Probing $Zb\bar{b}$ couplings at the CEPC

Jiayin Gu

CFHEP, IHEP, CAS

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based on current work with Stefania Gori and Lian-Tao Wang

Introduction

Current constraints

Constraints from CEPC

Comparison with ILC, FCC-ee

Conclusion

Overview

- Hadron colliders: directly search for heavy new particles.
- Lepton colliders: probe new physics indirectly by measuring couplings and parameters very precisely.
- What a future e^+e^- collider (such as the CEPC) can do
  - Higgs precision measurement (~ 240 GeV)
  - Electroweak precision measurements (Z-pole)
  - and more...
- (Future) electroweak precision measurements
  - Oblique corrections (S and T parameters) (see e.g. 1411.1054 by Fan, Reece, Wang)
  - Non-oblique corrections, e.g. the $Zb\bar{b}$ coupling.

What is the $Zb\bar{b}$ coupling(s)? (theory side)

- The $Zb\bar{b}$ couplings correspond to the following term in the Lagrangian

$$\mathcal{L} \supset \frac{g}{c_W} Z_\mu (g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R) \,, \quad (1)$$

where we parameterize the possible modifications in terms of δg_{Lb} and δg_{Rb} as

$$g_{Lb} = g_{Lb}^{\mathrm{SM}} + \delta g_{Lb} \,, \quad g_{Rb} = g_{Rb}^{\mathrm{SM}} + \delta g_{Rb} \,, \quad (2)$$

and the SM values are

$$g_{Lb}^{\mathrm{SM}} = -1/2 + s_W^2/3 \simeq -0.42 \,, \quad g_{Rb}^{\mathrm{SM}} = s_W^2/3 \simeq 0.077 \,. \quad (3)$$

What is the $Zb\bar{b}$ coupling(s)? (experiment side)

- Three measurements are directly related to the $Zb\bar{b}$ couplings,
  - R_b, the ratio of the $Z \to b\bar{b}$ partial width to the inclusive hadronic width,
  - A^b_{FB}, the forward-backward asymmetry of the bottom quark (LEP),
  - $\mathcal{A}_b$, the bottom quark asymmetry measured with beam polarization (SLC).
- At tree level, R_b, A^b_{FB} and $\mathcal{A}_b$ can be written as

$$R_b = \frac{g_{Lb}^2 + g_{Rb}^2}{\sum_q (g_L^2 + g_R^2)} \,, \tag{4}$$

$$\mathcal{A}_b = \frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2} \,, \quad A^b_{FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b = \frac{3}{4}\frac{g_{Le}^2 - g_{Re}^2}{g_{Le}^2 + g_{Re}^2}\frac{g_{Lb}^2 - g_{Rb}^2}{g_{Lb}^2 + g_{Rb}^2} \,. \tag{5}$$

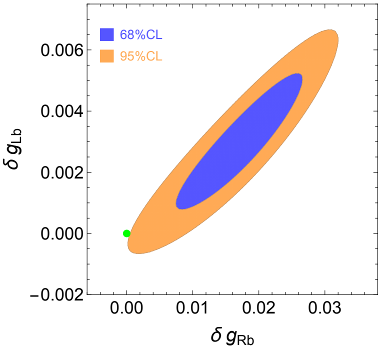
Why is $Zb\bar{b}$ interesting?

- Theory side: many new physics models predict a sizable correction to the $Zb\bar{b}$ couplings.
  - (t_L, b_L) are in the same EW doublet and new physics that couples to the top quark usually also affects the $Zb_L\bar{b}_L$ coupling.
- Experiment side: $\sim 2.5\,\sigma$ discrepancy between the LEP A^b_{FB} measurement and its SM prediction (requires a sizable modification to the $Zb_R\bar{b}_R$ coupling).

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

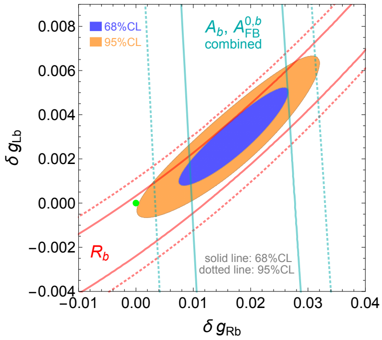
Table: From the most recent Gfitter paper (1407.3792).

Current constraints on the $Zb\bar{b}$ coupling



- Global fit with EW precision data (similar to what Gfitter did).

Current constraints on the $Zb\bar{b}$ coupling



- Individual constraints from R_b and A_{FB}^b, $\mathcal{A}_b$ combined, setting other parameters to best fit values.

Discrepancy?

- SM predictions are just outside 95% CL. Simultaneous modifications in both g_{Lb} and g_{Rb} are preferred.
- Statistical fluctuation? Systematic error? New physics?
- Possible new physics: the Beautiful Mirror Model (hep-ph/0109097, Choudhury, Tait, Wagner)
- Can only be resolved by the next e^+e^- collider!

Constraints from CEPC

- Circular Electron Position Collider
- Reference: the preliminary conceptual design report (preCDR).
- Large statistics ($\sim 10^{10}$ Z events or at least $\sim 2\times10^{9}$ Z events, compared with $\sim 2\times10^{7}$ Z events at LEP).
- We assume there will be no longitudinal beam polarization (but it could be a potential option).
- We consider 2 scenarios:
  - CEPC with conservative estimations (assuming $\sim 2\times10^{9}$ Zs as in the preCDR);
  - CEPC+ with more optimistic estimations (assuming $\sim 10^{10}$ Zs and the systematic uncertainties are reduced by half).
- We consider both the case that the results are SM-like and the one that the LEP A^b_{FB} discrepancy stays.

Key observables

- Which observables are most important for the improvement of the $Zb\bar{b}$ coupling constraints?
- R_b, A_{FB}^b, (no $\mathcal{A}_b$).
- Leptonic asymmetry observables, A_{FB}^l, $\mathcal{A}_l(\mathcal{P}_\tau)$,
  - assuming lepton universality, $e\ \mu\ \tau\ \to\ l$,
  - needed as an independent determination of the effective weak mixing angle,
  - $A_{FB}^b = \frac{3}{4}\mathcal{A}_e\mathcal{A}_b$.
- R_l, the ratio of the total hadronic Z decay width to the Z decay width to one lepton species,
  - is sensitive to the coupling combination $g_{Lb}^2 + g_{Rb}^2$,
  - relies more on the model assumption,
  - has relatively conservative estimation at CEPC?

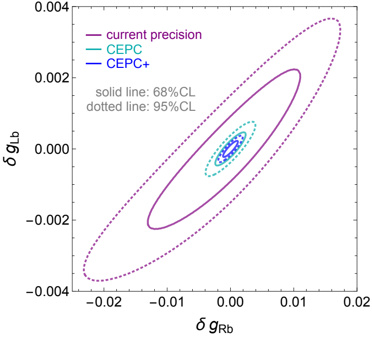
Input values

	Precision (1σ uncertainty)		
Observable	LEP	CEPC	CEPC+
R_b	0.00066	0.00017	0.00008
R_l	0.025	0.007	0.003
A_{FB}^b	0.0016	0.00015	0.00007
A_{FB}^l	0.0010	0.00014	0.00007
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.0033	0.0006	0.0003
# of Zs	$\sim 2 \times 10^7$	$\sim 2 \times 10^9$	$\sim 10^{10}$

Table: The numbers highlighted with color cyan are our own estimations.

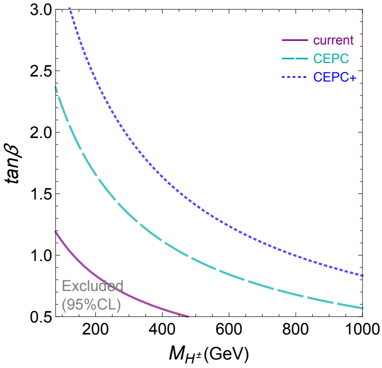
- Systematic uncertainties dominate.
- Other observables are less important (updated to CEPC values but not shown here).
- We have checked that the theoretical uncertainties have little impact on the $Zb\bar{b}$ coupling constraints, assuming the relevant loop corrections will be calculated with one more order in the future.

Assuming the results are SM-like



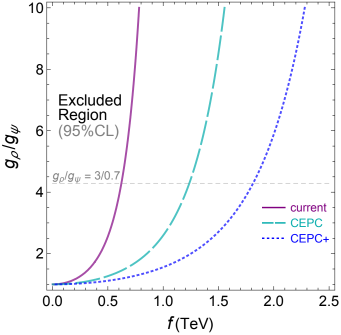
- What constraints can we set on new physics models?
- A bad case: Natrual SUSY (loop correction from stop and Higgsino), less constraining than current LHC bounds (see e.g. 1412.3107 by Fan, Reece, Wang).

Two Higgs-doublet model



- Type II 2HDM
- Most constraining in the region with small $\tan\beta$, where the loop contribution involving the charged Higgs dominates.
- Small $\tan\beta \to$ large $H^{\pm}\bar{b}_L t_R$ coupling $\to$ large δg_{Lb} .

Minimal composite Higgs models (with custodial protection)

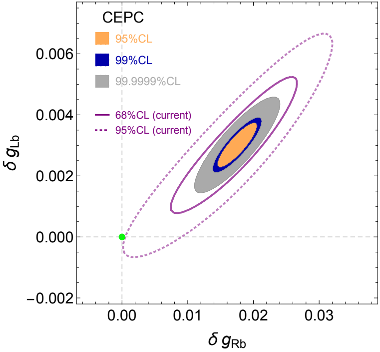


- Large correction to $Zb_L\bar{b}_L$ unless protected by an $O(4)$ symmetry ($SU(2)_L \otimes SU(2)_R + P_{LR}$).
- Several P_{LR} breaking effects in realistic models.
- Contribution from fermion loops:

$$\frac{\delta g_{Lb}}{g_{Lb}^{\rm SM}} \simeq \frac{y_t^2}{16\pi^2}\frac{v^2}{f^2}\log\left(\frac{m_\rho^2}{m_4^2}\right)$$

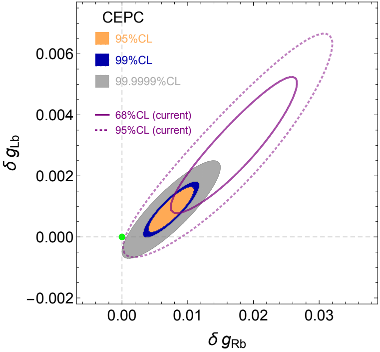
- CEPC Higgs measurement could constrain $f \gtrsim 2.8$ TeV (95%CL).
- $Zb\bar{b}$ strongly model dependent (can be useful for model discrimination).

Assuming new physics modifies $Zb\bar{b}$



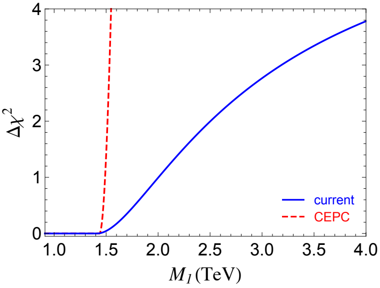
- If the LEP A_{FB}^{b} discrepancy does come from new physics, how well can we discriminate it from SM?
- Assuming true values coincide with current central values ($\delta g_{Lb}^{0} = 0.0030$, $\delta g_{Rb}^{0} = 0.0176$).
- SM is easily ruled out with $> 99.9999\%$ CL.

Assuming new physics modifies $Zb\bar{b}$



- The true values probably do not exactly equal the current central values due to statistical fluctuation!
- Assuming δg^0_{Lb} and δg^0_{Rb} are closer to 0 while still being consistent with the current measurements within 68%CL.
- Choose $\delta g^0_{Lb} = 0.0009$ and $\delta g^0_{Rb} = 0.0075$.
- SM is still ruled out with 99.9999% CL.

Beautiful mirror model



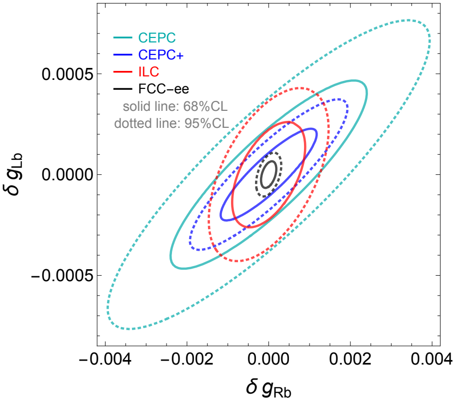
- Bottom partners, and an exotic quark with charge $-4/3$.
- To explain the LEP A_{FB}^b discrepancy without violating constraints on T parameter, the new quarks can not be too heavy.
- Current LHC bound ~ 912 GeV, expected to reach 2 to 2.5 TeV at LHC-14.
- Modification to $Hb\bar{b}$ coupling ($\sim 4\%$) can be probed at the Higgs factory.

Comparison with ILC, FCC-ee

- References
  - The International Linear Collider Technical Design Report - Volume 2: Physics (arXiv:1306.6352)
  - First Look at the Physics Case of TLEP (arXiv:1308.6176)
- Key differences
  - statistics: $\sim 10^9$ Zs for ILC, $\sim 10^{12}$ Zs for FCC-ee,
  - systematic uncertainties,
  - (longitudinal) beam polarization: $\mathcal{A}_b$ can be directly measured.
- How good could longitudinal beam polarization been implemented at circular colliders?

Observable	ILC	FCC-ee
R_b	0.00014	0.000060
R_l	0.007	0.0010
$\mathcal{A}_b$	0.001	0.00021
A_{LR}	0.0001	0.000021

Results, assuming data is SM like



- beam polarization $\rightarrow \mathcal{A}_b$ well measured $\rightarrow \delta g_{Rb}$ better constrained, correlation reduced.

Conclusion

- We estimated the constraints on the $Zb\bar{b}$ couplings that can be obtained at the CEPC.
- The measurements of the $Zb\bar{b}$ couplings at CEPC can
  - rule out SM, if the LEP A_{FB}^{b} discrepancy does come from new physic;
  - provide strong constraints on new physics, if the results are SM-like;
  - be complementary to the constraints from oblique corrections, Higgs precision measurements, direct searches at hadron colliders and results from B-factories;
  - help discriminate different models.
- Our results are preliminary but can hopefully serve as a guidance for the future prospectives of $Zb\bar{b}$ coupling constraints.
- Our results could further motivate the construction of CEPC.

Thank you!

backup slides

g_{Rb} flip sign

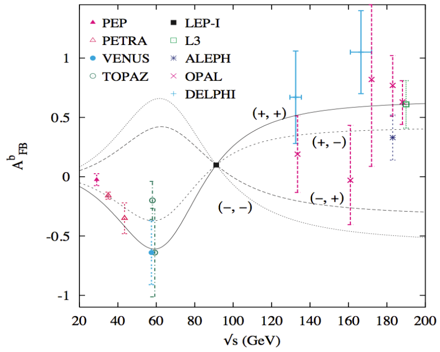
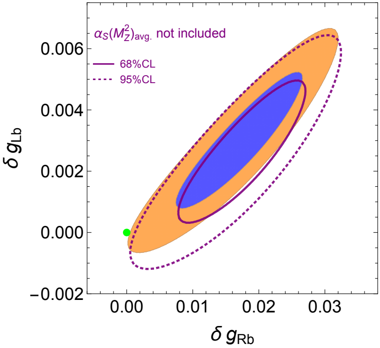


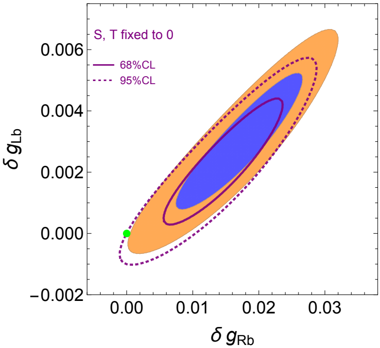
Figure: from hep-ph/0109097

Including $\alpha_S(M_Z^2)_{\text{avg.}}$



$$\alpha_S(M_Z^2)_{\text{avg.}} = 0.1185 \pm 0.0005 \quad \text{(world average w/o EWPT result)} \ .$$

fixing S & T to zero



$S, T, \delta g_{Lb}, \delta g_{Rb}$

	S	T	δg_{Lb}	δg_{Rb}
S	-0.047 ± 0.097			
T	0.91	0.015 ± 0.077		
δg_{Lb}	-0.34	-0.23	0.0030 ± 0.0015	
δg_{Rb}	-0.40	-0.30	0.91	0.0176 ± 0.0063

	Precision				
Observable	Current	CEPC	CEPC+	ILC	FCC-ee
R_b	0.00066 (0.00050)	0.00017 (0.00016)	0.00008 (0.00008)	0.00014	0.000060 (0.000060)
R_l	0.025 (0.007)	0.007 (0.006)	0.003 (0.003)	0.007? (0.007?)	0.0010 (0.0010)
A_{FB}^b	0.0016 (0.0007)	0.00015 (0.00014)	0.00007 (0.00007)		
A_{FB}^l	0.0010 (0.0003)	0.00014 (0.0001)	0.00007 (0.00005)		
$\mathcal{A}_l(\mathcal{P}_\tau)$	0.0033 (0.0015)	0.0006 (0.0005)	0.0003 (0.0003)		
$\mathcal{A}_b$	0.020 $(\sim 0.014?)$			0.001	0.00021 (0.00015)
A_{LR}	0.0022 (0.0011)			0.0001 (0.0001)	0.000021 (0.000015)
# of Zs	$\sim 2\times10^7$	$\sim 2\times10^9$	$\sim 10^{10}$	$\sim 10^9$	$\sim 10^{12}$

results in tables

	δg_{Lb}	δg_{Rb}	ρ	δg_{Lb} $(\delta g_{Rb} = 0)$	δg_{Rb} $(\delta g_{Lb} = 0)$
current	0.0015	0.0079	0.91	0.00061	0.0032
CEPC	0.00031	0.0016	0.87	0.00015	0.00079
CEPC+	0.00015	0.00078	0.88	0.000072	0.00037
ILC	0.00017	0.00059	0.53	0.00015	0.00050
FCC-ee	0.000044	0.00012	0.42	0.000040	0.00011

Beautiful mirror model

$$\Psi_{L,R} = \begin{pmatrix} B \\ X \end{pmatrix} \sim (3, 2, -5/6)\,, \tag{6}$$

$$\hat{B}_{L,R} \sim (3, 1, -1/3)\,, \tag{7}$$

$$-\mathcal{L} \supset M_1 \bar{\Psi}_L \Psi_R + M_2 \bar{\hat{B}}_L \hat{B}_R + y_1 \bar{Q}_L H b_R + y_L \bar{Q}_L H \hat{B}_R + y_R \bar{\Psi}_L \tilde{H} b_R + \text{h.c.}\,, \tag{8}$$

$$\delta g_{Lb} \approx \frac{Y_L^2}{2M_2^2}\,, \qquad \delta g_{Rb} \approx \frac{Y_R^2}{2M_1^2}\,. \tag{9}$$

$$T \approx \frac{3}{16\pi^2 \alpha v^2} \left[\frac{16}{3} \delta g_{Rb}^2 M_1^2 + 4\delta g_{Lb}^2 M_2^2 - 4\delta g_{Lb} \frac{M_2^2\, m_{\rm top}^2}{M_2^2 - m_{\rm top}^2} \log\left(\frac{M_2^2}{m_{\rm top}^2}\right) \right]\,. \tag{10}$$

Beautiful mirror model

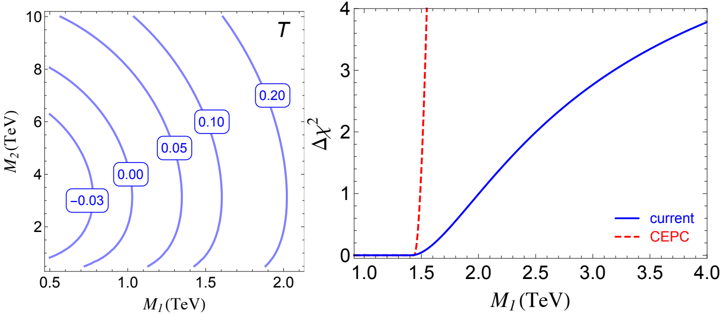
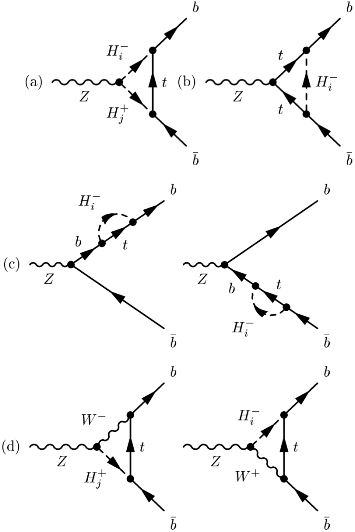
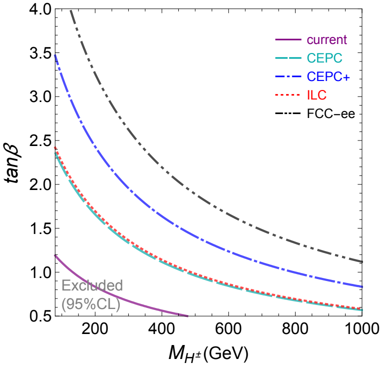


Figure: Left: δg_{Lb} and δg_{Rb} fixed to best fit value.

2HDM, diagrams



2HDM


4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
tanβ
200
400
600
800
1000
$M_{H^{\pm}}$(GeV)
current
CEPC
CEPC+
ILC
FCC–ee
Excluded
(95%CL)

Composite Higgs