Top and EW Physics at the LHeC and FCC-he

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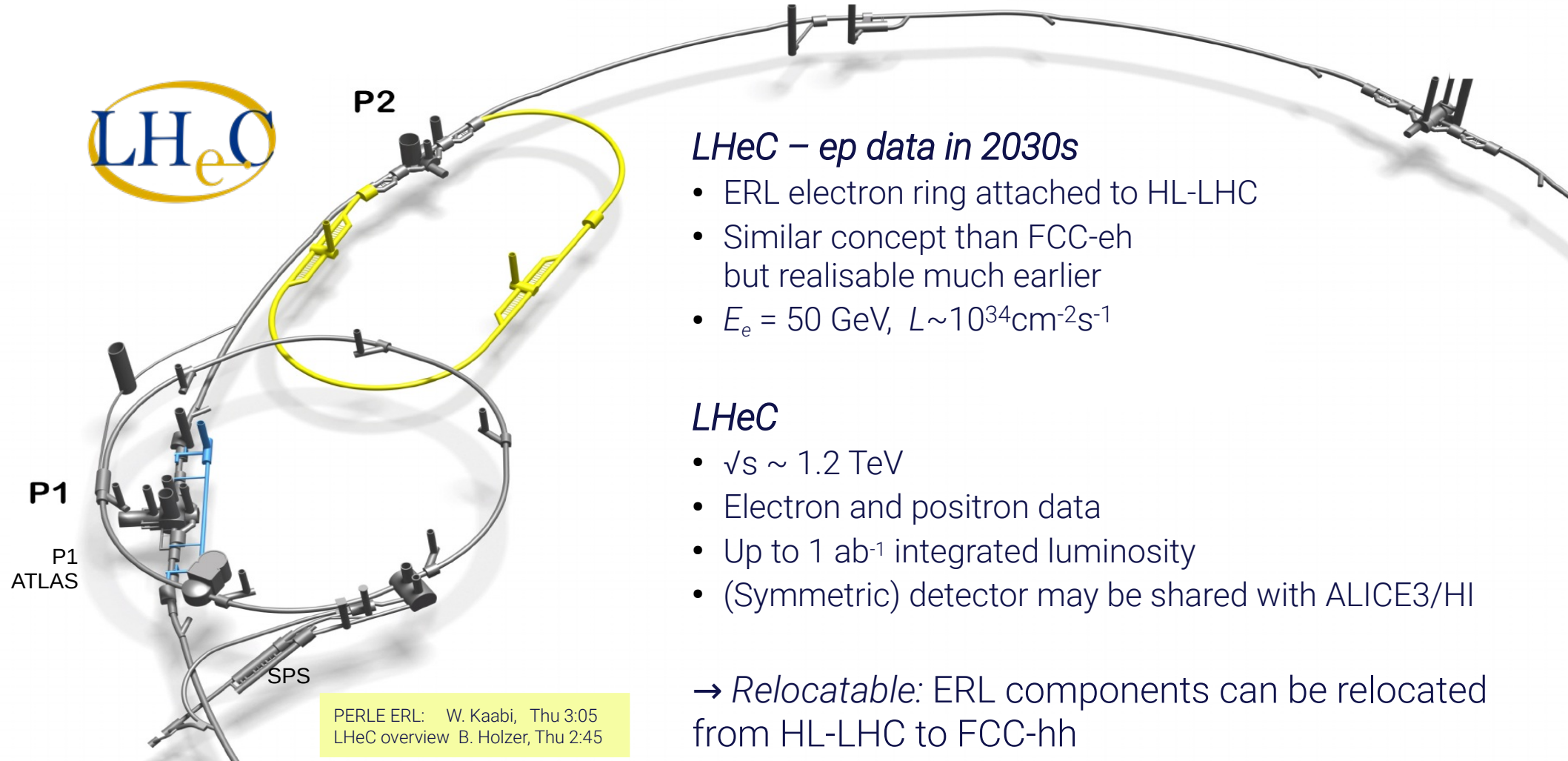
ICHEP22
Bologna, Italy
08.07.2022

MAX-PLANCK-INSTITUT
FÜR PHYSIK

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



PERLE ERL: W. Kaabi, Thu 3:05
LHeC overview B. Holzer, Thu 2:45

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, $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$

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

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

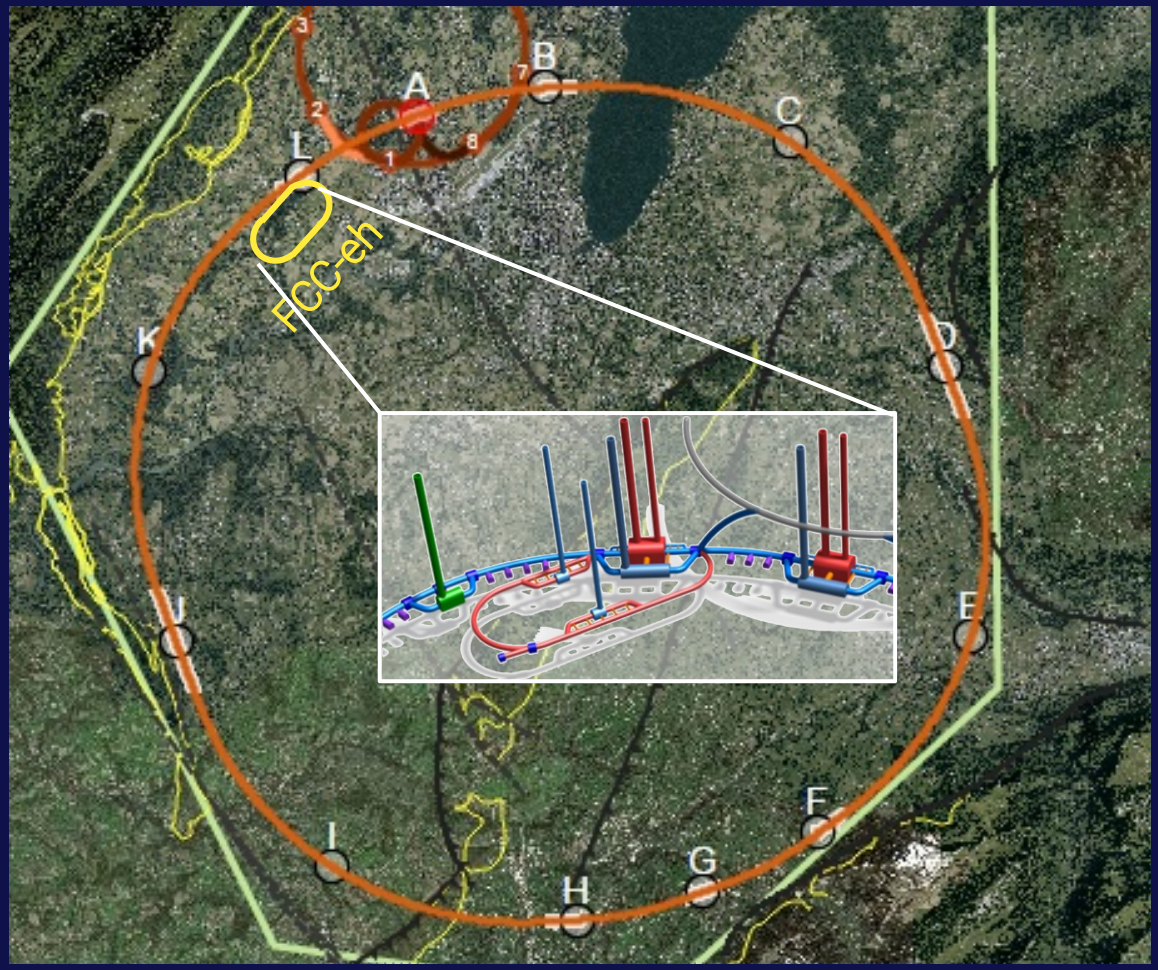
FCC-eh

Dedicated electron-ring attached to the FCC-hh

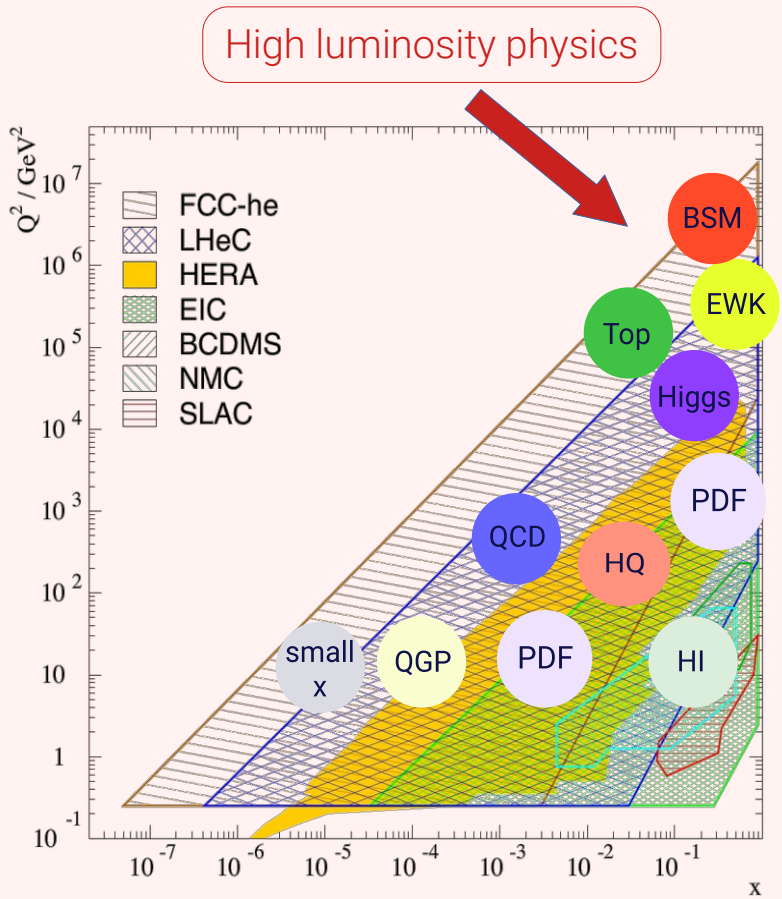
Energy recovery linac
E_e = 60 GeV
$\sqrt{s}$ ~ 3.5 TeV

High Luminosity of about 3 ab^{-1}

Concurrent operation with FCC-hh



Deep-inelastic scattering



DIS: Cleanest High Resolution Microscope
→ Extraordinary QCD laboratory
→ Precision QCD and matter
→ QCD Discoveries
→ talk by C. Gwenlan, Sat, 5:30pm

Empowering the HL-LHC & FCC-hh Search Programme

Transformation of HL-LHC & FCC-hh into the desired Higgs and discovery machine
→ talk by O. Fischer, Sat, 5:30pm

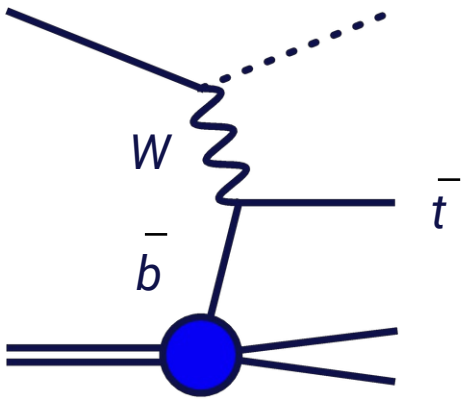
Unique Facility for Nuclear Physics
→ talk by N. Armesto, Thu, 12:25

Unique and complementary Higgs Programme
→ talk by U. Klein, Fri, 3:00pm

Top and EW Physics

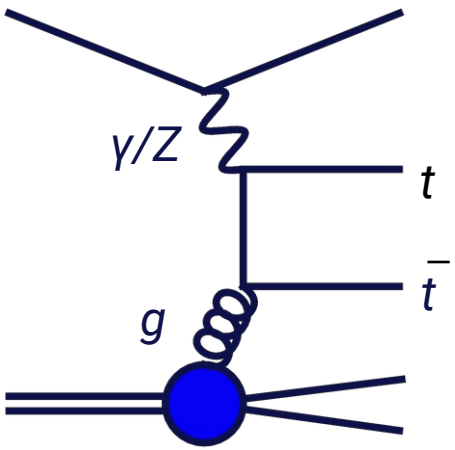
Top quark production in *ep*

CC DIS single-top quark production



LHeC σ~ 1.9pb
FCC-eh σ~15.3pb

NC (γp) top-quark pair production

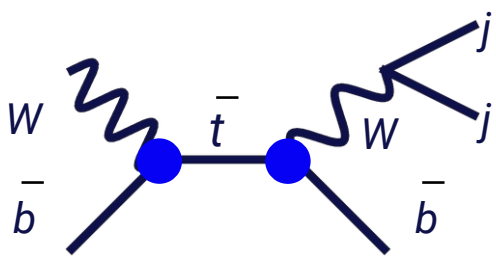


LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

Other channels are: top-quark pair in DIS (~0.6pb), single-top in DIS and *γp*

$|V_{tb}|$ in CC single-top production

Direct measurement of $|V_{tb}|$

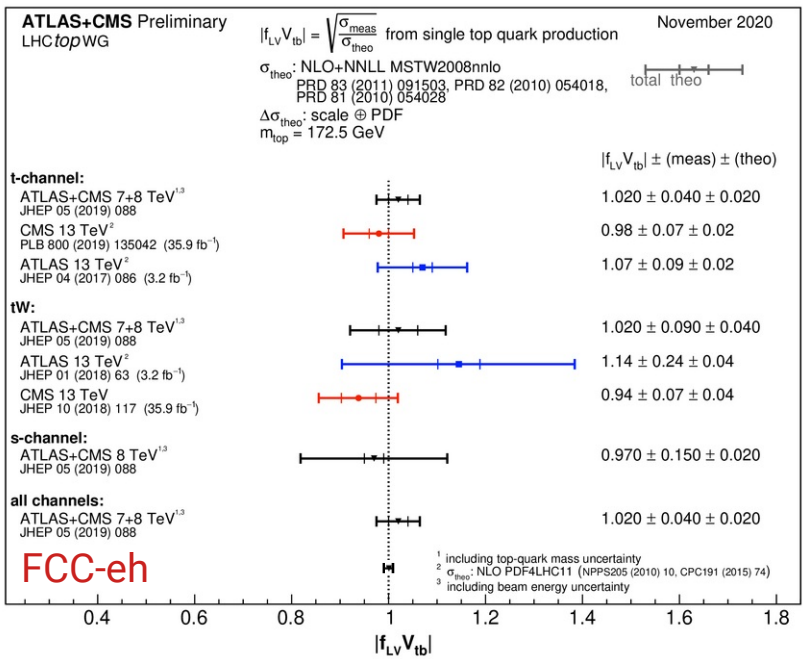


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cut-based pseudo-analysis in hadronic channel incl. backgrounds

→ Estimated precision on V_{tb} below 1% precision

→ Limits on anomalous *Wtb* couplings: < 0.01

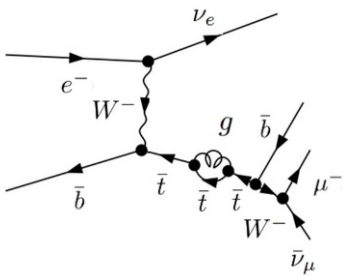


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$|V_{ts,td}|$<0.04 (@FCC-eh)

Many further subjects in top-quark sector: top-quark polarization, top-PDFs, CP-properties of *ttH* couplings, top-charge, anomalous tt-X couplings, ...

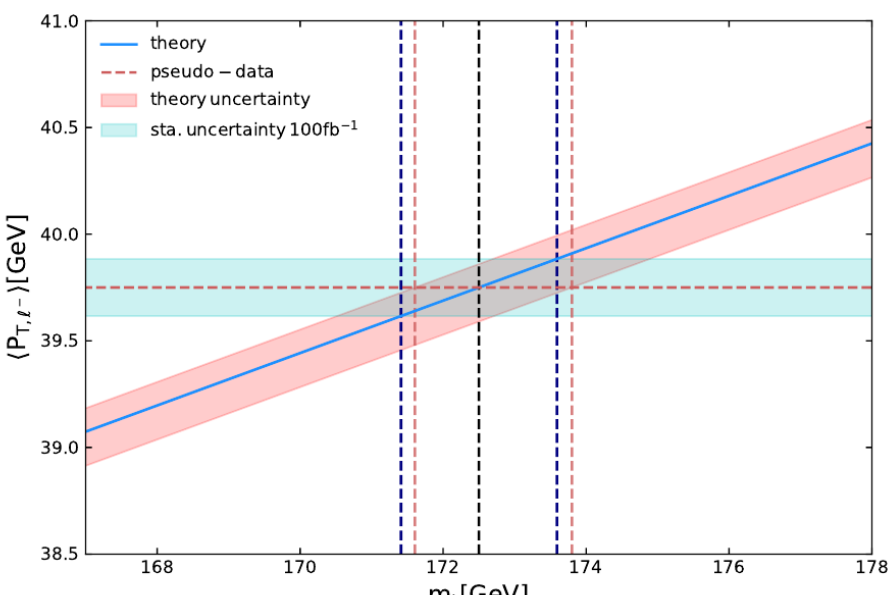
CC single-top production at NLO

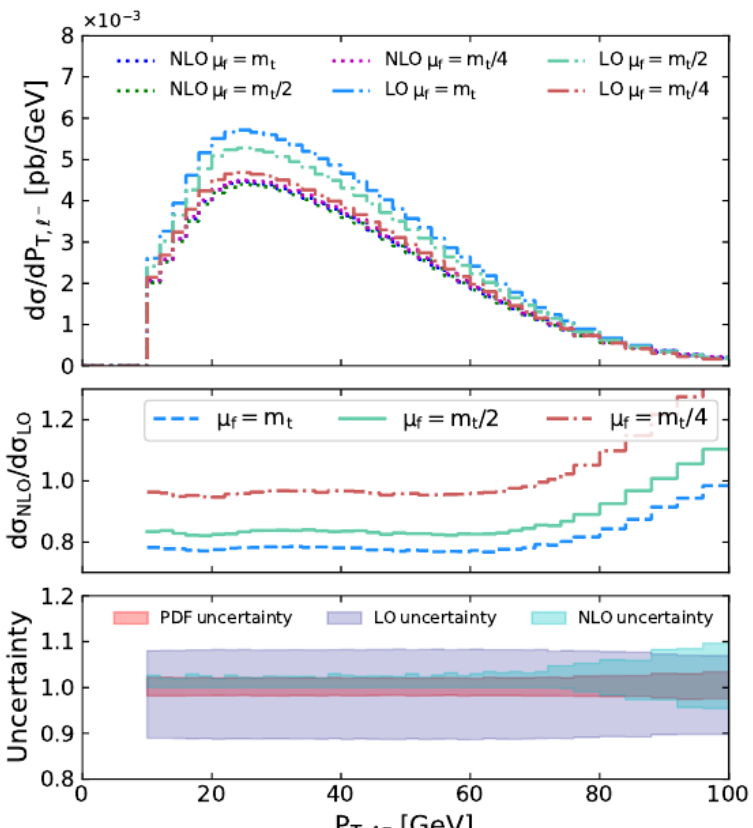


Recent calculation of single-top production at NLO

M. Gao, J. Gao,, Phys.Rev.D 104 (2021) 5, 053005

- *Negative NLO k-factor*
- *Good perturbative stability at NLO*
- *After (quite tight) fiducial cuts: σ ~ 0.2 pb*
- *theoretical uncertainties negligibly small in top-mass determinations*



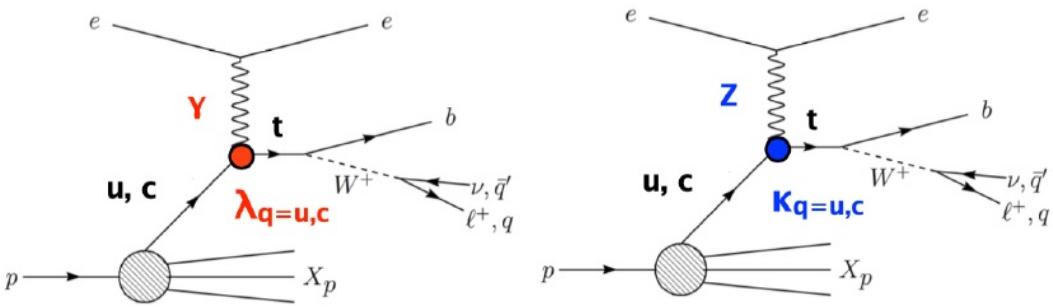


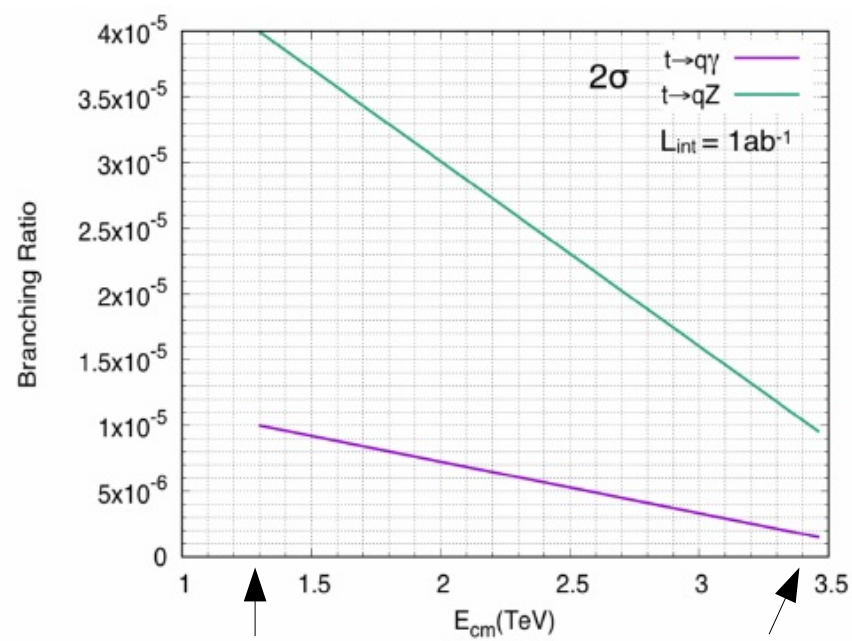
Search for anomalous FCNC

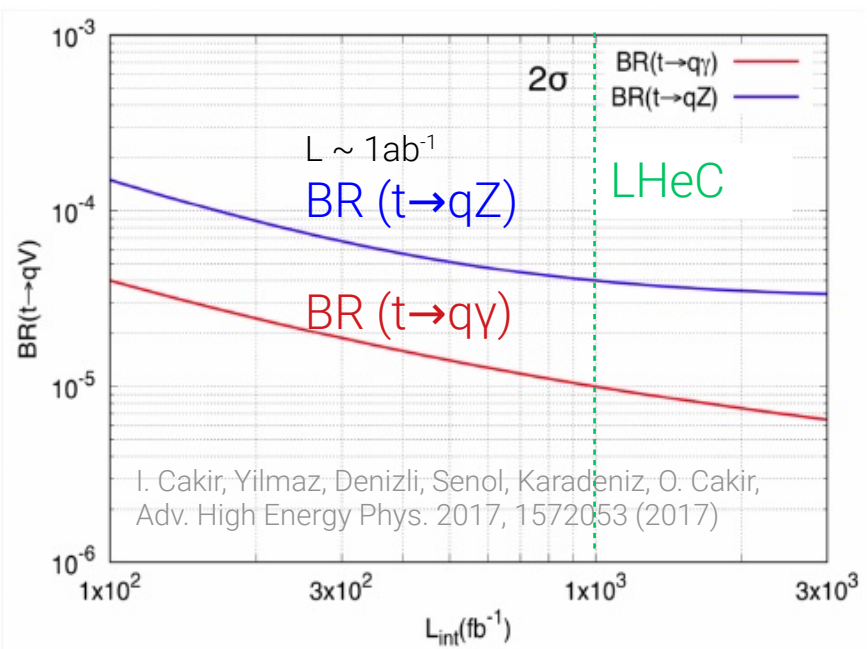
t-quark flavor changing neutral currents

→ Highly suppressed in SM

- Study tqγ and tqZ effective FCNC
- Expected limits vs. √s and int. luminosity







Top quark branching fractions

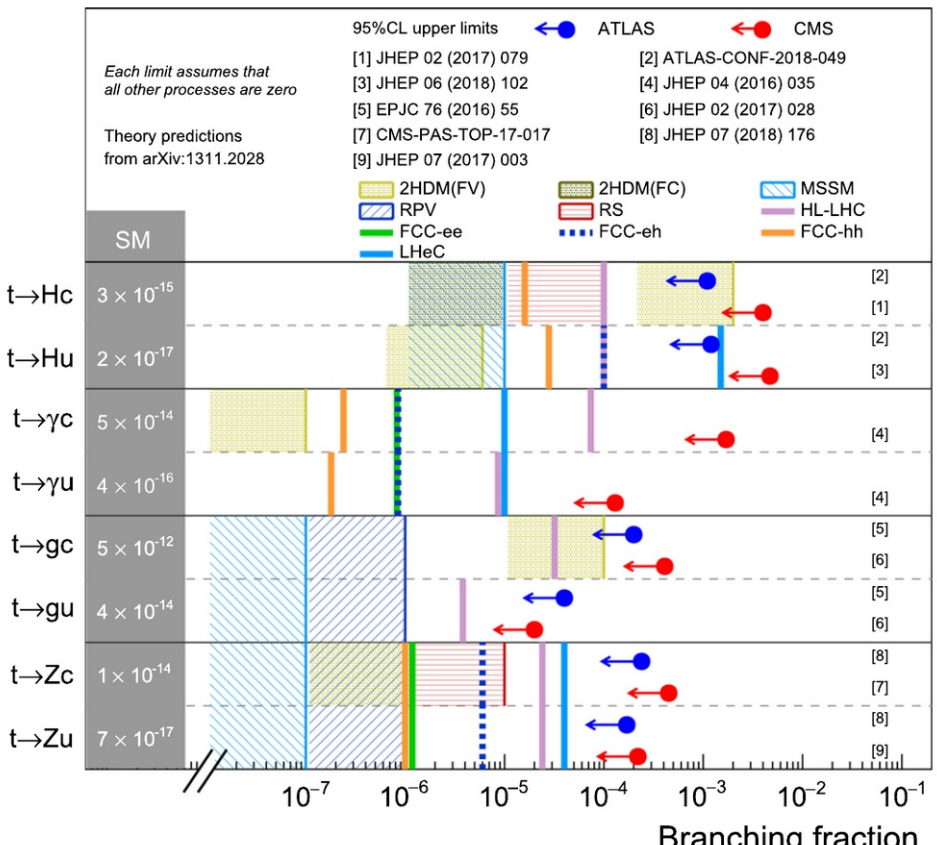
Top quark branching fractions
- Searches for FCNC
- 95% C.L.

Compare future experiments
- FCC-ee
- FCC-hh
- FCC-eh

- LHeC
- HL-LHC (3000 fb^{-1})
- ILC/CLIC

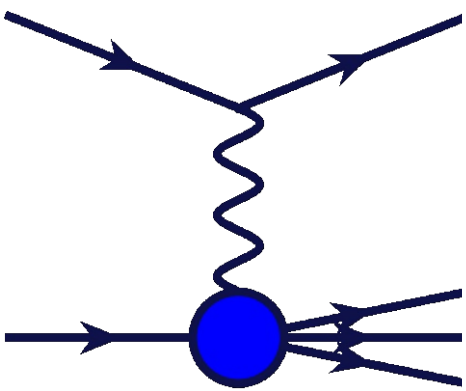
+ various theory predictions

pp, *ep* and *ee*
- LHeC complements HL-LHC in '30s
- FCC ee/hh/eh compete

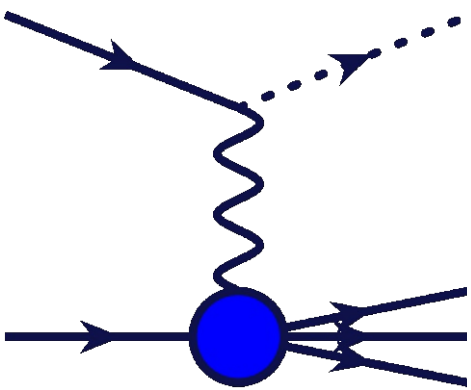


Electroweak physics in deep-inelastic scattering

Neutral current DIS
$ep \to e + X$



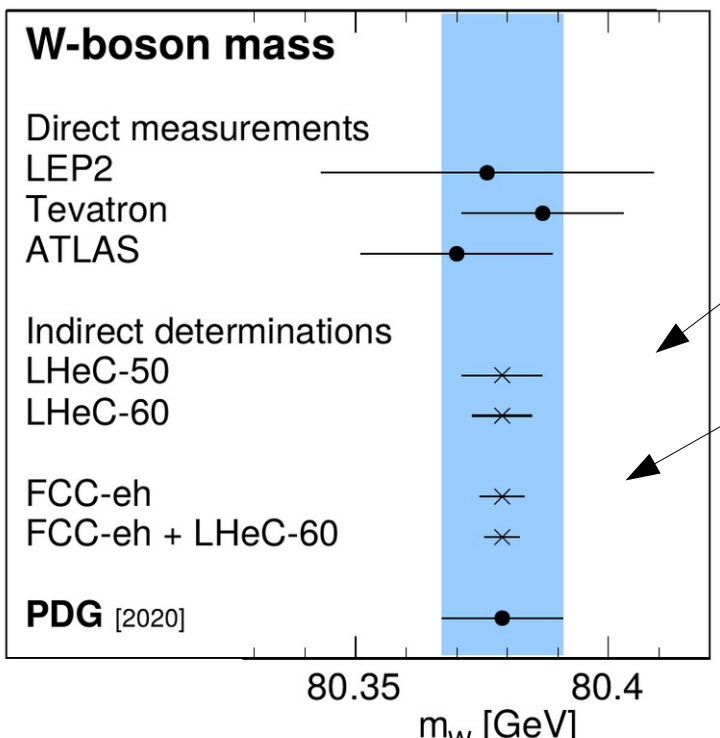
Charged current DIS
$ep \to \nu + X$



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

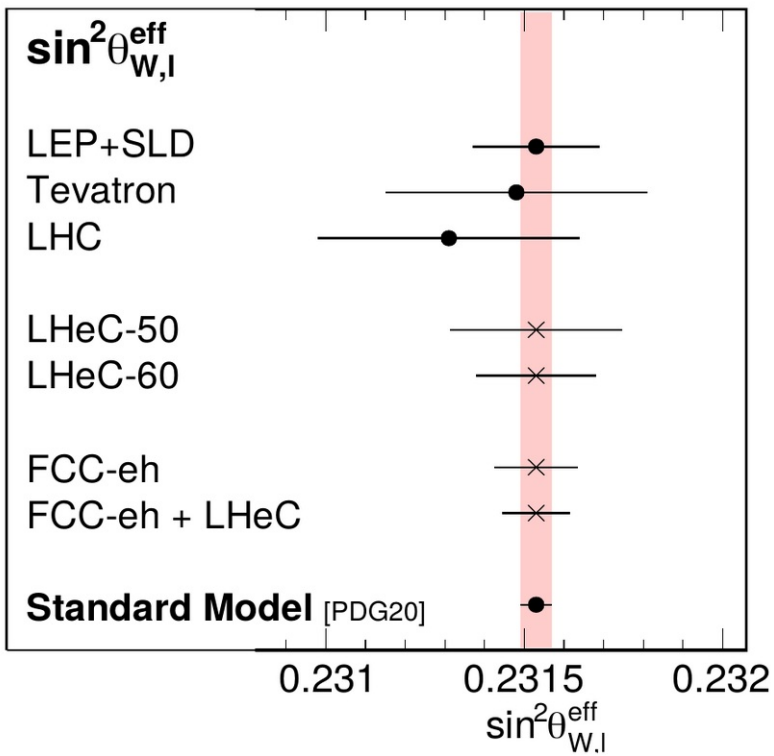
Expectations: m_W + PDF

Determine W-boson mass together with proton-PDFs



- LHeC with *L ~ 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 ~ 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*

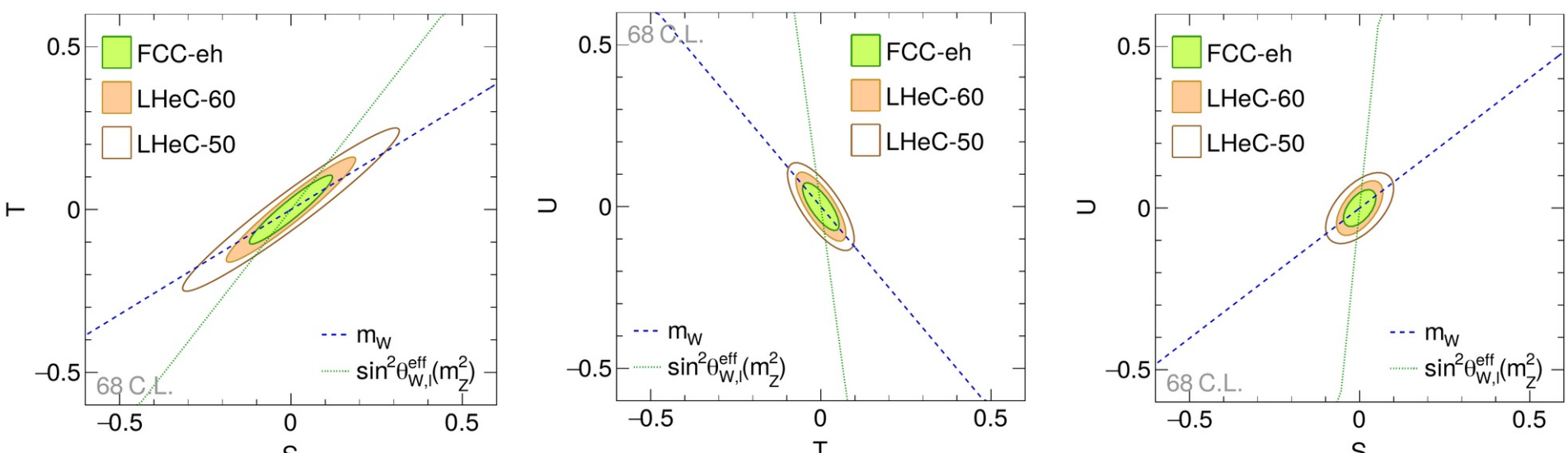
$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= $\pm0.00010_{(exp)}$ $\pm0.00004_{(PDF)}$

$\Delta\sin^2\theta_w$ (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



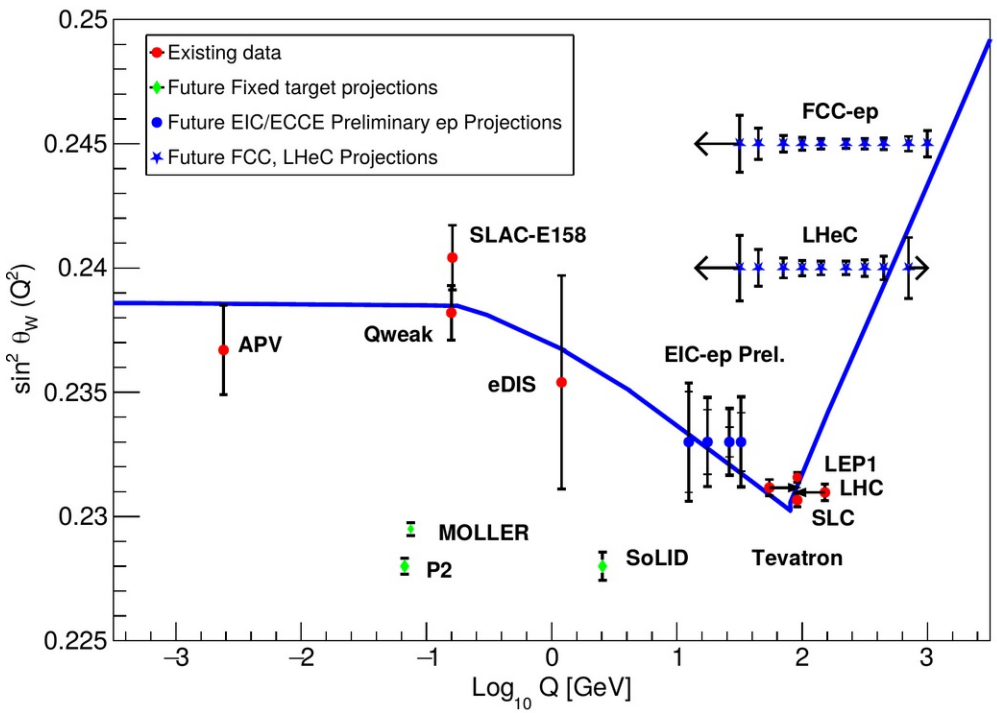
Scale dependent measurements

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



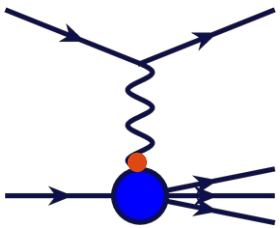
→ Unique measurement of the 'running' at high scales

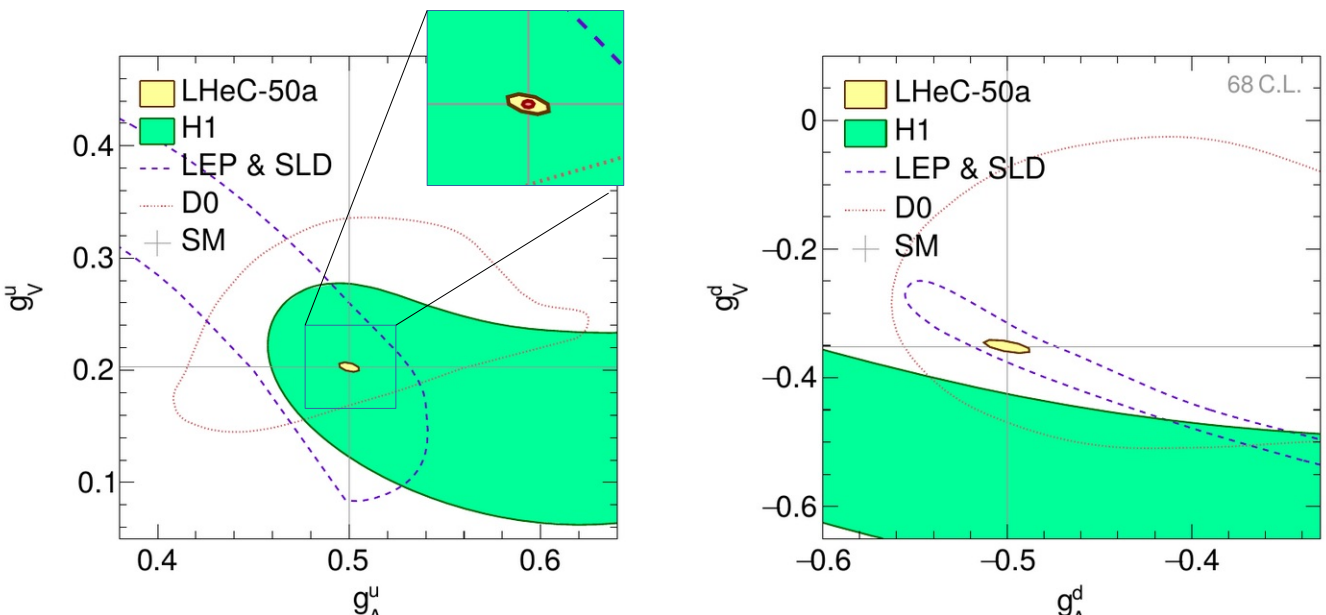
Electroweak physics

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

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





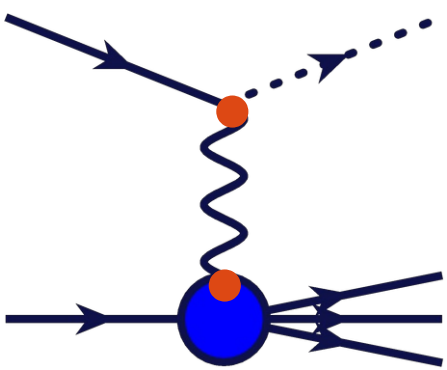
→ PDFs are not a limiting factor for EW physics
→ Also the scale dependence ('running') can be tested with high precision

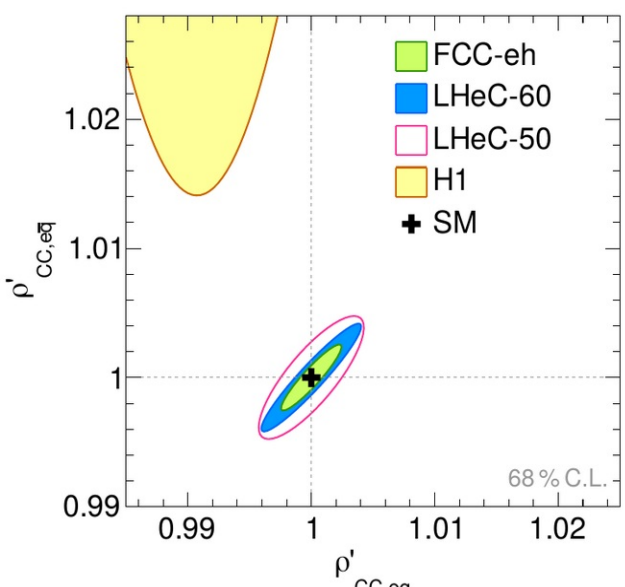
Weak couplings of the *W*-boson

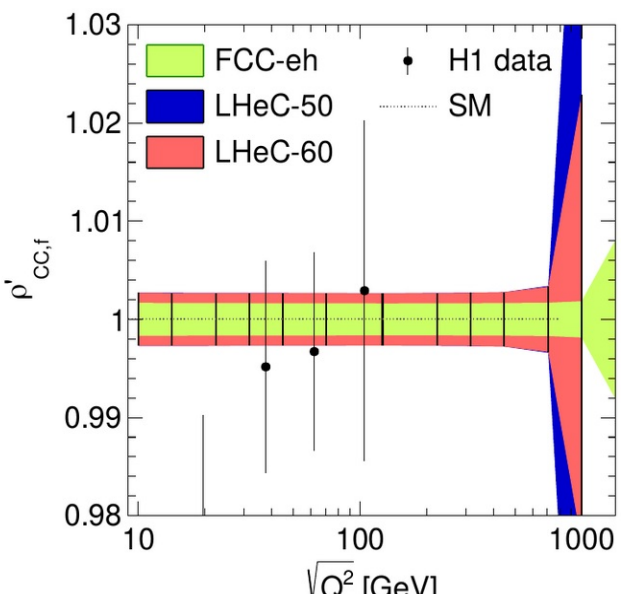
DB, M. Klein, H. Spiesberger,
Eur.Phys.J.C 80 (2020) 831
PoS(EPS-HEP2021)485

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







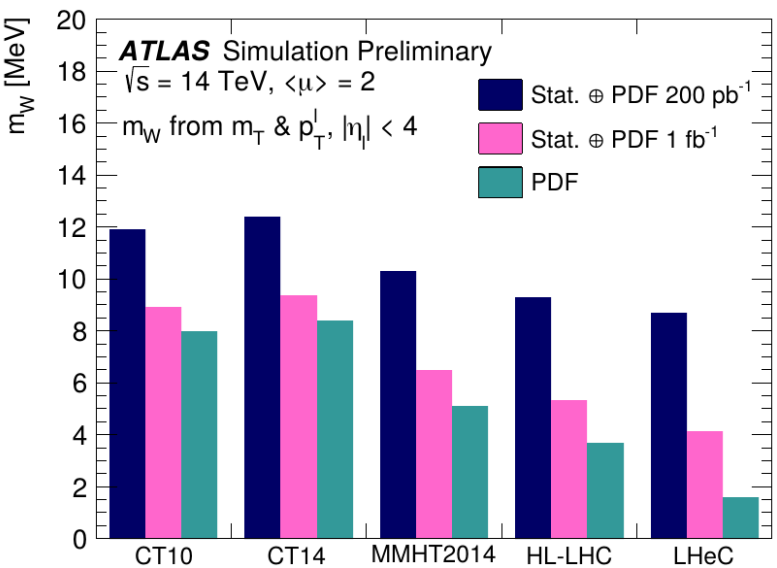
→ Weak couplings of the W-boson are precisely measured – even their scale dependence

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

The impact of LHeC on HL-LHC

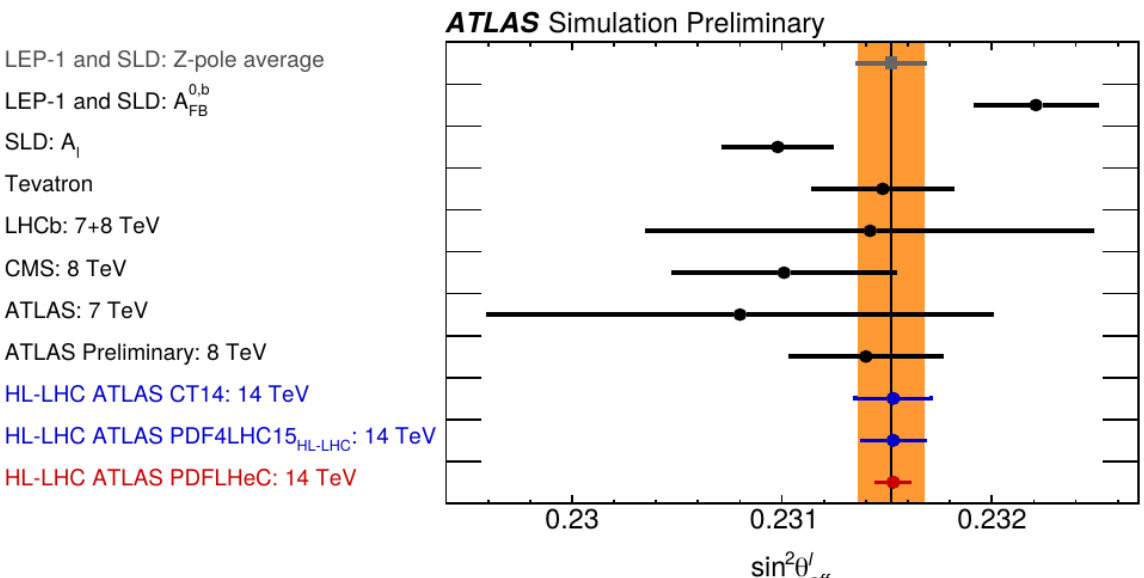
W-mass measurements in pp

- *Major uncertainty from PDFs*



Effective weak mixing angle in pp

- *Large uncertainty from PDFs*



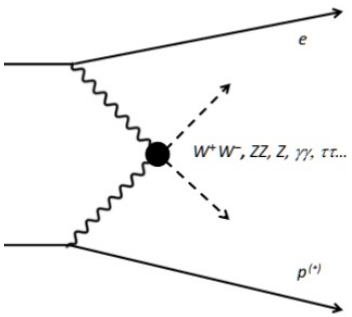
- *Reduction of PDF uncertainty only feasible with LHeC PDFs (Δm_W^{PDF}~2MeV)*

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

LHeC as a very unique, generic high energy γγ collider

Wide spectrum of γγ processes will be studied at the LHeC

- *γγ → γγ : orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging ⇒ kinematic fitting*
- *γγ → $\tau^+\tau^-$: orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging ⇒ new decay modes*
- *γγ → Z : search for the anomalous single Z boson exclusive production*
- *γγ → ZZ : possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, ZZ → l^+l^-jj*
- *γγ → W+W - : measurements of semi-leptonic decay modes, W+W- → lν 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*

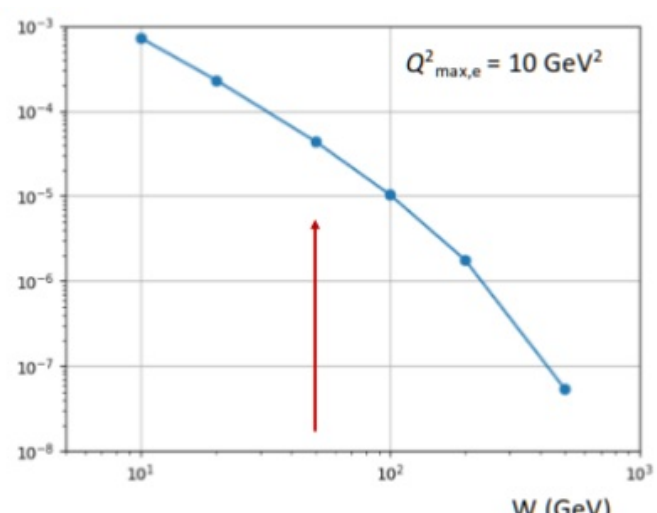


Large statistics:

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

≈ 20 000 for $W > 500$ GeV

Inelastic production dominant

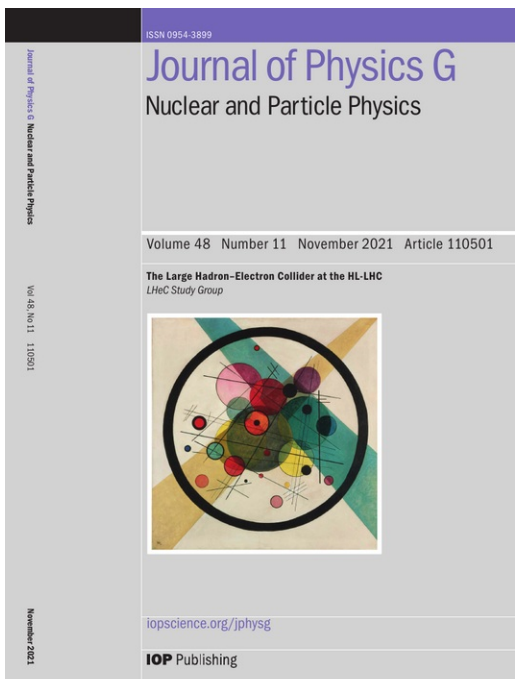


For $W < 50$ GeV the *fully* exclusive γγ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!

K. Piotrzkowski, Y. Yamazaki, in preparation

Summary

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



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),*

Top physics at LHeC/FCC-eh

- *Rich top-quark programme: Single-top factory |Vtb| (~1%),*
- *top quark couplings (Wtb, tty, ttZ, ttH, …), anom. couplings, FCNC, properties: polarisation, charge, PDFs; searches for new physics, CP violation in top-Yukawa, …*

Electroweak physics at LHeC/FCC-eh

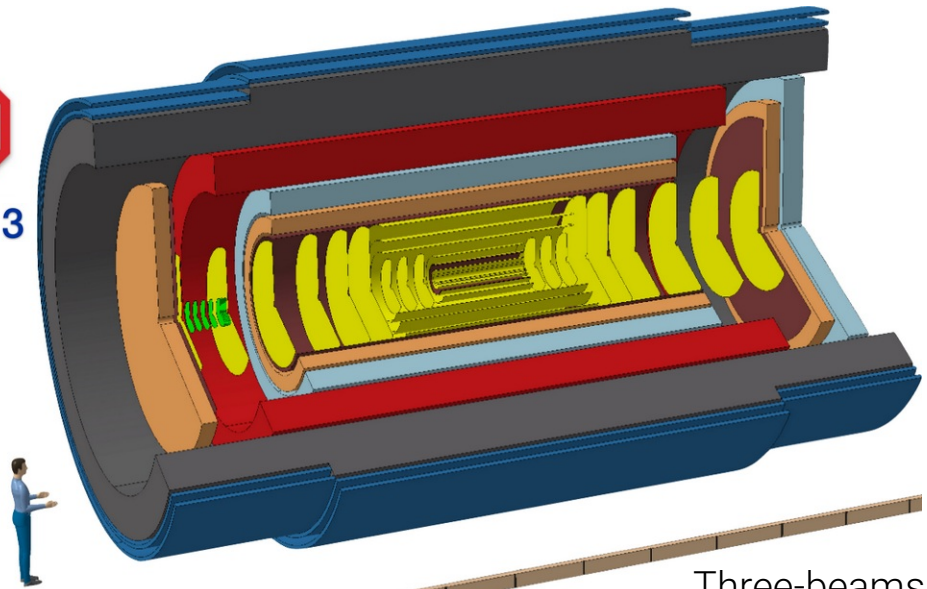
- *Fundamental EW parameters: Competitive with (HL-)LHC/LEP*
- *Unique measurments of scale dependence of EW interactions*
- *Complementary measurements to Z-pole data*
- *EW physics at HL-LHC needs LHeC-PDFs*

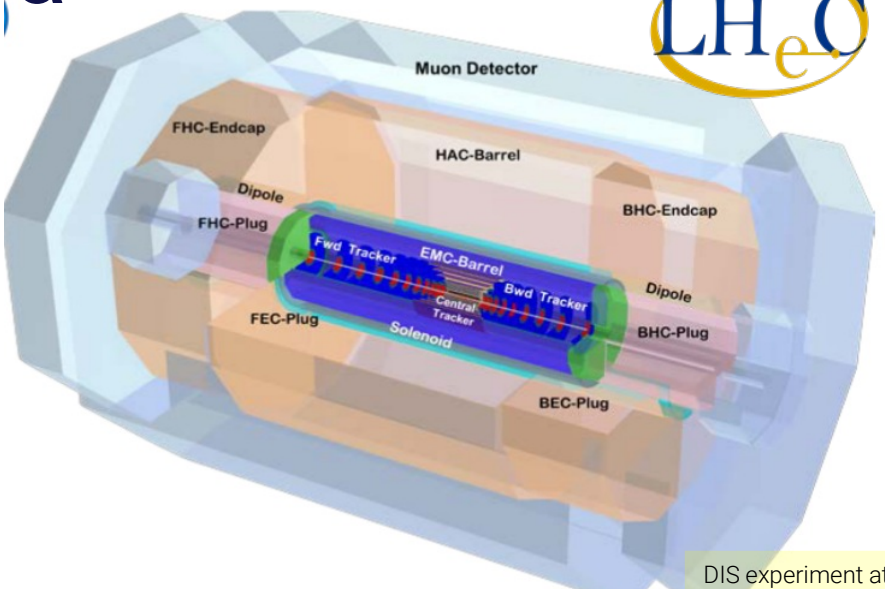
More talks at ICHEP:

W. Kaabi, Thu 3:05,	Perle & ERL
B. Holzer, Thu 2:45	LHeC overview
C. Gwenlan, Thu, 10:30	Parton structure & QCD
N. Armesto, Thu, 12:25	eA and small-x physics
U. Klein, Fri 3:00pm	Higgs physics
O. Fischer, Sat, 5:30pm	BSM physics
Poster, Fri, 7:05pm	eh/hh IR & detector

LHC-Point 2 in HL-LHC era

ALICE 3



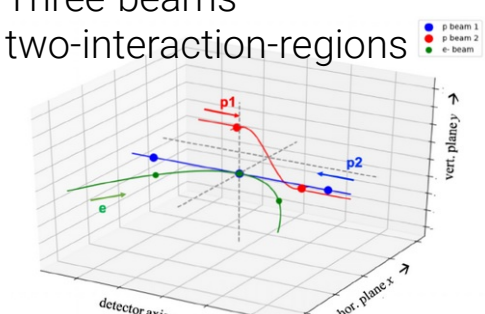


DIS experiment at the HL-LHC
EPJ C82 (2022) 40

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)

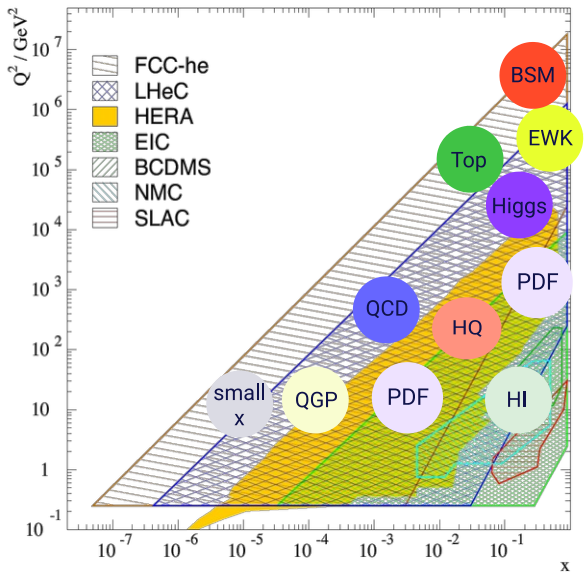
What may happen with a ~ 4-times better calibrated energy-scale from NC DIS in-situ calibration?

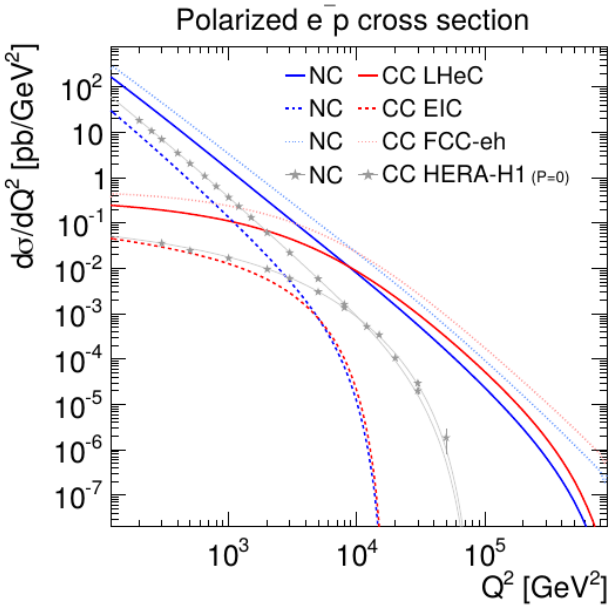
Deep-inelastic electron-proton scattering

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

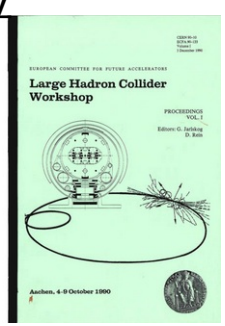




LHeC history

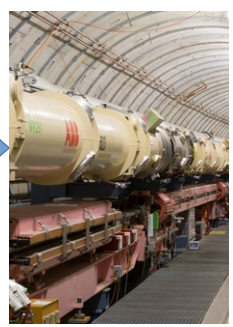
LEP×LHC → 1984

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})

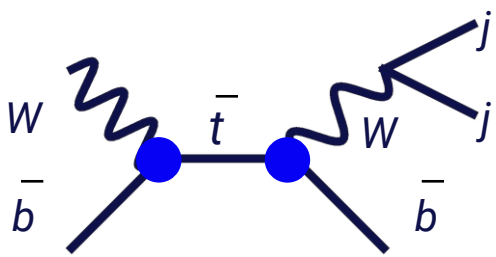
HL-LHC×ERL & Higgs → 2020

s ~√1.3TeV
L ~ 1 ab^{-1}

LHeC → '30

$|V_{tb}|$ in CC single-top production

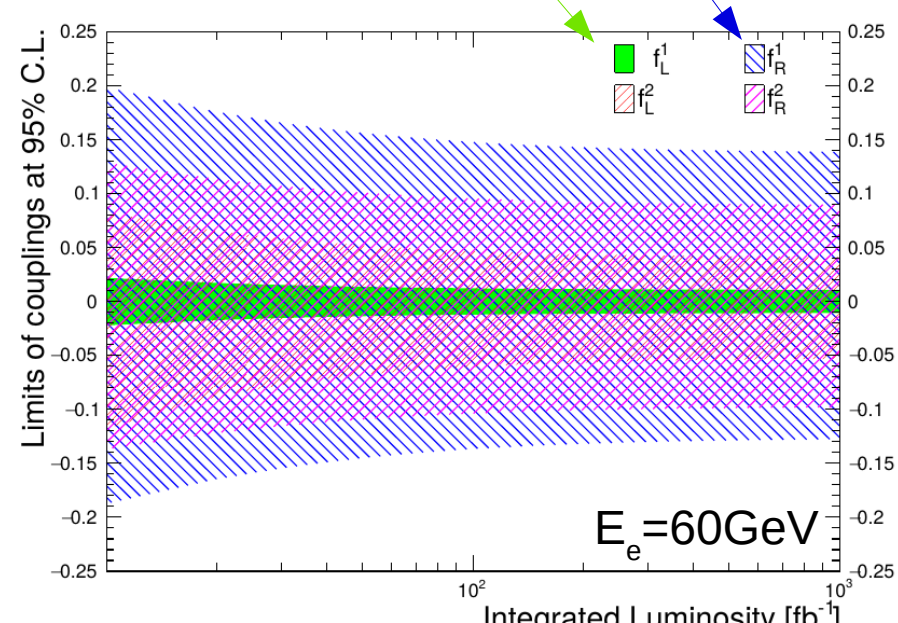
Limits on anomalous Wtb couplings



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathscr{L}_{Wtb} = \frac{g}{\sqrt{2}}\Big[W_\mu \bar{t}\gamma^\mu (V_{tb} f_1^L P_L + f_1^R P_R) b - \frac{1}{2\,m_W} W_{\mu\nu}\bar{t}\sigma^{\mu\nu}(f_2^L P_L + f_2^R P_R) b\Big] + h.c.$$

- *Fully hadronic channel*
- *cut-based analysis with backgrounds using Delphes*



Estimated precision on V_{tb}

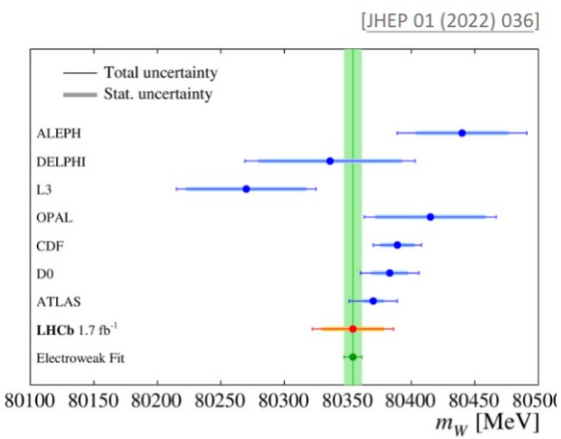
- V_{tb}: up to 1% precision (*with L=100 fb^{-1}*)
- *Presently best LHC measurement: ~7%*

See: S. Dutta, et al. Eur.Phys.J. C75 (2015) 577

δm_W with LHeC input

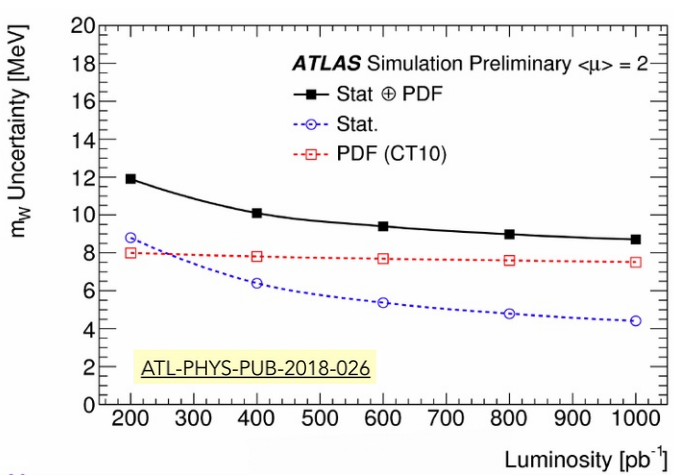
- m_W milestone measurements for consistency of SM and BSM searches
- Study of potential of m_W measurement with low pile-up runs

LHCb measurement

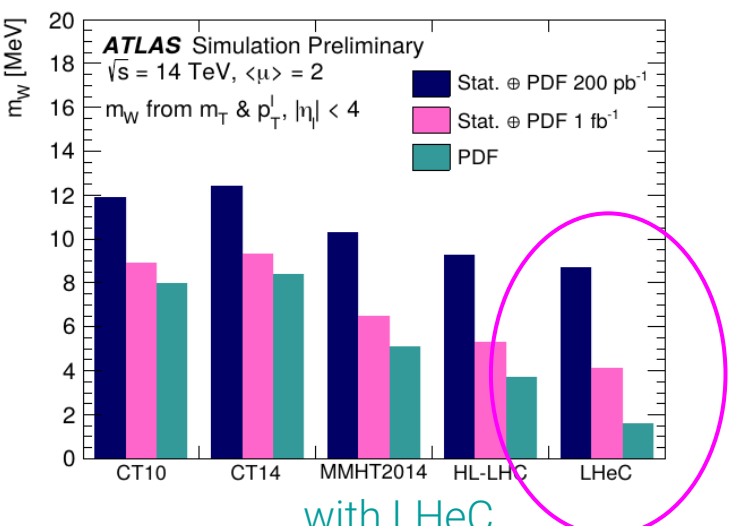


$m_W = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$ MeV

ATLAS low-<μ> prospects



ATLAS low-<μ> HL-LHC prospects



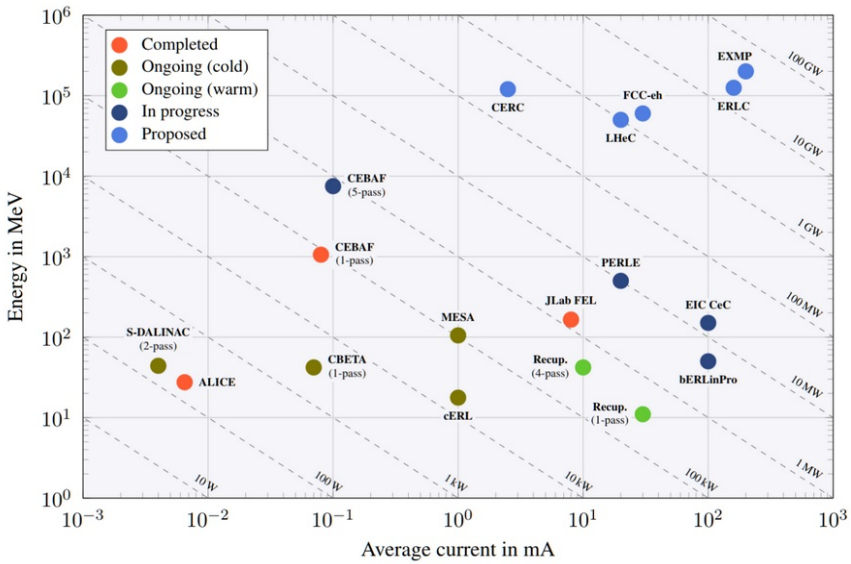
Large theory uncertainty originates from knowledge of PDFs
Similar size than experimental uncertainties

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

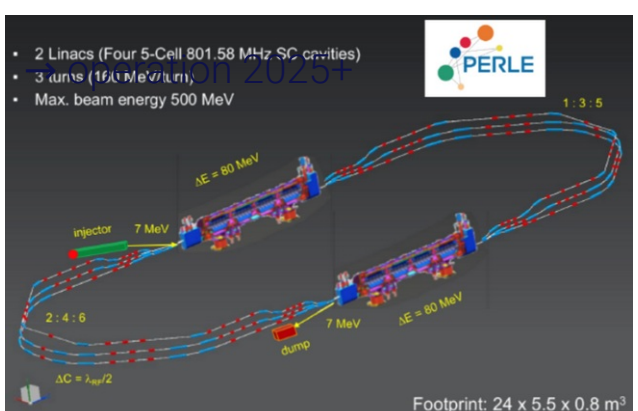
The FCC-eh energy recovery linac

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

A new facility comprising all essential features ?
→ high-current & high-energy & multi-pass
→ optimised cavities & cryo-modules and a beam for collider experiments



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

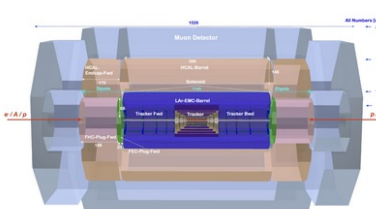


Accelerator R&D Roadmap [arXiv:2201.07895]

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

FCC Physics opportunities EPJ .C79 (2019) 474

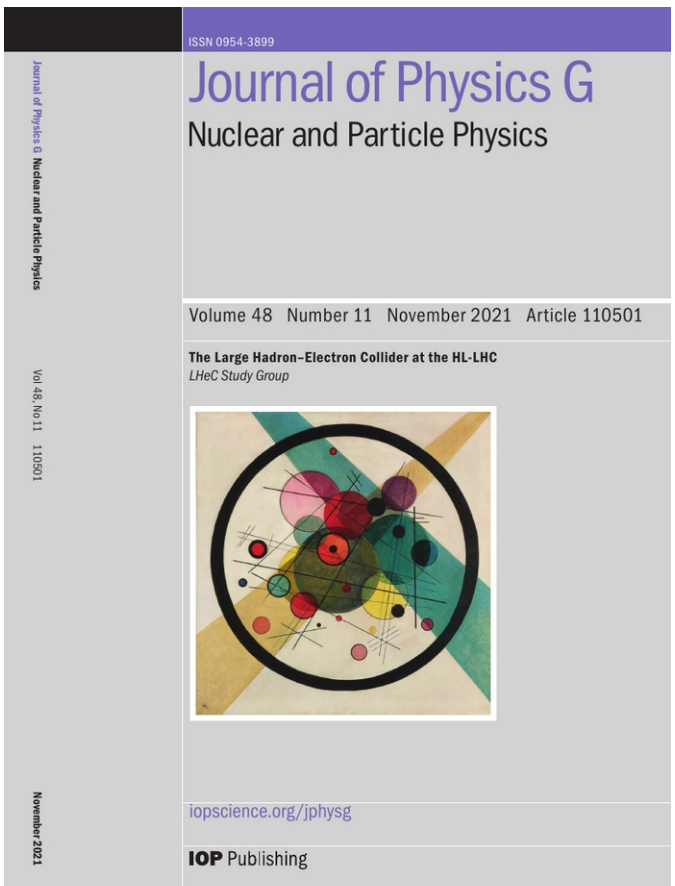
DIS experiment at the HL-LHC EPJ C82 (2022) 40



Symmetric detector to record ep and pp collisions at a single IP

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
JPhys.G 48 (2021) 110501