Transverse single-spin asymmetries within and beyond the Standard Model

Frank Petriello

Based on: Boughezal, de Florian, FP, Vogelsang PRD 107 (2023) 7, 075028

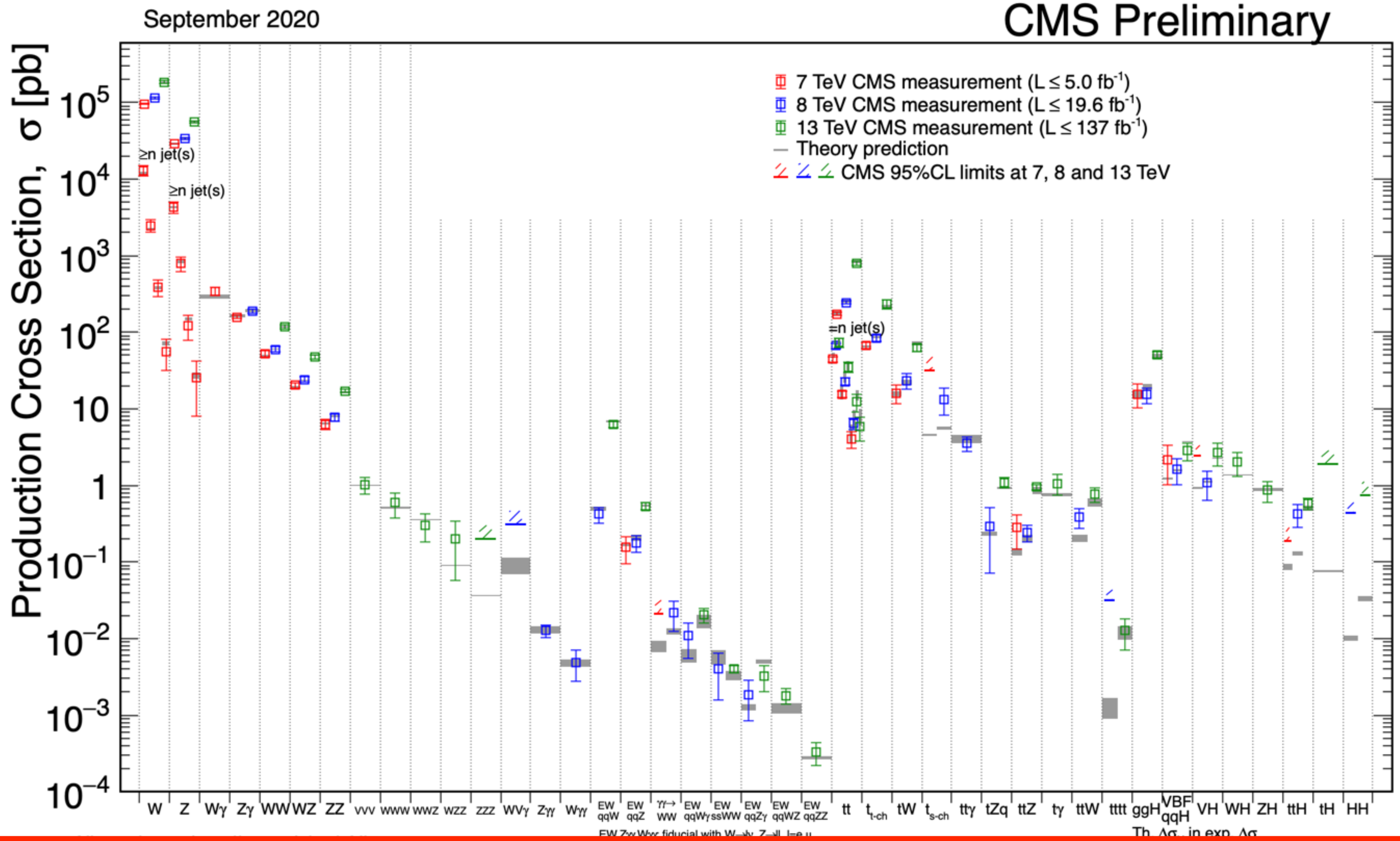
SPIN 2023

September 25, 2023

Northwestern University

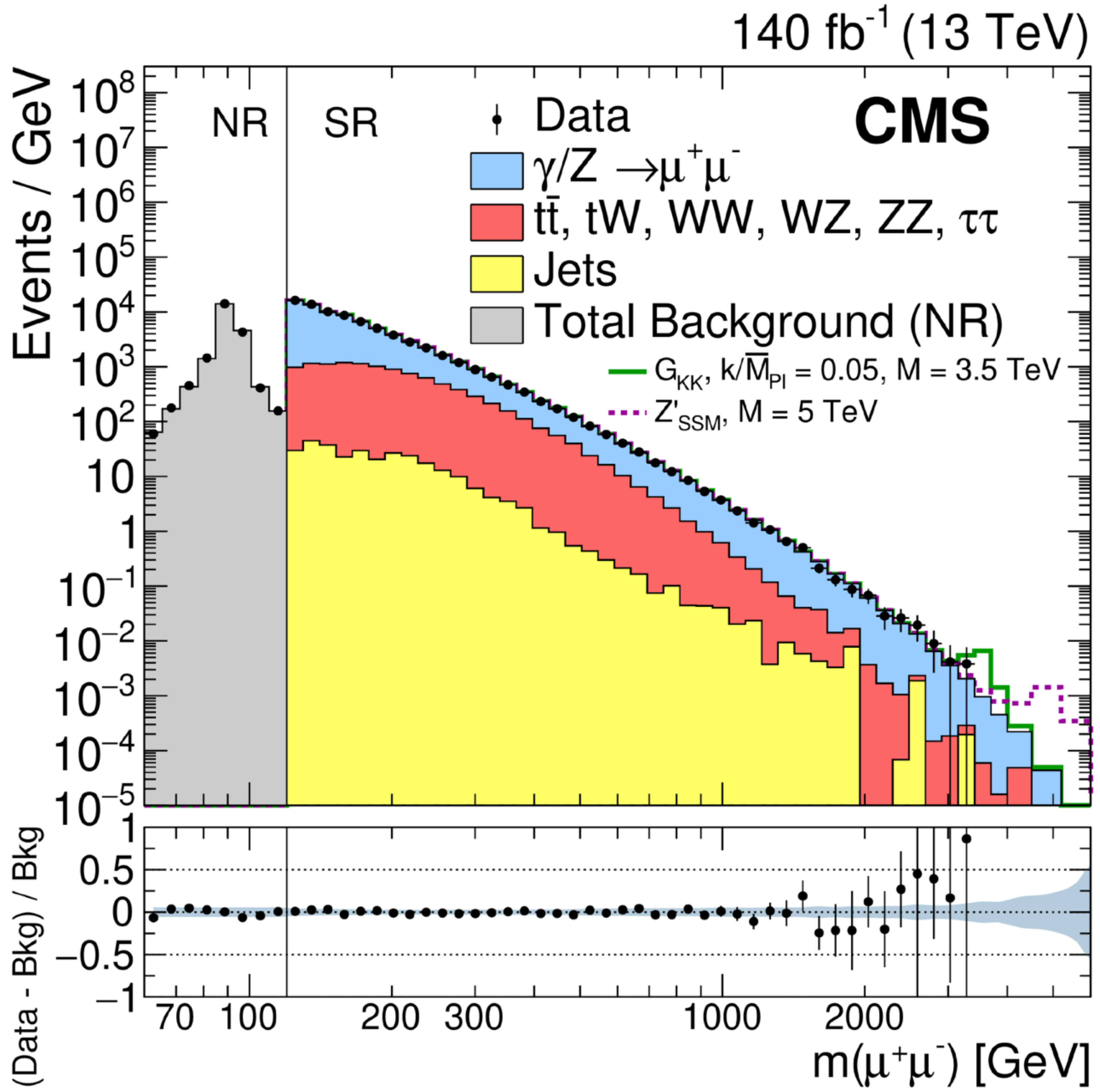
Argonne NATIONAL LABORATORY

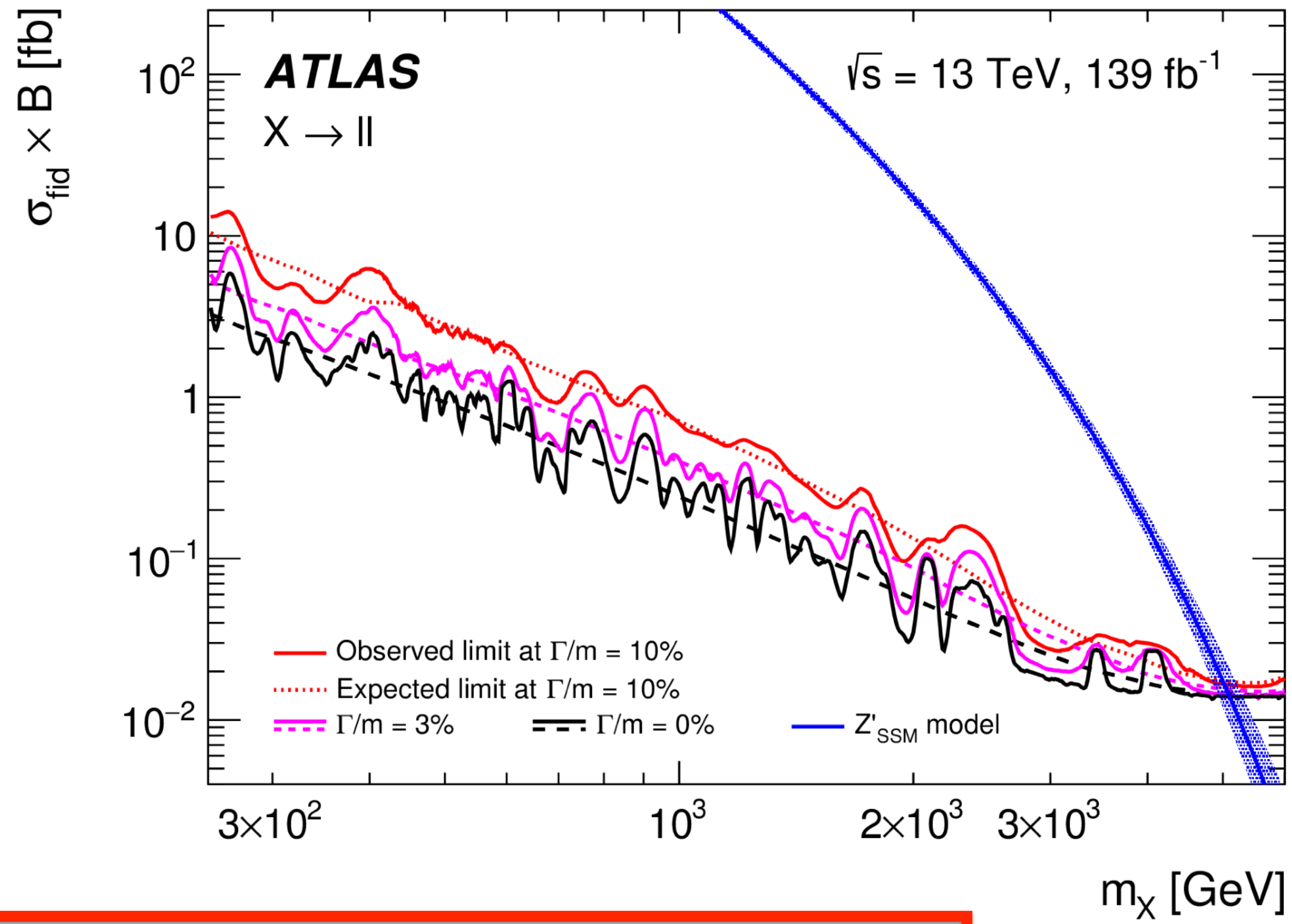
Status of the Standard Model



Remarkable agreement between SM theory and experiment over dozens of processes and orders of magnitude in cross section. No BSM deviation found so far!

Resonance searches





Sensitivity to new resonances has reached 5 TeV in some models. Suggests a mass gap between SM and new physics; indirect searches increasingly important

EFT frameworks for new physics searches

- The Standard Model Effective Field Theory is an EFT framework that encapsulates both the lack of new particles beyond the SM, and a mass gap between the SM and any new states. It provides a well-defined framework for current and future studies.

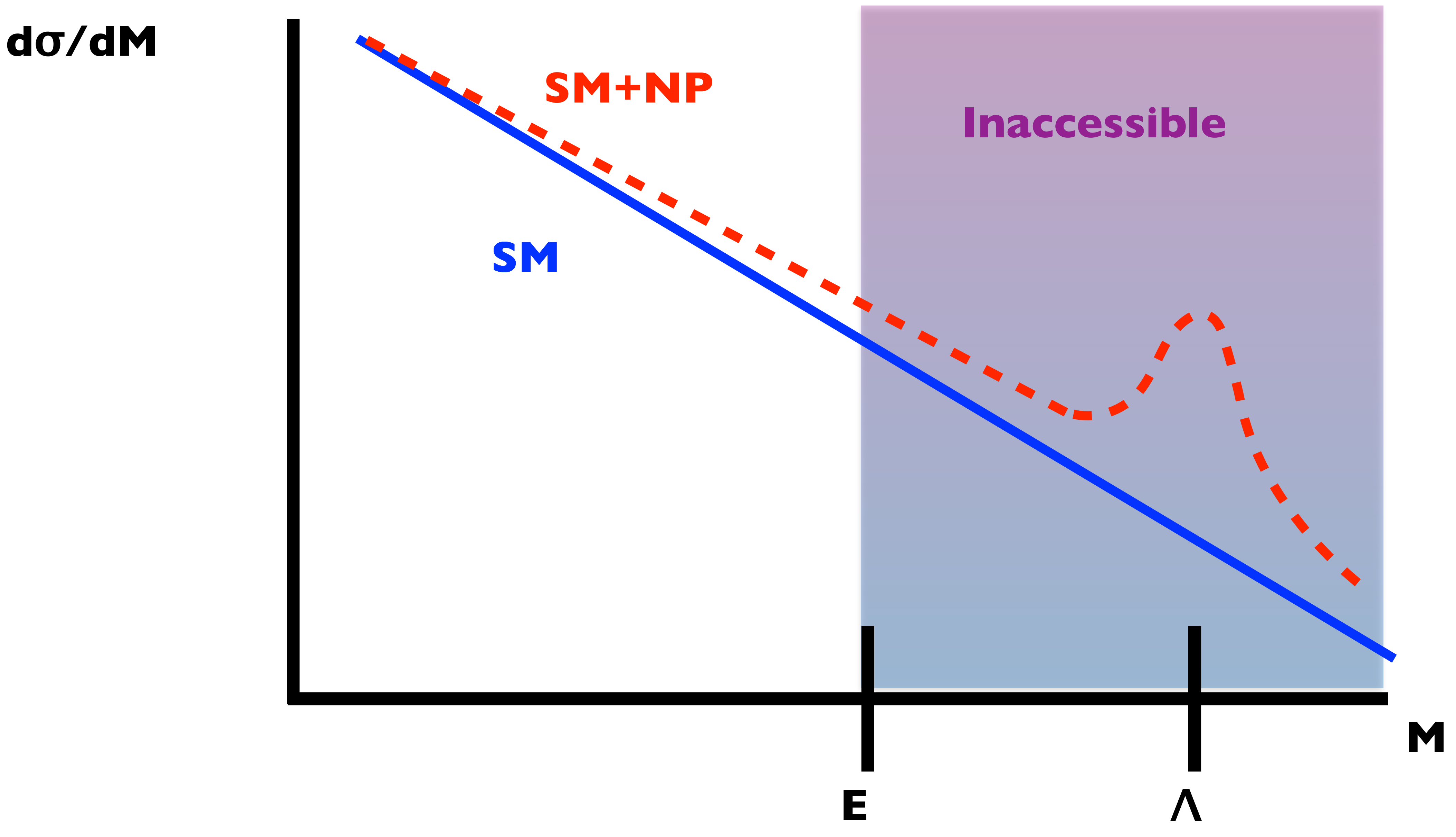
Λ≫vev, E

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i C_{6,i}\mathcal{O}_{6,i} + \frac{1}{\Lambda^4}\sum_i C_{8,i}\mathcal{O}_{8,i}$$

Dimension-6 **Dimension-8**

The theory contains all operators consistent with the SM gauge symmetries. It is a consistent and predictive QFT: it is renormalizable order-by-order in Λ.

What the SMEFT is designed to handle:



EFT frameworks for new physics searches

- The development of the SMEFT as a fully consistent QFT ready for comparison with experiment, with higher-order corrections and renormalization-group effects incorporated, has been a great success of the past decade.

Pure Gauge interactions

Accommodates a rich phenomenology in all sectors

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star (\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Gauge-Higgs interactions

Fermion-Higgs-gauge interactions

Four-fermion interactions

Baryon-number violating interactions

Dimension-6 basis:

Buchmuller, Wyler (1986); Grzadkowski et al (2010)

Dimension-6 RG running:

Alonso, Jenkins, Manojar, Trott (2013-2014)

Dimension-8 basis:

Murphy (2020)

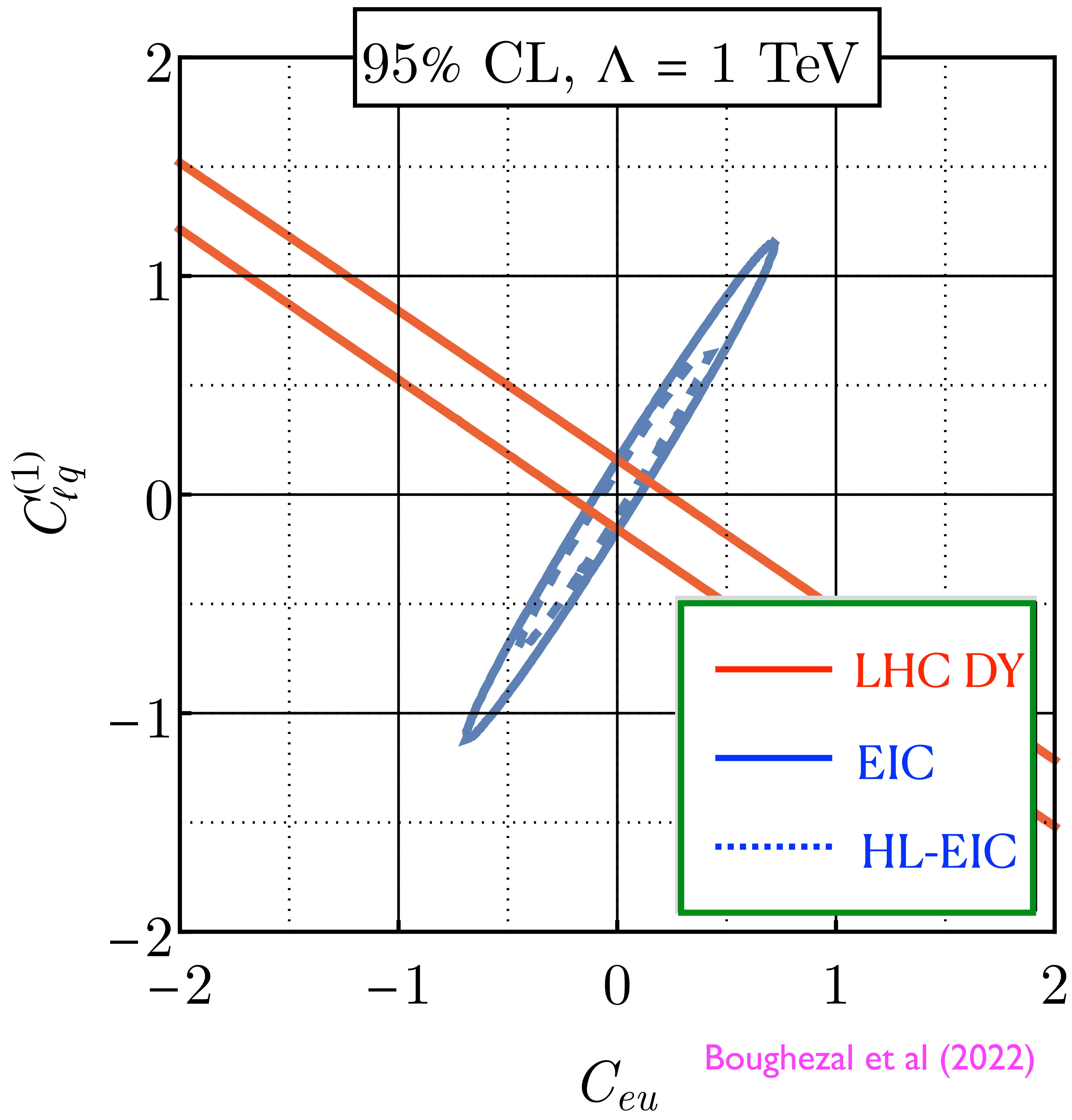
Li et al (2020)

Dimension-10,12 bases:

Harlander, Dempkens, Schaff (2023)

EFT frameworks for new physics searches

- The EFT framework makes manifest the strong synergies between searches at high-energy HEP facilities and those in other fields. They may feature different energies and may have been designed for other purposes, but they are revealing different aspects of the same physics.



Boughezal et al (2022)

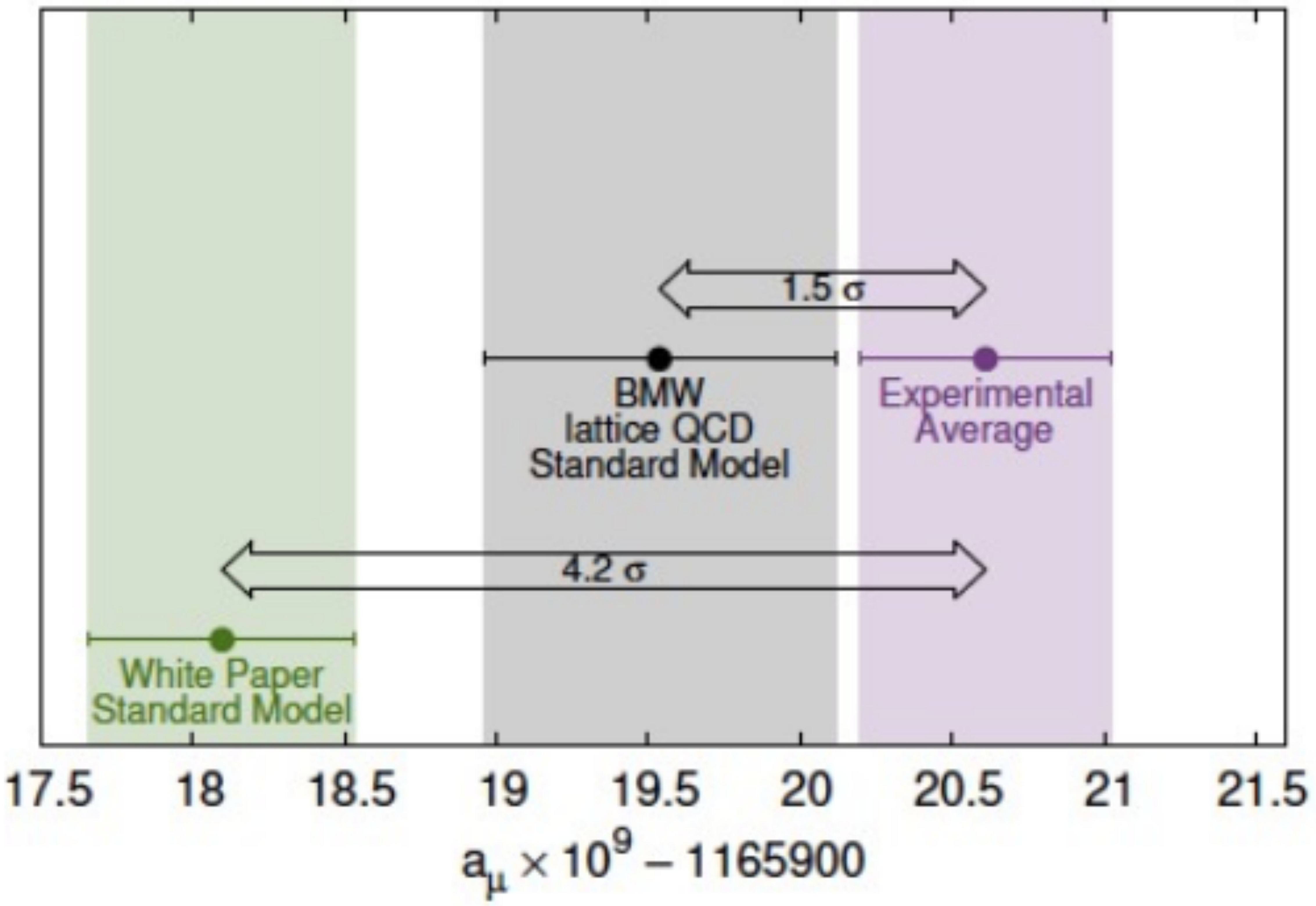
C_{eu}: $(\bar{e}\gamma^{\mu}e)(\bar{u}\gamma_{\mu}u)$

$C^{(1)}_{lq}$: $(\bar{l}\gamma^{\mu}l)(\bar{q}\gamma_{\mu}q)$

For example, a future Electron-Ion Collider can remove degeneracies that appear in LHC Drell-Yan probes of four-fermion operators.

Lepton anomalous magnetic moments

- One of the few measurements where there is a potential disagreement between the SM and experiments is the muon anomalous magnetic moment. The electron magnetic moment depends upon the fine structure constant. There is also a discrepancy between Cesium and Rubidium atomic recoil determinations of α, which lead to different electron magnetic moments.



4σ discrepancy between the two determinations of Δa_e

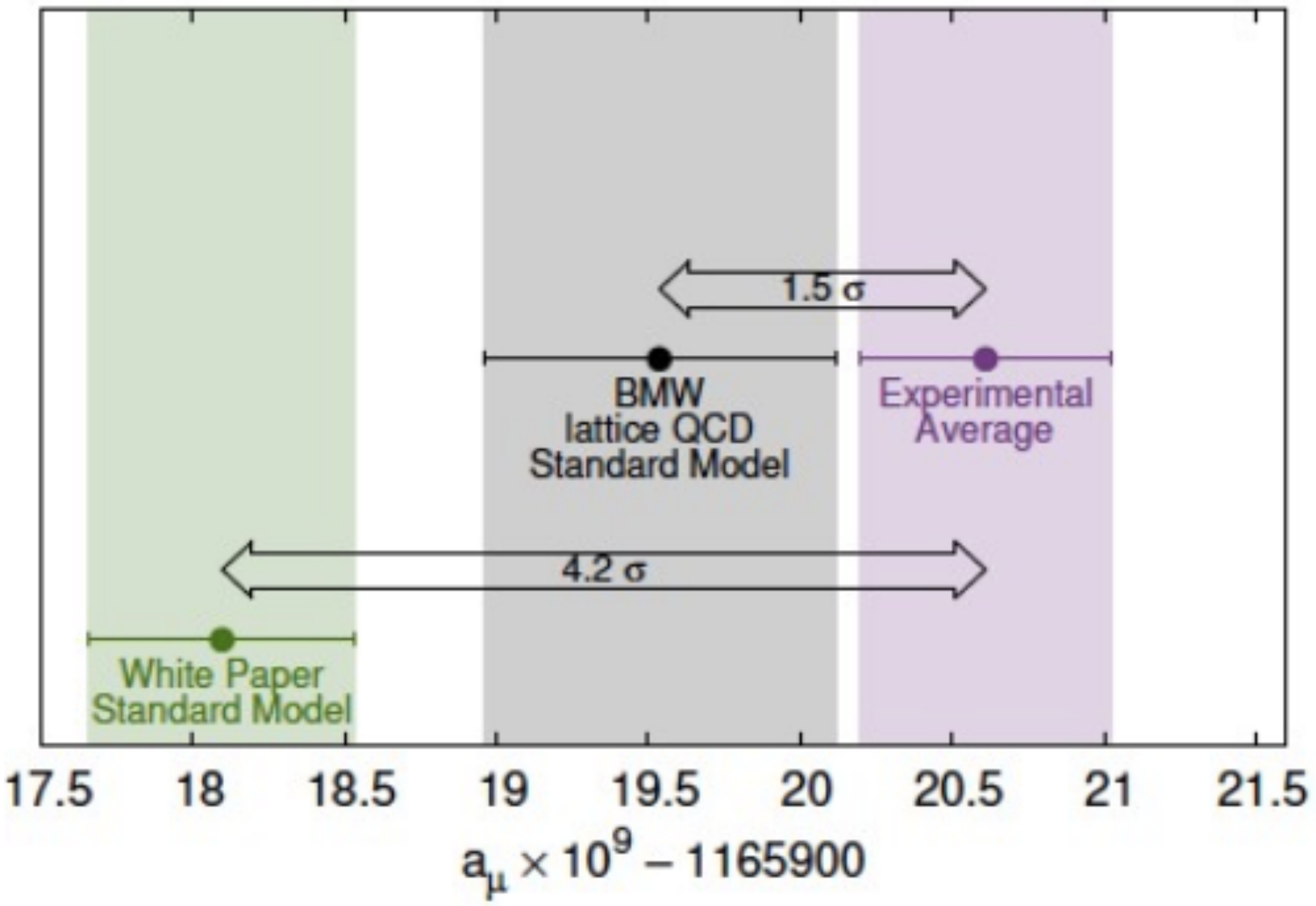
$$\Delta a_e^{\text{Cs}} = a_e^{\text{exp}} - a_e^{\text{SM,Cs}} = -0.88(36) \times 10^{-12}$$
$$\Delta a_e^{\text{Rb}} = a_e^{\text{exp}} - a_e^{\text{SM,Rb}} = 0.48(30) \times 10^{-12}$$

Questions:

Could new physics explain the muon g-2 discrepancy? Can it shift the electron g-2 by a similar size as the observed discrepancy?

Lepton anomalous magnetic moments

- One of the few measurements where there is a potential disagreement between the SM and experiments is the muon anomalous magnetic moment. The electron magnetic moment depends upon the fine structure constant. There is also a discrepancy between Cesium and Rubidium atomic recoil determinations of α, which lead to different electron magnetic moments.



4σ discrepancy between the two determinations of Δa_e

$$\Delta a_e^{\mathrm{Cs}} = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM,Cs}} = -0.88(36) \times 10^{-12}$$
$$\Delta a_e^{\mathrm{Rb}} = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM,Rb}} = 0.48(30) \times 10^{-12}$$

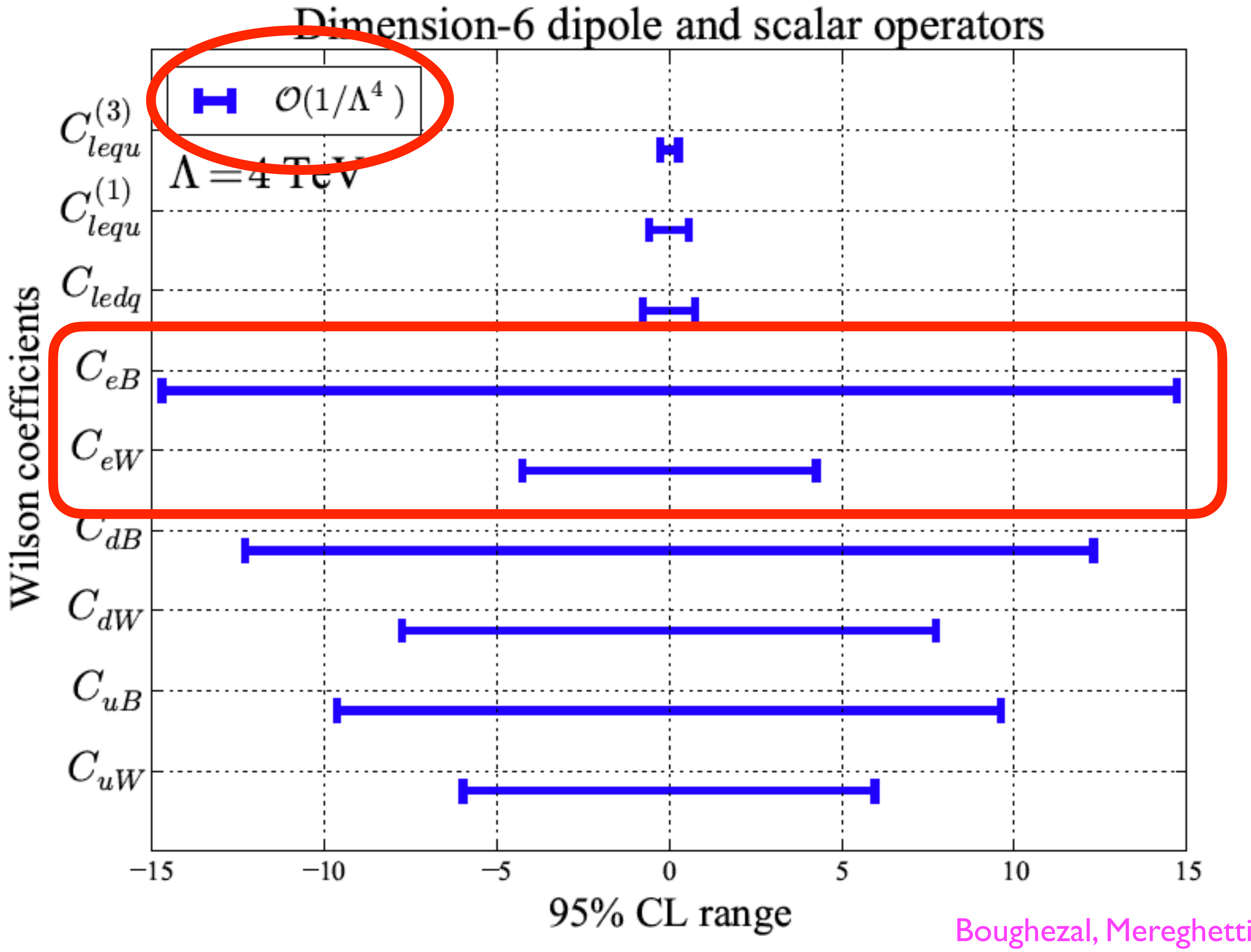
In the SMEFT, beyond-the-SM contributions to the anomalous magnetic moments are described by the operators:

$$\mathcal{O}_{eW} = (\bar{l}_e \sigma^{\mu\nu} e)\tau^I \phi W^I_{\mu\nu}$$
$$\mathcal{O}_{eB} = (\bar{l}_e \sigma^{\mu\nu} e)\phi B_{\mu\nu}$$
$$\mathcal{O}_{\mu W} = (\bar{l}_\mu \sigma^{\mu\nu} \mu)\tau^I \phi W^I_{\mu\nu}$$
$$\mathcal{O}_{\mu B} = (\bar{l}_\mu \sigma^{\mu\nu} \mu)\phi B_{\mu\nu}$$

(real parts of Wilson coefficients for these operators give magnetic moments, imaginary parts give electric dipole moments)

Other probes of the Wilson coefficients

- Given the discrepancies associated with the leptonic anomalous magnetic moments, we want to find other experimental measurements that access these same EFT operators. It is possible to probe them through Drell-Yan production at the LHC, but numerous SMEFT operators can affect Drell-Yan in a more significant way than these ones.

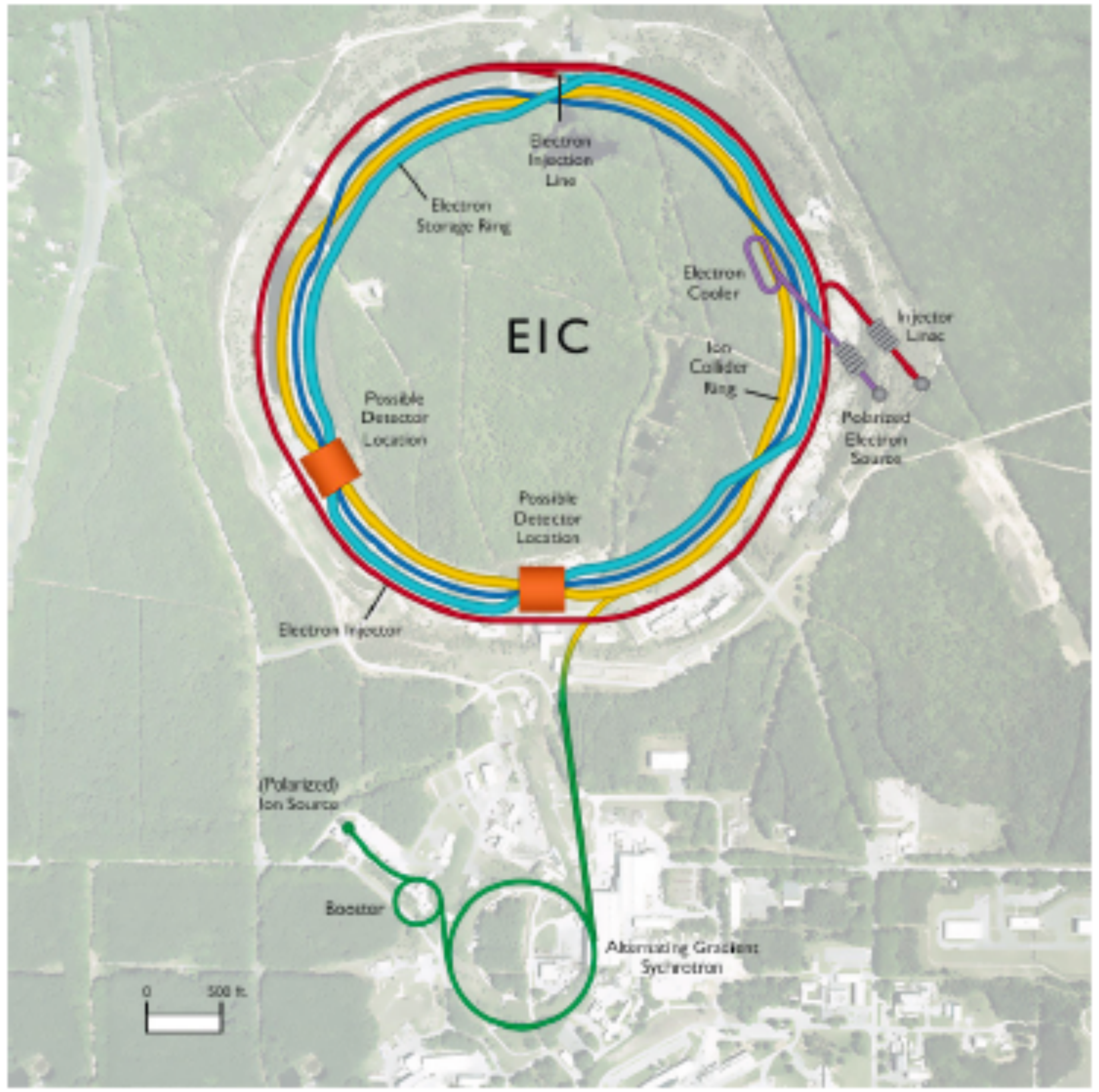


Weaker constraints than other operators, and these effects are sub-leading in the 1/Λ expansion and can be easily overwhelmed by the leading semi-leptonic, vector-like four-fermion operators

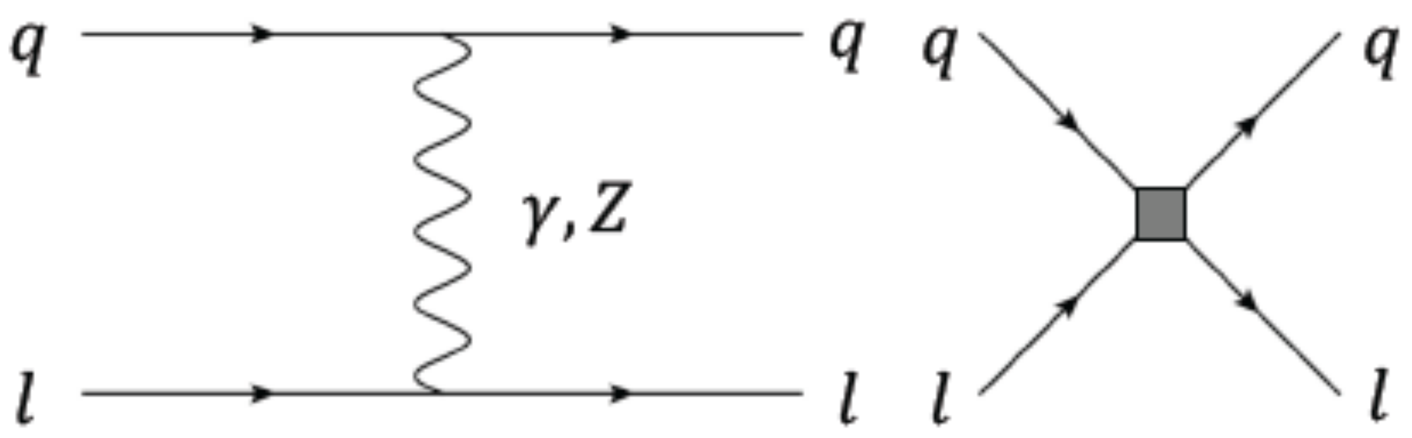
Boughezal, Mereghetti, FP (2021)

Transverse SSAs at the EIC

- Another way to access these operators and probe the parameter space relevant for the lepton g-2 discrepancies is through transverse single-spin asymmetries at the Electron-Ion Collider.



https://www.bnl.gov/eic/



The EIC is future electron-ion collider with a planned operation starting in the 2030s. Expected parameters are as follows:

- $\sqrt{s}$ reaching up to 140 GeV
- 70-80% polarized proton/ electron beams
- Luminosity: $\geq 10\ \text{fb}^{-1}$

Transverse single-spin asymmetries are defined as the difference of cross sections for positive and negative polarization of a single beam, transverse to the beam direction. In the case of the electron being polarized we have

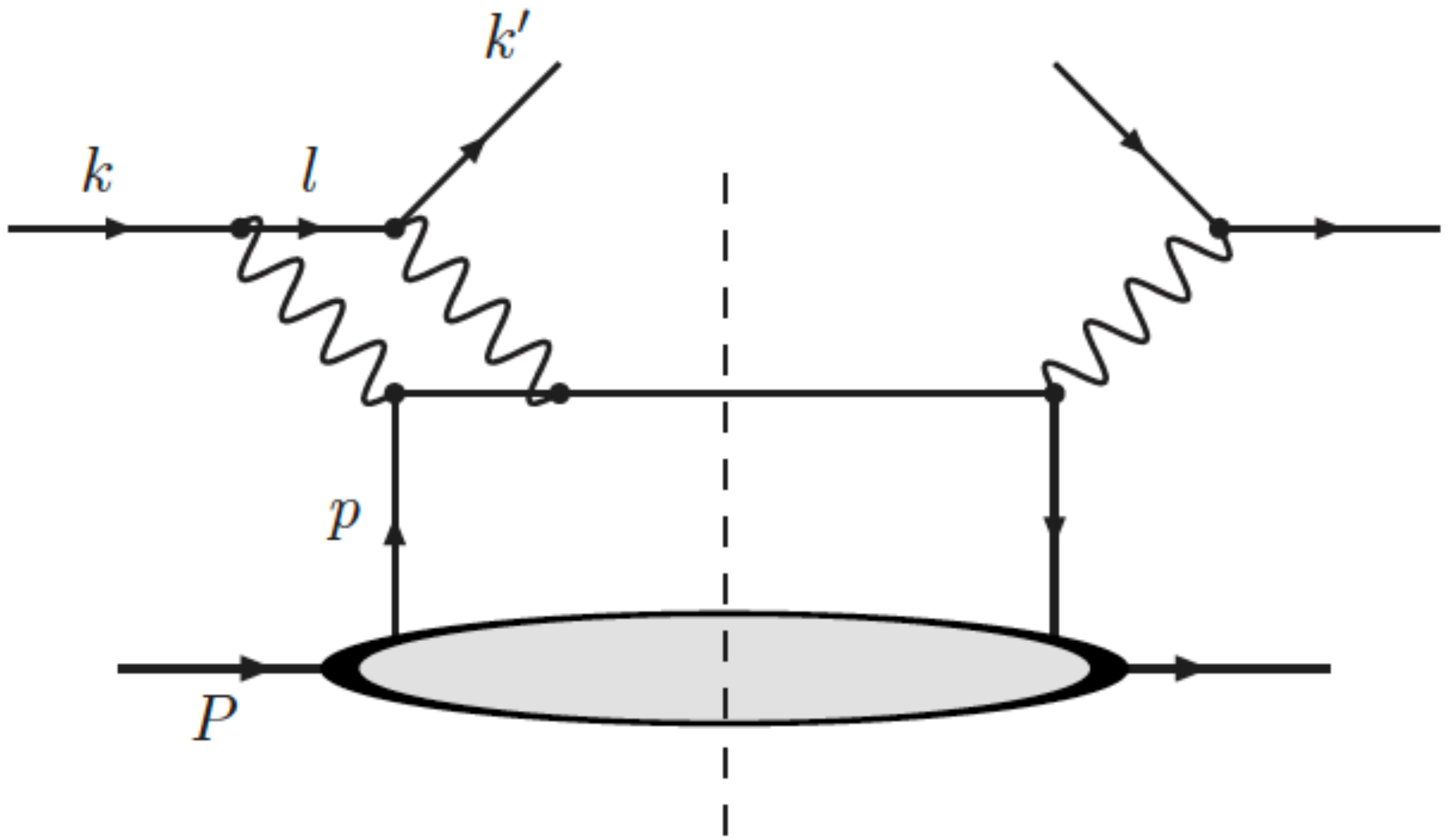
$$A_{TU} = \frac{\sigma(e^{\uparrow}) - \sigma(e^{\downarrow})}{\sigma(e^{\uparrow}) + \sigma(e^{\downarrow})}$$

Transverse polarization direction:

$$S_T^{\mu} = (0, \cos(\phi), \sin(\phi), 0)$$

Transverse SSAs in the SM

- There are two mechanisms that generate transverse SSAs in inclusive DIS in the SM. Historically the focus was on QED since these asymmetries were first considered at lower energies. One-photon exchange does not contribute due to the parity invariance of QED (Christ, Lee 1966) The leading mechanism is therefore two-photon exchange (Metz, Schlegel, Goeke 2006) :



- Suppressed with respect to tree-level by a power of α
- Suppressed by the electron mass; easiest to see by studying the transverse projection operator:

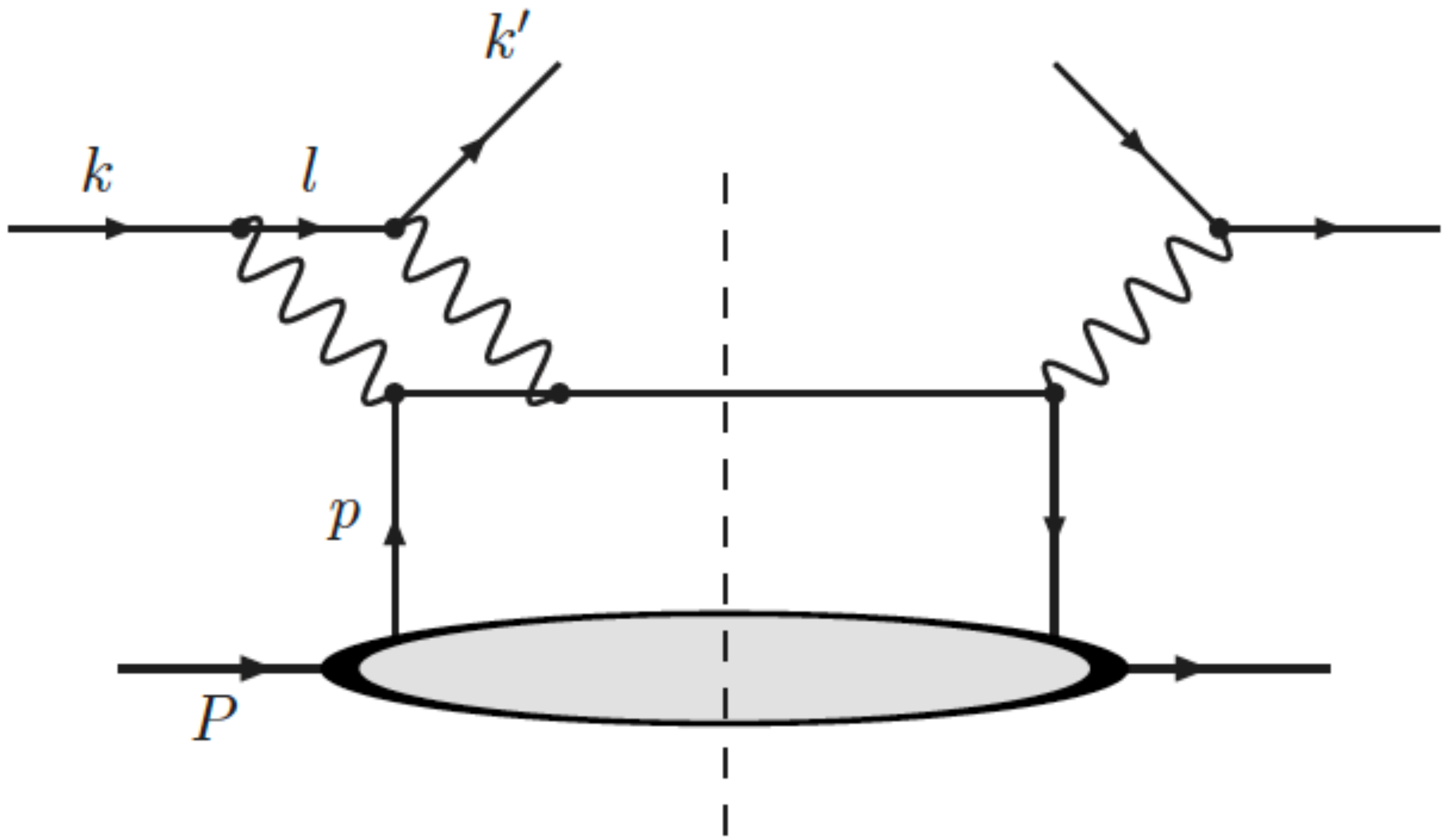
$$u(p)\bar{u}(p) = \frac{1}{2}(\not{p} + m)(1 + \gamma_5 \not{S}_T)$$

  S_T changes number of gamma matrices from odd↔even

- "Naive" time-reversal invariant, and therefore requires the absorptive part of the one-loop amplitude

Transverse SSAs in the SM

- There are two mechanisms that generate transverse SSAs in inclusive DIS in the SM. Historically the focus was on QED since these asymmetries were first considered at lower energies. One-photon exchange does not contribute due to the parity invariance of QED (Christ, Lee 1966) The leading mechanism is therefore two-photon exchange (Metz, Schlegel, Goeke 2006) :



$$A_{TU}^{\gamma\gamma} = \alpha \frac{m_l}{2Q} \sin(\phi) \frac{y^2\sqrt{1-y}}{1-y+y^2/2} \frac{\sum_q Q_q^3 f_q(x)}{\sum_q Q_q^2 f_q(x)}$$

Doubly-suppressed by two small quantities

Depends on the transverse-plance azimuthal angle between the initial polarization and the final-state lepton

Transverse SSAs in the SM

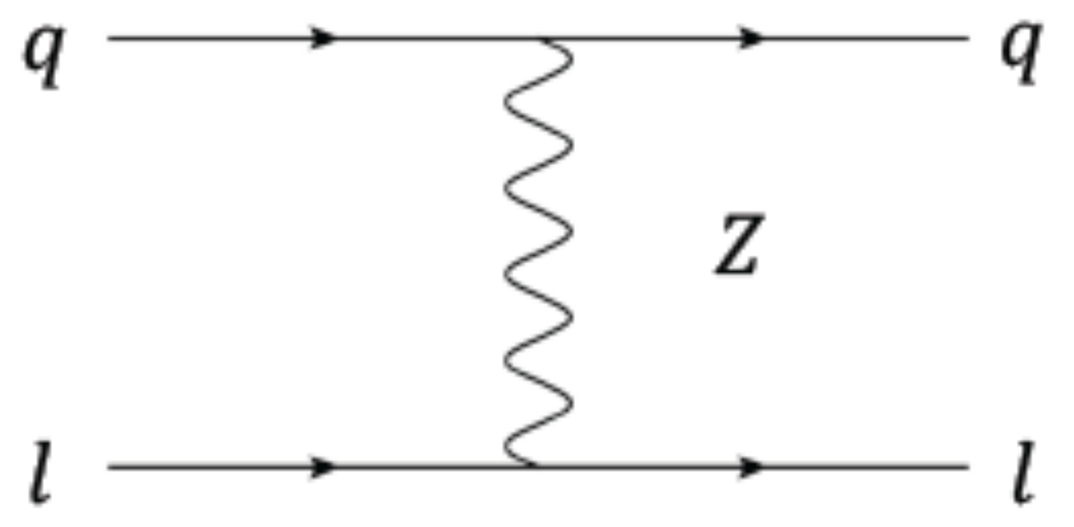
- We pointed out that a second mechanism exists at high energies, Z-exchange, which will be important at a future EIC. (Boughezal, de Florian, FP, Vogelsang 2023)

$$A_{TU}^{Z}(\phi) = \frac{2}{s_W^2 c_W^2}\frac{m_l Q}{M_Z^2}\frac{y\sqrt{1-y}}{1-y+y^2/2}\cos(\phi)\frac{\sum_q Q_q f_q(x)\left[g_{al}g_{vq}(1-y)+g_{vl}g_{aq}y\right]}{\sum_q Q_q^2 f_q(x)}$$

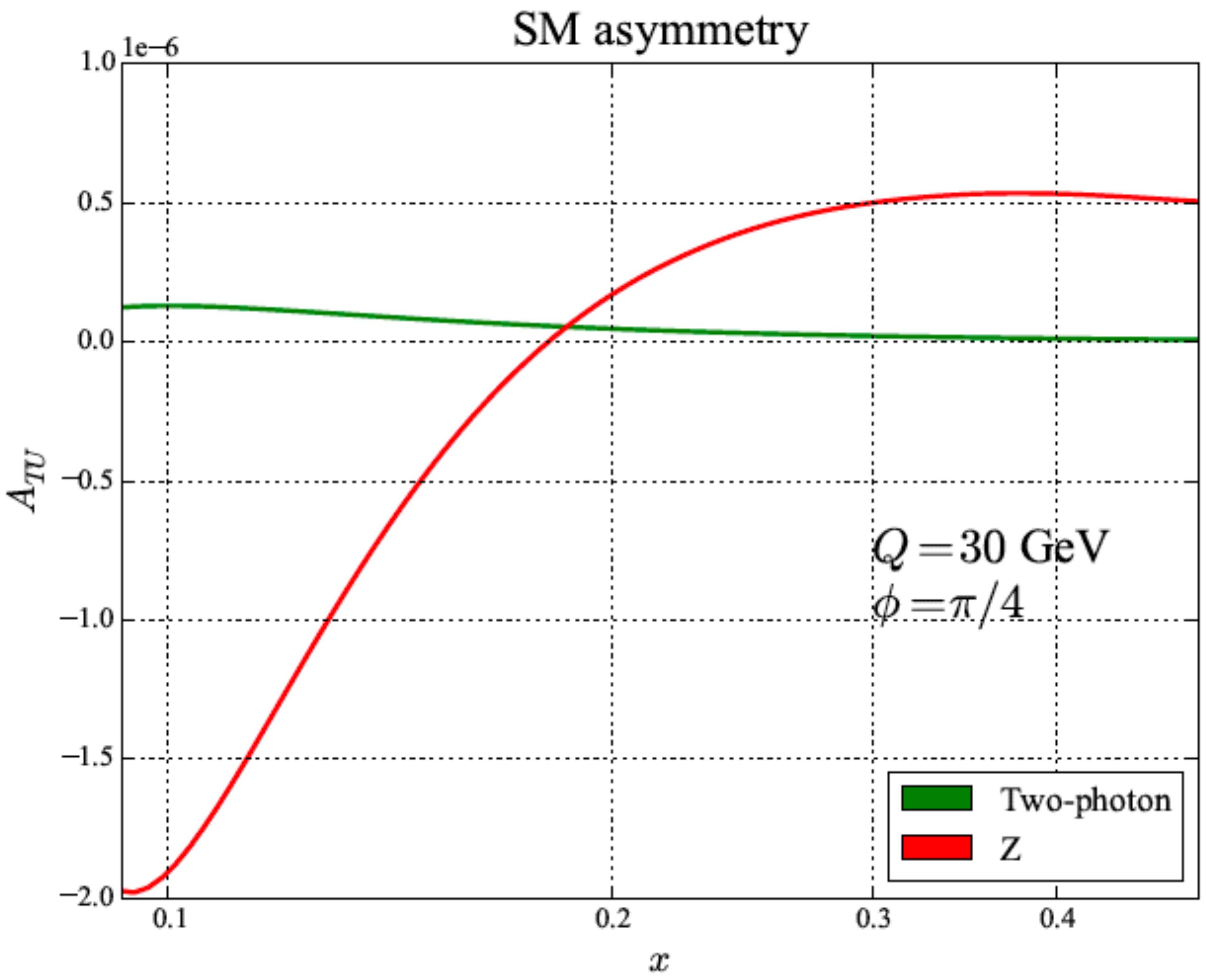
Grows with momentum transfer

Different azimuthal angle dependence than photon contribution

Parity violating $g_v g_a$ dependence



A_{TU}~10^{-6} in the SM; negligibly small and an excellent channel for new physics searches!



Transverse SSAs beyond the SM

- What kind of new physics can modify the transverse SSAs? We will discuss this in the context of the SMEFT. We will focus on chiral operators, to avoid an explicit mass suppression factor. The new Wilson coefficients can of course contain this chiral suppression, but we expect them to already be small due to the mass gap between new physics and the SM. We don't want two small factors.

Scalar/tensor four-fermion operators

$$\mathcal{O}_{ledq} = (\bar{l}^j e)(\bar{d} q^j),$$
$$\mathcal{O}^{(1)}_{lequ} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u),$$
$$\mathcal{O}^{(3)}_{lequ} = (\bar{l}^j \sigma^{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma_{\mu\nu} u)$$

Scalar Higgs exchanges

$$\mathcal{O}_{e\varphi} = (\varphi^\dagger \varphi)(\bar{l} e \varphi),$$
$$\mathcal{O}_{u\varphi} = (\varphi^\dagger \varphi)(\bar{q} u \tilde{\varphi}),$$
$$\mathcal{O}_{d\varphi} = (\varphi^\dagger \varphi)(\bar{q} d \varphi).$$

Dipole operators

$$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu} e)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu} e)\varphi B_{\mu\nu},$$
$$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu} u)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu} u)\varphi B_{\mu\nu},$$
$$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu} d)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu} d)\varphi B_{\mu\nu}.$$

Explicit calculation shows that both four-fermion and Higgs operators require an explicit lepton mass insertion to contribute to transverse SSAs. This is true when dim-6 is interfered with the SM and when we consider dim-6 squared.

Dipole operators contribute when interfered with the SM. Transverse SSAs can isolate these same contributions that affect anomalous magnetic (and electric as we'll see) moments!

Structure of the SMEFT asymmetry

- The expression for the SMEFT asymmetry takes the form shown below.

$$C_{e\gamma} = \frac{v}{\sqrt{2}}\left[-s_W C_{eW} + c_W C_{eB}\right]$$

$$C_{eZ} = \frac{v}{\sqrt{2}}\left[-c_W C_{eW} - s_W C_{eB}\right]$$

$$\Delta A_{TU}(\phi) = \frac{g_Z}{2\pi\alpha}\frac{Q^3}{M_Z^2}\frac{y\sqrt{1-y}}{1-y+\frac{y^2}{2}}\frac{\sum_q Q_q f_q(x)\left\{g_{aq}\mathrm{Re}[C_{eZ}e^{-i\phi}] - \frac{\mathrm{Re}[C_{e\gamma}e^{-i\phi}]}{s_W c_W}[g_{vq}g_{al}(1-2/y) - g_{aq}g_{vl}]\right\}}{\sum_q Q_q^2 f_q(x)}$$

This asymmetry is sensitive to both the real and imaginary parts of the Wilson coefficients. The real part has a cos(φ) dependence, while the imaginary part has sin(φ).

Can extract them separately with appropriate weight functions:

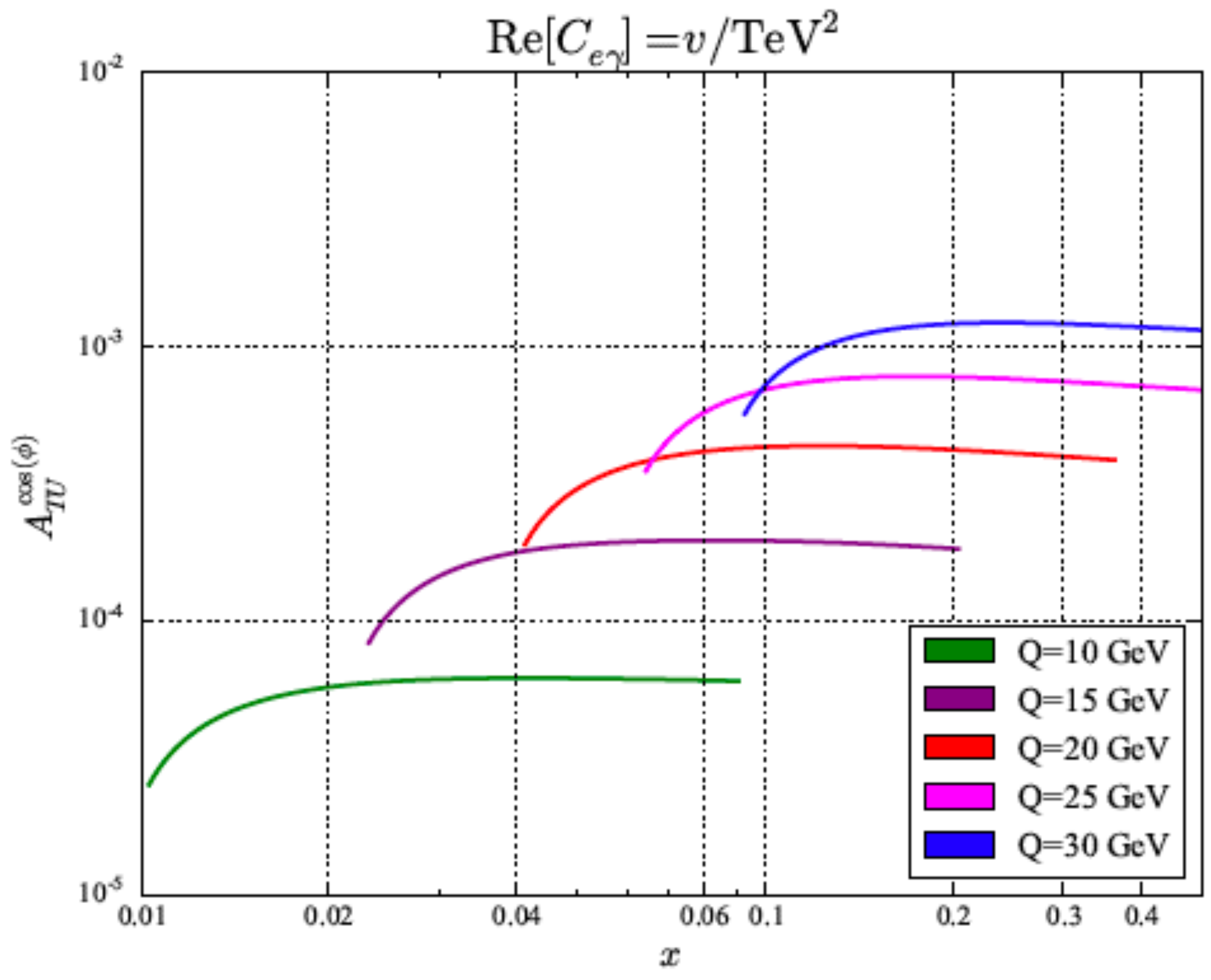
$$A_{TU}^{w} = \int_0^{2\pi} d\phi\, w(\phi)\, A_{TU}(\phi)$$

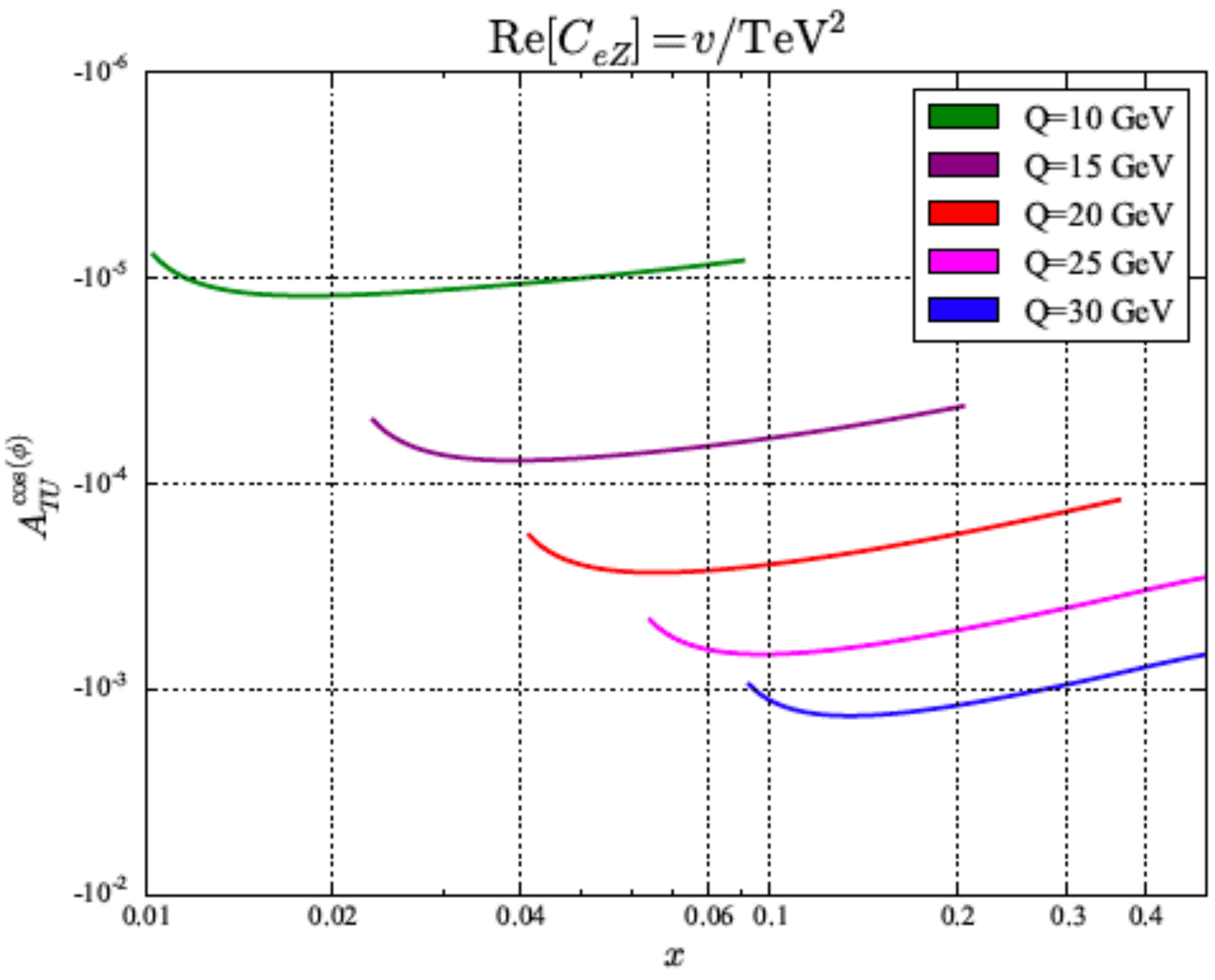
w= cos(φ),sin(φ)

Sensitive to same operators as anomalous magnetic and electron dipole moments; can probe them separately; small SM background: an ideal new physics probe!

Numerics at an EIC

- The asymmetries range from 10^{-4} to 10^{-3} for moderate-to-high values of momentum transfers at an EIC, for TeV-scale new physics. The magnitudes for imaginary Wilson coefficients are similar. The expected errors at the EIC are roughly the same magnitude, indicating that an analysis binned in Q and x should probe TeV-scale new physics affecting dipole operators.





Complementarity with other probes

- In terms of the photon and Z dipole couplings, the electron anomalous magnetic moment can be written as follows. Note that only a single linear combination of the two parameters can be probed!

Aeibischer et al (2021)

$$(\Delta a_e)^{SMEFT} = \frac{m_e}{m_\mu}\left\{1.4\times 10^{-3} C_{e\gamma} - 1.3\times 10^{-5} C_{eZ}\right\}(250\,\text{GeV})$$

$C_{e\gamma}$, C_{eZ} are MSbar parameters at the scale 250 GeV

- The low-energy theory below the EW scale contains only the photon dipole; C_{eZ} is generated by 1-loop running above the EW scale, hence the reduced sensitivity to this parameter
- The experiment-theory different is given by: $(\Delta a_e)^{exp-th} = \frac{m_e}{m_\mu}\left[\begin{matrix}-1.8(7)^{\text{Cs}} \\ 1.0(6)^{\text{Rb}}\end{matrix} \times 10^{-10}\right]$
- Assuming $C_{ei} \sim vev/\Lambda_{ei}^2$, $C_{e\gamma}$ scales of O(100 TeV) are needed to explain the experiment-theory difference above; few-TeV C_{eZ} scales are needed.

Transverse SSAs at the EIC can help probe this parameter space in two ways: by measuring a separate linear combination of $C_{e\gamma}$, C_{eZ}, and by directly probing the C_{eZ} scales needed to address the discrepancy

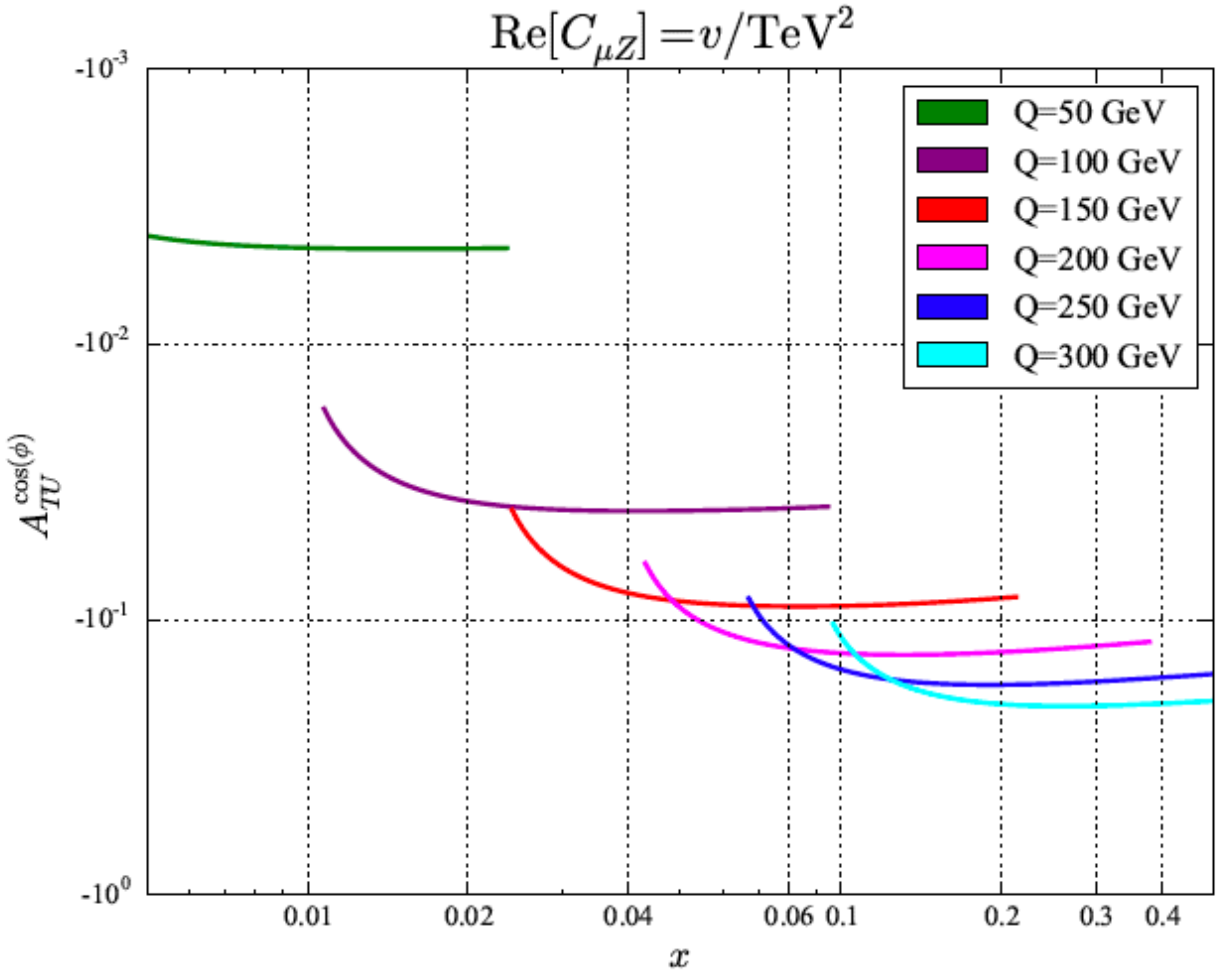
A muon-ion collider

- A proposed upgrade of the EIC involves replacing the electron beam with a high-energy muon beam. This would provide the first step toward a high-energy muon-muon collider. Beam polarization reaching 50% are possible at such a machine (Acosta, Li 2021). Transverse SSAs at this machine would directly probe the couplings $C_{\mu\gamma}$, $C_{\mu Z}$ that address the muon g-2 discrepancy!

Machine parameters:

- 960 GeV muons x 275 GeV protons, for a CM energy around 1 TeV
- Assume 50% polarization, 50 fb^{-1} of integrated luminosity

Large asymmetries, greater than anticipated statistical errors. Scales of several TeV should be accessible at a muon-ion collider.



A muon-ion collider

- A proposed upgrade of the EIC involves replacing the electron beam with a high-energy muon beam. This would provide the first step toward a high-energy muon-muon collider. Beam polarization reaching 50% are possible at such a machine (Acosta, Li 2021). Transverse SSAs at this machine would directly probe the couplings $C_{\mu\gamma}$, $C_{\mu Z}$ that address the muon g-2 discrepancy!

$$\Delta a_\mu^{SMEFT} = 1.1 \times 10^{-3} \left(\frac{\mathrm{Re}[C_{\mu\gamma}]}{1\,\mathrm{TeV}^{-1}}\right) - 1.1 \times 10^{-5} \left(\frac{\mathrm{Re}[C_{\mu Z}]}{1\,\mathrm{TeV}^{-1}}\right)$$

$C_{e\gamma}$, C_{eZ} are now evaluated at 1 TeV

Aeibischer et al (2021)

- The experiment-theory different is given by: $\Delta a_\mu^{exp-SM} = 251(59) \times 10^{-11}$

The muon g-2 discrepancy can be explained, for example, by TeV-scale new physics for $C_{\mu\gamma} \approx 0.01 C_{\mu Z}$, which is a loop-factor suppression. Such a scenario is testable at the EIC

Transverse SSAs at a muon-ion collider can probe the same parameter space as the muon g-2!

The muon EDM

- So far we have focused on the real parts of the Wilson coefficients and the anomalous magnetic moments. Imaginary parts can be probed as well. They lead to CP-violating effects that also contribute to electric dipole moments. The electron EDM is too well constrained for the EIC to probe interesting parameter space, but the muon EDM is far less constrained.

$$\left|\frac{\Delta d_\mu}{d_\mu^{\rm exp}}\right| = 7.3 \times 10^2 \left(\frac{{\rm Im}[C_{\mu\gamma}]}{1\,{\rm TeV}^{-1}}\right) + 1.8 \left(\frac{{\rm Im}[C_{\mu Z}]}{1\,{\rm TeV}^{-1}}\right)$$

This gives the SMEFT-induced shift over the 90% CL experimental bound

Aeibischer et al (2021)

- Turning on only a single coefficient at a time, we find that $\mathrm{Im}[C_{\mu\gamma}]$ scales around 10 TeV can be probed by EDM measurements, above muon-ion collider capabilities
- However, only $\mathrm{Im}[C_{\mu Z}]$~700 GeV can be probed with EDM measurements.

Transverse SSAs at a muon-ion collider can improve upon existing muon EDM constraints

Target transverse SSAs

- So far we have focused on the beam asymmetries that come from polarizing the electron beam. We can form target SSAs by polarizing the initial proton beam. The SM expression from photon and Z exchange take the following form:

$$A_{UT}^{\gamma\gamma}(\phi) = \alpha \frac{M}{2Q} \sin(\phi) \frac{y\sqrt{1-y}}{1-y+y^2/2} \left(\ln\left(\frac{Q^2}{\lambda^2}\right) + \text{finite} \right) \frac{\sum_q Q_q^3 g_q^T(x)}{\sum_q Q_q^2 f_q(x)}$$

$$A_{UT}^{Z}(\phi) = -\frac{2}{s_W^2 c_W^2} \frac{m_q Q}{M_Z^2} \frac{y\sqrt{1-y}}{1-y+y^2/2} \cos(\phi) \frac{\sum_q Q_q h_q(x) \left[g_{aq} g_{vl}(1-y) + g_{vq} g_{al} y \right]}{\sum_q Q_q^2 f_q(x)}$$

- g_q^T: twist-3 distribution function
- M: target nucleon mass
- λ: photon mass regulator. Canceled by qqg triple correlations in the nucleus, quark k_T effects
- h_q: twist-2 transversity, $h_q=f_{\uparrow}(x)-f_{\downarrow}(x)$

Strong sensitivity to higher-twist effects and poorly known transversity distributions; estimates give $A_{UT}<10^{-4}$ in the SM (Afanasev, Strikman, Weiss 2008)

Target transverse SSAs

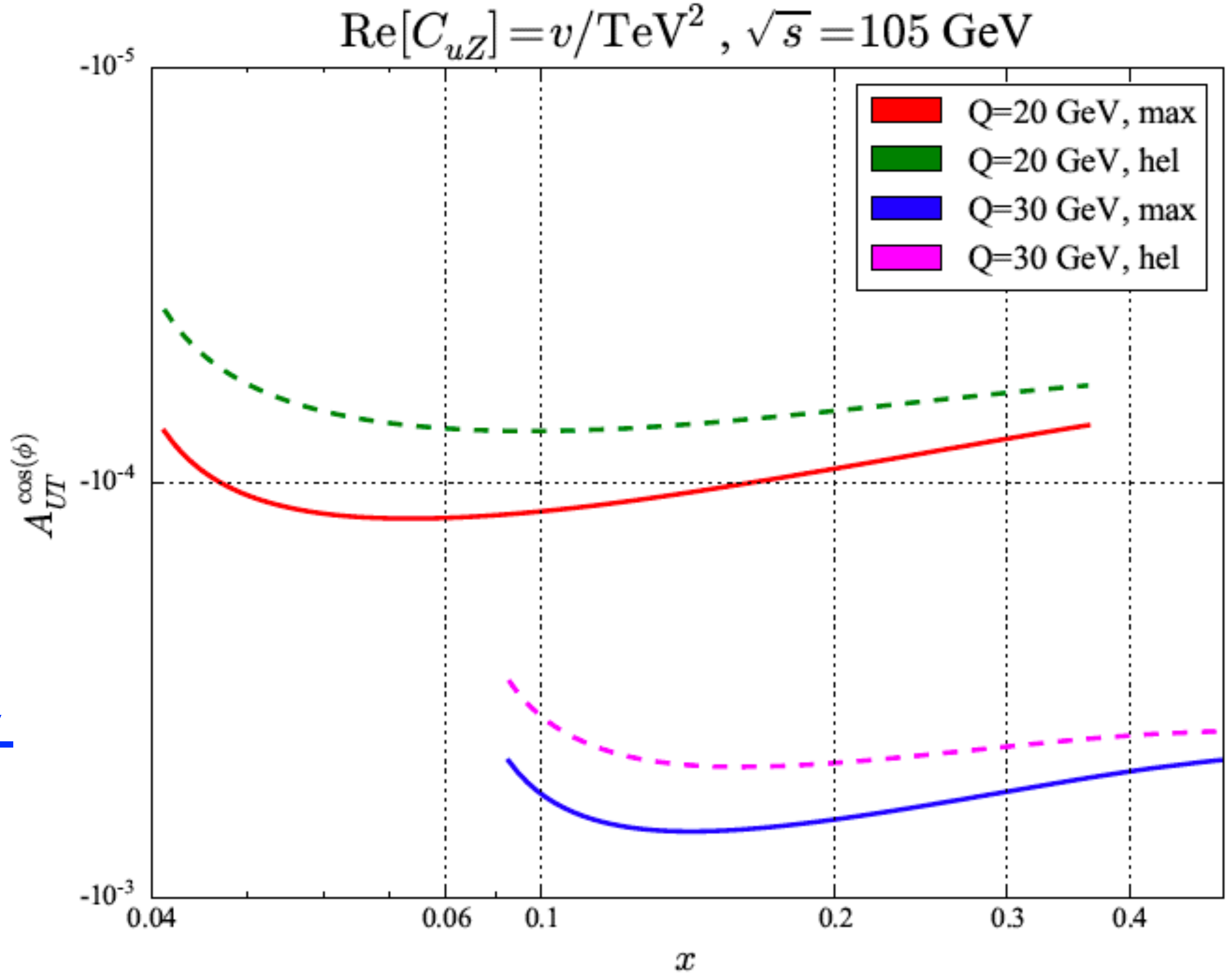
- Estimated corrections from SMEFT occur at twist-2. They depend on transversity distributions, for which little is known. However, higher momentum transfers should be able to probe physics beyond the SM at the TeV scale given anticipated errors; Wilson coefficients at this scale lead to effects O(10) times the SM estimate.

Soffer bound:

$$2|h(x,\mu)| \leq f(x,\mu) + \Delta f(x,\mu)$$

- *max scenario*: transversity saturates the Soffer bound
- *hel scenario*: equates transversity and the longitudinal helicity PDFs

(de Florian 2017)



Wilson coefficients that leads to TeV-scale quark dipole moments can be probed at an EIC

Conclusions

- The next accelerator facility built worldwide will be the EIC. It will probably be the only facility built within the next few decades.
- Although it is at lower energies than the LHC and is primarily designed to investigate lower-energy QCD , its relatively high luminosity (with respect to previous DIS experiments such as HERA) and polarization provide unique handles on issues of interest to high energy physics.
- We've shown here that transverse single-spin asymmetries at the EIC probe the same new physics parameter space as the muon and electron magnetic and electric dipole moment measurements.
- In particular a future muon-ion collider can improve upon existing muon EDM constraints, and can probe the new physics parameter space relevant for the muon g-2 anomaly.

Thank you!