Global Electroweak Fits at CEPC

Satoshi Mishima (KEK)

International Workshop on High Energy Circular Electron Positron Collider

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EW precision fit

- Electroweak precision fit offer a very powerful handle on NP behind the EW sector.
- No free SM parameter after the Higgs discovery.
- The precise measurements of the top, W and H masses at the LHC have improved the power of the fit.
- Solid progresses in theoretical calculations of higher-order corrections in the SM. *EW 2-loop and more*
- The fit have provided strong constraints on NP.

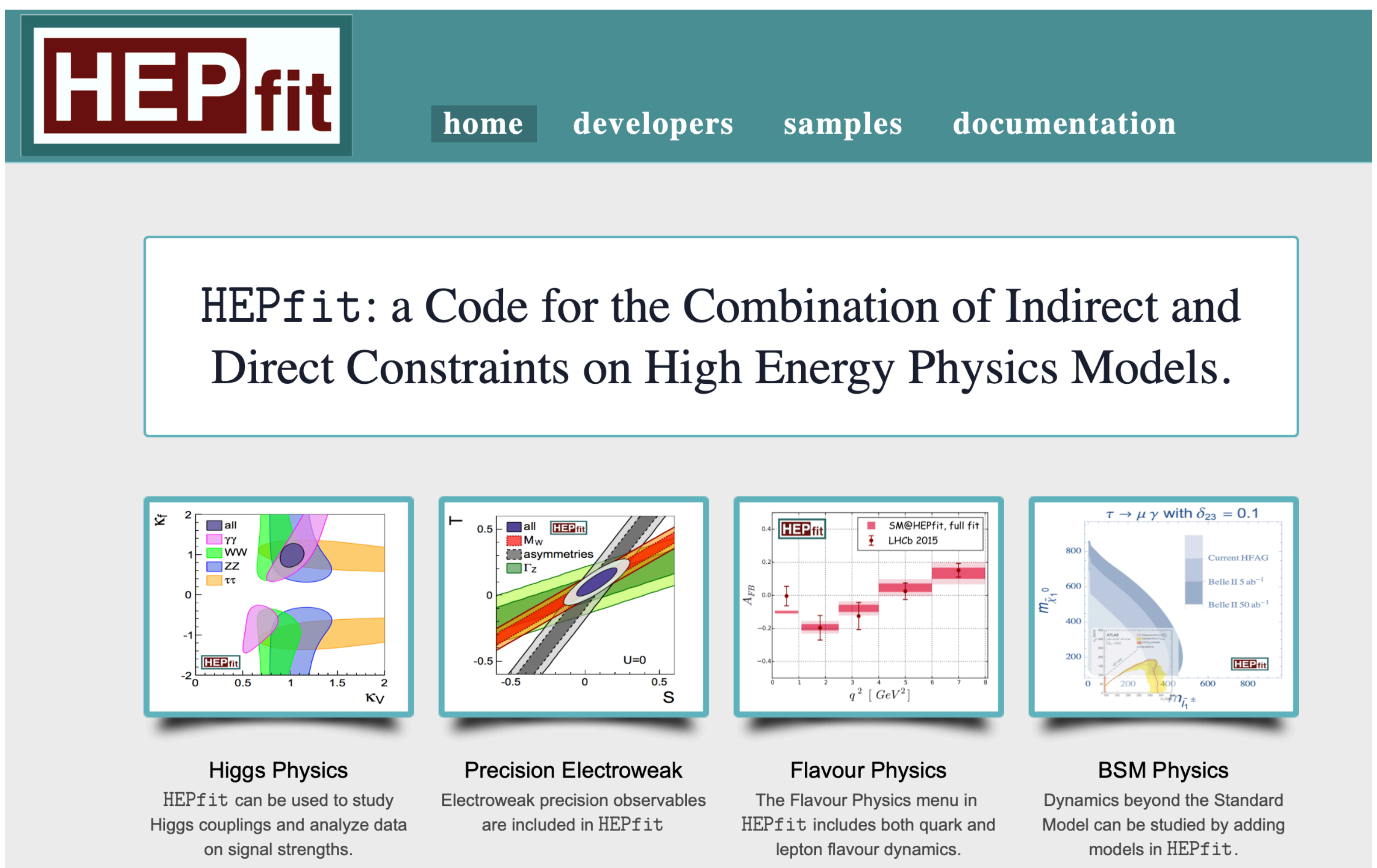
In this talk, I will present …

- the current status of the EW precision fit in the SM;
- our projection of model-independent constraint on NP for the CEPC era.

Numerical results in this talk have been obtained with the HEPfit code.

- ***HEPfit*** is a framework for calculating various observables (EWPO, Higgs, flavor…) in the SM and in its extensions and for constraining their parameter space with a global fit.

http://hepfit.roma1.infn.it



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- ***HEPfit*** is written in C++, supporting MPI parallelization.
- Dependencies: ROOT, GSL, Boost header files

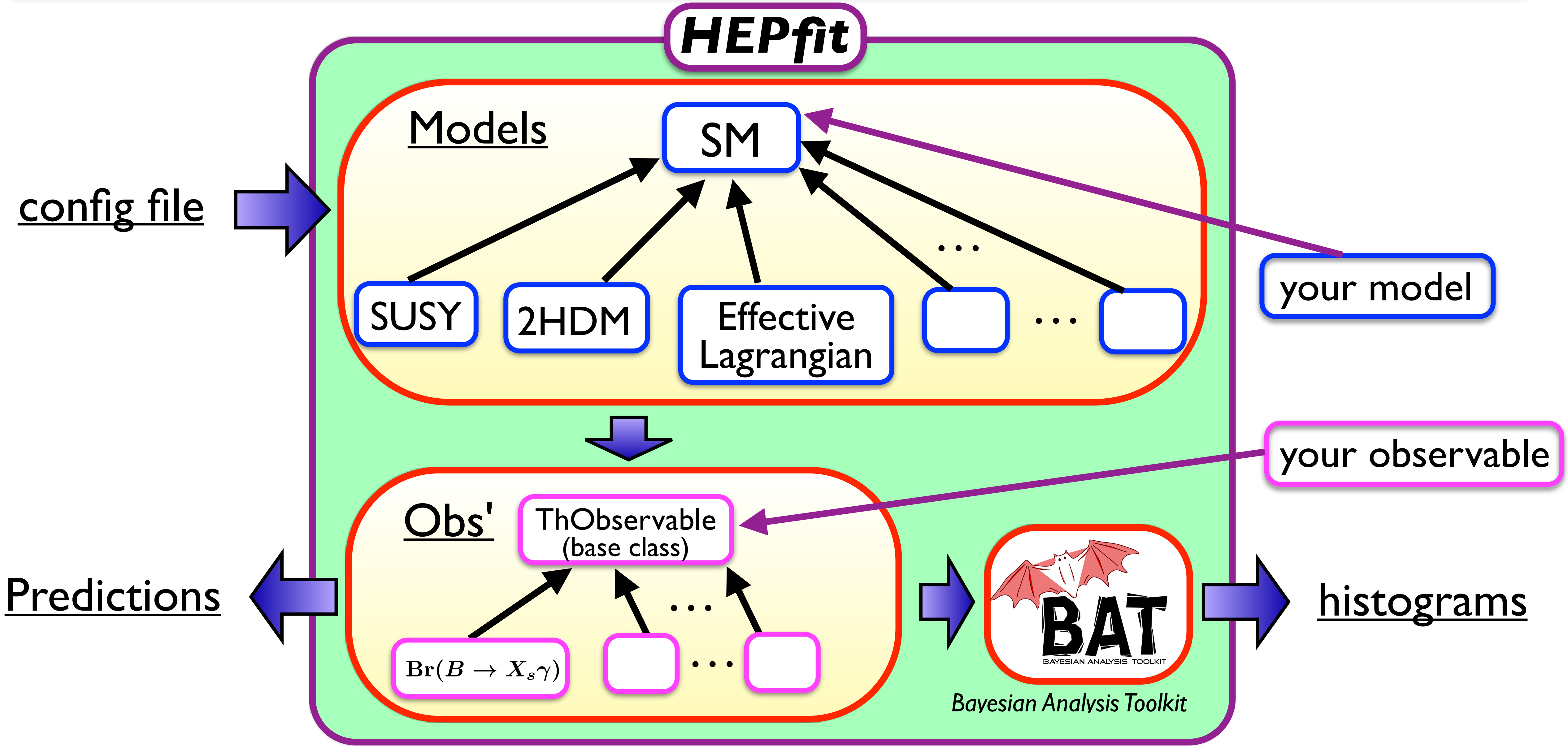
  Bayesian Analysis Toolkit (BAT) ⟵ *optional*

  Beaujean, Caldwell, Greenwald, Kollar & Kroninger
- ***HEPfit*** will be made available to the public under GPL.

  http://hepfit.roma1.infn.it
- Working developer versions, requiring ***NetBeans IDE***, are always available through ***github***.

  https://github.com/silvest/HEPfit

HEPfit



- a stand-alone program to perform a Bayesian statistical analysis.
- alternatively, a library to compute observables in a given model. (*libHEPfit.a* and *HEPfit.h*)
- add user's favorite models and observables as external modules.

Our publications (EW precision fit)

HEPfit

- *M. Ciuchini, E. Franco,* **S.M.**, *L. Silvestrini, JHEP08 (2013) 106 [arXiv:1306.4644]*
- *M. Ciuchini, E. Franco,* **S.M.**, *L. Silvestrini, EPJ Web Conf. 60 (2013) 08004* LHCP2013
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, Nucl.Part.Phys.Proc. 273-275 (2016) 834 [arXiv:1410.4204]* ICHEP2014
- *M. Ciuchini, E. Franco,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, Nucl.Part.Phys.Proc. 273-275 (2016) 2219 [arXiv:1410.6940]* ICHEP2014
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, PoS EPS-HEP2015 (2015) 187* EPS-HEP2015
- *J. de Blas, M. Ciuchini, E. Franco, D. Ghosh,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, PoS LeptonPhoton2015 (2016) 013* Lepton-Photon2015
- *J. de Blas, M. Ciuchini, E. Franco,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135 [arXiv:1608.01509]*
- *J. de Blas, M. Ciuchini, E. Franco,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, PoS ICHEP2016 (2017) 690 [arXiv:1611.05354]* ICHEP2016
- *J. de Blas, M. Ciuchini, E. Franco,* **S.M.**, *M. Pierini, L. Reina, L. Silvestrini, PoS EPS-HEP2017 (2017) 467 [arXiv:1710.05402]* LHCP2017 & EPS-HEP2017

People involved in this study

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Part of the HEPfit SM/New Physics studies

Special thanks to Jorge de Blas to make the results in this talk

EW precision observables (EWPO)

M_W, Γ_W and ~10 Z-pole observables
(LEP2/Tevatron) (LEP/SLD)

- Z-pole ob's are given in terms of effective couplings:

$$\mathcal{L} = \frac{e}{2 s_W c_W} Z_\mu \bar{f} \left(g_V^f \gamma_\mu - g_A^f \gamma_\mu \gamma_5 \right) f$$

$$A_{\rm LR}^{0,f} = \mathcal{A}_f = \frac{2\,{\rm Re}\left(g_V^f/g_A^f\right)}{1+\left[{\rm Re}\left(g_V^f/g_A^f\right)\right]^2} \qquad A_{\rm FB}^{0,f} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad (f=\ell,c,b)$$

$$P_\tau^{\rm pol} = \mathcal{A}_\tau \qquad \sin^2\theta_{\rm eff}^{\rm lept} = \frac{1}{4|Q_\ell|}\left[1-{\rm Re}\left(\frac{g_V^\ell}{g_A^\ell}\right)\right]$$

$\Big\}$ g_V^f/g_A^f

$$\Gamma_f = \Gamma(Z\to f\bar{f}) \propto \left|g_A^f\right|^2 \left[\left|\frac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right]$$

$$\Rightarrow \Gamma_Z,\ \sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_h}{\Gamma_Z^2},\ R_\ell^0 = \frac{\Gamma_h}{\Gamma_\ell},\ R_{c,b}^0 = \frac{\Gamma_{c,b}}{\Gamma_h}$$

$\Big\}$ $g_V^f,\ g_A^f$

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Experimental data

- Very precise measurements of the W & Z boson properties at e+ e- colliders:

$$M_Z,\ \Gamma_Z,\ \sigma_h^0,\ \sin^2\theta_{\rm eff}^{\rm lept},\ \mathcal{A}_f,\ A_{\rm FB}^{0,f},\ R_f^0$$

Z-pole obs. (LEP/SLD)

0.002% (M_Z) $O(0.1\%) - O(1\%)$

$$M_W,\ \Gamma_W$$

W obs. (LEP2)

0.04% 2%

- Measurements at hadron colliders (Tevatron & LHC):

m_t	m_h	M_W	$\sin^2\theta_{\rm eff}^{\rm lept}$
$\sim 0.4\%$	0.1%	0.020% (CDF + D0) 0.024% (ATLAS)	0.14% (CDF + D0) 0.16% (ATLAS) 0.23% (CMS) 0.46% (LHCb)

- $G_F,\ \alpha$ are fixed to be constant.

Theoretical status

- EWPO have been calculated with full EW 2-loop + leading 3- & 4-loop corrections.

See talks by Fulvio Piccinini & Ayres Freitas

	M_W [MeV]	Γ_Z [MeV]	R^0_ℓ $[10^{-4}]$	R^0_b $[10^{-5}]$	$\sin^2\theta^{\rm lept}_{\rm eff}$ $[10^{-6}]$
Exp. error	12	2.3	250	66	160
Th. Error	4	0.4	60	10	45

M. Awramik, et al., hep-ph/0311148
A. Blondel, et al., 1809.01830

Theory errors from missing higher-order corrections are safely below current experimental errors.

EW precision fits

- PDG (Erler et al.) http://www.fisica.unam.mx/erler/GAPPP.html

  GAPP (Global Analysis of Particle Properties)

  MSbar scheme & frequentist

- Gfitter group

  Gfitter (Generic fitting package) http://gfitter.desy.de

  on-shell scheme & frequentist

- Our group

  HEPfit http://hepfit.roma1.infn.it

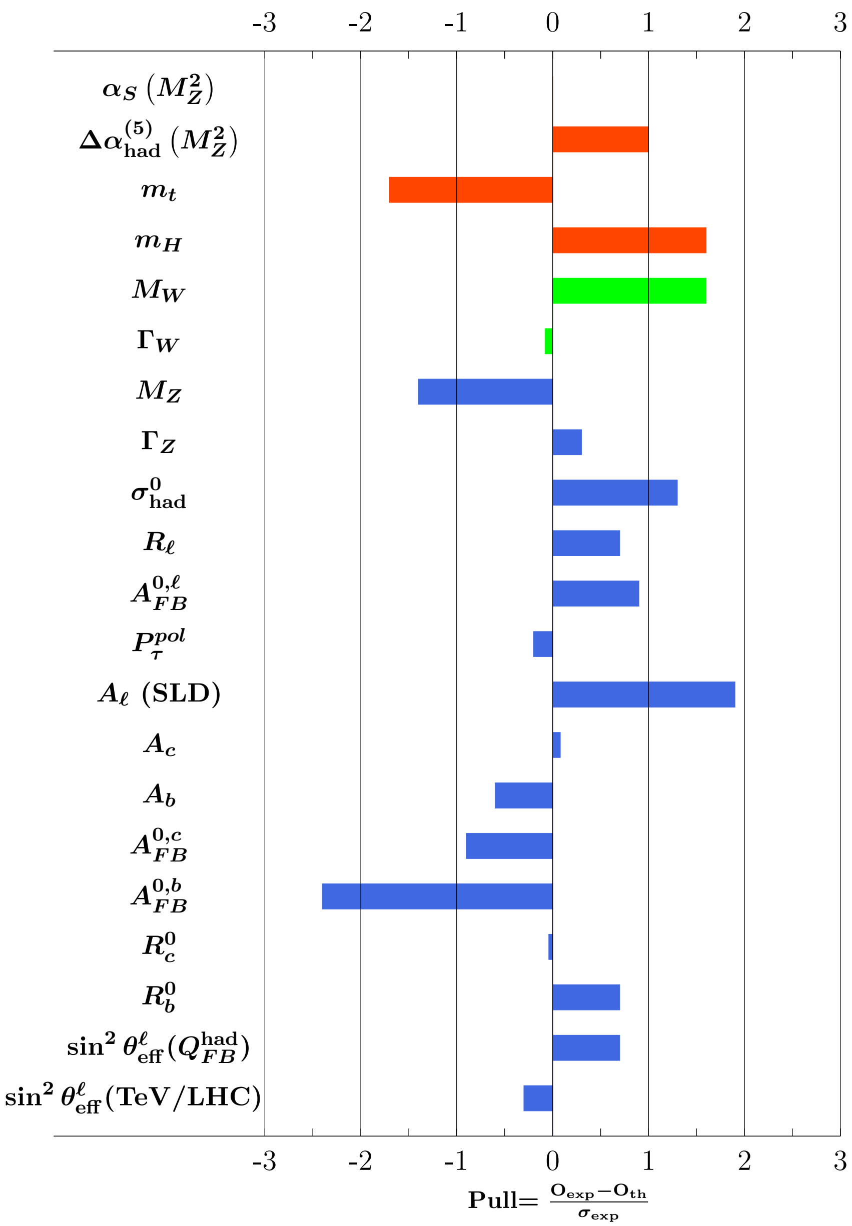
  on-shell scheme & Bayesian

- and many other groups ....

EW fit in the SM

input parameters

	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.11800 ± 0.00094	0.1180 ± 0.0029	0.00
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.027611 ± 0.000111	0.027576 ± 0.000106	0.02720 ± 0.00038	1.0
M_Z [GeV]	91.1875 ± 0.0021	91.1882 ± 0.0020	91.2005 ± 0.0091	-1.4
m_t [GeV]	172.8 ± 0.7	173.18 ± 0.66	176.27 ± 1.97	-1.7
m_H [GeV]	125.13 ± 0.17	125.13 ± 0.17	96.78 ± 18.23	1.6
M_W [GeV]	80.379 ± 0.012	80.3621 ± 0.0057	80.3570 ± 0.0065	1.6
Γ_W [GeV]	2.085 ± 0.042	2.08854 ± 0.00059	2.08855 ± 0.00059	-0.08
Γ_Z [GeV]	2.4952 ± 0.0023	2.49458 ± 0.00065	2.49446 ± 0.00069	0.3
σ_h^0 [nb]	41.540 ± 0.037	41.4924 ± 0.0077	41.4915 ± 0.0080	1.3
R_ℓ^0	20.767 ± 0.025	20.7495 ± 0.0081	20.7482 ± 0.0086	0.7
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.01623 ± 0.00010	0.01622 ± 0.00010	0.9
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14710 ± 0.00046	0.14712 ± 0.00047	-0.2
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14710 ± 0.00046	0.14714 ± 0.00049	1.9
$\mathcal{A}_c$	0.670 ± 0.027	0.66793 ± 0.00023	0.66793 ± 0.00023	0.08
$\mathcal{A}_b$	0.923 ± 0.020	0.934753 ± 0.000041	0.934754 ± 0.000041	-0.6
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07369 ± 0.00024	0.07371 ± 0.00026	-0.9
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.10313 ± 0.00032	0.10315 ± 0.00034	-2.4
R_c^0	0.1721 ± 0.0030	0.172210 ± 0.000054	0.172211 ± 0.000054	-0.04
R_b^0	0.21629 ± 0.00066	0.21586 ± 0.00010	0.21585 ± 0.00010	0.7
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231512 ± 0.000059	0.231509 ± 0.000059	0.7
$\sin^2\theta_{\rm eff}^{\rm lept}$(Tev/LHC)	0.23143 ± 0.00027	0.231512 ± 0.000059	0.231516 ± 0.000060	-0.3



Posterior: our fit results

Prediction: determined w/o using the corresponding experimental information

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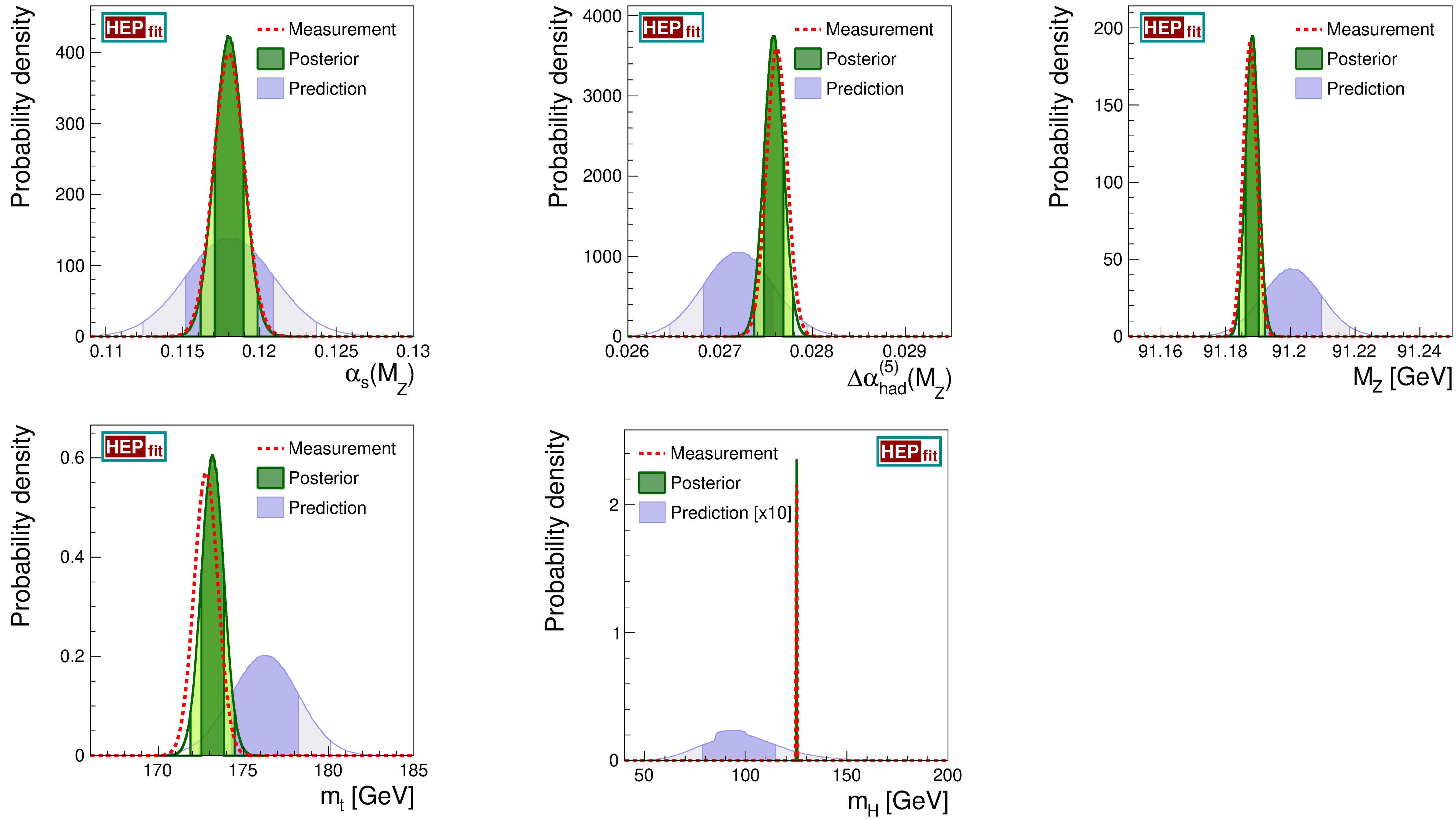
Fit results for the input parameters



Indirect determinations of the SM input parameters from the fit are consistent with the measurements.

Parametric uncertainties

	Prediction	α_s	$\Delta\alpha_{\rm had}^{(5)}$	M_Z	m_t
M_W [GeV]	80.3566 ± 0.0054	± 0.0007	± 0.0020	± 0.0027	± 0.0042
Γ_W [GeV]	2.08811 ± 0.00058	± 0.00040	± 0.00016	± 0.00021	± 0.00033
Γ_Z [GeV]	2.49435 ± 0.00057	± 0.00050	± 0.00011	± 0.00021	± 0.00016
σ_h^0 [nb]	41.4915 ± 0.0053	± 0.0049	± 0.0002	± 0.0020	± 0.0005
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.231542 ± 0.000047	± 0.000003	± 0.000039	± 0.000015	± 0.000022
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.14687 ± 0.00037	± 0.00003	± 0.00030	± 0.00012	± 0.00017
$\mathcal{A}_c$	0.66783 ± 0.00016	± 0.00001	± 0.00013	± 0.00005	± 0.00008
$\mathcal{A}_b$	0.934739 ± 0.000027	± 0.000001	± 0.000025	± 0.000010	± 0.000005
$A_{\rm FB}^{0,\ell}$	0.016178 ± 0.000082	± 0.000006	± 0.000067	± 0.000026	± 0.000038
$A_{\rm FB}^{0,c}$	0.07356 ± 0.00020	± 0.00002	± 0.00017	± 0.00006	± 0.00010
$A_{\rm FB}^{0,b}$	0.10296 ± 0.00026	± 0.00002	± 0.00022	± 0.00008	± 0.00012
R_ℓ^0	20.7486 ± 0.0062	± 0.0062	± 0.0007	± 0.0003	± 0.0003
R_c^0	0.172206 ± 0.000021	± 0.000019	± 0.000002	± 0.000001	± 0.000008
R_b^0	0.215869 ± 0.000026	± 0.000011	± 0.000001	± 0.000000	± 0.000024

Parametric uncertainties are well below the current experimental errors.

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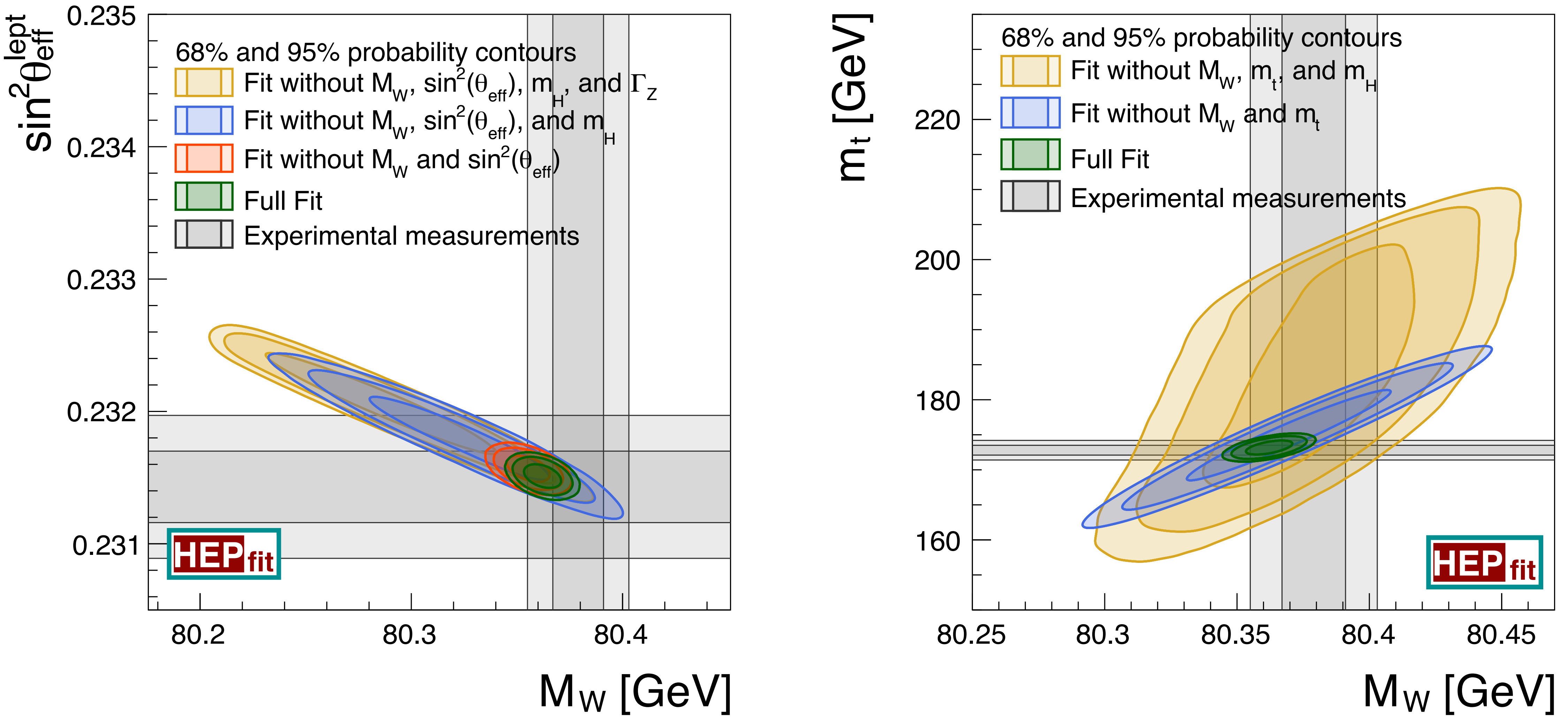
Key observables in the EW fit



Good consistency of predictions with data

More precision in the CEPC era?

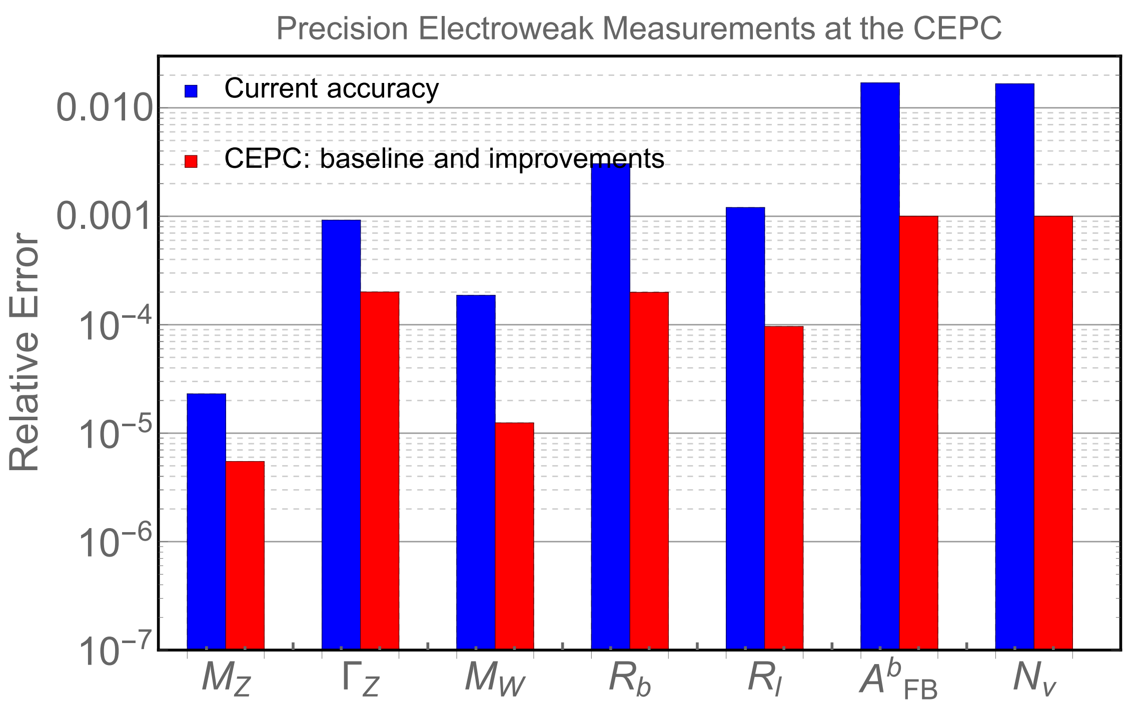
Our strategy for CEPC sensitivity study

- Follow the CEPC expected precision in a preliminary version of CDR, where a part of them needs to be updated to the latest values.
- Assume that theoretical and parametrical uncertainties will also be reduced.
- Use SM predictions as central values for future measurements

⇨ Limits provide future sensitivity to NP

Expected precision for EWPO

- CEPC expected precision for EWPO in CDR:



Observable	LEP precision	CEPC precision	CEPC runs	CEPC $\int \mathcal{L}dt$
m_Z	2.1 MeV	0.5 MeV	Z pole	8 ab^{-1}
Γ_Z	2.3 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	0.0016	0.0001	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	0.0013	0.00005	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	0.0025	0.00008	Z pole	8 ab^{-1}
$\sin^2\theta_W^{\rm eff}$	0.00016	0.00001	Z pole	8 ab^{-1}
R_b^0	0.00066	0.00004	Z pole	8 ab^{-1}
R_μ^0	0.025	0.002	Z pole	8 ab^{-1}
m_W	33 MeV	1 MeV	WW threshold	2.6 ab^{-1}
m_W	33 MeV	2–3 MeV	ZH run	5.6 ab^{-1}
N_ν	1.7%	0.05%	ZH run	5.6 ab^{-1}

Run at the Z pole (~10^{12} Z) and near the WW threshold (~10^7 W)

- In this talk, I don’t present global analysis combined with Higgs data.

Theoretical uncertainty

	M_W [MeV]	Γ_Z [MeV]	R^0_ℓ [10^{-4}]	R^0_b [10^{-5}]	$\sin^2\theta^{\rm lept}_{\rm eff}$ [10^{-6}]
Current exp. error	12	2.3	250	66	160
CEPC error	1	0.5	20	4	10
Current th. Error	4	0.4	60	10	45
Future (w/ $O(\alpha^3)$, $O(\alpha^2\alpha_s)$ and $O(\alpha\alpha_s^2 a)$)	1	0.15	15	5	15
Future (w/ leading 4-loop)		< 0.07	< 7	< 3	< 7

M. Awramik, et al., hep-ph/0311148
A. Freitas, et al., 1307.3962
A. Blondel, et al., 1809.01830

Theoretical efforts are necessary to match future experimental precision.

Expected precision in input parameters

- $\alpha_s(M_Z)$: lattice QCD projection

$$\delta\alpha_s(M_Z) = \pm 0.0010 \quad \Rightarrow \quad \delta\alpha_s(M_Z) \approx \pm 0.0002$$

- $\Delta\alpha^{(5)}_{\rm had}(M_Z)$: ongoing and future experiments for $\sigma(e^+e^- \to \text{hadrons})$

$$\delta\Delta\alpha^{(5)}_{\rm had}(M_Z) = \pm 0.000111 \quad \Rightarrow \quad \delta\Delta\alpha^{(5)}_{\rm had}(M_Z) \approx \pm 0.00005$$

- m_t: HL-LHC

$$\delta m_t = \pm 0.7\,\text{GeV} \quad \Rightarrow \quad \delta m_t = \pm 0.4\,\text{GeV}$$

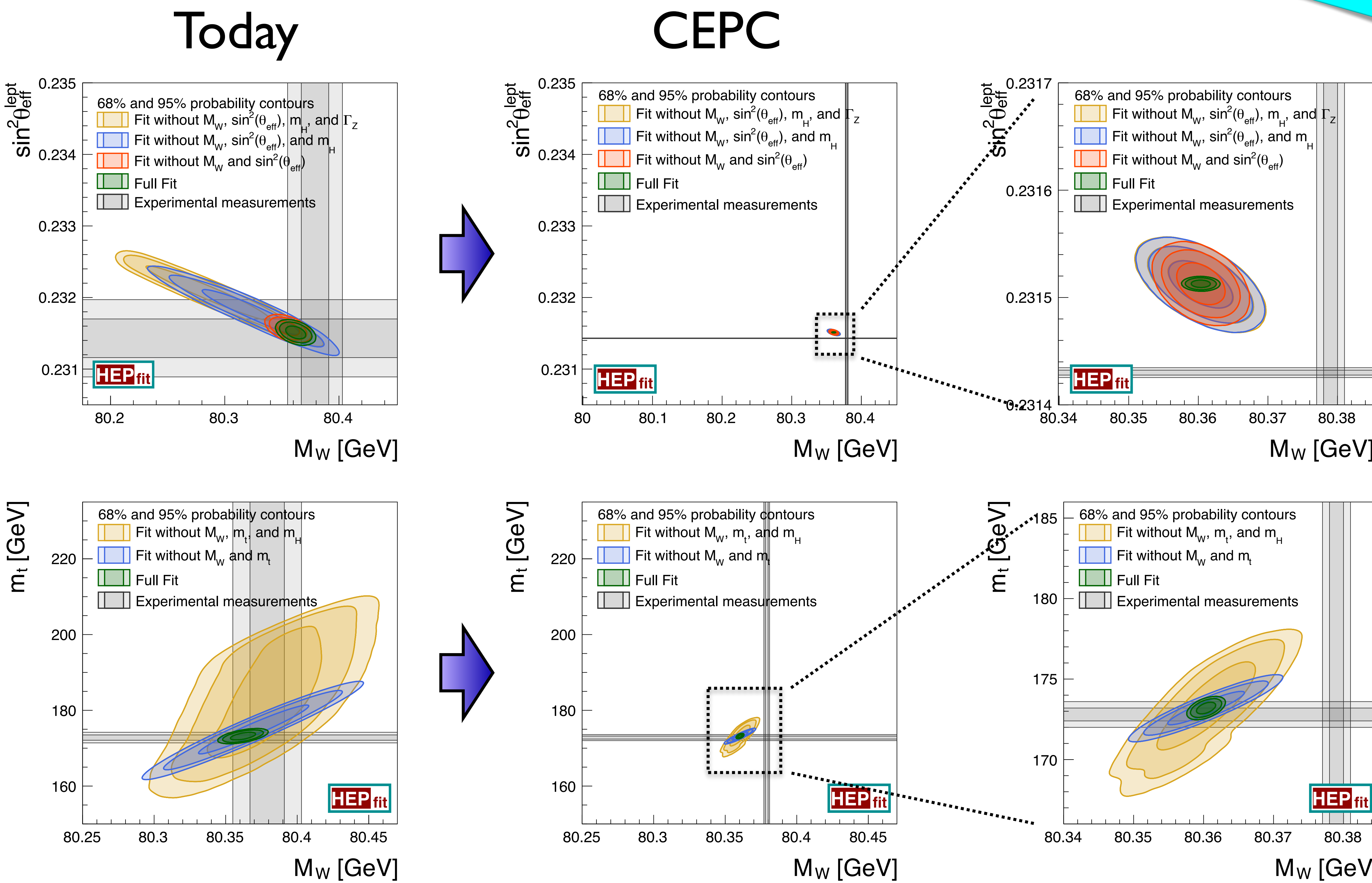
cf. $\delta m_t = \pm 17\,\text{MeV}$ at FCC-ee

- m_H: CEPC (ZH threshold)

$$\delta m_H = \pm 0.17\,\text{GeV} \quad \Rightarrow \quad \delta m_H = \pm 0.0059\,\text{GeV}$$

CEPC sensitivity

preliminary



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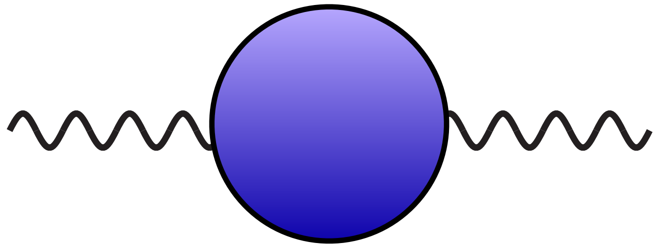
Oblique parameters

- Suppose that dominant NP effects appear in the vacuum polarizations of the gauge bosons:



$$\Pi_{11}(q^2) = \Pi_{11}(0) + q^2\,\Pi'_{11}(0)$$
$$\Pi_{33}(q^2) = \Pi_{33}(0) + q^2\,\Pi'_{33}(0)$$
$$\Pi_{3Q}(q^2) = q^2\,\Pi'_{3Q}(0)\,,$$
$$\Pi_{QQ}(q^2) = q^2\,\Pi'_{QQ}(0)$$

$\Pi'_{XY}(q^2) = d\Pi_{XY}(q^2)/dq^2$ for $q^2 \approx 0$

Three of the above can be fixed by $\alpha,\ M_Z,\ G_F$, and the others are

$$\boldsymbol{S = -16\pi\Pi'_{30}(0) = 16\pi\left[\Pi^{\mathrm{NP}\prime}_{33}(0) - \Pi^{\mathrm{NP}\prime}_{3Q}(0)\right]}$$
$$\boldsymbol{T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi^{\mathrm{NP}}_{11}(0) - \Pi^{\mathrm{NP}}_{33}(0)\right]}$$
$$\boldsymbol{U = 16\pi\left[\Pi^{\mathrm{NP}\prime}_{11}(0) - \Pi^{\mathrm{NP}\prime}_{33}(0)\right]}$$

Kennedy & Lynn (89); Peskin & Takeuchi (90,92)

- When the EW symmetry is realized linearly, U is associated with a dim. 8 operator and thus small.

Oblique parameters

preliminary

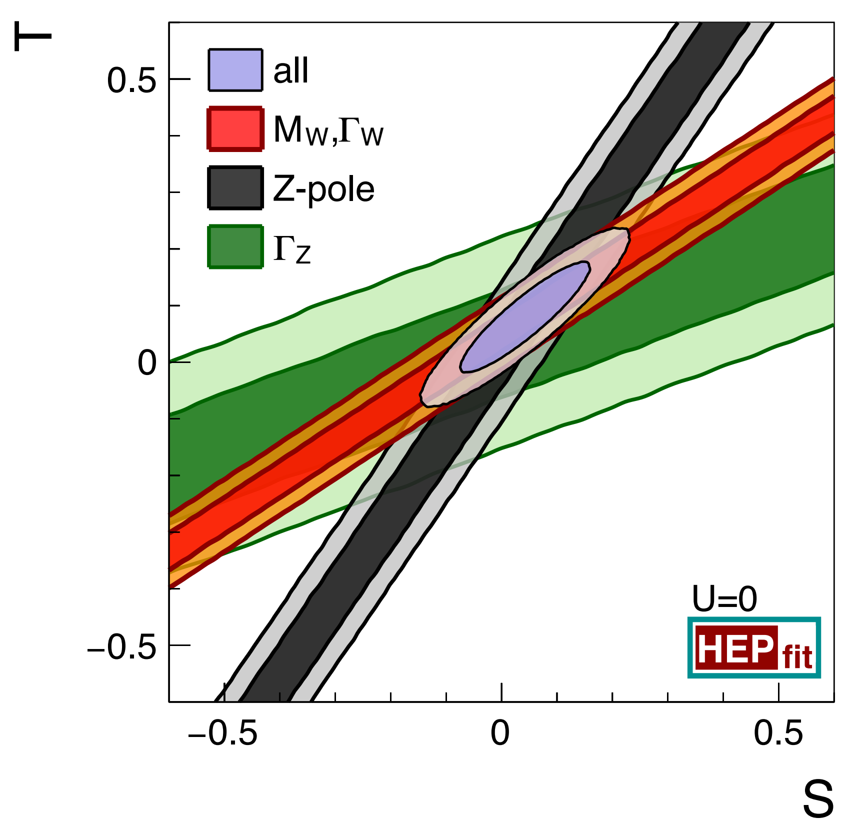
- EWPO depend on three combinations:

$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\, T + \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

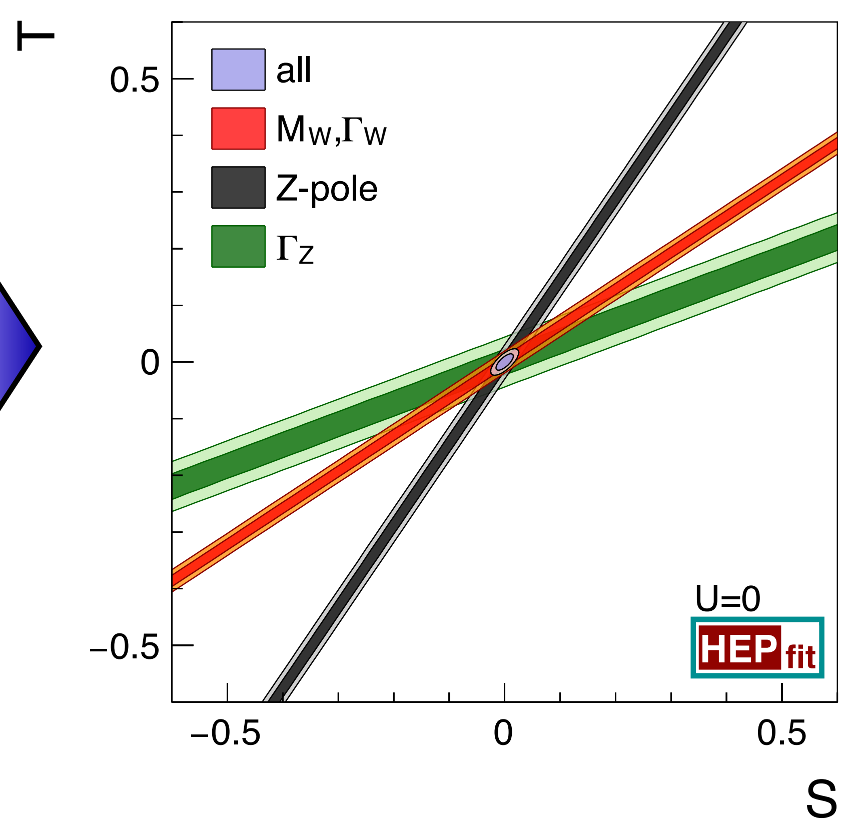
$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\, S + (63 - 126s_W^2 - 40s_W^4)\, T$$

$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$

Today

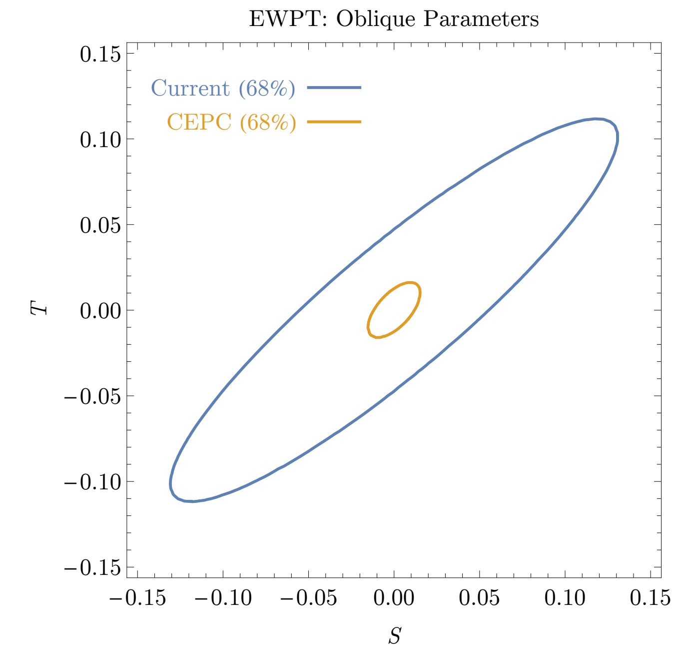


CEPC



$\Delta S,\ \Delta T \sim 0.01$

cf. CEPC CDR



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NP in $Zb\bar{b}$ couplings

$$\mathcal{L} = \frac{e}{s_W c_W} Z_\mu \bar{b} \left(g_R^b \gamma_\mu P_R + g_L^b \gamma_\mu P_L \right) b$$

$$g_R^b \to g_{R,\mathrm{SM}}^b + \delta g_R^b \,, \quad g_L^b \to g_{L,\mathrm{SM}}^b + \delta g_L^b$$

- Z-pole data yield four solutions.

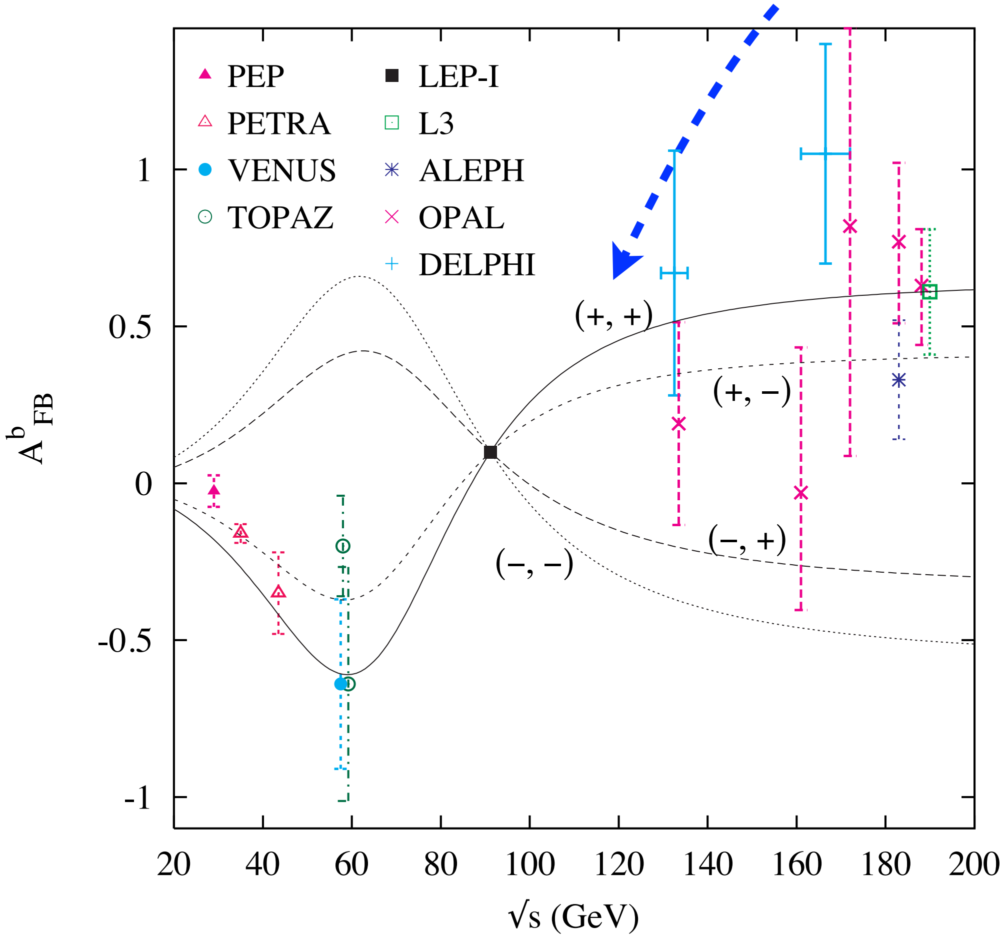
$$A_b \sim \frac{|\delta g_R^b|^2 - |\delta g_L^b|^2}{|\delta g_R^b|^2 + |\delta g_L^b|^2}$$

$$\Gamma_b \sim |\delta g_R^b|^2 + |\delta g_L^b|^2$$

- Two solutions are disfavored by the off Z-pole data for AFBb.

Choudhury et al. (2002)

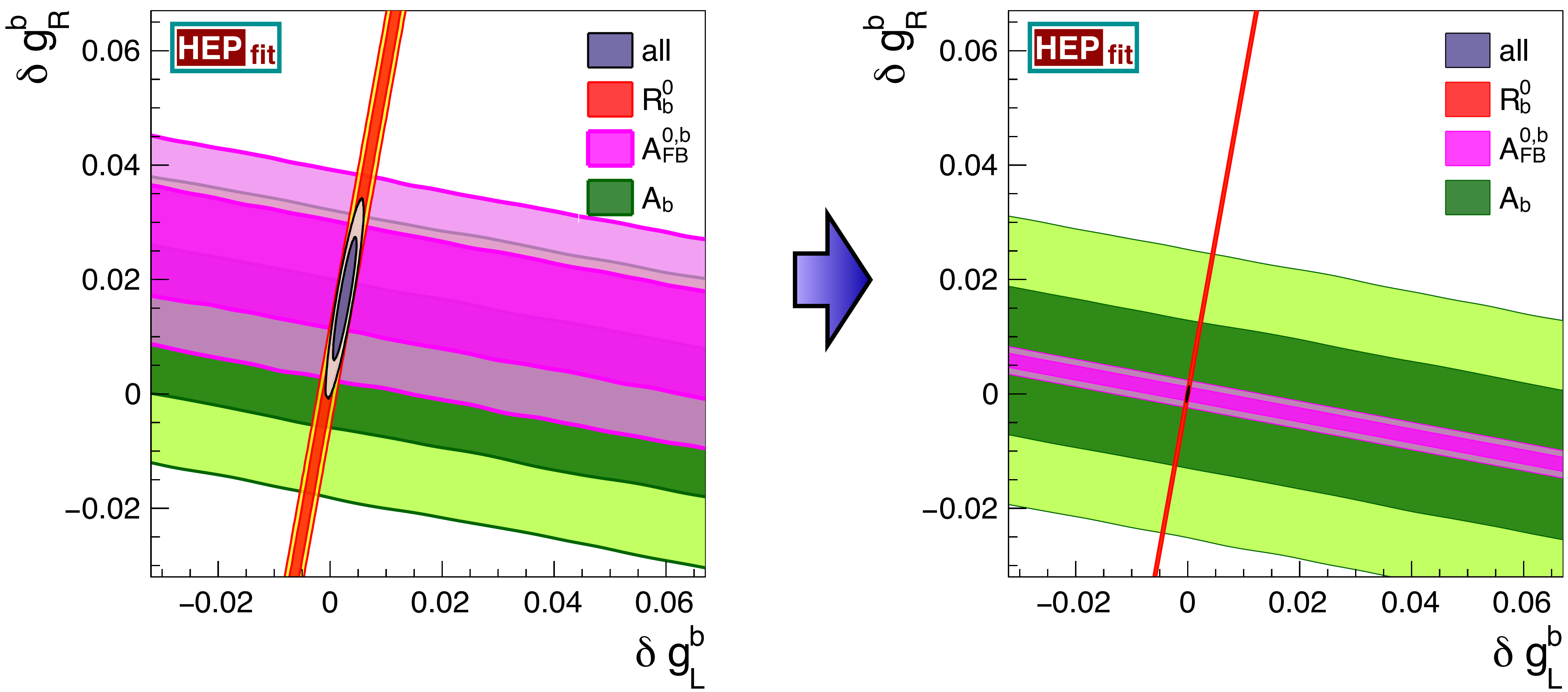
(g_L, g_R)



NP in $Zb\bar{b}$ couplings

preliminary

Today CEPC $\Delta(\delta g^b_{R,L}) \sim 10^{-4}$



- The current fit shows a deviation from the SM due to $A_{FB}^{0,b}$.
- In the CEPC plot, the precision of A_b is not updated.

cf. Gori, Gu & Wang, 1508.07010

More general analysis (SMEFT)

- LHC suggest that the NP scale is well above the EW scale.
- Consider an effective theory built exclusively from the SM fields with the SM gauge symmetries.

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Standard Model Effective Field Theory (SMEFT)

- Contributions from higher-dimensional operators are suppressed by powers of the NP scale.

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_j C_j^{(6)} O_j^{(6)} + O\left(\frac{1}{\Lambda^3}\right)$$

EFT approach

Pros:

- Model-independent
- Systematic power counting
- Correlations among observables are induced by gauge-invariant operators.

  ⇨ *Useful guide to look for NP effects*
- Constraints on the Wilson coefficients will give us clues for constructing the UV theory.

Cons:

- Too many operators in general.
- EFT analyses cannot capture the stronger correlations among operators that may arise in specific NP models.

59+ dim-six operators in Warsaw basis

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{L}eH)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{Q}u\widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star\,(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{Q}dH)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$(H^\dagger H)\,G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{L}\sigma^{\mu\nu}e)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$
$\mathcal{O}_{H\widetilde{G}}$	$(H^\dagger H)\,\widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{L}\sigma^{\mu\nu}e)H B_{\mu\nu}$	$\mathcal{O}^{(3)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)$
$\mathcal{O}_{HW}$	$(H^\dagger H)\,W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{Q}\sigma^{\mu\nu}T^A u)\widetilde{H}\,G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e)$
$\mathcal{O}_{H\widetilde{W}}$	$(H^\dagger H)\,\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{Q}\sigma^{\mu\nu}u)\tau^I\widetilde{H}\,W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$
$\mathcal{O}_{HB}$	$(H^\dagger H)\,B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{Q}\sigma^{\mu\nu}u)\widetilde{H}\,B_{\mu\nu}$	$\mathcal{O}^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)$
$\mathcal{O}_{H\widetilde{B}}$	$(H^\dagger H)\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{Q}\sigma^{\mu\nu}T^A d)H\,G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u)$
$\mathcal{O}_{HWB}$	$(H^\dagger\tau^I H)\,W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{Q}\sigma^{\mu\nu}d)\tau^I H\,W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d)$
$\mathcal{O}_{H\widetilde{W}B}$	$(H^\dagger\tau^I H)\,\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{Q}\sigma^{\mu\nu}d)H\,B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}\gamma^\mu d)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{LL}$	$(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$	$\mathcal{O}_{ee}$	$(\bar{e}\gamma_\mu e)(\bar{e}\gamma^\mu e)$	$\mathcal{O}_{Le}$	$(\bar{L}\gamma_\mu L)(\bar{e}\gamma^\mu e)$
$\mathcal{O}^{(1)}_{QQ}$	$(\bar{Q}\gamma_\mu Q)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{uu}$	$(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Lu}$	$(\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u)$
$\mathcal{O}^{(3)}_{QQ}$	$(\bar{Q}\gamma_\mu\tau^I Q)(\bar{Q}\gamma^\mu\tau^I Q)$	$\mathcal{O}_{dd}$	$(\bar{d}\gamma_\mu d)(\bar{d}\gamma^\mu d)$	$\mathcal{O}_{Ld}$	$(\bar{L}\gamma_\mu L)(\bar{d}\gamma^\mu d)$
$\mathcal{O}^{(1)}_{LQ}$	$(\bar{L}\gamma_\mu L)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{eu}$	$(\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)$	$\mathcal{O}_{Qe}$	$(\bar{Q}\gamma_\mu Q)(\bar{e}\gamma^\mu e)$
$\mathcal{O}^{(3)}_{LQ}$	$(\bar{L}\gamma_\mu\tau^I L)(\bar{Q}\gamma^\mu\tau^I Q)$	$\mathcal{O}_{ed}$	$(\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$	$\mathcal{O}^{(1)}_{Qu}$	$(\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u)$
		$\mathcal{O}^{(1)}_{ud}$	$(\bar{u}\gamma_\mu u)(\bar{d}\gamma^\mu d)$	$\mathcal{O}^{(8)}_{Qu}$	$(\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)$
		$\mathcal{O}^{(8)}_{ud}$	$(\bar{u}\gamma_\mu T^A u)(\bar{d}\gamma^\mu T^A d)$	$\mathcal{O}^{(1)}_{Qd}$	$(\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d)$
				$\mathcal{O}^{(8)}_{Qd}$	$(\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{LedQ}$	$(\bar{L}^j e)(\bar{d}Q^j)$	$\mathcal{O}_{duQ}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha)^T C u^\beta\right]\left[(Q^{\gamma j})^T C L^k\right]$
$\mathcal{O}^{(1)}_{QuQd}$	$(\bar{Q}^j u)\varepsilon_{jk}(\bar{Q}^k d)$	$\mathcal{O}_{QQu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(Q^{\alpha j})^T C Q^{\beta k}\right]\left[(u^\gamma)^T C e\right]$
$\mathcal{O}^{(8)}_{QuQd}$	$(\bar{Q}^j T^A u)\varepsilon_{jk}(\bar{Q}^k T^A d)$	$\mathcal{O}^{(1)}_{QQQ}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(Q^{\alpha j})^T C Q^{\beta k}\right]\left[(Q^{\gamma m})^T C L^n\right]$
$\mathcal{O}^{(1)}_{LeQu}$	$(\bar{L}^j e)\varepsilon_{jk}(\bar{Q}^k u)$	$\mathcal{O}^{(3)}_{QQQ}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(Q^{\alpha j})^T C q^{\beta k}\right]\left[(Q^{\gamma m})^T C L^n\right]$
$\mathcal{O}^{(3)}_{LeQu}$	$(\bar{L}^j\sigma_{\mu\nu}e)\varepsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}u)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha)^T C u^\beta\right]\left[(u^\gamma)^T C e\right]$

Grzadkowski, Iskrzynski, Misiak & Rosiek (10)

- 10 CP-even op's for EWPO.
- To avoid dangerous FCNC, we assume *flavor universality.*

(Alternatively, *MFV* may be assumed.)

- Other choices of the basis are possible.

direct connections to observables

operator mixing in the RG running

See, e.g., Giudice et al. (07); Contino et al. (13)

Dim-six contributions to EWPO

$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$ → S parameter (W3-B mixing)

$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$ → T parameter (Mz)

$$\mathcal{O}_{LL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I \gamma^\mu L)$$

$\mathcal{O}_{LL}$, $\mathcal{O}^{(3)}_{HL}$ → Fermi constant

$$\mathcal{O}^{(1)}_{HL} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$

$$\mathcal{O}^{(3)}_{HQ} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I \gamma^\mu Q)$$

$$\mathcal{O}^{(1)}_{HQ} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$

$\mathcal{O}^{(3)}_{HL}$, $\mathcal{O}^{(1)}_{HL}$, $\mathcal{O}^{(3)}_{HQ}$, $\mathcal{O}^{(1)}_{HQ}$ → Left-handed $Zf\bar{f}$

$$\mathcal{O}_{He} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$

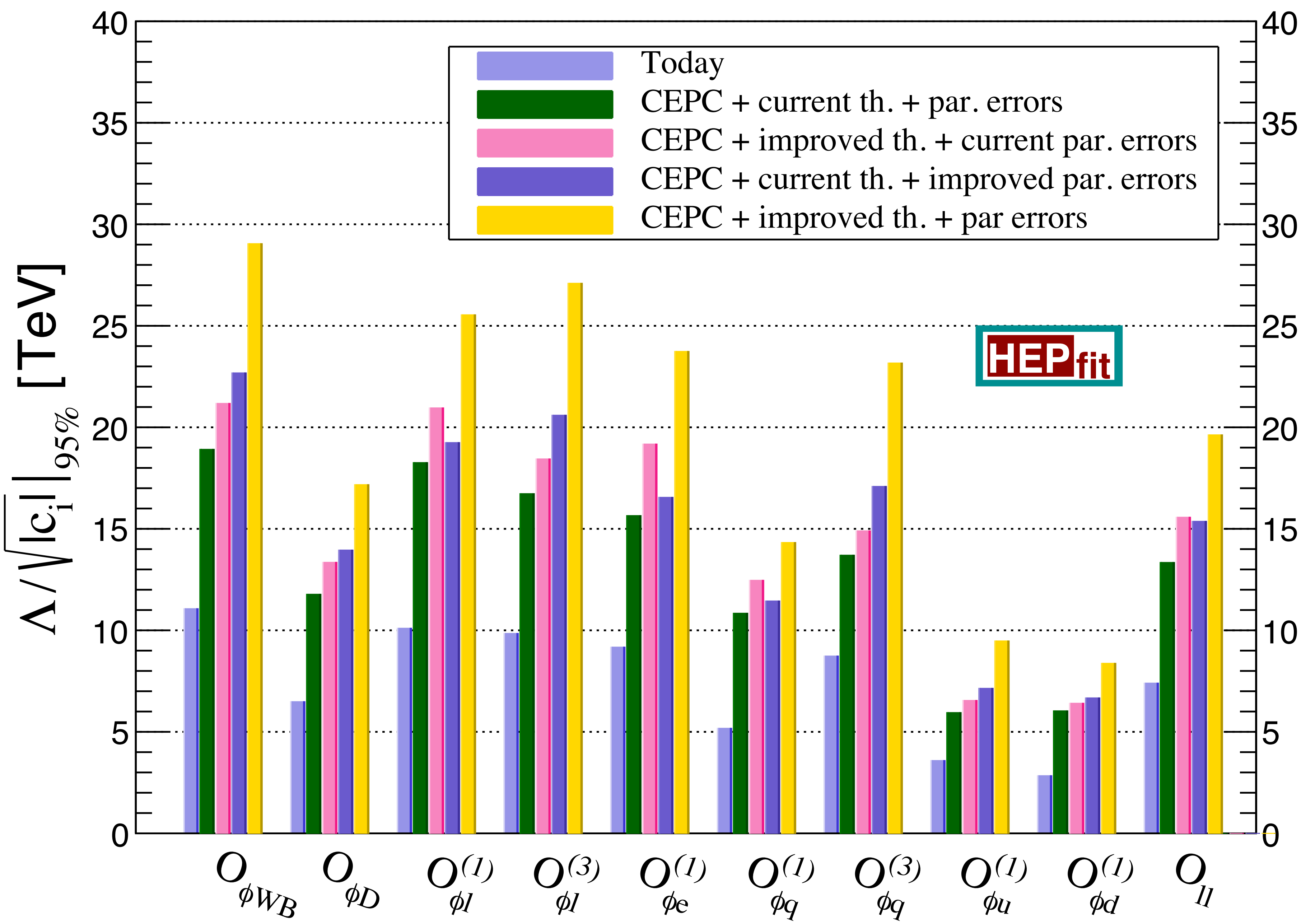
$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$$

$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$$

$\mathcal{O}_{He}$, $\mathcal{O}_{Hu}$, $\mathcal{O}_{Hd}$ → Right-handed $Zf\bar{f}$

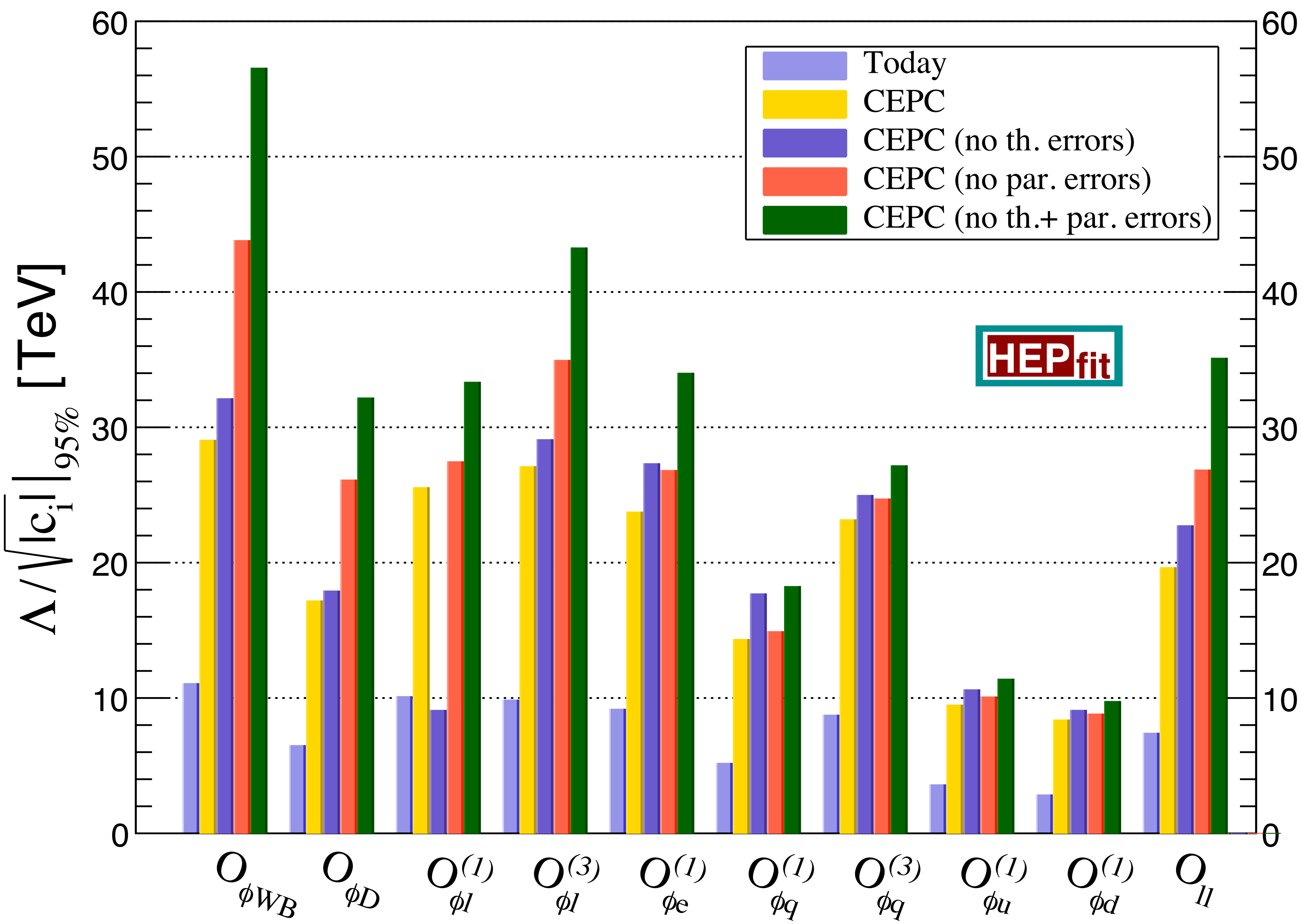
- There are two flat directions in the fit. *See, e.g., Han & Skiba (05)*
- switch on one operator at a time

Expected sensitivities at CEPC



- Improvements of th. and par. errors are highly desirable.
- NP scale > 3 to 10 TeV ⇨ > 8 to 29 TeV

Ultimate sensitivities at CEPC



- "CEPC" = "CEPC + improved th. + par. errors" in the previous slide.
- "CEPC" sensitivity is limited somewhat by the precision of m_t .

Satoshi Mishima (KEK)

Summary

- The current EW precision fit shows a good agreement with the SM predictions at the 2-loop level, and gives strong constraints on NP at the TeV scale.
- We have investigated CEPC sensitivities to NP:

$$\boldsymbol{\Delta S,\ \Delta T \sim 0.01}$$

$$\boldsymbol{\Delta(\delta g^{b}_{R,L}) \sim 10^{-4}}$$

$$\boldsymbol{\Lambda/\sqrt{|c_i|} > 8 \text{ to } 29\,\mathrm{TeV}}$$

- To achieve these precisions, the reduction of the theoretical uncertainties are highly desirable.
- We will update our fits with the latest CEPC errors in CDR.

Satoshi Mishima (KEK)