Global Bayesian Analysis of the Higgs Couplings

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In collaboration with
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Istituto Nazionale di Fisica Nucleare

European Research Council
Funding for top researchers from anywhere in the world

Motivation

- Direct searches for new states beyond the SM have so far turned out to be unsuccessful
- Indirect constraints from electroweak precision measurements and flavour data push the limits on masses of new particles well above the electroweak scale
- If NP is well separated from the electroweak scale, the couplings of the Higgs boson will be close to those of the SM and will only be modified by the effect of a higher dimensional operators

$\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$ invariant

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \ldots$$

Neutrino mass

Violates tree-level relations and Accidental symmetries

Bosonic Operators

Grzadkowski et.al.
1008.4884

$$\mathcal{O}_{HG} = (H^\dagger H) G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{HW} = (H^\dagger H) W^I_{\mu\nu} W^{I\mu\nu}$$

$$\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$$

Higgs production and decay

$$\mathcal{O}_{HWB} = (H^\dagger \tau^I H) W^I_{\mu\nu} B^{\mu\nu}$$

S parameter
$WW\gamma$, WWZ couplings

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

T parameter

$$\mathcal{O}_{H\Box} = (H^\dagger H) \Box (H^\dagger H)$$

wave function renormalization of the Higgs field

$$\mathcal{O}_H = (H^\dagger H)^3$$

Higgs potential

Single-fermionic-current operators

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

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

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

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

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

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

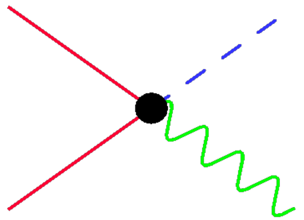
$$\mathcal{O}_{Hd} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\overline{d}_R\gamma^\mu d_R)$$

$$\mathcal{O}_{Hud} = i(\widetilde{H}^\dagger D_\mu H)(\overline{u}_R\gamma^\mu d_R)$$

Higgs interactions with two fermions

Z boson couplings to neutral currents

W boson couplings to charged currents



$pp \to HZ$, $pp \to HW$

Single-fermionic-current operators

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

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

Fermi Constant

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

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

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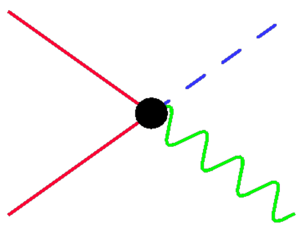

$pp \to HZ,\ pp \to HW$

Single-fermionic-current operators

$$\mathcal{O}_{eH} = (H^\dagger H)(\bar{L}\, e_R H)$$
$$\mathcal{O}_{uH} = (H^\dagger H)(\bar{Q}\, u_R \widetilde{H})$$
$$\mathcal{O}_{dH} = (H^\dagger H)(\bar{Q}\, d_R H)$$

Modifies Higgs interactions with two fermions

+

Yukawa couplings

Four-fermion operators

$$\mathcal{O}_{LL}^{pqrs} = (\overline{L}^p \gamma_\mu L^q)(\overline{L}^r \gamma^\mu L^s)$$

$\downarrow$

Affects the extraction of the Fermi constant from muon decay

Operators of dipole type

$$\mathcal{O}_{eW} = (\bar{L}\,\sigma^{\mu\nu} e_R)\tau^I H W^I_{\mu\nu}$$

$$\mathcal{O}_{eB} = (\bar{L}\,\sigma^{\mu\nu} e_R) H B_{\mu\nu}$$

$$\mathcal{O}_{uG} = (\bar{Q}\,\sigma^{\mu\nu} T^A u_R)\widetilde{H} G^A_{\mu\nu}$$

$$\mathcal{O}_{uW} = (\bar{Q}\,\sigma^{\mu\nu} u_R)\tau^I \widetilde{H} W^I_{\mu\nu}$$

$$\mathcal{O}_{uB} = (\bar{Q}\,\sigma^{\mu\nu} u_R)\widetilde{H} B_{\mu\nu}$$

$$\mathcal{O}_{dG} = (\bar{Q}\,\sigma^{\mu\nu} T^A d_R) H G^A_{\mu\nu}$$

$$\mathcal{O}_{dW} = (\bar{Q}\,\sigma^{\mu\nu} d_R)\tau^I H W^I_{\mu\nu}$$

$$\mathcal{O}_{dB} = (\bar{Q}\,\sigma^{\mu\nu} d_R) H B_{\mu\nu}$$

NOT considered in our analysis

Data

	$\alpha_s(M_Z^2)$	0.1185 ± 0.0006
	$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	0.02750 ± 0.00033
LEP	M_Z [GeV]	91.1875 ± 0.0021
Tevatron	m_t [GeV]	173.34 ± 0.9
LHC	m_h [GeV]	125.5 ± 0.3
LEPII Tevatron	M_W [GeV]	80.385 ± 0.015
LEPII Tevatron	Γ_W [GeV]	2.085 ± 0.042
LEP	Γ_Z [GeV]	2.4952 ± 0.0023
LEP	σ_h^0 [nb]	41.540 ± 0.037
LEP	$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012
LEP	$P_\tau^{\rm pol}$	0.1465 ± 0.0033
SLD	$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
LEP SLD	$\mathcal{A}_c$	0.670 ± 0.027
LEP SLD	$\mathcal{A}_b$	0.923 ± 0.020
LEP	$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
LEP SLD	$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035
LEP SLD	$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016
LEP	R_ℓ^0	20.767 ± 0.025
LEP SLD	R_c^0	0.1721 ± 0.0030
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For details of SM EW fit
See talk by Satoshi Mishima this afternoon

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$$\mu = \sum_i w_i r_i$$

$$r_i = \frac{[\sigma \times BR]_i}{[\sigma_{SM} \times BR_{SM}]_i}$$

$$w_i = \frac{\epsilon_i[\sigma \times BR]_i}{\sum_j \epsilon_j[\sigma_{SM} \times BR_{SM}]_j}$$

$H\gamma\gamma$ ATLAS-CONF-2013-012
CMS HIG-13-001

$H\tau\tau$ ATLAS-CONF-2013-012
CMS HIG-13-004

HWW ATLAS-CONF-2013-030
CMS HIG-13-023

HZZ ATLAS-CONF-2013-013
CMS HIG-13-002

Wilson Coefficients → **Observables**

Operator	Observables									Direct contribution to interactions					
	M_W	Γ_W	$\mathcal{A}_\ell$	$\mathcal{A}_c$	$\mathcal{A}_b$	$A_{\rm FB}^{0,\ell}$	$A_{\rm FB}^{0,c}$	$A_{\rm FB}^{0,b}$	Γ_Z	$Wf\bar{f}'$	$Zf\bar{f}$	hVV	$hf\bar{f}$	$hVq\bar{q}$	4ℓ
$\mathcal{O}_W$															
$\mathcal{O}_{HG}$												√			
$\mathcal{O}_{HW}$												√			
$\mathcal{O}_{HB}$												√			
$\mathcal{O}_{HWB}$	√	√	√	√	√	√	√	√	√			√			
$\mathcal{O}_{HD}$	√	√	√	√	√	√	√	√	√			√			
$\mathcal{O}_{H\Box}$															
$\mathcal{O}_H$															
$\mathcal{O}_{HL}^{(1)}$			√			√	√	√	√		√				
$\mathcal{O}_{HL}^{(3)}$	√	√	√	√	√	√	√	√	√	√	√				
$\mathcal{O}_{He}$			√			√	√	√	√		√				
$\mathcal{O}_{HQ}^{(1)}$				√	√		√	√	√		√			√	
$\mathcal{O}_{HQ}^{(3)}$		√		√	√		√	√	√	√	√			√	
$\mathcal{O}_{Hu}$				√			√		√		√			√	
$\mathcal{O}_{Hd}$					√			√	√		√			√	
$\mathcal{O}_{Hud}$		(√)								√				√	
$\mathcal{O}_{eH}$													√		
$\mathcal{O}_{uH}$													√		
$\mathcal{O}_{dH}$													√		
$\mathcal{O}_{LL}$	√	√	√	√	√	√	√	√	√						√

Cross-sections

$$\mathcal{L}_{\rm eff} = g^{(1)}_{hWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h + \left(g^{(2)}_{hWW} W^{+\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + \text{h.c.} \right) + g^{(3)}_{hWW} W^{+}_{\mu} W^{-\mu} h + ...$$

$$\begin{aligned} \sigma_{\rm WH} = & \quad \sigma^{\rm SM}_{\rm WH} \\ & + 0.770 \times {\rm K} \quad \times \ \delta g^{(1)}_{hWW} \\ & + 1.660 \times {\rm K} \quad \times \ \delta g^{(3)}_{hWW} \\ & + \quad .... \end{aligned}$$

7 TeV

$${\rm K} = \frac{\sigma^{\rm SM}_{\rm WH}}{0.4297}$$

Branching Ratios

Taken from Contino et.al., 1403.3381 after basis transformation

Cross-sections

$$\mathcal{L}_{\rm eff} = g^{(1)}_{hWW} W^{\mu\nu} W^{\dagger}_{\mu\nu} h + \left(g^{(2)}_{hWW} W^{+\nu} \partial^{\mu} W^{\dagger}_{\mu\nu} h + \text{h.c.} \right) + g^{(3)}_{hWW} W^{+}_{\mu} W^{-\mu} h + ...$$

$$\begin{aligned} \sigma_{\rm WH} = & \quad \sigma^{\rm SM}_{\rm WH} \\ & + 0.770 \times {\rm K} \quad \times \delta g^{(1)}_{hWW} \\ & + 1.660 \times {\rm K} \quad \times \delta g^{(3)}_{hWW} \\ & + \quad \quad \quad .... \end{aligned}$$

7 TeV

$${\rm K} = \frac{\sigma^{\rm SM}_{\rm WH}}{0.4297}$$

Branching Ratios

Theoretical uncertainties not taken into account yet

Taken from Contino et.al., 1403.3381 after basis transformation

Numerical implementation

- Bayesian analysis : MCMC implemented using BAT

  Caldwell, Kollar, Kröninger - The Bayesian Analysis Toolkit

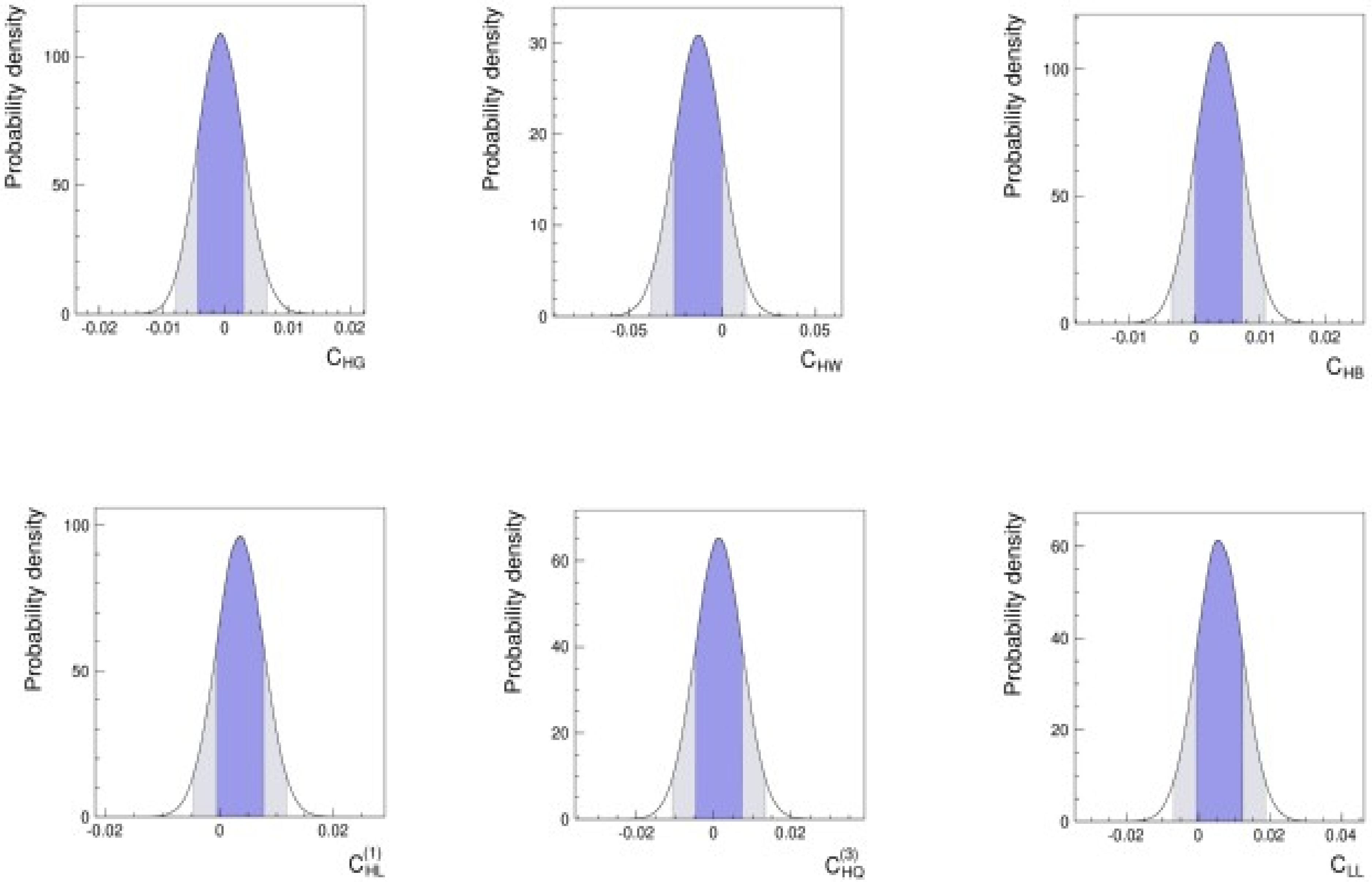
- Part of “SusyFit” HEP model fitting project

  “SusyFit” is a temporary name, waiting for a better one

- SusyFit is a flexible tool designed to constrain the parameter space of the SM or of any NP model :

  public code (not yet) written in c++
  MPI parallelization support

Posterior Probability



Switch on one operator at a time and get a bound on C_i for fixed Λ

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}	$--$	[−0.003, 0.011]	[−0.003, 0.011]
C_{HWB}	[−0.0082, 0.0030]	[−0.006, 0.020]	[−0.0063, 0.0039]
C_{HD}	[−0.025, 0.004]	[−3.1, 1.4]	[−0.026, 0.004]
$C_{H\Box}$		[−0.8, 1.0]	[−0.81, 1.00]
$C_{HL}^{(1)}$	[−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]

Switch on one operator at a time and get a bound on Λ for fixed C_i

	Only EW		Only Higgs		EW + Higgs	
	Λ [TeV]		Λ [TeV]		Λ [TeV]	
Coefficient	$C_i = -1$	$C_i = 1$	$C_i = -1$	$C_i = 1$	$C_i = -1$	$C_i = 1$
C_{HG}	$--$	$--$	11.4	12.3	11.4	12.3
C_{HW}	$--$	$--$	5.1	9.1	5.1	9.1
C_{HB}	$--$	$--$	17.1	9.7	17.1	9.6
C_{HWB}	11.1	18.4	12.5	7.1	12.6	15.9
C_{HD}	6.3	15.4	0.6	0.8	6.3	15.5
$C_{H\Box}$	$--$	$--$	1.1	1.0	1.1	1.0
$C_{HL}^{(1)}$	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}	$--$	$--$	0.0	0.0	0.0	0.0
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

$|C_i| = 1 \longrightarrow$ NP scale beyond the LHC reach (for most C_i)

but TeV NP possible if C_i perturbative

Fit to the scaled SM couplings

$$\kappa_W = 1 + \delta_h - \frac{1}{2(c_W^2 - s_W^2)}\left(4 s_W c_W \widehat{C}_{HWB} + c_W^2 \widehat{C}_{HD} + \delta_{G_F}\right)$$

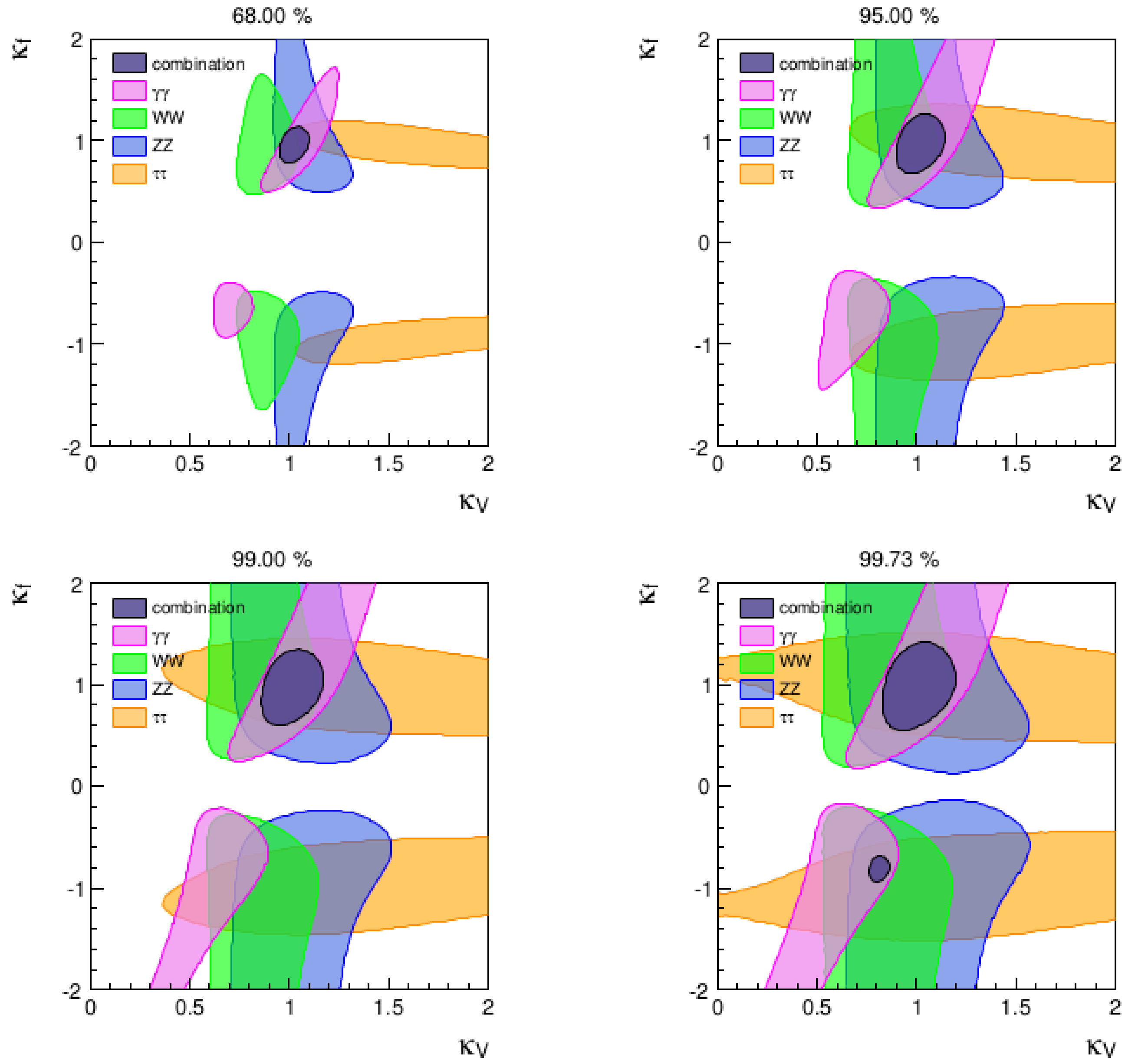
$$\kappa_Z = 1 + \frac{1}{2}\widehat{C}_{HD} + \delta_h - \frac{1}{2}\delta_{G_F}$$

$$\kappa_f = 1 + \delta\kappa_f$$

$$\delta\kappa_f = \delta_h - \frac{1}{2}\delta_{G_F} - \frac{v}{m_f}\frac{\widehat{C}_{fH}}{\sqrt{2}}$$

$$\delta_h = -\frac{1}{4}\widehat{C}_{HD} + \widehat{C}_{H\Box}$$

see also the talk by Satoshi Mishima



Only Higgs

	68%	95%	Correlations	
κ_V	1.02 ± 0.05	[0.92, 1.12]	1.00	
κ_f	0.96 ± 0.12	[0.73, 1.20]	0.29	1.00

Higgs + EW

	68%	95%	Correlations	
κ_V	1.02 ± 0.02	[0.99, 1.06]	1.00	
κ_f	0.95 ± 0.11	[0.75, 1.19]	0.12	1.00

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$$\kappa_Z = 1 + \frac{1}{2}\widehat{C}_{HD} + \delta_h - \frac{1}{2}\delta_{G_F}$$

$$\kappa_f = 1 + \delta\kappa_f$$

$$\delta\kappa_f = \delta_h - \frac{1}{2}\delta_{G_F} - \frac{v}{m_f}\frac{\widehat{C}_{fH}}{\sqrt{2}}$$

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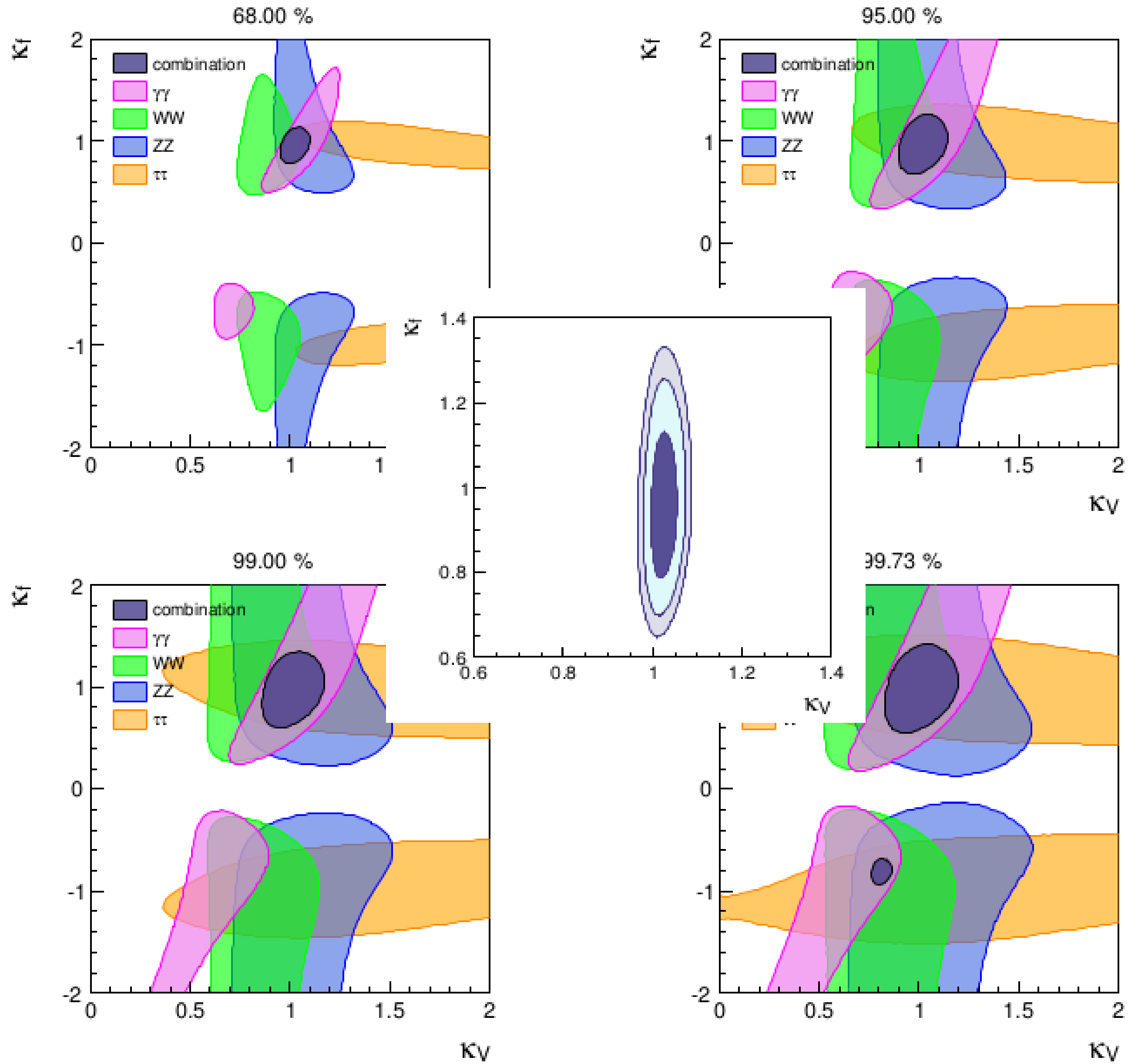

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Indirect searches for NP as relevant as ever after the LHC 7-8 TeV run

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SusyFit Status and Future

Models implemented :

-- **Standard Model (~100 parameters, including meson properties)**

-- **Modified SM couplings (EW+Higgs sectors)**

-- **Dimension-6 gauge invariant operators beyond the SM (EW+Higgs sectors)**

-- **General MSSM with SLHAII input (being tested now)**

Observables implemented :

-- **Electroweak precision observables (LEP, LEPII being tested)**

-- **Higgs properties (production cross sections & decay widths)**

Observables implemented under testing:

-- $\Delta F = 2$ processes

-- UT analysis

-- $\mathrm{b} \to \mathrm{s}\gamma, \mathrm{b} \to \mathrm{s}\,\ell\,\ell$

-- LFV decays

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First official release expected in summer!

Other works

Dumont et.al., arXiv:1304.3369
Einhorn et.al., arXiv:1307.0478
arXiv:1308.2255
Boos et.al., arXiv:1309.5410
Beneke et.al., arXiv:1406.1361

Jenkins et.al., arXiv:1308.2627
arXiv:1310.4838
Alonso et.al., arXiv:1312.2014

Corbett et.al., arXiv:1207.1344
arXiv:1211.4580
Masso et.al., arXiv:1211.1320
Brivio et.al., arXiv:1311.1823
Grojean et.al., arXiv:1301.2588

Contino et.al., arXiv:1303.3876
arXiv:1403.3381
Pomarol et.al., arXiv:1308.2803
Alloul et.al., arXiv:1310.5150
Ellis et.al., arXiv:1404.3667
Belusca-Maito et.al., arXiv:1404.5343
Biekötter et.al., arXiv:1406.7320

Elias-Miro et.al., arXiv:1302.5661
arXiv:1308.1879
arXiv:1312.2928

Djouadi et.al., arXiv:1301.4965
Godbole et.al., arXiv:1306.2573
Banejee et.al., arXiv:1207.3588
arXiv:1308.4860

and many more ....