Constraints on new physics from EW precision and Higgs data

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PPP11, Tamkang University, May 15, 2015

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, 08004 (2013)

+ M. Pierini, L. Reina, Contribution to ICHEP2014 [arXiv:1410.6940]

+ J. de Blas, D. Ghosh, Contribution to ICHEP2014 [arXiv:1410.4204]

and works in progress …

Outline

1. Introduction

   a global fitting project

2. Electroweak precision fit
3. Constraints on the dim-6 Lagrangian

   EW precision observables + Higgs-boson signal strengths

4. Summary

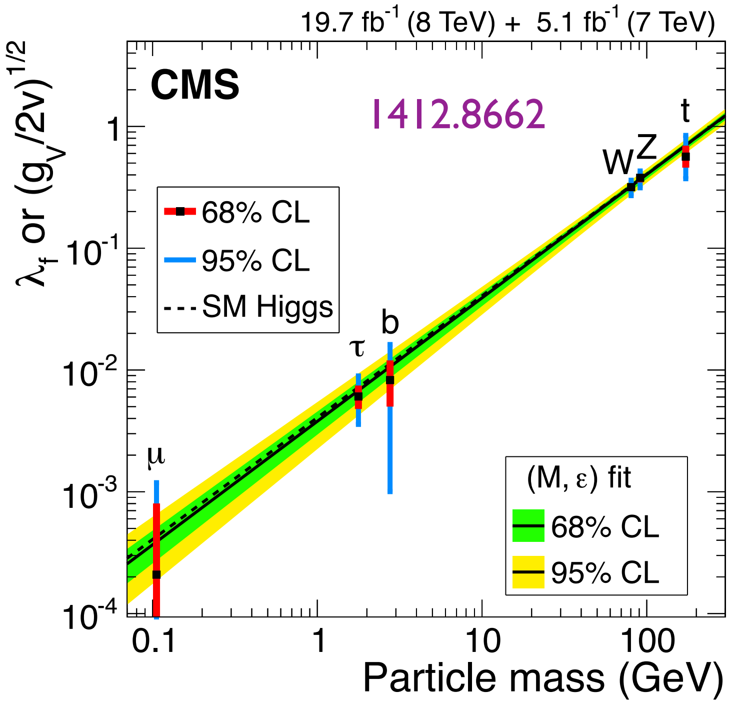
1. Introduction

- In 2012, the Higgs boson, which had been the last missing piece of the SM, was finally discovered at the LHC!

- It looks very much like the SM Higgs!

$$m_H \approx 125\ \mathrm{GeV}$$

$$J^P = 0^+$$



- However the SM is not satisfactory:

  finite neutrino masses, origins of the gauge and flavor structures, cosmological problems (dark matter, baryon asymmetry, inflation, dark energy), quantum gravity, naturalness, …

- But, no NP particle has been found so far at the LHC!

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Indirect searches for NP

- **Indirect searches are as relevant as ever after the LHC 7-8 TeV run.**

- Historically, indirect hints to unobserved heavy particles were obtained from low-energy experiments:

  e.g., the existence of charm quark from kaon decays,
  the heavy top mass from B-Bbar oscillation,
  the Higgs mass from the EW precision fit, …

- We would like to investigate the interplay of direct and indirect searches in the light of experimental data available currently and in the forthcoming years:

  LHC run2 (2015-), Belle-II (2018-), other flavor factories

“*SusyFit*” project

supported in part by erc

- We have been developing a computational framework to calculate various observables in the SM or in its extensions, and to constrain their parameter space.

“*SusyFit*”

A temporary name, waiting for a better one,
since we consider not only SUSY.

- Other developers:

Rome: Shehu S. AbdusSalam, Jorge de Blas, Debtosh Chowdhury, Otto Eberhardt, Marco Fedele, Enrico Franco, Ayan Paul, Luca Silvestrini
Rome Tre: Marco Ciuchini
ICTP/SISSA: Giovanni Grilli di Cortona, Ivan Girardi, Mauro Valli
Weizmann: Diptimoy Ghosh
Florida State U.: Laura Reina
Caltech: Maurizio Pierini (CMS)

“*SusyFit*” codes

- ***SusyFit*** is written in C++, supporting MPI parallelization.
- ***SusyFit*** will be made available to the public under GPL.

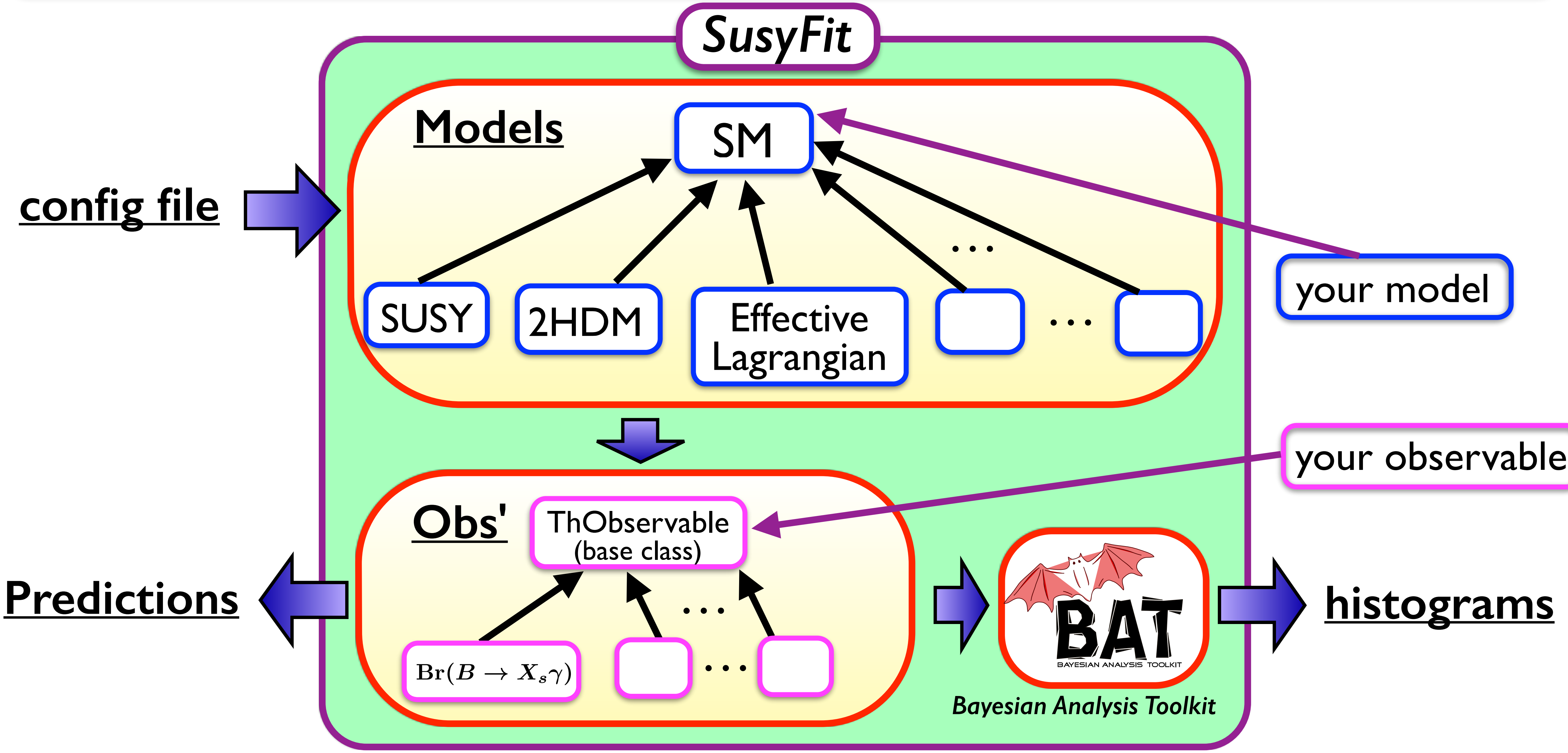
  Working developer versions are always available through ***github***
  (requires ***NetBeans IDE***).

- Dependencies: ROOT, GSL, Boost libraries, and
  Bayesian Analysis Toolkit (BAT).

  Beaujean, Caldwell, Greenwald, Kollar & Kroninger

- The first public release will be made available soon.

What can be done with “*SusyFit*” ?



- a stand-alone program to perform a Bayesian statistical analysis.
- alternatively, a library to compute observables in a given model.
- add your favorite models and observables as external modules.

Models

- Each ***model*** class contains the definitions of parameters, effective couplings (Wilson coefficients), RGEs, etc.

  - Standard Model (tested)
  - general MSSM (SLHA2 compatible, under testing)

    including MFV, pMSSM, …

    (*FeynHiggs* is used to compute Higgs masses, etc.)

  - Two-Higgs-doublet models (under construction)
  - Some NP extensions for model-independent studies of EW and Higgs (tested)

    dim-6 operators, oblique parameters, etc.

Observables

- ***Observables*** are computed from the parameters, the effective couplings and so on that are defined in each model class.

- EW precision observables (tested)

$$M_W,\ \Gamma_W,\ \Gamma_Z,\ \sigma_h^0,\ \sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had}),\ P_\tau^{\rm pol},\ \mathcal{A}_f,\ A_{\rm FB}^{0,f},\ R_f^0$$
$$\text{for}\ \ f=\ell, c, b$$

- Higgs-boson signal strengths (tested)

$$H\to\gamma\gamma,\ ZZ,\ WW,\ \tau^+\tau^-,\ b\bar{b}\ \ \text{for different categories}$$

- LEP2 two-fermion processes (in progress/testing)

$$\sigma\ \text{and}\ A_{\rm FB}\ \ \text{for}\ e^+e^-\to e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ c\bar{c},\ b\bar{b}$$

- Flavor observables ⇒ next slide

Flavor observables

- **UT-analysis observables:** (tested against UTfit)

  UT angles, $\Delta F = 2$ amplitudes, $B \to \tau\nu$, CKM elements

- **Rare decays:**

  $B \to X_s\gamma$, $B \to K^*\gamma$ (in progress)

  $B \to X_s\ell^+\ell^-$, $B \to K\ell^+\ell^-$ (in progress) , $B \to K^*\ell^+\ell^-$

  $B_{s,d} \to \mu^+\mu^-$

  $K \to \pi\nu\bar{\nu}$ (in progress)

  $K \to \mu^+\mu^-$ (in progress)

  $\tau \to \mu\gamma$, $\tau \to 3\ell$ (+other LFV processes, in progress)

- **Non-leptonic decays:**

  $B \to PP$, PV (in progress)

  ϵ'/ϵ (in progress)

Our tool will be used to contribute to the joint theory-experiment activity "*B2TiP*" (Belle II-Theory Interface Platform)
https://belle2.cc.kek.jp/~twiki/bin/view/B2TiP

Belle II

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In the rest of the talk, I will present a part of the fit results obtained with ***SusyFit*** :

- EW precision fit (SM, model-independent NP)

EW precision observables (EWPO)

- Constraints on the dimension-six effective Lagrangian

EWPO + Higgs signal strengths

2. Electroweak precision fit

M. Ciuchini, E. Franco, S.M. & L. Silvestrini, JHEP 08, 106 (2013);
+ M. Pierini and L. Reina, in preparation

EW precision physics

- Electroweak precision observables (EWPO) offer a very powerful handle on the mechanism of EWSB and allow us to strongly constrain NP models relevant to solve the naturalness (hierarchy) problem.
- Qualitative change: The Higgs mass has been measured.

  ⇨ No free SM parameter in the fit

- The precise measurements of the W and top masses at the Tevatron/LHC improve the power of the EW fit.
- Theoretical calculations of higher-order corrections in the SM have been improved in recent years.

EW precision observables (EWPO)

$M_W,\ \Gamma_W$ and 13 Z-pole observables
(LEP2/Tevatron) (LEP/SLD)

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

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

$$\left.\begin{array}{ll} A_{\mathrm{LR}}^{0,f} = \mathcal{A}_f = \dfrac{2\,\mathrm{Re}\left(g_V^f/g_A^f\right)}{1 + \left[\mathrm{Re}\left(g_V^f/g_A^f\right)\right]^2} & A_{\mathrm{FB}}^{0,f} = \dfrac{3}{4}\mathcal{A}_e \mathcal{A}_f \qquad (f = \ell, c, b) \\ P_\tau^{\mathrm{pol}} = \mathcal{A}_\tau & \sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = \dfrac{1}{4|Q_\ell|}\left[1 - \mathrm{Re}\left(\dfrac{g_V^\ell}{g_A^\ell}\right)\right] \end{array}\right\} g_V^f/g_A^f$$

$$\left.\begin{array}{l} \Gamma_f = \Gamma(Z \to f\bar{f}) \propto \left|g_A^f\right|^2 \left[\left|\dfrac{g_V^f}{g_A^f}\right|^2 R_V^f + R_A^f\right] \\ \Rightarrow\ \Gamma_Z,\ \sigma_h^0 = \dfrac{12\pi}{M_Z^2}\dfrac{\Gamma_e \Gamma_h}{\Gamma_Z^2},\ R_\ell^0 = \dfrac{\Gamma_h}{\Gamma_\ell},\ R_{c,b}^0 = \dfrac{\Gamma_{c,b}}{\Gamma_h} \end{array}\right\} g_V^f,\ g_A^f$$

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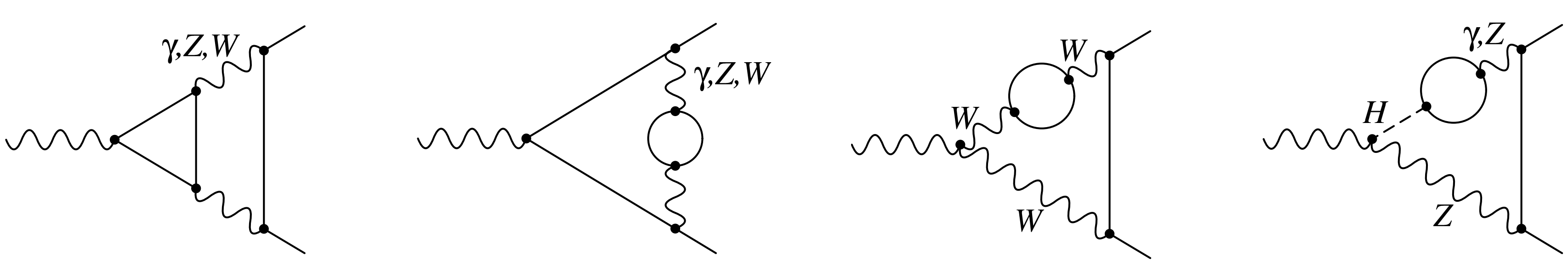
Theoretical status

- Mw has been calculated with full EW two-loop and leading higher-order contributions. *Awramik, Czakon, Freitas & Weiglein (04)*
- $\sin^2\theta^f_{\mathrm{eff}}$ have been calculated with full EW two-loop (bosonic is missing for f=b) and leading higher-order contributions. *Awramik, Czakon & Freitas (06); Awramik, Czakon, Freitas & Kniehl (09)*
- Full fermionic EW two-loop corrections to the Z-boson partial widths have been calculated recently. *Freitas & Huang (12); Freitas (13); Freitas (14)*



- We use the formulae calculated in the on-shell scheme.

See also Sirlin; Marciano&Sirlin; Bardin et al; Djouadi&Verzegnassi; Djouadi; Kniehl; Halzen&Kniehl; Kniehl&Sirlin; Barbieri et al; Fleischer et al; Djouadi&Gambino; Degrassi et al; Avdeev et al; Chetyrkin et al; Freitas et al; Awramik&Czakon; Onishchenko&Veretin; Van der Bij et al; Faisst et al; Awramik et al, and many other works

Theoretical status

A. Freitas, 1406.6980

	M_W	Γ_Z	σ^0_{had}	R_b	$\sin^2\theta^{\ell}_{\mathrm{eff}}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

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

EW precision fit

- Erler et al. (for PDG) 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

- Many other groups with ZFITTER http://zfitter.com

  on-shell scheme

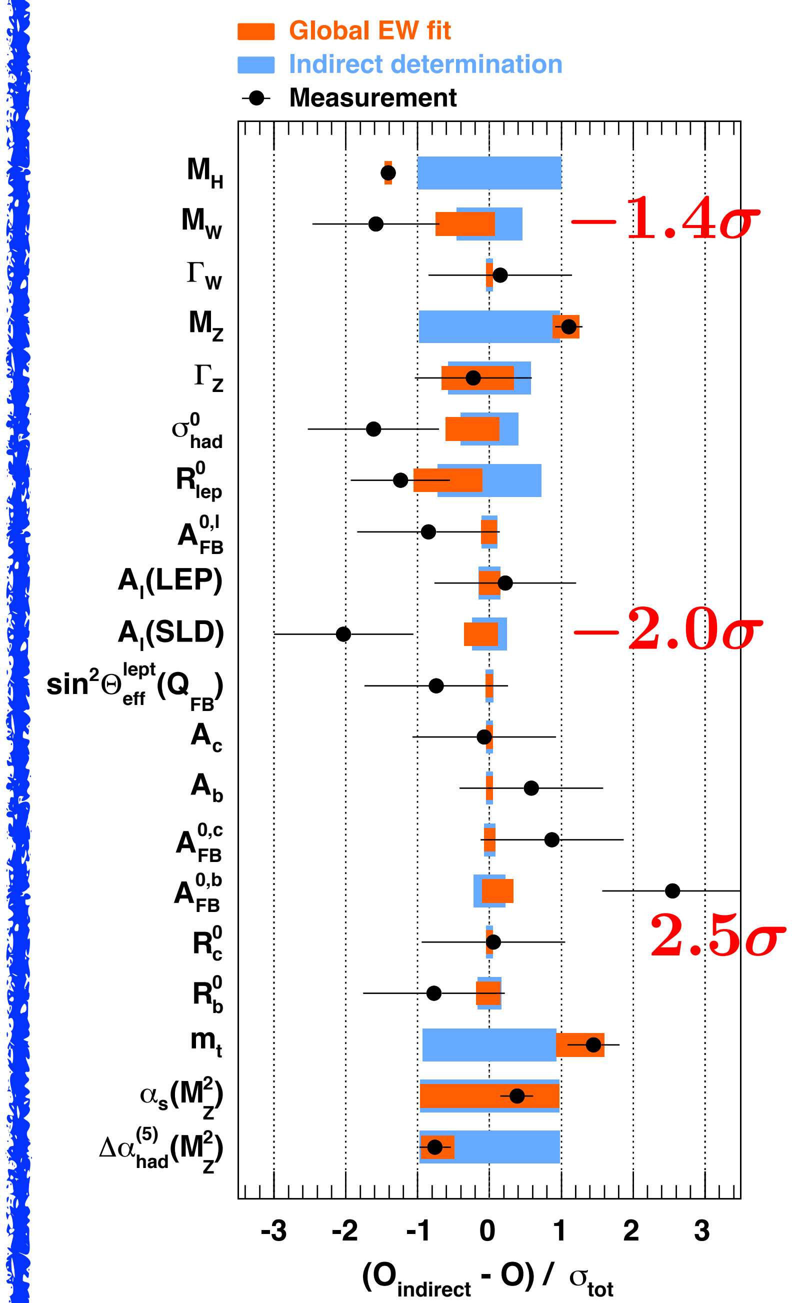
- Our group *M. Ciuchini, E. Franco, S.M., L. Silvestrini and others …*

  on-shell scheme & Bayesian

SM fit

	Data	Fit	Indirect	Pull
$\alpha_s(M_Z^2)$	0.1185 ± 0.0005	0.1185 ± 0.0005	0.1185 ± 0.0028	$+0.0$
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02750 ± 0.00033	0.02741 ± 0.00026	0.02727 ± 0.00042	-0.4
M_Z [GeV]	91.1875 ± 0.0021	91.1879 ± 0.0020	91.198 ± 0.011	$+0.9$
m_t [GeV]	173.34 ± 0.76	173.6 ± 0.7	176.6 ± 2.5	$+1.2$
m_H [GeV]	125.5 ± 0.3	125.5 ± 0.3	99.9 ± 26.6	-0.8
M_W [GeV]	80.385 ± 0.015	80.367 ± 0.006	80.363 ± 0.007	-1.3
Γ_W [GeV]	2.085 ± 0.042	2.0892 ± 0.0005	2.0892 ± 0.0005	$+0.1$
Γ_Z [GeV]	2.4952 ± 0.0023	2.4945 ± 0.0004	2.4944 ± 0.0004	-0.3
σ_h^0 [nb]	41.540 ± 0.037	41.488 ± 0.003	41.488 ± 0.003	-1.4
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.23145 ± 0.00009	0.23144 ± 0.00009	-0.8
$P_\tau^{\rm pol}$	0.1465 ± 0.0033	0.1476 ± 0.0007	0.1477 ± 0.0007	$+0.3$
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.1476 ± 0.0007	0.1471 ± 0.0007	-1.9
$\mathcal{A}_c$	0.670 ± 0.027	0.6682 ± 0.0003	0.6682 ± 0.0003	-0.1
$\mathcal{A}_b$	0.923 ± 0.020	0.93466 ± 0.00006	0.93466 ± 0.00006	$+0.6$
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.0163 ± 0.0002	0.0163 ± 0.0002	-0.8
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.0740 ± 0.0004	0.0740 ± 0.0004	$+0.9$
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016	0.1035 ± 0.0005	0.1039 ± 0.0005	$+2.8$
R_ℓ^0	20.767 ± 0.025	20.752 ± 0.003	20.752 ± 0.003	-0.6
R_c^0	0.1721 ± 0.0030	0.17224 ± 0.00001	0.17224 ± 0.00001	$+0.0$
R_b^0	0.21629 ± 0.00066	0.21578 ± 0.00003	0.21578 ± 0.00003	-0.8

Gfitter, 1407.3792



$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = 0.02757 \pm 0.00010$$

Indirect: determined w/o using the corresponding experimental information

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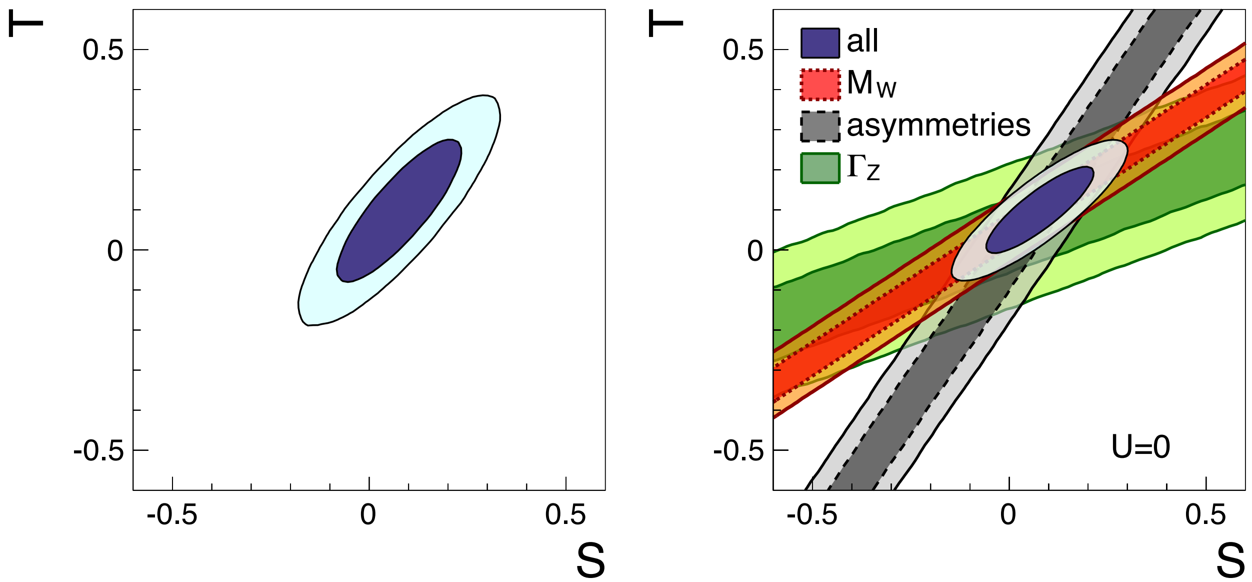
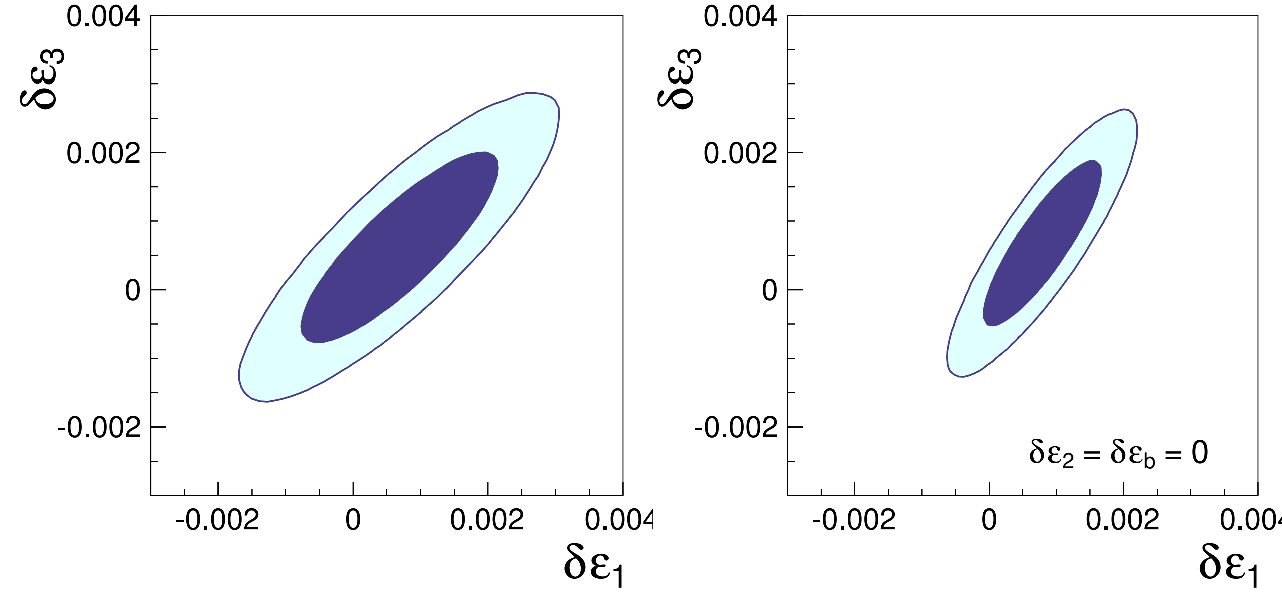
Model-independent constraints

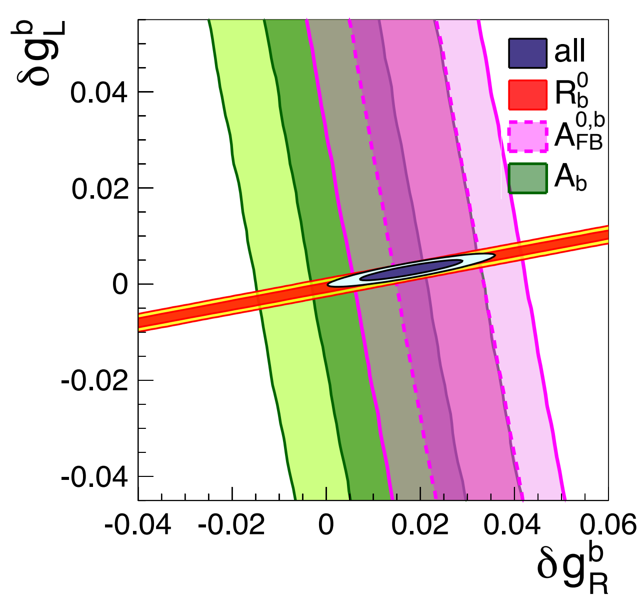
Oblique parameters



Epsilon parameters

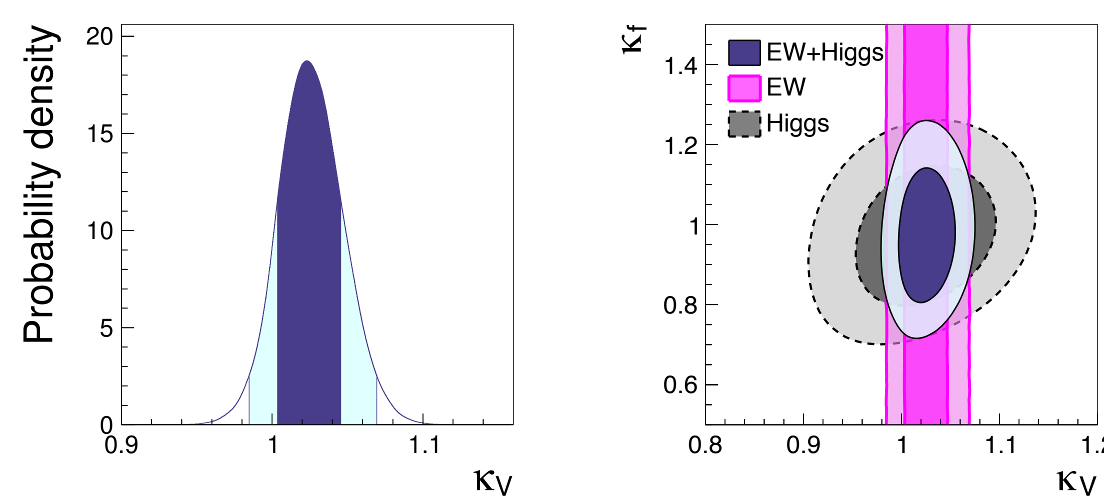


Zbb couplings



EW chiral Lagrangian

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2\kappa_V \frac{h}{v} + \cdots\right) + \cdots$$



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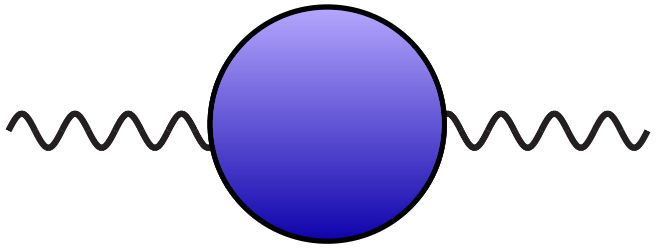
Oblique parameters

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

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



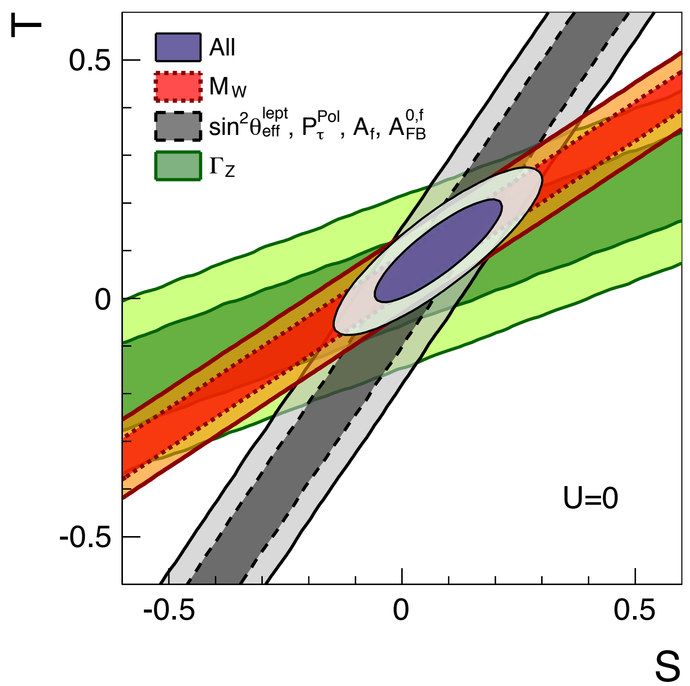
Kennedy & Lynn (89); Peskin & Takeuchi (90,92)

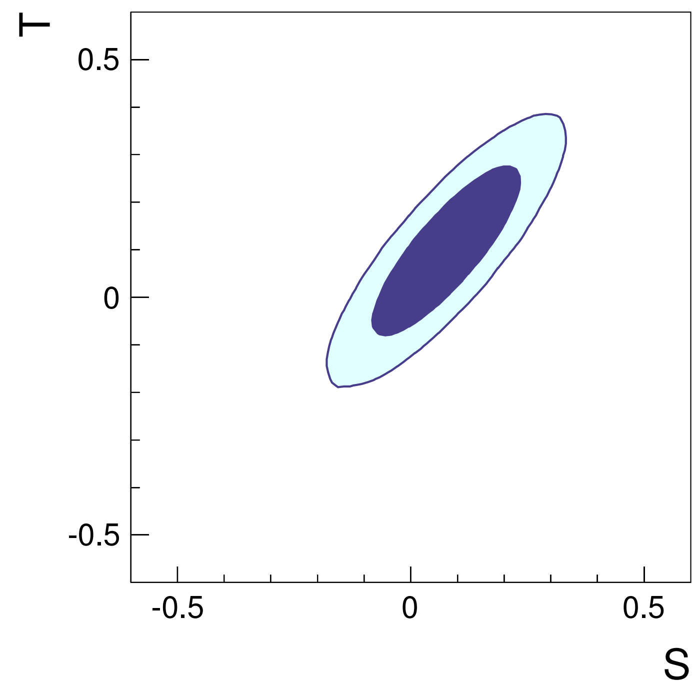
- EWPO depend on the three combinations:

$$\delta M_W,\ \delta\Gamma_W \propto -S + 2c_W^2\,T + \frac{(c_W^2 - s_W^2)\,U}{2s_W^2}$$
$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\,S + (63 - 126s_W^2 - 40s_W^4)\,T$$
$$\text{others} \propto S - 4c_W^2 s_W^2\,T$$

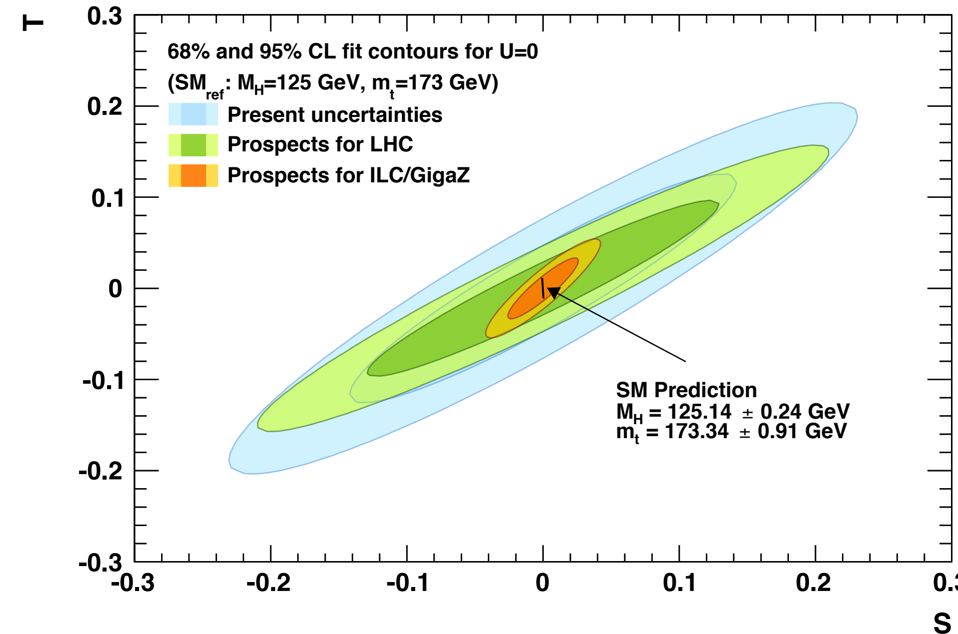
Constraints on the oblique parameters

68% & 95%





Gfitter, 1407.3792



	Fit result	Correlations	
S	0.08 ± 0.09	1.00	
T	0.10 ± 0.07	0.87	1.00

	Fit result	Correlations		
S	0.08 ± 0.10	1.00		
T	0.10 ± 0.12	0.85	1.00	
U	0.00 ± 0.09	-0.49	-0.79	1.00

	Fit result	Correlations	
S	0.06 ± 0.09	1.00	
T	0.10 ± 0.07	0.91	1.00

⇨ No evidence for NP!

Epsilon parameters

Altarelli et al. (91,92,93)

$$\epsilon_1 = \Delta\rho'$$

$$\epsilon_2 = c_0^2\Delta\rho' + \frac{s_0^2}{c_0^2 - s_0^2}\Delta r_W - 2s_0^2\Delta\kappa'$$

$$\epsilon_3 = c_0^2\Delta\rho' + (c_0^2 - s_0^2)\Delta\kappa'$$

and ϵ_b

$$s_W^2 c_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_\mu M_Z^2(1 - \Delta r_W)}$$

$$\sqrt{\mathrm{Re}\,\rho_Z^e} = 1 + \frac{\Delta\rho'}{2}$$

$$\sin^2\theta_{\mathrm{eff}}^e = (1 + \Delta\kappa')\, s_0^2$$

$$s_0^2\, c_0^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}G_\mu M_Z^2}$$

- ϵ_i involve the oblique corrections beyond S, T and U.

i.e., V, W, X, Y

$$\Pi_{VV'}(q^2) \simeq \Pi_{VV'}(0) + q^2\,\Pi'_{VV'}(0) + \frac{(q^2)^2}{2!}\,\Pi''_{VV'}(0) + \cdots$$

3 parameters

$VV' = \{WW, ZZ, Z\gamma, \gamma\gamma\}$

7 parameters

3 are absorbed in g, g', v

$\Pi_{\gamma\gamma}(0) = \Pi_{Z\gamma}(0) = 0$

- Unlike STU, ϵ_i involve non-oblique vertex corrections.
- Moreover, ϵ_i also involve SM(top/Higgs) contributions.

$$\Rightarrow \quad \boxed{\delta\epsilon_i = \epsilon_i - \epsilon_i^{\mathrm{SM}}}$$

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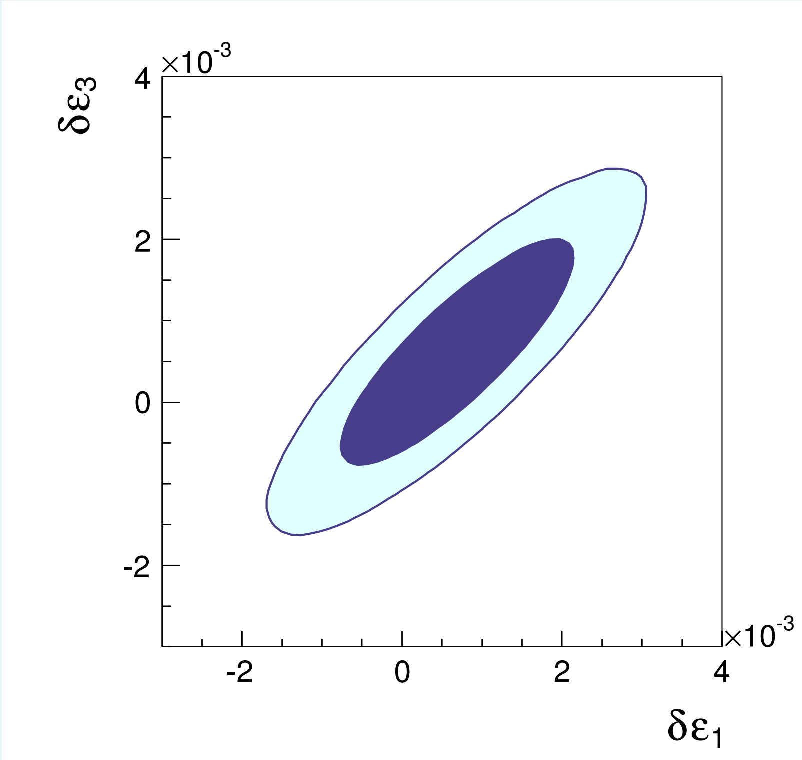
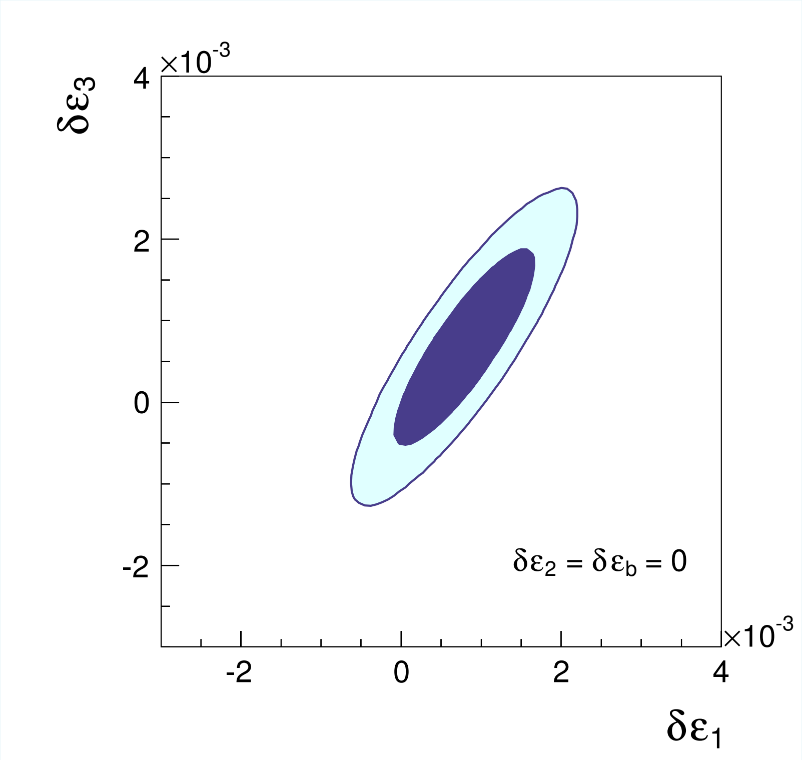
Modified epsilon parameters

$$\delta\epsilon_i = \epsilon_i - \epsilon_i^{\mathrm{SM}}$$





	Fit result	Correlations			
$\delta\epsilon_1$	0.0007 ± 0.0010	1.00			
$\delta\epsilon_2$	-0.0001 ± 0.0009	0.80	1.00		
$\delta\epsilon_3$	0.0006 ± 0.0009	0.86	0.51	1.00	
$\delta\epsilon_b$	0.0003 ± 0.0013	-0.33	-0.32	-0.22	1.00

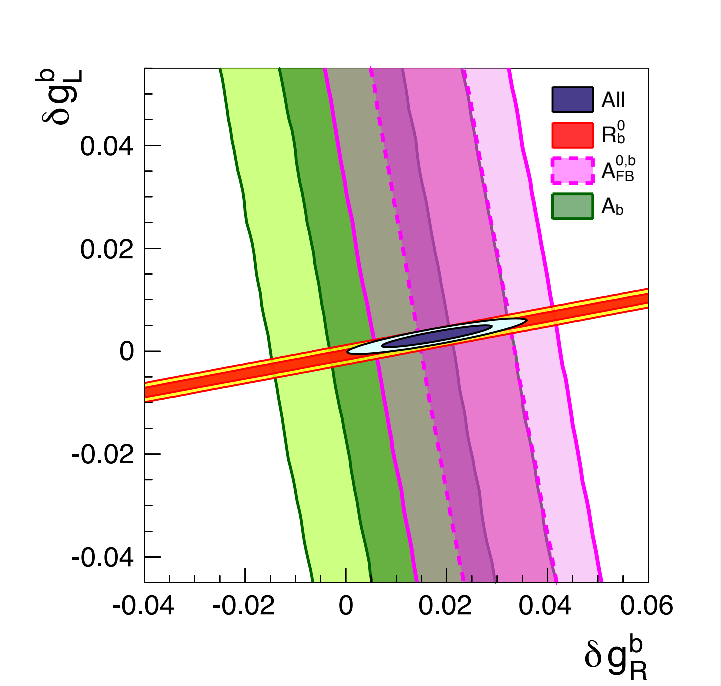
	Fit result	Correlations	
$\delta\epsilon_1$	0.0008 ± 0.0006	1.00	
$\delta\epsilon_3$	0.0007 ± 0.0008	0.87	1.00

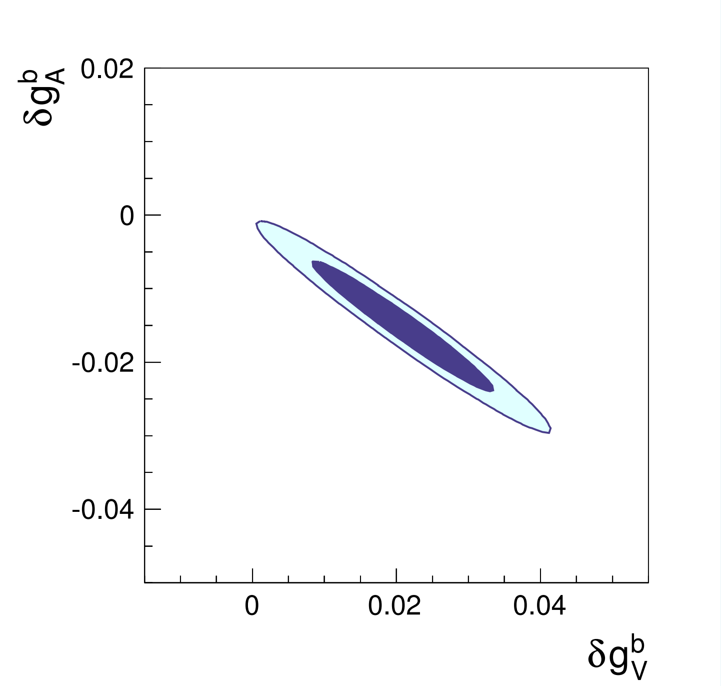
$Zb\bar{b}$ couplings

- Four solutions from Z-pole data, while two of them are disfavored by off Z-pole data for AFBb.

Choudhury et al. (02)

- The solution closer to the SM:





$$g_i^b = (g_i^b)_{\rm SM} + \delta g_i^b$$

	Fit result	Correlations	
δg_R^b	0.018 ± 0.007	1.00	
δg_L^b	0.0029 ± 0.0014	0.90	1.00
δg_V^b	0.021 ± 0.008	1.00	
δg_A^b	-0.015 ± 0.006	-0.98	1.00

See also Batell et al. (13)

- Deviation from the SM due to $A_{FB}^{0,b}$

EW chiral Lagrangian

- No new state below cutoff + custodial symmetry:

$$\mathcal{L} = \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2\kappa_V \frac{h}{v} + \cdots\right) + \cdots$$

Σ : Goldstone bosons

$\kappa_V = 1$ in the SM

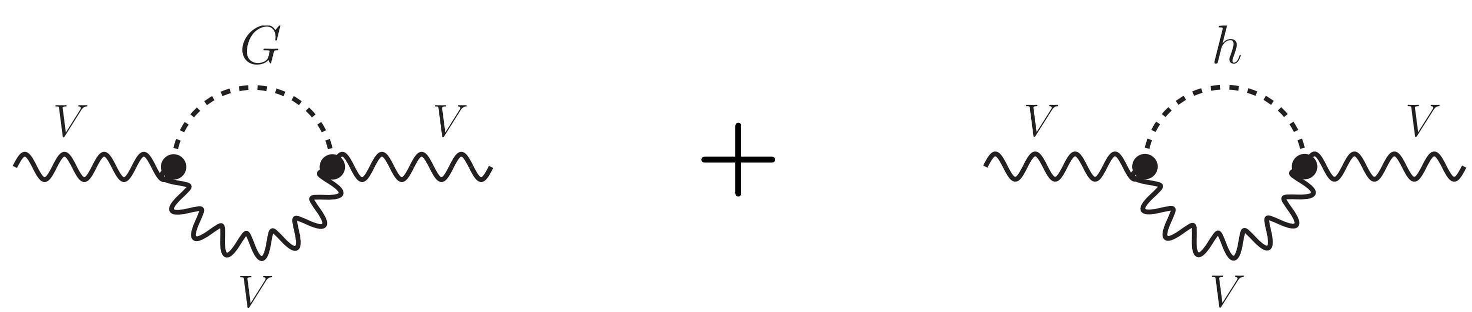
➡ The HVV coupling contributes to S and T at one-loop.

Barberi, Bellazzini, Rychkov & Varagnolo (07)

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right)$$

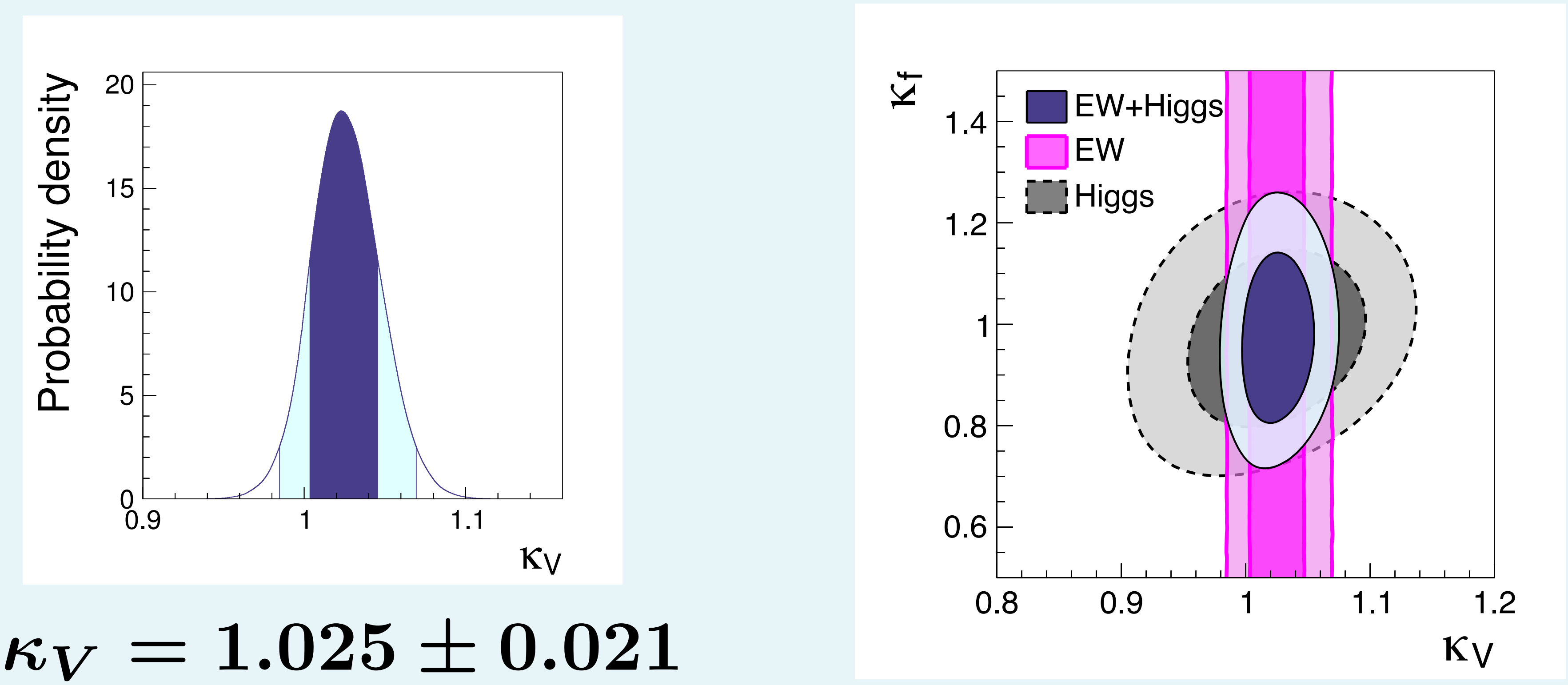
$$T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_h^2}\right)$$

$$\Lambda = 4\pi v/\sqrt{|1-\kappa_V^2|}$$



$$\ln(\Lambda^2/M_Z^2) - \kappa_V^2 \ln(\Lambda^2/m_h^2)$$

EW chiral Lagrangian



$\kappa_V = 1.025 \pm 0.021$

- EWPO constraint on Kv is stronger than Higgs one, but no constraint on Kf.
- $\kappa_V > 1$ ➡ WLWL scattering is dominated by isospin 2 channel

$$1 - \kappa_V^2 = \frac{v^2}{6\pi} \int_0^\infty \frac{ds}{s} \left(2\sigma_{I=0}^{\mathrm{tot}}(s) + 3\sigma_{I=1}^{\mathrm{tot}}(s) - 5\sigma_{I=2}^{\mathrm{tot}}(s) \right)$$

Falkowski, Rychkov & Urbano (12)
Bellazzini, Martucci & Torre (14)

- $\Lambda \gtrsim 18\ \mathrm{TeV}\ @\,95\%\ \ \mathrm{for}\ \kappa_V < 1$

Composite Higgs models

- Composite Higgs models typically generate $\kappa_V < 1$.

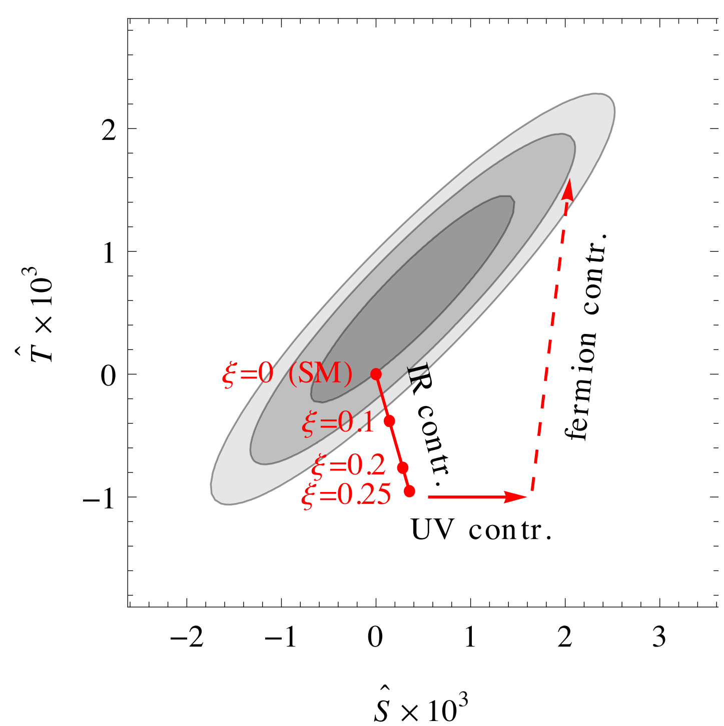
  e.g. Minimal Composite Higgs Models (MCHM) based on SO(5)/SO(4)

  Agashe, Contino & Pomarol (05)

$$\kappa_V = \sqrt{1-\xi} \qquad \xi = \left(\frac{v}{f}\right)^2$$

f : scale of compositeness

- Extra contributions to S and T are required to fix the EW fit under $\kappa_V < 1$.



Grojean et al. (13)

IR contribution

+

UV cont' from heavy vector resonances

+

Fermionic resonances

3. Constraints on the dim-6 Lagrangian

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Effective field theory approach

- We have found only a Higgs and no other new particle so far at the LHC.
- Experimental data suggest that the NP scale is well above the EW scale.
- We consider an effective theory built exclusively from the SM fields with the SM gauge symmetries.

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

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

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

Effective field theory approach

Pros:

- Model-independent
- 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.

Dim-6 operators

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

- The dim-5 operator (LH)(LH) violates lepton number.
- Dim-6 operators contribute to EW/Higgs physics.

Buchmuller & Wyler, NPB268, 621(1986)

A list of the dim-6 operators was presented.

80 op's (for one generation) that respect B/L.

Grzadkowski, Iskrzynski, Misiak & Rosiek, JHEP10, 085 (2010)

S-matrix elements have no contribution from particular combinations of operators, which vanish by the EOMs.

Politzer (80)

59 independent op's

Complete list of the dim-6 operators

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

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

EDMs, g-2,etc.

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

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

Grzadkowski, Iskrzynski, Misiak & Rosiek (10)

- Consider 18 CP-even op's for EW and Higgs physics.
- 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-6 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)

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

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

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

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

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

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

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

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

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

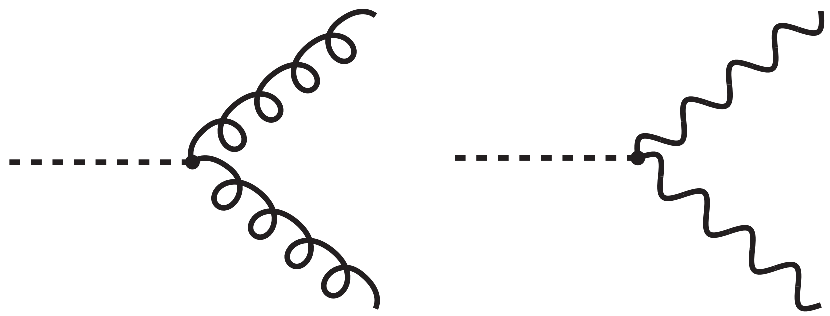
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R\gamma^\mu d_R)$$

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

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

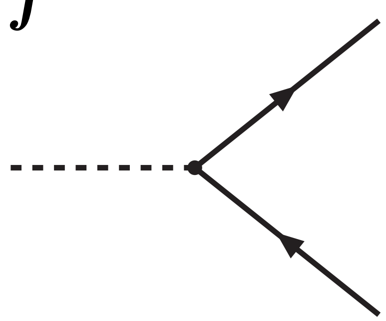
Dim-6 contributions to Higgs physics

hVV



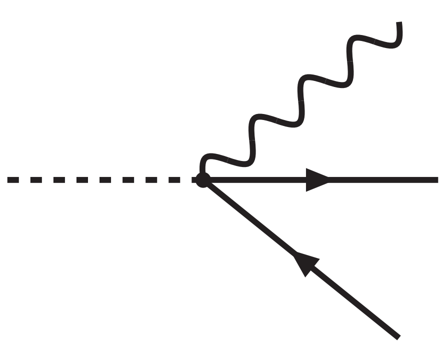
$$\begin{aligned}\mathcal{L}_{hVV} = &\left(\sqrt{2}\,G_F\right)^{1/2}\widehat{C}_{HG}\,G^A_{\mu\nu}G^{A\mu\nu}h\\
&+2\left(\sqrt{2}\,G_F\right)^{1/2}M_W^2\left(1-\frac{1}{4}\widehat{C}_{HD}+\widehat{C}_{H\Box}-\frac{1}{2}\delta_{G_F}\right)W^\dagger_\mu W^\mu h\\
&+2\left(\sqrt{2}\,G_F\right)^{1/2}\widehat{C}_{HW}\,W^{\mu\nu}W^\dagger_{\mu\nu}h\\
&+\left(\sqrt{2}\,G_F\right)^{1/2}M_Z^2\left(1+\frac{1}{4}\widehat{C}_{HD}+\widehat{C}_{H\Box}-\frac{1}{2}\delta_{G_F}\right)Z_\mu Z^\mu h\\
&+\left(\sqrt{2}\,G_F\right)^{1/2}\left(c_W^2\widehat{C}_{HW}+s_W^2\widehat{C}_{HB}+s_Wc_W\widehat{C}_{HWB}\right)Z_{\mu\nu}Z^{\mu\nu}h\\
&+\left(\sqrt{2}\,G_F\right)^{1/2}\left[2s_Wc_W\left(\widehat{C}_{HW}-\widehat{C}_{HB}\right)-(c_W^2-s_W^2)\widehat{C}_{HWB}\right]Z_{\mu\nu}F^{\mu\nu}h\\
&+\left(\sqrt{2}\,G_F\right)^{1/2}\left(s_W^2\widehat{C}_{HW}+c_W^2\widehat{C}_{HB}-s_Wc_W\widehat{C}_{HWB}\right)F_{\mu\nu}F^{\mu\nu}h\end{aligned}$$

$hf\bar{f}$



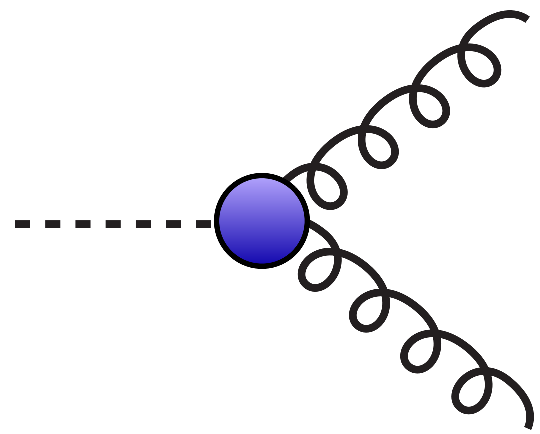
$$\mathcal{L}_{hf\bar{f}} = \left[-\left(\sqrt{2}G_F\right)^{1/2}m_f^p\,\delta_{pq}\left(1-\frac{1}{4}\widehat{C}_{HD}+\widehat{C}_{H\Box}-\frac{1}{2}\delta_{G_F}\right)+\frac{1}{\sqrt{2}}\widehat{C}^{\,pq}_{fH}\right]\bar{f}^p_L f^q_R h+\text{h.c.}$$

$hVq\bar{q}$



$$\begin{aligned}\mathcal{L}_{hVq\bar{q}} = &-\frac{2M_Z}{v^2}\left(\widehat{C}^{(1)}_{HQ}-\widehat{C}^{(3)}_{HQ}\right)Z_\mu(\overline{u}_L\,\gamma^\mu u_L)h-\frac{2M_Z}{v^2}\left(\widehat{C}^{(1)}_{HQ}+\widehat{C}^{(3)}_{HQ}\right)Z_\mu(\overline{d}_L\,\gamma^\mu d_L)h\\
&-\frac{2M_Z}{v^2}\,\widehat{C}_{Hu}Z^\mu(\overline{u}_R\gamma^\mu u_R)h-\frac{2M_Z}{v^2}\,\widehat{C}_{Hd}Z^\mu(\overline{d}_R\gamma^\mu d_R)h\\
&+\left[\frac{2\sqrt{2}M_Zc_W}{v^2}\,\widehat{C}^{(3)}_{HQ}W^+_\mu(\overline{u}_L\,\gamma^\mu d_L)h+\frac{\sqrt{2}M_Zc_W}{v^2}\,\widehat{C}_{Hud}W^+_\mu(\overline{u}_R\gamma^\mu d_R)h+\text{h.c.}\right]\end{aligned}$$

Effective hgg coupling



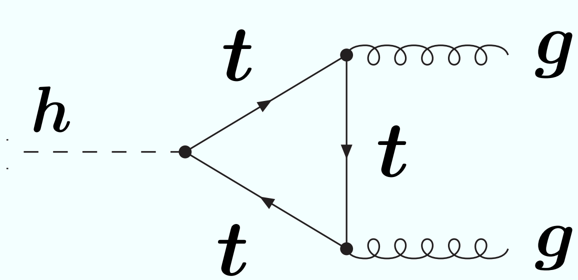
$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^* (H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$
$$\mathcal{O}^{(3)}_{HL} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L}\, \tau^I \gamma^\mu L)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{LL} = (\overline{L}\gamma_\mu L)(\overline{L}\gamma^\mu L)$$

$$\mathcal{L}_{hgg,\mathrm{eff}} = \left[g^{\mathrm{SM}}_{hgg,\mathrm{eff}} \left(1 - \frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box} - \frac{1}{2}\delta_{G_F} - \frac{v}{\sqrt{2}m_t}\widehat{C}_{tH} \right) + \frac{1}{v}\widehat{C}_{HG} \right] G^A_{\mu\nu} G^{A\mu\nu} h$$

SM coupling at one-loop

$$g^{\mathrm{SM}}_{hgg,\mathrm{eff}} = \frac{\alpha_s}{16\pi v} A^H_f (4m_t^2/m_h^2)$$

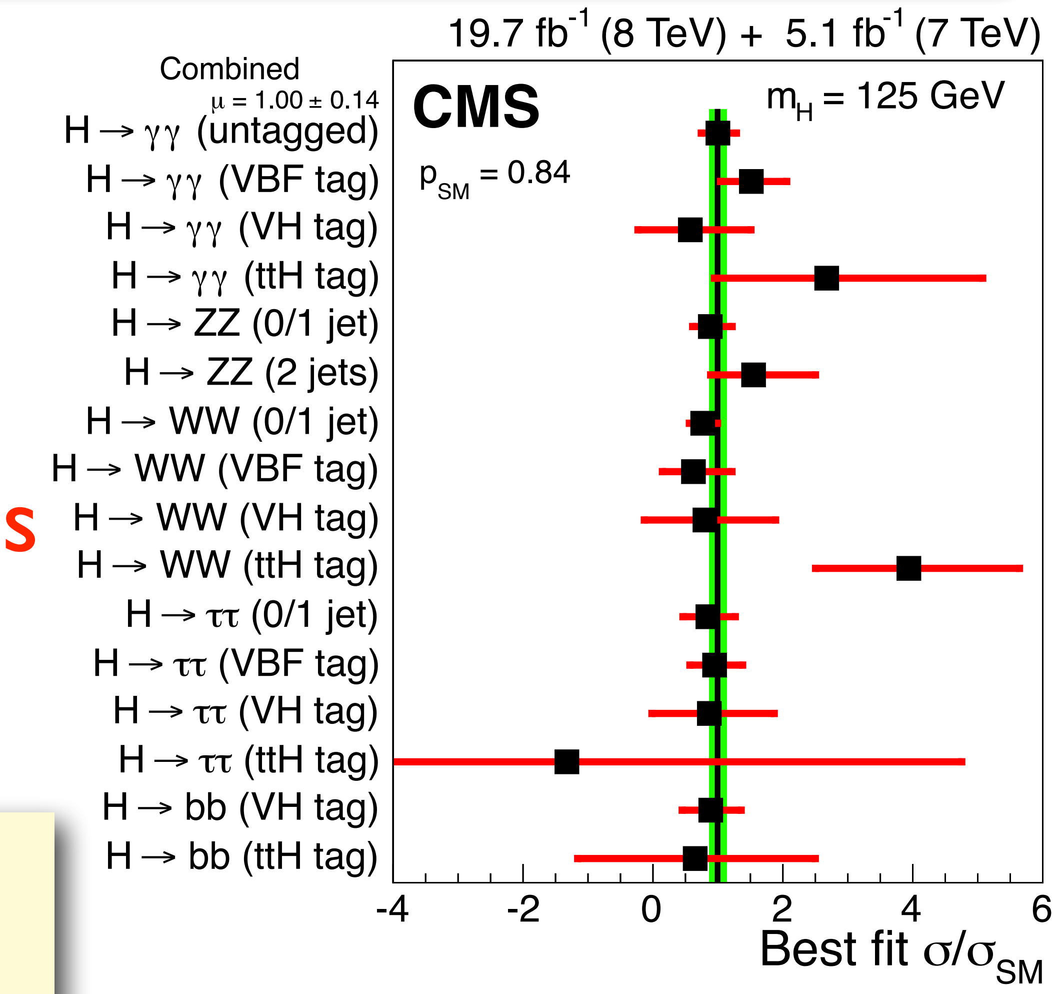
$$A^H_f(\tau) = 2\tau \left[1 + (1-\tau) \arcsin^2 \frac{1}{\sqrt{\tau}} \right]$$



- $hZ\gamma$ and $h\gamma\gamma$ are similar.

Higgs data

- We use the ATLAS/CMS (and CDF/D0) data for the Higgs signal strengths relative to the SM expectations, which are divided into different categories to improve sensitivity to each production mechanism



$$\mu = \frac{\sum_i \epsilon_i [\sigma \times \mathrm{Br}]_i}{\sum_j \epsilon_j^{\mathrm{SM}} [\sigma \times \mathrm{Br}]_j^{\mathrm{SM}}}$$

for one specific measurement

- We assume that the efficiencies of event selection are similar to those in the SM. *(This assumption is valid for small deviations from the SM couplings, which do not modify kinematic distributions significantly.)*

“The fits will be updated in our upcoming paper”

Fit results at 95% in units of $1/\Lambda^2\ \mathrm{TeV}^{-2}$

Coefficient	Only EW C_i/Λ^2 [TeV^{-2}] at 95%	Only Higgs C_i/Λ^2 [TeV^{-2}] at 95%	EW + Higgs C_i/Λ^2 [TeV^{-2}] at 95%
C_{HG}	—	[−0.0077, 0.0066]	[−0.0077, 0.0066]
C_{HW}	—	[−0.039, 0.012]	[−0.039, 0.012]
C_{HB}	—	[−0.011, 0.003]	[−0.011, 0.003]
C_{HWB}	[−0.0082, 0.0030]	[−0.006, 0.020]	[−0.0063, 0.0039]
C_{HD}	[−0.025, 0.004]	[−4.0, 1.4]	[−0.025, 0.004]
$C_{H\Box}$		[−1.2, 2.0]	[−1.2, 2.0]
$C_{HL}^{(1)}$	[−0.005, 0.012]	—	[−0.005, 0.012]
$C_{HL}^{(3)}$	[−0.010, 0.005]	[−1.2, 0.3]	[−0.010, 0.005]
C_{He}	[−0.015, 0.006]	—	[−0.015, 0.006]
$C_{HQ}^{(1)}$	[−0.026, 0.041]	[−28, 15]	[−0.026, 0.041]
$C_{HQ}^{(3)}$	[−0.011, 0.013]	[−0.6, 2.2]	[−0.011, 0.013]
C_{Hu}	[−0.067, 0.077]	[−5, 11]	[−0.067, 0.077]
C_{Hd}	[−0.14, 0.06]	[−33, 15]	[−0.14, 0.06]
C_{Hud}	—	—	—
C_{eH}	—	[−0.071, 0.024]	[−0.071, 0.024]
C_{uH}	—	[−0.50, 0.59]	[−0.50, 0.59]
C_{dH}	—	[−0.073, 0.078]	[−0.072, 0.078]
C_{LL}	[−0.007, 0.019]	[−0.7, 2.5]	[−0.007, 0.019]

$$
\begin{aligned}
\mathcal{O}_{HG} &= (H^\dagger H)G^A_{\mu\nu}G^{A\mu\nu}\\
\mathcal{O}_{HW} &= (H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu}\\
\mathcal{O}_{HB} &= (H^\dagger H)B_{\mu\nu}B^{\mu\nu}\\
\mathcal{O}_{HWB} &= (H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}\\
\mathcal{O}_{HD} &= (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)\\
\mathcal{O}_{H\Box} &= (H^\dagger H)\Box(H^\dagger H)\\
\mathcal{O}_{HL}^{(1)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)\\
\mathcal{O}_{HL}^{(3)} &= (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\tau^I\gamma^\mu L)\\
\mathcal{O}_{HQ}^{(1)} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)\\
\mathcal{O}_{HQ}^{(3)} &= (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\tau^I\gamma^\mu Q)\\
\mathcal{O}_{He} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)\\
\mathcal{O}_{Hu} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)\\
\mathcal{O}_{Hd} &= (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)\\
\mathcal{O}_{Hud} &= i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R\gamma^\mu d_R)\\
\mathcal{O}_{eH} &= (H^\dagger H)(\bar{L}\,e_R H)\\
\mathcal{O}_{uH} &= (H^\dagger H)(\bar{Q}\,u_R\widetilde{H})\\
\mathcal{O}_{dH} &= (H^\dagger H)(\bar{Q}\,d_R H)\\
\mathcal{O}_{LL} &= (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)
\end{aligned}
$$

$gg \to h$ (one-loop in the SM)

$$\mathcal{L}_{\rm NP} = \left(\frac{v}{\Lambda^2}C_{HG} + \cdots\right)G^A_{\mu\nu}G^{A\mu\nu}h$$

$h \to \gamma\gamma$ (one-loop in the SM)

$$\mathcal{L}_{\rm NP} = \frac{v}{\Lambda^2}(s_W^2 C_{HW} + c_W^2 C_{HB} - s_W c_W C_{HWB})F_{\mu\nu}F^{\mu\nu}h$$

$h \to f\bar{f}$ (suppressed by mf for light fermions in the SM) $\mathcal{L}_{\rm NP} = \frac{v^2}{\sqrt{2}\Lambda^2}C_{fH}\bar{f}_L f_R h + \text{h.c.}$

Satoshi Mishima (KIAS)

“The fits will be updated in our upcoming paper”

Lower bounds on the NP scale in TeV

Coefficient	Only EW Λ [TeV] $C_i=-1$	Only EW Λ [TeV] $C_i=1$	Only Higgs Λ [TeV] $C_i=-1$	Only Higgs Λ [TeV] $C_i=1$	EW + Higgs Λ [TeV] $C_i=-1$	EW + Higgs Λ [TeV] $C_i=1$
C_{HG}	—	—	11.4	12.3	11.4	12.3
C_{HW}	—	—	5.1	9.1	5.1	9.1
C_{HB}	—	—	9.6	17.2	9.6	17.2
C_{HWB}	11.1	18.4	12.5	7.1	12.6	15.9
C_{HD}	6.3	15.4	0.5	0.8	6.3	15.5
$C_{H\Box}$	—	—	0.9	0.7	0.9	0.7
$C_{HL}^{(1)}$	14.8	9.2	—	—	14.8	9.2
$C_{HL}^{(3)}$	9.8	14.8	0.9	1.7	9.8	14.9
C_{He}	8.2	12.8	—	—	8.2	12.8
$C_{HQ}^{(1)}$	6.2	5.0	0.2	0.3	6.2	5.0
$C_{HQ}^{(3)}$	9.6	8.7	1.3	0.7	9.7	8.7
C_{Hu}	3.9	3.6	0.4	0.3	3.9	3.6
C_{Hd}	2.7	4.1	0.2	0.3	2.7	4.1
C_{Hud}	—	—	—	—	—	—
C_{eH}	—	—	3.8	6.4	3.8	6.4
C_{uH}	—	—	1.4	1.3	1.4	1.3
C_{dH}	—	—	3.7	3.6	3.7	3.6
C_{LL}	12.0	7.3	1.2	0.6	12.0	7.3

$$\mathcal{O}_{HG} = (H^\dagger H)G^A_{\mu\nu}G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = (H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu}$$
$$\mathcal{O}_{HB} = (H^\dagger H)B_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HWB} = (H^\dagger\tau^I H)W^I_{\mu\nu}B^{\mu\nu}$$
$$\mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$$
$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$
$$\mathcal{O}_{HL}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$
$$\mathcal{O}_{HL}^{(3)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{L}\,\tau^I\gamma^\mu L)$$
$$\mathcal{O}_{HQ}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
$$\mathcal{O}_{HQ}^{(3)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{Q}\,\tau^I\gamma^\mu Q)$$
$$\mathcal{O}_{He} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_R\gamma^\mu e_R)$$
$$\mathcal{O}_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_R\gamma^\mu u_R)$$
$$\mathcal{O}_{Hd} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_R\gamma^\mu d_R)$$
$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\,e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\,u_R\widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\,d_R H)$$
$$\mathcal{O}_{LL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

EWPO and Higgs are complementary to each other.

Fits of multiple operators

- Adding more observables, one may perform a simultaneous fit of the multiple operators that are relevant to the processes under consideration, removing blind directions.

  EWPO

  Higgs-boson signal strengths

  WW productions at LEP2

  Di-boson production at the LHC

  Kinematic distributions in V+H production at Tevatron/LHC

See, e.g.,

J. Ellis, V. Sanz and T. You, JHEP 1407 (2014) 036 [arXiv:1404.3667];
JHEP 1503 (2015) 157 [arXiv:1410.7703]

A. Falkowski and F. Riva, JHEP 1502 (2015) 039 [arXiv:1411.0669]

4. Summary

- We have been developing the ***SusyFit*** framework for computing observables in given models and exploring their parameter space.
- We have studied the model-independent constraints on NP with the EW precision and Higgs data.
- The constraints from the EW precision and Higgs data are complementary to each other.
- **We will perform more physics analyses (incl. flavor, MSSM, etc.) with *SusyFit* !**

Satoshi Mishima (KIAS)

Backup

Statistical approaches

- Frequentist:

  model parameter: constant true value

  data: random variables

  68% confidence interval of a parameter:

  The interval covers the true value with a probability of 68%.

- Bayesian:

$$P(\vec{\theta}\,|\,\mathrm{Data}) = \frac{L(\mathrm{Data}\,|\,\vec{\theta})\,\pi(\vec{\theta})}{\int d\vec{\theta}'\,L(\mathrm{Data}\,|\,\vec{\theta}')\,\pi(\vec{\theta}')}$$

  model parameter: random variable

  68% credible interval:

  prior p.d.f. for parameters $\vec{\theta}$

  The parameter is in the interval with a probability of 68%.

Configuration file

- A *configuration file* specifies the model, the constraints on model parameters and observables used in the fit.

```
StandardModel

ModelParameter  mtop     173.2    0.9      0.
ModelParameter  mHl      125.6    0.3      0.

      :

Observable  Mw       Mw       M_{W}        80.3290 80.4064  MCMC weight  80.385 0.015 0.
Observable  GammaW   GammaW   #Gamma_{W}   2.08569 2.09249  MCMC weight  2.085  0.042 0.

      :
```

output ranges *data*

Hadronic corrections to the EM coupling

- We adopt a conservative value:

$$\Delta\alpha^{(5)}_{\rm had}(M_Z^2) = 0.02750 \pm 0.00033$$

measured with inclusive processes.

Burkhardt & Pietrzyk (11)
(see also Davier et al(11); Hagiwara et al(11) ; Jegerlehner(11))

Note: Smaller uncertainty has been obtained if using exclusive processes with pQCD:

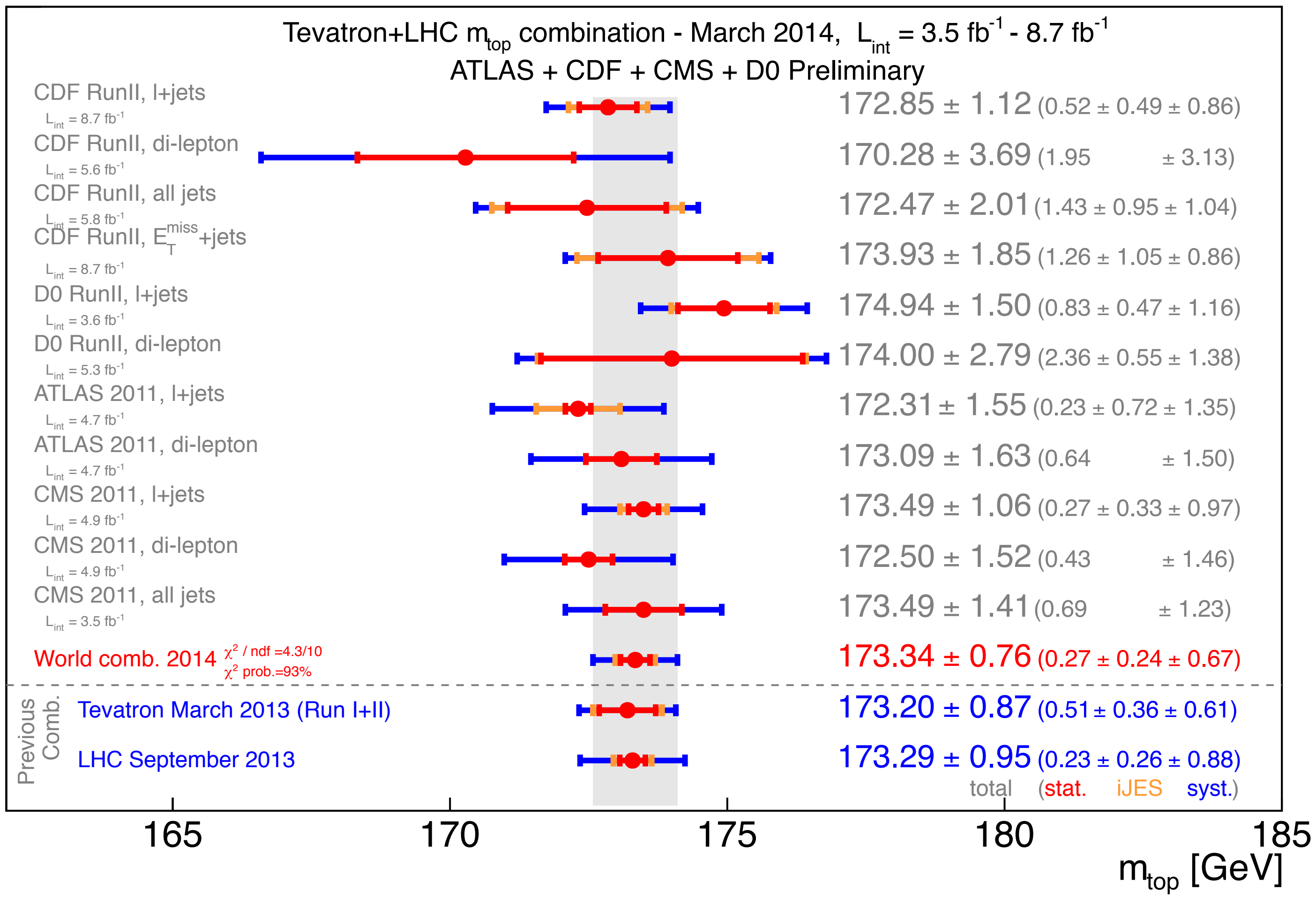
$$\delta\left(\Delta\alpha^{(5)}_{\rm had}(M_Z^2)\right) \sim \pm 0.00010$$

but discrepancy has been observed between inclusive and exclusive in low-energy data.

Measurements of the top pole mass

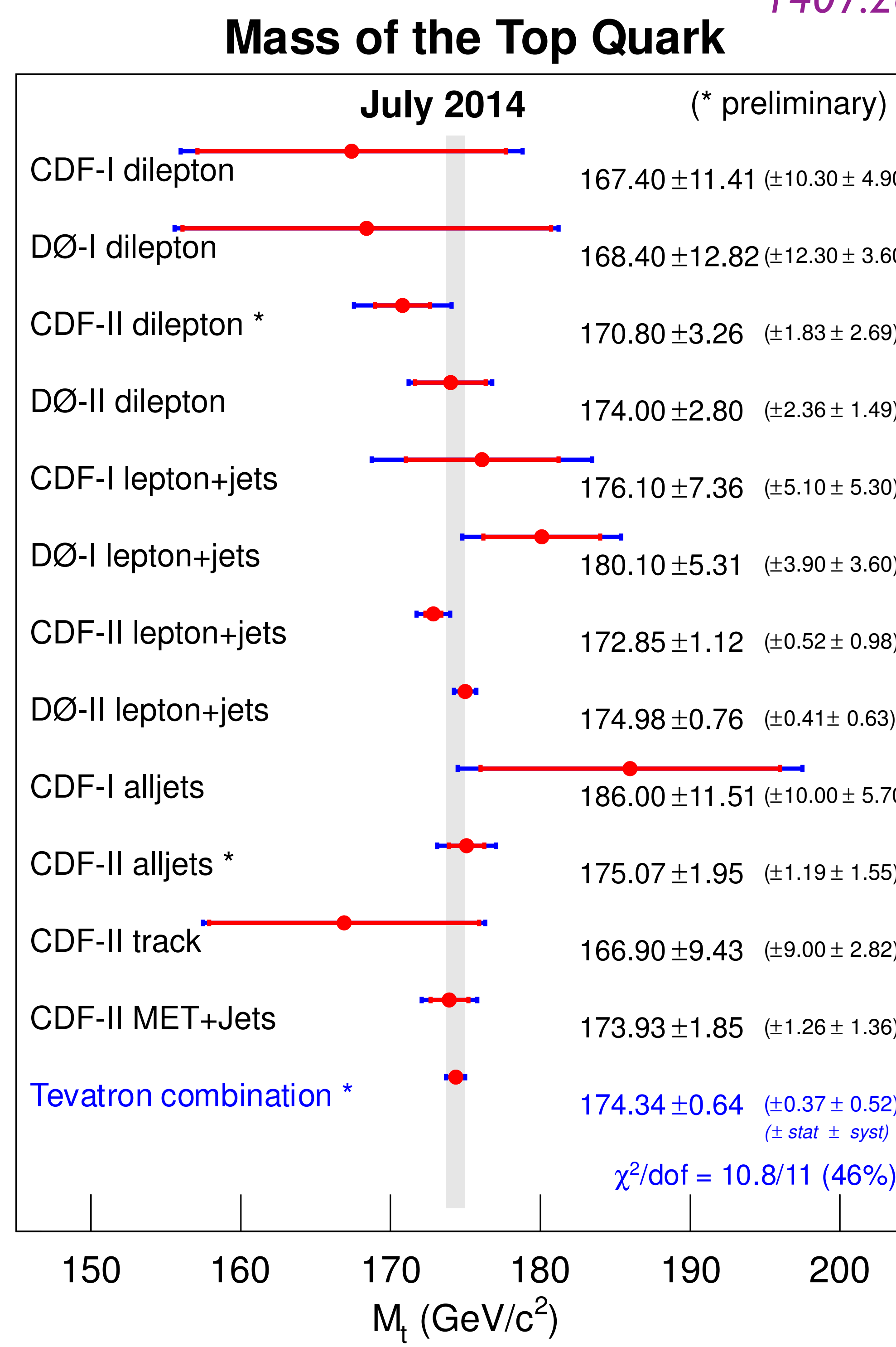
Tevatron + LHC combination

1403.4427



Tevatron combination

1407.2682



CMS lepton+jets *CMS-PAS-TOP-14-001*

$$m_t = 172.04 \pm 0.19 \pm 0.75 \text{ GeV}$$

CMS combination *CMS-PAS-TOP-14-015*

$$m_t = 172.38 \pm 0.10 \pm 0.65 \text{ GeV}$$

Ambiguity in the top pole mass

- The measurements of the pole mass of the top quark at Tevatron and LHC suffer from ambiguities:

M. Mangano at TOP2013:

"All in all I believe that it is justified to assume that MC mass parameter is interpreted as m_{pole} within the ambiguity intrinsic in the definition of m_{pole}, thus at the level of ~250-500 MeV."

S.O. Moch et al., 1405.4781 (report on the 2014 MITP scientific program):

"The uncertainty on the translation from the MC mass definition to a theoretically well defined short-distance mass definition at a low scale is currently estimated to be of the order of 1 GeV." (There is an additional uncertainty originating from the conversion of the short-distance mass to pole mass.)

S.O. Moch, 1408.6080: $\Delta m_t = {}^{+0.82}_{-0.62}\ \mathrm{GeV}$

Ambiguity in the top pole mass

S.O. Moch, 1408.6080

Nonetheless, the MC mass definition can be translated to a theoretically well-defined short-distance mass definition at a low scale with an uncertainty currently estimated to be of the order of 1 GeV, see [1,40]. This translation uses the fact that multi-observable analyses like in [39] effectively assign a high statistical weight to the invariant mass distribution of the reconstructed boosted top-quarks, because of the large sensitivity of the system on the mass parameter, especially around the peak region.

The top-quark invariant mass distribution can be computed to higher orders in perturbative QCD, cf., Fig. 3, and its peak position can also be described in an effective theory approach based on a factorization [41, 42] into a hard, a soft non-perturbative and a universal jet function. Each of those functions depends in a fully coherent and transparent way on the mass at a particular scale. The reconstructed top object largely corresponds to the jet function which is governed by a short-distance mass m_t^{MRS} at the scale of the top quark width Γ_t, see, e.g., [1,40]. This line of arguments allows one to systematically implement proper short-distance mass schemes for the description of the MC mass in Eq. (5), which can then indeed be converted to the pole mass.

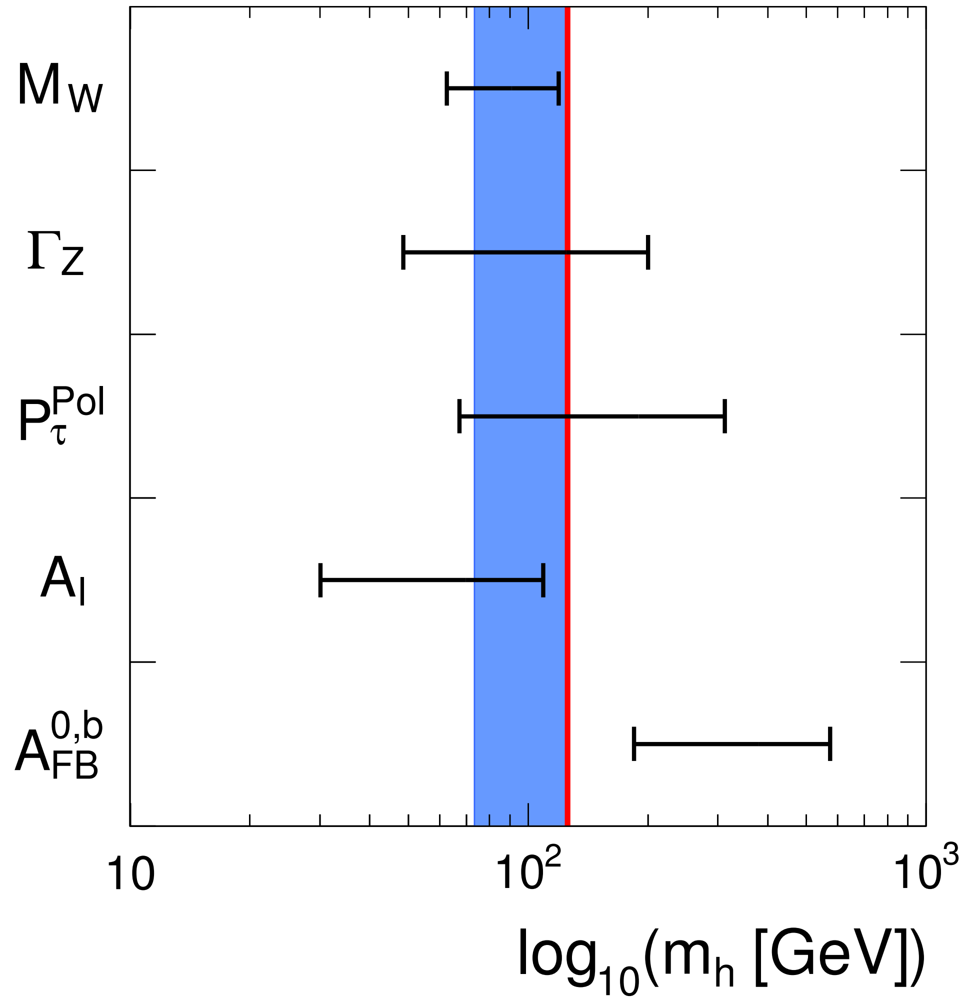
$$\Delta m_{\mathrm{th}} =^{+0.32}_{-0.62} \ \mathrm{GeV}\, (m_t^{\mathrm{MC}} \to m_t^{\mathrm{MSR}}(3\mathrm{GeV}))\ +\ 0.50\, \mathrm{GeV}\, (m_t(m_t) \to m_t^{\mathrm{pole}})\,,$$

Individual constraints on the Higgs mass

indirect determination from the EW fit:

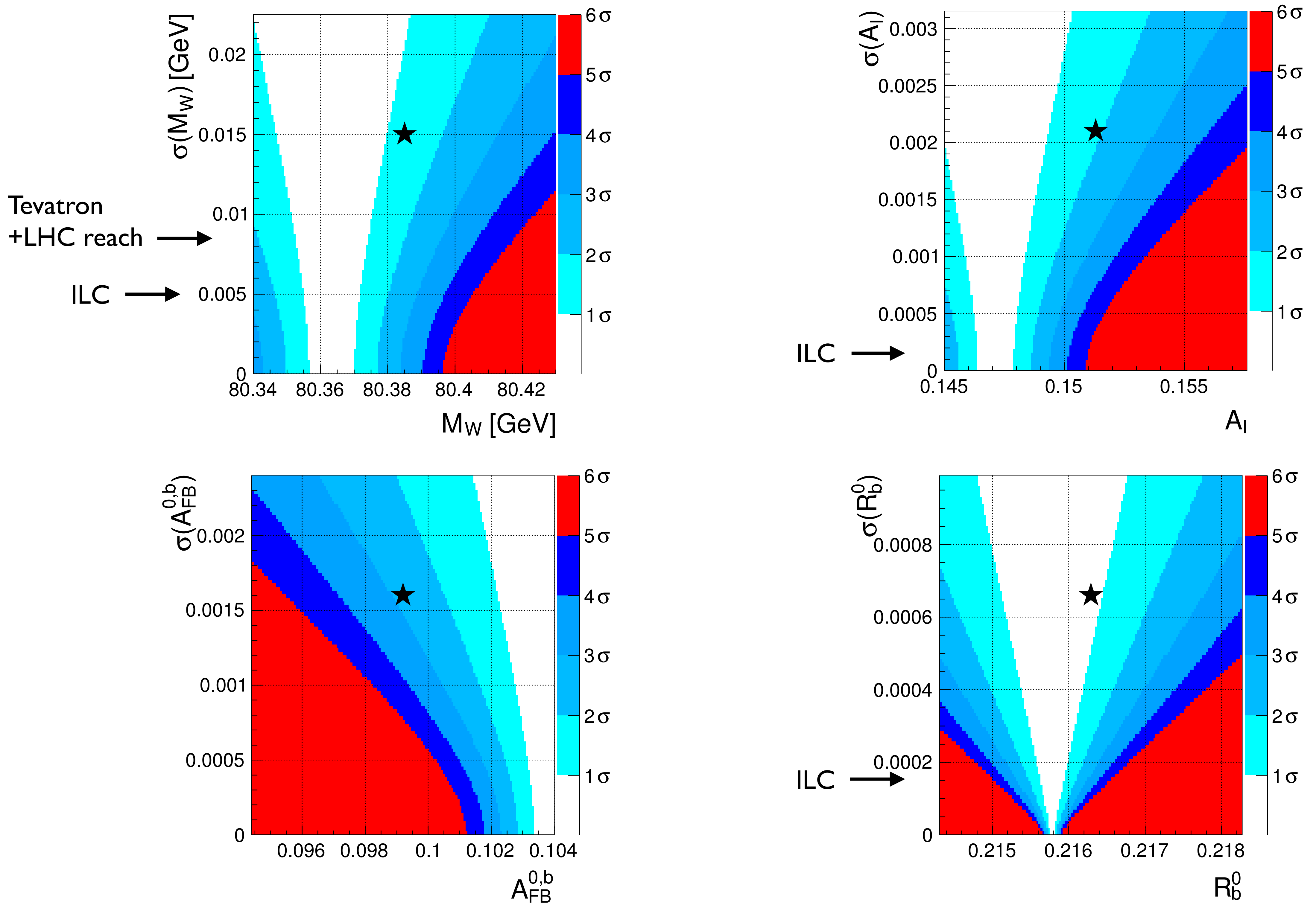
$$m_h = 99.9 \pm 26.6\ \mathrm{GeV}$$

direct measurement at LHC (ATLAS & CMS):

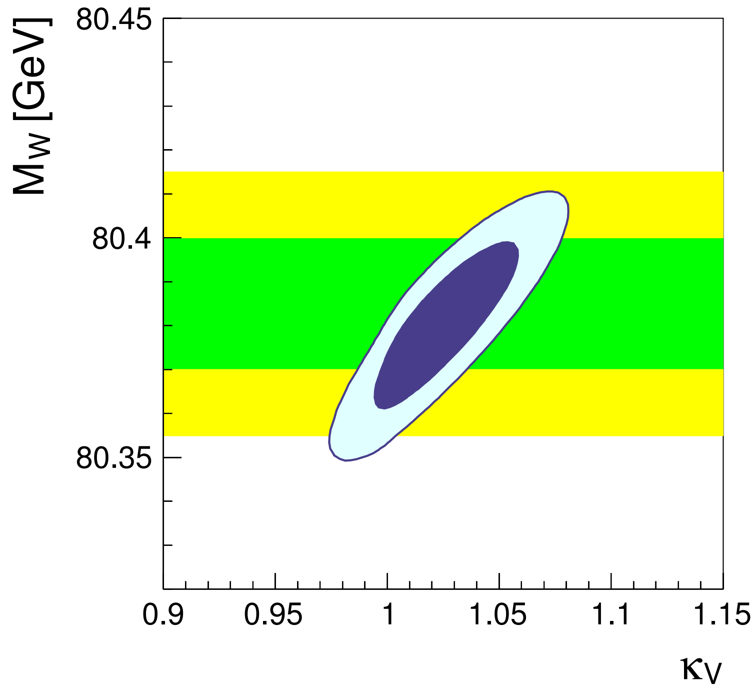


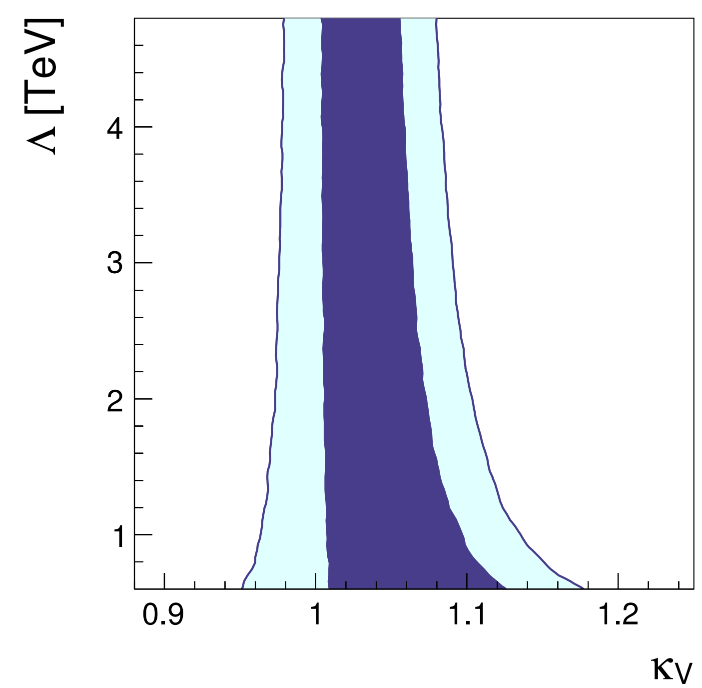
- Mw gives the most stringent constraint.
- Tension between Al(SLD) and AFBb.

Future prospect



EW chiral Lagrangian





$$\Lambda < \frac{4\pi v}{\sqrt{|1-\kappa_V^2|}}$$

- smaller Mw ⇨ smaller Kv
- Kv is tightly constrained for the scale compatible with direct searches.

Indirect and direct contributions

$$
\begin{aligned}
\mathcal{O}_{HD} &= (H^\dagger D^\mu H)^*(H^\dagger D_\mu H) \\
&= \frac{v^2}{4}\left(1+\frac{2h}{v}+\frac{h^2}{v^2}\right)(\partial^\mu h)(\partial_\mu h) + \frac{g^2 v^4}{16 c_W^2} Z^\mu Z_\mu \left(1+\frac{4h}{v}+\frac{6h^2}{v^2}+\frac{4h^3}{v^3}+\frac{h^4}{v^4}\right)
\end{aligned}
$$

- Indirect contribution via input parameters:

$$M_Z^2 = M_{Z,\mathrm{SM}}^2\left(1+\frac{v^2}{2\Lambda^2}C_{HD}\right)$$

➡ contributes to EW/Higgs observables.

- Direct contribution:

$$\mathcal{L}_{\mathrm{eff}} = \frac{M_Z^2}{v}\left(1+\frac{v^2}{\Lambda^2}C_{HD}\right) Z_\mu Z^\mu h$$

NP contributions

Operator	Kinetic terms					SM param's			Direct contribution to interactions						
	G^A	W^I	B	W^3B	H	M_Z	v	Y_f	WWV	$Wf\bar{f}'$	$Zf\bar{f}$	hVV	$hf\bar{f}$	$hVq\bar{q}$	4ℓ
$\mathcal{O}_{HG}$	√											√			
$\mathcal{O}_{HW}$		√										√			
$\mathcal{O}_{HB}$			√									√			
$\mathcal{O}_{HWB}$				√					√			√			
$\mathcal{O}_{HD}$					√	√						√			
$\mathcal{O}_{H\Box}$					√										
$\mathcal{O}_{HL}^{(1)}$											√				
$\mathcal{O}_{HL}^{(3)}$										√	√				
$\mathcal{O}_{HQ}^{(1)}$											√			√	
$\mathcal{O}_{HQ}^{(3)}$										√	√			√	
$\mathcal{O}_{He}$											√				
$\mathcal{O}_{Hu}$											√			√	
$\mathcal{O}_{Hd}$											√			√	
$\mathcal{O}_{Hud}$										√				√	
$\mathcal{O}_{eH}$								√					√		
$\mathcal{O}_{uH}$								√					√		
$\mathcal{O}_{dH}$								√					√		
$\mathcal{O}_{LL}$															√

$$
\begin{aligned}
\mathcal{O}_{HG} &= (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu} \\
\mathcal{O}_{HW} &= (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu} \\
\mathcal{O}_{HB} &= (H^\dagger H) B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{HWB} &= (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{HD} &= (H^\dagger D^\mu H)^* (H^\dagger D_\mu H) \\
\mathcal{O}_{H\Box} &= (H^\dagger H) \Box (H^\dagger H) \\
\mathcal{O}_{HL}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{L} \gamma^\mu L) \\
\mathcal{O}_{HL}^{(3)} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{L} \tau^I \gamma^\mu L) \\
\mathcal{O}_{HQ}^{(1)} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{Q} \gamma^\mu Q) \\
\mathcal{O}_{HQ}^{(3)} &= (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\overline{Q} \tau^I \gamma^\mu Q) \\
\mathcal{O}_{He} &= (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{e}_R \gamma^\mu e_R) \\
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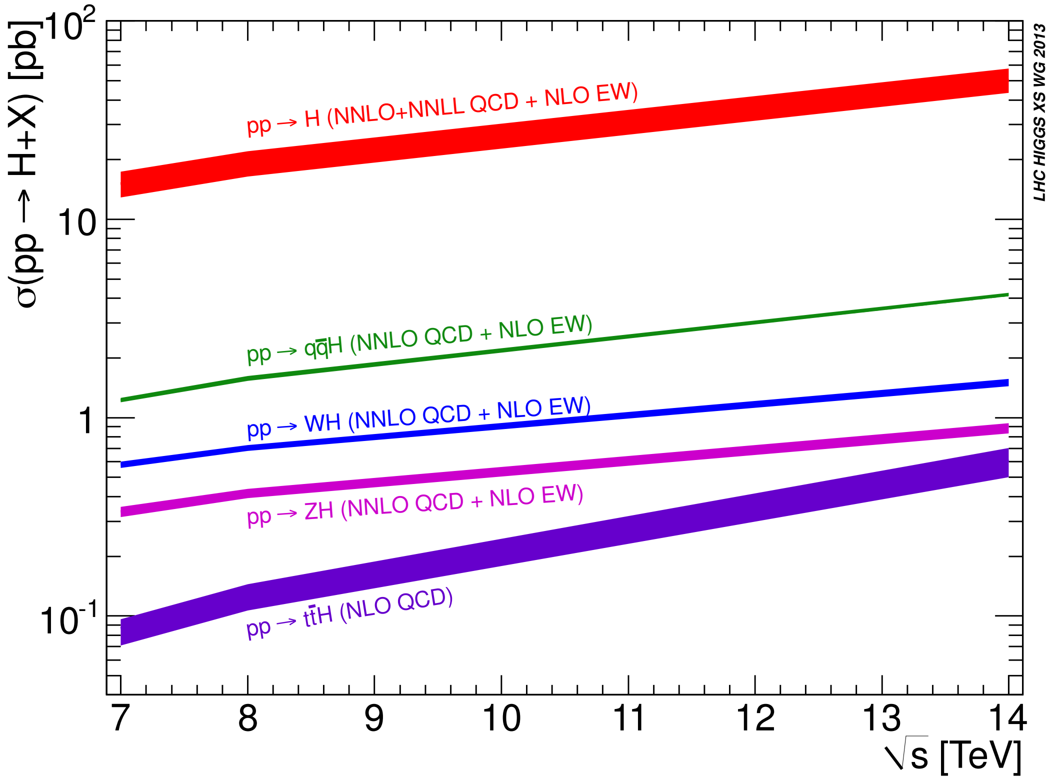
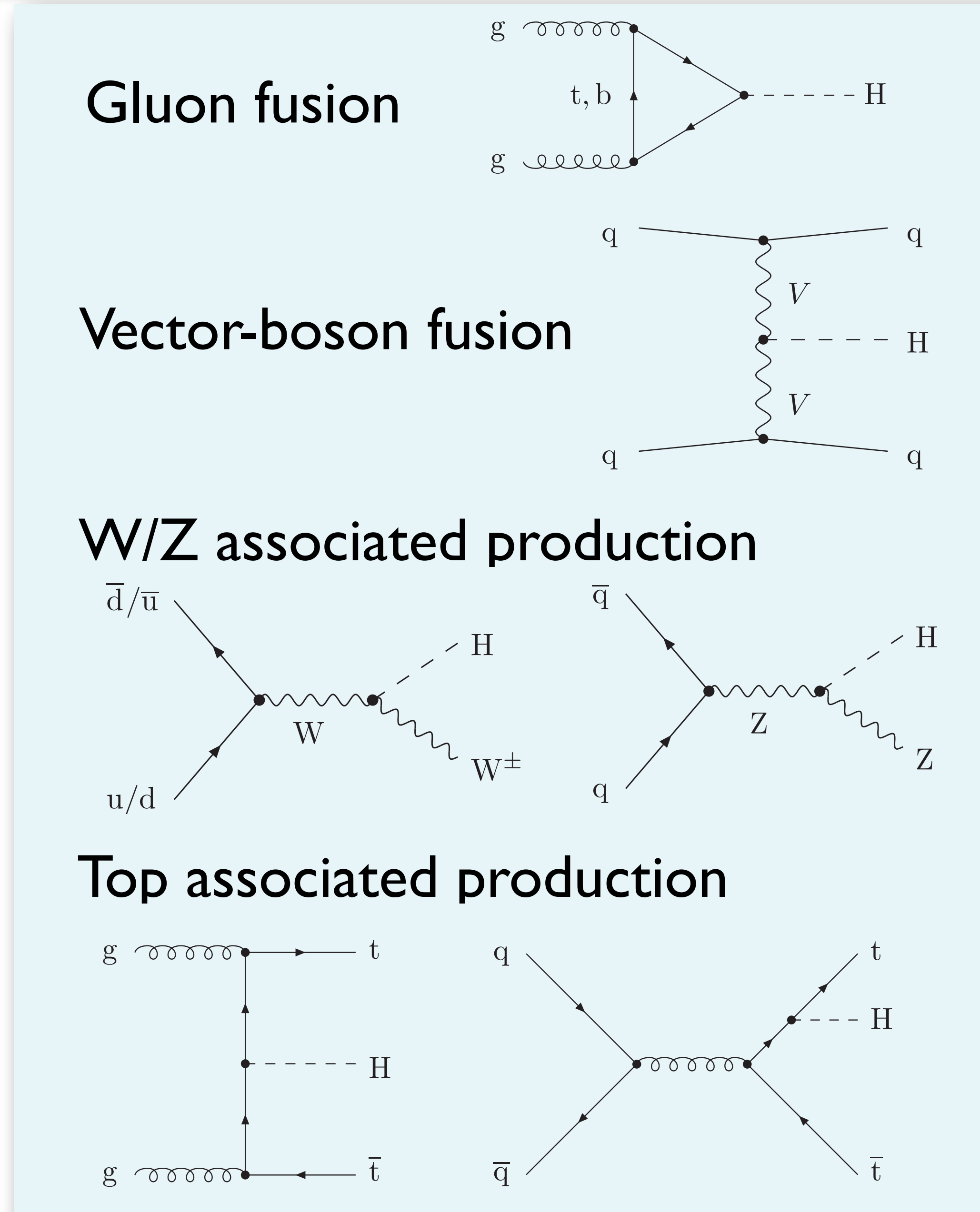
\mathcal{O}_{Hud} &= i(\widetilde{H}^\dagger D_\mu H)(\overline{u}_R \gamma^\mu d_R) \\
\mathcal{O}_{eH} &= (H^\dagger H)(\bar{L}\, e_R H) \\
\mathcal{O}_{uH} &= (H^\dagger H)(\bar{Q}\, u_R \widetilde{H}) \\
\mathcal{O}_{dH} &= (H^\dagger H)(\bar{Q}\, d_R H) \\
\mathcal{O}_{LL} &= (\overline{L} \gamma_\mu L)(\overline{L} \gamma^\mu L)
\end{aligned}
$$

derive NP contributions to observables.

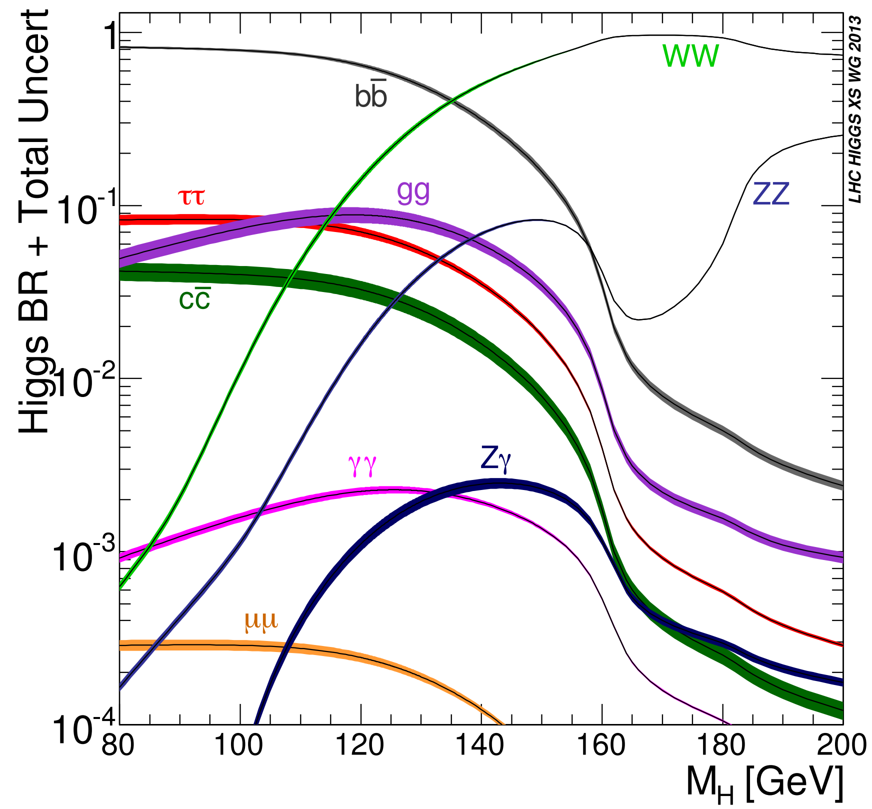
Higgs production cross sections





- NP contributions to the cross sections have been calculated at tree level with MadGraph.
- QCD corrections have then been taken into account by multiplying the corresponding K factors in the SM.

Higgs branching ratios



- We use the formulae of NP contributions to the branching ratios derived by Contino et al. in a different operator basis (SILH basis), applying basis transformation. *Contino et al. (14)*

- NLO (NNNLO for H to gg) QCD corrections have been included.