The impact of energy frontier DIS measurements on future hadron collider physics
(HL-LHC and FCC-hh)

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XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS22)
Santiago de Compostela
04.05.2022

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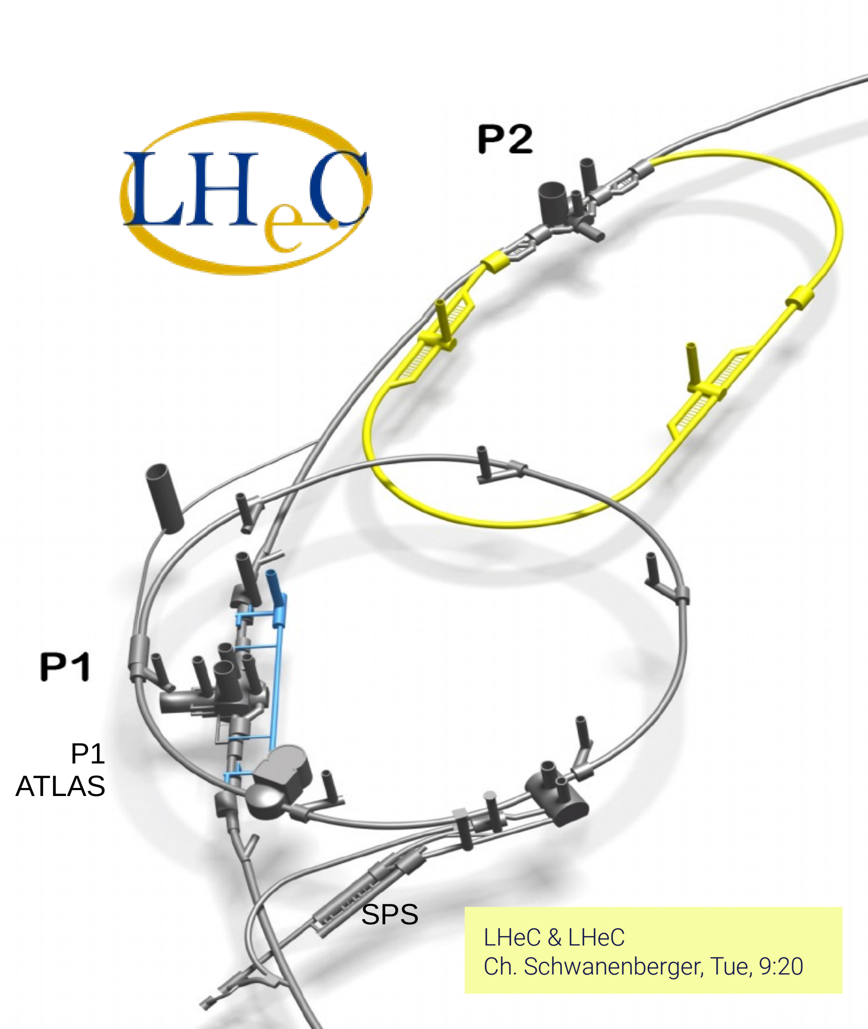
FÜR PHYSIK

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



LHeC & LHeC
Ch. Schwanenberger, Tue, 9:20

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

- $\sqrt{s} \sim 1.3$ 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

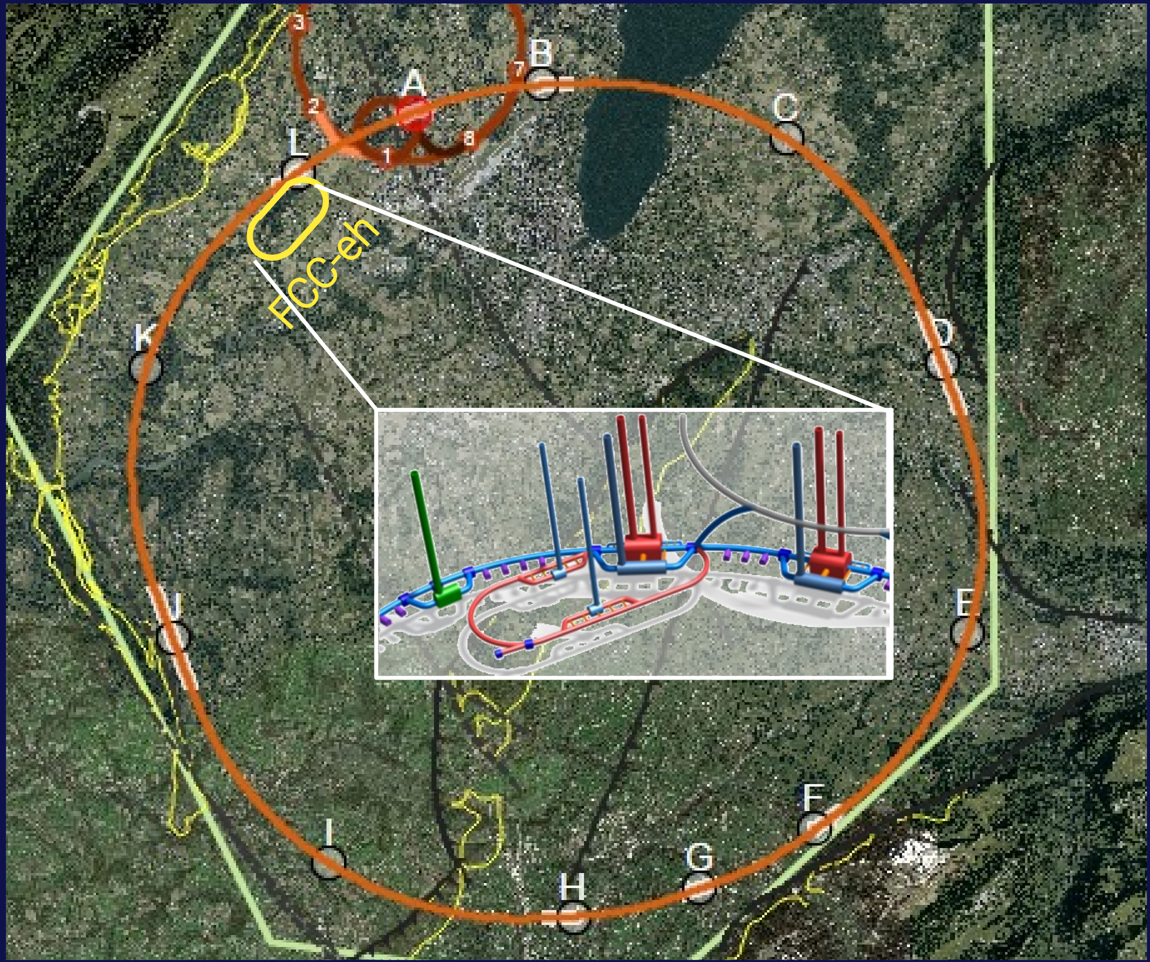
FCC-eh

Dedicated electron-ring attached to the FCC-hh

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

High Luminosity of about 3 ab^{-1}

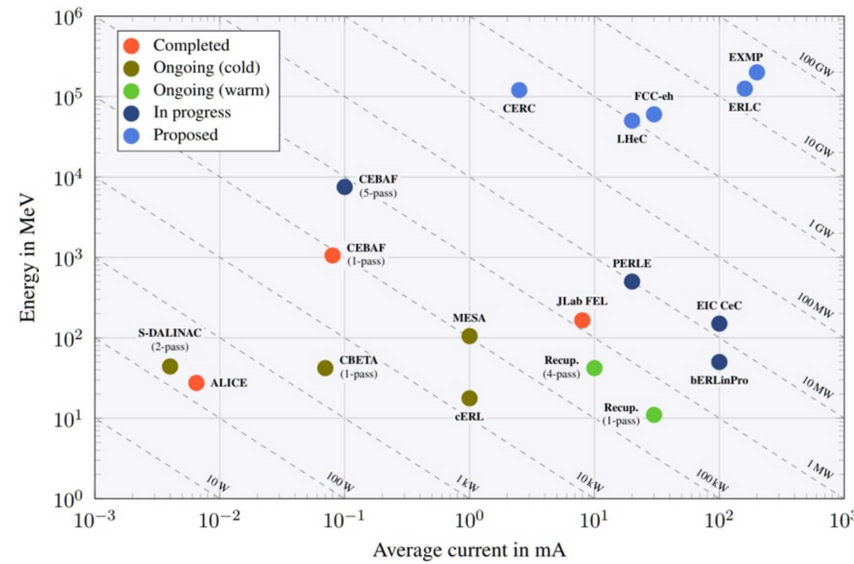
Concurrent operation with FCC-hh



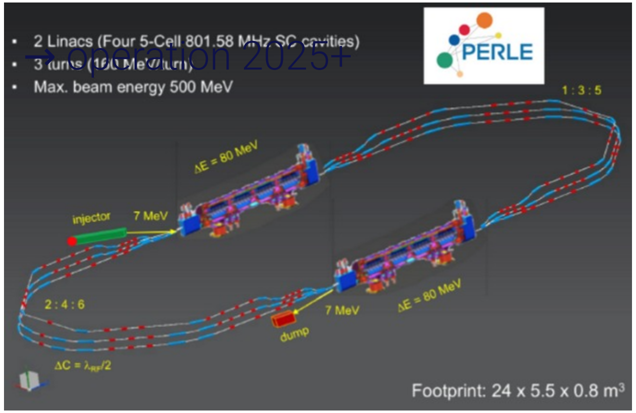
The FCC-eh energy recovery linac

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

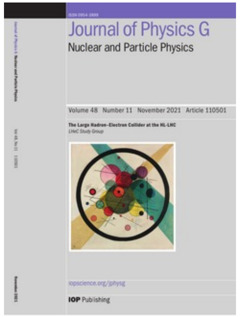
A new facility comprising all essential features ?
→ high-current & high-energy & multi-pass
→ optimised cavities & cryo-modules and a beam for collider experiments



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



Accelerator R&D Roadmap [arXiv:2201.07895]

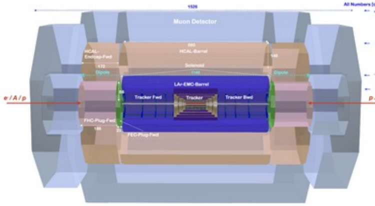


Update of LHeC-CDR JPhys.G 48 (2021) 110501

FCC Physics opportunities EPJ .C79 (2019) 474

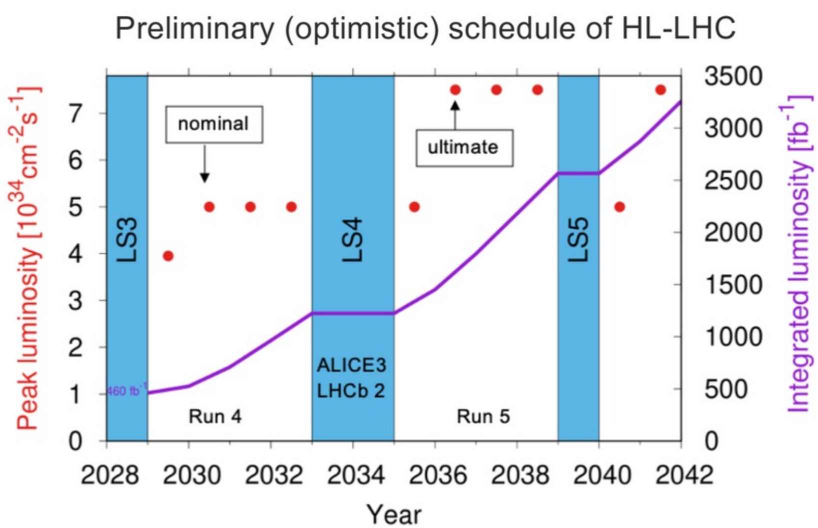
DIS experiment at the HL-LHC EPJ C82 (2022) 40

ERL accelerator & PERLE
→ A. Stocchi, WG6, Thu 9:00
IR and Common *hh* Detector
→ K. Andre, WG6, Thu 9:20



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

(HL-)LHC and FCC schedule



HL-LHC

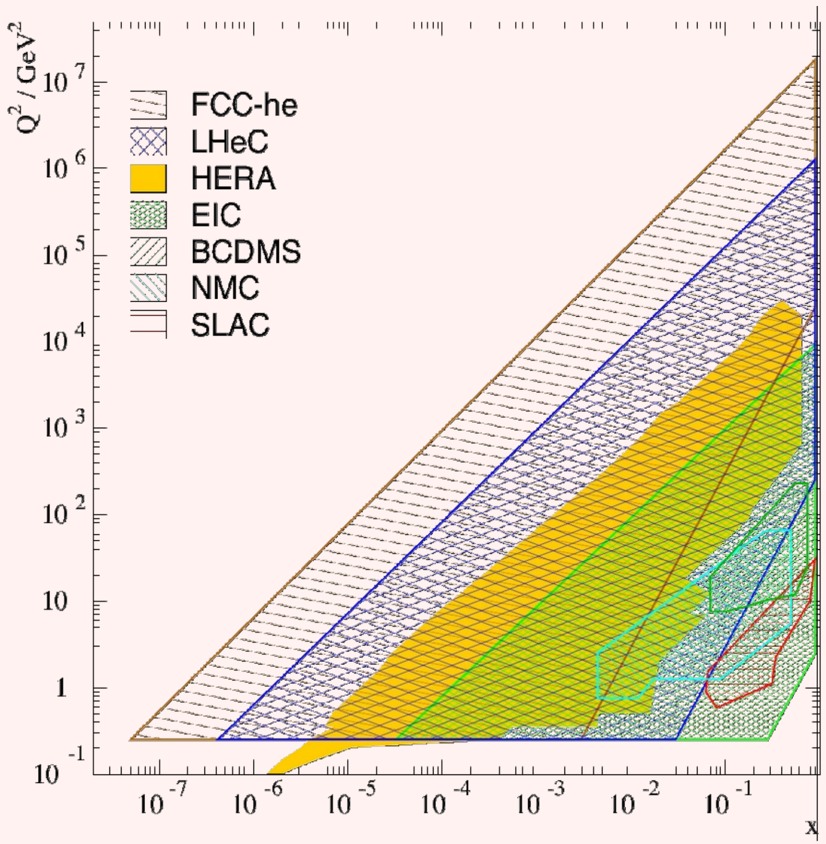
Extraordinary results obtained with the LHC Run-II physics program.
However, real sensitivity potential on several milestone analysis for the LHC physics program will be reached only in the HL-LHC era

Extensive upgrades to accelerator complex to maximise physics reach
3000 fb-1 at 14 TeV (ultimately 4000 fb-1)
Instantaneous luminosity: 5 × 1034 cm−2 s−1 (ultimately 7.5 × 1034 cm−2)
Proton interactions per bunch crossing: < μ > ~ 140 (ultimately < μ > ~ 200)

FCC-hh/FCC-eh

FCC-eh is an integral part of the FCC-hh program
Precision PDFs at the multi-TeV scale a mandatory for FCC-hh physics
High luminosity (and high energy) provide an exciting e—p physics program

Deep-inelastic scattering



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

Empowering the HL-LHC & FCC-hh Search Programme

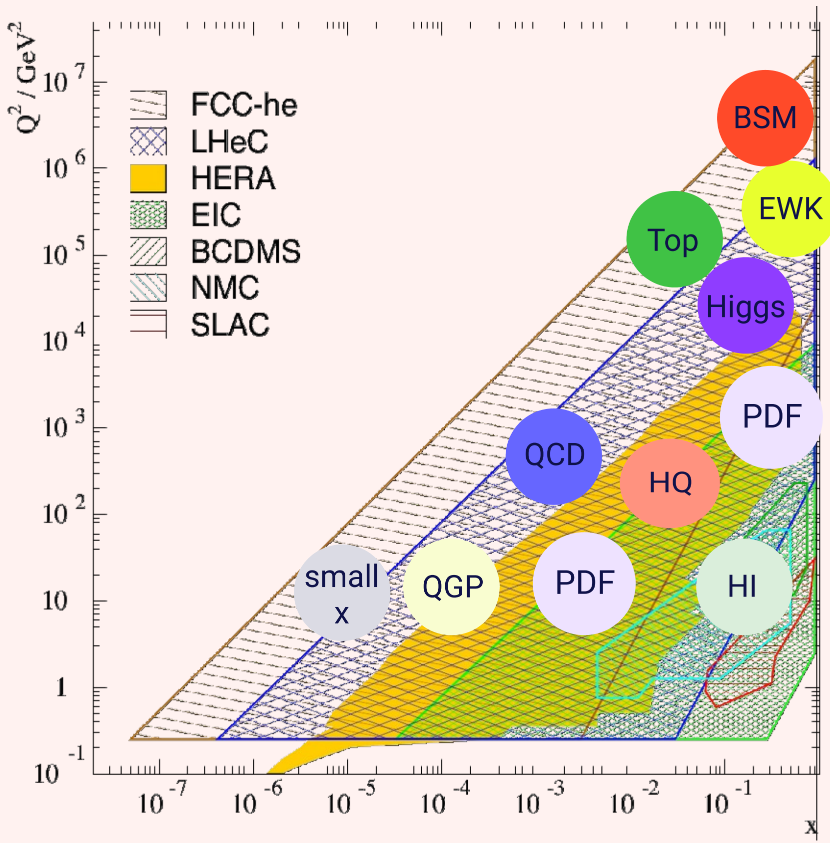
Transformation of HL-LHC & FCC-hh into the desired Higgs and discovery machine

Unique Facility for Nuclear Physics

Complementary Higgs Programme

Top and EW Physics

Deep-inelastic scattering



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Empowering the HL-LHC & FCC-hh Search Programme

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Unique Facility for Nuclear Physics

Complementary Higgs Programme

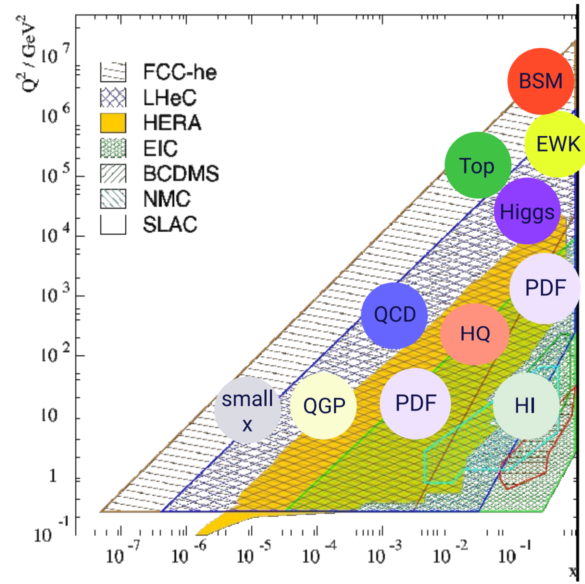
Top and EW Physics

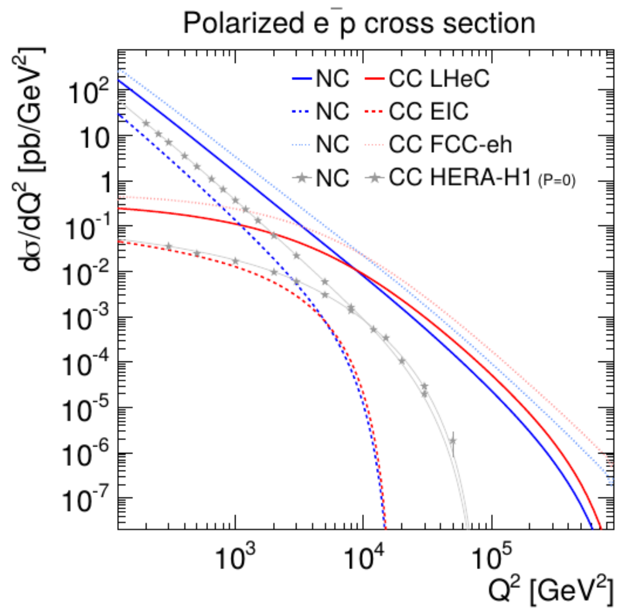
Deep-inelastic electron-proton scattering

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



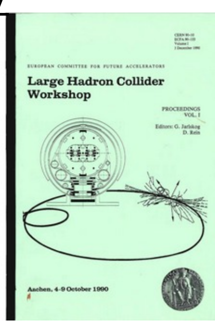


LHeC history

LEP×LHC

1984

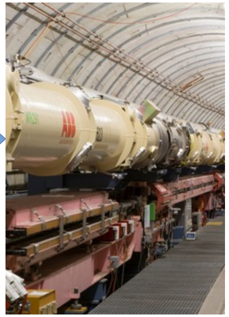
$s \sim \sqrt{1.3}$TeV
L ~ 1fb^{-1}/y



HERA *ep*

1992

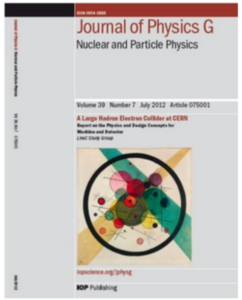
$s \sim \sqrt{0.3}$TeV
L ~ 0.5fb^{-1}



LHC × e⁻

2012

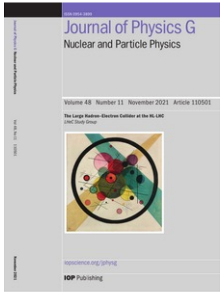
$s \sim \sqrt{1.5}$TeV
L ~ O(100fb^{-1})



HL-LHC×ERL & Higgs

2020

$s \sim \sqrt{1.3}$TeV
L ~ 1 ab^{-1}

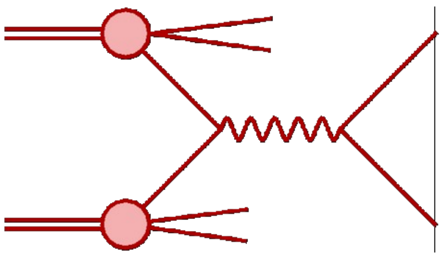


LHeC

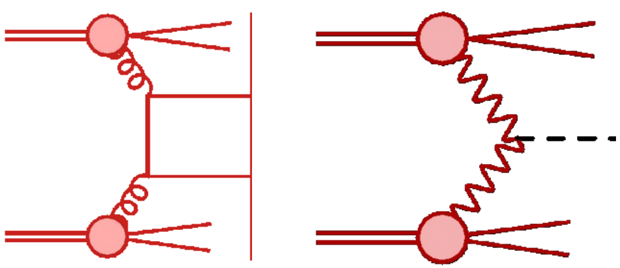
'30

proton—proton and electron—proton

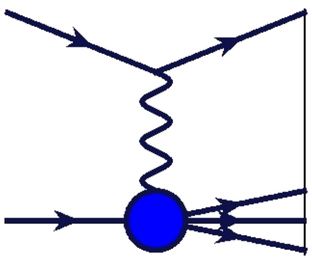
Important processes in proton—proton
Dominant s-channel process



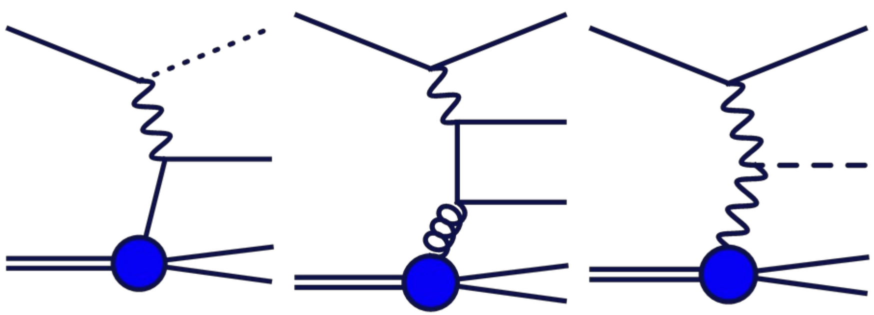
pair-production and VV-fusion, and many more...



Important processes in electron—proton
Dominant t-channel process

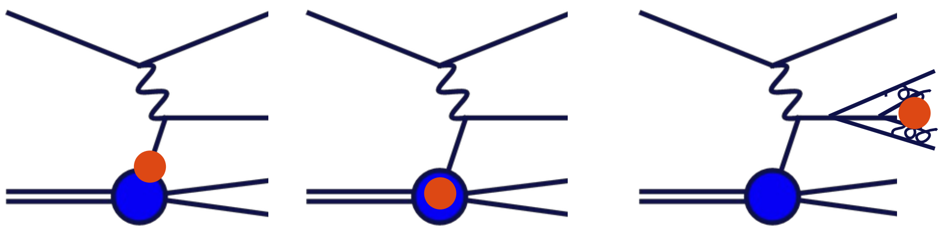


s-channel processes complementary to pp



Precision QCD

Strong coupling constant α_s is one of the least known fundamental constants

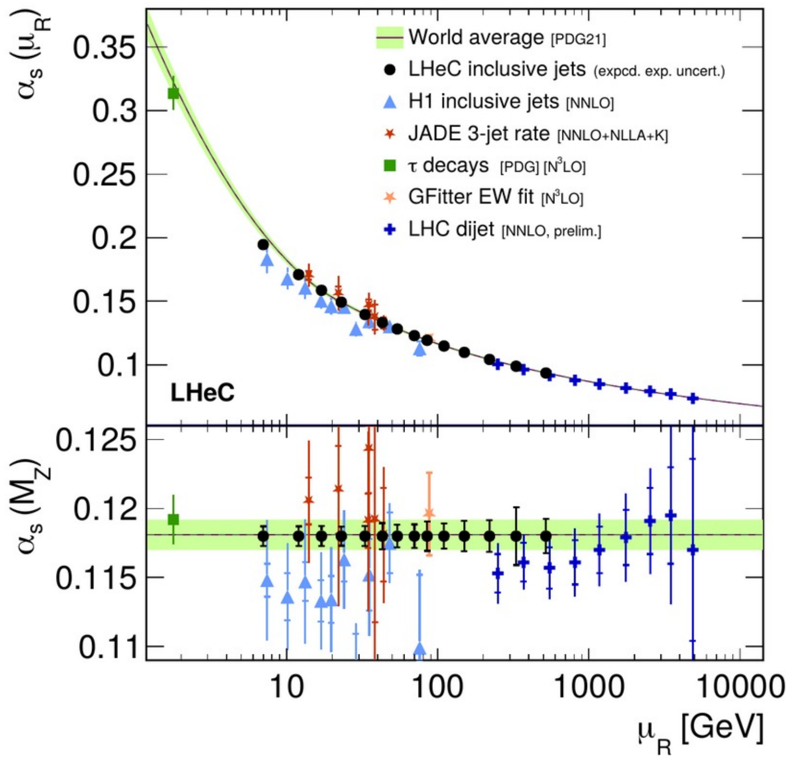


→ Jet production in Breit frame $O(\alpha_s)$
→ Proton internal dynamics (scaling)
→ Jet substructure and formation of hadrons

$\alpha_s(M_Z)$ from inclusive DIS

$$\Delta\alpha_s(M_Z)(\text{incl. DIS}) = \pm 0.00019_{(\text{exp+PDF})}$$

α_s from jet production (LHeC)
→ Fill gap between τ-deaycs and Z-pole & LHC
→ FCC-eh with higher precision and larger range



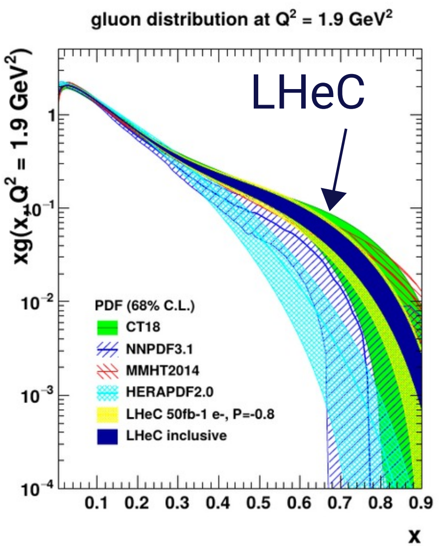
α_s seen as a benchmark parameter
→ A factor 10 more precise QCD measurements than nowadays possible

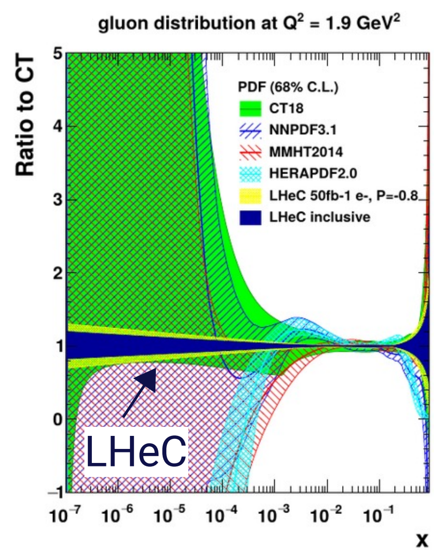
Hadron structure measurements

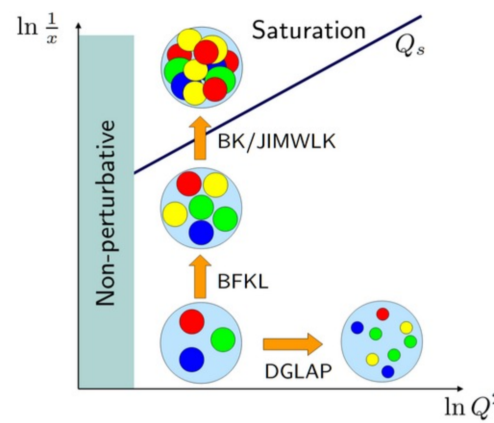
Color-neutral particle probes the interior of the proton
→ Parton distribution functions (PDFs) of the proton are determined with unprecedented precision

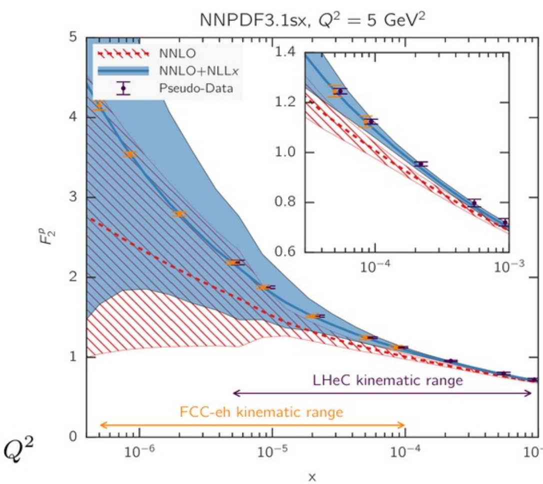
M. Bonvini, Eur.Phys.J.C 78 (2018)834

high-*x* – Gluon distribution – low-*x*









→ Full determination of all parton-flavors from heavy quark and jet cross section measurements
→ 3D structure of the proton (TMDs, GPDs) from elastic diffractive and deeply-virtual Compton scattering

C. Gwenlan, M. Klein, et al

Low-x:
an unexplored region with exciting QCD effects
Resummation effects affect the Higgs cross section in p—p through gg fusion by 10 %

LHeC & FCC-eh PDFs
C. Gwenlan, Tue, 12:50

small-x in ep and eA
A. Stasto, Thu, 9:40

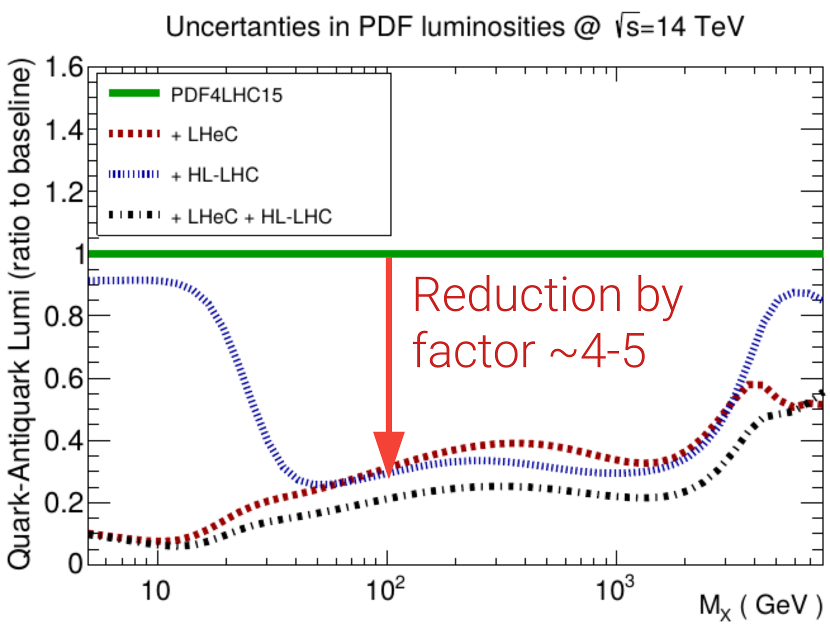
Improvement for parton luminosities at LHeC

LHeC, J.Phys.G 48 (2021) 11050
Khalek, Rojo, et al., SciPost Phys. 7 (2019) 4

PDFs are crucial ingredients to fully achieve the physics goals of HL-LHC (Higgs, high-mass,etc...)

The LHeC measurements will provide the most precise – and independent – constraints on PDFs

Important ingredients for ATLAS & CMS's physics programme for HL-LHC

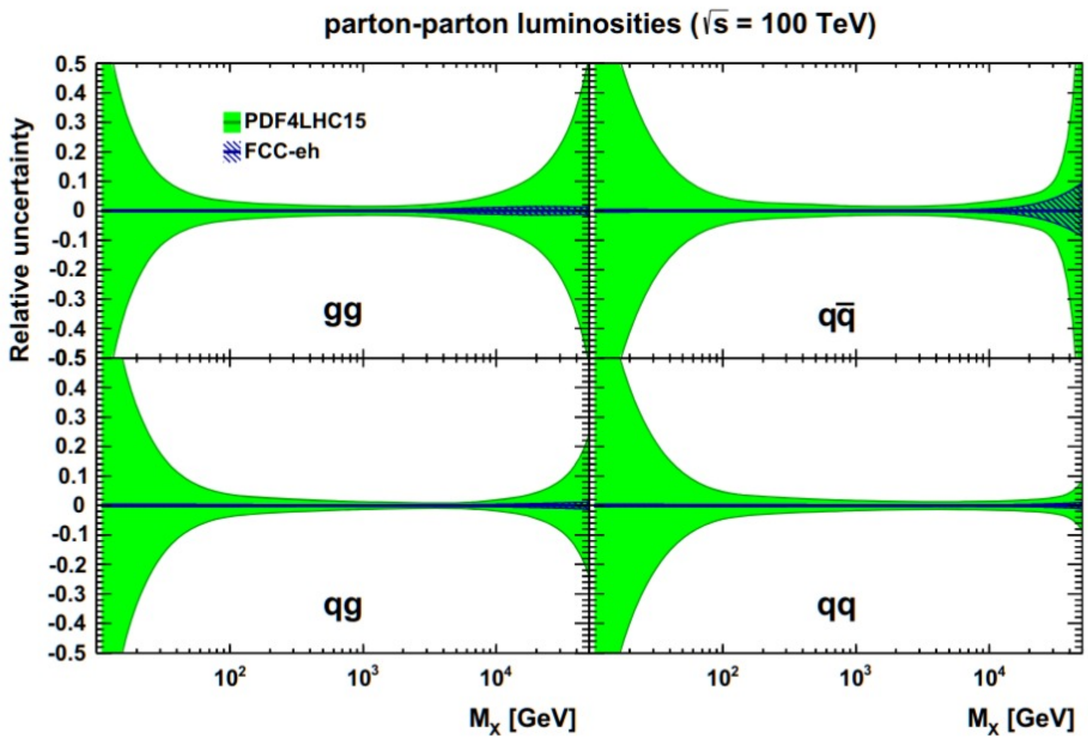


Improvement for parton luminosities at FCC-hh

PDFs are crucial ingredients to fully achieve the physics goals of FCC-hh (Higgs, high-mass,etc…)

The FCC-eh measurements will provide the most precise – and independent – constraints on PDFs

At the level of precision of FCC-eh PDFs many new effects will be investigated
→ Small-x behaviour, high-x, mass-effects, non-perturbative effects, quantum-enganglement, shadowing,...

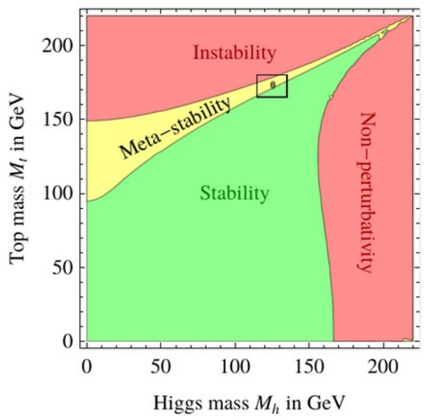


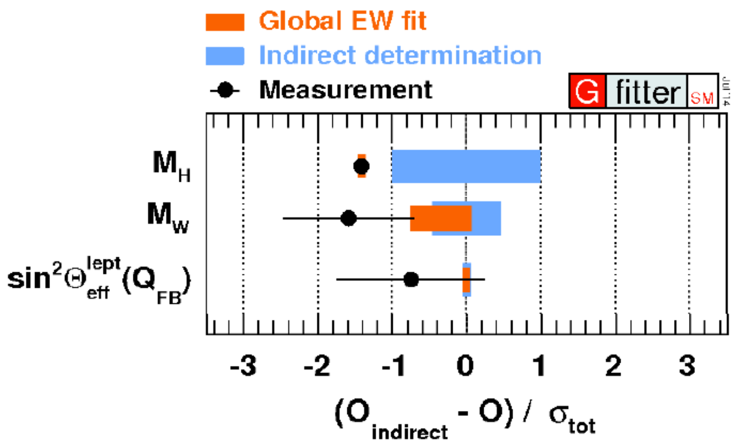
→ QCD evolution (DGLAP) from 1GeV up to ~50000 GeV

LHeC & LHeC PDFs
C. Gwenlan, Tue, 12:50

Electroweak sector

One of the **goal of HL-LHC physics program:** tests of the consistency of the EW sector in the SM through high precision measurements of its fundamental parameters (**$\sin^2\theta_W$** and **m_W**)





- Indirect determination of both m_W and $\sin^2\theta_{eff}$ more precise then the experimental measurement:
- This call for a precise direct Measurement
  - ✓ Stringent test of the self consistency of the SM
  - ✓ might reveal sign of new physics

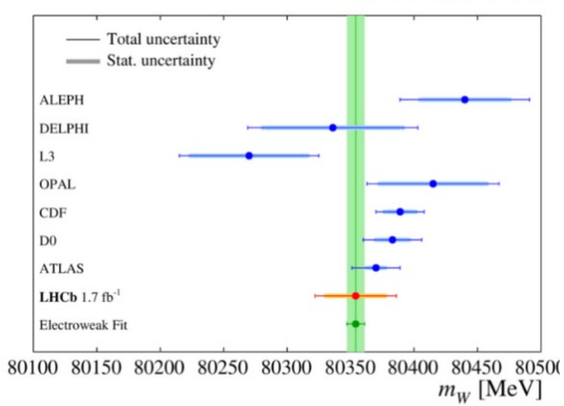
The EW precision measurements program at HL-LHC will highly **benefit from more precise knowledge of PDF.**

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

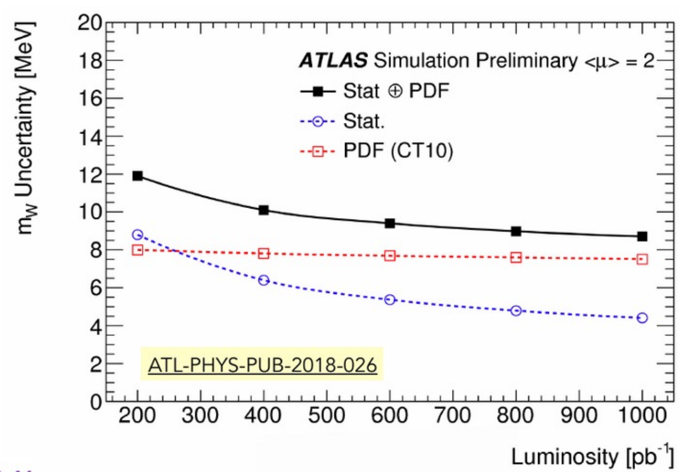
LHCb measurement

[JHEP 01 (2022) 036]

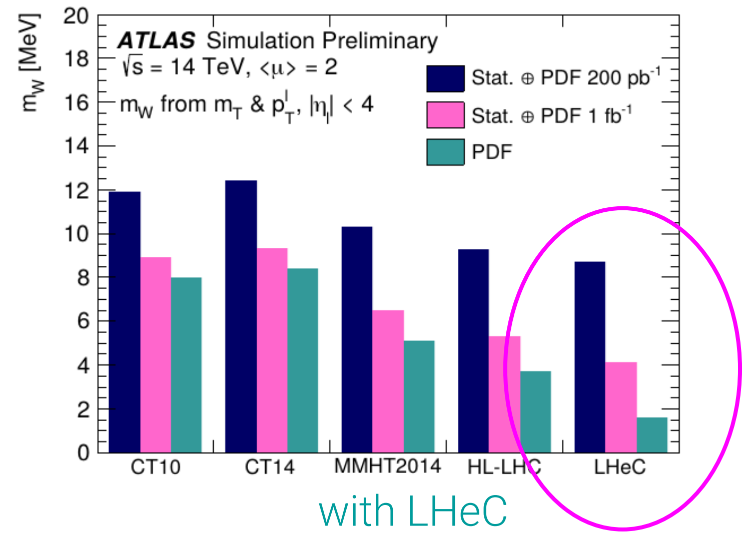


$$m_W = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

ATLAS low-<μ> prospects



ATLAS low-<μ> HL-LHC prospects



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

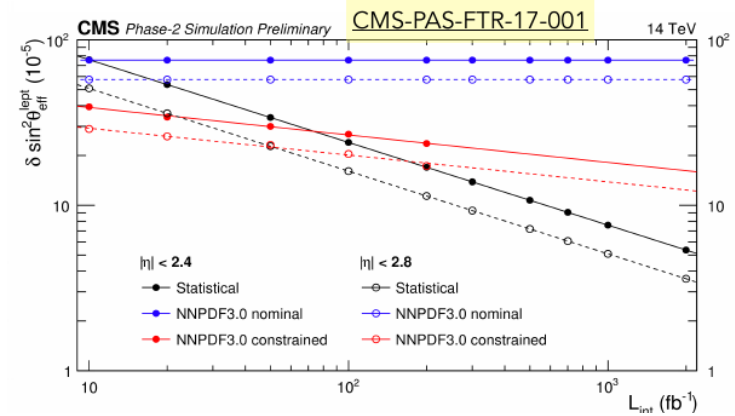
At HL-LHC, PDFs are expected to become the largest indiviual uncertainty
HL-LHC PDFs will reduce that, but will remain a limiting uncertainty
With LHeC PDFs, the W-mass measurements will be exceed LEP precision

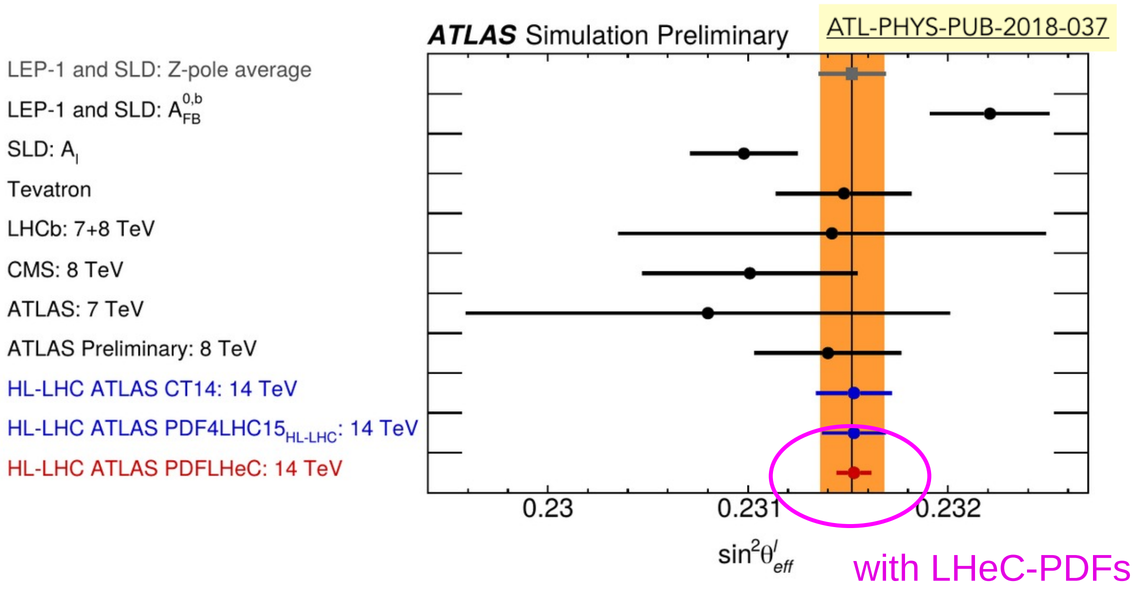
Weak mixing angle @HL-LHC

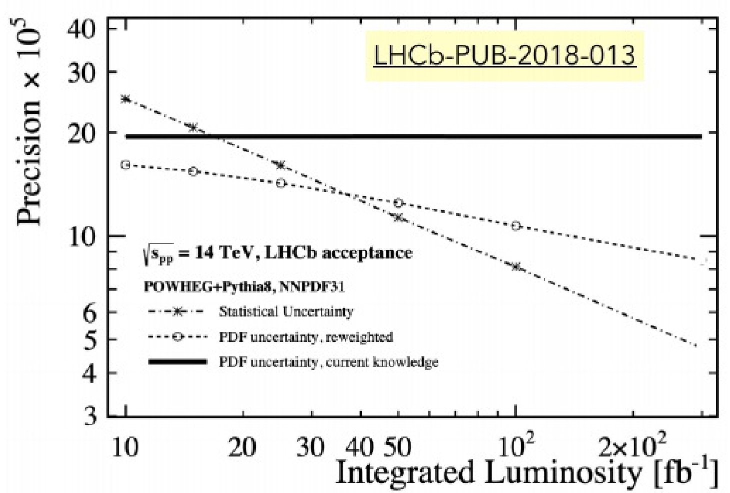
LHC experiments entered the precision electroweak race:

New analysis techniques (including in-situ PDF profiling and event categorisation) substantially reduced systematic uncertainties wrt. previous LHC measurements.

→ future measurements at p—p collider will be limited by PDF and further modelling uncertainties

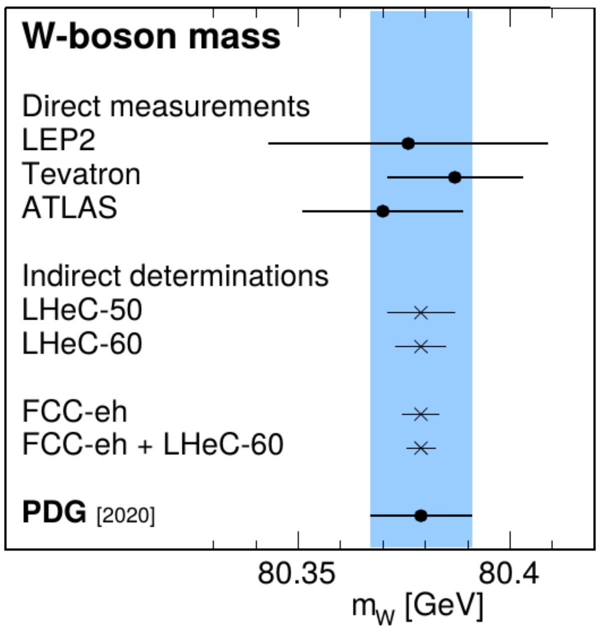


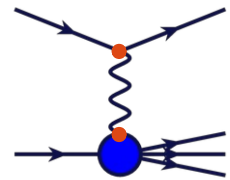




Electroweak Measurements in e—p

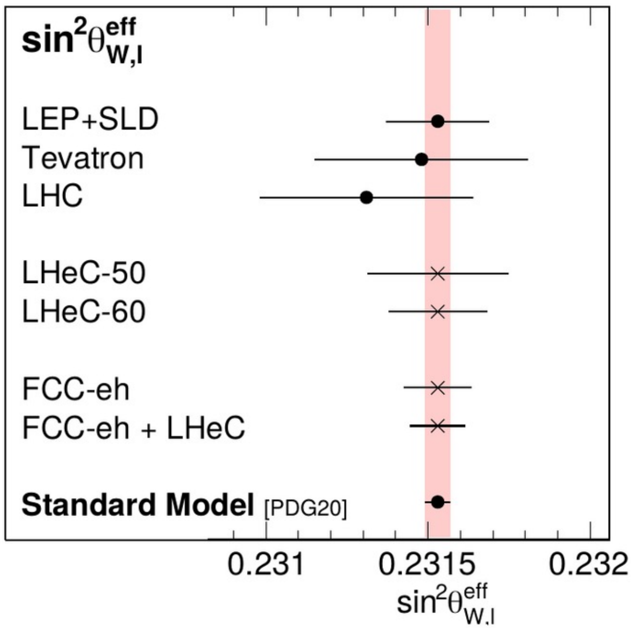
- Precision measurements of inclusive NC and CC DIS are sensitive to EW parameters
- Determination of EW parameters together with PDFs can be performed





Experimental and PDF-related uncertainties:

Facility	$\Delta \sin^2\theta^{\text{eff}}_{W,\ell}$	Δm_W
LHeC-50	±0.00021	±8 MeV
LHeC-60	±0.00015	±6 MeV
FCC-eh	±0.00011	±4.5 MeV
FCC+LHeC	±0.000086	±3.6 MeV



W-mass in on-shell scheme:
→ self-consistency test of SM
→ Precision higher than SM propsect

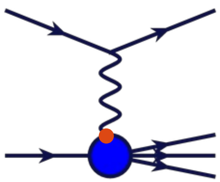
$\sin^2\theta_W^{\text{eff}}$ can be directly determined in e—p
Exp and PDF-related uncertainty compete with the LEP+SLD combination

Eur.Phys.J.C 80 (2020) 831
PoS(EPS-HEP2021)485

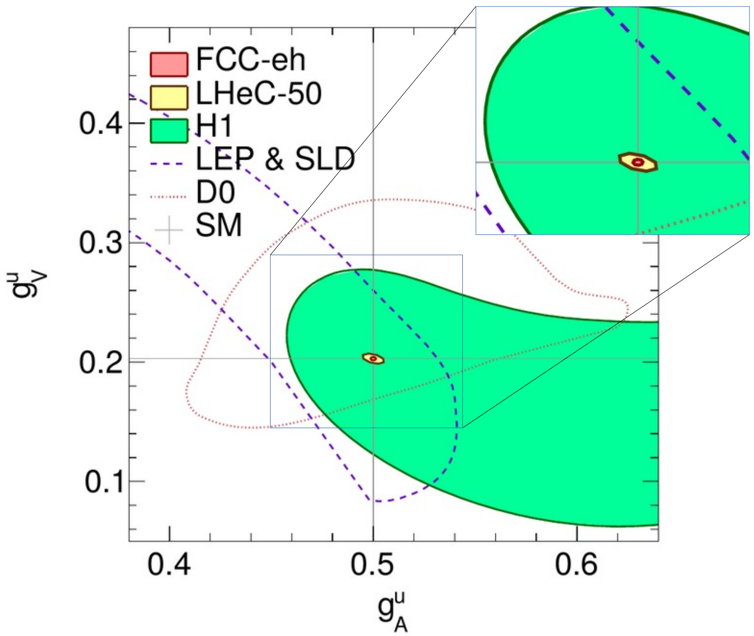
Complementary measurements in e—p

Neutral current sector

- EW couplings of 1st gen quarks

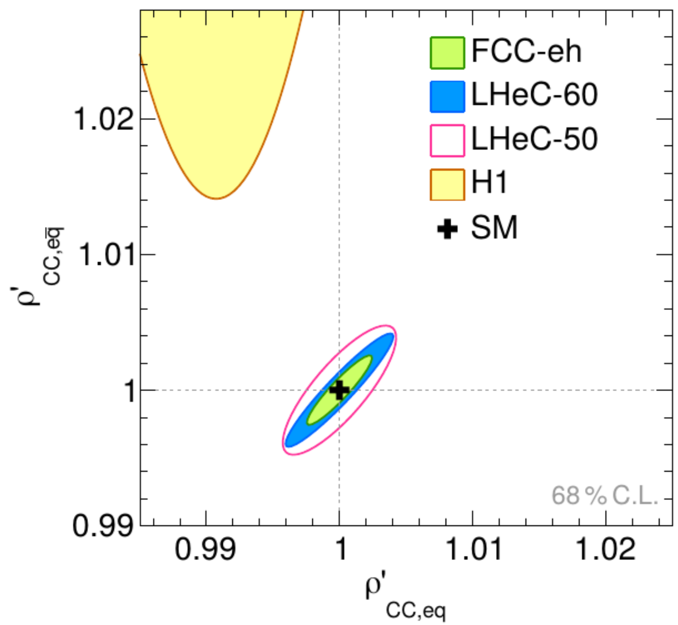


$$g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\,(I^3_{\mathrm{L},f} - 2Q_f\kappa_{\mathrm{NC},f}\,\sin^2\theta_{\mathrm{W}})$$
$$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\,I^3_{\mathrm{L},f}$$



Charged current sector

- Effective couplings of the W-boson
- Anomalous charged current couplings



In e—p collisions precision EW observables are measured, which are not (well) accessible in p—p or e—e collisions

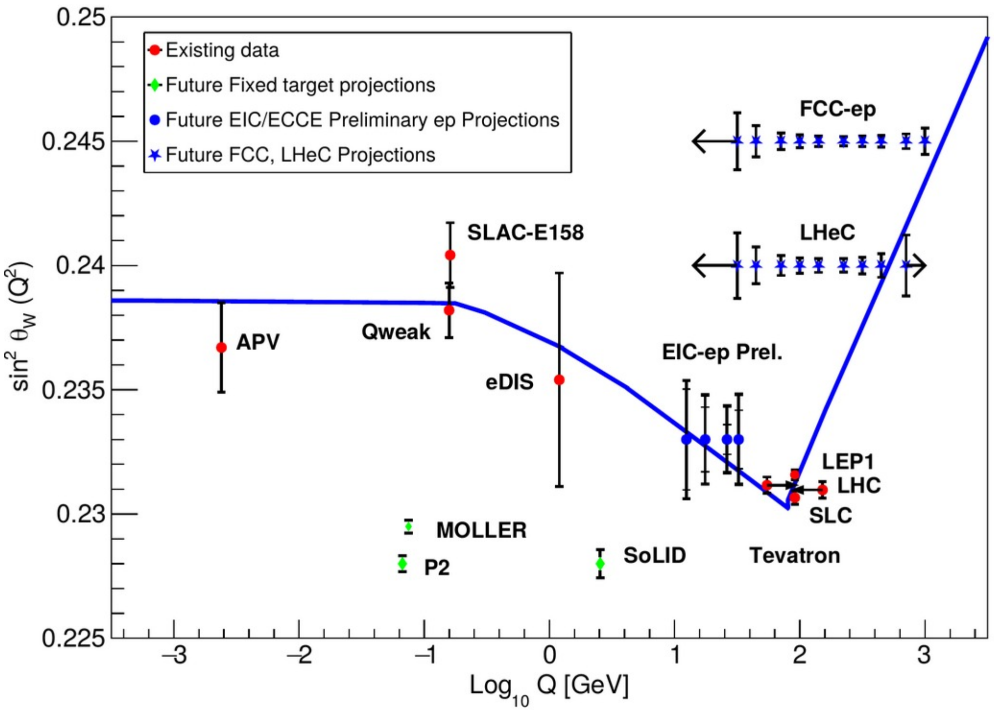
Scale dependent measurements

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

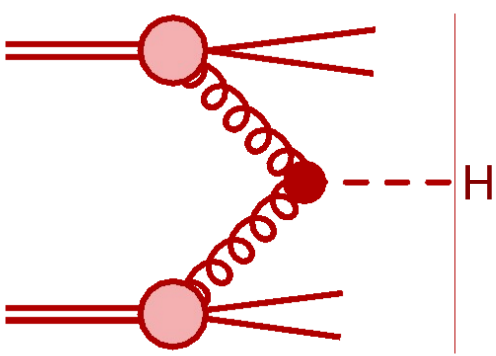
With high luminosity e—p experiments
Per mille uncertainties in range of
20 < Q < 700 GeV in spacelike regime

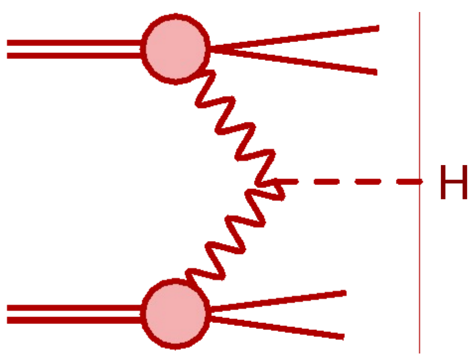


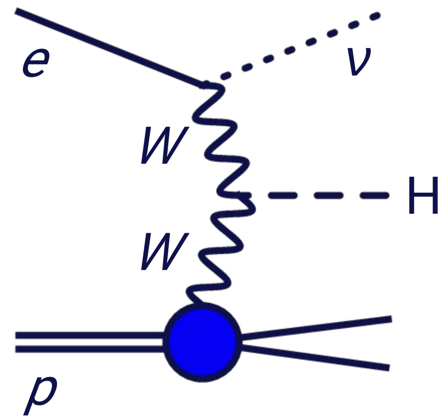
→ Unique measurement of the 'running' at high scales

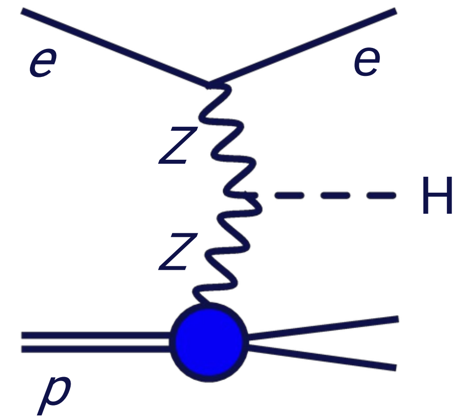
Higgs physics in p—p and e—p

Gluon fusion | Vector-boson fusion | Charged current | Neutral current









Higgs production through *gluon*-fusion (top-loop)

Higgs production through *WW*- or *ZZ*-fusion

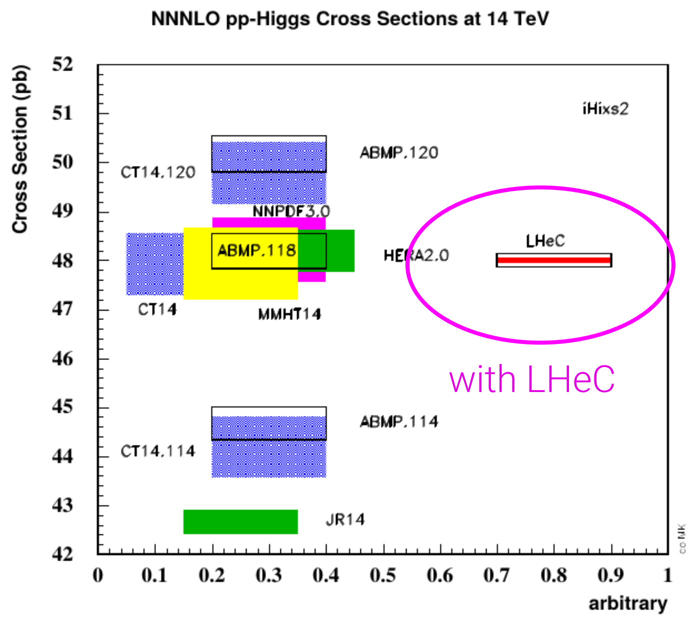
Higgs production through *WW*-fusion

Higgs production through *ZZ*-fusion

Additionally: Higgs-strahlung (VH) & associate production ttH/bbH

Higgs physics in p—p and e—p

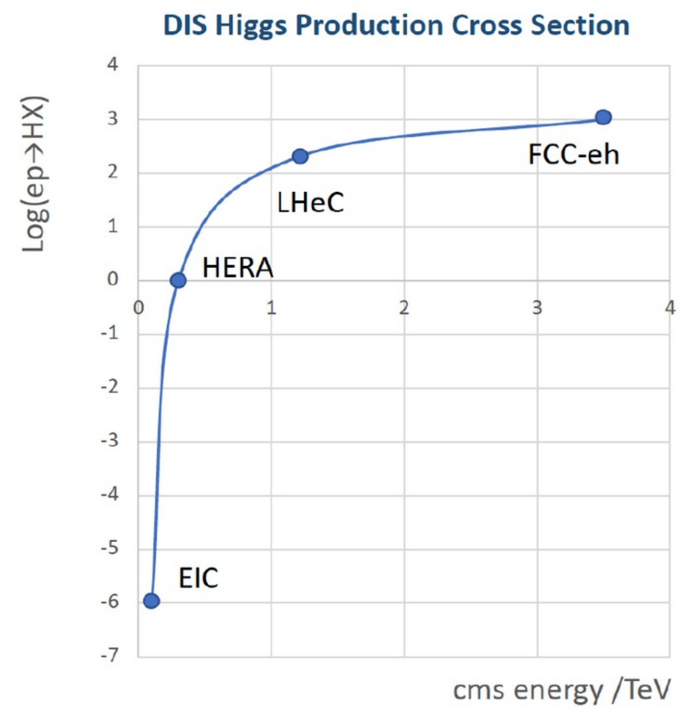
Higgs production cross section in p—p at the HL-LHC



- N3LO predictions are limited by PDF uncertianties (eigenvectors, and sets)

→ LHeC PDFs will significantly reduce the PDF-related uncertainties

Higgs production cross section in e—p

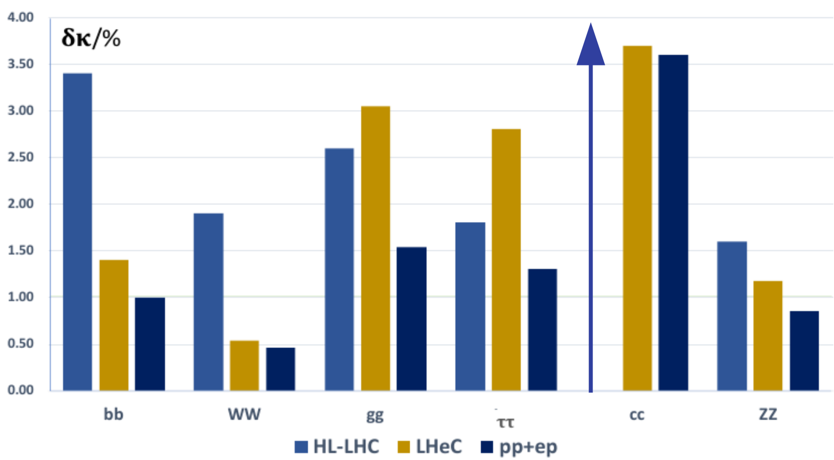


Higgs-production cross section at LHeC ~200fb
Sensitivity to the decay channels
bb, WW, gg, ττ, cc, ZZ, (γγ)

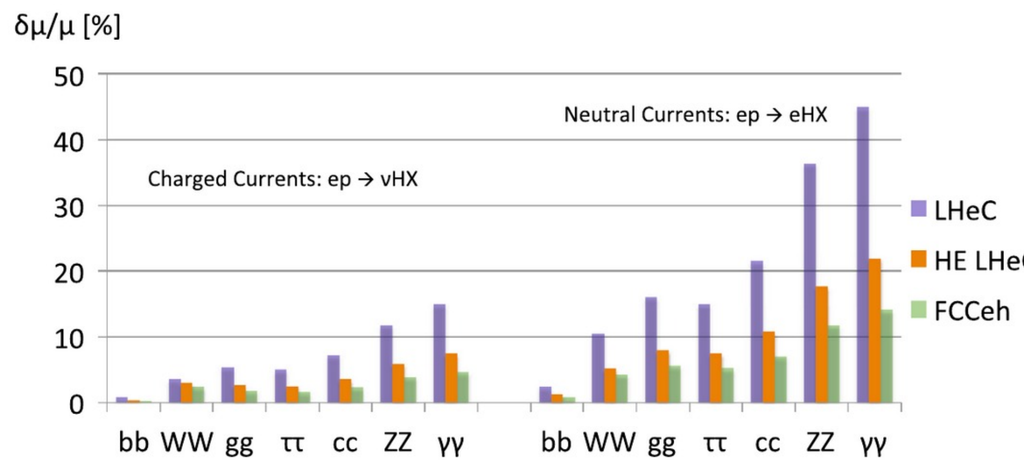
Higgs physics – interpretation in *κ* framework

Interplay between *pp* and *ep*

(shown here: LHeC & HL-LHC)



Signal strength in all decay channels



Complementarity between *pp* and *ep*

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

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

High sensitivity in all six decay channels

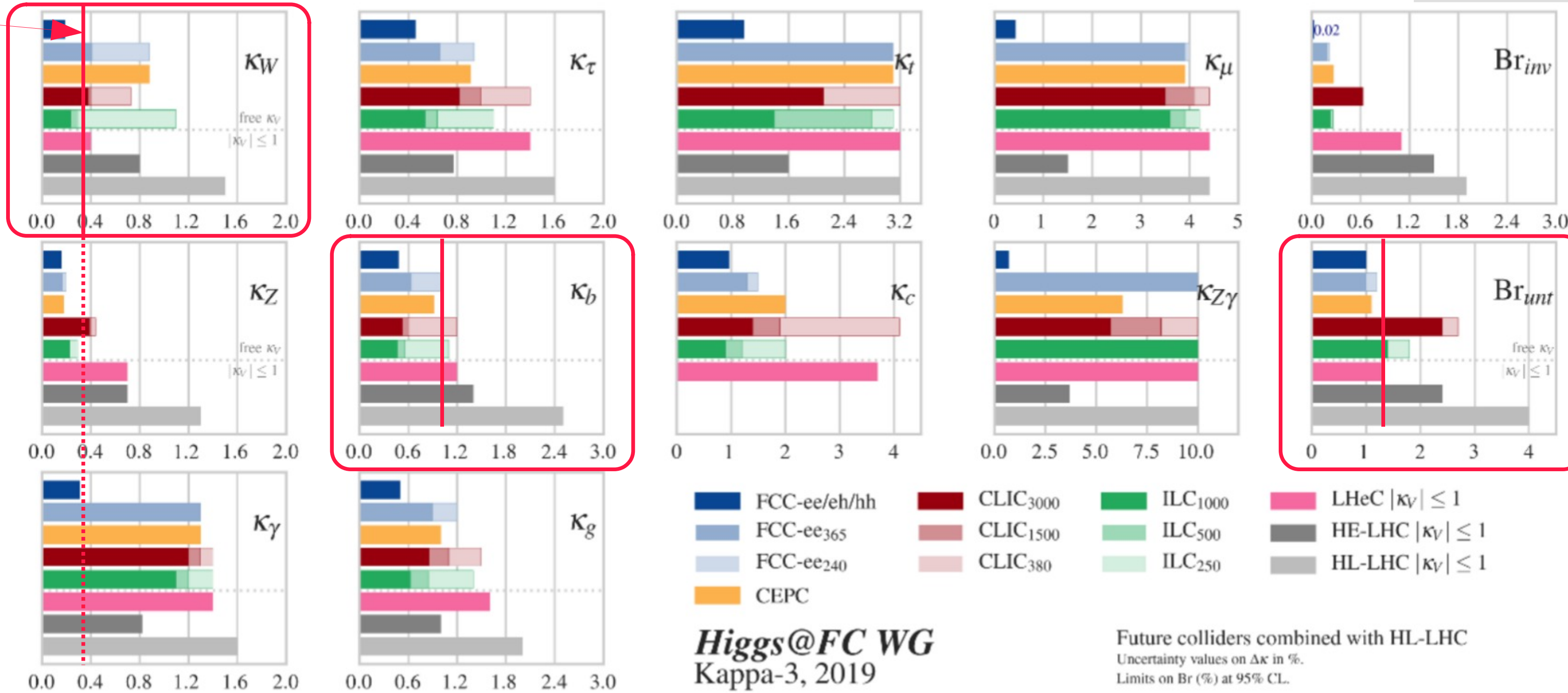
→ Significant improvement with increasing √s

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

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

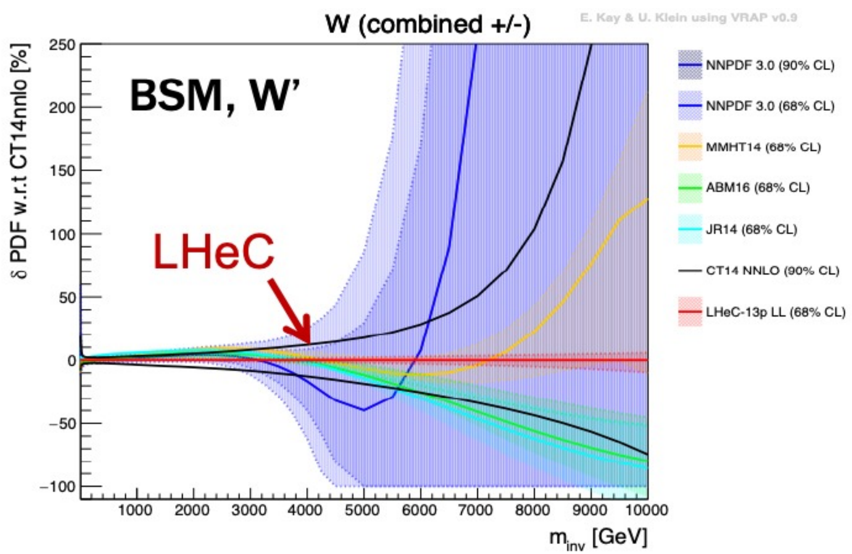
- *Complementary with HL-LHC*
- *Data in '30s*
- *1/10 of the cost than FCC or ILC*

BSM and Top-quark Physics
O. Fischer, Tue 14:50

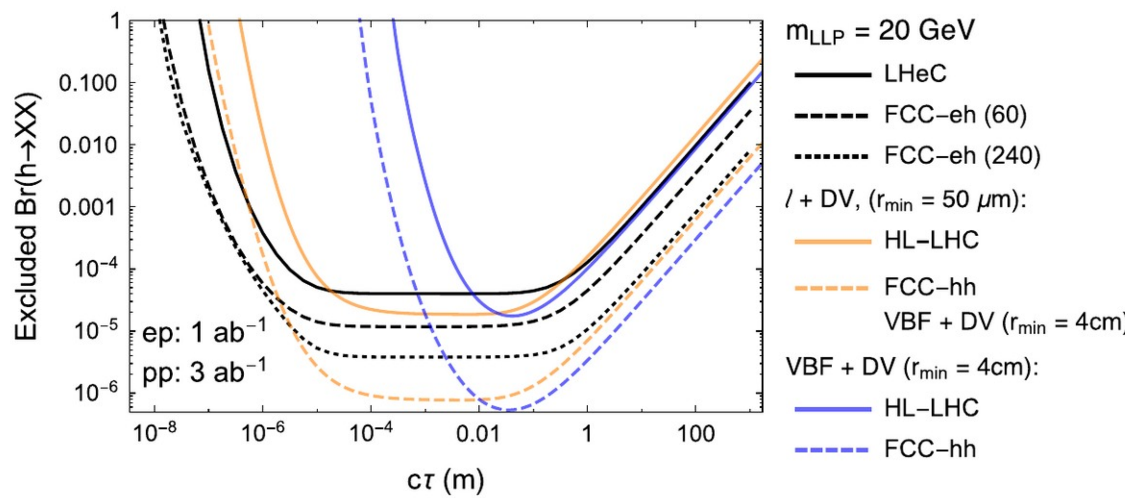
Experimental synergies between DIS and the LHC
M. D'Onofrio,,Fri, 9:20

BSM and searches

- BSM physics and searches in p—p are particular sensitive to high-*x* PDFs
- Searches in p—p can be improved with better knowledge of high-x PDFs from LHeC



- Data from e—p can cover search regions, which are not accessible in p—p, because of 'clean' experimental environment in e—p (no pile-up, no underlying event)
  → long-lived particles, degenerate SUSY scenarios, displaced vertices

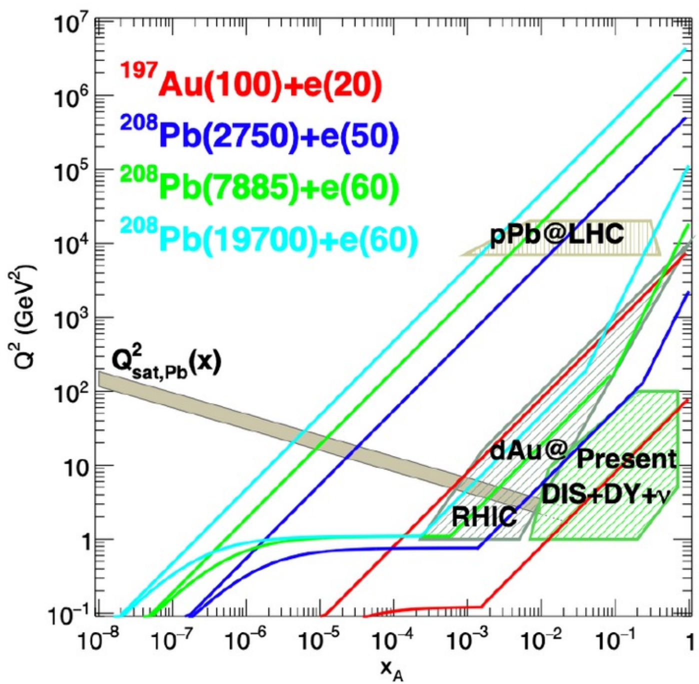


photon-photon interations in ep and eA
K. Piotrzkowski, Y. Yamazaki
Thu, 10:40

Electron—Ion scattering

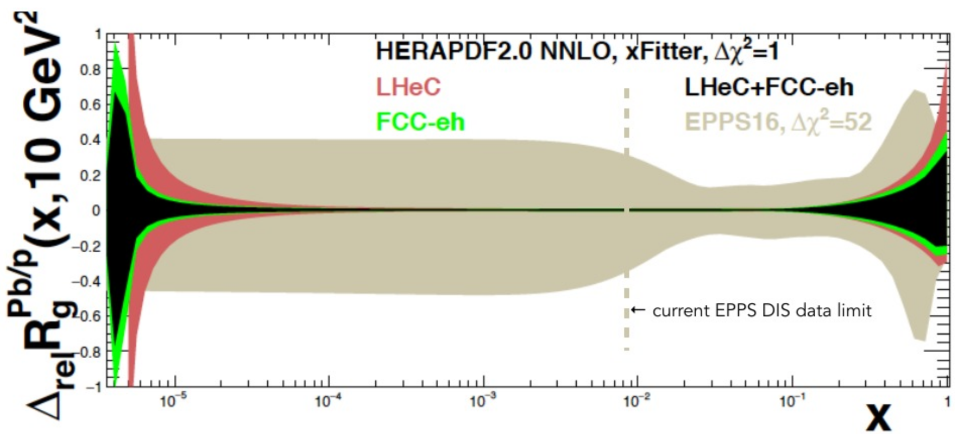
At LHeC and FCC-eh

- Unique nuclear/HI physics program
- Extension of fixed target range by $10^{3\text{ to }4}$
- nPDFs independent on pPDFs



Partons in nuclei

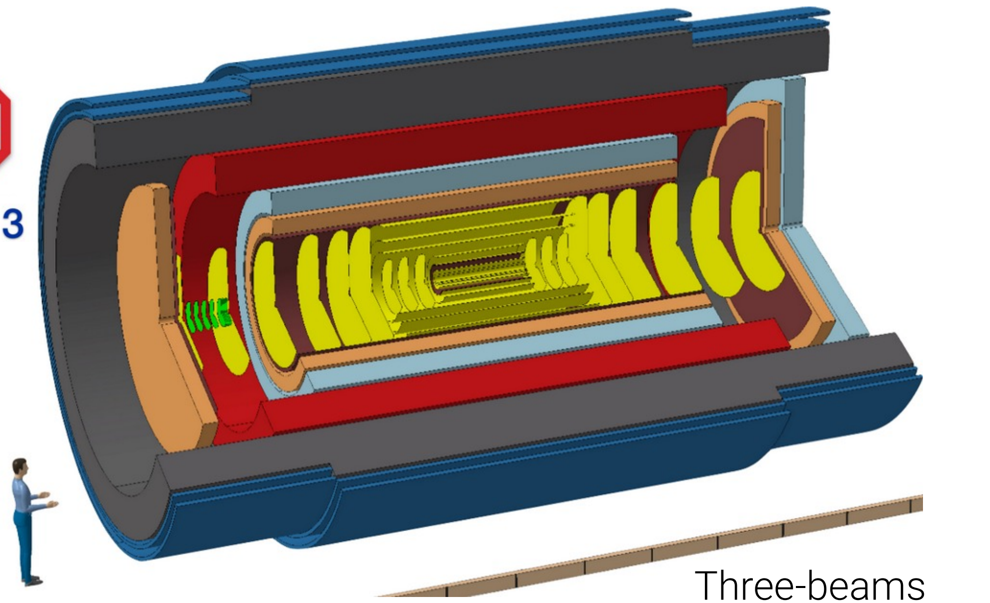
- nPDFs with uncertainties <10% down to few x~10^{-5}
- Direct measurement of R: $R_i(x,Q^2) = \frac{f_i^A(x,Q^2)}{A f_i^p(x,Q^2)}$,

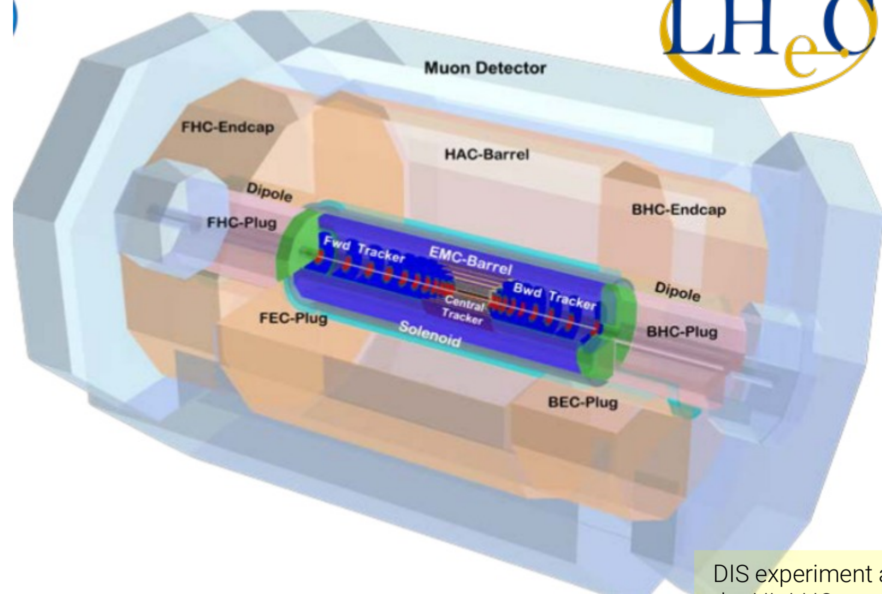


Direct determination of R_g with proton and lead data allows to DISENTANGLE small- x dynamics from nuclear effects.
→ Huge improvement over the EPPS16 global fit
→ Precision test for QCD of QGP, shadowing, antishadowing, de-confinement, saturation..

LHC-Point 2 in HL-LHC era

ALICE 3



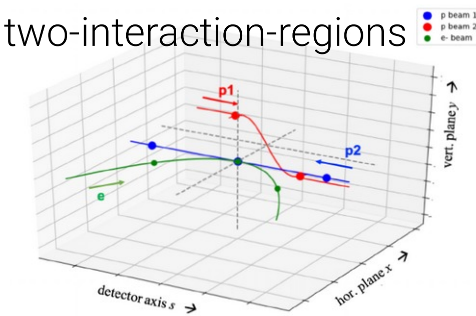


DIS experiment at the HL-LHC
EPJ C82 (2022) 40

ALICE3

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

Three-beams two-interaction-regions



LHeC

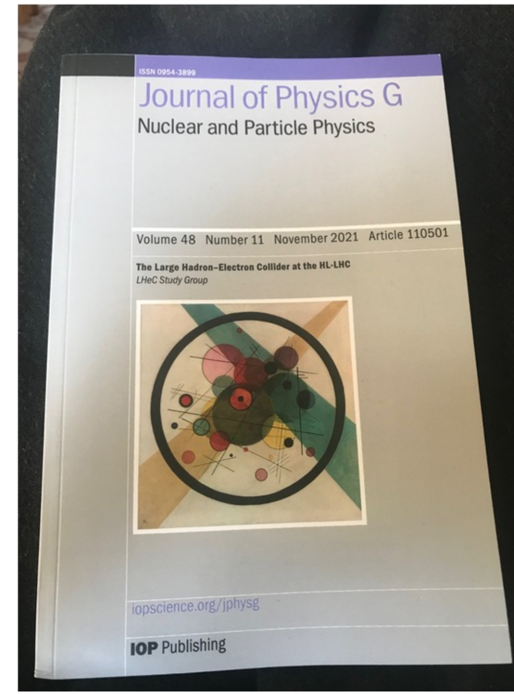
- Higgs
- EWK
- PDFs (for HL-LHC)
- BSM
- Top
- small-x
- eA
- ALICE3 (pp, AA)

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

Summary

Experimental synergies between DIS and the LHC
M. D'Onofrio,,Fri, 9:20

A ~~high-energy~~ high-luminosity electron-hadron scattering experiment substantially supports the program of a hadron-collider



Complementary I

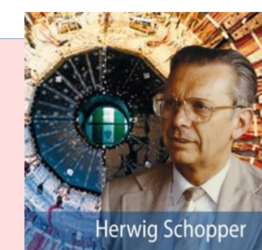
- *QCD precision measurements in e—p reduce uncertainties in p—p measurements and their interpretation (PDFs, hadronisation, fragmentation, parton shower, etc…)*

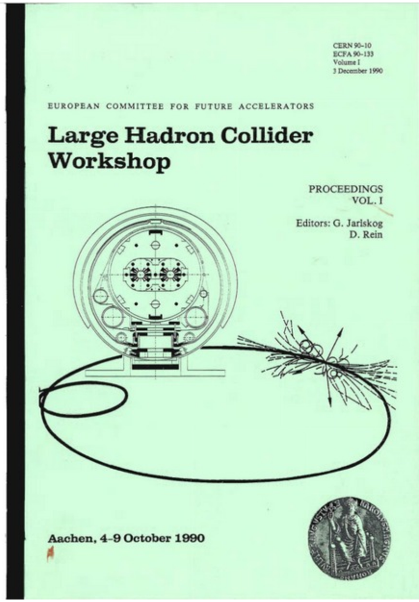
Complementary II

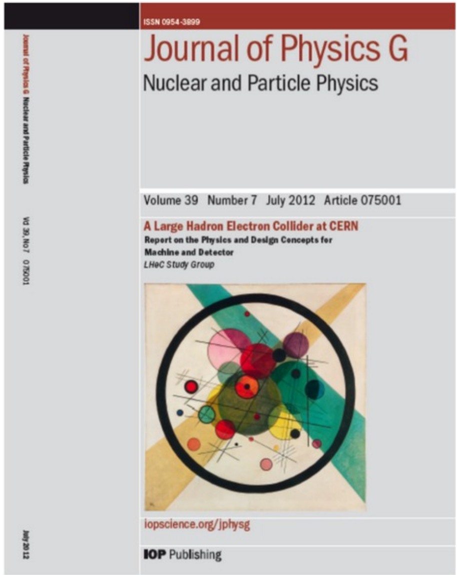
- *Measurements in DIS are often sensitive to complementary processes: H→bb, WW→H, $\alpha_s(m_Z)$, $\alpha_s(\mu)$, $\sin^2\theta_W$*

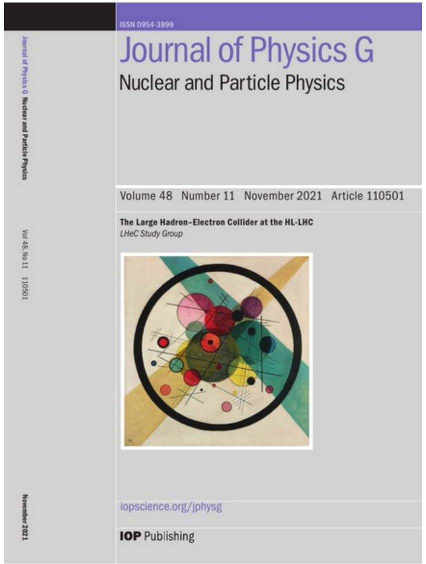
Statement from the IAC

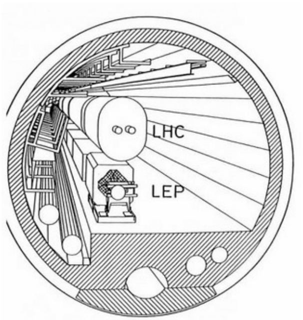
The addition of an ep/A experiment to the LHC substantially reinforces the physics program of the facility, especially in the areas of QCD, precision Higgs and electroweak as well as heavy ion physics;

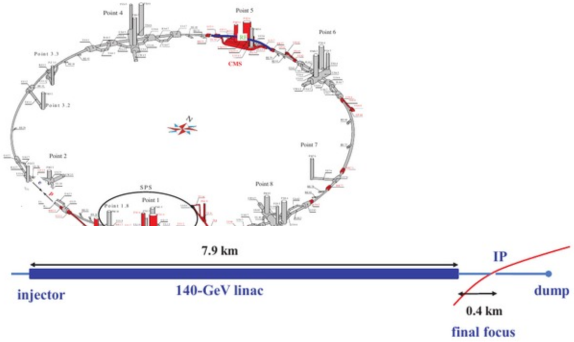


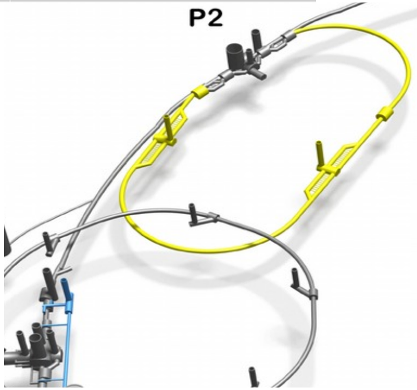

CERN 90-10
ECFA 90-133
Volume I
3 December 1990
EUROPEAN COMMITTEE FOR FUTURE ACCELERATORS
Large Hadron Collider Workshop
PROCEEDINGS
VOL. I
Editors: G. Jarlskog
D. Rein
Aachen, 4-9 October 1990


ISSN 0954-3899
Journal of Physics G
Nuclear and Particle Physics
Volume 39 Number 7 July 2012 Article 075001
A Large Hadron Electron Collider at CERN
Report on the Physics and Design Concepts for Machine and Detector
LHeC Study Group
iopscience.org/jphysg
IOP Publishing


ISSN 0954-3899
Journal of Physics G
Nuclear and Particle Physics
Volume 48 Number 11 November 2021 Article 110501
The Large Hadron–Electron Collider at the HL-LHC
LHeC Study Group
iopscience.org/jphysg
IOP Publishing


LHC
LEP


7.9 km
IP
injector
140-GeV linac
dump
0.4 km
final focus


P2