

Transverse spin asymmetry as a probe of new physics beyond the SM

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HENPIC seminar

Oct. 10 , 2024

Xin-Kai Wen, **Bin Yan**, Zhite Yu, C.-P. Yuan, PRL 131 (2023) 241801, 2408.07255

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

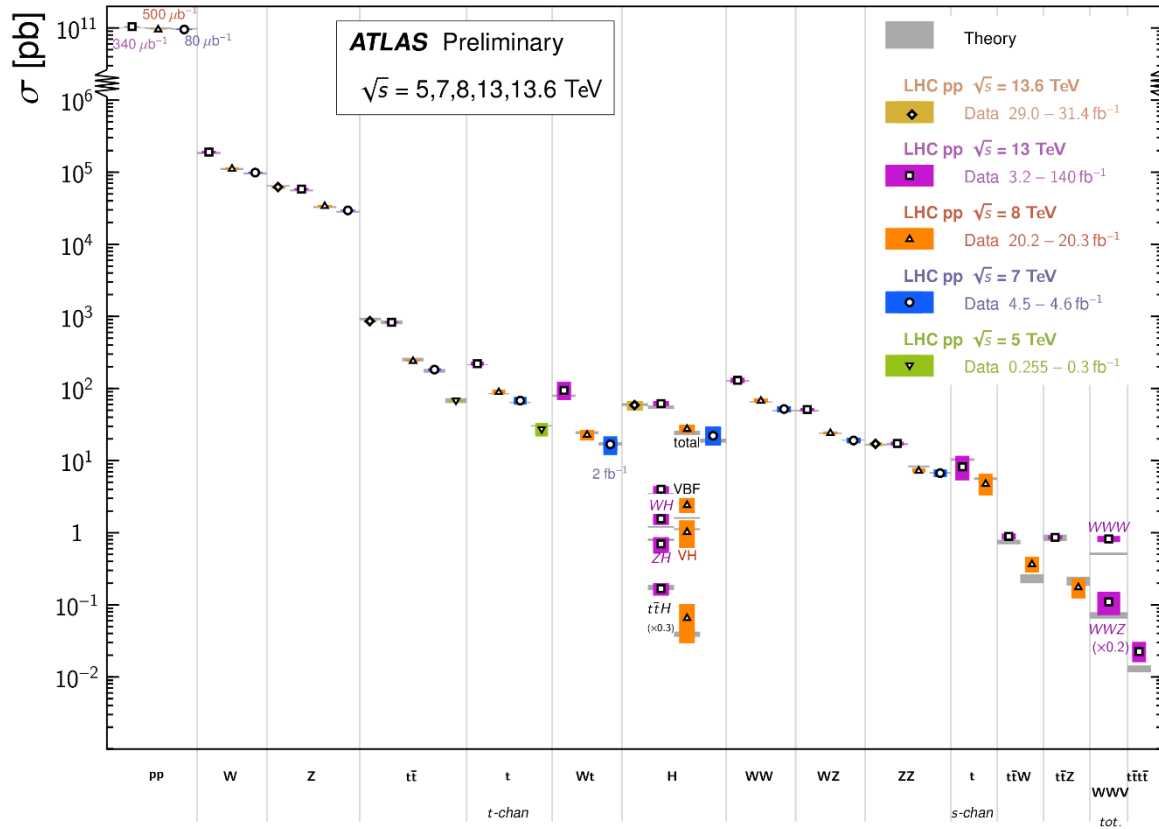
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, **Bin Yan**, PRD 109 (2024) 095025

Xu Li, **Bin Yan**, C.-P. Yuan, 2405.04069

The status of SM

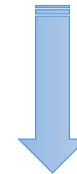
Standard Model Total Production Cross Section Measurements

Status: October 2023



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

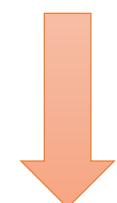
ATLAS Preliminary

$\sqrt{s} = 13 \text{ TeV}$

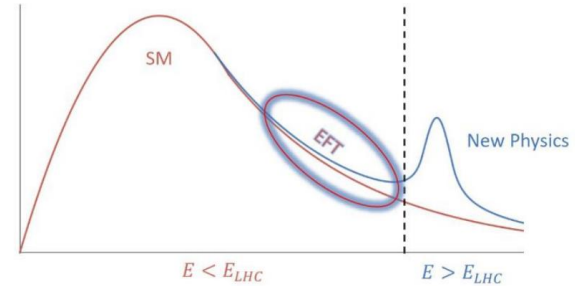
$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

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

Model	ℓ, γ	Jets †	$E_{\text{miss}}^{\dagger}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference	
Extra dimen.	ADD $G_{KK} + g/q$	$0 e, \mu, \tau, \gamma$	1-4 J	Yes	139	M_{Pl} 11.2 TeV, M_{S} 8.6 TeV, M_{H} 9.4 TeV, M_{A} 9.55 TeV	$n=2$ 2102.10874, $n=3$ HLZ NLO 1707.04147, $n=6$ 1910.08447, $n=6, M_{\text{Pl}} = 3 \text{ TeV, rot BH}$ 1512.02586
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	-	2102.15405
	ADD QBH	-	2 J	-	139	-	1808.02380
	ADD BH multijet	-	$\geq 3 J$	-	3.6	-	1804.10823
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	G_{KK} mass 36.1, g_{KK} mass 2.3 TeV, KK mass 3.8 TeV	1803.09678
Gauge bosons	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	-	-
	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2 J$	Yes	36.1	1.8 TeV	-
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 J$	Yes	36.1	-	-
	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV	1903.06248
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV	1709.07242
CI	Leptophobic $Z' \rightarrow bb$	-	$\geq 2 b$	-	36.1	Z' mass 2.1 TeV	1805.09299
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass 4.1 TeV	2005.05158
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV	1905.05609
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	139	W' mass 5.0 TeV	ATLAS-CONF-2021-025
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV	ATLAS-CONF-2021-043
DM	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 J / 1 J$	Yes	139	W' mass 4.3 TeV	2004.14636
	HVT $W' \rightarrow WZ$ model C	$3 e, \mu$	$2 J$ (VBF)	Yes	139	W' mass 340 GeV	2207.03925
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 J / 1 J$	Yes	139	Z' mass 3.9 TeV	2004.14636
	LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV	1904.12679
	CI $q\bar{q}q\bar{q}$	-	2 J	-	37.0	A 21.8 TeV, A_{LL} 35.8 TeV	1703.09127
LQ	CI $\ell\ell q\bar{q}$	$2 e, \mu$	-	-	139	A	2006.12946
	CI $e\bar{e}b\bar{b}$	$2 e$	$1 b$	-	139	A 1.8 TeV	2105.13847
	CI $\mu\bar{\mu}b\bar{b}$	2μ	$1 b$	-	139	A 2.0 TeV	2105.13847
	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	36.1	A 2.57 TeV	1811.02305
	Axial-vector med. (Dirac DM)	-	2 J	-	139	m_{had} 3.8 TeV	$g_{\text{B}}=0.25, g_{\text{W}}=1, m(\chi)=10 \text{ TeV}$ ATLAS-PUB-2022-036
Vector-like fermions	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 J	Yes	139	m_{had} 376 GeV	2102.10874
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	$2 b$	Yes	139	m_{had} 3.0 TeV	2108.13391
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_{H} 800 GeV	ATLAS-CONF-2021-036
	Scalar LQ 1 st gen	$2 e$	$\geq 2 J$	Yes	139	LO mass 1.8 TeV	$\beta = 1$ 2006.05872
	Scalar LQ 2 nd gen	2μ	$\geq 2 J$	Yes	139	LO mass 1.7 TeV	2006.05872
Excited ferm.	Scalar LQ 3 rd gen	1τ	$2 b$	Yes	139	LO mass 1.49 TeV	2303.01294
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 J, \geq 2 b$	Yes	139	LO mass 1.24 TeV	2004.14060
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1 \tau, \geq 1 J, \geq 1 b$	-	-	139	LO mass 1.43 TeV	2101.11582
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1 \tau, 0-2 J, 2 b$	Yes	139	LO mass 1.26 TeV	$\beta(LQ_1^0 \rightarrow \tau\nu) = 1$ 2101.12527	
	Vector LQ mix gen	multi-channel $\geq 1 J, \geq 1 b$	Yes	139	LO mass 2.0 TeV	$\beta(L_1^0 \rightarrow \nu\nu) = 1, \text{Y-M coupl.}$ ATLAS-CONF-2022-052	
Other	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LO mass 1.96 TeV	2303.01294
	VLO $TT \rightarrow Zt + X$	$2e2\mu/3e\mu \geq 1 b, \geq 1 J$	-	-	139	T mass 1.46 TeV	SU(2) doublet 2210.15413
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV	SU(2) doublet 1808.02343
	VLO $TS_{1/3}T_{5/3}T_{5/3} \rightarrow Wt + X$	$2(SS)/3(e\mu) \geq 1 b, \geq 1 J$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\beta(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ 1807.11883	
	VLO $T \rightarrow Ht/Zt$	$1 e, \mu, \geq 1 b, \geq 3 J$	Yes	139	T mass 1.8 TeV	SU(2) singlet, $\kappa_T = 0.5$ ATLAS-CONF-2021-040	
Magnetic monopoles	VLO $Y \rightarrow Wb$	$1 e, \mu, \geq 1 b, \geq 1 J$	Yes	36.1	Y mass 1.85 TeV	$\beta(Y \rightarrow Wb) = 1, c_{\text{B}}(Wb) = 1$ 1812.07343	
	VLO $B \rightarrow Hb$	$0 e, \mu, \geq 2b, \geq 1 J, \geq 1 J$	-	-	139	B mass 2.0 TeV	SU(2) doublet, $\kappa_B = 0.3$ ATLAS-CONF-2021-018
	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel $\geq 1 J$	Yes	139	τ' mass 898 GeV	SU(2) doublet 2303.05441	
	Excited quark $q^* \rightarrow qg$	-	2 J	-	139	q^* mass 6.7 TeV	only u' and d' , $A = m(q^*)$ 1910.08447
	Excited quark $q^* \rightarrow q\gamma$	1γ	-	-	36.7	q^* mass 5.3 TeV	only u' and d' , $A = m(q^*)$ 1709.10440
Magnetic monopoles	Excited quark $q^* \rightarrow b\bar{g}$	-	$1 b, 1 J$	-	139	b^* mass 3.2 TeV	1910.08447
	Excited lepton τ^*	2τ	$\geq 2 J$	-	139	τ^* mass 4.6 TeV	$A = 4.6 \text{ TeV}$ 2303.09444
	Type III Seesaw	$2.3, 4 e, \mu$	$\geq 2 J$	Yes	139	N^{P} mass 910 GeV	$m(W_0) = 4.1 \text{ TeV, } g_{\text{L}} = g_{\text{R}}$ 2202.02039
	LRSM Majorana ν	2ν	$2 J$	-	36.1	N_{M} mass 3.2 TeV	1809.11105
	Higgs triplet $H^{\text{H}} \rightarrow W^+ W^+$	$2.3, 4 e, \mu$ (SS)	various	Yes	139	H^{H} mass 350 GeV	DY production 2101.11961
Magnetic monopoles	Higgs triplet $H^{\text{H}} \rightarrow \ell\ell$	$2.3, 4 e, \mu$ (SS)	-	-	139	H^{H} mass 1.08 TeV	DY production 2211.07505
	Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	DY production, $ q = 5e$ ATLAS-CONF-2022-034
	Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	DY production, $ g = 1g_{\text{B}}, \text{spin } 1/2$ 1905.10130



SMEFT



*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).

Top-down approach

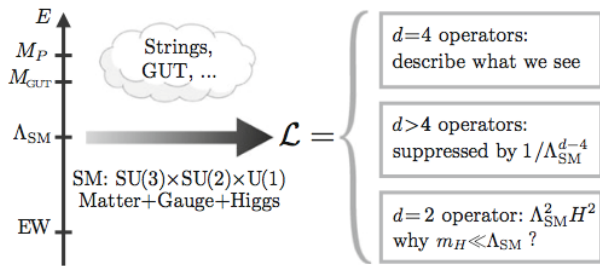
Bottom-up approach

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. Buchmuller, D. Wyler 1986

B. Grzadkowski et al, 2010

W. Buchmuller, D. Wyler 1986

B. Grzadkowski et al, 2010

L. Lehman, A. Marin, 2015

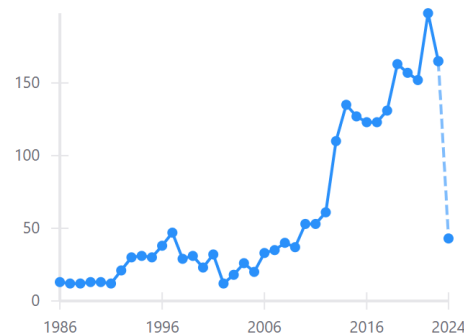
B. Henning et al, 2015

H-L. Li et al, 2020

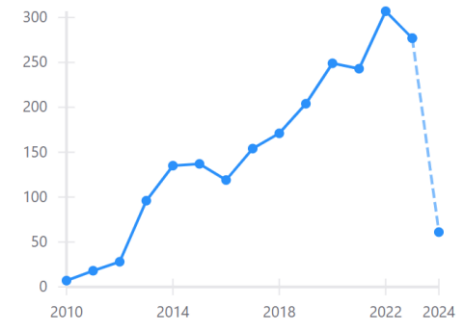
Murphy, 2020

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

Citations per year



Citations per year



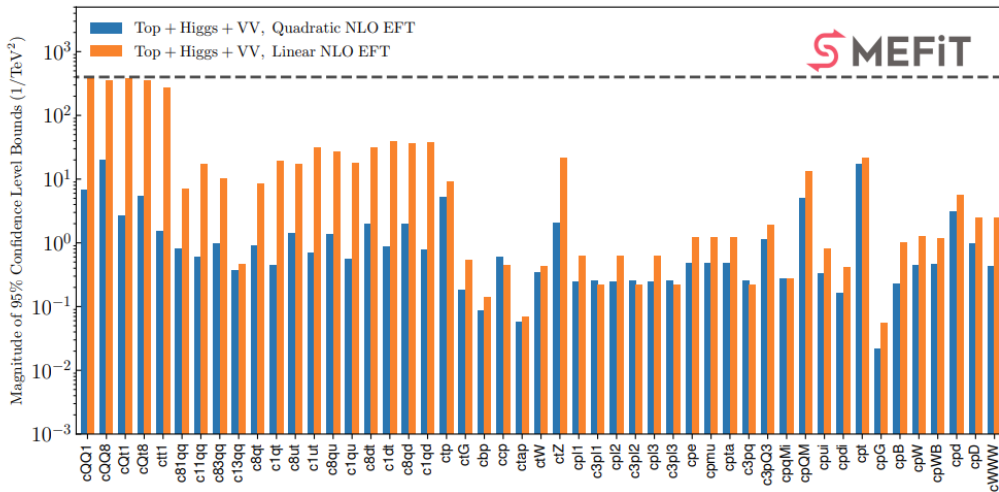
3. Higgs Effective Field Theory

Callan, Coleman, Wess, Zumino, 1969

The electroweak chiral Lagrangian+light Higgs, A.C. Longhitano, 1980,....

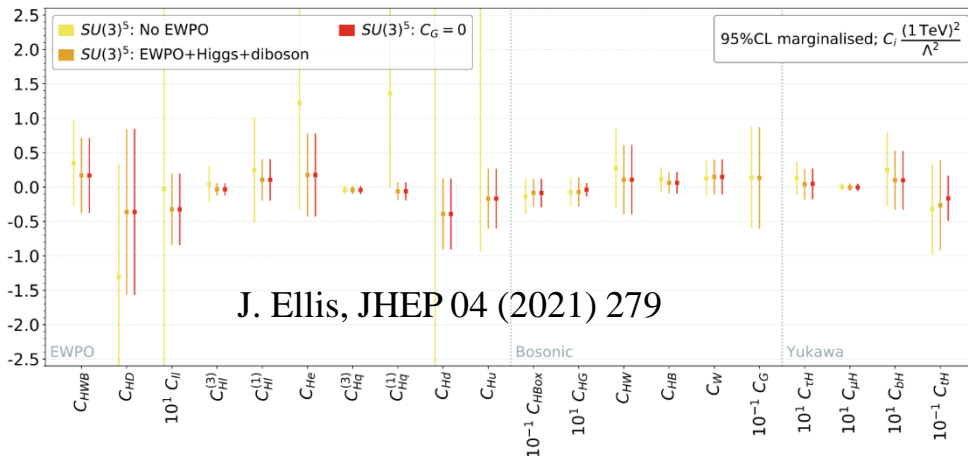
Global analysis @ SMEFT

SMEFT Collaboration, JHEP 11 (2021) 089



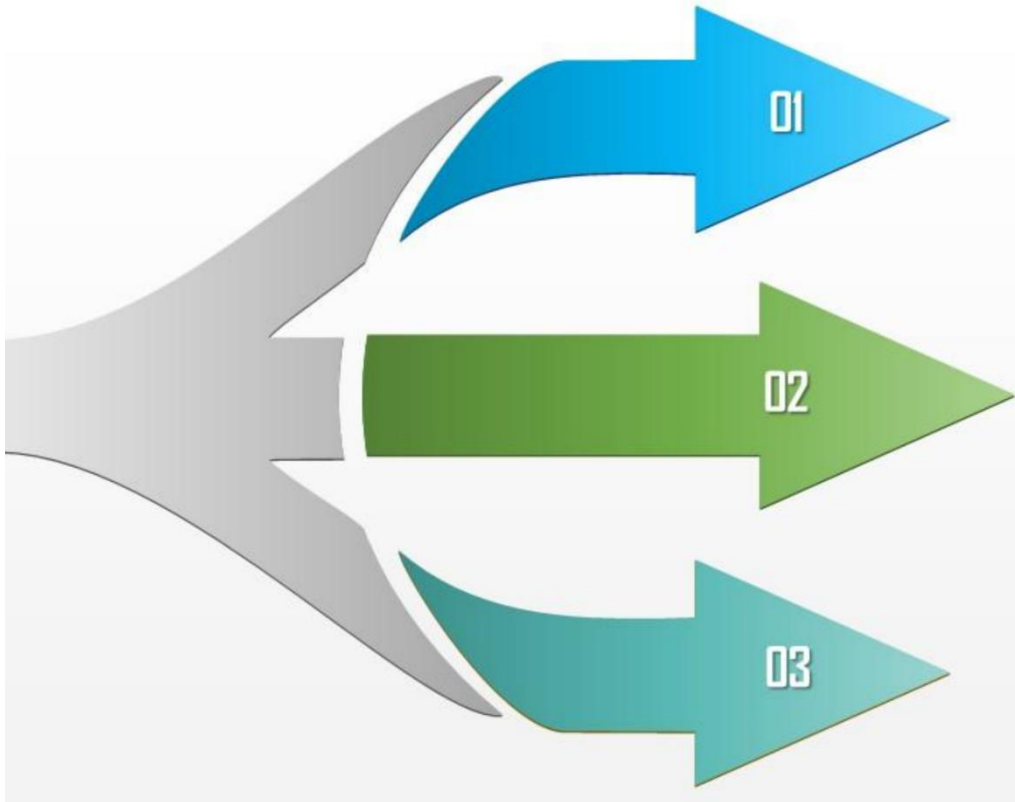
The SMEFT approach allows for the combination

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



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

So, what's the next step for the new physics searches from the theoretical point of view?



➤ Global analysis with more processes; the combination of low energy and high energy measurements

➤ QCD and EW correction to reduce the theoretical uncertainties

➤ **New observables and new measurements**

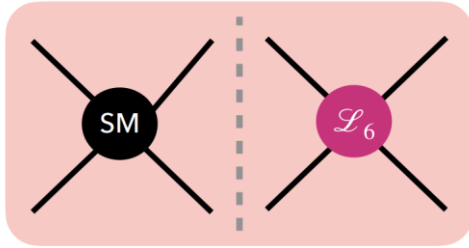


Transverse/linear polarization observables

New Physics and SMEFT

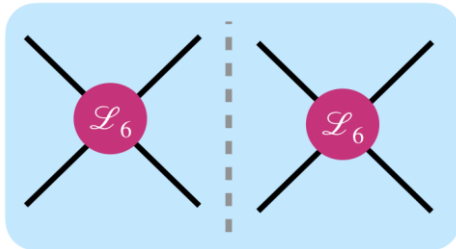
B. Grzadkowski et al, JHEP 10 (2010) 085

Interference effects



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

Chirality-flipped operators



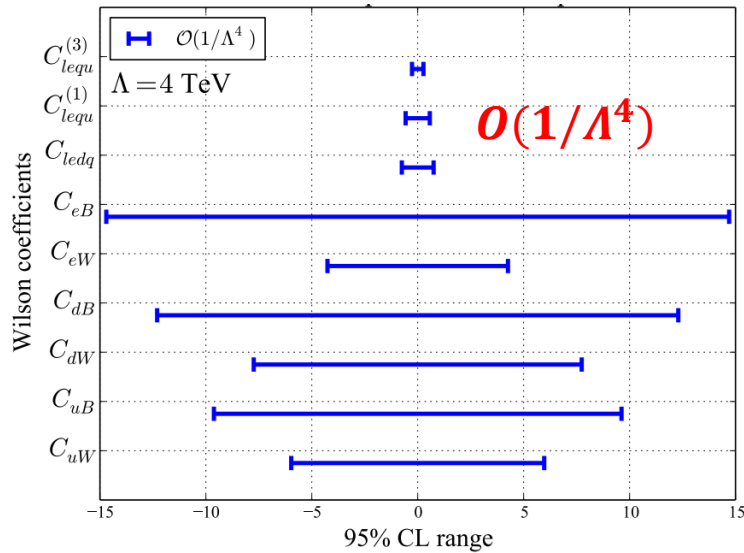
$$\sim \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

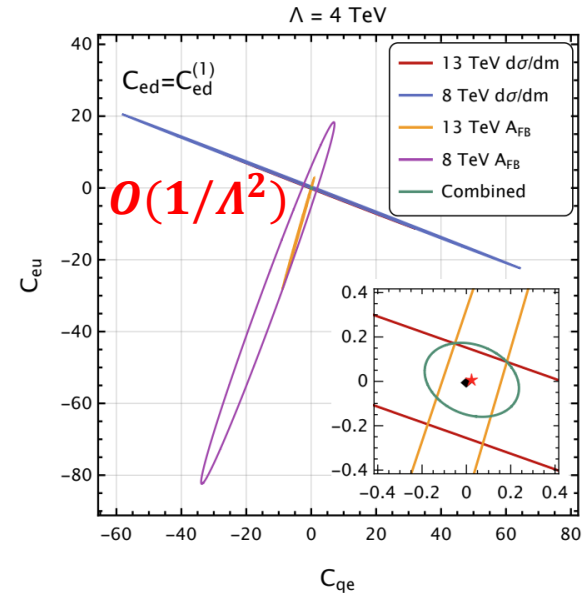
The constraints will be very weak

Example: Dipole Operator

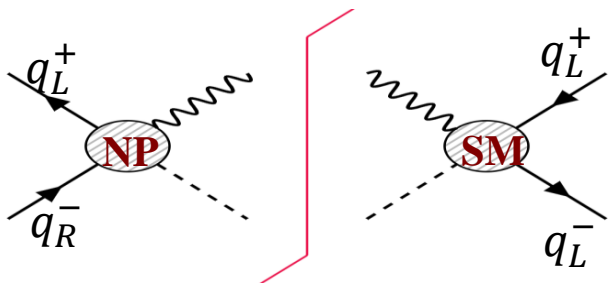
Single-Parameter-Analysis: EW dipole couplings are poorly constrained



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



R. Boughezal et al, 2303.08257



=0 for the cross section

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

New physics and Dipole Operator

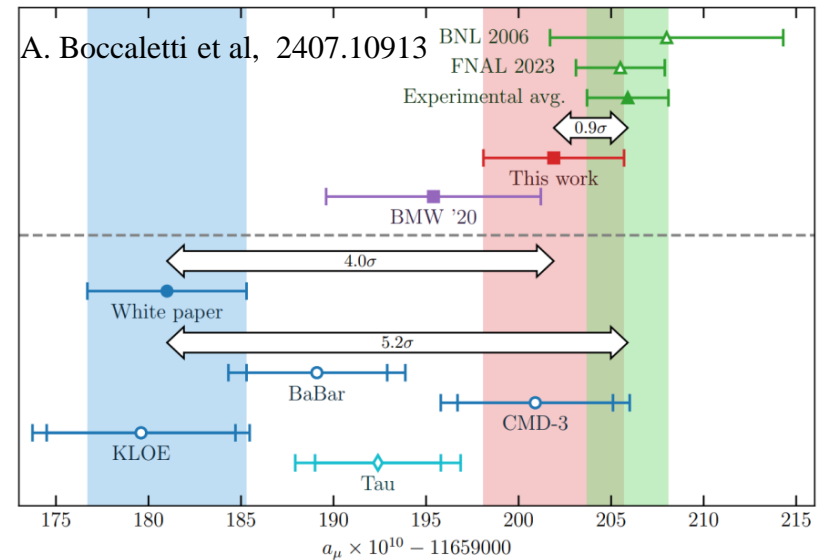
- Magnetic dipole moments: probing the **internal structures of particles**

Elementary particle:

Electron: $g/2=1.001159\dots$

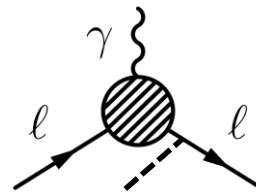
Muon: $g/2=1.0011659\dots$

- The Lattice's results agree with data, but different from data-driven approach



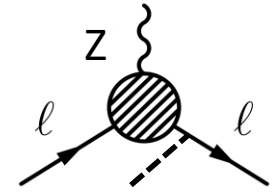
- New physics or non-perturbative issue?
Loop-induced by the BSM

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



May have same physics source

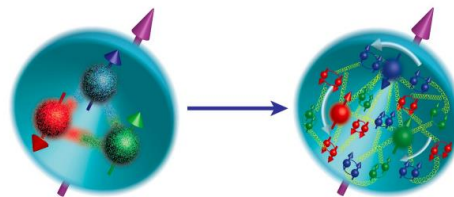
$$\vec{\text{Red Arrow}} \\ B_{\mu\nu}, W_{\mu\nu}$$



Composite particle:

Proton: $g/2=2.7928444\dots$

Neutron: $g/2=-1.91394308\dots$



New physics and Dipole Operator

➤ Magnetic dipole moments: probing the **internal structures of particles**

Elementary particle:

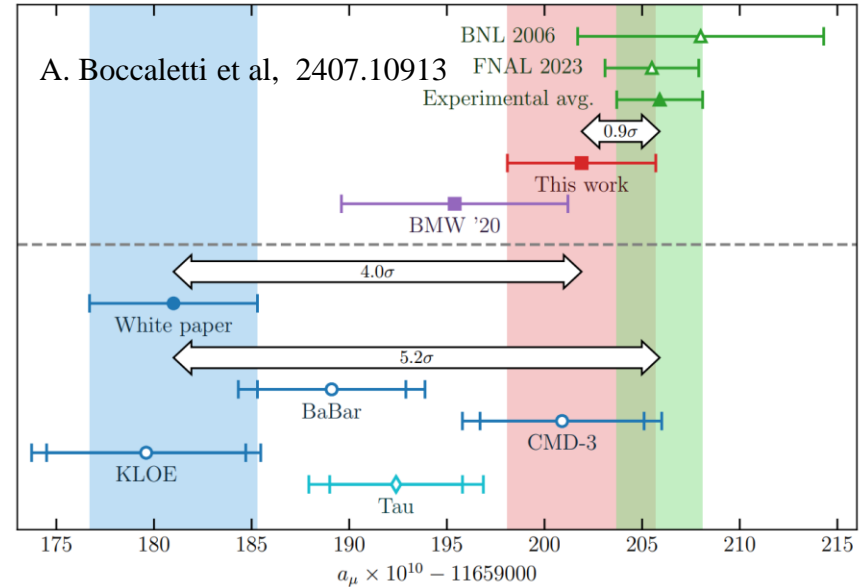
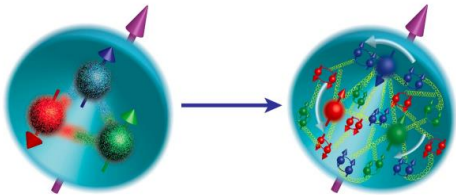
Electron: $g/2=1.001159\dots$

Muon: $g/2=1.0011659\dots$

Composite particle:

Proton: $g/2=2.7928444\dots$

Neutron: $g/2=-1.91394308\dots$

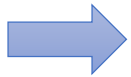


□ How to probe the electroweak dipole interactions?

□ Do quarks have any internal structures or probing quark dipole moments?

Electroweak dipole moments of leptons

Is it possible to probe the dipole operators at $\mathcal{O}\left(\frac{1}{\Lambda^2}\right)$?



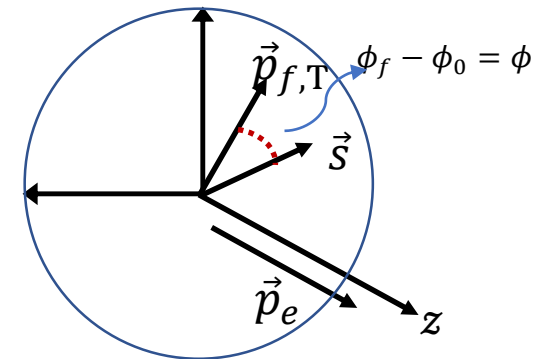
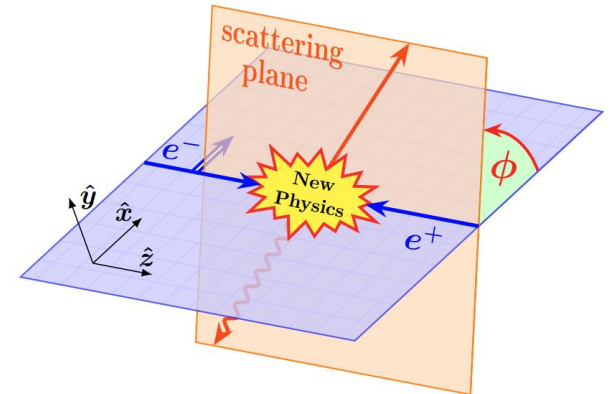
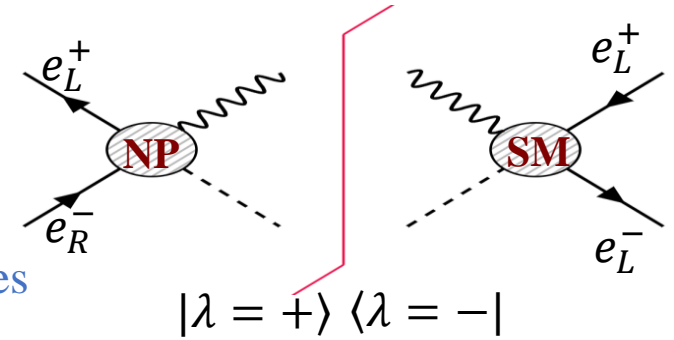
Transversely polarized effect of beams:

The interference between the different helicity states

$$\mathbf{s} = (b_1, b_2, \lambda) = (\underline{b_T \cos \phi_0}, b_T \sin \phi_0, \lambda)$$

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

Breaking the rotational invariance & A nontrivial azimuthal behavior

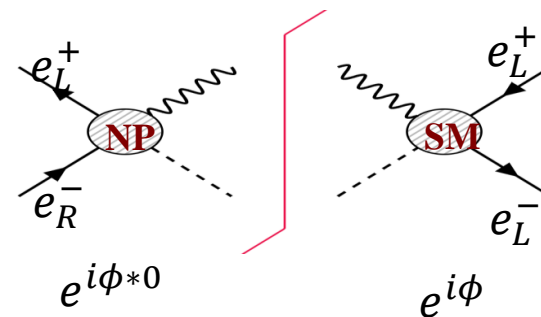


Transverse spin effects @ CEPC

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

Ken-ichi Hikasa, Phys.Rev.D 33 (1986) 3203, PhysRevD.38 (1988) 1439

G. Moortgat-Pick et al. Phys.Rept. 460 (2008), JHEP 01 (2006)



$$M \propto e^{i(\alpha_1 - \alpha_2)\phi} d(\theta)$$

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

$$\frac{2\pi d\sigma^i}{\sigma^i d\phi} = 1 + \underbrace{A_R^i(b_T, \bar{b}_T)}_{\text{Re}[C_{dipole}]} \cos \phi + \underbrace{A_I^i(b_T, \bar{b}_T)}_{\text{Im}[C_{dipole}]} \sin \phi + \underbrace{b_T \bar{b}_T B^i}_{\text{SM \& other NP}} \cos 2\phi + \mathcal{O}(1/\Lambda^4)$$

$\text{Re}[C_{dipole}]$

$\text{Im}[C_{dipole}]$

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

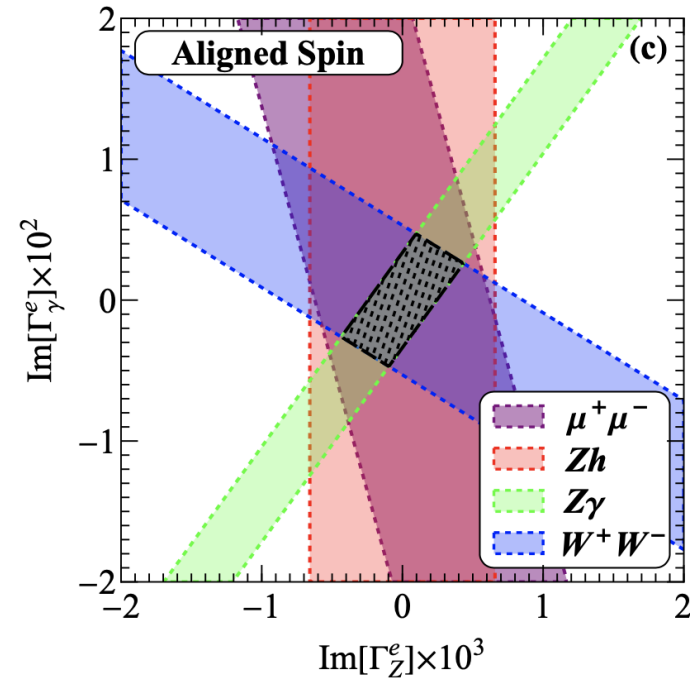
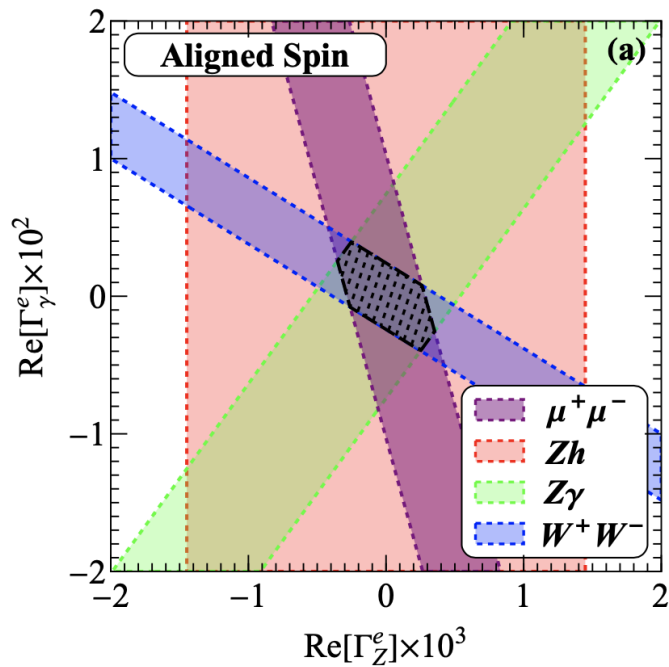
$$A_{LR}^i = \frac{\sigma^i(\cos \phi > 0) - \sigma^i(\cos \phi < 0)}{\sigma^i(\cos \phi > 0) + \sigma^i(\cos \phi < 0)} = \frac{2}{\pi} A_R^i$$

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

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

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

PRL 131 (2023) 241801



CP-conserved dipole operator

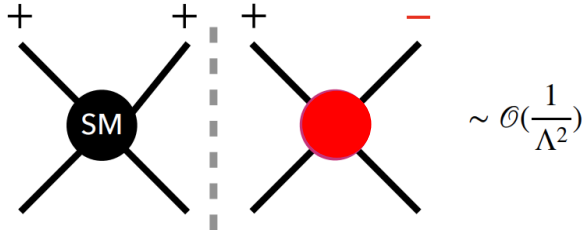
CP-violated dipole operator

- 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

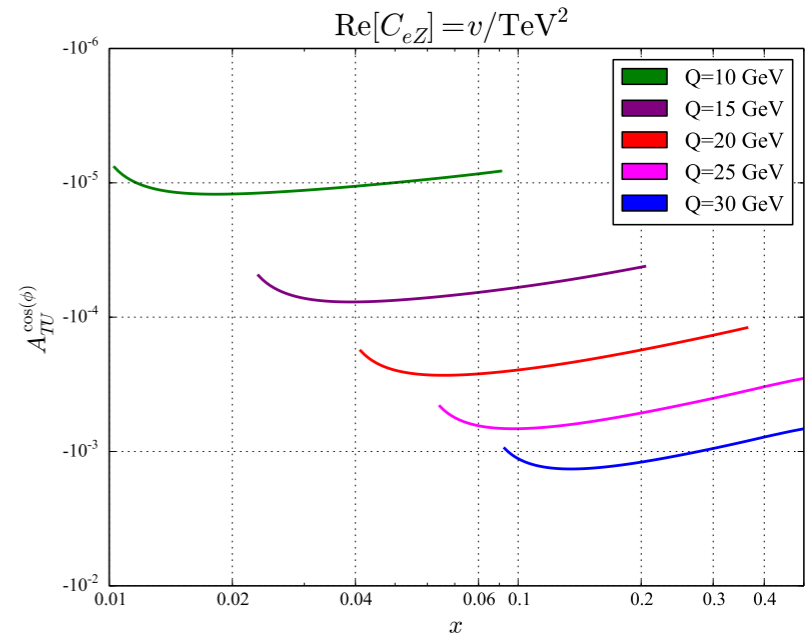
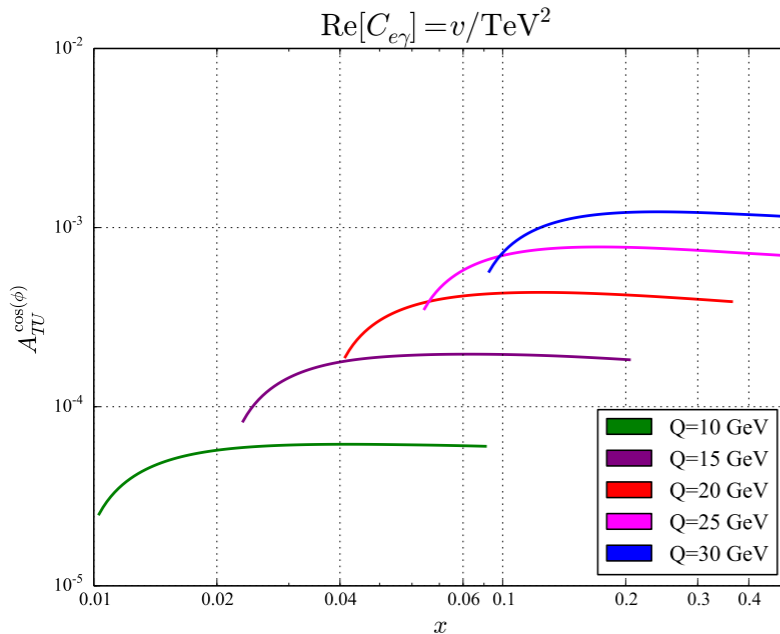
R. Boughezal, D. Florian, F. Petriello, W. Vogelsang,
PRD 107 (2023) 7, 075028



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

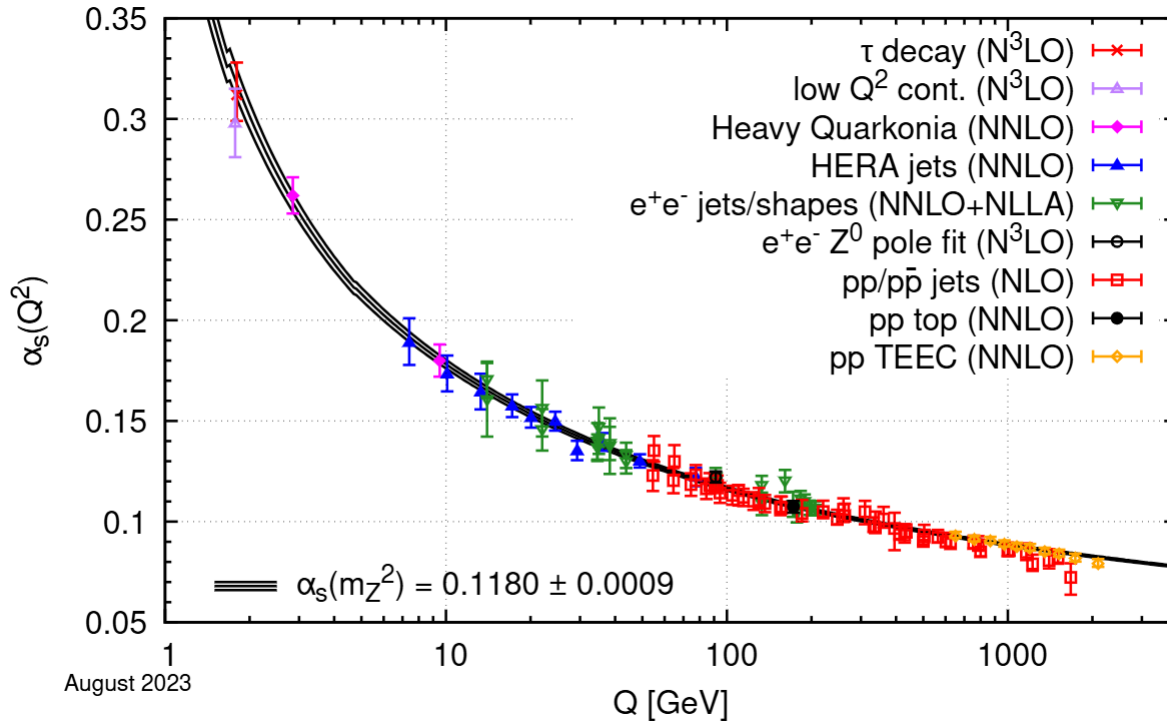
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},$$

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

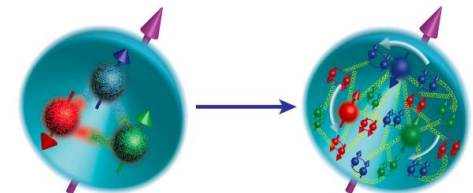


Electroweak dipole moments of quarks

- 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 distribution functions and the fragmentation functions

Transverse spin effects of quark @ EIC

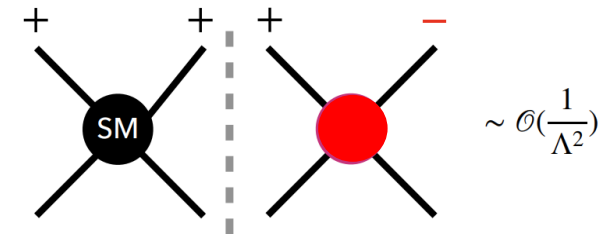
➤ Quark dipole operators

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

Leading Quark TMDPDFs  Nucleon Spin  Quark Spin

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

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



➤ The transversity is difficult to be constrained

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

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

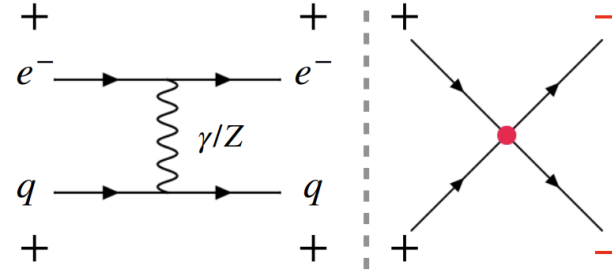
Kang, Prokudin, Sun, Yuan, PRD 93 (2016) 014009; Zeng, Dong, Liu, Sun, Zhao, PRD 109 (2024) 056002; JAM Collaboration, PRD 106 (2022) 034014

Transverse spin effects @ EIC

➤ Scalar and tensor four fermion operators

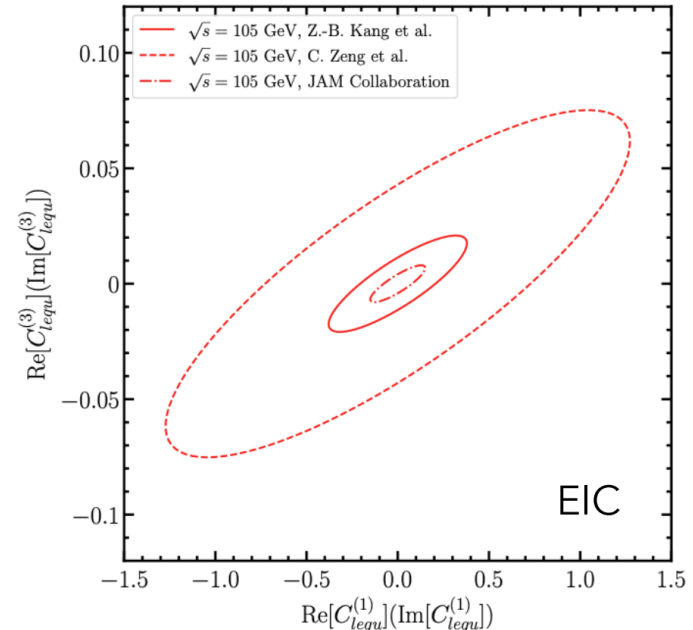
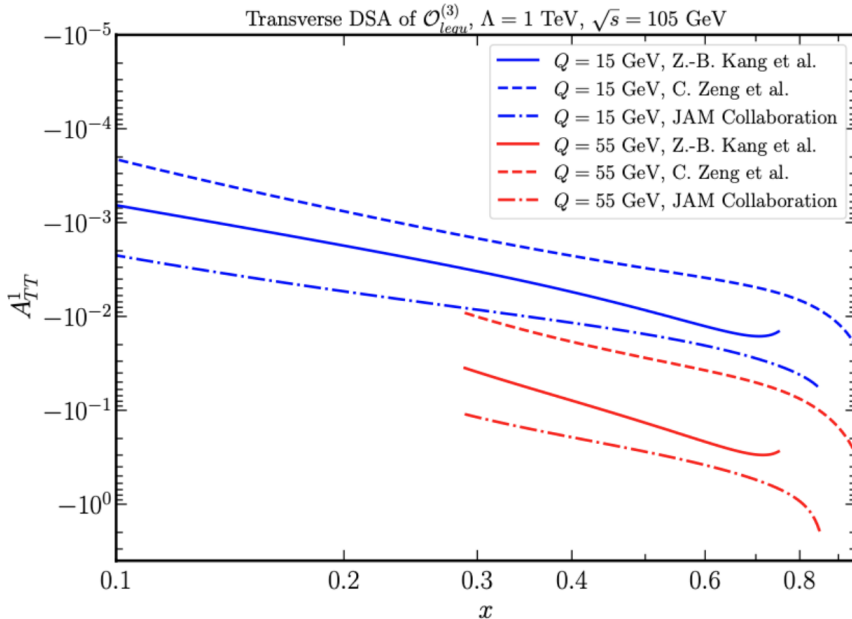
$$P_{T,e} = P_{T,p} = 0.7, \mathcal{L} = 100 \text{ fb}^{-1}$$

$$\begin{aligned} \mathcal{O}_{ledq} &= (\bar{L}^j e) (\bar{d} Q^j), \\ \mathcal{O}_{lequ}^{(1)} &= (\bar{L}^j e) \epsilon_{jk} (\bar{Q}^k u), \\ \mathcal{O}_{lequ}^{(3)} &= (\bar{L}^j \sigma^{\mu\nu} e) \epsilon_{jk} (\bar{Q}^k \sigma_{\mu\nu} u), \end{aligned}$$



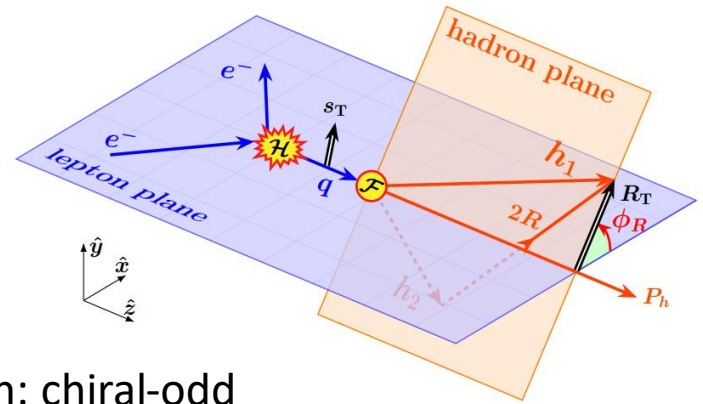
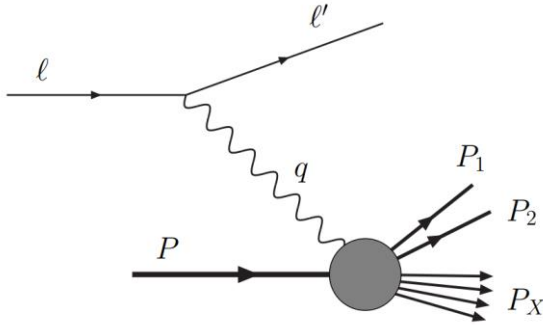
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, **Bin Yan**,
PRD 109 (2024) 095025

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



Transverse spin effects of quark @ EIC

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



- The interference dihadron fragmentation function: chiral-odd

$$\frac{d\sigma}{dx dy dz dM_h d\phi_R} = \frac{N}{2\pi} \sum_q f_q(x, Q) [D_{h_1 h_2/q}(z, M_h; Q) - (\mathbf{s}_{T,q}(x, Q) \times \hat{\mathbf{R}}_T)^z H_{h_1 h_2/q}(z, M_h; Q)] C_q(x, Q)$$

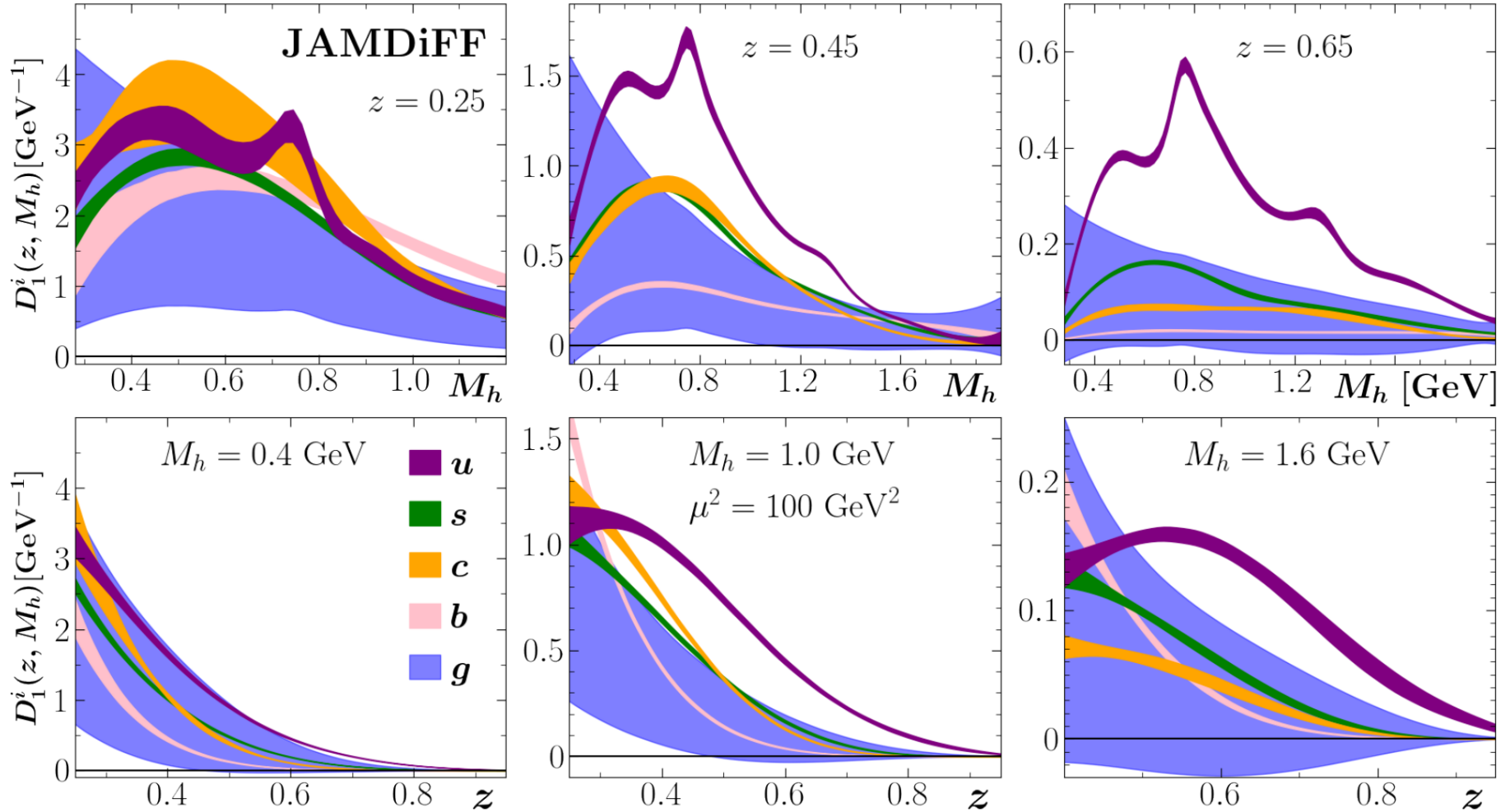
$$s_q^x = \frac{2}{C_q} (w_\gamma^q \text{Re} \Gamma_\gamma^q + w_Z^q \text{Re} \Gamma_Z^q)$$

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

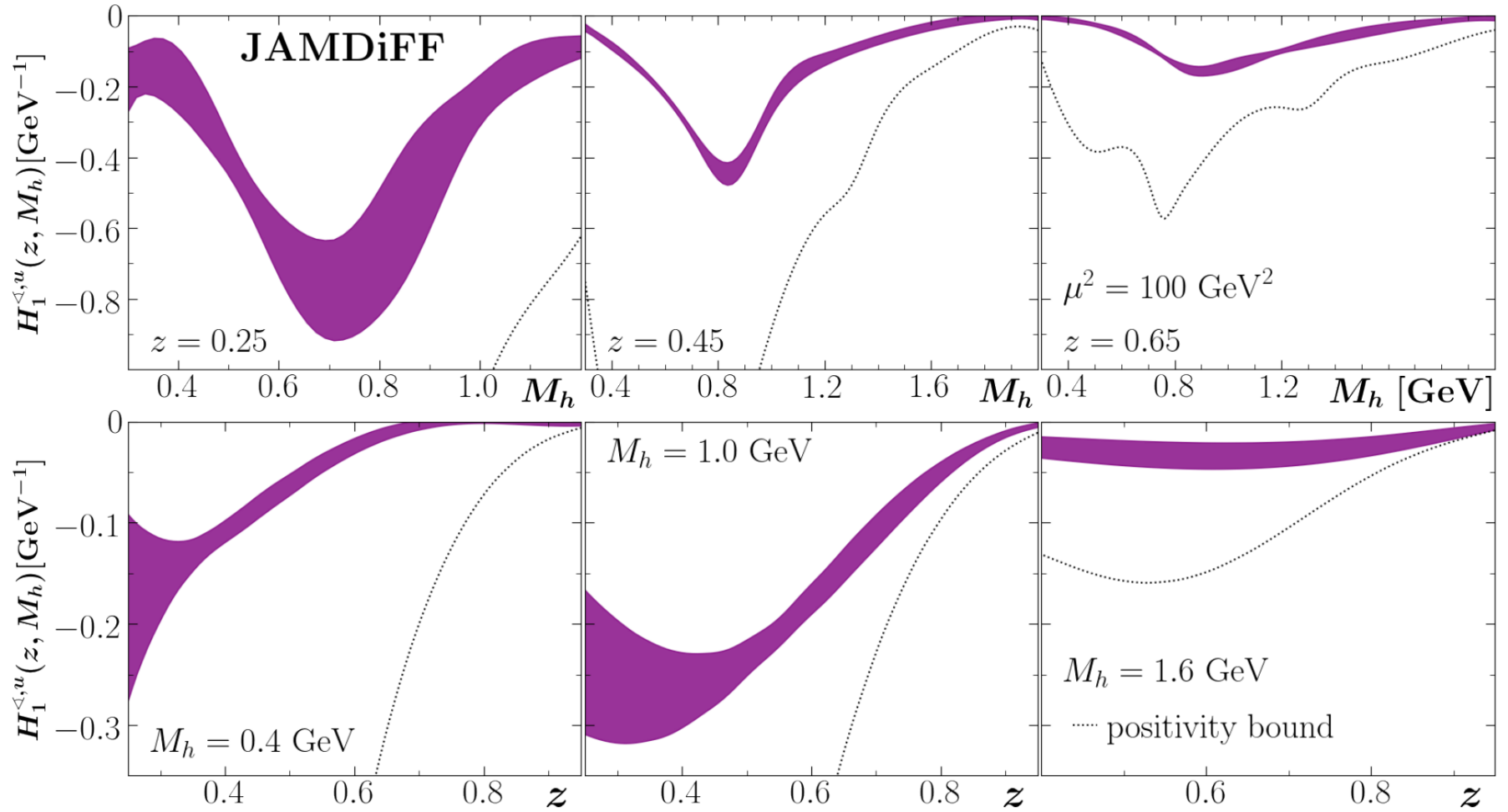
$$(\mathbf{s}_{T,q} \times \hat{\mathbf{R}}_T)^z = s_q^x \sin \phi_R - s_q^y \cos \phi_R$$

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

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



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

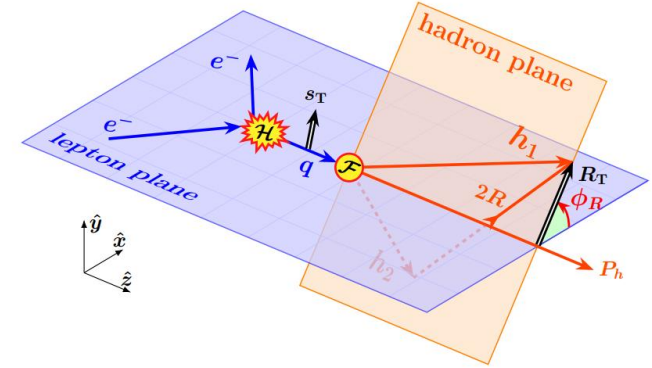


Transverse spin effects of quark @ EIC

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

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

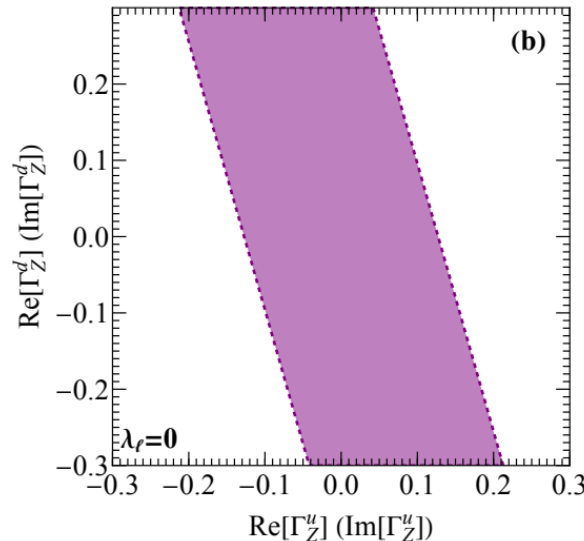
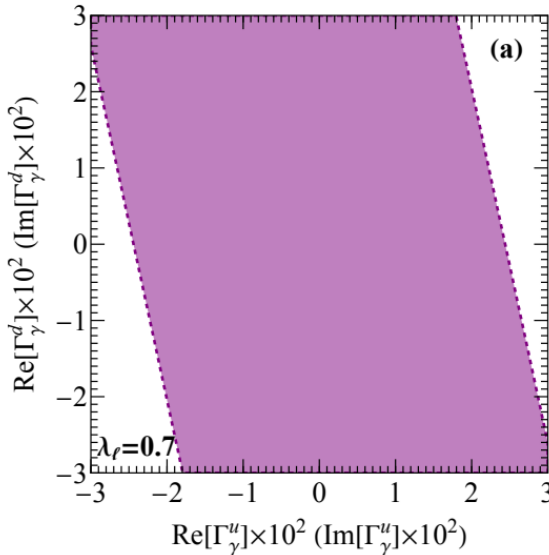
- ❑ the longitudinal polarization of the electron
- ❑ the parity-violating Z interactions



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

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

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

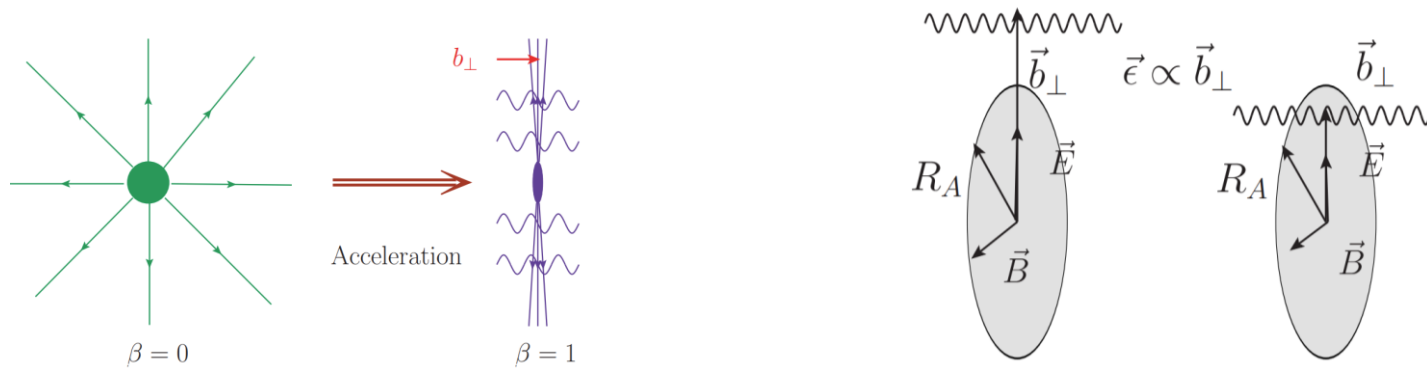


$$\sqrt{s} = 105 \text{ GeV}, \mathcal{L} = 1 \text{ ab}^{-1}$$

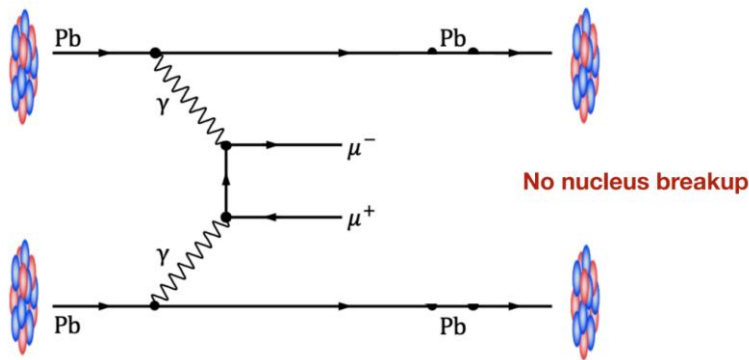
- ❑ Photon: $\mathcal{O}(0.01)$
- ❑ Z-boson: $\mathcal{O}(0.1)$

The flat direction in dipole couplings?

Linear polarization @ UPCs



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



- 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 $b_{\perp} > 2R_A$

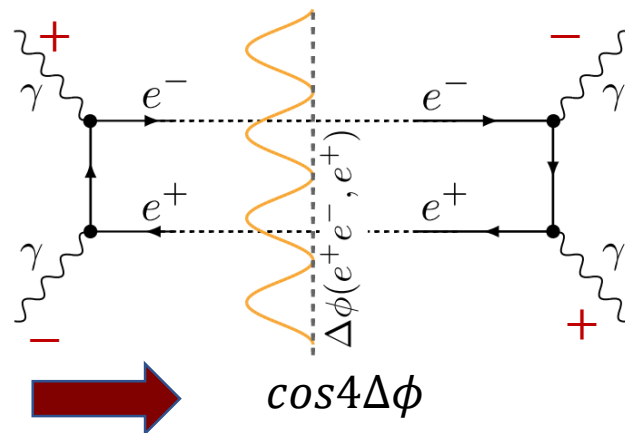
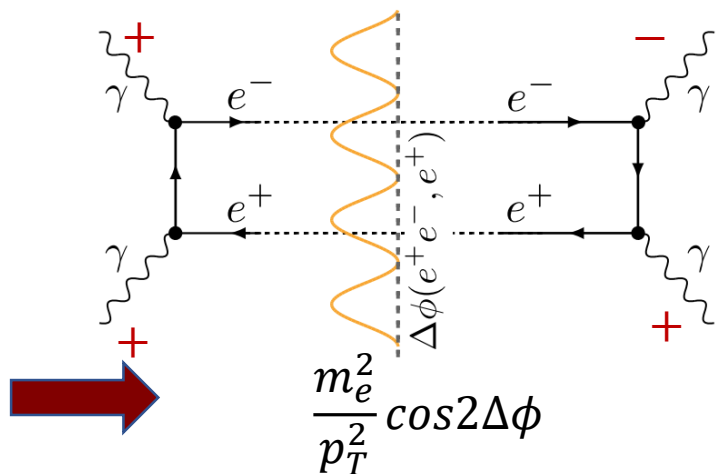
The linear polarization for gluons based on the NEEC:

Yuxun Guo, Xiaohui Liu, Feng Yuan, HuaXing Zhu, 2406.05880

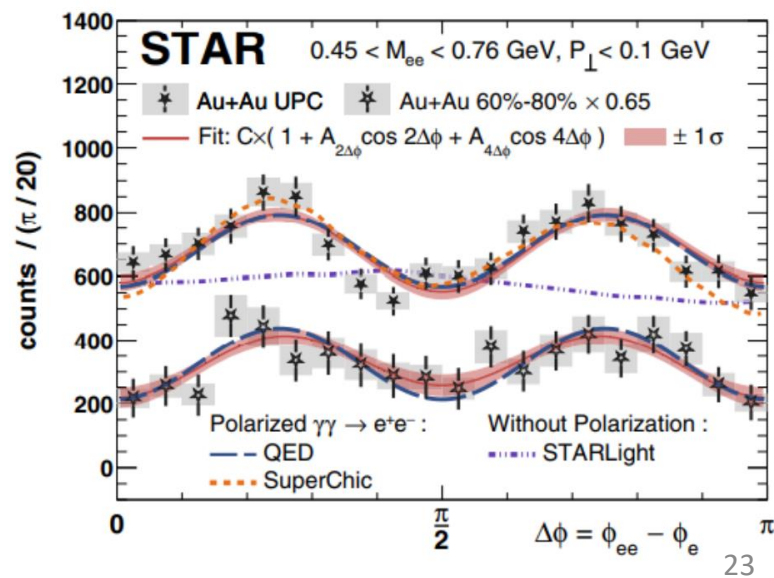
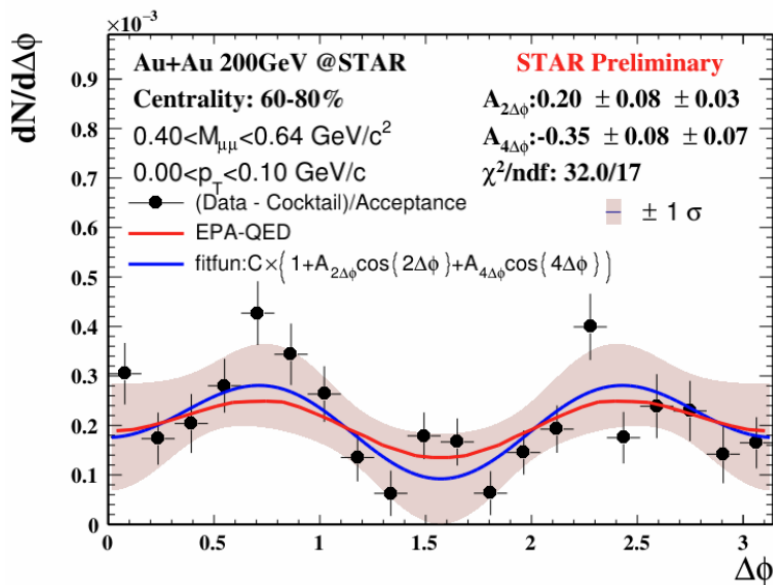
Xiao Lin Li, Xiaohui Liu, Feng Yuan, HuaXing Zhu, PRD 108 (2023) L091502

Linear polarization @ UPCs

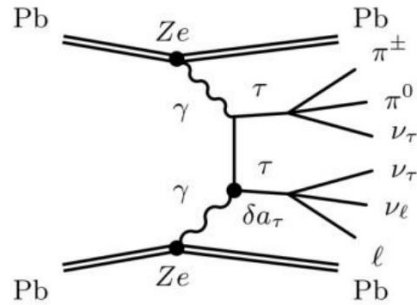
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



PRL 127 (2021) 5, 052302

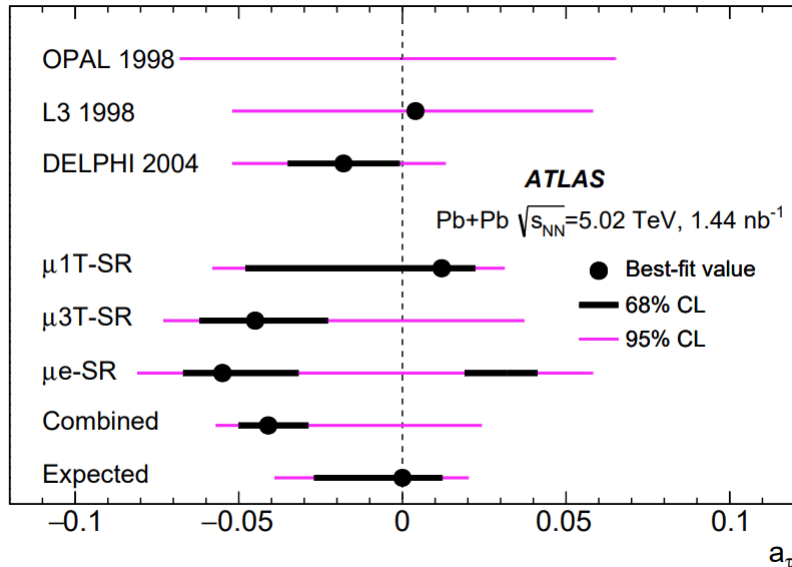


Tau pair production @ UPCs



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

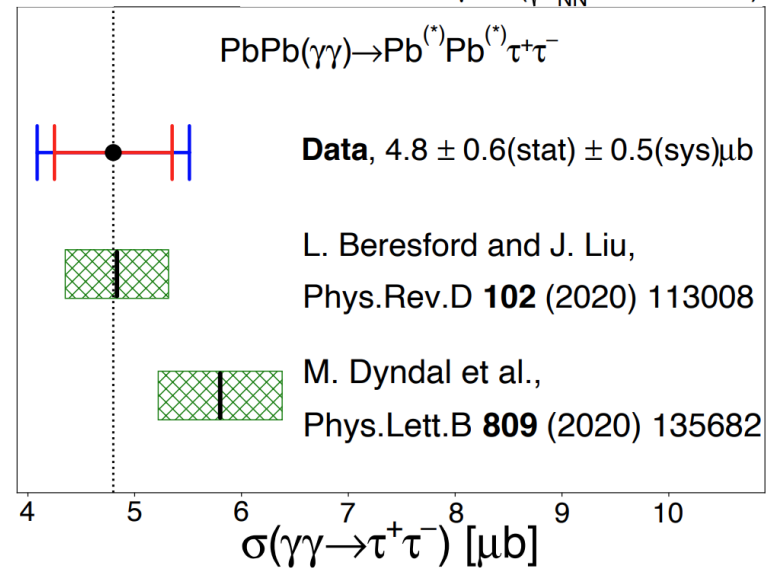
$$F_2(0) = a_{\tau}, \quad F_3(0) = 2 \frac{m_{\tau} d_{\tau}}{e}$$



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

CMS

PbPb - $404 \mu\text{b}^{-1}$ ($\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$)



Phys. Rev. Lett. 131 (2023) 151803

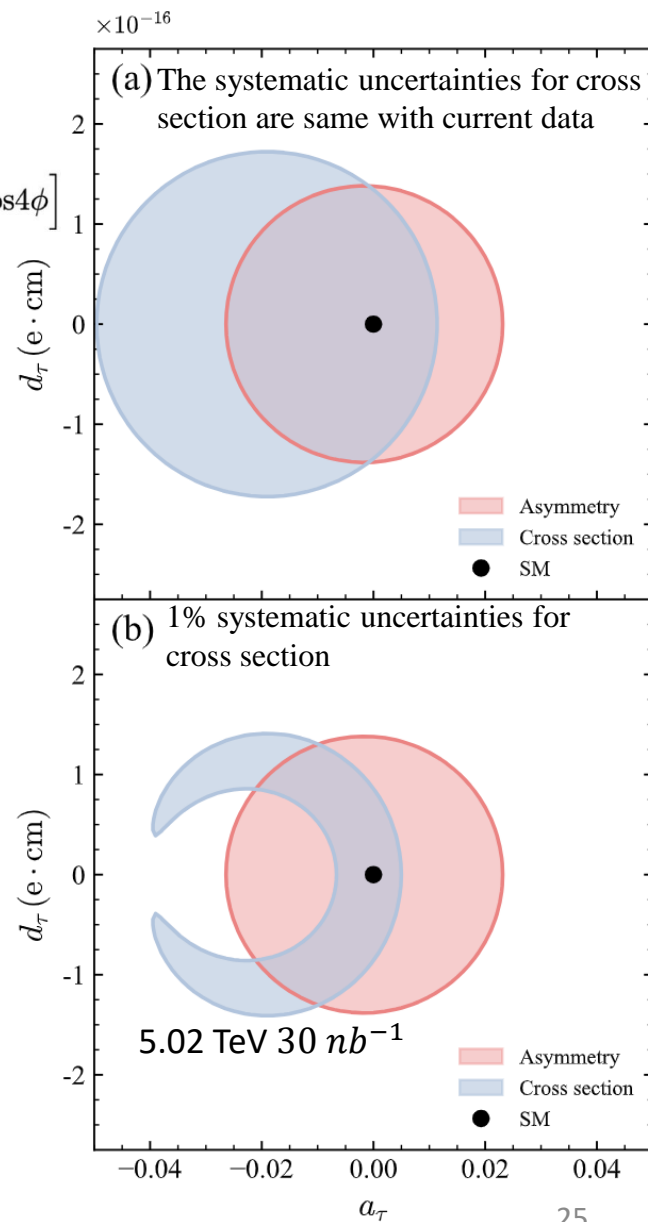
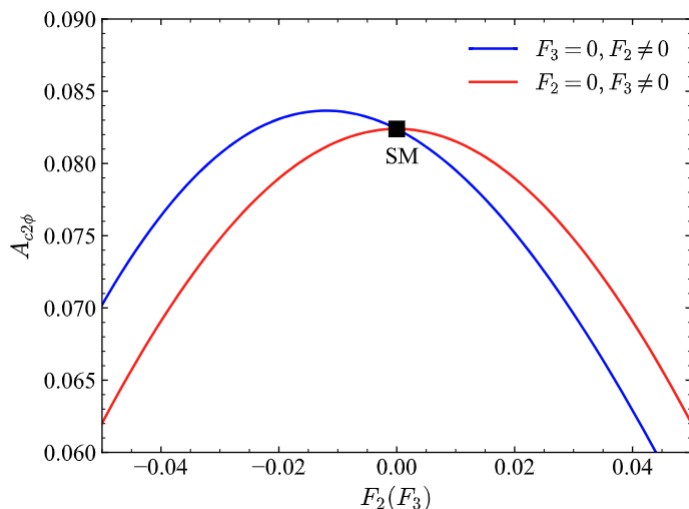
Linear polarization @ UPCs

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

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

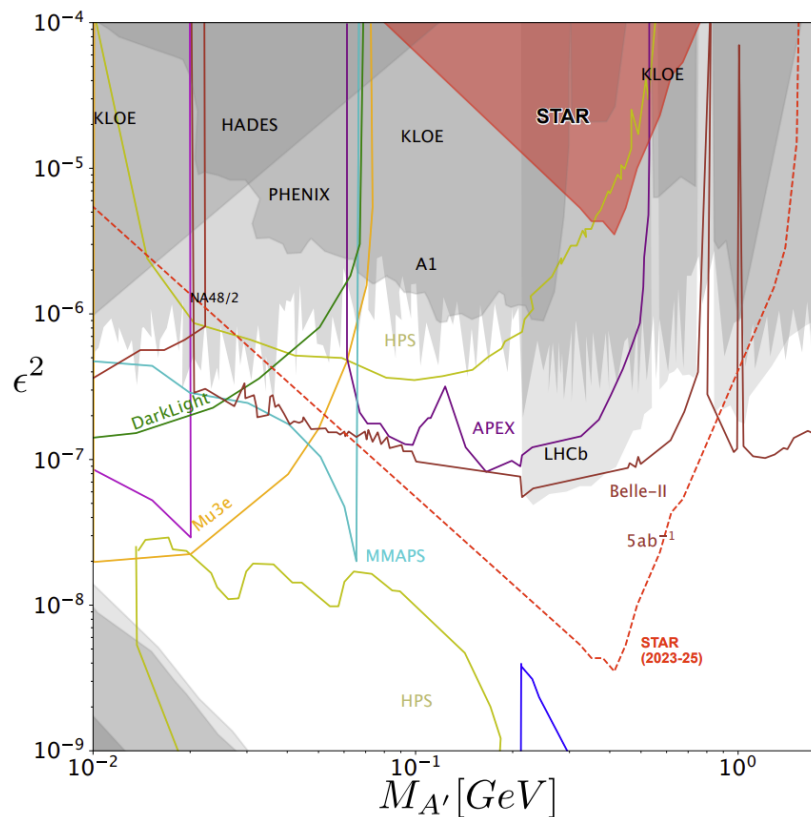
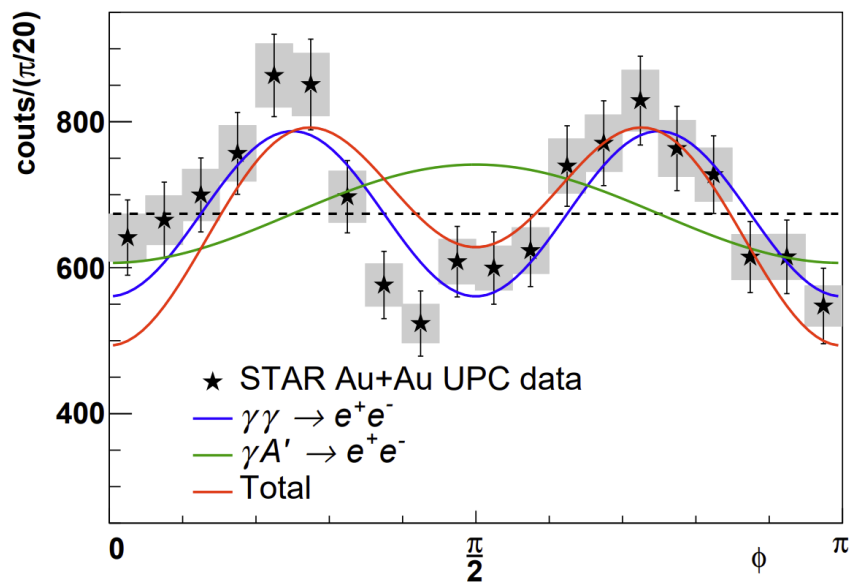
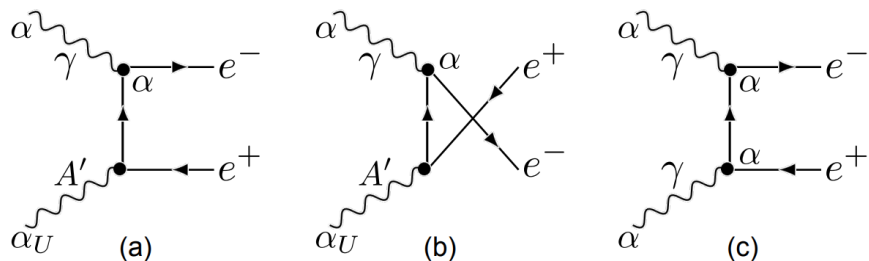
$$F_2(0) = a_\tau, \quad F_3(0) = 2 \frac{m_\tau d_\tau}{e} \quad \text{Suppressed by lepton mass}$$

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



Linear polarization @ UPCs

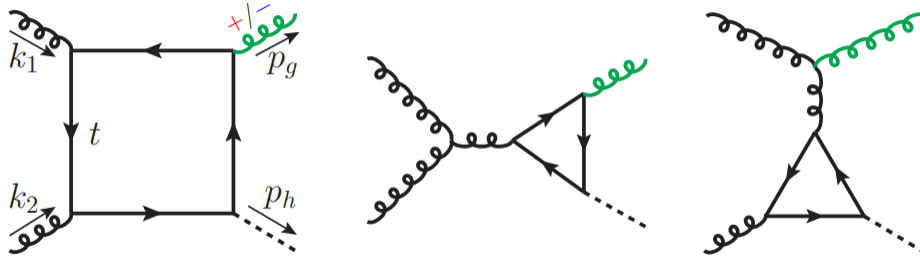
Dingyu Shao, Yujie Tian, **Bin Yan**, Cheng Zhang, working in progress



I. Xu et al, arXiv:2211.02132

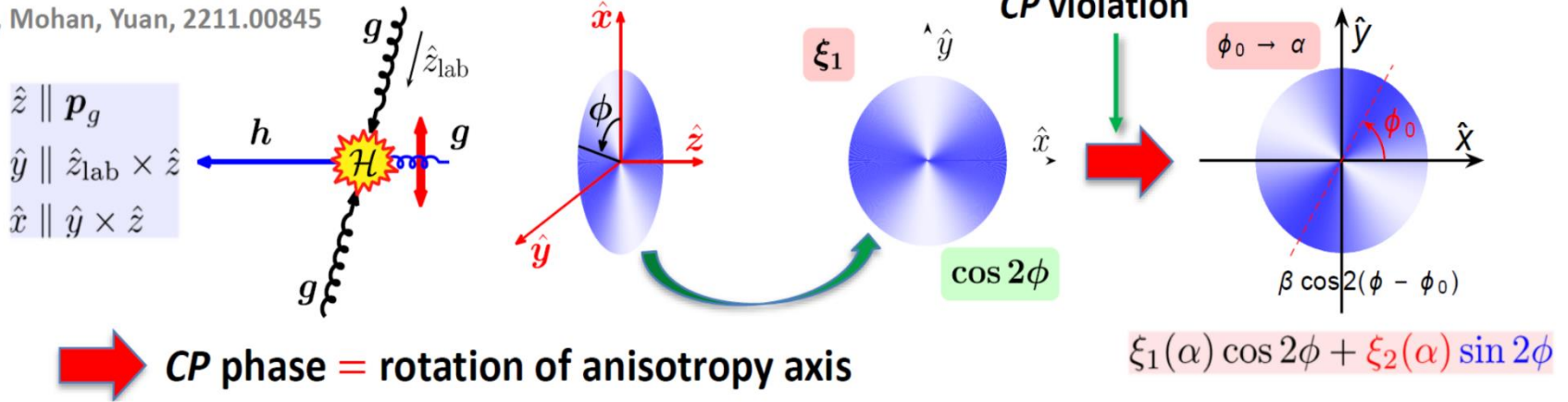
$$A_{2\phi}(\epsilon, M_{A'}) \simeq \left(\frac{\epsilon^2}{\alpha}\right)^{1/2} \left(2\frac{M_{A'}}{M_{ee}}\right)^2$$

Linear polarization of gluon



$$\rho_{\lambda\lambda'} = \frac{1}{2} (1 + \boldsymbol{\xi} \cdot \boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2} \begin{pmatrix} 1 + \xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1 - \xi_3 \end{pmatrix}$$

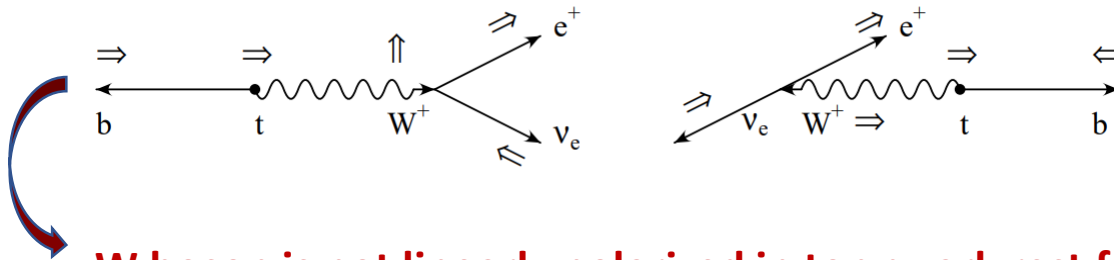
Yu, Mohan, Yuan, 2211.00845



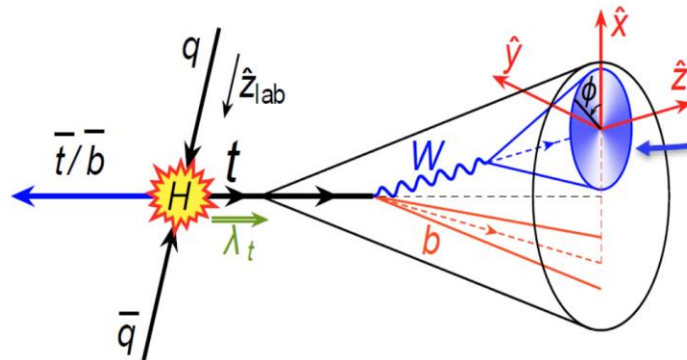
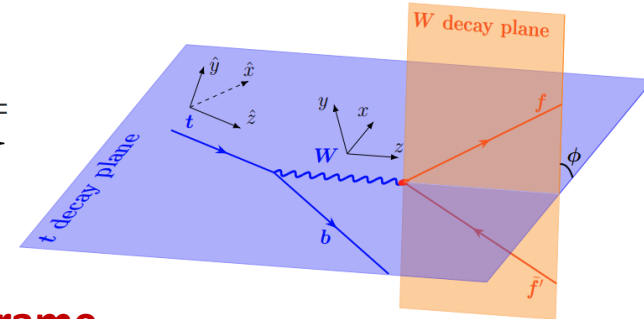
C.-P. Yuan's talk @ MBI 2023

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



$$\frac{dE}{d\phi} = \frac{E_{\text{tot}}}{2\pi} [1 + \xi \cos 2\phi] \quad \text{Infrared safe}$$

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

[Assuming SM tbW coupling]

Azimuthal correlation

Boosted top polarization

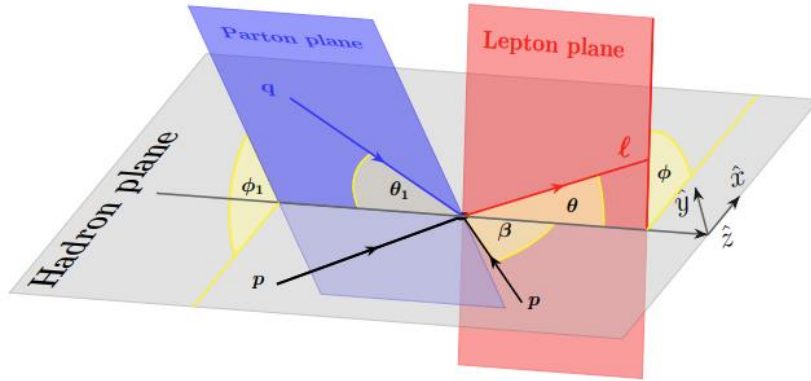
- Measuring longitudinal polarization of boosted top
- New top tagger against QCD jets



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

Qi Bi, Bin Yan, Zhite Yu, working in progress

Lam-Tung relation and polarization



Collins-Soper frame

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

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

Lam-Tung relation: $A_0 = A_2$

Linear and Longitudinal polarization of Z boson

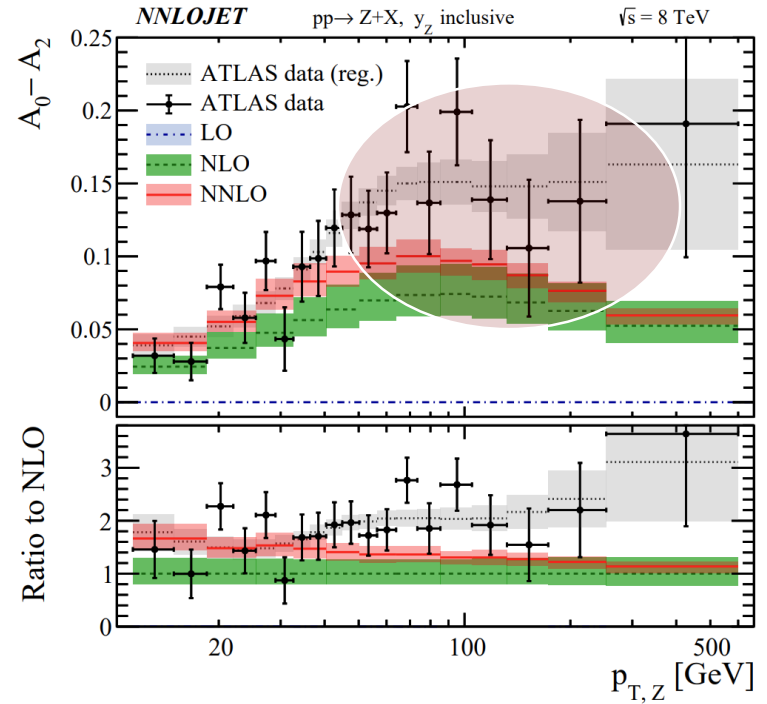
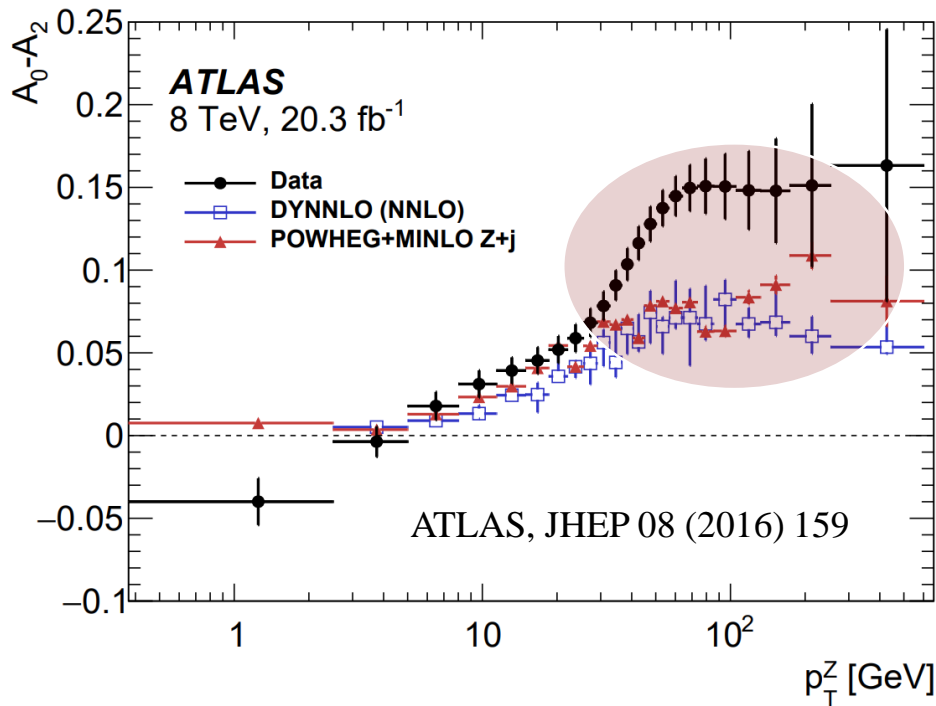
$$\frac{\Gamma}{\Omega_f^*} \propto \frac{|B_+|^2 + |B_-|^2}{2} \left[\frac{2}{3} + \frac{\delta_L}{3} (1 - 3\cos^2\theta_f^*) + \lambda_T \sin^2\theta_f^* \cos 2\phi_f^* \right. \\ \left. + Q_{yz} \sin 2\theta_f^* \sin \phi_f^* + Q_{xz} \sin 2\theta_f^* \cos \phi_f^* + Q_{xy} \sin^2\theta_f^* \sin 2\phi_f^*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

$A_0 \neq A_2$ @ NNLO in QCD

non-coplanarity between the hadron and parton planes

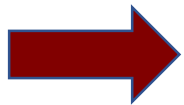
J.C. Peng et al, PLB 758,384 (2016)

Lam-Tung relation and polarization



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 ?

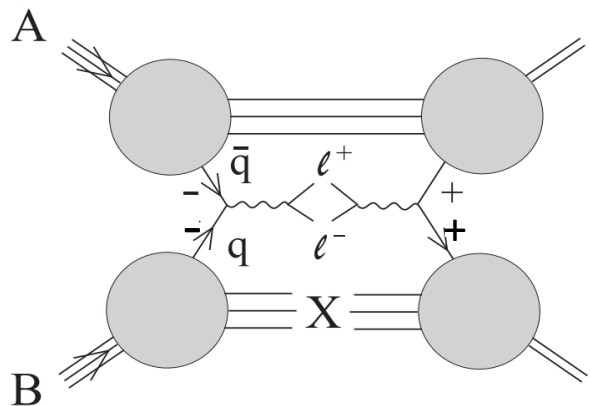
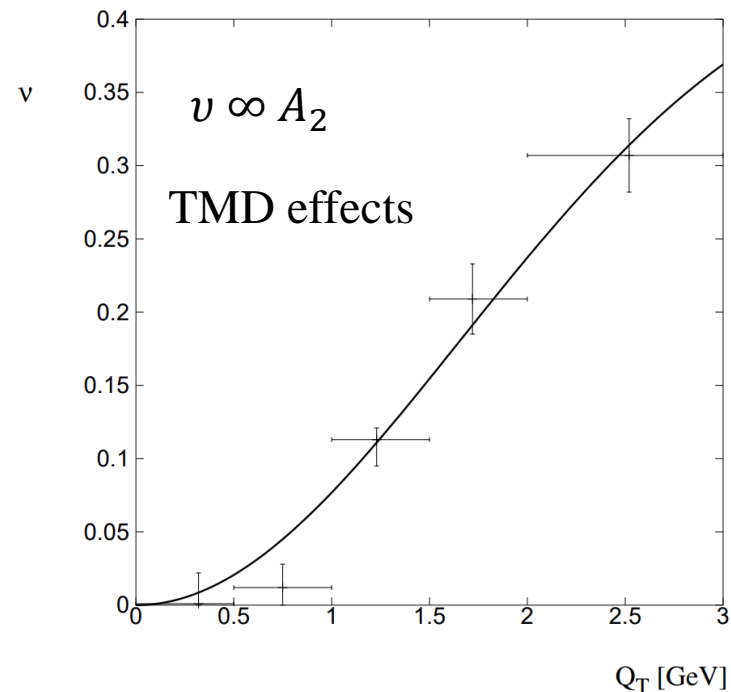
Boer-Mulders function

The $\cos 2\phi$ 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	$f_1 = \text{Unpolarized}$ 		$h_1^\perp = \text{Boer-Mulders}$ 
	L		$g_1 = \text{Helicity}$ 	$h_{1L}^\perp = \text{Worm-gear}$ 
	T	$f_{1T}^\perp = \text{Sivers}$ 	$g_{1T}^\perp = \text{Worm-gear}$ 	$h_1 = \text{Transversity}$  $h_{1T}^\perp = \text{Pretzelosity}$ 

Boer, PRD 60 (1999) 014012



Transversely polarized quark

Lam-Tung relation and NP

Center-of-mass frame:

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

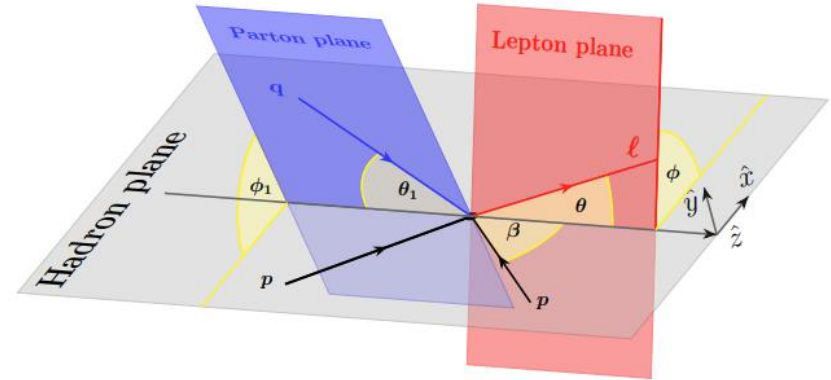
$$\cos \hat{\theta} = \cos \theta \cos \theta_1 + \sin \theta \sin \theta_1 \cos(\phi - \phi_1)$$

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

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

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

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

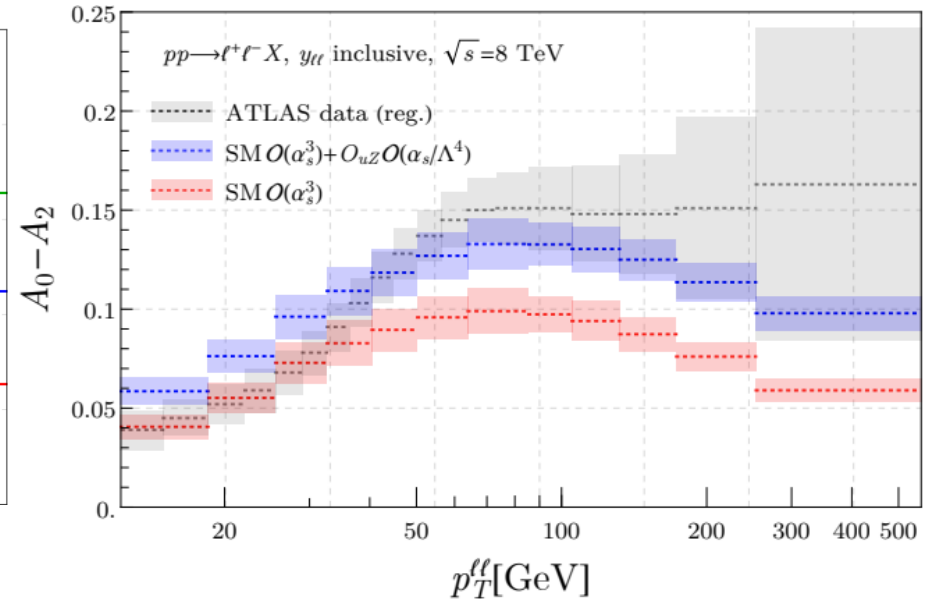
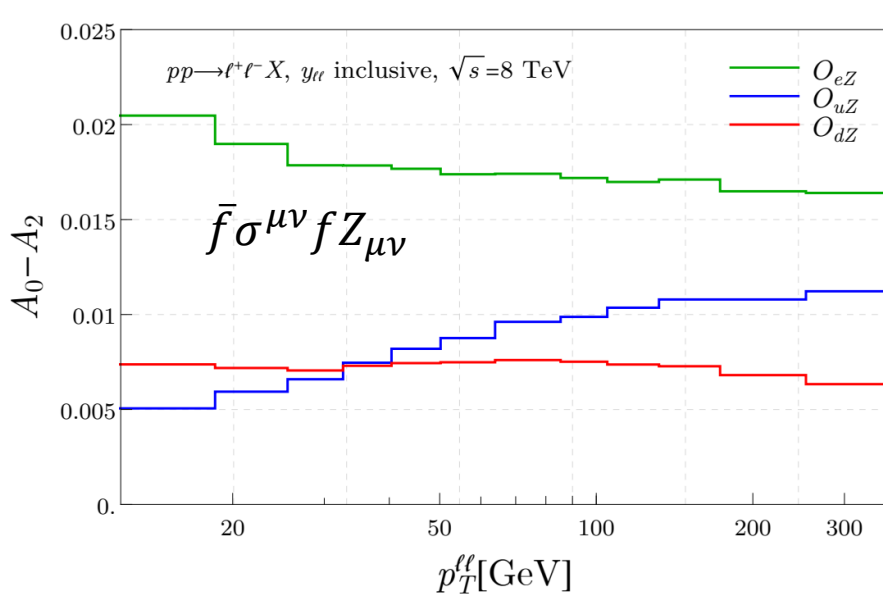


$$A_0 \neq A_2$$

- 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

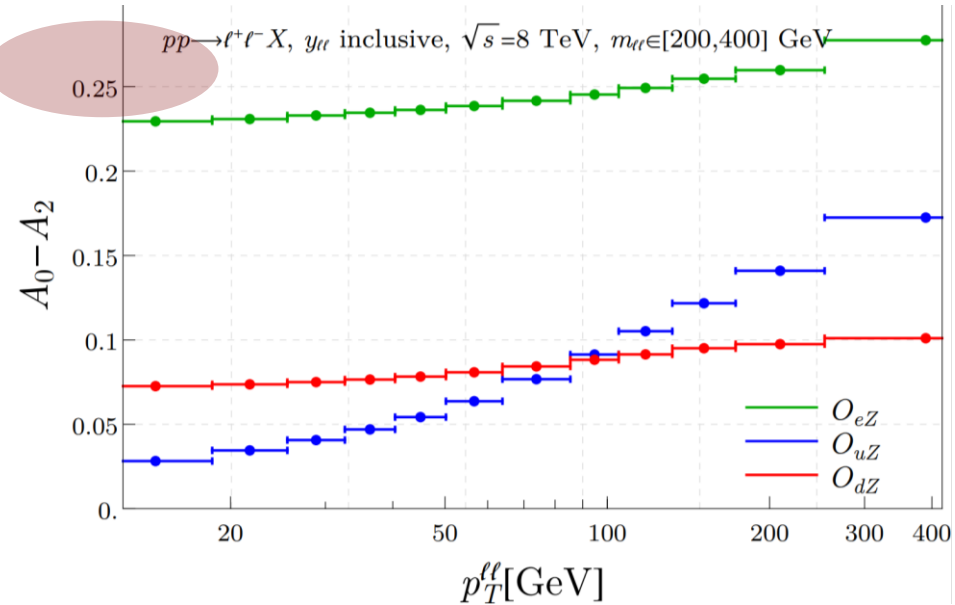
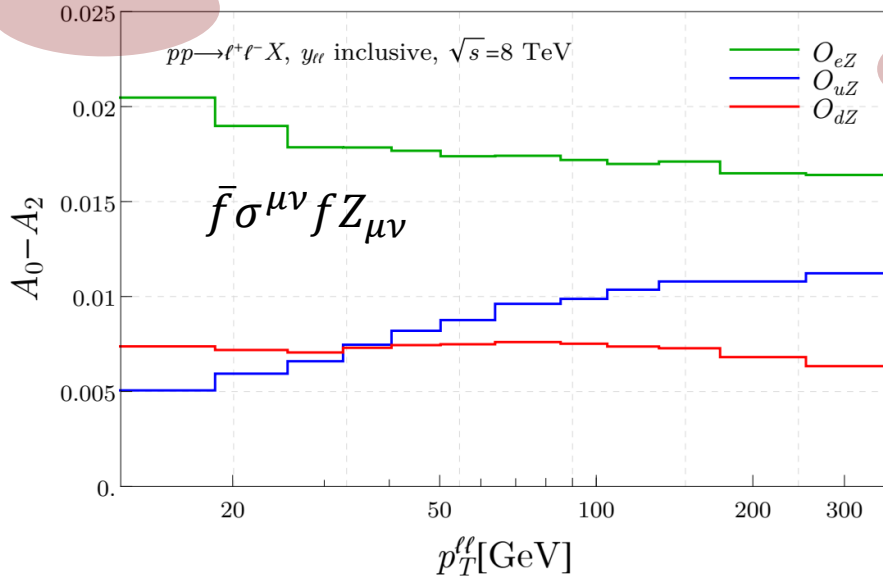
Lam-Tung relation and polarization



- 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

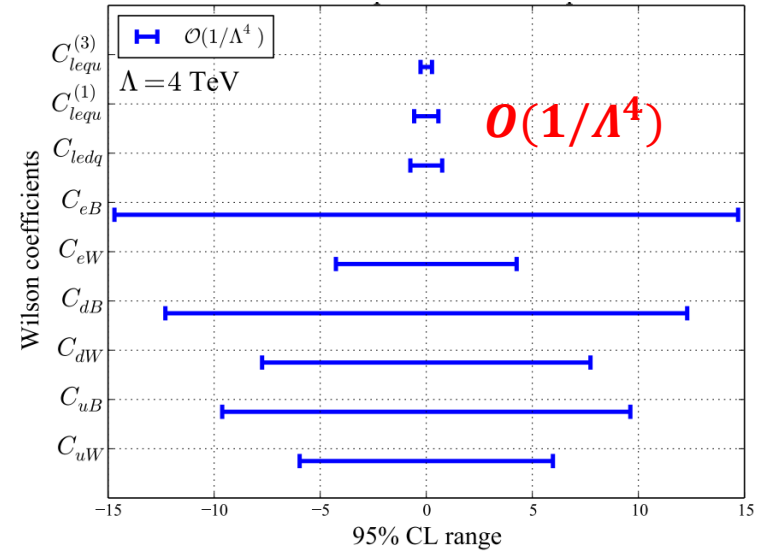
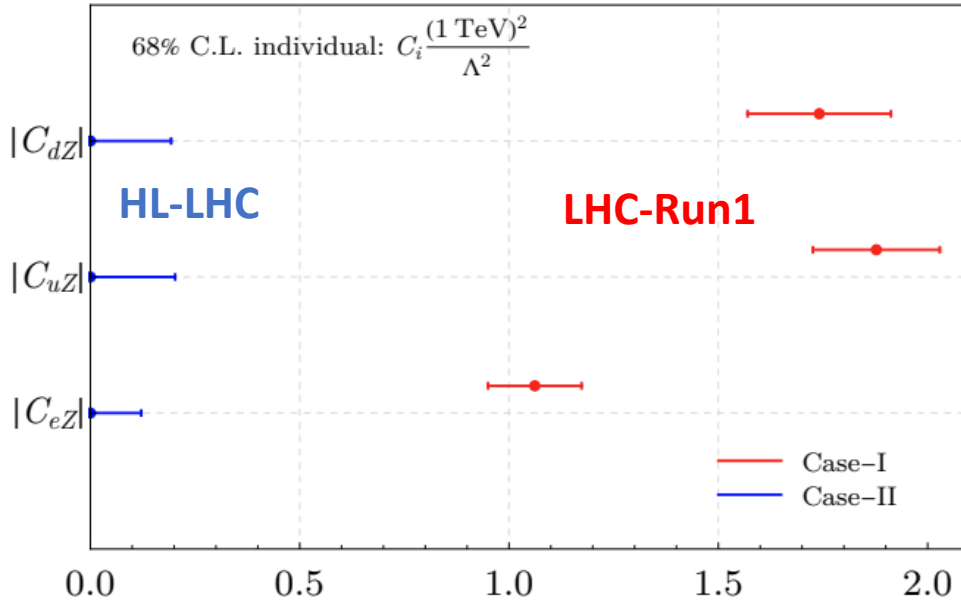
Lam-Tung relation and polarization



- The accuracy for the normalization of the angular coefficients in high invariant mass: $O(\alpha_s)$
- The breaking effects from the weak dipole interactions could be enhanced **by one order of magnitude**

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 electroweak dipole operators are difficult to be probed at colliders since their leading effects are from $1/\Lambda^4$
- These operators can be probed at $1/\Lambda^2$ via **transverse spin effects (beams or non-perturbative 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** by 1~2 orders of magnitude
- The photons from UPCs are **linearly polarized** and can be used to probe the NP
- Polarized Muon collider, hadron colliders, electron-Ion collider
- The linear polarization of the gauge bosons: photon, gluon and W/Z

Thank you