The anomalous Zbb couplings at the LHC and ep colliders

Bin Yan
Los Alamos National Laboratory

SUSY2021
Aug 23-28, 2021

Bin Yan, C.-P. Yuan, PRL127,051801
Bin Yan, Zhite Yu and C.-P. Yuan, arxiv: 2107.02134

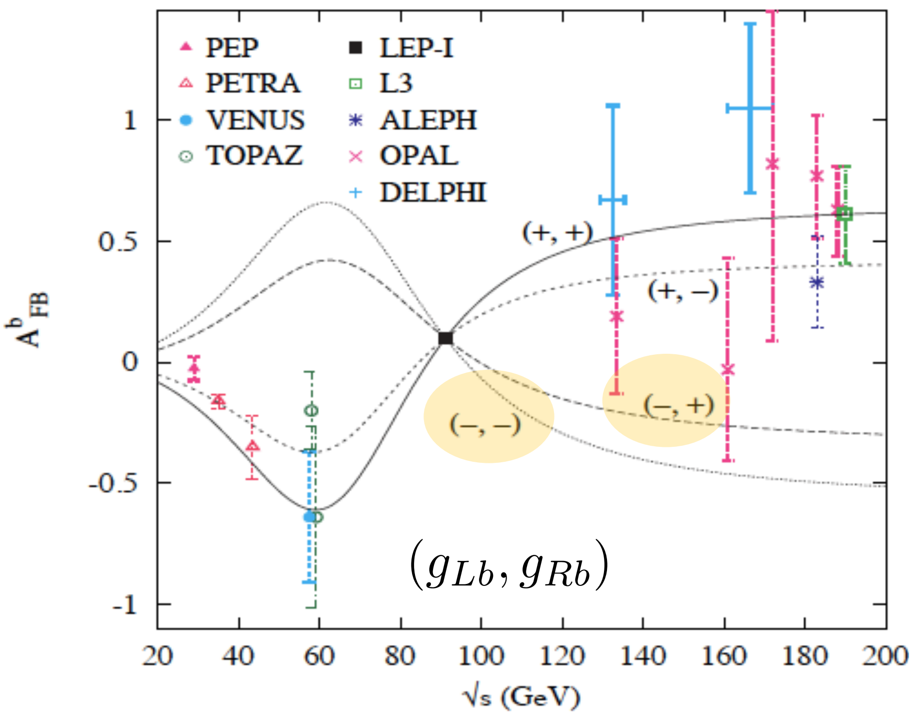
Status of Zbb couplings

	measured value	SM prediction
R_b^0	0.21629 ± 0.00066	0.21578 ± 0.00011
$A_{FB}^{0,b}$	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

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

2.1σ deviation with SM prediction



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

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

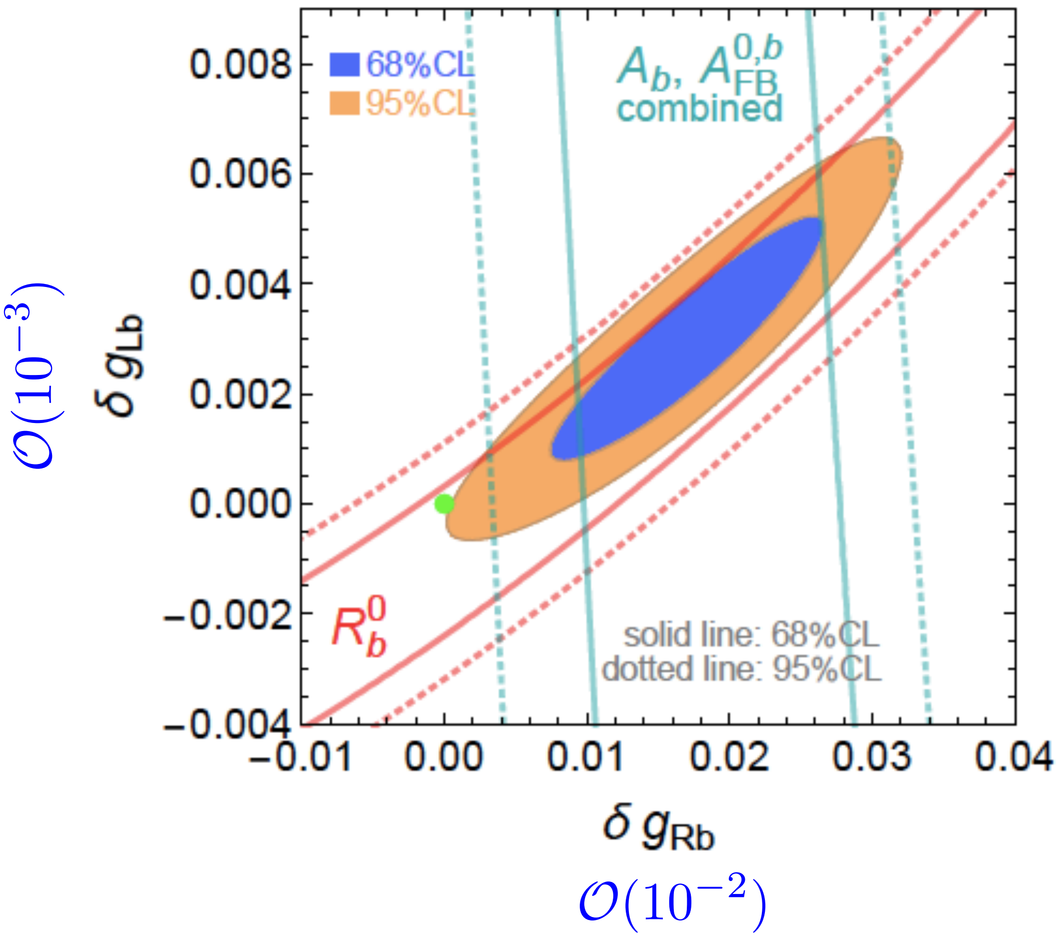
$g_{Lb} < 0$ was Excluded

g_{Rb} Could be positive *or* negative

Status of Zbb couplings

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

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



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

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

- 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

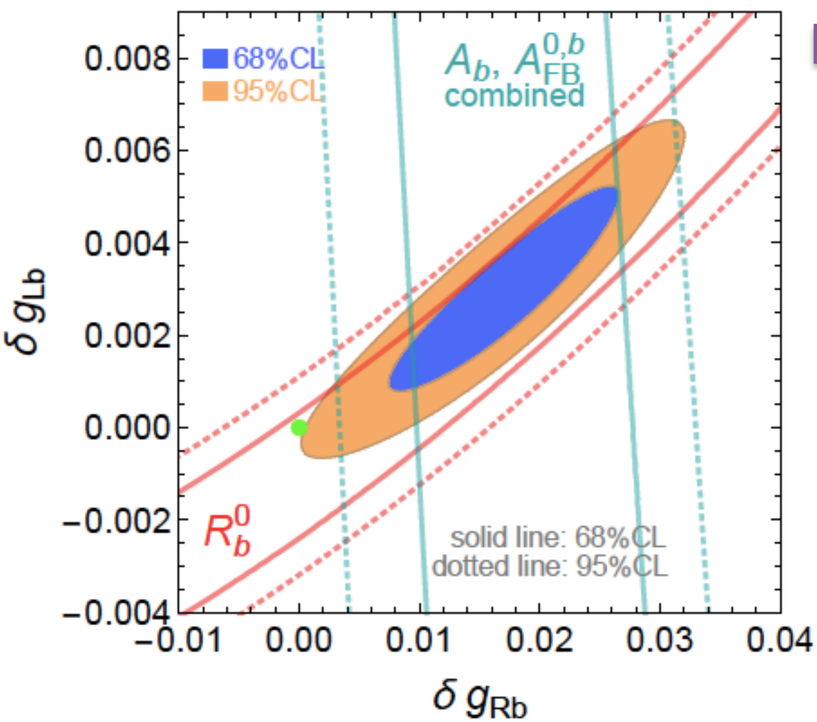
Zbb couplings@ future e+e- colliders

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

The degeneracy of right-handed Zbb coupling could be broken by scanning the energy at the e+e- colliders

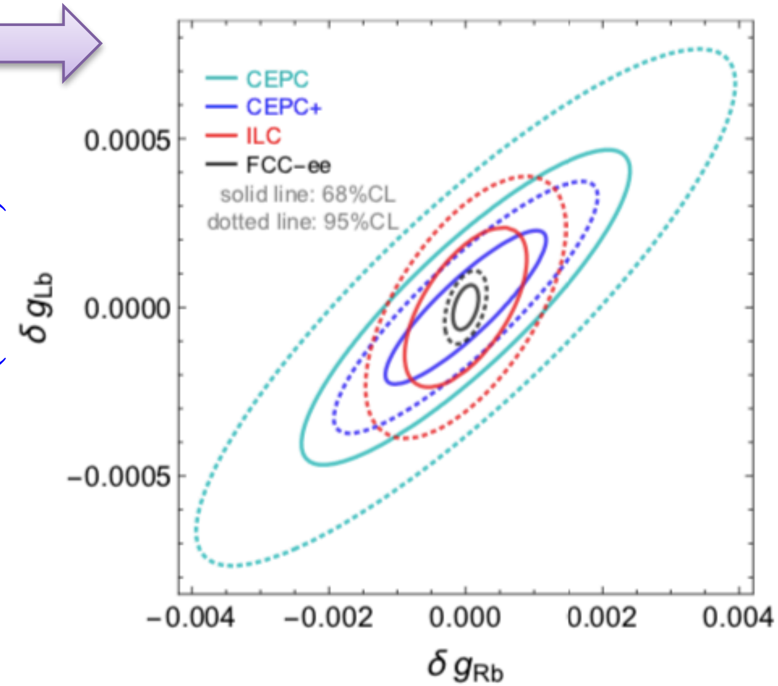
S. Gori, J. Gu, L. T. Wang, JHEP04(2016)062

$\mathcal{O}(10^{-3})$



$\mathcal{O}(10^{-2})$

$\mathcal{O}(10^{-4})$



$\mathcal{O}(10^{-3})$

So…

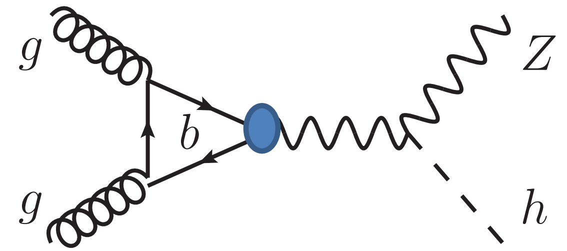
Should we just wait for the next generation lepton colliders?

<u>Any possibility from LHC and ep colliders (HERA and EIC)?</u>

Zbb couplings@ LHC and ep colliders

A. LHC

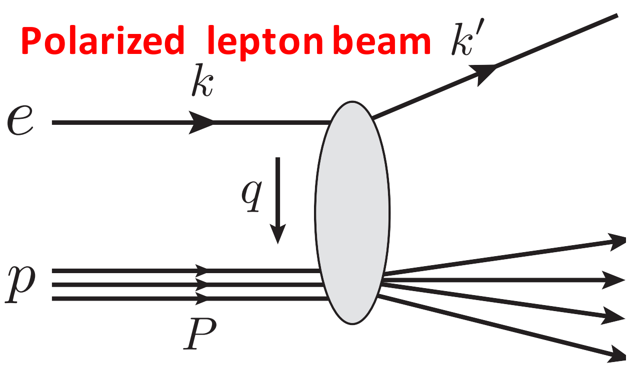
$$\mathcal{L} = \frac{g_W}{2c_W}\bar{b}\gamma_\mu(\kappa_v^b v_b^{\mathrm{SM}} - \kappa_a^b a_b^{\mathrm{SM}}\gamma_5)bZ_\mu$$



axial-vector component of Zbb coupling

B. HERA and EIC

Polarized lepton beam

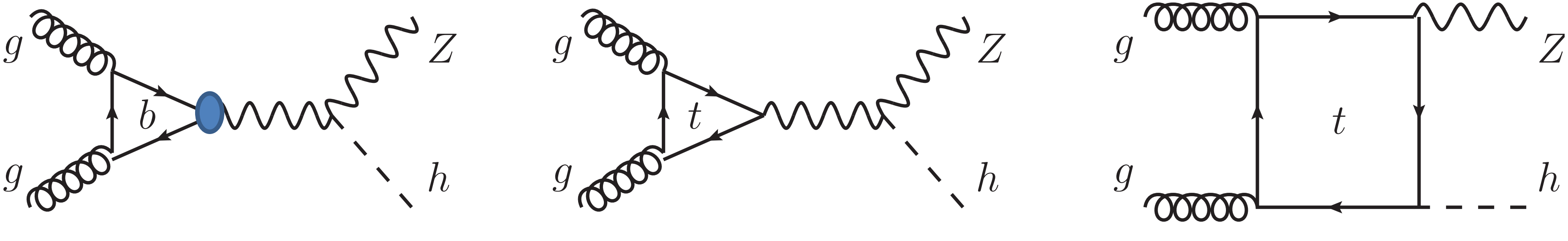


Single-Spin Asymmetry (SSA)

Complementary

vector component of Zbb coupling

A. Zbb couplings @LHC



$y_b = 0$

charge conjugation invariance + isospin asymmetry:

(1) Only axial-vector components contribute to the cross section;

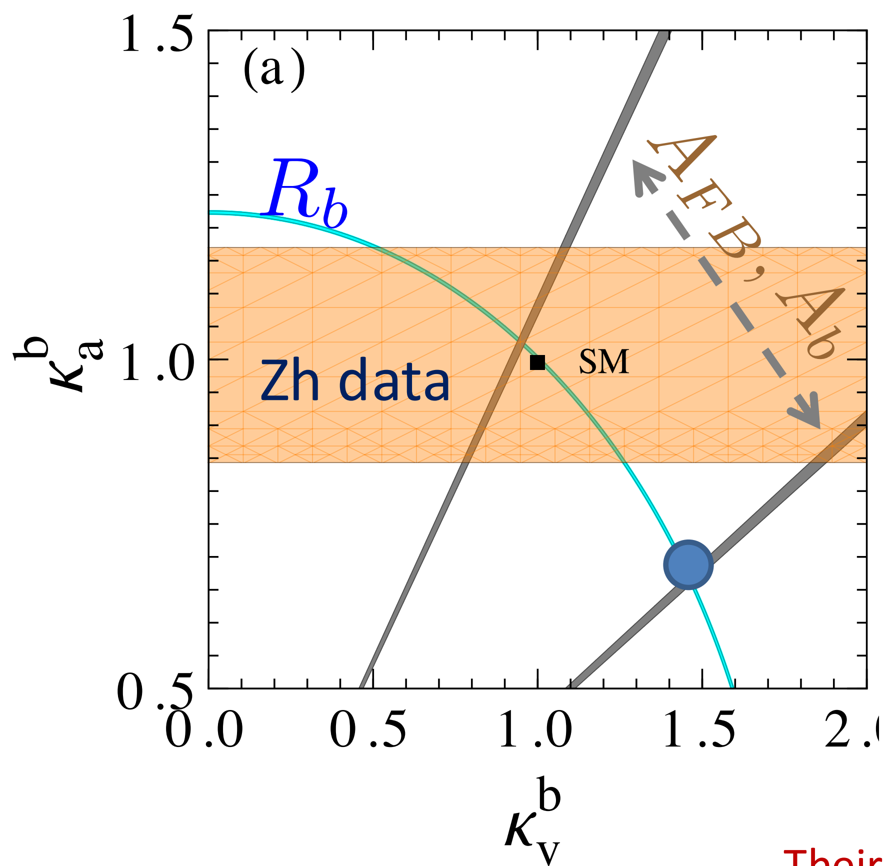
(2) Only top and bottom quarks contribute to the scattering;

(3) Bottom quark's contribution is comparable to the top quark, i.e. $\sigma(b)/\sigma(t) \simeq 1.1$

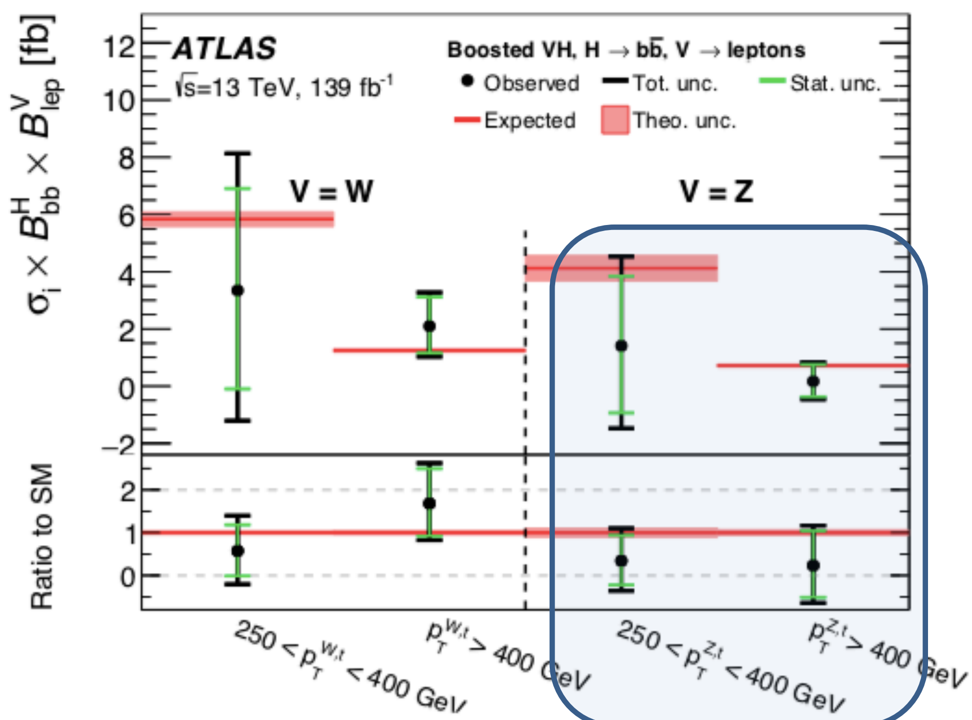
$$\mathcal{L} = \frac{g_W}{2c_W}\bar{b}\gamma_\mu(\kappa_v^b v_b^{\rm SM} - \kappa_a^b a_b^{\rm SM}\gamma_5)bZ_\mu + \frac{m_Z^2}{v}\kappa_Z h Z_\mu Z^\mu + \frac{g_W}{2c_W}\bar{t}\gamma_\mu(\kappa_v^t v_t^{\rm SM} - \kappa_a^t a_t^{\rm SM}\gamma_5)tZ_\mu - \frac{m_t}{v}\kappa_t \bar{t}th, \quad (1)$$

Break the Zbb coupling degeneracy

Current Zh data could break the degeneracy



ATLAS: 2008.02508



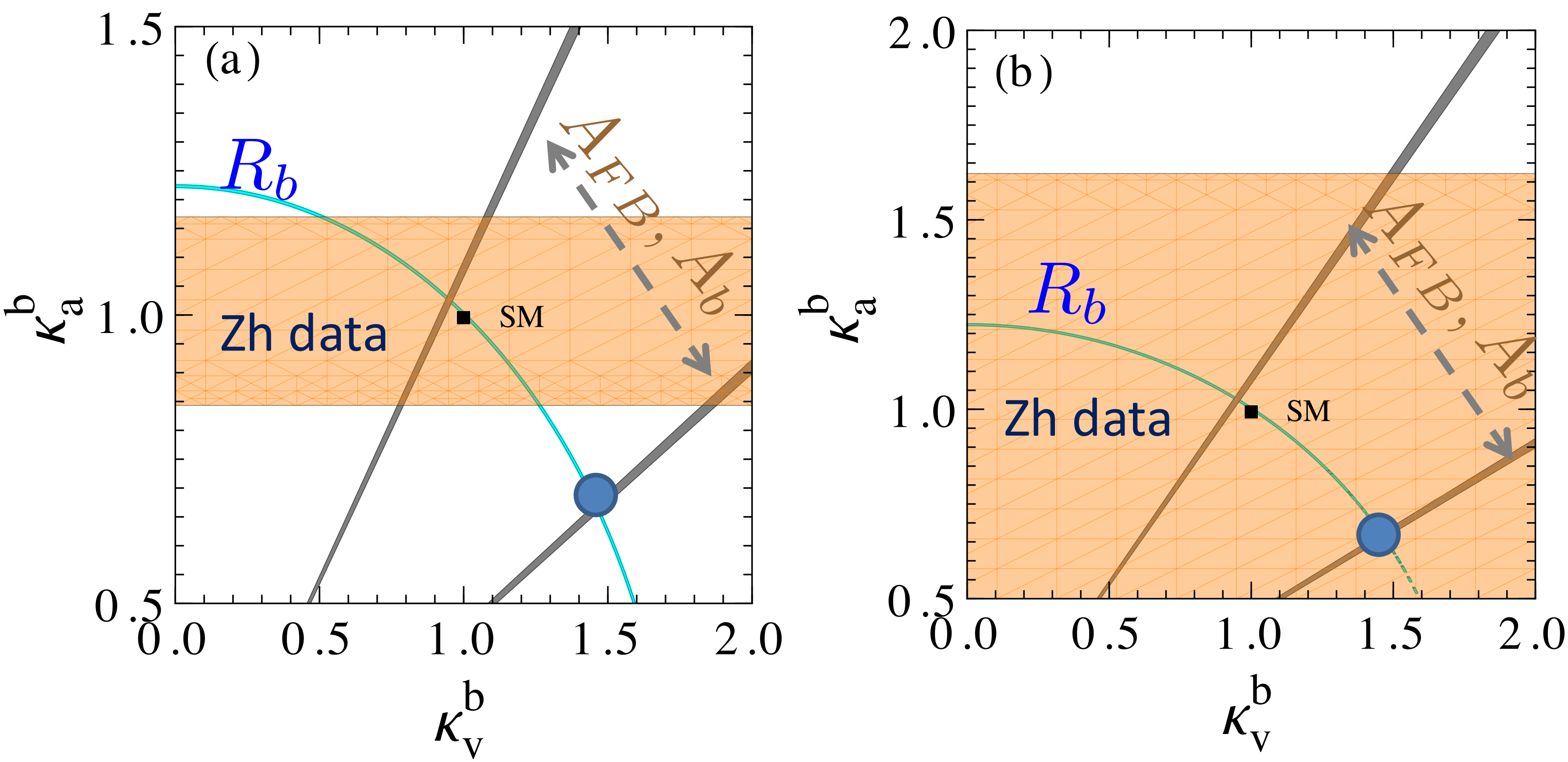
Their central values are smaller than SM predictions

Including all Zh data

the two high P_T^Z data play an important role

Break the Zbb coupling degeneracy

Current Zh data could break the degeneracy

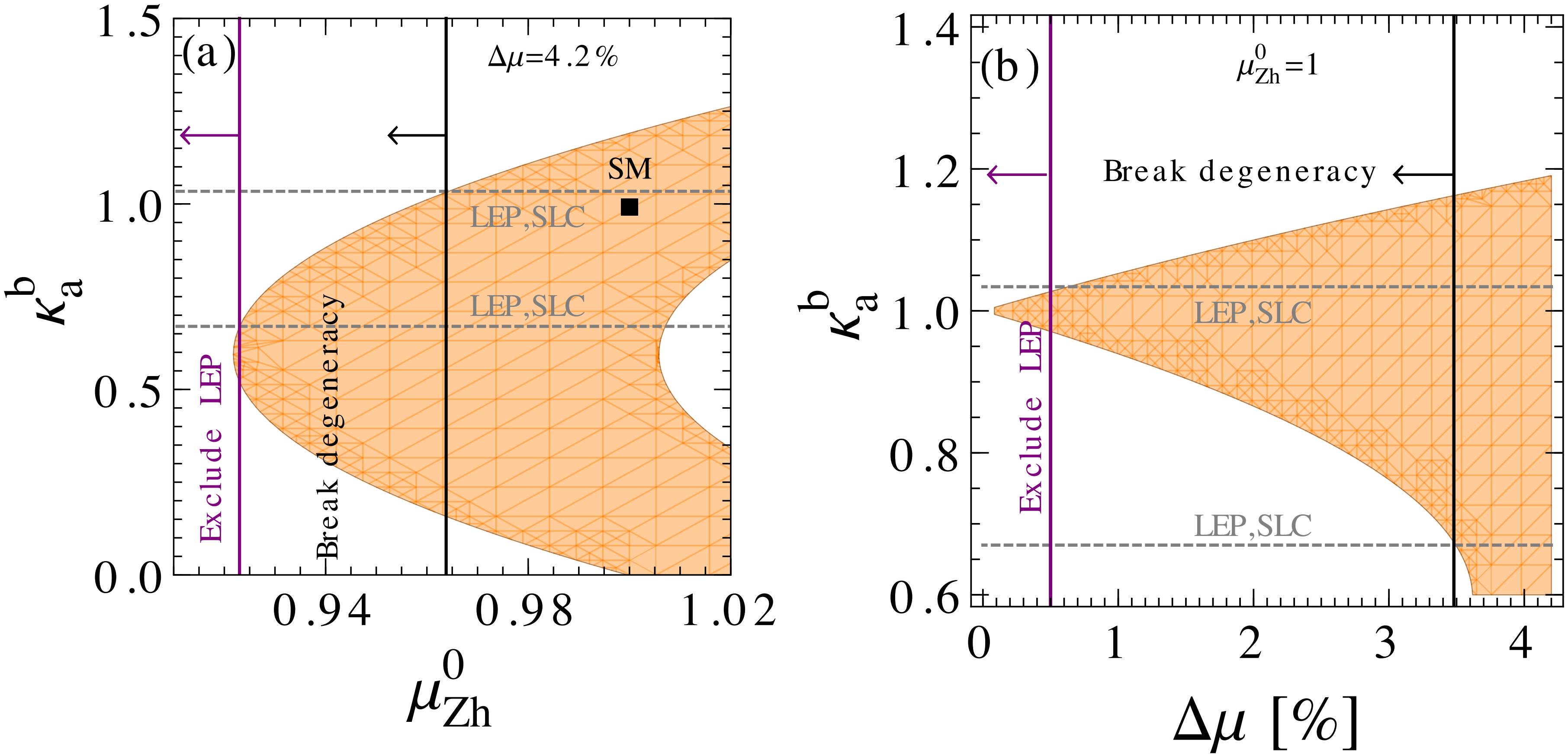


Including all Zh data

Removing the two high P_T^Z data

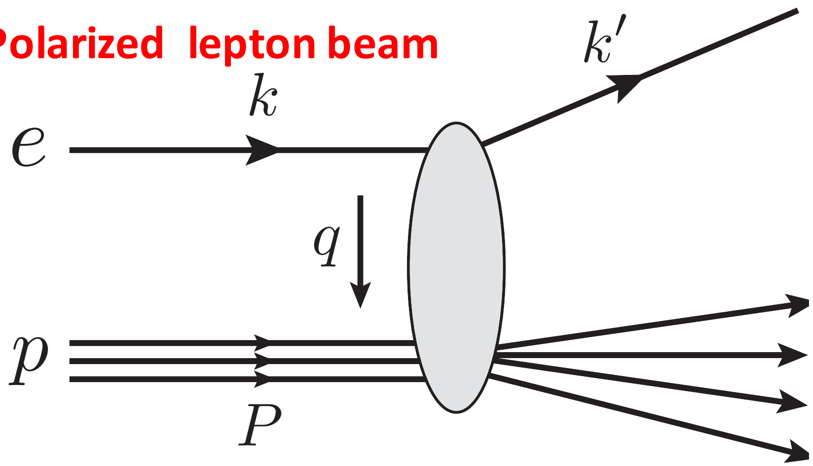
Break the Zbb coupling degeneracy

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



B. Zbb couplings@HERA and EIC

Polarized lepton beam



Single-Spin Asymmetry (SSA):

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

$+/-$: 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

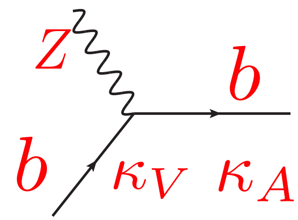
H1	R	L
e^-p	$47.3\,\text{pb}^{-1}$, 0.36	$104.4\,\text{pb}^{-1}$, -0.258
e^+p	$101.3\,\text{pb}^{-1}$, 0.325	$80.7\,\text{pb}^{-1}$, -0.37
ZEUS	R	L
e^-p	$71.2\,\text{pb}^{-1}$, 0.29	$98.7\,\text{pb}^{-1}$, -0.27
e^+p	$78.8\,\text{pb}^{-1}$, 0.32	$56.7\,\text{pb}^{-1}$, -0.36

JHEP 09, 061 (2012)

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

Phys. Rev. D 87, 052014 (2013)

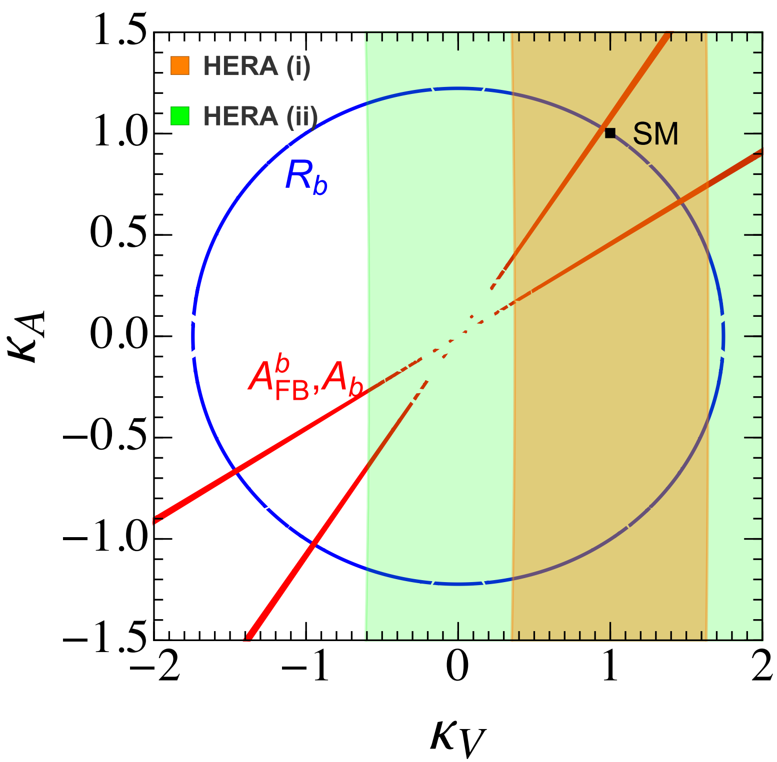
Simplified-ACOT-χ scheme@NNLO



$Q \sim m_b$

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

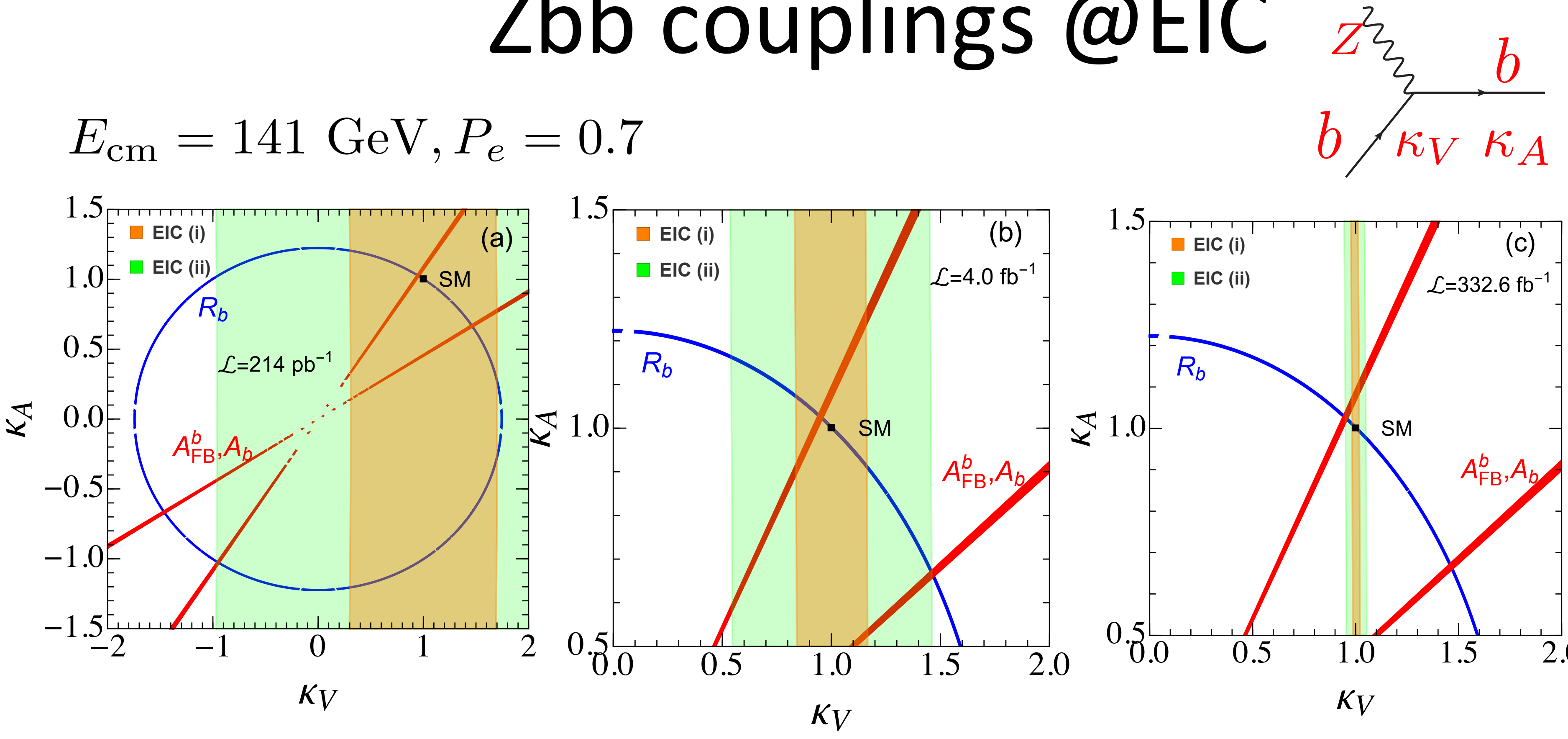
$(ii)\ \epsilon_q^b = 0.01, \quad \epsilon_c^b = 0.2, \quad \epsilon_b = 0.5.$



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

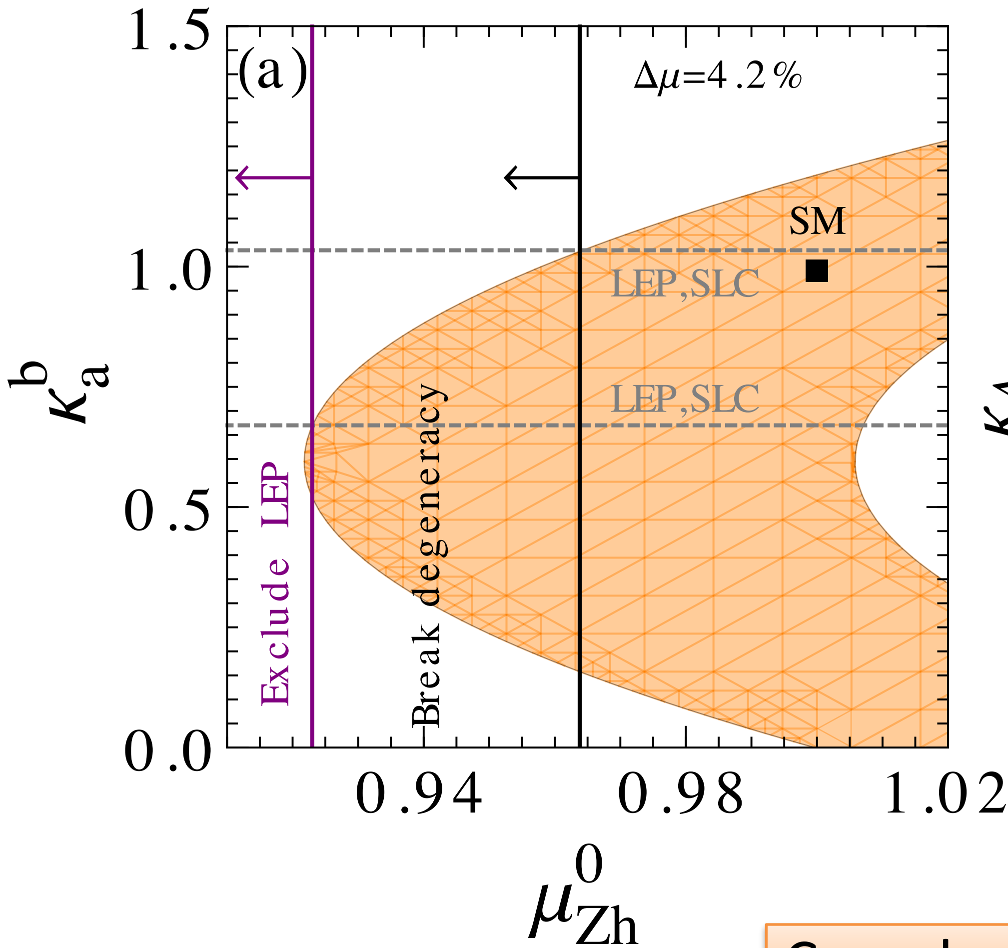
$E_{\text{cm}} = 141 \text{ GeV}, P_e = 0.7$

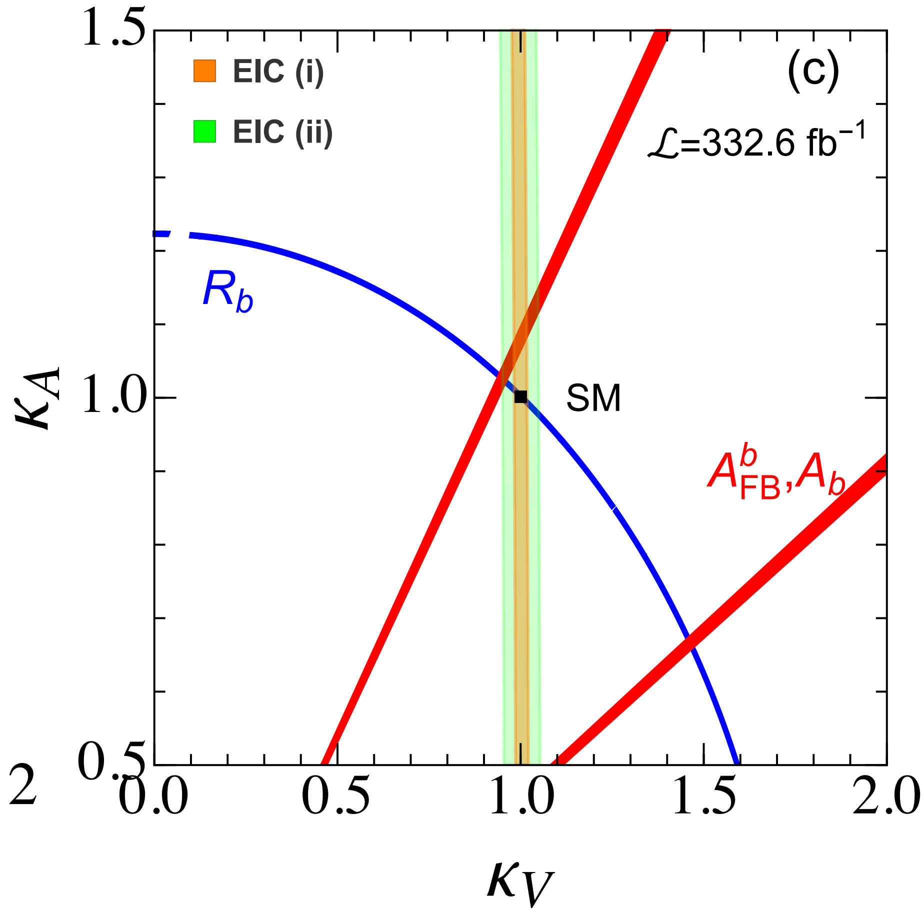


$(i) : \mathcal{L} > 27 \text{ pb}^{-1};$ $(i) : \mathcal{L} > 0.5 \text{ fb}^{-1};$ $(i) : \mathcal{L} > 42.0 \text{ fb}^{-1};$

$(ii) : \mathcal{L} > 214 \text{ pb}^{-1}.$ $(ii) : \mathcal{L} > 4.0 \text{ fb}^{-1}.$ $(ii) : \mathcal{L} > 332.6 \text{ fb}^{-1}.$

LHC vs. EIC





LHC: axial-vector component of Zbb coupling

Complementary ↔

EIC: vector component of Zbb coupling

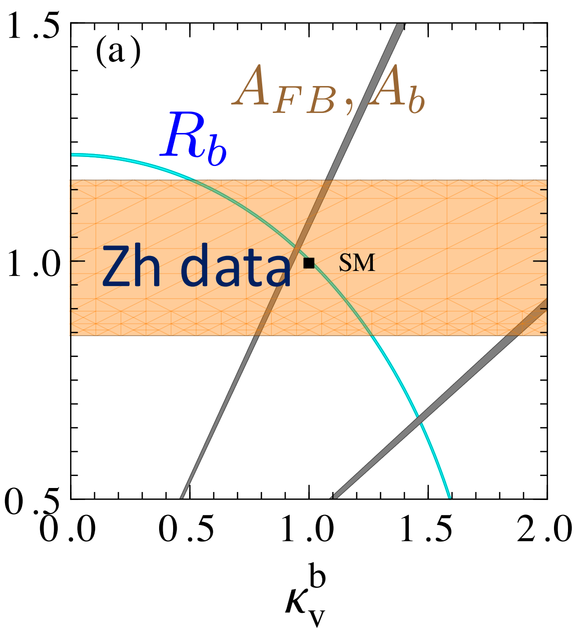
Summary

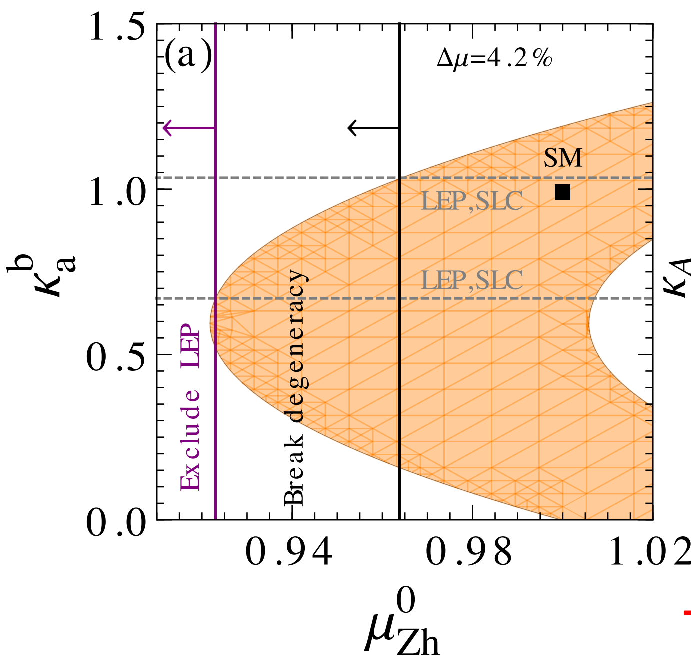
A. We proposed two new methods to probe the Zbb coupling at the LHC and ep colliders

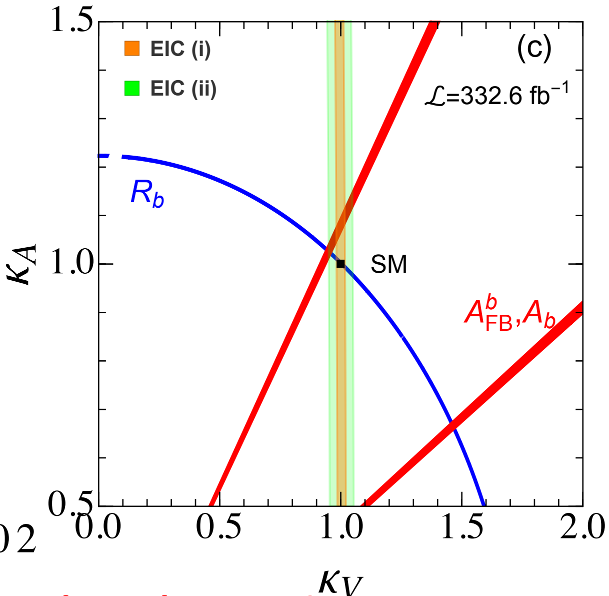
B. The Zh data at the 13 TeV LHC can resolve the apparent degeneracy of the Zbb coupling;

C. Zh cross section depends on the axial-vector Zbb coupling, while the SSA in HERA or EIC is sensitive to the vector Zbb coupling ;

D. It is hopeful to verify or exclude the LEP measurement by those new methods.







Thank you!

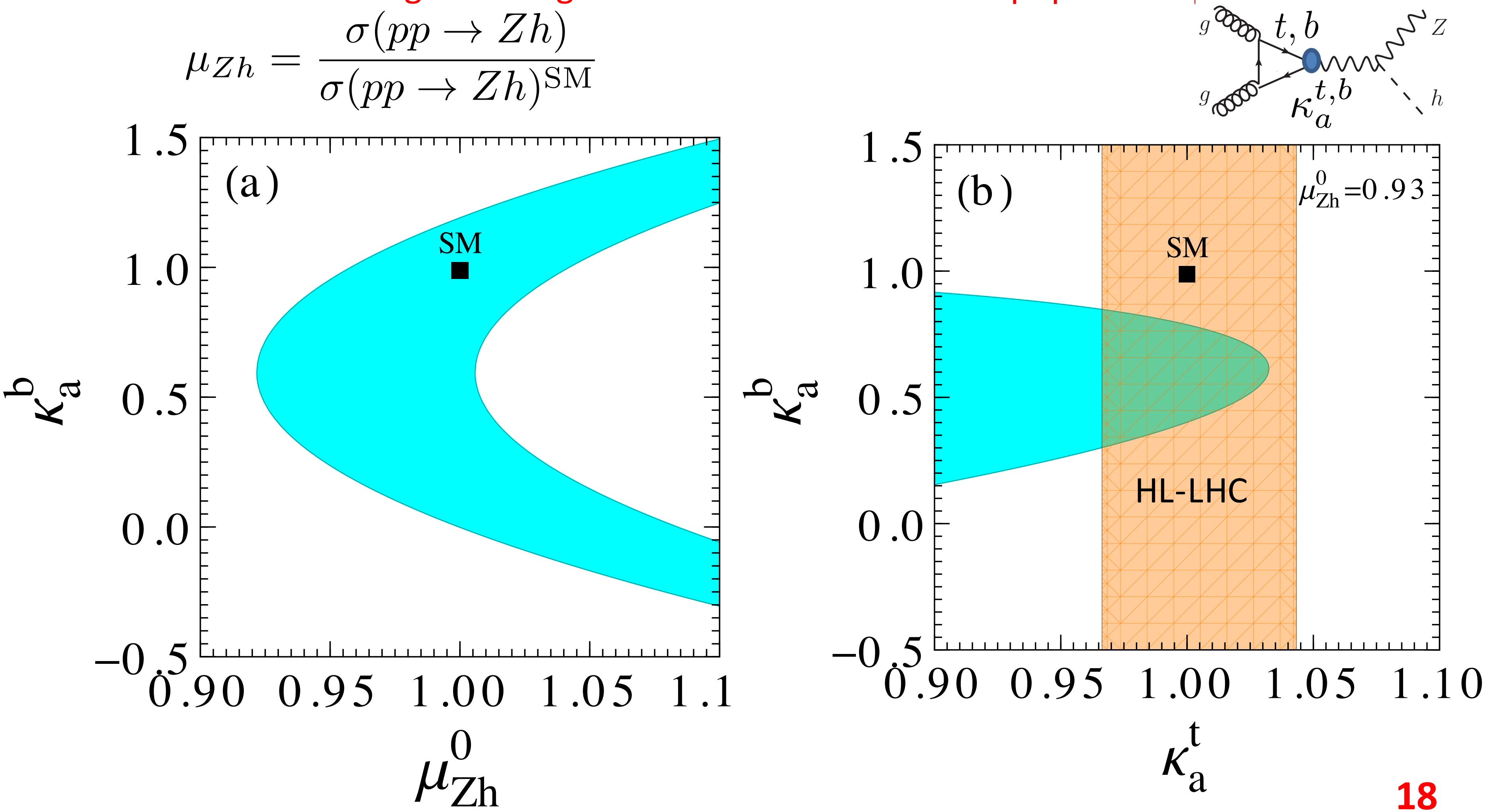
Backup

Sensitivity@HL-LHC

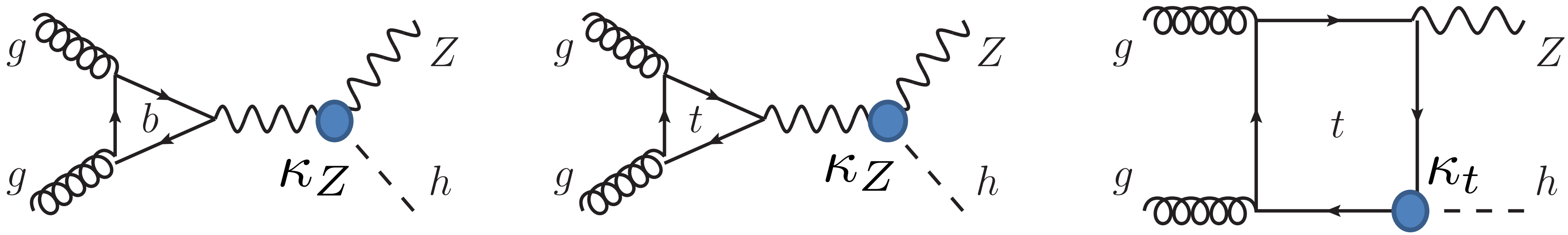
The expected limit is sensitive to the central value of the signal strength

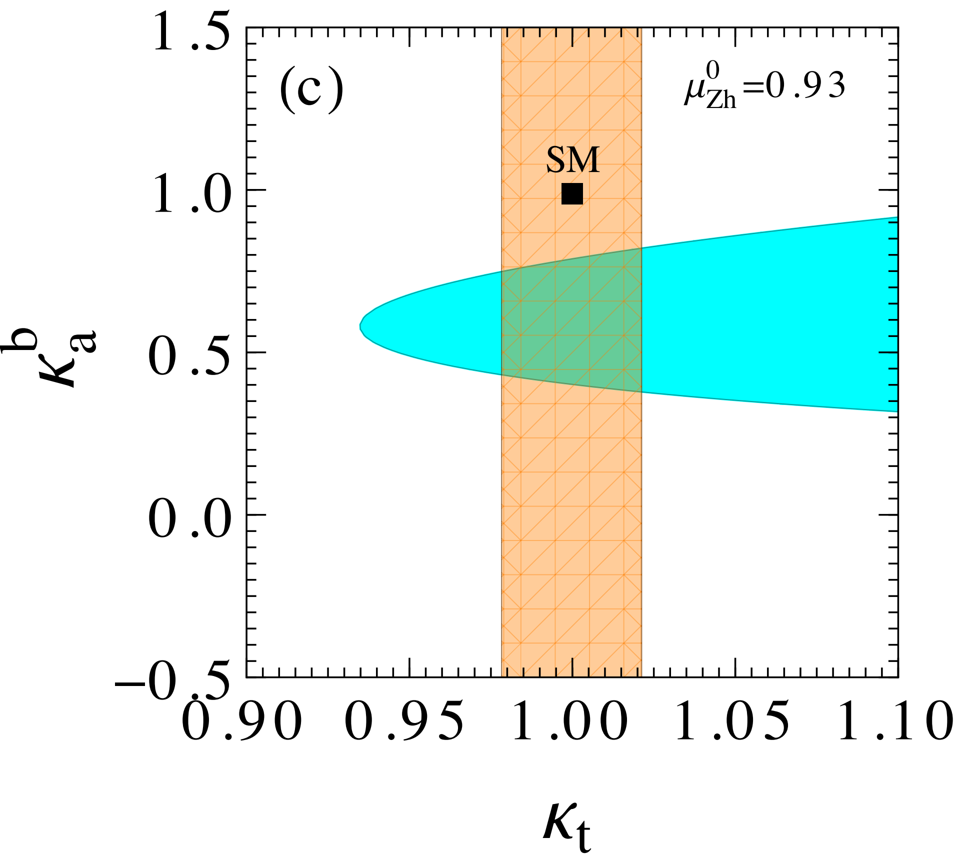
$$\mu_{Zh} = \frac{\sigma(pp \to Zh)}{\sigma(pp \to Zh)^{\rm SM}}$$

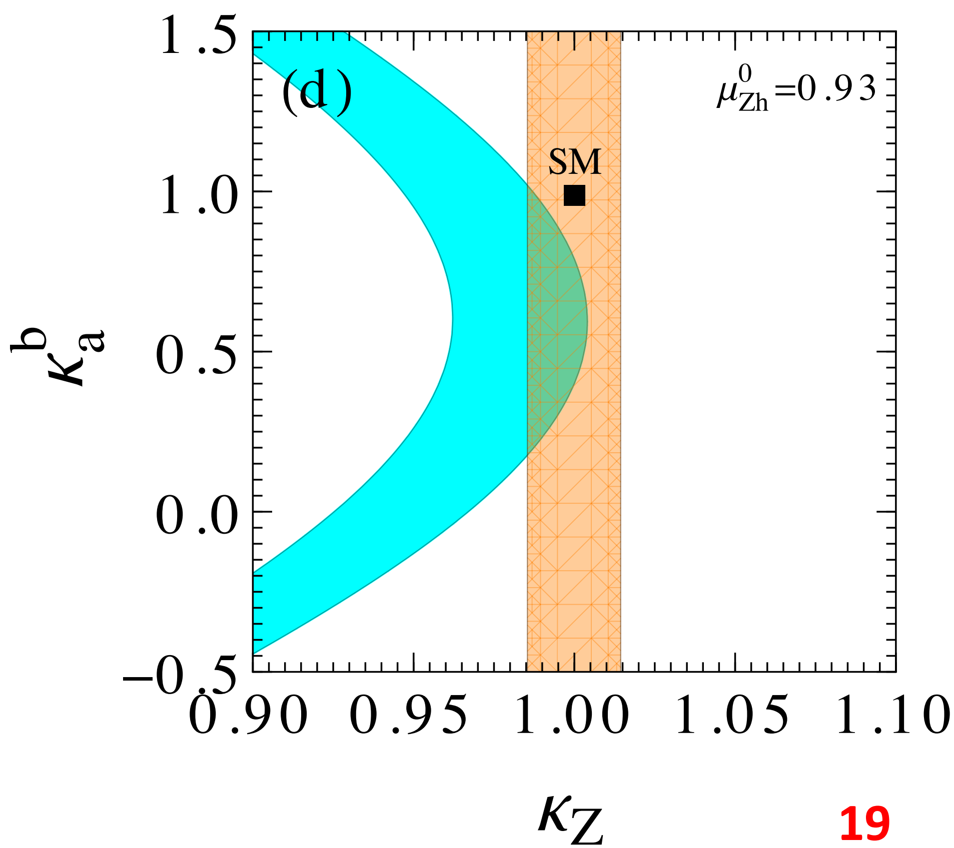
The conclusion is not sensitive to the other top quark couplings



Sensitivity@HL-LHC







DIS cross section

Polarized cross section

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

$\lambda_e = \pm 1$: lepton helicity

DIS variables:

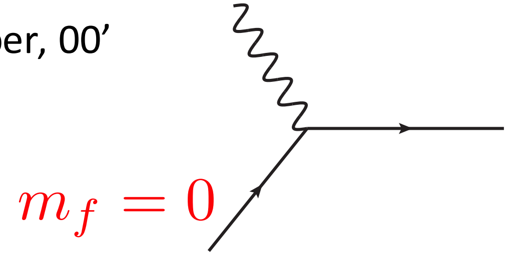
$$Q^2 = -q^2, \quad x = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot k}, \quad xyS = Q^2,$$

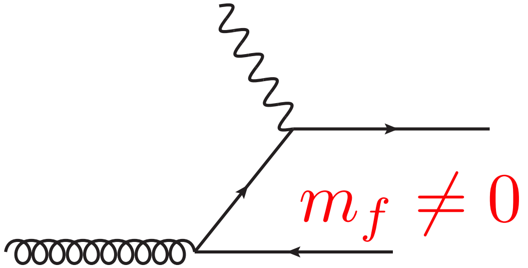
Simplified-ACOT-χ scheme@NNLO

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

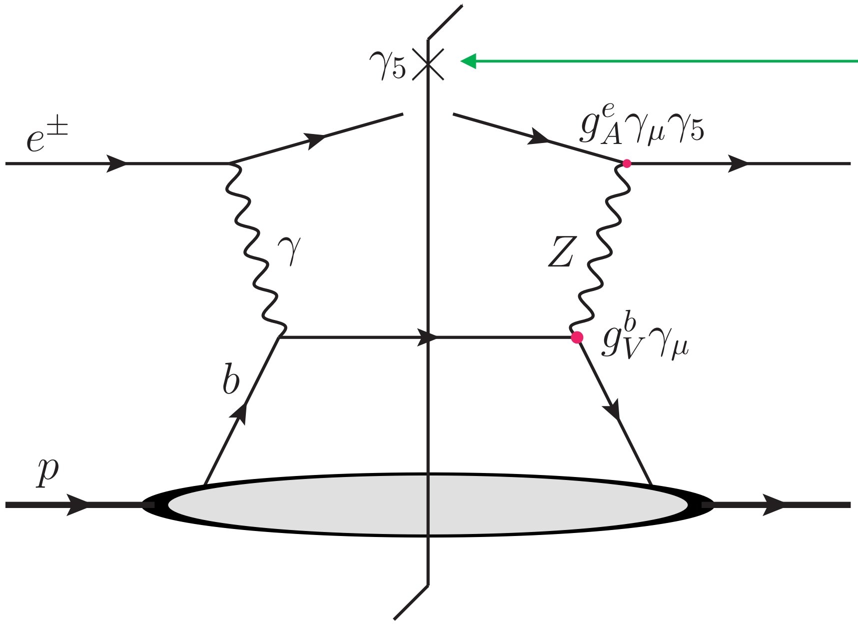
M. A. G. Aivazis, F.I. Olness, W.-K. Tung, 94'
M. A. G. Aivazis, J.C. Collins, F.I. Olness, W.-K. Tung, 94'
J.C. Collins, 98'
M.Kramer, F.I. Olness, D. E. Soper, 00'
....

$Q \sim m_f$





Dependence on Zbb coupling



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

- Photon-only channel cancels.
- **$\boldsymbol{\gamma Z}$ channel dominates.**
- ZZ channel is suppressed for $Q^2 \in [10^2, 10^4]\ GeV^2$
- 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 $\boldsymbol{g_V^e\ g_A^b}$ is further suppressed by **PDFs** and **high orders** since

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

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

⇒
- **SSA is sensitive to the vector component of the $\boldsymbol{Zbb}$ coupling.**
- **The dependence on axial part is suppressed by $\boldsymbol{(i)}$ $\boldsymbol{Z}$ propagator, $\boldsymbol{(ii)}$ small $\boldsymbol{g_V^e}$, $\boldsymbol{(iii)}$ 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

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

$P_e = P_e'$