The general-purpose LHeC and FCC-eh high-energy precision programme: Top and EW measurements

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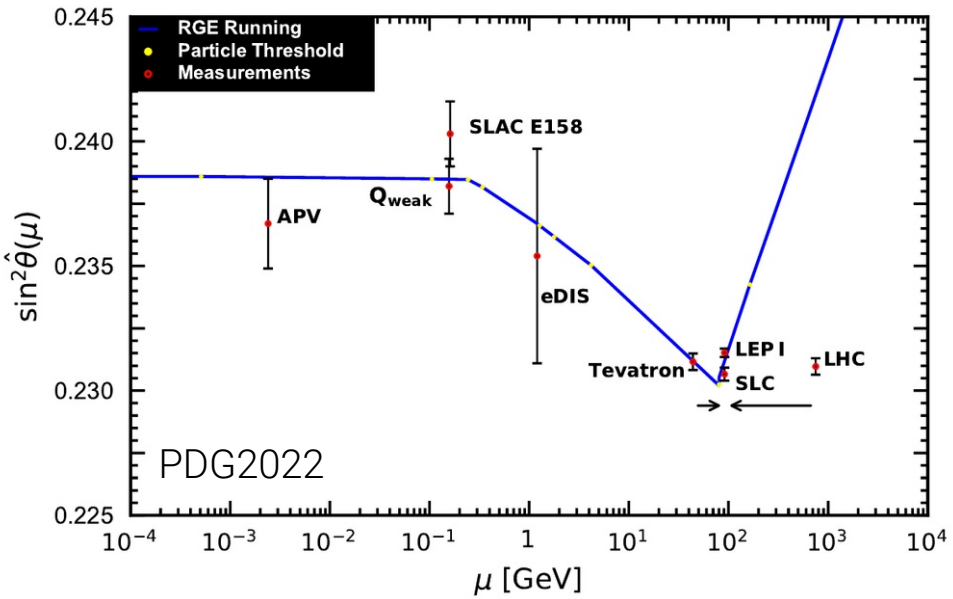
Max-Planck-Institut für Physik München, Germany

ICHEP24 Conference
Prague, Czech Republic
18. – 24. July 2024

The Electroweak Physics Landscape

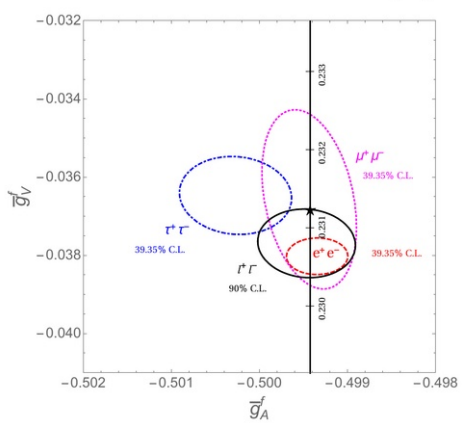


Important Electroweak relations

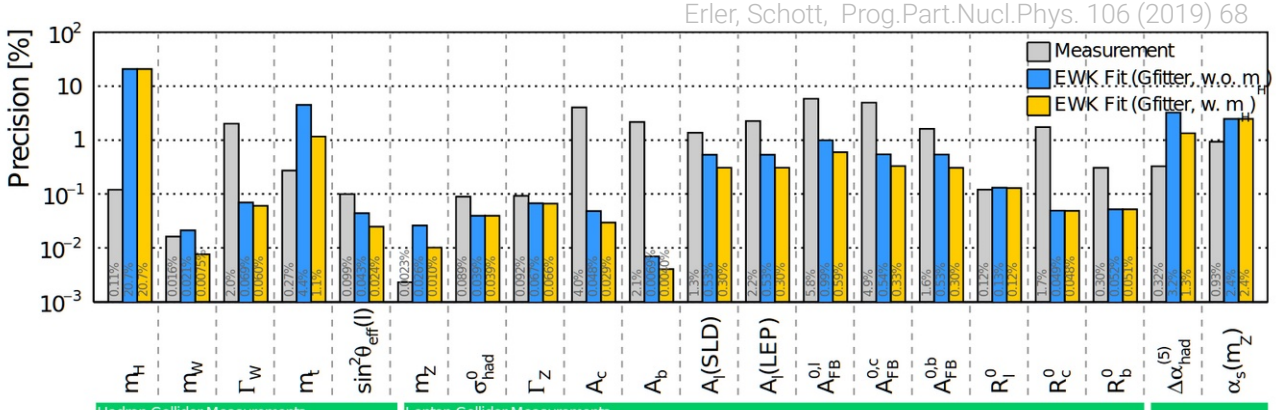
- Virtual EW corrections are parameterized
  → very successfull: predicted m_{top} and ~m_{Higgs}

$$
\begin{aligned}
M_W^2 &= \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)\\
\sin^2\theta_{\text{eff}}^f &= \kappa_Z^f \sin^2\theta_W\,,\\
g_V^f &= \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f\sin^2\theta_{\text{eff}}^f\right),\\
g_A^f &= \sqrt{\rho_Z^f} I_3^f\,,
\end{aligned}
$$

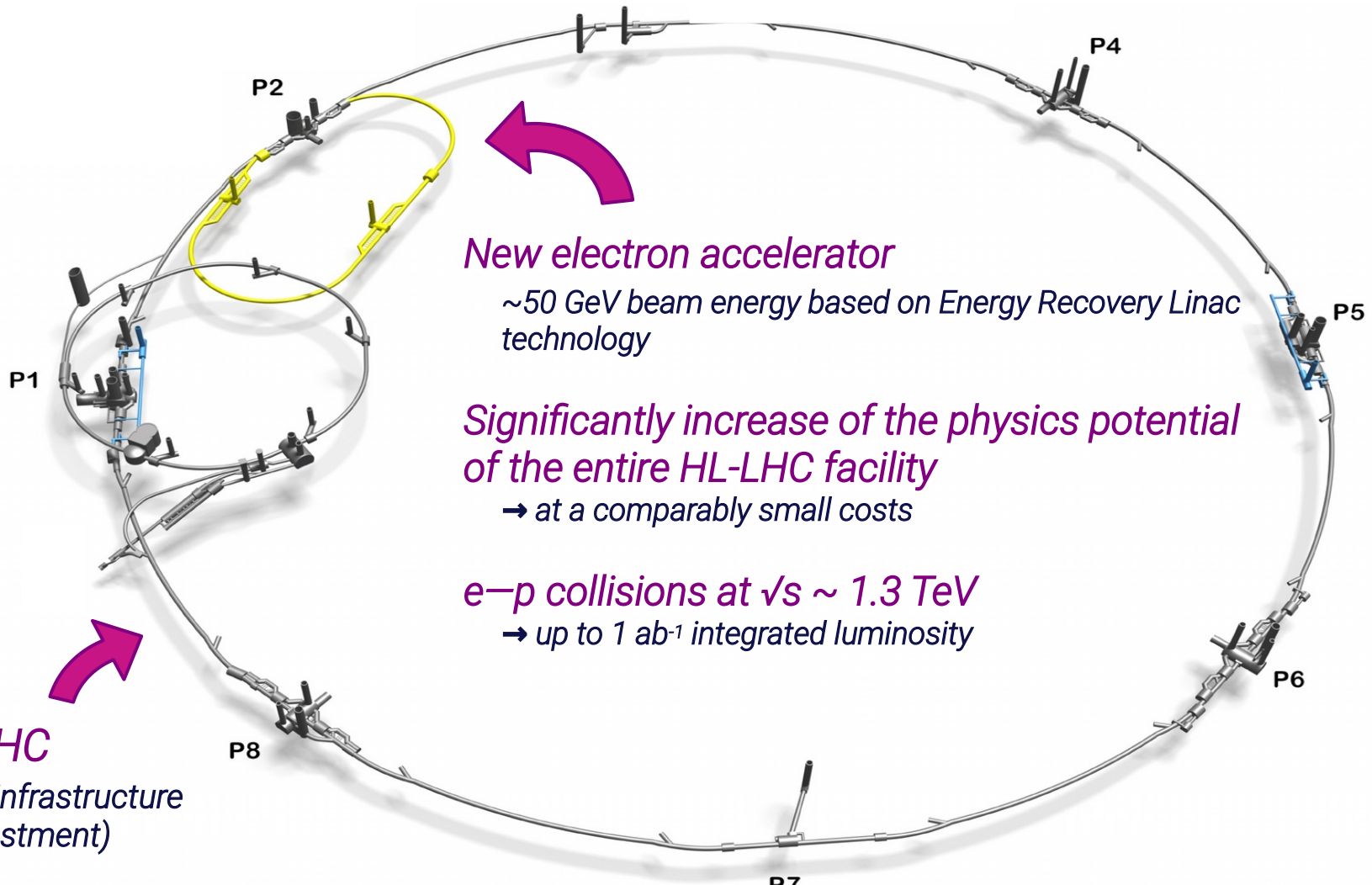
- Future of EW physics is on tests of these quantum corrections: most comprehensive & most precise



Erler, Schott, Prog.Part.Nucl.Phys. 106 (2019) 68



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



New electron accelerator

~50 GeV beam energy based on Energy Recovery Linac technology

Significantly increase of the physics potential of the entire HL-LHC facility

➞ *at a comparably small costs*

e—p collisions at √s ~ 1.3 TeV

➞ *up to 1 ab^{-1} integrated luminosity*

HL-LHC

existing/future infrastructure (major investment)

FCC-eh

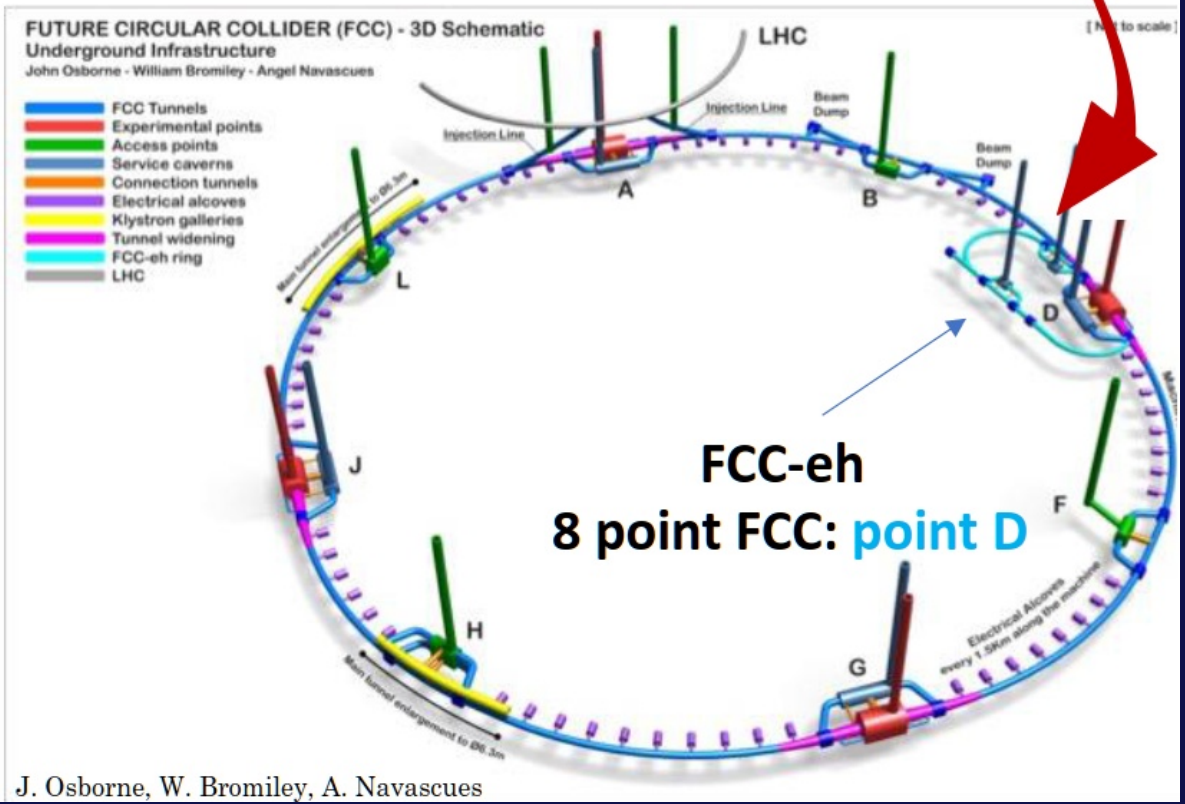
Dedicated electron-ring attached to the FCC-hh

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

FCC-eh (60 GeV electron beams)
E_{cms} = 3.5 TeV, described in CDR of the FCC
run ep/pp together: FCC-hh + FCC-eh



Energy-/Luminosity-frontier DIS

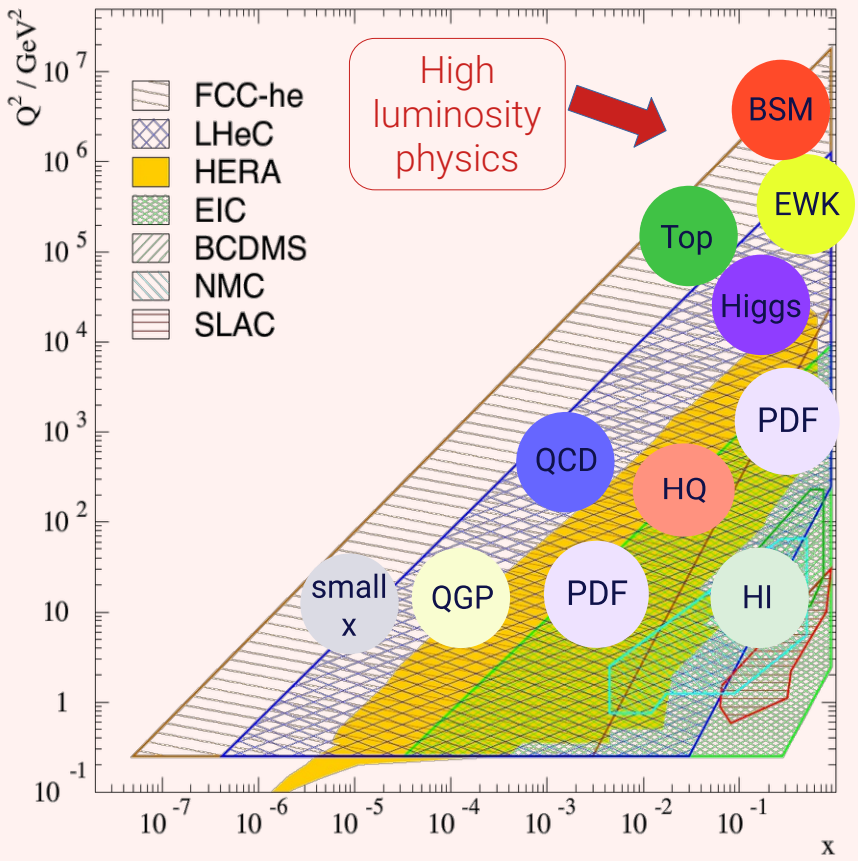
LHeC/FCC-eh

- Considerably higher center-of-mass energy than any (previous) DIS experiment
  → QCD and hadronic matter precision measurements
  → Empowering *pp*-physics programme at HL-LHC/FCC-hh

High √s provides opportunities for

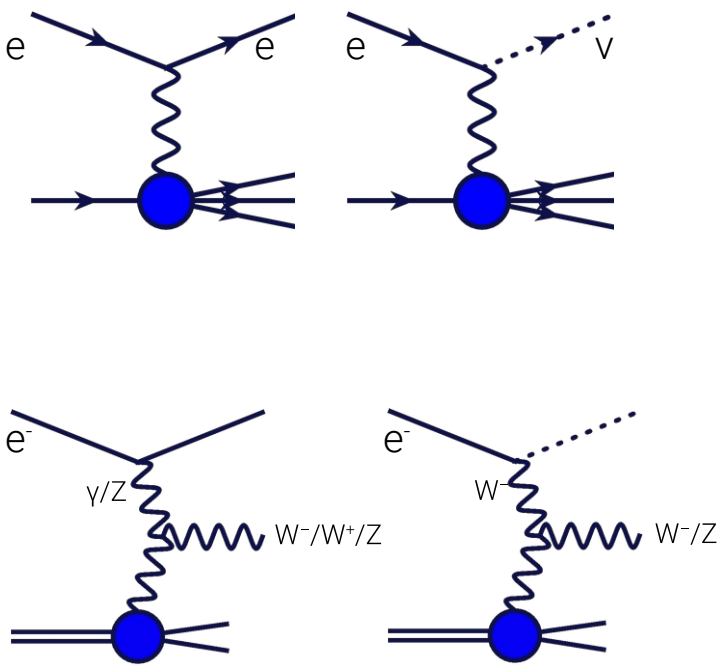
- Electroweak, Higgs and top-quark physics but this is

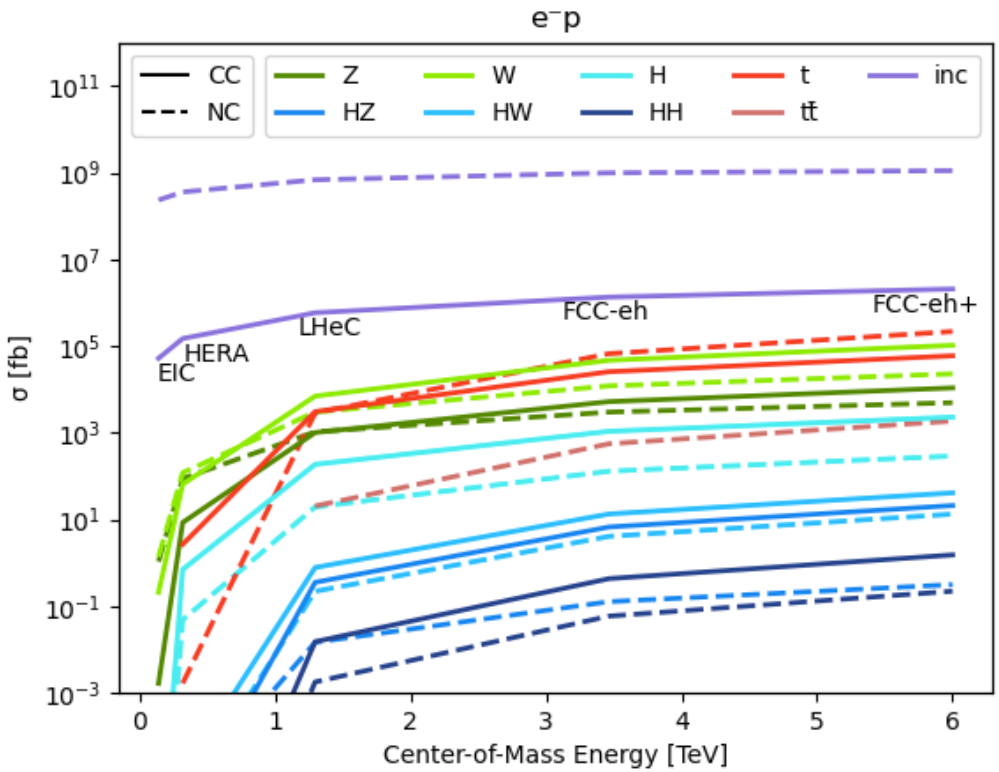
High luminosity is a game-changer for DIS (e.g. when compared to HERA)

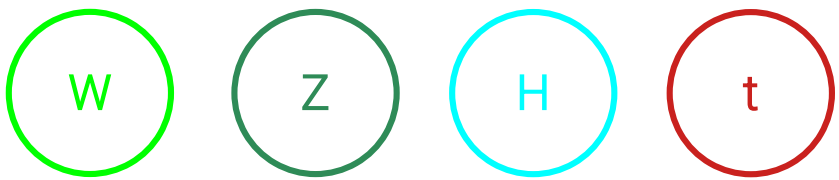


Electron–proton collisions at HL-LHC

Electroweak processes at LH(e)C
→ *7 TeV proton beam collides with new electron beam*

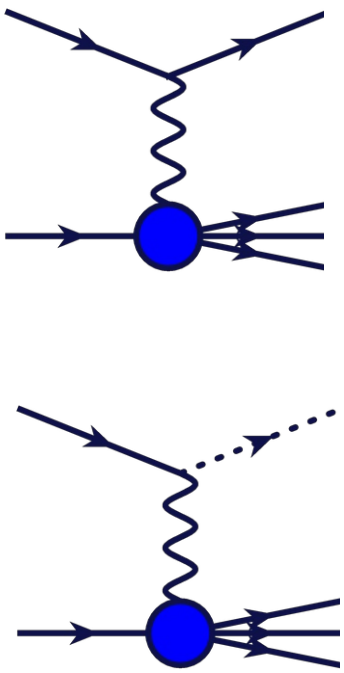






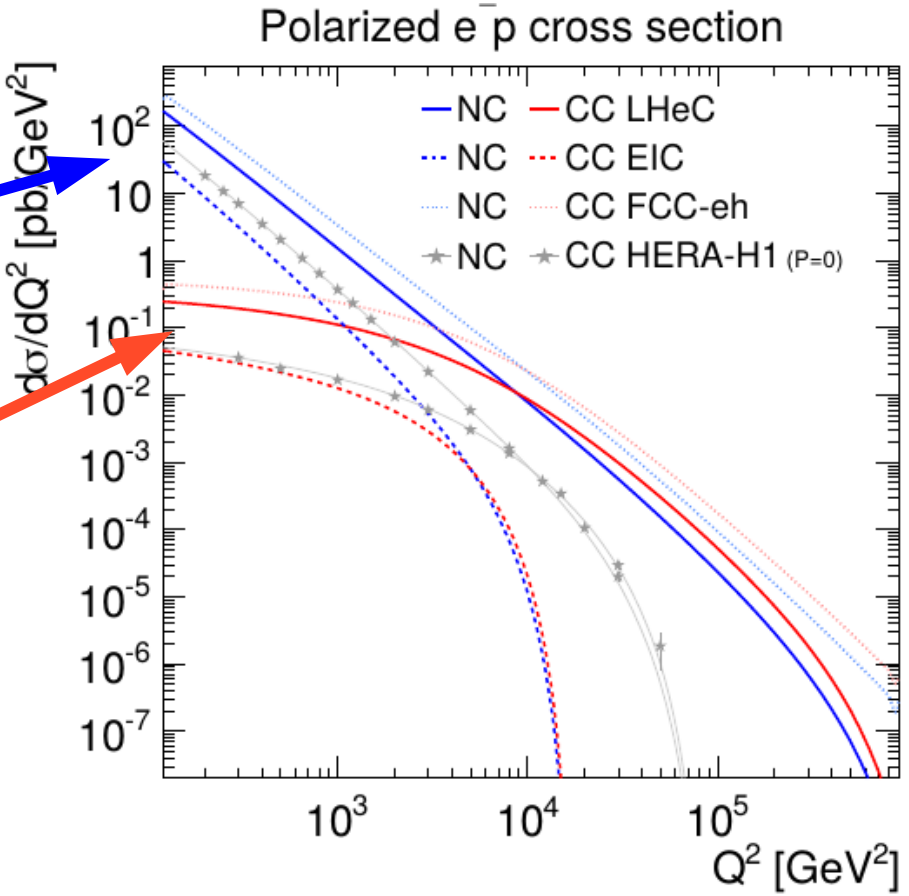
Inclusive DIS: neutral and charged currents

Neutral and charged current interactions at √s=1.3TeV

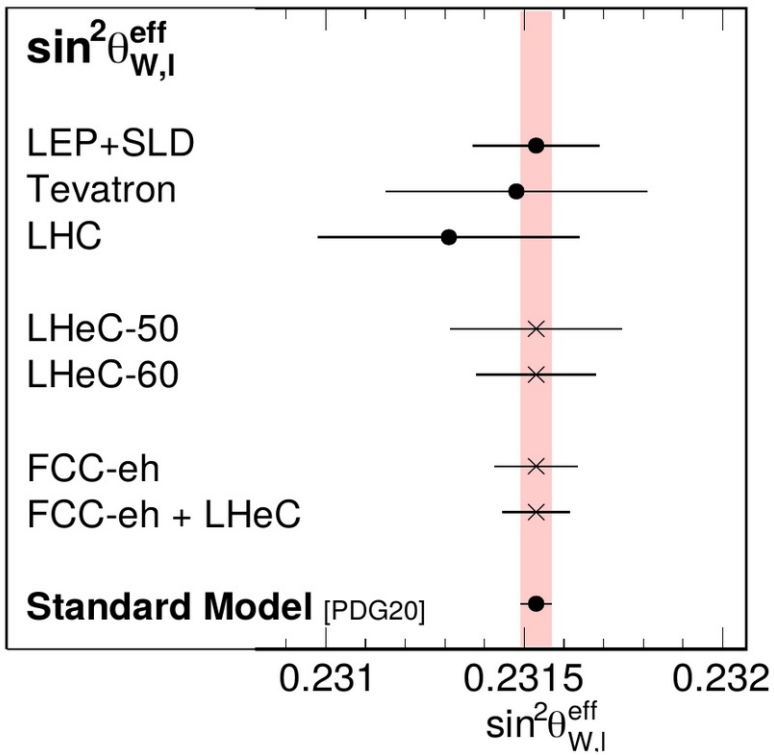


Neutral Current

Charged Current



The weak mixing angle



Weak mixing angle

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

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

$\sin^2\theta_W$ + 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
= $\pm 0.00010_{(\text{exp})}$ $\pm 0.00004_{(\text{PDF})}$

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

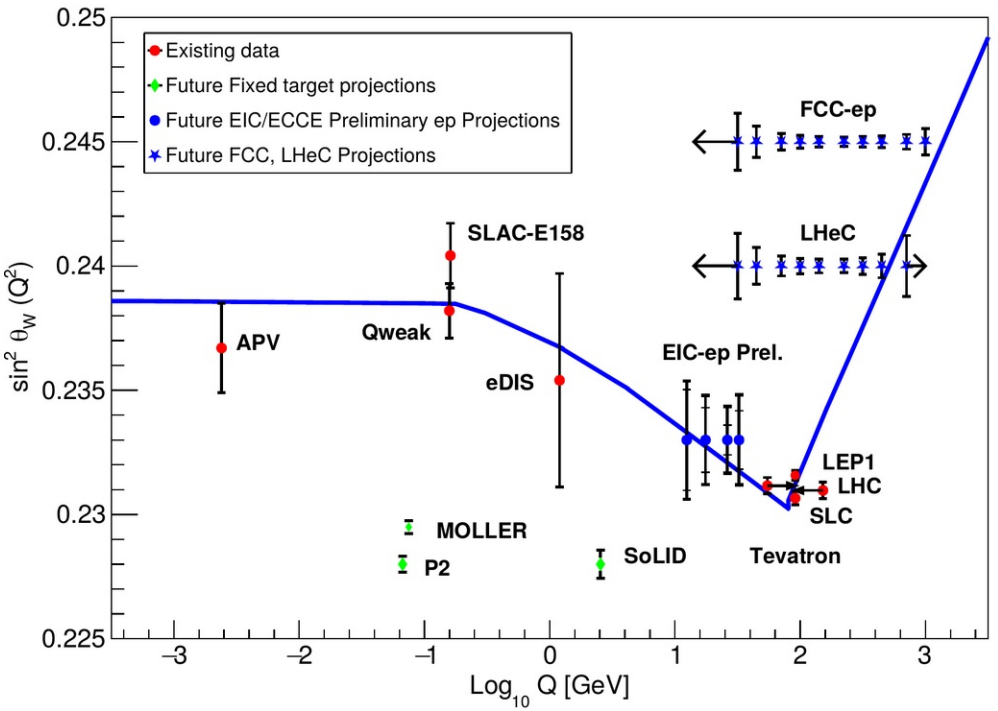
Scale dependent measurements

Running of $\sin^2\theta_W^{\text{eff}}$
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

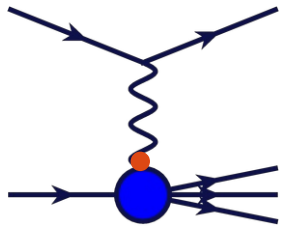
Electroweak physics

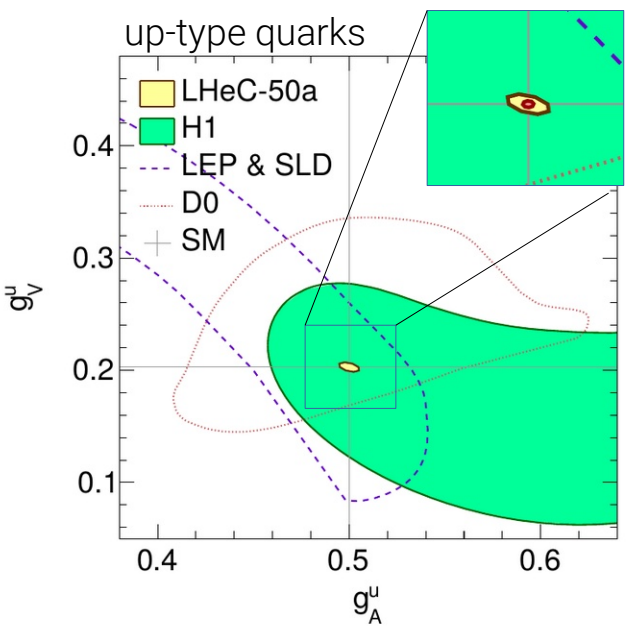
DB, M. Klein, H. Spiesberger, Eur.Phys.J.C 80 (2020) 831 PoS(EPS-HEP2021)485

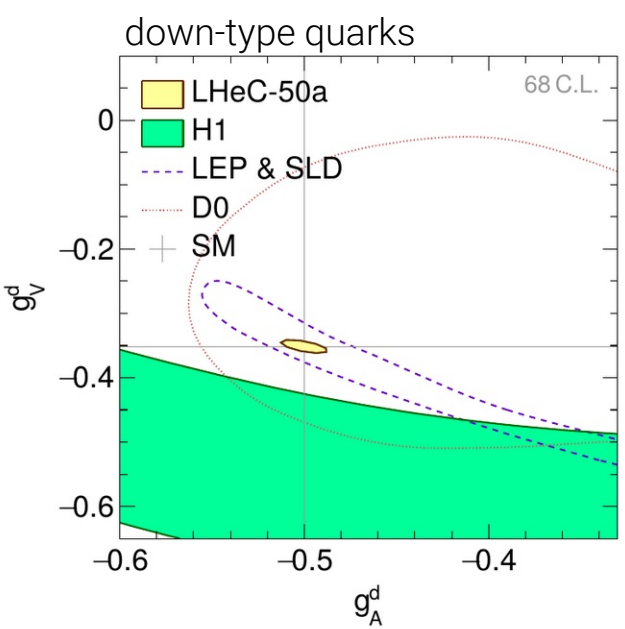
Electroweak physics of 1st gen. quarks

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

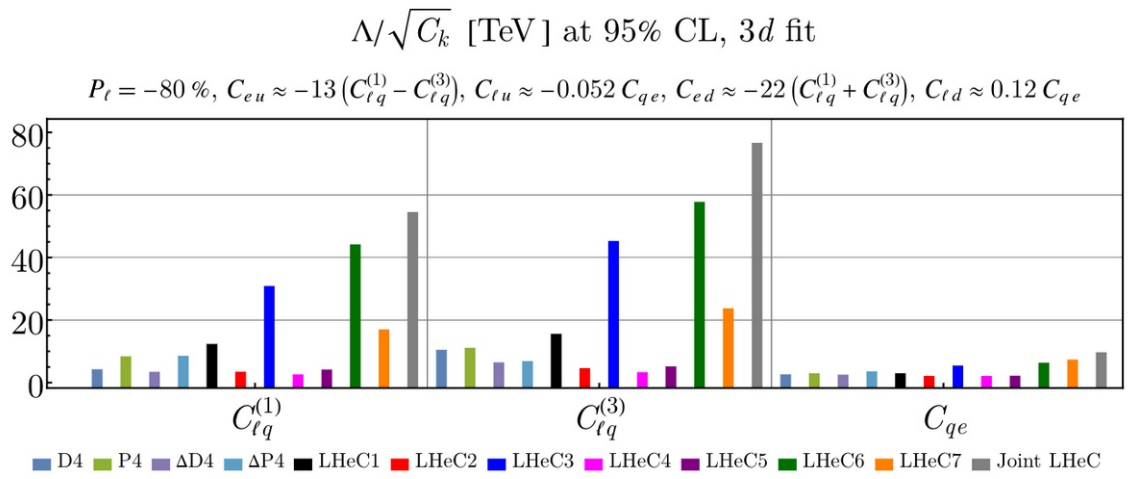
→ Also the scale dependence ('running') can be tested with high precision

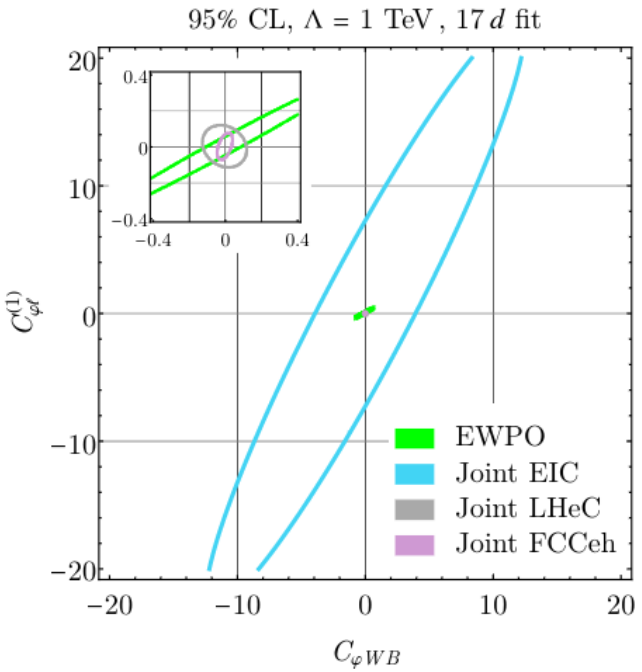
SMEFT probes in DIS experiments

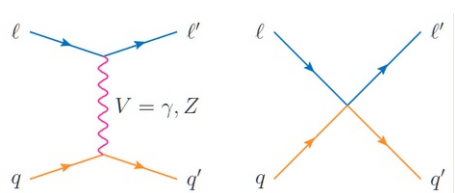
Ch. Bissolotti, R. Boughezal, K. Simsek
PRD 108 (2023) 075007

SMEFT extension in NC DIS

- *17 dim-6 operators in Warsaw basis*
  - *10 op's shift ffV vertex*
  - *7 op's: semi-leptonic four-fermion CI*
- *NC DIS resolves some degeneracies that are present in global EW(PO) fit*
- *Significant improvement over existing bounds*





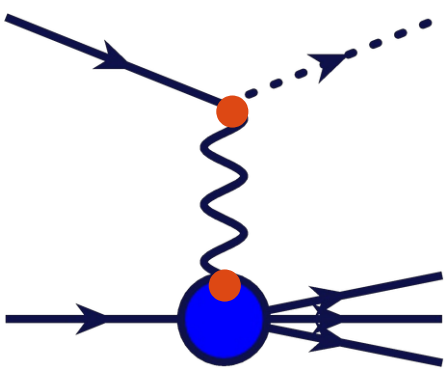


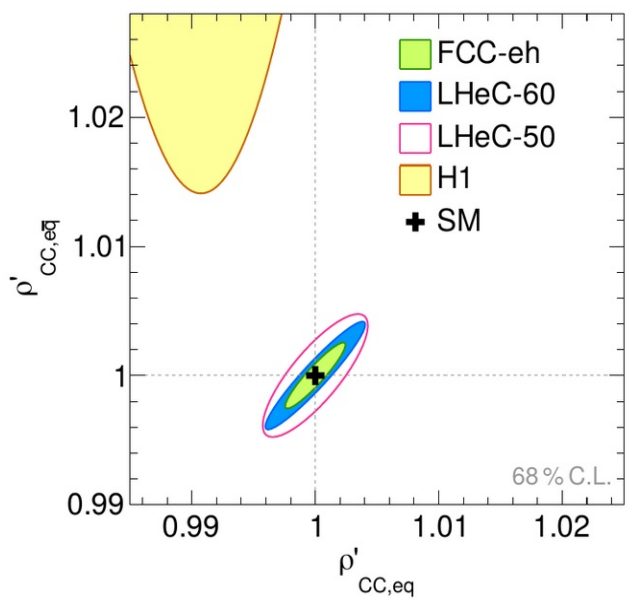
Weak couplings of the *W*-boson

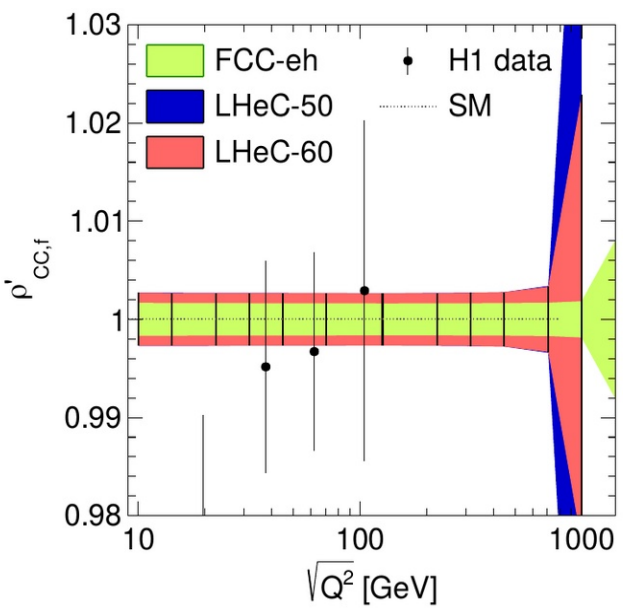
DB, M. Klein, H. Spiesberger,
Eur.Phys.J.C 80 (2020) 831
PoS(EPS-HEP2021)485

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

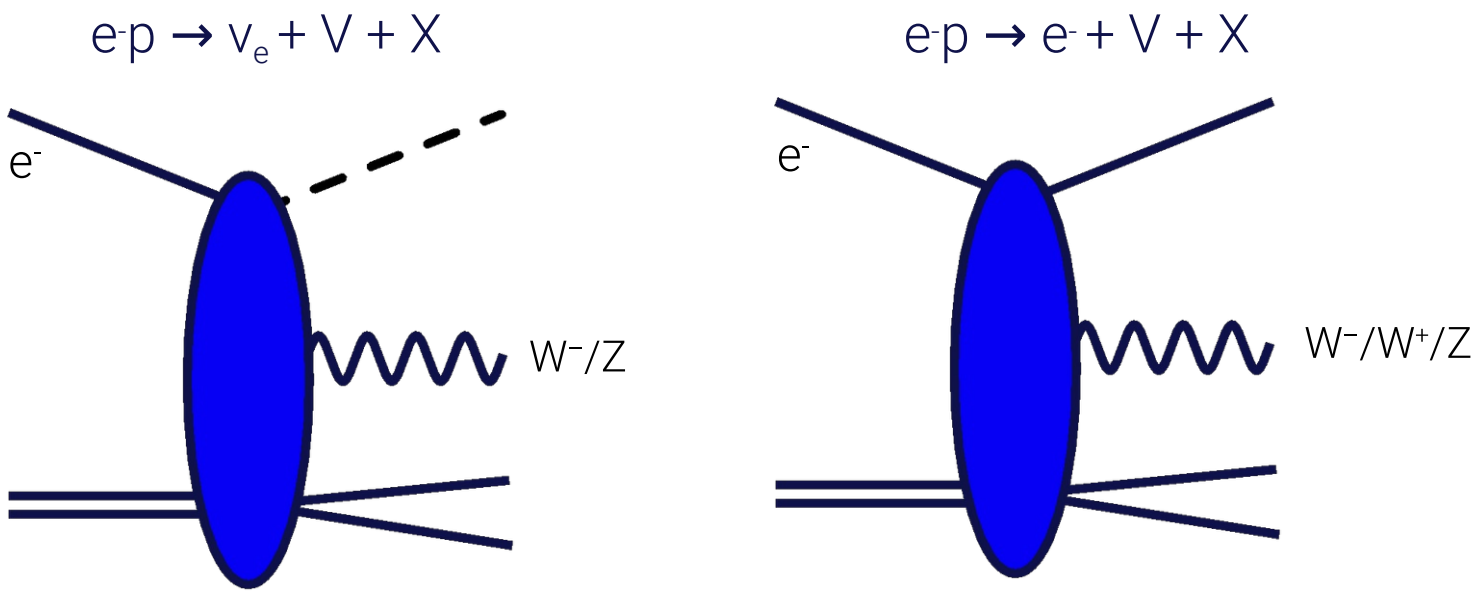






→ Weak couplings of the W-boson are precisely measured – even their scale dependence

Direct *W* and *Z* production



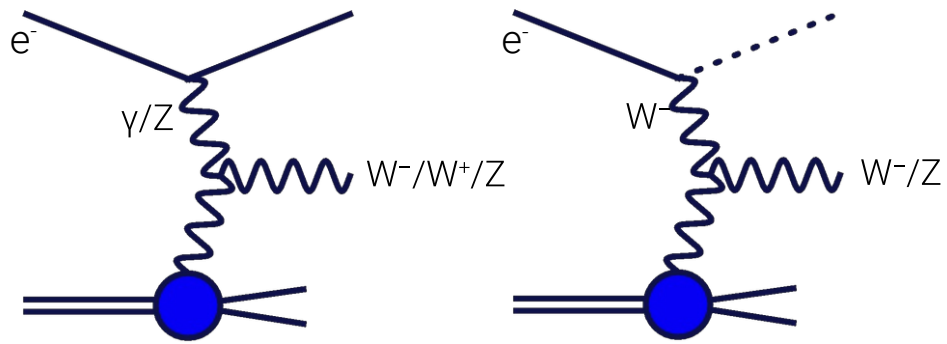
Total cross sections:

$e^-p \to W^+X$	~O(14pb)
$e^-p \to W^-X$	~O(15pb)
$e^-p \to ZX$	~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

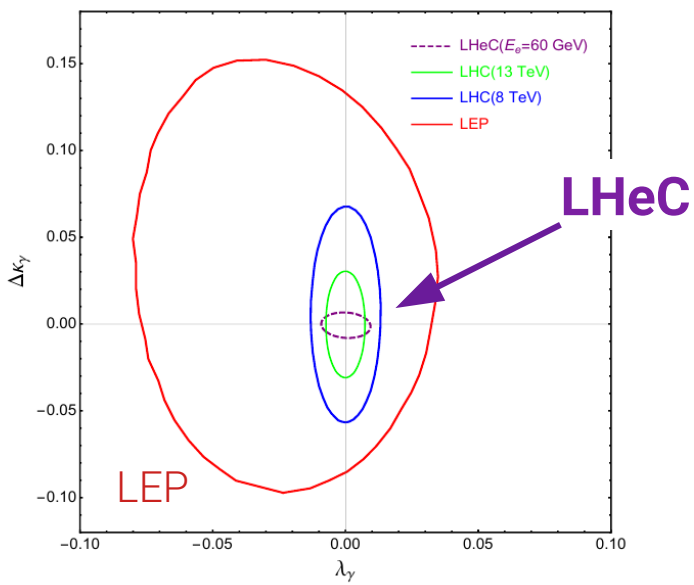
W and Z-boson production through 5 production channels in electron-proton scattering
Important VBF channels:



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

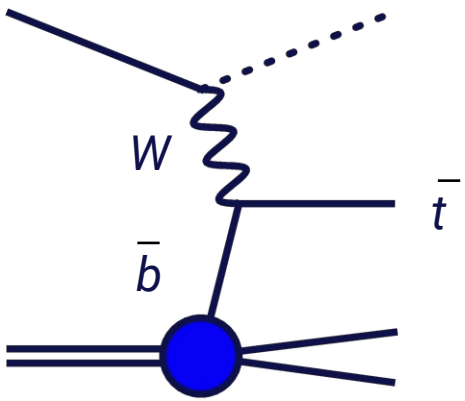
With 1ab^{-1} of LHeC data
O(0.5 – 1.5 million events)
→ high sensitivity to aTGC



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

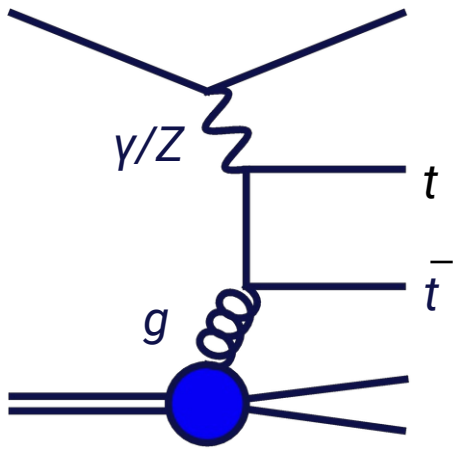
Top quark production in *ep*

CC DIS single-top quark production



LHeC σ~ 1.9pb
FCC-eh σ~15.3pb

NC (γp) top-quark pair production

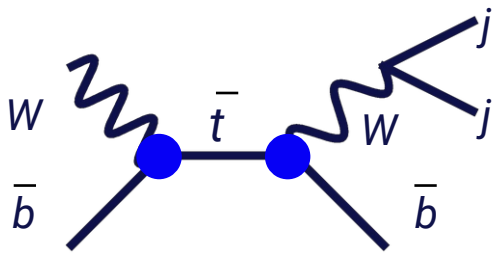


LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

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

$|V_{tb}|$ in charged-current single-top production

Direct measurement of $|V_{tb}|$

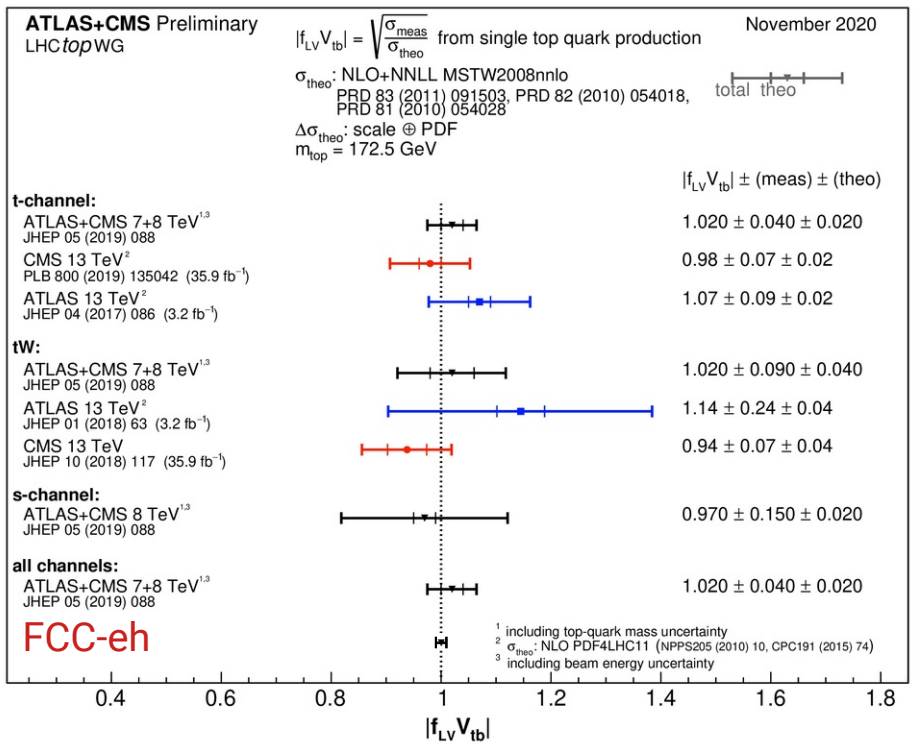


$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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

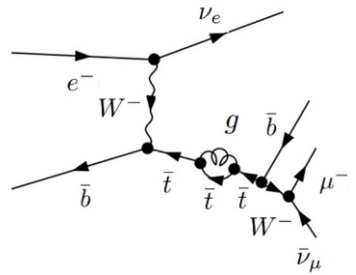
→ Limits on anomalous *Wtb* couplings: < 0.01



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

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

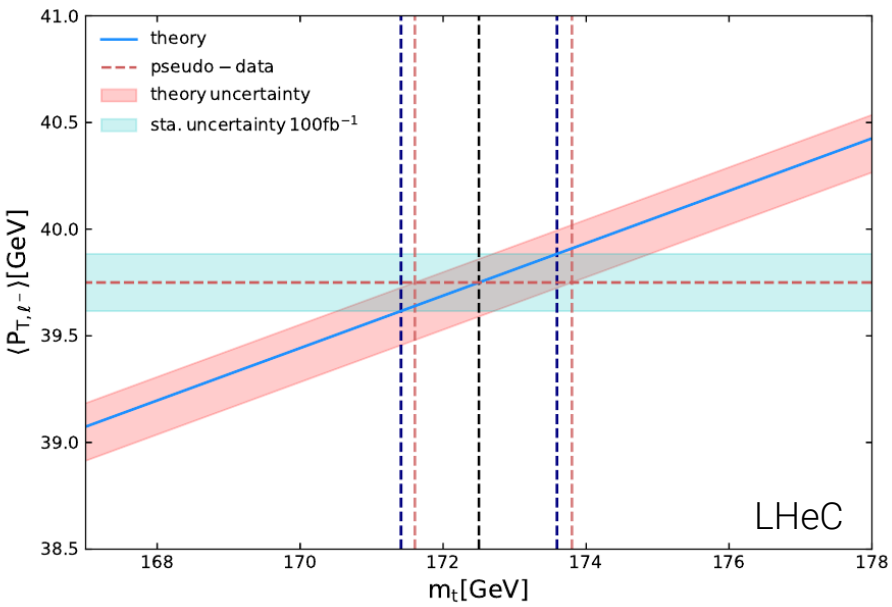
CC single-top production at NLO

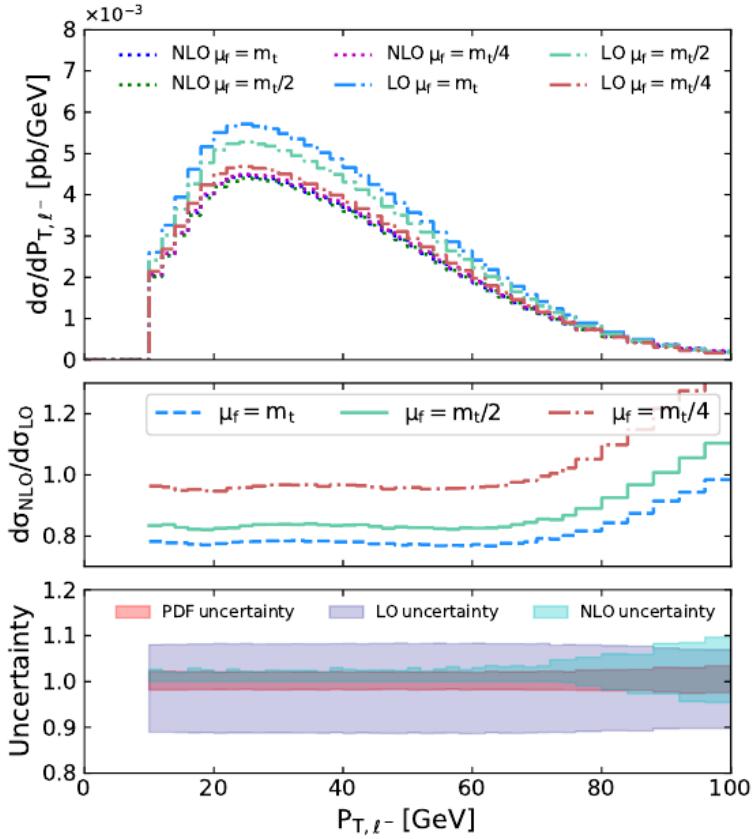


Recent calculation of single-top production at NLO

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

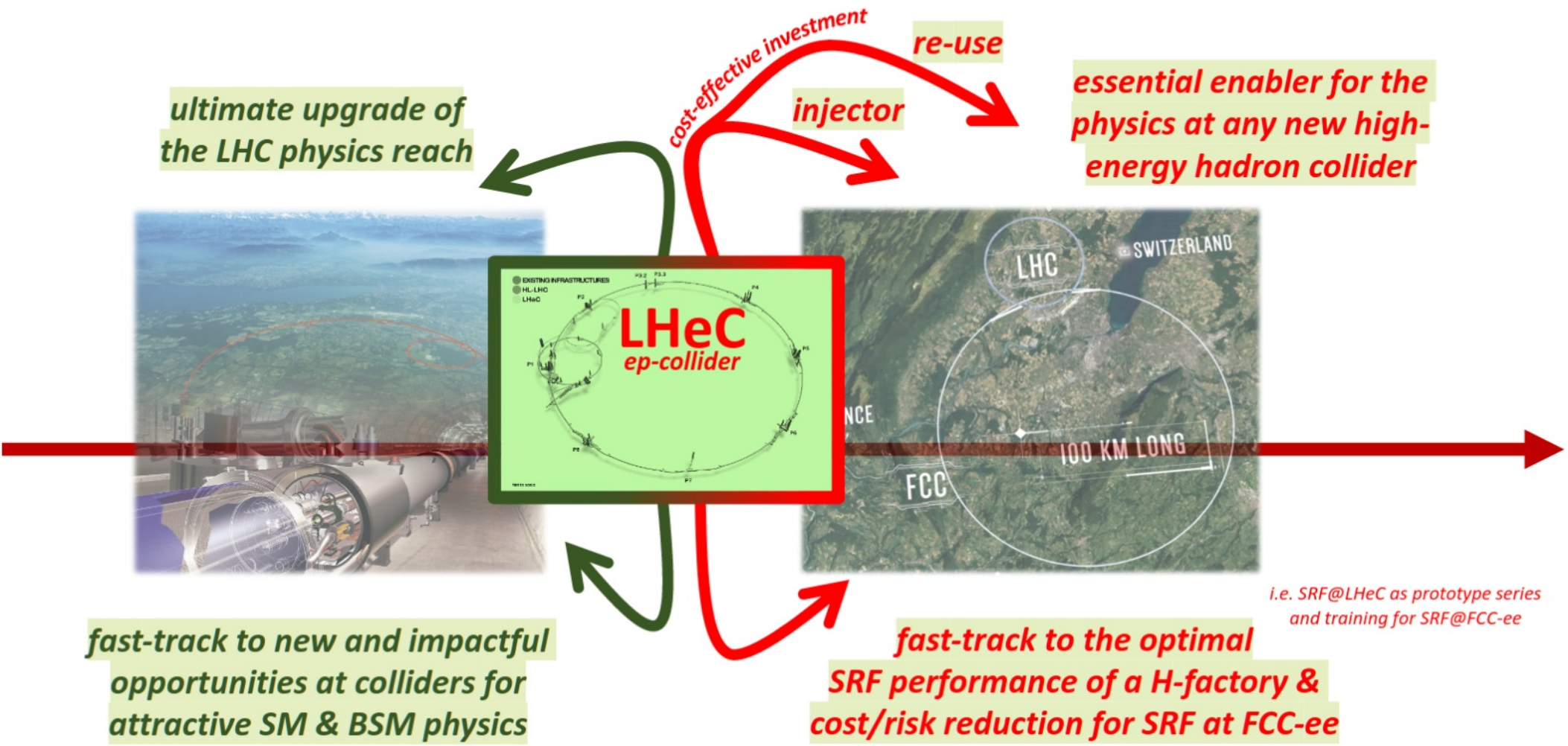
- *Negative NLO k-factor*
- *Good perturbative stability at NLO*
- *After (quite tight) fiducial cuts: σ ~ 0.2 pb*
- *further theoretical uncertainties negligibly small in top-mass determinations*





e—p upgrade of the HL-LHC

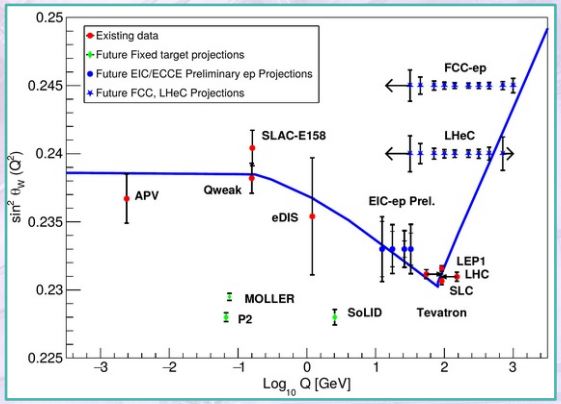
Final upgrade of the HL-LHC
→ Exploit full physics potential of LHC
(see talk by J. d'Hondt)



Summary

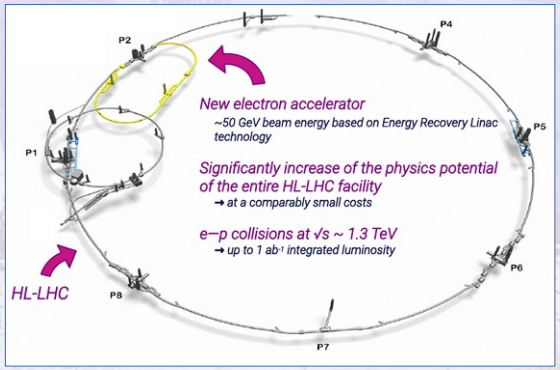
Electroweak physics at LHeC & FCC-eh

- *Unique measurements of scale dependence of EW interactions*
- *O(millions) directly produced W and Z-bosons → aTGC*
- *EW physics in pp at HL-LHC needs LHeC-PDFs (see talk by C. Gwenlan)*
- *Complementary measurements to Z-pole data*
- *Outstanding γγ collider prospects (see talk by. K. Piotrzkowski)*
- *Exciting Higgs prospects (HWW,Hbb,Hcc) (see talk by U. Klein)*



Top physics at LHeC & FCC-eh

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



Backup

The ep/eA study at the LHC and FCC – new impactful goals for the community

More information:
https://indico.cern.ch/event/1335332/

2023 WS 2024 WS 2025 *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces
Nestor Armesto, Claire Gwenlan, Paul Newman

general-purpose high-energy physics program: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions
Monica D'Onofrio, Uta Klein, Christian Schwanenberger

ep/eA-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics program
Maarten Boonekamp, Daniel Britzger, Christian Schwanenberger

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics
Paul Newman, Yuji Yamazaki

developing a sustainable LHeC and FCC-eh collider program
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …
Oliver Bruning, Yannis Papaphilippou

- five thematic physics and technology working groups
- annual ep/eA workshops (**WS**)

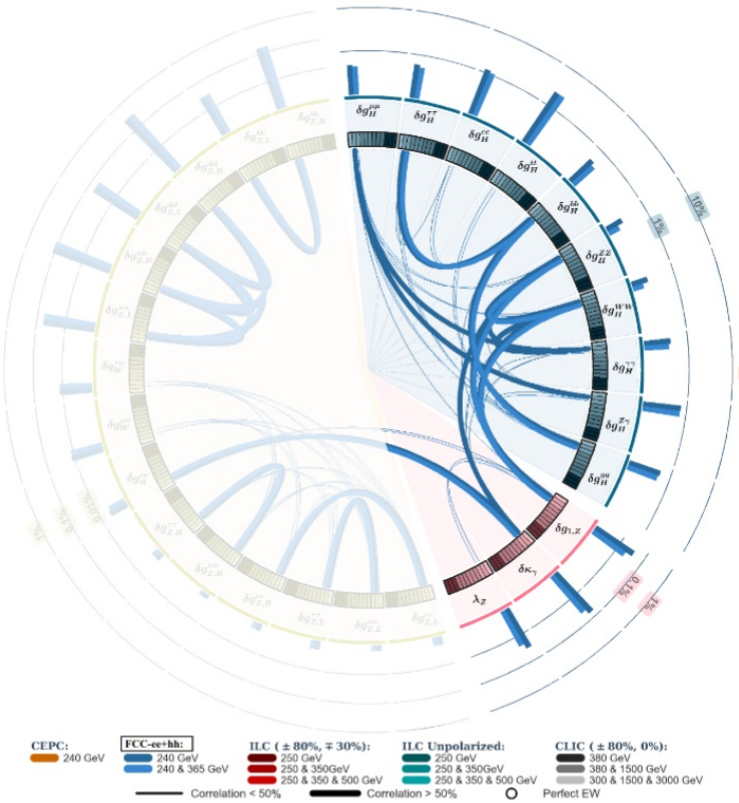
Subscribe to mailing lists via https://e-groups.cern.ch/ : use the search option, and search for "lhec-fcceh-all" or "ep-eA-WG" in all e-groups

SMEFT fit results after FCC era

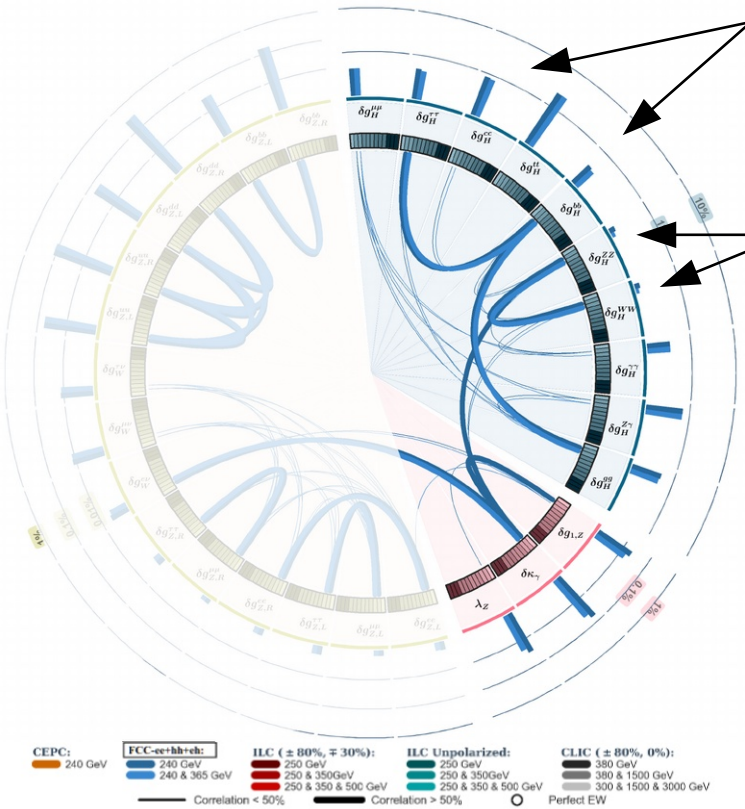
Higgs and Electroweak ep Physics at FCC-eh
Ch. Schwanenberger, Tue 8:30

Couplings and correlations

FCCee+hh



FCCee+eh+hh



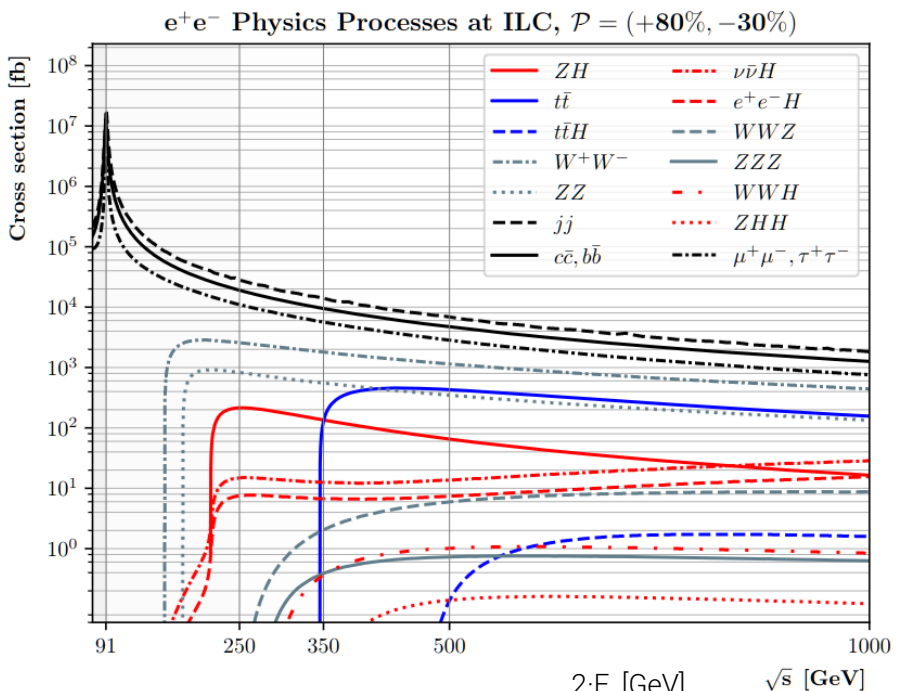
Significant reductions for *Hcc* and *Hbb*

eh contributes to the *HWW* and *HZZ* couplings and resolves their correlation.

PRELIMINARY

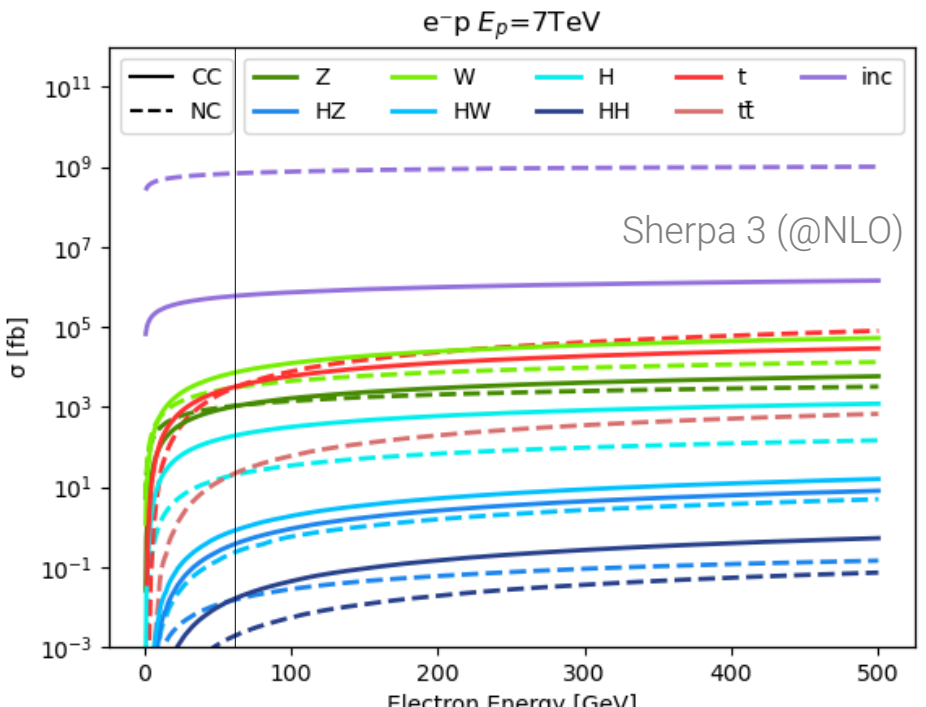
s-channel (e^+e^-) vs. t-channel ($e^\pm p$)

Electroweak physics in e^+e^- collisions



ZZ WW HZ tt

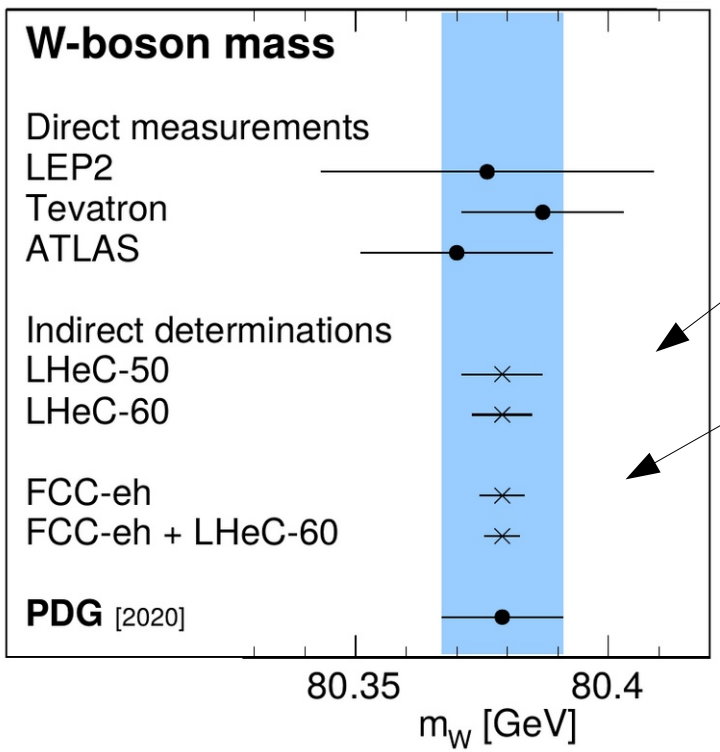
Electroweak processes in DIS at LH(e)C



W Z H t

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*

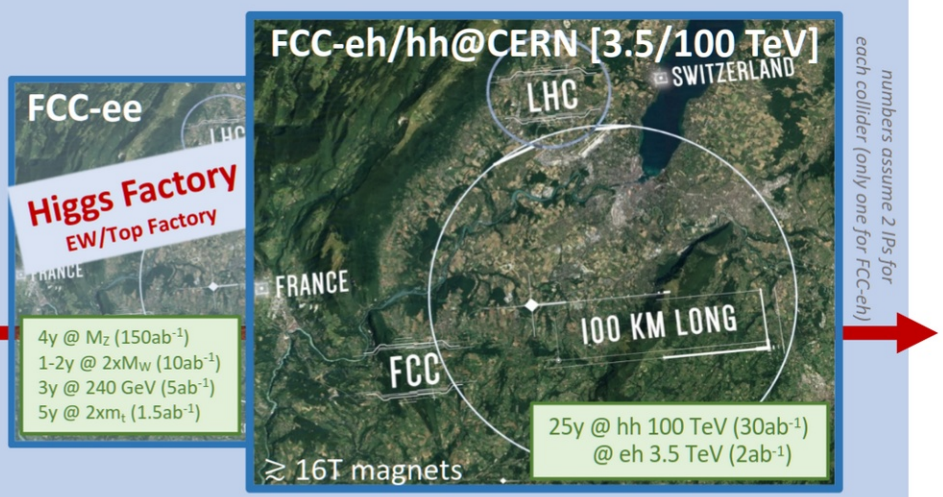
- Indirect determination of m_W
- Complementary to 'direct' measurements
  → Consistency test of EW Standard Model
- Smallest uncertainties from a single experiment

e–p upgrade of the HL-LHC

Final upgrade of the HL-LHC
→ Exploit full physics potential of LHC
→ a bridge towards a major new collider facility

Large Hadron Collider (HL-LHC)
until early 2040'ies

Future Circular Collider (FCC)
from late 2040'ies



feasibility of the FCC is being investigated