A global view on the Higgs self coupling

Thibaud Vantalon
DESY - IFAE

Based on:

JHEP09(2017)069, S. Di Vita, C. Grojean, G. Panico, M.Riembau, T. Vantalon

DESY THEORY WORKSHOP
26 - 29 September 2017

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Fundamental physics in the cosmos:
The early, the large and the dark Universe

DESY Hamburg, Germany

Motivation

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

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

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

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h^3 challenging to measure at LHC

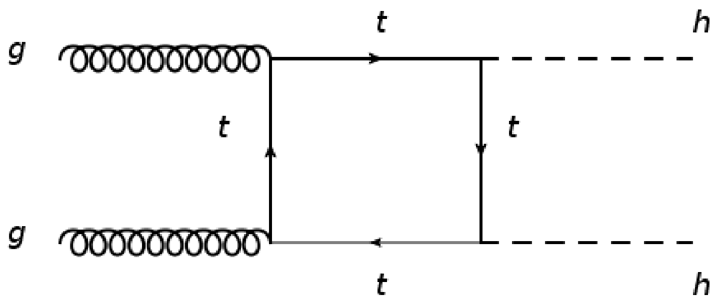
h^4 ~~out of reach of LHC~~

Double Higgs production

Small production cross section:

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

Negative interference decrease cross section:



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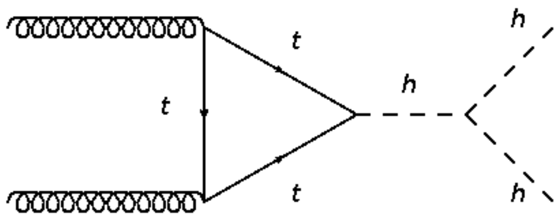

Most promising channel is a trade off between cleanness and statistic:

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

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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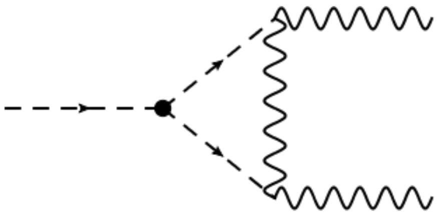
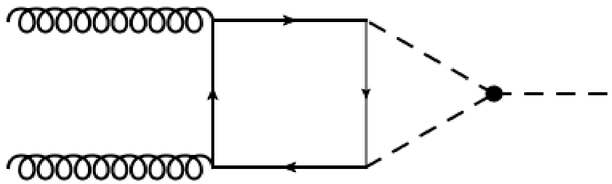
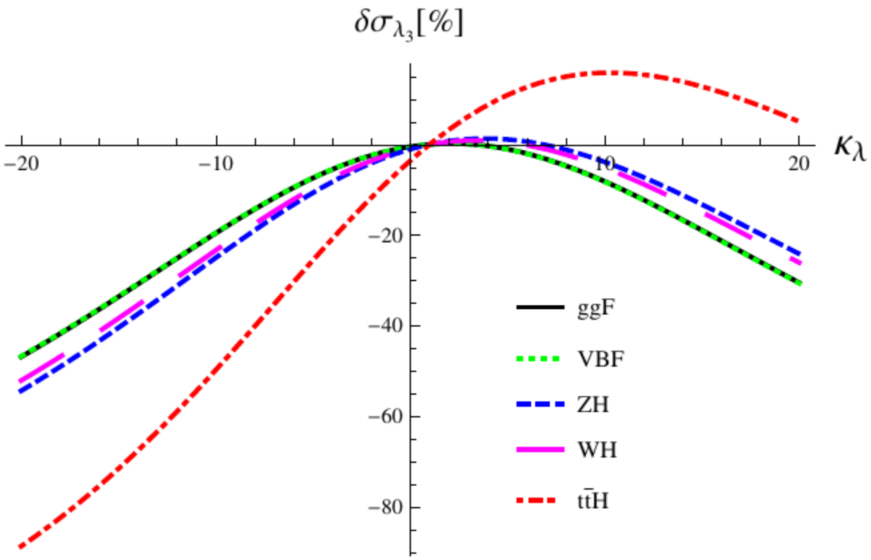
The trilinear coupling enter at loop level in single Higgs observables







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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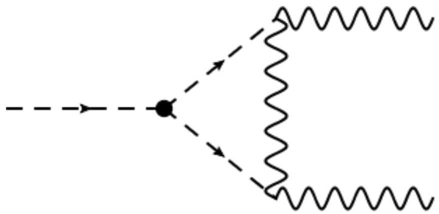

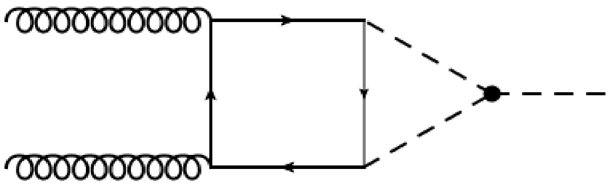

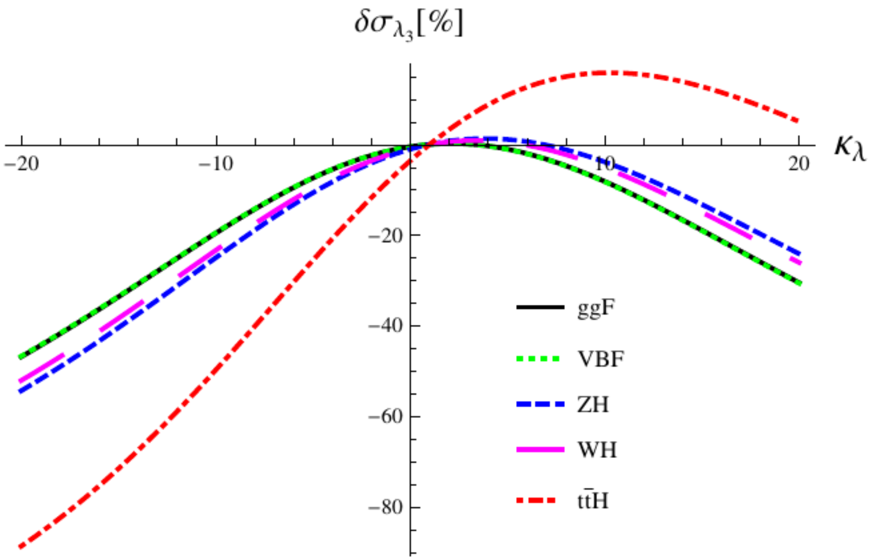

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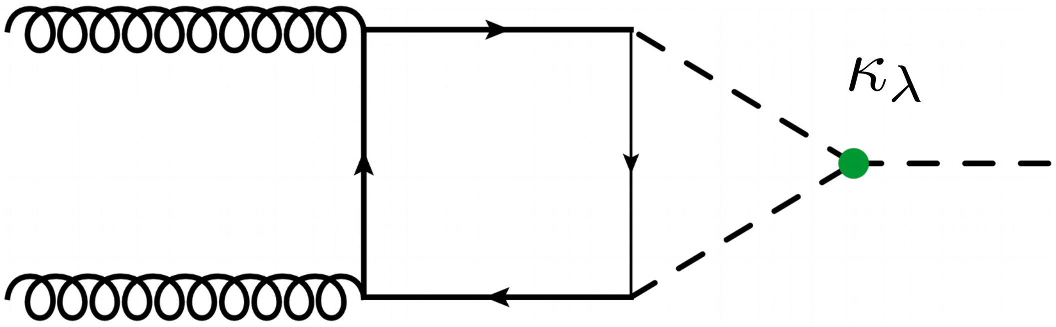
Azatov et al. 1502.00539

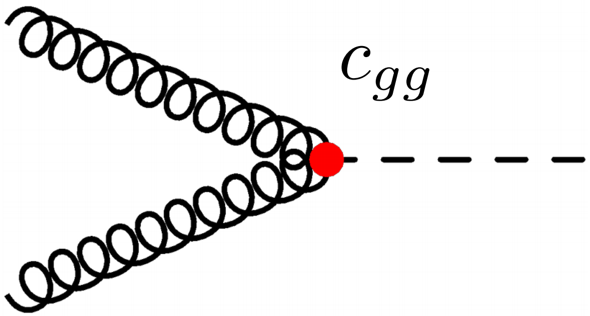
But my comparison is not fair
The bounds rely on different theoretical assumptions

Other deviations?

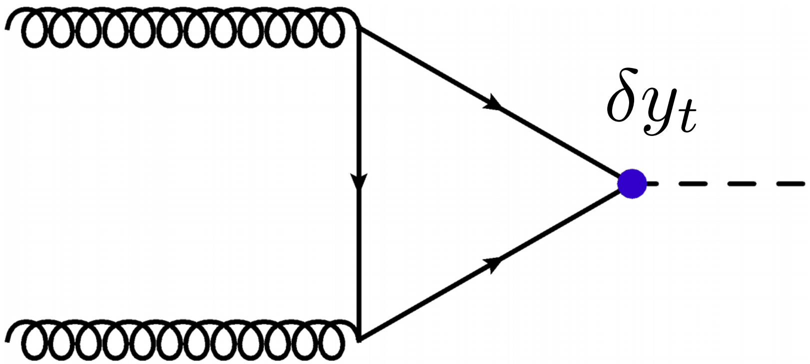
Setting on one anomalous coupling at a time is a strong assumption.



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

$$\kappa_\lambda\,.$$

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
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$H \to WW$	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

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

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

Inclusive observables at 8 TeV

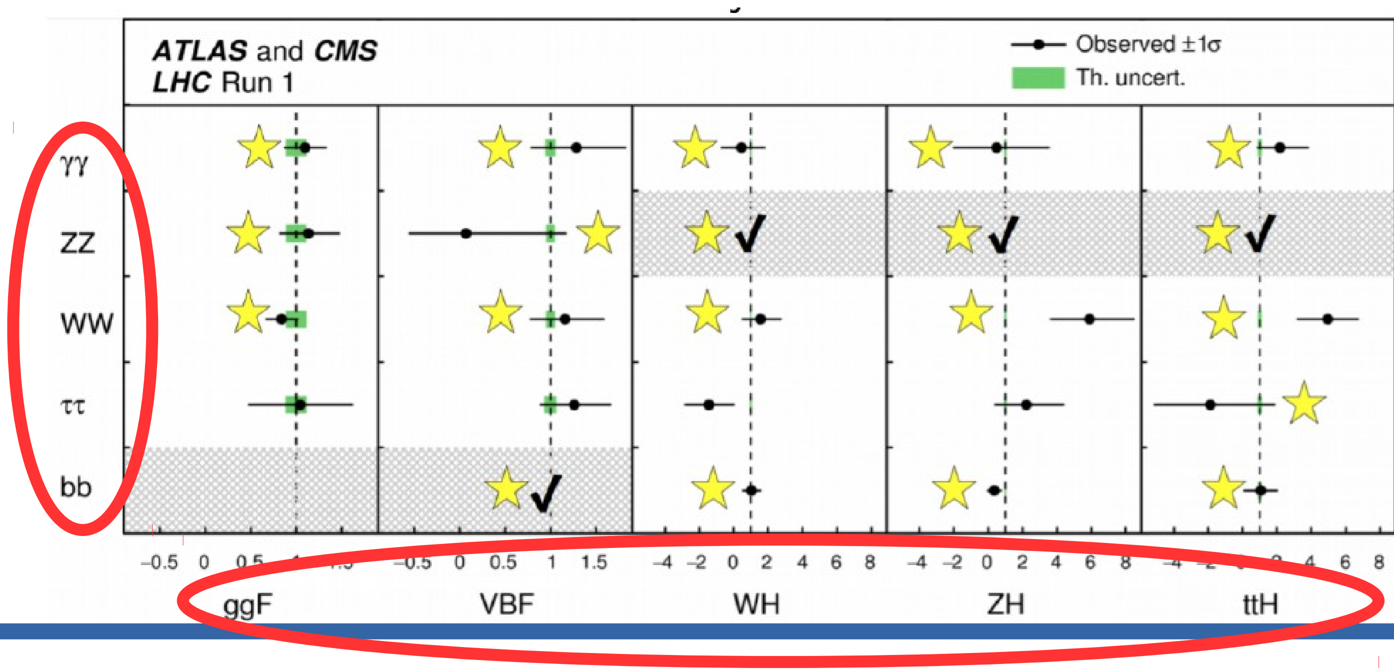
We have 10 quantities

✓ = 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 signal strengths

This is not possible

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

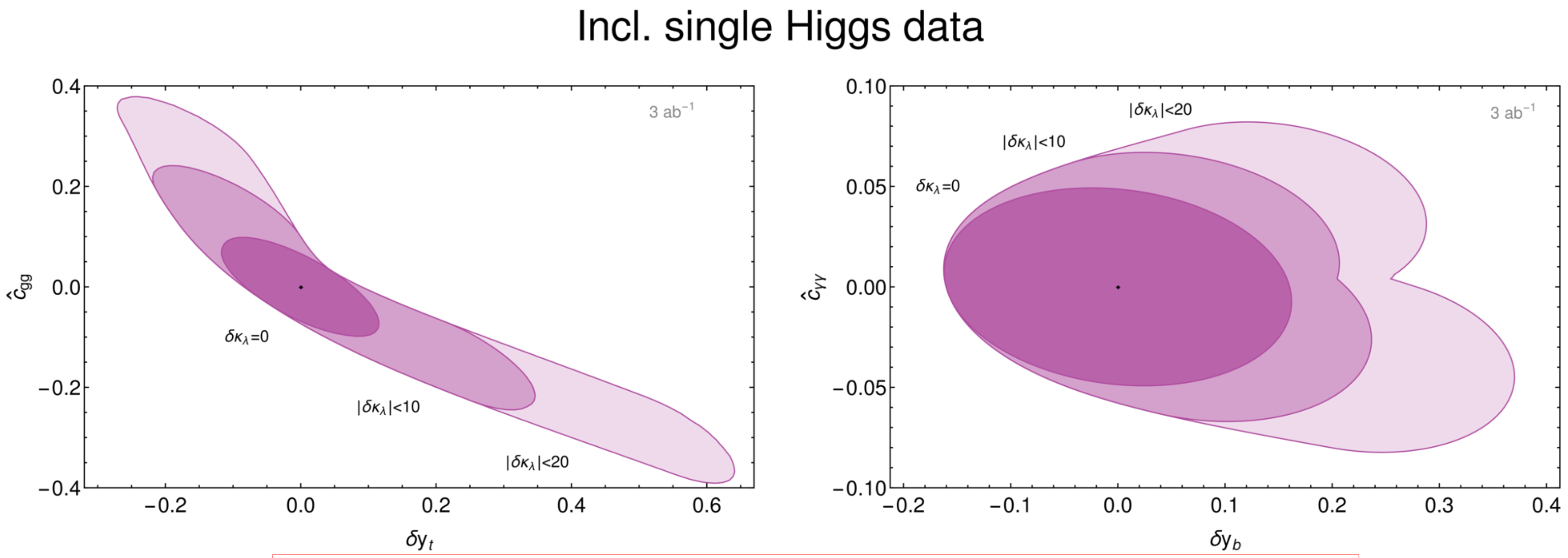
$$\mu \approx 1 + \delta\sigma + \delta\mathrm{BR}$$

Shift in production can be compensated by opposite shift in decay

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

Effect of the flat direction

Single Higgs without NLO effect validity

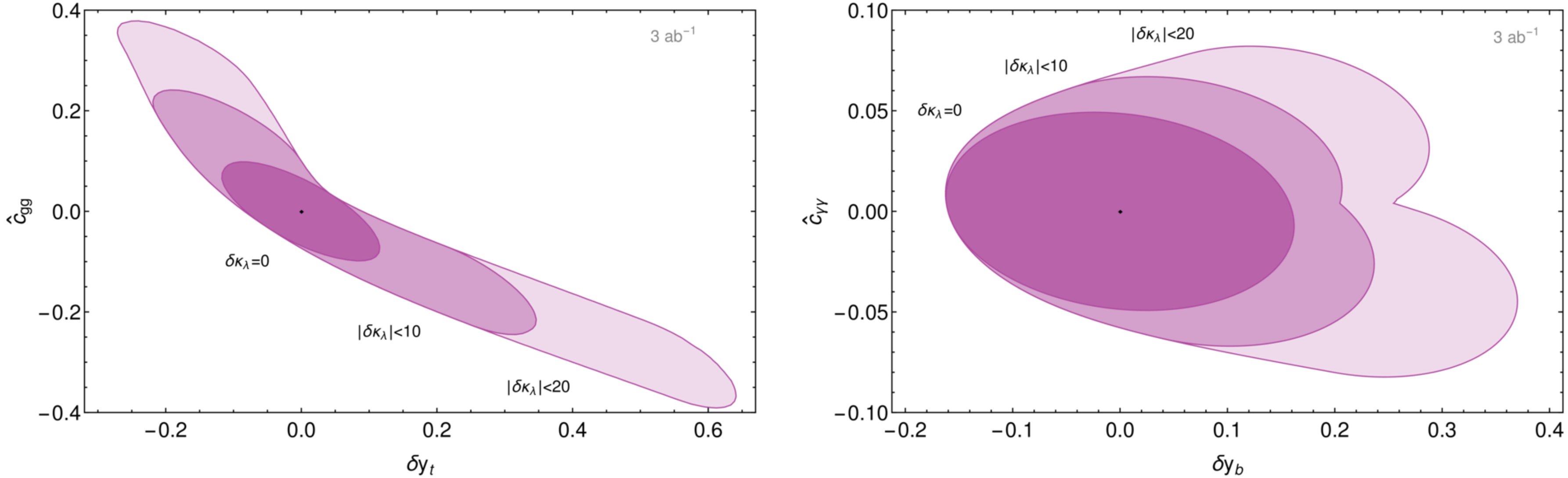


Only valid for reasonable value of the trilinear coupling

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

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

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

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:

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

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

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

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

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

$$\delta c_z \simeq 0.1\,, \quad \delta\kappa_\lambda \simeq 6$$

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**

(Higgs total width, compare different energies, decay $\mu\mu$:) 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

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

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

$H \to Z\gamma$

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

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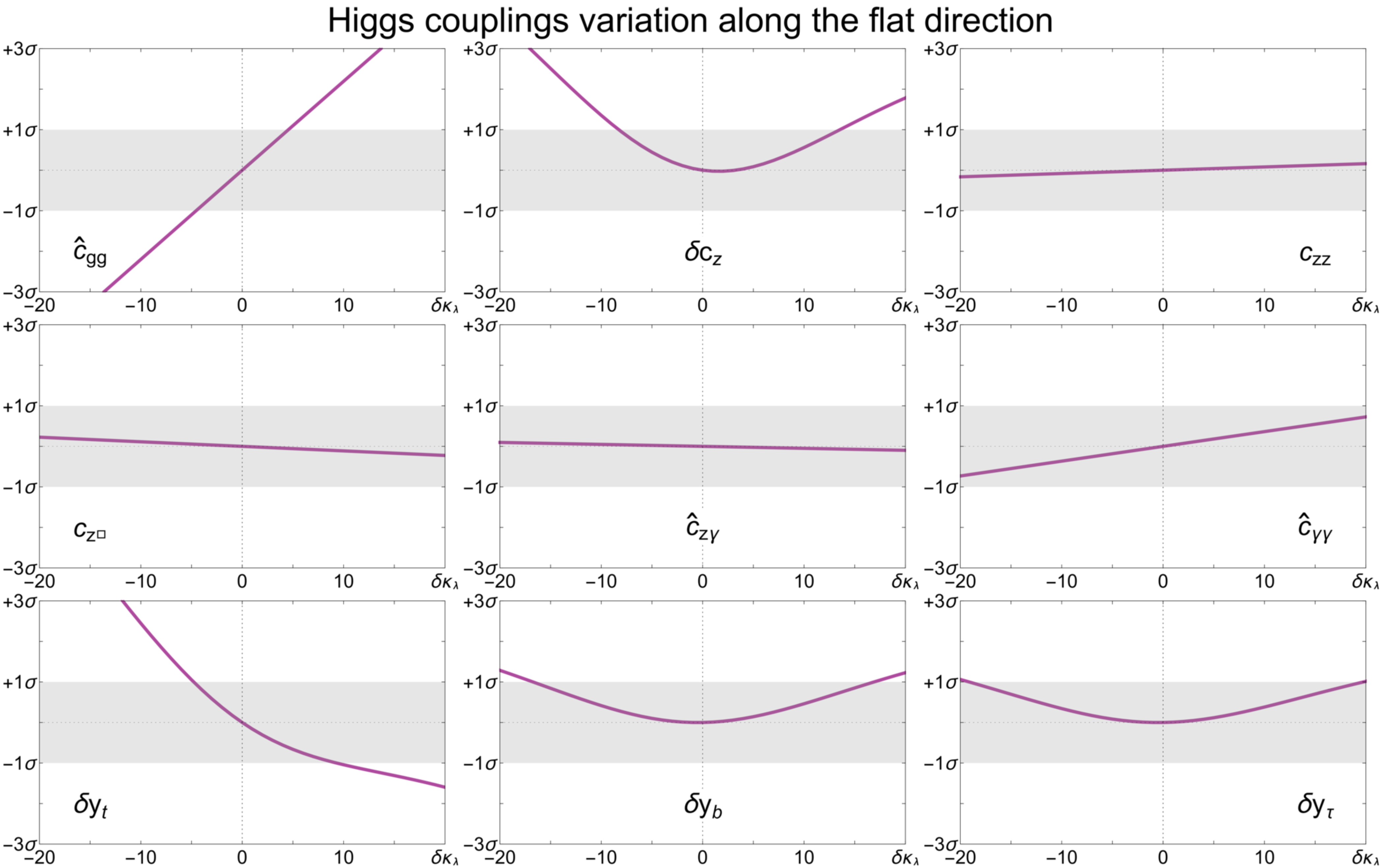
The flat direction

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



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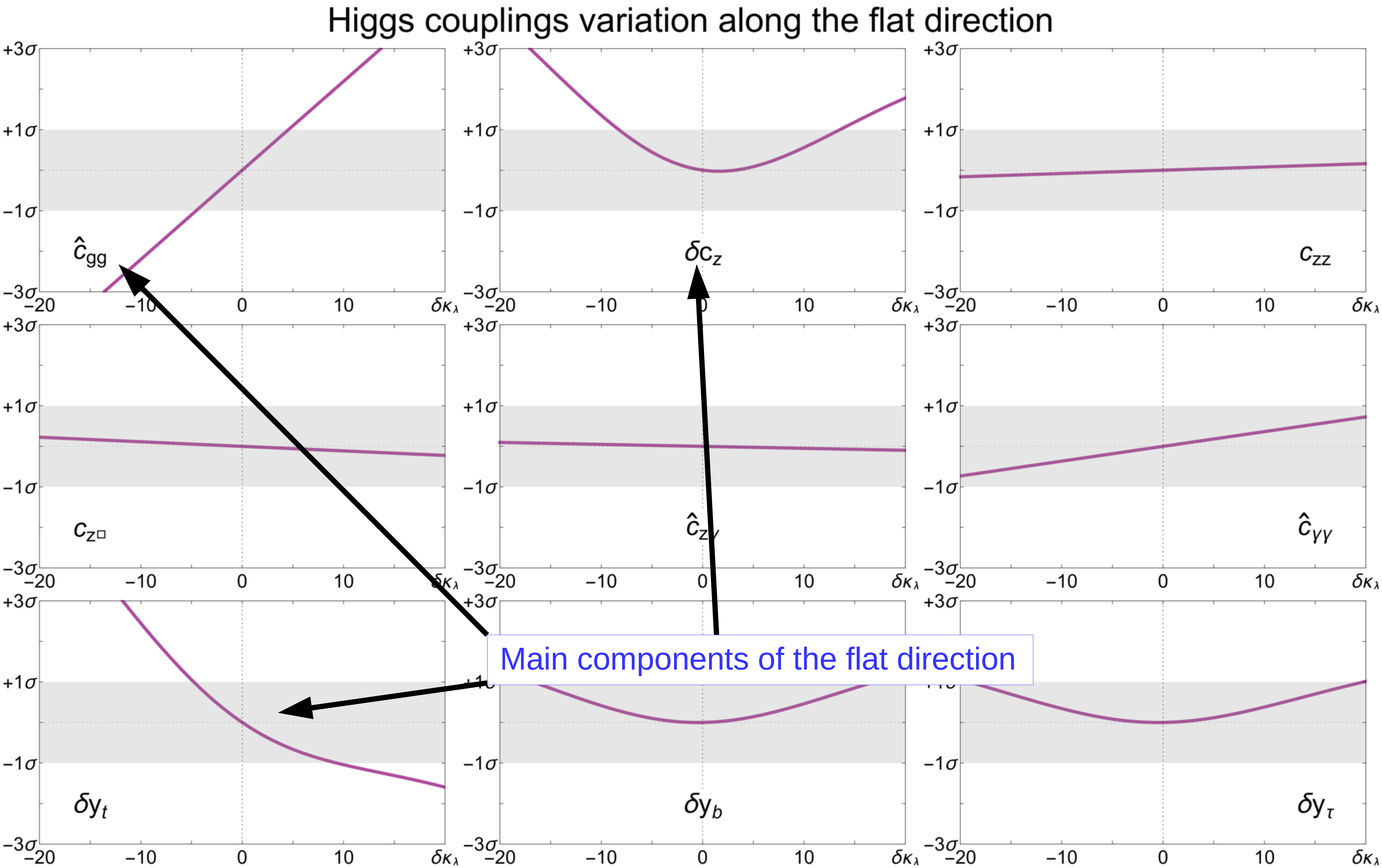
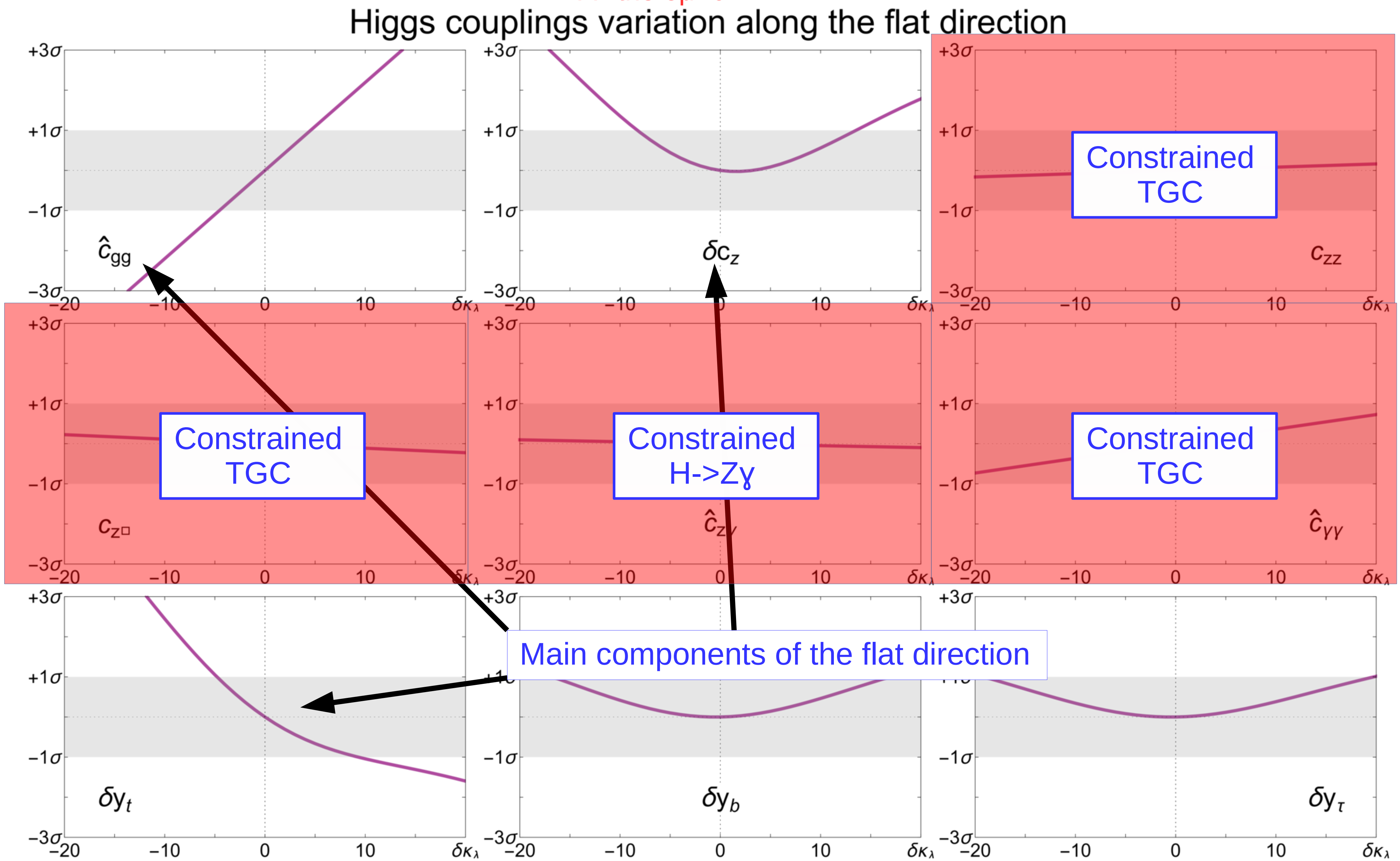


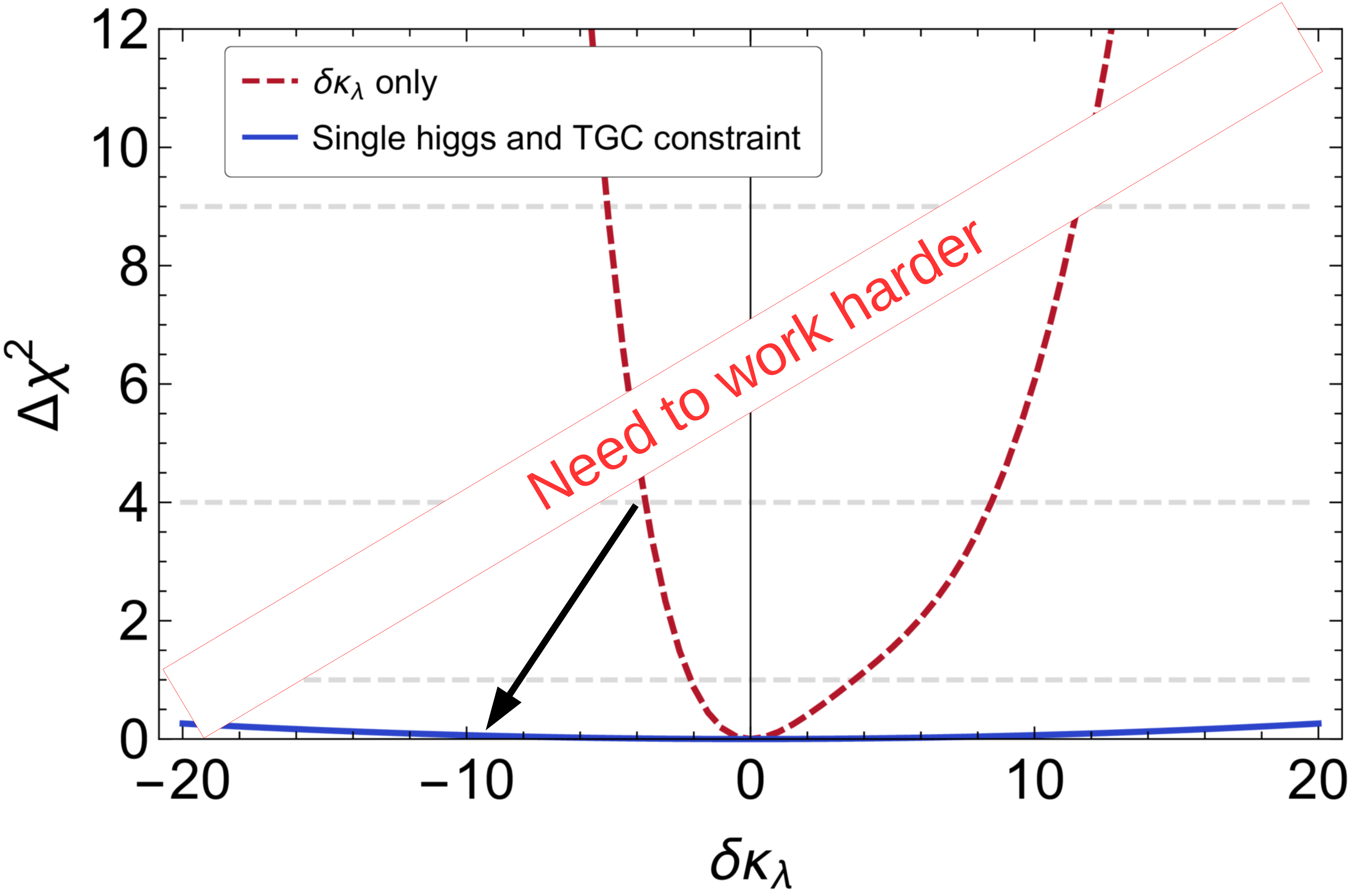
What we constrained

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

All the $\delta\mu=0$



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.

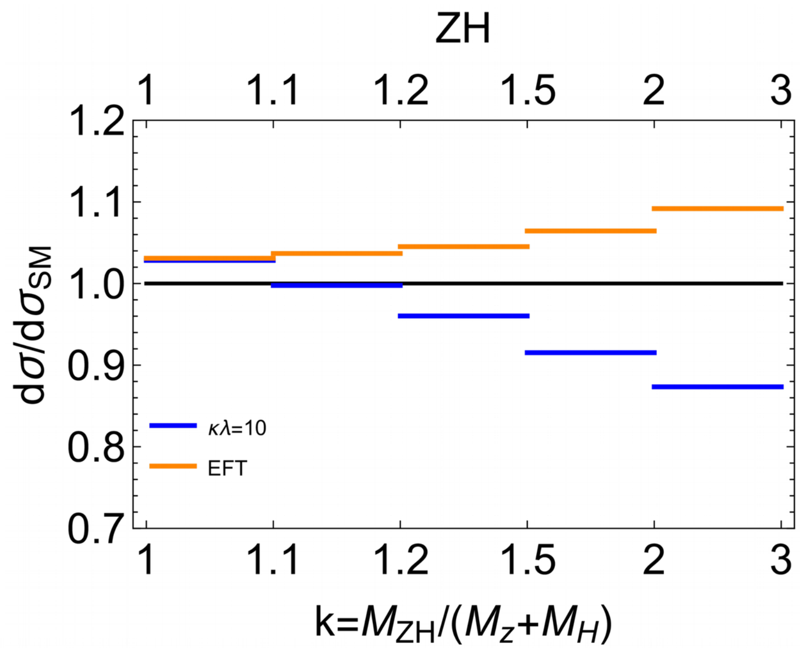
Dependence on Higgs trilinear computed in Degrassi, et al. 1607.04251

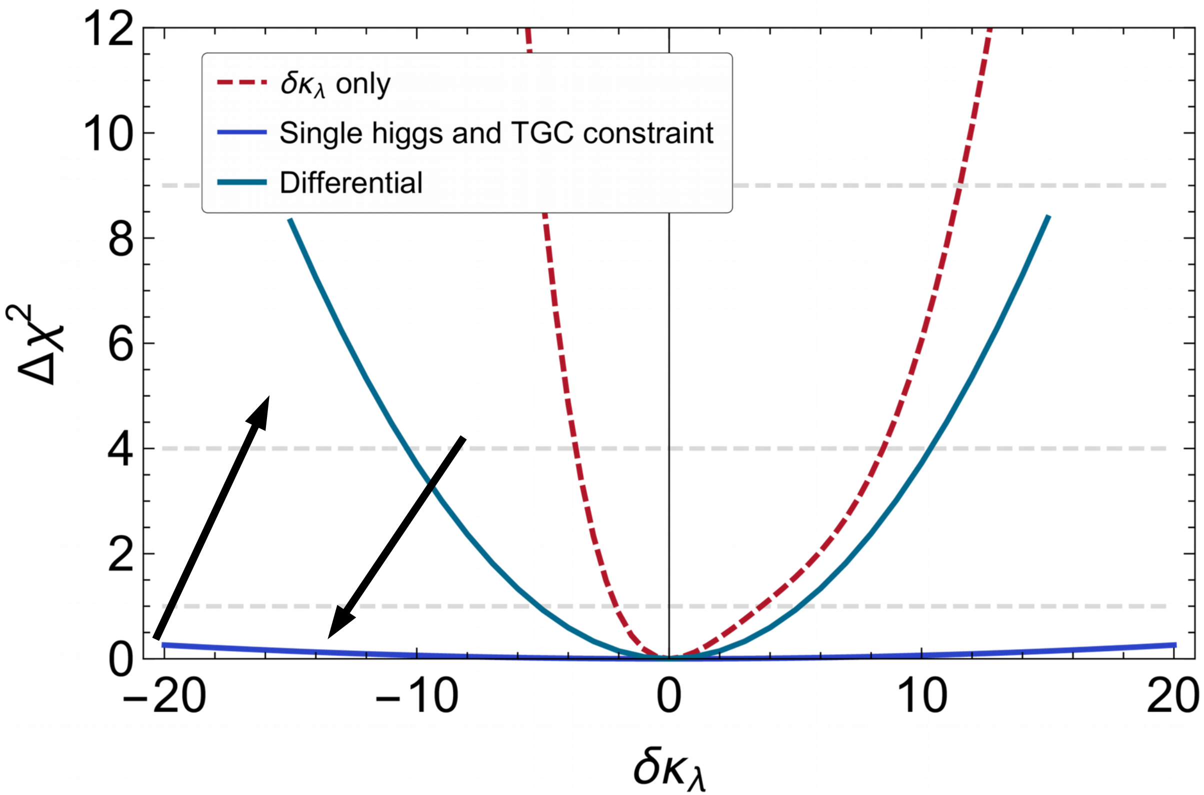
Restore some power to the method, may be seen as complement to double Higgs

Maybe other differential observable can be more powerful

68% CL, $3ab^{-1}$

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

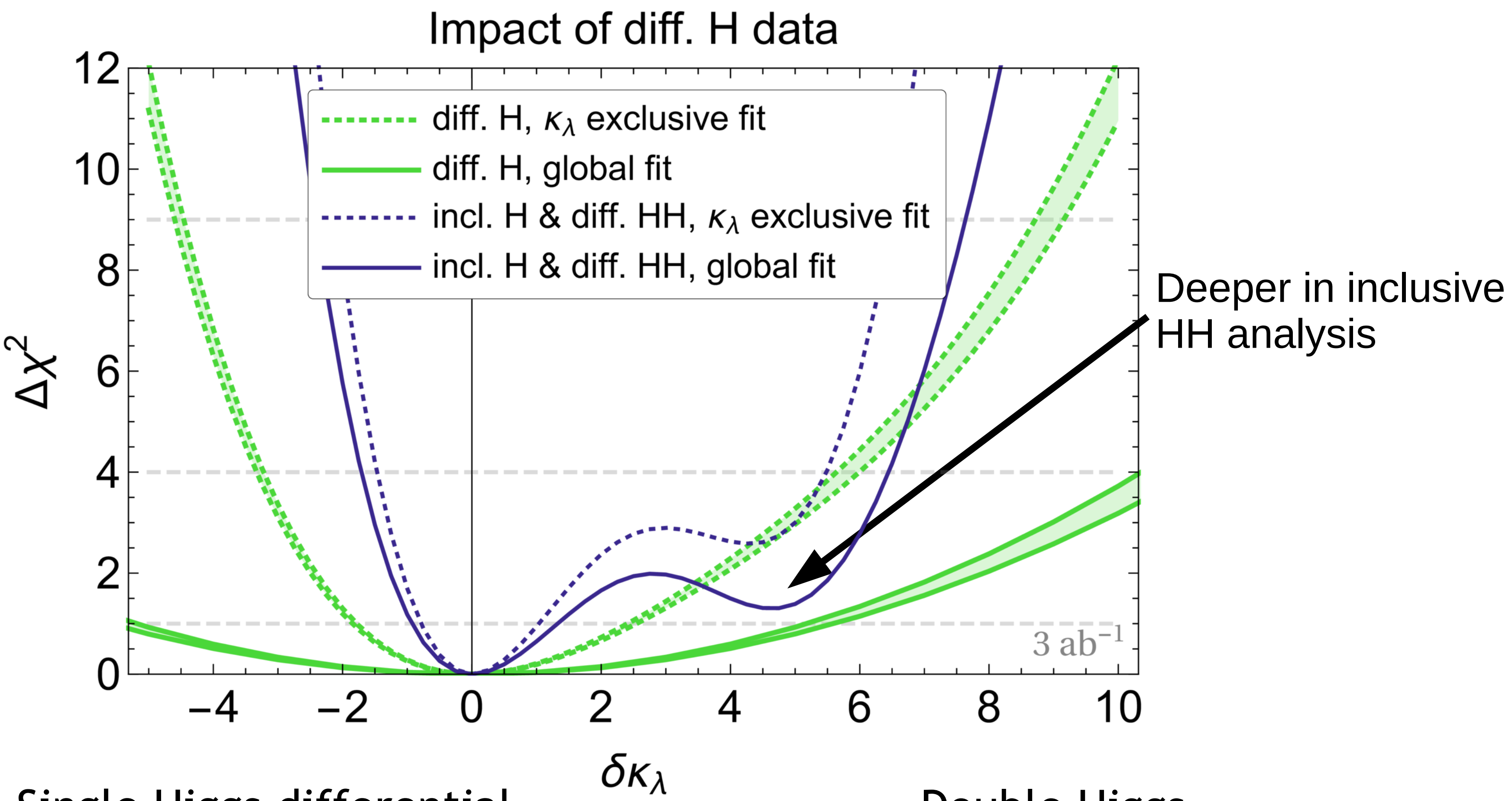




Differential Observables versus double Higgs

Double Higgs analysis more powerful

It also solves the flat direction issue in single Higgs



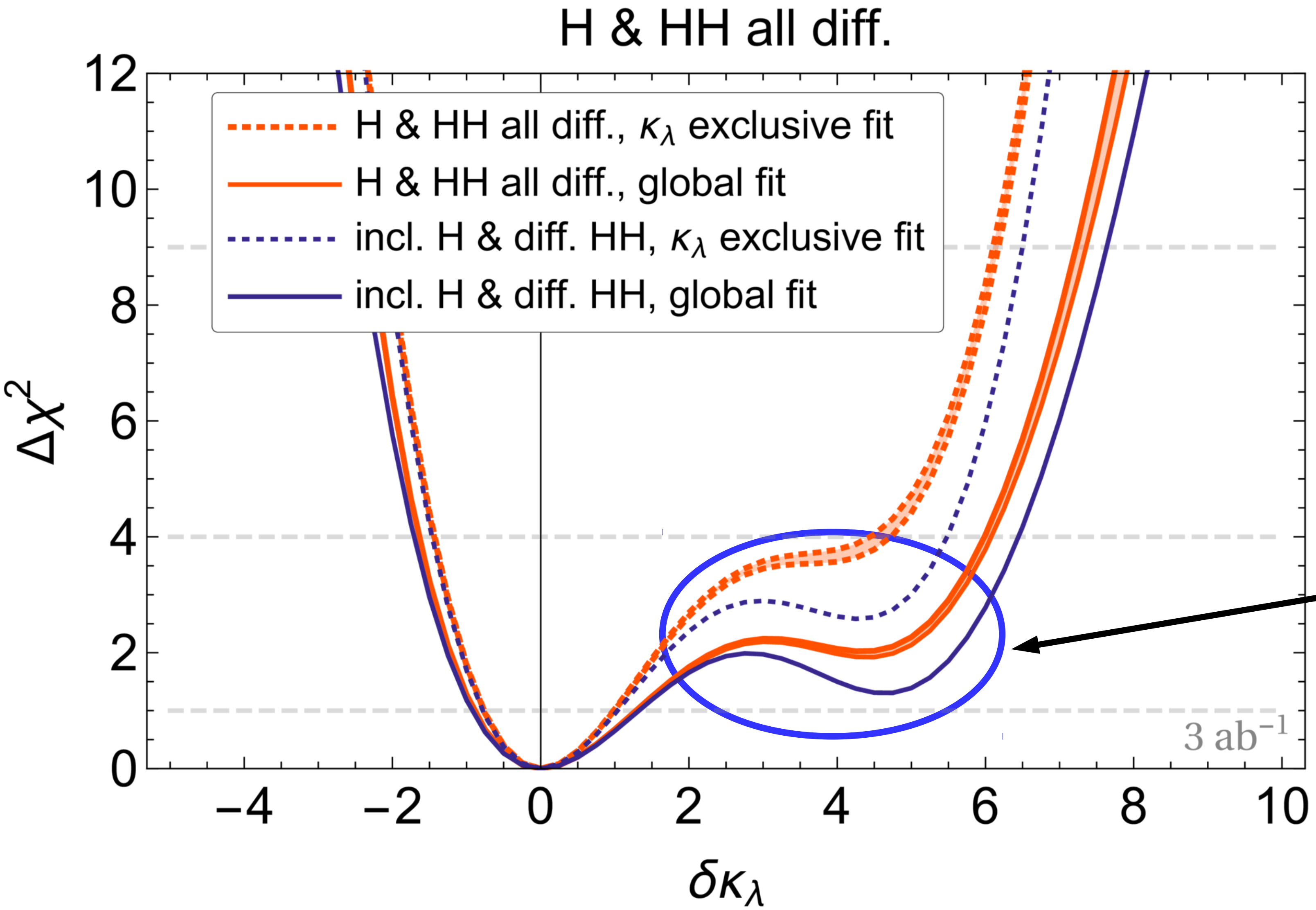
Single Higgs differential

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

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.

Single Higgs help lifting this minimum
(More clear for Inclusive double Higgs)

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

More results in
JHEP09(2017)069

What about the future?

Extension of arXiv:1704.02333
G. Durieux, C. Grojean, J. Gu, K. Wang

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

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

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

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

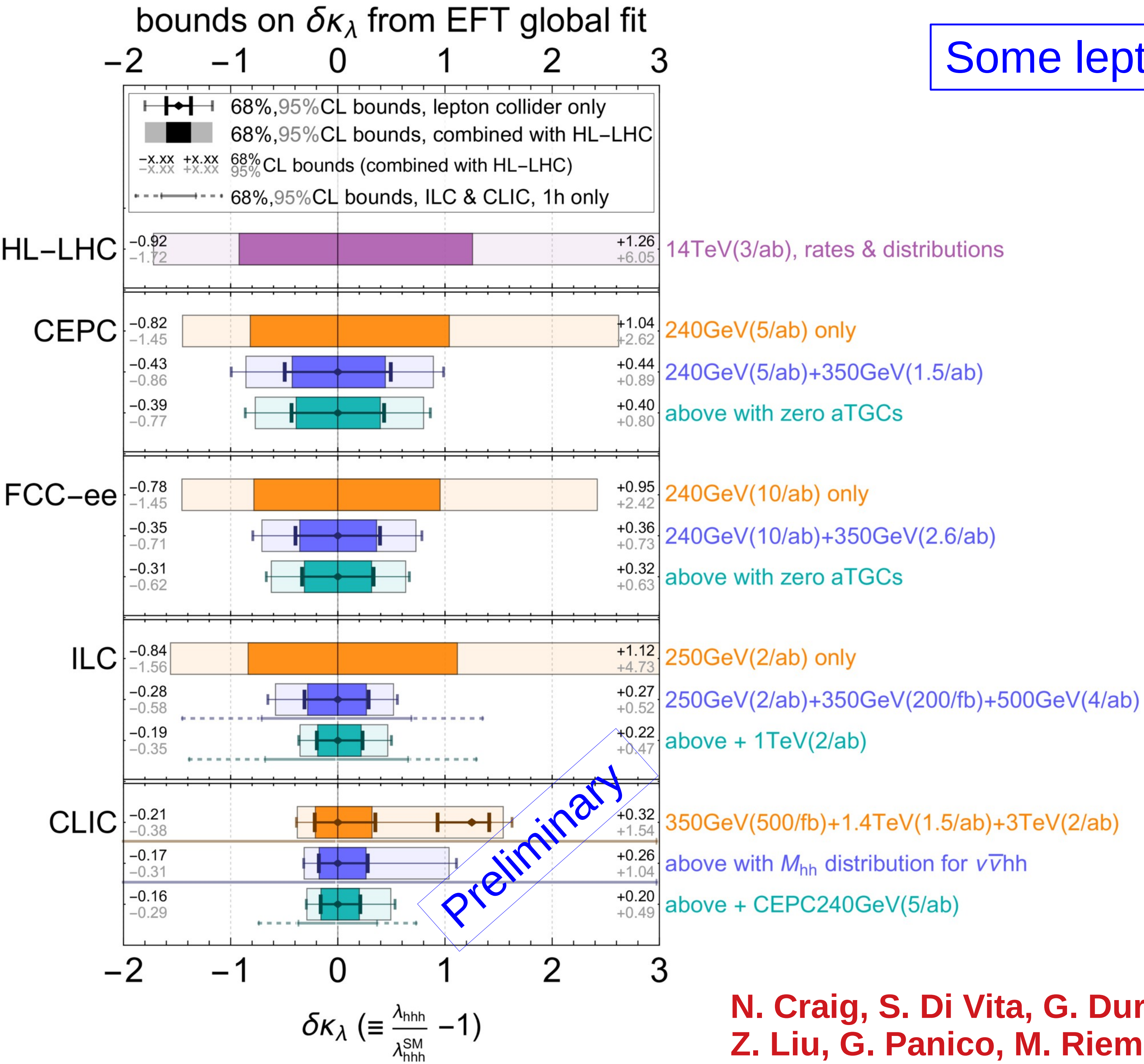
Maximum around threshold

Example: $\Delta\mu(e^-e^+ \to zh,\, h \to b\bar{b}) < 1\% \; @CLIC$

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

In collaboration with N. Craig, S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon

Some lepton collider results



Running at different energies help

Linear collider have access to double Higgs production channels

N. Craig, S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon

Conclusion

- **At the inclusive level the trilinear corrections to single Higgs observables introduce a flat direction in the global fit.**
- **This flat direction degrades the precision achievable on the wilson coefficients. Some control on the trilinear is needed to solve this issue.**
- **Double Higgs is still the best way to extract Higgs trilinear and to restore the control over single Higgs fit.**
- **Most promising way to remove the flat direction without using double Higgs is to use differential distribution. More work in this direction is needed.**

Work in progress

- **Lepton colliders will give us more precision and observables to constraint the single Higgs.**

More results in
JHEP09(2017)069

Thank you

Our parametrisation:

Parametrization of dominating BSM effects in Higgs couplings couplings:

$$\mathcal{L}^{\rm NP} \supset \frac{h}{v}\Big[\delta c_w \frac{g^2v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu$$

$$+ c_{ww}\frac{g^2}{2} W_{\mu\nu}^+ W_{-\mu\nu} + c_{w\Box} g^2 \left(W_\mu^+ \partial_\nu W_{+\mu\nu} + \text{h.c.}\right)$$

$$+ \hat{c}_{\gamma\gamma}\frac{e^2}{4\pi^2} A_{\mu\nu}A^{\mu\nu} + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu}$$

$$+ c_{zz}\frac{g^2+g'^2}{4} Z_{\mu\nu}Z^{\mu\nu} + \hat{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu}A^{\mu\nu}\Big]$$

$$+ \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}_{gg}^{(2)}\frac{h^2}{2v^2}\right) G_{\mu\nu}G^{\mu\nu}$$

$$- \sum_f \left[m_f\left(\delta y_f \frac{h}{v} + \delta y_f^{(2)}\frac{h^2}{2v^2}\right)\bar{f}_R f_L + \text{h.c}\right]$$

$$+ (\kappa_\lambda - 1)\lambda_{SM} v h^3$$

$\delta y_\tau,\ \delta y_b,\ \delta y_t$

Only enter at loop level in single Higgs observable

Single Higgs observable without the trilinear

Run 1 channel, Observable = SM exactly

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

Global fit | Fit with only 1 wilson

$c_{zz} - c_{z\Box}$

$c_{zz} - \delta y_\tau$

$\hat{c}_{gg} - \delta y_t$

$\delta c_z - \delta y_b$

$\delta c_{z\Box} - \delta y_\tau$

} Very correlated → **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
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(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]				

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Correlation with new observables

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

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!)

Robustness of the analysis

Sensibility to single Higgs uncertainties