



Nucleon energy correlators as a probe of light-quark dipole operators at the EIC

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In collaboration with Yingsheng Huang and Xuan-Bo Tong
arxiv: 2508.08516



Energy correlator

- One of the very first event-shape observable:

Basham et al., 1978

Energy correlator observables are
infrared & collinear safe

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

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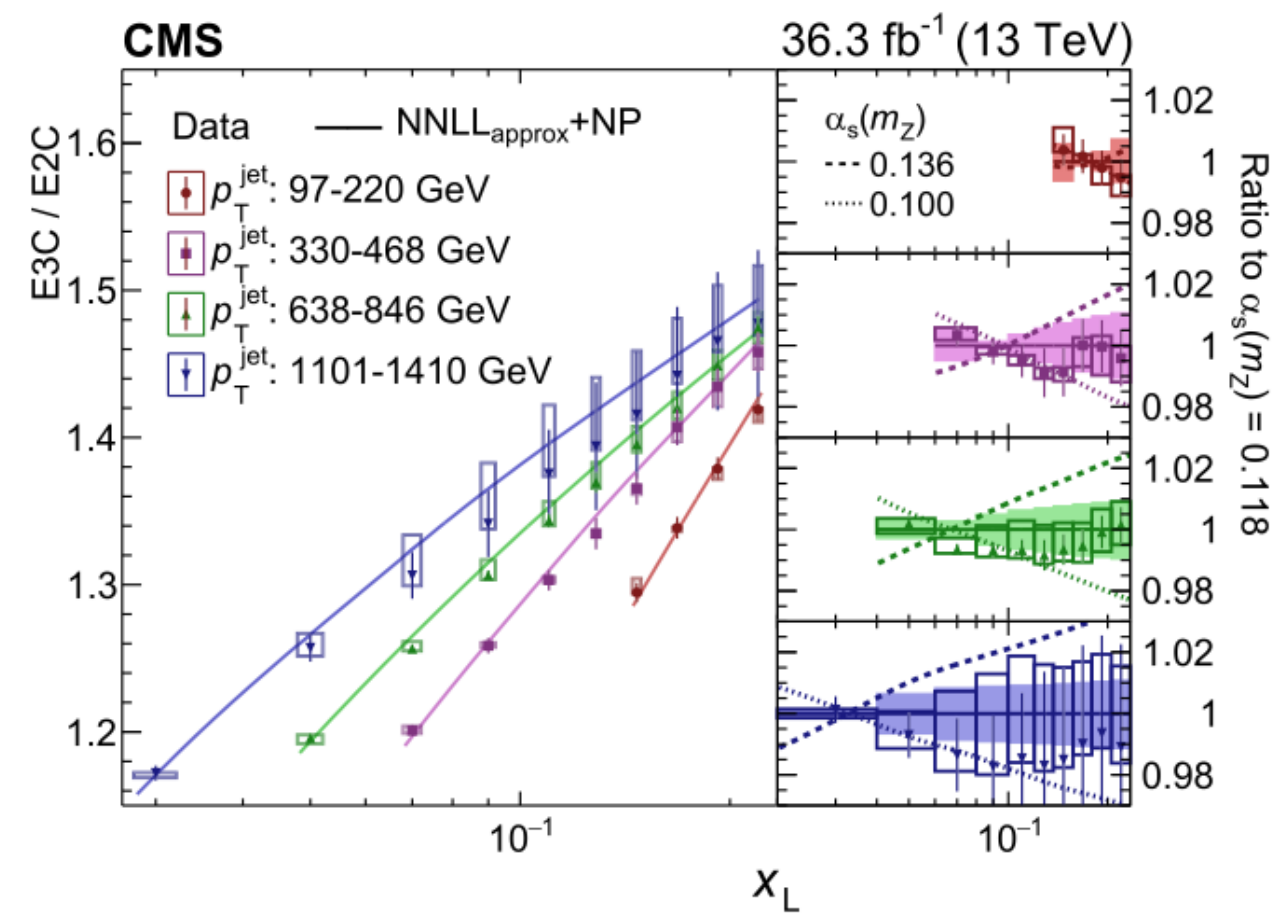


- ✓ α_s extraction by the scaling behavior

$$E3C/E2C \propto \theta^{\gamma(4)-\gamma(3)} \sim \alpha_s(Q) \ln \theta$$

Chen et al., 2020
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$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$



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- Weighing the top quark

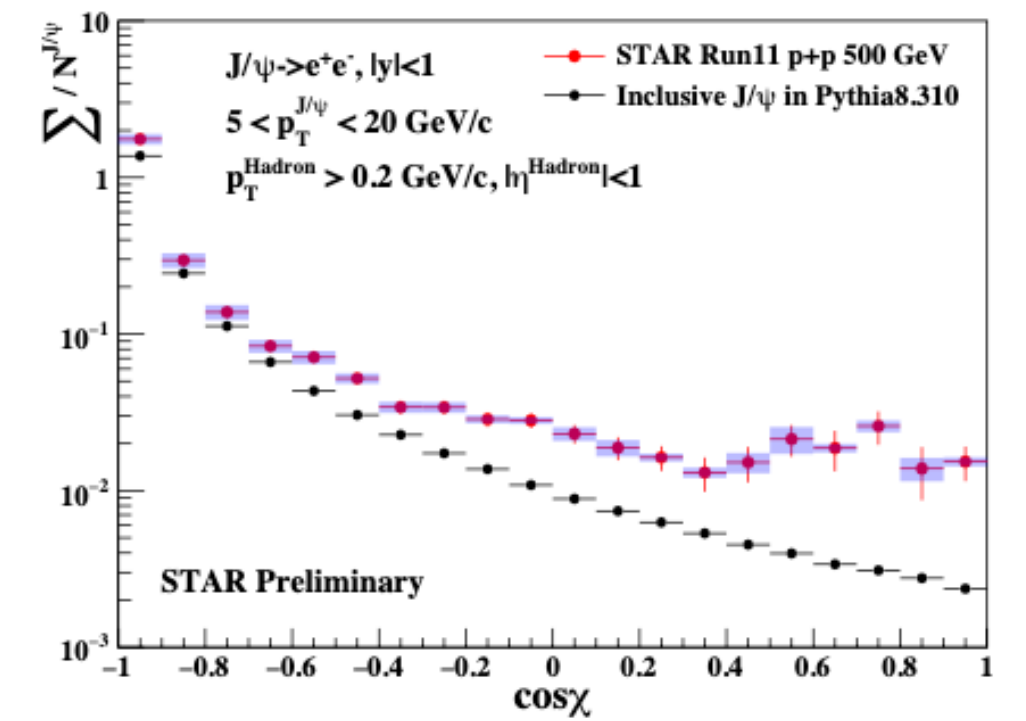
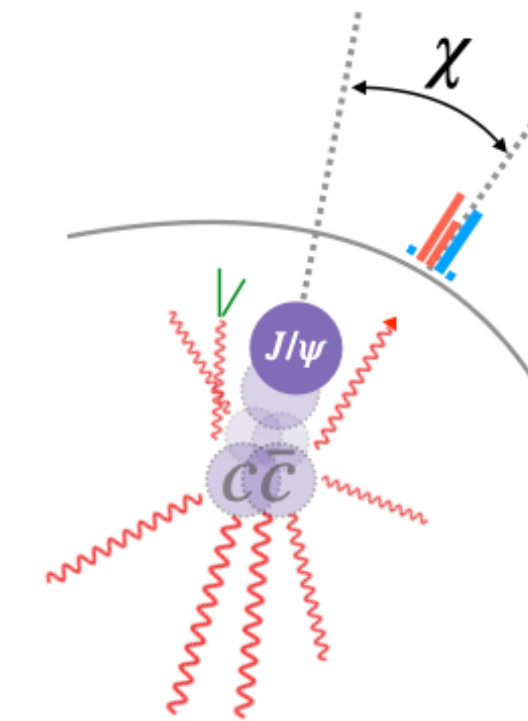
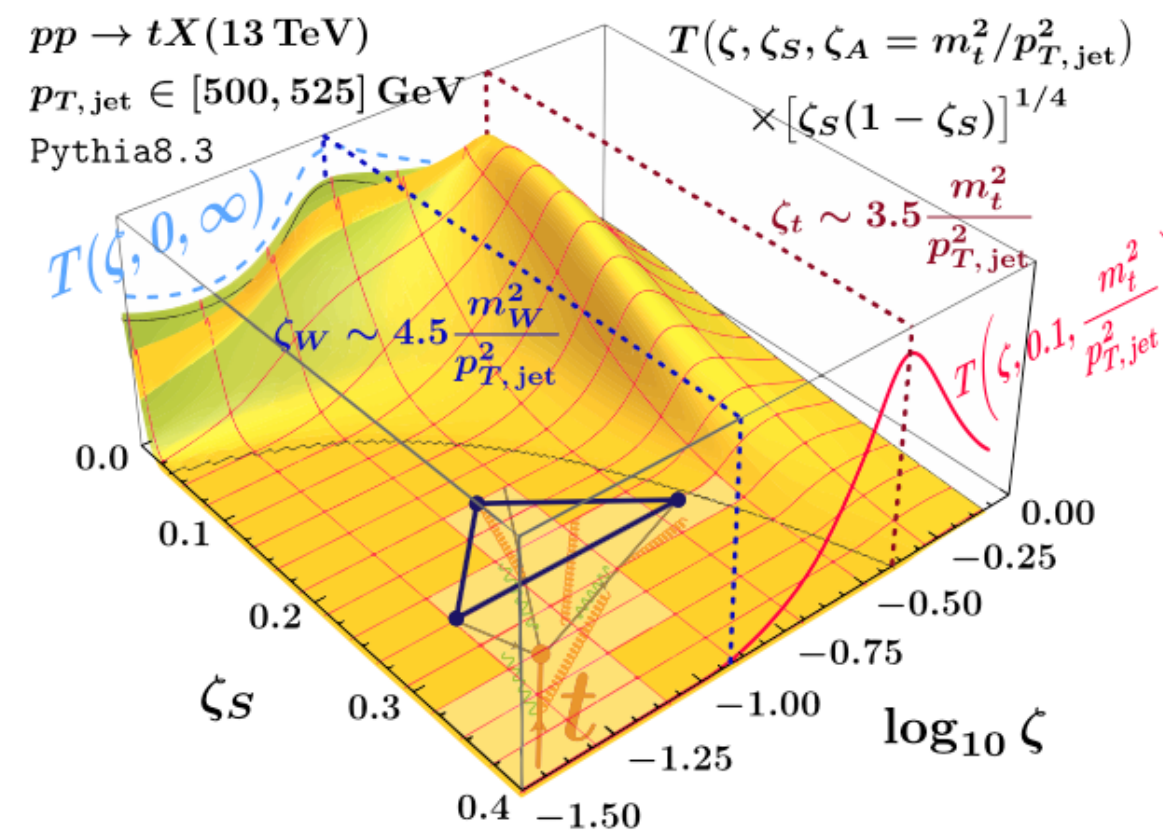
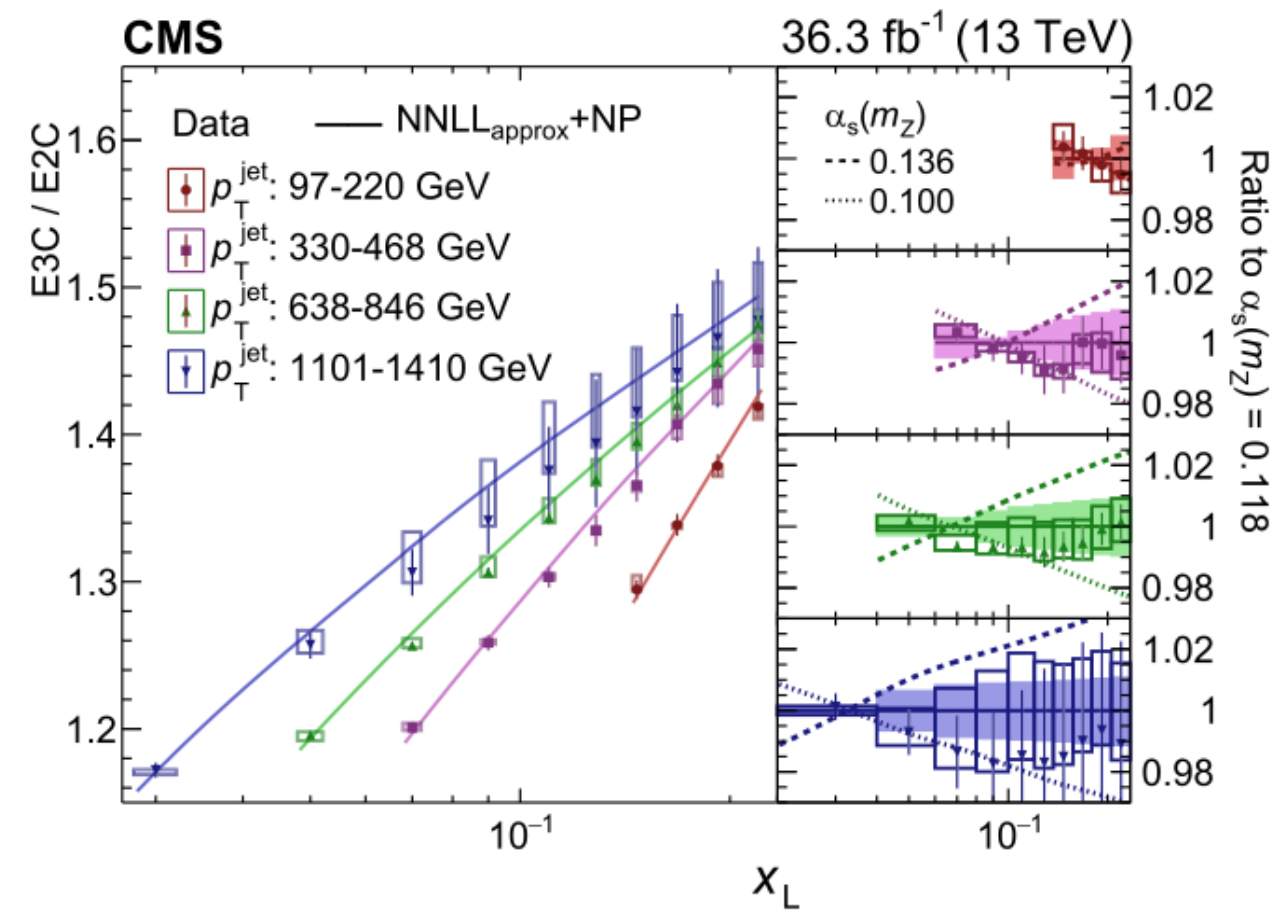
Holguin et al., 2022, 2023, 2024

Xiao et al., 2024

- Quarkonium dynamics

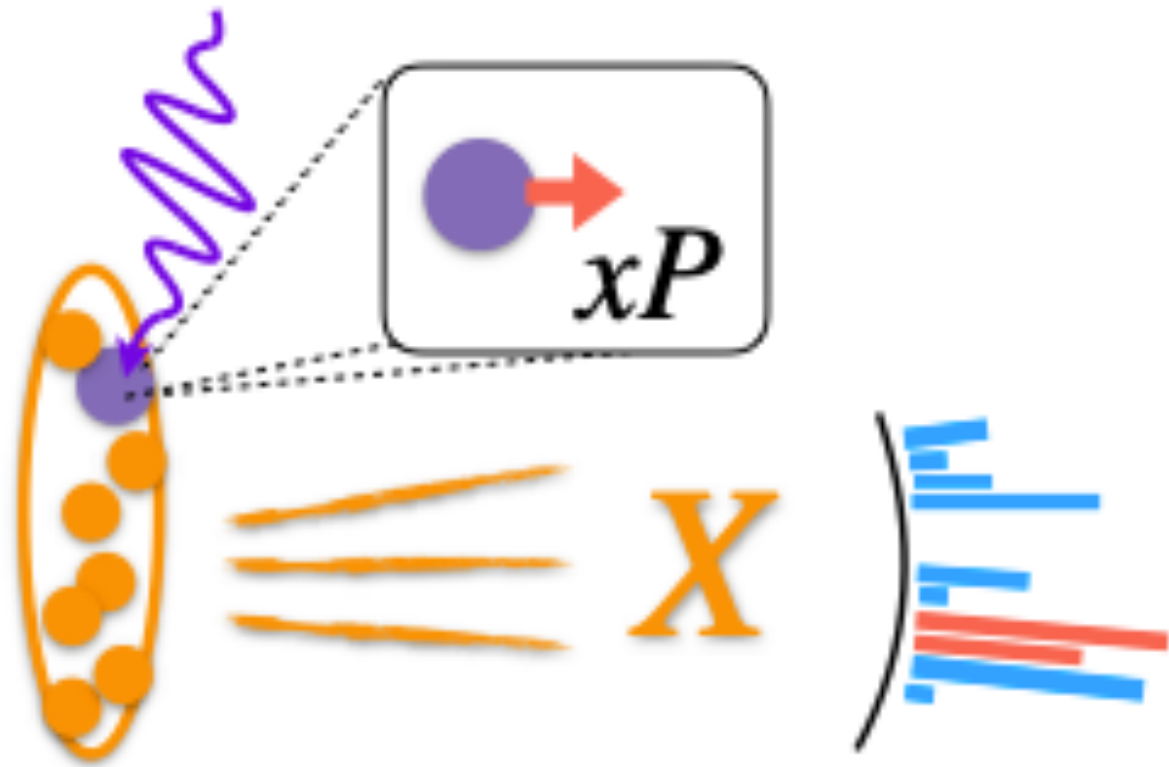
Chen et al., 2024

Shen, STAR



For more examples, see the review: [Moult, and Zhu, 2506.09119](#)

Nucleon energy correlator (NEC)

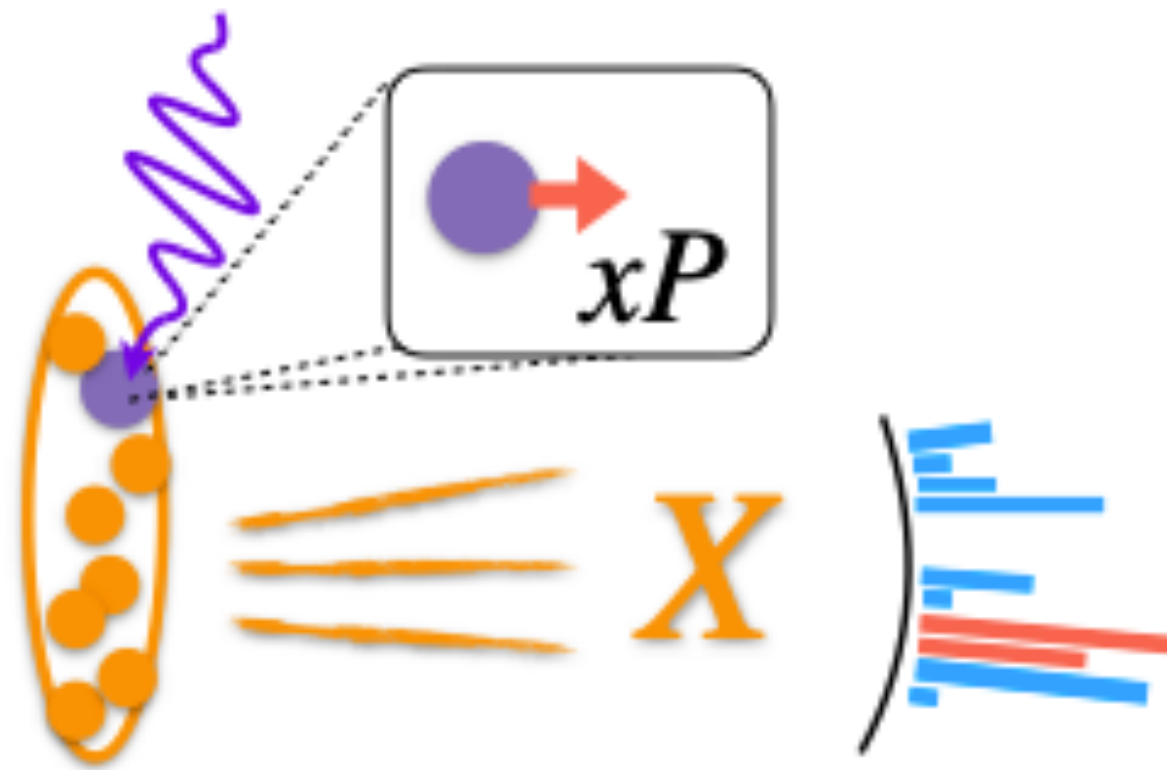


- Proposed as a powerful tool for nucleon tomography by measuring the energy flow in the target fragmentation region (TFR)

[Liu and Zhu, PRL 2023](#)

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Like EECs, NECs also have many powerful applications

- Observing gluon saturation and measuring the saturation scale

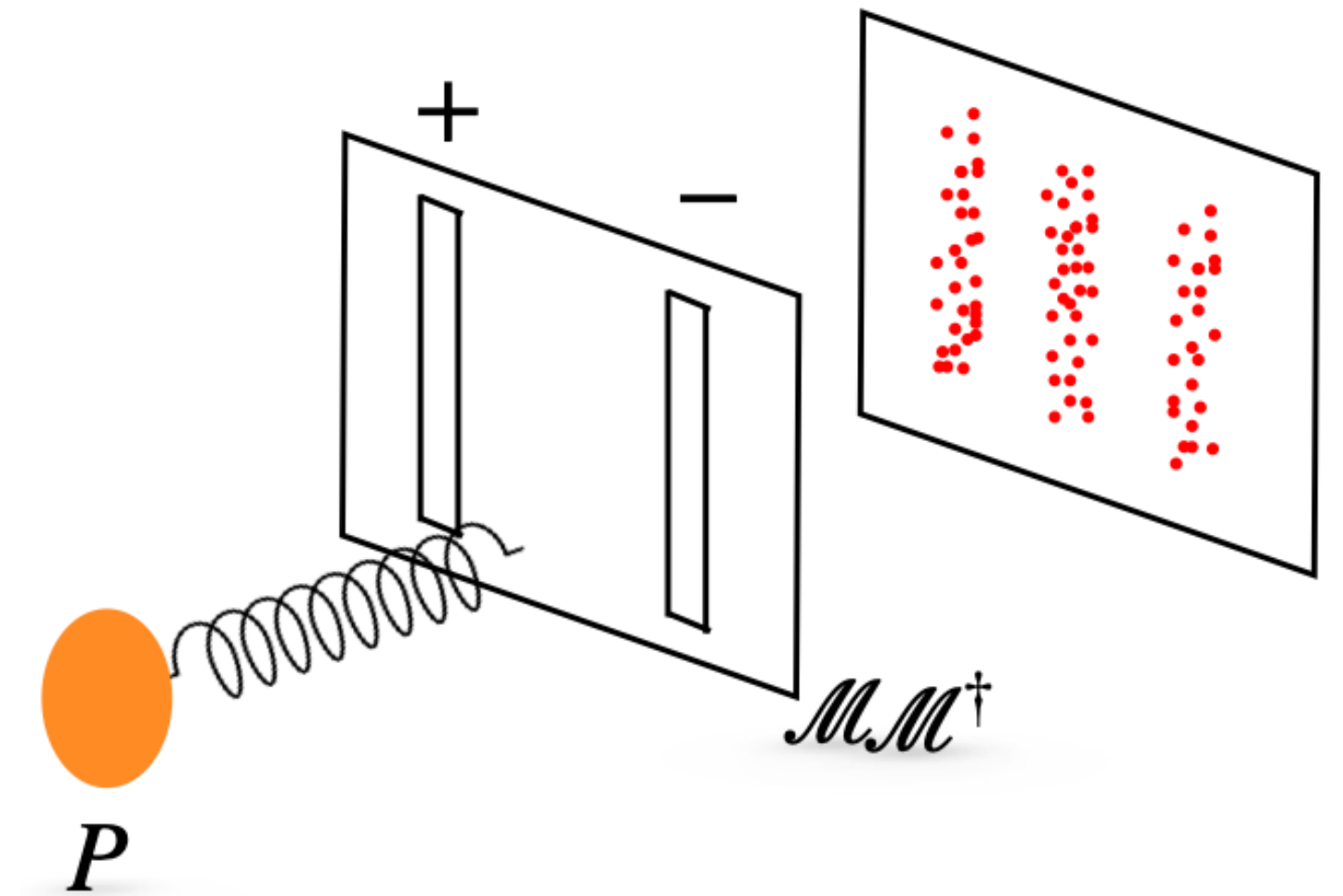
[Liu, Liu, Pan, Yuan, and Zhu, PRL 2023](#)

- As a tool to hunt for the spin dependent odderon in DIS

[Mantysaari, Tawabutr, and Tong, 2503.20157](#)

- A polarimeter for gluon linear polarization

[Li, Liu, Yuan, and Zhu PRD, 2025](#)



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In SMEFT framework

$$\begin{aligned}\mathcal{O}_{eW} &= (\bar{L}\sigma^{\mu\nu}e)\tau^I\tilde{H}W_{\mu\nu}^I \\ \mathcal{O}_{eB} &= (\bar{L}\sigma^{\mu\nu}e)\tilde{H}B_{\mu\nu}\end{aligned}$$

Dim-6: $C_i \sim 1/\Lambda^2$

Dipole operators

Chirality-flipping for fermions

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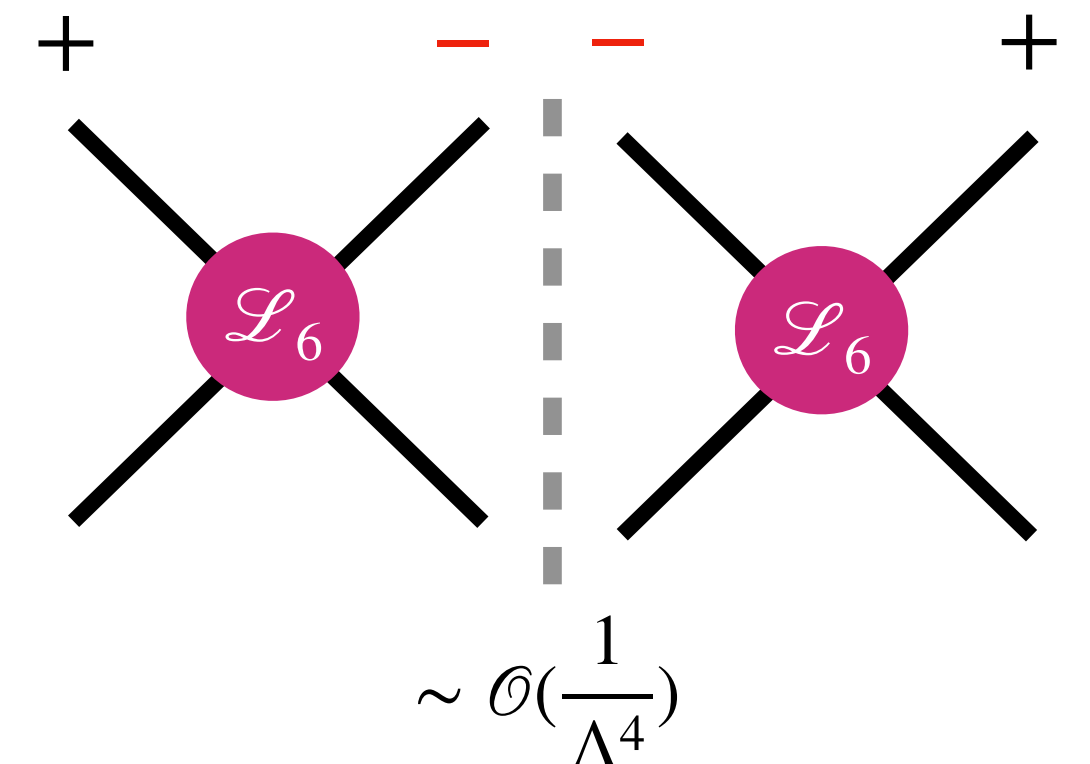
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- Essential for understanding anomalous magnetic moments and P, T violating electric dipole moments of baryons
- The dipole operators are usually quadratically suppressed in unpolarized xsec, and polluted by dim-8 operators



Transverse SSAs for light-quark dipole operators

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

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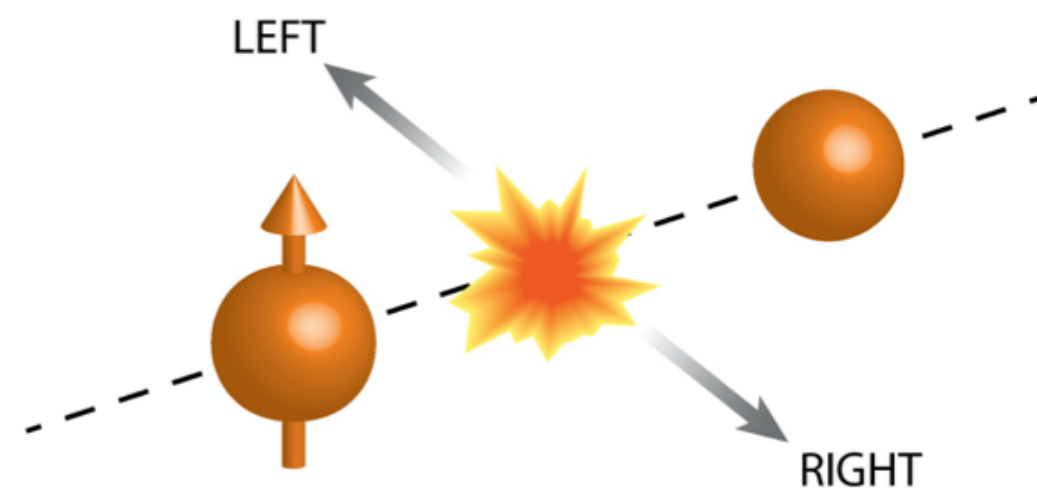
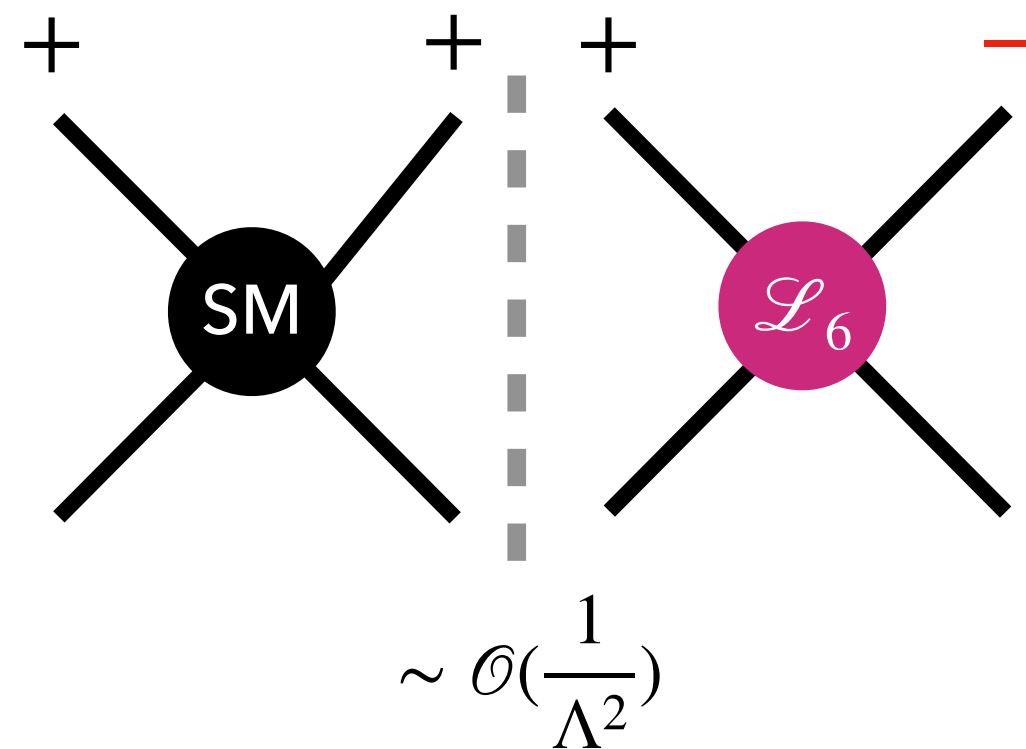
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- Polarized protons

[Boughezal, Florian, Petriello and Vogelsang, PRD 2023](#)

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



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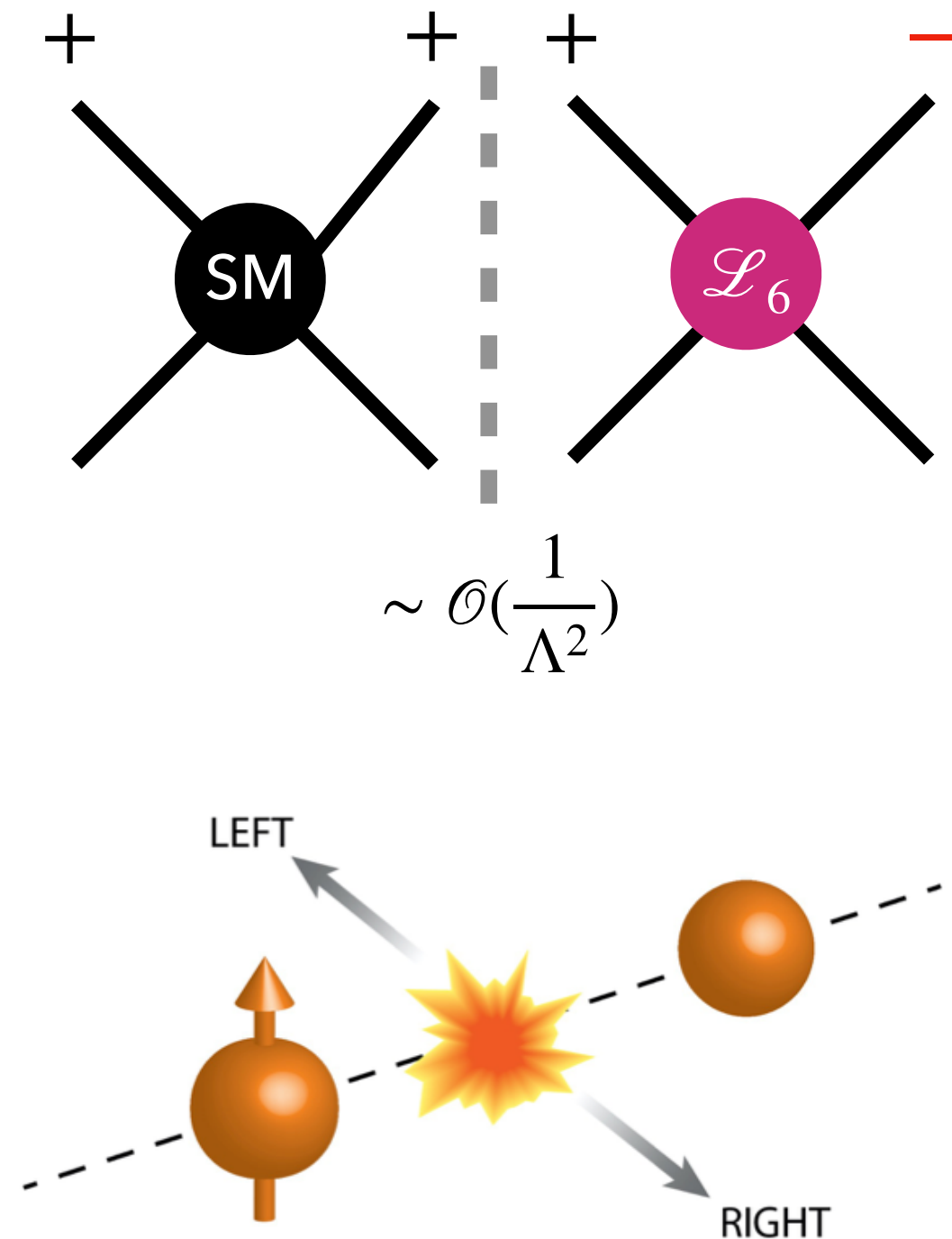
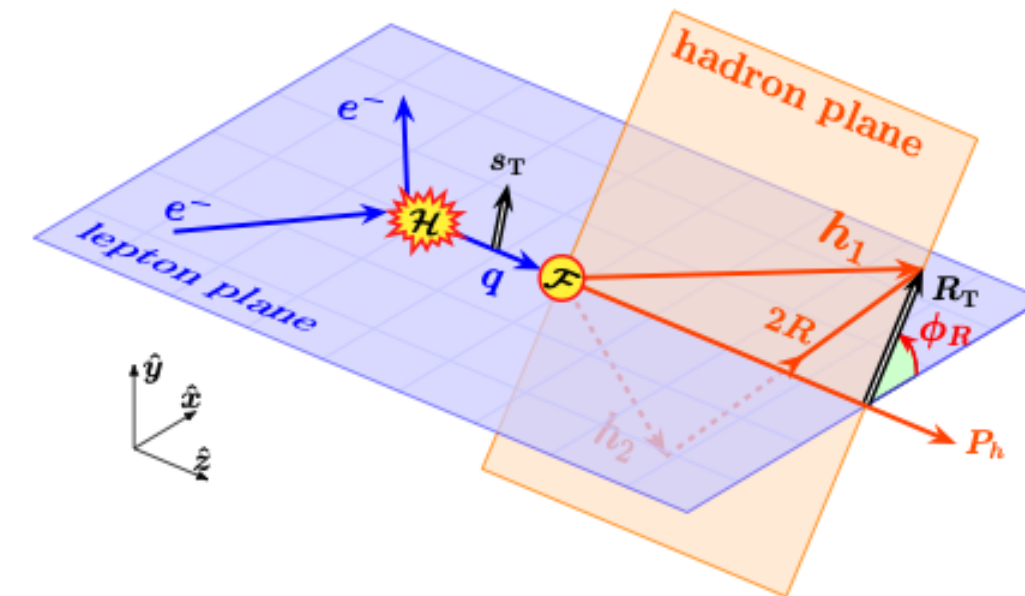
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Wen, Yan, Yu and Yuan, 2408.07255

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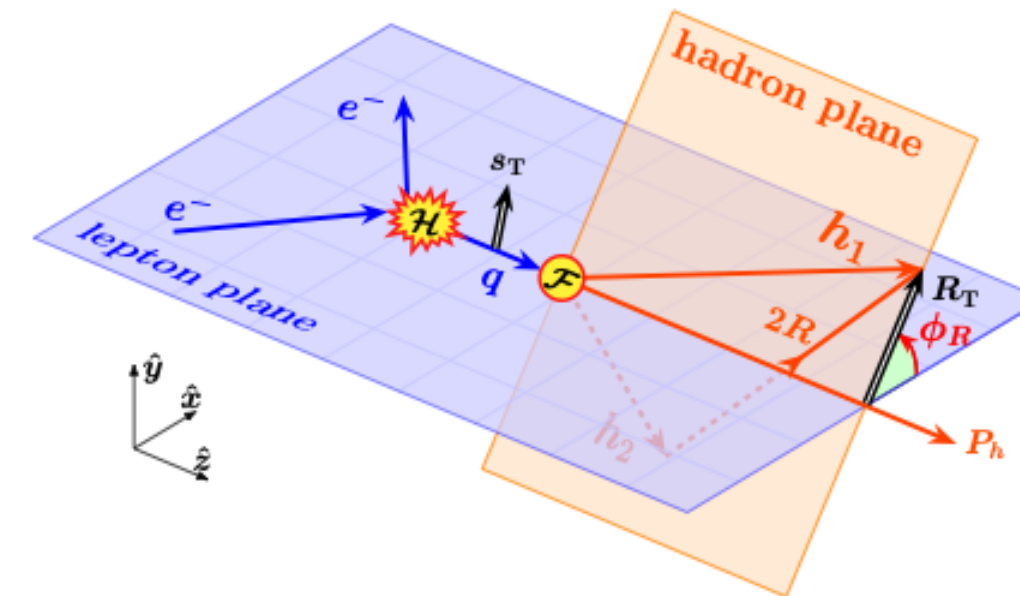
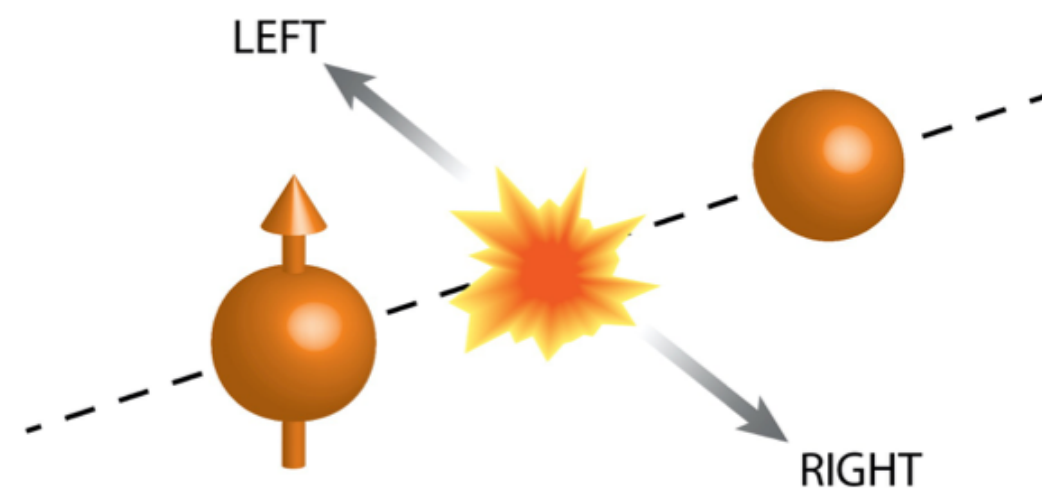
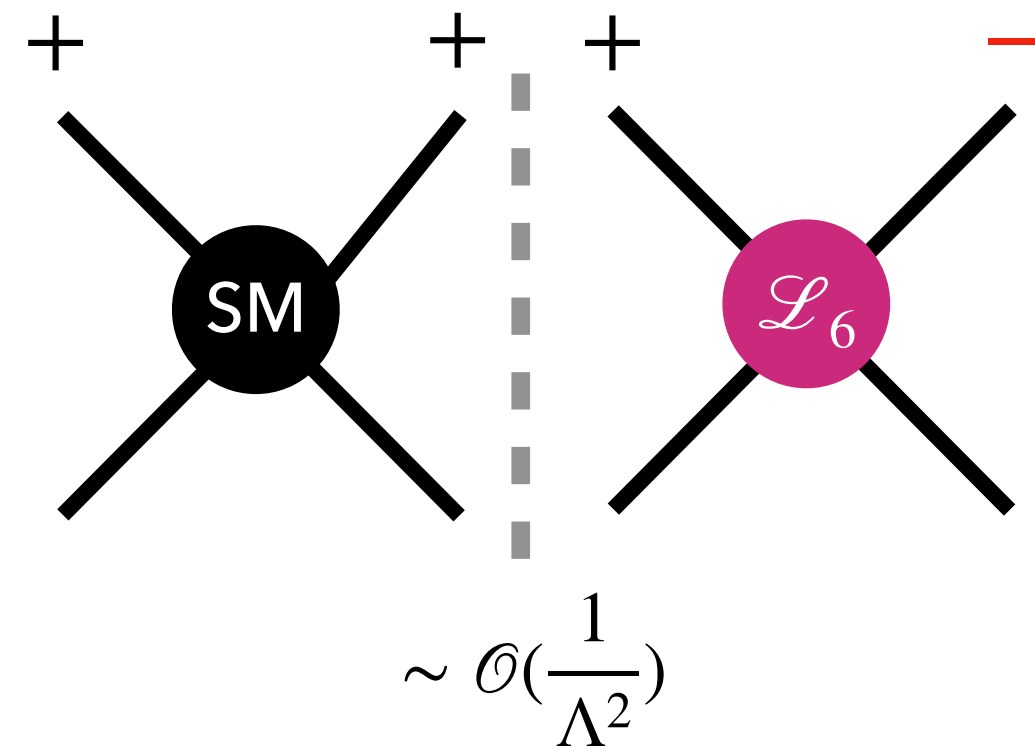
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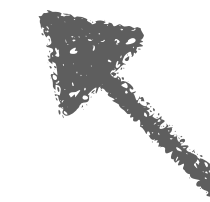
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Transversity PDF

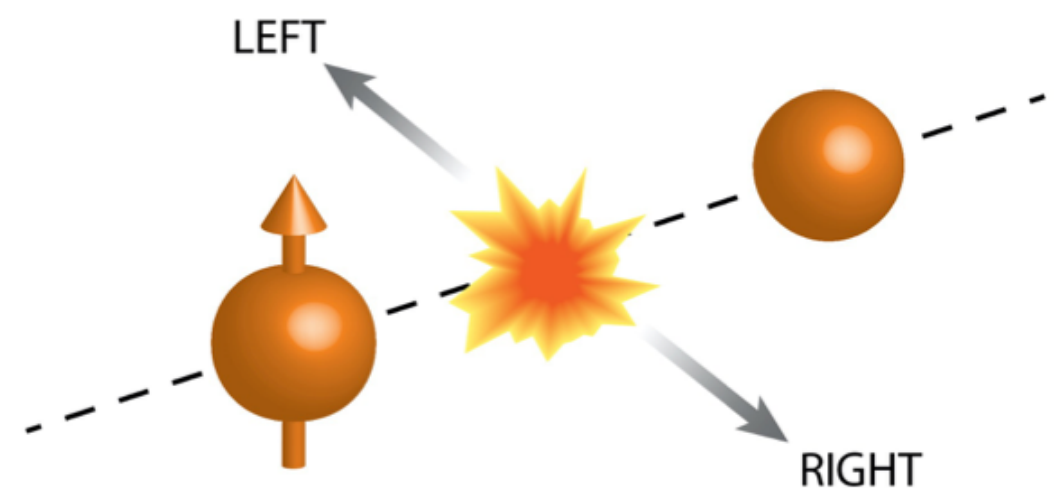
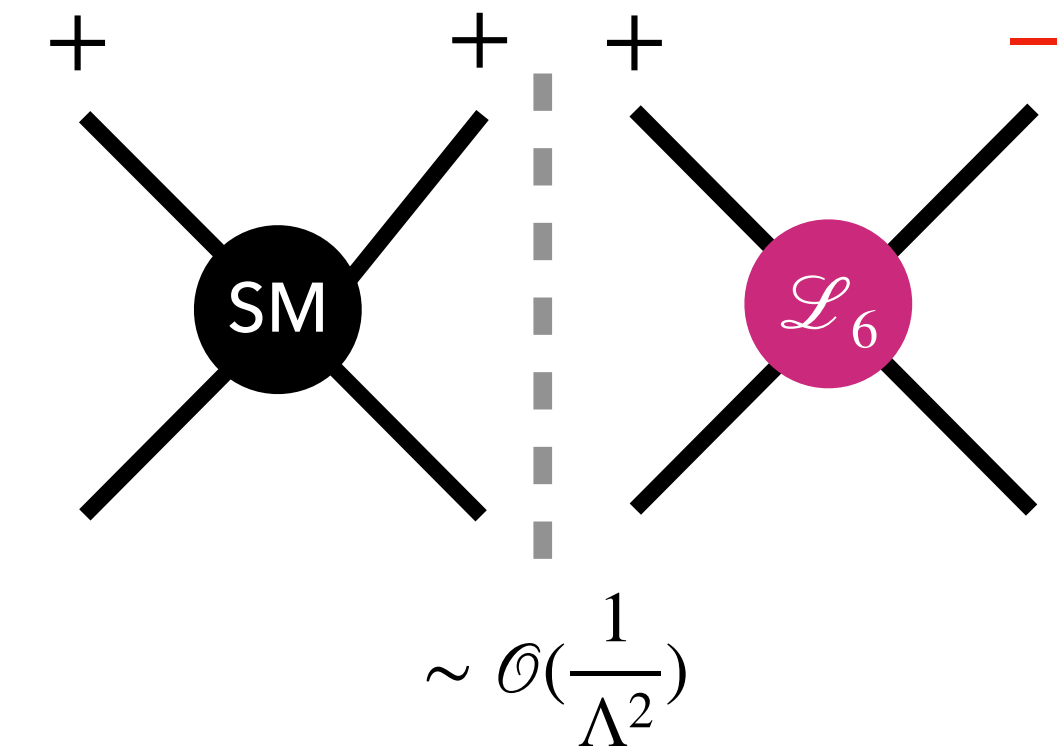
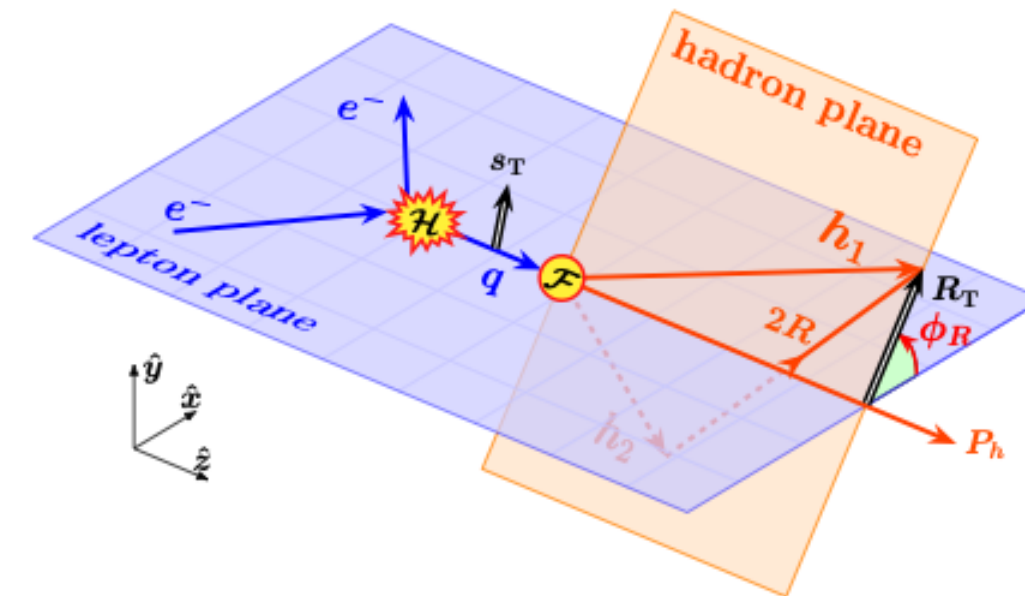


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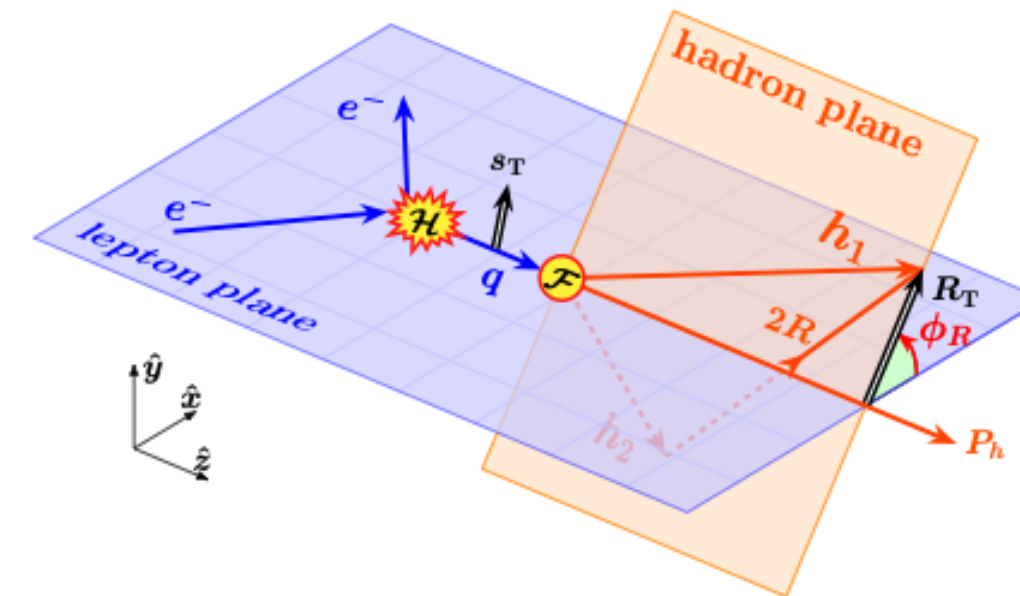
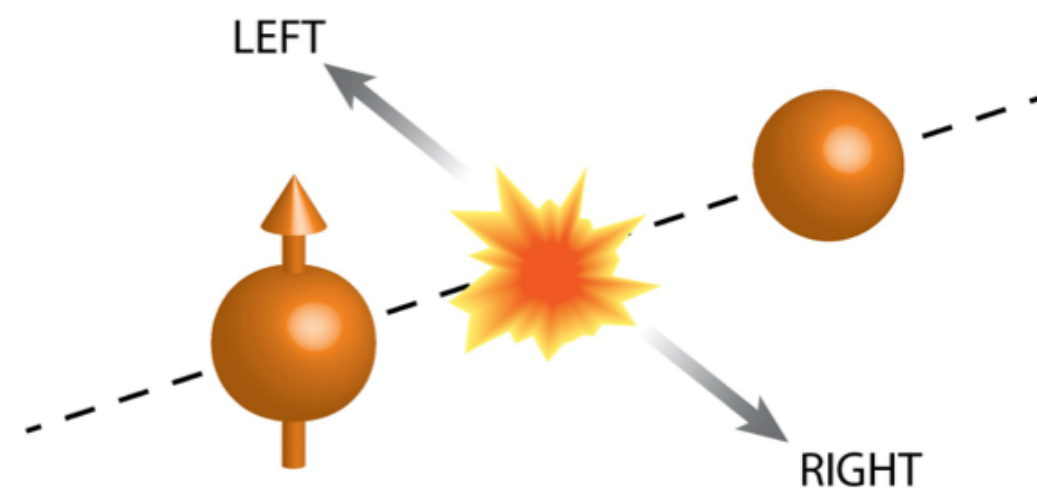
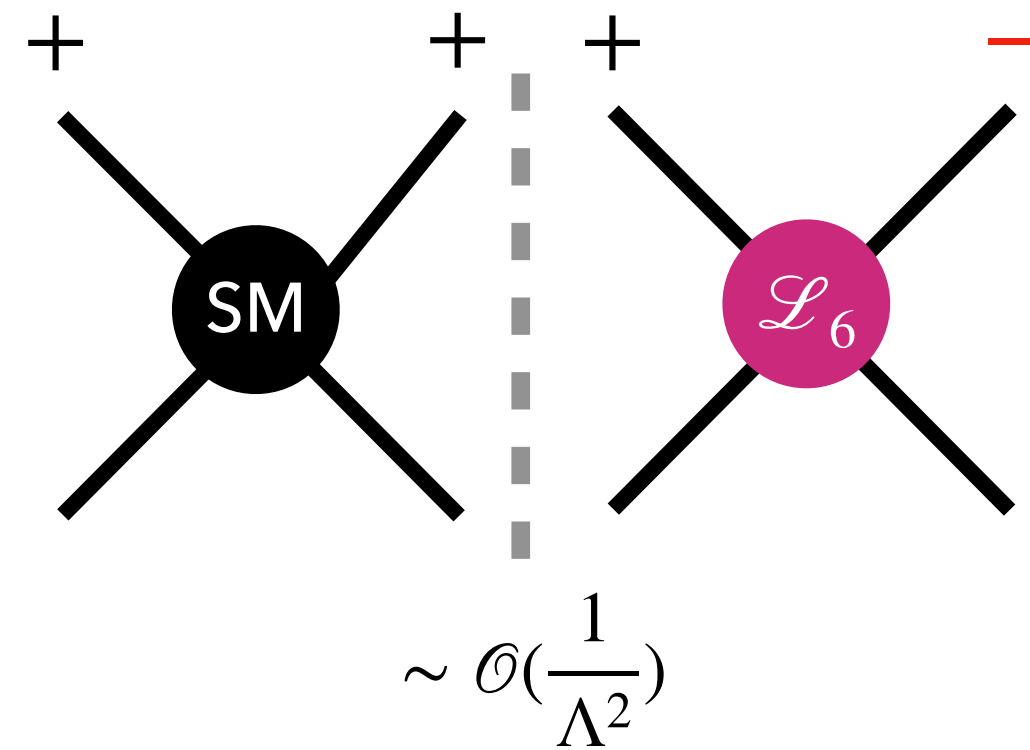
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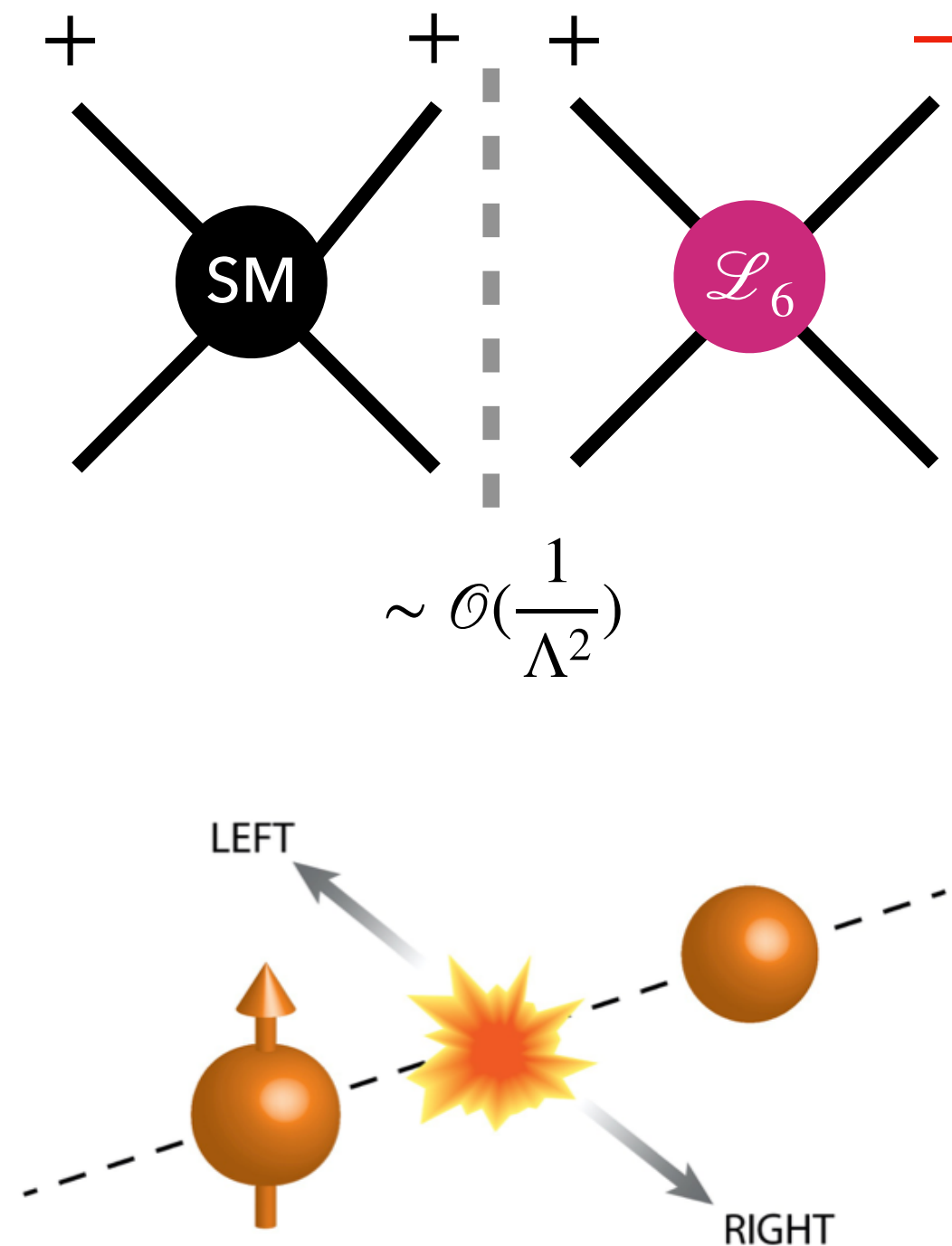
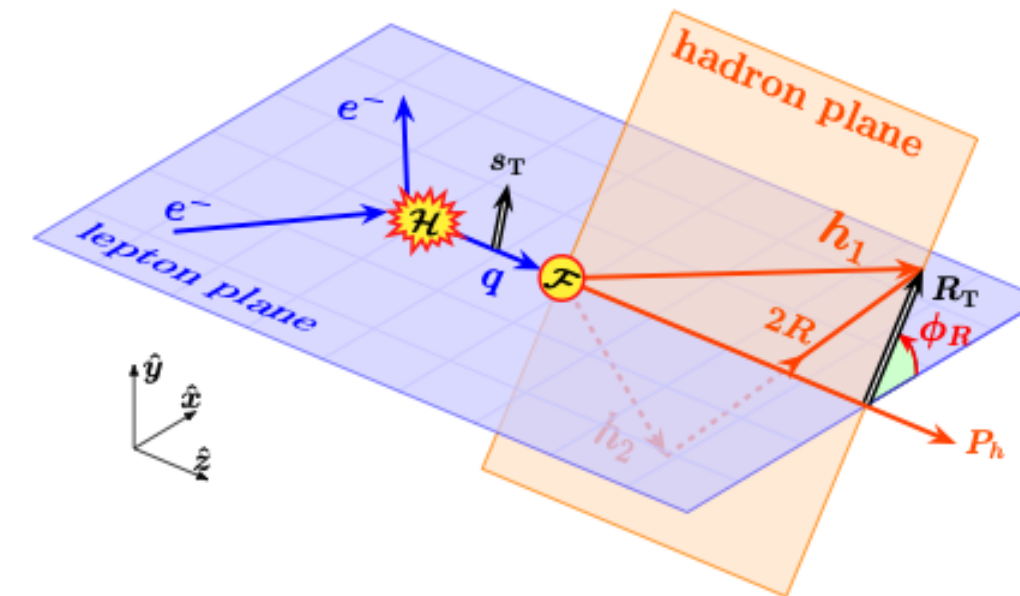
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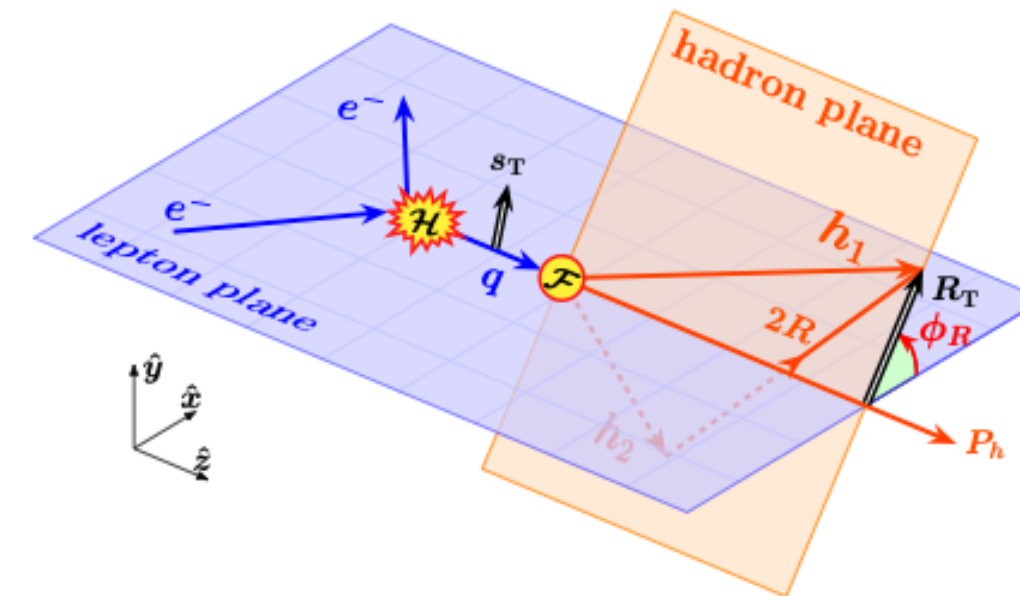
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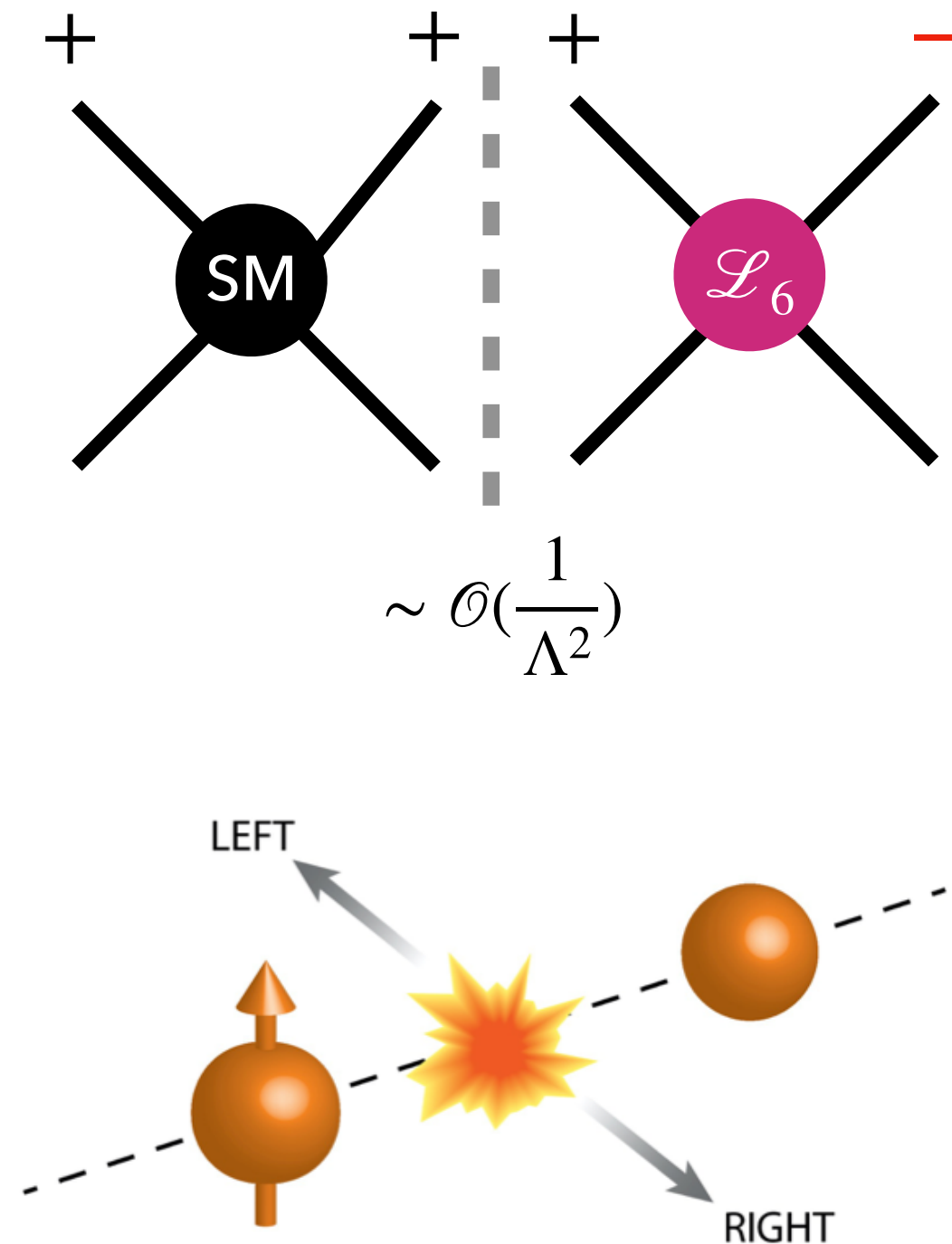
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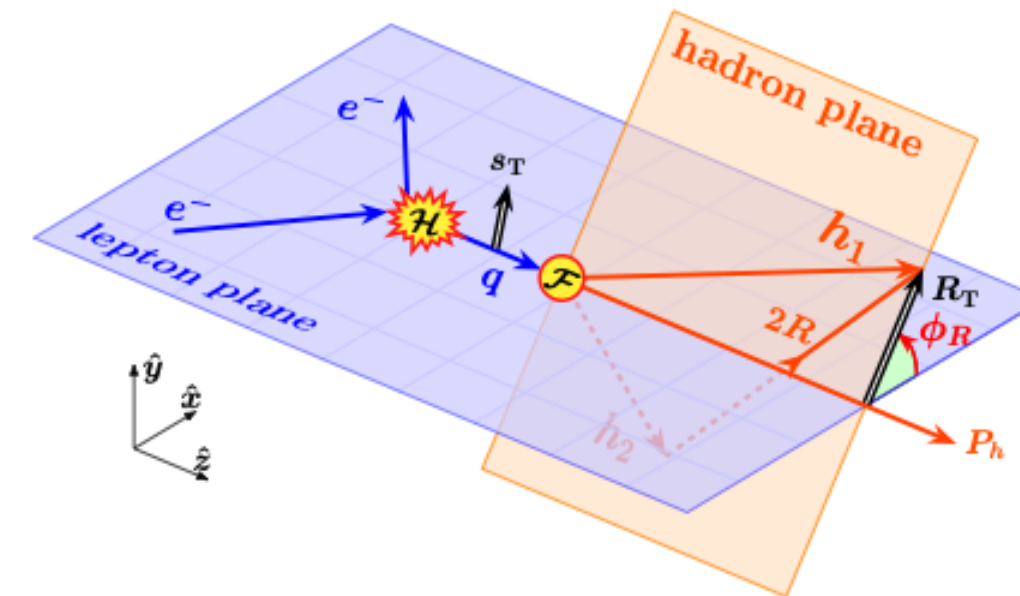
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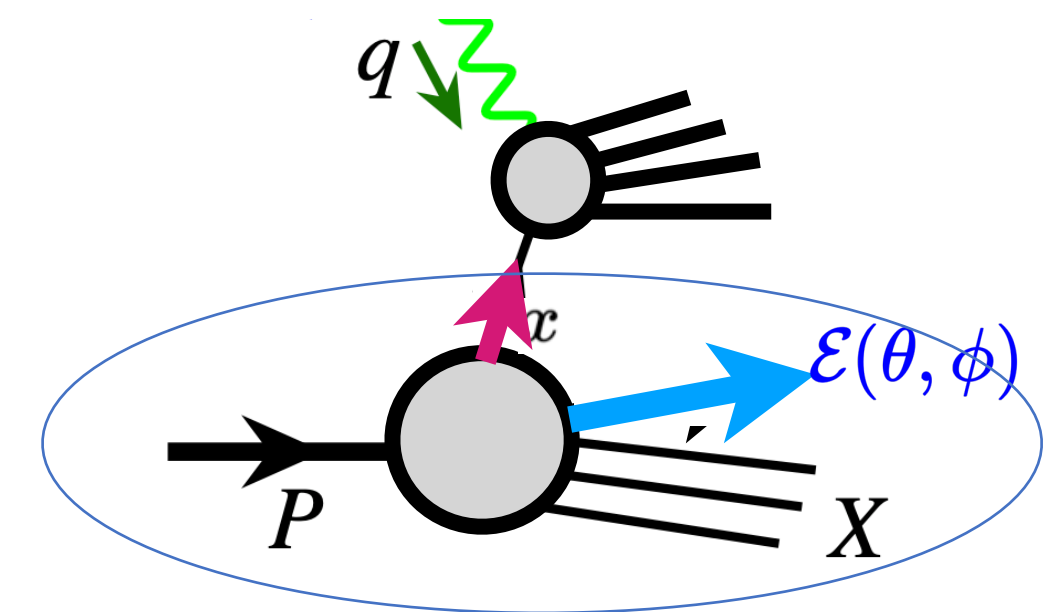
NEC combines the best of the two!

Quark transversity NEC

- Operator definition for quark NECs:

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

The conditional probability of **finding a quark with x** inside the target nucleon, while observing **an energy flux at the solid angle (θ, ϕ)** in the TFR



Quark transversity NEC

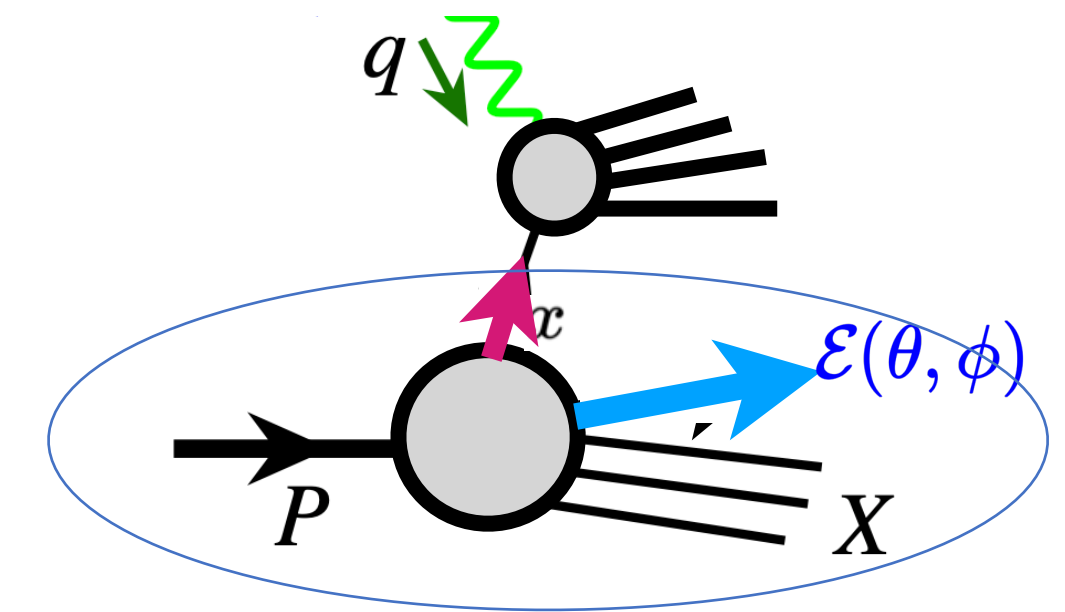
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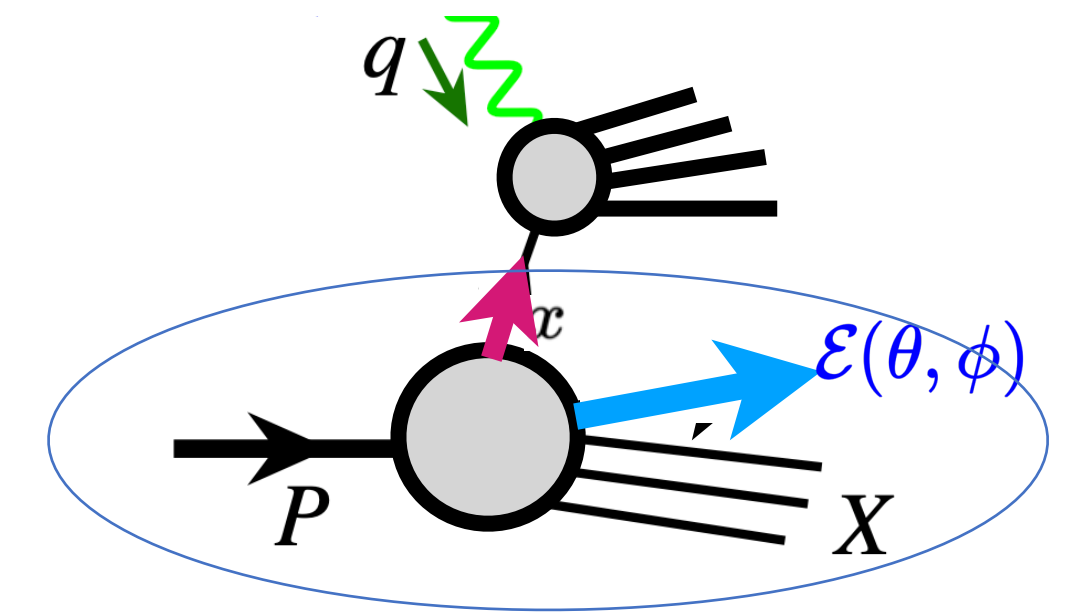
- The leading-twist **chiral-even** unpolarized quark NEC ($\Gamma = \gamma^+$):

See more in [Chen-Ma-Tong, JHEP 2024](#)

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

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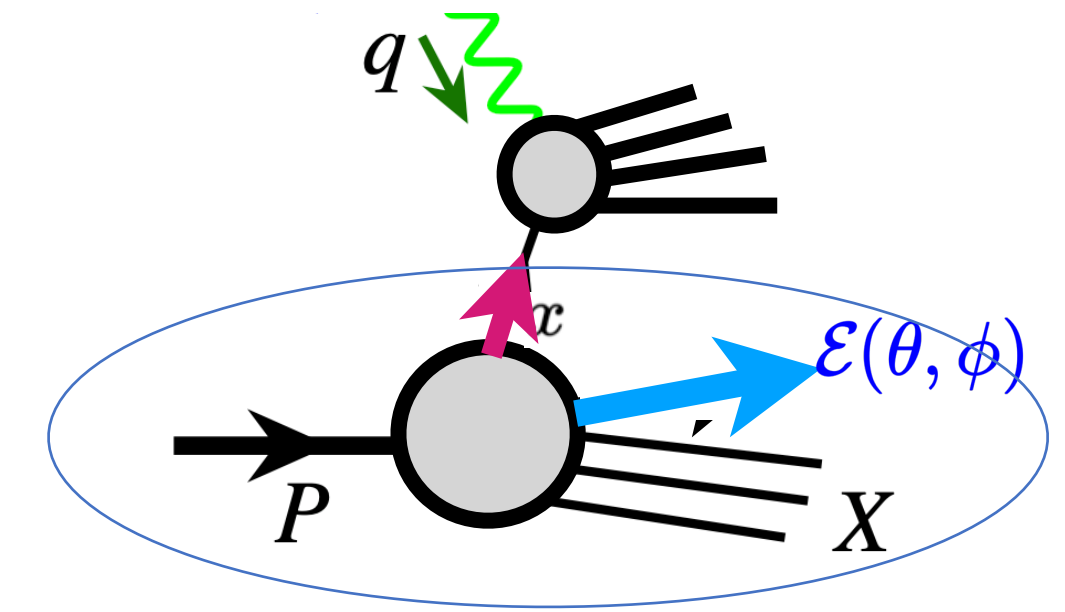
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The conditional probability of **finding a quark with x** inside the target nucleon, while observing **an energy flux at the solid angle (θ, ϕ)** in the TFR



- The leading-twist **chiral-even** unpolarized quark NEC ($\Gamma = \gamma^+$):

See more in [Chen-Ma-Tong, JHEP 2024](#) $f_1^q(x, \theta^2) = \mathcal{M}^{[\gamma^+]}(x, \theta, \phi)$

- We introduce the **chiral-odd** quark NEC ($\Gamma^\alpha = i\sigma^{\alpha+}\gamma_5$, $\alpha = 1, 2$) **in the unpolarized nucleon**:

azimuthal angular correlation of energy flux

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

Difference in probability of finding a quark polarized along the transverse direction of the energy flow vs in the opposite direction

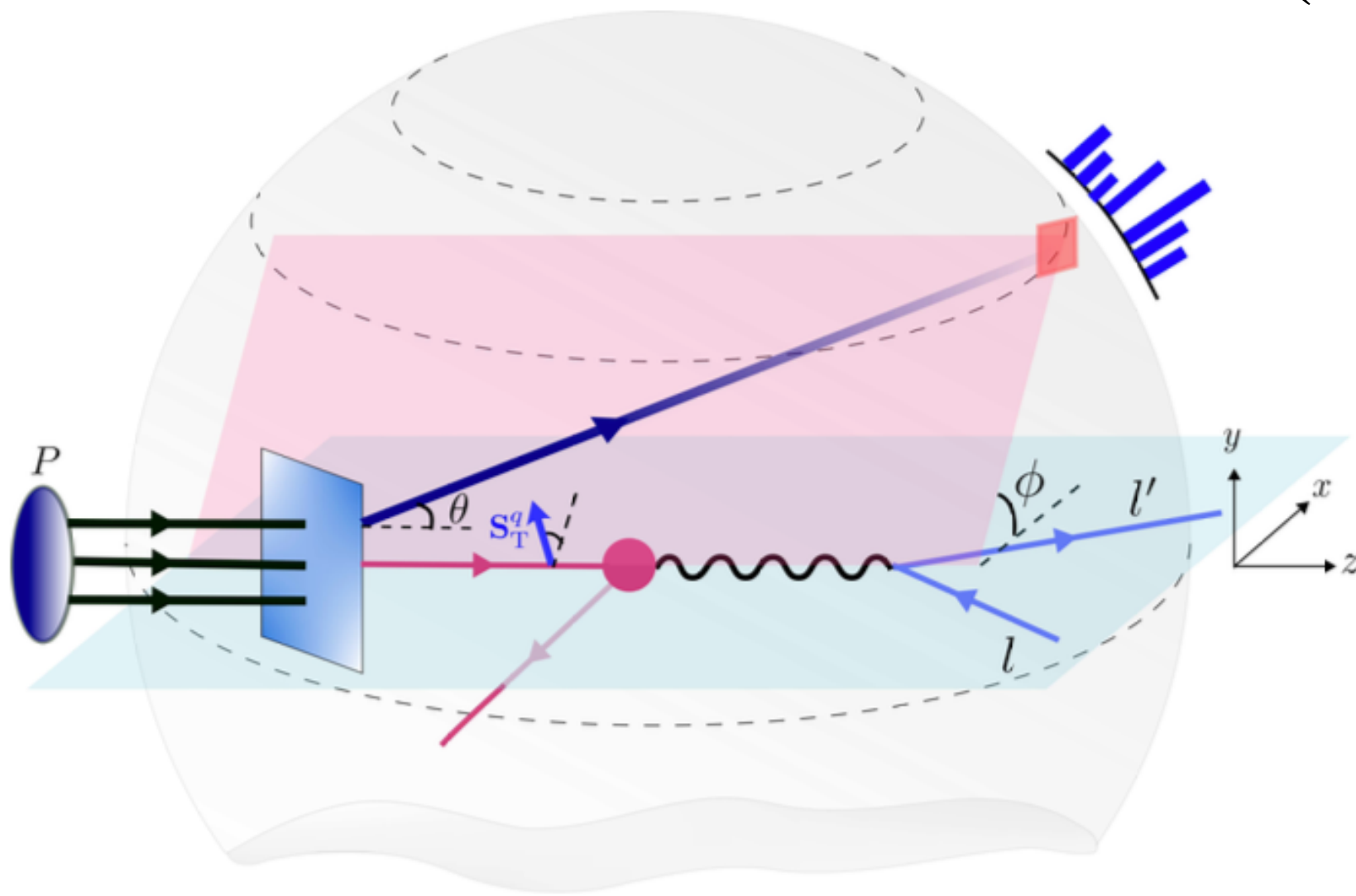
Probing the quark dipole operators with transversity NEC

- We consider the energy pattern within the TFR in inclusive DIS with *an unpolarized nucleon*:

$$e + P \rightarrow e + X$$

- We define the energy pattern xsec as:

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



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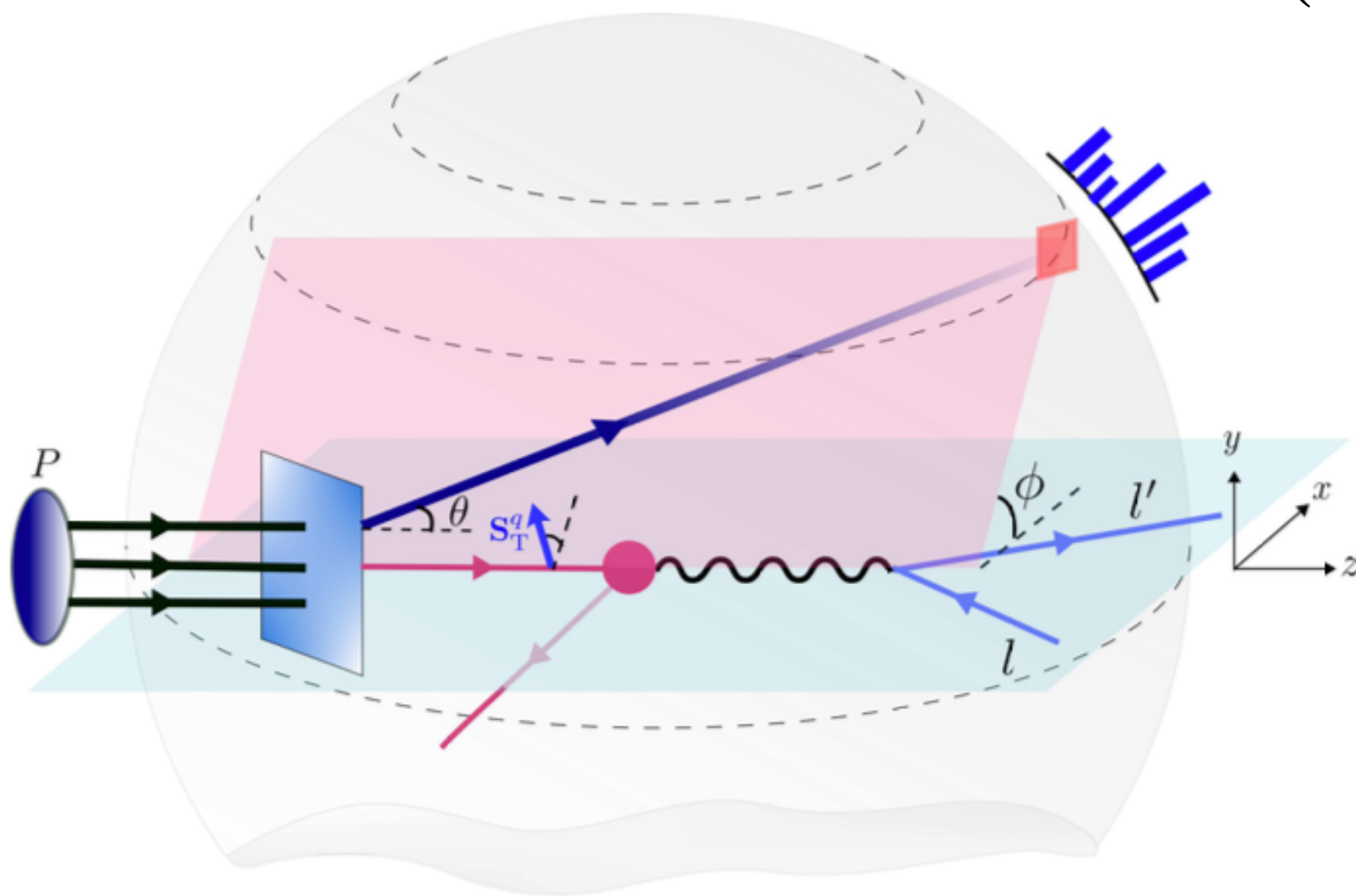
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TFR: $\theta P^+ \ll Q$

Collinear factorization:

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

Same as in standard
inclusive DIS



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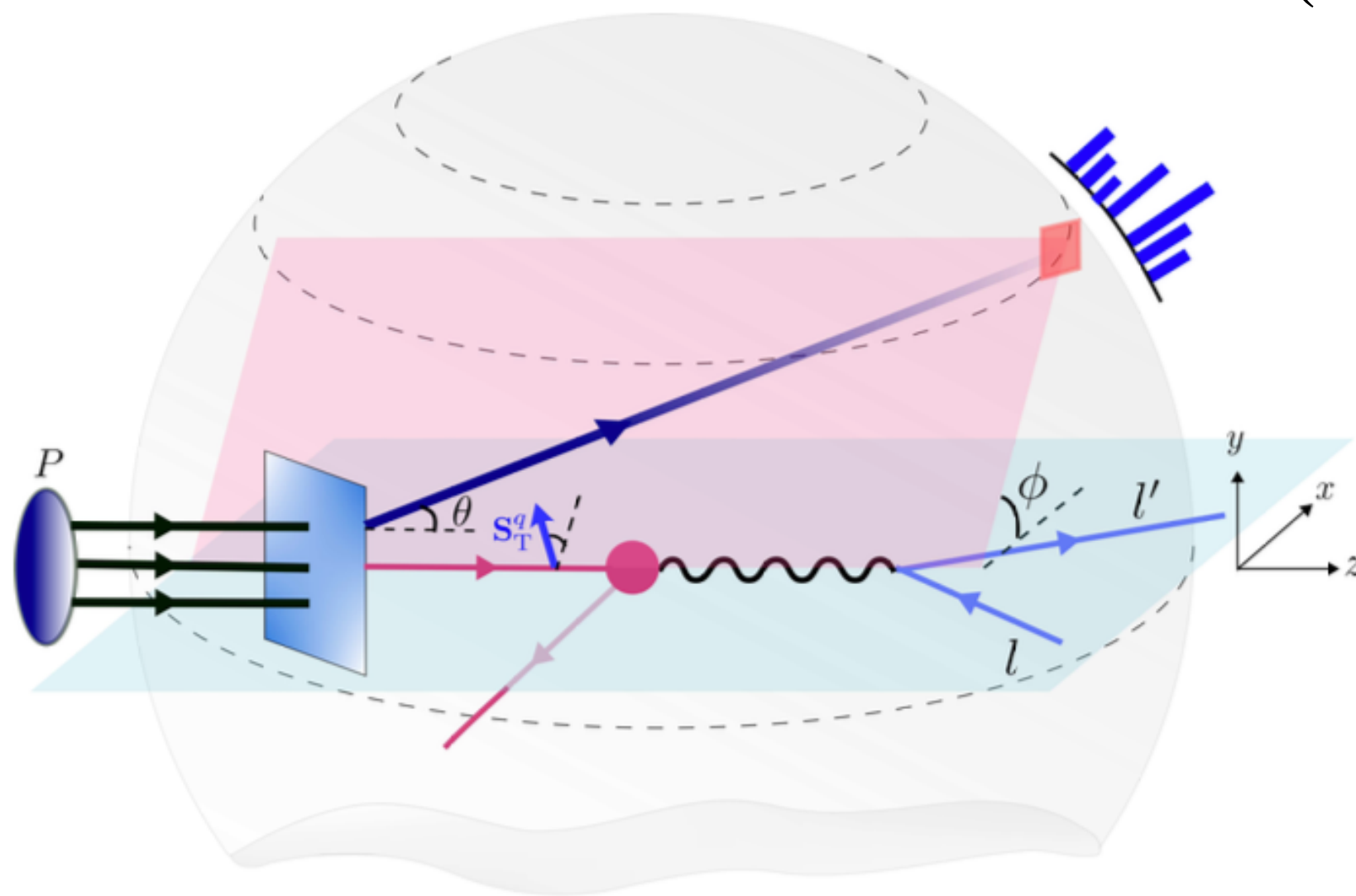
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NEC as a quark polarizer

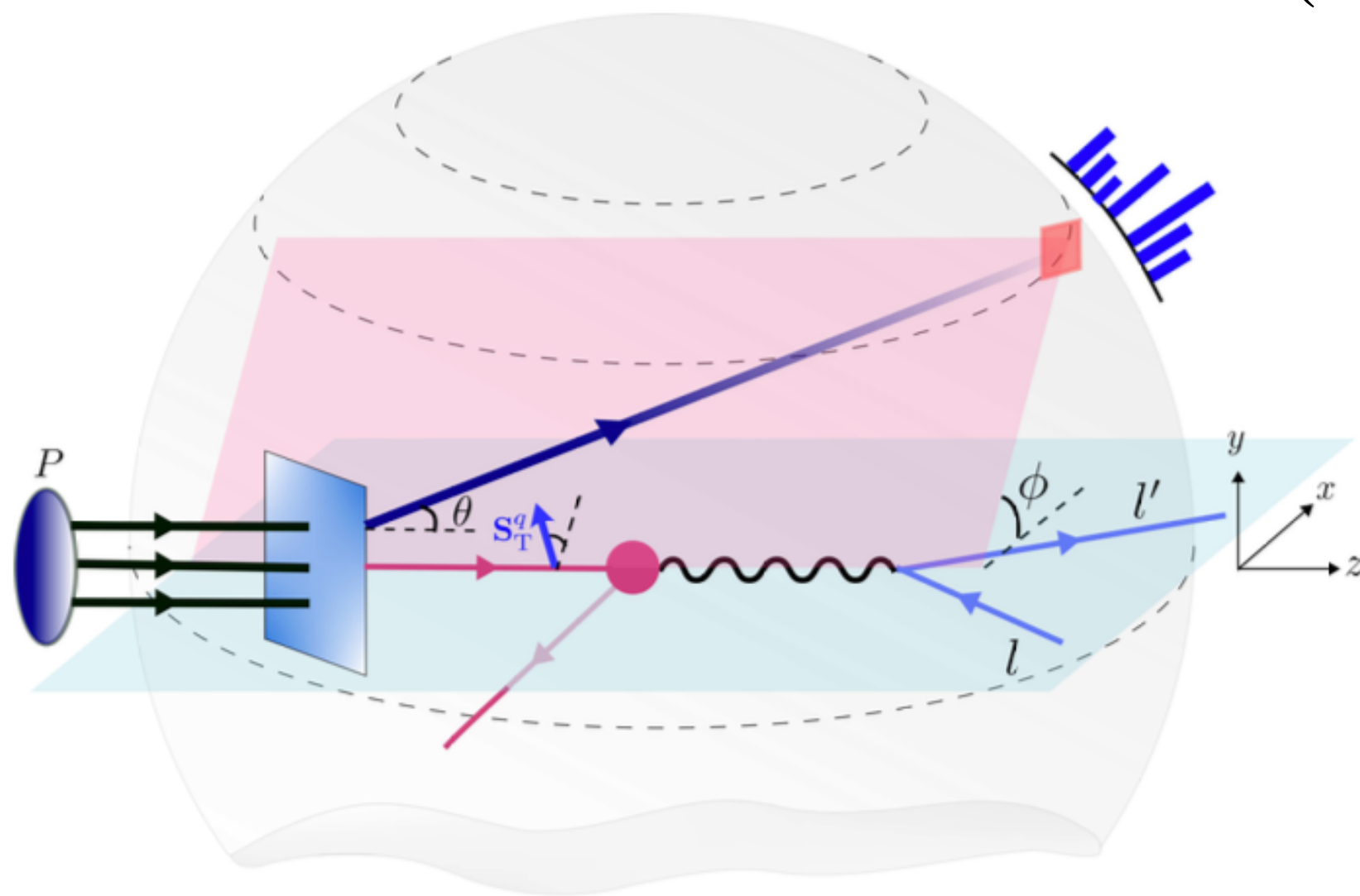
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Consider first both electron and proton beams are unpolarized:

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

NEC as a quark polarizer

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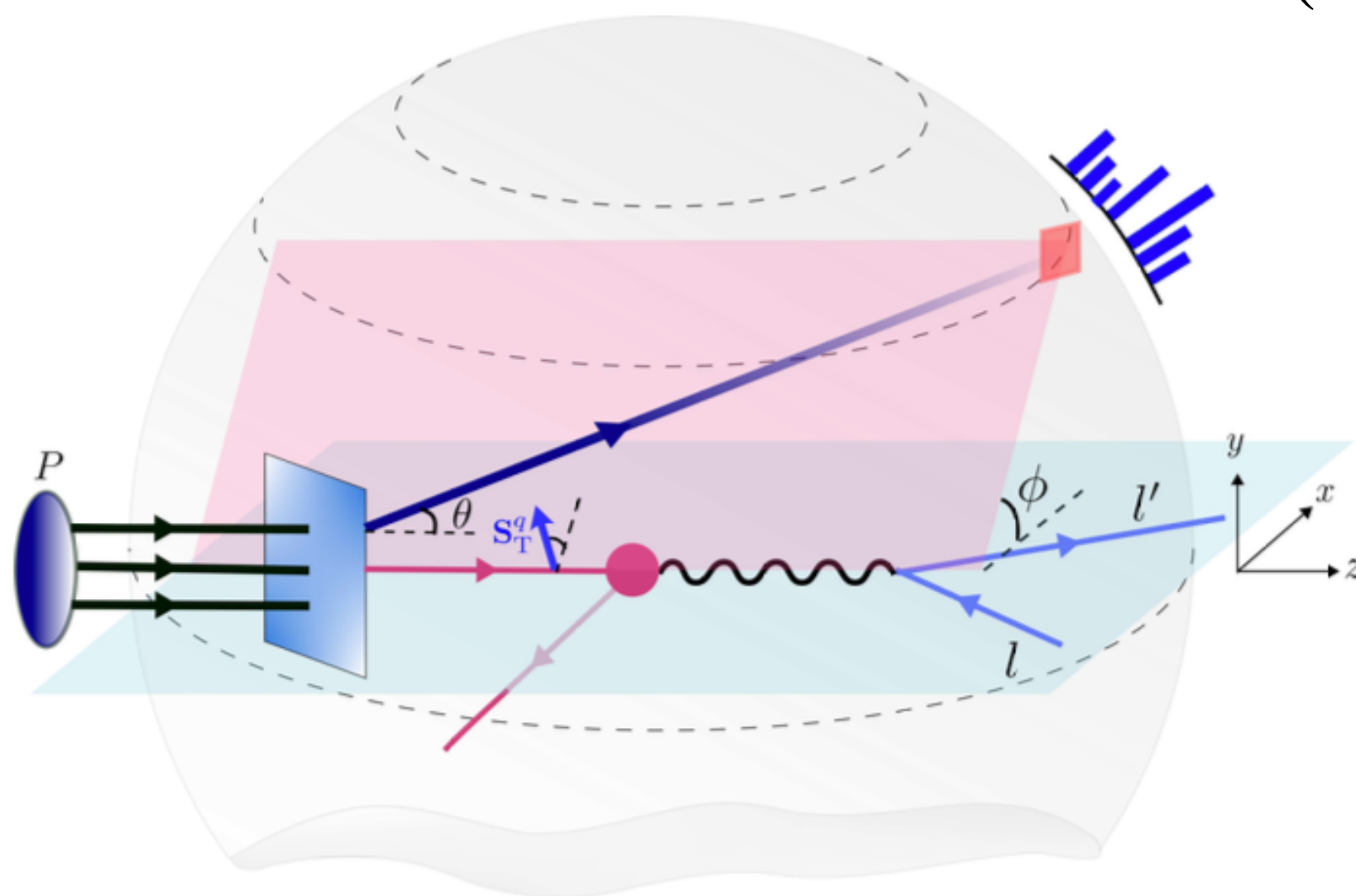
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$$\Sigma_{UU}(\theta) \sim f_1(x, \theta^2) \quad \text{Unpolarized quark NEC}$$

$$\Sigma_{UU}^{\sin \phi}, \Sigma_{UU}^{\cos \phi} \sim h_1^t(x, \theta^2) \quad \text{Transversity NEC}$$

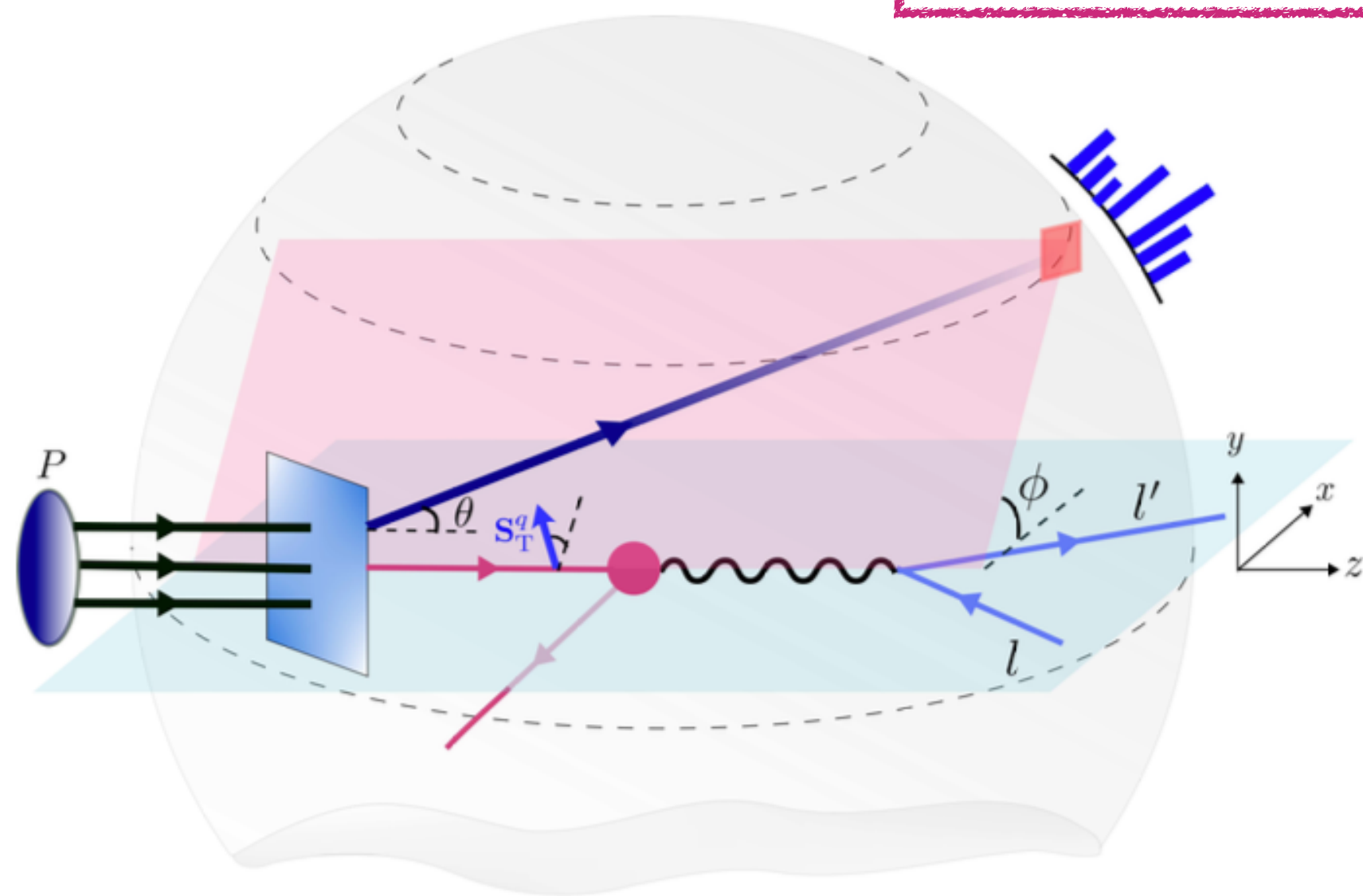


NEC as a quark polarizer

Probing the quark dipole operators with transversity NEC

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Within the SM



$$\Sigma_{UU}(\theta) \sim f_1(x, \theta^2) \quad \text{Unpolarized quark NEC}$$



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Vanishing to all orders in α_S

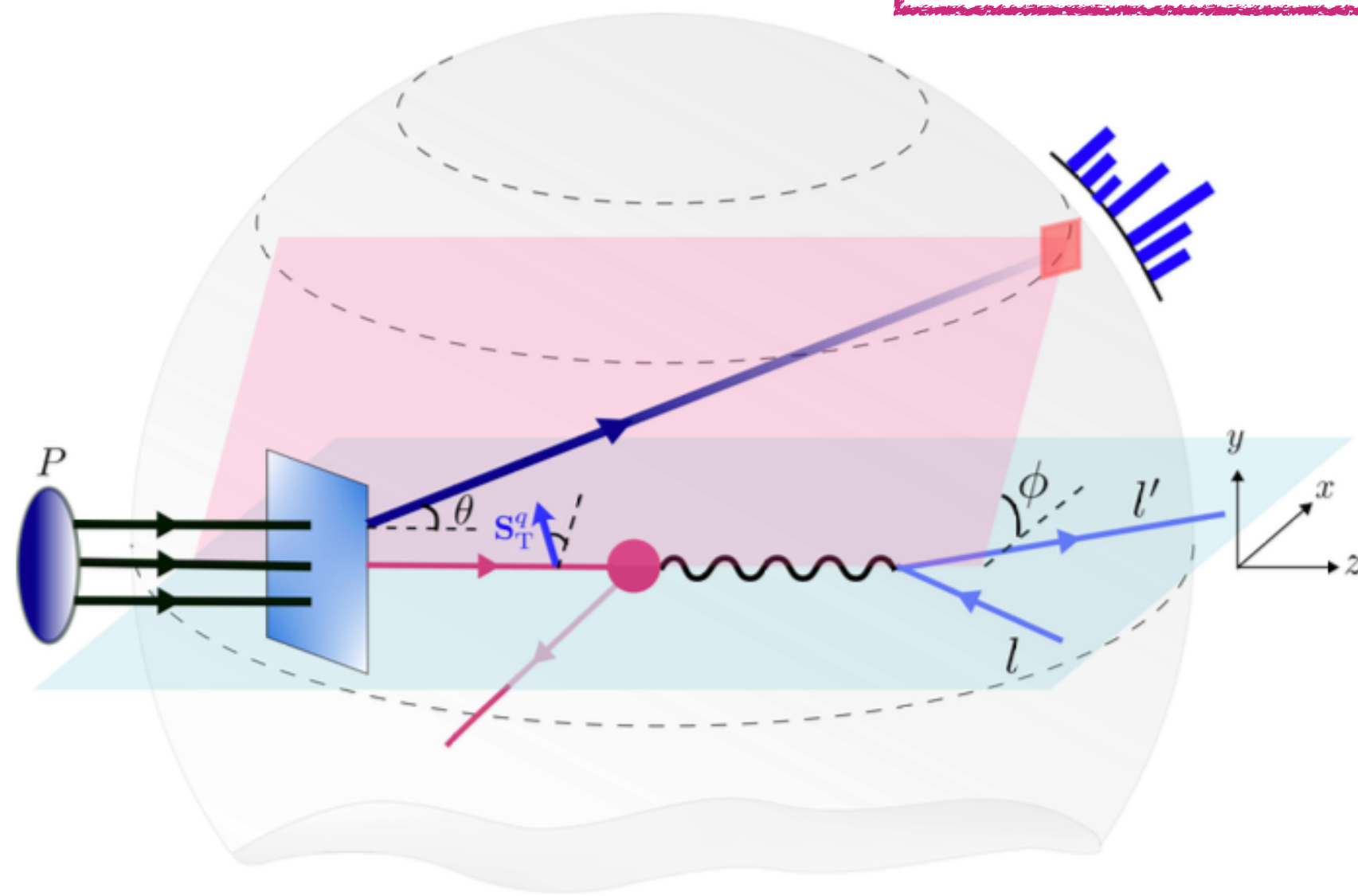
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Vanishing to all orders in α_S

$$\frac{d\Sigma_{UU}}{dx_B dQ^2} = \frac{2\pi\alpha_{\text{em}}^2}{Q^4} (y^2 - 2y + 2) \sum_q Q_q^2 f_1^q(x_B, \theta^2)$$

Probing the quark dipole operators with transversity NEC

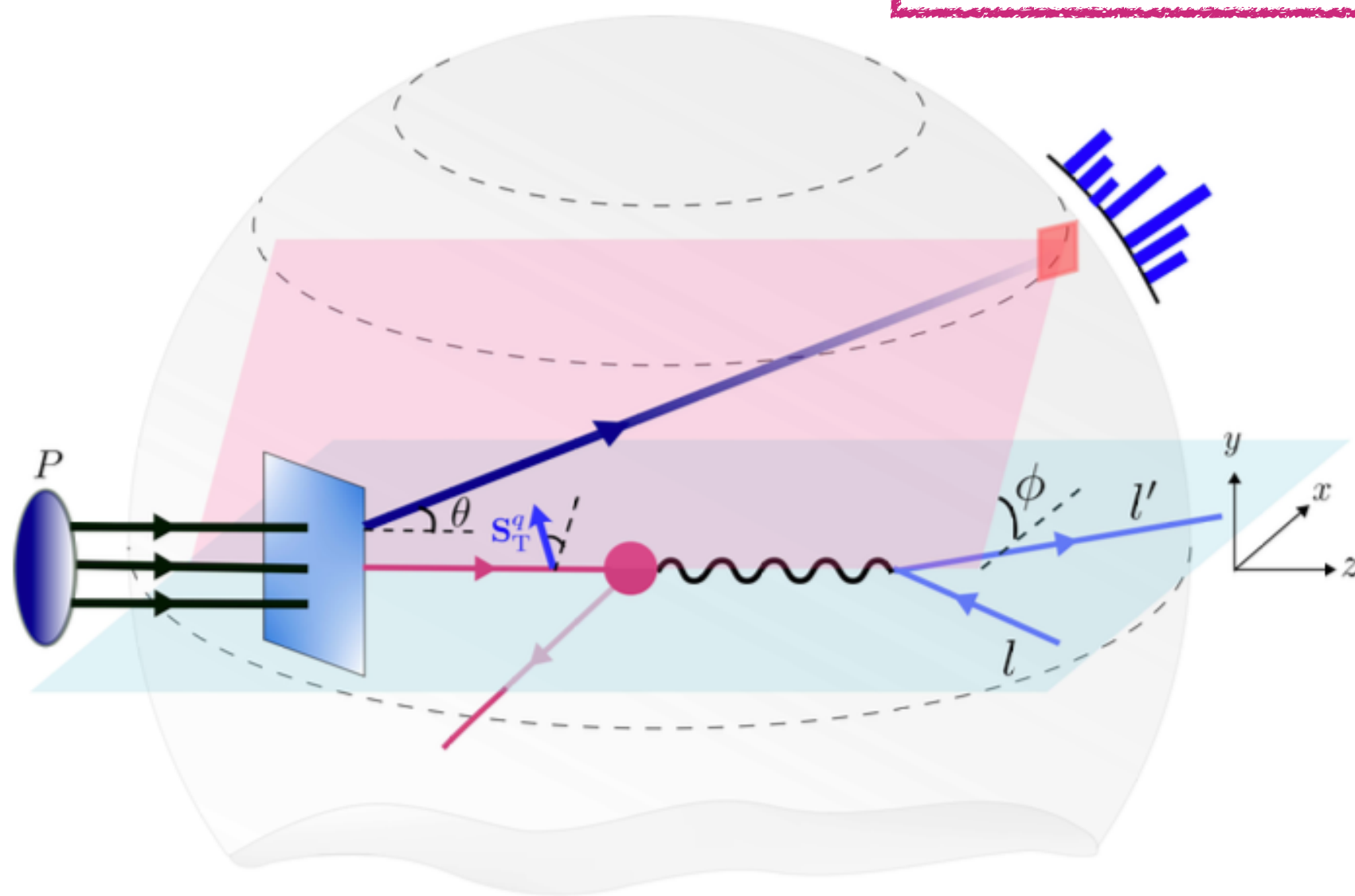
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With the dipole operators

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

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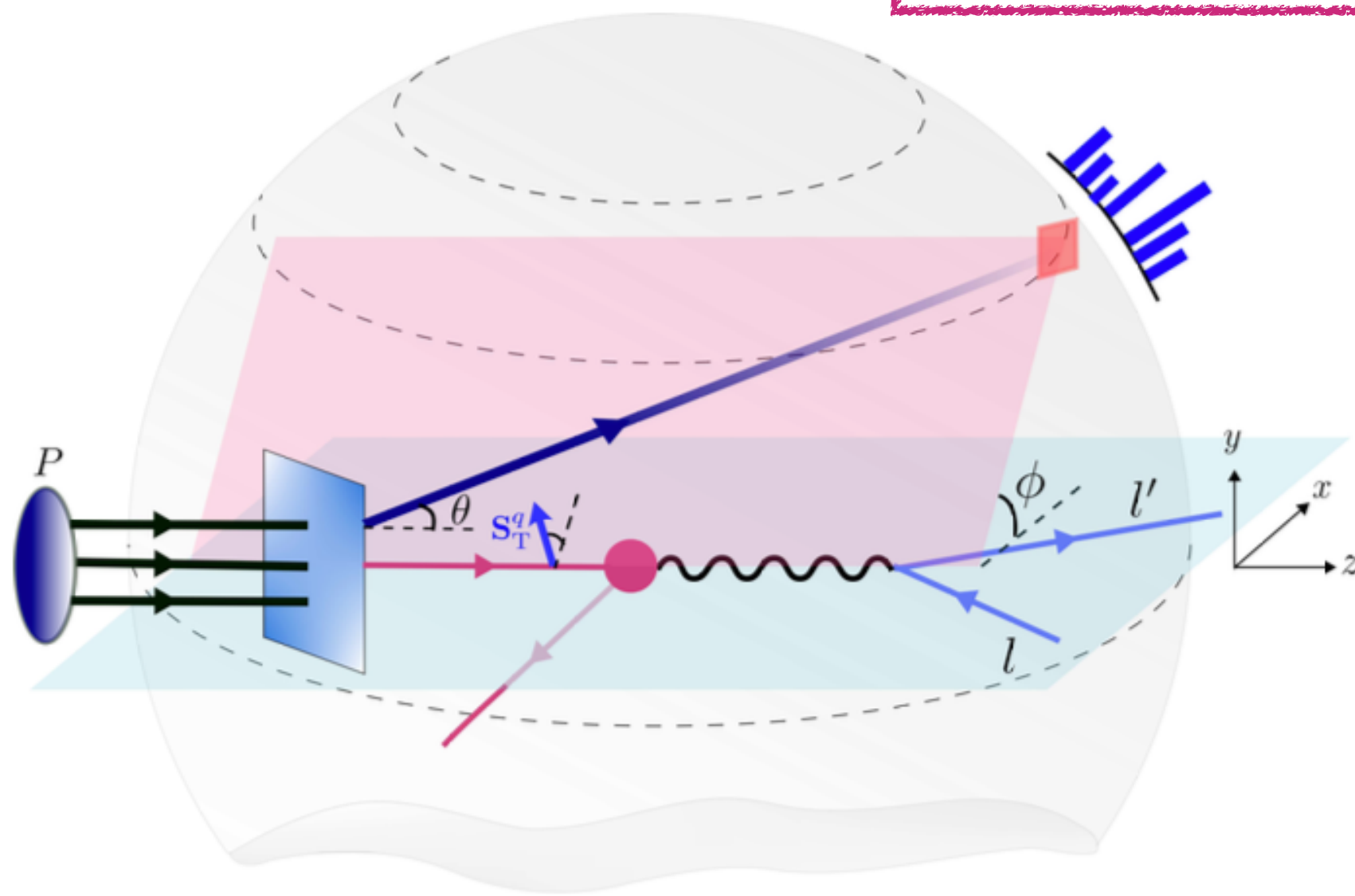
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$$\frac{d\Sigma_{UU}^{\sin \phi}}{dx_B dQ^2} = \frac{4\pi\alpha_{\text{em}}^2}{ec_W s_W} \frac{y\sqrt{1-y}}{Q(Q^2 + m_Z^2)} \sum_q h_1^{t,q}(x_B, \theta^2) \times \left\{ \left[\frac{2-y}{y} g_A^q g_V^e + g_V^q g_A^e \right] \frac{\text{Re}[c_{q\gamma}]}{c_W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

Probing the quark dipole operators with transversity NEC

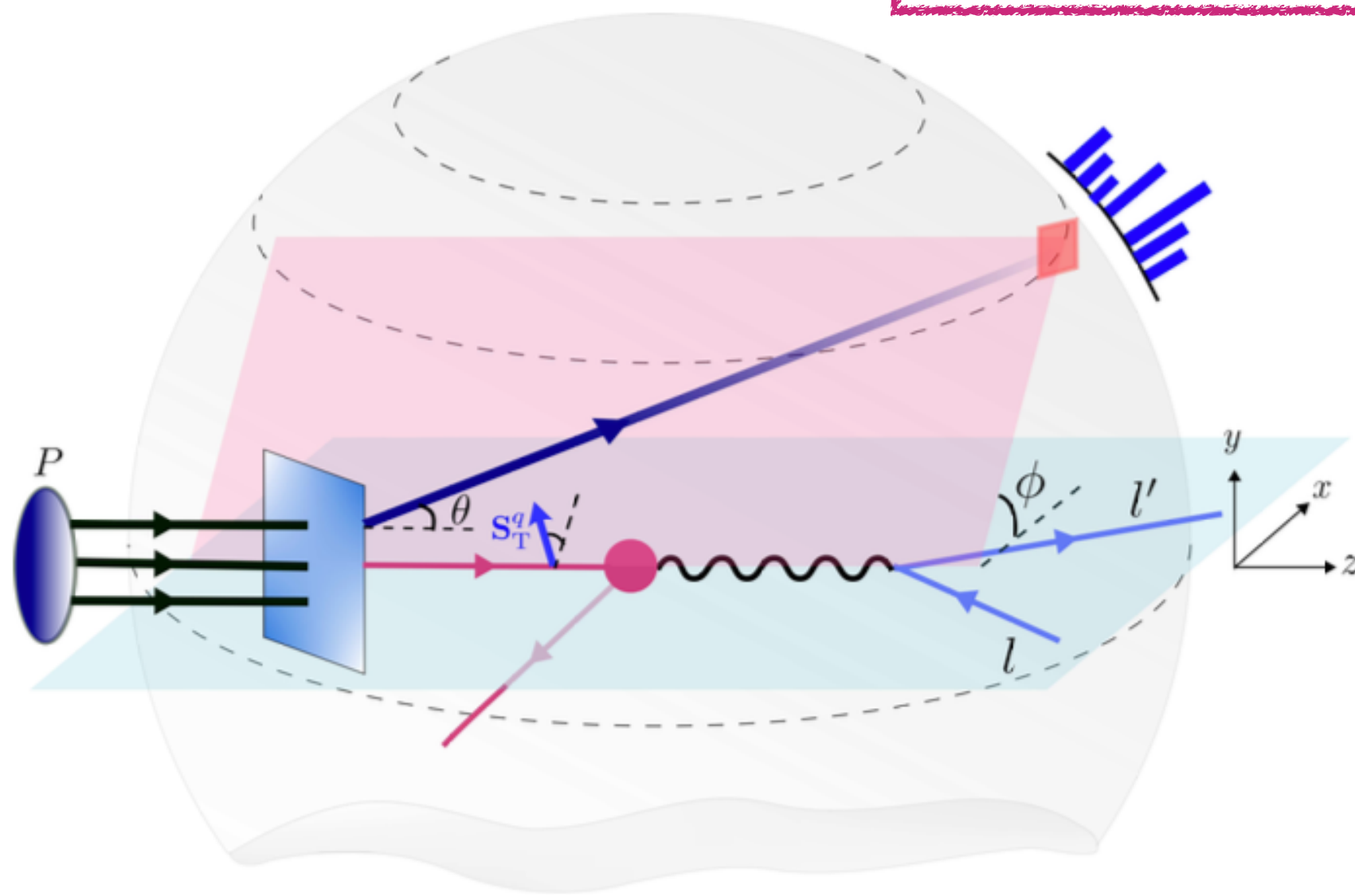
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- Linearly determined by the Re or Im of C_i individually

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Probing the quark dipole operators with transversity NEC

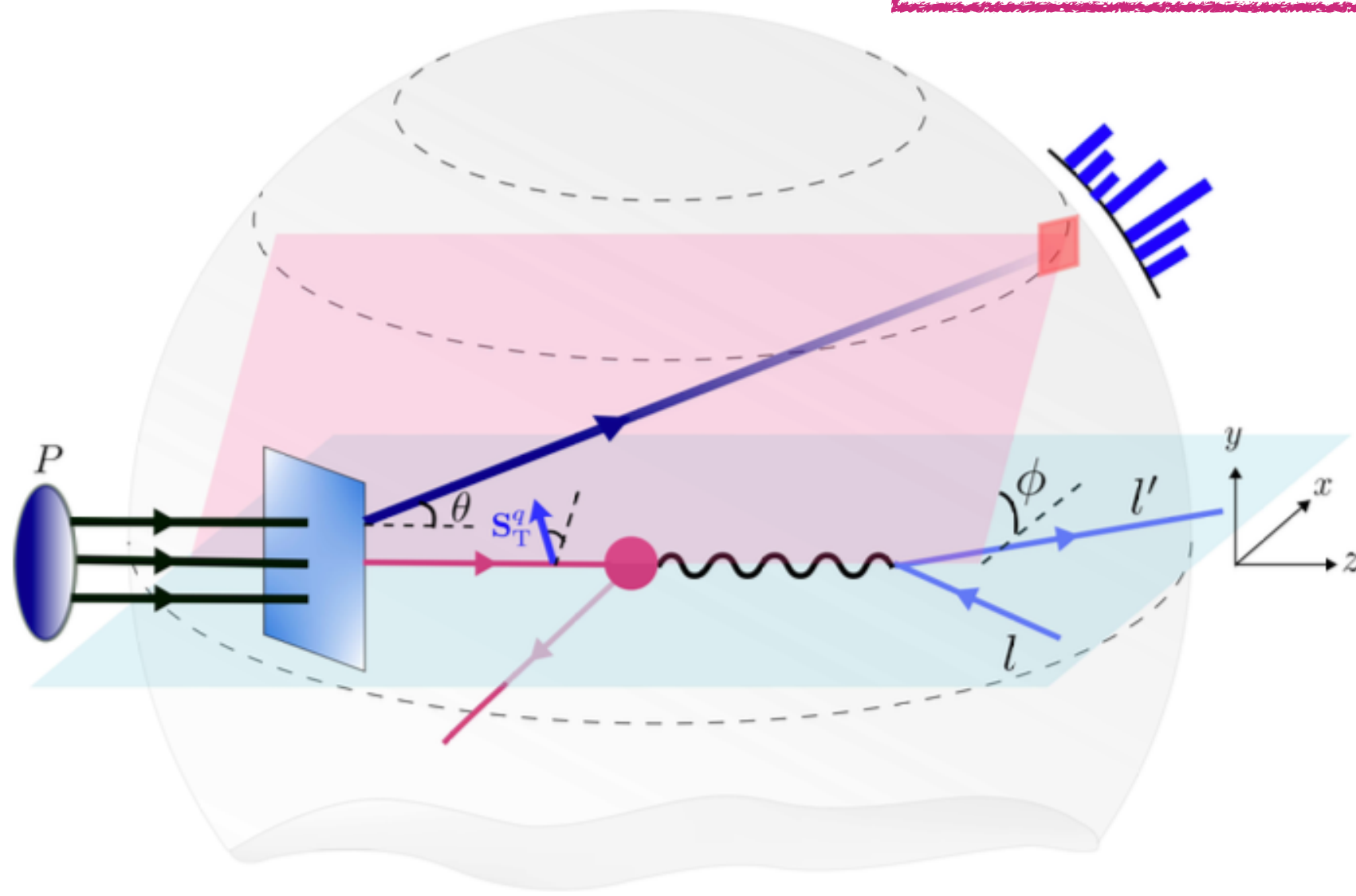
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- Linearly determined by the Re or Im of C_i individually
- Uniquely generated by the light-quark dipole operators

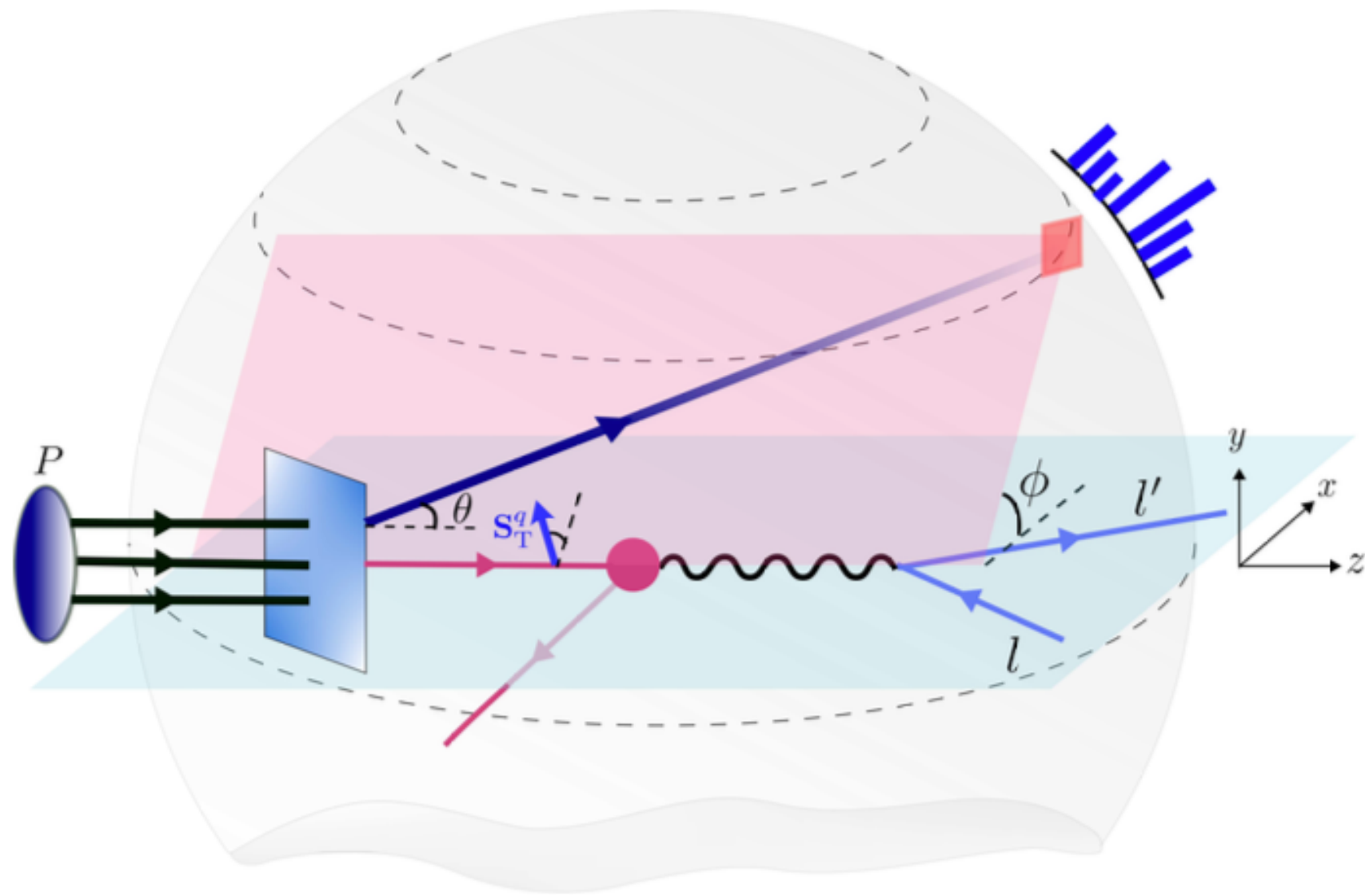
$$\frac{d\Sigma_{UU}^{\sin \phi}}{dx_B dQ^2} = \frac{4\pi\alpha_{\text{em}}^2}{ec_W s_W} \frac{y\sqrt{1-y}}{Q(Q^2 + m_Z^2)} \sum_q h_1^{t,q}(x_B, \theta^2) \times \left\{ \left[\frac{2-y}{y} g_A^q g_V^e + g_V^q g_A^e \right] \frac{\text{Re}[c_{q\gamma}]}{c_W s_W} - Q_q g_A^e \text{Re}[c_{qZ}] \right\}$$

$$\text{Re}[c_{q\gamma, Z}] \rightarrow -\text{Im}[c_{q\gamma, Z}] \longrightarrow \frac{d\Sigma_{UU}^{\cos \phi}}{dx_B dQ^2}$$

Probing the quark dipole operators with transversity NEC

Extend to include a longitudinally polarized electron beam:

$$\Sigma(\theta, \phi) = \Sigma_{UU}(\theta) + \Sigma_{UU}^{\sin \phi}(\theta) \sin \phi + \Sigma_{UU}^{\cos \phi}(\theta) \cos \phi + \lambda_e \left[\Sigma_{LU}^{\sin \phi}(\theta) \sin \phi + \Sigma_{LU}^{\cos \phi}(\theta) \cos \phi \right]$$

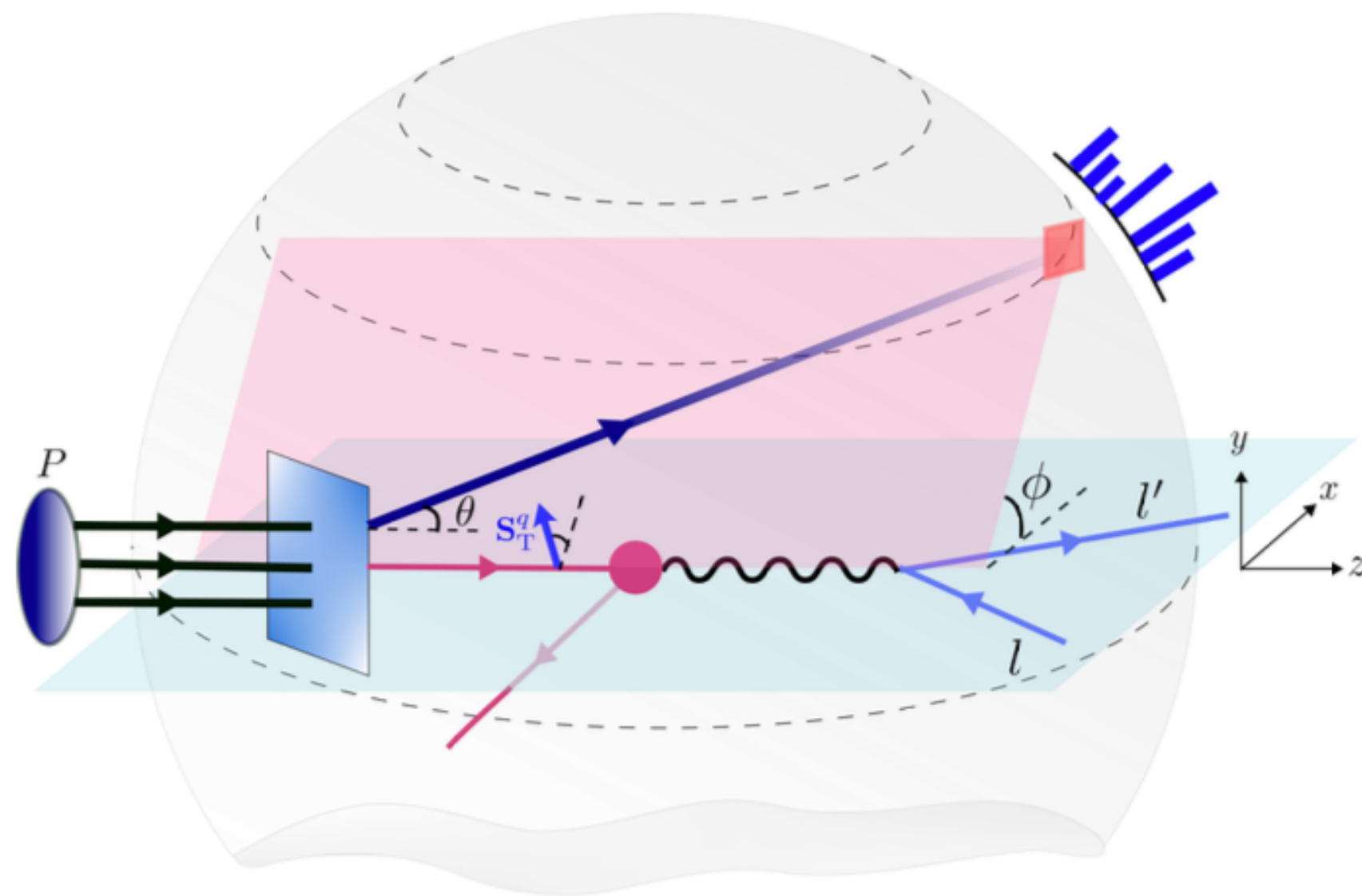


$$\frac{d\Sigma_{LU}^{\sin \phi}}{dx_B dQ^2} = + \frac{4\pi\alpha_{\text{em}}^2}{Q^3} \frac{y\sqrt{1-y}}{e} \sum_q h_1^{t,q}(x_B, \theta) \times \left\{ Q_q \text{Re}[c_{q\gamma}] - \frac{Q^2}{Q^2 + m_Z^2} \frac{1}{c_W s_W} \left[\left[\frac{2-y}{y} g_A^q g_A^e + g_V^q g_V^e \right] \frac{\text{Re}[c_{q\gamma}]}{c_W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

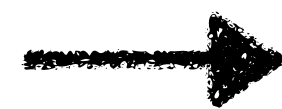
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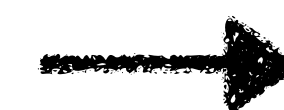
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Parity violation from
electron longitudinal
polarization



Generated via $\gamma\gamma$
interference, without Q^2/m_Z^2
suppression



Enhanced sensitivity

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

Calorimetric asymmetries

- We introduce azimuthal angle asymmetries of the energy pattern:

Unpolarized e^- beam

$$A_{UU}^u = \frac{\pi}{2} \frac{\Sigma(u > 0) - \Sigma(u < 0)}{\Sigma(u > 0) + \Sigma(u < 0)} \quad u = \sin \phi \text{ or } \cos \phi$$

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$\Sigma(u > 0)$: the θ -weighted energy pattern xsec integrated over the region with $u > 0$:

$$\Sigma(u > 0) \equiv \int_{\theta_{\min}^2}^{\theta_{\max}^2} d\theta^2 w(\theta) \int_0^{2\pi} d\phi \Sigma(\theta, \phi) \Theta(u)$$

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- The θ -weighting introduced here is to making use of the following remarkable correspondences:

$$E_N \int d\theta^2 |\sin \theta| f_1(x, \theta^2) = \int \frac{d^2 \mathbf{k}_\perp}{2\pi} |\mathbf{k}_\perp| \ell_1(x, \mathbf{k}_\perp^2) \longrightarrow \text{Unpolarized quark TMD}$$

Liu and Zhu, arxiv: 2403.08874

$$E_N \int d\theta^2 |\sin \theta| h_1^t(x, \theta^2) = \int \frac{d^2 \mathbf{k}_\perp}{2\pi} \frac{\mathbf{k}_\perp^2}{M} \hbar_1^\perp(x, \mathbf{k}_\perp^2) \longrightarrow \text{Boer-Mulder quark TMD}$$

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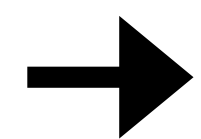
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Allow us to infer the NECs from
existing global fits of TMDs!



☑ Non-perturbative inputs
for quark NECs

Calorimetric asymmetries

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Unpolarized e^- beam

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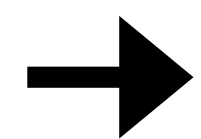
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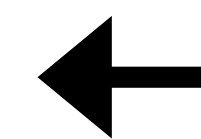
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Allow us to infer the NECs from existing global fits of TMDs!



✓ Non-perturbative inputs for quark NECs



Measurements of NECs are expected to be accomplished at EIC, JLab...

Calorimetric asymmetries

Longitudinally polarized e^- beam

$$A_{LU}^{\sin \phi} = \frac{\pi}{2} \frac{\left[\Sigma(\sin \phi > 0) |_{\lambda_e=+1} - \Sigma(\sin \phi < 0) |_{\lambda_e=+1} \right] - \left[\Sigma(\sin \phi > 0) |_{\lambda_e=-1} - \Sigma(\sin \phi < 0) |_{\lambda_e=-1} \right]}{\Sigma(\sin \phi > 0) |_{\lambda_e=+1} + \Sigma(\sin \phi < 0) |_{\lambda_e=+1} + \Sigma(\sin \phi > 0) |_{\lambda_e=-1} + \Sigma(\sin \phi < 0) |_{\lambda_e=-1}}$$

Incorporating the spin
asymmetry

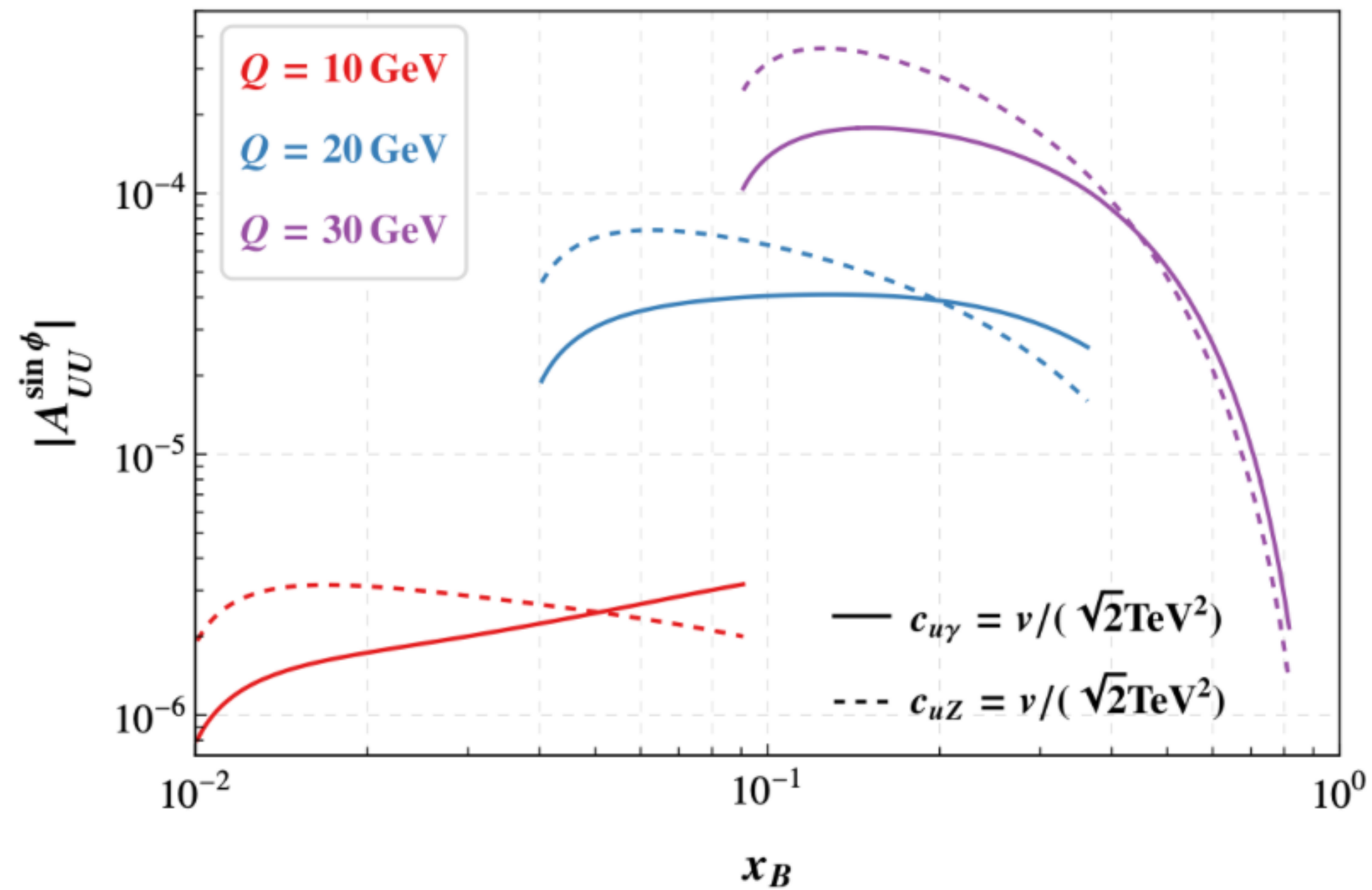
Calorimetric asymmetries

Longitudinally polarized e^- beam

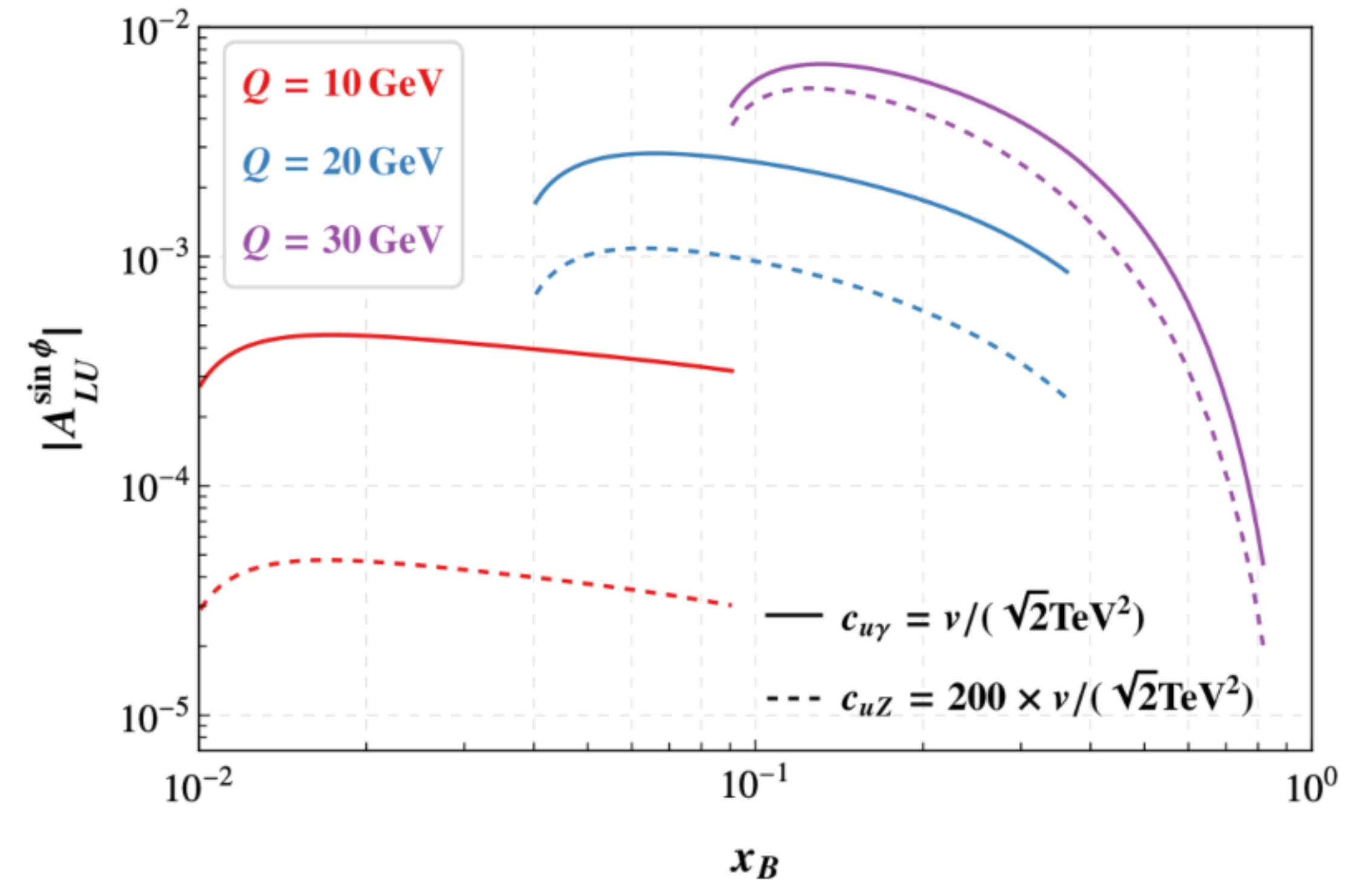
$$A_{LU}^{\sin \phi} = \frac{\pi}{2} \frac{\left[\Sigma(\sin \phi > 0) |_{\lambda_e=+1} - \Sigma(\sin \phi < 0) |_{\lambda_e=+1} \right] - \left[\Sigma(\sin \phi > 0) |_{\lambda_e=-1} - \Sigma(\sin \phi < 0) |_{\lambda_e=-1} \right]}{\Sigma(\sin \phi > 0) |_{\lambda_e=+1} + \Sigma(\sin \phi < 0) |_{\lambda_e=+1} + \Sigma(\sin \phi > 0) |_{\lambda_e=-1} + \Sigma(\sin \phi < 0) |_{\lambda_e=-1}}$$

Incorporating the spin asymmetry

A_{UU}



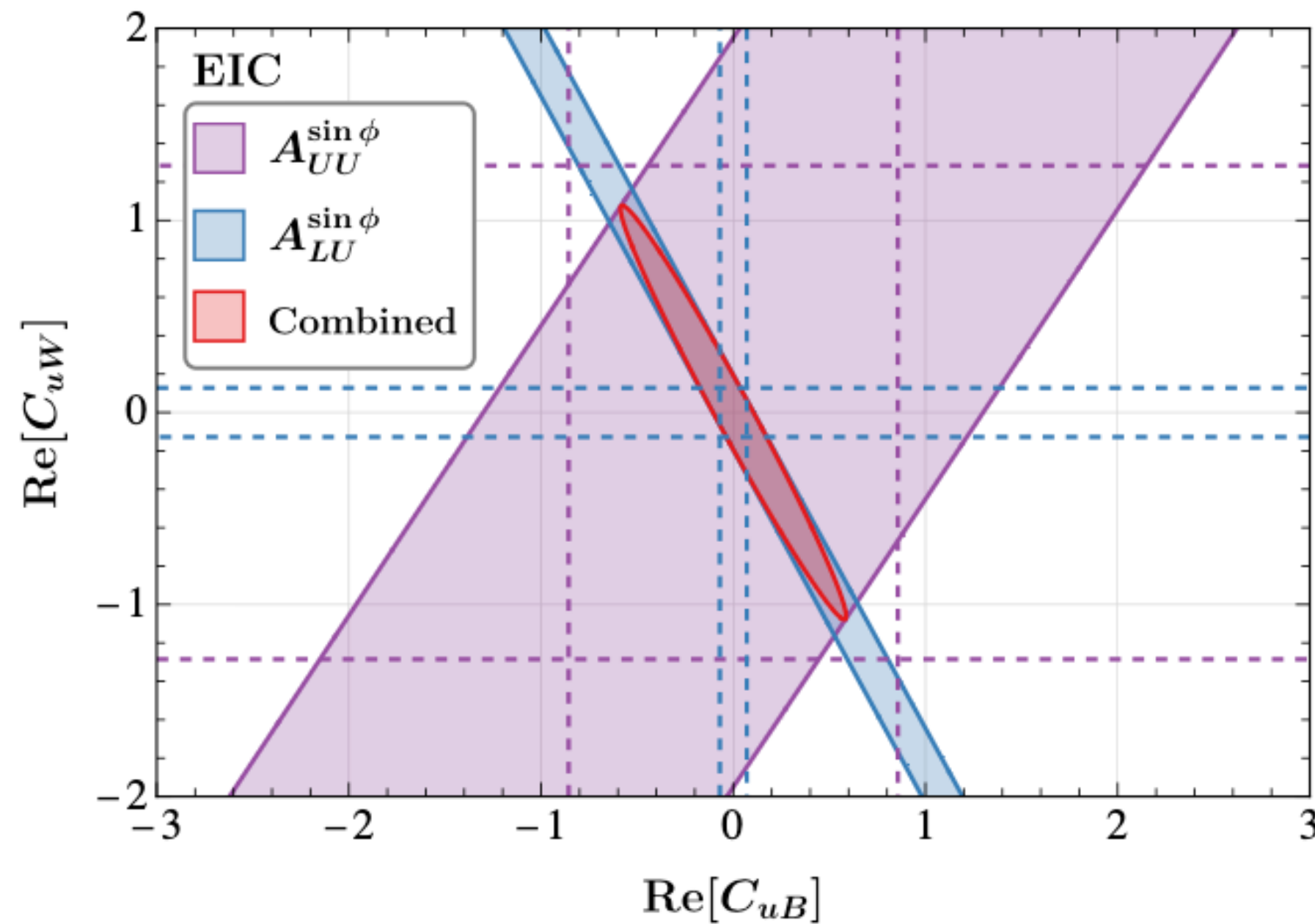
A_{LU}



Projected sensitivity at the EIC

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

$\Lambda = 1 \text{ TeV}$



$$\sqrt{s} = 105 \text{ GeV}, \quad \mathcal{L} = 100 \text{ fb}^{-1}$$

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

$$\text{Inelasticity cut: } 0.1 \leq y \leq 0.9$$

- $A_{UU}^{\sin \phi}$:
- Assuming single-operator dominance, it constrains the Wilson coefficients almost at the $\mathcal{O}(1)$ level (purple dashed lines)
 - Both coefficients considered simultaneously, the resulting constraint ellipse elongated into a purple band →
Strong correlation between C_{uW} and C_{uB}

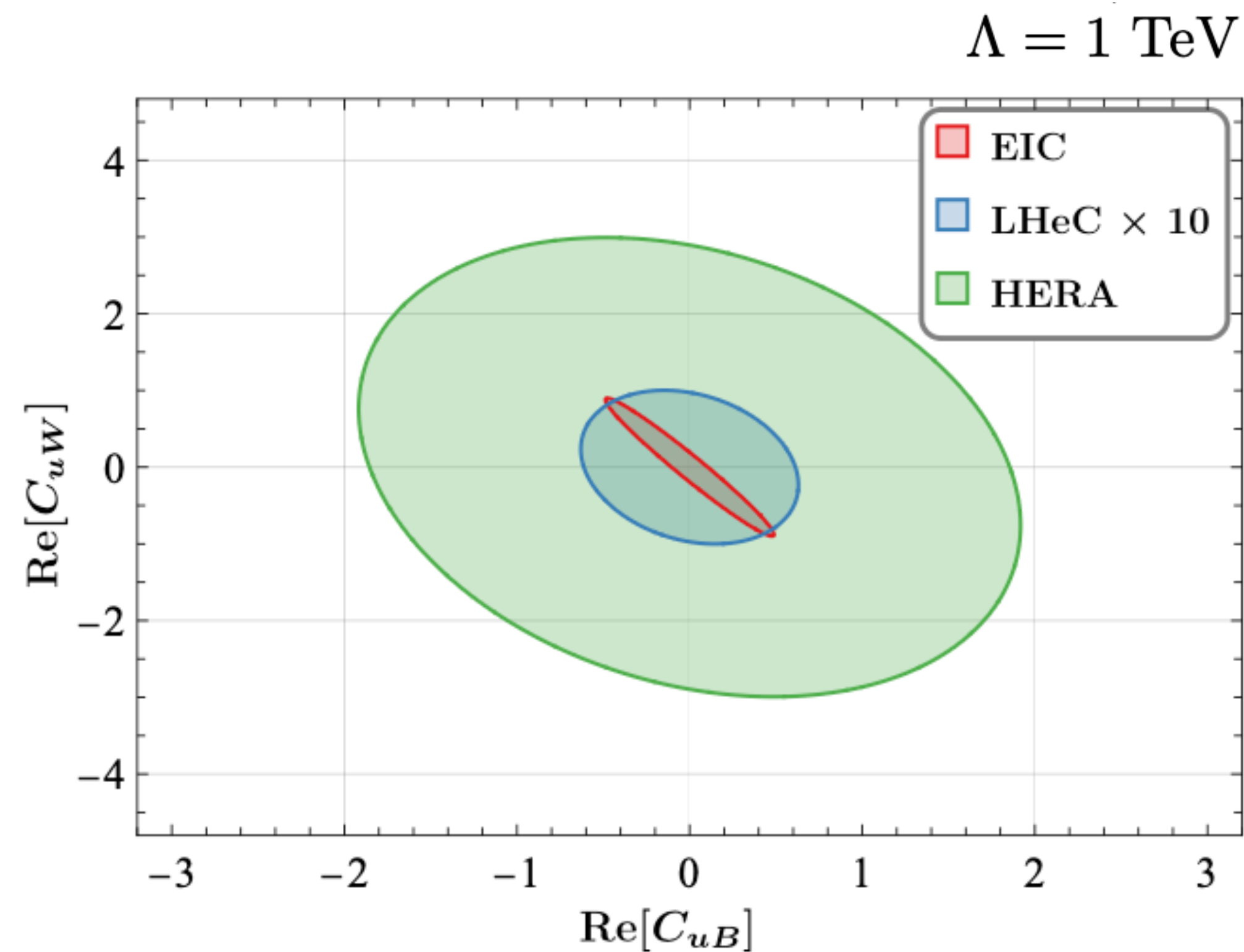
- $A_{LU}^{\sin \phi}$:
- Single-operator constraints can reach $\mathcal{O}(0.01) \sim \mathcal{O}(0.1)$ level
 - The orientation of corresponding blue band is different from that of $A_{UU}^{\sin \phi}$



Their combination confines the allowed region to a very narrow area highlighted in red!

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

Comparison among HERA, the EIC and the LHeC



- No requirement on a polarized nucleon beam
➔ Available HERA data can be used!
- HERA benefits from higher- Q^2 coverage, while lower luminosity results in slightly weaker sensitivity compared to the EIC
- HERA provides better discrimination between operators
- With even higher energy and better luminosity, the LHeC could outperform both HERA and EIC by an order of magnitude

Summary

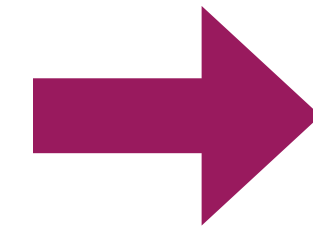
- We introduce a **chiral-odd NEC** that provides a powerful framework to *probe EW light-quark dipole operators* in inclusive DIS **without requiring a polarized proton beam**
- Our approach **eliminates the need for nucleon polarization** and **relies entirely on inclusive calorimetric measurements**, without particle identification or hadron reconstruction
- Our work offers a new technique to search for new physics

Thank You!

Backup: operators

$$\begin{aligned}\mathcal{O}_{uW} &= (\bar{Q}\sigma^{\mu\nu}u)\tau^I\tilde{H}W_{\mu\nu}^I, \\ \mathcal{O}_{uB} &= (\bar{Q}\sigma^{\mu\nu}u)\tilde{H}B_{\mu\nu}, \\ \mathcal{O}_{dW} &= (\bar{Q}\sigma^{\mu\nu}d)\tau^IHW_{\mu\nu}^I, \\ \mathcal{O}_{dB} &= (\bar{Q}\sigma^{\mu\nu}d)HB_{\mu\nu}\end{aligned}$$

SSB



$$\begin{aligned}\mathcal{L} &= C_{d\gamma} \left(\bar{d}_L \sigma_{\mu\nu} d_R \right) F^{\mu\nu} + C_{u\gamma} \left(\bar{u}_L \sigma_{\mu\nu} u_R \right) F^{\mu\nu} \\ &\quad + C_{dZ} \left(\bar{d}_L \sigma_{\mu\nu} d_R \right) Z^{\mu\nu} + C_{uZ} \left(\bar{u}_L \sigma_{\mu\nu} u_R \right) Z^{\mu\nu} + \text{h.c.}\end{aligned}$$

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

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

Backup: complete analytical formulas

SM:

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

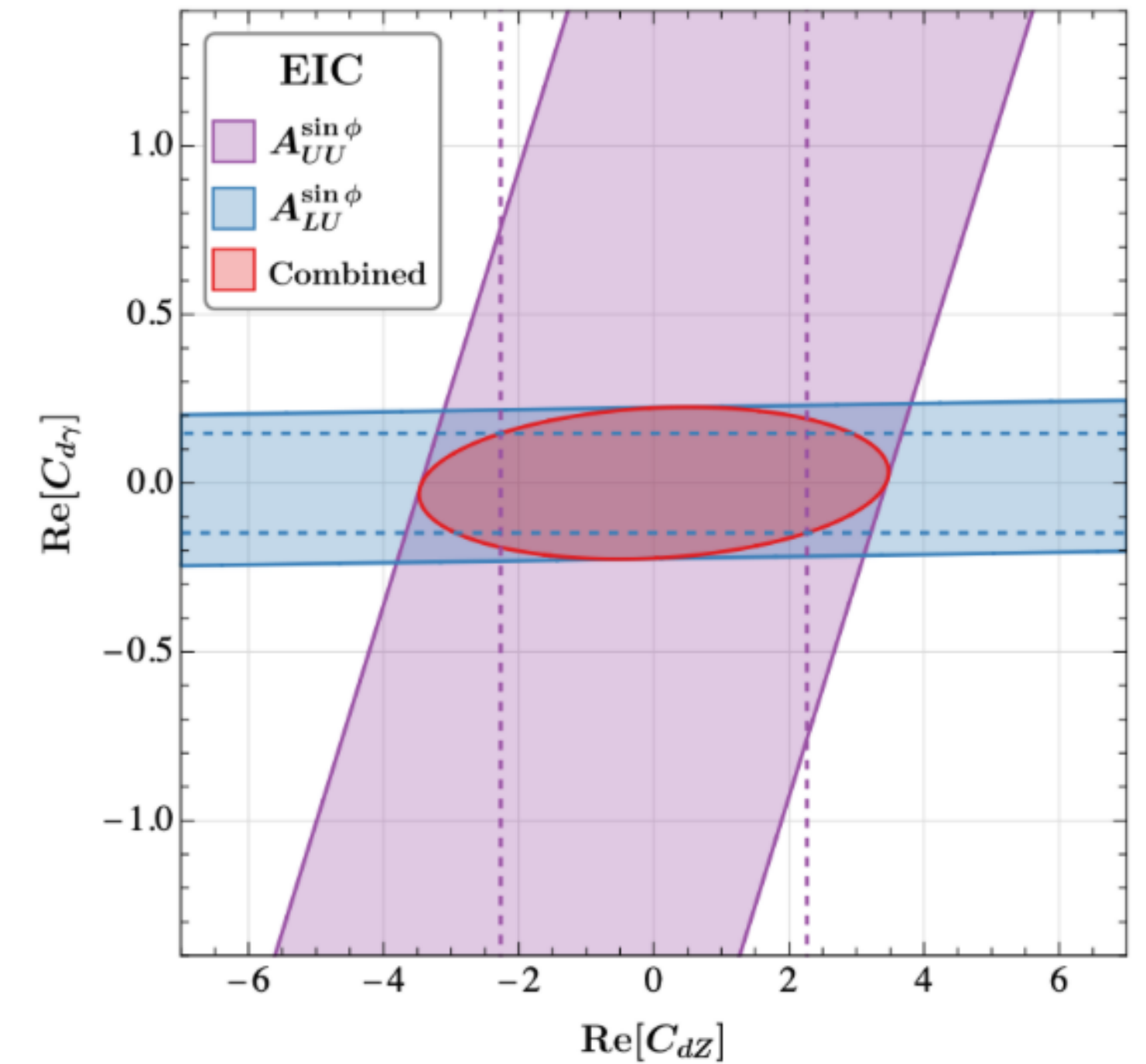
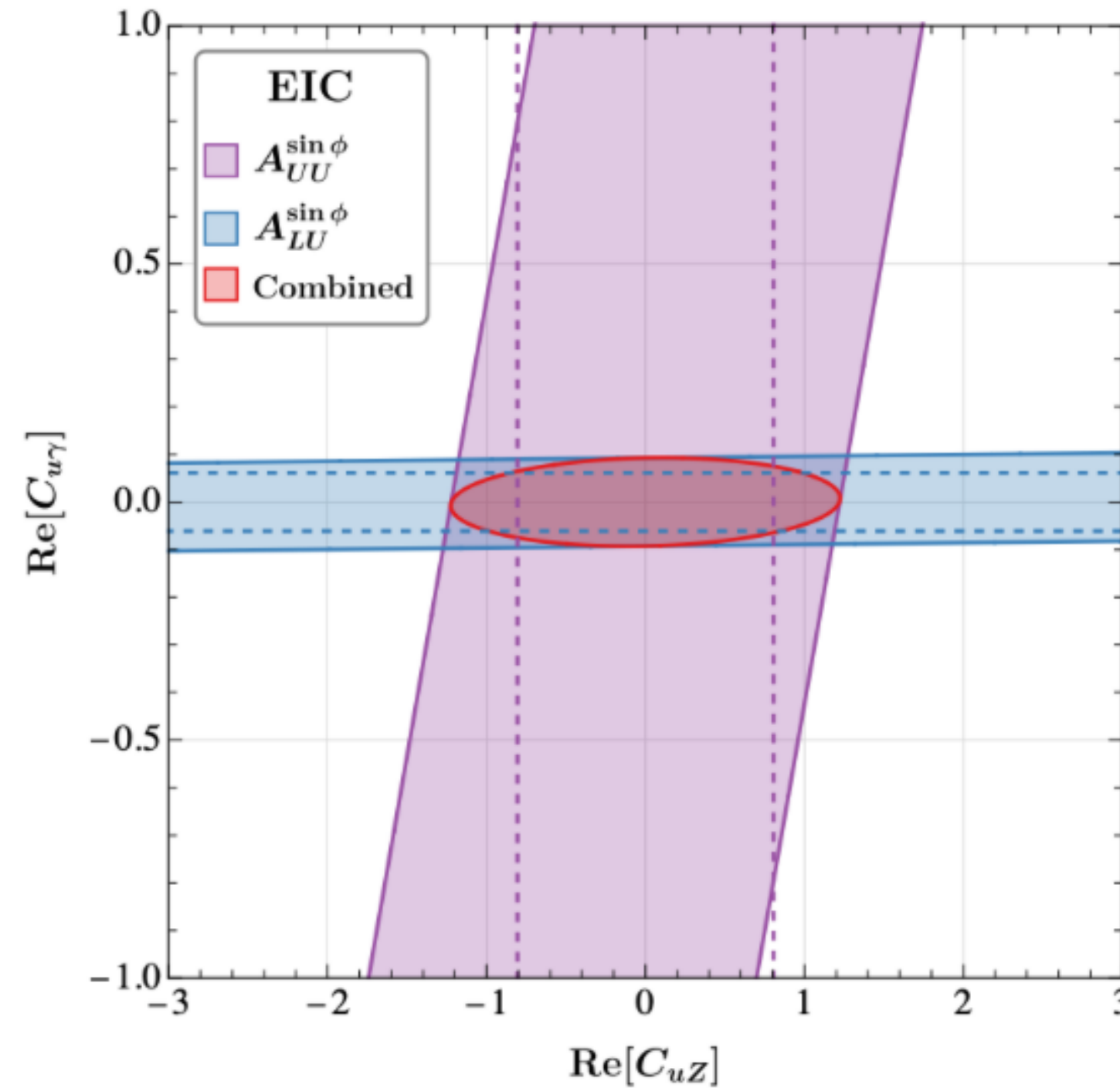
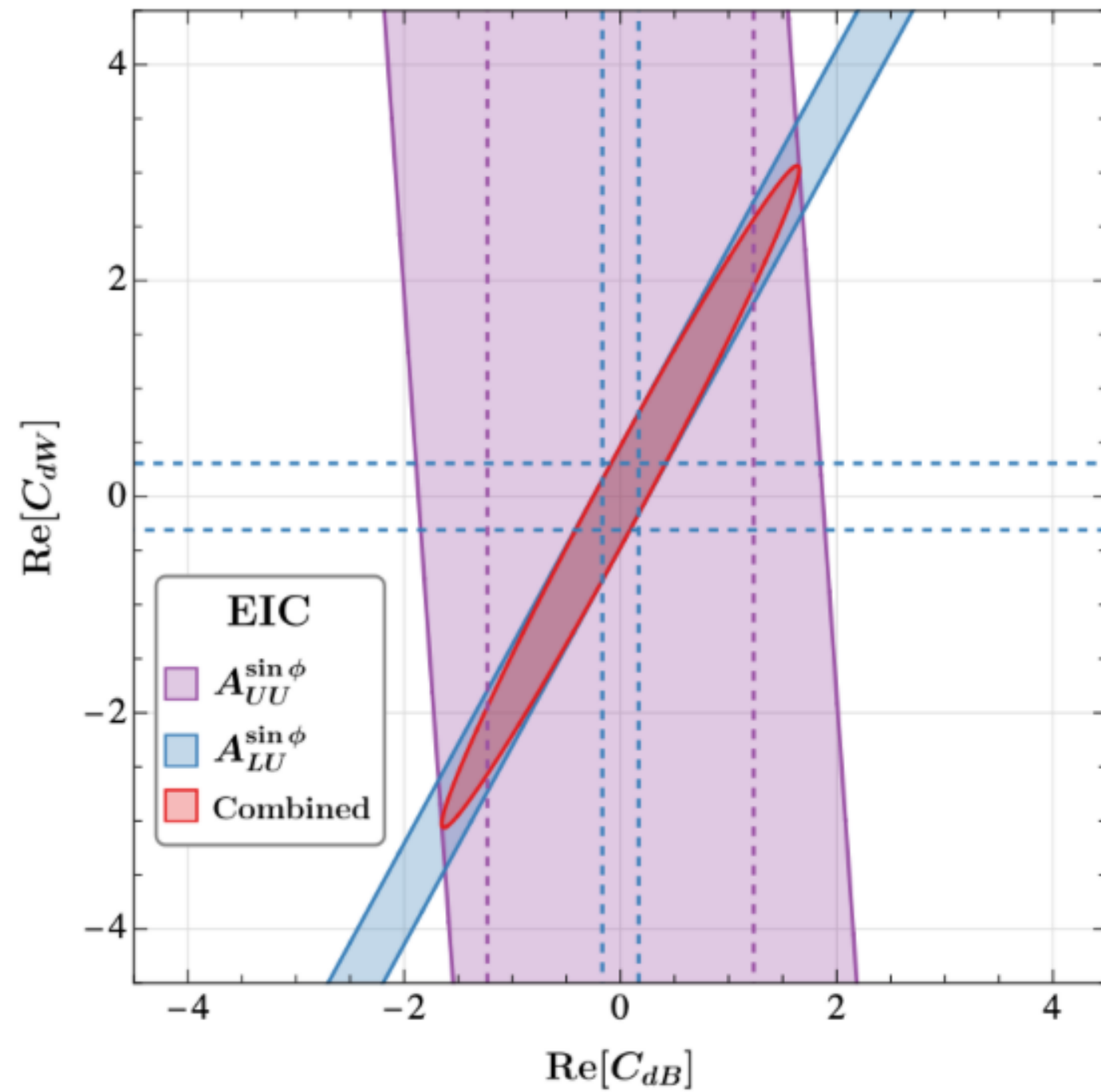
Dipole ops.:

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

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

Backup: more results

Collider	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [fb $^{-1}$]	P_e	Q [GeV]	y	x_B
EIC [1]	105	100	70%	[10, 60]	[0.1, 0.9]	[0.01, 0.5]
HERA [4, 5]	318	0.4	40%	[30, 150]	[0.1, 0.9]	[0.01, 0.5]
LHeC [6]	1300	50	80%	[100, 1000]	[0.1, 0.9]	[0.005, 0.9]



Backup: more results

