Precision test of the Zbb anomalous couplings at colliders

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The 8th China LHC Physics Workshop
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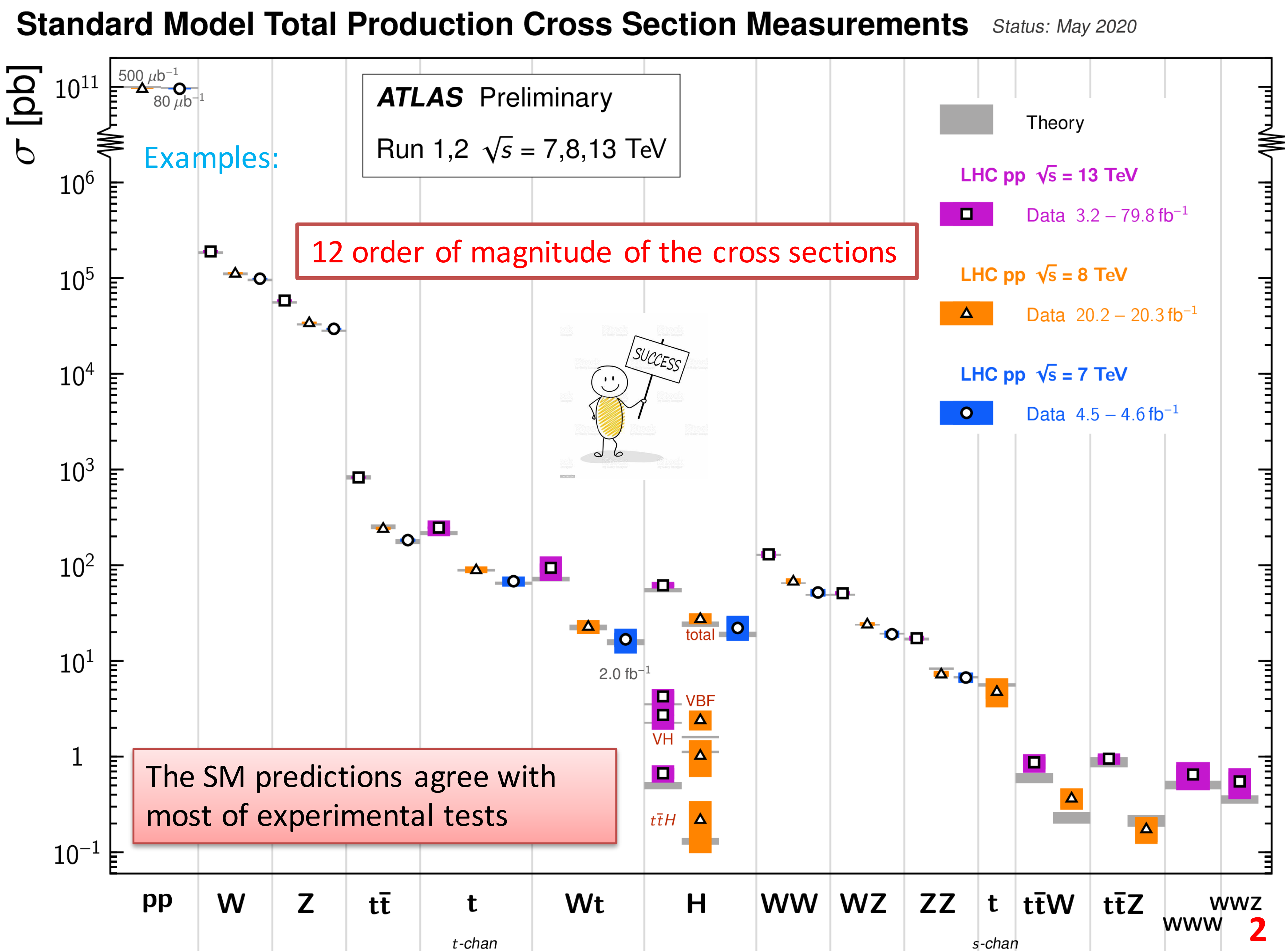
Bin Yan, C.-P. Yuan, PRL127(2021)5,051801
Bin Yan, Zhite Yu and C.-P. Yuan, PLB822(2021)136697
Hai Tao Li, Bin Yan and C.-P. Yuan, PLB833(2022)137300
Hongxin Dong, Peng Sun, Bin Yan and C.-P. Yuan, PLB829(2022)137076



Standard Model Total Production Cross Section Measurements
Status: May 2020
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
Examples:
12 order of magnitude of the cross sections
SUCCESS
The SM predictions agree with most of experimental tests
σ [pb]
500 μb⁻¹
80 μb⁻¹
2.0 fb⁻¹
total
VBF
VH
tt̄H
Theory
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
pp
W
Z
tt̄
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
tt̄W
tt̄Z
www
wwz

Why we need the New Physis?

Some open questions:

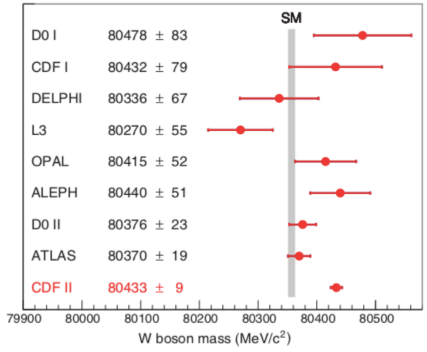
1. What is Dark Matter ?
2. What is the origin of the neutrino mass?
3. What is the nature of the electroweak symmetry breaking?
4. What is the nature of the Higgs boson (Composite or elementary particle)?
5. ……

New Physics Models and new measurements to answer these questions

The New Physics Signals?

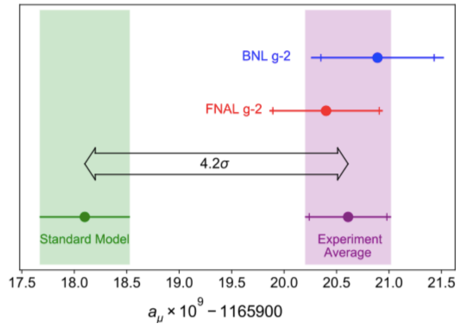
1. W-boson mass? 7σ

   CDF, Science 376(2022)6589



2. Muon g-2? 4.2σ

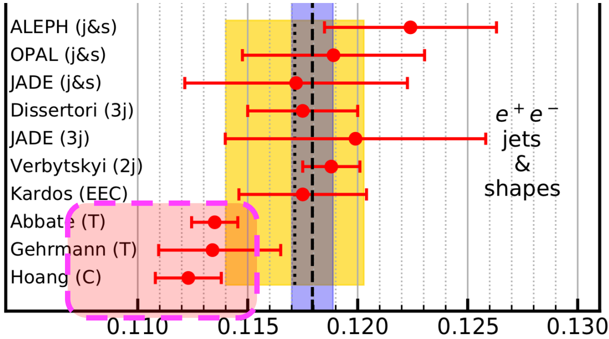
   PRL126(2021)14,141801



3. Strong coupling? $\sim 4\sigma$

   PDG2020

   G. Bell, C. Lee, Y. Makris, J. Talbert and Bin Yan, in preparation

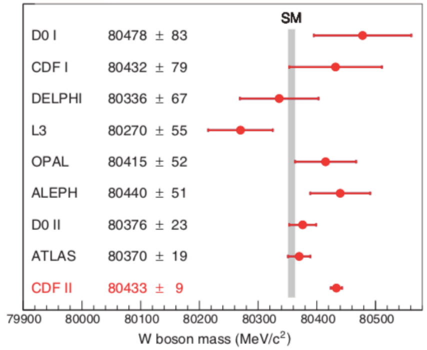


4. Forward-backward asymmetry of bottom quark @ LEP

   PDG2020 2.1σ

5. Anomaly of B physics

The New Physics Signals?



1. W-boson mass? 7σ

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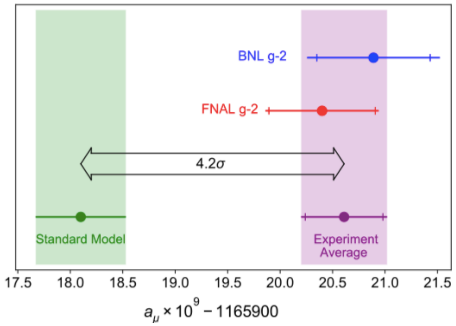

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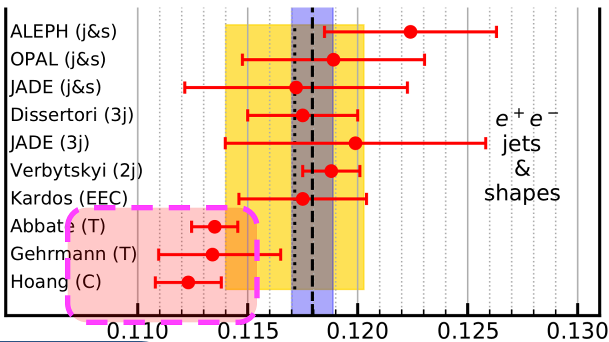

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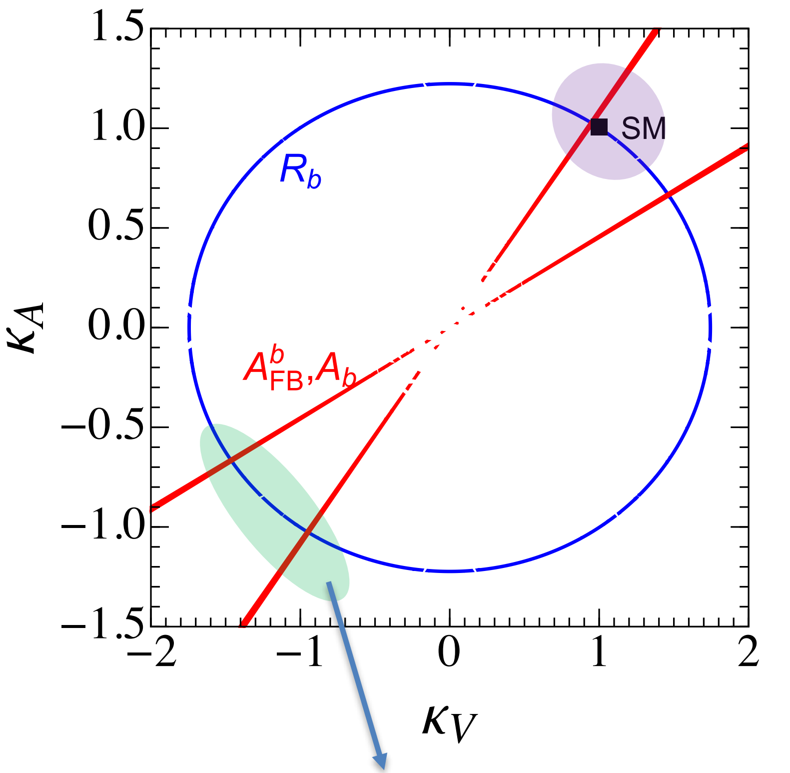
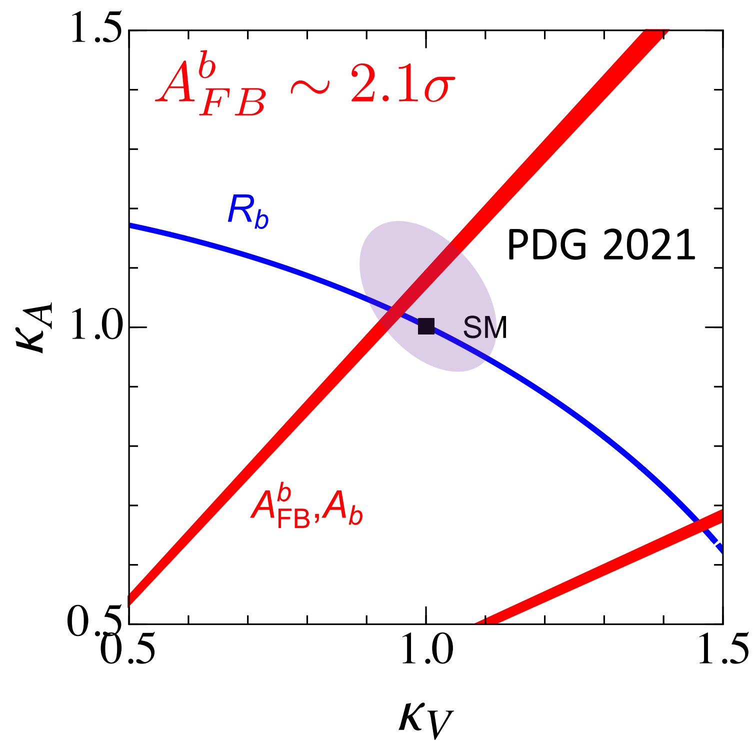
5. Anomaly of B physics

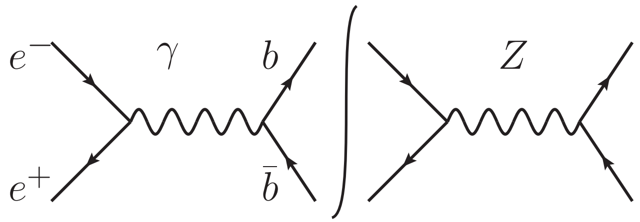
Status of Zbb couplings





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

Status of Zbb couplings

A. How to break the degeneracy of the 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 + heavy B’ quark

K. Agashe, R. Contino, L. Rold, A. pomarol, 2006’

Statistical Fluctuation or Systematic error?

New experiments: e.g. CEPC

So…

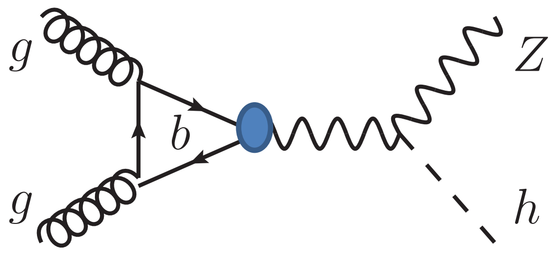
Should we just wait for the next generation lepton colliders?

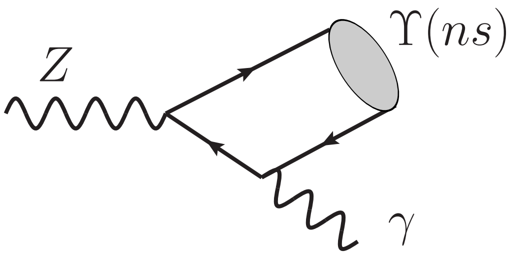
<u>Any possibility from LHC and ep colliders (HERA and EIC)?</u>

In 2020, The United States Department of Energy announced that an EIC will be built over the next ten years at Brookhaven National Laboratory

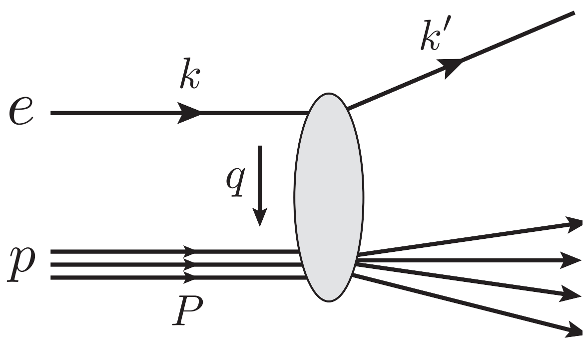
Zbb couplings@ LHC and ep colliders

A. LHC





B. HERA and EIC

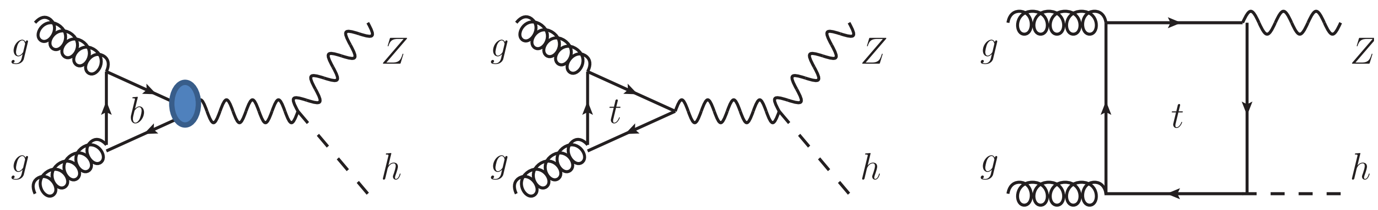


Single-Spin Asymmetry

Jet charge weighted Single-Spin Asymmetry

A. Zbb couplings @LHC

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



$y_b = 0$

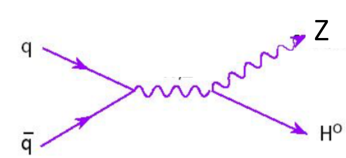
Charge conjugation invariance

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

Only axial-vector components contribute to the cross section

Isospin symmetry

Massless quark doublet will vanish, only top and bottom quarks can contribute to the scattering



Goldstone boson equivalence theorem

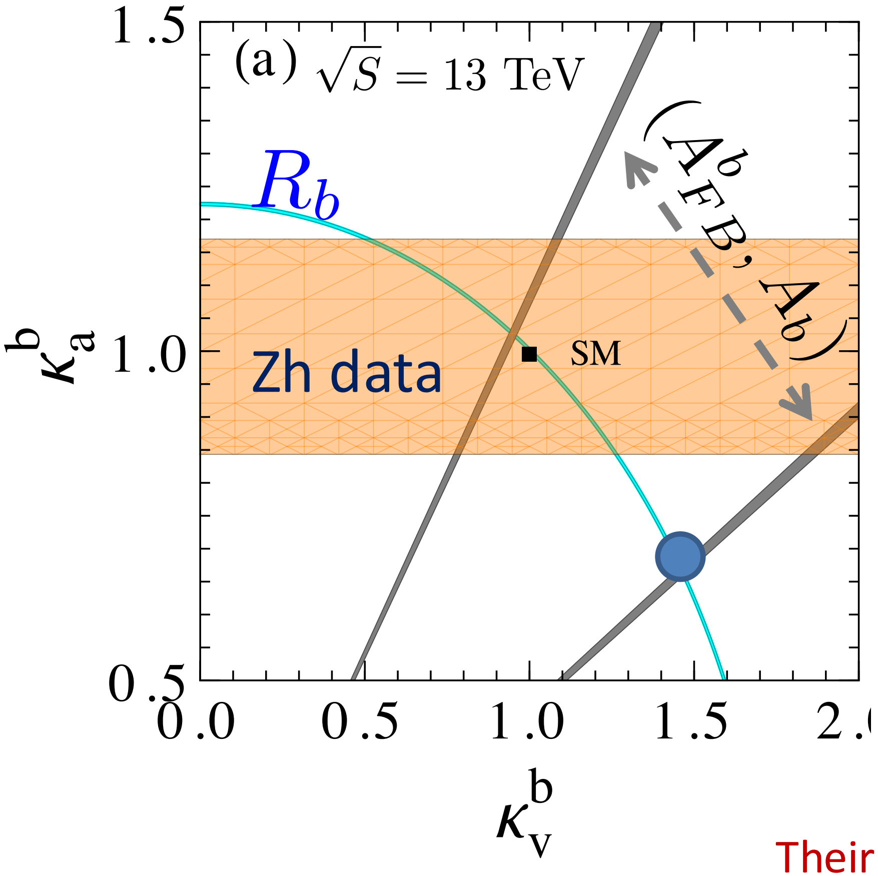
The polarization of Z boson is different from quark initial state

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

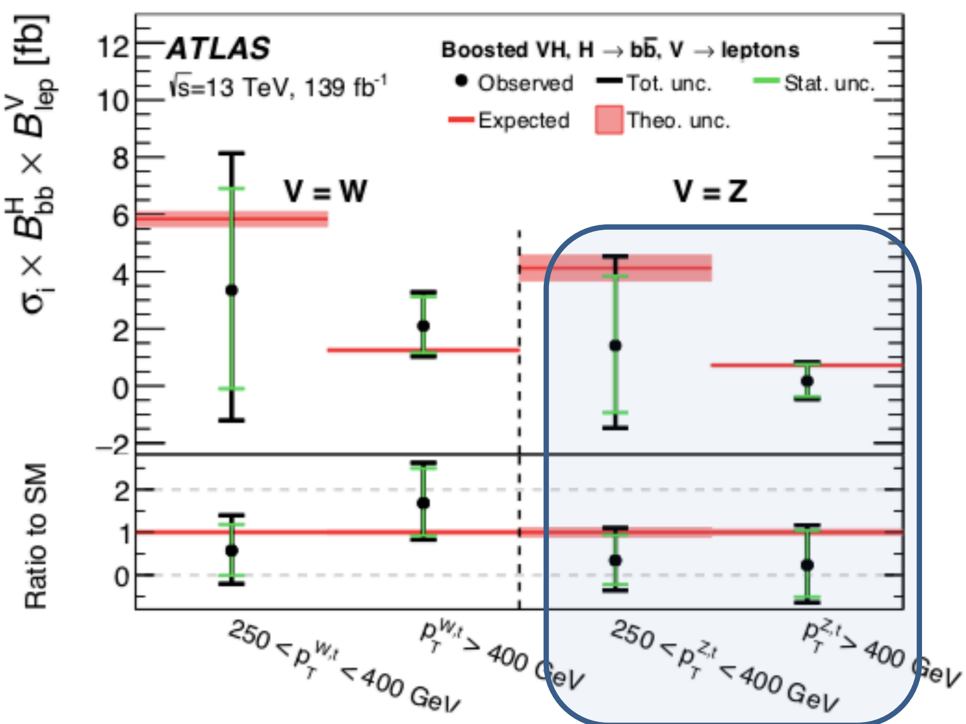
Break the Zbb coupling degeneracy

Current Zh data could break the degeneracy

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



ATLAS: 2008.02508



Their central values are smaller than SM predictions

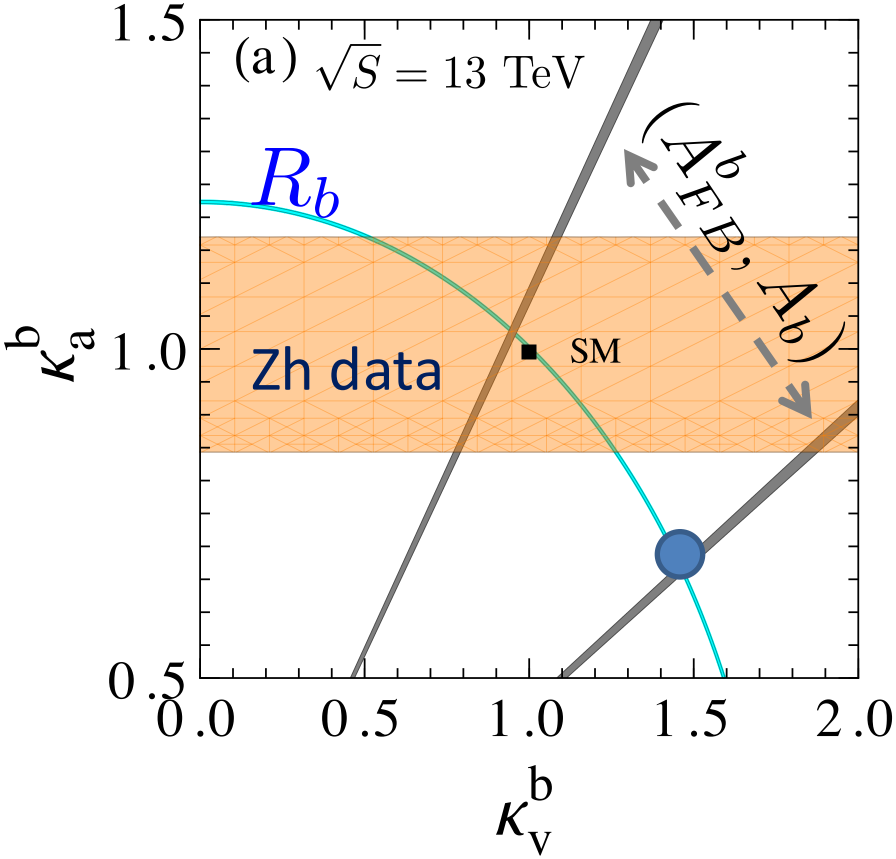
Including all Zh data

The two high P_T^Z data play an important role

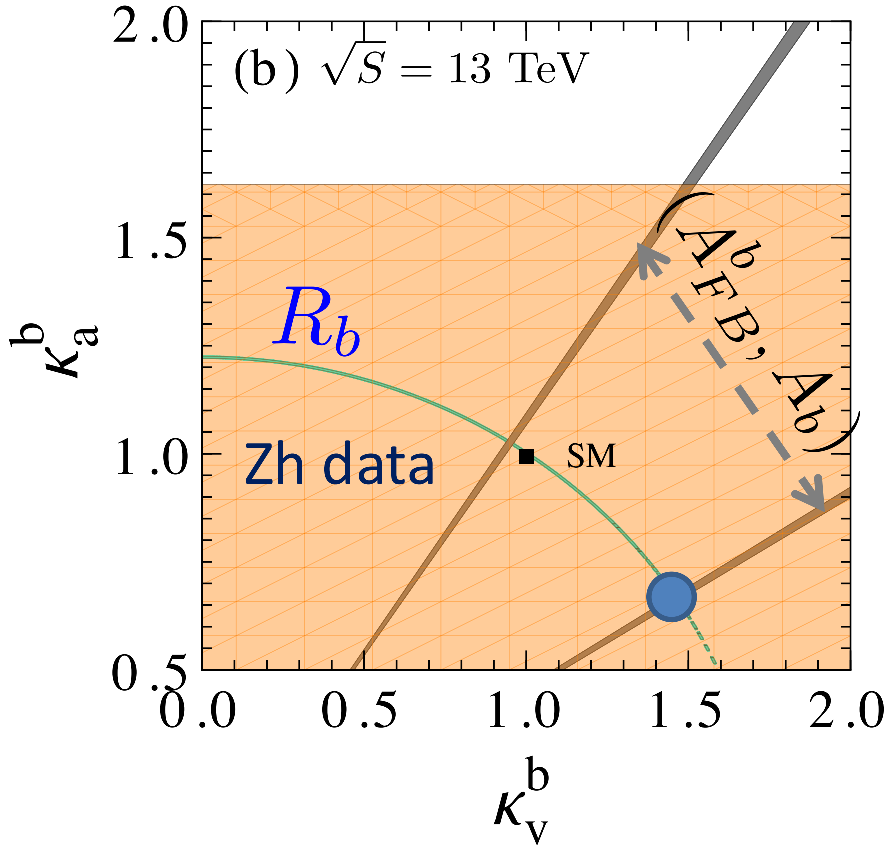
Break the Zbb coupling degeneracy

Current Zh data could break the degeneracy

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

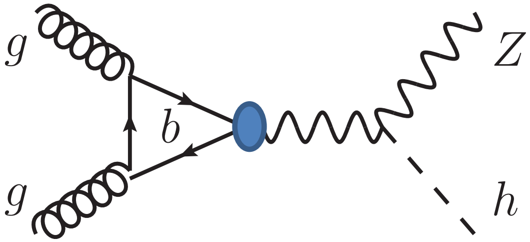


Including all Zh data



Removing the two high P_T^Z data

B. Zbb couplings@LHC



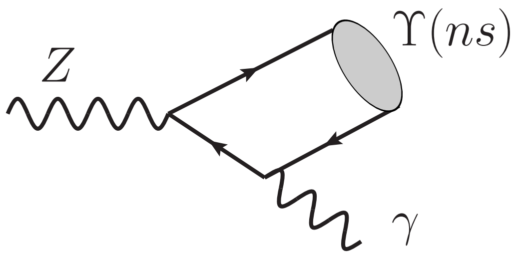
Hongxin Dong, Peng Sun, Bin Yan and C.-P. Yuan

Indirectly search

Is it possible to probe the Zbb coupling directly at the LHC?

$Z \to b\bar{b}?$

1. Huge backgrounds at hadron colliders;
2. The dependence on Zbb couplings is similar to R_b



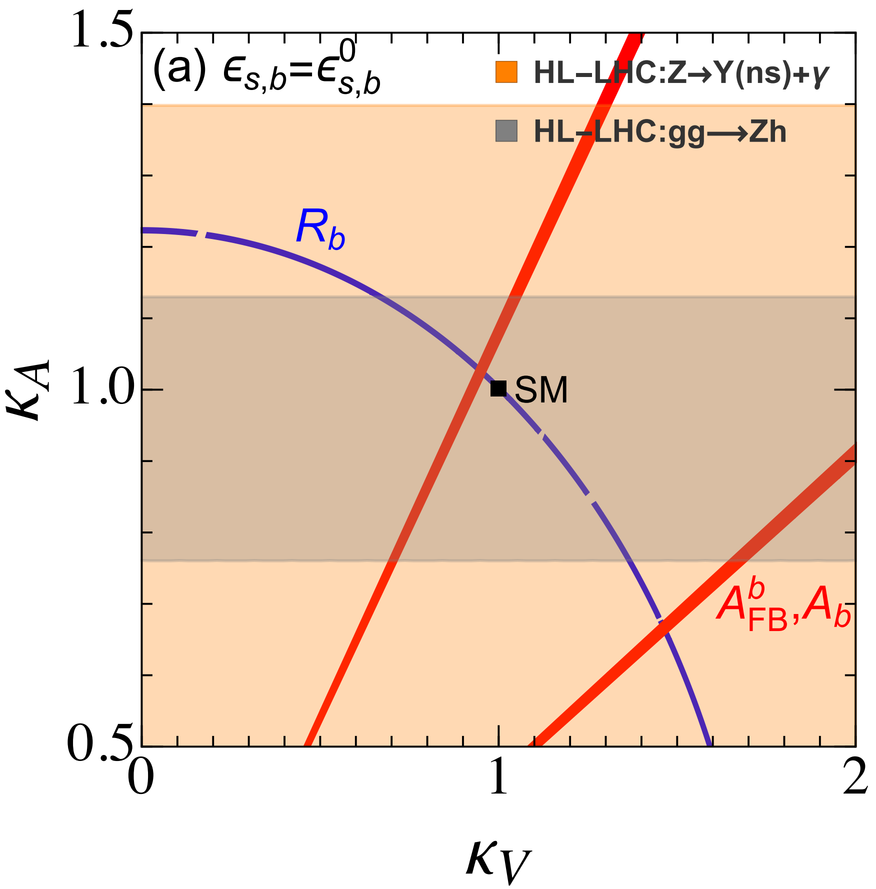
$\Upsilon(ns) \to \ell^+\ell^-$

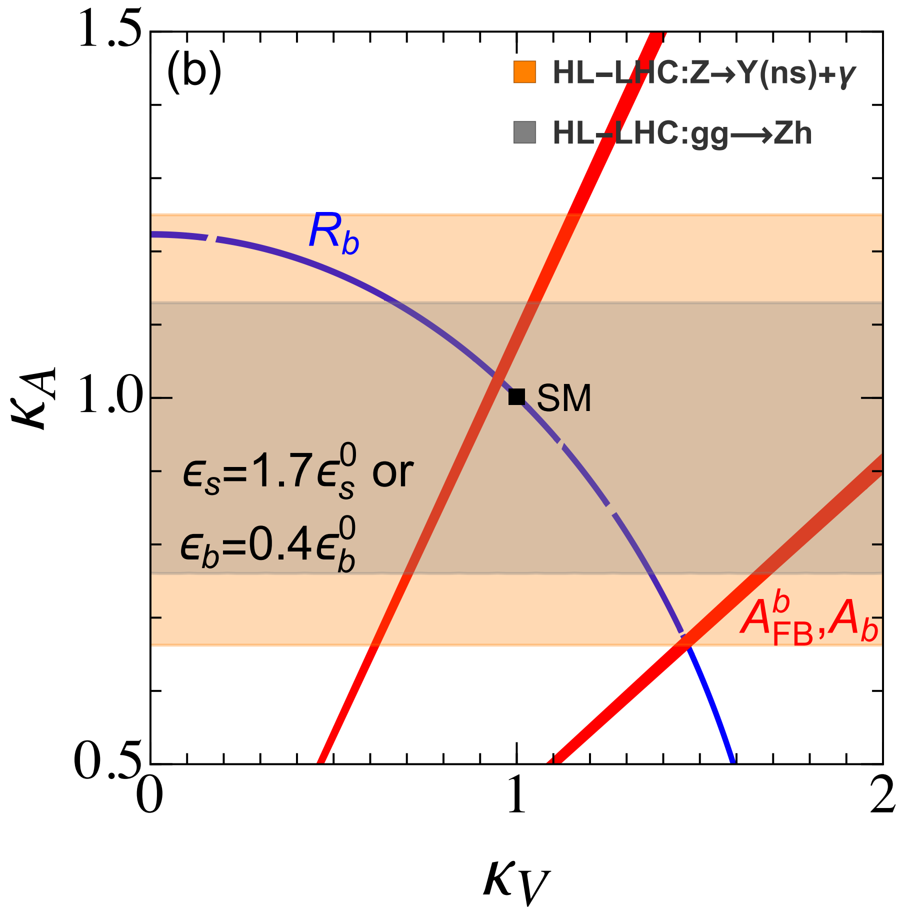
$J^{PC}(\gamma, \Upsilon(ns)) = 1^{--}$

charge conjugation invariance ⟹ axial-vector component of Zbb coupling

Sensitivity @ HL-LHC

ATLAS+CMS $\Upsilon(1s, 2s, 3s) \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$



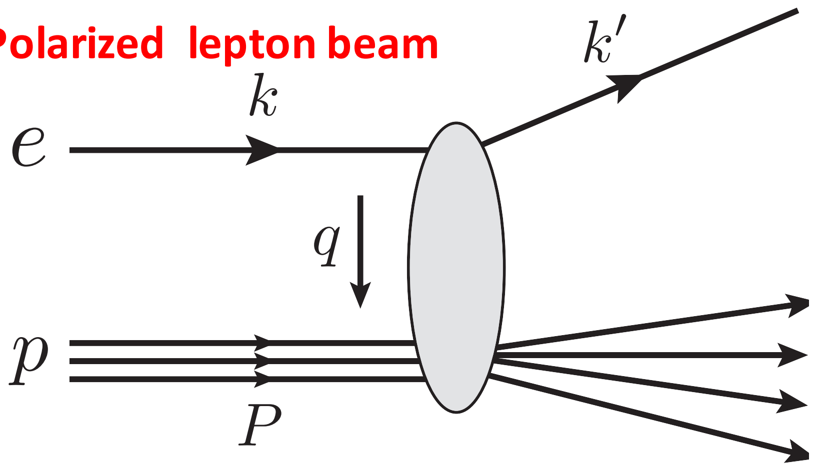


$$\mathcal{L} = \bar{b}\gamma_\mu(\kappa_V g_V - \kappa_A g_A \gamma_5) b Z_\mu$$

C. Zbb couplings@HERA and 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
4. It plays a complementary role to the HL-LHC, which is sensitive to the axial-vector component of the Zbb coupling

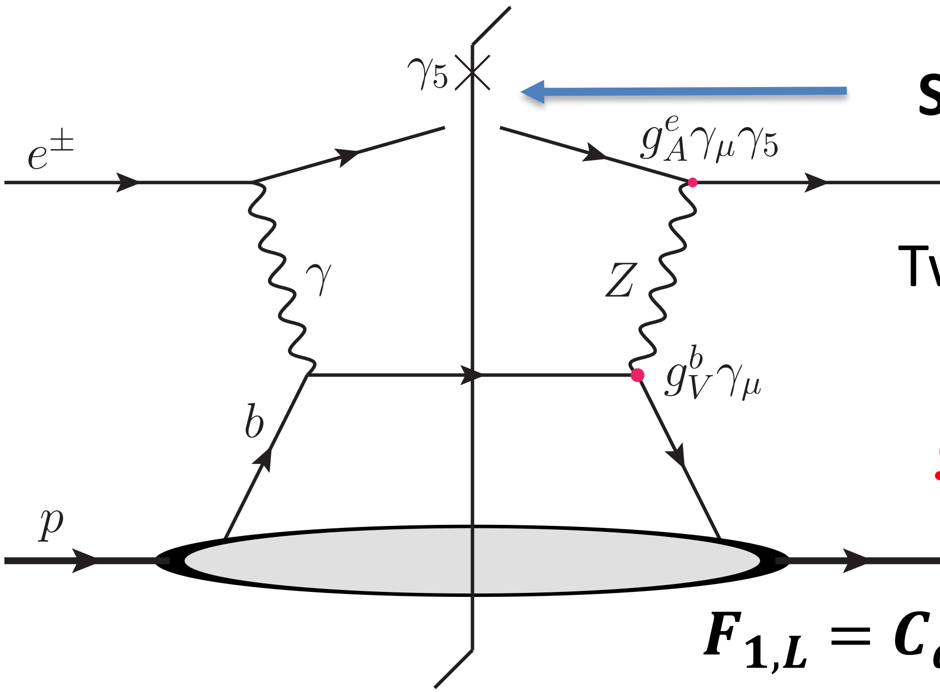
DIS cross section

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:

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

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

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

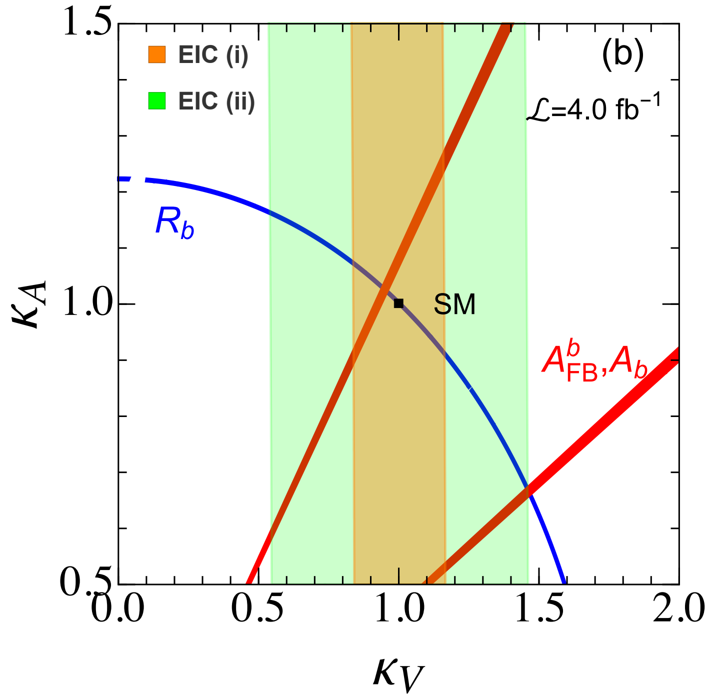
Zbb couplings @EIC

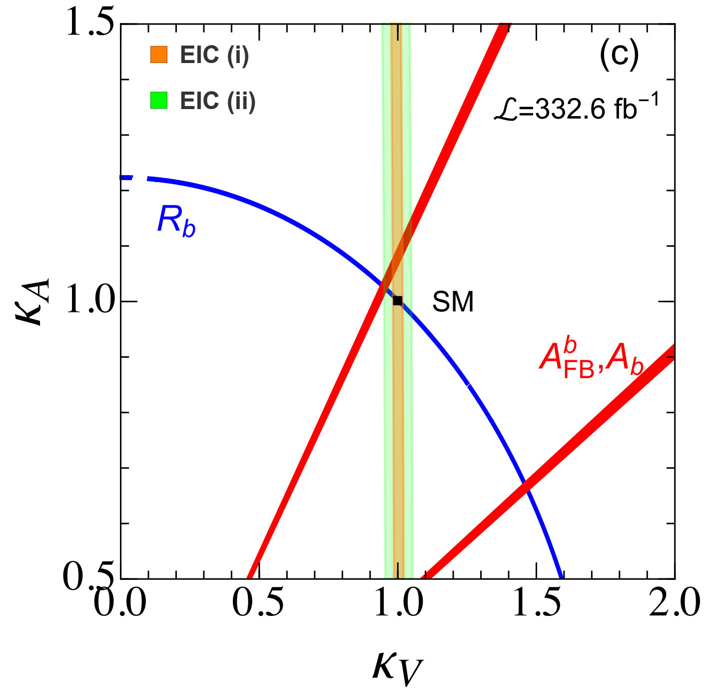
$(i)\ \epsilon_q^b = 0.001, \quad \epsilon_c^b = 0.03, \quad \epsilon_b = 0.7;$

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

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

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





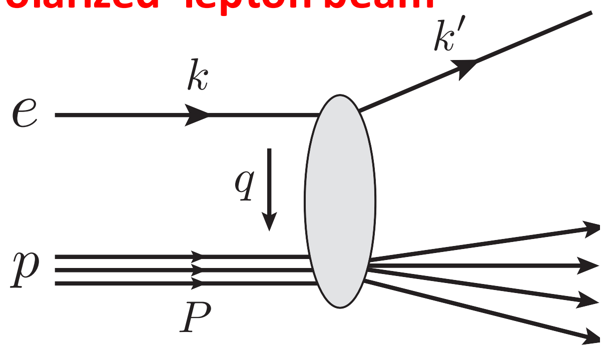
The minimal luminosities needed to resolve the degeneracy or exclude LEP AFB data:

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

D. Zbb couplings @EIC

Hai Tao Li, Bin Yan and C.-P. Yuan, arxiv:2112.07747

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?

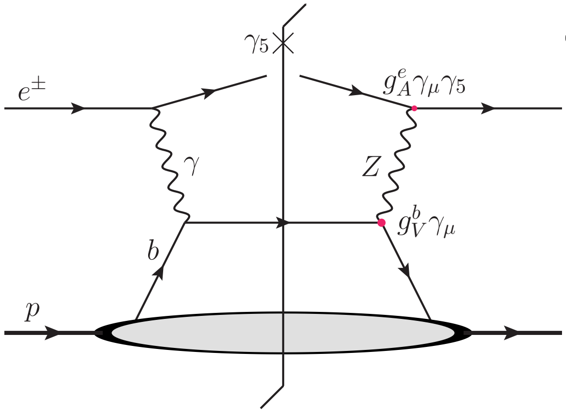
Average jet charge weighted Single-Spin Asymmetry (WSSA):

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

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

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

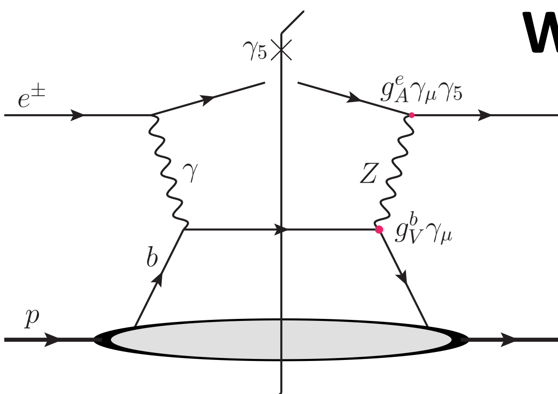
$g_A^e g_V^b$

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

$g_V^e g_A^b$

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

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



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

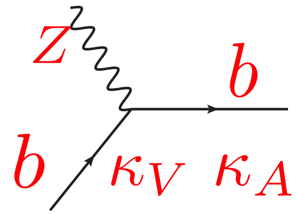
$g_A^e g_V^b$

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

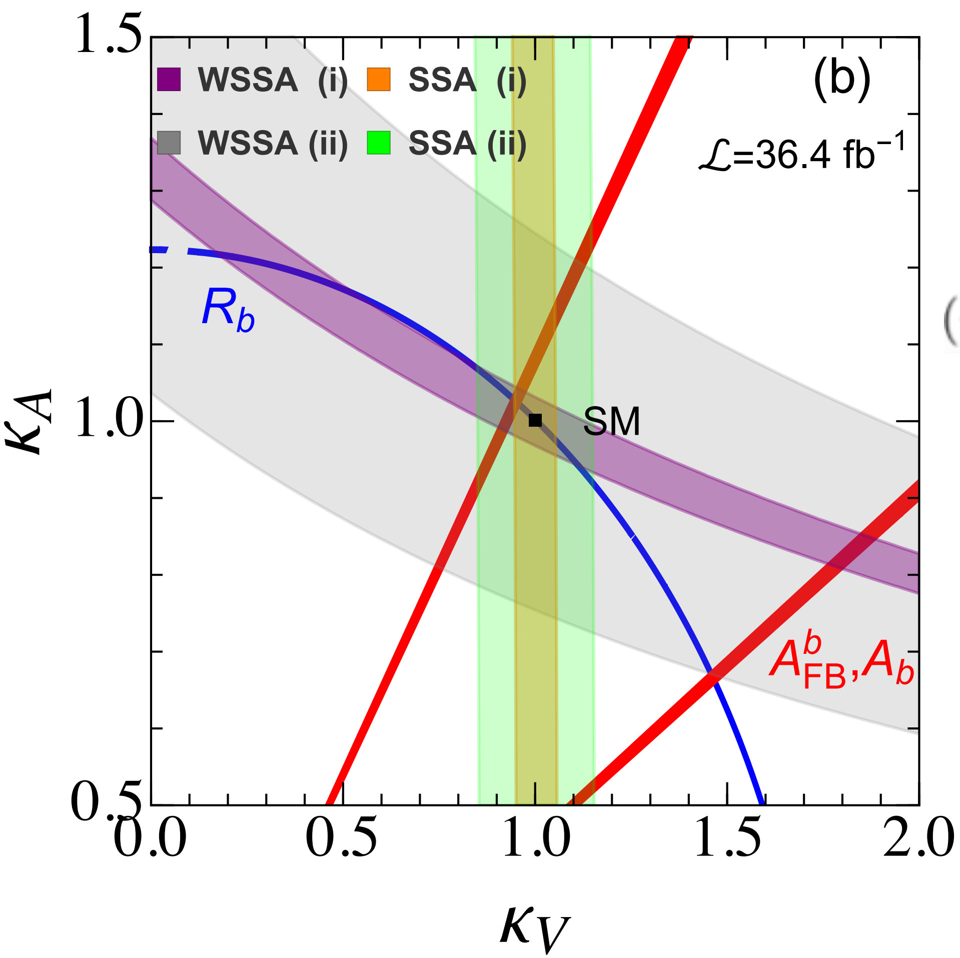
$g_V^e g_A^b$

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

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



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

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

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

SSA

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

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

Summary

A. We proposed four different 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, exclusive Z boson decay at the LHC and WSSA at the EIC depend 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

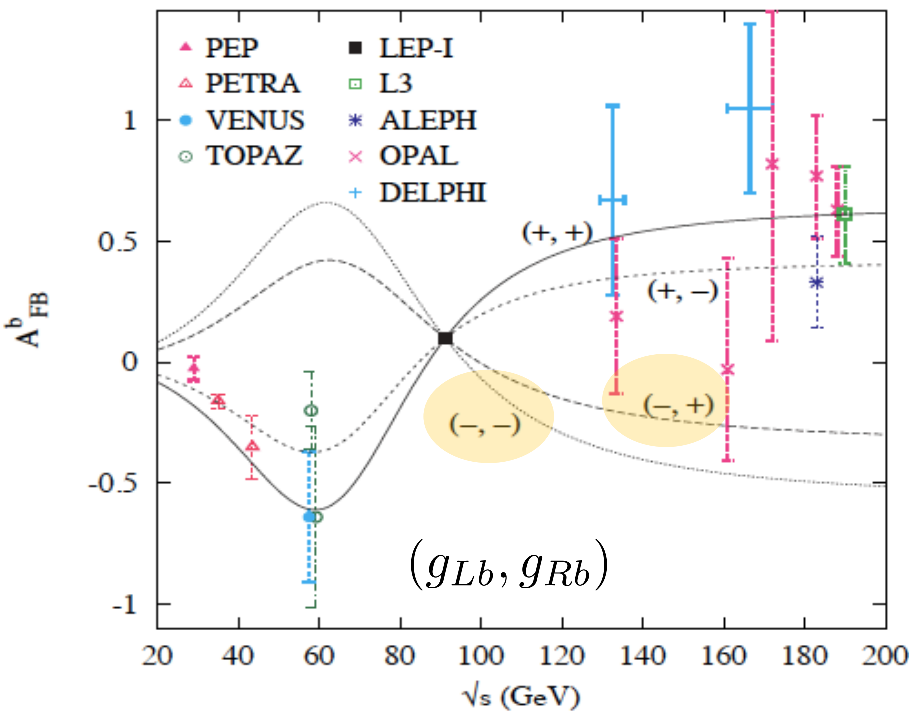
Status of Zbb couplings

	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

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

$A_{FB}^b \sim 2.1\sigma$ deviation with SM prediction



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

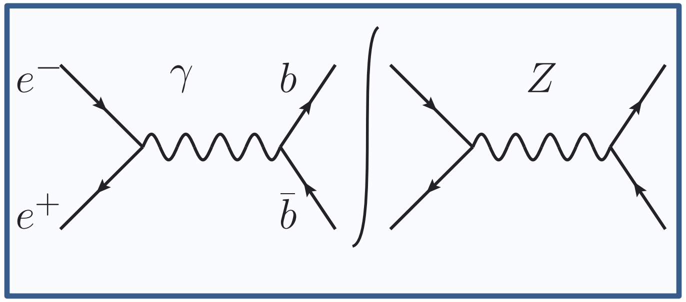
$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R)$$

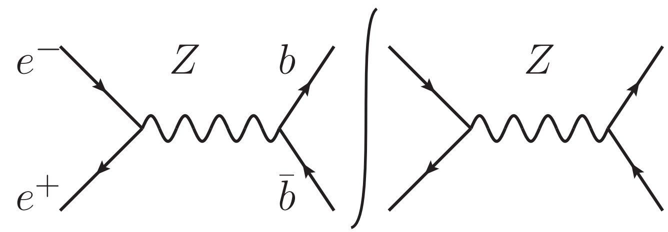
$g_{Lb} < 0$ was Excluded

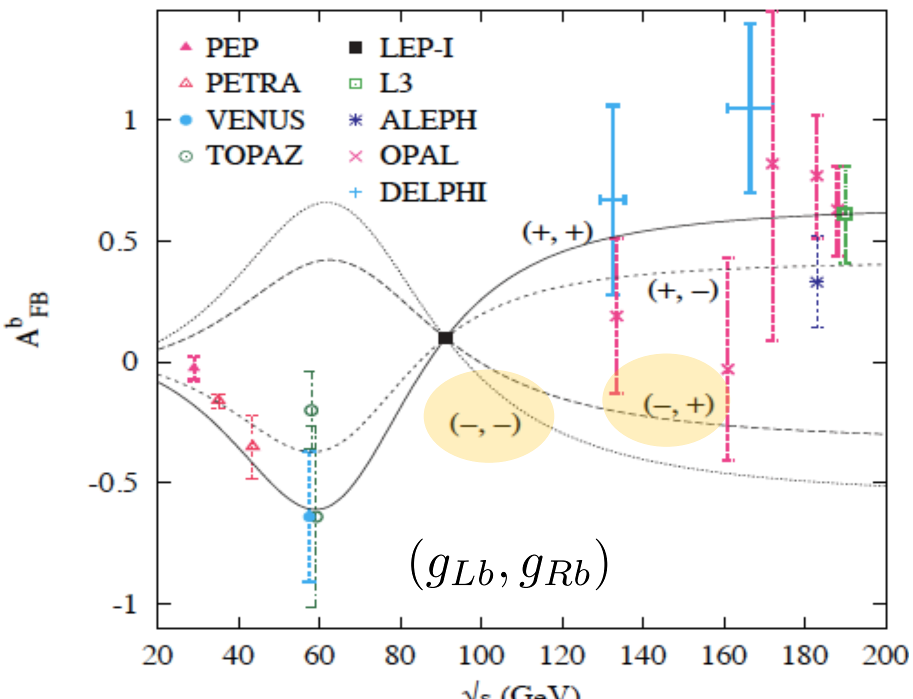
g_{Rb} Could be positive and negative

Status of Zbb couplings

Off Z-pole data is sensitive to the sign of the Zbb couplings







$$\mathcal{L}_{\text{eff}} = -\frac{g_W}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R)$$

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

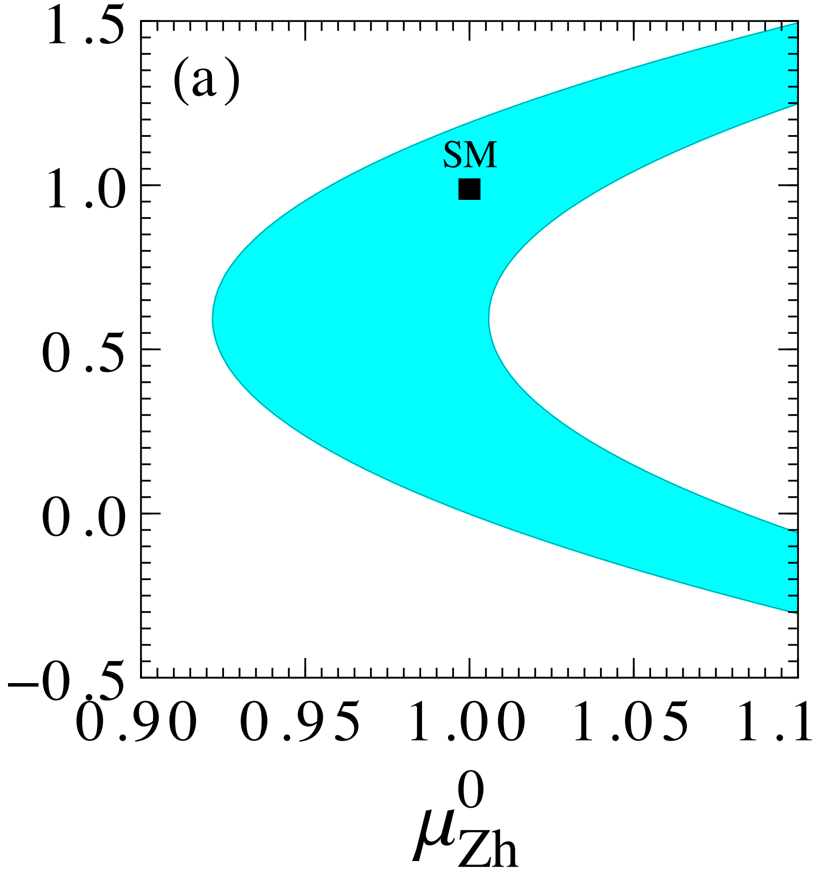
$g_{Lb} < 0$ was Excluded

g_{Rb} Could be positive *or* negative

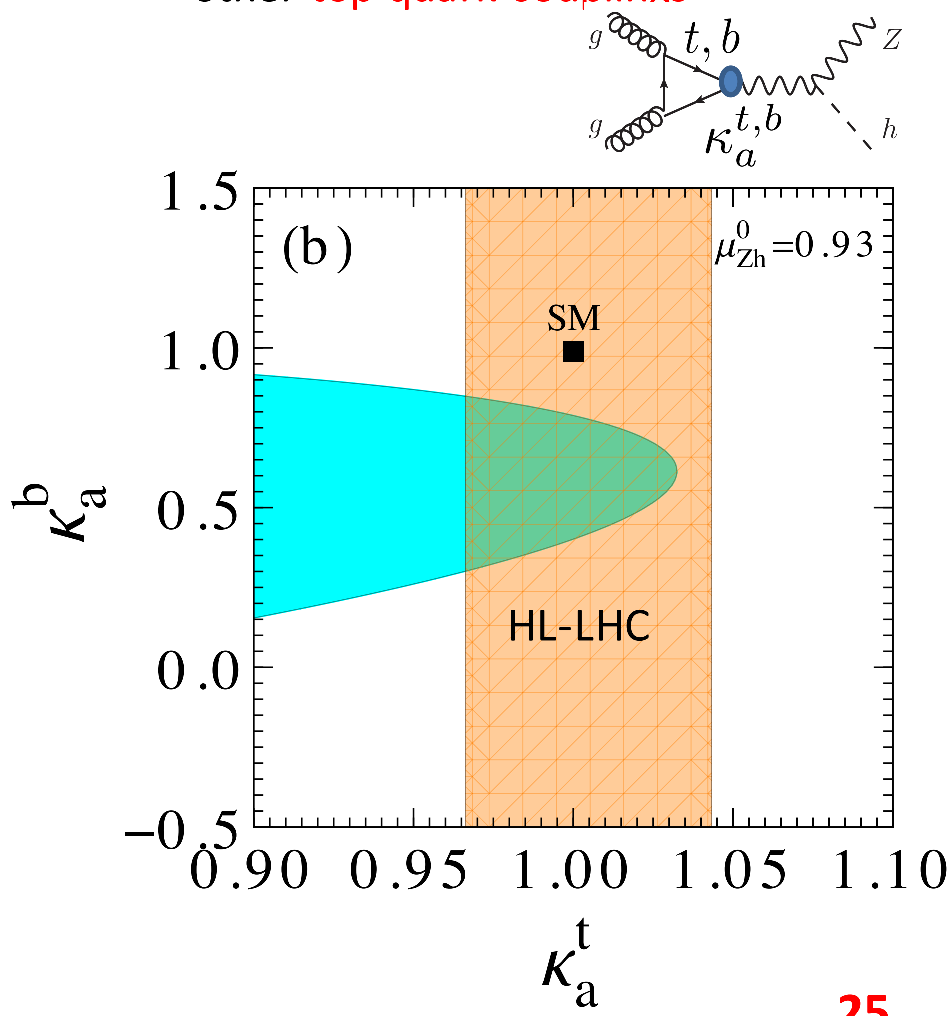
Sensitivity@HL-LHC

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

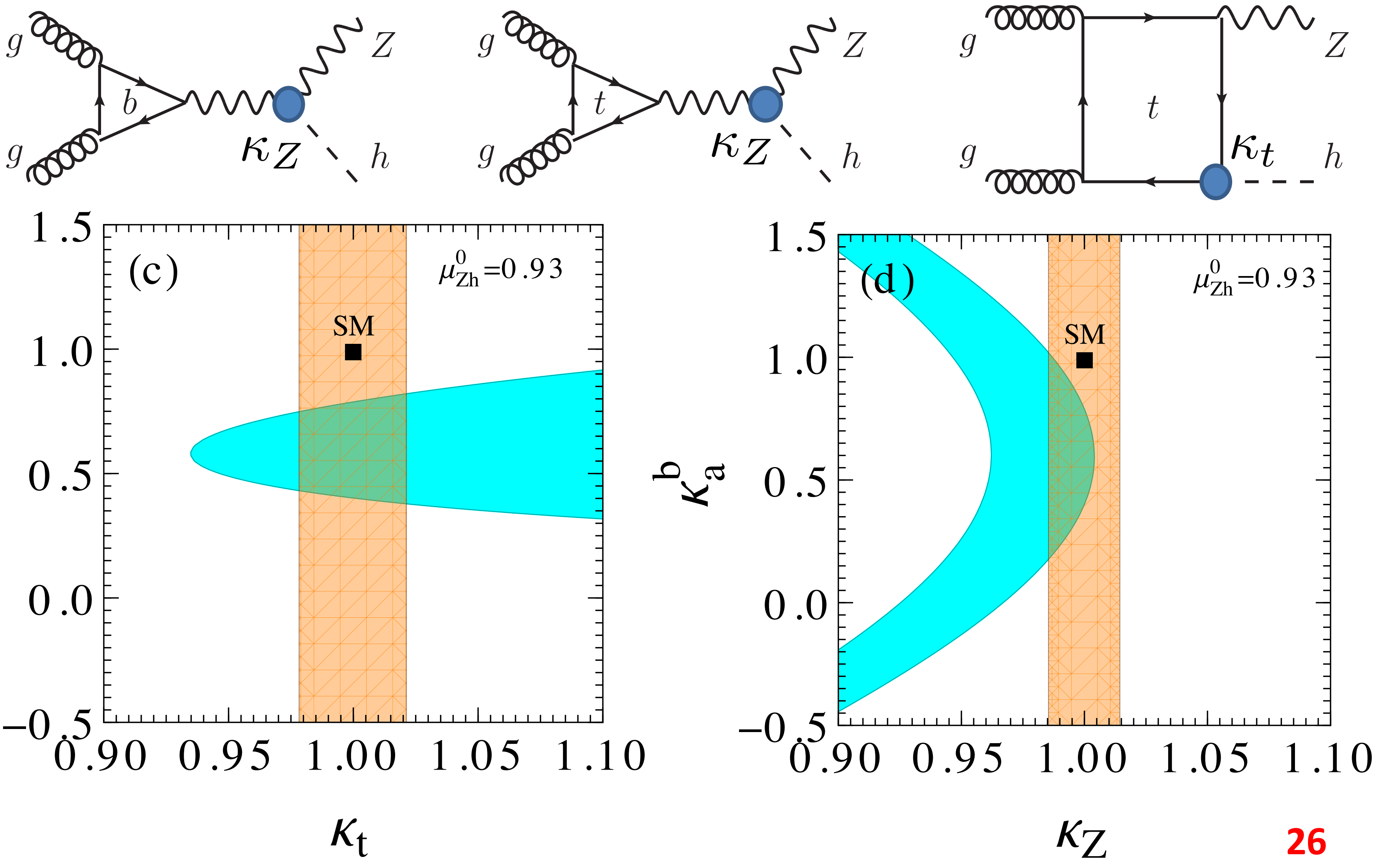
$$\mu_{Zh} = \frac{\sigma(pp \to Zh)}{\sigma(pp \to Zh)^{\rm SM}}$$



The conclusion is not sensitive to the other top quark couplings

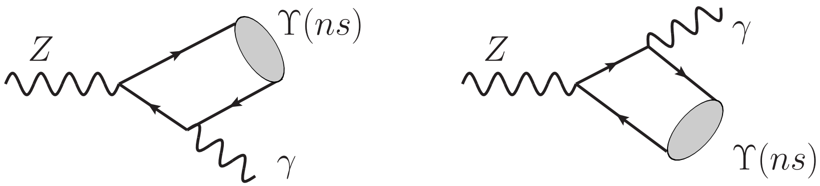


Sensitivity@HL-LHC



Exclusive Z boson decay@ NRQCD

LO:



NLO:

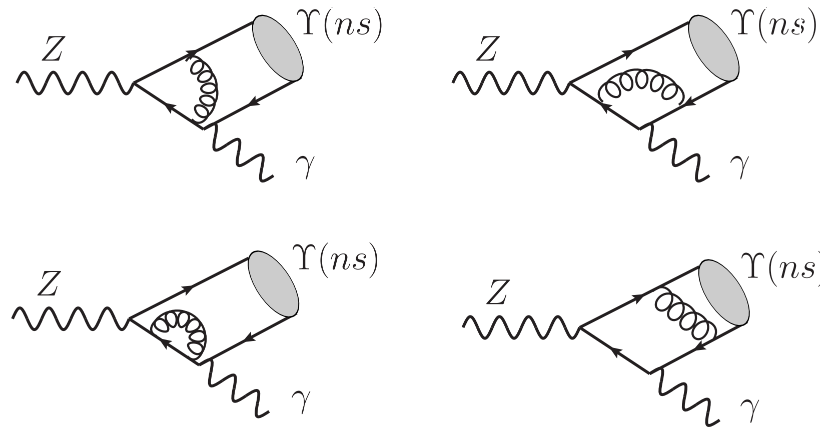


TABLE II. The branching ratios of $Z \to \Upsilon(ns) + \gamma$ at the LO and NLO in unites of 10^{-8} with renormalization scale $\mu = m_Z$.

$BR(Z \to \Upsilon(ns) + \gamma)$	$\Upsilon(1s)$	$\Upsilon(2s)$	$\Upsilon(3s)$
LO	3.83 ± 0.20	1.82 ± 0.21	1.32 ± 0.17
NLO	5.61 ± 0.29	2.66 ± 0.31	1.93 ± 0.25

The relativistic correction is very small
T.- C. Huang and F. Petriello, PRD92,014007(2015)

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:

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

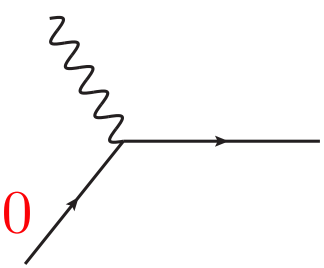
Simplified-ACOT-χ scheme@NNLO

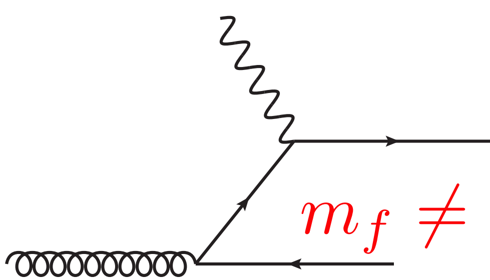
M. Guzzi et al, PRD86,053005(2012)

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'
....

$Q \sim m_f$

$m_f = 0$





$m_f \neq 0$

SSA@HERA and EIC

SSA definition:

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

To physics Observables

SSA@HERA (Run-II)

$$A_e^b = \frac{\sigma_b^{\mathrm{tot}}(P_e) - \sigma_b^{\mathrm{tot}}(-P_e')}{P_e'\,\sigma_b^{\mathrm{tot}}(P_e) + P_e\,\sigma_b^{\mathrm{tot}}(-P_e')}$$

P_e, P_e'

Lepton beam polarization

SSA@EIC

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

$P_e = P_e'$

Zbb couplings @HERA

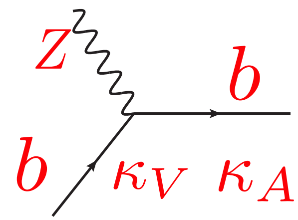
H1	R	L
e^-p	$47.3\,\text{pb}^{-1}$, 0.36	$104.4\,\text{pb}^{-1}$, -0.258
e^+p	$101.3\,\text{pb}^{-1}$, 0.325	$80.7\,\text{pb}^{-1}$, -0.37
ZEUS	R	L
e^-p	$71.2\,\text{pb}^{-1}$, 0.29	$98.7\,\text{pb}^{-1}$, -0.27
e^+p	$78.8\,\text{pb}^{-1}$, 0.32	$56.7\,\text{pb}^{-1}$, -0.36

JHEP 09, 061 (2012)

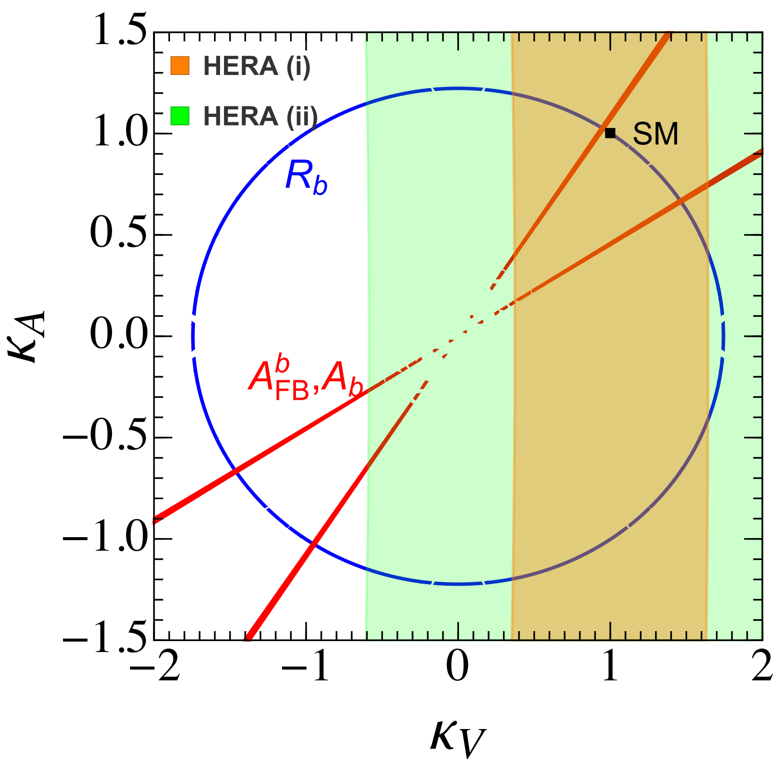
Eur. Phys. J. C 62, 625 (2009)

Phys. Rev. D 87, 052014 (2013)

Simplified-ACOT-χ scheme@NNLO



$Q \sim m_b$



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

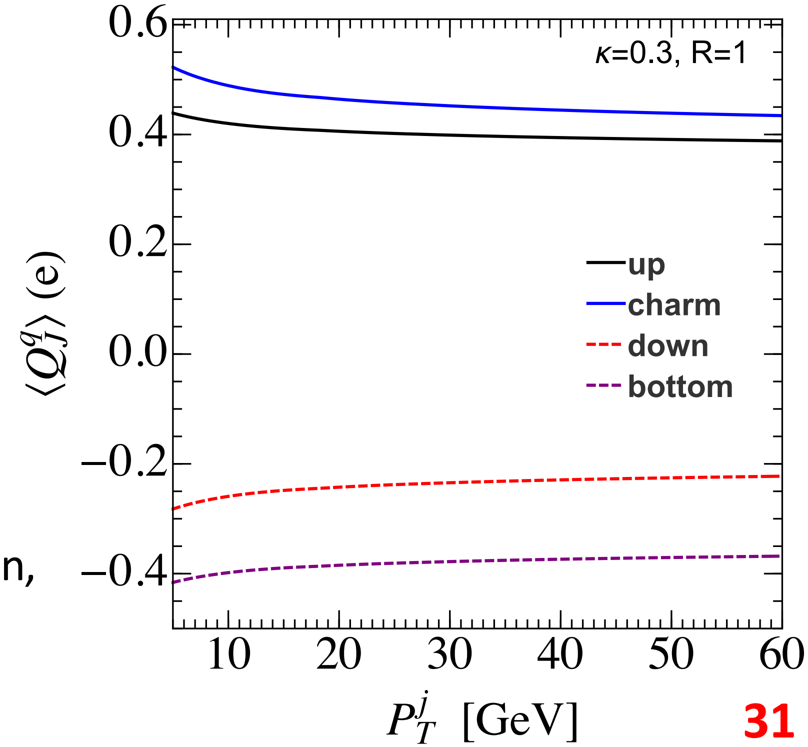
1. The SSA is sensitive to κ_V
2. $\kappa_{V,A} < 0$ could be excluded by HERA data
3. It could be used to crosscheck the off-Z-pole data

Jet Charge

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

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

$$\langle Q_J^q \rangle = \frac{\widetilde{J}_{qq}(p_T^j, R, \kappa, \mu)}{J_q(p_T^j, R, \mu)} \widetilde{D}_q^Q(\kappa) \times \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \frac{\alpha_s(\mu')}{\pi} \tilde{f}_{q \to qg}(\kappa)\right]$$



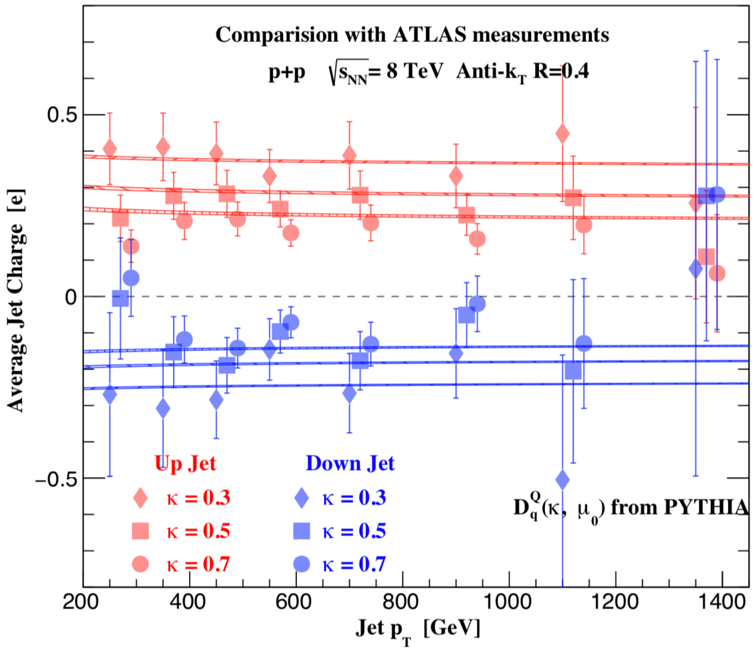
D. Krohn, M. D. Schwartz, T. Lin and W. J. Waalewijn, PRL 110,212001(2013)
W.J.Waalewijn, PRD86,094030(2012)

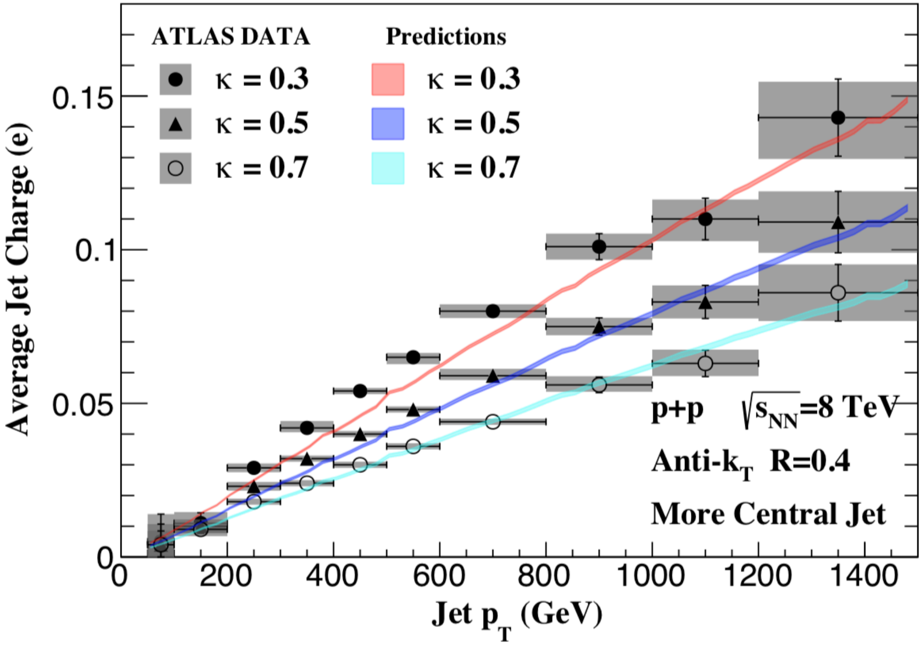
Jet Charge

Transverse-momentum-weighting scheme: R.D. Field and R.P. Feynman, NPB136,1(1978)

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

H. T. Li and I. Vitev, PRD 101(2020)076020





Perfect agreement between theory and data