

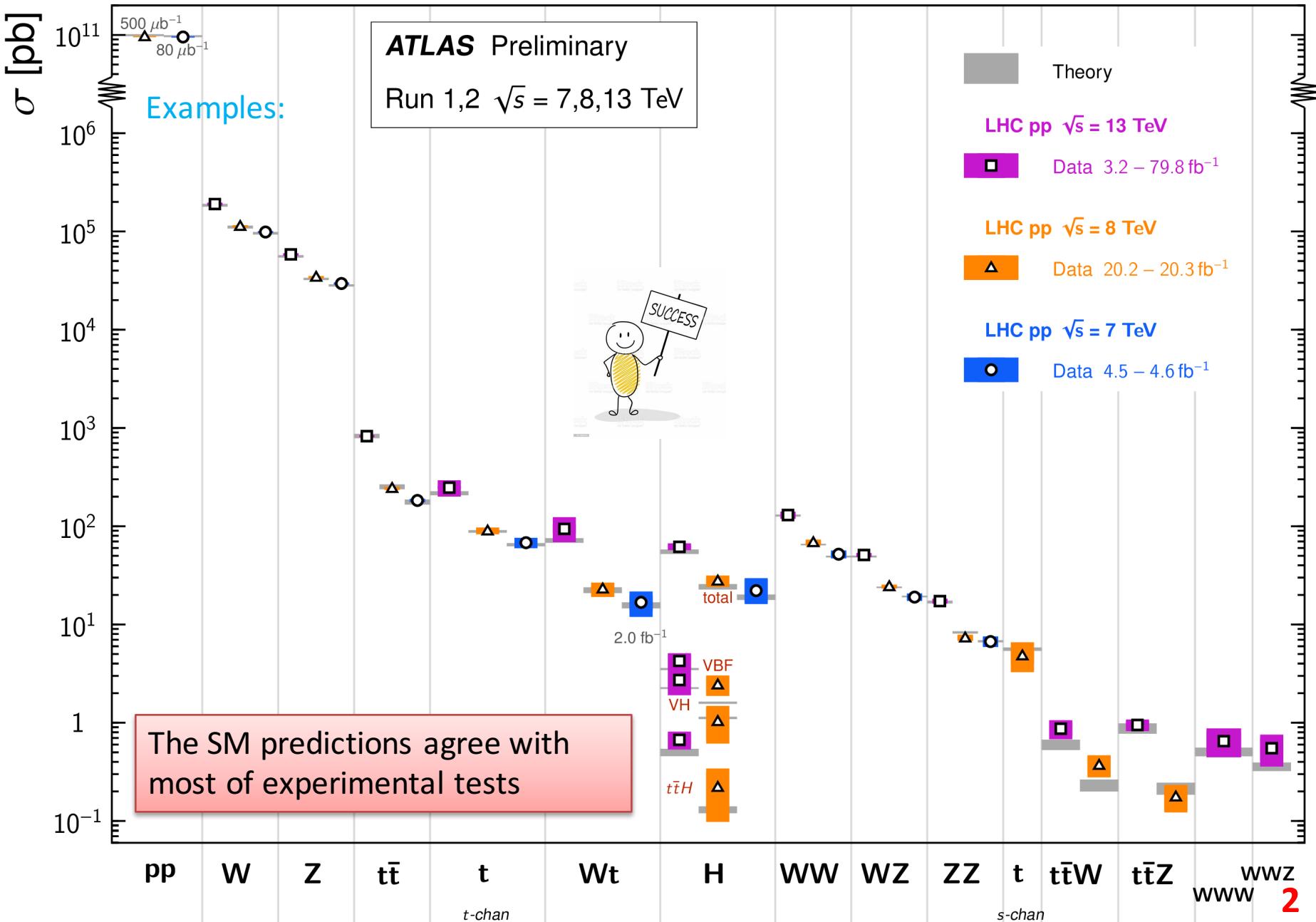
Searching for new physics at the EIC

Bin Yan
Institute of High Energy Physics

16th TeV Physics Workshop
Nov 8-11, 2022

Standard Model Total Production Cross Section Measurements

Status: May 2020



Why we need the New Physics?

Some open questions:

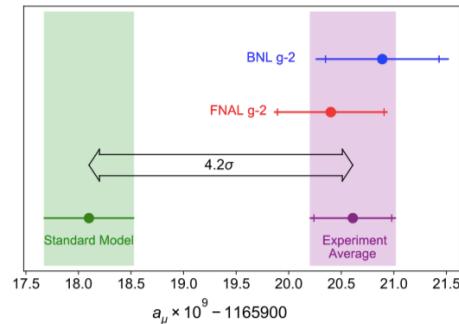
1. What is Dark Matter ?
2. What is the origin of the neutrino mass?
3. What is the nature of the electroweak symmetry breaking?
4. What is the nature of the Higgs boson (Composite or elementary particle)?
5.

New Physics Models and new measurements to answer these questions

The New Physics Signals?

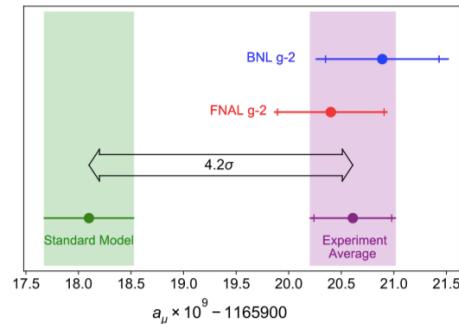
1. W-boson mass? 7σ

CDF, Science 376(2022)6589



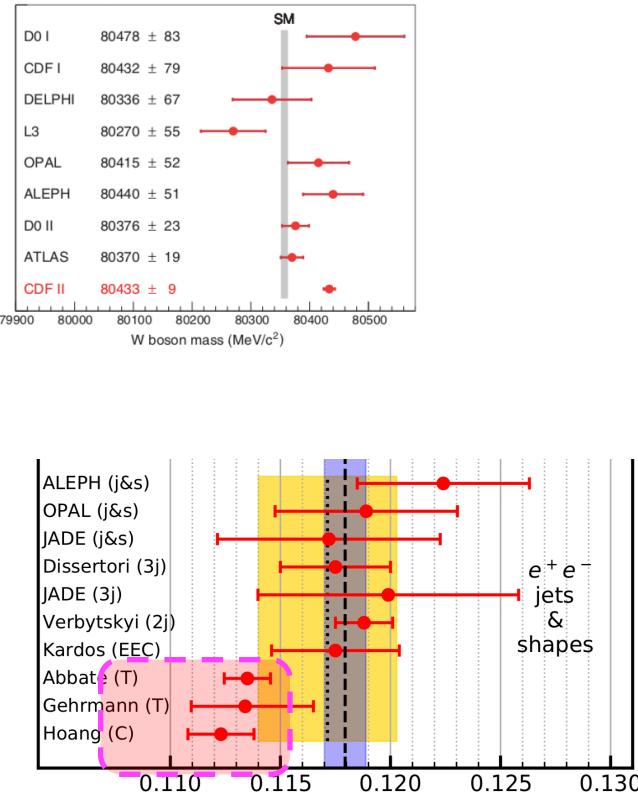
2. Muon g-2? 4.2σ

PRL126(2021)14,141801



3. Strong coupling?

PDG2020 $\sim 4\sigma$

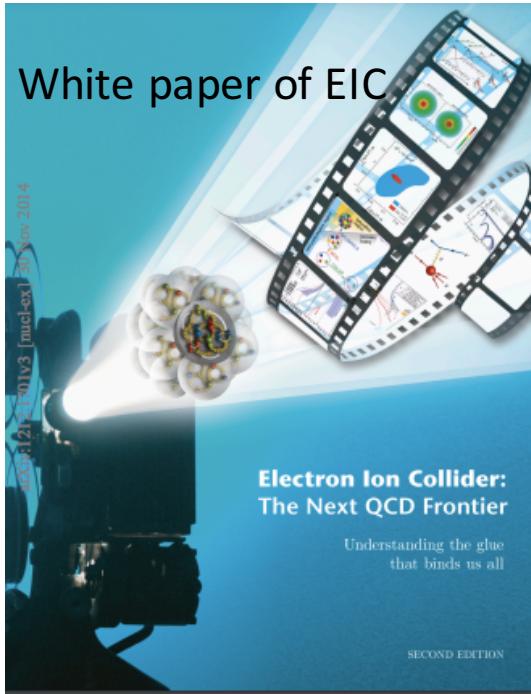


4. Forward-backward asymmetry of bottom quark @ LEP

PDG2020 2.1σ

5. Anomaly of B physics

Why Electron-Ion Collider?

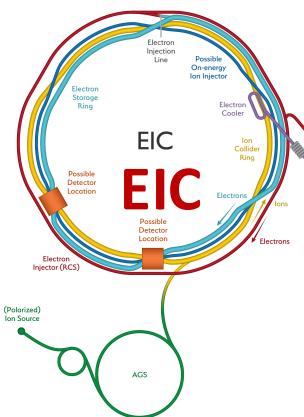


1. Explore and image the **spin and 3D structure** of the nucleon
2. Discover the **role of gluons** in structure and dynamics
3. Constraint for the PDFs, Polarized and unpolarized
4. Possibilities of **Beyond the Standard Model?**

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, arxiv: 2112.02477

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

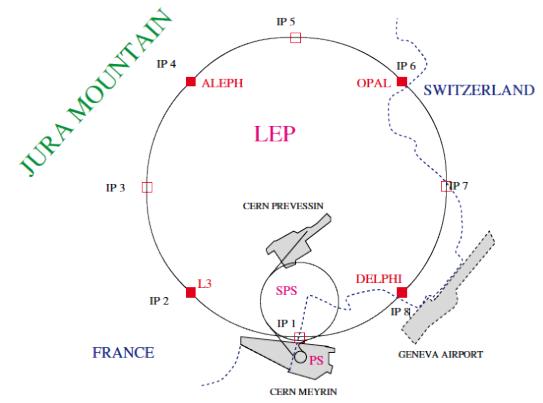
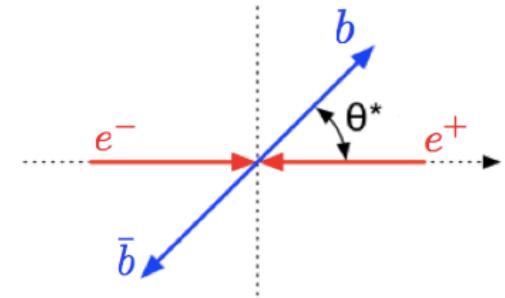
The electroweak precision measurements

Electroweak Precision measurement

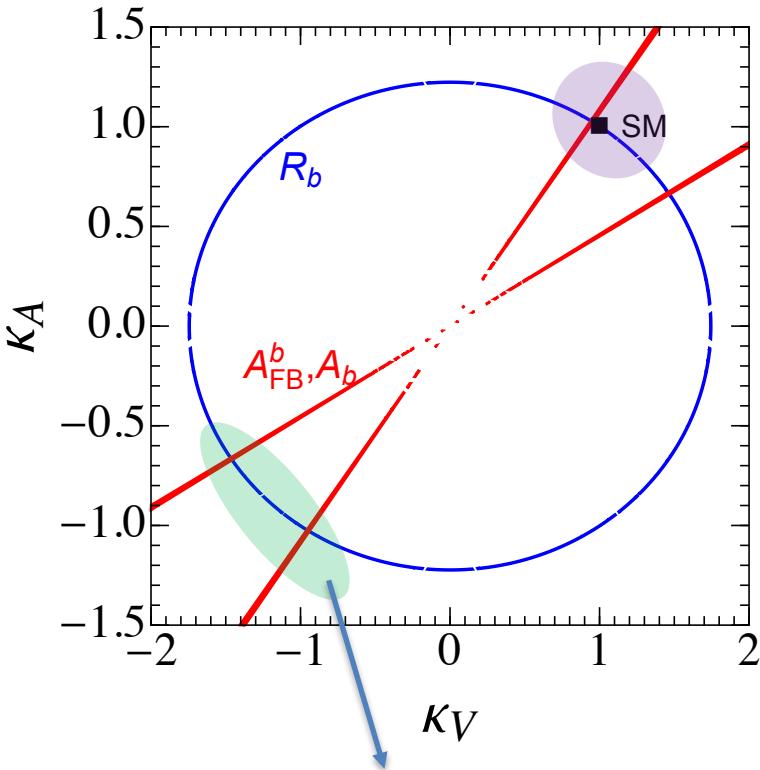
	Measurement with Total Error	Systematic Error	Standard Model High- Q^2 Fit	Pull
$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2)$ [59]	0.02758 ± 0.00035	0.00034	0.02767 ± 0.00035	0.3
m_Z [GeV]	91.1875 ± 0.0021	^(a) 0.0017	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	^(a) 0.0012	2.4965 ± 0.0015	0.6
σ_{had}^0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

Phys.Rept. 427 (2006) 257-454

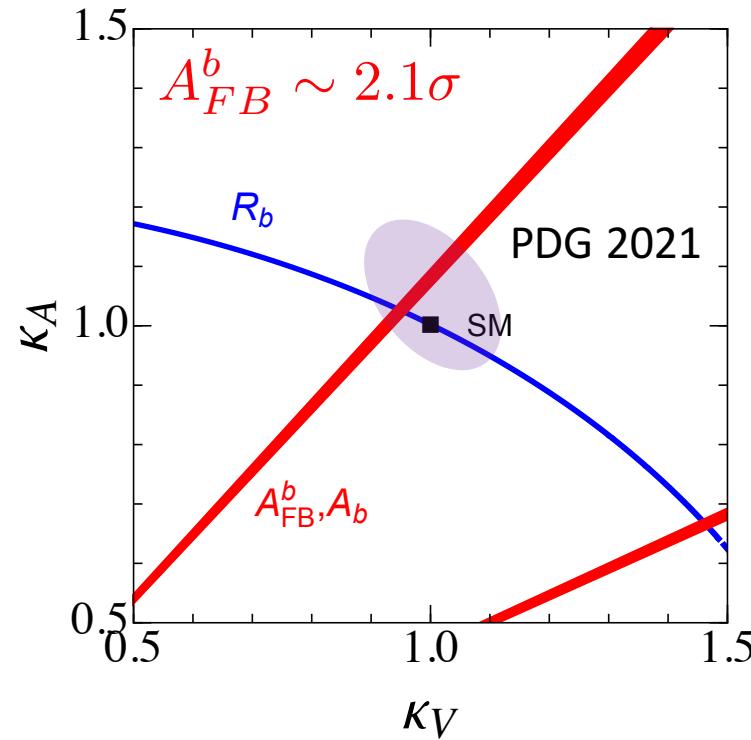
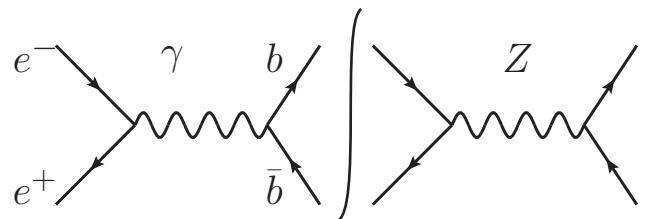
LEP: 1989-2000



Electroweak Precision measurement



Excluded by off-Z pole data

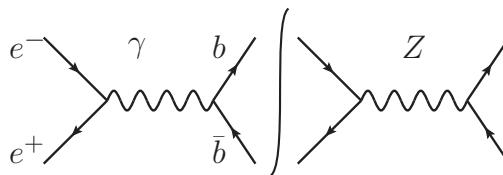


$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5)bZ_\mu$$

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

Zbb couplings@ colliders

A. Lepton colliders:

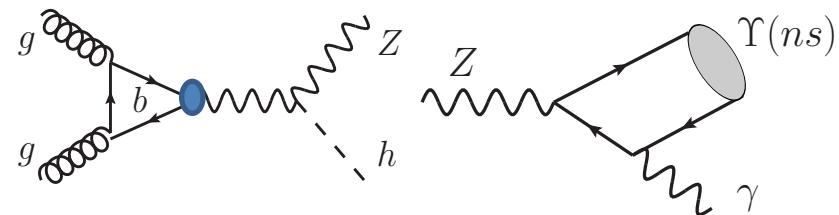


S. Gori, Jiayin Gu, Lian-Tao Wang, JHEP 04(2016) 062

B. LHC Zh production and Z boson rare decay:

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

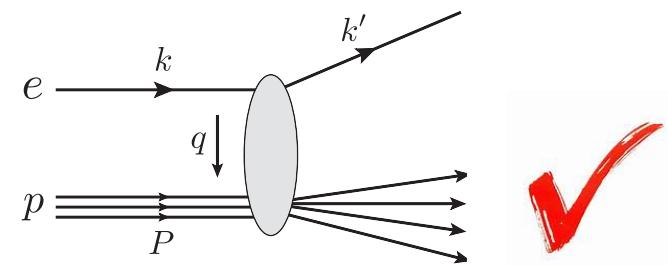
Hongxin Dong, Peng Sun, Bin Yan and C.-P. Yuan, PLB829(2022)137076



C. HERA and EIC with polarized lepton beam:

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

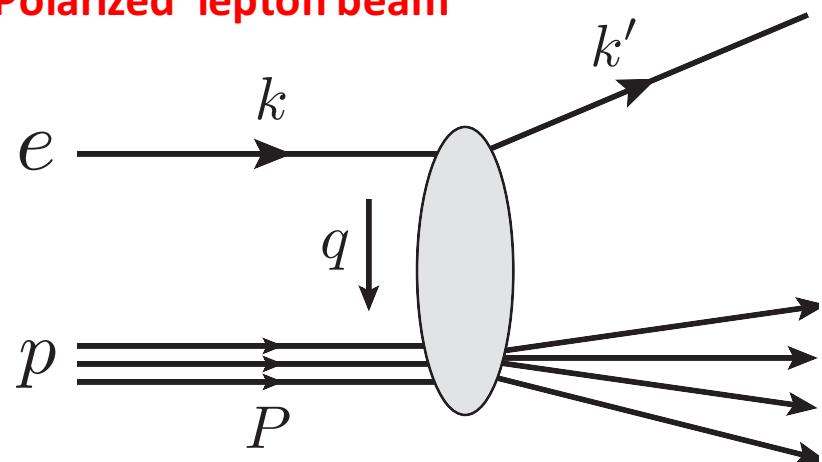
Hai Tao Li, Bin Yan and C.-P. Yuan, PLB833(2022)137300



Zbb couplings@ EIC

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

Polarized lepton beam



Single-Spin Asymmetry (SSA):

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

+/-: right/left-handed lepton

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

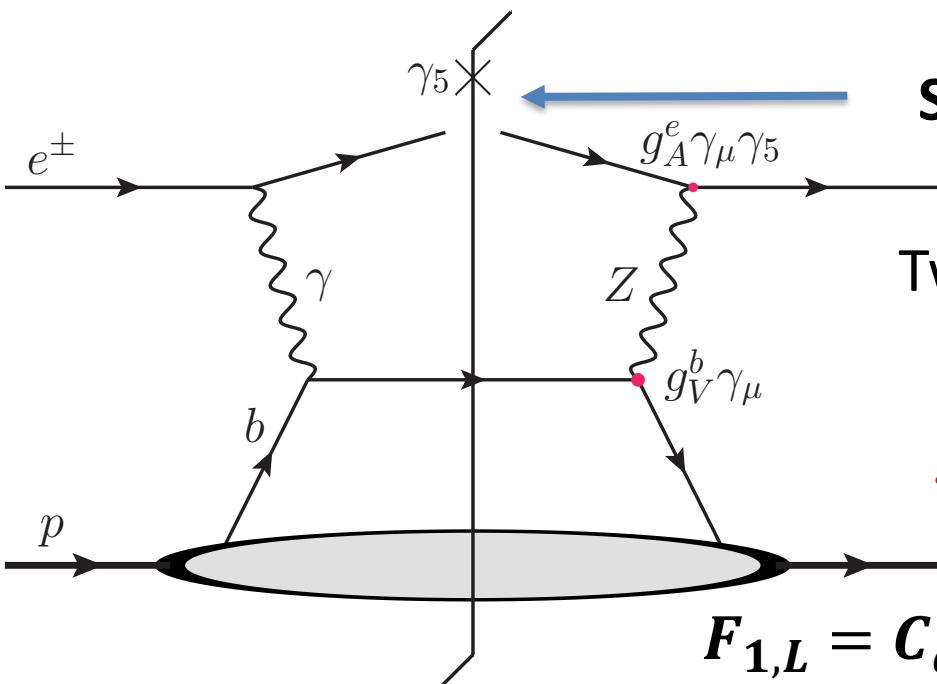
DIS cross section

Polarized cross section

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

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

$\lambda_e = \pm 1$: lepton helicity



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

Two possible combination:

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

$$g_V^e g_A^b$$

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

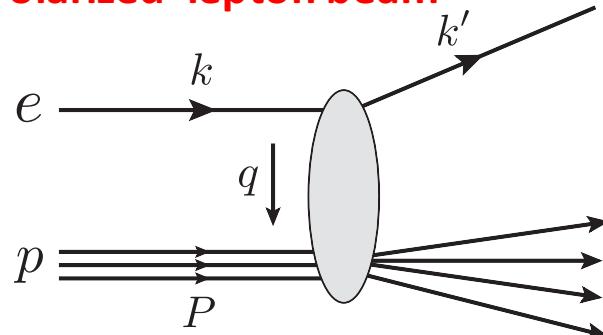
$$F_3 = C_q \otimes (q - \bar{q})$$

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

Zbb couplings @EIC

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):

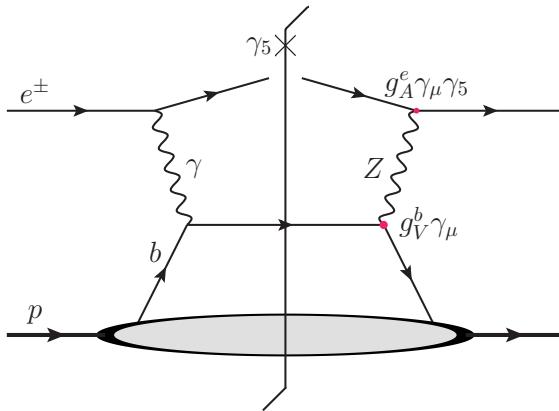
$$A_e^{bQ} = \frac{\sigma_{b,+}^Q - \sigma_{b,-}^Q}{\sigma_{b,+}^Q + \sigma_{b,-}^Q}$$

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

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

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



$$g_A^e g_V^b$$

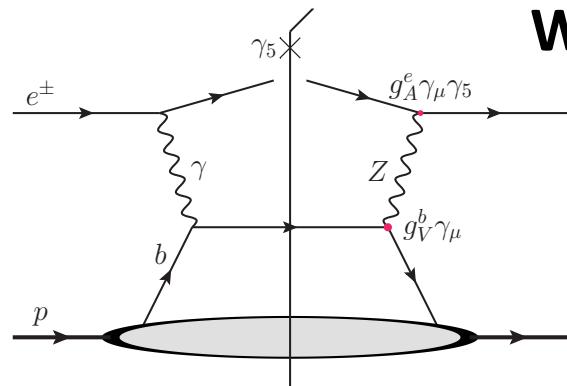
$$g_V^e g_A^b$$

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

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

Key point:

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



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

$$g_A^e g_V^b$$

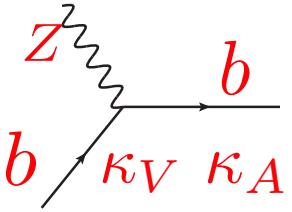
$$g_V^e g_A^b$$



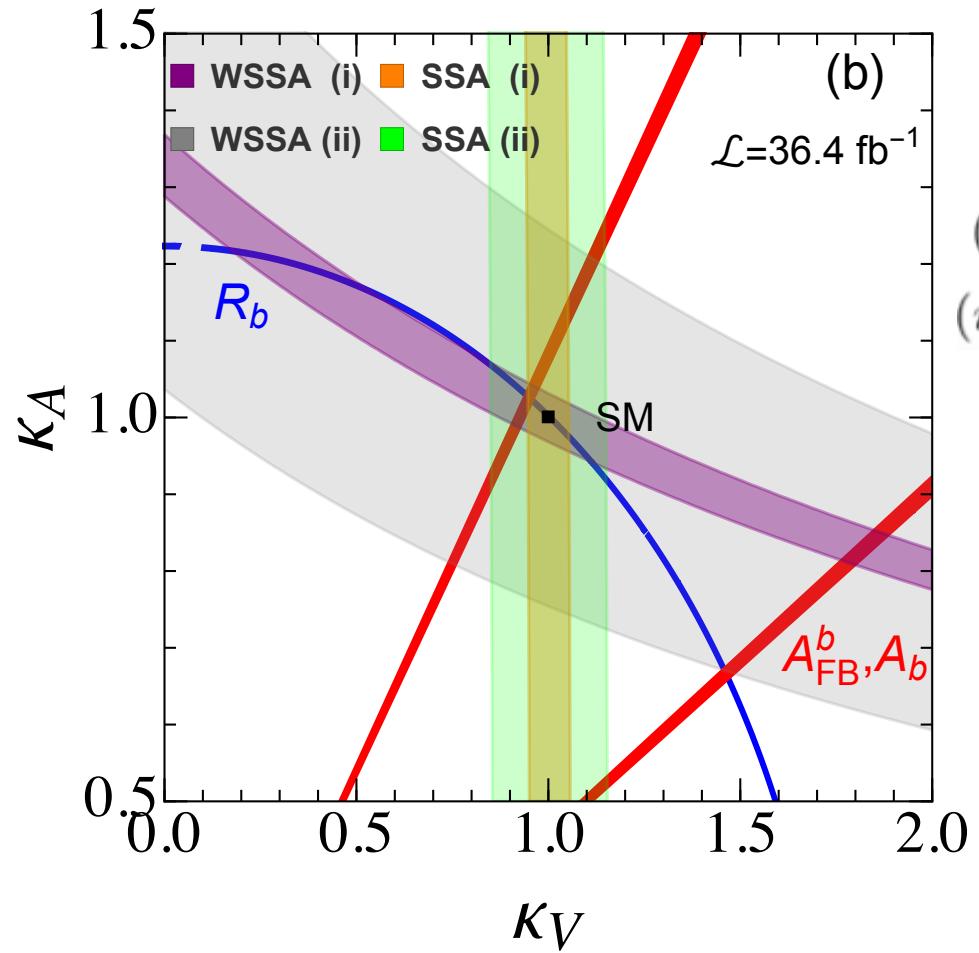
$$F_{1,L} = C_q \otimes (q - \bar{q}) \langle Q_J^q \rangle$$

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

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



Zbb couplings @EIC



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

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

WSSA

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

SSA

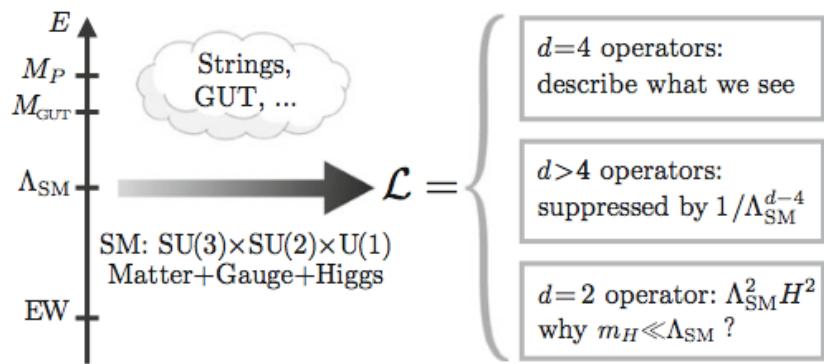
$$(i) : \mathcal{L} > 0.5 \text{ fb}^{-1}; \\ (ii) : \mathcal{L} > 4.0 \text{ fb}^{-1}.$$

The new physics effects from the SMEFT

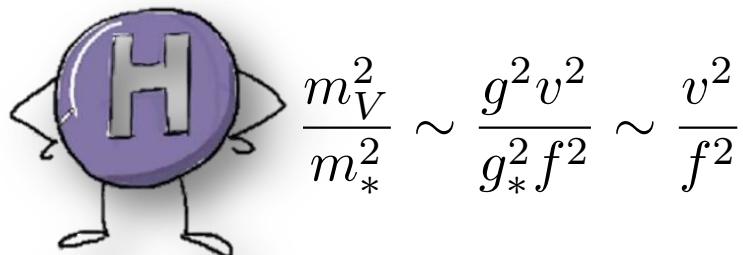
Effective Field Theory

Linear realized EFT

Higgs is a **fundamental particle**
Weak interacting

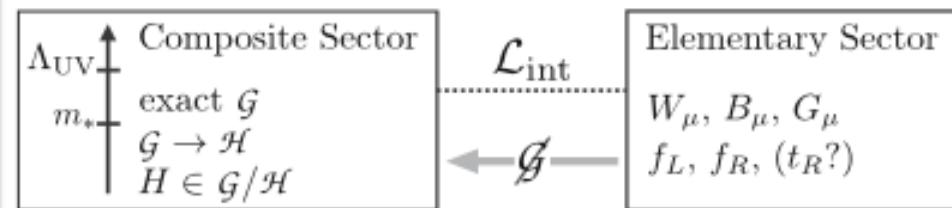


$$\mathcal{L} = C_6 O_6 + C_8 O_8 + \dots$$



Non-Linear realized EFT

Higgs is a **composite particle (PNGB)**
Strongly interacting



$$\mathcal{L} = C_2 O(p^2) + C_4 O(p^4) + \dots$$

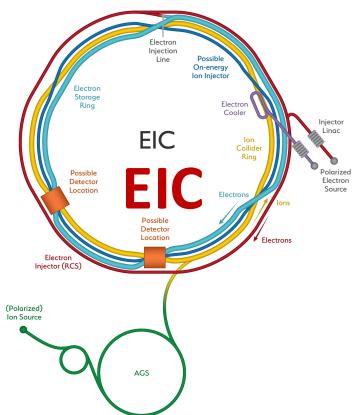
$$g \ll g_* \sim 4\pi$$

$$\frac{m_V^2}{m_*^2} \sim \frac{g^2 v^2}{g_*^2 f^2} \ll \frac{v^2}{f^2}$$

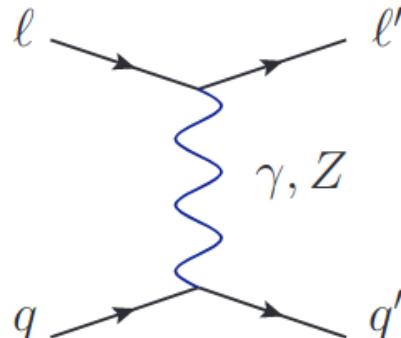
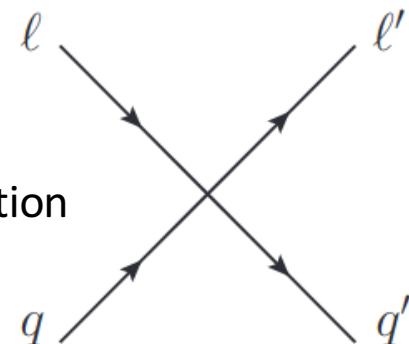
Effective Field Theory

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

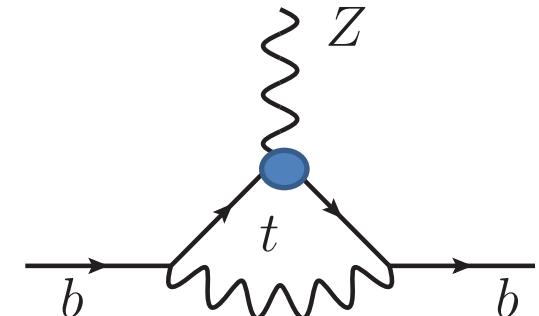
The SMEFT is perfectly applicable at the EIC



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



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

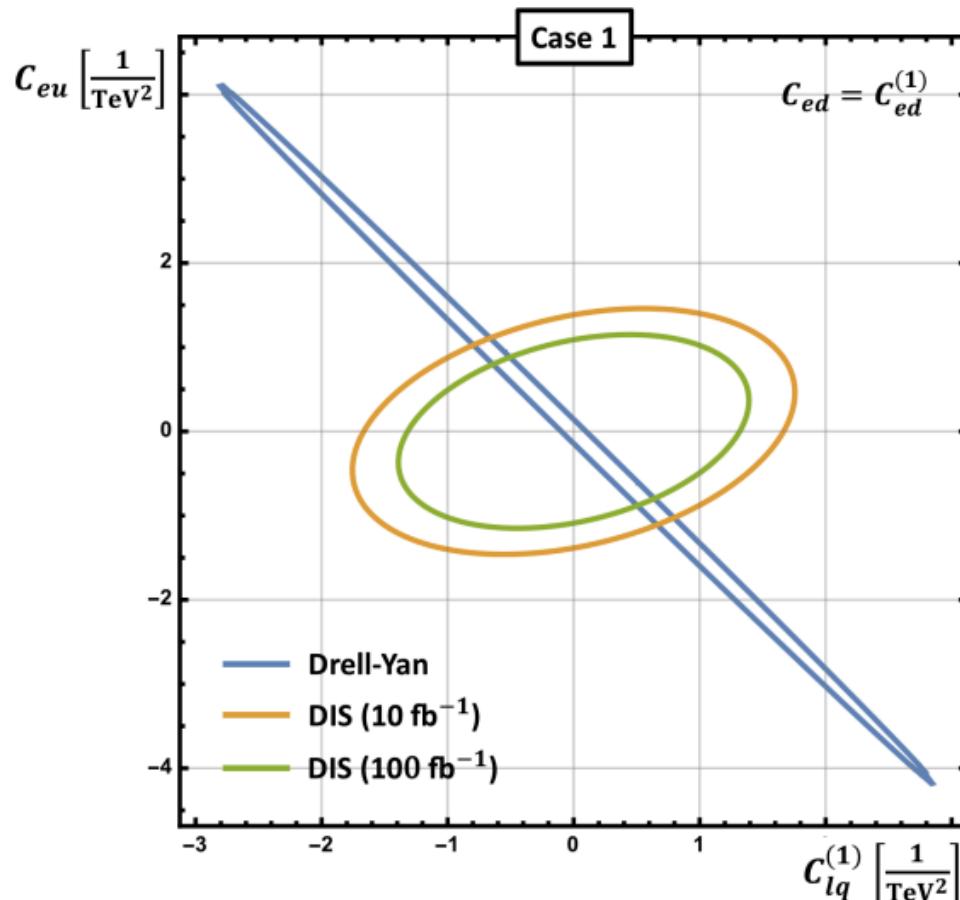


Four-fermion operators

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

$$P_e = \pm 0.7$$

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



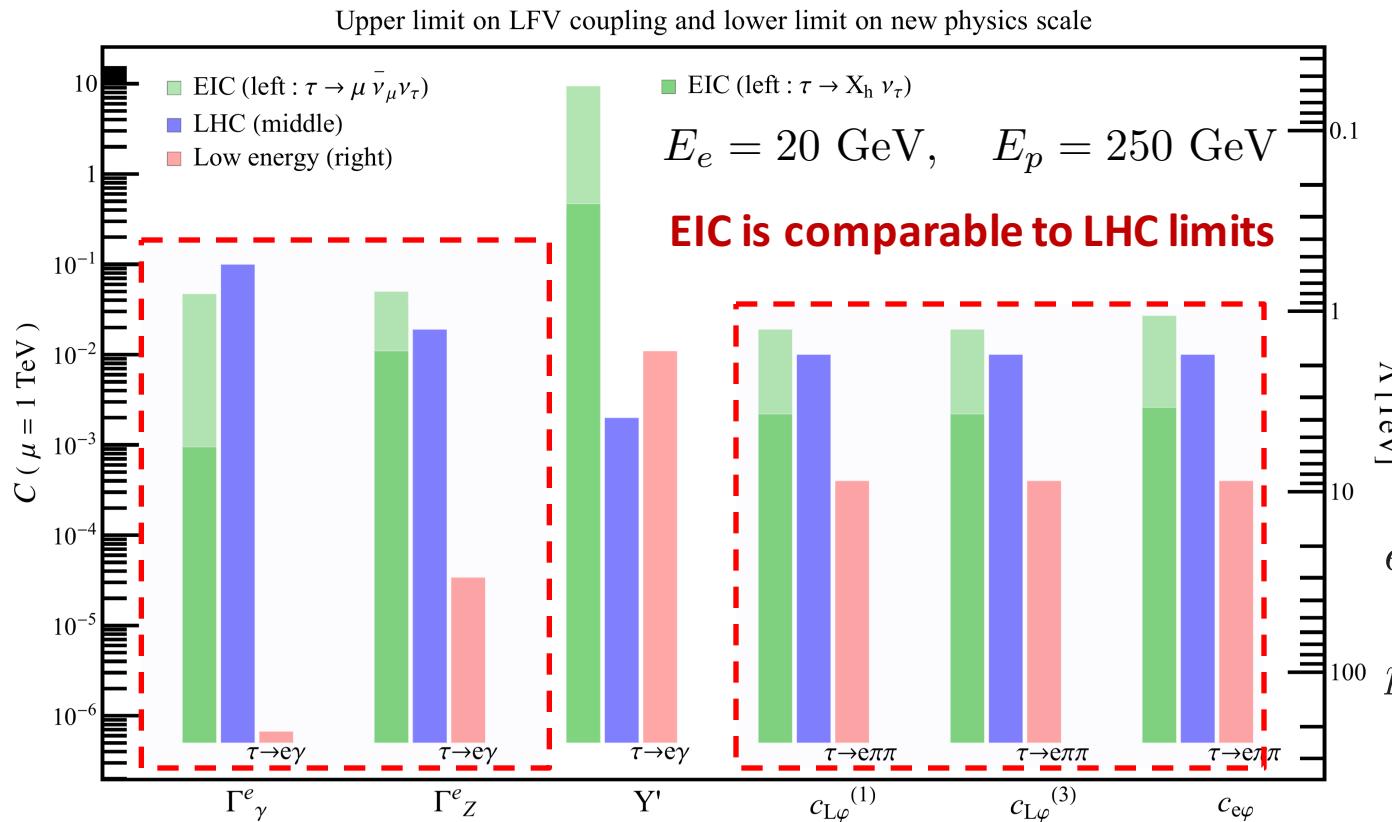
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$	\mathcal{O}_{lu}	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^I l)(\bar{q}\gamma_\mu \tau^I l q)$	\mathcal{O}_{ld}	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d)$
\mathcal{O}_{eu}	$(\bar{e}\gamma^\mu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

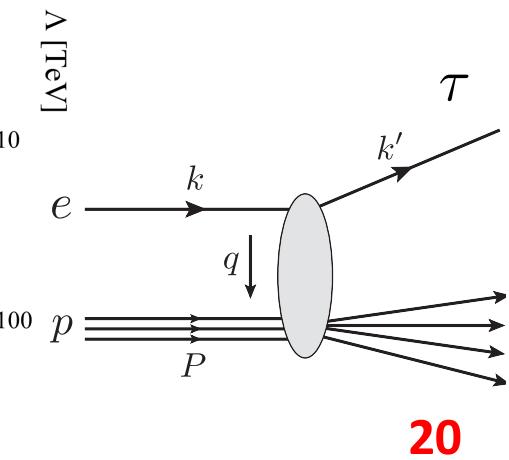
Charged Lepton Flavor Violation

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

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

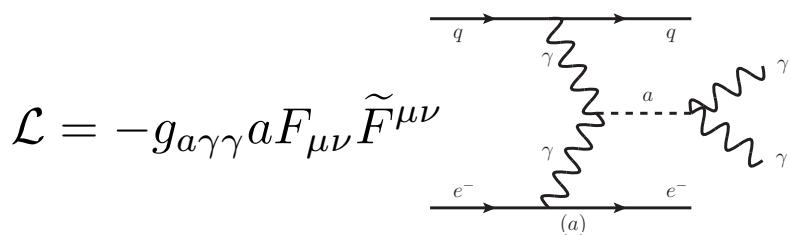


$$\mathcal{L} = 100 \text{ fb}^{-1}$$

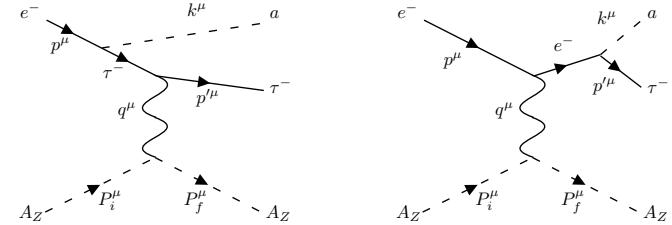
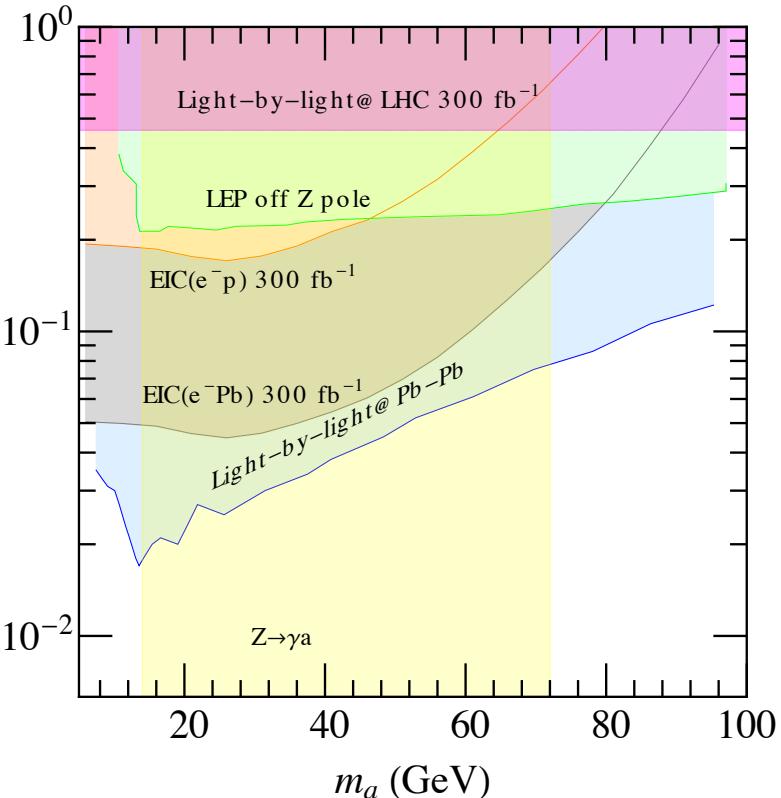


The light new physics particles

Searching for the ALPs

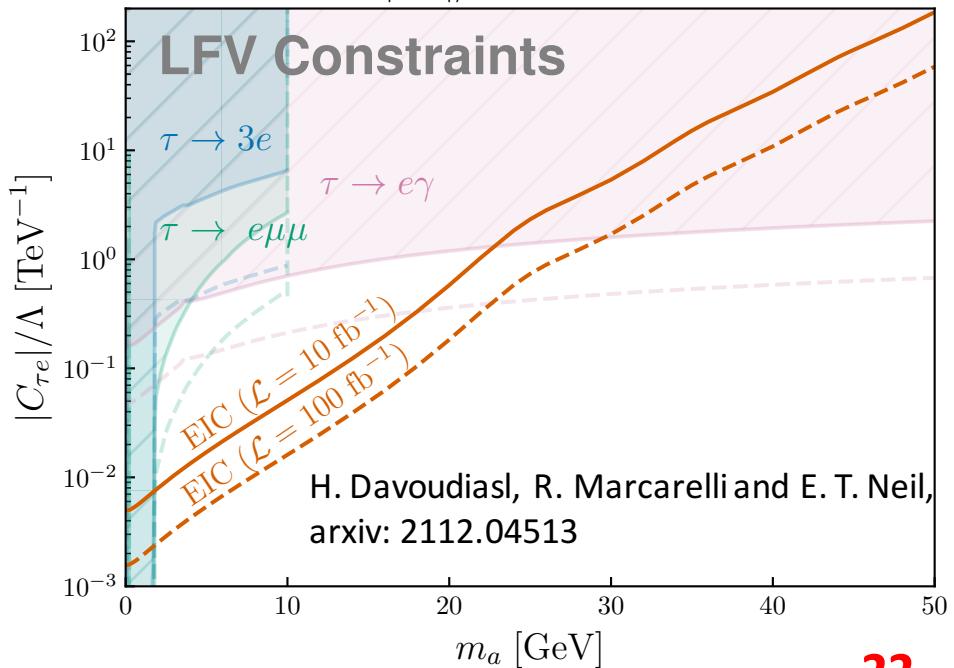


Yandong Liu and Bin Yan, arxiv:2112.02477



$$\mathcal{L}_\ell = \frac{C_{\ell\ell'}}{\Lambda} \partial_\mu a \sum_{\ell\ell'} \bar{\ell} \gamma^\mu (\sin \theta_{\ell\ell'} - \cos \theta_{\ell\ell'} \gamma_5) \ell' + h.c.$$

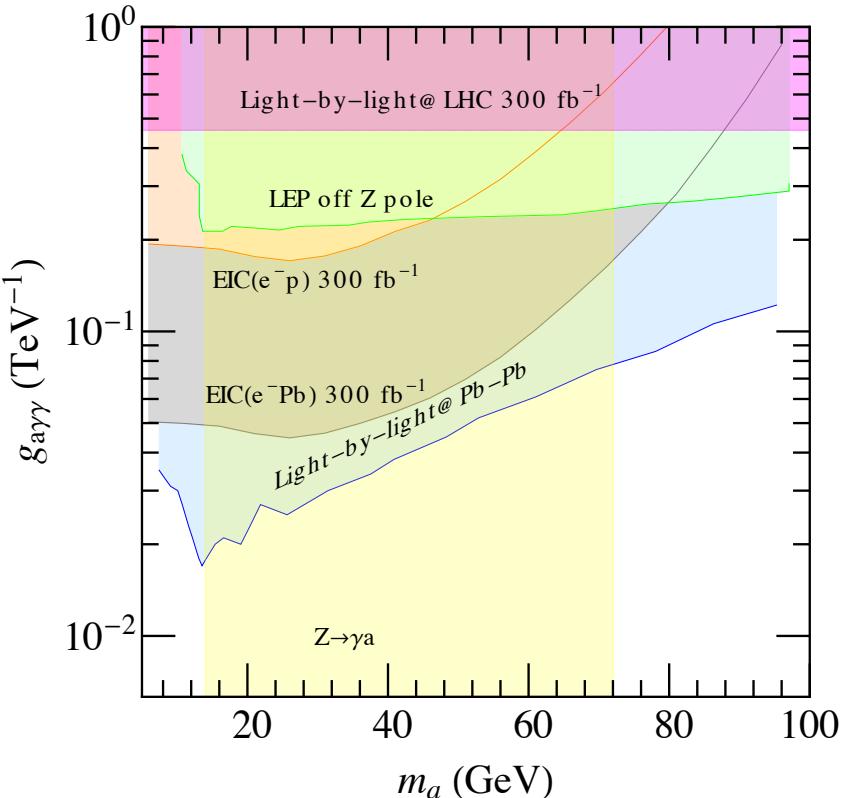
$$|C_{\ell\ell}|/\Lambda = 1 \text{ TeV}^{-1}$$



Searching for the ALPs

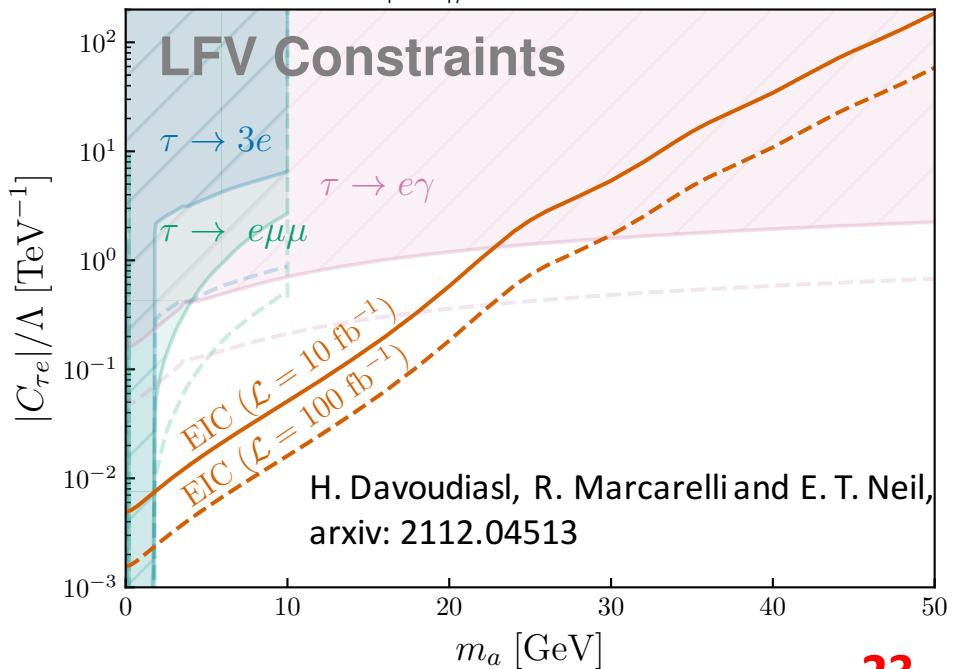
EIC plays a complementary role in probing ALPs

Yandong Liu and Bin Yan, arxiv:2112.02477



$$\mathcal{L}_\ell = \frac{C_{\ell\ell'}}{\Lambda} \partial_\mu a \sum_{\ell\ell'} \bar{\ell} \gamma^\mu (\sin \theta_{\ell\ell'} - \cos \theta_{\ell\ell'} \gamma_5) \ell' + h.c.$$

$$|C_{\ell\ell}|/\Lambda = 1 \text{ TeV}^{-1}$$



Searching for the dark photon

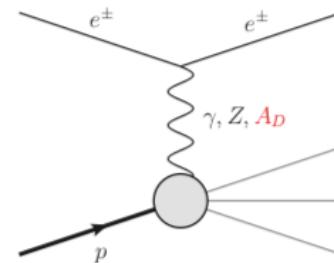
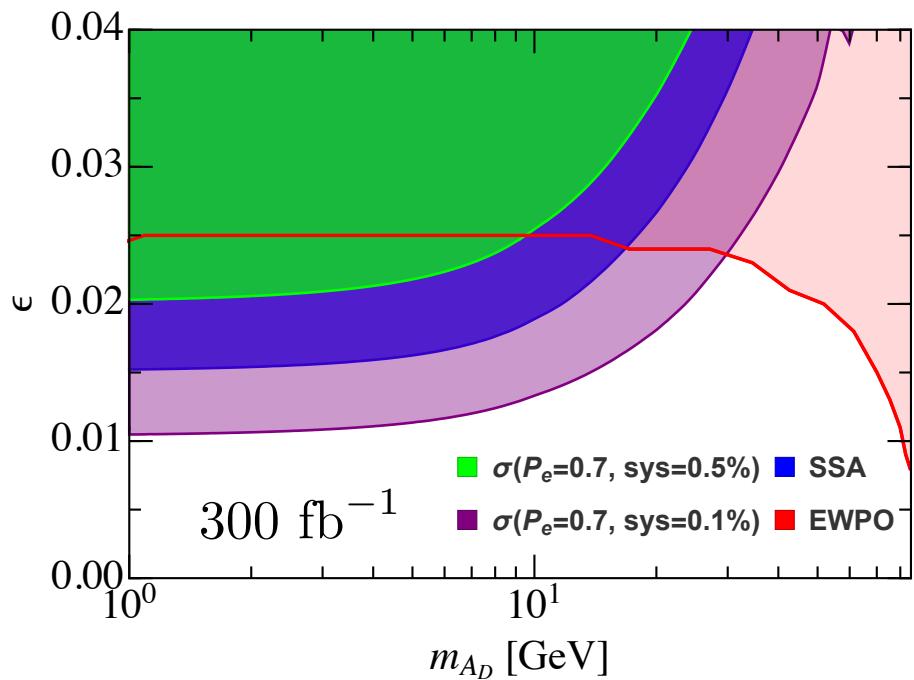
Bin Yan, PLB 833 (2022) 137384

$$\mathcal{L} = \frac{\epsilon}{2c_W} F'_{\mu\nu} B^{\mu\nu}$$

HERA unpolarized data:

G. D. Kribs, D. McKeen, N. Raj, PRL126(2021)1,011801

A.W. Thomas, X.G.Wang, A.G. Williams, PRD 105(2022)3,LO31901



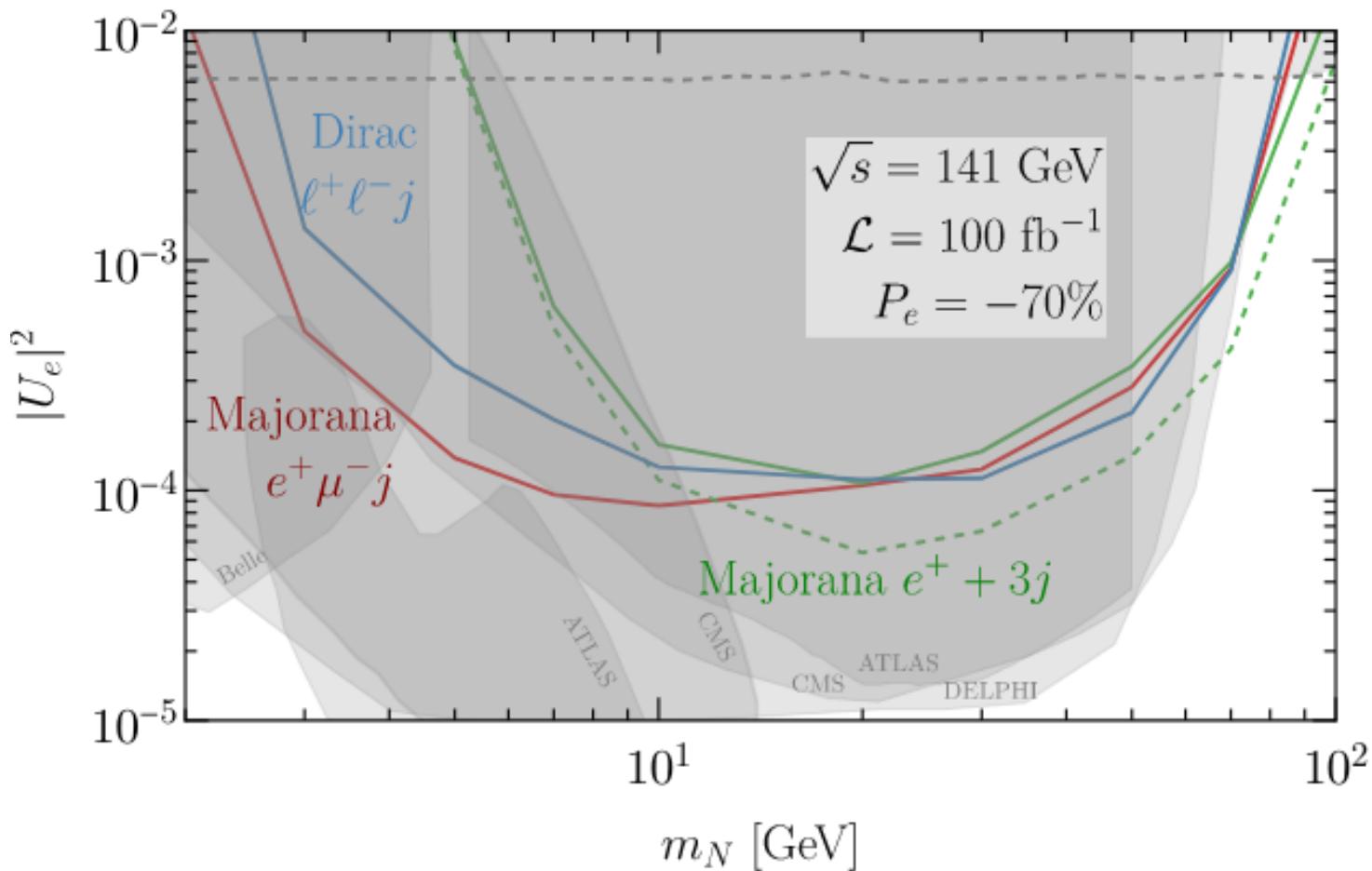
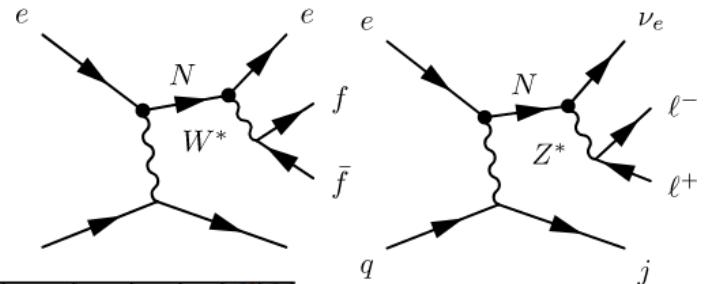
Single-spin asymmetry (SSA)

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

The bounds are not depending on the assumption of dark sector

Searching for the heavy neutrino

B. Batell, T. Ghosh, T. Han, K. Xie, 2210.09287



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;
- D. The light particles: Axion-like particles, dark photon, heavy neutrino

The search for new physics at the EIC is just beginning

Thank you!