WG6 Future experiments

Top and EW studies at the LHeC and FCC-he

Sookhyun Lee (U Michigan/U Tennessee)

on behalf of the LHeC/FCC-eh study group

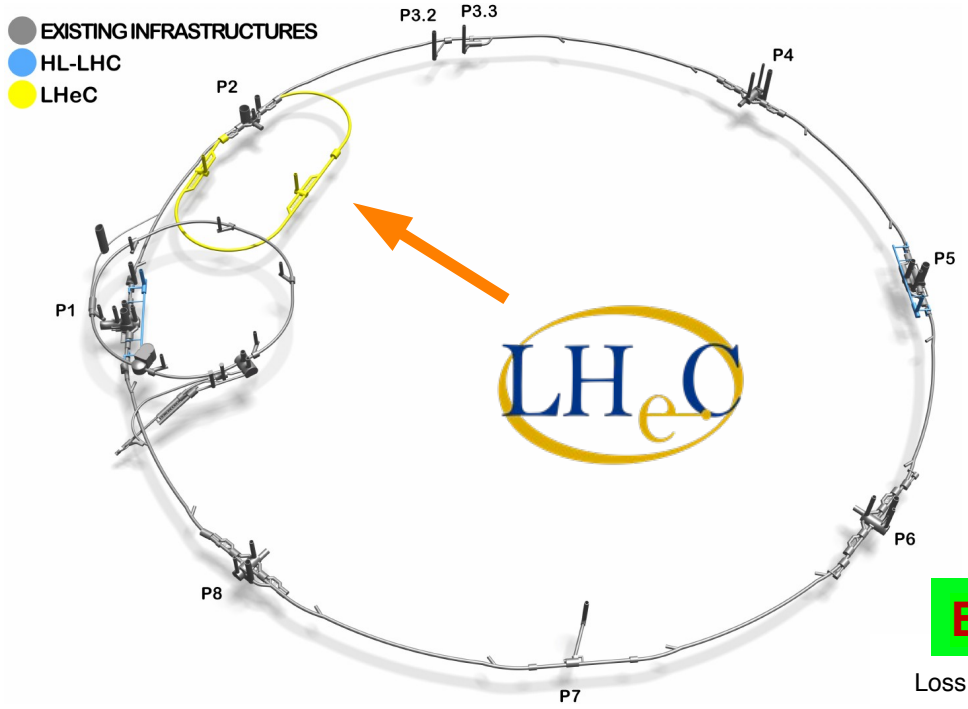
XXX International Workshop on Deep-inelastic Scattering and Related Subjects

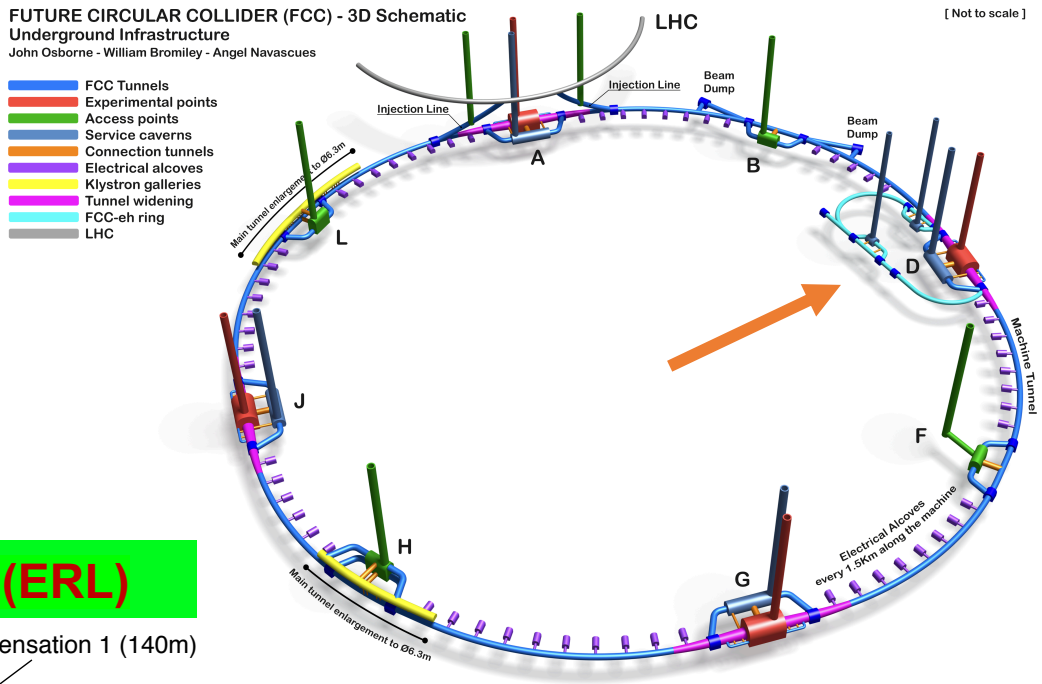
March 30, 2023

- **LHeC CDR :**
  J. Phys. G 39 (2012) 075001, 1206.2913
  J. Phys. G 48 (2021) 11, 110501, 2007.14491

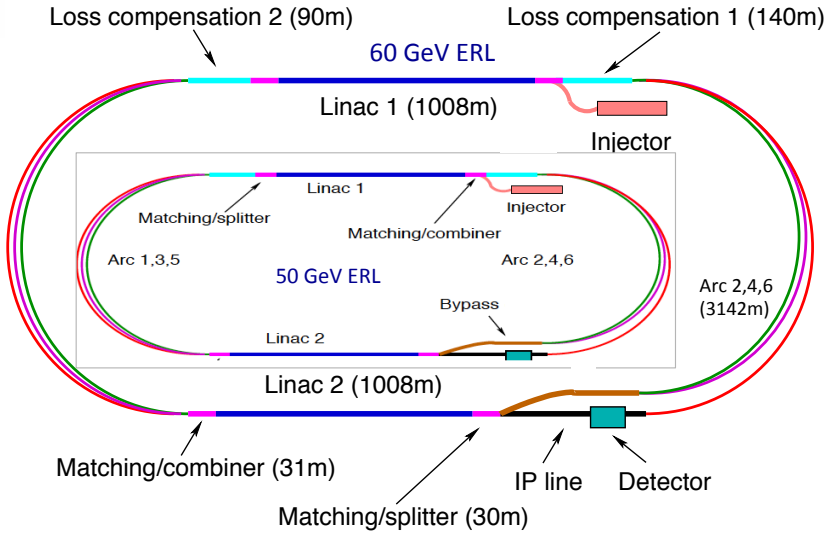
- **FCC CDR:**
  EPJ. C 79, no. 6, 474 (2019) - Physics
  EPJ. ST 228, no. 4, 755 (2019) - FCC-hh/eh

LHeC and FCC-eh (Linac-Ring Collider)





Energy Recovery Linac (ERL)



LHeC

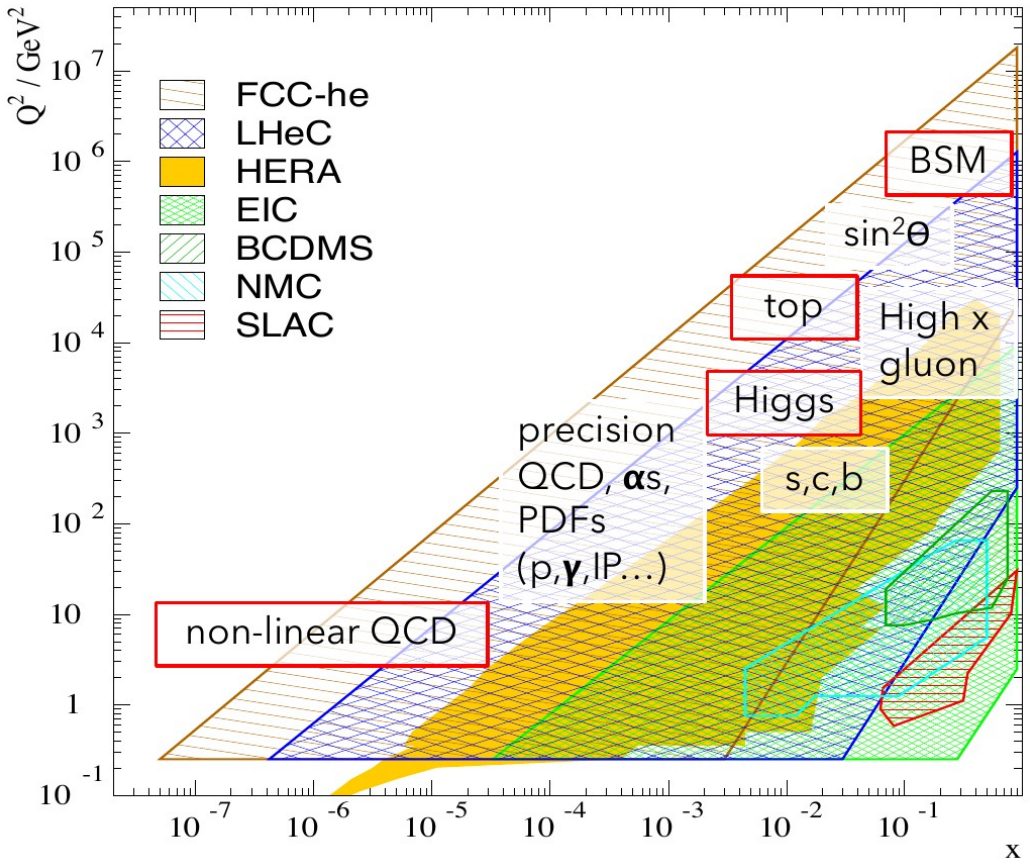
- Operated synchronously with *HL-LHC*
  √s =1.2 TeV, E_e (= 50 GeV) × E_p (=7 TeV)
- Time scale: 2035+
- Luminosity: 10^{34} cm^{-2} s^{-1}

FCC-eh

- Operated synchronously with *FCC-hh*
  √s =3.5 TeV, E_e (= 60 GeV) × E_p (=50 TeV)
- Time scale: 2050+

Sookhyun Lee, DIS 2023

LHeC/FCC-eh kinematics



L_{int} = 1-3 ab^{-1} (2000×HERA!)

- Clean and high resolution QCD factory with ep/eA at energy frontier
- Rich physics at all scales, precision and discovery
- Strengthen LHC/FCC program while keeping energy cost low with ERL technology
- **Top** and **EW** and **Higgs** physics:

  require high Q^2 and high luminosity

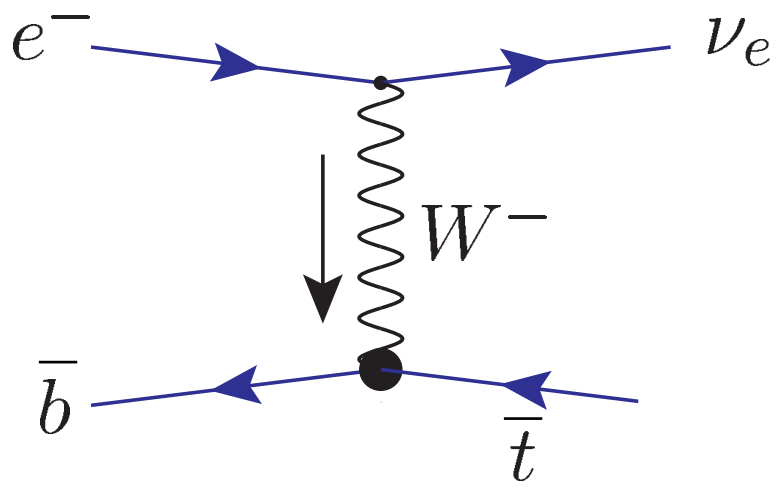
See talks:

IR and Detectors (Paul Newman, Tues)
Overview, and Higgs and BSM physics (Nestor Armesto, Wed 11.50)
Proton structure/precision QCD (Francesco Giuli, Thurs 17.10)
Diffraction/forward physics (Anna Stasto, Thurs 17.30)
High energy QCD and eA (Claire Gwenlan, Thurs 17.50)

Top production in ep

Charged Current (CC)

DIS *single top-quark* production

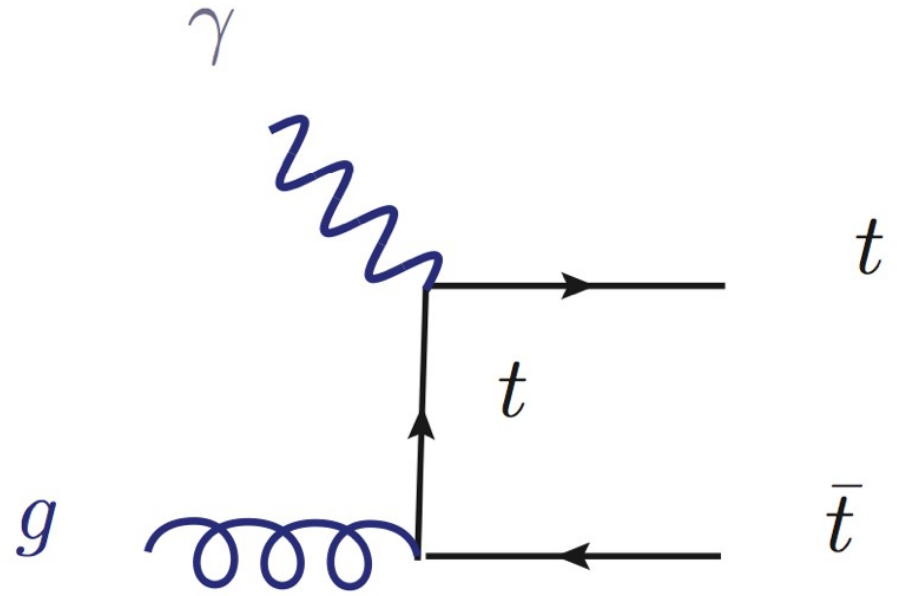


- **σ = 1.89pb (LHeC)**

  σ = 15.3pb (FCC-eh) with **E_e=60 GeV**
- CKM matrix (V_{tx}); Wtb couplings, V_{td}, V_{ts}

Neutral Current (NC)

top-quark pair photoproduction

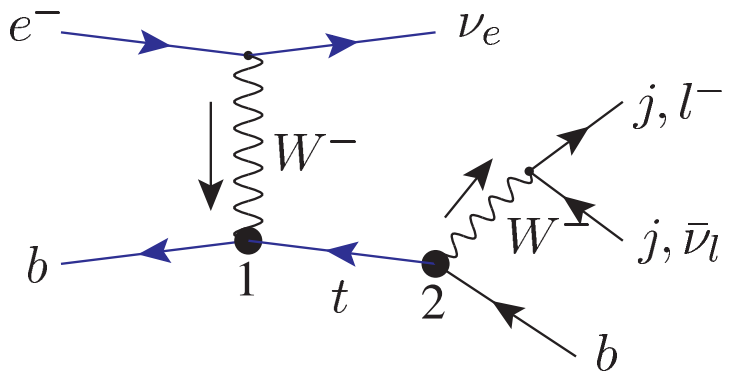


- **σ = 0.05pb (LHeC)**

  σ = 1.14pb (FCC-eh) with **E_e=60 GeV**
- Top charge and anomalous form factors

Wtb couplings

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



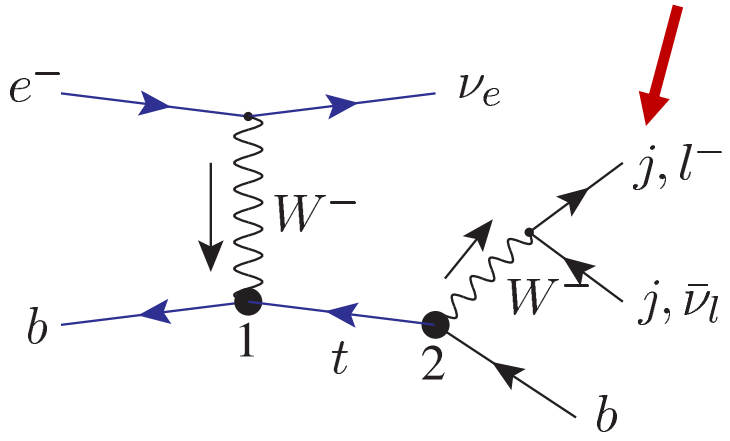
SM : $V_{tb} f_1^L \cong 1$,
$f_1^R = f_2^L = f_2^R = 0$

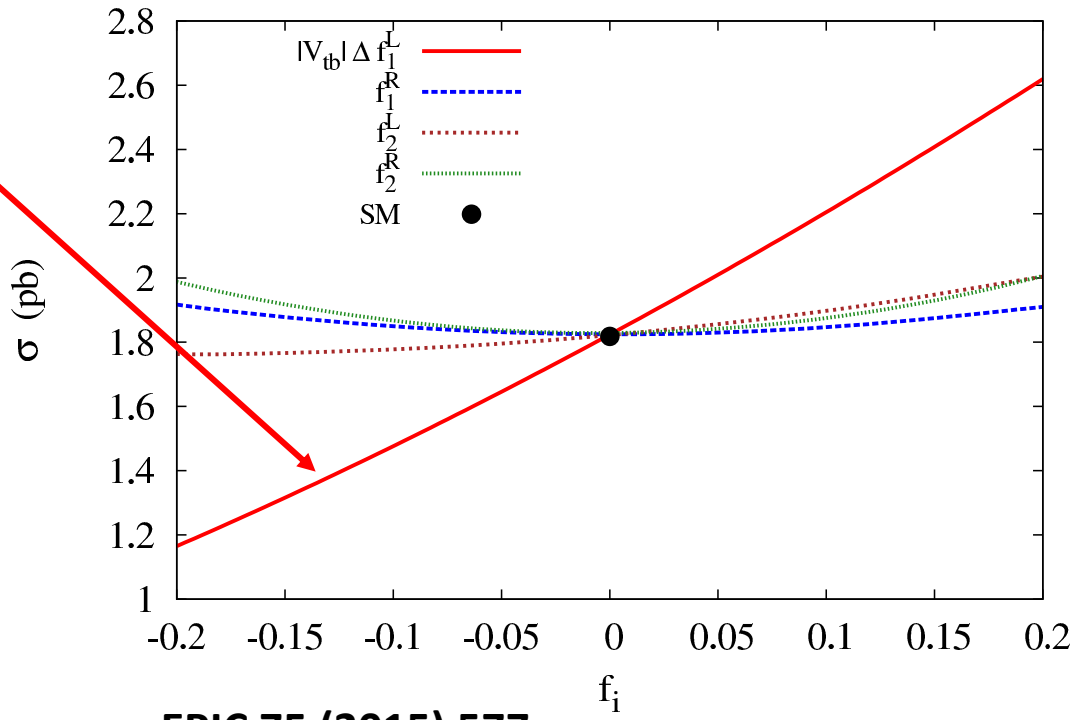
- Wtb couplings via single top production at LHeC
  - Direct access to anomalous couplings
  - Clean measurements and suppressed background from strong interaction initiated processes

$V_{tb}\, f_1^L$

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

$$f_1^L \equiv 1 + \Delta f_1^L$$



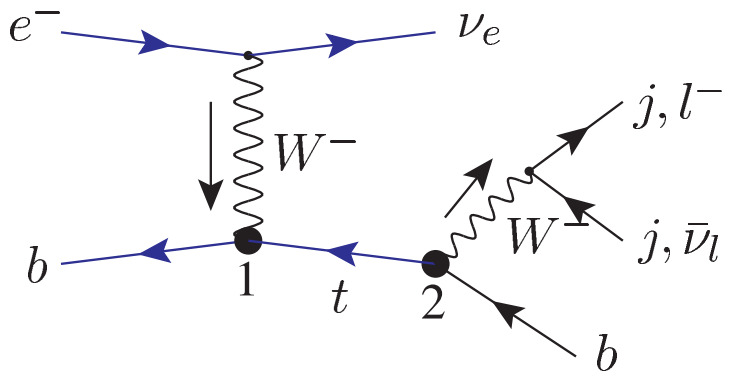


- Wtb couplings via single top production at LHeC
  - Hadronic and leptonic decays studied using DELPHE and analysis cuts with E_e= 60 GeV

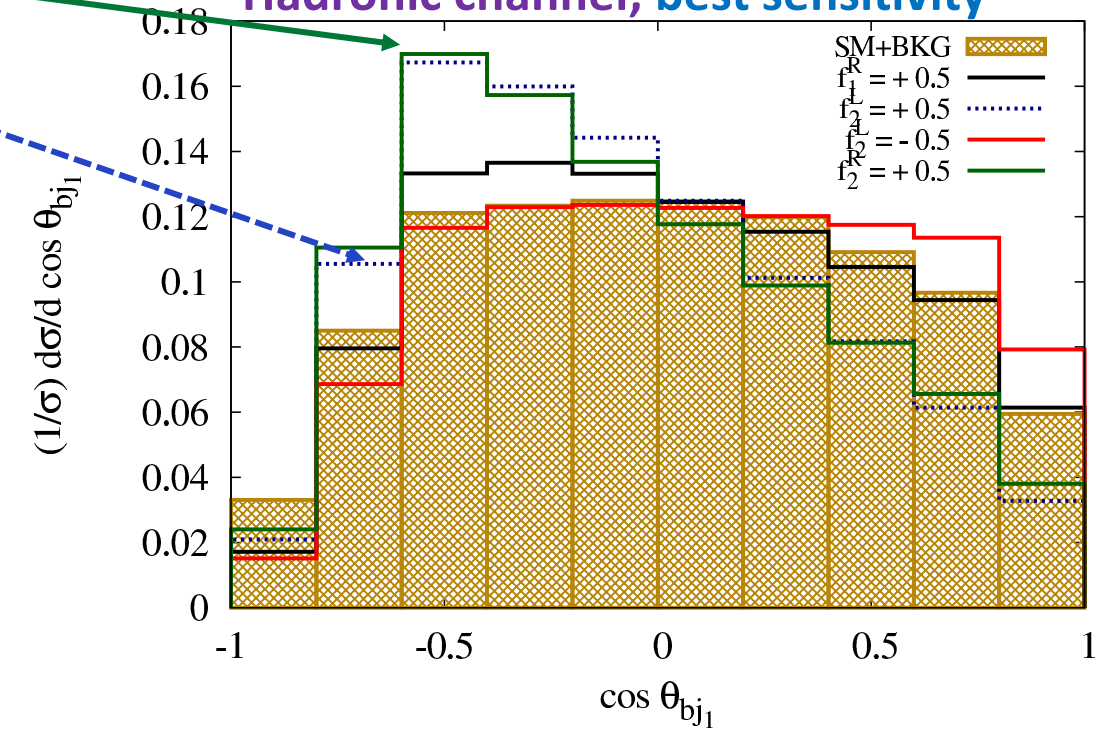
EPJC 75 (2015) 577,
Dutta, Goyal, Kumar, Mellado,

f_1^R, f_2^L and f_2^R

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



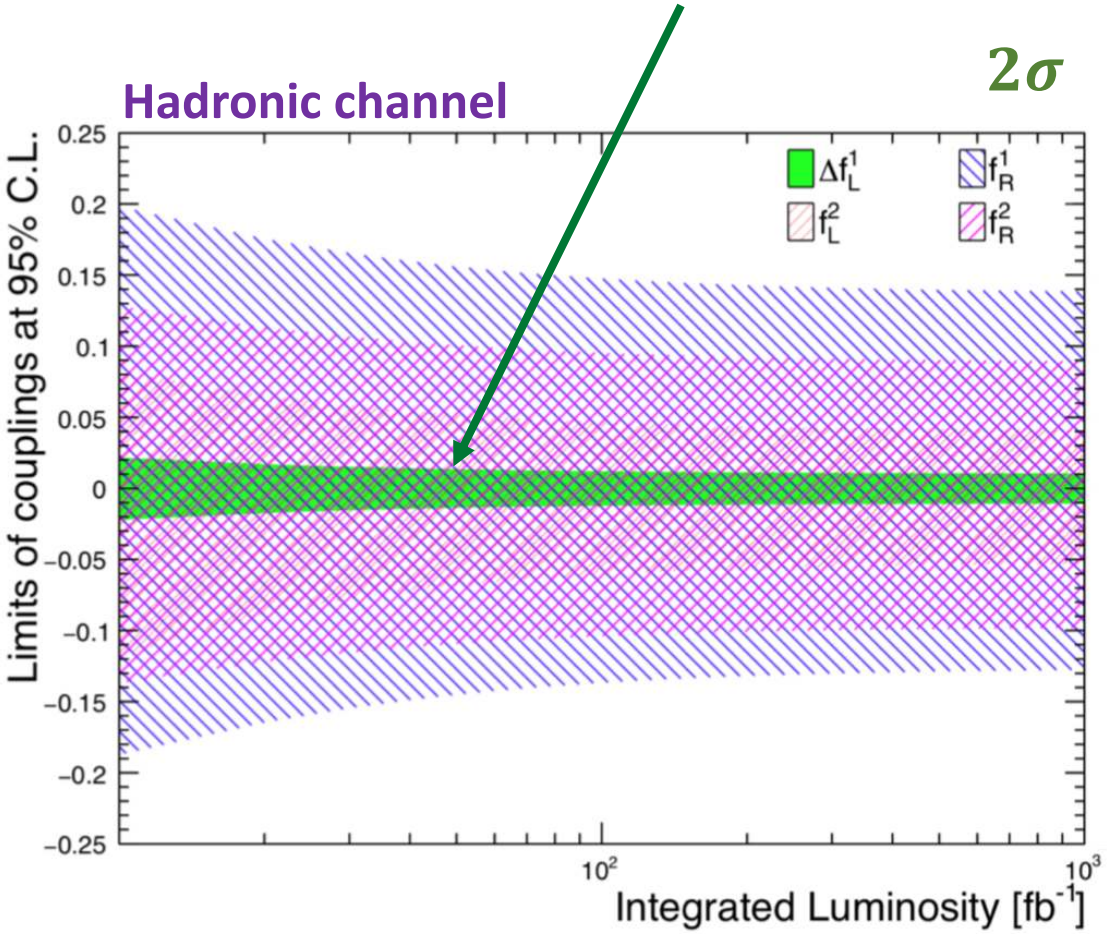
Hadronic channel; best sensitivity



- Wtb couplings via single top production at LHeC
  - Hadronic and leptonic decays studied using DELPHE and analysis cuts with E_e= 60 GeV

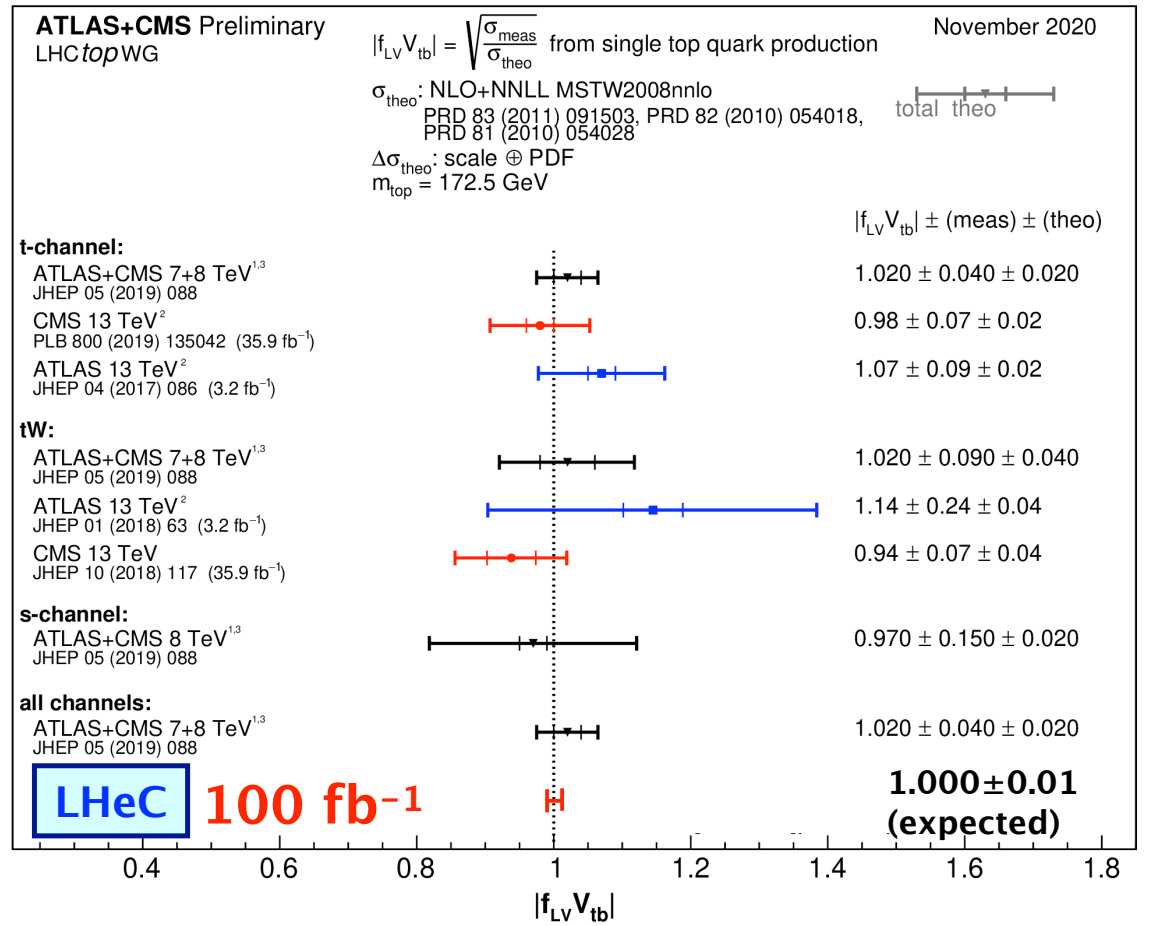
- j_1: hardest p_T jet
- Distributions normalized to unity

Anomalous Wtb Couplings

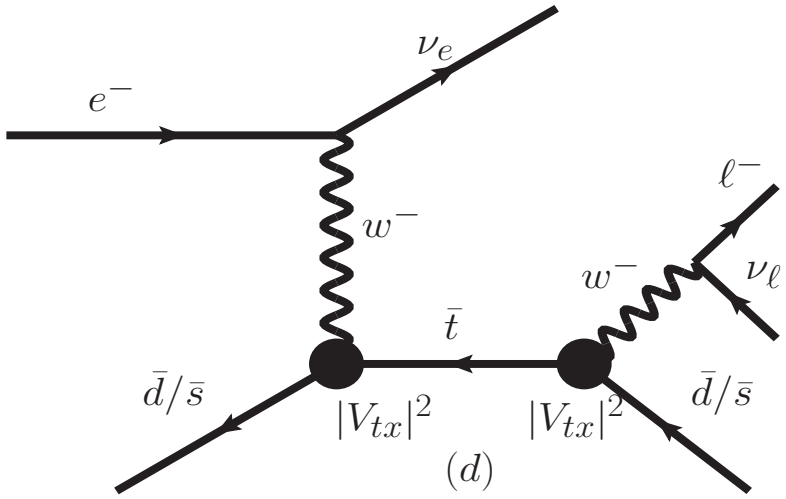


EPJC 75 (2015) 577, arXiv:1307.1688,
Dutta, Goyal, Kumar, Mellado,

$V_{tb}f_1^L$



Even smaller than 1% with 1 ab^{-1}!

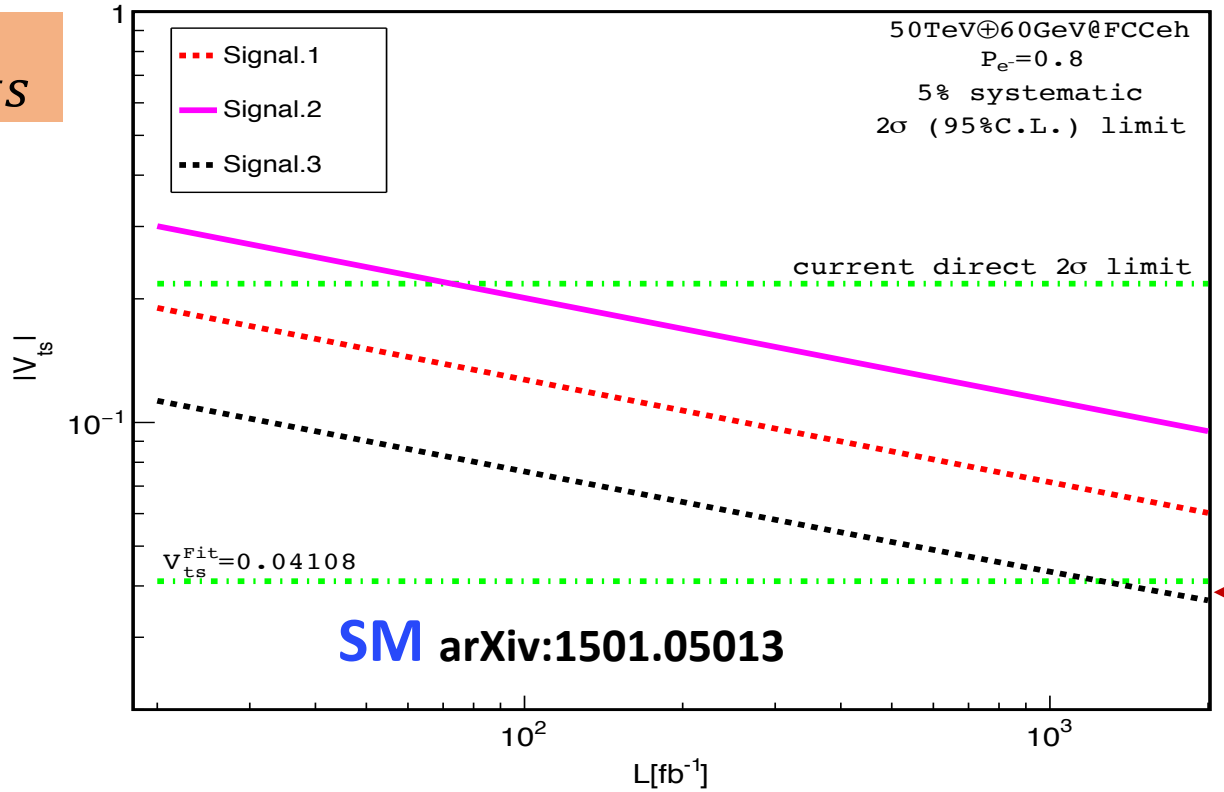


V_{td} and V_{ts}

- Direct measurements of V_{td} and V_{ts}
- Top-pair production background suppressed
- Probing SM predictions directly for the first time

PoS DIS 2018 (2018) 167, H. Sun

V_{ts}



LHC arXiv:1709.07887

SM arXiv:1501.05013

FCC-eh $|V_{ts}|<0.037$

Leptonic channel

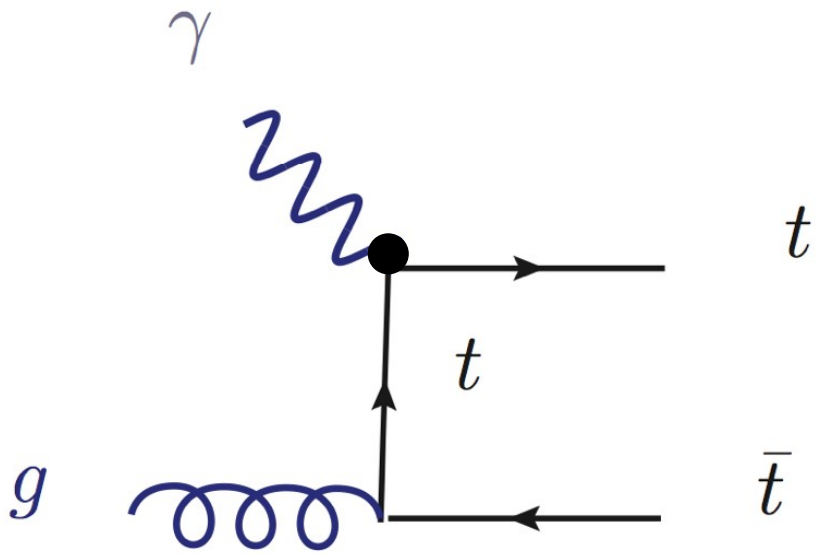
Top-quark form factors

κ : magnetic dipole moment (MDM)

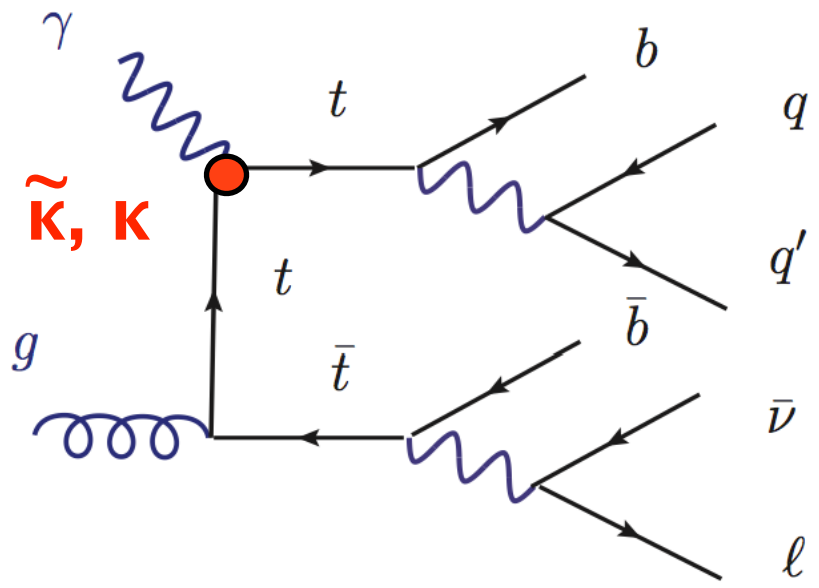
$\tilde{\kappa}$: electric dipole moment (EDM)

$$\mathcal{L}_{t\bar{t}\gamma} = e\bar{t}\left(Q_t\gamma^\mu A_\mu + \frac{1}{4m_t}\sigma^{\mu\nu}F_{\mu\nu}(\kappa + i\tilde{\kappa}\gamma_5)\right)t$$

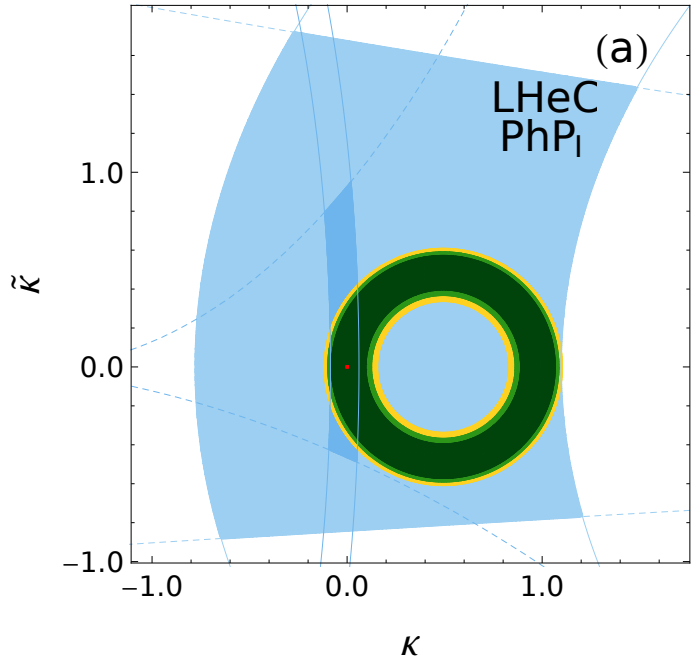
eQ_t : electric charge

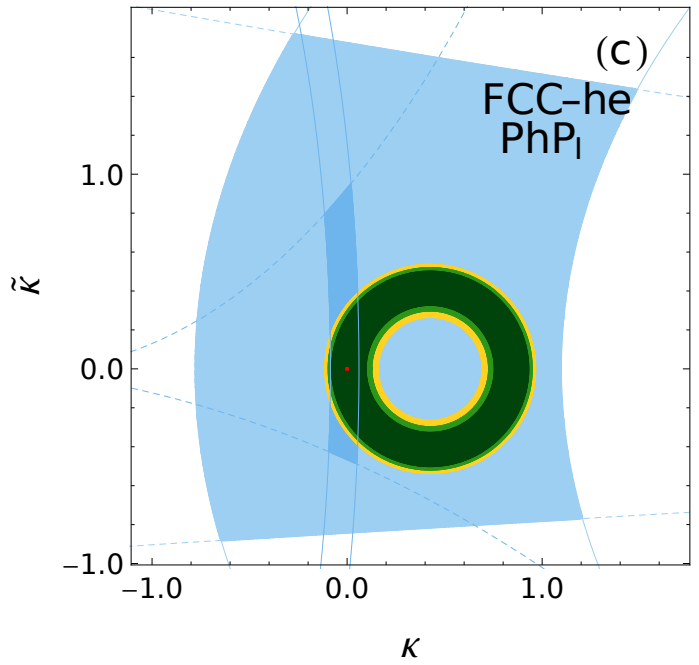


- Photoproduction of top-quark pairs
- Clean measurements thanks to absence of final state radiation



- Semi-leptonic weak decay mode, most sensitive
- Realistic analysis with SMEFT + full QED + parton shower + hadronization + fast detector simulation
- Pseudo-data with experimental uncertainties of 12% (dark green), 15% (light green), and 18% (yellow)
- Corona thickness increase from 0.1 (parton-level) to 0.15 (detector-level) for 18% uncertainty



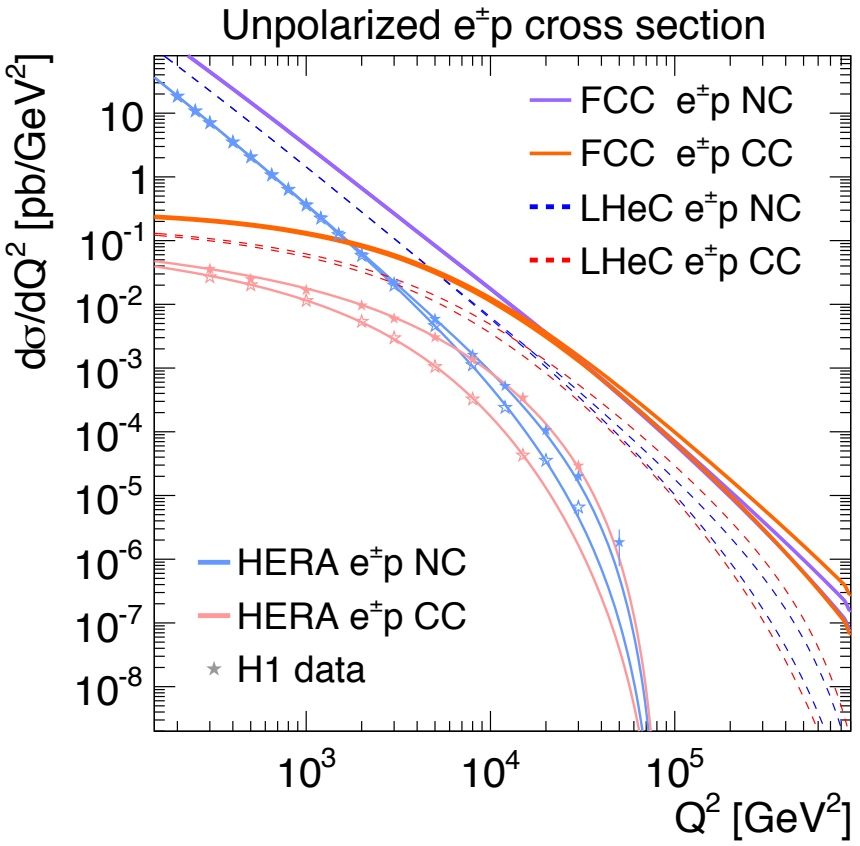


Bouzas, Larios
PRD 88 (2013) 094007
PRD 105 (2022) 115002

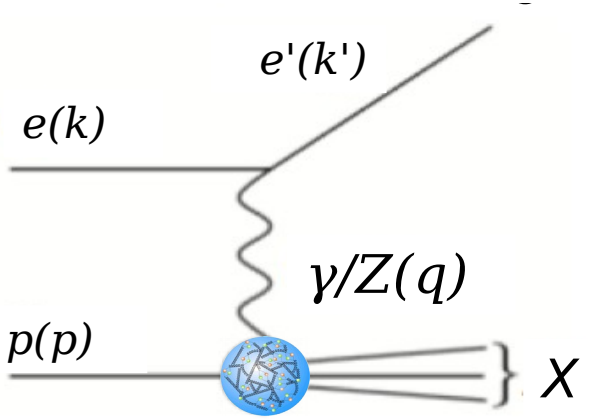
(blue) Branching ratio and CP asymmetries of $B \to X_s\gamma$

Electroweak physics in DIS

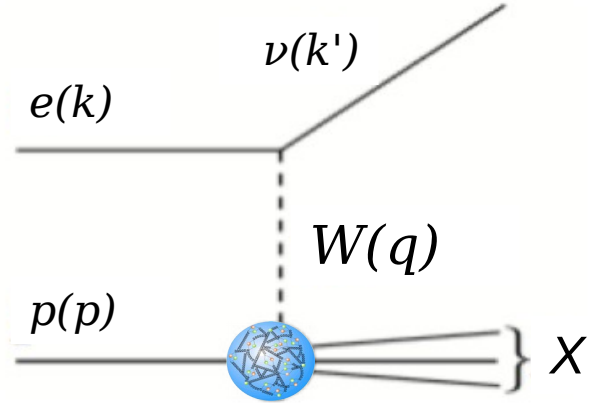
- Electron/positron beam polarizations of ±80%
- Precision determination of parameters in NC+CC
  - Weak-mixing angle
  - Gauge boson masses
  - NC/CC couplings of the gauge bosons



NC inclusive DIS



CC inclusive DIS



Neutral Current inclusive DIS

$$\frac{d^2\sigma^{\mathrm{NC}}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\pm}(x,Q^2) \mp Y_-x\tilde{F}_3^{\pm}(x,Q^2) - y^2\tilde{F}_L^{\pm}(x,Q^2)\right] ,$$

where $\tilde{F}_2^{\pm} = F_2 - (g_V^e \pm P_e g_A^e)\kappa_Z F_2^{\gamma Z} + [(g_V^e g_V^e + g_A^e g_A^e) \pm 2P_e g_V^e g_A^e]\,\kappa_Z^2 F_2^Z$,

and $\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q \left[Q_q^2, 2Q_q g_V^q, g_V^q g_V^q + g_A^q g_A^q\right]\{q+\bar{q}\}$ in quark-parton model

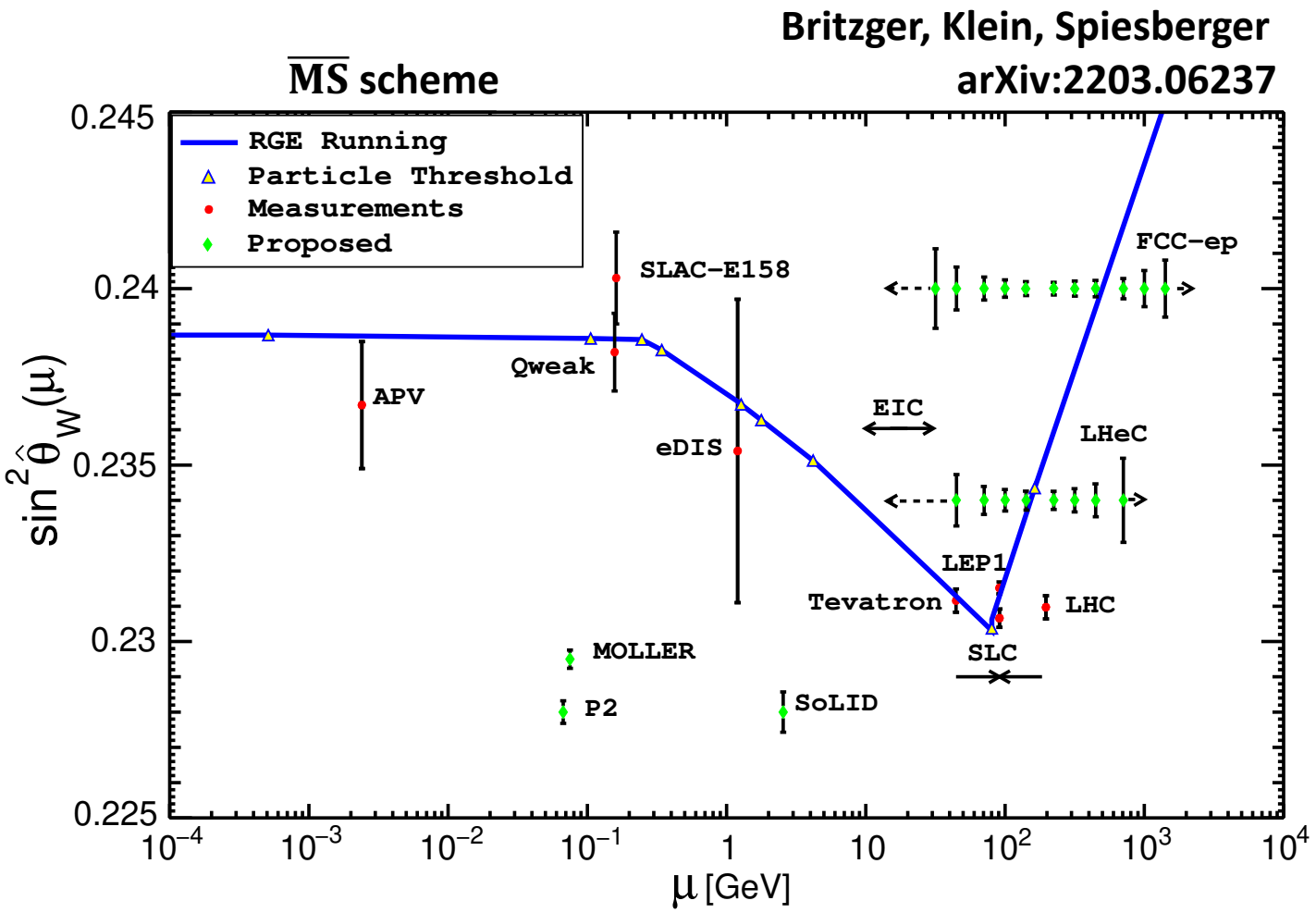
Z normalization $\varkappa_Z(Q^2) = \frac{Q^2}{Q^2+m_Z^2}\frac{1}{4\sin^2\theta_W\cos^2\theta_W}$

NC couplings $g_V^f = \sqrt{\rho_{\mathrm{NC},f}}\left(I_{\mathrm{L},f}^3 - 2Q_f\kappa_{\mathrm{NC},f}\sin^2\theta_{\mathrm{W}}\right)$ in SM

$g_A^f = \sqrt{\rho_{\mathrm{NC},f}}\, I_{\mathrm{L},f}^3$

- Independent SM parameters:
  - α, m_Z, m_W + PDFs

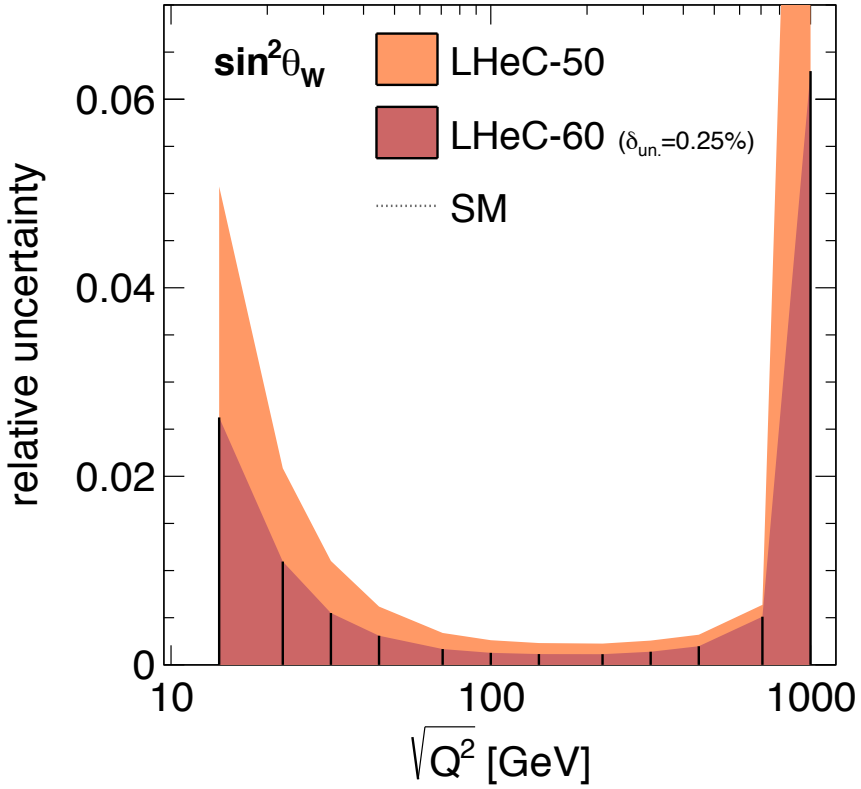
Scale dependence of weak mixing angle



- Most high energy data measured at Z-pole
- Existing low energy data with large uncertainties
- LHeC/FCC-ep together access a wide range of scale at energy frontier
- Test of SM, potential discovery of BSM

Uncertainties on weak mixing angle

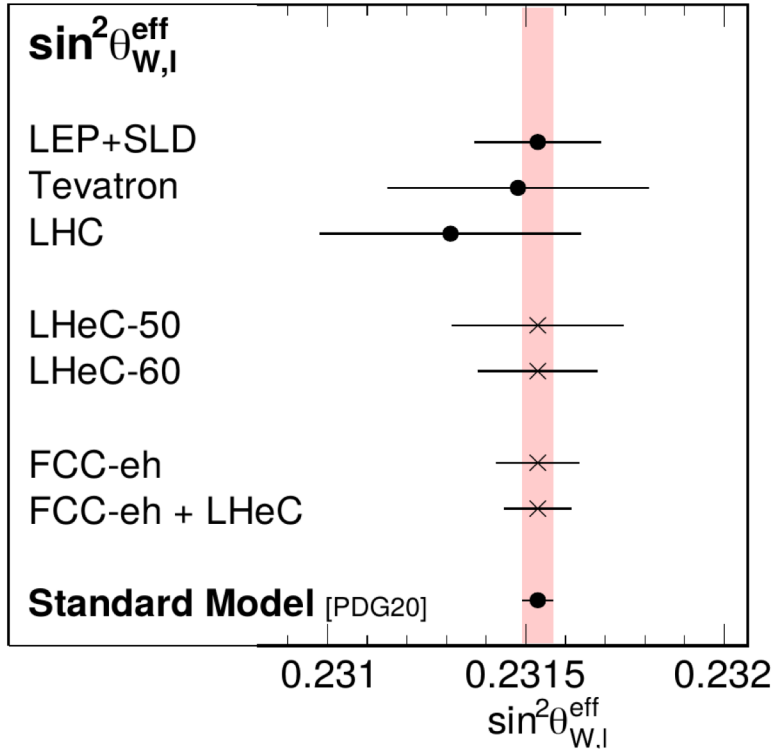
Britzger, Klein, Spiesberger
arXiv:2203.06237



On shell scheme:

$$\sin^2\theta_W \equiv 1 - \frac{m_W^2}{m_Z^2}$$

- Fit $\sin^2\theta_W$+ PDFs
- Comparison to Z-pole data

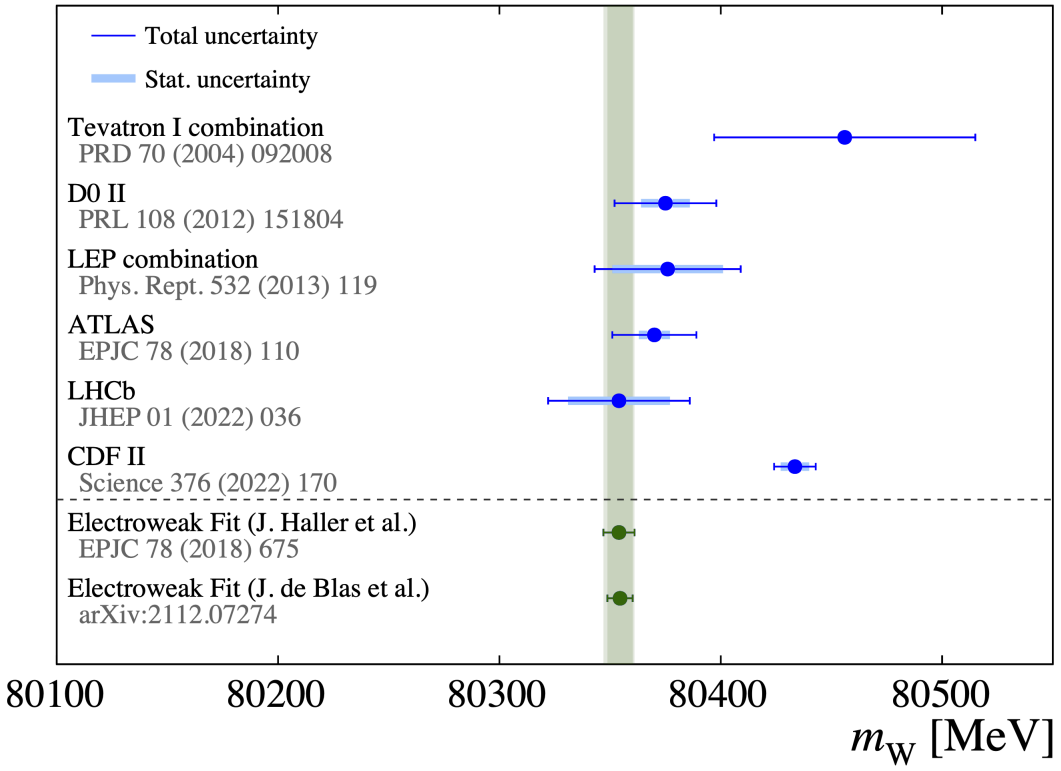


$\Delta\sin^2\theta_w$ (FCC-eh) = ±0.00011
= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

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

W-boson mass

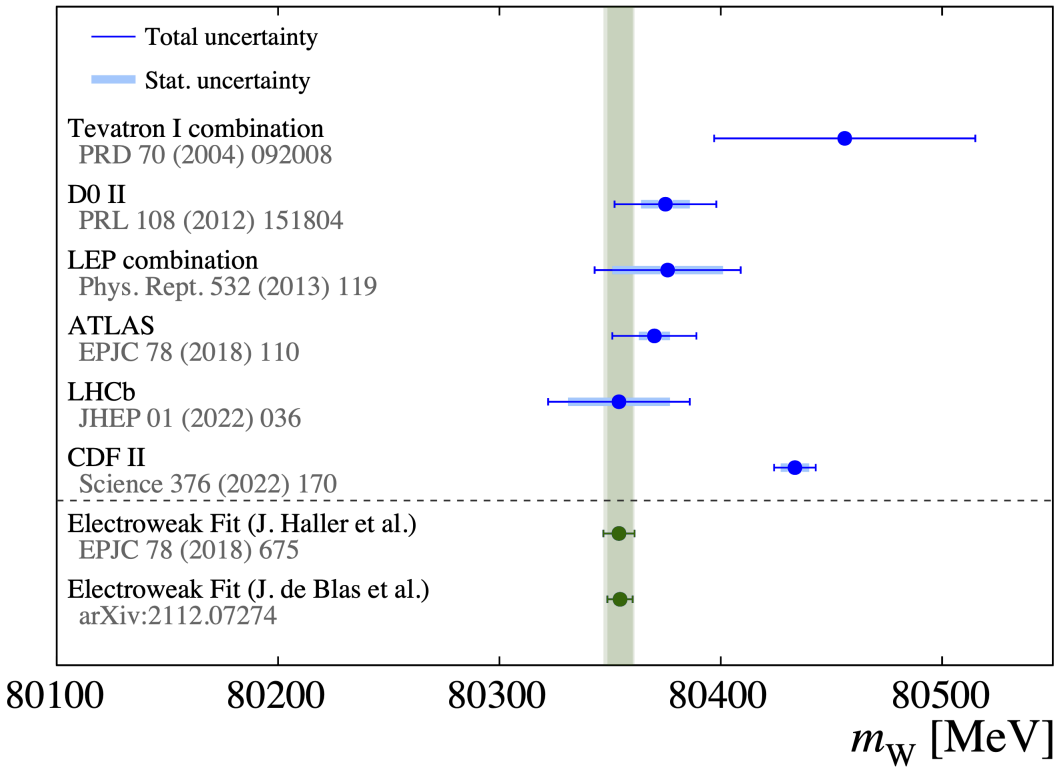
Credit: LHCb



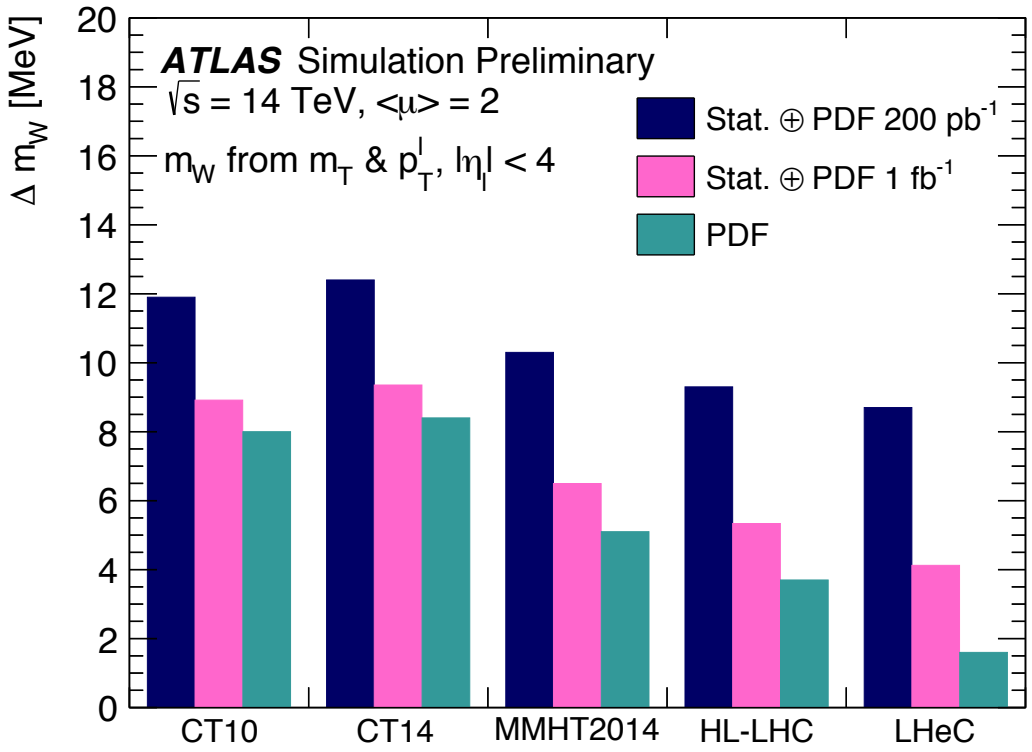
- Currently Large theory uncertainty originates from knowledge of **PDFs**

W-boson mass

Credit: LHCb



ATL-PHYS-PUB-2018-026

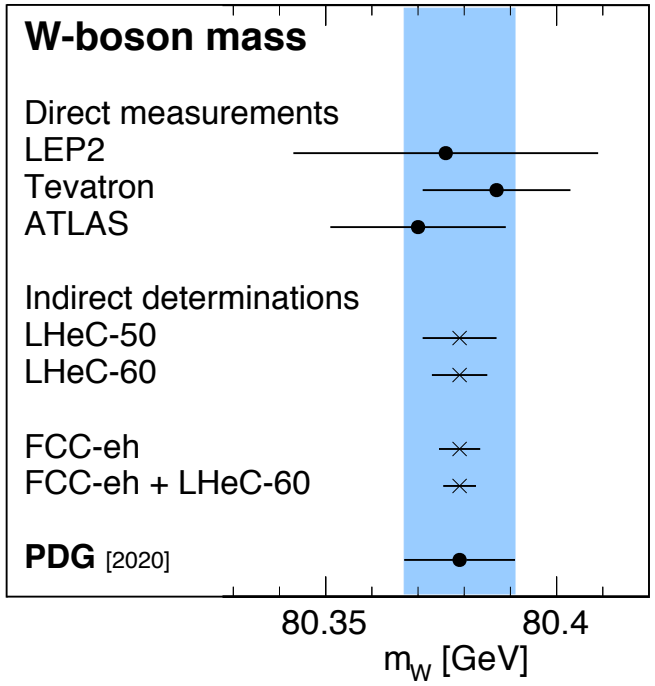


- Currently Large theory uncertainty originates from knowledge of **PDFs**

Δm_W(PDF):

± 8 MeV (CT10) → ± 3.6 MeV (HL-LHC) → **± 1.6 MeV (LHeC)**

W-boson mass

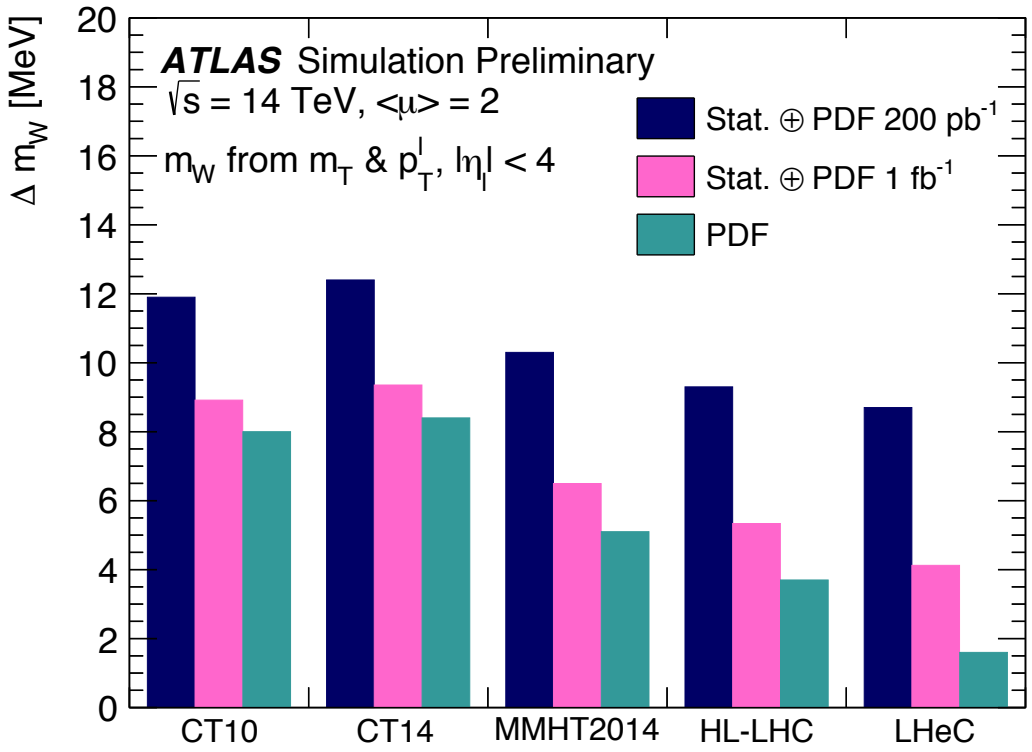


$\Delta\, m_W$ (FCC-eh) = ±4.5 MeV
including ±3.6 MeV$_{(PDF)}$

$\Delta\, m_W$ (LHeC-50)	= ±8 MeV
$\Delta\, m_W$ (LHeC-60)	= ±6 MeV
$\Delta\, m_W$ (FCC-eh+LHeC)	= ±3.6 MeV

arXiv:2203.06237

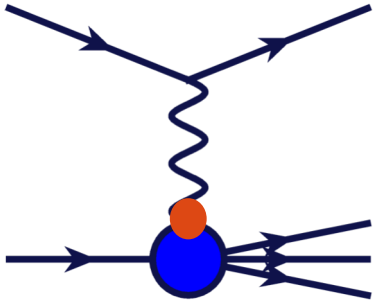
ATL-PHYS-PUB-2018-026

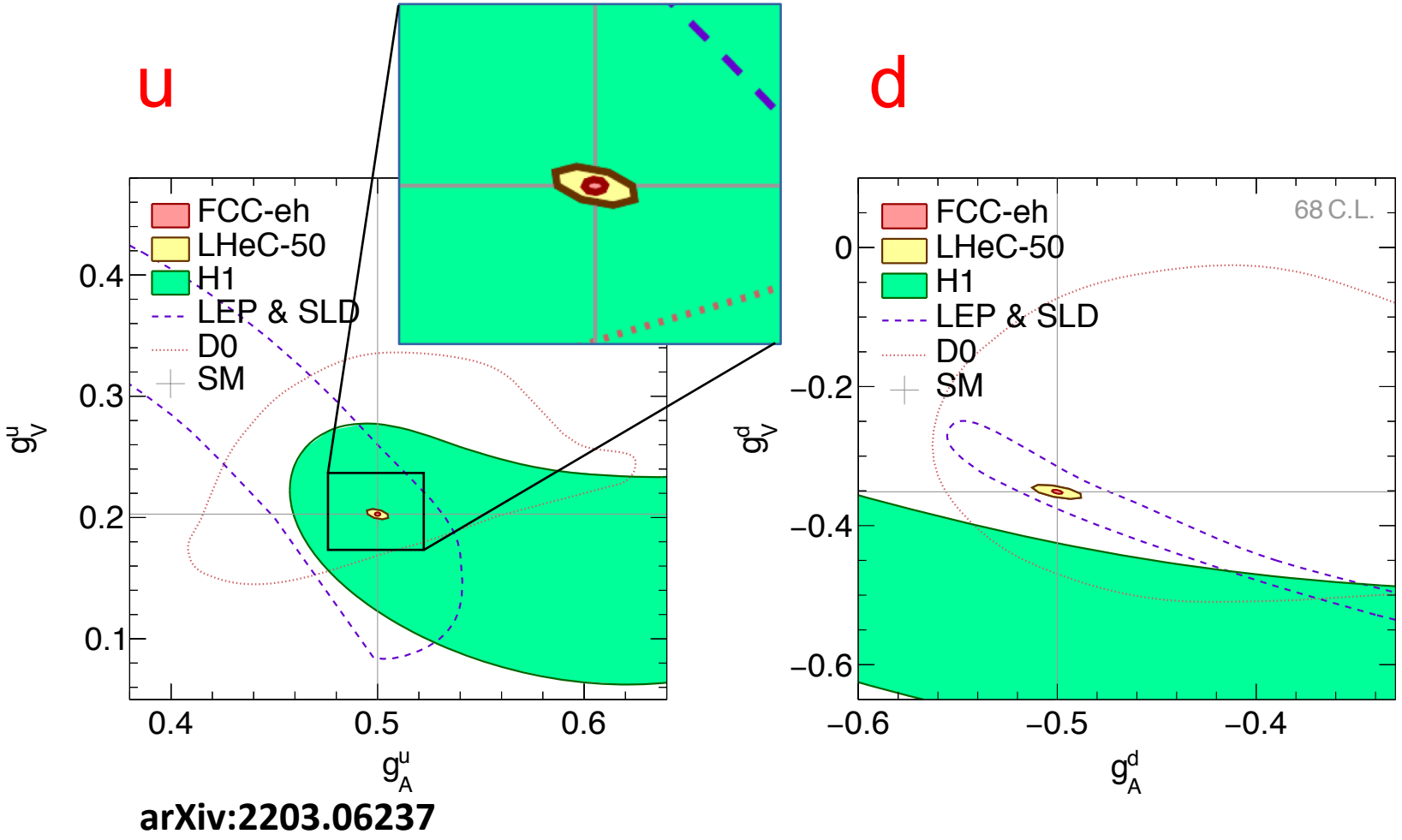


Δm_W(PDF):

± 8 MeV (CT10) → ± 3.6 MeV (HL-LHC) → **± 1.6 MeV (LHeC)**

Neutral Current DIS
Electroweak light-quark couplings



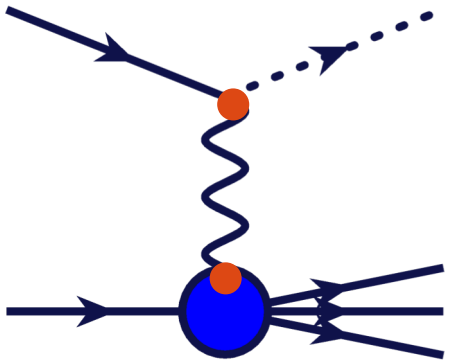


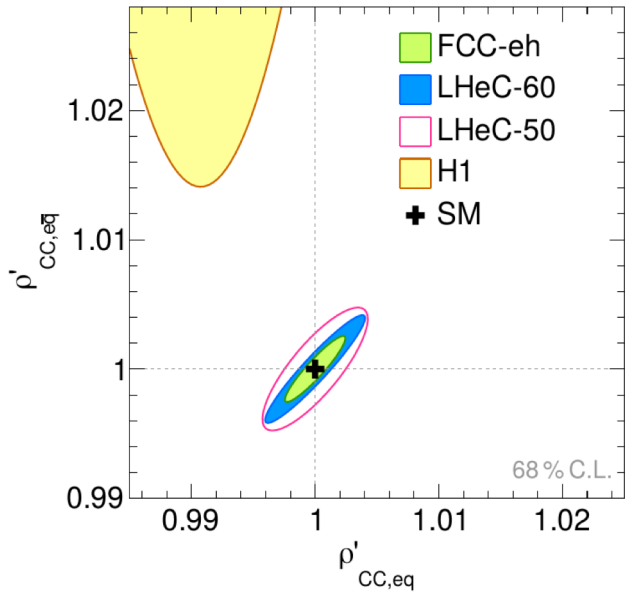
arXiv:2203.06237

- Precision per mille level – largely inaccessible in e+e-
- Complementary to lepton coupling
- PDFs are not a limiting factor for EW couplings
- Scale dependence ('running') can be tested with high precision

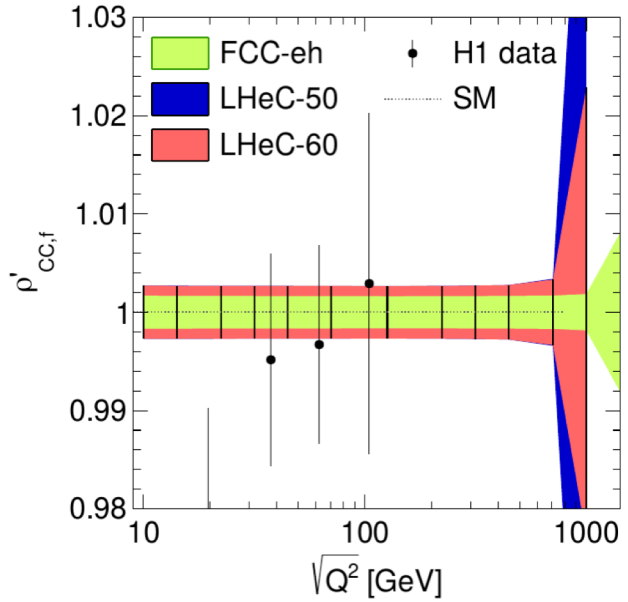
Anomalous form factors in Charged Current DIS

- EW theory provides precise predictions for charged currents, but they are poorly measured in other processes
  → neutrino escapes undetected



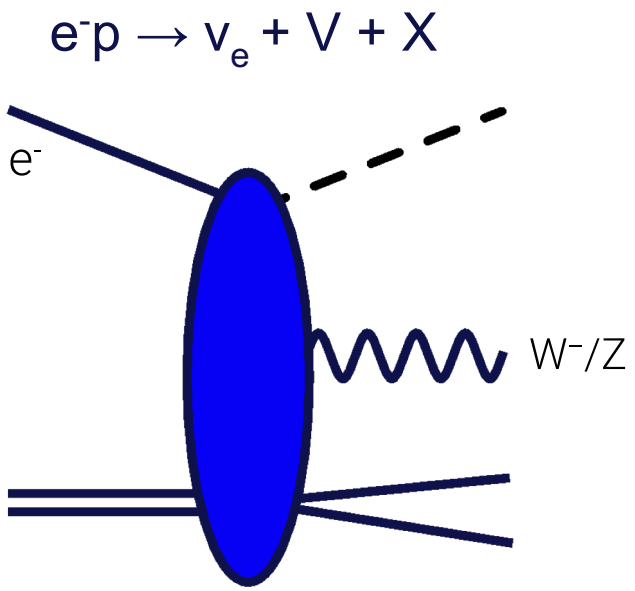


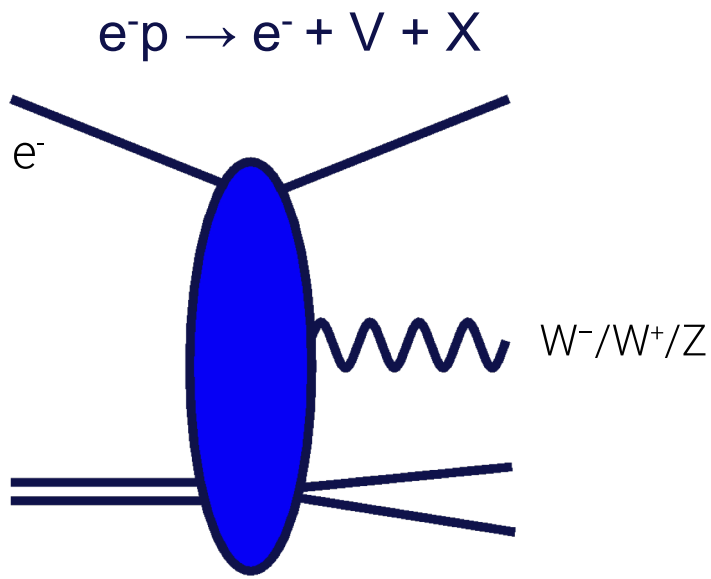
arXiv:2203.06237



- In DIS, the kinematics of charged currents are completely measured from final state and incoming electron
  → Weak couplings of the W-boson measured at a couple per mille level– even their scale dependence

Direct W and Z productions





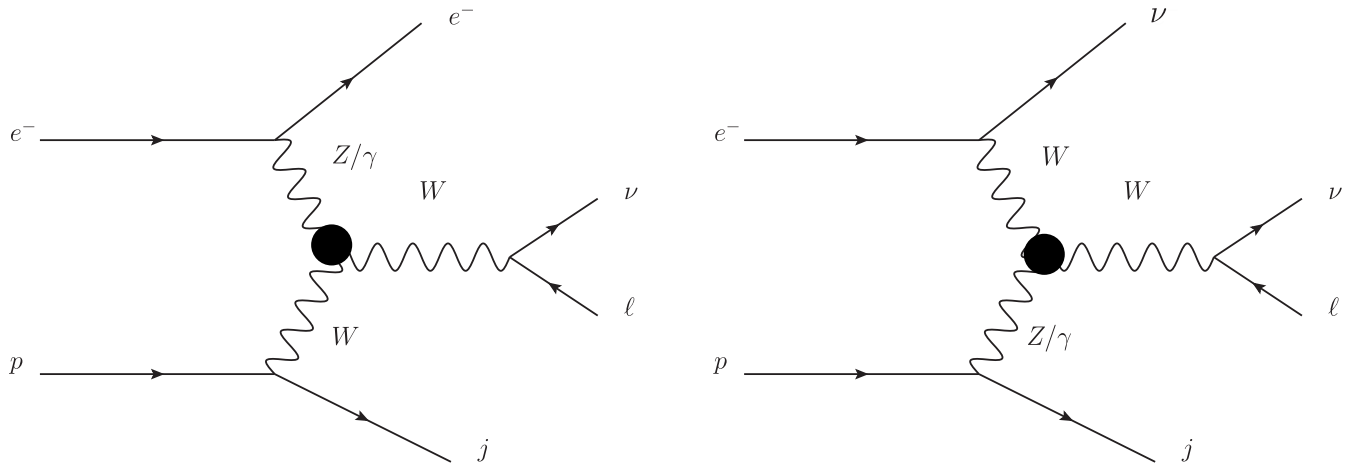
- Through 5 production channels
- Total cross sections: $\boldsymbol{\sigma}\,(e^-p \rightarrow \boldsymbol{W^-}X)$ ~ **15pb**

  $\boldsymbol{\sigma}\,(e^-p \rightarrow \boldsymbol{W^+}X)$ ~ **14pb**

  $\boldsymbol{\sigma}\,(e^-p \rightarrow \boldsymbol{Z}X)$ ~ **5pb**

Anomalous Triple Gauge Couplings

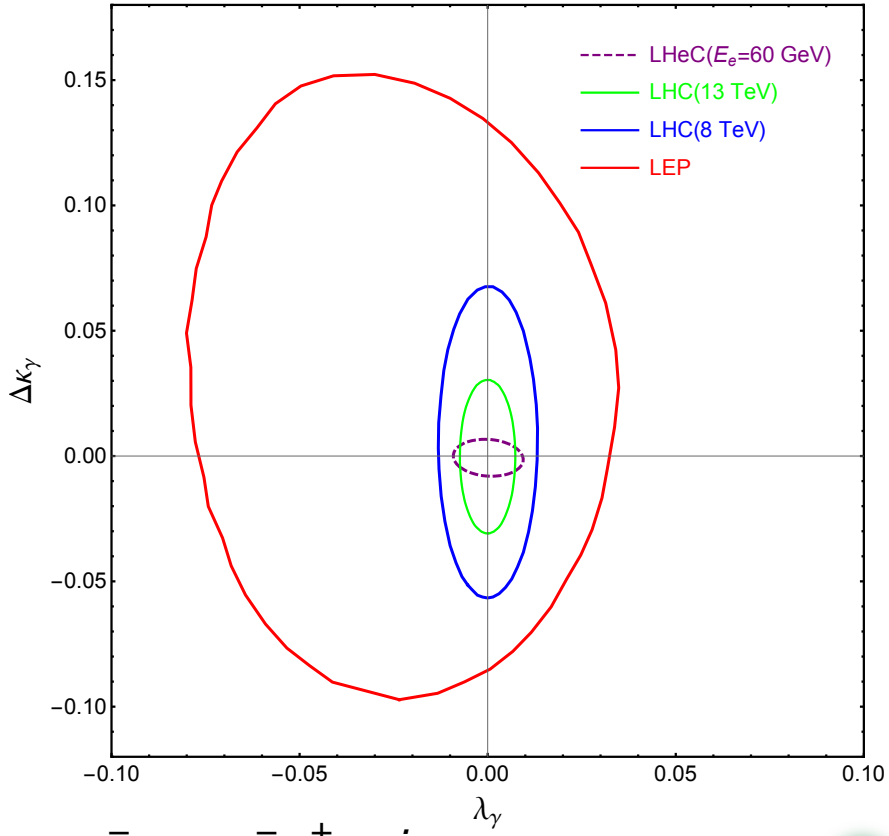
- 5 anomalous TGCs $[\Delta g_{1Z}, \Delta\kappa_V, \lambda_V]$
- 3 are independent



- Above Vector Boson Fusion process sensitive to WWγ couplings; WWZ suppressed due to Z mass (no interference)
- LHeC-60 significantly improves constraints on $\Delta\kappa_\gamma$

LHeC-60
1 ab^{-1}
2σ (95% C.L.)

NPB **375** (1992) 3, U. Baur, et al.
PRD **97** (2018) 075043, R. Li, et al.



$e^- p \to e^- \mu^+ \nu_\mu j$
χ^2analysis of $\Delta\phi_{ej}$ at parton level

Summary

- LHeC and FCC-eh
  - Energy frontier electron hadron collider
    with E_e = 50 GeV (LHeC) and 60 (FCC-eh) GeV
    synchronously run with HL-LHC (LHeC) and FCC-hh (FCC-eh)
- Top physics
  - Rich top-physics with single top production, photoproduction of top-quark pairs and FCNC
  - CKM third-row, MDM, EDM, electric charge, polarization, PDFs …
- Electroweak physics
  - Precision measurements of fundamental EW parameters
  - Weak mixing angle, W mass, anomalous couplings to light quarks and TGC
  - Unprecedented precise determination of PDFs using LHeC data needed at HL-LHC
  - Complementary to Z-pole and (planned) low energy data

Thank you!