Probing light-quark dipole operators with nucleon energy correlators

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In collaboration with:
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Phys. Rev. Lett. 136 (2026) 13, 131902

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The dipole moments

- *SM suppression:* loop-suppressed, making dipole moments sensitive to New Physics
    - ✦ **Lepton dipole moments**: muon g-2; eletron EDM
- *Light-quark dipole moments:* inferred from hadronic observables with nonperturbative QCD input
    - ✦ nEDM; Hadronic magnetic moments
- Collider probes provide complementary sensitivity to low-energy measurements

Dipole moments in the SMEFT

- Induced from the **dim-6** EW dipole operators :

Chirality-flipping structure for fermion currents

$$\mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W^I_{\mu\nu}$$
$$\mathcal{O}_{uB} = (\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$$
$$\mathcal{O}_{dW} = (\bar{Q}\sigma^{\mu\nu}d)\tau^I HW^I_{\mu\nu}$$
$$\mathcal{O}_{dB} = (\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}$$

Quadraticly suppressed for collider searching

- After EWSB :

$$\mathcal{L} = \sum_{q=u,d} C_{q\gamma}\left(\bar{q}_L\sigma_{\mu\nu}q_R\right)F^{\mu\nu} + C_{qZ}\left(\bar{q}_L\sigma_{\mu\nu}q_R\right)Z^{\mu\nu} + \text{h.c.}$$

$$c_{q\gamma} = (v/\sqrt{2}\Lambda^2)\left(c_W C_{qB} \pm s_W C_{qW}\right)$$
$$c_{qZ} = (v/\sqrt{2}\Lambda^2)\left(-s_W C_{qB} \pm c_W C_{qW}\right)$$

Real parts and imaginary parts correspond to the MDM & EDM of the light quarks, respectively.

The chirality bottleneck at colliders

$$d\sigma \sim |\mathscr{M}_{\rm SM}|^2 + 2\,{\rm Re}\left[\mathscr{M}_{\rm SM}\mathscr{M}^*_{(6)}\right] + \left(|\mathscr{M}_{(6)}|^2 + 2\,{\rm Re}\left[\mathscr{M}_{\rm SM}\mathscr{M}^*_{(8)}\right]\right) + \cdots$$

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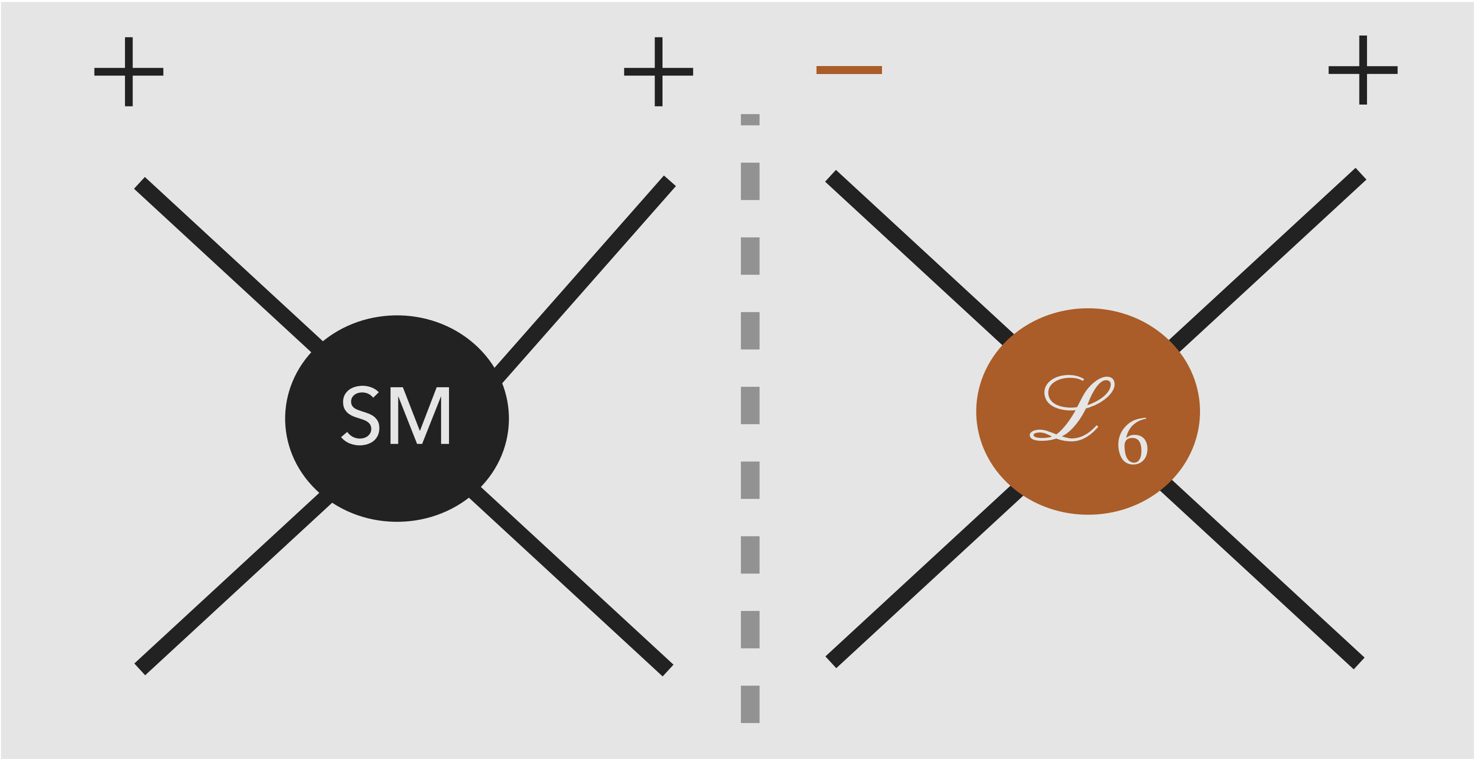

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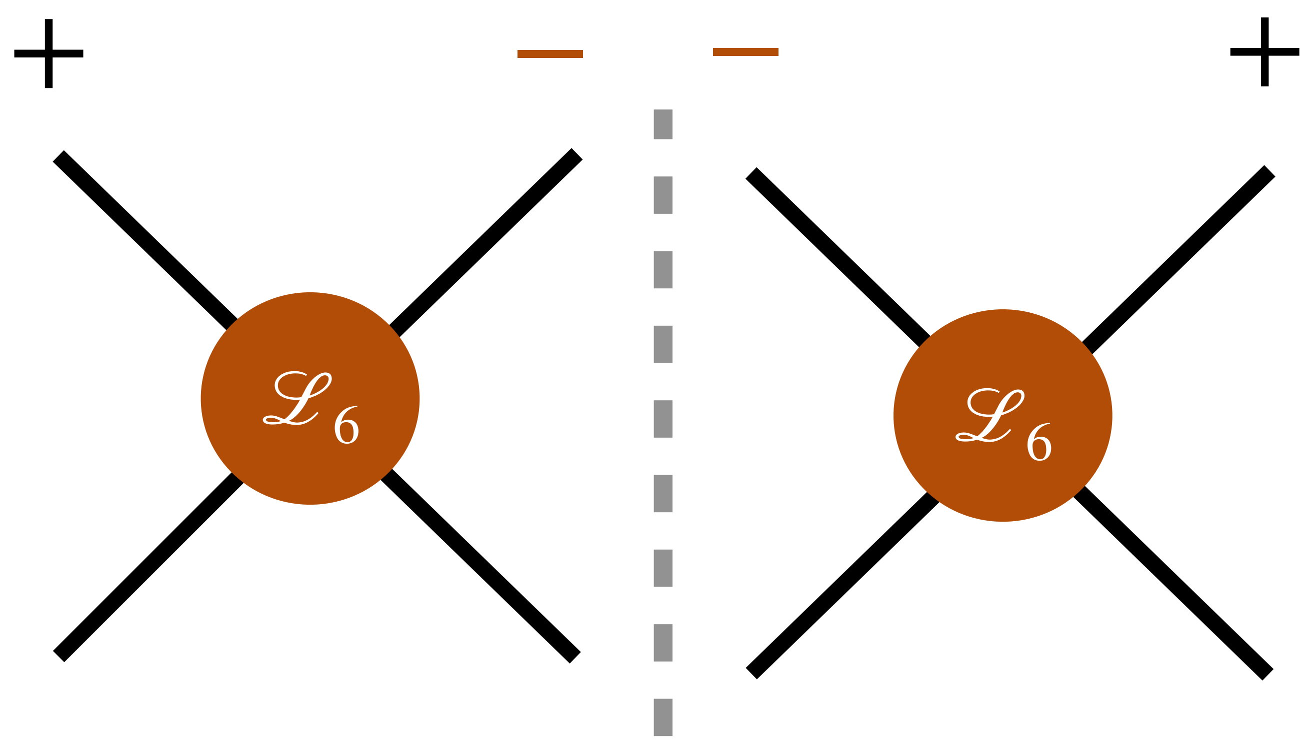
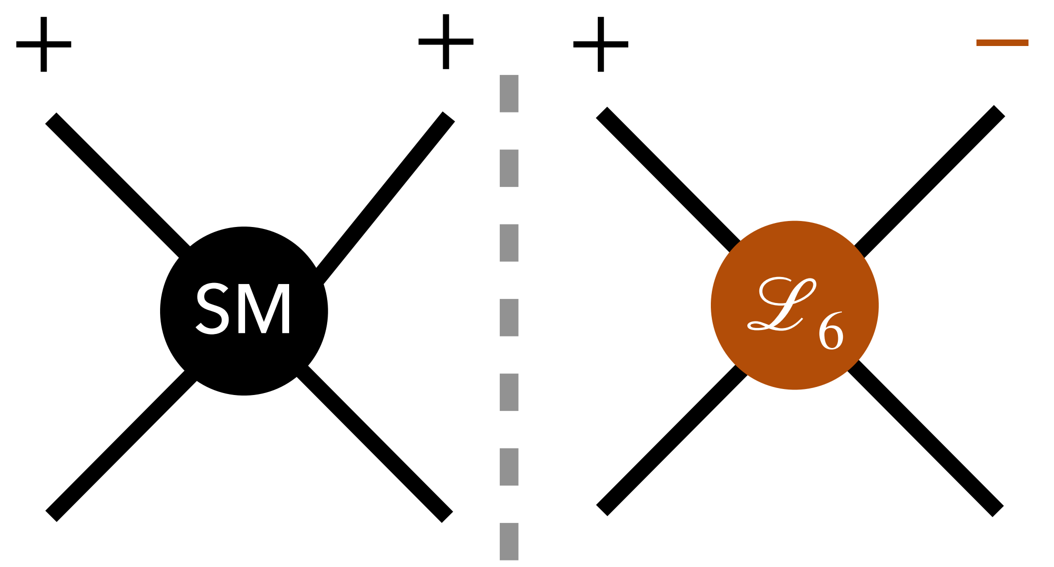


$\sim \mathcal{O}(\frac{1}{\Lambda^4}) \quad + \cdots$

- ***Quadratically suppressed in unpolarized measuments***
- ***Polluted by vast dim-8 operators***

Interference recurring



$\sim \mathcal{O}(\frac{1}{\Lambda^2})$

- The linear $\mathcal{O}(\Lambda^{-2})$ interference can be restored by quark transverse spin

$$|\phi\rangle = \frac{1}{\sqrt{2}}\left(e^{i\phi}|-\rangle - e^{-i\phi}|+\rangle\right)$$

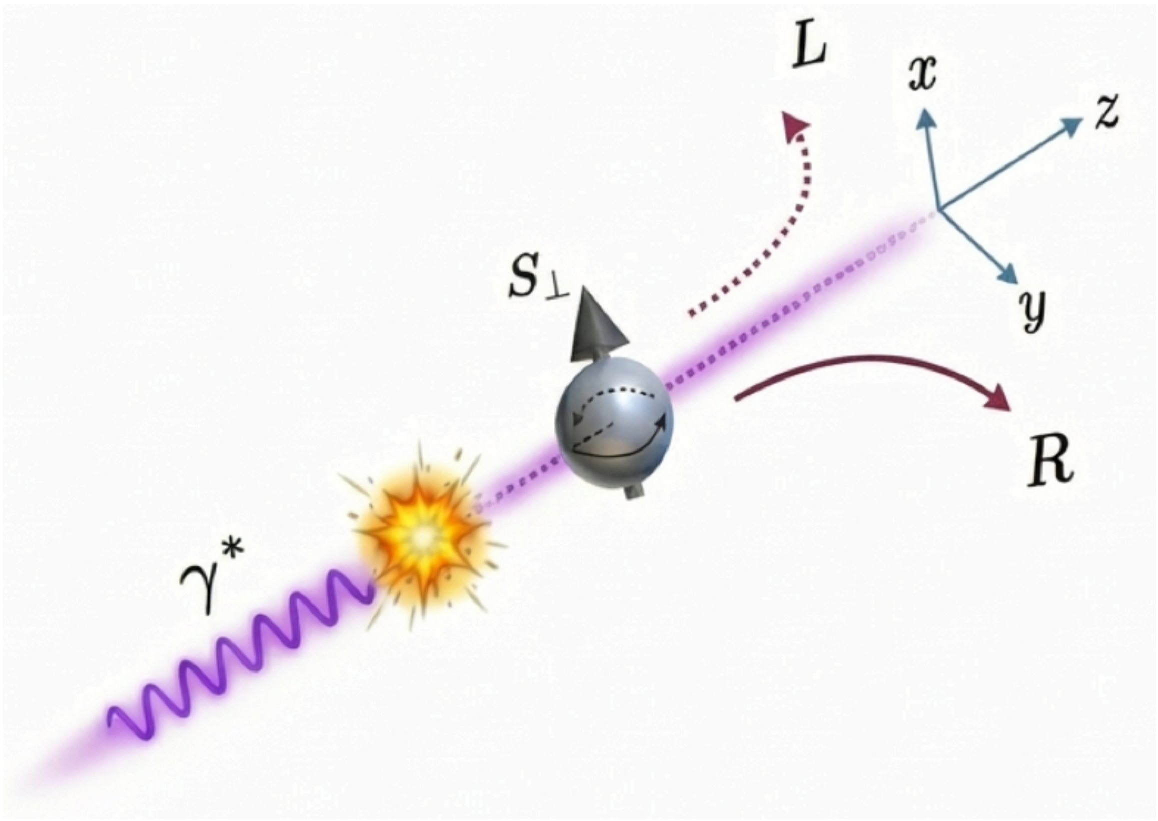
Transverse spin asymmetry

Boughezal et al., PRD 107, 075028 (2023)

For electron dipole Wen et al., PRL. 131, 241801(2023)

For 4F ops. **HW**, Wen, Xing, and Yan, PRD 109, 095025 (2024)

- S_T^q from a polarized nucleon beam
- Require polarized nucleon beams

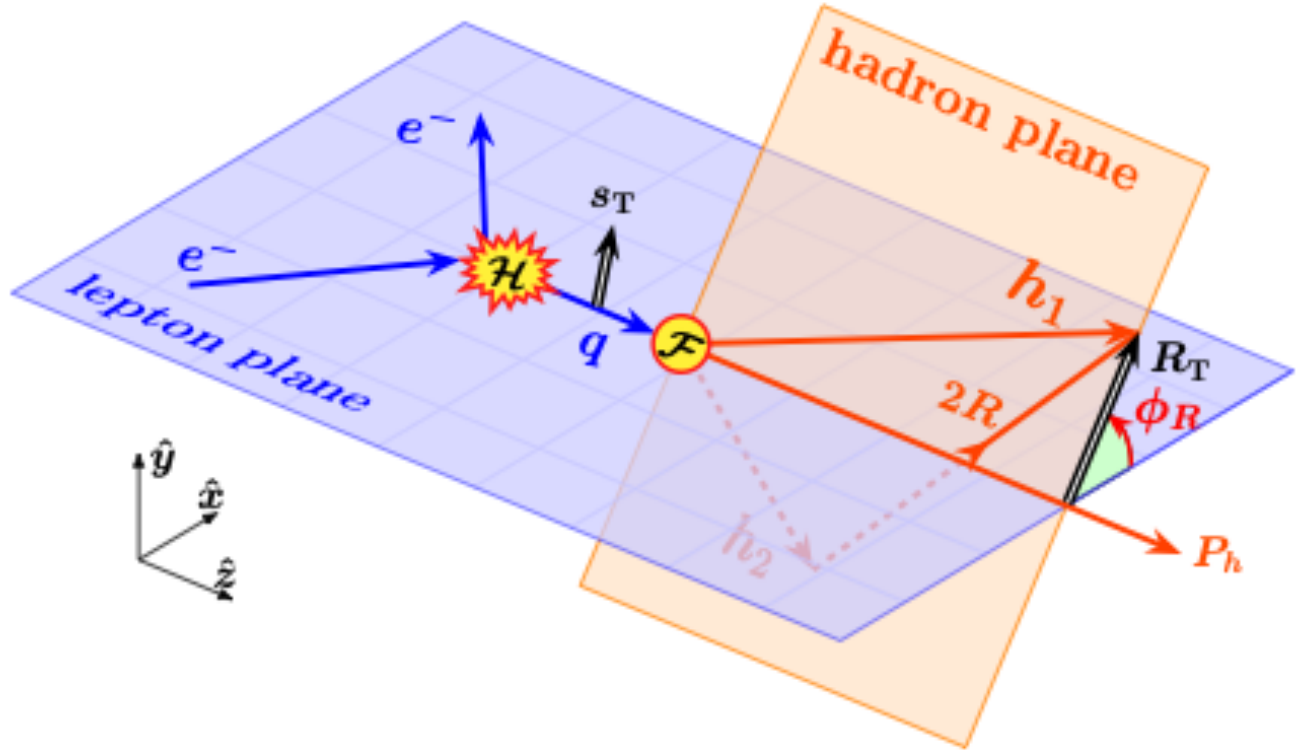


Dihadron azimuthal asymmetry

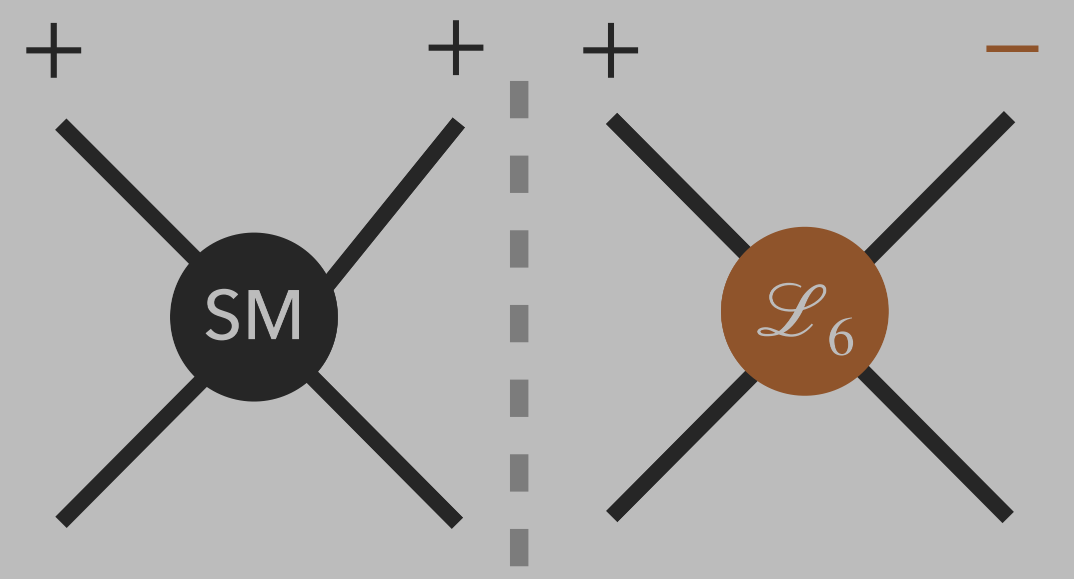
Wen et al., arXiv: 2408.07255

Wen et al., PRD 112 (2025) 5, 053004

- S_T^q from dihadron fragmentation
- Unpolarized proton, but requires hadron id. & tracking



Interference recurring



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Transverse sp … asymmetry

Boughezal et al., P … 7255

For electron dipole Wen et al., PRL. 13 … 25) 5, 053004

For 4F ops. **HW**, Wen, Xing, ar …

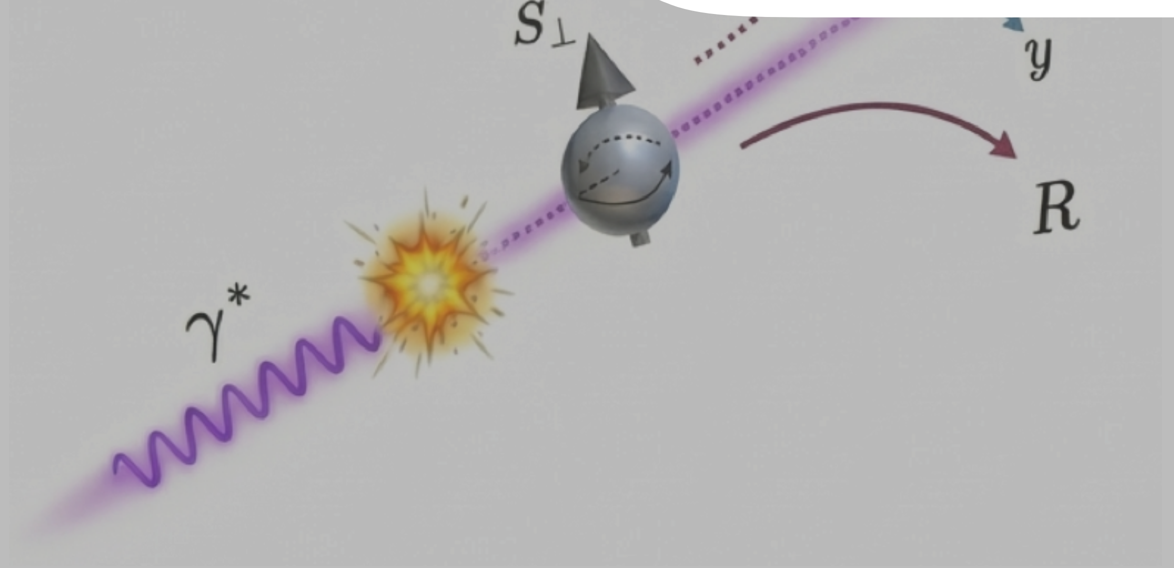
- S_T^q from a polar … on
- Require polariz … ires hadron id. &

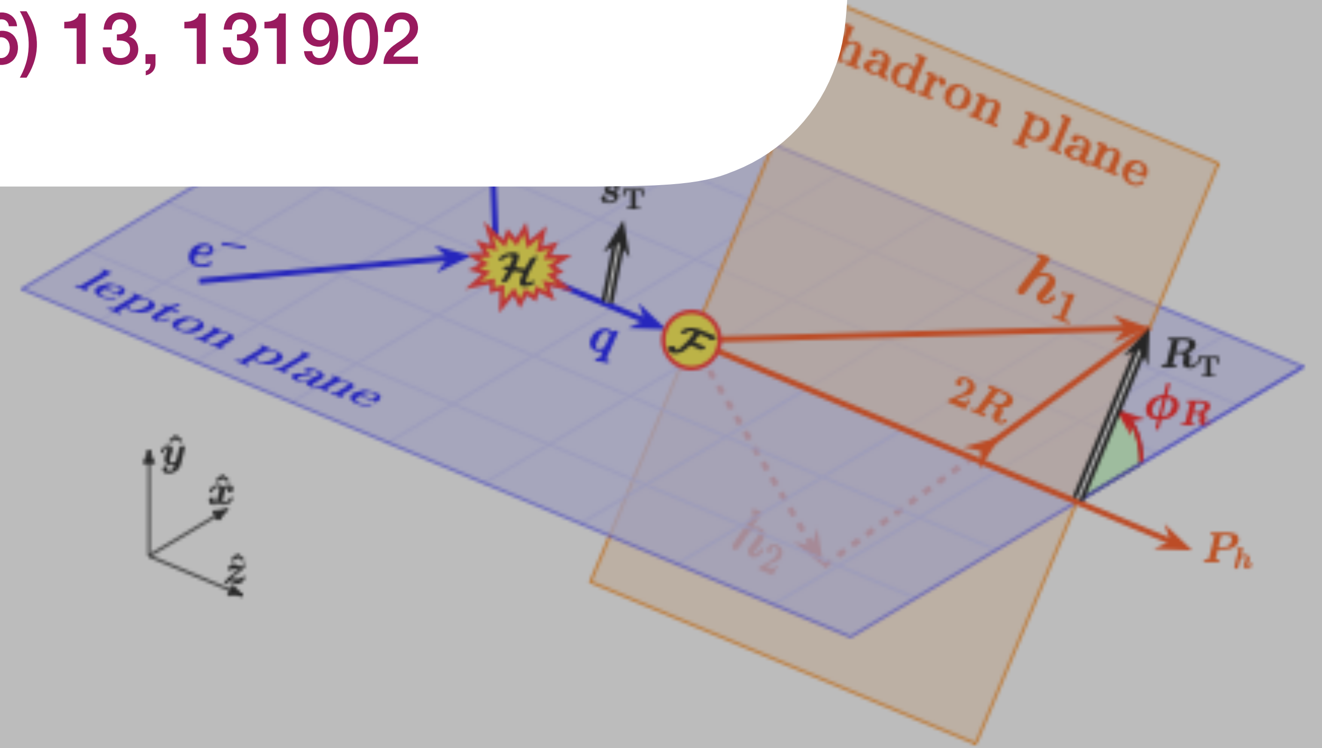
We propose use **transversity nucleon energy correlators** to access a **transversely polarized struck quark** from an **unpolarized nucleon**

Unpol. nucleon beam
Calorimetric } ➡ { Simpler exp. setup
More statistics

(No PID/tracking)

Huang, Tong, and HW, PRL 136 (2026) 13, 131902





Energy correlators

- One of the very first event-shape observable: Basham et al., 1978

See also Xiaohui Liu and Huaxing Zhu's talks

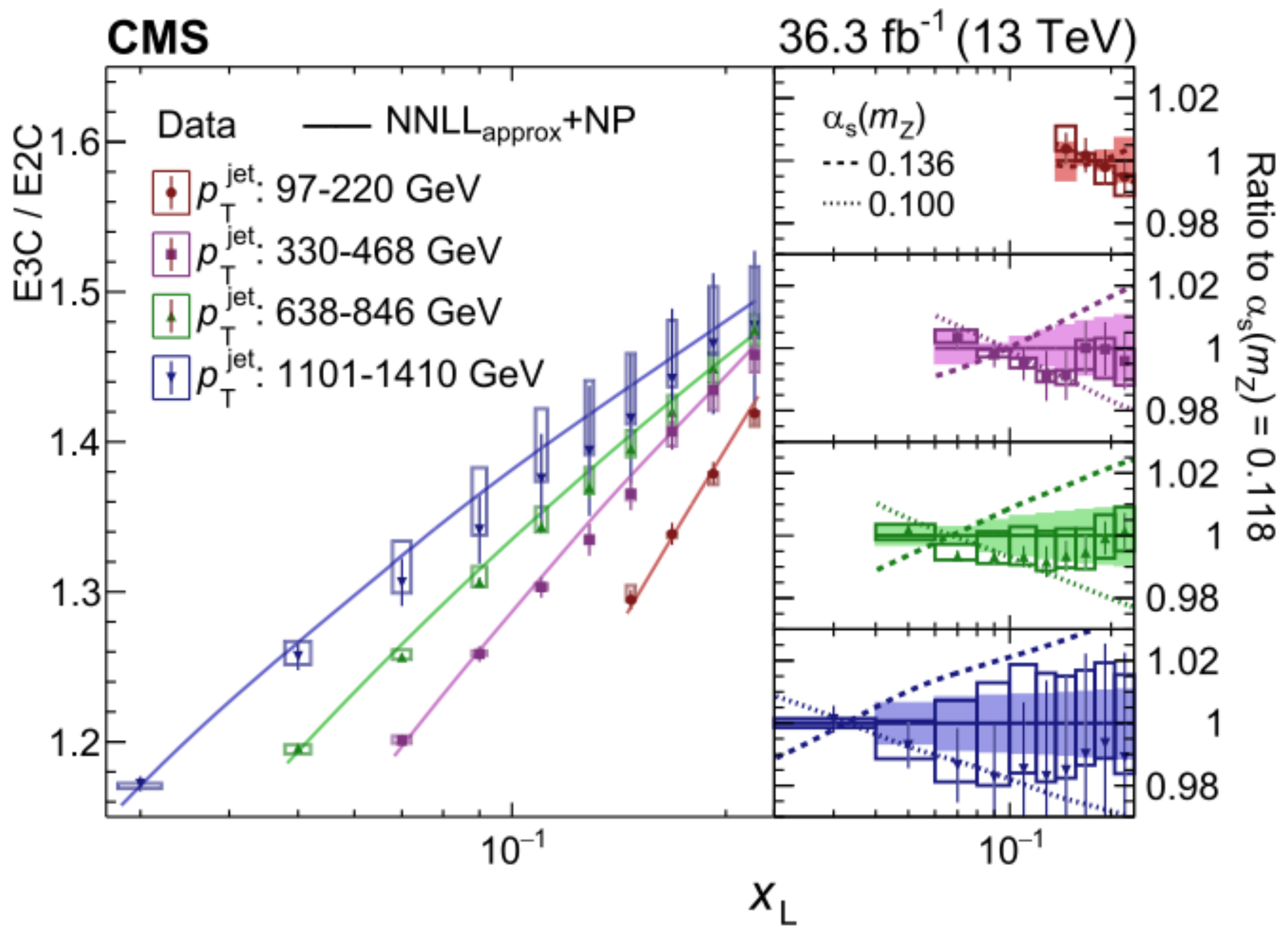
IRC safe

$$\text{EEC} = \frac{1}{\sigma}\sum_{i,j}\int d\sigma \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij}) \sim \langle \Psi | \mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) | \Psi \rangle$$

Inclusive

☑ α_S extraction by the scaling behavior

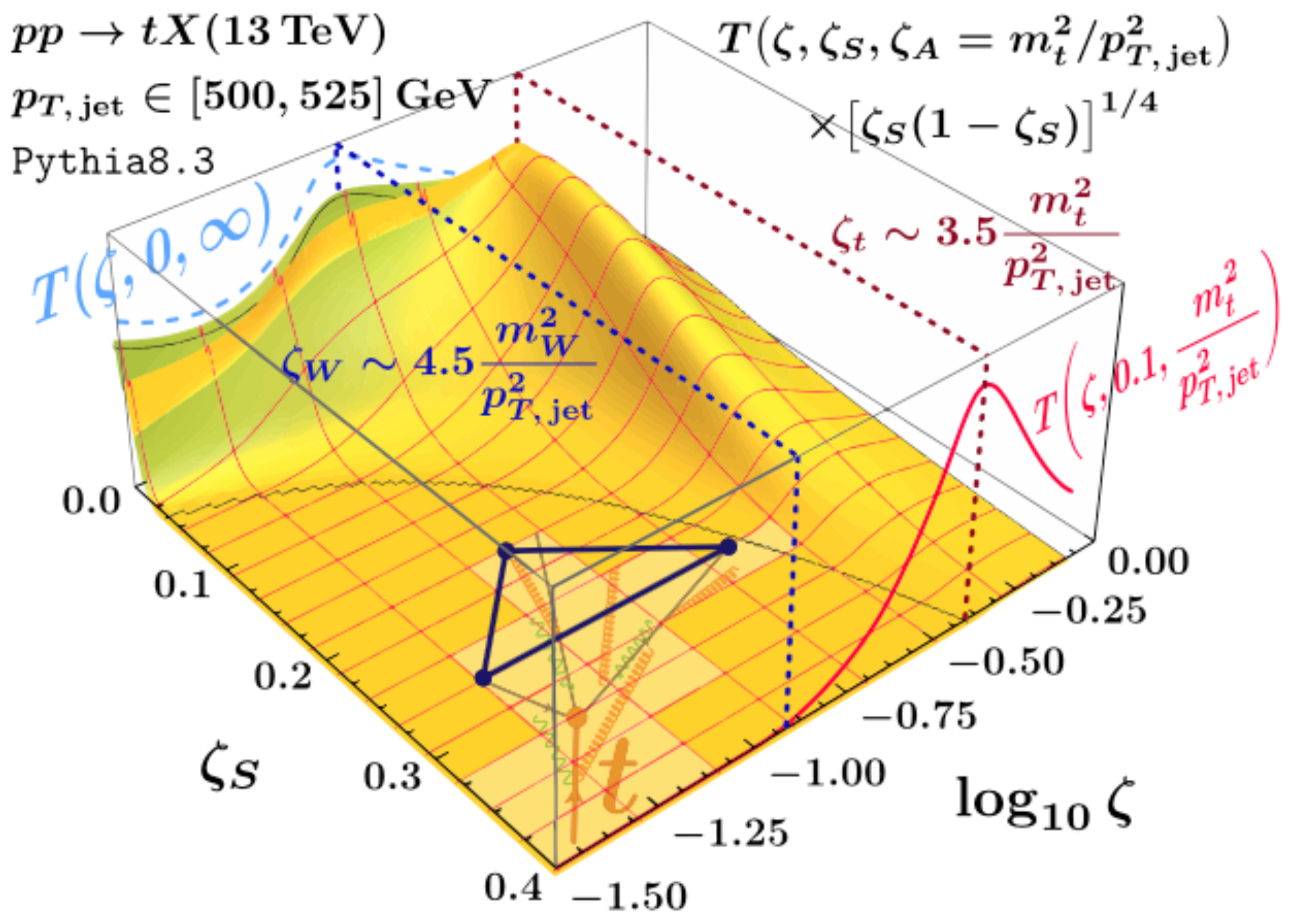
Chen et al., PRD 102, 054012 (2020)
Chen et al., JHEP 05 (2024) 043



CMS, PRL 133 (2024) 071903

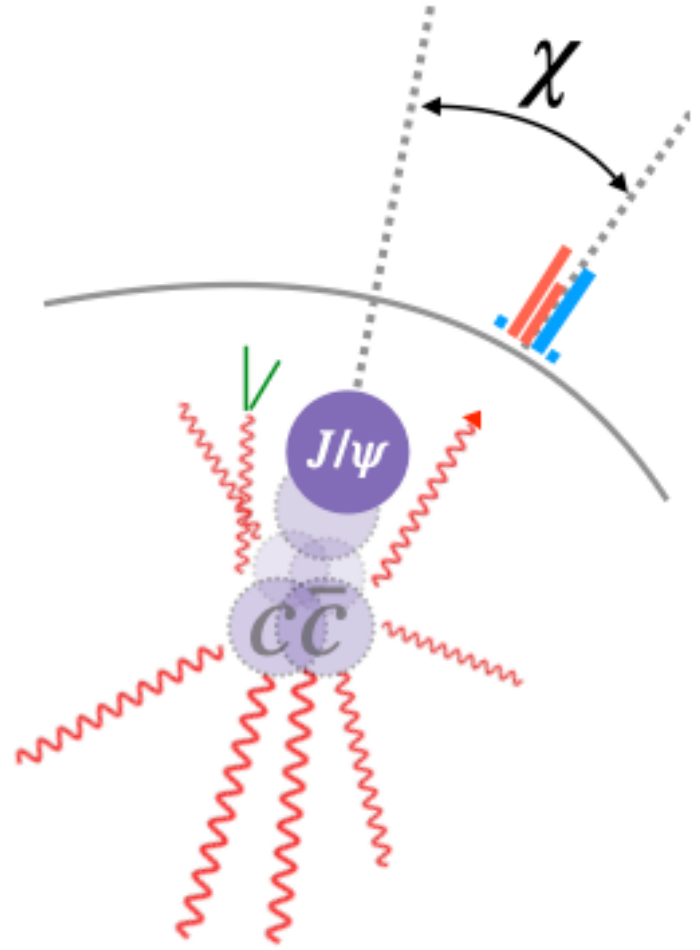
☐ Weighing the top quark

Holguin et al., PRL 134 (2025) 23, 231903
Xiao et al., JHEP 10, 088 (2024)



☐ Quarkonium dynamics

Chen et al., PRL 133, 19 (2024)

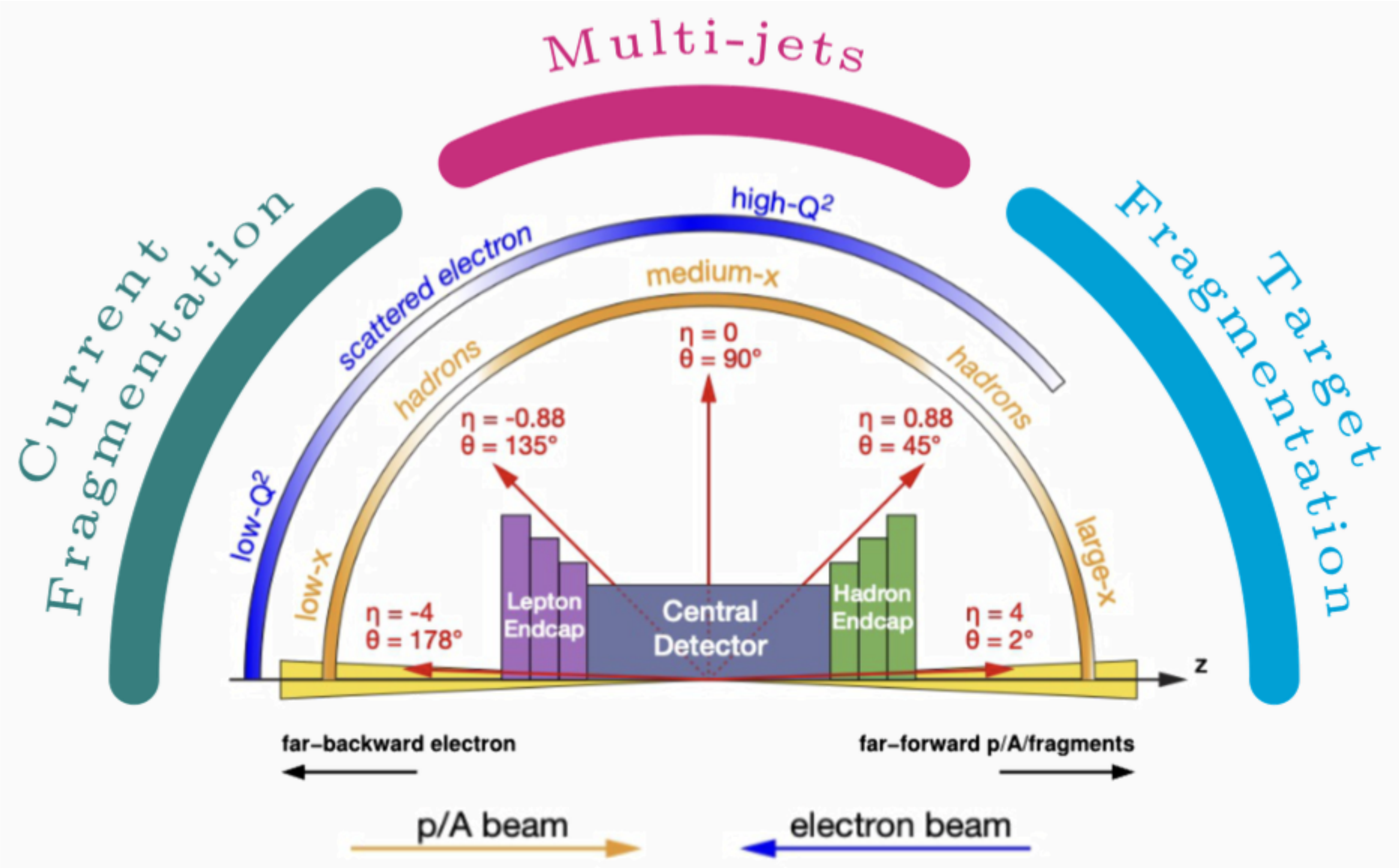


For more examples, see the review: Moult, and Zhu, 2506.09119

Nucleon energy correlators (NECs)

- Proposed as a powerful tool for nucleon tomography by measuring the energy flow in the target fragmentation region (TFR)

Liu and Zhu, PRL, 130, 091901 (2023)



Kinematic regions @EIC. Figure from 2506.09119

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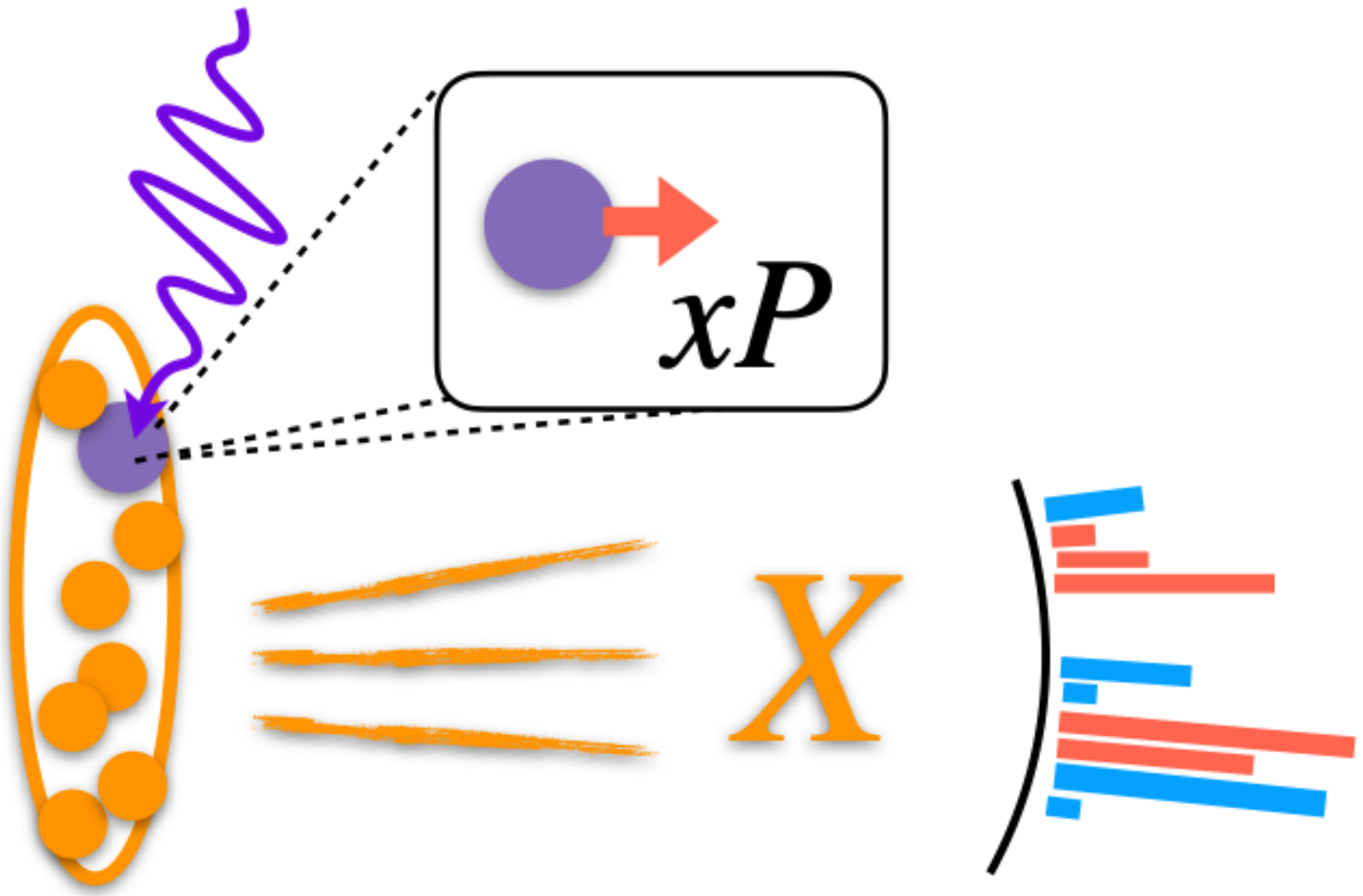
Liu and Zhu, PRL, 130, 091901 (2023)

- Definition: the conditional probability of finding a parton with momentum fraction x while observing an energy flux from the target remnants in (θ, ϕ)



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Liu and Zhu, PRL, 130, 091901 (2023)

- Definition: the conditional probability of finding a parton with momentum fraction x while observing an energy flux from the target remnants in (θ, ϕ)

$$\mathscr{M}^{[\Gamma]}(x, \theta, \phi) = \int \frac{d\eta^-}{4\pi} e^{-ixP^+\eta^-} \langle P | \bar{\psi}(\eta^-) \mathscr{L}_n^\dagger(\eta^-) \Gamma \mathscr{E}(\theta, \phi) \mathscr{L}_n(0) \psi(0) | P \rangle$$

Energy flow operator $$\mathscr{E}(\theta, \phi) | X \rangle = \sum_{i \in X} \frac{E_i}{E_N} \delta(\theta_i^2 - \theta^2) \delta(\phi_i - \phi) | X \rangle$$

The transversity NEC h_1^t

- The leading-twist decomposition of the general quark NEC correlation matrix:

$$\mathcal{M}_{ij}(x,\vec{v}) = \frac{1}{2}\left[(\gamma^-)_{ij}\mathcal{M}^{[\gamma^+]} + (\gamma_5\gamma^-)_{ij}\mathcal{M}^{[\gamma^+\gamma_5]} - i\frac{(\sigma^-_{\alpha_\perp}\gamma_5)_{ij}}{2}\mathcal{M}^{[i\sigma^{\alpha_\perp+}\gamma_5]}\right] + \mathcal{O}\left(\frac{M}{P^+}\right)$$

$$\mathcal{M}^{[\Gamma]} = \frac{1}{2}\mathrm{Tr}[\Gamma\mathcal{M}]$$

- Chiral-even unpolarized NEC f_1:

$$f_1^q(x,\theta^2) = \mathcal{M}^{[\gamma^+]}(x,\theta,\phi)$$

Liu and Zhu, PRL, 130, 091901 (2023)

See more in Chen, Ma, and Tong, JHEP (2024)

azimuthal angular correlation of energy flux

- Chiral-odd transversity NEC h_1^t in the unpolarized nucleon:

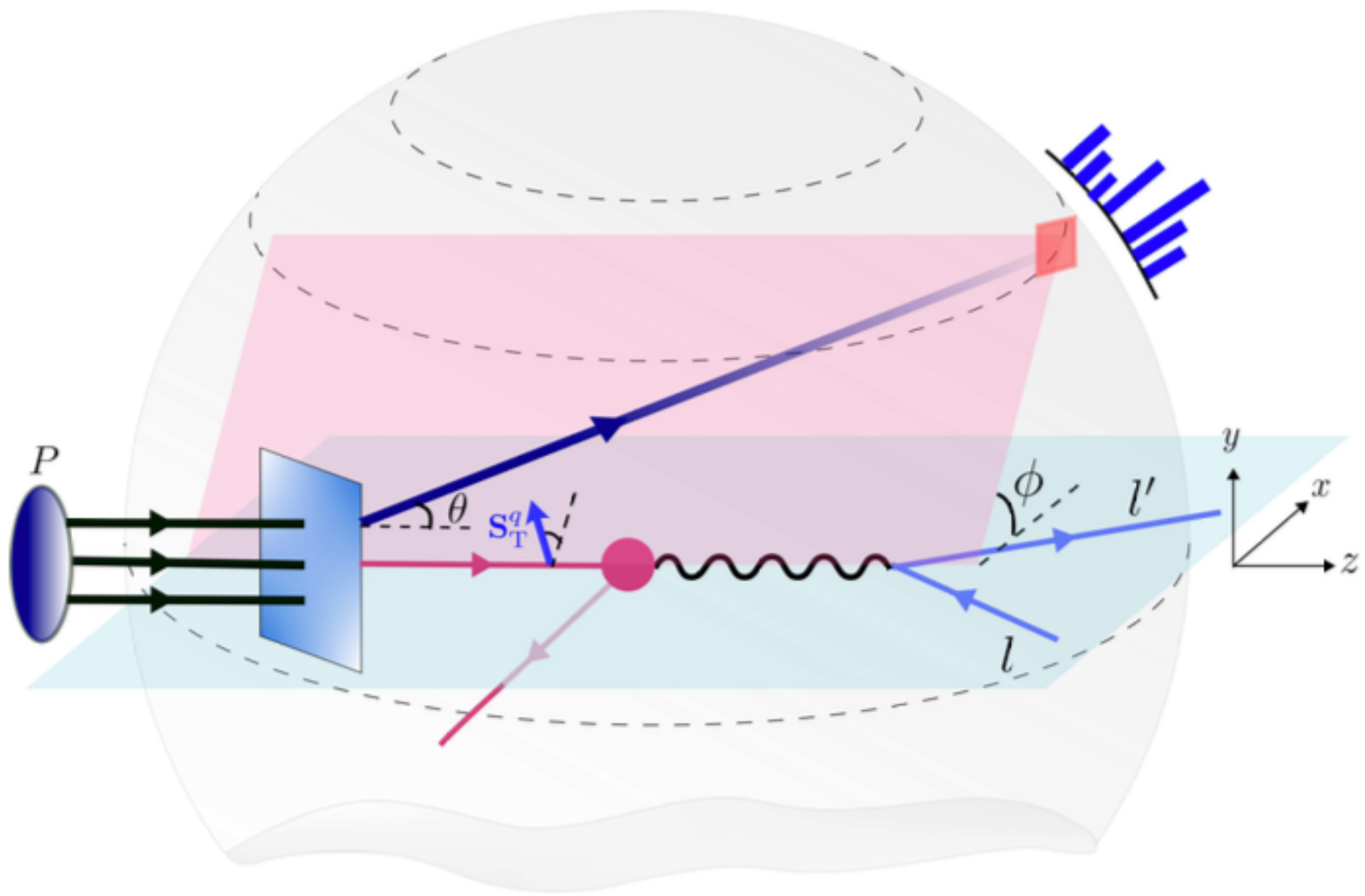
$$\epsilon_\perp^{\alpha\rho}\hat{n}_{T,\rho}\, h_1^{t,q}(x,\theta^2) = \mathcal{M}^{[i\sigma^{\alpha+}\gamma_5]}(x,\theta,\phi)$$

Huang, Tong, and HW, PRL 136 (2026) 13, 131902

- h_1^t: difference in probability of finding a quark polarized along the transverse direction of the energy flow vs in the opposite direction

- **Chiral-odd** nature of h_1^t enables interference with dipole operators
  - Linear order $\mathcal{O}(\Lambda^{-2})$ contribution is restored

Observable: energy pattern xsec $\Sigma(\theta, \phi)$



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Looking at the **energy deposited** in the calorimeters

$$\Sigma(\theta, \phi) = \sum_{i \in X} \int d\sigma^{l+p \to l'+X} \frac{E_i}{E_N} \delta(\theta^2 - \theta_i^2) \delta(\phi - \phi_i)$$

TFR: $\theta P^+ \ll Q$

Collinear factorization

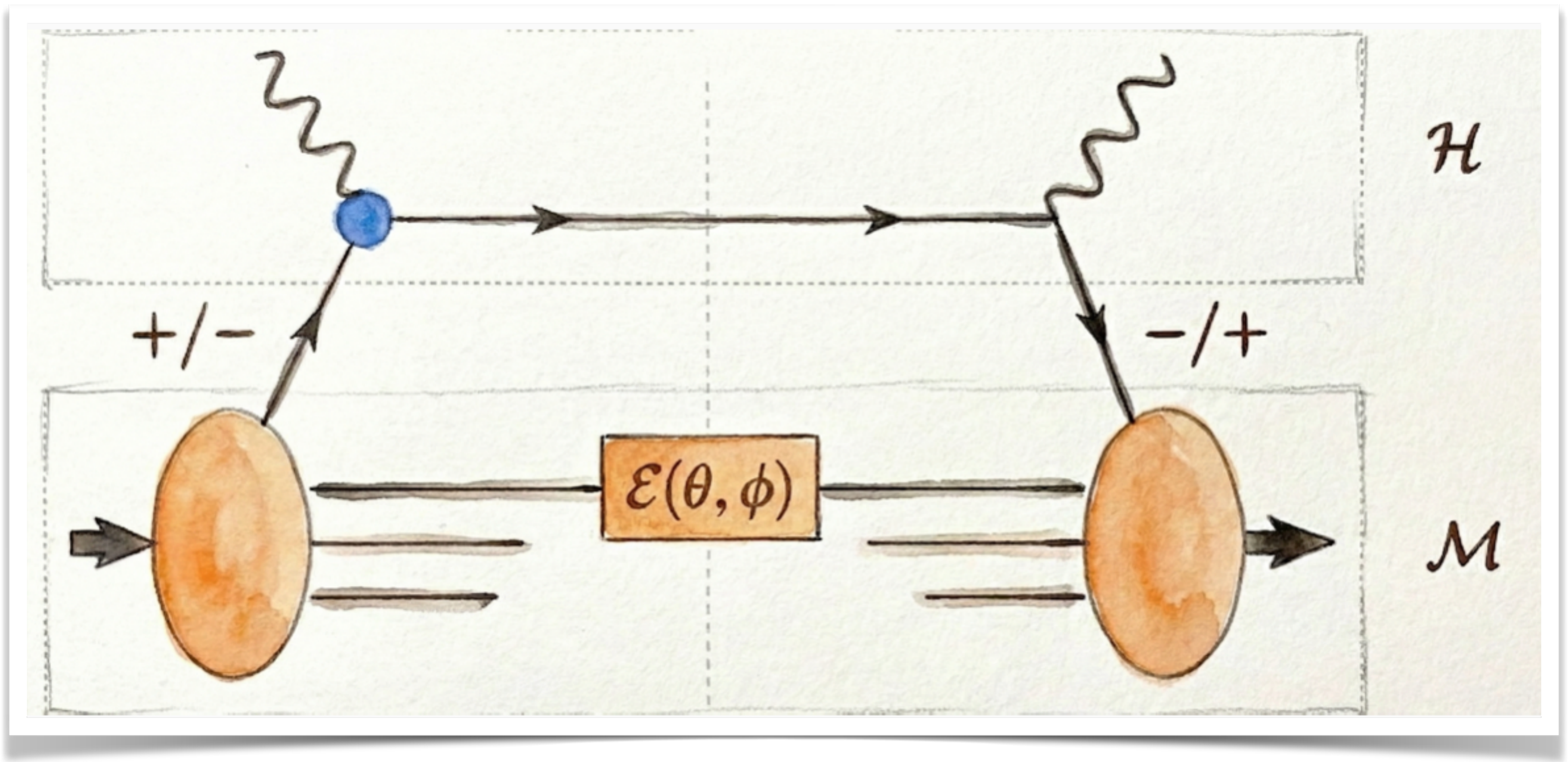
$$\Sigma \propto H(Q, \mu, x) \otimes f_{\mathrm{NEC}}(x, \theta, \phi, \mu)$$

Same as in standard inclusive DIS

Coupling of h_1^t with dipole-SM interference

$$\frac{d\Sigma(\theta, \phi)}{dx_B dQ^2} \propto \left[\mathcal{C}_1 \sin\phi + \mathcal{C}_2 \cos\phi \right] h_1^t(x_B, \theta^2)$$

$\mathrm{Re}[c_{q\gamma,Z}]$ $\mathrm{Im}[c_{q\gamma,Z}]$



Calorimetric asymmetries

- Azimuthal Modulation of the energy pattern:

SM $\sim f_1(x, \theta^2)$

$$\Sigma(\theta, \phi) = \Sigma_{UU}(\theta) + \Sigma_{UU}^{\sin\phi}(\theta)\sin\phi + \Sigma_{UU}^{\cos\phi}(\theta)\cos\phi$$

$\mathrm{Re}[c_{q\gamma,Z}]$
$\mathrm{Im}[c_{q\gamma,Z}]$ $\sim h_1^t(x, \theta^2)$

- To quantify the effects, we define azimuthal asymmetries of the calorimetric energy pattern:

$$A_{UU} = \frac{\pi}{2}\frac{\Sigma(u > 0) - \Sigma(u < 0)}{\Sigma(u > 0) + \Sigma(u < 0)}$$

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$u = \sin\phi, \cos\phi$ isolate the real/imaginary part of the dipole couplings

- **NEC inputs**: resort to TMD PDFs

Liu and Zhu, arXiv: 2403.08874

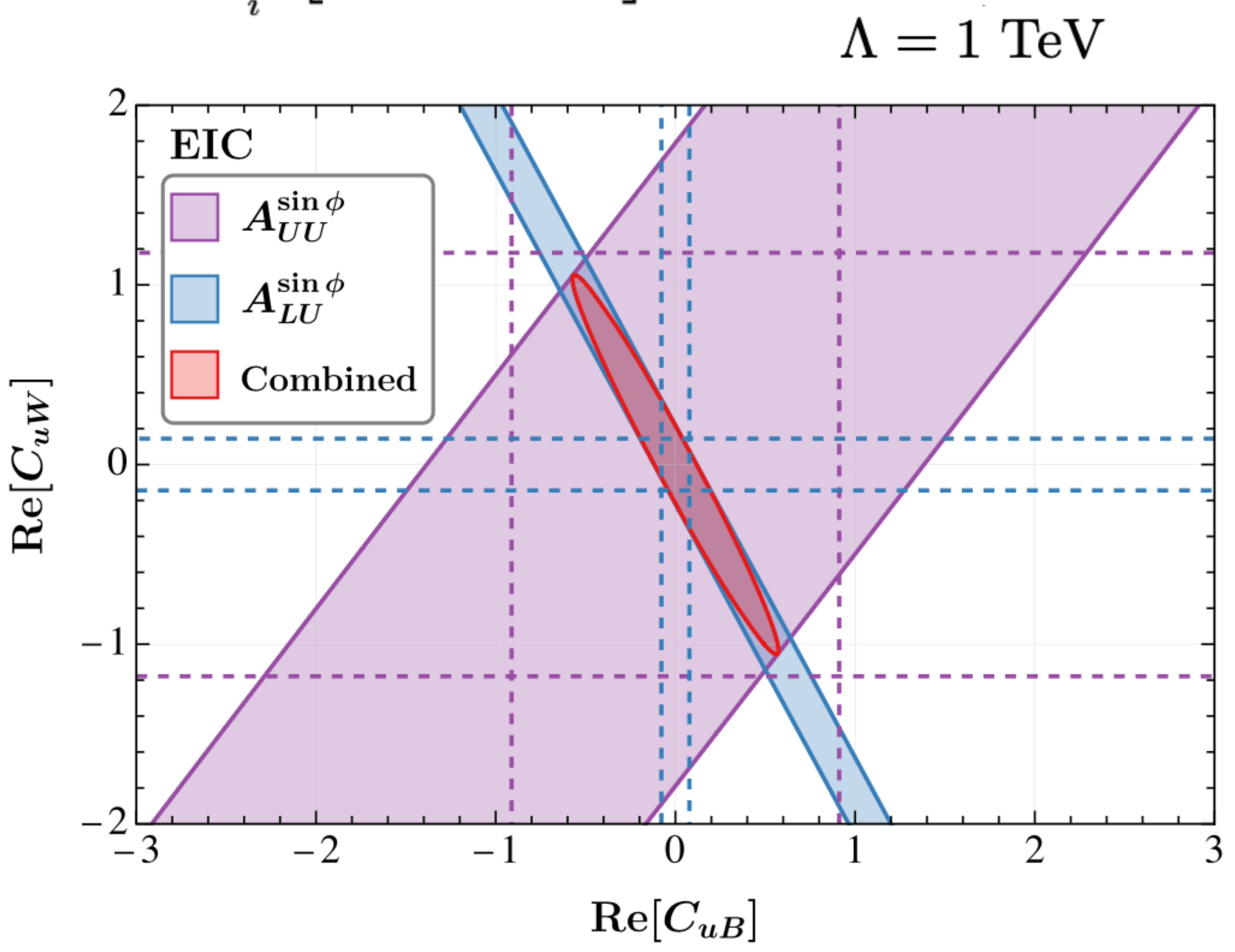
$$E_N \int d\theta^2 \, |\sin\theta| \, f_1(x, \theta^2) = \int \frac{d^2\boldsymbol{k}_\perp}{2\pi} |\boldsymbol{k}_\perp| f_1(x, \boldsymbol{k}_\perp^2)$$ → *Unpolarzied quark TMD*

$$E_N \int d\theta^2 \, |\sin\theta| \, h_1^t(x, \theta^2) = \int \frac{d^2\boldsymbol{k}_\perp}{2\pi} \frac{\boldsymbol{k}_\perp^2}{M} h_1^\perp(x, \boldsymbol{k}_\perp^2)$$ → *Boer-Mulder quark TMD*

Measuments of NECs are expected to be accomplished at EIC, EicC, and JLab…

Projected sensitivity @ EIC

$$\chi^2 = \sum_i \left[\frac{A_{\mathrm{th},i} - A_{\mathrm{exp},i}}{\delta A_i}\right]^2$$



$\sqrt{s} = 105\,\mathrm{GeV}$, $\mathscr{L} = 100\,\mathrm{fb}^{-1}$

$Q \in [10, 60]\,\mathrm{GeV}$, $x \in [0.01, 0.5]$

Inelasticity cut: $0.1 \leq y \leq 0.9$

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$A_{UU}^{\sin\phi}$:

- Strong correlation between C_{uW} and C_{uB} → purple band

$A_{LU}^{\sin\phi}$:

- More sensitive, single-operator constraints can reach $\mathcal{O}(0.01) \sim \mathcal{O}(0.1)$ level
- The correlation is different from that of $A_{UU}^{\sin\phi}$

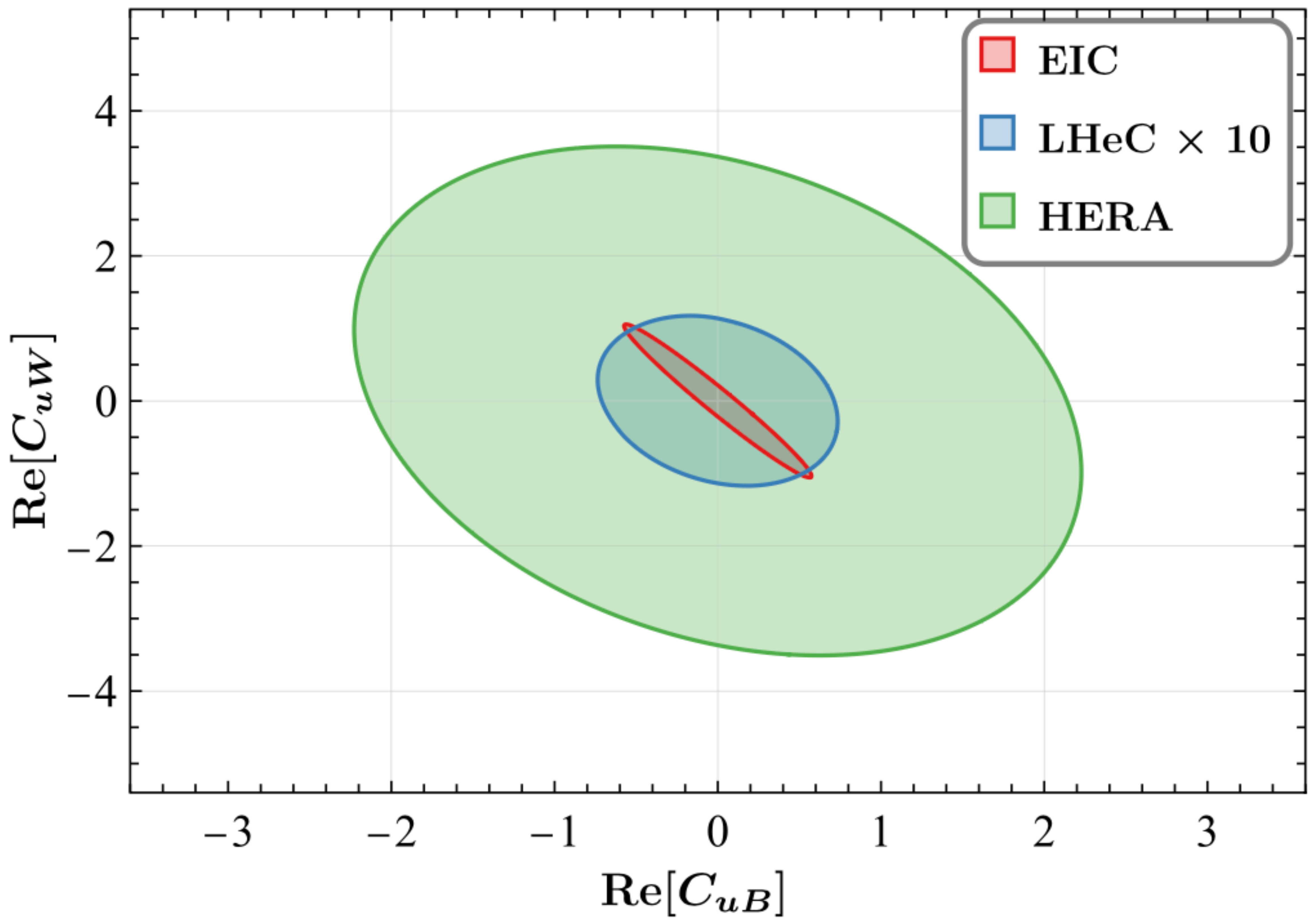
→ Their combination confines the allowed region to **a very narrow area**

Similar for $\mathrm{Im}[C_i]$ from the $\cos\phi$-asymmetry

Comparision btw. electron-ion colliders

- The method also works without polarized proton beams, so **HERA data are relevant** and **LHeC could do even better**

	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb^{-1}]	P_e
HERA	318	0.4	40%
EIC	105	100	70%
LHeC	1300	50	80%



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Summary

- We introduce a chiral-odd NEC that provides a powerful framework to probe EW light-quark dipole operators in inclusive DIS without requiring a polarized proton beam

- Our approach eliminates the need for nucleon polarization and relies entirely on inclusive calorimetric measurements, without particle identification or hadron reconstruction

- Opening a new avenue for **Energy Correlators** in BSM searches (for an effort in other directions, see PRD 106, 114010 (2022))

Thank You!

Backup: complete analytical results

SM:

$$\frac{\mathrm{d}\Sigma_{UU}}{\mathrm{d}x_B\mathrm{d}Q^2} = \frac{2\pi\alpha_{\rm em}^2}{Q^4}\sum_q f_1^q(x_B,\theta^2)\Bigg\{Q_q^2(y^2-2y+2) + \frac{2Q^2}{Q^2+m_Z^2}\frac{Q_q}{(c_W s_W)^2}\left[g_A^e g_A^q(y-2)y - g_V^e g_V^q(y^2-2y+2)\right]$$
$$+\frac{1}{(c_W s_W)^4}\left(\frac{Q^2}{Q^2+m_Z^2}\right)^2\left[(y^2-2y+2)[(g_A^e)^2+(g_V^e)^2][(g_A^q)^2+(g_V^q)^2] - 4y(y-2)g_A^e g_A^q g_V^e g_V^q\right]\Bigg\}\,.$$

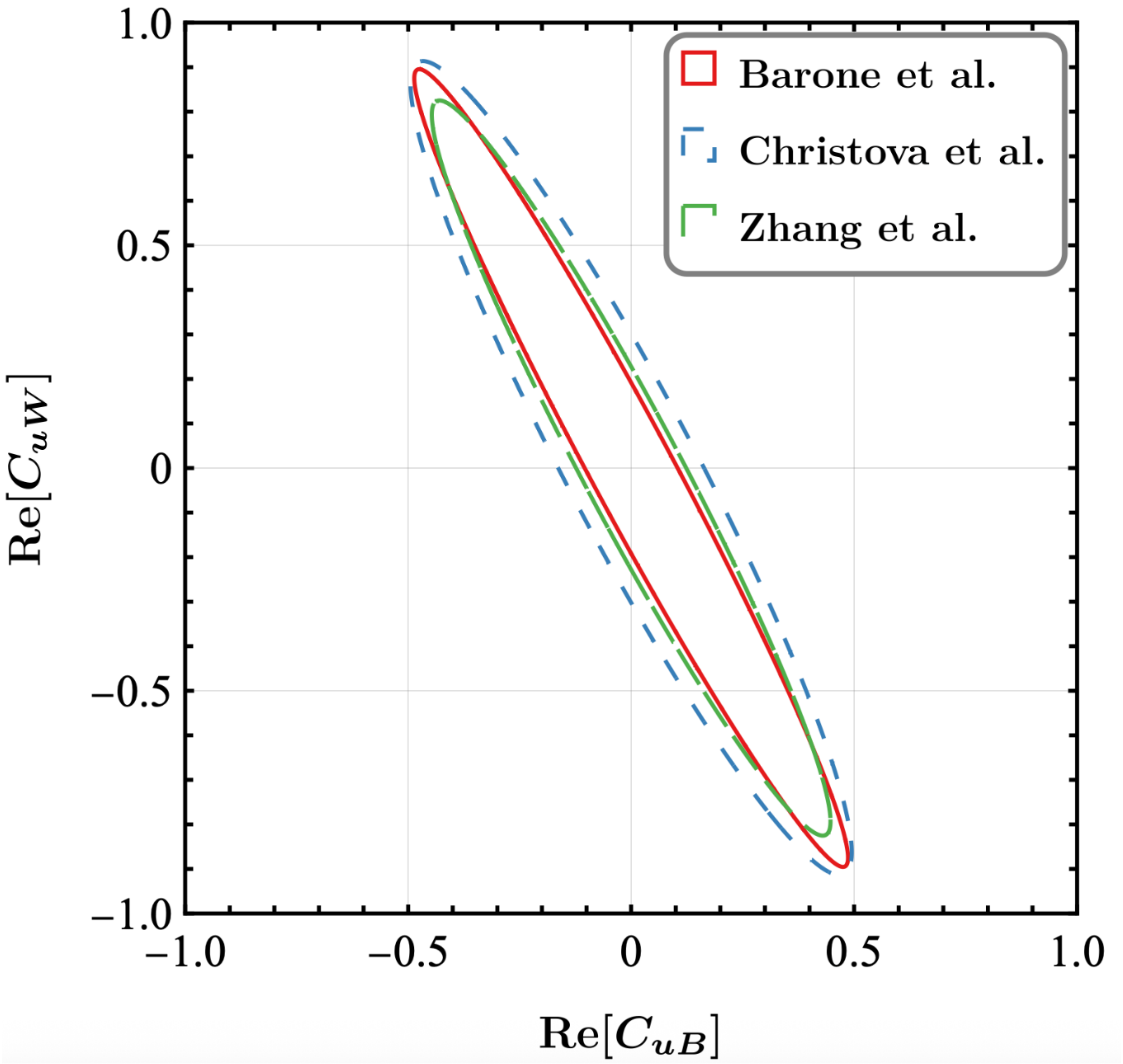
Dipole ops.:

$$\frac{\mathrm{d}\Sigma_{UU}^{\sin\phi}}{\mathrm{d}x_B\mathrm{d}Q^2} = \frac{4\pi\alpha_{\rm em}^2}{e c_W s_W}\frac{y\sqrt{1-y}}{Q(Q^2+m_Z^2)}\sum_q h_1^{t,q}(x_B,\theta^2)\Bigg\{\left[\frac{2-y}{y}g_A^q g_V^e + g_V^q g_A^e\right]\frac{\mathrm{Re}[c_{q\gamma}]}{c_W s_W} - Q_q g_A^e \mathrm{Re}[c_{qZ}]$$
$$+\frac{1}{(c_W s_W)^2}\frac{Q^2}{Q^2+m_Z^2}\left[\frac{2-y}{y}[(g_A^e)^2+(g_V^e)^2]g_A^q + 2g_A^e g_V^e g_V^q\right]\mathrm{Re}[c_{qZ}]\Bigg\},$$

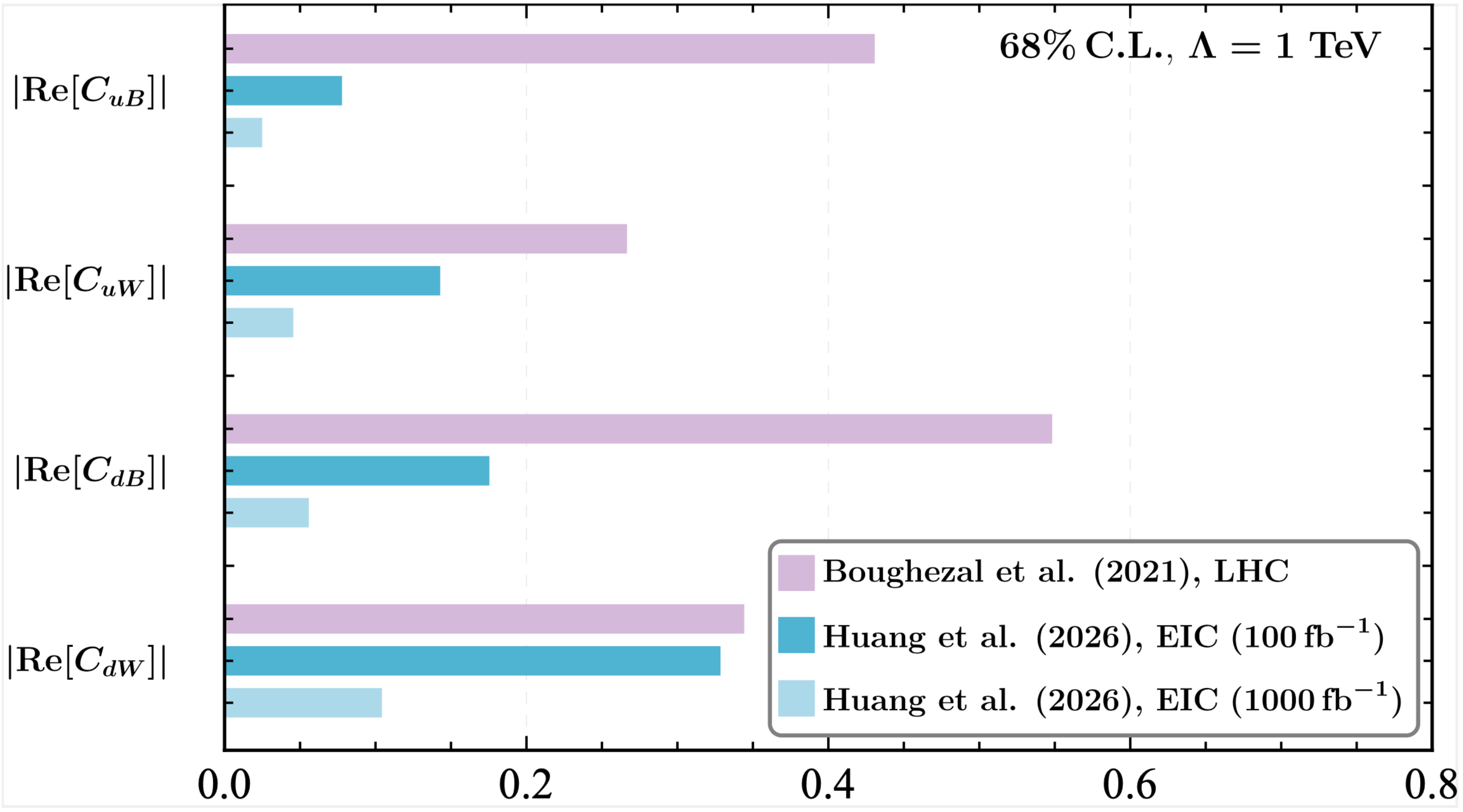
$$\frac{\mathrm{d}\Sigma_{LU}^{\sin\phi}}{\mathrm{d}x_B\mathrm{d}Q^2} = \frac{4\pi\alpha_{\rm em}^2}{Q^3}\frac{y\sqrt{1-y}}{e}\sum_q h_1^{t,q}(x_B,\theta)$$
$$\times\Bigg\{Q_q\mathrm{Re}[c_{q\gamma}] - \frac{Q^2}{Q^2+m_Z^2}\frac{1}{c_W s_W}\left[\left[\frac{2-y}{y}g_A^q g_A^e + g_V^q g_V^e\right]\frac{\mathrm{Re}[c_{q\gamma}]}{c_W s_W} - Q_q g_V^e \mathrm{Re}[c_{qZ}]\right]$$
$$-\frac{1}{(c_W s_W)^3}\left(\frac{Q^2}{Q^2+m_Z^2}\right)^2\left[[(g_A^e)^2+(g_V^e)^2]g_V^q + \frac{2(2-y)}{y}g_A^e g_A^q g_V^e\right]\mathrm{Re}[c_{qZ}]\Bigg\}$$

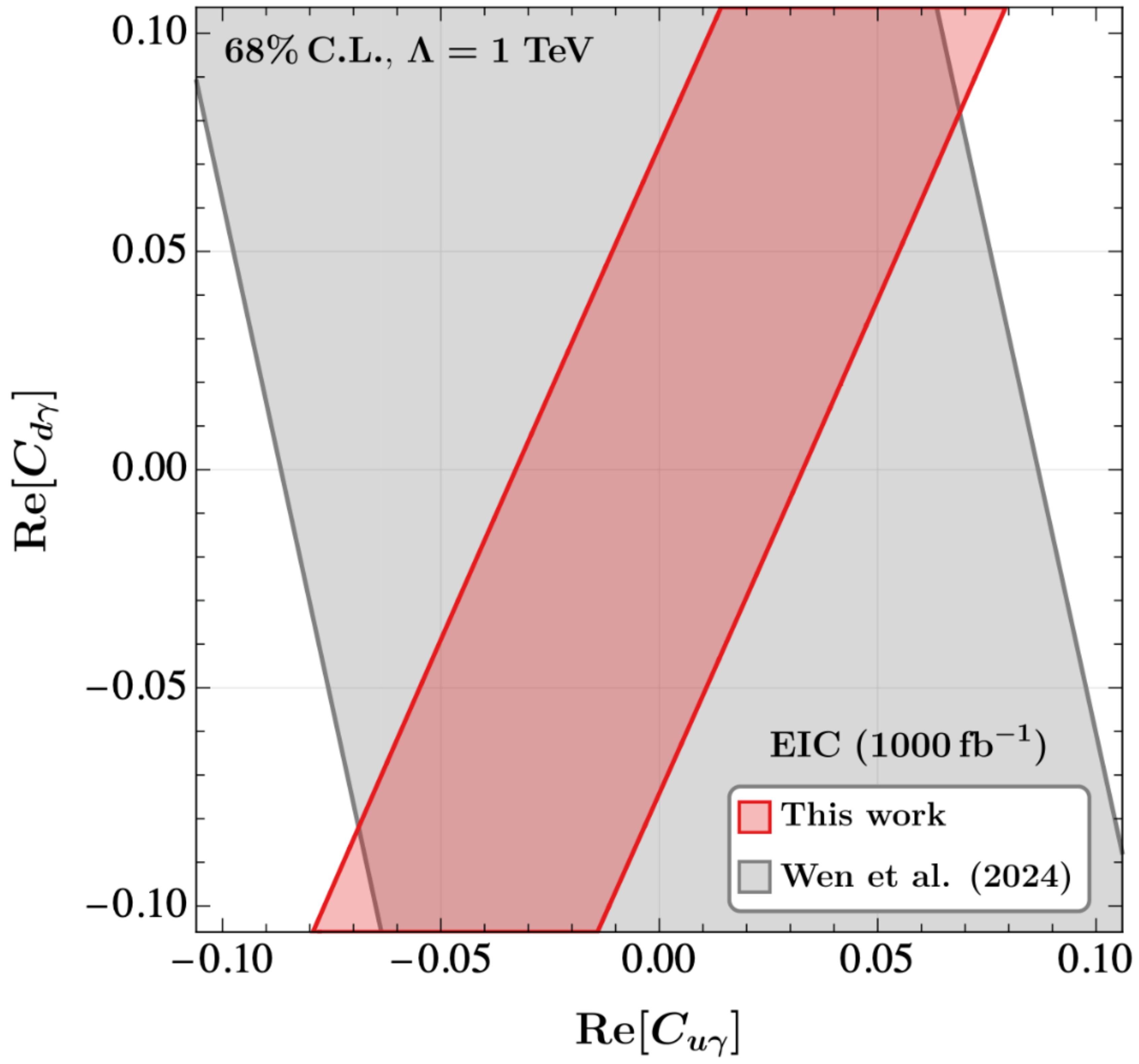
Backup: uncertainties

- Input: Boer-Mulders TMD $h_1^\perp$
- Comparison of 3 fits
- Constrsints are robust against fit choice
- Why? Observable sensitive to $k_\perp$-weighted moment, integrating out local shape differences



Backup: comparison





Backup: evolution of the NEC moments

- Momentum scale: the virtuality Q
- Adopt the TMD fits as the initial conditions at $Q_0 = 2\,\mathrm{GeV}$
- The evolution is performed assuming the θ-moments of the NECs obey the same evolution equations as the corresponding NECs themselves
- The evolution of the unpolarized NEC moment is included through the collinear evolution encoded in the TMD fits
- The evolution of the transversity NEC moment:

$$\frac{\partial}{\partial \ln Q^2} H_1^t(x, Q) = \frac{\alpha_s}{2\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} P^{h_1}_{q\to q}(\hat{x})\, H_1^t\left(\frac{x}{\hat{x}}, Q\right)$$

Where the splitting kernal

$$P^{h_1}_{q\to q}(\hat{x}) = C_F \left[\frac{2\hat{x}}{(1-\hat{x})_+} + \frac{3}{2}\delta(1-\hat{x})\right]$$