Electroweak physics at LHeC & FCC-eh
and
complementarity between LHeC and HL-LHC

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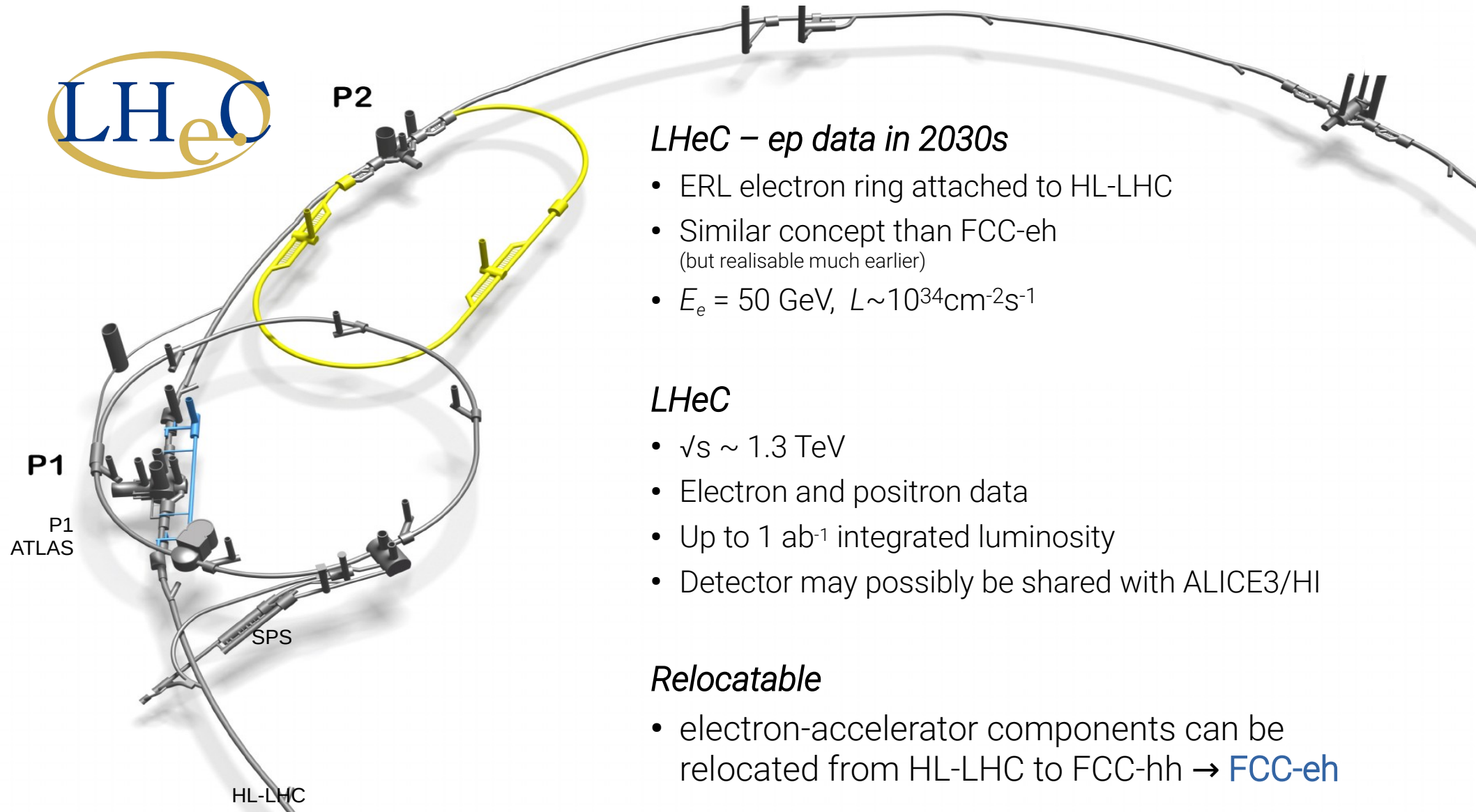
for the LHeC & FCC-eh study group
EPS-HEP 2021, Hamburg (virtual)
27.07.2021

Proposal for the 2030s – 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, $L \sim 10^{34} cm^{-2} s^{-1}$

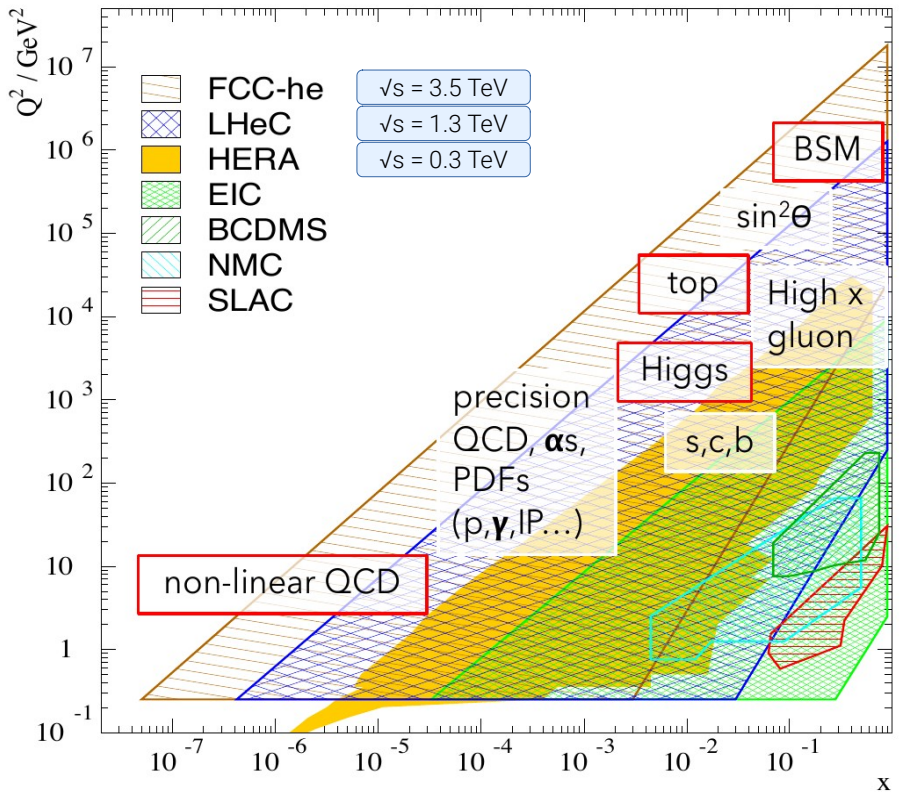
LHeC

- √s ~ 1.3 TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- Detector may possibly be shared with ALICE3/HI

Relocatable

- electron-accelerator components can be relocated from HL-LHC to FCC-hh → FCC-eh

Kinematic plane – LHeC and FCC-eh



Rich physics program at all scales

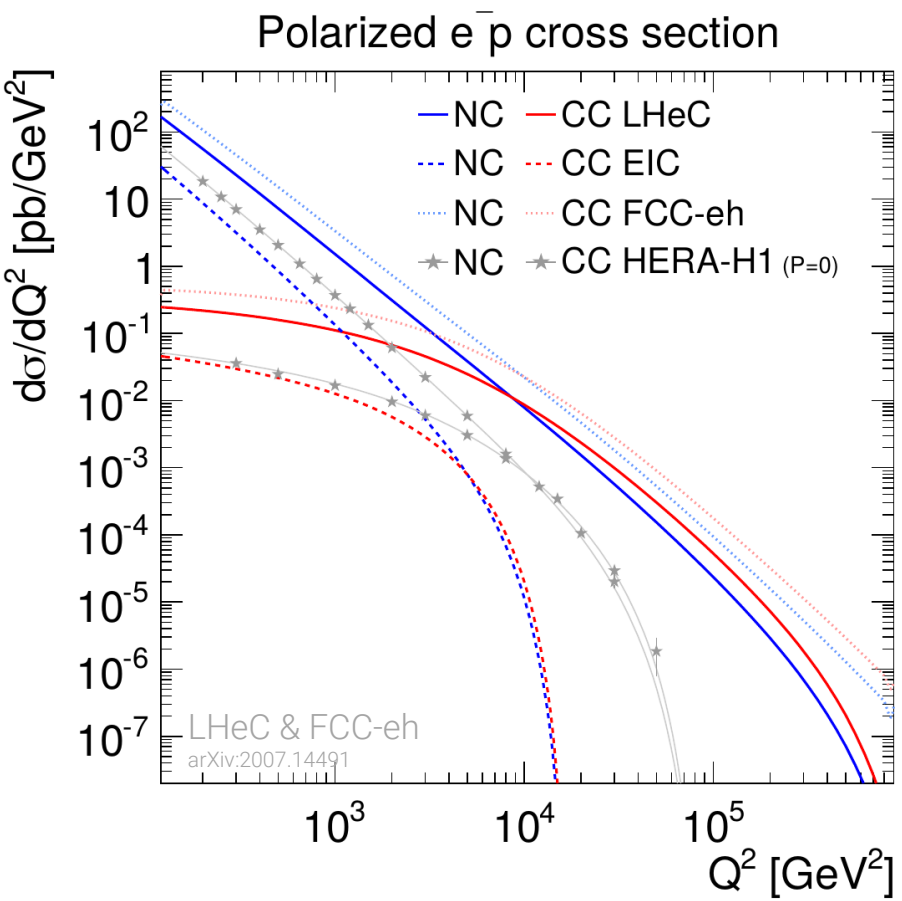
- Higgs physics in NC and CC DIS (talk by U. Klein)
- Top quark production (talk by S. Behera)
- BSM physics and searches (talk by O. Fischer)
- Precision QCD: proton structure, substructure, strong coupling constant, jet physics, heavy quarks, … (talk by C. Gwenlan)
- Heavy ion programme (talk by G. Milhano)
- Electroweak physics

High luminosity

- Intense electron beam from ERL (talk by B. Hounsell)

→ Status and plans (poster by K. Andre)

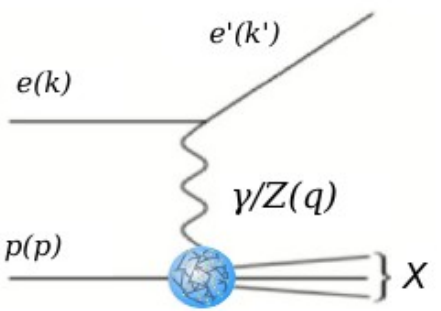
Electroweak physics in inclusive DIS



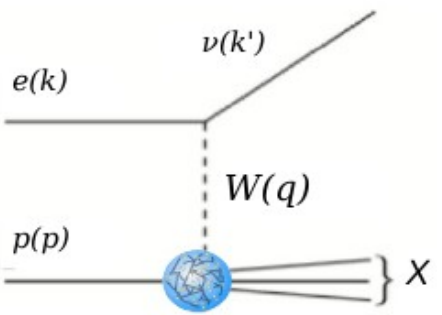
Future e±p DIS experiments *(t-channel)*

- neutral- and charged-current exchange
- measurements up to TeV scale and beyond
- Luminosity >1000 times higher than HERA
- CC: mediated by W-boson
- NC: Z-exchange important at high scales

Neutral-current (NC)

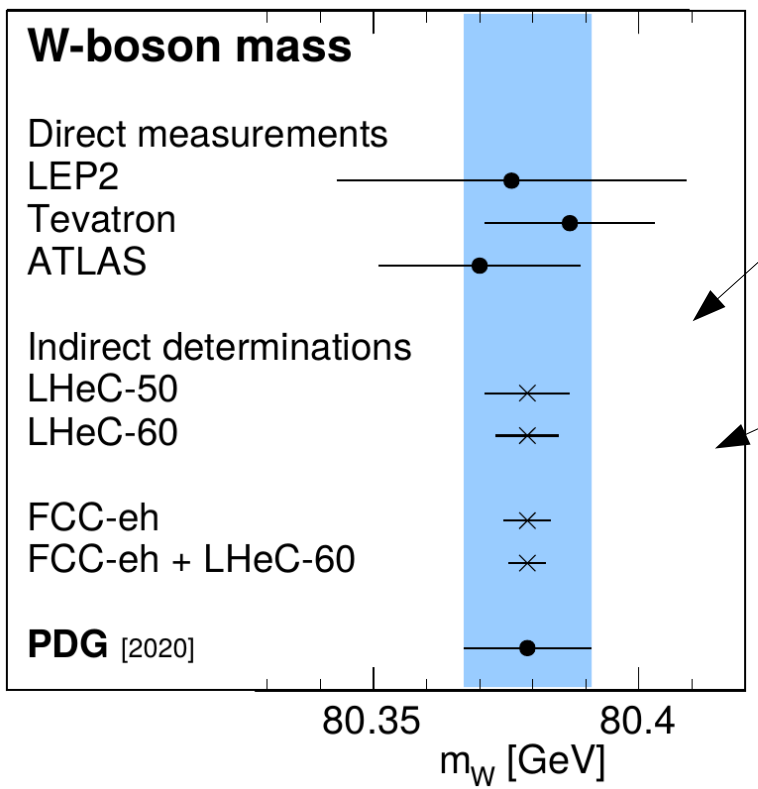


Charged-current (CC)



Expectations: m_W + PDF

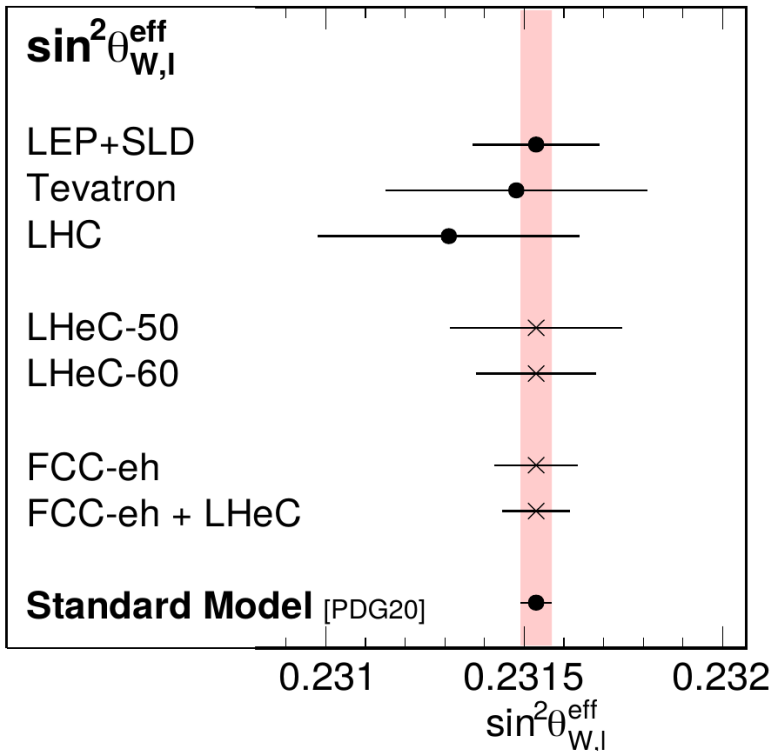
Determine W-boson mass together with proton-PDFs



- 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



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

Weak mixing angle

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

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

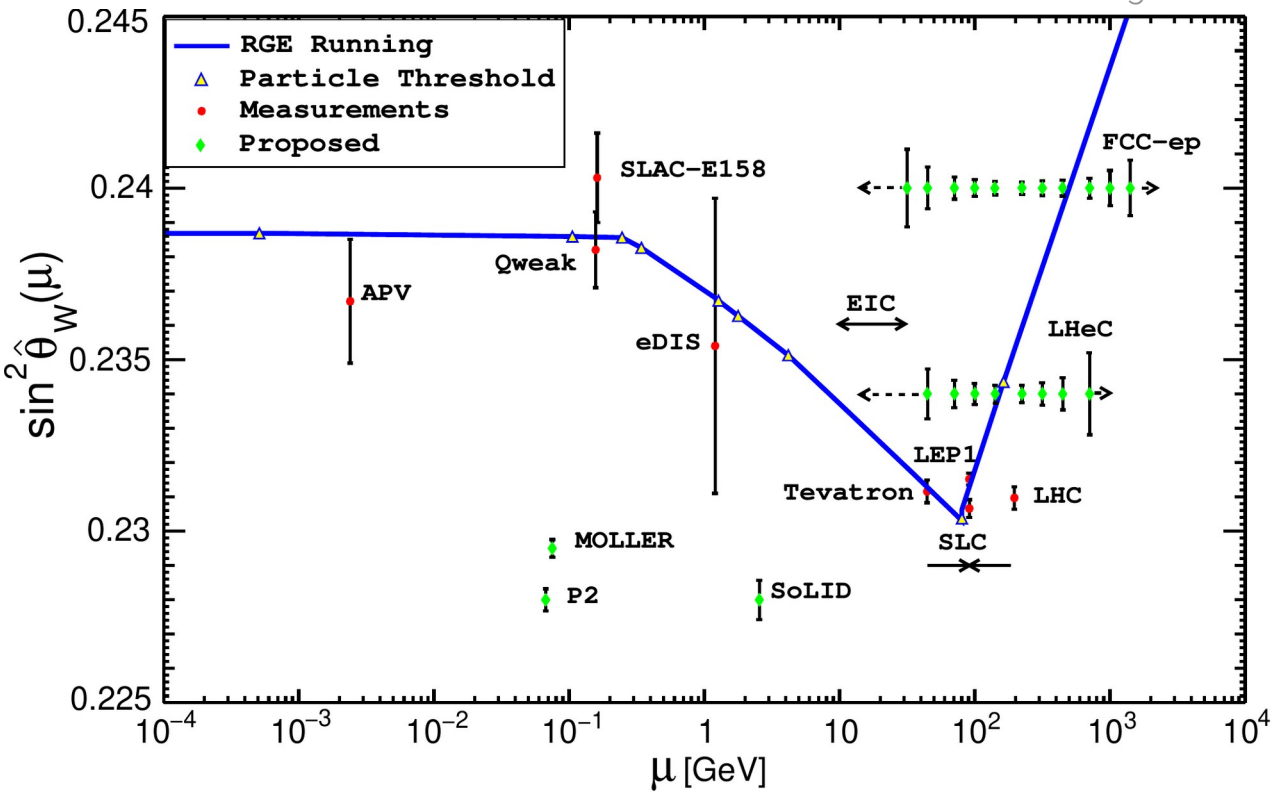
$\sin^2\theta_W$ + PDF fit

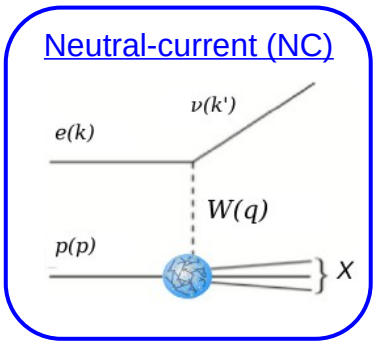
- Comparison to Z-pole data
- At future DIS facilities:
  Most precise single measurement possible
- Note: need theory to map $\sin^2\theta_W$ to effective leptonic weak mixing angle

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

Running of the weak mixing angle

X. Zheng et al.

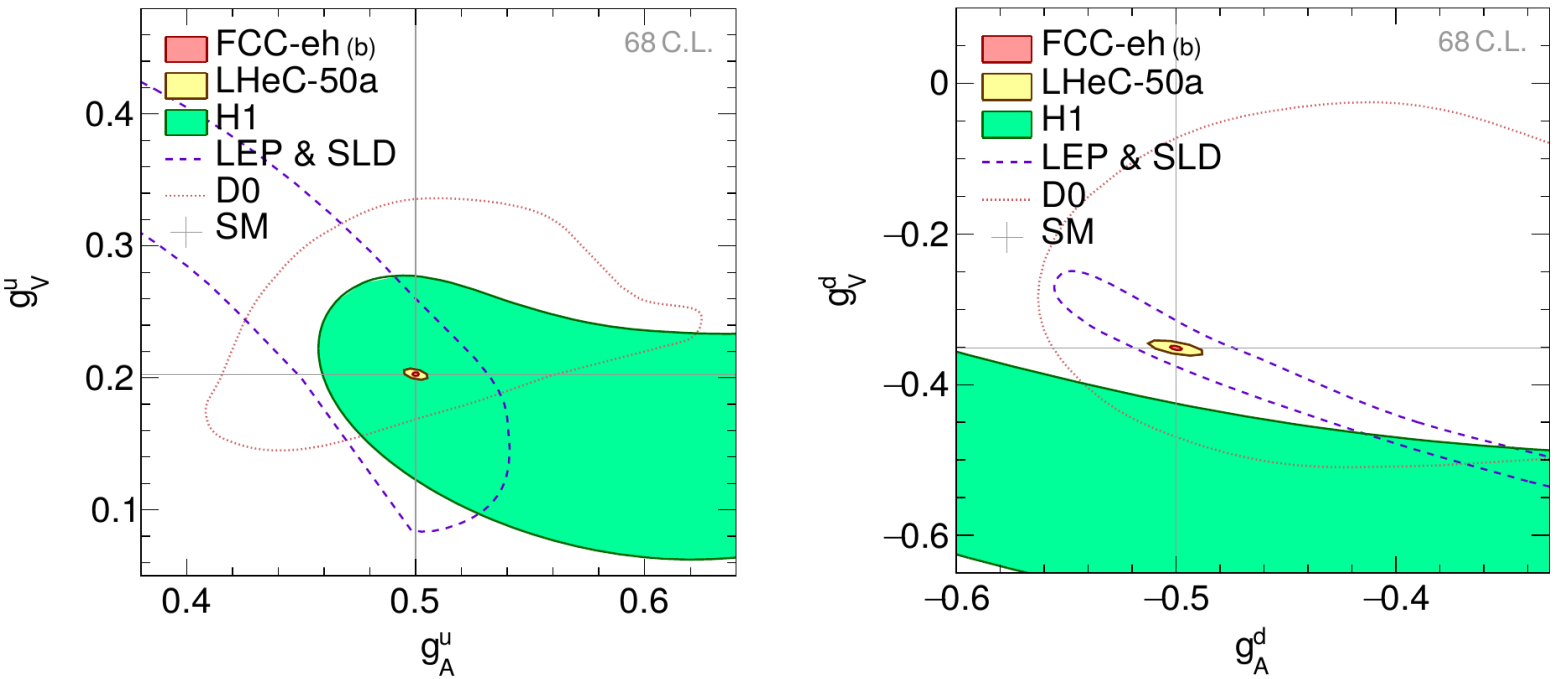




- Simultaneous determination of multiple values of $\sin^2\theta_W$ together with PDFs at different Q^2
- Per mille uncertainties in $20 < Q < 2000$ (700) GeV in spacelike regime
- Unique measurement of 'running' at high scales

Light quark NC couplings

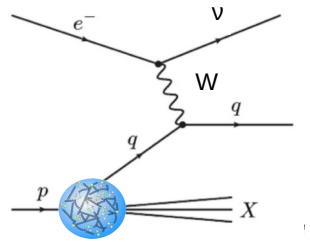
Light quark (*u*- & *d*-type quarks) neutral-current couplings to the *Z*-boson



- LHeC already improves by more than an order of magnitude
- FCC-eh with per-mille precision
- *u*-type and *d*-type can be separated – no sign ambiguity as in *Z*-pole data due to *γZ* terms

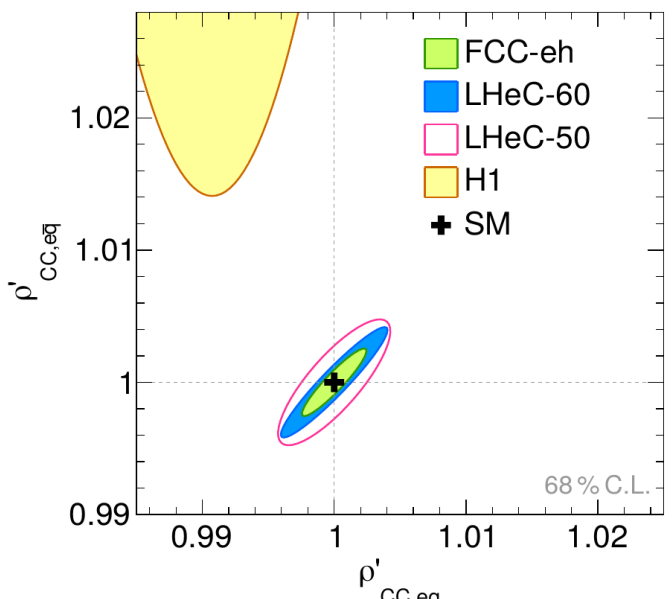
Charged current

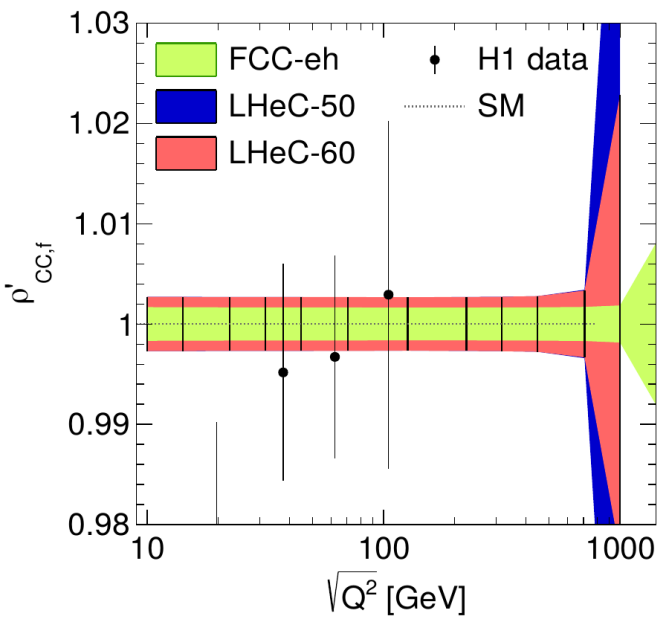
Charged-current (CC)



Study charged current cross sections in DIS

$$W_2^- = x\left((\rho_{CC,eq}\rho'_{CC,eq})^2 U + (\rho_{CC,e\bar{q}}\rho'_{CC,e\bar{q}})^2 \overline{D}\right)$$
$$xW_3^- = x\left((\rho_{CC,eq}\rho'_{CC,eq})^2 U - (\rho_{CC,e\bar{q}}\rho'_{CC,e\bar{q}})^2 \overline{D}\right)$$

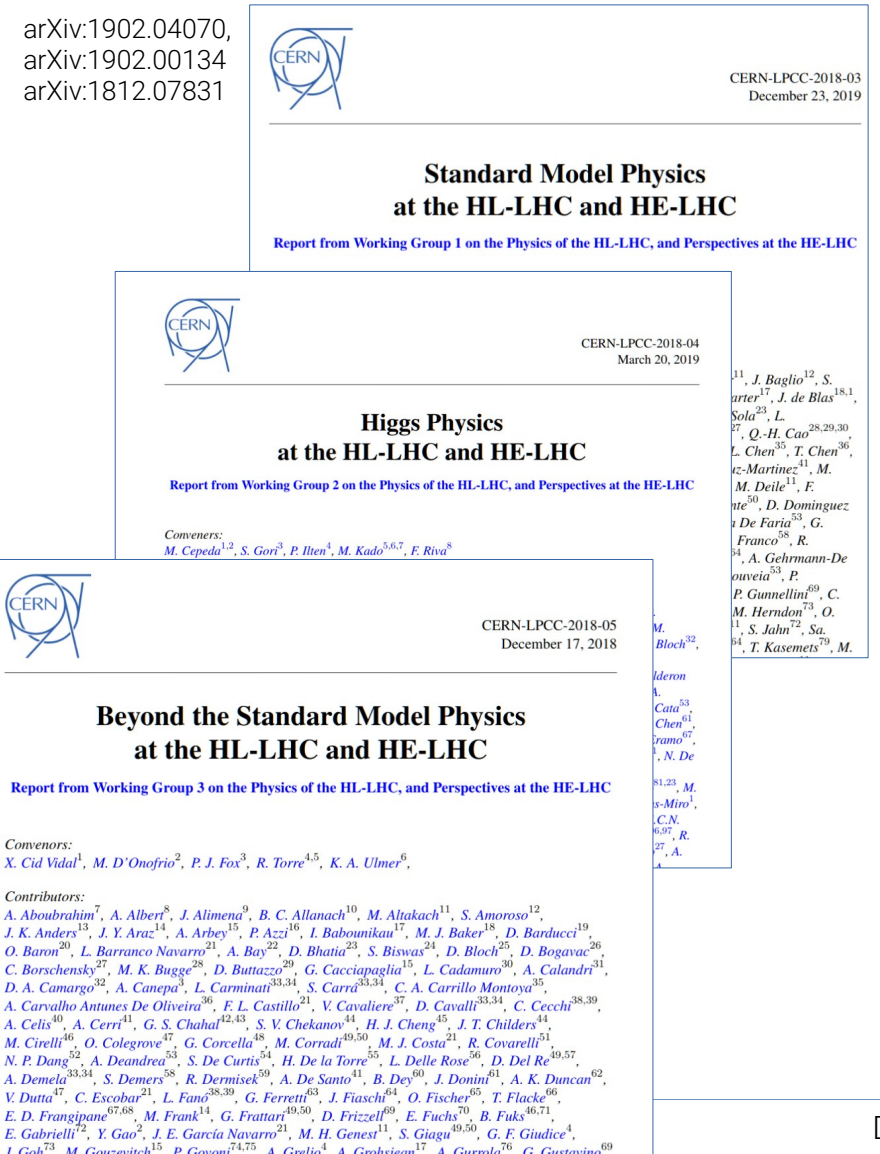




Charged current couplings not well studied experimentally – unique to DIS

(LHC) physics in the 30s

arXiv:1902.04070,
arXiv:1902.00134
arXiv:1812.07831



CERN-LPCC-2018-03
December 23, 2019

Standard Model Physics at the HL-LHC and HE-LHC

Report from Working Group 1 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

CERN-LPCC-2018-04
March 20, 2019

Higgs Physics at the HL-LHC and HE-LHC

Report from Working Group 2 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

Conveners:
M. Cepeda[1,2], S. Gori[3], P. Ilten[4], M. Kado[5,6,7], F. Riva[8]

CERN-LPCC-2018-05
December 17, 2018

Beyond the Standard Model Physics at the HL-LHC and HE-LHC

Report from Working Group 3 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

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EPPSU 2013

- "Europe's top priority should be the exploitation of the full potential of the LHC"

Complementary measurements

Supportive measurements

Competeing measurements

PDFs for phenomenology

- LHeC 'supports' proton-proton progamme through many different aspects

From the LHeC to the HL-LHC

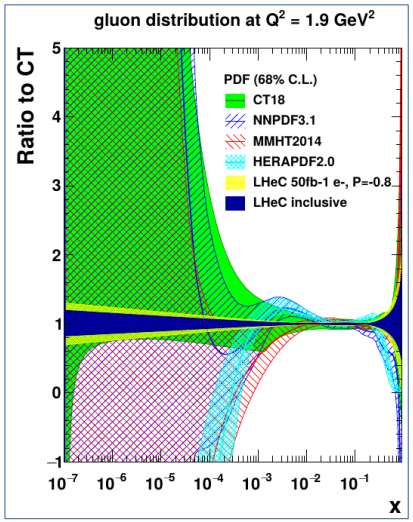
SciPost Phys. 7 (2019) 4, 051
LHeC-CDR2020 [arXiv:2007.14491
See also talk by C. Gwenlan

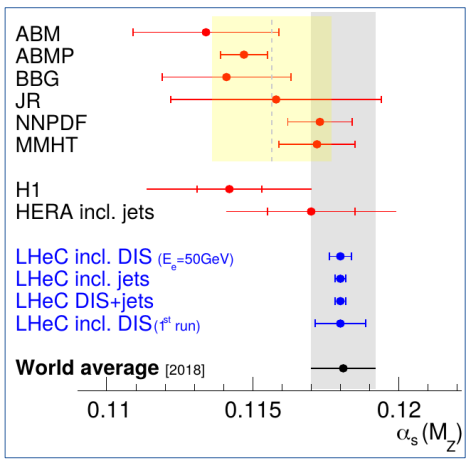
PDFs at the LHeC

- All PDF flavors are precisely determined from LHeC data alone
- Gluon density: very import for LHC

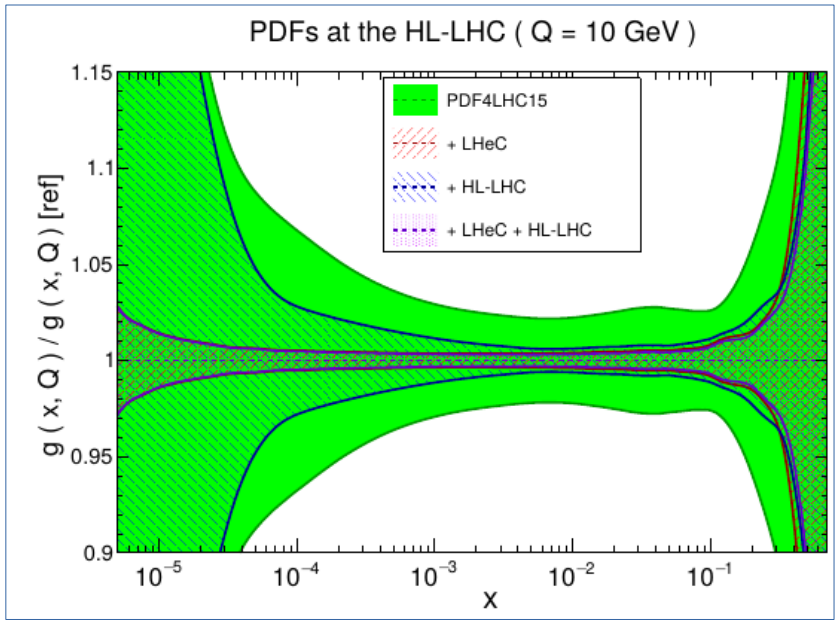
Many further parameters

- α_s (~0.15%)
- parton-shower & hadronisation
- fragmentation func'
- PDFs at quark thresholds
- ...





Parton luminosities at the *pp*-LHC

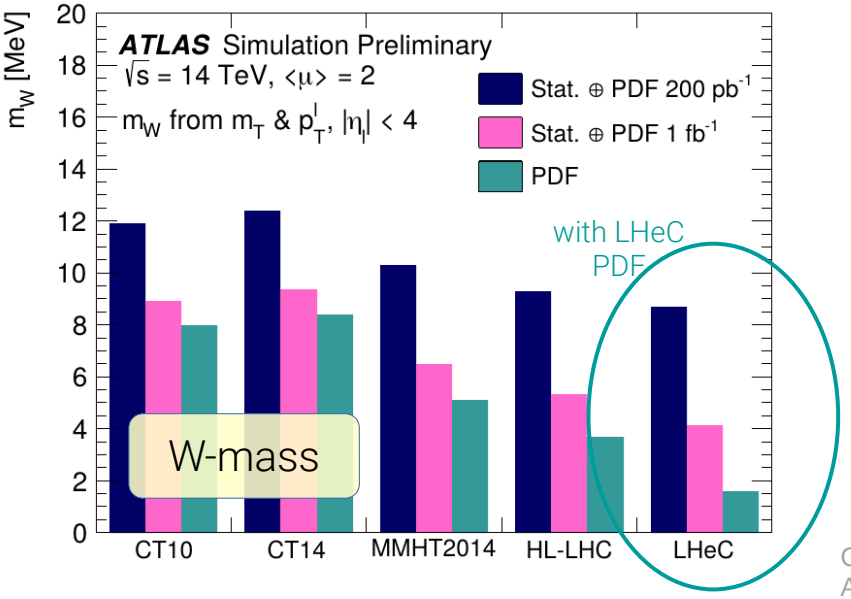


- Significiant reduction of gluon-gluon luminosities with LHeC than nowadays PDFs, or HL-LHC prospects
- Quark-PDFs with similar reductions !

The impact of LHeC on HL-LHC (through PDFs)

W-mass measurements in pp

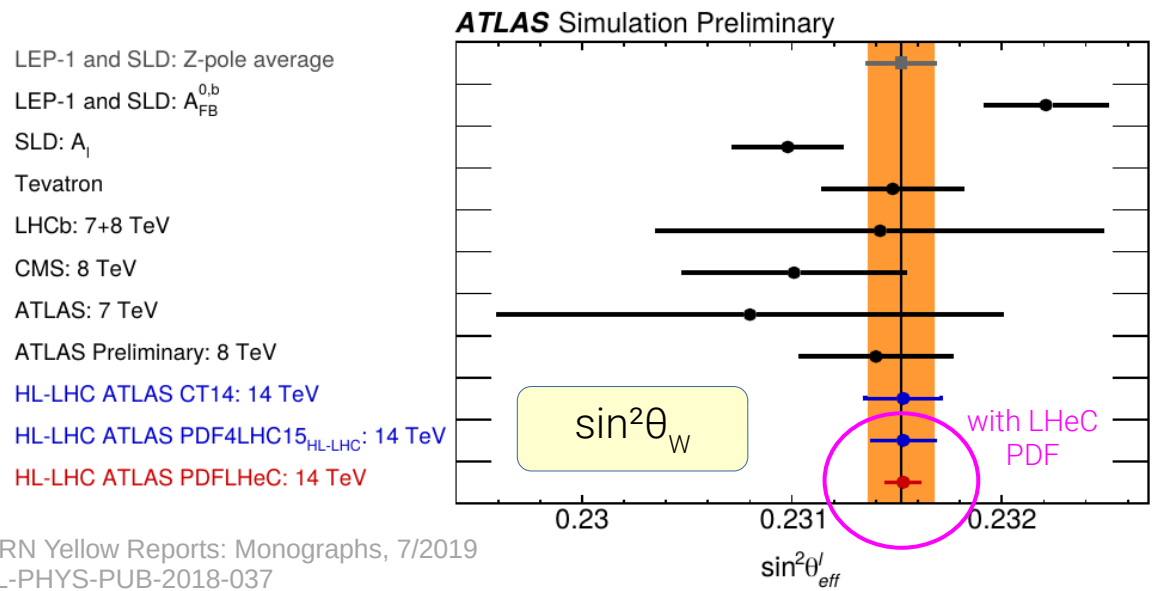
- Major uncertainty from PDFs



- Reduction of PDF uncertainty only feasible with LHeC PDFs ($\Delta m_W^{PDF} \sim 2$MeV)

Effective weak mixing angle in pp

- Large uncertainty from PDFs

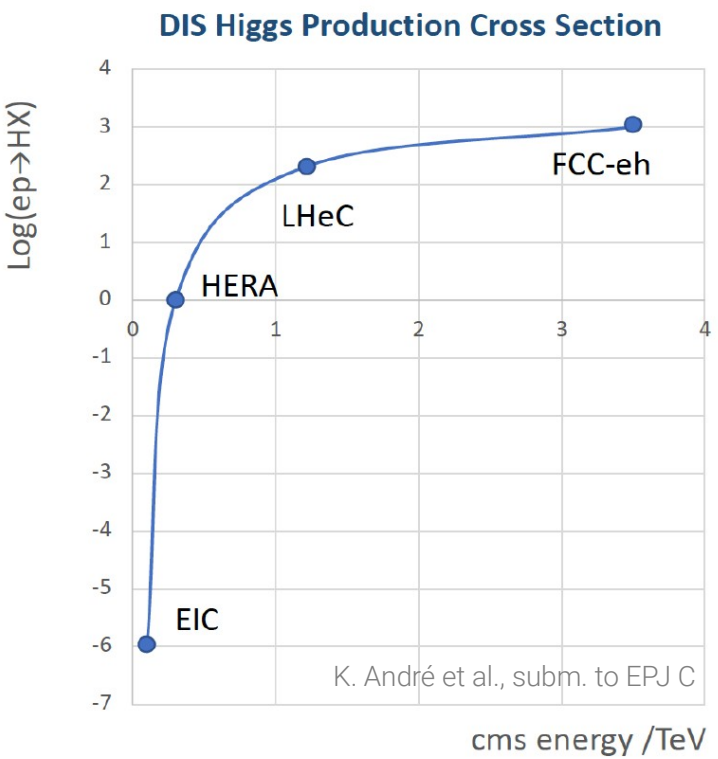


CERN Yellow Reports: Monographs, 7/2019
ATL-PHYS-PUB-2018-037

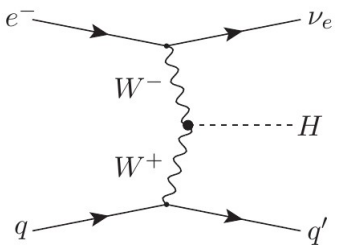
- HL-LHC–PDF reduces uncertainty by 10-25%
- → LHeC *ep* data would provide needed factor of 5–10 in PDF improvement to exceed LEP precision

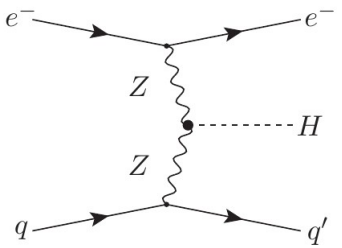
Higgs physics at LHeC

See also talk by U. Klein



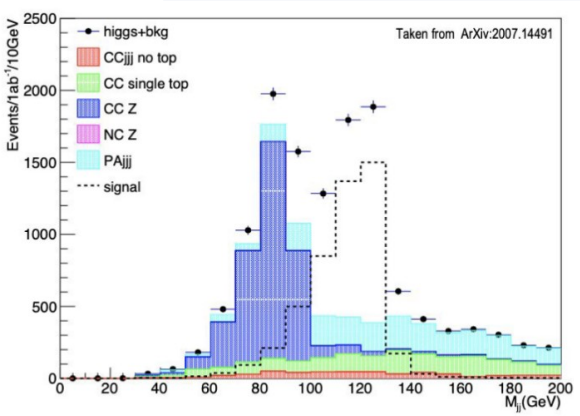
Higgs in CC and NC DIS

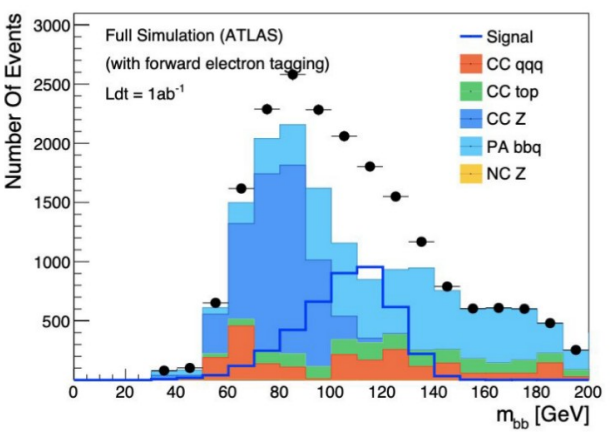




Example of ***H→bb*** analysis using DELPHES or a full (ATLAS) detector simulation

[M. Schott, off-shell conference 2021; see also arXiv:2007:14491]



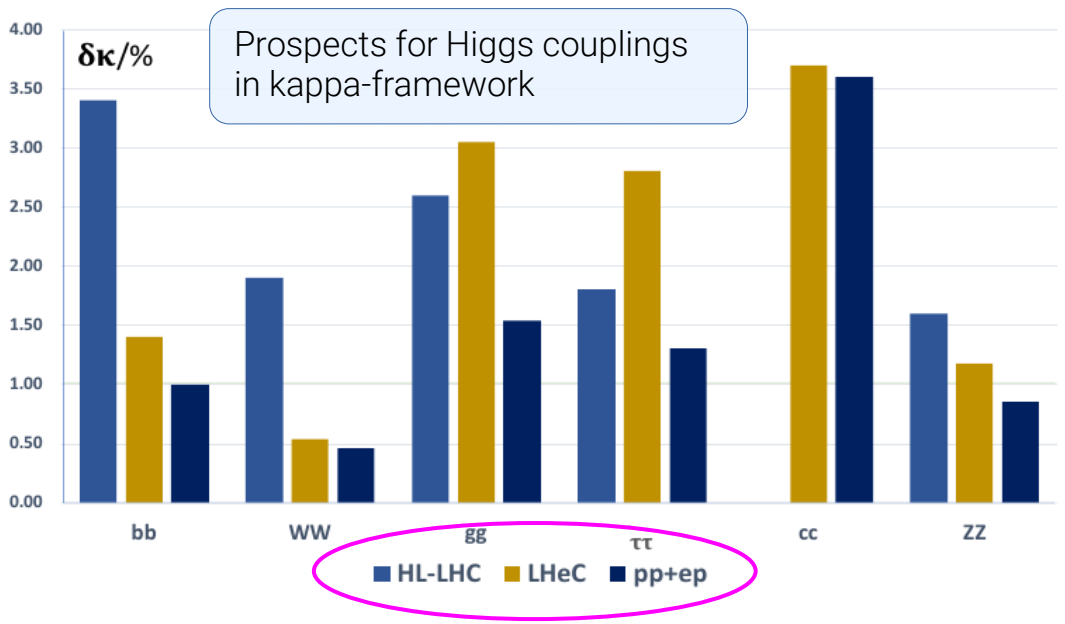


- Higgs-production cross section ~ 200pb
- Sensitivity to six decay channels
  bb, *WW*, *gg*, *ττ*, *cc*, *ZZ*

Higgs physics

Higgs couplings in κ framework

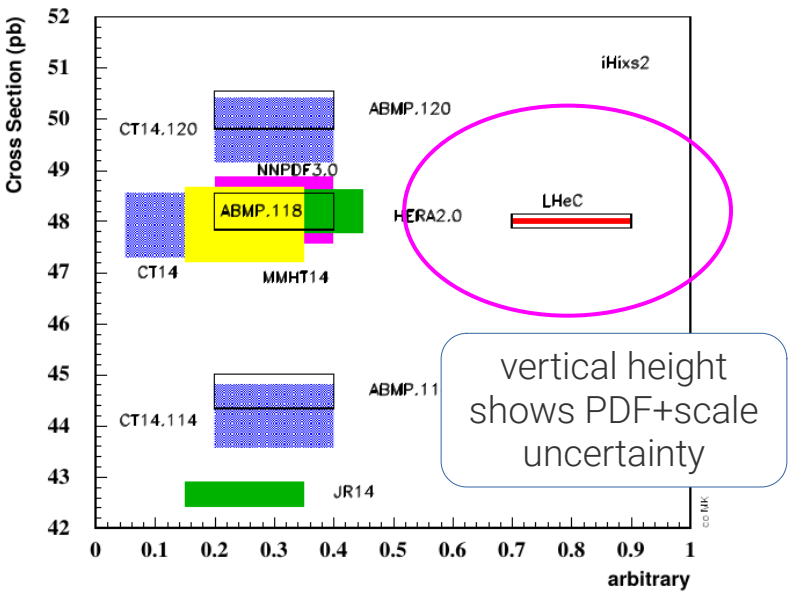
- Common analysis of *p-p* and *e-p* data



- Highest precision achieved only in common analysis
- Complete view of Higgs couplings only achieved in common analysis

Higgs phenomenology

- N3LO pp-Higgs cross section at 14 TeV



- Predictions limited by PDF uncertainties
- only LHeC predictions by N3LO scale uncertainties

Searches

LHeC-PDFs for searches in *pp*

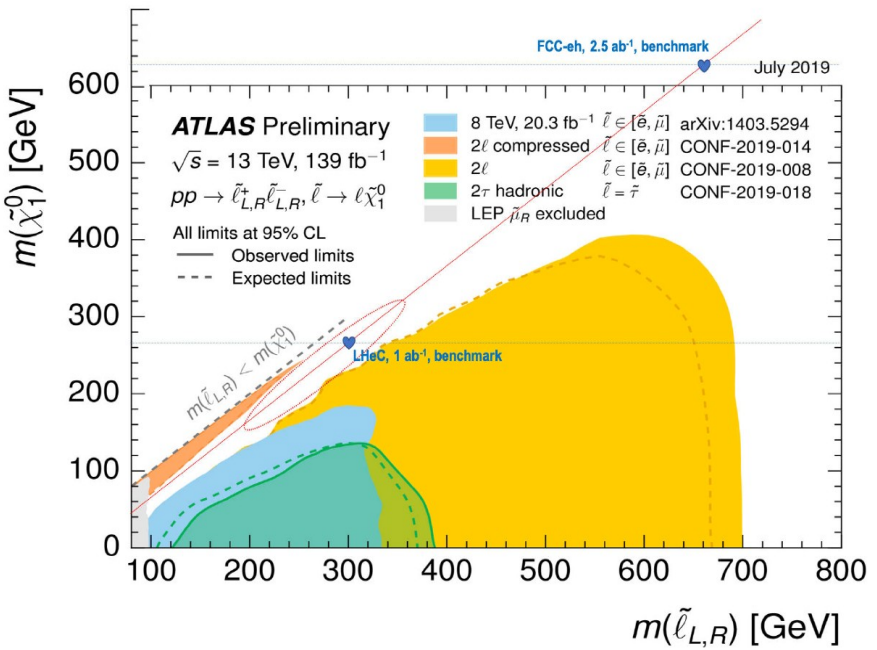
- Limits on contact interactions at LHC are limited by PDF uncertainties

Model	ATLAS (Ref. [709])	HL-LHC	
	$\mathcal{L} = 36\,\text{fb}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\text{ab}^{-1}$ (CT14nnlo)	$\mathcal{L} = 3\,\text{ab}^{-1}$ (LHeC)
LL (constr.)	28 TeV	58 TeV	96 TeV
LL (destr.)	21 TeV	49 TeV	77 TeV
RR (constr.)	26 TeV	58 TeV	84 TeV
RR (destr.)	22 TeV	61 TeV	75 TeV
LR (constr.)	26 TeV	49 TeV	81 TeV
LR (destr.)	22 TeV	45 TeV	62 TeV

- Precise PDFs from LHeC extent limits significantly (almost a factor of 2)
- LHeC limits are of similar reach → Competition!
- Searches in *ep* are often complementary to those in pp:
  - s-channel vs. t-channel exchange
  - *ep* (leptoquark) vs. e^+e^-, $q\bar{q}$, *gg*-annihiliation

Complementary searches

- As example: compressed SUSY scenarios



- Compressed-slepton scenario: Maximum sensitivity in *ep* for Δm~20GeV

Summary

The LHeC project

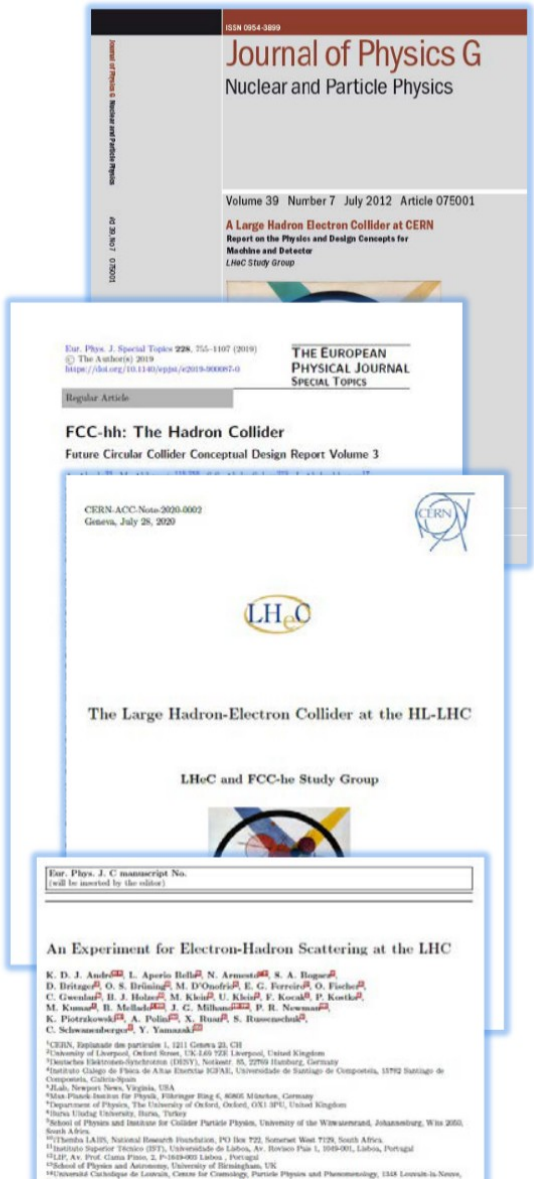
- 50 GeV electron from ERL on 7TeV proton ($\sqrt{s}$=1.3TeV), synchronous with LHC & high-luminosity *ep* collisions
- Very rich & diverse physics programme

Electroweak physics (Eur.Phys.J.C 80 (2020) 831 & CDR-2020 [arXiv:2007.14491])

- Fundamental EW parameters: competitive with other measurements
- Complementary to Z-pole data – different aspects of GSW theory are measured
- Several unique measurements possible (Q^2-dependence, charged current, light-quarks couplings,...)

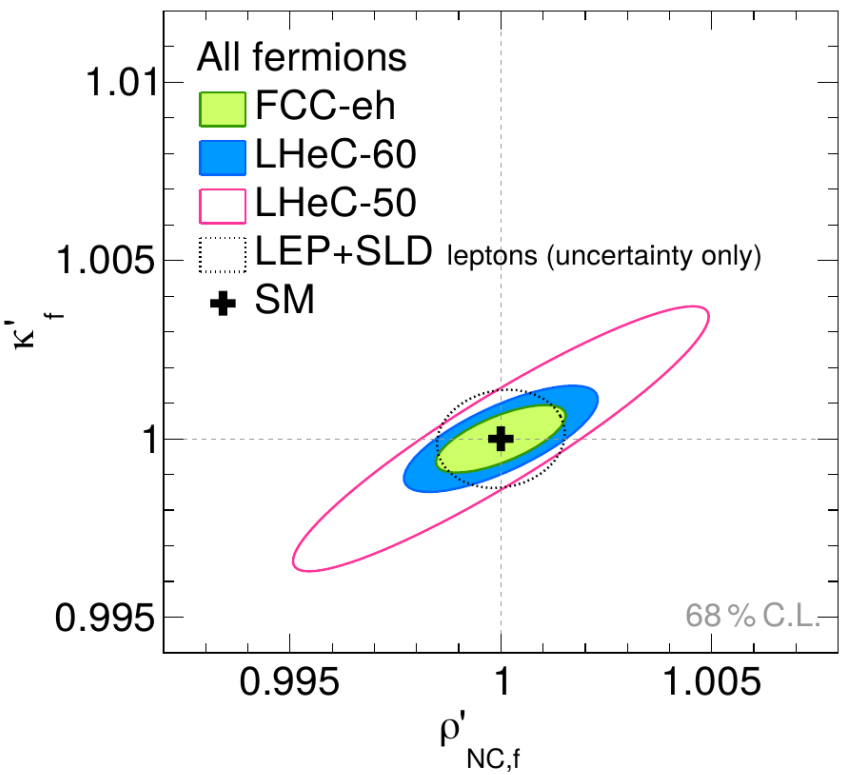
Support of HL-LHC proton-proton programme

- Complementary measurements (s-channel vs. t-channel, clean low-p_T measurements, clean QCD final-state [H→bb] , etc...)
- Supportive measurements (PDFs, parton shower, hadronisation, fragm. functions, etc...)
- Competeing measurements (Higgs, EW, etc...)
- PDFs for phenomenology
- clarification of initial versus final state effects in hadronic collisions (the small system problem)



Anomalous form factors

Generically parameterise new physics by modified EW-couplings



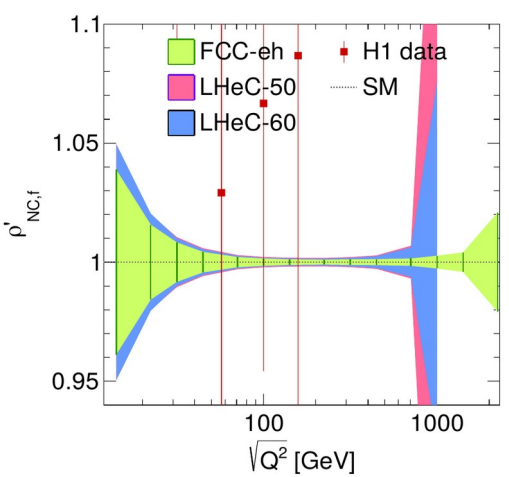
- Introduce anomalous form factors ρ' and κ'

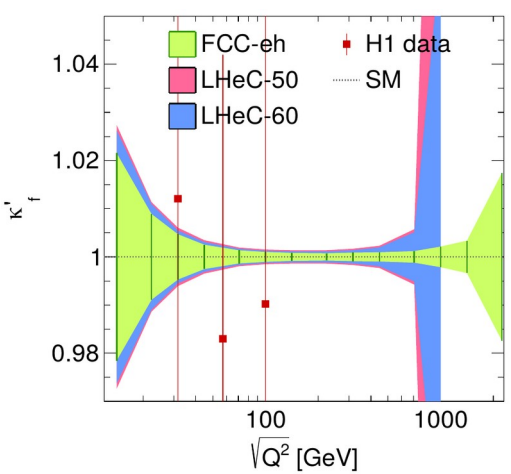
  In SM: ρ' and κ' = 1

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

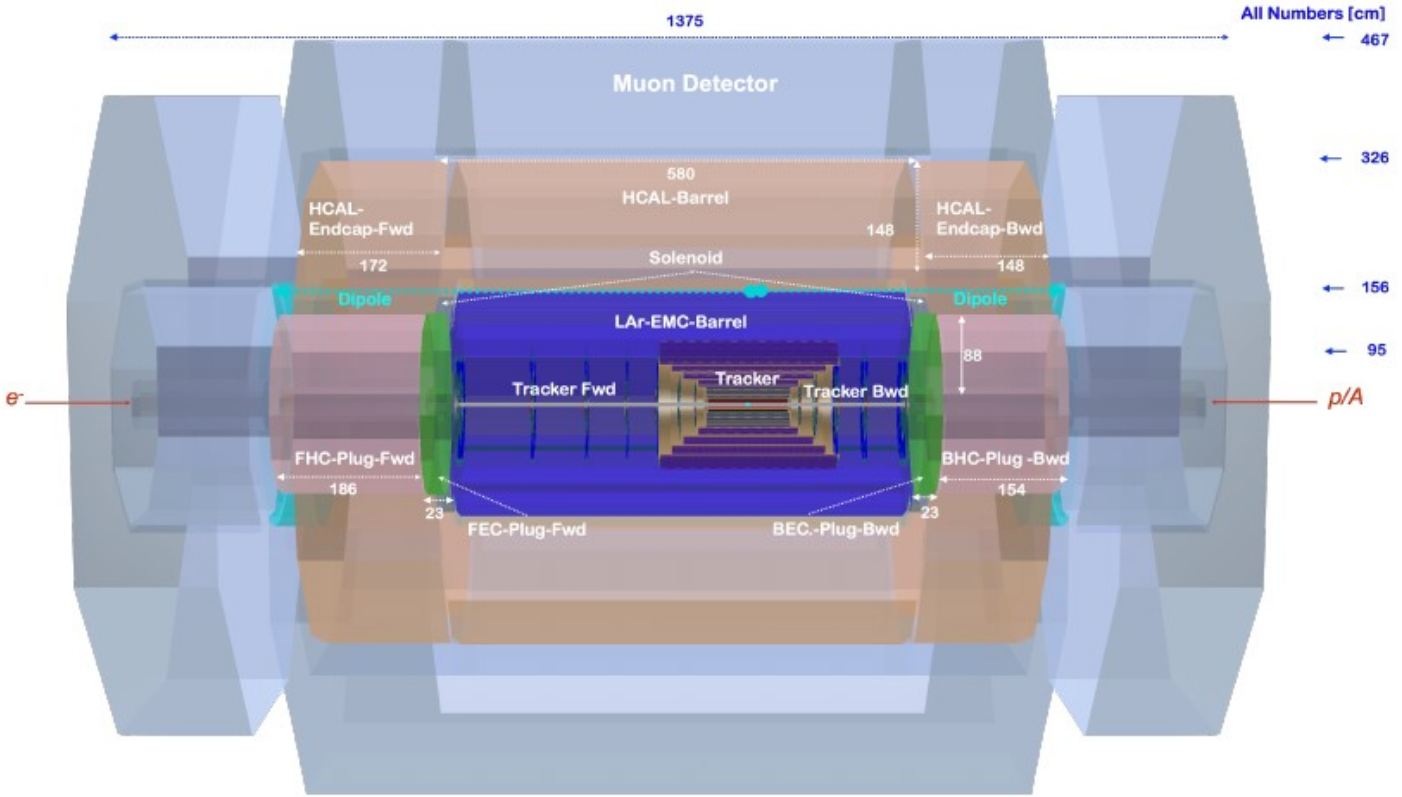
- Parameters may be Q² dependent

  (similar to running weak mixing angle)





Updated baseline detector design

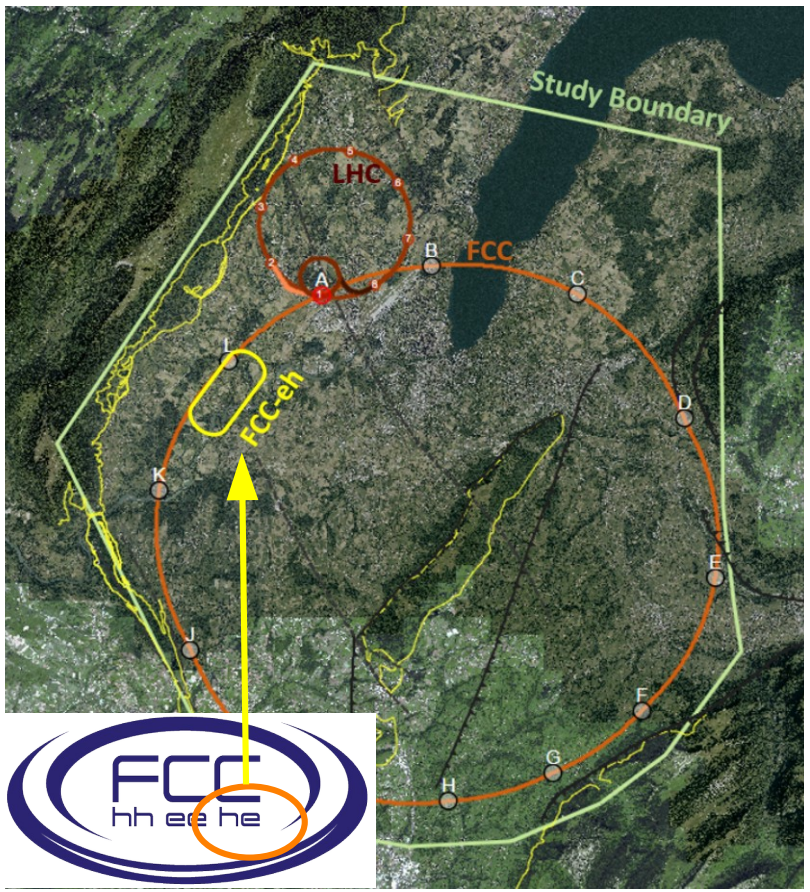


- Based on LHC & HERA experience & HL-LHC plans
- Aim: compact, modular and very hermetic detector
- Coverage: 1 to 179 degrees

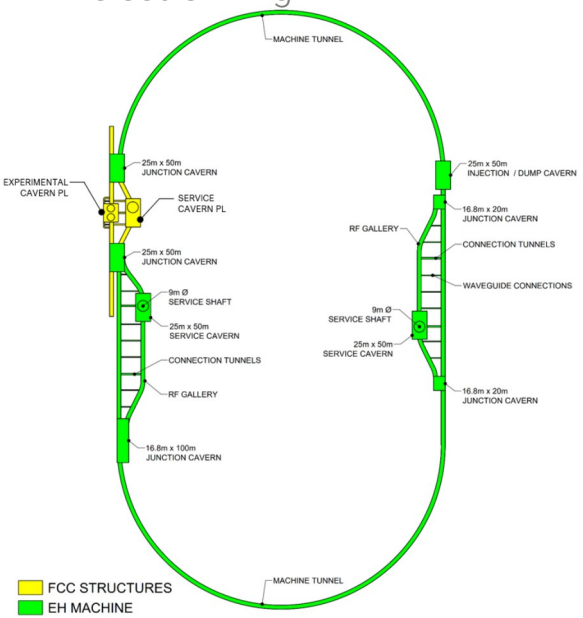
Main components

- High acceptance silicon tracking system
- LAr electromagnetic calorimeter
- Detector & steering magnets
- Iron-Scintillator hadronic calorimeter
- Forward backward calo (Si/W, Si/Cu, …)
- Forward (p/n) & Backward (e/γ) taggers
- Muon system

FCC-eh



Energy-recovery linac electron ring



FCC-eh

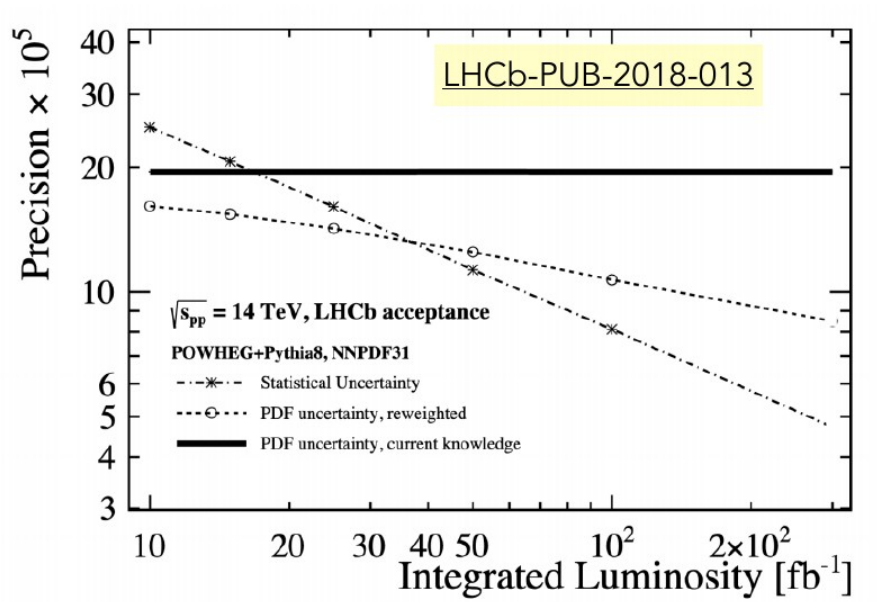
- Dedicated electron-ring attached to FCC-hh
- Energy recovery linac: E_e = 60 GeV
- Longitudinal beam polarisation of ~ ±80%
- Three-turn configuration → 3 arcs

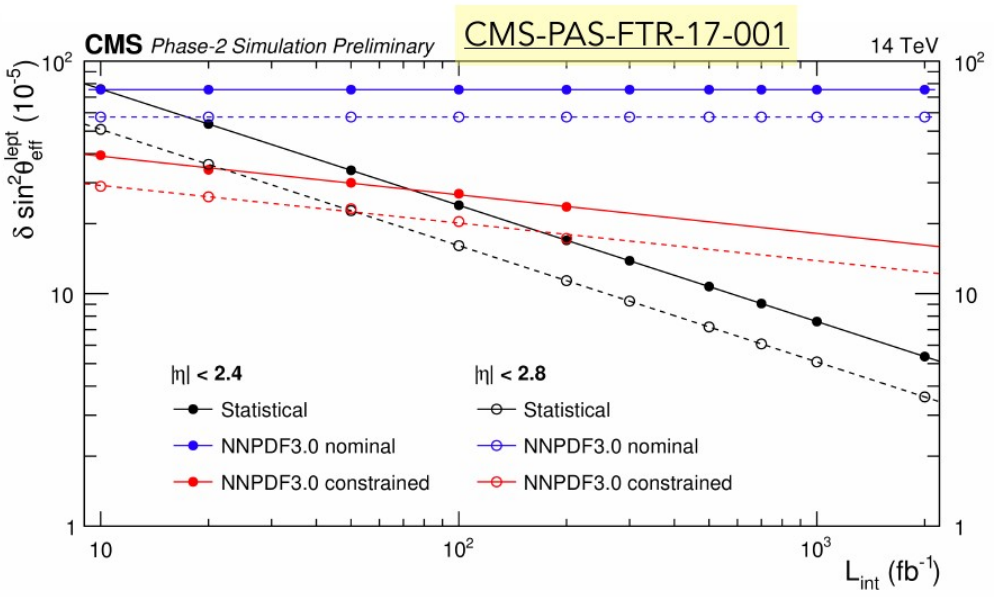
ep-collision data

- $\sqrt{s}$ ~ 3.5 TeV
- More than 1 ab^{-1} integrated luminosity
- Mainly e^- data
  e^+ data with O(10fb^{-1})

Weak mixing angle at the HL-LHC

LHC experiments entered the precision electroweak race: New analysis techniques, including in-situ PDF profiling and event categorisation substantially reduced statistical and systematic uncertainties wrt previous LHC measurements.





Current and future measurement at pp collider limited by PDF uncertainty