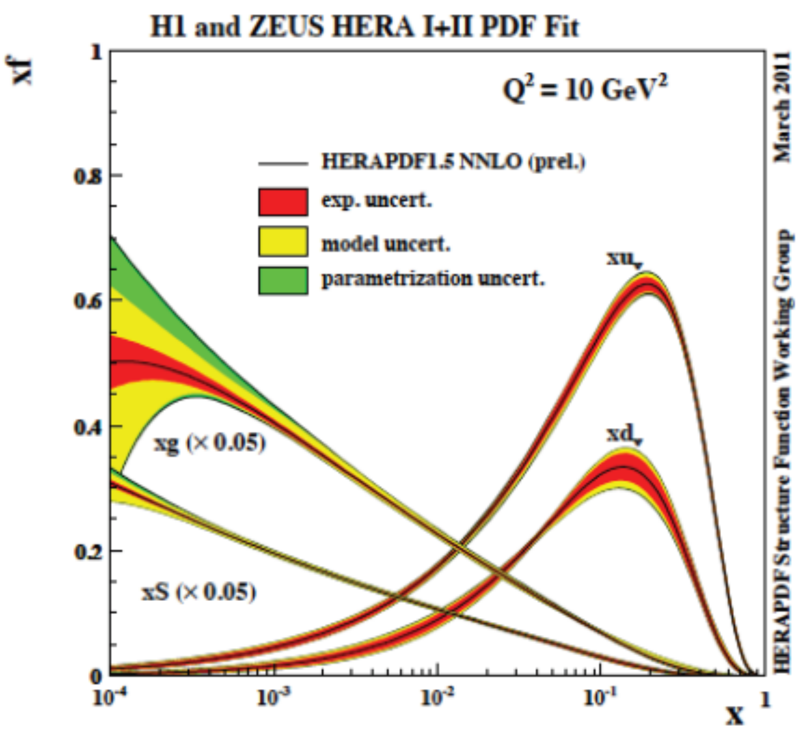
The LHeC (and FCC-eh) opportunity

Monica D'Onofrio, University of Liverpool

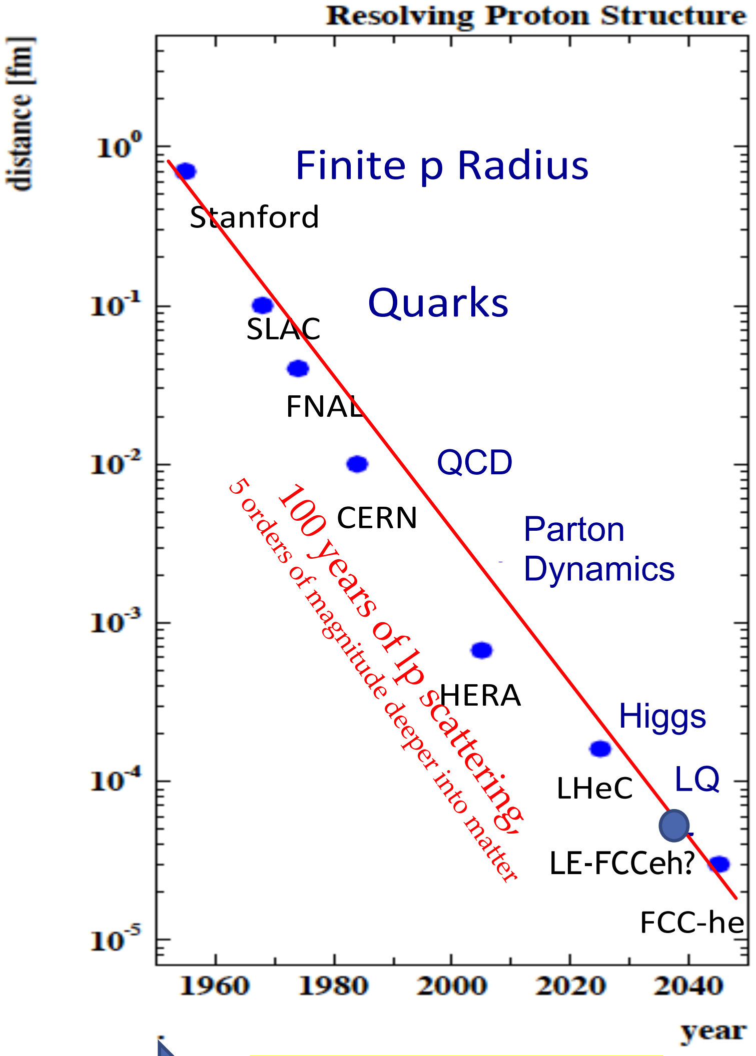
XXI Roma Tre Topical Workshop on Subnuclear Physics

Rome, 29/1/2020

Electron-proton colliders in hystory



- At HERA, extensive tests of QCD, measurements of α_S and base for PDF fits in x range relevant for hadron colliders
- But also:
  - New limits for leptoquarks, excited electrons and neutrinos, quark substructure and compositness, RPV SUSY etc.



The idea of an e-p collider at CERN, the LHeC, proposed in 2005, has been developed in the last years: http://cern.ch/LHeC

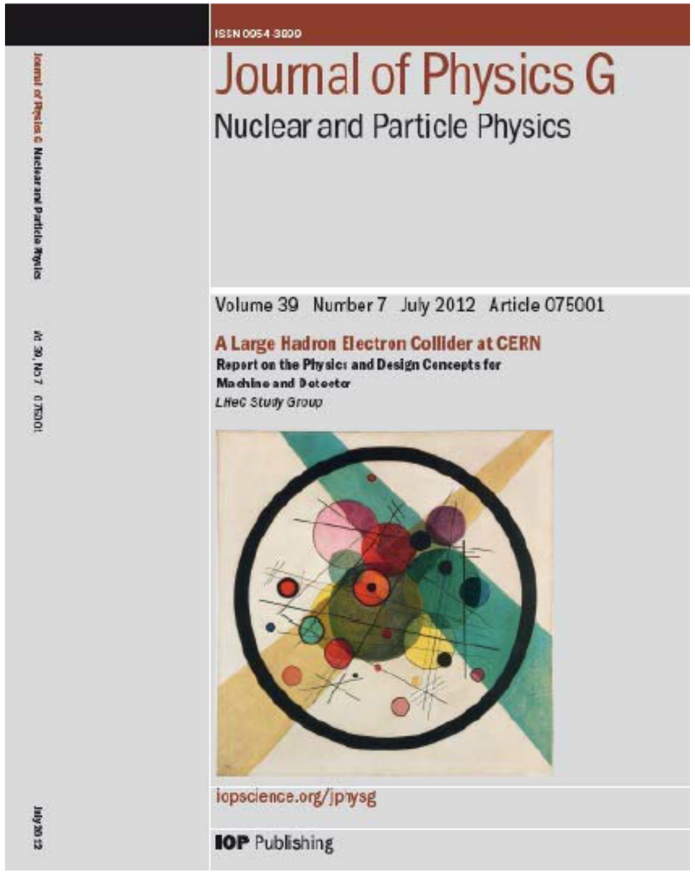
Tevatron/HERA/LEP → HL-LHC/LHeC/(CepC?)

(fermiscale) (Terascale)

(or, the complimenatarity pattern)

→ **FCC-ee/hh/eh**

LHeC: Conceptual Design Report (July 2012) and its updates

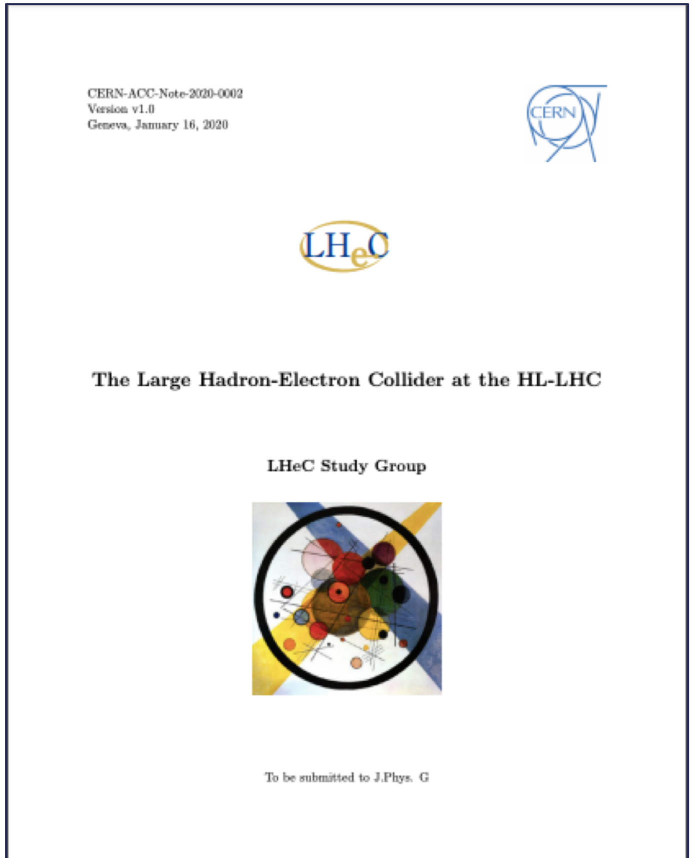


- CDR 2012: 5 years of studies commissioned by CERN, ECFA and NuPECC
- About 200 participants, 69 institutes
- Several further updates
  - *'A Large Hadron Electron Collider at CERN'* arXiV:1211.4831
  - *'On the relation of the LHeC and the LHC'* arXZiV:1211.5102
  - *'The Large Hadron Electron Collider'* arXiV:1305.2090
  - *'Dig Deeper'* Nature Physics 9 (2013) 448
- **Most recent:**

https://cds.cern.ch/record/2706220

300+ pages document, ~300 authors among experimentalists and theorists,

+ documents submitted for the European Strategy



Final version expected end Feb

Annual workshops (e.g. https://indico.cern.ch/event/835947) and presentations in Conferences

Organisation

International Advisory Committee

Mandate by CERN (2014+17) to define
"..Direction for ep/A both at LHC+FCC"

Sergio Bertolucci (CERN/Bologna)
Nichola Bianchi (Frascati)
Frederick Bordry (CERN)
Stan Brodsky (SLAC)
Hesheng Chen (IHEP Beijing)
Eckhard Elsen (CERN)
Stefano Forte (Milano)
Andrew Hutton (Jefferson Lab)
Young-Kee Kim (Chicago)
Victor A Matveev (JINR Dubna)
Shin-Ichi Kurokawa (Tsukuba)
Leandro Nisati (Rome)
Leonid Rivkin (Lausanne)
Herwig Schopper (CERN) - Chair
Juergen Schukraft (CERN)
Achille Stocchi (LAL Orsay)
John Womersley (ESS)

prev. Guido Altarelli.

Coordination Group

Accelerator+Detector+Physics

Gianluigi Arduini
Nestor Armesto
Oliver Brüning – Co-Chair
Andrea Gaddi
Erk Jensen
Walid Kaabi
Max Klein – Co-Chair
Peter Kostka
Bruce Mellado
Paul Newman
Daniel Schulte
Frank Zimmermann

5(12) are members of the FCC coordination team

OB+MK: co-coordinate FCCeh

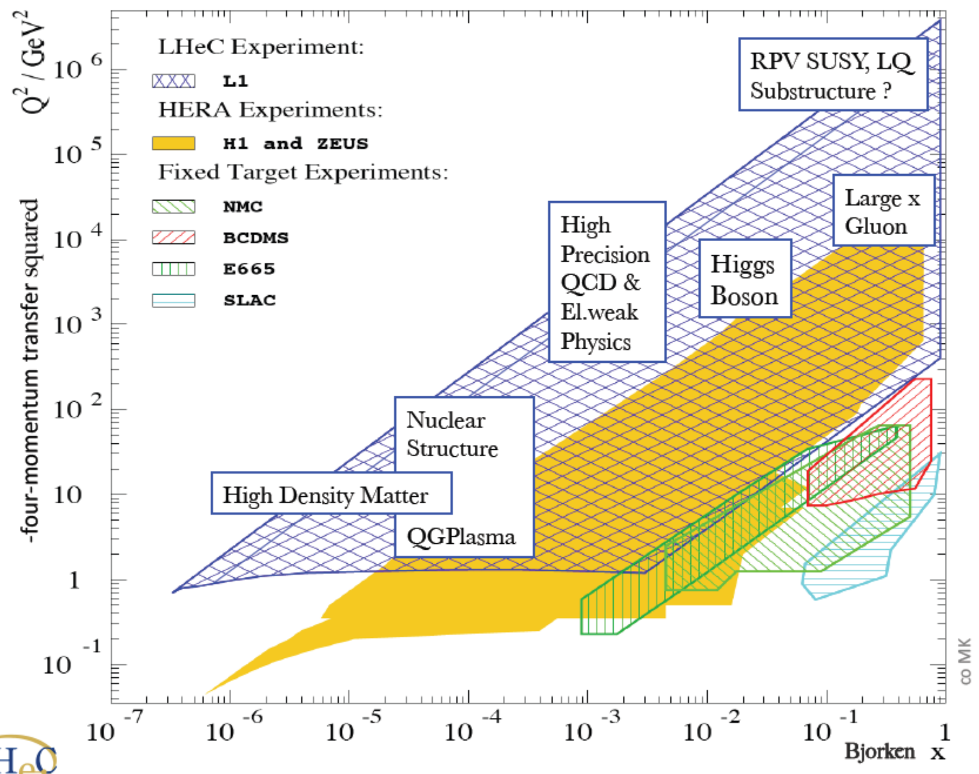
Working Groups

PDFs, QCD
Fred Olness,
Claire Gwenlan
Higgs
Uta Klein,
Masahiro Kuze
BSM
Georges Azuelos,
Monica D'Onofrio
Oliver Fischer
Top
Olaf Behnke,
Christian Schwanenberger
eA Physics
Nestor Armesto
Small x
Paul Newman,
Anna Stasto
Detector
Alessandro Polini
Peter Kostka

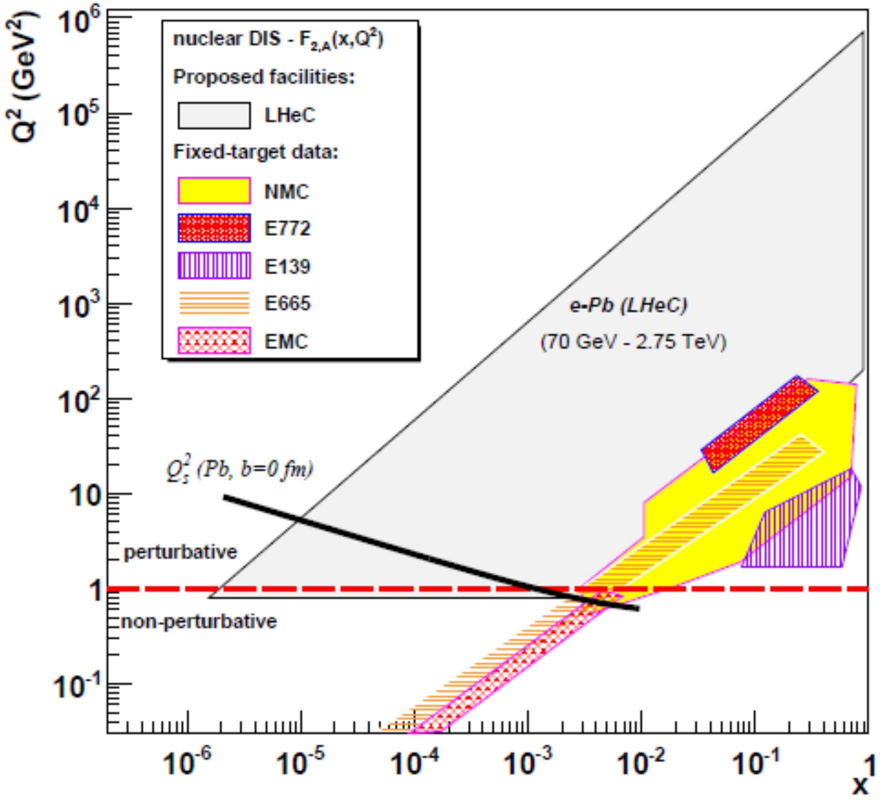
The LHeC as e-p and e-Ion collider and its update – the FCCeh

- Unique opportunity to take lepton-hadron physics to the TeV centre-of-mass scale at high Lumi

LHeC e-p: E_e=60 (*) GeV, E_p=7 TeV √s = 1.3 TeV
→ For **FCC-eh**: 50 TeV protons



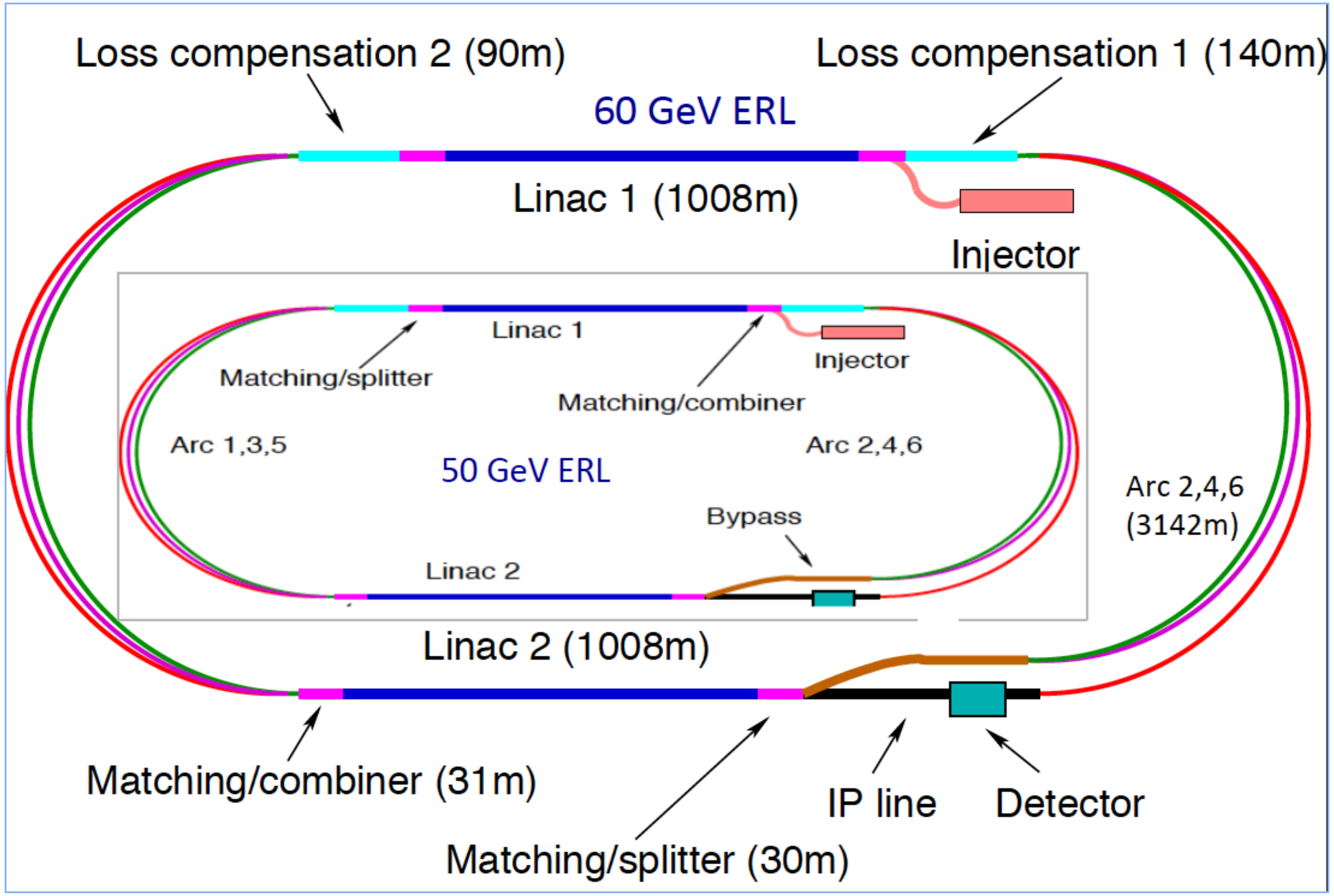
LHeC e-Ion: E_e=60 (*) GeV, Eion=2.76 TeV
→ For **FCC-eh**: increase up to ~20 TeV



Concurrent ep + pp operation with LHC

Designed to exploit intense **hadron beams** in high luminosity phase of LHC running from ~2030+:
→ Use 7 TeV protons/2.75 TeV Heavy Ions **Add an electron beam (*) to the LHC**

Energy Recovery Linac



for two electron beam energies [CERN, BNL, Jlab for CDR]

3-turn energy recovery racetrack configuration. Modular for LHeC/FCC-eh

(*) Electron E depends on the linac!

- ERL: 20mA I_e
- Allow inst lumi 10^{-34} cm^{-2} s^{-1} and integrated lumi in e^-p up to O(1) ab^{-1}
- U(ep) = 1/n U(LHC), with n=3 (for CDR) → now more n=4

  This gains 20-30% cost but E< 60 GeV

Higgs, BSM, top, low x. physics require E > 50 GeV

Frequency set to 802 MHz, commensurate with LHC and 401/802 at CERN+FCC, beam-beam stability

PERLE Test Facility being built in Orsay [*phase 1 start 2025*]

(see back up)

Possible locations

LHeC

FCC-eh

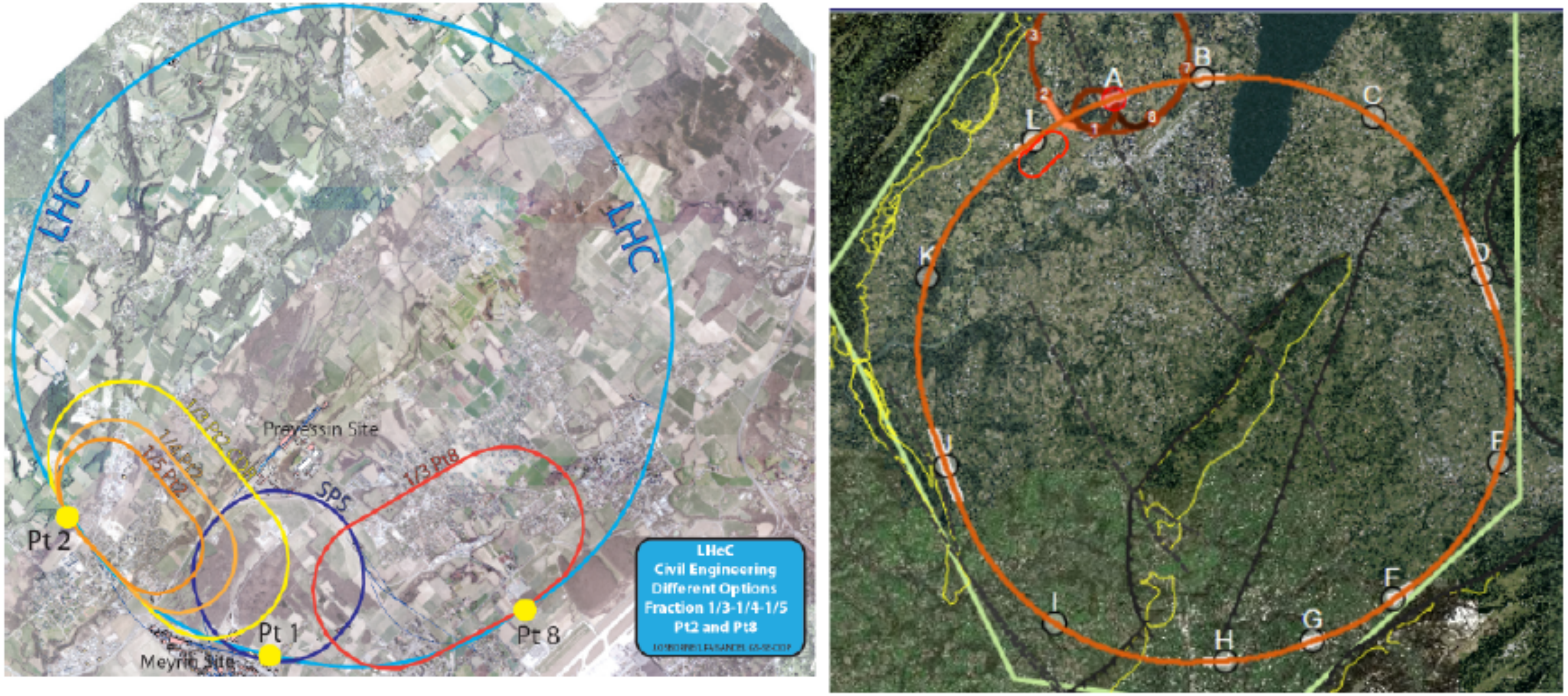
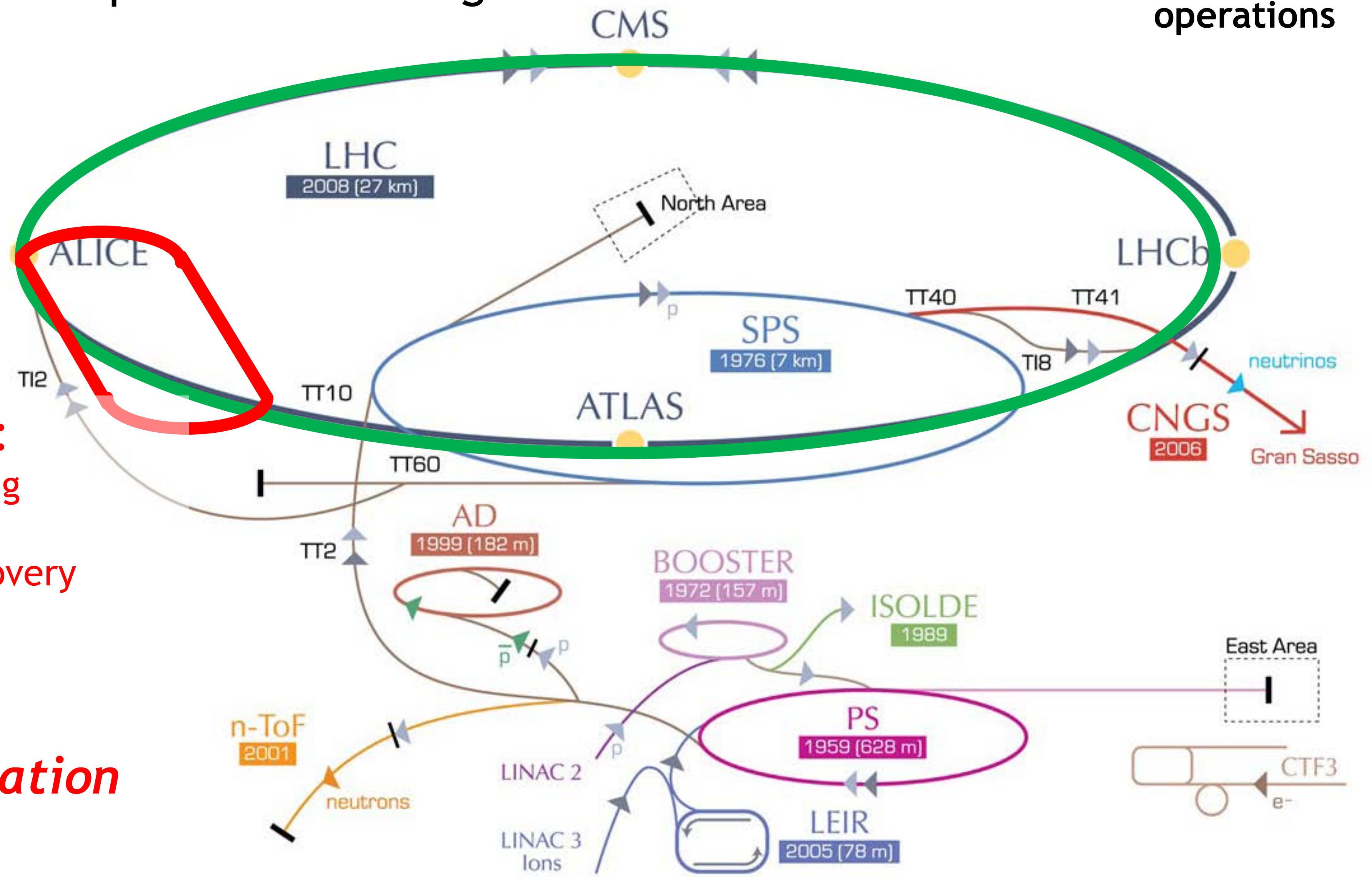


Figure 2: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\text{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\text{GeV}$) and 1/5 (most inner track, $E_e = 52\,\text{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Present considerations suggest that Point L may be preferred as the position of the ERL, while two GPDs would be located at A and G.

The LHeC facility

e± beam main option: Linac-Ring

Aim is to accumulate up to 500/fb - 1/ab in 10+ yrs of operations

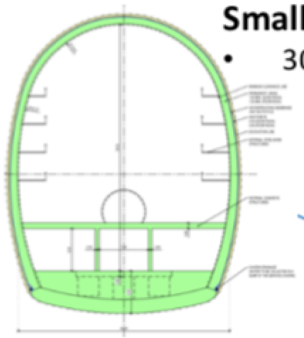


LR LHeC:
recirculating linac with energy recovery

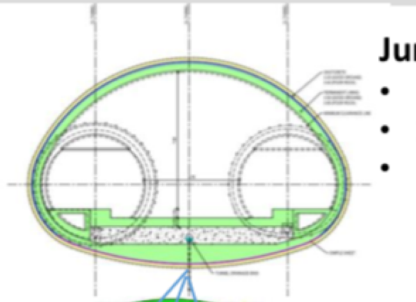
↓

baseline configuration

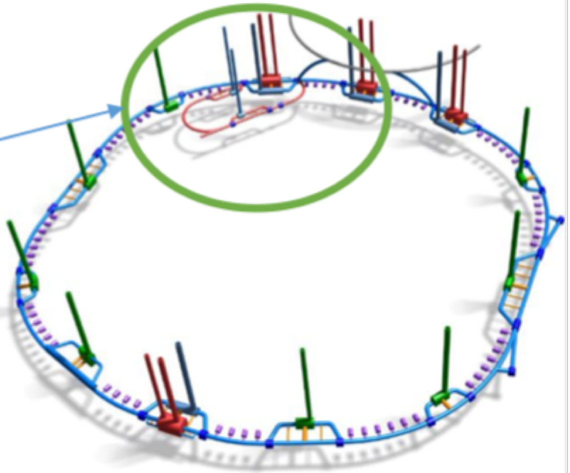
Scope of FCC-eh Structures

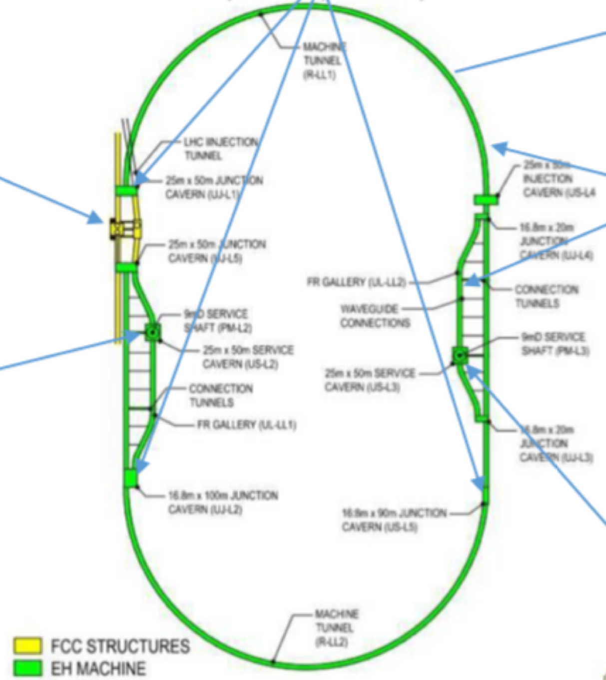


Small Experimental Caverns
- 30 m x 35 m x 66m



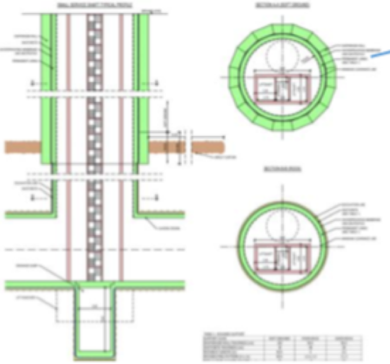
Junction Caverns
- 16.8 m x 15 m x 100 m
- 25 m x 15 m x 50 m
- 16.8 m x 15 m x 90 m

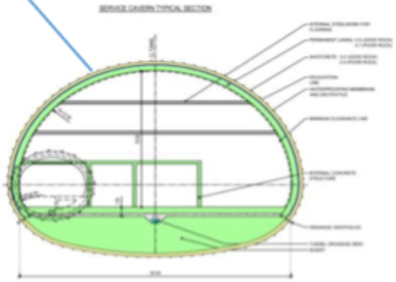




Tunnels:
- 9.091 km of 5.5m dia. machine tunnel.
- 2 x 1.04 km of 5.5m dia RF tunnel.

Shafts:
2 x Service shafts:
9 m dia. x 175 m depth





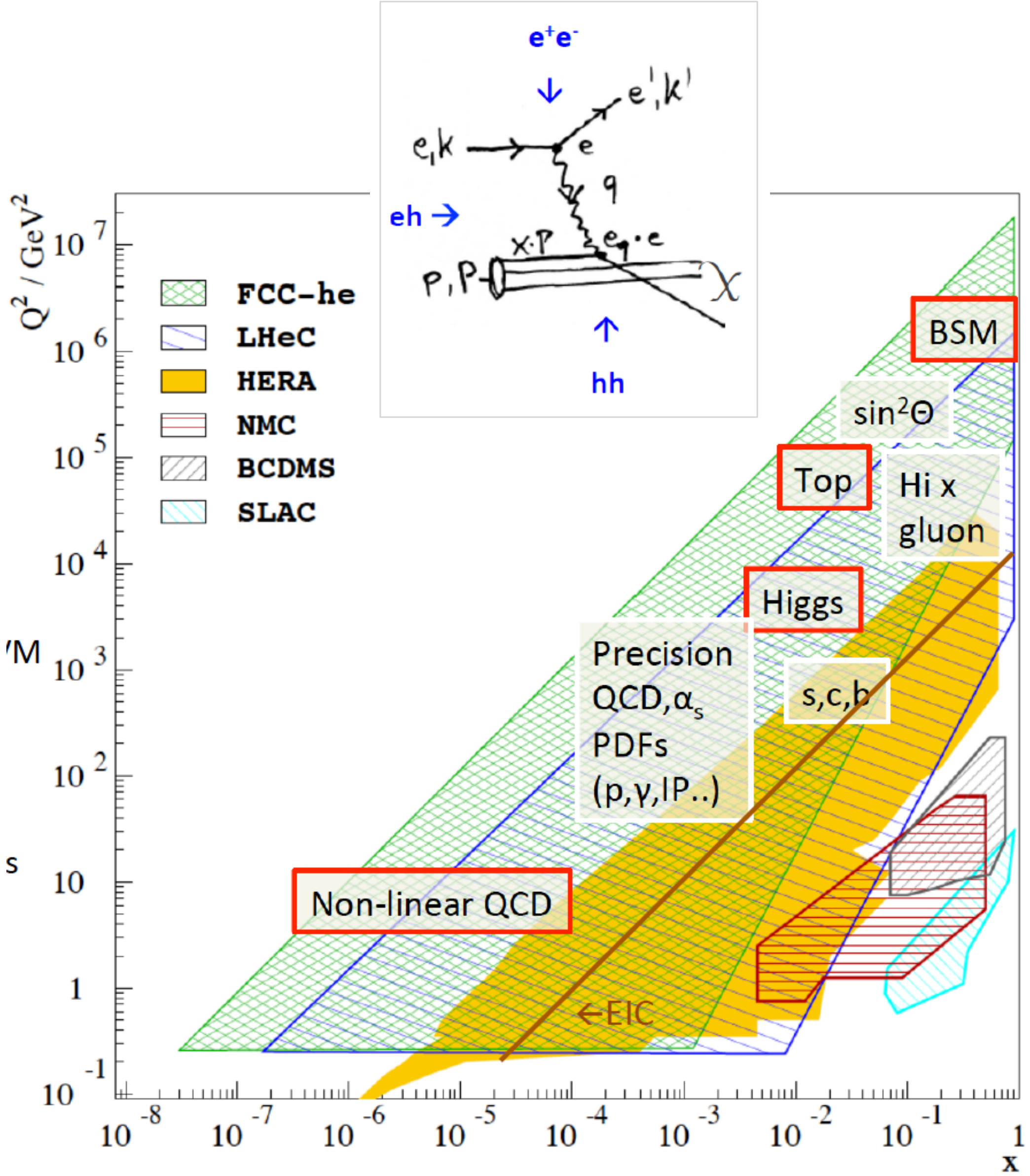
Service Caverns
- 25 m x 15 m x 50 m

Aim is to accumulate up to 3/ab in 10+ yrs of operations

Physics with Energy Frontier DIS

- e-p colliders can be seen as the cleanest High Resolution Microscope:
  - QCD Discovery
  - Study of EW / VBF production, LQ, multi-jet final states, forward objects
- Can empower the LHC Search Programme (e.g. PDF, EWK measurements)
- Can transform the LHC into high precision Higgs facility
- Can contribute to possible discoveries of BSM particles (prompt and long-lived)

Overall: **A Unique Particle Physics Facility**



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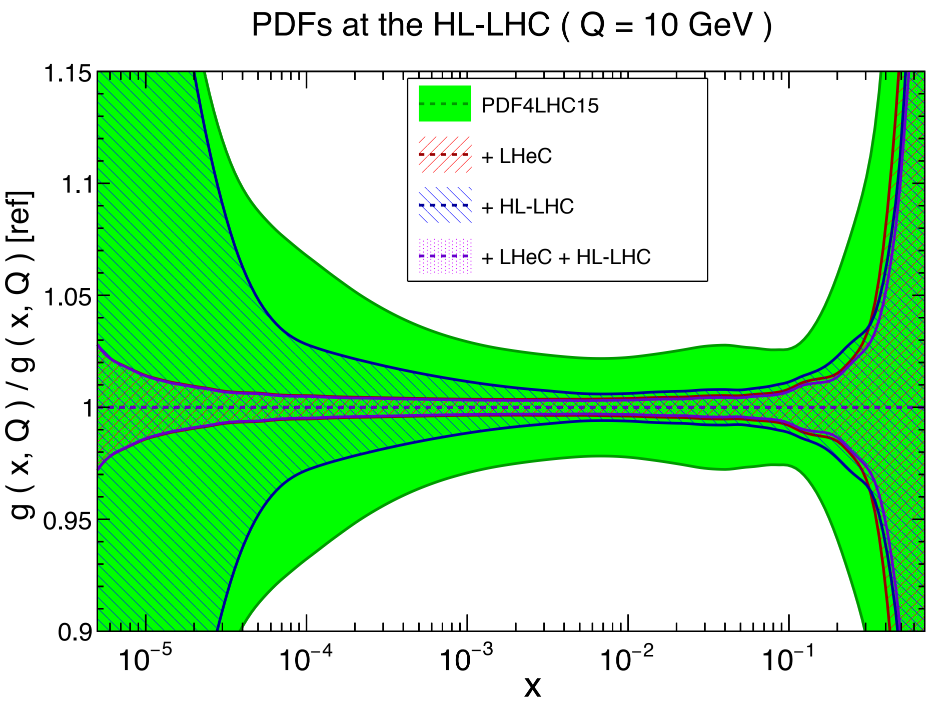
- Overall: **A Unique Nuclear Physics Facility**

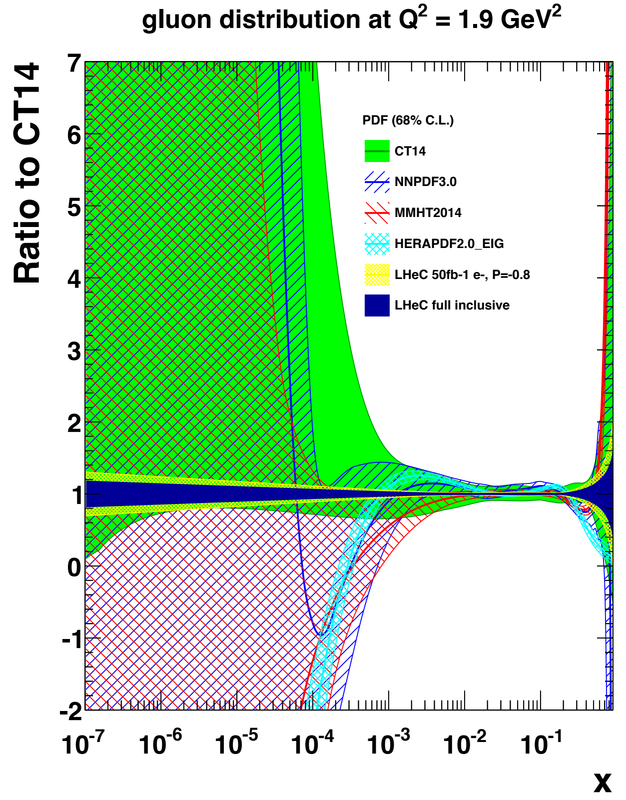
- PDF, physics at small x, alphaS
- Impact of LHeC on W mass and more
- Top measurements, FCNC
- Higgs physics
  - Higgs in bb and cc
  - LHeC and HL-LHC combinations
- BSM studies (some examples):
  - New scalars from Higgs, SUSY
  - Heavy neutrinos
  - Dark photons

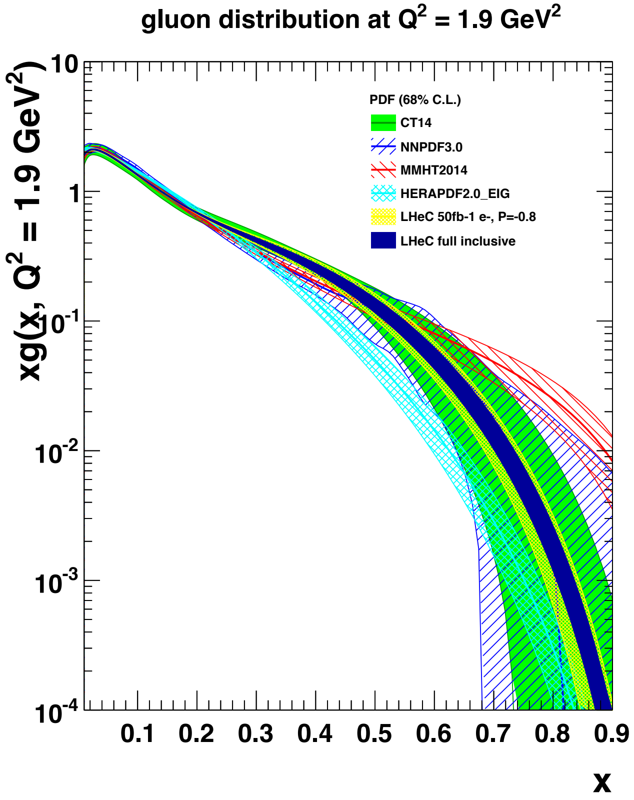
I will mostly discuss LHeC physics reach with some of the prospects for FCC-eh

Strong interactions: PDF

- Complete unfolding of parton contents in unprecedented kinematic range: **u,d,s,c,b,t, xg**







Crucial for HL-LHC:

high precision electro-weak, Higgs measurements (e.g. remove essential party of QCD uncertainties of gg→ H)

Extension of high mass search range

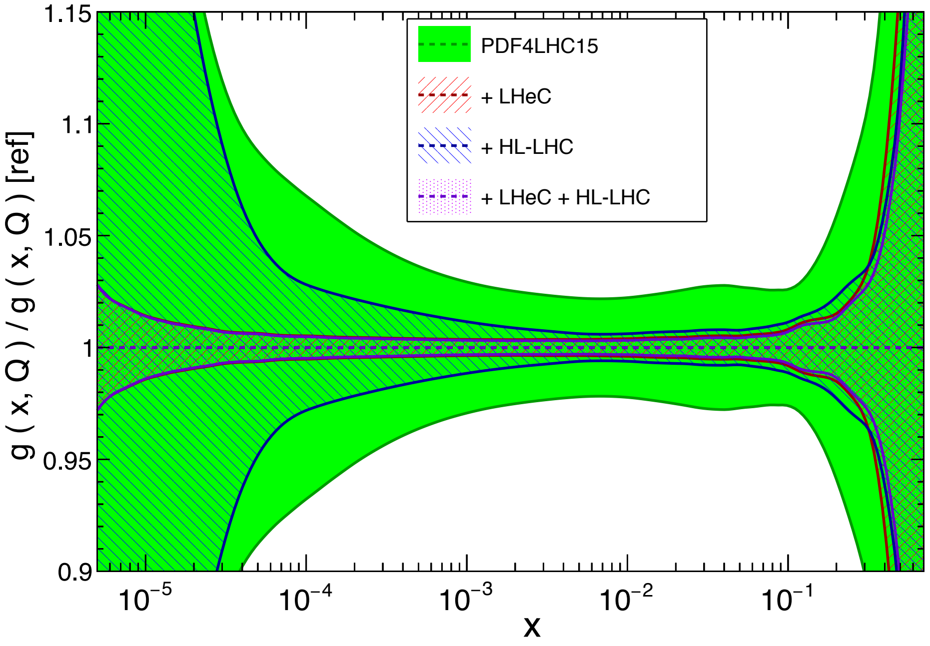
Non-linear low x parton evolution; saturation?

Range relevant for new heavy particles (e.g. gluinos in SUSY)

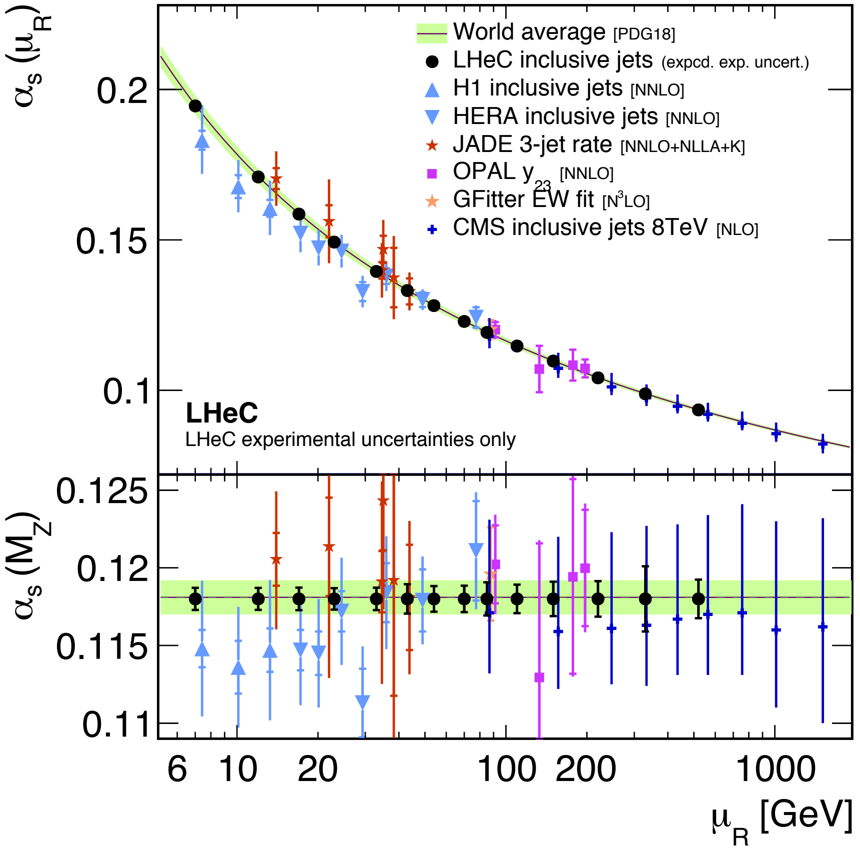
Strong interactions: PDF and alphaS

- Complete unfolding of parton contents in unprecedented kinematic range: **u,d,s,c,b,t, xg**

PDFs at the HL-LHC (Q = 10 GeV)



Strong coupling to permille accuracy (incl + jets):



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

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

Crucial for HL-LHC:

high precision electro-weak, Higgs measurements (e.g. remove essential party of QCD uncertainties of gg→ H)

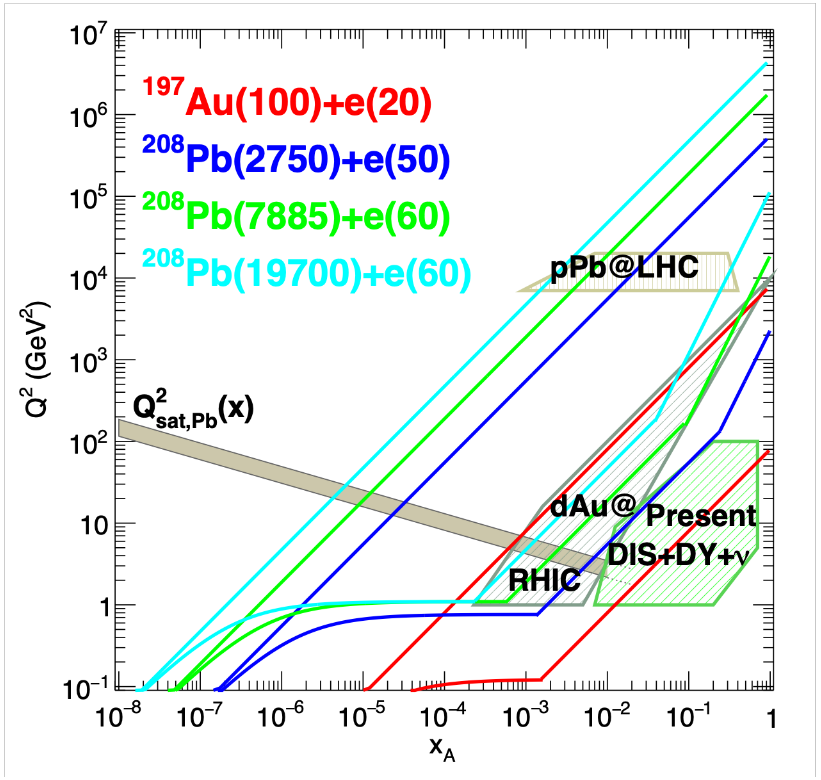
Extension of high mass search range

Non-linear low x parton evolution; saturation?

Strong interactions: eA and nuclear structure

- Extraction of **Pb-only** PDFs by fitting NC+CC pseudodata, using xFitter

parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-he
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2



Large improvements at all x

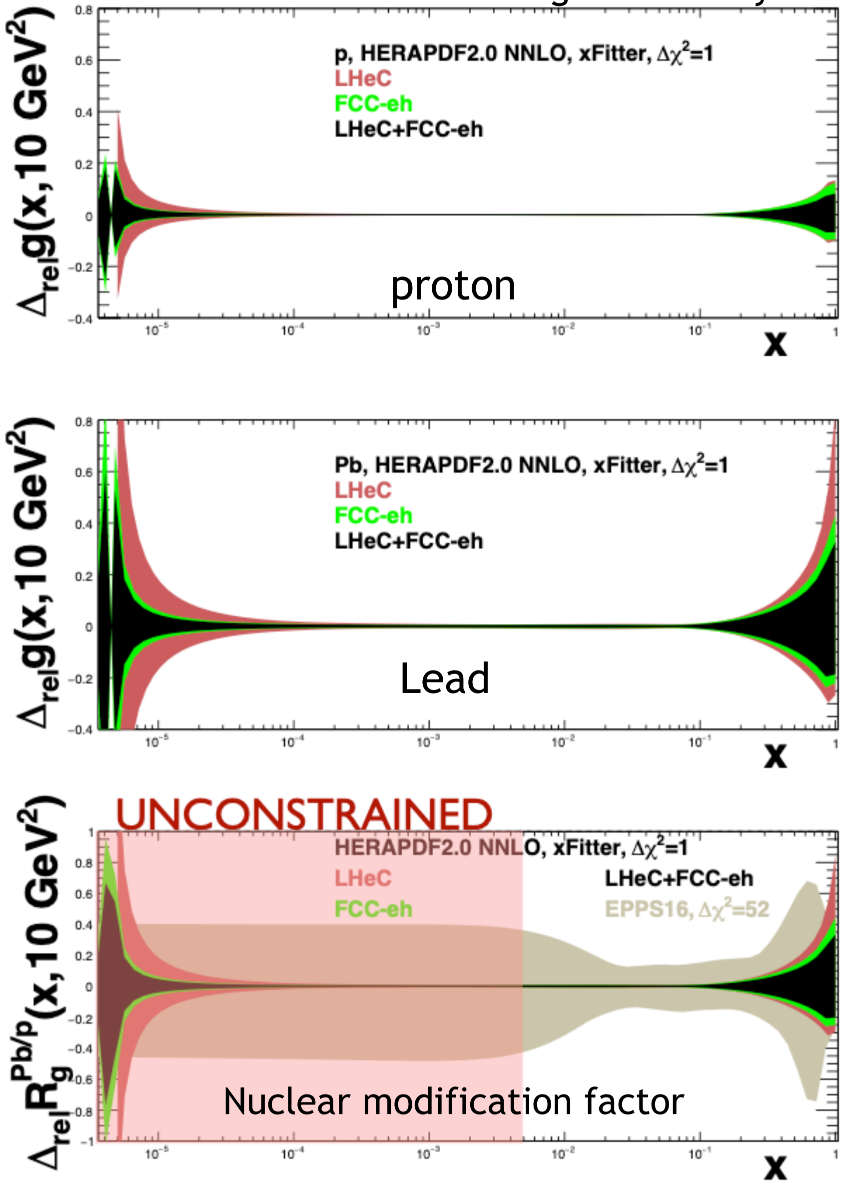
Fit to a single nucleus possible

Extension of fixed target range by $10^{3\text{-}4}$

de-confinement, saturation

nPDFs independent of p PDFs

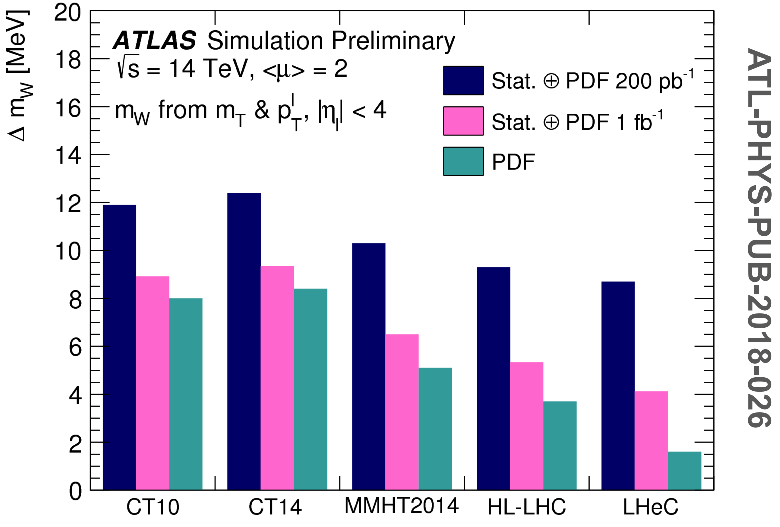
Relative uncertainties of gluon density



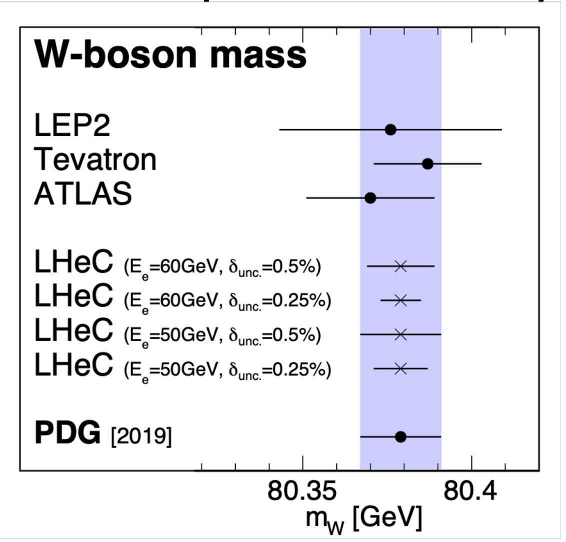
EWK measurements: W mass

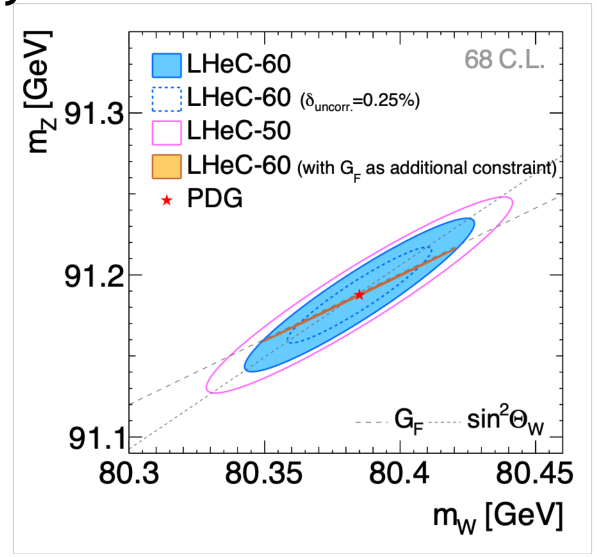
- **@ HL-LHC W mass** precision measurement uses dedicated dataset at low <mu>
  → exploit the extended leptonic coverage
  → LHeC will provide additional precision through PDF

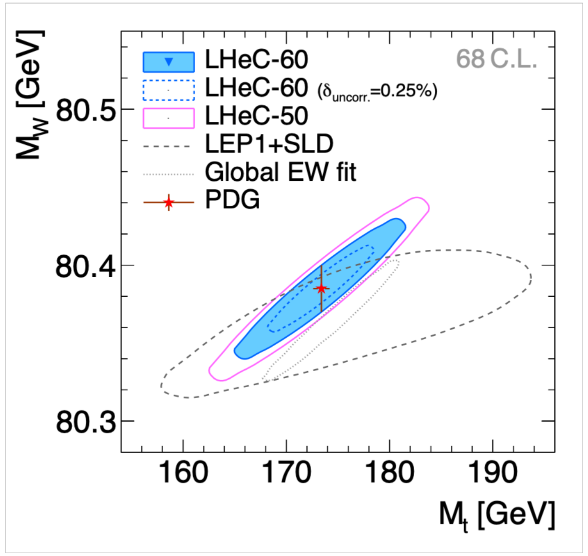
Δm_W = ±6 MeV (with reduced PDF unc from HL LHC)
Δm_W = ±2 MeV (with improved PDF from LHeC)



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







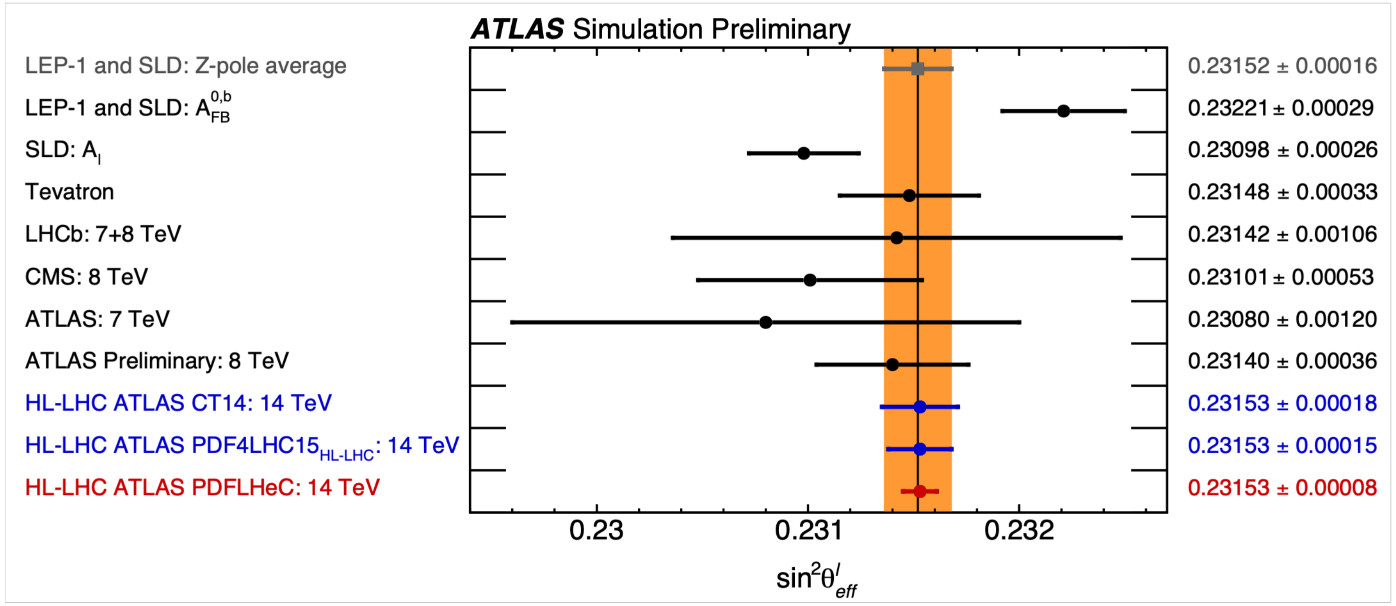
EWK measurements: $\sin^2\theta_{eff}$

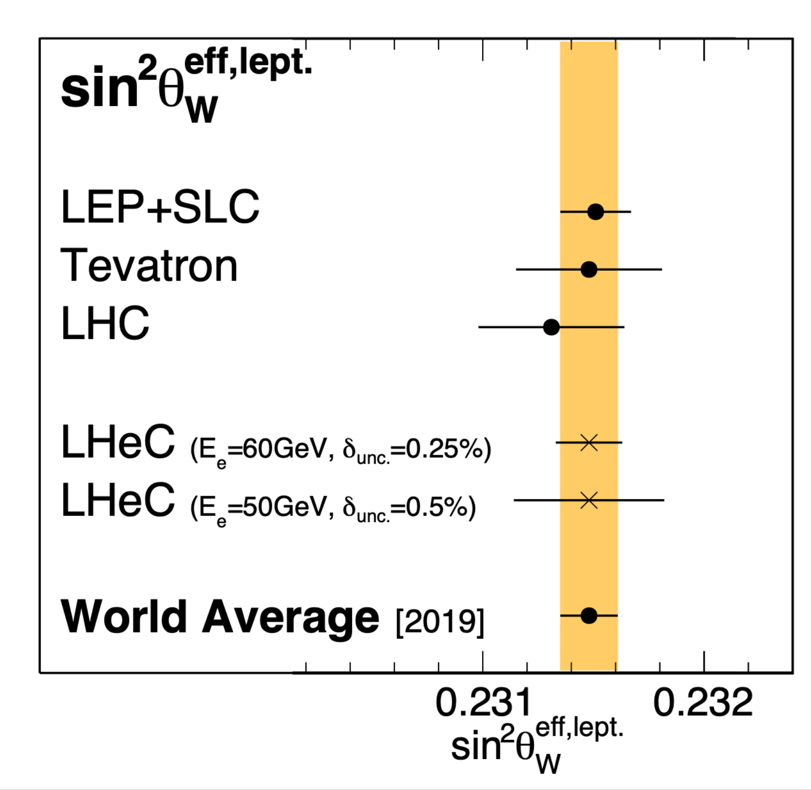
LHeC will contribute to $\sin^2\theta_{eff}$ precision measurements directly and indirectly

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

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

- 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

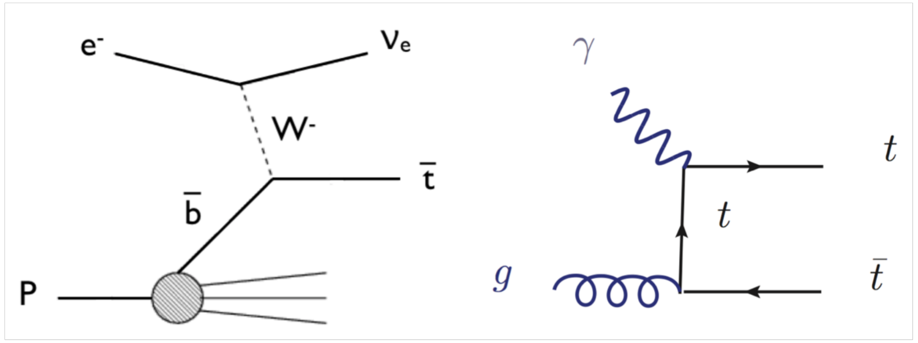




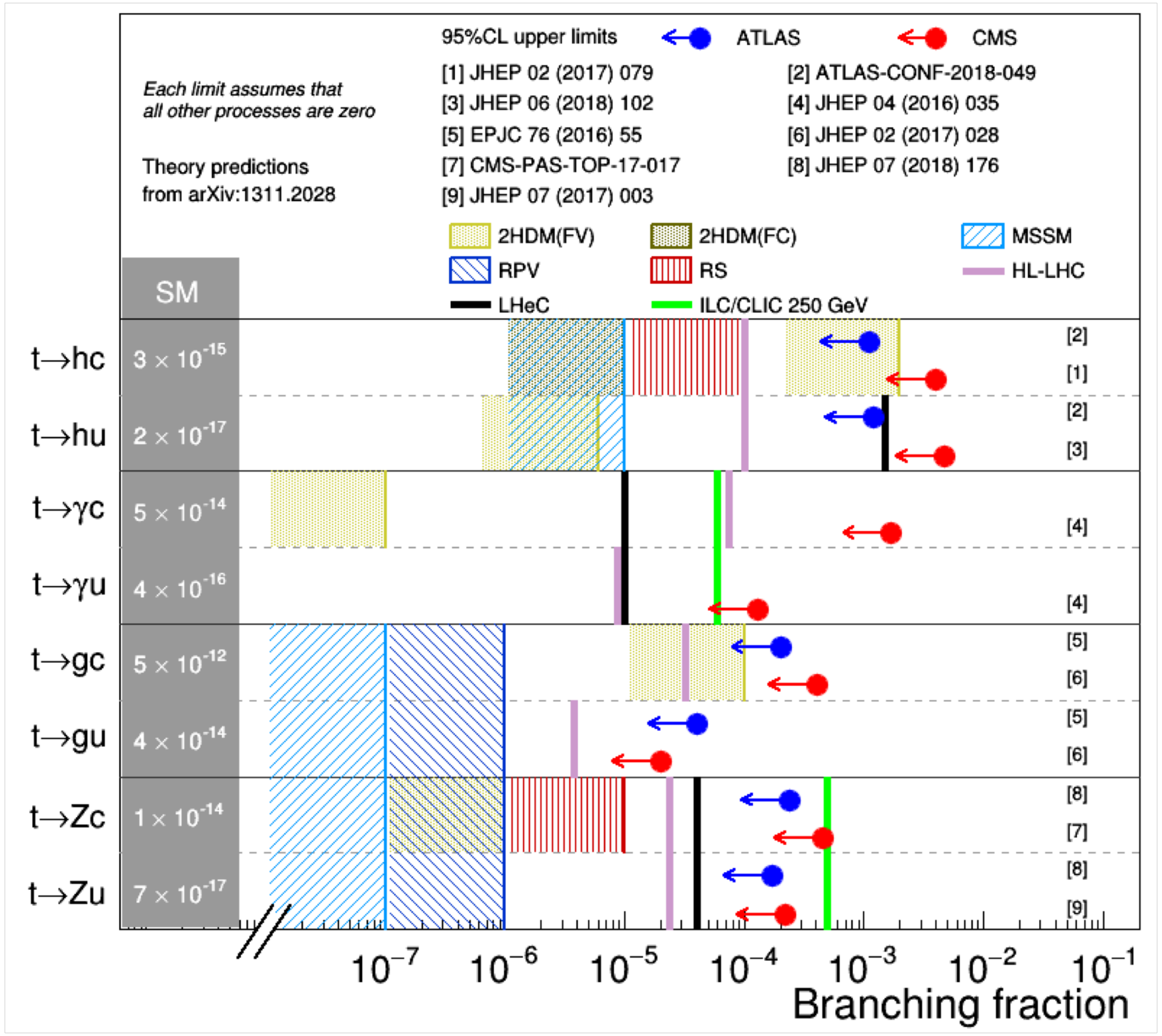
Precisions → $1 \cdot 10^{-5}$ if PDF uncertainties are improved with LHeC

Top physics: e.g. FCNC

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



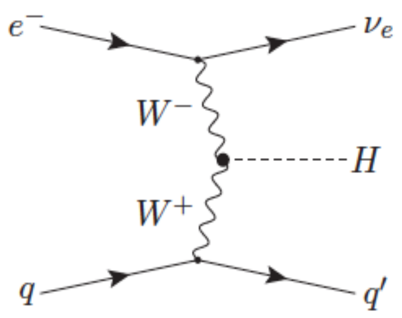
- Can do precision measurements and measurements of rare processes: FCNC
- Excellent complementarities with ee and pp colliders
  - Shown: HL-LHC and ILC 250 GeV



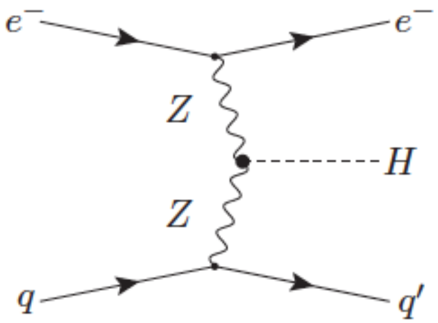
Higgs physics at ep

- Production of Higgs boson via Vector-Boson-Scattering

Charged Currents



Neutral Currents



N events here shown for FCC-eh
~ 1/5-10 less predicted for LHeC

A large dataset of Higgs events for precision measurements !

Total cross section (mH=125 GeV)

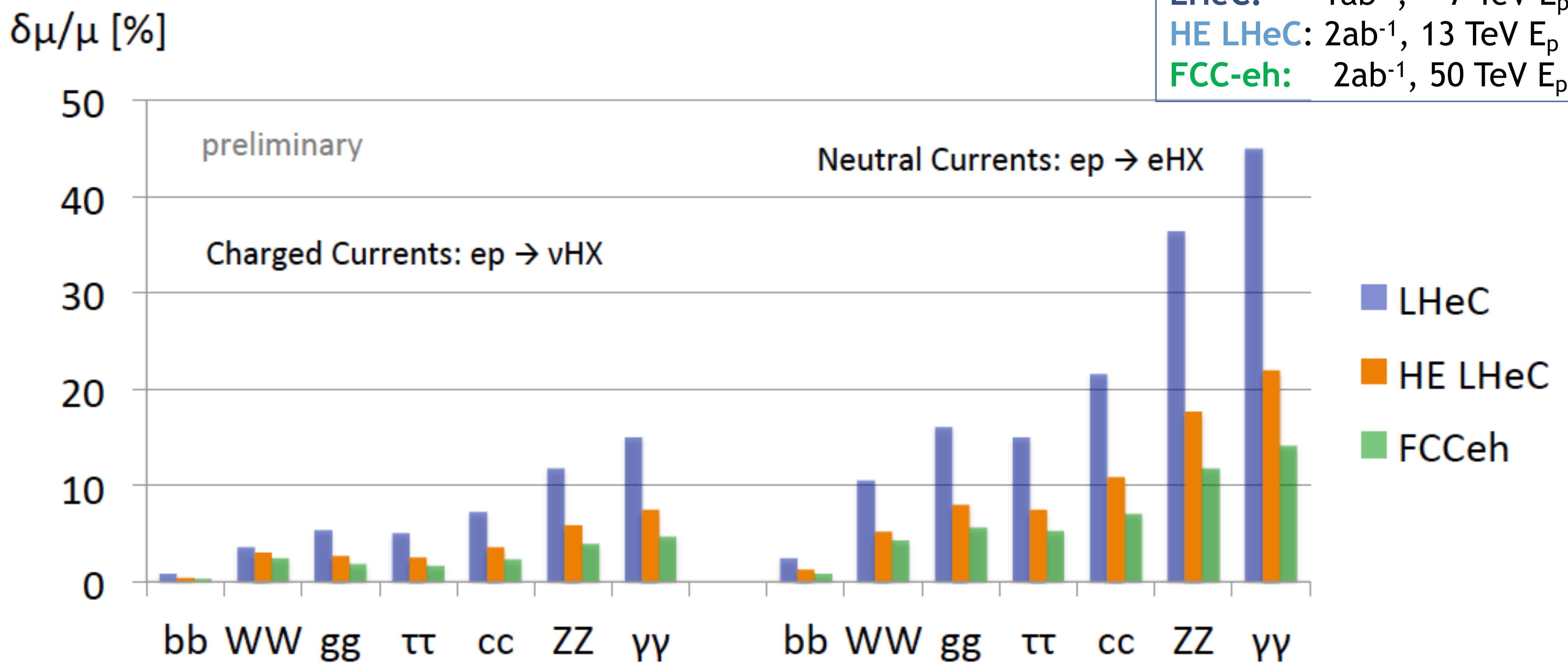
Parameter	Unit	LHeC	HE-LHeC	FCC-eh	FCC-eh
E_p	TeV	7	13.5	20	50
$\sqrt{s}$	TeV	1.30	1.77	2.2	3.46
σ_{CC} $(P=-0.8)$	fb	197	372	516	1038
σ_{NC} $(P=-0.8)$	fb	24	48	70	149
σ_{CC} $(P=0)$	fb	110	206	289	577
σ_{NC} $(P=0)$	fb	20	41	64	127
HH in CC	fb	0.02	0.07	0.13	0.46

Channel	Fraction	No. of events at FCC-eh	
		Charged Current	Neutral Current
$b\bar{b}$	0.581	1 208 000	175 000
W^+W^-	0.215	447 000	64 000
gg	0.082	171 000	25 000
$\tau^+\tau^-$	0.063	131 000	20 000
$c\bar{c}$	0.029	60 000	9 000
ZZ	0.026	54 000	7 900
$\gamma\gamma$	0.0023	5 000	700
$Z\gamma$	0.0015	3 000	450
$\mu^+\mu^-$	0.0002	400	70
σ [pb]		1.04	0.15

Prospects for Higgs in ep

- Prospects for signal strength measurements of Higgs decays

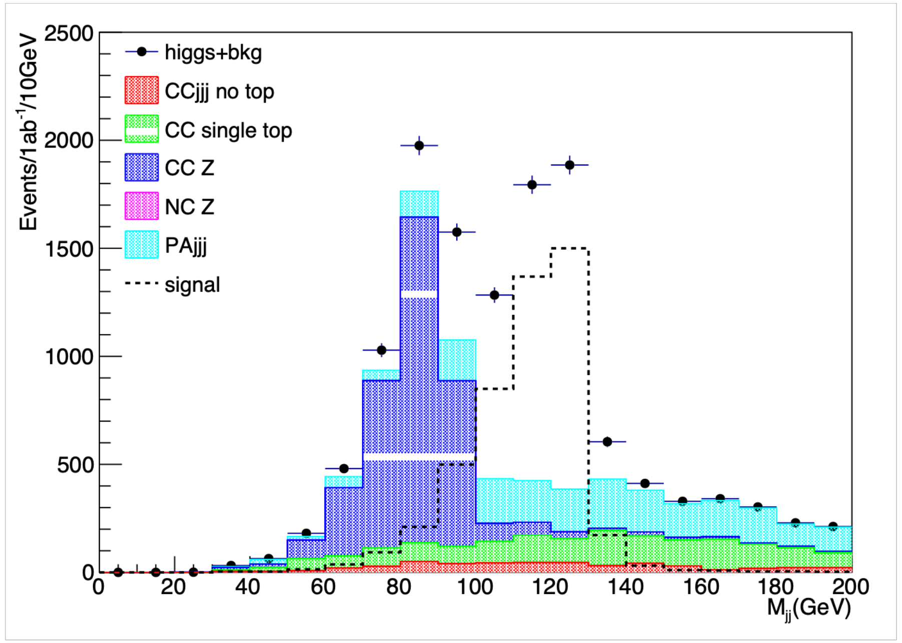
LHeC:	$1ab^{-1}$,	7 TeV E_p
HE LHeC:	$2ab^{-1}$,	13 TeV E_p
FCC-eh:	$2ab^{-1}$,	50 TeV E_p



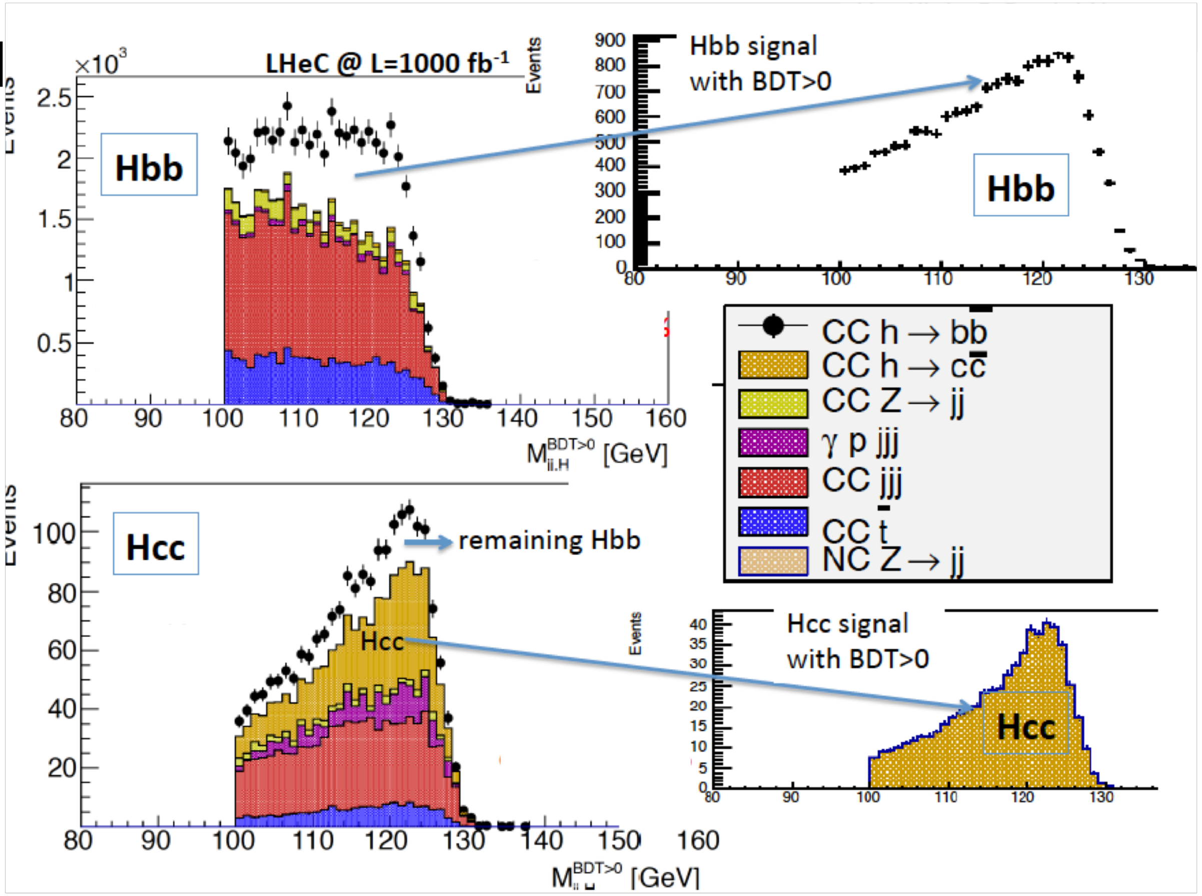
Higgs to bbar and ccbar

- 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

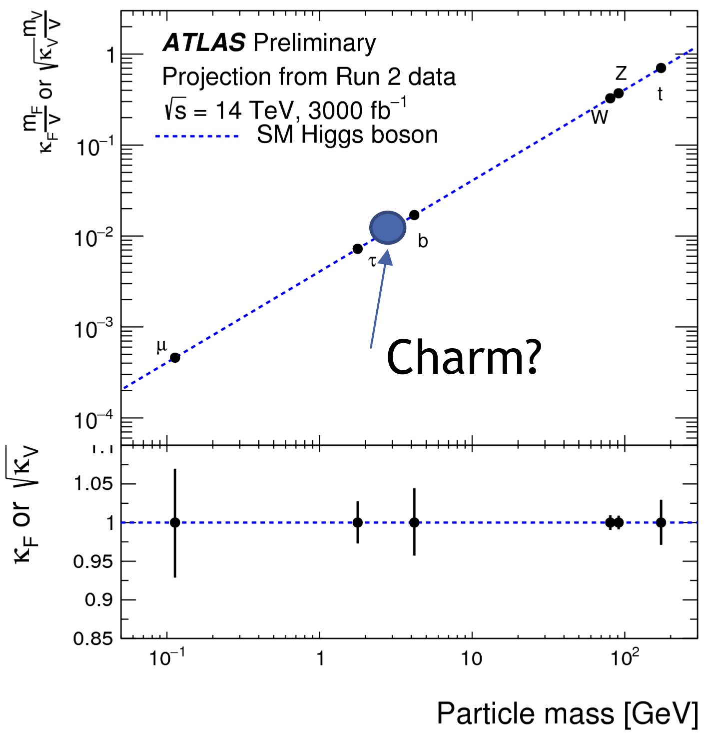


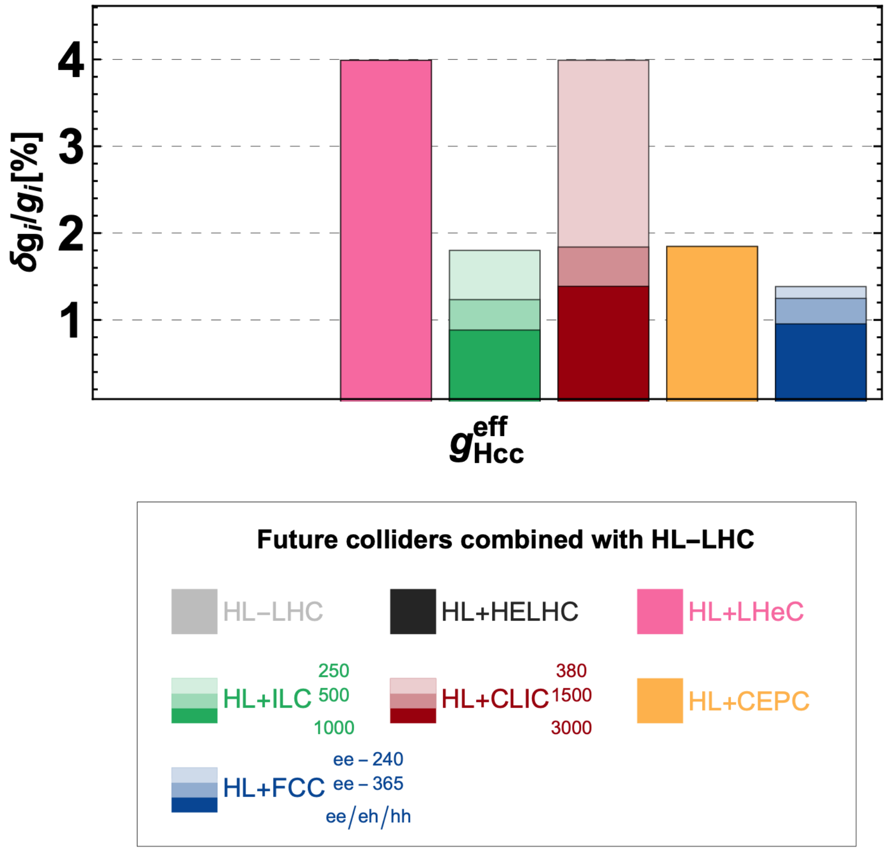
Signal strength μ constraints to 0.8% (bb) and 7.4% (cc)



Higgs physics eh and hh

- At the end of HL-LHC, rate measurements will reach **percent level precision for most couplings - no real sensitivity expected for charm couplings**





Source: Briefing book ES

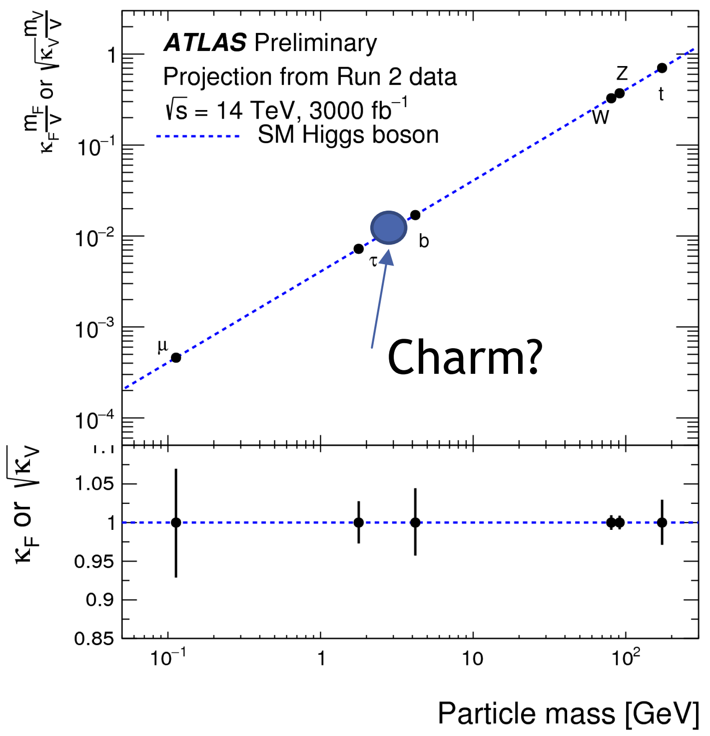
Results of a fit corresponding on the Effective Field Theory benchmark, expressed in terms of effective couplings

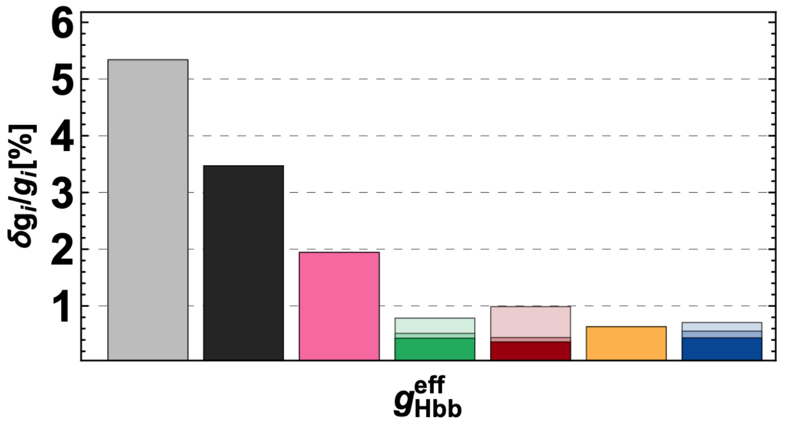
Hcc not estimated for HL-LHC

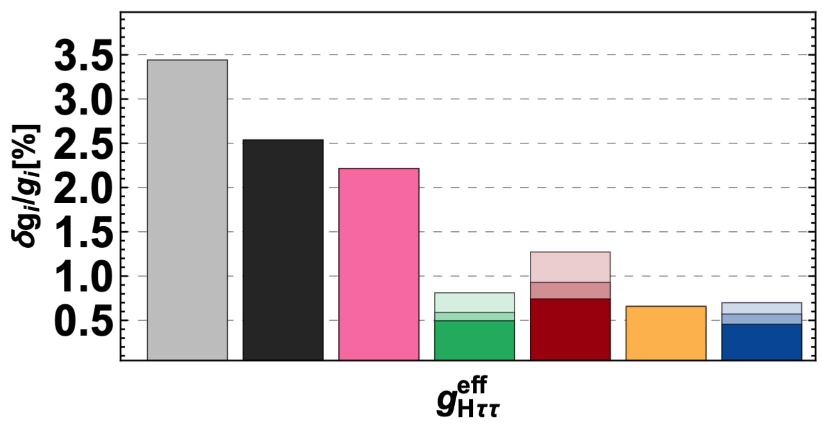
HL-LHC+LHeC and HL+FCC ee/eh/hh (dominated by eh) will be as effective as e+e- colliders

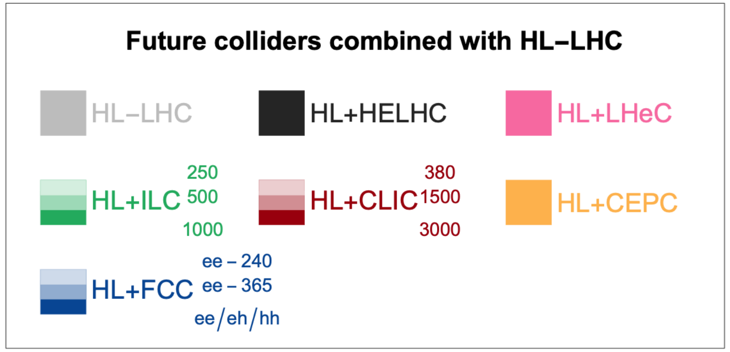
Higgs physics at eh and hh

- At the end of HL-LHC, rate measurements will reach **percent level precision for most couplings - no real sensitivity expected for charm couplings → LHeC!**







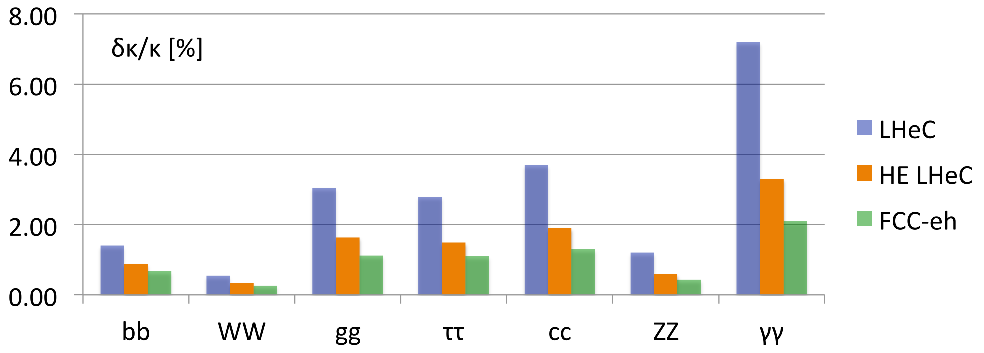


Significant improvements from LHeC also for Hbb and Hττ → better than HL+HE

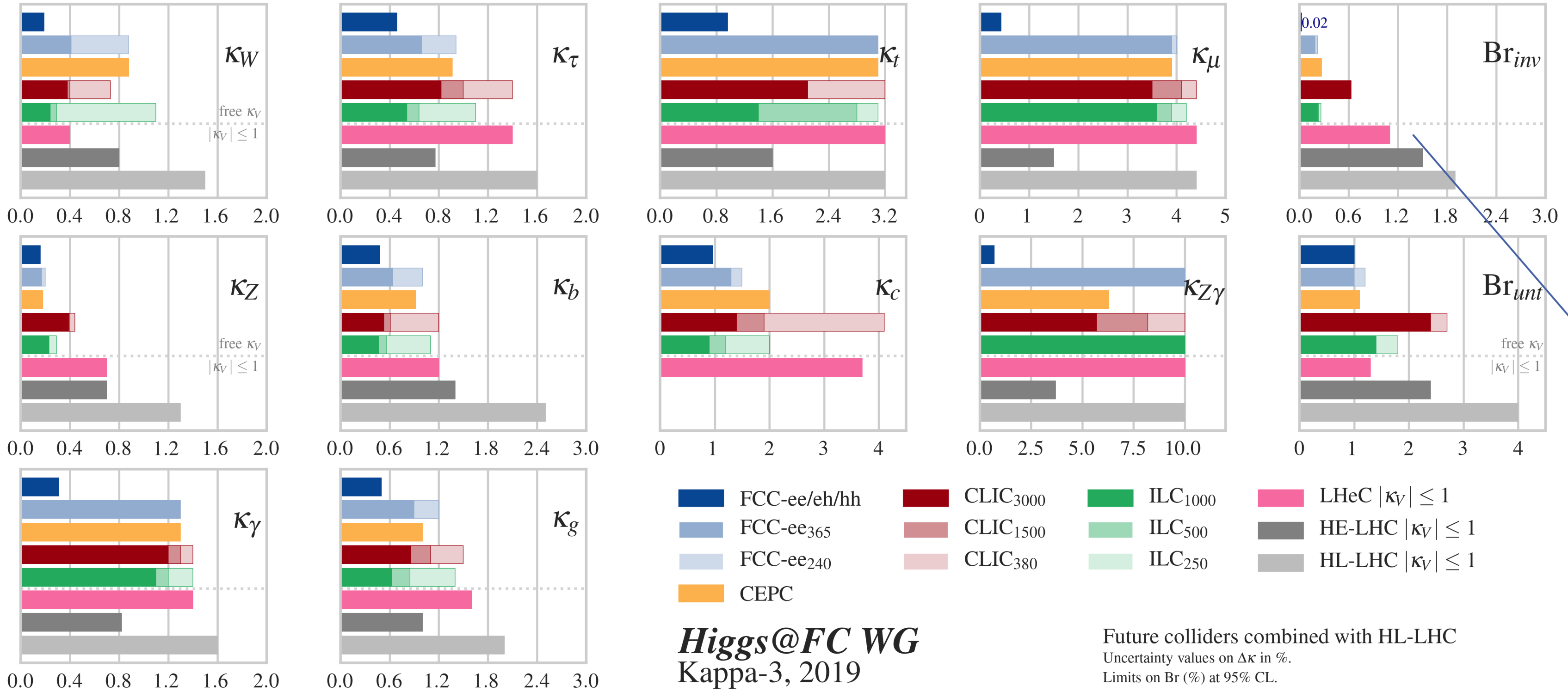
H to WW to be better investigated at LHeC

Kappa factor framework

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



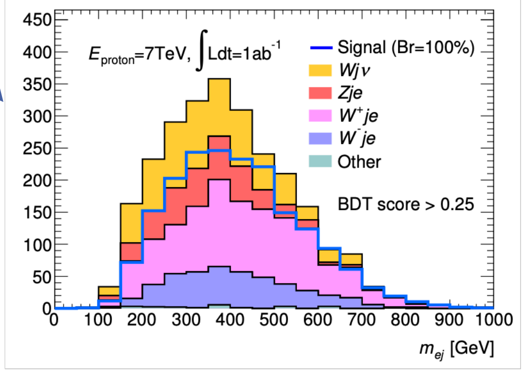
From the briefing book: uncertainties on κ_i



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

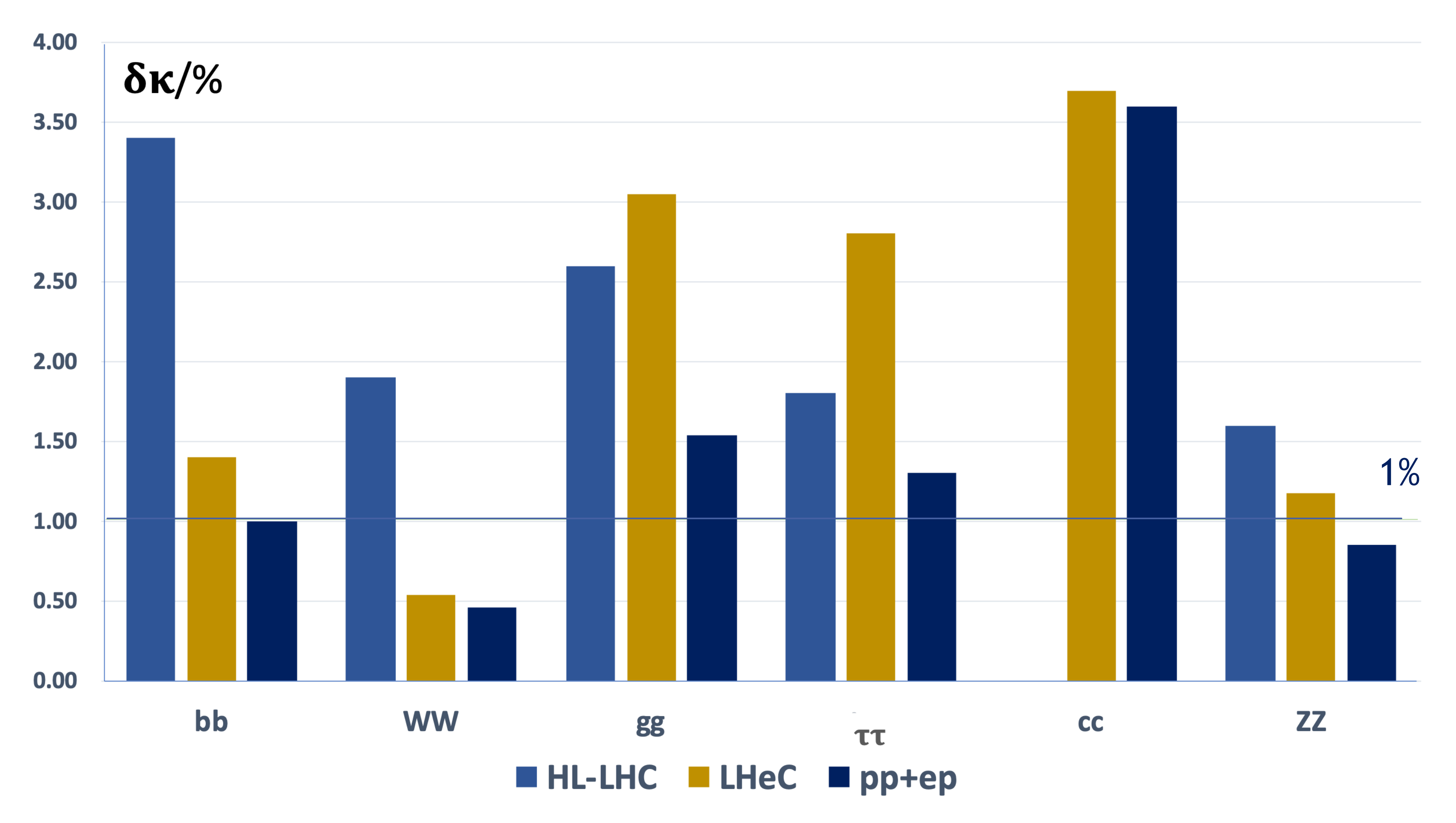
$\mathrm{Br}(h \rightarrow \mathrm{invisible}) = 6\,\%$ at 2σ level

Electron-jet invariant mass



Combinations of LHeC + HL-LHC

Determination of SM Higgs couplings jointly from pp + ep



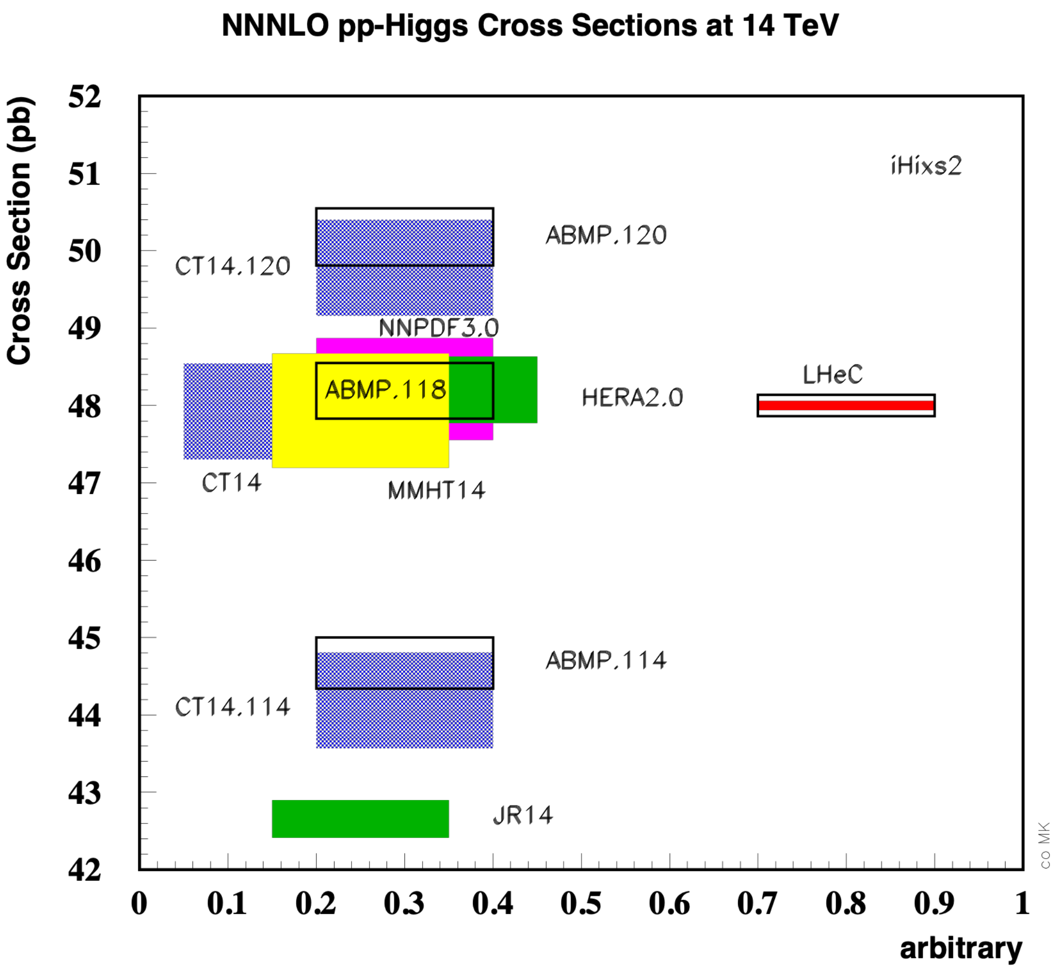
The combined ep+pp at LHC reaches below 1% for dominant channels
ep adds charm.

Analysis in EFT framework work in progress

Indirect impact of LHeC on pp: Higgs cross section

- Calculation of all production modes improved by PDF
- Even clearer for pp→HX recently calculated at N^{3}LO in pQCD

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 calculated to N$_3$LO using the iHix program for existing PDF parameterisation sets (left side) and for the LHeC PDFs (right side)

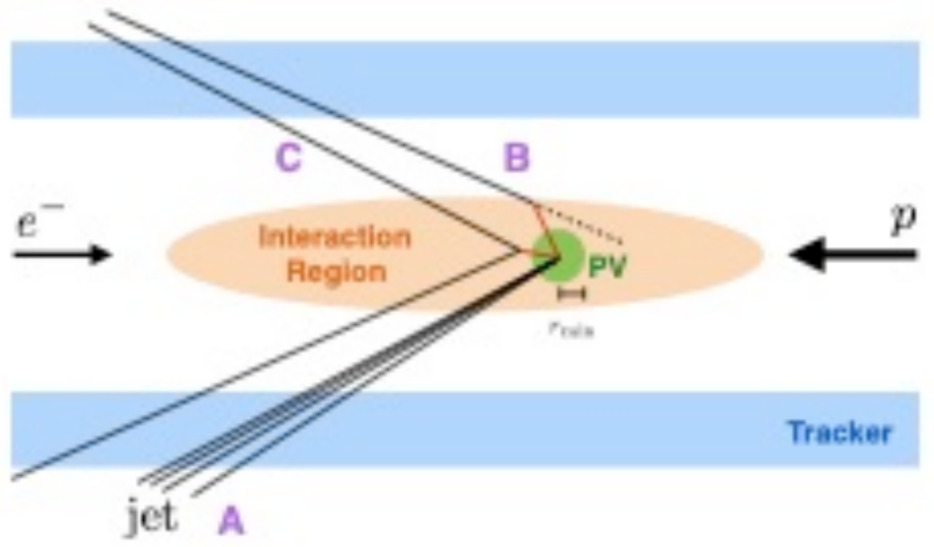
Searches for new physics

- ep collider is ideal to study common features of electrons and quarks with
  - EW / VBF production, LQ, forward objects, long-lived particles
- BSM programme at e-p aims to
  - Explore new and/or challenging scenarios
  - Characterize hints for new physics if some excess or deviations from the SM are found at pp colliders
- Differences and complementarities with *pp* colliders
  - Some promising aspects:
    - → small background due to absence of QCD interaction between *e* and *p*
    - → very low pileup
  - Some difficult aspects:
    - → low production rate for NP processes due to small s

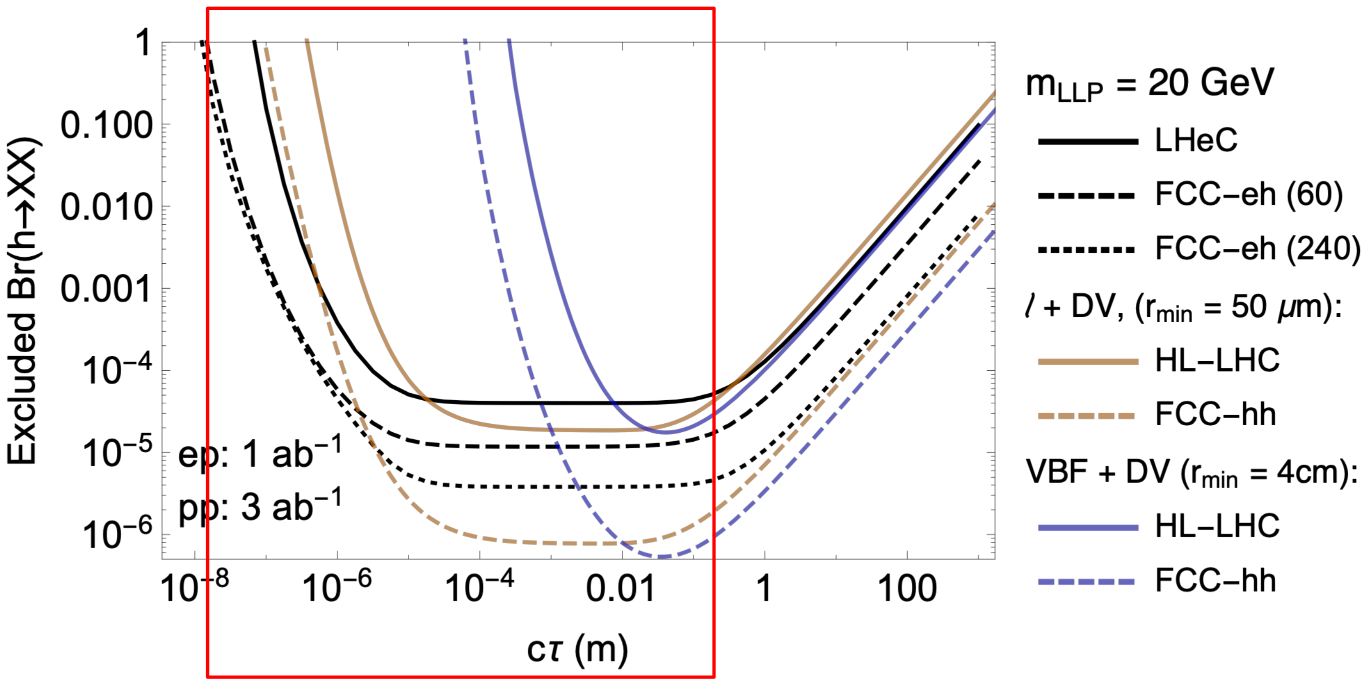
Only a few specific examples given here

Exotics higgs decays in LLP

- New exotics scalars (X) could arise from Higgs decay
- If long-lived, scalars could leave a very interesting displaced signature
  - X decays to at least two charged particles with energies above p_T detection threshold to uniquely identify a DV for the LLP decay.
- 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



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

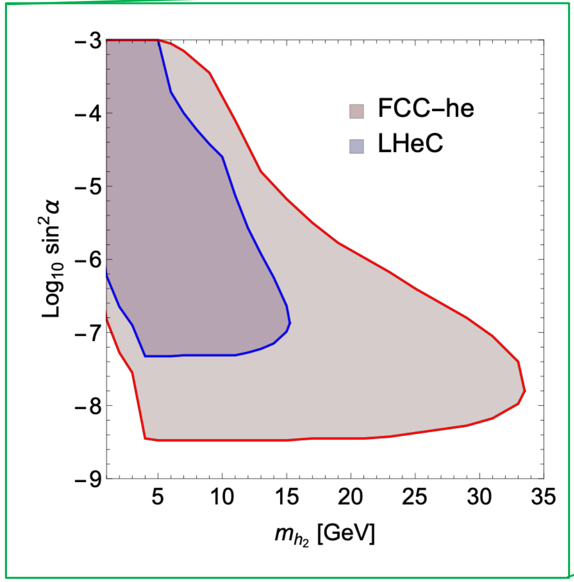


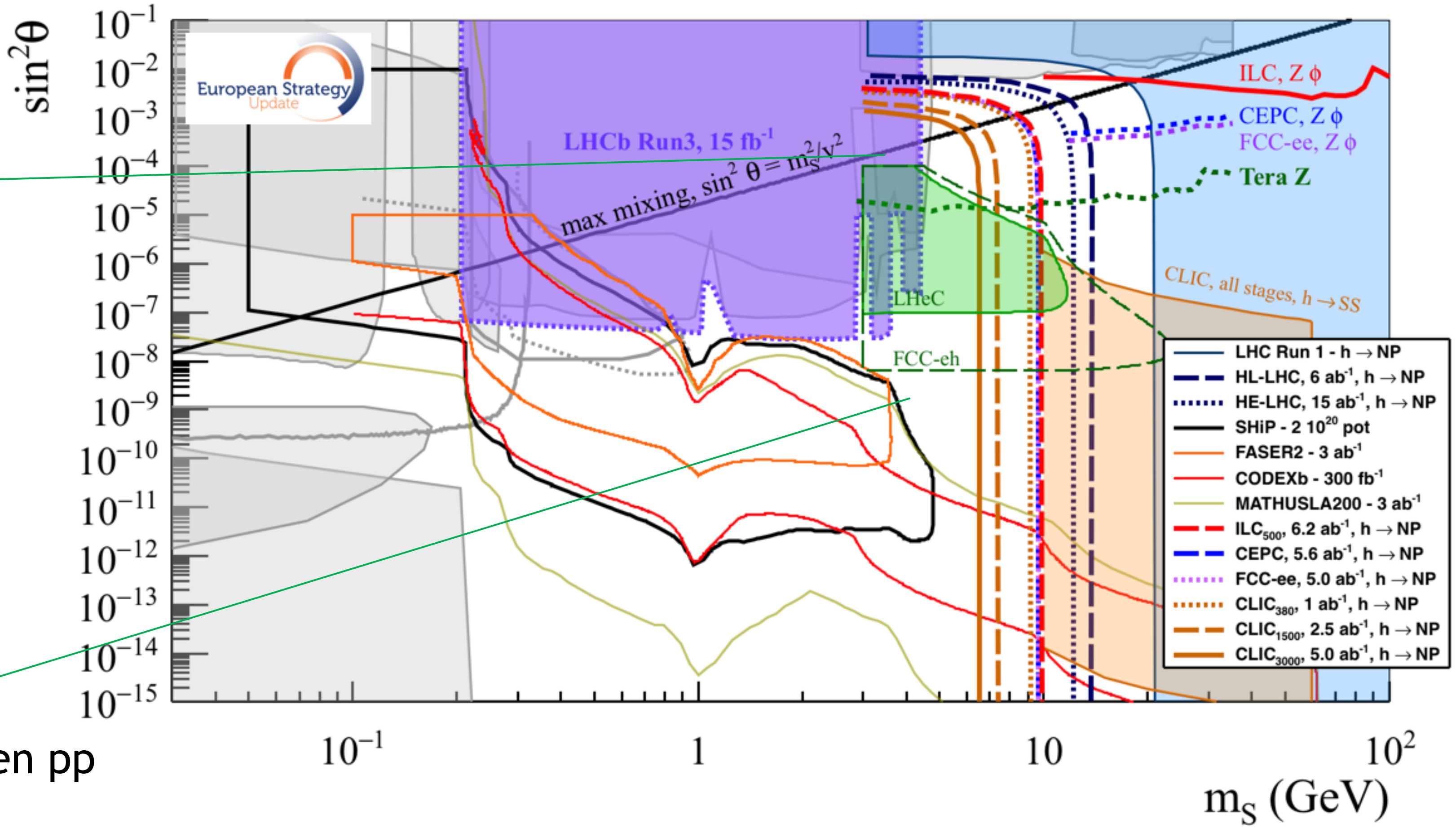
Large improvements wrt HL-LHC

Complementarity of e-p for 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.

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

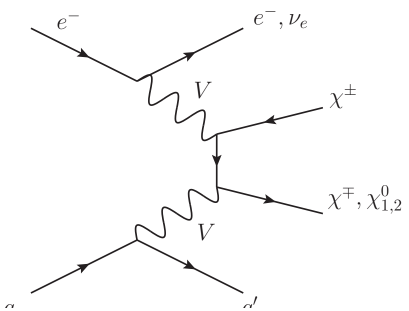


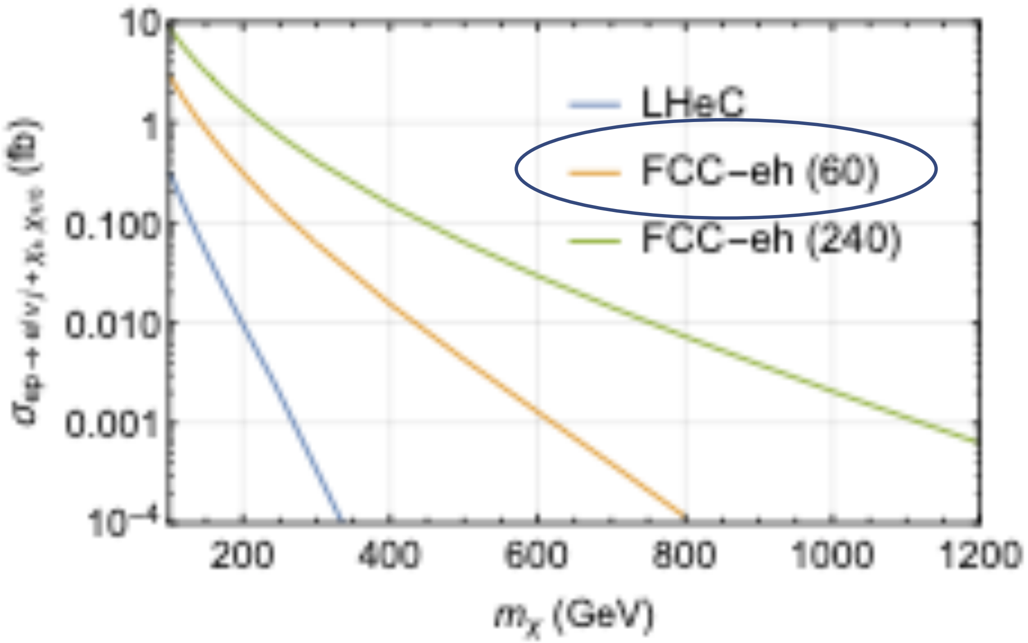


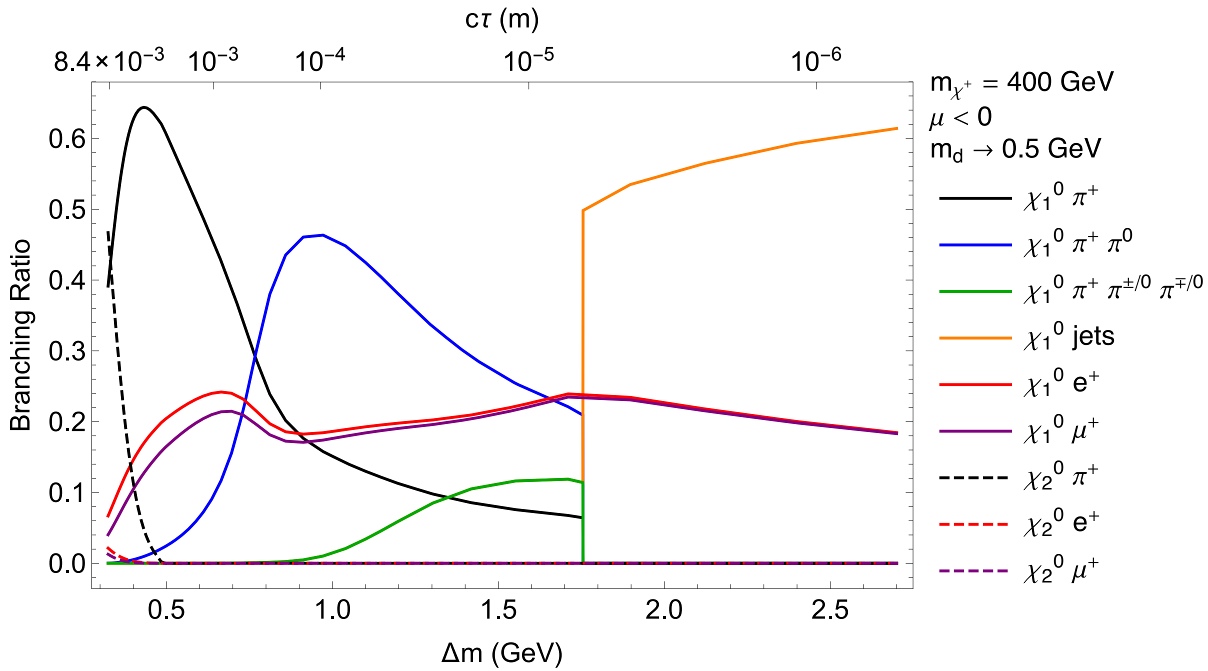
Covering important regions between pp and ee / low-energy experiments

Higgsino production in disappearing tracks

- https://arxiv.org/abs/1712.07135





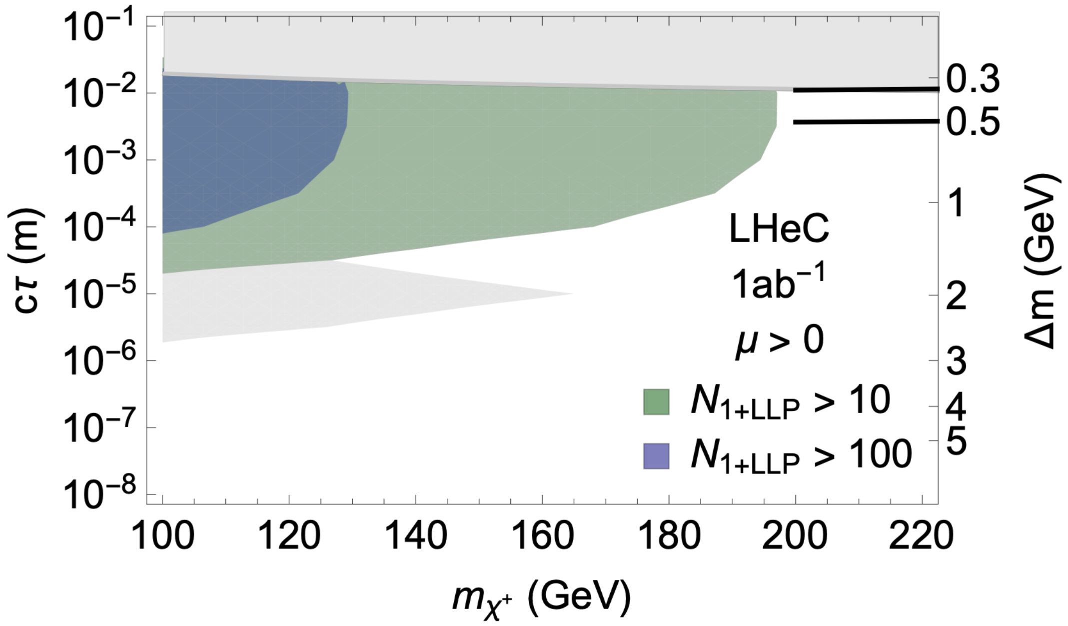


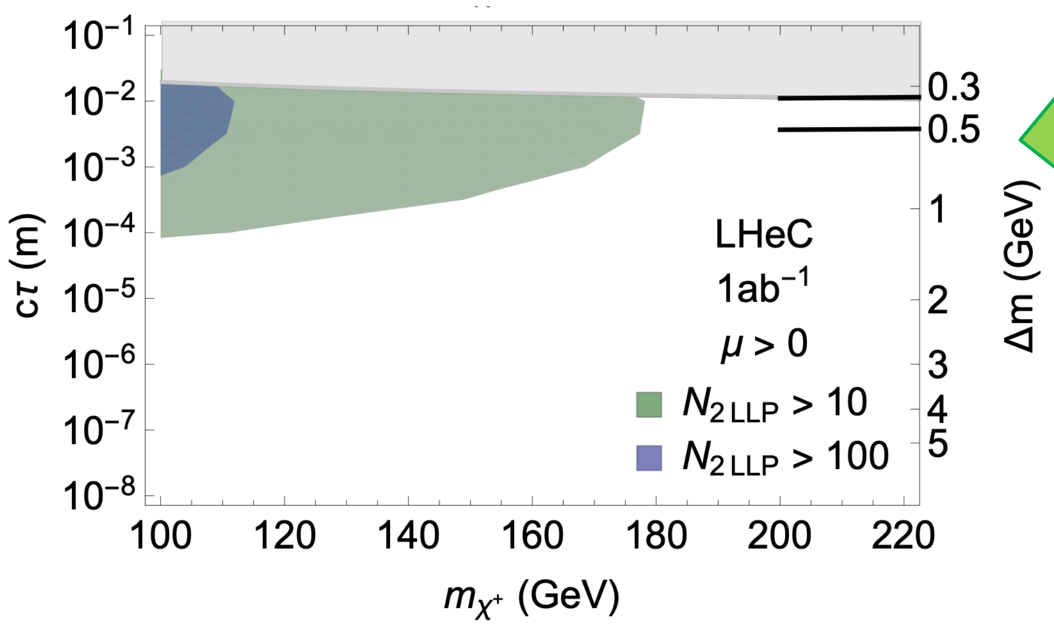
Minimal mass splitting is given by $\Delta_{1\text{-loop}}$ and larger mass splittings are possible when the MSSM M_1 is closer to μ,

Higgsino cross sections lower than wino ones

Results for disappearing track analysis

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

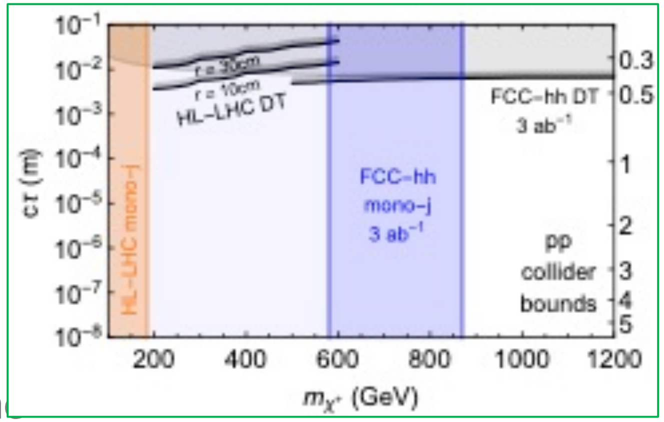




green region: 2σ sensitivity estimate in the presence of τ backgrounds

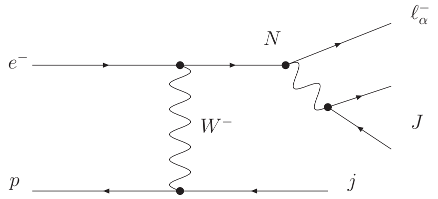
black curves: projected bounds from disappearing track searches for HL-LHC (optimistic and pessimistic)

Sensitive to very short lifetimes exceeds that of hh colliders

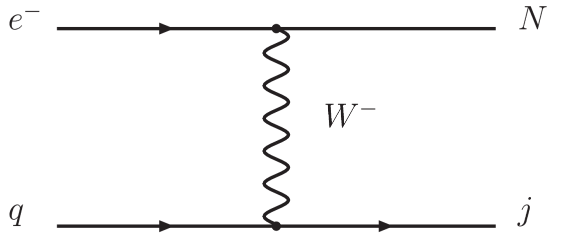


Sterile neutrinos

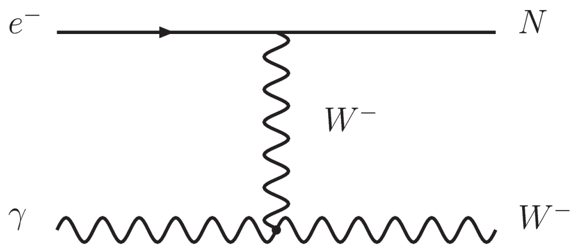
- In general weakly produced and/or non-promptly decaying particles very challenging at pp and ee colliders → good complementarity with e-p colliders
- Similarly to the case of the Higgs exotics decays, sterile neutrinos



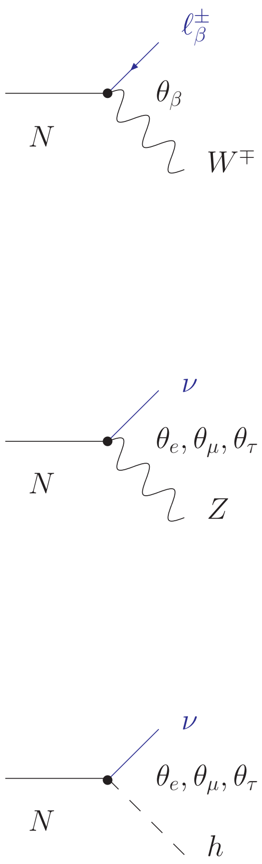
active-sterile neutrino mixing with the electron flavour → $|\theta_e|^2$



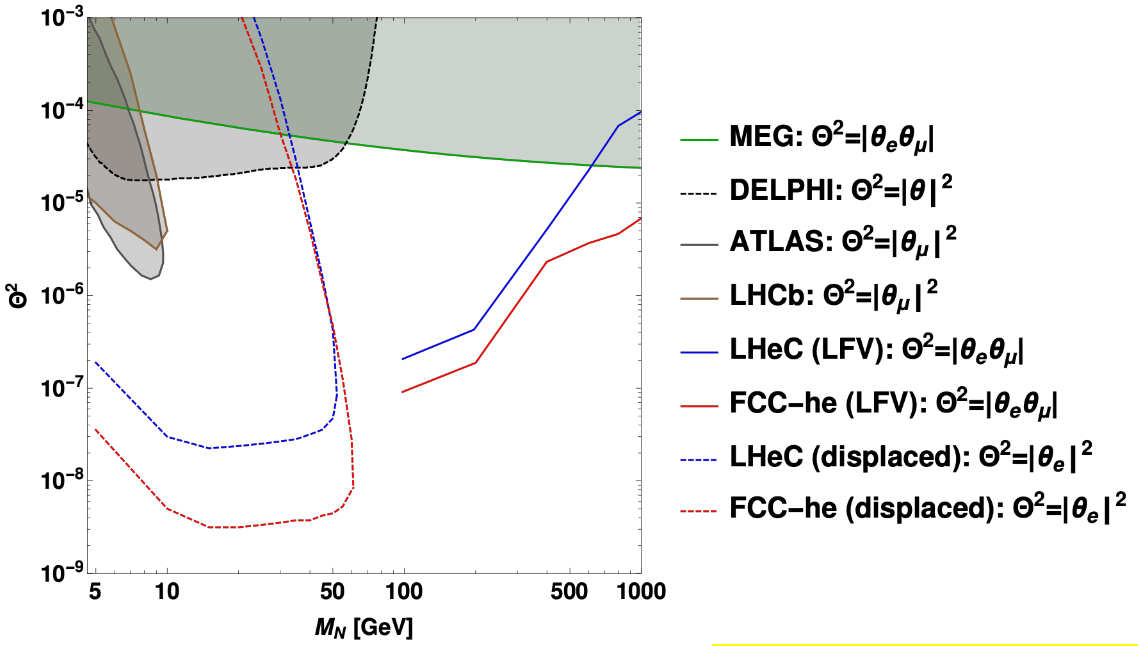
production channel: $\mathbf{W_t}^{(q)}$



production channel: $\mathbf{W_t}^{(\gamma)}$



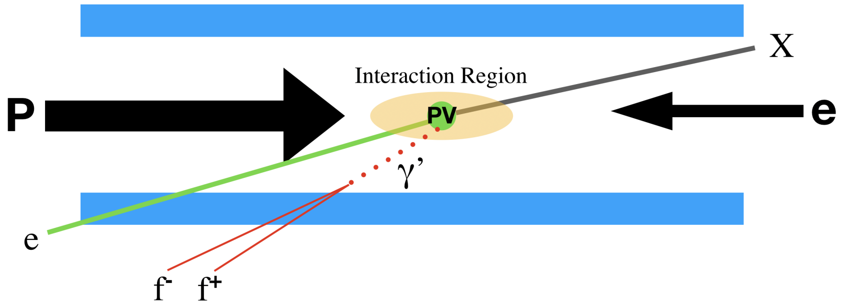
Sensitivity of the LFV lepton-trijet searches (at 95 % C.L.) and DV one

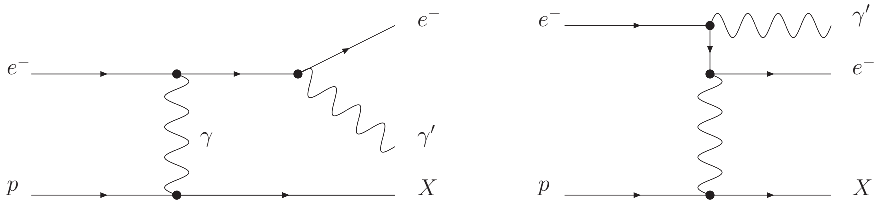


Different analyses depending on m(N) and m(W) relations

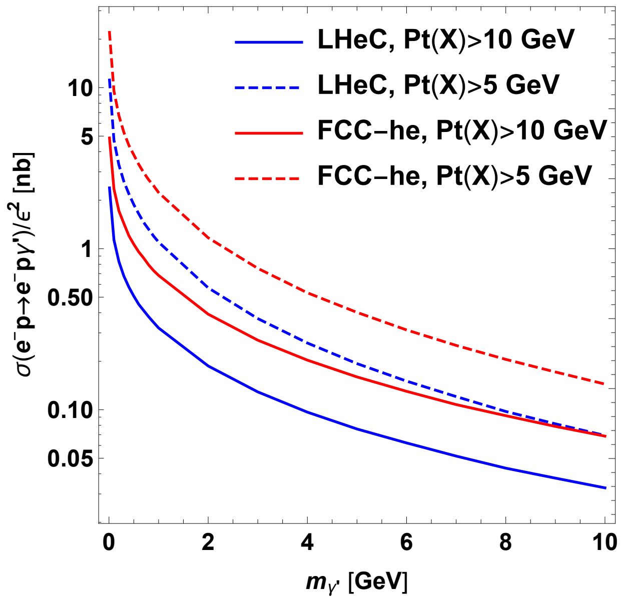
Dark photons

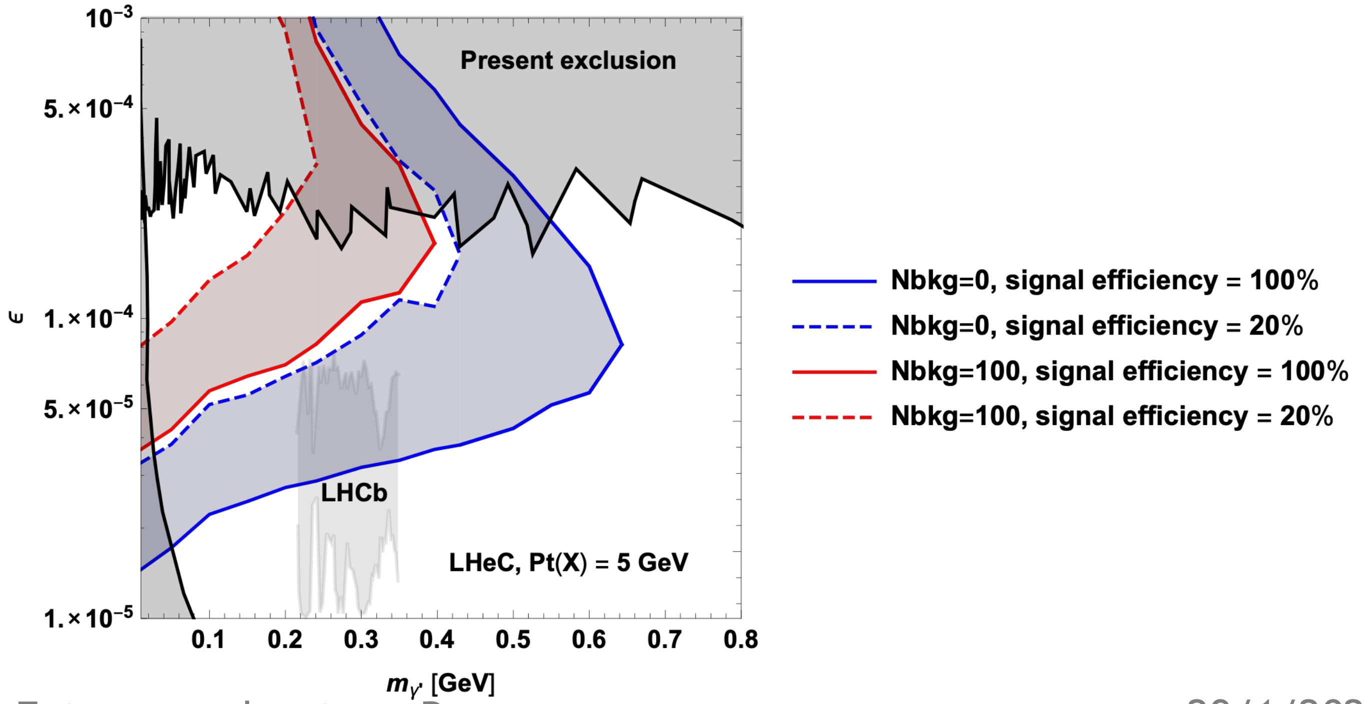
- additional gauge boson that naturally mixes with the U(1)Y factor of the SM kinetically
- have masses around the GeV scale and their interactions are QED-like, scaled with the small mixing parameter ε.





decay to pairs of leptons, hadrons, or quarks, which can give rise to a displaced vertex

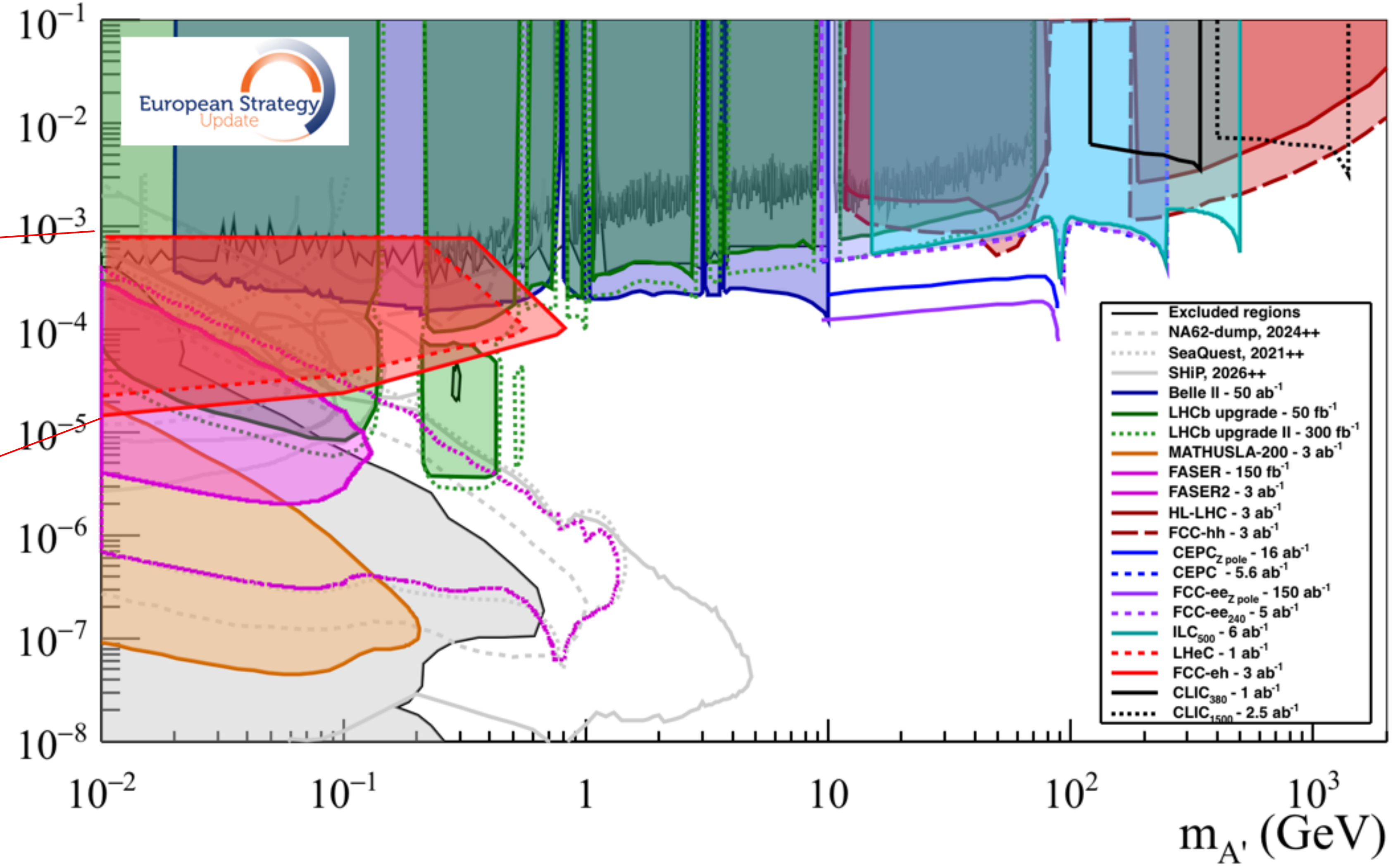




Complementarity of e-p for dark photons

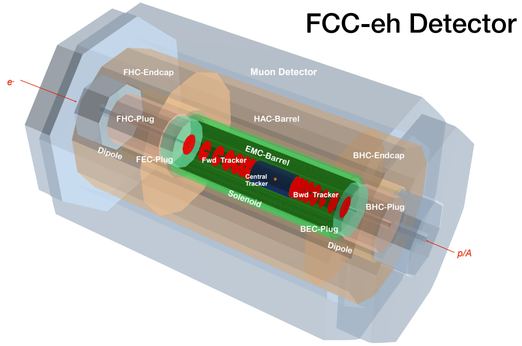
- Preliminary contours under assumptions considered for the European Strategy:

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



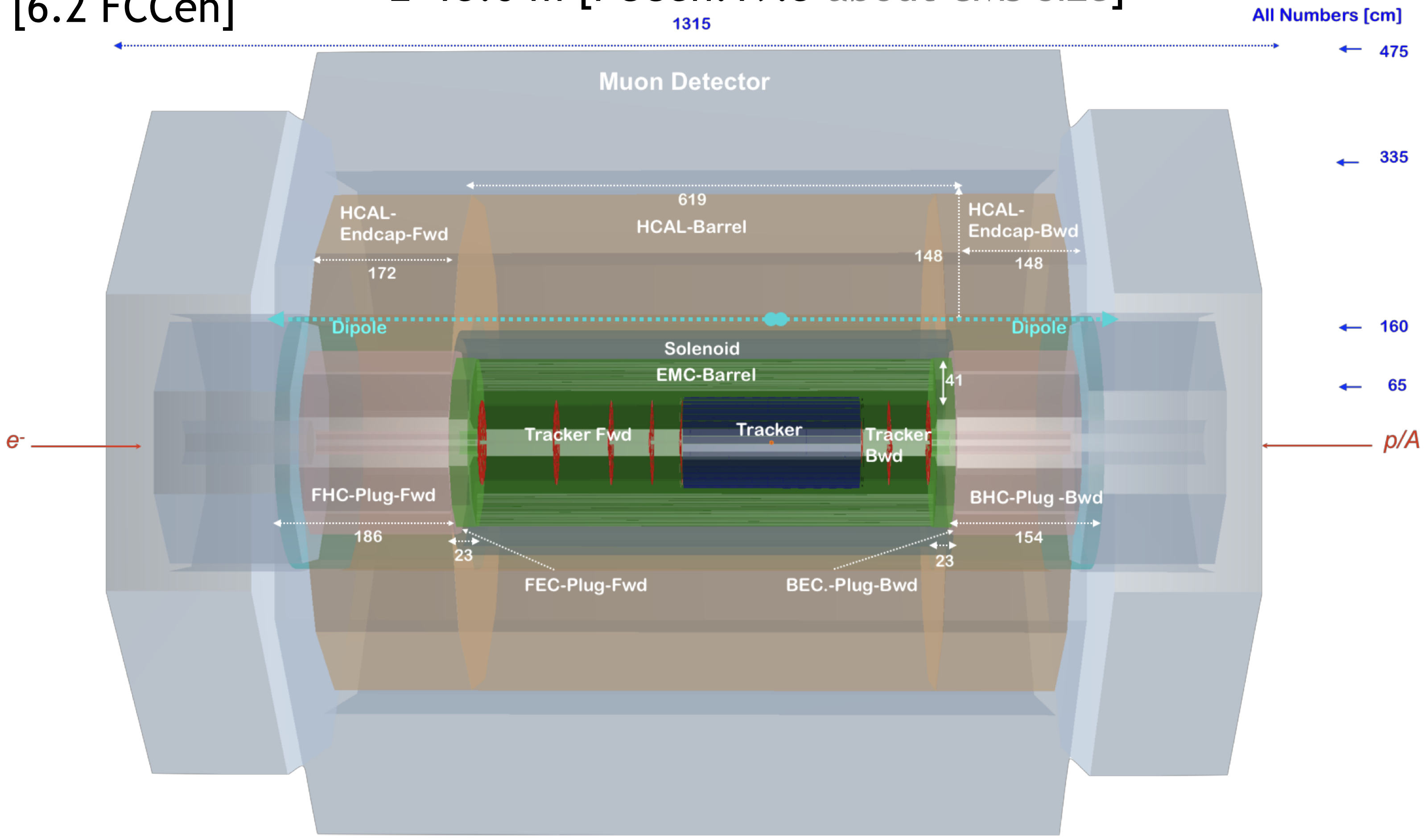
Covering important regions between pp and ee / low-energy experiments

How-to: the LHeC Detector

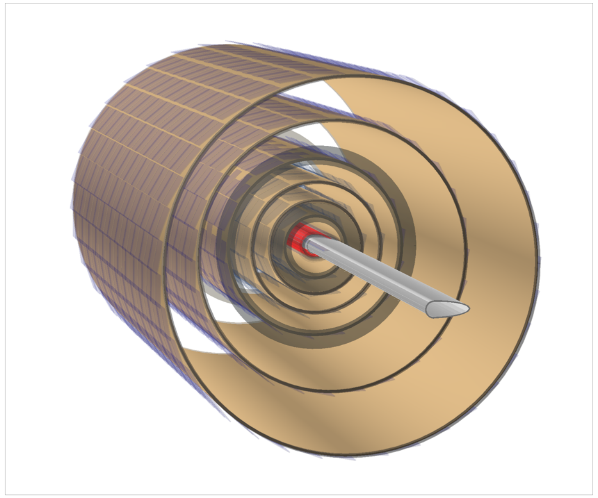


R=4.6 m
[6.2 FCCeh]

L=13.6 m [FCCeh:19.3 about CMS size]



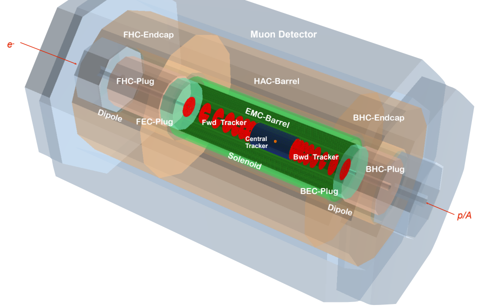
Study of installation (sequence) of LHeC detector in IP2 cavern using L3 magnet support structure [commensurate with 2 year shutdown]



Arrangement of the inner barrel tracker layers around the beam pipe

How-to: the LHeC Detector

FCC-eh Detector



R=4.6 m
[6.2 FCCeh]

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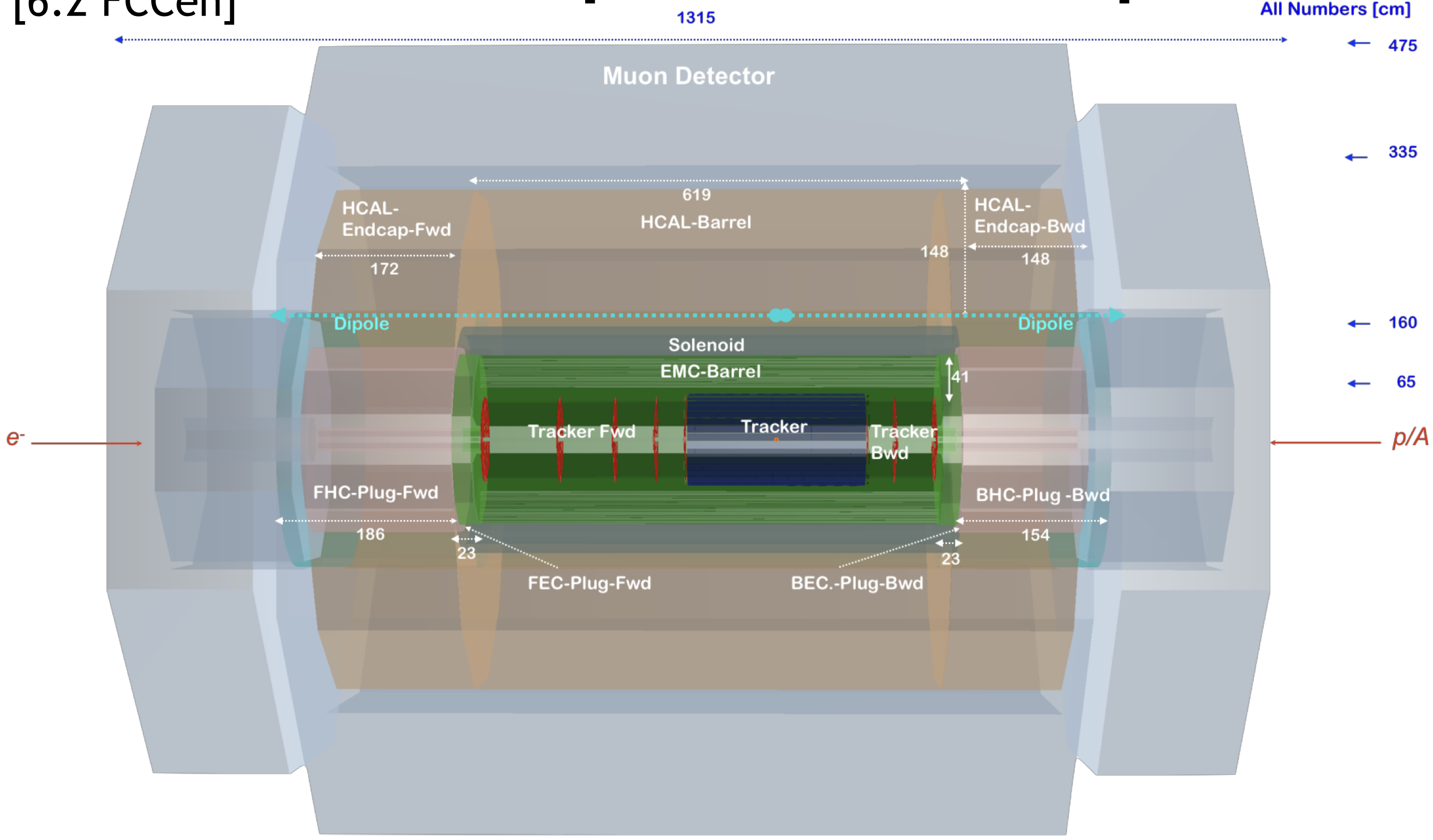

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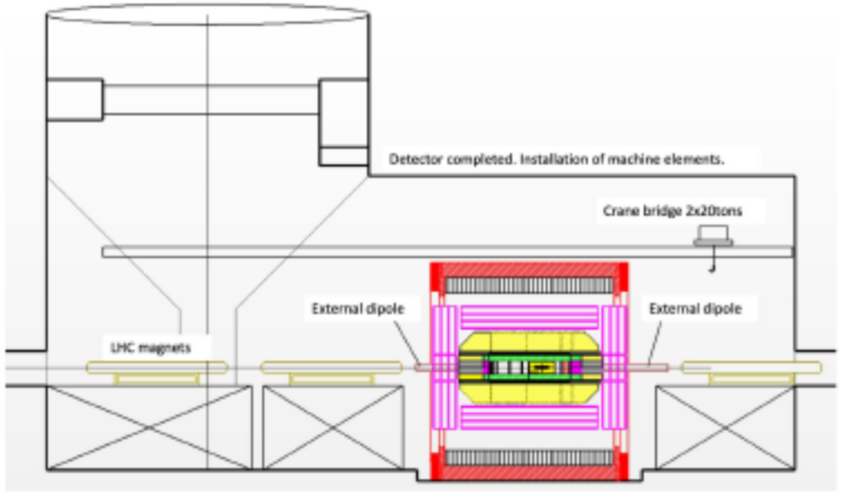
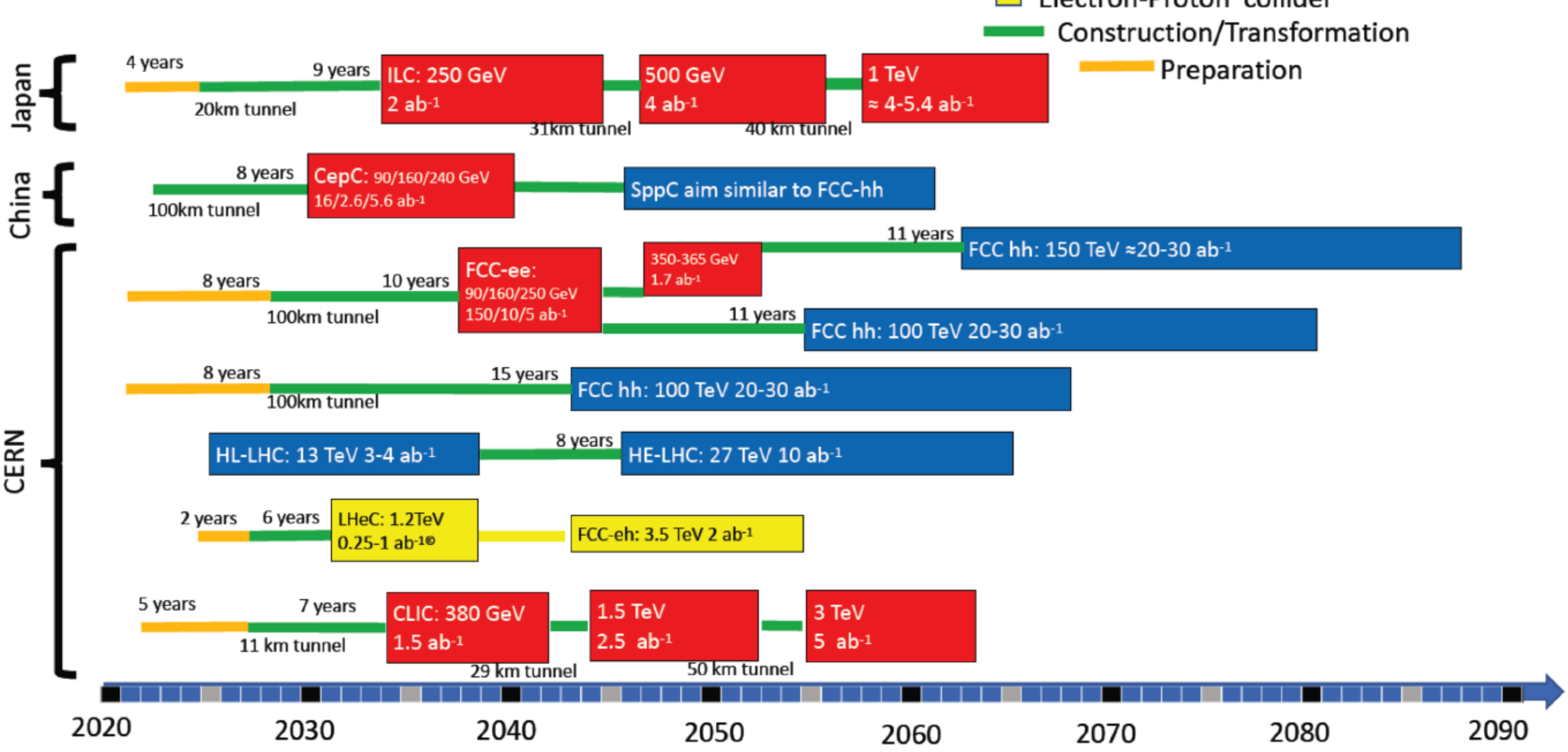


Possible scenarios of future colliders



conclusions

- An electron-proton facility represents a seminal opportunity to develop and explore QCD, to study high precision Higgs and electroweak physics and to substantially extend the range and prospects for accessing BSM physics, on its own and in combination of pp with ep.
  - **sustains HL-LHC and bridges to CERN's long term future**
  - In eA scattering mode it has a unique discovery potential on nuclear structure, dynamics and QGP physics.
- On the technology side, it leads to novel accelerator studies:
  - Energy Recovery Linacs are a green power facility nowdays very interesting
  - An international collaboration has been formed to realise the first multi-turn 10 MW ERL facility, **PERLE** at Orsay, with its main parameters set by the LHeC and producing the first encouraging results on 802 MHz cavity technology
- Detectors could also benefit of novel high tech (eg. CMOS..)

Overall, the LHeC would keep accelerator and detector developments up to date while preparing for colliders that cost O(10)BSF

- …Without mentioning that LHeC paves the way to the FCC complex in its full hh-eh capacity

Recommendations

i) It is recommended to further develop the ERL based ep/A scattering plans, both at LHC and FCC, as attractive options for the mid and long term programme of CERN, resp. Before a decision on such a project can be taken, further development work is necessary, and should be supported, possibly within existing CERN frameworks (e.g. development of SC cavities and high field IR magnets).

ii) The development of the promising high-power beam-recovery technology ERL should be intensified in Europe. This could be done mainly in national laboratories, in particular with the PERLE project at Orsay. To facilitate such a collaboration, CERN should express its interest and continue to take part.

iii) It is recommended to keep the LHeC option open until further decisions have been taken. An investigation should be started on the compatibility between the LHeC and a new heavy ion experiment in Interaction Point 2, which is currently under discussion.

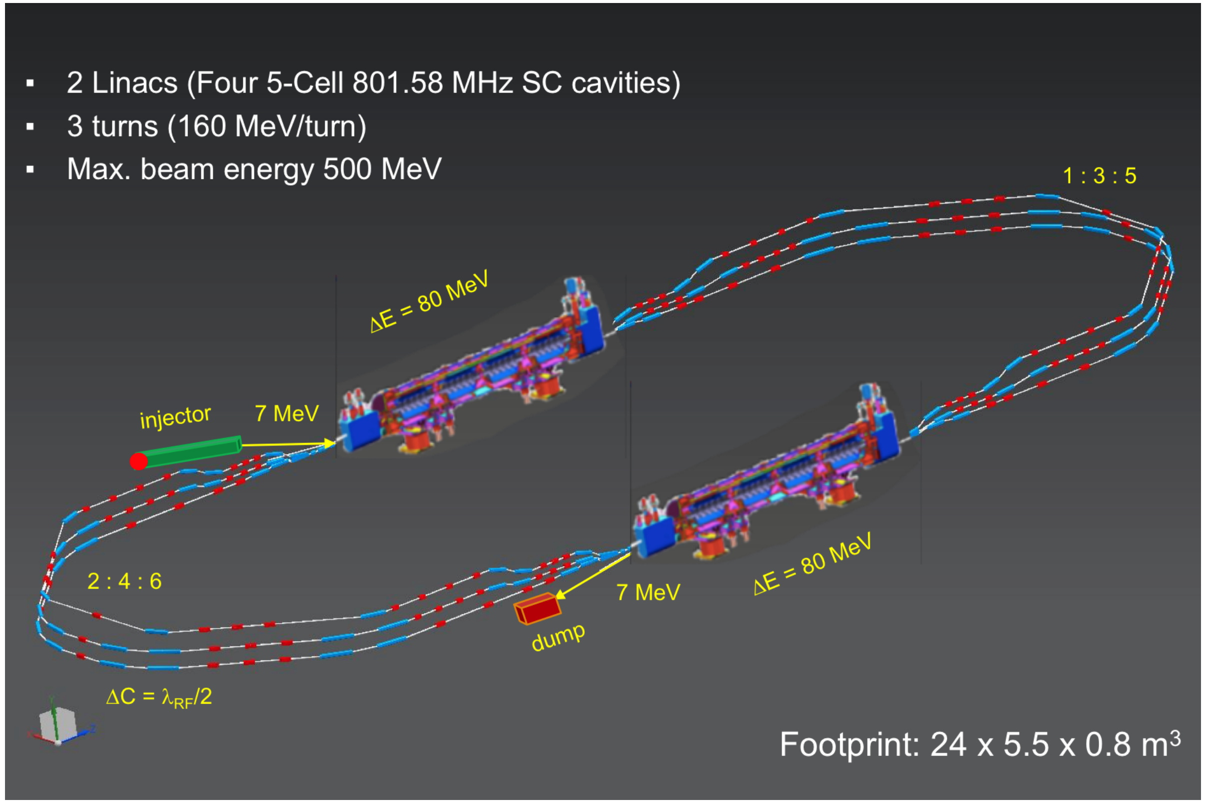
After the final results of the European Strategy Process will be made known, the IAC considers its task to be completed. A new decision will then have to be taken for how to continue these activities.

Herwig Schopper, Chair of the Committee, Geneva, November 4, 2019

Back up

Test facility: PERLE

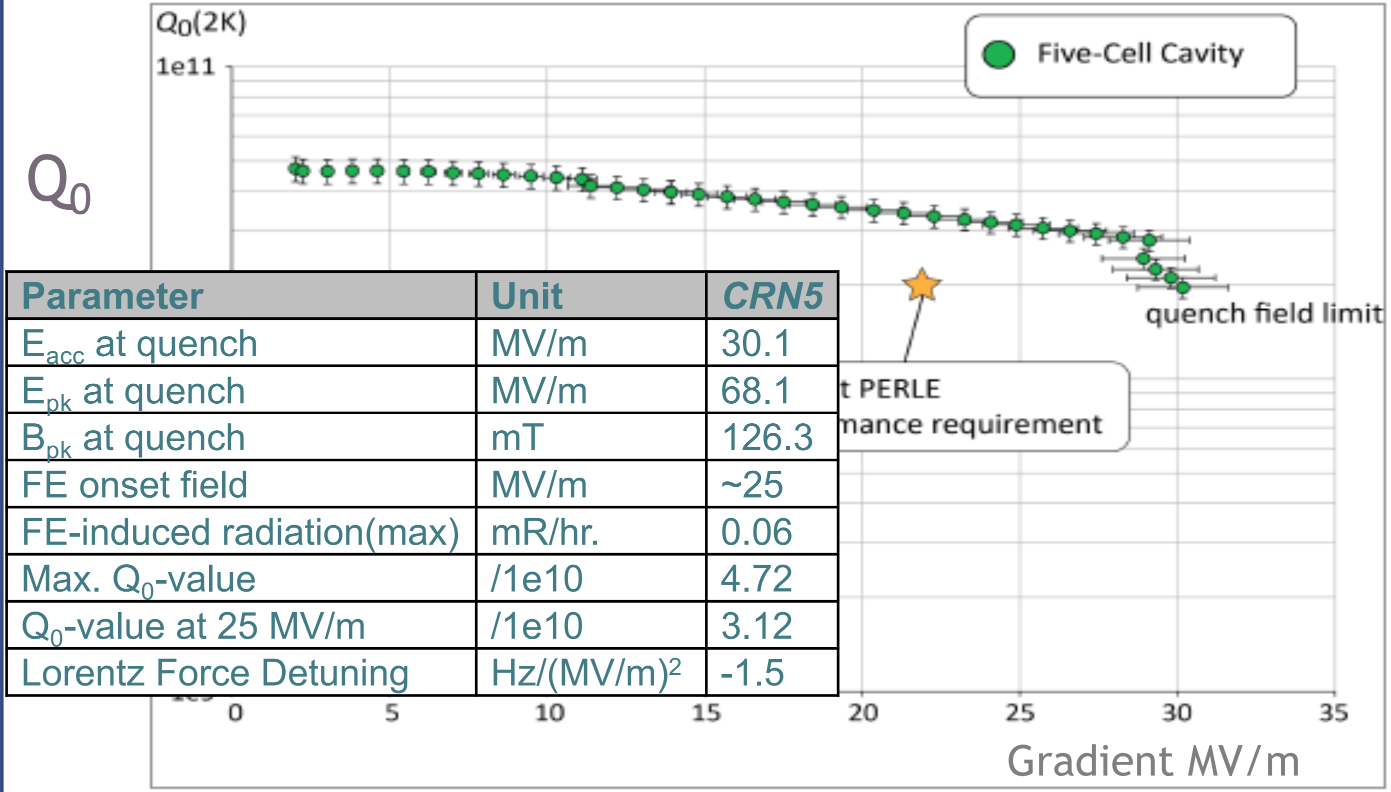
- Low energy ERL facility in Orsay
- Collaboration involving CERN, Jefferson Laboratory, STFC-Daresbury, University of Liverpool, BINP-Novosibirsk and the Irene Curie Lab at Orsay.
- Major parameters taken from LHeC:
  - 3-turn configuration, source
  - 802MHz frequency
  - cavity-cryomodule technology
- suitable facility for the development of LHeC ERL technology and the accumulation of operating experience prior to and later in parallel with the LHeC
- It has its own low energy physics programme and industrial applications



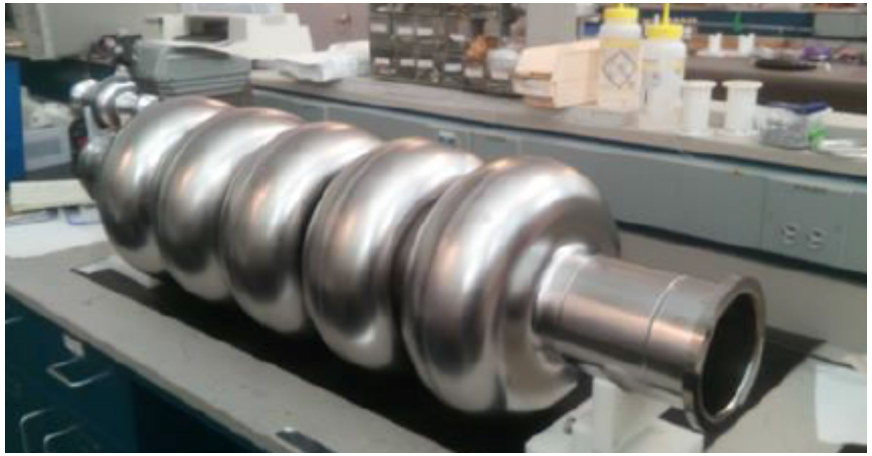
Target parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Norm. emittance $\gamma\epsilon_{x,y}$	mm·mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.6
Duty factor		CW

Phase I operation by 2025

Recent ERL achievements



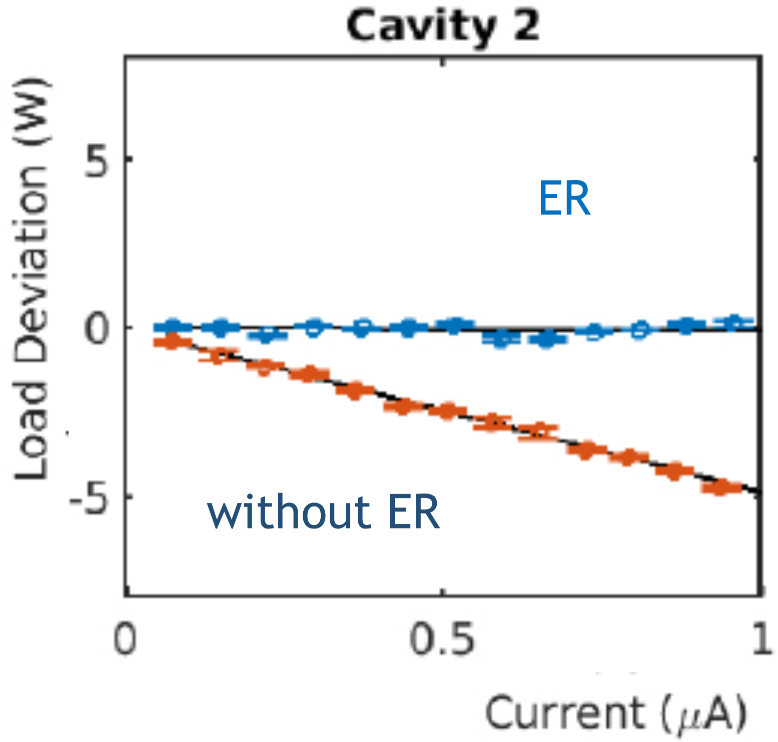
Parameter	Unit	*CRN5*
E_{acc} at quench	MV/m	30.1
E_{pk} at quench	MV/m	68.1
B_{pk} at quench	mT	126.3
FE onset field	MV/m	~25
FE-induced radiation(max)	mR/hr.	0.06
Max. Q_0-value	/1e10	4.72
Q_0-value at 25 MV/m	/1e10	3.12
Lorentz Force Detuning	Hz/(MV/m)[2]	-1.5



F Marhauser et al.
Jlab, CERN

First 5 cell Niobium Cavity, 802 MHz

High Q_0, high stability



Demonstration of energy recovery in new cBETA facility at Cornell, with BNL

G Hoffstaetter et al 19.6.2019

Project staging strategy:

The PERLE configuration entails the possibility to construct PERLE in stages. We propose in the following two main phases to attend the final configuration.

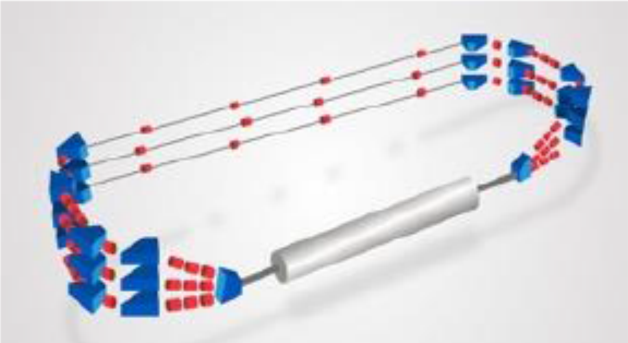
Phase 1: Installation of a single cryomodule in the first straight and three beam lines in the second (consideration motivated by the SPL cryomodule availability)

→ To allow a rather rapid realisation of a 250 MeV machine.

→ To test with beam the various SRF components.

→ To prove the multi-turn ERL operation.

→ to gain essential operation experience.



PERLE Phase 1 layout

Phase 2 : Realisation of PERLE at its design parameters as a 10MW machine:

→ Upgrade of the e- gun

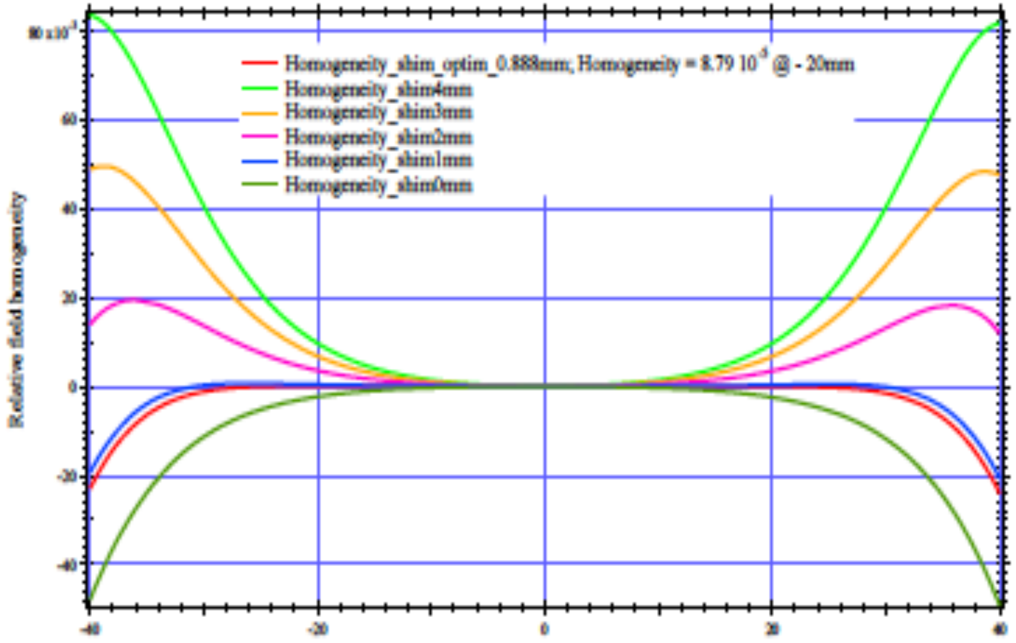
→ Installation of the 2^{nd} Spreader and recombinar

→ Installation of the second cryomodule in the second straight.

PERLE Phase 2 layout

Recent PERLE Progress

Field homogeneity 8 10^{-2}



Bending magnets: field homogeneity with optimized shim of 8.8 10^{-5} at ± 20 mm (GFR), better than expected (5 10^{-4}).

Transfer of ALICE (Daresbury) gun + equipment to LAL (5/19)

Hiring of personell at Orsay

Design of source/booster/injector at Daresbury/Liverpool

Encouraging radiation protection survey at Orsay

...

LAL/IPNO and BINP-Novosibirsk applied for the H2020 European program (CRIMLINplus) and ask for fund for dipole design & prototyping and for a post-doc position.

arrival of the ALICE gun in the PERLE hall 10.5.19

cf Walid Kaabi 27.6. in FCCeh

Costs

- Costs are partially driven by the ERL size

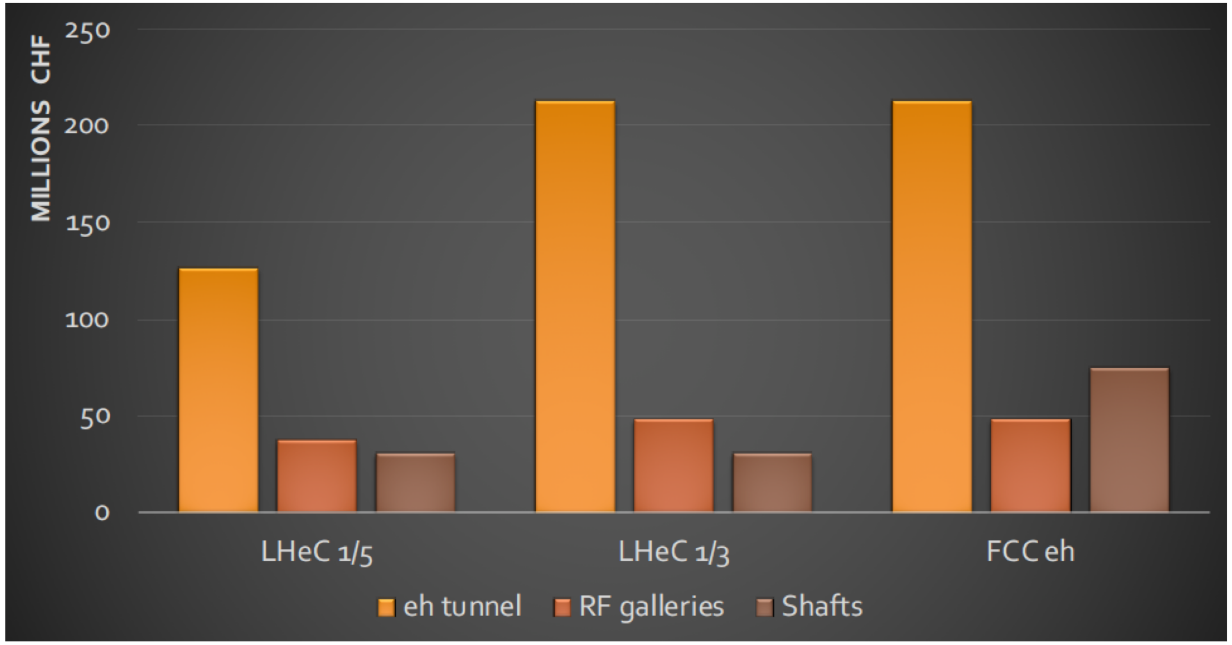


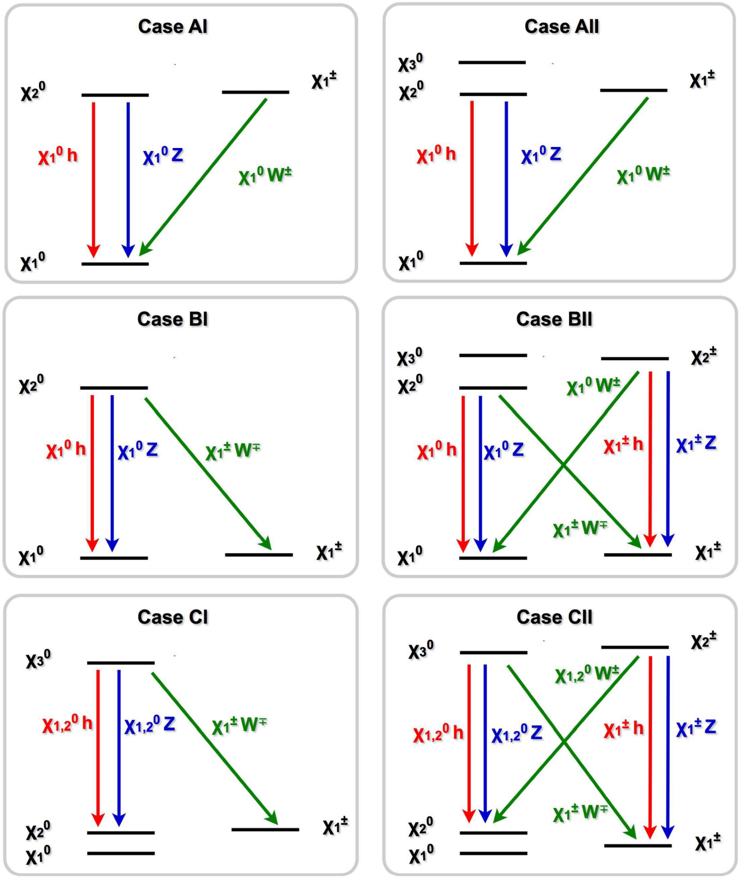
Figure 2.1: Cost estimate for the civil engineering work for the tunnel, rf galleries and shafts for the LHeC at 1/5 of the LHC circumference (left), at 1/3 (middle) and the FCC-eh (right). The unit costs and percentages are consistent with FCC and CLIC unit prices. The estimate is considered reliable to 30 %. The cost estimates include: Site investigations: 2 %, Preliminary design, tender documents and project changes: 12 % and the Contractors profit: 3 %. Surface site work is not included, which for LHeC exists with IP2.

High Electron Energy beams achievable with longer linacs

Parameter	Unit	LHeC option			
		1/3 LHC	1/4 LHC	1/5 LHC	1/6 LHC
Circumference	m	9000	6750	5332	4500
Arc radius	$m \cdot 2\pi$	1058	737	536	427
Linac length	$m \cdot 2$	1025	909	829	758
Spreader and recombiner length	$m \cdot 4$	76	76	76	76
Electron energy	GeV	61.1	54.2	49.1	45.2

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 χ^0_1, $\chi^{\pm}_1$, χ^0_2
  (2) Consider triplets for cross sections
  (3) Role of high-multiplicity neutralinos and charginos also relevant

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

[depending on masses!]

Prompt SUSY EWK production

- Target two kind of EWK mass spectra:

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

Slepton mass

Large gap

Chargino ~ Neutralino1 masses
Mass difference ~ 1-2 GeV

"compressed-slepton scenario"

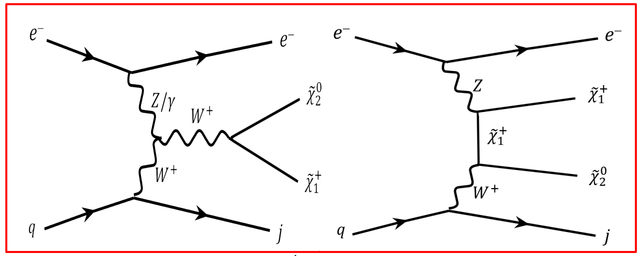
Slepton (selectron) mass

~35 GeV

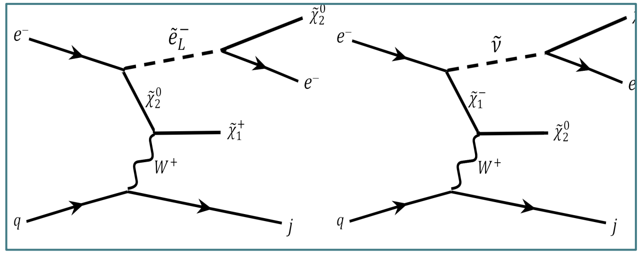
Higher order corrections might be as high as 20% as for pp collisions - not taken into account (conservative!)

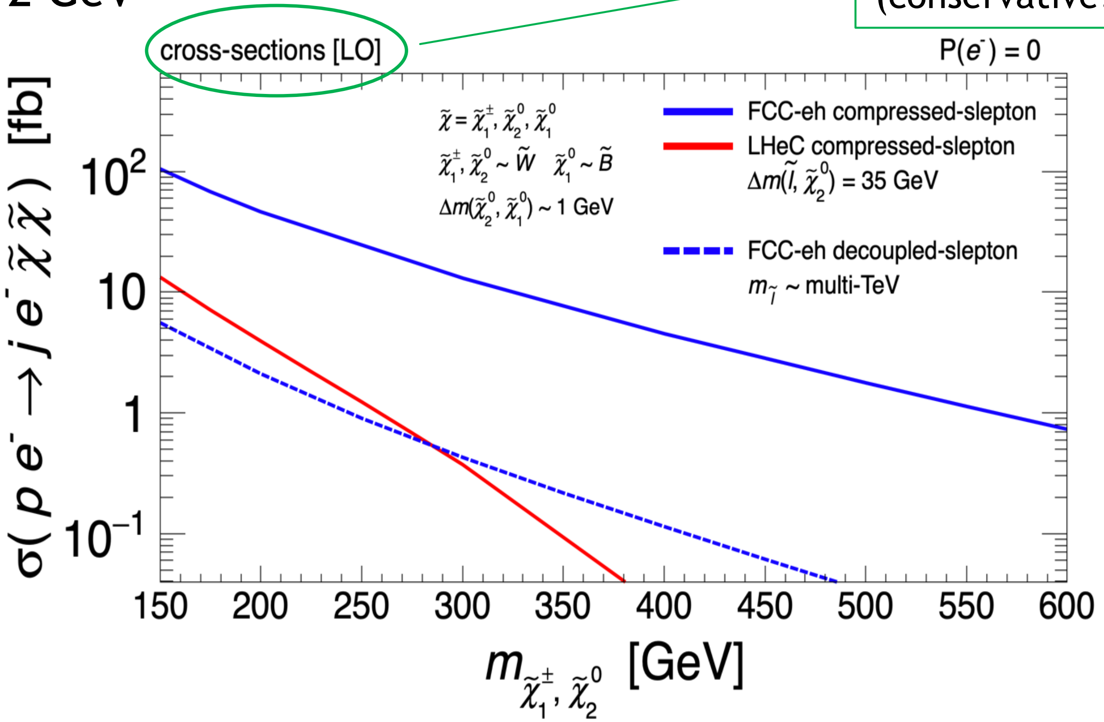
$$pe^- \to je^-\tilde{\chi}\tilde{\chi}\ (\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$$

VBF production



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





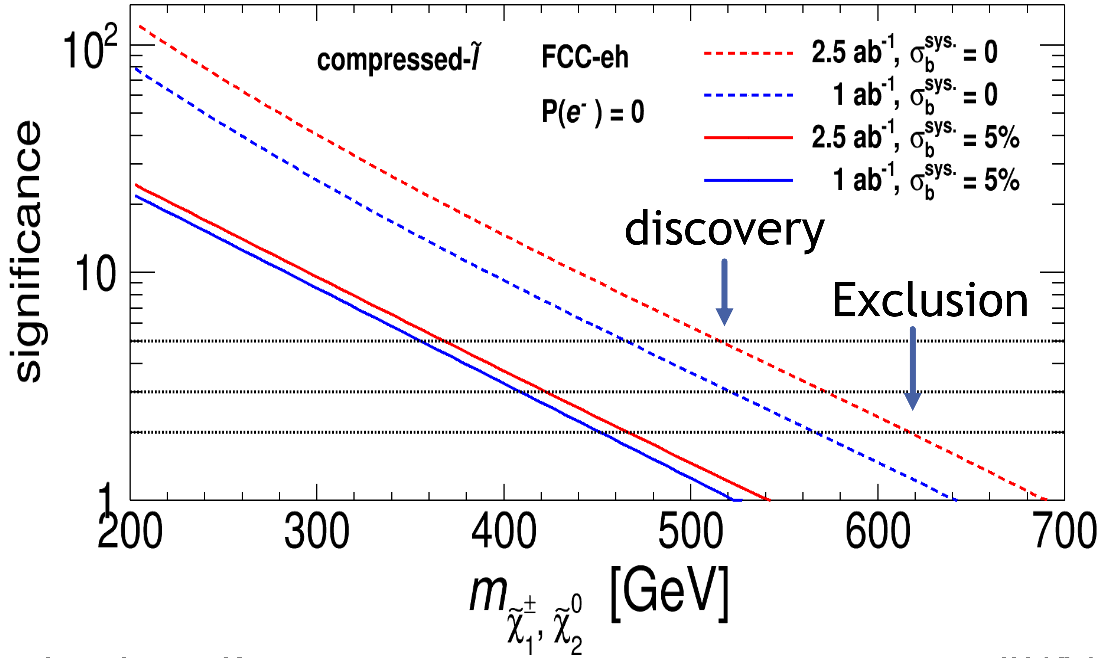
Compressed slepton scenarios: results

- Evaluate significance with statistical and systematic uncertainties

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

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

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
$\sigma_{\rm stat+syst}$	3.3		



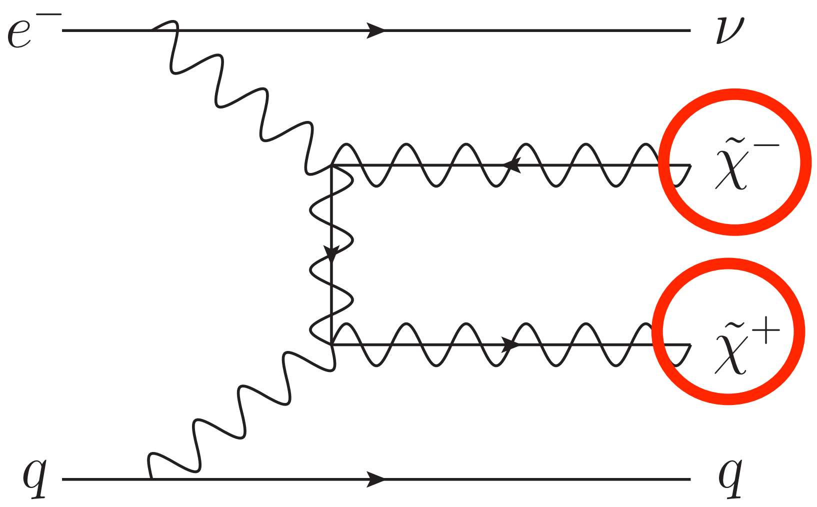
- Of course, systematic uncertainties play a crucial role, as in monojet searches at pp
  - → **Here we consider 0-5%**
  - → Projections for HL-LHC consider 1-3%

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

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

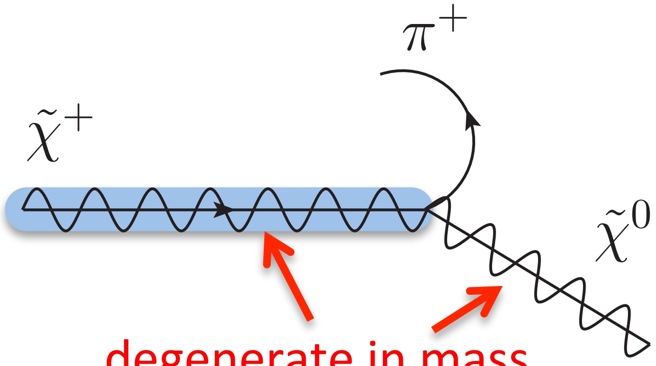
Simplest models at FCC-he: four-body process and tiny cross section

- Charginos (Wino or Higgsino)



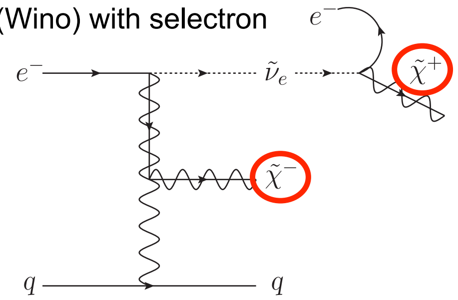
LLCPs

disappearing track



Cross section enhanced with "co-production"

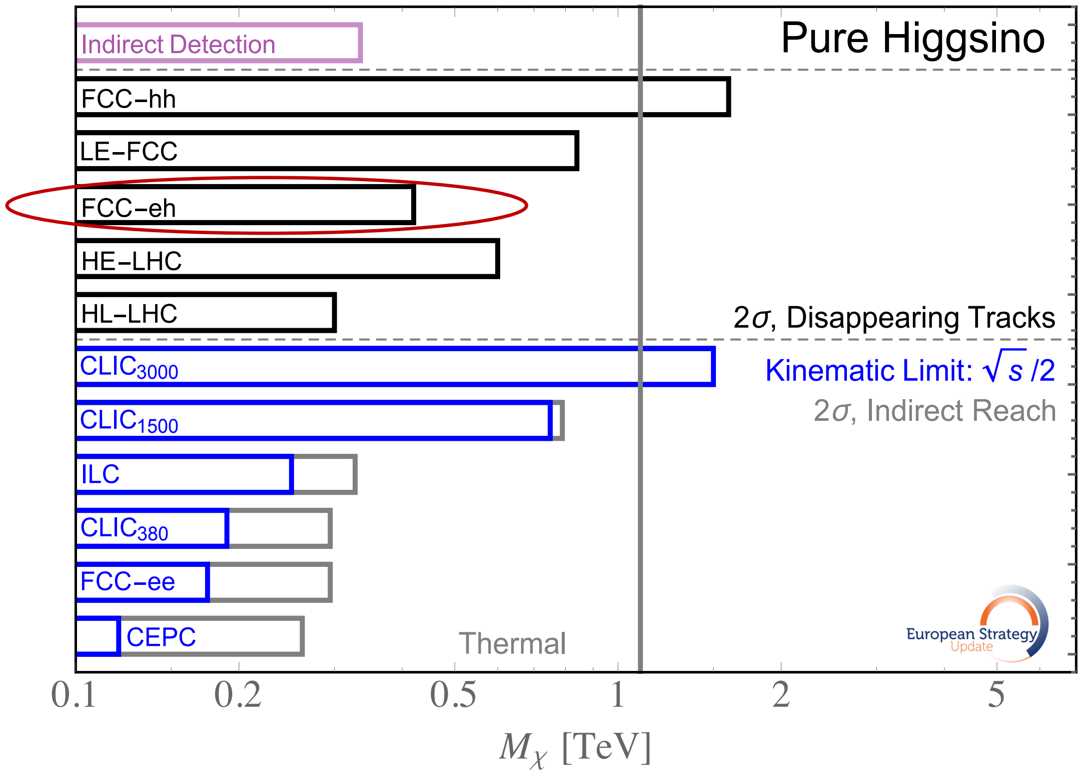
- Chargino (Wino) with selectron

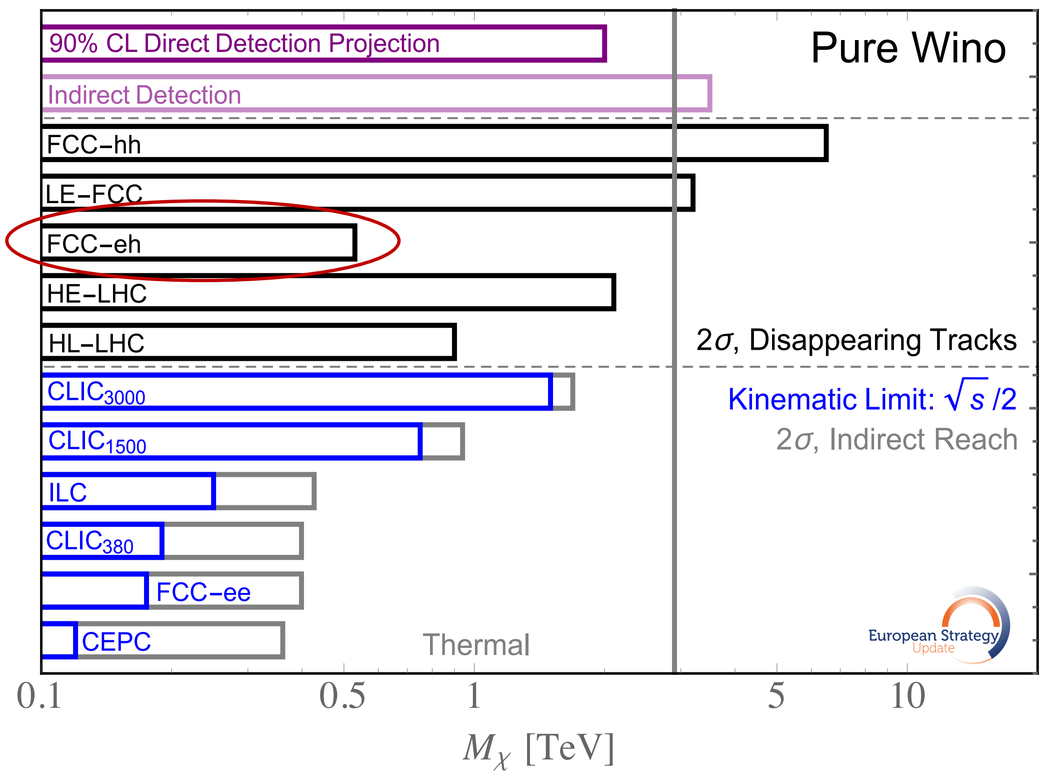


In this case, only the scenario with heavy (decoupled) sleptons is considered (most conservative)

Comparisons with other facilities

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

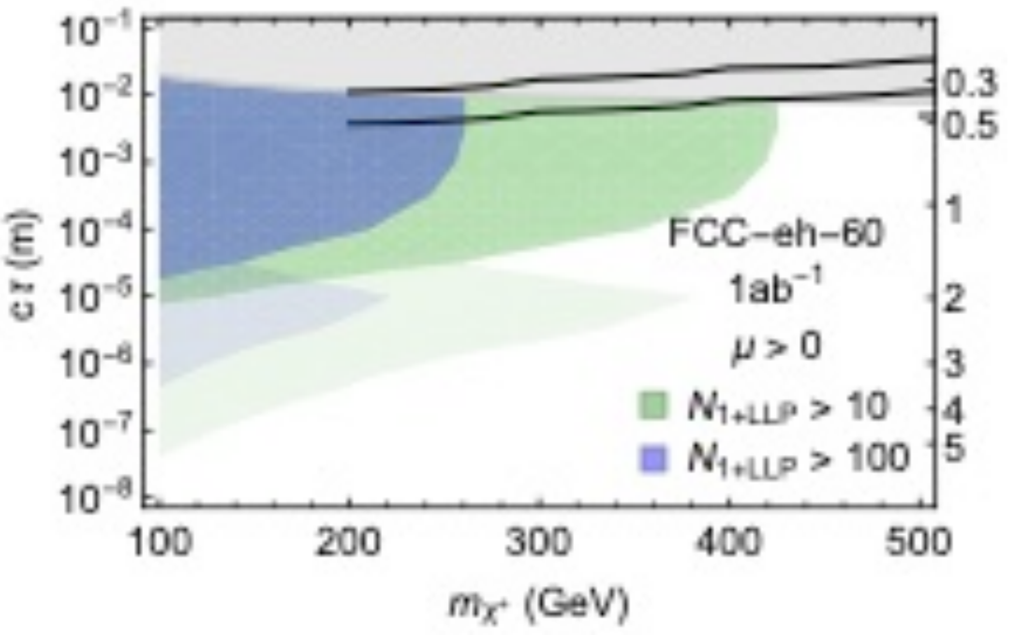


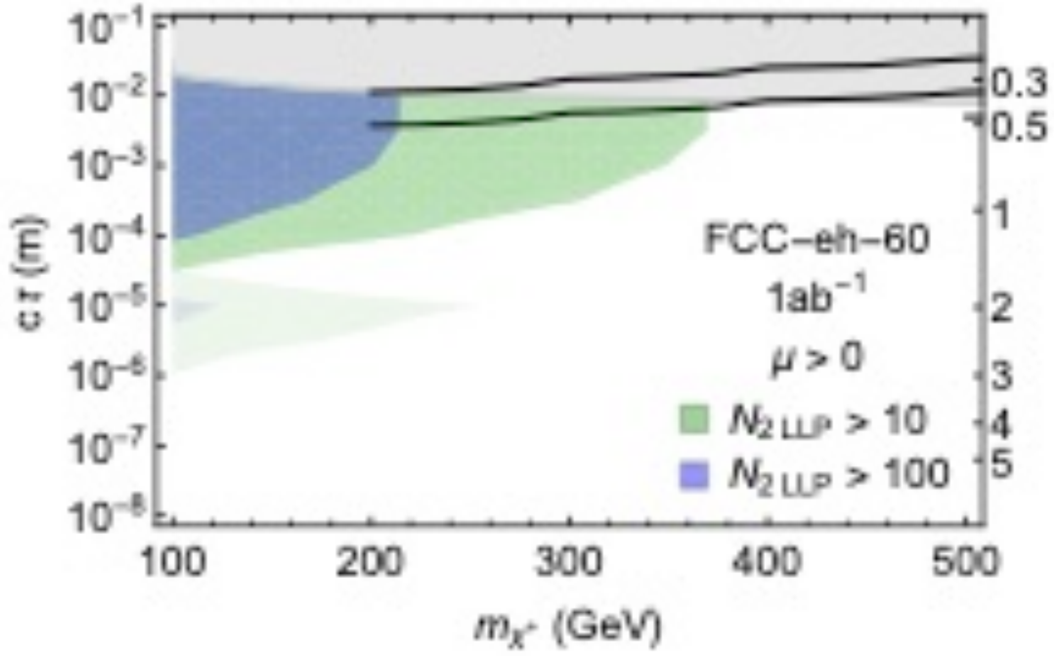


- FCC-eh not directly competitive with FCC-hh but **still reasonable reach**
- In all cases FCC-eh sensitivity to **short decay lengths**, possibly much less than a single micron, improves with respect to what the FCC-hh can accomplish with disappearing track searches

Results for disappearing track analysis @ FCC

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

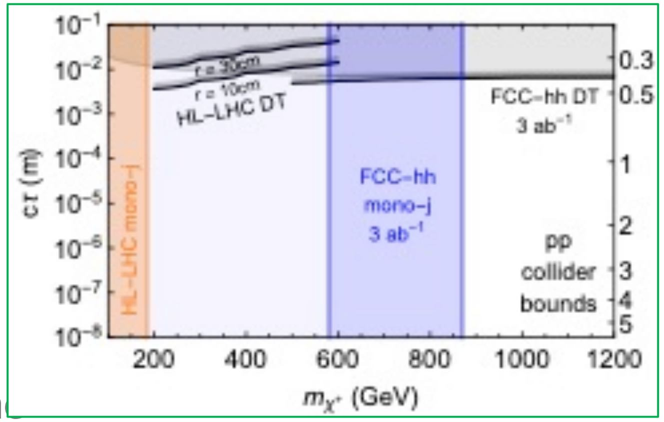




green region: 2σ sensitivity estimate in the presence of τ backgrounds

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



SUSY EWK production

- 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

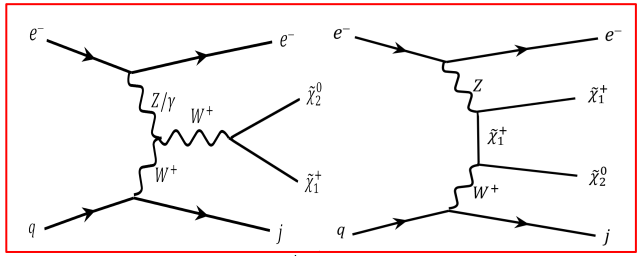
Slepton (selectron) mass

~35 GeV

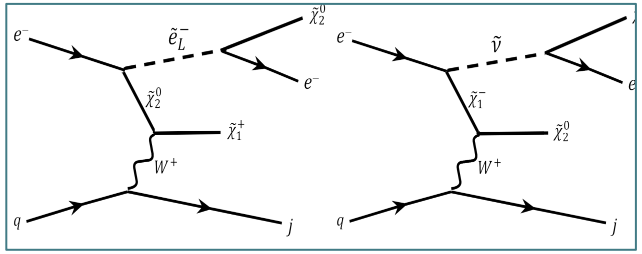
(Note: as sleptons are heavier than charginos and neutralinos, they do not play a role in the pp cross sections)

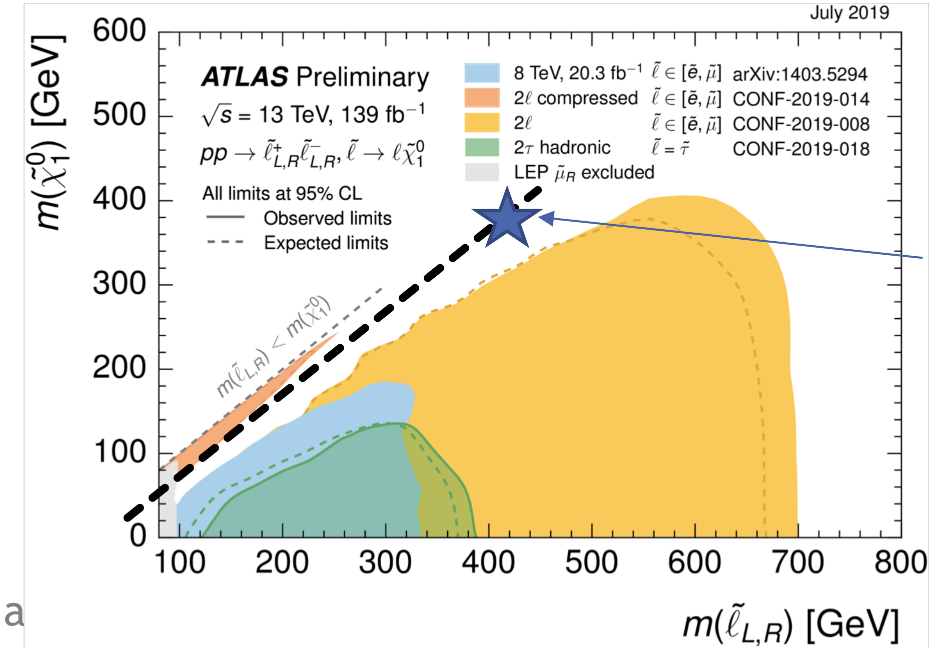
$$pe^- \to je^-\tilde{\chi}\tilde{\chi}\ (\tilde{\chi} = \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm)$$

VBF production



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



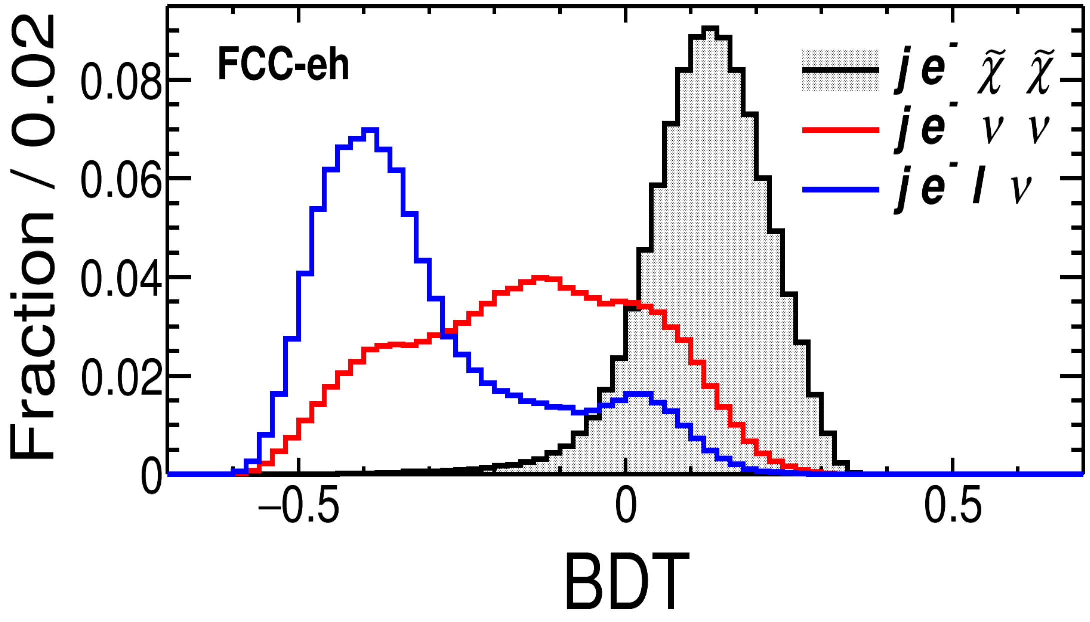


Benchmark slepton mass

Compressed slepton scenarios: 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): $p e^- \rightarrow j e^- \nu\nu$, $p e^- \rightarrow j e^- \ell\nu$
- 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

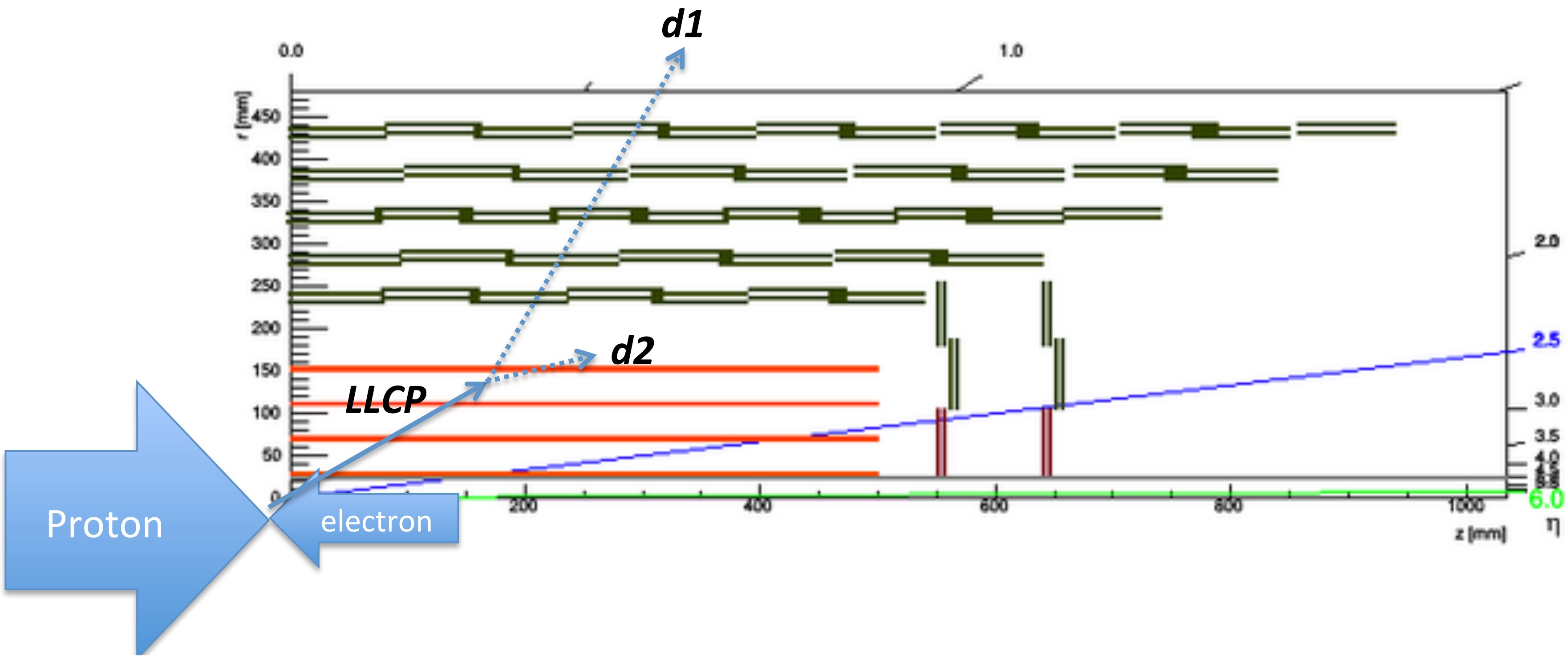
and angular correlations as input



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.

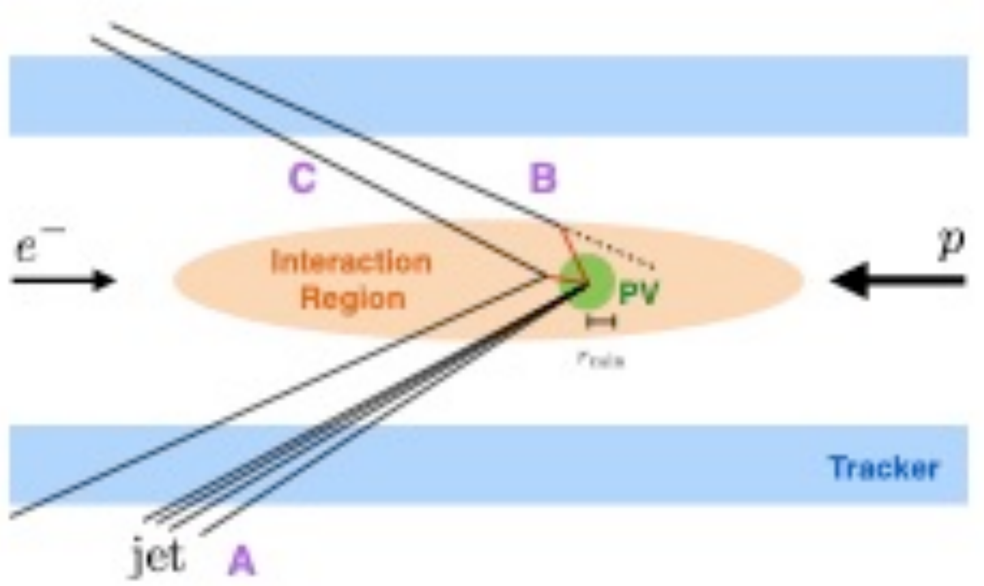
$$b_{\mathrm{com}} \approx \frac{1}{2}\sqrt{E_e/E_p} \approx 5.5$$



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**