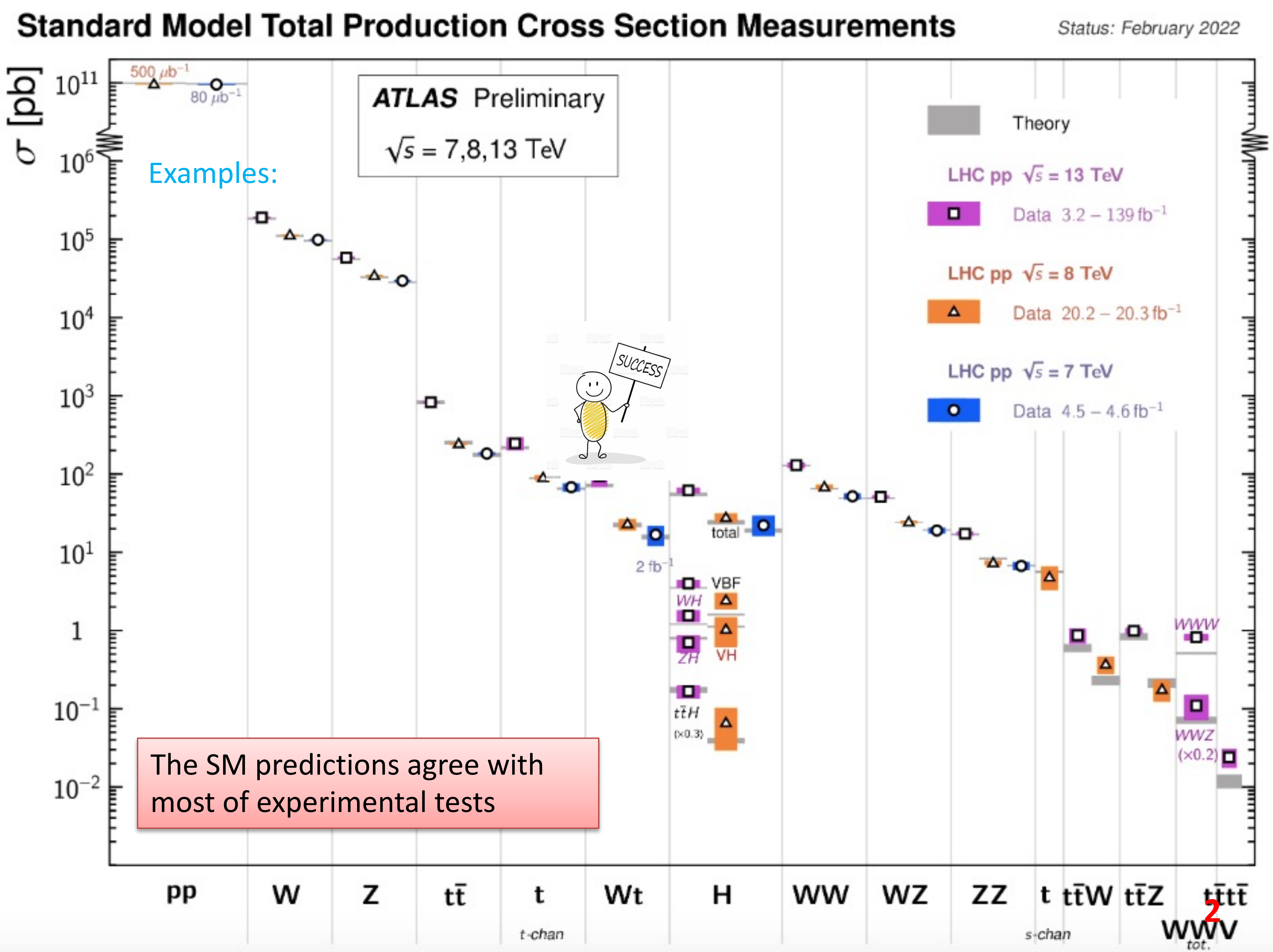
SMEFT analysis at the EIC

Bin Yan
Institute of High Energy Physics

第十二届新物理研讨会
July 23-29, 2023

Examples:



The SM predictions agree with most of experimental tests

Why we need the New Physis?

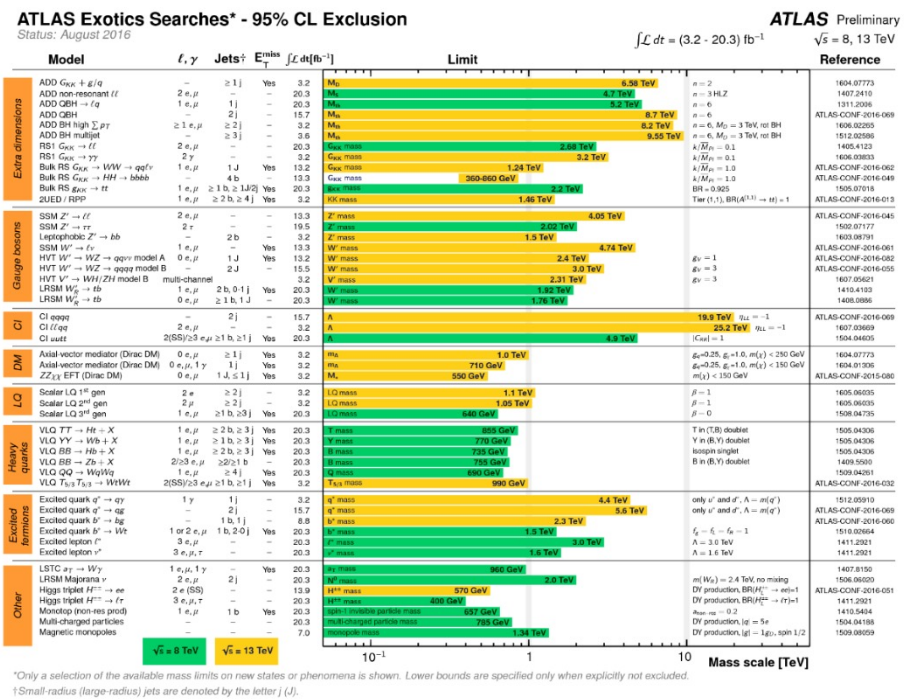
Some open questions:

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

How to probe the NP

SUSY   Little Higgs   Composite   .....

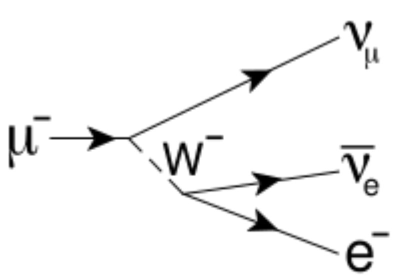


Top down approach

$O(\mathrm{TeV})$

W', Z', T, B, scalar …

Bottom up approach



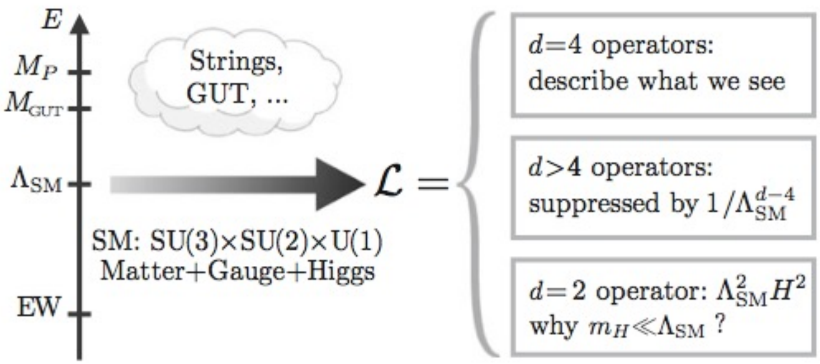
Effective Field Theory ← Experimental Data

SMEFT and NP

Linear realized EFT

Higgs is a fundamental particle

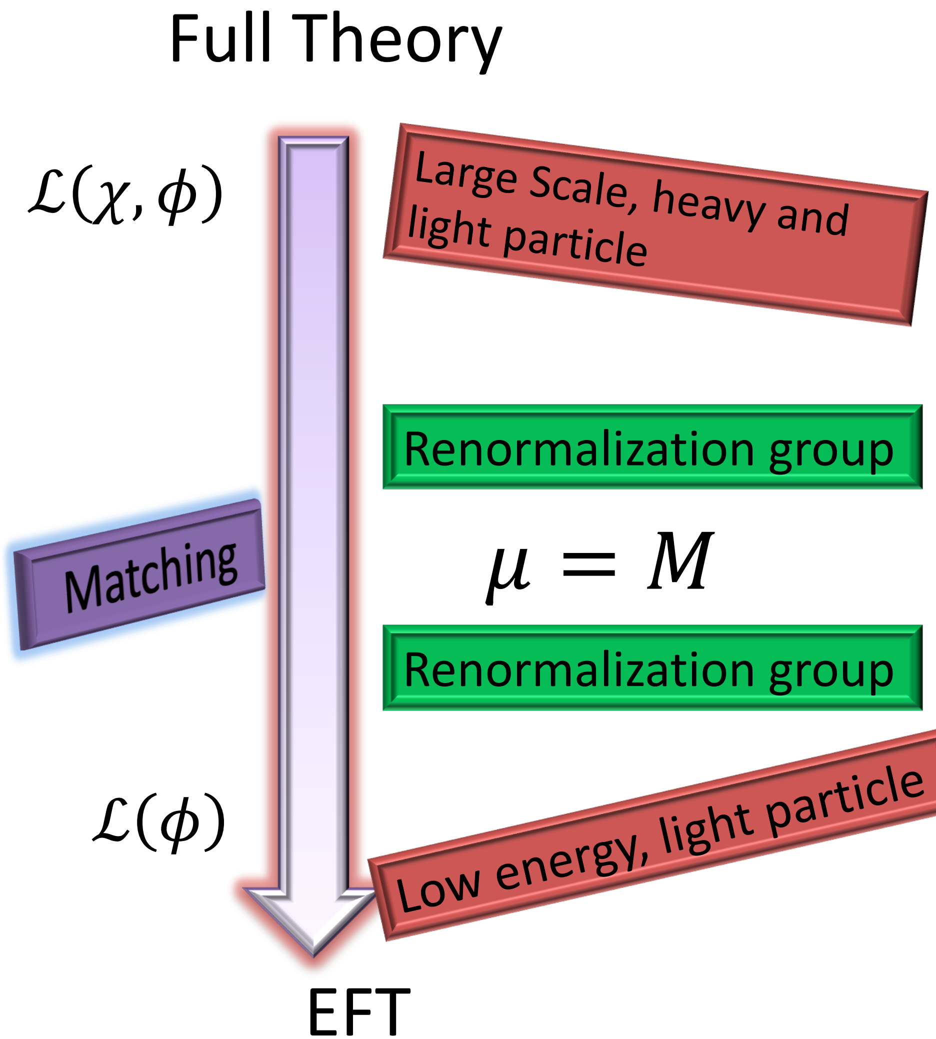
Weak interacting



W. Buchuller, D. wyler 1986
B. Grzadkowski et al, 2010
L. Lehman, A. Marin, 2015
B. Henning et al, 2015
H-L. Li et al, 2020

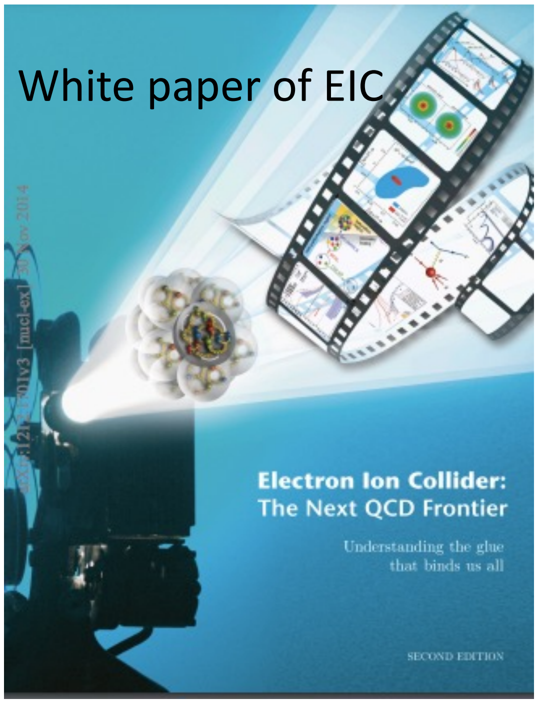
Appelquist-Carazzone Decoupling theorem:

$$\mathcal{L} = C_6 O_6 + C_8 O_8 + \ldots$$



Howard Georgi, Annu.Rev.Nucl.Part.Sci.1993.43:209-52

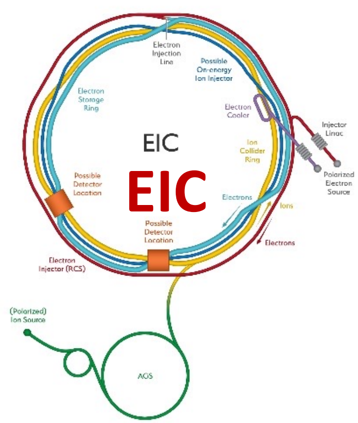
Why Electron-Ion Collider?



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: $10 \sim 100 \ \mathrm{fb}^{-1}$ per year

High Polarization: $P_e = P_p = 0.7$



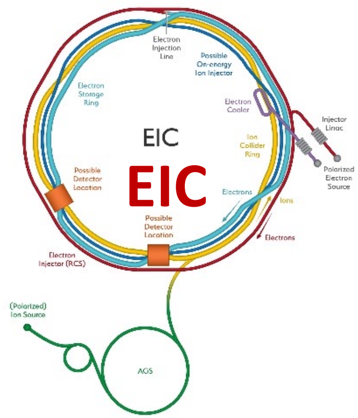
Electroweak properties

EIC is also an important machine for the New Physics

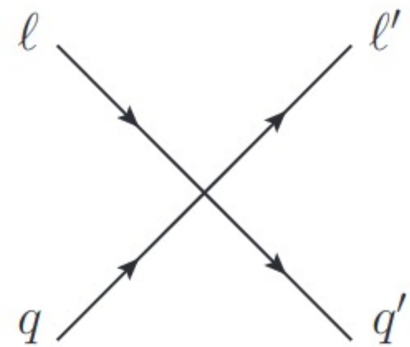
Effective Field Theory

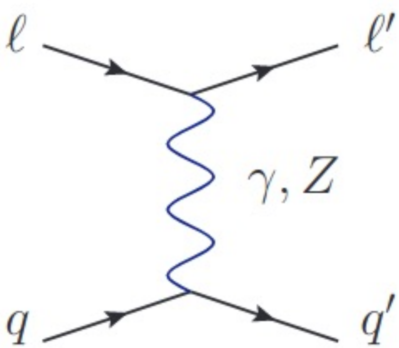
$$\sqrt{S} = 140 \text{ GeV} \ll \text{TeV}$$

The SMEFT is perfectly applicable at the EIC

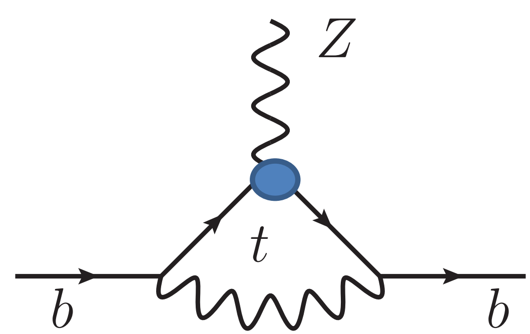


Tree-level effects:
Four-fermion operators
Charged Lepton flavor violation signals
…





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



Outline

- The electroweak precision measurements
- New Physics effects from SMEFT

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

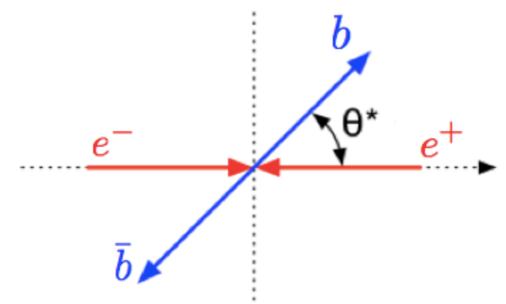
The electroweak precision measurements

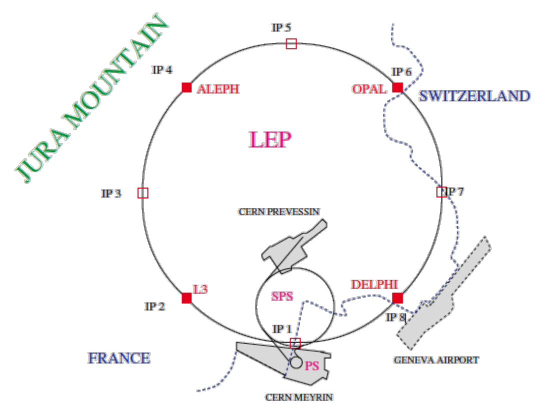
Electroweak Precision measurement

	Measurement with Total Error	Systematic Error	Standard Model High-Q^2 Fit	Pull
$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)$ [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^0_{had} [nb]	41.540 ± 0.037	$^{(a)}0.028$	41.481 ± 0.014	1.6
R^0_ℓ	20.767 ± 0.025	$^{(a)}0.007$	20.739 ± 0.018	1.1
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	$^{(a)}0.0003$	0.01642 ± 0.00024	0.8
+ correlation matrix Table 2.13				
$\mathcal{A}_\ell$ (P_τ)	0.1465 ± 0.0033	0.0015	0.1480 ± 0.0011	0.5
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0011	0.1480 ± 0.0011	1.6
R^0_b	0.21629 ± 0.00066	0.00050	0.21562 ± 0.00013	1.0
R^0_c	0.1721 ± 0.0030	0.0019	0.1723 ± 0.0001	0.1
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016	0.0007	0.1037 ± 0.0008	2.8
$A^{0,c}_{\mathrm{FB}}$	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				
$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ ($Q^{\mathrm{had}}_{\mathrm{FB}}$)	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				

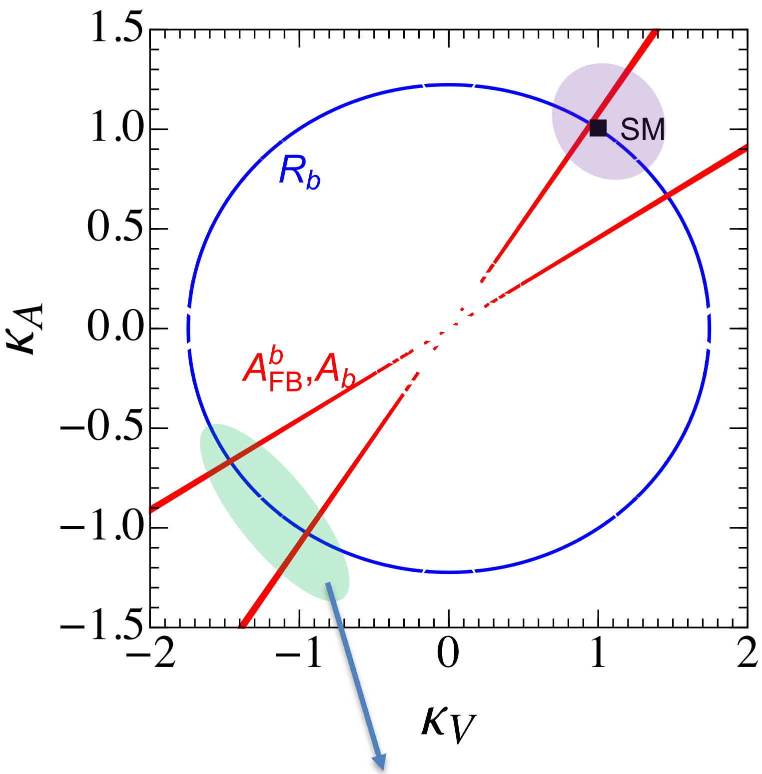
Phys.Rept. 427 (2006) 257-454

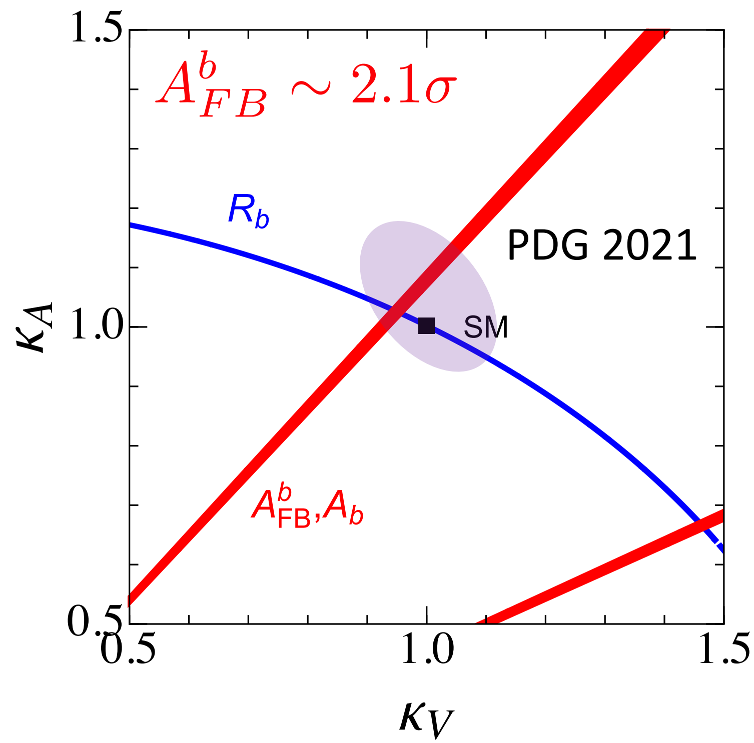
LEP： 1989-2000





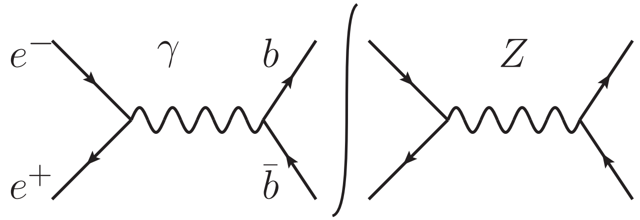
Electroweak Precision measurement





Excluded by off-Z pole data

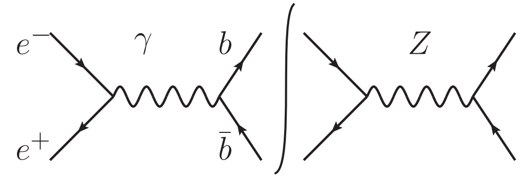
$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$



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

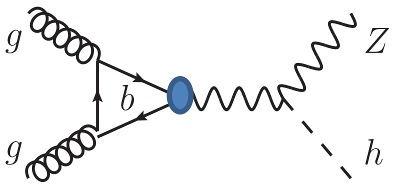
Zbb couplings@ colliders

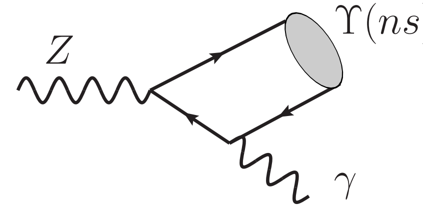
A. Lepton colliders:



S. Gori, Jiayin Gu, Lian-Tao Wang, JHEP 04(2016) 062
Bin Yan, C.-P. Yuan and Shu-Run Yuan, 2307.08014

B. LHC Zh production and Z boson rare decay:



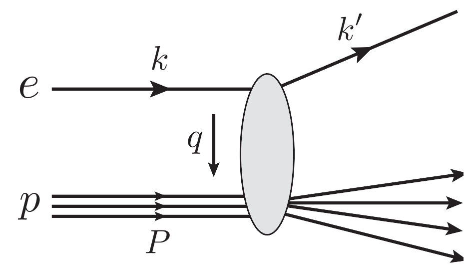


Bin Yan, C.-P. Yuan, PRL127(2021)5,051801

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:

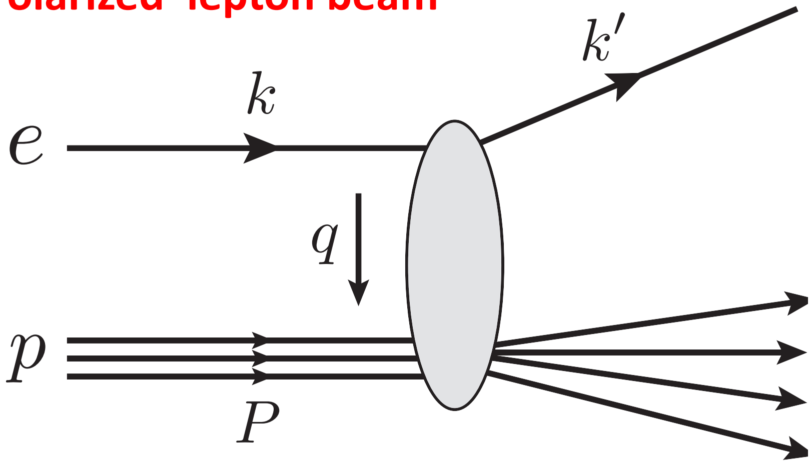


Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697
Hai Tao Li, Bin Yan and C.-P. Yuan, PLB833(2022)137300

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

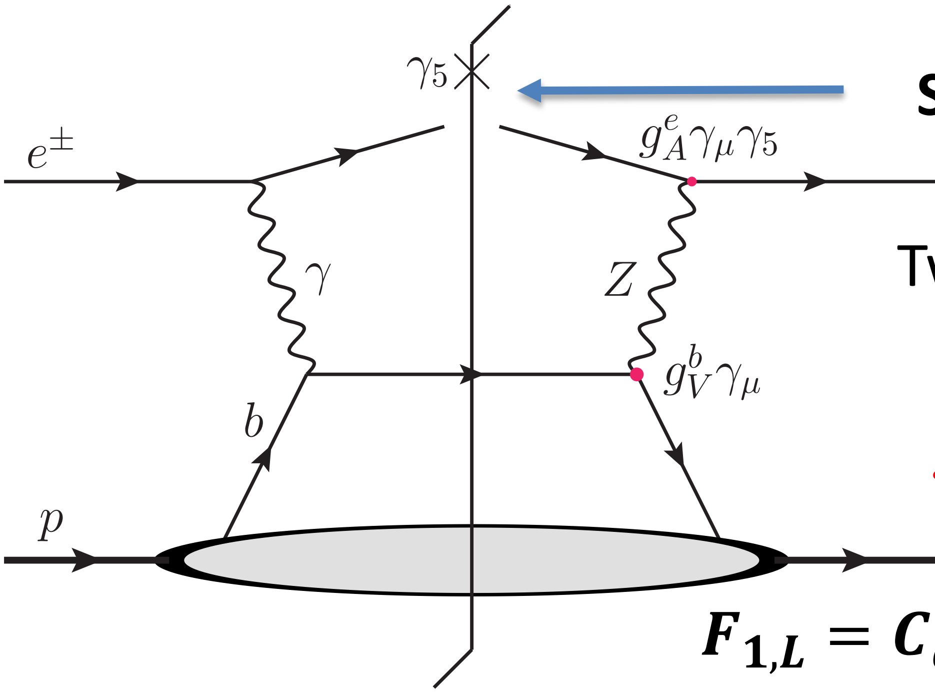
DIS cross section

Polarized cross section

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

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

$\lambda_e = \pm 1$: lepton helicity



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

Two possible combination:

$g_A^e g_V^b$ ✓ $\qquad g_V^e g_A^b$

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

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

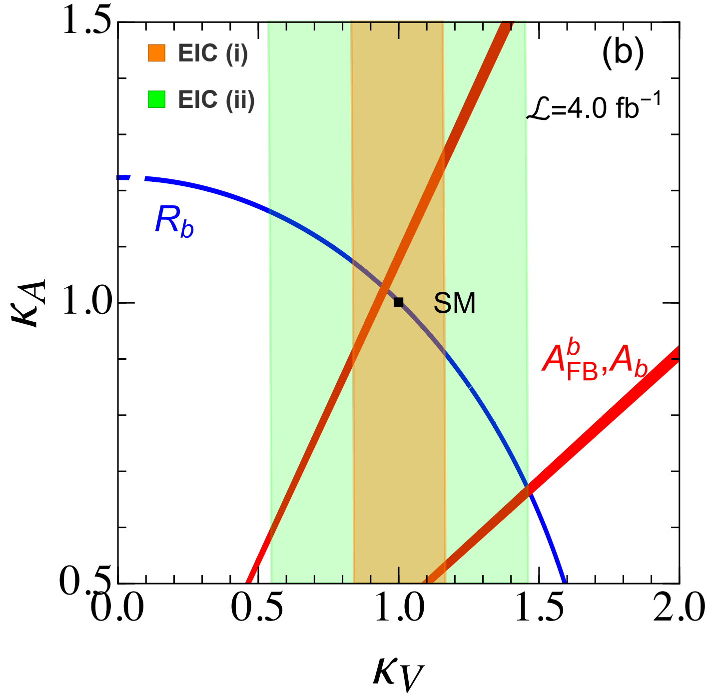
Zbb couplings @EIC

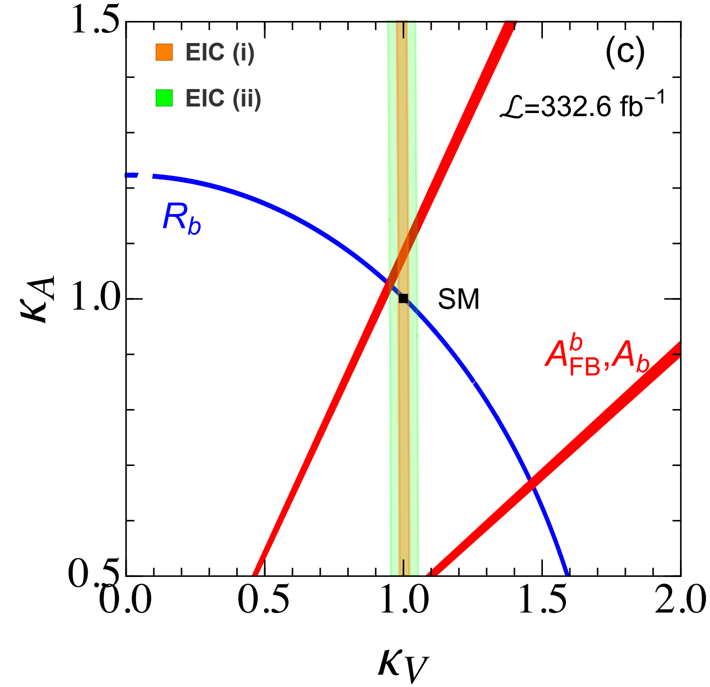
$(i)\ \epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$

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

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

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





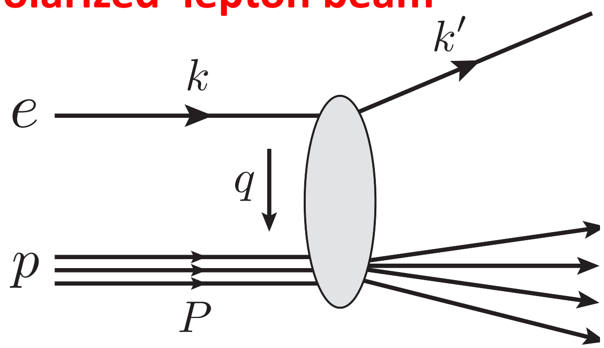
The minimal luminosities needed to resolve the degeneracy or exclude LEP AFB data:

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

Zbb couplings @EIC

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

Polarized lepton beam



Single-Spin Asymmetry:

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

vector component of the Zbb coupling

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

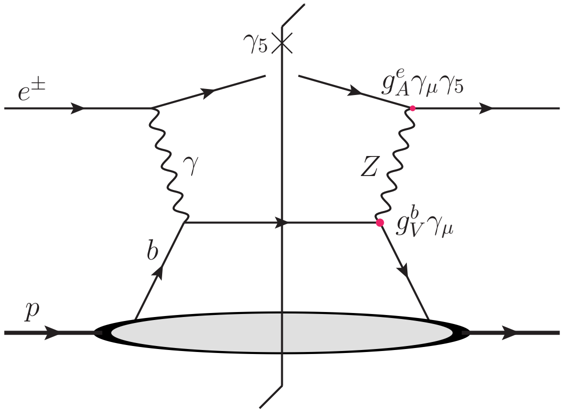
Average jet charge weighted Single-Spin Asymmetry (WSSA):

$$A_e^{bQ} = \frac{\sigma_{b,+}^{Q} - \sigma_{b,-}^{Q}}{\sigma_{b,+}^{Q} + \sigma_{b,-}^{Q}} \qquad \sigma_{b,\pm}^{Q} = \int dp_T^j \frac{d\sigma_{b,\pm}^{\rm tot}}{dp_T^j} \langle Q_J \rangle_b (p_T^j)$$

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

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

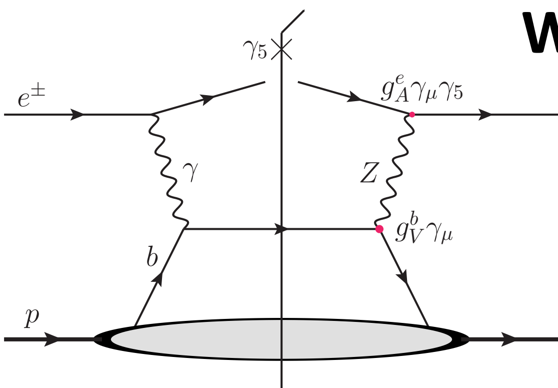


SSA: $\boldsymbol{\sigma_{b,+} - \sigma_{b,-}}$

$g_A^e g_V^b$ | $g_V^e g_A^b$

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

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



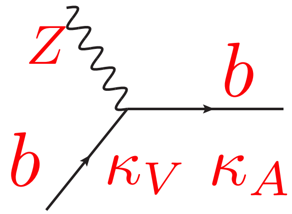
WSSA: $\sigma_{b,+}^{Q} - \sigma_{b,-}^{Q}$

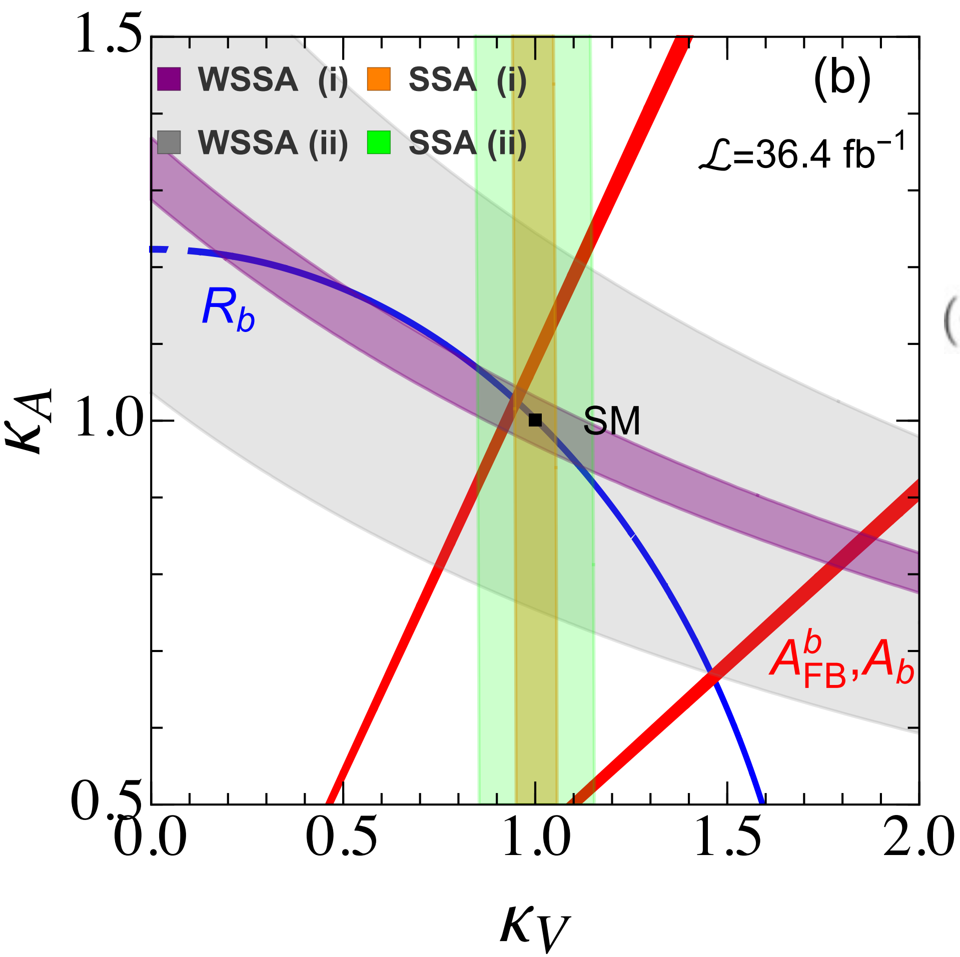
$g_A^e g_V^b$ | $g_V^e g_A^b$

$F_{1,L} = C_q \otimes (q - \bar{q}) \langle Q_J^q \rangle$ | $F_3 = C_q \otimes (q + \bar{q}) \langle Q_J^q \rangle$

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

Zbb couplings @EIC





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

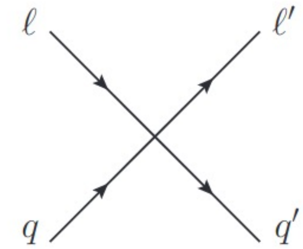
$(i)\ \epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$

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

WSSA	**SSA**
$(i) : \mathcal{L} > 0.6\ \mathrm{fb}^{-1};$	$(i) : \mathcal{L} > 0.5\ \mathrm{fb}^{-1};$
$(ii) : \mathcal{L} > 36.4\ \mathrm{fb}^{-1}.$	$(ii) : \mathcal{L} > 4.0\ \mathrm{fb}^{-1}.$

The new physics effects from the SMEFT

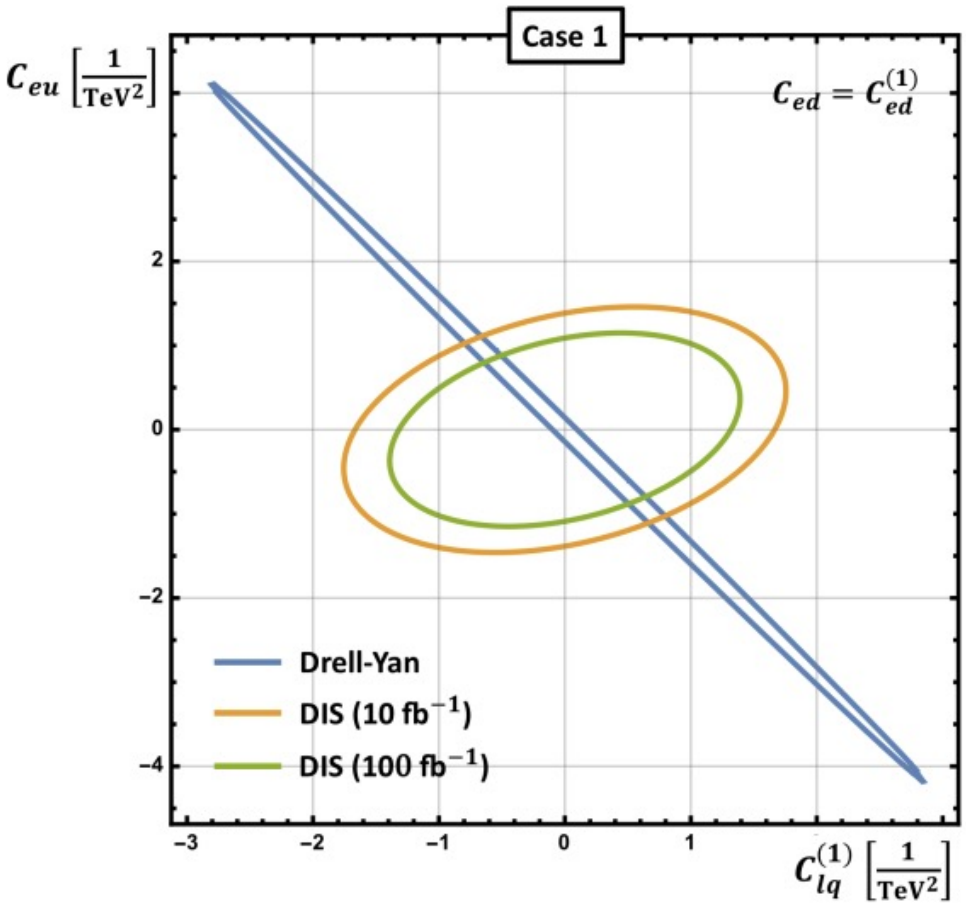
Four-fermion operators



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

$$P_e = \pm 0.7$$

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



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

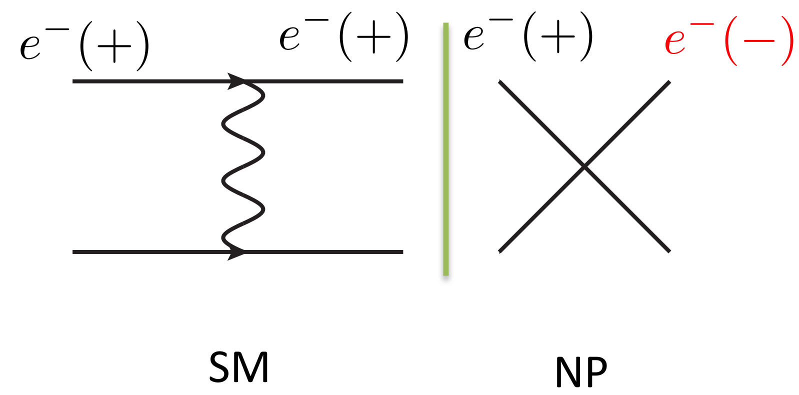
Polarization of the electron plays the key role to resolve the degeneracies from LHC data

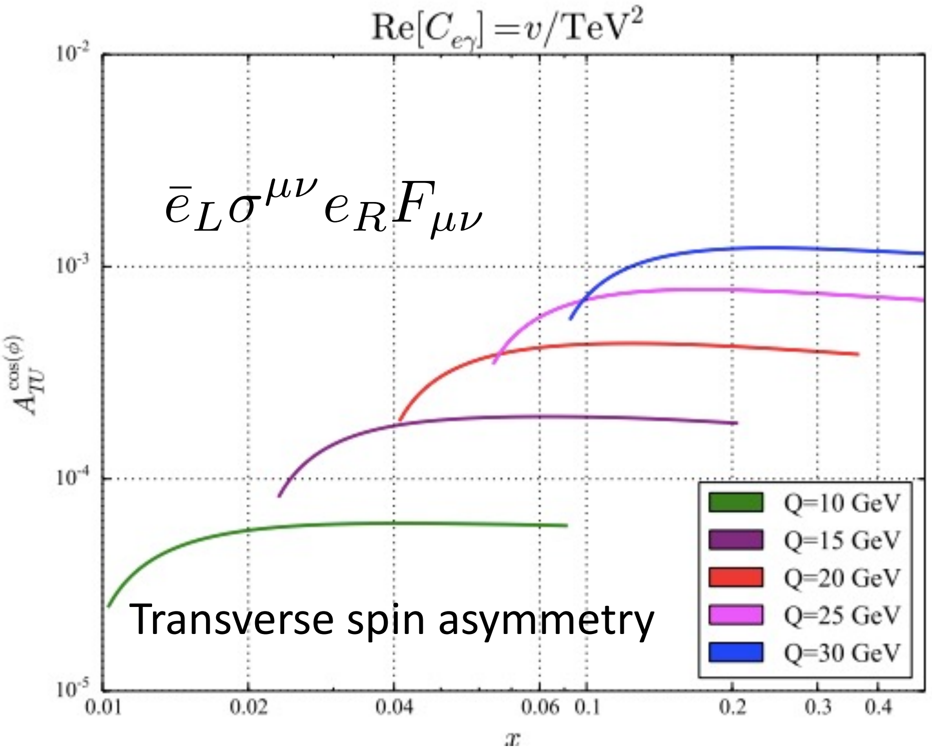
Dipole operators

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

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

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





$$\mathcal{O}_{eW} = (\bar{l}\sigma^{\mu\nu} e)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{eB} = (\bar{l}\sigma^{\mu\nu} e)\varphi B_{\mu\nu},$$
$$\mathcal{O}_{uW} = (\bar{q}\sigma^{\mu\nu} u)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{uB} = (\bar{q}\sigma^{\mu\nu} u)\varphi B_{\mu\nu},$$
$$\mathcal{O}_{dW} = (\bar{q}\sigma^{\mu\nu} d)\tau^I \varphi W^I_{\mu\nu},$$
$$\mathcal{O}_{dB} = (\bar{q}\sigma^{\mu\nu} d)\varphi B_{\mu\nu}.$$

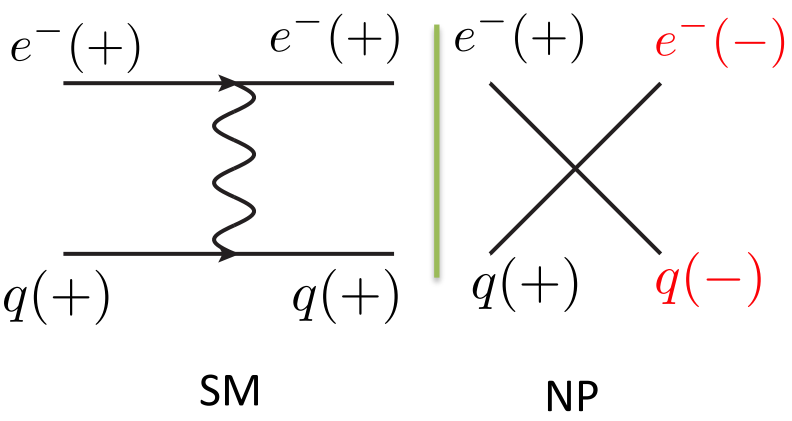
Scalar and tensor operators

Hao-Lin Wang, Xin-Kai Wen, HongXi Xing and Bin Yan, work in progress

Transverse double spin asymmetry $\mathcal{O}(1/\Lambda^2)$

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

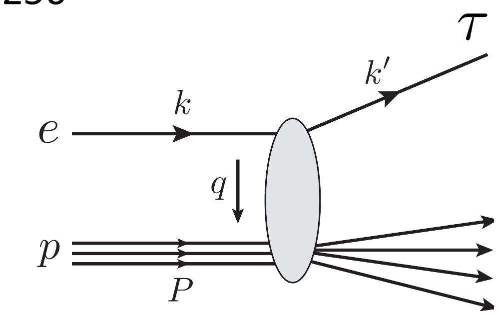
$$\mathcal{O}_{ledq} = (\bar{l}^j e)(\bar{d} q^j),$$
$$\mathcal{O}^{(1)}_{lequ} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u),$$
$$\mathcal{O}^{(3)}_{lequ} = (\bar{l}^j \sigma^{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma_{\mu\nu} u).$$

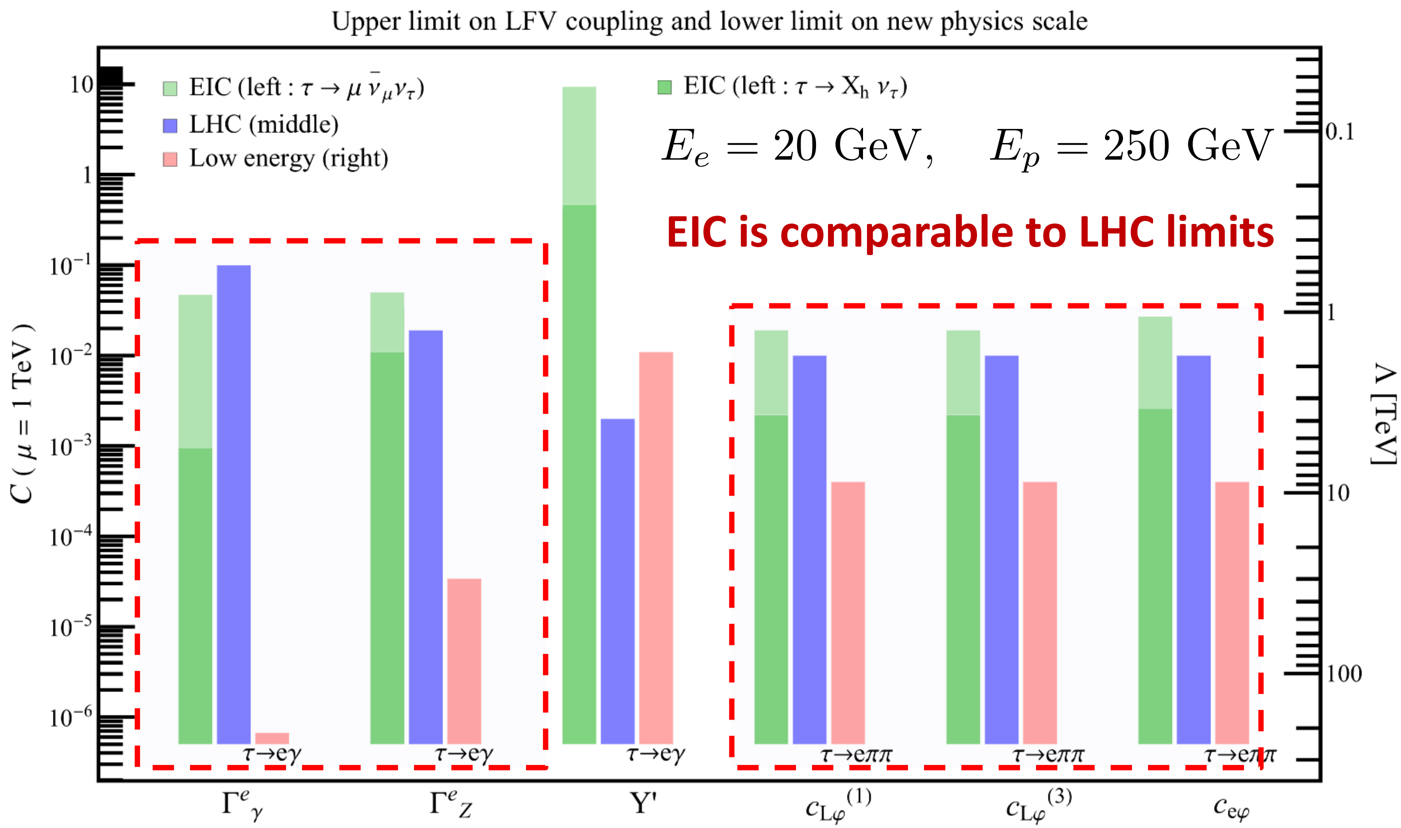


Charged Lepton Flavor Violation

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

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





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

Summary

A. EIC is an important machine for probing the new physics;

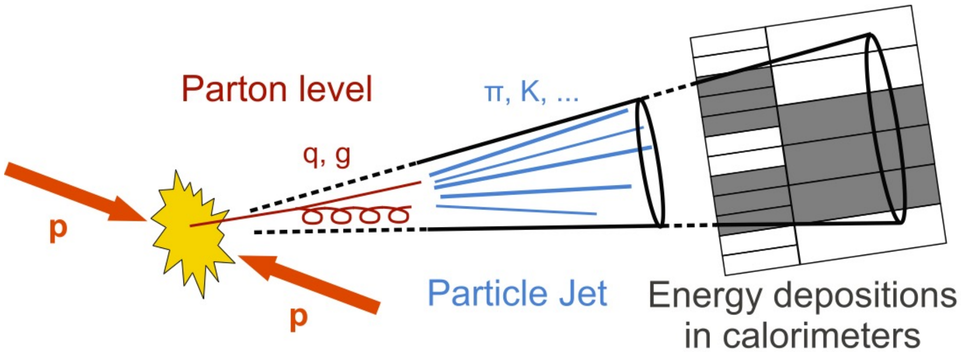
B. The electroweak precision measurements: Zbb couplings;

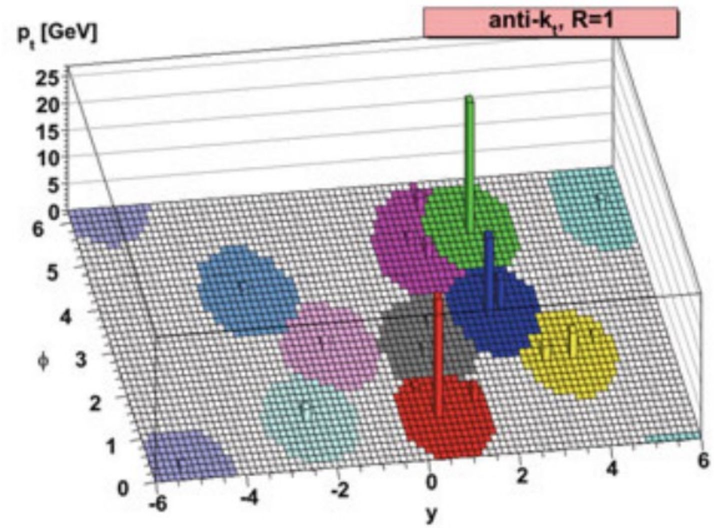
C. New signals: SMEFT, Charged Lepton Flavor violation;

The search for new physics at the EIC is just beginning

Thank you!

Jet charge definition





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

Transverse-momentum-weighting scheme:

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

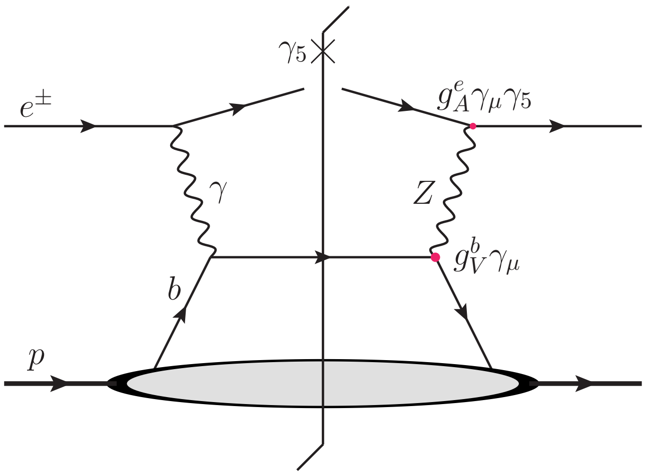
K: To regulate the sensitivity of the soft gluon radiation

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

Weak mixing angle @EIC

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

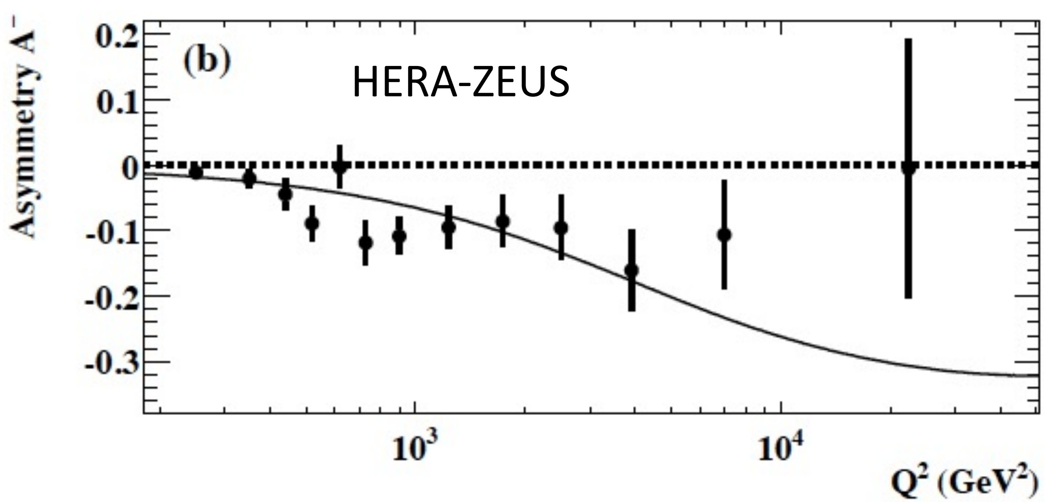
The SSA would be sensitive to the weak mixing angle



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

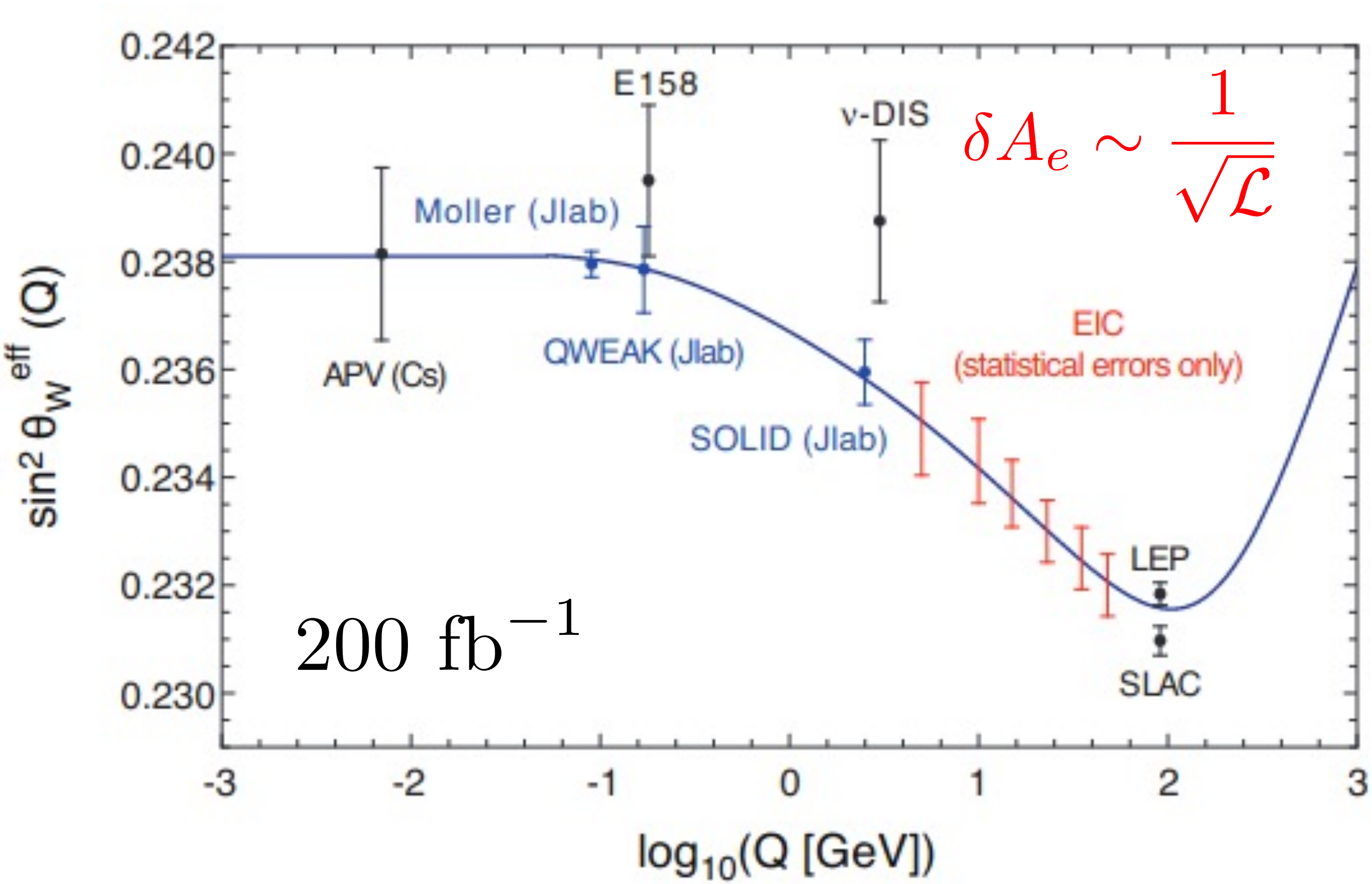
$\boldsymbol{F_{1,L} = C_q \otimes (q + \bar{q})}$ $\quad$ $\boldsymbol{F_3 = C_q \otimes (q - \bar{q})}$

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



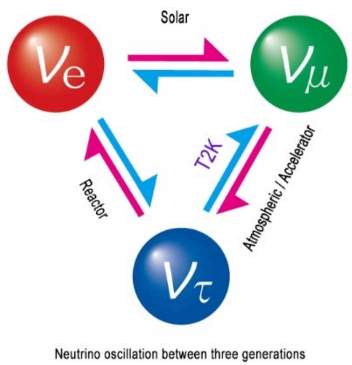
Weak mixing angle @EIC

1212.1701



Charged Lepton Flavor Violation

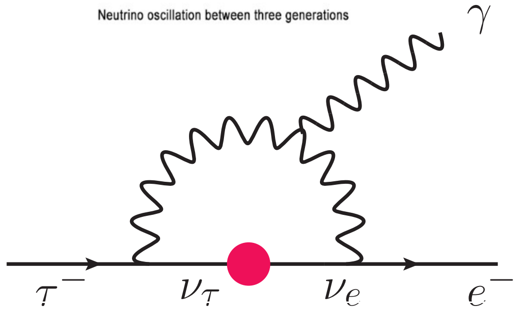
Lepton Flavor is not conserved:
Neutrino Oscillations



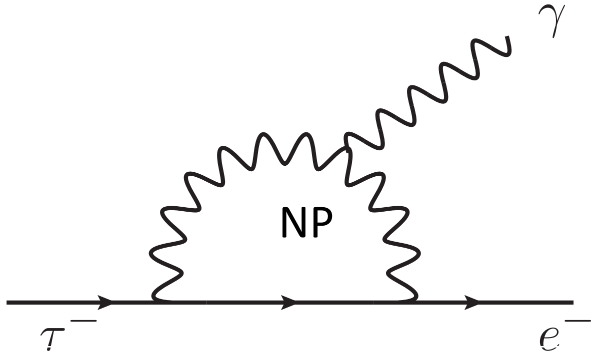
Charged Lepton Flavor Violation (CLFV):

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

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