PROBING BEYOND THE STANDARD MODEL PHYSICS USING EFFECTIVE FIELD THEORY

Thibaud Vantalon
DESY - IFAE

Based on:

JHEP09(2017)069, S. Di Vita, C. Grojean, G. Panico, M.Riembau, T. Vantalon
JHEP02(2018)178, S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon
Phys.Lett. B760 (2016) 220-227, M. Chala, C. Grojean, M. Riembau, T. Vantalon
ArXiv:1712.06337, G. Panico, M. Riembau, T. Vantalon

Prospects for measuring the Higgs trilinear self-coupling at the LHC and future colliders

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Measuring couplings

How to measure coupling at LHC?

We count the number of event

$$N = L\sigma\epsilon$$

Small width approximation

$$\sigma = \sigma_{pp\to h}(?)\mathrm{Br}_{h\to XX}(?)$$

Both the production cross section and the branching ratio are function of the couplings

Normalize with the SM value

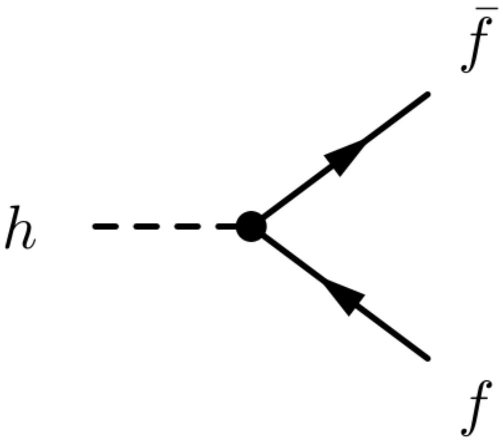
$$\mu = \frac{\sigma_{pp\to h}(?)\mathrm{Br}_{h\to XX}(?)}{\sigma^{\mathrm{SM}}_{pp\to h}\mathrm{Br}^{\mathrm{SM}}_{h\to XX}}$$

Make some assumption on the physics and fit the results

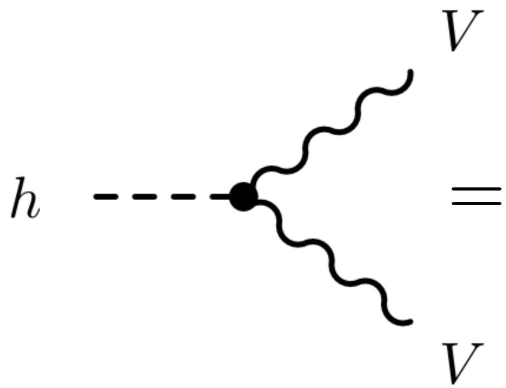
Coupling values depend on the physics assumptions

Which assumption should we make?

Just allow for rescaling of SM coupling?



$$= \frac{m_F}{v}\kappa_F$$



$$= g^{\mu\nu} g_V M_V \kappa_V$$

Kappa framework

Typical LO form of a signal strength

$$\mu = \frac{\kappa_i^2 \kappa_f^2}{\kappa_h^2}$$

Some Underlying assumptions:

- No new light resonance
- No new tensors structure
- No enforcement of the gauge symmetries

With: $\kappa_h^2 = \dfrac{\Gamma_h}{\Gamma_h^{\text{sm}}}$

Which assumption should we make?

What about Lorentz and gauge symmetry?

What about new tensors structure?

More physics motivated Framework $\longrightarrow$ EFT

Assuming new physics is heavy it is natural to allow for Higher dimension operators

Leading contribution

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \ldots,$$

Majorana masses fo neutrino and lepton number conservation violation (neutrinoless double beta decay)

Higher odd dimension odd operator break b-l → Dimension 8 less constrained

Quick important note on EFT

Not all higher dimensional operators are independent

$\longrightarrow$ We can choose a basis some famous are
- SILH
- Warsaw
- Higgs

We assume here that the Higgs is part of a doublet!

Squared dimension 6 Diagrams are of the same order as dimension 8 interfering with the SM

$$\left|\text{SM}\right|^2 \propto \mathcal{O}(1) \qquad Re\left(\text{SM}\ \text{dim-6}\right) \propto \mathcal{O}(\frac{1}{\Lambda^2})$$

$$\left|\text{dim-6}\right|^2 \propto Re\left(\text{SM}\ \text{dim-8}\right) \propto \mathcal{O}\frac{1}{\Lambda^4}$$

Subleading

The signal strengths can be linearized

$$\mu \approx 1 + \underbrace{\delta\sigma}_{\text{Linear functions}}(c_i) + \underbrace{\delta\text{Br}}_{\text{Linear functions}}(c_i) + \mathcal{O}(\frac{1}{\Lambda^4})$$

Exception to this rules exist

SILH basis

Operators in the Gauge eingenstates

Table 99: Four-fermion operators in the SILH basis. They are the same as in the Warsaw basis [616], except that the operators $[O_{\ell\ell}]_{1221}$, $[O_{\ell\ell}]_{1122}$, $[O_{uu}]_{3333}$ are absent by definition. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. A flavour index is implicit for each fermion field. For complex operators the complex conjugate operator is implicit.

$(\bar{L}L)(\bar{L}L)$ and $(\bar{L}R)(\bar{L}R)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$O_{\ell\ell}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{\ell}\gamma_\mu \ell)$	O_{ee}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{e}\gamma_\mu e)$	$O_{\ell e}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{e}\gamma_\mu e)$
O_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{q}\gamma_\mu q)$	O_{uu}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{u}\gamma_\mu u)$	$O_{\ell u}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{u}\gamma_\mu u)$
O'_{qq}	$\frac{1}{v^2}(\bar{q}\gamma_\mu \sigma^i q)(\bar{q}\gamma_\mu \sigma^i q)$	O_{dd}	$\frac{1}{v^2}(\bar{d}\gamma_\mu d)(\bar{d}\gamma_\mu d)$	$O_{\ell d}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{d}\gamma_\mu d)$
$O_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \ell)(\bar{q}\gamma_\mu q)$	O_{eu}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{u}\gamma_\mu u)$	O_{qe}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{e}\gamma_\mu e)$
$O'_{\ell q}$	$\frac{1}{v^2}(\bar{\ell}\gamma_\mu \sigma^i \ell)(\bar{q}\gamma_\mu \sigma^i q)$	O_{ed}	$\frac{1}{v^2}(\bar{e}\gamma_\mu e)(\bar{d}\gamma_\mu d)$	O_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{u}\gamma_\mu u)$
O_{quqd}	$\frac{1}{v^2}(\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)$	O_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu u)(\bar{d}\gamma_\mu d)$	O'_{qu}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{u}\gamma_\mu T^a u)$
O'_{quqd}	$\frac{1}{v^2}(\bar{q}^j T^a u)\epsilon_{jk}(\bar{q}^k T^a d)$	O'_{ud}	$\frac{1}{v^2}(\bar{u}\gamma_\mu T^a u)(\bar{d}\gamma_\mu T^a d)$	O_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu q)(\bar{d}\gamma_\mu d)$
$O_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)$			O'_{qd}	$\frac{1}{v^2}(\bar{q}\gamma_\mu T^a q)(\bar{d}\gamma_\mu T^a d)$
$O'_{\ell equ}$	$\frac{1}{v^2}(\bar{\ell}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$				
$O_{\ell edq}$	$\frac{1}{v^2}(\bar{\ell}^j e)(\bar{d}q^j)$				

Table 97: Bosonic D=6 operators in the SILH basis.

Bosonic CP-even		Bosonic CP-odd	
O_H	$\frac{1}{2v^2}\left[\partial_\mu (H^\dagger H)\right]^2$		
O_T	$\frac{1}{2v^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$		
O_6	$-\frac{\lambda}{v^2}(H^\dagger H)^3$		
O_g	$\frac{g_s^2}{m_W^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu}$	$\widetilde{O}_g$	$\frac{g_s^2}{m_W^2} H^\dagger H\, \widetilde{G}^a_{\mu\nu} G^a_{\mu\nu}$
O_γ	$\frac{g'^2}{m_W^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}$	$\widetilde{O}_\gamma$	$\frac{g'^2}{m_W^2} H^\dagger H\, \widetilde{B}_{\mu\nu} B_{\mu\nu}$
O_W	$\frac{ig}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D}_\mu H\right) D_\nu W^i_{\mu\nu}$		
O_B	$\frac{ig'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right) \partial_\nu B_{\mu\nu}$		
O_{HW}	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu}$	$\widetilde{O}_{HW}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger \sigma^i D_\nu H\right) \widetilde{W}^i_{\mu\nu}$
O_{HB}	$\frac{ig'}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}$	$\widetilde{O}_{HB}$	$\frac{ig}{m_W^2}\left(D_\mu H^\dagger D_\nu H\right) \widetilde{B}_{\mu\nu}$
O_{2W}	$\frac{1}{m_W^2} D_\mu W^i_{\mu\nu} D_\rho W^i_{\rho\nu}$		
O_{2B}	$\frac{1}{m_W^2} \partial_\mu B_{\mu\nu} \partial_\rho B_{\rho\nu}$		
O_{2G}	$\frac{1}{m_W^2} D_\mu G^a_{\mu\nu} D_\rho G^a_{\rho\nu}$		
O_{3W}	$\frac{g^3}{m_W^2}\epsilon^{ijk} W^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$	$\widetilde{O}_{3W}$	$\frac{g^3}{m_W^2}\epsilon^{ijk} \widetilde{W}^i_{\mu\nu} W^j_{\nu\rho} W^k_{\rho\mu}$
O_{3G}	$\frac{g_s^3}{m_W^2} f^{abc} G^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$	$\widetilde{O}_{3G}$	$\frac{g_s^3}{m_W^2} f^{abc} \widetilde{G}^a_{\mu\nu} G^b_{\nu\rho} G^c_{\rho\mu}$

Table 98: Two-fermion dimension-6 operators in the SILH basis. They are the same as in the Warsaw basis, except that the operators $[O_{H\ell}]_{11}$, $[O'_{H\ell}]_{11}$ are absent by definition. We define $\sigma_{\mu\nu} = i[\gamma_\mu, \gamma_\nu]/2$. In this table, e, u, d are always right-handed fermions, while ℓ and q are left-handed. For complex operators the complex conjugate operator is implicit.

Vertex		Yukawa and Dipole	
$[O_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i \gamma_\mu \ell_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_e]_{ij}$	$\frac{\sqrt{2m_{e_i} m_{e_j}}}{v^3} H^\dagger H \bar{\ell}_i H e_j$
$[O'_{H\ell}]_{ij}$	$\frac{i}{v^2}\bar{\ell}_i \sigma^k \gamma_\mu \ell_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_u]_{ij}$	$\frac{\sqrt{2m_{u_i} m_{u_j}}}{v^3} H^\dagger H \bar{q}_i \widetilde{H} u_j$
$[O_{He}]_{ij}$	$\frac{i}{v^2}\bar{e}_i \gamma_\mu e_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_d]_{ij}$	$\frac{\sqrt{2m_{d_i} m_{d_j}}}{v^3} H^\dagger H \bar{q}_i H d_j$
$[O_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \gamma_\mu q_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{eW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{e_i} m_{e_j}}}{v}\bar{\ell}_i \sigma^k H \sigma_{\mu\nu} e_j W^k_{\mu\nu}$
$[O'_{Hq}]_{ij}$	$\frac{i}{v^2}\bar{q}_i \sigma^k \gamma_\mu q_j H^\dagger \sigma^k \overleftrightarrow{D}_\mu H$	$[O_{eB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{e_i} m_{e_j}}}{v}\bar{\ell}_i H \sigma_{\mu\nu} e_j B_{\mu\nu}$
$[O_{Hu}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu u_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v}\bar{q}_i \tilde{H} \sigma_{\mu\nu} T^a u_j G^a_{\mu\nu}$
$[O_{Hd}]_{ij}$	$\frac{i}{v^2}\bar{d}_i \gamma_\mu d_j H^\dagger \overleftrightarrow{D}_\mu H$	$[O_{uW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v}\bar{q}_i \sigma^k \tilde{H} \sigma_{\mu\nu} u_j W^k_{\mu\nu}$
$[O_{Hud}]_{ij}$	$\frac{i}{v^2}\bar{u}_i \gamma_\mu d_j \tilde{H}^\dagger D_\mu H$	$[O_{uB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{u_i} m_{u_j}}}{v}\bar{q}_i \tilde{H} \sigma_{\mu\nu} u_j B_{\mu\nu}$
		$[O_{dG}]_{ij}$	$\frac{g_s}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v}\bar{q}_i H \sigma_{\mu\nu} T^a d_j G^a_{\mu\nu}$
		$[O_{dW}]_{ij}$	$\frac{g}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v}\bar{q}_i \sigma^k H \sigma_{\mu\nu} d_j W^k_{\mu\nu}$
		$[O_{dB}]_{ij}$	$\frac{g'}{m_W^2}\frac{\sqrt{2m_{d_i} m_{d_j}}}{v}\bar{q}_i H \sigma_{\mu\nu} d_j B_{\mu\nu}$

Higgs basis (with some small change in normalisation)

Unitary Gauge + mass eigenstates

Less constrained deviation to the Higgs sector (we will use them later)

$$\mathcal{L}^{\rm NP} \supset \frac{h}{v}\Big[\delta c_w \frac{g^2 v^2}{2} W^+_\mu W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu + c_{ww}\frac{g^2}{2} W^+_{\mu\nu} W_{-\mu\nu} + c_{w\Box} g^2 \left(W^+_\mu \partial_\nu W_{+\mu\nu} + \text{h.c.}\right)$$
$$+ \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu}\Big]$$
$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}^{(2)}_{gg}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu} - \sum_f \left[m_f \left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c}\right] + (\kappa_\lambda - 1)\lambda_{SM} v h^3$$

Due to Lorentz and Gauge invariance, not everything is independent!

$$\begin{aligned}
\delta c_w &= \delta c_z\,, \\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + \left(g^2+g'^2\right) c_{zz} - \frac{e^2}{\pi^2}\hat{c}_{\gamma\gamma} - \frac{g^2-g'^2}{\pi^2}\hat{c}_{z\gamma}\right], \\
\hat{c}^{(2)}_{gg} &= \hat{c}_{gg}\,, \\
\delta y_f^{(2)} &= 3\delta y_f - \delta c_z \\
&\dots
\end{aligned}$$

Naturally captured by EFT

The Higgs Trilinear self-coupling

Motivation

$$V_{\rm SM} = \frac{1}{2} m_h^2 + \lambda_3^{\rm SM} h^3 + \lambda_4^{\rm SM} h^4$$

$$\lambda_3^{\rm SM} = \frac{m_h^2}{2v} \qquad \lambda_4^{\rm SM} = \frac{m_h^2}{8v^2}$$

Standard model Higgs potential depends on only 2 parameters and is indirectly precisely measured

Direct measurements of h^3 and h^4 are challenging but an important consistency check.
- **Stability of EW vacuum**
- **Baryogenesis through first order phase transition?**

h^3 challenging to measure at LHC

h^4 out of reach of LHC

Motivation

$$V_{\mathrm{SM}} = \frac{1}{2} m_h^2 + \lambda_3^{\mathrm{SM}} h^3 + \lambda_4^{\mathrm{SM}} h^4$$

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Direct measurements of h^3 and h^4 are challenging but an important consistency check.

- Stability of EW vacuum

- Baryogenesis through first order phase transition?

$\boxed{h^3 \text{ challenging to measure at LHC}}$

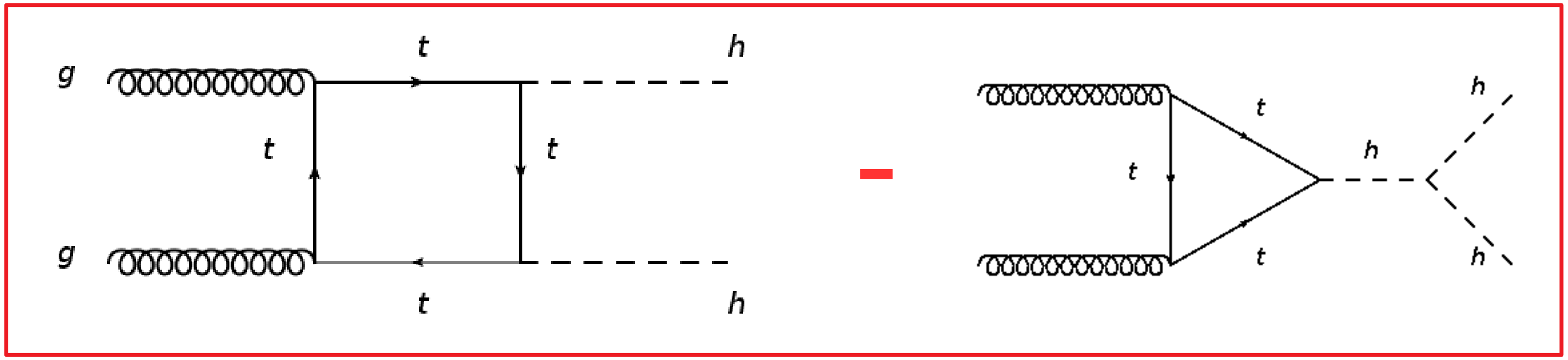
h^4 ~~out of reach of LHC~~

Double Higgs production in the SM

Small production cross section:

$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3}$$

Negative interference decrease cross section:



Two diagram have very dependant energy dependence. In the high $\sqrt{s}$ limit

$$A_{\square} = \frac{\alpha_s}{4\pi} y_t^2 \,, \qquad A_{\triangle} = \lambda_3 \frac{\alpha_s}{4\pi} y_t^2 \frac{m_h^2}{\hat{s}} \left(\log \frac{m_t^2}{\hat{s}} + i\pi \right)^2$$

Best Significance for double Higgs production not necessarily the best to constrain the trilinear

Double Higgs production

Current constraints:

Obs.(exp.) limit on σ_{hh}/σ_{SM}:

Final state	ATLAS	CMS
$b\bar{b}\gamma\gamma$	177 (162)	19 (16)
$b\bar{b}\tau\tau$		30 (25)
$b\bar{b}b\bar{b}$	29 (38)	342 (308)
$b\bar{b}WW^*$		79 (89)
$\gamma\gamma WW^*$	750 (386)	

2015 (2.3-3.2 fb^{-1})

2015+2016 (13.3 fb^{-1})

2016 (35.9 fb^{-1})

S. Wertz,

Higgs Couplings 2017

$$\longrightarrow \quad -8,8 < \kappa_\lambda < 15$$

Most promising channel is a trade off between cleanness and statistic:

$$\mathrm{Br}(h \to b\bar{b}) \times \mathrm{Br}(h \to \gamma\gamma) \sim 60\% \times 0.1\%$$

HL-LHC @ 3 ab^{-1}, 95% CL $\kappa_\lambda \in [-0.8\,,\,7.7]$ ATL-PHYS_PUB_2017-001

Idea, since the bounds are so loose and trilinear enter at NLO in single Higgs process

Can single Higgs process help?

McCullough, 1312.3322
Gorbahn, Haisch 1607.03773
Degrassi, et al. 1607.04251
Bizon, et al. 1610.05771

LHC from discovery to high precision

McCullough, 1312.3322
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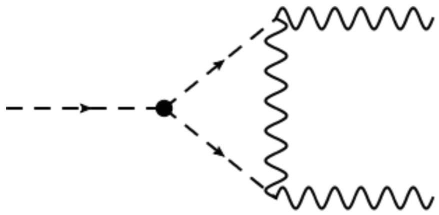
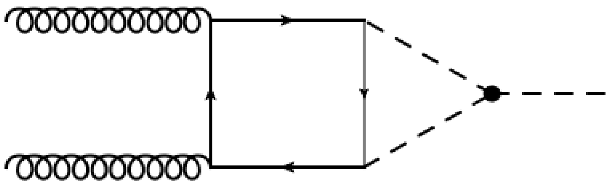
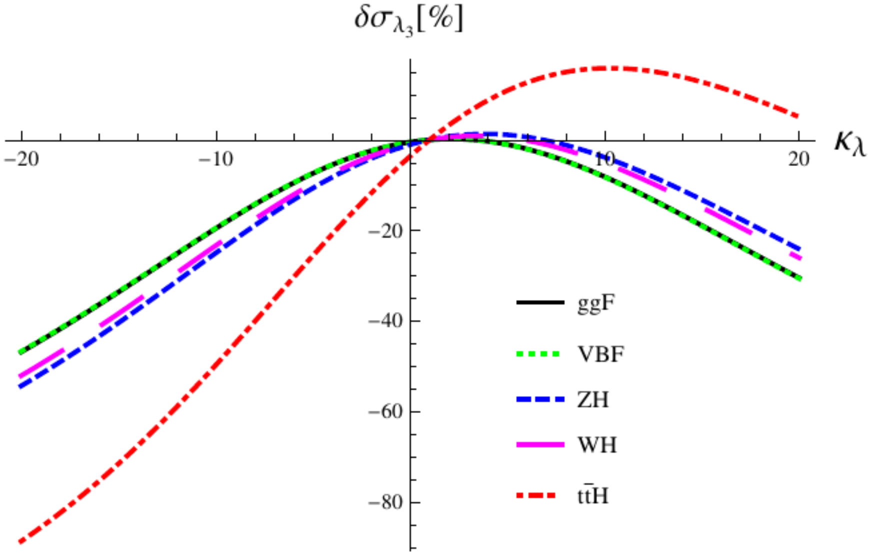
The trilinear coupling enter at loop level in single Higgs observables







Degrassi, et al. 1607.04251

Only κ_λ deviate from SM :
(68% CL at 3ab^{-1})

$$\longrightarrow \quad \kappa_\lambda \in [-0.7, 4.2]$$

Compared to an other double Higgs expected bound in $\mathrm{HH} \to b\bar{b}\gamma\gamma$

Dim. 6 EFT

$$\kappa_\lambda \in [0, 2.8] \cup [4.5, 6.1]$$

Azatov et al. 1502.00539

LHC from discovery to high precision

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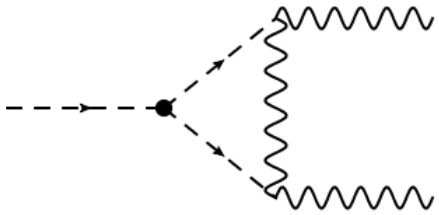

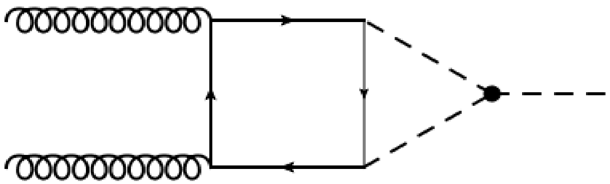

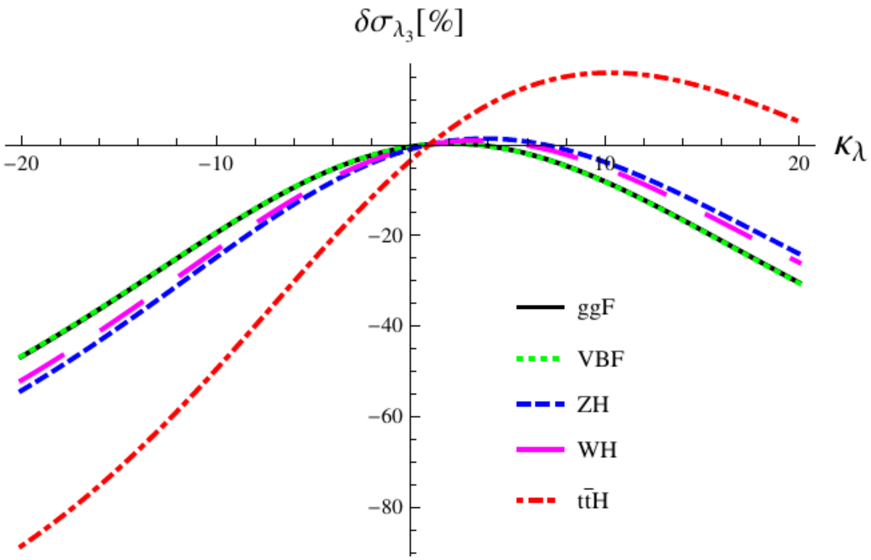

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Dim. 6 EFT

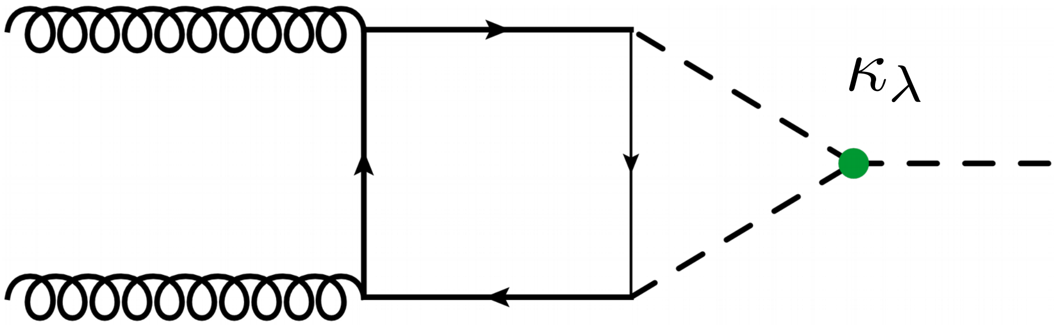
$$\kappa_\lambda \in [0, 2.8] \cup [4.5, 6.1]$$

Azatov et al. 1502.00539

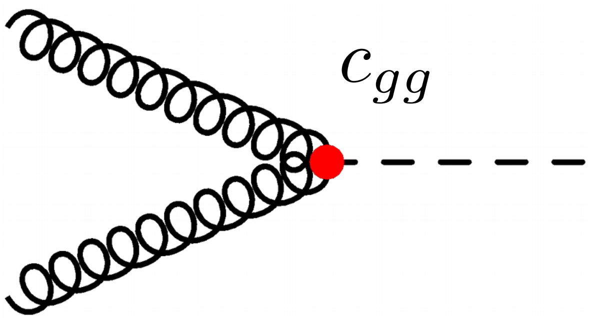
But my comparison is not fair
The bounds rely on different theoretical assumptions

Other deviations?

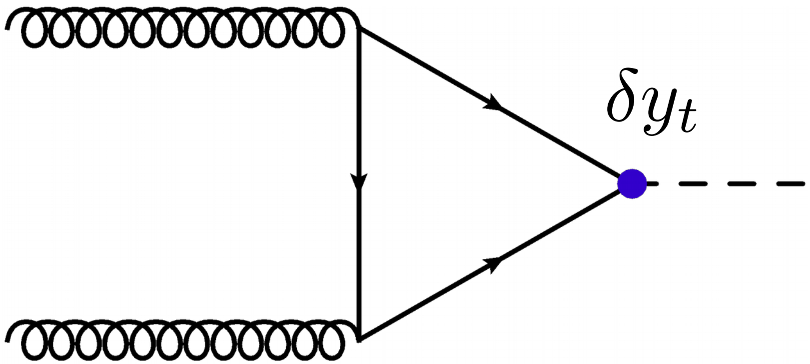
Setting on one anomalous coupling at a time is a strong assumption.



Versus



?



Is it possible to disentangle the different contributions?

The setup

Parametrization of dominating BSM effects in Higgs physics using dimension 6 Lagrangian in the "Higgs basis"

Assuming flavour universality and no CP violating operator

Tested in TGC

8 (+2) Independent operators that affect Higgs physics at leading order and have not been tested in existing precision measurements

6 parameters controlling deformations of the couplings to the SM gauge bosons

$$\delta c_z \;, \;\; c_{zz} \;, \;\; c_{z\Box} \;, \;\; \hat{c}_{z\gamma} \;, \;\; \hat{c}_{\gamma\gamma} \;, \;\; \hat{c}_{gg} \;,$$

3 related to the deformations of the fermion Yukawa's

$$\delta y_t \;, \;\; \delta y_d \;, \;\; \delta y_\tau \;,$$

1 distortion to the Higgs trilinear self-coupling

$$\boxed{\kappa_\lambda \;.}$$ **Today's focus**

Inclusive observables

Global Chi squared fit of the signal strengths

We explore the sensitivity of HL-LHC at 3/ab, using the ATLAS projection.

ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008

ATL-PHYS-PUB-2016-018

+ Updated ggF uncertainties

Process		Combination	Theory	Experimental
$H \to \gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H \to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H \to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
$H \to Z\gamma$	incl.	0.30	0.13	0.27
$H \to b\bar{b}$	WH	0.37	0.09	0.36
	ZH	0.14	0.05	0.13
$H \to \tau^+\tau^-$	VBF	0.19	0.12	0.15

We assume that in our EFT the dim 6 level is a good approximation.

Higher order therm can be neglected so we linearized the signal strength in the wilson coefficient

$$\mu = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \times \frac{\mathrm{BR}[f]}{(\mathrm{BR}[f])_{\mathrm{SM}}}$$

$$\approx 1 + \delta\sigma + \delta\mathrm{BR}$$

Inclusive observables at 8 TeV

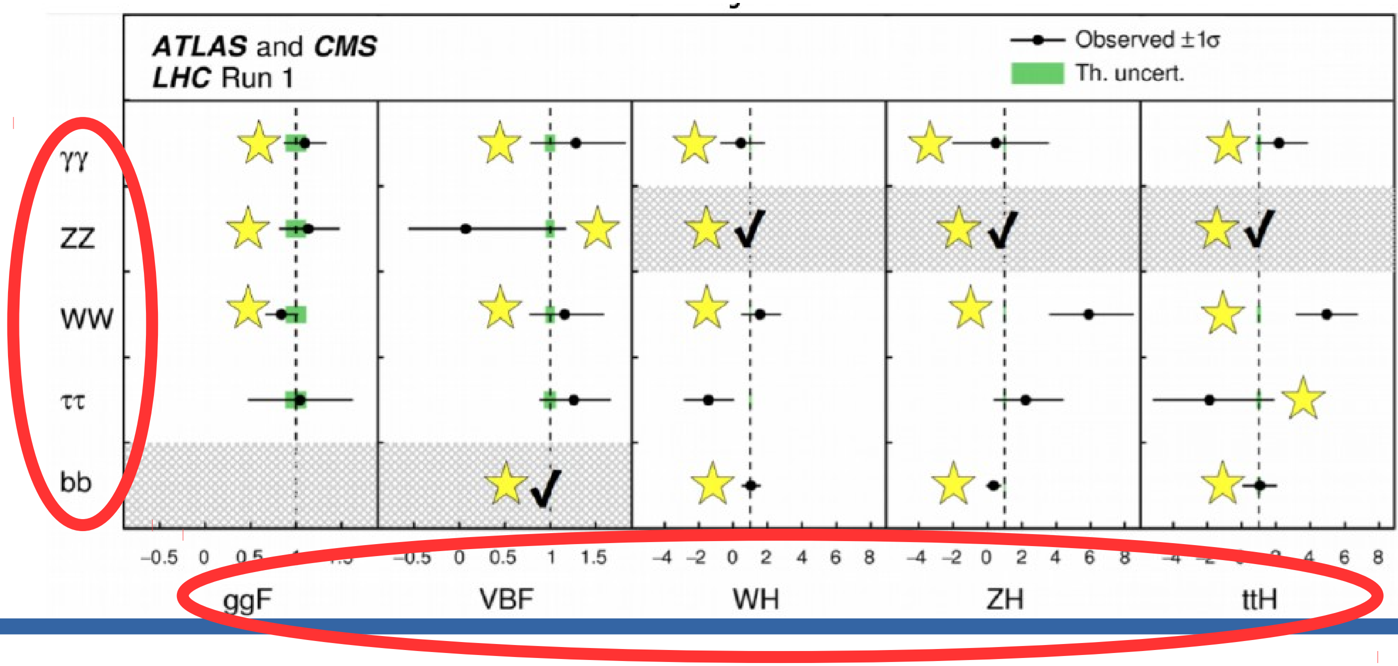
We have 10 quantities

✓ = done since Run 1 combination

☆ = 13 TeV results

σxBr normalised to SM

5 Decays



Diaconu @ Planck '17

5 Productions

Receiving modifications from 9+1 parameters

So, we should be able to constrain them by looking at the <u>signal strengths</u>

This is not possible

Only 9 Independent signal strength combinations (at the linear level)

$$\mu \approx 1 + \delta\sigma + \delta\mathrm{BR}$$

Shift in production can be compensated by opposite shift in decay

$\delta\sigma = -\delta\mathrm{BR}$ → **Unconstrained direction**

Single Higgs observable without the trilinear

Run 1 channel, Observable = SM exactly

$$
\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07 & (0.02) \\ 0.07 & (0.01) \\ 0.64 & (0.02) \\ 0.24 & (0.01) \\ 4.94 & (0.65) \\ 0.08 & (0.02) \\ 0.09 & (0.02) \\ 0.14 & (0.03) \\ 0.17 & (0.09) \end{pmatrix} \qquad \begin{bmatrix} 1 & -0.01 & -0.02 & 0.03 & 0.08 & 0.01 & -0.71 & 0.03 & 0.01 \\ & 1 & -0.45 & 0.36 & -0.61 & -0.33 & 0.18 & 0.89 & 0.53 \\ & & 1 & -0.99 & 0.69 & 0.11 & 0.38 & -0.47 & -0.74 \\ & & & 1 & -0.58 & -0.23 & -0.42 & 0.42 & 0.71 \\ & & & & 1 & -0.58 & 0.09 & -0.46 & -0.63 \\ & & & & & 1 & 0.14 & 0.04 & 0.04 \\ & & & & & & 1 & 0.25 & -0.08 \\ & & & & & & & 1 & 0.57 \\ & & & & & & & & 1 \end{bmatrix}.
$$

Global fit | Fit with only 1 wilson

$$
\left.\begin{array}{l} c_{zz} - c_{z\Box} \\ c_{zz} - \delta y_\tau \\ \hat{c}_{gg} - \delta y_t \\ \delta c_z - \delta y_b \\ \delta c_{z\Box} - \delta y_\tau \end{array}\right\} \text{Very correlated}
$$

$\rightarrow$ Global fit is needed!

Falkowski:1505.00046

Using 8 TeV channel

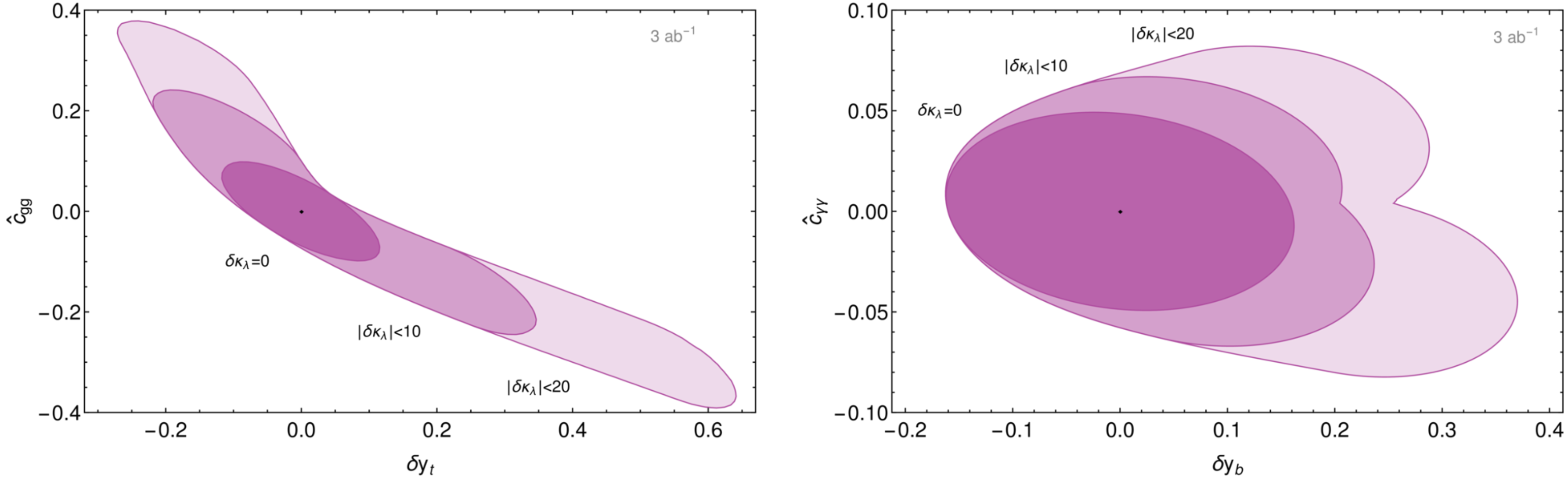
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$H \to \gamma\gamma$ (comb.)	0.13	0.09	0.09	0.04
(0j)	0.19	0.12	0.16	0.05
(1j)	0.27	0.14	0.23	0.05
(VBF-like)	0.47	0.43	0.22	0.15
(WH-like)	0.48	0.48	0.19	0.17
(ZH-like)	0.85	0.85	0.28	0.27
(ttH-like)	0.38	0.36	0.17	0.12
$H \to ZZ$ (comb.)	0.11	0.07	0.09	0.04
(VH-like)	0.35	0.34	0.13	0.12
(ttH-like)	0.49	0.48	0.20	0.16
(VBF-like)	0.36	0.33	0.21	0.16
(ggF-like)	0.12	0.07	0.11	0.04
$H \to WW$ (comb.)	0.13	0.08	0.11	0.05
(0j)	0.18	0.09	0.16	0.05
[redacted]				
(VBF-like)	0.21	0.20	0.15	0.09
[redacted]				
$H \to b\bar{b}$ (comb.)	0.26	0.26	0.14	0.12
(WH-like)	0.57	0.56	0.37	0.36
(ZH-like)	0.29	0.29	0.14	0.13
$H \to \tau\tau$ (VBF-like)	0.21	0.18	0.19	0.15
[redacted]				

ATL-PHYS-PUB-2014-016

Effect of the flat direction

Single Higgs without NLO effect validity

Incl. single Higgs data

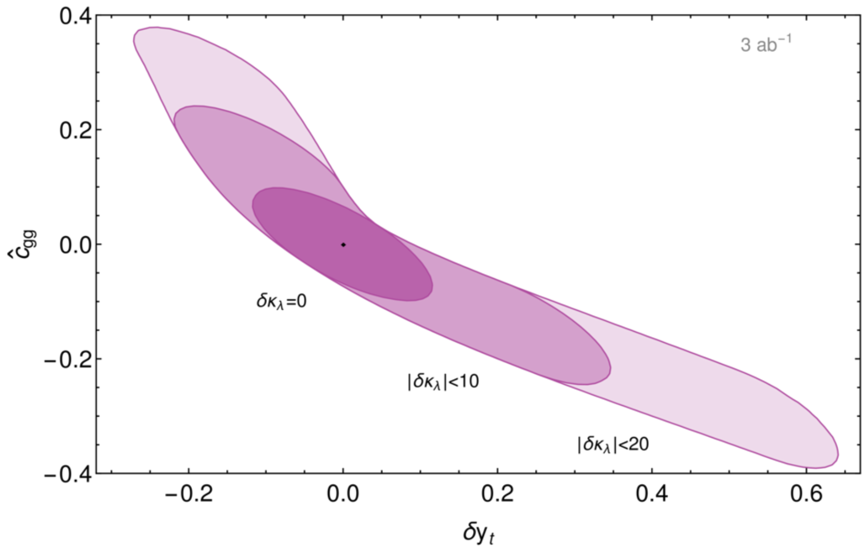


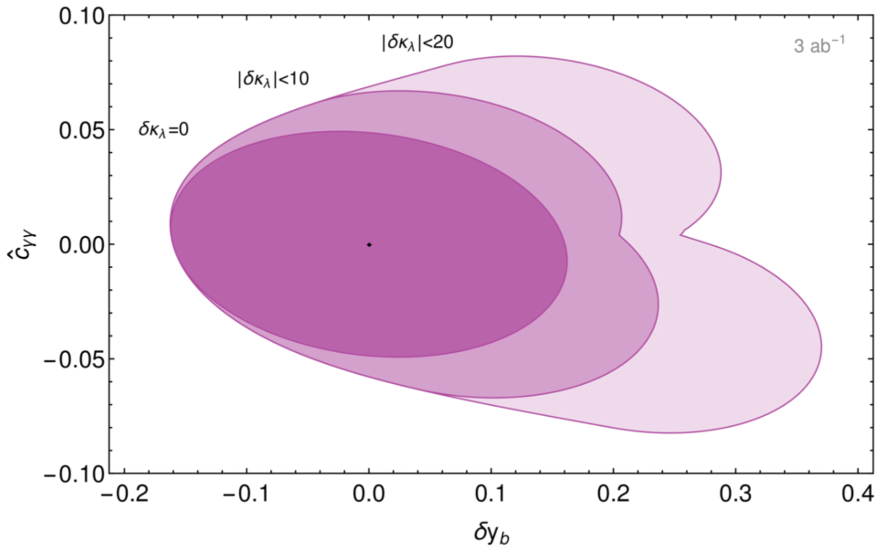
Only valid for reasonable value of the trilinear coupling

Effect of the flat direction

Single Higgs without NLO effect validity

Incl. single Higgs data





Only valid for reasonable value of the trilinear coupling

Valid in a SILH model

$$\delta c_z \sim v^2/f^2$$

$$\delta\kappa_\lambda \equiv \kappa_\lambda - 1 \sim v^2/f^2\,, \qquad f \sim \frac{m*}{g*} \qquad \delta c_z \sim \delta\kappa_\lambda$$

This is true for a broad class of model

A counter example

May not be valid for Higgs portal

$$\mathcal{L} \supset \theta g_* m_* H^\dagger H \varphi - \frac{m_*^4}{g_*^2} V(g_* \varphi / m_*)$$

Will generate:

$$\delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_3^2} \qquad \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{\rm SM}} \frac{v^2}{m^2}$$

With a typical tuning of $\Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$

Perturbative expansion $\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1$

$$\theta \simeq 1,\ g_* \simeq 3 \text{ and } m_* \simeq 2.5 \text{ TeV}$$

$$\varepsilon \simeq 0.1\,, \quad 1/\Delta \simeq 1.5\%$$

$$\boxed{\delta c_z \simeq 0.1\,, \quad \delta\kappa_\lambda \simeq 6}$$

Hard to have model with large deviation only in $\delta\kappa$ → **Single Higgs fit valid for most model**

Inclusive observables

Way out:

Extra constraints

1 - Higgs total width
$ - Compare different energies
1 - decay $\mu\mu$
2 - Anomalous triple gauge couplings(aTGCs)
1 - decay $Z\gamma$
L - Differential distributions
1 - Add double Higgs

Not helping too much
See paper for detail

But we are not using all the data available at 14 TeV 3ab^{-1}

Anomalous TGCs

At dimension 6, the aTGCs can be written in terms of the Higgs basis parameters

$$\delta g_{1,z} = \frac{1}{2(g-g')}\left[c_{\gamma\gamma}e^2 g' + c_{z\gamma}\left(g^2 - g'^2\right)g'^2 - c_{zz}\left(g^2+g'^2\right)g'^2 - c_{z\Box}\left(g^2+g'^2\right)g^2\right],$$

$$\delta\kappa_\gamma = -\frac{g^2}{2}\left(c_{\gamma\gamma}\frac{e^2}{g^2+g'^2} + c_{z\gamma}\frac{g^2-g'^2}{g^2+g'^2} - c_{zz}\right)$$

$H \to Z\gamma$

Process		Combination	Theory	Experimental
$H\to\gamma\gamma$	ggF	0.07	0.05	0.05
	VBF	0.22	0.16	0.15
	$t\bar{t}H$	0.17	0.12	0.12
	WH	0.19	0.08	0.17
	ZH	0.28	0.07	0.27
$H\to ZZ$	ggF	0.06	0.05	0.04
	VBF	0.17	0.10	0.14
	$t\bar{t}H$	0.20	0.12	0.16
	WH	0.16	0.06	0.15
	ZH	0.21	0.08	0.20
$H\to WW$	ggF	0.07	0.05	0.05
	VBF	0.15	0.12	0.09
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	ZH	0.14	0.05	0.13
$H\to\tau^+\tau^-$	VBF	0.19	0.12	0.15

ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008

ATL-PHYS-PUB-2016-018

+ Updated ggF uncertainties

Correlation with new observables

$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07 & (0.02) \\ 0.07 & (0.01) \\ 0.64 & (0.02) \\ 0.24 & (0.01) \\ 4.94 & (0.65) \\ 0.08 & (0.02) \\ 0.09 & (0.02) \\ 0.14 & (0.03) \\ 0.17 & (0.09) \end{pmatrix} \begin{bmatrix} 1 & -0.01 & -0.02 & 0.03 & 0.08 & 0.01 & \mathbf{-0.71} & 0.03 & 0.01 \\ & 1 & -0.45 & 0.36 & -0.61 & -0.33 & 0.18 & \mathbf{0.89} & 0.53 \\ & & 1 & \mathbf{-0.99} & 0.69 & 0.11 & 0.38 & -0.47 & \mathbf{-0.74} \\ & & & 1 & -0.58 & -0.23 & -0.42 & 0.42 & \mathbf{0.71} \\ & & & & 1 & -0.58 & 0.09 & -0.46 & -0.63 \\ & & & & & 1 & 0.14 & 0.04 & 0.04 \\ & & & & & & 1 & 0.25 & -0.08 \\ & & & & & & & 1 & 0.57 \\ & & & & & & & & 1 \end{bmatrix}.$$

New channels help the correlations

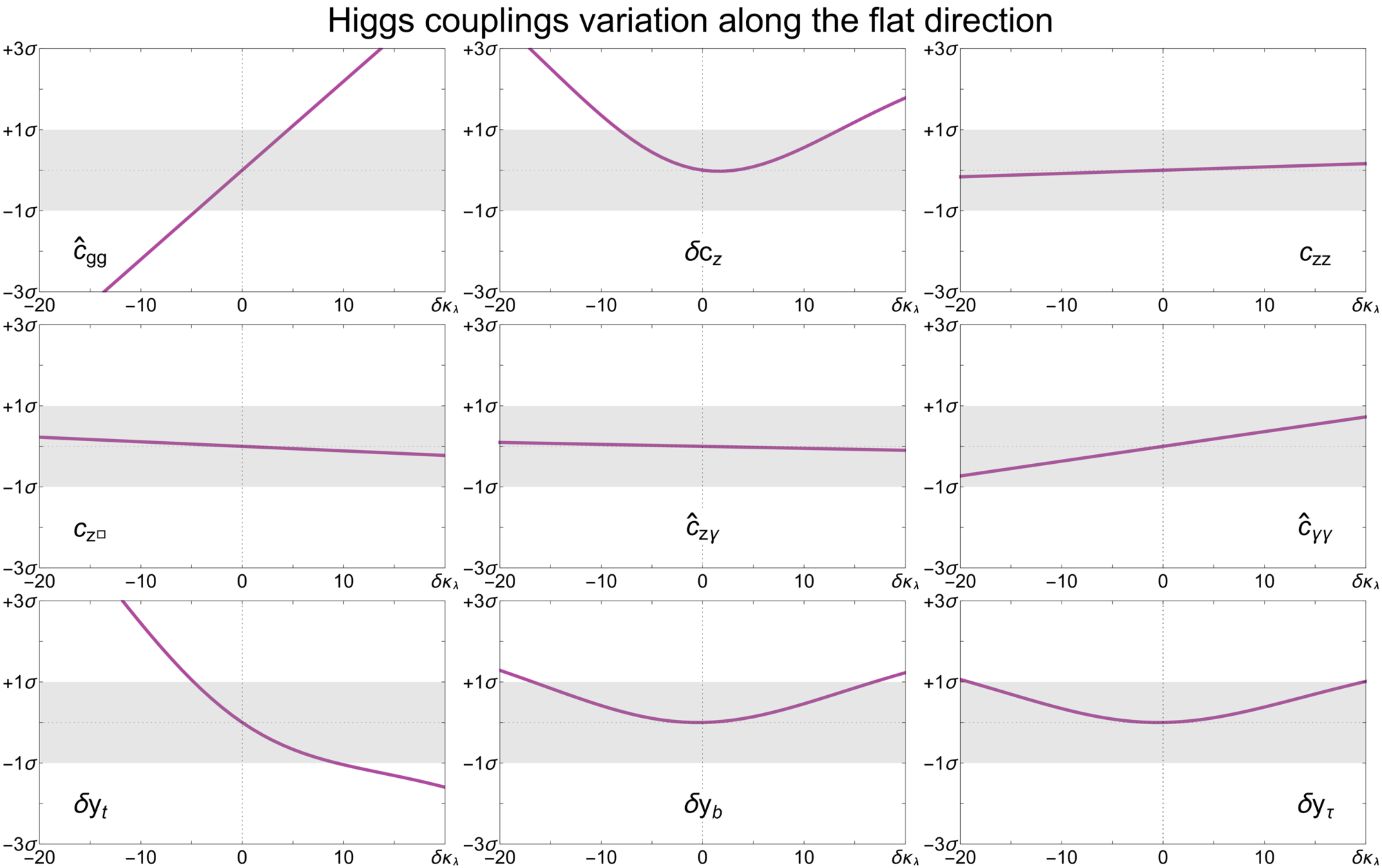
$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \end{pmatrix} = \pm \begin{pmatrix} 0.07 & (0.02) \\ 0.05 & (0.01) \\ 0.05 & (0.02) \\ 0.02 & (0.01) \\ 0.09 & (0.09) \\ 0.03 & (0.02) \\ 0.08 & (0.02) \\ 0.12 & (0.03) \\ 0.11 & (0.09) \end{pmatrix} \begin{bmatrix} 1 & 0.04 & -0.01 & -0.01 & 0.04 & 0.31 & -0.76 & 0.05 & 0.02 \\ & 1 & -0.07 & -0.26 & 0.01 & 0.01 & 0.36 & 0.88 & 0.27 \\ & & 1 & -0.87 & 0.13 & 0.20 & 0.03 & -0.07 & -0.06 \\ & & & 1 & -0.09 & -0.09 & -0.09 & -0.17 & 0.08 \\ & & & & 1 & 0.05 & -0.02 & -0.02 & -0.03 \\ & & & & & 1 & -0.32 & -0.19 & -0.12 \\ & & & & & & 1 & 0.50 & 0.28 \\ & & & & & & & 1 & 0.36 \\ & & & & & & & & 1 \end{bmatrix}.$$

Linear fit become a good approximation
(If we can constrain the trilinear!)

The flat direction

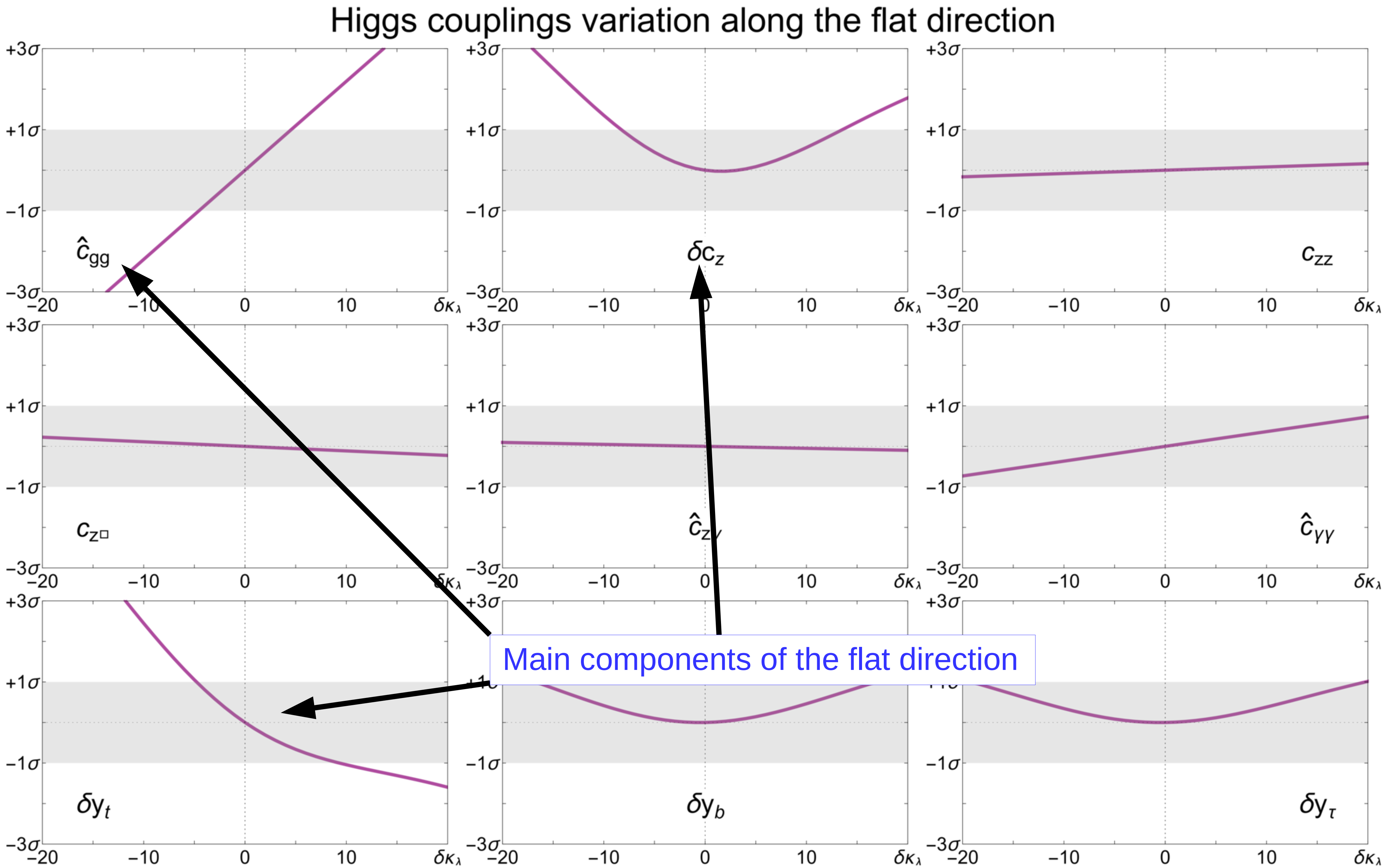
Value of all the couplings in function of $\delta\kappa_\lambda$ such that

All the $\delta\mu=0$



The flat direction

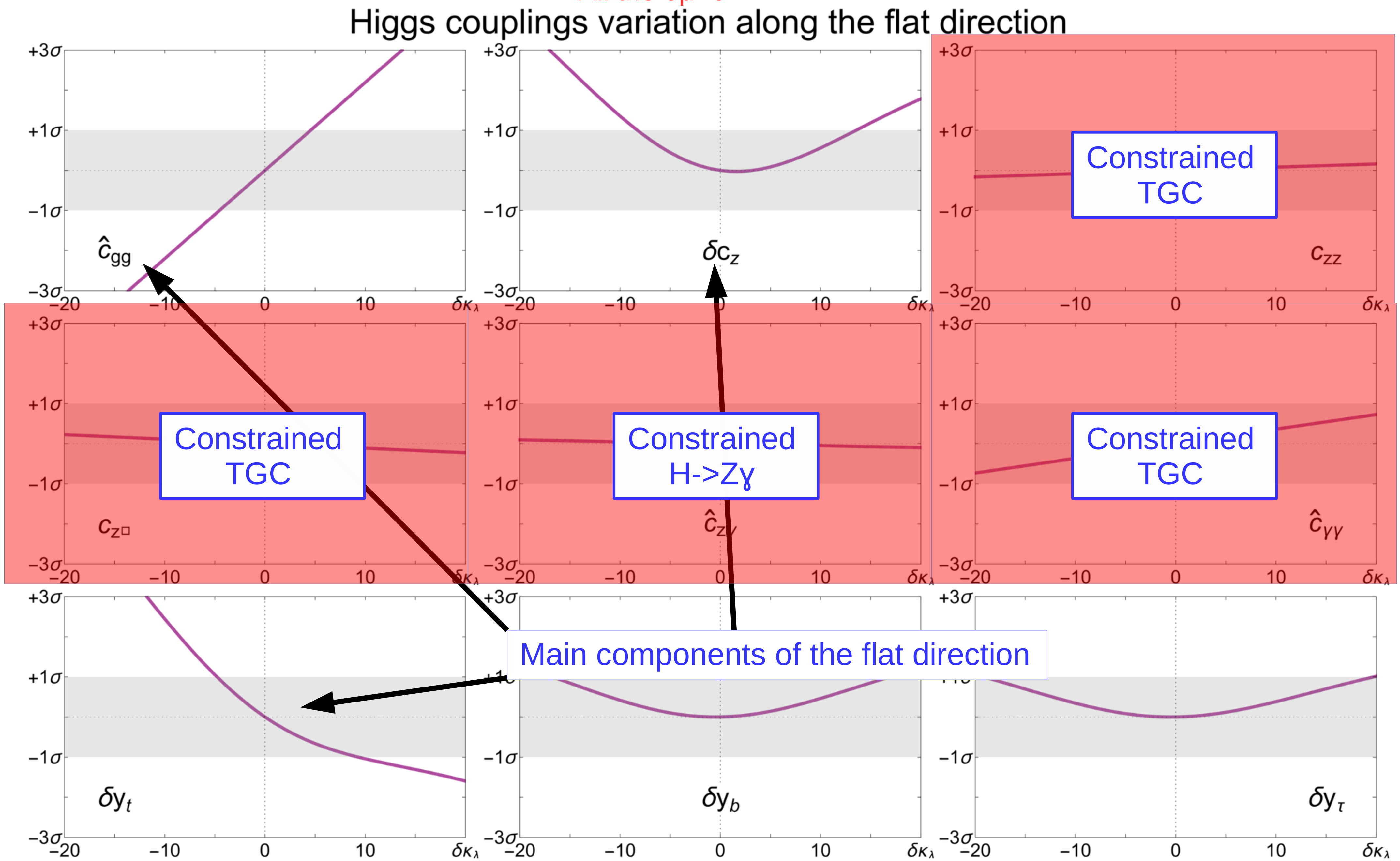
Value of all the couplings in function of $\delta\kappa_\lambda$ such that
All the δμ=0



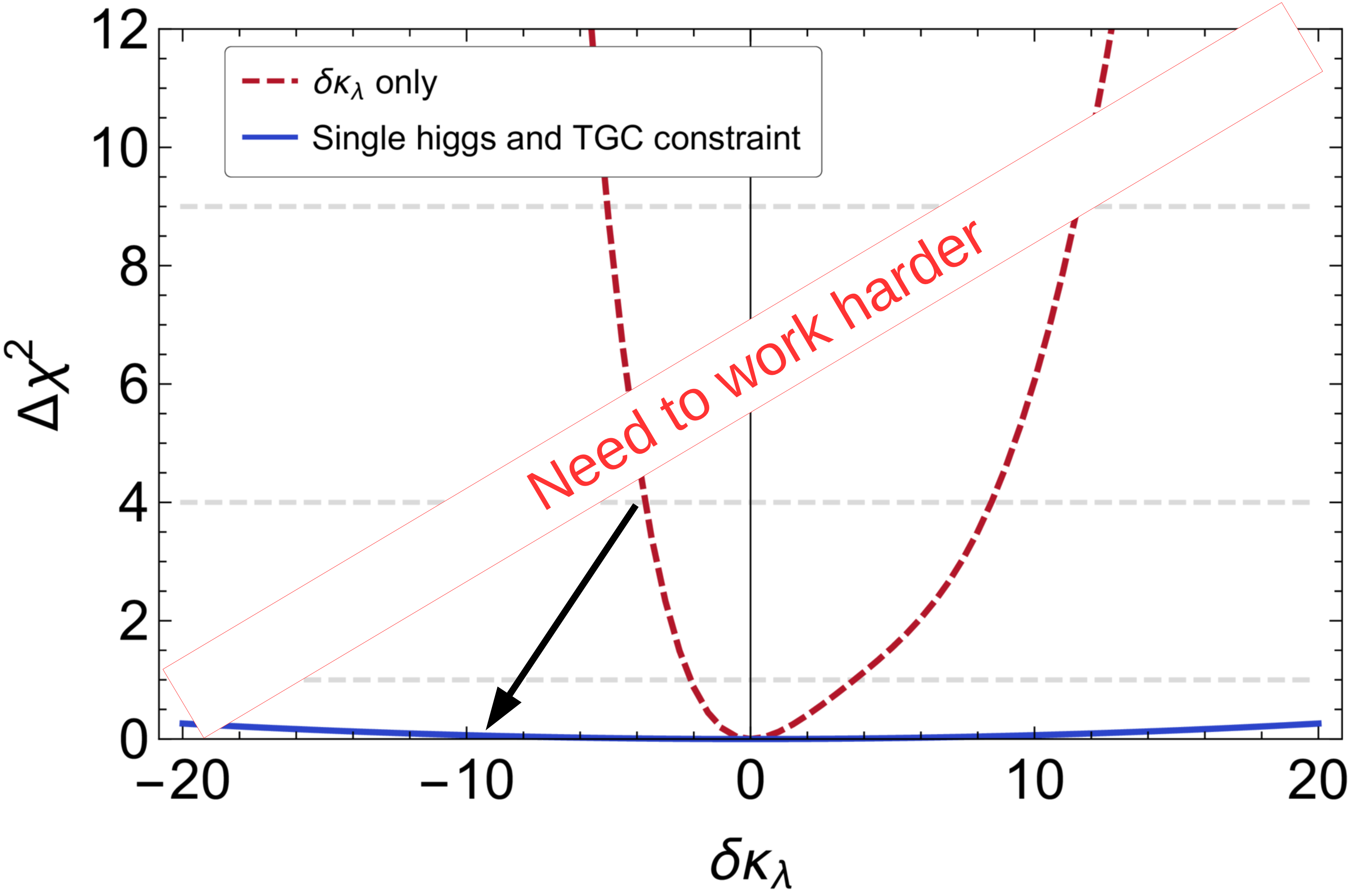
What we constrained

Value of all the couplings in function of $\delta\kappa_\lambda$ such that

All the δμ=0



Not enough constraints



Differential Observables

<u>Rough</u> analysis looking at the prospects of differential observables

Cross section in each bin in terms of the EFT parameters computed using MadGraph.

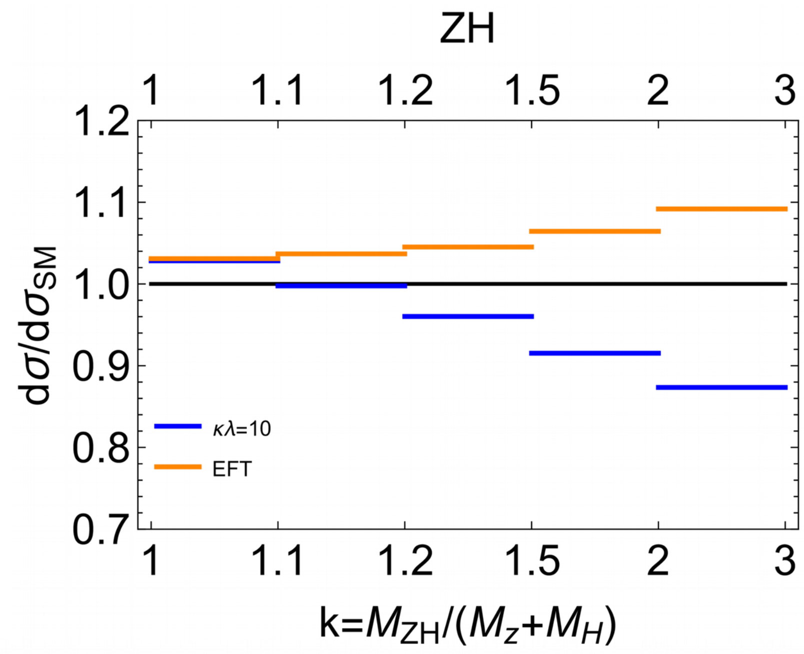
Dependence on Higgs trilinear computed in Degrassi, et al. 1607.04251

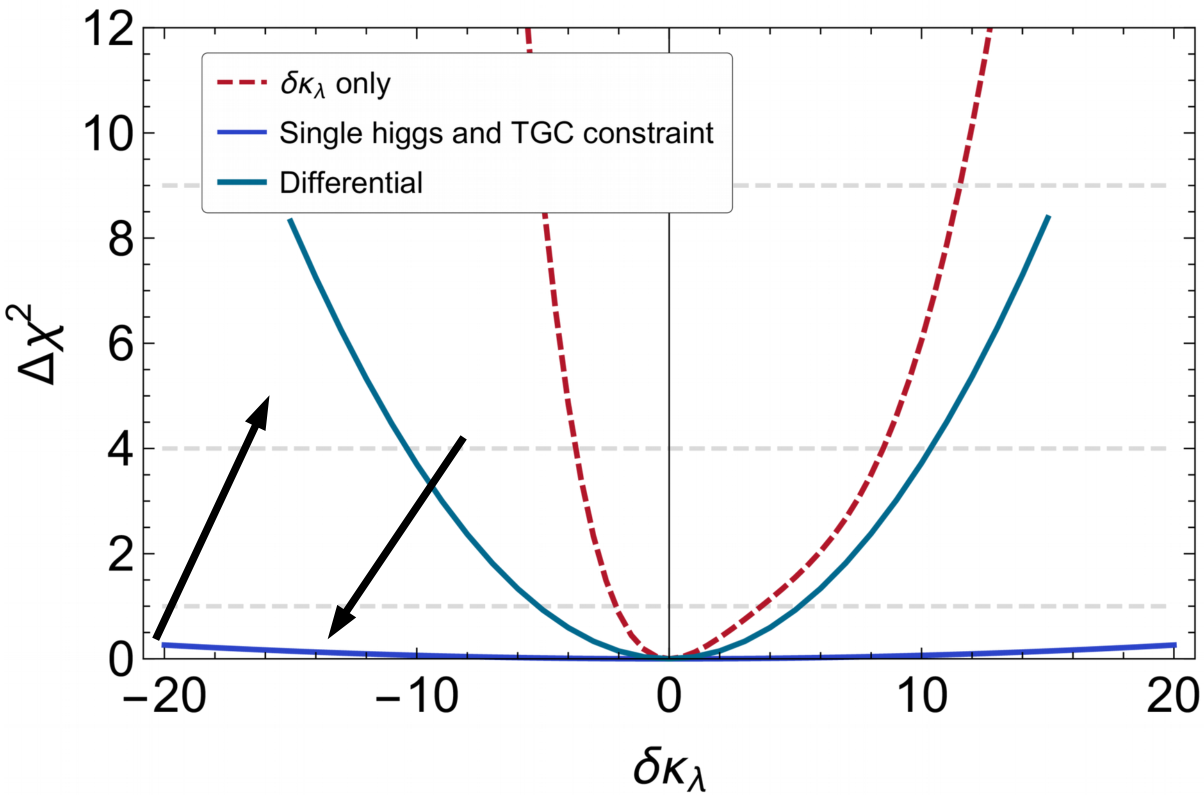
Restore some power to the method, may be seen as complement to double Higgs

Maybe other differential observable can be more powerful

68% CL, 3ab^{-1}

$\kappa_\lambda \in [-3.4, 6.4]$

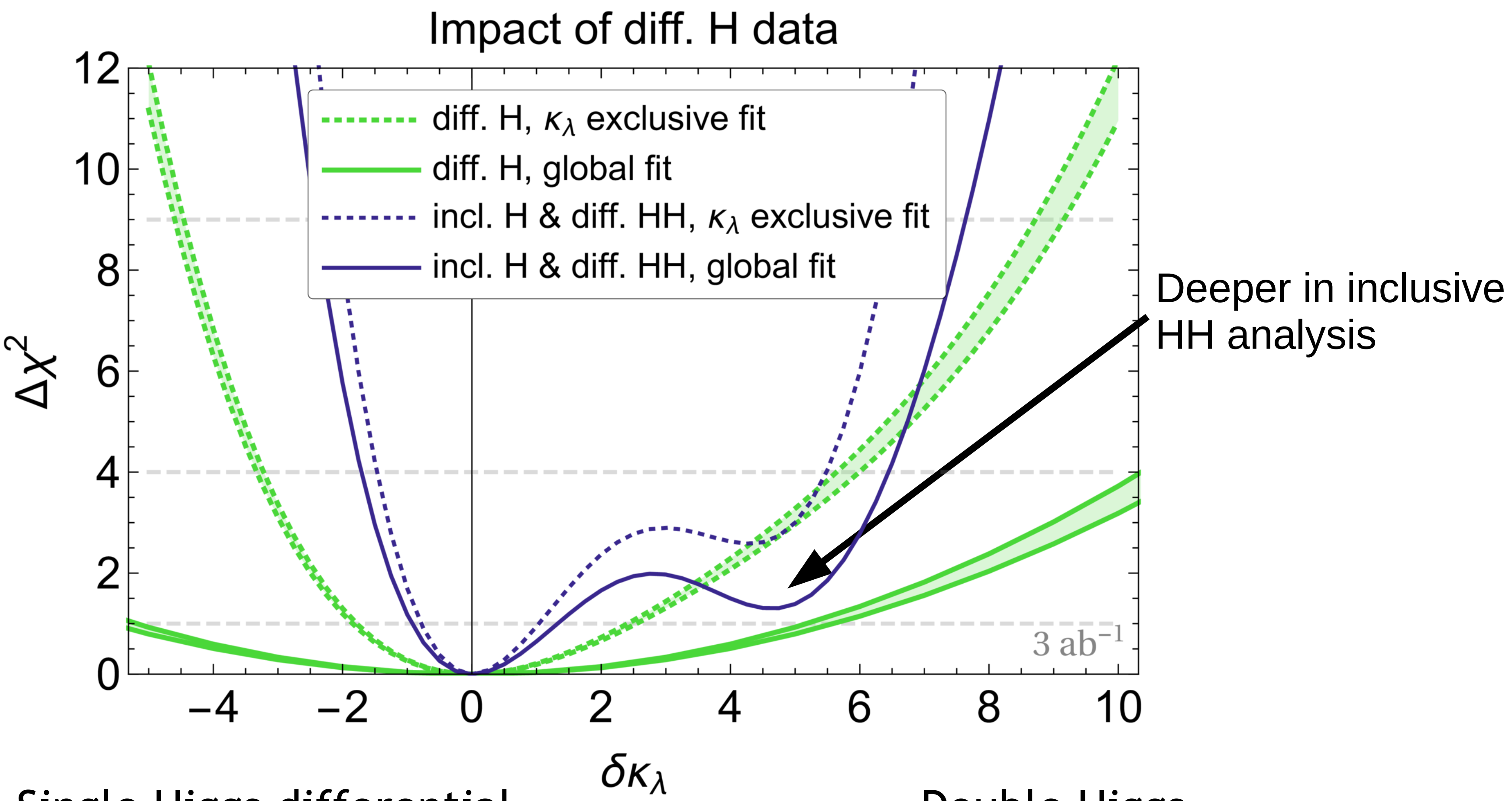




Differential Observables versus double Higgs

Double Higgs analysis more powerful

It also solves the flat direction issue in single Higgs



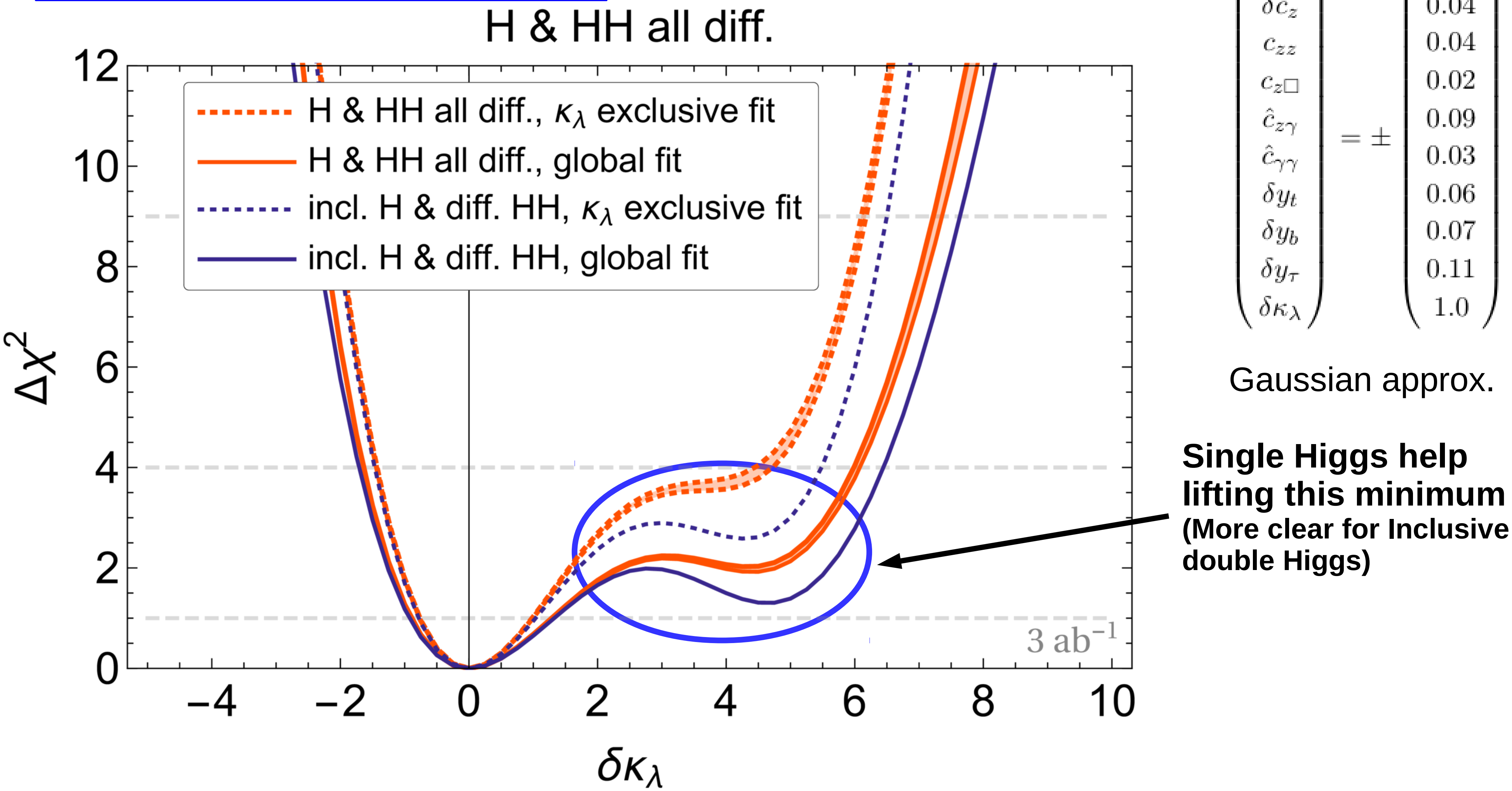
Single Higgs differential

$\delta\kappa_\lambda \in [-5.4, 5.4]$

Double Higgs

$\delta\kappa_\lambda \in [-0.9, 1.2]$

Adding double Higgs



$$\begin{pmatrix} \hat{c}_{gg} \\ \delta c_z \\ c_{zz} \\ c_{z\Box} \\ \hat{c}_{z\gamma} \\ \hat{c}_{\gamma\gamma} \\ \delta y_t \\ \delta y_b \\ \delta y_\tau \\ \delta\kappa_\lambda \end{pmatrix} = \pm \begin{pmatrix} 0.06 \\ 0.04 \\ 0.04 \\ 0.02 \\ 0.09 \\ 0.03 \\ 0.06 \\ 0.07 \\ 0.11 \\ 1.0 \end{pmatrix}$$

Gaussian approx.

68% CL, 3ab^{-1} $\kappa_\lambda \in [0.12, 2.24]$

More results in **JHEP09(2017)069**

What about the future?

Possible future colliders will measure signal strength with high precision and open new channels

McCullough, 1312.3322

$$e^-e^+ \to \nu\bar{\nu}h$$

$$e^-e^+ \to \nu\bar{\nu}hh$$

Grow with energy

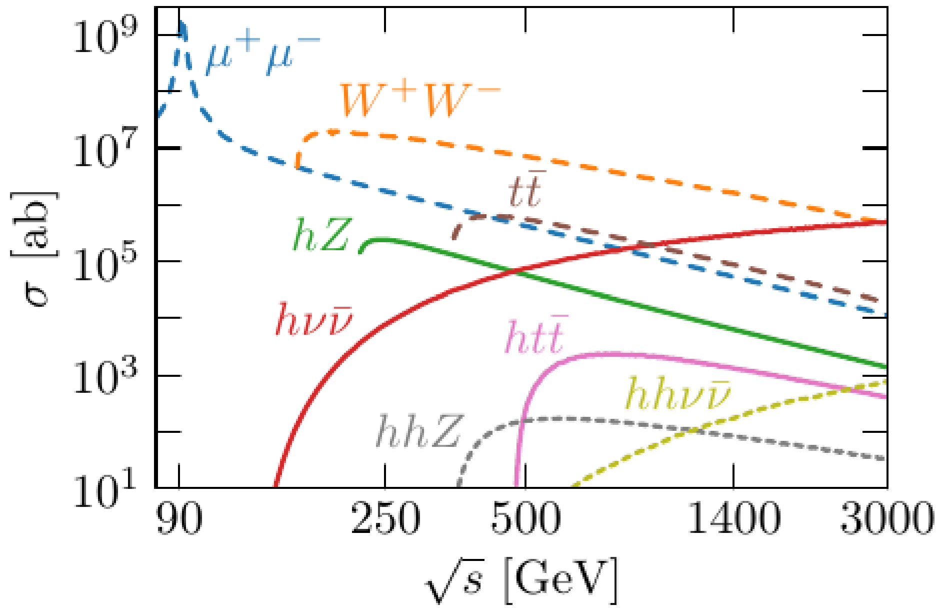
$$e^-e^+ \to zh$$

$$e^-e^+ \to zhh$$

$$e^-e^+ \to t\bar{t}h$$

Maximum around threshold

What can CLIC, ILC , CEPC, FCC-ee tell us about the trilinear?



G. Durieux 11th Annual Meeting of the Helmholtz Alliance "Physics at the Terascale"

Future lepton collider

Circular CEPC, FCC-ee

single Higgs process only

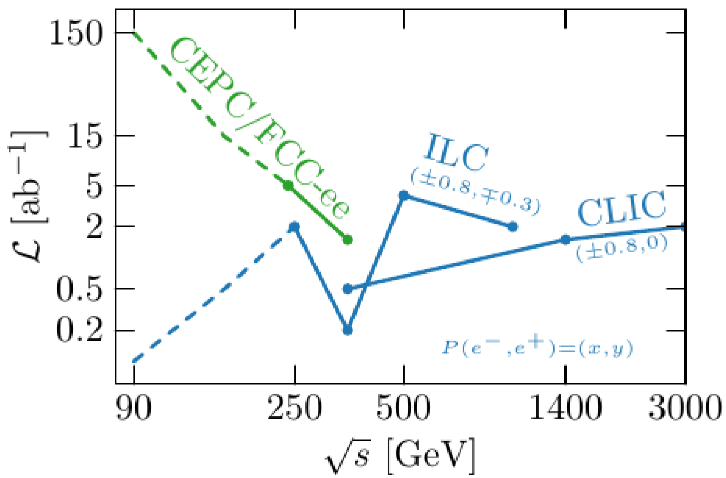
Pro:
- High low energy luminosity
- Tunnel can be reused for pp machine

Con:
- Can not reach High energy. Max planned ~ 350 GeV (Bremsstrahlung), tth need ~500GeV

Linear ILC, CLIC

Can probe pair production

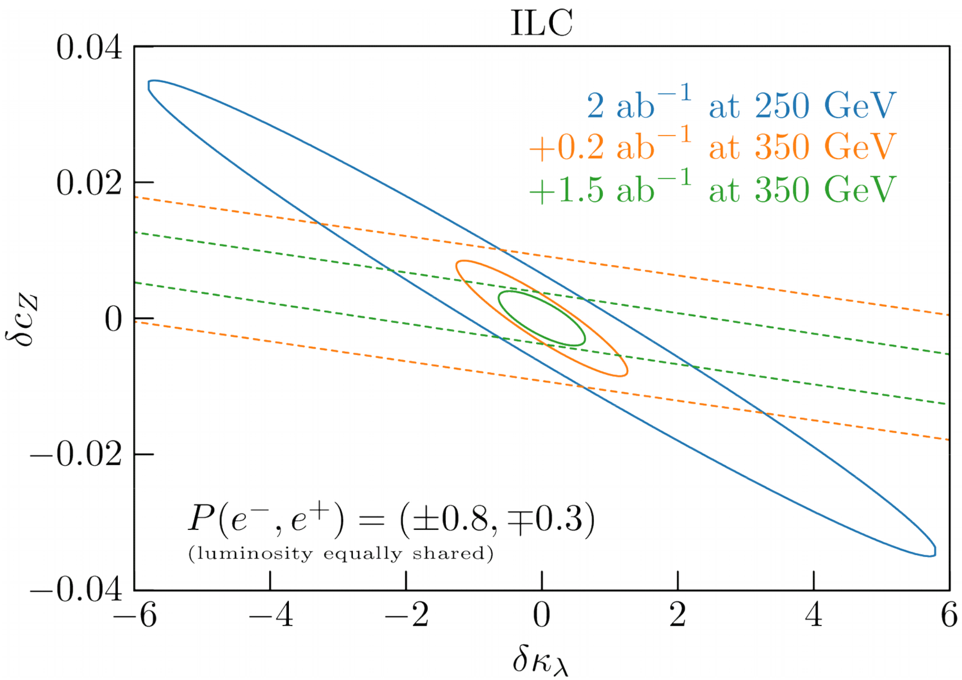
Pro:
- High energy, can reach the double Higgs threshold

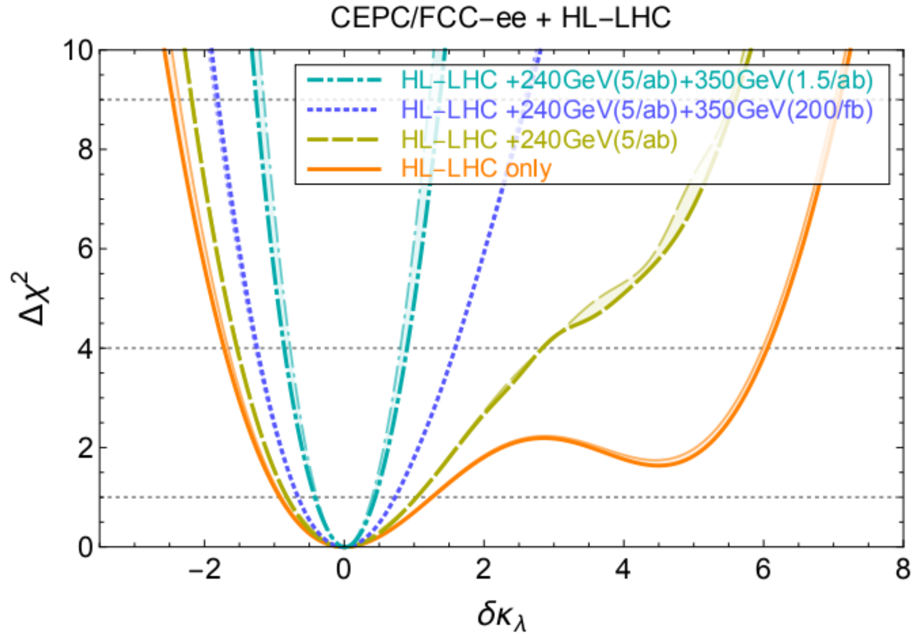


G. Durieux

If someone know why luminosity goes up with energy I am interested

Low energy collider





Correlated directions make global fit important to extract bounds

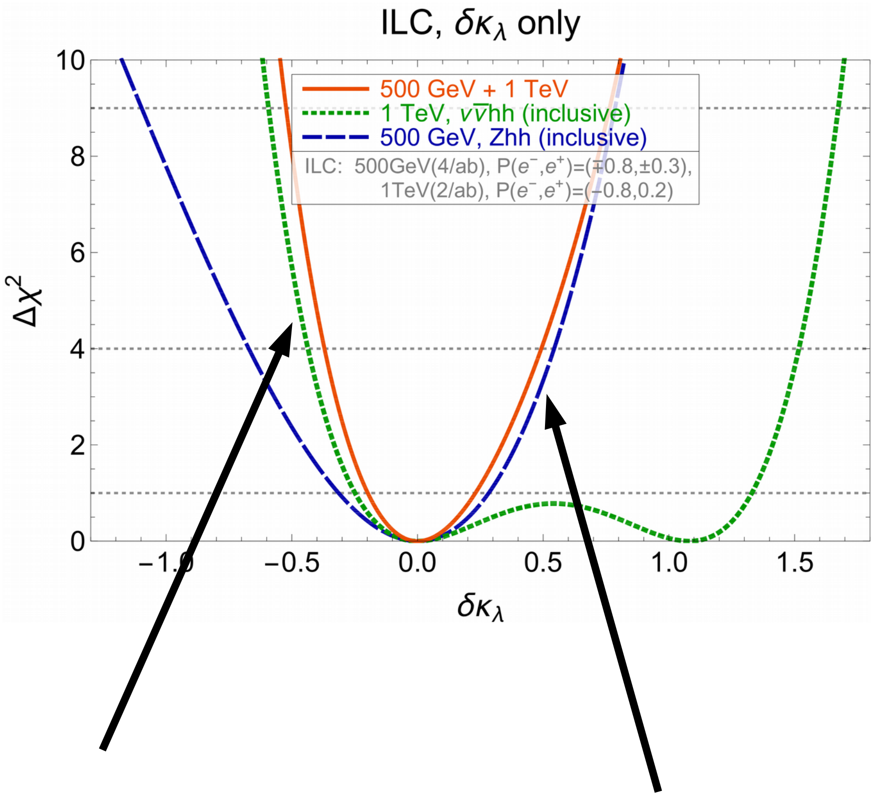
250 GeV run need LHC data to lift degeneracy but lift the second minima.

ILC 250 and 350 GeV are complementary.

After 1.5 ab^{-1} lepton collider dominate bound.

High energy colliders

Complementarity between 500 and 1 TeV run!

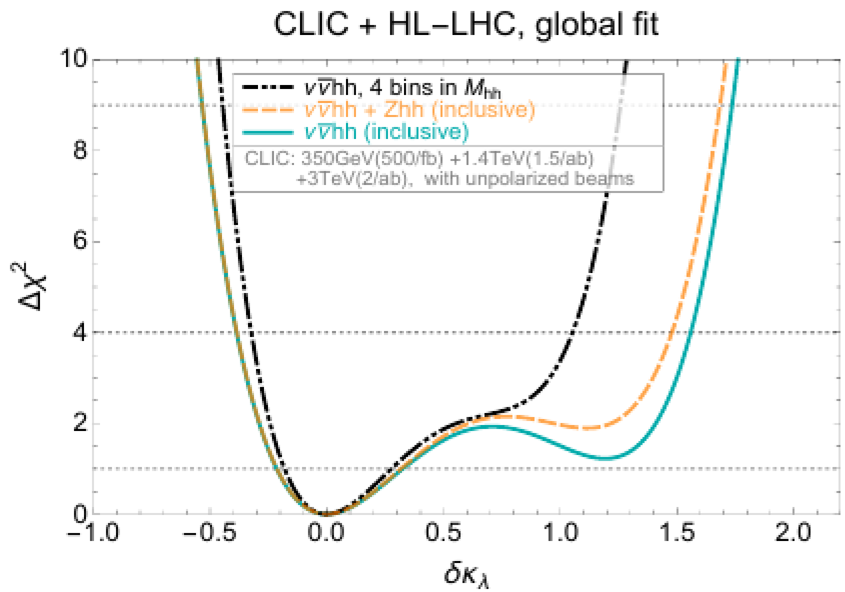


1 TeV constrain negative value

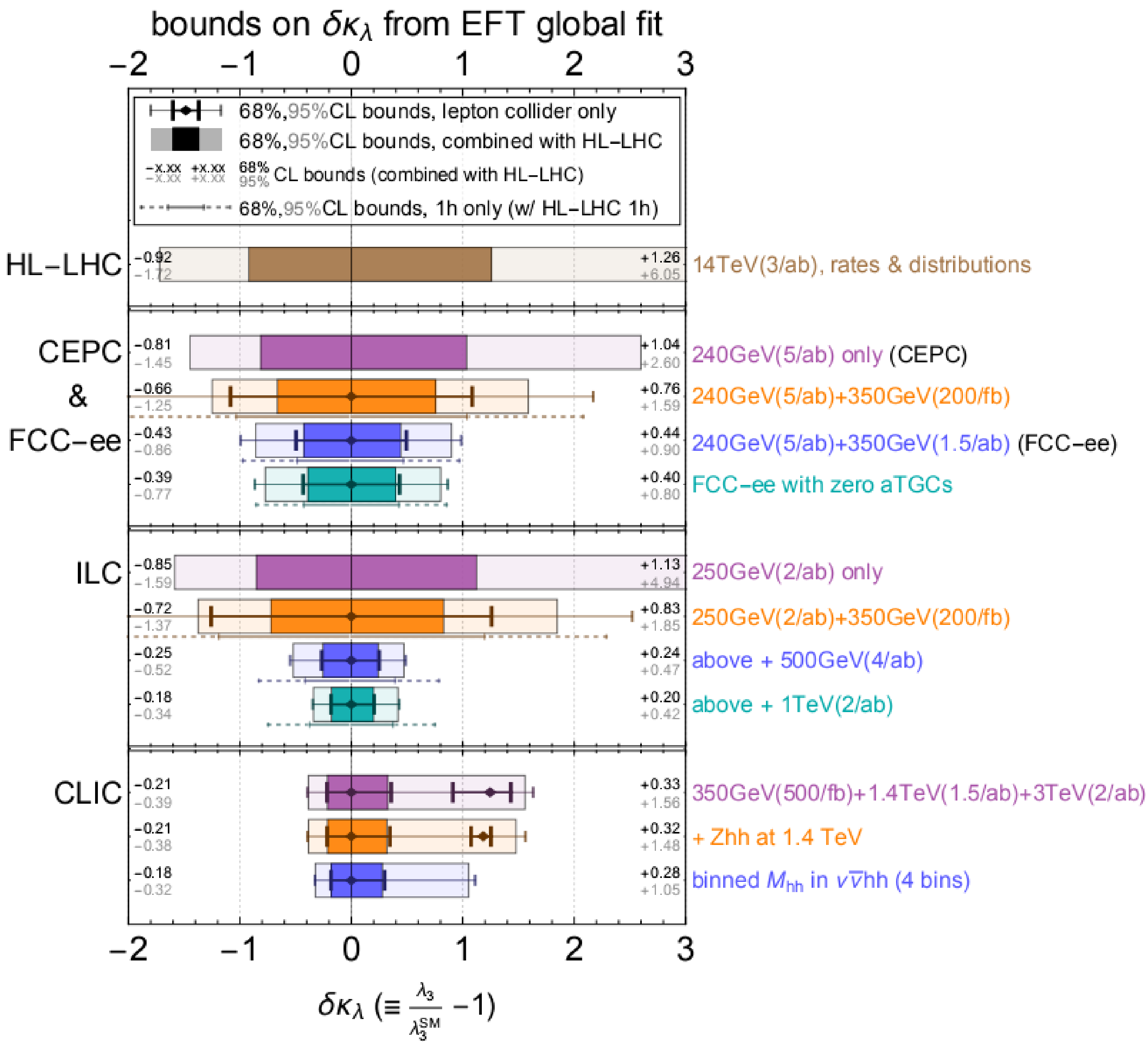
500 GeV constrain positive value

CLIC miss the 500 run to constrain positive trilinear value.

Differential information can compensate for it

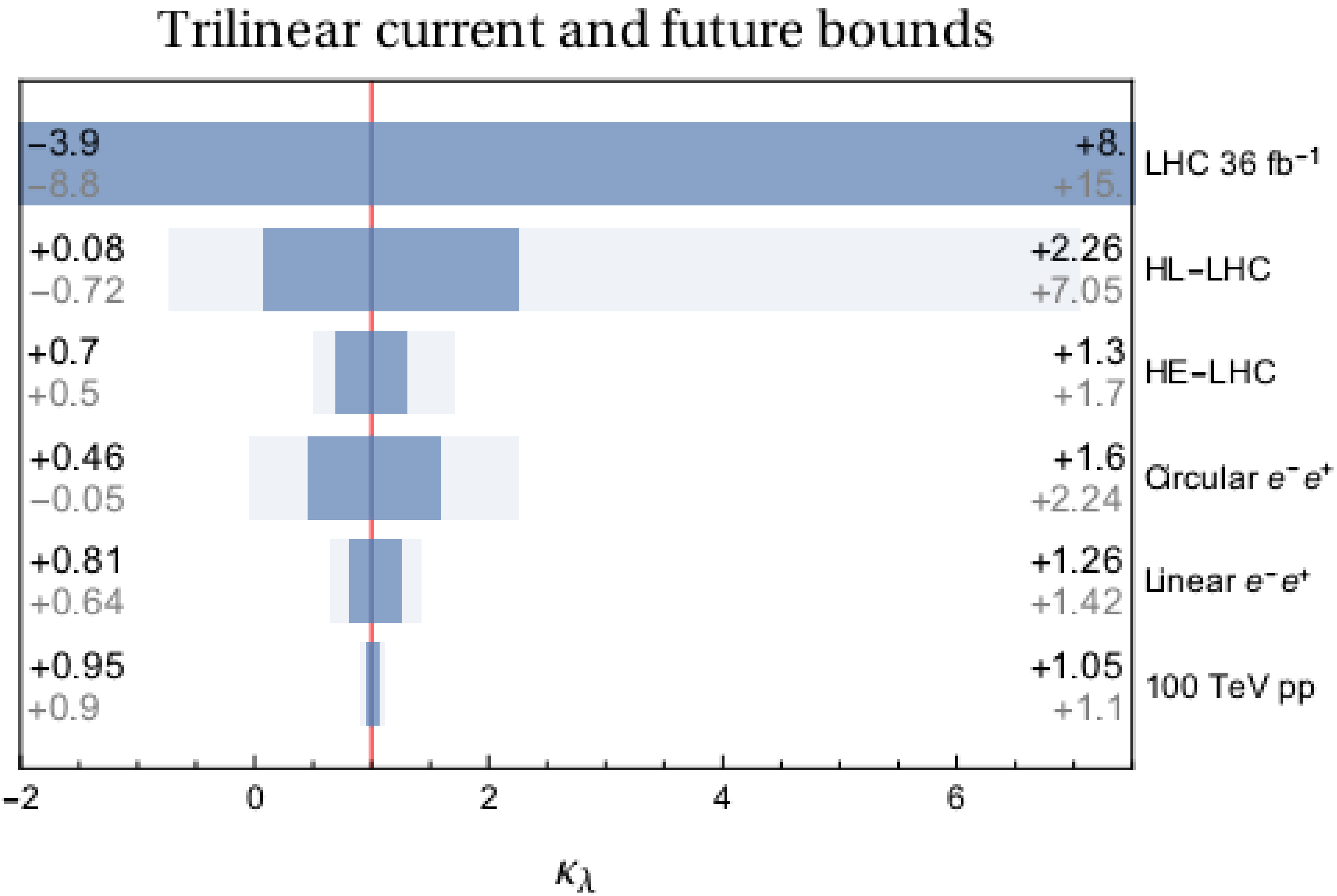


Big summary



bounds on $\delta\kappa_\lambda$ from EFT global fit
68%,95%CL bounds, lepton collider only
68%,95%CL bounds, combined with HL-LHC
68% 95% CL bounds (combined with HL-LHC)
68%,95%CL bounds, 1h only (w/ HL-LHC 1h)
HL-LHC
−0.92 −1.72 +1.26 +6.05
14TeV(3/ab), rates & distributions
CEPC & FCC-ee
−0.81 −1.45 +1.04 +2.60
240GeV(5/ab) only (CEPC)
−0.66 −1.25 +0.76 +1.59
240GeV(5/ab)+350GeV(200/fb)
−0.43 −0.86 +0.44 +0.90
240GeV(5/ab)+350GeV(1.5/ab) (FCC-ee)
−0.39 −0.77 +0.40 +0.80
FCC-ee with zero aTGCs
ILC
−0.85 −1.59 +1.13 +4.94
250GeV(2/ab) only
−0.72 −1.37 +0.83 +1.85
250GeV(2/ab)+350GeV(200/fb)
−0.25 −0.52 +0.24 +0.47
above + 500GeV(4/ab)
−0.18 −0.34 +0.20 +0.42
above + 1TeV(2/ab)
CLIC
−0.21 −0.39 +0.33 +1.56
350GeV(500/fb)+1.4TeV(1.5/ab)+3TeV(2/ab)
−0.21 −0.38 +0.32 +1.48
+ Zhh at 1.4 TeV
−0.18 −0.32 +0.28 +1.05
binned M_{hh} in $\nu\bar{\nu}hh$ (4 bins)
−2 −1 0 1 2 3
$\delta\kappa_\lambda \left(\equiv \frac{\lambda_3}{\lambda_3^{SM}} - 1\right)$

Recapitulation



Concluding remark

Extracting coupling is model dependant.

Direct measurement of the Higgs potential is challenging.

NLO effect in single-Higgs physics are an interesting idea to constrain the trilinear and will show it full potential for leptonic machines

A 100 TeV collider will probably be needed for sub 10% determination of the trilinear (however, the quartic self-coupling will still be missing)

Thank you