PDFs, strong coupling and electroweak physics at FCC-eh

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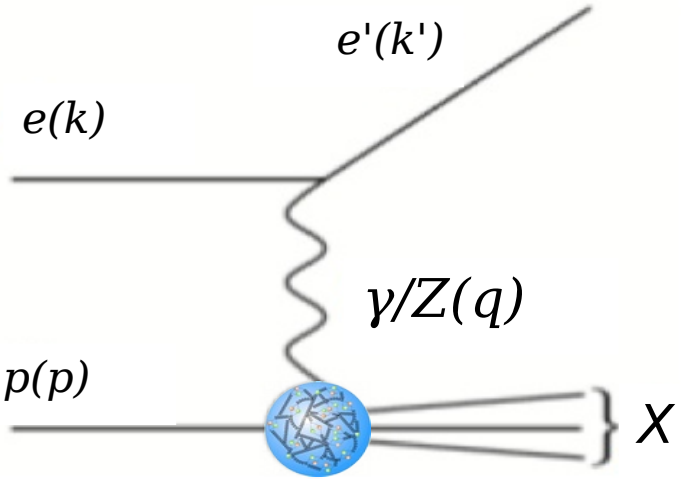
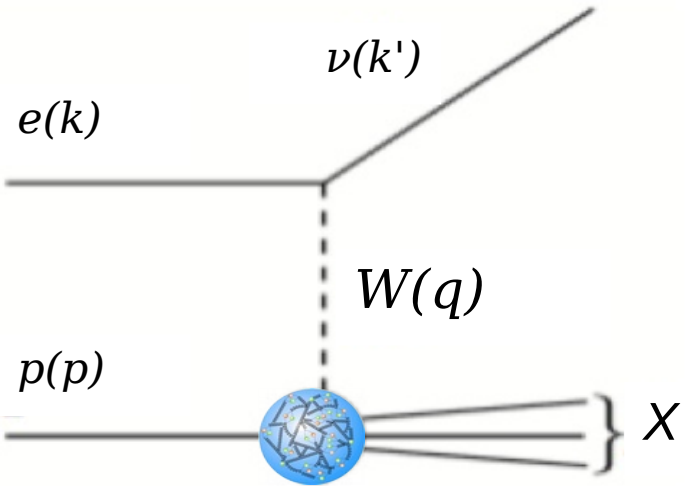
Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \to e'X$



Charged current scattering
$ep \to \nu_e X$



R-D. Heuer

"The point-like electron "probes" the interior of the proton via the electroweak force, while acting as a neutral observer with regard to the strong force."

-> FCC-eh: Electroweak (EW) and QCD physics are equally important

PDFs at FCC-hh and FCC-eh

FCC-hh cross section

- Convolution of two parton density functions f_p

$$\sigma = \sum_{i,j=q,\bar{q},g} f_{i/p} \otimes f_{j/p} \otimes \hat{\sigma}_{i,j \to X}$$

Parton density functions (PDFs)

- at LO QCD : probability of finding a parton of a given flavour that carries a fraction x of the total proton's momentum
- PDFs cannot be calculated only their evolution with the scale is predicted
- Their *x*-shapes have to be determined data

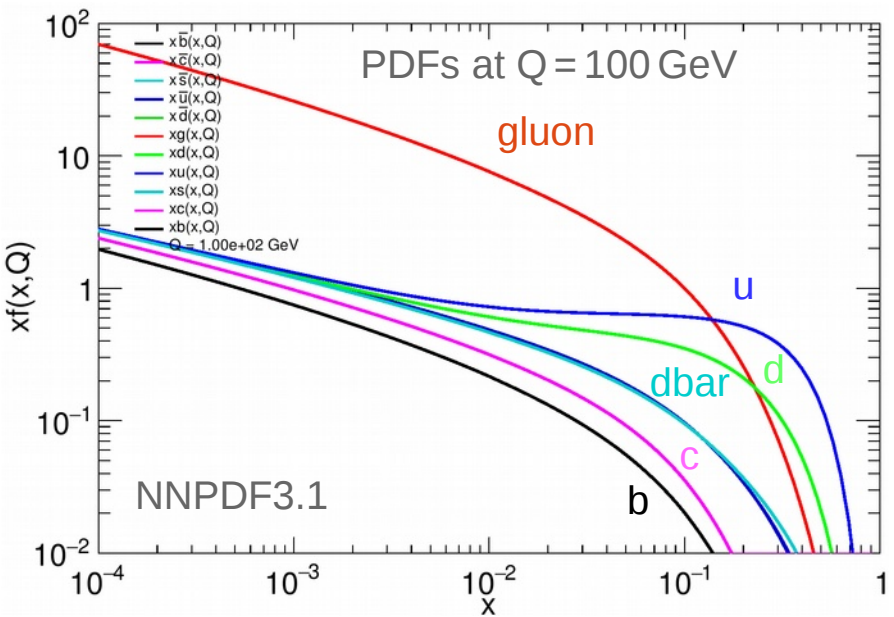
Precise knowledge of PDFs is mandatory for precision SM measurements and a number of searches for BSM signals

FCC-eh cross section

- Convolution with only one PDF

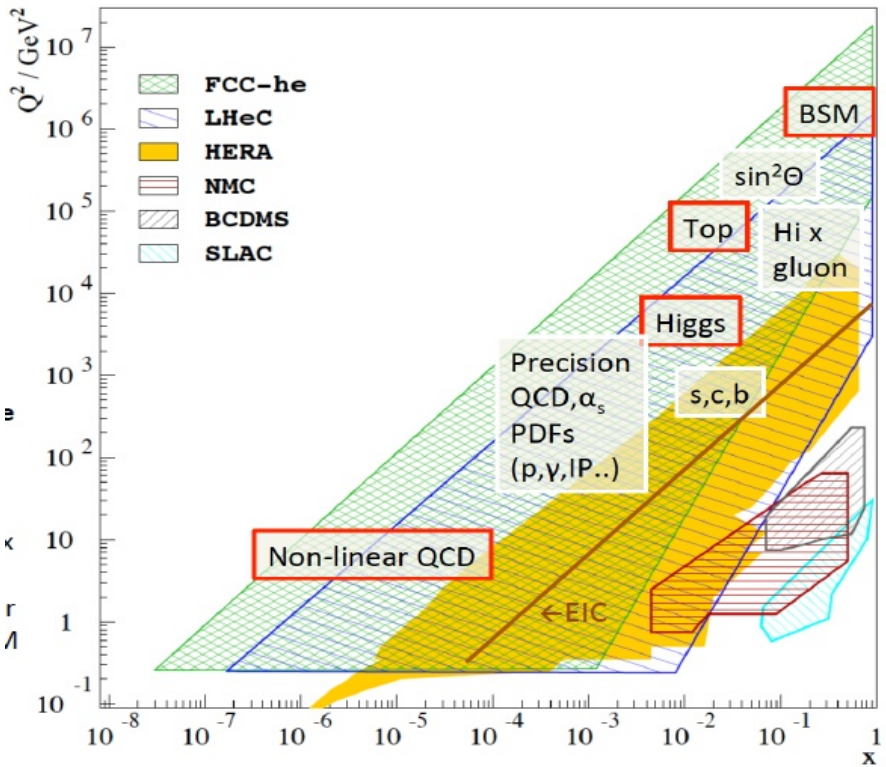
$$\sigma = \sum_{i=q,\bar{q},g} f_{i/p} \otimes \hat{\sigma}_{e+i \to X}$$

- Cleanest way to determine PDFs



FCC-eh – kinematic range

e.g.: P. Newman [NPPS 191 (2009) 307]



FCC-eh:
Provide QCD constraints for FCC-hh

- PDFs
- strong coupling
- Monte Carlo optimizations

Comprehensive physics programme

- Higgs physics
- Top-Quark (properties, top-PDFs)
- Heavy-quarks (s,c,b-quarks)
- low-x physics (non-linear QCD?), also e-Ion
- Precision QCD physics (strong coupling, PDFs)
- Electroweak physics...

Huge increase of kinematical reach over previous DIS experiments
Coverage of previous kinematic range

Methodology: simulated FCC-eh data

New simulated data for latest FCC-eh running scenarios

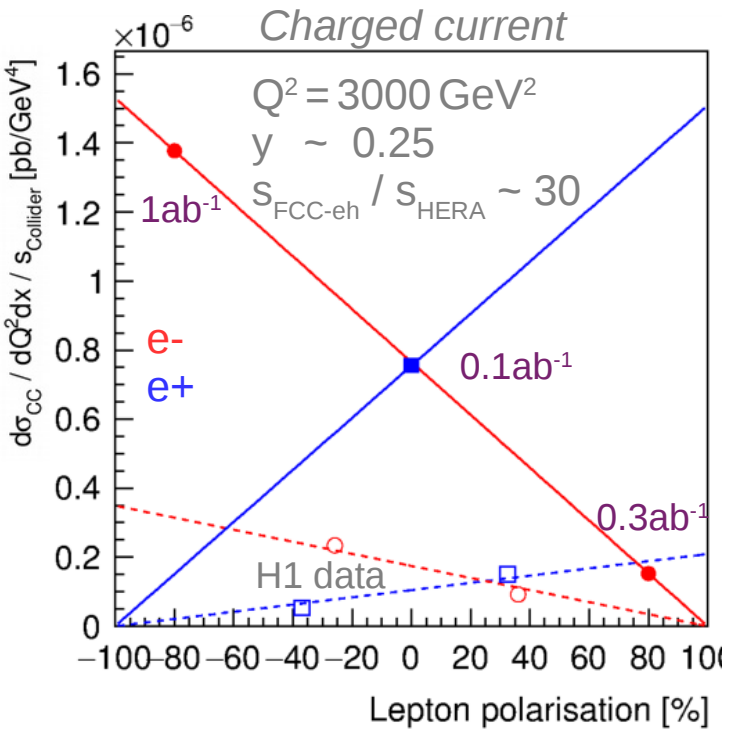
- Energy recovery linac: E_e = 60 GeV
- Polarisation up to P_e ~ 80%
- FCC-eh: $\sqrt{s}$ ~ 3.5 TeV
- Up to 1 ab^{-1} integrated luminosity
- Inclusive polarized NC & CC DIS
- Low-E_p run

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]
NC	60 (60)	50 (7)	−0.8	−1	1000
CC	60 (60)	50 (7)	−0.8	−1	1000
NC	60 (60)	50 (7)	+0.8	−1	300
CC	60 (60)	50 (7)	+0.8	−1	300
NC	60 (60)	50 (7)	0	+1	100
CC	60 (60)	50 (7)	0	+1	100
NC	20 (60)	7 (1)	0	−1	100
CC	20 (60)	7 (1)	0	−1	100

* second and third columns show FCC-eh (LHeC)

(M.Klein)

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%



FCC-eh PDF

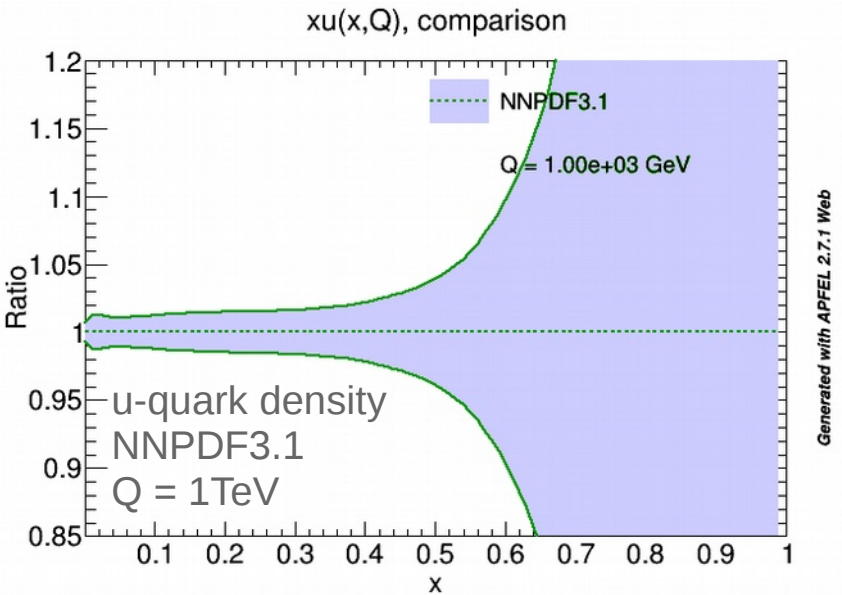
- Data is input to a PDF-fit -> '*FCC-eh PDF*'

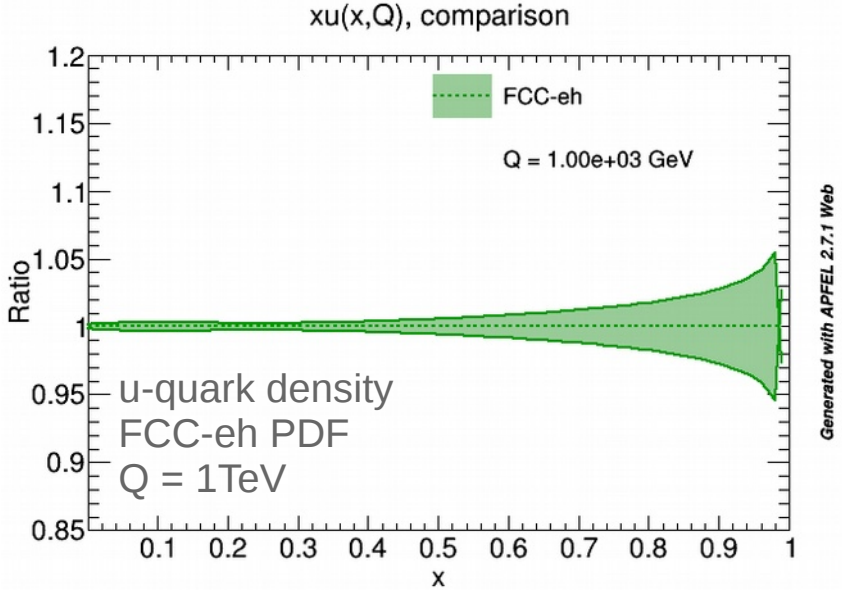
PDFs with FCC-eh

High-x: valence quarks

High-x valence quarks: important for high-mass searches

- Currently unconstraint at high-x
- High luminosity of FCC-eh allows to constrain high-x PDFs





- Today: PDFs are 'evolved' up to O(TeV)
- FCC-eh: PDFs are 'measured' up to O(TeV)

With FCC-eh (or LHeC) PDFs are under control with < 1% accuracy up to O(10 TeV)

Gluon PDF with FCC-eh data

Gluon PDF

- Most important parton for most SM and BSM scenarios
- Precise knowledge at all scales and x-values is imminent

Low-x

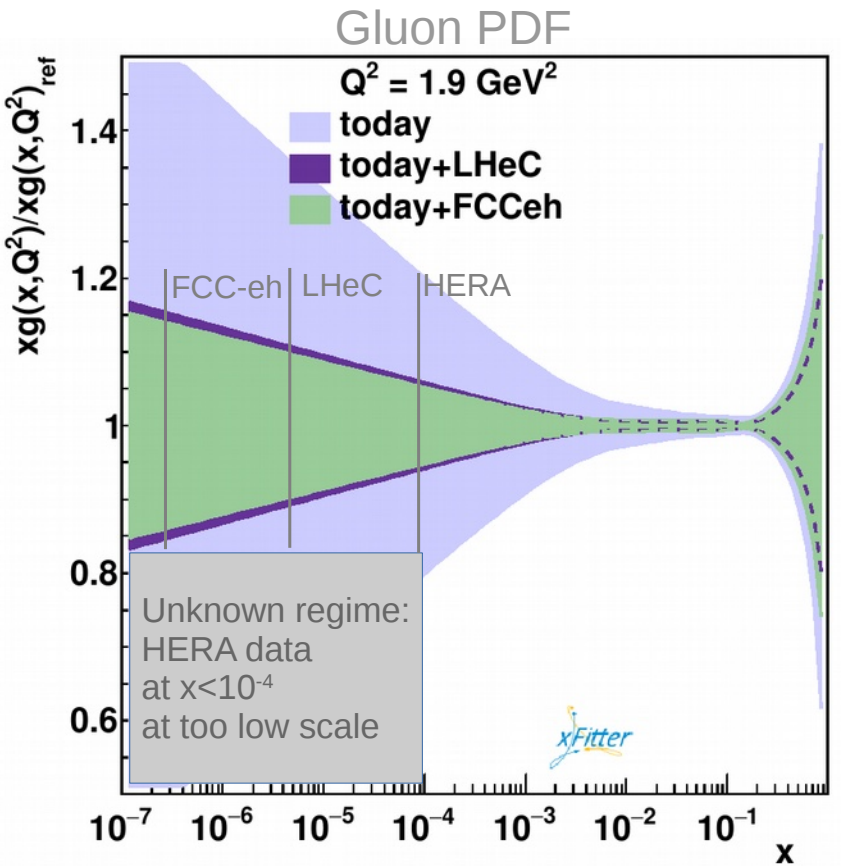
- Important for boosted topologies at FCC-eh
- Currently no data at $x<10^{-4}$
- Uncertainty only from 'extrapolation' but

High-x

- poorly constraint because of limited statistics

FCC-eh

- Explore region of x down to $x\sim10^{-7}$
- Small-x phenomenology:
  BFKL or saturation effects may show up
  -> Physics topics on their own



PDF uncertainties at FCC-hh

M_x: final-state invariant mass

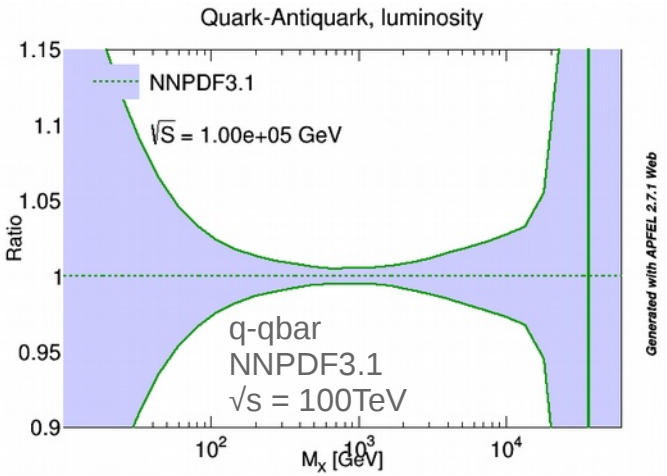
- √s = 100TeV

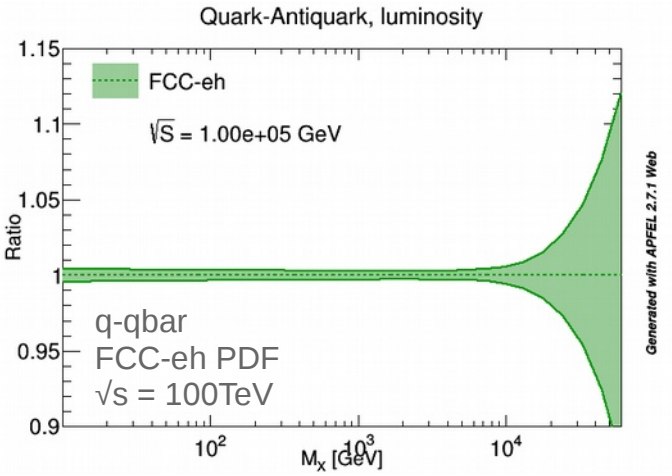
Three distinct regions

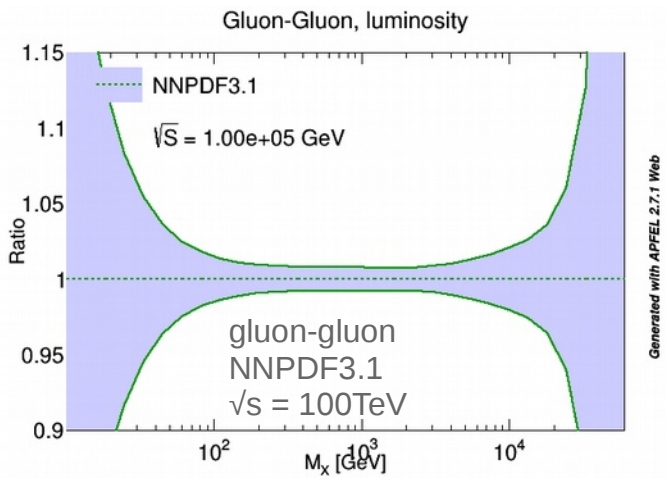
- High-x, high-M_x
  new particle mass frontier
- Medium-x, medium-M_x
  precision SM physics (EW,H,t)
- Low-x, low-M_x
  novel QCD / unitarity

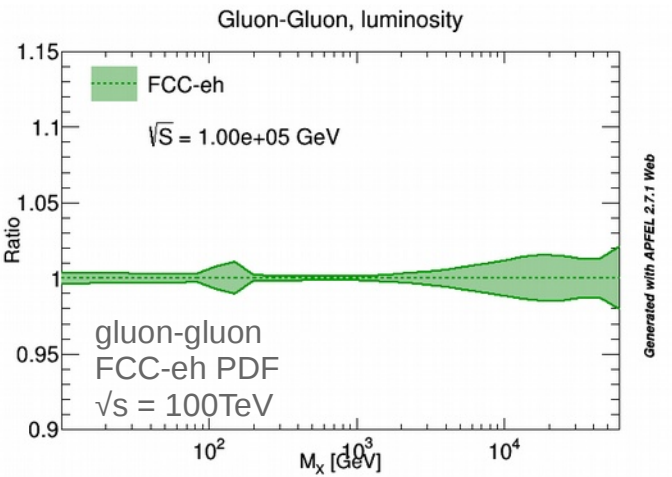
FCC-eh PDFs

- 0.5% precision in bulk region
  -> H-couplings, etc...
- Low- and high-x also well constraint







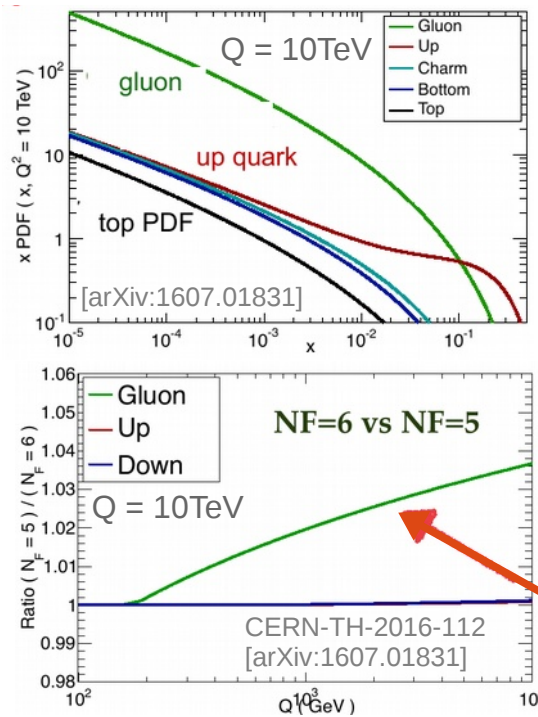


PDFs at FCC-eh

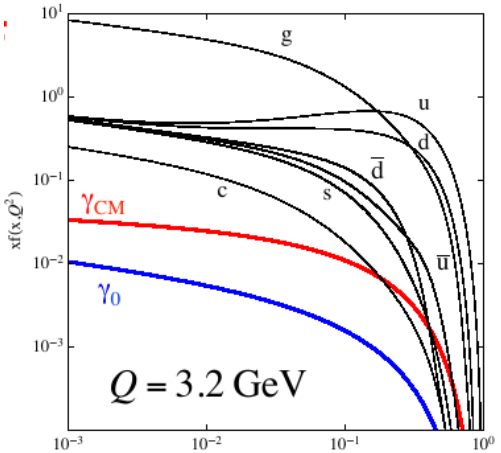
New research fields open up at FCC-eh

- The high precision and high center-of-mass energy of a new ep experiments opens up a new research topics

top-quark PDF

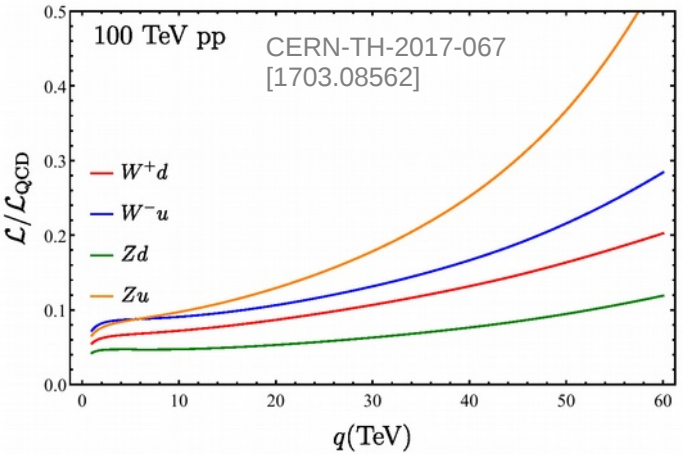


photon PDF



photon-PDF: At higher scales significant γγ cross sections

EW PDFs



EW PDFs: important for precision measurements and searches (*Z'*)

top-quark factorisation: significant impact also on gluon

Strong coupling at FCC-eh

Strong coupling constant $\alpha_s(m_Z)$

Strong coupling $\alpha_s(m_Z)$

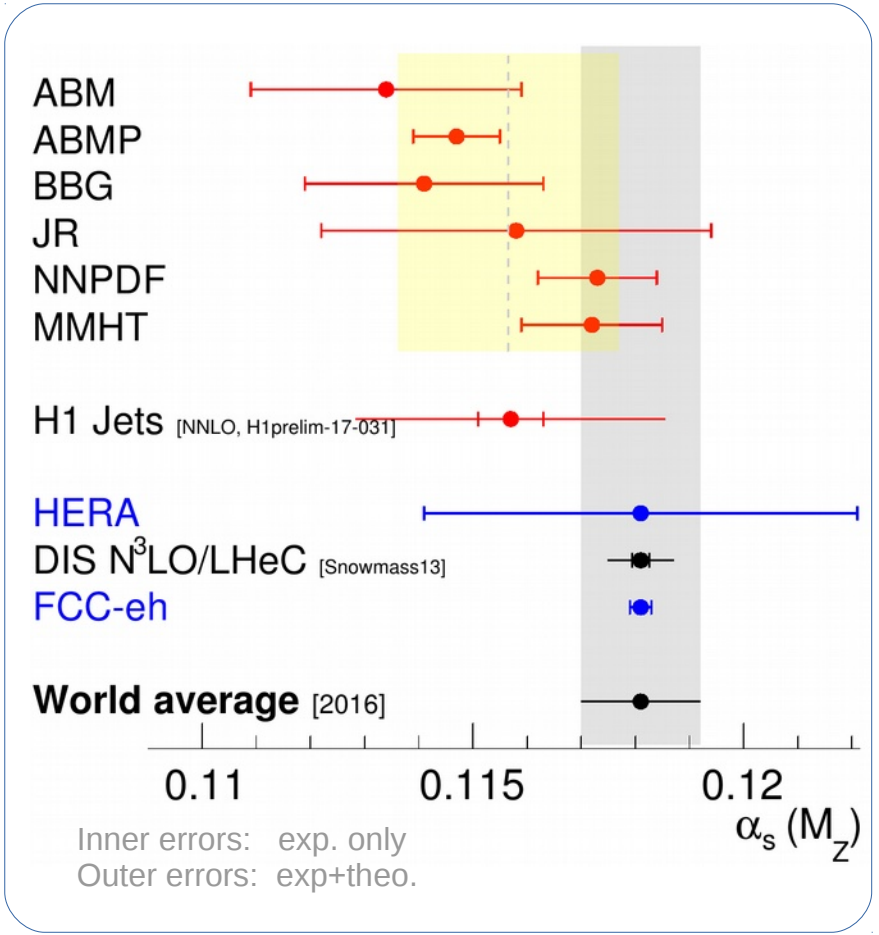
- *Least known SM parameter*
- *Crucial for precision physics*
- *Mainly limited by theory*

DIS

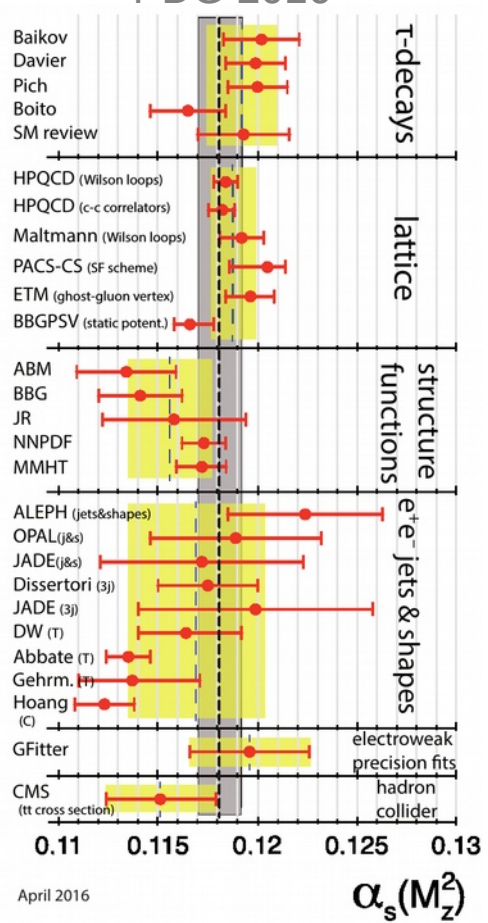
- *Highest precision feasible [snowmass13]*
- *N³LO almost available*

FCC-eh prospects

- *Highest precision expected incl. PDF uncert.*
- *Prospects depend on assumptions made for PDF*



PDG 2016



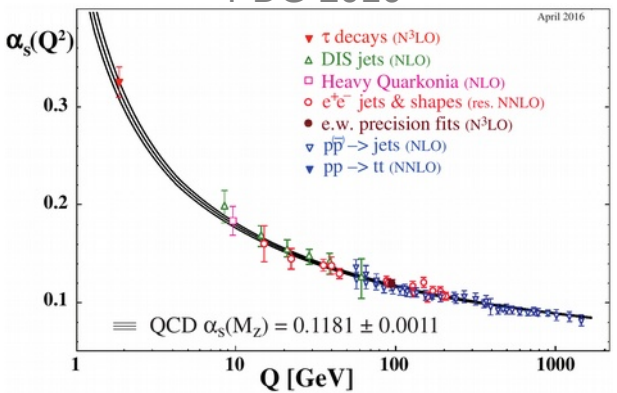
Running of strong coupling

Running of strong coupling constant

- Important test of SU(3) structure of QCD

Today's status

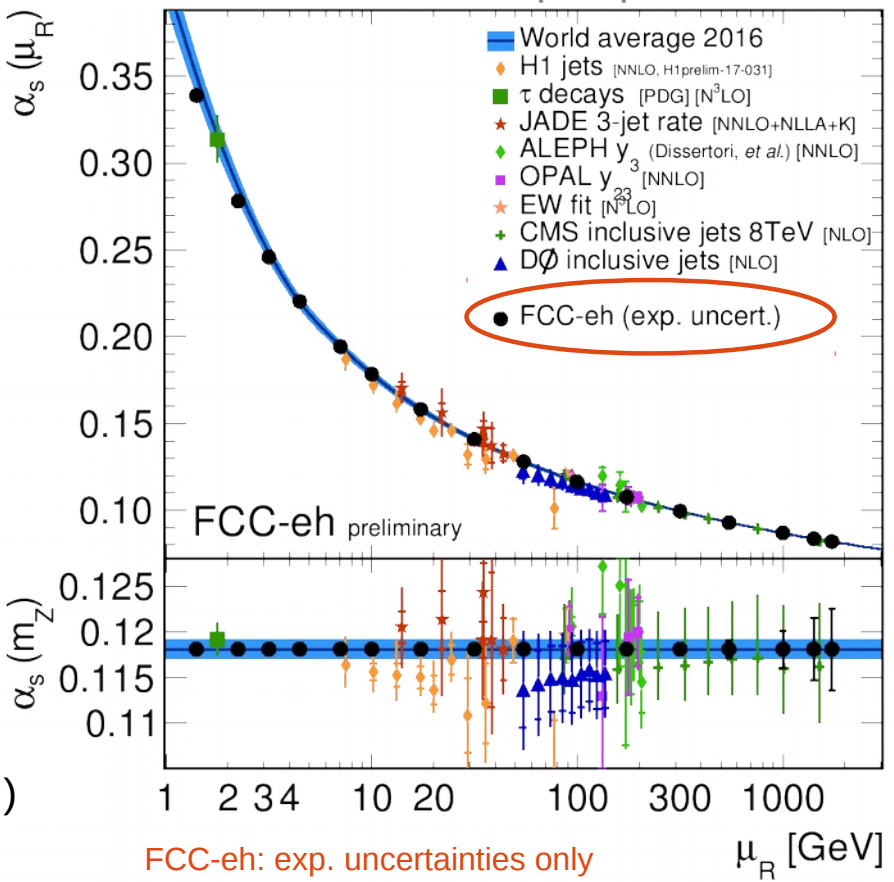
PDG 2016



FCC-eh prospects

- High <u>exerimental</u> precision
  - ~ 0.1 % for 2 < Q < 100 GeV
  - ~ 1% for Q~1TeV
- Precision clearly limited by PDFs and theory (0.5 – 1%)
- Large kinematical range accessible in a single process
- Jet measurements will further improve precision

FCC-eh prospects



FCC-eh: exp. uncertainties only
Precision will be limited by PDFs and theory (not shown)

EW physics with inclusive DIS data at FCC-eh

Electroweak effects at HERA

(unpolarised) inclusive DIS as a function of Q^2

NC & CC DIS

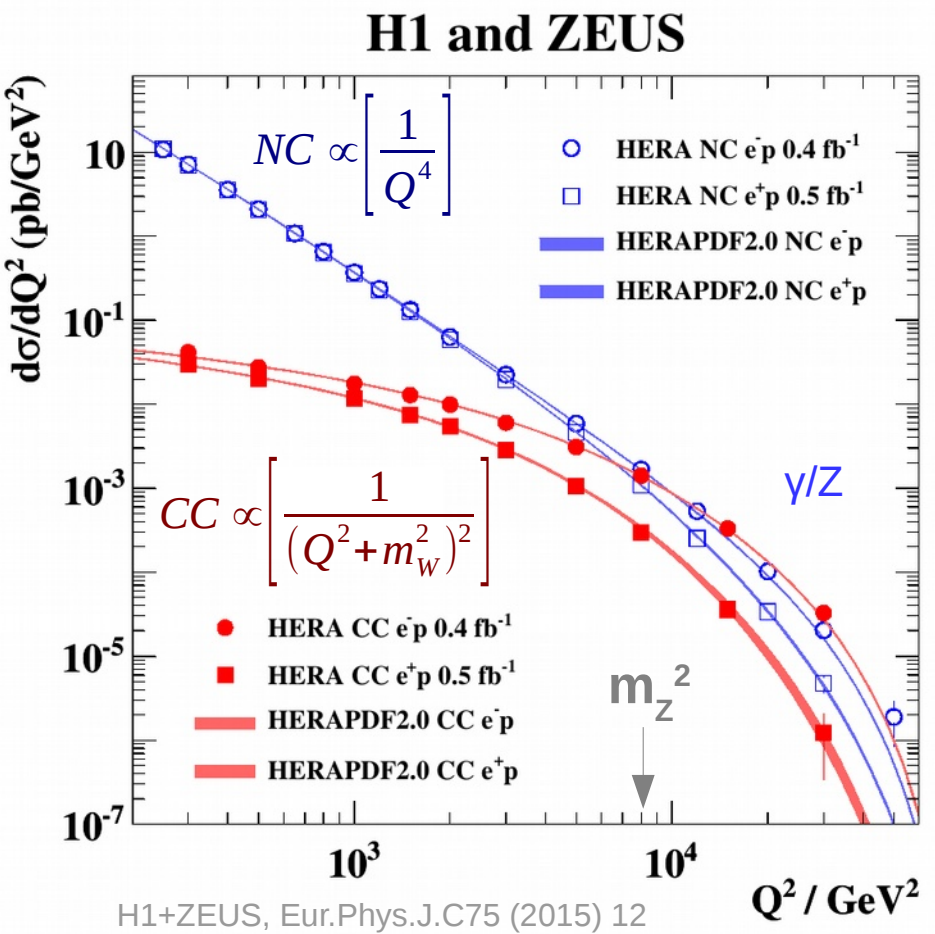
- NC is mediated by massless photon
- CC is 'suppressed' due to W-boson mass

Around EW unification scale

- NC and CC of similar size

e^+p and e^-p differ due to W or Z-exchange

- NC: γ/Z-interference
- CC: Helicity factor $(1-y)^2$ applies to d-quarks for e^+



H1+ZEUS, Eur.Phys.J.C75 (2015) 12

Polarised NC DIS: from HERA to FCC-eh

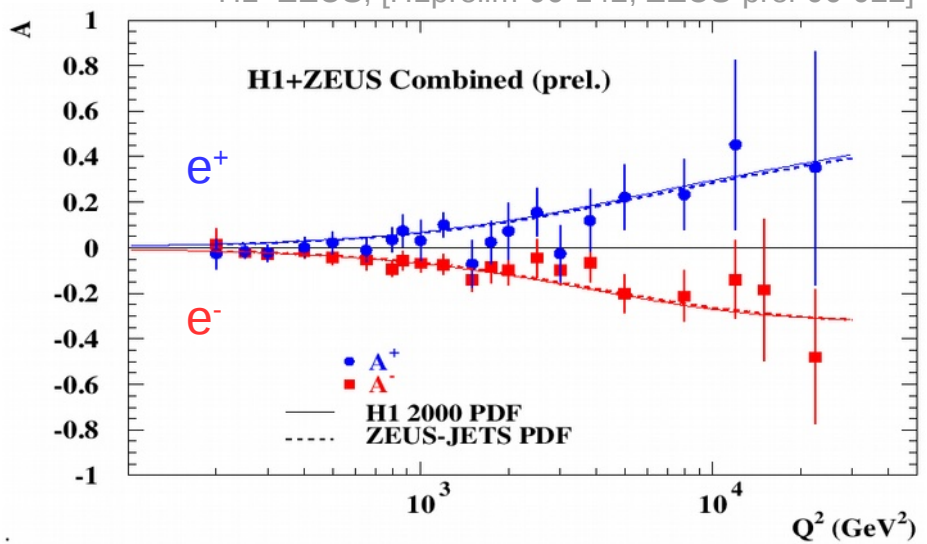
Polarisation asymmetry at HERA

- Z-exchange as a function of Q^2

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

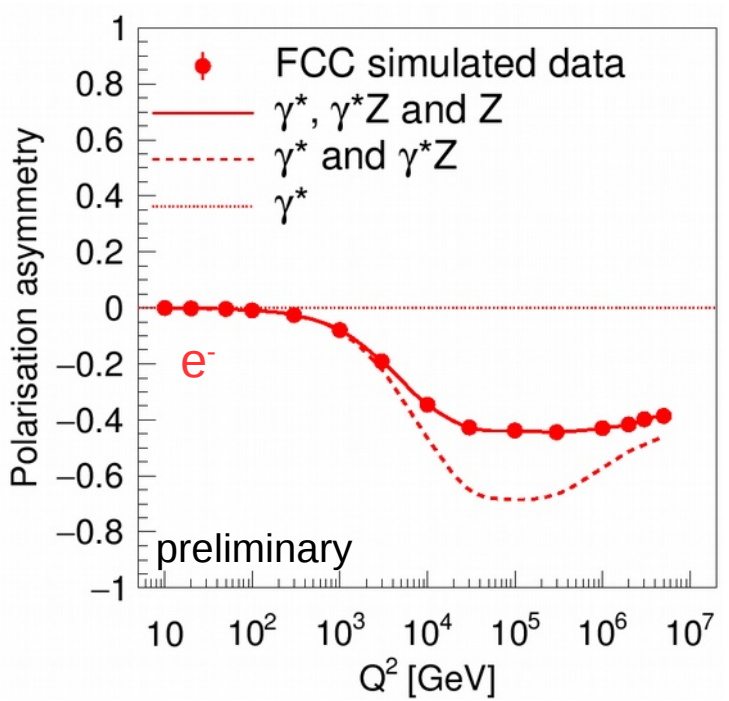
- Parity violation effects in NC EW interactions

H1+ZEUS, [H1prelim-06-142, ZEUS-prel-06-022]



Polarisation asymmetry at FCC-eh

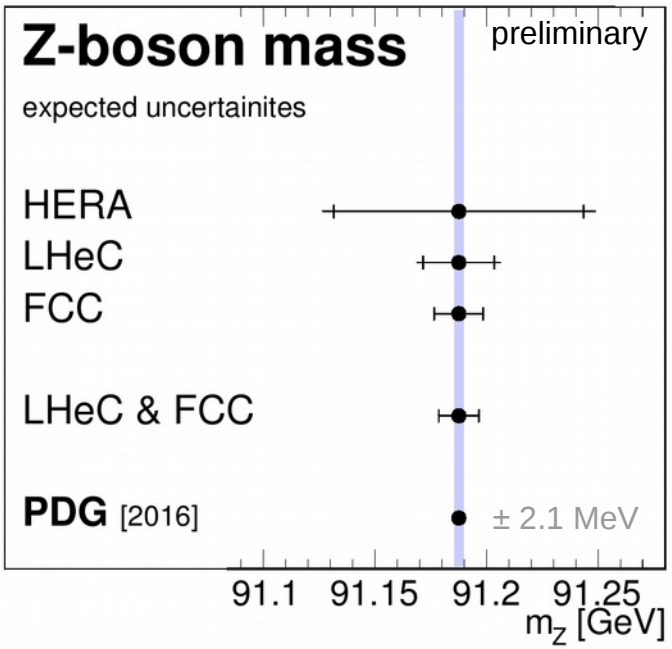
- Accessible range up to $Q^2 \sim 10^7$
- 'pure' Z-exchange becomes significant at FCC-eh

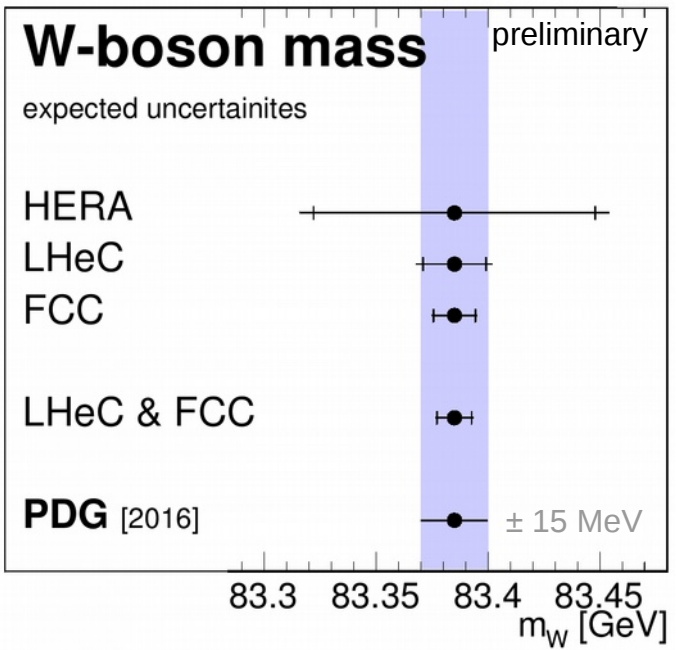


Weak-boson masses

Weak-boson masses from 'EW+PDF fit' to inclusive NC&CC DIS data

- PDFs are determined simultaneously





Inner errors: exp. only
Outer errors: exp. + PDF

Z-mass errors [MeV]

HERA	±56(exp) 25(PDF)
LHeC	±16(exp) 10(PDF)
FCC-eh	±11(exp) 3(PDF)

W-mass errors [MeV]

HERA	± 63(exp) 29(PDF)
LHeC	± 14(exp) 10(PDF)
FCC-eh	± 9(exp) 4(PDF)

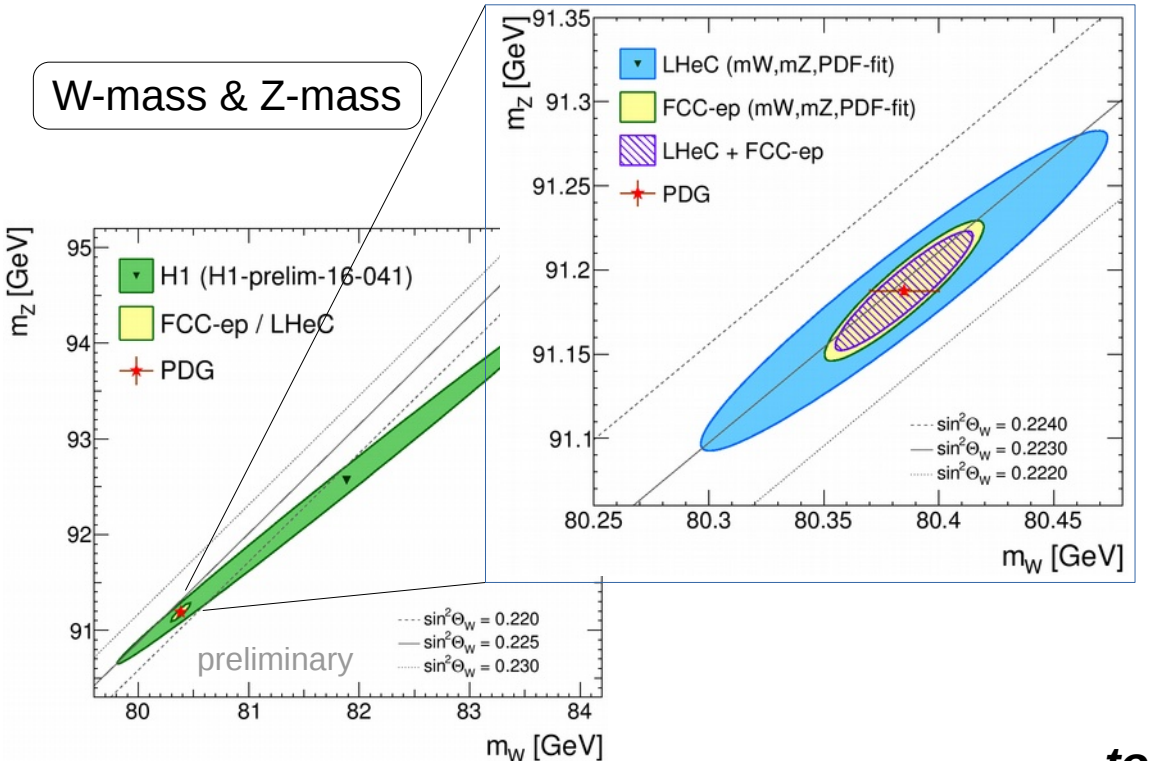
HERA prospects (1987)
Δm_W ~ ± 80-100 MeV

-> EW measurements are not limited by PDFs
-> high precision for W-boson mass, due to full kinematic reconstruction of CC DIS
-> direct measurements will further improve these direct determinations

Tests of EW sector

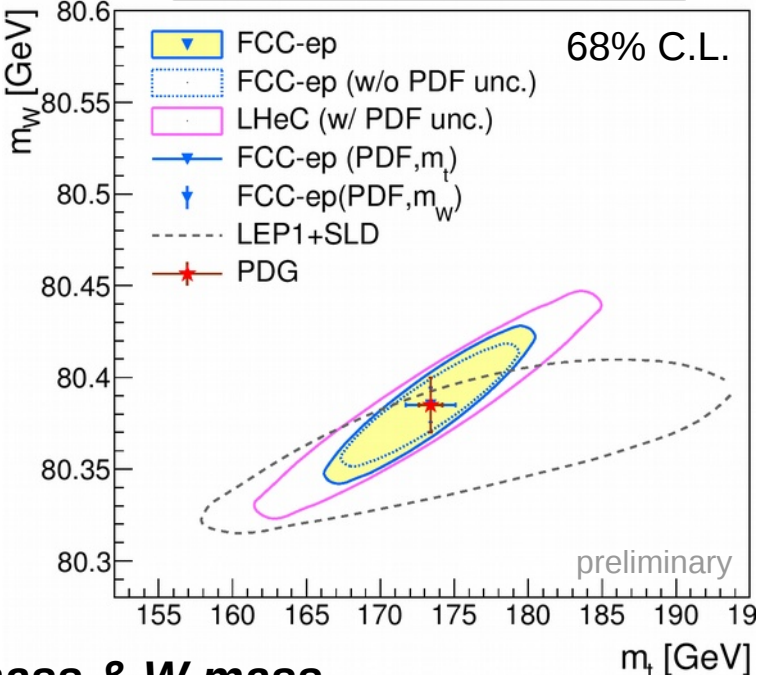
Simultaneous determination of two mass parameters together with PDFs

W-mass & Z-mass



- W- and Z-boson masses with reasonable

W-mass & top-quark mass

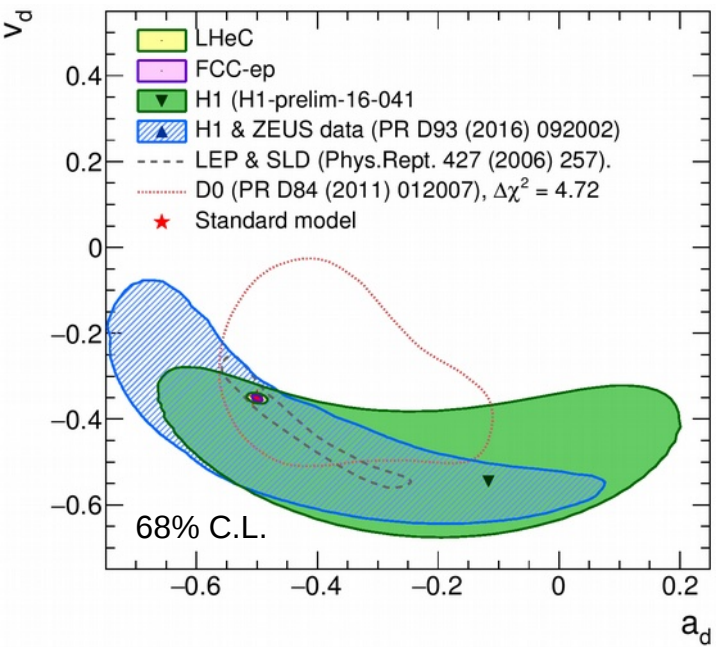


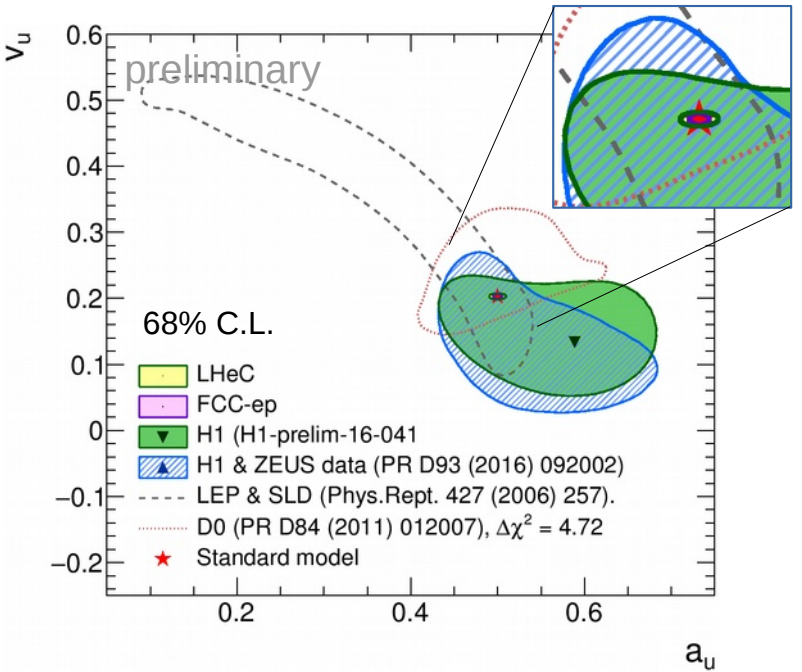
top-mass & W-mass

- better than LEP
- top-mass constraints only indirectly here !

Light-quark couplings

***Vector* and *axial-vector* couplings of quarks to Z-boson**



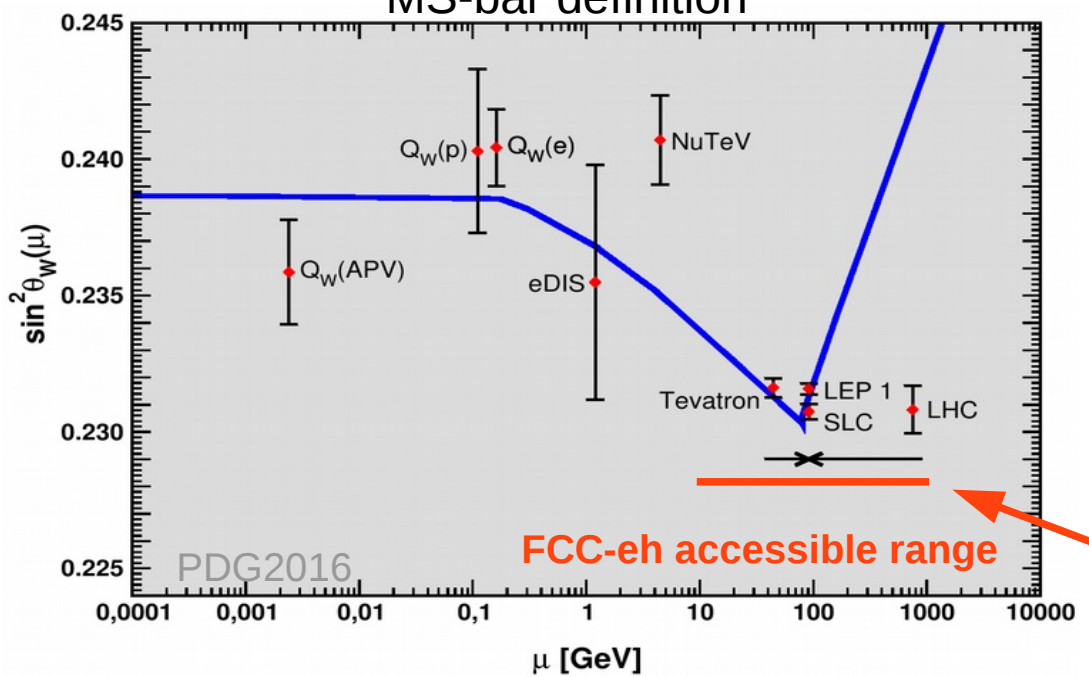


- Simultaneous determination of PDFs & up- & down-type couplings from simulated data
- Very precise measurements of light-quark's weak couplings

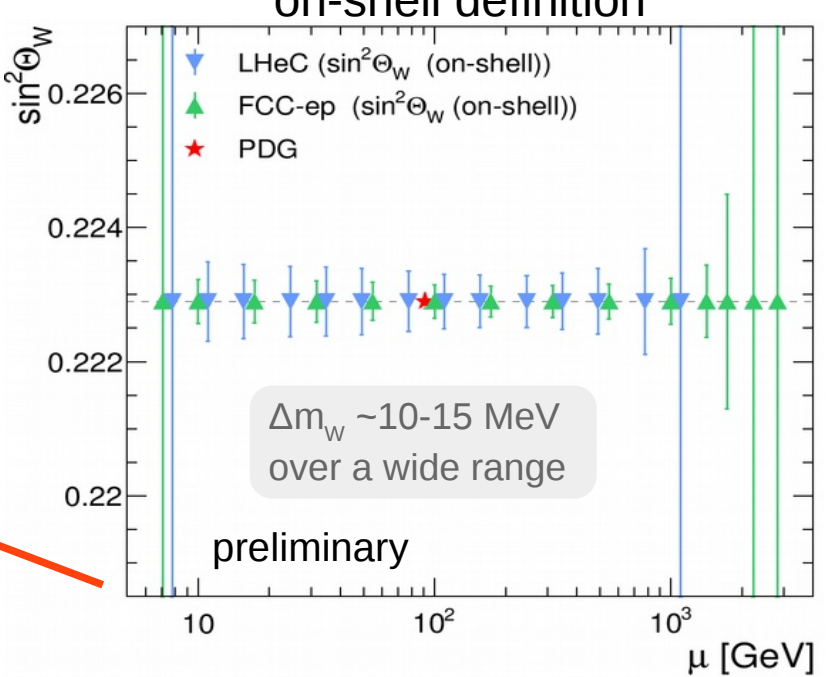
High precision test of electroweak sector of Standard Model

Weak mixing angle

MS-bar definition



on-shell definition



- Inclusive data will be competitive to direct measurements at the Z-pole
- Tests of EW theory over large kinematic range

Precise tests of scale dependence of EW theory from 10 GeV up to few TeV
Inclusive DIS: complementary to s-channel extractions

Conclusions

Studies with simulated inclusive DIS data for FCC-eh were presented

PDFs

- *PDF uncertainty for FCC-hh will be reduced to below 0.5% from EW scale up to few TeV*
- *New research topics open up (EW-PDFs, top-PDFs, etc...) and low-x physics will be explored*

Strong coupling α_s

- *FCC-eh detector is a precision QCD experiment*
- *Strong coupling constant determined up to 0.1%*
- *Test running of α_s over 3 orders of magnitude with highest precision*

Electroweak physics

- *FCC-eh provides high accuracy from 10 GeV up to few TeV regime (e.g. $\sin^2\theta_w$)*
- *Competitive with LEP+SLD results in case of indirect determinations*
- *'ultimate' measurement of weak couplings of light-quarks*
- *Competitive measurements to LHC of the W-boson mass*

Important final remarks

- *precision EW physics in ep is not limited by PDFs or QCD*
- *precision QCD physics in ep is not limited by EW corrections (because of high precision at lower scales)*
- *Additional direct measurements (e.g. jets, Z, W, top, H production) will further improve precision*

All conclusions hold with similar precision also for the LHeC