



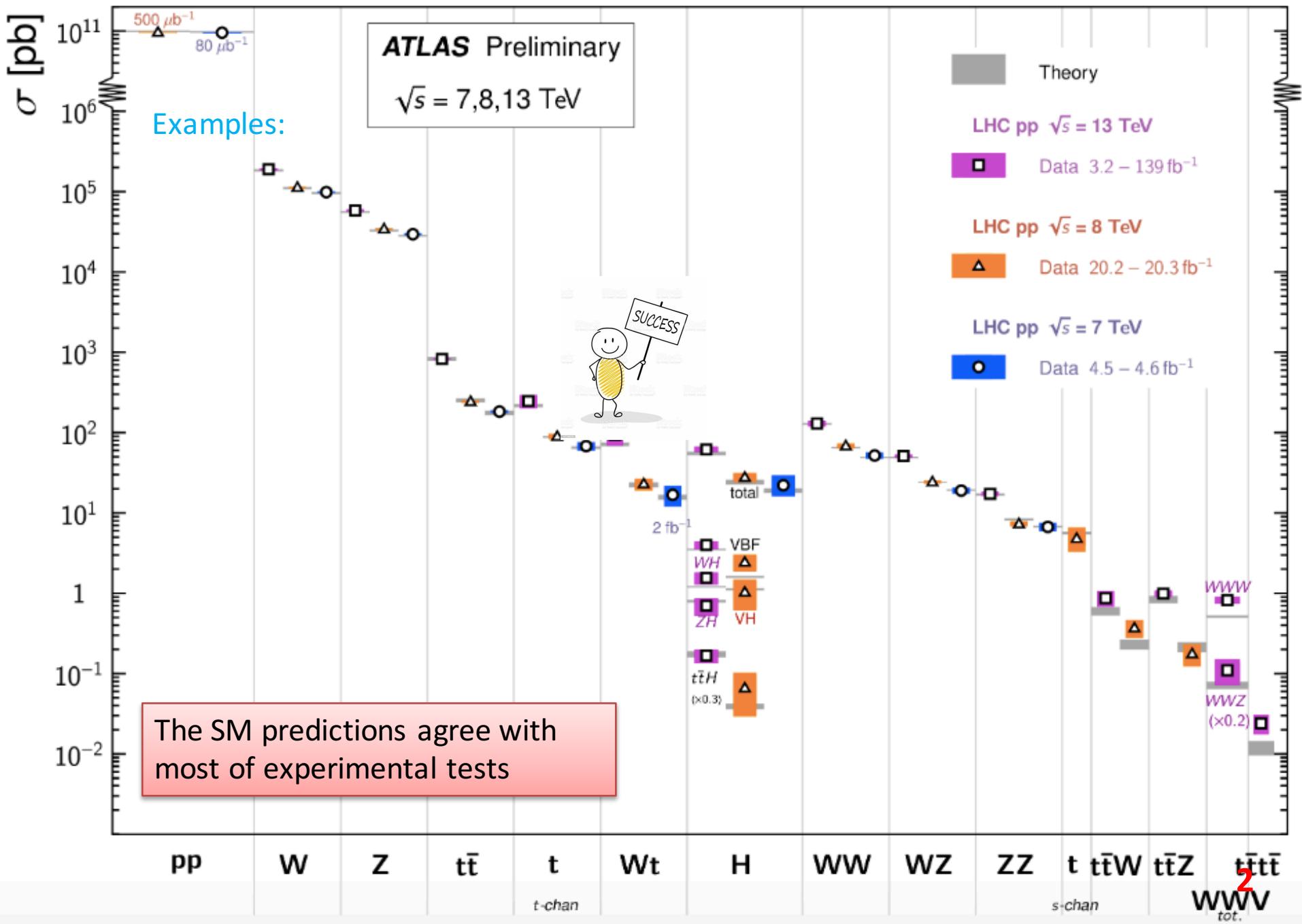
# Searching for new physics at the EIC

Bin Yan  
Institute of High Energy Physics

第五届重味物理与量子色动力学研讨会  
April 20-23, 2023

# Standard Model Total Production Cross Section Measurements

Status: February 2022



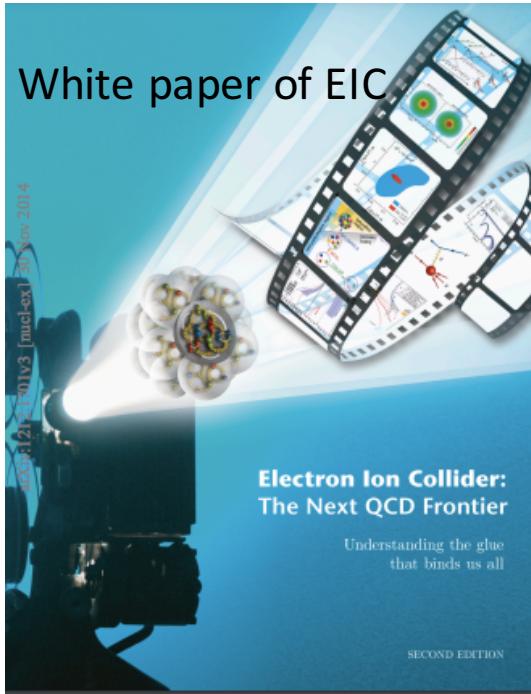
# Why we need the New Physics?

Some open questions:

1. What is Dark Matter ?
2. What is the origin of the neutrino mass?
3. What is the nature of the electroweak symmetry breaking?
4. What is the nature of the Higgs boson (Composite or elementary particle)?
5. .....

New Physics Models and new measurements to answer these questions

# Why Electron-Ion Collider?

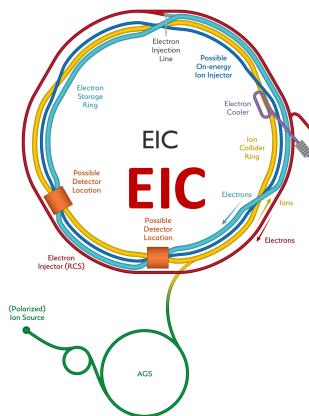


1. Explore and image the **spin and 3D structure** of the nucleon
2. Discover the **role of gluons** in structure and dynamics
3. Constraint for the PDFs, Polarized and unpolarized
4. Possibilities of **Beyond the Standard Model?**

**High Luminosity:**  $10 \sim 100 \text{ fb}^{-1}$  per year

**High Polarization:**  $P_e = 0.7$

Electroweak properties



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

# Outline

- The electroweak precision measurements
- New Physics effects from SMEFT
- Searching for the light new particles

Bin Yan, PLB 833 (2022) 137384

Hai Tao Li, Bin Yan and C.-P. Yuan, PLB 833 (2022) 137300

Yandong Liu and Bin Yan, CPC 47 (2023) 4, 043113

Bin Yan, Zhite Yu, C.-P. Yuan, PLB 822 (2021) 136697

V. Cirigliano, K. Fuyuto, C. Lee, E. Mereghetti and Bin Yan, JHEP 03 (2021) 256

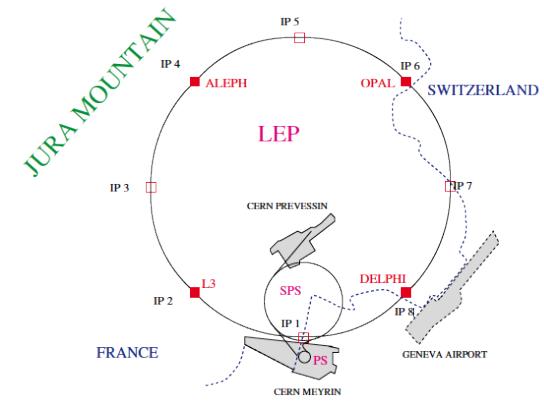
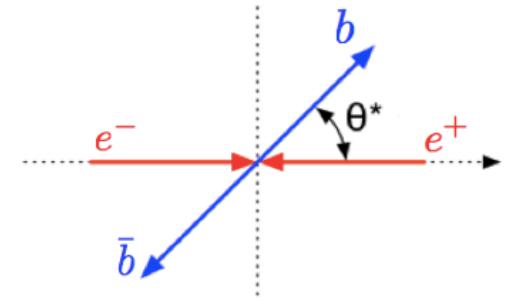
# The electroweak precision measurements

# Electroweak Precision measurement

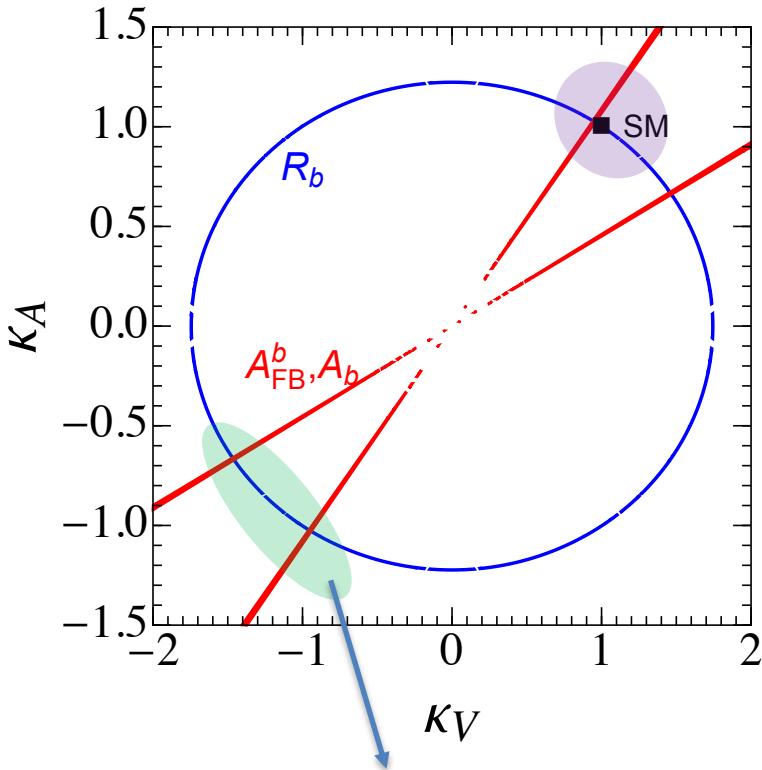
	Measurement with Total Error	Systematic Error	Standard Model High- $Q^2$ Fit	Pull
$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ [59]	$0.02758 \pm 0.00035$	0.00034	$0.02767 \pm 0.00035$	0.3
$m_Z$ [GeV]	$91.1875 \pm 0.0021$	<sup>(a)</sup> 0.0017	$91.1874 \pm 0.0021$	0.1
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$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

Phys.Rept. 427 (2006) 257-454

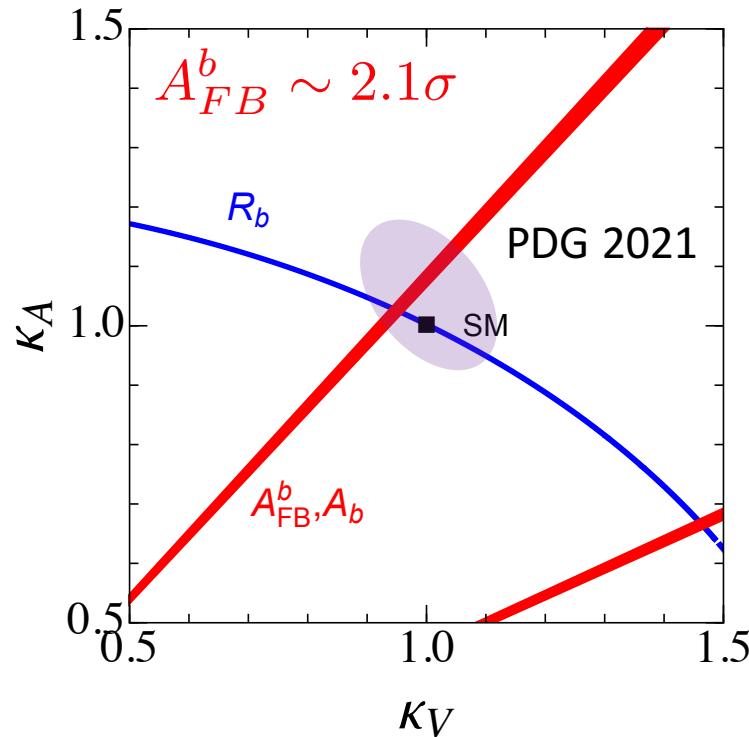
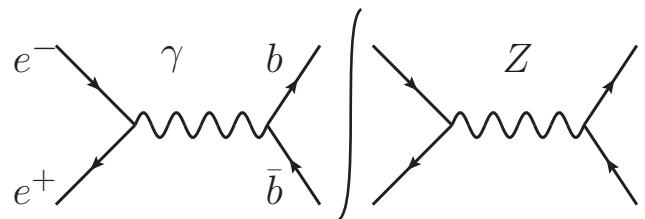
LEP: 1989-2000



# Electroweak Precision measurement



Excluded by off-Z pole data



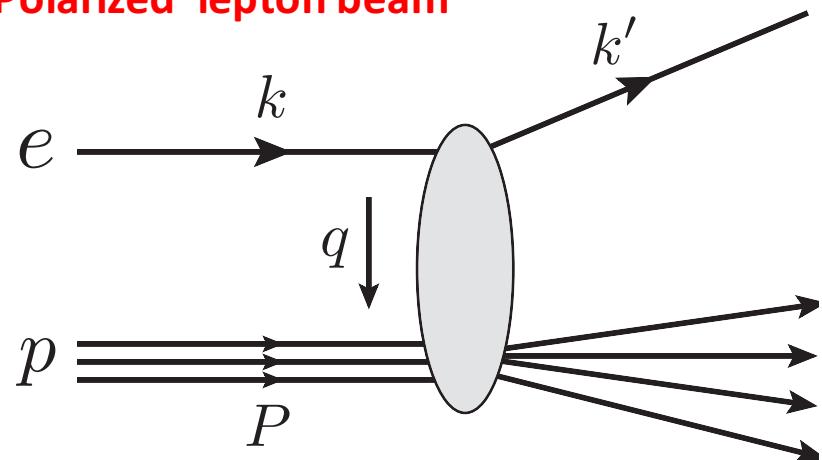
$$\mathcal{L} = \bar{b} \gamma_\mu (\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$

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

# 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:  $\gamma$ -Z interference
3. Only sensitive to the **vector component** of the Zbb coupling

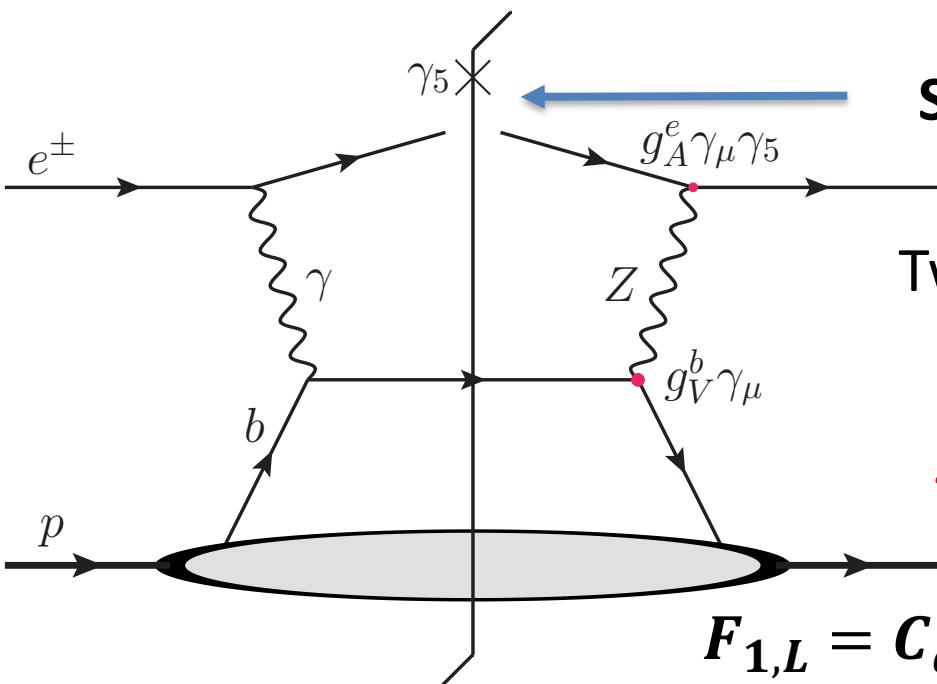
# DIS cross section

Polarized cross section

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

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

$\lambda_e = \pm 1$ : lepton helicity



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

Two possible combination:

$$g_A^e g_V^b \quad \checkmark$$

$$g_V^e g_A^b$$

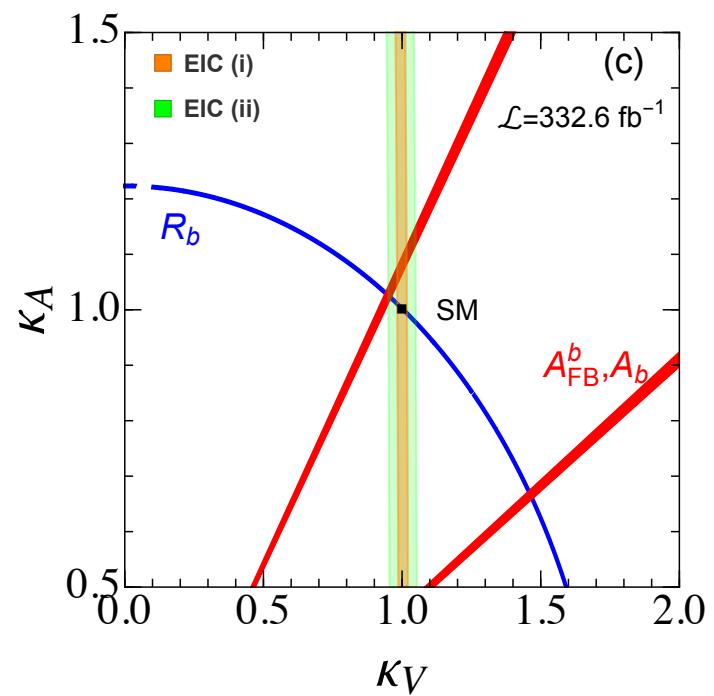
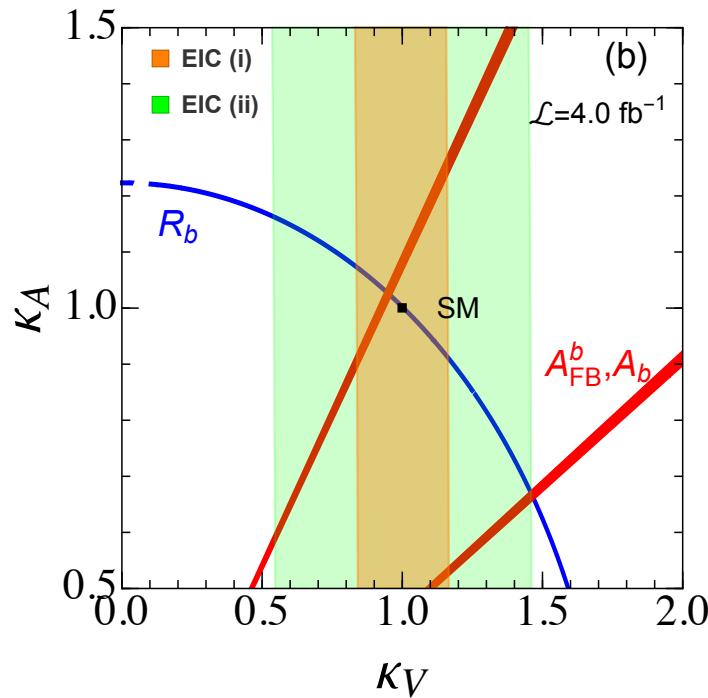
$$F_{1,L} = C_q \otimes (q + \bar{q})$$

$$F_3 = C_q \otimes (q - \bar{q})$$

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

# 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)  $\epsilon_q^b = 0.01$ ,  $\epsilon_c^b = 0.2$ ,  $\epsilon_b = 0.5$ .  $\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$



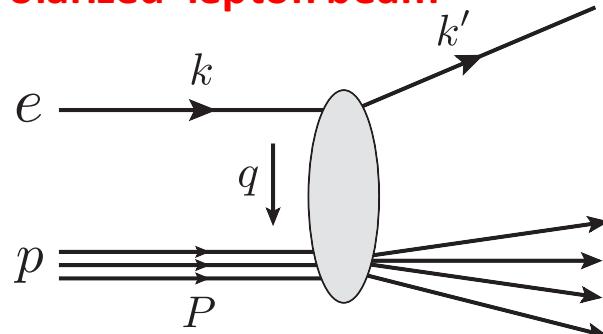
The minimal luminosities needed to resolve the degeneracy or exclude LEP AFB data:

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

# Zbb couplings @EIC

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

Polarized lepton beam



Single-Spin Asymmetry:

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

vector component of the Zbb coupling

Is it possible to probe the axial-vector component at the EIC?

Average jet charge weighted Single-Spin Asymmetry (WSSA):

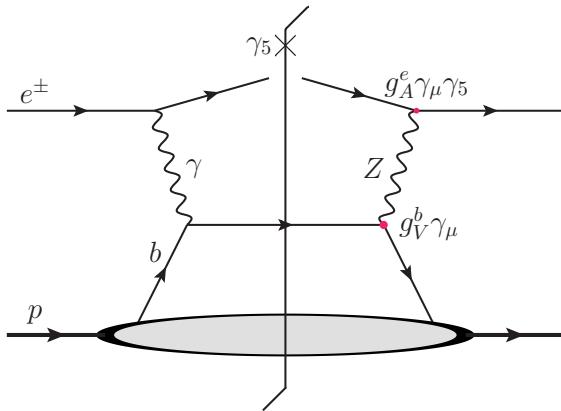
$$A_e^{bQ} = \frac{\sigma_{b,+}^Q - \sigma_{b,-}^Q}{\sigma_{b,+}^Q + \sigma_{b,-}^Q}$$

$$\sigma_{b,\pm}^Q = \int dp_T^j \frac{d\sigma_{b,\pm}^{\text{tot}}}{dp_T^j} \langle Q_J \rangle_b(p_T^j)$$

$$\langle Q_J \rangle_b(p_T^j) = \sum_{q=u,d,c,s,b} \left[ f_J^q(p_T^j, \epsilon_q^b) - f_J^{\bar{q}}(p_T^j, \epsilon_q^b) \right] \langle Q_J^q \rangle_b(p_T^j)$$

D. Krohn, M. D. Schwartz, T. Lin and W. J. Waalewijn, PRL 110,212001(2013)  
W.J.Waalewijn, PRD86,094030(2012)

# Jet Charge Weighted SSA



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



$$g_A^e g_V^b$$

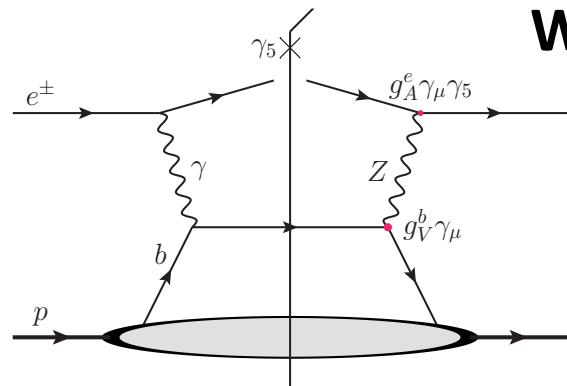
$$g_V^e g_A^b$$

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

$$F_3 = C_q \otimes (q - \bar{q})$$

**Key point:**

$$\langle Q_J^q \rangle = -\langle Q_J^{\bar{q}} \rangle$$



**WSSA:**  $\sigma_{b,+}^Q - \sigma_{b,-}^Q$

$$g_A^e g_V^b$$

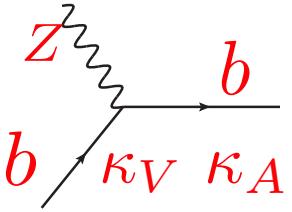
$$g_V^e g_A^b$$



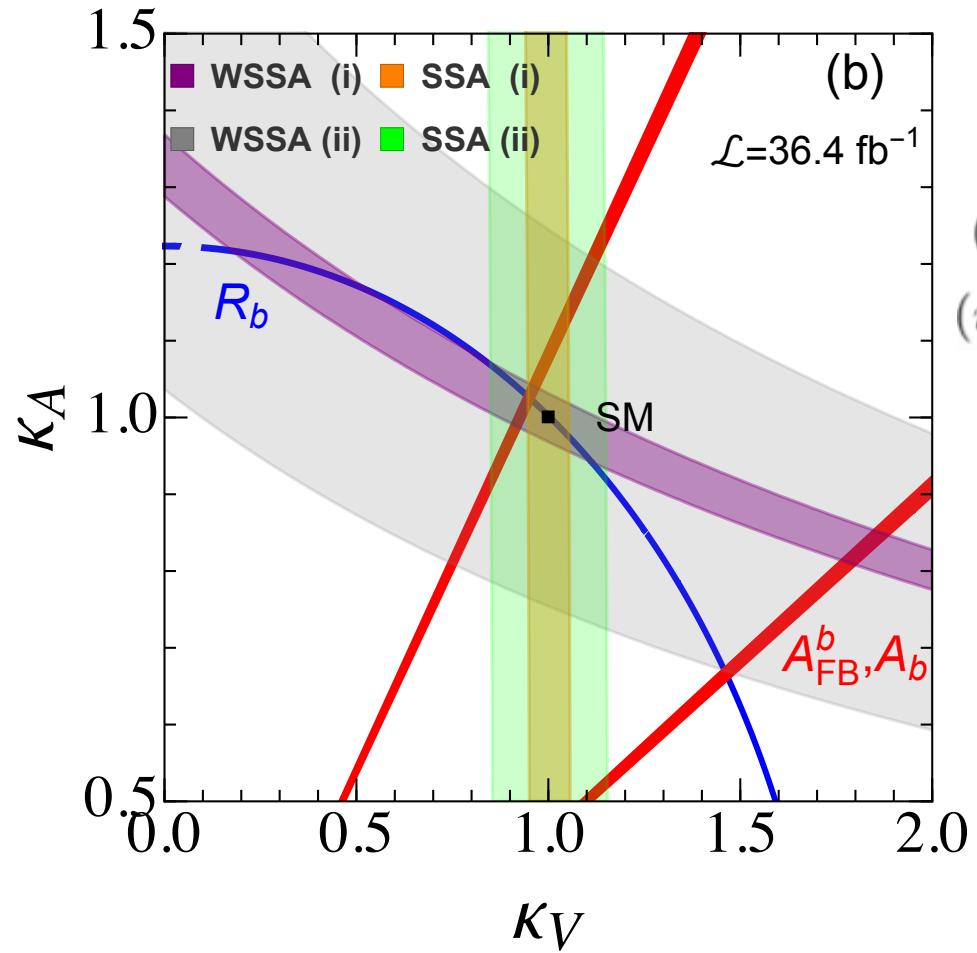
$$F_{1,L} = C_q \otimes (q - \bar{q}) \langle Q_J^q \rangle$$

$$F_3 = C_q \otimes (q + \bar{q}) \langle Q_J^q \rangle$$

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



# Zbb couplings @EIC



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

(i)  $\epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$   
 (ii)  $\epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$

**WSSA**

(i) :  $\mathcal{L} > 0.6 \text{ fb}^{-1};$   
 (ii) :  $\mathcal{L} > 36.4 \text{ fb}^{-1}.$

**SSA**

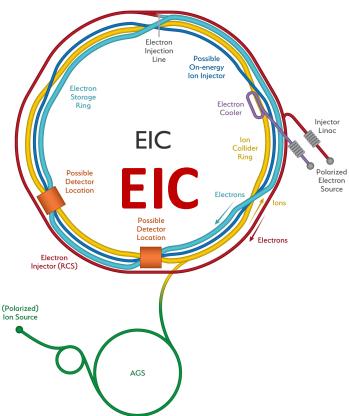
(i) :  $\mathcal{L} > 0.5 \text{ fb}^{-1};$   
 (ii) :  $\mathcal{L} > 4.0 \text{ fb}^{-1}.$

# The new physics effects from the SMEFT

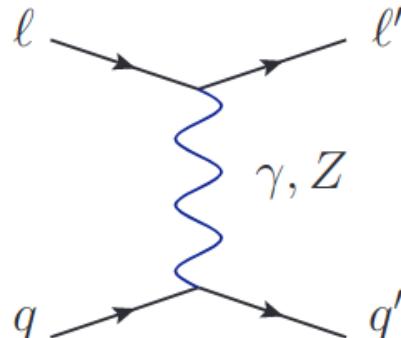
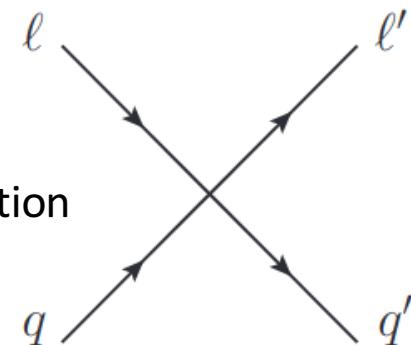
# Effective Field Theory

$$\sqrt{S} = 140 \text{ GeV} \ll \text{TeV}$$

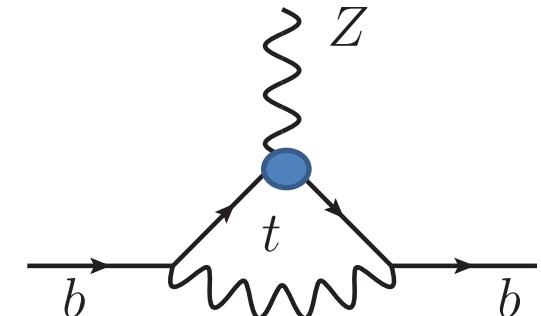
The SMEFT is perfectly applicable at the EIC



Tree-level effects:  
Four-fermion operators  
Charged Lepton flavor violation  
signals  
...



Loop-level effects:  
Top quark couplings  
TGC anomalous couplings  
...

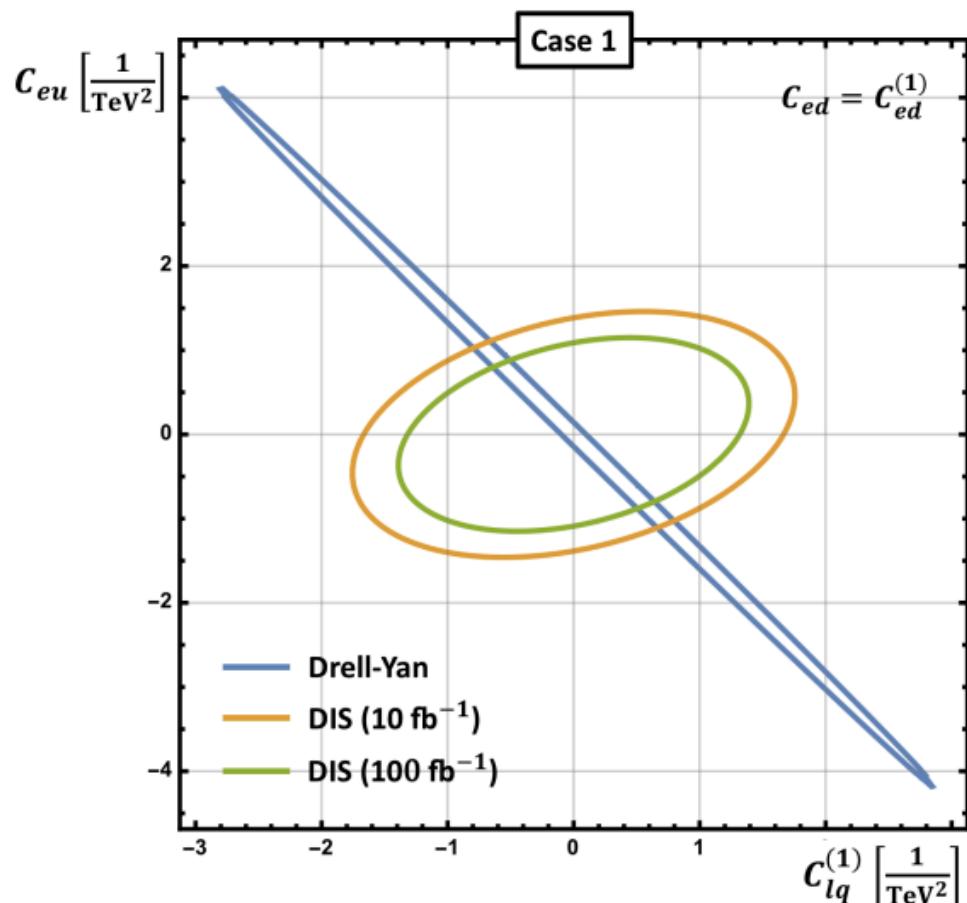
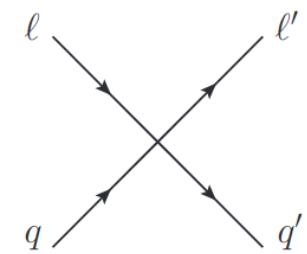


# Four-fermion operators

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

$$P_e = \pm 0.7$$

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



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

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

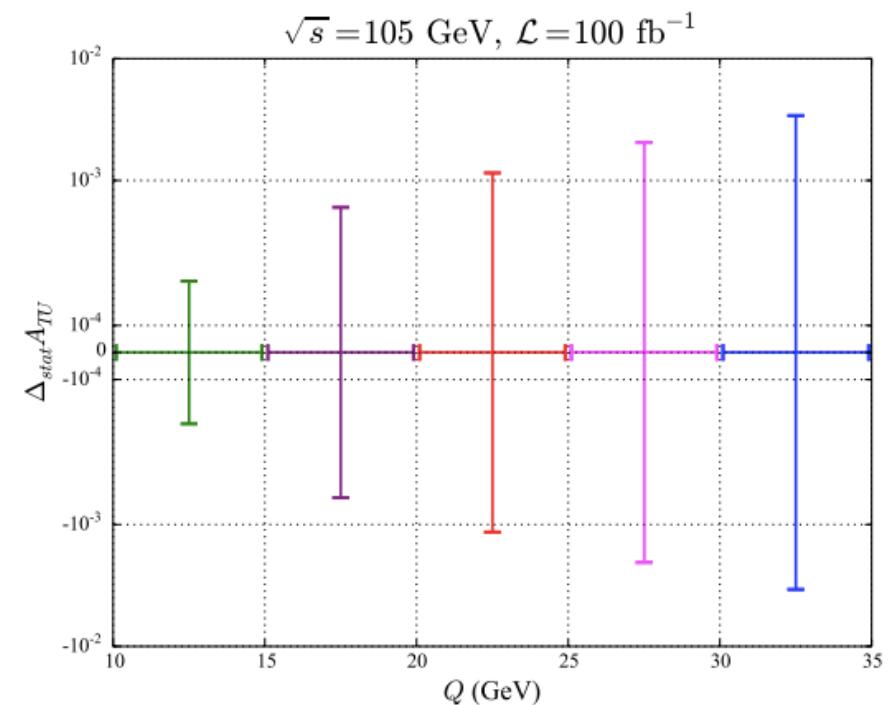
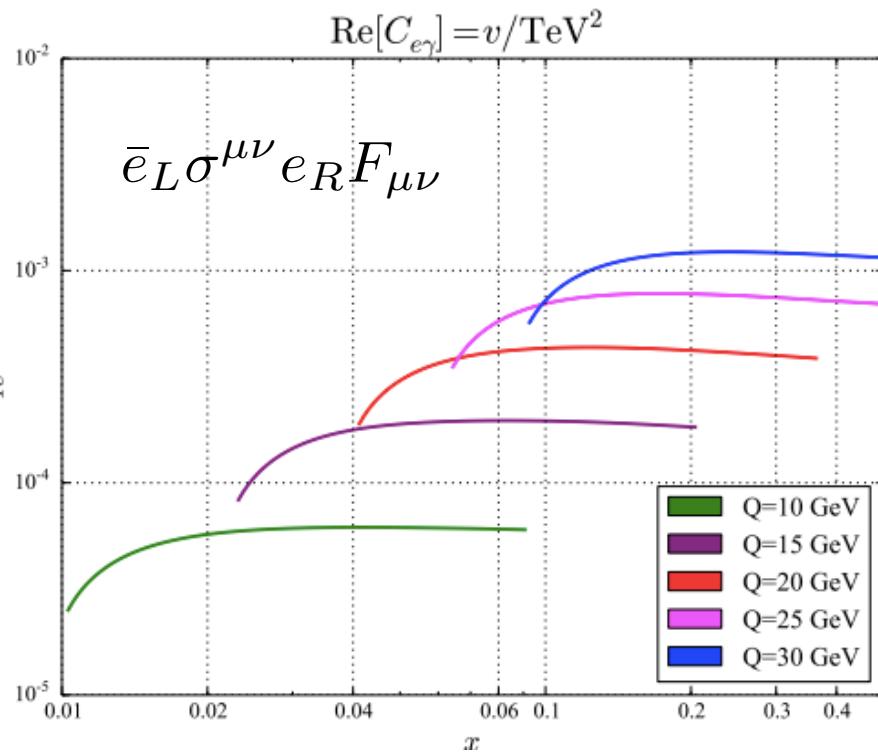
# Dipole operators

R. Boughezal, D. Florian, F. Petriello, W. Vogelsang, arxiv: 2301.02304

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

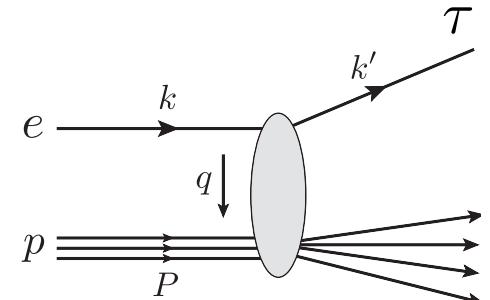
Transverse spin asymmetry

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

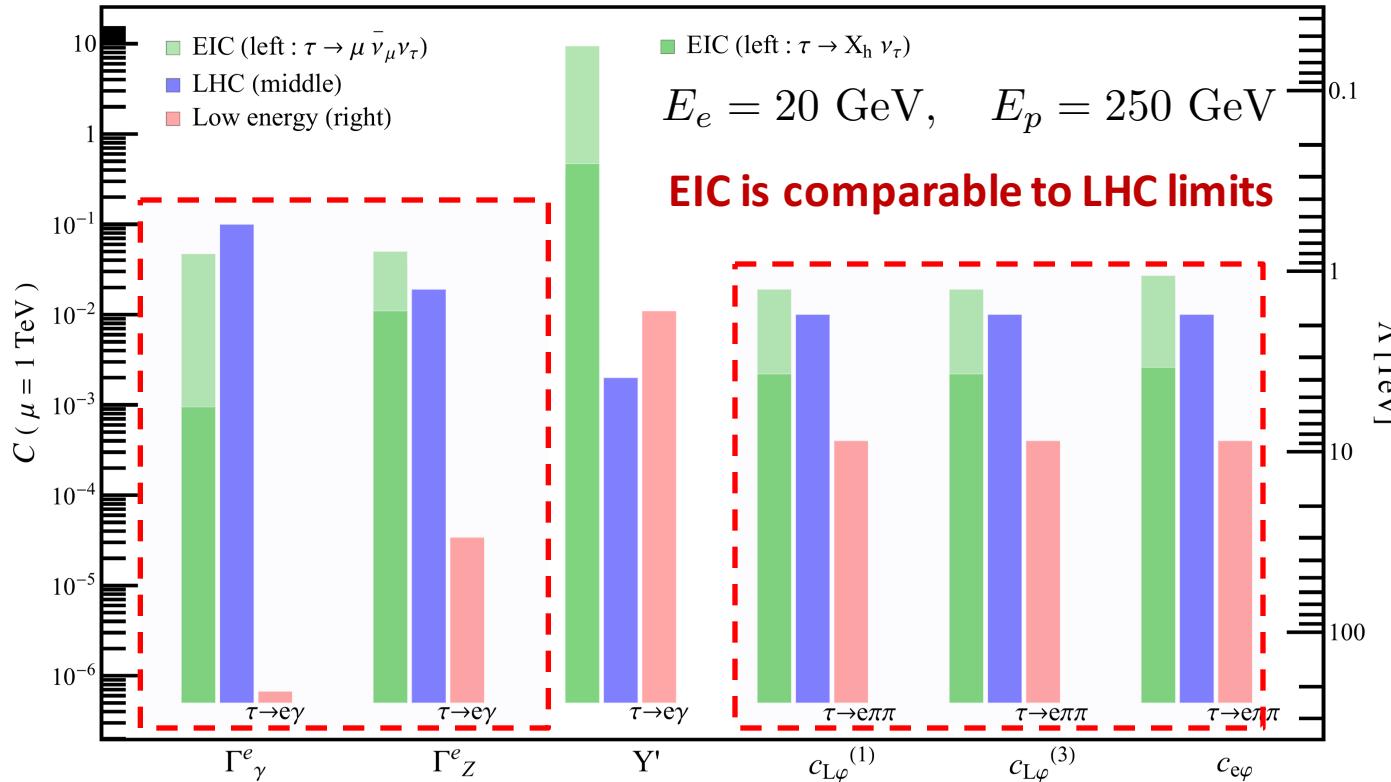


# Charged Lepton Flavor Violation

$$\begin{aligned} \mathcal{L} = & -\frac{g}{2c_W} Z_\mu \left[ \left( c_{L\varphi}^{(1)} + c_{L\varphi}^{(3)} \right)_{\tau e} \bar{\tau}_L \gamma^\mu e_L + c_{e\varphi} \bar{\tau}_R \gamma^\mu e_R \right] \\ & - \frac{e}{2v} [\Gamma_\gamma^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R F_{\mu\nu} - \frac{g}{2c_W v} [\Gamma_Z^e]_{\tau e} \bar{\tau}_L \sigma^{\mu\nu} e_R Z_{\mu\nu} \end{aligned}$$

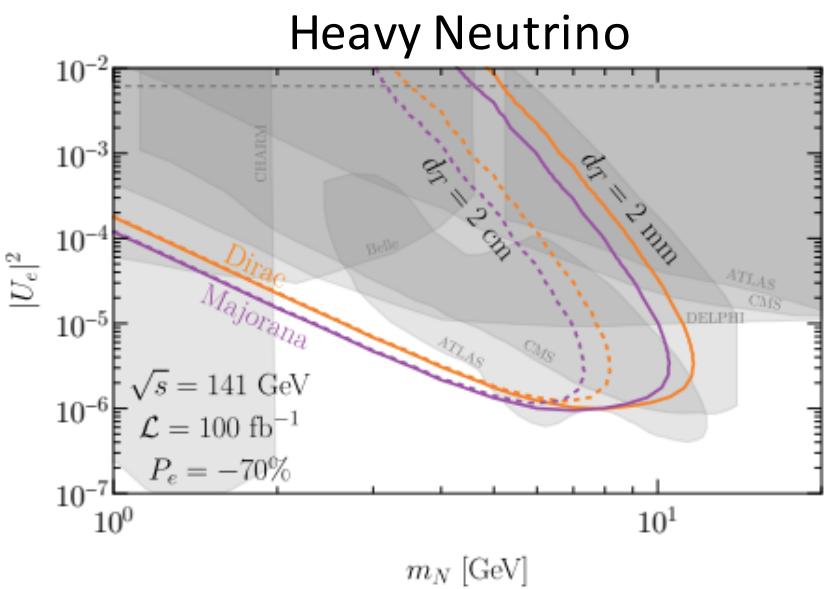
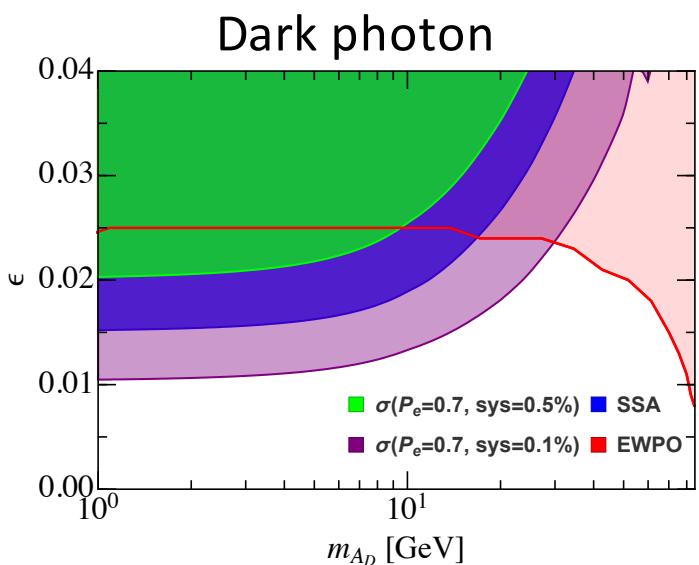
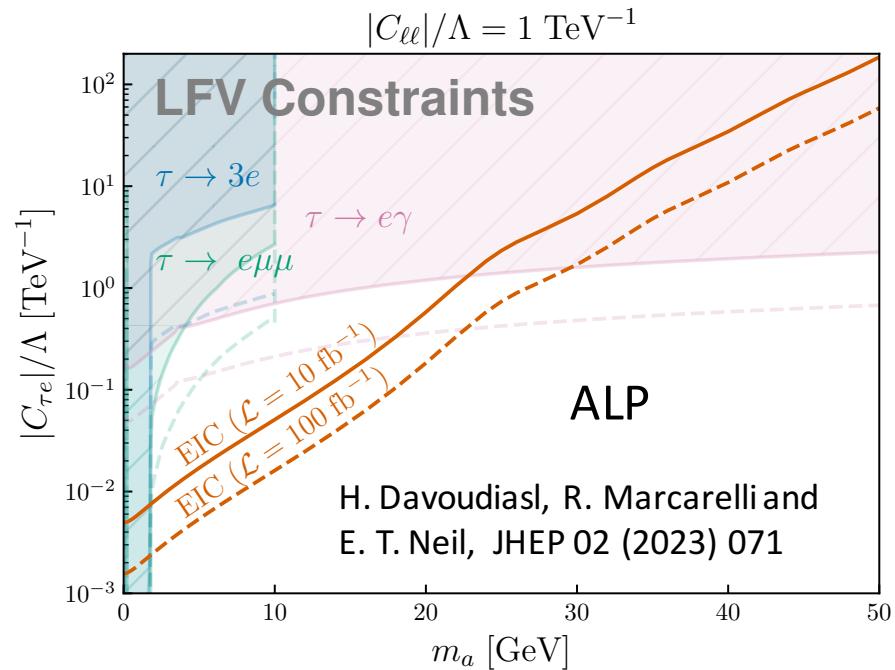
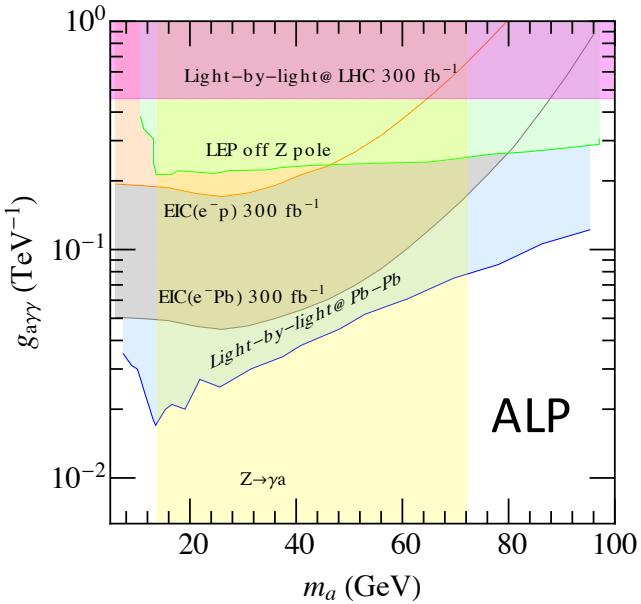


Upper limit on LFV coupling and lower limit on new physics scale



$$\mathcal{L} = 100 \text{ fb}^{-1}$$

# The light new physics particles



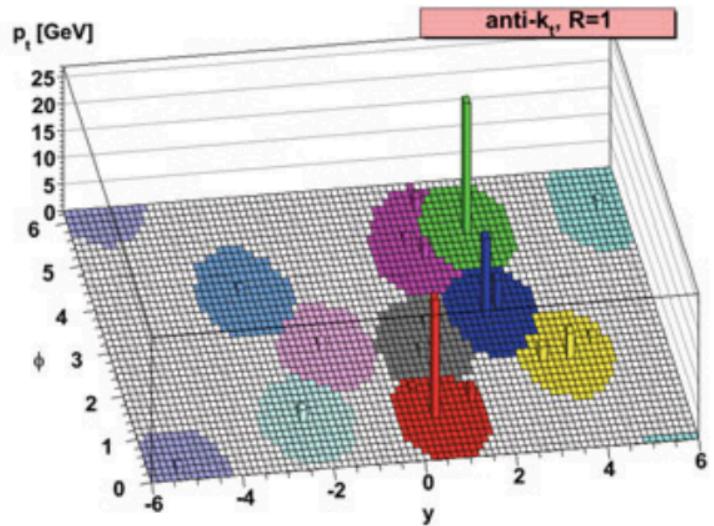
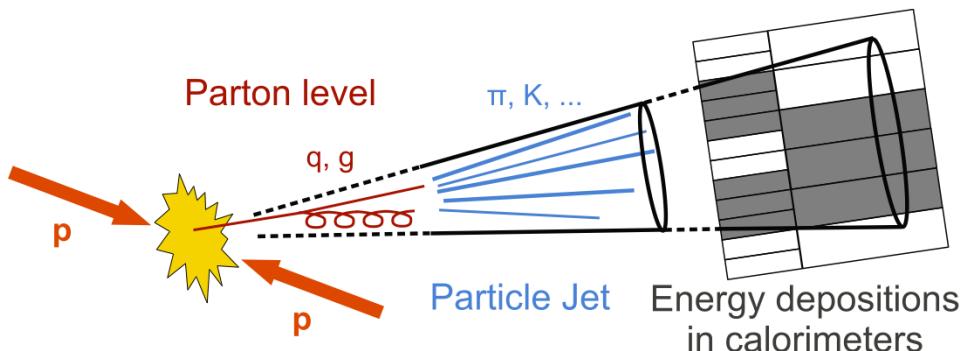
# Summary

- A. EIC is an important machine for probing the new physics;
- B. The electroweak precision measurements: Zbb couplings, weak mixing angle;
- C. New signals: SMEFT, Charged Lepton Flavor violation;
- D. The light particles: Axion-like particles, dark photon, heavy neutrino

The search for new physics at the EIC is just beginning

Thank you!

# Jet charge definition



Transverse-momentum-weighting scheme:

$$Q_J = \frac{1}{(p_T^j)^\kappa} \sum_{i \in jet} Q_i (p_T^i)^\kappa, \quad \kappa > 0$$

$$d_{ij} = \min \left( \frac{1}{p_{ti}^2}, \frac{1}{p_{tj}^2} \right) \frac{\Delta R_{ij}^2}{R^2}$$

K: To regulate the sensitivity  
of the soft gluon radiation

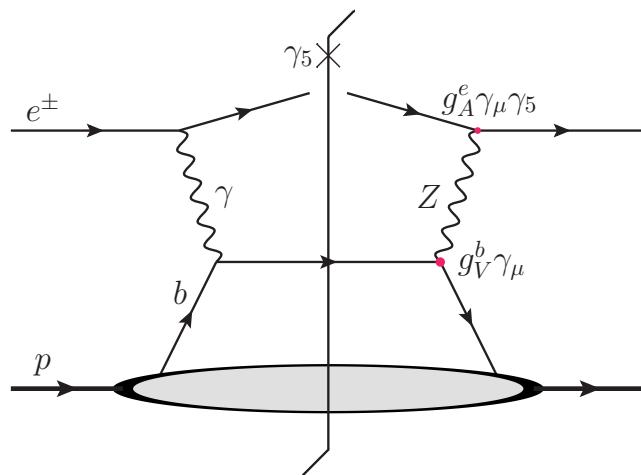
R.D. Field and R.P. Feynman, NPB136,1(1978)

# Weak mixing angle @EIC

The Zqq coupling:  $g_V^q = T_3 - 2Q s_W^2$



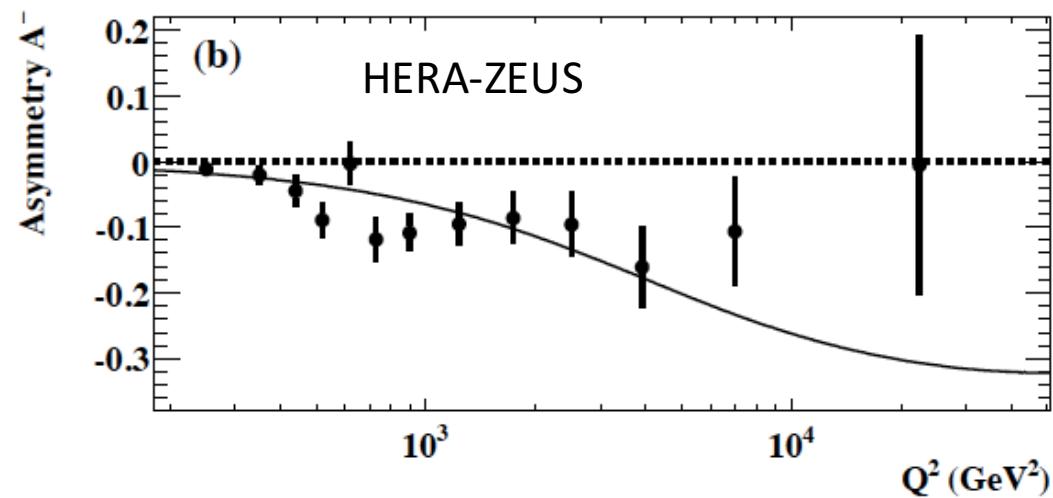
The SSA would be sensitive to the weak mixing angle



$$A_e = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

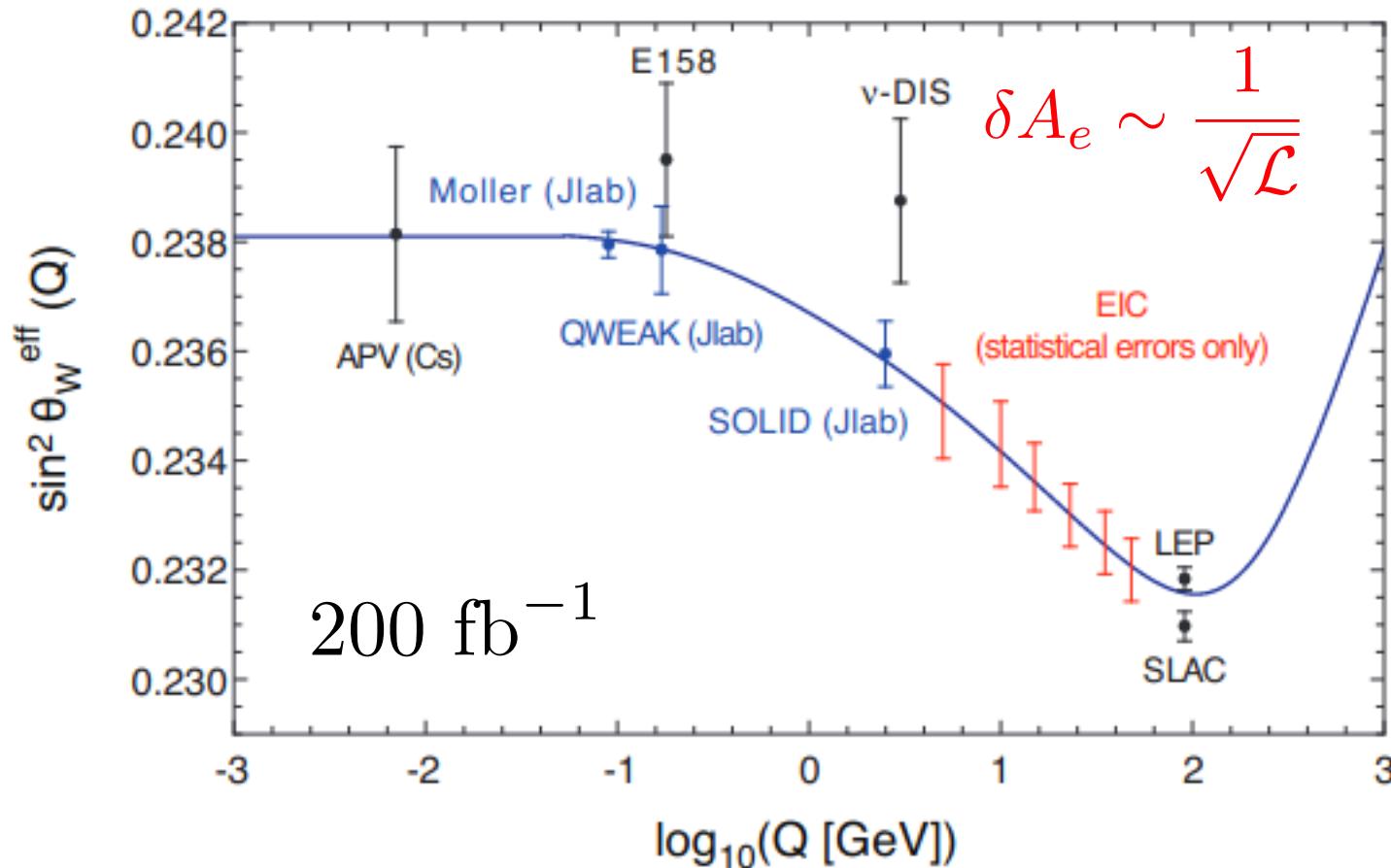
$$F_{1,L} = C_q \otimes (q + \bar{q}) \quad F_3 = C_q \otimes (q - \bar{q})$$

$$g_A^e g_V^q \quad g_V^e g_A^q$$



# Weak mixing angle @EIC

1212.1701



# Charged Lepton Flavor Violation

Lepton Flavor is not conserved:  
Neutrino Oscillations

Charged Lepton Flavor Violation (CLFV):

$$BR \sim \left( \frac{m_\nu}{m_W} \right)^2 \sim 10^{-44}$$

S. Petcov, '77; W. Marciano and A. Sanda, '77



- A. CLFV is sensitive to the NP
- B. CLFV could be related to the neutrino mass generation mechanism;  
Tree level or Loop level

For example: Two loop neutrino mass model  
QHC, SLC, E. Ma, Bin Yan, DMZ, PLB779 (2018)430-435

