26th International Symposium on Spin Physics

A Century of Spin

中国科学院高能物理研究所
Institute of High Energy Physics, Chinese Academy of Sciences

中国高等科学技术中心
China Center of Advanced Science and Technology

Transverse spin effects and light-quark dipole moments at colliders

Xin-Kai Wen (文新锴)

Institute of High Energy Physics (IHEP, CAS)

China Center of Advanced Science and Technology (CCAST)

Base on: **Xin-Kai Wen**, Bin Yan, Zhite Yu and C.-P. Yuan

Phys.Rev.Lett. **131** (2023) 24, 241801; *Phys.Rev.D* 112 (2025) 5, 053004; and *arXiv:* 2408.07255

2025/09/23 @ SDU, Tsingtao, Shandong, China

Dipole Moments in the SM

Its investigation is essential for internal structure and intrinsic properties of particles

Elementary particle

$$\mu_e = +2.002319\,\mu_B$$
$$\mu_\mu = +2.002332\,\mu_B$$

Composite particle

$$\mu_p = +2.792847\,\mu_N$$
$$\mu_n = -1.913043\,\mu_N$$

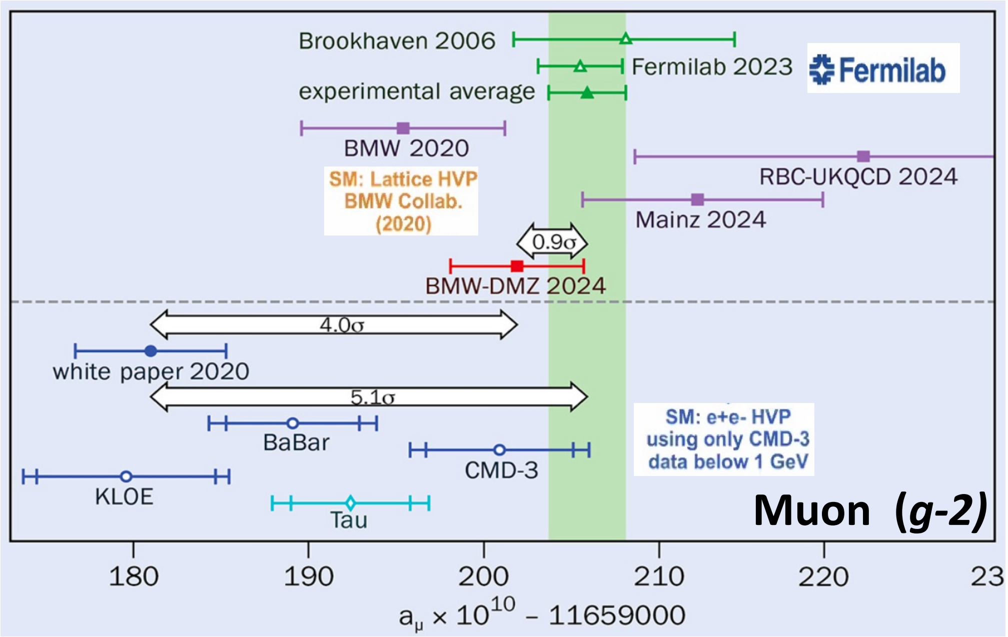
Quarks: any internal structure?

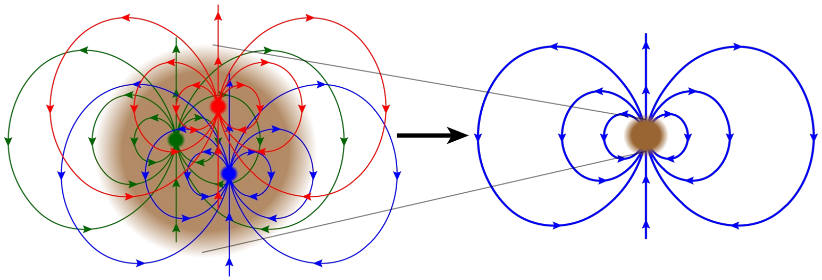
$$\mu_q = ???\ (q = u, d, s, \ldots)$$

How about:

*Electroweak (**Weak**) dipole moments?*

***Light-quark** dipole moments?*





S. Blundell, J. Griffith, J. Sapirstein, Phys. Rev. D (86) 025023 (2012)

Dipole Moments and New Physics

Its measurement is crucial for testing the Standard Model and probing New Physics

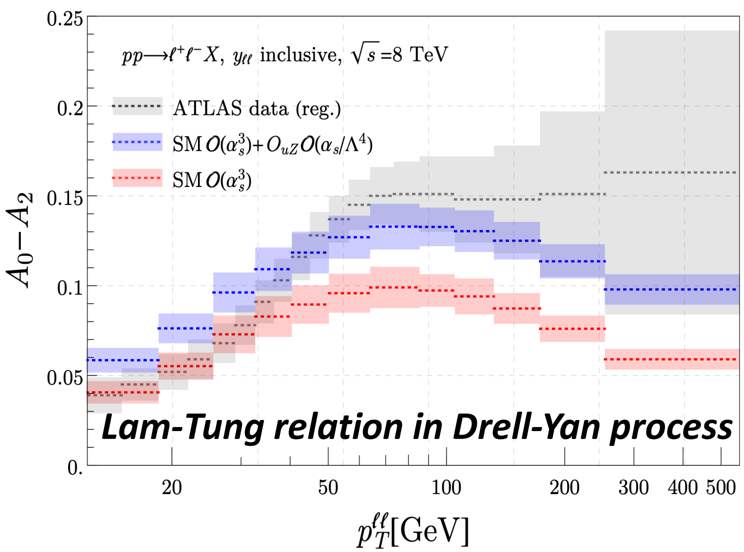
EDM >> CP violation >> Baryogenesis

$|d_e| < 1.1\times10^{-29} e\text{cm}$

$|d_n| < 1.8\times10^{-26} e\text{cm}$

$|d_q| = ???$

A. D. Sakharov, *Pisma Zh. Eksp. Teor. Fiz.* 5 (1967) 32-35



X. Li, B. Yan, C.-P. Yuan, *Phys.Rev.D* 111 (2025) 7, 073007

	Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\text{BNL}}$, Δa_μ^{2021}
	1	0	$(\mathbf{1},\mathbf{1},1)$	Excluded: $\Delta a_\mu < 0$
	2	0	$(\mathbf{1},\mathbf{1},2)$	Excluded: $\Delta a_\mu < 0$
2HDM →	3	0	$(\mathbf{1},\mathbf{2},-1/2)$	Updated in Sec. 3.2
	4	0	$(\mathbf{1},\mathbf{3},-1)$	Excluded: $\Delta a_\mu < 0$
	5	0	$(\overline{\mathbf{3}},\mathbf{1},1/3)$	Updated Sec. 3.3.
	6	0	$(\overline{\mathbf{3}},\mathbf{1},4/3)$	Excluded: LHC searches
Scalar leptoquarks	7	0	$(\overline{\mathbf{3}},\mathbf{3},1/3)$	Excluded: LHC searches
	8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.3.
	9	0	$(\mathbf{3},\mathbf{2},1/6)$	Excluded: LHC searches
	10	1/2	$(\mathbf{1},\mathbf{1},0)$	Excluded: $\Delta a_\mu < 0$
	11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Excluded: Δa_μ too small
	12	1/2	$(\mathbf{1},\mathbf{2},-1/2)$	Excluded: LEP lepton mixing
	13	1/2	$(\mathbf{1},\mathbf{2},-3/2)$	Excluded: $\Delta a_\mu < 0$
	14	1/2	$(\mathbf{1},\mathbf{3},0)$	Excluded: $\Delta a_\mu < 0$
	15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Excluded: $\Delta a_\mu < 0$
Dark photon →	16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
	17	1	$(\mathbf{1},\mathbf{2},-3/2)$	UV completion problems
	18	1	$(\mathbf{1},\mathbf{3},0)$	Excluded: LHC searches
	19	1	$(\overline{\mathbf{3}},\mathbf{1},-2/3)$	UV completion problems
	20	1	$(\overline{\mathbf{3}},\mathbf{1},-5/3)$	Excluded: LHC searches
	21	1	$(\overline{\mathbf{3}},\mathbf{2},-5/6)$	UV completion problems
	22	1	$(\overline{\mathbf{3}},\mathbf{2},1/6)$	Excluded: $\Delta a_\mu < 0$
	23	1	$(\overline{\mathbf{3}},\mathbf{3},-2/3)$	Excluded: proton decay

SUSY......

Scalar extensions......

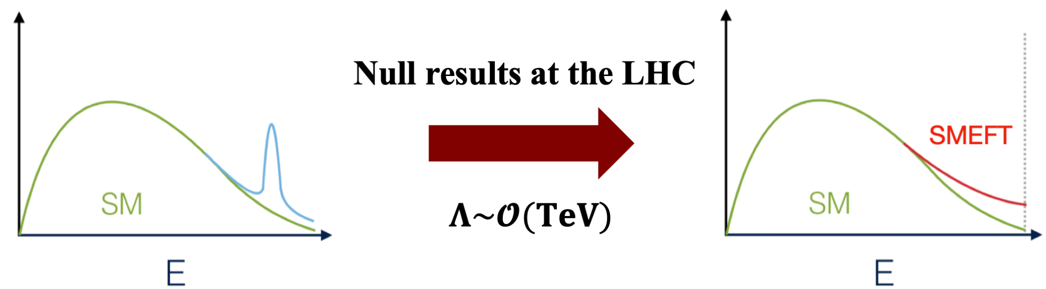
Peter Athron et al., *JHEP* 09 (2021) 080

Many new physics models can produce dipole moments, but...

Dipole Moments in the SMEFT

Many new physics models can produce dipole moments, but…

- Test NP model by model: Too tedious
- Discover new particles: Null



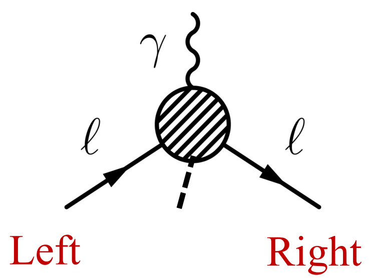
SMEFT : Global fitting

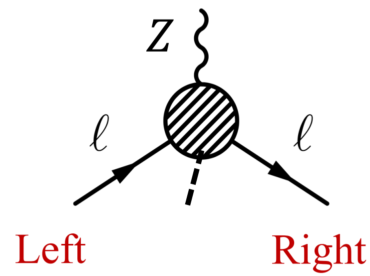
- A standard and systematic tool
- Model independent

$$(\bar{f}_L \sigma^{\mu\nu} f_R)\tau^I \varphi W^I_{\mu\nu}$$

$$(\bar{f}_L \sigma^{\mu\nu} f_R)\varphi B_{\mu\nu}$$

[Chirality-Flip]

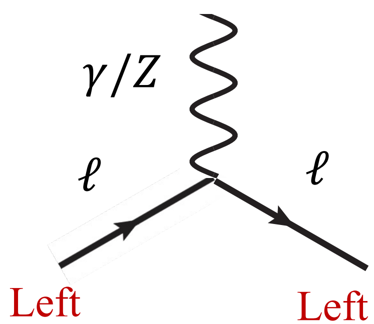


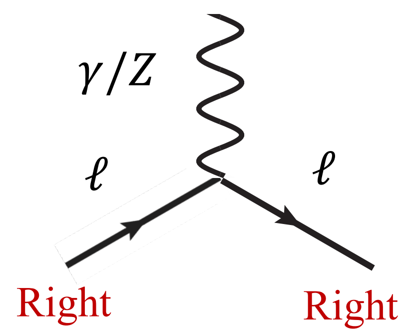


$$(\bar{f}\gamma^{\mu} P_L \tau^I f)W^I_{\mu}$$

$$(\bar{f}\gamma^{\mu} f)B_{\mu}$$

[SM]

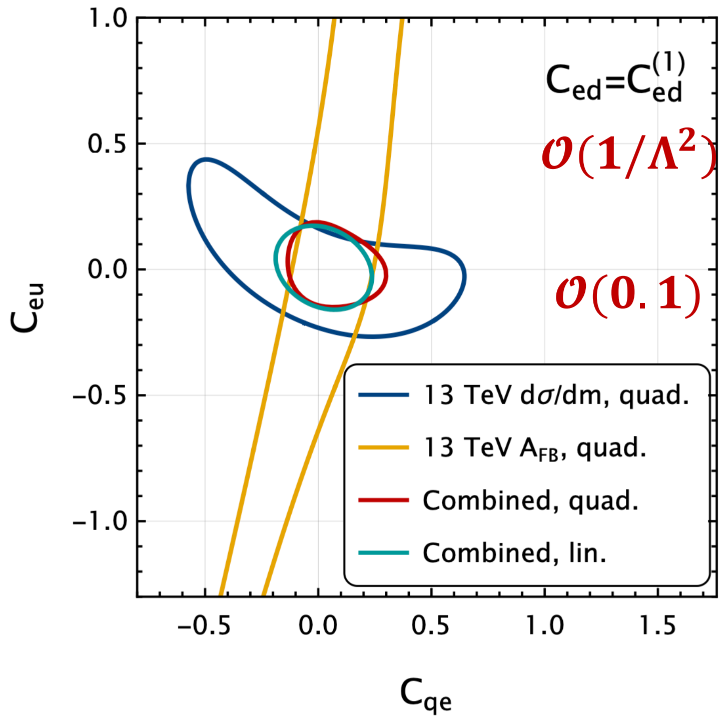


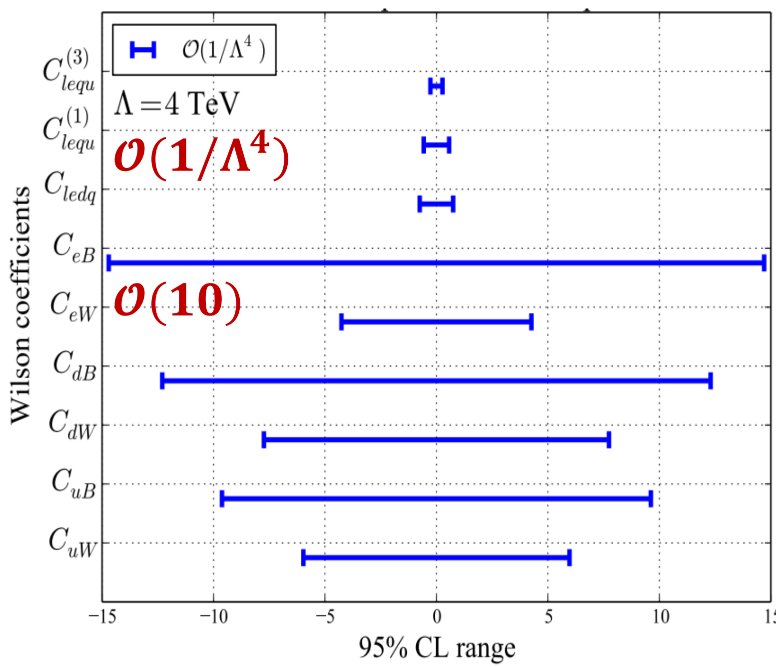


Dipole Moments in Current Data

Chirality-flip of fermion ⟹ Difficult to probe at colliders

Leading contribution





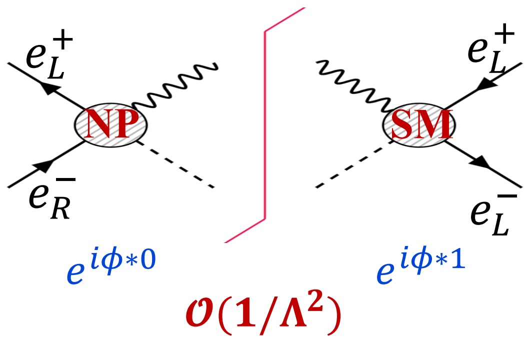
Single-Parameter-Analysis: EW dipole couplings are poorly constrained by Drell-Yan data

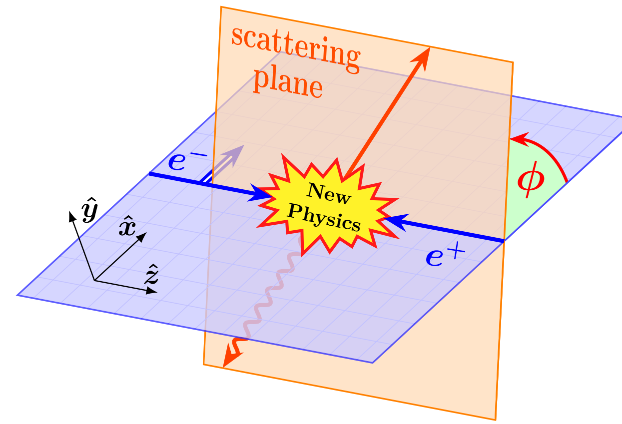
R. Boughezal et al. *Phys.Rev.D* 104 (2021), 9, 095022 *Phys.Rev.D* 108 (2023) 7, 076008

Lepton Dipole Moments

Transverse spin effect of initial leptons ⟹ Interference of the different helicity amplitudes

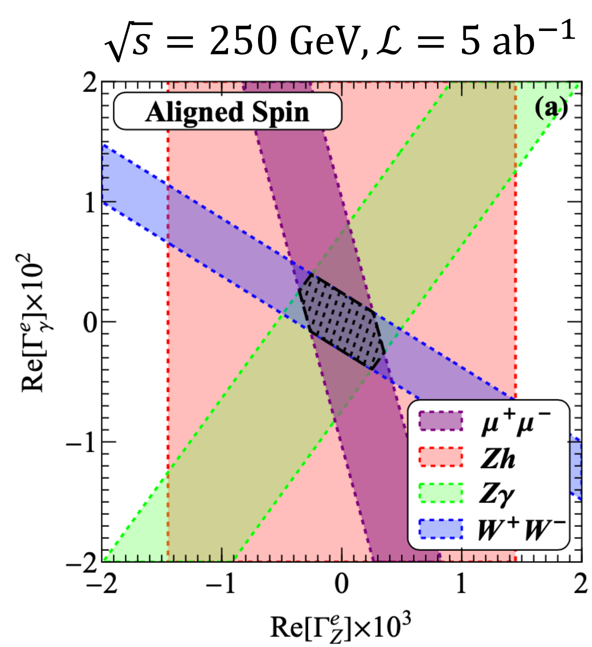
$$\rho = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}} e^{-i\phi_0} \\ b_{\mathrm{T}} e^{i\phi_0} & 1-\lambda \end{pmatrix}$$





$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + A_R^i(b_T, \bar{b}_T)\cos\phi + A_I^i(b_T, \bar{b}_T)\sin\phi$$

Linearly → $\mathrm{Re}[\Gamma_f]$ CP-conserving; $\mathrm{Im}[\Gamma_f]$ CP-violating



Transverse Spin Asymmetry

Much stronger sensitivity: $\mathcal{O}(10^{-4}\sim10^{-3})$, others: $\mathcal{O}(10^{-2}\sim10^{-1})$

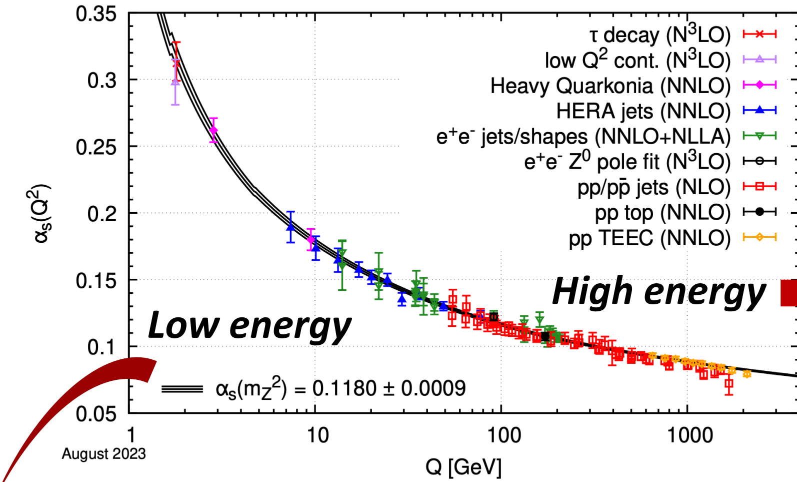
Directly probing potential CP violation effects

Null contaminations; $|Weak| < |EM|$

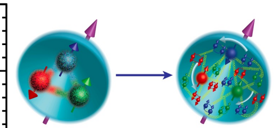
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys.Rev.Lett.* 131 (2023) 24, 241801

From Lepton to Light-quark: QCD Spin

QCD color confinement prevents the direct measurement of quark interactions



Particle Data Group, *Phys.Rev.D* 110 (2024) 3, 030001

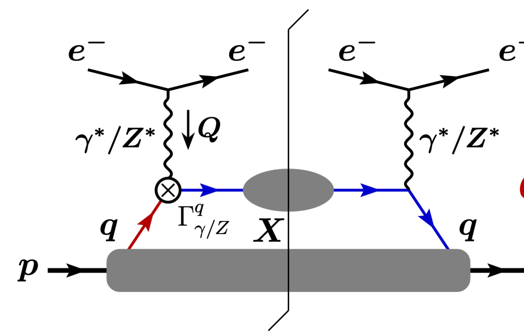


Asymptotic freedom

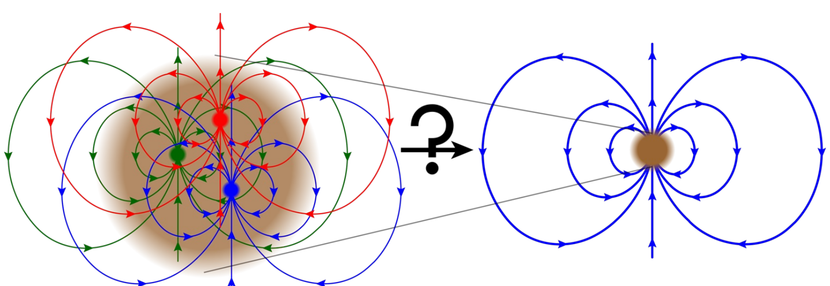
Transversity PDFs** or **Collins FFs

Leading Quark TMDPDFs — Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity $h_{1T}^\perp$ = Pretzelosity



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



S. Blundell, et al., *Phys.Rev.D* 86 (2012) 025023

Nucleon dipole moment measurements ?

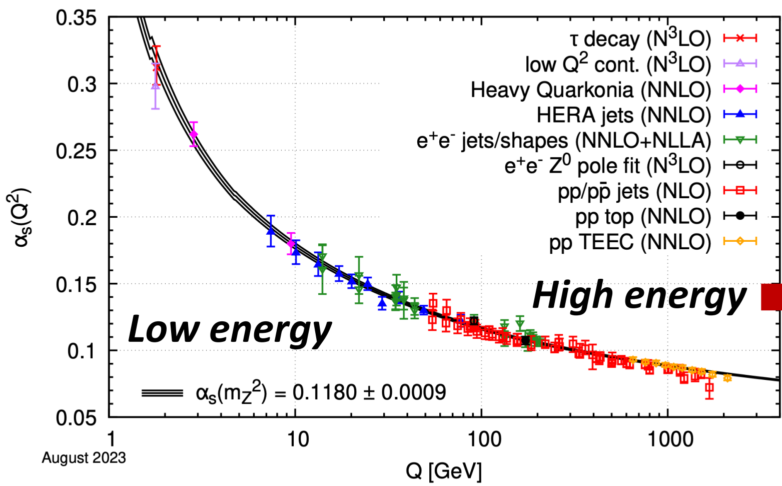
Nonperturbative input of nucleon spin structure !

H.-L. Wang, **X.-K. Wen**, H. Xing and B. Yan, *Phys.Rev.D* **109** (2024) 9, 095025

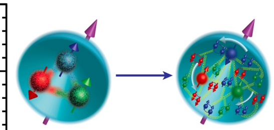
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, *Phys.Rev.D* **107** (2023) 7, 075028

From Lepton to Light-quark: QCD Spin

QCD color confinement prevents the direct measurement of quark interactions

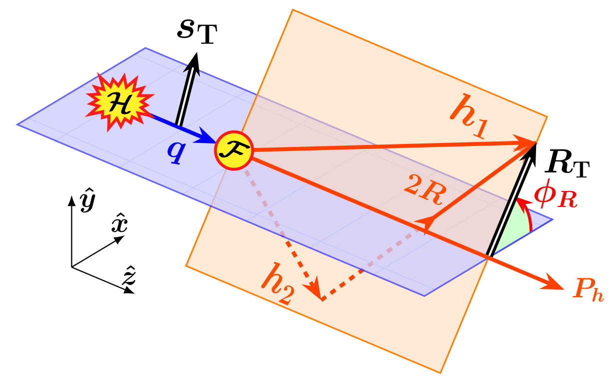


Particle Data Group, *Phys.Rev.D* 110 (2024) 3, 030001



Asymptotic freedom

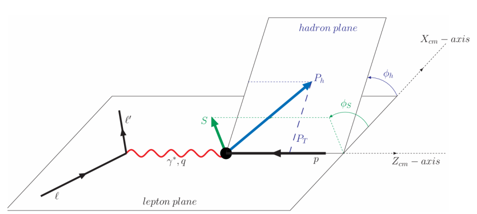
Independent of hadron spin ?
Collinear factorization ?
Dihadron FFs !

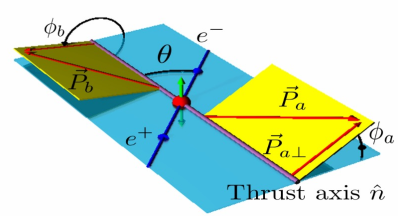


spin transfer

Nucleon structure: *chiral-odd* Transverse PDFs or Collins FFs

- Difficult to be constrained
- Measure hadron polarization or transverse momentum





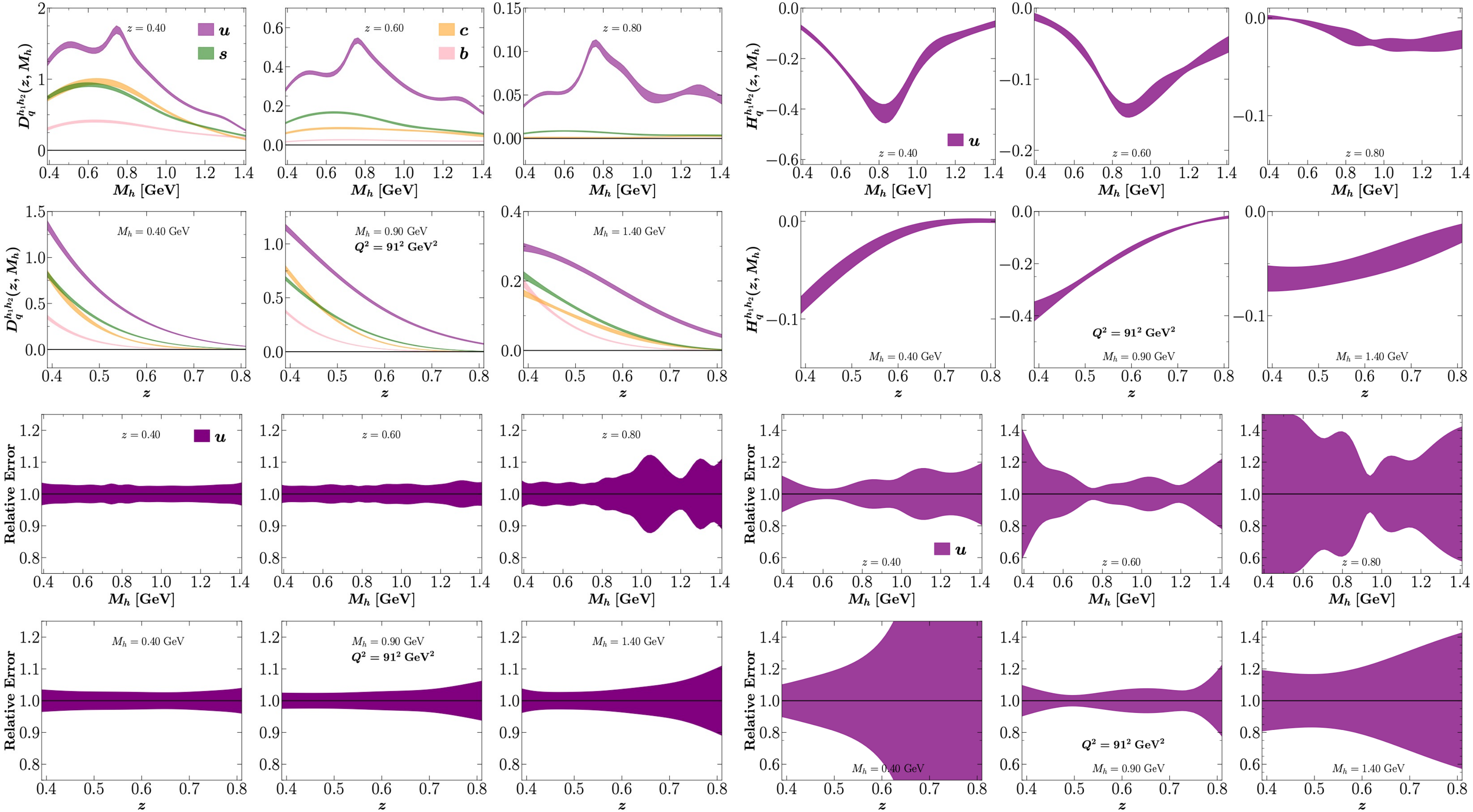
Kang, Prokudin, Sun, Yuan, *Phys.Rev.D* **93** (2016) 014009;
Zeng, Dong, Liu, Sun, Zhao, *Phys.Rev.D* **109** (2024) 056002; ……

$$A_{UT}^{\mathrm{SIDIS}} = c(y)\frac{\sum_q e_q^2\, h_1^q(x)\, H_1^{\sphericalangle,q}(z,M_h)}{\sum_q e_q^2\, f_1^q(x)\, D_1^q(z,M_h)}$$

$$A^{e^+e^-} = \frac{\sin^2\theta \sum_q e_q^2\, H_1^{\sphericalangle,q}(z,M_h) H_1^{\sphericalangle,\bar{q}}(\bar{z},\overline{M}_h)}{(1+\cos^2\theta)\sum_q e_q^2\, D_1^q(z,M_h) D_1^{\bar{q}}(\bar{z},\overline{M}_h)}$$

Global fitting !

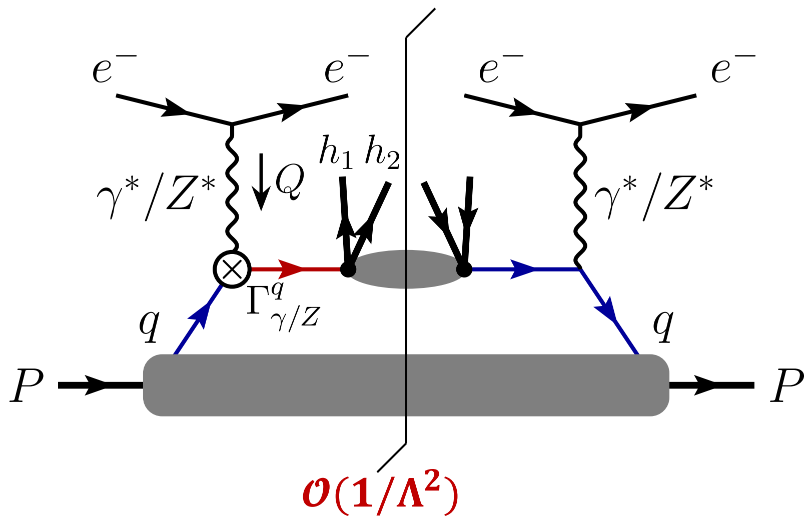
$\pi^+\pi^-$ Dihadron fragmentation functions

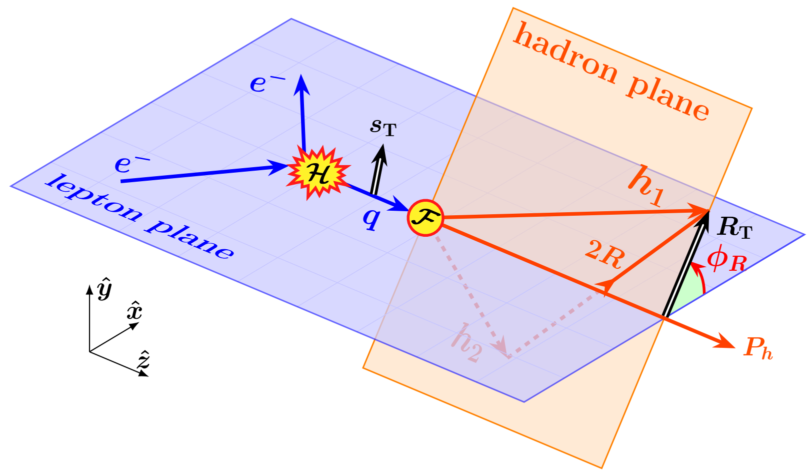


JAM Collaboration, *Phys.Rev.Lett* **132** (2024) 091901 , *Phys.Rev.D* **109** (2024) 034024

Light-quark Dipole Moments at EIC

Light-quark dipole moments produce transverse spin of quarks via interference effects





$$\frac{d\sigma}{dx\,dy\,dz\,dM_h\,d\phi_R} = \frac{N}{2\pi}\sum_q f_q(x,Q)\Big[D_q^{h_1h_2}(z,M_h;Q) - (\boldsymbol{s}_{T,q}(x,Q)\times\hat{\boldsymbol{R}}_T)^z H_q^{h_1h_2}(z,M_h;Q)\Big]C_q(x,Q)$$

Dihadron chiral-odd interference fragmentation function

$\Longrightarrow$ ***To project out transverse spin of quarks with azimuthal asymmetry***

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *arXiv:* 2408.07255

Light-quark Dipole Moments at EIC

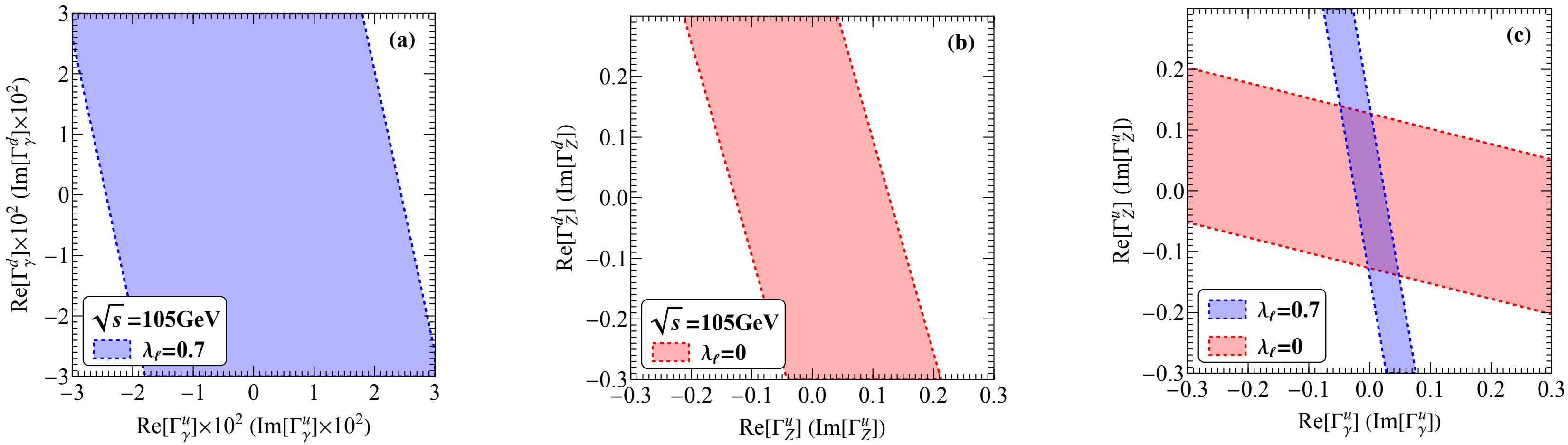
$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R \quad \begin{cases} s_q^x = \dfrac{2}{C_q}\left(w_\gamma^q \,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q \,\mathrm{Re}\,\Gamma_Z^q\right) \\ s_q^y = \dfrac{2}{C_q}\left(w_\gamma^q \,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q \,\mathrm{Im}\,\Gamma_Z^q\right) \end{cases}$$

Requiring parity-violation effects

- the electron longitudinal polarization
- the Z-boson axial couplings

$$\frac{2\pi}{\sigma_{\rm tot}}\frac{d\sigma}{d\phi_R} = 1 + A_R \sin\phi_R + A_I \cos\phi_R$$

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



$\sqrt{s} = 105$ GeV, $\mathcal{L} = 1000$ fb^{-1} : $\mathcal{O}(10^{-2})$ for $\Gamma_\gamma^{u,d}$ $\quad$ $\mathcal{O}(10^{-1})$ for $\Gamma_Z^{u,d}$

Exclusive to quark dipole moments and independent of hadron spin, but a flat direction ?

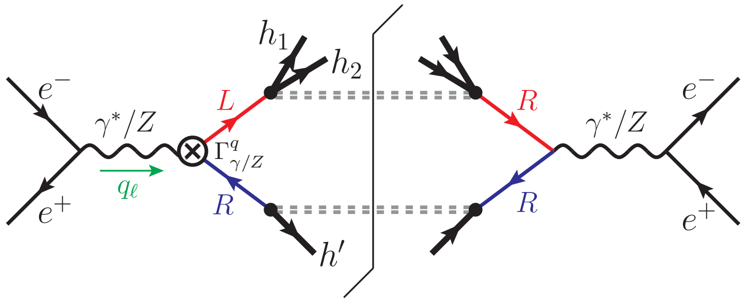
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *arXiv:* 2408.07255

Light-quark Dipole Moments at e^+e^- colliders

Dihadron-hadron pairs exclusively disentangle the up and down quark dipole moments

$\Longrightarrow$ ***Individual and stronger constraints***

$$\frac{d\sigma}{dy\,dz\,d\bar{z}\,dM_h\,d\phi_R} = \frac{1}{32\pi^2 s}\sum_{q,\,q\to\bar{q}} C_q(y)\, D_{\bar{q}}^{h'}(\bar{z})$$
$$\times \left[D_q^{h_1h_2}(z, M_h) - (\boldsymbol{s}_{T,q}(y)\times\hat{\boldsymbol{R}}_T)^z H_q^{h_1h_2}(z, M_h)\right]$$



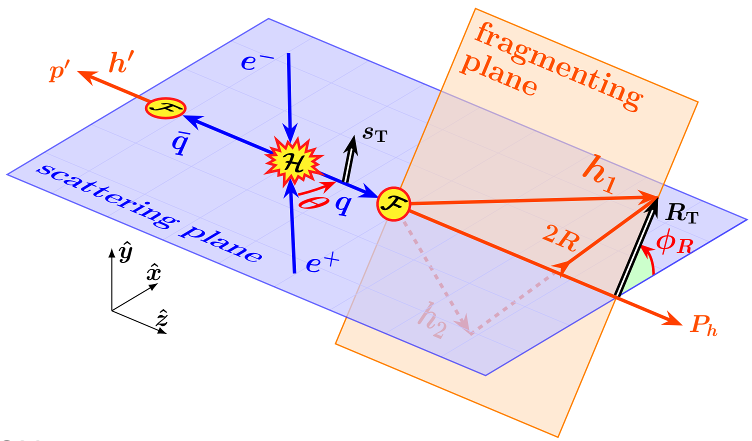
$\mathcal{O}(1/\Lambda^2)$

For Photon dipole:

- Low energy
- Electron longitudinal polarization

For Z-boson dipole:

- Z-pole energy
- Z boson axial vector couplings



Electron longitudinal polarization and C.M. energy

$\Longrightarrow$ ***Effectively distinguish between the photon and Z-boson dipole moments***

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys.Rev.D* 112 (2025) 5, 053004

Light-quark Dipole Moments at e^+e^- colliders

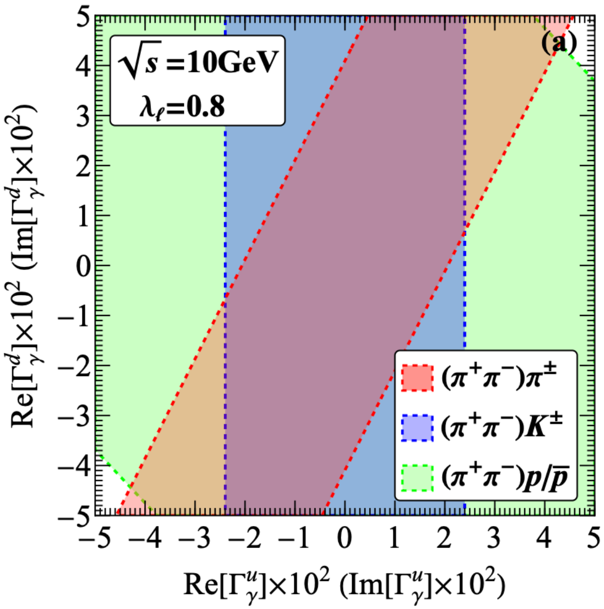
Flat direction close: Various channels impose distinct constraints on up and down quarks

Flavor relations: SM couplings, isospin, and charge conjugation symmetries

$$\frac{d\sigma}{dz\, d\bar{z}\, dM_h\, d\phi_R} = \frac{B^0 - B^x \sin\phi_R + B^y \cos\phi_R}{32\pi^2 s}$$

$$B^i = H_u^{\pi^+\pi^-} \left[\langle S_u^i \rangle \left(D_{\bar{u}}^{h'} - D_u^{h'} \right) - \langle S_d^i \rangle \left(D_{\bar{d}}^{h'} - D_d^{h'} \right) \right]$$

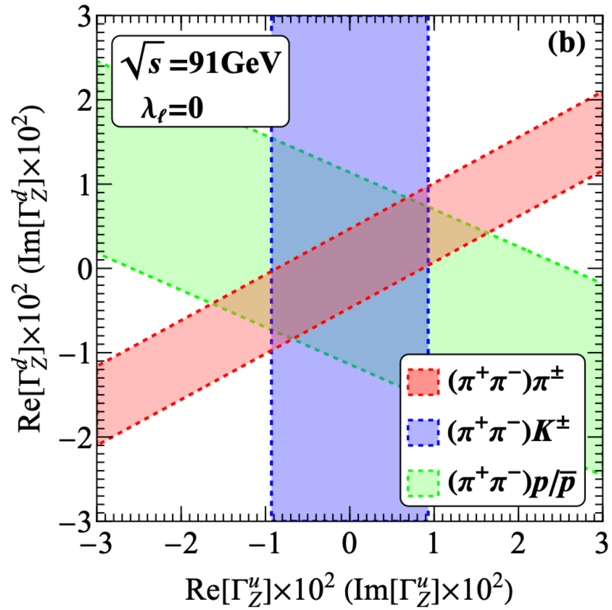
- $(\pi^+\pi^-)\pi^\pm$ — $\left(\langle S_u^i \rangle + \langle S_d^i \rangle \right)$
- $(\pi^+\pi^-)K^\pm$ — $D_d^{K^\pm} = D_{\bar{d}}^{K^\pm}$
- $(\pi^+\pi^-)p/\bar{p}$ — $\left(\langle S_u^i \rangle - \langle S_d^i \rangle /2 \right)$



$\mathcal{L} = 1\ \text{ab}^{-1}$

$\mathcal{O}(10^{-2})$ for $\Gamma_\gamma^{u,d}$

$\mathcal{O}(10^{-3})$ for $\Gamma_Z^{u,d}$

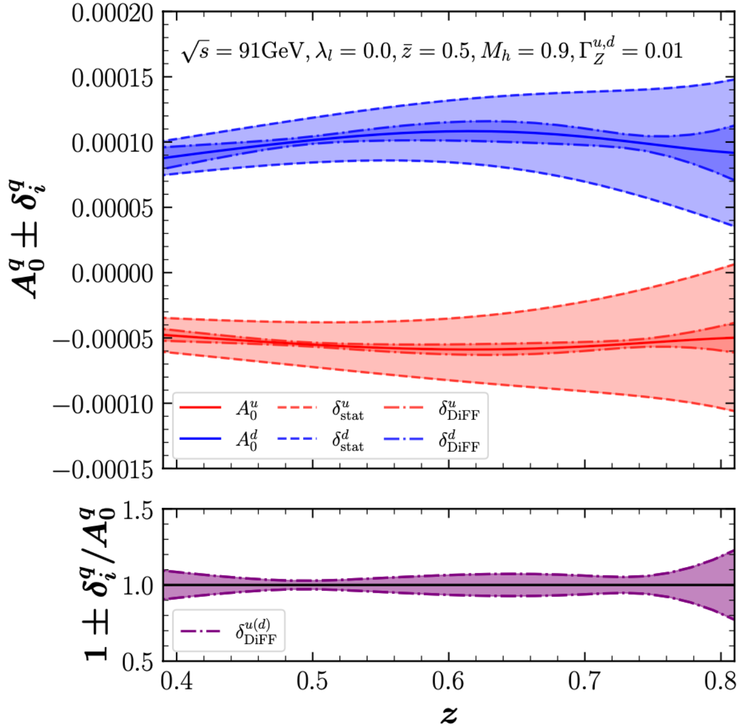


Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, *Phys.Rev.D* 112 (2025) 5, 053004

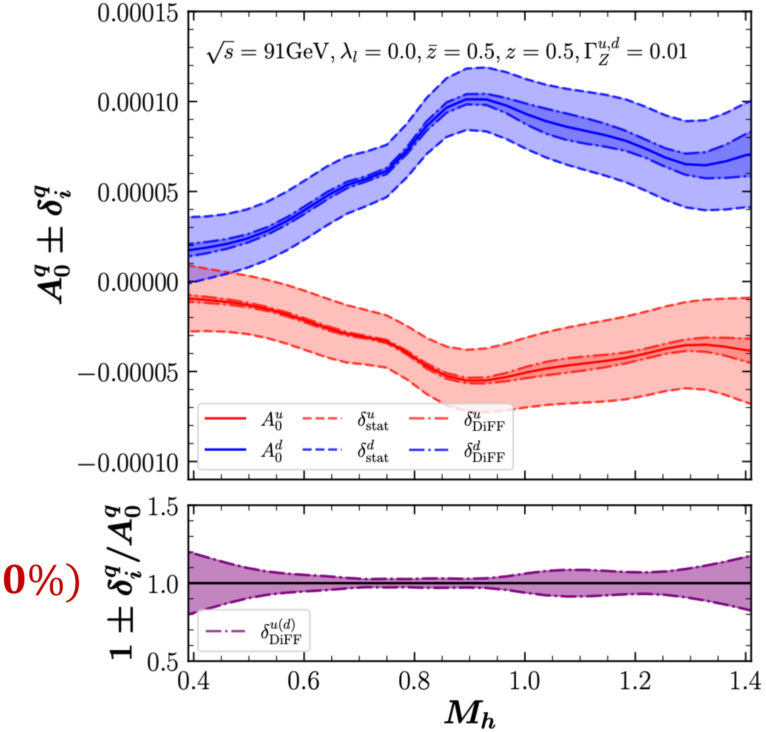
Light-quark Dipole Moments at e^+e^- colliders

Differential asymmetry and its error from statistics and dihadron fragmentation function

$\mathcal{L} = 1\ \text{ab}^{-1}$ $\qquad \mathcal{O}(10^{-3})$ for $\Gamma_Z^{u,d}$



$\mathcal{O}(10\%)$



Statistic uncertainty dominates over theoretical error of DiFFs

Uncertainty of DiFFs have little impact on our conclusions and negligible

Summary

- ✓ Light-quark dipole moment is crucial for testing SM and probing New Physics
- ✓ These Chirality-flip moments are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$, and quark cannot be directly seen due to QCD confinement
- ✓ Transverse spin effect linearly detects them at $1/\Lambda^2$ via asymmetries leveraging lepton transverse spin and nonperturbative functions, e.g., Transversity and **Dihadron IFF**
- ✓ Both real and imaginary parts can be well constrained without impact from SM and other NP, and offering a new opportunity for directly probing potential CP-violating effects
- ✓ By combining all possible channels, the degeneracy issue of the up and down quark dipole moments is resolved, also giving individual constraints to photon's and Z-boson's
- ✓ Our bounds are much stronger than other approaches, such as LHC and LEP

*In summary, **QCD transverse spin effect** improve the detection of **light-quark dipole moment**.*

Thank you

One More Thing...

From **Transverse Spin of Single Quark** to **Spin Correlation of Entangled Quark Pairs:**

$$\rho = \frac{I_2 \otimes I_2 + B_i \sigma_i \otimes I_2 + \bar{B}_i I_2 \otimes \sigma_i + C_{ij} \sigma_i \otimes \sigma_j}{4}$$

"Probing Quark Electromagnetic Properties via Entangled Quark Pairs in Fragmentation Hadrons at Lepton Colliders"

Q.-H. Cao, G. Li, **X.-K. Wen**, B. Yan, to appear soon

In Belle, diFFs global fitting on $\mathbf{e^-e^+ \to \gamma^* \to q\bar{q} \to (\pi^+\pi^-) + (\pi^+\pi^-) + X}$ via $\cos(\phi_1 + \phi_2)$:

$$A^{e^+e^-} = \frac{\sin^2\theta \sum_q e_q^2 H_1^{\sphericalangle,q}(z, M_h) H_1^{\sphericalangle,\bar{q}}(\bar{z}, \overline{M}_h)}{(1+\cos^2\theta) \sum_q e_q^2 D_1^q(z, M_h) D_1^{\bar{q}}(\bar{z}, \overline{M}_h)}$$

Bell variable for entanglement and CHSH violation:

$$C_{xx} - C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta}\left(2 + \frac{1}{\Lambda^2}\mathcal{F}_1 + \frac{1}{\Lambda^4}\mathcal{F}_2\right) \qquad |1,0\rangle_y = \frac{1}{\sqrt{2}}\left(|\uparrow_y\downarrow_y\rangle + |\downarrow_y\uparrow_y\rangle\right)$$

Another Bell variable absent in the SM and other NP, but sensitive to quark MDM and EDM:

$$C_{xx} + C_{yy} = \frac{\sin^2\theta}{1+\cos^2\theta} \frac{sv^2}{\pi\alpha\Lambda^4 Q_q^2}\left([\mathrm{Re}C_\gamma^q]^2 - [\mathrm{Im}C_\gamma^q]^2\right) \qquad |1,0\rangle_z, \quad |0,0\rangle$$

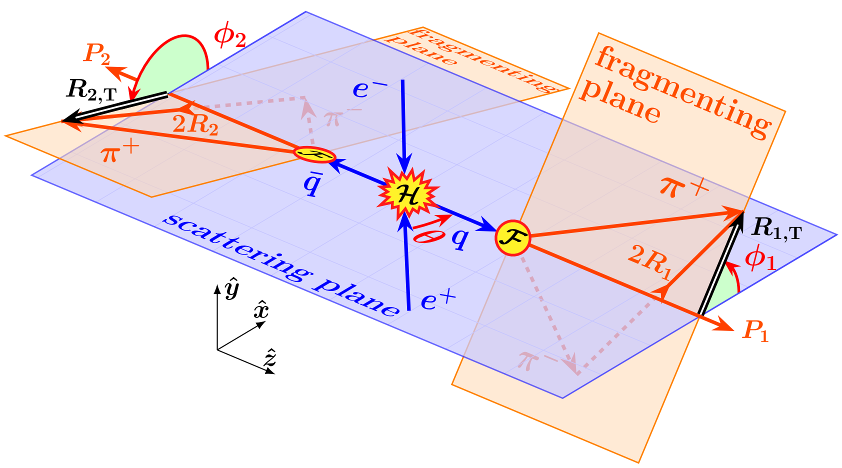
One More Thing...

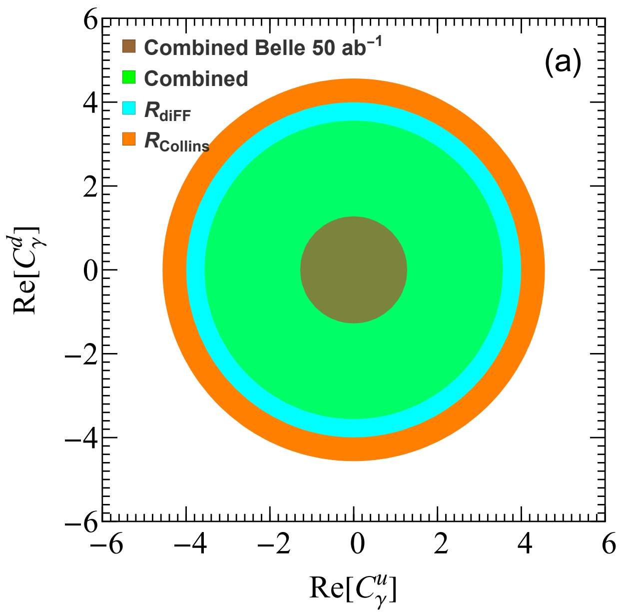
$$C_{xx}+C_{yy}=\frac{\sin^2\theta}{1+\cos^2\theta}\frac{sv^2}{\pi\alpha\Lambda^4Q_q^2}([\mathrm{Re}C_\gamma^q]^2-[\mathrm{Im}C_\gamma^q]^2)$$

$|1,0\rangle_z$, $|0,0\rangle$

To revisit existing data at *Belle* and *BaBar* within both the collinear and TMD factorization frameworks to

- Global fitting on new $\cos(\phi_1-\phi_2)$ to extract FFs or test the present of MDM / EDM
- The ratios of $\cos(\phi_1-\phi_2)$ and $\cos(\phi_1+\phi_2)$ to robustly constrain dipole couplings





Thanks again

Isospin and Charge Conjugation Symmetries

$$D_{\pi^+\pi^-/q} = D_{\pi^+\pi^-/\bar{q}}, \quad H_{\pi^+\pi^-/q} = -H_{\pi^+\pi^-/\bar{q}}$$
$$D_{\pi^+\pi^-/u} = D_{\pi^+\pi^-/d}, \quad H_{\pi^+\pi^-/u} = -H_{\pi^+\pi^-/d}$$

$$D_u^{\pi^+\pi^-} = D_d^{\pi^+\pi^-}, \quad H_u^{\pi^+\pi^-} = -H_d^{\pi^+\pi^-}, \quad H_{s,\bar{s},c,\bar{c},b,\bar{b}}^{\pi^+\pi^-} = 0$$
$$D_q^{\pi^+\pi^-} = D_{\bar{q}}^{\pi^+\pi^-}, \quad H_q^{\pi^+\pi^-} = -H_{\bar{q}}^{\pi^+\pi^-}$$

$$D_{\pi^+/u} = D_{\pi^+/\bar{d}}, \qquad D_{\pi^+/d} = D_{\pi^+/\bar{u}},$$
$$D_{K^+/d} = D_{K^+/\bar{u},\bar{d}}, \qquad D_{p/u} = 2D_{p/d},$$
$$D_{\pi^-,K^-,p/q} = D_{\pi^+,K^+,\bar{p}/\bar{q}}.$$