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# Beyond-the-Standard-Model searches at the **L**arge **H**adron-**e**lectron **C**ollider and the **E**lectron-**I**on **C**ollider

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2304._____

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*Prelude*

# LHeC and EIC

## *A Tale of Two Colliders*

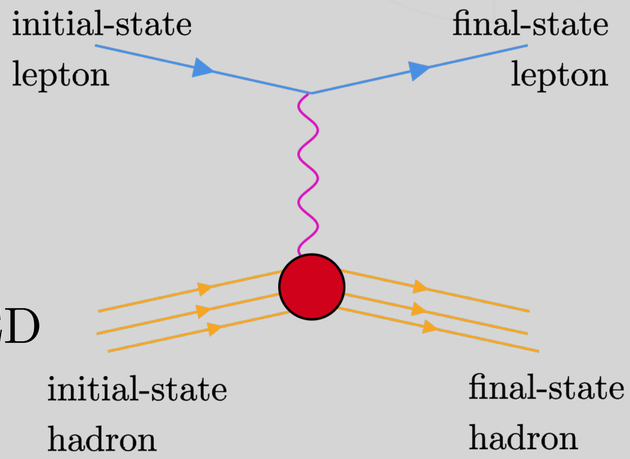
*"It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way—in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil, in the superlative degree of comparison only."*

*C. Dickens*

# Next-gen $e^-$-hadron colliders: LHeC and EIC

$e^-$-hadron colliders: [Brüning *et al.* FPhy(2022)]

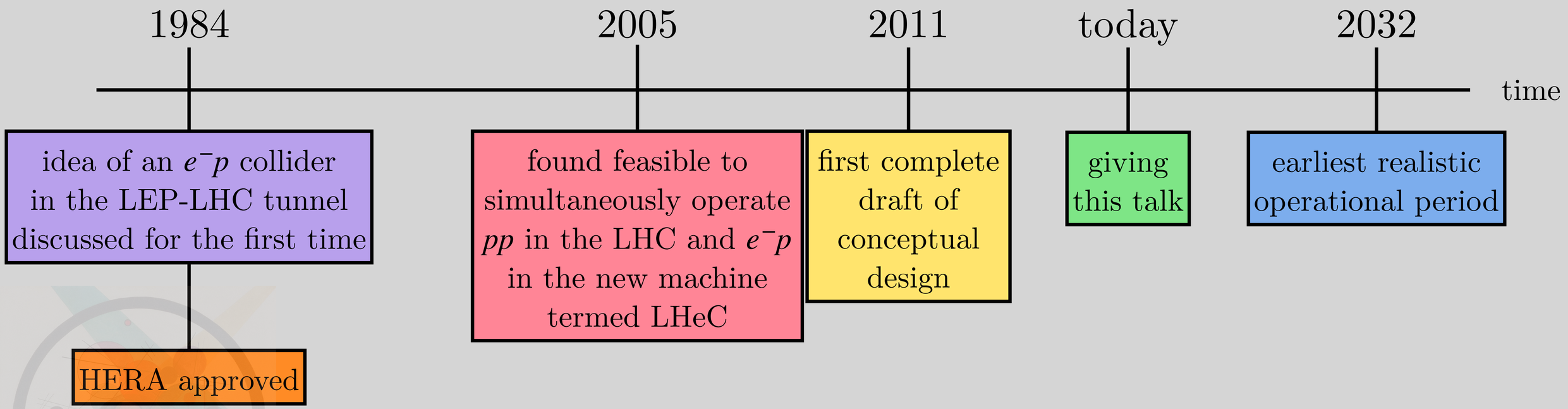
- Ultimate tool for high-precision QCD studies
- Ultimate *microscope* for probing internal structure of hadrons
- $e^-$ is an ideal probe of proton structure due to unmatched precision of QED
  - ➡ Clean environment (no color interactions)
  - ➡ Kinematics uniquely determined by $e^-$ beam, scattered lepton, or hadronic final state




- *Hadron-Elektron-Ringanlage* (HERA@DESY, Germany) was the only $e^-H$ collider ever operated (1991-2007).
- **L**arge **H**adron-**e**lectron **C**ollider (LHeC@CERN, Switzerland) is awaiting approval.
- Construction of **E**lectron-**I**on **C**ollider (EIC@BNL, NY) will start in 2024.

# Large Hadron-electron Collider

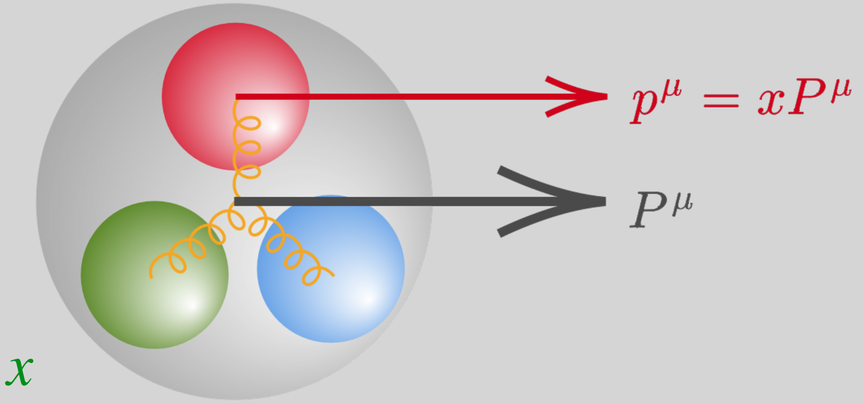
*A next-gen electron-hadron collider* [Fernandez *et al.* 1206.2913]



# Large Hadron-electron Collider

*A next-gen electron-hadron collider* [Fernandez *et al.* 1206.2913]

- Center-of-mass energies of $\sqrt{s} \simeq 1.5$ TeV for cross-section measurements:
  - ➡ Searches and analysis for BSM physics
  - ➡ Novel measurements in QCD
  - ➡ Electroweak physics to unprecedented precision
  - ➡ Deep-inelastic-scattering (DIS) physics at low Bjorken $x$




- Upgrade of the LHC, an $e^- p$ collider operating at an energy frontier
- Needs the LHC proton/ion beams so synchronous $pp$ and $e^- p$ runs

# Electron-Ion Collider

*A next-gen electron-hadron collider* [Accardi *et al.* 1212.1701]

- A US DOE project under design at BNL, Upton, NY.
- It will use the Relativistic Heavy Ion Collider acceleration complex.
- It will be the first lepton-ion collider with both beams polarized.
- Center-of-mass energies between fixed-target scattering and high-energy collisions, 70 to 140 GeV, with electron beams of 5 to 18 GeV, proton beams of 41 to 275 GeV, and heavy ion beams of 137 GeV ($^2$H) and 166 GeV ($^3$He).
- Luminosity will be orders of magnitude higher than HERA.
- Reduced point-to-point luminosities $\sim 10^{-4}$.
- It is planned to start operating in a decade.

# Observables of interest

At the LHeC:

$\sigma^{\pm}_{\mathrm{NC}}$ : unpolarized NC $e^{-}H$ DIS cross section with only lepton beam polarized

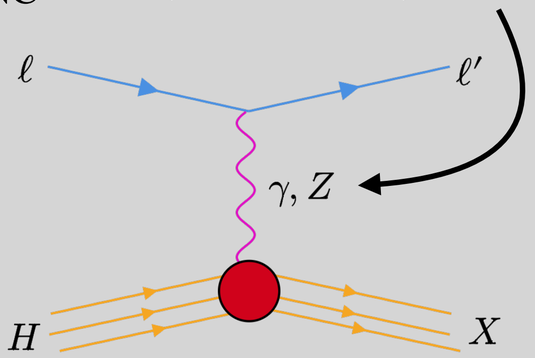
At the EIC:

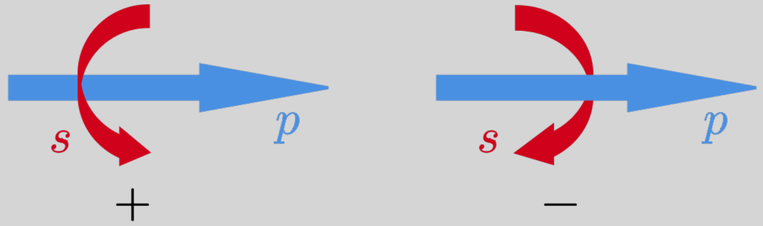
$$A_{\mathrm{PV}} = \frac{\sigma^{+}_{\mathrm{NC}} - \sigma^{-}_{\mathrm{NC}}}{\sigma^{+}_{\mathrm{NC}} + \sigma^{-}_{\mathrm{NC}}}$$ unpolarized PV asymmetry

$$\Delta A_{\mathrm{PV}} = \frac{\Delta\sigma^{0}_{\mathrm{NC}}}{\sigma^{0}_{\mathrm{NC}}}$$ polarized PV asymmetry

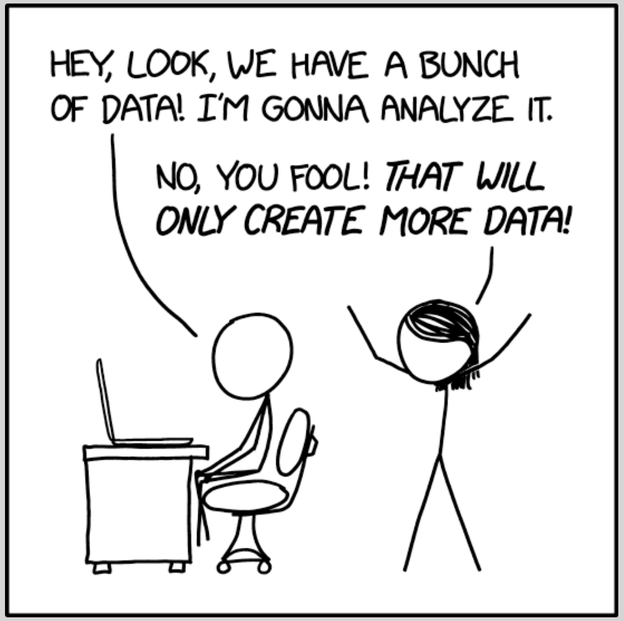
$(\Delta)\sigma^{\pm}_{\mathrm{NC}}$ : un(polarized) NC $e^{-}H$ DIS cross section with only one beam polarized

$(\Delta)\sigma^{0}_{\mathrm{NC}}$ : un(polarized) NC $e^{-}H$ DIS cross section with no beams polarized

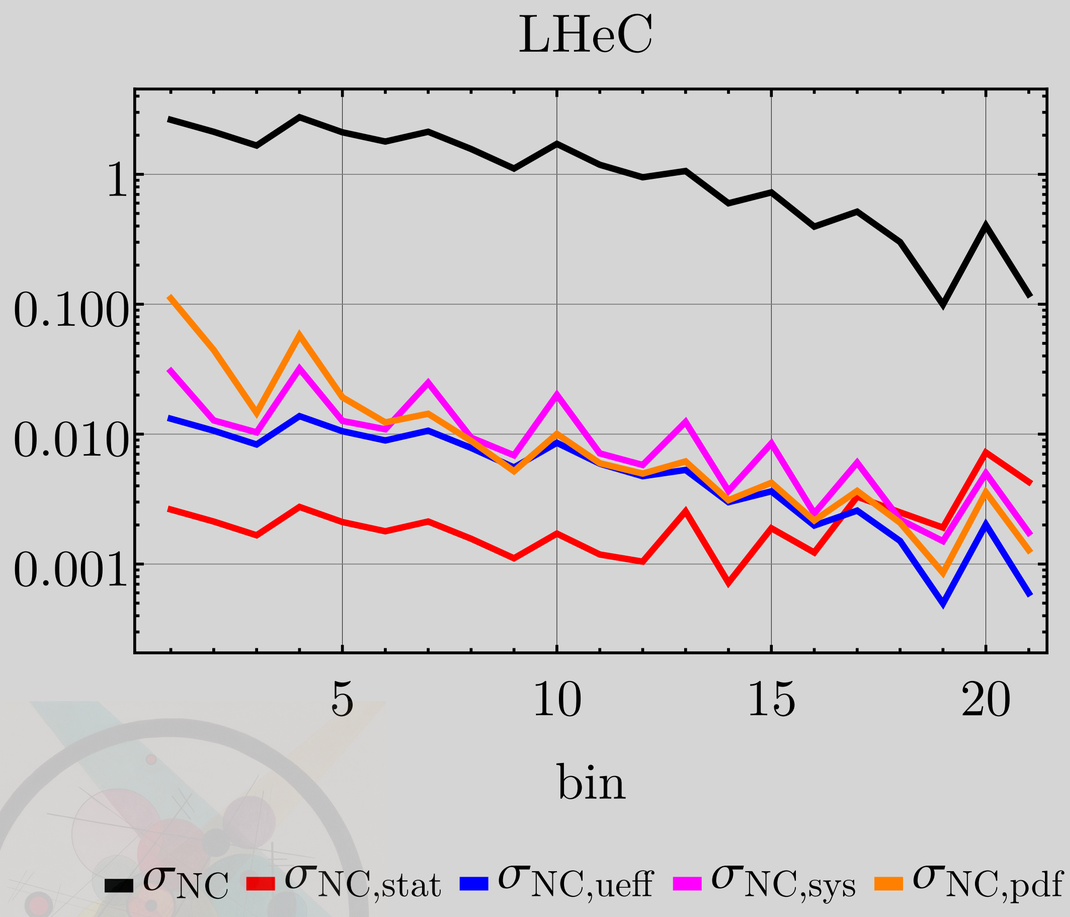


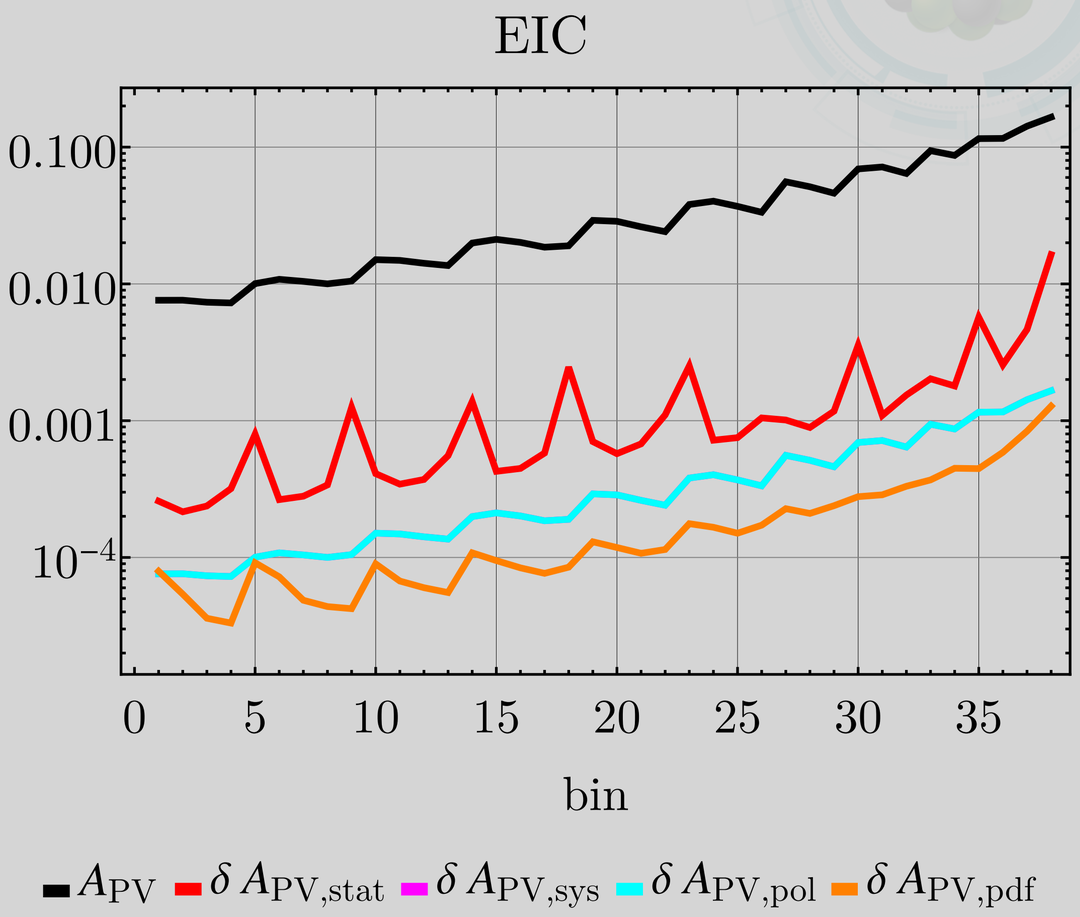
# Data analysis



# Error budget




Systematics dominate.




Statistical uncertainties dominate.

# BSM framework: **S**tandard **M**odel **E**ffective **F**ield **T**heory

What is SMEFT?

Model-independent extension of the SM Lagrangian with higher-dimensional operators, $O_k^{(n)}$, built up of SM fields at an energy scale $\Lambda$ that is heaver than all SM fields and accessible collider energy, introducing Wilson coefficients, $C_k^{(n)}$, as effective couplings:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_{n>4} \frac{1}{\Lambda^{n-4}} \sum_k C_k^{(n)} O_k^{(n)}$$

Why SMEFT?

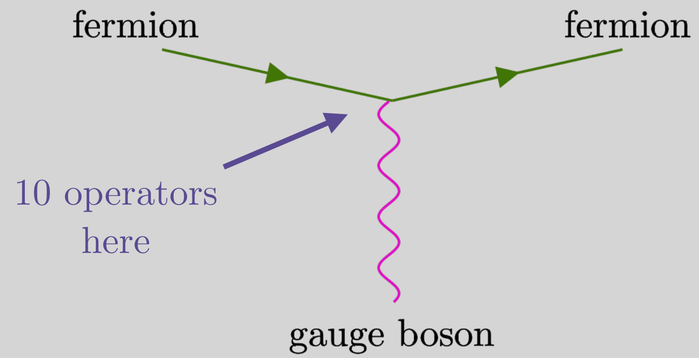
There has been no conclusive evidence for particles beyond the SM.

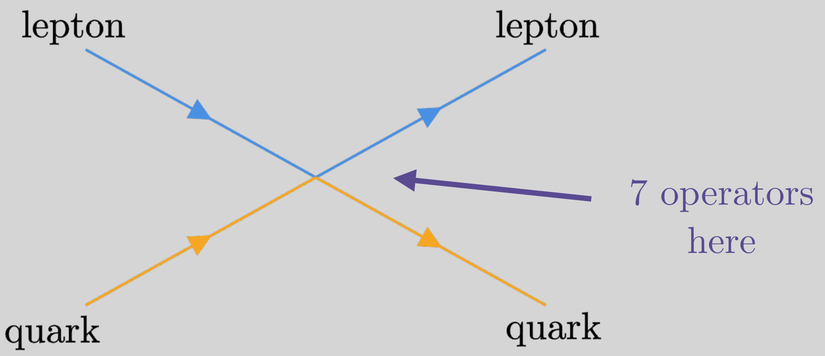
# BSM framework: **S**tandard **M**odel **E**ffective **F**ield **T**heory

Case of dimension 6 relevant to our study:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda^2} \sum_{k=1}^{17} C_k O_k$$

SMEFT Lagrangian obeys the symmetries of the SM Lagrangian, i.e. SM couplings are shifted in a gauge invariant manner.




$$V^{\mu}_{ffV} = V^{\mu(\mathrm{SM})}_{ffV}[1 + \mathscr{O}(C_k)]$$



$$V_{\ell\ell qq} = \mathscr{O}(C_k)$$

# Fitting procedure

Observables, unpolarized cross section and un(polarized) PV asymmetries, are linearized w.r.t. $C_k$:

$$\mathcal{Q} = \mathcal{Q}_{\rm SM} + \sum_k C_k \; \delta\mathcal{Q}_k \qquad\qquad \mathcal{Q} = \sigma_{\rm NC}, (\Delta) A_{\rm PV}$$

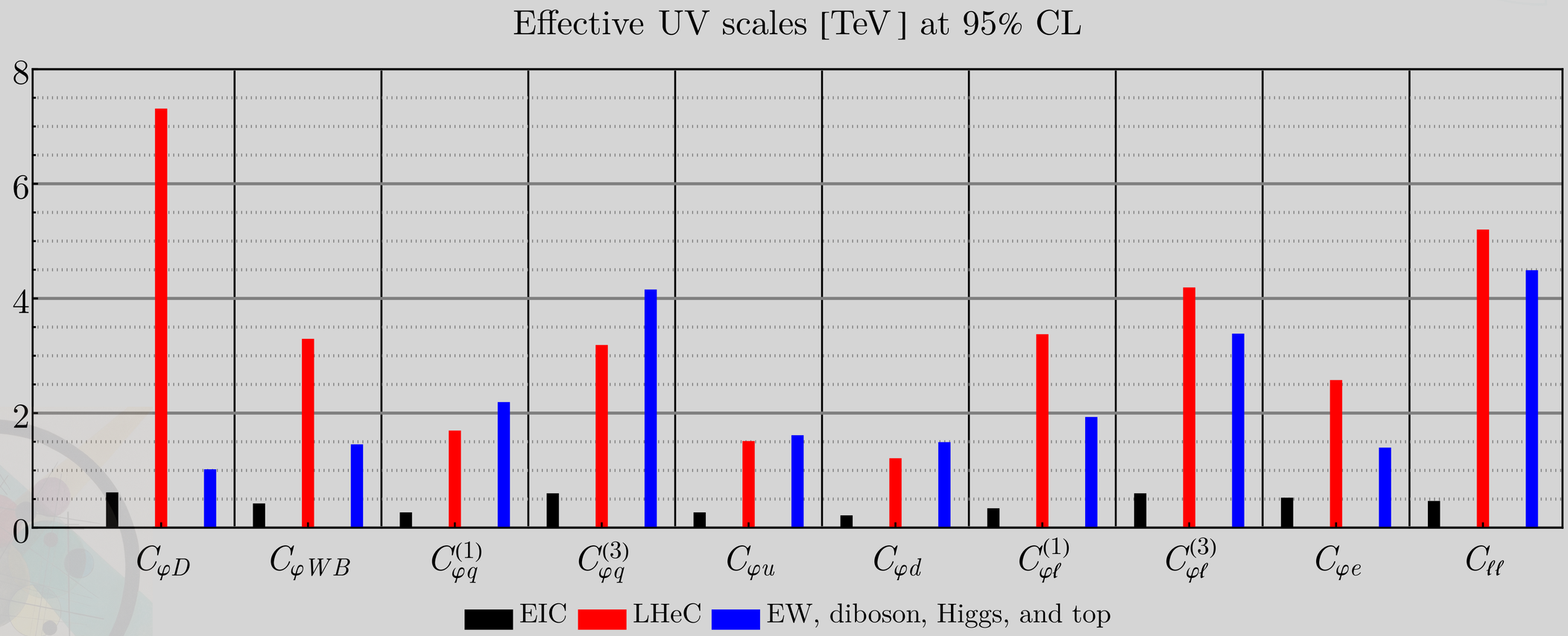
Fitting procedure:

$$\chi^2 = (\mathcal{Q} - \mathcal{Q}_{\rm pseudodata})^\top H (\mathcal{Q} - \mathcal{Q}_{\rm pseudodata})$$

where pseudodata is generated by smearing uncertainties around the SM predictions with a Gaussian profile.

# Fit results

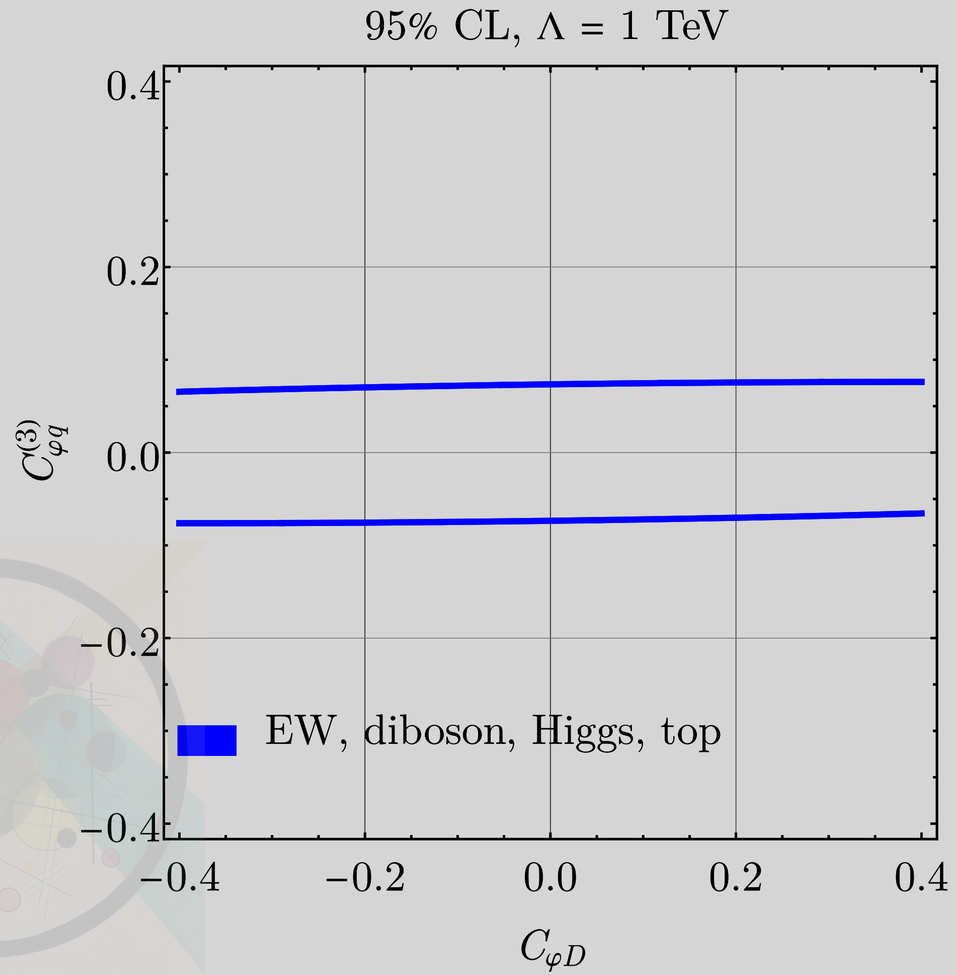
Marginalized effective UV scales that can be probed for BSM searches:

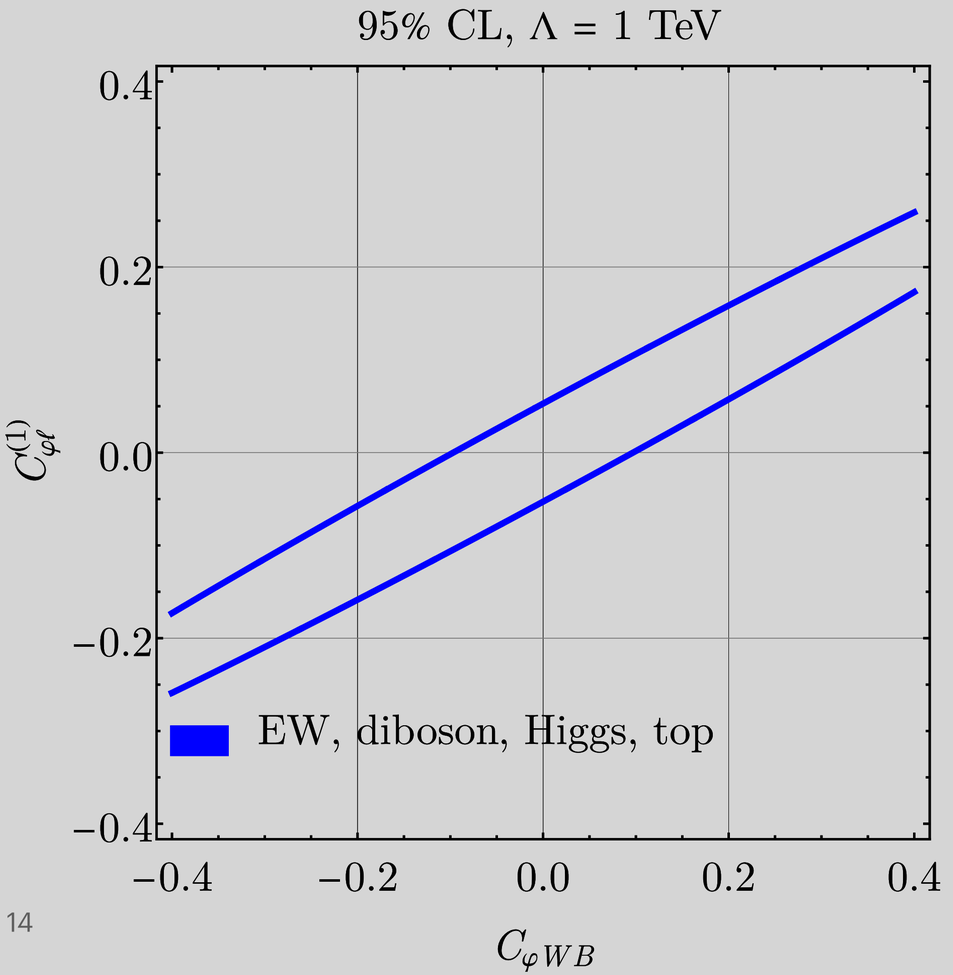



34-parameter EW, diboson, Higgs, and top data fit is adapted from [Ellis *et al.* 2012.02779].

# Fit results

Marginalized confidence ellipses:

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# Fit results

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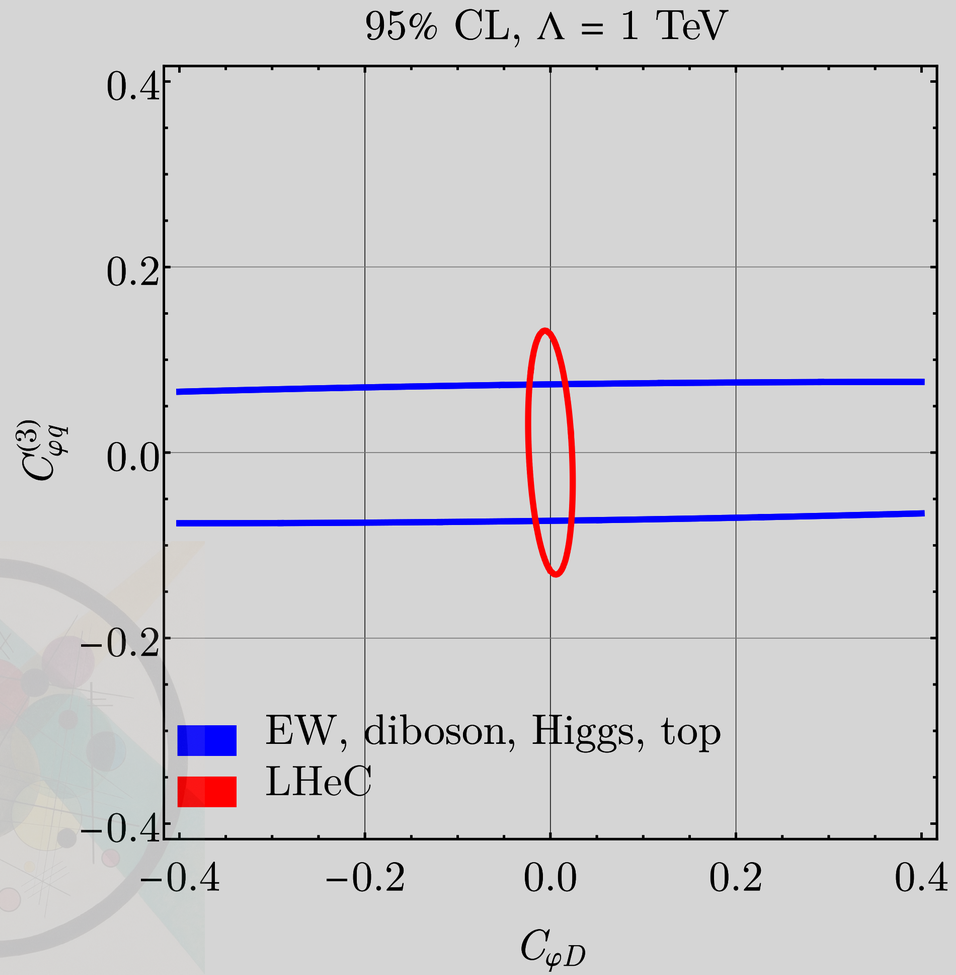


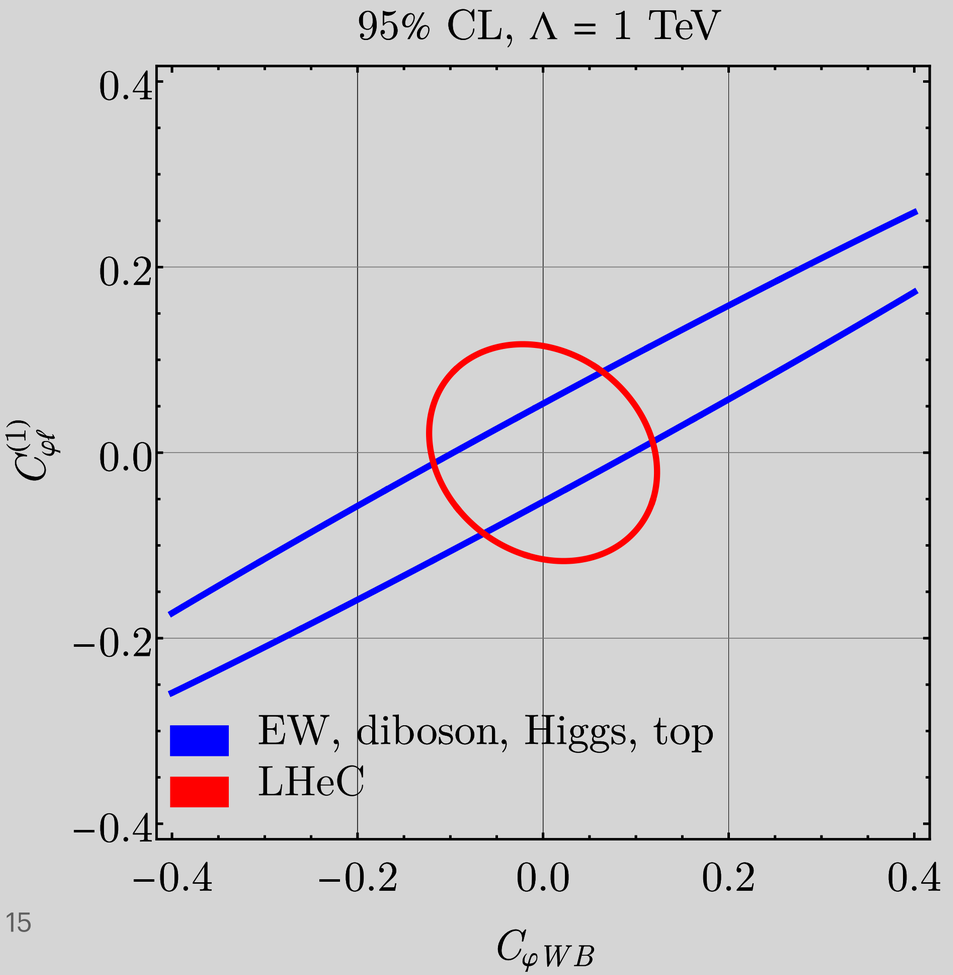


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# *Coda*

# Conclusion

- The LHeC and the EIC will offer distinct correlations, showing complementarity.
- The LHeC will be superior to the EIC in constraining BSM parameters, therefore in probing deeper energy levels, thanks to higher energy reach.
- Both promise to resolve blind spots in more extensive fits with electroweak pole measurements, diboson, Higgs, and top quark data.

The LHeC and the EIC are designed as EW and QCD machines but seem promising as useful probes of new physics. Therefore, the taxpayer's money is wisely spent.