

Spin asymmetry and electroweak properties of SM and beyond at the EIC

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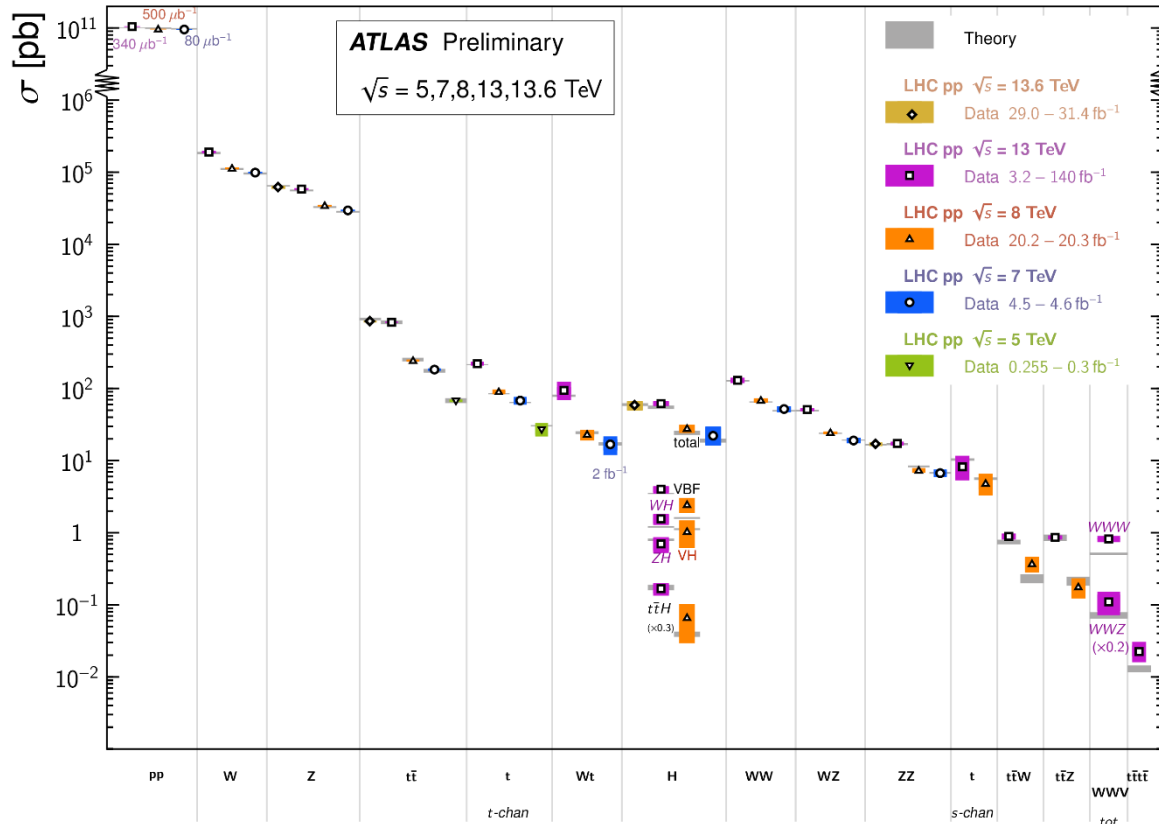
The 4th EIC-Asia Workshop

July 1-5, 2024

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

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

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

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_0 11.2 TeV, $n=2$
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_0 8.6 TeV, $n=3$ HLZ NLO
	ADD GBH	-	2 j	-	139	M_{th} 9.4 TeV, $n=6$
	ADD BH multijet	-	$\geq 3 j$	-	3.6	M_{th} 9.55 TeV, $n=6, M_0 = 3 \text{ TeV, rot BH}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	139	$k_1^2/M_{\text{Pl}}^2 = 0.1$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$k_1^2/M_{\text{Pl}}^2 = 1.0$
Gauge bosons	Bulk RS $g_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1 J/2$	Yes	36.1	$\Gamma/m = 15\%$
	2UED / RPP	$1 e, \mu$	$\geq 2 b, \geq 3 j$	Yes	36.1	Tier (1,1), $2(A^{(1,1)} \rightarrow tt) = 1$
	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	Z' mass 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	Z' mass 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	$\geq 2 b$	-	36.1	Z' mass 2.1 TeV
	Leptophobic $Z' \rightarrow tt$	$0 e, \mu$	$\geq 1 b, \geq 2 j$	Yes	139	Z' mass 4.1 TeV, $\Gamma/m = 1.2\%$
CI	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	Yes	139	W' mass 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	Yes	139	W' mass 5.0 TeV
	SSM $W' \rightarrow tb$	-	$\geq 1 b, \geq 1 J$	-	139	W' mass 4.4 TeV
	HVT $W' \rightarrow WZ$ model B	$0-2 e, \mu$	$2 j / 1 J$	Yes	139	W' mass 4.3 TeV
	HVT $W' \rightarrow WZ + \ell\nu (\ell' \nu')$ model C	$3 e, \mu$	$2 j$ (VBF)	Yes	139	W' mass 340 GeV
	HVT $Z' \rightarrow WW$ model B	$1 e, \mu$	$2 j / 1 J$	Yes	139	Z' mass 3.9 TeV
DM	LRSM $W_R \rightarrow \mu N_R$	2μ	$1 J$	-	80	W_R mass 5.0 TeV
	CI $q\bar{q}q\bar{q}$	-	2 j	-	37.0	A 21.8 TeV, η_{LL}
	CI $\ell\ell q\bar{q}$	$2 e, \mu$	-	-	139	A 35.8 TeV, η_{LL}
	CI $e\bar{e}b\bar{b}$	$2 e$	1 b	-	139	$g_s = 1$
	CI $\mu\bar{\mu}b\bar{b}$	2μ	1 b	-	139	$g_s = 1$
	CI $t\bar{t}t\bar{t}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 j$	Yes	36.1	$ C_{\text{eff}} = 4\pi$
LQ	Axial-vector med. (Dirac DM)	-	2 j	-	139	m_{had} 3.8 TeV
	Pseudo-scalar med. (Dirac DM)	$0 e, \mu, \tau, \gamma$	1-4 j	Yes	139	m_{had} 376 GeV
	Vector med. Z' -2HDM (Dirac DM)	$0 e, \mu$	2 b	Yes	139	$m_{Z'}$ 3.0 TeV
	Pseudo-scalar med. 2HDM+a	multi-channel	-	-	139	m_{th} 800 GeV
	Scalar LQ 1 st gen	$2 e$	$\geq 2 j$	Yes	139	LO mass 1.8 TeV
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	Yes	139	LO mass 1.7 TeV
Vector-like fermions	Scalar LQ 3 rd gen	1τ	2 b	Yes	139	LO mass 1.49 TeV
	Scalar LQ 3 rd gen	$0 e, \mu$	$\geq 2 j, \geq 2 b$	Yes	139	LO mass 1.24 TeV
	Scalar LQ 3 rd gen	$\geq 2 e, \mu, \geq 1\tau, \geq 1 b$	-	-	139	LO mass 1.43 TeV
	Scalar LQ 3 rd gen	$0 e, \mu, \geq 1\tau, 0-2 j, 2 b$	Yes	139	LO mass 1.26 TeV	
	Vector LQ mix gen	multi-channel	$\geq 1 j, \geq 1 b$	Yes	139	LO mass 2.0 TeV
	Vector LQ 3 rd gen	$2 e, \mu, \tau$	$\geq 1 b$	Yes	139	LO mass 1.98 TeV
Excited ferm.	VLO $T\bar{T} \rightarrow Zt + X$	$2e, 2\mu, \geq 3e, \mu, \geq 1 b, \geq 1 j$	-	-	139	T mass 1.46 TeV
	VLO $B\bar{B} \rightarrow WZb + X$	multi-channel	-	-	36.1	B mass 1.34 TeV
	VLO $T_{5/3} T_{5/3} \rightarrow Wt + X$	$2(SS)/\geq 3 e, \mu, \geq 1 b, \geq 1 j$	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	
	VLO $T \rightarrow Ht/Zt$	$1 e, \mu, \geq 1 b, \geq 3 j$	Yes	139	T mass 1.8 TeV	
	VLO $Y \rightarrow Wb$	$1 e, \mu, \geq 1 b, \geq 1 j$	Yes	36.1	Y mass 1.85 TeV	
	VLO $B \rightarrow Hb$	$0 e, \mu, \geq 2b, \geq 1 j, \geq 1 j$	-	-	139	B mass 2.0 TeV
Other	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel	$\geq 1 j$	Yes	139	τ' mass 898 GeV
	Excited quark $q^* \rightarrow qg$	-	2 j	-	139	q^* mass 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1γ	1 j	-	36.7	q^* mass 5.3 TeV
	Excited quark $q^* \rightarrow b\bar{g}$	-	$1 b, 1 j$	-	139	b^* mass 3.2 TeV
	Excited lepton e^*	2τ	$\geq 2 j$	-	139	e^* mass 4.6 TeV
	Type III Seesaw	$2, 3, 4 e, \mu$	$\geq 2 j$	Yes	139	N^c mass 910 GeV
LRSM Majorana ν	2μ	2 j	-	36.1	N_{th} mass 3.2 TeV	
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$	$2, 3, 4 e, \mu$ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV	
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	139	$H^{\pm\pm}$ mass 1.08 TeV	
Multi-charged particles	-	-	-	139	multi-charged particle mass 1.59 TeV	
Magnetic monopoles	-	-	-	34.4	monopole mass 2.37 TeV	

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

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

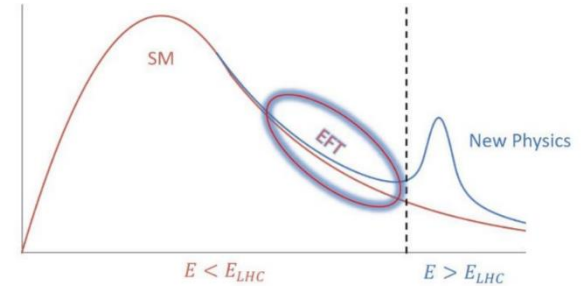
*Only a selection of the available mass limits on new states or phenomena is shown.

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

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



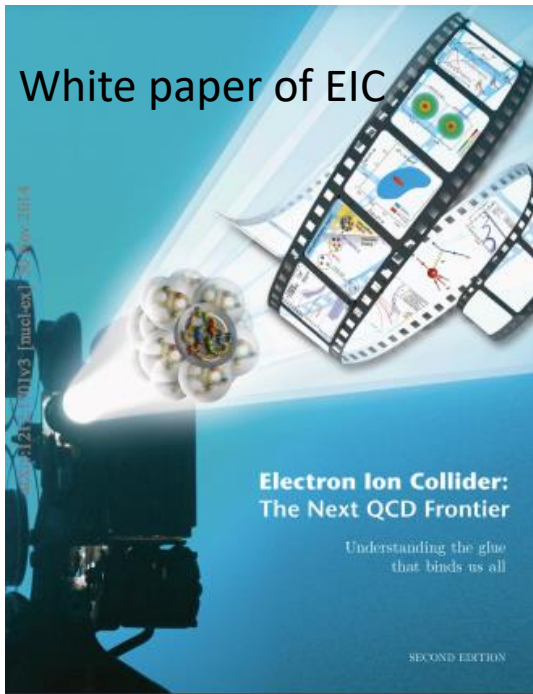
SMEFT



Top-down approach

Bottom-up approach

Why Electron-Ion Collider?



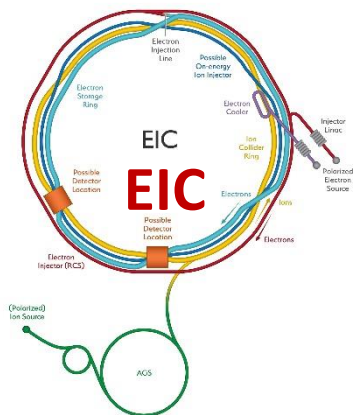
1. Explore and image the **spin and 3D structure** of the nucleon
2. Discover the **role of gluons** in structure and dynamics
3. Constraint for the PDFs, Polarized and unpolarized
4. Possibilities of **Beyond the Standard Model?**

$$10 \sim 100 \text{ fb}^{-1}$$

High Polarization: $P_e = P_p = 0.7$

Electroweak properties

EIC is also an important machine for the **New Physics**



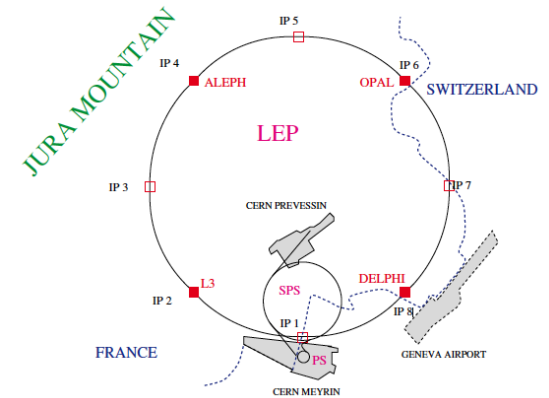
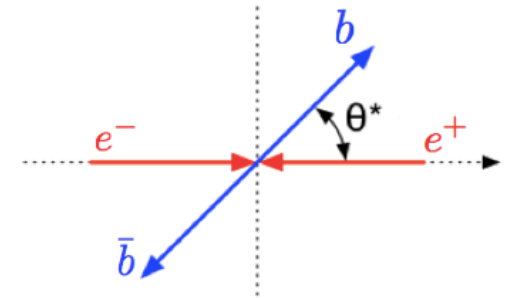
Longitudinal polarization of the electron

Electroweak Precision measurement

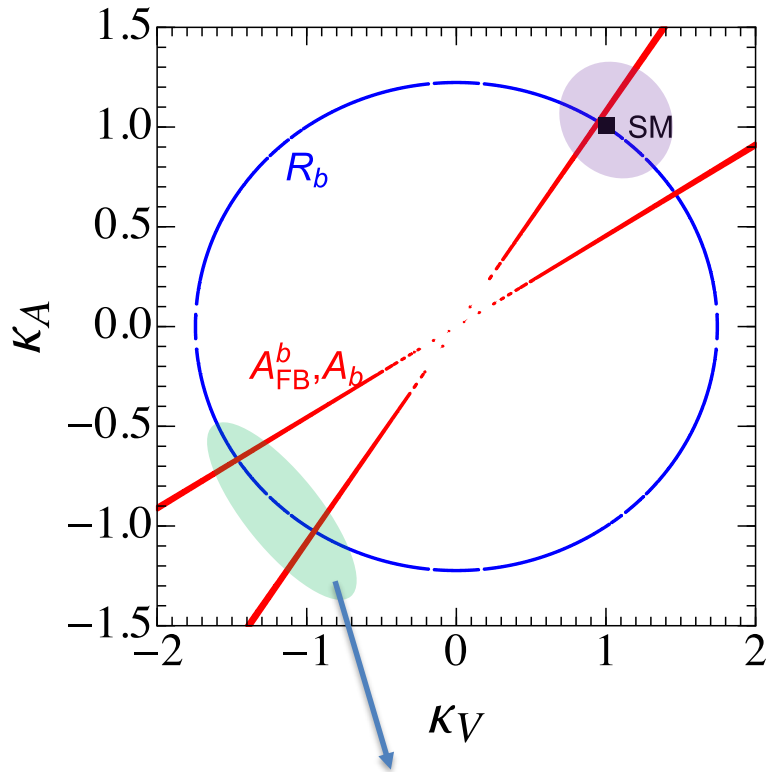
	Measurement with Total Error	Systematic Error	Standard Model High- Q^2 Fit	Pull
$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ [59]	0.02758 ± 0.00035	0.00034	0.02767 ± 0.00035	0.3
m_Z [GeV]	91.1875 ± 0.0021	^(a) 0.0017	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	^(a) 0.0012	2.4965 ± 0.0015	0.6
σ_{had}^0 [nb]	41.540 ± 0.037	^(a) 0.028	41.481 ± 0.014	1.6
R_ℓ^0	20.767 ± 0.025	^(a) 0.007	20.739 ± 0.018	1.1
$A_{\text{FB}}^{0,\ell}$	0.0171 ± 0.0010	^(a) 0.0003	0.01642 ± 0.00024	0.8
+ correlation matrix Table 2.13				
$\mathcal{A}_\ell(P_\tau)$	0.1465 ± 0.0033	0.0015	0.1480 ± 0.0011	0.5
$\mathcal{A}_\ell(\text{SLD})$	0.1513 ± 0.0021	0.0011	0.1480 ± 0.0011	1.6
R_b^0	0.21629 ± 0.00066	0.00050	0.21562 ± 0.00013	1.0
R_c^0	0.1721 ± 0.0030	0.0019	0.1723 ± 0.0001	0.1
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	0.0007	0.1037 ± 0.0008	2.8
$A_{\text{FB}}^{0,c}$	0.0707 ± 0.0035	0.0017	0.0742 ± 0.0006	1.0
\mathcal{A}_b	0.923 ± 0.020	0.013	0.9346 ± 0.0001	0.6
\mathcal{A}_c	0.670 ± 0.027	0.015	0.6683 ± 0.0005	0.1
+ correlation matrix Table 5.11				
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	0.2324 ± 0.0012	0.0010	0.23140 ± 0.00014	0.8
m_t [GeV] (Run-I [212])	178.0 ± 4.3	3.3	178.5 ± 3.9	0.1
m_W [GeV]	80.425 ± 0.034		80.389 ± 0.019	1.1
Γ_W [GeV]	2.133 ± 0.069		2.093 ± 0.002	0.6
+ correlation given in Section 8.3.2				

Phys.Rept. 427 (2006) 257-454

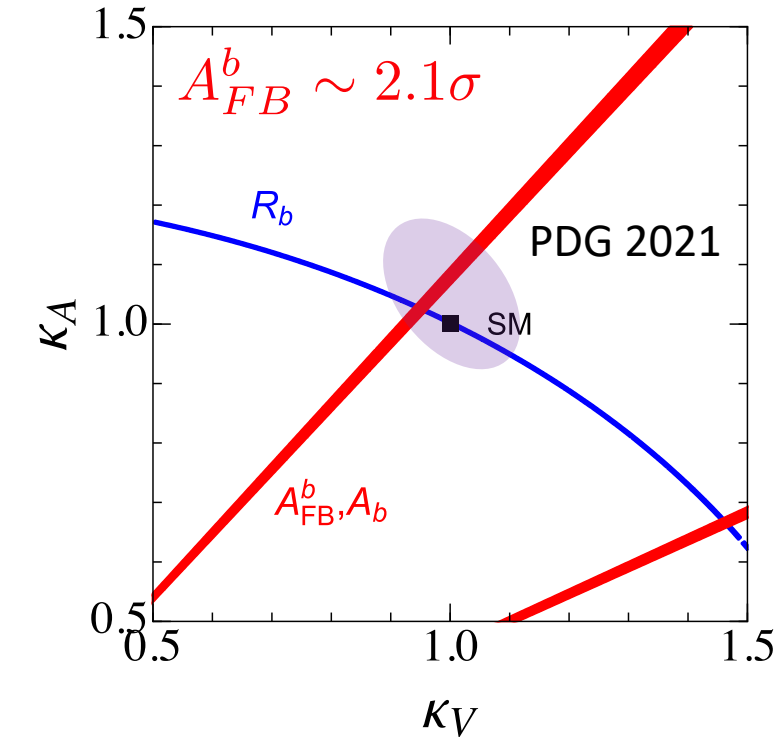
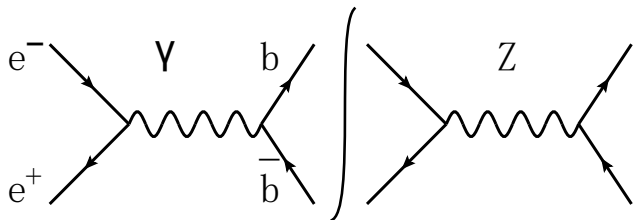
LEP: 1989-2000



Electroweak Precision measurement



Excluded by off-Z pole data



$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$$

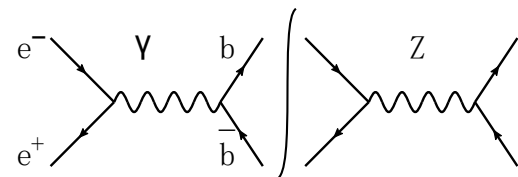
- Large deviation of the Zbb coupling
- The **degeneracy** of the Zbb coupling

Zbb couplings @ Colliders

A. Lepton colliders:

S. Gori, Jiayin Gu, Lian-Tao Wang, JHEP 04(2016) 062

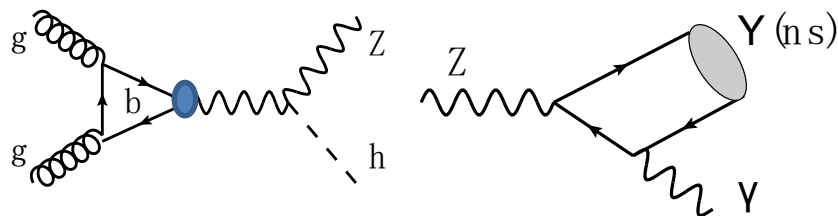
Bin Yan, C.-P. Yuan and Shu-Run Yuan, PRD108(2023)5, 053001



B. LHC Zh production and Z boson rare decay:

Bin Yan, C.-P. Yuan, PRL127(2021)5,051801

Hongxin Dong, Peng Sun, Bin Yan and C.-P. Yuan, PLB829(2022)137076



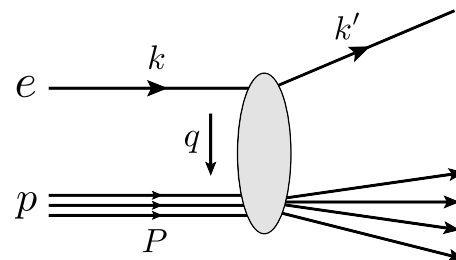
C. LHC Z+2b-jet production

F. Bishara and Zhuoni Qian, 2306.15109

D. HERA and EIC with polarized lepton beam:

Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697

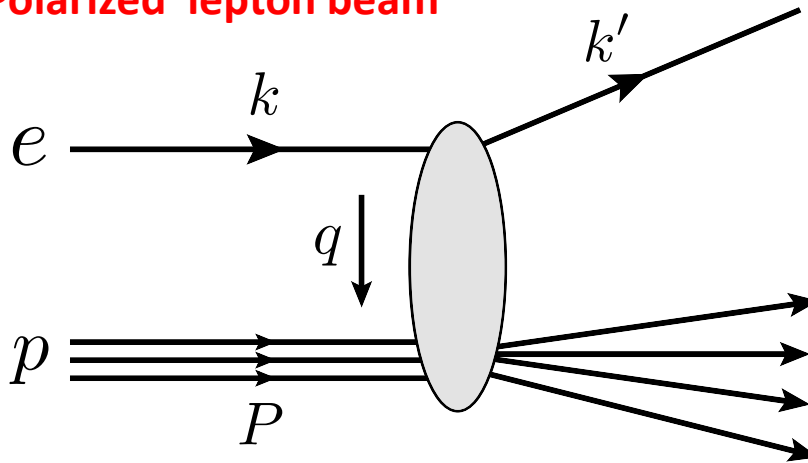
Hai Tao Li, Bin Yan and C.-P. Yuan, PLB833(2022)137300



Zbb couplings @ EIC

Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697

Polarized lepton beam



Single-Spin Asymmetry (SSA):

$$A_e^b = \frac{\sigma_{b,+}^{\text{tot}} - \sigma_{b,-}^{\text{tot}}}{\sigma_{b,+}^{\text{tot}} + \sigma_{b,-}^{\text{tot}}}$$

+/-: right/left-handed lepton

1. Photon-only diagrams will **cancel** in SSA
2. Leading contribution: **γ -Z interference**
3. Only sensitive to the **vector component** of the Zbb coupling

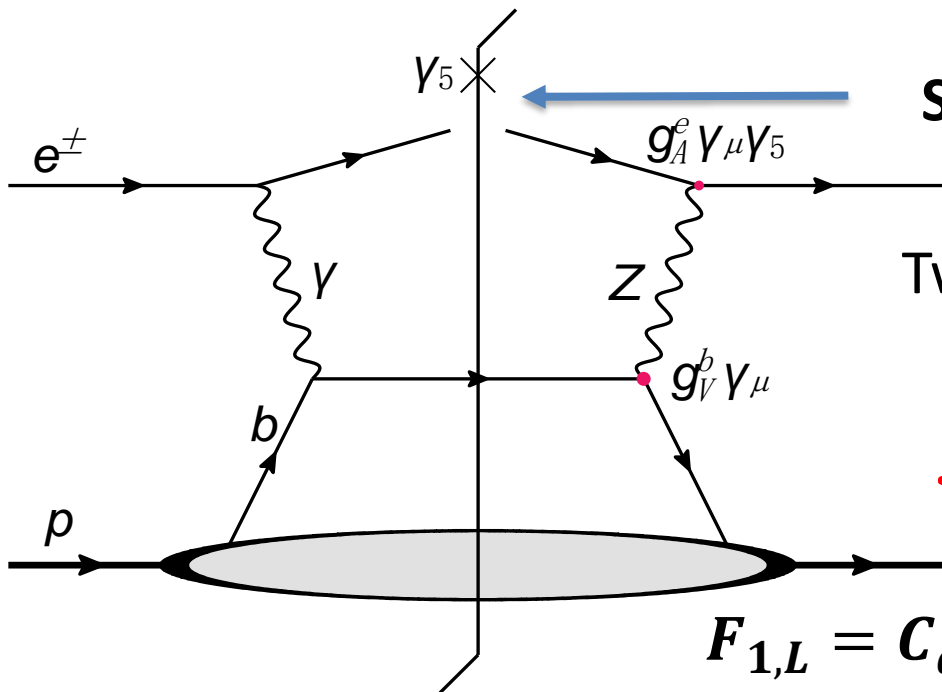
DIS cross section

Polarized cross section

$$F_{1,L,3} \equiv F_{1,L,3}(\lambda_e)$$

$$\frac{d\sigma_{\lambda_e}^{\pm}}{\sigma_0 dx dy} = F_1 \left((1-y)^2 + 1 \right) + F_L \frac{1-y}{x} \mp \underline{F_3} \lambda_e \left(y - \frac{y^2}{2} \right)$$

$\lambda_e = \pm 1$: lepton helicity



SSA: $\sigma_{b,+} - \sigma_{b,-}$

Two possible combination:

$$g_A^e g_V^b$$



$$g_V^e g_A^b$$

$$F_{1,L} = C_q \otimes (q + \bar{q}) \quad F_3 = C_q \otimes (q - \bar{q})$$

$$\mathcal{L}_{\text{eff}} = \frac{g_W}{2c_W} \bar{f} \gamma_\mu (g_V^f - g_A^f \gamma_5) f Z_\mu$$

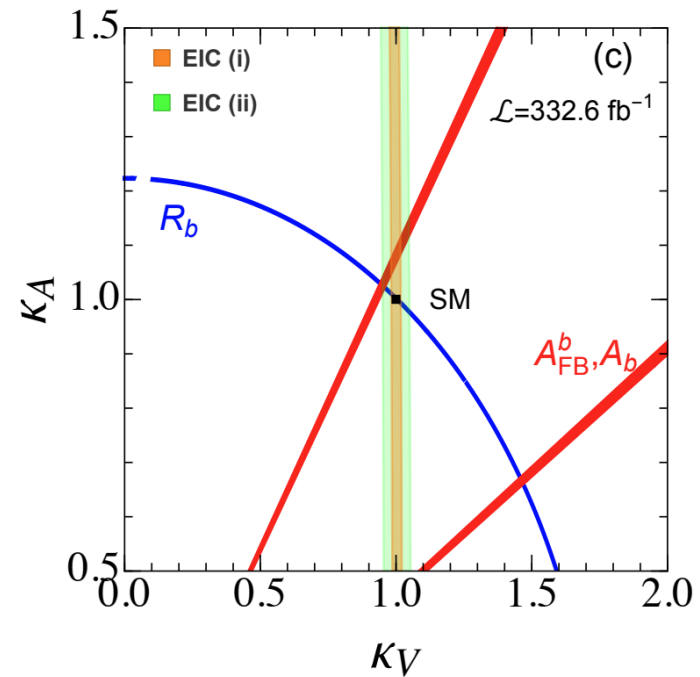
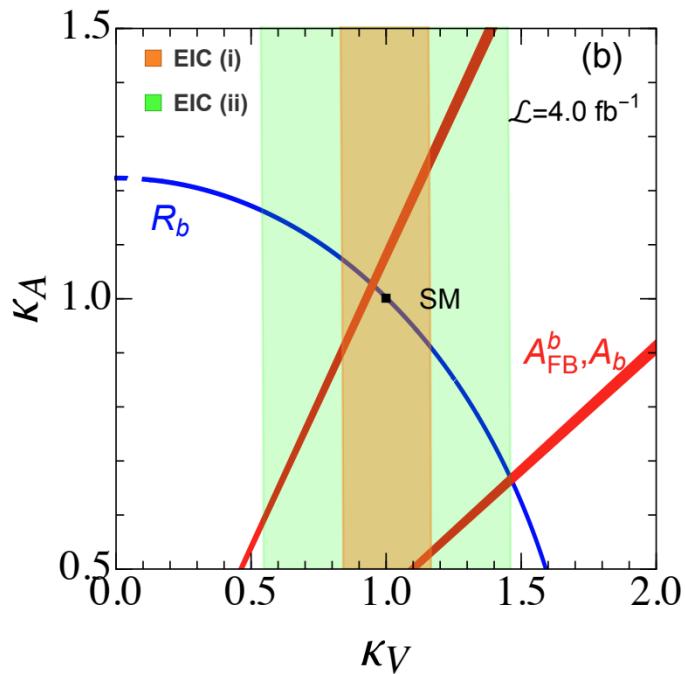
Zbb couplings @ EIC

(i) $\epsilon_q^b = 0.001$, $\epsilon_c^b = 0.03$, $\epsilon_b = 0.7$;

$E_{\text{cm}} = 141 \text{ GeV}, P_e = 0.7$

(ii) $\epsilon_q^b = 0.01$, $\epsilon_c^b = 0.2$, $\epsilon_b = 0.5$.

$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$



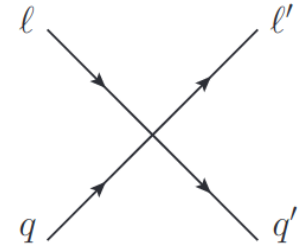
The minimal luminosities needed to resolve the degeneracy or exclude LEP AFB data:

(i) : $\mathcal{L} > 0.5 \text{ fb}^{-1}$; (ii) : $\mathcal{L} > 4.0 \text{ fb}^{-1}$. (i) : $\mathcal{L} > 42.0 \text{ fb}^{-1}$; (ii) : $\mathcal{L} > 332.6 \text{ fb}^{-1}$.

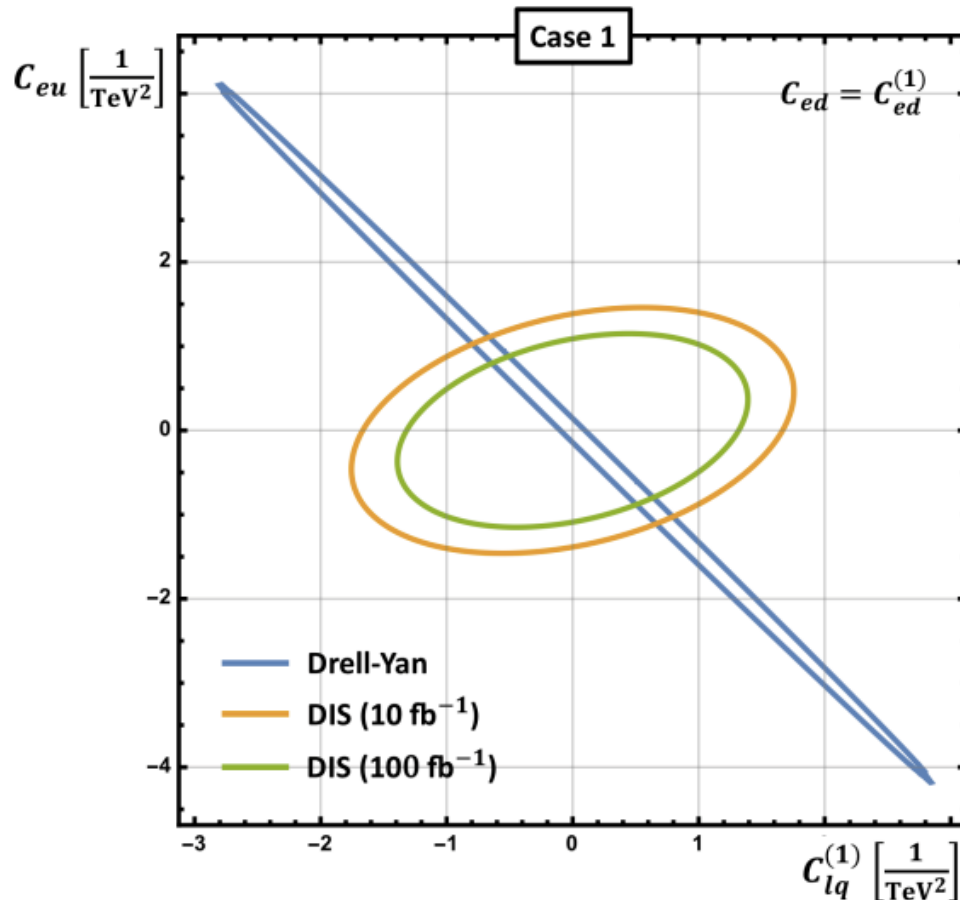
Four-fermion operators

R. Boughezal, F. Petriello, D. Wiegand, PRD 101 (2020) 11,116002

$$P_e = \pm 0.7$$



$$M_{\text{int}}^\gamma \sim C_{eu}(1 + P_e) + C_{lq}^{(1)}(1 - P_e)$$



$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$	\mathcal{O}_{lu}	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^I l)(\bar{q}\gamma_\mu \tau^I q)$	\mathcal{O}_{ld}	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d)$
\mathcal{O}_{eu}	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$	\mathcal{O}_{qe}	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$
\mathcal{O}_{ed}	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$		

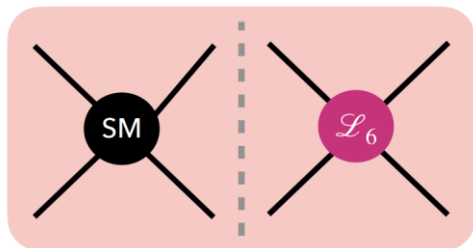
Polarization of the electron plays the key role to resolve the degeneracies from LHC data

Transverse polarization of electron and proton

New Physics and SMEFT

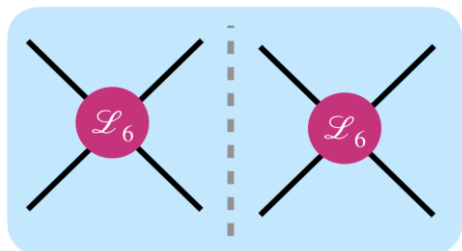
B. Grzadkowski et al, 2010

Interference effects



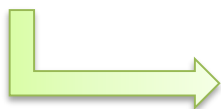
$$\sim \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

Chirality-flipped operators



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

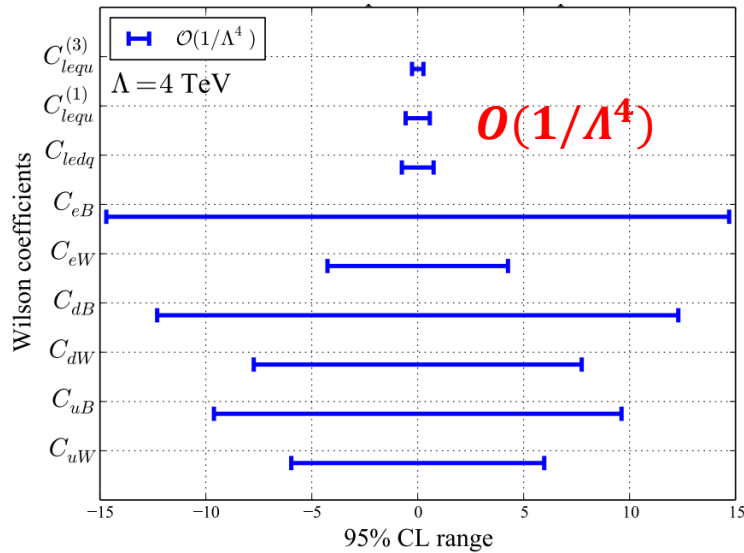
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
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}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



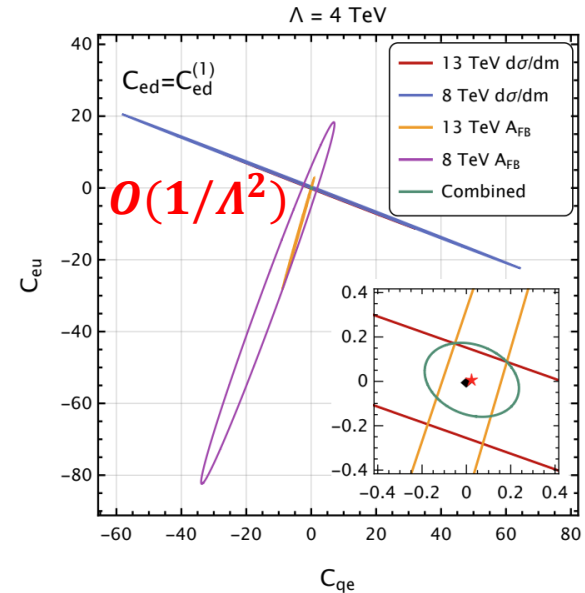
The constraints will be very weak

Example: Dipole Operator

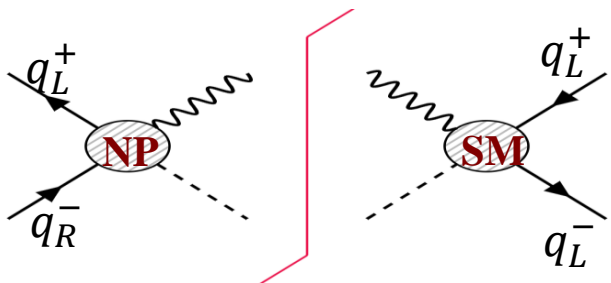
Single-Parameter-Analysis: EW dipole couplings are poorly constrained



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



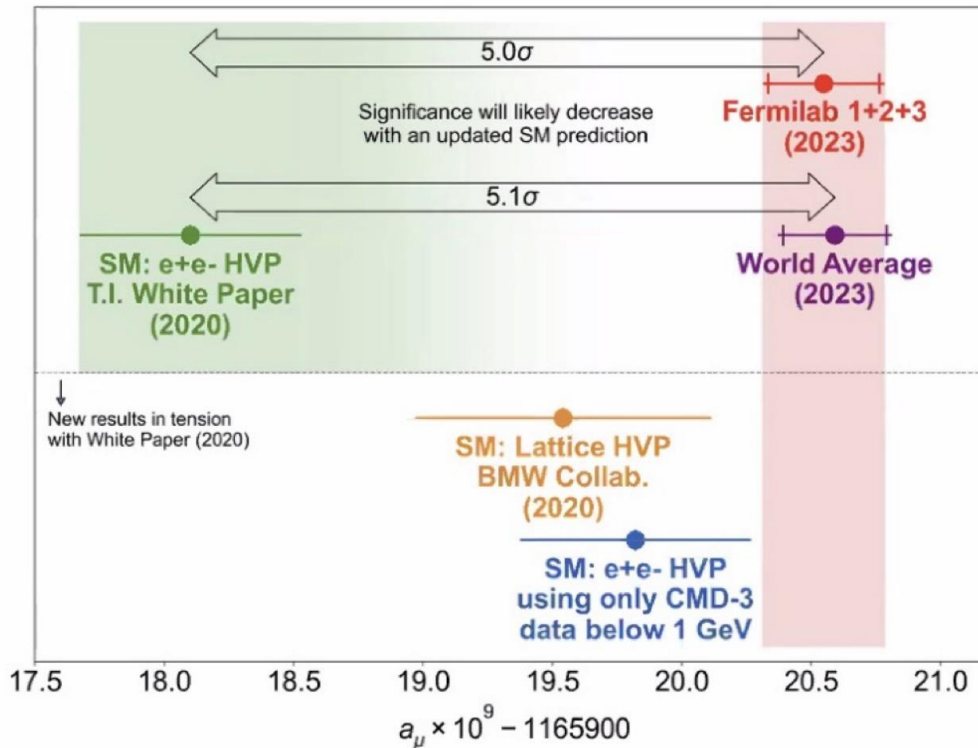
R. Boughezal et al, 2303.08257



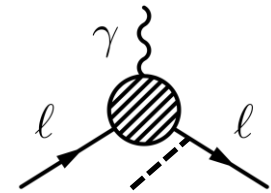
=0 for the cross section

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

New Physics and Dipole Operator

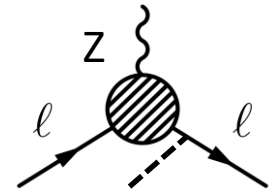


Loop-induced by the BSM

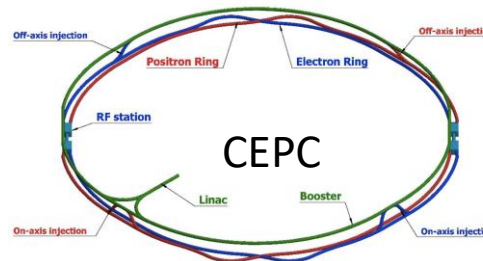
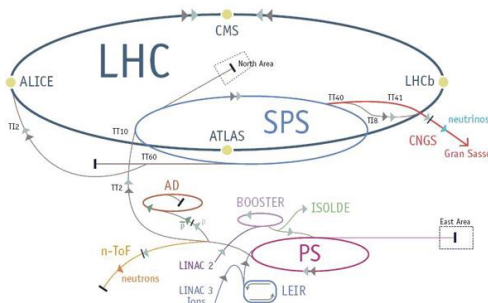


May have same physics source

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



How to probe the electroweak dipole operators?



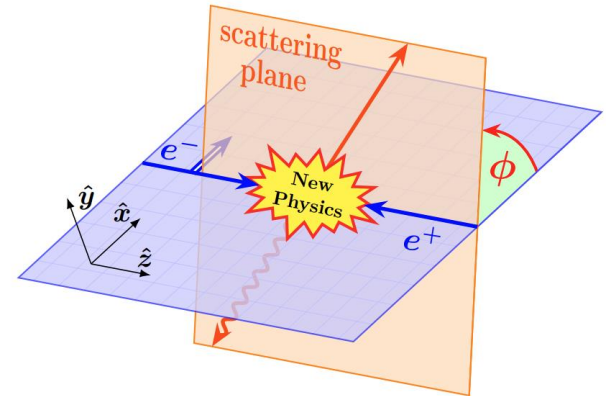
How to Probe Dipole Operator

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



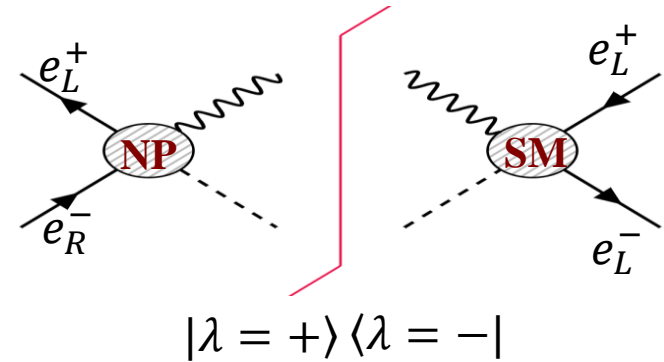
Transversely polarized effect of beams:

The interference between the different helicity states

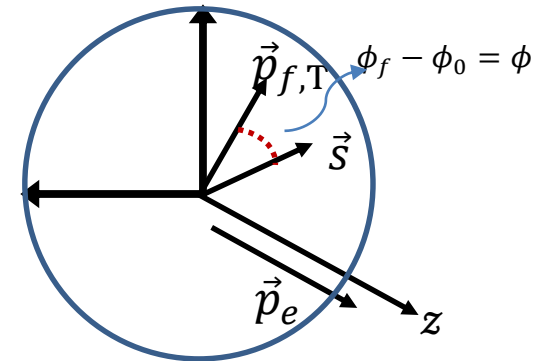


$$\mathbf{s} = (b_1, b_2, \lambda) = \underline{(b_T \cos \phi_0, b_T \sin \phi_0, \lambda)}$$

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



Breaking the rotational invariance & A nontrivial azimuthal behavior

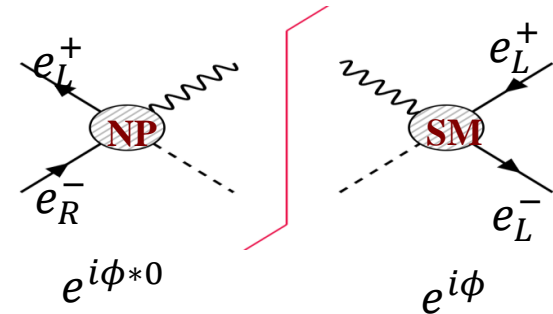


Transverse Spin Polarization

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)



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

	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

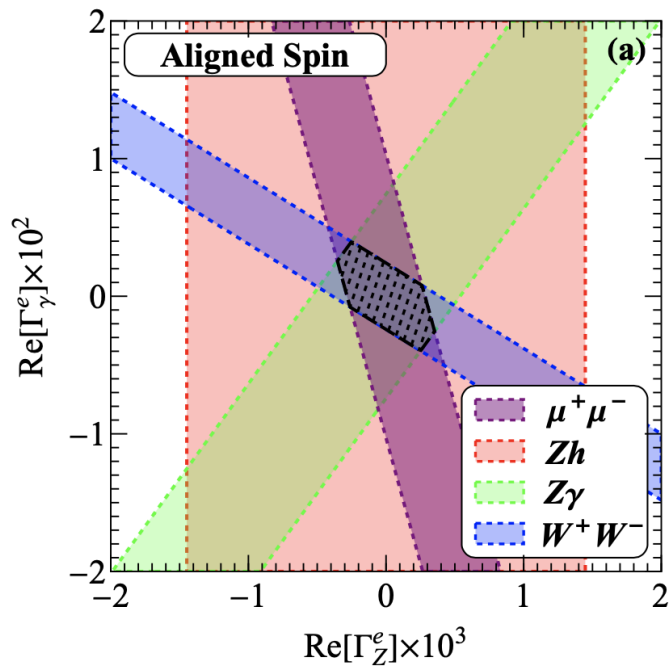
$$A_{LR}^i = \frac{\sigma^i(\cos \phi > 0) - \sigma^i(\cos \phi < 0)}{\sigma^i(\cos \phi > 0) + \sigma^i(\cos \phi < 0)} = \frac{2}{\pi} A_R^i$$

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

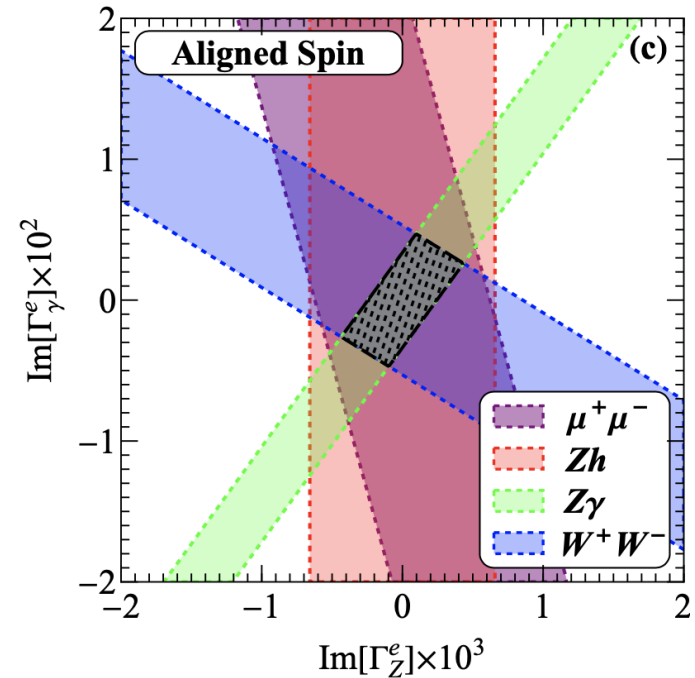
$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1} \quad (b_T, \bar{b}_T) = (0.8, 0.3)$$

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

Transverse spin effects@ EIC

➤ Dipole operators

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

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

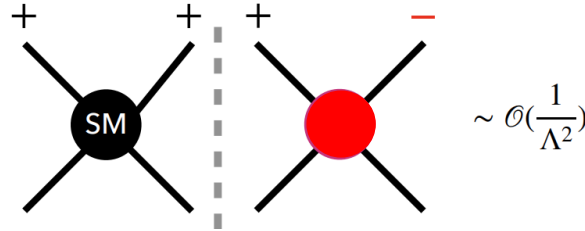
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu}e)\varphi B_{\mu\nu},$$

$$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu}u)\tau^I\varphi W_{\mu\nu}^I,$$

$$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu}u)\varphi B_{\mu\nu},$$

$$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu}d)\tau^I\varphi W_{\mu\nu}^I,$$

$$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu}d)\varphi B_{\mu\nu}.$$



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

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

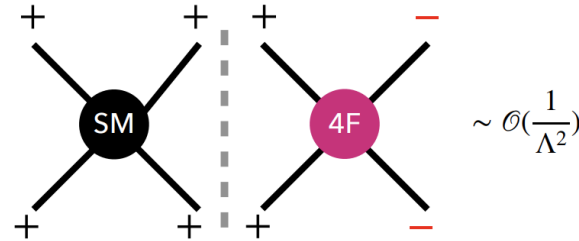
$$A_{UT} = \frac{\sigma(e^U p^\uparrow) - \sigma(e^U p^\downarrow)}{\sigma(e^U p^\uparrow) + \sigma(e^U p^\downarrow)}$$

➤ Scalar and tensor four fermion operators

$$\mathcal{O}_{ledq} = (\bar{L}^j e) (\bar{d} Q^j),$$

$$\mathcal{O}_{lequ}^{(1)} = (\bar{L}^j e) \epsilon_{jk} (\bar{Q}^k u),$$

$$\mathcal{O}_{lequ}^{(3)} = (\bar{L}^j \sigma^{\mu\nu} e) \epsilon_{jk} (\bar{Q}^k \sigma_{\mu\nu} u),$$



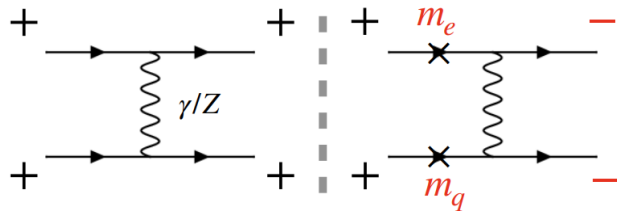
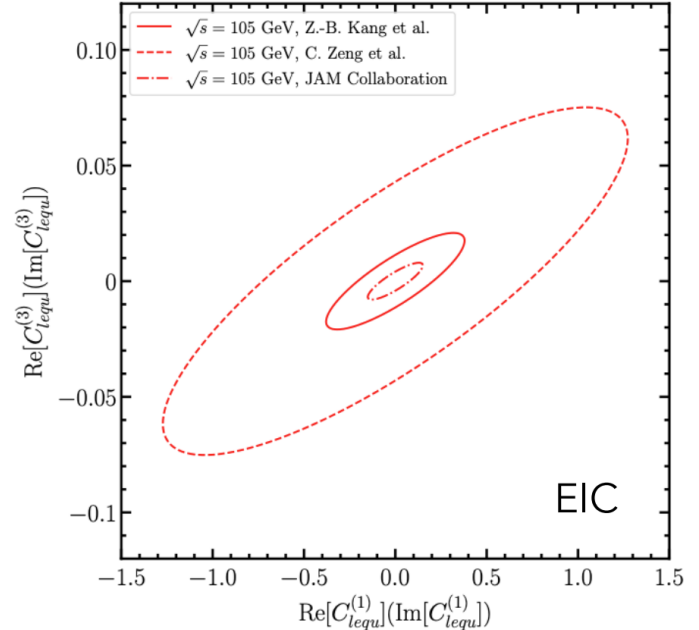
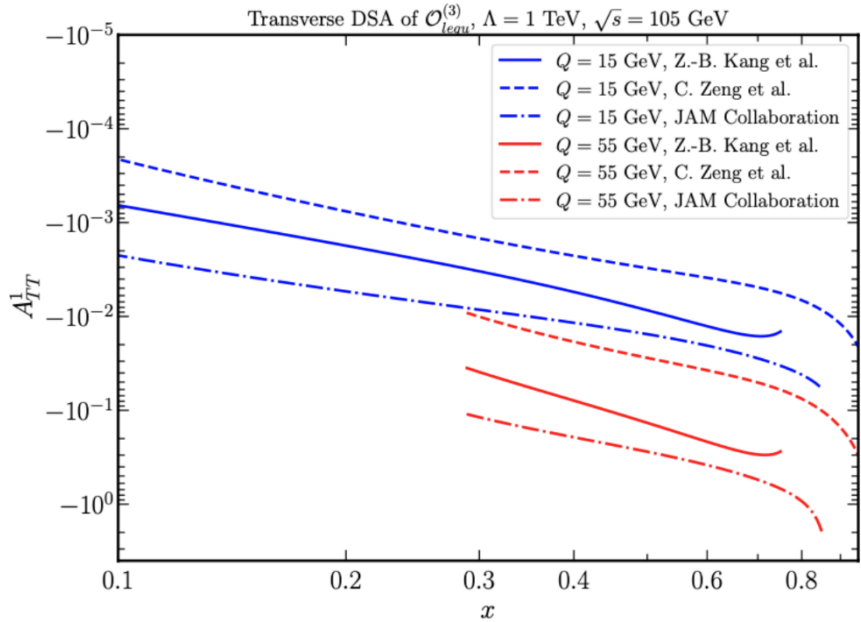
$$\sim \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

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

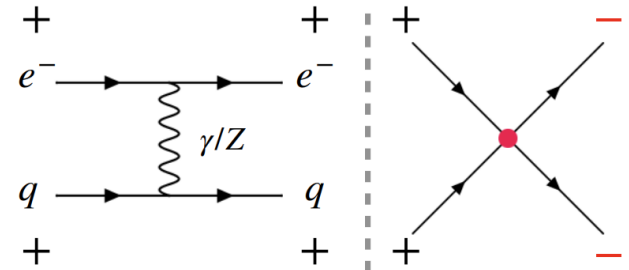
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan,
2401.08419 (PRD)

Transverse spin effects@ EIC

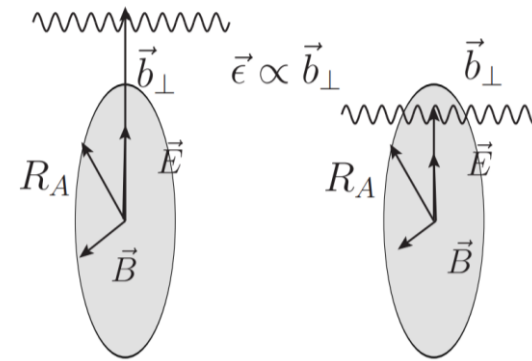
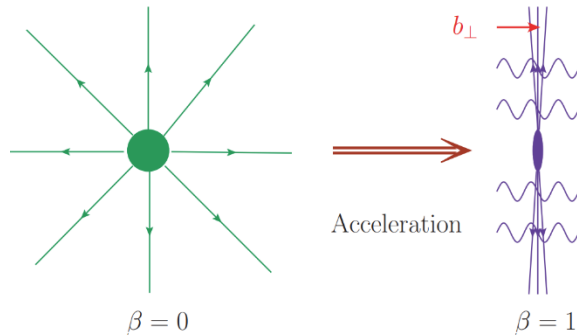
Hao-Lin Wang, Xin-Kai Wen, Hongxi Xing, Bin Yan, PRD 109 (2024) 095025 $P_{T,e} = P_{T,p} = 0.7, \mathcal{L} = 100 \text{ fb}^{-1}$



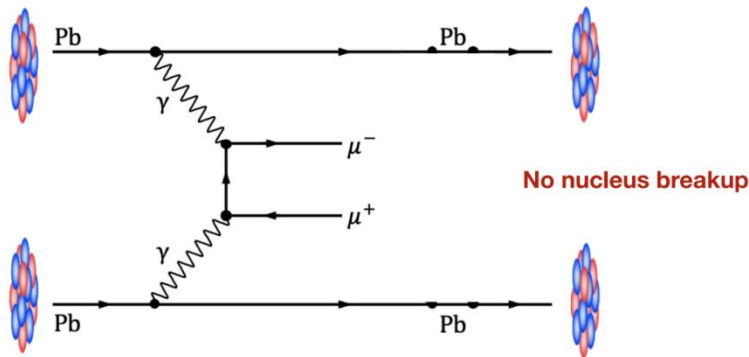
DSA in SM will be suppressed by electron and quark masses $O(10^{-7} \sim 10^{-9})$



Linear polarization @ UPCs



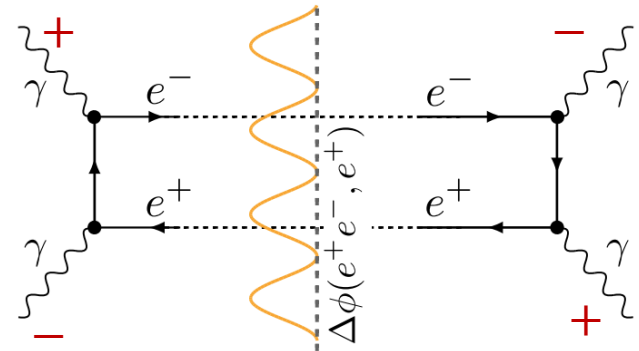
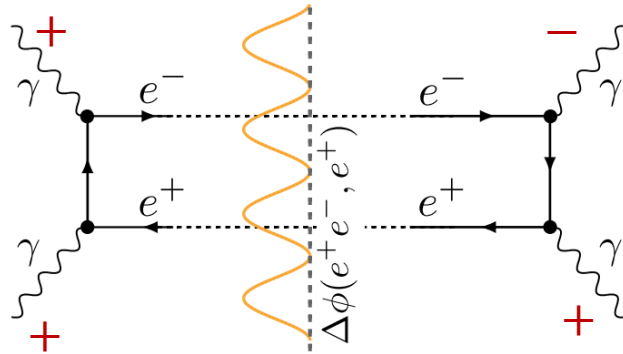
C.Li, J.Zhou, Y.J.Zhou, Phys. Lett. B. 795, 576 (2019)



- 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 $b_{\perp} > 2R_A$

Linear polarization @ UPCs

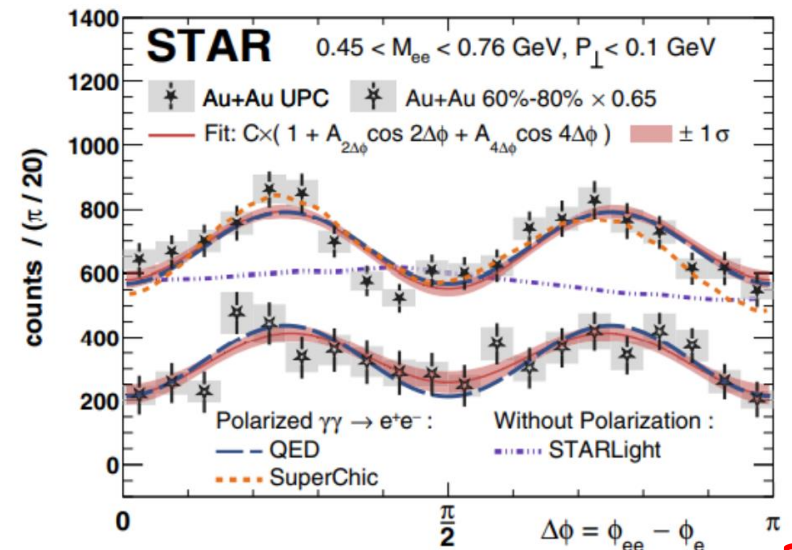
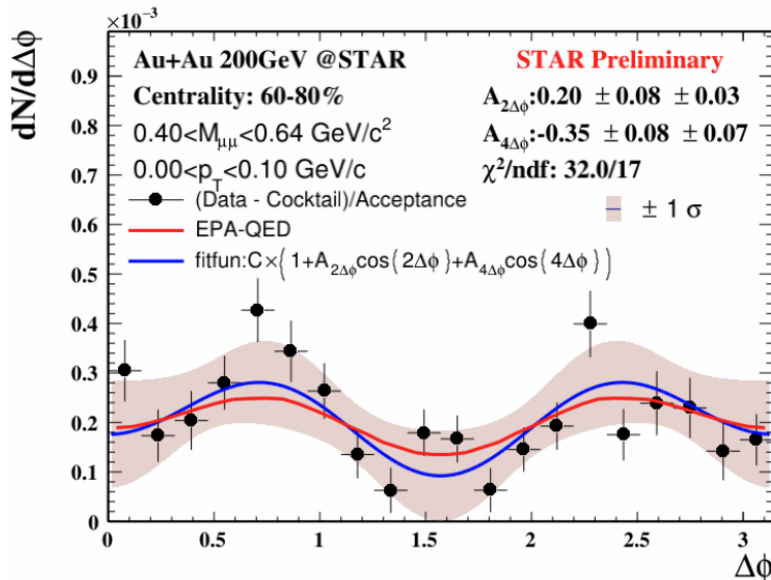
D. Y. Shao, C. Zhang, J. Zhou, Y. Zhou, PRD107 (2023) 3, 036020



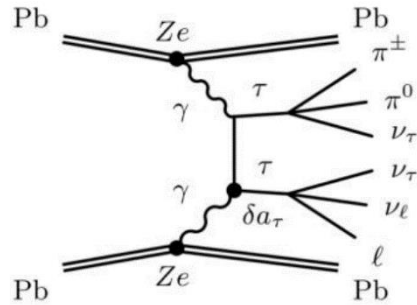
$$\frac{m_e^2}{p_T^2} \cos 2\Delta\phi$$



$$\cos 4\Delta\phi$$

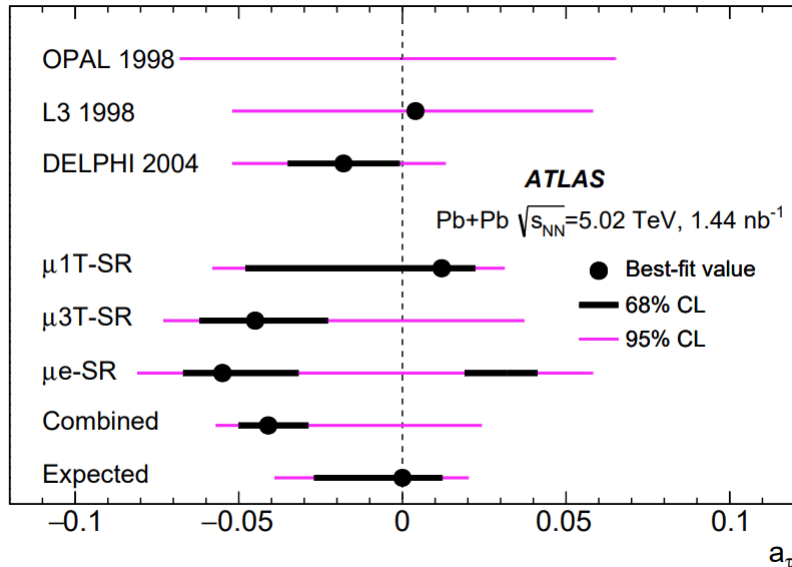


Tau pair production @ UPCs



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

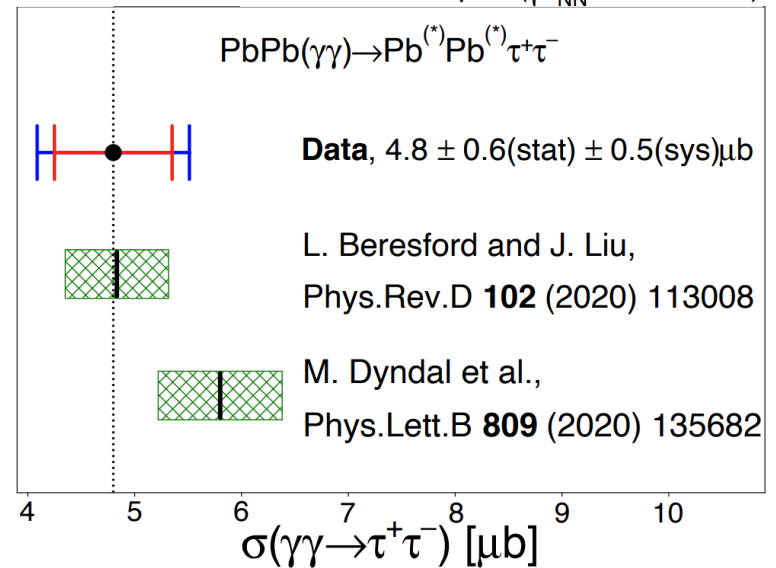
$$F_2(0) = a_{\tau}, \quad F_3(0) = 2 \frac{m_{\tau} d_{\tau}}{e}$$



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

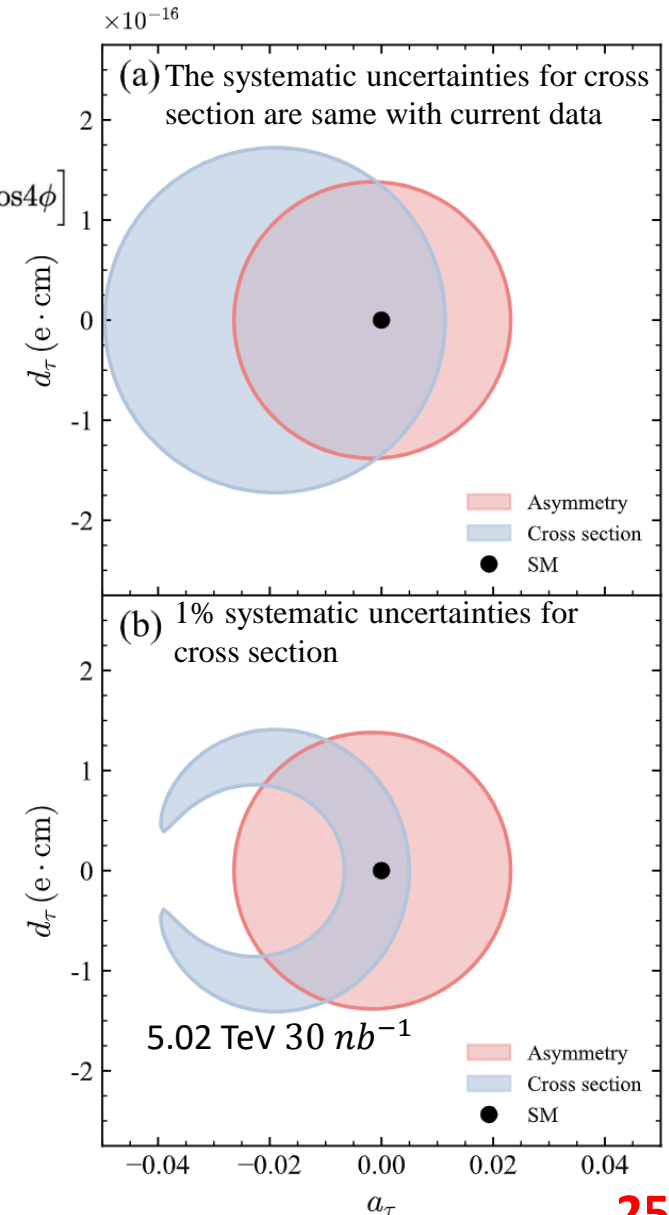
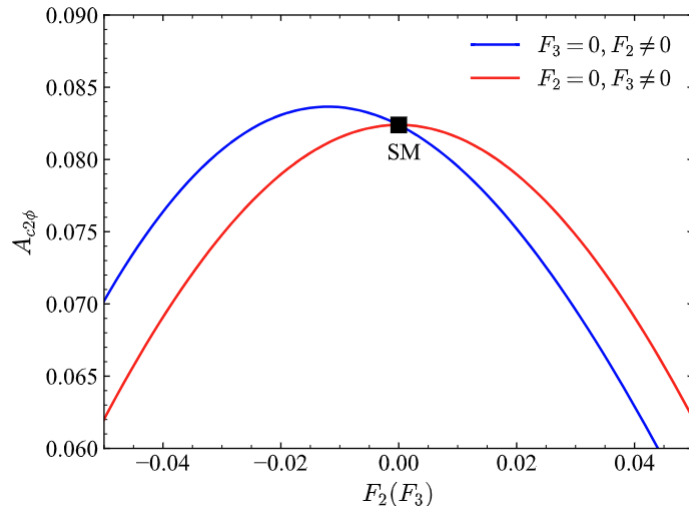
Linear polarization @ UPCs

Dingyu Shao, Bin Yan, Shu-Ruan Yuan, Cheng Zhang, 2310.14153

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

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

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



Summary

- EIC is an important machine for probing the new physics;
- The longitudinal polarized beams: Z_{bb} couplings;
- The transversely polarized beams : Chirality-flipped interactions
- The photons from UPCs are **linearly polarized** and can be used to probe the NP

The search for new physics at the EIC is just beginning

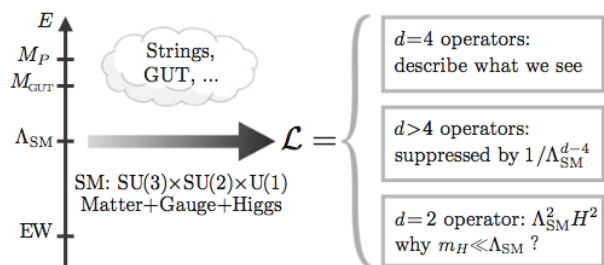
Thank you!

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

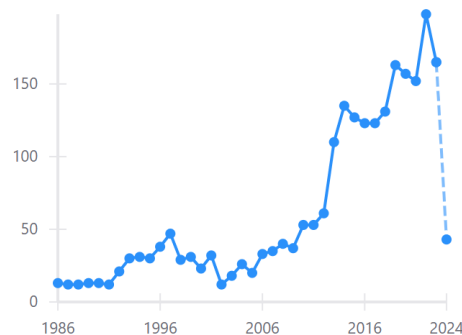
B. Henning et al, 2015

H-L. Li et al, 2020

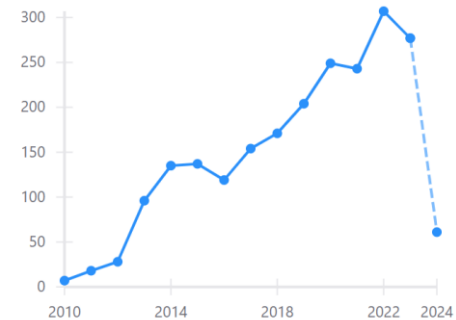
Murphy, 2020

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

Citations per year



Citations per year



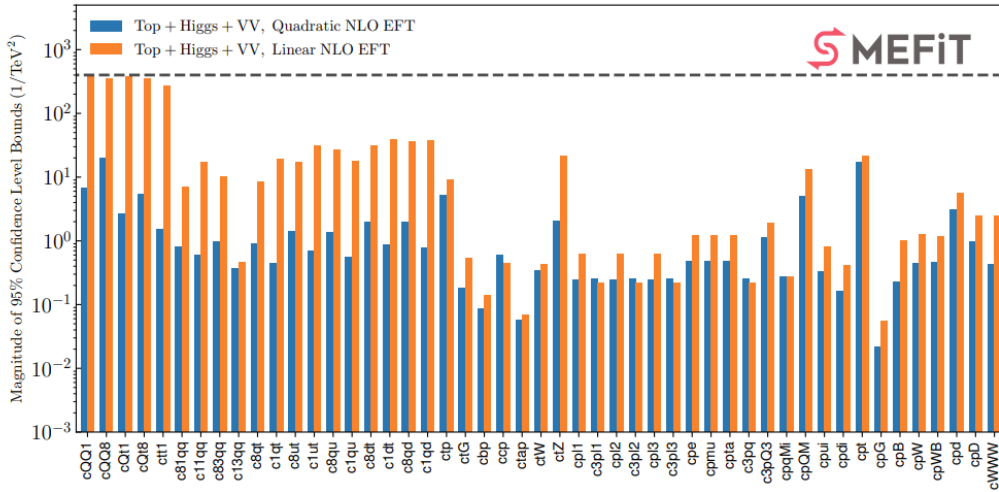
3. Higgs Effective Field Theory

Callan, Coleman, Wess, Zumino, 1969

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

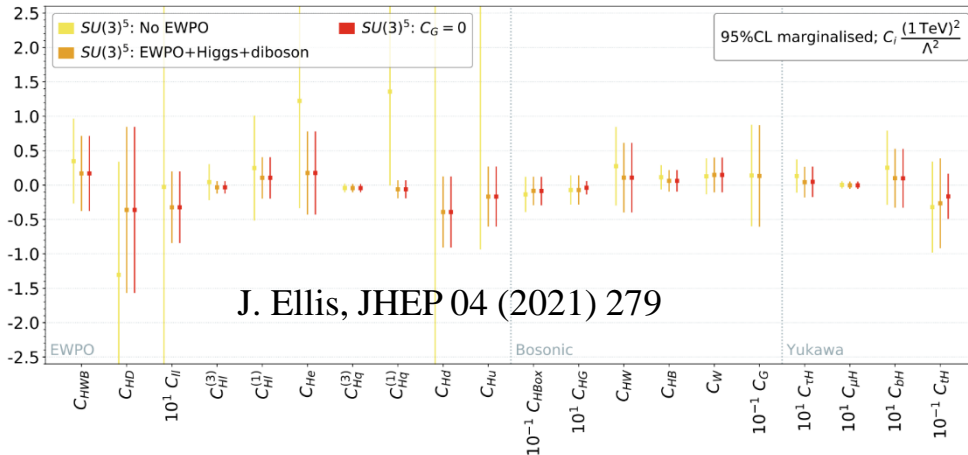
Global analysis @ SMEFT

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