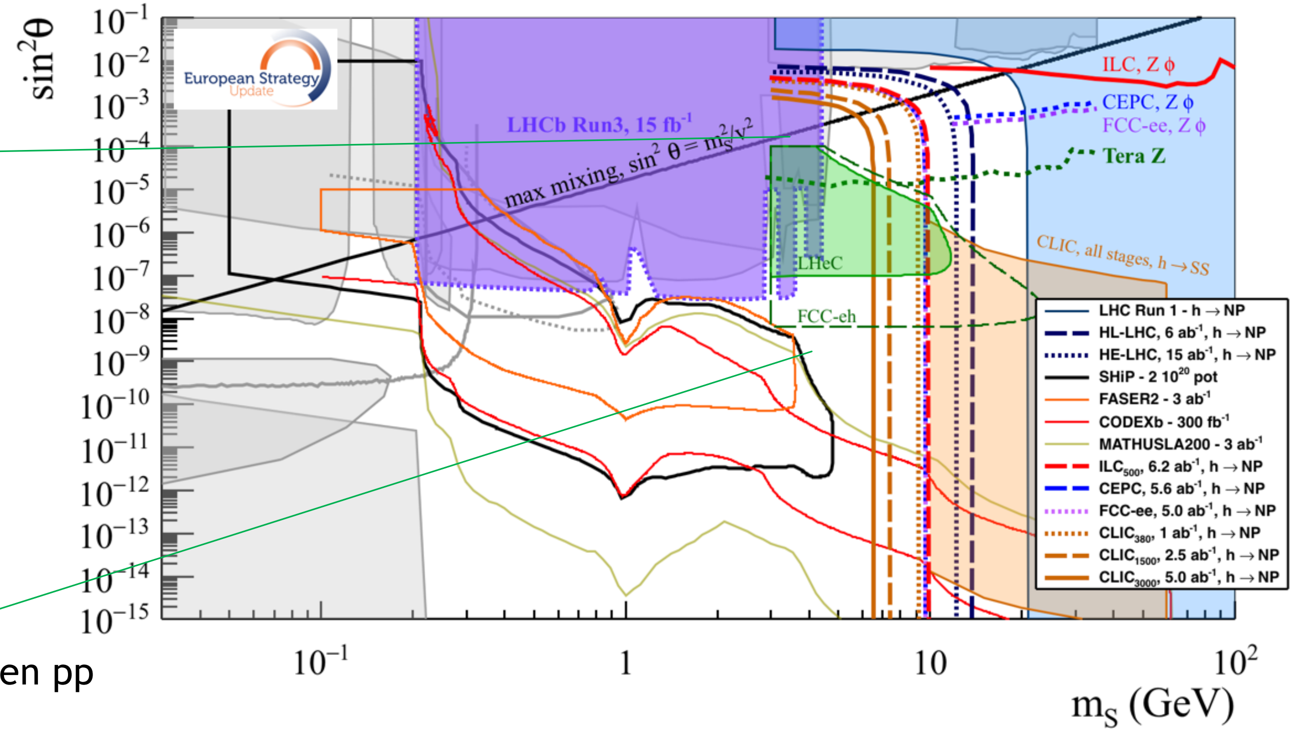
Covering important regions between pp and ee / low-energy experiments

Complementarity of e-p: new scalars

- Interpreting the results for a specific model, where lifetime and production rate of the LLP are governed by the scalar mixing angle.
- The contours are for 3 events and consider displacements larger than 50 μm to be free of background.

$$(\mu S + \lambda_{HS} S^2) H^\dagger H$$





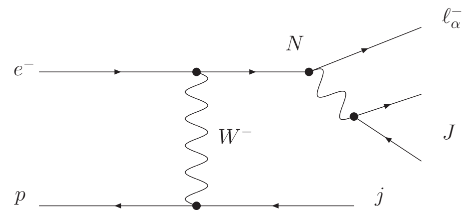
Covering important regions between pp and ee / low-energy experiments

Heavy neutral leptons at ep

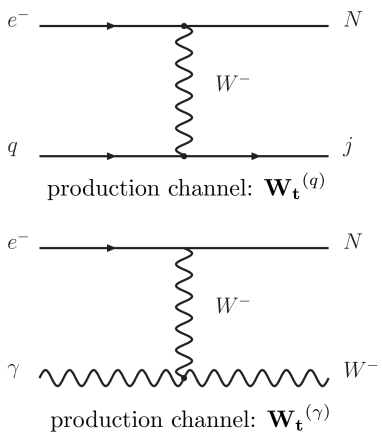
- Similarly to the case of the Higgs exotics decays, sterile neutrinos

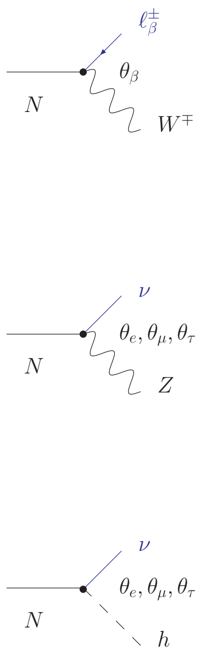
$$y_N LHN$$

Sensitivity of the LFV lepton-trijet searches (at 95 % C.L.) and DV one

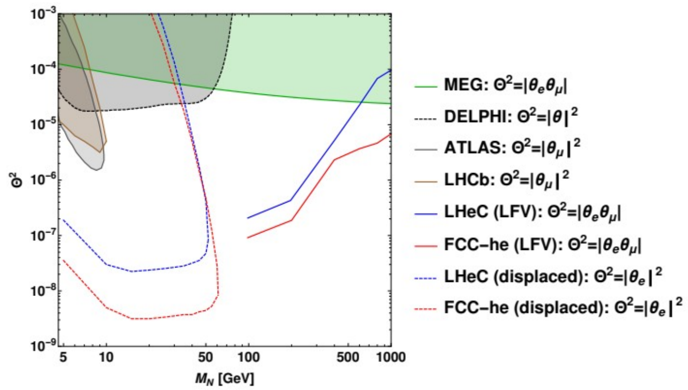


active-sterile neutrino mixing with the electron flavour → |θe|2

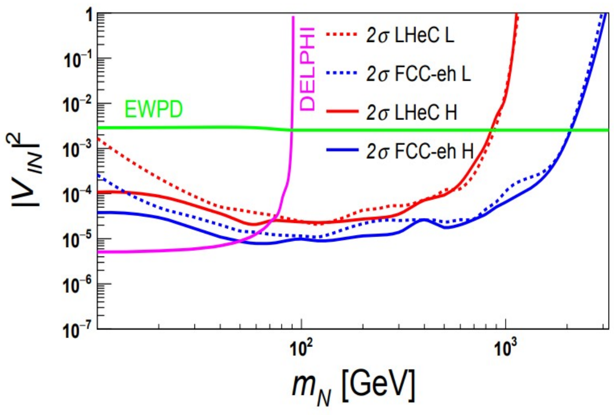




Coupling to electrons and muons
Antusch et al., arXiv:1908.02852



Coupling to electrons and taus
Gu et al., arXiv:2210.17050

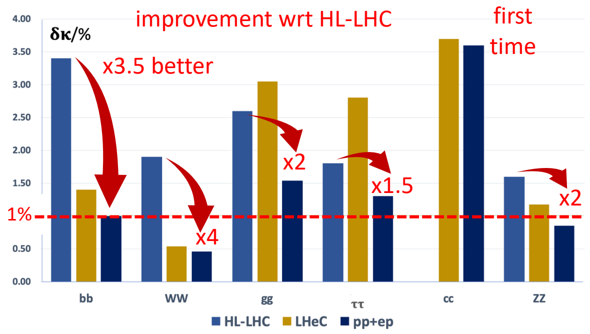


Different analyses depending on m(N) and m(W) relations

Conclusions

- In a snapshot: great potential for a **compelling and competitive physics programme**

Higgs physics



EW physics

- Δm_W down to 2 MeV (today at ~10 MeV)
- $\Delta \sin^2\theta_W^{eff}$ to 0.00015 (same as LEP)

Top quark physics

- $|V_{tb}|$ precision better than 1% (today ~5%)
- top quark FCNC and γ, W, Z couplings

\+ 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)

50 years Max's fest
(December 2022)

https://indico.ph.liv.ac.uk/event/743/timetable/#20221209

Back up

SUSY EWK production

PhysRevD.101.095015

- Target two kind of EWK mass spectra:

"Classic" compressed spectrum
→ **"decoupled-slepton scenario"**

"compressed-slepton scenario"

Slepton mass

Large gap

Chargino ~ Neutralino1 masses
Mass difference ~ 1-2 GeV

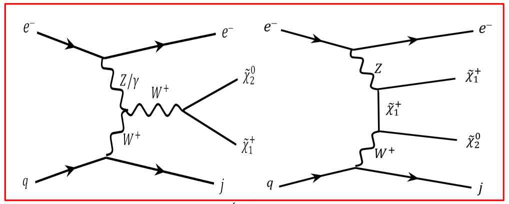
Slepton (selectron) mass

~35 GeV

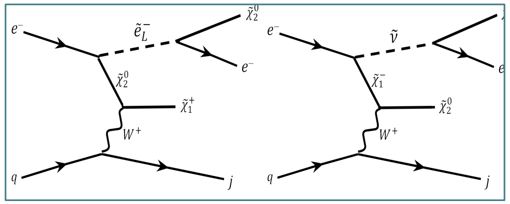
(Note: as sleptons are heavier than charginos and neutralinos, they do not play a role in the pp cross sections)

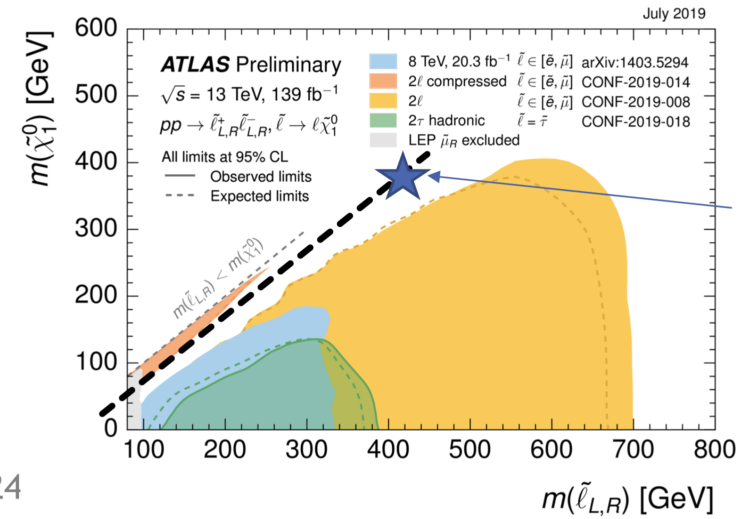
$pe^- \to je^-\tilde{\chi}\tilde{\chi}\ (\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$

VBF production



$+\ pe^- \to j\tilde{\chi}\tilde{e}_L^-, j\tilde{\chi}\tilde{\nu} \to je^-\tilde{\chi}\tilde{\chi}$





Benchmark slepton mass

Compressed slepton scenarios: results

PhysRevD.101.095015

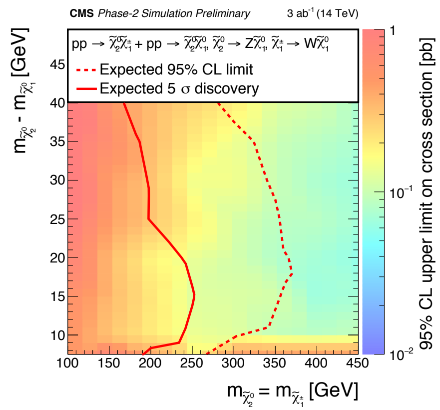
- Evaluate significance with stat and syst uncertainties

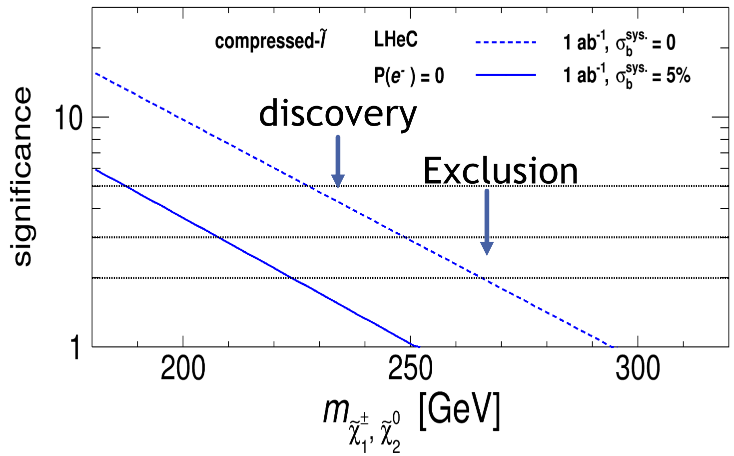
$$\sigma_{\rm stat} = \sqrt{2[(N_s+N_b)\ln(1+\frac{N_s}{N_b}) - N_s]}.$$

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

LHeC [1 ab^{-1}]	Signal	Background	
$m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0}$ [GeV]	250	$j\,e^-\,\nu\nu$	$j\,e^-\,\ell\nu$
$m_{\tilde{\ell}}$ [GeV]	285		
initial	1231	2.80×10^5	2.01×10^6
Pre-selection	453	6.60×10^4	1.66×10^5
BDT > 0.172	49	486	278
$\sigma_{\rm stat+syst}$	1.0		

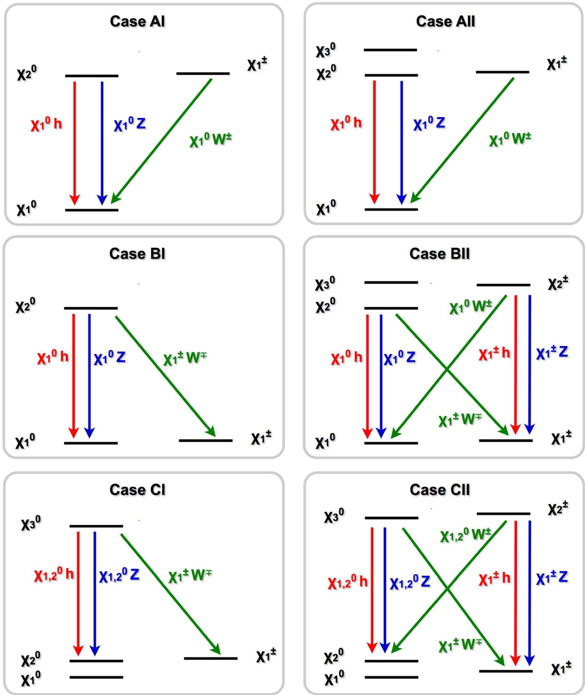
- Of course, systematic uncertainties play a crucial role (0-5% here)
- Comparisons with HL-LHC:
  - Not straightforward because of differences in models but similar mass range





SUSY EWK production: Phenomenology

- Mass and hierarchy of the four neutralinos and the two charginos, as well as their production cross sections and decay modes, depend on the M_1, M_2, μ (bino, wino, higgsino) values and hierarchy
  - EWK phenomenology broadly driven by the LSP and Next-LSP nature
  - Examples of classifications (cf: arXiV: 1309.5966)



- **Scenario A:** $M_1 < M_2, |\mu|$

  Bino LSP

- **Scenario B:** $M_2 < M_1, |\mu|$

  Wino LSP

- **Scenario C:** $|\mu| < M_1, M_2$

  Higgsino LSP

Used as benchmarks:

- Bino LSP, wino-bino cross sections
  (1) Mass($\chi^{\pm}_1$) = Mass (χ^0_2)
  (2) $\chi^+_1\chi^-_1$ and $\chi^{\pm}_1\chi^0_2$ processes

- Higgsino-LSP, higgsino-like cross sections
  (1) Small mass splitting $\chi^0_1, \chi^{\pm}_1, \chi^0_2$
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

$$\sigma_H(\chi^{\pm}_1\chi^0_2 + \chi^+_1\chi^-_1 + \chi^{\pm}_1\chi^0_1) < \text{or} \ll \sigma_W(\chi^{\pm}_1\chi^0_2)$$

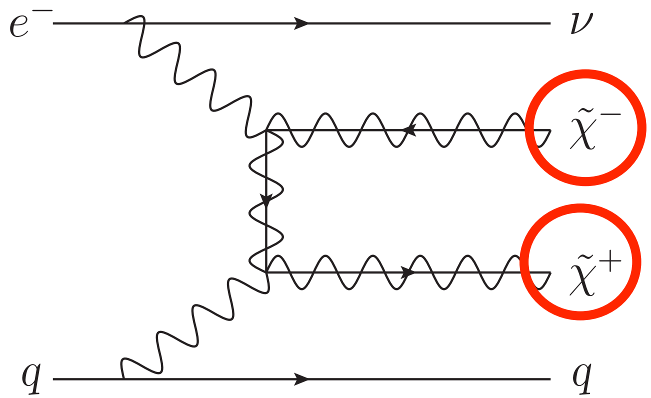
[depending on masses!]

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

- The decay of chargino is **NOT prompt → long-lived particles (LLP)**!

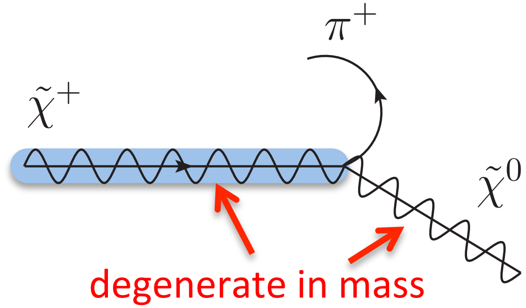
Simplest models at FCC-he: **four-body process** **and** **tiny cross section**

- Charginos (Wino or Higgsino)



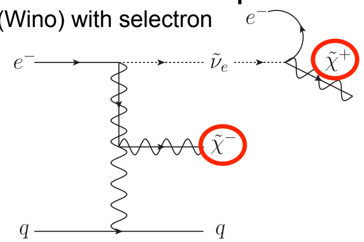
LLCPs

disappearing track



Cross section enhanced with "co-production"

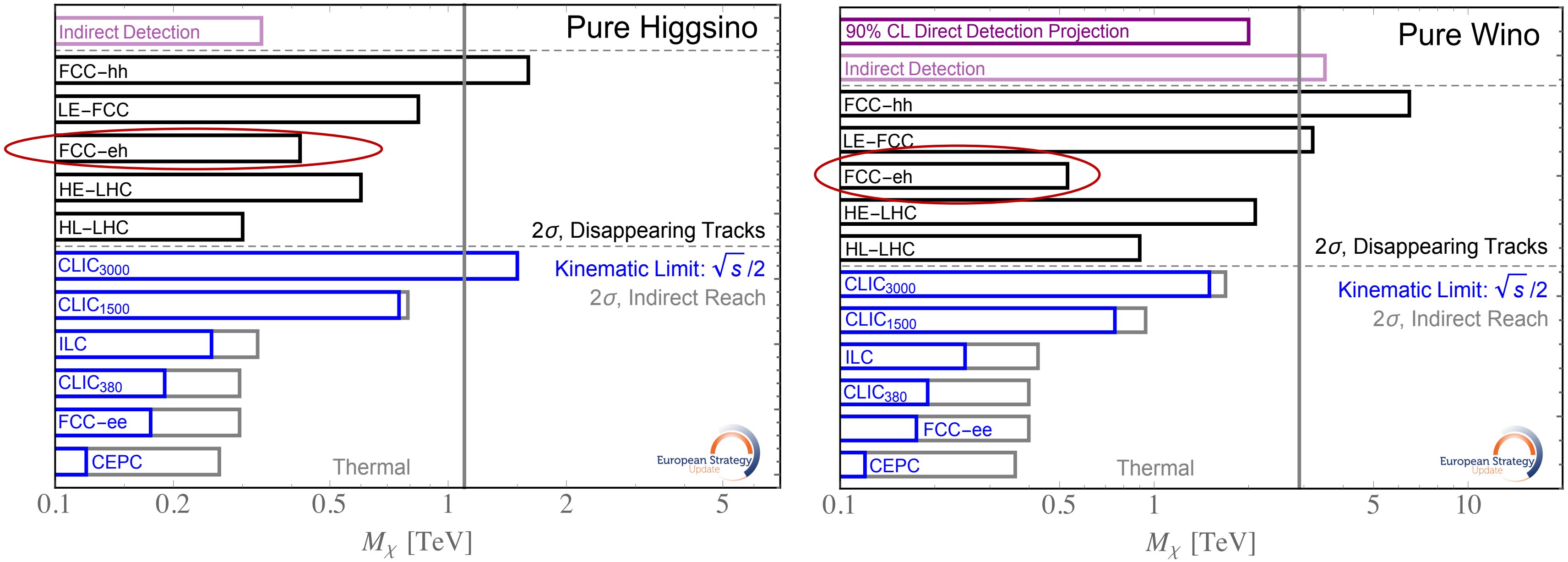
- Chargino (Wino) with selectron



In this case, only the scenario with heavy (decoupled) sleptons is considered (most conservative)

Comparisons with other facilities

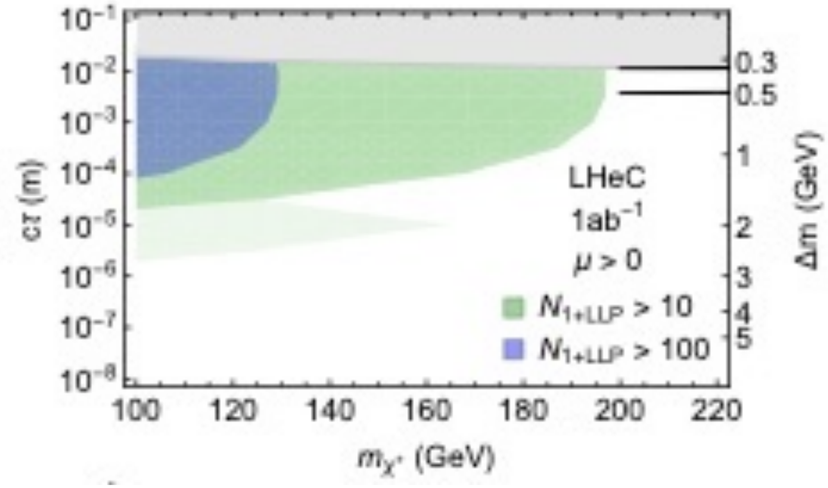
- Thermal Higgsino/Wino dark matter mass
- Comparisons computed for the European strategy

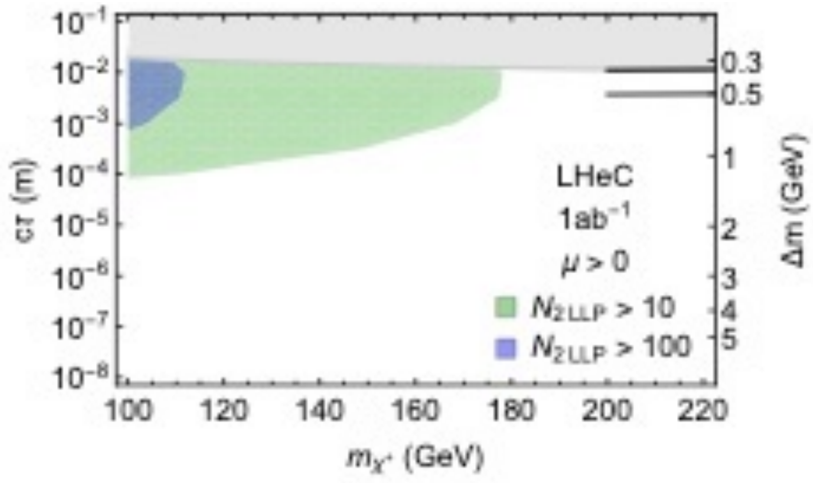


- FCC-eh not directly competitive with FCC-hh but **still reasonable reach**
- In all cases FCC-eh sensitivity to **short decay lengths**, possibly much less than a single micron, improves with respect to what the FCC-hh can accomplish with disappearing track searches

Results for disappearing track analysis

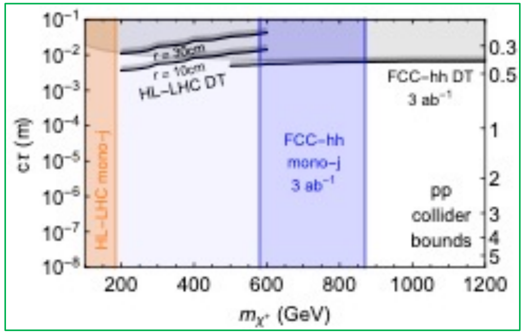
- contours of N_{1+LLP} and $N_{2\ LLP}$





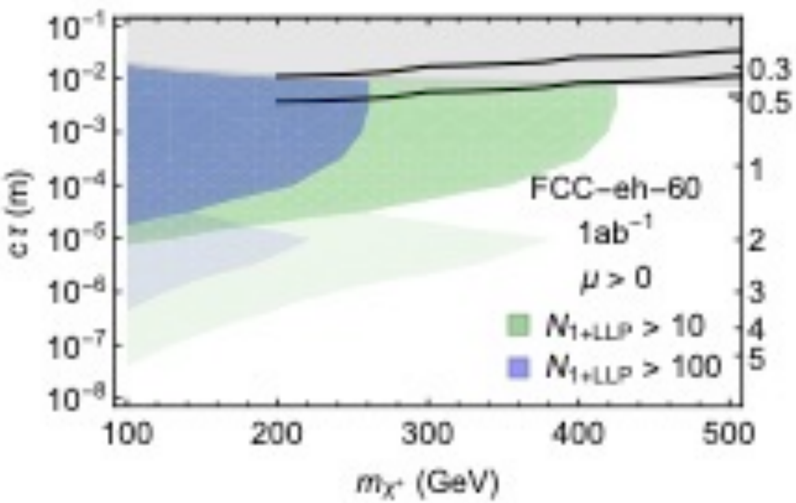
green region: 2σ sensitivity estimate in the presence of τ backgrounds
black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

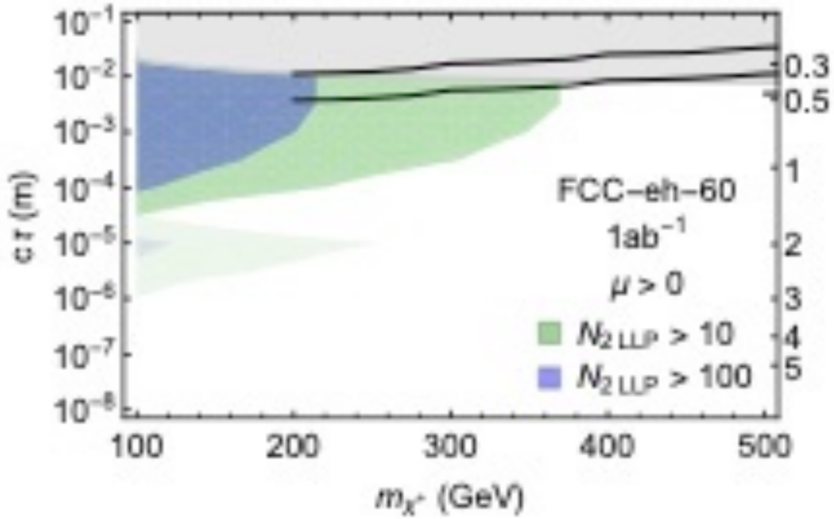
Sensitive to very short lifetimes exceeds that of hh colliders



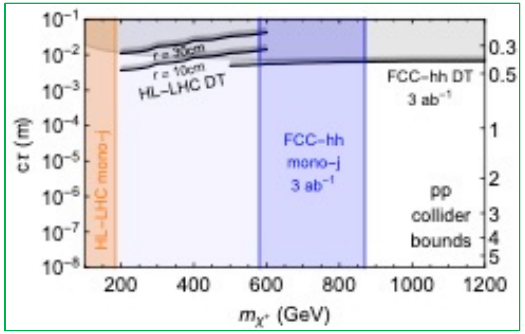
Results for disappearing track analysis @ FCC

- contours of N_{1+LLP} and $N_{2\ LLP}$





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

Compressed slepton scenarios: results

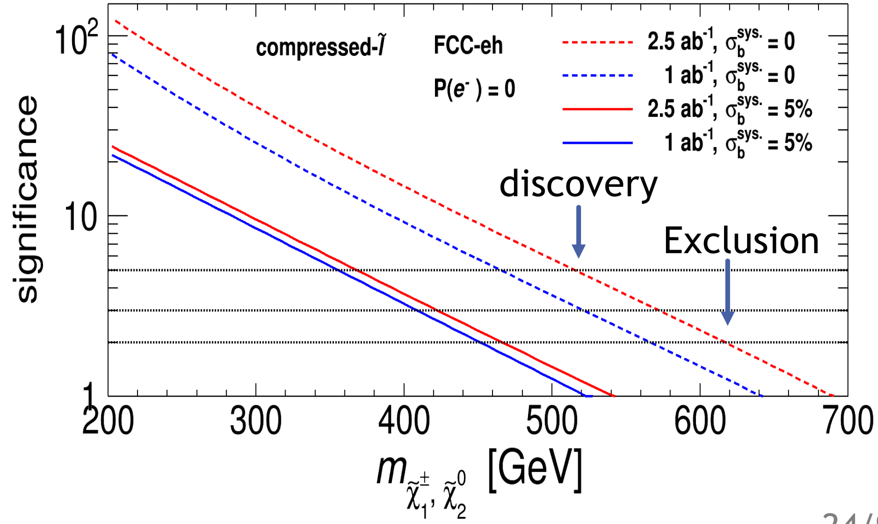
- Evaluate significance with statistical and systematic uncertainties

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

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

FCC-eh [1 ab^{-1}]	Signal	Background	
$m_{\tilde{\chi}_1^\pm,\tilde{\chi}_2^0}$ [GeV]	400	$j\,e^-\,\nu\nu$	$j\,e^-\,\ell\nu$
$m_{\tilde{\ell}}$ [GeV]	435		
initial	4564	1.08×10^6	7.96×10^6
Pre-selection	3000	3.87×10^5	5.71×10^5
BDT > 0.262	149	600	86
$\sigma_{\text{stat+syst}}$	3.3		

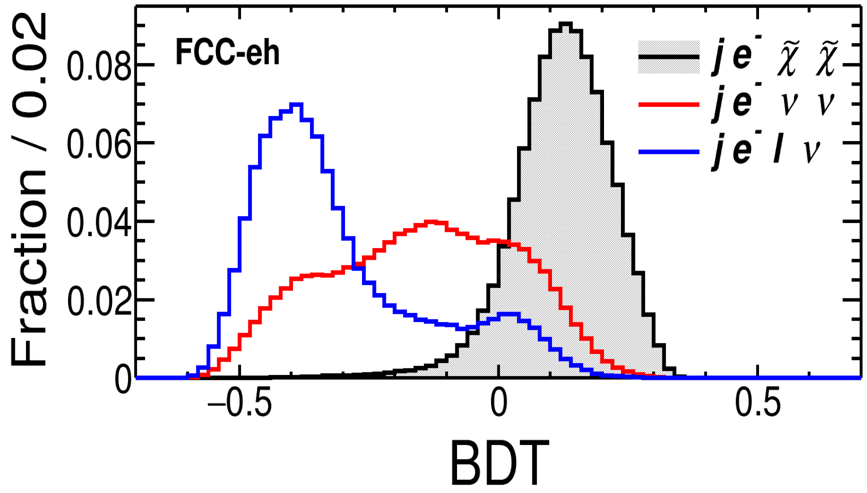
- Of course, systematic uncertainties play a crucial role, as in monojet searches at pp
  - → **Here we consider 0-5%**
  - → Projections for HL-LHC consider 1-3%



Compressed slepton scenarios: the analysis

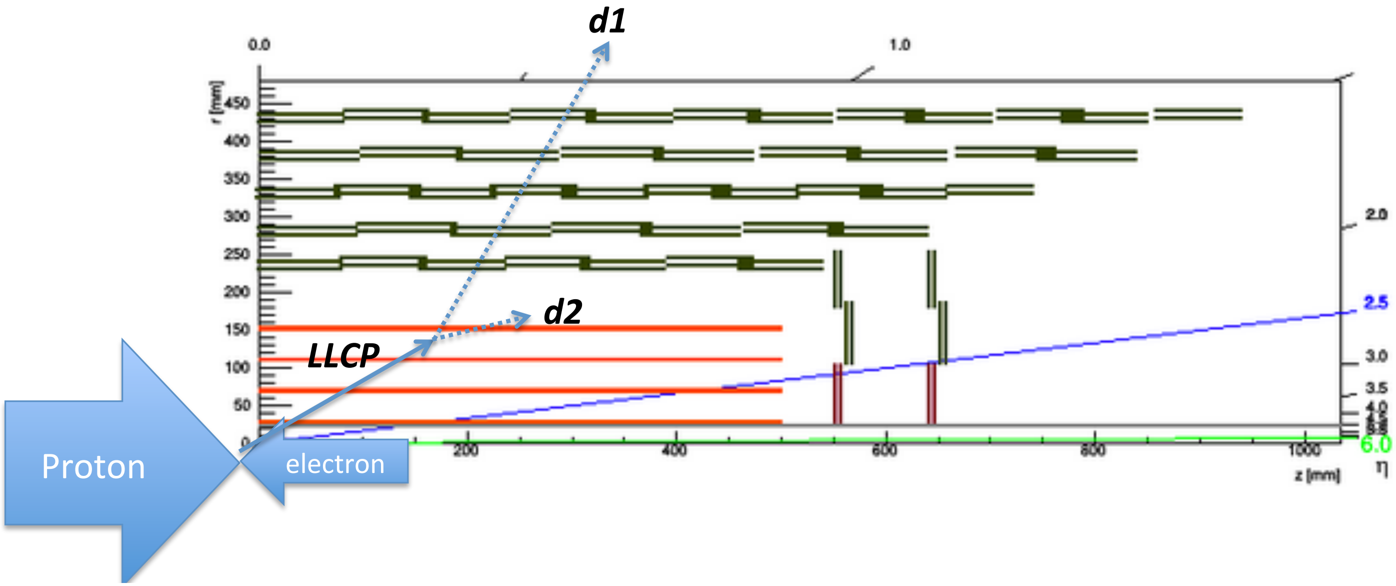
- **Final state**: 1 e- + 1 j + MET
- Analysis at detector-level using a simple Boost Decision Tree.
- Backgrounds: all processes with one or two neutrinos (to also take into account mis-identified leptons): $p\,e^- \to j\,e^-\,\nu\nu$, $p\,e^- \to j\,e^-\,\ell\nu$
- Pre-selections:
  - At least one jet with $p_T > 20$ GeV, $|\eta| \leq 6.0$;
  - Exactly one electron with $p_T > 10$ GeV, $-5.0 < \eta < 5.2$;
  - No b-jet with $p_T > 20$ GeV;
  - No muon or tau with $p_T > 10$ GeV;
  - Missing transverse momentum $E^{miss}_T > 50$ GeV
- Use BDT with simple kinematic variables

and angular correlations as input



Long-lived EWKinos: disappearing tracks

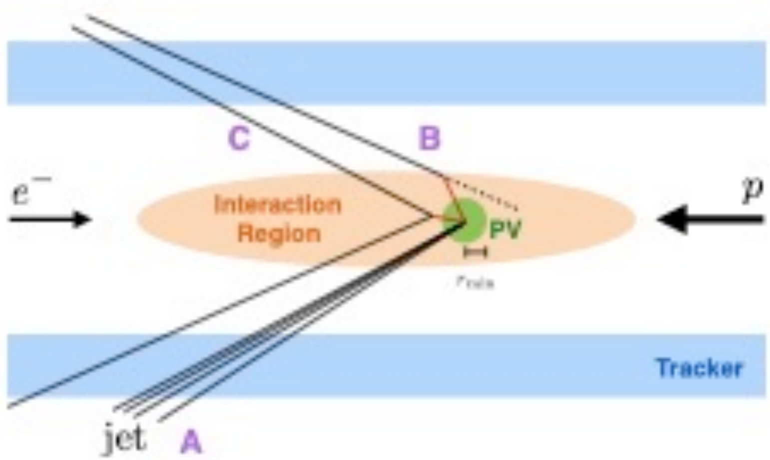
- long lived charginos are typically significantly boosted along the proton beam direction, which increases their lifetime in the laboratory frame. $b_{\rm com} \approx \frac{1}{2}\sqrt{E_e/E_p} \approx 5.5$



3-4 hits only in the inner-most tracker àmissing (disappearing track)
(or a “kink” if the harder daughter ***d1*** is charged)

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

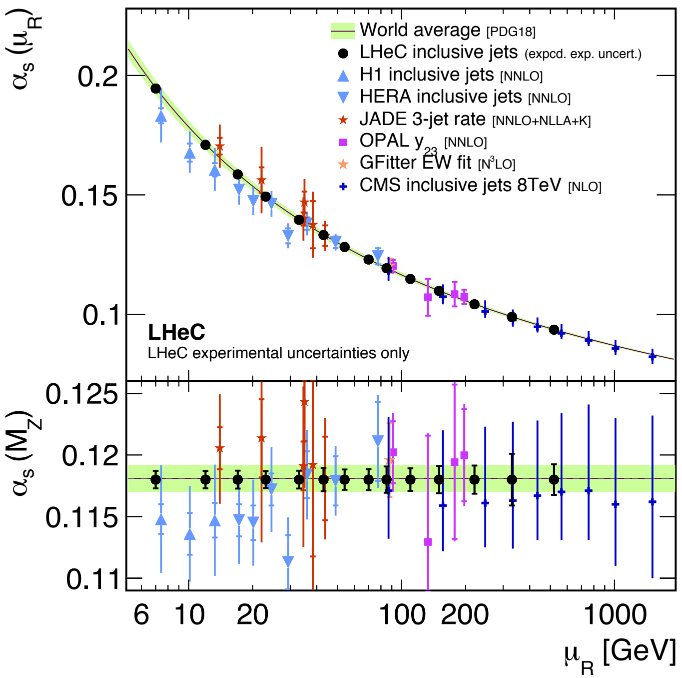


- heavily relies on backgrounds due to pile-up being either absent or controllable.
  - benchmark value is r_{min} = 40μm (~ 5 nominal detector resolutions); p_T threshold for reconstruction of a single charged particle is chosen as 100 MeV
  - Assume 100% efficiency
- Estimate probability of detecting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

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)τ**

alpha_S and Higgs cross section

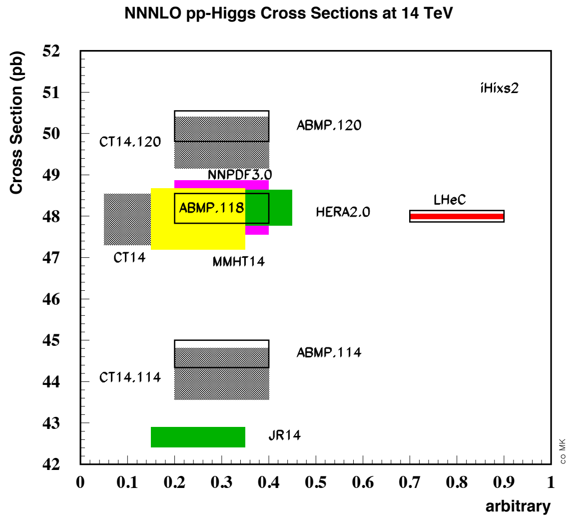
- Strong coupling constant could be measured to the permille accuracy (incl. + jets analysis)



$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00022_{(\text{exp+PDF})}$$
$$\Delta\alpha_s(M_Z)(\text{incl. DIS \& jets}) = \pm 0.00018_{(\text{exp+PDF})}$$

- Improvement in the calculation of pp→HX calculated at N^{3}LO in pQCD thanks to PDF

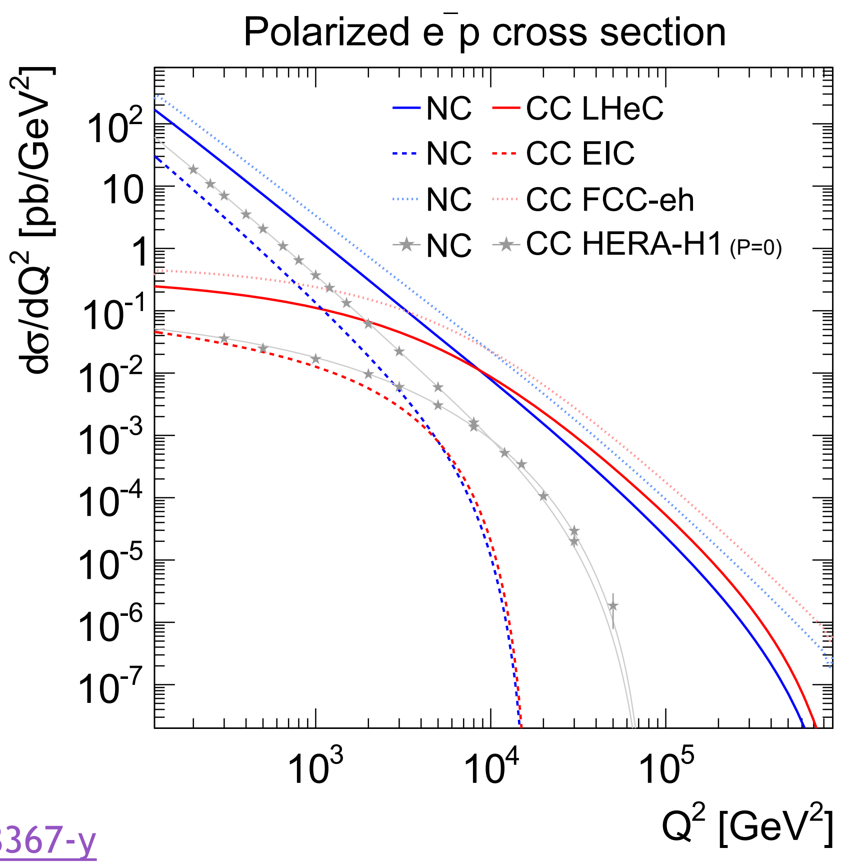
Process	σ_H [pb]	$\Delta\sigma_{\text{scales}}$	$\Delta\sigma_{\text{PDF}+\alpha_s}$	
			HL-LHC PDF	LHeC PDF
Gluon-fusion	54.7	5.4 %	3.1 %	0.4 %
Vector-boson-fusion	4.3	2.1 %	0.4 %	0.3 %
$pp \to WH$	1.5	0.5 %	1.4 %	0.2 %
$pp \to ZH$	1.0	3.5 %	1.9 %	0.3 %
$pp \to t\bar{t}H$	0.6	7.5 %	3.5 %	0.4 %



Cross sections of Higgs production N$_3$LO for existing PDF sets (left side) and for the LHeC PDFs (right side)

EWK cross section EIC, LHeC, FCC-eh

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



Daniel Britzger, Max Klein & Hubert Spiesberger

https://link.springer.com/article/10.1140/epjc/s10052-020-8367-y