A global view on the Higgs self-coupling at future colliders

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Seminar @ Dipartimento di Fisica, Università degli Studi di Genova

Oct 3, 2018

Based on

- Grojean, Panico, Riembau, Vantalon, DV [1704.01953]
- Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon, DV [1711.03978]

Outline

- Testing BSM deformations with Higgs physics
- Higgs trilinear self-coupling at the HL-LHC
- Prospects at the HE-LHC and future e^+e^- colliders

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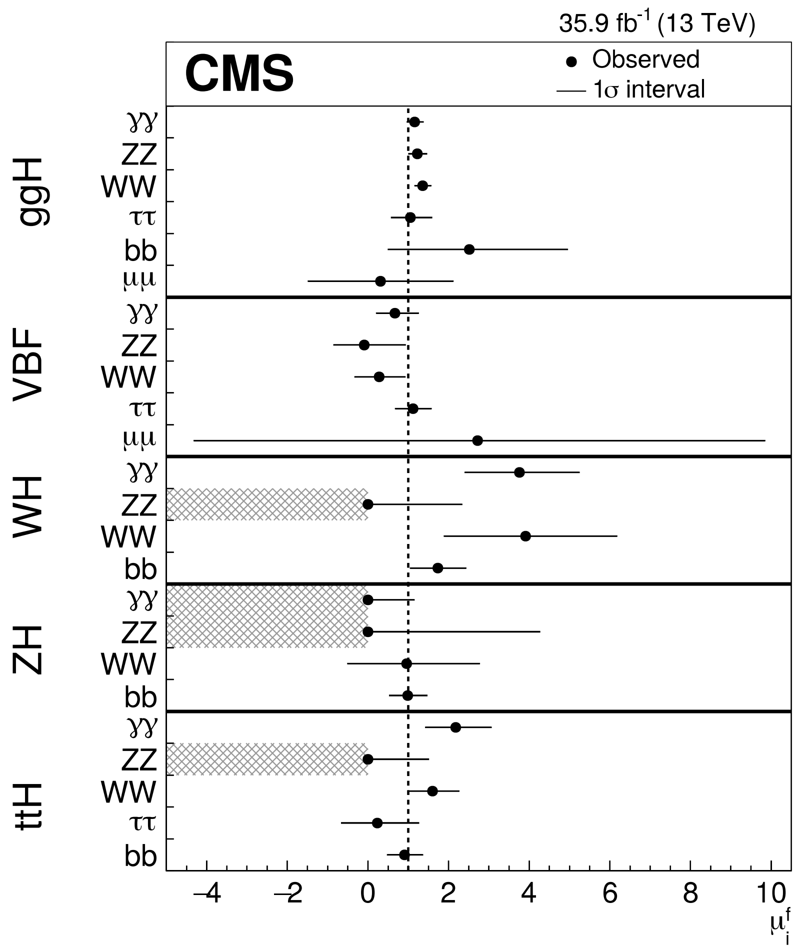
Single-Higgs rates & κ-framework interpretation

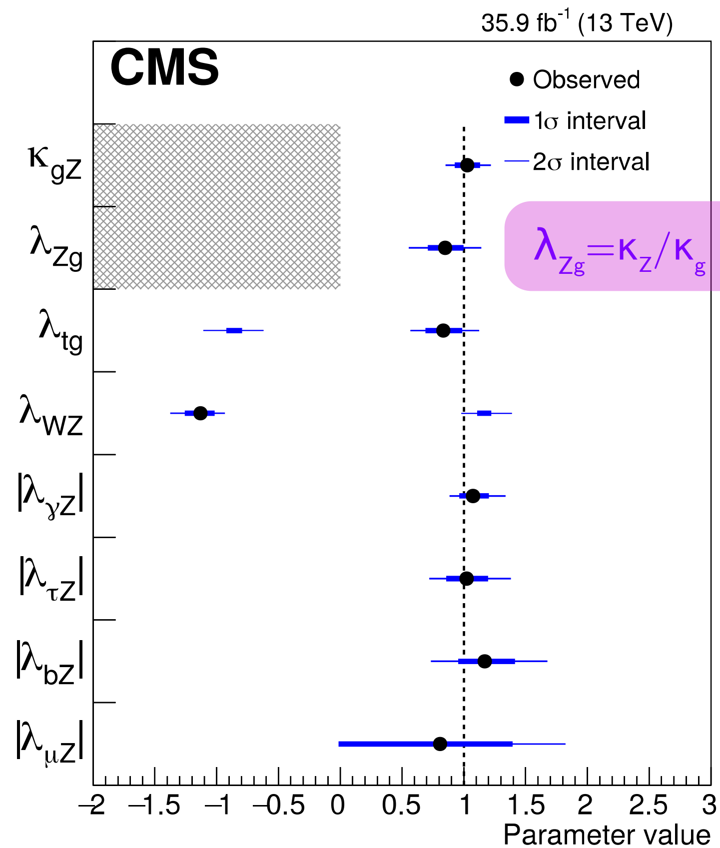
(ideally) 5x6 different $\mu_i \times \mu^f$

CMS-CERN-EP-2018-263



$\sigma_i \times BR_f$ normalized to SM value

8-parameters "κ-framework"



$\lambda_{Zg} = \kappa_Z / \kappa_g$ etc

- Only total rates modified
- Only SM tensor structures allowed

$$(\sigma \cdot \mathrm{BR})(gg \to H \to ZZ) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to ZZ) \cdot \frac{\kappa_g^2 \cdot \kappa_Z^2}{\kappa_H^2}$$

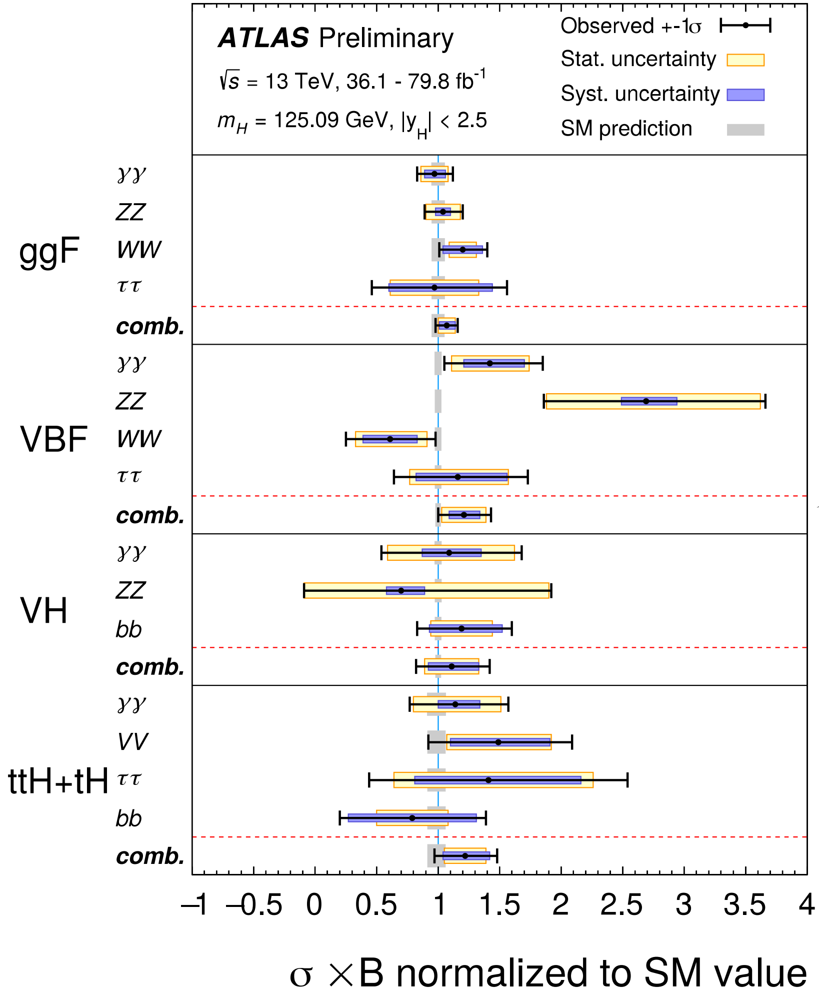
$\kappa_{gZ}{}^2$

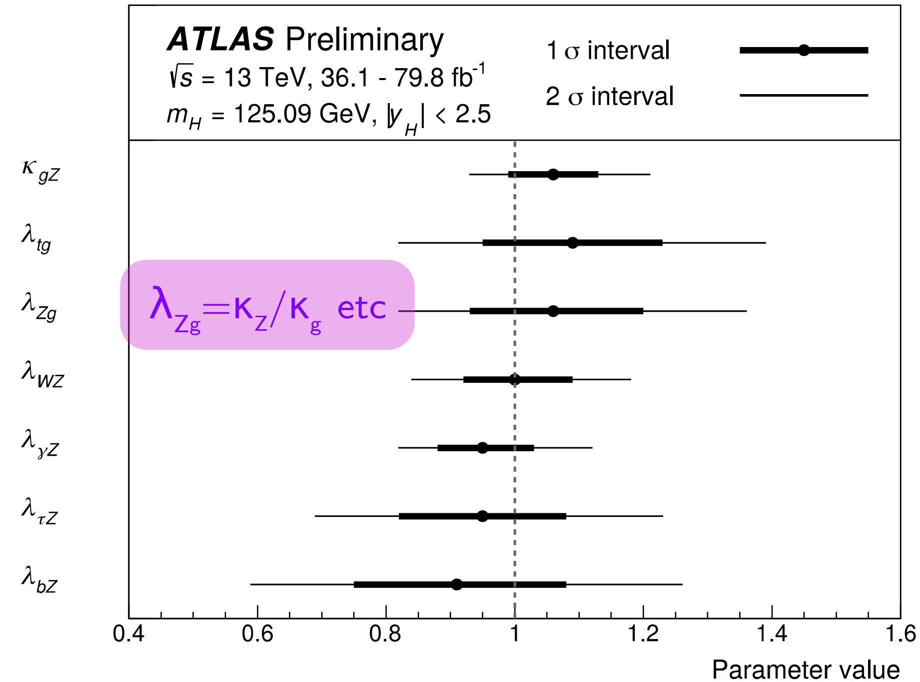
Single-Higgs rates & κ-framework interpretation

(ideally) 5x5 different $\mu_i \times \mu^f$

ATLAS-CONF-2018-031

7-parameters “κ-framework”





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$$(\sigma\cdot\mathrm{BR})(gg\to H\to ZZ)=\sigma_{\rm SM}(gg\to H)\cdot\mathrm{BR}_{\rm SM}(H\to ZZ)\cdot\frac{\kappa_g^2\cdot\kappa_Z^2}{\kappa_H^2}$$

$\kappa_{gZ}{}^2$

Still missing: Higgs self-couplings

$$\left.\begin{array}{c} V^{\rm SM}(H^\dagger H) = -\boldsymbol{\mu^2} H^\dagger H + \boldsymbol{\lambda}(H^\dagger H)^2 \\ \boldsymbol{v} = \sqrt{-\mu^2/\lambda} \\ \boldsymbol{m_h^2} = 2\lambda v^2 \end{array}\right\} \Rightarrow$$

$$V^{\rm SM}(h) = \frac{1}{2}m_h^2 h^2 + \lambda_3^{\rm SM} v h^3 + \lambda_4^{\rm SM} h^4$$

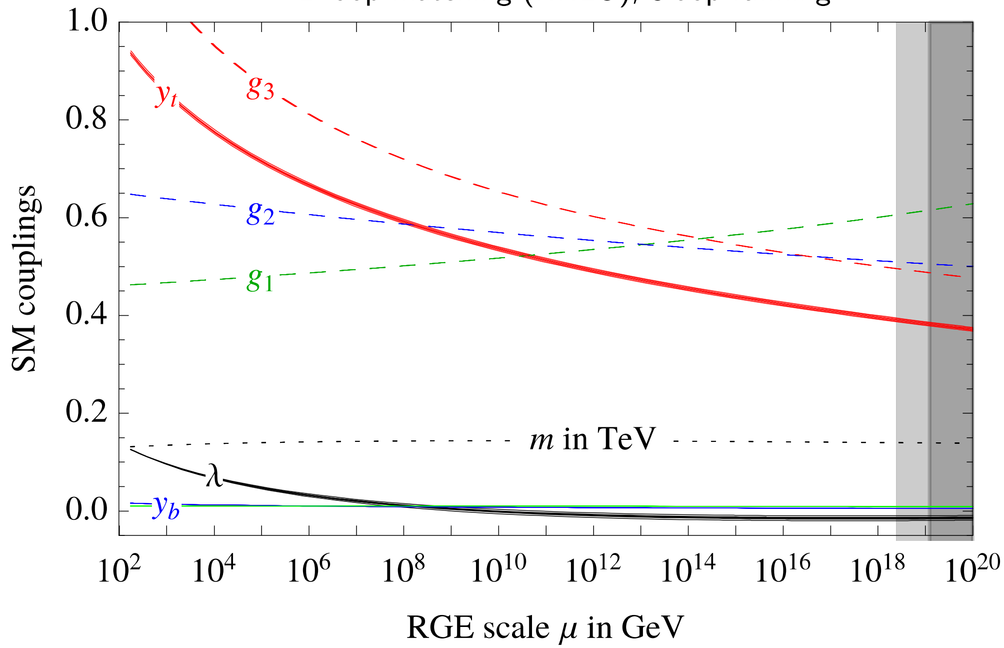
$$\lambda_3^{\rm SM} = \frac{m_h^2}{2v^2} \qquad \lambda_4^{\rm SM} = \frac{m_h^2}{8v^2}$$

(at tree level)

- SM (classical)
  - $(\lambda_3,\lambda_4) \Leftrightarrow (m_h,v) \rightarrow$ **verify it!**
- SM (quantum)
  - λ controls **vacuum stability** (together with y_t, α_s)
  - $\lambda(\mu) = f(G_F,m_Z,m_W,m_h,m_t,\alpha_s,\ldots)$ **@NNLO** in the SM

[Degrassi et al '12, Buttazzo et al '13, Bednyakov et al '15]

2-loop matching (NNLO), 3loop running



Within the SM, all couplings remain perturbative up to M_{Pl}

Still missing: Higgs self-couplings

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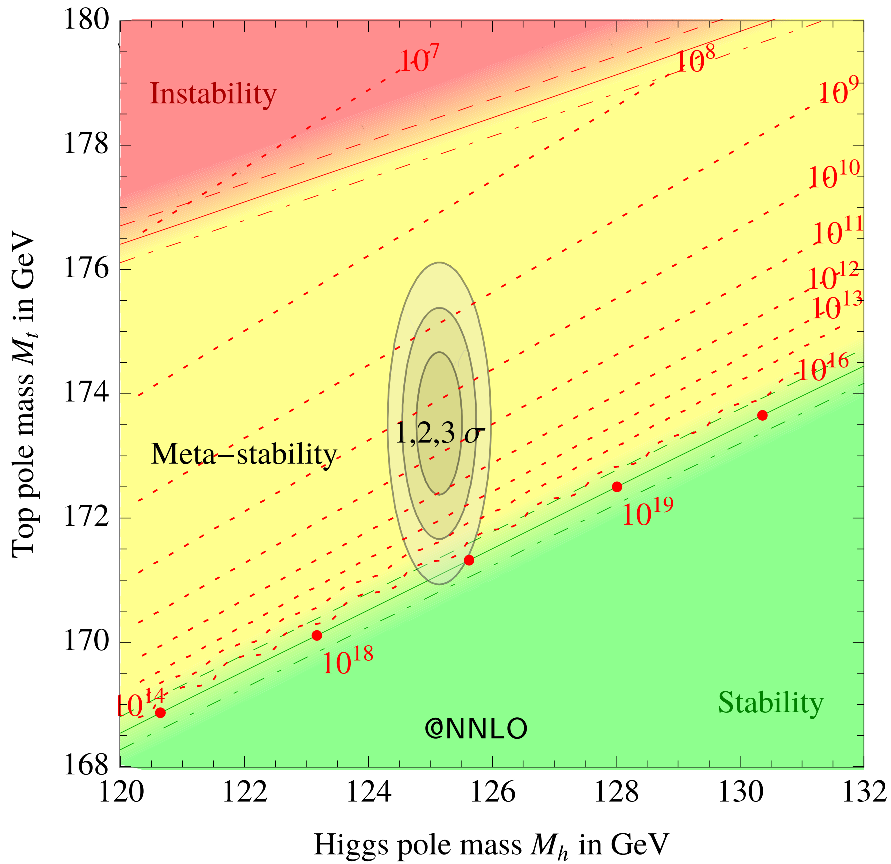
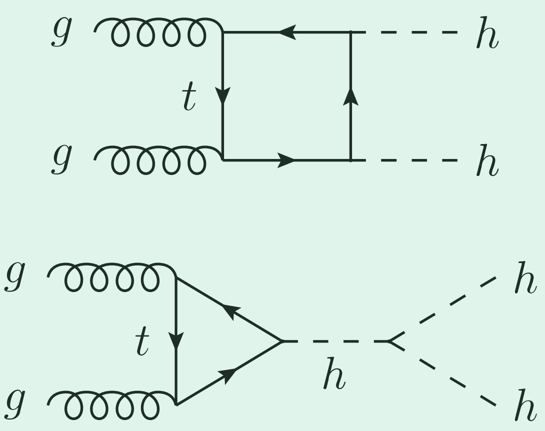


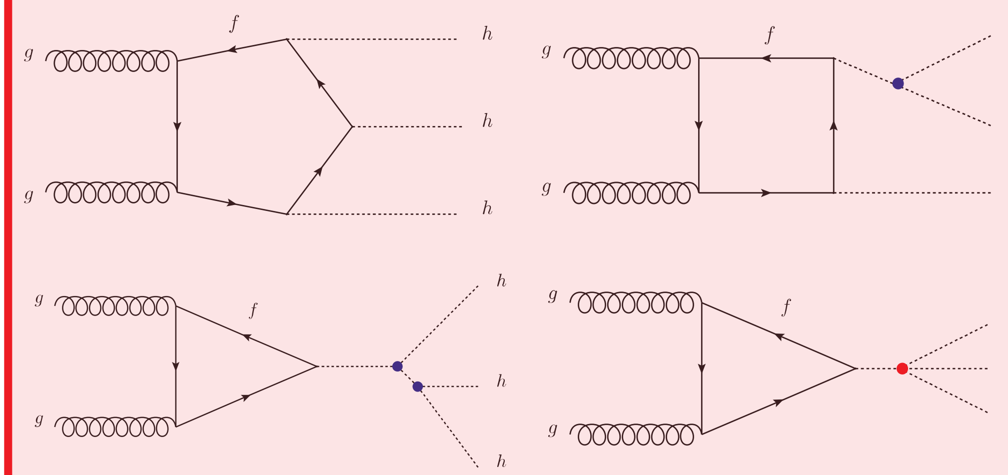
Obviously: multi-Higgs production



- double-Higgs ⇒ λ_3
- σ_{hh}(SM)
  - ✔ 35fb @LHC14

    ⇒ O(1) bound on λ_3 at HL-LHC
  - ✔ 1750fb @FCC100

    ⇒ ~10% on λ_3



- triple-Higgs ⇒ λ_3,λ_4
- σ_{hhh}(SM)
  - ✗ 0.1fb @LHC14

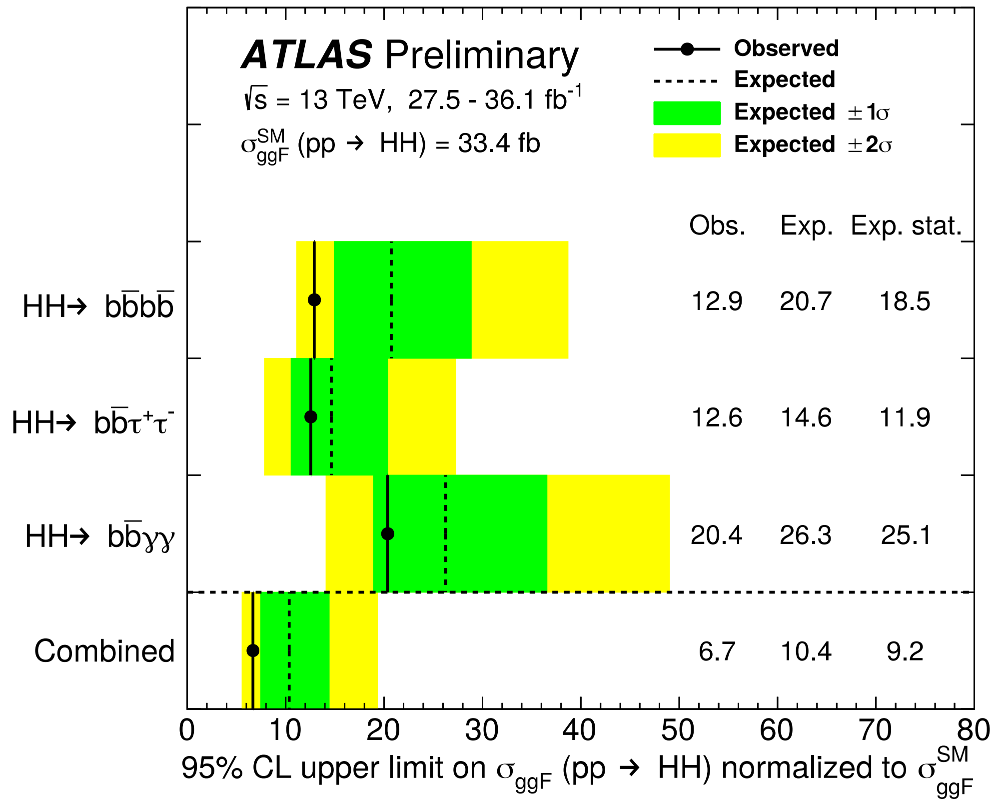
    ⇒ no hope!
  - ✗ 5fb @FCC100

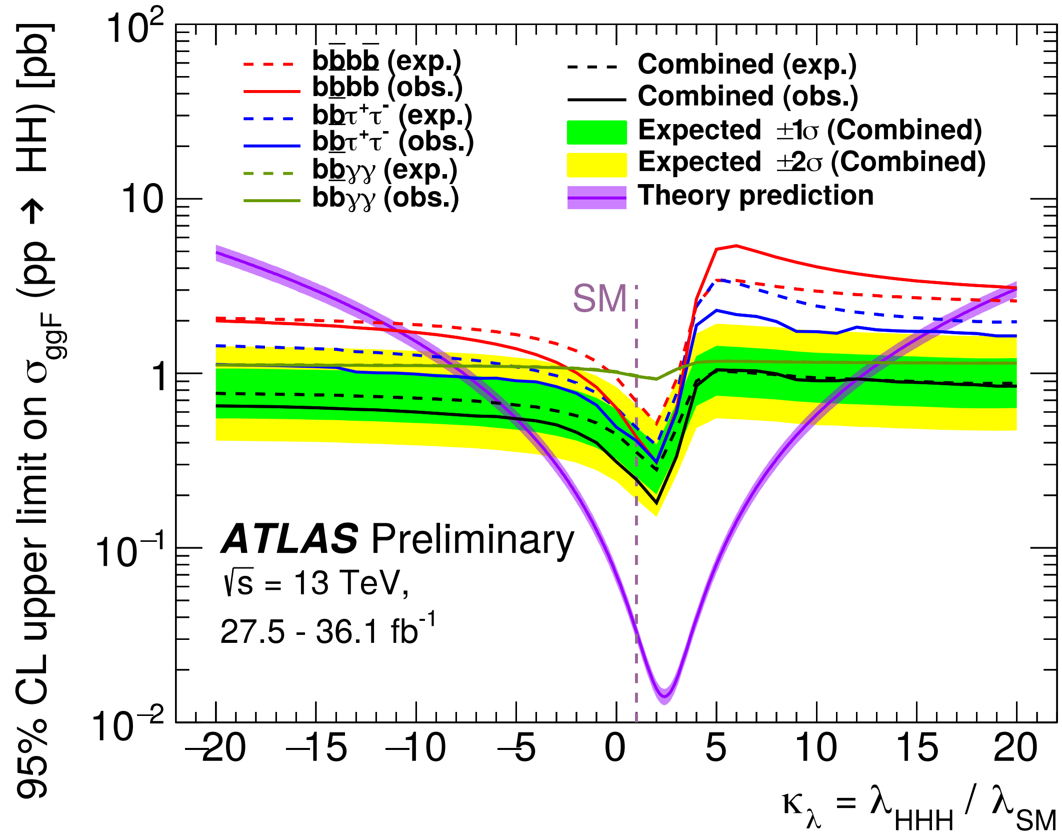
    ⇒ 2σ sensitivity on SM cross-section

[Contino et al '16 CERN-TH-2016-113

Limits on HH production: ATLAS

ATLAS-CONF-2018-043

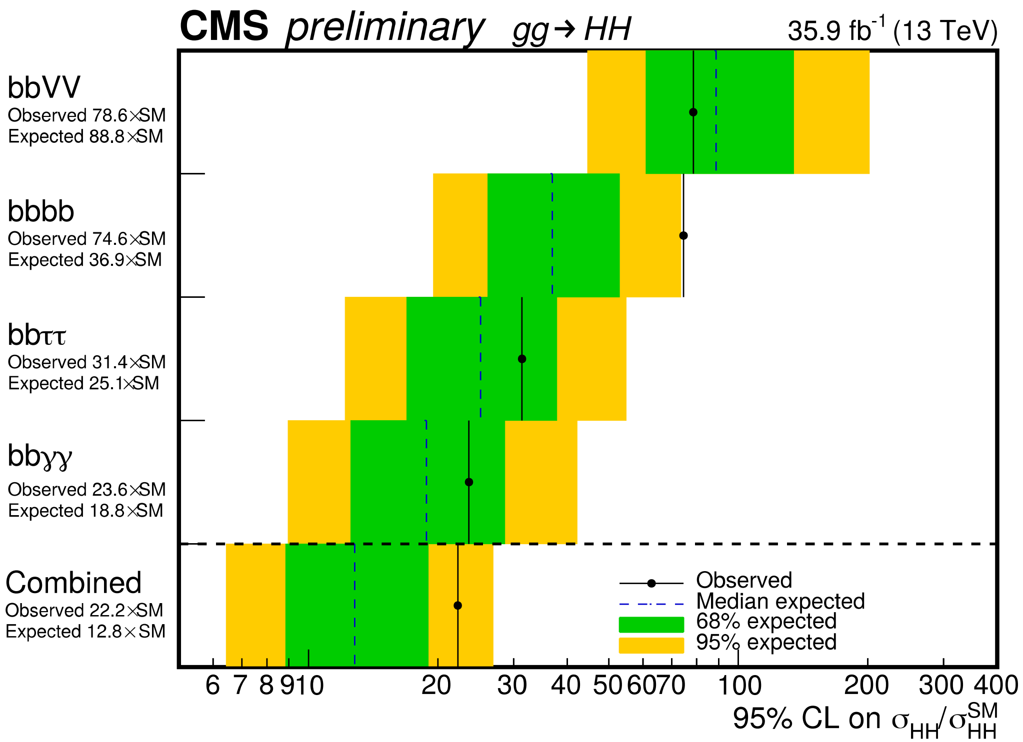


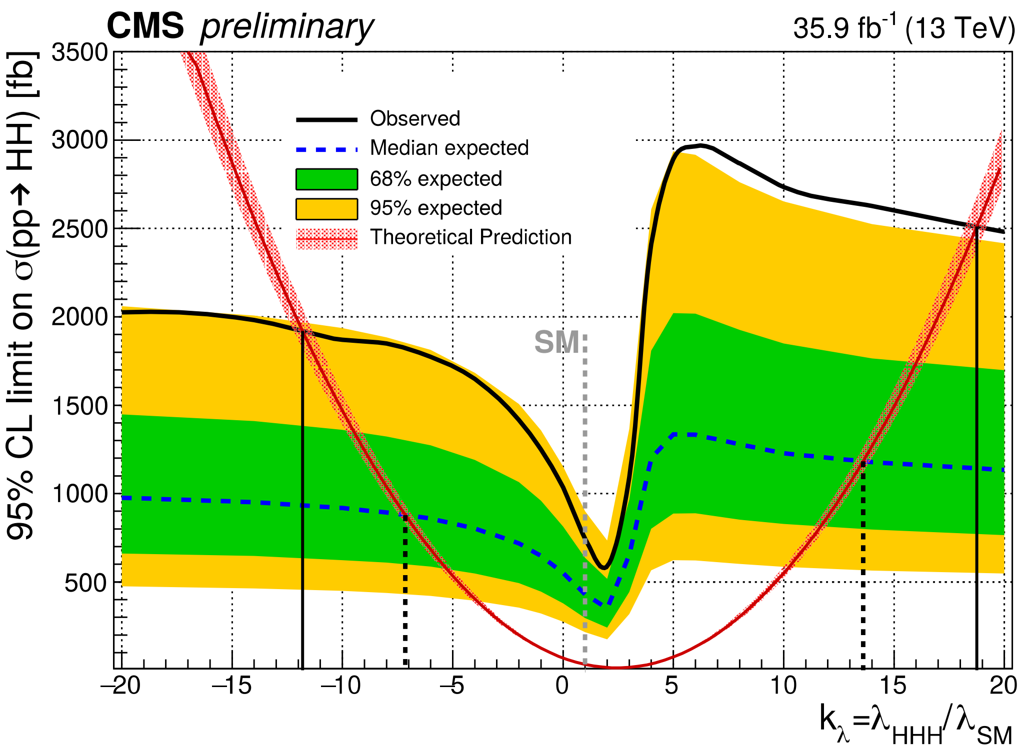


- $\sigma_{hh} < 0.22$ pb (0.35 pb) combined observed (expected) 95% CL limit
- $\Rightarrow \sigma_{hh}/\sigma_{hh}(SM) < 6.7\ (10.4)$
- $\Rightarrow -5.0 < \lambda_3\ /\lambda_3^{SM} < 12.1$ ($-5.8 < \lambda_3\ /\lambda_3^{SM} < 12.0$) (only anomalous λ_3!)

Limits on HH production: CMS

CMS-PAS-HIG-17-030





- $\sigma_{hh} < 0.72$ pb (0.41 pb) combined observed (expected) 95% CL limit
- $\Rightarrow \sigma_{hh}/\sigma_{hh}(SM) < 21.8$ (12.4)
- $\Rightarrow -11.8 < \lambda_3 / \lambda_3^{SM} < 18.8$ ($-7.1 < \lambda_3 / \lambda_3^{SM} < 13.6$) (only anomalous λ_3!)

Higgs self-couplings are interesting!

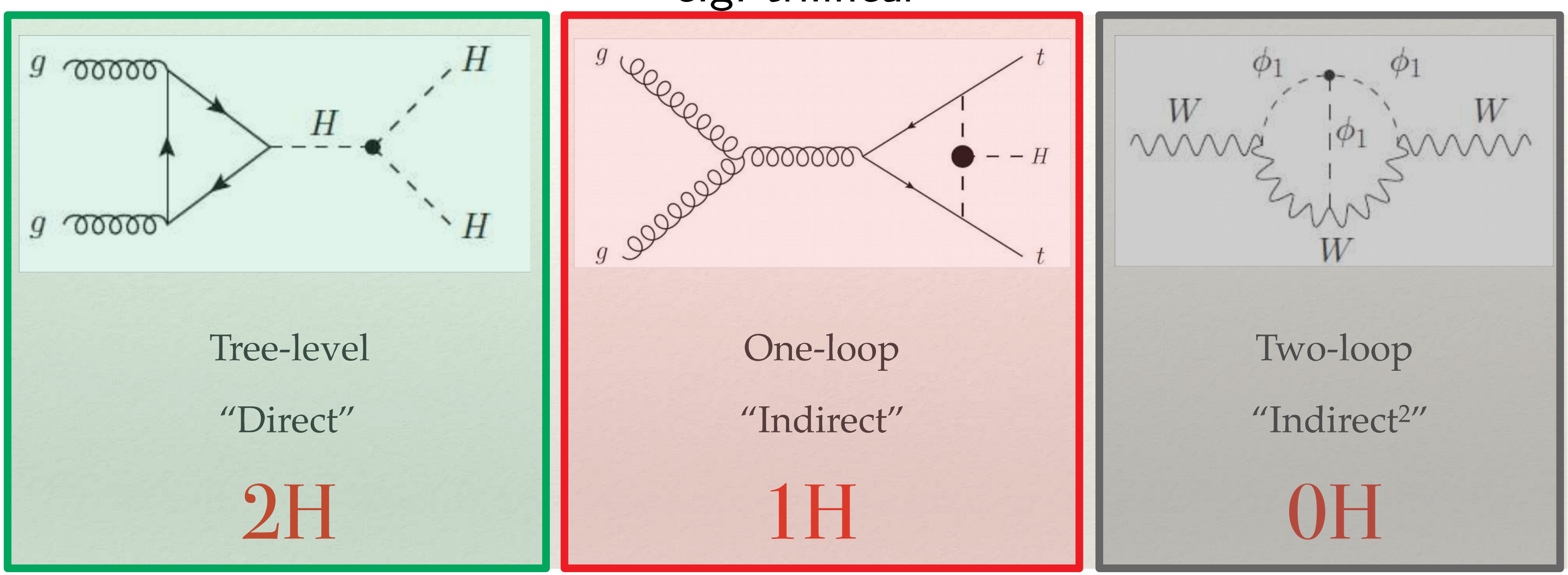
- Non-standard λ_3 and λ_4 affect physics in several ways
  - **hh** and hhh production @ LO
  - **h** and hh production @ **NLO** (EW)
  - EWPO (no h!) and h production @ **NNLO** (EW)

(EFT ref's)
Azatov et al '15
Goertz et al '15
Cao et al '15

McCullough '13
Gorbahn,Haisch '14 (+Bizon,Zanderighi '16)
Degrassi,Giardino,Maltoni,Pagani '14

van der Bij '86
Degrassi,Fedele,Giardino '17
Kribs,Maier,Rzehak,Spannowsky,Waite '17

e.g. trilinear



from Fabio Maltoni's talk at the LHCHXSWG General meeting, July 2017 @ CERN

Higgs self-couplings are interesting!

- Current constraints on $\sigma_{hh}^{(SM)}$ are quite loose

  $\rightarrow$ still room for BSM there!

- High precision Single-Higgs rates

  $\rightarrow$ can constrain some BSM directions (that also affect HH!)

- Probe the scalar potential V(h)

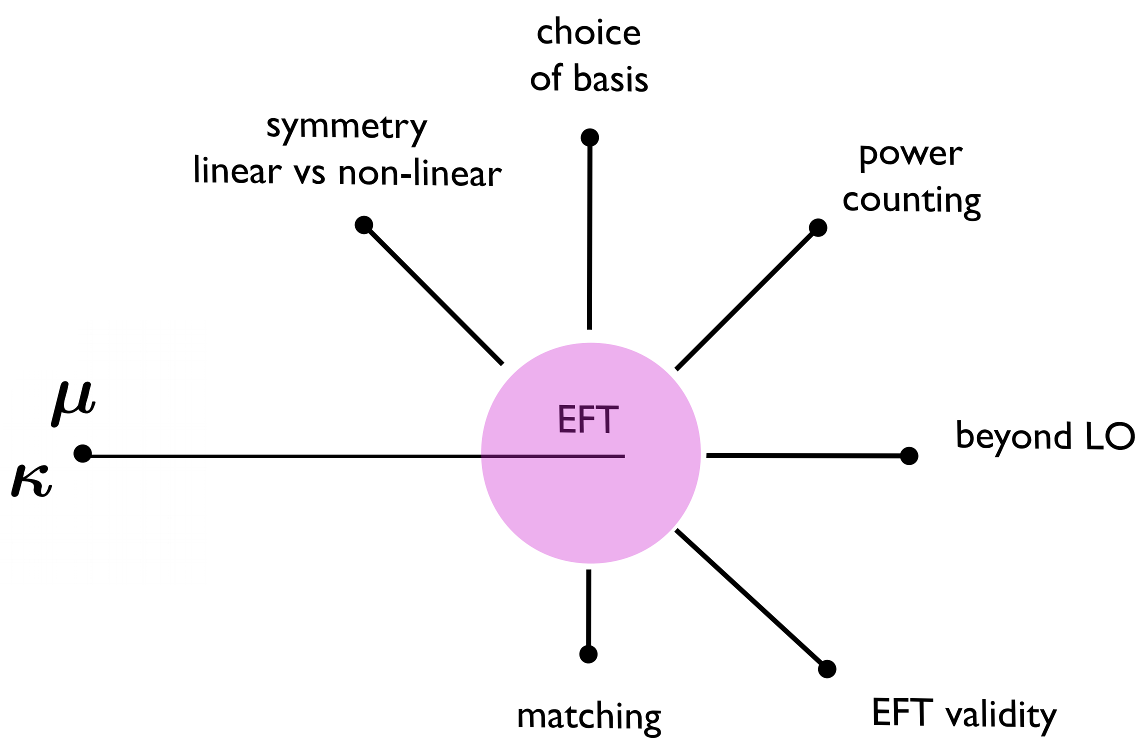
  $\rightarrow$ learn about dynamics of EW phase transition

- Interesting consequences for cosmology, e.g.
  - EW baryogenesis — see e.g. Huang, Joglekar, Li, Wagner 16; Carena, Liu, Wagner 18
  - Primordial gravitational waves — see e.g. Huang, Long, Wang 16; Hashino, Kakizaki, Kanemura, Ko, Matsui 16

Beyond the κ-framework: EFT

Scale "Λ" of new physics » typical energy of the process "E" ⇒ EFT

Grojean @ Jeju '17



Pros:

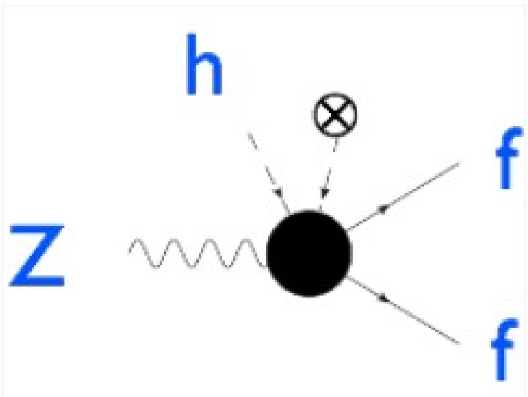
- correlations between different channels/observables
- combination of measurements at different energies
  e.g. EW precision data and Higgs measurements
- test of self-consistency

unique to EFT

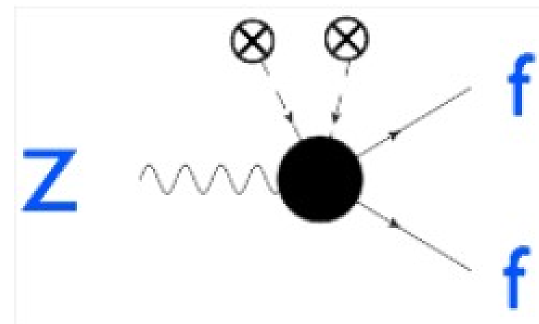
allow to focus on channels yet unconstrained and more likely to offer new discovery opportunities

BSM deformations and Higgs physics

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



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



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

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

Modifications in h→Zff related to Z→ff

already constrained at LEP

(courtesy of A. Pomarol@HiggsHunting2014)

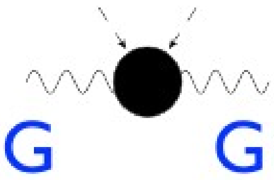
BSM deformations and Higgs physics

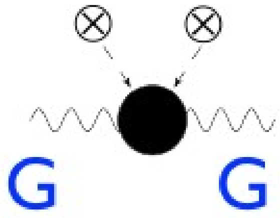
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

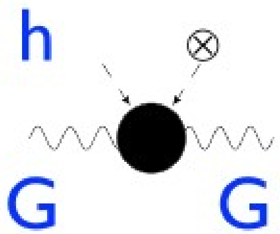
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

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





But can affect h physics:



affects GG →h!

My working assumptions

- Linearly realized EW symmetry (h belongs to Higgs doublet) ⇒ SMEFT
- Keep operators O_i up to dimension-6
- Operators tested in processes w/o Higgs assumed to be constrained
- Work in the Higgs basis ⇒ trilinear interaction $\lambda_3 = \kappa_\lambda \lambda_{SM} = (1+\delta\kappa_\lambda)\lambda_{SM}$
- Further simplifying assumptions (just to limit # of O_i)
  - no CP,L,B-L, violating O_i
  - no dipole O_i
  - flavor universality
  - no ψ^4 (t^4,ttqq,q^4)

$$\mathcal{L} \supset \boxed{\mathcal{L}_{\mathrm{SM}}} + \cancel{\mathcal{L}_{d=5}} + \boxed{\mathcal{L}_{d=6}} + \cancel{\mathcal{L}_{d=7}} + \cancel{\mathcal{L}_{d=8}} + \dots$$

L violating

B-L violating

subleading wrt d=6

Focus on 10 O_i relevant at the LHC (not just SM tensor structures! EFT ≠ k-framework)
⇒ 10 independent deformations of hGG, hψψ, hWW, hZZ, hγγ, hZγ, hhGG, hhψψ, **hhh**

Pomarol '14; +Gupta,Riva '14; Falkowski '15; HXSWG YR4

Higgs deformations in the Higgs basis

Pomarol '14; +Gupta,Riva '14; Falkowski '15; HXSWG YR4

$$\begin{aligned}
\mathcal{L} \supset \frac{h}{v}\Bigg[& \boxed{\delta c_w} \frac{g^2 v^2}{2} \boxed{W_\mu^+ W^{-\mu}} + \boxed{\delta c_z} \frac{(g^2+g'^2)v^2}{4} \boxed{Z_\mu Z^\mu} \\
& + \boxed{c_{ww}} \frac{g^2}{2} \boxed{W_{\mu\nu}^+ W^{-\mu\nu}} + \boxed{c_{w\Box}} g^2 \left(\boxed{W_\mu^- \partial_\nu W^{+\mu\nu}} + \text{h.c.} \right) + \boxed{\hat{c}_{\gamma\gamma}} \frac{e^2}{4\pi^2} \boxed{A_{\mu\nu} A^{\mu\nu}} \\
& + \boxed{c_{zz}} \frac{g^2+g'^2}{4} \boxed{Z_{\mu\nu} Z^{\mu\nu}} + \boxed{\hat{c}_{z\gamma}} \frac{e\sqrt{g^2+g'^2}}{2\pi^2} \boxed{Z_{\mu\nu} A^{\mu\nu}} + \boxed{c_{z\Box}} g^2 \boxed{Z_\mu \partial_\nu Z^{\mu\nu}} + \boxed{c_{\gamma\Box}} g g' \boxed{Z_\mu \partial_\nu A^{\mu\nu}} \Bigg] \\
& + \frac{g_s^2}{48\pi^2} \left(\boxed{\hat{c}_{gg}} \frac{h}{v} + \boxed{\hat{c}_{gg}^{(2)}} \frac{h^2}{2v^2} \right) \boxed{G_{\mu\nu} G^{\mu\nu}} - \sum_f \left[m_f \left(\boxed{\delta y_f} \frac{h}{v} + \boxed{\delta y_f^{(2)}} \frac{h^2}{2v^2} \right) \boxed{\bar{f}_R f_L} + \text{h.c.} \right] \\
& - \left(\boxed{\kappa_\lambda} - 1 \right) \lambda_3^{SM} \boxed{v h^3} ,
\end{aligned}$$

f=t,b,τ (+ c,μ)

parametrize space of d=6 operators in a way more directly connected to observable quantities in Higgs physics

SM tensor structures

"SM" tensor structures

"New" tensor structures

10 Independent couplings

8 Dependent couplings

Triple gauge couplings – Higgs interplay

Butter et al '16, Falkowski et al '16

$$
\begin{aligned}
\mathcal{L}_{\rm tgc} = {} & i g s_{\theta_W} A^\mu (W^{-\nu} W^+_{\mu\nu} - W^{+\nu} W^-_{\mu\nu}) \\
& + i g (1 + \boxed{\delta g_1^Z) c_{\theta_W} Z^\mu (W^{-\nu} W^+_{\mu\nu}} - W^{+\nu} W^-_{\mu\nu}) \\
& + i g \left[(1 + \delta\kappa_Z) c_{\theta_W} Z^{\mu\nu} + (1 + \boxed{\delta\kappa_\gamma) s_{\theta_W} A^{\mu\nu} \right] W^-_\mu W^+_\nu} \\
& + \frac{i g}{m_W^2} (\boxed{\lambda_Z} c_{\theta_W} Z^{\mu\nu} + \lambda_\gamma s_{\theta_W} A^{\mu\nu}) W^{-\rho}_v W^+_{\rho\mu} \,,
\end{aligned}
$$

1 extra indep

WWγ and WWZ data help constrain single-Higgs couplings

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

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

Ideally → global fit of Higgs, diboson, EW data

e.g. Ellis, Murphy, Sanz, You 18

How to approach the self-coupling?

- hVV & h$\psi\psi$ tested at $\sim$10%: is it theoretically sound to **deform only $\boldsymbol{\lambda_3}$**?
- **How large** can λ_3 be, from the theoretical point of view?
- If λ_3 is large, does it **spoil** the previous **single-Higgs fits**?
- Is the **bound** on λ_3 **stable** if we allow other BSM deformations?
- Will it be **enough** to look at **inclusive rates**?
- Can we really avoid performing **global fits** for BSM?
- Can we "replace" pp$\rightarrow$hh with **single-Higgs observables** for λ_3?

Only large anomalous λ_3? Not really…

Remark: up to NLO, single-Higgs observables are **insensitive to h^4,h^5,…**

- They enter only at higher loop level
- Modifications of the full V(h) could still be allowed, in principle
- At NLO, κ_λ framework = EFT w/ O_6

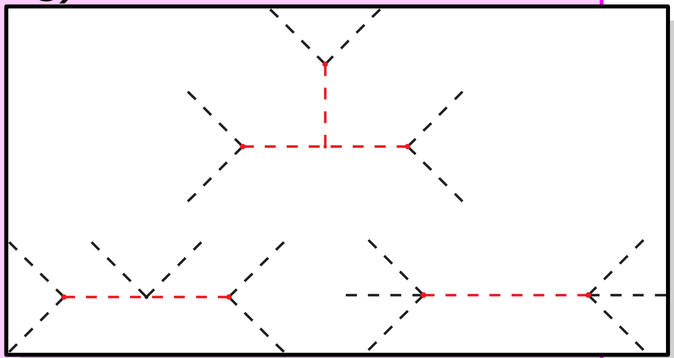
Modification of **h^3 only** leads to loss perturbative unitarity at low energy scales in processes like

$$V_L V_L \to V_L V_L h^n$$

- for $|\kappa_\lambda| < 10$ one gets $\Lambda \sim$ 5TeV [Falkowski, Rattazzi (to appear)]
- see also Di Luzio, Gröber, Spannowsky [1704.02311

Are there **classes** of BSM models that, in an EFT description:

- **Either deform just Higgs self-interactions (tree-level matching)**
  - e.g. SU(2) scalar quadruplets (not quite a "class")
  - still, 1-loop matching→ other single-Higgs couplings!
- **Or enhance $\delta\kappa_\lambda$** wrt the single-Higgs couplings?
  - e.g. **tuned** Higgs Portal can get $\delta\kappa_\lambda$~6 vs other couplings O(0.1)
- See also De Blas et al [1412.8480], Jiang, Trott [1612.02040], Di Luzio, Gröber, Spannowsky [1704.02311]



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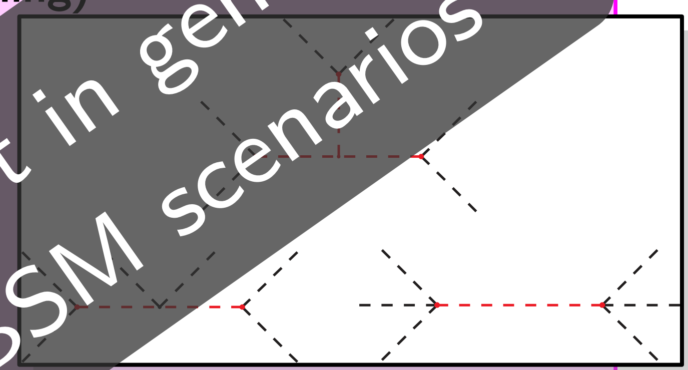


Not in generic BSM scenarios

Large λ$_3$ in tuned Higgs Portal

1 dimensionless parameter, 1 coupling, 1 scale, singlet, potential, dimensionless argument

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

Linear EFT valid if
(expansion in h/v)

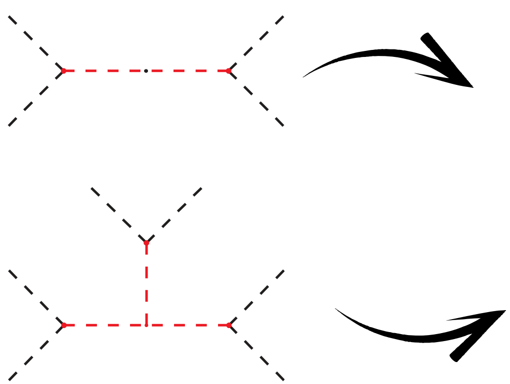
$$\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1$$

Otherwise only derivative expansion is allowed, many more couplings!!

parametrically large λ$_3$
(paying some tuning)

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

$$\varepsilon \simeq 0.1\,, \;\; 1/\Delta \simeq 1.5\%\,, \;\; \delta c_z \simeq 0.1\,, \;\; \boldsymbol{\delta\kappa_\lambda \simeq 6}$$



$$\begin{cases} (H^\dagger H)^2 & \Rightarrow \text{tuning of quartic } \Delta \sim \dfrac{\theta^2 g_*^2}{\lambda_3^{\rm SM}} \\ \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) & \Rightarrow \delta c_z \sim \theta^2 g_*^2 \dfrac{v^2}{m_*^2} = \theta\varepsilon \end{cases}$$

$$(H^\dagger H)^3 \quad \Rightarrow \delta\kappa_\lambda \sim \theta^3 g_*^4 \frac{1}{\lambda_3^{SM}} \frac{v^2}{m_*^2} = \varepsilon\Delta$$

DV, Grojean, Panico, Riembau, Vantalon [1704.01953]

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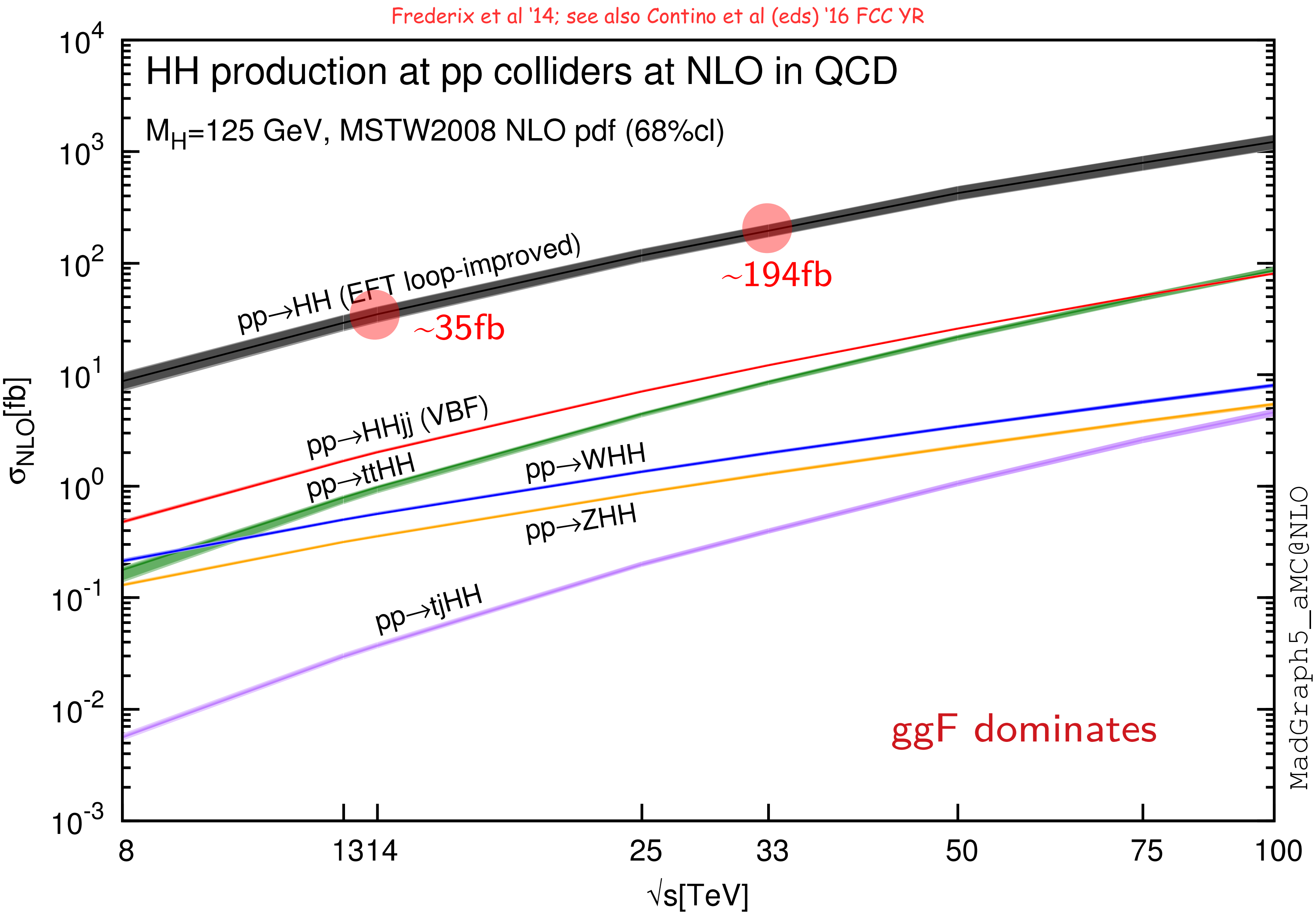
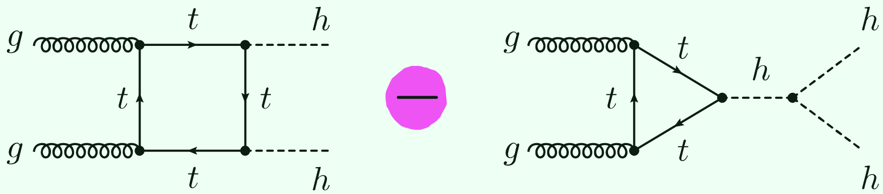
Obviously: double-Higgs production



Double-Higgs deformation(s) [ggF]

(U. Haisch@MoriondEW2017)

Anatomy of hh production



$$R = \frac{\sigma(pp \to hh)}{\sigma(pp \to hh)_{\rm SM}} = 2.1 - 10.8\lambda + 17.2\lambda^2$$

$$R = 1 \implies \lambda_{1,2} = \{\lambda_{\rm SM}, 3.8\lambda_{\rm SM}\}$$

Limits on λ from hh production

LHC Run I, 20.3 fb^{-1} $\longrightarrow$ $\dfrac{\lambda}{\lambda_{\rm SM}} \in [-14.5,\ 19.1]$

2γ2b, 1406.5053;
4b, 1506.00285;
2b2τ, 2γ2W, 1509.04670

LHC Run II, 13.3 fb^{-1} $\longrightarrow$ $\dfrac{\lambda}{\lambda_{\rm SM}} \in [-8.4,\ 13.4]$

4b, ATLAS-CONF-2016-049

HL-LHC, 3 ab^{-1} $\longrightarrow$ $\dfrac{\lambda}{\lambda_{\rm SM}} \in [-0.8, 7.7]$

2γ2b, ATL-PHYS-PUB-2017-001

1-param

$\lambda=\kappa_\lambda \lambda_3^{SM}$

EFT dim-6

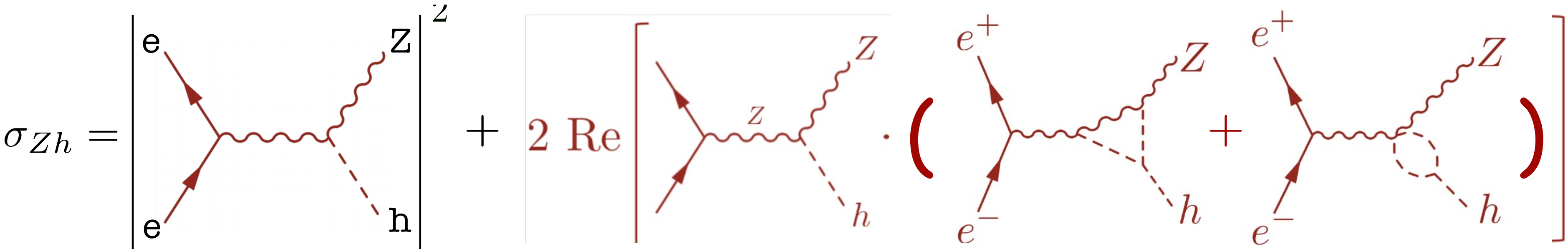
$$\begin{aligned}\frac{\sigma(pp \to hh)}{\sigma_{\rm SM}(pp \to hh)} = {} & A_1\,(1+\delta y_t)^4 + A_2\,(\delta y_t^{(2)})^2 + A_3\,\kappa_\lambda^2\,(1+\delta y_t)^2 + A_4\,\kappa_\lambda^2\,\hat{c}_{gg}^2 \\ & + A_5\,(\hat{c}_{gg}^{(2)})^2 + A_6\,(1+\delta y_t)^2\,\delta y_t^{(2)} + A_7\,\kappa_\lambda\,(1+\delta y_t)^3 \\ & + A_8\,\kappa_\lambda\,(1+\delta y_t)\,\delta y_t^{(2)} + A_9\,\kappa_\lambda\,\hat{c}_{gg}\,\delta y_t^{(2)} + A_{10}\,\hat{c}_{gg}^{(2)}\,\delta y_t^{(2)} \\ & + A_{11}\,\kappa_\lambda\,\hat{c}_{gg}\,(1+\delta y_t)^2 + A_{12}\,\hat{c}_{gg}^{(2)}\,(1+\delta y_t)^2 + A_{13}\,\kappa_\lambda^2\,\hat{c}_{gg}\,(1+\delta y_t) \\ & + A_{14}\,\kappa_\lambda\,\hat{c}_{gg}^{(2)}\,(1+\delta y_t) + A_{15}\,\kappa_\lambda\,\hat{c}_{gg}\,\hat{c}_{gg}^{(2)}\end{aligned}$$

Azatov et al '15 Goertz et al '15 Cao et al '15

Self-coupling & single-Higgs @NLO

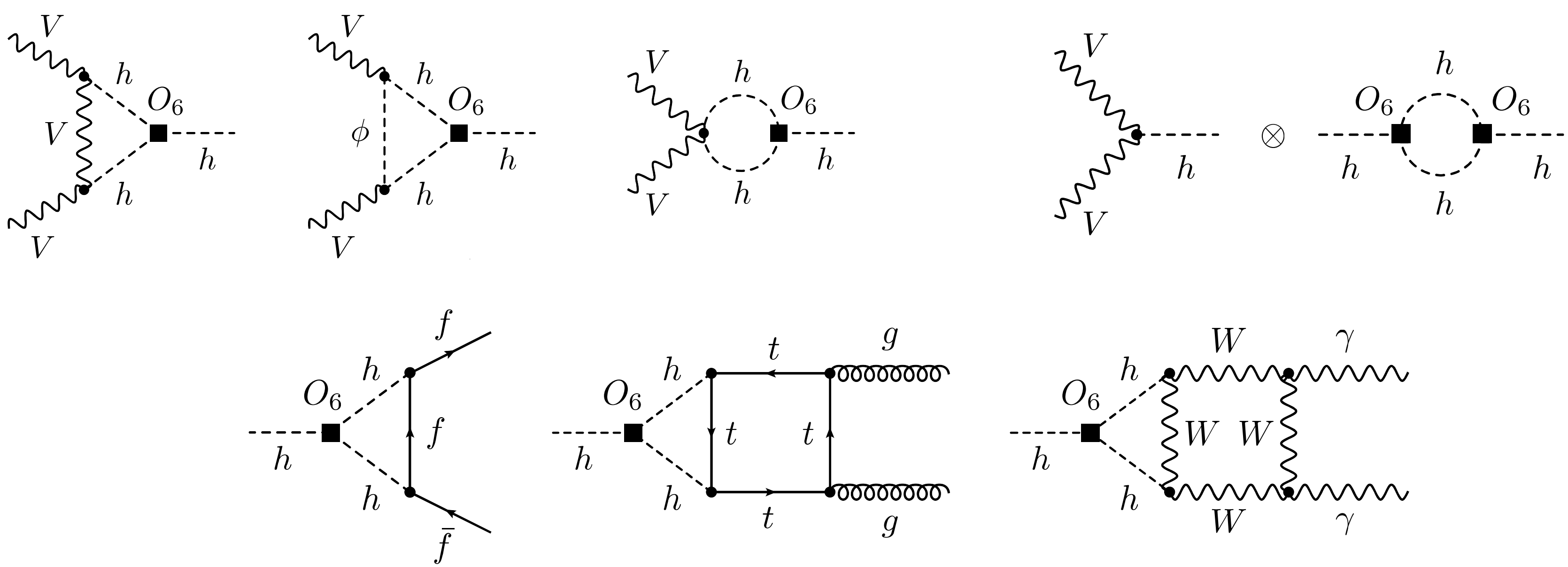
Idea: trilinear coupling affects also single-Higgs rates, but **@NLO. Still, if $\boldsymbol{\lambda_3}$ is large** ...

McCullough '13



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

Gorbahn, Haisch '16 Degrassi, Giardino, Maltoni, Pagani '16 Bizon, Gorbahn, Haisch, Zanderighi '16



Single-Higgs at the HL-LHC

End of LHC Run 3 → 300 fb^{-1} @ 14 TeV → End of HL-LHC → 3000 fb^{-1} @ 14 TeV

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

- Good sensitivity on 16 channels, O(5-10-20)%
- Estimated relative uncertainties on signal strengths μ, with pile-up 140 events/bunch crossing
- Large luminosity allows for good statistics in bins of differential measurements → exploit!

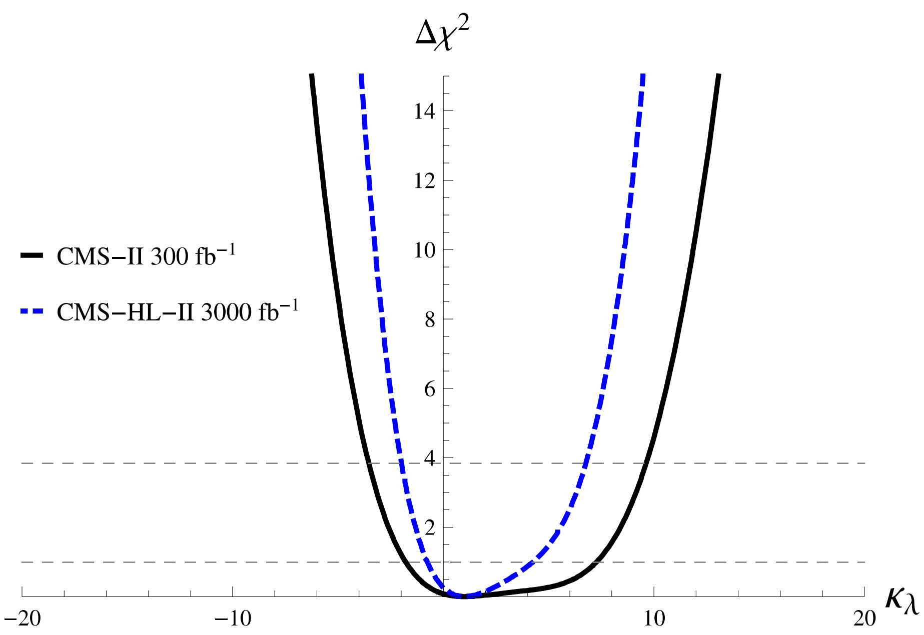
ATL-PHYS-PUB-2014-016 + ATL-PHYS-PUB-2016-008 + ggF N^{3}LO uncertainty+ VH (H→ZZ) split in WH,ZH

Only an anomalous $\lambda_3 = \kappa_\lambda \lambda_{SM}$

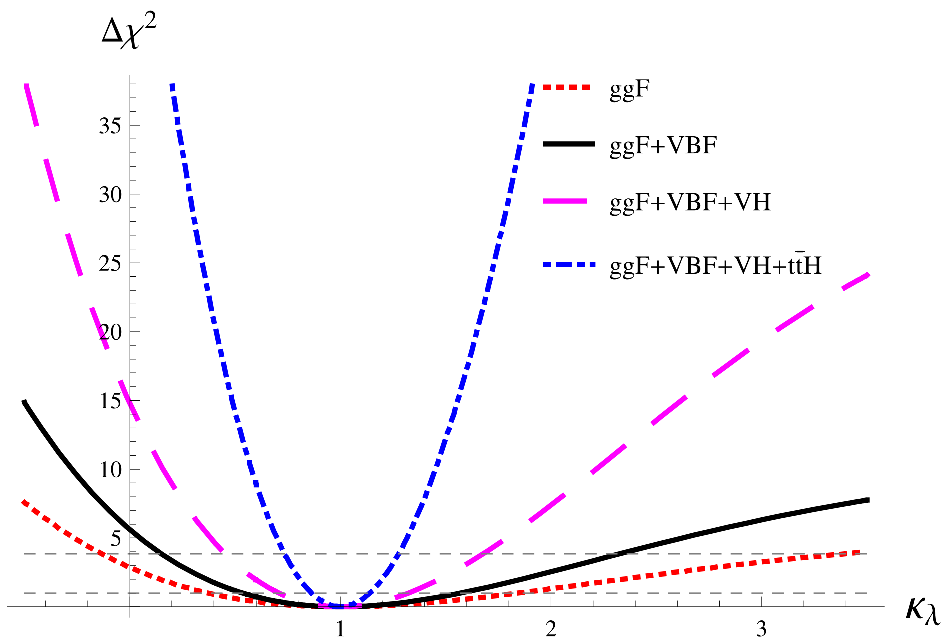
Use only indirect constraint from single-Higgs

[first sensitivity study by Degrassi et al '16]

Optimistic CMS projections for HL-LHC



Exercise: assume 1% combined th/exp uncert



$\kappa_\lambda^{1\sigma} \in [-0.7, 4.2]$ $\kappa_\lambda^{2\sigma} \in [-2.0, 6.8]$

$\kappa_\lambda^{1\sigma} \in [0.86, 1.14]$ $\kappa_\lambda^{2\sigma} \in [0.74, 1.28]$

a bit worse than ATLAS HL-LHC HH projection (less optimistic assumptions)

$\kappa_\lambda^{2\sigma} \in [-0.8, 7.7]$

A global view on the Higgs self-coupling

Grojean, Panico, Riembau, Vantalon, **DV** [1704.01953]

HL-LHC prospects on $\delta\kappa_\lambda$ with ATLAS projections ($\sim$ CMS "Scenario 1")

14TeV, 3/ab, pile-up μ=140

ATL-PHYS-PUB-2014-016 + ATL-PHYS-PUB-2016-008 + ggF N^{3}LO uncertainty HXSWG YR4 + VH (H→ZZ) split in WH,ZH

Keep only interference SM-BSM

Allow for NLO corrections due to κ_λ

With my assumptions, **10 parameters**

Perform χ^2 fit with SM signal ($\mu_i^f=1$)

Signal strength measurements

$\mu_i^f=\sigma_i \text{x} BR^f/(\sigma_i \text{x} BR^f)_{SM} \sim 1+\delta\sigma_i+\delta BR^f$

Production channels: ggF,WH,ZH,VBF,ttH

Decay modes: $\gamma\gamma$,WW,ZZ,bb,$\tau\tau$

A fit of the "usual" inclusive rates is insensitive to simultaneous global shift

$\sigma_i \to \sigma_i + \Delta$ & $BR^f \to BR^f - \Delta$

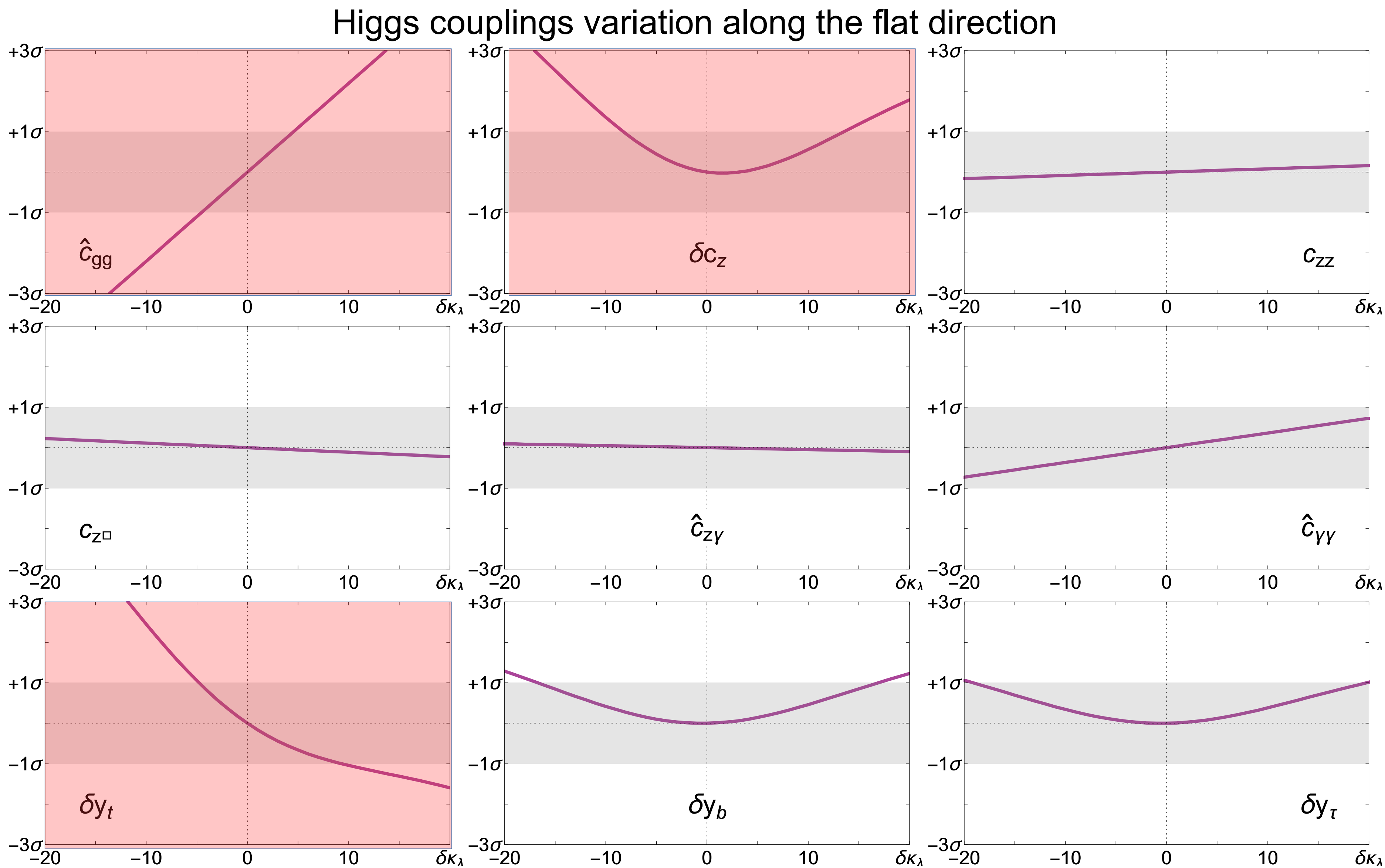
In principle have 5x5=25 observables, in fact only 9 directions are independent

⇒ we expect 1 exact flat direction in a 10 parameters fit

Sorry: including Triple Gauge Couplings constraints, BR(h→Zγ), BR(h→$\mu\mu$) does not really help :(

Also: Higgs width (on-shell vs off-shell) has no impact (moreover EFT interpretation problematic)

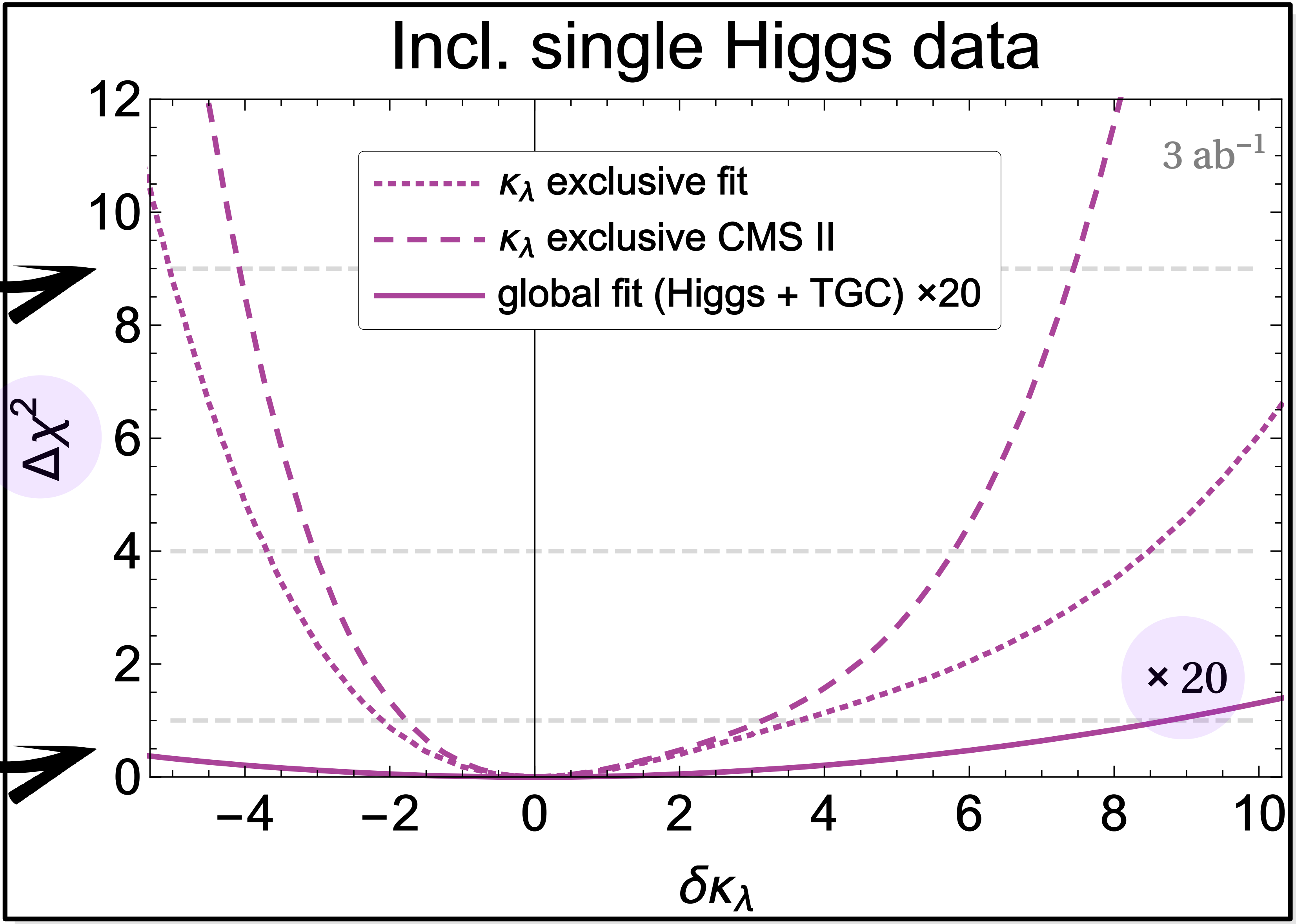
Exact flat direction in the global fit



Bound on $\delta\kappa_\lambda$ from inclusive rates

allow only $\delta\kappa_\lambda$

$\delta\kappa_\lambda$ & 7 single-Higgs deformations

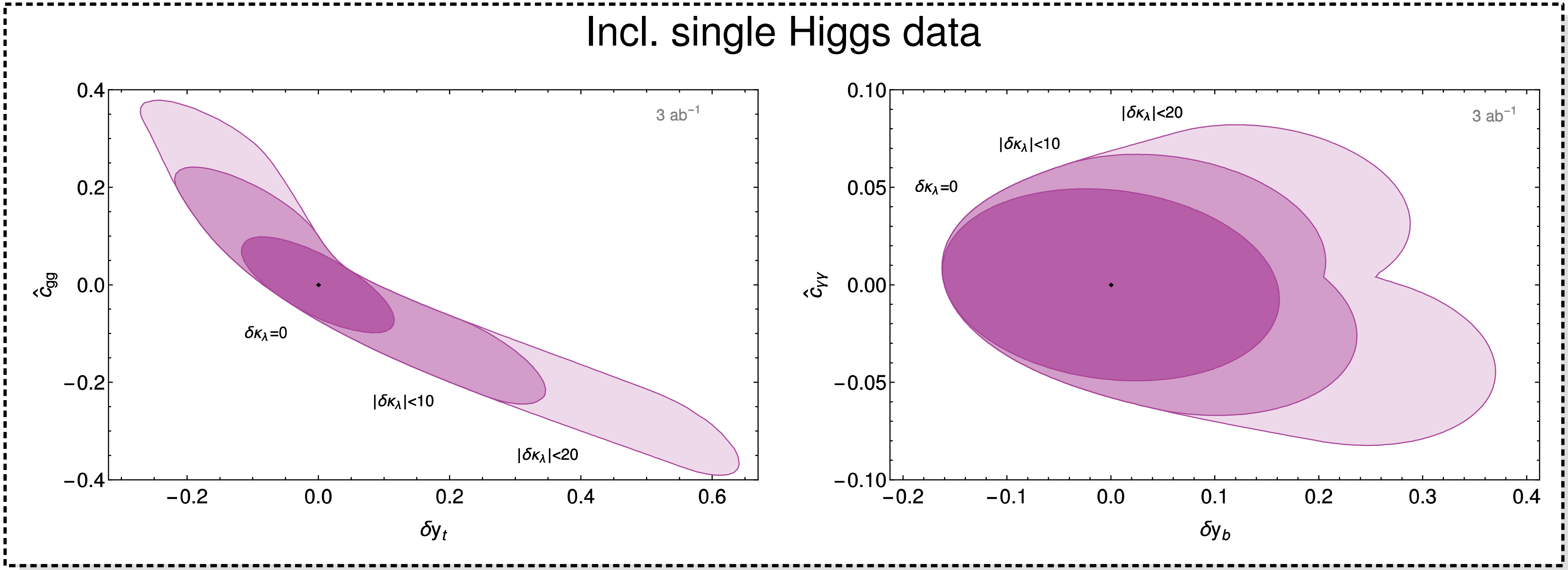


FLAT!

the flat direction is rather insensitive to the TGC constraint

Single-Higgs couplings fit w/κ_λ@NLO

$(\delta y_t, \hat{c}_{gg})$ $(\delta y_b, \hat{c}_{\gamma\gamma})$

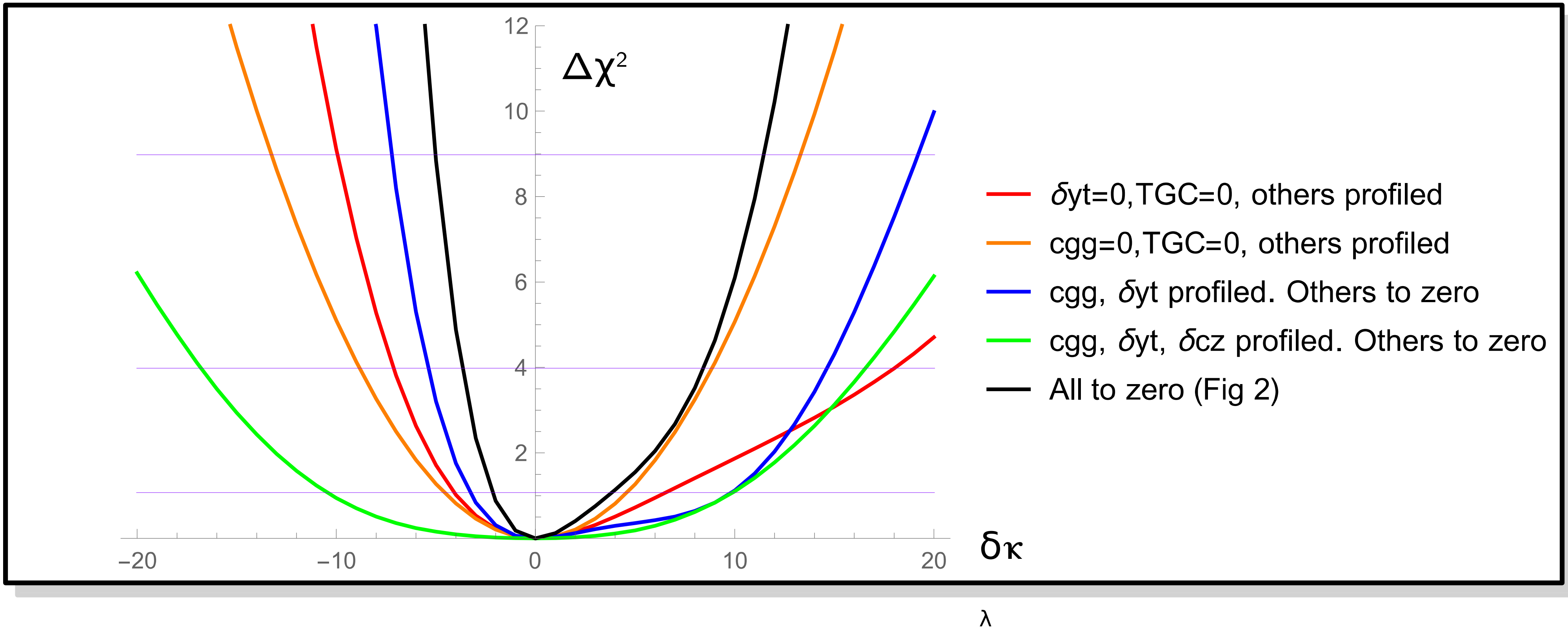


$\Delta\chi^2$=2.3 contours (68% CL in the gaussian limit)
[other 8 couplings profiled]

If large κ_λ is allowed, it feeds back into single-Higgs couplings fits

Constrained “intermediate” scenarios

A game: let's pretend we have scenarios with some of $(\delta y_t, c_{gg}, \delta cz)$ switched off

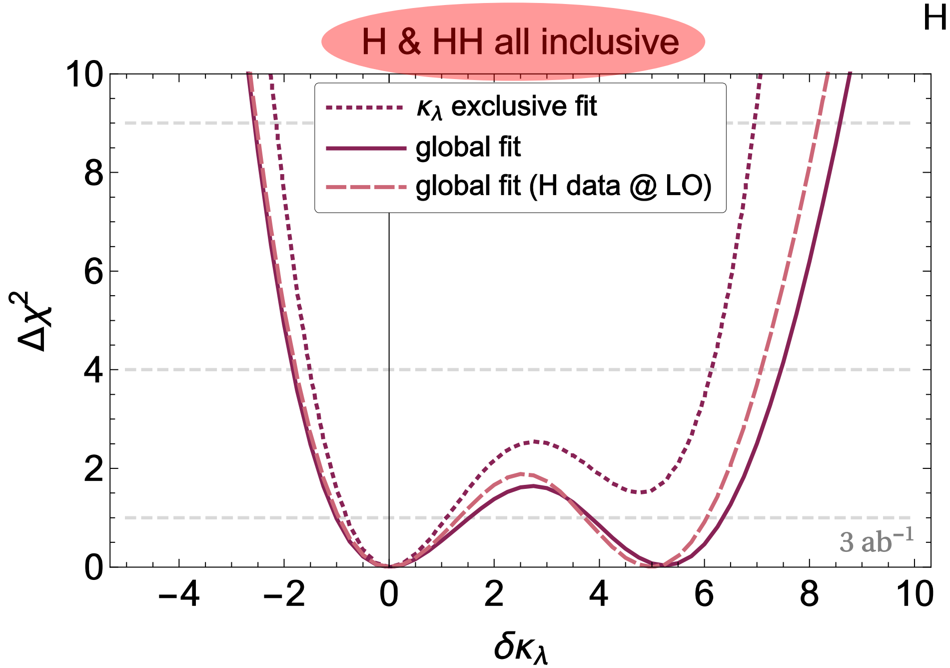


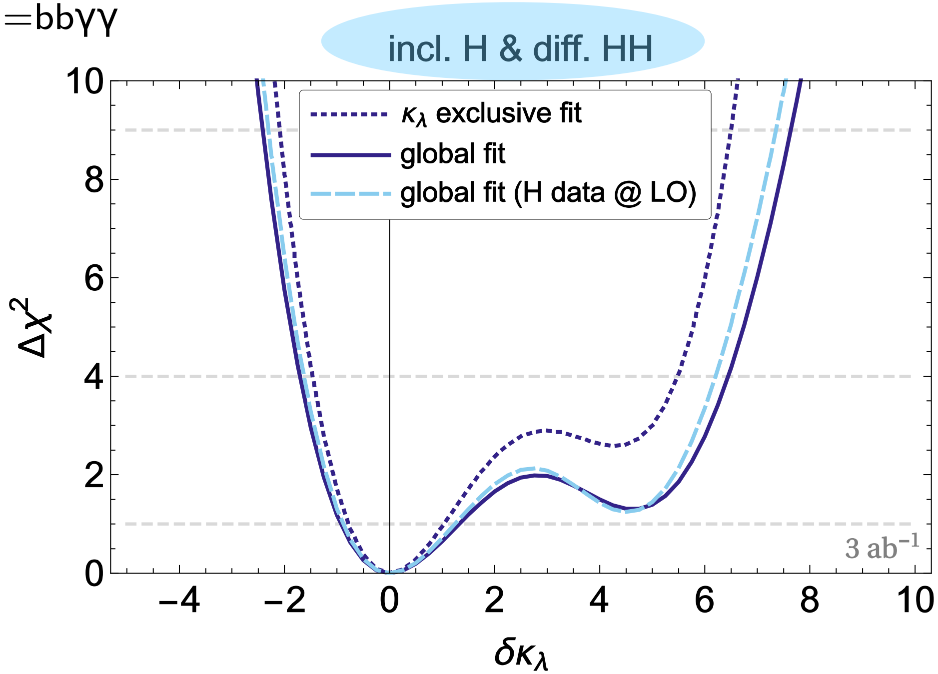
As expected, constraining “by hand” the coefficients that control the flat direction, the bound on κ_λ shrinks

Any model builder willing to explore how motivated such scenarios are?

Compare & combine w/double-Higgs

HH=bbγγ





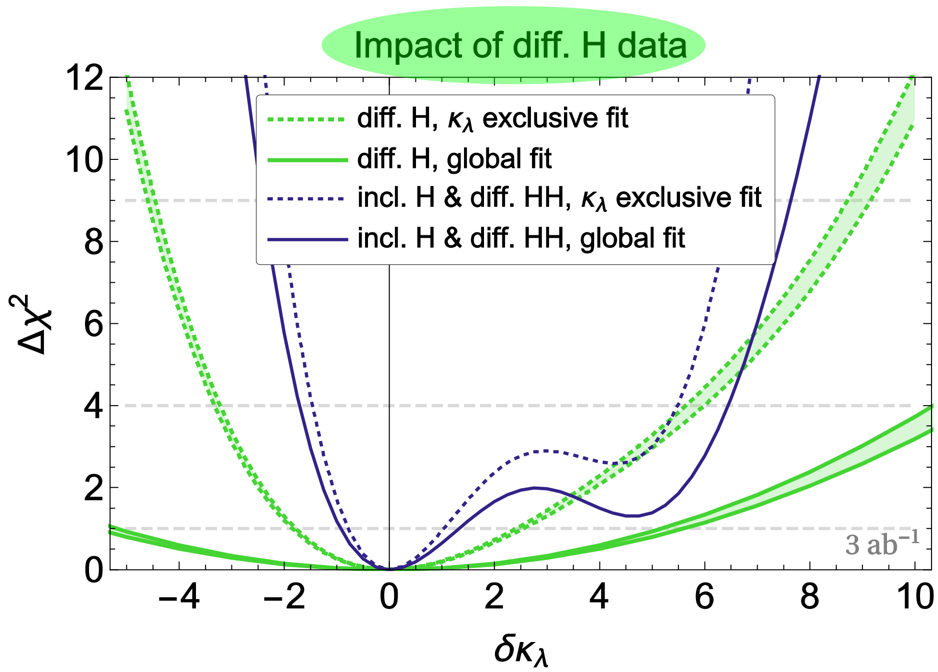
Double-Higgs drives the bound on κ_λ while, single-Higgs observables are essential in order to constrain the other coefficients deforming σ(hh)

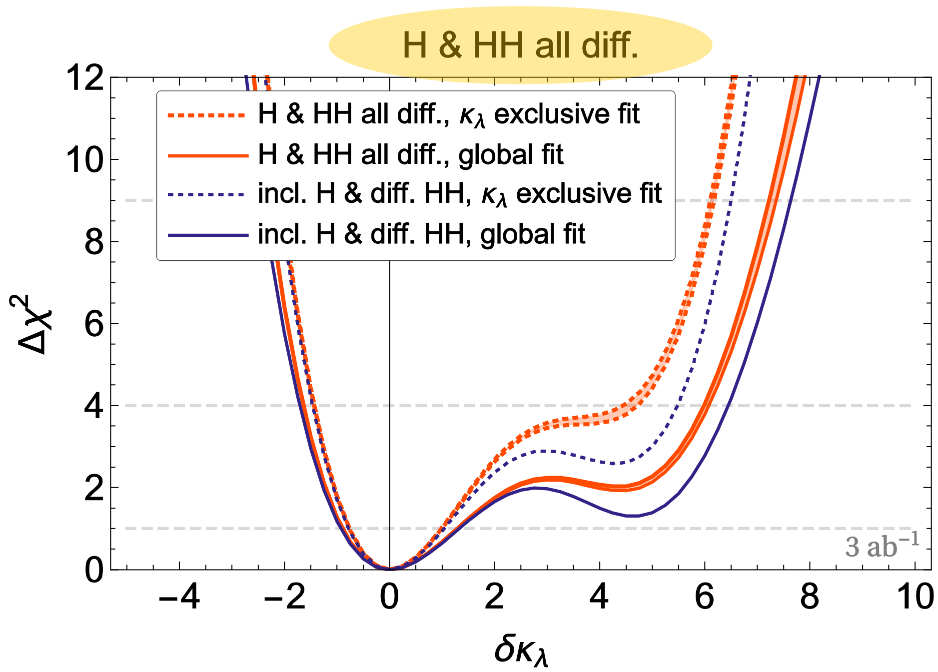
Differential (m_{hh}) double-Higgs removes degeneracy due to second minimum

"Exclusive" κ_λ fits benefit from NLO single-Higgs, global don't

Warning: here the assumption is that of linearly realized EW symmetry.
Non-linear EFT⇒{1,h,h^2}XY couplings unrelated⇒more parameters, global fit w/ EWPO!

Impact of differential VH and ttH





Inclusion of differential data ($d\sigma/dm_{inv}$) for single-Higgs observables seems promising, but more detailed estimates of the experimental systematics are required, as well as more refined analyses.

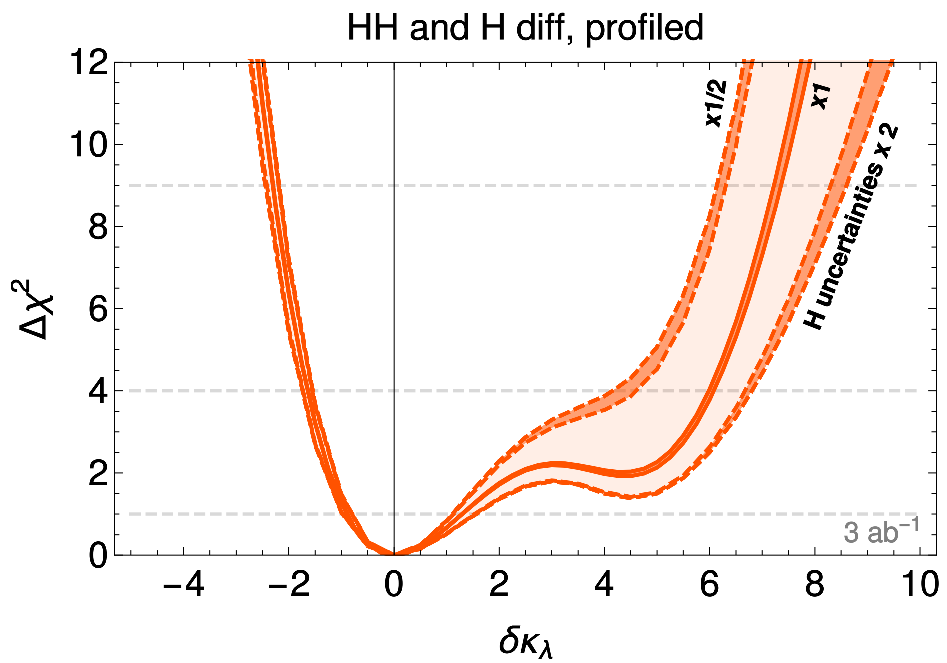
See Maltoni, Pagani, Shivaji, Zhao [1709.08649] for the impact of $\delta\kappa_\lambda$ on single-Higgs differential distributions and for a simplified κ-framework analysis
* see backup a couple of their plots

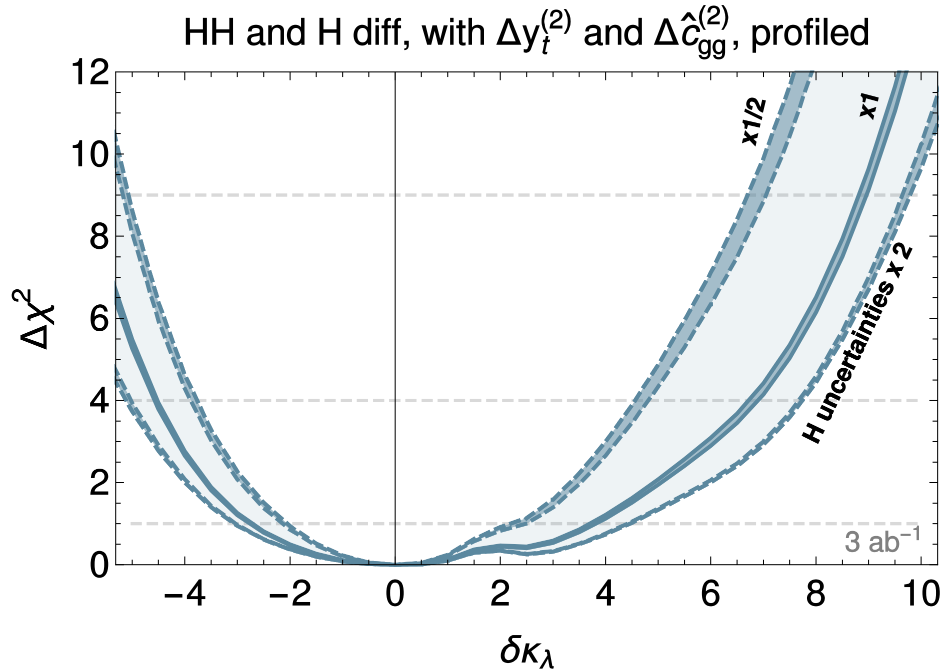
Combining differential data from single- and double-Higgs, the minimum at large $\delta\kappa_\lambda$ is further lifted. Synergy!

Bound from single-H not competitive but has totally different systematics
⇒ complementary to HH

Some simple robustness checks

(HH=bbγγ)





simple global rescaling of single-Higgs uncertainties doesn't impact too much

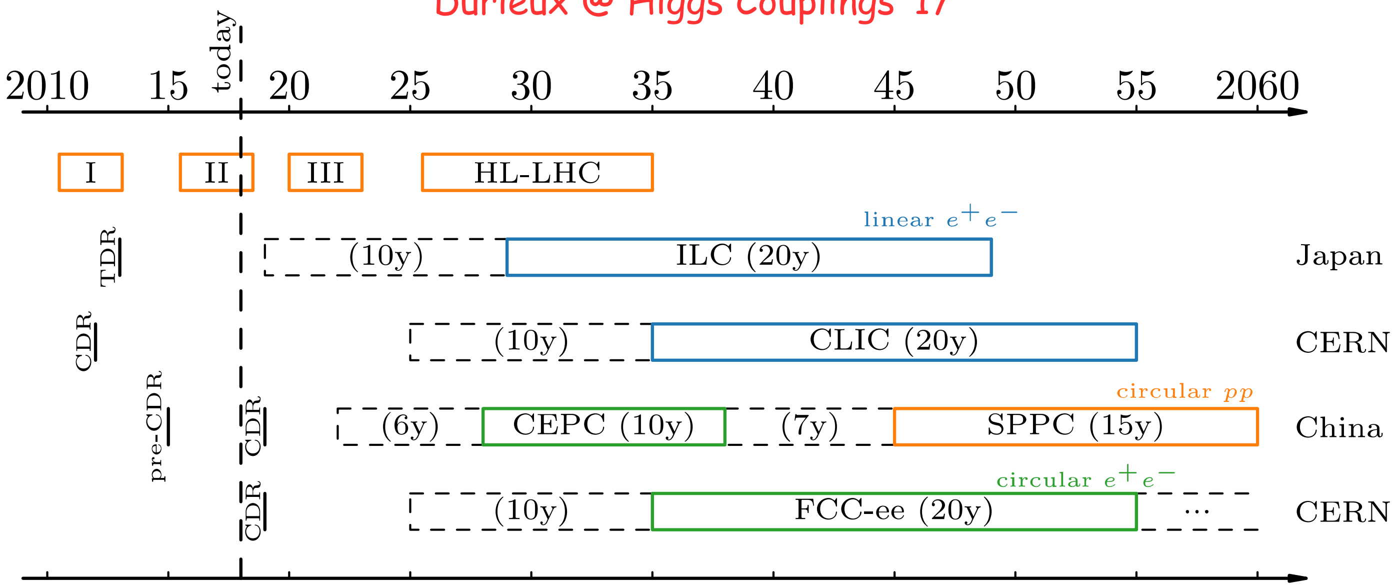
relaxing the assumption of linear EFT for double-Higgs weakens the bound
→ also, more operators have to be considered

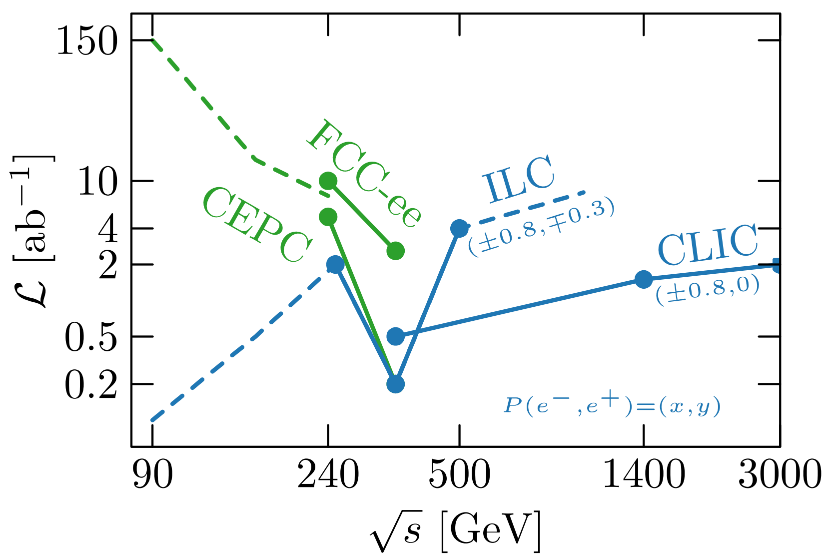
Outline

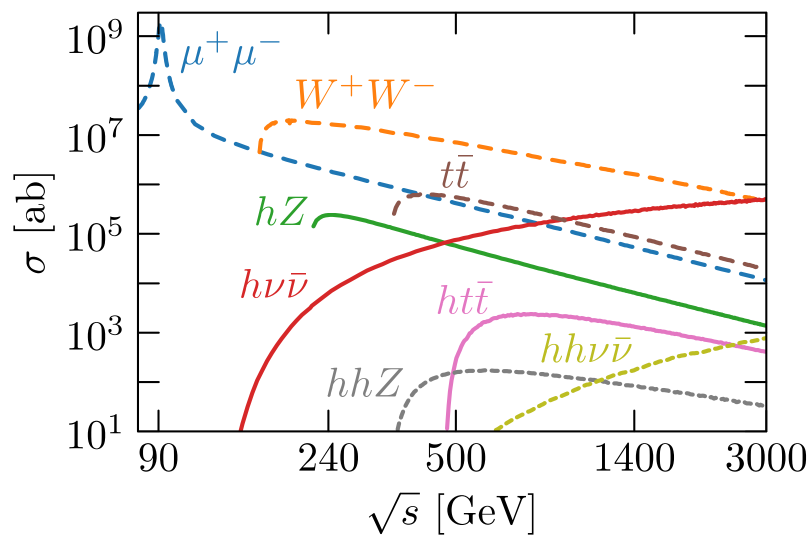
- Testing BSM deformations with Higgs physics
- Higgs trilinear self-coupling at the HL-LHC
- Prospects at the HE-LHC and future e^+e^- colliders

Future colliders: a timeline

Durieux @ Higgs Couplings '17







Higgs self-coupling @ HE-LHC

Stay tuned for the HL/HE-LHC YR

HL-LHC

14 TeV, 3/ab
σ(hh,ggF)~35fb

Grojean, Panico, Riembau, Vantalon, **DV** [1704.01953]

- Inclusive single-Higgs rates can't constrain $\delta\kappa_\lambda$ (w/ NLO effects) in generic BSM scenarios
- Double-Higgs production drives the bound (single-Higgs LO crucial for other deformations)
- Differential measurements of both h and hh help eliminate the extra minimum $\delta\kappa_\lambda$~5
- HL-LHC is **the machine** for accurate differential Higgs measurements → explore prospects!

HE-LHC

33 TeV, 10/ab
σ(hh,ggF)~194fb

- Both high E and high lumi
- Probe BSM in distrib's tails
- Exploit non-SM tensor structures to disentangle flat directions in BSM fits
- Also VBF channel See e.g. Contino et al '10, '12
- Work to be done!

- HE here is just naive extrapolation! (FCC=100TeV)
- Old machine parameters, just for illustrative purposes

$\delta\kappa_\lambda$ bound / scenario	68%	95%
HL: h incl, hh incl	[-1, 1.5] U [3.9, 6.4]	[−1.8, 7.5]
HL: h incl, hh diff	[-1.1, 1.3]	[−1.7, 6.5]
HE: h incl, hh incl	[-0.3, 0.3] U [5.0, 6.0]	[-0.5, 0.7] U [4.5, 6.7]
HL + HE	[-0.3, 0.3]	[-0.5, 0.6] U [4.8, 6.0]
FCC 100 TeV 30/ab h incl, hh diff	[−0.03, 0.03]	[−0.06, 0.06]

- Uncertainties on single-H μ's: naively extrapolated from HL-LHC
- Double-H EFT: interpolation between HL-LHC and FCC of Azatov et al '15
- NLO $\delta\kappa_\lambda$ effect on single-H: courtesy of D.Pagani

The lepton collider option

Hadron

- High-energy $\rightarrow$ discovery?
- No direct handle on partonic c.o.m. energy $\rightarrow$ pdf's
- Large QCD backgrounds
- Sensitivity to couplings to quarks

Lepton

- Lower energies but clean environment $\rightarrow$ Higgs factories
- Lower energies achievable
- Beam polarization (extra handle)
- Sensitivity to EW couplings

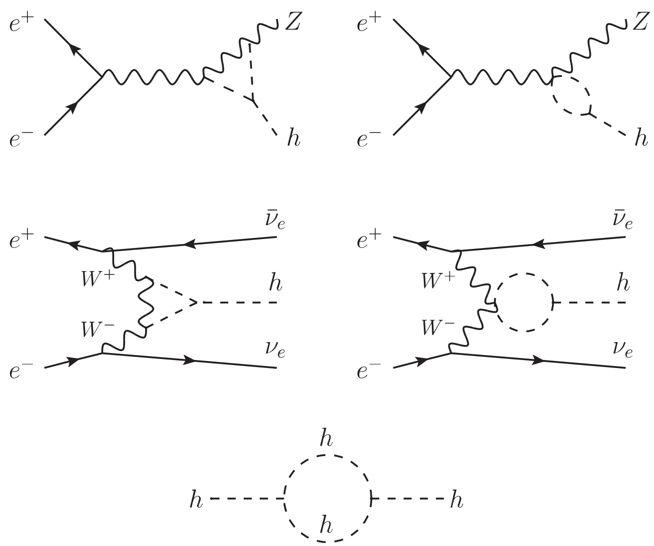
Circular

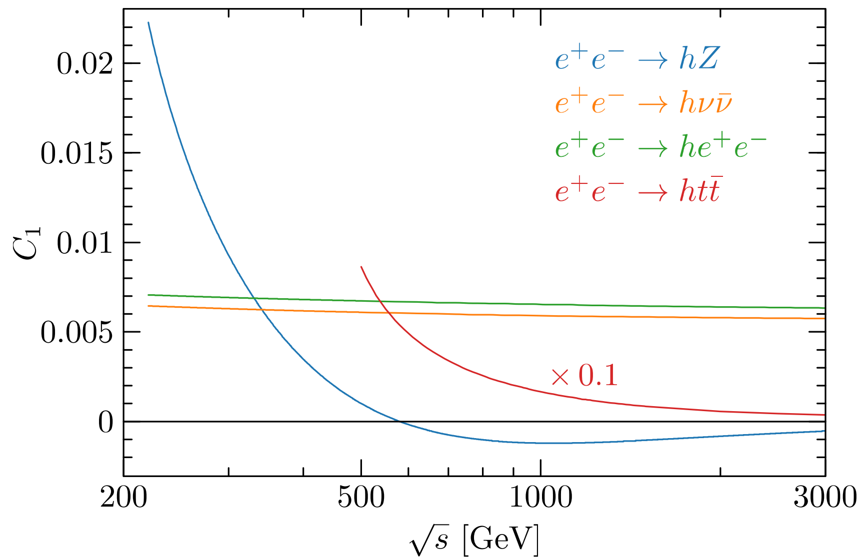
- Energy limited by synchrotron radiation
- Higher luminosity
- Several interaction points
- Precise determination of beam energy

Linear

- Allows for staged development (gradual energy increase)
- Easier to control beam polarization
- Bremsstrahlung

Low-energy lepton colliders

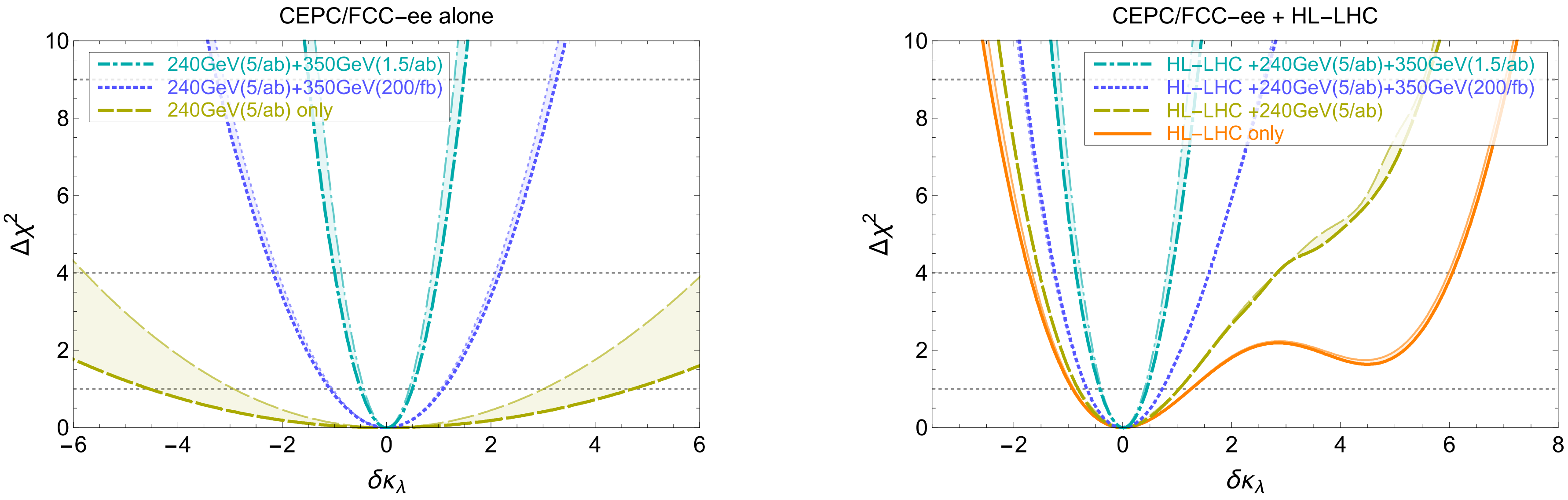




- 2 main production modes
- 4 angular distributions in Zh
- 2 beam polarization runs ($\pm$80%,$\mp$30%)
- 7+2 decay modes ZZ, WW, γγ, Zγ, ττ, bb, gg, (cc, μμ)
- no flat direction expected

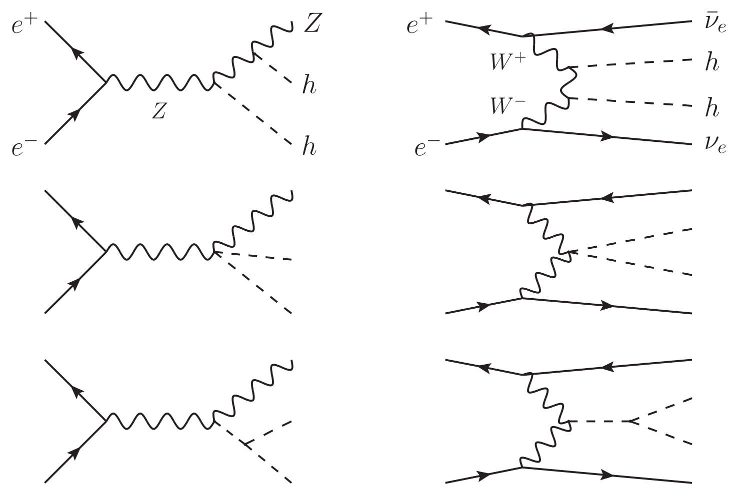
Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon, **DV** [1711.03978]

Low-energy lepton colliders

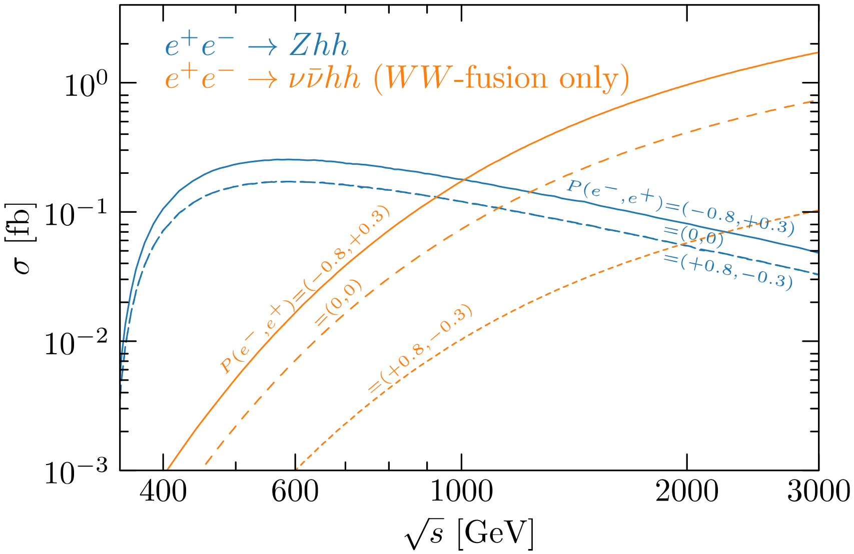


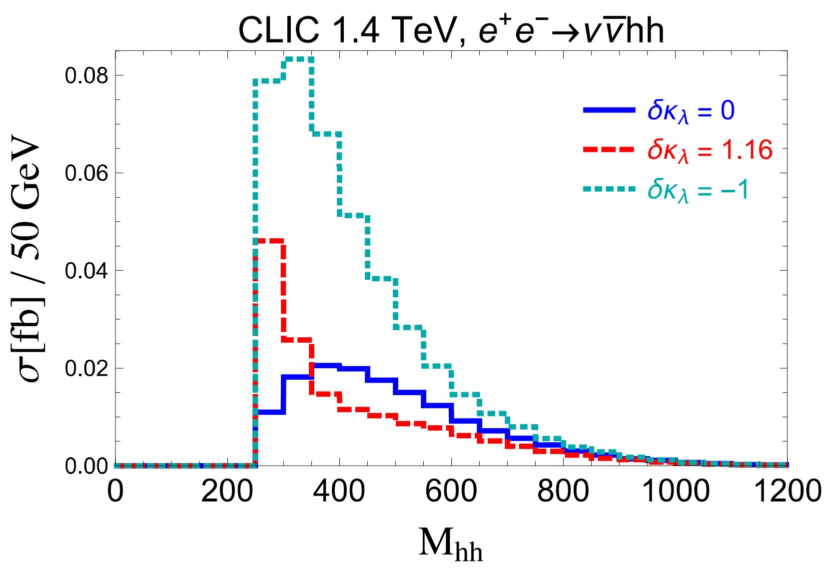
- shaded band reflects different assumptions on TGCs $\rightarrow$ large impact! global analysis needed to constrain single-Higgs deformations
- low-energy circular collider needs either combination with HL-LHC or 2 energy runs to set meaningful bounds

High-energy lepton colliders



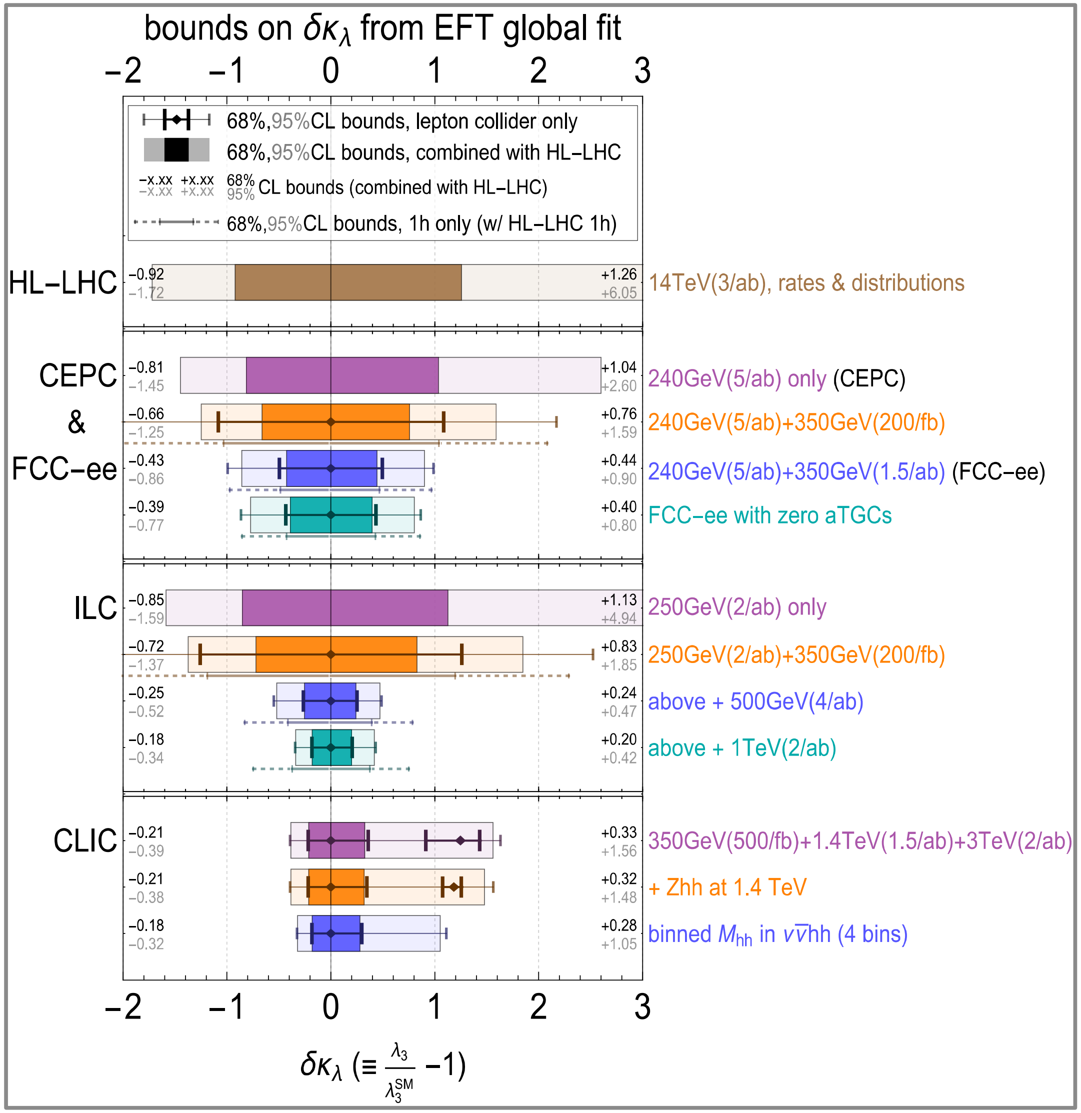
more sensitive to $\delta\kappa_\lambda > 0$ more sensitive to $\delta\kappa_\lambda < 0$





- access to double-Higgs production, ZHH / WBF complementary
- differential data in m_{hh} add useful info
- exploit impact of polarization at ILC
- dependence on $\delta\kappa_\lambda$ stronger at low energy $\rightarrow$ILC runs at 500GeV and 1TeV maximize sensitivity

Comparison of future colliders reach



Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon, **DV** [1711.03978]

- HL/HE-LHC
  - HL will be able to put only O(1) bound, **driven by hh production**
  - HE with cross-section and lumi increase → factor 10 better
- Low energy e^+e^-
  - only a 240GeV circular collider is not enough: need to combine with HL-LHC or run at other energy
  - 40% precision from **indirect bound (h)**, provided runs at both 240/250 GeV and 350 GeV are available (~few ab^{-1} lumi)
- High-energy e^+e^-
  - **direct bound (hh) dominates**
  - ILC maximizes sensititvity (Zh, WBF)
  - CLIC loses access to Zh → residual minimum for $\delta\kappa_\lambda$~1