Assessing the Higgs (self-)couplings

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DESY HELMHOLTZ GEMEINSCHAFT HUMBOLDT-UNIVERSITÄT ZU BERLIN

Christophe Grojean
DESY (Hamburg)
Humboldt University (Berlin)

(christophe.grojean@desy.de)

This talk is based upon...

A global view on the Higgs self-coupling

S. Di Vita,[a] C. Grojean,[1a,b] G. Panico,[c] M. Riembau,[a,c] T. Vantalon[a,c]

[a] *DESY, Notkestraße 85, D-22607 Hamburg, Germany*

[b] *Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*

[c] *IFAE, Barcelona Institute of Science and Technology (BIST) Campus UAB, E-08193 Bellaterra, Spain*

E-mail: stefano.divita@desy.de, christophe.grojean@desy.de, gpanico@ifae.es, marc.riembau@desy.de, tvantalon@ifae.es

arXiv:1704.01953v1 [hep-ph]

see T. Vantalon's talk on Thursday

The leptonic future of the Higgs

Gauthier Durieux,[a] Christophe Grojean,[a,b 1] Jiayin Gu,[a,c] Kechen Wang[a,c]

[a] *DESY, Notkestraße 85, D-22607 Hamburg, Germany*

[b] *Institut für Physik, Humboldt-Universität zu Berlin, D-12489 Berlin, Germany*

[c] *Center for Future High Energy Physics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*

gauthier.durieux@desy.de, christophe.grojean@desy.de, jiayin.gu@desy.de, kechen.wang@desy.de

arXiv:1704.02333v1 [hep-ph]

see J. Gu's talk on Thursday

but see also

Gorbahn et al '16
arXiv:1607.03773 [hep-ph]

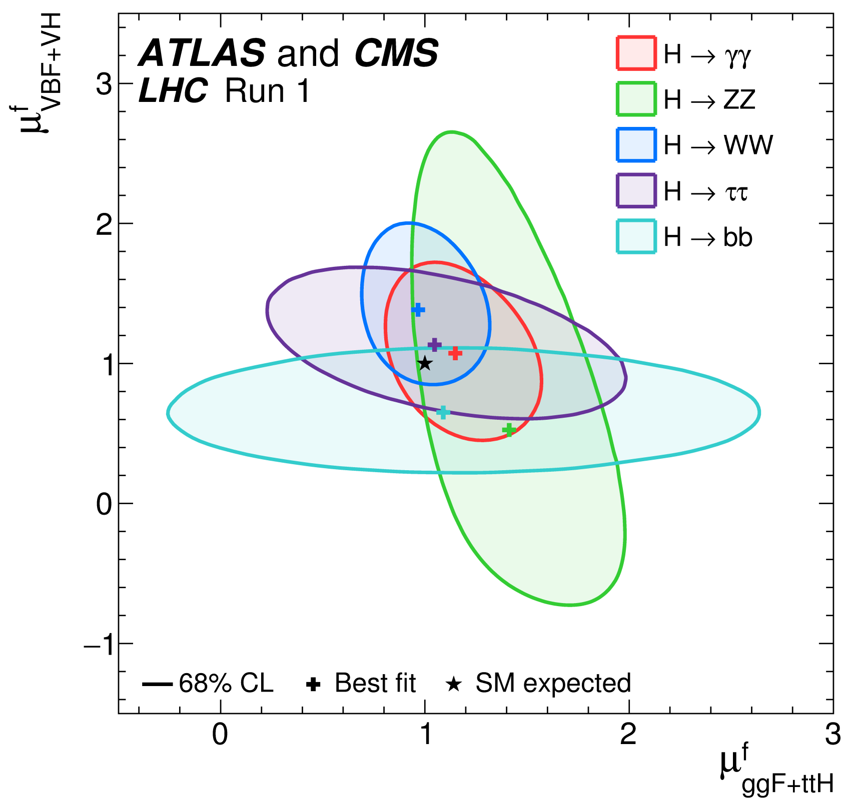
Degrassi et al '16
arXiv:1607.04251 [hep-ph]

Bizon et al '16
arXiv:1610.05771 [hep-ph]

How to report Higgs data: from κ to EFT

LHCHXSWG '12

$$\mu_i = \frac{\sigma[i \to h]}{(\sigma[i \to h])_{\rm SM}} \qquad \mu_f = \frac{{\rm BR}[h \to f]}{({\rm BR}[h \to f])_{\rm SM}}$$



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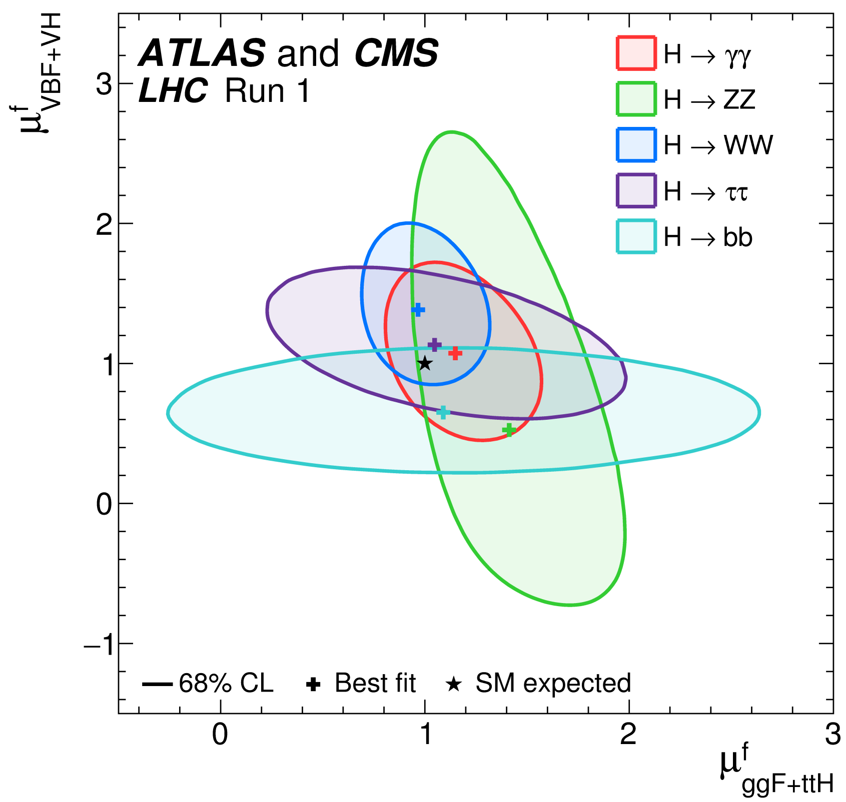
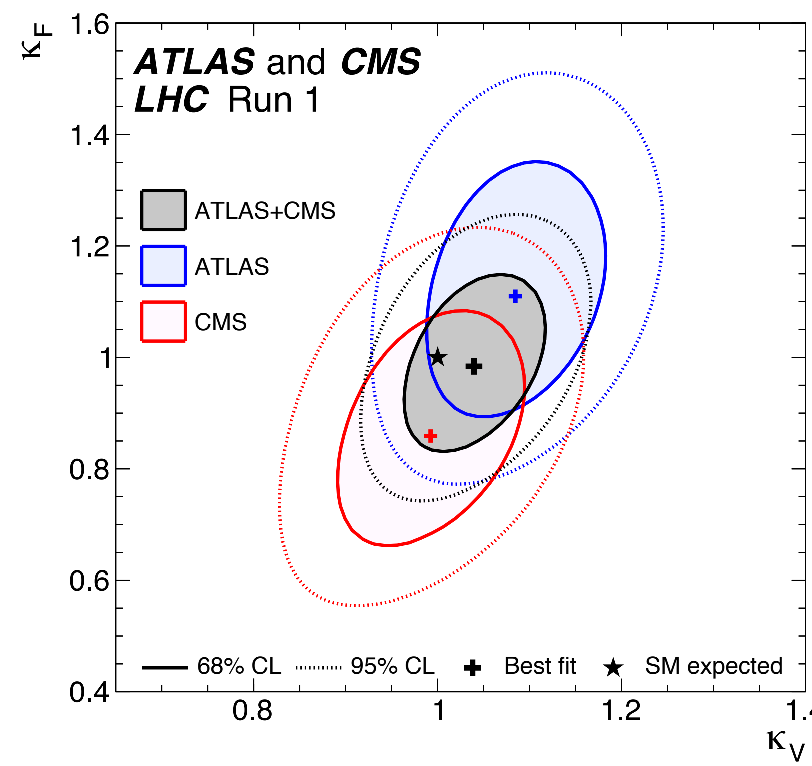


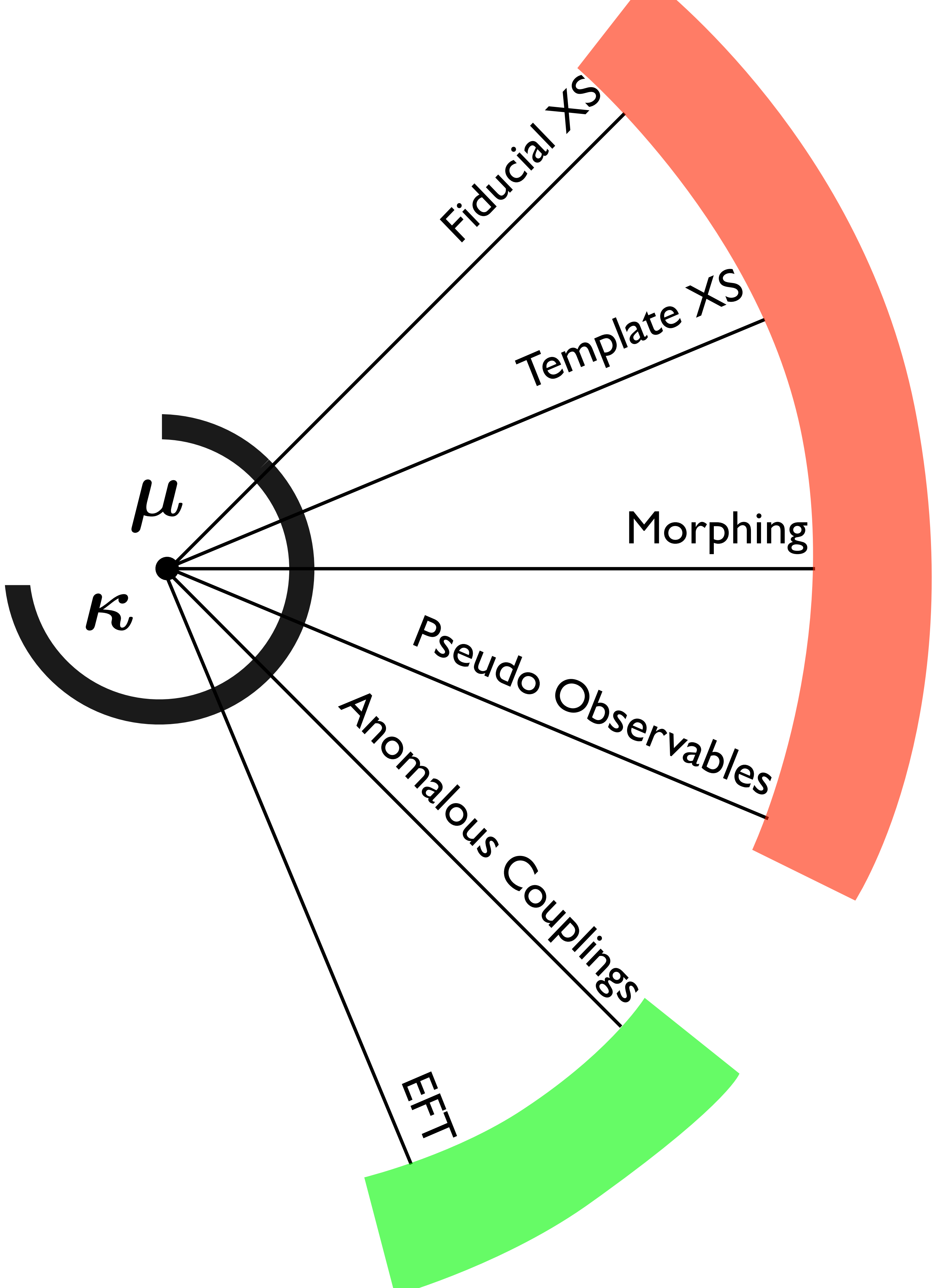


$$(\sigma \cdot {\rm BR})\,(gg \to H \to \gamma\gamma) = \sigma_{\rm SM}(gg \to H) \cdot {\rm BR}_{\rm SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

individual coupling rescaling factors

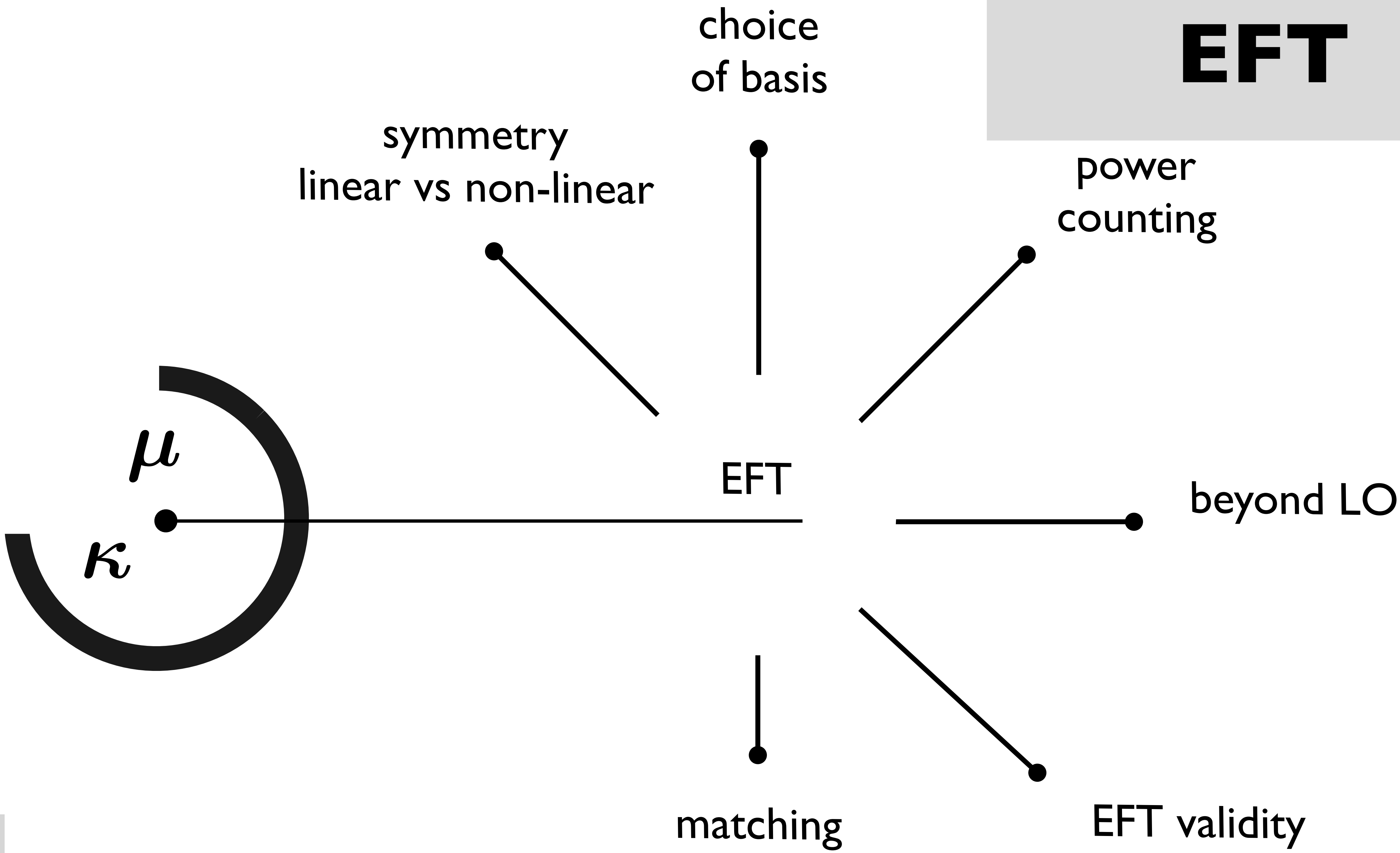
Well suited parametrization for inclusive measurements
but doesn't do justice to full possible deformations of SM & other rich diff. information

EFT



μ
κ
Fiducial XS
Template XS
Morphing
Pseudo Observables
Anomalous Couplings
EFT

EFT



Pros:

- correlations between different channels/observables
- combination of measurements at different energies
  e.g. EW precision data and Higgs measurements
- test of self-consistency

unique to EFT

allow to focus on channels yet unconstrained and more likely to offer new discovery opportunities

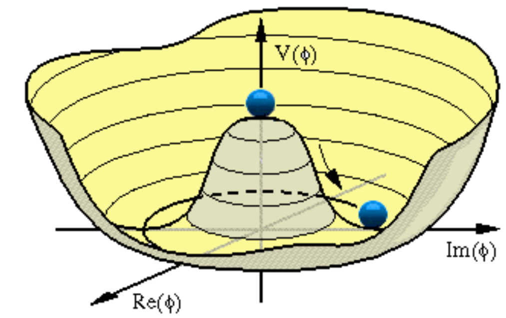
Higgs physics vs BSM

Several deformations away from the SM affecting Higgs properties are already probed in the vacuum

(assuming EW symmetry linearly realized and that new physics is heavy)

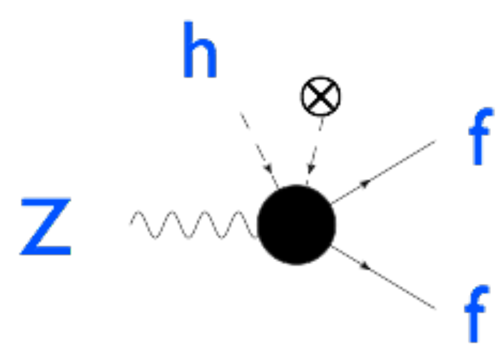
$\phi = v + h$

→ vacuum

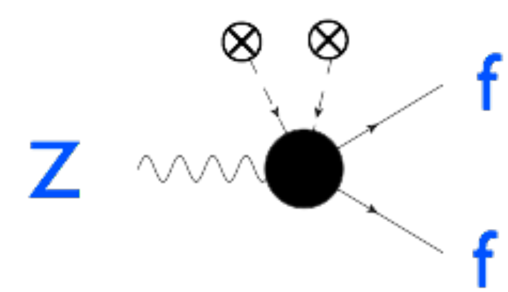


Potentially new BSM-effects in h physics could have been already tested in the vacuum

e.g.



$= \frac{1}{2v} \times$



$H^\dagger D_\mu H \bar{f} \gamma^\mu f$

(assuming that the Higgs boson is part of a doublet)

Modifications in h→Zff related to Z→ff

One can use h→ZZ→4l to probe this deformation but hard time to compete with LEP bounds

consistency check not discovery mode

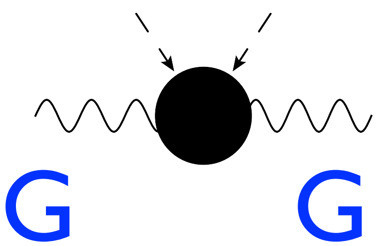
(courtesy of A. Pomarol@Moriond2014)

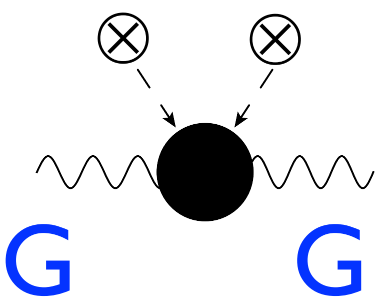
Higgs/BSM Primaries

There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

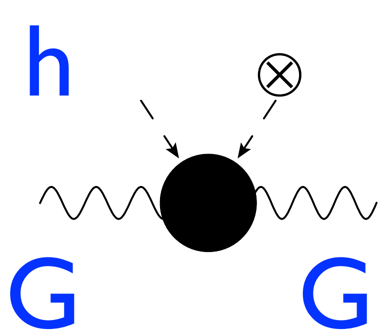
e.g. $$\frac{1}{g_s^2}G^2_{\mu\nu} + \frac{|H|^2}{\Lambda^2}G^2_{\mu\nu} \to \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right) G^2_{\mu\nu}$$

operator not visible in the vacuum
(redefinition of input parameter)





But can affect h physics:



affects GG →h!

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13
Elias-Miro et al '13
Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8**

for one family

(assuming CP-conservation)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	→ GGh coupling
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	→ hγγ coupling
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	→ hZγ coupling
m_W	$\|H\|^2 \|D_\mu H\|^2$	→ hVV* (custodial invariant)
m_h	$\|H\|^6$	→ h^3 coupling
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	→ htt, hbb, hττ

yet to be measured at the LHC

the 6 others have been measured (~15%)

(courtesy of A. Pomarol@HiggsHunting2014)

Higgs/BSM Primaries

How many of these effects can we have?

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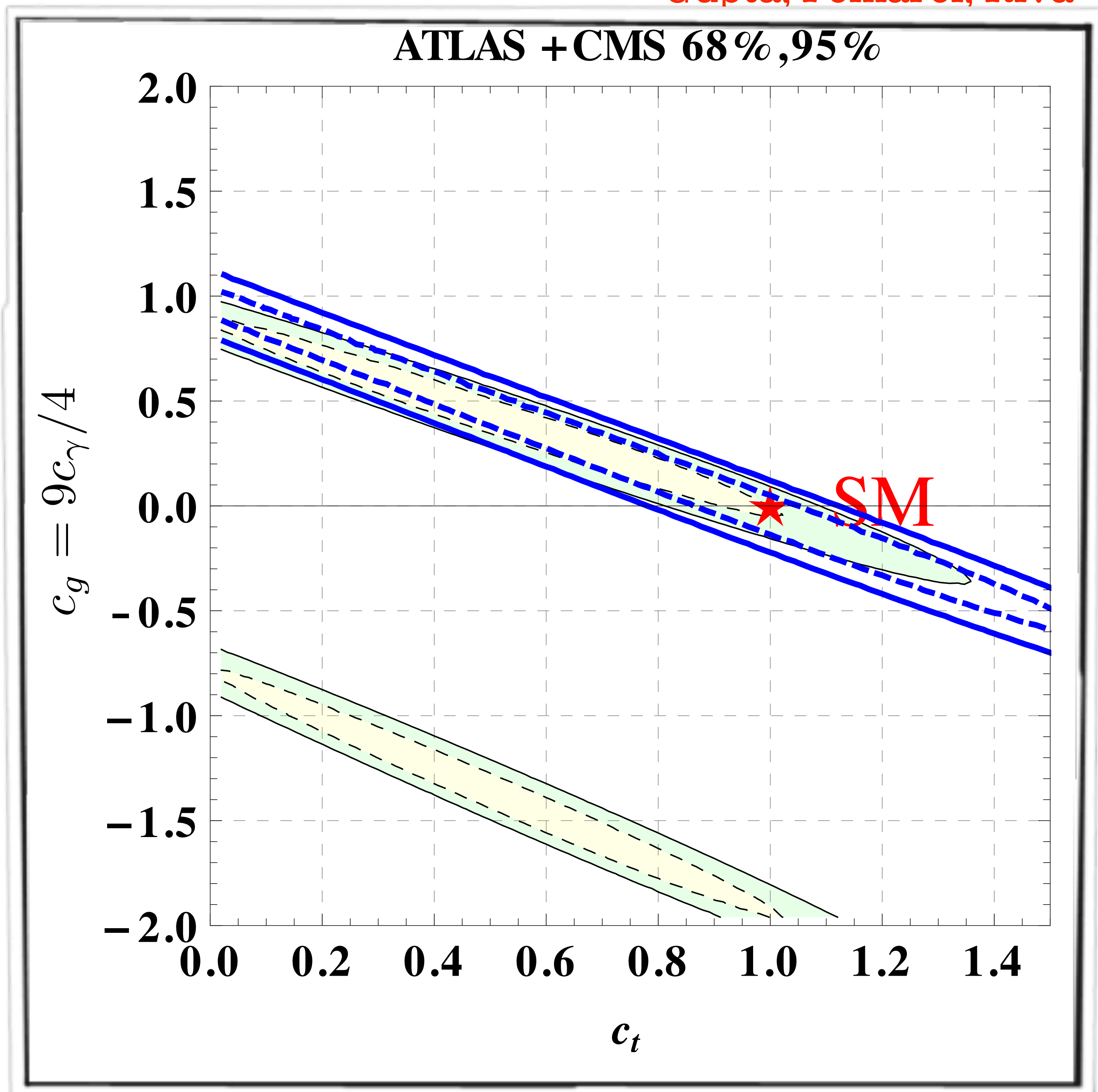
Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Atlas projection



Azatov '15

With some important differences:

1) width hypothesis built-in

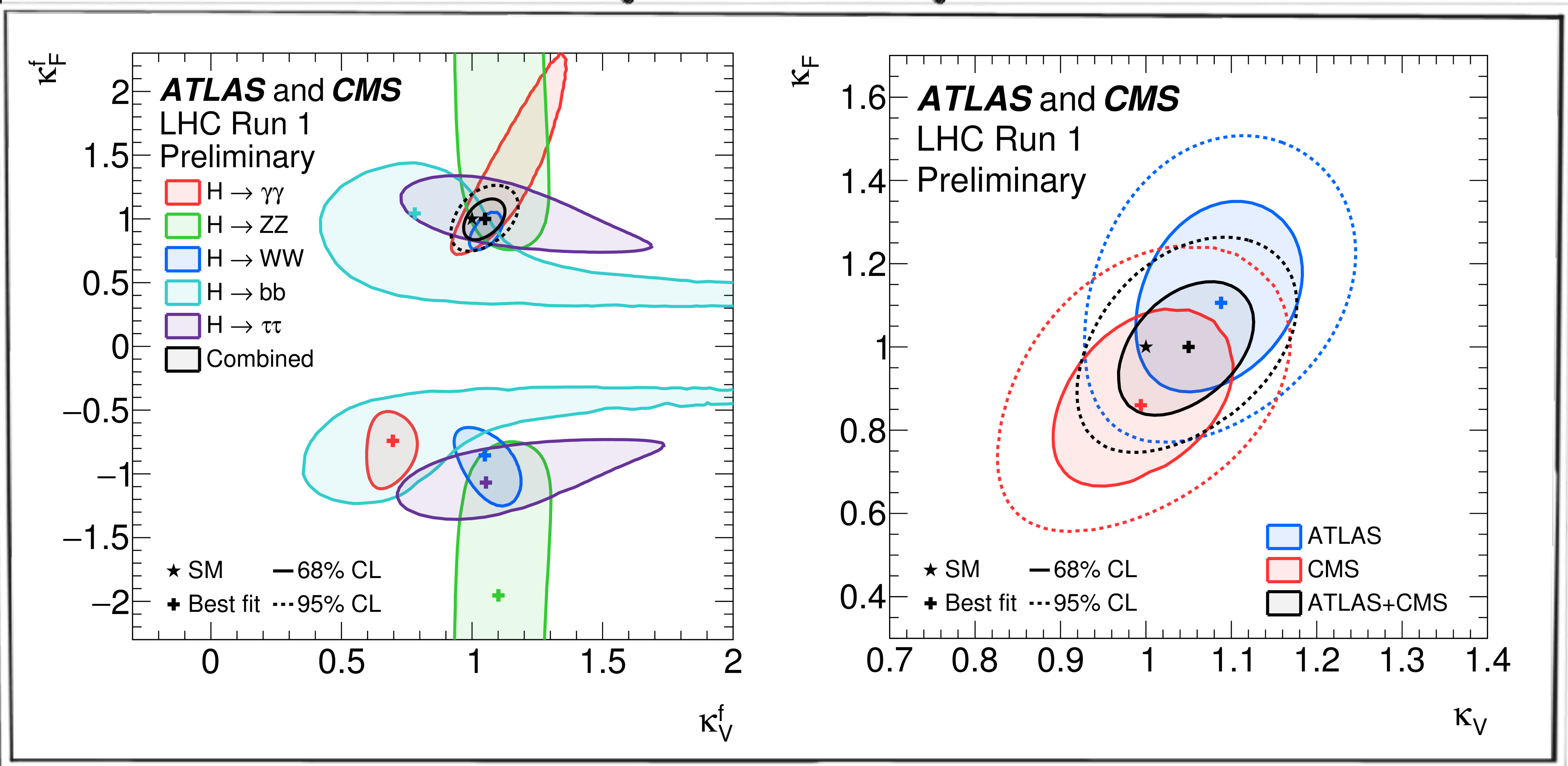
2) κ_W/κ_Z is not a primary (constrained by $\Delta\rho$ and TGC)

3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$



Why going beyond inclusive Higgs processes?

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⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Examples of interesting channels to explore further:

1. off-shell $gg \to h^* \to ZZ \to 4l$
2. boosted Higgs: Higgs+ high-p_T jet
3. double Higgs production

Why going beyond inclusive Higgs processes?

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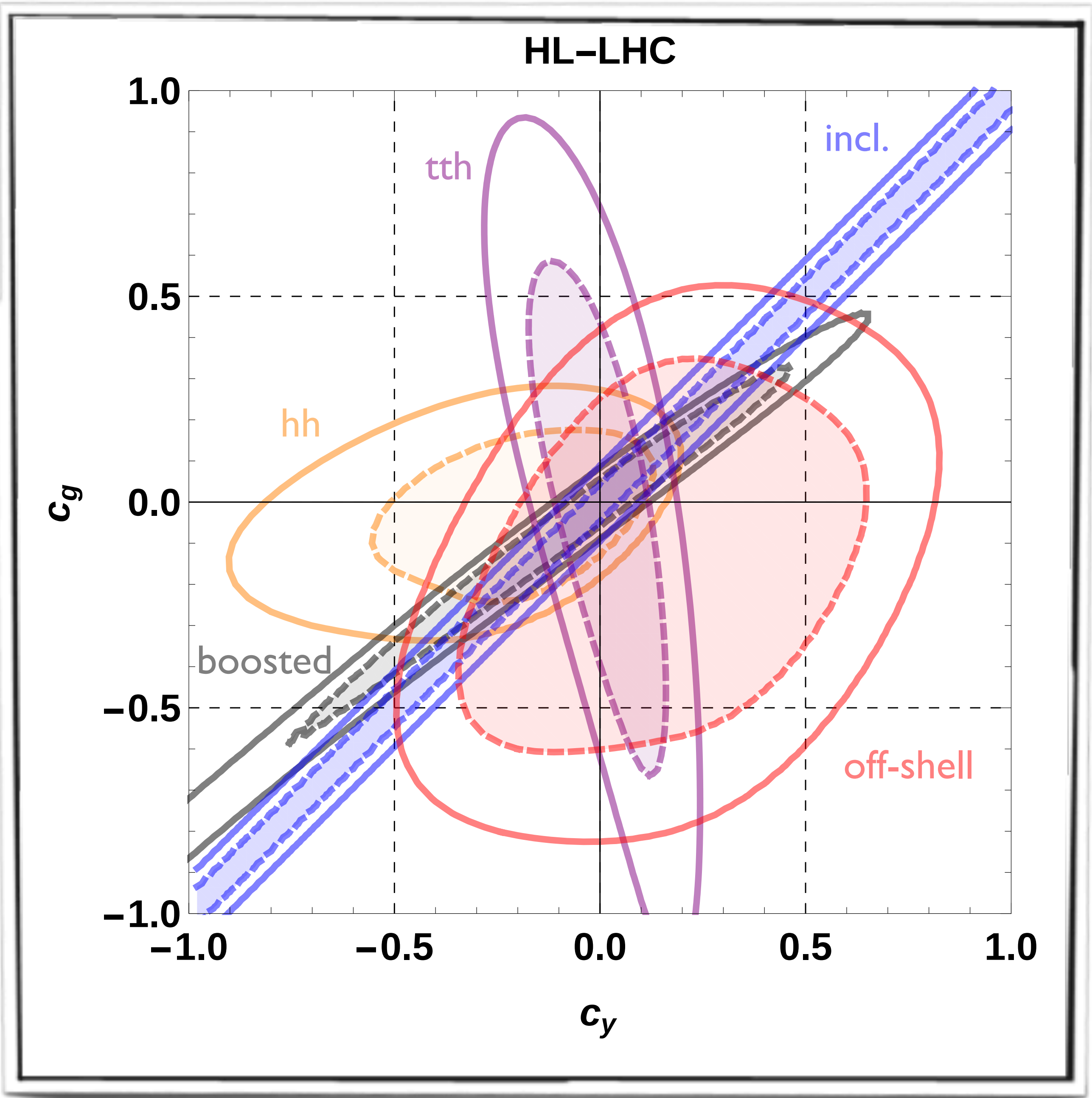
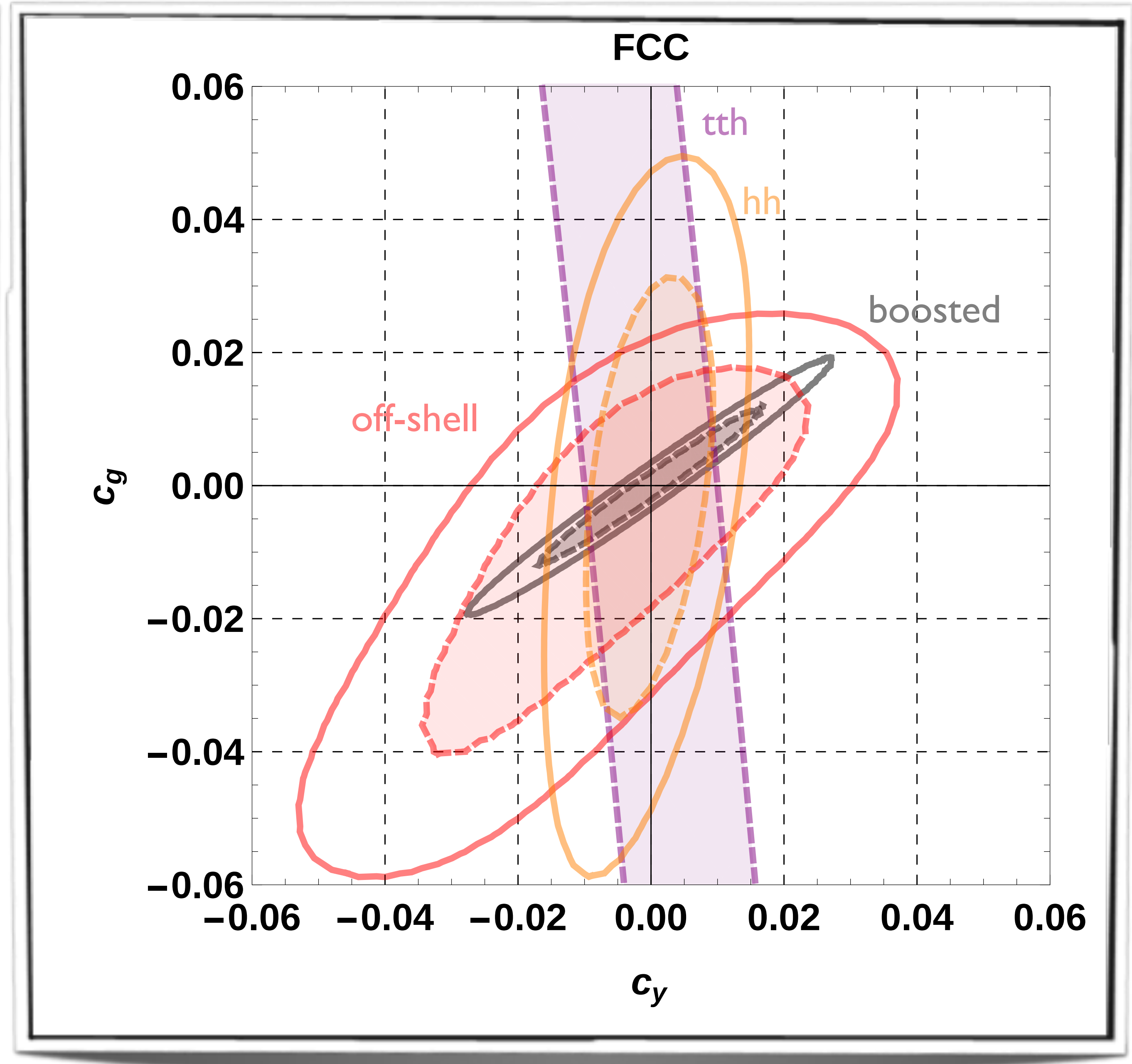


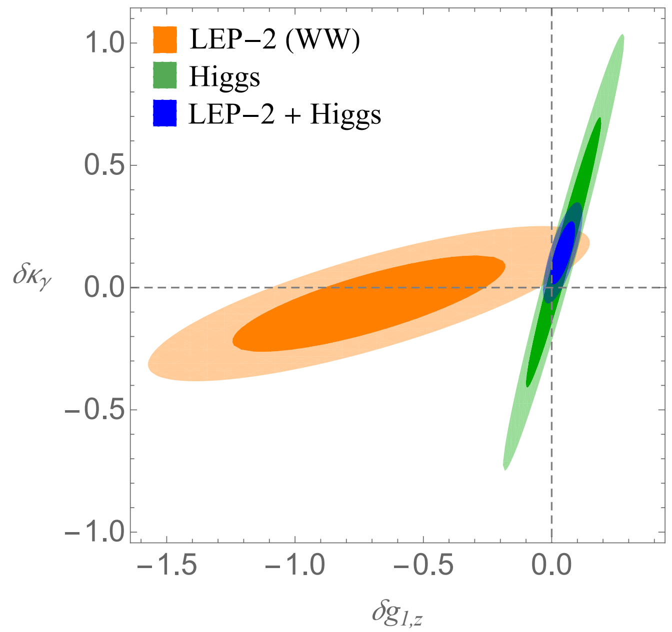


Azatov, Grojean, Paul, Salvioni '16

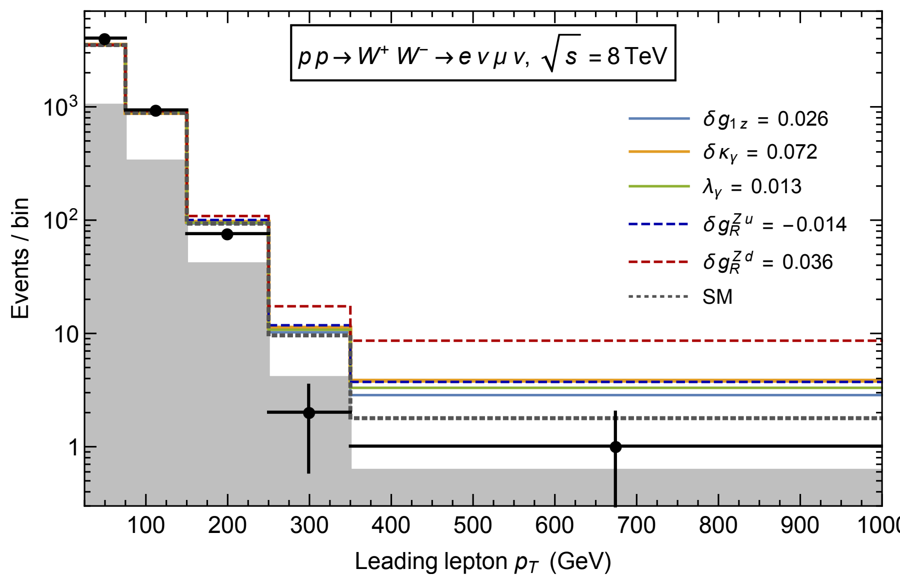
Questioning the (non-explicit) assumptions

1. Does data factorization (EW/di-boson/Higgs) hold?

Falkowski et al '15



Zhang '16



(TGC+Higgs)>(TGC)∪(Higgs)

Strong correlations between 2 data sets

Better to do a (8+2) parameter fit!

can we impose LEP EW when looking at LHC TGC?

Caution required but conclusion might not be as dramatic as inferred from this plot (done by turning one parameter at a time) since global fit of LEP+LHC ≈ LEP∪LHC

Questioning the (non-explicit) assumptions

1. Does data factorization (EW/di-boson/Higgs) hold?
2. What about CPV couplings?
3. Is an EFT analysis valid?
4. Can we truncate EFT Lagrangian to dim-6?
5. Should we include NLO effects?
6. Should we trust an EFT analysis with EW symmetry linearly realized?
7. Shouldn't we use PO's, anomalous couplings, template XS, fiducial XS?
8. Are we missing something?

There is no truly model-independent fit!
One should always be aware of the assumptions behind any result
to understand how robust the result is
and to know if the analysis done is the best way to probe what is fitted

One missing beast: h^3

The Higgs self-couplings plays important roles

1) controls the stability of the EW vacuum

2) dictates the dynamics of EW phase transition and potentially conditions the generation of a matter-antimatter asymmetry via EW baryogenesis

Does it need to be measured with high accuracy?

difficult to design new physics scenarios that dominantly affect the Higgs self-couplings and leave the other Higgs coupling deviations undetectable

Higgs self-coupling prospects

	HL LHC 3/ab	ILC/CLIC	FCC 100TeV
Precision on λ_{HHH}	$b\bar{b}\gamma\gamma$: poor, only $\sim O(1)$ determination Other channels: needs more detailed studies	ILC • DHS alone at 500 GeV and 1TeV gives only $\sim O(1)$ determination • ~28% via VBF at 1TeV, 1/ab CLIC at 3TeV, 2/ab • ~12% via VBF	$b\bar{b}\gamma\gamma$: golden channel. 5-10% determination might be possible with 30/ab. ~3x less sensitivity with 3/ab
Comments	Combining various channels might be important	The role of VBF is important High CM energy and high luminosity are crucial	Improvements on heavy flavor tagging, fakes, mass resolution etc are crucial to achieve our goal

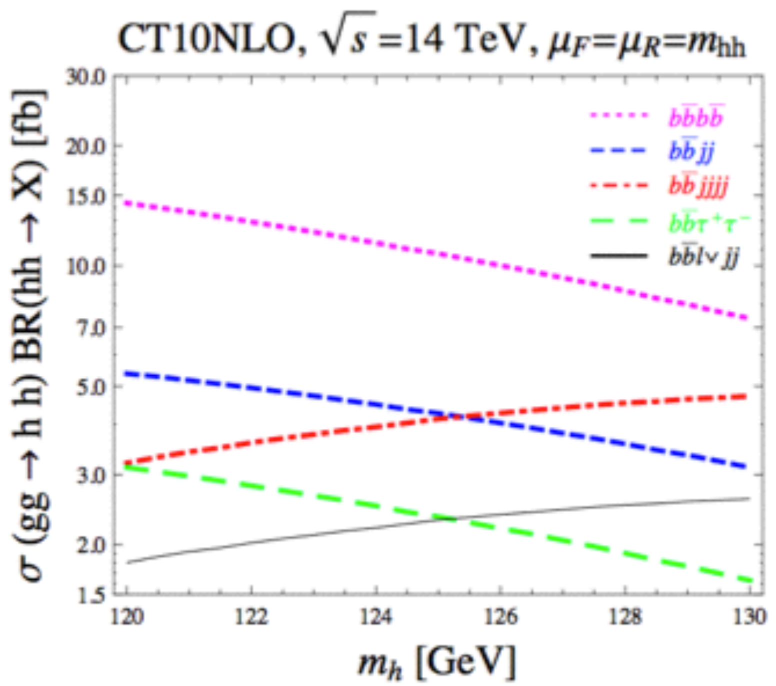
M. Son, Washington '15

h^3 from hh@LHC

Measuring this small cross section in an inclusive search is very challenging at the HL-LHC: compromise between branching ratio and cleanliness of the signal

M. Spannowsky, Mainz '15

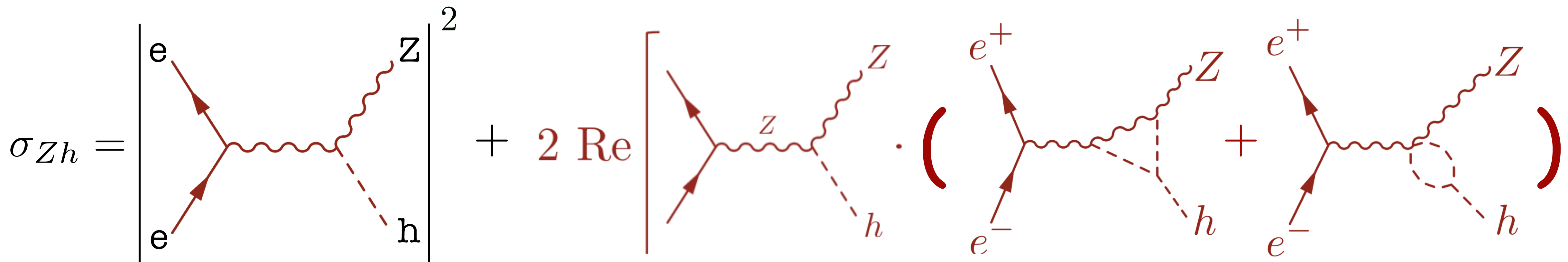
Channel	BR (%)	Events/3 ab
$bbWW$	24.7	30000
$bb\tau\tau$	7.3	9000
$WWWW$	4.3	5200
$bb\gamma\gamma$	0.27	330
$bbZZ(\to e^+e^-\mu^+\mu^-)$	0.015	19
$\gamma\gamma\gamma\gamma$	0.00052	1



Decay	Issues	Expectation 3000 ifb	References
$b\bar{b}\gamma\gamma$	• Signal small • BKG large & difficult to asses • Simple reconst.	$S/B \simeq 1/3$ $S/\sqrt{B} \simeq 2.5$	[Baur, Plehn, Rainwater] [Yao 1308.6302] [Baglio et al. JHEP 1304]
$b\bar{b}\tau^+\tau^-$	• tau rec tough • largest bkg tt • Boost+MT2 might help	**differ a lot** $S/B \simeq 1/5$ $S/\sqrt{B} \simeq 5$	[Dolan, Englert, MS] [Barr, Dolan, Englert, MS] [Baglio et al. JHEP 1304]
$b\bar{b}W^+W^-$	• looks like tt • Need semilep. W to rec. two H • Boost + BDT proposed	**differ a lot** best case: $S/B \simeq 1.5$ $S/\sqrt{B} \simeq 8.2$	[Dolan, Englert, MS] [Baglio et al. JHEP 1304] [Papaefstathiou, Yang, Zurita 1209.1489]
$b\bar{b}b\bar{b}$	• Trigger issue (high pT kill signal) • 4b background large difficult with MC • Subjets might help	$S/B \simeq 0.02$ $S/\sqrt{B} \leq 2.0$	[Dolan, Englert, MS] [Ferreira de Lima, Papaefstathiou, MS] [Wardrope et al, 1410.2794]
others	• Many taus/W not clear if 2 Higgs • Zs, photons no rate		

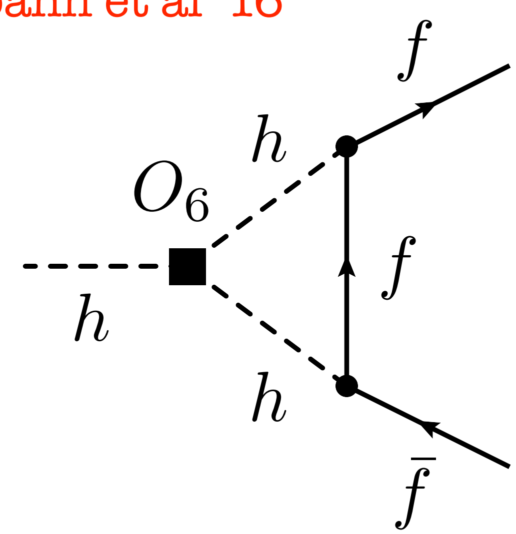
h^3 from h@NLO@LHC

M. McCullough '14

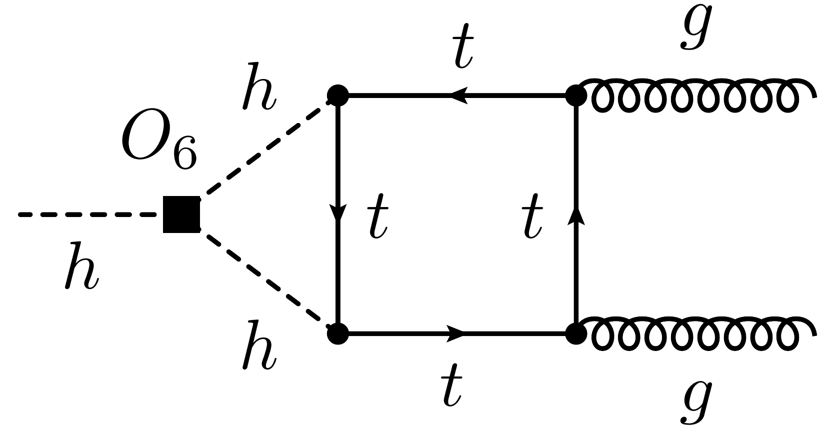


$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

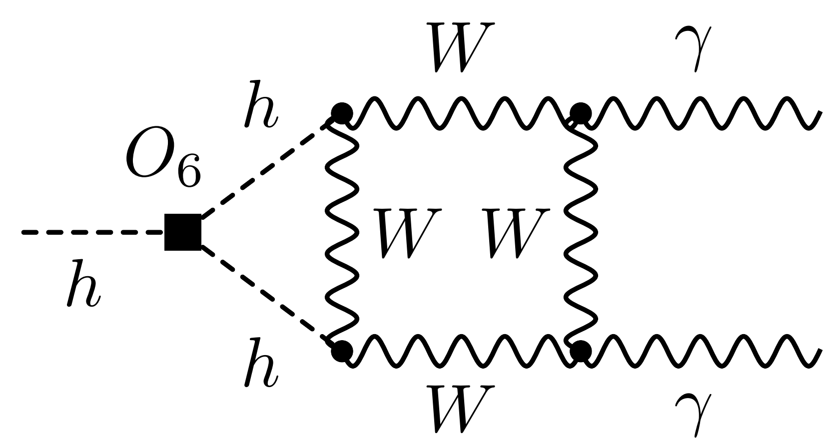
Gorbahn et al '16

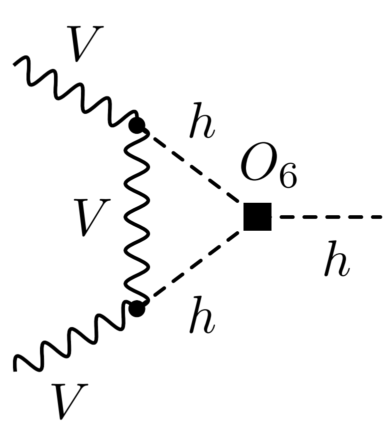


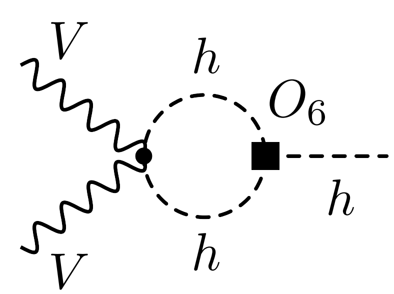
Degrassi et al '16

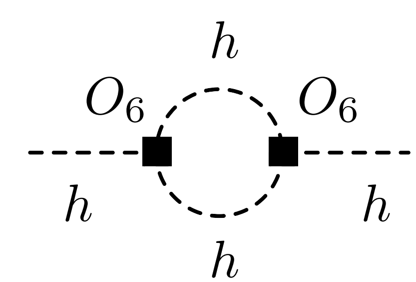


Bizon et al '16

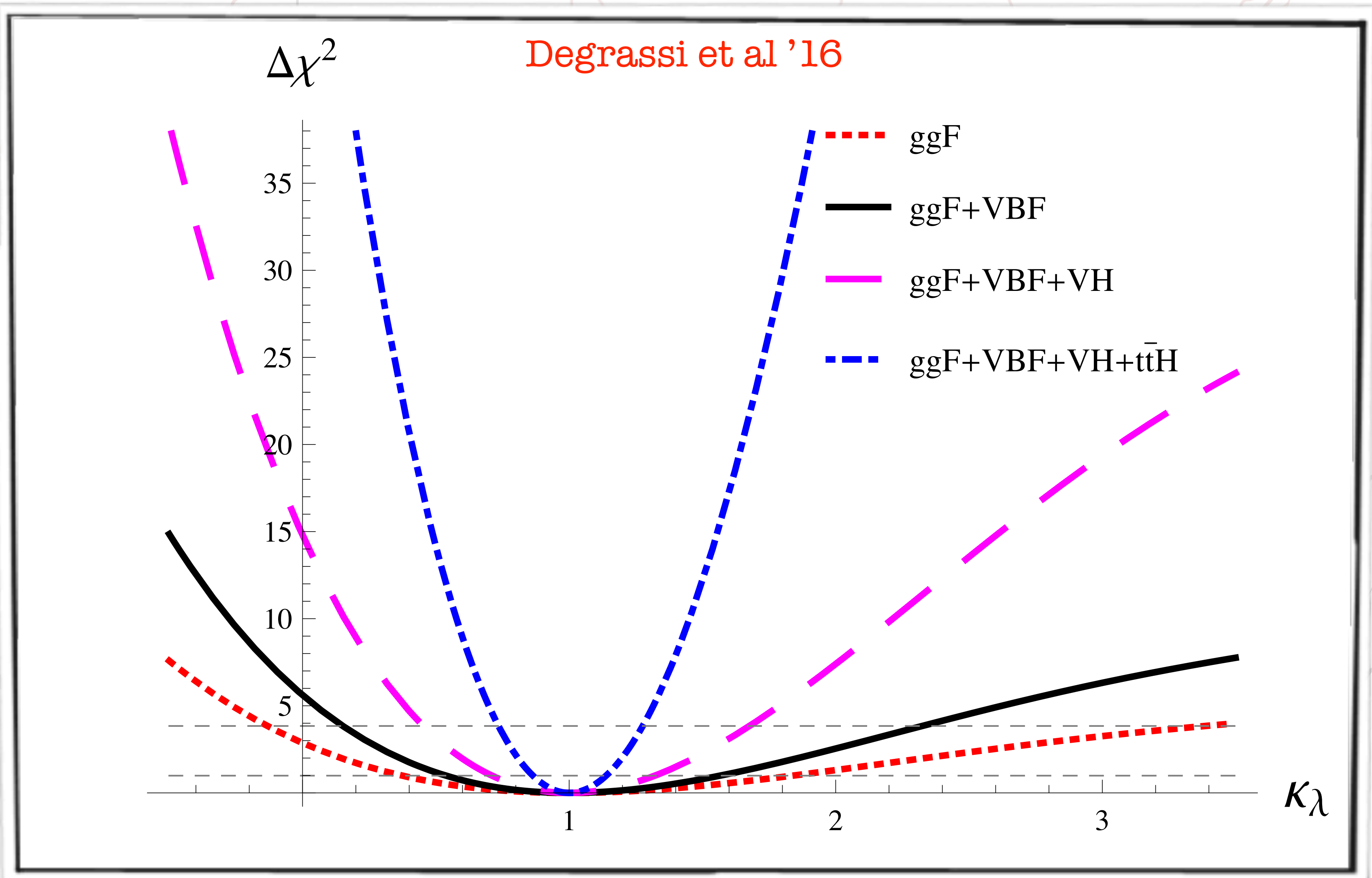






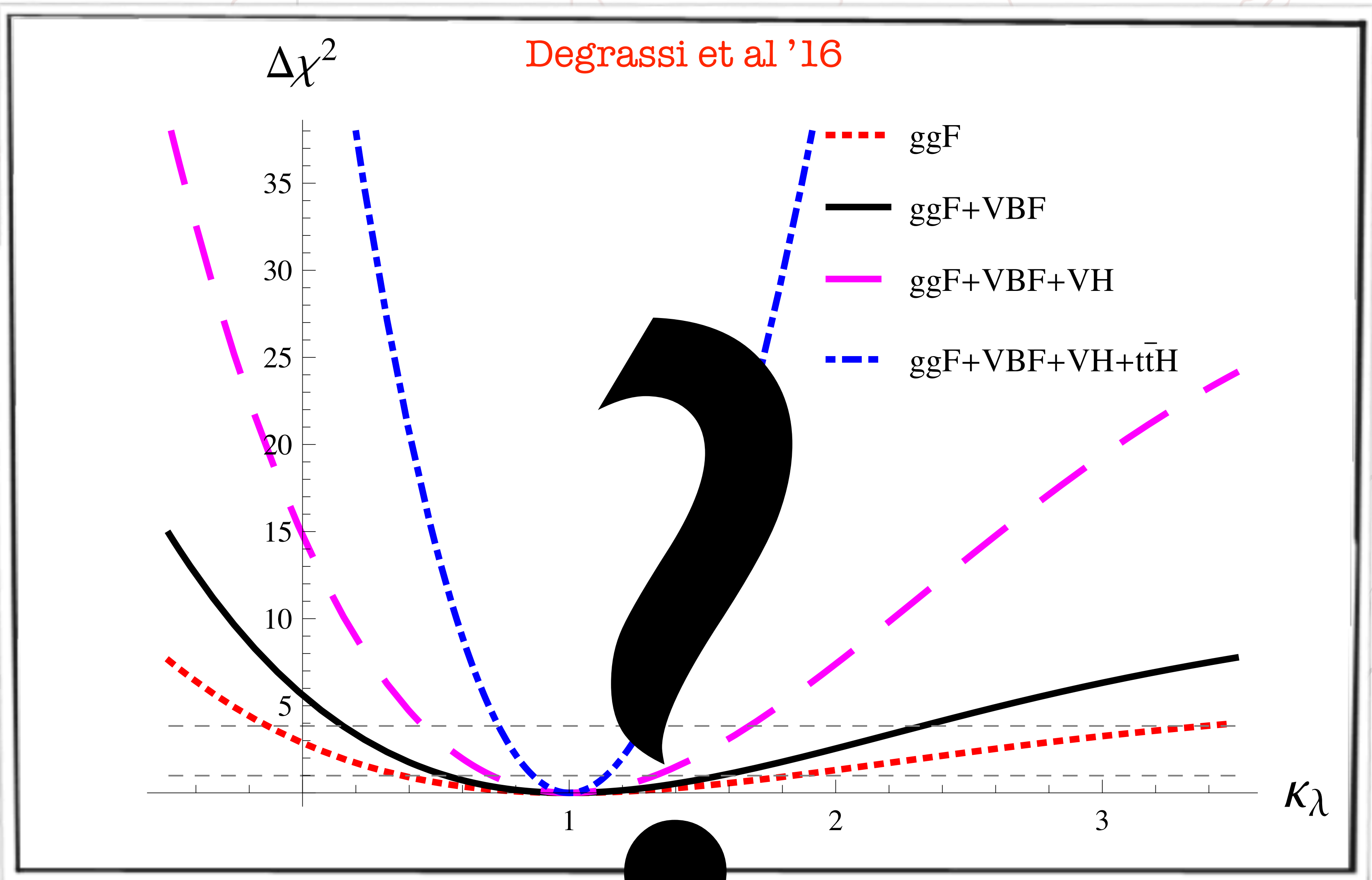


h^3 from h@NLO@LHC



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

h³ from h@NLO@LHC

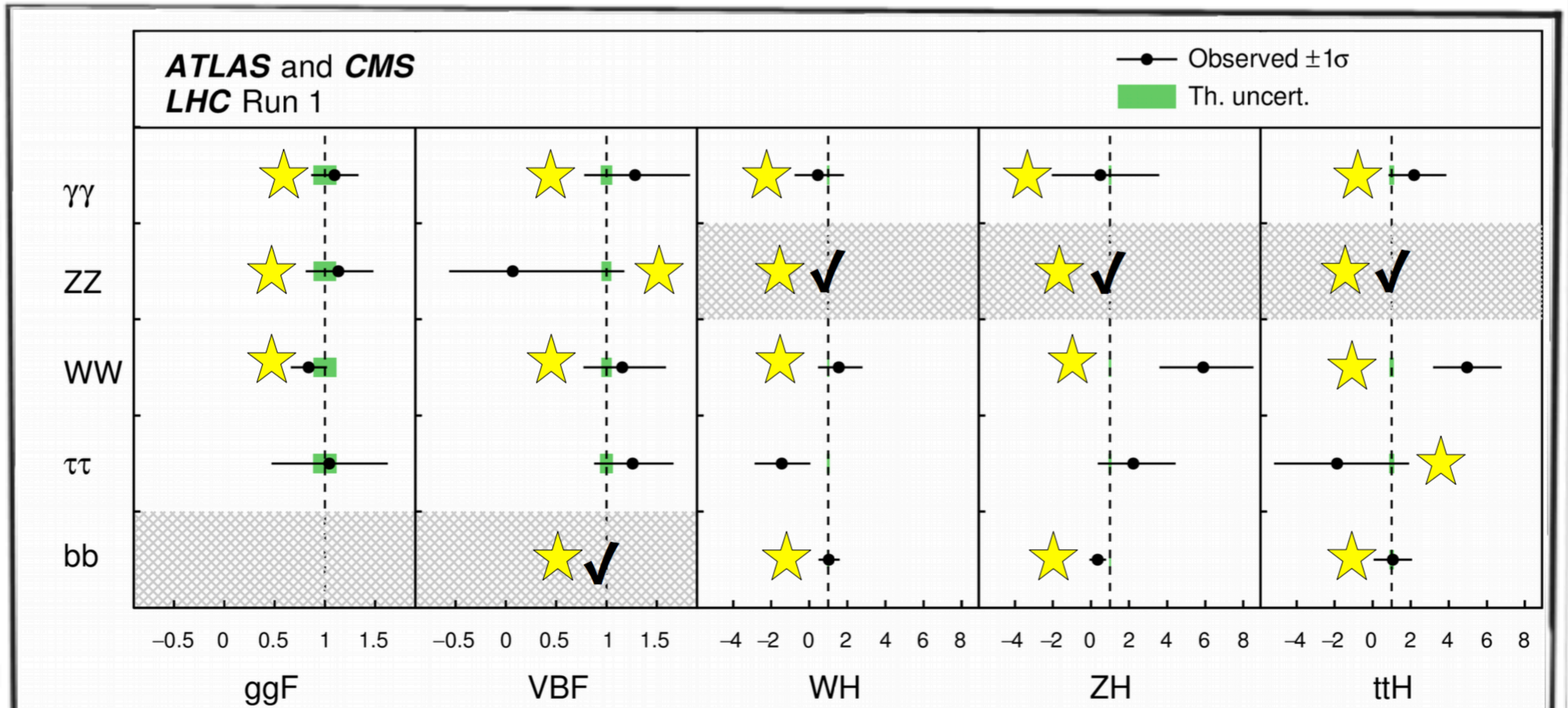


$$\kappa_\lambda \in [-0.7, 4.2]$$

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb



σxBr normalised to SM

√ = done since Run 1 combination

★ = 13 TeV results

C. Diaconu's talk this morning

h^3 @NLO vs h @ LO in global fit

Good sensitivity (O(5-10-20)%) on 16 channels @ **HL-LHC**

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

Estimated relative uncertainties on the determination of single-Higgs production channels at the HL-LHC(14 TeV center of mass energy, 3/ab integrated luminosity and pile-up 140 events/bunch-crossing).

ATL-PHYS-PUB-2014-016 ATL-PHYS-PUB-2016-008 ATL-PHYS-PUB-2016-018

h^3 @NLO vs h @ LO in global fit

The fabulous 5^2 channels

5 main production modes: ggF, VBF, WH, ZH, ttH
5 main decay modes: ZZ, WW, γγ, ττ, bb

a priori up to **25** measurements
but for an on-shell particles, at most **10** physical quantities
since only products σxBR are measured
only **9** independent constraints

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

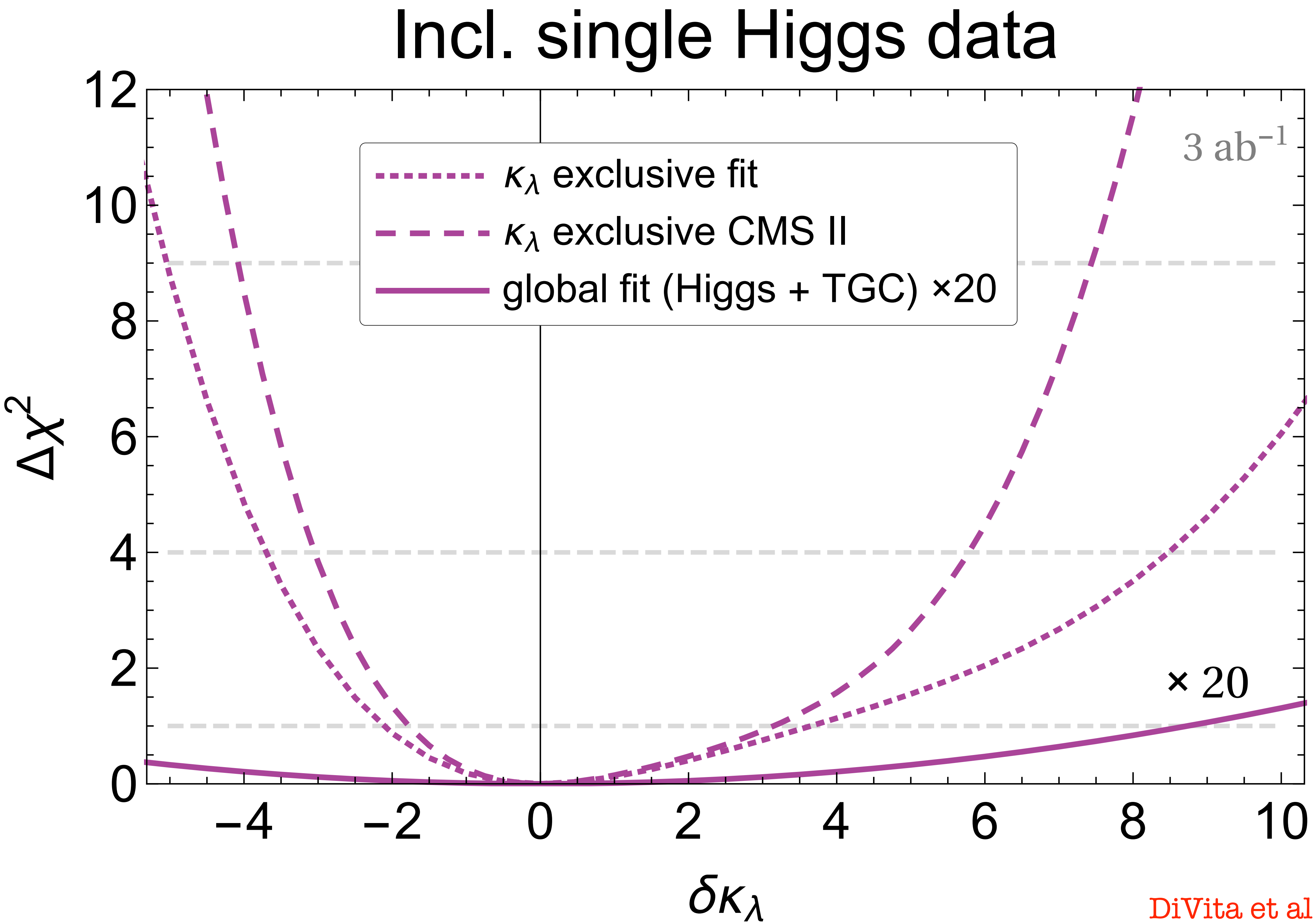
$$\mu_i^f \simeq 1 + \delta\mu_i + \delta\mu^f$$

$$\mu_i \to \mu_i + \delta \qquad \mu^f \to \mu^f - \delta$$

cannot determine univocally 10 EFT parameters!

one flat direction is expected!

h^3 @NLO vs h @ LO in global fit

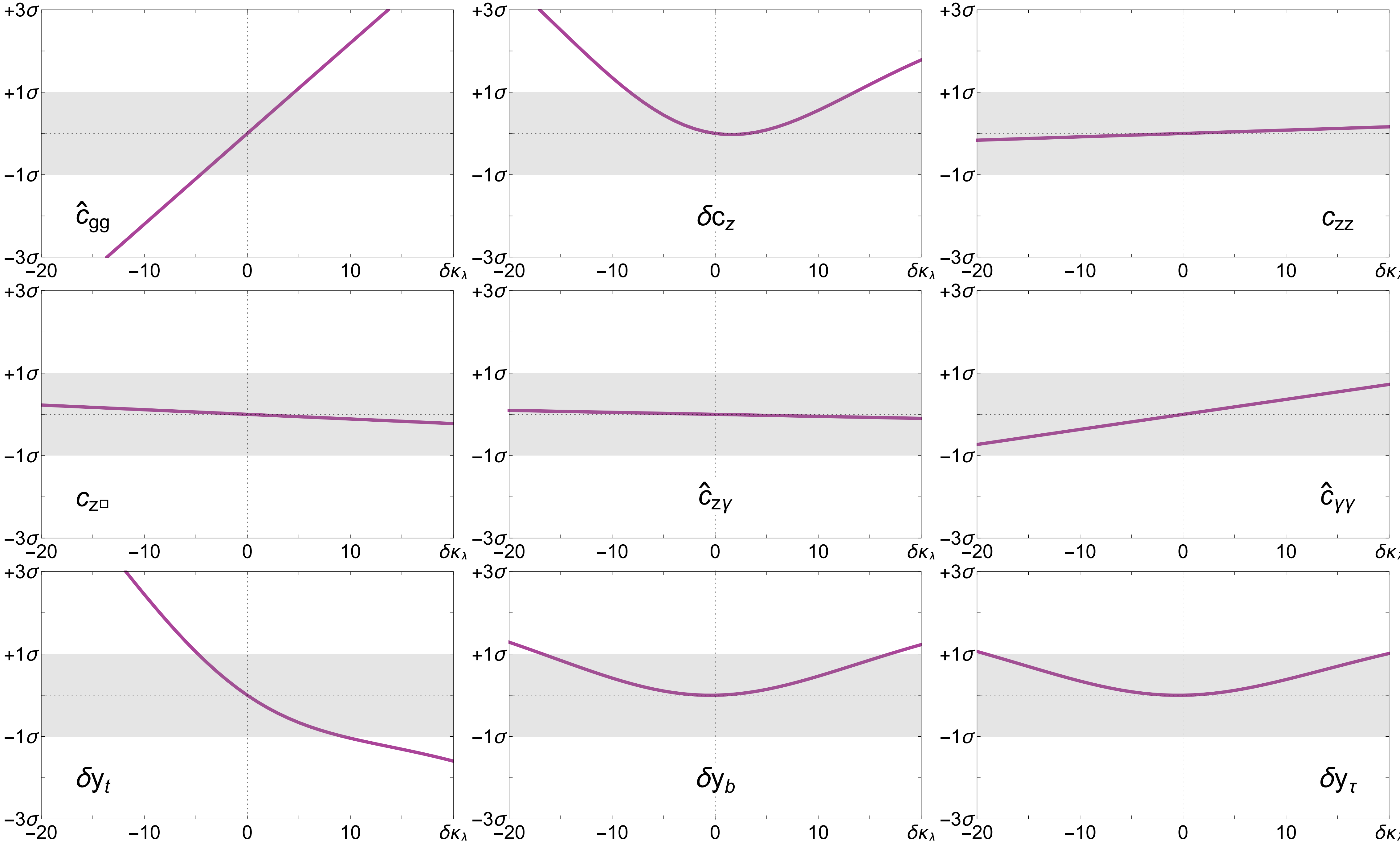


DiVita et al '17

one flat direction is expected!

h^3 @NLO vs h @ LO in global fit

Higgs couplings variation along the flat direction



DiVita et al '17

The particular structure of this flat direction

tells that adding new data on diboson or h→Zγ won't help much

one flat direction is expected!

h^3 @NLO vs h @ LO in global fit

?

>

NLO w/ dominant h^3 = LO w/ subdominant other h

<

Minimal Composite Higgs

SILH

$\xi = \frac{v^2}{f^2} \ll 1$

$\frac{1}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad \frac{\lambda_4}{f^2}|H|^6$

$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\xi$ $\quad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\xi$

NLO h^3 irrelevant

Partly Composite Higgs

$\xi = \frac{v^2}{f^2} \ll 1$

$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad \frac{\varepsilon^6}{f^2}|H|^6$

$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^4\xi$ $\quad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\varepsilon^2\frac{g_*^2 v^2}{m_h^2}\varepsilon^4\xi$

NLO h^3 could be relevant

Bosonic Technicolor

Induced EWSB

$\varepsilon = \frac{f}{v} \ll 1$

$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2$ $\quad \frac{\varepsilon^6}{f^2}|H|^6$

$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1+\varepsilon^2$ $\quad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1+\mathcal{O}(1)$

NLO h^3 a priori relevant

h^3 in Higgs portal

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

$\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)$	$\delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2}$	parametric enhancement of h^3
$(H^\dagger H)^3$	$\delta \kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$	

but tuning of quartic couplings $\Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$

$\delta \kappa_\lambda \sim \varepsilon \Delta$ where ε controls validity of h expansion $\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2}$

large h^3: either tuning (Δ>1) or give-up on linear h-expansion (ε >1)

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

$$\varepsilon \simeq 0.1\,, \quad 1/\Delta \simeq 1.5\%\,, \quad \delta c_z \simeq 0.1\,, \quad \delta\kappa_\lambda \simeq 6$$

Does h³ modify the fit to other couplings?

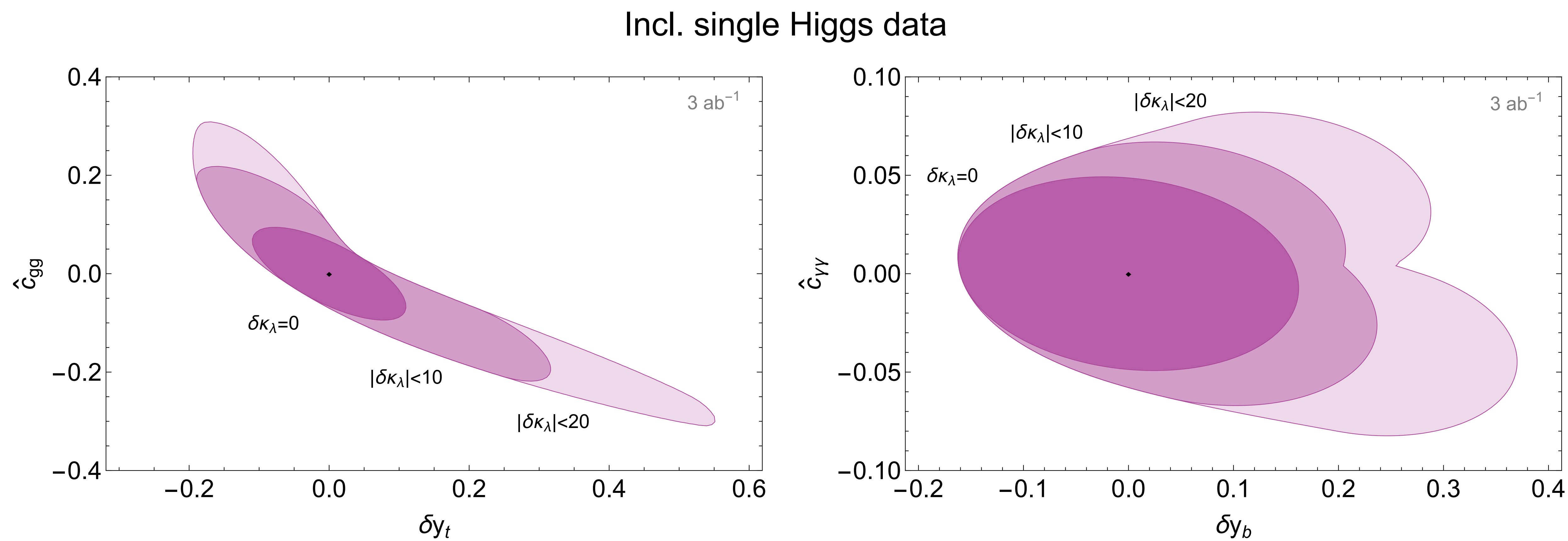
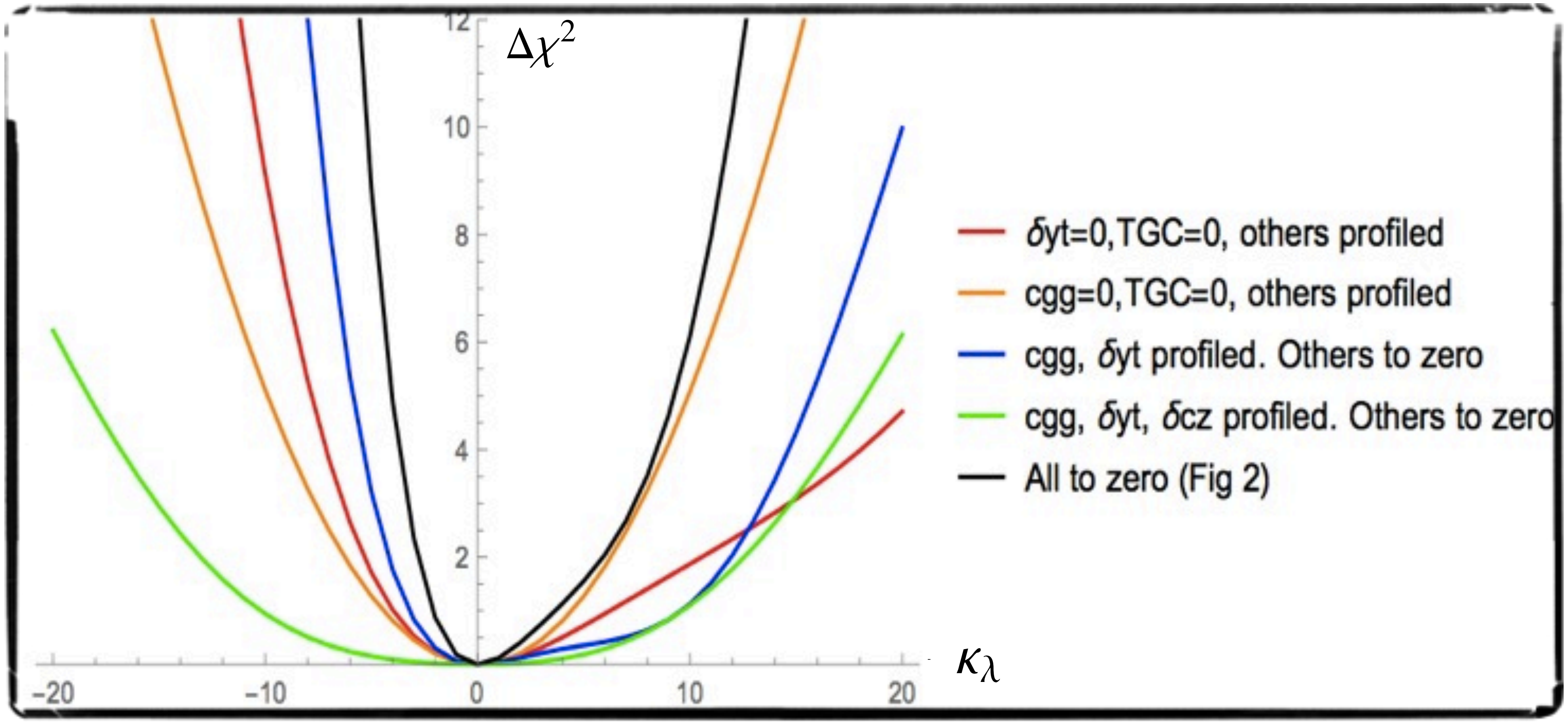


Figure 3. Constraints in the planes $(\delta y_t, \hat{c}_{gg})$ (left panel) and $(\delta y_b, \hat{c}_{\gamma\gamma})$ (right panel) obtained from a global fit on the single-Higgs processes. The darker regions are obtained by fixing the Higgs trilinear to the SM value $\kappa_\lambda = 1$, while the lighter ones are obtained through profiling by restricting $\delta\kappa_\lambda$ in the ranges $|\delta\kappa_\lambda| \leq 10$ and $|\delta\kappa_\lambda| \leq 20$ respectively. The regions correspond to 68% confidence level (defined in the Gaussian limit corresponding to $\Delta\chi^2 = 2.3$).

in models with parametrically large h³,
a LO fit to single Higgs couplings could be erroneous

Intermediate scenarios?



NLO single Higgs
might do well
(w/o the need for HH)
in intermediate
scenarios
with not the full
set of couplings

... model building required ...

single Higgs couplings:

simple dynamics = few parameters (κ_F/κ_V, κ_g/κ_γ)

more dynamics = more parameters

h3 fit:

simple dynamics = flat direction

more dynamics (e.g. twin portal) = fewer parameters = less degeneracy

NLO single H vs double Higgs

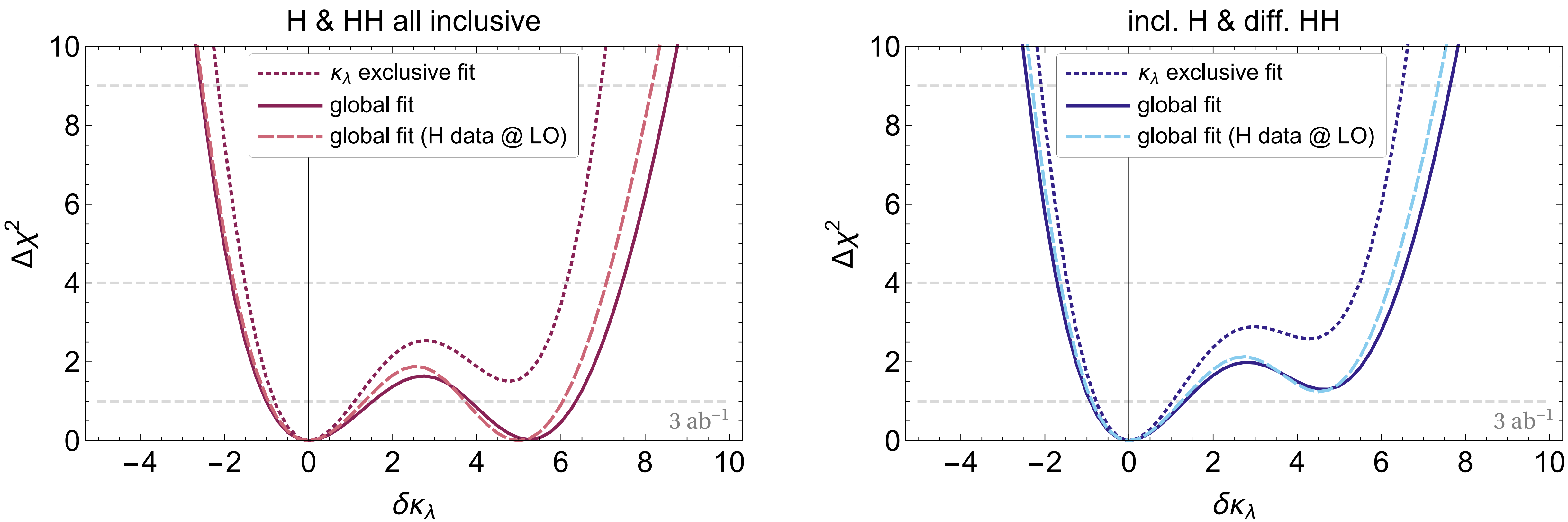


Figure 4. *Left:* The solid curve shows the global χ^2 as a function of the corrections to the Higgs trilinear self-coupling obtained from a fit exploiting inclusive single Higgs and inclusive double Higgs observables. The dashed line shows the fit obtained by neglecting the dependence on $\delta\kappa_\lambda$ in single-Higgs observables. The dotted line is obtained by exclusive fit in which all the EFT parameters, except for $\delta\kappa_\lambda$, are set to zero. *Right:* The same but using differential observables for double Higgs.

double Higgs first!

single Higgs observables at NLO plays a marginal role in determining h^3

differential double Higgs removes degenerate minima

Be careful: if non-linear EFT, more parameters are needed!

Is differential single H @ NLO a good option?

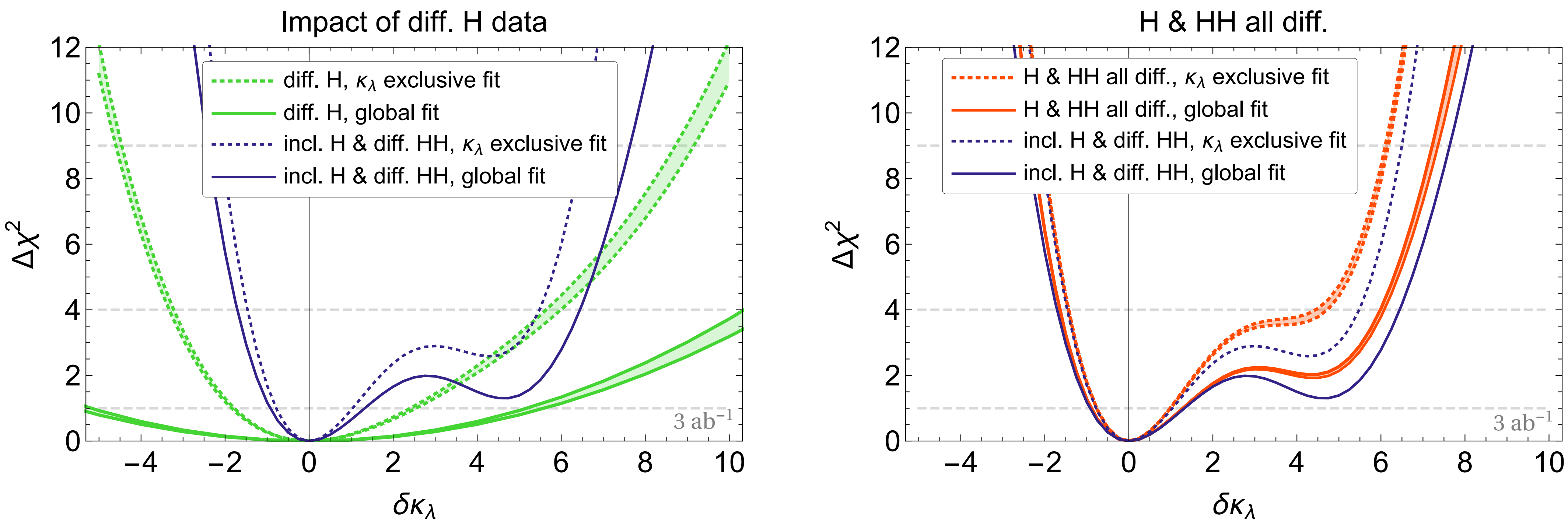


Figure 5. *Left:* χ^2 as a function of the Higgs trilinear self-coupling. The green bands are obtained from the differential analysis on single-Higgs observables and are delimited by the fits corresponding to the optimistic and pessimistic estimates of the experimental uncertainties. The dotted green curves correspond to a fit performed exclusively on $\delta\kappa_\lambda$ setting to zero all the other parameters, while the solid green lines are obtained by a global fit profiling over the single-Higgs coupling parameters. *Right:* The red lines show the fits obtained by a combination of single-Higgs and double-Higgs differential observables. In both panels the dark blue curves are obtained by considering only double-Higgs differential observables and coincide with the results shown in fig. 4.

diff. single Higgs observables to asses h^3 = interesting potential option
but more detailed estimates of exp. uncertainties are required
to fully asses its potential

Is the fit robust against systematics?

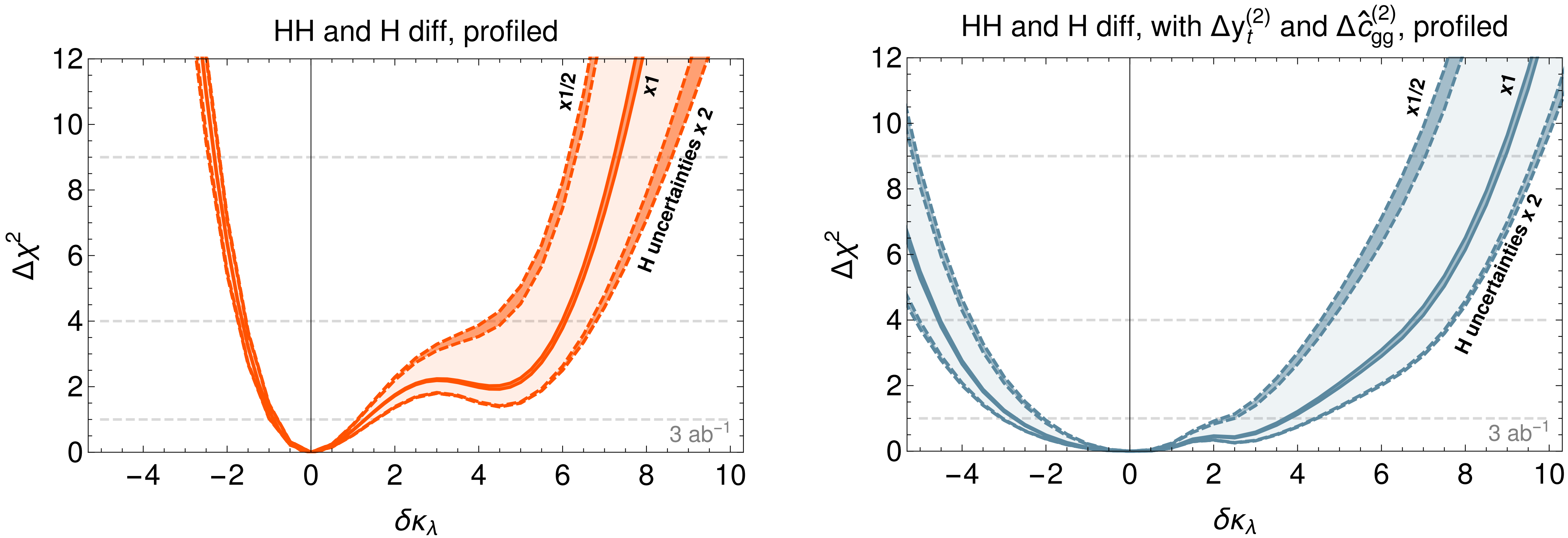


Figure 6. Band of variation of the global fit on the Higgs self-coupling obtained by rescaling the single-Higgs measurement uncertainties by a factor in the range $x \in [1/2, 2]$. The lighter shaded bands show the full variation of the fit due to the rescaling. The darker bands show how the fits corresponding to the 'optimistic' and 'pessimistic' assumptions on the systematic uncertainties (compare fig. 5) change for $x = 1/2, 1, 2$. The left panel shows the fit in the linear Lagrangian, while the right panel corresponds to the non-linear case in which $\Delta y_f^{(2)}$ and $\Delta \hat{c}_{gg}^{(2)}$ are treated as independent parameters.

in scenarios where h^3 can be naturally large,
Higgs expansion expected to break down
more parameters are needed
(in particular due do fewer constraints from EW precision data)

no robust determination of h^3 possible yet in that case

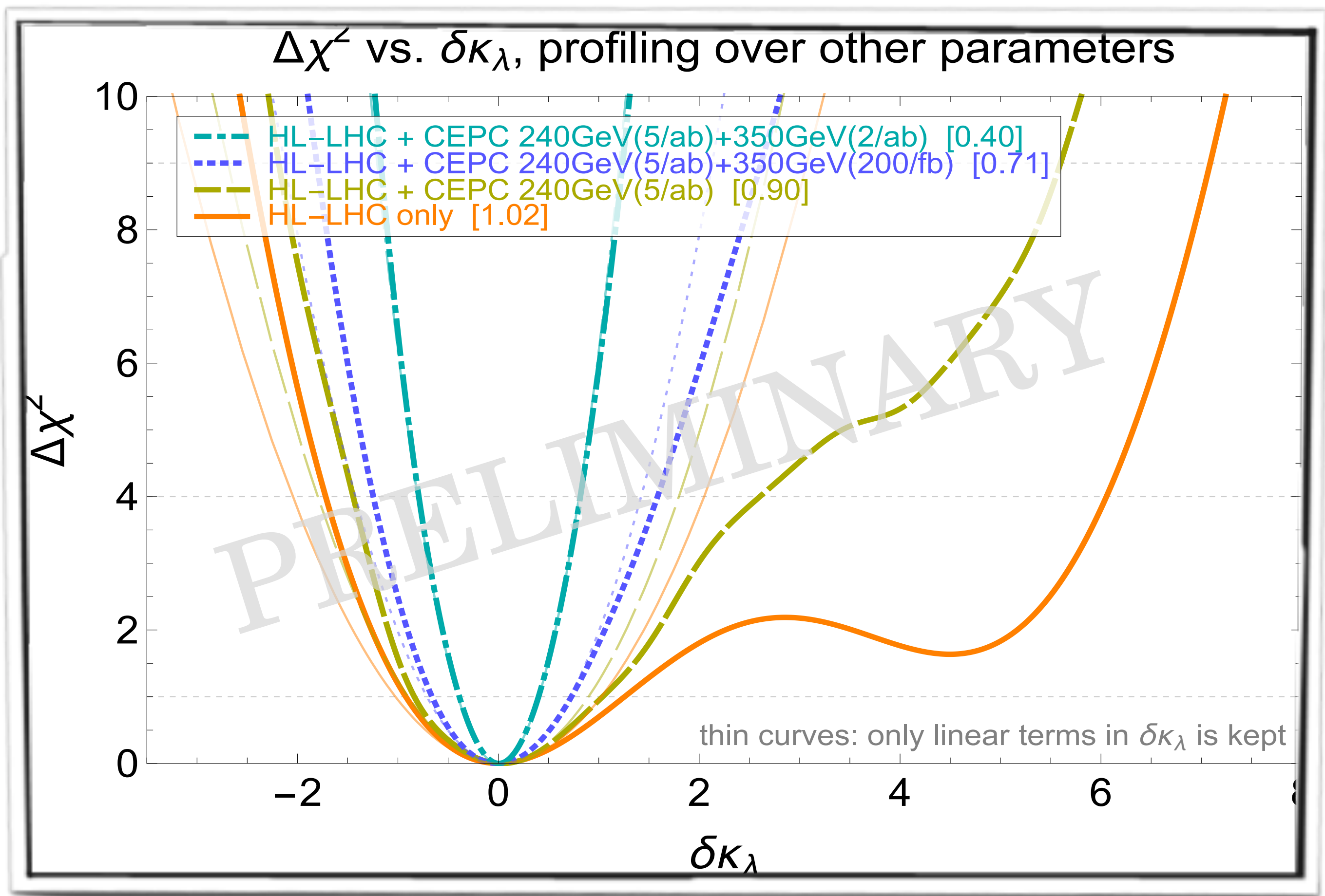
What about (low energy) e^+e^- colliders?

Access to more decay modes

1 main production mode: ZH & 1 subdominant production: VBF
+ access to full angular distributions (4) and/or beam polarizations (2)
7 (+2) accessible decay modes: ZZ, WW, γγ, Zγ, ττ, bb, gg, (cc, μμ)

at least **10** solid independent constraints to fit **10** parameters

a priori no flat direction is expected!



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What about (low energy) e⁺e⁻ colliders?

I mai … n:VBF

+ access … tions (2)

7 (+2) … cc, μμ)

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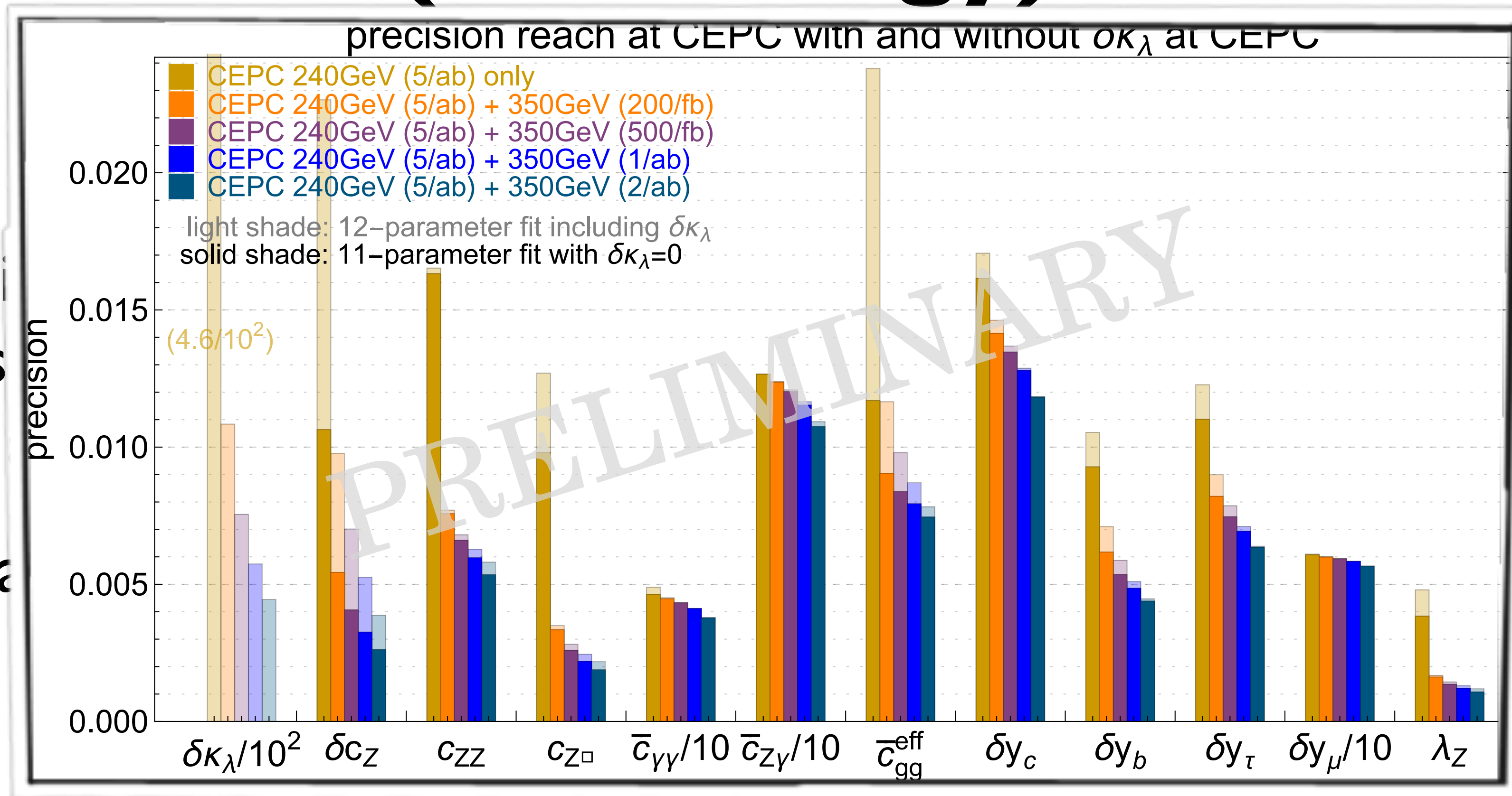

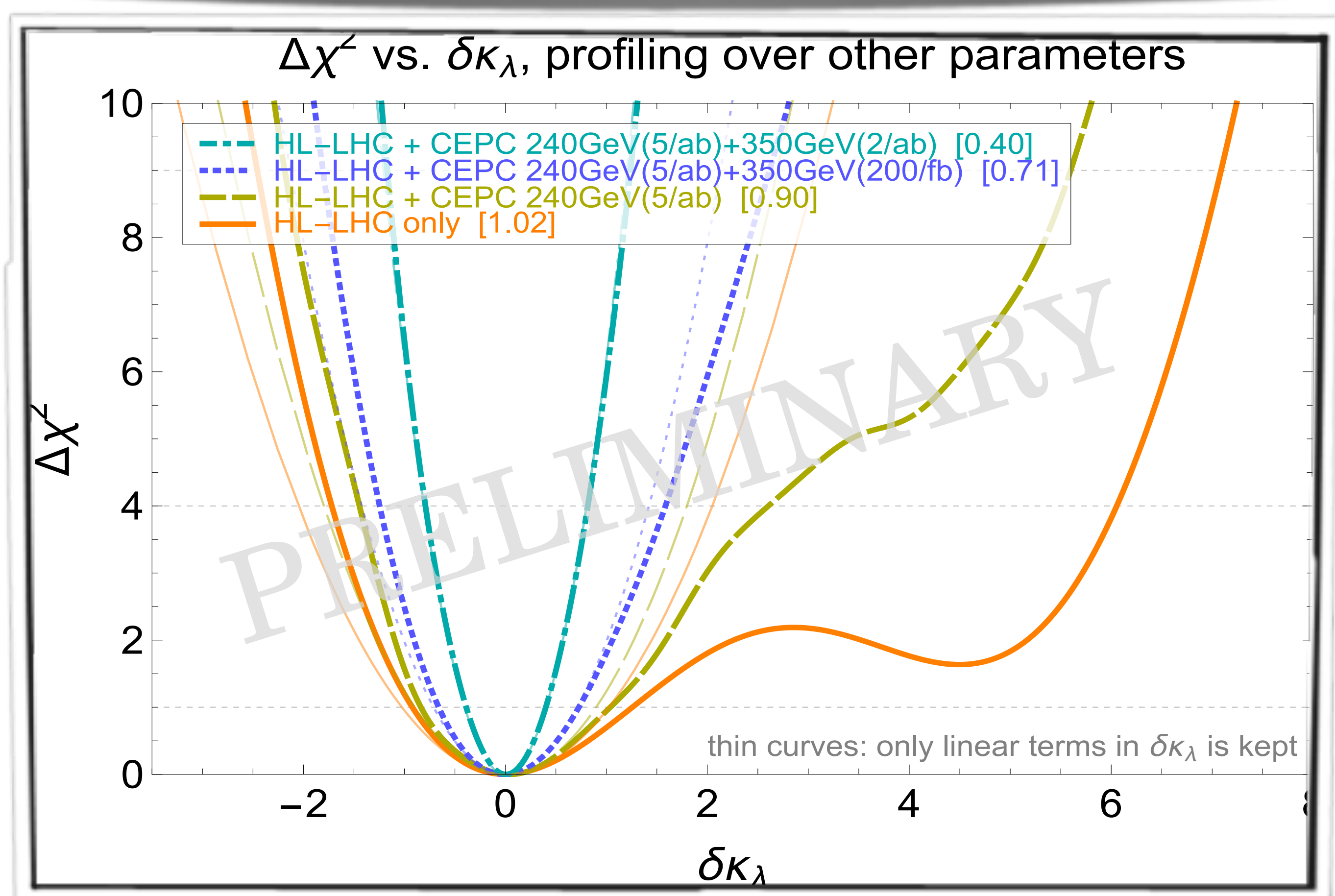

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Conclusions

Often it is claimed that h^3 measurement is needed
1) to understand EW symmetry breaking
2) to probe new physics at the origin of EWSB

Usually, h^3 is not the best access to new physics
but it can help figure out
the thermodynamics of EW phase transition
and the Higgs thermal potential
with important consequences:
1) EW baryogenesis
2) stochastic GW background

Let us try and help the experimentalists telling us its value!

in memoriam

2017 = 5th Planck conference in Poland

The organization of the first four benefited from the dedicated help of Zygmunt Ajduk

We are sorely missing him today