Top and electroweak physics at LHeC

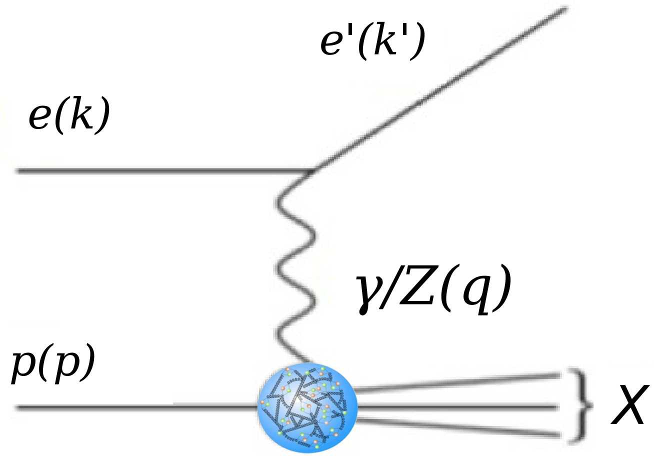
D. Britzger
for the LHeC and FCC-eh Study Group

ICHEP 2020, Prague, Czech Republic
Virtual conference
31.07.2020

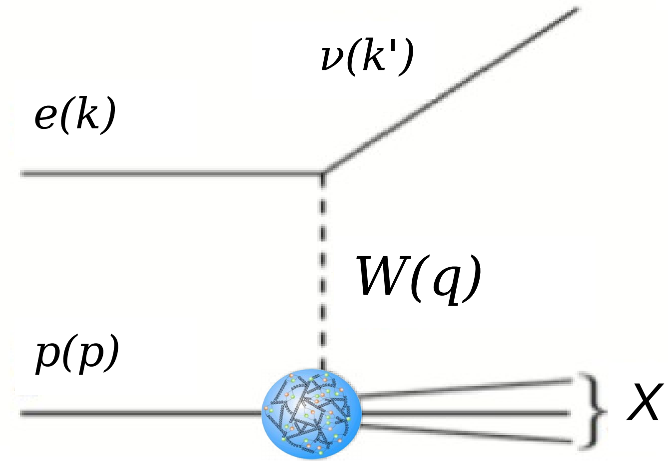
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \to e'X$



Charged current scattering
$ep \to \nu_e X$

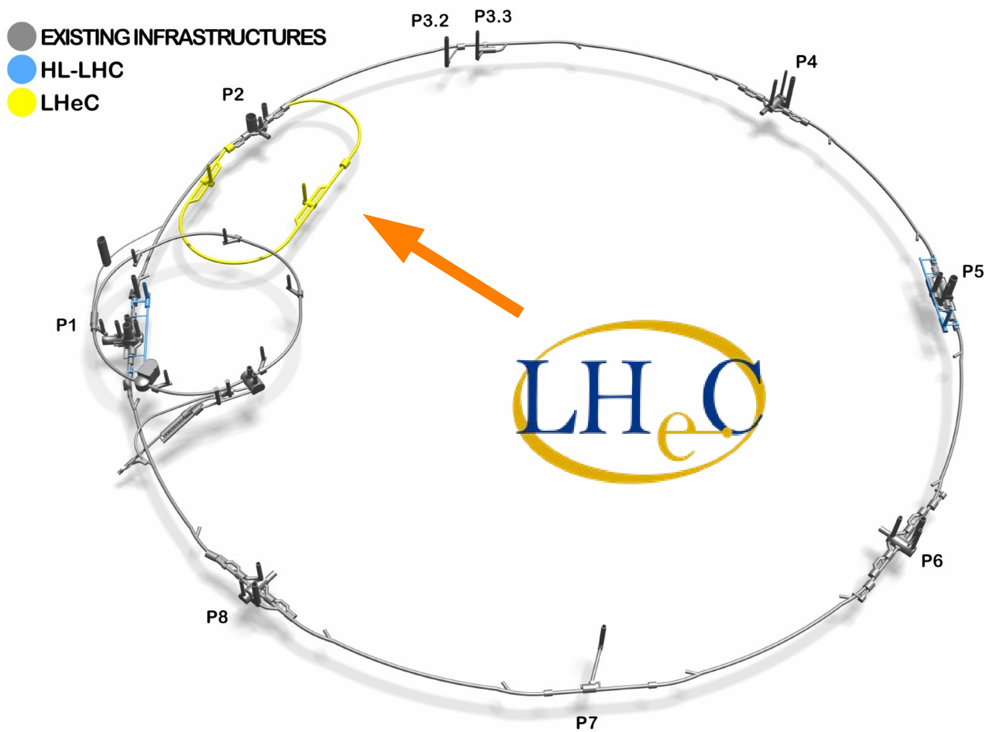


Deep-inelastic electron-proton scattering
mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

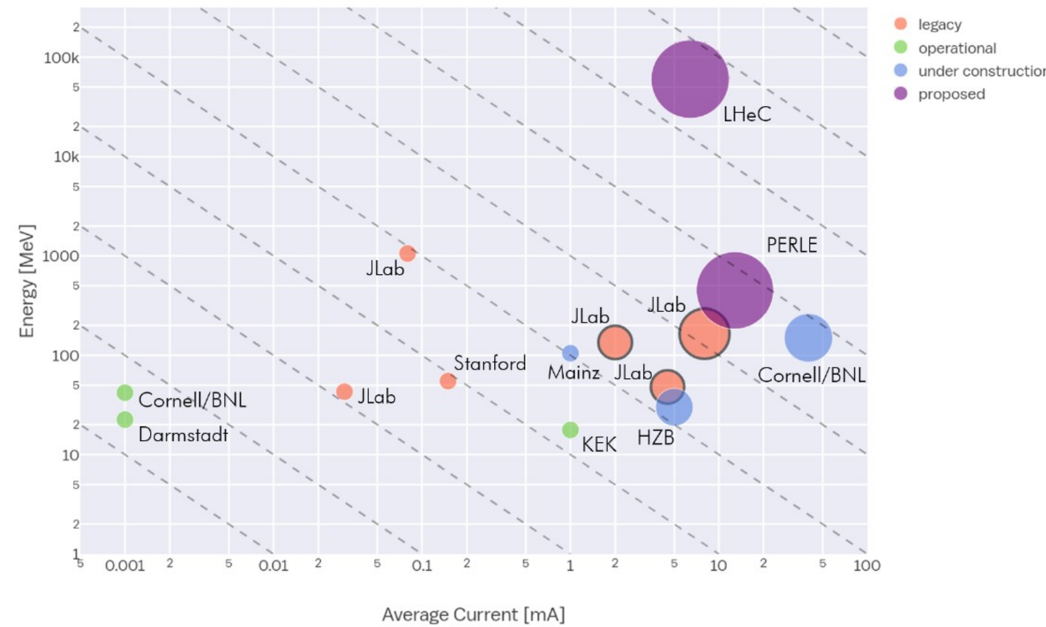
Direct probe the structure of the proton → bound together by QCD dynamics

-> Ideal QCD and Electroweak laboratory

Future electron-proton collider at CERN: LHeC



ERL "landscape"



Electron ring attached to HL-LHC

- Energy recovery linac (ERL): E_e = 60 GeV (or 50 GeV)
- ESPPU: ERL is a "high-priority future initiative" for CERN

LHeC

- $\sqrt{s}$ ~ 1.3 TeV
- Polarisation up to P_e ~ 80%
- Up to 1 ab^{-1} integrated luminosity

Update of the LHeC CDR 2020

Yesterday on arXiv

- Update of the CDR

- 373 pages about
  - Partonic structure of the proton
  - QCD studies, α_s, low-x, diffraction
  - Electroweak and top-quark physics
  - Nuclear physics
  - Higgs in DIS
  - BSM
  - Impact on the HL-LHC
  - Accelerator (Energy recovery linac)
  - PERLE facility
  - LHeC Detector

CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

CERN

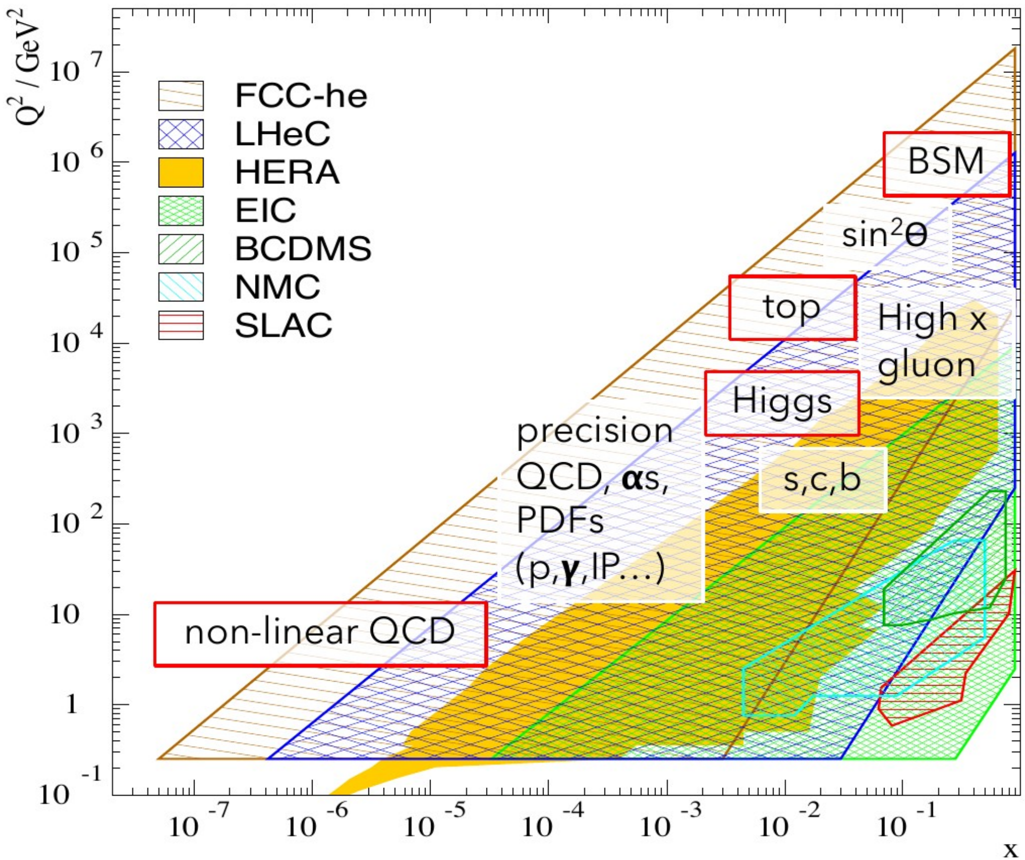
LHeC

The Large Hadron-Electron Collider at the HL-LHC

LHeC Study Group

To be submitted to J. Phys. G

LHeC kinematic plane



LHeC

- Rich physics program at all scales
- See further talks:

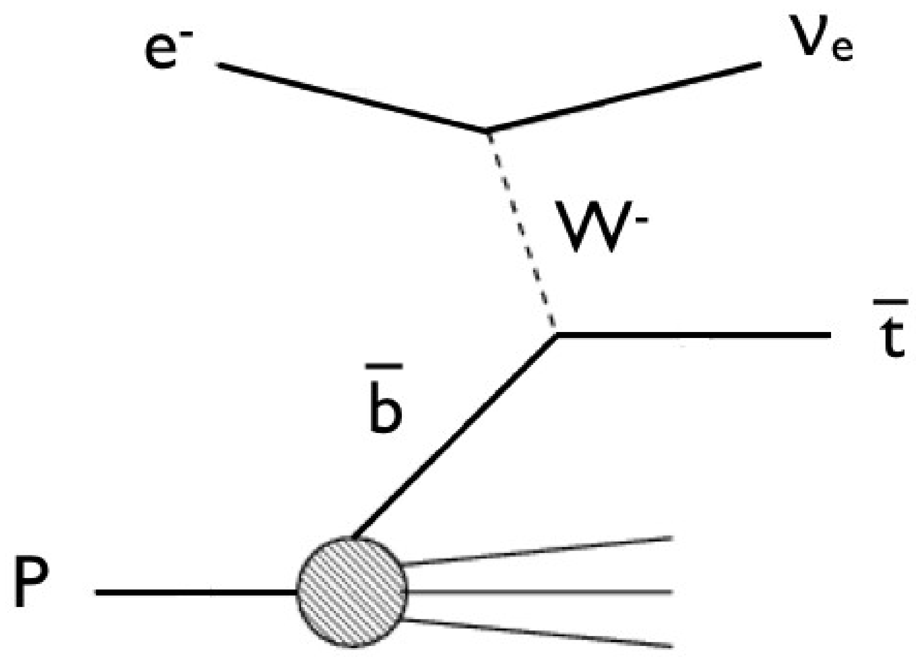
BSM	G. Azuelos
Higgs	U. Klein
Heavy Ion	H. Mäntysaari
QCD	C. Gewlan
Detector	Y. Yamazaki

Top and EW physics

- high Q^2 is important
- high luminosity is important
  → Intense electron beam from ERL
  Talks on ERL
  - LHeC: B. Holzer
  - PERLE: B. Hounsell

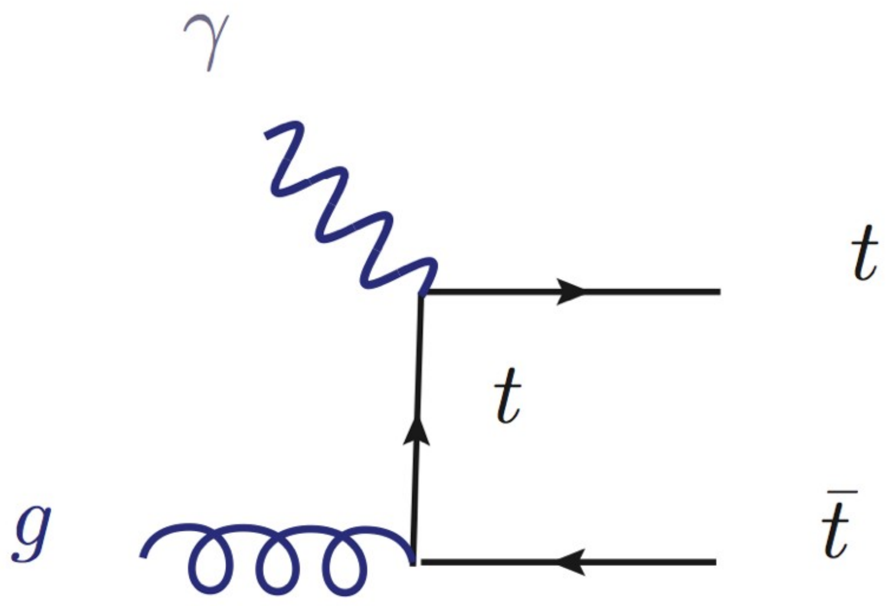
Top quark production in ep

CC DIS single-top quark production



LHeC: σ_{tot}~1.9pb

NC (γp) top-quark pair production

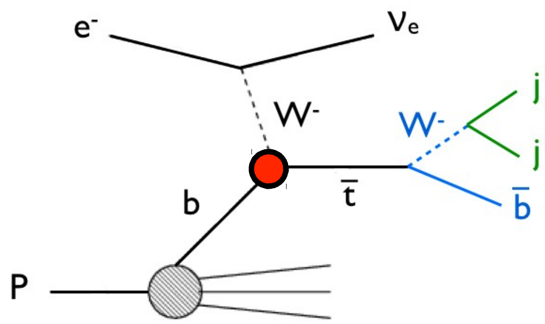


LHeC: σ_{tot} ~ 0.05pb

Other channels are: top-pair in DIS (~0.02pb), single-top in DIS and γp

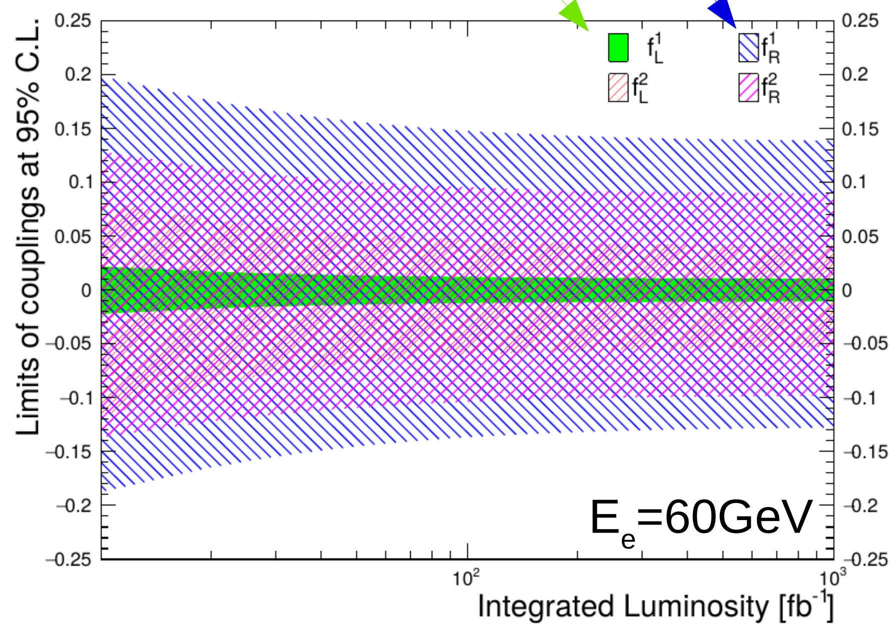
$|V_{tb}|$ in CC single-top production

Limits on anomalous Wtb couplings



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

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



- 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})
- Presently best LHC measurement: ~7%

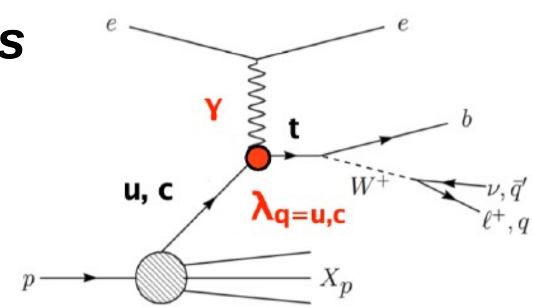
See: S. Dutta, et al. Eur.Phys.J. C75 (2015) 577

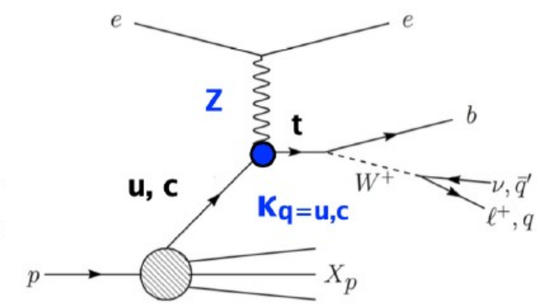
Search for anomalous FCNC

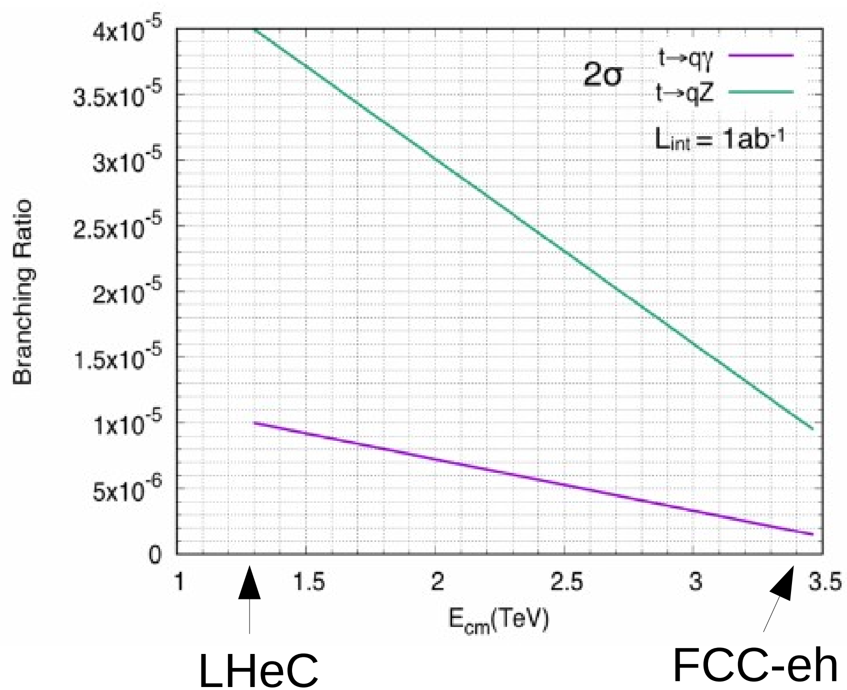
t-quark flavor changing neutral currents

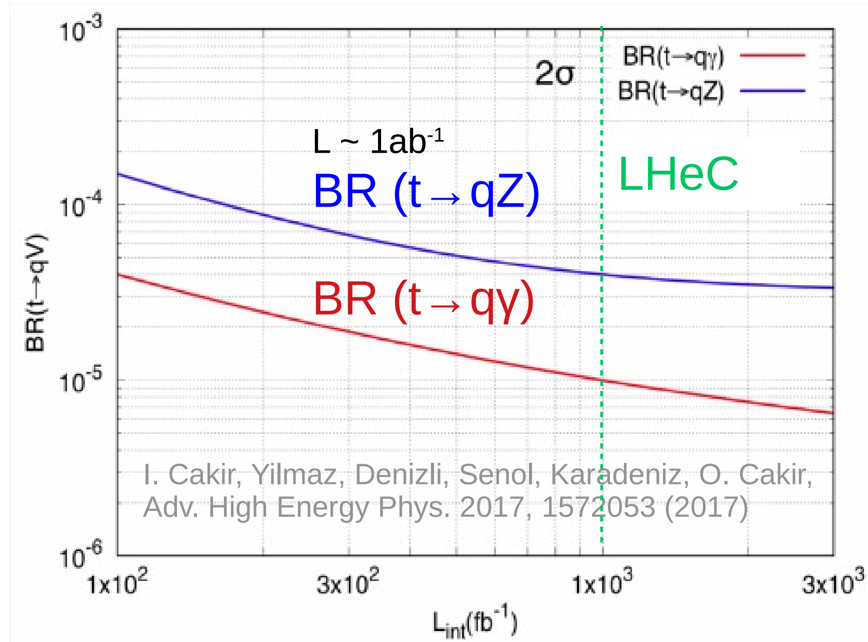
→ Highly suppressed in SM

- Study tqγ and tqZ effective FCNC
- Expected limits vs. √s and int. luminosity









Top quark branching fractions

Top quark branching fractions

- Searches for FCNC
- 95% C.L.

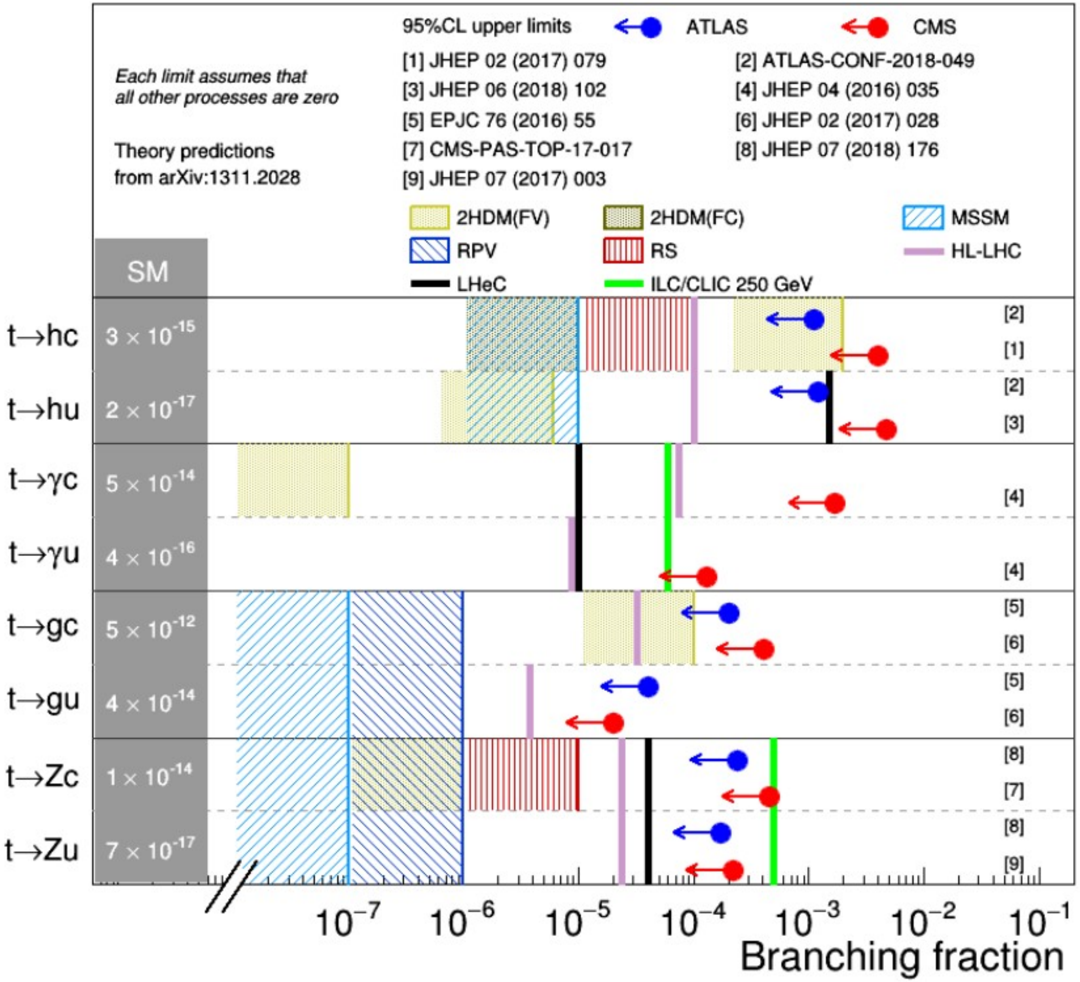
Compare future experiments

- LHeC
- HL-LHC (3000 fb^{-1})
- ILC/CLIC

+ various theory predictions

pp and ep

- LHeC is competitive
  … and complementary
- See also talk by U. Klein on t→hu



Electroweak physics in inclusive DIS

Inclusive DIS (neutral-current)

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

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

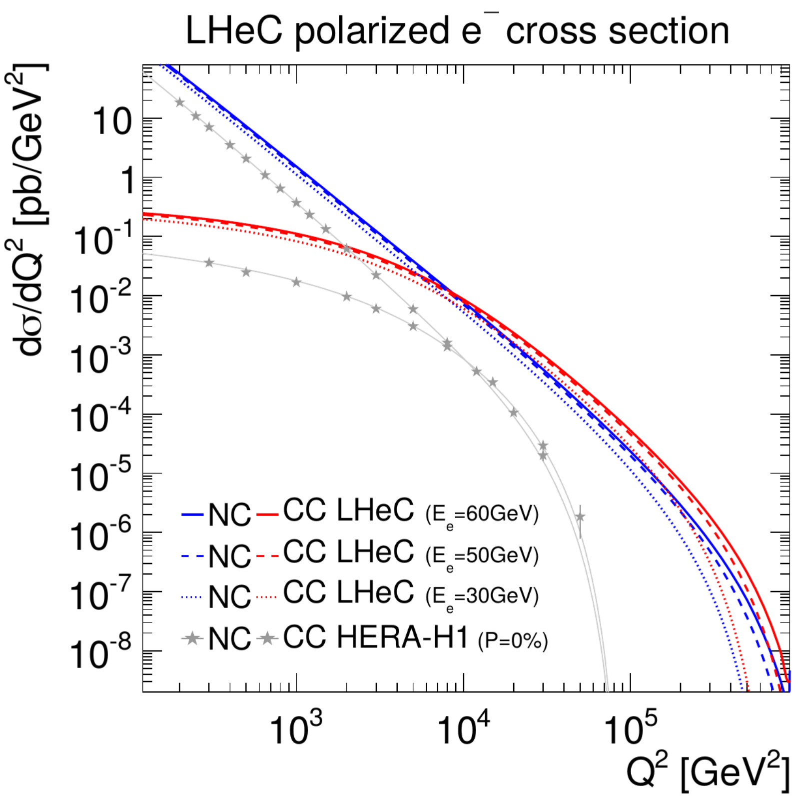
$$\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x\sum_q \left[Q_q^2, 2Q_q g_V^q, g_V^q g_V^q + g_A^q g_A^q\right]\{q+\bar{q}\}$$

On-shell scheme $\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$

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

NC couplings

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



Independent SM paramters: α, m_Z, m_W + PDFs

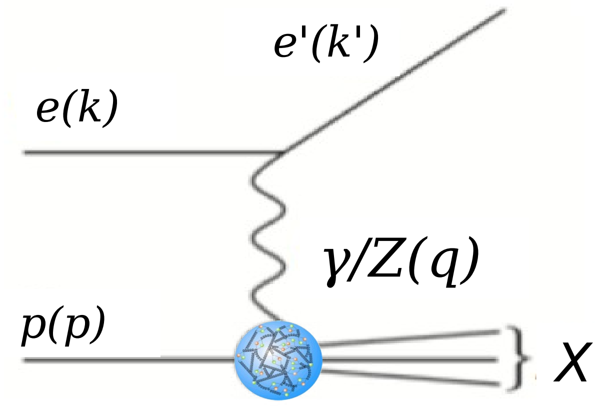
Electroweak physics

Simulated NC and CC DIS data

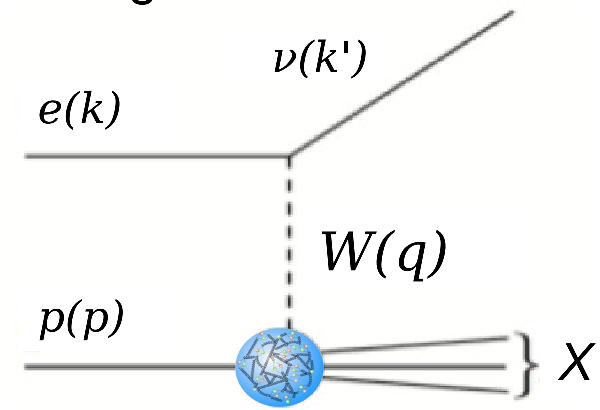
Source of uncertainty	Size of uncertainty	Uncertainty on cross section	
		$\Delta\sigma_{NC}$	$\Delta\sigma_{CC}$
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %	0.1 – 1.7 %	–
Scattered electron polar angle	0.1 mrad	0.1 – 0.7 %	–
Hadronic energy scale $\Delta E_h/E_h$	0.5 %	0.1 – 4 %	1.0 – 8.6 %
Calorimeter noise (only $y < 0.01$)		0.0 – 1.1 %	included above
Radiative corrections		0.3 %	–
Photoproduction background ($y > 0.5$)	1 %	0.0 or 1.0 %	–
Uncorrelated uncertainty (efficiency)		0.5 %	0.5 %
Luminosity uncertainty (normalization)		1.0 %	1.0 %

- Luminosity of 1 ab^{-1} expected
- Full set of systematic uncertainties

Neutral current scattering



Charged current scattering



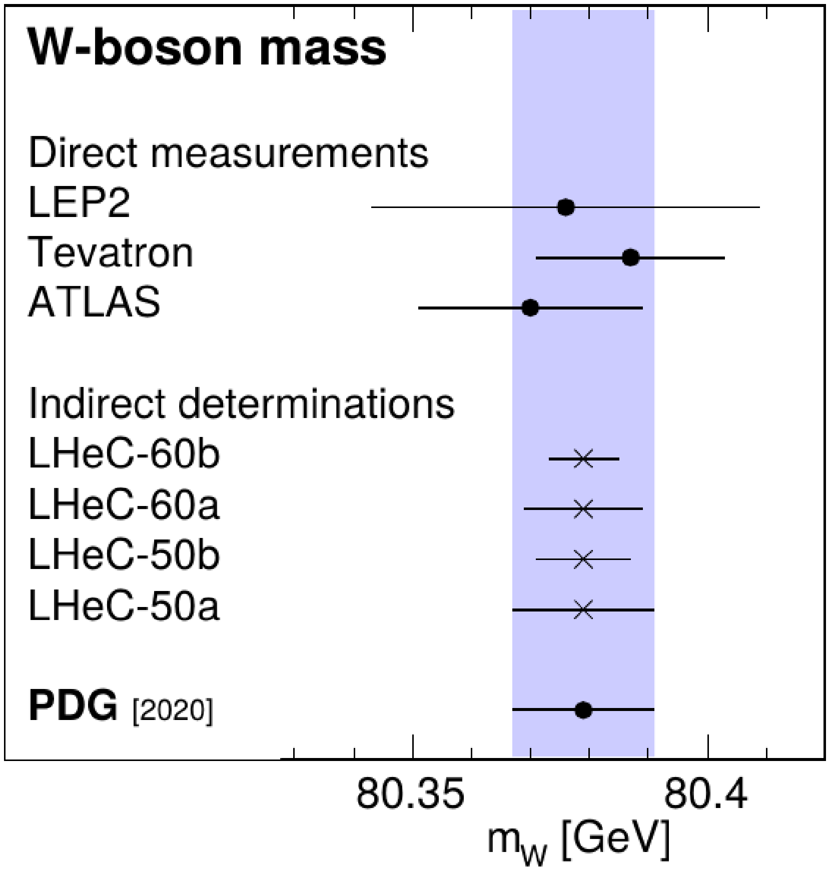
In the following

perform PDF determination + electroweak parameters

→ see also talk by C. Gwenlan on PDFs

Expectations: m_W + PDF

Fit W-boson mass together with PDFs



Scenario	E_e	Uncorrelated uncertainty
LHeC-50a	50 GeV	0.5 %
LHeC-50b	50 GeV	0.25 %
LHeC-60a	60 GeV	0.5 %
LHeC-60b	60 GeV	0.25 %

Results

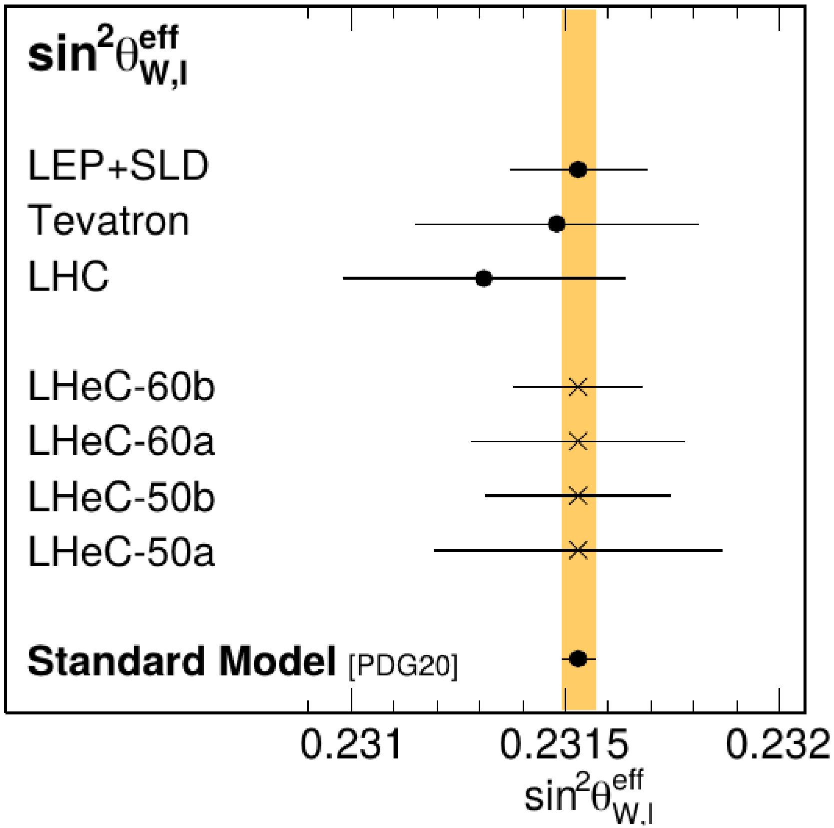
$\delta m_W = \pm 6$ MeV (LHeC-60b)

$\delta m_W = \pm 12$ MeV (LHeC-50a)

$(= \pm 9_{\mathrm{exp}} \pm 8_{\mathrm{PDF}}$ MeV)

- Indirect determination of m_W
- Complementary to 'direct' measurements
- Smallest uncertainties from a single experiment

The weak mixing angle



Weak mixing angle

- in NC vector couplings only (both: quarks and electron)

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

$\sin^2\theta_W$ + PDF fit

- Compare to Z-pole data (mostly 'combined' results)
- Most precise single measurement possible
- Note: need theory to map $\sin^2\theta_W$ to effective leptonic weak mixing angle

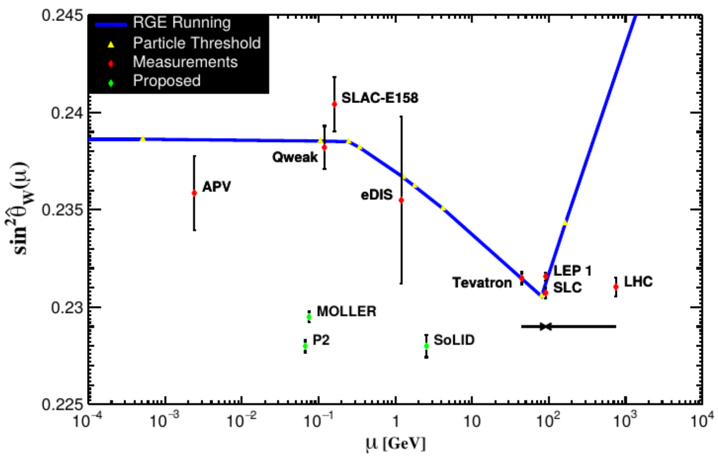
$$\Delta\sin^2\theta_W\ (\text{LHeC-50a}) = \pm 0.00028_{(\text{exp})} \pm 0.00019_{(\text{PDF})} = \pm 0.00034_{(\text{tot})}$$

$$\Delta\sin^2\theta_W\ (\text{LHeC-60b}) = \pm 0.00014_{(\text{exp})} \pm 0.00006_{(\text{PDF})} = \pm 0.00015_{(\text{tot})}$$

Running of the weak mixing angle

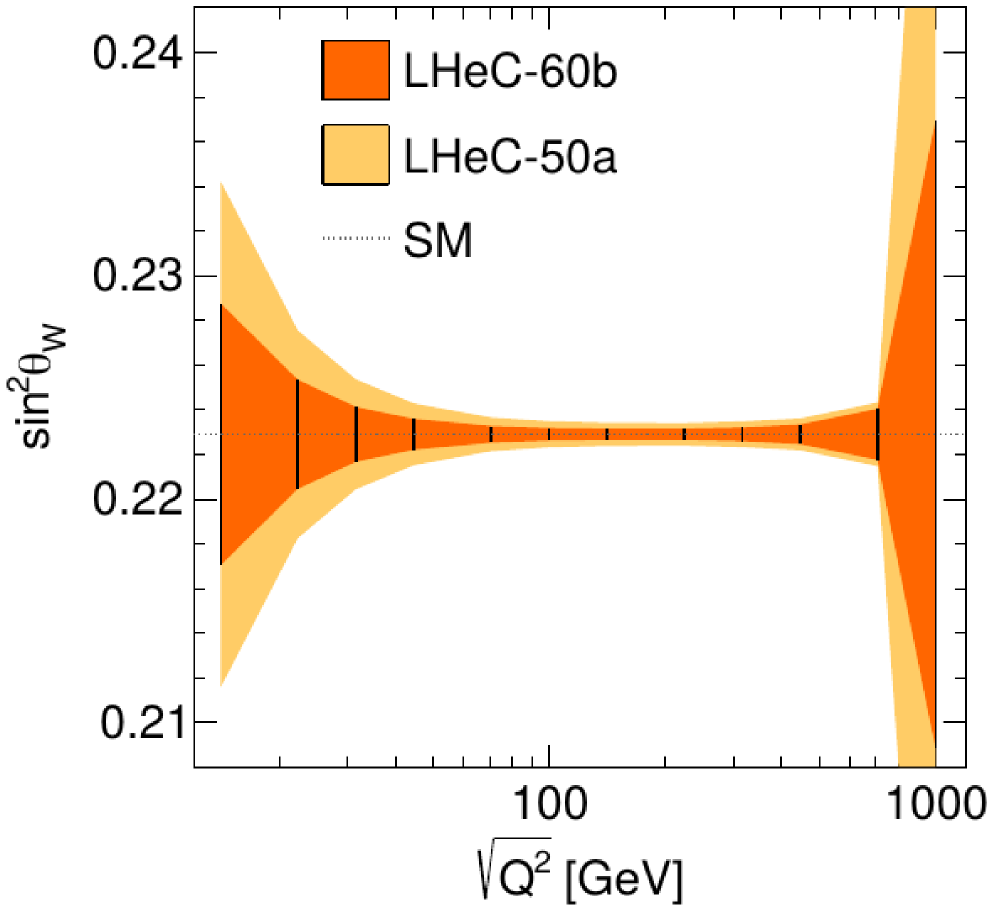
Running in MSbar scheme in

- links low-E and high-E PV data



We studied on-shell scheme

- Fit 12 values of $\sin^2\theta_W$ + PDFs
- $\sin^2\theta_W$ single parameter in OS
- Per mille uncertainties in 25 <Q < 700 GeV in spacelike region



Beyond the tree level

At leading order

- Three independent input parameters

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W) \quad \text{and} \quad d\sigma_{CC} = d\sigma_{CC}(\alpha, m_Z, m_W)$$

Beyond the leading order

- higher order corrections

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, m_t, m_H, \ldots)$$

- Generic parameterisations of virtual corrections

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, v_f, a_f)$$

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, \rho, \kappa)$$

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, S, T, U)$$

Top-quark mass through EW correction

Higher order corrections

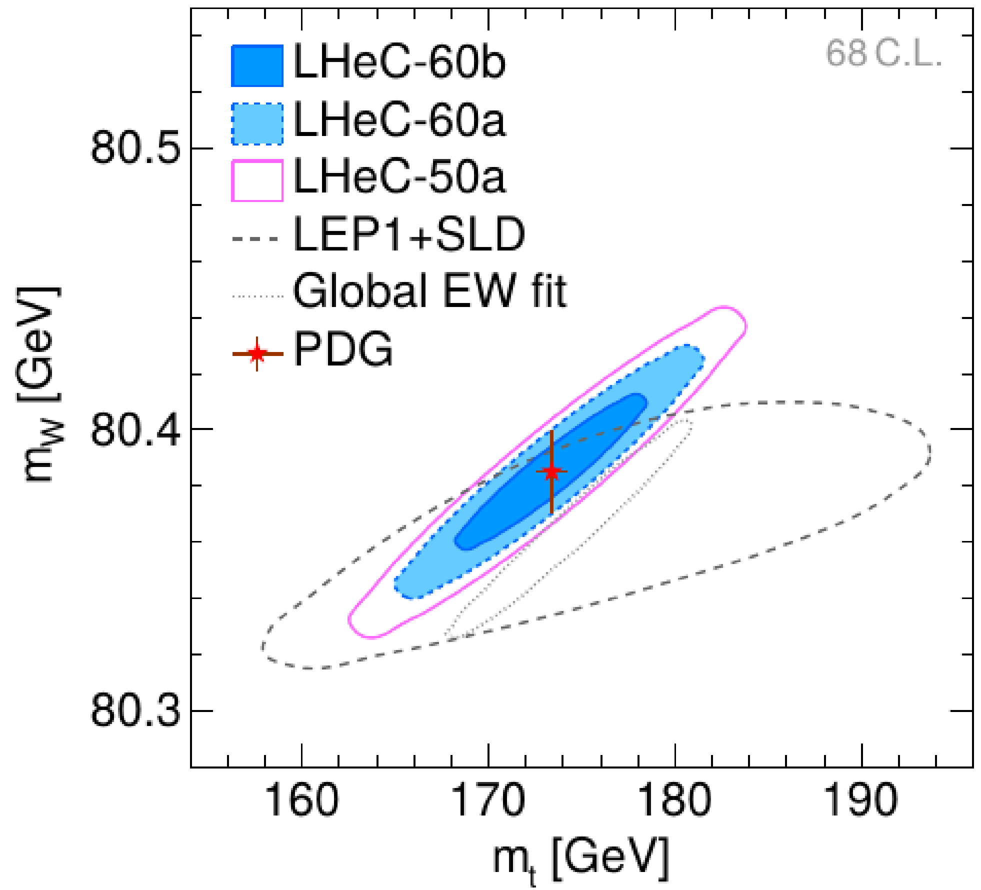
- Dominant term ρ_t proportional to m^2_t/m^2_W
- Same relation as in Z-pole physics

LHeC

- similar sensitivity to 'global EW fit'
- Significantly better than LEP+SLD combination

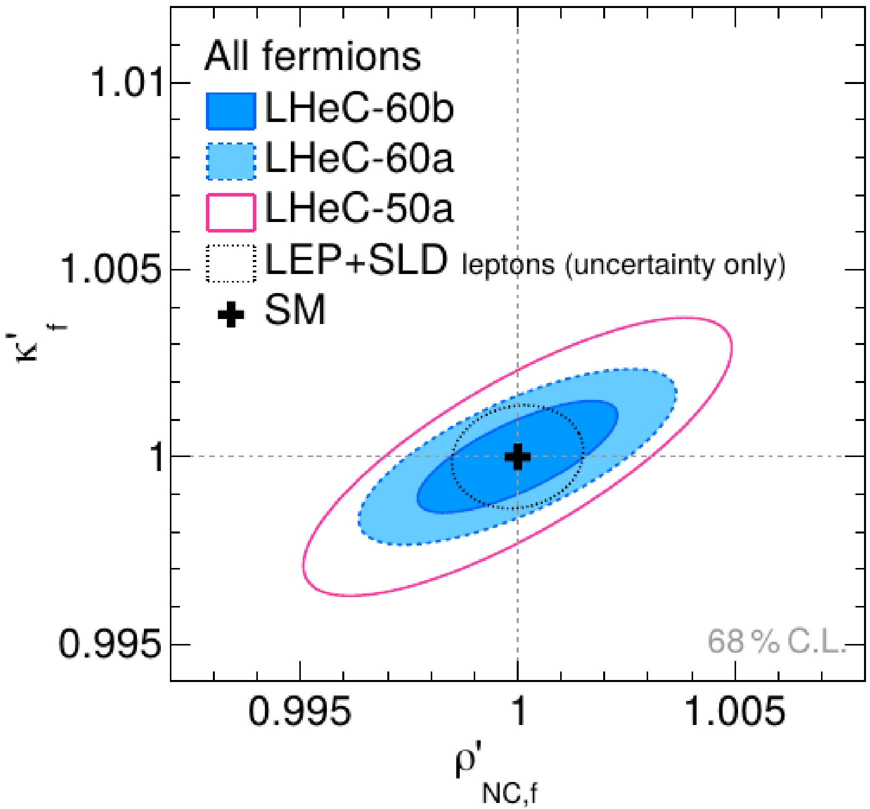
Top-mass alone

- Δm_t ~ 1.1 GeV (including PDF uncert.)



Anomalous form factors

Generically parameterize new physics by modified couplings

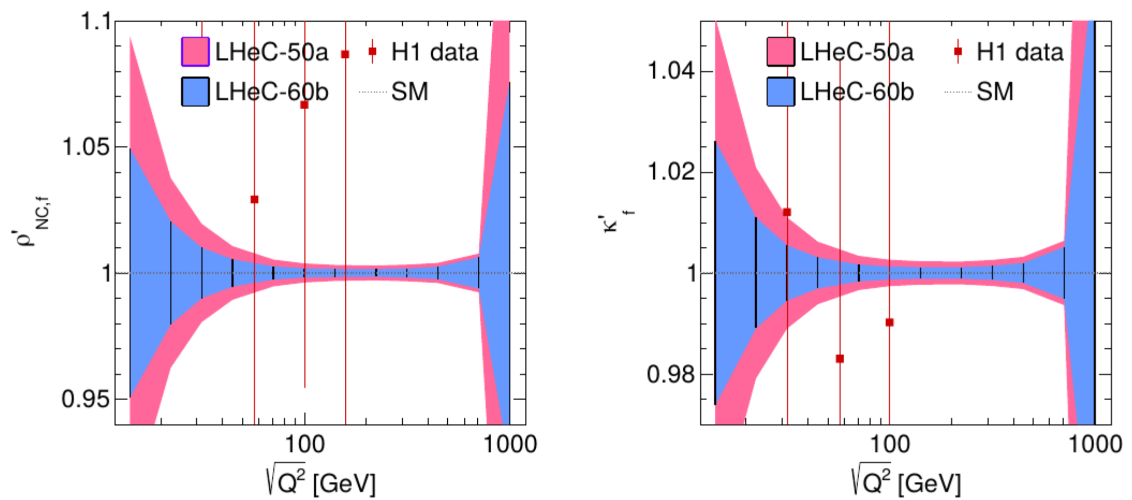


- In SM: ρ' and κ' = 1

$$g_A^f = \sqrt{\rho'_{\mathrm{NC},f}\rho_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$

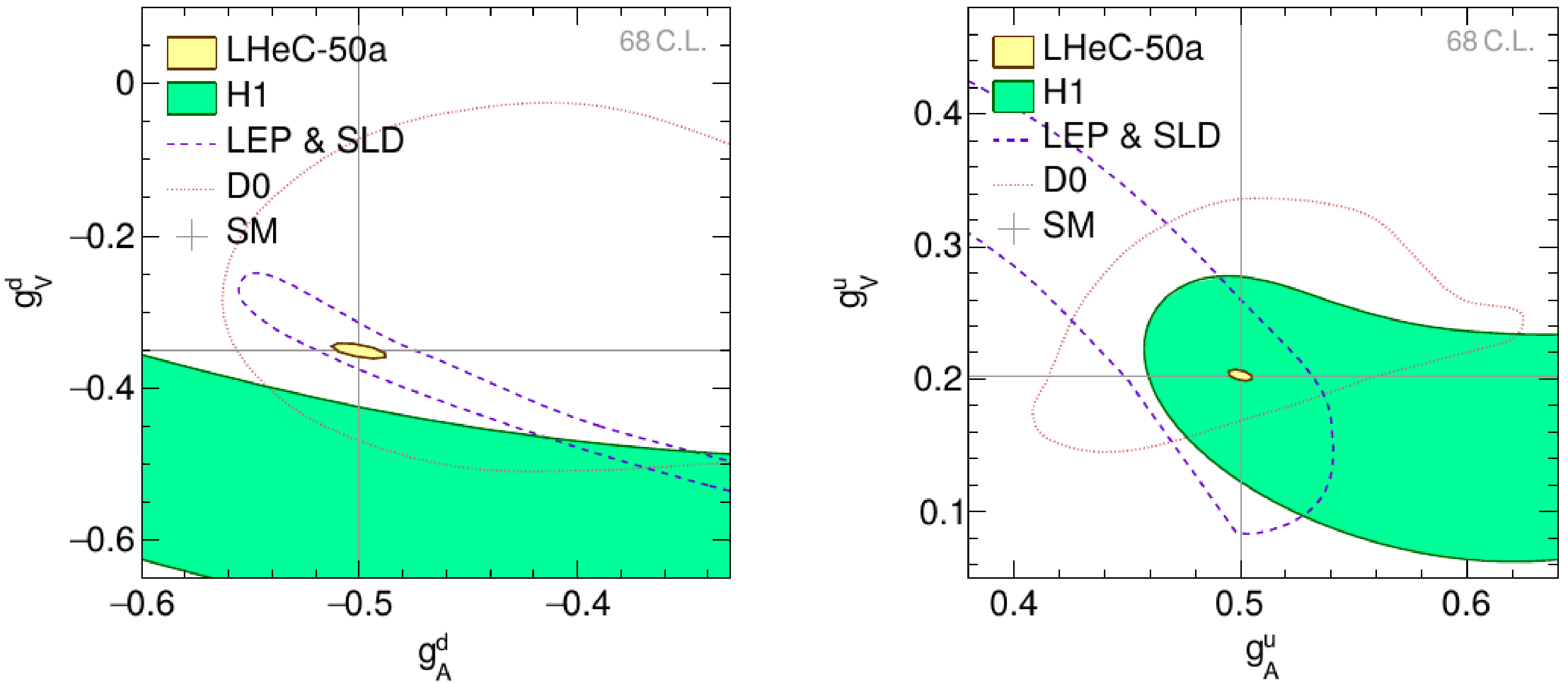
$$g_V^f = \sqrt{\rho'_{\mathrm{NC},f}\rho_{\mathrm{NC},f}}\, \left(I^3_{\mathrm{L},f} - 2Q_f\kappa'_f\kappa_f\sin^2\theta_W\right)$$

- Parameters may be Q^2 dependent
  (similar to running weak mixing angle)



Light quark NC couplings

4-parameter fit plus PDFs

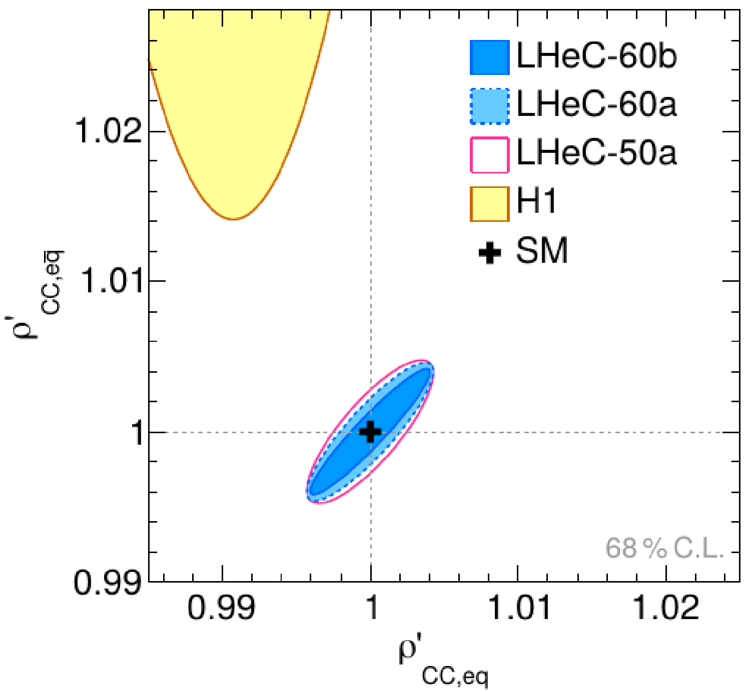


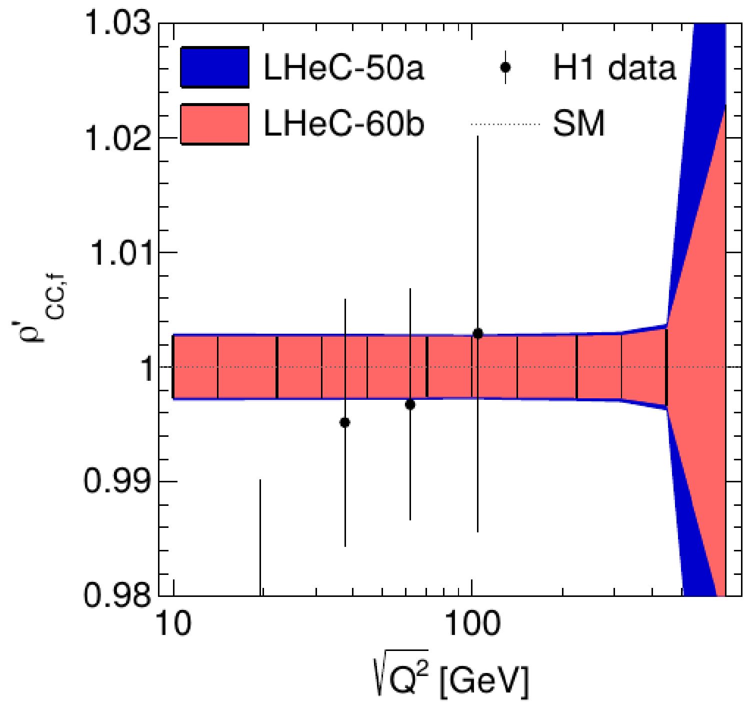
- LHeC improves by more than an order of magnitude
- u- and d- can be separated – no sign ambiguity due to γZ terms

Charged currents

Study charged current cross sections in DIS

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

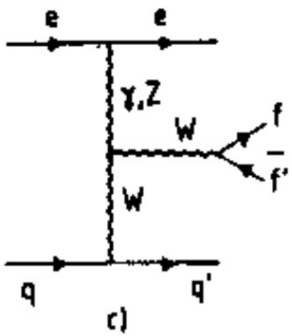




Charged currents couplings not well studied experimentally – unique to LHeC

Direct W and Z production

Weak boson production @ LHeC



W production

$$e^- p \to e^- W^+ j, \quad e^- p \to e^- W^- j,$$
$$e^- p \to \nu_e^- W^- j, \quad e^- p \to \nu_e^- Z j$$

Z production $e^- p \to e^- Z j.$

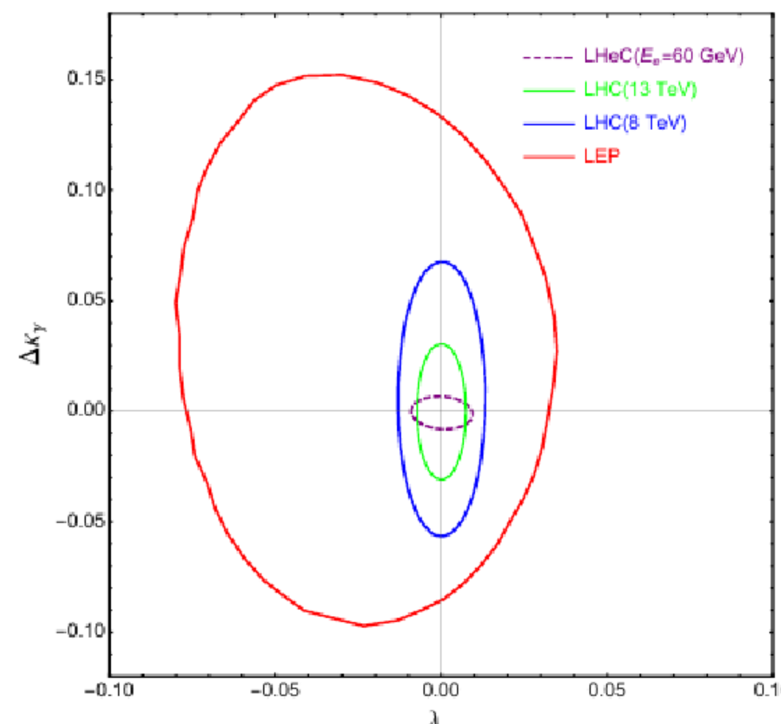
Expected cross sections in e-p

Process	$E_e = 60\,\mathrm{GeV},\ E_p = 7\,\mathrm{TeV}$ $p_T^e > 5\,\mathrm{GeV}$
$e^- W^+ j$	1.60 pb
$e^- W^- j$	1.41 pb
$\nu_e^- W^- j$	0.956 pb
$\nu_e^- Z j$	0.502 pb
$e^- Z j$	0.242 pb

LHeC CDR 2020

Anomalous triple gauge couplings

- EFT approach for: λ_γ and $\Delta\kappa_\gamma$
- WWγ coupling from e-p → $e^- \mu \nu_\mu j$

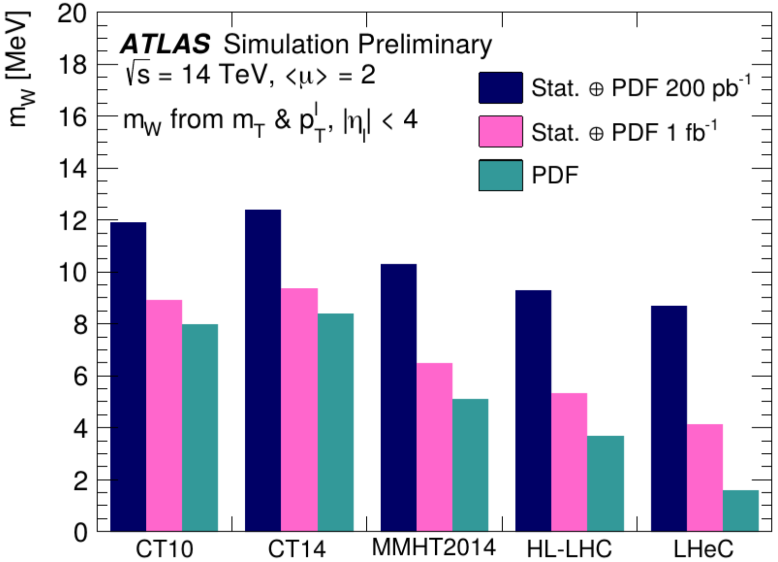


R. Li, et al., Phys. Rev. D 97, 075043 (2018)

The impact of LHeC on HL-LHC

W-mass measurements in pp

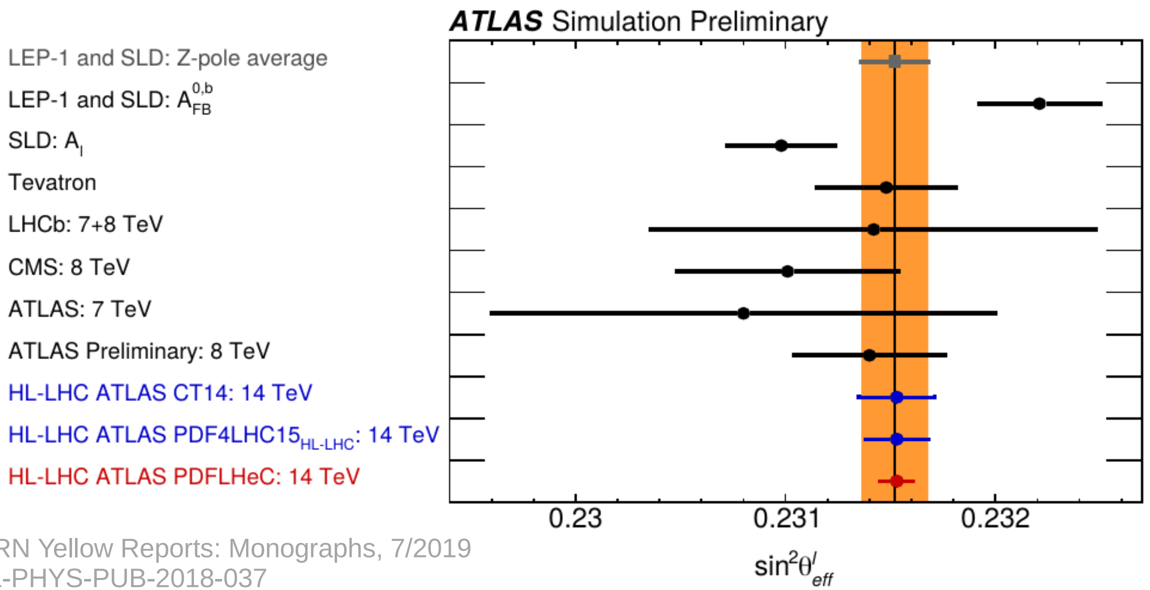
- Major uncertainty from PDFs



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

Effective weak mixing angle in pp

- Large uncertainty from PDFs



CERN Yellow Reports: Monographs, 7/2019
ATL-PHYS-PUB-2018-037

- HL-LHC–PDF reduces uncertainty by 10-25%
- LHeC–PDFs reduces PDF uncertainties by an additional factor of 5

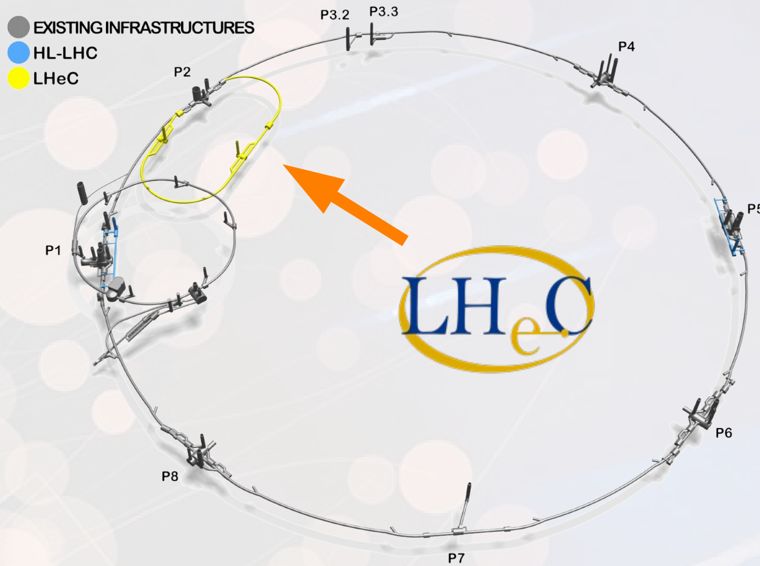
Summary

LHeC & FCC-eh projects

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

Top physics at LHeC/FCC-eh

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



Electroweak physics at LHeC/FCC-eh (arXiv:11799)

- Fundamental EW parameters: Competitive with (HL-)LHC/LEP
- Complementary to Z-pole data; unique measurements possible
- EWK physics at HL-LHC needs LHeC-PDFs

Update on CDR on arXiv yesterday: arXiv:2007.14491

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

Measurement of $|V_{td}|$

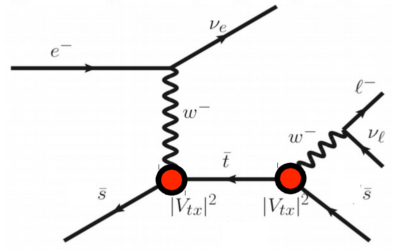
$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Signal.1 : $pe^- \to \nu_e \bar{t} \to \nu_e W^- \bar{b} \to \nu_e \ell^- \nu_\ell \bar{b}$,

Signal.2 : $pe^- \to \nu_e W^- b \to \nu_e \ell^- \nu_\ell b$,

Signal.3 : $pe^- \to \nu_e \bar{t} \to \nu_e W^- j \to \nu_e \ell^- \nu_\ell j$,

Signal.4 : $pe^- \to \nu_e W^- j \to \nu_e \ell^- \nu_\ell j$.

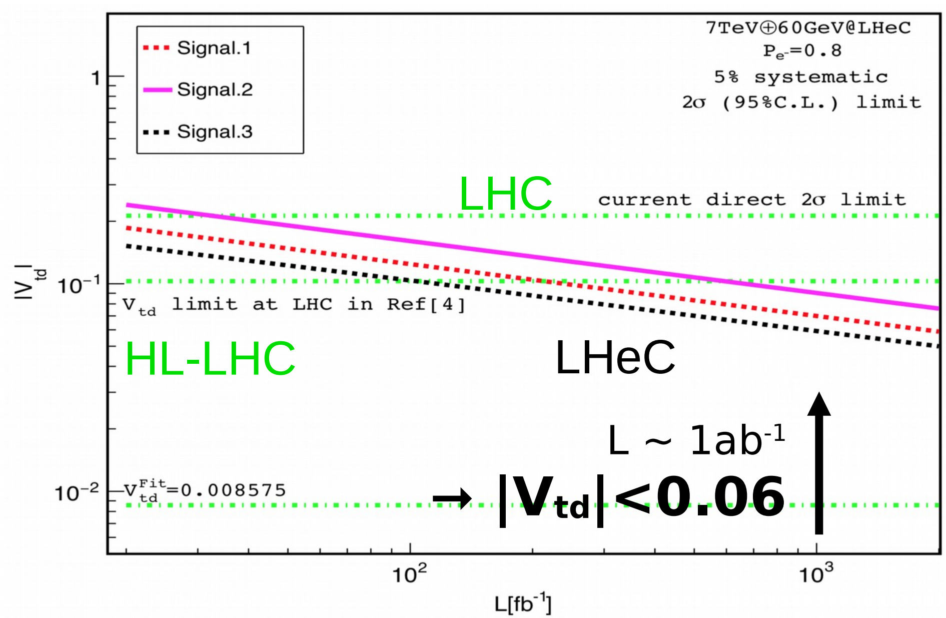


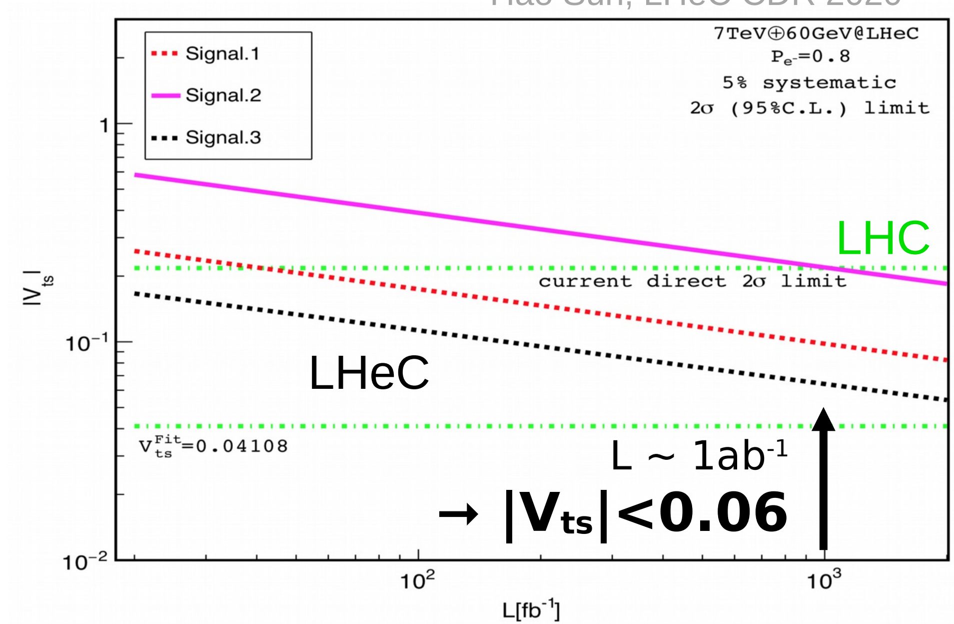
Measurement of $|V_{ts}|$

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

simplified analysis, using 4 signal channels

Hao Sun, LHeC CDR 2020

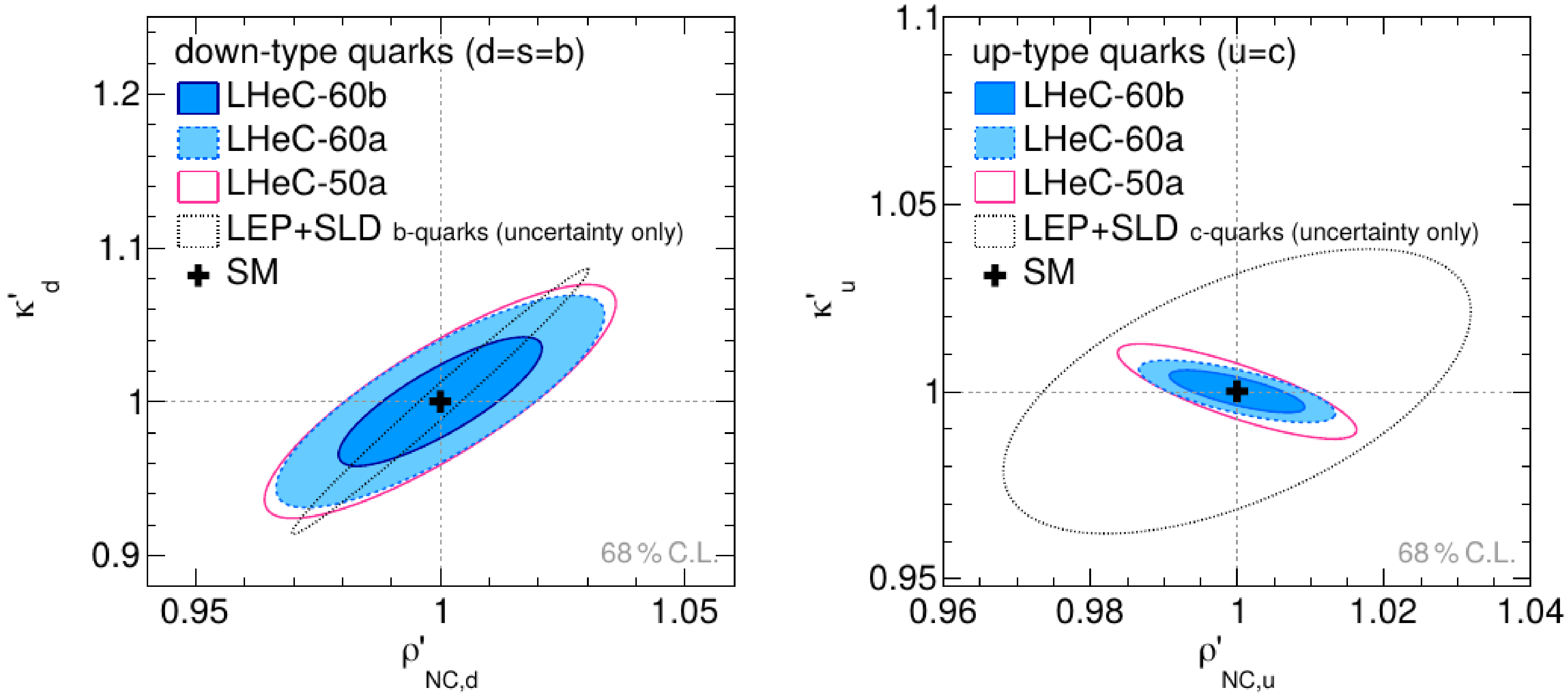




Quark couplings

4-parameter fit for up and down-type couplings

- tagged c- and b-quark measurements at LEP
- LHeC mainly light quarks, u and d



STU parameters from inclusive DIS

S, T, U parameters are non-SM contributions to Z, W boson self-energies

Shown

- 2-parameter fits
  incl. PDF fit
- Scheme dependence
  On-shell (OS)
  Modified on-shell (MOMS)
- Inclusive DIS
  Possible to disentangle
  S, T and U
- Complementary to
  Z-pole