Trace $Zb\bar{b}$ dipole operators at future lepton colliders (CEPC)

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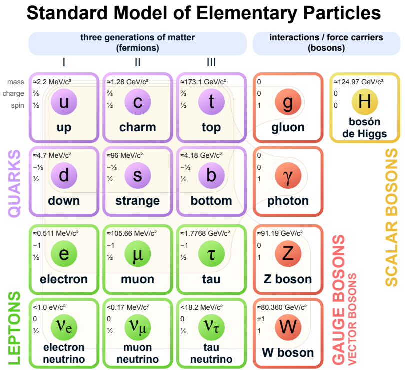
Is SM complete, what's next?



Directly search for BSM

- Larger collider: higher energy → new massive particles
- Other searches: SUSY particles, Dark matters, Exotics, ALPs, LLPs ...

Precision measurements indirectly

- Higgs is a new portal → Higgs factories
- EW precision test → lepton colliders
- A telescope to high scale physics
- Interplay of theory and experiment is essential
- Effective tool → SMEFT (model independent)

Z-pole status

Some Z pole observables [PDG2022]

Quantity	Value	SM prediction
M_Z [GeV]	91.1876 ± 0.0021	91.1882 ± 0.0020
Γ_Z [GeV]	2.4955 ± 0.0023	2.4941 ± 0.0009
σ_{had} [nb]	41.481 ± 0.033	41.482 ± 0.008
R_e	20.804 ± 0.050	20.736 ± 0.010
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01617 ± 0.00007
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1029 ± 0.0002
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0002
A_e	0.1498 ± 0.0049	0.1468 ± 0.0003
A_b	0.923 ± 0.020	0.9347
A_c	0.670 ± 0.027	0.6677 ± 0.0001

* For A_e, only LEP 1 results shown here

- Most observables are measured precisely and consistent with theoretical prediction.
- Except A_{FB} for b-quark, still exist $\sim 2\,\sigma$ deviation.
- At future lepton colliders, such as CEPC, trillion Z bosons could be produced.

$\Rightarrow$ Opportunity to reveal potential BSM NP with much improved precision.

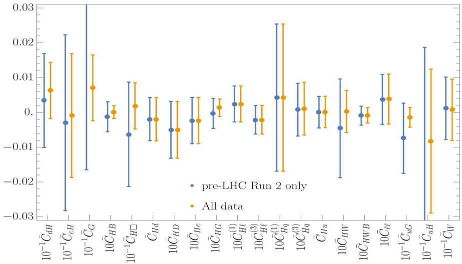
SMEFT & dipole operators

Stand Model Effective Field Theory

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{C_j^{(8)}}{\Lambda^4} O_j^{(8)} + \cdots$$

- Λ denotes the new physics scale.
- For scale $\Lambda \gg E, v$, the new physics effects around EW scale could be well approximated by dimension-6 operators.
- 59 (76) dimension-6 operators for 1 generation, usually less than half of them are concerned on EW/Higgs measurements.

Many global fit analysises are performed



Dipole operators are not included!

(95% CL, in Warsaw basis)

[1803.03252]

SMEFT & dipole operators

SMEFT dim-6 dipole operators

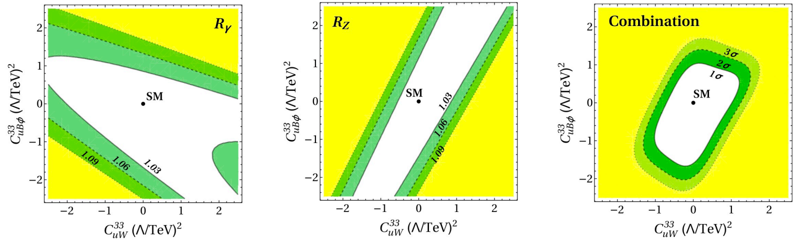
(Warsaw basis, 3rd generation quarks)

$$\mathcal{O}_{uW}^{33} = \left(\bar{q}_{\rm L}\sigma^{\mu\nu}\tau^I t_{\rm R}\right)\tilde{H}W_{\mu\nu}^I, \qquad \mathcal{O}_{dW}^{33} = \left(\bar{q}_L\sigma^{\mu\nu}b_R\right)\sigma^i H W_{\mu\nu}^i,$$

$$\mathcal{O}_{uB}^{33} = \left(\bar{q}_{\rm L}\sigma^{\mu\nu}t_{\rm R}\right)\tilde{H}B_{\mu\nu}, \qquad \mathcal{O}_{dB}^{33} = \left(\bar{q}_L\sigma^{\mu\nu}b_R\right)HB_{\mu\nu}.$$

where, $\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu,\gamma^\nu]$, $W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g_W\varepsilon^{ijk}W_\mu^j W_\nu^k$ (similar form of $B_{\mu\nu}$)

- Generally, at the amplitude level $\mathcal{M}_{\rm dipole} \propto m_f v/\Lambda^2$
- Top is the exception, its dipole was "pinned down" at LHC:



$C_{uw}^{33} = [-1.2, +1.4](\Lambda/\ \mathrm{TeV})^2$ and $C_{uB}^{33} = [-1.9, +1.2](\Lambda/\ \mathrm{TeV})^2$

(ttZ/γ measurement @ LHC Run2, 95% CL) [M. Schulze, Y. Soreq 1603.08911]

$Zb\bar{b}$ dipole could be traced

- Future lepton colliders (CEPC): tremendous amount of events + higher precision
  ⇒possible to trace $Zb\bar{b}$ dipole
- Effective Lagrangian with dim-6 $Zb\bar{b}$ dipole operators

$$\mathcal{L}_{Zb\bar{b}} \supset \frac{g}{c_W} Z_\mu \left(g_{Lb} \bar{b}_L \gamma^\mu b_L + g_{Rb} \bar{b}_R \gamma^\mu b_R \right) + \frac{C_{dW}}{\Lambda^2} O_{dW} + \frac{C_{dB}}{\Lambda^2} O_{dB} + ...$$

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

- Z pole observables

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

$$A_\ell = \frac{\Gamma\left(Z \to \ell_L \bar{\ell}_L\right) - \Gamma\left(Z \to \ell_R \bar{\ell}_R\right)}{\Gamma(Z \to \ell\bar{\ell})}$$

$$A_b = \frac{\Gamma\left(Z \to b_L \bar{b}_L\right) - \Gamma\left(Z \to b_R \bar{b}_R\right)}{\Gamma(Z \to b\bar{b})}$$

$$A_{FB}^b = \frac{3}{4} A_\ell A_b$$

- Off pole scattering

$$A_{FB}^b = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- Projections at CEPC

Quantity	CEPC precision	Runs
R_b	$1.5 \times 10^{-5} \left(1.5 \times 10^{-5}\right)$	Z pole
A_e	$20 \times 10^{-5} \left(3 \times 10^{-5}\right)$	Z pole
A_b	$0.0002 \left(5 \times 10^{-6}\right)$	Z pole
$\sigma(b\bar{b})$[fb]	275.64 ± 0.1174	$\sqrt{s} = 240$ GeV
$A_{FB}(b\bar{b})$	0.592 ± 0.0003434	$\sqrt{s} = 240$ GeV
$\sigma(b\bar{b})$[fb]	108.33 ± 0.329	$\sqrt{s} = 360$ GeV
$A_{FB}(b\bar{b})$	0.602 ± 0.002425	$\sqrt{s} = 360$ GeV

($[c_\theta^{min}, c_\theta^{max}]$=[-0.9,0.9], $\epsilon = 0.15$)

[Snowmass arXiv:2205.08553, 2206.08326]

$Zb\bar{b}$ dipole and χ^2

- For convenience, set $\Lambda = 1$ TeV and only keep real parts of dipole Wilson coefficients (unit: $(\Lambda/\text{ TeV})^2$)
- **SMEFTsim** package was used to extract dipole coupling and calculate observables

  [Brivio et al. 2012.11343]

$$\delta\Gamma^{\text{dipole}}_{Vb\bar{b}} = \mathrm{i}\sigma^{\mu\nu}k_\nu\bar{b}\left(g^V_{\mathrm{L}}P_{\mathrm{L}} + g^V_{\mathrm{R}}P_{\mathrm{R}}\right)b\varepsilon^V_\mu$$

$$g^Z_{\mathrm{L}} = g^{Z*}_{\mathrm{R}} = \frac{1}{\sqrt{2}\Lambda^2}\left(\cos\theta_w C^*_{dW} + \sin\theta_w C^*_{dB}\right)$$

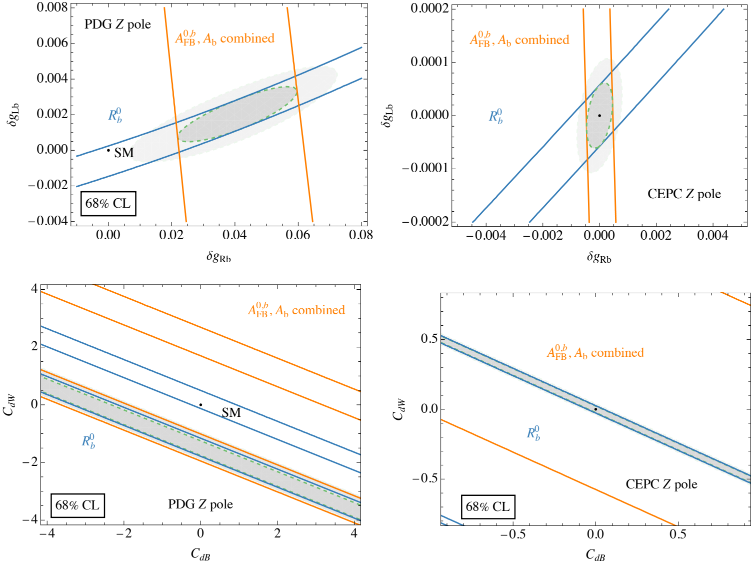
$$g^\gamma_{\mathrm{L}} = g^{\gamma*}_{\mathrm{R}} = \frac{1}{\sqrt{2}\Lambda^2}\left(\cos\theta_w C^*_{dB} - \sin\theta_w C^*_{dW}\right)$$

- Previous observables on Z pole and off pole scattering were used to construct χ^2

$$\chi^2 = \sum_i \left(\frac{x_i - x_0}{\Delta x_i}\right)^2$$

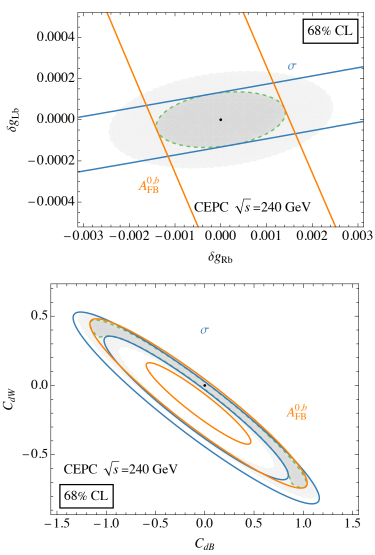
χ^2 constrain analysis

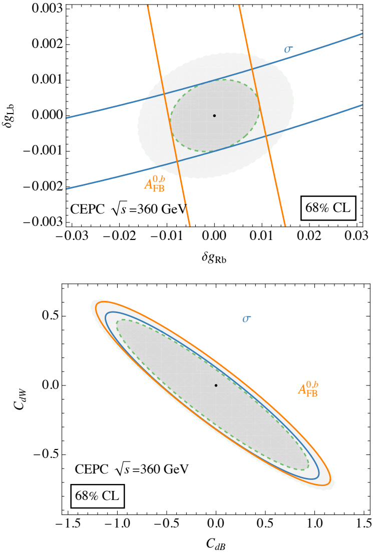
Present Z pole data (PDG) vs CEPC Z pole estimation



χ^2 constrain analysis

CEPC @ $\sqrt{s}$ = 240 and 360 GeV

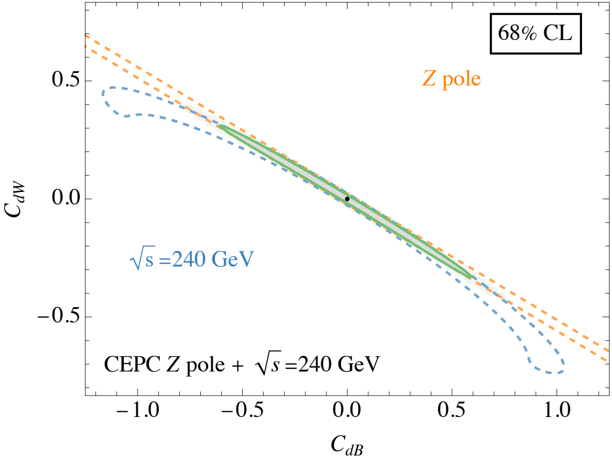




C_{dB} = [−1.17, 1.03], C_{dW} = [−0.739, 0.472] C_{dB} = [−1.01, 0.94], C_{dW} = [−0.610, 0.475]

χ^2 constrain analysis

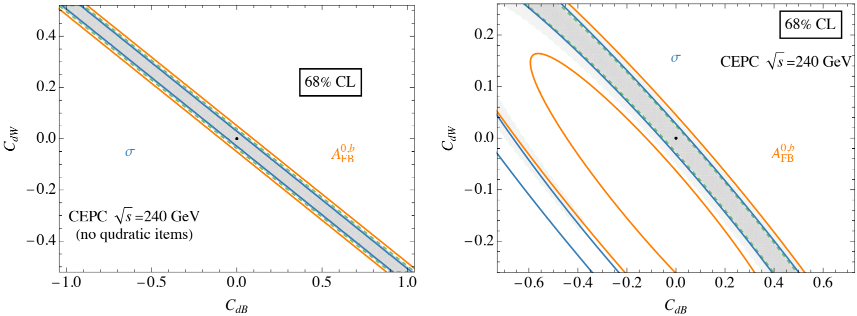
Combine Z pole & $\sqrt{s}$ = 240 GeV run



- $C_{dB} = [-0.608, 0.599]$, $C_{dW} = [-0.336, 0.311]$

Quadratic items effect

e.g. $\sqrt{s}$ = 240 GeV run



- * C_{dB}^2, C_{dW}^2, $C_{dW}C_{dB}$

Summary

- **Small gaps on EW measurements with theory**
  - Existing $Zb\bar{b}$ measurements are still not consistent with SM very well (A_{FB}).
  - Possible BSM corrections(δg_{Lb}, δg_{Lb} ...) exist.
- **SMEFT & dipole**
  - SMEFT is an effective tool to parameterize BSM effects in the EW scale (model independent).
  - dim-6 dipole operators could also contribute to the small A_{FB} inconsistency.
  - Dipoles are usually overlooked in global fit and other analysises.
    Except top (heavy) $\Rightarrow$ ttZ/γ at LHC $\Rightarrow$ $C^{33}_{uw} = [-1.2, +1.4]$ and $C^{33}_{uB} = [-1.9, +1.2](\Lambda/\text{ TeV})^2$
- **CEPC offers opportunity to trace $Zb\bar{b}$ dipole**
  - Pole measurements $\Rightarrow$ only flat constrain.
  - Off pole measurement $\Rightarrow$ interference of γ and Z diagram $\Rightarrow$ possible closed constrain.
  - Quadratic items could have contribution.
  - Our pre-estimation (Z pole + 240 GeV): $C^{33}_{dw} = [-0.608, 0.599]$, $C^{33}_{dB} = [-0.336, 0.311](\Lambda/\text{ TeV})^2$.
- **More efforts are needed and in progress**
  - Further combined analysis, distributions ...
  - More off pole analysises at other future lepton colliders ...

Thank you!

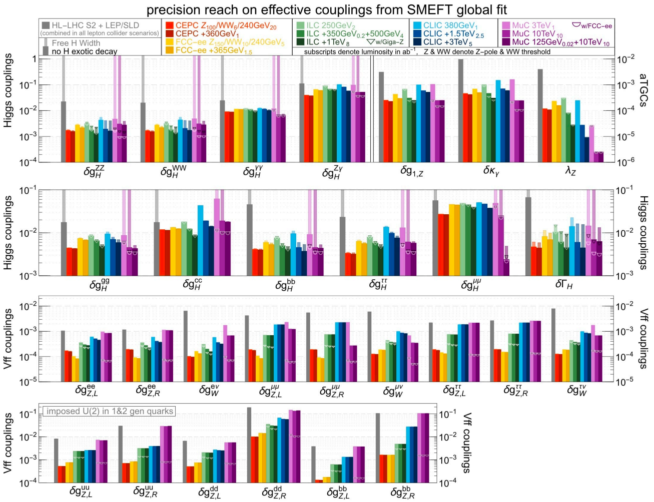
Backups

$\mathcal{L}_6^{(6)} - \psi^2 XH$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\sigma^i H W^i_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^a u_r)\widetilde{H}\, G^a_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\sigma^i \widetilde{H}\, W^i_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^a d_r) H\, G^a_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\sigma^i H\, W^i_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

[arXiv:2012.11343]

Dipole operators of dim-6 SMEFT in the Warsaw basis.

Global SMEFT fit



[arXiv:2206.08326]

EWPOs CEPC

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (6.9)	570
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	200
$\Delta\sigma^0_{\text{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	3.0*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

Table 3: EWPOs at future e^+e^-: statistical error (experimental systematic error). Δ

CEPC $\sqrt{s}$ [GeV]	Final state	$\mathcal{L}$ [fb^{-1}]	σ [fb]	A_{FB}	$[c_\theta^{\min}, c_\theta^{\max}]$	ϵ
240	e^-e^+	5000	77330.4±1.937	0.96±0.00000694	[-0.9, 0.9]	0.98
	$\mu^-\mu^+$		1870.84±0.306	0.521±0.0001395	[-0.95, 0.95]	0.98
	$\tau^-\tau^+$		1589.15±0.282	0.506±0.000153	[-0.9, 0.9]	0.9
	$c\bar{c}$		93.38±0.0683	0.62±0.000574	[-0.9, 0.9]	0.03
	$b\bar{b}$		275.64±0.1174	0.592±0.0003434	[-0.9, 0.9]	0.15
360	e^-e^+	1500	35147.9±5.85	0.957±0.0000482	[-0.9, 0.9]	0.98
	$\mu^-\mu^+$		810.18±0.9	0.4885±0.00097	[-0.95, 0.95]	0.98
	$\tau^-\tau^+$		688.17±0.83	0.474±0.001061	[-0.9, 0.9]	0.9
	$c\bar{c}$		39.22±0.198	0.596±0.004056	[-0.9, 0.9]	0.03
	$b\bar{b}$		108.33±0.329	0.602±0.002425	[-0.9, 0.9]	0.15

[arXiv:2206.08326]

O_{uB} and O_{uW}

$$g_{\mathrm{L}}^{\gamma} = g_{\mathrm{R}}^{\gamma *} = -\frac{\sqrt{2}\, m_t\, v}{\Lambda^2}\left(c_{\mathrm{W}} C_{uB\phi}^{33*} + s_{\mathrm{W}} C_{uW}^{33*}\right),$$

$$g_{\mathrm{L}}^{Z} = g_{\mathrm{R}}^{Z *} = -\frac{e\, m_t\, v^2}{\sqrt{2} s_{\mathrm{W}} c_{\mathrm{W}} M_Z \Lambda^2}\left(c_{\mathrm{W}} C_{uW}^{33*} - s_{\mathrm{W}} C_{uB\phi}^{33*}\right),$$

[arXiv:1603.08911]

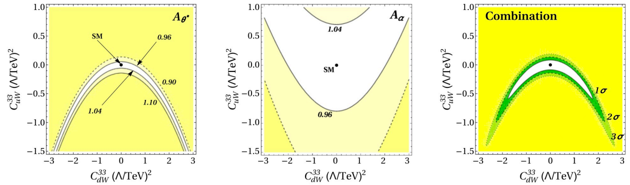
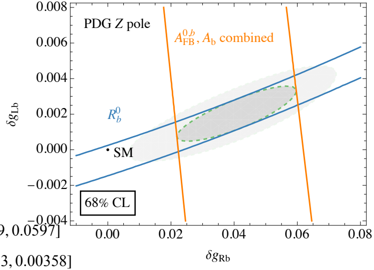


Fig. 3 Angular asymmetries $A_{\theta_\ell^*}(-0.1)$ (*left*) and $A_\alpha(0.0)$ (*middle*) as a function of the two Wilson coefficients in $t\bar{t}$ production relative to the their SM values. *Right* χ^2 combination of the two asymmetries assuming an uncertainty of ± 4 %

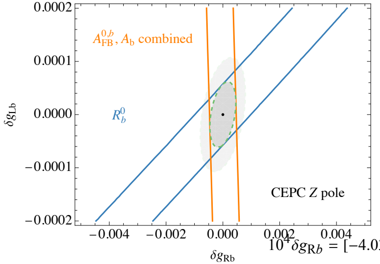
χ^2 constrain analysis backup

Present Z pole data (PDG) vs CEPC Z pole estimation



$\delta g_{Rb} = [0.0219, 0.0597]$

$\delta g_{Lb} = [0.000483, 0.00358]$



$10^4 \delta g_{Rb} = [-4.0355, 4.0283]$

$10^5 \delta g_{Lb} = [-6.0436, 6.0435]$