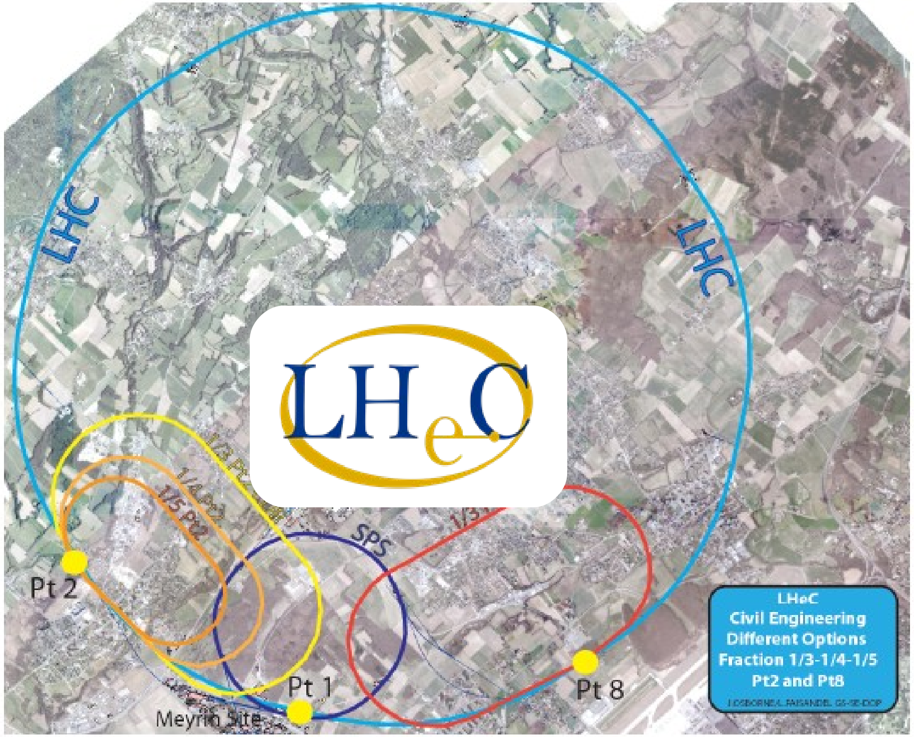
Top and electroweak physics at LHeC

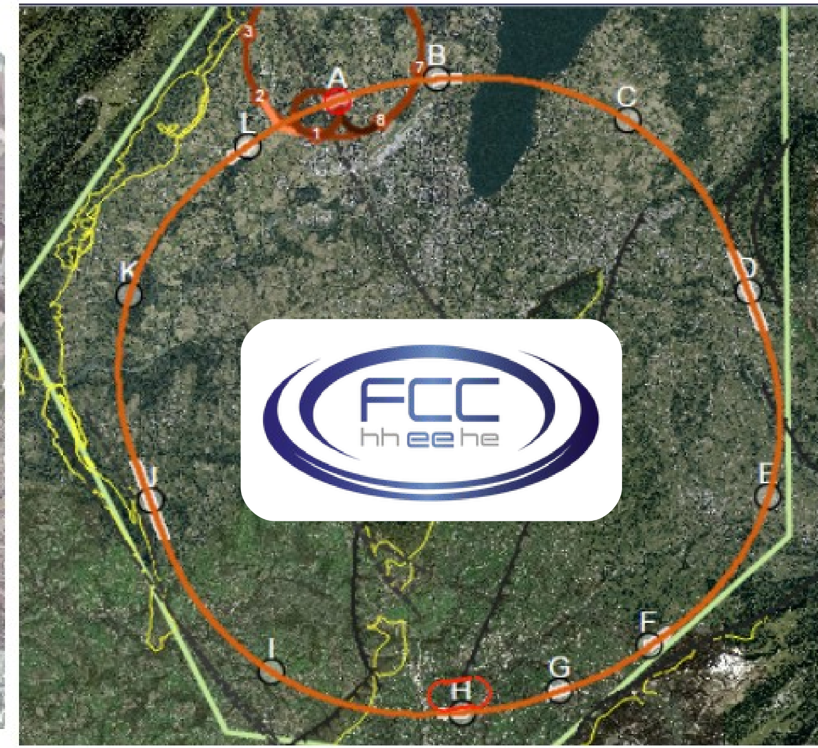
D. Britzger, S. Schwanenberger, et al.,
for the LHeC/FCC-eh EW+top group

DIS19, Torino, Italy
10.04.2019

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Future proposed ep-colliders: LHeC & FCC-eh





Electron ring

- Energy recovery linac: E_e = 60 GeV
- Polarisation up to P_e ~ 80%
- Similar concept for LHeC & FCC-eh

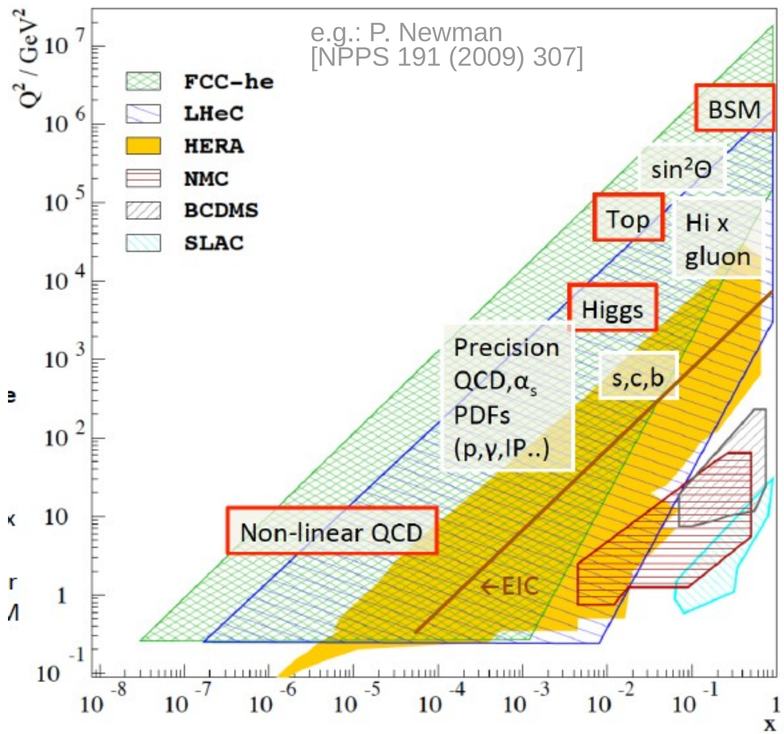
Center-of-mass energies

- LHeC: √s ~ 1.3 TeV
- FCC-eh: √s ~ 3.5 TeV
- Up to 1 ab^{-1} integrated luminosity

LHeC kinematic reach

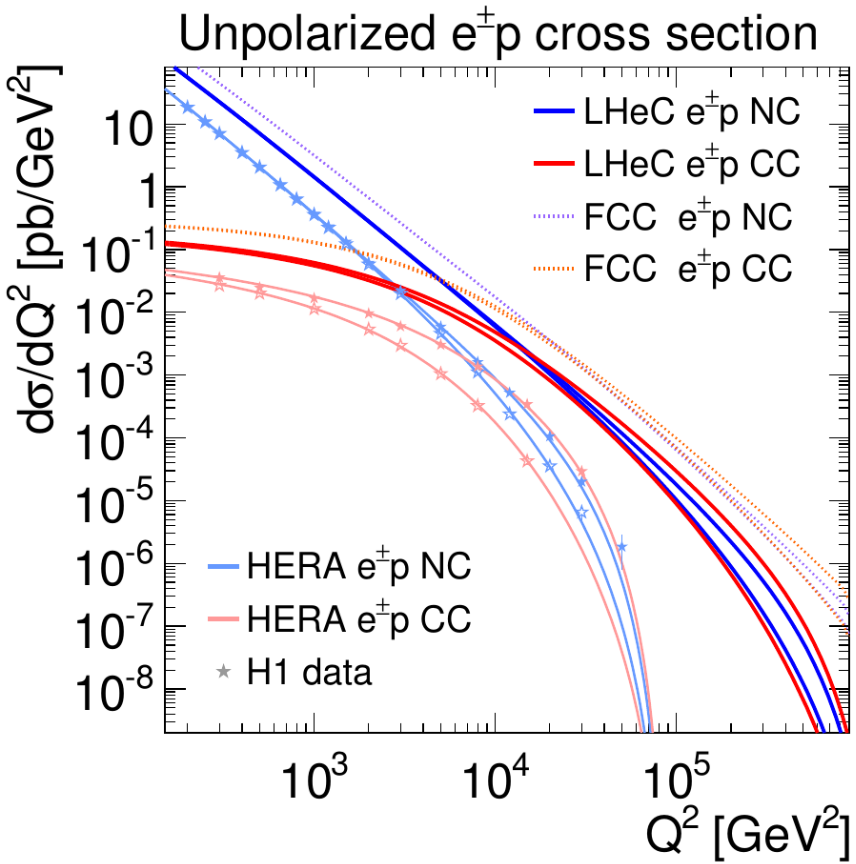
x-Q² plane

- Rich physics program at all scales
- Top and EW physics at higher scales: not accessible at HERA



Unpolarised ep cross section

- NC & CC DIS cross section vs. Q²



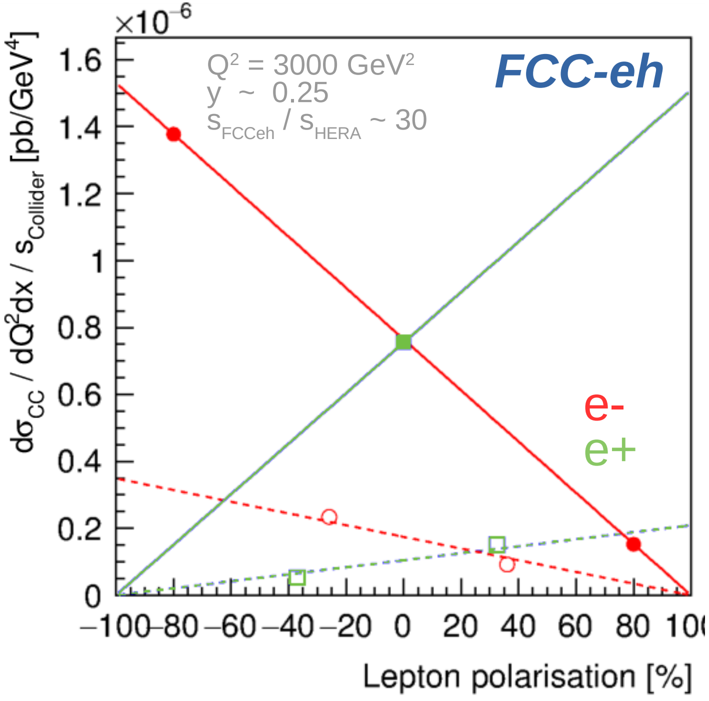
Huge liminosity of up to 3ab^{-1} further increases physics potential

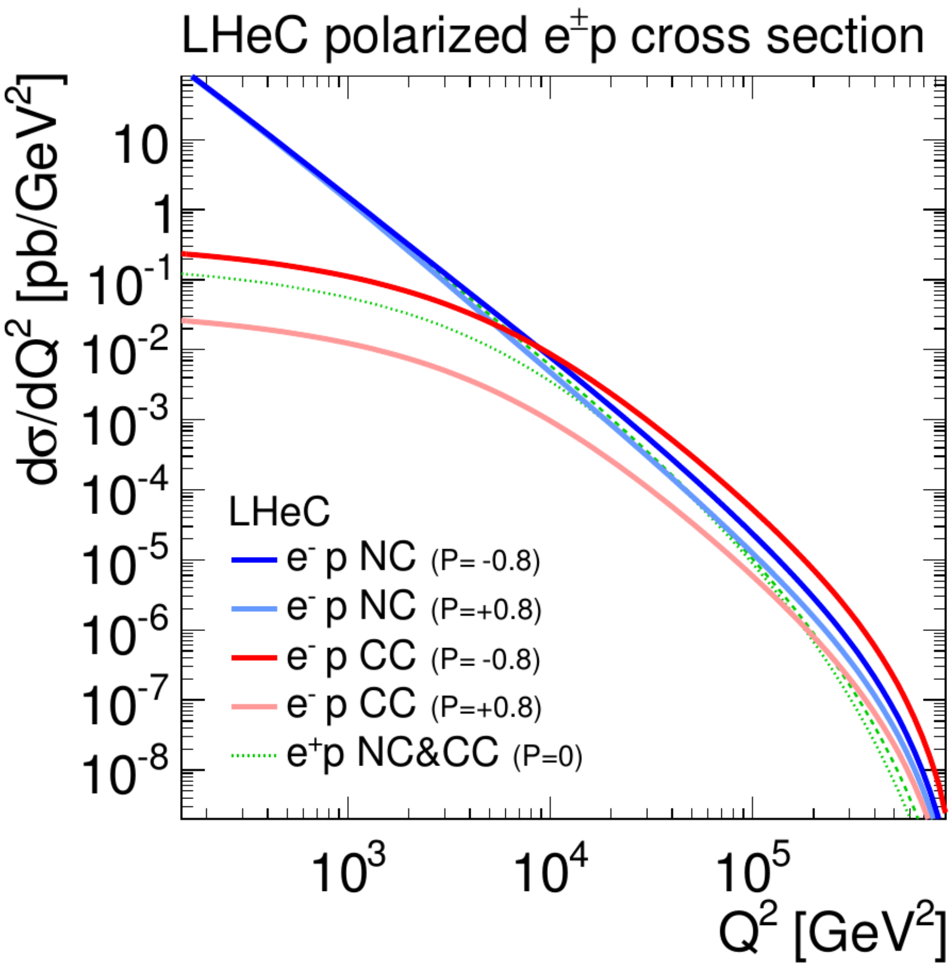
Polarized lepton beams at LHeC

LHeC/FCCeh running scenario

- e- +80%, -80% (1ab-1)
- e+ unpolarised lepton beam (0.3ab-1)

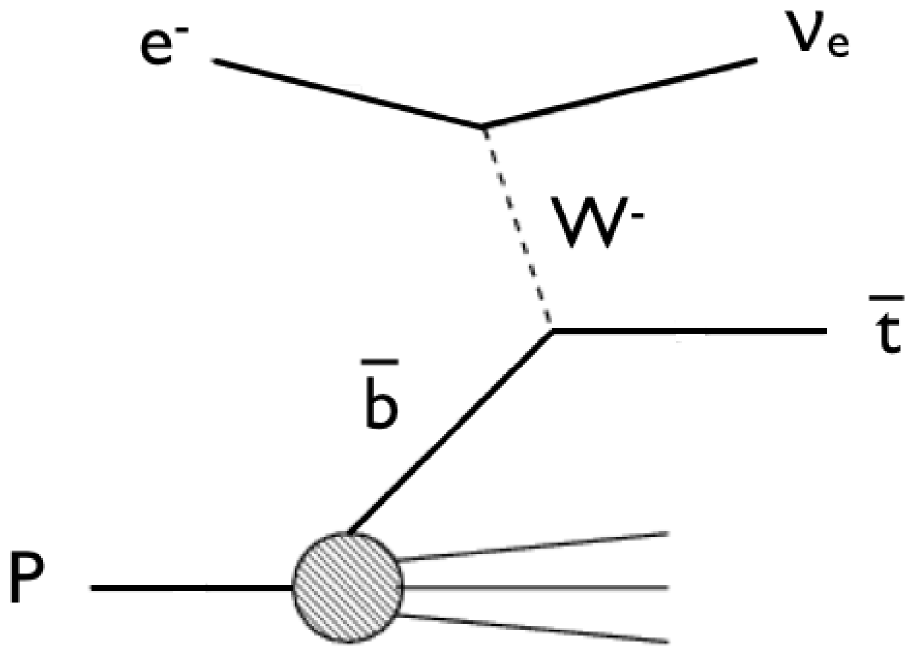
CC proportional to P_e





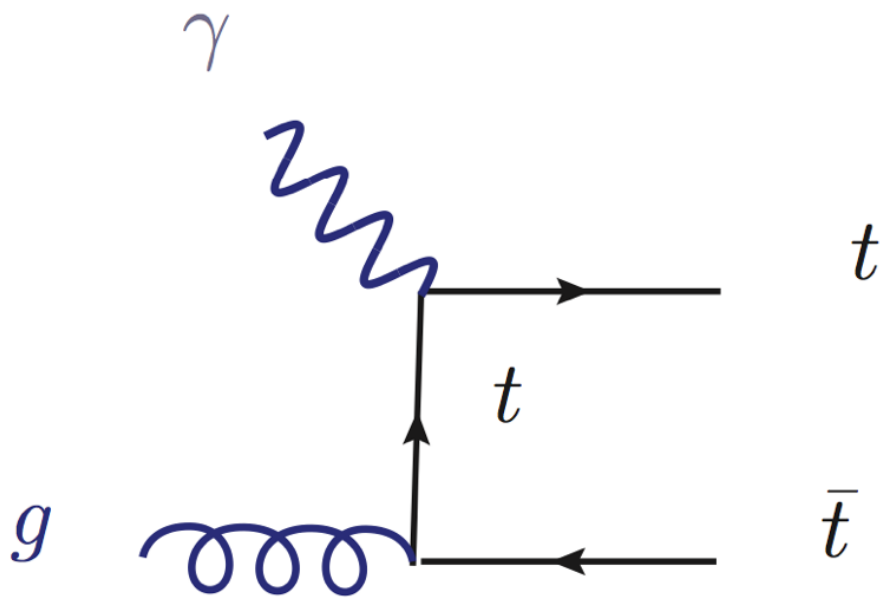
Introduction – top quark production in ep

CC DIS top quark production



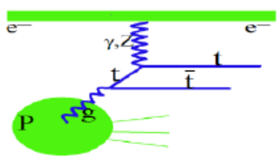
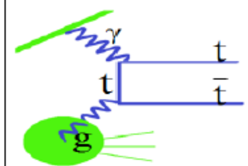
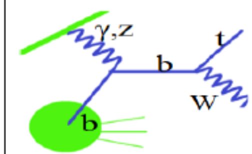
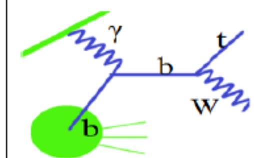
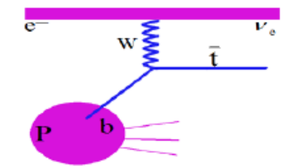
LHeC: σ_{tot}~1.9pb

NC (γp) top quark production



LHeC: σ_{tot} ~ 0.05pb

Introduction – top quark production in ep

		top pair			single top		
		NC		CC	NC		CC
		DIS	γp	W-exch.	DIS	γp	W-exch.
				–			
30GeV	7TeV	0.0040pb	0.0091pb		4.653fb	12.54fb	0.7599pb
40GeV	7TeV	0.0090pb	0.0205pb		9.193fb	24.16fb	1.1850pb
50GeV	7TeV	0.0165pb	0.0354pb		14.85fb	38.27fb	1.6270pb
60GeV	7TeV	0.0253pb	0.0531pb		21.37fb	54.31fb	2.0835pb
60GeV	50TeV	0.6268pb	1.1660pb		40.29fb	942.8fb	16.701pb

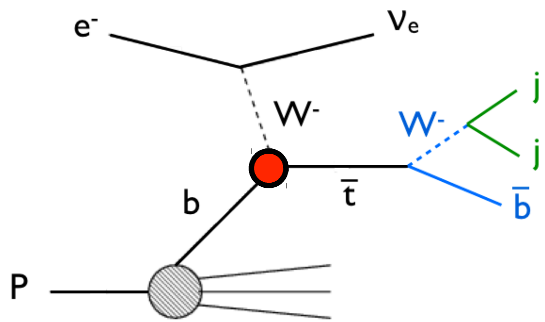
Hao Sun, 2018

- future ep collider is ideal to study EWK interactions of the top quark
- O(100k) top quark events are expected with 1ab^{-1}
- Low backgrounds: S/B(CC, leptonic) ~ 1.2; S/B(CC,hadronic) ~ 11

Dutta, Goyal, Kumar, Mellado,
Eur. Phys. J. C75 (2015) no.12, 577

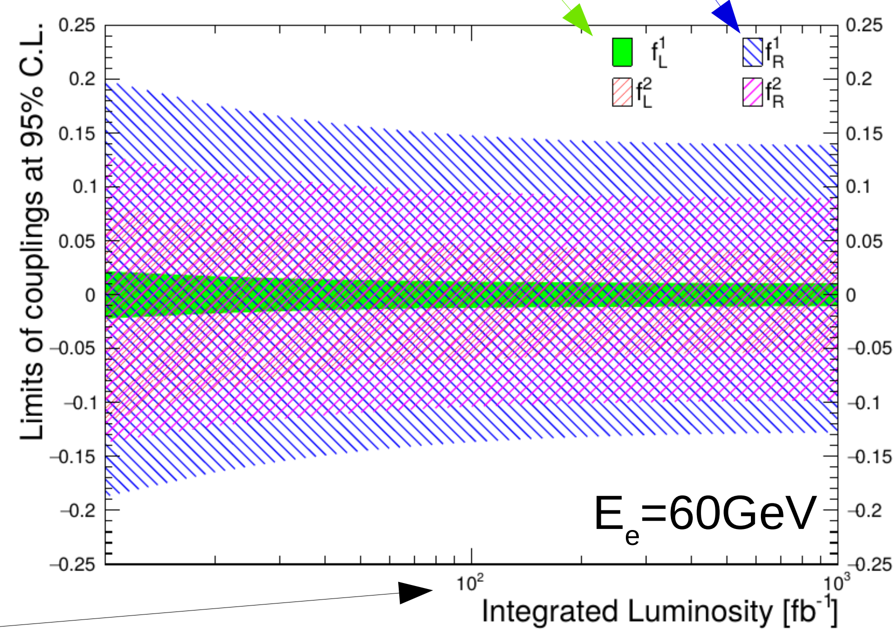
$|V_{tb}|$ in CC single-top production

Limits on anomalous Wtb couplings



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

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



- Fully hadronic channel
- cut-based analysis with backgrounds using Delphes

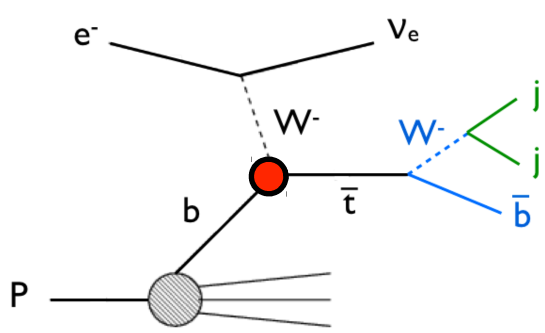
Estimated precision on V_{tb}

- V_{tb}: up to 1% precision (with L=100 fb^{-1})
- anomalous Wtb couplings at 95%CL in fully hadronic events

See: S. Dutta, et al. Eur.Phys.J. C75 (2015) 577; S. Dutta et al. in prep.

$|V_{tb}|$ in CC single-top production

Limits on anomalous Wtb couplings



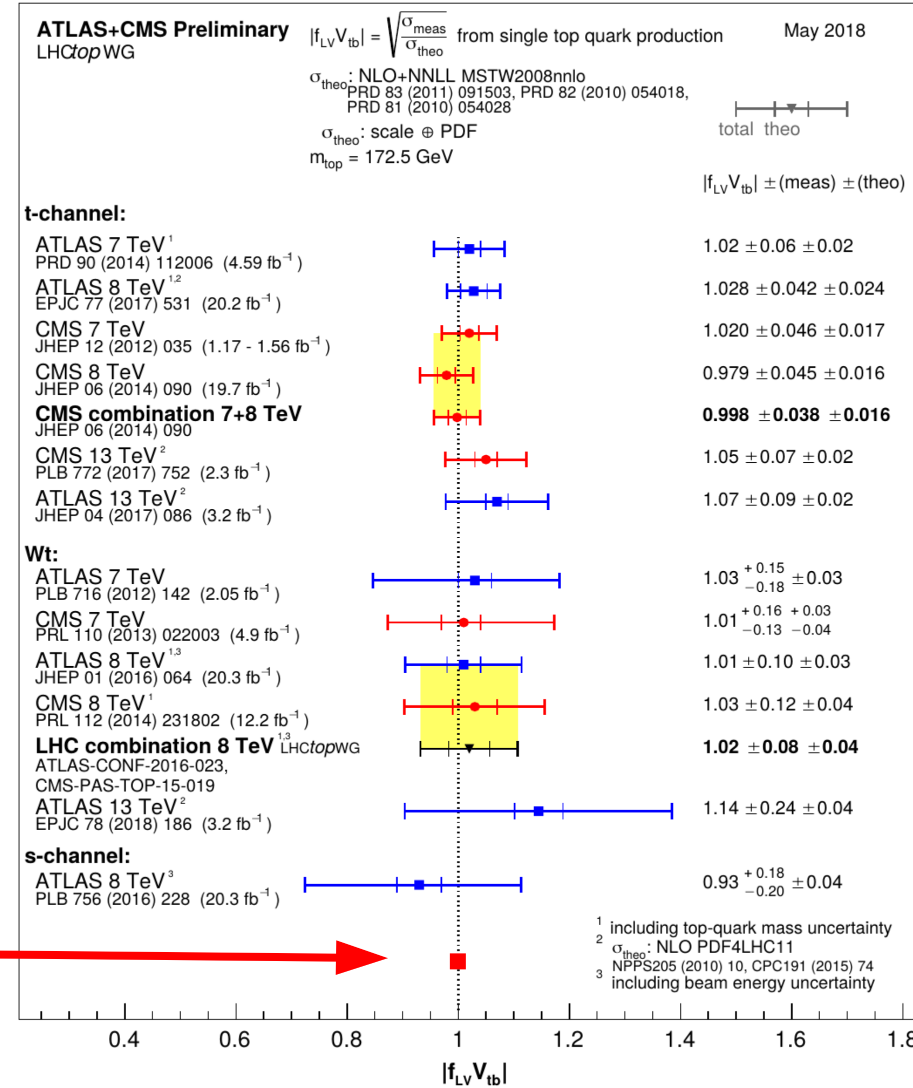
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Fully hadronic channel
-

Estimated precision on V_{tb}

- V_{tb}: up to 1% precision (with L=100 fb^{-1})

LHeC



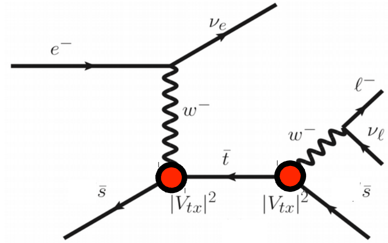
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

$|V_{td}|$ and $|V_{ts}|$ in CC single-top production

Measurement of $|V_{td}|$

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

$$\text{Signal.1}: \quad pe^- \to \nu_e \bar{t} \to \nu_e W^- \bar{b} \to \nu_e \ell^- \nu_\ell \bar{b},$$
$$\text{Signal.2}: \quad pe^- \to \nu_e W^- b \to \nu_e \ell^- \nu_\ell b,$$
$$\text{Signal.3}: \quad pe^- \to \nu_e \bar{t} \to \nu_e W^- j \to \nu_e \ell^- \nu_\ell j,$$
$$\text{Signal.4}: \quad pe^- \to \nu_e W^- j \to \nu_e \ell^- \nu_\ell j.$$

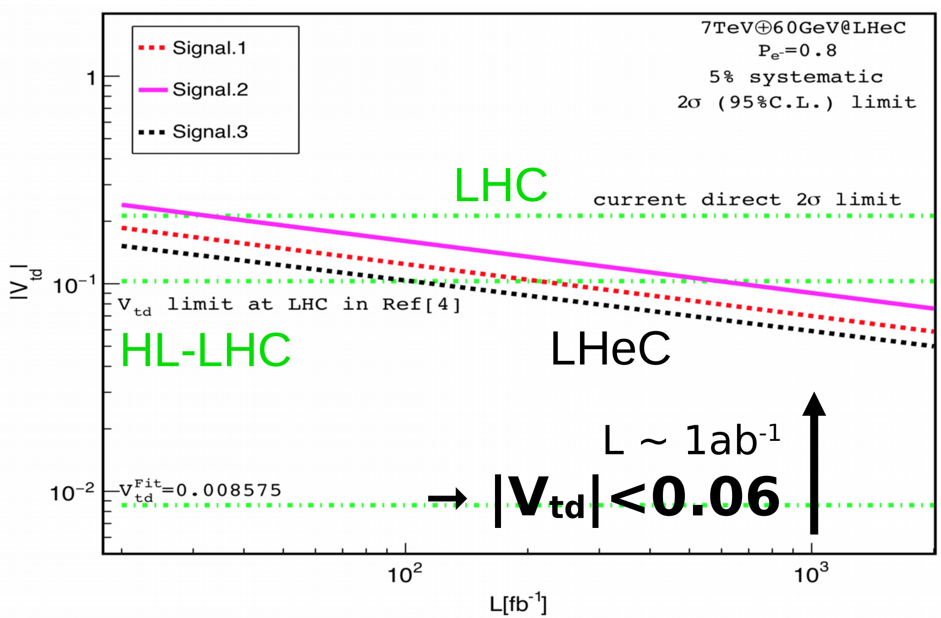


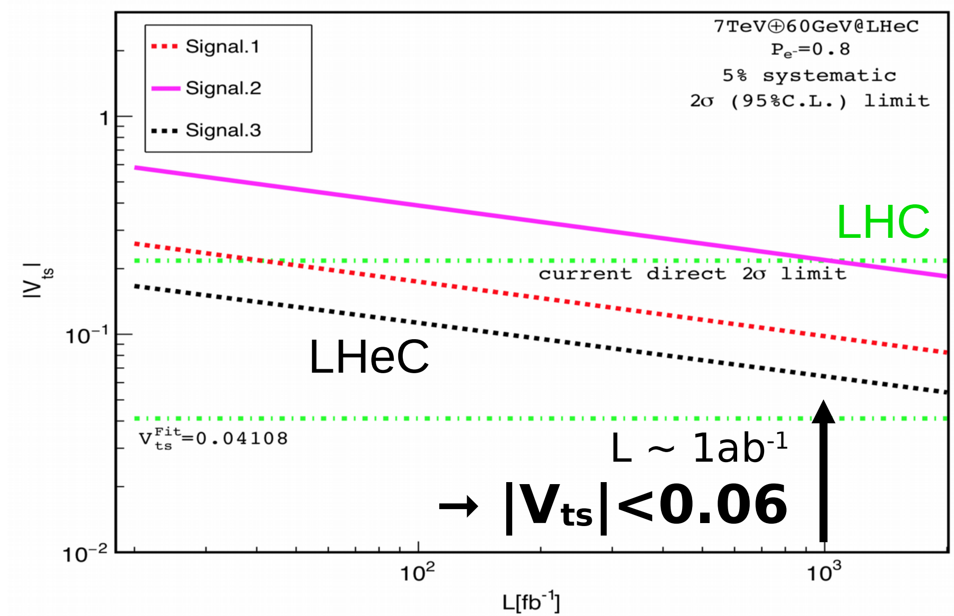
Measurement of $|V_{ts}|$

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

- simplified analysis, using 4 signal channels

Hao Sun, to be publ.



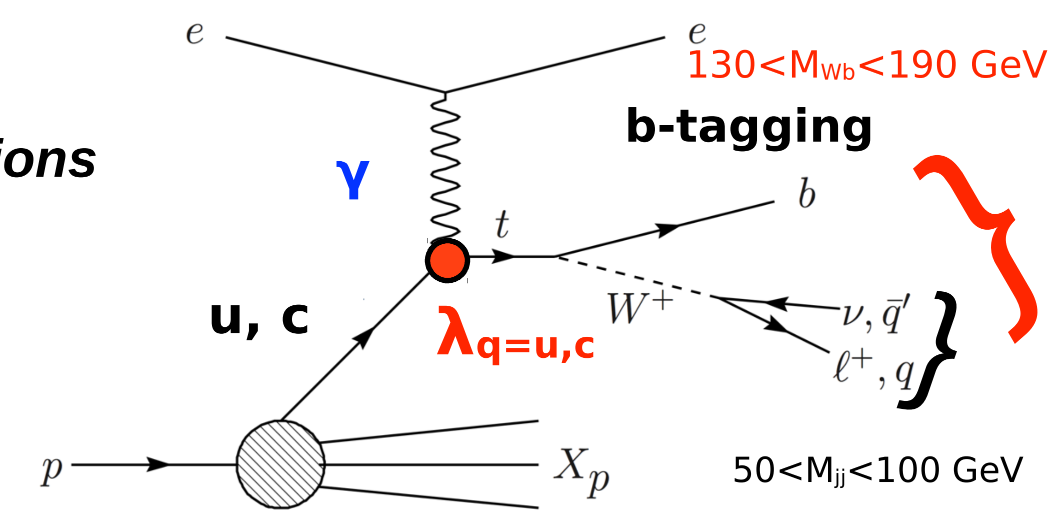


Search for anomalous FCNC

Top quark flavor changing neutral currents (FCNC)

I. Cakir, Yilmaz, Denizli, Senol, Karadeniz, O. Cakir, Adv. High Energy Phys. 2017, 1572053 (2017)

→ Extremely suppressed in SM



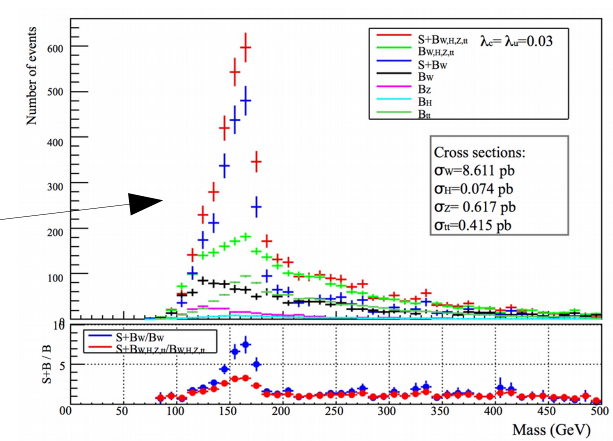
Enhancement through BSM contributions

→ effective Lagrangian

$$L = -g_e \sum_{q=u,c} Q_q \frac{\lambda_q}{\Lambda} \bar{t}\sigma^{\mu\nu}(f_q + h_q\gamma_5)qA_{\mu\nu} + h.c.$$

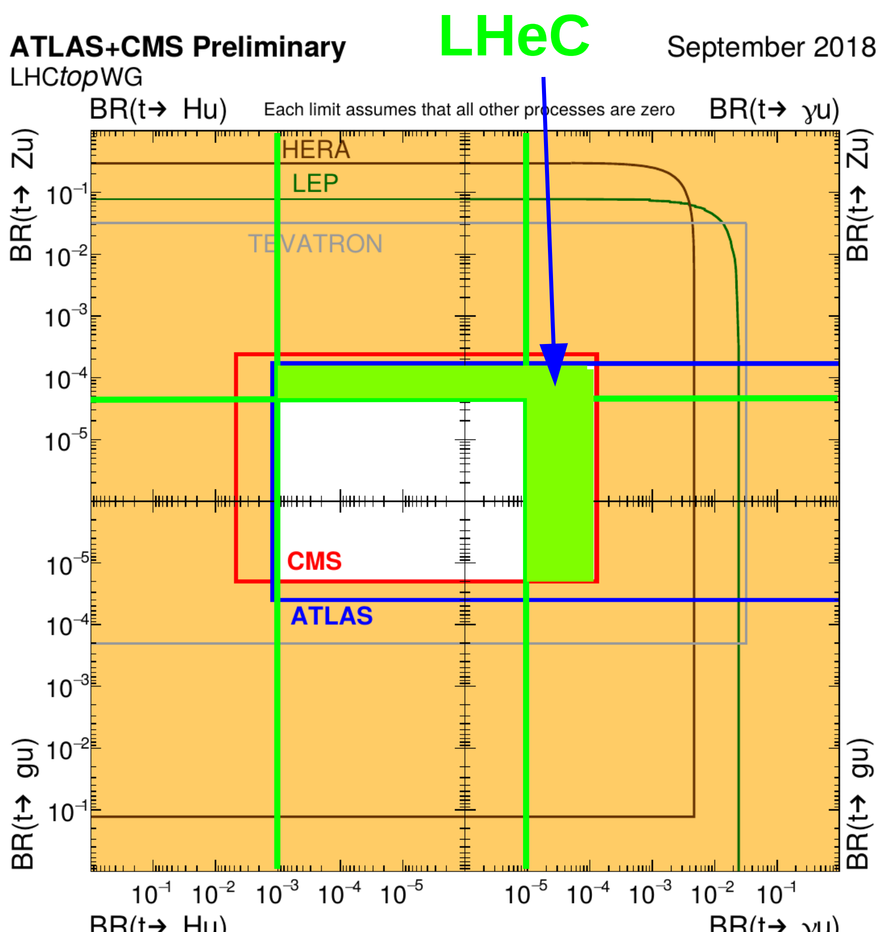
Study tqγ and tqZ effective FCNC

- Full event simulation including DELPHES detector simulation and background contributions is performed



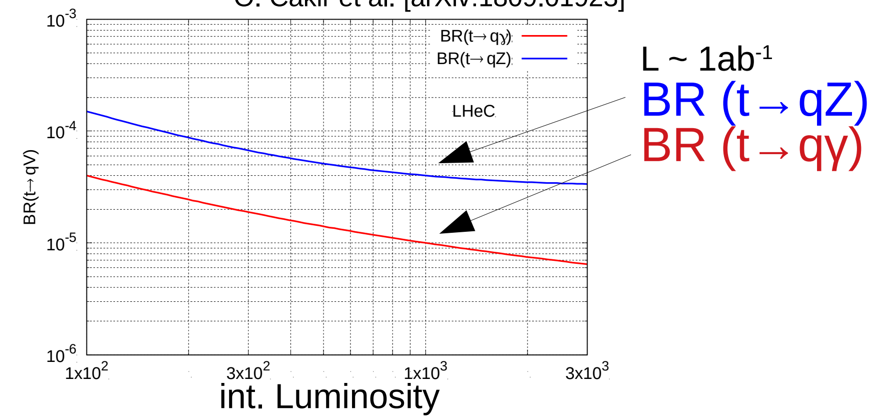
Search for anomalous FCNC

LHeC put on present landscape

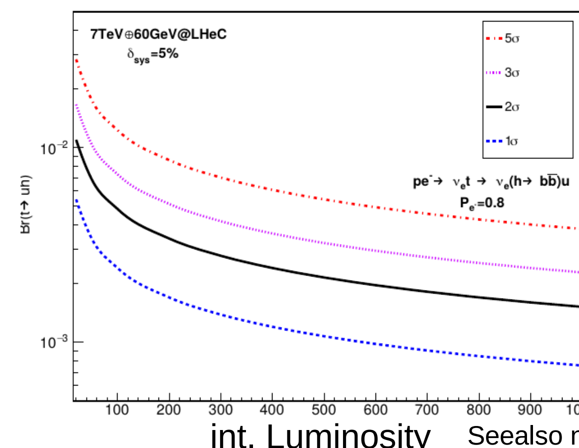


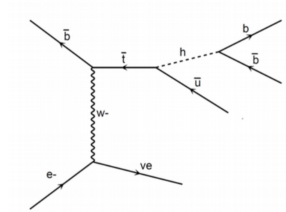
LHeC expected limits vs. int. Lumi

O. Cakir et al. [arXiv:1809.01923]



Sun, Luo, Li, Eur. Phys. J. C (2018) 78





BR(t->uh)

Seealso new study: S. Behera et al. [arXiv:1811.04681]

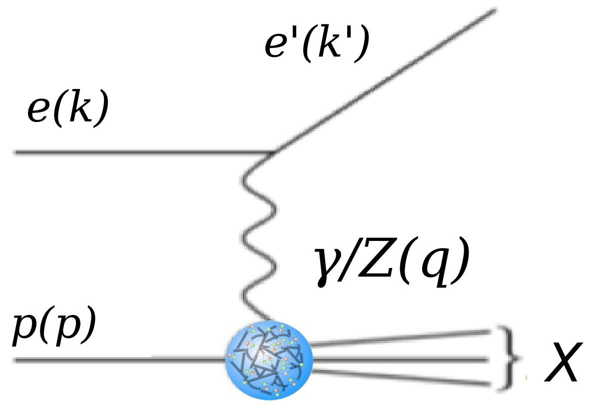
Electroweak physics

Exploit simulated NC and CC DIS data

- Equivalent to PDF prospects

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E_e'/E_e'$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

Neutral current scattering

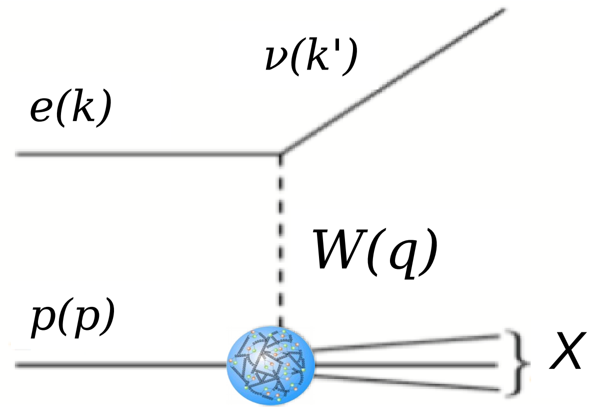


Neutral currents

$$\tilde{F}_2^{\pm} = F_2 - (g_V^e \pm P_e g_A^e)\varkappa_Z F_2^{\gamma Z} + [(g_V^e g_V^e + g_A^e g_A^e) \pm 2P_e g_V^e g_A^e]\,\varkappa_Z^2 F_2^Z \,,$$
$$\tilde{F}_3^{\pm} = \quad -(g_A^e \pm P_e g_V^e)\varkappa_Z F_3^{\gamma Z} + [2g_V^e g_A^e \pm P_e(g_V^e g_V^e + g_A^e g_A^e)]\,\varkappa_Z^2 F_3^Z \,,$$

$$\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q \left[Q_q^2, 2Q_q g_V^q, g_V^q g_V^q + g_A^q g_A^q\right]\{q + \bar{q}\}$$
$$x\left[F_3^{\gamma Z}, F_3^Z\right] = x\sum_q \left[2Q_q g_A^q, 2g_V^q g_A^q\right]\{q - \bar{q}\}\,.$$

Charged current scattering



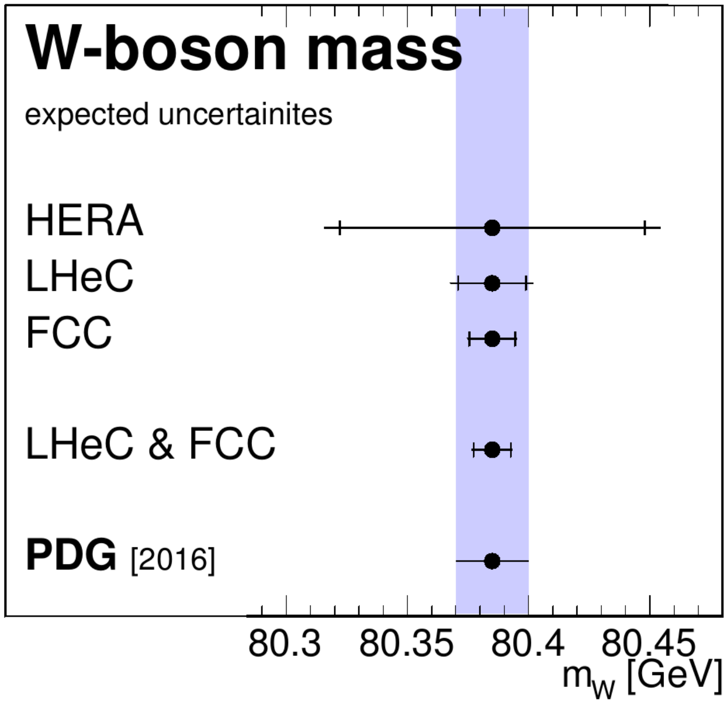
Charged currents

$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = (1 \pm P_e)\,\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2 + Q^2}\right]^2 \left(Y_+ W_2^{\pm}(x,Q^2) \mp Y_- x W_3^{\pm}(x,Q^2) - y^2 W_L^{\pm}(x,Q^2)\right)$$

Mass parameters

Mass parameter determination

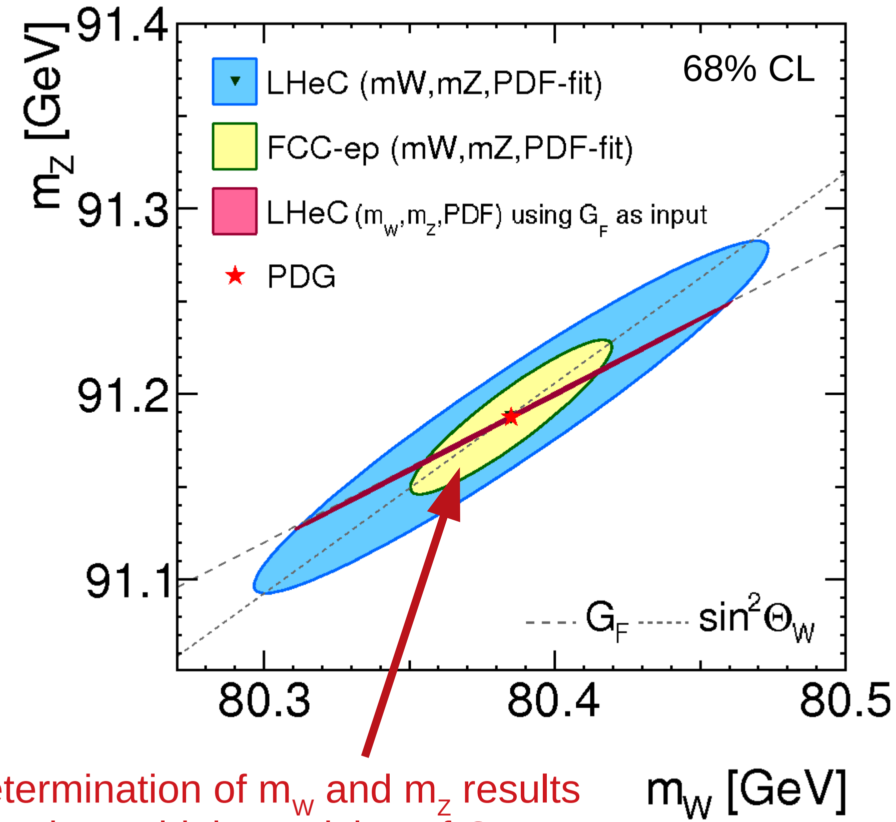
- Perform fits of PDFs+m_W



- W-mass: Δm_W ~ 10MeV

Simultaneous W and Z-boson mass

- with and w/o contraint by G_F



Simultaneous determination of m_W and m_Z results in very thin ellipse due to high precision of G_F

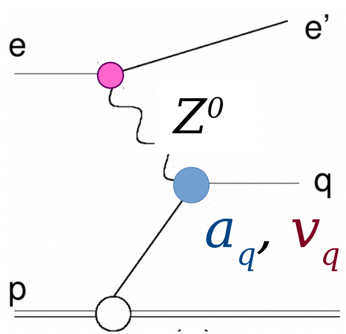
G_F=1.1663787(6) x 10^{-5} GeV^2

Weak neutral current couplings: light-quarks

Weak neutral-current coupling

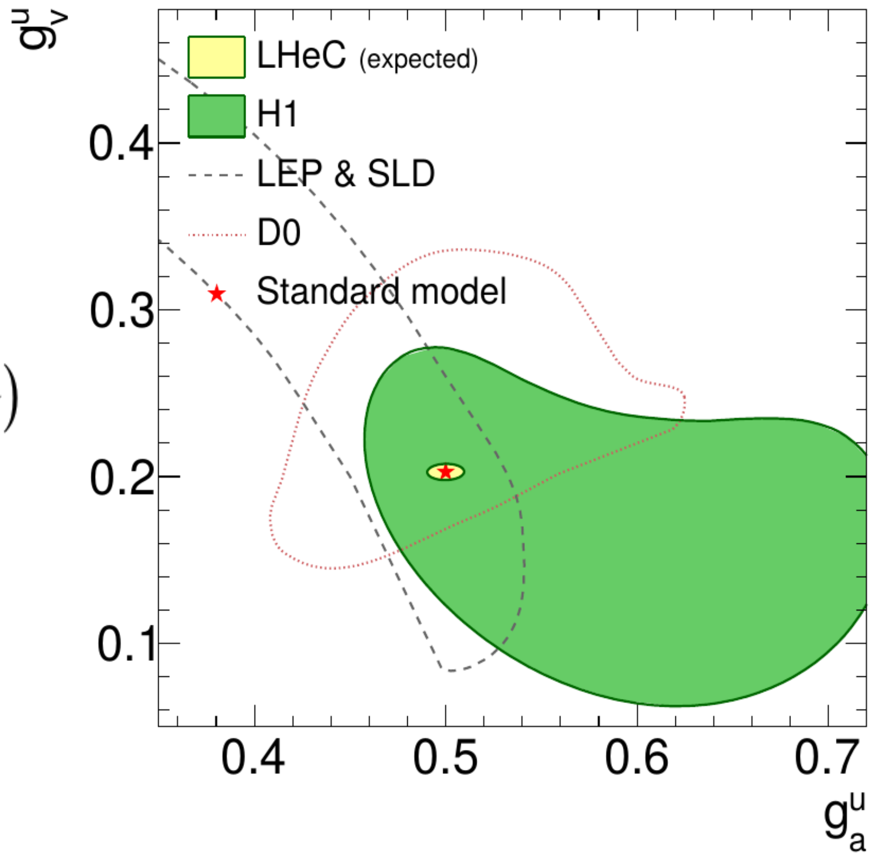
- Perform fit of PDFs+electroweak parameters

Couplings given by EW theory



$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}} I^3_{\mathrm{L},q} ,$$
$$g_V^q = \sqrt{\rho_{\mathrm{NC},q}} \left(I^3_{\mathrm{L},q} - 2 Q_q \kappa_{\mathrm{NC},q} \sin^2\theta_W \right)$$

At tree level: ρ,κ=1



Couplings for 'u-type' and 'd-type' quarks

- Here: fit of PDFs+g_A^u+g_V^u+g_A^d+g_V^d
  → conservative estimate

ρ and κ parameters

Beyond tree-level approximation

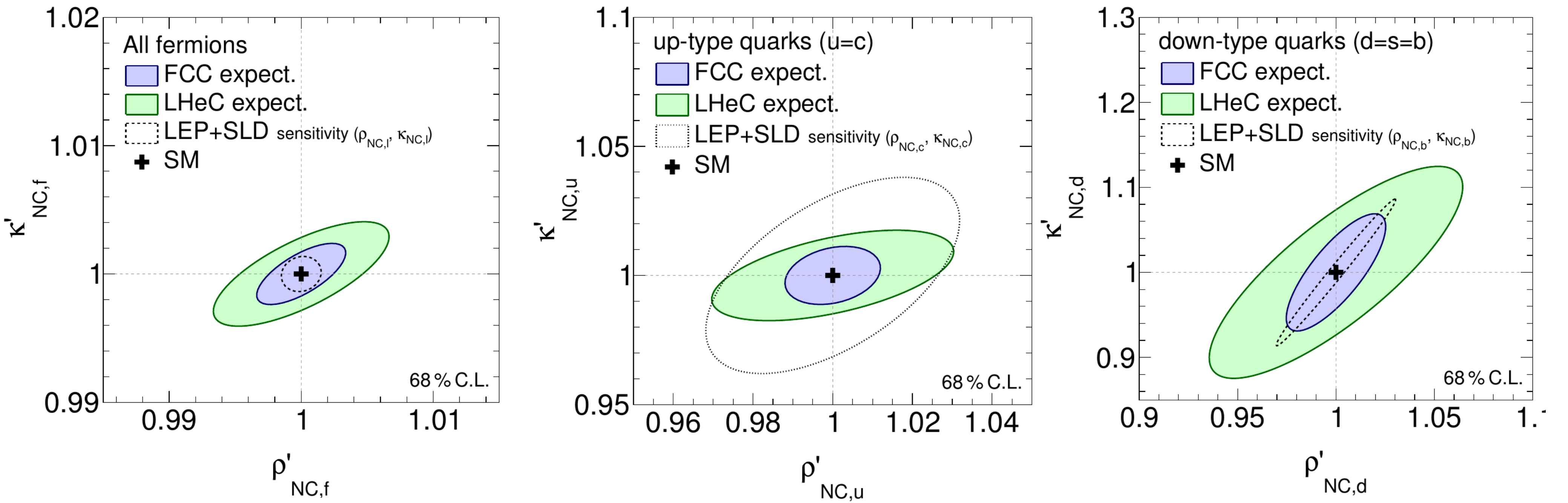
$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}} I_{\mathrm{L},q}^3 ,$$
$$g_V^q = \sqrt{\rho_{\mathrm{NC},q}} \left(I_{\mathrm{L},q}^3 - 2 Q_q \kappa_{\mathrm{NC},q} \sin^2\theta_W \right)$$

- Couplings are scale-dependent

Study non-standard form factors

$$\rho_{\mathrm{NC}} \rightarrow \rho'_{\mathrm{NC}} \rho_{\mathrm{NC}} ,$$
$$\kappa_{\mathrm{NC}} \rightarrow \kappa'_{\mathrm{NC}} \kappa_{\mathrm{NC}} ,$$

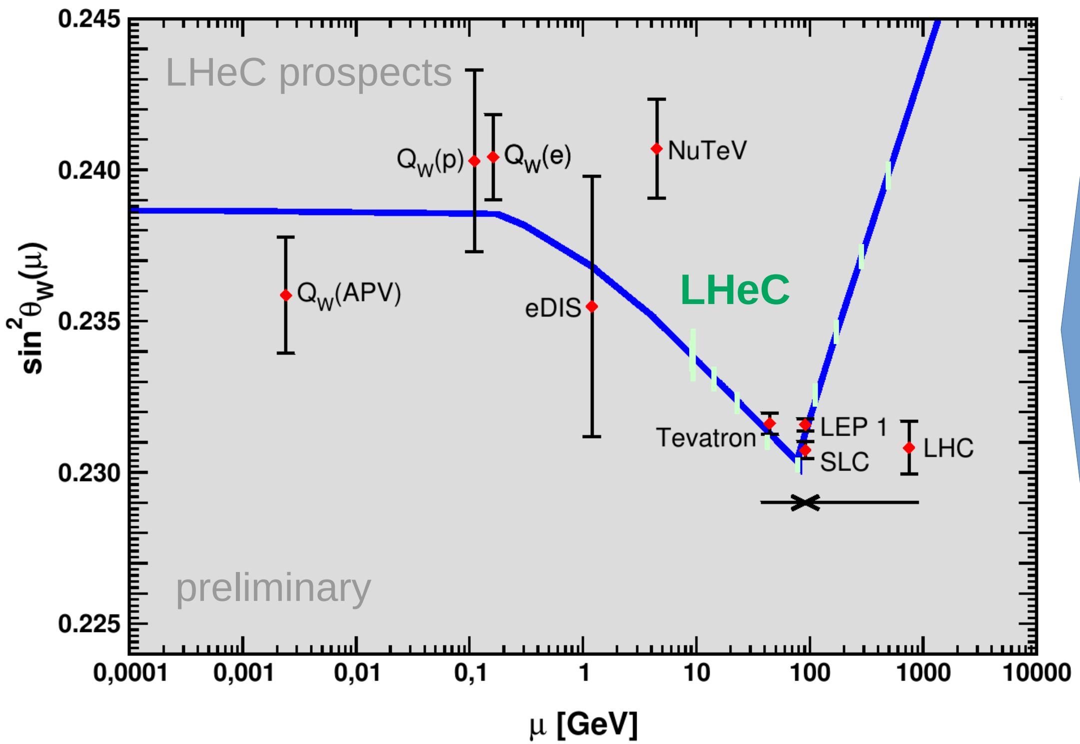
- Sensitivity similar to LEP+SLD combination, albeit comlementary sensitivity (light quarks)



Weak mixing angle $\sin^2\theta_w$

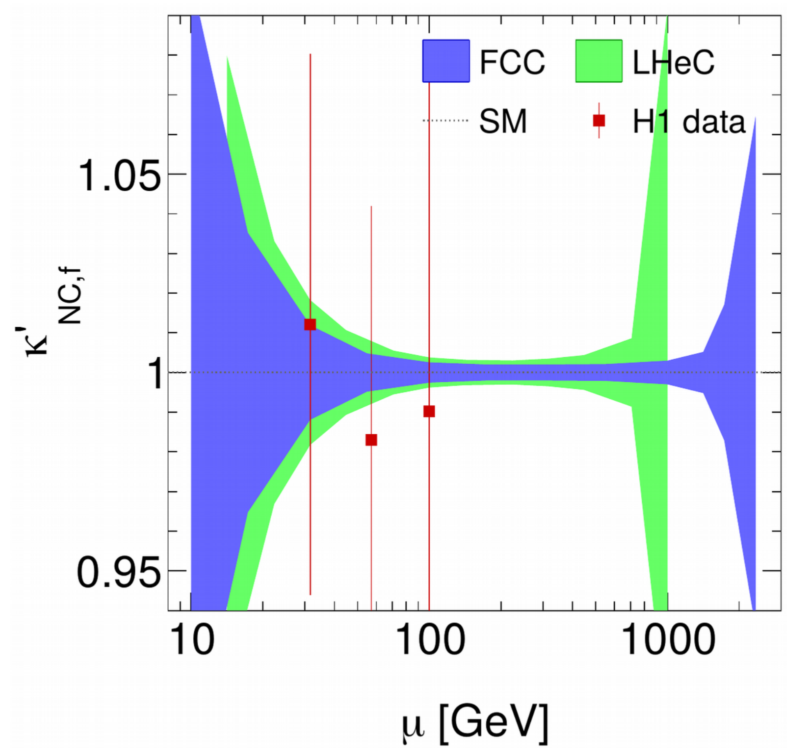
Effective weak mixing angle

- (charged leptons) in MSbar scheme



Scale dependence of κ' parameter

- Here: OS scheme, f=fermions



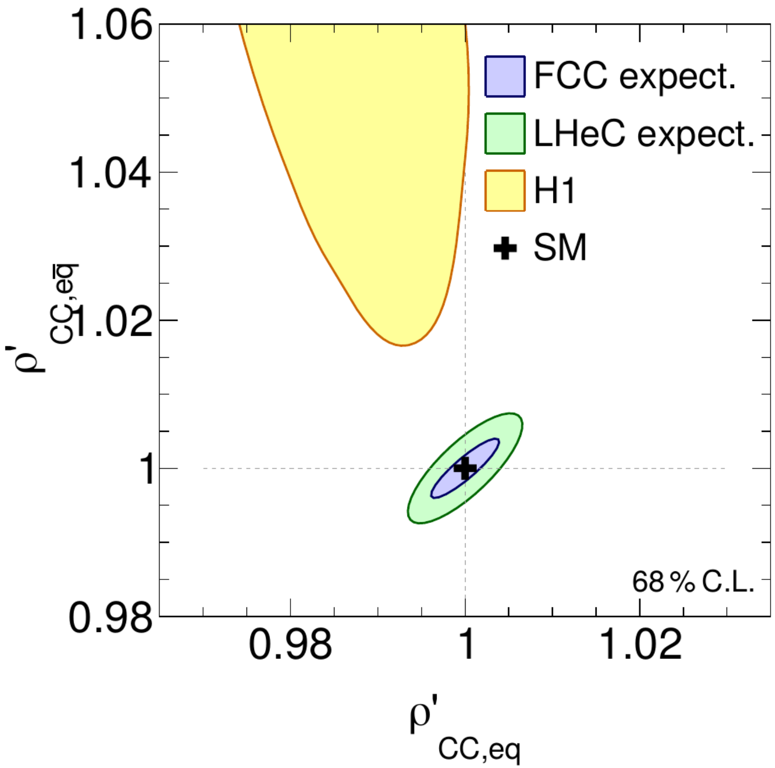
Weak mixing angle ($\sin^2\theta_w^{lept.}$) measureable over wide kinematic range with O(0.1%) precision at LHeC

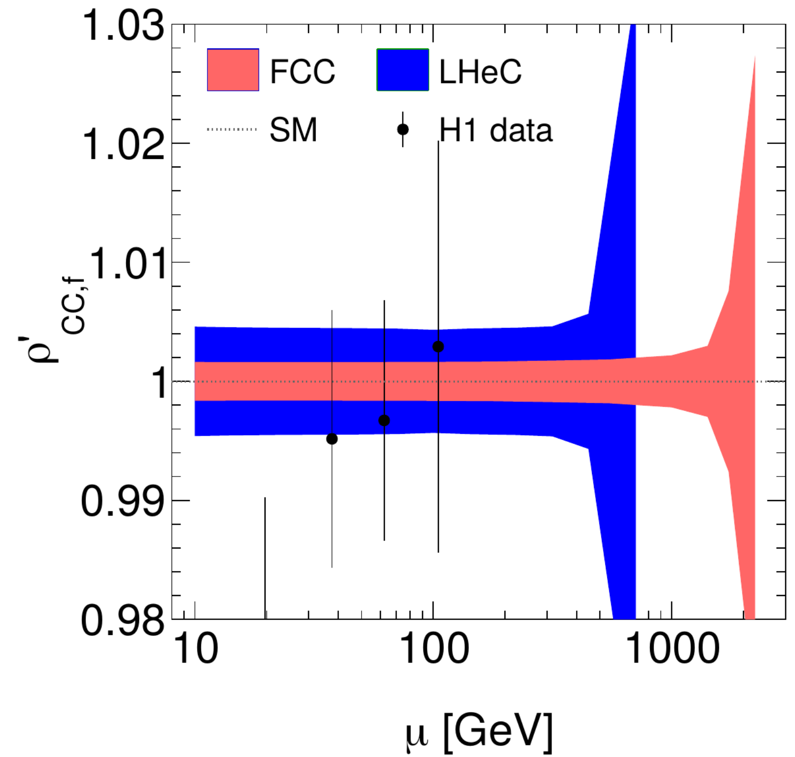
EW physics – charged currents

Unique test of virtual corrections in charged current interactions

- Precision better than 1% achievable at LHeC
- Wide kinematic range, and high precision
- non-SM physics will introduce systematic deviation ρ'_{CC}

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

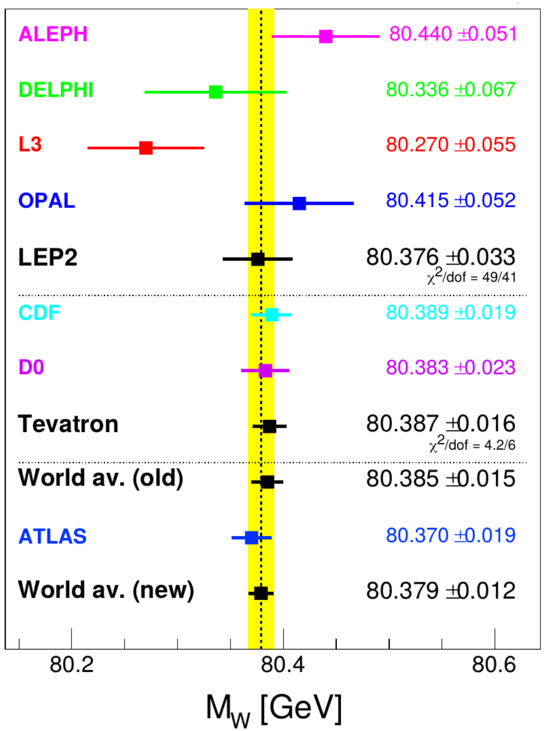




W-mass at (HL)-LHC

W-mass measurement @LHC

- Precision limited by PDFs (Δm_W^{PDF}~9.2MeV)



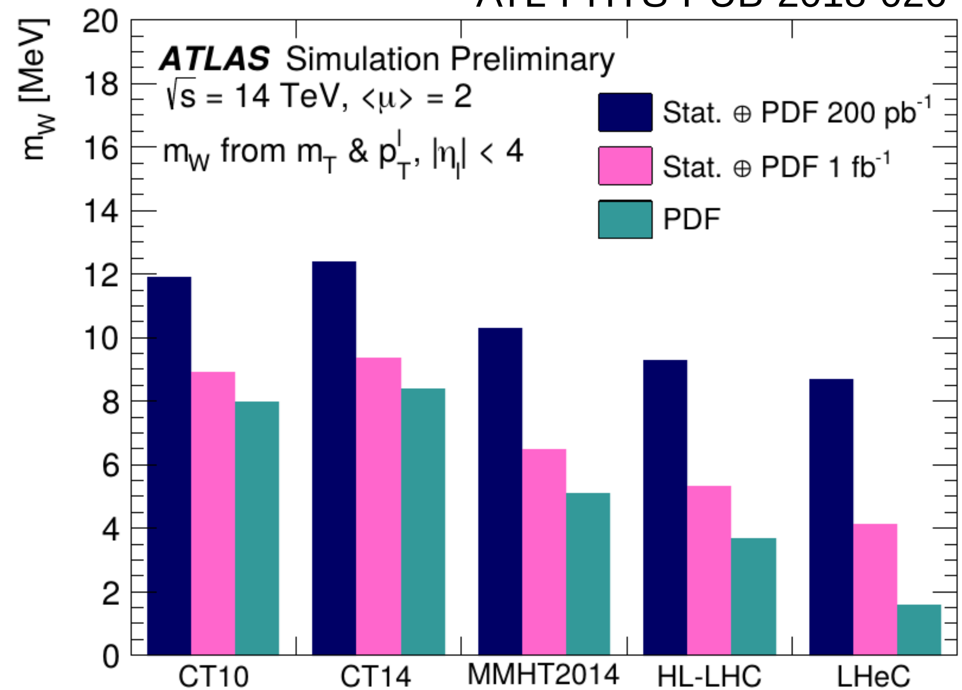
Eur. Phys. J. C 78 (2018) 110; PDG (2017)

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27

Future W-mass measurements in pp

- Major reduction of PDF uncertainty only feasible with LHeC PDFs (Δm_W^{PDF}~2MeV)

ATL-PHYS-PUB-2018-026

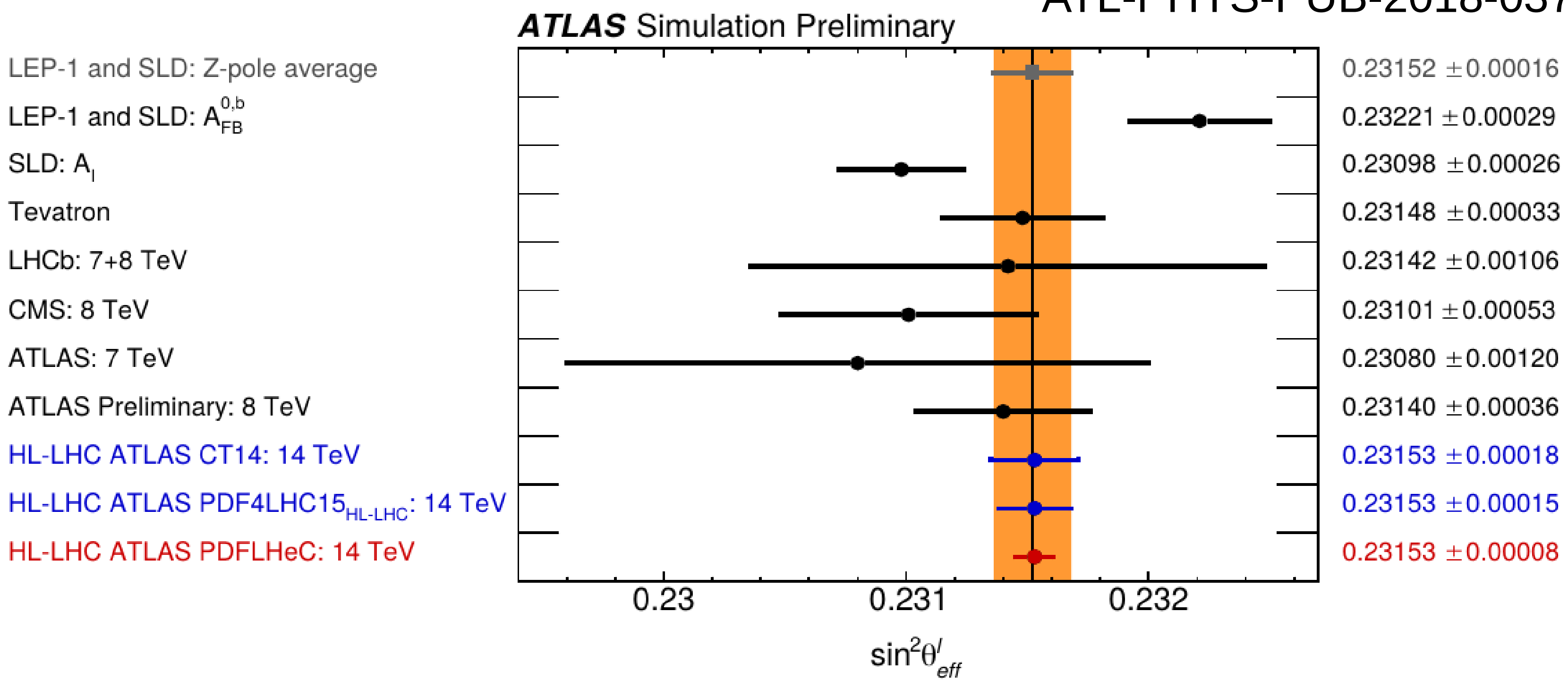


Effective weak mixing angle

Effective weak mixing angle at Z-pole

- Precision test of EW theory

ATL-PHYS-PUB-2018-037



- Data from HL-LHC can reduce PDF uncertainty by 10-25%
- Data from LHeC have potential to reduce PDF uncertainties by an additional factor of 5

EW higher-orders in DIS for PDF fits

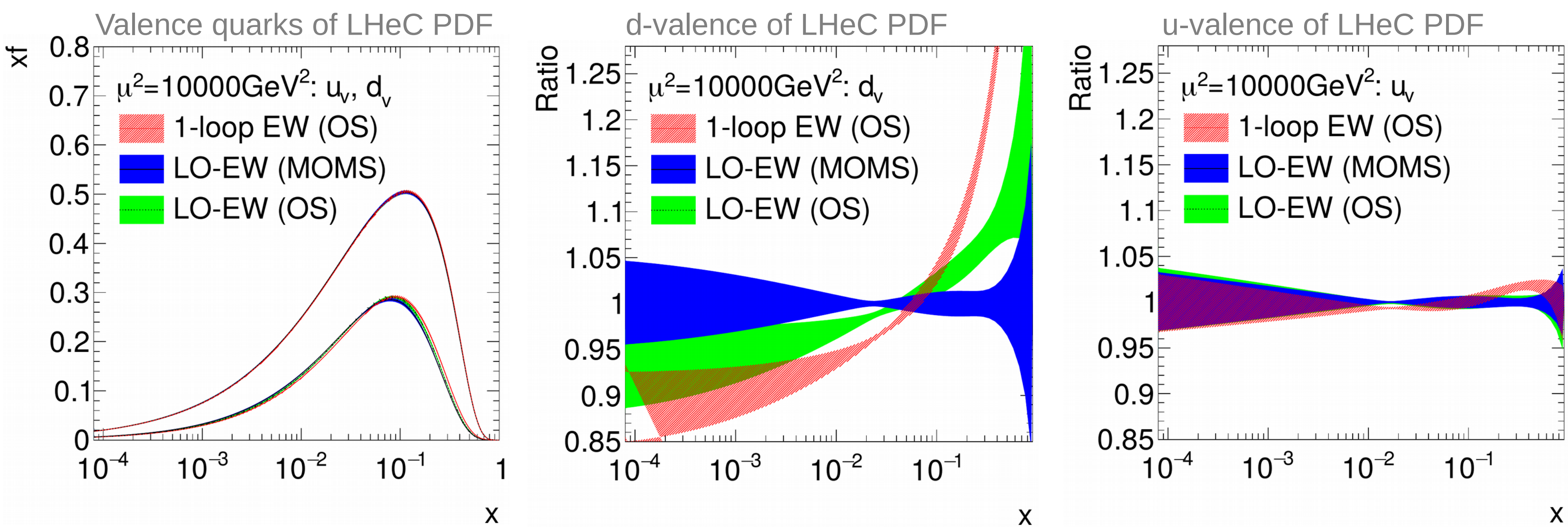
Assess impact of higher-order EW effects in LHeC-PDF fits Preliminary

- Repeat LHeC PDF determination with three EW schemes:
  on-shell (m_W,m_Z), modified-on-shell (m_Z,G_F), on-shell w/ 1-loop corrections

LHeC PDFs

- Valence quarks known up to percent precision
- LHeC: increase in χ^2 by O(490 to 750 units) for 611 data points [FCCeh: >6000 units, 619pts]

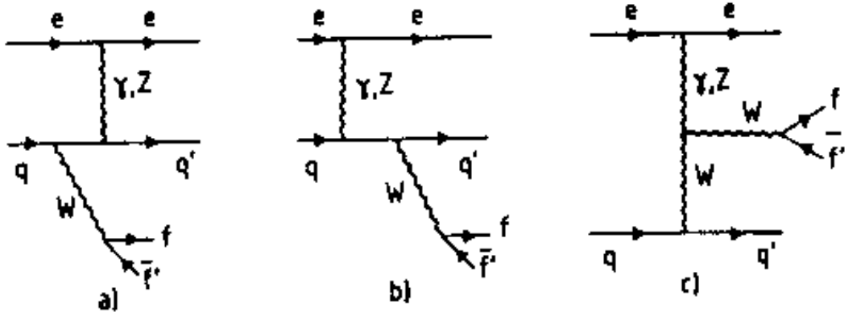
Higher-order EW effects in inclusive DIS must be accounted for in PDF fits



Single W and Z production

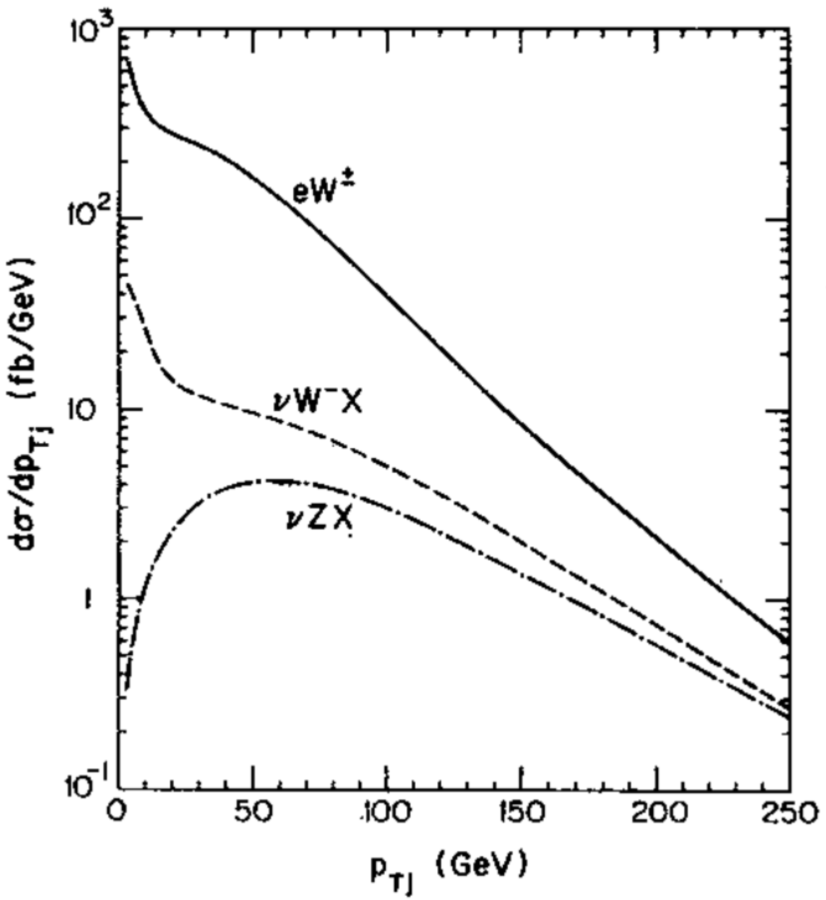
U. Baur et al, Nucl.Phys. B375 (1992) 3
U. Baur et al., Conf. Proc. C90-10-04 (1990) 956 (ECFA Workshop, Aachen)

Weak boson production @ 'LHeC'



- Significant cross sections: O(million) events

process	$E_e = 55$ GeV, $E_p = 8$ TeV σ [pb]
eW^+X	9.6
eW^-X	7.8
νW^-X	1.5
νW^-p	0.66
νZX	0.52



- Measurement of WWγ and WWZ vertices
- With L~1ab^{-1}: limits on aTGC ~ O(±0.01)

Summary

The proposed LHeC & FCC-eh project

- LHeC: 60 GeV electron times 7TeV proton ($\sqrt{s}$=1.3TeV), synchronous with HL-LHC
- FCC-eh: 60 GeV electron times 50TeV proton ($\sqrt{s}$=3.5TeV), synchronous with FCC-hh

Top physics at LHeC/FCC-eh

- future ep collider has a rich analysis programme for top quark physics
- single top quark factory: |Vtb| (~1%), top quark couplings to electroweak bosons (Wtb, ttγ, ttZ, ttH, …), top quark properties: polarisation, charge, PDFs of tops, ... many stringent searches for new physics: anomalous couplings, FCNC, CP violation in top-Yukawa, ...

Electroweak physics at LHeC/FCC-eh

- Fundamental EW parameters: competitive with (HL-)LHC
- Electroweak precision observables: competitive/complementary to LEP
- Precision EWK physics at HL-LHC needs LHeC-PDFs

Recent developments

- Subm. paper to the European strategy (Dec. 2018)
- Update on CDR will be written in autumn 2019