Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP 2024),
Beijing, China, April 19-22, 2024

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

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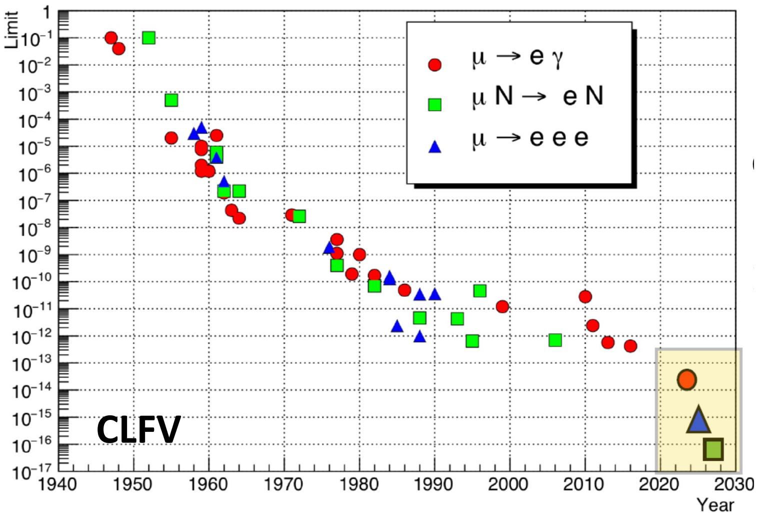
In collaboration with Bin Yan, Zhite Yu and C.-P. Yuan
Phys.Rev.Lett. **131** (2023) 24, 241801
In collaboration with Hao-Lin Wang, Hongxi Xing and Bin Yan
arXiv: 2401.08419, accepted by PRD

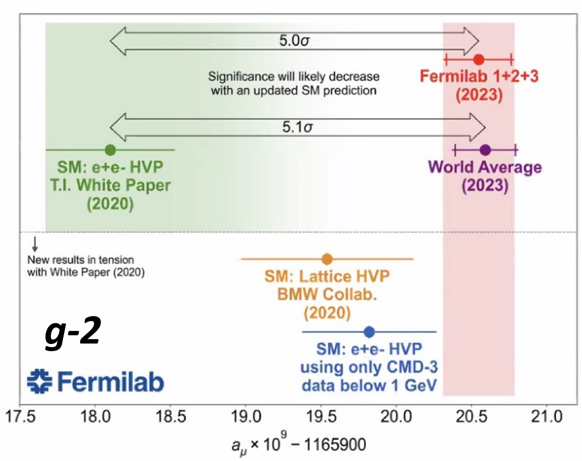
2024/04/21, PKU, Beijing

Bias warning: mostly on electron as an example, but work for muon as well.

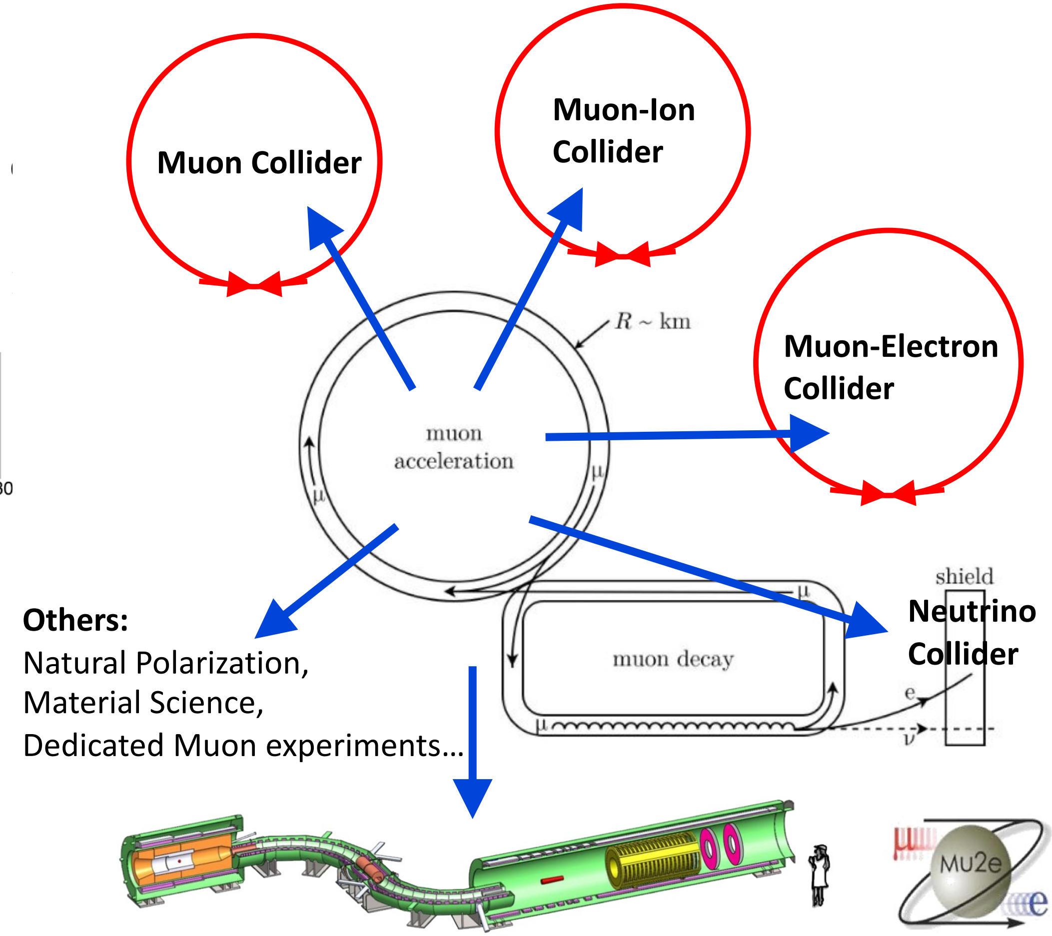
Muon Inspires/Hunts New Physics

Muon-related new physics arises.





Muon-related technology develops.

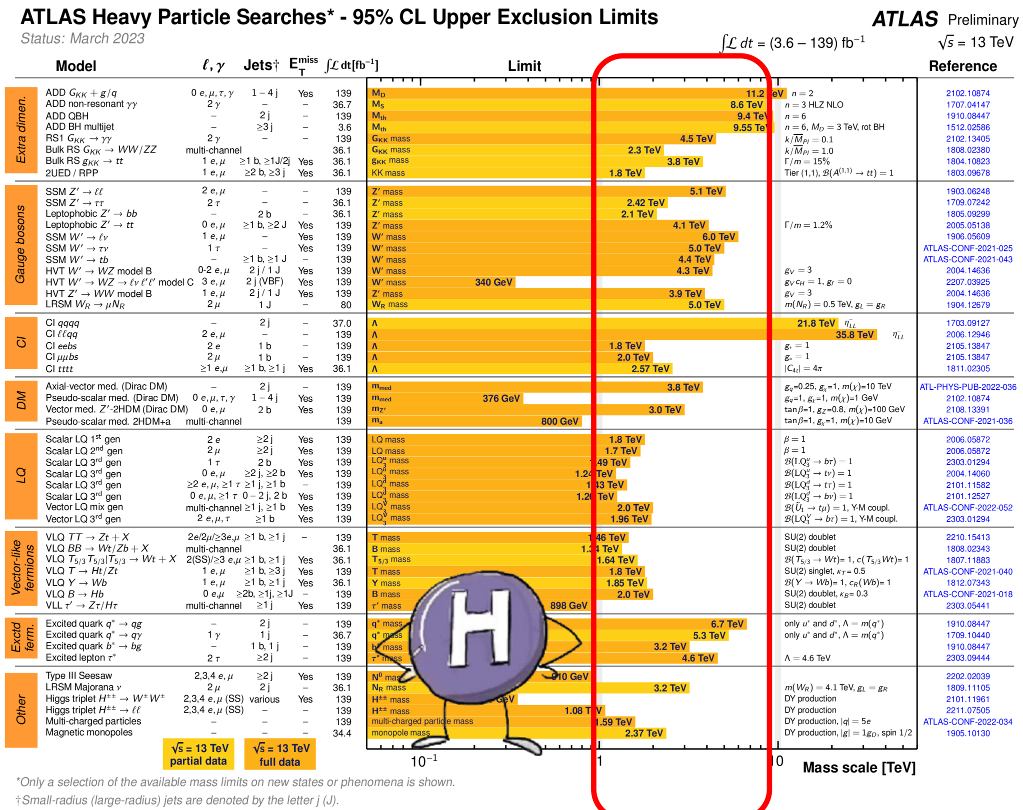


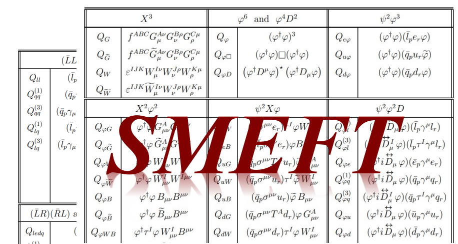
Inspired by Qiang Li's slide@MIP2023

Muon gains more and more interest.

New Physics and SMEFT

BUT none new fundamental resonance has been discovered.





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

B. Grzadkowski, et al. *JHEP* 10 (2010)
W. Buchuller, D. wyler, 1986

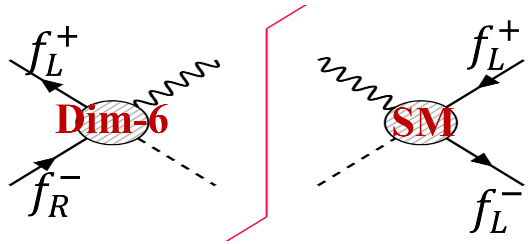
Powerful Tool @ EW

New Physics models excluded to **Multi-TeV** @ LHC. → $\boldsymbol{\Lambda \sim \mathcal{O}(\mathrm{TeV})}$

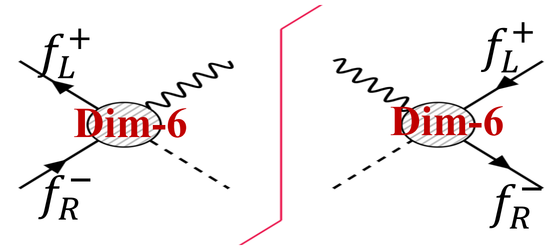
SMEFT Chirality-Flip Operator

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

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



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



interference~**0** for tiny mass

Non-interfering Leading effect

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	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	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}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

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

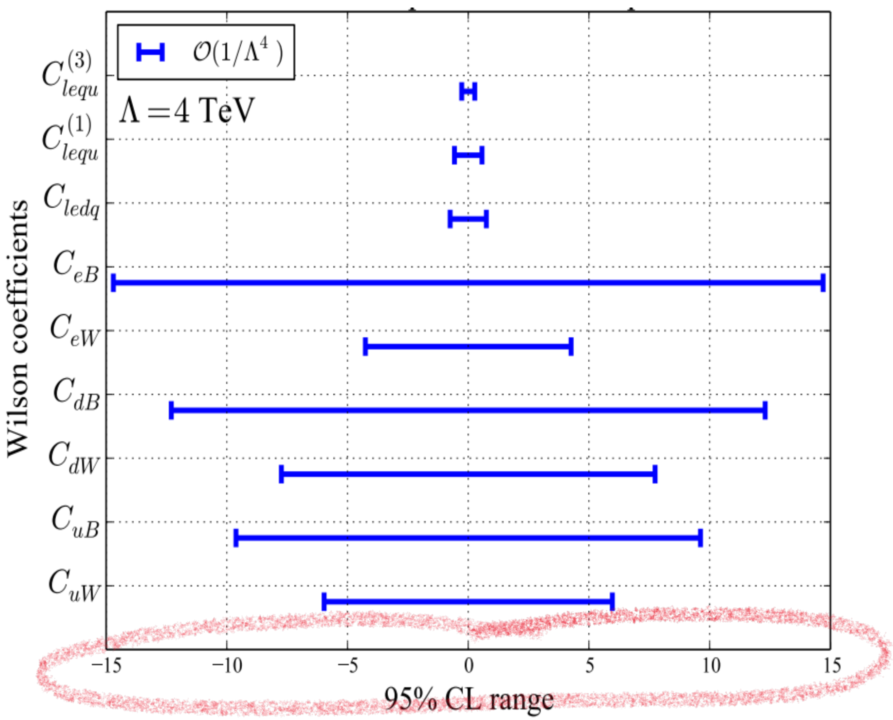
$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	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}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Table 3: Four-fermion operators.

Data for Chirality-Flip Operator

Constrained poorly in traditional methods via cross-section and width

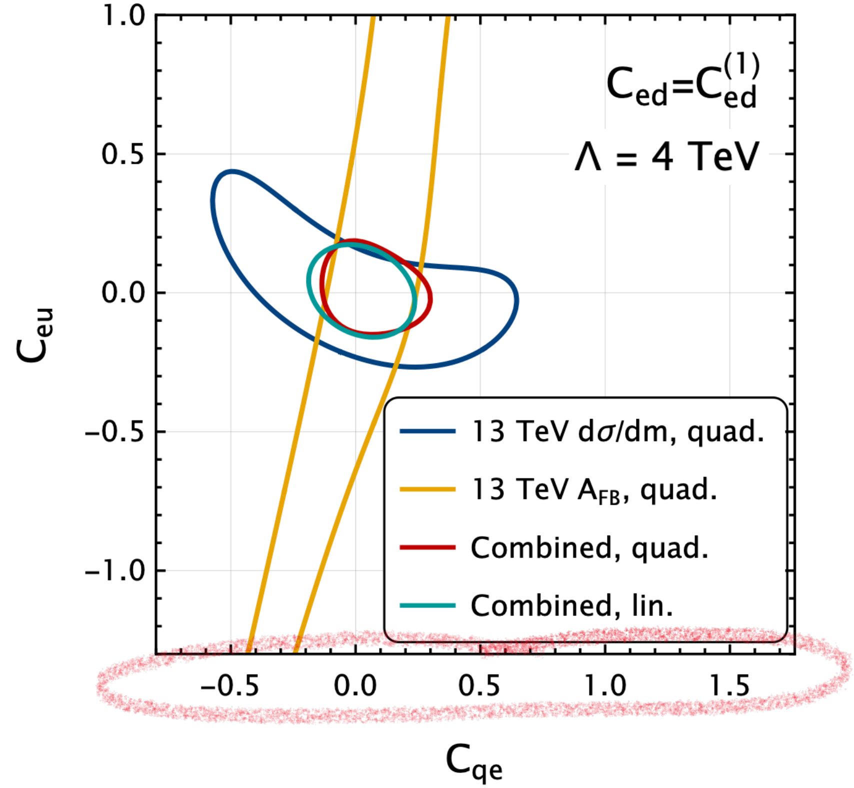
$\mathcal{O}(1/\Lambda^4)$



Single-Parameter-Analysis DY@LHC

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

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

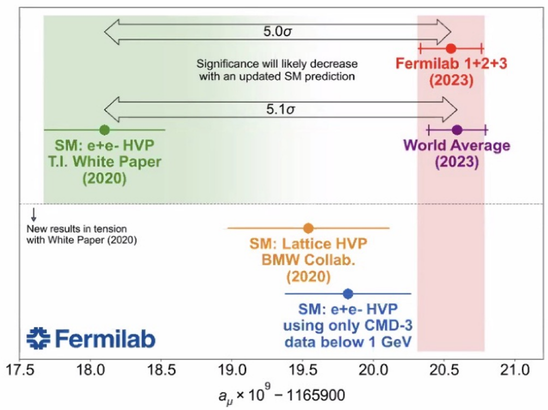


(R. Boughezal et al., *Phys.Rev.D* 108 (2023) 7)

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

same NP source ?
Z only detected by colliders

Indirect probes of NP quantum effects

Scalar/Tensor Four-Fermion operator:

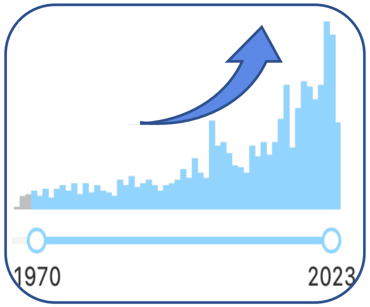
Leptoquark ?
New scalar or gauge boson ?

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

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

Low-energy data ?

CLFV ?



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

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

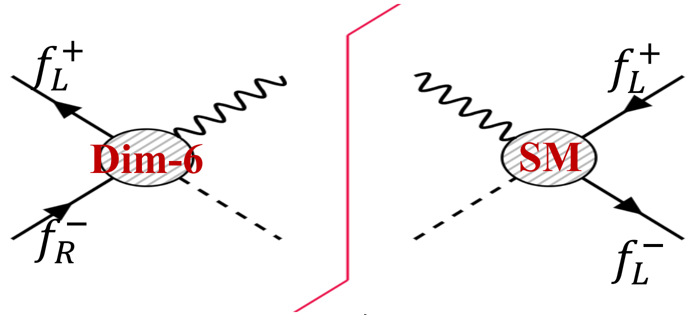
Our proposal:

- Transverse polarization effect of beams

Interference of the different helicity amplitudes

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

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



$|h=+\rangle\langle h=-|$

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

- Breaking rotational invariance

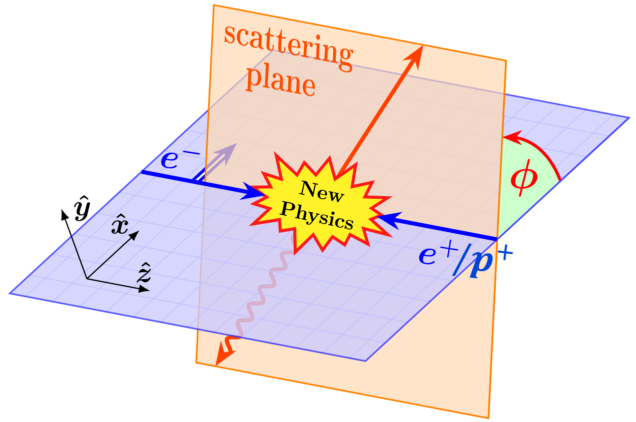
Nontrivial azimuthal behavior

- **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, accepted by *PRD*

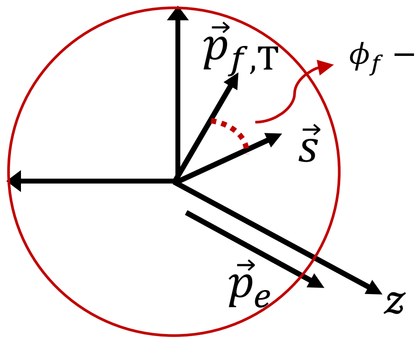


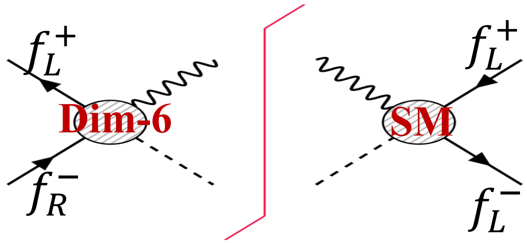
Transverse Spin Polarization

Spin dependent amplitude square:

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

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





$e^{i\phi * 0}$ $e^{i\phi * 1}$

STSAA@l^+l^- collider:

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

DSA@l^-P collider:

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

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

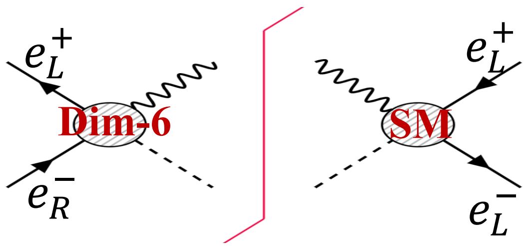
	U	L	T	
U	$\|\mathcal{M}\|^2_{UU} \to 1$	$\|\mathcal{M}\|^2_{UL} \to 1$	$\|\mathcal{M}\|^2_{UT} \to \cos\phi, \sin\phi$	→ **STSAA**
L	$\|\mathcal{M}\|^2_{LU} \to 1$	$\|\mathcal{M}\|^2_{LL} \to 1$	$\|\mathcal{M}\|^2_{LT} \to \cos\phi, \sin\phi$	
T	$\|\mathcal{M}\|^2_{TU} \to \cos\phi, \sin\phi$	$\|\mathcal{M}\|^2_{TL} \to \cos\phi, \sin\phi$	$\|\mathcal{M}\|^2_{TT} \to 1, \cos 2\phi, \sin 2\phi$	→ **DSA**

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

A New Probe of Dipole Operators @l^+l^- collider

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

$\mathrm{Re}[C_{dipole}]$	$\mathrm{Im}[C_{dipole}]$	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	



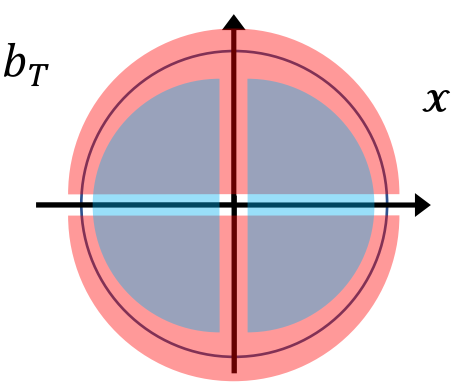
Single Transverse Spin Azimuthal Asymmetry (STSAA)

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

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

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



Pinning down Dipole Operators @l^+l^- collider

$$\mathcal{L}_{\rm eff} = -\frac{1}{\sqrt{2}}\bar{\ell}_L\sigma^{\mu\nu}\left(g_1\Gamma^e_B B_{\mu\nu} + g_2\Gamma^e_W\sigma^a W^a_{\mu\nu}\right)\frac{H}{v^2}e_R + \text{h.c.}$$

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

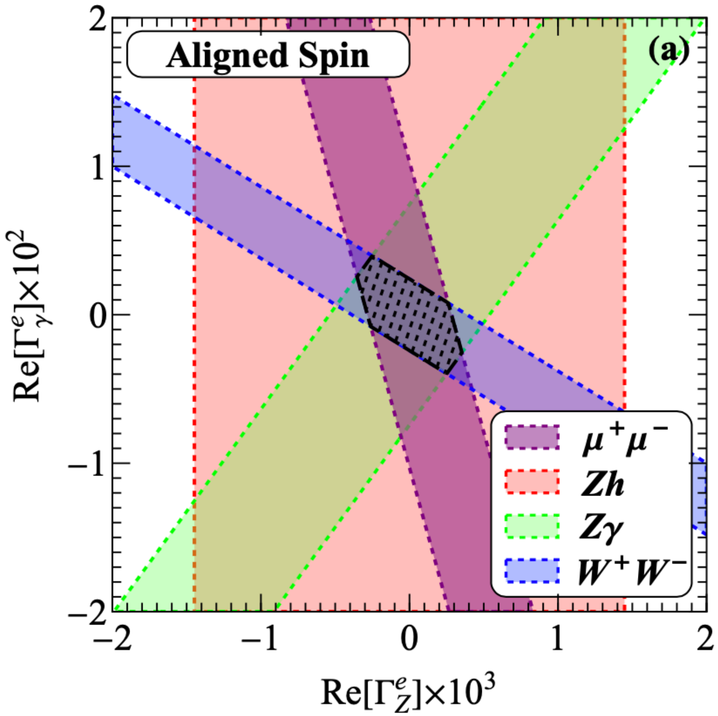
Aligned Spin

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

Opposite Spin

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

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



$$\Gamma^e_\gamma = \Gamma^e_W - \Gamma^e_B$$

$$\Gamma^e_Z = c^2_W\Gamma^e_W + s^2_W\Gamma^e_B$$

Much stronger sensitivity than other approaches by 1~2 orders

The sensitivity to Γ^e_Z is much stronger than Γ^e_γ

- Parity property of helicity amplitude

Pinning down Dipole Operators @l^+l^- collider

For the imaginary parts of dipole couplings, things are similar

Aligned Spin

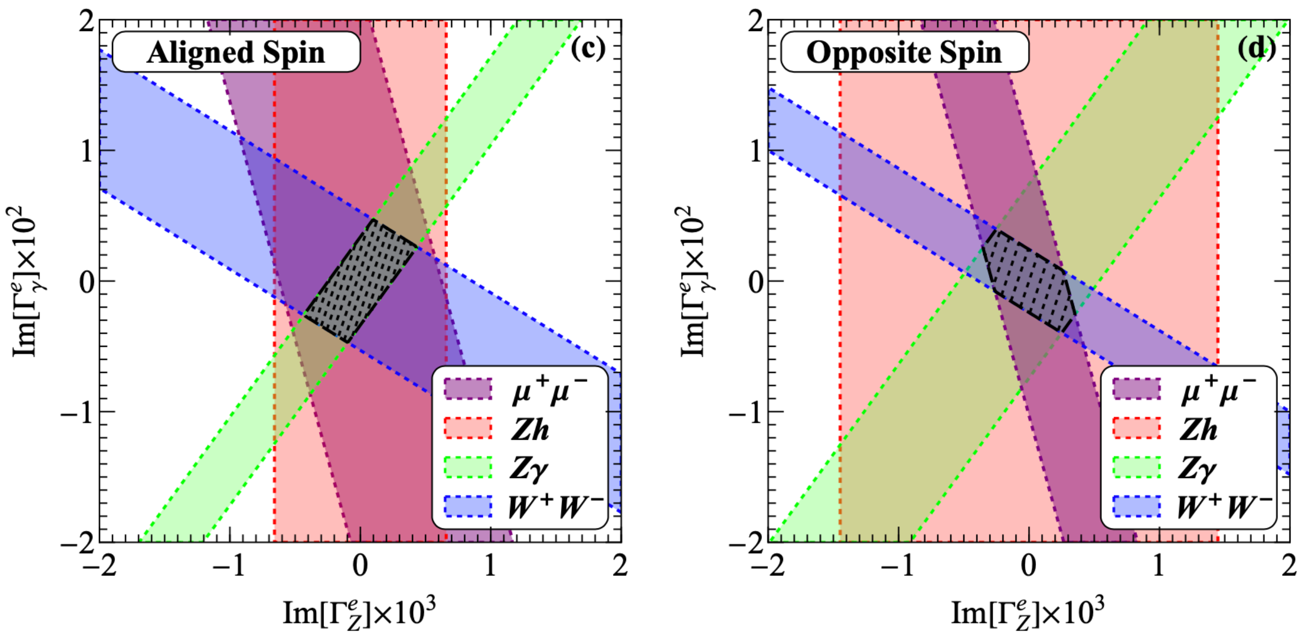
$$\phi_0 = \bar{\phi}_0 = 0$$

Opposite Spin

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

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

$\sqrt{s} = 250$ GeV, $\mathcal{L} = 5$ 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 Lepton-Ion Collider

Electron Ion Collider:

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

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

Muon–Ion collider at BNL:

D. Acosta and W. Li, *Nucl.Instrum.Meth.A* 1027 (2022) 166334

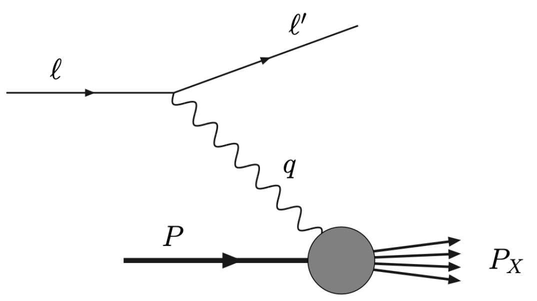
"The future QCD frontier and path to a new energy frontier of $\mu^+\mu^-$ colliders"

- 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 ~ 0.5-0.7
✓ High luminosity ~ 50-100fb^{-1}
✓ Moderate energy ~ 120 GeV-1TeV



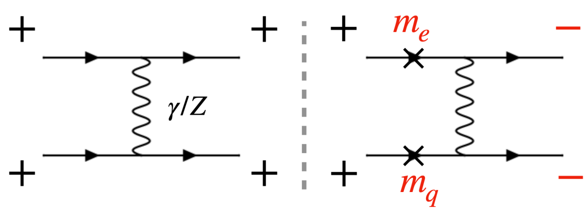
EICs as an example, MuICs work also well!

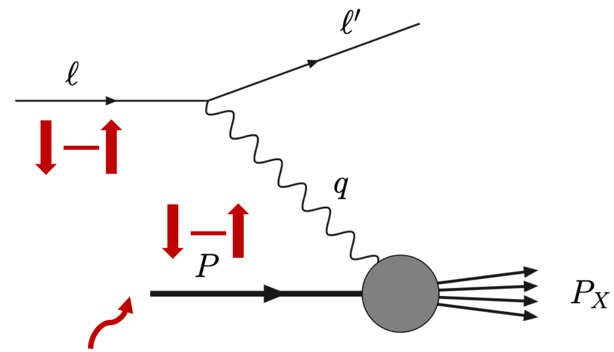
Transverse DSA @EICs

Transverse Double-Spin-Asymmetry (DSA)

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

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

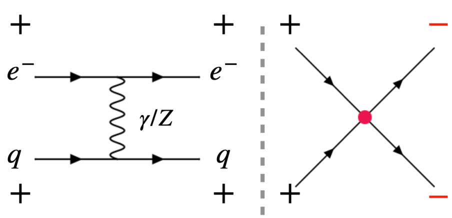




$\boldsymbol{h(x,\mu)}$: transversity distribution

Z.-B. Kang et al., *Phys.Rev.D* 93 (2016) 1
C. Zeng et al., *Phys.Rev.D* 109 (2024) 5
JAM collaboration, *Phys.Rev.D* 106 (2022) 3

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



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

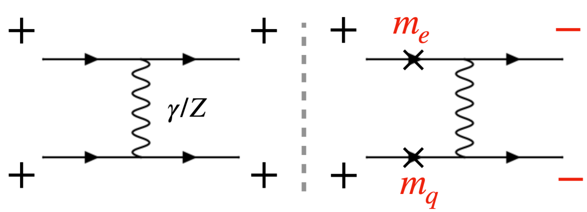
$$A_{TT}^{SMEFT}\sim\frac{Q^2}{\Lambda^2}\cdot h(x,\mu)\cdot Re\left[C_{ledq}\cdot e^{-i2(\phi_1+\phi_2)}+C_{lequ}^{(1,3)}\cdot e^{-i2(\phi_1-\phi_2)}\right]$$

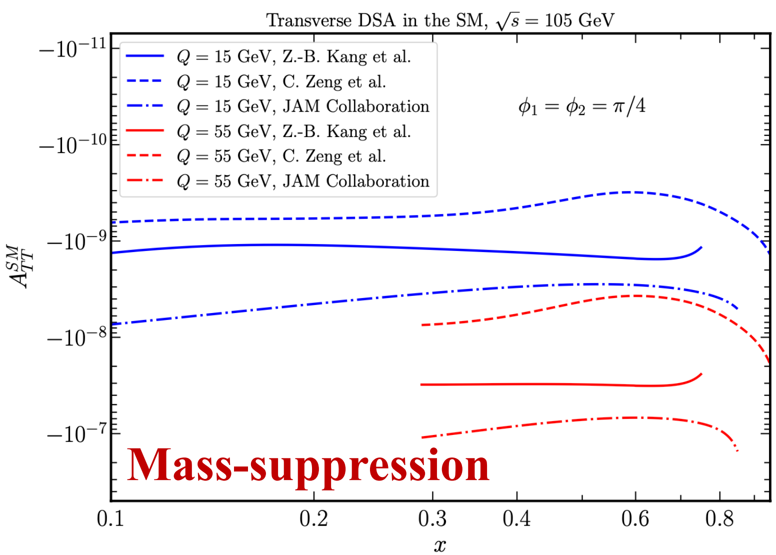
2ϕ and **flat** shape

The azimuthal behavior due to parity property of bilinear in operators

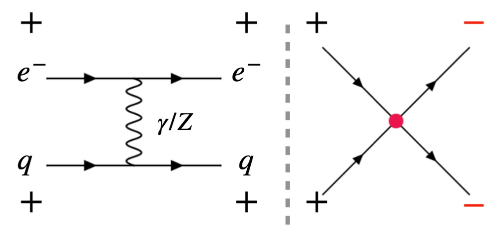
Probing four-fermion operators @EIC & EicC

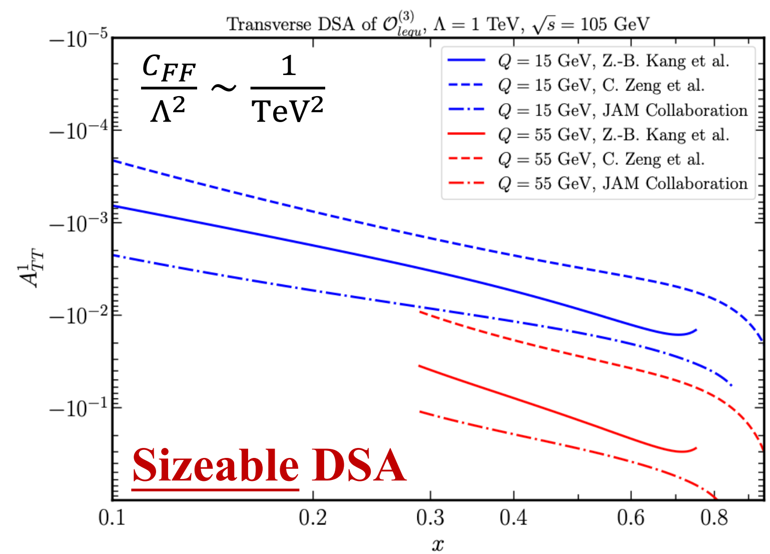
SM





Scalar/Tensor four-fermion operator





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

- 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 , accepted by *PRD*

scalar/tensor four-fermion operator

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

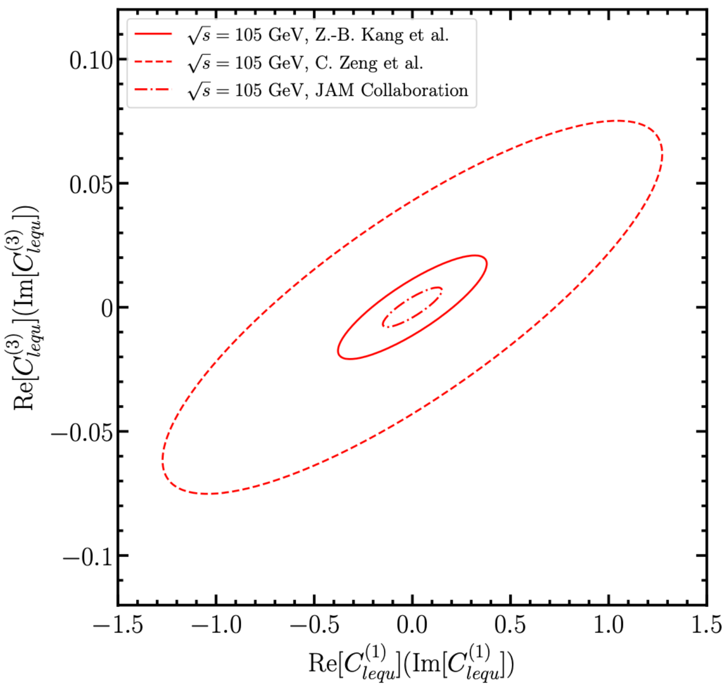
Transversity	Limits on Re$[C_{ledq}]$(Im$[C_{ledq}]$)	
	EIC (105 GeV)	EicC (16.7 GeV)
Z.-B. Kang et al [63]	5.16	34.60
C. Zeng et al [64]	4.53	13.72
JAM Collaboration [65]	5.12	29.69

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

$0.01 \leq y \leq 0.95$

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

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

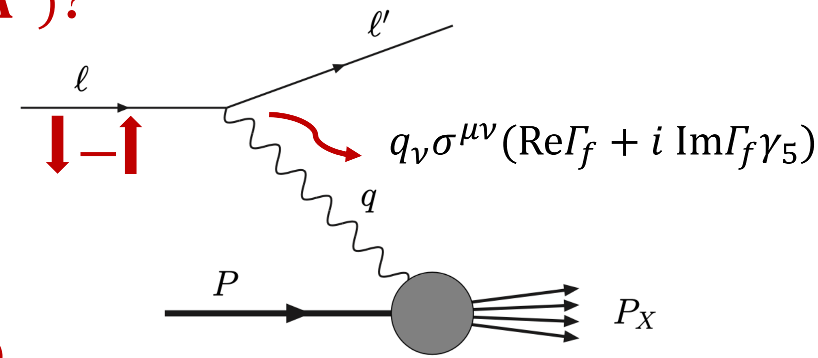


- ✓ Our results are *stronger or comparable* to other $\mathcal{O}(1/\Lambda^4)$-approaches
- ✓ Enabling direct study of potential CP-violating effects.

Transverse Beam SSA @MuIC

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

- Polarized DIS
- Need transverse muon

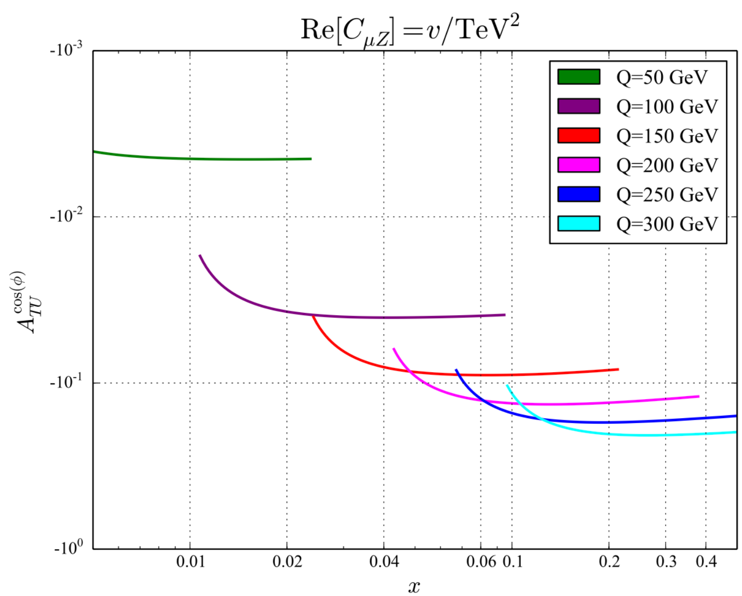


Transverse Beam Single-Spin-Asymmetry (SSA)

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

$$\mathrm{Re}\Gamma_f \rightarrow \cos(\phi_S - \phi_l)$$

$$\mathrm{Im}\Gamma_f \rightarrow \sin(\phi_S - \phi_l)$$



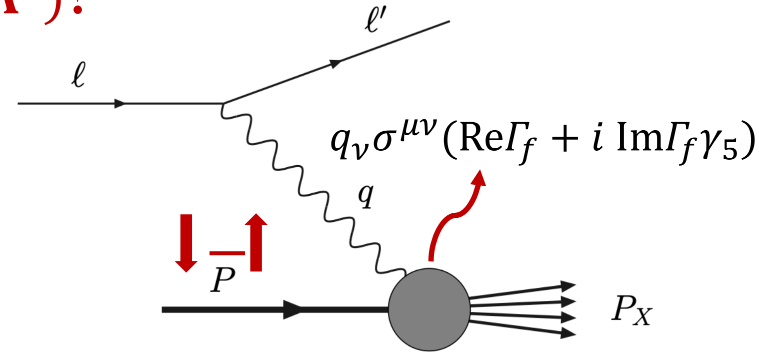
R. Boughezal, et al., *Phys.Rev.D* 107 (2023) 7

Transverse Target SSA @MuIC and EIC

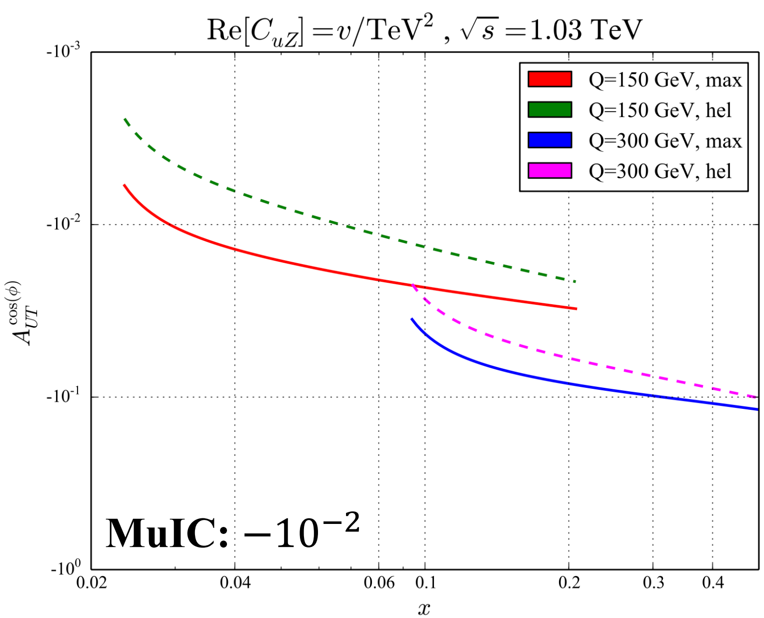
How to probe **quark** dipole operator **at $\mathcal{O}(1/\Lambda^2)$?**

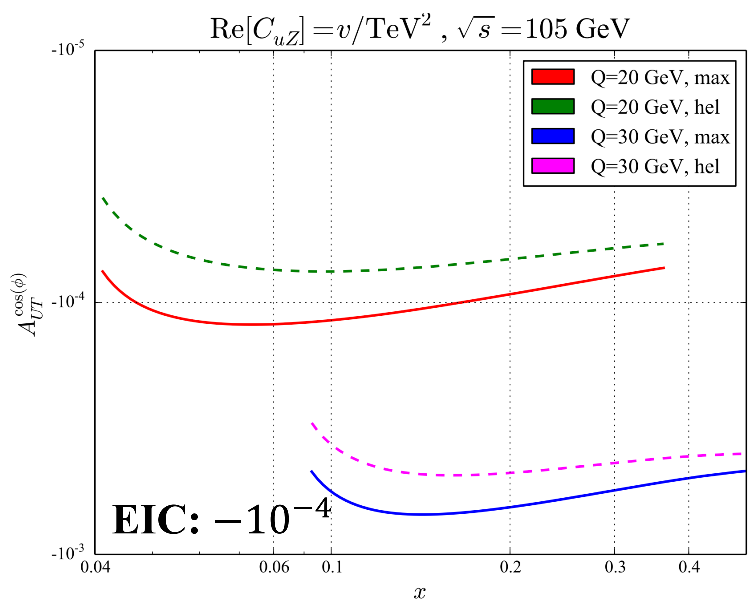
- Need transverse PDF

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



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





The asymmetry is significantly larger than at the nominal EIC

Summary

- ✓ 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 @$1/\Lambda^4$
- ✓ We propose a new method to linearly probe them @$1/\Lambda^2$ 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, Muon-Ion 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 $\vec{s}(\Theta,\chi)$

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

2-to-2 rotational invariance

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

$$|\mathcal{M}|^2(\boldsymbol{s},\bar{\boldsymbol{s}},\theta,\phi) = \sum_{\alpha_1,\alpha_2,\alpha_1',\alpha_2'} \rho_{\alpha_1,\alpha_1'}(\boldsymbol{s})\,\bar{\rho}_{\alpha_2,\alpha_2'}(\bar{\boldsymbol{s}})\,\mathcal{M}_{\alpha_1,\alpha_2}(i\to f;\theta,\phi)\,\mathcal{M}^\dagger_{\alpha_1',\alpha_2'}(i\to f;\theta,\phi)$$

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

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

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

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

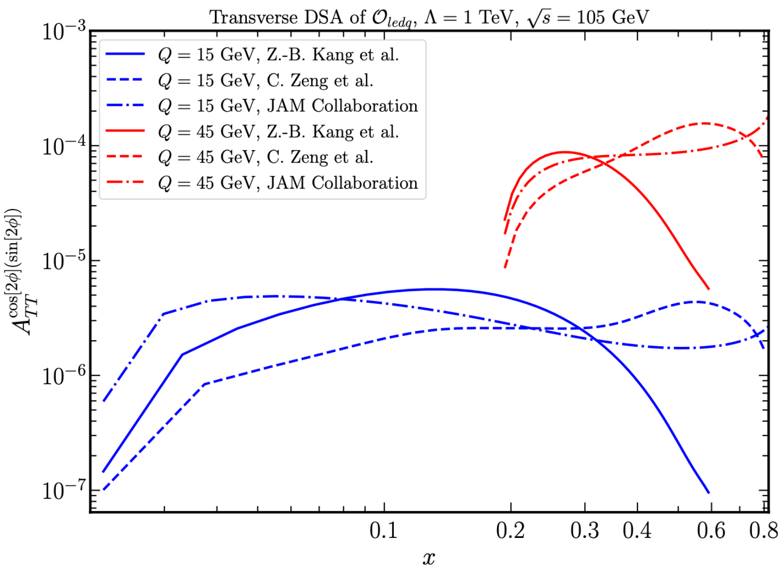
$$T_{-\lambda_a,-\lambda_b,-\lambda_c,-\lambda_d}(\theta) = \eta\cdot(-1)^{\lambda-\mu}\cdot T_{\lambda_a,\lambda_b,\lambda_c,\lambda_d}(\theta)$$

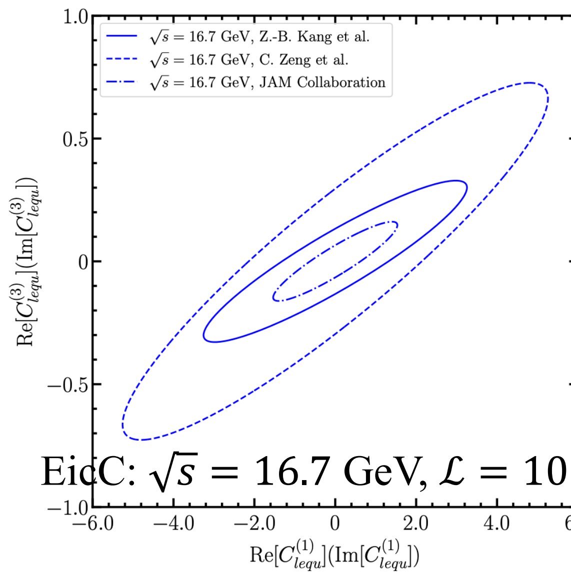
$$\eta = \frac{\eta_c\eta_d}{\eta_a\eta_b}\cdot(-1)^{s_a+s_b-s_c-s_d}$$

$$\begin{aligned}|M|^2 = |M|^2_{\mathrm{unpol}} &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[T^*_{++}T_{--}] \\ &- \frac{1}{2}\lambda_T\bar{\lambda}_T\mathrm{Re}[e^{-2i\phi}T^*_{+-}T_{-+}] \\ &+ \frac{1}{2}\lambda_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{--}+T^*_{++}T_{-+})\right] \\ &- \frac{1}{2}\bar{\lambda}_T\mathrm{Re}\left[e^{-i\phi}(T^*_{+-}T_{++}+T^*_{--}T_{-+})\right]\end{aligned}$$

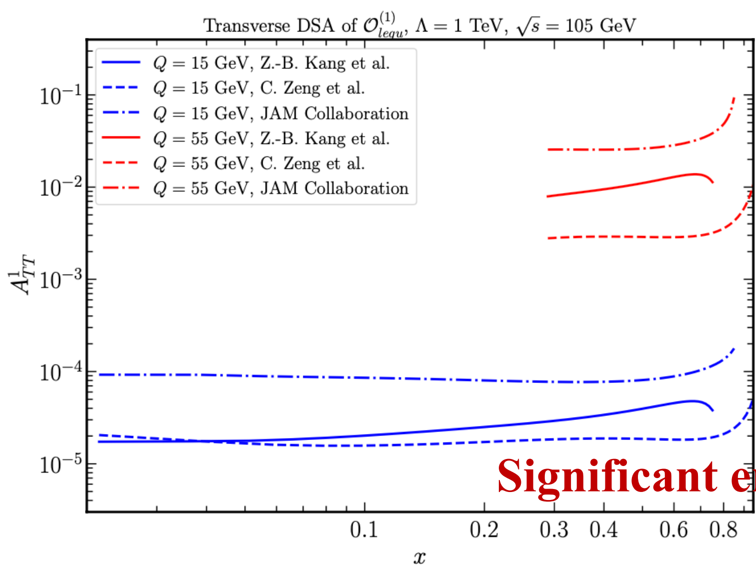
X.-K.W, BY, ZY, C.-P.Y, works in progress

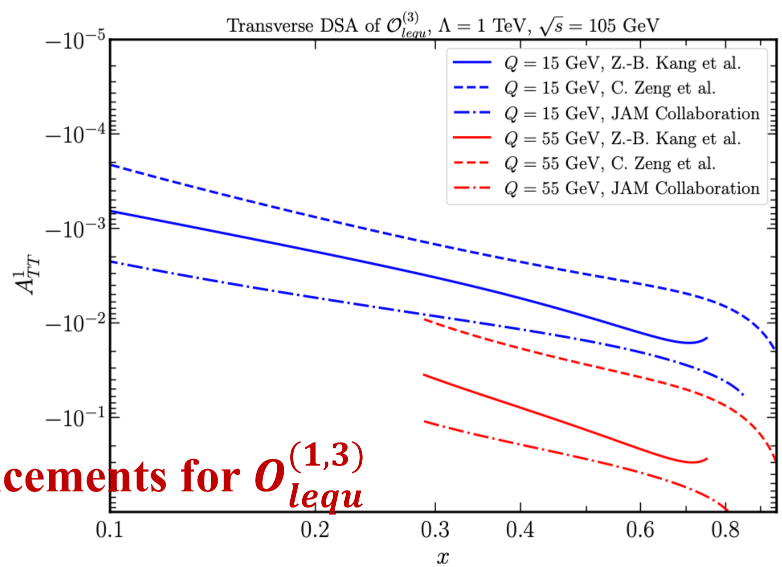
Backup





EicC: $\sqrt{s} = 16.7$ GeV, $\mathcal{L} = 100\ \mathrm{fb}^{-1}$





Significant enhancements for $O_{lequ}^{(1,3)}$

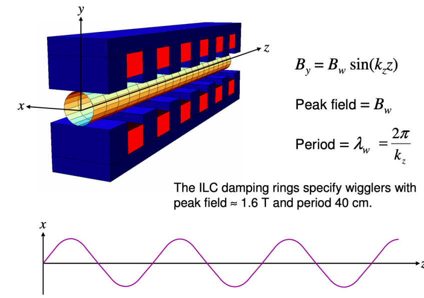
Backup: Polarized beam realization

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 (~ 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 (>~ 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 |Pe+ | ≥ 90% is reported.

Muons produced from pion decays are naturally polarized. The level of polarization in the lab frame depends on the initial pion energy and decay angle.

G. Moortgat-Pick et al. *Phys.Rept.* 460 (2008), hep-ph/0507011

D. Acosta and W. Li, Nucl.Instrum.Meth.A 1027 (2022) 166334