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

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South China Normal University

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

SPIN2025@Qingdao

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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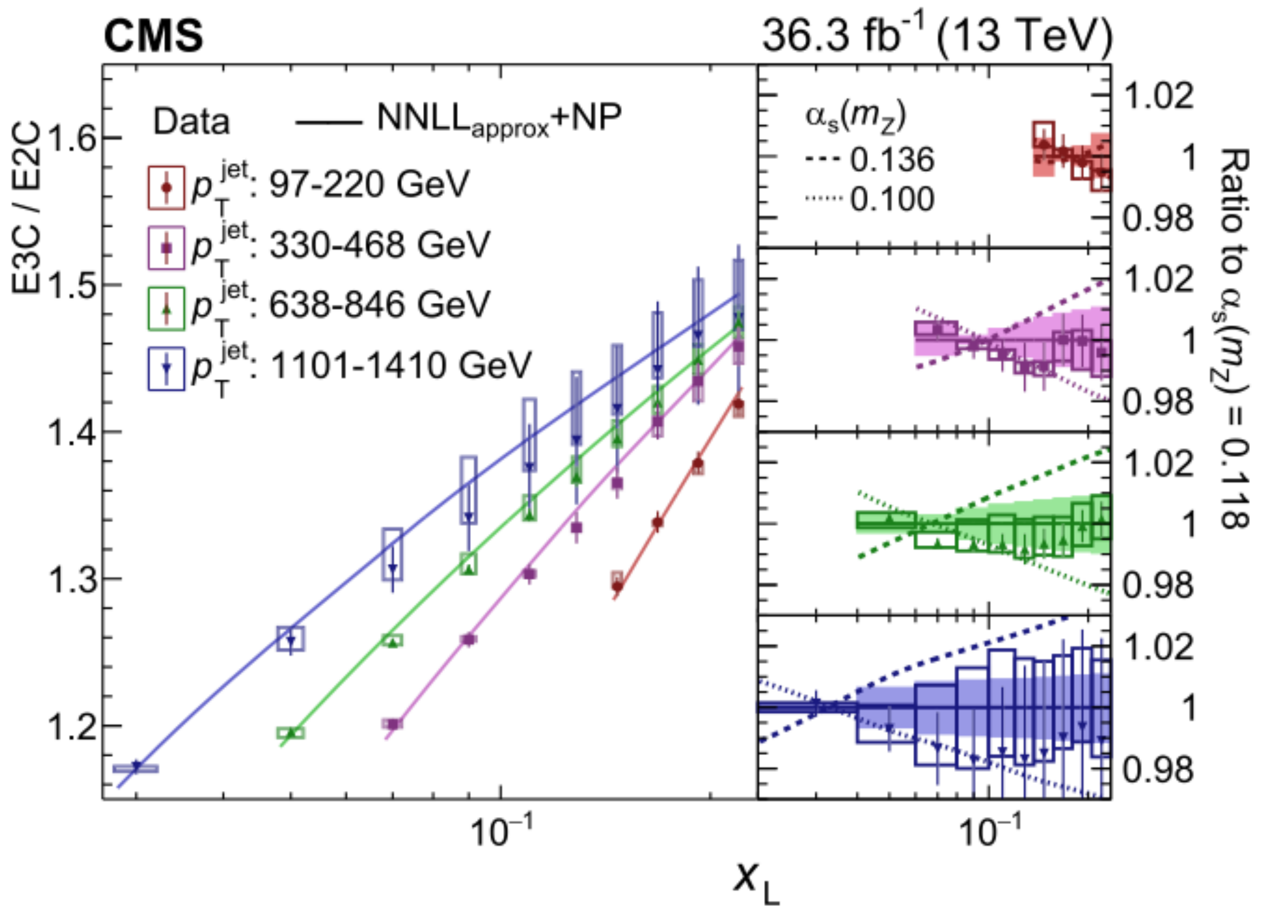
☑ α_S extraction by the scaling behavior

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

Chen et al., 2020

Chen et al., 2023

$\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050}$



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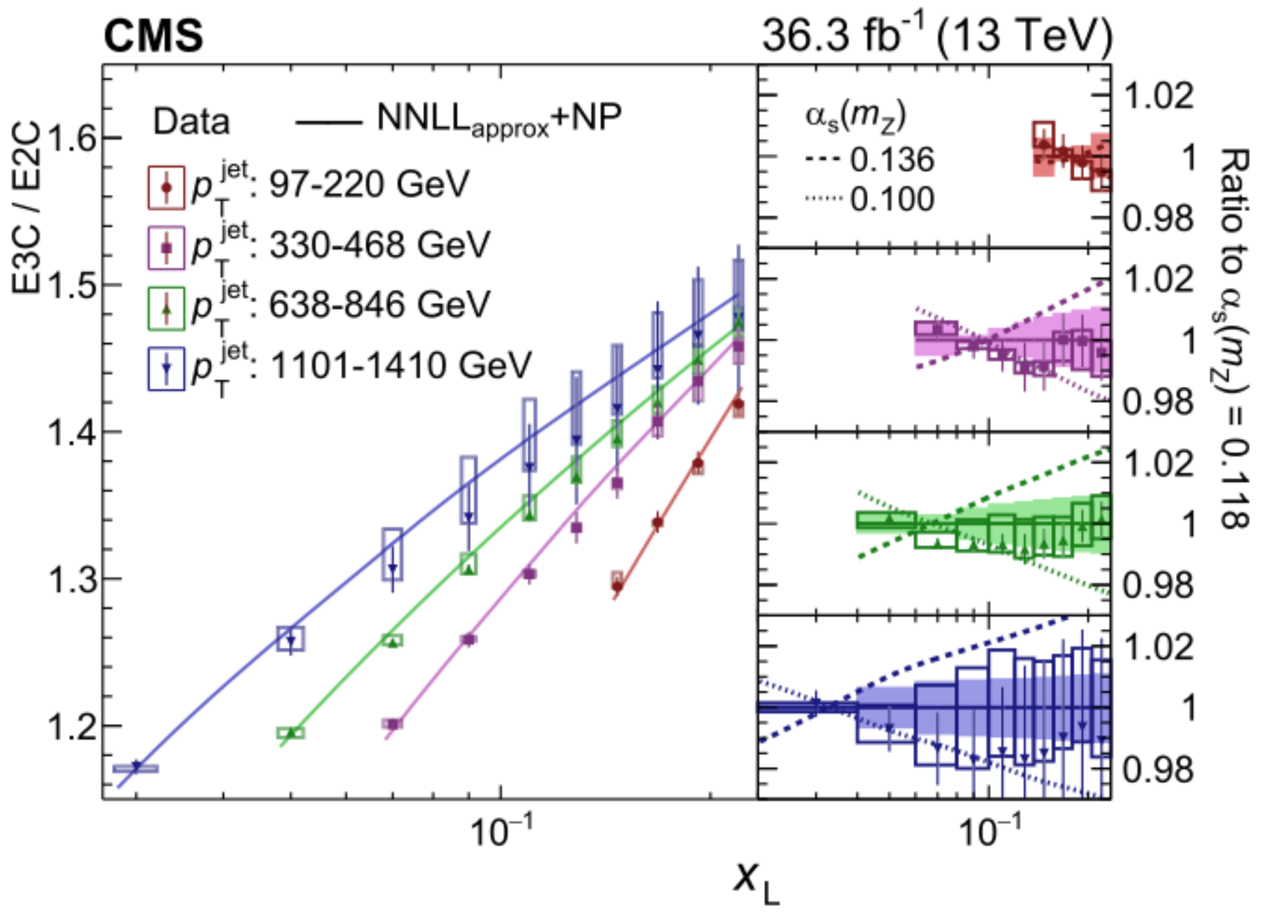
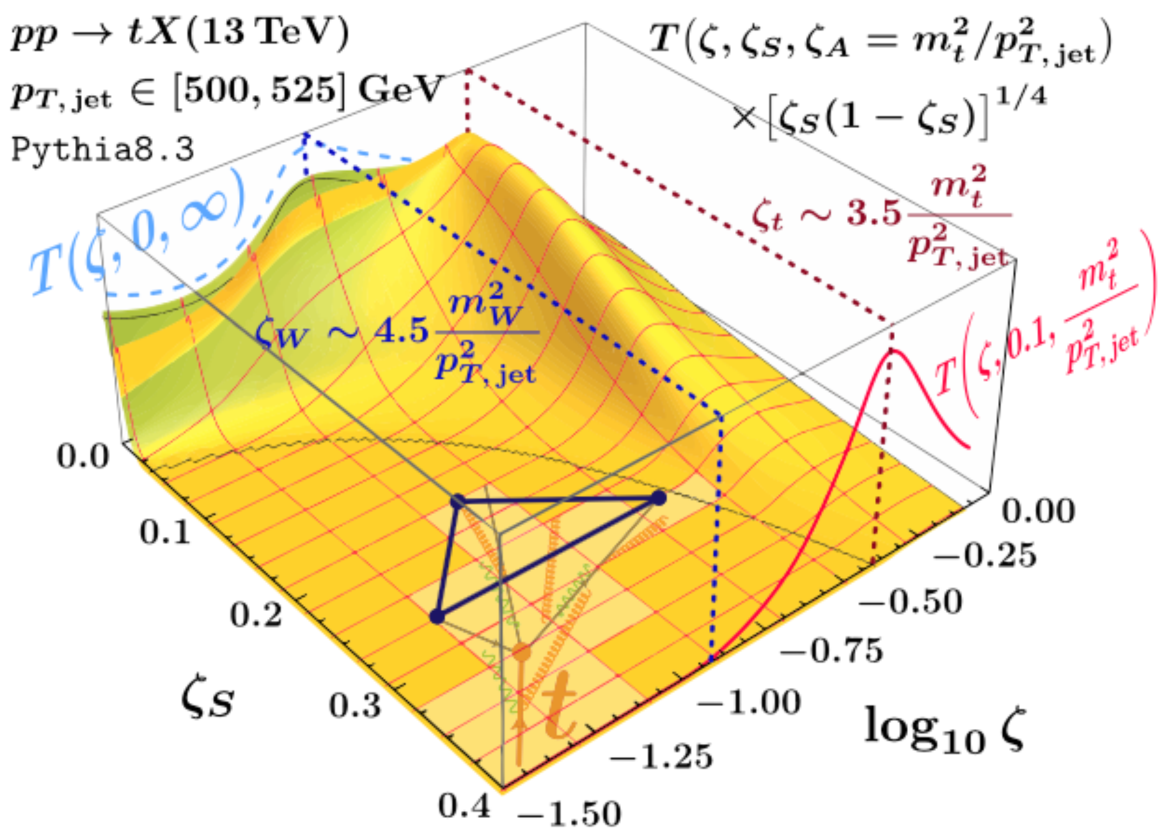


☐ Weighing the top quark

Holguin et al., 2022, 2023, 2024

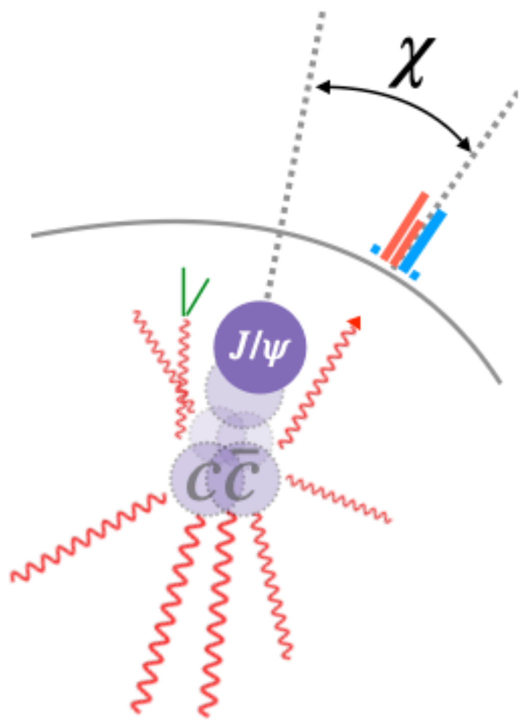
Xiao et al., 2024

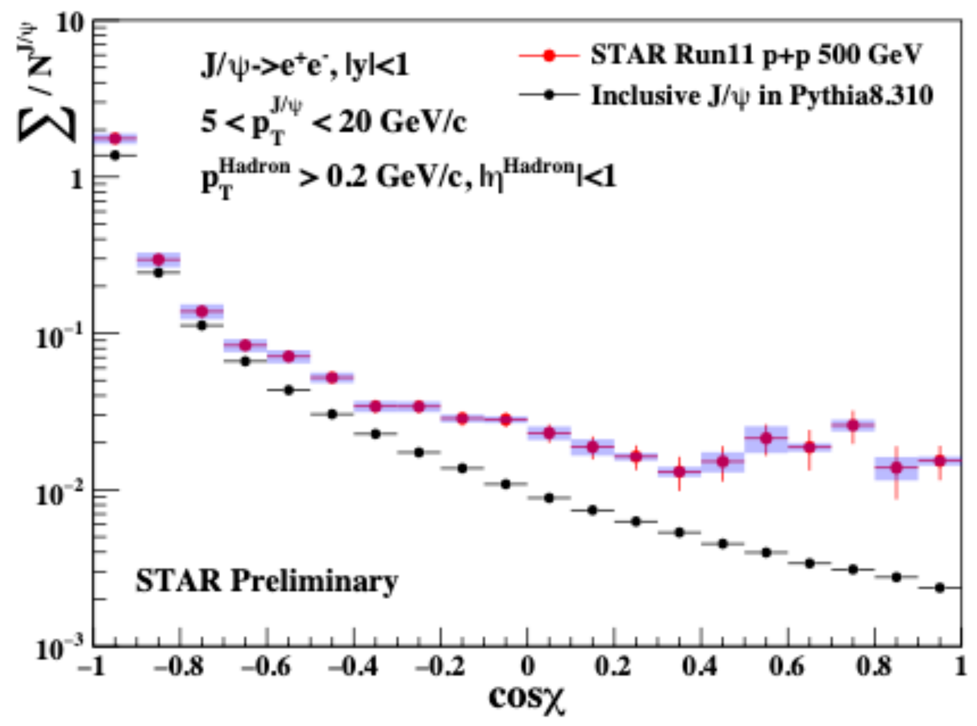


☐ Quarkonium dynamics

Chen et al., 2024

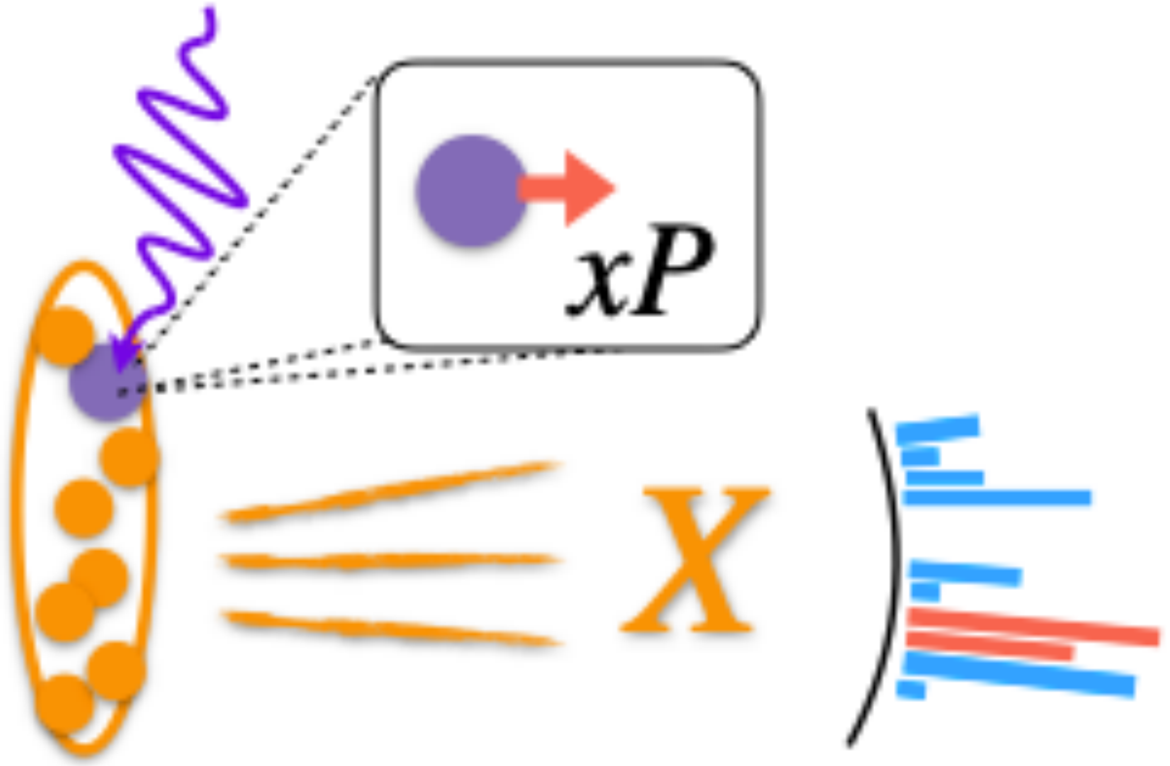
Shen, STAR





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

  - $f_{q,EEC}(x, \theta, \phi)$: The conditional probability of finding a parton with x while observing an energy flux from the target remnants in (θ, ϕ)

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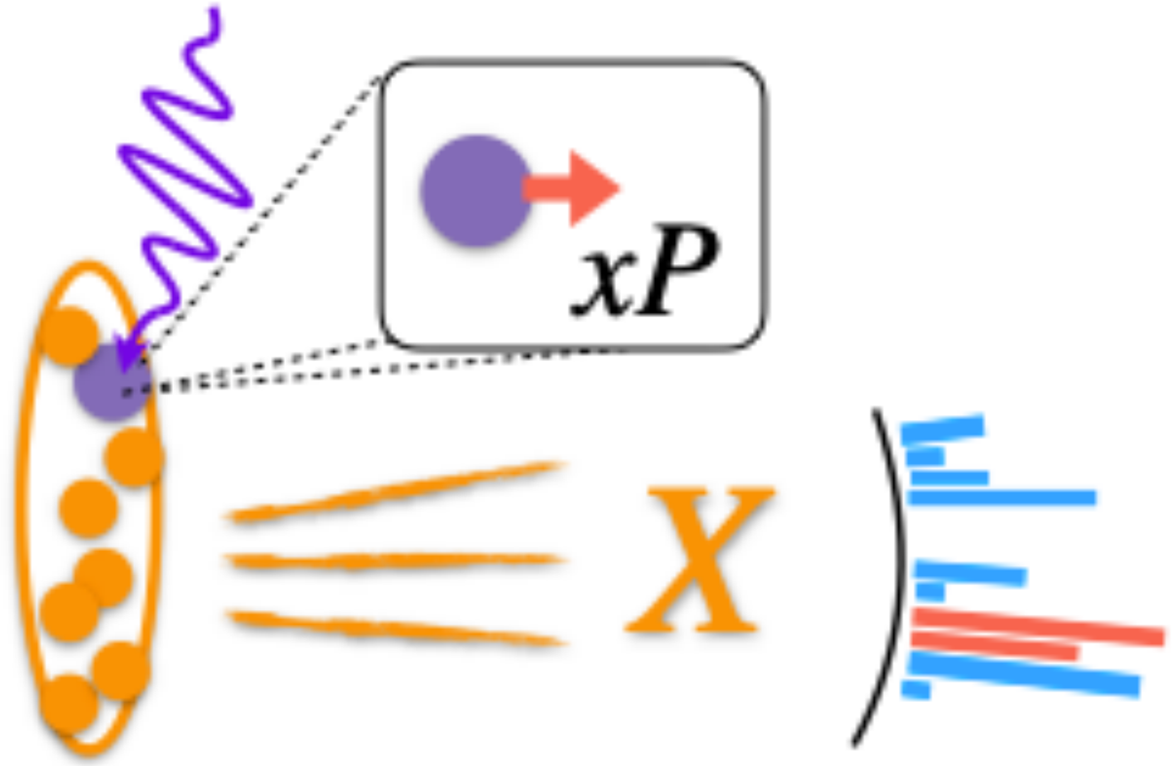

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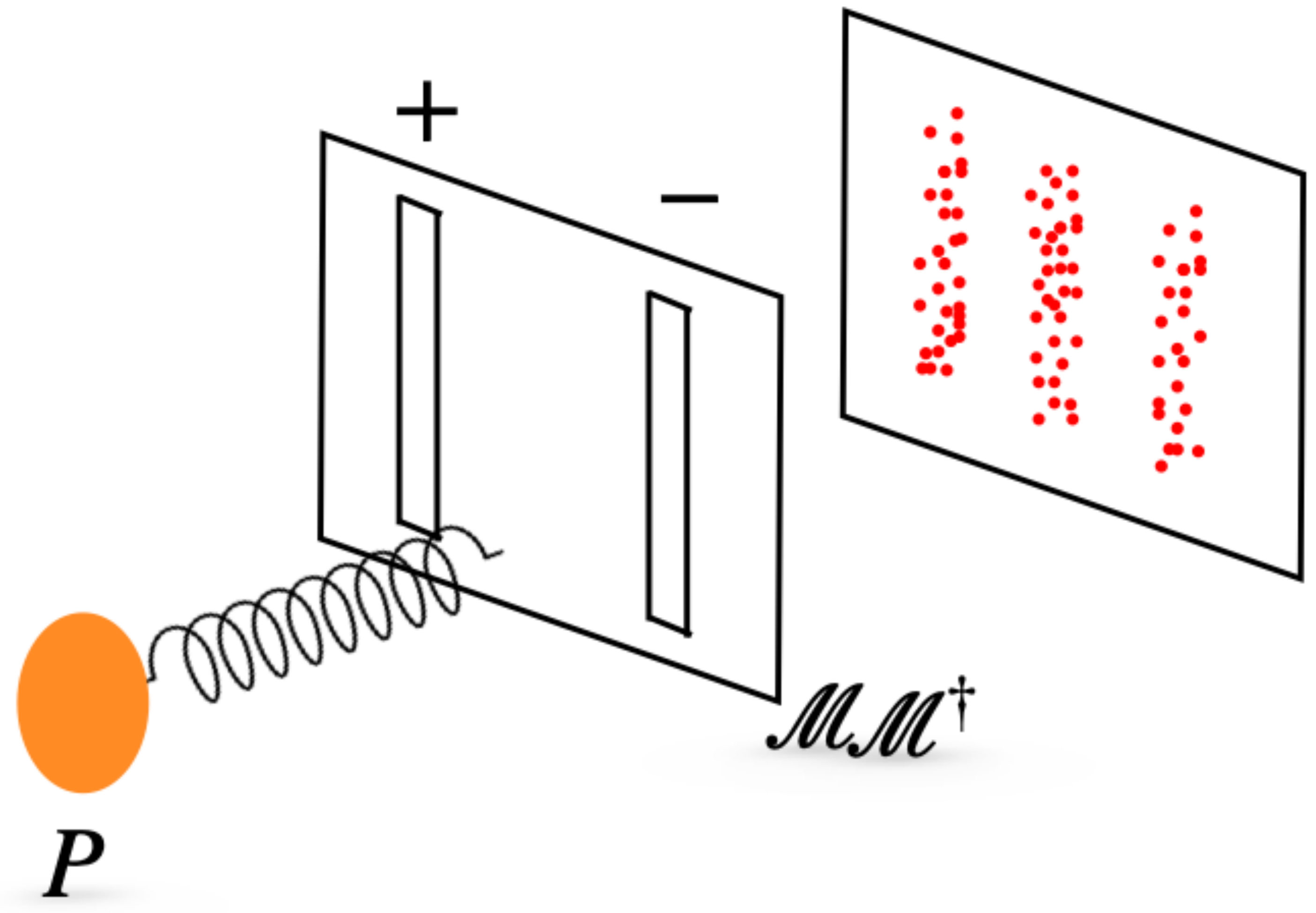
Like EECs, NECs also have many powerful applications

- 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

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

$$\mathcal{O}_{eW} = (\bar{L}\sigma^{\mu\nu}e)\tau^I \tilde{H} W^I_{\mu\nu}$$
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Chirality-flipping for fermions

$$\mathcal{O}_{uW} = (\bar{Q}\sigma^{\mu\nu}u)\tau^I \tilde{H} W^I_{\mu\nu}$$
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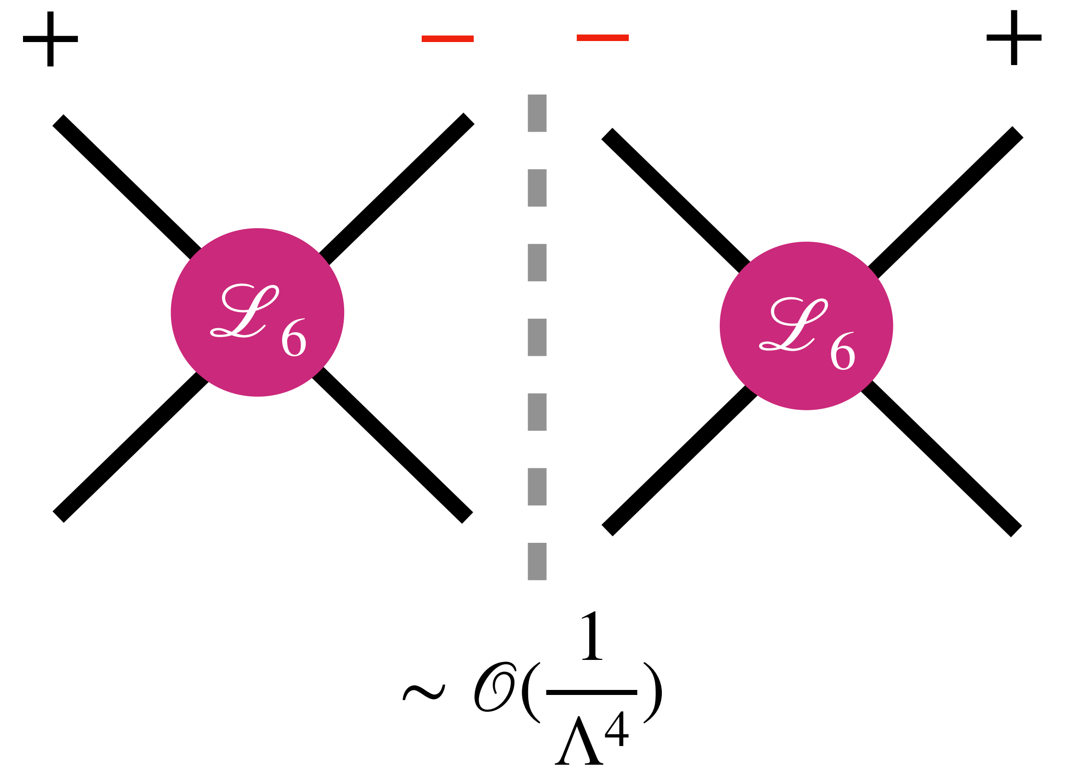
- Essential for understanding anomalous magnetic moments and P, T violating electric dipole moments of baryons
- The dipole operators are usually quadratically suppressed in unpolarized xsec, and polluted by dim-8 operators



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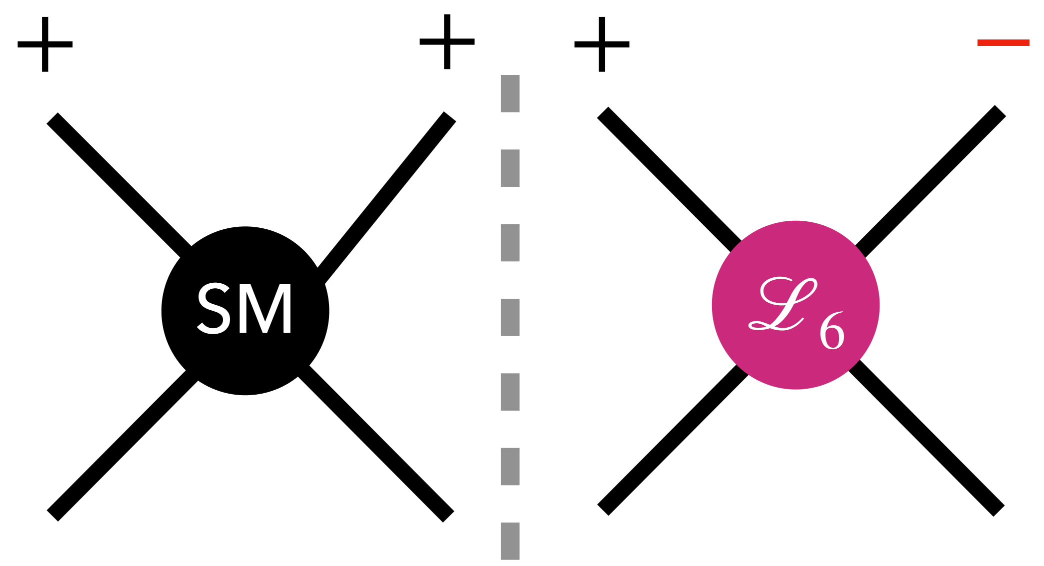

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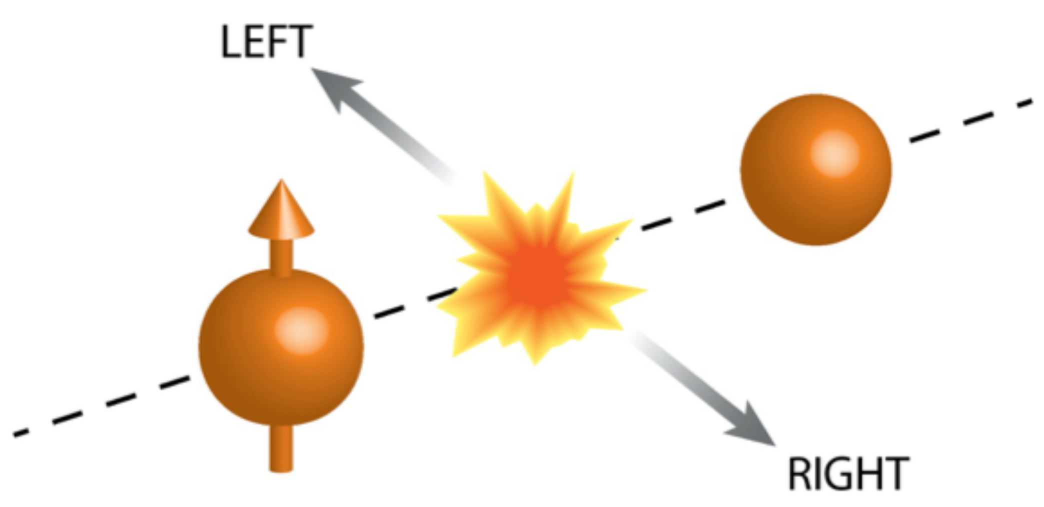

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Boughezal, Florian, Petriello and Vogelsang, PRD 2023

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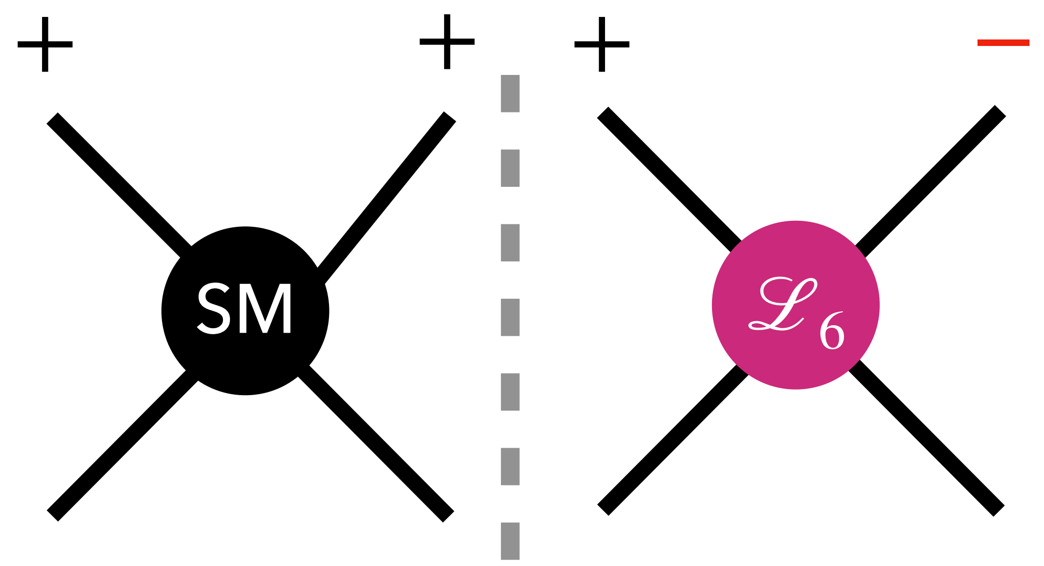

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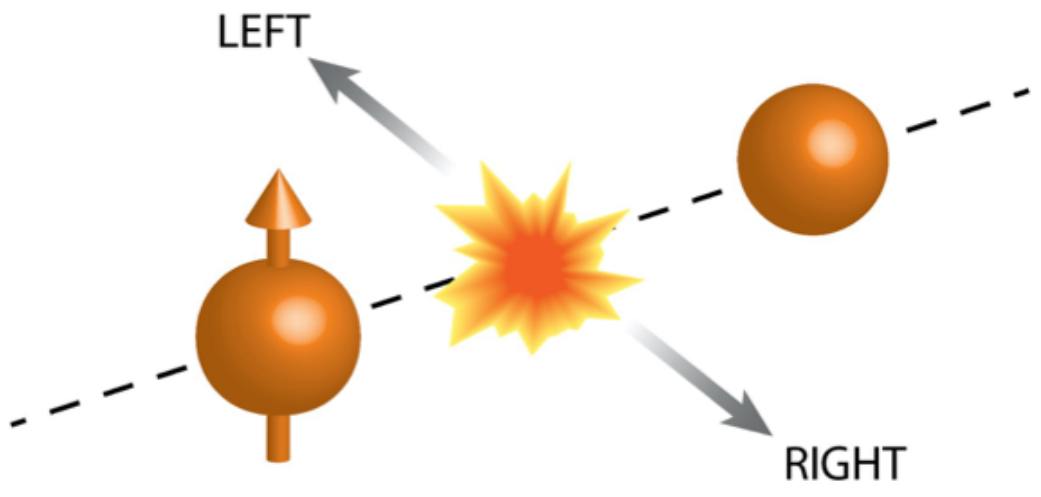

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Wen, Yan, Yu and Yuan, 2408.07255
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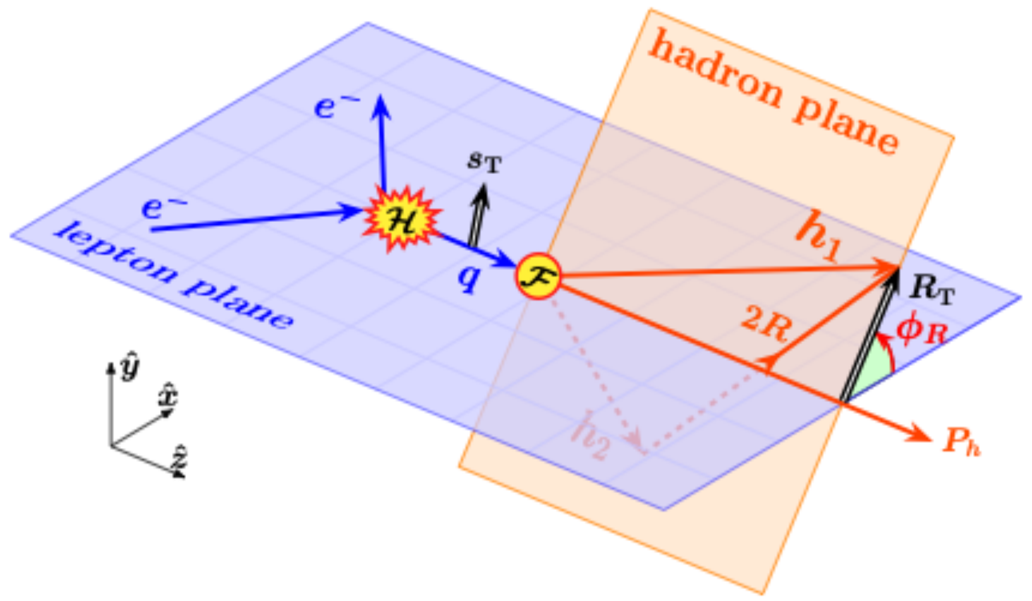

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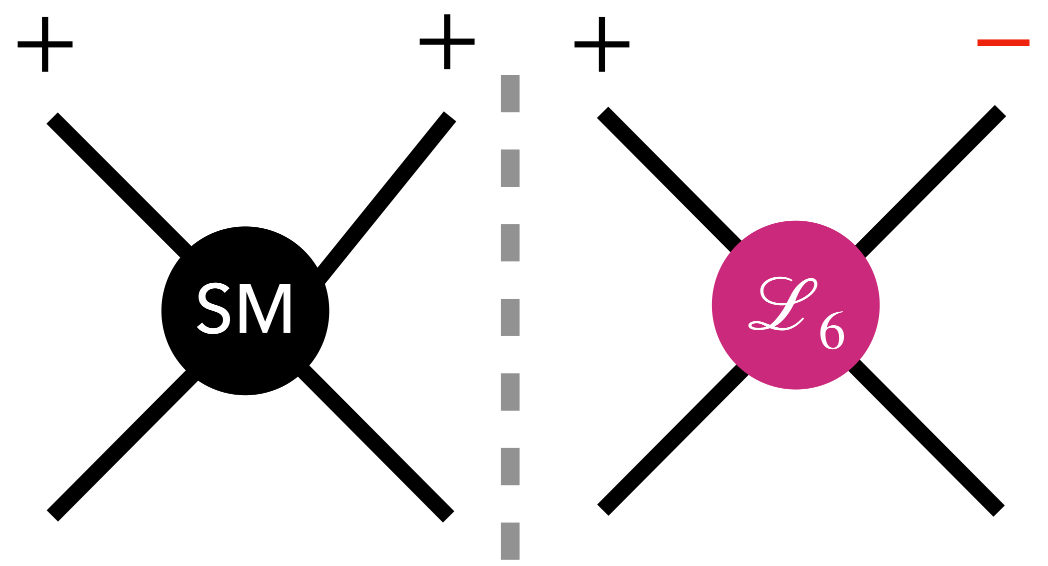

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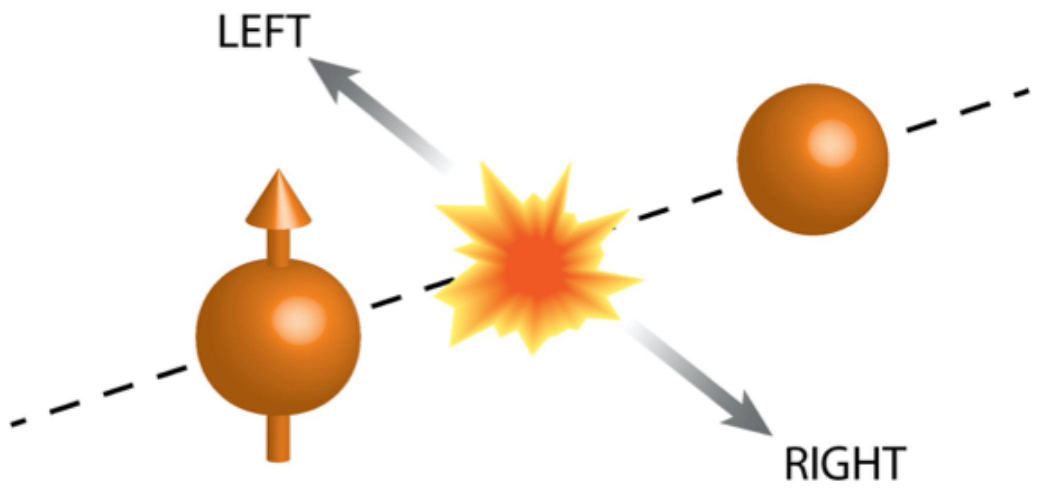

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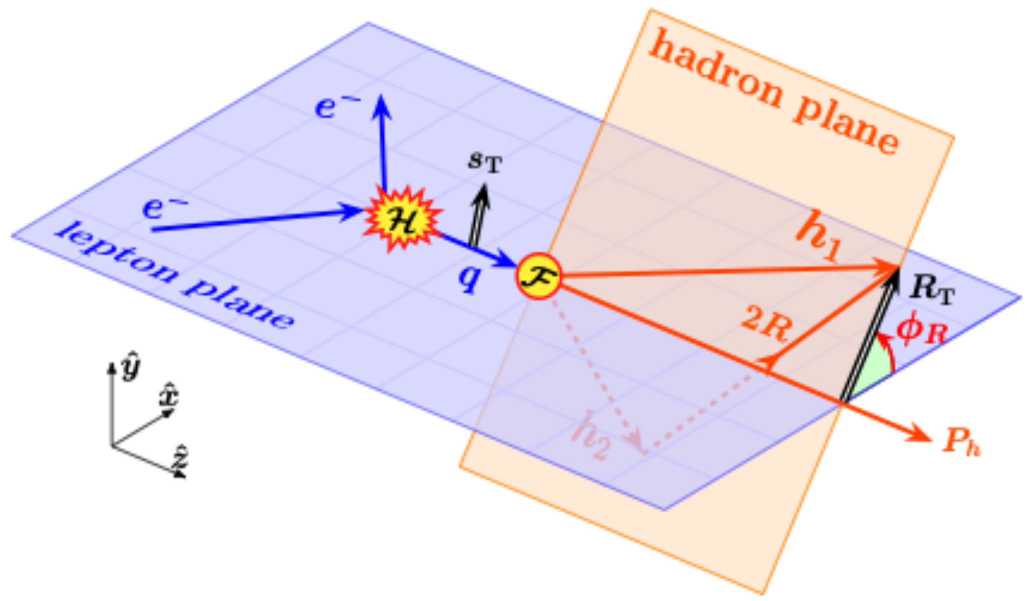

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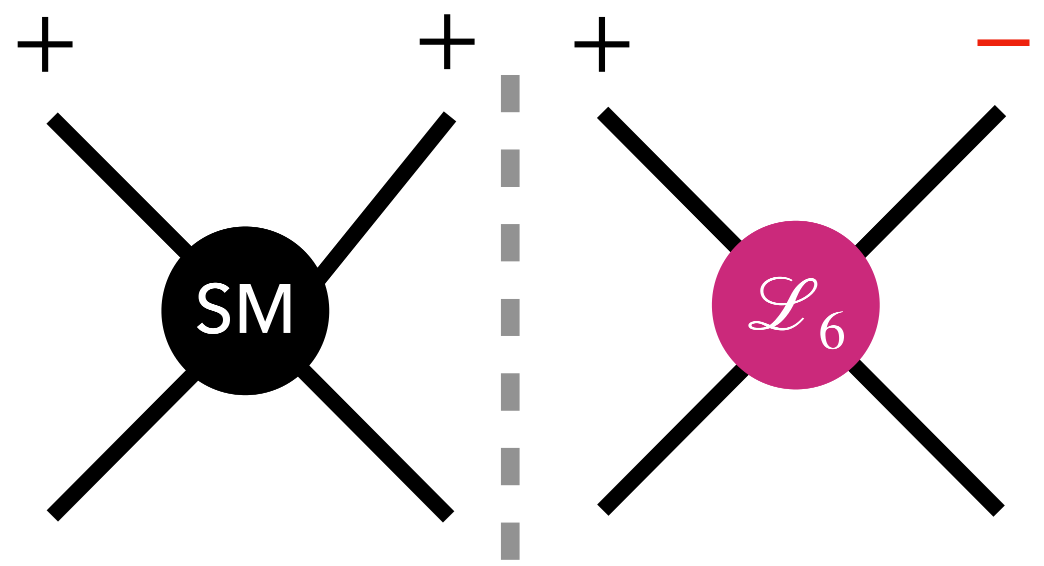

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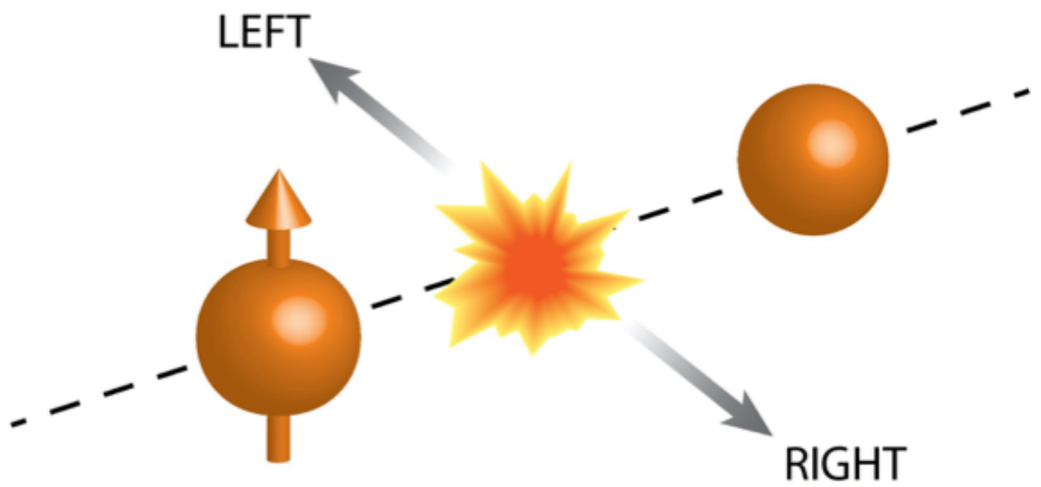

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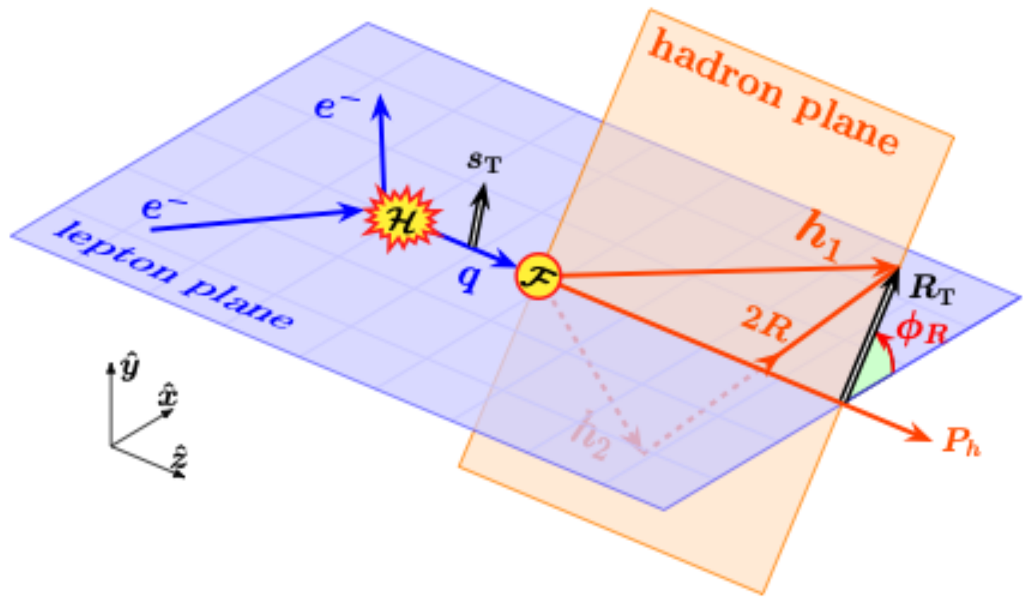

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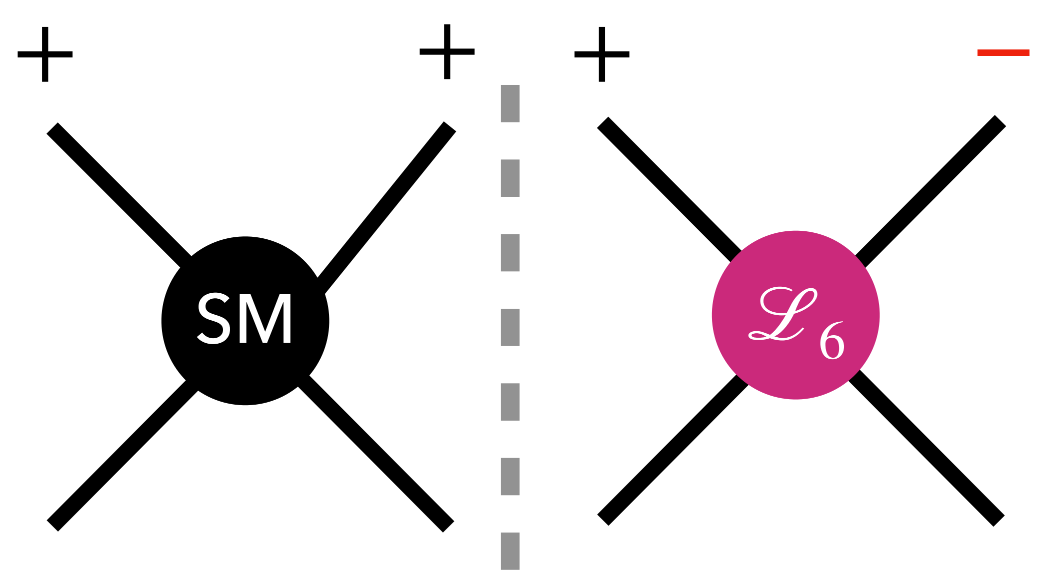

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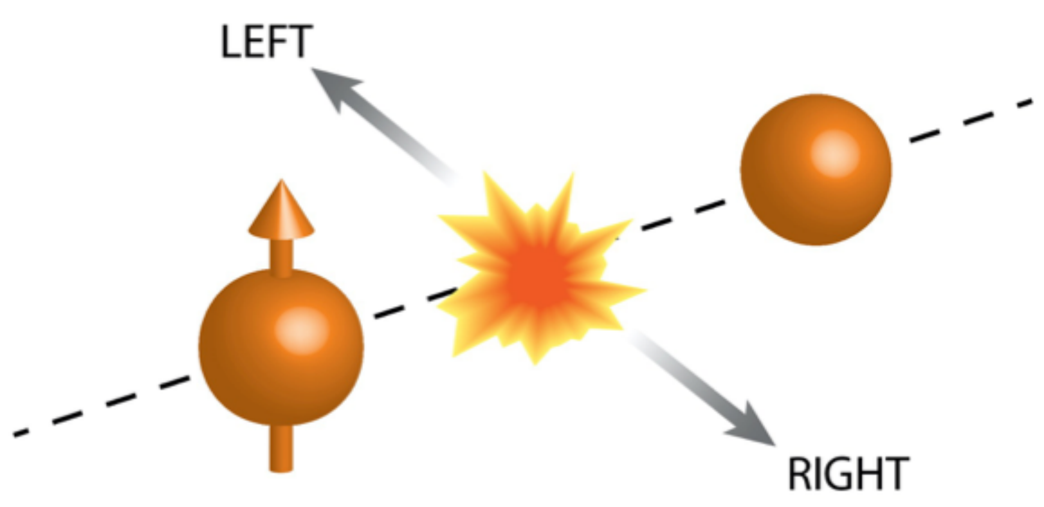

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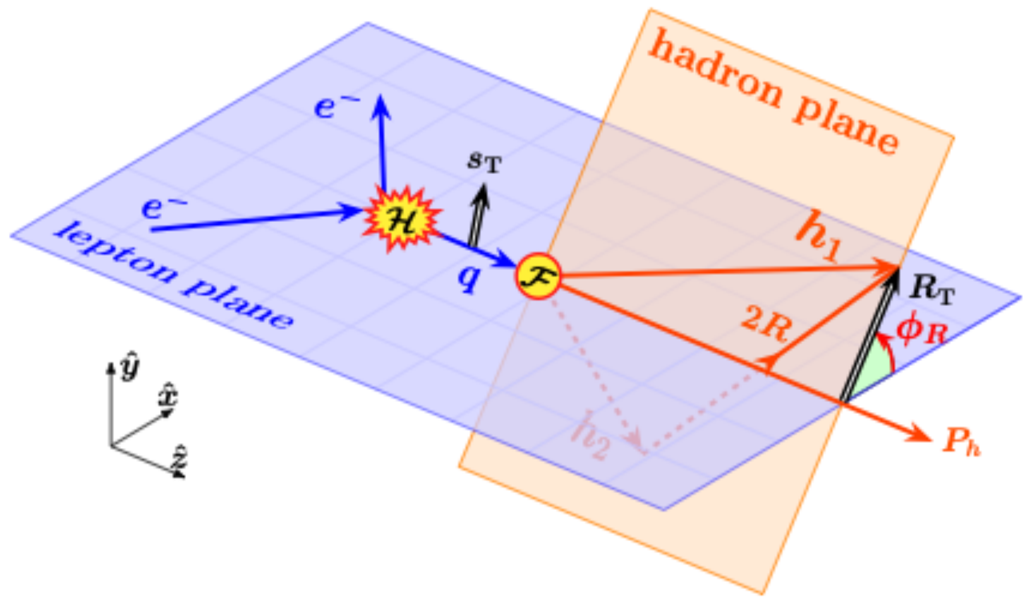

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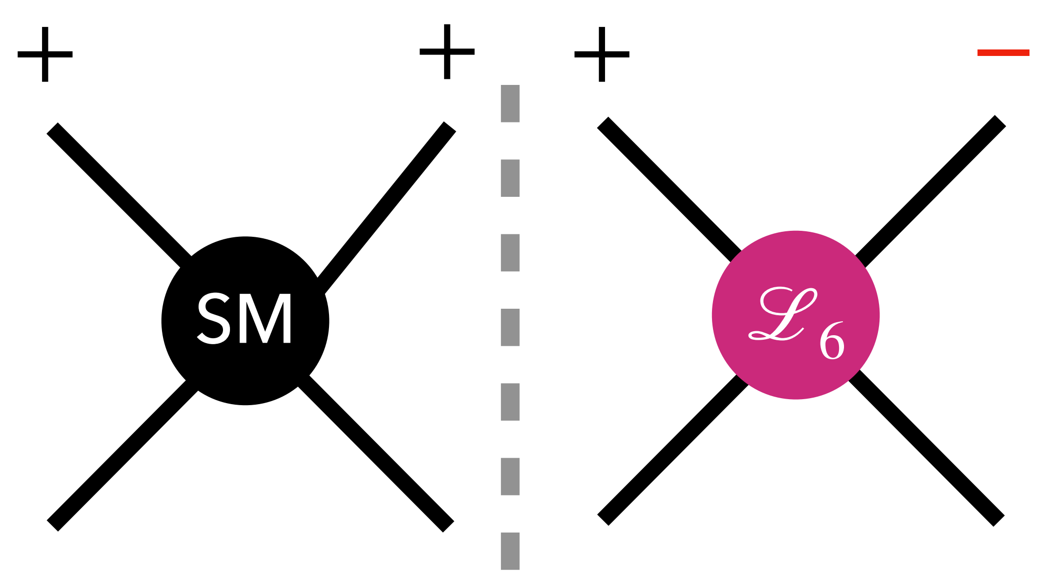

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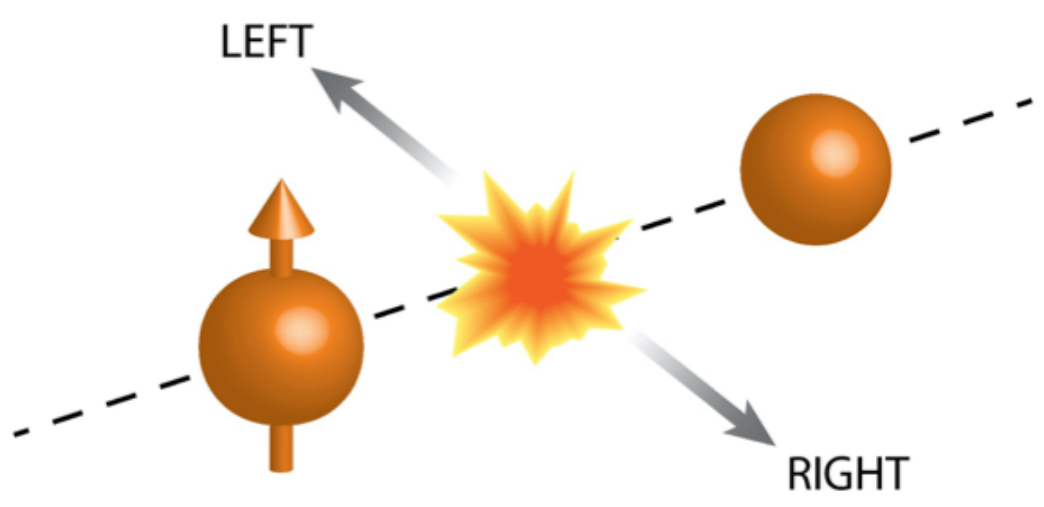

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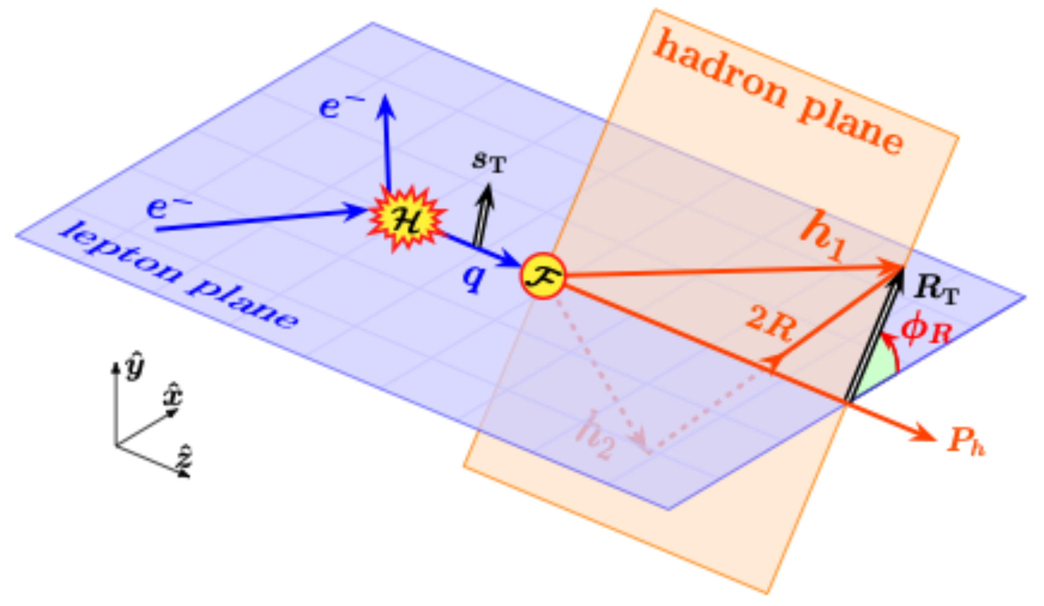

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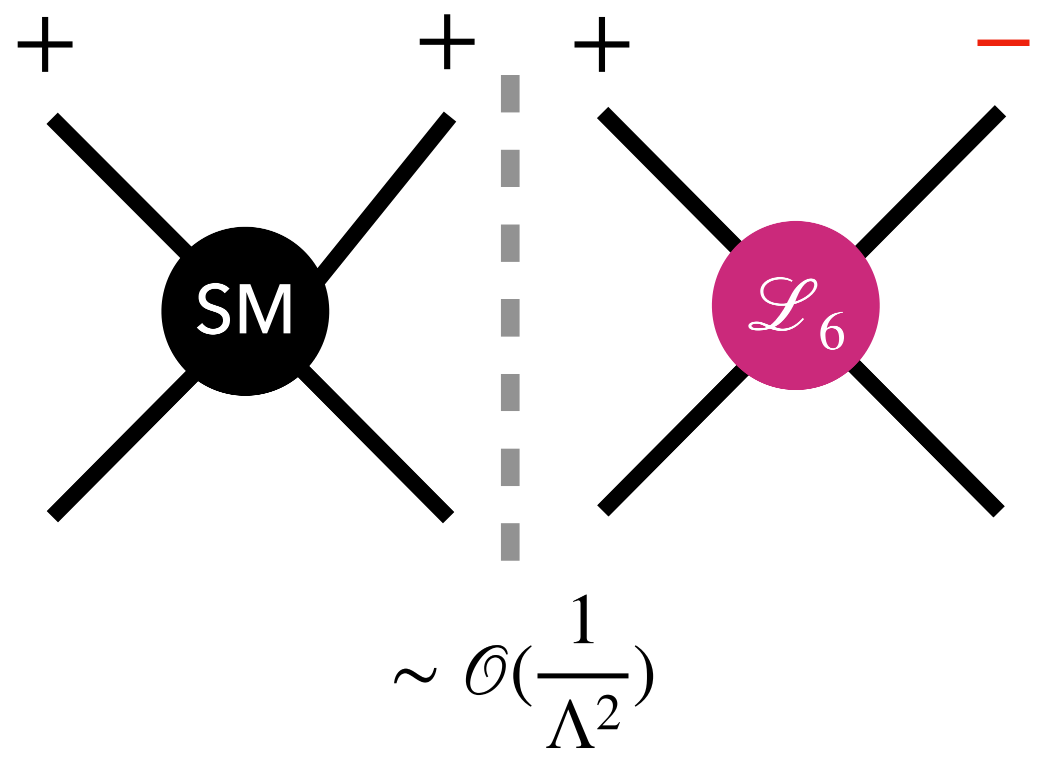

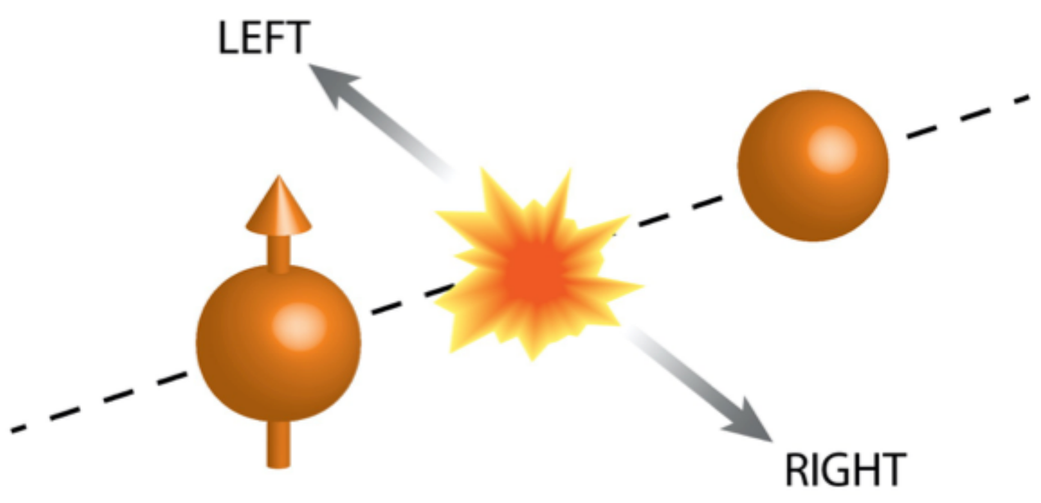

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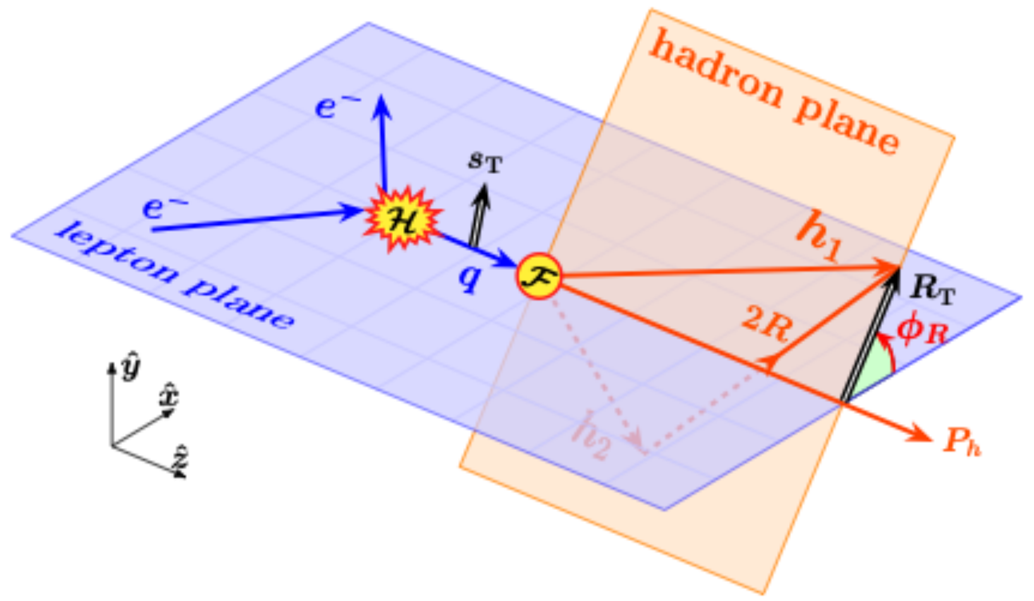

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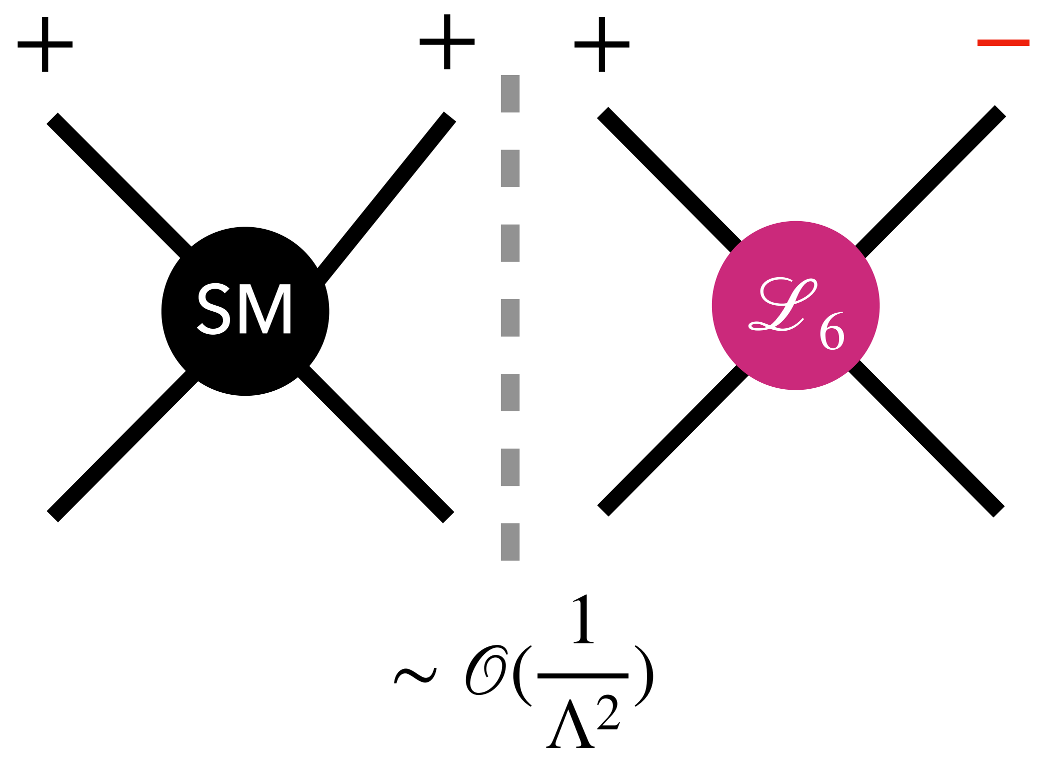

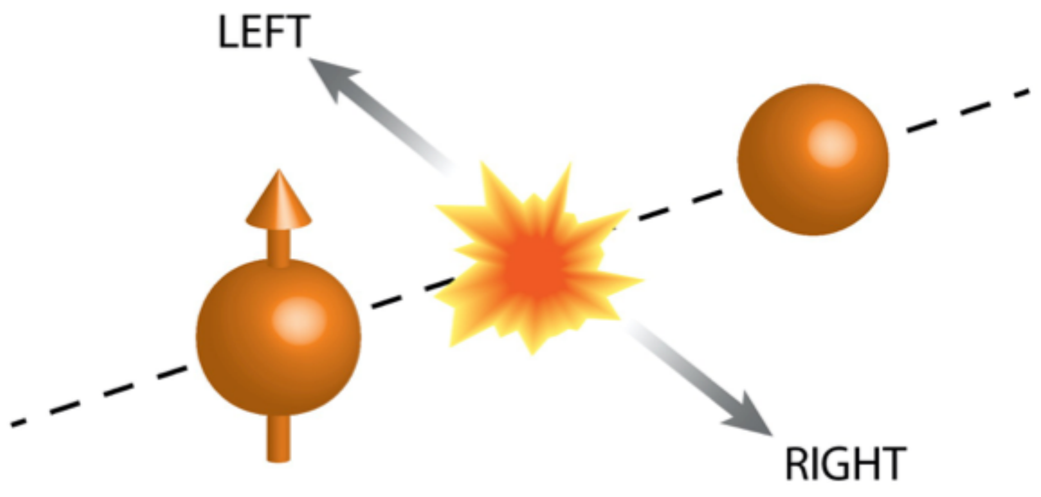

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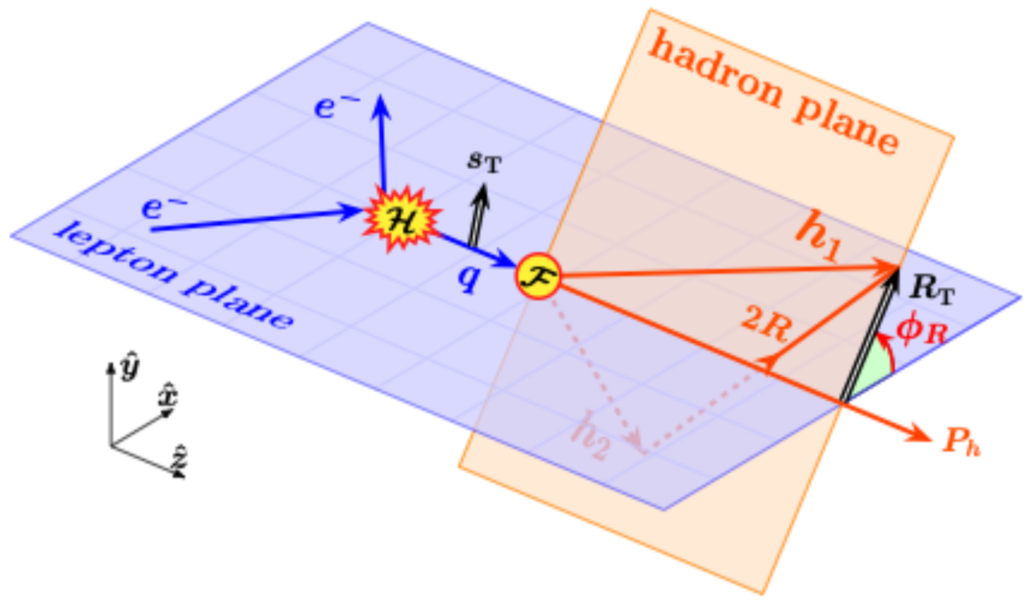

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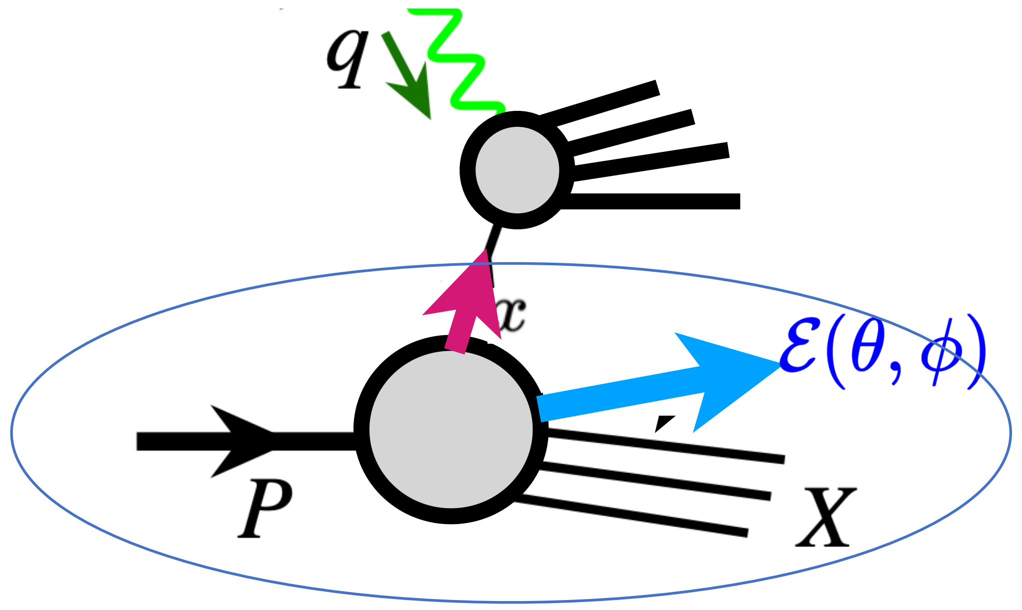
NEC combines the best of the two!

Quark transversity NEC

- Operator definition for quark NECs:

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

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



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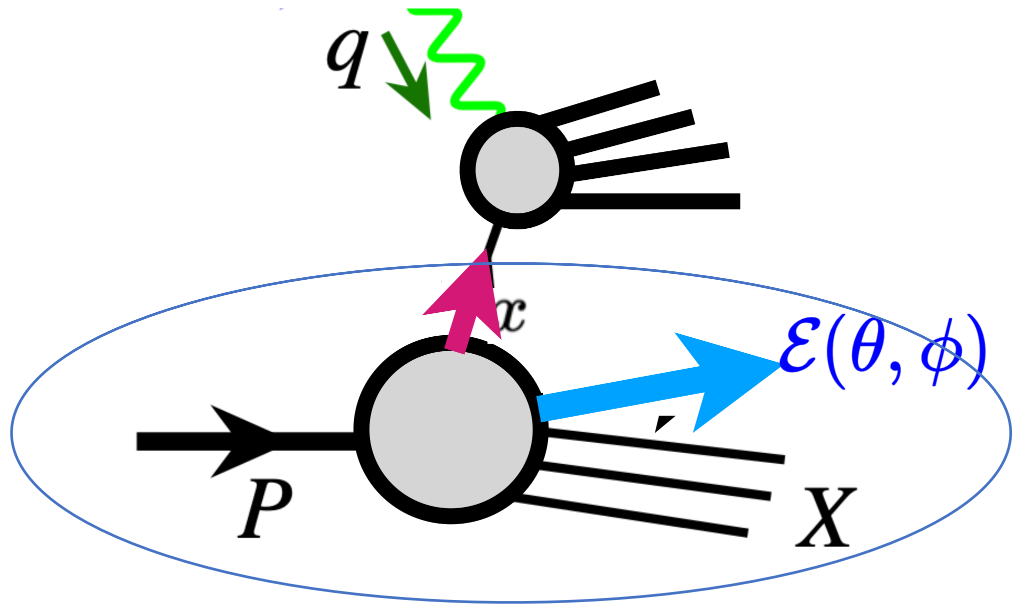
- Operator definition for quark NECs:

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

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 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



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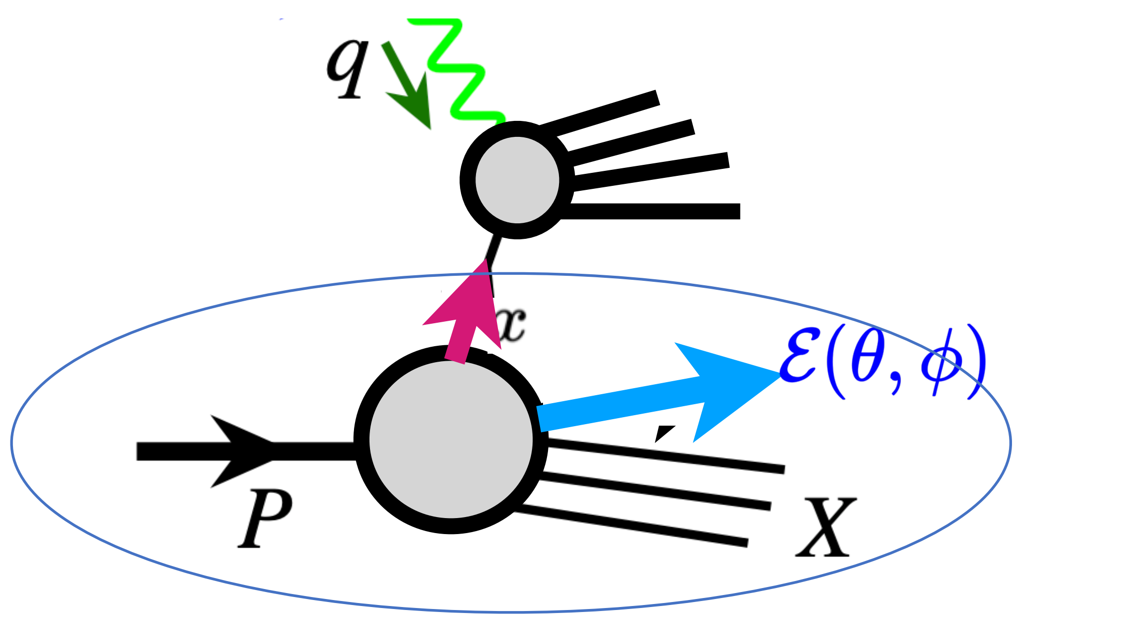

- The leading-twist chiral-even unpolarized quark NEC ($\Gamma = \gamma^+$):

See more in Chen-Ma-Tong, JHEP 2024

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

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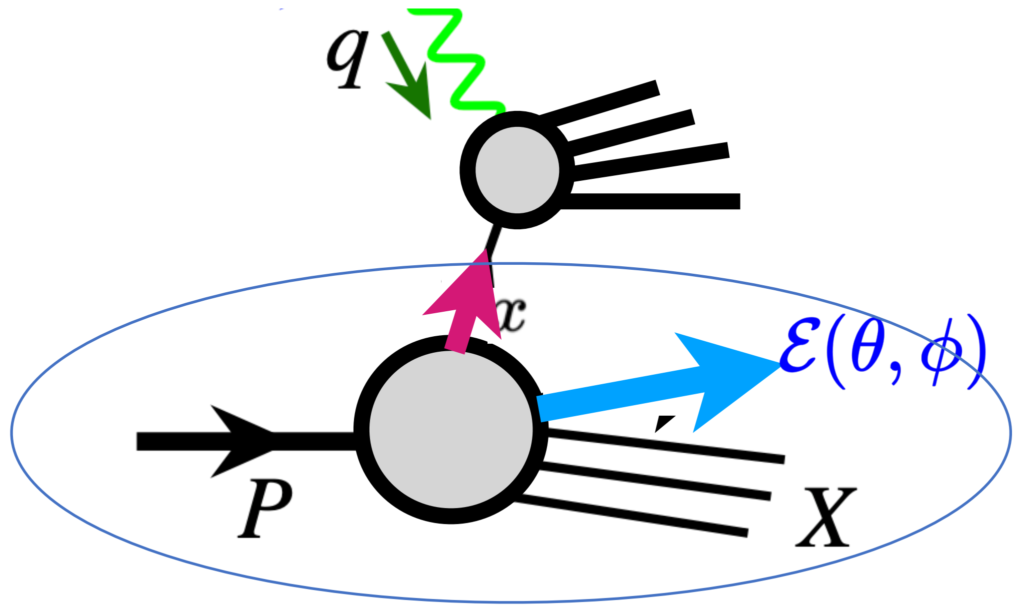

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$$f_1^q(x,\theta^2) = \mathscr{M}^{[\gamma^+]}(x,\theta,\phi)$$

- 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

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

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

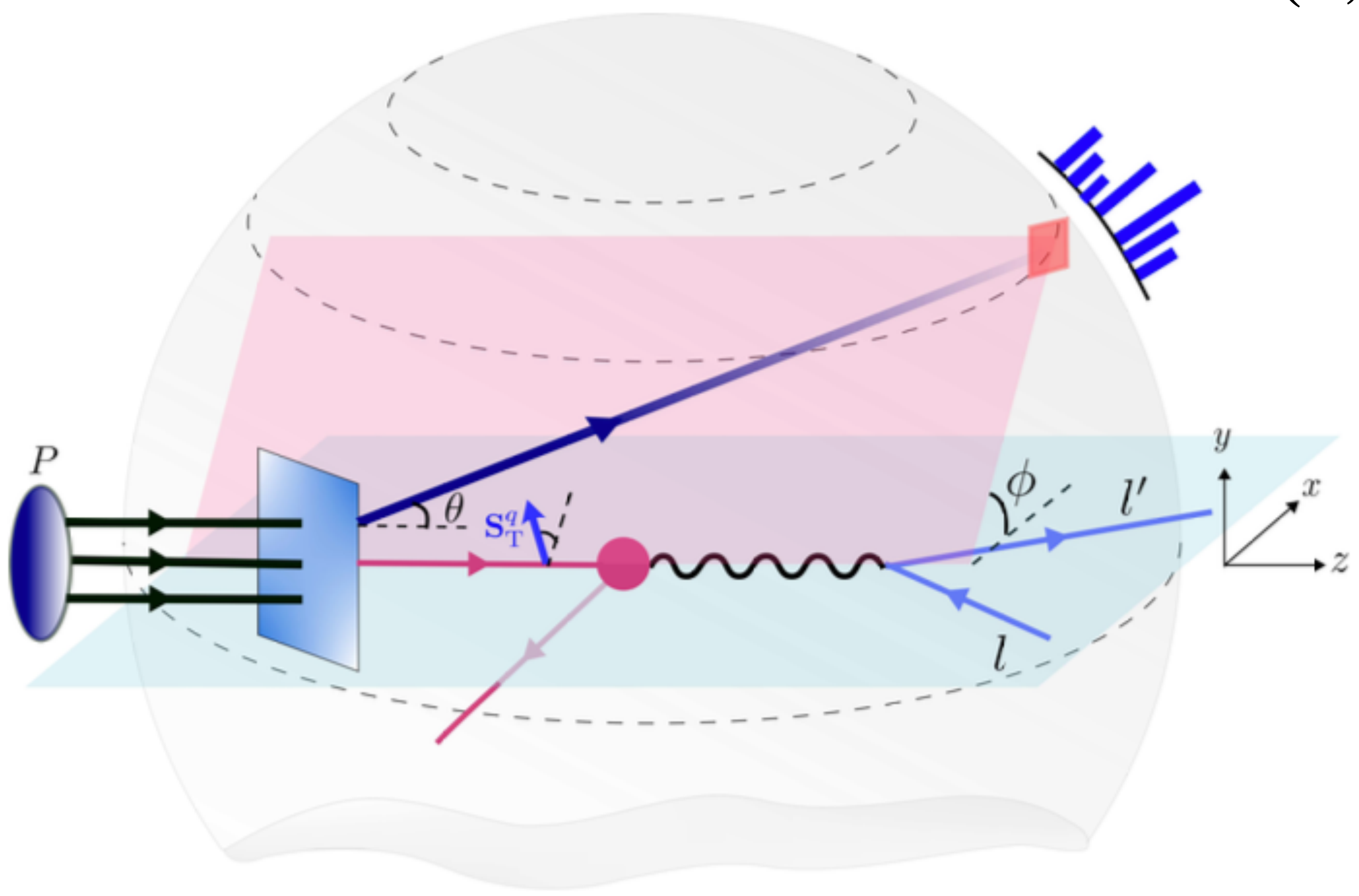
Probing the quark dipole operators with transversity NEC

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

$$e + P \to e + X$$

- We define the energy pattern xsec as:

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



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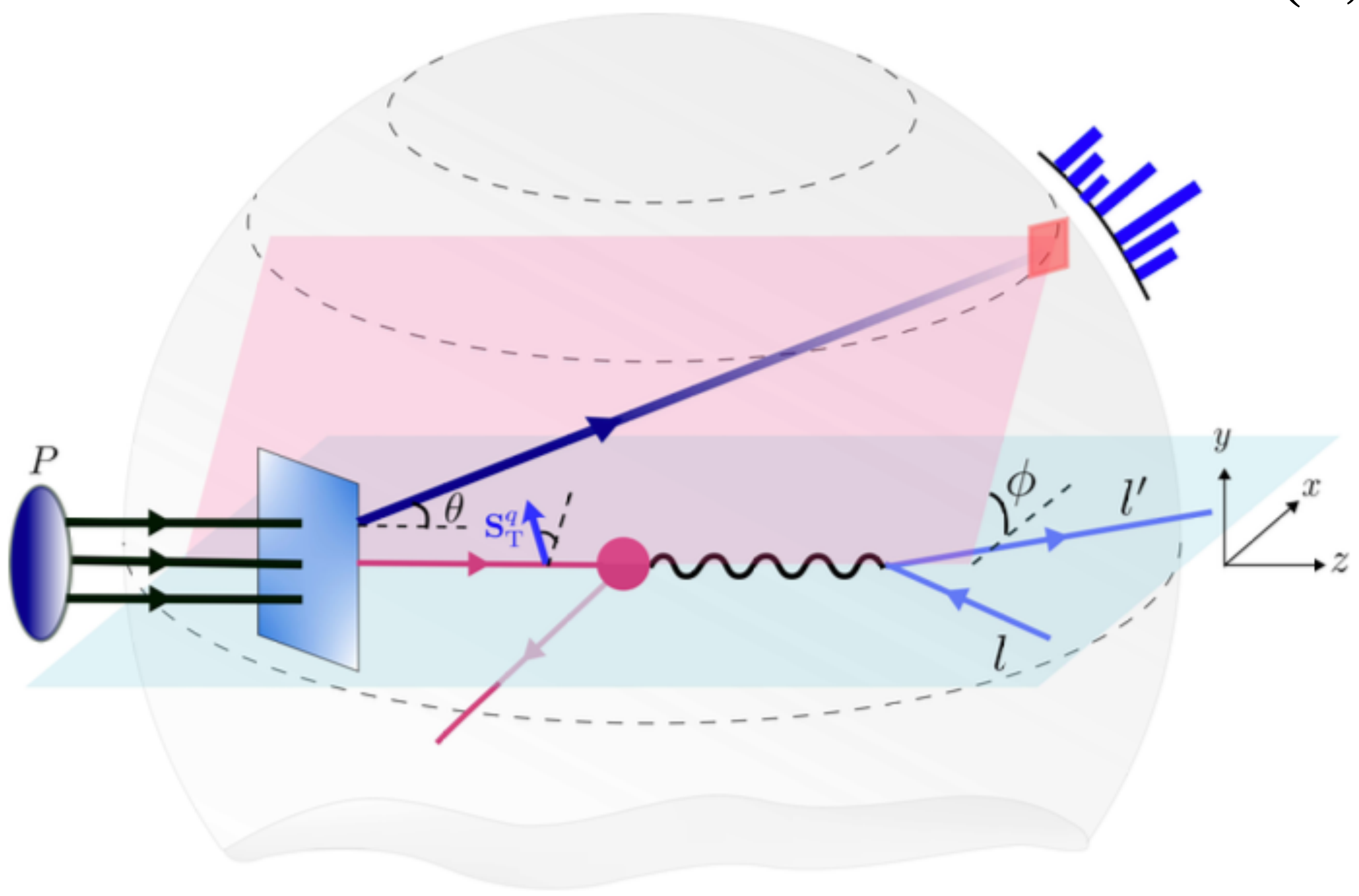

TFR: $\theta P^+ \ll Q$

Collinear factorization:

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

Same as in standard inclusive DIS

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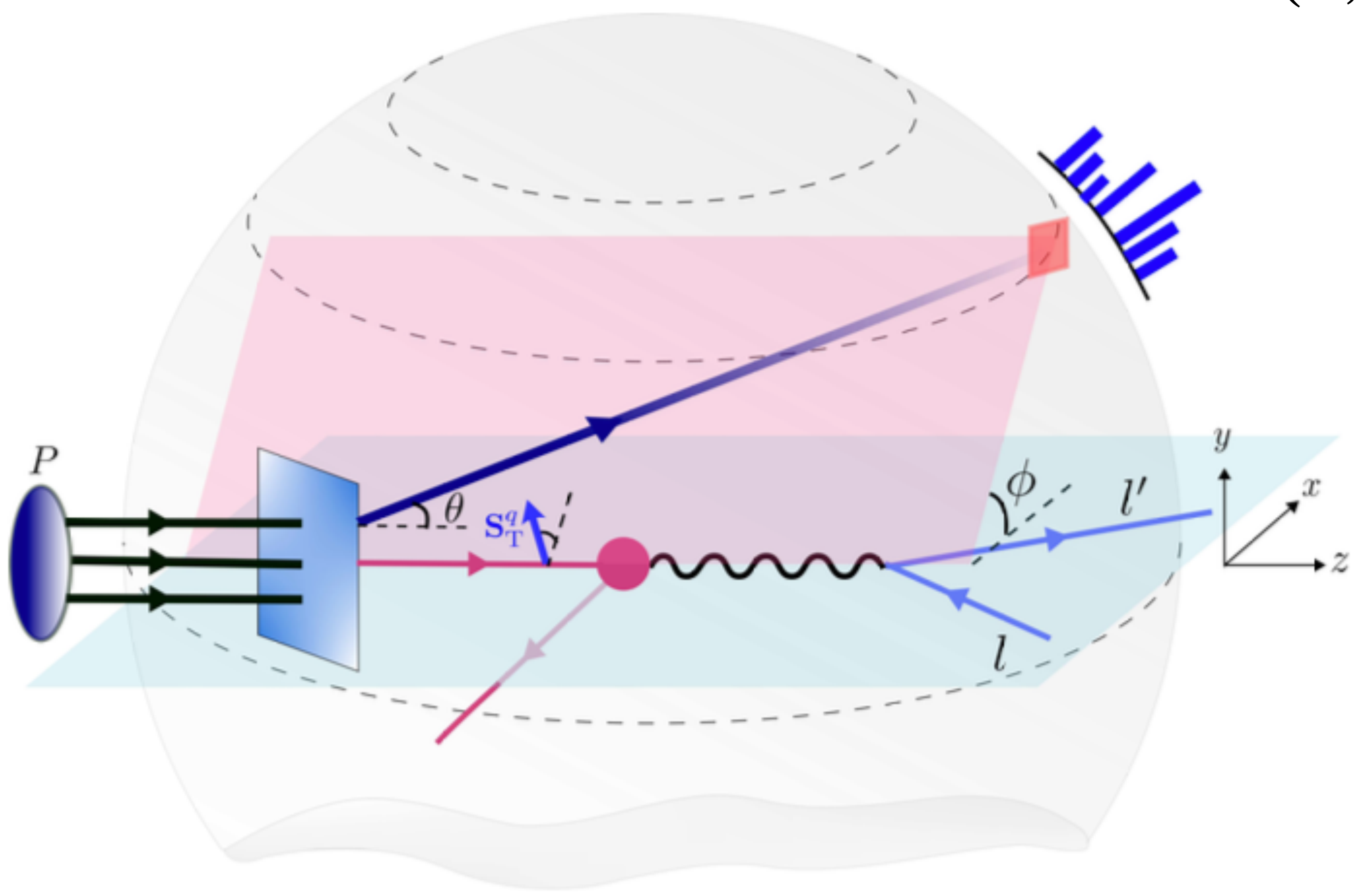

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NEC as a quark polarizer

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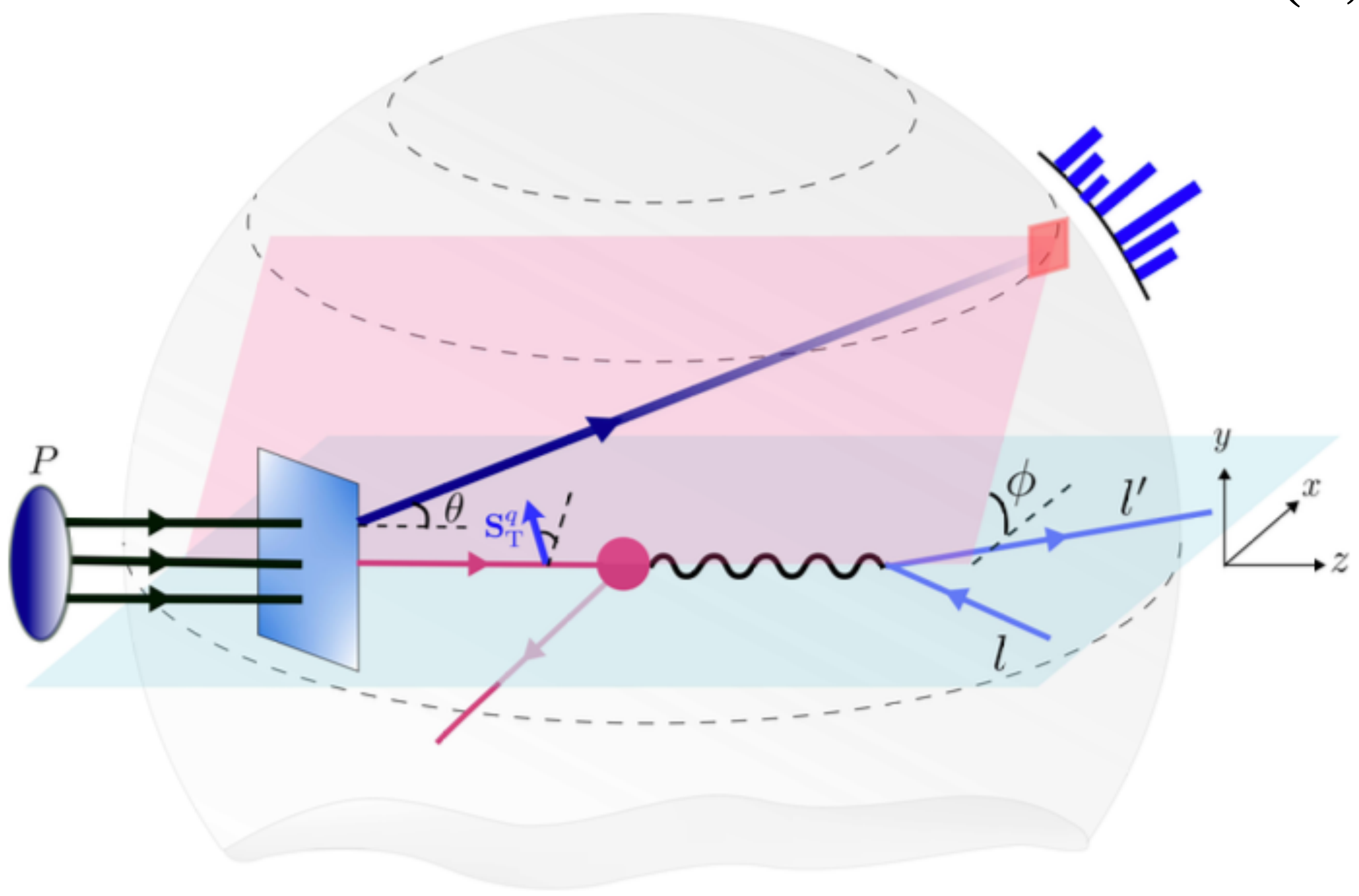

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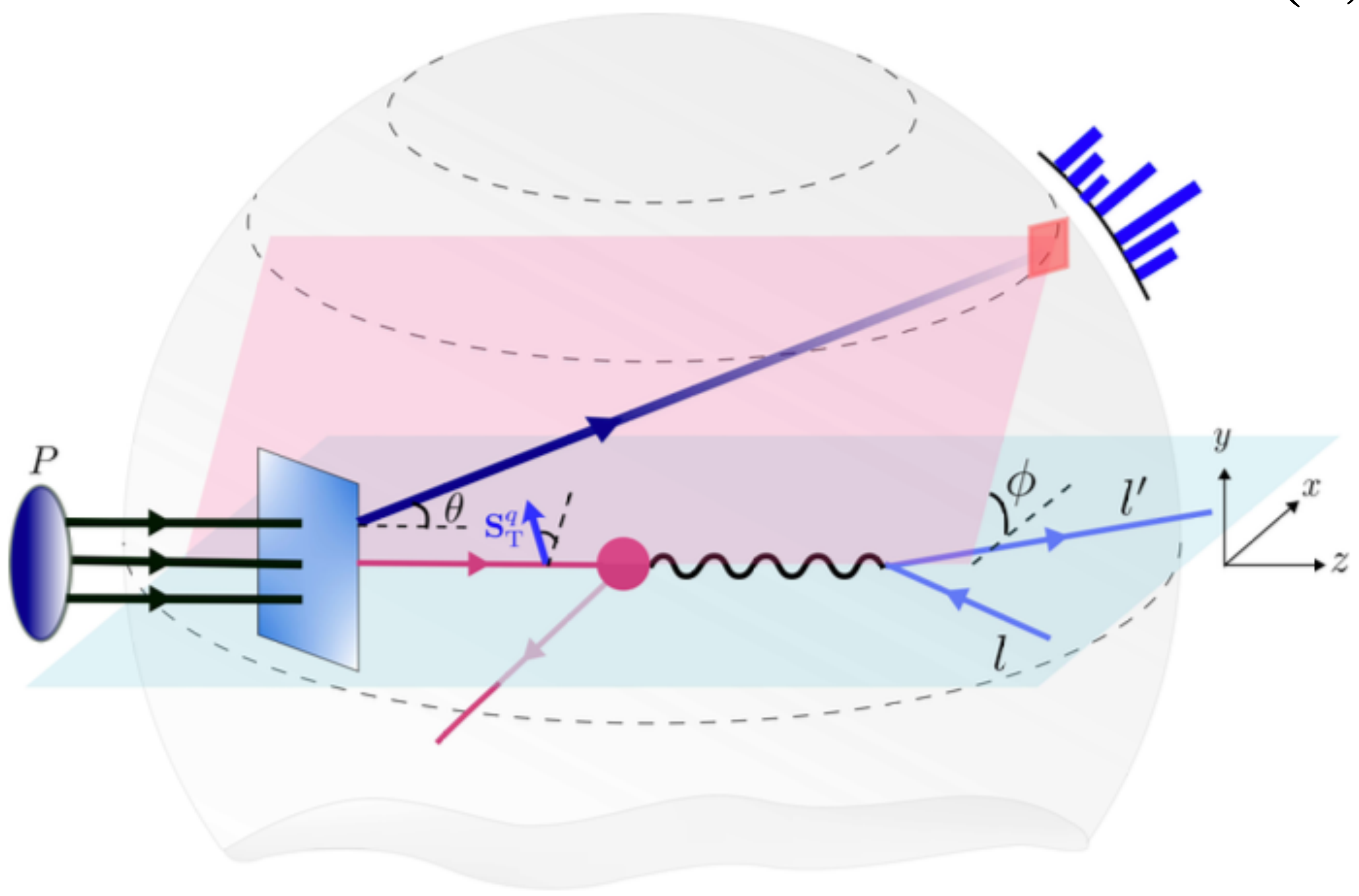

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NEC as a quark polarizer

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

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

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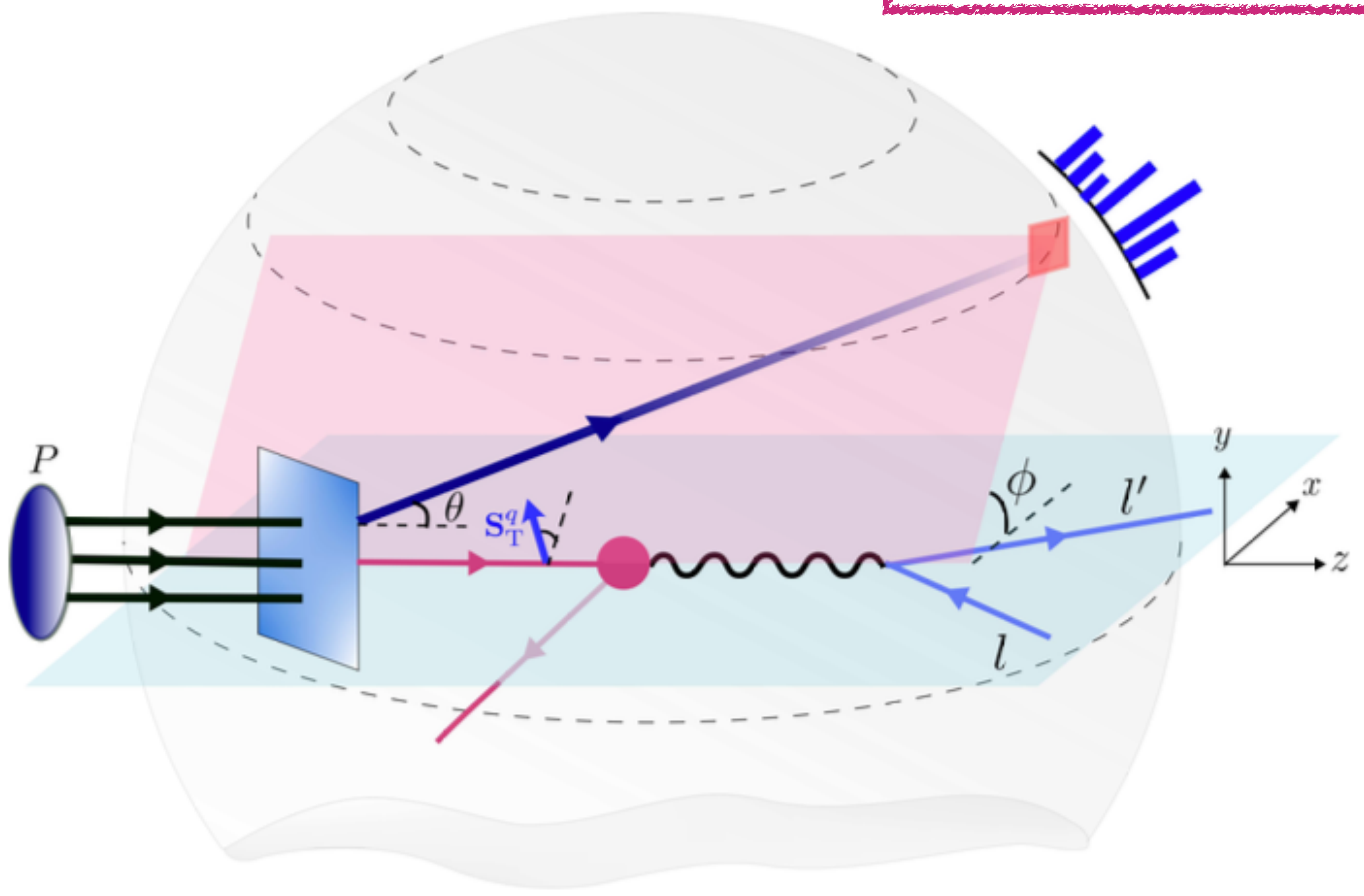

Within the SM

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

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

Vanishing to all orders in α_S

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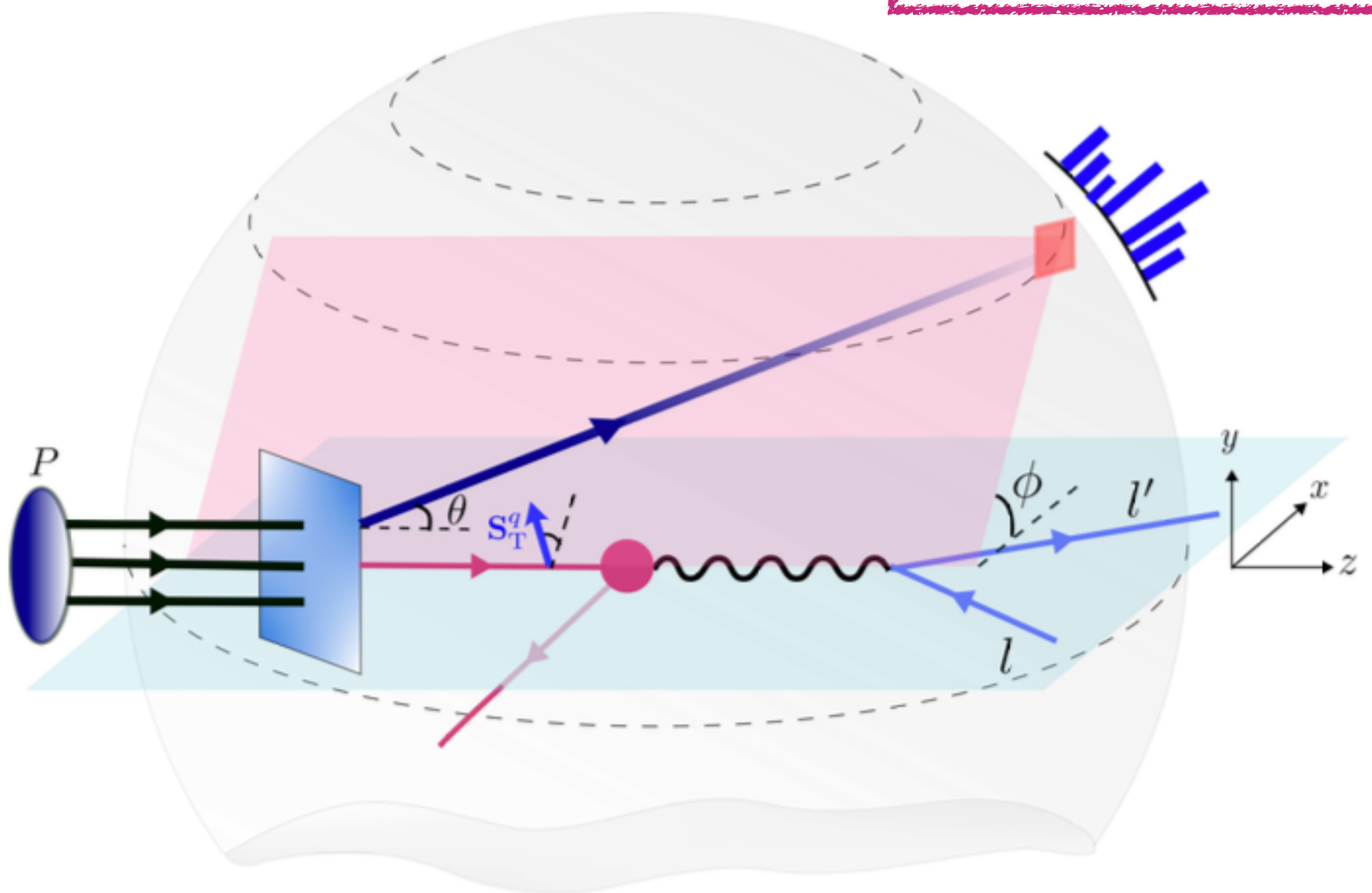

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NEC as a quark polarizer

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

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

Probing the quark dipole operators with transversity NEC

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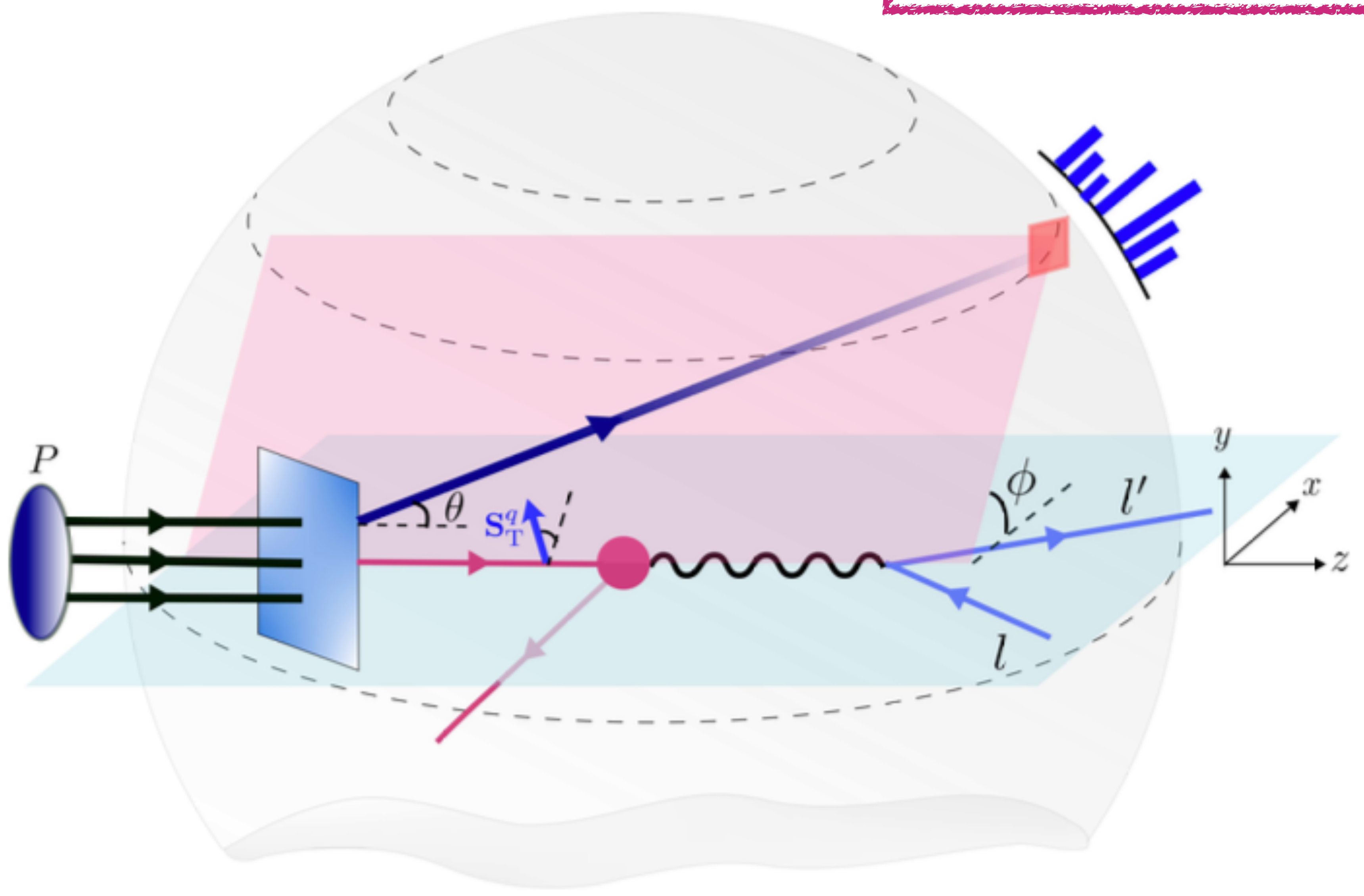

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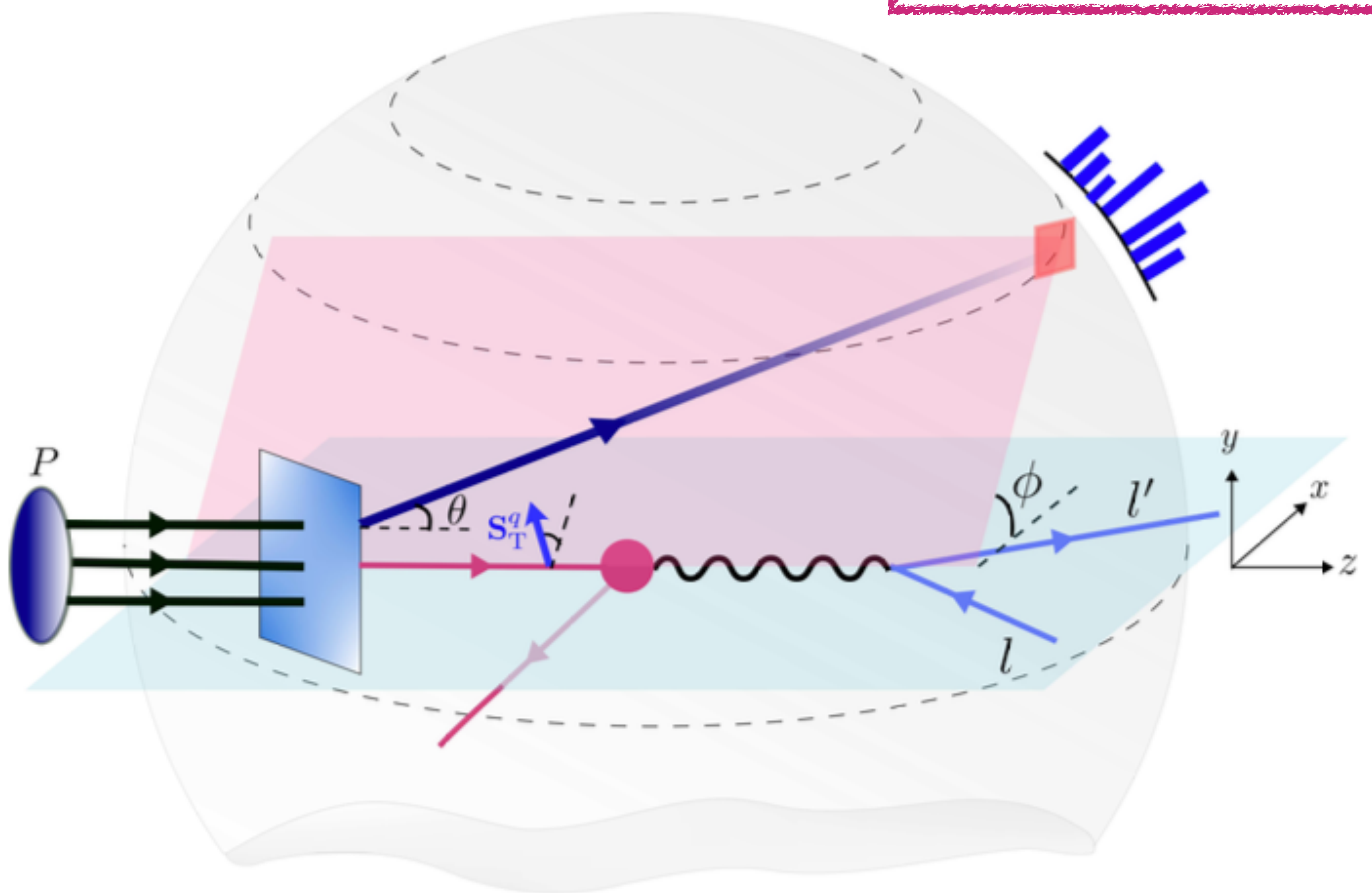

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$$\frac{d\Sigma_{UU}^{\sin\phi}}{dx_B dQ^2} = \frac{4\pi\alpha_{\rm em}^2}{e c_W s_W}\frac{y\sqrt{1-y}}{Q(Q^2+m_Z^2)}\sum_q h_1^{t,q}(x_B,\theta^2) \times \left\{\left[\frac{2-y}{y}g_A^q g_V^e + g_V^q g_A^e\right]\frac{{\rm Re}[c_{q\gamma}]}{c_W s_W}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

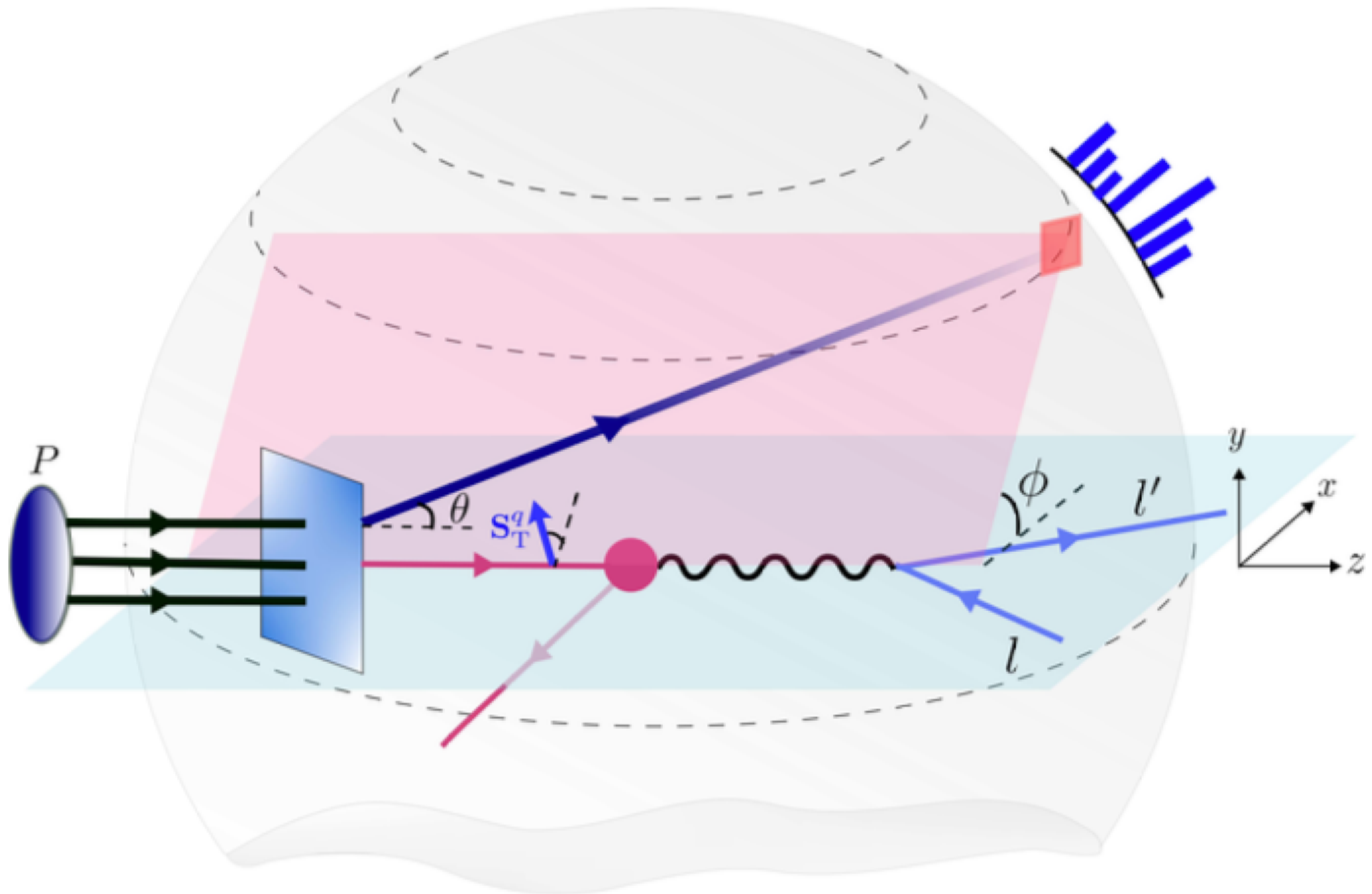
- Linearly determined by the Re or Im of C_i individually
- Uniquely generated by the light-quark dipole operators

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

Probing the quark dipole operators with transversity NEC

Extend to include a longitudinally polarized electron beam:

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



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

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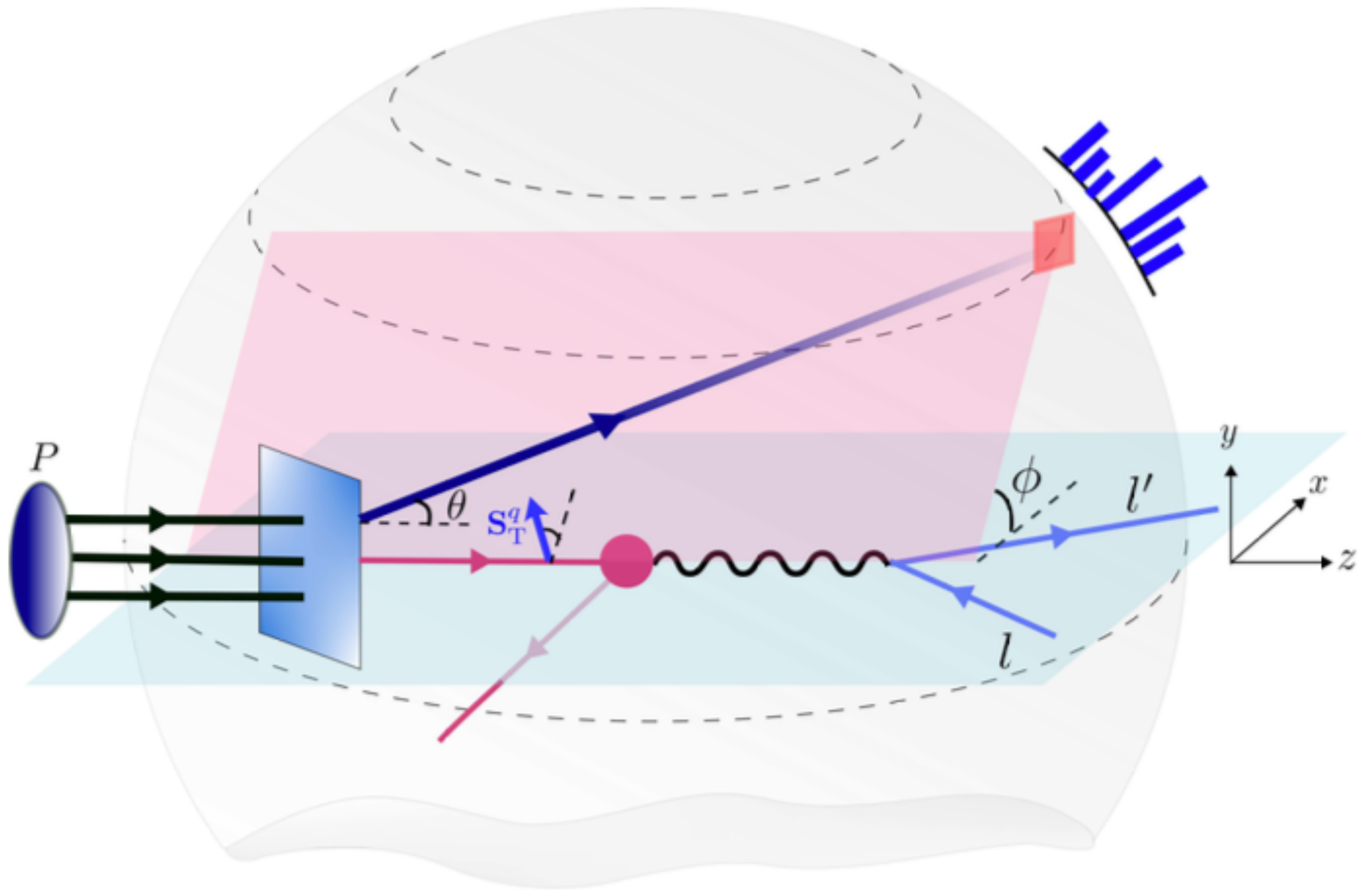

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Parity violation from electron longitudinal polarization → Generated via $\gamma\gamma$ interference, without Q^2/m_Z^2 suppression → Enhanced sensitivity

Calorimetric asymmetries

- We introduce azimuthal angle aymmetries of the energy pattern:

Unpolarized e^- beam

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

$\boldsymbol{u} = \sin\phi$ or $\cos\phi$

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

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

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

Liu and Zhu, arxiv: 2403.08874

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

→ ☑ *Non-perturbative inputs for quark NECs*

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Allow us to infer the NECs from existing global fits of TMDs! → ☑ *Non-perturbative inputs for quark NECs* ← Measuments 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

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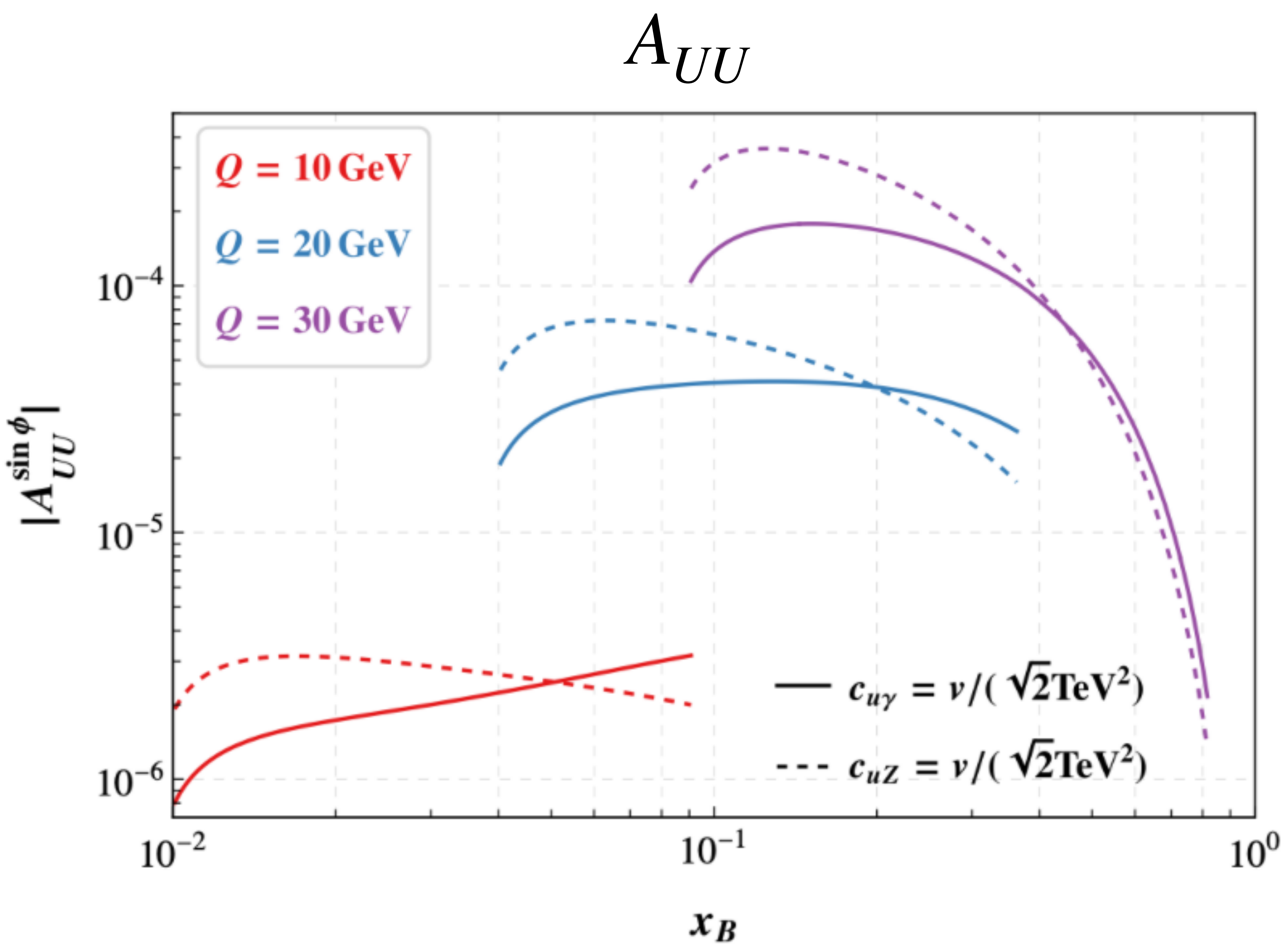
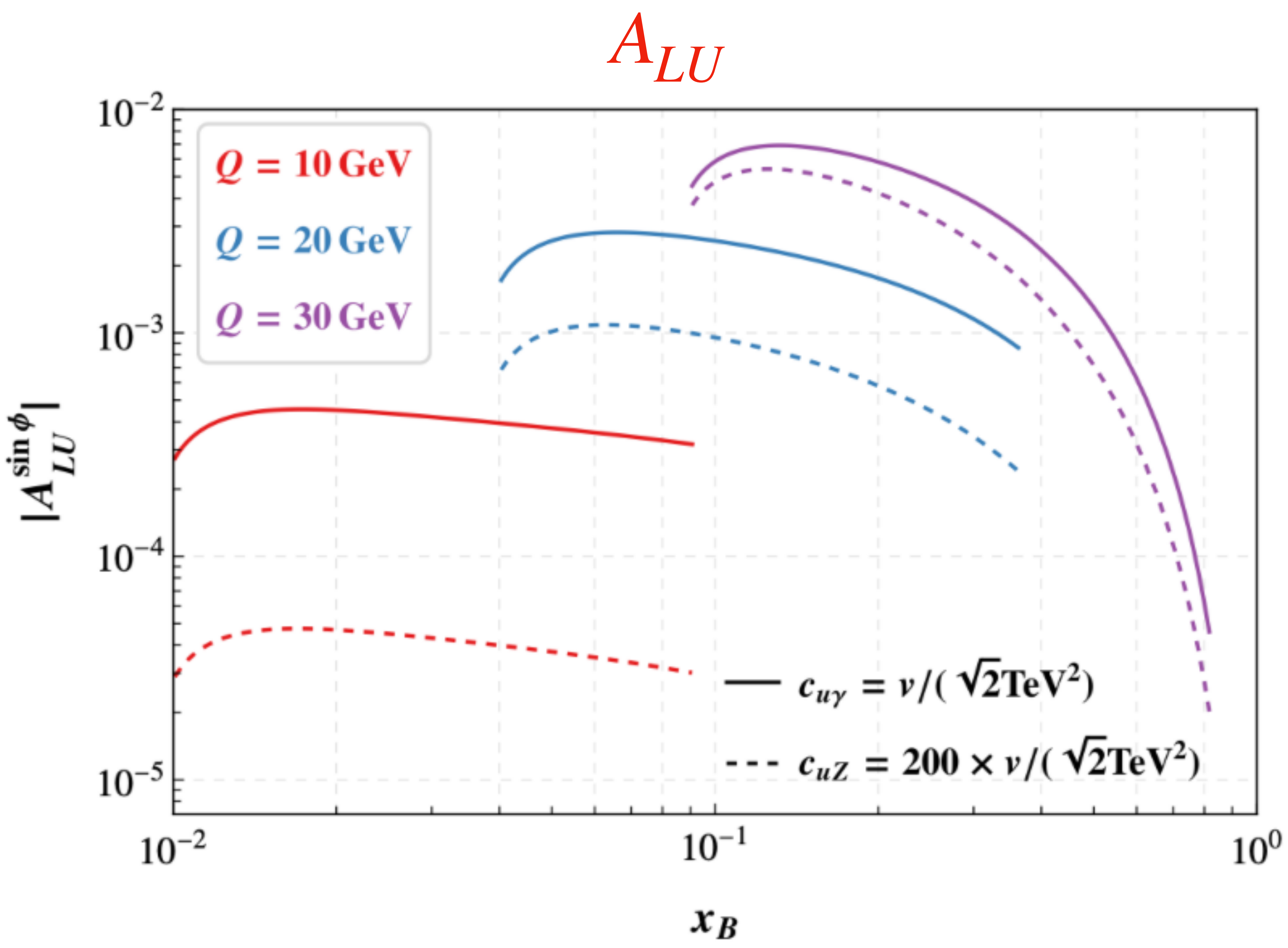
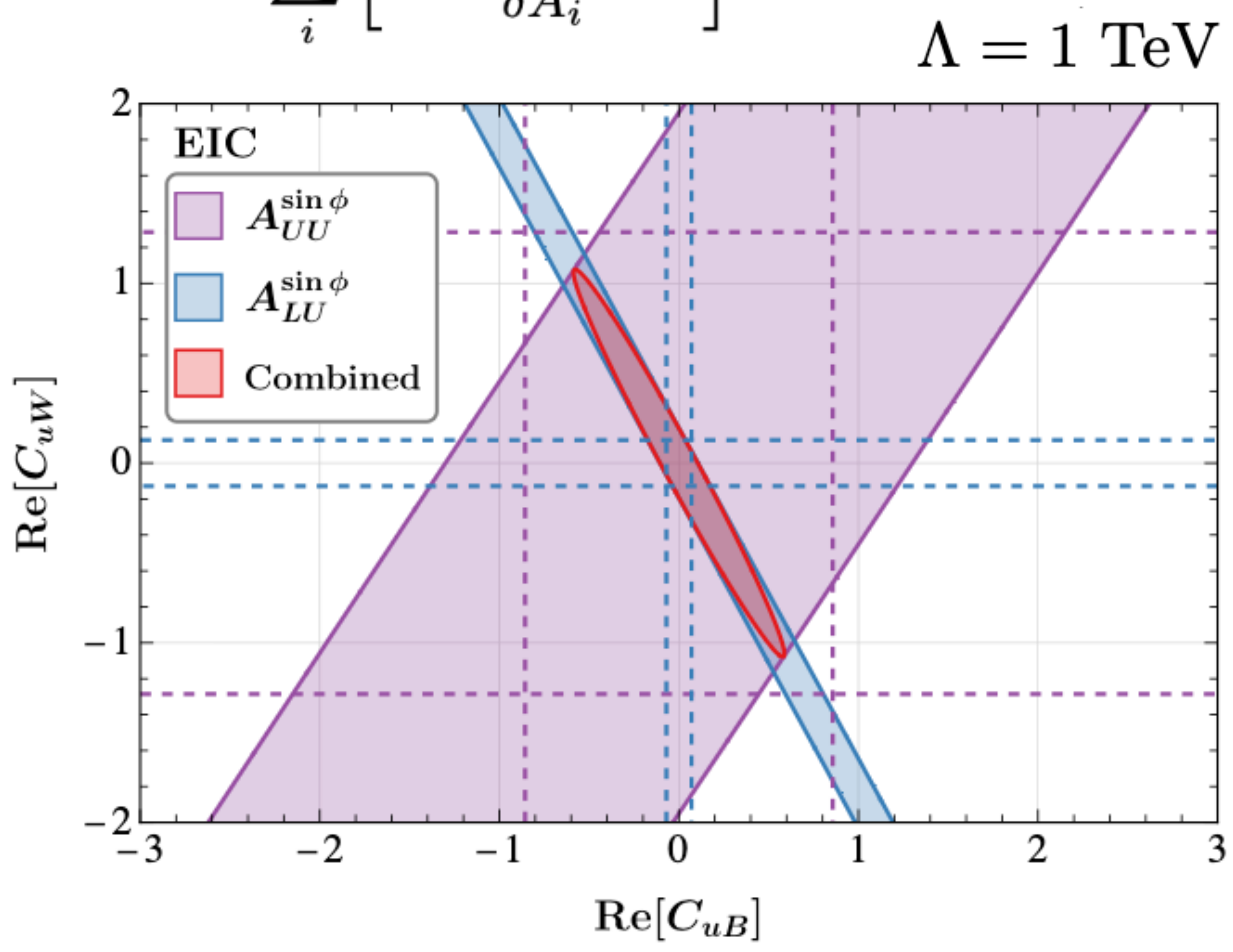
Incorporating the spin asymmetry





Projected sensitivity at the 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: $0.1 \leq y \leq 0.9$

$A_{UU}^{\sin\phi}$:
- 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 →

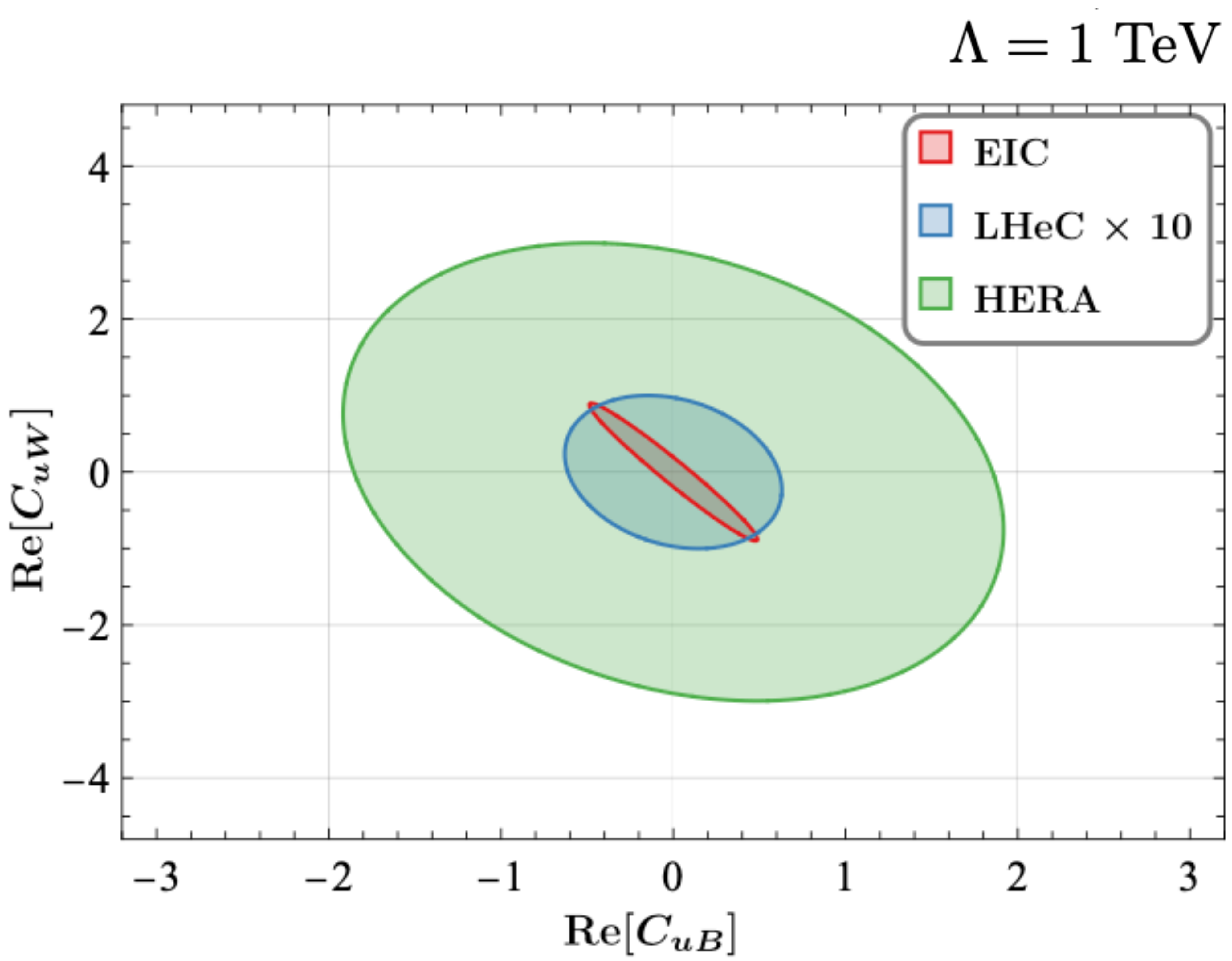
Strong correlation between C_{uW} and C_{uB}

$A_{LU}^{\sin\phi}$:
- Single-operator constraints can reach $\mathcal{O}(0.01) \sim \mathcal{O}(0.1)$ level
- The orentation 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 $\mathrm{Im}[C_i]$ from the $\cos\phi$-asymmetry

Comparision 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

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

SSB

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

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

Backup: complete analytical formulas

SM:

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

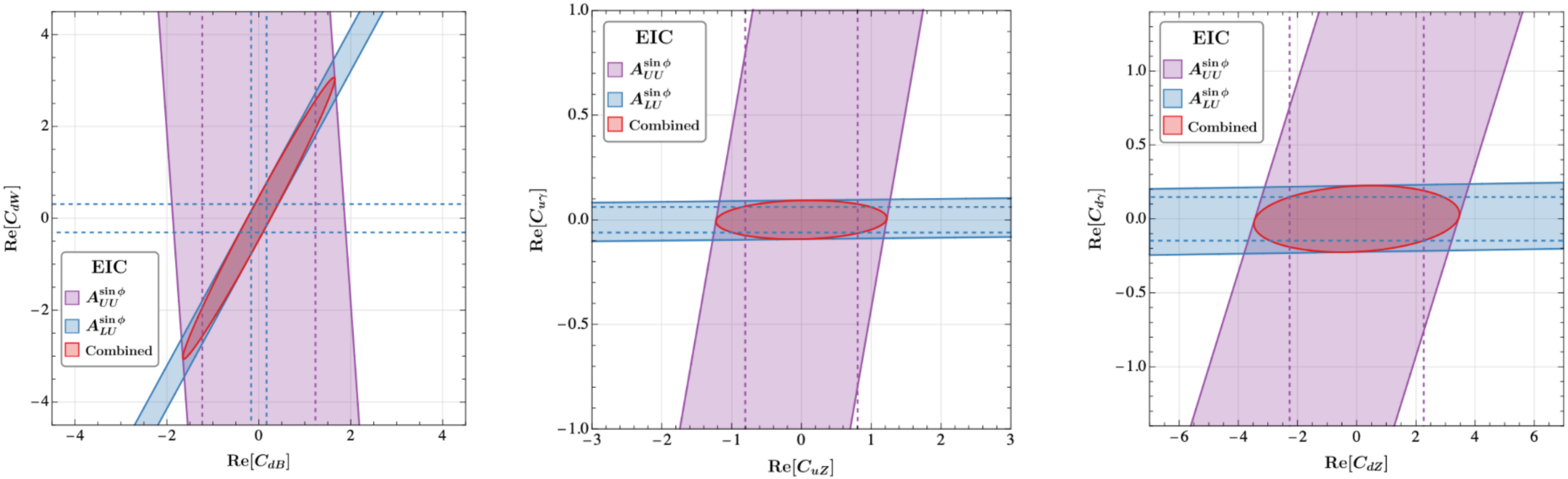
Dipole ops.:

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

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

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