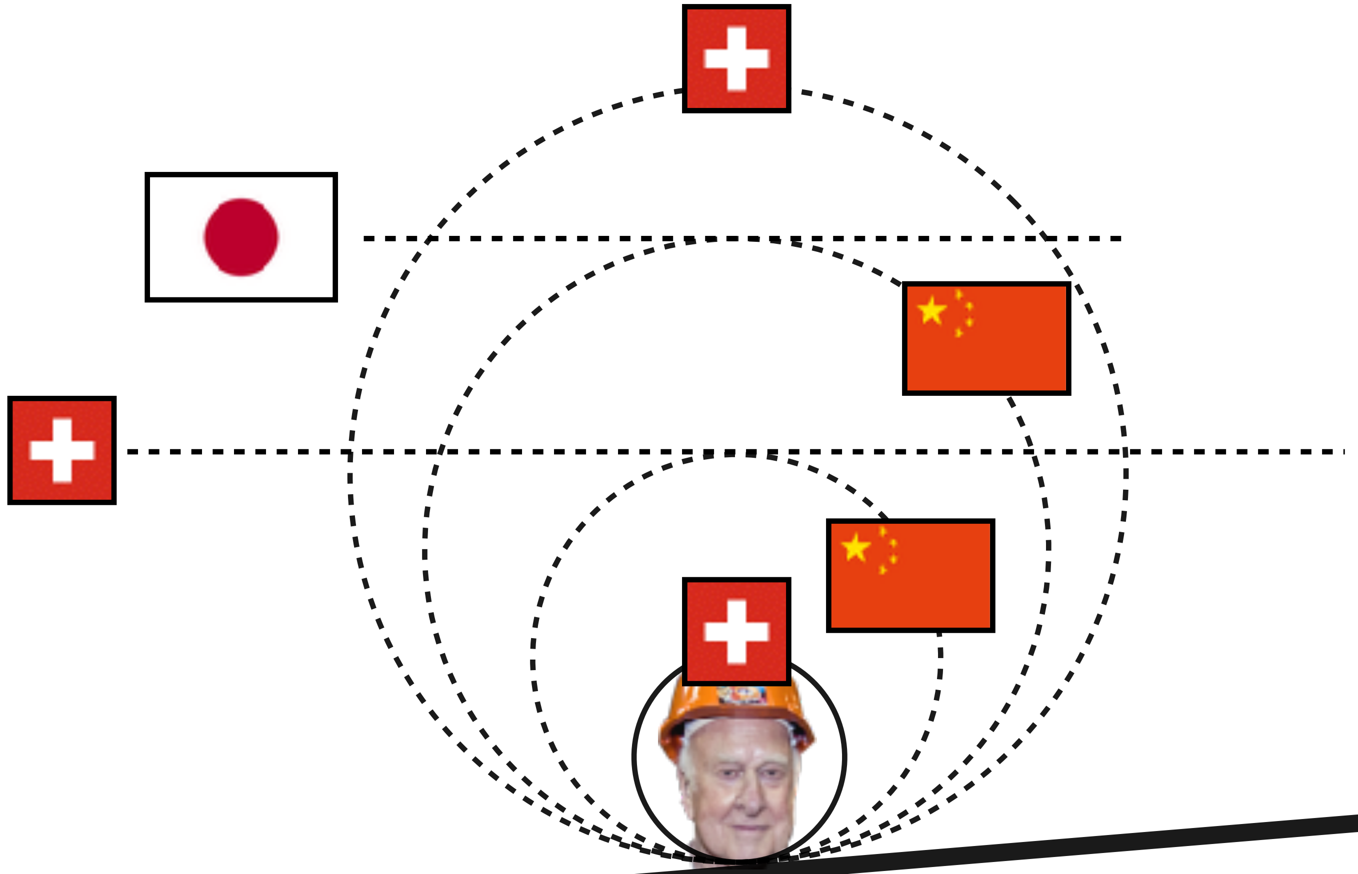
Trilinear Couplings

— global interpretation —

Ultimate Precision at Hadron Colliders

Institut Pascal, December 3, 2019



Christophe Grojean

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The importance of being cubic…

The Higgs self-coupling plays important roles

1) linked to **naturalness**/**hierarchy** problem

2) controls the **stability** of the EW vacuum (… like many other BSM parameters)

3) dictates the dynamics of EW **phase transition** and potentially conditions the generation of (1) matter-antimatter imbalance via **EW baryogenesis** & (2) a stochastic **GW** background

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Does it need to be measured with high accuracy?

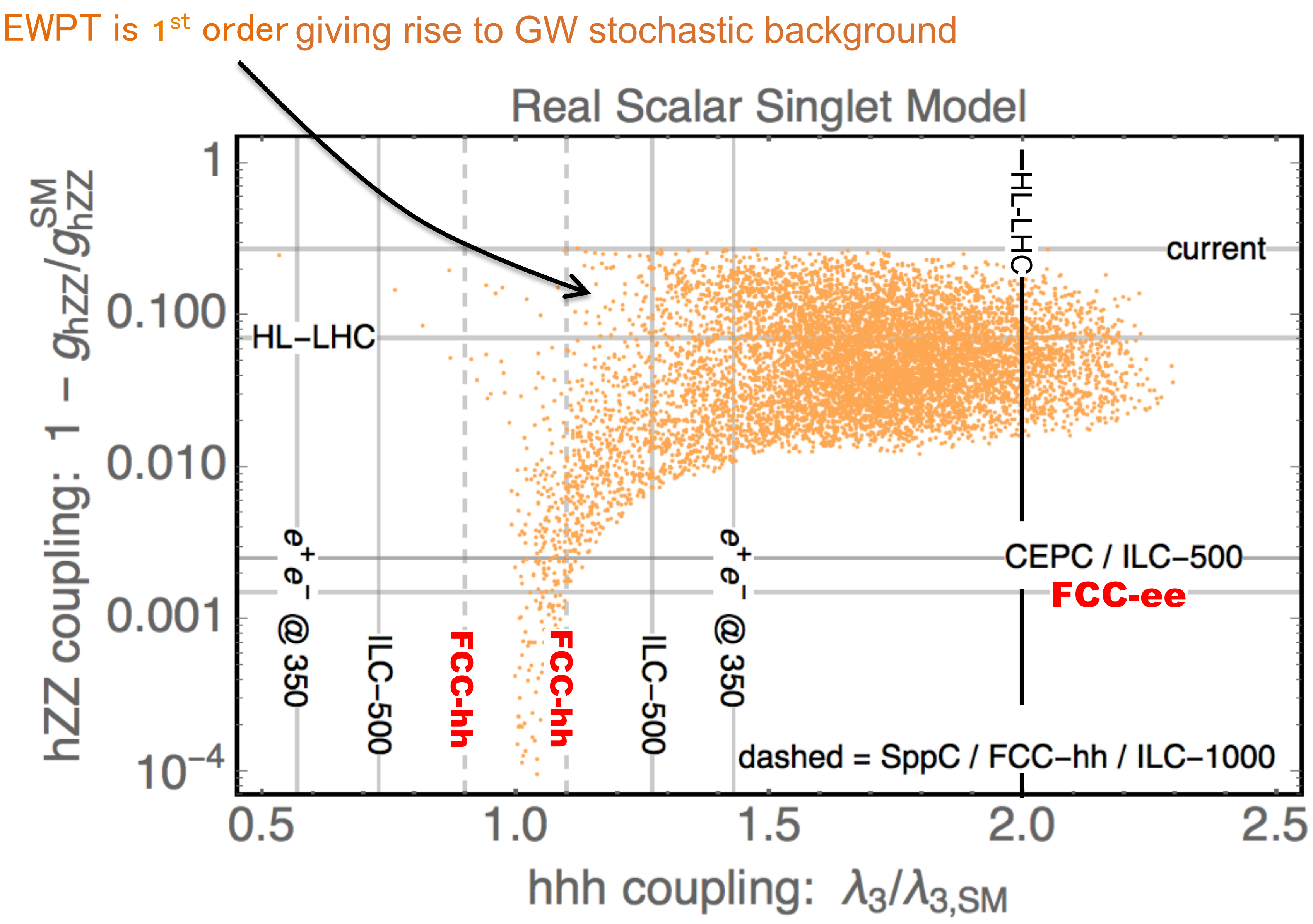
Only a few new physics scenarios (but they exist) that will be revealed in the measurements of h^3
But this measurement is the only way to understand the dynamics of EWSB (Cooper pair or elementary scalar?)

M. McCullough, DESY'18

What sort of precision should we aim for?

- 95% confidence it exists: Around 50% accuracy
- 5σ discovery: Around 20 % accuracy.
- Quantum structure: Around 5% accuracy.

Window to early universe: GW - Colliders



Huang, Long, Wang ’16

Which Higgs couplings?

Within the SM, all the Higgs couplings are uniquely fixed by known quantities
(G_F, m_W, m_Z, m_{quark}, m_{lepton})

This is a **curse** (nothing more to learn) and a **blessing** (can asses the inconsistency of the SM)

M. Mangano

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Two approaches to go BSM

Study
specific models

Try to introduce
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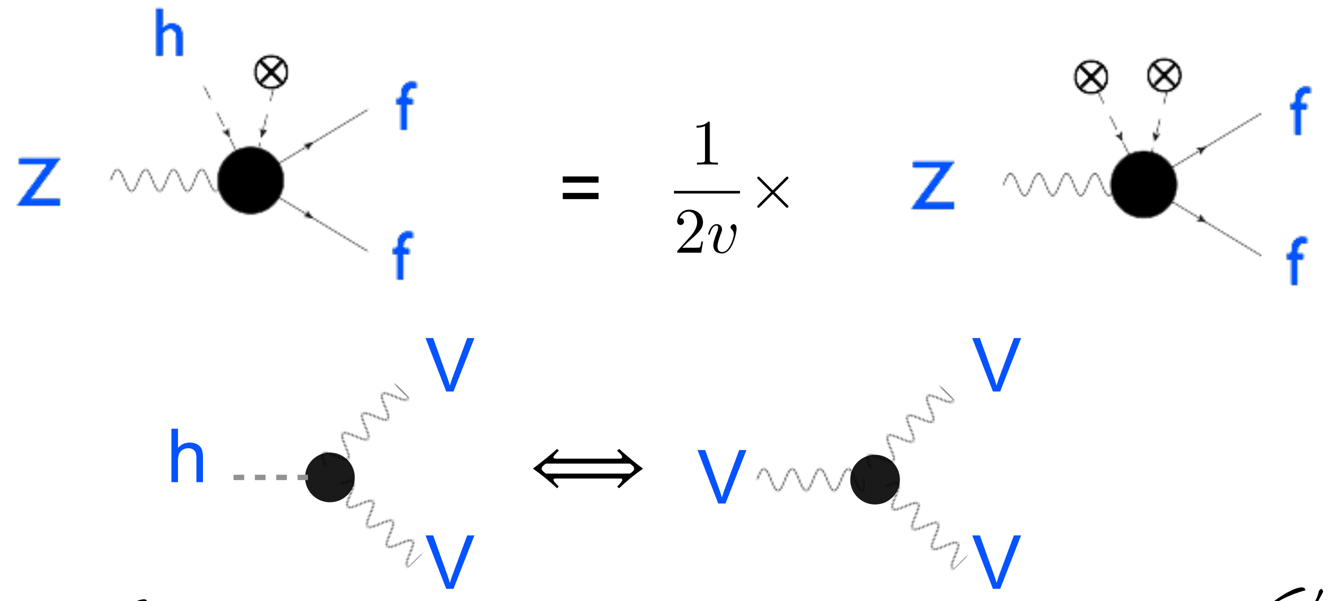
Higgs & the rest of the world

Assuming h is part of
a SU(2) doublet



At LHC: EW/VV precision strong enough not
to interfere with Higgs measurements
(at least if Higgs part of EW doublet)

Not necessarily true at future colliders
Need a more global strategy

Higgs/BSM Primaries

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

How many SM deformations are not affecting precisely measured observables outside Higgs physics?

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, h$\tau\tau$**

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m_h	$\lvert H\rvert^6$	→ h^3 coupling
m_f (f=t,b,τ)	$\lvert H\rvert^2 \bar{f}_L H f_R + h.c.$	

yet to be measured at the LHC (hZγ coupling, h^3 coupling)

Synergy Higgs and diboson

In $\text{EFT}_{(\text{dim-6})}$

8 deformations affecting Higgs physics alone

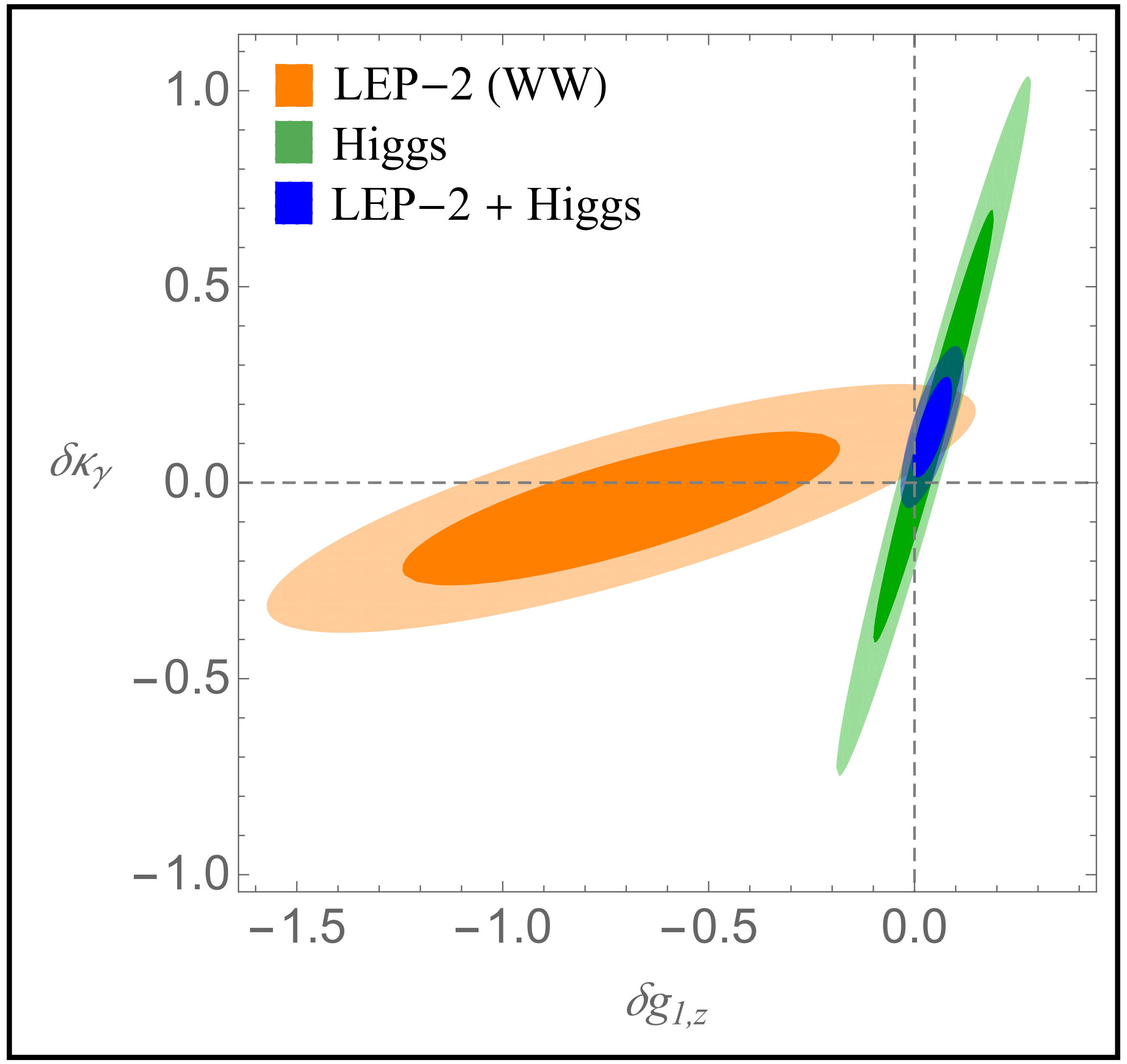
2 deformations affecting Higgs and diboson data

diboson (1%) are a priori more constraining than Higgs (10%)

Is there any value in doing a global fit?

Synergy Higgs and diboson

Falkowski et al '15



(TGC+Higgs)>(TGC)∪(Higgs)

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

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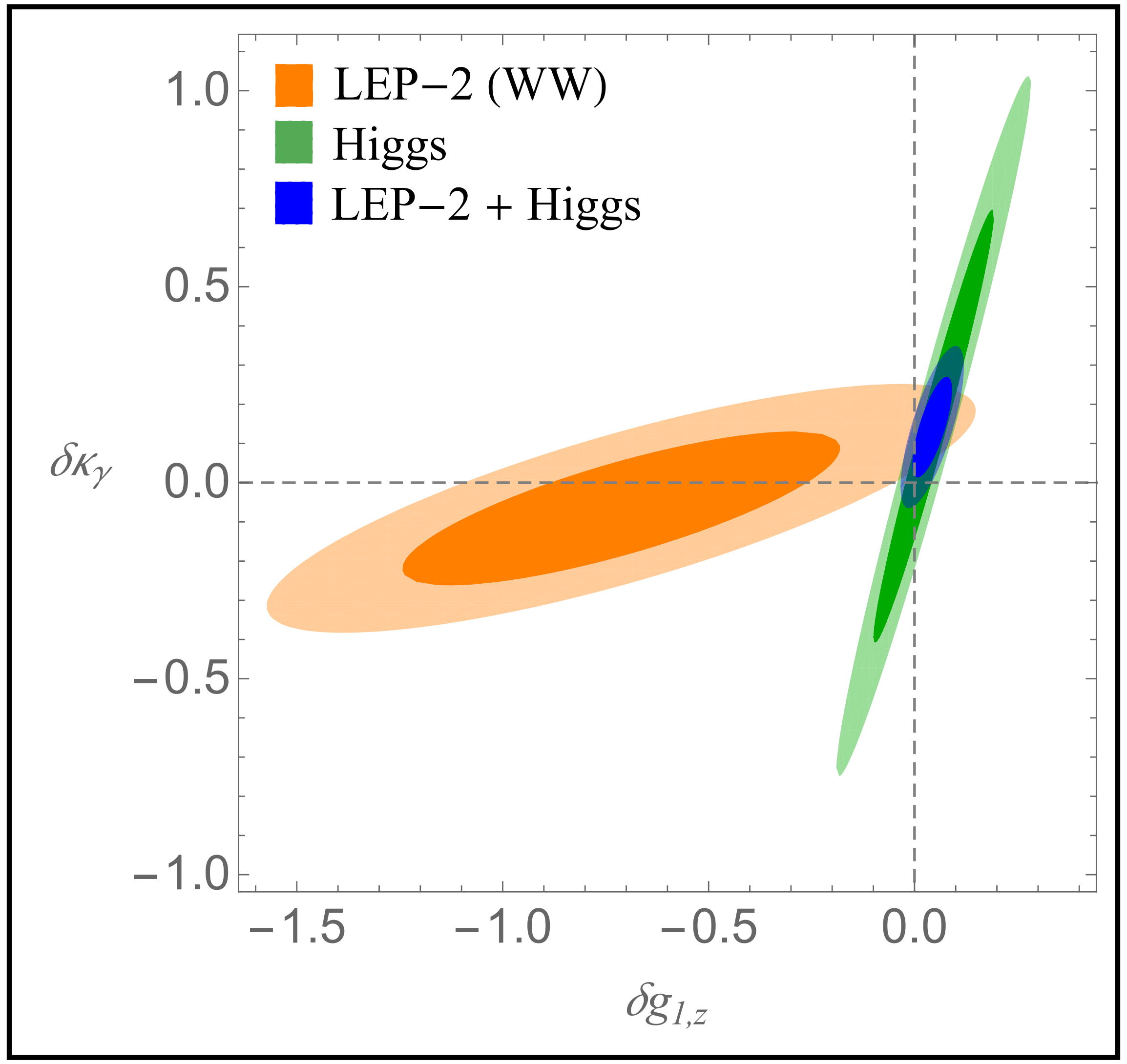

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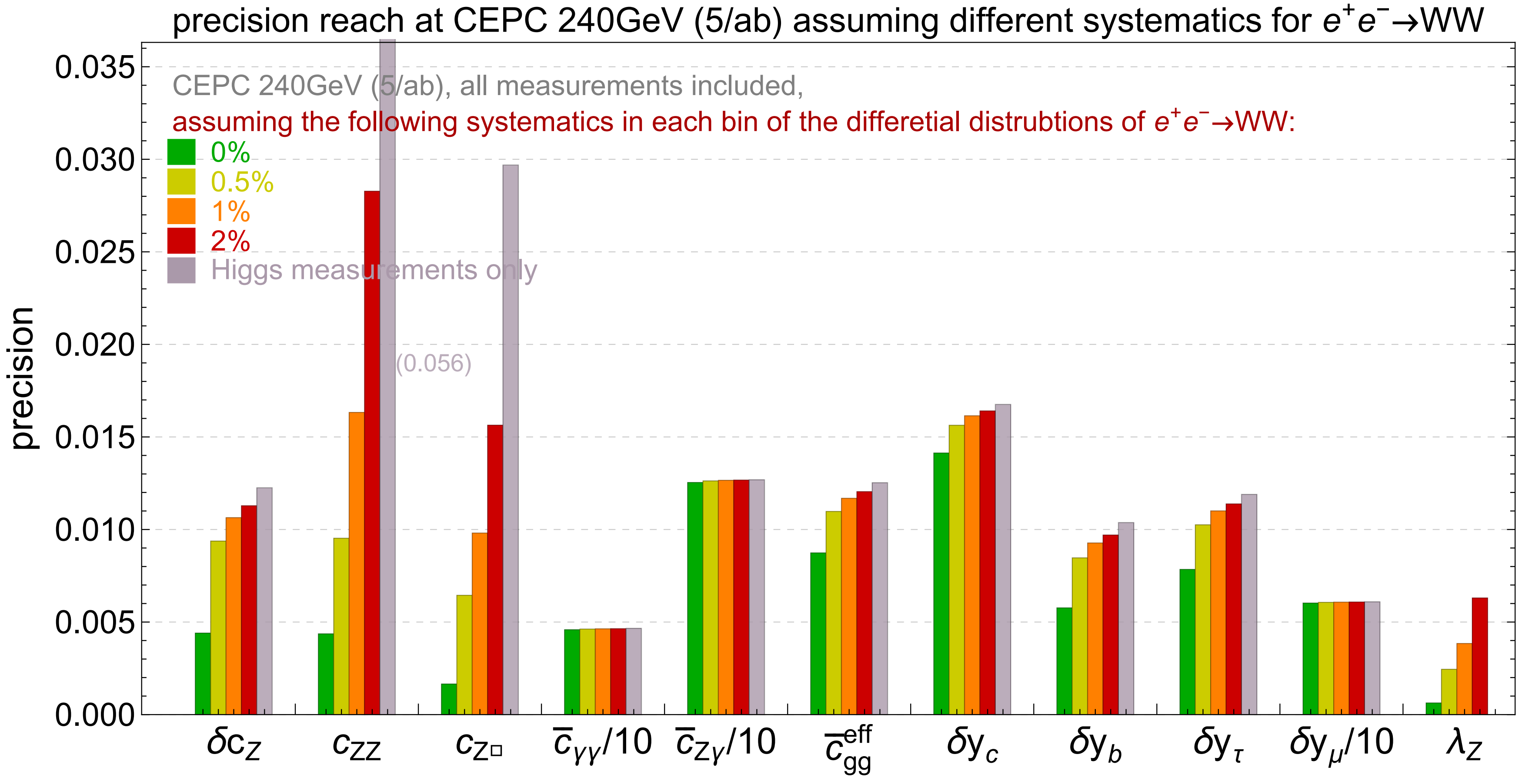
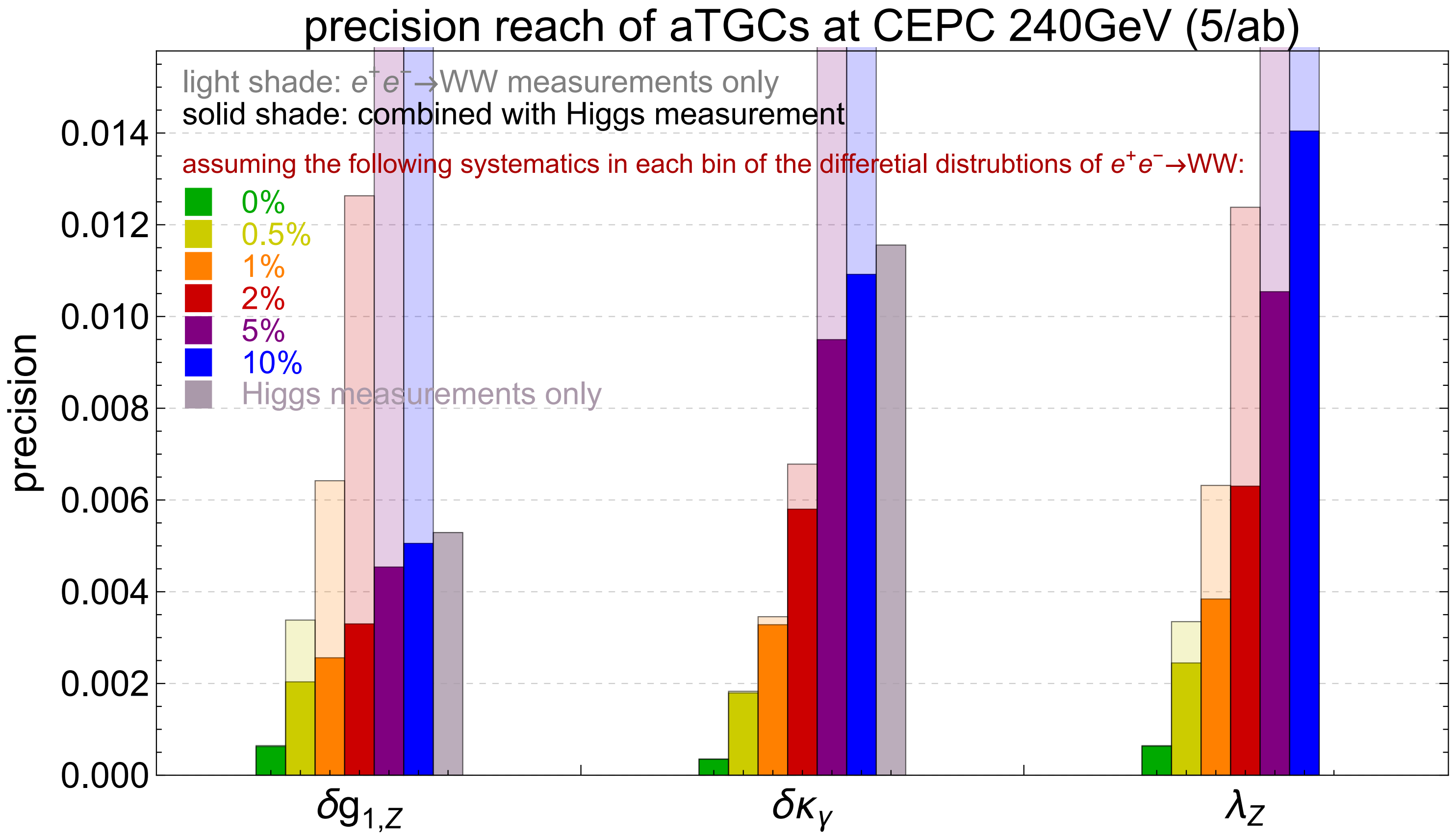
Impact of HL-LHC WW data?

we assumed 1% syst. and also studied the impact of this assumption

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)





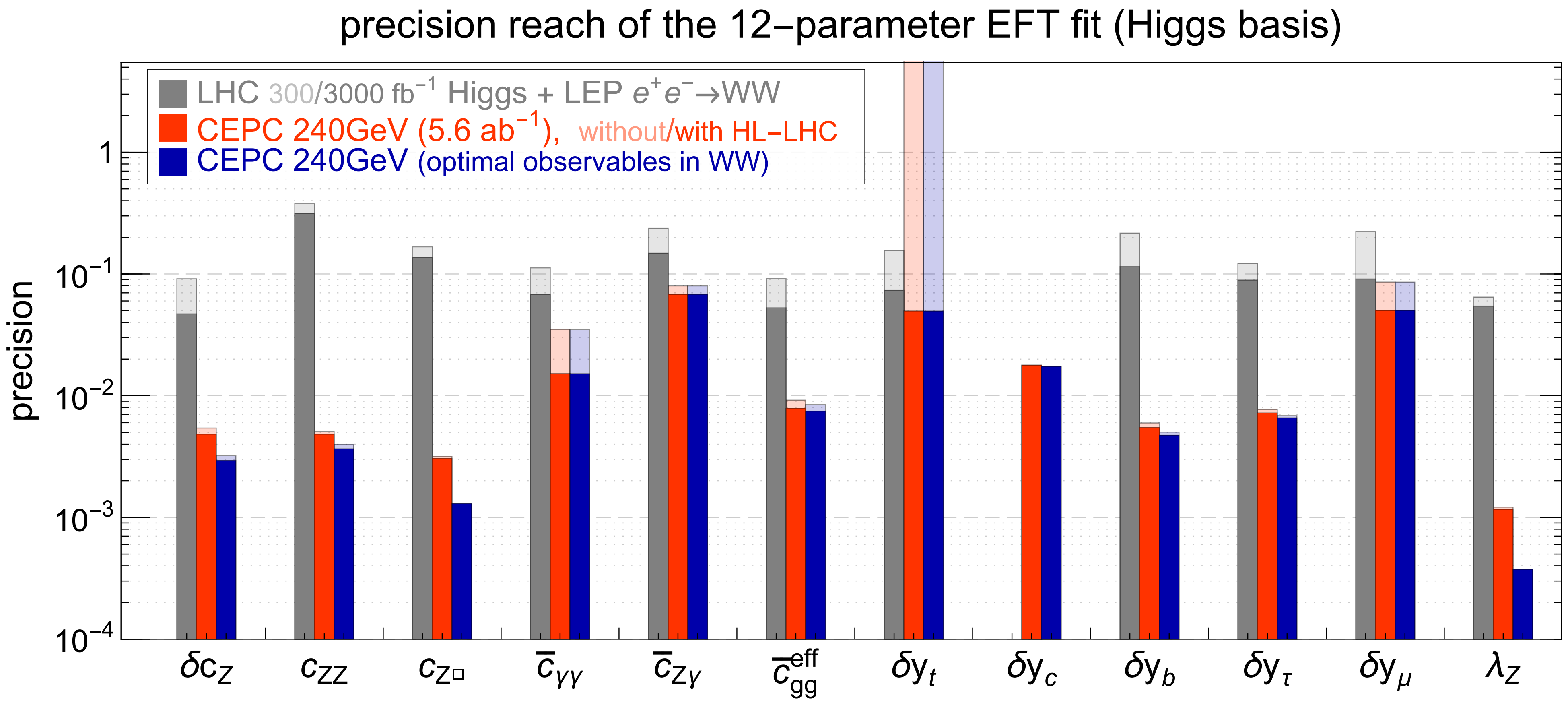
Durieux, Grojean, Gu, Wang '17

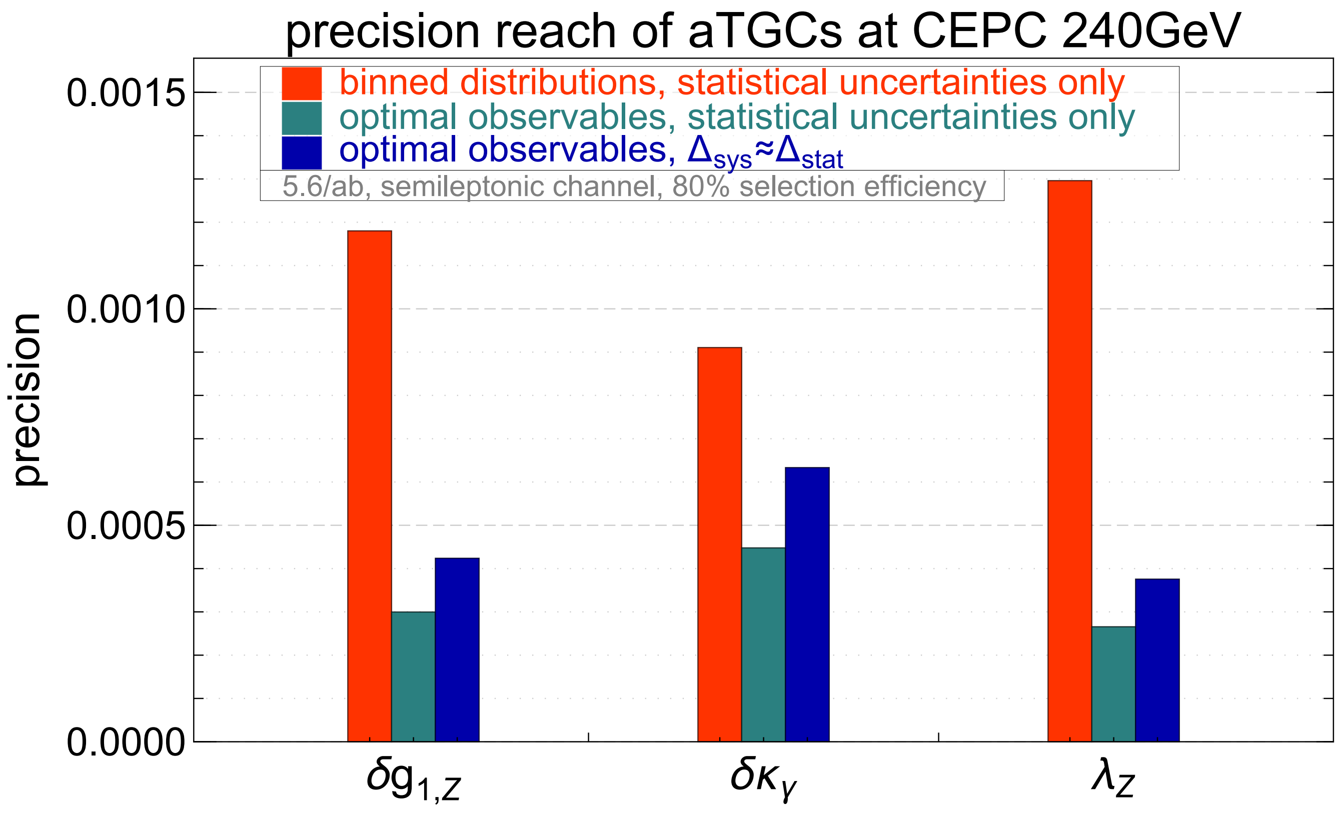
Beware of TGC dominance assumption

Importance of WW run

(TGC+Higgs)>(TGC)∪(Higgs)

Diboson analysis can still be improved, e.g., using optimised observables



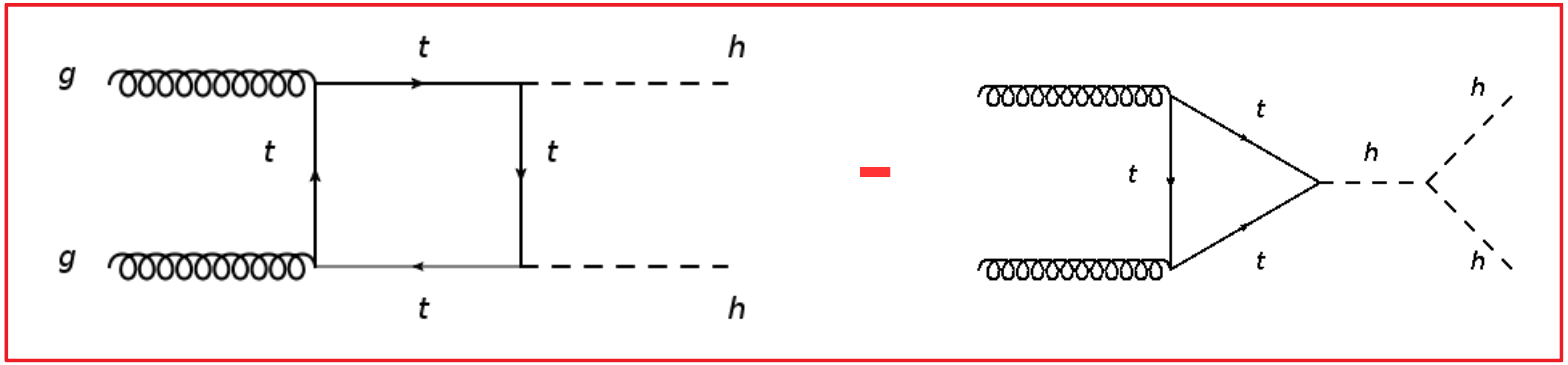


J. De Blas, G. Durieux, C. Grojean, J. Gu, A. Paul 1907.04311

Beware of TGC dominance assumption

h³ Extraction @ LHC

Notoriously difficult in particular because of strong interference



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

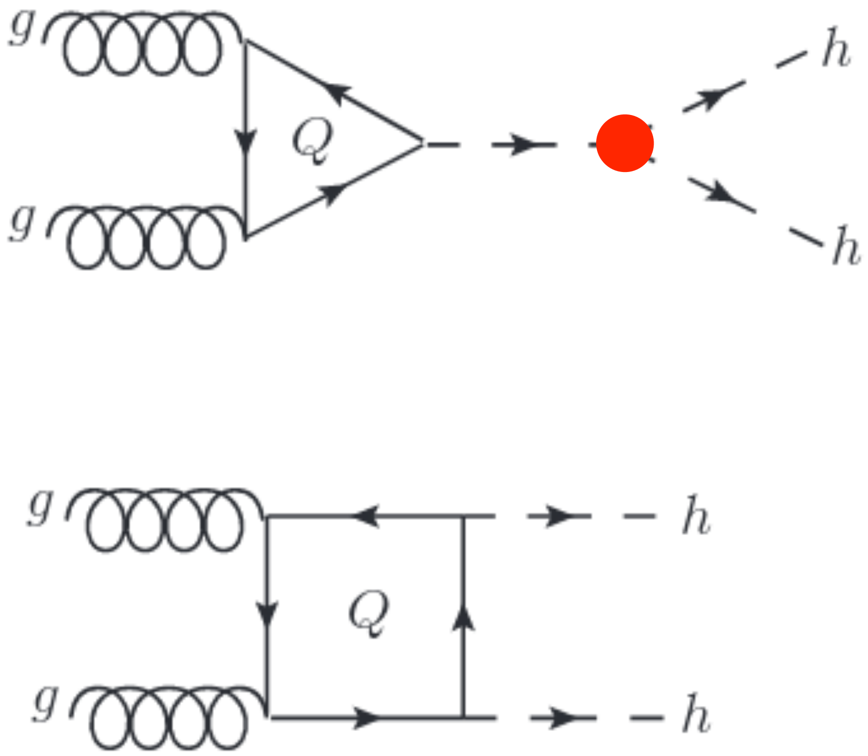
$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3}$$

Note 1: The two diagrams have different energy behaviour: look at differential distributions

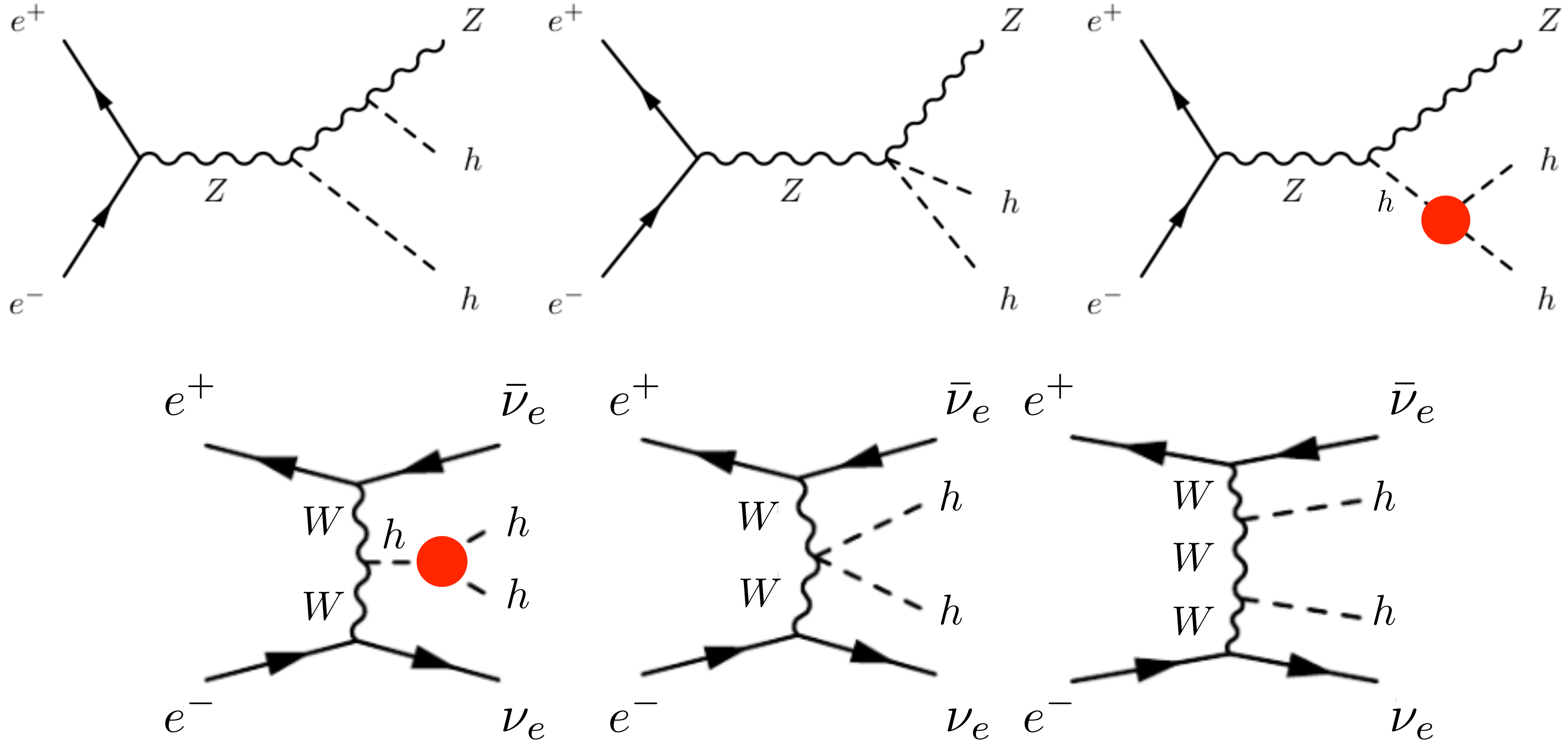
Note 2: also: 2% uncertainty on tth → 5% uncertainty on h³ . Good control of parametric uncertainties is needed

h^3 from HH

pp colliders

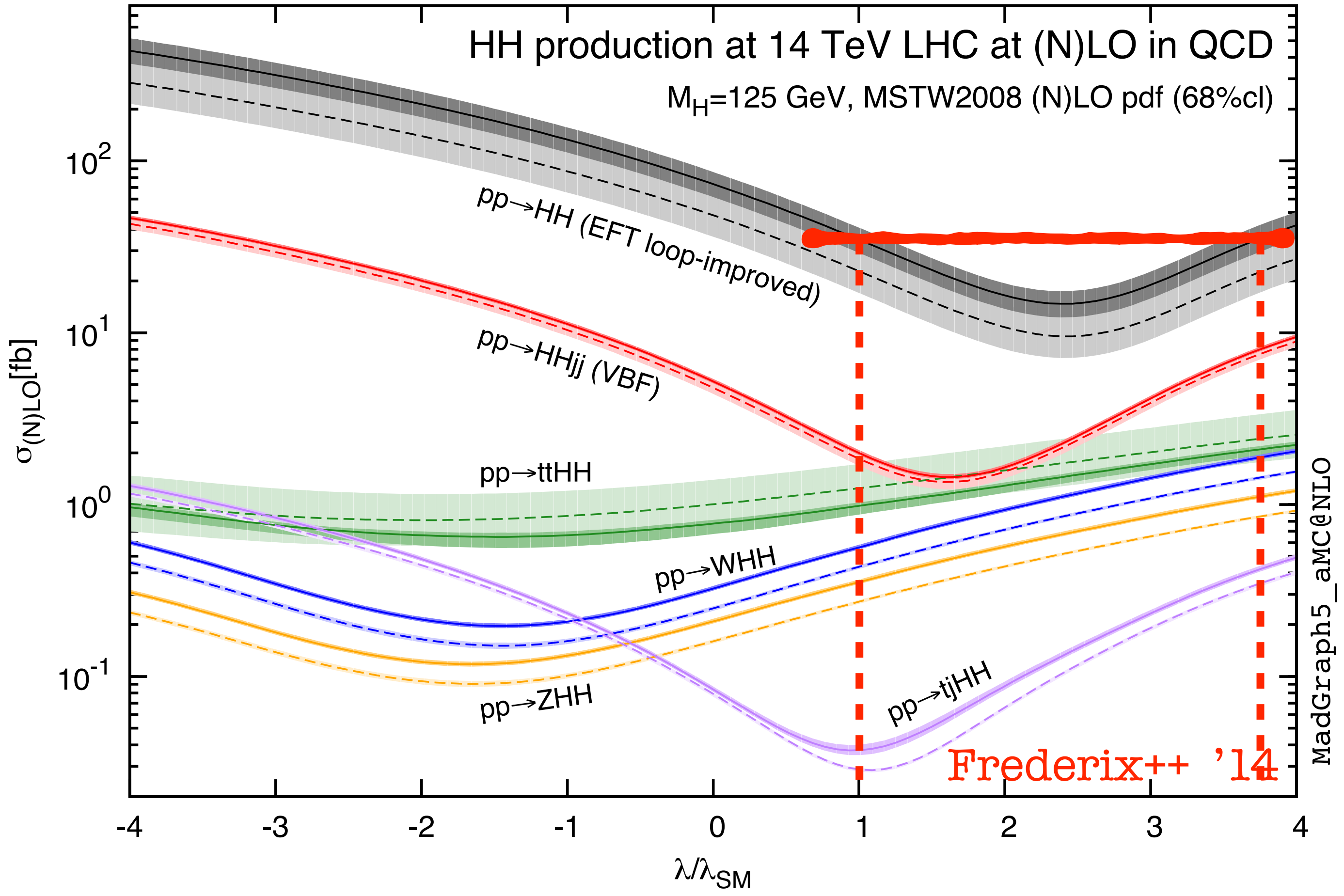


ee colliders



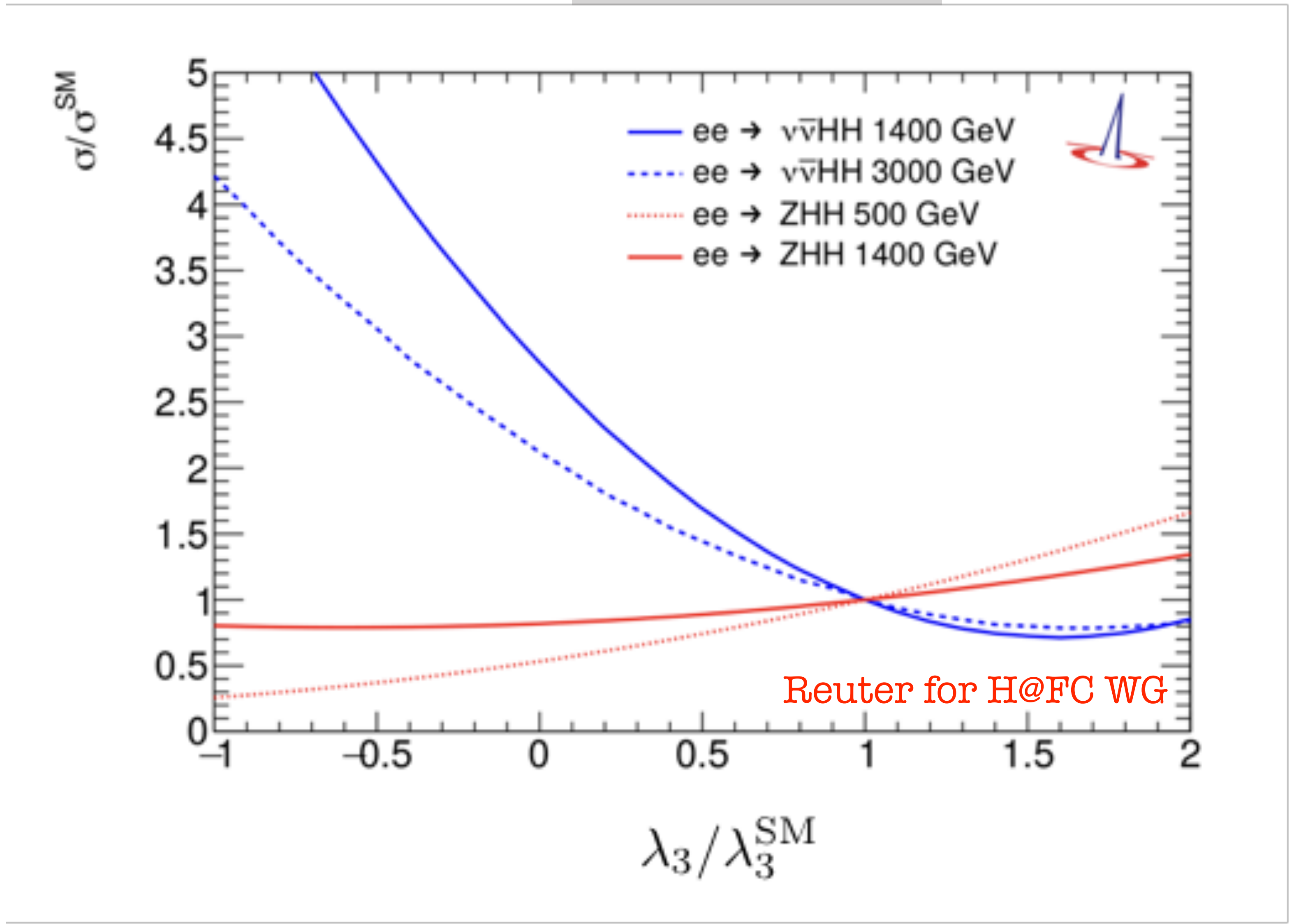
h^3 from HH: issue with second minimum

pp colliders



m_{hh} distribution needed to separate the two degenerate points
(larger h^3, m_{hh} more picked close to threshold)

ee colliders



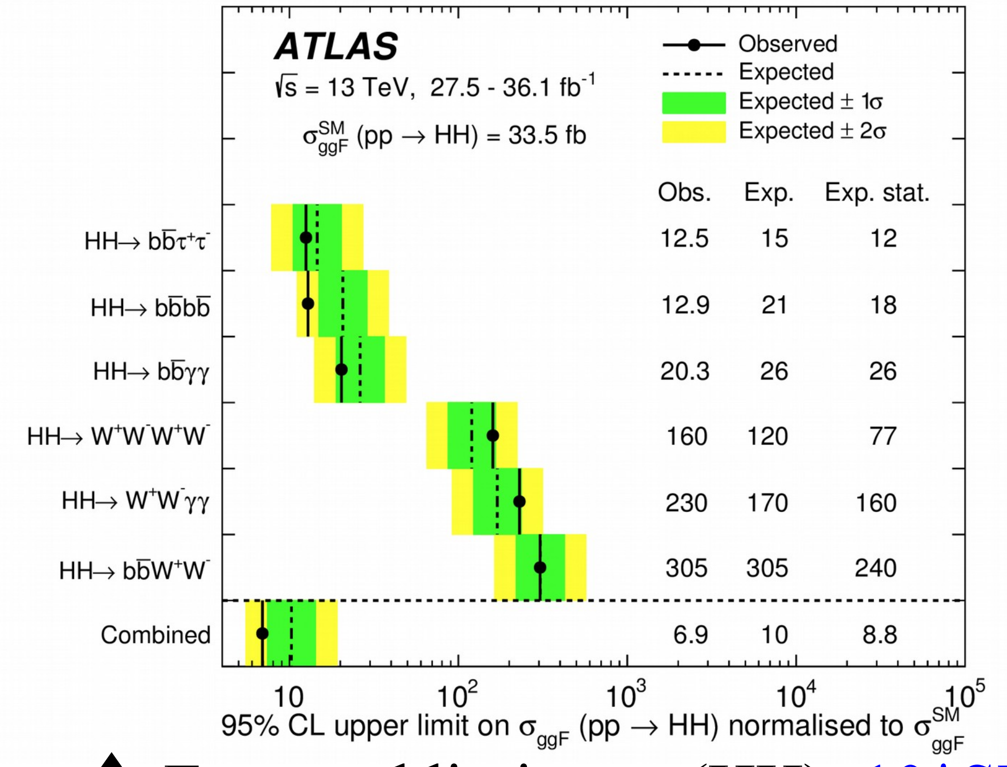
ZHH gives stronger constraints on $\delta\kappa_\lambda > 0$

$\nu\bar{\nu}HH$ gives stronger constraints on $\delta\kappa_\lambda < 0$

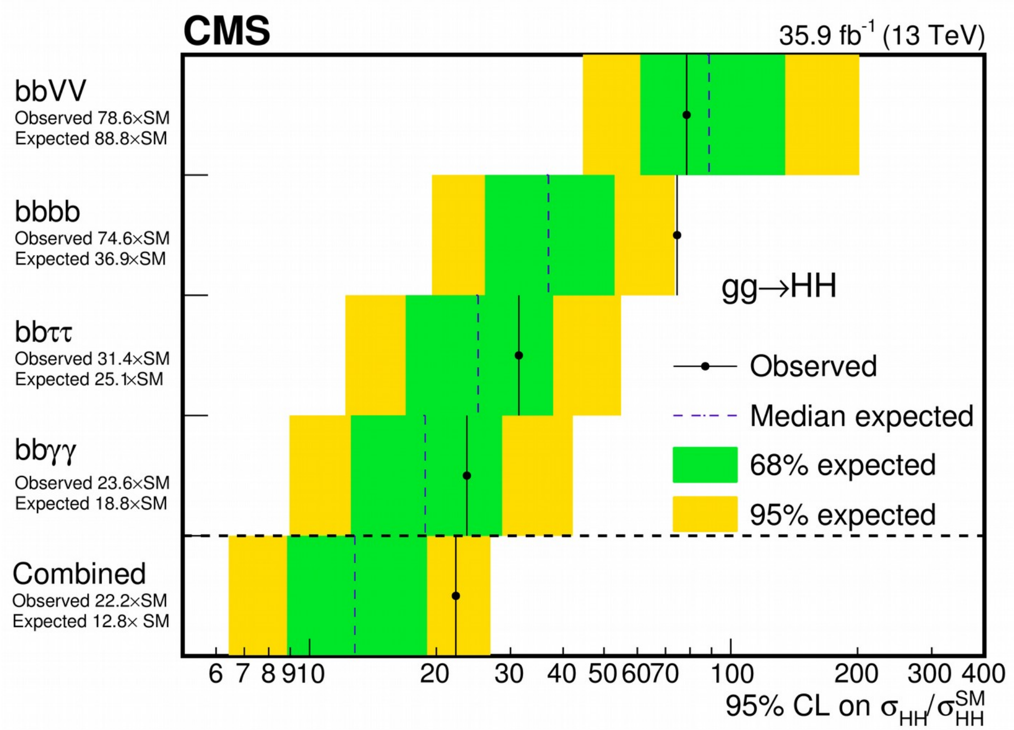
h³ from hh@LHC now

See E. Petit talk yesterday

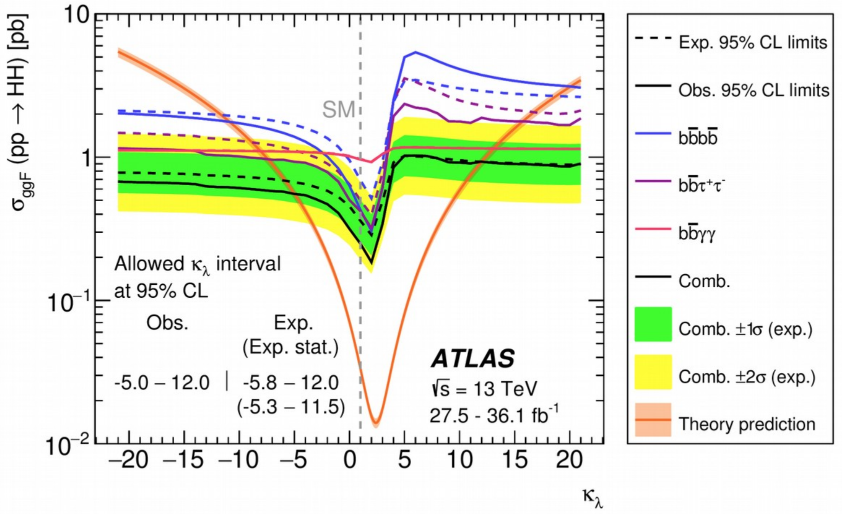
- ATLAS



- CMS

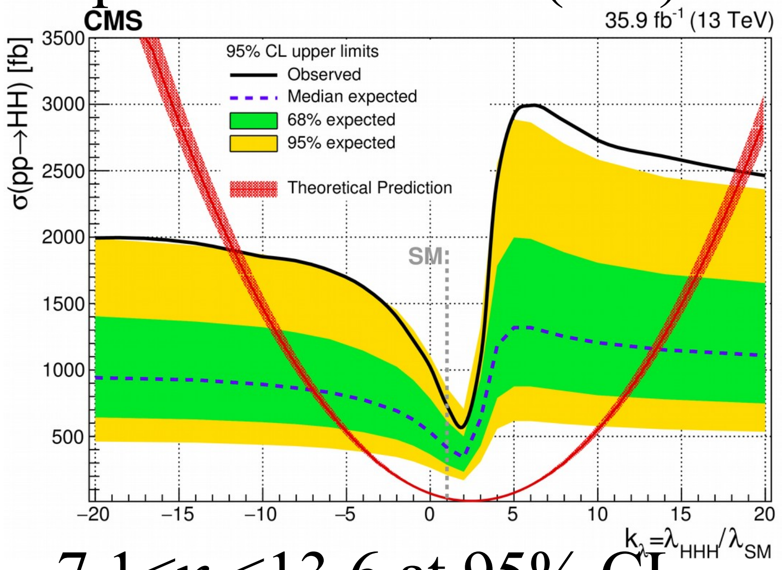


- Expected limit on σ(HH): 10*SM



- $-5.0<\kappa_\lambda<12.0$ at 95% CL

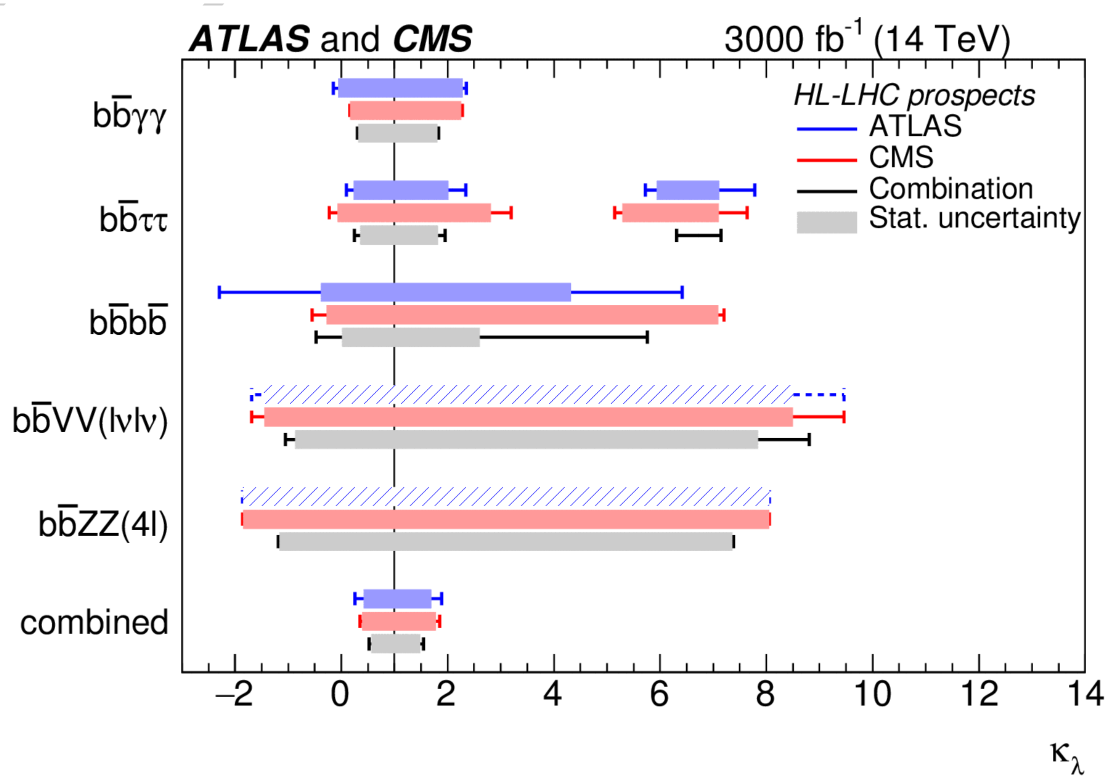
- Expected limit on σ(HH): 12.8*SM

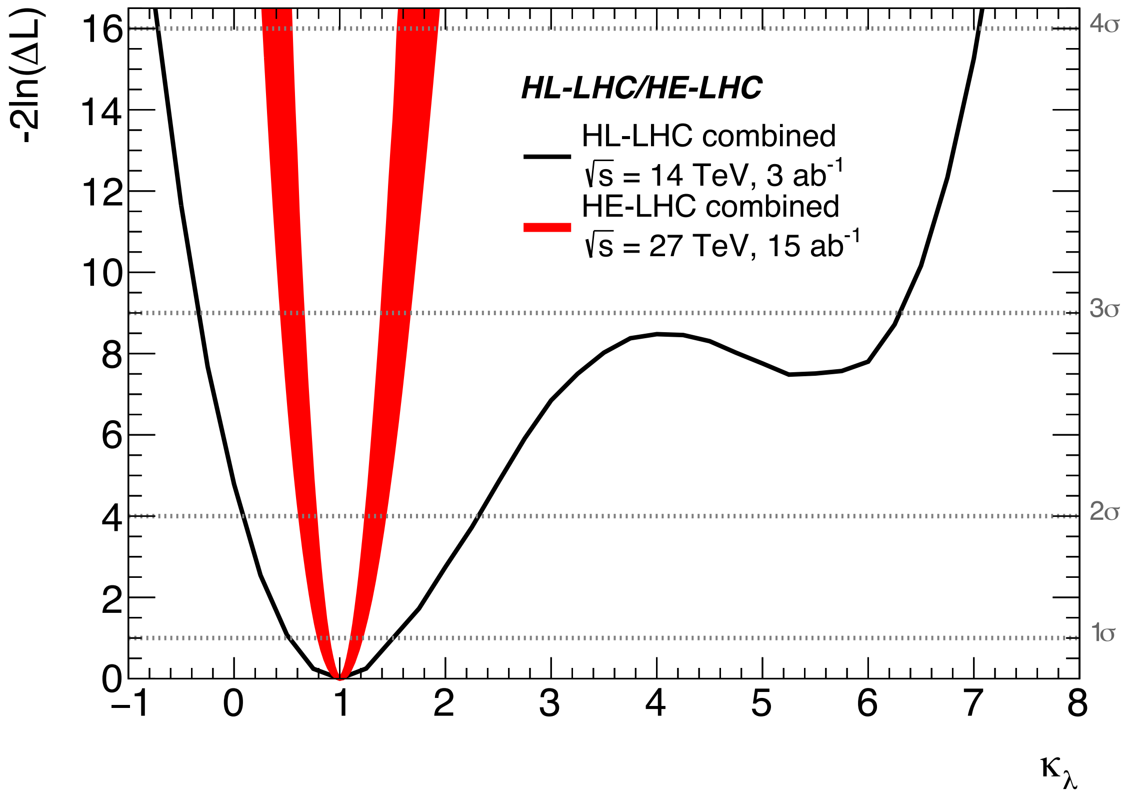


- $-7.1<\kappa_\lambda<13.6$ at 95% CL

h^3 from hh@HL/HE-LHC

HL/HE-LHC Higgs WG report





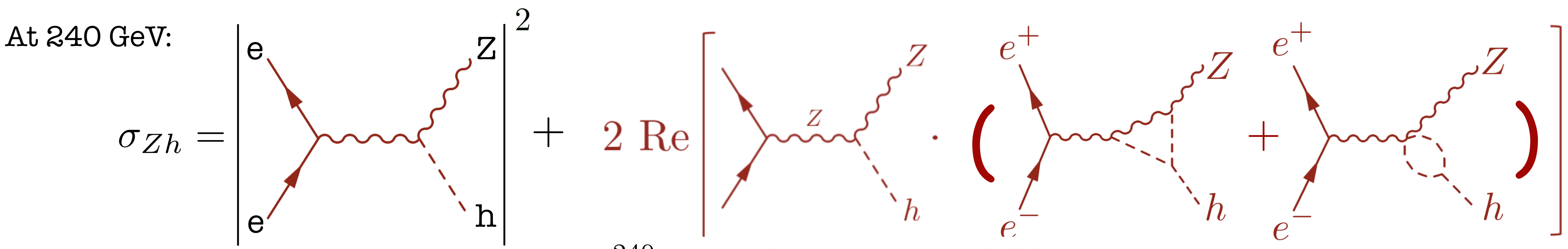
✦ HL-LHC can test the Higgs trilinear with O(50%) precision

$$0.57 \leq \kappa_\lambda \leq 1.5 \quad \text{at} \quad 68\% \text{ C.L.}$$

✦ HE-LHC could test the Higgs trilinear with O(15-30%) precision
(projections vary significantly between different analyses)

h³ from h@NLO@HL-LHC

M. McCullough ’14



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

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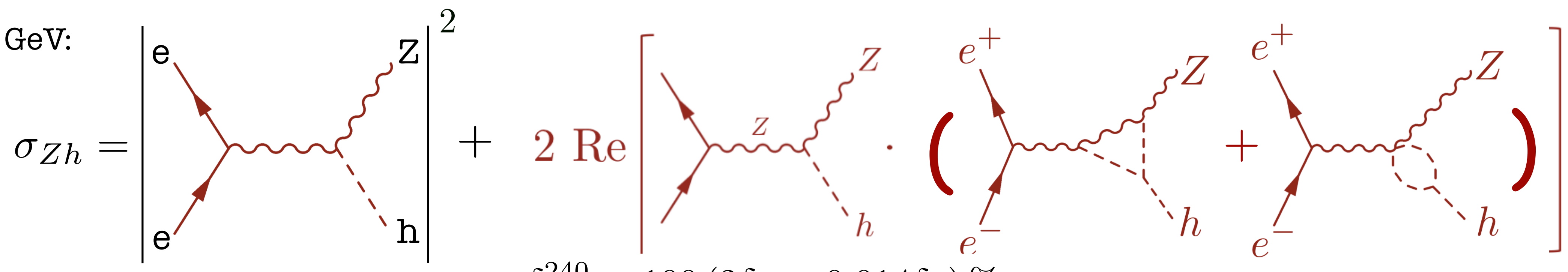
At 240 GeV:



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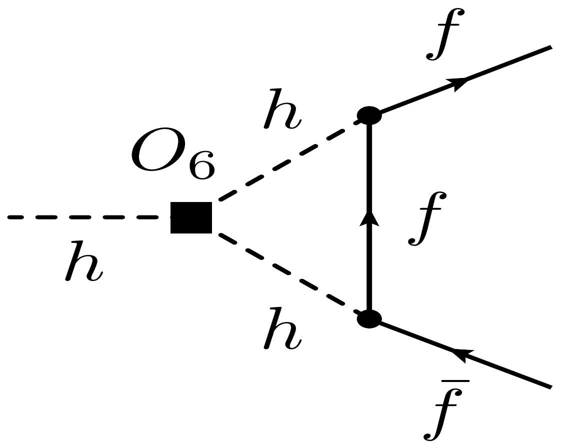
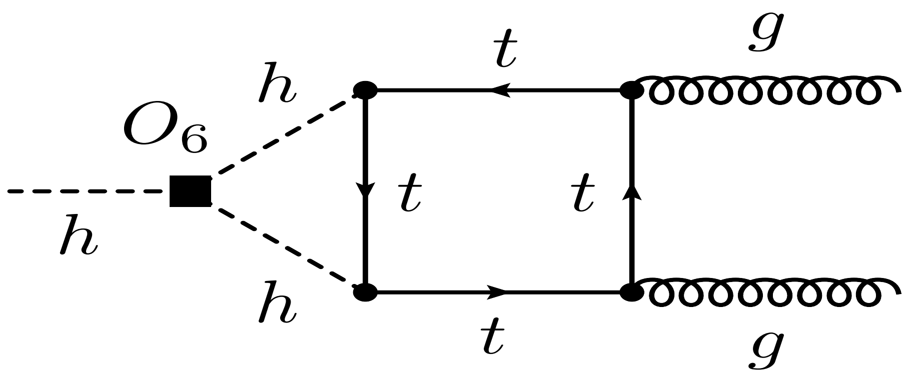
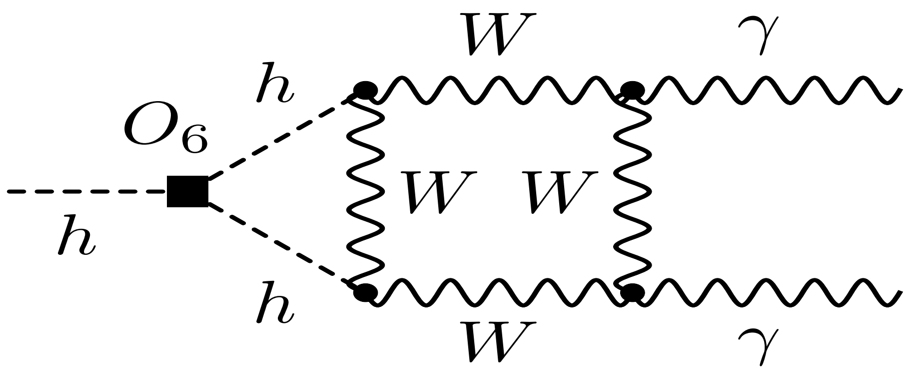
Gorbahn et al '16

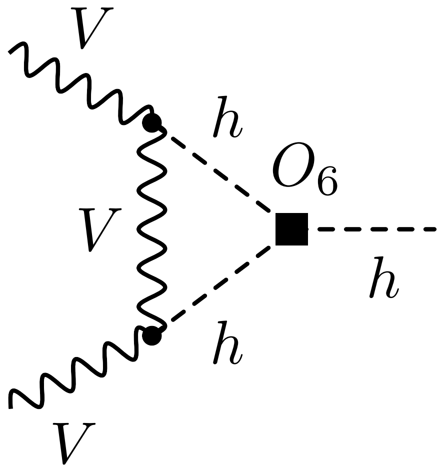
Degrassi et al '16

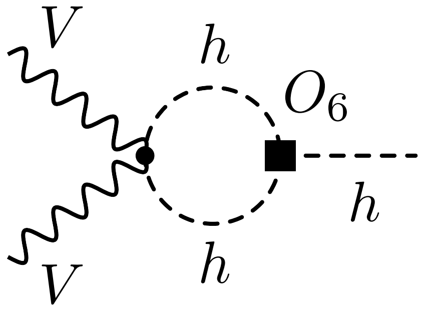
Bizon et al '16

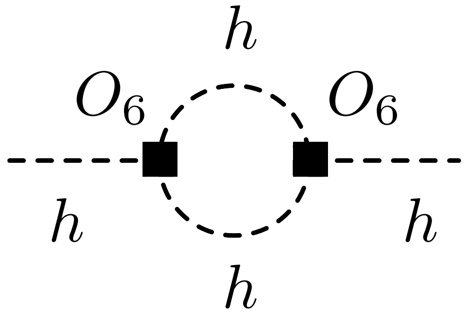




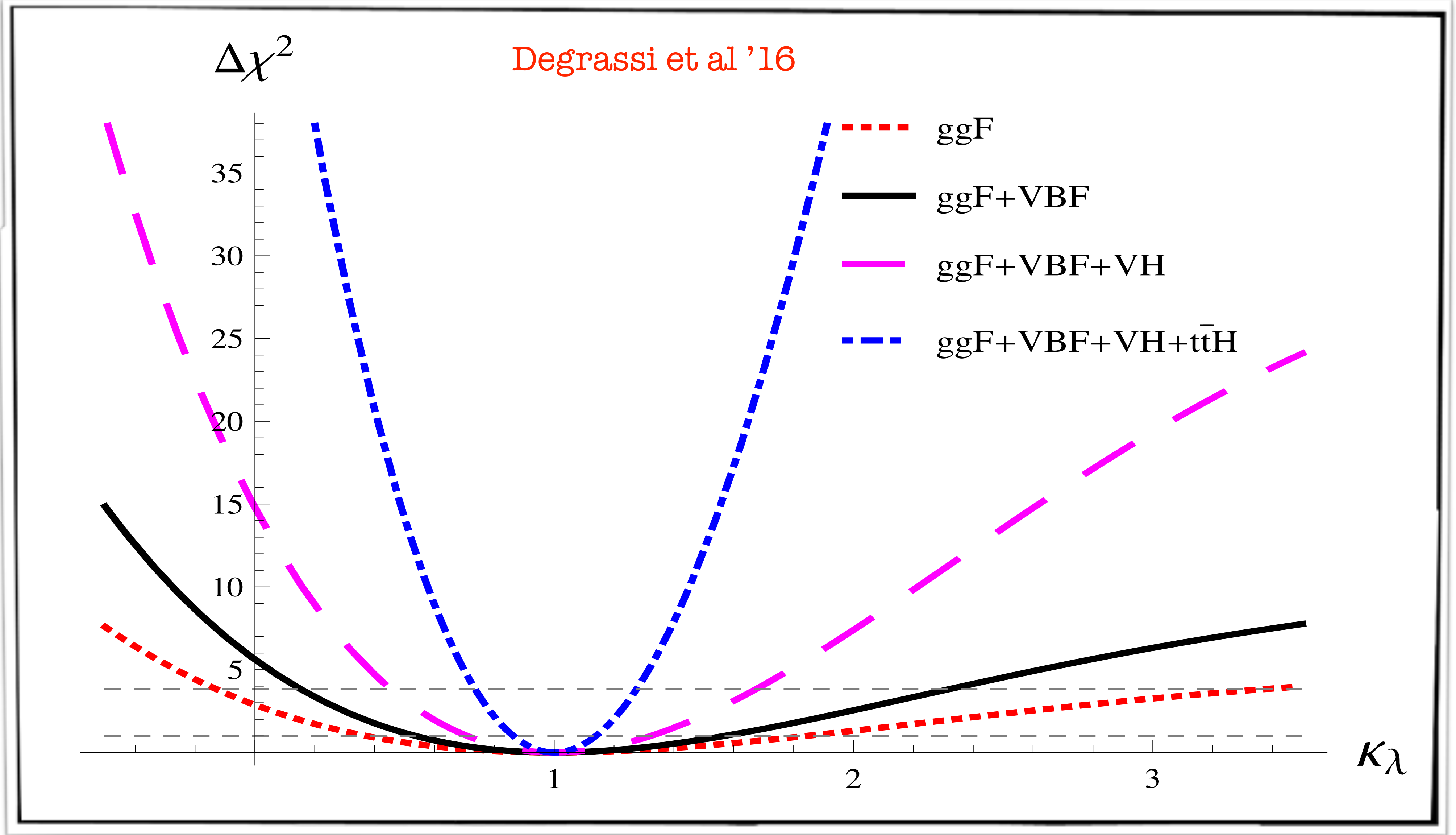








h^3 from h@NLO@HL-LHC



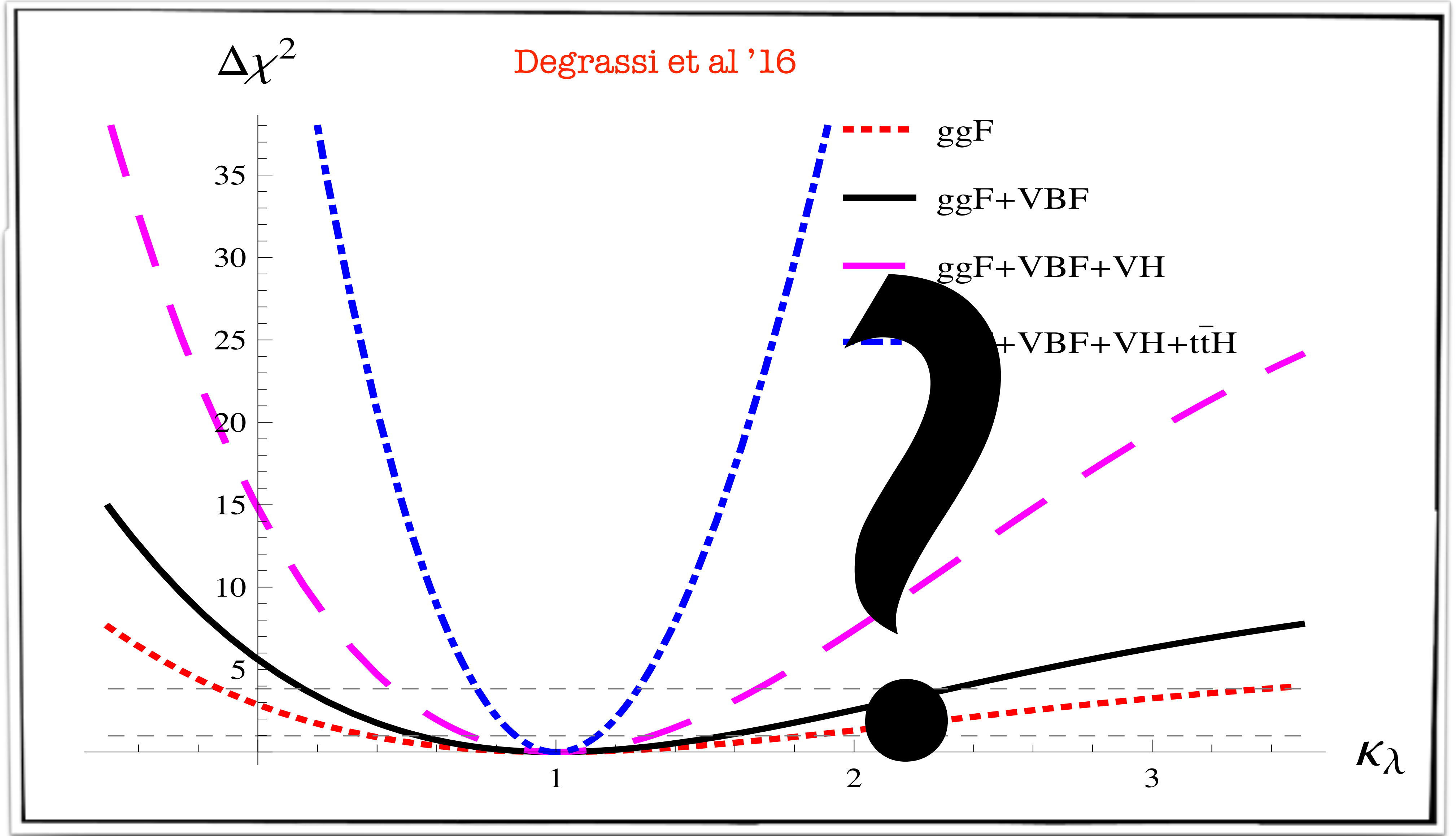
$$\kappa_\lambda = \frac{g_{h^3}}{g_{h^3}^{\rm SM}}$$

$$\mathcal{L} \supset \frac{c_6}{\Lambda^2}|H|^6 \Longleftrightarrow \kappa_\lambda = 1 + \frac{c_6 G_F^{-2}}{m_H^2 \Lambda^2}$$

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

Worse than direct determination via double Higgs production but different systematics and "easier" analysis

h^3 from h@NLO@HL-LHC



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Make h³ great again: Higgs portal models

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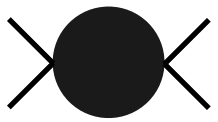
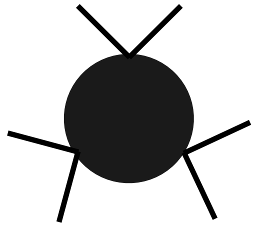


$$\frac{\theta^2 g_*^2}{m_*^2} \; \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) \quad \Rrightarrow \quad \delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2}$$



$$\frac{m_*^4}{g_*^2} \frac{g_*^3}{m_*^3} \left(\frac{\theta g_*}{m_*} \right)^3 (H^\dagger H)^3 \quad \Rrightarrow \quad \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$$

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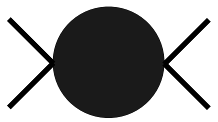

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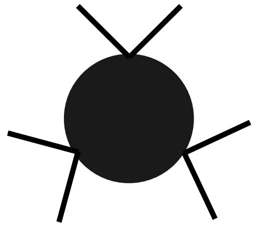

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parametric enhancement of h³

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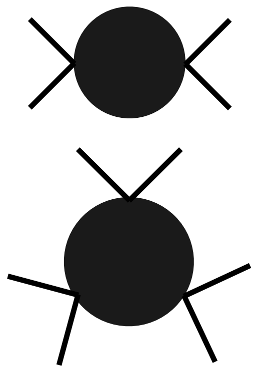

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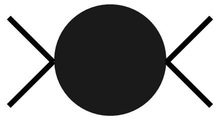
parametric enhancement of h³

but also **tuning** of Higgs quartic coupling



$$\frac{m_*^4}{g_*^2} \frac{g_*^2}{m_*^2} \left(\frac{\theta g_*}{m_*} \right)^2 |H|^4 \quad \Rightarrow \quad \Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$$

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

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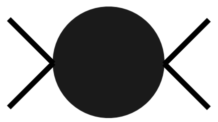

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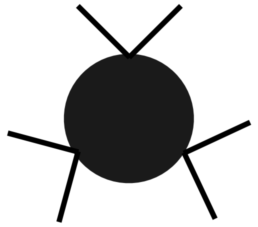

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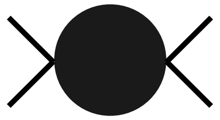

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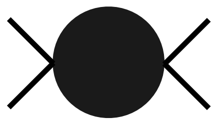
~~ large h³ ~~
either tuning (Δ>1)
or
give-up on linear h-expansion (ε >1)

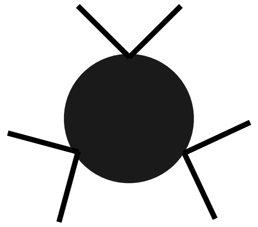
Make h³ great again: Higgs portal models

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

$$\varphi \sim \frac{\theta\, g_* |H|^2}{m_*}$$



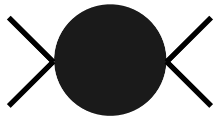
$$\frac{\theta^2 g_*^2}{m_*^2} \quad \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) \quad \Rrightarrow \quad \delta c_z \sim \theta^2 g_*^2 \frac{v^2}{m_*^2}$$



$$\frac{m_*^4}{g_*^2} \frac{g_*^3}{m_*^3} \left(\frac{\theta g_*}{m_*}\right)^3 (H^\dagger H)^3 \quad \Rrightarrow \quad \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2}$$

parametric enhancement of h³

but also **tuning** of Higgs quartic coupling



$$\frac{m_*^4}{g_*^2} \frac{g_*^2}{m_*^2} \left(\frac{\theta g_*}{m_*}\right)^2 |H|^4 \quad \Rrightarrow \quad \Delta \sim \frac{\theta^2 g_*^2}{\lambda_3^{SM}}$$

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

~~ large h³ ~~

either tuning (Δ>1)

or

give-up on linear h-expansion (ε >1)

a possible benchmark of large h³

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

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

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

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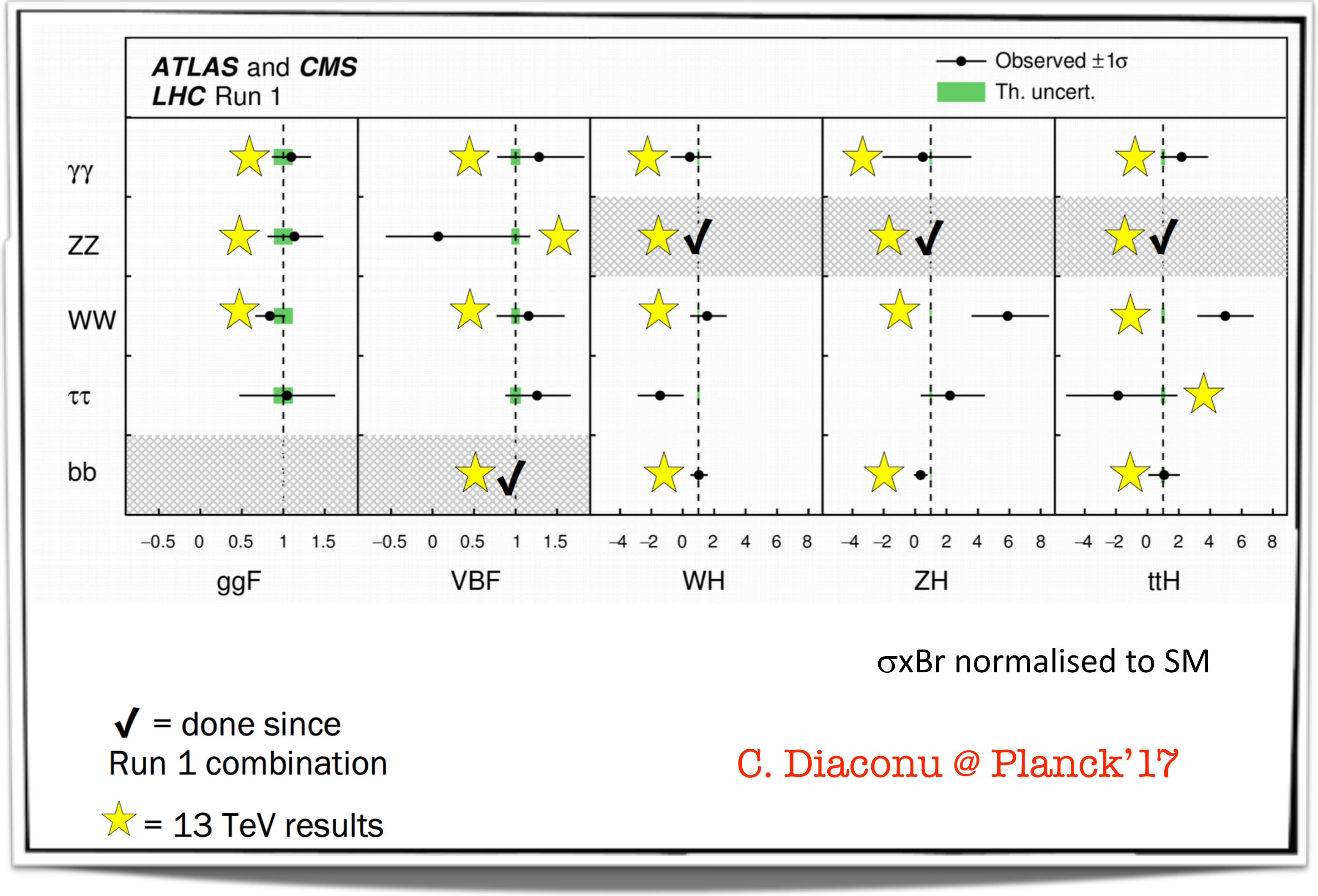

h³ @NLO vs h @ LO in global fit

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

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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

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

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

linearized BSM perturbations

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

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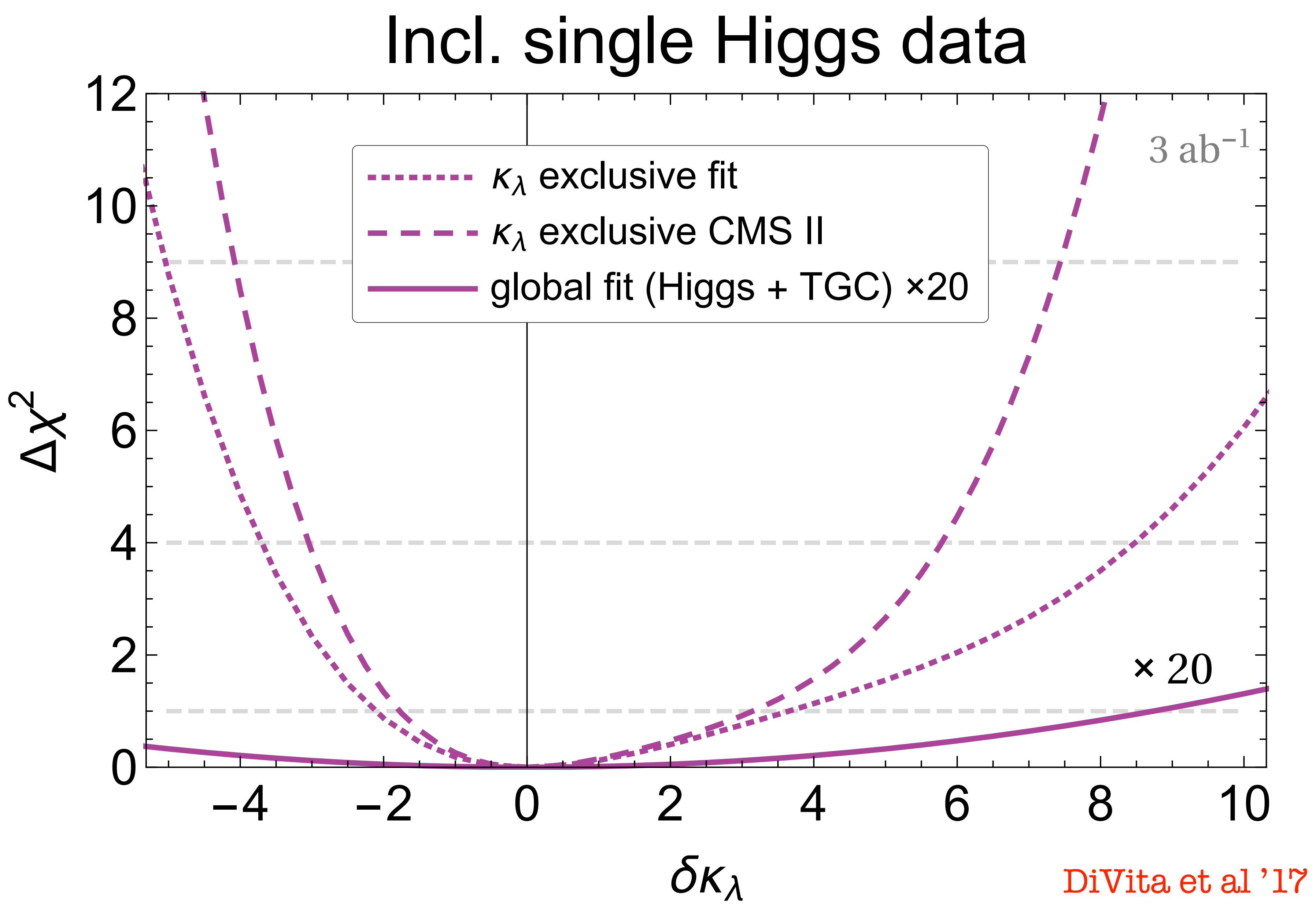
cannot determine univocally 10 EFT parameters!

one flat direction is expected!

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

The fabulous 5^2 channels



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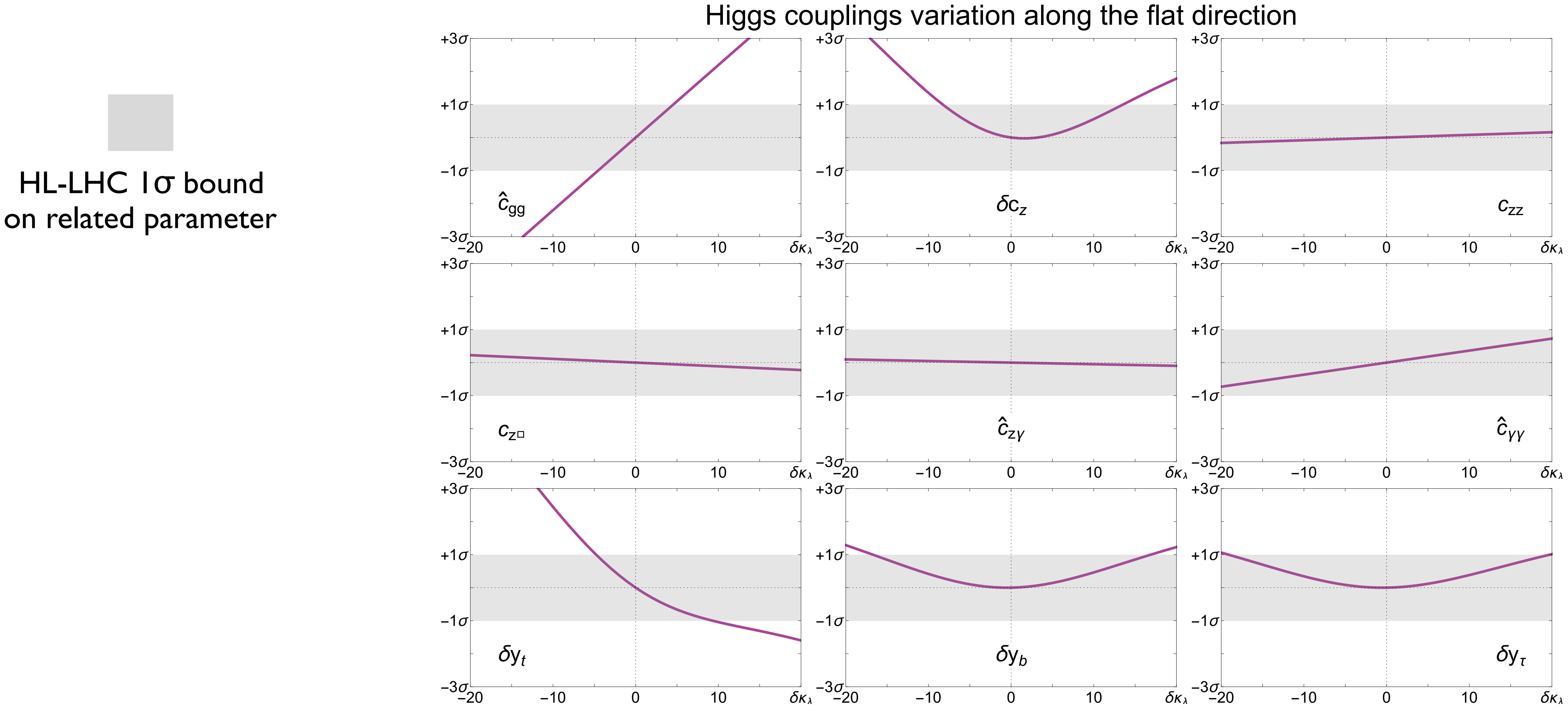

DiVita et al '17

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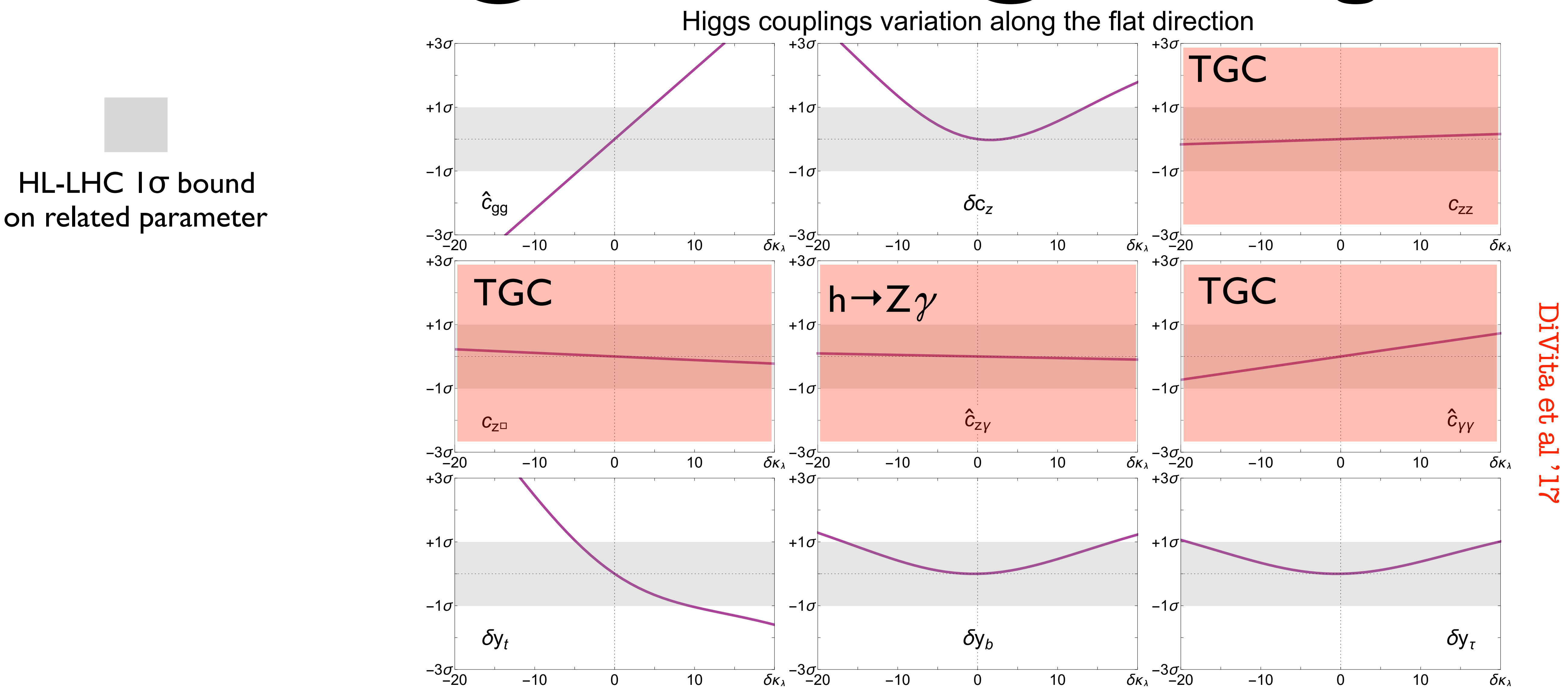

The particular structure of this flat direction tells that adding new data on diboson or h→Zγ won't help much

cannot determine univocally 10 EFT parameters!

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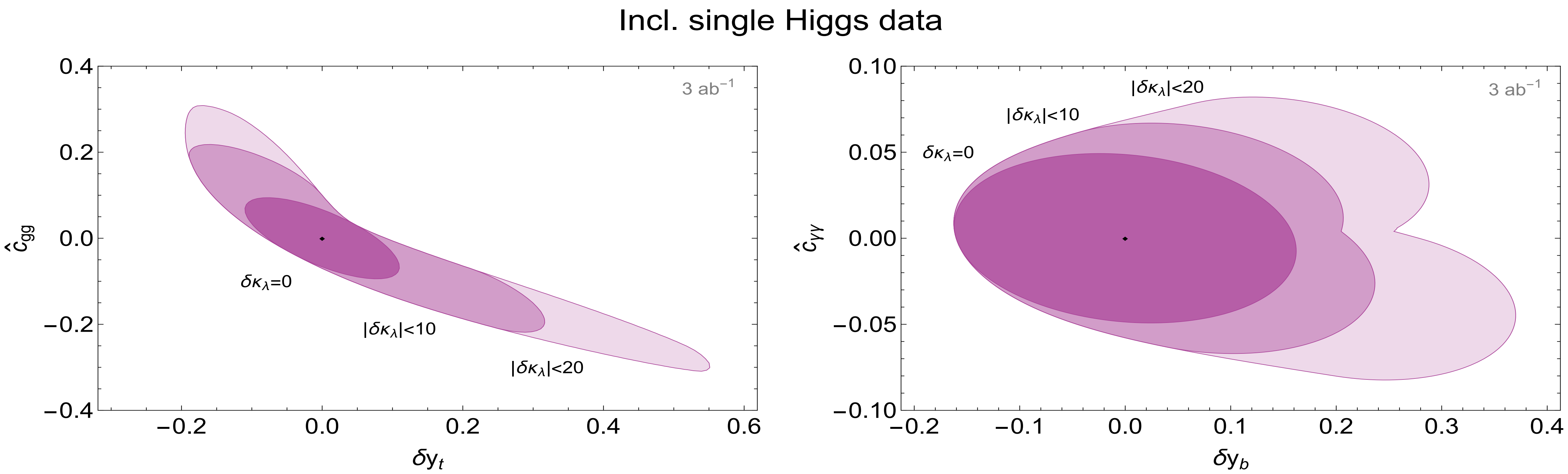
Does h³ modify the fit to other couplings?



DiVita et al '17

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, fit with κ_λ @ NLO can differ from LO fit by a factor 2.

But this concerns only particular BSM models, in most models $\kappa_\lambda \sim \kappa_i$ and NLO effects are negligible.

Furthermore, HL-LHC will already measure h³ at 50%,

so even in the extreme case, the NLO effects are limited to 20-30%

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

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, $\gamma\gamma$, Zγ, $\tau\tau$, bb, gg, (cc, μμ)

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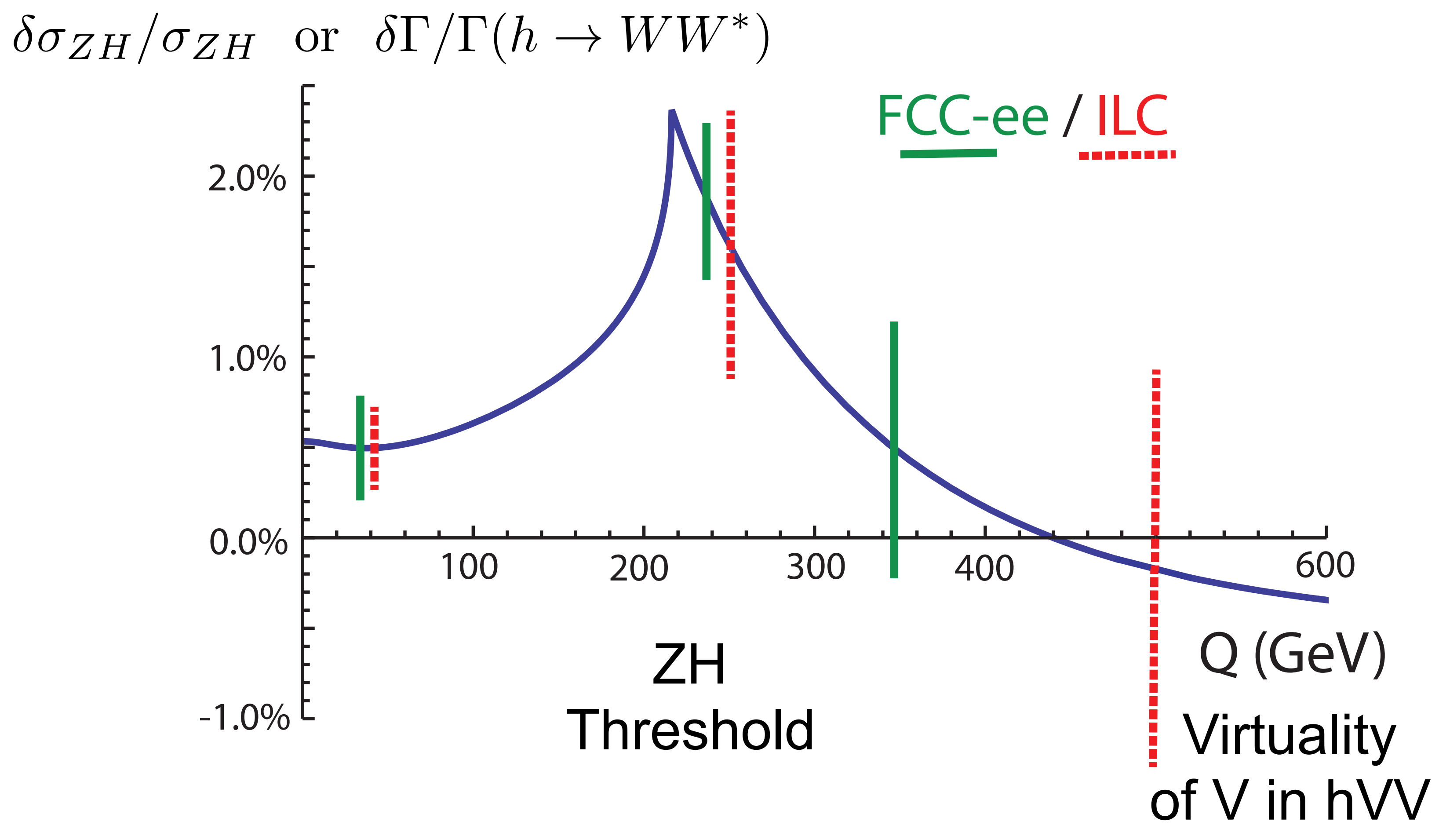
But 2 runs at different energies are better.



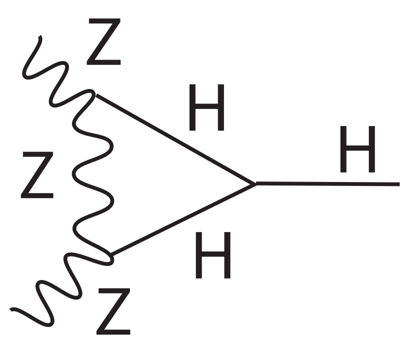


Figure 9.11: Relative enhancement of the $e^+e^- \to ZH$ cross section and the $h \to W^+W^-$ partial width, in %, for $\kappa_\lambda = 1$, due to the 1-loop diagrams shown in Fig. 9.1. One Z or W leg is off-shell at the invariant Q^2 while the other Z or W and the Higgs boson are kept on-shell. The vertical lines show the uncertainties expected from proposed e^+e^- colliders from single measurements of the relevant quantities, green/solid for FCC-ee, red/dashed for ILC. For $Q > 200$ GeV, these are 1 σ error bars for measurements of $\sigma(e^+e^- \to ZH)$. For $Q \sim 40$ GeV, these are 1 σ errors on $\Gamma(h \to WW^*)$ from the SMEFT fits to the full collider programs for FCC-ee and ILC

M. Peskin in HH white paper '19

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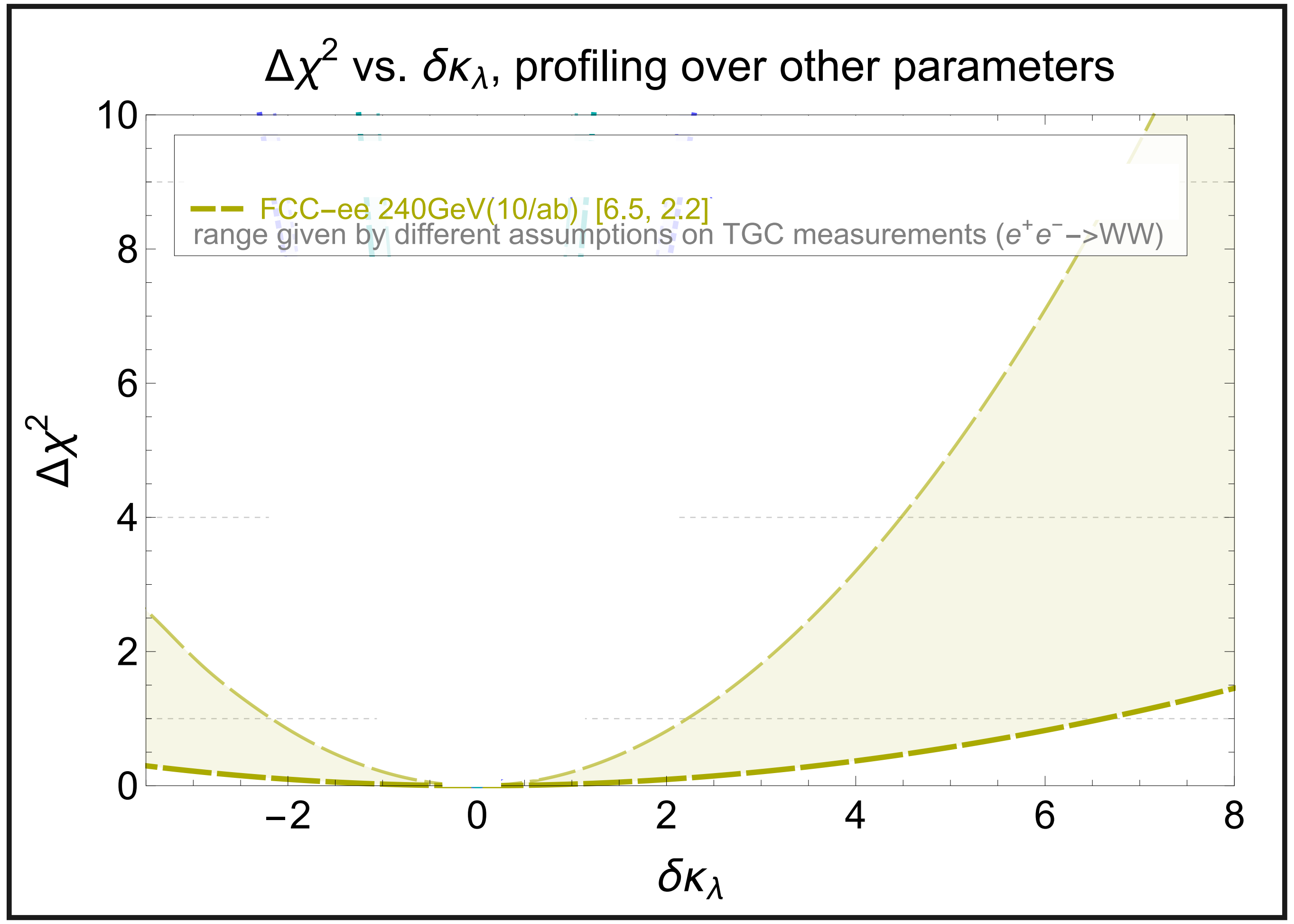

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon '17

See also F. Maltoni, D. Pagani, X. Zhao '18

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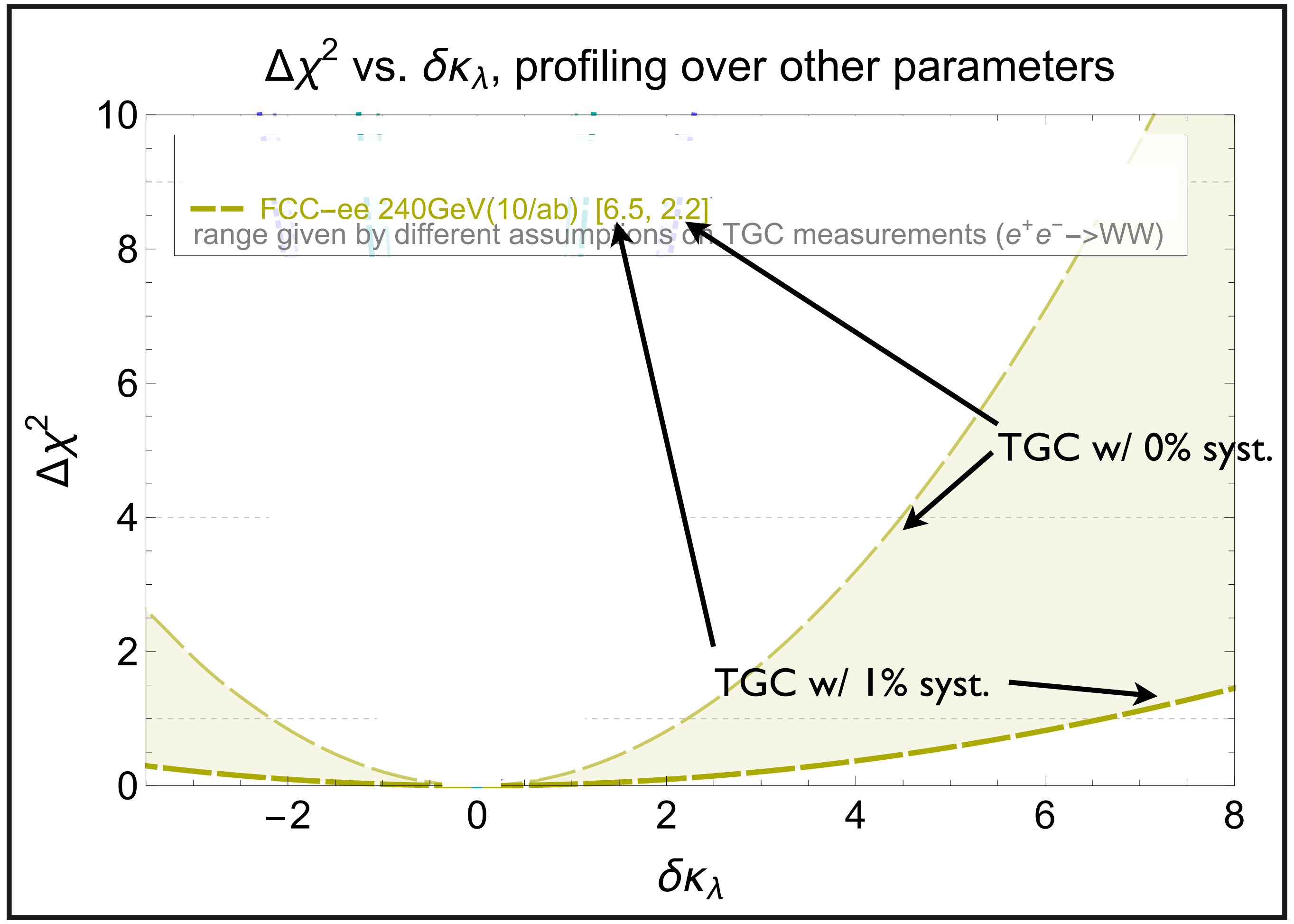

1) with a run at 240 GeV only, bound starts to become meaningful only if perfect control of di-boson

S. Di Vita, G. Durieux, C. Grojean, J. Gu, Z. Liu, G. Panico, M. Riembau, T. Vantalon '17

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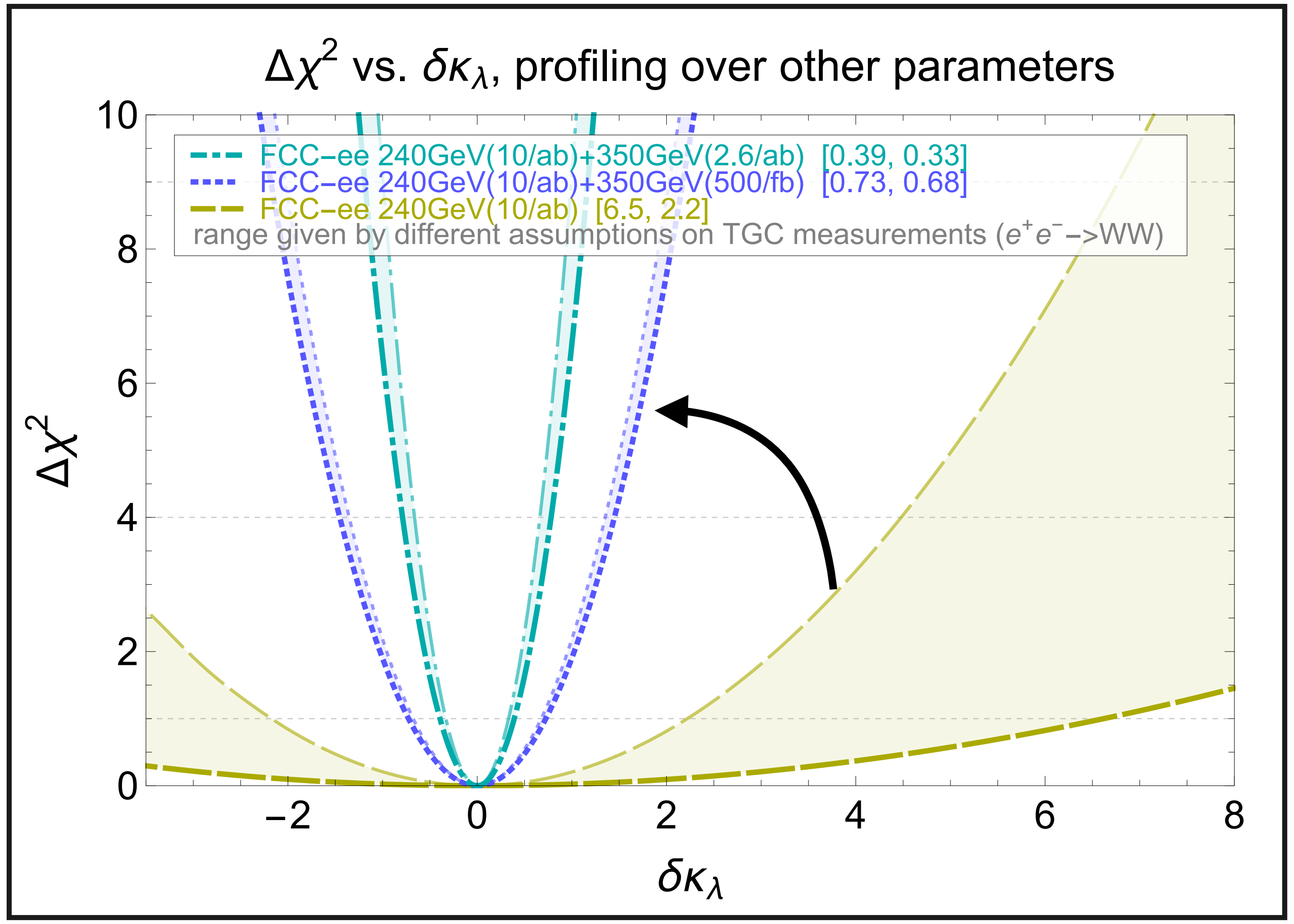

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2) combining 240+350 improves significantly the bounds on h^3

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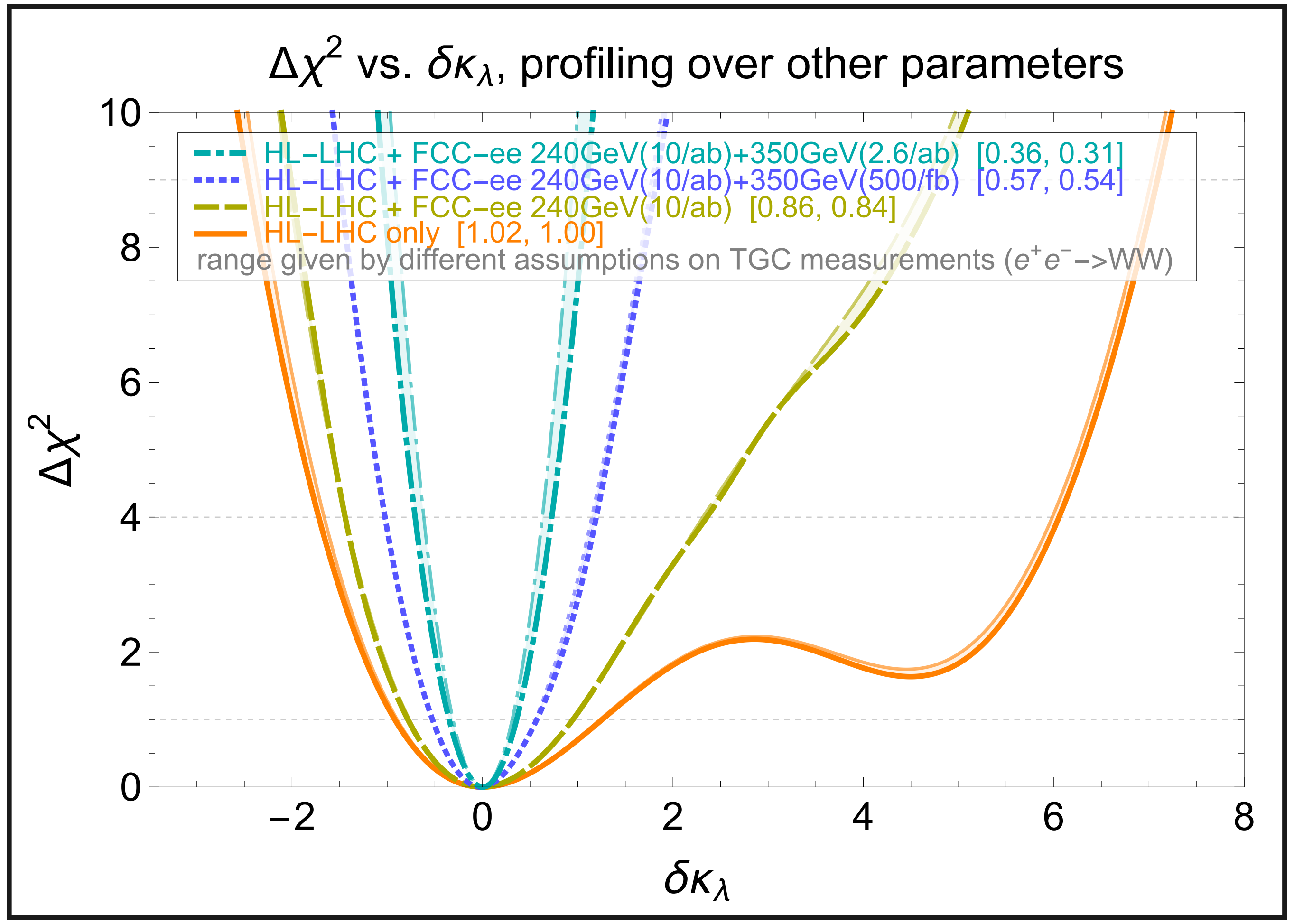

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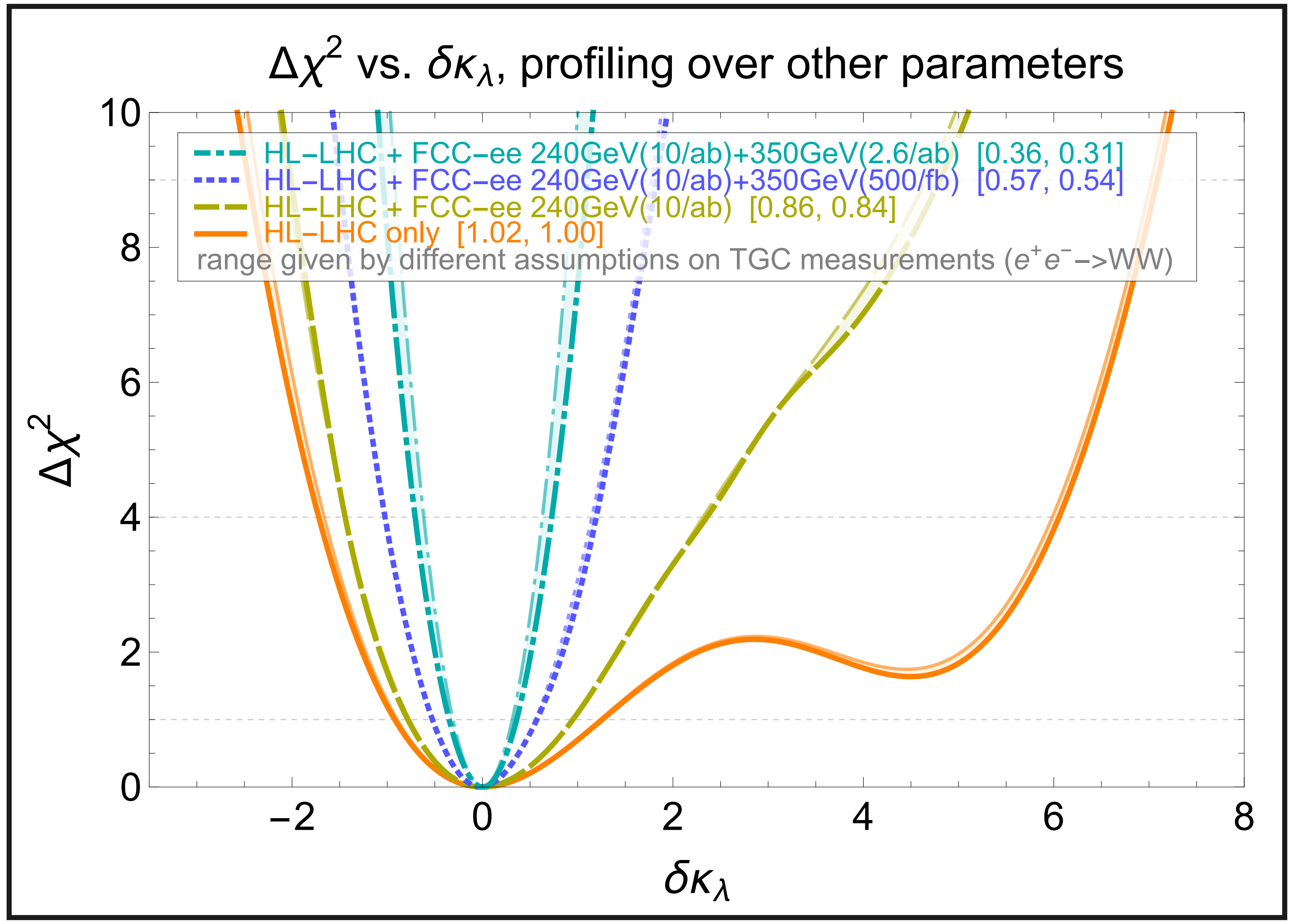

Don't need high-energy ee to measure h^3

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Future prospects for h³ measurements

ECFA Higgs @FC WG '19