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# Nucleon Energy Correlators as a Probe of Light-Quark Dipole Operators at the EIC

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PRL 136 (2026), 131902

2026.08.27 · 第八届粒子物理天问论坛 · 广西桂林



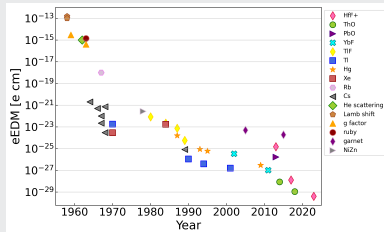
# DIPOLE MOMENTS IN SEARCH FOR BSM

Dipole moments: stringent SM tests and sensitive BSM probes.

## Electron electric dipole moment

$d_e$  (Electron EDM)

- $|d_e| < 4.1 \times 10^{-30} \text{ e} \cdot \text{cm}$  (JILA).
- Constraints on BSM at  $\Lambda \sim 100 \text{ TeV}$ .



arXiv: 2505.22281



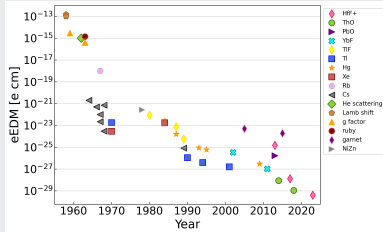
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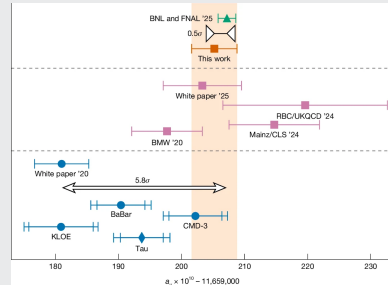


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## Lepton $g - 2$ (magnetic dipole moments)

Muon  $g - 2$  ( $a_\mu$ )

- FNAL '23 (190 ppb):  $\sim 5\sigma$  tension.
- WP25: Tension eased (Lattice/CMD-3 HVP).



Nature **653**, 373 (2026)

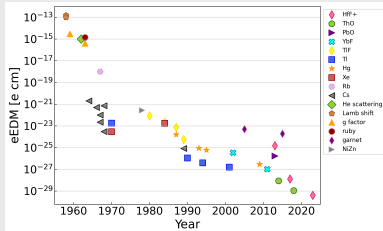
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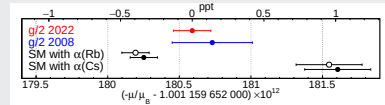
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**Electron  $g - 2$  ( $a_e$ )**

- Gabrielse '23 (0.13 ppt): Tension between  $\alpha$  determined by Cs and Rb experiments.



PRL 130, 071801 (2023)

**Lepton dipoles** have shown why dipoles are powerful on probing/eliminating BSM  
⇒ extend the program to **light-quark dipoles**

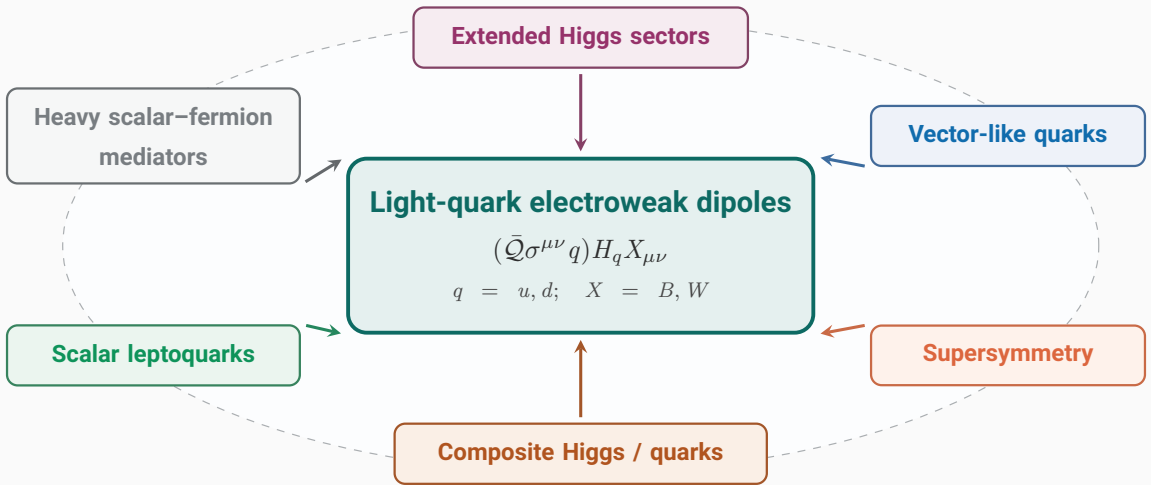
## Low-energy constraints

- **Neutron EDM (nEDM):** stringent bounds on light-quark EDMs.
- **Hadronic magnetic moments:** light-quark MDM bounds remain weak due to SM background.

## Collider opportunity

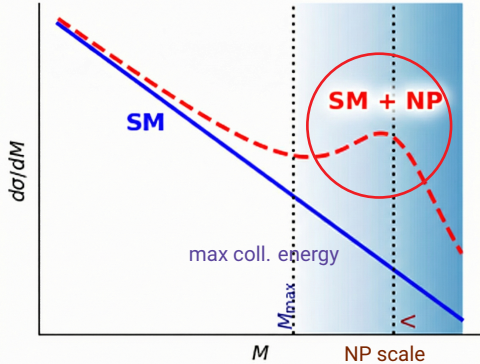
- High-energy searches can probe *both* MDM and EDM.
- Direct access to dipole effects in a complementary kinematic regime.

**Goal:** precision complementary to low-energy EDM searches

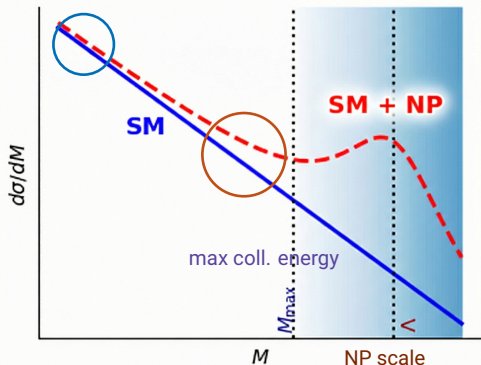


How do we  
systematically  
search for *heavy*  
*new physics* without  
committing to a  
specific UV model?





- **Separation of scales:** new particles are too heavy to be produced,  $E_{\text{exp}} \ll \Lambda$ .



- **Separation of scales:** new particles are too heavy to be produced,  $E_{\text{exp}} \ll \Lambda$ .
- **SM is reliable at low energy:** retain the SM fields and symmetry.
- **Heavy-physics imprint:** encode short-distance effects systematically in local, higher-dimensional operators.
- **Power counting:** organize operators by their mass dimension,  $d > 4$ , and suppress by powers of  $\Lambda$ .

$$\mathcal{L}_{\text{SMEFT}} = \boxed{\mathcal{L}_{\text{SM}}} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)} + \frac{1}{\Lambda^4} \sum_i C_i^{(8)} \mathcal{O}_i^{(8)} + \dots$$

## Bottom-Up

### Experimental Data

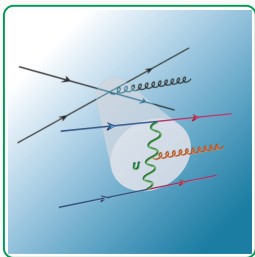
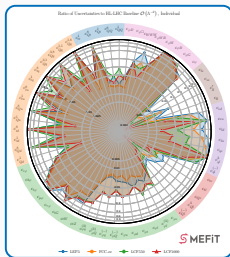
LEP, LHC, flavor,  
low energy

### Global Fits

constrain coefficients  
order by order

### Test the SM

identify nonzero  
directions



## Top-Down

### Specific UV Models

e.g.  $Z'$ , leptoquarks

### Matching

integrate out heavy  
modes

### SMEFT Wilson Coefficients

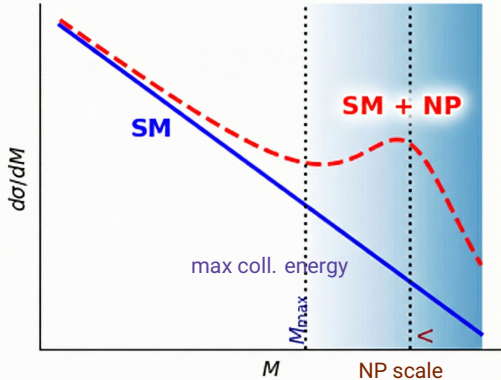
High-dimensional global fit  
 $\Rightarrow$  each process selects  
 specific subset of operators.

### Constrain UV Space

translate SMEFT bounds  
to UV models



# DIPOLE OPERATORS within SMEFT



SMEFT up to dimension-6:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \boxed{\frac{1}{\Lambda^2} \sum_i C_i^{(6)} \mathcal{O}_i^{(6)}} + \dots$$

We focus on dimension-6 electroweak dipole operators (+h.c.):

$$\mathcal{O}_{uB} = (\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$$

$$\mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}\tau^I u)\tilde{H}W_{\mu\nu}^I$$

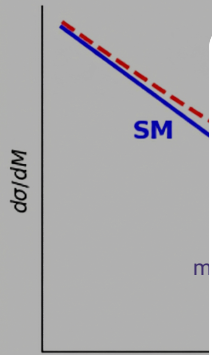
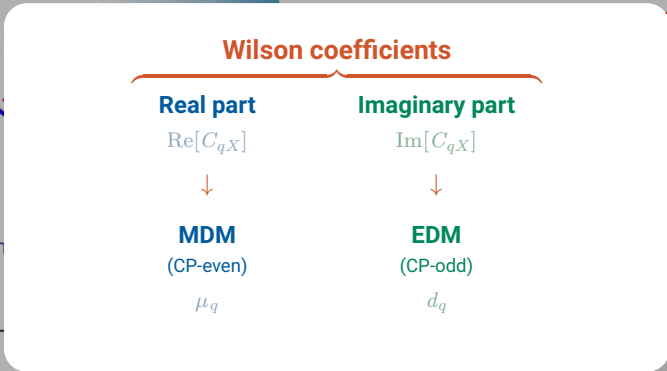
$$\mathcal{O}_{dB} = (\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}$$

$$\mathcal{O}_{dW} = (\bar{Q}\sigma^{\mu\nu}\tau^I d)HW_{\mu\nu}^I$$

$\bar{Q}$ : left-handed doublet;  $u$ ,  $d$ : right-handed singlets;  $\tau^I$ : SU(2) generators;  $\tilde{H}_I = \epsilon_{IJ}H_J^*$ .



SMEFT up to dimension-6:



$$C_i^{(6)} \mathcal{O}_i^{(6)} + \dots$$

weak dipole operators

$$B_{\mu\nu} \\ \tilde{H} W_{\mu\nu}^I \\ B_{\mu\nu} \\ H W_{\mu\nu}^I$$

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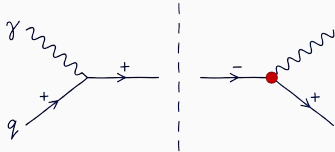
# THE CHIRALITY BOTTLENECK AT HIGH ENERGY

However, precision collider searches face a fundamental suppression mechanism rooted in the operator structure.

## Operator Structure:

- Chirality-flipping operators:

$$\mathcal{O}_{\text{dipole}} \sim \bar{\psi}_L \sigma^{\mu\nu} F_{\mu\nu} \psi_R$$



## Chirality Mismatch:

- SM:**  $\gamma^\mu$  (odd no. of  $\gamma$ )  $\implies$  Conserves chirality ( $L \rightarrow L$ ).
- Dipole:**  $\sigma^{\mu\nu}$  (even no. of  $\gamma$ )  $\implies$  Flips chirality ( $L \rightarrow R$ ).

$\implies$  Interference term  $\mathcal{M}_{\text{SM}} \times \mathcal{M}_{\text{dipole}}^* \rightarrow 0$  in massless limit

$$\text{Interference} \propto \text{Tr}[\not{k}' \gamma^\mu \not{k} \sigma^{\alpha\beta}] \xrightarrow{\text{assumed } m_q \rightarrow 0} 0 \quad (\text{Trace of odd \# of } \gamma\text{'s})$$

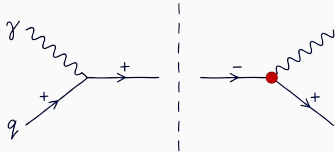
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Consequence: only quadratic BSM sensitivity remains at leading order e.g. Boughezal et al., PRD 104, 095022 (2021)

$$\sigma \sim |\mathcal{M}_{\text{SM}}|^2 + \frac{1}{\Lambda^2} \left( \mathcal{M}_{\text{SM}} \times \mathcal{M}_{\text{dipole}}^* + \text{h.c.} \right) + \frac{1}{\Lambda^4} |\mathcal{M}_{\text{dipole}}|^2$$

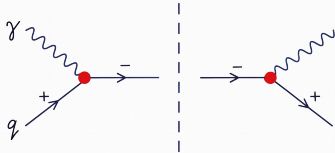
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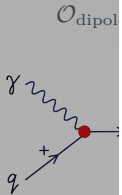
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# THE CHIRALITY BOTTLENECK AT HIGH ENERGY

However, precision collider searches face a fundamental suppression mechanism rooted in the operator structure.

## Operator Structure

- Chirality-flipping



### A few issues w/ vanishing linear order

- worse sensitivity
- depends on  $|C|^2$ , no sensitivity to the complex phase
  - cannot constrain  $\text{Re}[C]$  and  $\text{Im}[C]$  individually
- same order as linear dim-8 contributions ( $1/\Lambda^4$ )
  - cannot ignore dim-8 contribution

conserves chirality

⇒ Flips chirality

\* dipole → 0 in

Consequence: only

al., PRD 104, 095022 (2021)

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The linear  $\Lambda^{-2}$  interference can be restored by **quark transverse spin**.

- **Why?** Transverse spin is a superposition of helicity states:

$$|\uparrow\rangle \propto |-\rangle + i|+\rangle.$$

- The helicity-conserving SM amplitude can therefore interfere with the helicity-flipping dipole amplitude.

## Transverse-spin projector

$$u(p)\bar{u}(p) \propto \not{p}(1 + \gamma^5 \not{\mathcal{S}}_T)$$

Restores an even number of  $\gamma$  matrices.

# INTERFERENCE RESTORATION

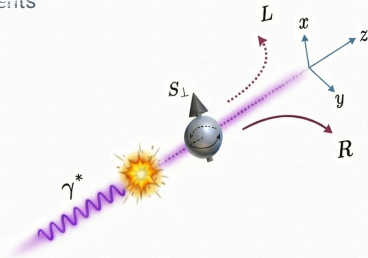
The linear  $\Lambda^{-2}$  interference can be restored by **quark transverse spin at the EIC**.

## Existing Approaches:

### *Transverse spin asymmetry @EIC*

Boughezal et al. PRD 107, 075028 (2023)

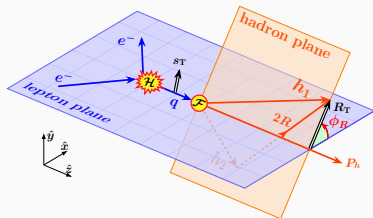
- quark transverse spin from a polarized nucleon beam
- *Limitation:* Requires polarized hadron beams, less events



### *Dihadron fragmentation @EIC*

Wen et al., arXiv: 2408.07255

- transverse plane formed by dihadron, no need for polarized nucleon beam
- *Limitation:* requires hadron id. & tracking





# INTERFERENCE RESTORATION

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## Existing Approach

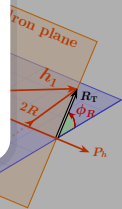
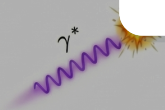
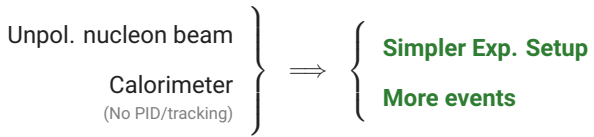
Transverse

Boughezal et al.

- quark transverse beam
- Limitation: Requires PID/tracking events

## Our proposal

use **transversity nucleon energy correlators @EIC** to induce a **transversely polarized** struck quark from an **unpolarized nucleon**



# ENERGY CORRELATORS (see Moulton & Zhu, arXiv:2506.09119 for a review)

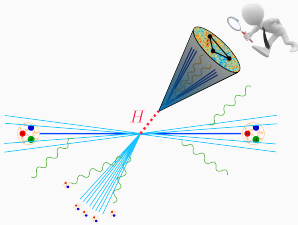
**Energy correlators** measure the energy-weighted angular correlations of particles in the detector.

## Why use them?

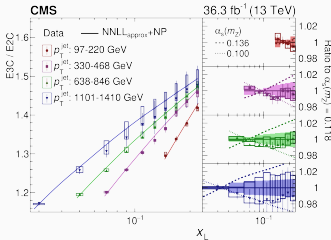
- Theoretically simple
- No jet clustering ambiguities
- IRC safe  $\rightarrow$  Insensitive to low-energy radiation
- ...

## Applications in HEP:

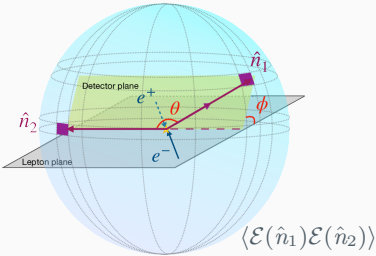
### Jet substructure



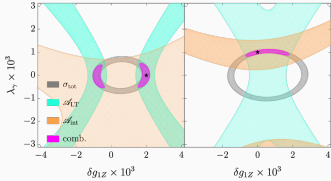
### Measuring $\alpha_s$



PRL 133, 071903 (2024)



### BSM with TEEC



PRD 106, 114010 (2022)

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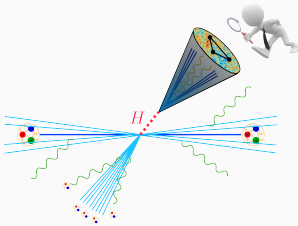
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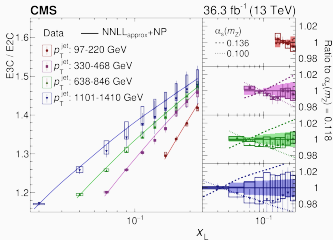
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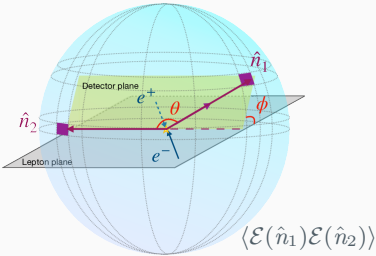
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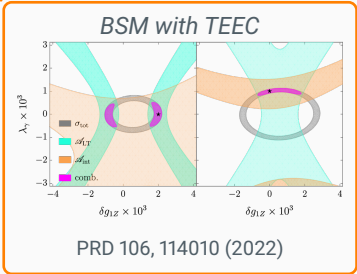
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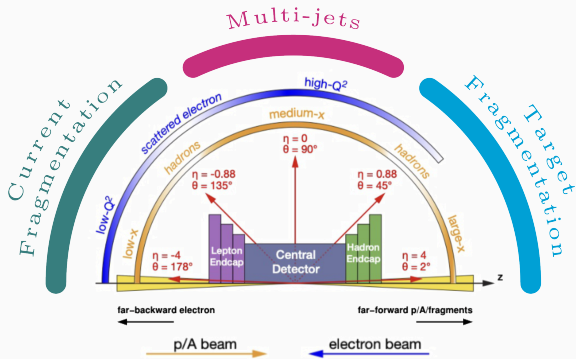


one of the few  
EC appl. to BSM

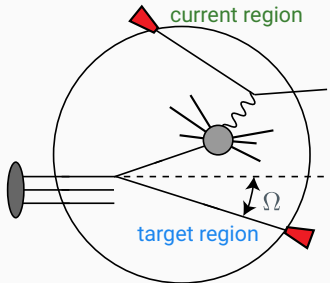


PRD 106, 114010 (2022)

- Ordinary Energy Correlators → **current fragmentation region**
- **nucleon energy correlators (NECs)** are defined in the **target fragmentation region (TFR)** and probe the **initial-state nucleon remnant**.

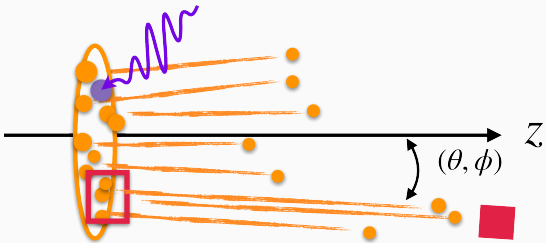


Kinematic regions @EIC. Figure from 2506.09119

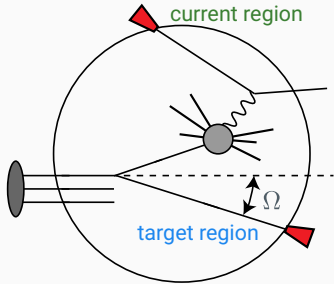


Geometry: target vs current region

- Ordinary Energy Correlators → **current fragmentation region**
- **nucleon energy correlators (NECs)** are defined in the **TFR** and probe the **initial-state nucleon remnant**.



NEC: probability to find a quark with long. momentum fraction  $x$  in the target, conditioned on energy flux at  $(\theta, \phi)$  in the TFR



Geometry: target vs current region

**NEC:** energy-weighted quark correlator

$$\mathcal{M}^{[\Gamma]}(x, \vec{\Omega}) = \int \frac{d\eta^-}{4\pi} e^{-ixP^+\eta^-} \langle P | \bar{\psi}(\eta^-) \Gamma \overset{\text{energy-flow operator}}{\mathcal{E}(\vec{\Omega})} \psi(0) | P \rangle$$



Leading-twist decomposition of the NEC correlator:

$$\mathcal{M}_{ij}(x, \vec{\Omega}) = \frac{1}{2} \left[ \underbrace{(\gamma^-)_{ij} \mathcal{M}^{[\gamma^+]}}_{\text{unpol. quark}} + \underbrace{(\gamma^5 \gamma^-)_{ij} \mathcal{M}^{[\gamma^+ \gamma^5]}}_{\text{long. quark}} + \underbrace{-i \frac{(\sigma_{\alpha\perp}^- \gamma^5)_{ij}}{2} \mathcal{M}^{[i\sigma^{\alpha\perp} + \gamma^5]}}_{\text{trans. quark}} \right] + \dots$$

Leading-twist decomposition of the NEC correlator:

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- Chiral-even** unpolarized NEC  $f_1$

isolated from  $\Gamma = \gamma^+$ :

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

- Chiral-odd** transversity NEC  $h_1^t$

isolated from  $\Gamma = i\sigma^{\alpha+} \gamma_5$ :

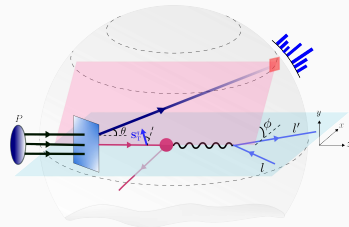
$$\epsilon_{\perp}^{\alpha\rho} \hat{n}_{T,\rho} h_1^t(x, \theta^2) \subset \mathcal{M}^{[i\sigma^{\alpha+} \gamma_5]}$$

$h_1^t(x, \theta^2)$ : a filter selecting the quark transverse spin in an **unpolarized nucleon**.

- $\Rightarrow$  **Chiral-odd nature** enables **intf. with dipole operators**.

- Linear order** ( $\Lambda^{-2}$ ) contribution is restored.

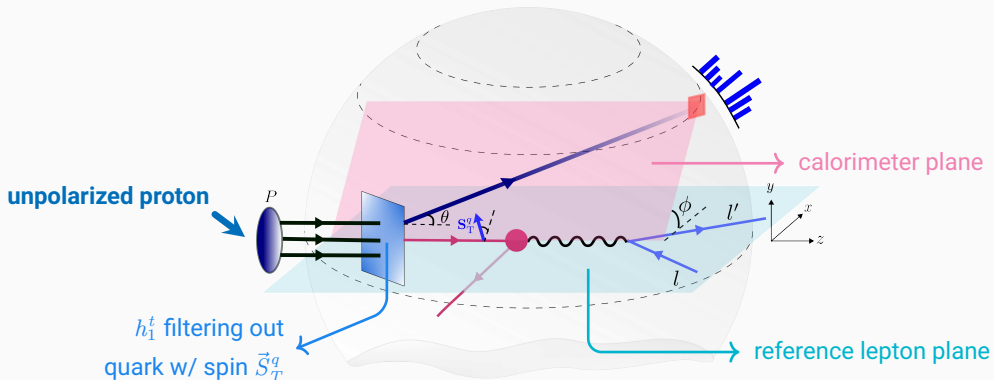
- $h_1^t$  also probes the remnant energy angular distribution.



Observable: **Energy Pattern xsec.**  $\Sigma(\theta, \phi)$

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

$\Sigma$ : angular distribution of the total energy deposited in the calorimeters





## Factorization of the **energy pattern** cross section (similar to coll. factorization)

- General NEC:

Liu & Zhu, PRL 130, 091901 (2023)  
Chen, Ma & Tong, JHEP 08, 227 (2024)

$$\frac{d\Sigma(\theta, \phi)}{dx_B dQ^2} \propto L_{\mu\nu} \mathcal{H}_{ji}^{\mu\nu} \otimes \mathcal{M}_{ij}$$

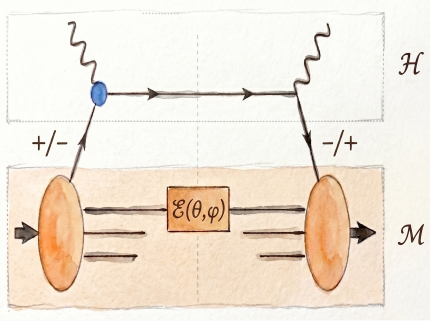
- Transversity NEC ( $\hat{n}_T = (\cos \phi, \sin \phi)$ ):

$$\frac{d\Sigma}{dx_B dQ^2} \propto L_{\mu\nu} \text{Tr} \left[ \mathcal{H}^{\mu\nu} \sigma^{-\alpha} \gamma_5 \right]$$

$$\times \epsilon_{\perp}^{\alpha\beta} \hat{n}_{T\beta} h_1^t(x_B, \theta^2)$$

$\phi$ -dependence from  
transverse spin direction

$\theta$ -dependence



## Azimuthal Modulation of the energy pattern

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

SM, unpolarized NEC

$\text{Re}(c_{qZ/\gamma}), h_1^t$

$\text{Im}(c_{qZ/\gamma}), h_1^t$



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Chen, Ma & Tong, JHEP 08, 227 (2024)

$$\frac{d\Sigma(\theta, \phi)}{dx_B dQ^2} \propto L_{\mu\nu} \mathcal{H}_{ji}^{\mu\nu} \otimes \mathcal{M}_{ij}$$

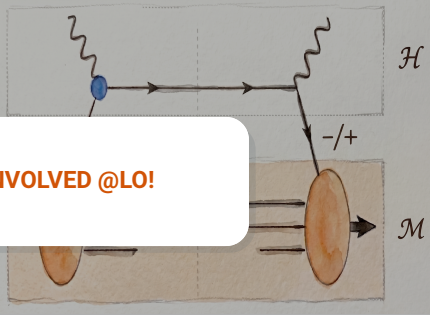
- Transversity NEC ( $\hat{n}_T = (\cos \phi, \sin \phi)$ ):

$\overline{dx}$

**NO OTHER SMEFT OPERATORS INVOLVED @LO!**

$\phi$ -dependence from  
transverse spin direction

$\theta$ -dependence



Azimuthal Modulation of the energy pattern

$$\Sigma(\theta, \phi) = \underbrace{\Sigma_{UU}(\theta)}_{\text{SM, unpolarized NEC}} + \underbrace{\Sigma_{UU}^{\sin \phi}(\theta)}_{\text{Re}(c_{qZ/\gamma}), h_1^t} \sin \phi + \underbrace{\Sigma_{UU}^{\cos \phi}(\theta)}_{\text{Im}(c_{qZ/\gamma}), h_1^t} \cos \phi$$

**General correspondence:**  $\theta$ -weighted moments of **NECs**  $\leftrightarrow$   $k_{\perp}$ -weighted moments of **transverse momentum dependent PDFs (TMDs)**.

## Weighted NEC-TMD moments

**Liu et al., arXiv:2403.08874**

$$E_N \int d\theta^2 |\sin \theta| f_1(x, \theta^2) = \int \frac{d^2 k_{\perp}}{2\pi} |\mathbf{k}_{\perp}| f_1(x, k_{\perp}^2)$$

**YH, Tong & Wang, PRL 136, 131902**

$$E_N \int d\theta^2 |\sin \theta| h_1^t(x, \theta^2) = \int \frac{d^2 k_{\perp}}{2\pi} \frac{k_{\perp}^2}{M} h_1^{\perp}(x, k_{\perp}^2)$$

Diagram illustrating the correspondence between NEC and TMD moments:

- unpol. NEC** (green box) corresponds to **unpol. TMD** (blue box) via the first equation.
- transversity NEC** (green box) corresponds to **Boer-Mulders TMD** (blue box) via the second equation.

## Observable used below

Weight the energy pattern with  $|\sin \theta|$ :

$$\Sigma(\phi) = \int d\theta^2 |\sin \theta| \Sigma(\theta, \phi).$$

## Numerical input

- Boer-Mulders fit from **Barone et al., PRD 81, 114026 (2010)**.
- The weighted moment suppresses sensitivity to local TMD-shape differences.

Transverse spin superposition states



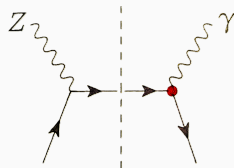
$\Sigma(\phi)$  contains a **chirality-conserving** contribution



Extract **chirality-flipping BSM effects** with **azimuthal asymmetries**

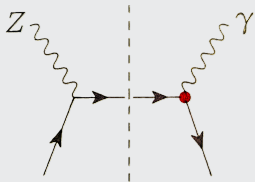
Unpolarized beams  $A_{UU}$

$$A_{UU}^u = \frac{\pi}{2} \frac{\Sigma(u > 0) - \Sigma(u < 0)}{\Sigma(u > 0) + \Sigma(u < 0)}, \quad u = \begin{cases} \sin \phi \rightsquigarrow \text{Re } C, \\ \cos \phi \rightsquigarrow \text{Im } C. \end{cases}$$



$\gamma Z$  interference:  $Q^2/m_Z^2$  suppression

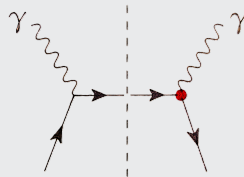
## Unpolarized beams $A_{UU}$



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

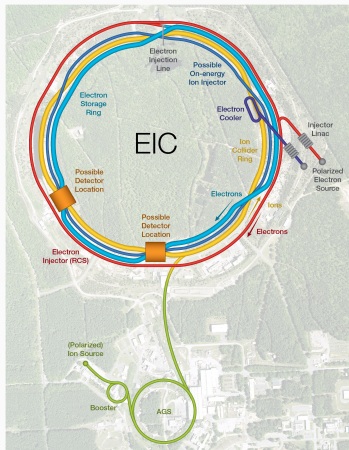
Dominated by  $\gamma Z$  interference and suppressed by  $Q^2/m_Z^2$ .

## Longitudinally polarized electrons $A_{LU}$



The same angular partition is applied.

- Polarization activates a **nonzero**  $\gamma\gamma$  channel.
- The leading sensitivity avoids  $Q^2/m_Z^2$  suppression.



## Where to probe it?

**EIC (under construction, 2034–)**

$ep/eA$

Highly polarized collider at BNL

$\sqrt{s} \sim 20\text{--}140 \text{ GeV}$

Moderate center-of-mass energy

$10\text{--}100 \text{ fb}^{-1}$

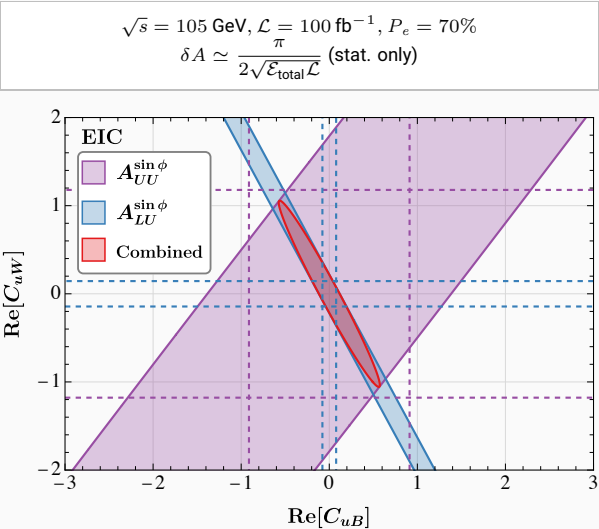
High integrated luminosity

The EIC combines high luminosity with polarized  $ep/eA$  collisions.

# CONSTRAINTS W/ EIC

- $A_{UU}^{\sin\phi}$ : Strong correlation between  $C_{uW}$  and  $C_{uB}$ , leaving a "flat direction" unconstrained.
- $A_{LU}^{\sin\phi}$ : Polarized electron beam  
 $\implies$  nonzero  $\gamma\gamma$  interference  
 $\implies$  seemingly tighter constraints pointing at another direction.
- Single-operator constraints reach  $\mathcal{O}(10^{-2})$  at  $\Lambda = 1$  TeV.

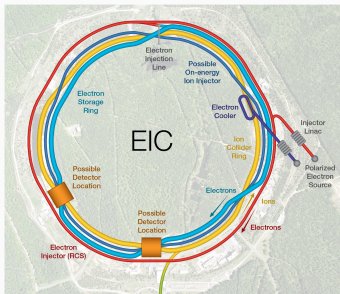
The combined fit breaks the degeneracy and improves parameter resolution by orders of magnitude.



# APPLICATIONS AT ELECTRON-ION COLLIDERS

## Under construction: EIC (2034–)

- First highly polarized  $ep/eA$  collider.
- $\sqrt{s} \sim 20\text{--}140\text{ GeV}$ .
- High luminosity:  $10\text{--}100\text{ fb}^{-1}$ .



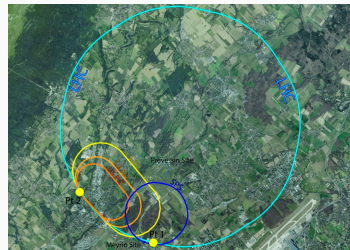
## Past: HERA (1991–2007)

- DESY  $ep$  collider.
- $\sqrt{s} \simeq 318\text{ GeV}$ .
- Low luminosity.
- Existing data provide constraints.



## Future: LHeC (?)

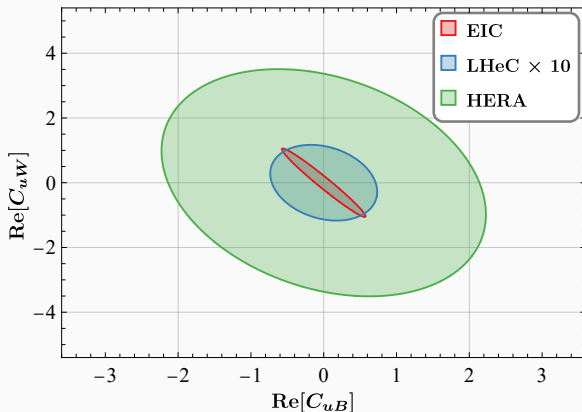
- Proposed  $ep$  collider using the LHC proton beam.
- $\sqrt{s} \sim 1.3\text{ TeV}$  (run 6).
- High energy and luminosity.
- Future uncertain.



HERA and LHeC may also constrain light-quark dipole operators.



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



### Collider Sensitivity:

- **HERA:** High  $Q^2$  coverage but limited by luminosity and lack of polarization.
- **EIC:** Polarization breaks  $\gamma/Z$  degeneracy; high  $\mathcal{L}$  drives precision.
- **LHeC:** Potential to improve bounds by another order of magnitude.

The angular dist. of energy flow lets the EIC linearly probe light-quark dipole operators.

- **Transversity NEC**  $h_1^t$  filters transverse quark polarization from an unpolarized nucleon.
  - Linear interference between the SM and dipole amplitudes reappears at  $\mathcal{O}(\Lambda^{-2})$ .
- $\sin \phi$  and  $\cos \phi$  probe the real (MDM) and imaginary (EDM) parts, respectively.
  - No other SMEFT operators enter at leading order.
- No polarized nucleon beam is required.
  - Inclusive calorimetry avoids particle id. and track reconstruction.
  - EIC precision can compete with traditional BSM probes.

Nucleon energy correlators open a new avenue to BSM searches through energy flow.

**Backup**

We focus on dimension-6 electroweak dipole operators ( $+h.c.$ ):

$$\mathcal{O}_{uB} = (\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}$$

$$\mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}\tau^I u)\tilde{H}W_{\mu\nu}^I$$

$$\mathcal{O}_{dB} = (\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}$$

$$\mathcal{O}_{dW} = (\bar{Q}\sigma^{\mu\nu}\tau^I d)HW_{\mu\nu}^I$$

$Q$ : Left-handed doublet;  $u, d$ : Right-handed singlets,  $\tau^I$ : SU(2) generators.

**Effective couplings after EWSB:**

$$\mathcal{L}_{\text{eff}} \supset \sum_{q=u,d} \bar{q}_L \sigma^{\mu\nu} q_R \left( c_{q\gamma} F_{\mu\nu} + c_{qZ} Z_{\mu\nu} \right) + h.c.$$

The complex coefficients ( $c_{q\gamma}, c_{qZ}$ ) are rotations of SMEFT ( $C_{qB}, C_{qW}$ ):

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

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

## Extended Higgs sectors

Charged/neutral extra scalars and heavy-quark Yukawas enter loop matching.

## Composite Higgs / quarks

Fermion partners/vector resonances coupled through quark compositeness or mixing.

## Vector-like quarks

SM-VLQ mixing with Higgs/electroweak-gauge couplings; heavy-fermion loop matching.

## Scalar leptoquarks

Leptoquark-lepton loops with chiral leptoquark couplings.

## Supersymmetry

Squark-gaugino or squark-higgsino loops, with chirality/flip insertions.

## Heavy scalar + fermion mediators

Generic scalar-fermion one-loop matching topology.

*Representative weakly-coupled loop scaling; not universal:*

$$\frac{C_{qV}}{\Lambda^2} \sim \frac{g_V}{16\pi^2} \frac{\text{coupling products}}{M^2}$$

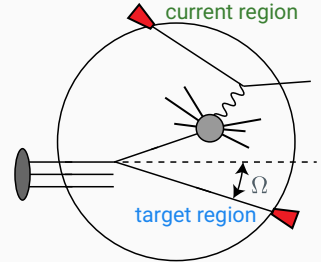
# BACKUP: Nucleon Energy Correlators (NEC)

- Unlike Energy Correlators in the **Current Region**, NECs are defined in the **target fragmentation region (TFR)** and probe the **initial-state nucleon remnant**.
- **Definition:** Probability of finding a quark with momentum fraction  $x$  inside the target, given energy flux at  $(\theta, \phi)$  in the **TFR**.

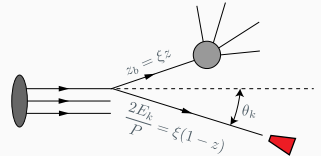
$$\mathcal{M}_{ij}(x, \theta, \phi) = \int \frac{d\eta^-}{2\pi} e^{-ixP^+\eta^-} \langle PS | \bar{\psi}_j(\eta^-) \mathcal{L}_n^\dagger(\eta^-) \mathcal{E}(\theta, \phi) \mathcal{L}_n(0) \psi_i(0) | PS \rangle ,$$

where the *Energy Flow Operator*  $\mathcal{E}$  follows

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



Geometry: target vs current region



Energy flux from target remnants measured in forward calorimeters

The diagram illustrates the NNPDF2.1 NN architecture. It shows the flow from input variables  $(x, \theta, \phi, S)$  through a series of neural network layers to produce the final NN output. The layers are represented by colored boxes:

- Input Layer (Orange):**  $\mathcal{M}^{[i\sigma^{\alpha+}\gamma_5]}(x, \theta, \phi, S)$ . An arrow labeled "trans. quark" points to this layer.
- First Hidden Layer (Blue):**  $S_T^\alpha h_1(x, \theta)$ . An arrow labeled "trans. proton" points to this layer.
- Second Hidden Layer (Green):**  $\frac{S_L \mathbf{n}_t^\alpha}{|\mathbf{n}_t|} h_{1L}^t(x, \theta)$ . An arrow labeled "long. proton" points to this layer.
- Third Hidden Layer (Blue):**  $-\left(\frac{g_T^{\alpha\rho}}{2} + \frac{\mathbf{n}_t^\alpha \mathbf{n}_t^\rho}{|\mathbf{n}_t|^2}\right) S_{T\rho} h_{1T}^t(x, \theta)$ . An arrow labeled "trans. proton (pretzelosity)" points to this layer.
- Output Layer (Purple):**  $+\frac{\epsilon_\perp^{\alpha\rho} \mathbf{n}_{t,\rho}}{|\mathbf{n}_t|} h_1^t(x, \theta)$ . An arrow labeled "unpol. proton" points to this layer.

The final NN output is the sum of the outputs from the first and third hidden layers, and the output from the output layer.



How does an unpolarized nucleon provide polarized quarks?

- **Decomposition:** The quark correlator  $\mathcal{M}_{ij}$  contains a chiral-odd term:

$$\mathcal{M}^{[\Gamma_\perp^\alpha]} = \frac{1}{2} \text{Tr} [(i\sigma^{\alpha\perp} + \gamma_5) \mathcal{M}]$$

- **Spin Projector:** This operator projects onto transverse spin states along direction  $\alpha_\perp$ :

$$i\sigma^{\alpha\perp} + \gamma_5 = \gamma^+ \left( \underbrace{\mathcal{Q}_+^\alpha}_{\text{Spin } \uparrow} - \underbrace{\mathcal{Q}_-^\alpha}_{\text{Spin } \downarrow} \right)$$

where  $\mathcal{Q}_\pm^\alpha = \frac{1}{2}(1 \mp \gamma^5 \gamma_\perp^\alpha)$  selects quarks with spin  $\parallel$  or anti- $\parallel$  to the transverse vector  $\alpha_\perp$ .



## How does an unpolarized nucleon provide polarized quarks?

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$$\mathcal{M}^{[\Gamma_\perp^\alpha]} = \frac{1}{2} \text{Tr} [(i\sigma^{\alpha\perp} + \gamma_5) \mathcal{M}]$$

- **Symmetry Argument:** In an unpolarized nucleon, the *only* transverse reference vector is the energy flow direction  $\hat{n}_T = (\cos \phi, \sin \phi)$ .
- **Form Factor:** Rotational invariance dictates the structure:

$$\mathcal{M}^{[\Gamma_\perp^\alpha]} \propto \epsilon_\perp^{\alpha\beta} \hat{n}_{T,\beta} h_1^t(x, \theta^2)$$

- **Mechanism:** Selecting an energy flow direction  $\phi$  breaks rotational symmetry and "filters" the quark bath, preferentially selecting quarks with transverse spin correlated with  $\phi$ .

## Factorization of the **energy pattern** cross section

- General NEC:

$$\frac{d\Sigma(\theta, \phi)}{dx_B dQ^2} \propto \int_{x_B}^1 \frac{dx}{x} L_{\mu\nu}(l, l') \mathcal{H}_{ji}^{\mu\nu}\left(\frac{x_B}{x}\right) \delta\left(1 - \frac{x_B}{x}\right) \mathcal{M}_{ij}(x, \theta, \phi)$$

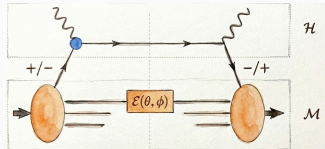
- Transversity NEC:

$$\frac{d\Sigma}{dx_B dQ^2} \propto L_{\mu\nu} \text{Tr} \left[ \mathcal{H}^{\mu\nu} i\sigma^{-\alpha} \gamma_5 \right] \epsilon_{\perp}^{\alpha\beta} \hat{n}_{T\beta} h_1^t(x_B, \theta^2)$$

## Coupling of $h_1^t$ with dipole-SM interference

$$d\Sigma \propto \left[ C_1 \sin \phi + C_2 \cos \phi \right] h_1^t(x_B, \theta^2)$$

$C_1$ :  $\text{Re}(c_{qZ/\gamma})$   $C_2$ :  $\text{Im}(c_{qZ/\gamma})$   $h_1^t$ : transversity NEC



## SM Background:

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

## SMEFT Signal (Interference):

$$\begin{aligned} \frac{d\Sigma_{UU}^{\sin\phi}}{dx_B dQ^2} = & \frac{4\pi\alpha_{\text{em}}^2}{ec_W s_W} \frac{y\sqrt{1-y}}{Q(Q^2 + m_Z^2)} \sum_q h_1^{t,q}(x_B, \theta^2) \left\{ \left[ \frac{2-y}{y} g_A^q g_V^e + g_V^q g_A^e \right] \frac{\text{Re}[c_{q\gamma}]}{c_W s_W} - Q_q g_A^e \text{Re}[c_{qZ}] \right. \\ & \left. + \frac{1}{(c_W s_W)^2} \frac{Q^2}{Q^2 + m_Z^2} \left[ \frac{2-y}{y} [(g_A^e)^2 + (g_V^e)^2] g_A^q + 2g_A^e g_V^e g_V^q \right] \text{Re}[c_{qZ}] \right\} \end{aligned}$$

## Beam and phase space

- **CM energy:**  $\sqrt{s} = 105$  GeV.
- **Luminosity:**  $\mathcal{L} = 100 \text{ fb}^{-1}$ .
- $Q \in [10, 60]$  GeV,  $x \in [0.01, 0.5]$ .
- Inelasticity cut:  $0.1 \leq y \leq 0.9$ .
- TMD moment range:

$$k_{\perp}^{\min} \sim E_{\min} \theta_{\min}, \quad k_{\perp}^{\max} \sim Q \theta_{\max},$$

implemented as  $k_{\perp} \in [0, 5]$  GeV.

## Statistical sensitivity

$$\delta A \simeq \frac{\pi}{2\sqrt{\mathcal{E}_{\text{total}}}}, \quad \mathcal{E}_{\text{total}} = [\Sigma(u > 0) + \Sigma(u < 0)]\mathcal{L}.$$

Limits follow from

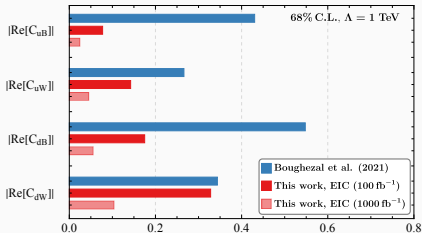
$$\chi^2 = \sum_i \left[ \frac{A_{\text{th},i} - A_{\text{exp},i}}{\delta A_i} \right]^2.$$

## Observables

1.  $A_{UU}^{\sin \phi}$ : unpolarized  $e^-$  and  $p$ .
2.  $A_{LU}^{\sin \phi}$ :  $P_e = 70\%$  and unpolarized  $p$ .

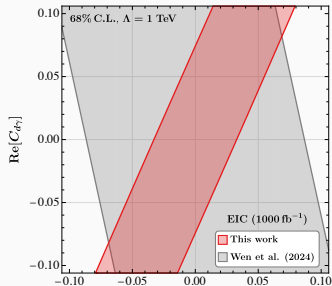
## vs. LHC Drell-Yan ( $pp \rightarrow Z/\gamma^* \rightarrow \ell\ell$ )

- DY: Dipole effects at  $\mathcal{O}(\Lambda^{-4})$  (squared)  $\Rightarrow$  weaker bounds despite higher energy.
- Contamination from other dim-6/8 operators.
- Cannot resolve complex phase.
- **NEC Advantage:** Leading  $\mathcal{O}(\Lambda^{-2})$  contrib., clean separation of Re/Im.



## vs. EIC Dihadron ( $ep \rightarrow e(h_1 h_2)X$ )

- Relies on interference in dihadron fragmentation.
- Requires particle ID and tracking.
- **NEC Advantage:** Simpler inclusive calorimetric measurement;  $\sim 10\times$  better sensitivity (for same lumi).



## Input Dependence:

- Input: Boer-Mulders TMD  $h_1^\perp$ .
- Comparison of 3 fits: Barone et al. (default), Christova et al., Zhang et al.
- Result: Constraints are robust against fit choice.
- Reason: Observable sensitive to  $k_\perp$ -weighted moment, integrating out local shape differences.

