



Brookhaven
National Laboratory

Impact of QCD corrections on light-quark dipole sensitivity at the EIC

Zhite Yu (BNL, High Energy Physics)

In collaboration with Sally Dawson.

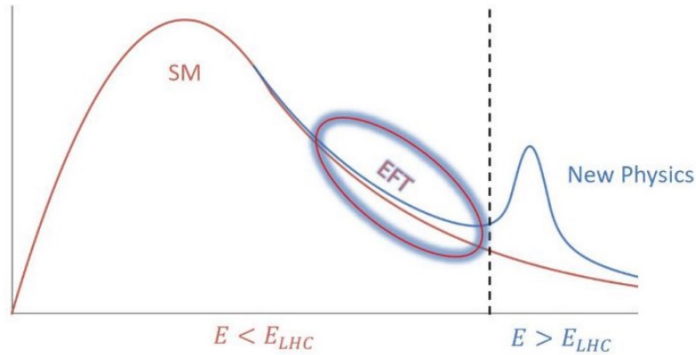
Paper to appear, all results preliminary.

Precision QCD predictions for ep physics at the EIC (IV)

CFNS, Sep 22, 2026

SMEFT and dipole operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \left(\frac{C_i}{\Lambda^2} O_i + \text{h.c.} \right)$$



Bottom-up EFT
 $\Lambda = \mathcal{O}(\text{TeV})$



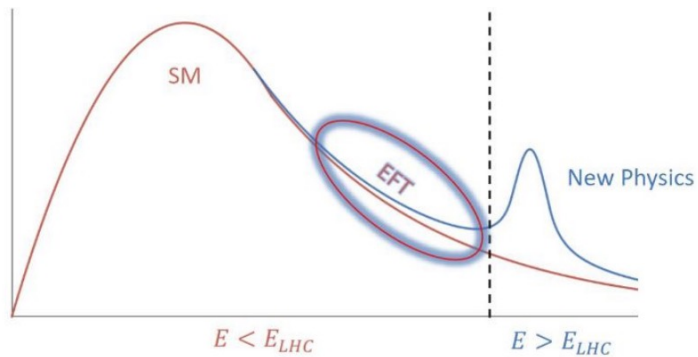
SMEFT

B. Grzadkowski et al, JHEP 10 (2010) 085

$X^2 \varphi^2$		$\psi^2 X \varphi$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$

SMEFT and dipole operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \left(\frac{C_i}{\Lambda^2} O_i + \text{h.c.} \right)$$

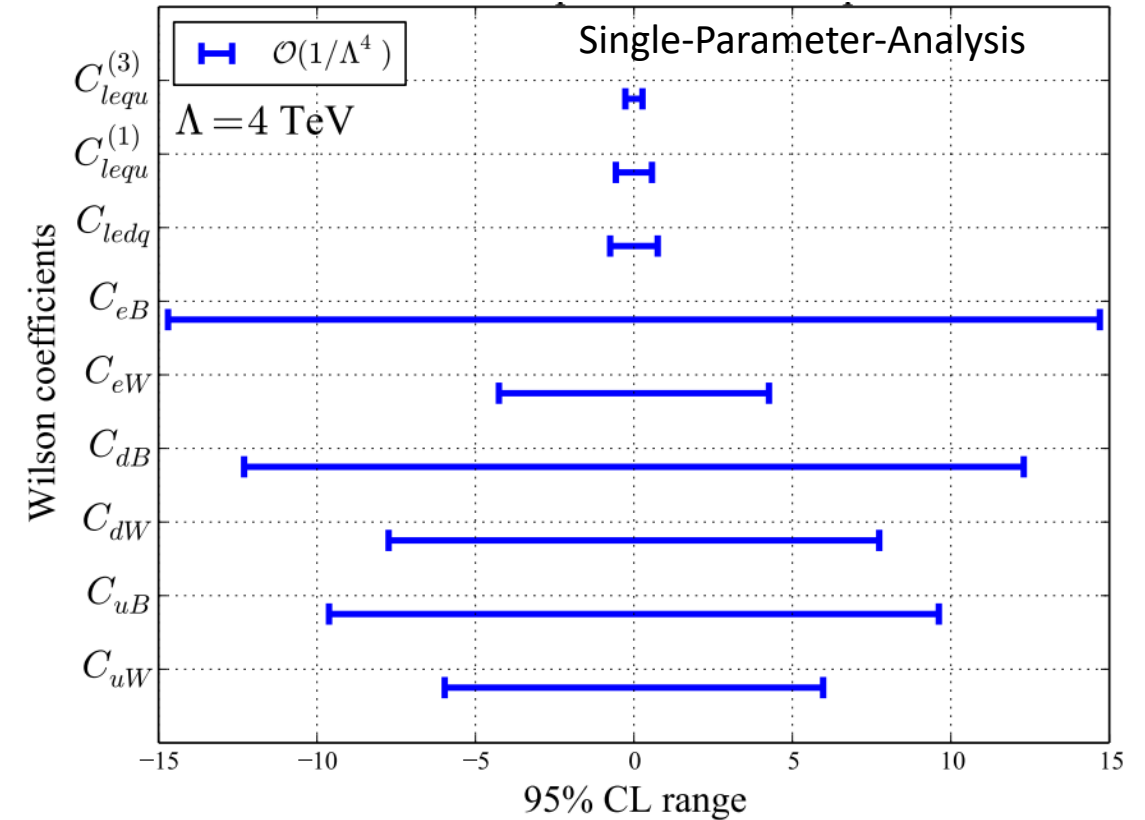


Bottom-up EFT
 $\Lambda = \mathcal{O}(\text{TeV})$



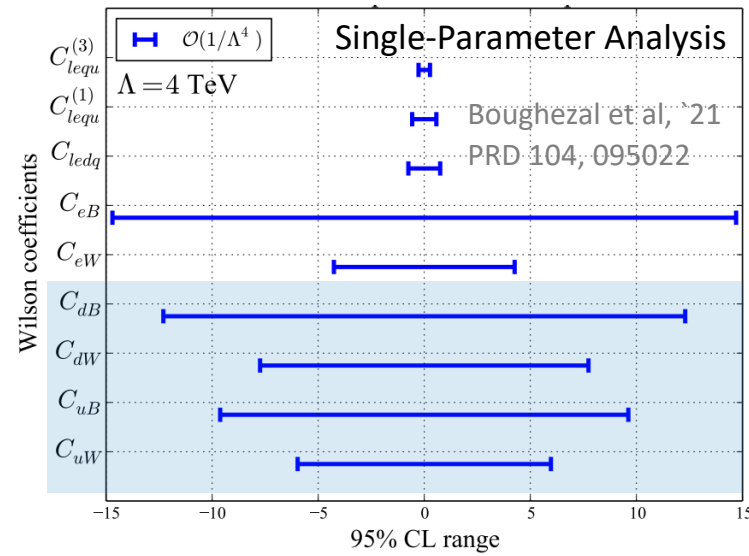
SMEFT

Boughezal et al, '21 PRD 104, 095022



Special at high energy

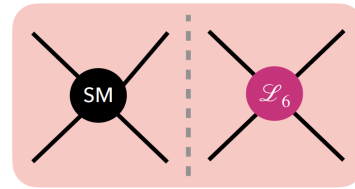
□ Suppressed interference with SM



$$\sigma \propto |\mathcal{M}_{\text{SM}} + \Lambda^{-2} \mathcal{M}_{\text{NP}}|^2$$

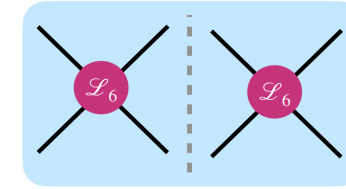


Interference effects



$$\mathcal{O}(\Lambda^{-2})$$

But, dipole operators flip chirality



$$\mathcal{O}(\Lambda^{-4})$$



Weak constraints!

□ Chiral-odd property

$$16\pi^2 \frac{dC_{uW}}{d \ln \mu} = [2C_{F,3}g_3^2 + \mathcal{O}(g_2^2, g_1^2)] C_{uW} + \mathcal{O}(g_1 g_2) C_{uB} + 2C_{F,3}g_2 g_3 C_{uG}$$

$$- Y_u^\dagger \left[\mathcal{O}(g_2) (C_{HW} + i C_{H\widetilde{W}}) + \mathcal{O}(g_1) (C_{HWB} + i C_{H\widetilde{W}B}) \right]$$

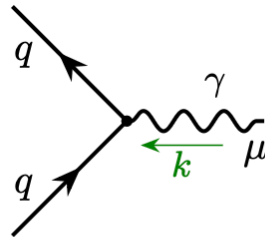
$$\simeq 2C_{F,3}g_3^2 C_{uW}$$

Mix with **dipole** SMEFTs, or with others via **Yukawa** couplings.  Self-contained subset for light fermions.

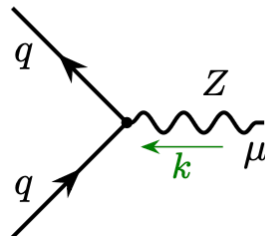
Light-quark dipole operators

□ Dipoles in (γ, Z) basis: 4 dipole couplings = 8 real d.o.f.

$$\mathcal{L} \supset \mathcal{L}_{\text{SM}} - \frac{v+h}{2v^2} \left[e A_{\mu\nu} \bar{u} \sigma^{\mu\nu} (\text{Re} \Gamma_\gamma^u + i \text{Im} \Gamma_\gamma^u \gamma_5) u + g_Z Z_{\mu\nu} \bar{u} \sigma^{\mu\nu} (\text{Re} \Gamma_Z^u + i \text{Im} \Gamma_Z^u \gamma_5) u + (u \rightarrow d) \right]$$



$$= -ie \left\{ e_q \gamma^\mu + \frac{i \sigma^{\mu\nu} k_\nu}{v} [\text{Re}(\Gamma_\gamma^q) + i \text{Im}(\Gamma_\gamma^q) \gamma_5] \right\},$$

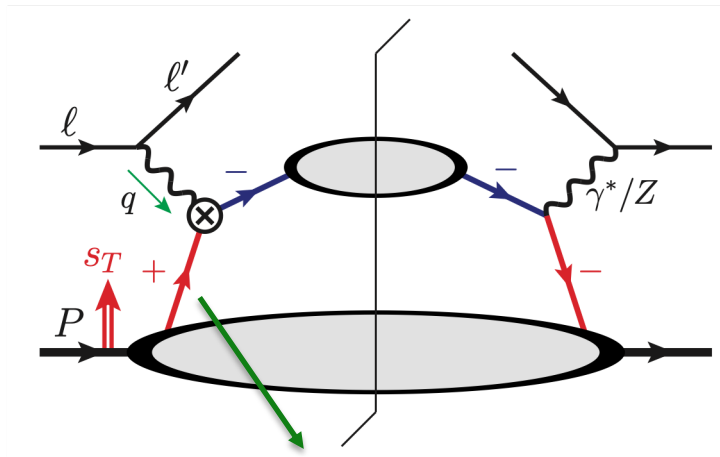


$$= -ig_Z \left\{ \gamma^\mu (g_V^q - g_A^q \gamma_5) + \frac{i \sigma^{\mu\nu} k_\nu}{v} [\text{Re}(\Gamma_Z^q) + i \text{Im}(\Gamma_Z^q) \gamma_5] \right\},$$

$$g_Z = \frac{g_2}{2 \cos \theta_W}$$

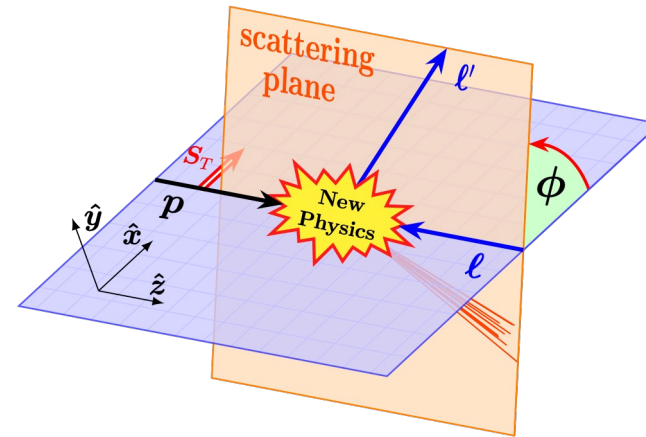
Chiral-odd probe yields **linear** sensitivity

□ Transverse spin asymmetry



$$\frac{\not{k}}{2} \rightarrow \frac{\not{k}}{2}(1 + \gamma_5 \not{S}_T)$$

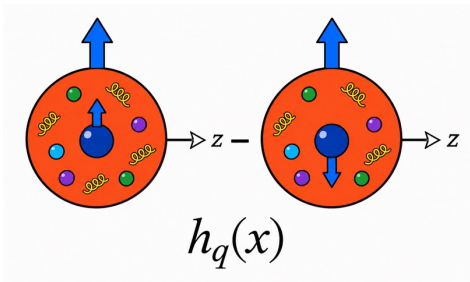
S_T introduces another γ -matrix $\longrightarrow$ **Chiral-odd!**



Observable:

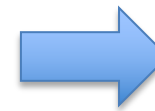
lepton's **azimuthal** asymmetry
in the **Lab frame**

□ Quark transverse spin comes from proton via **transversity PDF**



$$h_q(x) S_T = \frac{dN_q^\uparrow}{dx} - \frac{dN_q^\downarrow}{dx}$$

$$f_q(x) = \frac{dN_q^\uparrow}{dx} + \frac{dN_q^\downarrow}{dx}$$



Quark spin

$$s_{T,q}(x) = \frac{h_q(x)}{f_q(x)} S_T$$

Proton spin

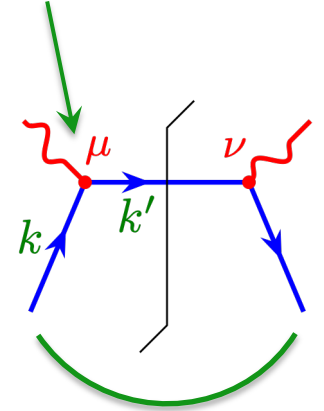
Results for $\gamma\gamma$ channel

□ Leading order

$$\frac{d\sigma_{\gamma}^{(0)}}{dx_B dQ^2 d\phi} = \frac{\alpha_e^2}{Q^4} \left\{ (1 + (1 - y)^2) \cdot \sum_q e_q^2 [f_q(x_B, \mu) + f_{\bar{q}}(x_B, \mu)] \right. \\ \left. + \underbrace{\lambda_e S_T}_{\text{Double spin asymmetry: (LT)}} \cdot \frac{2Q}{v} \cdot y \sqrt{1 - y} \sum_{q=u,d} e_q \text{Re} \left[\Gamma_{\gamma}^q e^{i(\phi - \phi_S)} \right] [h_q(x_B, \mu) + h_{\bar{q}}(x_B, \mu)] \right\}$$

Double spin asymmetry: (LT)

$$e_q \gamma^{\mu} + \frac{i \sigma^{\mu\nu} q_{\nu}}{v} [\text{Re}(\Gamma_{\gamma}^q) + i \text{Im}(\Gamma_{\gamma}^q) \gamma_5]$$



$$\frac{\not{k}}{2} (1 + \gamma_5 \not{S}_T)$$

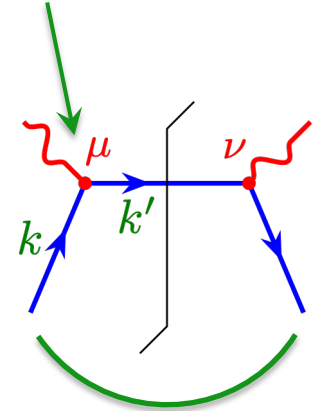
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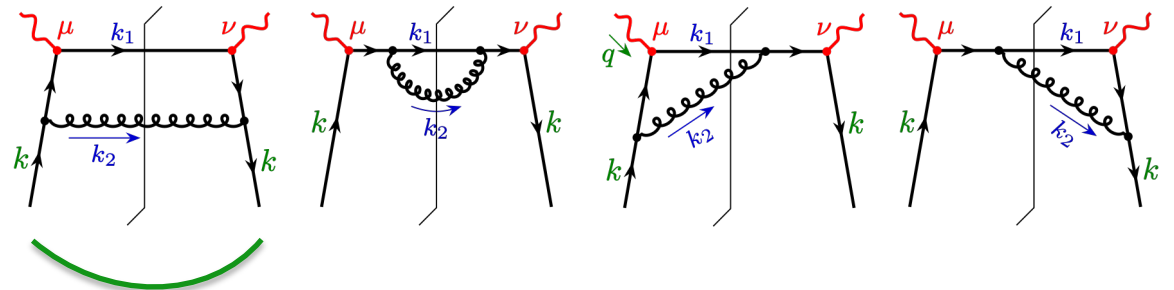
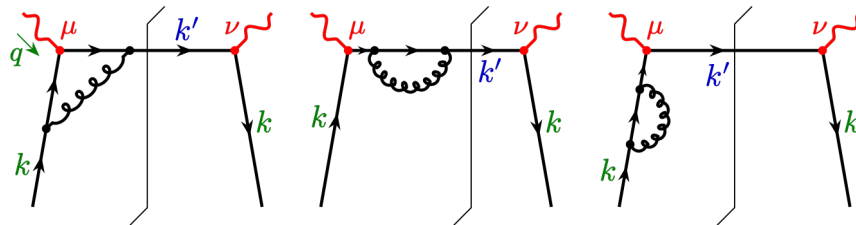
Double spin asymmetry: (LT)

$$e_q \gamma^{\mu} + \frac{i \sigma^{\mu\nu} q_{\nu}}{v} [\text{Re}(\Gamma_{\gamma}^q) + i \text{Im}(\Gamma_{\gamma}^q) \gamma_5]$$



$$\frac{\not{k}}{2} (1 + \gamma_5 \not{S}_T)$$

Next-to-leading order of QCD



Kreimer's scheme: reading point

$$\frac{\not{k}}{2} (1 + \gamma_5 \not{S}_T)$$

Preserve chiral symmetry: $\text{Re} \left[\Gamma_{\gamma}^q e^{i(\phi-\phi_S)} \right]$

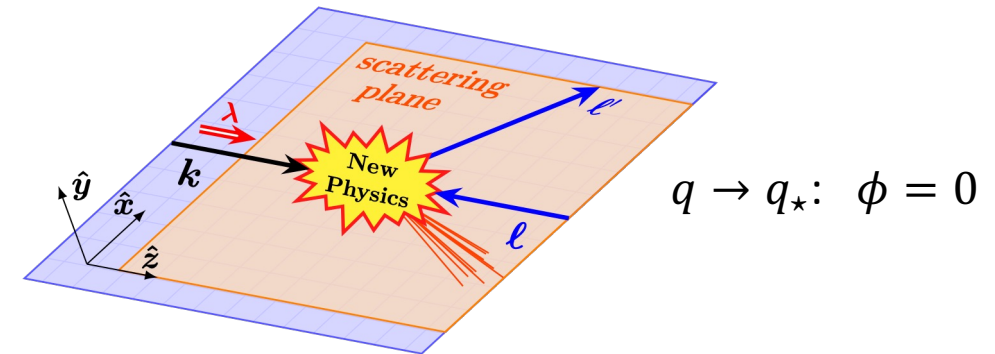
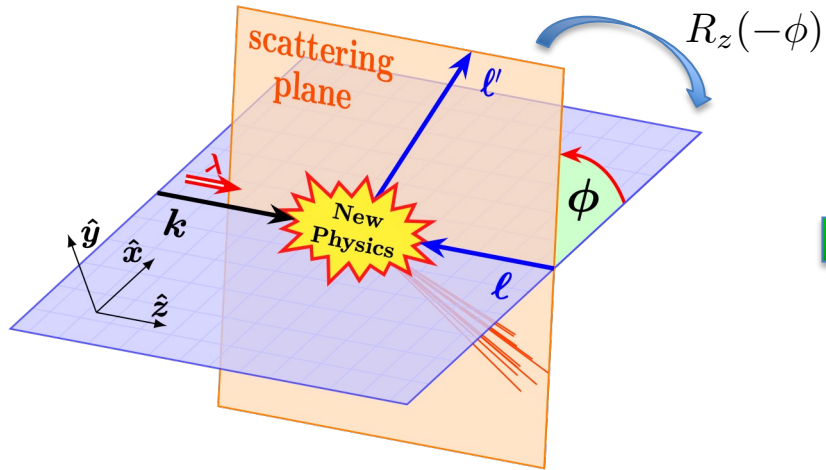
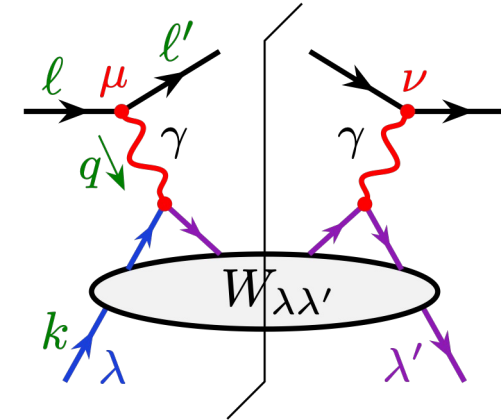
General argument for the azimuthal form

□ Rotation symmetry

$$W_{\lambda\lambda'}^{\mu\nu}(k, q) = \frac{1}{2\pi} \int d^4x e^{-iq \cdot x} \langle k, \lambda' | J^\nu(0) J^\mu(x) | k, \lambda \rangle$$

ϕ is carried by ℓ' or $q = \ell - \ell'$

Can be rotated out in **helicity space**



$$[L \cdot W]_{\lambda\lambda'}(k, \ell, q) = e^{i(\lambda - \lambda')\phi} [L \cdot W]_{\lambda\lambda'}(k, \ell, q_*)$$

General argument for the azimuthal form

□ Time reversal

Christ-Lee Theorem, Phys. Rev. 143 (1966), 1310

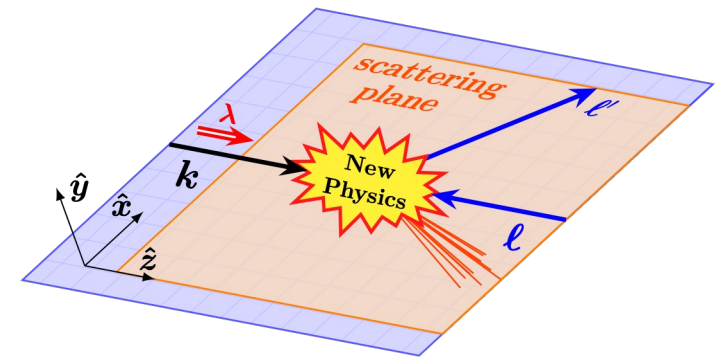
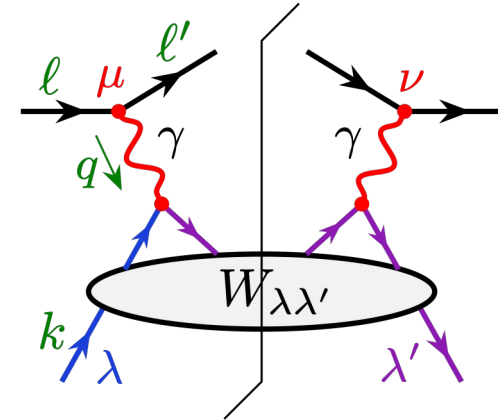
$$[L \cdot W]_{\lambda\lambda'}(k, \ell, q) = e^{i(\lambda - \lambda')\phi} [L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star)$$

Time reversal + **Rotation $R_y(\pi)$ around $\hat{y}$ by π** + **Hermiticity**



Kinematics is unchanged

$$[L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \mathbf{\Gamma}_j) = \left\{ [L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \mathbf{\Gamma}_j^*) \right\}^*$$



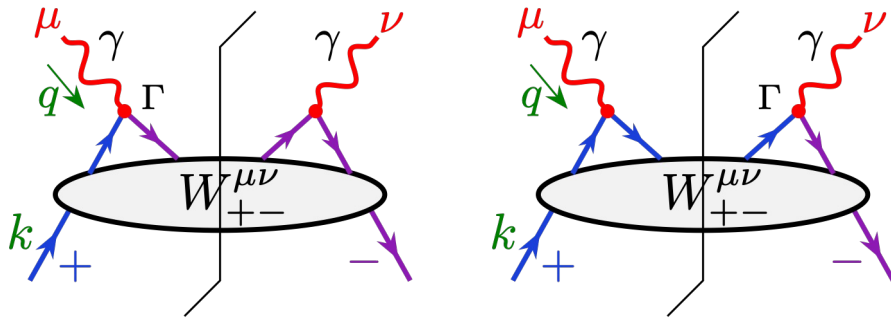
General argument for the azimuthal form

□ Time reversal

$$[L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \Gamma_j) = \left\{ [L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \Gamma_j^*) \right\}^*$$

□ Chiral symmetry on partonic tensor

$$[L \cdot \hat{W}]_{+-}(k, \ell, q_\star; \Gamma_j) = \sum_j t_j \Gamma_j \quad \longrightarrow \quad t_j \text{ is real}$$



General argument for the azimuthal form

□ Time reversal

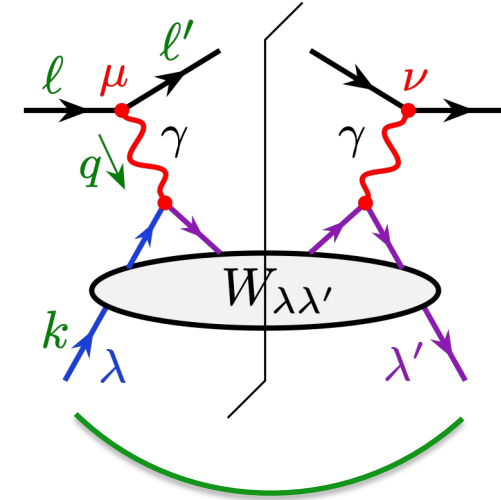
$$[L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \mathbf{\Gamma}_j) = \left\{ [L \cdot W]_{\lambda\lambda'}(k, \ell, q_\star; \mathbf{\Gamma}_j^*) \right\}^*$$

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$$[L \cdot \hat{W}]_{+-}(k, \ell, q_\star; \mathbf{\Gamma}_j) = \sum_j t_j \mathbf{\Gamma}_j \quad \longrightarrow \quad t_j \text{ is real}$$

□ Contract with spin density matrix

$$\begin{aligned} [L \cdot \hat{W}](k, \ell, q; \mathbf{\Gamma}_j) &= \sum_{\lambda, \lambda'} \rho_{\lambda\lambda'}(\mathbf{s}_T) e^{i(\lambda - \lambda')\phi} [L \cdot \hat{W}]_{\lambda\lambda'}(k, \ell, q_\star; \mathbf{\Gamma}_j) \\ &= \frac{1}{2} \underbrace{\left\{ [L \cdot \hat{W}]_{++}(k, \ell, q_\star) + [L \cdot \hat{W}]_{--}(k, \ell, q_\star) \right\}}_{\text{Non-dipole, no } \phi} + \underbrace{s_T \operatorname{Re} \left\{ e^{i(\phi - \phi_s)} [L \cdot \hat{W}]_{+-}(k, \ell, q_\star; \mathbf{\Gamma}_j) \right\}}_{\sum_j t_j \operatorname{Re} \left\{ \mathbf{\Gamma}_j e^{i(\phi - \phi_s)} \right\}} \end{aligned}$$

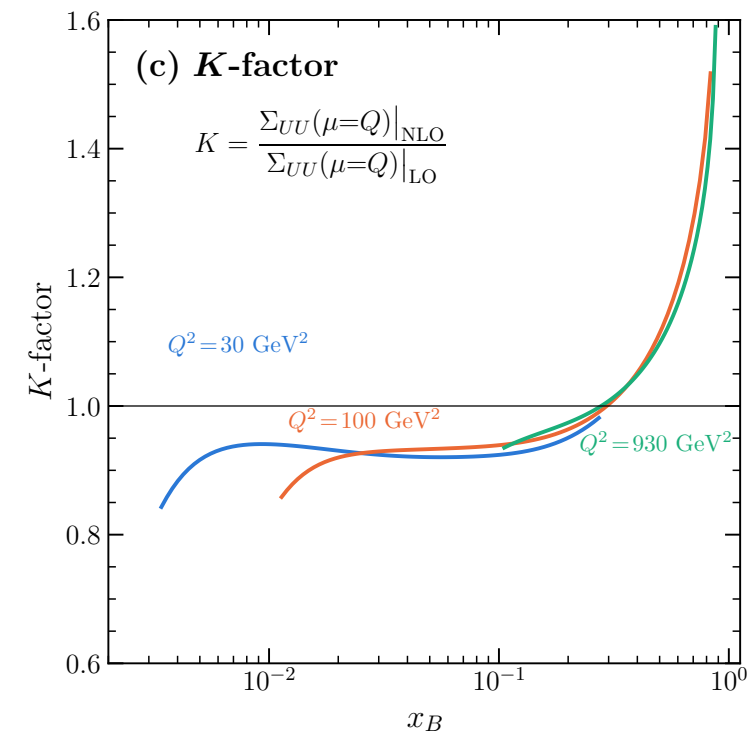
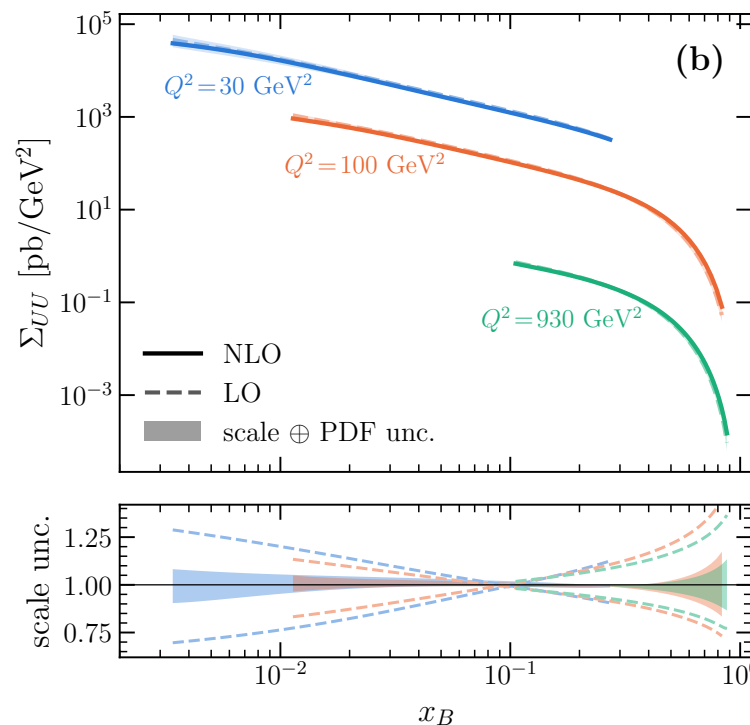
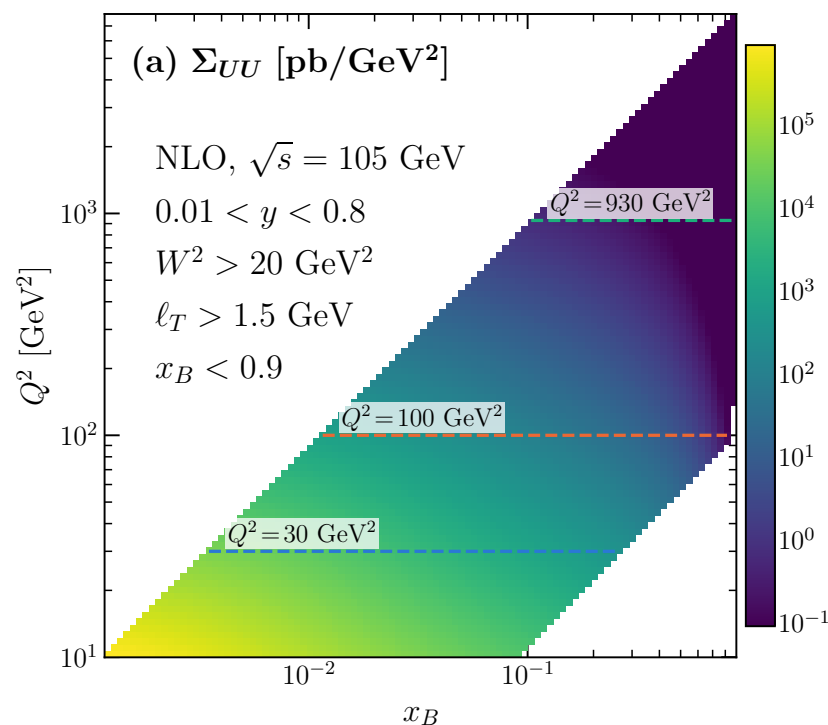


$$\rho_{\lambda\lambda'}(\mathbf{s}_T) = \frac{1}{2} \begin{pmatrix} 1 & s_T e^{-i\phi_s} \\ s_T e^{i\phi_s} & 1 \end{pmatrix}_{\lambda\lambda'}$$

Cross section: unpolarized part

$$\Delta\phi \equiv \phi - \phi_S$$

$$\frac{d\sigma}{dx_B dQ^2 d\Delta\phi} = \frac{1}{2\pi} \left[\Sigma_{UU}(x_B, Q^2) + \lambda_e \Sigma_{LU}(x_B, Q^2) + S_T \Sigma_{UT}(x_B, Q^2, \Delta\phi) + \lambda_e S_T \Sigma_{LT}(x_B, Q^2, \Delta\phi) \right]$$



Unpolarized cross section = $f_{i/p} \otimes$ unpolarized hard coefficients of $(\gamma\gamma, \gamma Z, ZZ)$

[JAM22-PDF NLO](#), 96 replica PDFs

PDF uncertainty $\lesssim 1\%$

Cross section: single transverse spin part

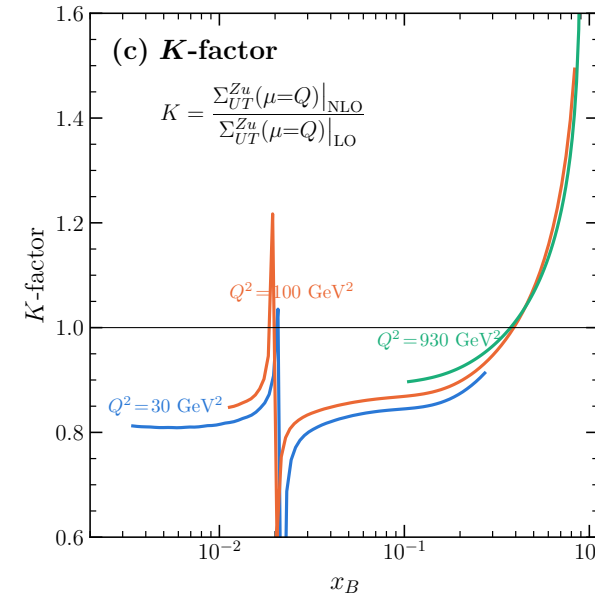
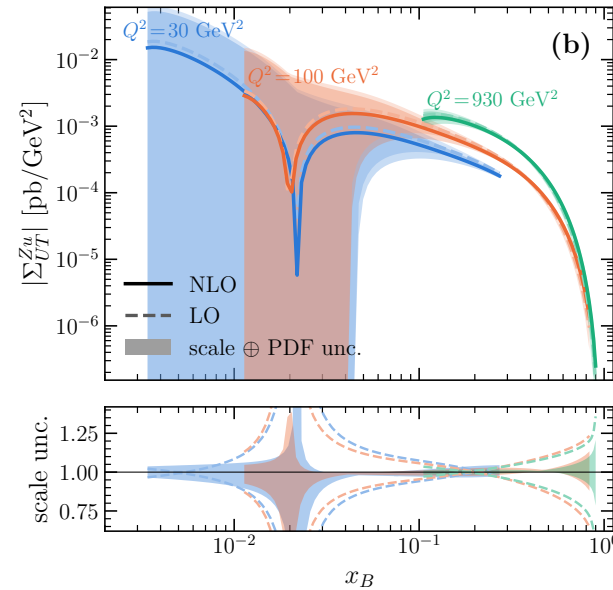
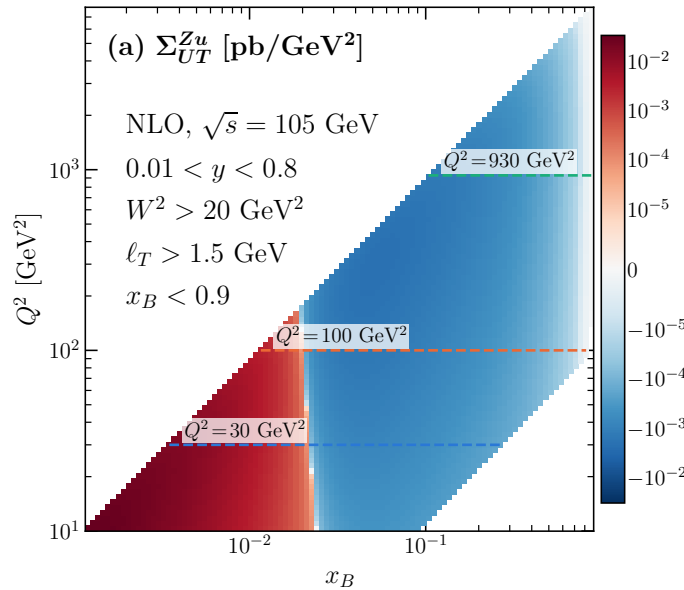
$$\Delta\phi \equiv \phi - \phi_S$$

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$$\Sigma_{UT}(x_B, Q^2, \Delta\phi) = \sum_{q=u,d} \left[\text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \Sigma_{UT}^{Zq}(x_B, Q^2) + \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) \Sigma_{UT}^{\gamma q}(x_B, Q^2) \right]$$

$(\gamma Z, ZZ)$ channels

γZ channel



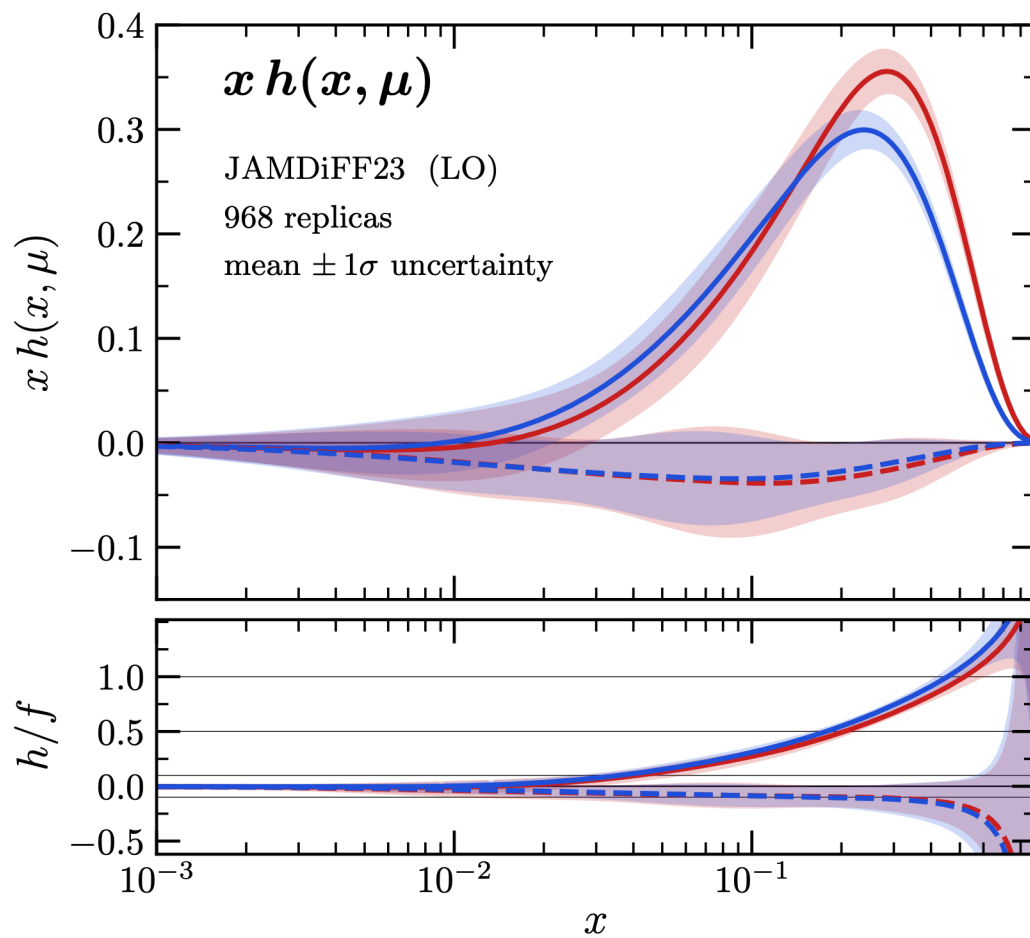
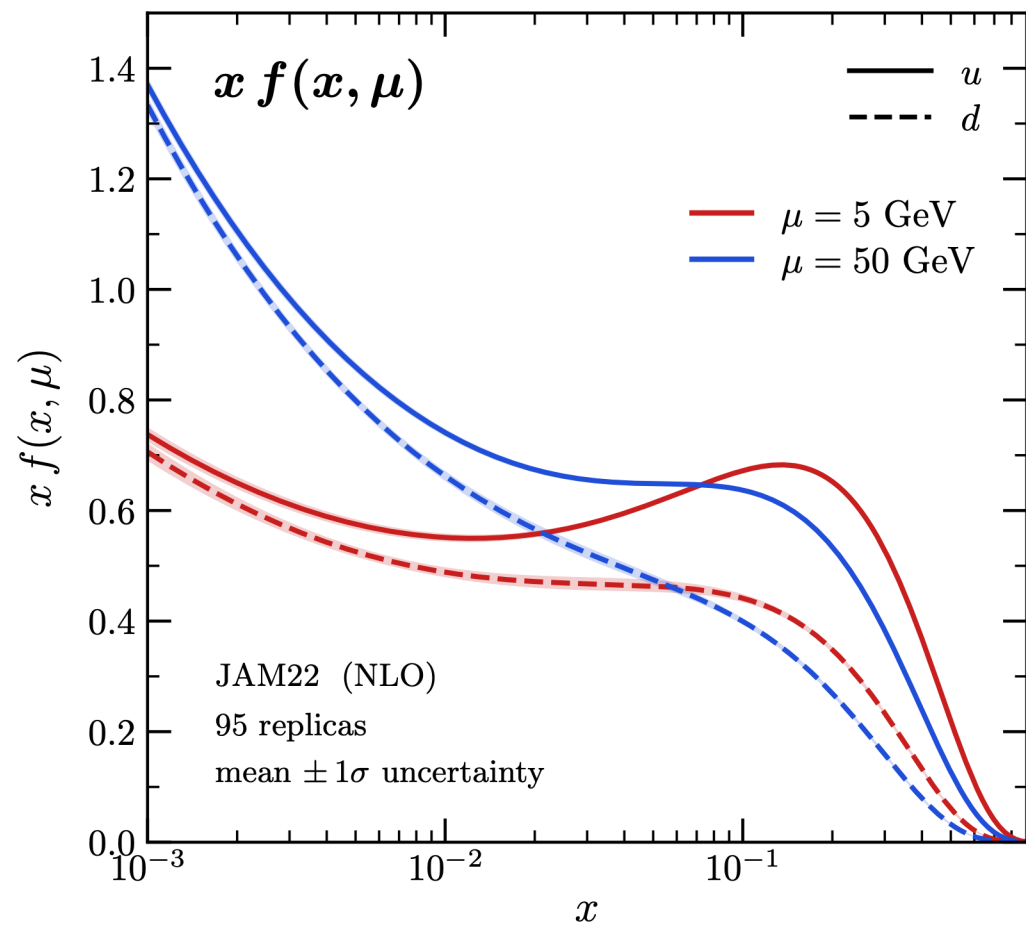
Σ_{UT}^{Zu} dominates

Single polarized cross section = $h_{q/p} \otimes$ polarized hard coefficients of $(\gamma Z, ZZ)$

PDF uncertainty dominates!

[JAMDiff23-transversity LO](#), 969 replica PDFs

JAM PDF



Cross section: double spin part

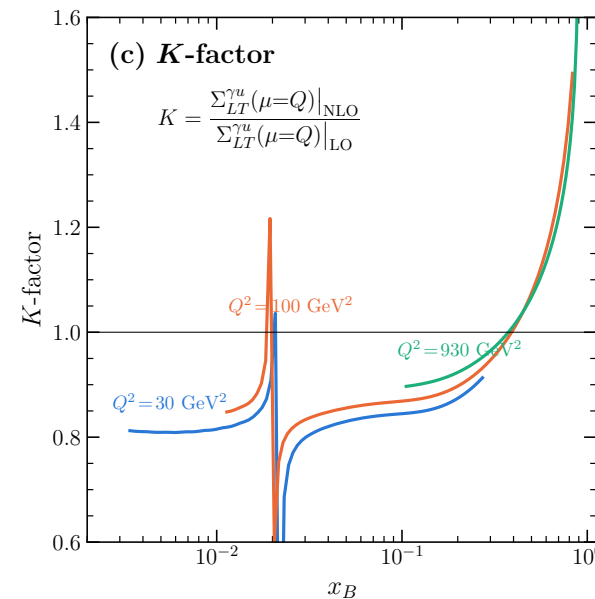
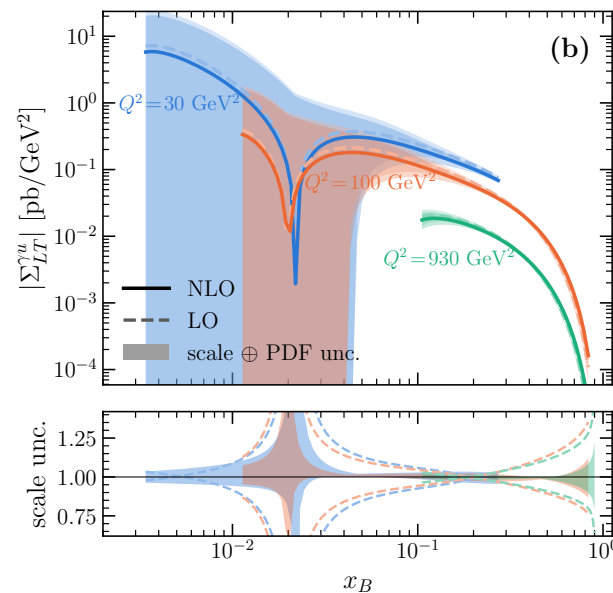
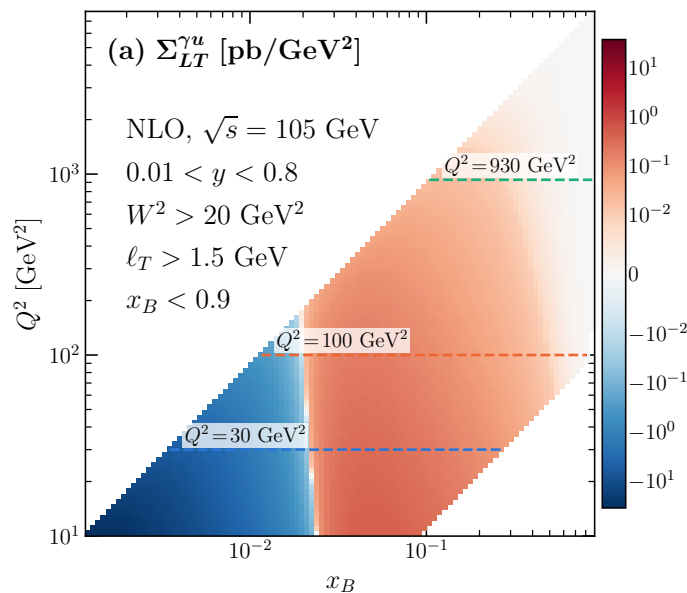
$$\Delta\phi \equiv \phi - \phi_S$$

$$\frac{d\sigma}{dx_B dQ^2 d\Delta\phi} = \frac{1}{2\pi} \left[\Sigma_{UU}(x_B, Q^2) + \lambda_e \Sigma_{LU}(x_B, Q^2) + S_T \Sigma_{UT}(x_B, Q^2, \Delta\phi) + \lambda_e S_T \Sigma_{LT}(x_B, Q^2, \Delta\phi) \right]$$

$$\Sigma_{LT}(x_B, Q^2, \Delta\phi) = \sum_{q=u,d} \left[\text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \Sigma_{LT}^{Zq}(x_B, Q^2) + \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) \Sigma_{LT}^{\gamma q}(x_B, Q^2) \right]$$

($\gamma Z, ZZ$) channels

($\gamma\gamma, \gamma Z$) channels



$\Sigma_{LT}^{\gamma u}$ dominates

Double polarized cross section = $h_{q/p} \otimes$ polarized hard coefficients of ($\gamma\gamma, \gamma Z, ZZ$)

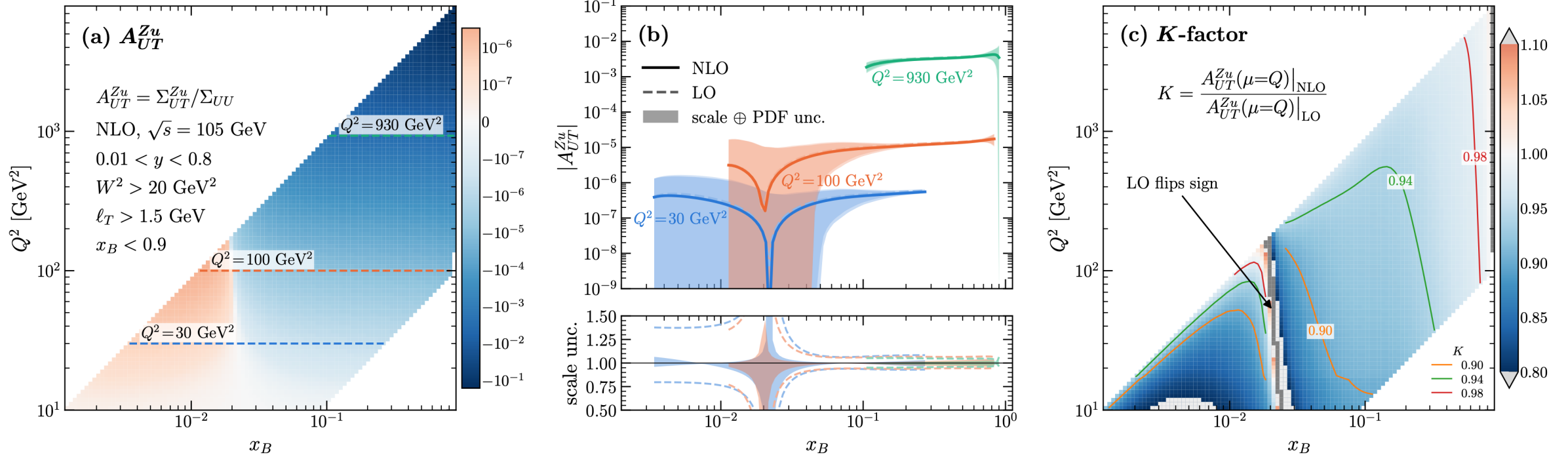
PDF uncertainty dominates!

[JAMDiff23-transversity LO](#), 969 replica PDFs

Asymmetry: magnitude and K -factor

$$A_{UT}^{Zu}(x_B, Q^2) \equiv \frac{\Sigma_{UT}^{Zu}(x_B, Q^2)}{\Sigma_{UU}(x_B, Q^2)}$$

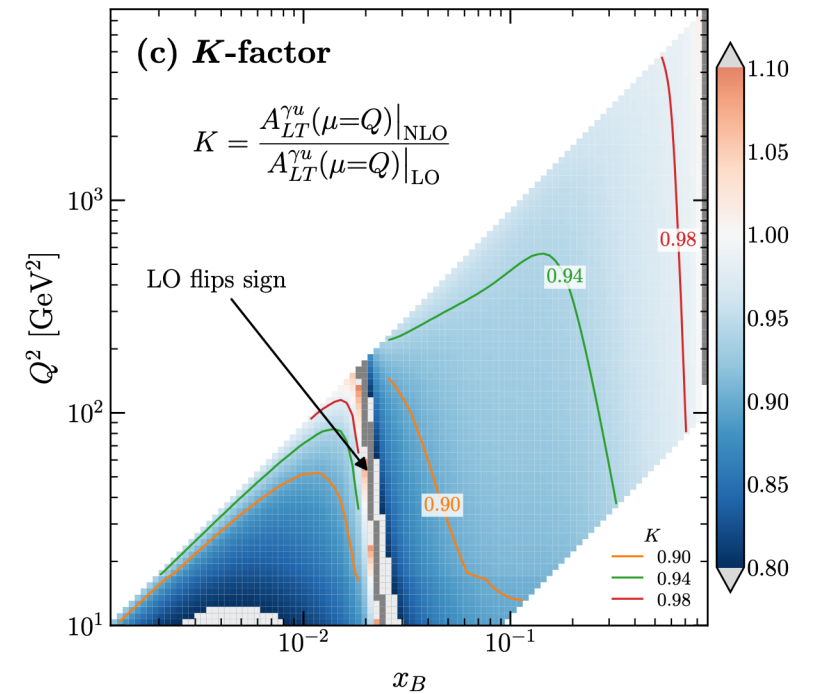
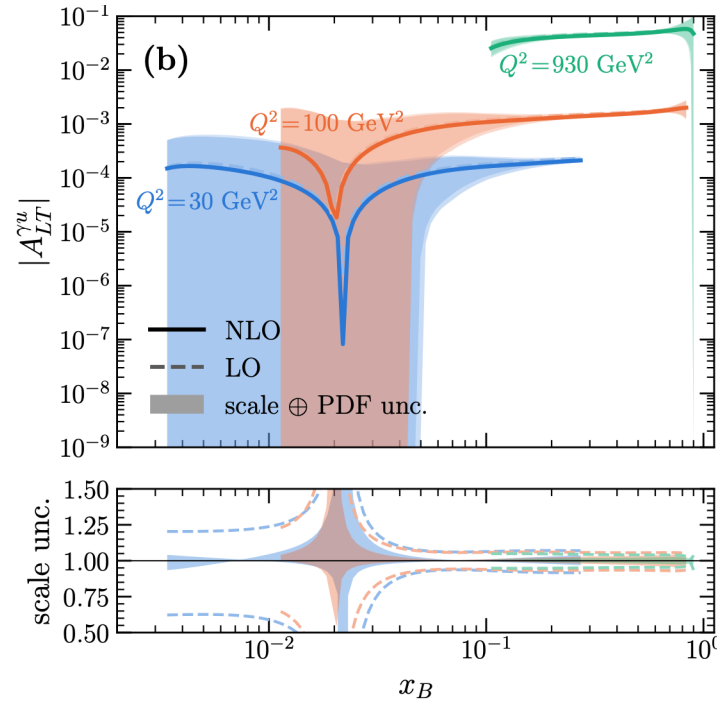
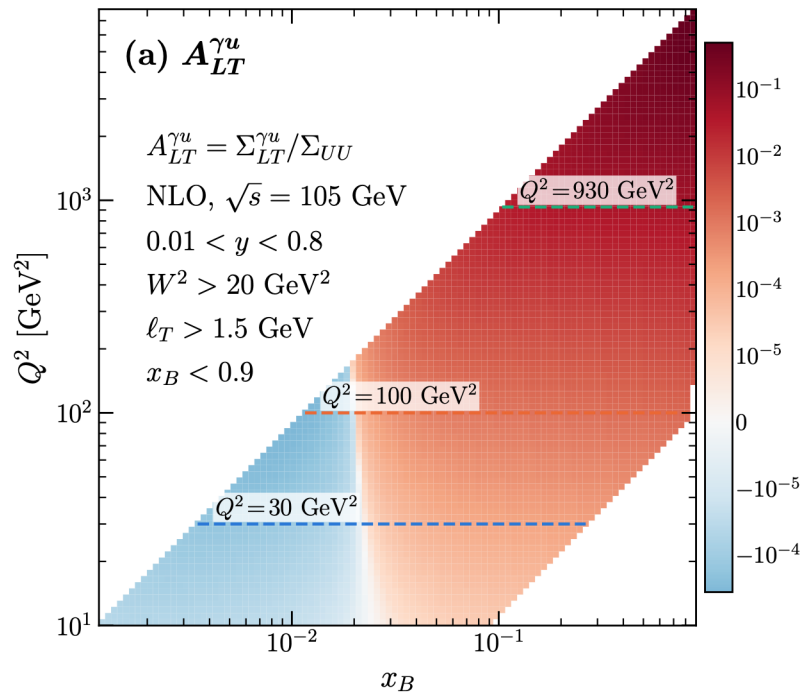
Single spin asymmetry



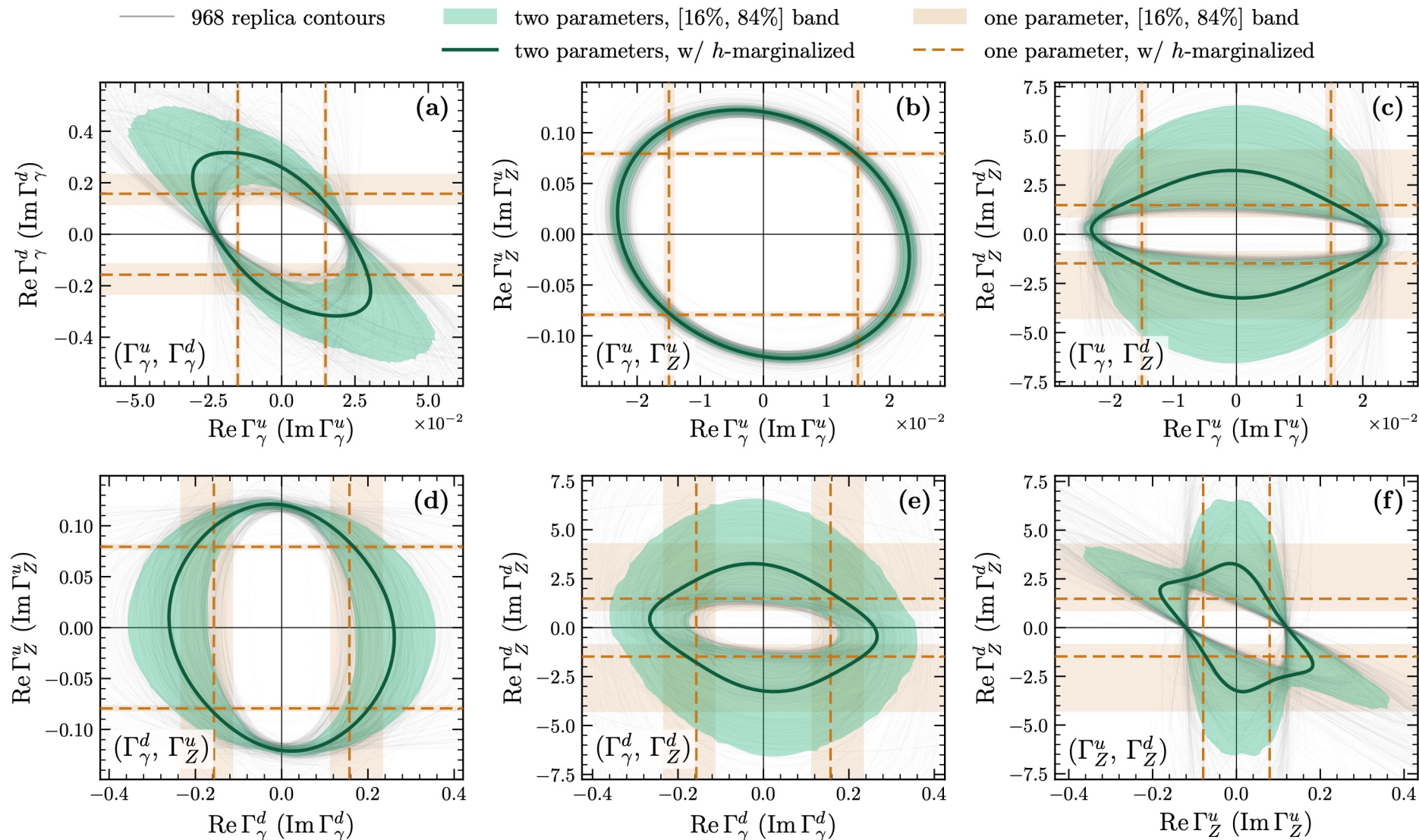
Asymmetry: magnitude and K -factor

$$A_{LT}^{\gamma u}(x_B, Q^2) \equiv \frac{\Sigma_{LT}^{\gamma u}(x_B, Q^2)}{\Sigma_{UU}(x_B, Q^2)}$$

Double spin asymmetry



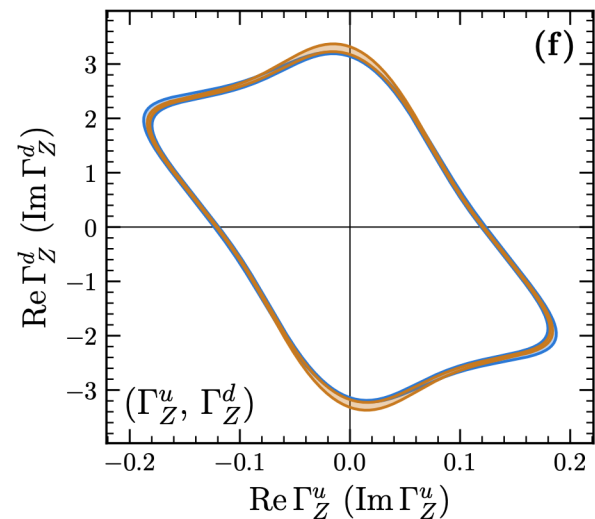
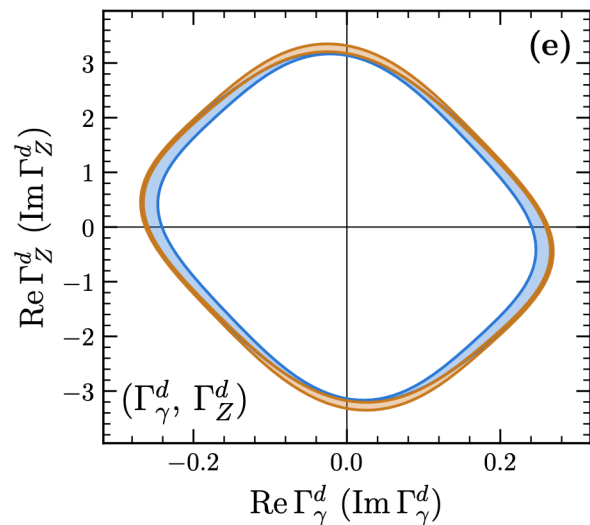
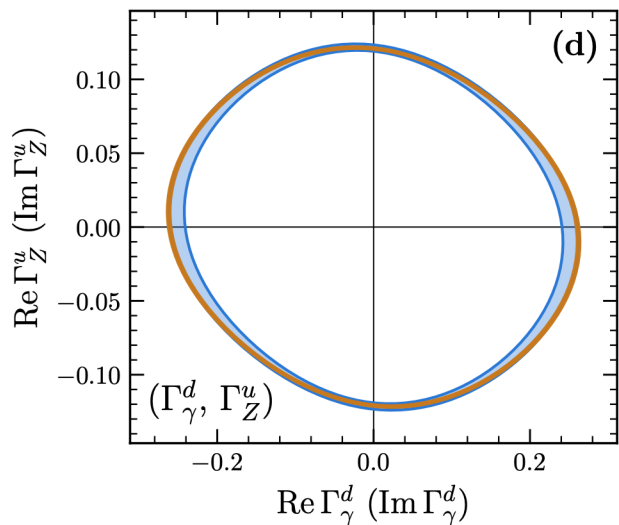
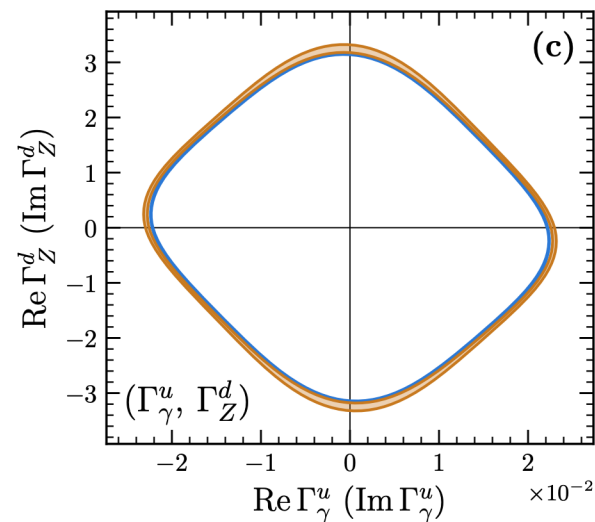
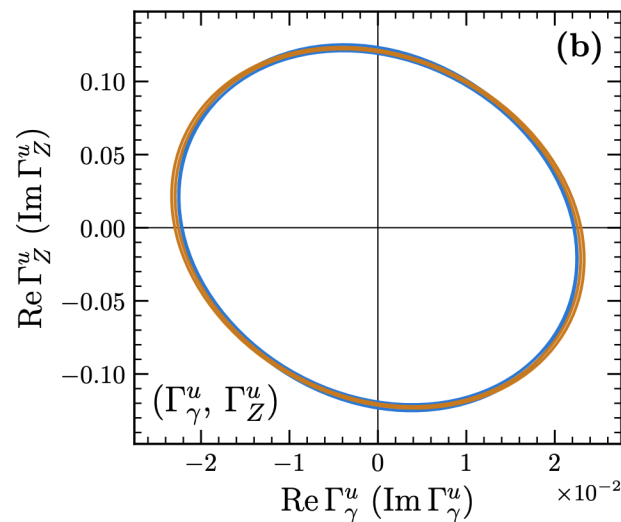
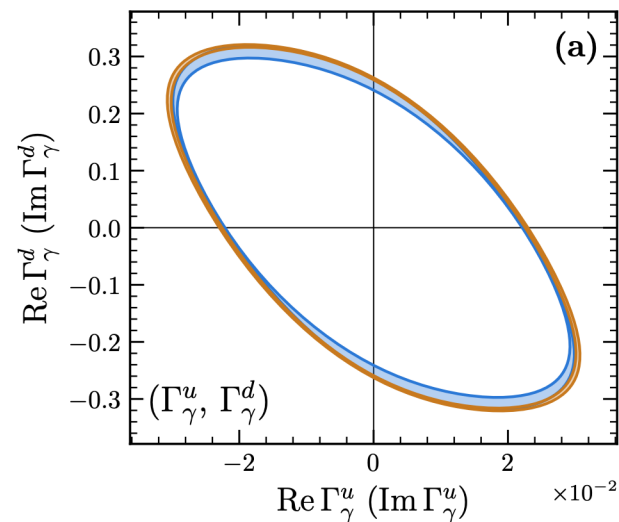
Bounds on dipole couplings at NLO



- ✓ Real and imaginary parts are simultaneously constrained
- ✓ Photon and Z dipoles almost uncorrelated
- ✓ u and d dipoles highly correlated
- ✓ d dipoles are very affected by PDF uncertainty

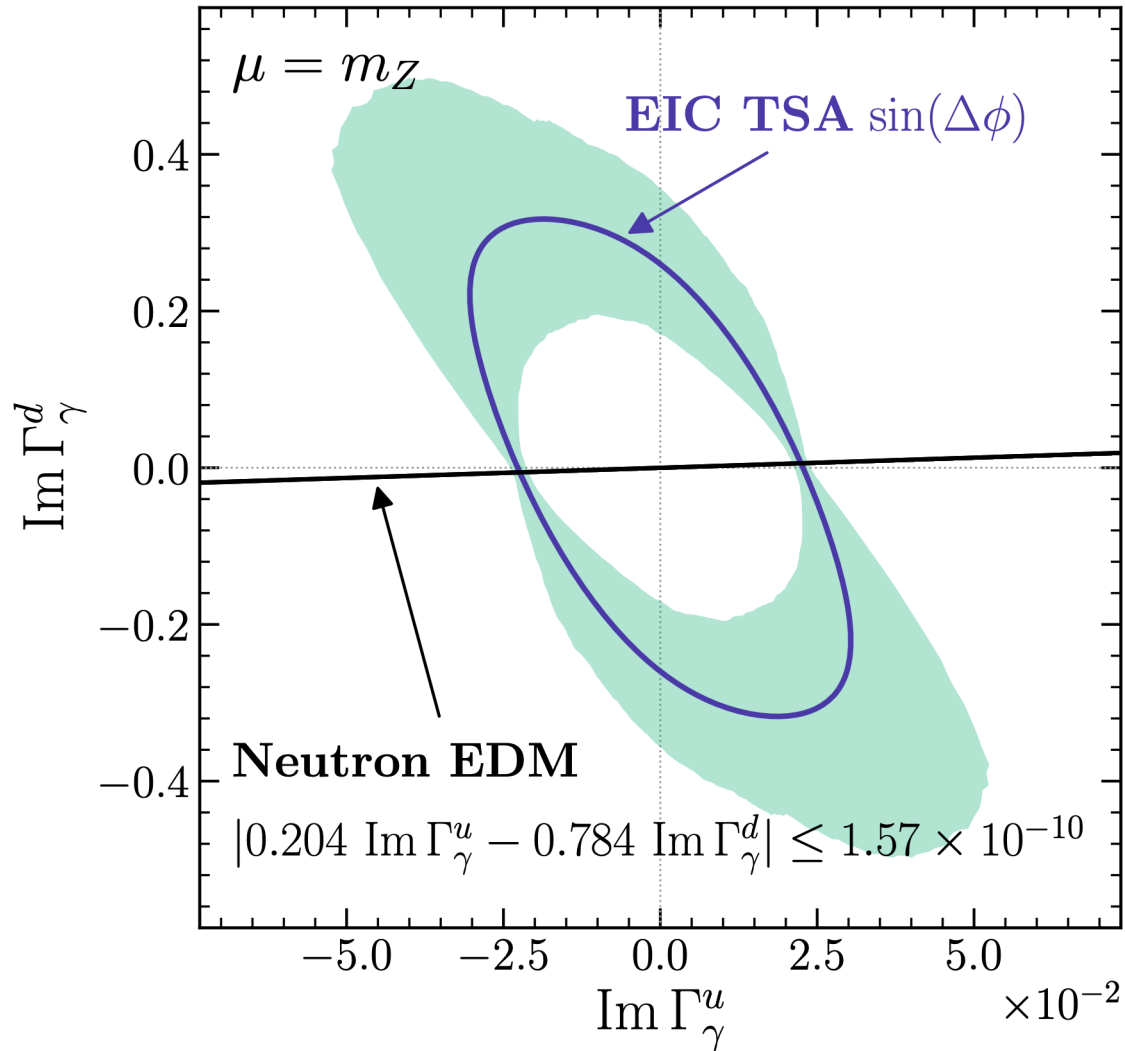
Bounds on dipole couplings: NLO vs. LO

LO, $\mu \in [Q/2, 2Q]$ NLO, $\mu \in [Q/2, 2Q]$



- ✓ Constraint bound is not much affected by NLO corrections
- ✓ Scale uncertainty negligible
- ✓ Uncertainties dominated by PDFs.

Comparison with low-energy neutron EDM constraint



Neutron EDM

$$d_n = g_T^d d_u + g_T^u d_d$$

$$= \frac{e}{v} \left(g_T^d \operatorname{Im} \Gamma_\gamma^u + g_T^u \operatorname{Im} \Gamma_\gamma^d \right)$$

At $\mu = 2\text{GeV}$, tensor charges from Lattice

$$g_T^u = +0.784 \pm 0.030$$

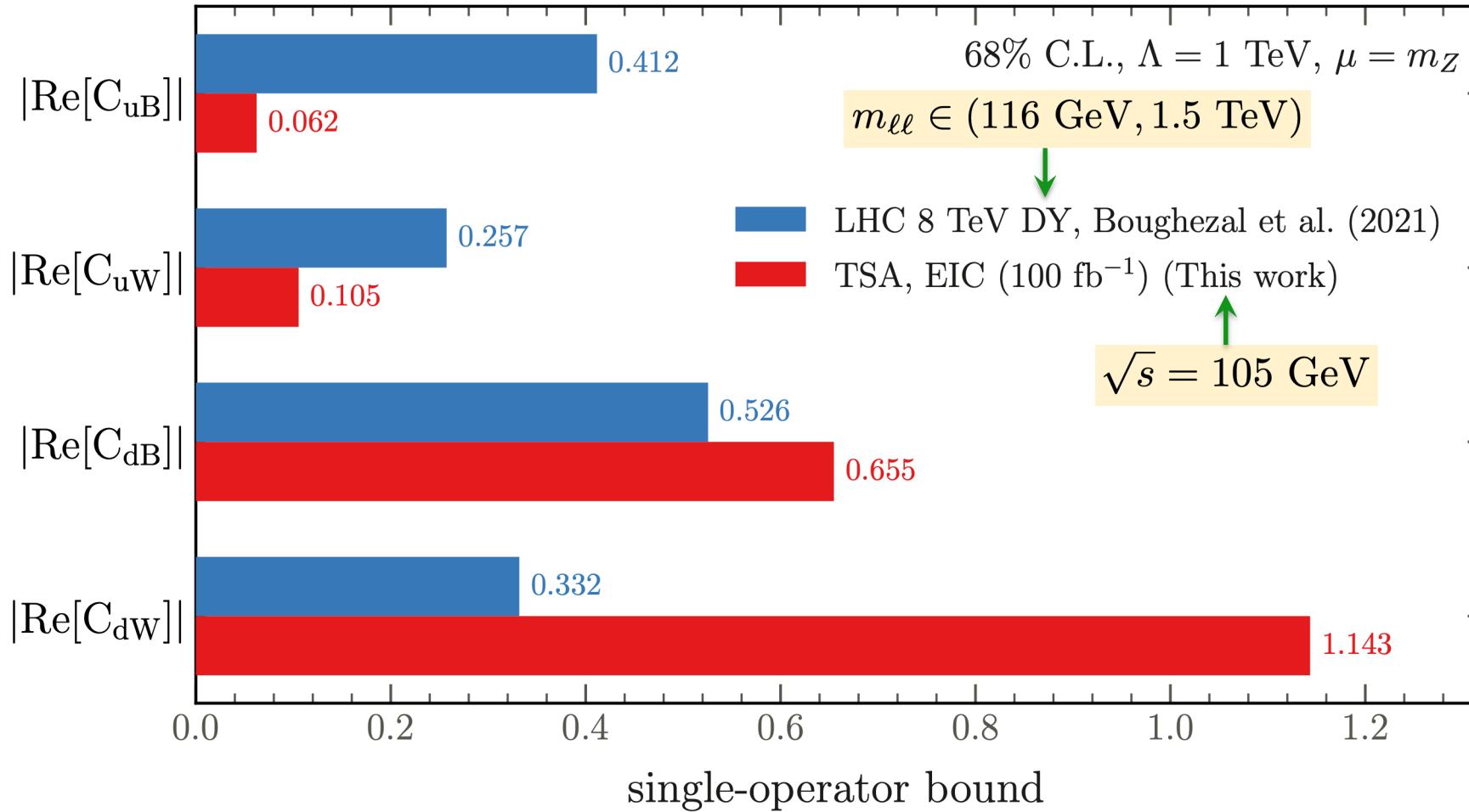
$$g_T^d = -0.204 \pm 0.015$$

At EIC, TSA contains extra QED charge

$$A \sim \underbrace{e_u h_u}_{+} \operatorname{Re} [\Gamma_\gamma^u e^{i\Delta\phi}] + \underbrace{e_d h_d}_{+} \operatorname{Re} [\Gamma_\gamma^d e^{i\Delta\phi}]$$

Complementary, and also to real part

Comparison with Drell-Yan measurement at LHC



Summary

- **High luminosity** + **polarization** give EIC opportunities for probing new physics
- Phenomenologically, transverse spin asymmetry at EIC
 - ❖ Linear sensitivity to light-quark SMEFT dipole operators
 - ❖ Significant constraining power
 - ❖ Perturbatively stable
 - ❖ Limited by transversity PDF uncertainties, especially of down quark
- Theoretically, γ_5 scheme in tensor interaction

Thank you!

Statistical methods for bounding dipole couplings

□ For a fixed PDF replica

Either polarized cross section takes the form $\frac{d\sigma}{dx_B dQ^2 d\phi} = U(x_B, Q^2) + P \Gamma_a V^a(x_B, Q^2) \cos \phi$

Take to be real
Polarization degree

- Divide the measured region of (x_B, Q^2, ϕ) into many small bins, i
- Expected event yield μ_i in each bin: $\mu_i = \mu_i(\Gamma_a) = \mathcal{L} \Delta x_B \Delta Q^2 \Delta \phi \cdot [U_i + P \Gamma_a V_i^a \cos \phi_i]$
- Actual event number n_i in bin i follows a Poisson distribution: $p(n_i | \mu_i) = e^{-\mu_i} \frac{\mu_i^{n_i}}{n_i!}$

For theory estimates, take $n_i = \mu_i(\Gamma_a = 0) = \mathcal{L} \Delta x_B \Delta Q^2 \Delta \phi \cdot U_i$

- **Likelihood** $L = L(\Gamma_a) = \prod_i p(n_i | \mu_i(\Gamma_a))$
- **Log-likelihood ratio** $q(\Gamma_a) = -2 \ln \left[\frac{L(\Gamma_a)}{L(0)} \right]$

Statistical methods for bounding dipole couplings

□ To include scale uncertainty

$$q(\Gamma_a) \rightarrow \min_{\mu \in \{Q, 2Q, Q/2\}} q(\Gamma_a, \mu)$$

□ One-parameter bounds from LLR

Keep only one parameter Γ_a , setting all others to 0. $|q(\Gamma_a)| \leq 1$ 68% CL. bound

□ Two-parameter bounds from LLR

Keep only two parameters (Γ_a, Γ_b) , setting all others to 0. $|q(\Gamma_a, \Gamma_b)| \leq 2.3$ 68% CL. bound

□ To include PDF uncertainty...

Loop through all replicas, and find [16%, 84%] quantiles as the “68% C.L. of the bounds”