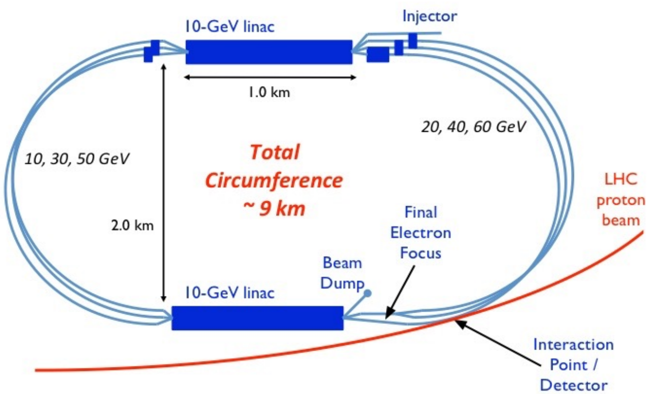
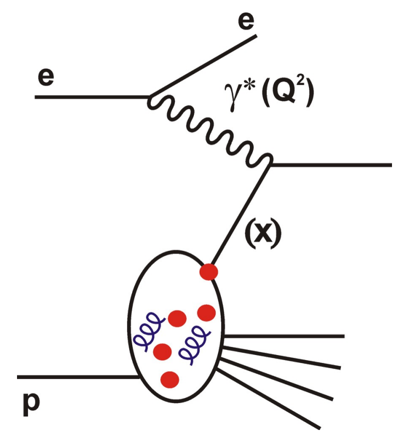
Top and Electroweak Physics at the Large Hadron electron Collider

Paul Newman (Birmingham)

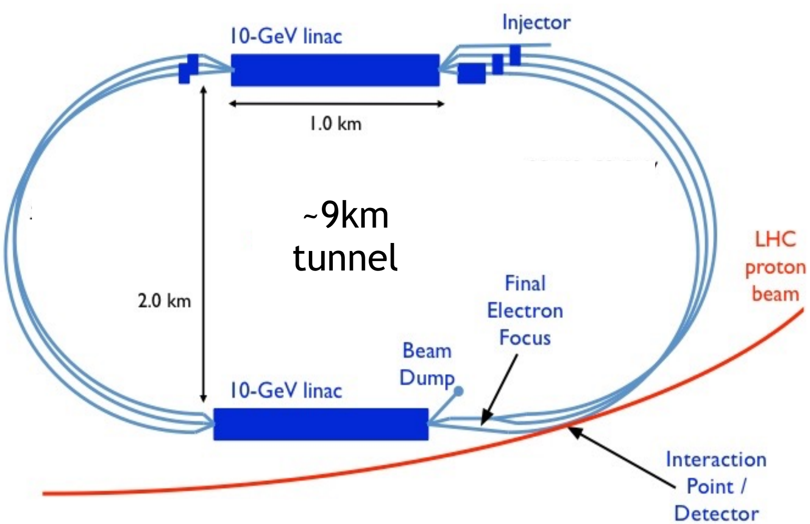




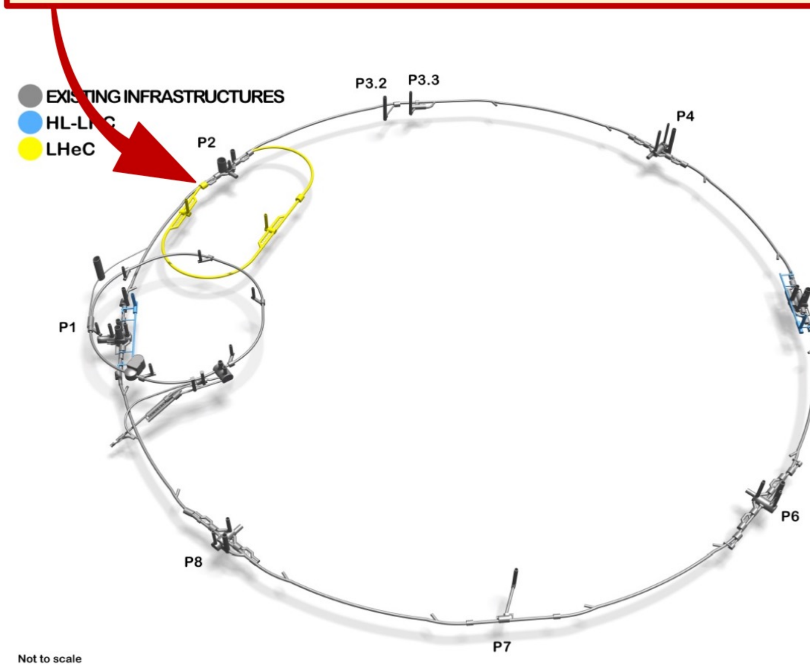
DIS'26, Bologna
5 May 2026

The CERN Large Hadron electron Collider

- Proposal for CERN to further-exploit the LHC in the 2040s
- Add a Recirculating Energy-Recovery Linac (ERL) electron accelerator
- Baseline plan is several years standalone running after HL-LHC → 1ab^{-1}



LHeC (>50 GeV electron beams)
E_{cms} = 0.2 – 1.3 TeV, (Q^2,x) range far beyond HERA
run ep/pp together with the HL-LHC (≳ Run5)



ERL Prototype
(PERLE @ IJCLab, Paris)
… first stage (one turn) 2028.

- ‘Sustainable’ acceleration: ~100 MW for ERL

Input to 2025 European PP Strategy Update

The Large Hadron electron Collider as a bridge project for CERN

[2503.17727]

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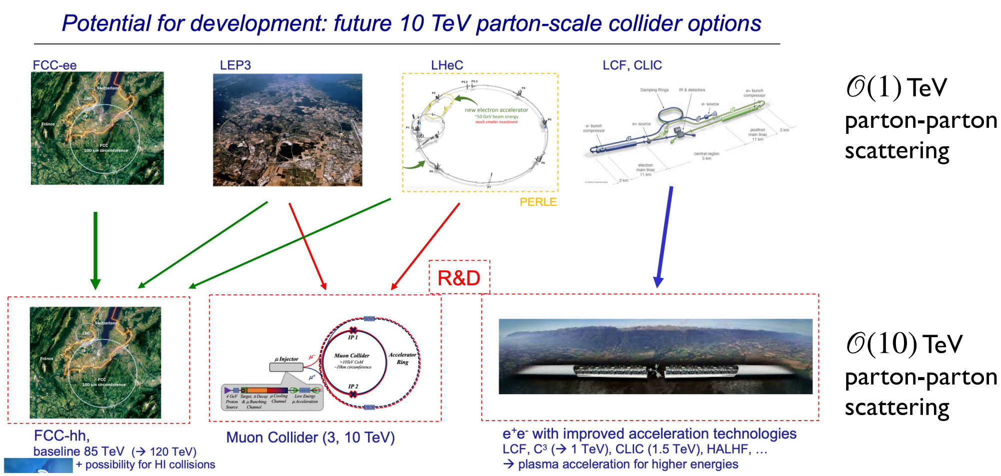
Outcome: one of several 'alternative O(1TeV) plans' to FCC-ee

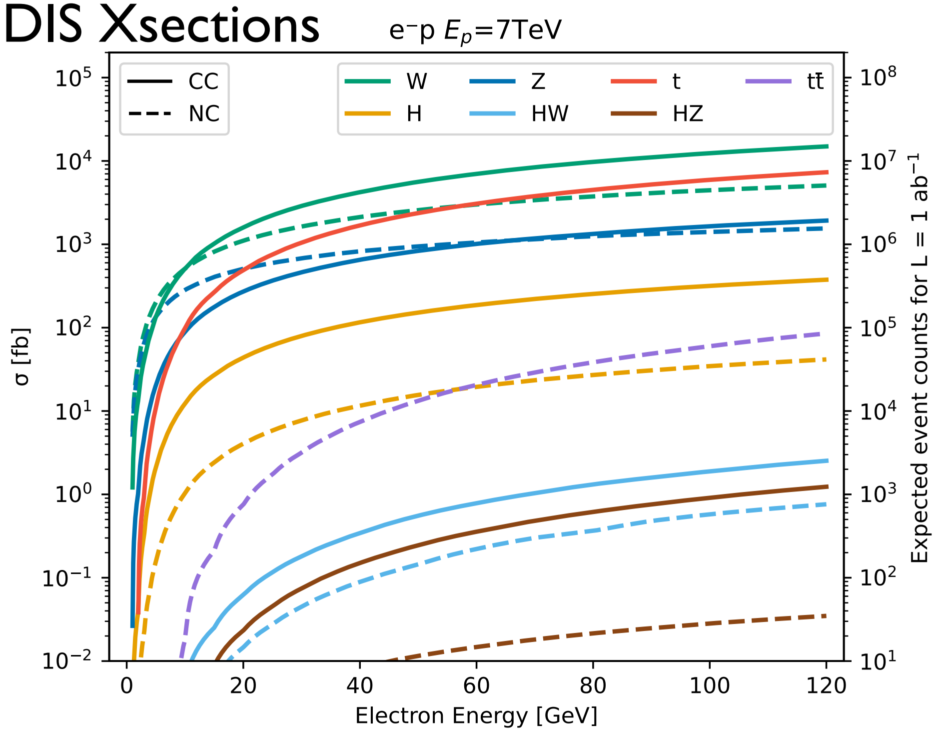


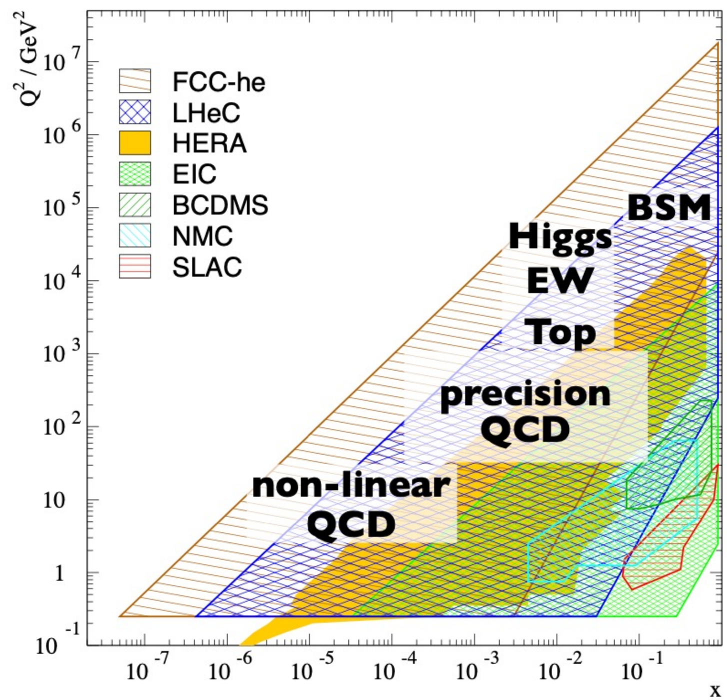
[Karl Jakobs]

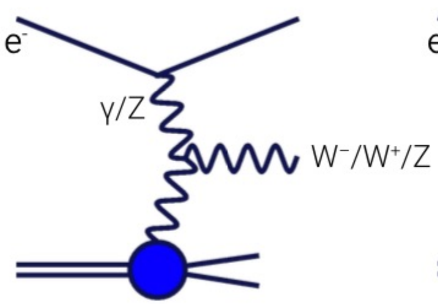
Why Energy Frontier DIS?

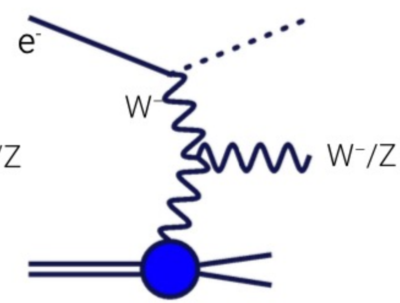
In contrast to many aspects of future DIS programme, EW boson physics and top quark physics only become accessible at large CMS energies.

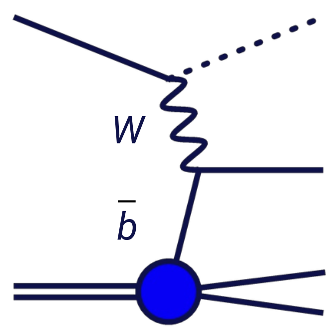
DIS Xsections

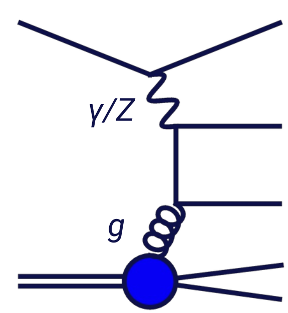




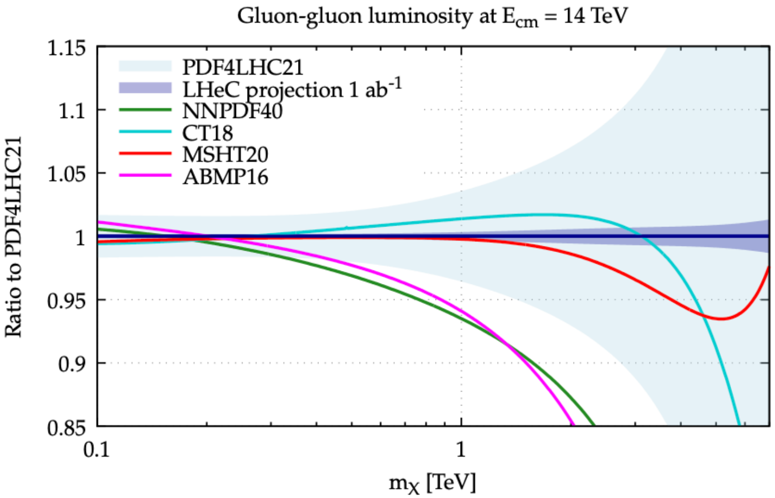


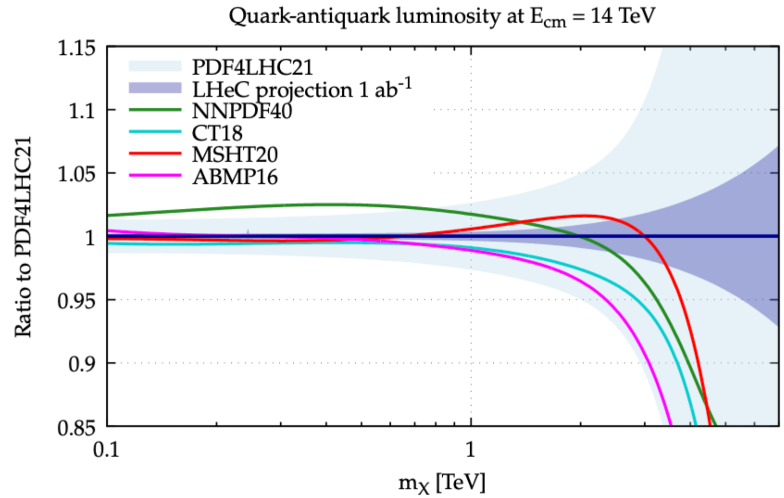






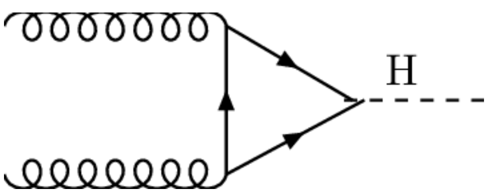
LHeC Enabling HL-LHC through PDFs





- Extends upper mass reach of many LHC BSM searches
- Facilitates LHC precision measurements

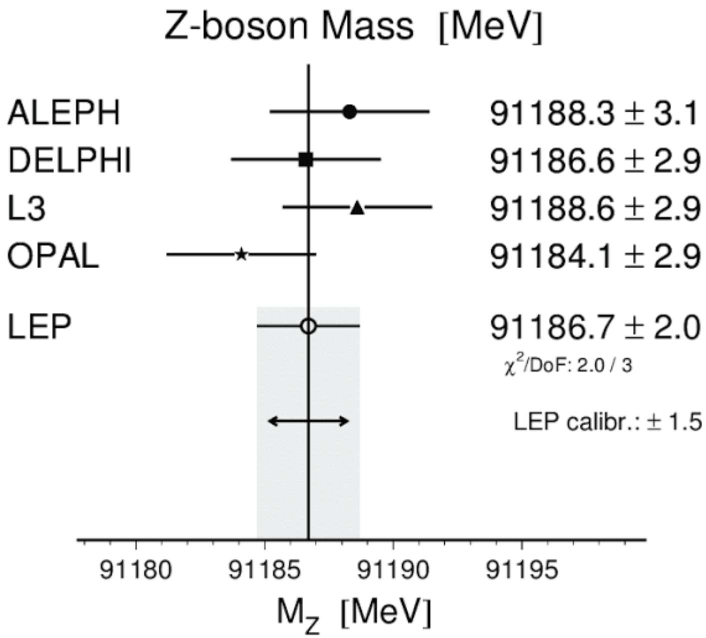
… e.g. Theory uncertainty on LHC Higgs cross section …

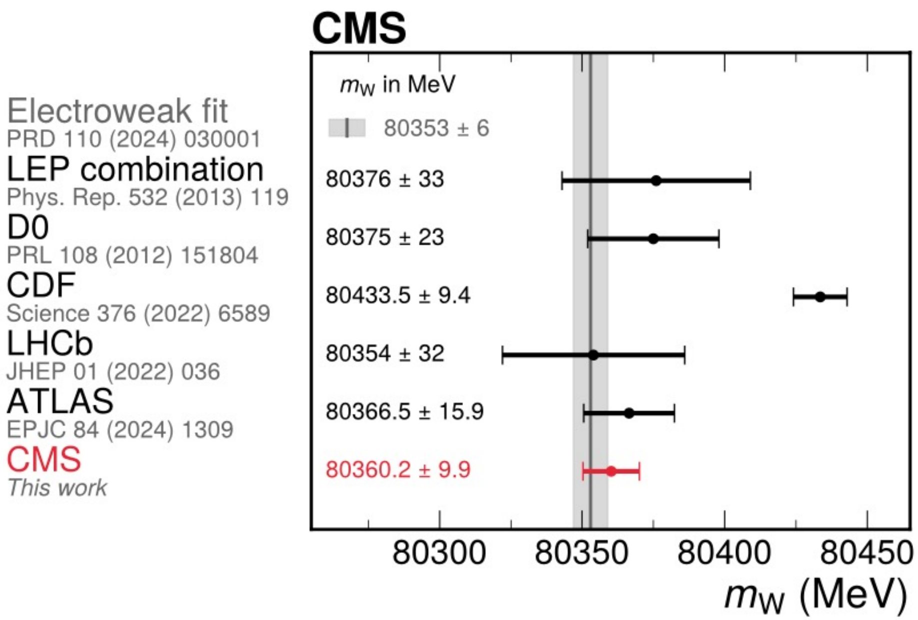


Current theoretical, PDF, α_s uncertainties compared with ‘S2’ scenario of halving in HL-LHC era → progress could be driven by LHeC PDFs

$\sqrt{s}$ [TeV]	$\sigma_{gg \to H}$ [pb]	TH uncertainty		PDF+α_S uncertainty			Total		
		Ref.	S2	Ref.	S2	S2+LHeC	Ref.	S2	S2+LHeC
14	54.7	3.9%	2.0%	3.2%	1.6%	0.5%	5.1%	2.6%	2.0%
27	146.6	4.0%	2.0%	3.3%	1.7%	0.6%	5.2%	2.6%	2.1%
100	804.4	4.2%	2.1%	3.7%	1.9%	0.7%	5.6%	2.8%	2.2%

Electroweak Gauge Boson Masses





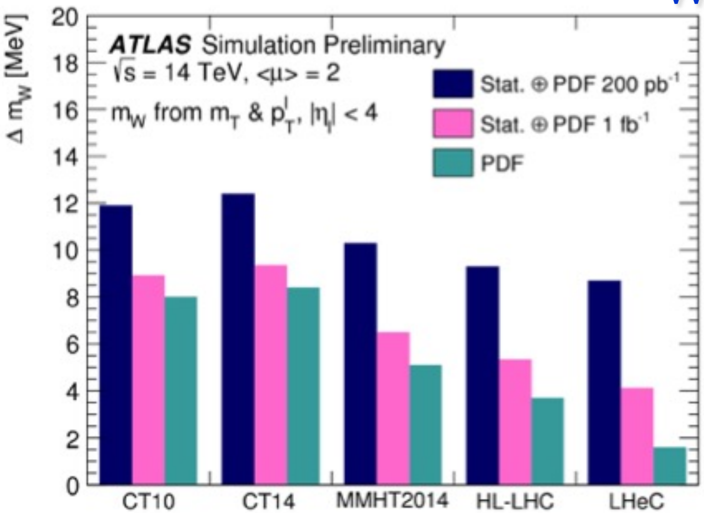
- M_Z dominated by LEP for foreseeable future

- EW SM fits predict M_W to 6 MeV

- LHC Collaborations had a remarkable impact on knowledge of M_W , now at 10 MeV level (CMS)

- Knowledge of initial state (PDFs) is a dominant systematic (5.7 MeV ATLAS, 4.4 MeV CMS)

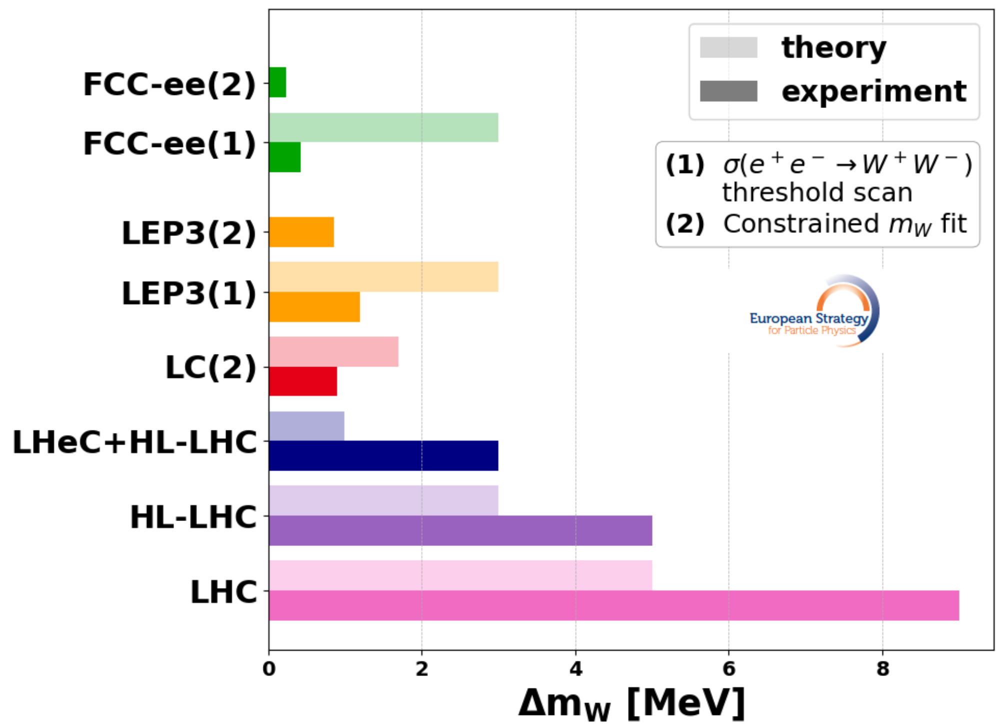
LHeC PDFs Empowering LHC through PDFs: M_W Measurement



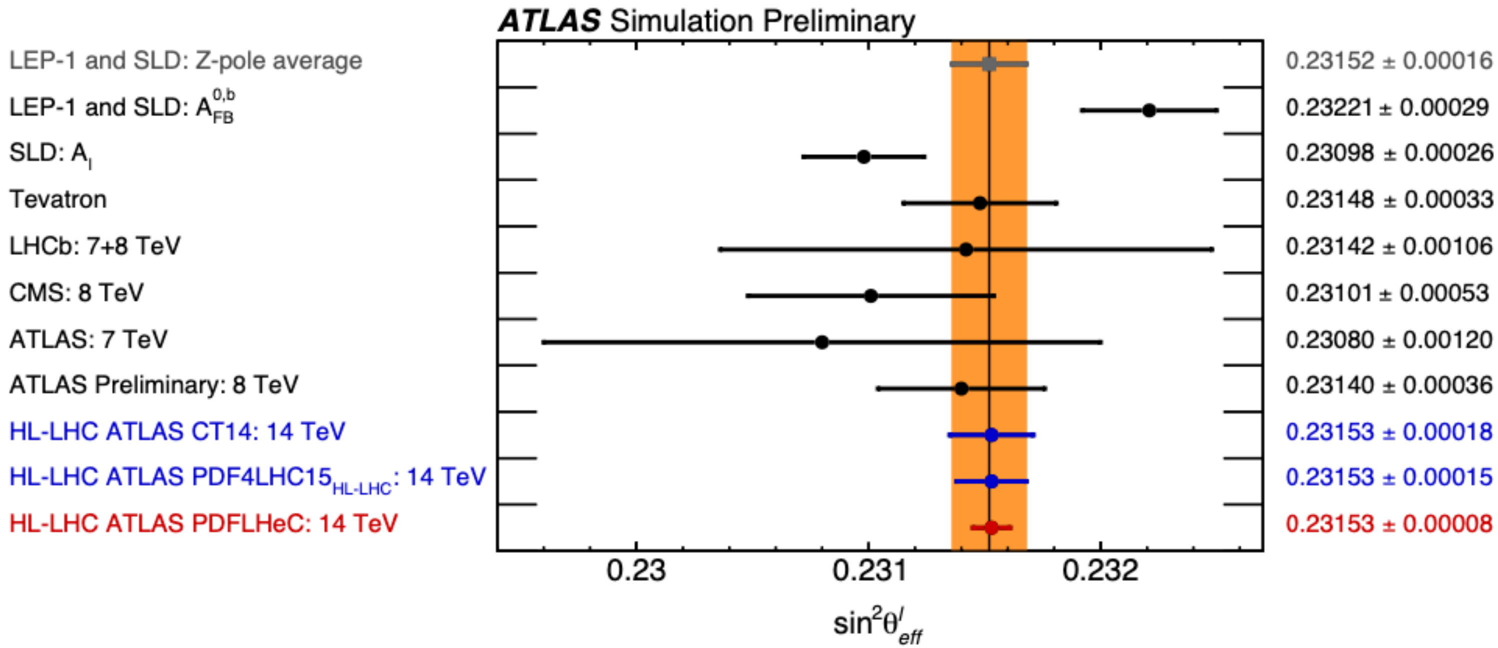
- PDF-related systematics on LHC M_W measurements are significant.

- Ultimate HL-LHC result anticipated to be ΔM_W ~ 5-6 MeV.
- Could be reduced to ~ 3 MeV with LHeC PDFs.

… would be the state of the art until the next energy-frontier collider



LHeC PDFs Empowering LHC through PDFs: EW Mixing Angle, $\sin^2\theta_W$



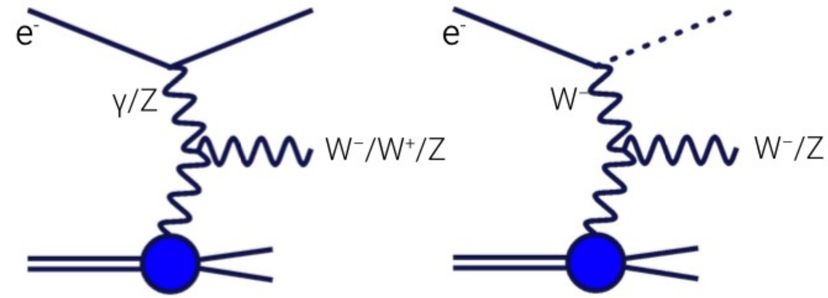
Parameter	Unit	ATLAS (Ref. [440])	HL-LHC projection		
		MMHT2014	CT14	HL-LHC PDF	LHeC PDF
Centre-of-mass energy, $\sqrt{s}$	TeV	8	14	14	14
Int. luminosity, $\mathcal{L}$	fb^{-1}	20	3000	3000	3000
Experimental uncert.	10^{-5}	± 23	± 9	± 7	± 7
PDF uncert.	10^{-5}	± 24	± 16	± 13	± 3
Other syst. uncert.	10^{-5}	± 13	–	–	–
Total uncert., $\Delta \sin^2\theta_W$	10^{-5}	± 36	± 18	± 15	± 8

- LHC measurements through A_{FB} in Drell-Yan ultimately limited by initial state PDF knowledge

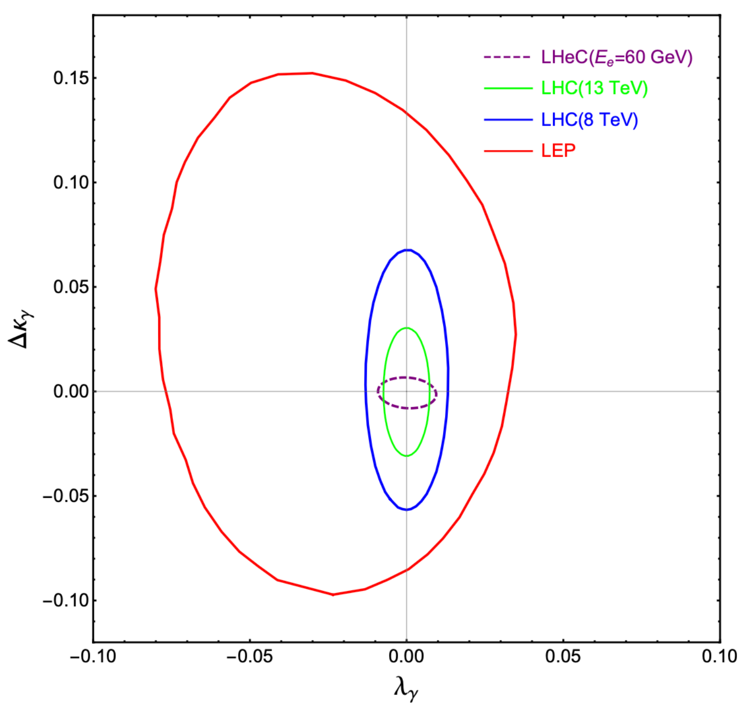
- LHeC PDFs enable measurement to $\Delta\sin^2\theta$ ~ 0.03%
  → factor 2 improvement on current or HL-LHC knowledge

Direct EW Boson Sensitivity at LHeC: Time-like

σ(W)~ 3pb,   σ(Z)~ 2pb



- W, Z samples ~10^6 events expected in LHeC data
- interesting, but not competitive for W, Z property measurements



Anomalous triple gauge couplings

… real Z production has sensitivity to
e.g. WWZ vertex

… real W production has sensitivity to
e.g. WWγ and WWZ vertices

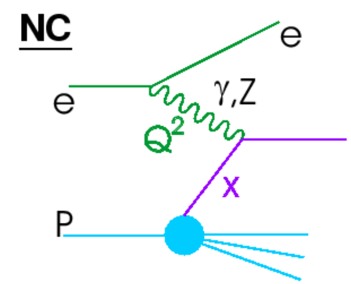
Interesting constraints, but probably not competitive in HL-LHC++ era

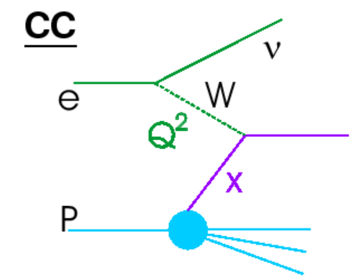
To be investigated further?

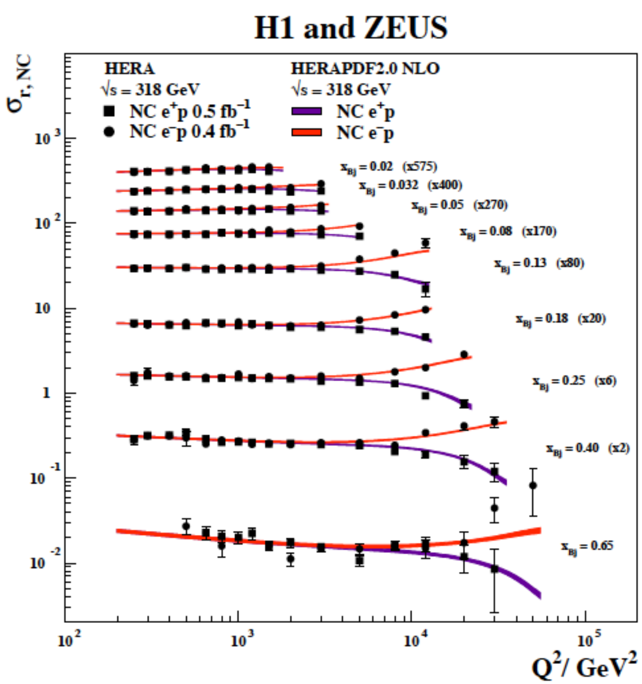
Direct EW Boson Sensitivity at LHeC: Space-like

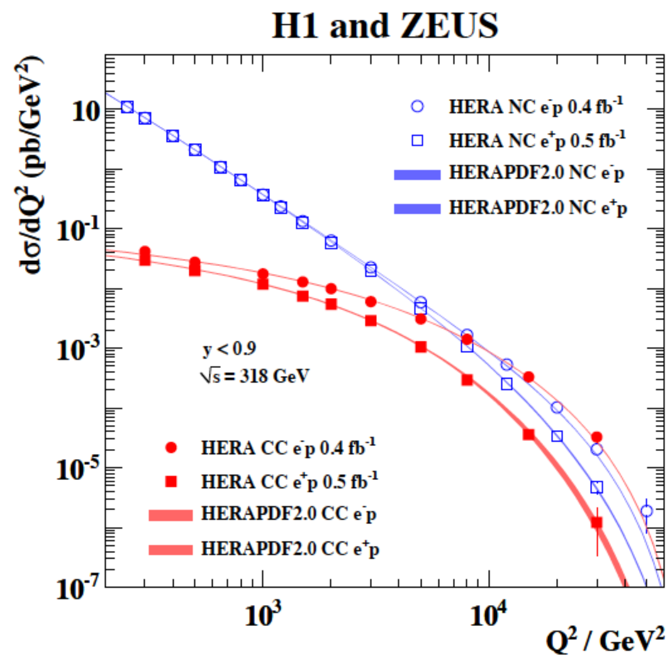
Electroweak effects via t-channel W and Z exchange give sensitivity to propagator properties and couplings at large Q^2

… inclusion in / extensions to PDF fits …





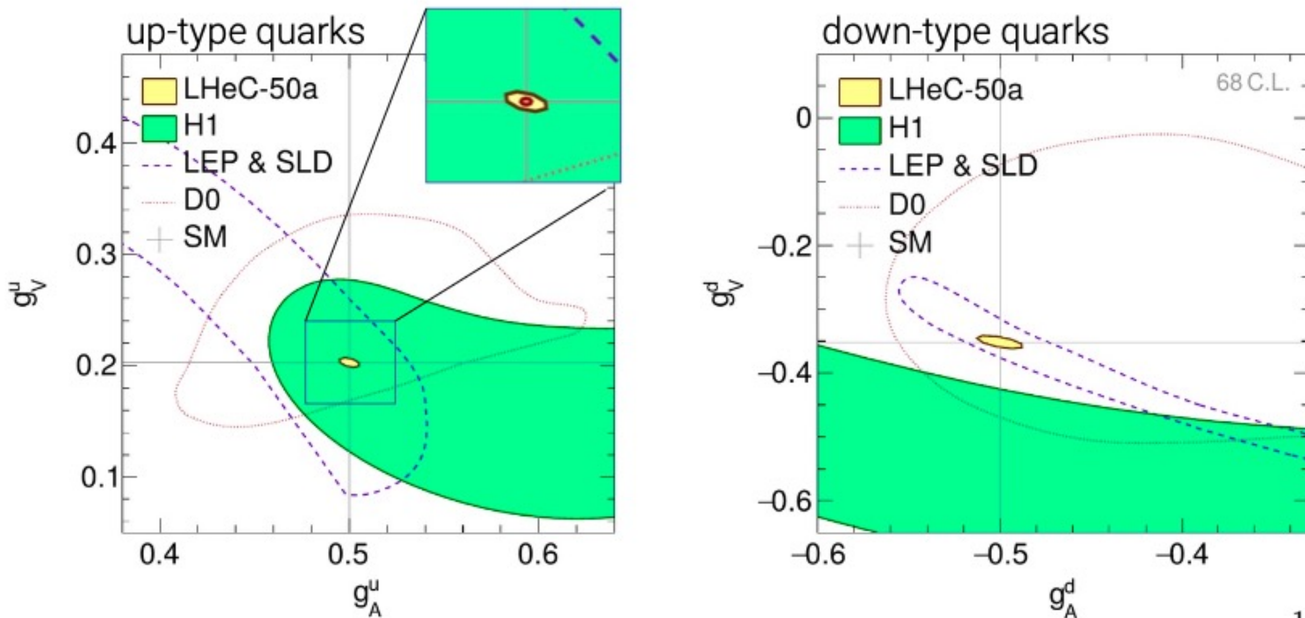




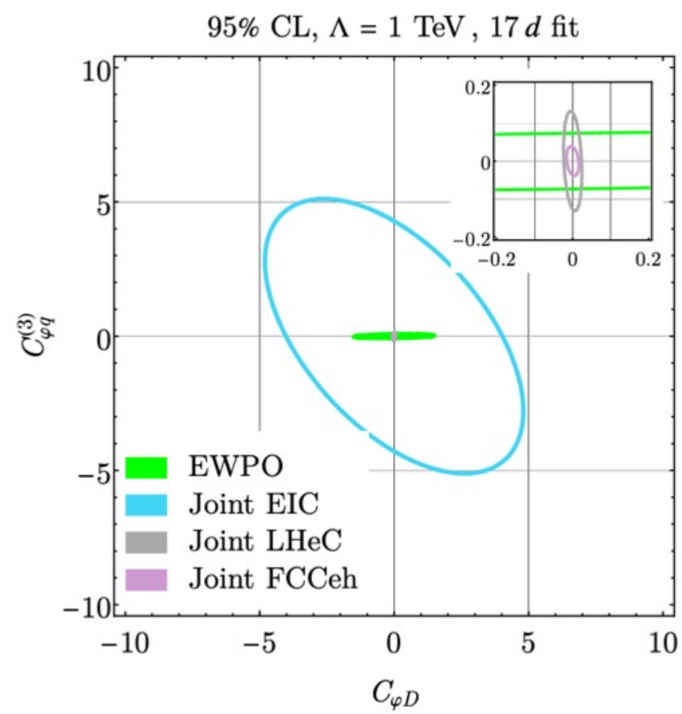
$$\Delta M_W(\text{LHeC-50}) = \pm 9_{(\text{exp})} \pm 8_{(\text{PDF})}\ \text{MeV} = 12_{(\text{tot})}\ \text{MeV}$$

(… interesting, but not world-leading)

Light quark Z couplings at LHeC



DIS is ideally suited to measuring light quark (vector & axial) Z couplings
→ Free parameters in PDF fits



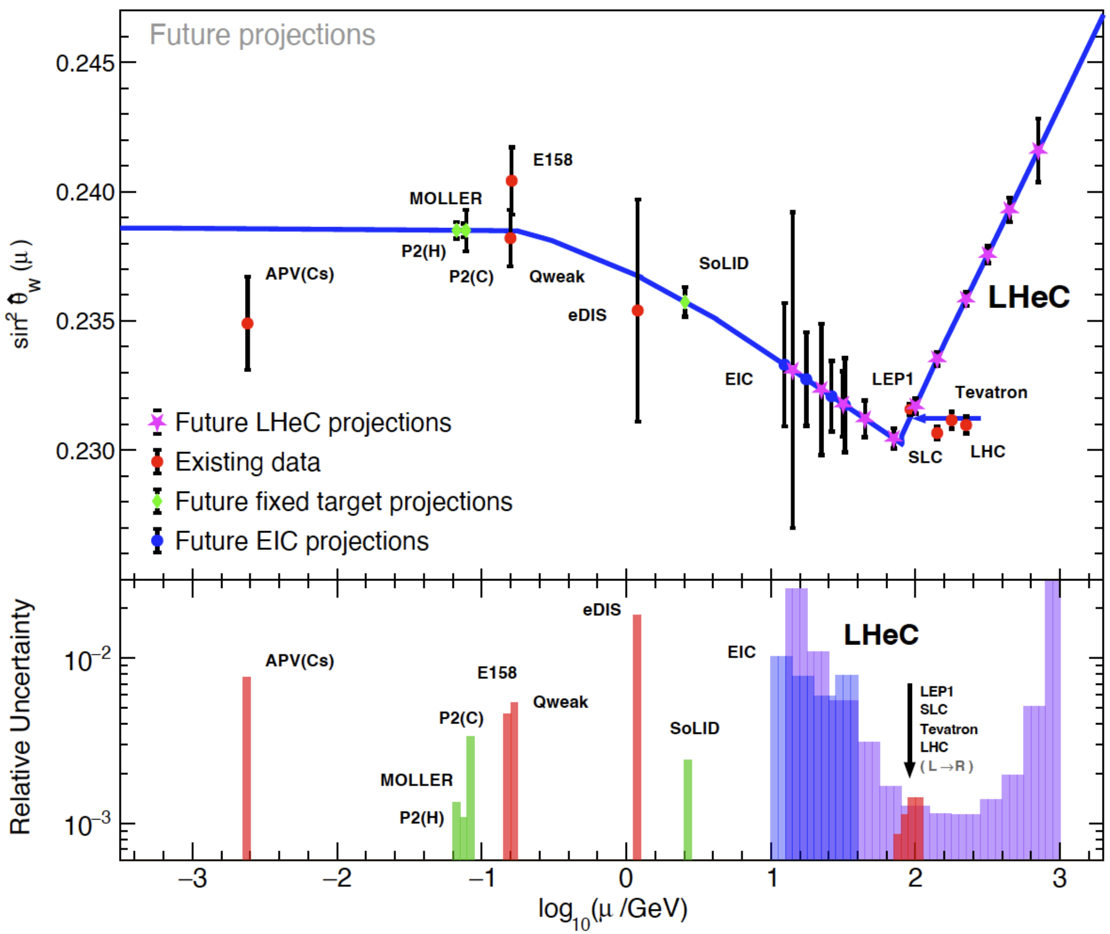
- Huge improvement over LEP / HERA

- 1% precision → order of magnitude improvement on now and would be world-leading in many future scenarios

- Can be reinterpreted in terms of competitive limits on dimension-6 SMEFT operators at 1 TeV UV cut-off scale

Electroweak Mixing Angle $\sin^2\theta_W$ at LHeC

LHeC sensitivity through polarization asymmetry and NC/CC ratios in fits



Globally: LHeC precision

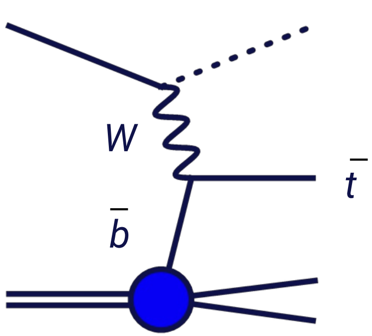
$$\Delta \sin^2\theta_W = \pm 0.00022$$

cf LEP precision ± 0.00016

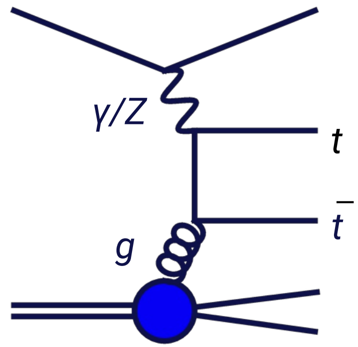
Global uncertainty will be similar to LEP and HL-LHC, but scale variation is unique (and complementary EIC – LHeC)

→ First high scale precision test of weak gauge structure

Top Physics at LHeC



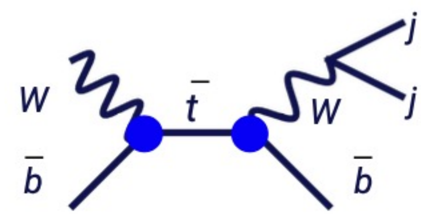
LHeC σ~ 1.9pb
FCC-eh σ~15.3pb



LHeC σ ~ 0.05pb
FCC-eh σ ~ 1.14pb

- Expect ~10^6 single top events in DIS
- ~10^4 t-tbar pairs (more in γp?)
- Complementary to LHC, where large t-tbar cross section makes single top studies more difficult

- Single top lends itself very well to investigating W boson couplings to quarks (i.e. the CKM mixing matrix elements)

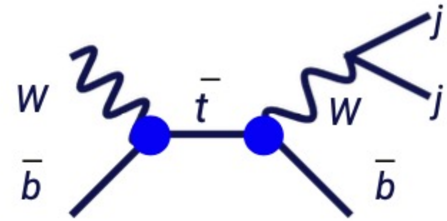


[PDG 2023]

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{bmatrix}$$

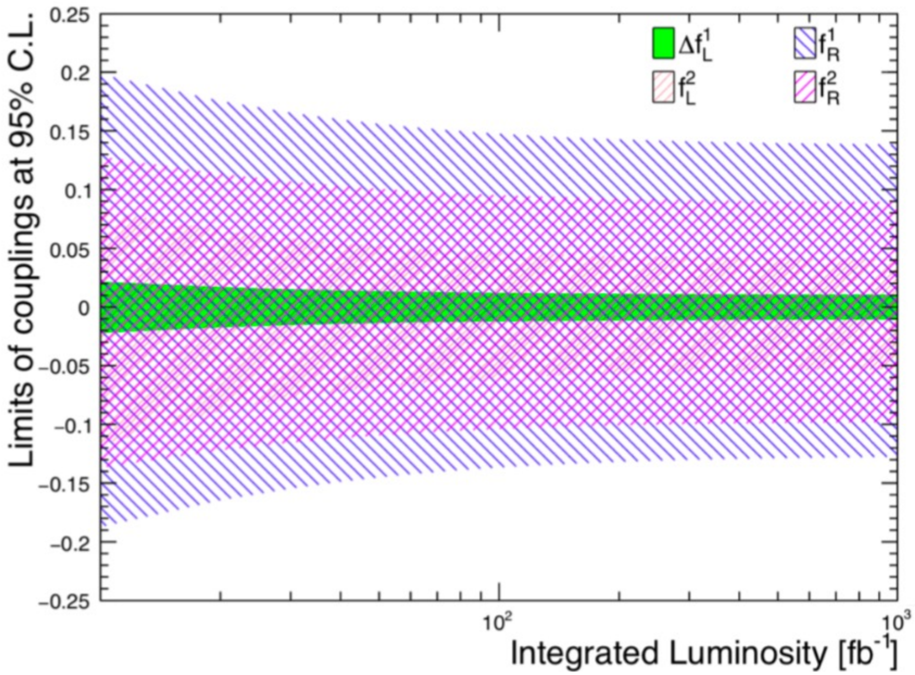
… V_{tb} very heavily dominant

CKM Matrix elements: Vtb



- Detailed cut-based simulation in hadronic W-decay channel suggests LHeC highly competitive among direct measurements

→ Expect ~1% V_{tb} precision (cf ATLAS 3.1%, CMS 2.4%)



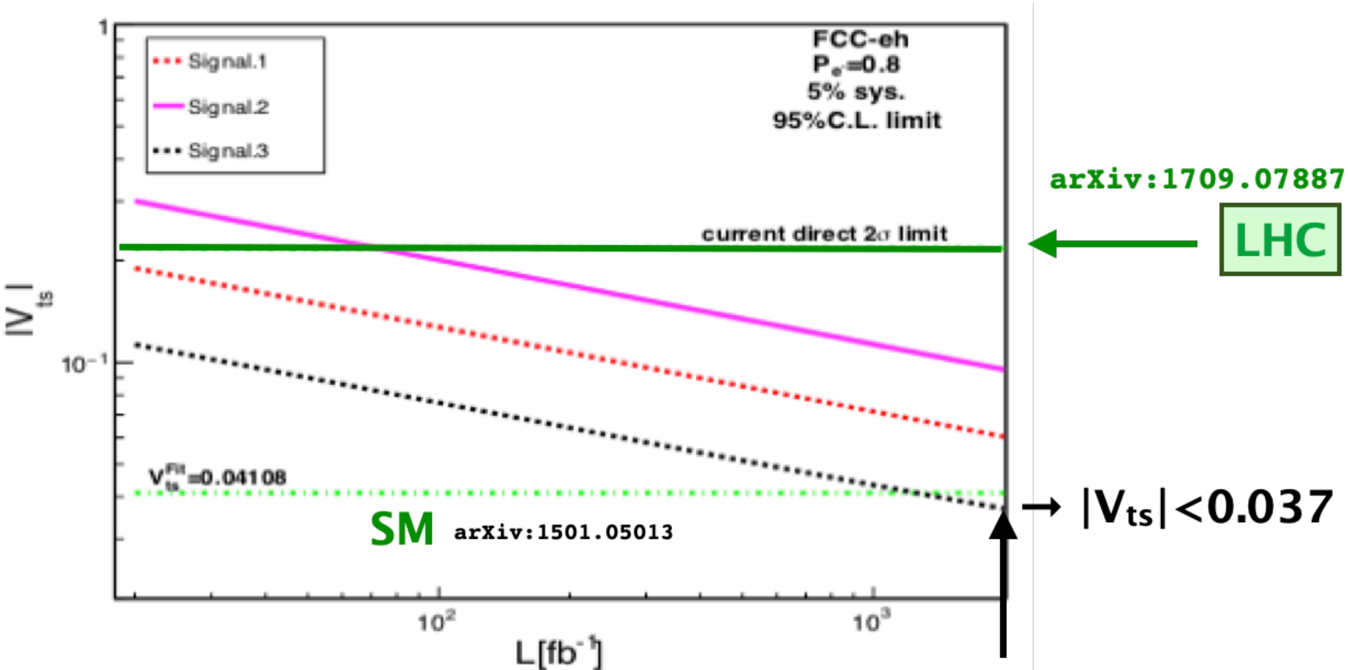
- Sensitivity to anomalous left & right handed W_{tb} vector (f_1^L, f_1^R) and tensor (f_2^L, f_2^R) couplings …

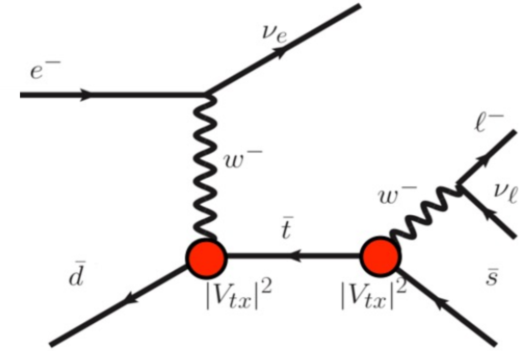
- In SM only f_1^L exists

- Expected 95% confidence limits on f_1^R , f_2^L exotic couplings better at LHeC than HL-LHC

Anomalous Wtb Coupling	f_R^1	f_L^2	f_R^2
HL-LHC, 3000 fb^{-1} ($\mathcal{R}e$)	[-0.28,0.32]	[-0.17,0.19]	[-0.05,0.02]
HL-LHC, 3000 fb^{-1} ($\mathcal{I}m$)	[-0.30,0.32]	[-0.19,0.18]	[0.11,0.10]
LHeC, 1000 fb^{-1} ($\mathcal{R}e$)	[-0.13,0.14]	[-0.05,0.04]	[-0.10,0.09]

CKM Matrix Element V_{ts} (and V_{td})





S1: $\nu_e \ell^- \nu_\ell \bar{b}$

S2: $\nu_e \ell^- \nu_\ell b$

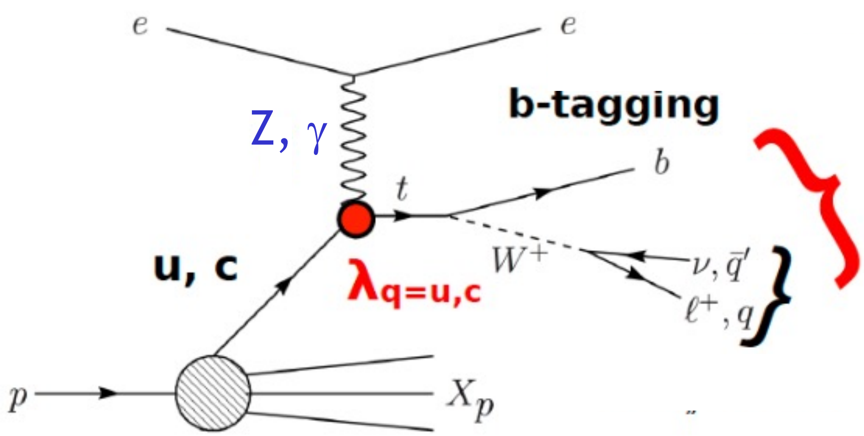
S3: $\nu_e \ell^- \nu_\ell j$

- Three different signals studied: statistically limited
- Projected V_{ts} limit/sensitivity at level of value obtained from indirect global CKM fit ($|V_{ts}| = 0.04108^{+0.0030}_{-0.0057}$).

→ Potential for first direct measurement?

- V_{td} limit at similar level to V_{ts}

Anomalous Flavour Changing Neutral Current Top Couplings

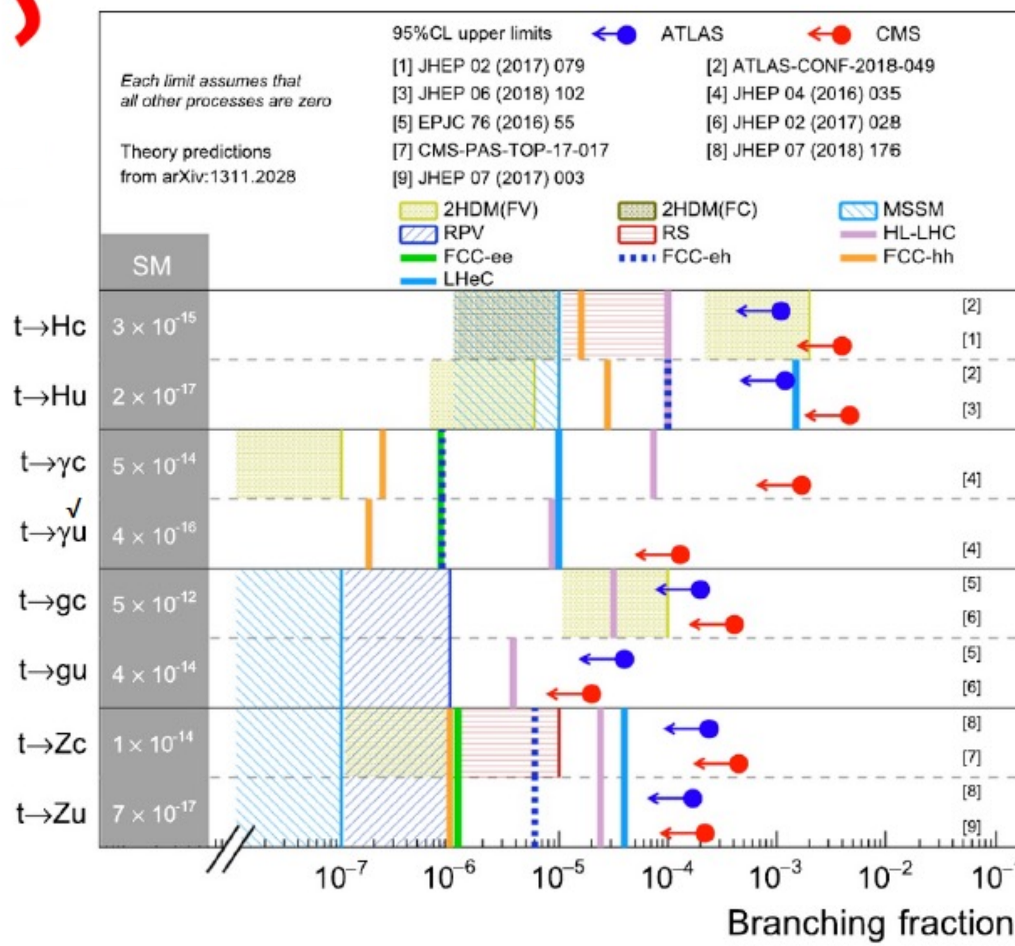


Sensitivity through channel:

$$e^- p \rightarrow e^- W b + X$$

From detailed cut-based study, LHeC gives …

- Better sensitivity than HL-LHC for tγc coupling
- Comparable sensitivity to HL-LHC for tγu coupling
- Slightly worse than HL-LHC for tZc and tZu



Summary

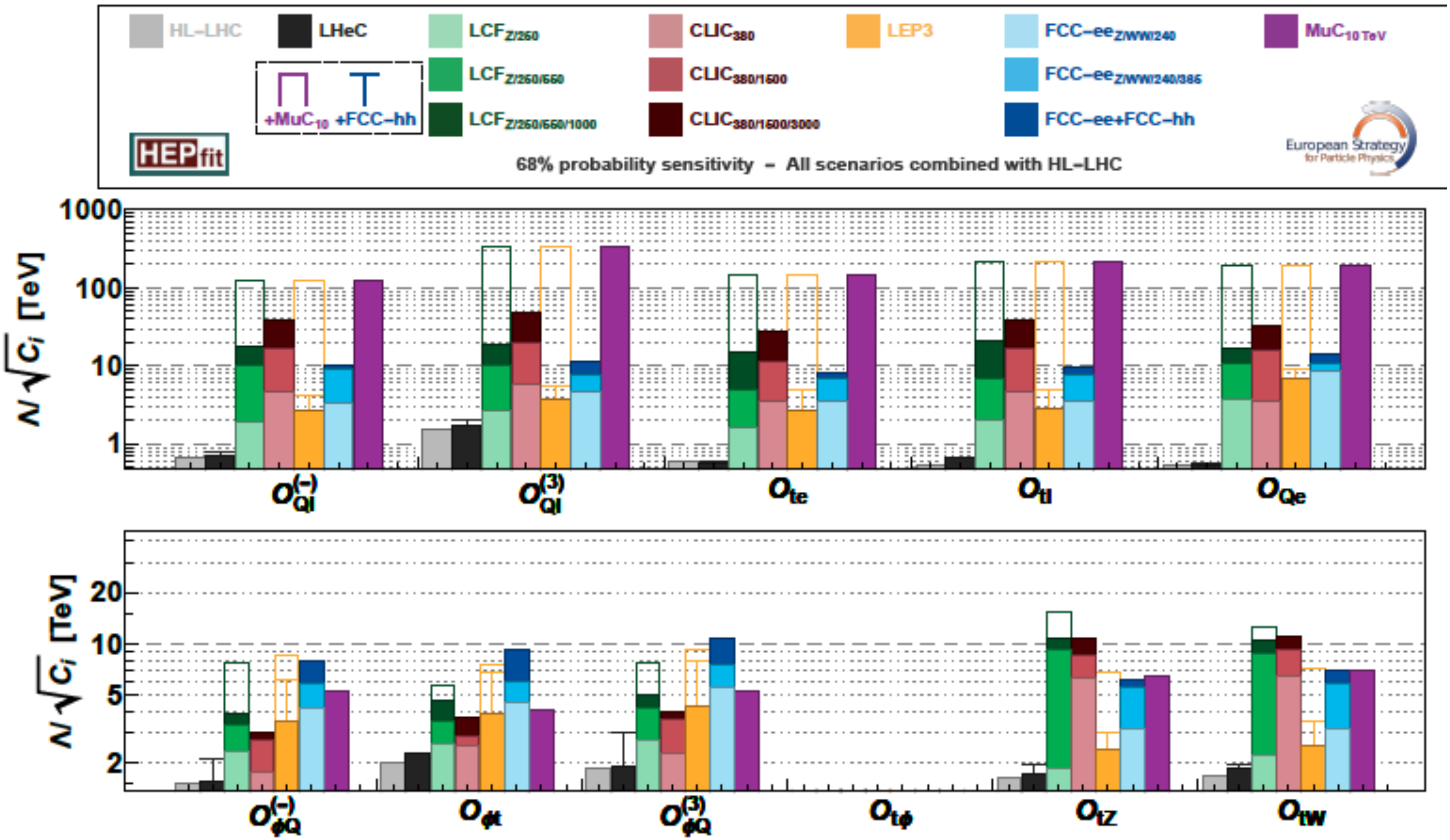
- LHeC enables significant opportunities in EW physics:
  … Improving HL-LHC programme through PDFs, eg in M_W and $\sin^2\theta_W$
  … Standalone sensitivity to light quark EW couplings

- LHeC enables significant opportunities in top Physics:
  … Sensitivity to single top / CKM complementary to HL-LHC
  … Competitive sensitivity to top FCNC couplings

- Also on LHeC at DIS26:
  - QCD at the LHeC, Francesco Giuli, 05/05/2026, 09:20, WG6
  - A detector for top energy DIS, Laurent Forthomme, 05/05/2026, 09:40, WG6
  - Two-photon interactions at the LHeC, Laurent Forthomme, 06/05/2026, 10:20, WG6
  - Energy recovery linacs: from PERLE to the LHeC, Achille Stocchi, 06/05/2026, 11:40, WG6
  - Higgs and BSM physics at the LHeC, Néstor Armesto, 06/05/2026, 15:10, WG6
  - The EPPS proposal and LHeC perspectives, Jorgen D'Hondt, 08/05/2026, 09:00, Plenary

“Circles in a circle”, Wassily Kandinsky (1923), Philadelphia Museum of Art

Vtb and sensitivity to SMEFT Operators



I'm sure this means something! HELP!

FCNC and Sensitivity to SMEFT Operators