Transverse spin effects and light-quark dipole moments at colliders

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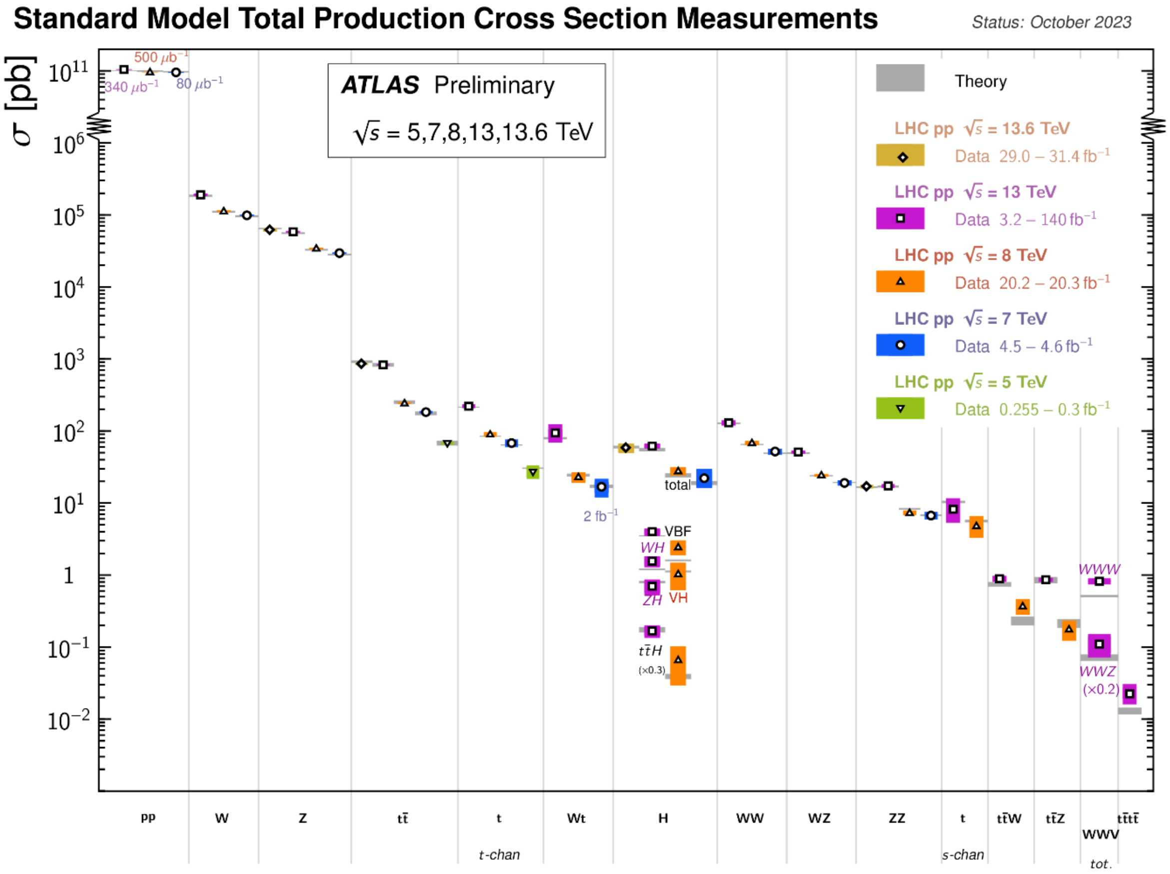
ASU-AUST-USTC online Colloquium
Dec. 18, 2024

Based on Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801 , 2408.07255, 2411.13845
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang, Sci. China Phys. Mech. Astron. 67 (2024) 281062
Xu Li, Bin Yan, C.-P. Yuan, 2405.04069

The status of SM



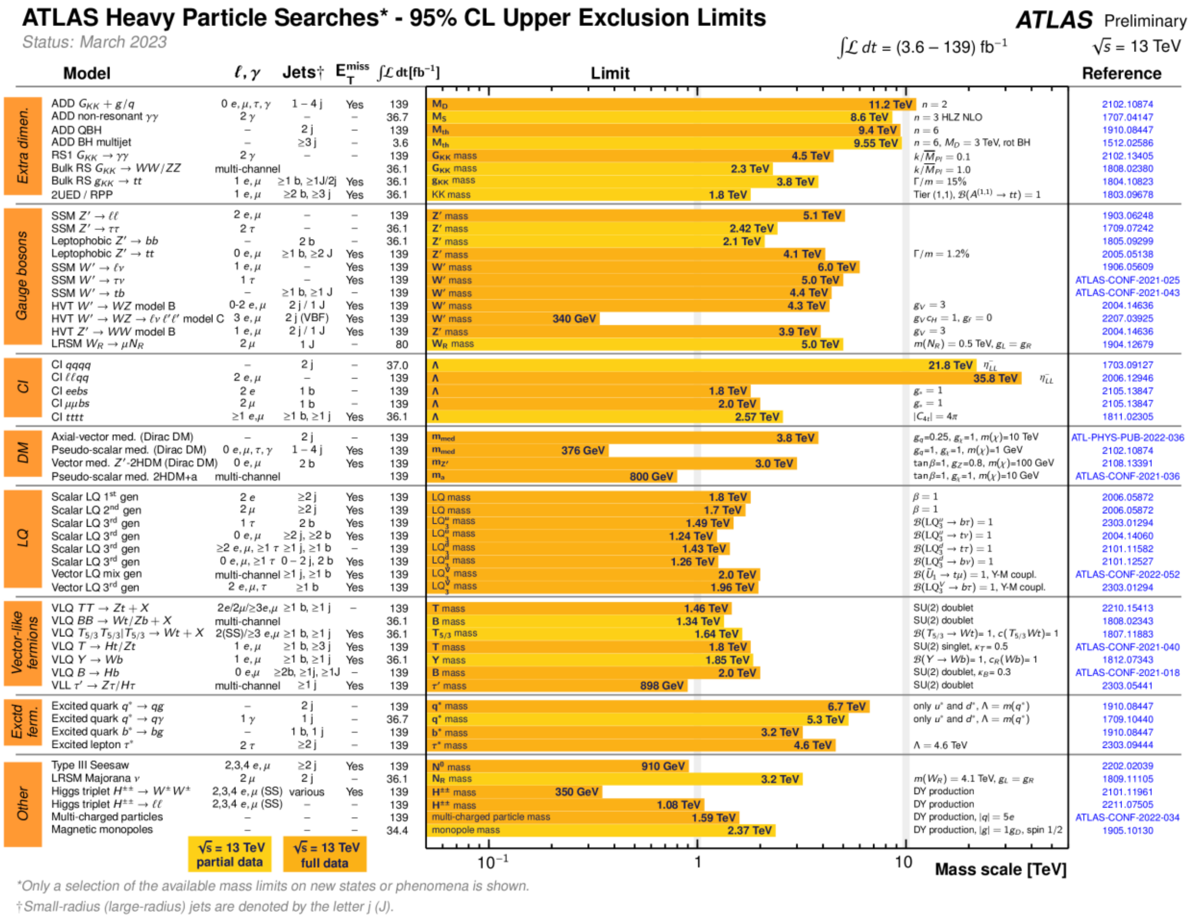
Open questions:

- Dark Matter ?
- neutrino mass?
- matter-antimatter asymmetry?
- W-mass anomaly, muon g-2
- electroweak symmetry breaking?
- Higgs boson (Composite or elementary particle)?
- …

Remarkable agreement between SM theory and data

New Physics beyond the SM
new measurements

New Physics Searches @ LHC



ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.6 - 139)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 13$ TeV

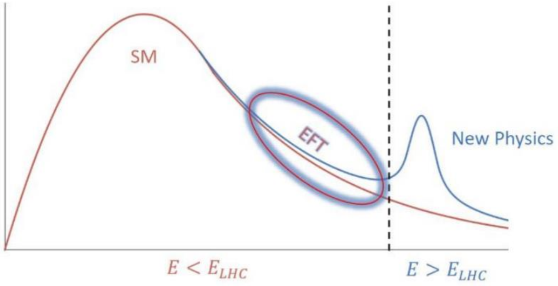
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimen.	ADD $G_{KK} + g/q$	0 e, μ, τ, γ	1 – 4 j	Yes	139	M_D 11.2 TeV	$n = 2$	2102.10874
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	139	M_{th} 9.4 TeV	$n = 6$	1910.08447
	ADD BH multijet	–	≥3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	139	G_{KK} mass 4.5 TeV	$k/\overline{M}_{Pl} = 0.1$	2102.13405
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥1 b, ≥1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥2 b, ≥3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W' mass 5.0 TeV		ATLAS-CONF-2021-025
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W' mass 4.4 TeV		ATLAS-CONF-2021-043
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $W' \to WZ \to \ell\nu\,\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W' mass 340 GeV	$g_V c_H = 1$, $g_f = 0$	2207.03925
	HVT $Z' \to WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z' mass 3.9 TeV	$g_V = 3$	2004.14636
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^{-}	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^{-}	2006.12946
	CI $eebs$	2 e	1 b	–	139	Λ 1.8 TeV	$g_* = 1$	2105.13847
	CI $\mu\mu bs$	2 μ	1 b	–	139	Λ 2.0 TeV	$g_* = 1$	2105.13847
	CI $tttt$	≥1 e,μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector med. (Dirac DM)	–	2 j	–	139	m_{med} 3.8 TeV	g_q=0.25, g_χ=1, $m(\chi)$=10 TeV	ATL-PHYS-PUB-2022-036
	Pseudo-scalar med. (Dirac DM)	0 e, μ, τ, γ	1 – 4 j	Yes	139	m_{med} 376 GeV	g_q=1, g_χ=1, $m(\chi)$=1 GeV	2102.10874
	Vector med. Z'-2HDM (Dirac DM)	0 e, μ	2 b	Yes	139	$m_{Z'}$ 3.0 TeV	tanβ=1, g_Z=0.8, $m(\chi)$=100 GeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel			139	m_a 800 GeV	tanβ=1, g_χ=1, $m(\chi)$=10 GeV	ATLAS-CONF-2021-036
LQ	Scalar LQ 1st gen	2 e	≥2 j	Yes	139	LQ mass 1.8 TeV	$\beta = 1$	2006.05872
	Scalar LQ 2nd gen	2 μ	≥2 j	Yes	139	LQ mass 1.7 TeV	$\beta = 1$	2006.05872
	Scalar LQ 3rd gen	1 τ	2 b	Yes	139	LQ_3^u mass 1.49 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	2303.01294
	Scalar LQ 3rd gen	0 e, μ	≥2 j, ≥2 b	Yes	139	LQ_3^u mass 1.24 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to t\nu) = 1$	2004.14060
	Scalar LQ 3rd gen	≥2 e, μ, ≥1 τ	≥1 j, ≥1 b	–	139	LQ_3^d mass 1.43 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 1$	2101.11582
	Scalar LQ 3rd gen	0 e, μ, ≥1 τ	0 – 2 j, 2 b	Yes	139	LQ_3^d mass 1.26 TeV	$\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$	2101.12527
	Vector LQ mix gen	multi-channel	≥1 j, ≥1 b	Yes	139	LQ_3^V mass 2.0 TeV	$\mathcal{B}(\tilde{U}_1 \to t\mu) = 1$, Y-M coupl.	ATLAS-CONF-2022-052
	Vector LQ 3rd gen	2 e, μ, τ	≥1 b	Yes	139	LQ_3^V mass 1.96 TeV	$\mathcal{B}(\mathrm{LQ}_3^V \to b\tau) = 1$, Y-M coupl.	2303.01294
Vector-like fermions	VLQ $TT \to Zt + X$	2e/2μ/≥3e,μ	≥1 b, ≥1 j	–	139	T mass 1.46 TeV	SU(2) doublet	2210.15413
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $T \to Ht/Zt$	1 e, μ	≥1 b, ≥3 j	Yes	139	T mass 1.8 TeV	SU(2) singlet, κ_T= 0.5	ATLAS-CONF-2021-040
	VLQ $Y \to Wb$	1 e, μ	≥1 b, ≥1 j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb$	0 e,μ	≥2b, ≥1j, ≥1J	–	139	B mass 2.0 TeV	SU(2) doublet, κ_B= 0.3	ATLAS-CONF-2021-018
	VLL $\tau' \to Z\tau/H\tau$	multi-channel	≥1 j	Yes	139	τ' mass 898 GeV	SU(2) doublet	2303.05441
Exctd ferm.	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	139	b^* mass 3.2 TeV		1910.08447
	Excited lepton τ^*	2 τ	≥2 j	–	139	τ^* mass 4.6 TeV	$\Lambda = 4.6$ TeV	2303.09444
Other	Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV		2202.02039
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	DY production	2101.11961
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV	DY production	2211.07505
	Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV	DY production, $\lvert q\rvert = 5e$	ATLAS-CONF-2022-034
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

**Only a selection of the available mass limits on new states or phenomena is shown.*

†Small-radius (large-radius) jets are denoted by the letter j (J).

$\mathcal{O}(\mathrm{TeV})$

SMEFT



Top-down approach

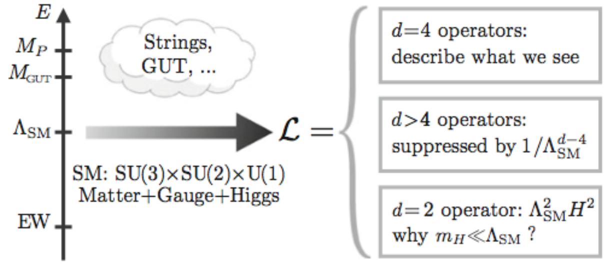
Bottom-up approach

New Physics and EFT

1. The κ framework for the couplings:

BSM physics is expected to affect the production modes and decay channels by a SM like interactions

2. The Standard Model Effective Field Theory



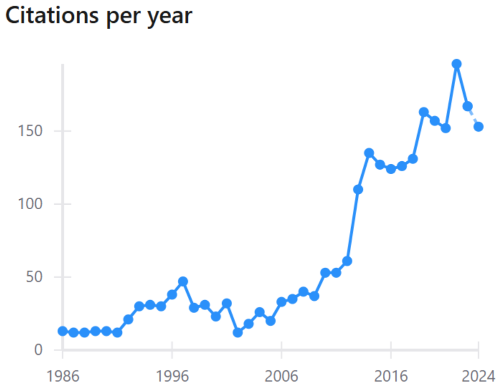
Linear realized EFT

Higgs is a fundamental particle
Weak interacting

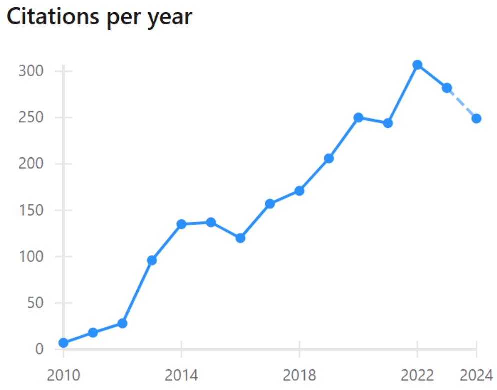
W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020
Murphy, 2020

$$\mathcal{L} = \frac{C_6}{\Lambda^2}\mathcal{O}_6 + \frac{C_8}{\Lambda^4}\mathcal{O}_8 + \ldots$$

W. Buchuller, D. wyler 1986



B. Grzadkowski et al, 2010

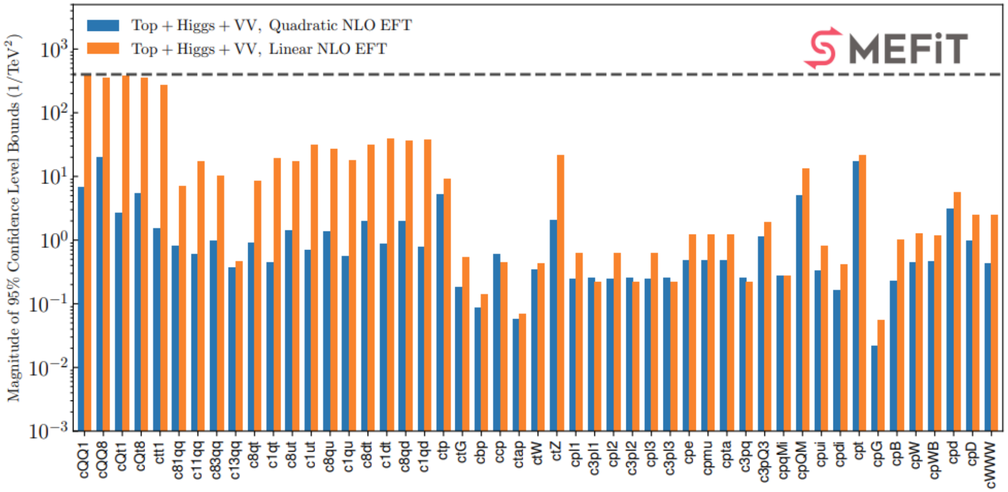


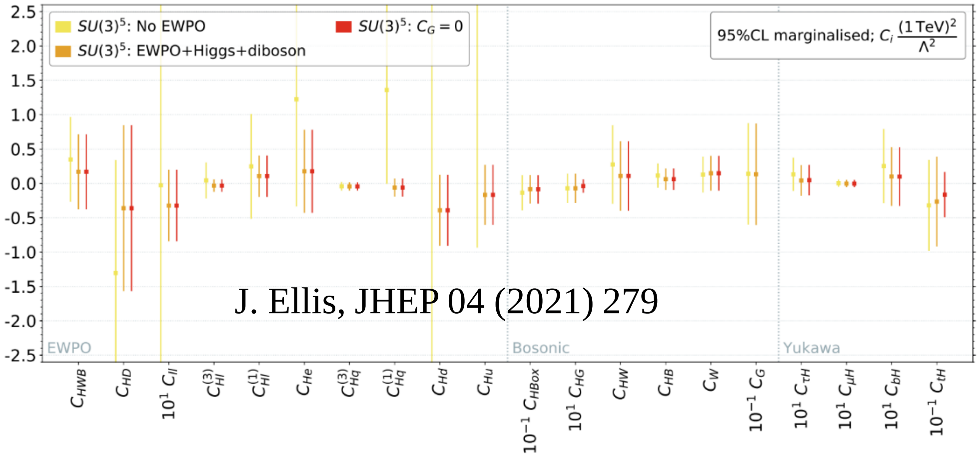
3. Higgs Effective Field Theory

Callan, Coleman, Wess, Zumino, 1969
The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,….

Global analysis @ SMEFT

SMEFiT Collaboration, JHEP 11 (2021) 089





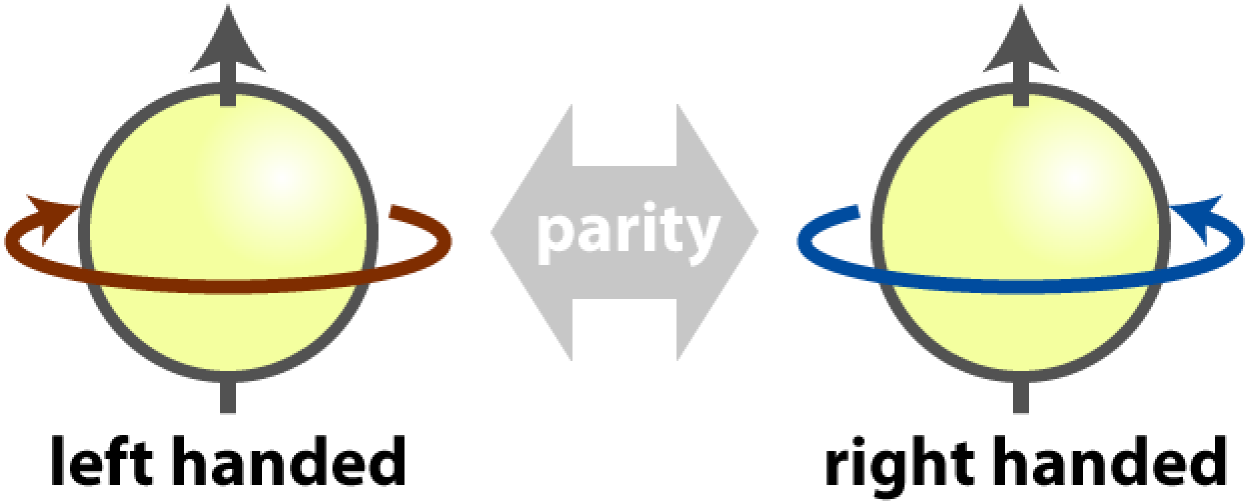
J. Ellis, JHEP 04 (2021) 279

The SMEFT approach allows for the combination

- Higgs data
- Electroweak precision observables
- Diboson production
- Top quark Physics
- ……

SMEFT is becoming one of the standard tool for the LHC experimental analysis

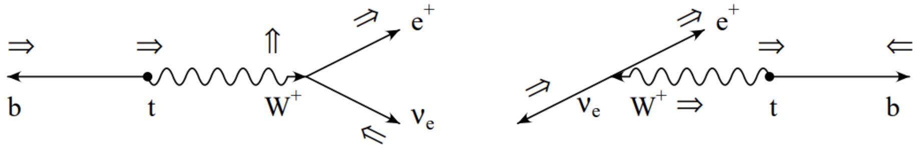
Spin effects and New Physics

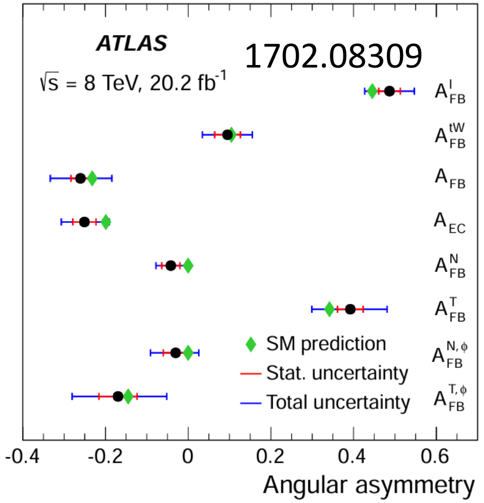


Polarization of particles would be sensitive to the weak interactions

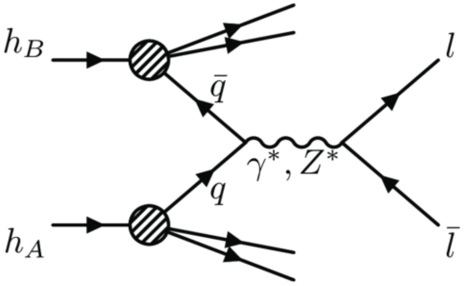
Spin effects and New Physics

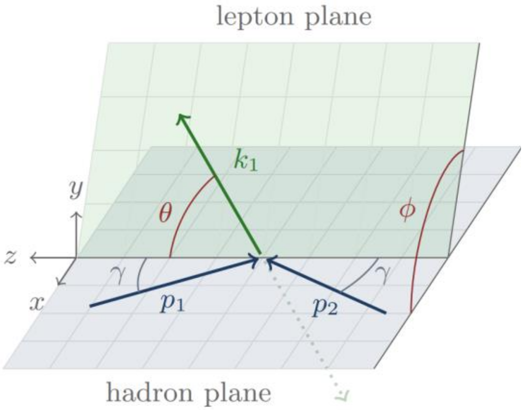
- Top quark polarization:

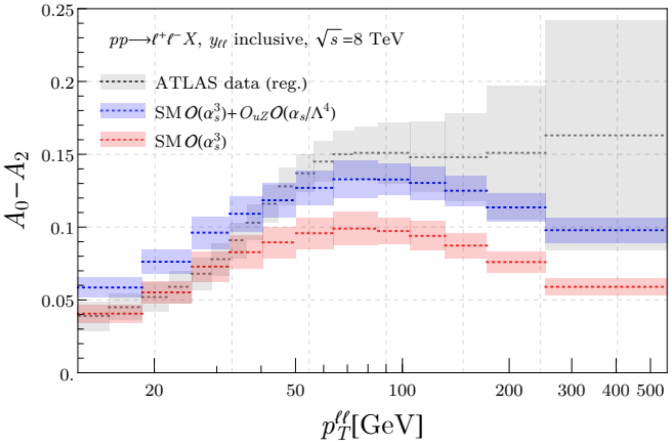




- Gauge boson polarization





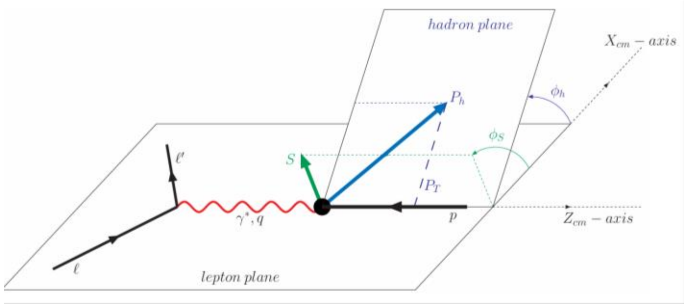


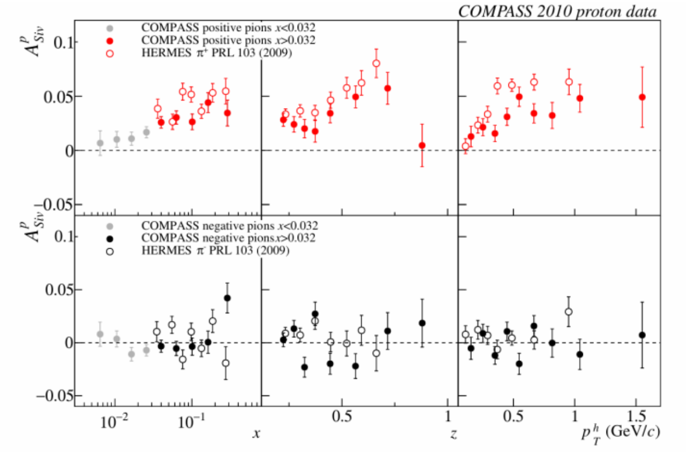
$$A_0(1 - 3\cos^2\theta) + A_2 \sin^2\theta\cos(2\phi)$$

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

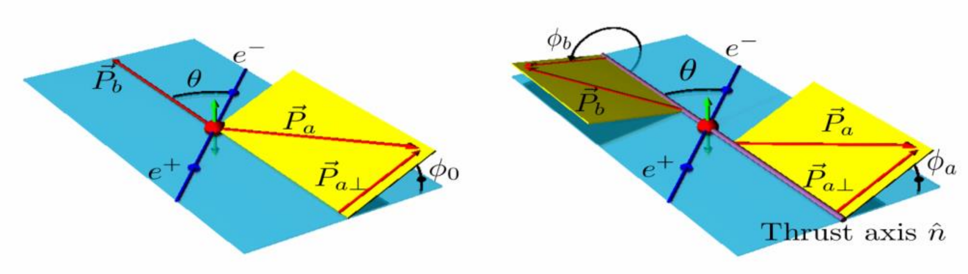
Spin effects in QCD

- Nucleon structure: PDFs

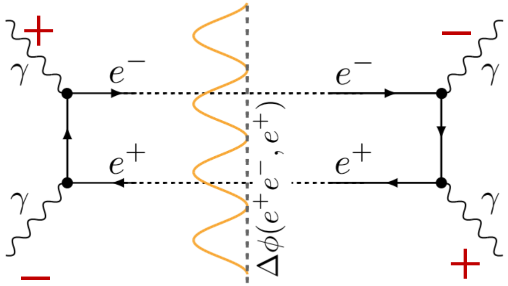


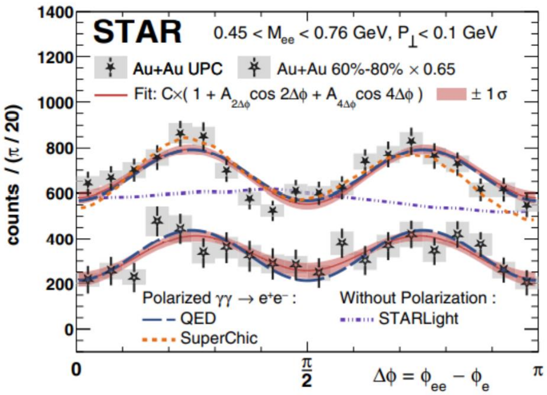


- Nucleon structure: FFs



- UPCs





QCD Spin effects and New physics

- **What type of new physics would exhibit sensitivity to the effects of QCD spin?**

➡ **Dipole moments**

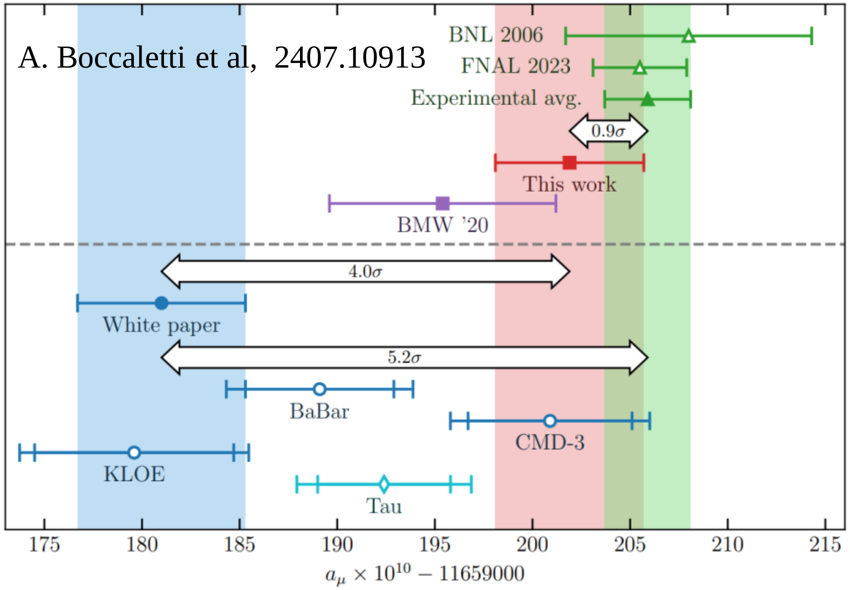
$$-\mu_e \frac{\vec{S}}{|\vec{S}|}\cdot\vec{B} \quad \Leftrightarrow \quad e\left(\bar{e}\gamma_\mu e\right)A^\mu + a_e\frac{e}{4m_e}\left(\bar{e}\sigma_{\mu\nu}e\right)F^{\mu\nu}$$

$$-d_e \frac{\vec{S}}{|\vec{S}|}\cdot\vec{E} \quad \Leftrightarrow \quad +d_e\frac{i}{2}\left(\bar{e}\sigma_{\mu\nu}\gamma_5 e\right)F^{\mu\nu}$$

$$\mu_e = g_e\frac{e}{2m_e} \quad \text{and} \quad \left(g_e-2\right)=2a_e$$

New physics and Dipole Operator

- Magnetic dipole moments: probing the internal structures of particles

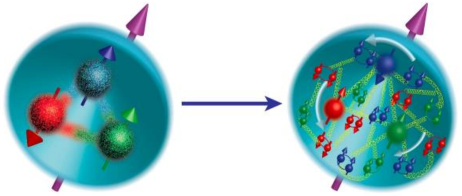


☐ Elementary particle:

Electron: g/2=1.001159…
Muon: g/2=1.0011659..

☐ Composite particle:

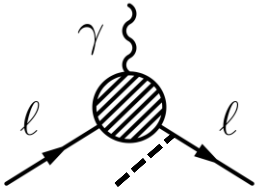
Proton: g/2=2.7928444..
Neutron: g/2=-1.91394308..



☐ Quarks: any internal structures?

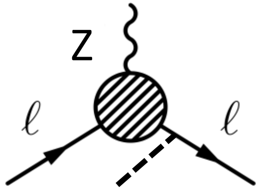
☐ From MDM and EDM to weak dipole moments?

$$\bar{\ell}\,\sigma^{\mu\nu} e \tau^I \varphi W^I_{\mu\nu}\,,\ \bar{\ell}\,\sigma^{\mu\nu} e \varphi B_{\mu\nu}$$



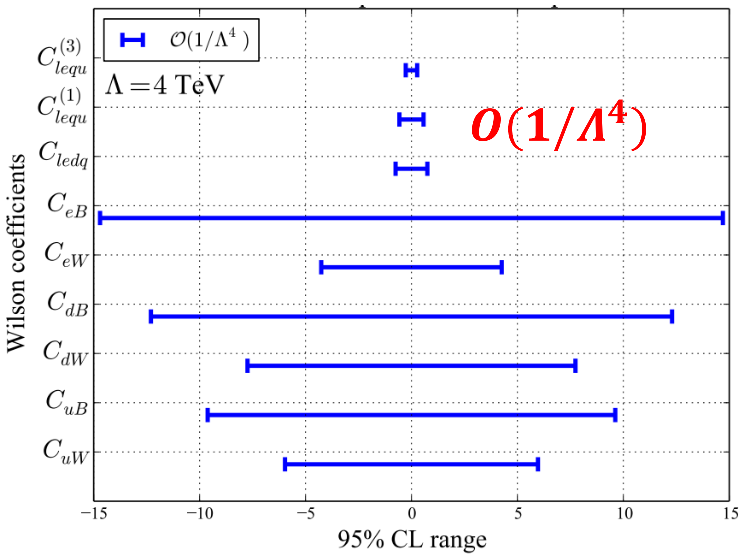
May have same physics source

$B_{\mu\nu}, W_{\mu\nu}$

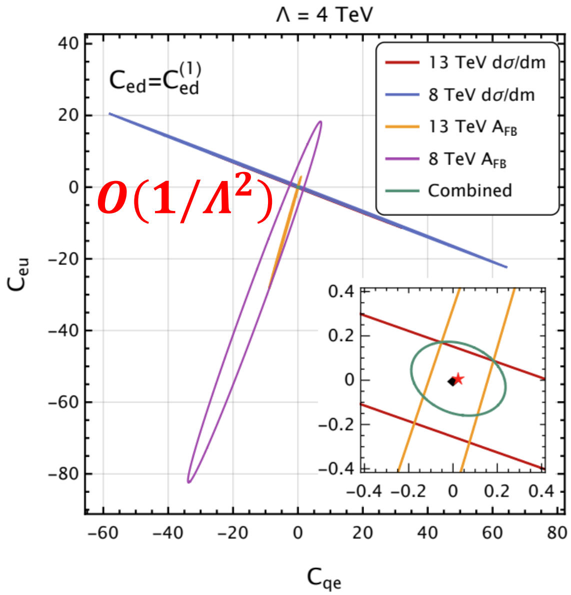


Example: Electroweak Dipole Operator

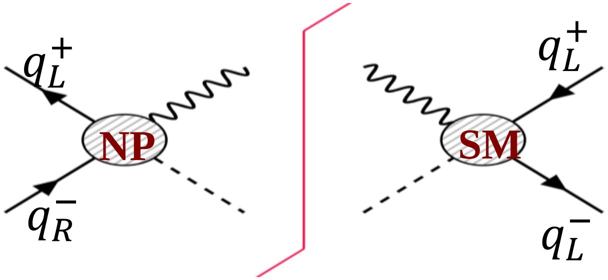
Single-Parameter-Analysis: EW dipole couplings are poorly constrained by Drell-Yan data



R. Boughezal et al, PRD 104 (2021) 095022



R. Boughezal et al, 2303.08257



=0 for the cross section

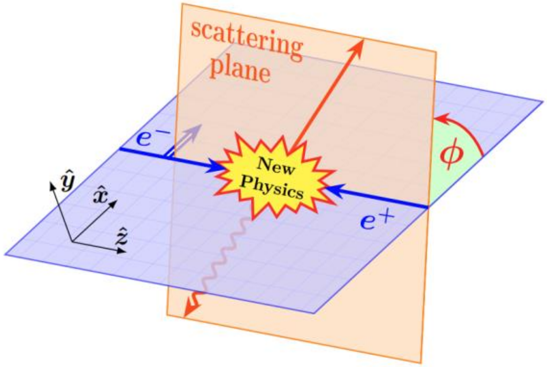
Leading contribution: $\left|\frac{c_{dipole}}{\Lambda^2}\right|^2$

- It is difficult to probe the electroweak dipole interactions at colliders

Electroweak dipole moments of leptons

- Transversely polarized effect of beams @ lepton collider

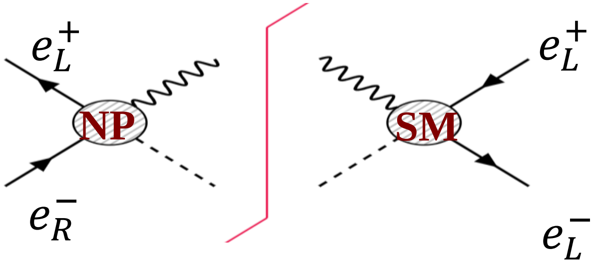
The interference between the different helicity states



$$\boldsymbol{s} = (b_1, b_2, \lambda) = (\underline{b_{\mathrm{T}} \cos\phi_0, b_{\mathrm{T}} \sin\phi_0}, \lambda)$$

$$\rho = \frac{1}{2}(1 + \boldsymbol{\sigma}\cdot\boldsymbol{s}) = \frac{1}{2}\begin{pmatrix} 1+\lambda & b_{\mathrm{T}} e^{-i\phi_0} \\ b_{\mathrm{T}} e^{i\phi_0} & 1-\lambda \end{pmatrix}$$

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801



$$\bar{e}_L \sigma_{\mu\nu} e_R A^{\mu\nu}, \bar{e}_L \sigma_{\mu\nu} e_R Z^{\mu\nu}$$

$$M \propto e^{i(\alpha 1 - \alpha 2)\phi} d(\theta)$$

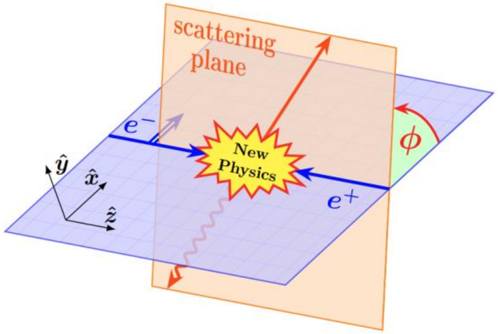
	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

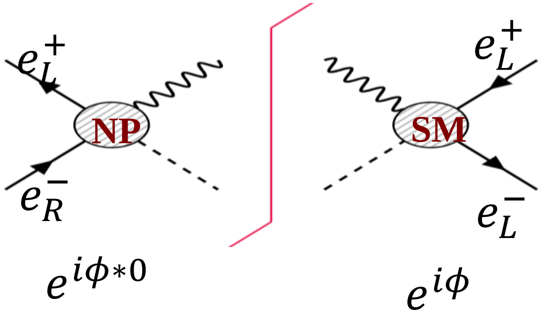
Breaking the rotational invariance & A nontrivial azimuthal behavior

Electroweak dipole moments of leptons

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801





$M\infty e^{i(\alpha 1-\alpha 2)\phi}d(\theta)$

	U	L	T
U	$\lvert\mathcal{M}\rvert^2_{UU} \to 1$	$\lvert\mathcal{M}\rvert^2_{UL} \to 1$	$\lvert\mathcal{M}\rvert^2_{UT} \to \cos\phi, \sin\phi$
L	$\lvert\mathcal{M}\rvert^2_{LU} \to 1$	$\lvert\mathcal{M}\rvert^2_{LL} \to 1$	$\lvert\mathcal{M}\rvert^2_{LT} \to \cos\phi, \sin\phi$
T	$\lvert\mathcal{M}\rvert^2_{TU} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TL} \to \cos\phi, \sin\phi$	$\lvert\mathcal{M}\rvert^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$

$$\frac{2\pi\, d\sigma^i}{\sigma^i\, d\phi} = 1 + \underline{A_R^i(b_T,\bar{b}_T)}\cos\phi + \underline{A_I^i(b_T,\bar{b}_T)}\sin\phi + \underline{b_T\,\bar{b}_T\,B^i}\cos 2\phi + \mathcal{O}\left(1/\Lambda^4\right)$$

Re[C_{dipole}] Im[C_{dipole}] SM & other NP

CP-conserving CP-violation

- Linearly dependent on the dipole couplings C_{dipole} and spin b_T
- Without depending on other NP operators

Single Transverse Spin Asymmetries

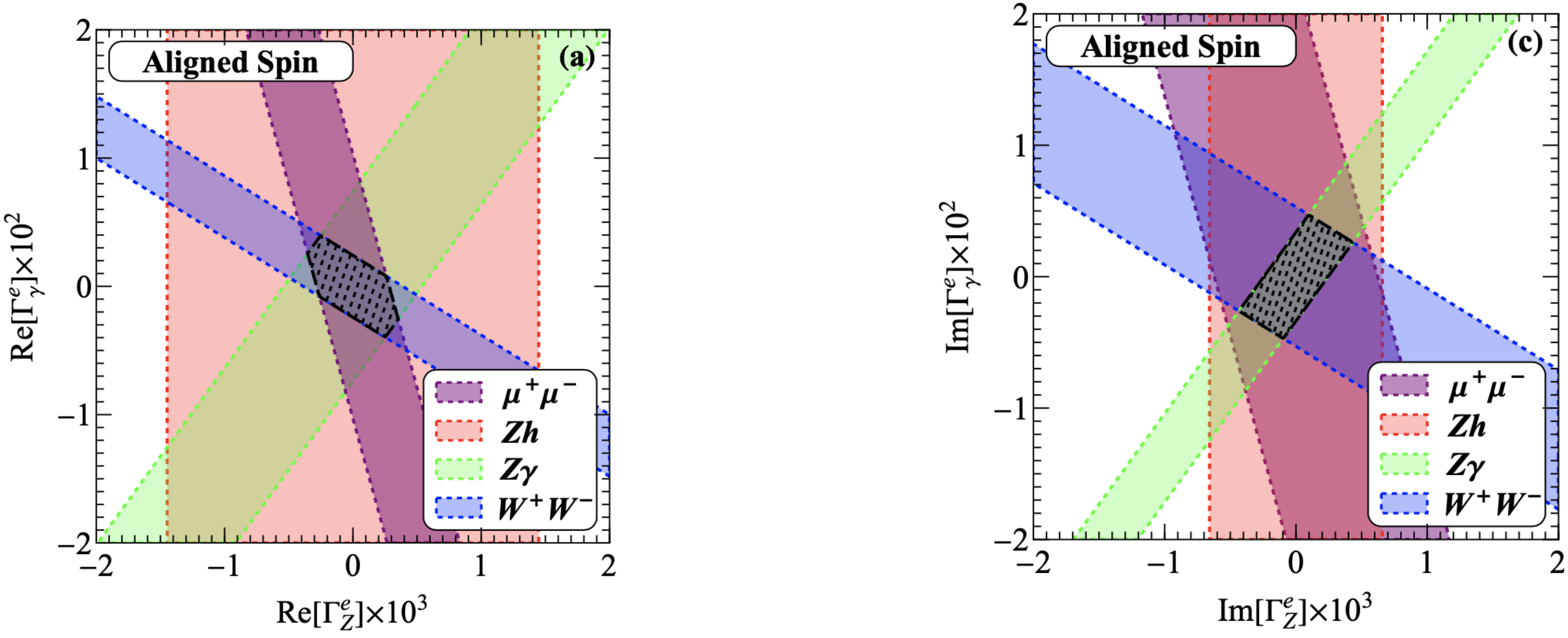
$$A_{LR}^i = \frac{\sigma^i(\cos\phi>0)-\sigma^i(\cos\phi<0)}{\sigma^i(\cos\phi>0)+\sigma^i(\cos\phi<0)} = \frac{2}{\pi}A_R^i$$

$$A_{UD}^i = \frac{\sigma^i(\sin\phi>0)-\sigma^i(\sin\phi<0)}{\sigma^i(\sin\phi>0)+\sigma^i(\sin\phi<0)} = \frac{2}{\pi}A_I^i,$$

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan,

PRL 131 (2023) 241801

$\sqrt{s} = 250$ GeV, $\mathcal{L} = 5$ ab^{-1} $\quad (b_T, \bar{b}_T) = (0.8, 0.3)$



CP-conserved dipole operator

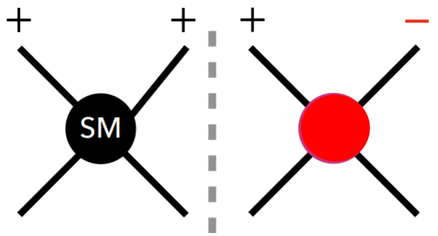
CP-violated dipole operator

- Our bounds are much stronger than other approaches by 1~2 orders of magnitude
- Weak dipole coupling, SSA: 0.01%, LHC: 1%

Transverse spin effects of electron @ EIC

- Electron dipole operators

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

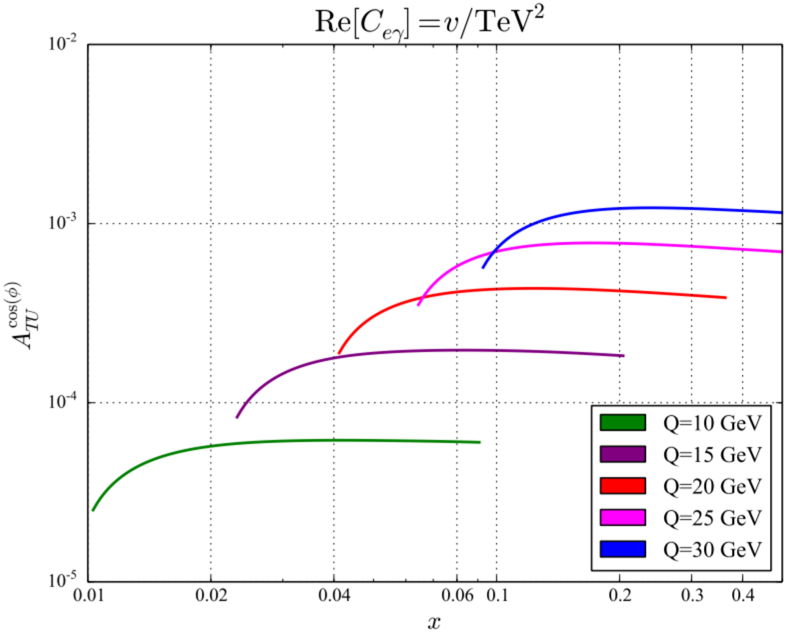


$\sim \mathcal{O}(\frac{1}{\Lambda^2})$

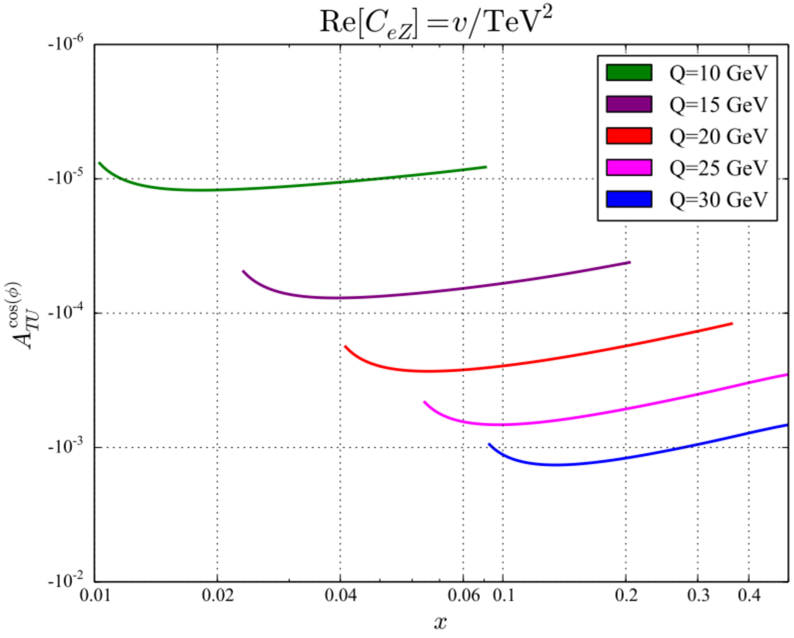
$$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu}e)\tau^I\varphi W^I_{\mu\nu},$$

$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},$$

$$A_{TU} = \frac{\sigma\left(e^{\uparrow}p^{U}\right) - \sigma\left(e^{\downarrow}p^{U}\right)}{\sigma\left(e^{\uparrow}p^{U}\right) + \sigma\left(e^{\downarrow}p^{U}\right)}$$



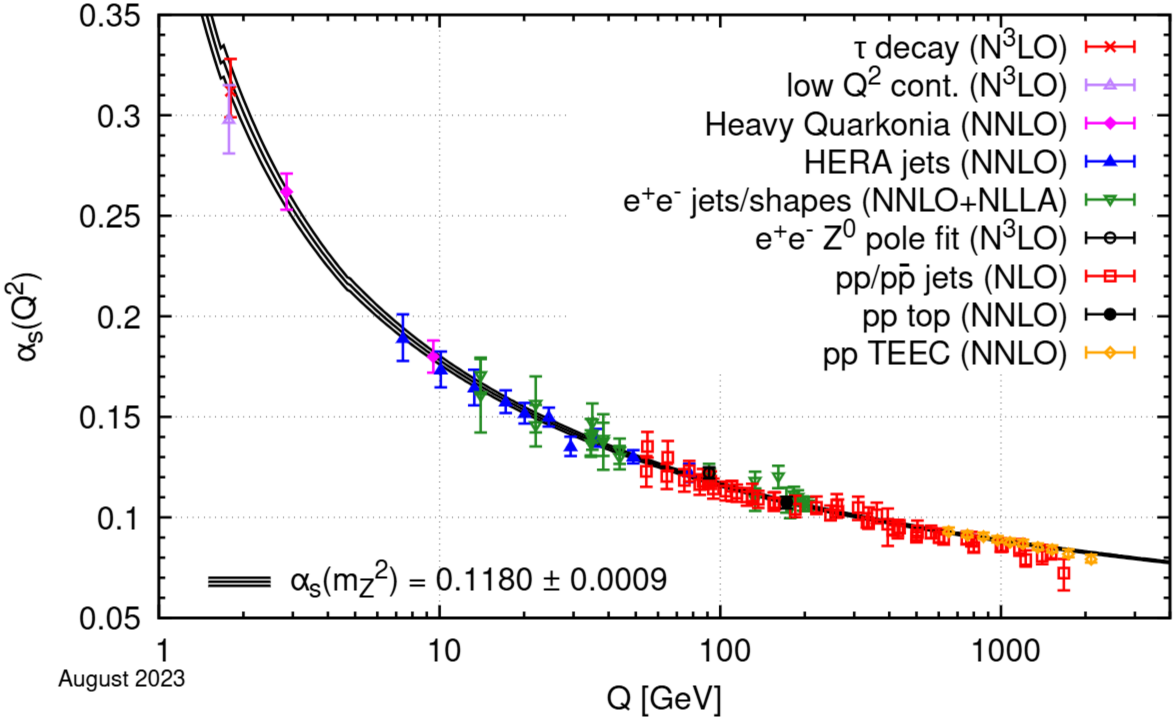
$\mathrm{Re}[C_{e\gamma}] = v/\mathrm{TeV}^2$



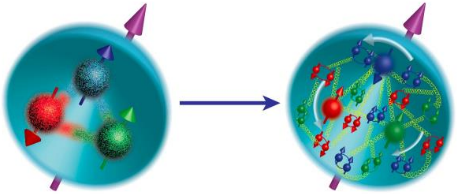
$\mathrm{Re}[C_{eZ}] = v/\mathrm{TeV}^2$

Electroweak dipole moments of quarks

- The quark can not be a free particle due to the QCD confinement



Asymptotic freedom of QCD theory



- How to probe the spin information of quarks?

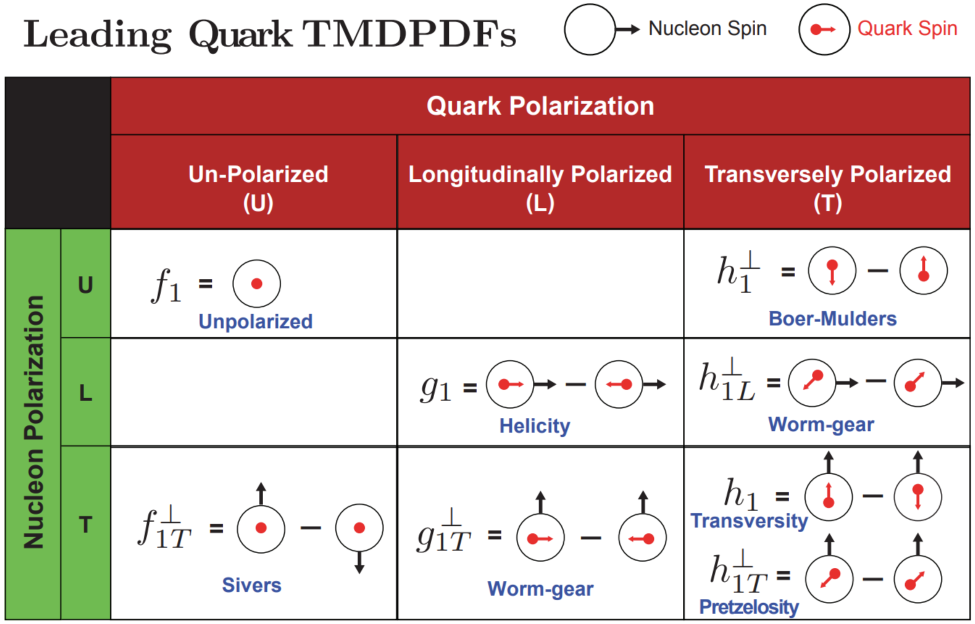
The non-perturbative functions, i.e., the parton distirbuion functions and the fragmentation functions

Transverse spin effects of quark @ EIC

- Quark dipole operators

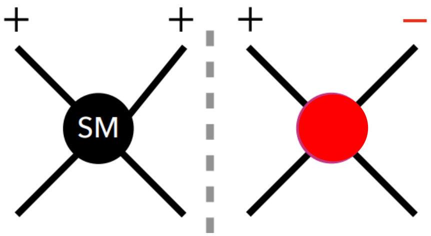
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, PRD 107 (2023) 7, 075028
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025

Leading Quark TMDPDFs



		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	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

$$\begin{aligned} \mathcal{O}_{uW} &= (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W^I_{\mu\nu}, \\ \mathcal{O}_{uB} &= (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu}, \\ \mathcal{O}_{dW} &= (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W^I_{\mu\nu}, \\ \mathcal{O}_{dB} &= (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}. \end{aligned}$$



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

- The transversity is difficult to be constrained: chiral-odd

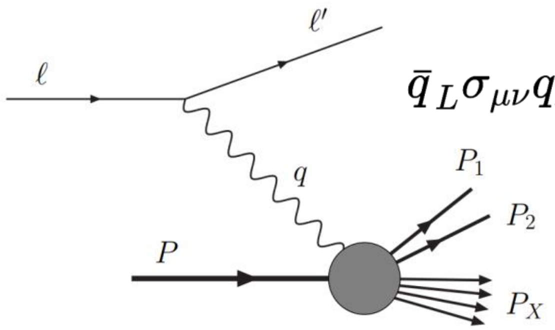
$$A_{UT} = \frac{\sigma(e^U p^\uparrow) - \sigma(e^U p^\downarrow)}{\sigma(e^U p^\uparrow) + \sigma(e^U p^\downarrow)}$$

  - Collins Azimuthal Asymmetries in SIDIS, Collins function
  - Low energy Drell-Yan process
  - Dihadron production in SIDIS, Interference dihadron fragmentation

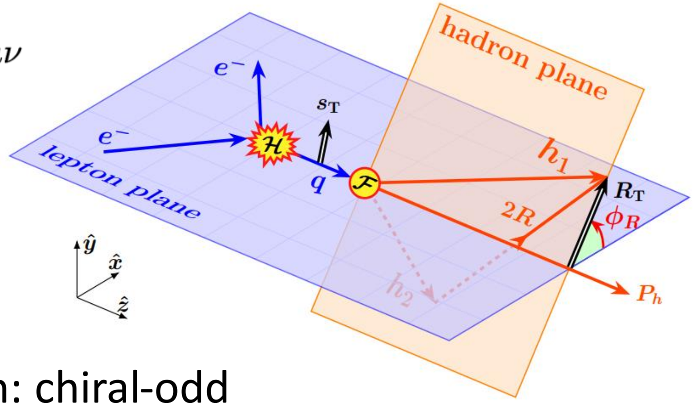
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002;
JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects of quark @ EIC

- The transverse spin of quarks can be generated by the quark dipole moments



$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$



- The interference dihadron fragmentation function: chiral-odd

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

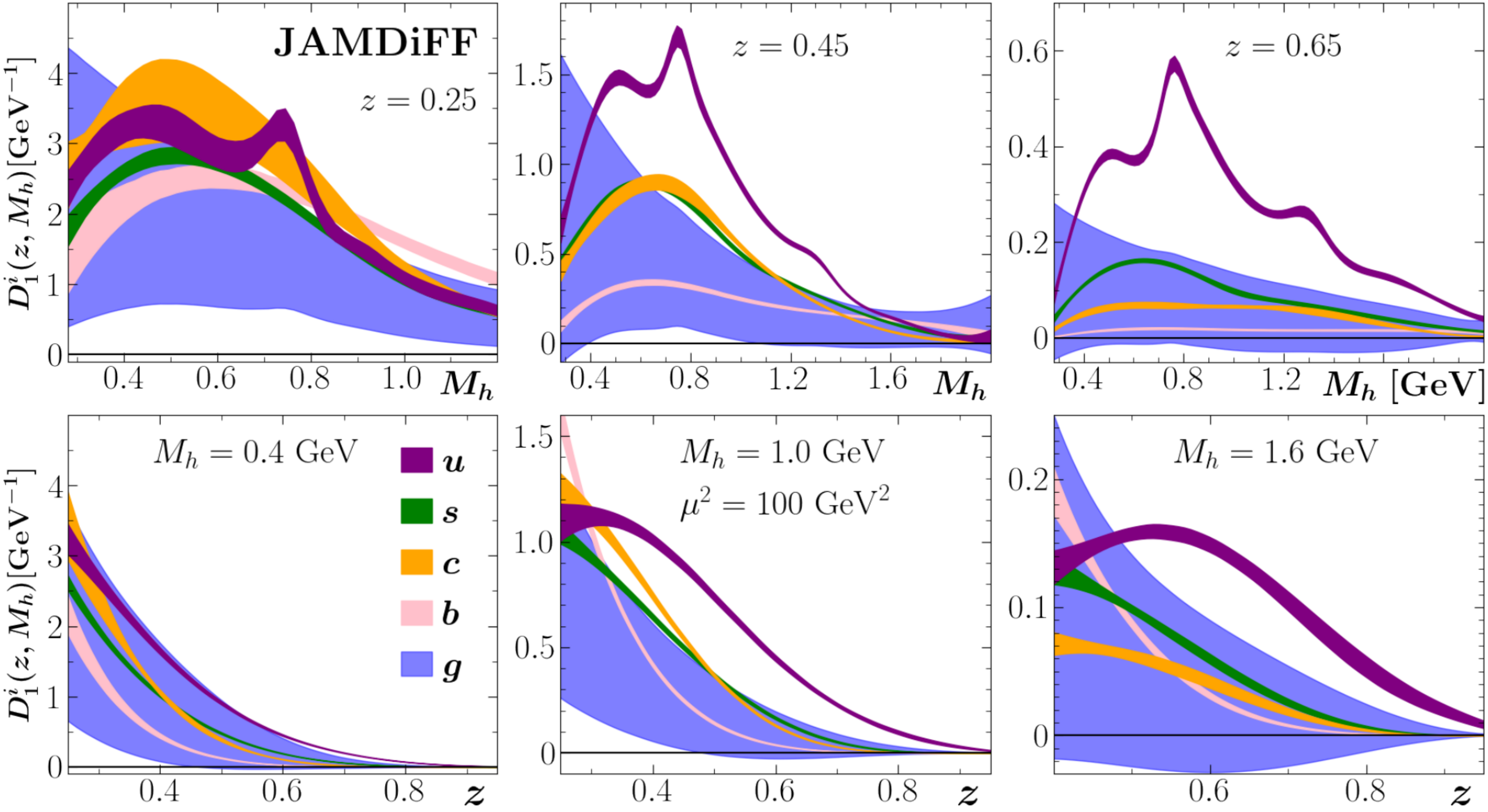
$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Re}\,\Gamma_Z^q\right)$$

$$(\boldsymbol{s}_{T,q}\times\hat{\boldsymbol{R}}_T)^z = s_q^x\sin\phi_R - s_q^y\cos\phi_R$$

$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\,\mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\,\mathrm{Im}\,\Gamma_Z^q\right)$$

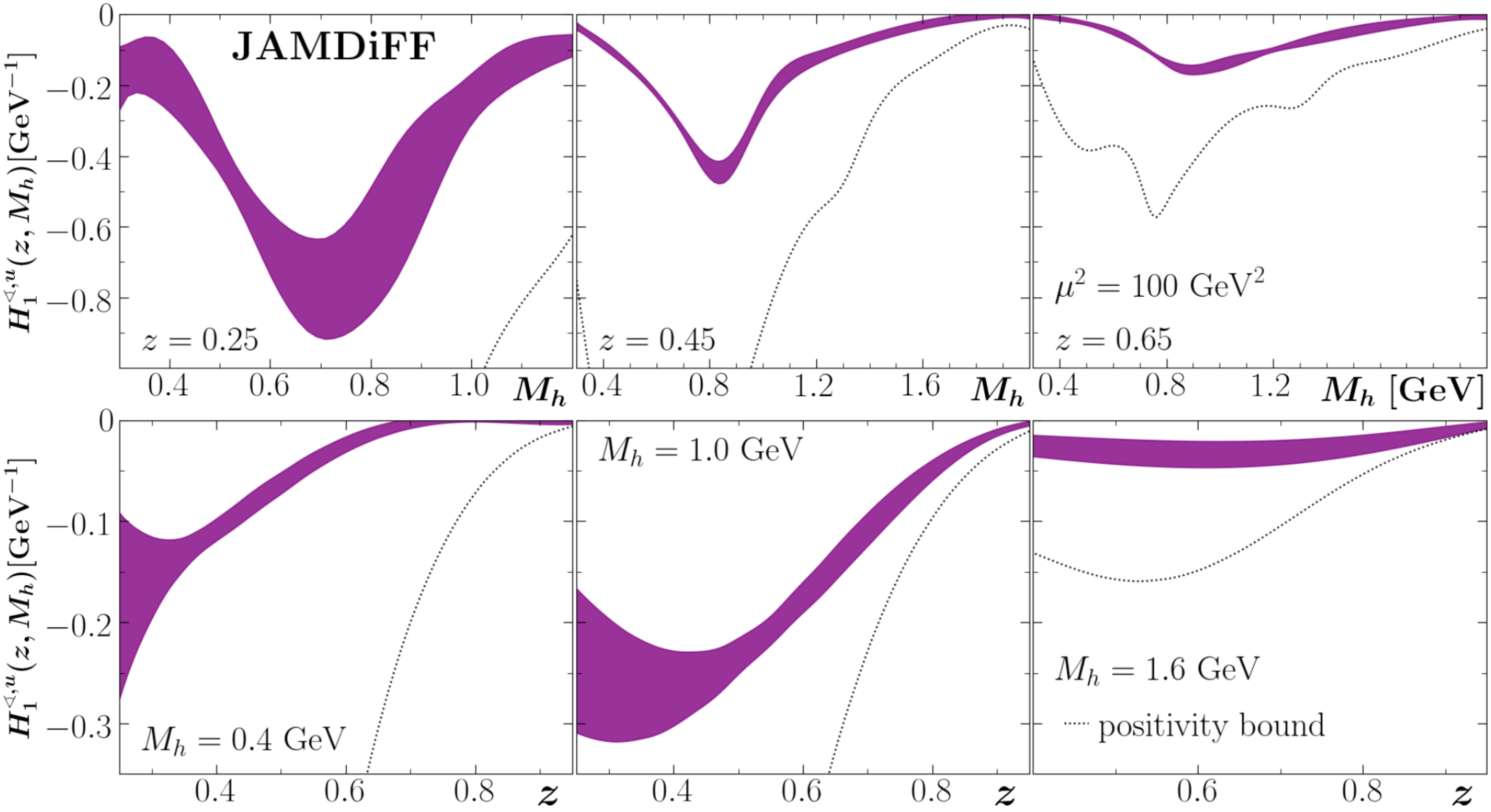
Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 2408.07255

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



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

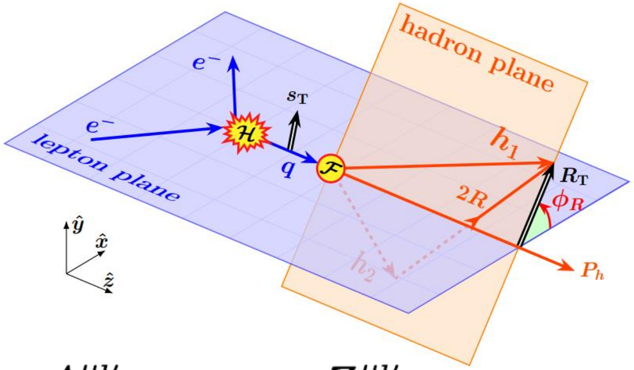
$\pi^+\pi^-$ Dihadron fragmentation functions



JAM Collaboration, PRL 132 (2024) 091901 , PRD 109 (2024) 034024

Transverse spin effects of quark @ EIC

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



The non-trivial azimuthal distribution requires parity-violation effects:

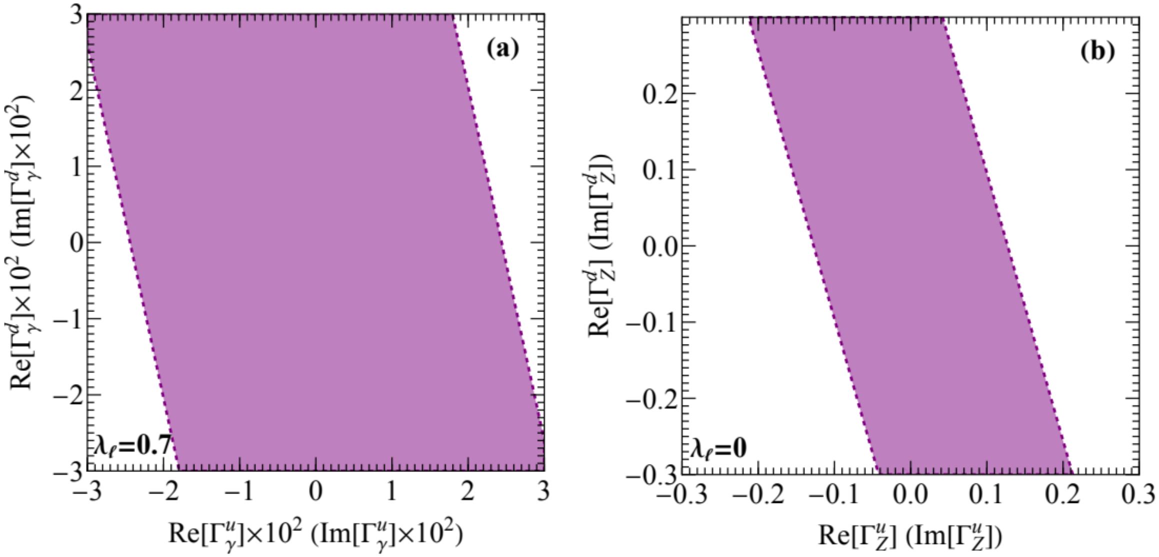
- ☐ the longitudinal polarization of the electron
- ☐ the parity-violating Z interactions

$$(\boldsymbol{s}_{T,q} \times \hat{\boldsymbol{R}}_T)^z = s_q^x \sin\phi_R - s_q^y \cos\phi_R$$

$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

$$A_{LR} = \frac{\sigma(\cos\phi_R > 0) - \sigma(\cos\phi_R < 0)}{\sigma(\cos\phi_R > 0) + \sigma(\cos\phi_R < 0)} = \frac{2}{\pi} A_I$$

$$A_{UD} = \frac{\sigma(\sin\phi_R > 0) - \sigma(\sin\phi_R < 0)}{\sigma(\sin\phi_R > 0) + \sigma(\sin\phi_R < 0)} = \frac{2}{\pi} A_R$$



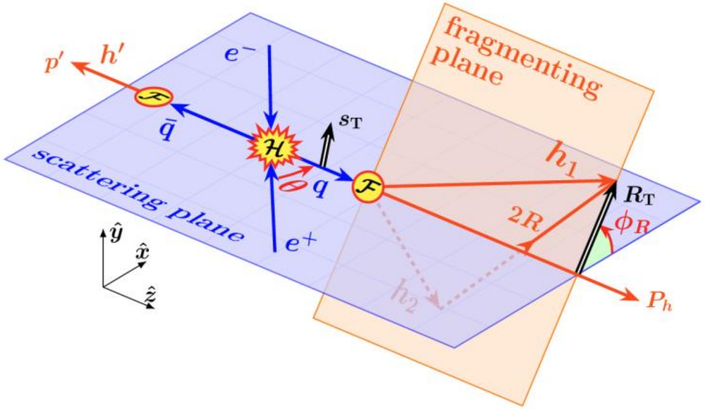
$$\sqrt{s} = 105 \text{ GeV}, \mathcal{L} = 1 \text{ ab}^{-1}$$

- ☐ Photon dipole: O(0.01)
- ☐ Z-boson dipole: O(0.1)

The flat direction in dipole couplings?

Transverse spin effects of quark @ CEPC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



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

$$s_q^x = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Re}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Re}\,\Gamma_Z^q\right)$$
$$s_q^y = \frac{2}{C_q}\left(w_\gamma^q\ \mathrm{Im}\,\Gamma_\gamma^q + w_Z^q\ \mathrm{Im}\,\Gamma_Z^q\right)$$

$$\bar{q}_L\sigma_{\mu\nu}q_R A^{\mu\nu},\, \bar{q}_L\sigma_{\mu\nu}q_R Z^{\mu\nu}$$

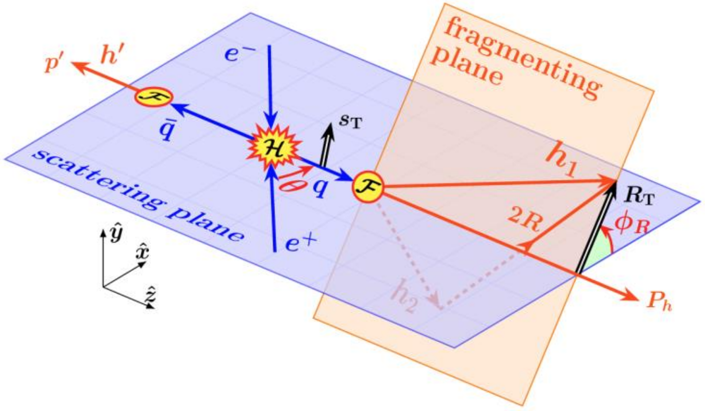
Isospin and charge conjugation symmetries:

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

$$D_q^{\pi^+\pi^-} = D_{\bar{q}}^{\pi^+\pi^-},\quad H_q^{\pi^+\pi^-} = -H_{\bar{q}}^{\pi^+\pi^-}$$

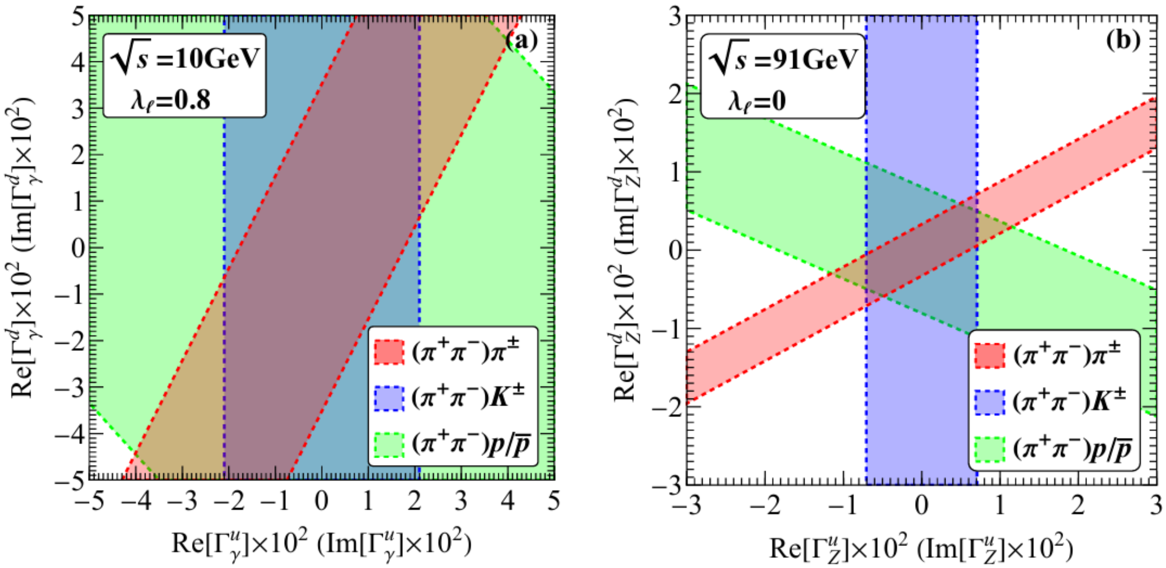
Transverse spin effects of quark @ CEPC

Xin-Kai Wen, Bin Yan, Zhite Yu, C.-P. Yuan, 24011.13845



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

$$B^0 = \sum_q \langle C_q \rangle D_q^{\pi^+\pi^-}\left(D_q^{h'} + D_{\bar{q}}^{h'}\right) \qquad B^i = H_u^{\pi^+\pi^-}\left[\langle S_u^i \rangle \left(D_{\bar{u}}^{h'} - D_u^{h'}\right) - \langle S_d^i \rangle \left(D_{\bar{d}}^{h'} - D_d^{h'}\right)\right]$$

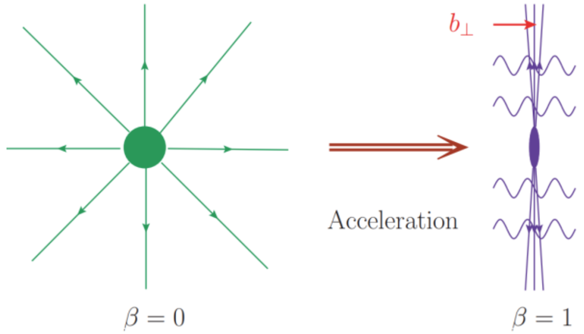


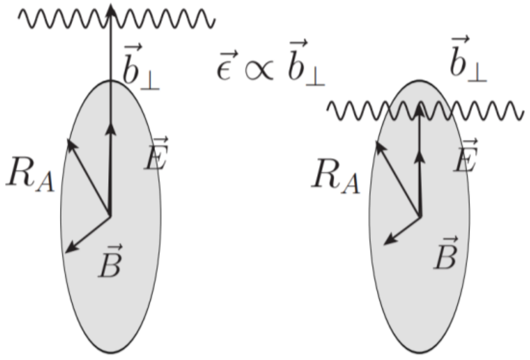
$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$

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

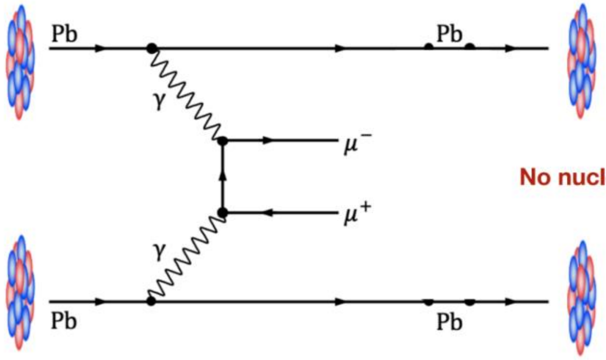
- ☐ The flat direction can be closed by combing more processes
- ☐ Photon dipole: O(0.01)
- ☐ Z-boson dipole: O(0.001)

Linear polarization @ UPCs





C. Li, J. Zhou, Y. J. Zhou, Phys. Lett. B. 795, 576 (2019)



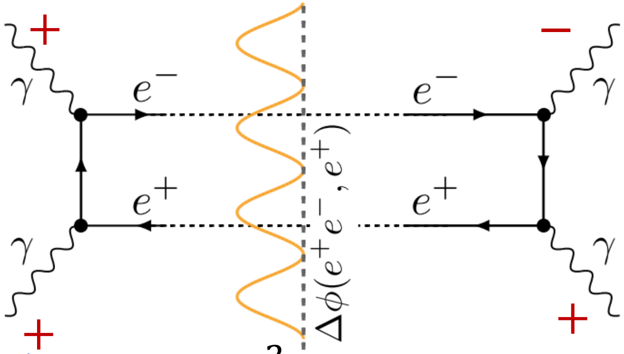
No nucleus breakup

- ➢ Ultra-relativistic charged nuclei produce highly Lorentz contracted electromagnetic field
- ➢ Weizsacker-Williams equivalent photon approximation
- ➢ Photons are linearly polarized
- ➢ Large quasi-real photon flux $\propto Z^2$
- ➢ The impact parameter $b_\perp > 2R_A$

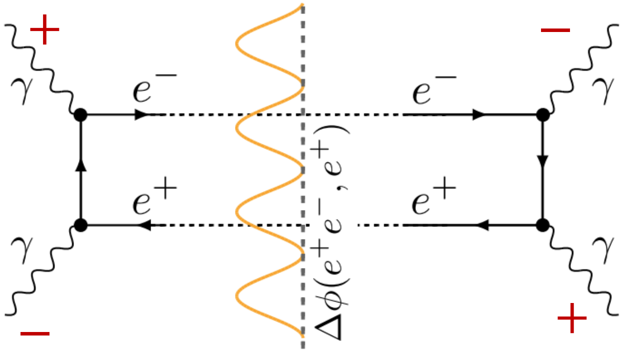
The linear polarization for gluons based on the NEEC:
Yuxun Guo, Xiaohui Liu, Feng Yuan, HuaXing Zhu, 2406.05880
Xiao Lin Li, Xiaohui Liu, Feng Yuan, HuaXing Zhu, PRD 108 (2023) L091502

Linear polarization @ UPCs

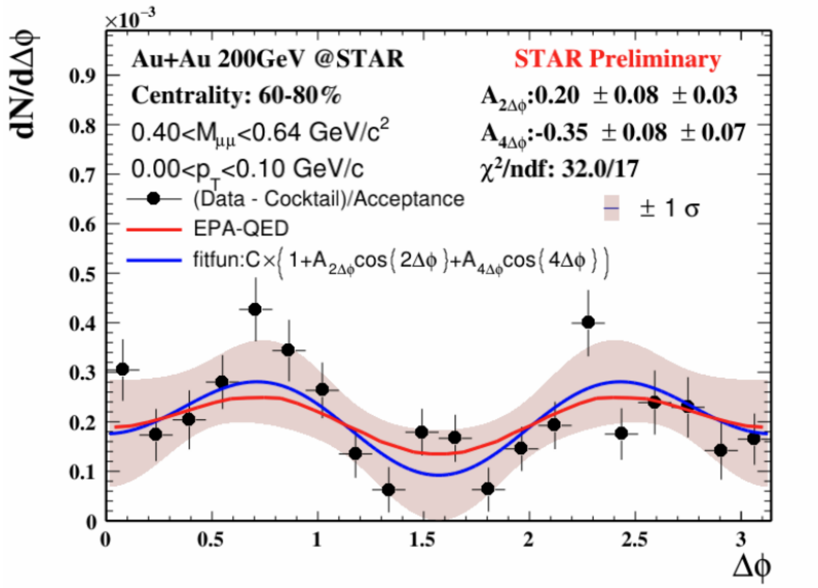
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



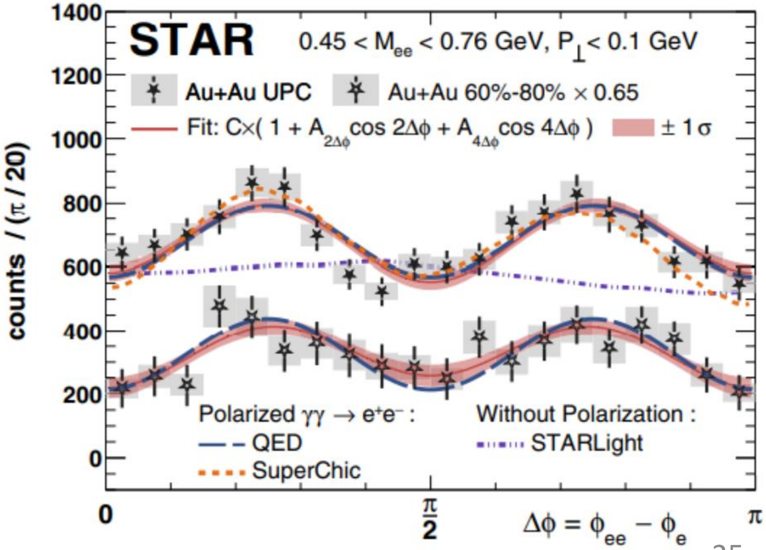
$$\frac{m_e^2}{p_T^2}cos2\Delta\phi$$



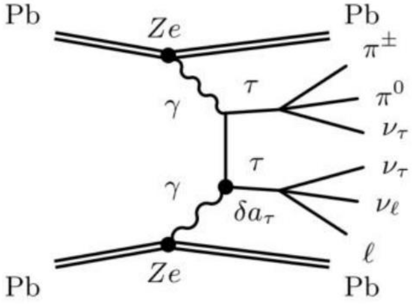
$$cos4\Delta\phi$$



PRL 127 (2021) 5, 052302

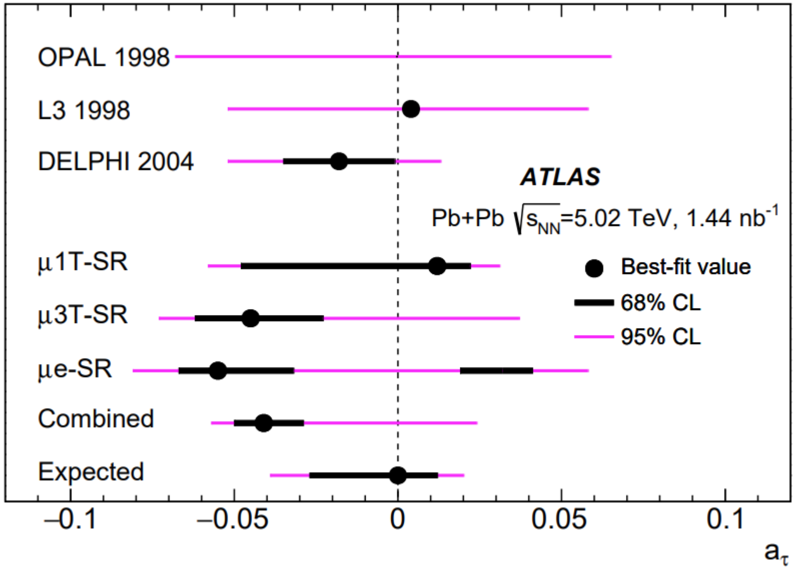


Tau pair production @ UPCs

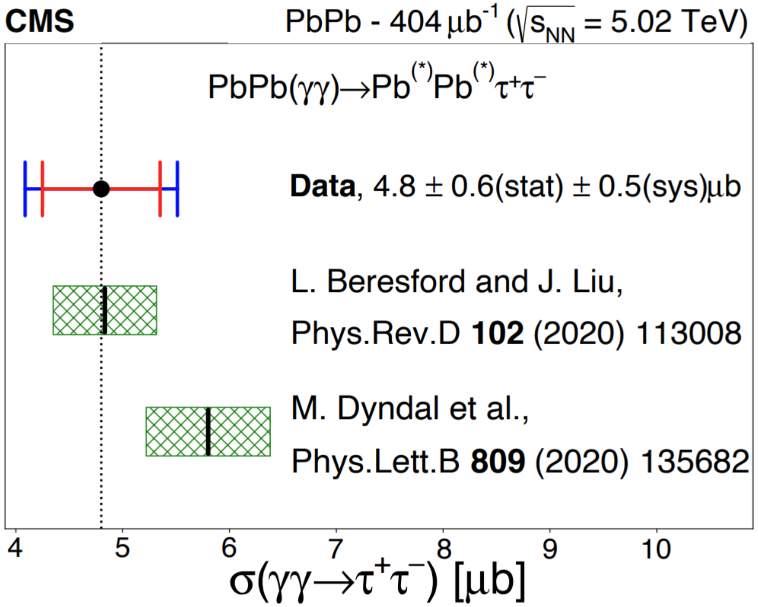


$$\Gamma^{\mu}_{\text{eff.}}(q^2) = -ie\left[iF_2(q^2)+F_3(q^2)\gamma^5\right]\frac{\sigma^{\mu\nu}q_\nu}{2m_\tau}$$

$$F_2(0)=a_\tau,\quad F_3(0)=2\frac{m_\tau d_\tau}{e}$$



Phys. Rev. Lett. 131 (2023) 15, 151802



Phys. Rev. Lett. 131 (2023) 151803

Linear polarization @ UPCs

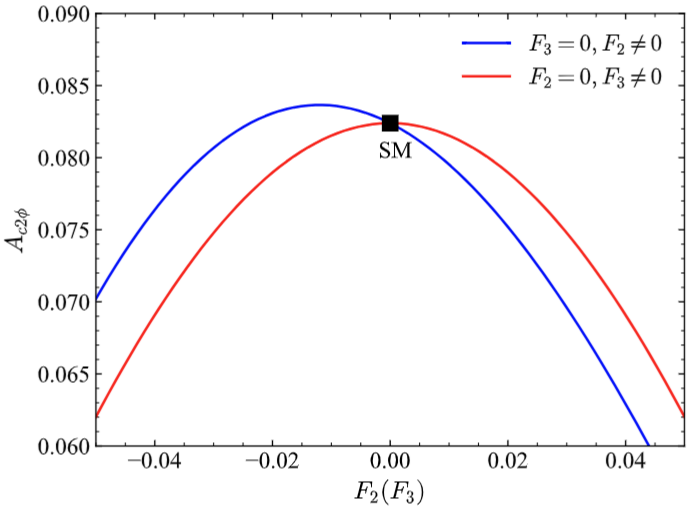
Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang,
Sci. China Phys. Mech. Astron. 67 (2024) 281062

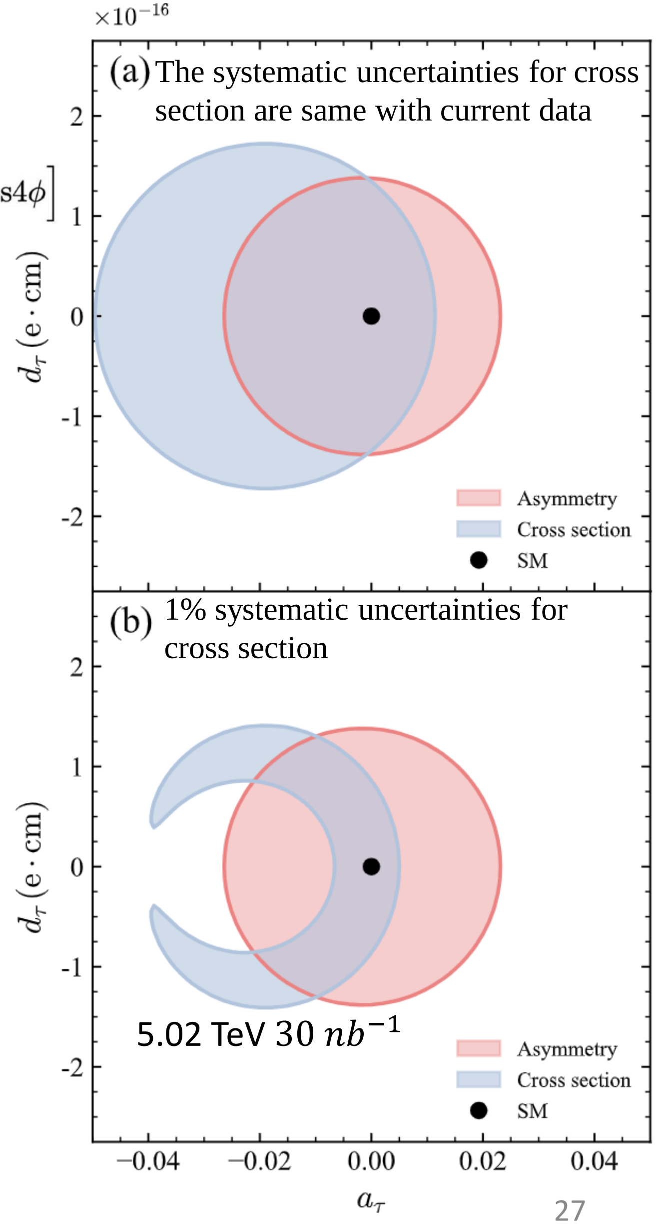
$$d\sigma \sim \left[A_0 + B_0^{(1)}F_2 + B_0^{(2)}F_2^2 + C_0^{(2)}F_3^2 + \left(A_2 + B_2^{(2)}F_2^2 + C_2^{(2)}F_3^2\right)\cos 2\phi + A_4 \cos 4\phi\right]$$

$$F_2(0) = a_\tau, \quad F_3(0) = 2\frac{m_\tau d_\tau}{e}$$

Suppressed by lepton mass

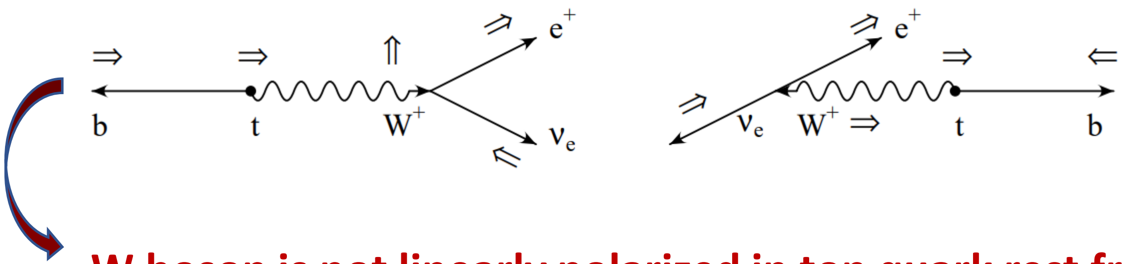
$$A_{c2\phi} = \frac{\sigma(\cos 2\phi > 0) - \sigma(\cos 2\phi < 0)}{\sigma(\cos 2\phi > 0) + \sigma(\cos 2\phi < 0)}$$

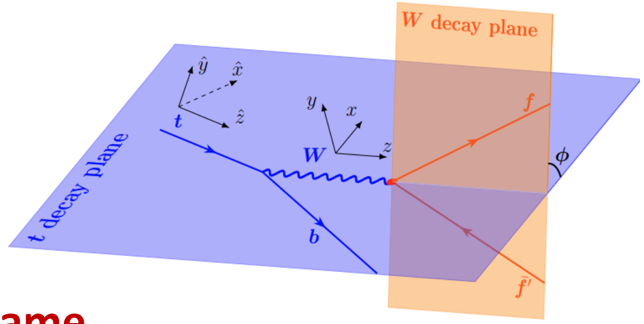




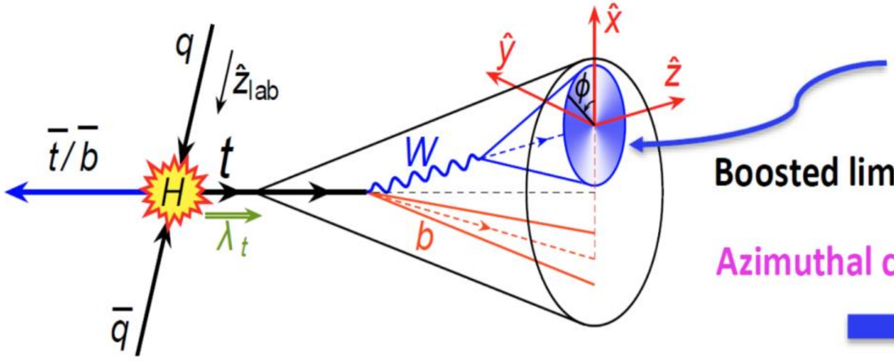
Linear polarization of W boson

Zhite Yu, C.-P. Yuan, PRL 129 (2022) 11,11





W boson is not linearly polarized in top quark rest frame



$$\frac{\mathrm{d}E}{\mathrm{d}\phi} = \frac{E_{\mathrm{tot}}}{2\pi}\left[1 + \xi \cos 2\phi\right]$$ **Infrared safe**

Boosted limit: $\xi = \xi(\lambda_t) = 0.145(\lambda_t - 1)$

[Assuming SM tbW coupling]

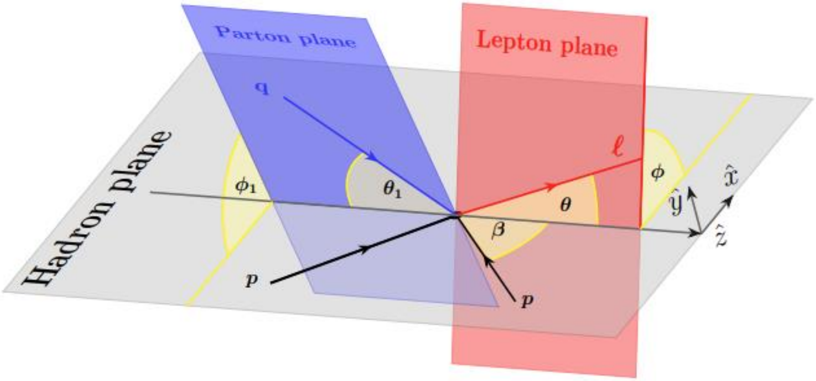
Azimuthal correlation

Boosted top polarization

- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets

A new tool to probe the NP effects,
e.g. the CP violation in top quark decay

Lam-Tung relation and polarization



Collins-Soper frame

$$\frac{d\sigma}{d^4q\ d\cos\theta\ d\phi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{d^4q}\left\{(1+\cos^2\theta) + \frac{1}{2}A_0\ (1-3\cos^2\theta)\right.$$
$$+ A_1\ \sin(2\theta)\cos\phi + \frac{1}{2}A_2\ \sin^2\theta\ \cos(2\phi)$$
$$+ A_3\ \sin\theta\ \cos\phi + A_4\ \cos\theta + A_5\ \sin^2\theta\ \sin(2\phi)$$
$$\left. + A_6\ \sin(2\theta)\ \sin\phi + A_7\ \sin\theta\ \sin\phi\right\},$$

$$\rho_{\lambda_Z\lambda'_Z} = \begin{pmatrix} \frac{1-\delta_L}{3} + \frac{J_3}{2} & \frac{J_1+2Q_{xz}-i(J_2+2Q_{yz})}{2\sqrt{2}} & \lambda_T - iQ_{xy} \\ \frac{J_1+2Q_{xz}+i(J_2+2Q_{yz})}{2\sqrt{2}} & \frac{1+2\delta_L}{3} & \frac{J_1-2Q_{xz}-i(J_2-2Q_{yz})}{2\sqrt{2}} \\ \lambda_T + iQ_{xy} & \frac{J_1-2Q_{xz}+i(J_2-2Q_{yz})}{2\sqrt{2}} & \frac{1-\delta_L}{3} - \frac{J_3}{2} \end{pmatrix}$$

$$\frac{\Gamma}{\Omega_f^*} \propto \frac{|B_+|^2+|B_-|^2}{2}\left[\frac{2}{3} + \frac{\delta_L}{3}(1-3\cos^2\theta_f^*) + \lambda_T\sin^2\theta_f^*\cos 2\phi_f^*\right.$$
$$\left. + Q_{yz}\sin 2\theta_f^*\sin\phi_f^* + Q_{xz}\sin 2\theta_f^*\cos\phi_f^* + Q_{xy}\sin^2\theta_f^*\sin 2\phi_f^*\right]$$
$$+ \frac{|B_+|^2-|B_-|^2}{2}\left(J_1\sin\theta_f^*\cos\phi_f^* + J_2\sin\theta_f^*\sin\phi_f^* + J_3\cos\theta_f^*\right).$$

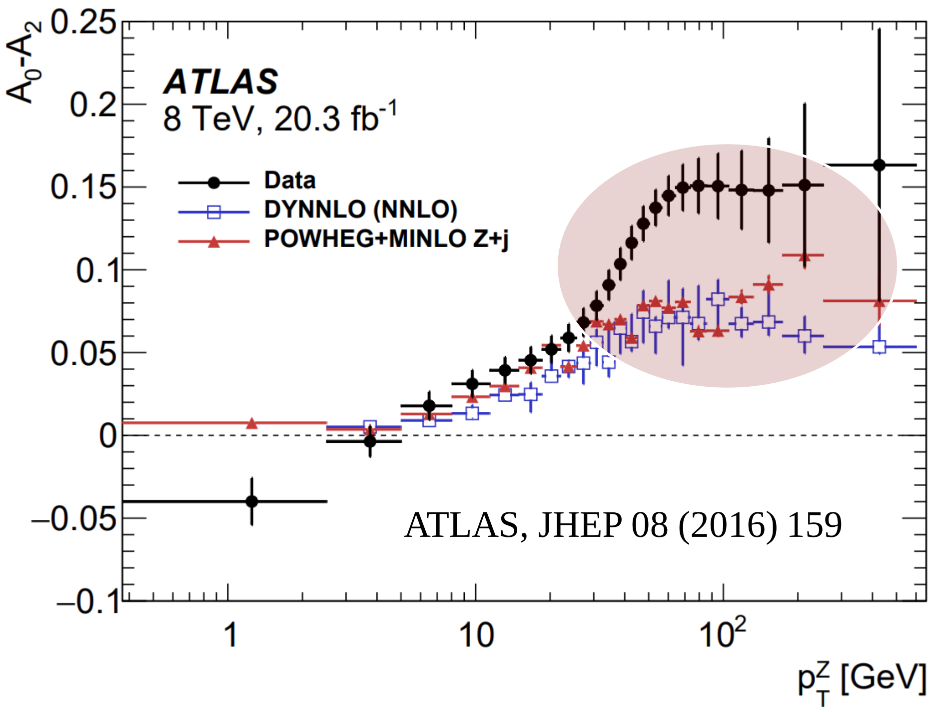
Lam-Tung relation: $A_0 = A_2$

Linear and Longitudinal polarization of Z boson

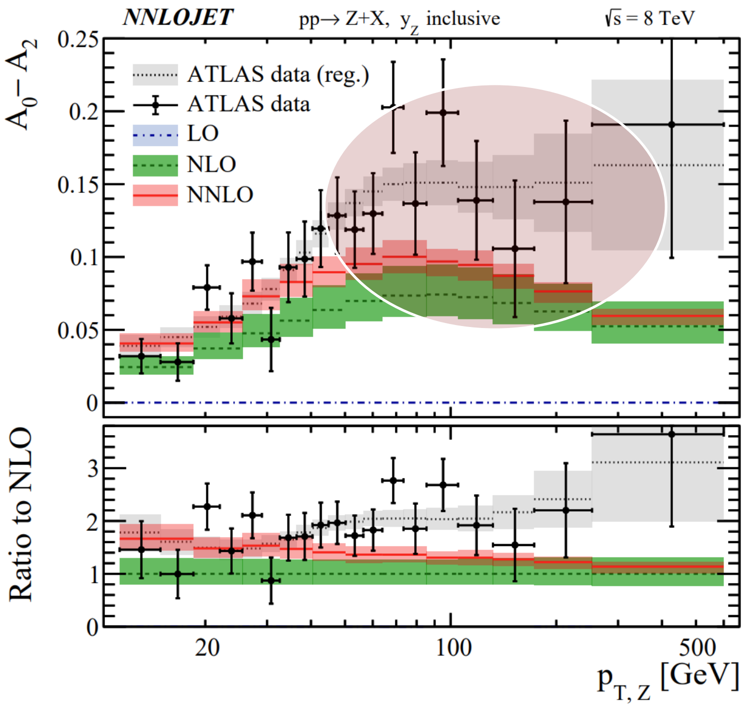
$A_0 \neq A_2$ @ NNLO in QCD
non-coplanarity between the hadron and parton planes

J.C. Peng et al, PLB 758,384 (2016)

Lam-Tung relation and polarization



ATLAS, JHEP 08 (2016) 159



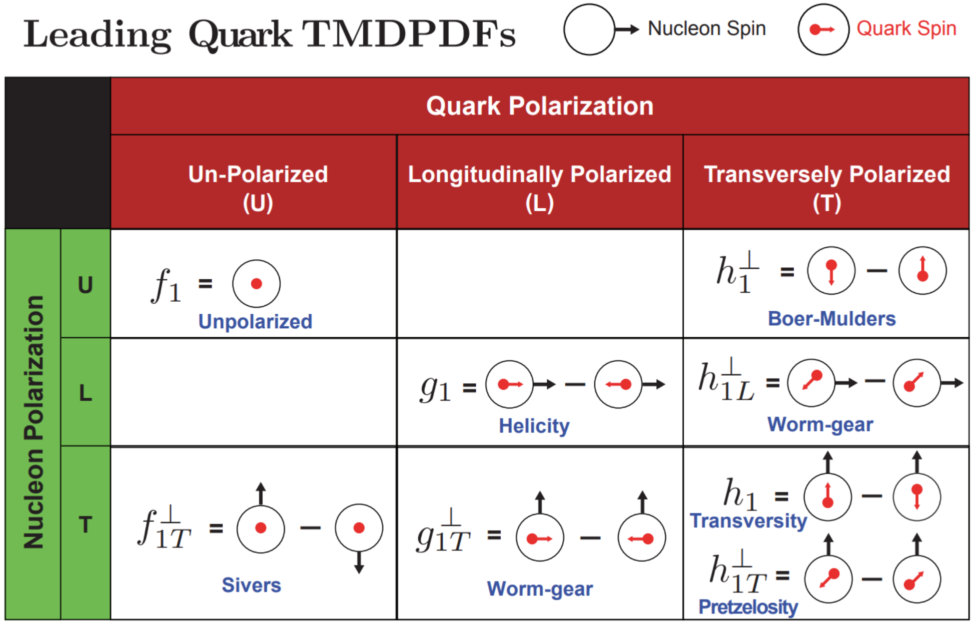
R. Gauld et al, JHEP 2017, N3LO

These results are confirmed by CMS (PLB750, 154 (2015)) and LHCb (PRL 129 (2022) 091801) collaborations

The discrepancy with the SM prediction
NP effects or non-perturbative effects ?

Boer-Mulders function

The $cos2\phi$ dependence can be induced by the Boer-Mulders function



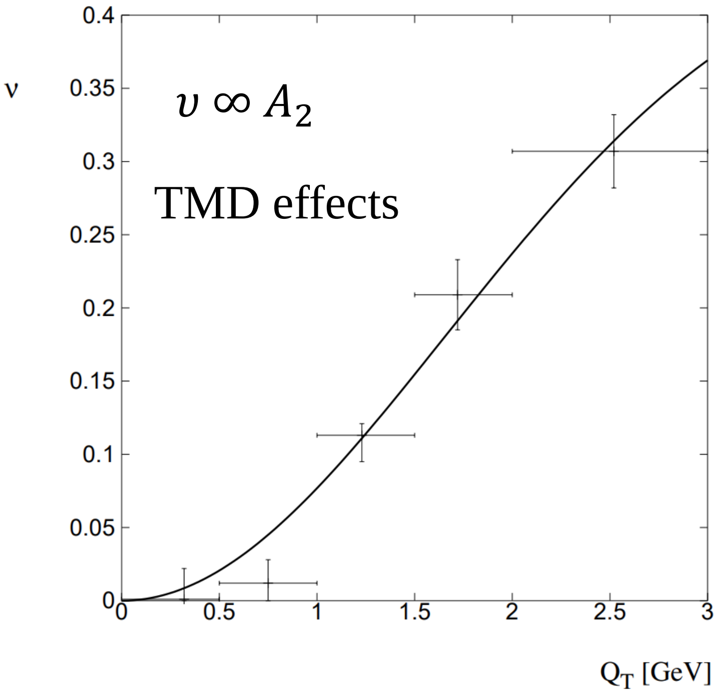
Leading Quark TMDPDFs

Nucleon Spin

Quark Spin

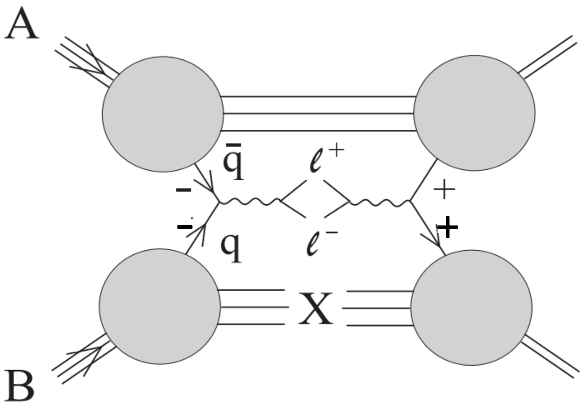
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 = Unpolarized		$h_1^\perp$ = − Boer-Mulders
	L		g_1 = − Helicity	$h_{1L}^\perp$ = − Worm-gear
	T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = − Worm-gear	h_1 = − Transversity $h_{1T}^\perp$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

Boer, PRD 60 (1999) 014012



$\upsilon \propto A_2$

TMD effects



Transversely polarized quark

Lam-Tung relation and NP

Center-of-mass frame:

$$\frac{d\sigma}{d\Omega} = a\cos\hat{\theta} + b\cos^2\hat{\theta} + c\cos^3\hat{\theta} + d$$

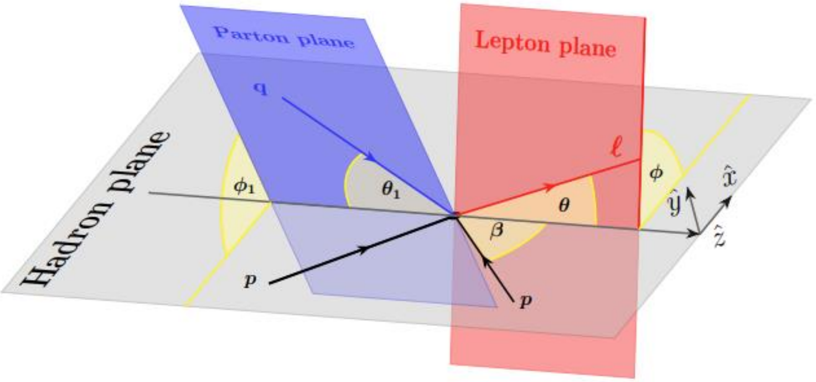
$$\cos\hat{\theta} = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi-\phi_1)$$

$$A_0 = \left\langle \frac{2(d-b)+4b\sin^2\theta_1}{b+3d} \right\rangle,$$

$$A_2 = \left\langle \frac{4b\sin^2\theta_1\cos 2\phi_1}{b+3d} \right\rangle.$$

$$\langle P_l(\cos\theta,\phi)\rangle = \frac{\int P_l(\cos\theta,\phi)\, d\sigma d\cos\theta d\phi}{\int d\sigma d\cos\theta d\phi}$$

J.C. Peng et al, PLB 758,384 (2016)

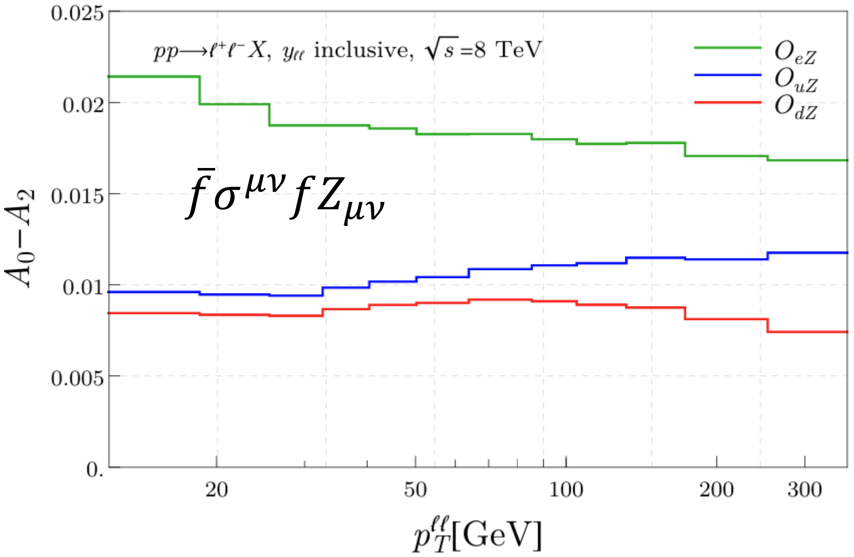


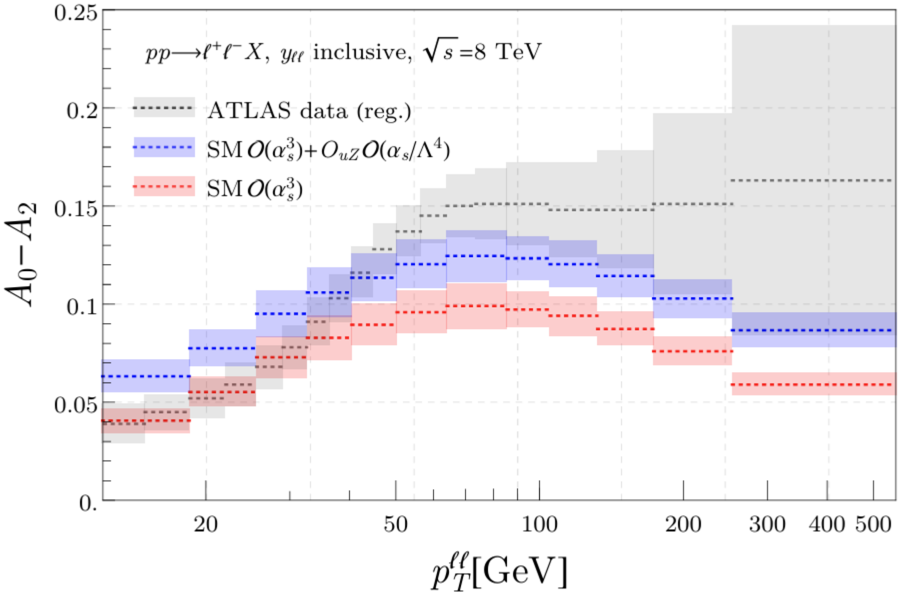
$A_0 \neq A_2$

- Coplanarity case: $b \neq d$, BSM effects
- Non-coplanarity case: $\phi_1 \neq 0$, NNLO and beyond or by the nonperturbative effects

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization

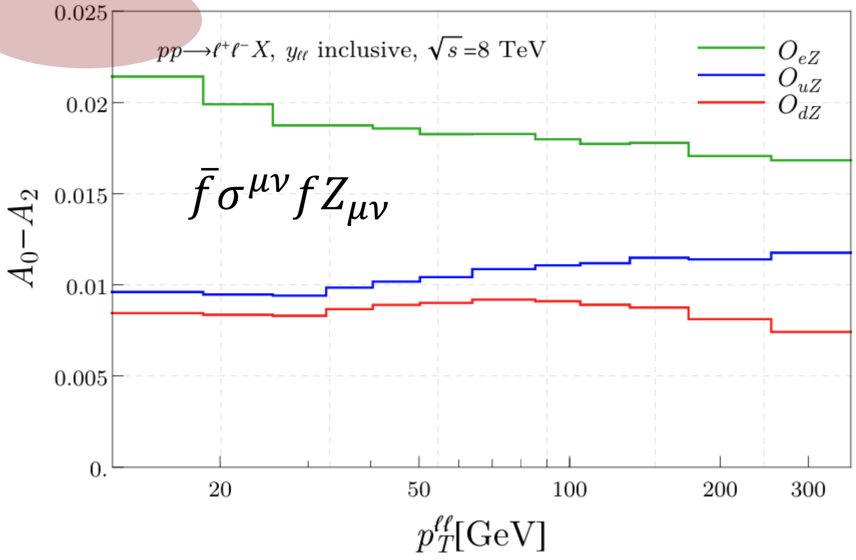




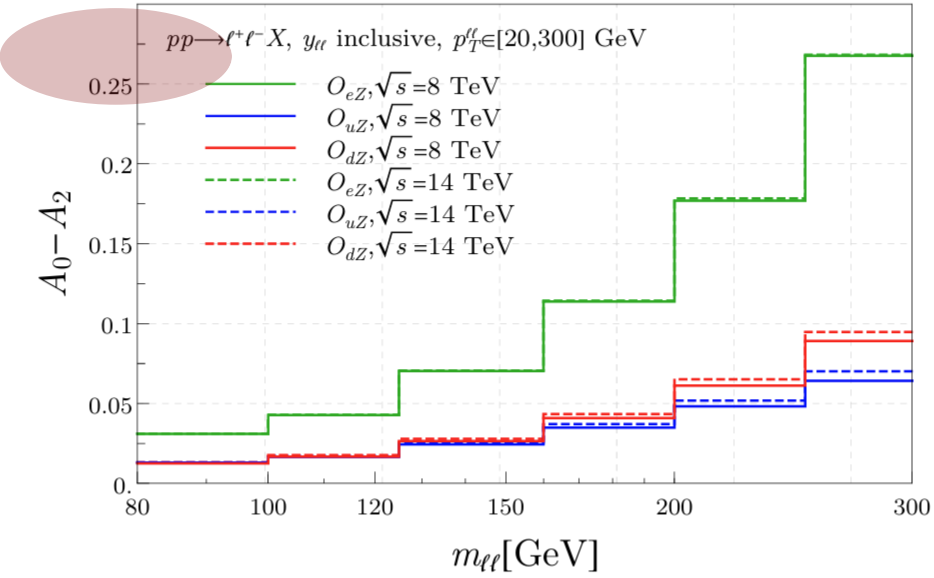
- ➢ The discrepancy in Lam-Tung relation could be explained by electroweak dipole interactions (transversely polarized quark or lepton)
- ➢ It could be more significant in high-invariant mass region

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization



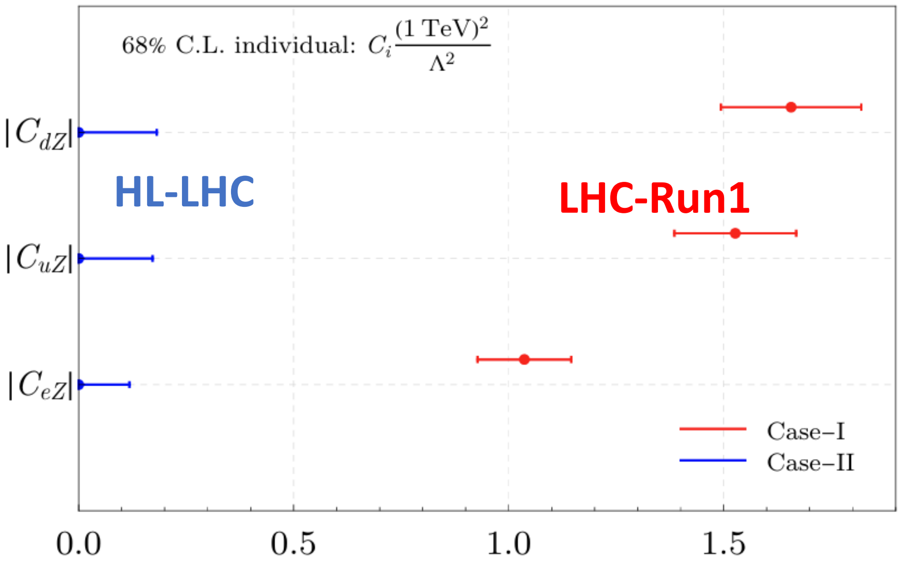
$\bar{f}\sigma^{\mu\nu} f Z_{\mu\nu}$

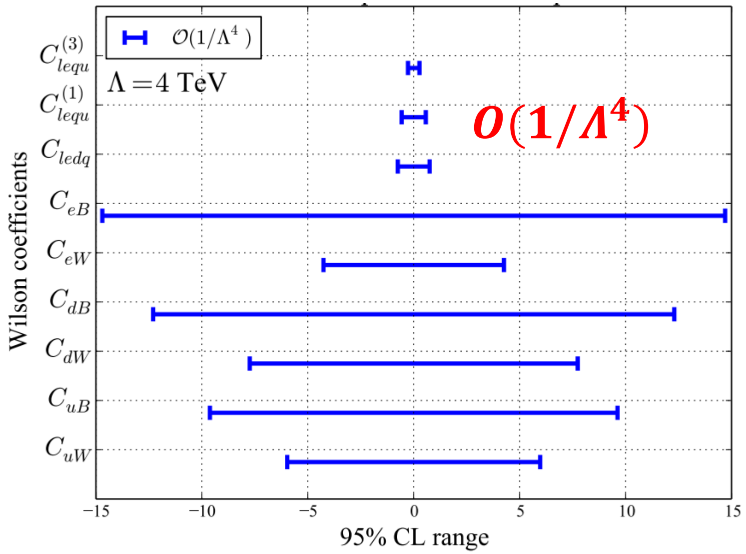


The breaking effects from the weak dipole interactions could be enhanced by one order of magnitude in high invariant mass region

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Lam-Tung relation and polarization





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

- ➢ The accuracy from A0-A2 would be comparable to the results from cross section, but the violation effects will dominantly depend on the dipole interactions.

Xu Li, Bin Yan, C.-P. Yuan, arxiv: 2405.04069

Summary

- The quark dipole moments is crucial for probing the internal structure of quarks
- The electroweak dipole operators are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$
- They can be probed at $1/\Lambda^2$ via transverse spin effects from non-perturbative functions: transversity and interference dihadron fragmentation functions
- Both Re & Im parts can be well constrained, *without impact from other NP and* offering a new opportunity for directly probing potential CP-violating effects.
- Our bounds are much stronger than other approaches, such as LHC and LEP
- The photons from UPCs are linearly polarized and can be used to probe the NP
- The linear polarization of the gauge bosons: photon, gluon and W/Z

Thank you