



Transverse Spin Asymmetry as a New Probe of SMEFT Chirality-Flip Operators

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arXiv: 2401.08419

2024/01/23, HKUST-IAS, Hong Kong

New Physics and SMEFT

None new fundamental resonance has been discovered.

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

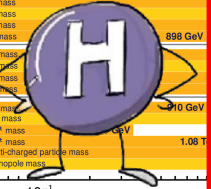
Status: March 2023

ATLAS Preliminary

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

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

Model	ℓ, γ	Jets [†]	E^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimen.	ADD $G_{KK} + g/q$	$0 \ e, \mu, \tau, \gamma$	$1-4 \ j$	Yes	139	$M_{KK} \geq 11.2 \text{ TeV}$
	ADD non-resonant $\gamma\gamma$	$2 \ \gamma$	-	-	36.7	$M_{KK} \geq 8.6 \text{ TeV}$
	ADD BH	$2 \ j$	-	-	3.6	$M_{KK} \geq 9.4 \text{ TeV}$
	ADD BH multijet	$\geq 3 \ j$	-	-	3.6	$M_{KK} \geq 9.55 \text{ TeV}$
	RS1 $G_{KK} \rightarrow \gamma\gamma$	$2 \ \gamma$	-	-	139	$G_{KK} \text{ mass} \geq 2.3 \text{ TeV}$
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass} \geq 4.5 \text{ TeV}$
	Bulk RS $G_{KK} \rightarrow tt$	$1 \ e, \mu \geq 1 \ b, \geq 1 \ 2 \ j$	Yes	36.1	36.1	$G_{KK} \text{ mass} \geq 3.8 \text{ TeV}$
	2UED / RPP	$1 \ e, \mu \geq 2 \ b, \geq 3 \ j$	Yes	36.1	36.1	$KK \text{ mass} \geq 1.8 \text{ TeV}$
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 \ e, \mu$	-	-	139	$Z' \text{ mass} \geq 2.42 \text{ TeV}$
	SSM $Z' \rightarrow \tau\tau$	$2 \ \tau$	-	-	36.1	$Z' \text{ mass} \geq 2.1 \text{ TeV}$
	Leptophobic $Z' \rightarrow bb$	$2 \ b$	-	-	36.1	$Z' \text{ mass} \geq 2.1 \text{ TeV}$
	Leptophobic $Z' \rightarrow tt$	$0 \ e, \mu \geq 1 \ b, \geq 2 \ j$	Yes	139	139	$Z' \text{ mass} \geq 4.1 \text{ TeV}$
	SSM $W' \rightarrow \ell\nu$	$1 \ e, \mu$	-	-	139	$W' \text{ mass} \geq 5.0 \text{ TeV}$
	SSM $W' \rightarrow \tau\nu$	$1 \ \tau$	-	-	139	$W' \text{ mass} \geq 5.0 \text{ TeV}$
	SSM $W' \rightarrow tb$	$\geq 1 \ b, \geq 1 \ j$	Yes	139	139	$W' \text{ mass} \geq 4.4 \text{ TeV}$
	HVT $W' \rightarrow WZ \text{ model B}$	$0-2 \ e, \mu \ 2 \ j \ 1 \ j$	Yes	139	139	$W' \text{ mass} \geq 4.3 \text{ TeV}$
	HVT $W' \rightarrow WZ \rightarrow \ell\nu \ell' \text{ model C}$	$3 \ e, \mu \ 2 \ j \ 1 \ j$	Yes	139	139	$W' \text{ mass} \geq 3.9 \text{ TeV}$
	HVT $Z' \rightarrow WW \text{ model B}$	$1 \ e, \mu \ 2 \ j \ 1 \ j$	Yes	139	139	$Z' \text{ mass} \geq 3.9 \text{ TeV}$
	LRSM $W'_K \rightarrow \mu N_K$	$2 \ \mu \ 1 \ j$	-	-	80	$W'_K \text{ mass} \geq 5.0 \text{ TeV}$
CI	CI $qqqq$	$2 \ j$	-	-	37.0	$A \geq 21.8 \text{ TeV}$
	CI ℓqq	$2 \ e, \mu$	-	-	139	$A \geq 35.8 \text{ TeV}$
	CI $e\bar{e}e\bar{e}$	$2 \ e \ 1 \ b$	-	-	139	$A \geq 1.9 \text{ TeV}$
	CI $qq\bar{q}\bar{q}$	$2 \ \mu \ 1 \ b$	-	-	139	$A \geq 2.0 \text{ TeV}$
	CI $t\bar{t}t\bar{t}$	$\geq 1 \ e, \mu \ \geq 1 \ b, \geq 1 \ j$	Yes	36.1	36.1	$A \geq 2.57 \text{ TeV}$
DM	Axial-vector med. (Dirac DM)	$2 \ j$	-	-	139	$m_{\text{DM}} \geq 376 \text{ GeV}$
	Pseudo-scalar med. (Dirac DM)	$0 \ e, \mu, \tau, \gamma \ 1-4 \ j$	Yes	139	139	$m_{\text{DM}} \geq 376 \text{ GeV}$
	Vector med. Z' -2HDM (Dirac DM)	$0 \ e, \mu, \tau, \gamma \ 2 \ b$	Yes	139	139	$m_{\text{DM}} \geq 376 \text{ GeV}$
	Pseudo-scalar med. 2HDM+A	multi-channel	-	-	139	$m_{\text{DM}} \geq 800 \text{ GeV}$
LO	Scalar LO 1 st gen	$2 \ e \ \geq 2 \ j$	Yes	139	139	$LQ \text{ mass} \geq 1.8 \text{ TeV}$
	Scalar LO 2 nd gen	$2 \ \mu \ \geq 2 \ j$	Yes	139	139	$LQ \text{ mass} \geq 1.7 \text{ TeV}$
	Scalar LO 3 rd gen	$1 \ \tau \ 2 \ b$	Yes	139	139	$LQ \text{ mass} \geq 4.9 \text{ TeV}$
	Scalar LO 3 rd gen	$0 \ e, \mu \ \geq 1 \ b, \geq 2 \ j$	Yes	139	139	$LQ \text{ mass} \geq 1.2 \text{ TeV}$
	Scalar LO 3 rd gen	$\geq 2 \ e, \mu, \geq 1 \ \tau \ \geq 1 \ b, \geq 1 \ j$	Yes	139	139	$LQ \text{ mass} \geq 1.9 \text{ TeV}$
	Scalar LO 3 rd gen	$0 \ e, \mu, \geq 1 \ \tau \ 0-2 \ j, \geq 2 \ b$	Yes	139	139	$LQ \text{ mass} \geq 1.2 \text{ TeV}$
	Vector LO mix gen	multi-channel $\geq 1 \ j, \geq 1 \ b$	Yes	139	139	$LQ \text{ mass} \geq 2.0 \text{ TeV}$
	Vector LO 3 rd gen	$2 \ e, \mu, \tau \ \geq 1 \ b$	Yes	139	139	$LQ \text{ mass} \geq 1.96 \text{ TeV}$
Vector-like fermions	VLO $TZ \rightarrow Z + X$	$2e2\mu \geq 3e\mu \geq 1 \ b, \geq 1 \ j$	-	-	139	$T \text{ mass} \geq 4.6 \text{ TeV}$
	VLO $BB \rightarrow W/Z + X$	multi-channel	-	-	36.1	$B \text{ mass} \geq 1.5 \text{ TeV}$
	VLO $T_{3/3} T_{3/3} \rightarrow Wt + X$	$2(SIS) \geq 3 \ e, \mu \ \geq 1 \ b, \geq 1 \ j$	Yes	36.1	36.1	$T_{3/3} \text{ mass} \geq 1.64 \text{ TeV}$
	VLO $T \rightarrow Ht/Zt$	$1 \ e, \mu \ \geq 1 \ b, \geq 3 \ j$	Yes	139	139	$T \text{ mass} \geq 1.8 \text{ TeV}$
	VLO $Y \rightarrow Wb$	$1 \ e, \mu \ \geq 1 \ b, \geq 1 \ j$	Yes	36.1	36.1	$Y \text{ mass} \geq 1.65 \text{ TeV}$
	VLO $B \rightarrow Hb$	$0 \ e, \mu \ \geq 2 \ b, \geq 1 \ j, \geq 1 \ j$	Yes	139	139	$B \text{ mass} \geq 2.0 \text{ TeV}$
	VLL $\tau \rightarrow Z\tau/H\tau$	multi-channel $\geq 1 \ j$	Yes	139	139	$\tau' \text{ mass} \geq 898 \text{ GeV}$
Exotic ferm.	Excited quark $q^* \rightarrow qg$	$2 \ j$	-	-	139	$q^* \text{ mass} \geq 6.7 \text{ TeV}$
	Excited quark $q^* \rightarrow q\gamma$	$1 \ \gamma \ 1 \ j$	-	-	139	$q^* \text{ mass} \geq 5.3 \text{ TeV}$
	Excited quark $q^* \rightarrow qg$	$2 \ j$	-	-	139	$q^* \text{ mass} \geq 3.2 \text{ TeV}$
	Excited lepton $\tau^* \rightarrow \tau g$	$2 \ \tau \ \geq 2 \ j$	-	-	139	$\tau^* \text{ mass} \geq 4.6 \text{ TeV}$
Other	Type II Seesaw	$2,3,4 \ e, \mu \ \geq 2 \ j$	Yes	139	139	$N \text{ mass} \geq 10 \text{ GeV}$
	LRSM Majorana ν	$2 \ \mu \ 2 \ j$	-	-	36.1	$N \text{ mass} \geq 3.2 \text{ TeV}$
	Higgs triplet $H^{\pm\pm} \rightarrow W^+ W^+$	$2,3,4 \ e, \mu \ (SS)$	various	Yes	139	$H^{\pm\pm} \text{ mass} \geq 1.08 \text{ TeV}$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2,3,4 \ e, \mu \ (SS)$	various	Yes	139	$H^{\pm\pm} \text{ mass} \geq 1.08 \text{ TeV}$
	Multi-charged particles	-	-	-	139	multi-charged particles mass $\geq 1.59 \text{ TeV}$
	Magnetic monopoles	-	-	-	34.4	monopole mass $\geq 2.37 \text{ TeV}$



⁺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).

	X^3	φ^6 and $\varphi^4 D^2$	$\varphi^2 \varphi^4$
Q_6	$f^{ABCD} G_{AB}^a G_{CD}^a$	Q_6	$(\varphi^a \varphi^a)^2$
Q_7	$f^{ABCD} G_{AB}^a G_{CD}^b$	Q_7	$(\varphi^a \varphi^a)(\varphi^b \varphi^b)$
Q_8	$f^{ABCD} G_{AB}^a G_{CD}^c$	Q_8	$(\varphi^a \varphi^a)(\varphi^b \varphi^c)$
Q_9	$f^{ABCD} G_{AB}^a G_{CD}^d$	Q_9	$(\varphi^a \varphi^a)(\varphi^b \varphi^d)$
Q_{10}	$f^{ABCD} G_{AB}^a G_{CD}^e$	Q_{10}	$(\varphi^a \varphi^a)(\varphi^b \varphi^e)$
Q_{11}	$f^{ABCD} G_{AB}^a G_{CD}^f$	Q_{11}	$(\varphi^a \varphi^a)(\varphi^b \varphi^f)$
Q_{12}	$f^{ABCD} G_{AB}^a G_{CD}^g$	Q_{12}	$(\varphi^a \varphi^a)(\varphi^b \varphi^g)$
Q_{13}	$f^{ABCD} G_{AB}^a G_{CD}^h$	Q_{13}	$(\varphi^a \varphi^a)(\varphi^b \varphi^h)$
Q_{14}	$f^{ABCD} G_{AB}^a G_{CD}^i$	Q_{14}	$(\varphi^a \varphi^a)(\varphi^b \varphi^i)$
Q_{15}	$f^{ABCD} G_{AB}^a G_{CD}^j$	Q_{15}	$(\varphi^a \varphi^a)(\varphi^b \varphi^j)$
Q_{16}	$f^{ABCD} G_{AB}^a G_{CD}^k$	Q_{16}	$(\varphi^a \varphi^a)(\varphi^b \varphi^k)$
Q_{17}	$f^{ABCD} G_{AB}^a G_{CD}^l$	Q_{17}	$(\varphi^a \varphi^a)(\varphi^b \varphi^l)$
Q_{18}	$f^{ABCD} G_{AB}^a G_{CD}^m$	Q_{18}	$(\varphi^a \varphi^a)(\varphi^b \varphi^m)$
Q_{19}	$f^{ABCD} G_{AB}^a G_{CD}^n$	Q_{19}	$(\varphi^a \varphi^a)(\varphi^b \varphi^n)$
Q_{20}	$f^{ABCD} G_{AB}^a G_{CD}^o$	Q_{20}	$(\varphi^a \varphi^a)(\varphi^b \varphi^o)$
Q_{21}	$f^{ABCD} G_{AB}^a G_{CD}^p$	Q_{21}	$(\varphi^a \varphi^a)(\varphi^b \varphi^p)$
Q_{22}	$f^{ABCD} G_{AB}^a G_{CD}^q$	Q_{22}	$(\varphi^a \varphi^a)(\varphi^b \varphi^q)$
Q_{23}	$f^{ABCD} G_{AB}^a G_{CD}^r$	Q_{23}	$(\varphi^a \varphi^a)(\varphi^b \varphi^r)$
Q_{24}	$f^{ABCD} G_{AB}^a G_{CD}^s$	Q_{24}	$(\varphi^a \varphi^a)(\varphi^b \varphi^s)$
Q_{25}	$f^{ABCD} G_{AB}^a G_{CD}^t$	Q_{25}	$(\varphi^a \varphi^a)(\varphi^b \varphi^t)$
Q_{26}	$f^{ABCD} G_{AB}^a G_{CD}^u$	Q_{26}	$(\varphi^a \varphi^a)(\varphi^b \varphi^u)$
Q_{27}	$f^{ABCD} G_{AB}^a G_{CD}^v$	Q_{27}	$(\varphi^a \varphi^a)(\varphi^b \varphi^v)$
Q_{28}	$f^{ABCD} G_{AB}^a G_{CD}^w$	Q_{28}	$(\varphi^a \varphi^a)(\varphi^b \varphi^w)$
Q_{29}	$f^{ABCD} G_{AB}^a G_{CD}^x$	Q_{29}	$(\varphi^a \varphi^a)(\varphi^b \varphi^x)$
Q_{30}	$f^{ABCD} G_{AB}^a G_{CD}^y$	Q_{30}	$(\varphi^a \varphi^a)(\varphi^b \varphi^y)$
Q_{31}	$f^{ABCD} G_{AB}^a G_{CD}^z$	Q_{31}	$(\varphi^a \varphi^a)(\varphi^b \varphi^z)$



SMEFT

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

B. Grzadkowski, et al. *JHEP* 10 (2010)
W. Buchmuller, D. Wyler, 1986

Powerful Tool @ EW

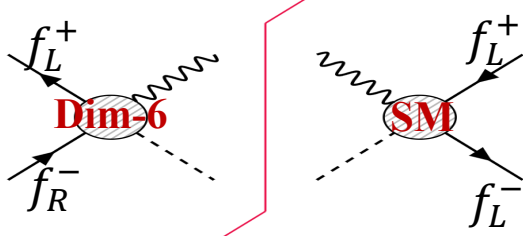
New Physics models excluded to **Multi-TeV @ LHC.**

$\rightarrow \Lambda \sim \mathcal{O}(\text{TeV})$

SMEFT Chirality-Flip Operator

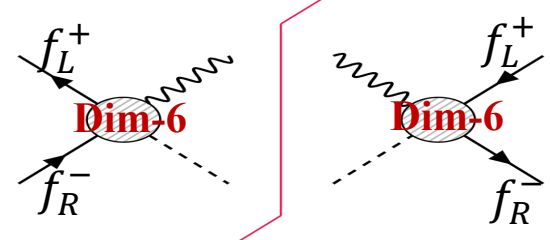
$$d\sigma = d\sigma_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} a_i^{(6)} + \sum_{ij} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} b_{ij}^{(6)}$$

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



interference ~ 0 for tiny mass

$\mathcal{O}(1/\Lambda^4)$



Non-interfering Leading effect

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

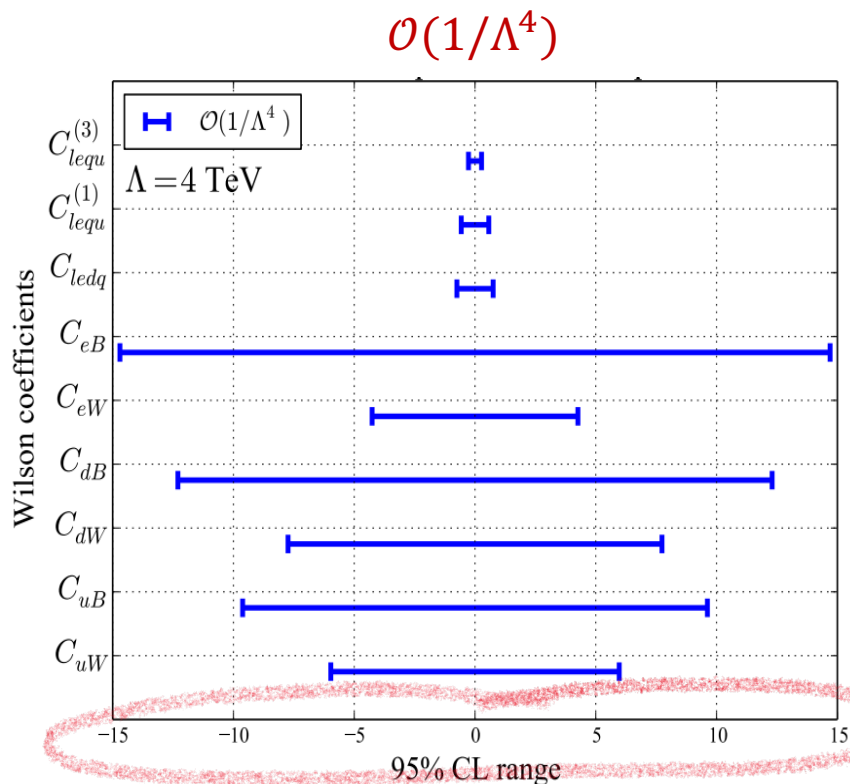
Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
Q_{ledq}	$(\bar{l}_p e_r)(\bar{d}_s q_t^k)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} [(d_p^\alpha)^T C u_r^\beta] [(q_s^\gamma)^T C l_t^k]$		
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jkl} (\bar{q}_s^k d_t)$	Q_{quq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C e_l]$		
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jkl} (\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jkl} [(q_p^{\alpha j})^T C q_r^{\beta k}] [(u_s^\gamma)^T C l_t^l]$		
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jkl} (\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_l]$		
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jkl} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$				

Table 3: Four-fermion operators.

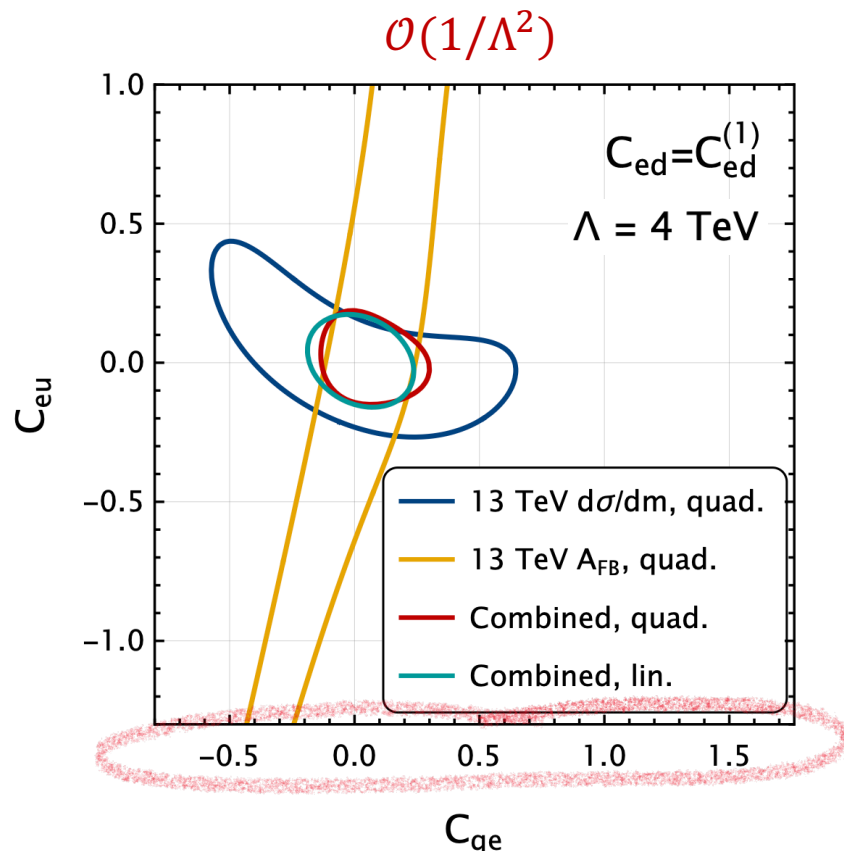
Data for Chirality-Flip Operator

Constrained poorly in traditional methods via cross-section and width



Single-Parameter-Analysis DY@LHC

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

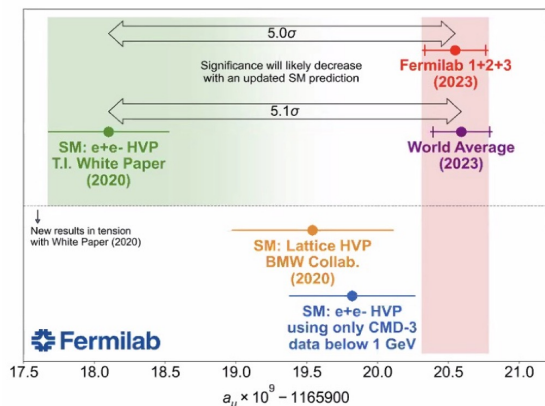


(R. Boughezal et al. *arXiv*: 2303.08257)

New Physics with Chirality-Flip Operator

Direct & Dominant Effect

Dipole Operator: $(g - 2) ?$ EDM ?



D.P. Aguillard et al., (Muon $g-2$), *Phys.Rev.Lett.* 131 (2023) 16

Indirect probes of NP quantum effects

Scalar/Tensor Four-Fermion operator:

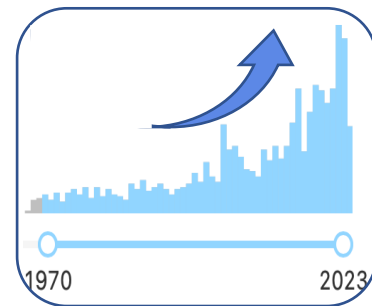
Leptoquark ?

New scalar or gauge boson ?

$$R_\pi = \frac{\Gamma(\pi^+ \rightarrow e^+\nu)}{\Gamma(\pi^+ \rightarrow \mu^+\nu)}$$

$$R_K, R_{D^{(*)}}$$

Low-energy data ?



same NP source ?

Z only detected by colliders

How to probe Chirality-Flip operators at $\mathcal{O}(1/\Lambda^2)$?

How to Probe Chirality-Flip Operator at $1/\Lambda^2$

Traditional method: @ $|C_{CF}|^2/\Lambda^4$, suffer from contaminations

Our proposal:

- Transverse polarization effect of beams

Interference of the different helicity amplitudes

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

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

- Breaking rotational invariance

Nontrivial azimuthal behavior

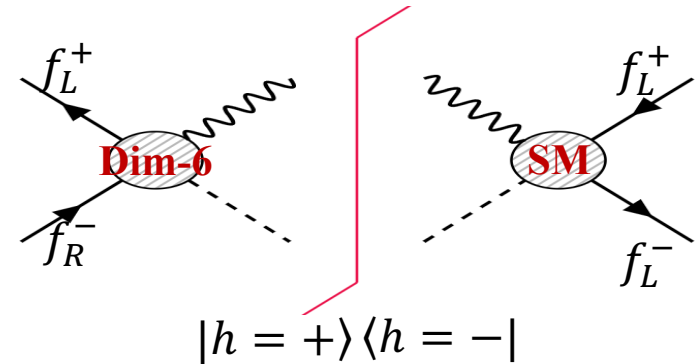
- **Transverse Spin Asymmetries**

X.-K.W, BY, ZY, C.-P.Y, *Phys.Rev.Lett.* 131 (2023) 24

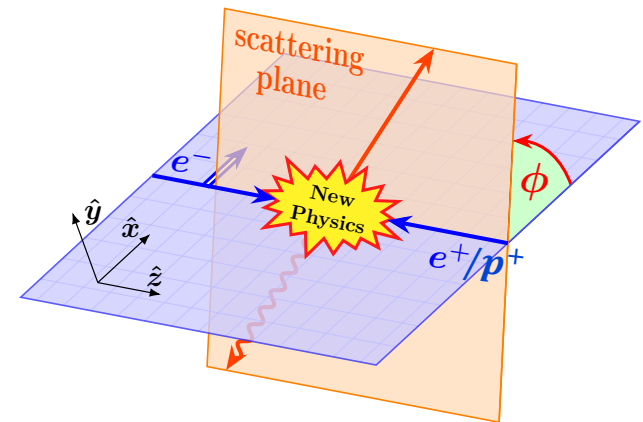
R. Boughezal et al., *Phys.Rev.D* 107 (2023) 07

H.-L. W, X.-K.W, HX, BY *arXiv:* 2401.08419

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



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

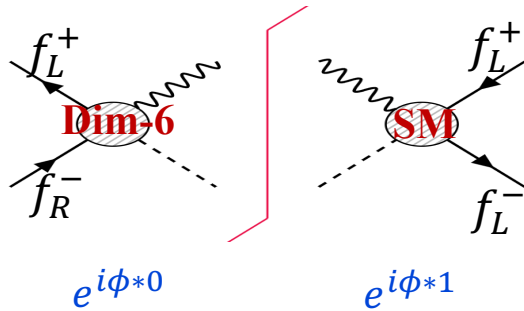
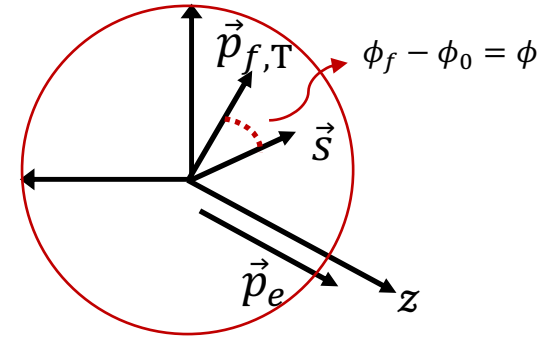


Transverse Spin Polarization

Spin dependent amplitude square:

$$|\mathcal{M}|^2 = \rho_{\alpha_1 \alpha'_1}(\mathbf{s}) \rho_{\alpha_2 \alpha'_2}(\bar{\mathbf{s}}) \mathcal{M}_{\alpha_1 \alpha_2}(\phi) \mathcal{M}_{\alpha'_1 \alpha'_2}^*(\phi)$$

$$\mathcal{M}_{\lambda_1, \lambda_2}(\theta, \phi) = e^{i(\lambda_1 - \lambda_2)\phi} \mathcal{T}_{\lambda_1, \lambda_2}(\theta)$$



STSAA@ee collider:

dipole operator $\rightarrow \mathcal{M}_{\pm\pm}$, massless SM $\rightarrow \mathcal{M}_{\pm\mp}$

DSA@eP collider:

Four-F operator $\rightarrow \mathcal{M}_{-i,-j}$, massless SM $\rightarrow \mathcal{M}_{ij}$

X.-K.W, BY, ZY, C.-P.Y, work in progress

	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$	\rightarrow STSAA
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$	\rightarrow DSA

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

A New Probe of Dipole Operators @ee collider

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

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

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

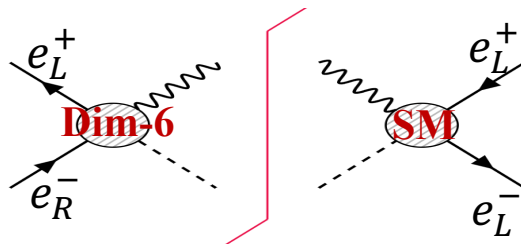
SM & other NP

$$\vec{s} \cdot \vec{p}_f \propto \cos \phi$$

$$\vec{s} \times \vec{p}_f \propto \sin \phi$$

CP-conserving

CP-violation



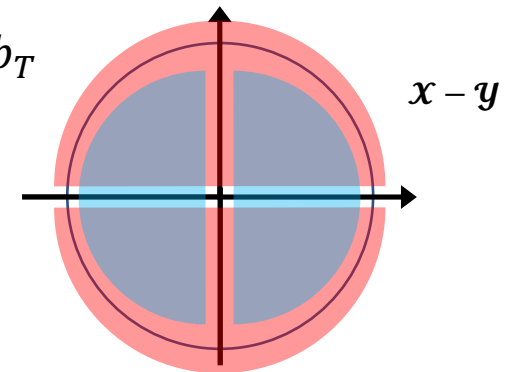
Single Transverse Spin Azimuthal Asymmetry (STSAA)

X.-K.W, BY, ZY, C.-P.Y, *Phys.Rev.Lett.* 131 (2023) 24

Linearly dependent on the dipole couplings C_{dipole} and spin b_T

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

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



Pinning down Dipole Operators @ee collider

$$\mathcal{L}_{\text{eff}} = -\frac{1}{\sqrt{2}} \bar{\ell}_L \sigma^{\mu\nu} (g_1 \Gamma_B^e B_{\mu\nu} + g_2 \Gamma_W^e \sigma^a W_{\mu\nu}^a) \frac{H}{v^2} e_R + \text{h.c.}$$

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

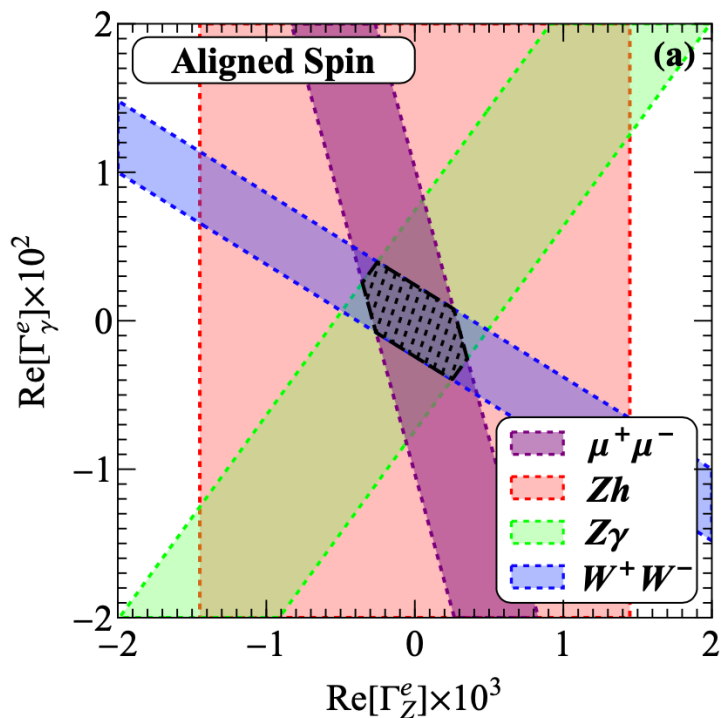
Aligned Spin

$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

$$(\phi_0, \bar{\phi}_0) = (0, \pi)$$

$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1}$$



$$\Gamma_\gamma^e = \Gamma_W^e - \Gamma_B^e$$

$$\Gamma_Z^e = c_W^2 \Gamma_W^e + s_W^2 \Gamma_B^e$$

Much stronger sensitivity than other approaches by 1~2 orders

The sensitivity to Γ_Z^e is much stronger than Γ_γ^e ➤ Parity property of helicity amplitude

Pinning down Dipole Operators @ee collider

For the imaginary parts of dipole couplings, things are similar

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

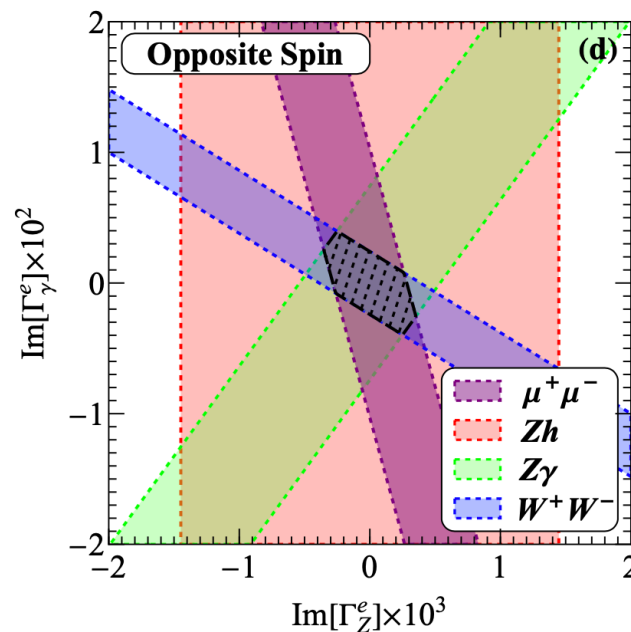
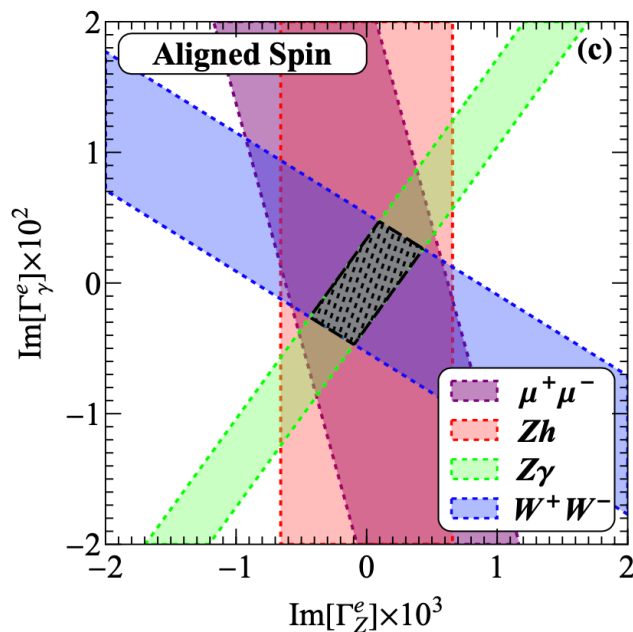
Aligned Spin

$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

$$(\phi_0, \bar{\phi}_0) = (0, \pi)$$

$$\sqrt{s} = 250 \text{ GeV}, \mathcal{L} = 5 \text{ ab}^{-1}$$



Why the limit difference between the Aligned Spin and the Opposite Spin? ➤ CP property

Offering a new opportunity for directly probing potential CP-violating effects.

From Lepton Collider to EICs

Upcoming Electron-Ion Collider in USA and planned EIC in China (EicC)

A. Accardi et al., *Eur.Phys.J.A* 52 (2016) 9, 268

R. A. Khalek et al., *Nucl.Phys.A* 1026 (2022) 122447

D. P. Anderle et al., *Front.Phys.(Beijing)* 16 (2021) 6, 64701

Electron Ion Collider:

The Next QCD Frontier : Understanding the glue that binds us all

- Explore and image the **spin and 3D structure** of the nucleon
- Discover the role of gluons in structure and dynamics
- Precisely determine the **spin-(in)dependent PDFs**
- Probe the electroweak properties of the SM
- Search for potential **NP effects**
-

B. Yan, *Phys.Lett.B* 833 (2022) 137384

H.-T. Li et al., *Phys.Lett.B* 833 (2022) 137300

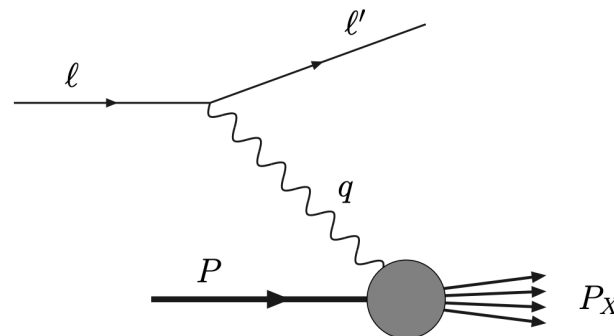
R. Boughezal, et al., *Phys.Rev.D* 107 (2023) 7

Y. Liu et al., *Chin.Phys.C* 47 (2023) 4, 043113

B. Yan et al., *Phys.Lett.B* 822 (2021) 136697

V. Cirigliano, *JHEP* 03 (2021) 256

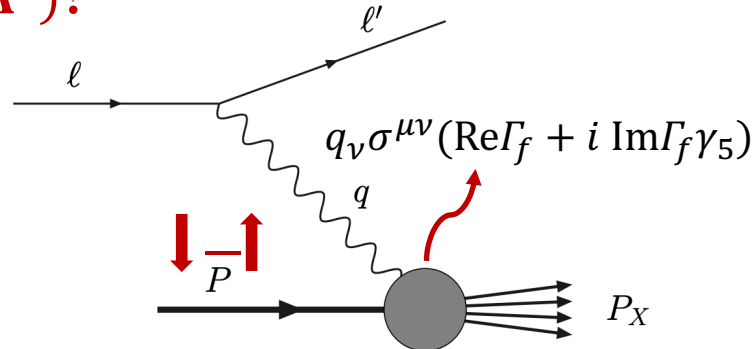
- As we expected:**
- ✓ High Polarization ~ 0.7
 - ✓ High luminosity $\sim 100\text{fb}^{-1}$
 - ✓ Moderate energy $\sim 120\text{ GeV}$



Transverse SSA @EICs

How to probe **quark dipole operator at $\mathcal{O}(1/\Lambda^2)$** ?

- Polarized DIS
- Need transverse PDF

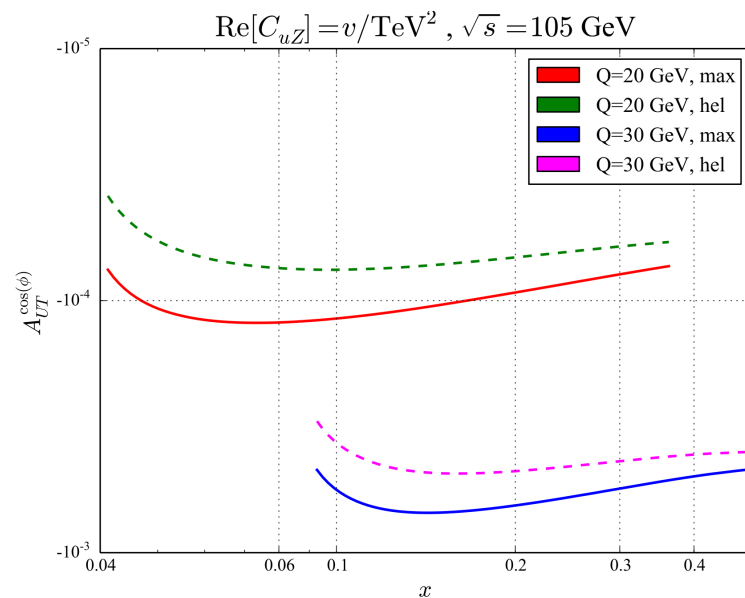


Transverse Single-Spin-Asymmetry (SSA)

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

➔

$$\begin{aligned} \text{Re}\Gamma_f &\rightarrow \cos(\phi_S - \phi_l) \\ \text{Im}\Gamma_f &\rightarrow \sin(\phi_S - \phi_l) \end{aligned}$$



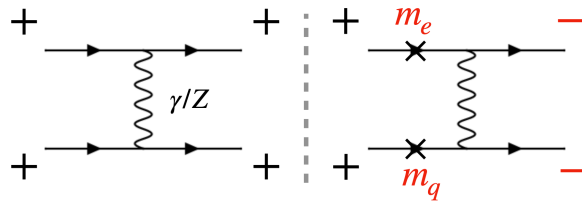
R. Boughezal, et al., *Phys.Rev.D* 107 (2023) 7

Transverse DSA @EICs

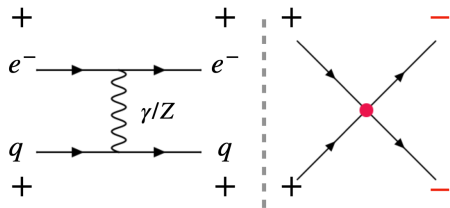
Transverse Double-Spin-Asymmetry (DSA)

H.-L. Wang, X.-K. Wen, H. Xing and Y. Bin, *arXiv*: 2401.08419

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



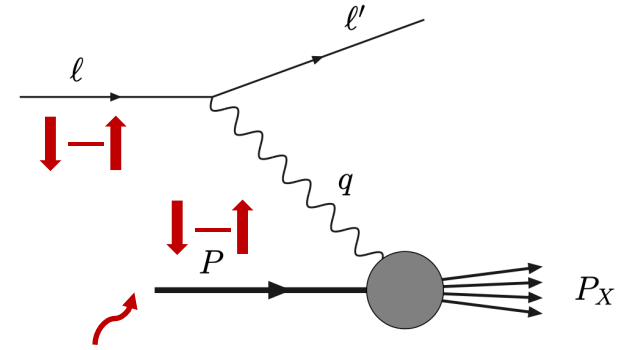
$$A_{TT}^{SM} \sim m_e m_q \cdot h(x, \mu)$$



$$A_{TT}^{SMEFT} \sim \frac{Q^2}{\Lambda^2} \cdot h(x, \mu) \cdot \text{Re} \left[C_{ledq} \cdot e^{-i2(\phi_1 + \phi_2)} + C_{lequ}^{(1,3)} \cdot e^{-i2(\phi_1 - \phi_2)} \right]$$

2φ and **flat** shape

The azimuthal behavior due to parity property of bilinear in operators



$h(x, \mu)$: transversity distribution

Z.-B. Kang et al., *Phys.Rev.D* 93 (2016) 1

C. Zeng et al., *arXiv*: 2310.15532

JAM collaboration *arXiv*:2205.00999

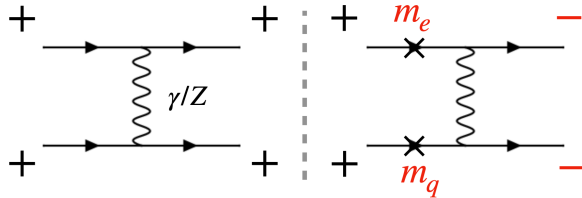
$$\mathcal{O}_{ledq} = (\bar{L}^j e) (\bar{d} Q^j),$$

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

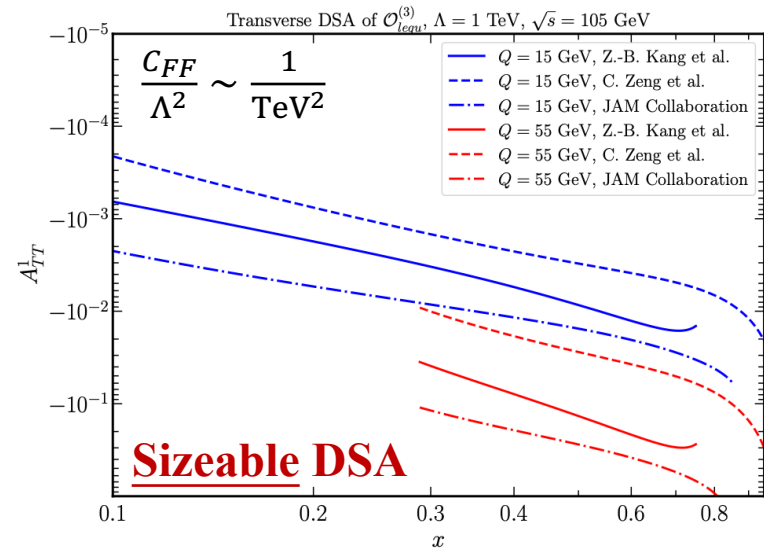
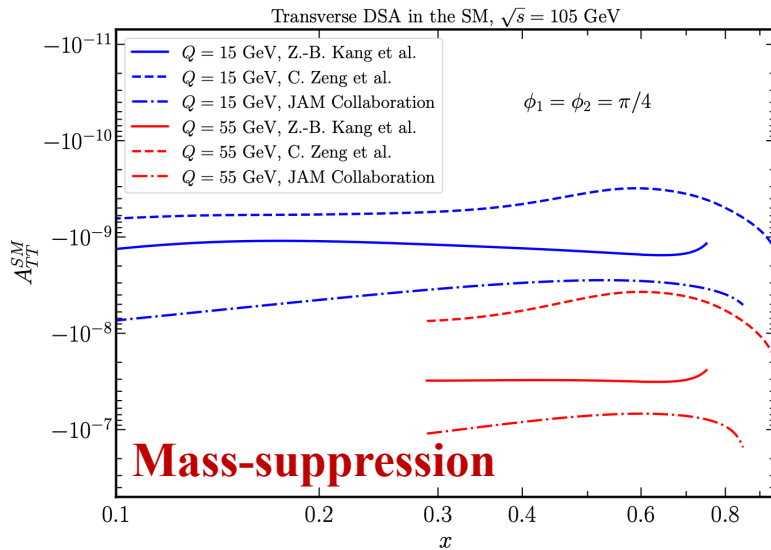
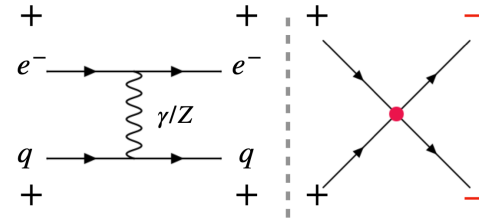
$$\mathcal{O}_{lequ}^{(3)} = (\bar{L}^j \sigma^{\mu\nu} e) \epsilon_{jk} (\bar{Q}^k \sigma_{\mu\nu} u),$$

Probing four-fermion operators @EIC & EicC

SM



Scalar/Tensor four-fermion operator



H.-L. Wang, X.-K. Wen, H. Xing and Y. Bin, *arXiv*: 2401.08419

- without contamination from the SM and other NP
- without mass-suppression

Probing four-fermion operators @EIC & EicC

H.-L. Wang, X.-K. Wen, H. Xing and Y. Bin, *arXiv*: 2401.08419

scalar/tensor four-fermion operator

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

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

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

Transversity	Limits on $\text{Re}[C_{ledq}](\text{Im}[C_{ledq}])$	
	EIC (105 GeV)	EicC (16.7 GeV)
Z.-B. Kang et al [63]	5.16	34.60
C. Zeng et al [64]	4.53	13.72
JAM Collaboration [65]	5.12	29.69

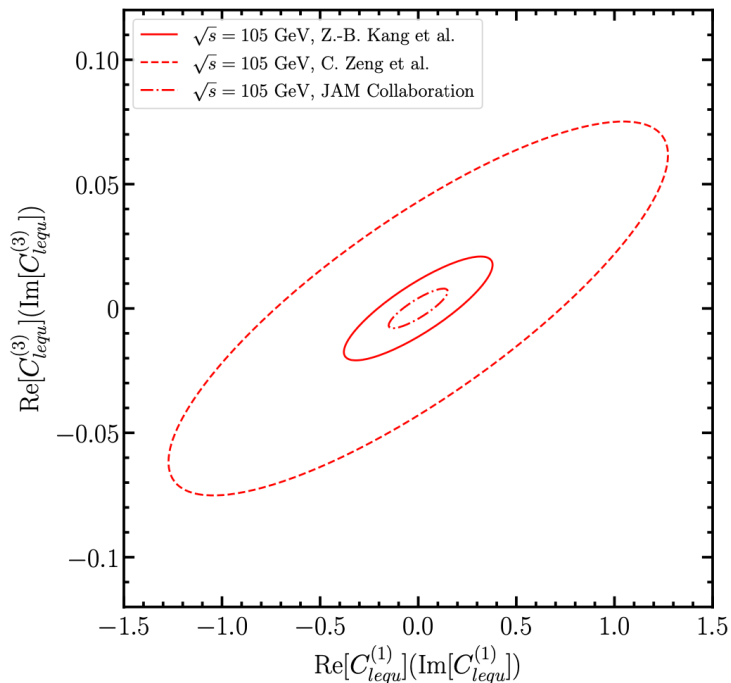
$$x \in [0.1, 0.8], Q \in [15, 65] \text{ GeV}$$

$$0.01 \leq y \leq 0.95$$

$$|P_{T,e}| = |P_{T,p}| = 0.7$$

- ✓ Our results are *stronger or comparable* to other $\mathcal{O}(1/\Lambda^4)$ -approaches
- ✓ Enabling direct study of potential CP-violating effects.

EIC: $\sqrt{s} = 105 \text{ GeV}, \mathcal{L} = 100 \text{ fb}^{-1}$



- ✓ The muon $g-2$ data and many NP models may hint SMEFT chirality-flip operators
- ✓ Chirality-flip operators are difficult to be probed since the leading effects $\sim 1/\Lambda^4$
- ✓ We propose a new method to linearly probe them $\sim 1/\Lambda^2$ via *transverse polarized beams*
- ✓ Simultaneously constraining well both Re & Im parts
 - without contaminations from other NP and SM, without mass-suppression
 - offering a new opportunity for directly probing potential CP-violating effects.
- ✓ Our bound have much stronger sensitivity than other approaches by 1~2 orders
- ✓ Future colliders (Z/Higgs/Top factory...)
 - Polarized Muon collider, **hadron colliders**, **Electron-Ion Collider**

Thank you

Backup

BACKUP

Backup: Some Formulae

$$|\Theta, \chi\rangle_1 = \cos \frac{\Theta}{2} |h = +\rangle + \sin \frac{\Theta}{2} e^{i\chi} |h = -\rangle$$

Superposition of the two helicity states along polarization $\vec{s}(\Theta, \chi)$

$$T_{h\bar{h}} = \langle \phi, \dots | T | \chi, \bar{\chi} \rangle = \langle \phi = 0, \dots | T | \chi - \phi, \bar{\chi} - \phi \rangle$$

2-to-2 rotational invariance

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

$$|\mathcal{M}|^2(\mathbf{s}, \bar{\mathbf{s}}, \theta, \phi) = \sum_{\alpha_1, \alpha_2, \alpha'_1, \alpha'_2} \rho_{\alpha_1, \alpha'_1}(\mathbf{s}) \bar{\rho}_{\alpha_2, \alpha'_2}(\bar{\mathbf{s}}) \mathcal{M}_{\alpha_1, \alpha_2}(i \rightarrow f; \theta, \phi) \mathcal{M}_{\alpha'_1, \alpha'_2}^\dagger(i \rightarrow f; \theta, \phi)$$

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

$$\rho = \frac{1}{2} (1 + \boldsymbol{\sigma} \cdot \mathbf{s})$$

$$\mathcal{M}_{\lambda_1, \lambda_2}(\theta, \phi) = e^{i(\lambda_1 - \lambda_2)\phi} \mathcal{T}_{\lambda_1, \lambda_2}(\theta)$$

$$|M|^2 = |M|_{\text{unpol}}^2 - \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[T_{++}^* T_{--}]$$

$$|\mathcal{M}|_{TU}^2 = \frac{1}{2} b_T \text{Re} \left[e^{i(\phi - \phi_0)} \left(\mathcal{T}_{++} \mathcal{T}_{-+}^\dagger + \mathcal{T}_{+-} \mathcal{T}_{--}^\dagger \right) \right]$$

$$- \frac{1}{2} \lambda_T \bar{\lambda}_T \text{Re}[e^{-2i\phi} T_{+-}^* T_{-+}]$$

$$+ \frac{1}{2} \lambda_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{--} + T_{++}^* T_{-+})]$$

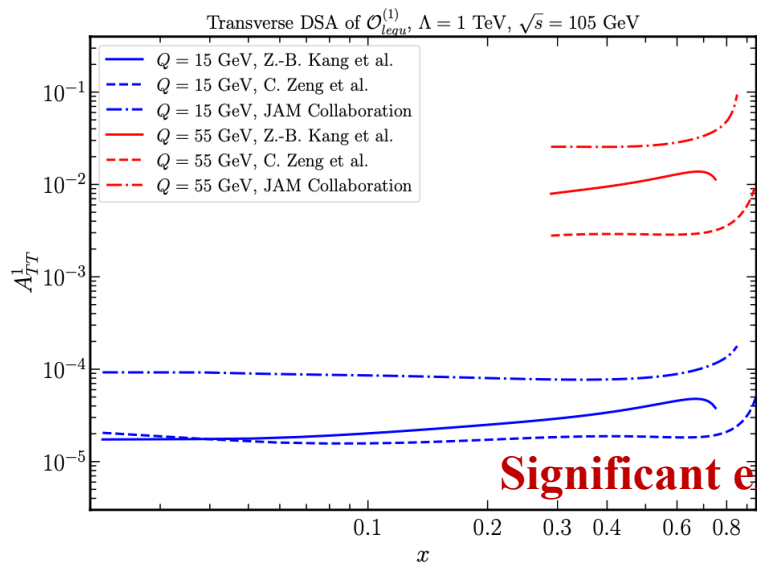
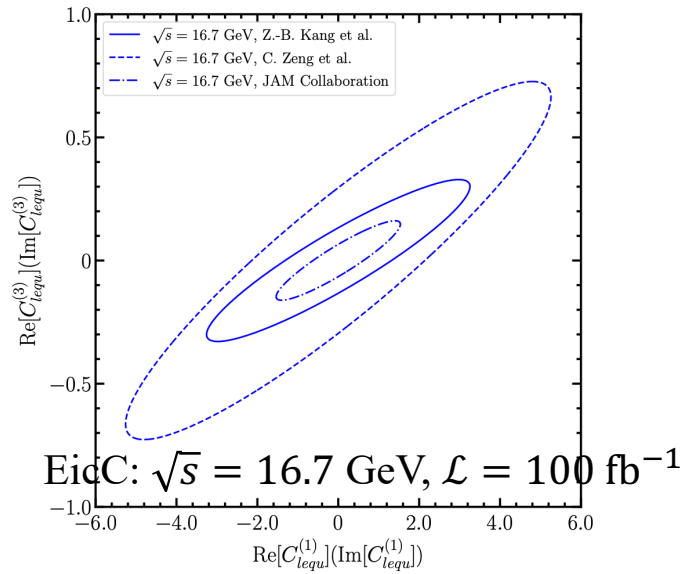
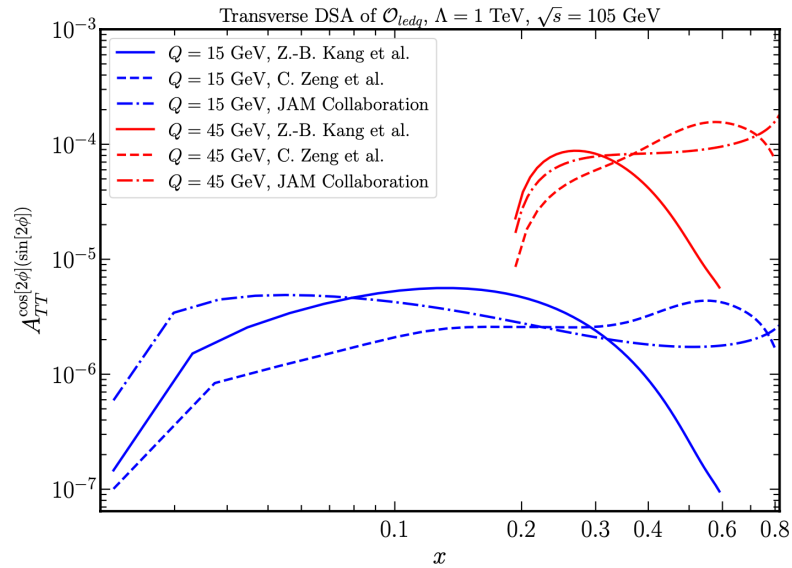
$$T_{-\lambda_a, -\lambda_b, -\lambda_c, -\lambda_d}(\theta) = \eta \cdot (-1)^{\lambda - \mu} \cdot T_{\lambda_a, \lambda_b, \lambda_c, \lambda_d}(\theta)$$

$$- \frac{1}{2} \bar{\lambda}_T \text{Re} [e^{-i\phi} (T_{+-}^* T_{++} + T_{--}^* T_{-+})]$$

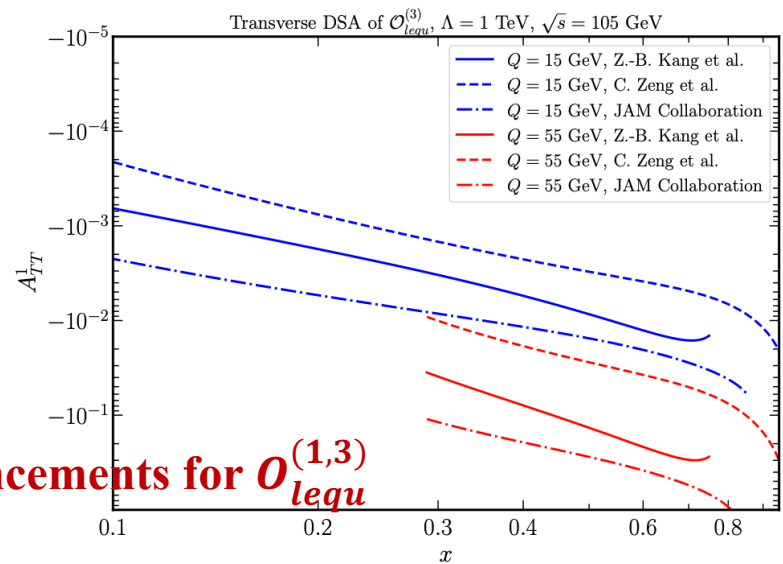
$$\eta = \frac{\eta_c \eta_d}{\eta_a \eta_b} \cdot (-1)^{s_a + s_b - s_c - s_d}$$

X.-K.W, BY, ZY, C.-P.Y, works in progress

Backup



Significant enhancements for $\mathcal{O}_{lequ}^{(1,3)}$



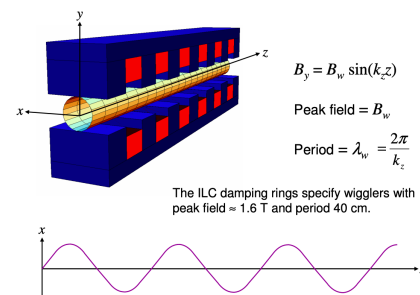
Backup: Polarized beam realization

Transverse polarization is more natural

Sokolov-Ternov effect (92.4%, minutes-hours, 50GeV)

Laser-assistant

Spin-precession



Photon-based scheme:

Polarized positrons are produced via pair production in a thin target from circularly-polarized photons with energy of multi-MeV (up to about 100 MeV). The cost difference between an polarized source and an upgrade from a unpolarized source is small ($\sim 1\%$). At 500 GeV, loss of polarization $<1\%$, at IP $<0.25\%$.

Polarized electron source consists of a polarized high-power laser beam and a high-voltage dc gun with a semiconductor photocathode.

Only polarization parallel or anti-parallel to the guide fields of the damping ring is preserved. Need to avoid spin-orbit coupling resonance depolarizing effects.

The spin rotator systems between the damping rings and the main linacs *permit the setting of arbitrary polarization vector orientations* at the IP.

Polarized-photons source:

I. a high-energy electron beam ($>\sim 150$ GeV) passing through a short period, helical undulator. (E-166, SLAC)

II. Compton backscattering of laser light off a GeV energy-range electron beam. (KEK)

In both schemes a polarization of about $|\text{Pe}^+| \geq 90\%$ is reported.