Transverse single-spin asymmetries within and beyond the Standard Model

Frank Petriello

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

Electroweak and BSM physics at the EIC

February 14, 2024

Northwestern University

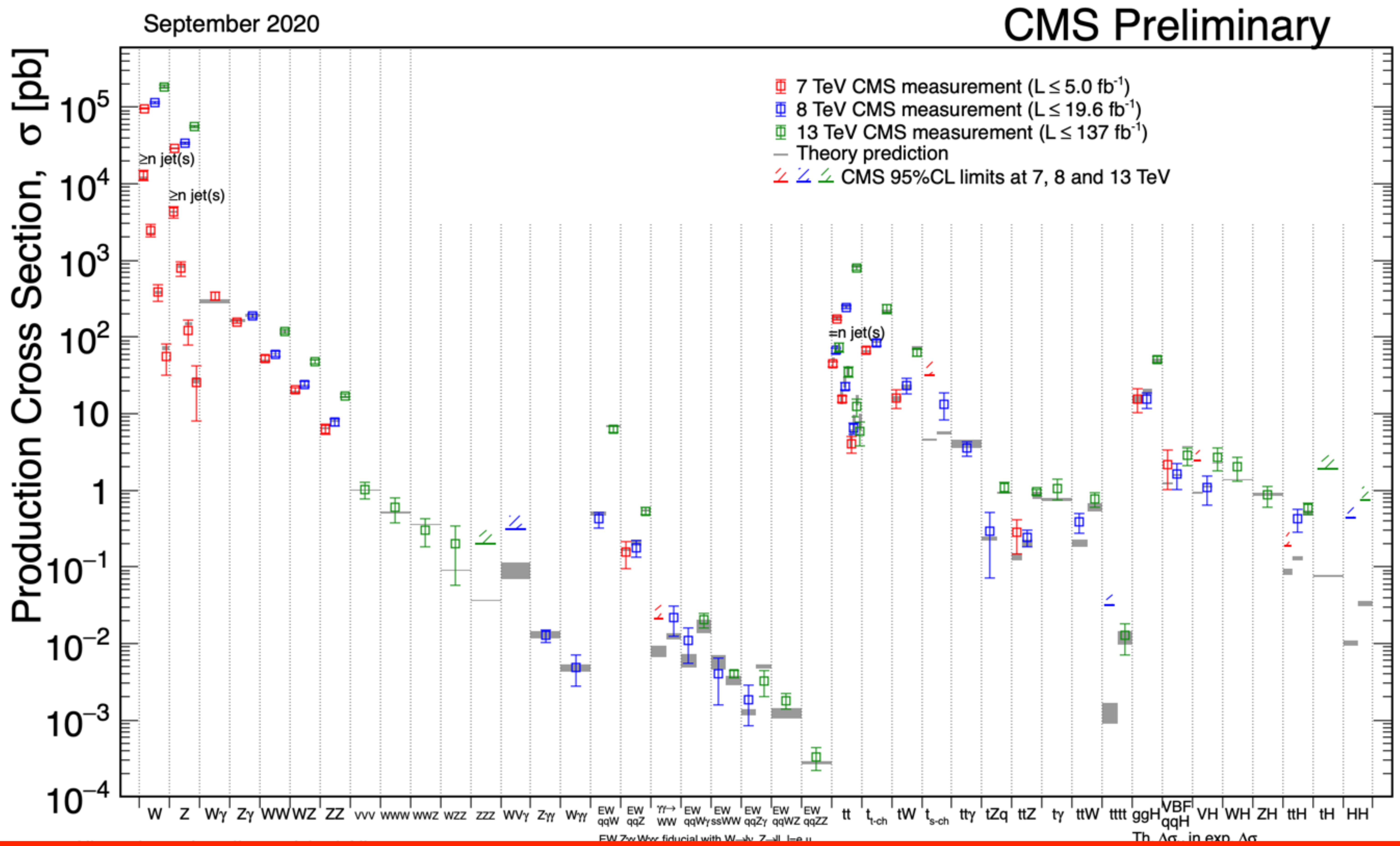
Argonne NATIONAL LABORATORY

Outline of the talk

- Introduction: experimental landscape and the Standard Model Effective Field Theory
- A review of transverse single-spin asymmetries in the SM
- Transverse single-spin asymmetries in the SMEFT
- Numerics at an EIC and the connection with anomalous dipole moments
- Hoping for a discussion of interesting targets for future studies!

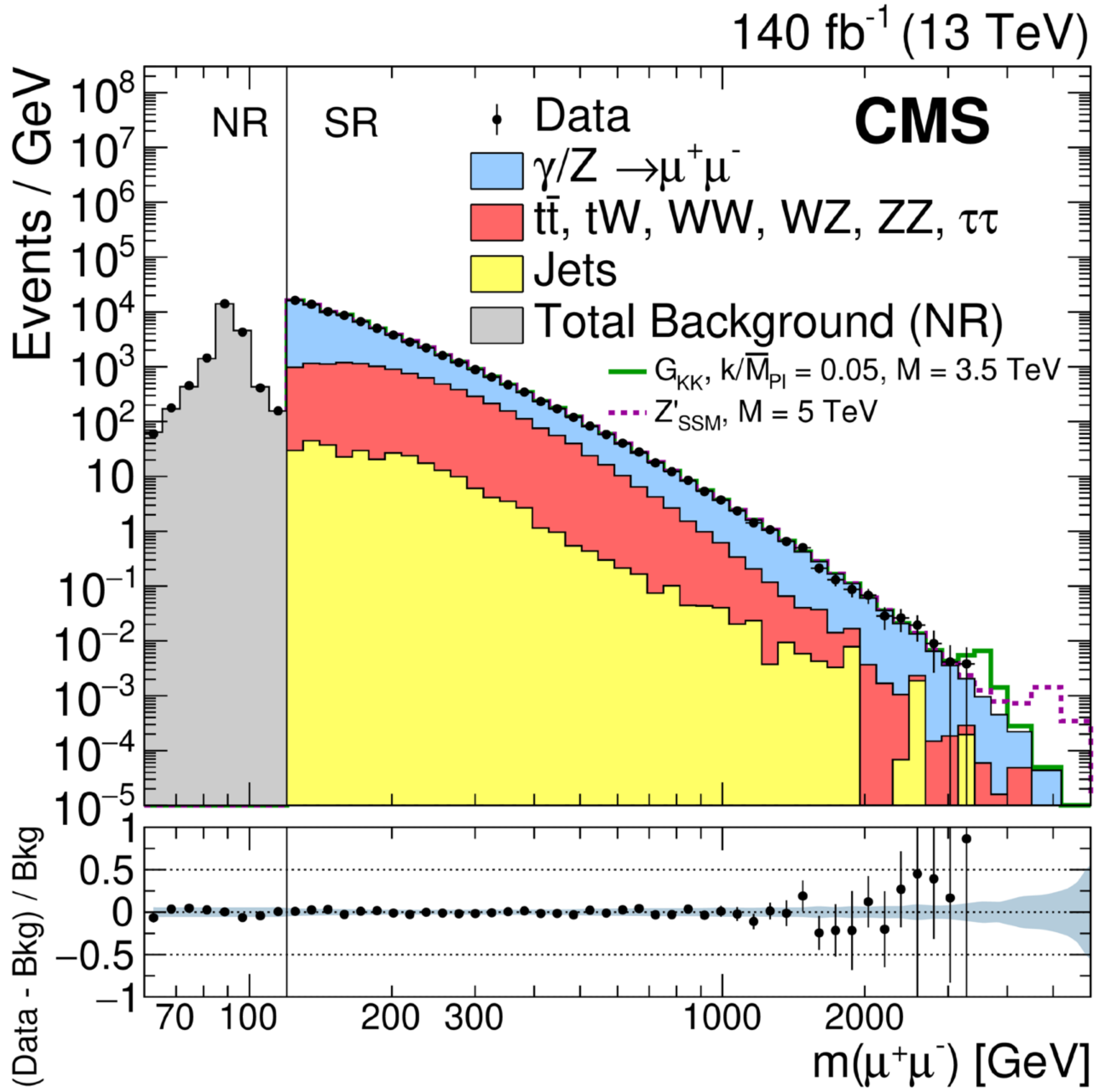
Introduction: EFTs for beyond the SM, the LHC program and the role of future DIS experiments

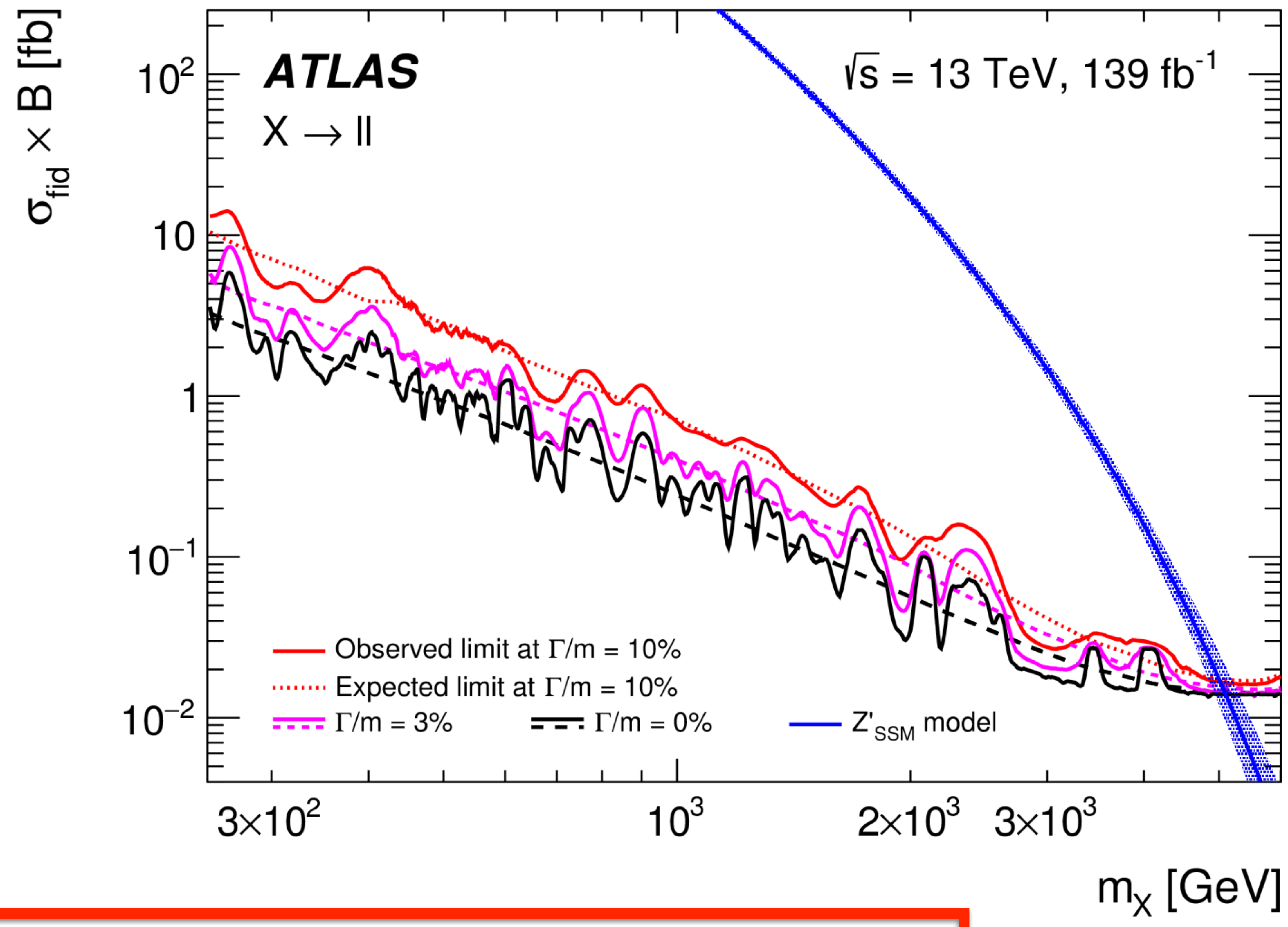
Status of the Standard Model



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.

$\Lambda \gg$ 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.

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^*(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

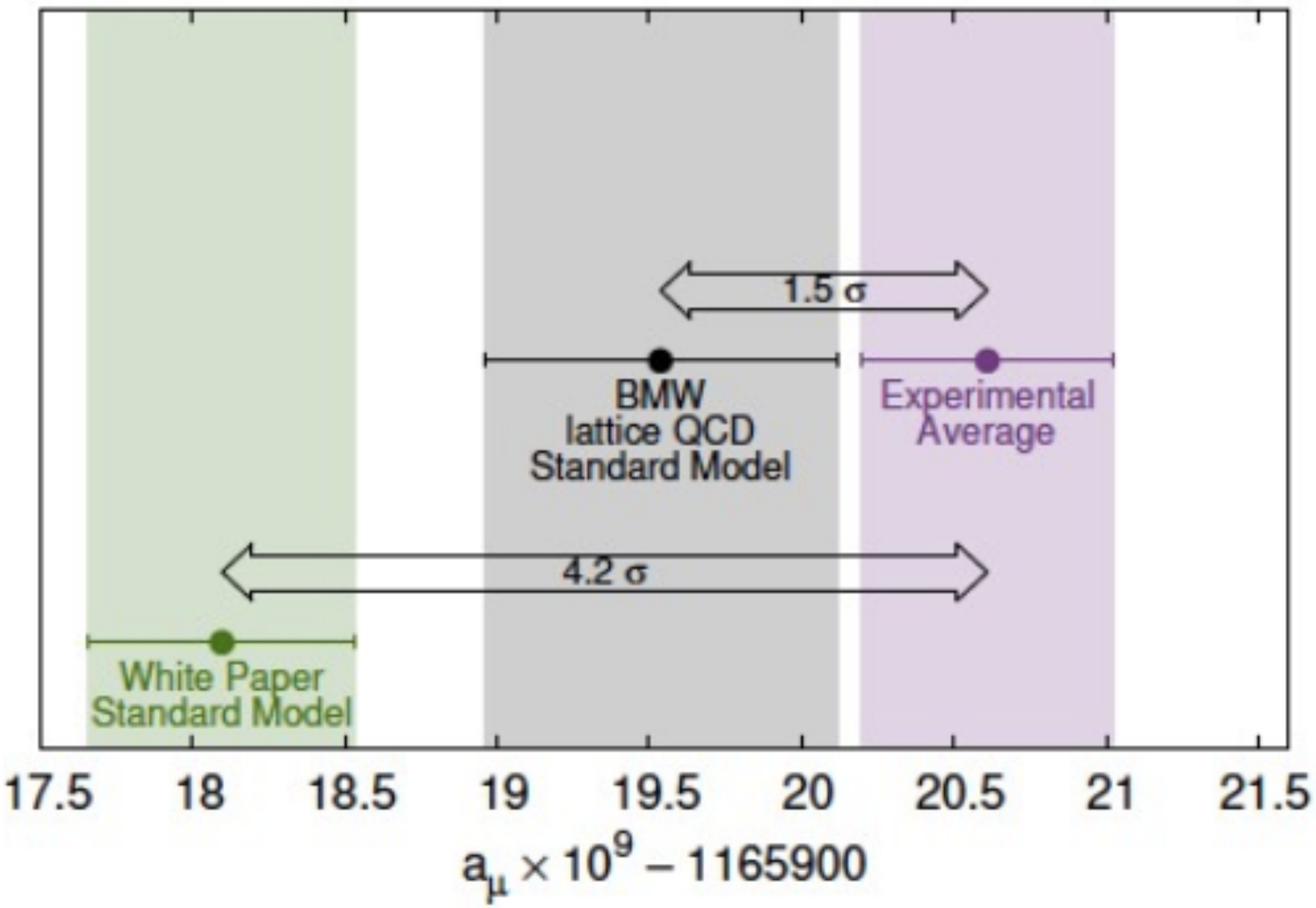
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

More details on the SMEFT in Radja's Monday talk

Open questions

- While there are no clear signals of physics beyond the SM, there are several lingering discrepancies that may eventually turn into our first evidence of new physics. Prominent among these is the muon g-2. Can other experiments shed light on the SMEFT parameter space that can accommodate this measurement?



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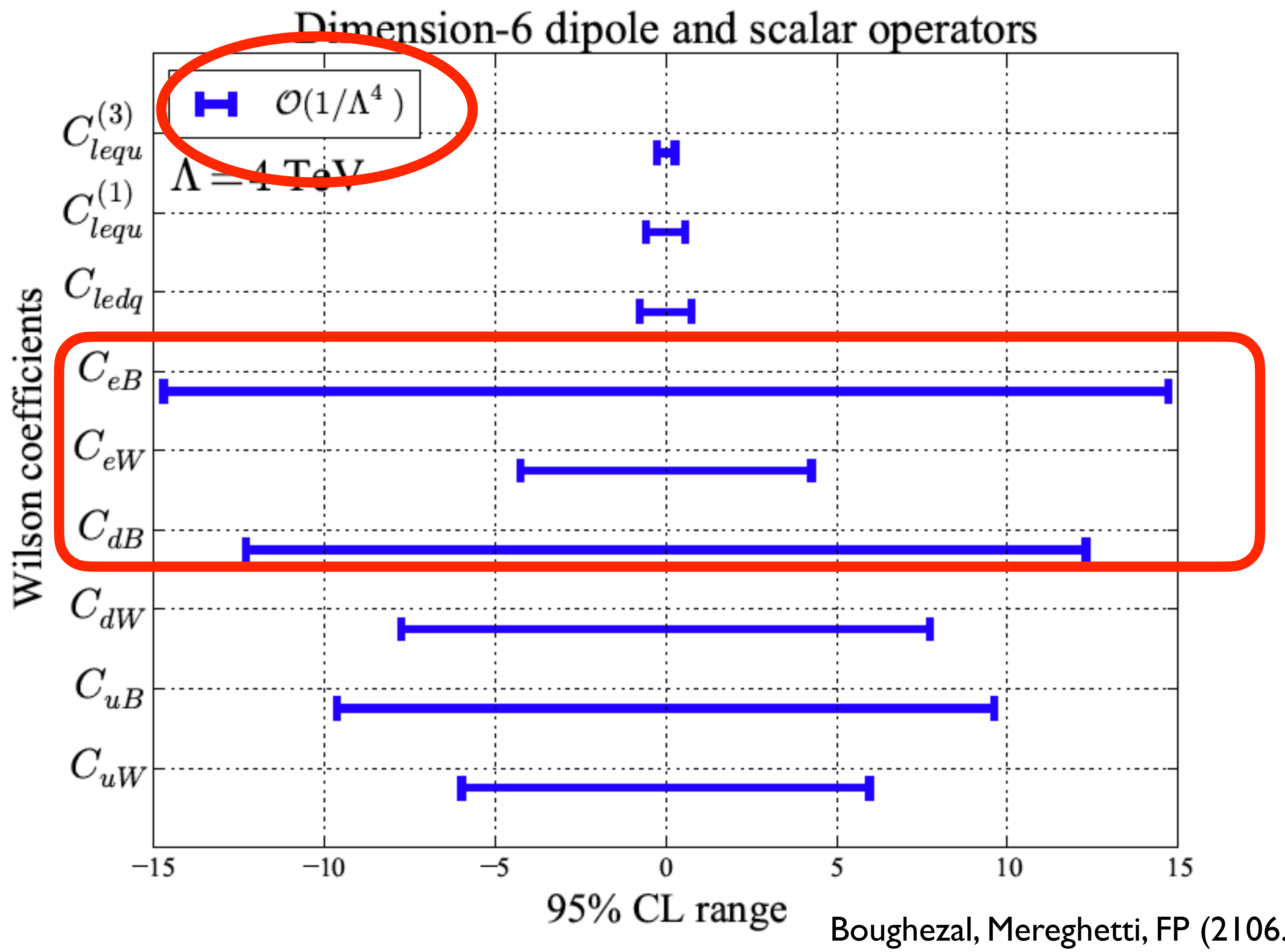
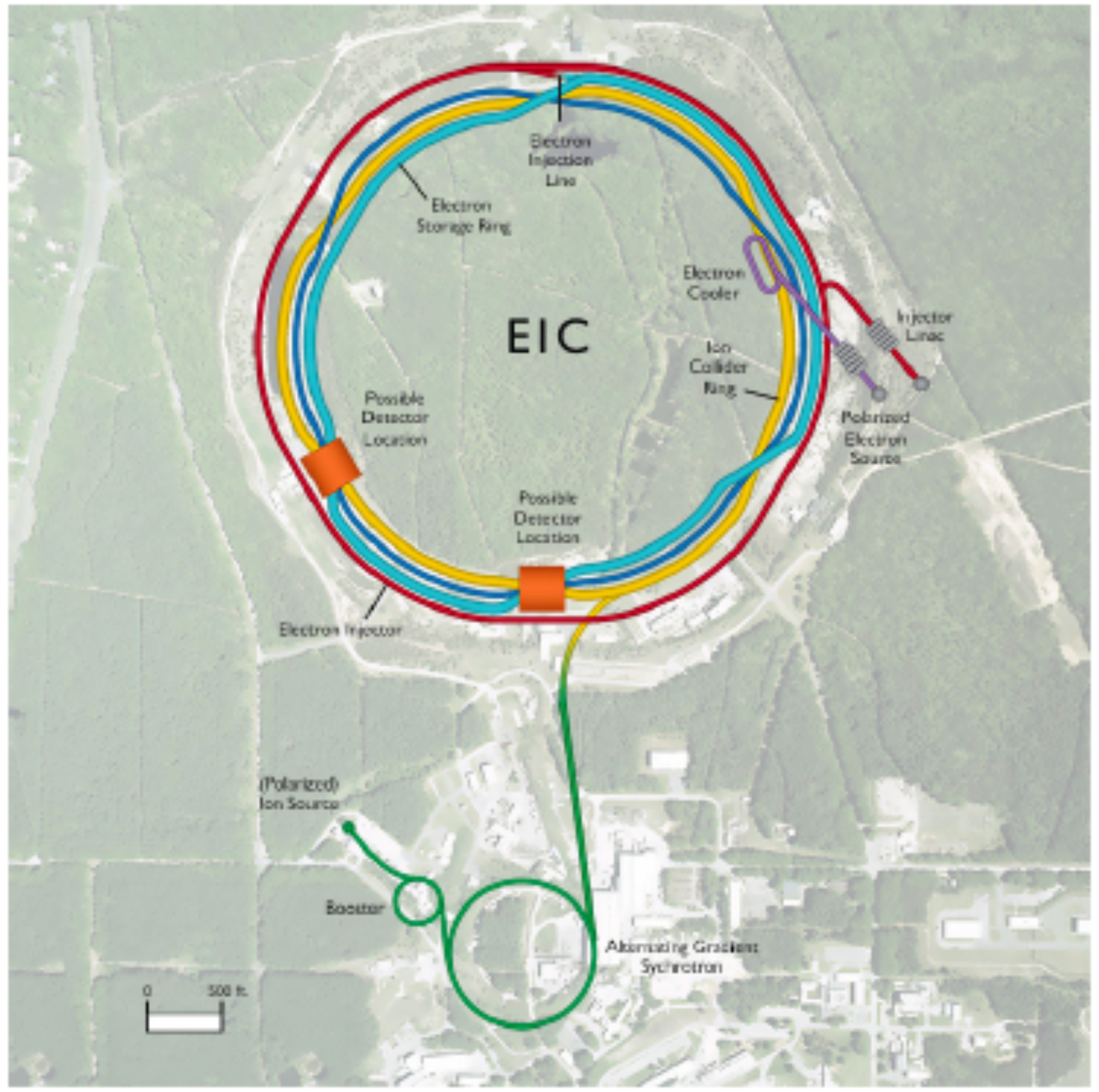
The relevant dipole operators are weakly constrained at the LHC. These effects are also sub-leading in the $1/\Lambda$ expansion and can be easily overwhelmed by the leading semi-leptonic, four-fermion operators



Boughezal, Mereghetti, FP (2106.05337)

Polarization at the EIC

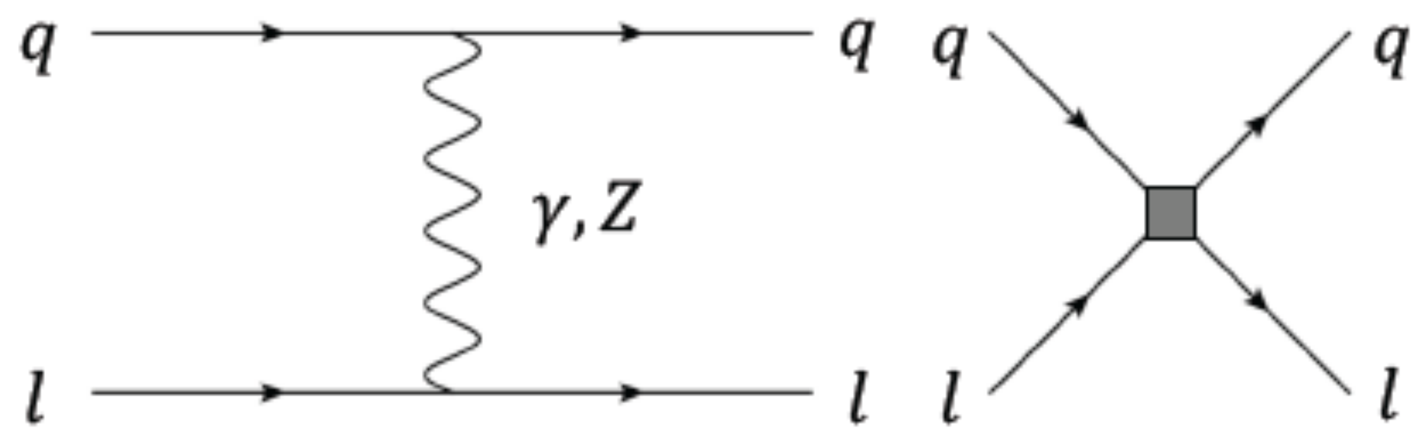
- Other measurements are needed to close these holes in our study of the vast BSM parameter space, and to provide confirmation (or not) of the possible cracks in the SM foundation.



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: $\geq 10\ fb^{-1}$



The key difference with respect to the LHC is the ability to polarize both beams. This gives access to spin asymmetry measurements that probe parameter space complementary to that of the LHC.

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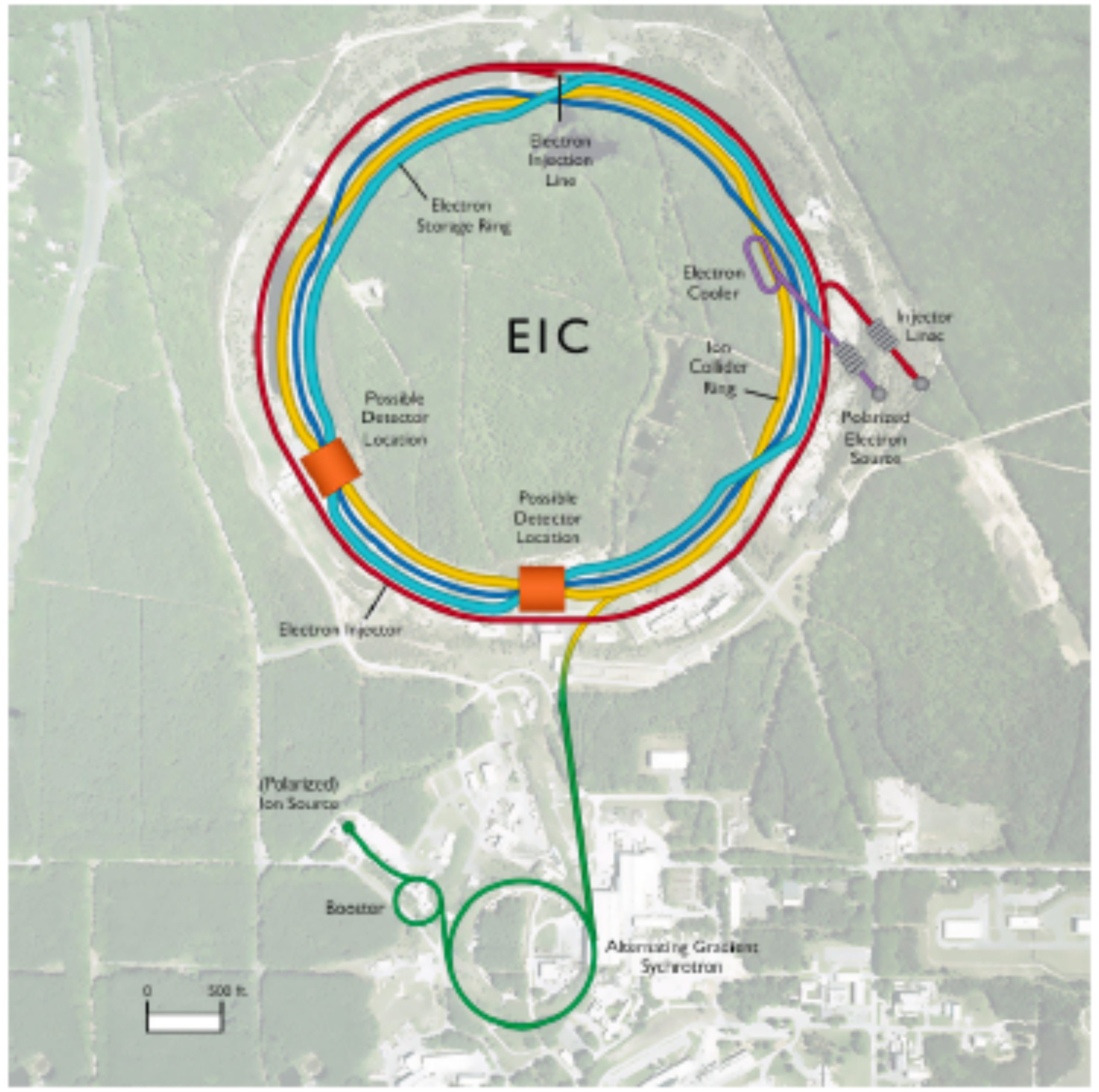

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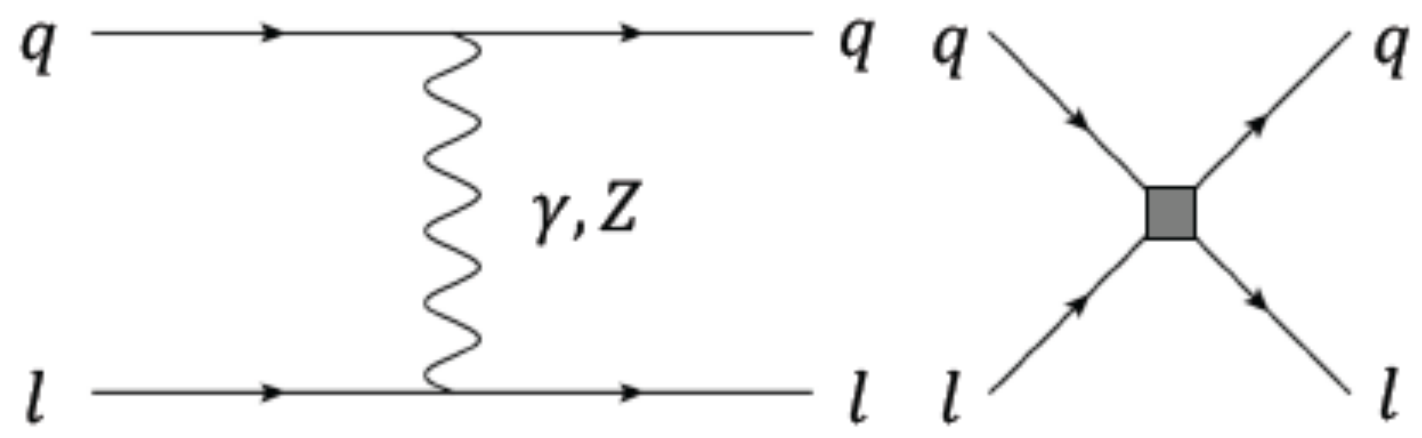
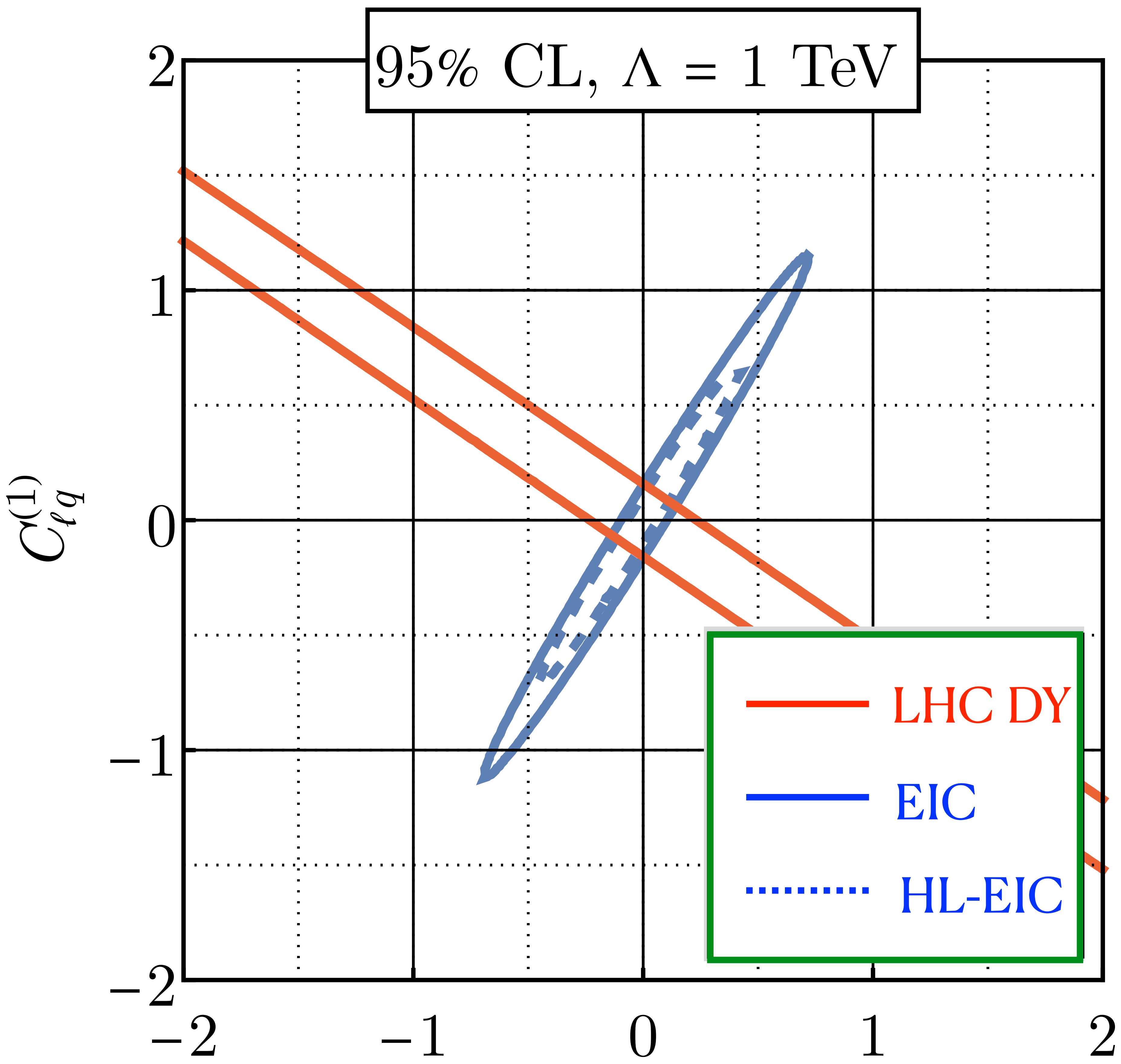


What unique handles on physics beyond the SM does this polarization provide to us?

Polarization at the EIC

- For the Drell-Yan example discussed previously, the use of longitudinal single-spin asymmetries with a polarized electron allows a resolution of the observed degeneracy.



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

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

$$A_{PV} = \frac{d\sigma_{\ell}}{d\sigma_0}$$

$$d\sigma_0 = \frac{1}{4}\sum_q f_{q/H}[d\sigma^{++} + d\sigma^{+-} + d\sigma^{-+} + d\sigma^{--}]$$

$$d\sigma_{\ell} = \frac{1}{4}\sum_q f_{q/H}[d\sigma^{++} + d\sigma^{+-} - d\sigma^{-+} - d\sigma^{--}]$$

$$d\sigma_H = \frac{1}{4}\sum_q \Delta f_{q/H}[d\sigma^{++} - d\sigma^{+-} + d\sigma^{-+} - d\sigma^{--}]$$

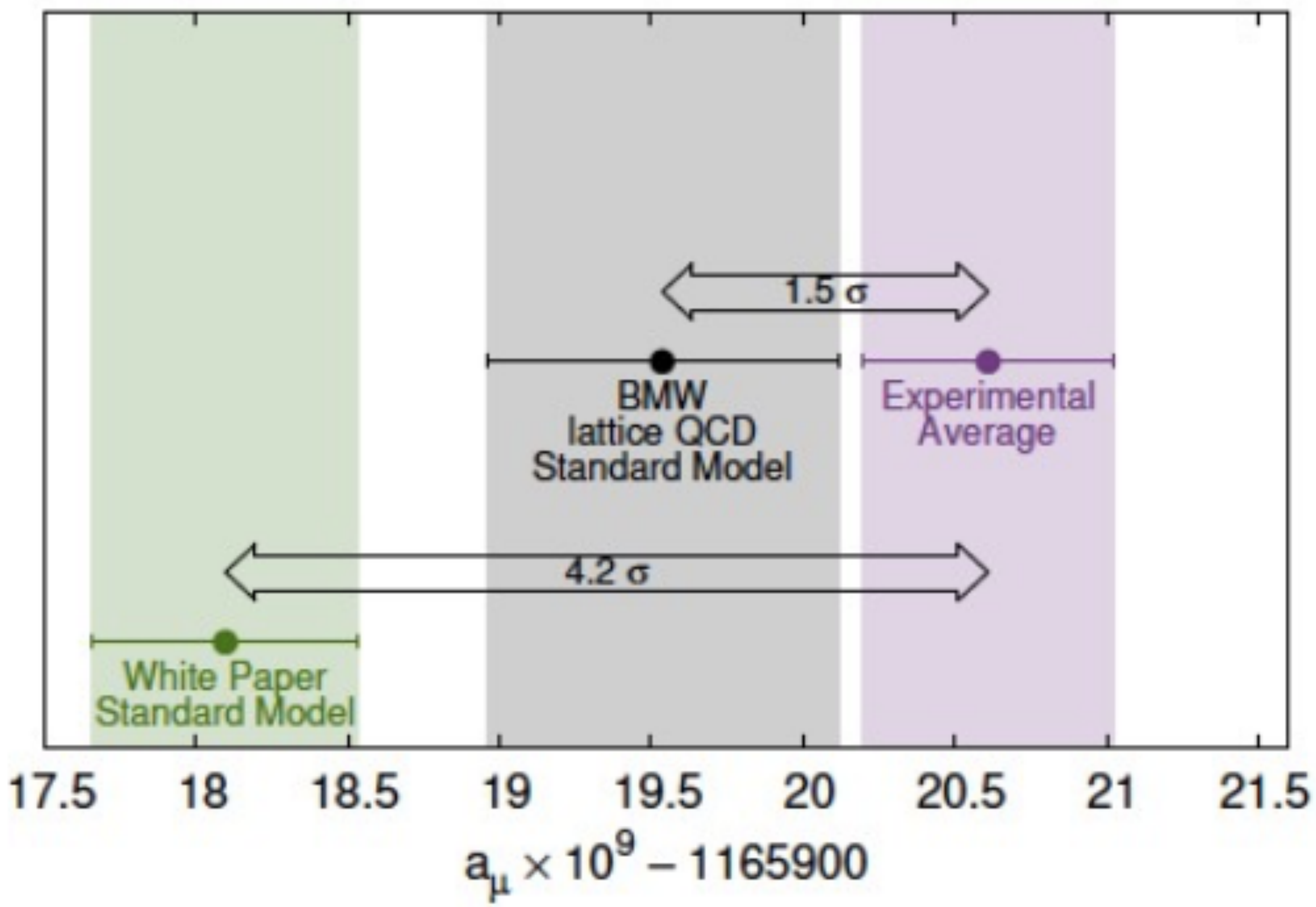
More details in Radja's Monday talk

Boughezal et al (2204.07557)

Boughezal et al (2004.00748)

More on lepton anomalous magnetic moments

- Besides the muon anomalous magnetic moment discrepancy, 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)

More on lepton anomalous magnetic moments

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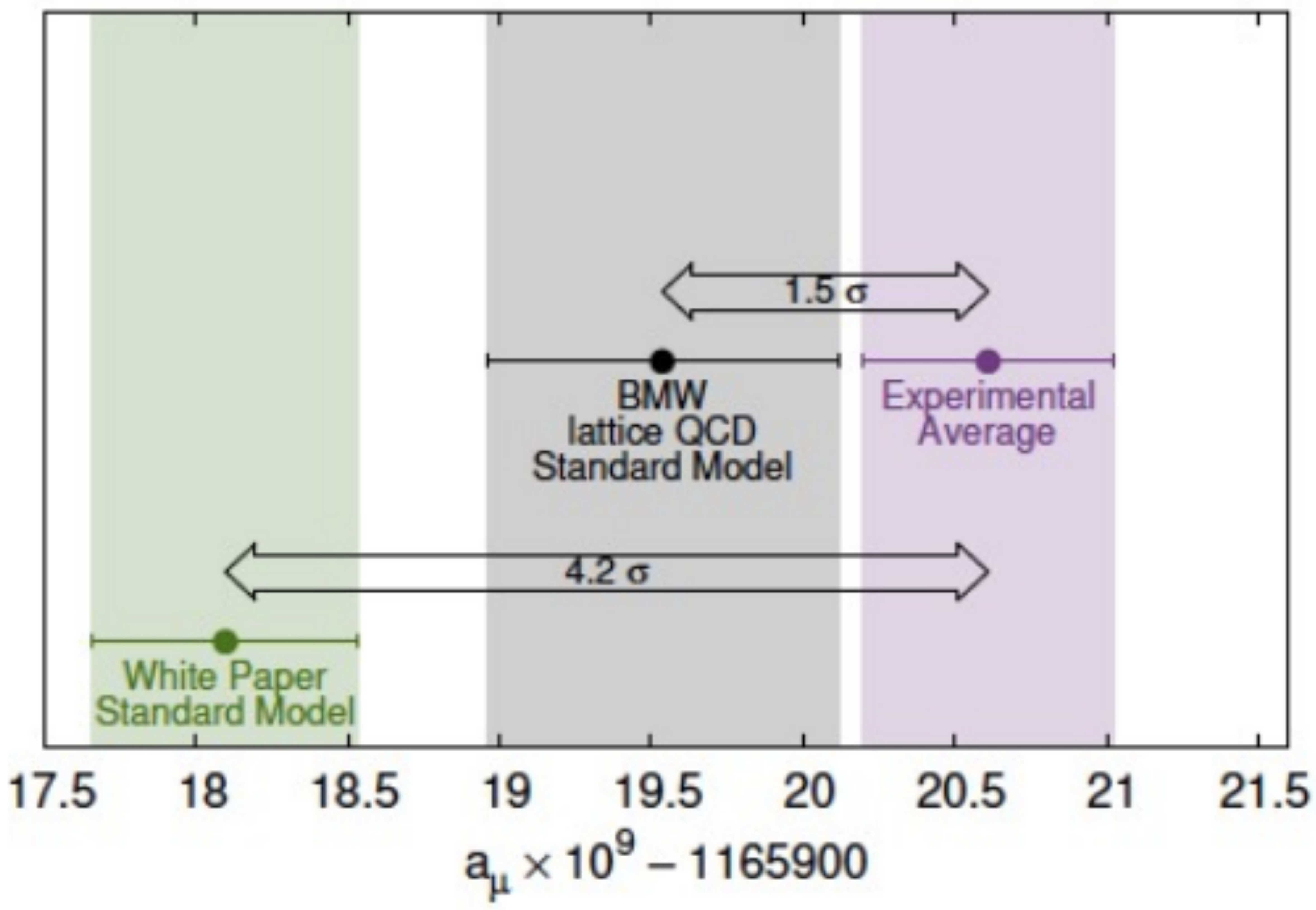

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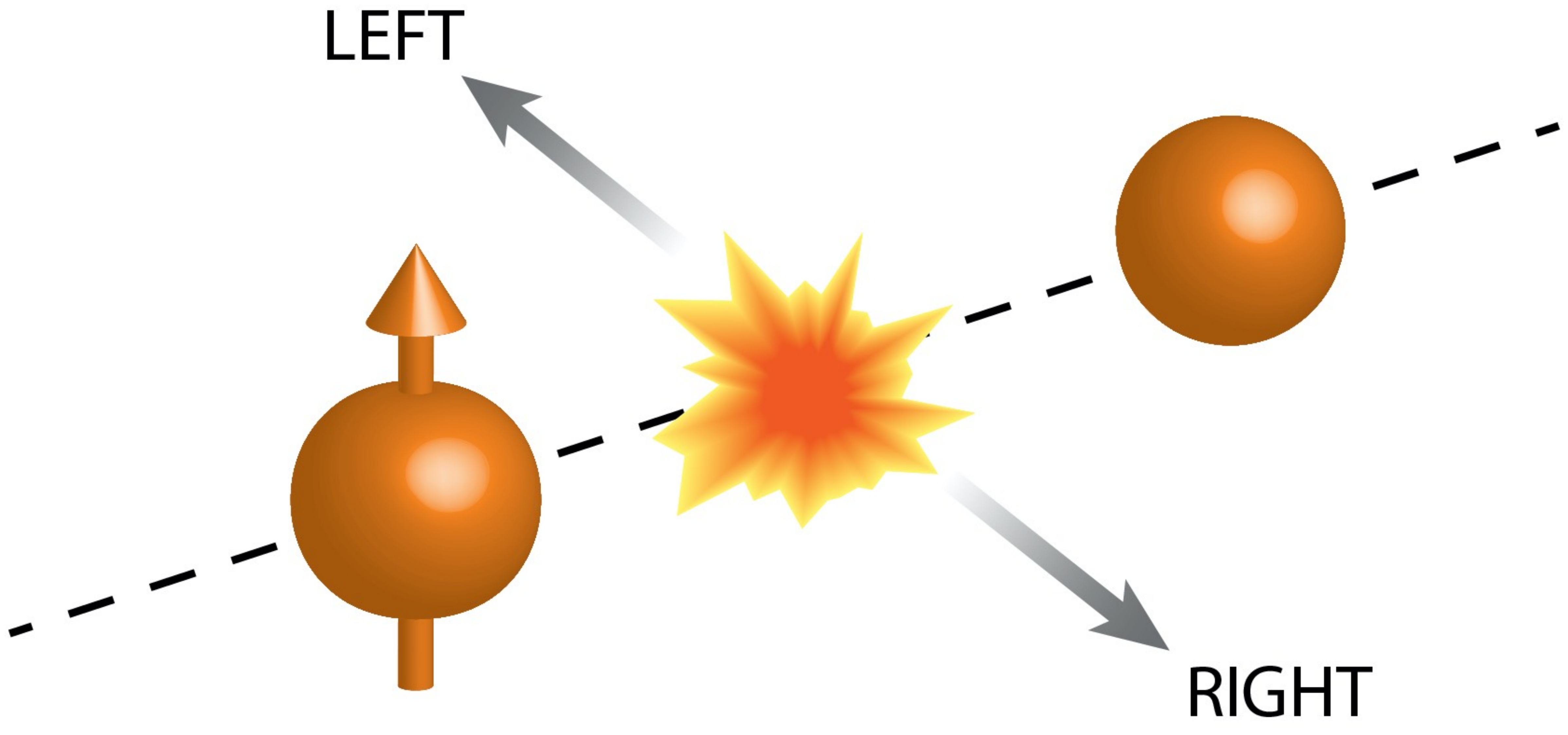
Questions:

Could new physics explain the muon g-2 discrepancy? Can it shift the electron g-2 by a similar size as the observed discrepancy? In general what are other probes of possible BSM in dipole operators? Can the polarization possible at the EIC help address these questions?

Transverse single-spin asymmetries within the Standard Model

Transverse SSAs

- Transverse spin asymmetries in DIS arise when the polarization of an initial particle is transverse to the beam direction. In DIS can either have the initial electron or the initial hadron polarized.



Measurements of SSAs in various final states have previously been measured at RHIC; we will visit this toward the end of the talk

Polarized electrons:

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

Polarized protons:

$$A_{UT} = \frac{\sigma(p^{\uparrow}) - \sigma(p^{\downarrow})}{\sigma(p^{\uparrow}) + \sigma(p^{\downarrow})}$$

Transverse polarization direction:

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

Transverse SSAs and discrete symmetries

- The structure of transverse spin asymmetries is dictated by the discrete symmetries of the Standard Model.

Recall the transformations of quantum operators under parity and time-reversal:

$$P\, c a^s_{\vec{p}}\, P^{-1} = c a^s_{-\vec{p}}$$
$$T\, c a^s_{\vec{p}}\, T^{-1} = c^* a^{-s}_{-\vec{p}}$$

c is a c-number; time reversal is an anti-unitary operator

It is useful to also consider a linear transformation related to time-reversal invariance, often called "naive" time-reversal (Sivers 1996):

$$A_t\, c a^s_{\vec{p}}\, A_t^{-1} = c a^{-s}_{-\vec{p}}$$

Note that the combined transformation PA_t leaves a particle momentum unchanged but flips its spin; single-spin asymmetries are necessarily odd under this transformation

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For transverse spin S_T, we can form the following structures in the asymmetry which can contribute to A_{UT} or A_{TU}:

$\epsilon_{\mu\nu\rho\sigma} S_T^{\mu} P^{\nu} k^{\rho} k'^{\sigma}$	⇒P even, A_t odd
$S_T \cdot k'$	⇒P odd, A_t even

Process under study: $l(k) + p(P) \rightarrow l'(k') + X$

Transverse SSAs and discrete symmetries

- The structure of transverse spin asymmetries is dictated by the discrete symmetries of the Standard Model.

$$P\, ca^s_{\vec{p}}\, P^{-1} = ca^s_{-\vec{p}}$$

$$T\, ca^s_{\vec{p}}\, T^{-1} = c^* a^{-s}_{-\vec{p}}$$

$$A_t\, ca^s_{\vec{p}}\, A_t^{-1} = ca^{-s}_{-\vec{p}}$$

Within the SM:

- The single-photon exchange current is P even, T even and A_t even.
- The Z-exchange current is P-odd, but T and A_t even.
- Two-photon exchange is P even, T even. However, the associated loop integral has an imaginary part; this imaginary part leads to an A_t odd contribution.

Except a contribution to this structure from the interference of one-photon exchange and the imaginary part of two-photon exchange. →

$\epsilon_{\mu\nu\rho\sigma} S_T^\mu P^\nu k^\rho k'^\sigma$ ⇒P even, A_t odd

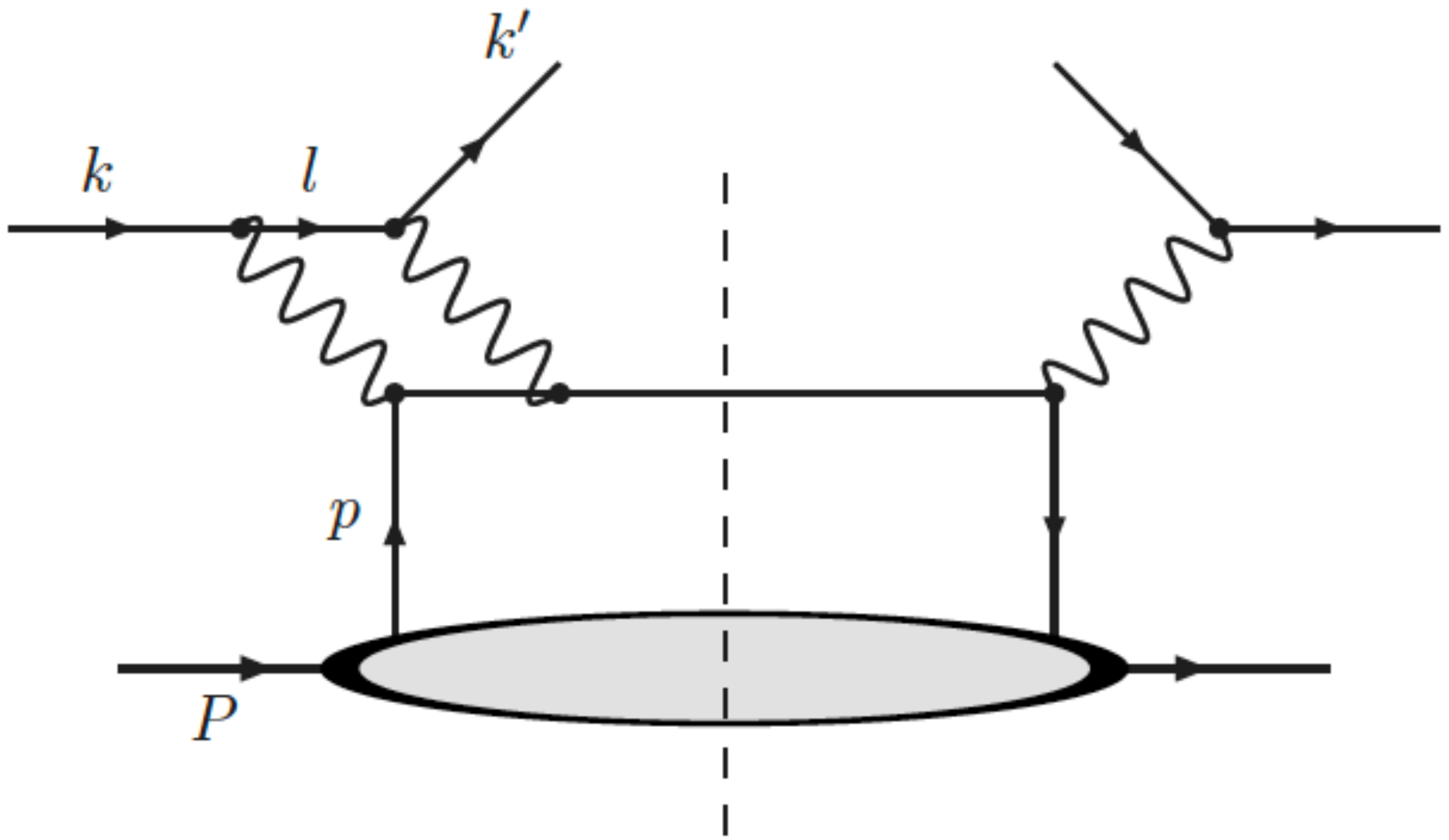
Except a contribution to this structure from the interference of one-photon exchange and Z exchange at tree-level. →

$S_T \cdot k'$ ⇒P odd, A_t even

Process under study: $l(k) + p(P) \to l'(k') + X$

Two-photon exchange contribution

- Historically the focus for SSAs was on QED, since these asymmetries were first considered at lower energies. The two-photon exchange mechanism has been previously considered in the literature (Metz, Schlegel, Goeke hep-ph/0610112). We will begin by considering the beam SSA with the electron transversely polarized.



- 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 requires the absorptive part of the one-loop amplitude

Two-photon exchange beam SSA

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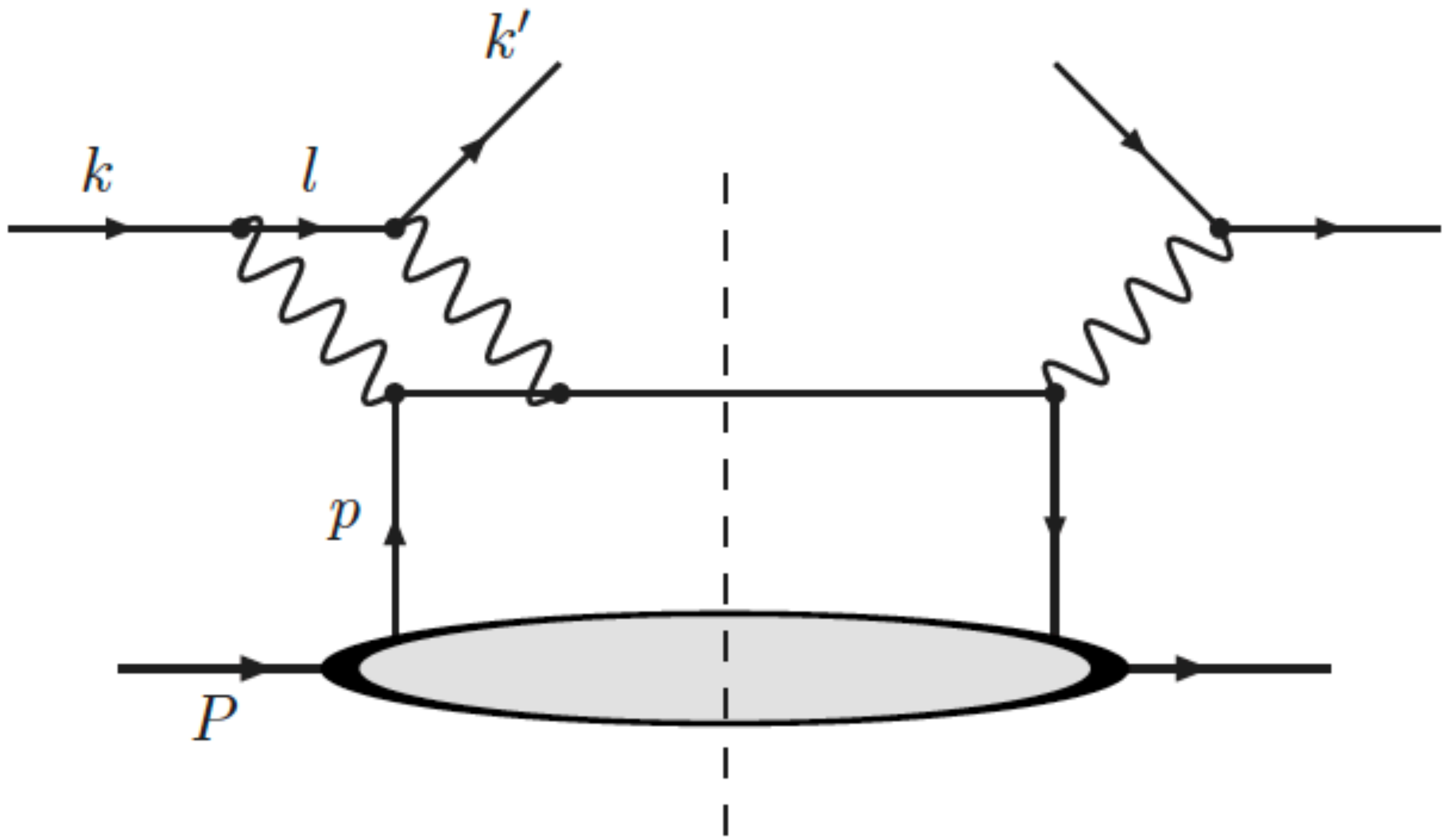


$$A_{TU}^{\gamma\gamma} = \alpha \frac{m_l}{2Q} \sin(\phi) \frac{y^2\sqrt{1-y}}{1-y+y^2/2} \frac{\sum_q Q_q^3 f_q(x)}{\sum_q Q_q^2 f_q(x)}$$

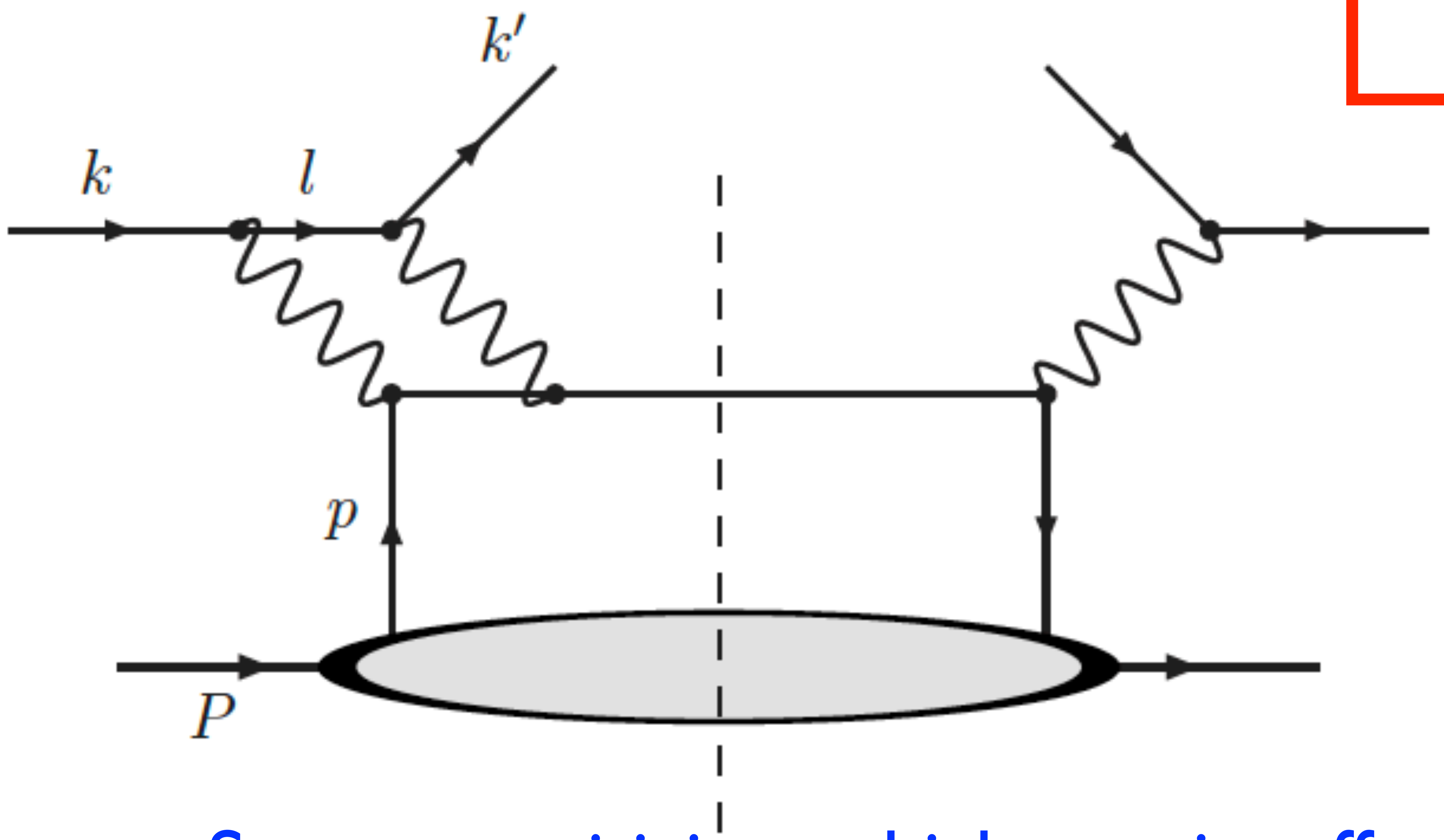
Doubly-suppressed by two small quantities

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

Note: $\epsilon_{\mu\nu\rho\sigma} S_T^\mu P^\nu k^\rho k'^\sigma = \frac{Q^3\sqrt{1-y}}{y} S_T s_\phi$

Two-photon exchange target SSA

- We now consider the target SSA with the proton transversely polarized. This calculation turns out to be extremely sensitive to the IR behavior of QCD.



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

- 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

Strong sensitivity to higher-twist effects in QCD; for our purposes, we rely upon estimates that suggest $A_{UT}<10^{-4}$ in the SM

(Afanasev, Strikman, Weiss 0709.0901; see also Accardi, Signori 1903.04458)

Transverse SSAs in the SM

- The second P-odd mechanism grows with momentum transfer, and should be more important at a future higher-energy EIC. Since the effect comes from tree-level Z exchange both the target and beam asymmetries are IR finite

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

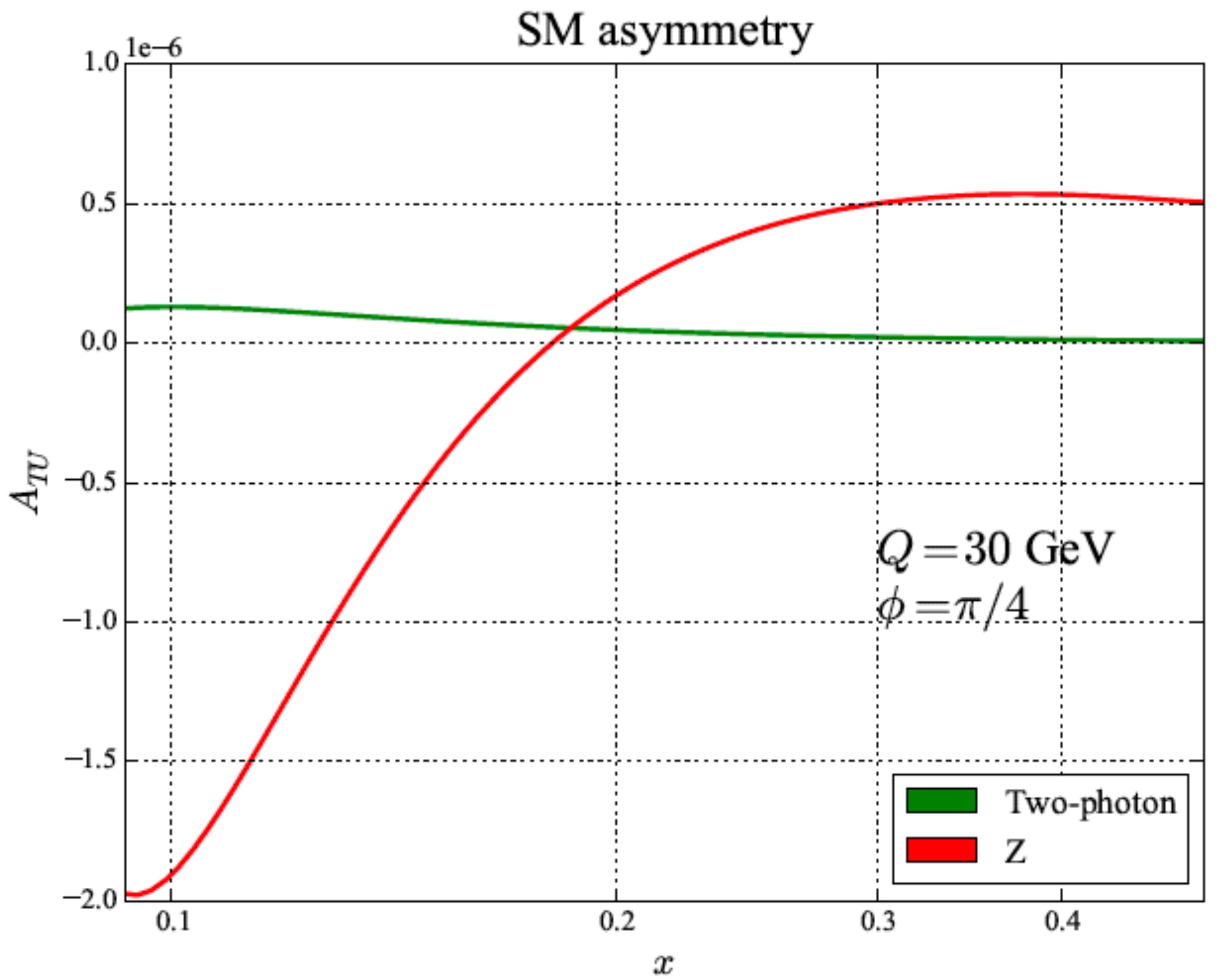
$$A_{UT}^{Z}(\phi) = -\frac{2}{s_W^2 c_W^2}\frac{m_q Q}{M_Z^2}\frac{y\sqrt{1-y}}{1-y+y^2/2}\cos(\phi)\frac{\sum_q Q_q h_q(x)\left[g_{aq}g_{vl}(1-y)+g_{vq}g_{al}y\right]}{\sum_q Q_q^2 f_q(x)}$$

Note transversity distributions

Note the different azimuthal angle dependence than photon contribution

$$S_T \cdot k = Q\sqrt{1-y}S_T c_\phi$$

Parity violating $g_v g_a$ dependence



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

Transverse single-spin asymmetries beyond the Standard Model

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:

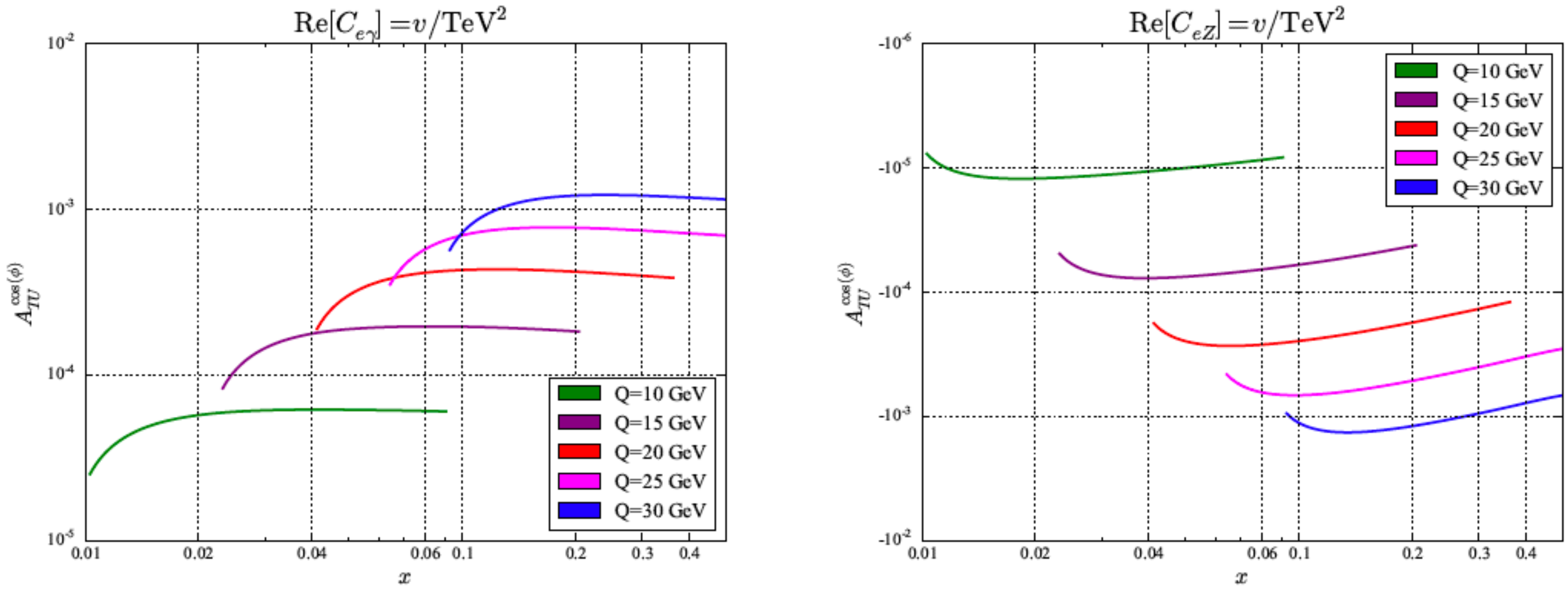
$$A_{TU}^w = \int_0^{2\pi} d\phi\, w(\phi)\, A_{TU}(\phi)$$

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!

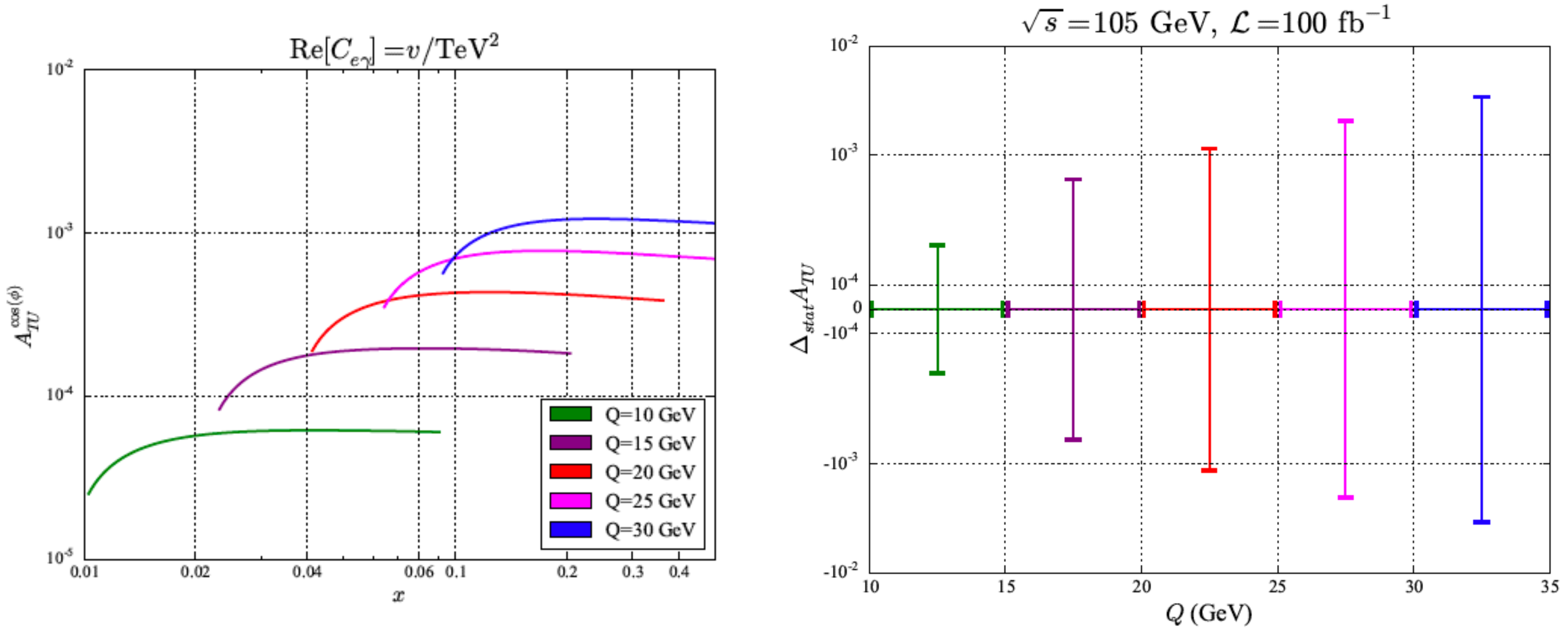
Numerics at an EIC

- 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. An analysis binned in Q and x should be able to probe TeV-scale new physics affecting dipole operators.



Numerics at an EIC

- Since we are unaware of any EIC simulation of transverse spin asymmetry data at the EIC, we can only do a rough calculation of the expected statistical uncertainty at the EIC. This figure show the uncertainty integrated over Bjorken-x. Integrating the asymmetry over x in each Q bin leads to a several sigma deviation from the SM for TeV-scale Wilson coefficients.



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!

Aebischer et al (2102.08954)

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

$C_{e\gamma}$, 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: $$(\Delta a_e)^{exp-th} = \frac{m_e}{m_\mu}\begin{bmatrix} -1.8(7)^{\text{Cs}} \\ 1.0(6)^{\text{Rb}} \end{bmatrix} \times 10^{-10}$$

- 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 by directly probing the C_{eZ} scales needed to address the discrepancy. The direct anomalous magnetic moment measurement is relatively insensitive to C_{eZ}.

Target transverse SSAs

- Estimated corrections depend strongly on the assumed 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.

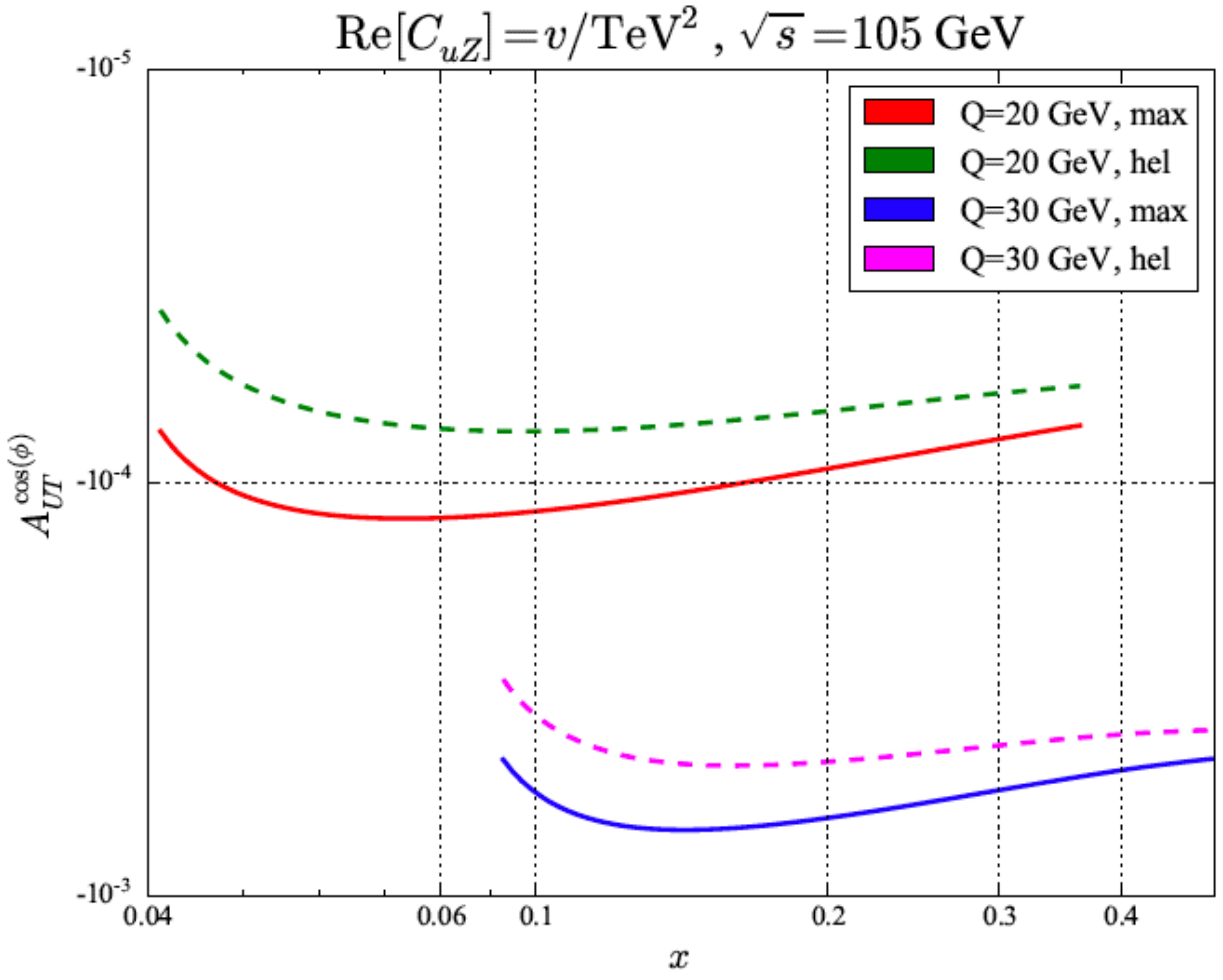
Soffer bound:

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

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

(de Florian 2017)

Larger asymmetries than expected in the SM, but need EIC transversity distribution measurements for intepretation



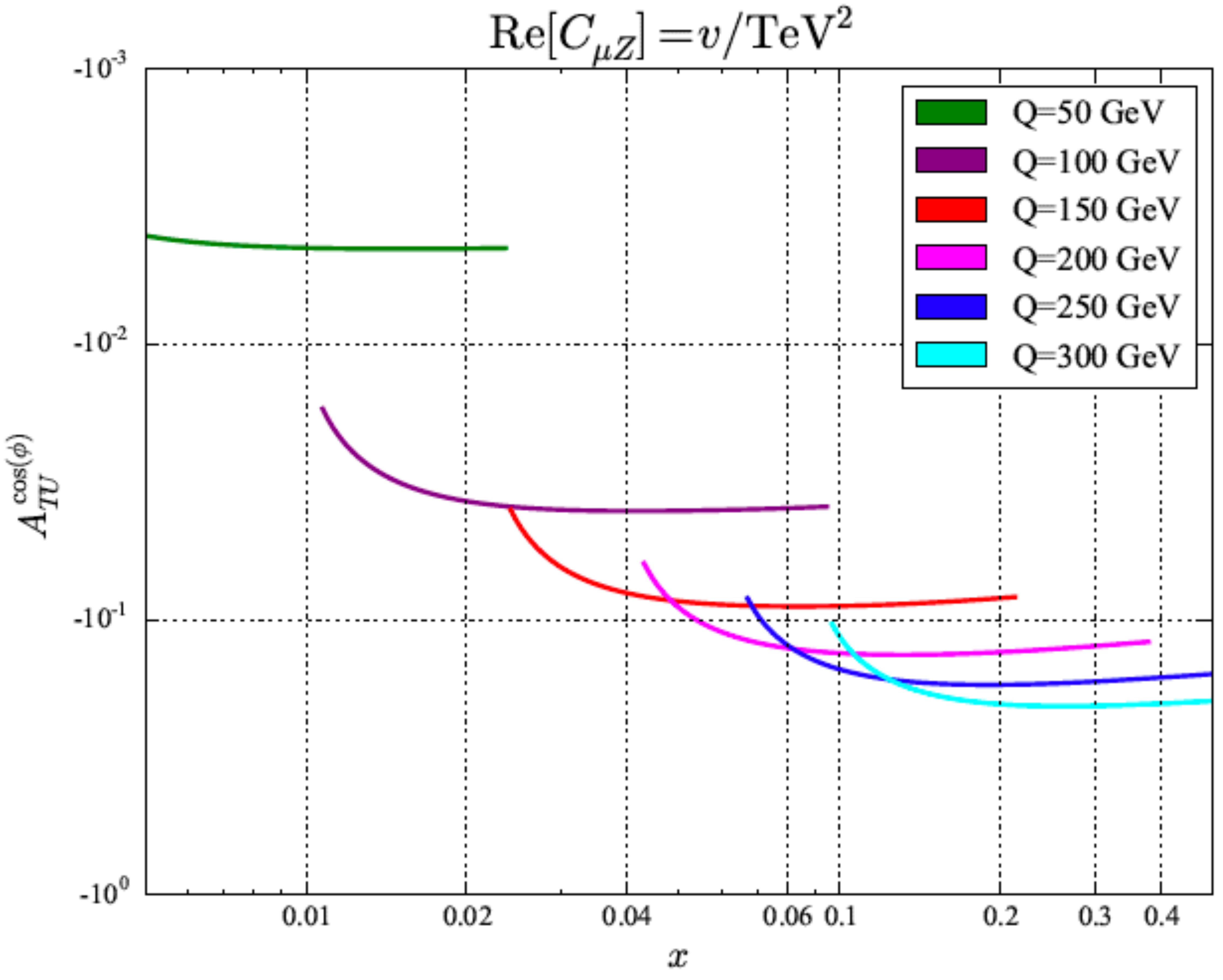
A muon-ion collider

- 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 2107.02073). 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.



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

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

Aebischer et al (2102.08954)

- 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 interesting parameter space as the muon g-2! It probes a very different linear combination of the two Wilson coefficients that lead to the muon anomalous magnetic moment.

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

Aebischer et al (2102.08954)

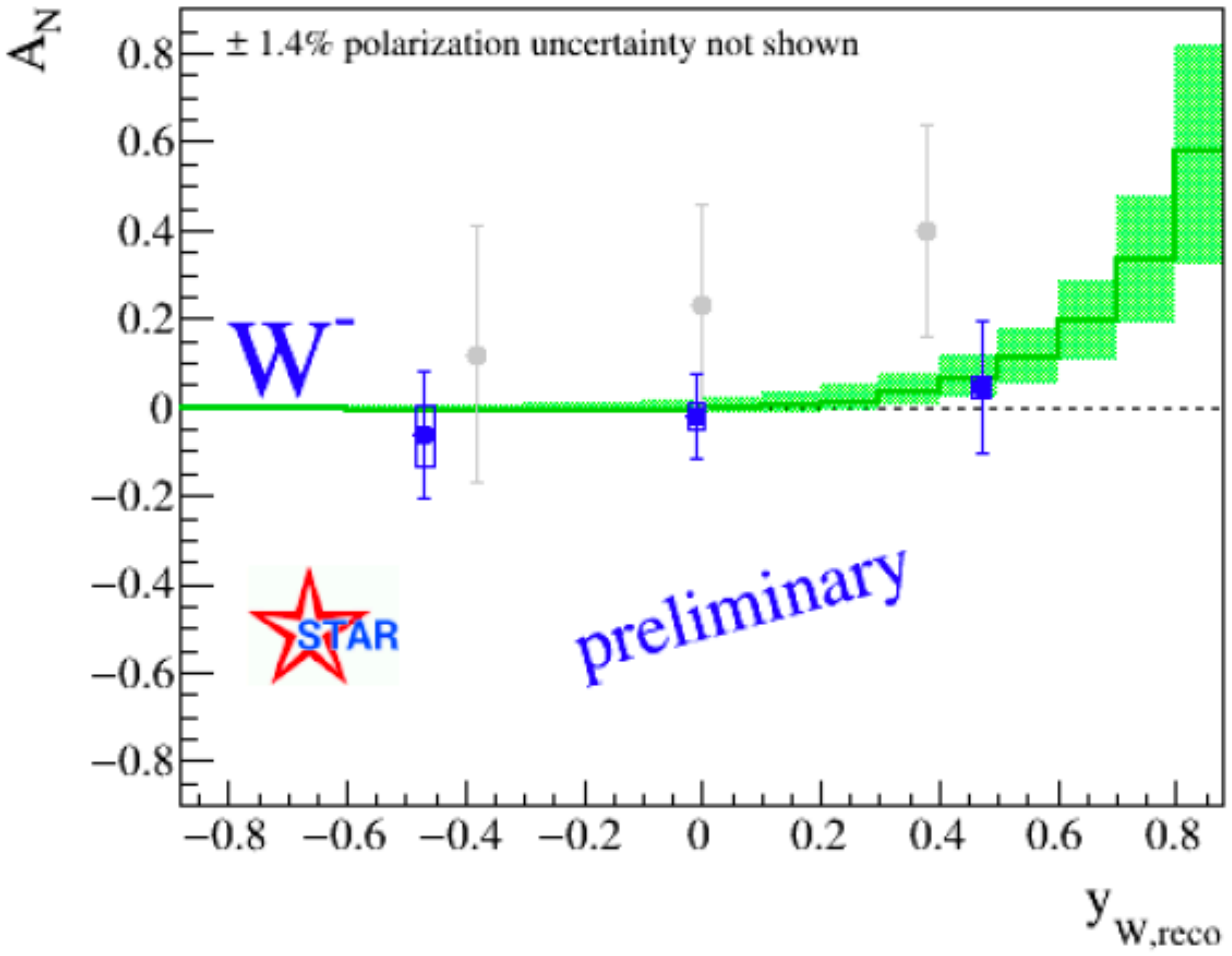
- Turning on only a single coefficient at a time, we find that $\mathrm{Im}[C_{\mu\gamma}]$ scales around 10 TeV can be probed by EDM measurements, above muon-ion collider capabilities
- However, only $\mathrm{Im}[C_{\mu Z}]$~700 GeV can be probed with EDM measurements.

Transverse SSAs at a muon-ion collider can improve upon existing muon EDM constraints; target asymmetries provide probes of quark EDMs

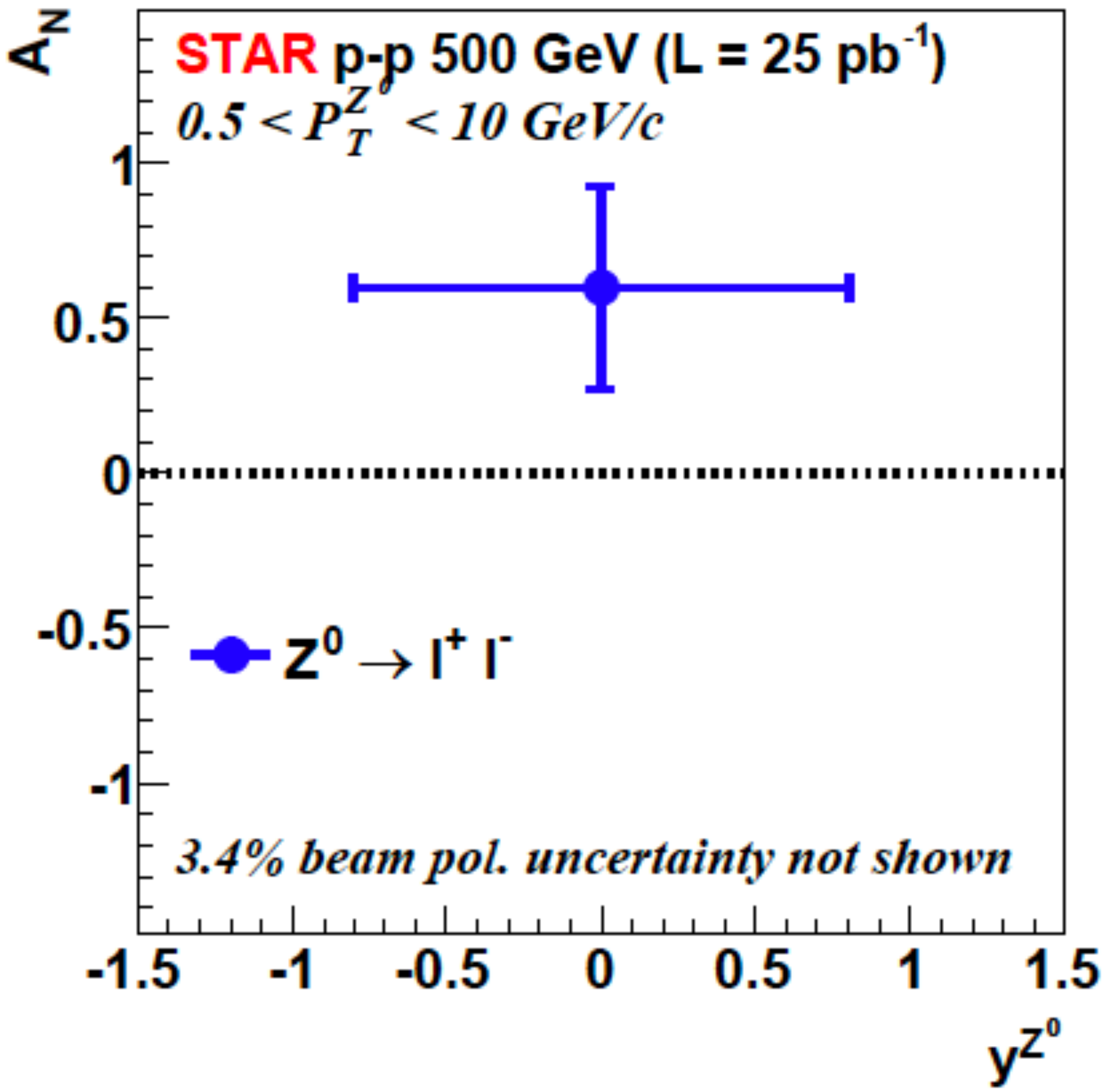
Transverse single-spin asymmetries and Drell-Yan at RHIC

Transverse SSAs at RHIC

- The RHIC experiments have measured high-pT transverse SSAs in the variety of channels. Focus on W and Z boson production, which have the requisite parity violation to lead to a tree-level effect.

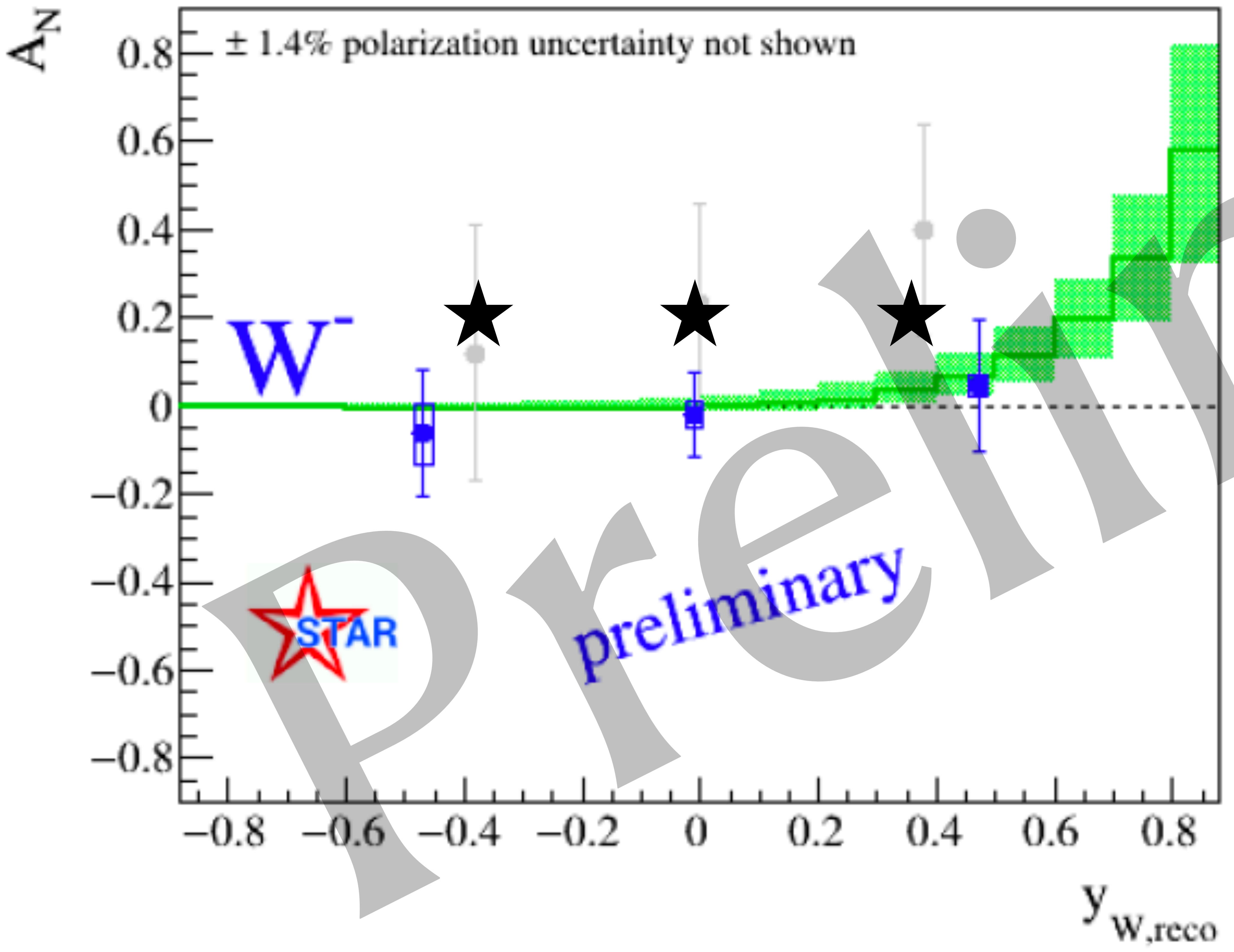


A_N measured in a single y, P_T bin



Transverse SSAs at RHIC

- Focus on W production, for which more statistics are available. As a preliminary check evaluate for central rapidity asymmetry.



$$A_N(y_W = 0) \approx \frac{3\pi}{2\sqrt{2}g_{EW}} M_{ll}\left[c_\phi \mathrm{Re}[C_{qW}] - s_\phi \mathrm{Im}[C_{qW}]\right]$$

Transverse SSAs can reach A_N=0.2 for new physics at the 500 GeV scale; is a more detailed analysis interesting?

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.
- 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.
- Measurement of target SSAs probes quark anomalous magnetic and electric dipole moments.

Thank you!