EW Physics at the LHeC and FCC-he

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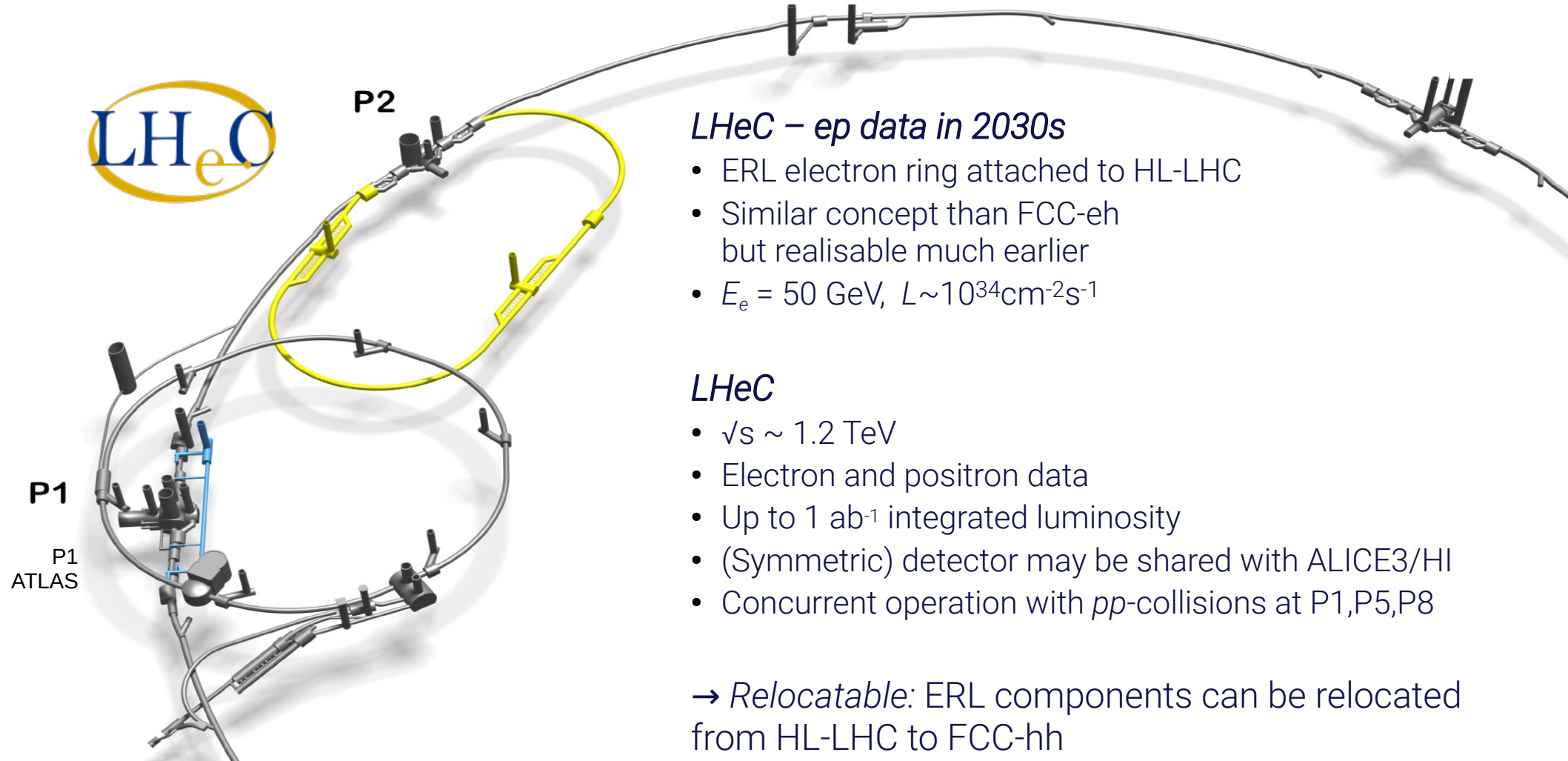
University of Washington, Seattle
20.07.2022

MAX-PLANCK-INSTITUT
FÜR PHYSIK

Energy-frontier *ep* physics in the '30s – the LHeC



LHeC – ep data in 2030s

- ERL electron ring attached to HL-LHC
- Similar concept than FCC-eh but realisable much earlier
- E_e = 50 GeV, $L \sim 10^{34} cm^{-2} s^{-1}$

LHeC

- $\sqrt{s}$ ~ 1.2 TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- (Symmetric) detector may be shared with ALICE3/HI
- Concurrent operation with *pp*-collisions at P1,P5,P8

→ *Relocatable:* ERL components can be relocated from HL-LHC to FCC-hh

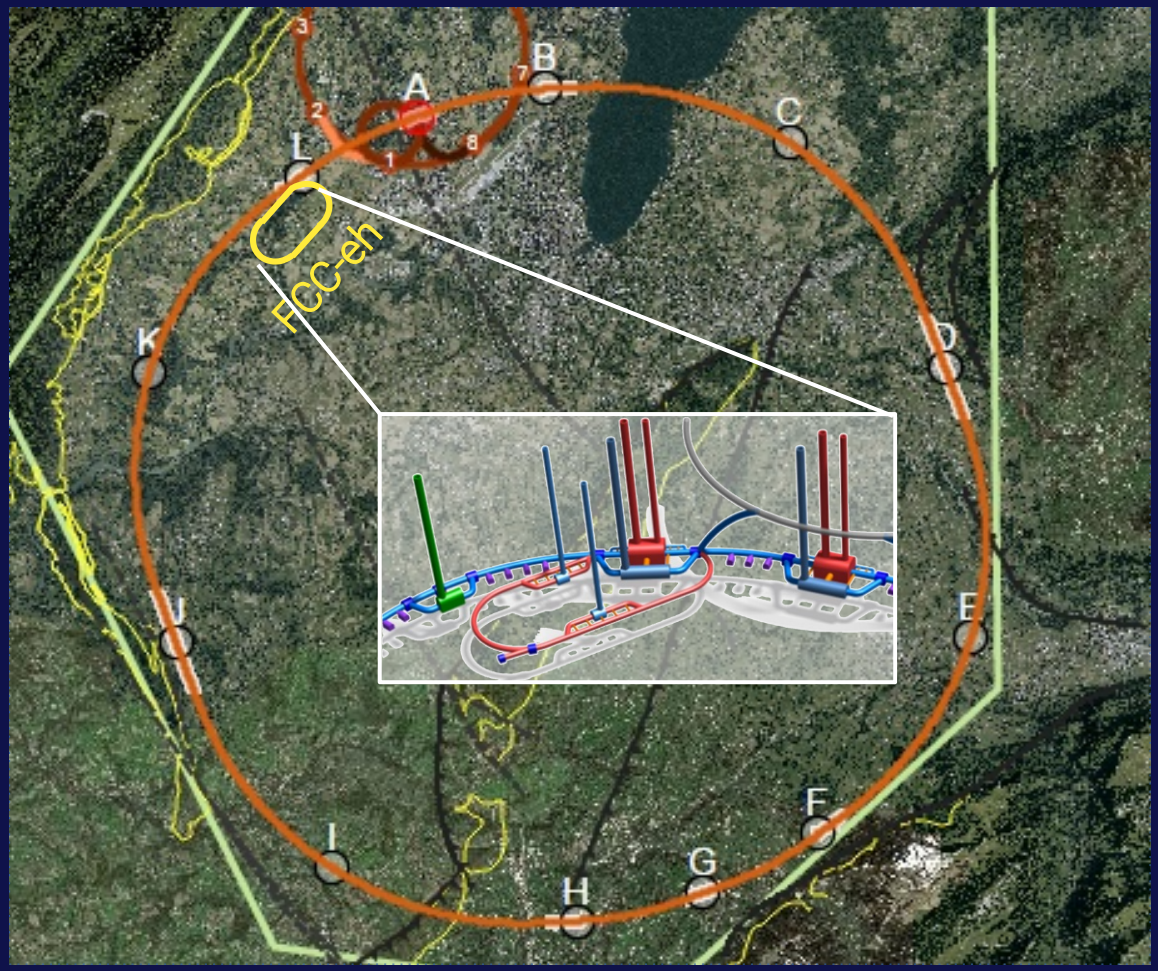
FCC-eh

Dedicated electron-ring attached to the FCC-hh

Energy recovery linac
E_e = 60 GeV
$\sqrt{s}$ ~ 3.5 TeV

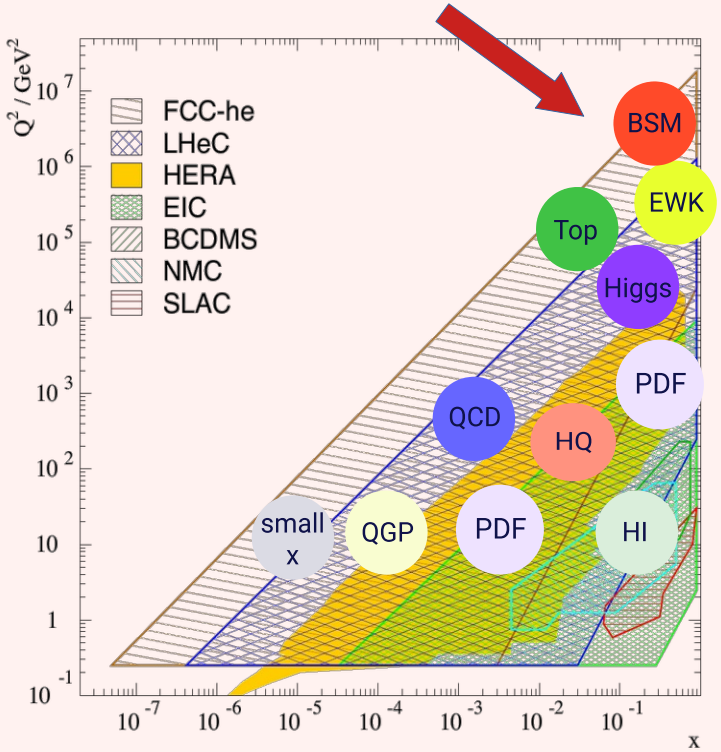
High Luminosity of about 3 ab^{-1}

Concurrent operation with FCC-hh



Deep-inelastic scattering

High luminosity physics



DIS: Cleanest High Resolution Microscope
- → Extraordinary QCD laboratory
- → Precision QCD and matter
- → QCD Discoveries

Empowering the HL-LHC & FCC-hh Search Programme

Transformation of HL-LHC & FCC-hh into the desired Higgs and discovery machine

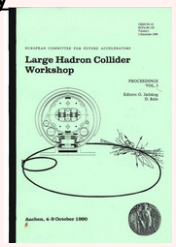
Unique Facility for Nuclear Physics

Unique and complementary Higgs & Top-quark programme

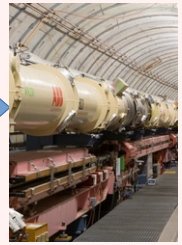
Electroweak Physics

LHeC history

LEP×LHC → 1984: $s \sim \sqrt{1.3}$TeV, L ~ 1fb^{-1}/y

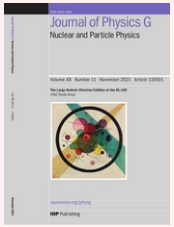


HERA *ep* → 1992: $s \sim \sqrt{0.3}$TeV, L ~ 0.5fb^{-1}



LHC × e$^-$ → 2012: $s \sim \sqrt{1.5}$TeV, L ~ O(100fb^{-1})

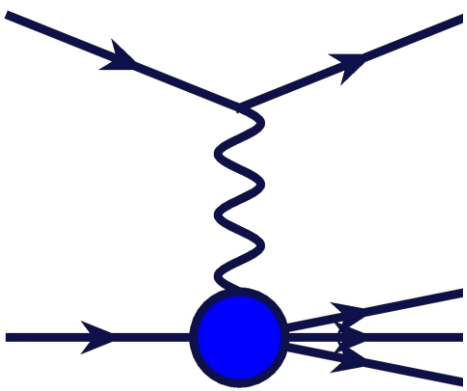
HL-LHC×ERL & Higgs → 2020: $s \sim \sqrt{1.3}$TeV, **L ~ 1 ab^{-1}**



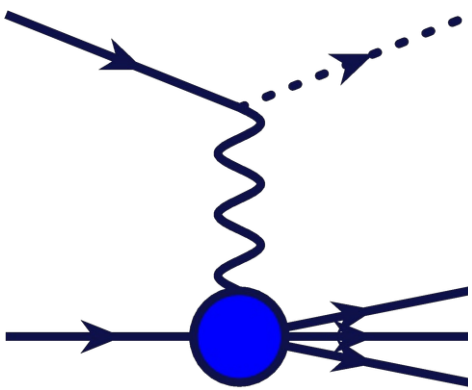
LHeC → '30

Electroweak physics in deep-inelastic scattering

Neutral current DIS
$ep \to e + X$



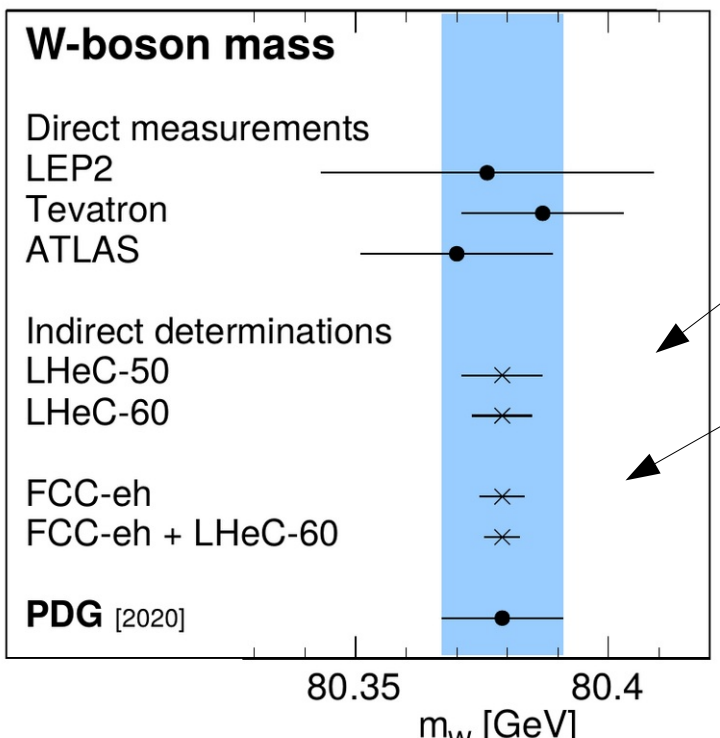
Charged current DIS
$ep \to \nu + X$



Deep-inelastic electron-proton scattering
mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

Expectations: m_W + PDF

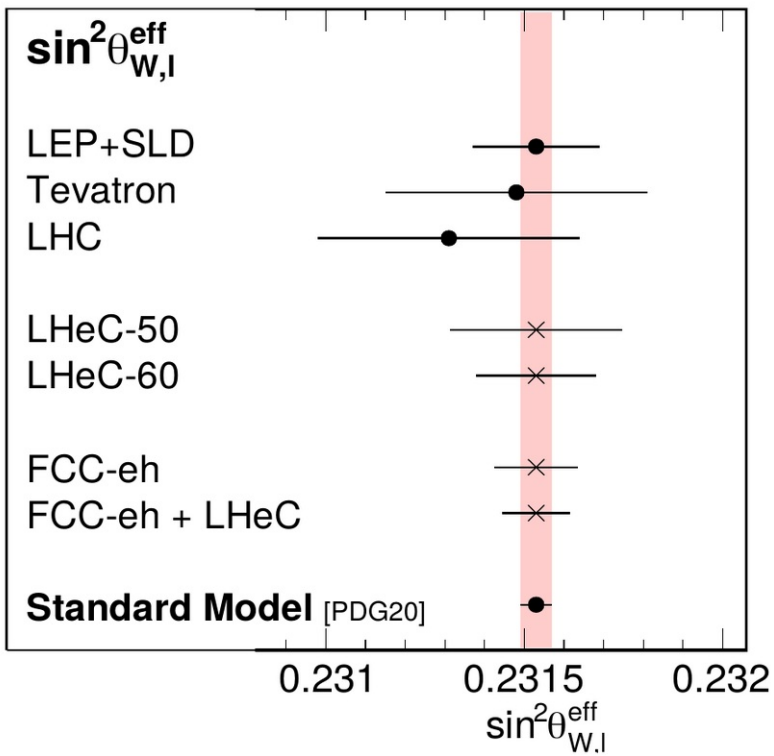
Determine W-boson mass together with proton-PDFs



- LHeC with $L \sim 1ab^{-1}$
  - LHeC (E_e=50GeV): $\Delta m_W = \pm 8$ MeV
  - LHeC (E_e=60GeV): $\Delta m_W = \pm 6$ MeV
- *FCC-eh with $L \sim 1ab^{-1}$* $\Delta m_W = \pm 4.5$ MeV
  (includes PDF uncertainty of about ±3.6 MeV)
  - FCC-eh + LHeC: $\Delta m_W = \pm 3.6$ MeV

- Indirect determination of m_W
- Complementary to 'direct' measurements
  → Consistency test of EW Standard Model
- Smallest uncertainties from a single experiment

The weak mixing angle



Weak mixing angle

- *$\sin^2\theta_w$ in neutral-current vector couplings (only)*

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,\left(I^3_{\mathrm{L},f} - 2Q_f\,\kappa_f\,\sin^2\theta_W\right)$$

$\sin^2\theta_W$ + PDF fit

- *Comparison to Z-pole data*
- *At future DIS facilities:*
  Most precise single measurement possible
- *Note: need theory to map $\sin^2\theta_W$ to effective leptonic weak mixing angle*

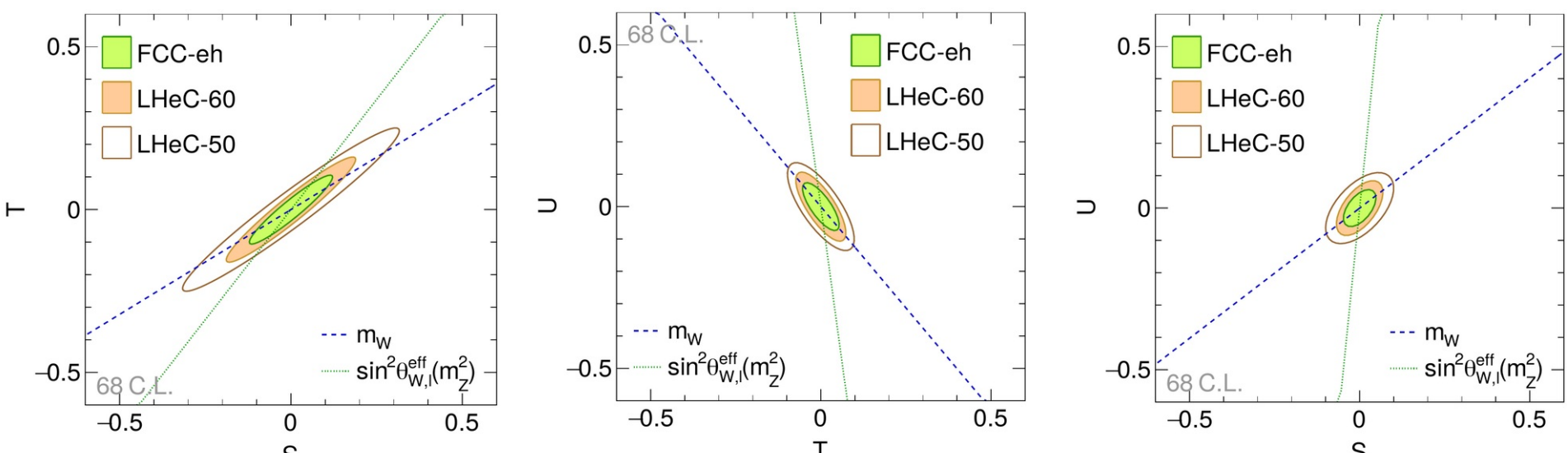
$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

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

STU parameters from inclusive DIS

S, T, U parameters are non-SM contributions to Z & W-boson self-energies

- Studied here: 2-parameter fits incl. PDF fit
- Scheme dependence: Modified on-shell (MOMS)
- With inclusive NC&CC DIS: Possible to disentangle S, T and U
  → Complementary to Z-pole



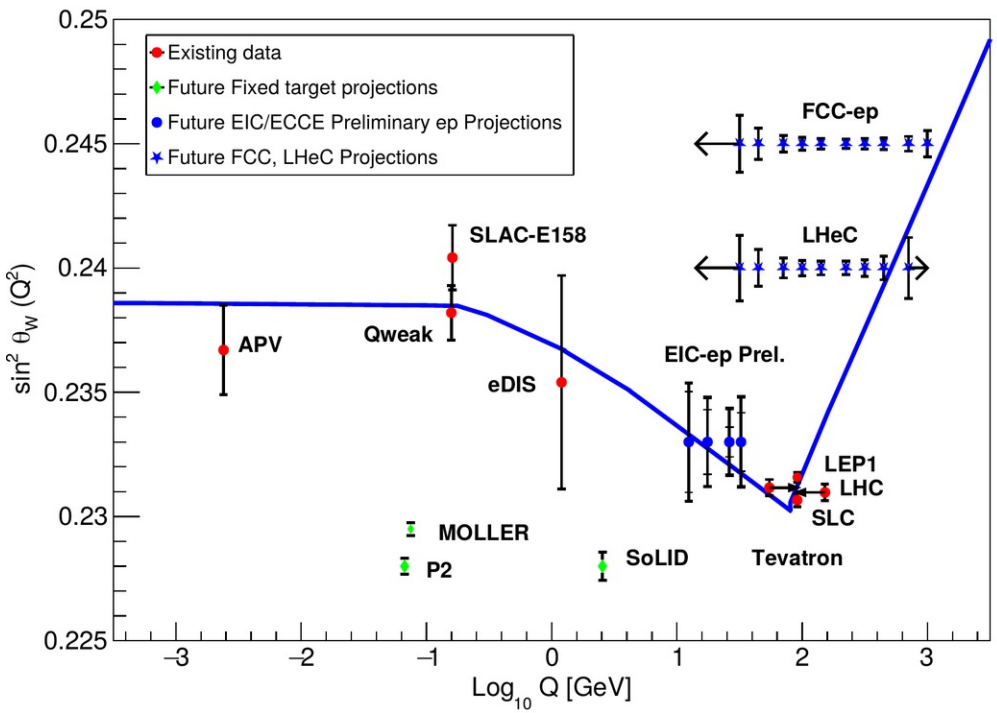
Scale dependent measurements

Running of $\sin^2\theta_W^{eff}$
the effective weak mixing angle is precisely measured at the Z-pole in e—e and p—p

New low-Q measurements will reach higher precision in the future

Scale dependence at high-Q is only poorly tested experimentally

With high luminosity e—p experiments
Per mille uncertainties in range of
20 < Q < 700 GeV in spacelike regime



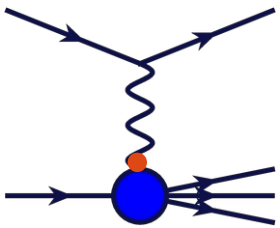
→ Unique measurement of the 'running' at high scales

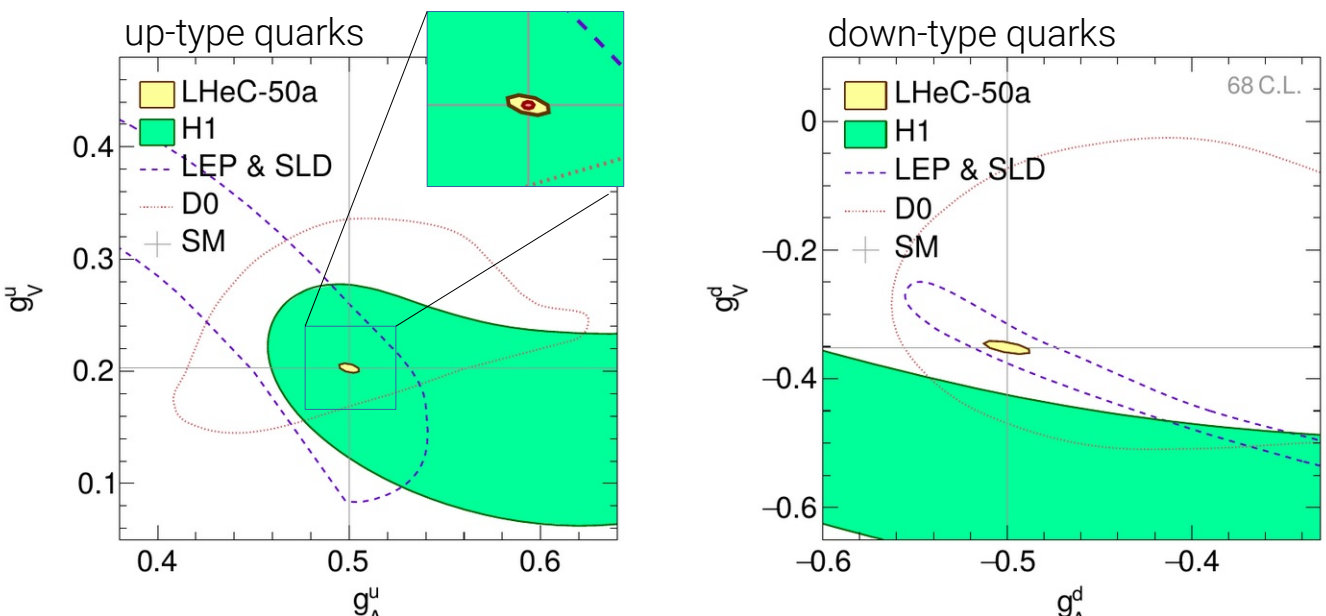
Electroweak physics

DB, M. Klein, H. Spiesberger, Eur.Phys.J.C 80 (2020) 831 PoS(EPS-HEP2021)485

Electroweak physics of 1st gen. quarks
g_V and g_A of 1st gen. quarks ar largely inaccessible in other processes

$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\left(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\sin^2\theta_{\mathrm{W}}\right)$$
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}$$





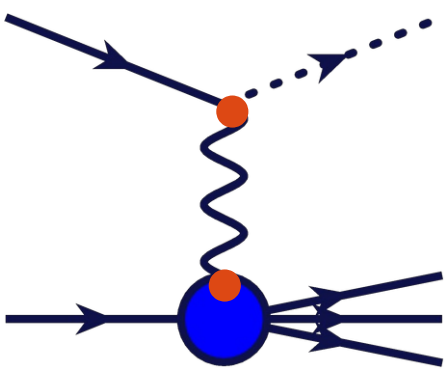
→ PDFs are not a limiting factor for EW physics
→ Also the scale dependence ('running') can be tested with high precision

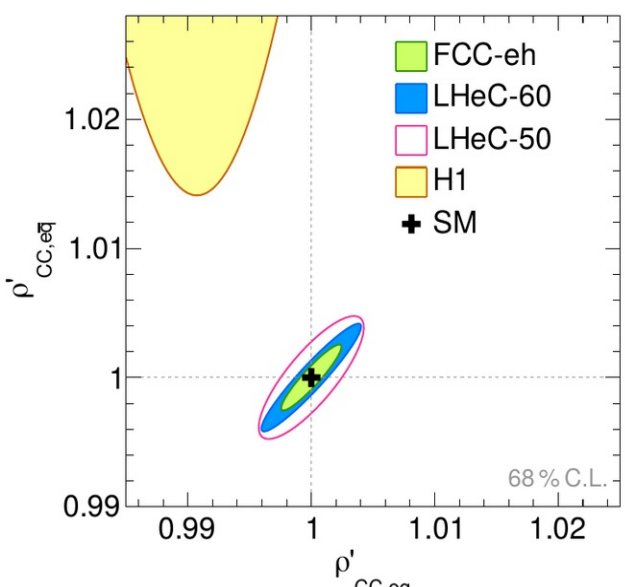
Weak couplings of the *W*-boson

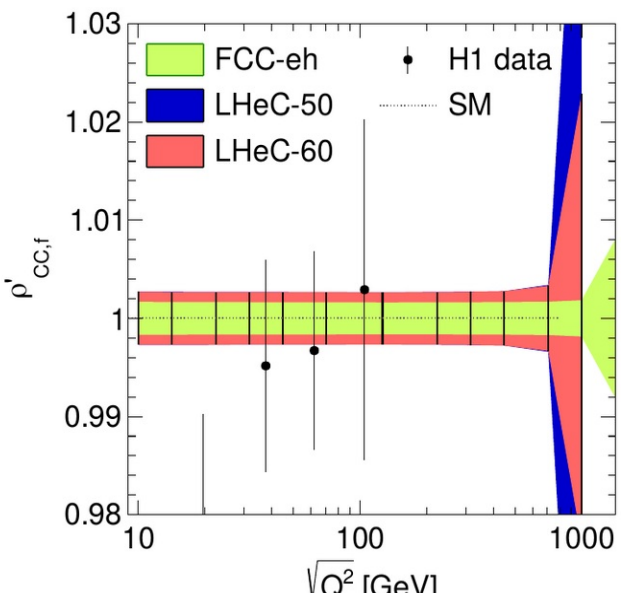
DB, M. Klein, H. Spiesberger,
Eur.Phys.J.C 80 (2020) 831
PoS(EPS-HEP2021)485

EW theory provides precise predictions for charged currents, but CC processes are poorly measured
→ neutrino escapes undetected

In DIS, the kinematics of charged currents are completely measured from final state and incoming electron







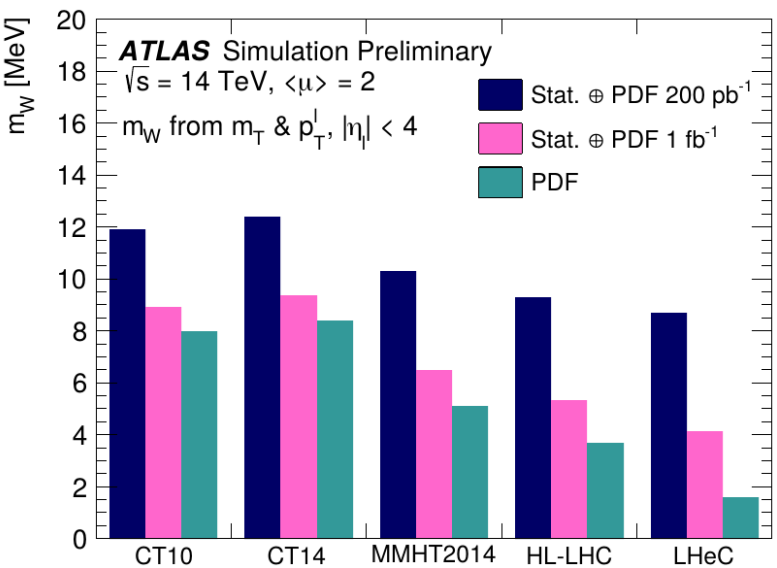
→ Weak couplings of the W-boson are precisely measured – even their scale dependence

CERN Yellow Reports: Monographs, 7/2019
ATL-PHYS-PUB-2018-037

The impact of LHeC on HL-LHC

W-mass measurements in pp

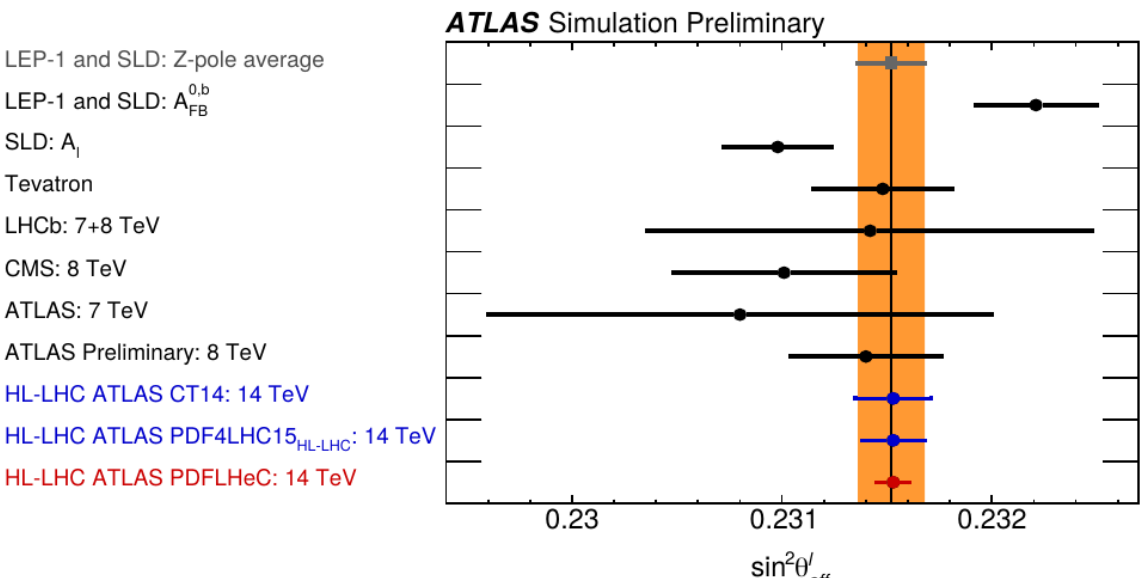
- *Major uncertainty from PDFs*



- *Reduction of PDF uncertainty only feasible with LHeC PDFs (Δm_W^{PDF}~2MeV)*

Effective weak mixing angle in pp

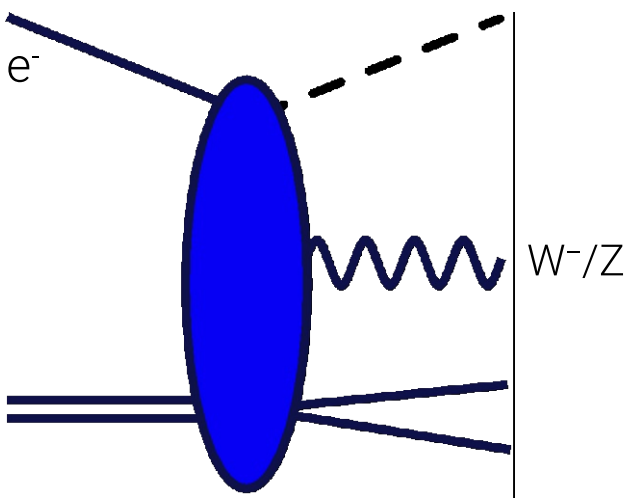
- *Large uncertainty from PDFs*



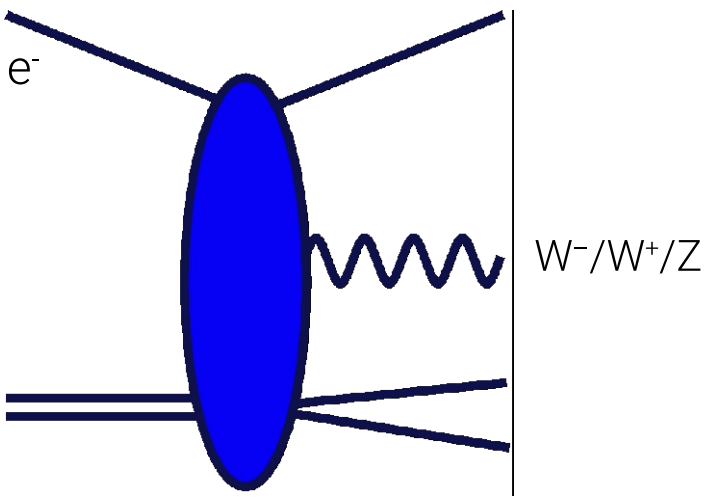
- *HL-LHC–PDF reduces uncertainty by 10-25%*
- *LHeC–PDFs reduces PDF uncertainties by an additional factor of 5*

Direct *W* and *Z* production

$e^-p \rightarrow \nu_e + V + X$



$e^-p \rightarrow e^- + V + X$

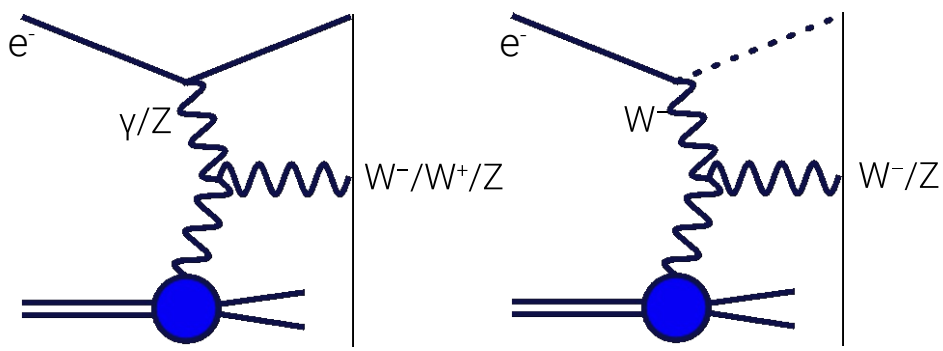


Total cross sections:	$e^-p \rightarrow W^+X$	~O(14pb)
	$e^-p \rightarrow W^-X$	~O(15pb)
	$e^-p \rightarrow ZX$	~O(5pb)

Direct *W* and *Z* production

U. Baur, et al, Nucl. Phys. B 375 (1992) 3
R. Li, et al., PRD 97 (2018) 075043
LHeC, J.Phys.G 48 (2021) 110501

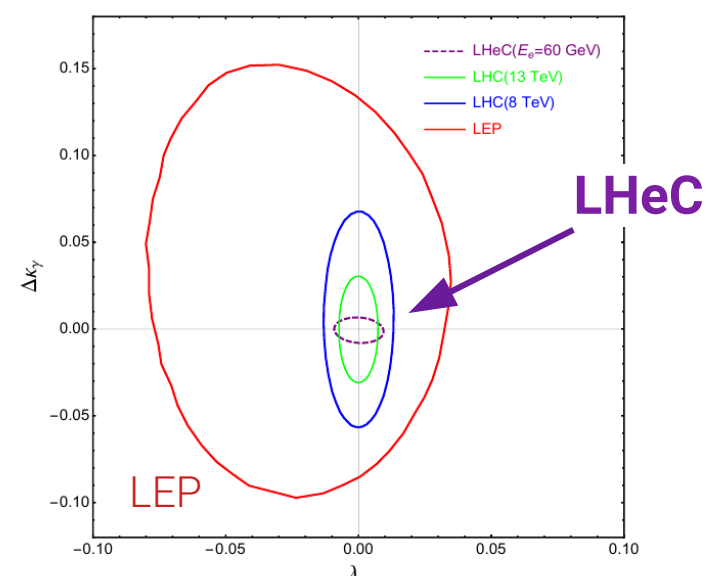
W and Z-boson production through 5 production channels in electron-proton scattering
Important VBF channels:



Sizeable (fiducial) cross section with leptonic decay

Process	$E_e = 50\,\text{GeV},\ E_p = 7\,\text{TeV}$ $p_T^e > 10\,\text{GeV}$	$E_e = 60\,\text{GeV},\ E_p = 7\,\text{TeV}$ $p_T^e > 10\,\text{GeV}$	$E_e = 60\,\text{GeV},\ E_p = 7\,\text{TeV}$ $p_T^e > 5\,\text{GeV}$
$e^- W^+ j$	1.00 pb	1.18 pb	1.60 pb
$e^- W^- j$	0.930 pb	1.11 pb	1.41 pb
$\nu_e^- W^- j$	0.796 pb	0.956 pb	0.956 pb
$\nu_e^- Z j$	0.412 pb	0.502 pb	0.502 pb
$e^- Z j$	0.177 pb	0.204 pb	0.242 pb

With 1ab^{-1} of LHeC data
O(0.5 – 1.5 million events)
→ high sensitivity to aTGC

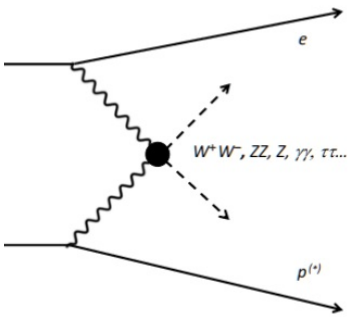


→ Sensitivity to: $\Delta\kappa_\gamma$ and λ_γ

LHeC as a very unique, generic high energy γγ collider

Wide spectrum of γγ processes will be studied at the LHeC

- *$\gamma\gamma \to \gamma\gamma$: orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging ⇒ kinematic fitting*
- *$\gamma\gamma \to \tau^+\tau^-$: orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging ⇒ new decay modes*
- *$\gamma\gamma \to Z$: search for the anomalous single Z boson exclusive production*
- *$\gamma\gamma \to ZZ$: possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, $ZZ \to l^+l^-jj$*
- *$\gamma\gamma \to W^+W^-$: measurements of semi-leptonic decay modes, $W^+W^- \to l\nu jj$, will allow for a use of Optimal Observable methods (even with single γγ tagging) for probing aQGCs; yet high statistics (≈ as at the HL-LHC) is expected for fully leptonic W^+W^- decays + tagging*

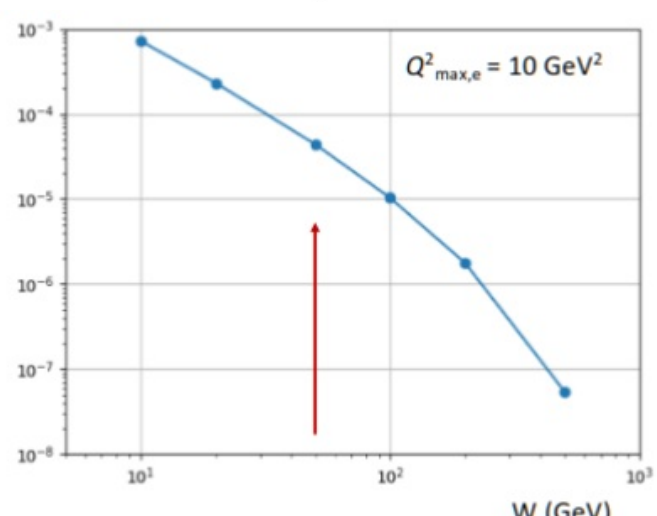


Large statistics:

⇒ > 100 000 W boson pairs produced at 1 ab^{-1}

≈ 20 000 for $W > 500$ GeV

Inelastic production dominant

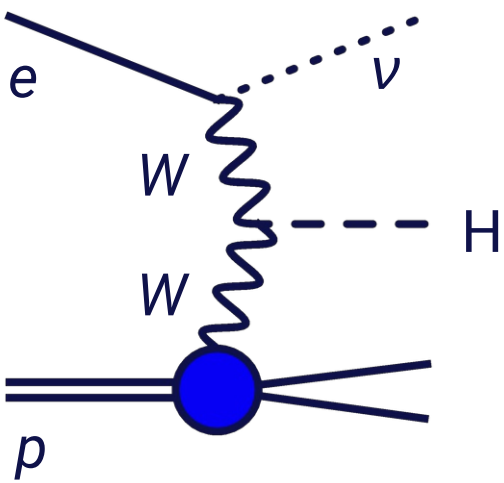


For $W < 50$ GeV the *fully* exclusive γγ luminosity spectrum is **higher** at the LH*e*C than at the HL-LHC!

K. Piotrzkowski, Y. Yamazaki, in preparation

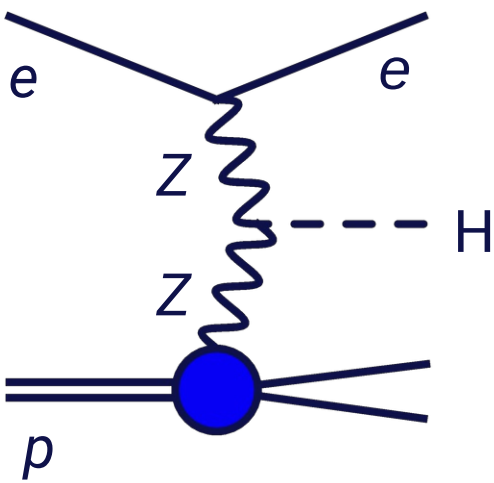
Higgs physics

Charged current



Higgs production through *WW*-fusion

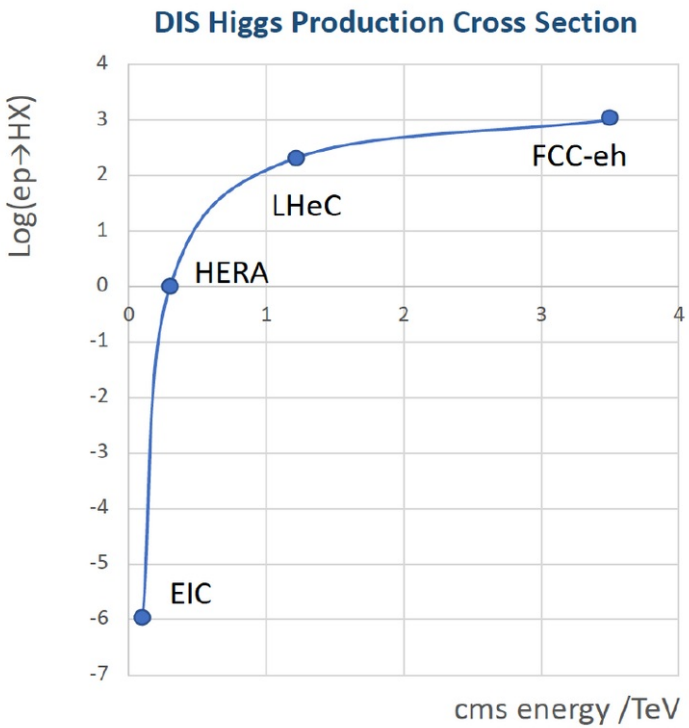
Neutral current



Higgs production through *ZZ*-fusion

Higgs physics

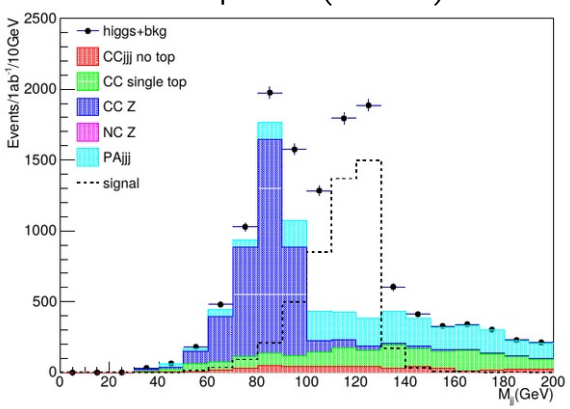
U. Klein, M. Kumar, et al. LHeC JPhysG 48 (2021) 11050
S. Behera, B. Brickwedde, M. Schott [arXiv:2201.04037]



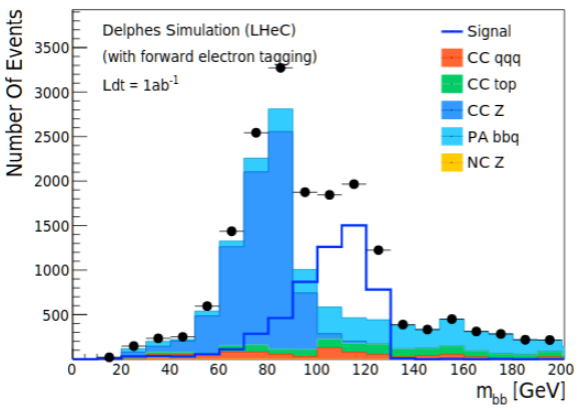
$ep \rightarrow H + \nu + X \rightarrow bb + \nu + X$

Studies with full data-analyses of simulated data

Delphes (LHeC)



Full sim using ATLAS

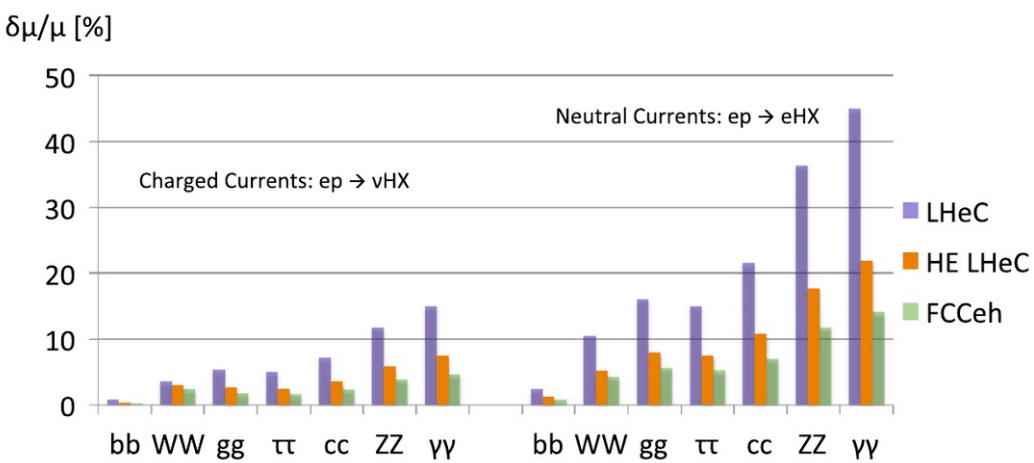


Higgs-production cross section ~200fb
Sensitivity to the decay channels
bb, *WW*, *gg*, *ττ*, *cc*, *ZZ*, *(γγ)*

→ simulations show great signal over background ratio
→ symmetric detector is possible
→ Prospects validated with 'real' detector

Higgs physics – interpretation in κ framework

Signal strength in all decay channels

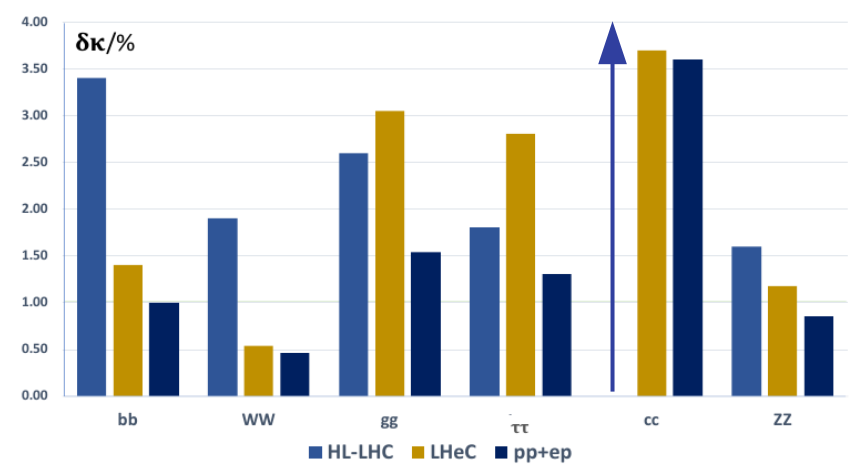


High sensitivity in all six decay channels
→ Significant improvement with increasing √s

HWW and *HZZ* signal strengths measured at once in DIS via selection of the final state (e or ν)

Interplay between *pp* and *ep*

(shown here: LHeC & HL-LHC)



Complementarity between *pp* and *ep*

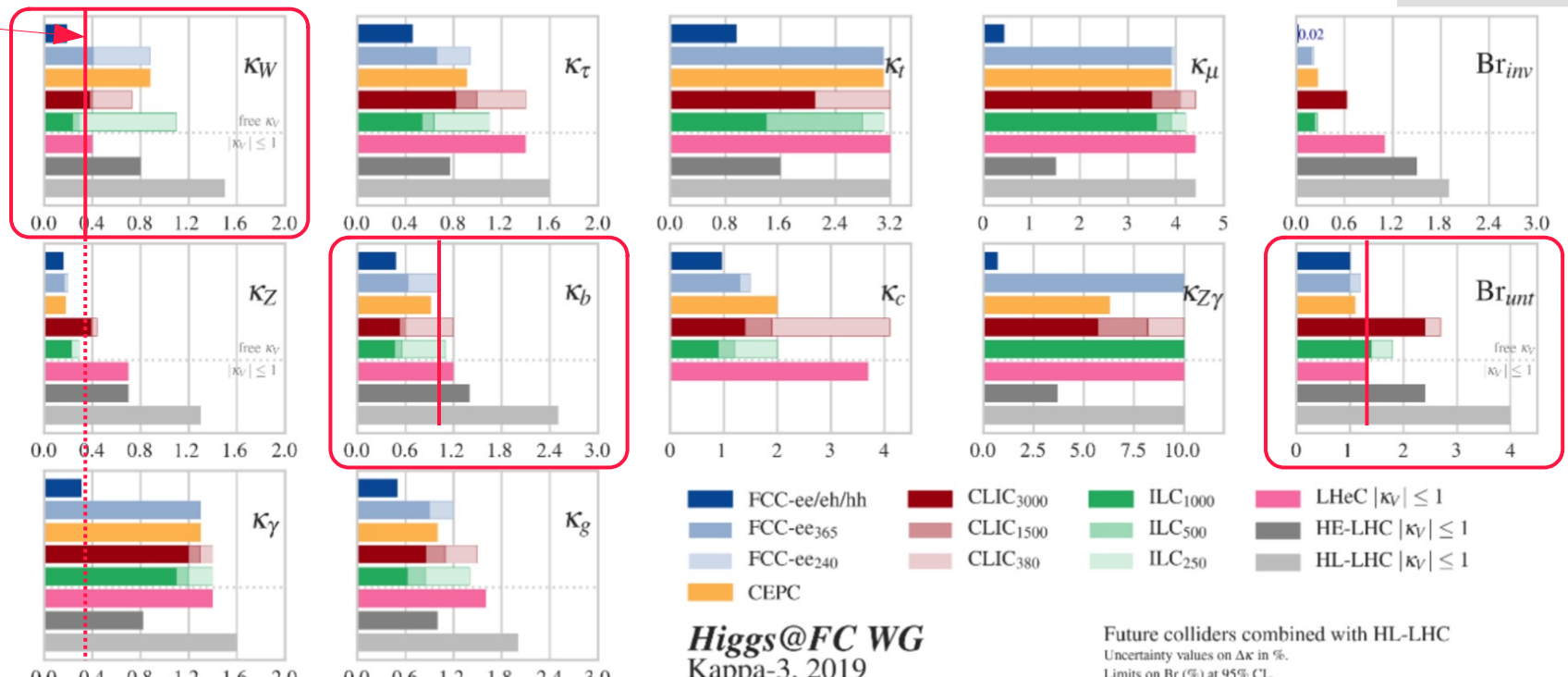
- *ep*: *bb*, *WW*, *ZZ*, *cc*
- *pp*: *gg*, *ττ*, *γγ*

LHeC with superior precision for H→ ff and H→VV

Future competition: *ee*, *pp* and/or *ep*

J. de Blas, JHEP01(2020)139

LHeC+
HL-LHC



LHeC with high(est) constraints on

- *H → ff (bb, Yukawa)*
- *H → VV (WW, EWSB)*
- *H → 2nd gen. (cc)*

LHeC

- *Complementary with HL-LHC*
- *Data in '30s*
- *1/10 of the cost than FCC or ILC*

Summary

LHeC & FCC-eh projects

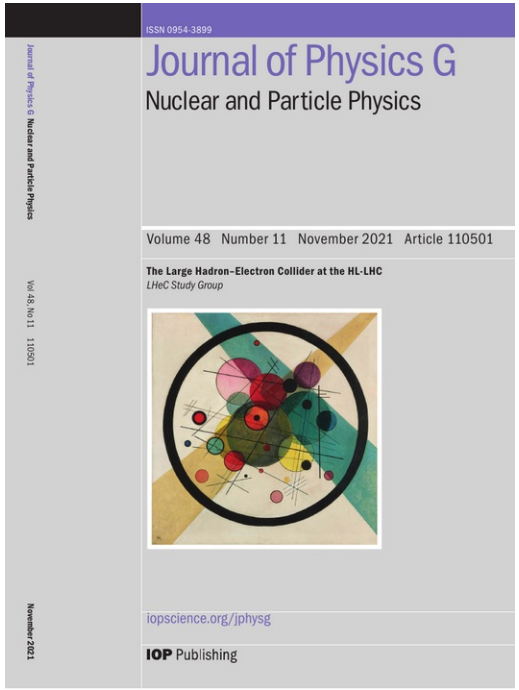
- *LHeC: 60 GeV electron times 7TeV proton (√s=1.3TeV),*
- *FCC-eh: 60 GeV electron times 50TeV proton (√s=3.5TeV),*

Electroweak physics at LHeC & FCC-eh

- *Fundamental EW parameters: Competitive with (HL-)LHC/LEP*
- *Complementary measurements to Z-pole data*
- *Unique measurements of scale dependence of EW interactions*
- *EW physics at HL-LHC needs LHeC-PDFs*
- *O(millions) directly produced W and Z-bosons → aTGC*
- *Outstanding γγ collider prospects → aQGC*
- *Extraordinary Higgs program*
  - *High precision to H→VV through HWW vertex*
  - *High precision to H→ff through Hbb vertex*

  → Feasibility studies with fast and full detector simulations

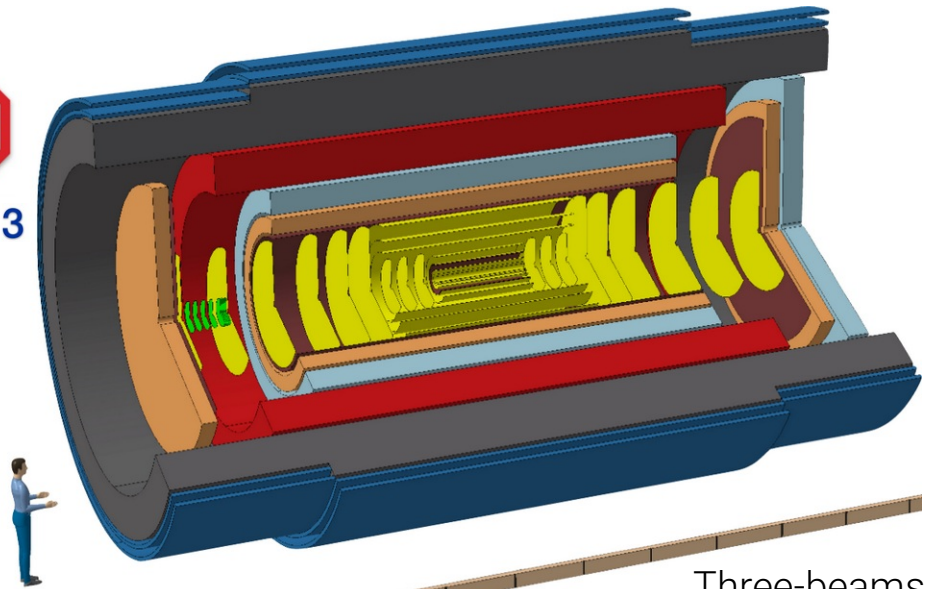
Update of LHeC-CDR
JPhys.G 48 (2021) 110501

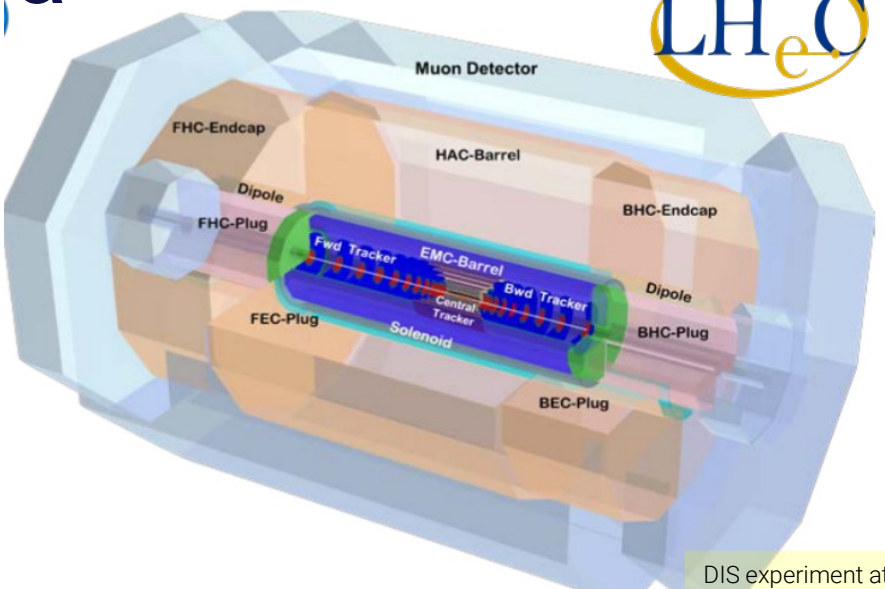


Backup

LHC-Point 2 in HL-LHC era

ALICE 3



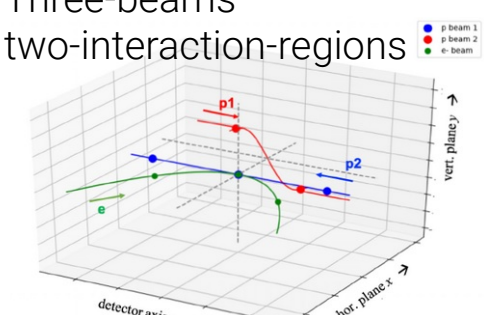


DIS experiment at the HL-LHC
EPJ C82 (2022) 40

ALICE3

- HI physics
  - QGP, fluid expansion
  - Color-glass condensate
  - HQ transport, Thermalisation, Hadronisation

Three-beams
two-interaction-regions



LHeC

- Higgs
- EWK
- PDFs (for HL-LHC)
- BSM
- Top
- small-x
- eA
- ALICE3 (pp, AA)

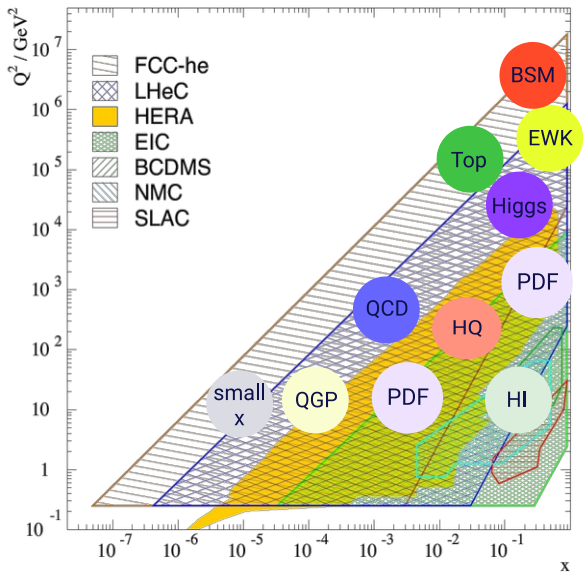
What may happen with a ~ 4-times better calibrated energy-scale from NC DIS in-situ calibration?

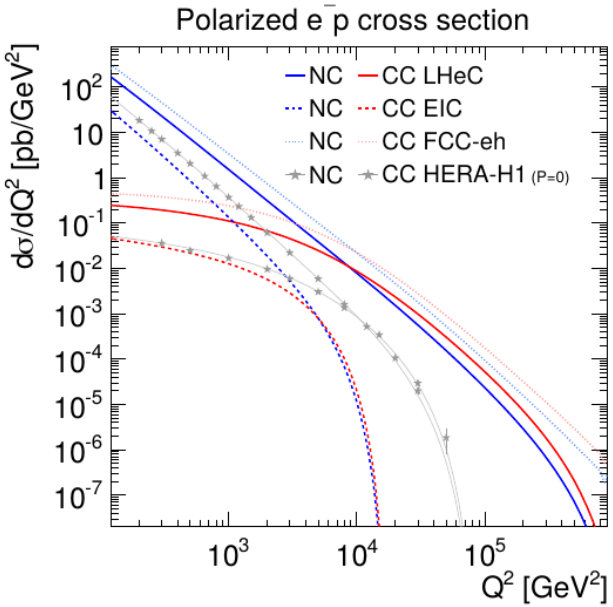
Deep-inelastic electron-proton scattering

C. Rubbia in 1992 CERN open council meeting when LHC was approved

- Further progress needs higher energy – 1 TeV is next major goal
- Proton-proton collisions are the only open road to 1 TeV now
- LHC – most cost effective route
  – heavy ion and ep collisions as bonus

LHC must be the next project for CERN

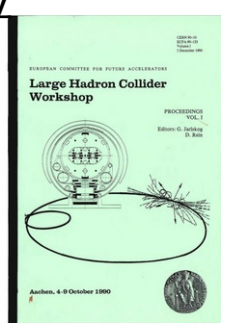




LHeC history

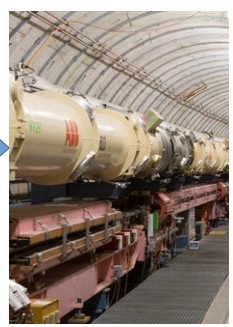
LEP×LHC → 1984

s ~√1.3TeV
L ~ 1fb^{-1}/y



HERA *ep* → 1992

s ~√0.3TeV
L ~ 0.5fb^{-1}



LHC × e$^-$ → 2012

s ~√1.5TeV
L ~ O(100fb^{-1})

HL-LHC×ERL & Higgs → 2020

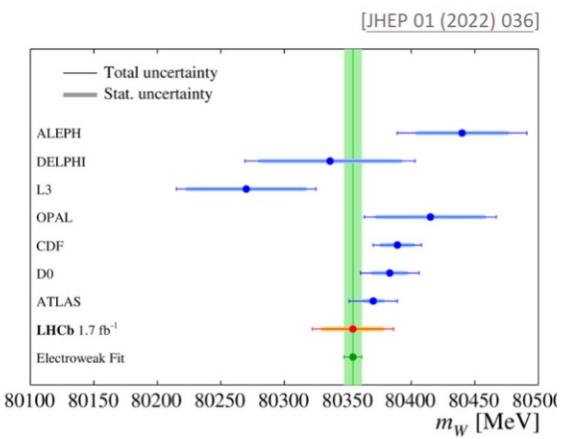
s ~√1.3TeV
L ~ 1 ab^{-1}

LHeC → '30

δm_W with LHeC input

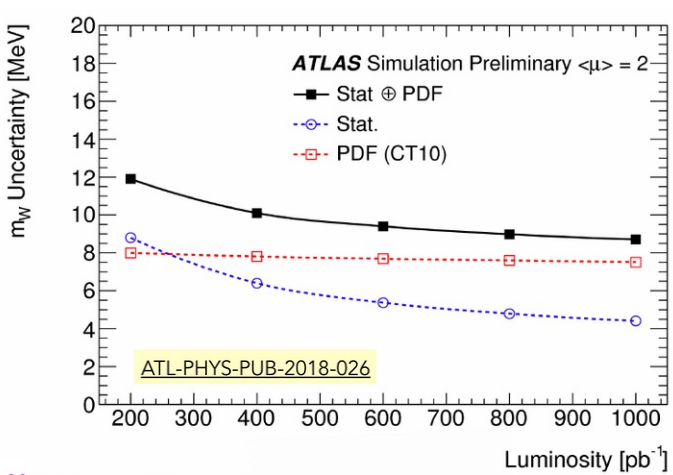
- m_W milestone measurements for consistency of SM and BSM searches
- Study of potential of m_W measurement with low pile-up runs

LHCb measurement

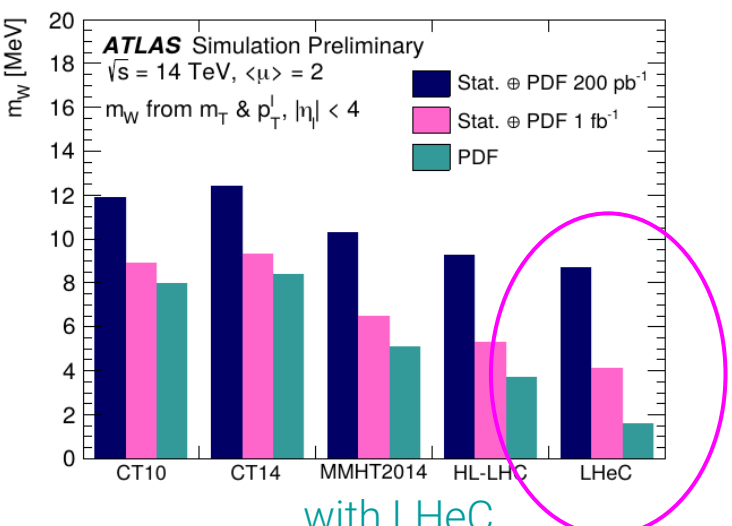


$m_W = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV

ATLAS low-<μ> prospects



ATLAS low-<μ> HL-LHC prospects

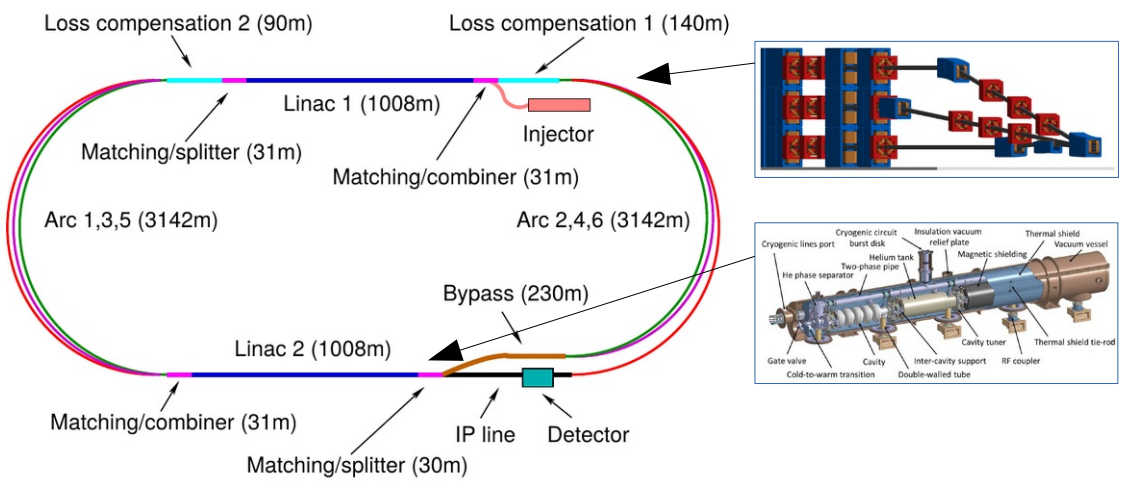


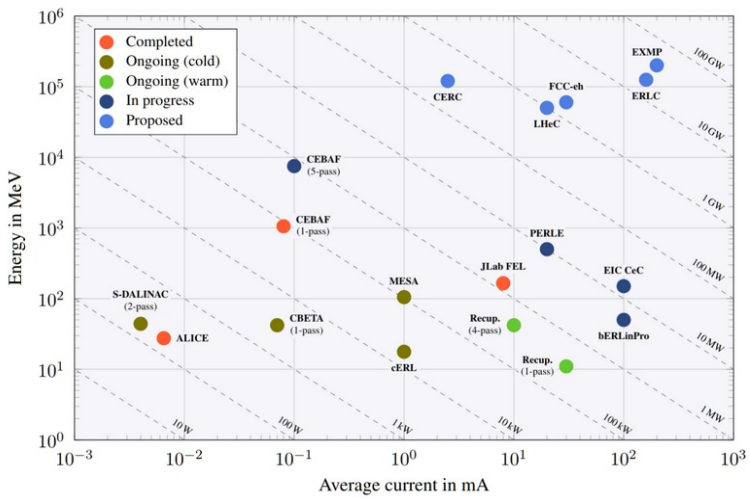
Large theory uncertainty originates from knowledge of PDFs
Similar size than experimental uncertainties

At HL-LHC, PDFs are expected to become the largest indiviual uncertainty
HL-LHC PDFs will reduce that, but will remain a limiting uncertainty
With LHeC PDFs, the W-mass measurements will be exceed LEP precision

The Energy Recovery Linac – ERL

Energy-recovery linacs (ERL)
→ Well-proven accelerator concept

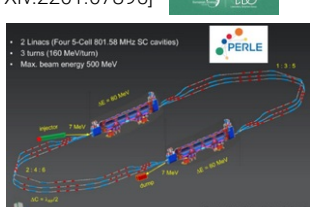


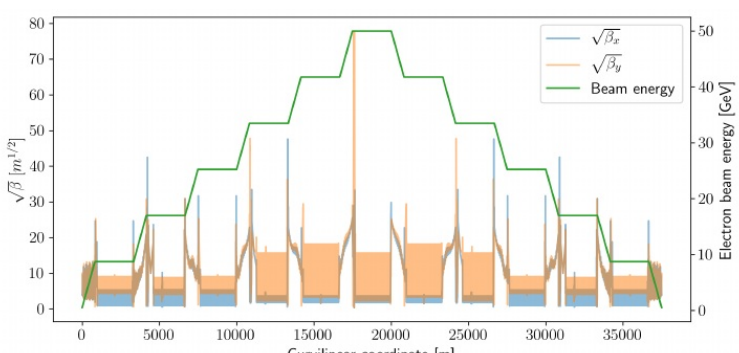


→ high-current & high-energy & multi-pass
→ optimised cavities & cryo-modules and a beam for collider experiments

Accelerator R&D Roadmap [arXiv:2201.07895]

PERLE at Orsay: ERL demonstrator facility for FCC-eh/LHeC needs 20mA, 802 MHz SRF, 3 turns
→ operation 2025+





β-functions and beam-energy for 3-turn ERL

Concurrent *eh* & *hh* Operation

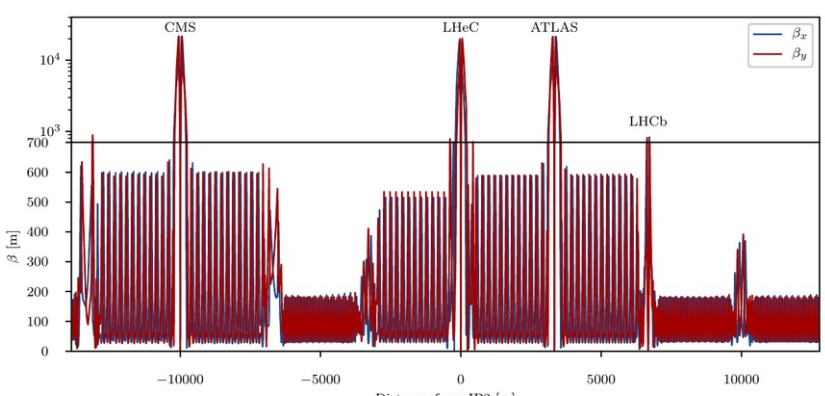
N. Armesto, et al., EPJ C82 (2022) 40

Two HL-LHC operation modes

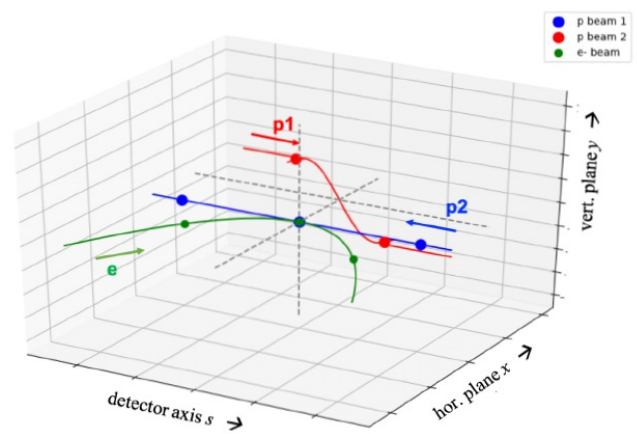
- *hh* collisions at IP1,2,5,8 – no e beam
- *eh* collisions at IP2 and *hh* at IP1, 5, 8
  → non-colliding *p*-beam: symmetric orbit bump & vert. crossing

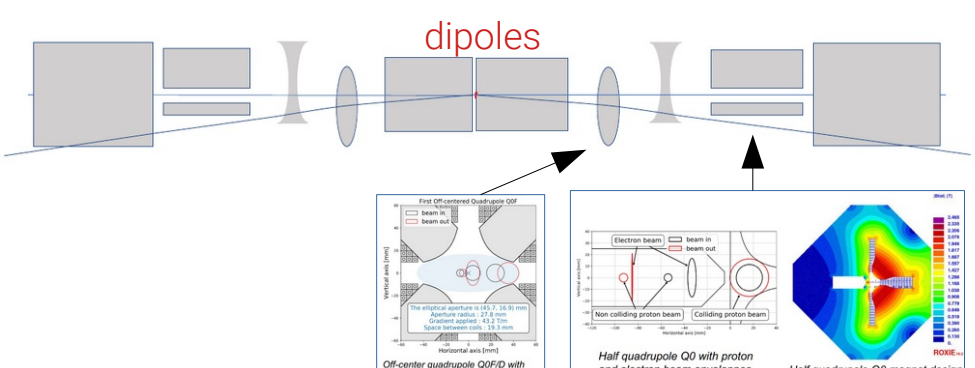
Three beam interaction region

- LHC proton beam optics



Schematic view of the three beams at IP2

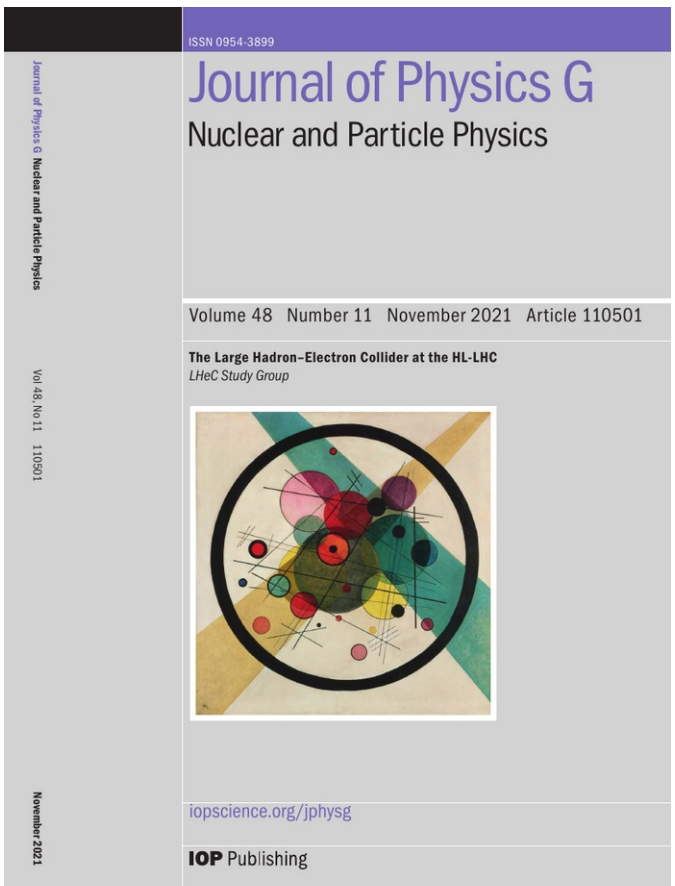




At IP2: same vertex for all interaction types (ep, eA, pp, AA) → optional hh running with LHeC-detector.

Update of the LHeC CDR 2020

- *Update of the CDR*
- *373 pages about*
  - *Partonic structure of the proton*
  - *QCD studies, α_S, low-x, diffraction*
  - *Electroweak and top-quark physics*
  - *Nuclear physics*
  - *Higgs in DIS*
  - *BSM*
  - *Impact on the HL-LHC*
  - *Accelerator (Energy recovery linac)*
  - *PERLE facility*
  - *LHeC Detector*



Update of LHeC-CDR
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