

The anomalous Zbb couplings at the LHC and ep colliders

Bin Yan

Los Alamos National Laboratory

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

Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136709

Status of Zbb couplings

	measured value	SM prediction
R_b^0	0.21629 ± 0.00066	0.21578 ± 0.00011
$A_{\text{FB}}^{0,b}$	0.0992 ± 0.0016	0.1032 ± 0.0004
\mathcal{A}_b	0.923 ± 0.020	0.93463 ± 0.00004

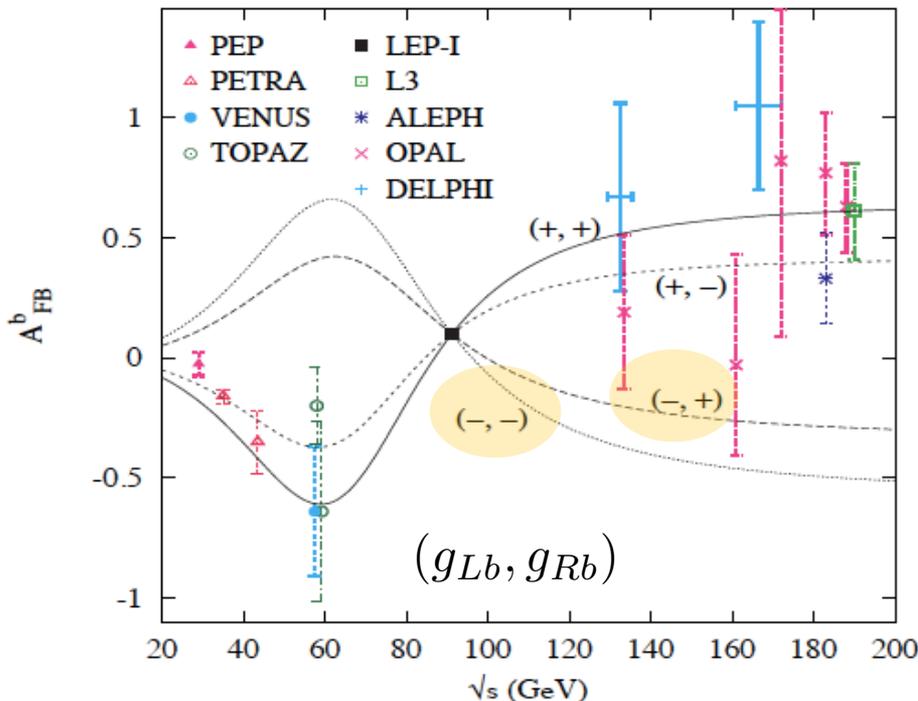
Gfitter Group:

EPJC74 (2014)3046

PDG2020

$$R_b = \frac{\Gamma(Z \rightarrow b\bar{b})}{\sum_q \Gamma(Z \rightarrow q\bar{q})}$$

2.1 σ deviation with SM prediction



D. Choudhury, T. M. P. Tait, C.E.M. Wagner,
PRD 65(2002)053002

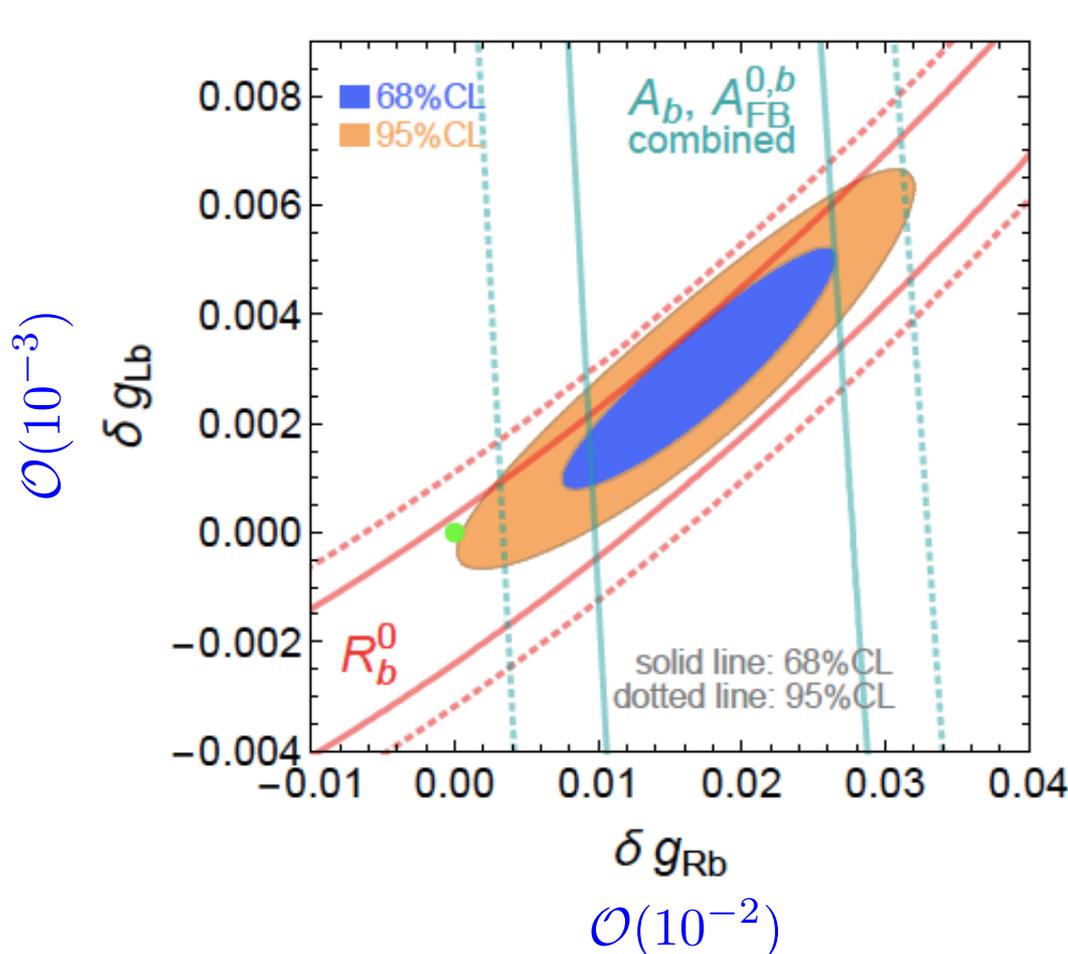
$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R)$$

$g_{Lb} < 0$ was Excluded

g_{Rb} Could be positive or negative

Status of Zbb couplings

$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R) \quad \text{S. Gori, J. Gu, L. T. Wang, JHEP04(2016)062}$$



$$g_{Lb/Rb} = g_{Lb/Rb}^{\text{SM}} + \delta g_{Lb/Rb}$$

$$g_{Lb}^{\text{SM}} = -0.42, \quad g_{Rb}^{\text{SM}} = 0.077$$

- Strong constraint for the **left-handed** Zbb coupling
- ***large deviation*** of the **right-handed** Zbb coupling

Status of Zbb couplings

- A. How to **break the degeneracy** of the right-handed Zbb coupling?

New experiments: CEPC (e+e- collider), etc.



- B. How to **explain** the LEP data?



New Physics?

Many new physics models

e.g. Custodial symmetry $O(3)$ + heavy quark

K. Agashe, R. Contino, L. Rold, A. Pomarol, 2006'



Statistical Fluctuation or Systematic error?

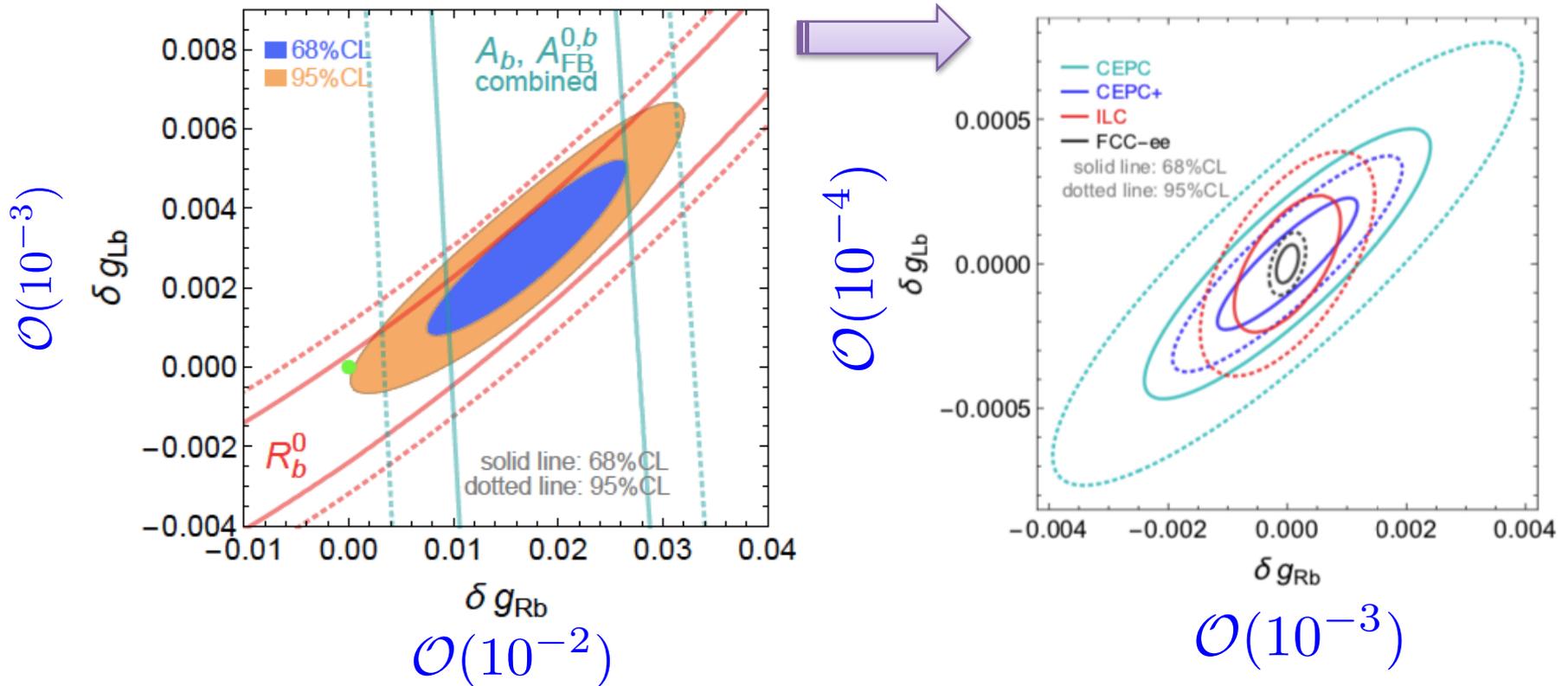
New experiments: e.g. CEPC

Zbb couplings@ future e+e- colliders

$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R)$$

The degeneracy of right-handed Zbb coupling could be broken by [scanning the energy at the e+e- colliders](#)

S. Gori, J. Gu, L. T. Wang, JHEP04(2016)062



So...

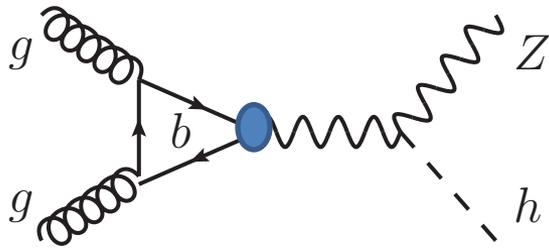
Should we just wait for the next generation lepton colliders?

Any possibility from LHC and ep colliders (HERA and EIC)?



Zbb couplings@ LHC and ep colliders

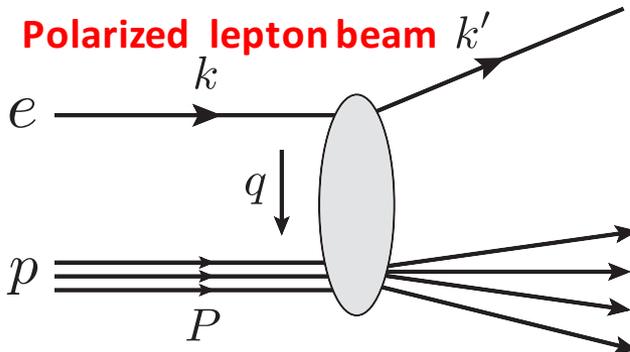
A. LHC



$$\mathcal{L} = \frac{g_W}{2c_W} \bar{b} \gamma_\mu (\kappa_v^b v_b^{\text{SM}} - \kappa_a^b a_b^{\text{SM}} \gamma_5) b Z_\mu$$

axial-vector component of Zbb coupling

B. HERA and EIC

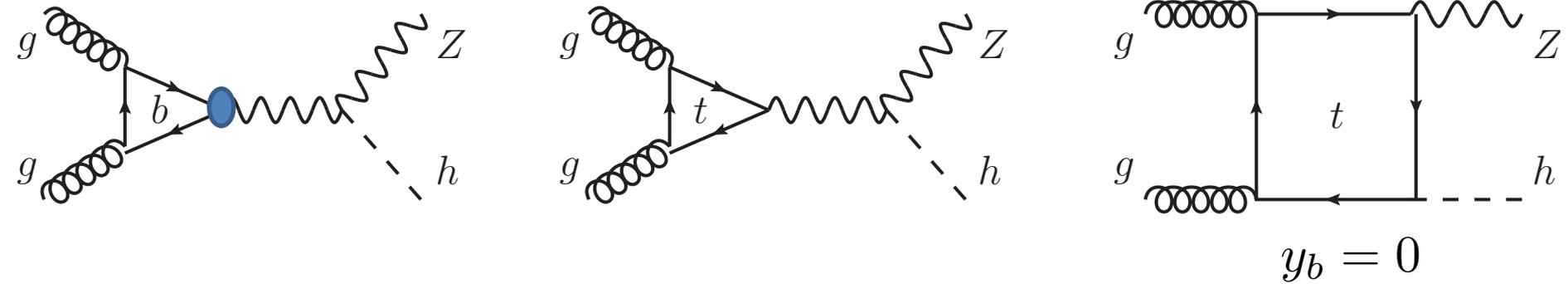


Single-Spin Asymmetry (SSA)

vector component of Zbb coupling

Complementary

A. Zbb couplings @LHC



charge conjugation invariance + isospin asymmetry:

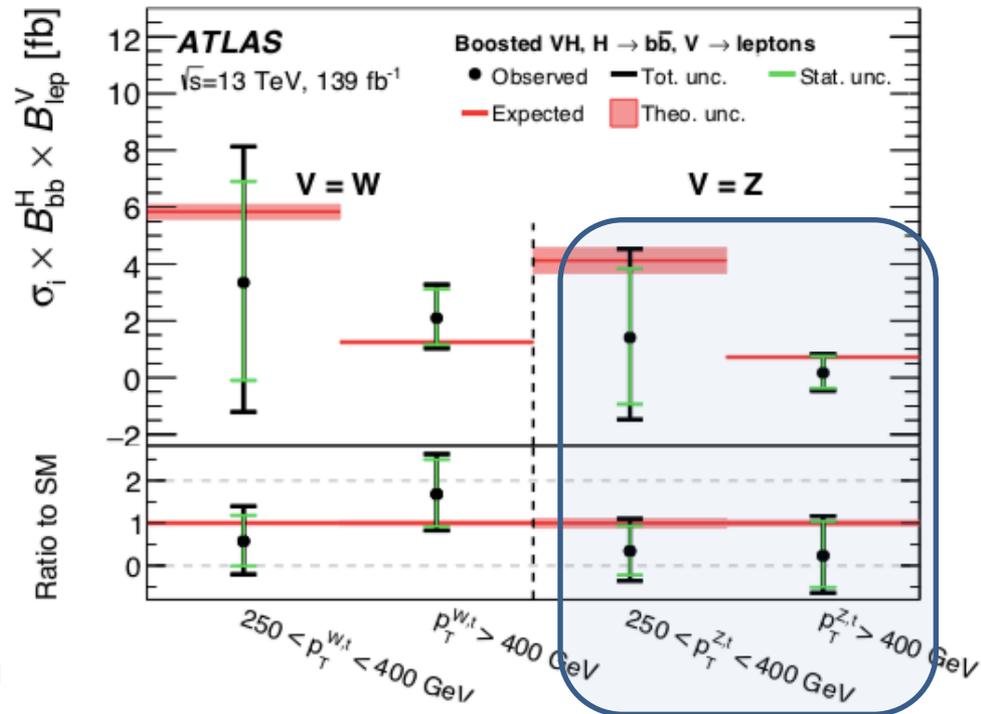
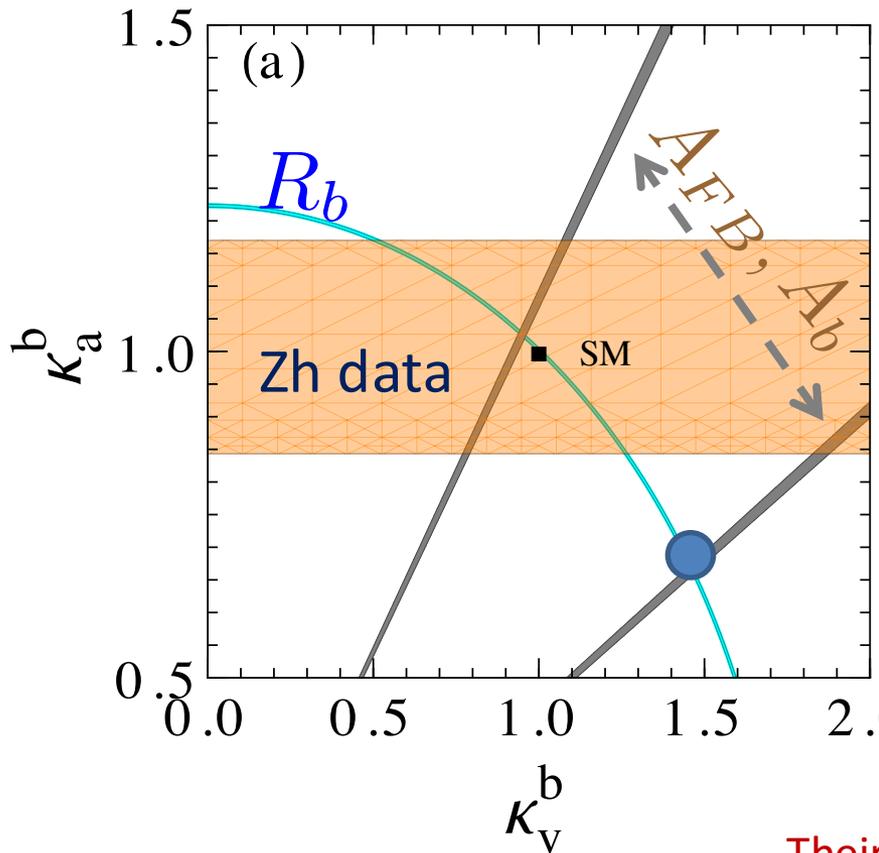
- (1) Only **axial-vector components** contribute to the cross section;
- (2) Only **top and bottom** quarks contribute to the scattering;
- (3) Bottom quark's contribution is comparable to the top quark, i.e. $\sigma(b)/\sigma(t) \simeq 1.1$

$$\mathcal{L} = \frac{g_W}{2c_W} \bar{b} \gamma_\mu (\kappa_v^b v_b^{\text{SM}} - \kappa_a^b a_b^{\text{SM}} \gamma_5) b Z_\mu$$

Break the Zbb coupling degeneracy

Current Zh data could break the degeneracy

ATLAS: 2008.02508



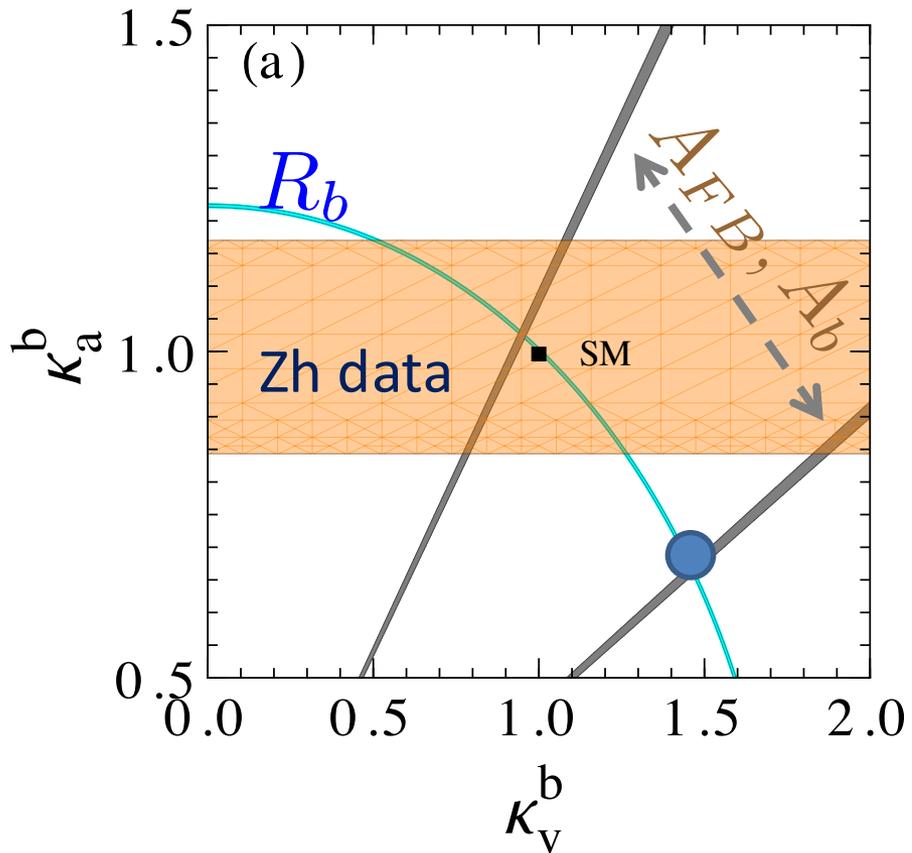
Their central values are smaller than SM predictions

Including all Zh data

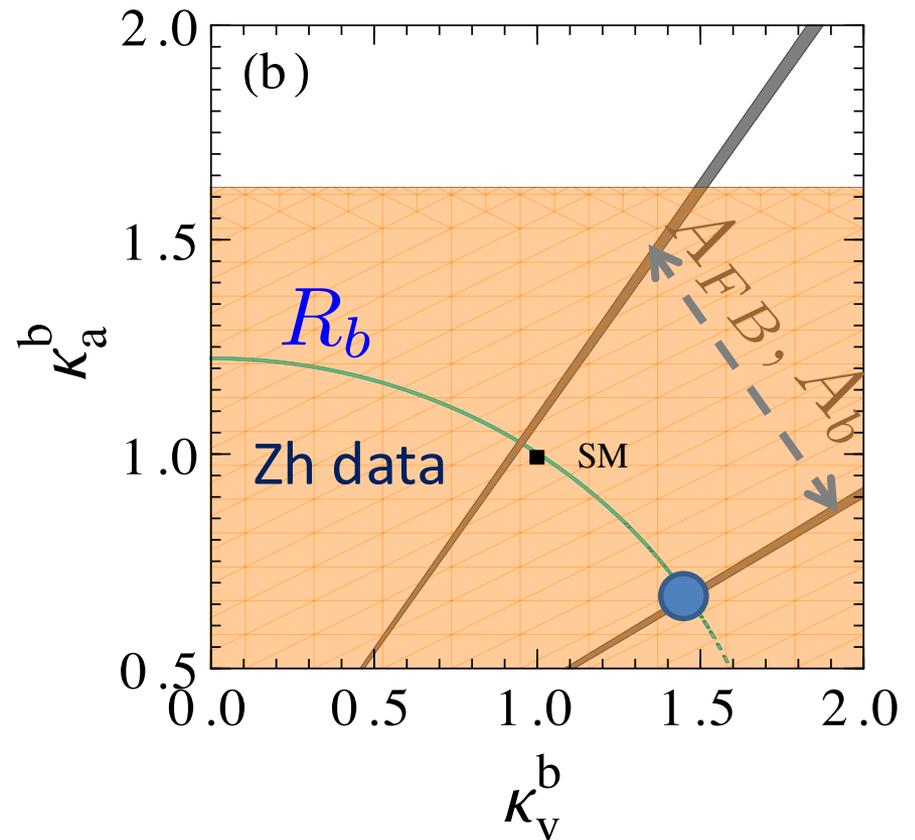
the two high P_T^Z data play an important role 9

Break the $Zb\bar{b}$ coupling degeneracy

Current Zh data could break the degeneracy



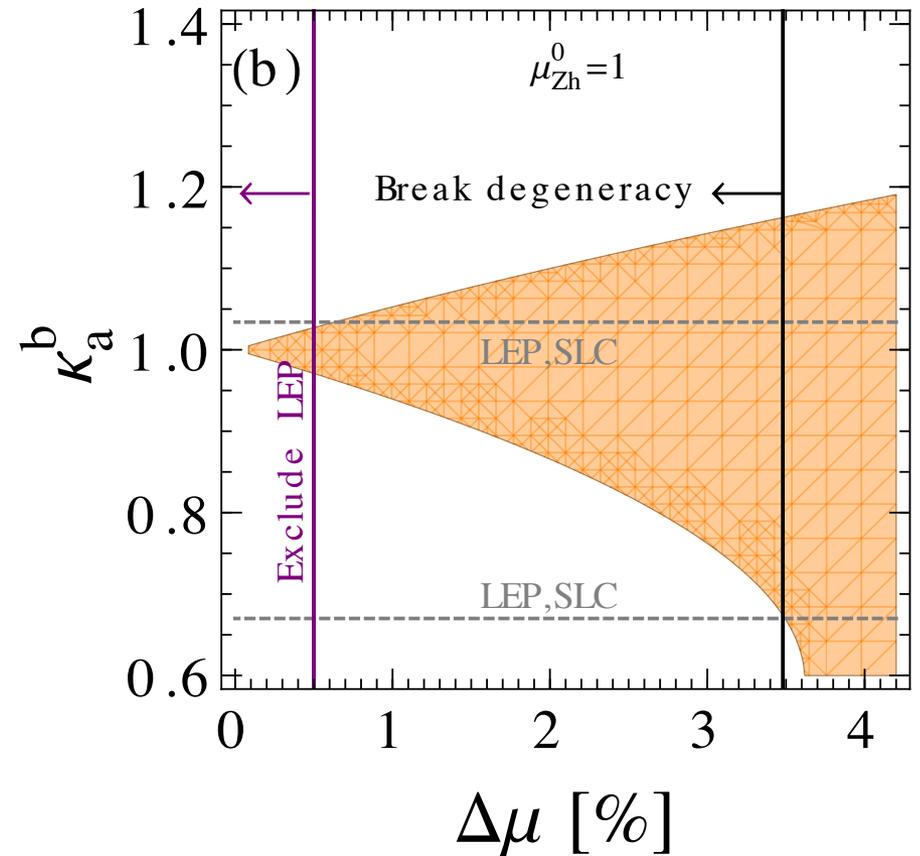
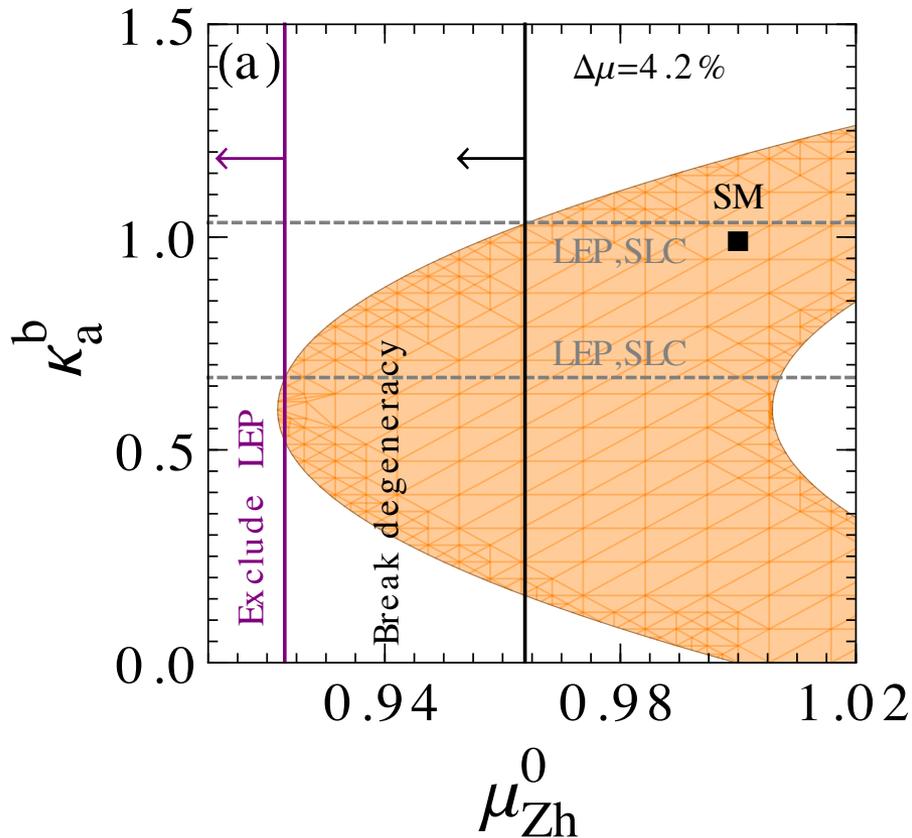
Including all Zh data



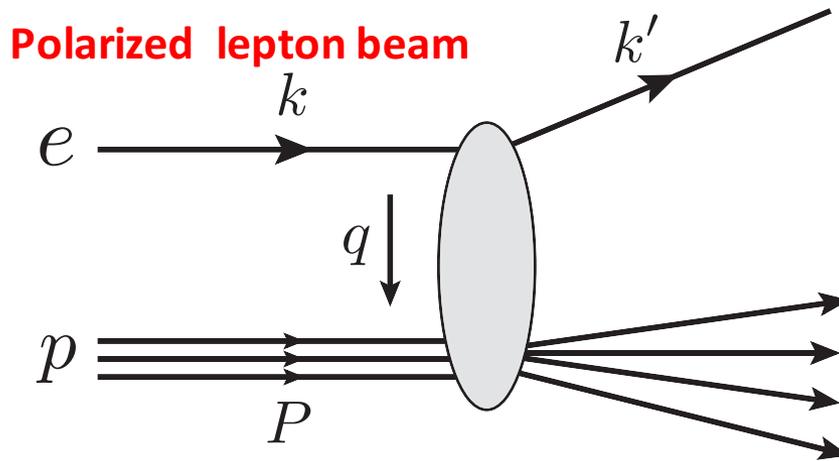
Removing the two high P_T^Z data 10

Break the Zbb coupling degeneracy

$$\mu_{Zh} = \frac{\sigma(pp \rightarrow Zh)}{\sigma(pp \rightarrow Zh)_{\text{SM}}} \equiv \mu_{Zh}^0 (1 \pm \Delta\mu)$$



B. Zbb couplings@HERA and EIC



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

Zbb couplings @HERA

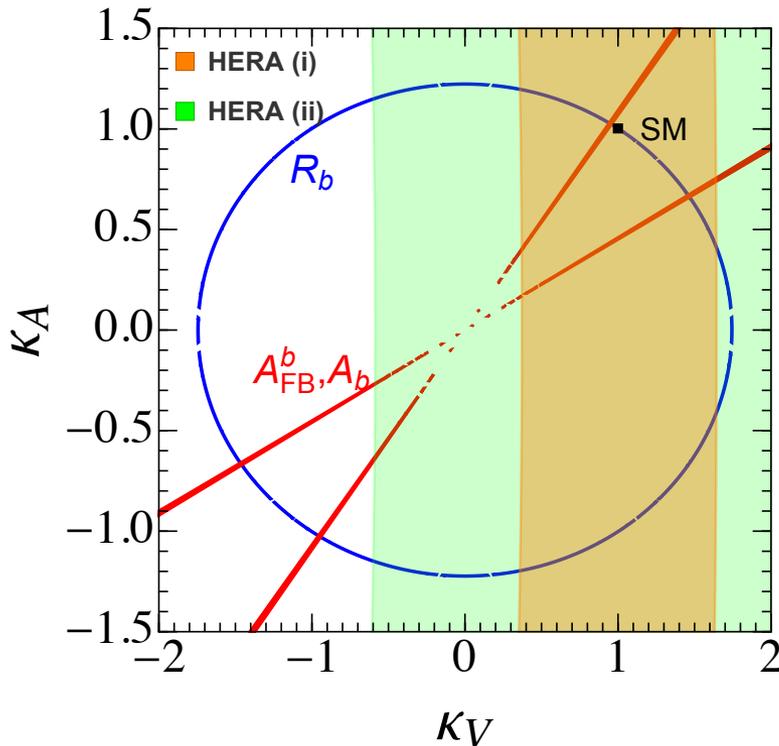
H1	R	L
e^-p	$47.3 \text{ pb}^{-1}, 0.36$	$104.4 \text{ pb}^{-1}, -0.258$
e^+p	$101.3 \text{ pb}^{-1}, 0.325$	$80.7 \text{ pb}^{-1}, -0.37$
ZEUS	R	L
e^-p	$71.2 \text{ pb}^{-1}, 0.29$	$98.7 \text{ pb}^{-1}, -0.27$
e^+p	$78.8 \text{ pb}^{-1}, 0.32$	$56.7 \text{ pb}^{-1}, -0.36$

JHEP 09, 061 (2012)

Eur. Phys. J. C 62, 625 (2009)

Phys. Rev. D 87, 052014 (2013)

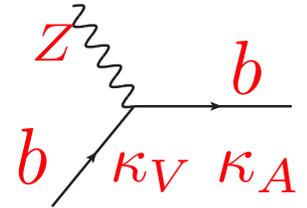
Simplified-ACOT- χ scheme@NNLO



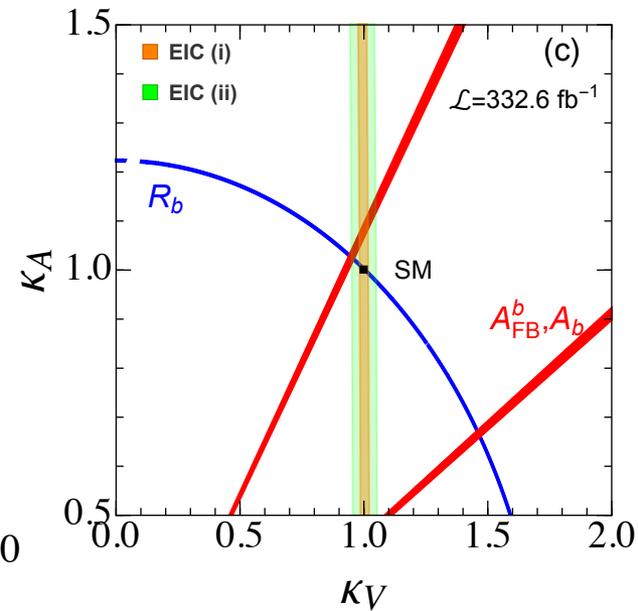
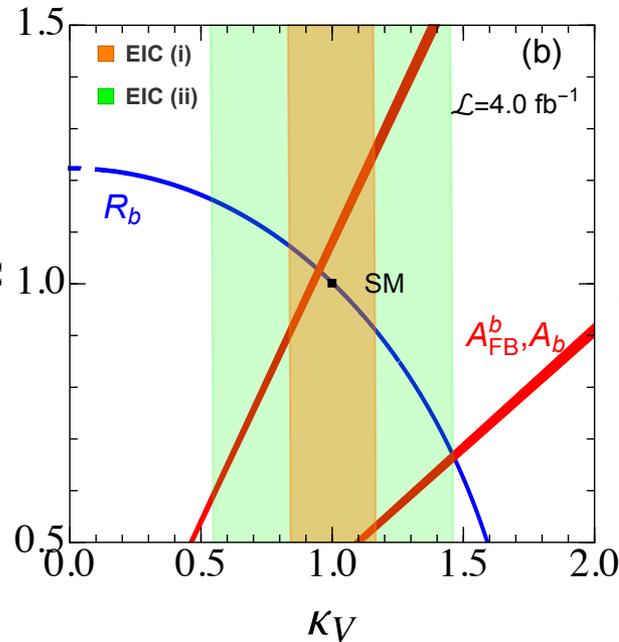
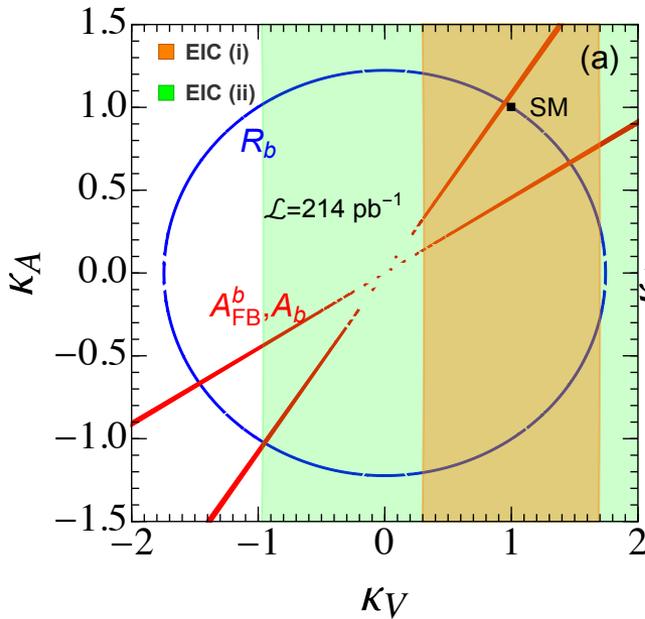
- (i) $\epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$
- (ii) $\epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$

1. The SSA is sensitive to κ_V
2. $\kappa_{V,A} < 0$ could be excluded by HERA data
3. It could be used to crosscheck the off-Z-pole data

Zbb couplings @EIC



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



(i) : $\mathcal{L} > 27 \text{ pb}^{-1}$;

(ii) : $\mathcal{L} > 214 \text{ pb}^{-1}$.

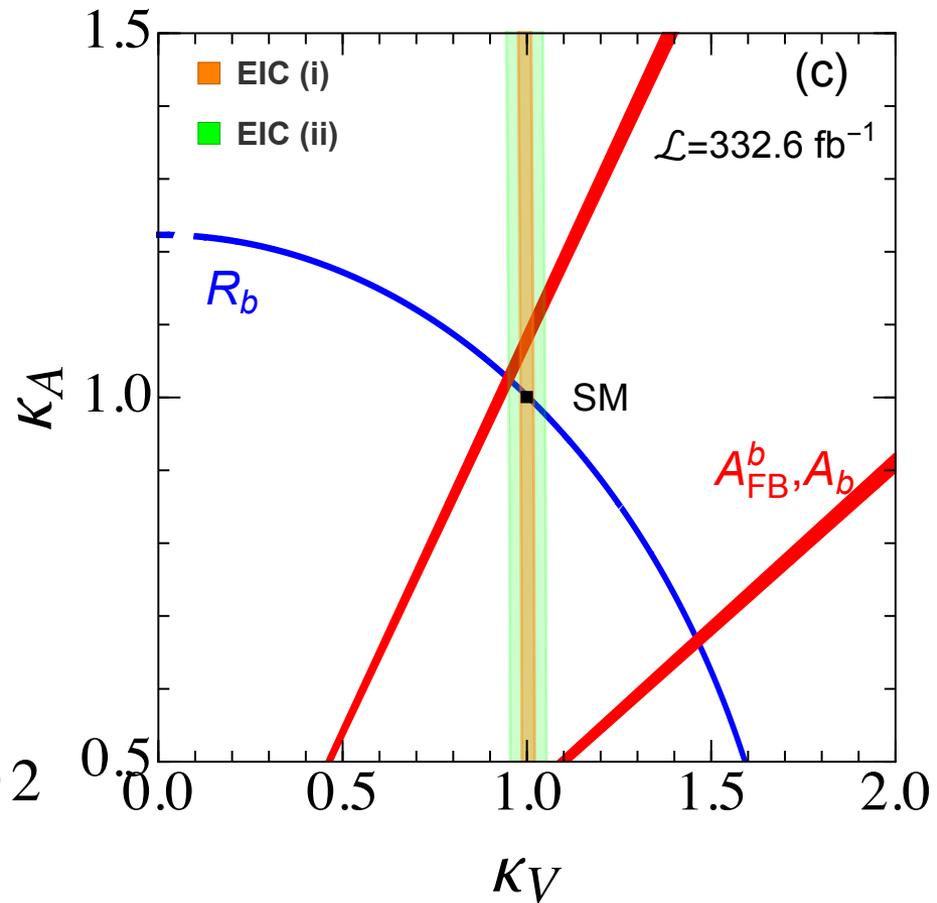
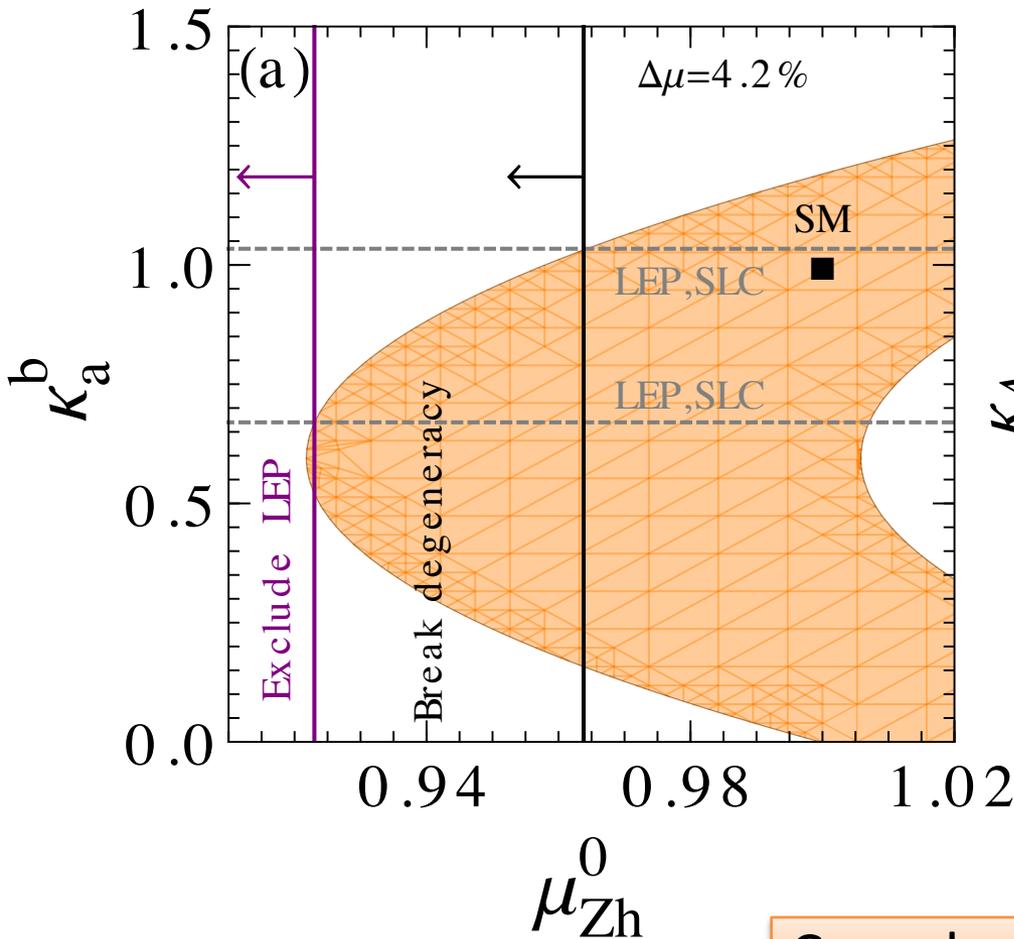
(i) : $\mathcal{L} > 0.5 \text{ fb}^{-1}$;

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

(i) : $\mathcal{L} > 42.0 \text{ fb}^{-1}$;

(ii) : $\mathcal{L} > 332.6 \text{ fb}^{-1}$.

LHC vs. EIC



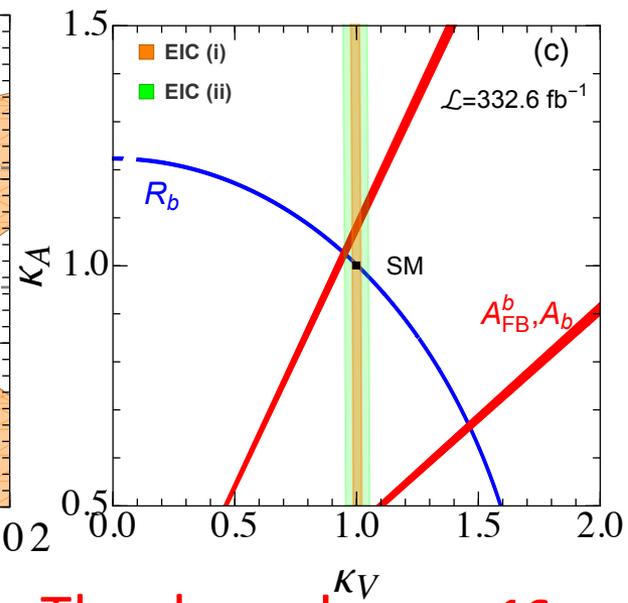
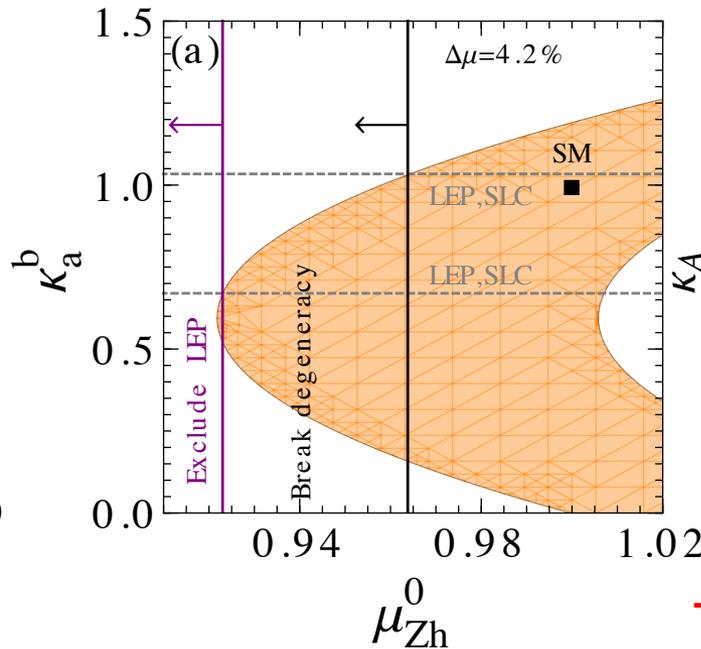
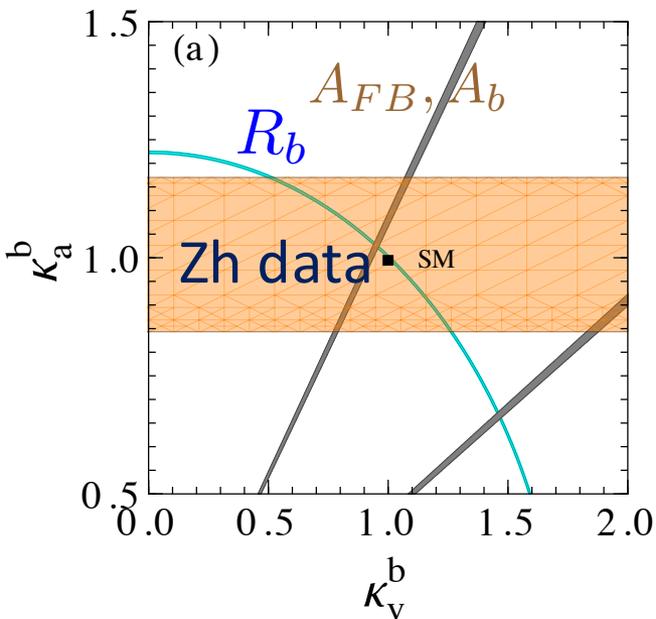
LHC: **axial-vector**
component of Zbb coupling

Complementary

EIC: **vector** component
of Zbb coupling

Summary

- A. We proposed two new methods to probe the $Zb\bar{b}$ coupling at the LHC and ep colliders
- B. The **Zh data** at the 13 TeV LHC can **resolve the apparent degeneracy** of the $Zb\bar{b}$ coupling;
- C. **Zh cross section** depends on the **axial-vector** $Zb\bar{b}$ coupling, while the SSA in **HERA or EIC** is sensitive to **the vector** $Zb\bar{b}$ coupling ;
- D. It is hopeful to **verify or exclude** the LEP measurement by those new methods.



Thank you!

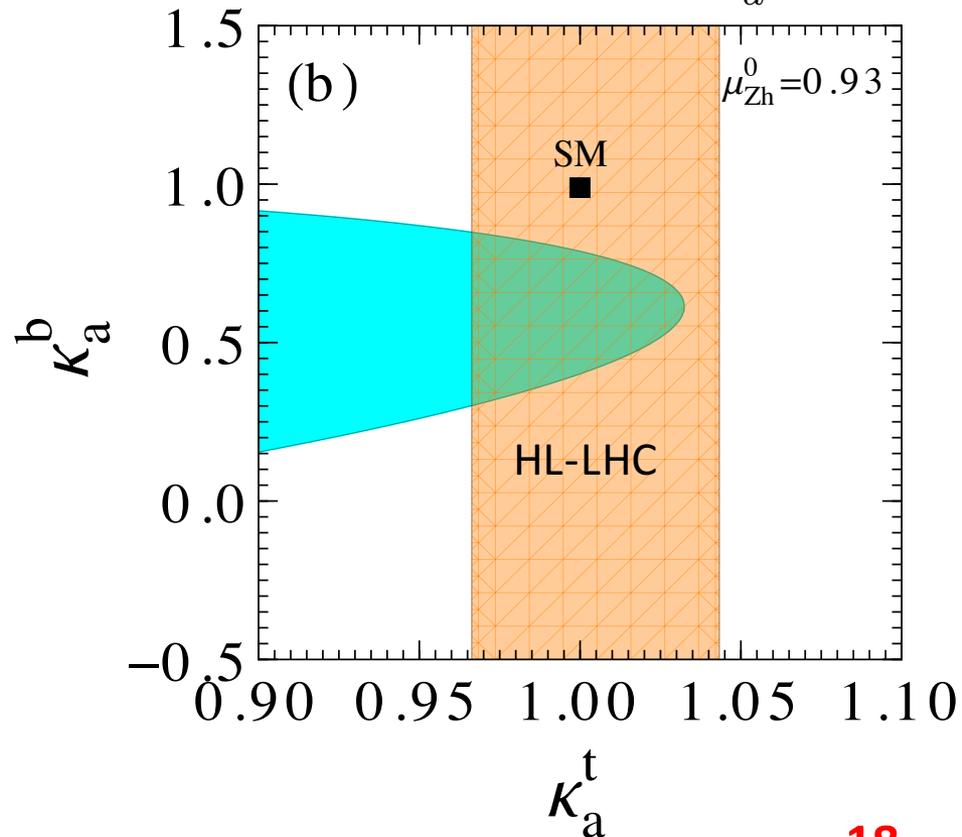
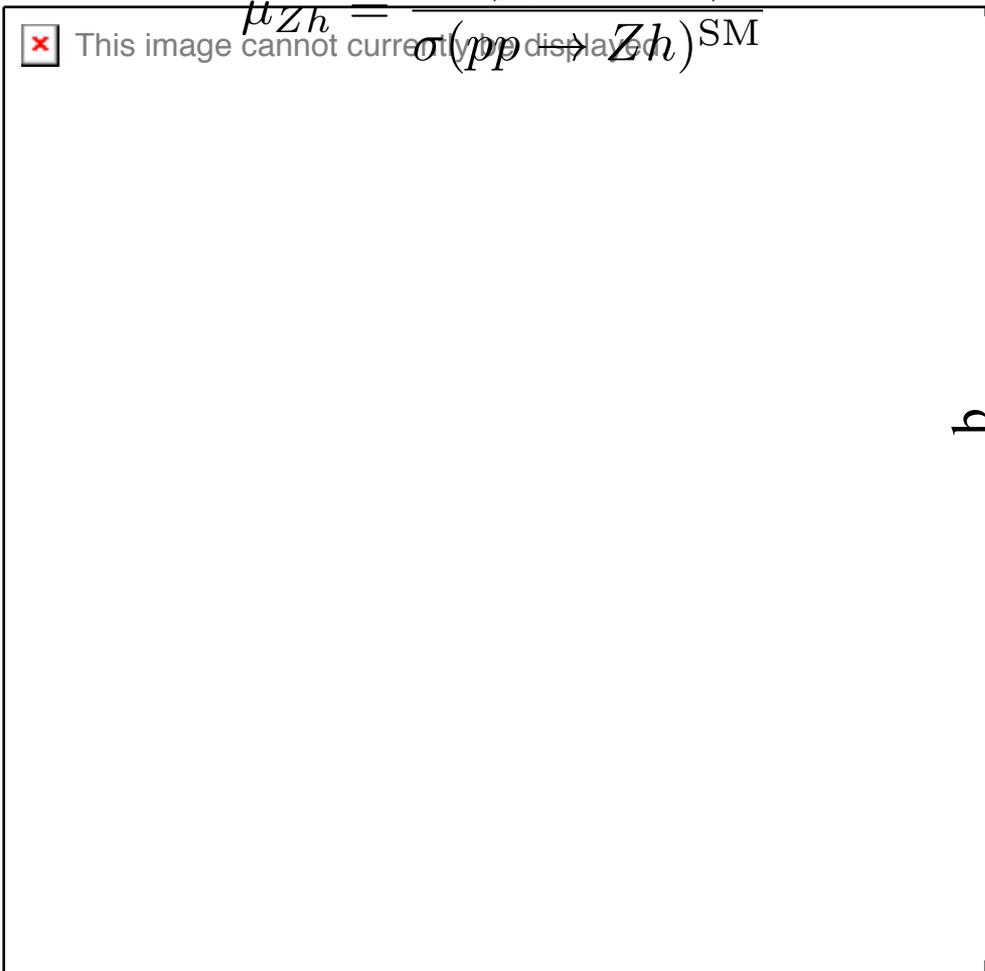
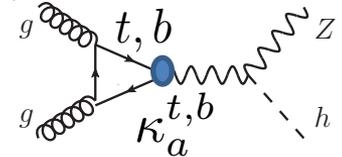
Backup

Sensitivity@HL-LHC

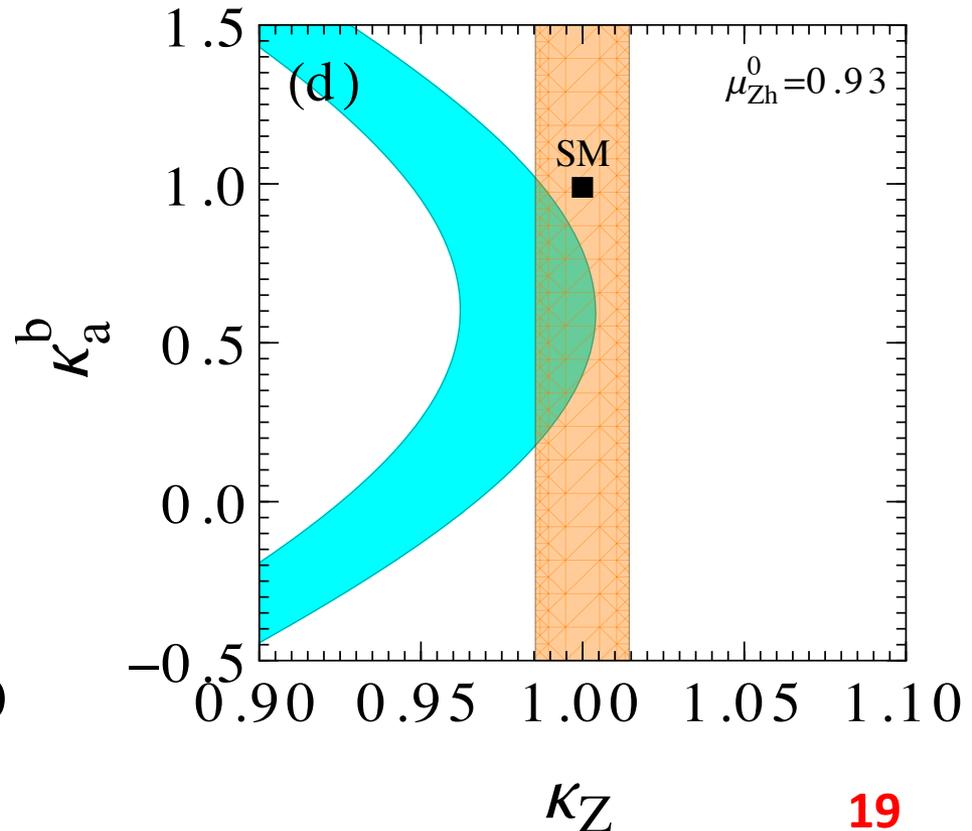
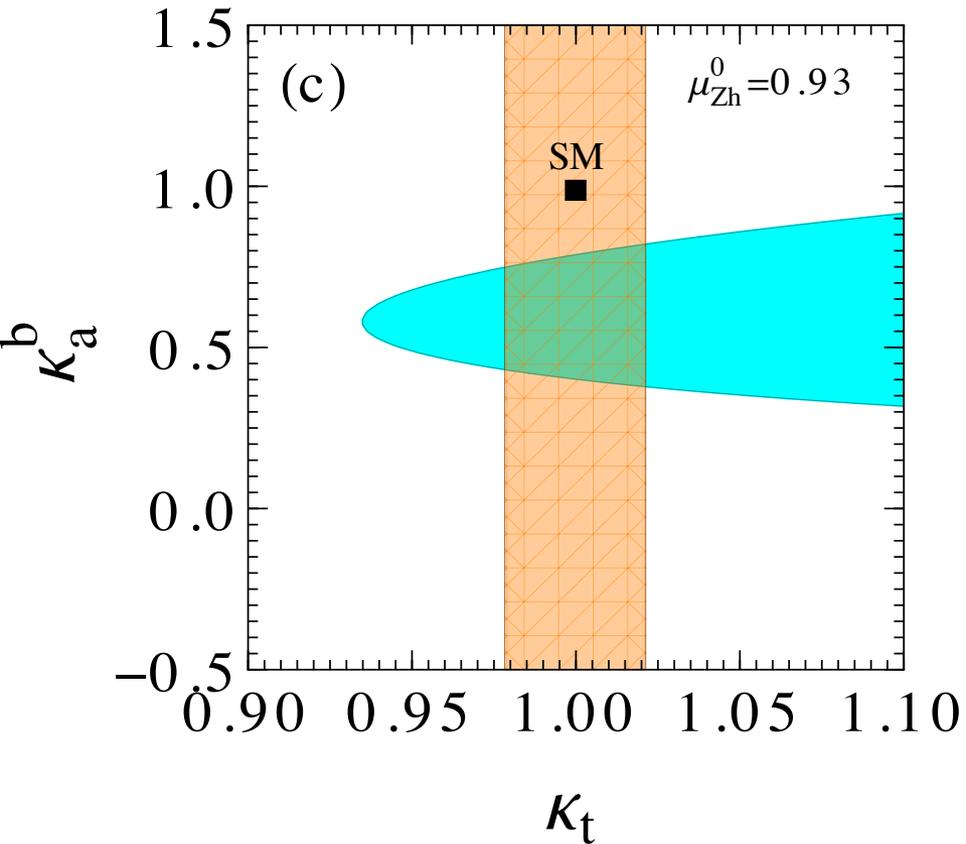
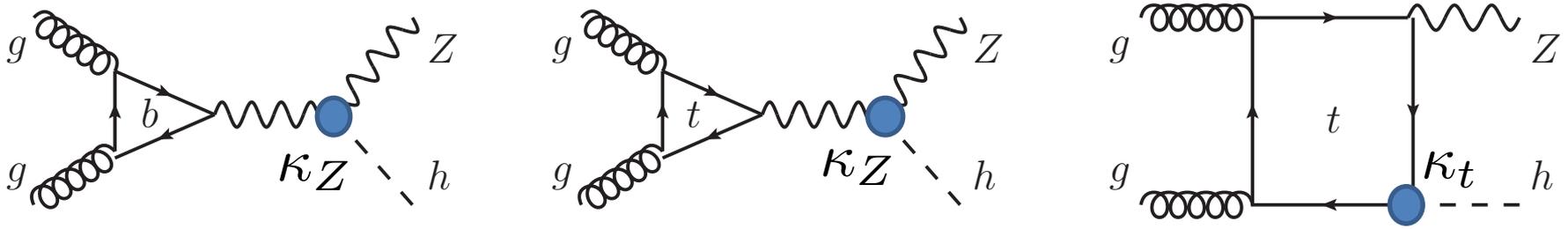
The expected limit is sensitive to the central value of the signal strength

$$\mu_{Zh} = \frac{\sigma(pp \rightarrow Zh)}{\sigma(pp \rightarrow Zh)^{SM}}$$

The conclusion is **not sensitive** to the other top quark couplings



Sensitivity@HL-LHC



DIS cross section

Polarized cross section

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

$\lambda_e = \pm 1$: lepton helicity

DIS variables:

$$Q^2 = -q^2, \quad x = \frac{Q^2}{2P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot k}, \quad xyS = Q^2,$$

Simplified-ACOT- χ scheme@NNLO

M. Guzzi et al, PRD86,053005(2012)

M. A. G. Aivazis, F.I. Olness, W.-K. Tung, 94'

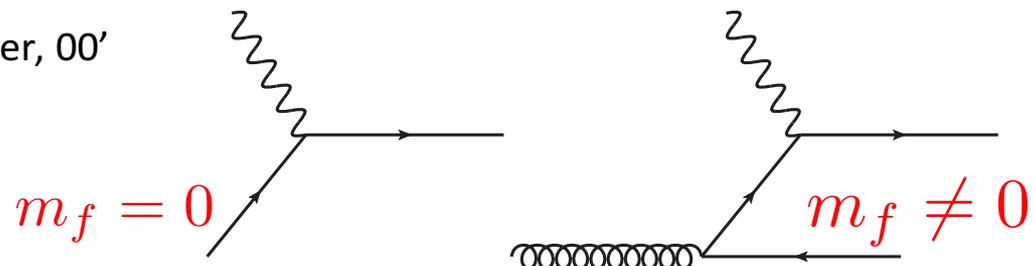
M. A. G. Aivazis, J.C. Collins, F.I. Olness, W.-K. Tung, 94'

J.C. Collins, 98'

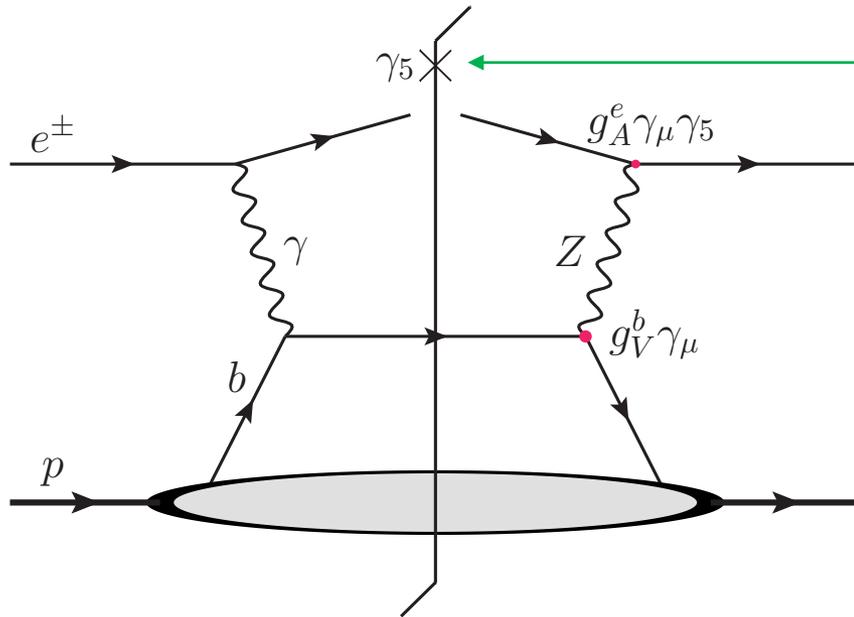
M.Kramer, F.I. Olness, D. E. Soper, 00'

....

$$Q \sim m_f$$



Dependence on Zbb coupling



SSA: $\sigma_+ - \sigma_-$

- Photon-only channel cancels.
- γZ channel dominates.
- ZZ channel is suppressed for $Q^2 \in [10^2, 10^4] \text{ GeV}^2$
- Zee coupling \simeq **axial**-vector coupling:
 $g_A^e = -0.5, g_V^e = -0.038$

➡ $g_A^e g_V^b$ dominates

The combination of $g_V^e g_A^b$ is further suppressed by PDFs and high orders since

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

- At LO and NLO, $q = b$ and $b - \bar{b} = 0 \Rightarrow F_3 = 0$
- At NNLO, q can be other flavors and $b - \bar{b} \neq 0 \Rightarrow F_3 \neq 0$, but suppressed by α_s^2

- ➡
- SSA is sensitive to the **vector component** of the Zbb coupling.
 - The dependence on axial part is suppressed by
(i) Z propagator, *(ii)* small g_V^e , *(iii)* PDFs (NNLO effect).

SSA@HERA and EIC

SSA definition:

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

To physics Observables



SSA@HERA (Run-II)

$$A_e^b = \frac{\sigma_b^{\text{tot}}(P_e) - \sigma_b^{\text{tot}}(-P'_e)}{P'_e \sigma_b^{\text{tot}}(P_e) + P_e \sigma_b^{\text{tot}}(-P'_e)}$$

P_e, P'_e

Lepton beam polarization

SSA@EIC

$$A_e^b = \frac{1}{P_e} \frac{\sigma_b^{\text{tot}}(P_e) - \sigma_b^{\text{tot}}(-P_e)}{\sigma_b^{\text{tot}}(P_e) + \sigma_b^{\text{tot}}(-P_e)}$$

$P_e = P'_e$