Trilinear Higgs self-coupling extraction from single Higgs measurements

Stefano Di Vita (INFN Milano)

Double Higgs Production at Colliders Workshop @ Fermilab/LPC

Sep 4, 2018

Based on

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

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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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Still missing: Higgs self-couplings

See talk by B.Di Micco

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

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

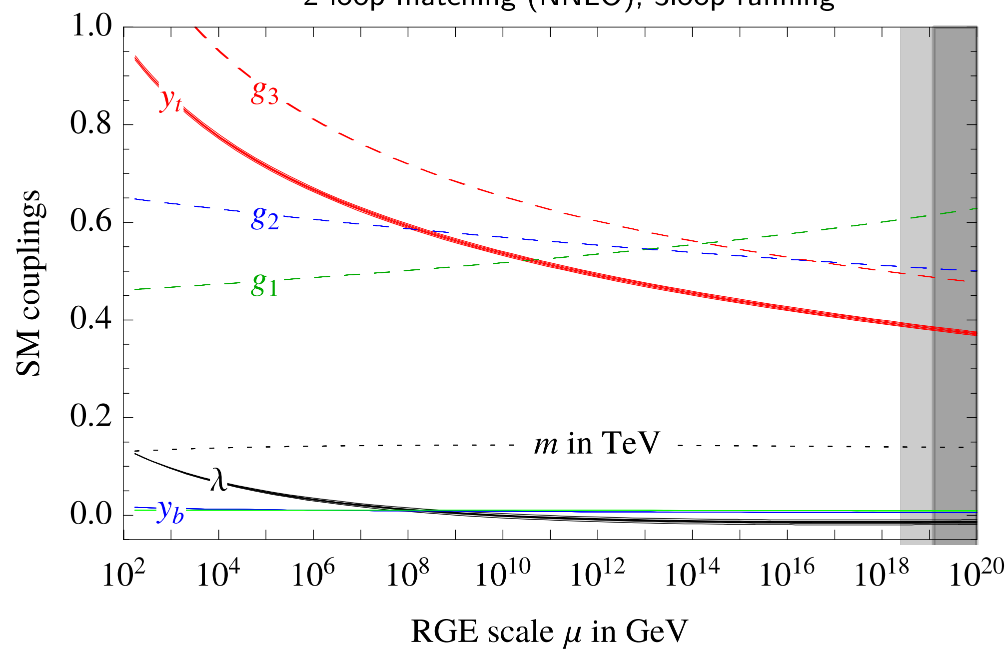
$$\lambda_3^{\rm SM} = \frac{m_h^2}{2v^2} \qquad \lambda_4^{\rm SM} = \frac{m_h^2}{8v^2}$$

(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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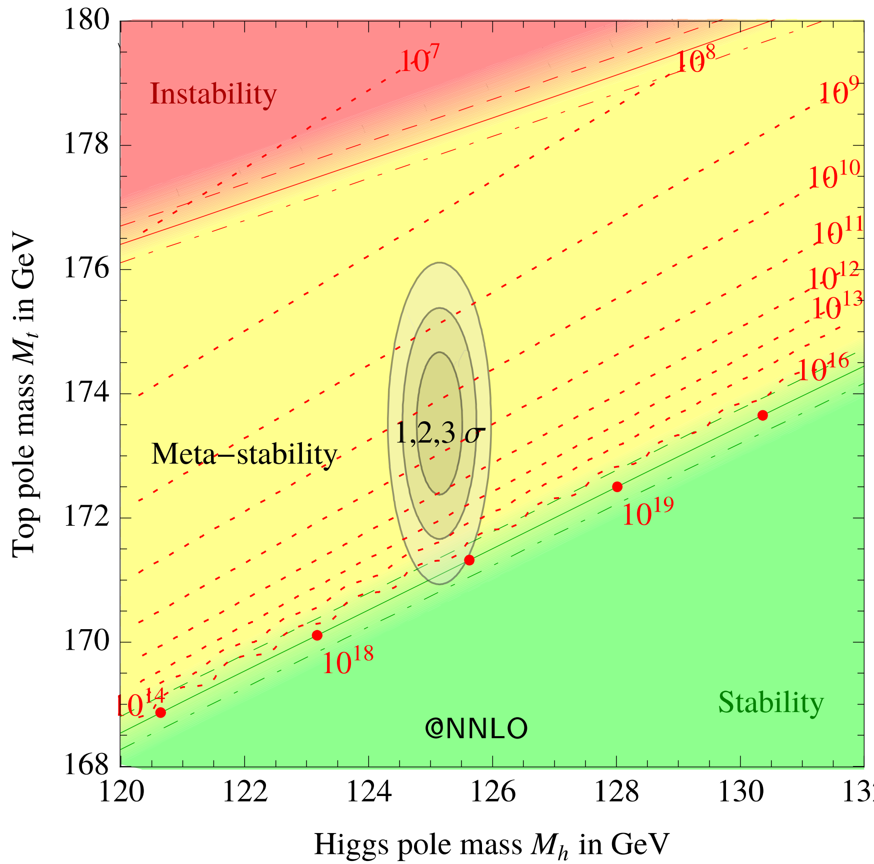

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(at tree level)

Direct test of self-couplings still needed

- SM (classical)
  - $(\lambda_3, \lambda_4) \Leftrightarrow (m_h, v) \rightarrow$ **verify it!**
- SM (quantum)
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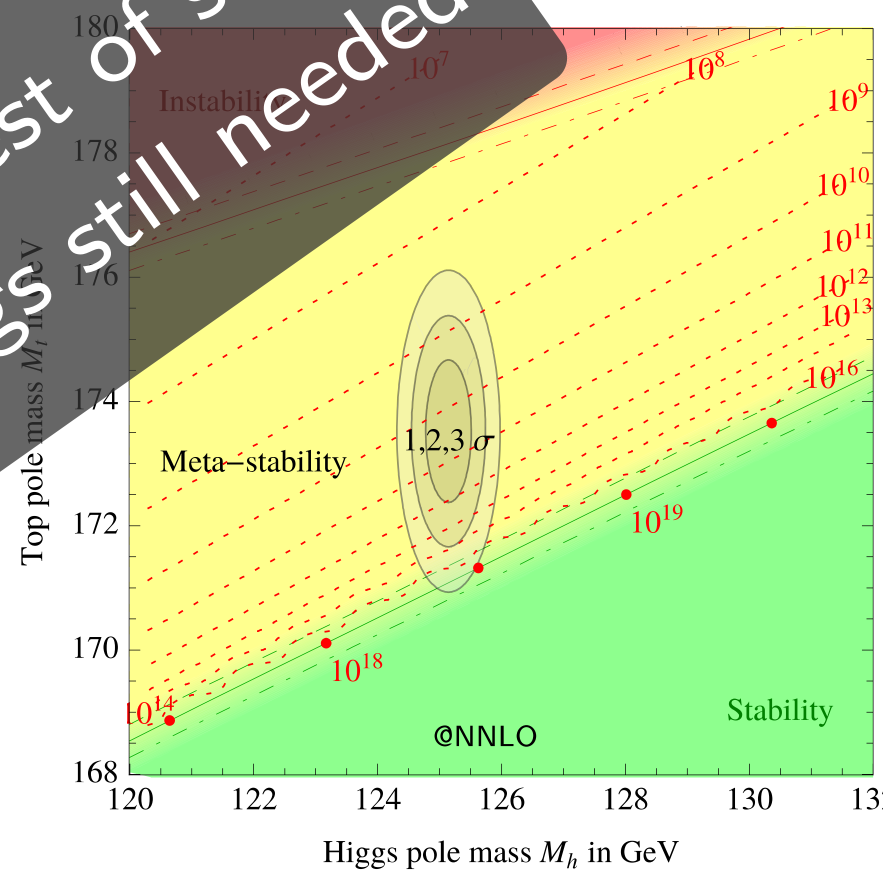


Higgs self-couplings are interesting!

- 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)

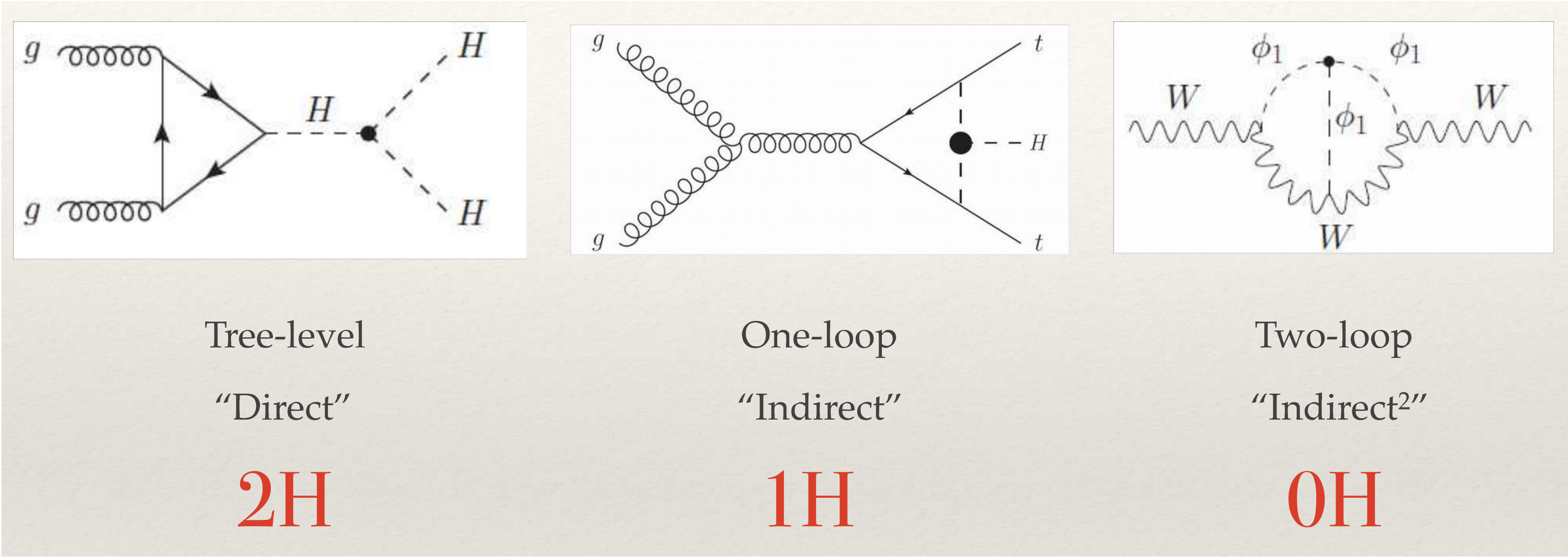
EFT ref's

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

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van der Bij '86;
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Kribs,Maier,Rzehak,Spannowsky,Waite '17

- Current constraints on $\sigma_{hh}^{(SM)}$ are quite loose $\rightarrow$ still room for BSM!
- Probe V(h) to get information on the 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

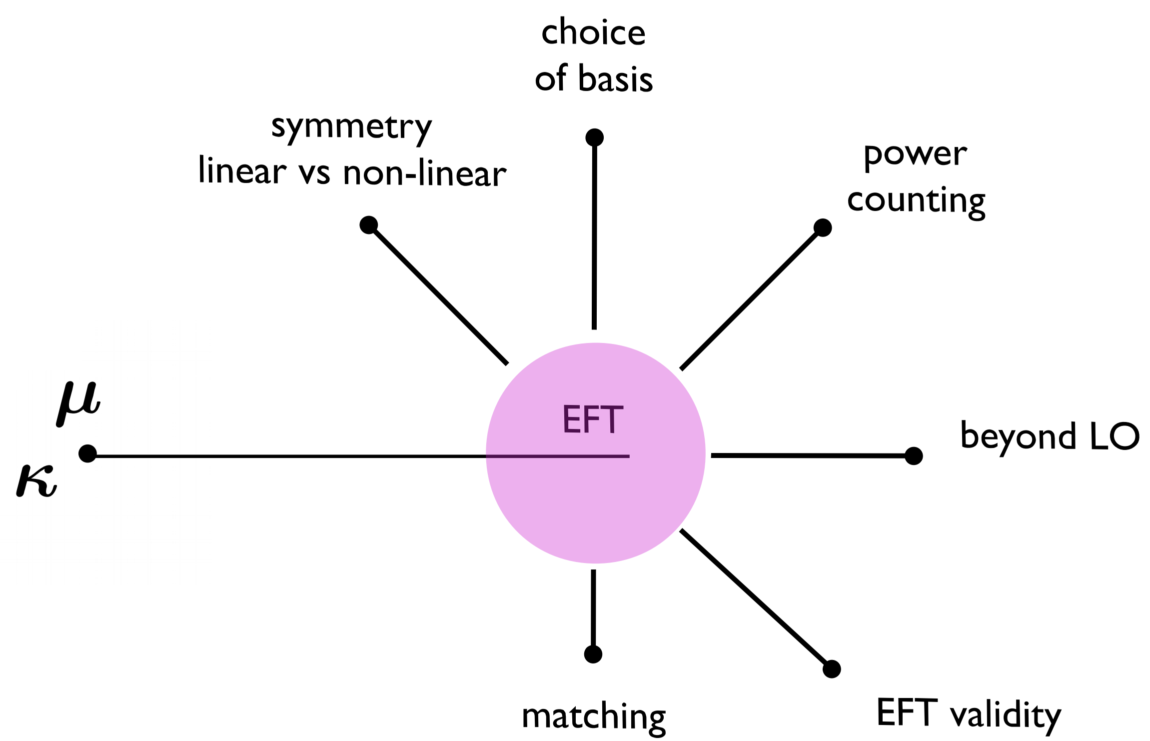
How to approach the self-coupling?

- hVV & hψψ tested at ~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→hh with **single-Higgs observables** for λ_3?

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

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)

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

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

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**

Higgs deformations in the Higgs basis

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

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

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

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

1 extra indep

WWγ and WWZ data can constrain single-Higgs couplings

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

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

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

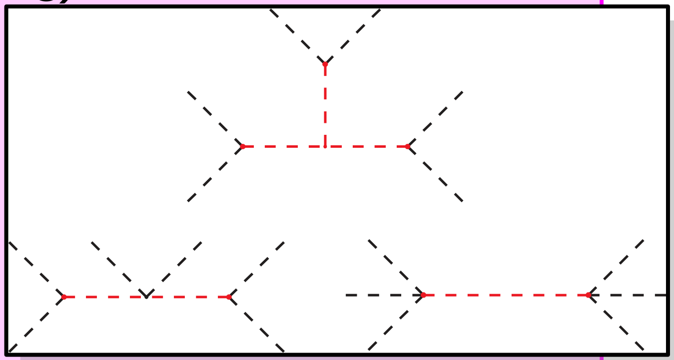
Modification of **h^3 only** leads to loss perturbative unitarity at low energy scales in processes like

$V_L V_L \to V_L V_L h^n$

- 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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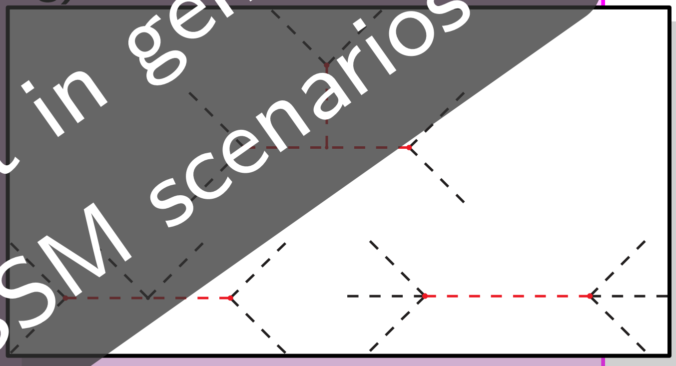


Not in generic BSM scenarios

See also talk by I.Low

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)

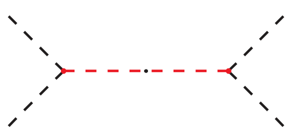
$$\varepsilon \equiv \frac{\theta g_*^2 v^2}{m_*^2} \ll 1$$

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

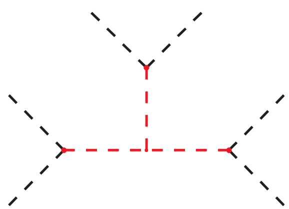
parametrically large λ_3
(paying some tuning)

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

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



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



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

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

Outline

- Testing BSM deformations with Higgs physics
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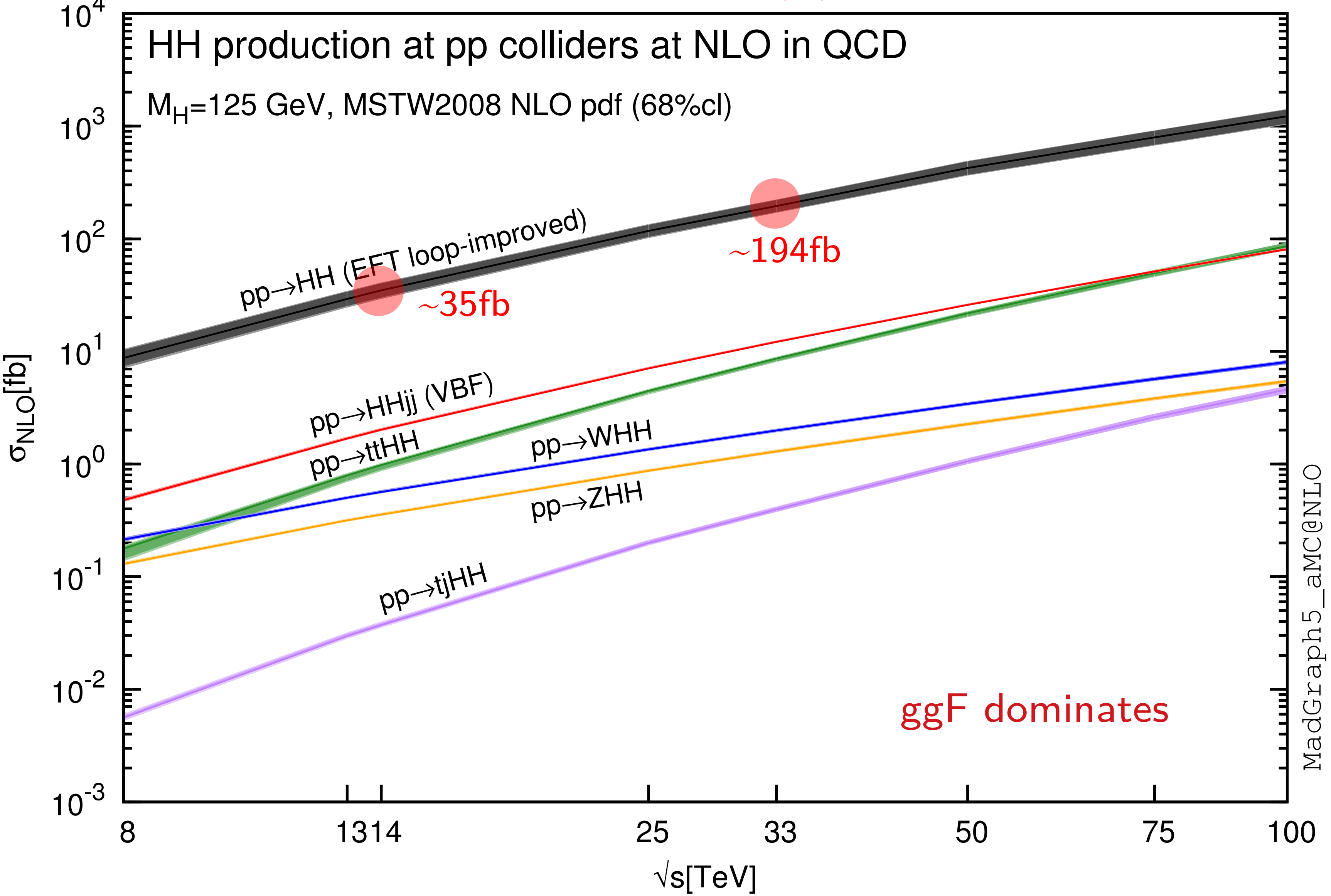
Obviously: double-Higgs production

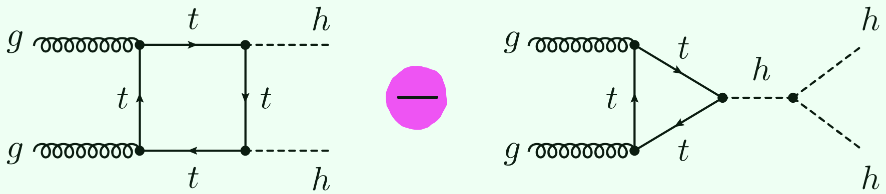
Frederix et al '14; see also Contino et al (eds) '16 FCC YR



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

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

EFT dim-6

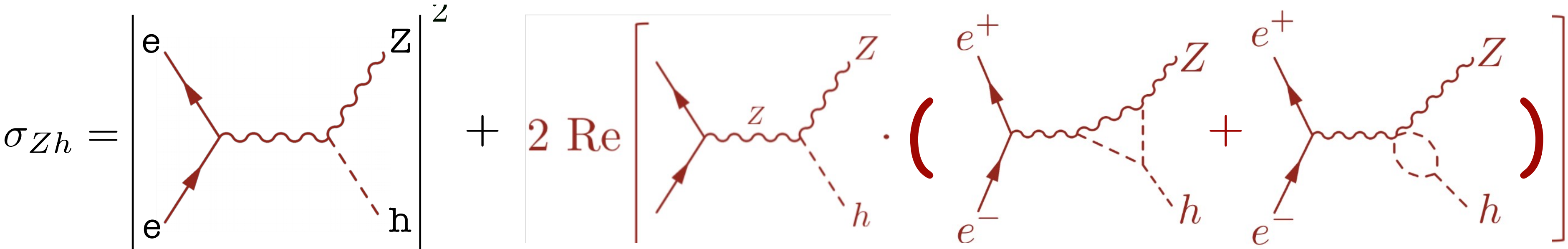
$$\begin{aligned}\frac{\sigma(pp \to hh)}{\sigma_{\rm SM}(pp \to hh)} = {} & A_1\,(1+\delta y_t)^4 + A_2\,(\delta y_t^{(2)})^2 + A_3\,\kappa_\lambda^2\,(1+\delta y_t)^2 + A_4\,\kappa_\lambda^2\,\hat{c}_{gg}^2 \\ & + A_5\,(\hat{c}_{gg}^{(2)})^2 + A_6\,(1+\delta y_t)^2\,\delta y_t^{(2)} + A_7\,\kappa_\lambda\,(1+\delta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

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

Self-coupling & single-Higgs @NLO

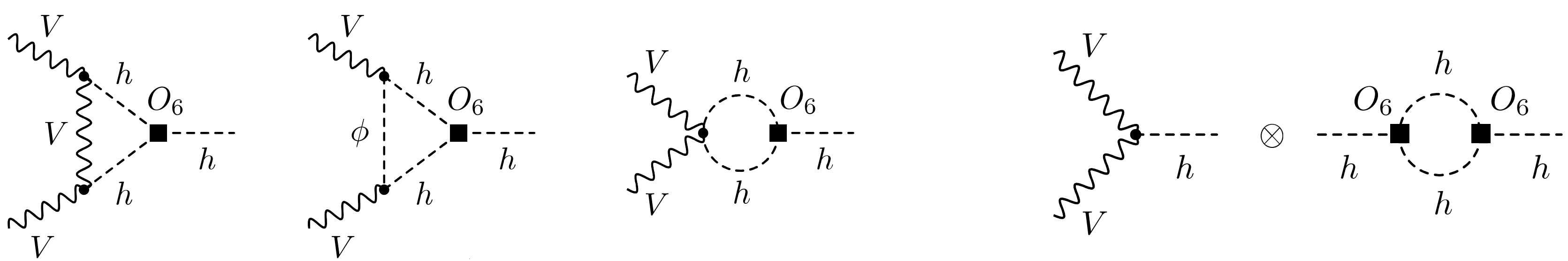
Idea: trilinear coupling affects also single-Higgs rates, but **@NLO. Still, if $\boldsymbol{\lambda_3}$ is large** …

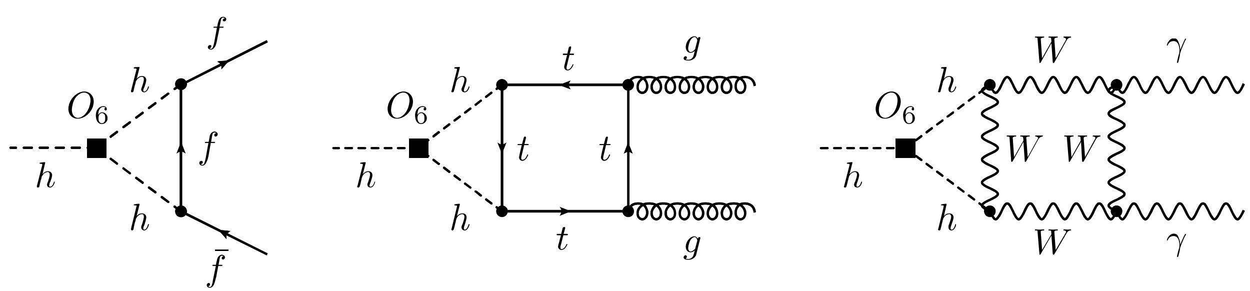
McCullough '13



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

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





Single-Higgs at the HL-LHC

End of LHC Run 3 $\rightarrow$ 300 fb^{-1} @ 14 TeV $\rightarrow$ End of HL-LHC $\rightarrow$ 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 $\rightarrow$ exploit!

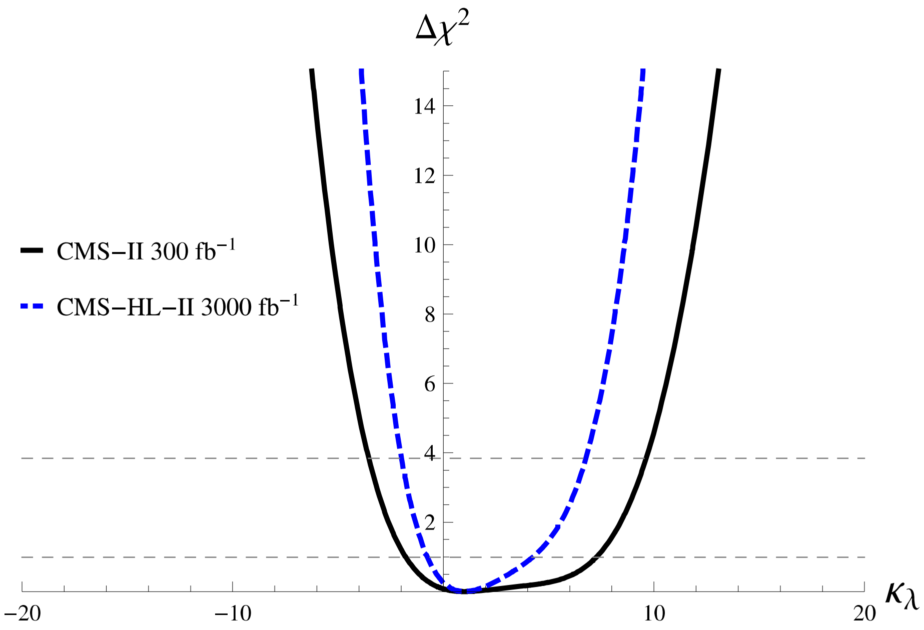
ATL-PHYS-PUB-2014-016 + ATL-PHYS-PUB-2016-008 + ggF N^{3}LO uncertainty+ VH (H→ZZ) split in WH,ZH

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

Use only indirect constraint from single-Higgs

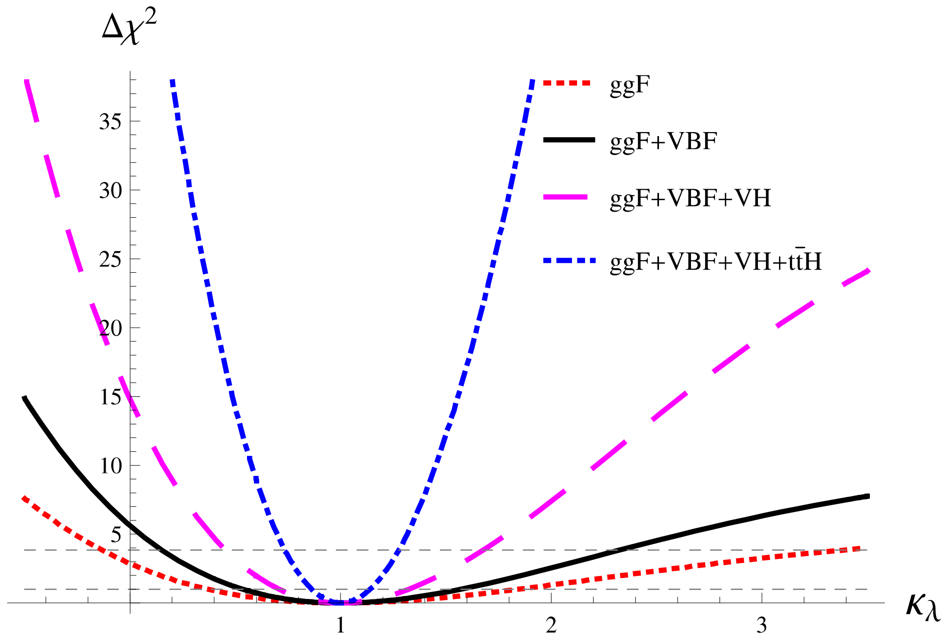
[first sensitivity study by Degrassi et al '16]

Optimistic CMS projections for HL-LHC



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

Exercise: assume 1% combined th/exp uncert



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

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

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

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

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

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

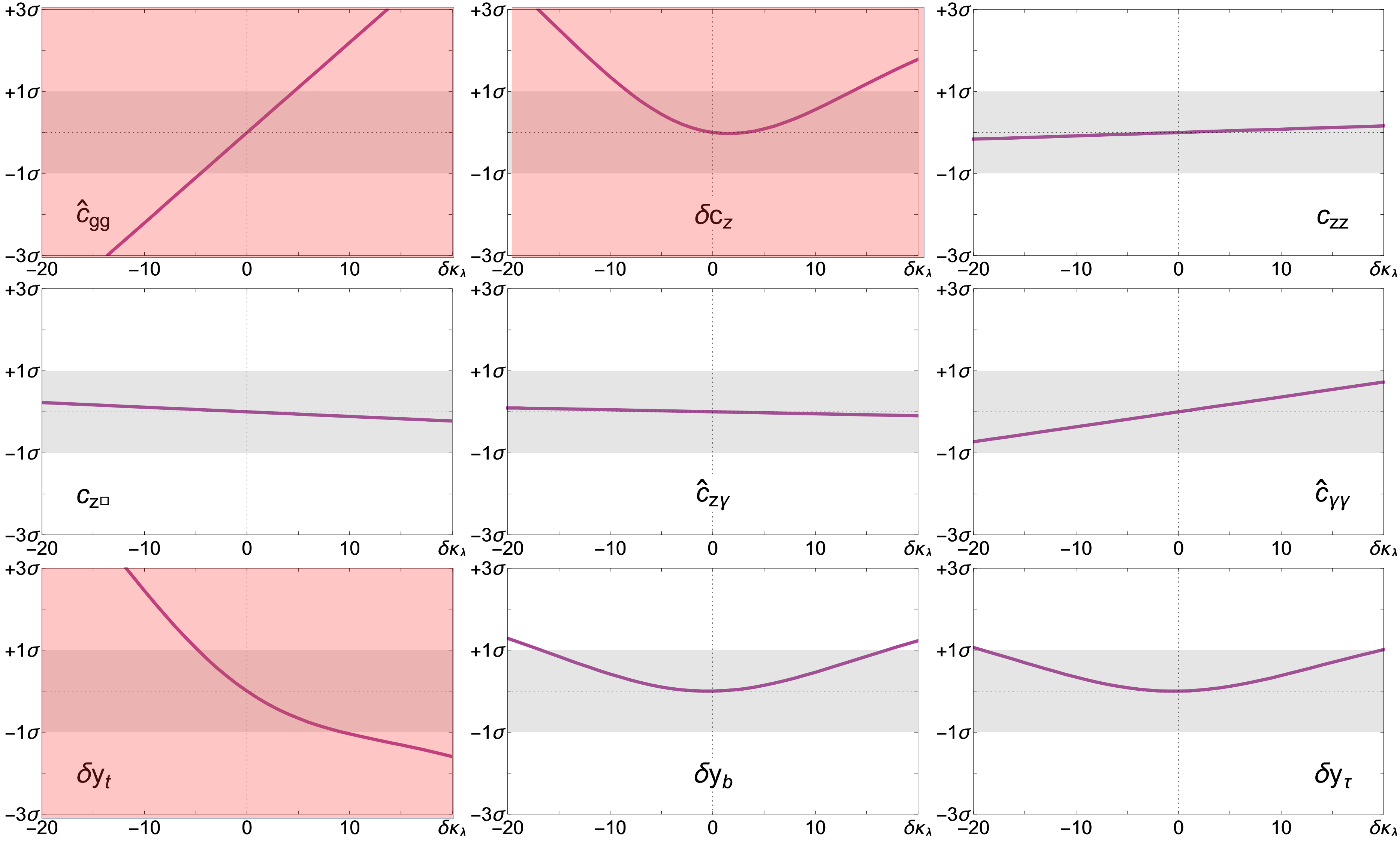
⇒ we expect 1 exact flat direction in a 10 parameters fit

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

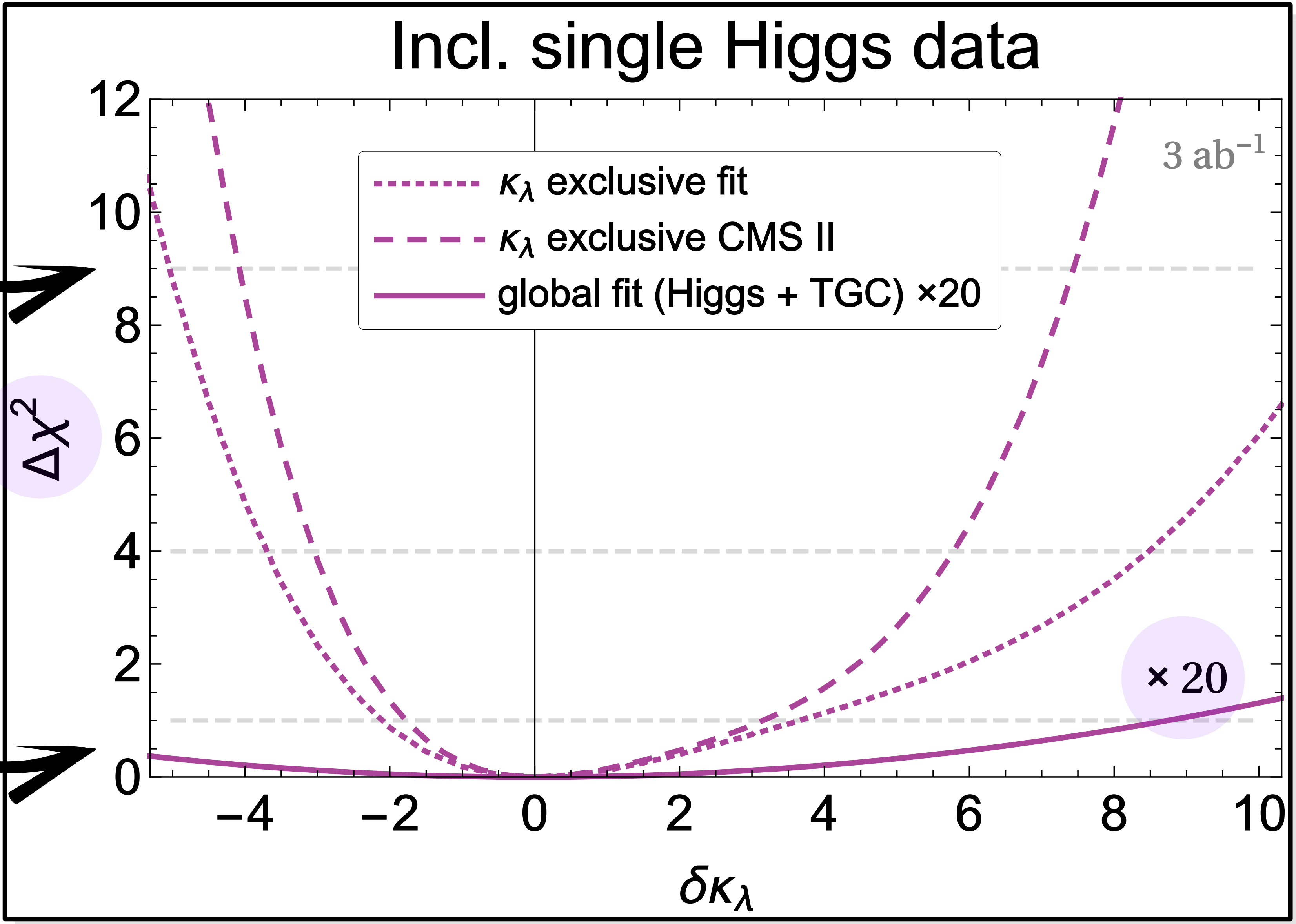
Higgs couplings variation along the flat direction



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

allow only $\delta\kappa_\lambda$

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



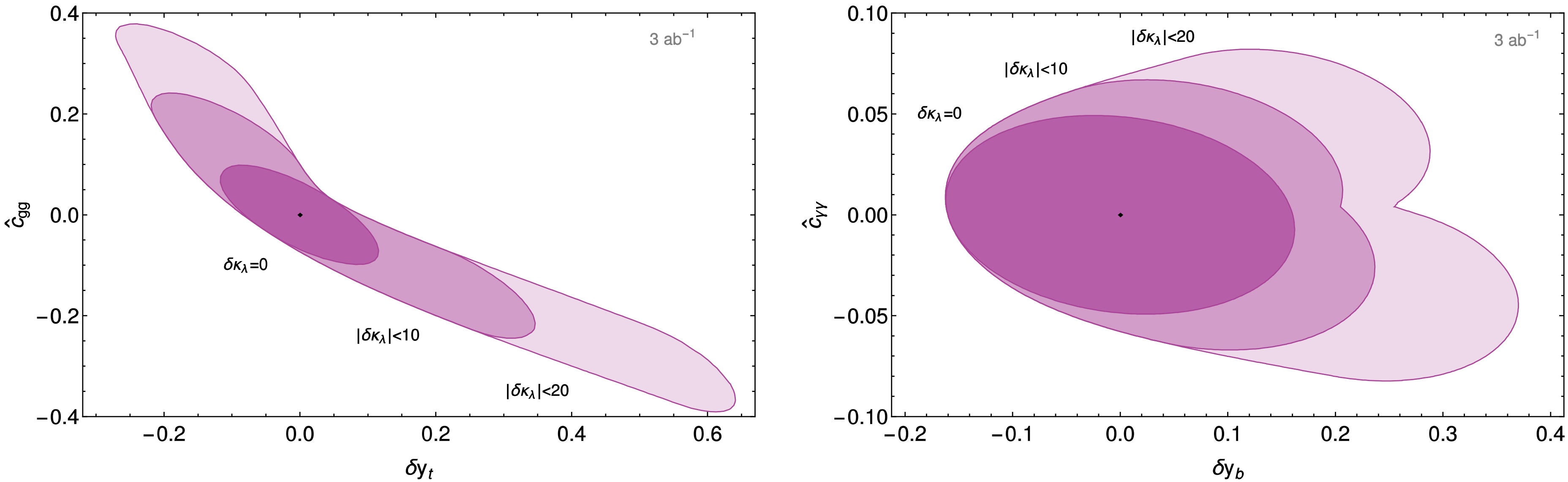
FLAT!

the flat direction is rather insensitive to the TGC constraint

Single-Higgs couplings fit w/κ_λ@NLO

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

Incl. single Higgs data

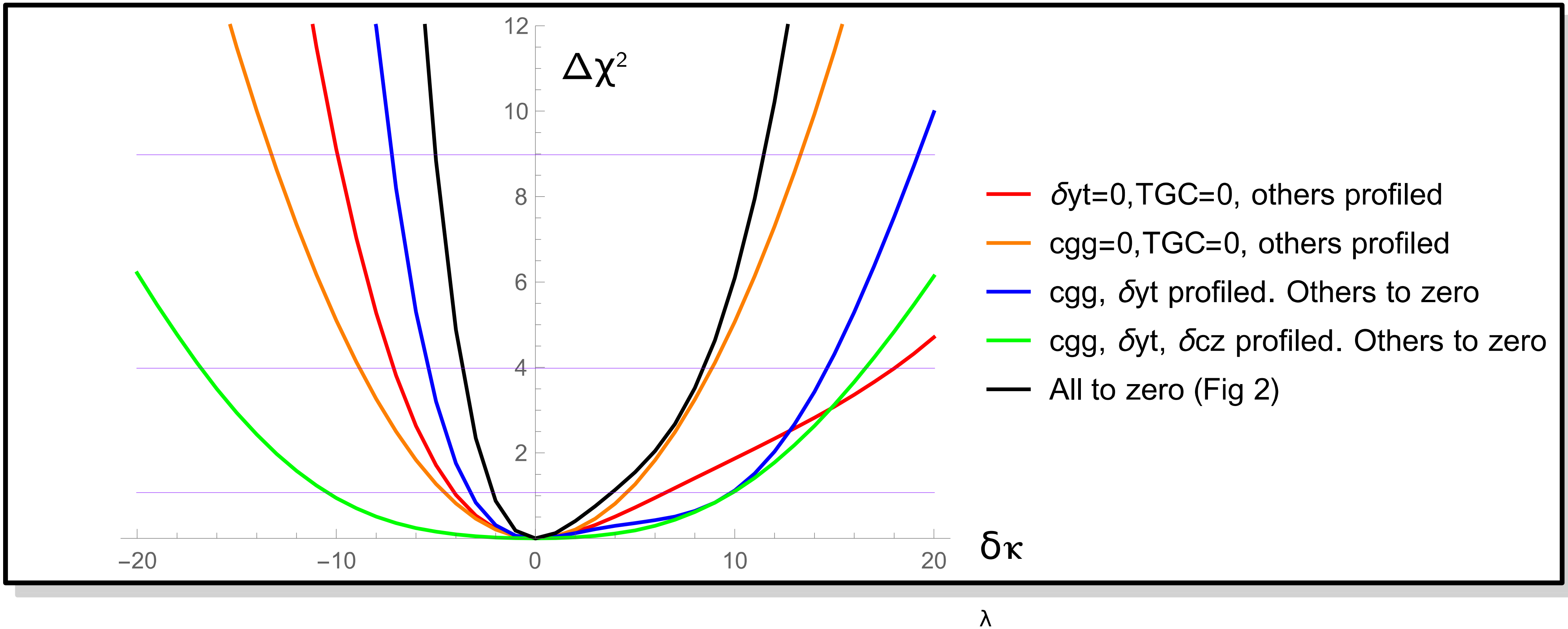


$\Delta\chi^2$=2.3 contours (68% CL in the gaussian limit)
[other 8 couplings profiled]

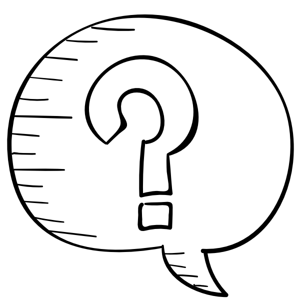
If large κ_λ is allowed, it feeds back into single-Higgs couplings fits

Constrained "intermediate" scenarios

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



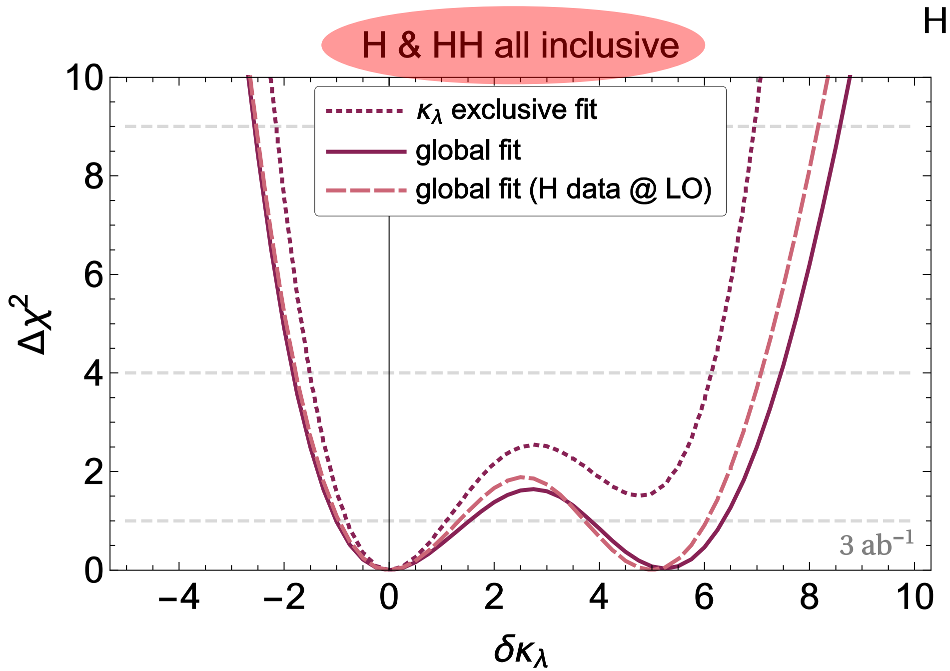
As expected, constraining "by hand" the coefficients that control the flat direction, the bound on κ_λ shrinks

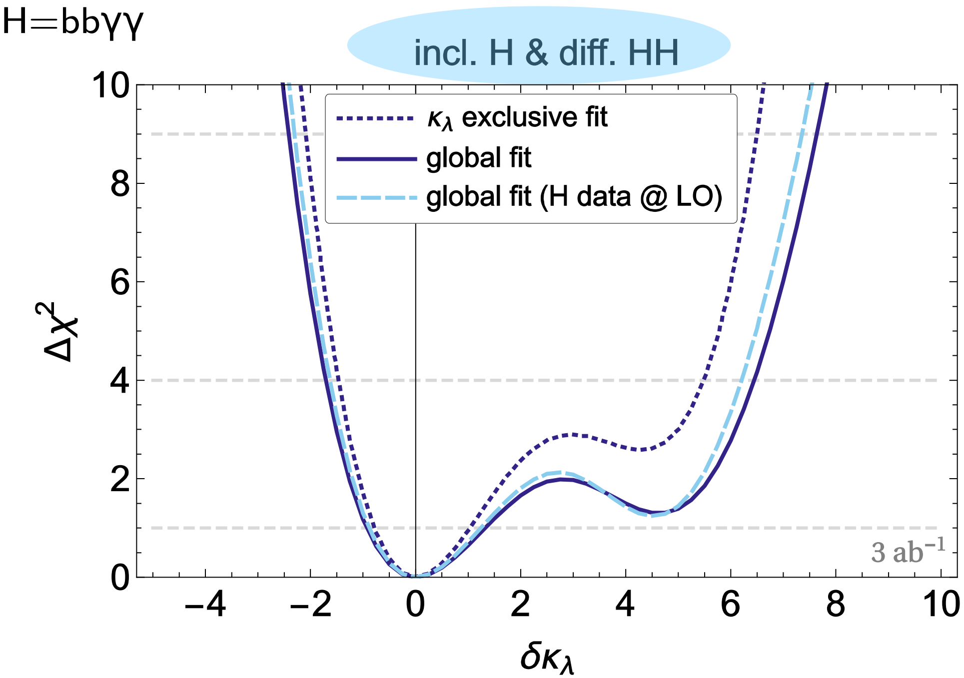


Any model builder willing to explore how motivated such scenarios are?

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 $\sigma(hh)$

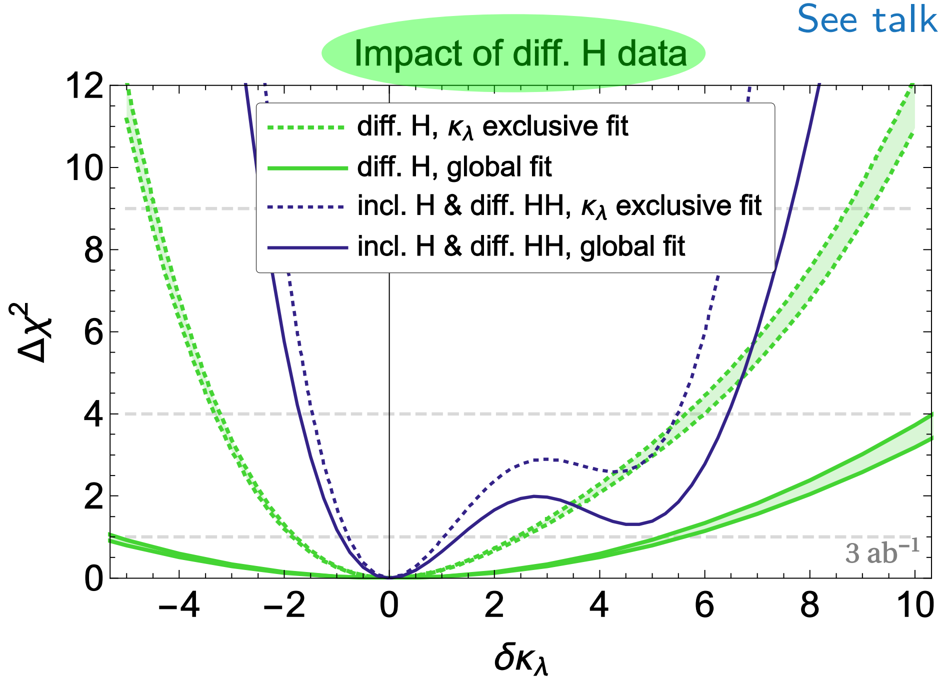
Differential (m_{hh}) double-Higgs removes degeneracy due to second minimum

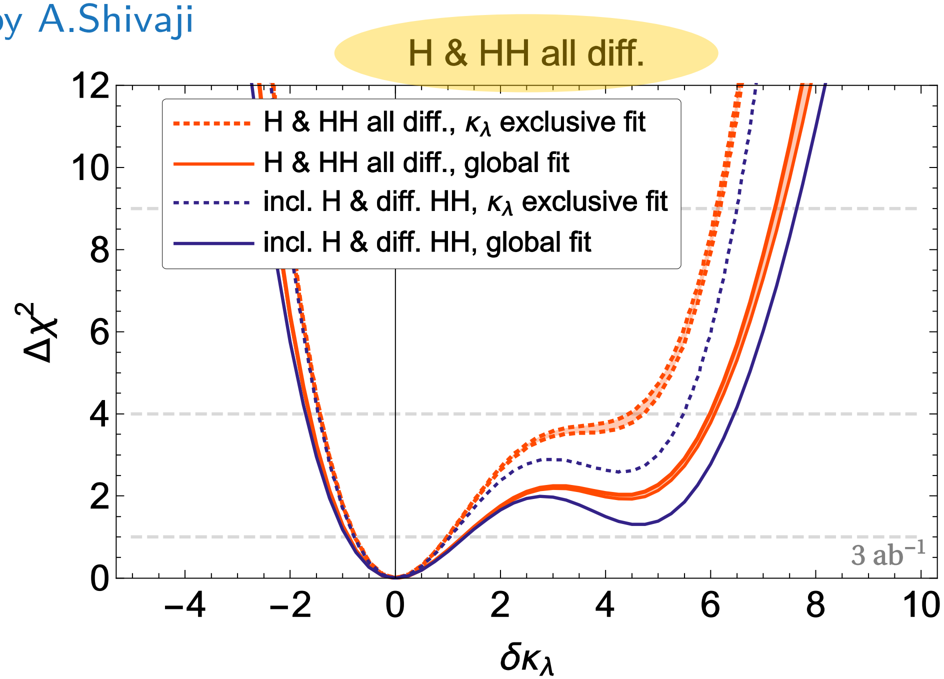
"Exclusive" κ_λ fits benefit from NLO single-Higgs, global don't

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

See talk by A.Shivaji





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.

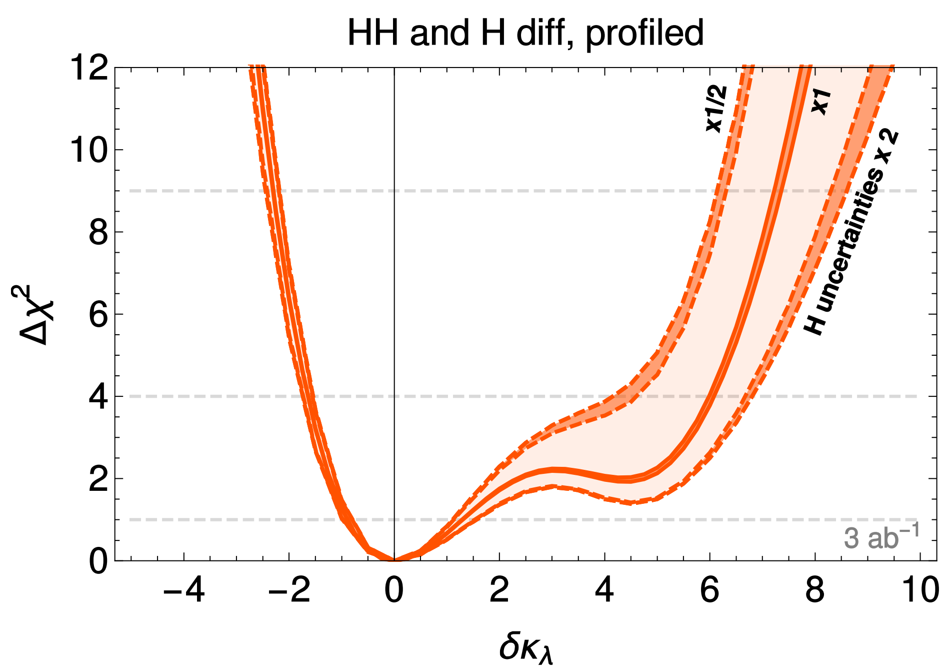
See Maltoni, Pagani, Shivaji, Zhao [1709.08649] for the impact of $\delta\kappa_\lambda$ on single-Higgs differential distributions and for a simplified κ-framework analysis
* see backup a couple of their plots

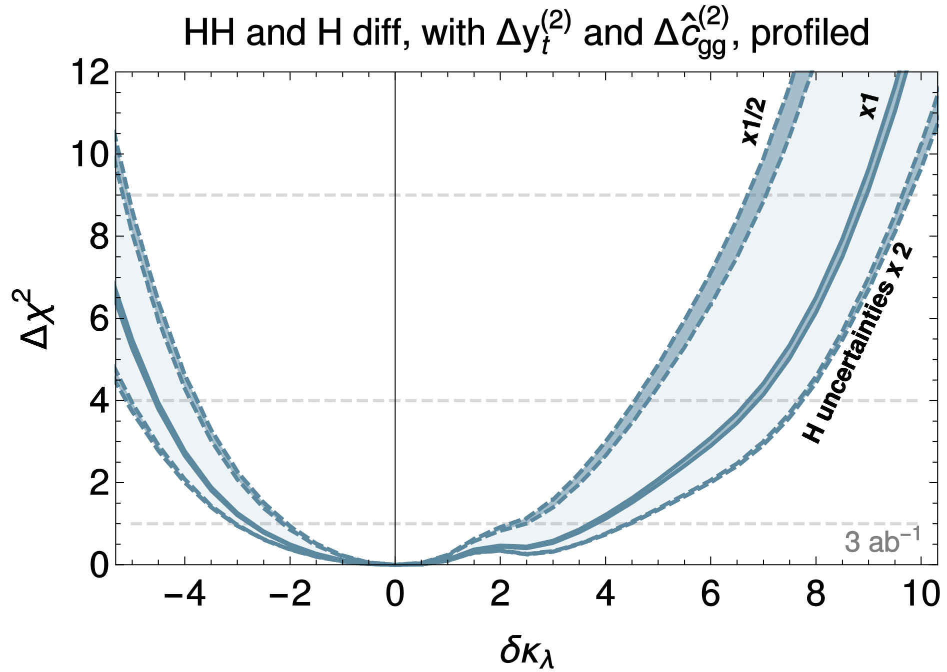
Combining differential data from single- and double-Higgs, the minimum at large $\delta\kappa_\lambda$ is further lifted. Synergy!

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
$\rightarrow$ 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

See also talks by A.Canepa and P.Roloff

Higgs self-coupling @ HE-LHC

Stay tuned for the HL/HE-LHC YR
See talk by S.Gori

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 $\delta\kappa_\lambda \sim 5$
- 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]

- Uncertanties 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

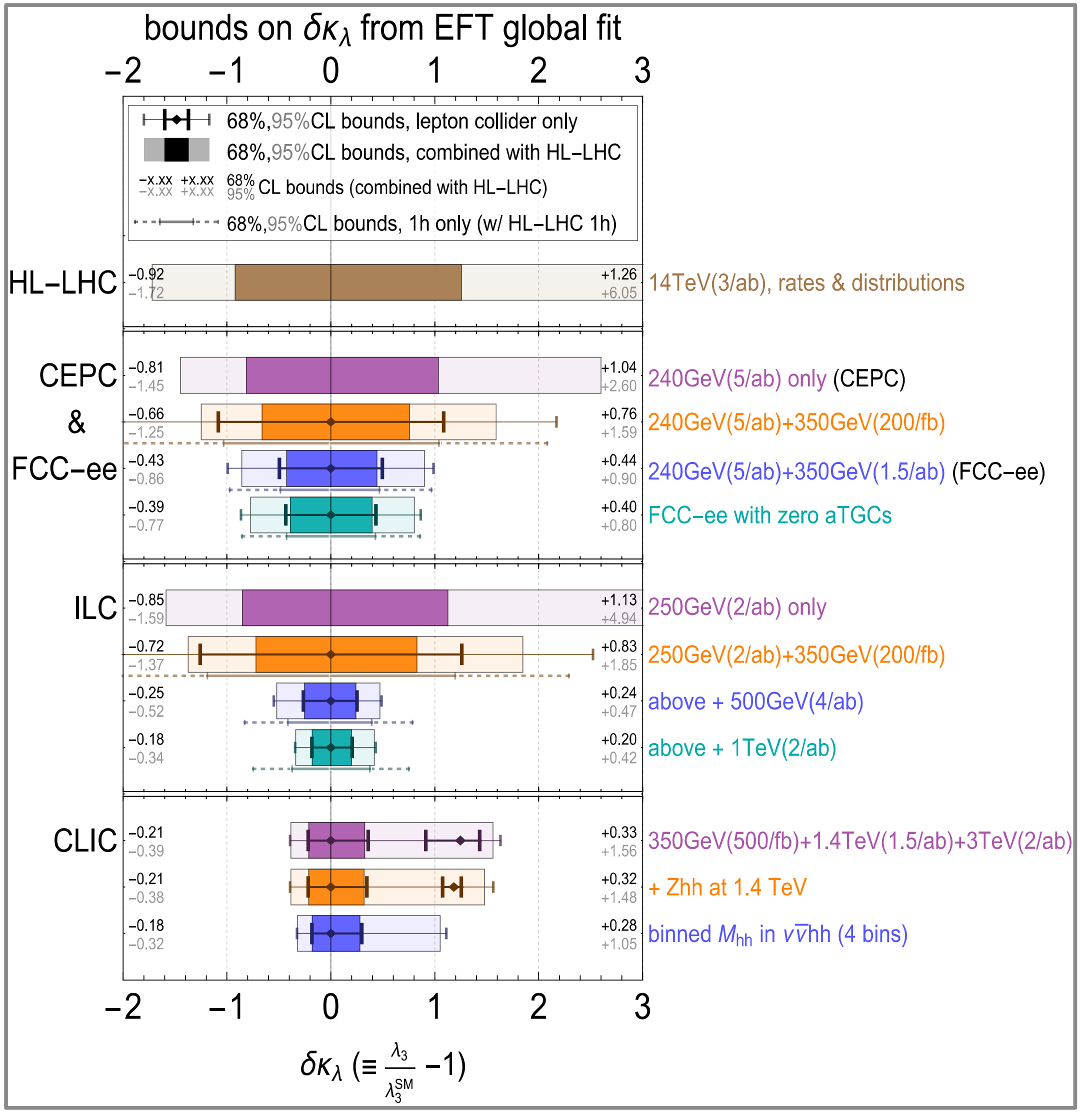
Circular

- 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

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 $\delta\kappa_\lambda \sim 1$

Items for discussion at the LHC

- Keep up with the hard work in measuring inclusive & diff rates
- Use simplified scenarios (e.g. κ_λ or κ_λ-κ_t) just as a training ground
- Bounds on κ_λ from simplified fits have a physical interpretation only in very non-generic scenarios

  $\Rightarrow$ they are **not** model-independent statements on the Higgs self-coupling!

- Bounds on κ_λ from single-H can't compete with HH

  $\Rightarrow$ but somehow complementary

- Come up with optimized observables (e.g. best differential distrib's)
- Include new channels to resolve flat directions (e.g. h+j, h+γ)

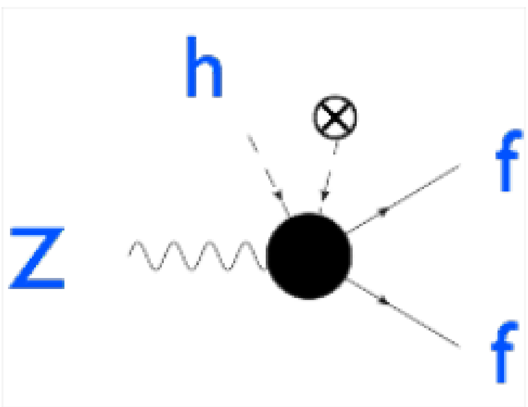
- More/updated HL-LHC projections (incl. and diff) very welcome!
- Is it reasonable to neglect the other operators in these extrapolations?
- Are there BSM scenarios that can be tested today? $\Rightarrow$ Model building effort

Backup

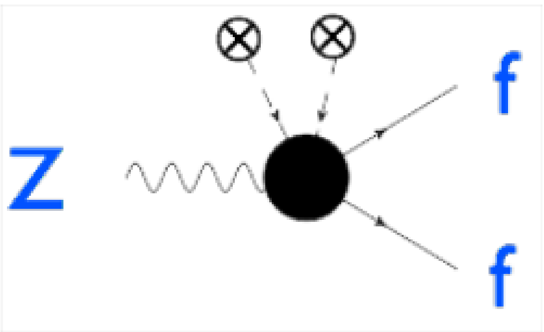
BSM deformations and Higgs physics

(courtesy of A. Pomarol@HiggsHunting2014)

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

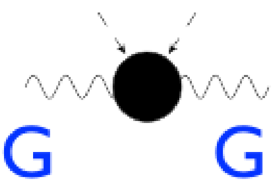
BSM deformations and Higgs physics

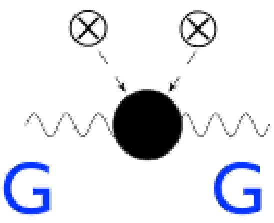
There are others deformations away from the SM that are harmless in the vacuum and need a Higgs field to be probed

(courtesy of A. Pomarol@HiggsHunting2014)

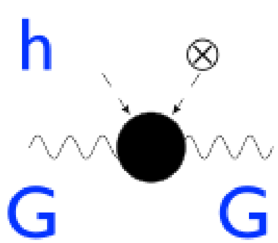
e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \to \left(\frac{1}{g_s^2}+\frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

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





But can affect h physics:



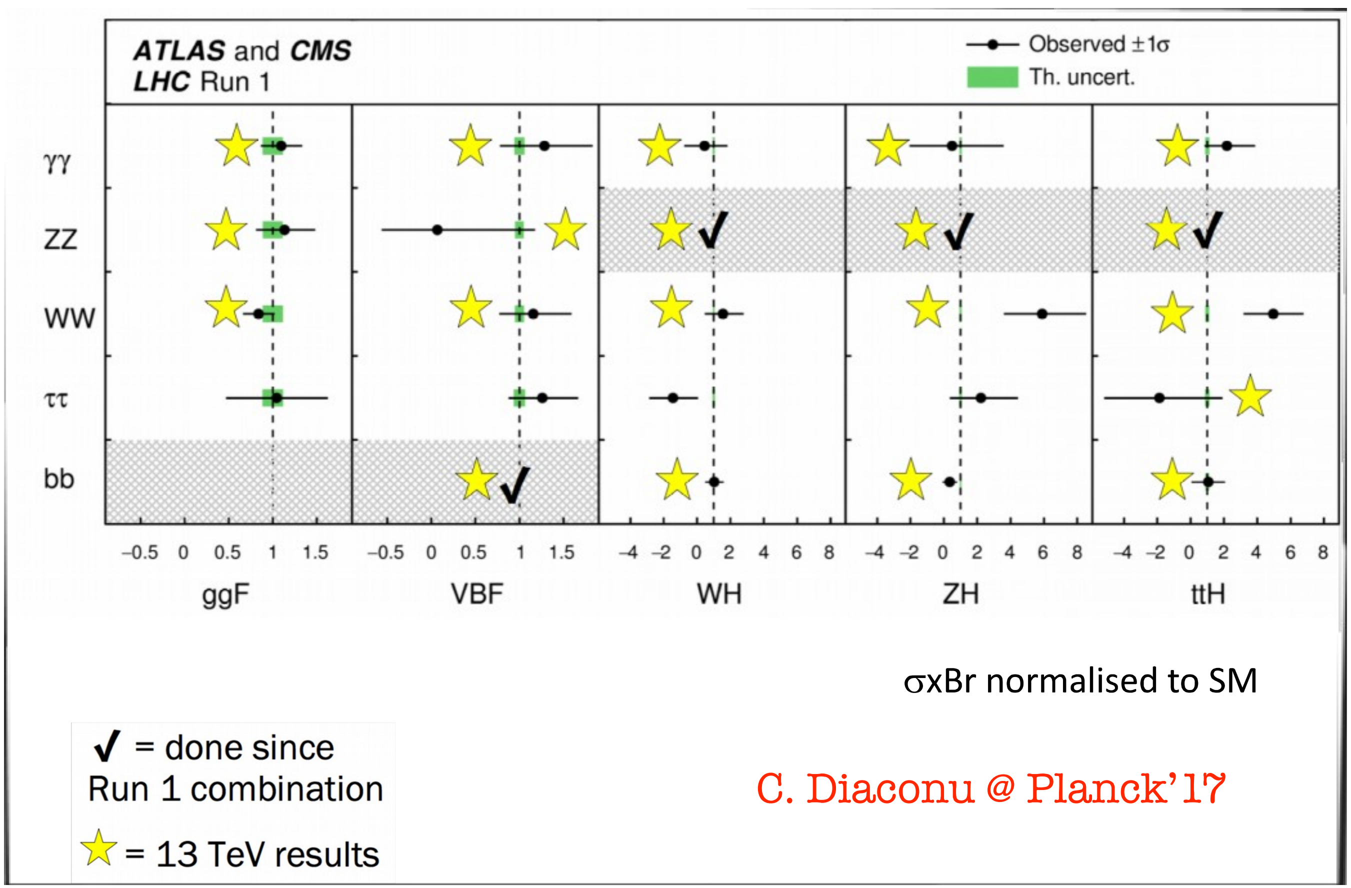
affects GG →h!

Single-Higgs couplings at the LHC today

signal strengths $\mu_i \times \mu^f$ = **inclusive** rates (σ_ixBR_f) relative to SM prediction

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

decay

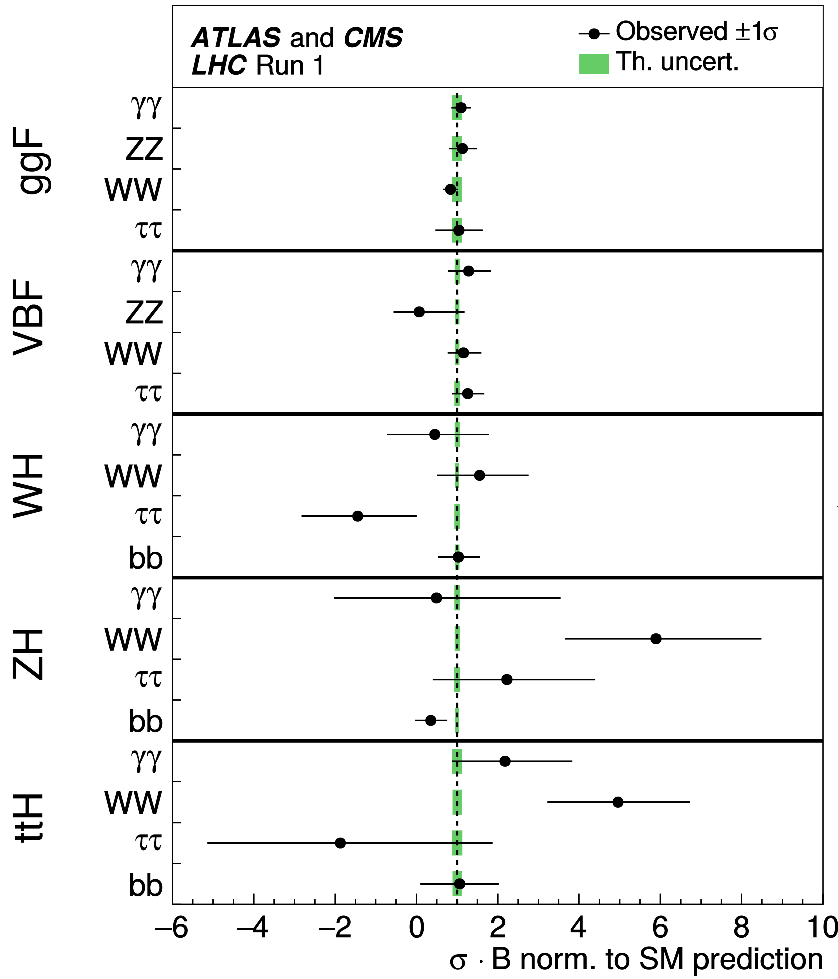


production

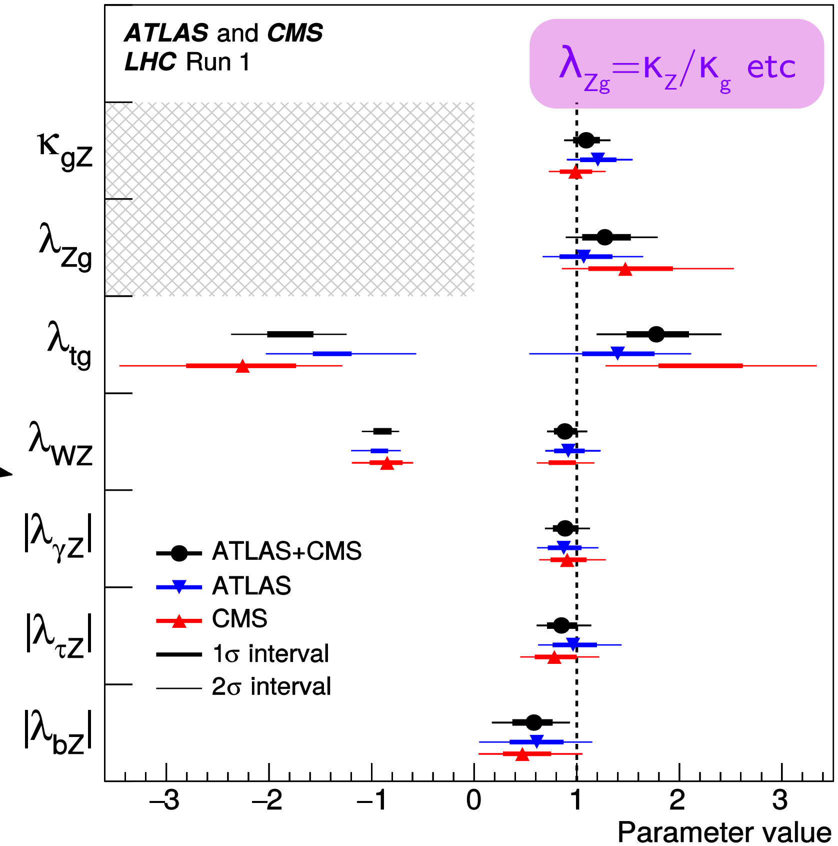
A (too) simple interpretation: κ-framework

ATLAS+CMS [1606.02266]

(ideally) 5^2 $\mu_i \times \mu^f$



7-parameters "κ-framework"



- Only total rates modified
- No new tensor structures allowed

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

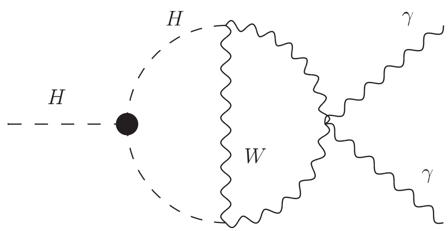
$\kappa_{g\gamma}{}^2$

Self-coupling & single-Higgs @NLO

LO can include QCD corrections

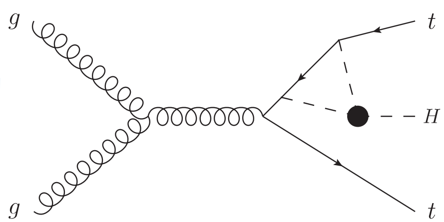
$$\Sigma_{\rm NLO} = Z_H\, \Sigma_{\rm LO}\, (1 + \kappa_\lambda \boxed{C_1})$$

$$C_1^\Gamma = \frac{\int d\Phi\; 2\Re\left(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}}\right)}{\int d\Phi\; |\mathcal{M}^0|^2}$$



$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

$$C_1^\sigma = \frac{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}^{0*}_{ij}\mathcal{M}^1_{\lambda_3^{\rm SM},ij}\right) d\Phi}{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}^0_{ij}|^2 d\Phi}$$



$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

dΦ inclusive or differential

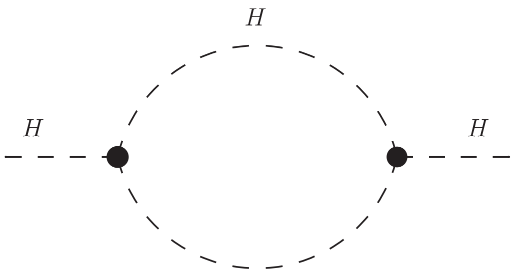
Courtesy of D. Pagani @ Turin '17

Self-coupling & single-Higgs @NLO

$$\Sigma_{\rm NLO} = \boxed{Z_H}\, \Sigma_{\rm LO}\,(1 + \kappa_\lambda C_1)$$

$$Z_H = \frac{1}{1 - \kappa_\lambda^2\, \delta Z_H}$$

$$\delta Z_H = -\frac{9}{16}\, \frac{2(\lambda_3^{\rm SM})^2}{m_H^2\, \pi^2} \left(\frac{2\pi}{3\sqrt{3}} - 1\right)$$



$\sim \quad \kappa_\lambda^2$

The wave-function normalization receives corrections that depend quadratically on λ_3. For large κ_λ, the result cannot be linearized and must be resummed.

$$\kappa_\lambda^2\, \delta Z_H \lesssim 1 \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 25$$

For a sensible resummation

20

Courtesy of D. Pagani @ Turin '17

Self-coupling & single-Higgs @NLO

$$\Sigma_{\rm NLO} = Z_H \, \Sigma_{\rm LO} \, (1 + \kappa_\lambda C_1)$$

$$\Sigma_{\rm NLO}^{\rm SM} = \Sigma_{\rm LO} \, (1 + C_1 + \delta Z_H)$$

universal

$$\delta\Sigma_{\lambda_3} \equiv \frac{\Sigma_{\rm NLO} - \Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda - 1)\boxed{C_1} + (\kappa_\lambda^2 - 1)\boxed{C_2} + \mathcal{O}(\kappa_\lambda^3 \, \alpha^2)$$

Process and kinetic dependent

(inclusive or differential in m_{inv} and p_T^H)

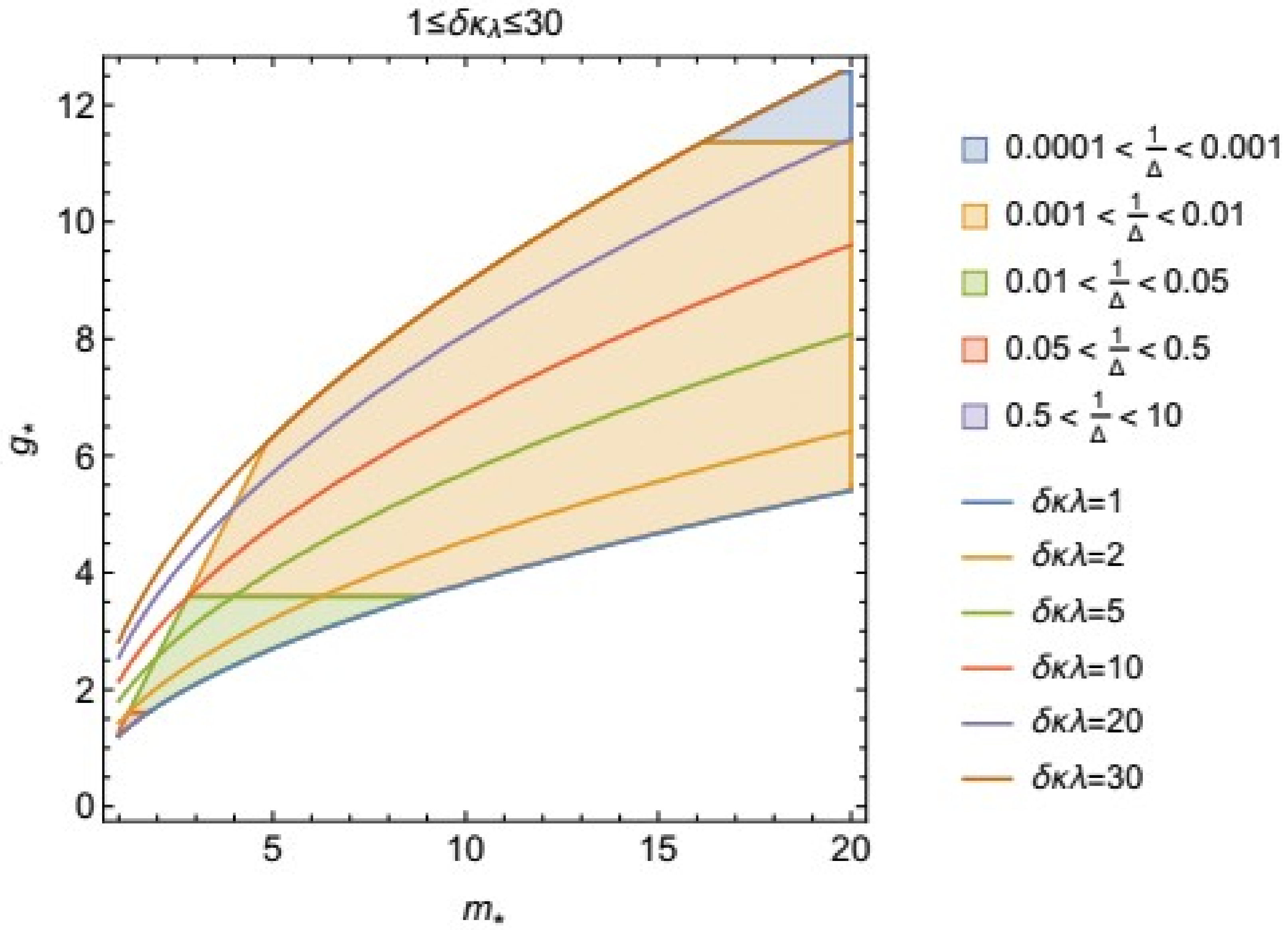
$$C_2 = \frac{\delta Z_H}{(1 - \kappa_\lambda^2 \delta Z_H)}$$

$$\mathcal{O}(\kappa_\lambda^3 \, \alpha^2) \simeq \kappa_\lambda^3 C_1 \delta Z_H \lesssim 10\% \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 20$$

21

Courtesy of D. Pagani @ Turin '17

Large λ_3 in tuned Higgs Portal



How large can λ_3 be?

Think in terms of model classes

No analysis is truly model independent!

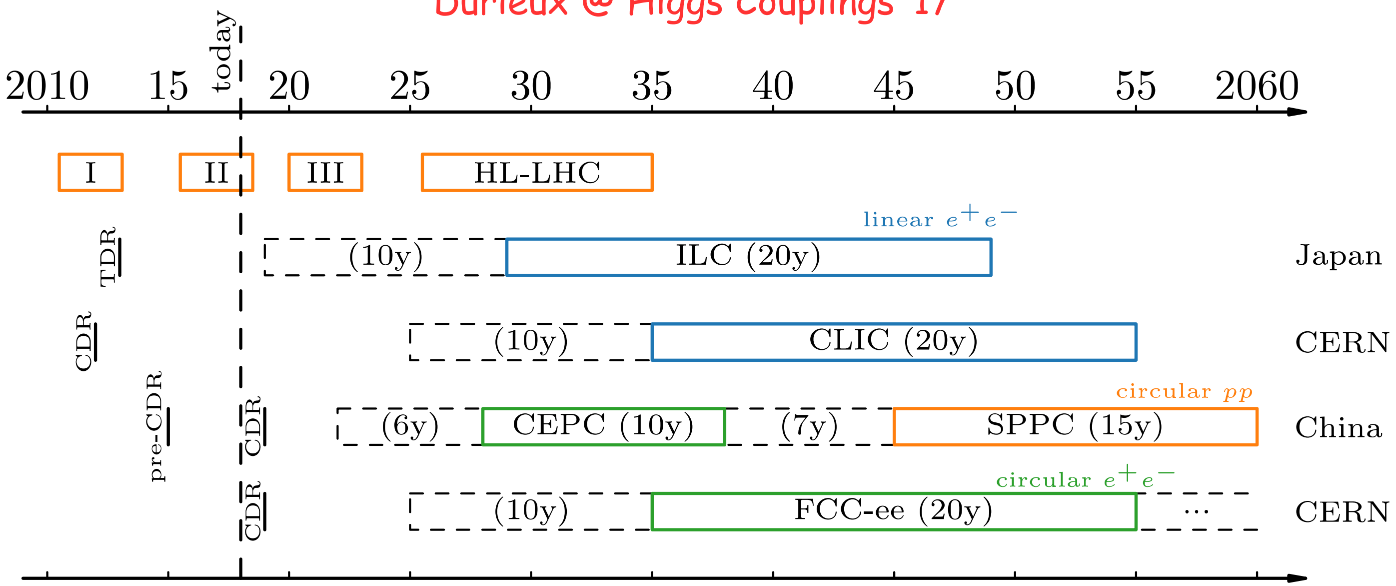
NLO w/ dominant h^3 $\overset{?}{\gtreqless}$ LO w/ subdominant other h

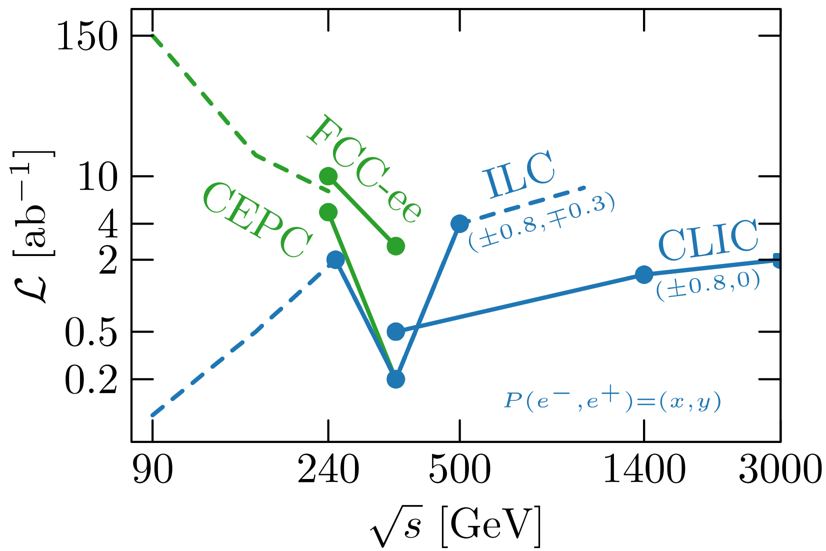
Courtesy of *C. Grojean @ Portorož '17*

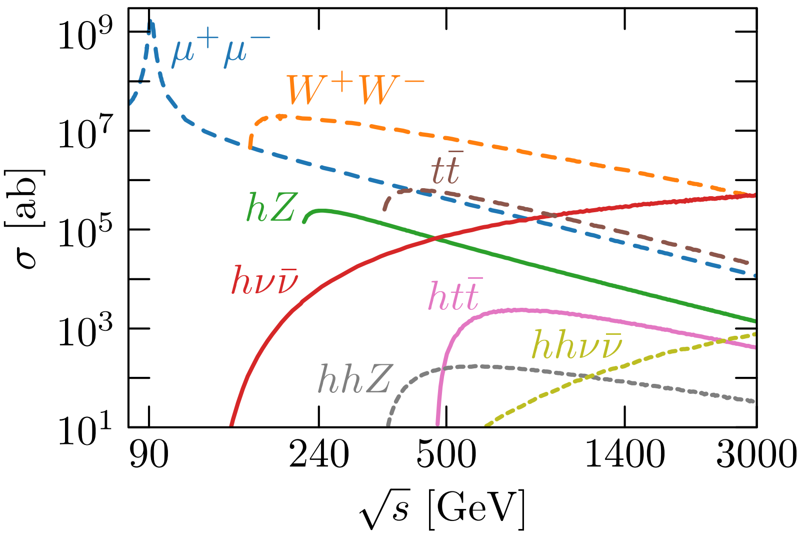
Minimal Composite Higgs SILH $\xi = \frac{v^2}{f^2} \ll 1$	$\frac{1}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \xi$	$\frac{\lambda_4}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \xi$	NLO h^3 irrelevant
Partly Composite Higgs $\xi = \frac{v^2}{f^2} \ll 1$	$\frac{\varepsilon^4}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \varepsilon^4 \xi$	$\frac{\varepsilon^6}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \varepsilon^2 \frac{g_*^2 v^2}{m_h^2}\varepsilon^4 \xi$	NLO h^3 could be relevant
Bosonic Technicolor Induced EWSB $\varepsilon = \frac{f}{v} \ll 1$	$\frac{\varepsilon^4}{f^2}\left(\partial_\mu \lvert H\rvert^2\right)^2$ $\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\rm SM}} = 1 + \varepsilon^2$	$\frac{\varepsilon^6}{f^2}\lvert H\rvert^6$ $\kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\rm SM}} = 1 + \mathcal{O}(1)$	NLO h^3 a priori relevant

A future history of lepton colliders

Durieux @ Higgs Couplings '17



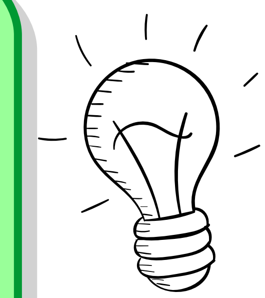




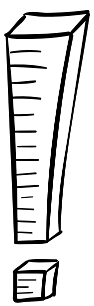
Will further constraints help?

- Triple Gauge Couplings
  - currently WWZ and WWγ tested at 5% $\to$ expect 1%
  - can be converted in constraints on 2 linear combinations of

$$\hat{c}_{\gamma\gamma}, \hat{c}_{z\gamma}, c_{zz}, c_{z\Box}$$



- BR(h$\to$Zγ)
  - Will be measured w/ 30% accuracy
  - Can be used to constrain $c_{z\gamma}$ $\to$ not relevant for $\kappa_{\lambda!}$
- BR(h$\to\mu\mu$)
  - Either one extra parameter δy_{μ}
  - Or (w/ flavor universality) just helps to better bound δy_{e}



Gauge invariant operators in the Higgs basis

$$
\begin{aligned}
O_{\delta\lambda_3} &= -\frac{1}{v^2}(H^\dagger H)^3, \\
O_{c_{gg}} &= \frac{g_s^2}{4v^2} H^\dagger H\, G^a_{\mu\nu} G^a_{\mu\nu} \\
O_{\delta c_z} &= -\frac{1}{v^2}\left[\partial_\mu (H^\dagger H)\right]^2 + \frac{3\lambda}{v^2}(H^\dagger H)^3 + \left(\sum_f \frac{\sqrt{2} m_{f_i}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,i} + \text{h.c.}\right), \\
O_{c_{z\Box}} &= \frac{i g^3}{v^2(g^2 - g'^2)} \left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} - \frac{i g^2 g'}{v^2(g^2 - g'^2)} \left(H^\dagger \overleftrightarrow{D_\mu} H\right) \partial_\nu B_{\mu\nu}, \\
O_{c_{zz}} &= \frac{i g (g^2 + g'^2)}{2v^2(g^2 - g'^2)} \left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} - \frac{i g' (g^2 + g'^2)}{2v^2(g^2 - g'^2)} \left(H^\dagger \overleftrightarrow{D_\mu} H\right) \partial_\nu B_{\mu\nu} \\
&- \frac{i g}{v^2} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} - \frac{i g'}{v^2} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{z\gamma}} &= -\frac{2 i g g'^2}{v^2(g^2 + g'^2)} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{2 i g' g^2}{v^2(g^2 + g'^2)} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu}, \\
O_{c_{\gamma\gamma}} &= -\frac{i g g'^4}{2v^2(g^4 - g'^4)} \left(H^\dagger \sigma^i \overleftrightarrow{D_\mu} H\right) D_\nu W^i_{\mu\nu} + \frac{i g'^5}{2v^2(g^4 - g'^4)} \left(H^\dagger \overleftrightarrow{D_\mu} H\right) \partial_\nu B_{\mu\nu} \\
&- \frac{i g g'^4}{v^2(g^2 + g'^2)^2} \left(D_\mu H^\dagger \sigma^i D_\nu H\right) W^i_{\mu\nu} + \frac{i g'^3 (2g^2 + g'^2)}{(g^2 + g'^2)^2 v^2} \left(D_\mu H^\dagger D_\nu H\right) B_{\mu\nu} + \frac{g'^2}{4v^2} H^\dagger H\, B_{\mu\nu} B_{\mu\nu}, \\
[O_{\delta y_f}]_{ij} &= -\frac{\sqrt{2 m_{f_i} m_{f_j}}}{v^3} H^\dagger H \bar{f}_{L,i} H f_{R,j} + \text{h.c.},
\end{aligned}
$$

Estimated precision @ circular colliders

O(1%) on most channels

	CEPC				FCC-ee			
	[240 GeV, 5 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[240 GeV, 10 ab^{-1}]		[350 GeV, 2.6 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	0.50%	—	2.4%	—	0.40%	—	0.67%	—
	$\sigma \times$ BR				$\sigma \times$ BR			
$h \to b\bar{b}$	0.21%*	0.39%$^\diamond$	2.0%	2.6%	0.20%	0.28%$^\diamond$	0.54%	0.71%
$h \to c\bar{c}$	2.5%	—	15%	26%	1.2%	—	4.1%	7.1%
$h \to gg$	1.2%	—	11%	17%	1.4%	—	3.1%	4.7%
$h \to \tau\tau$	1.0%	—	5.3%	37%	0.7%	—	1.5%	10%
$h \to WW^*$	1.0%	—	10%	9.8%	0.9%	—	2.8%	2.7%
$h \to ZZ^*$	4.3%	—	33%	33%	3.1%	—	9.2%	9.3%
$h \to \gamma\gamma$	9.0%	—	51%	77%	3.0%	—	14%	21%
$h \to \mu\mu$	12%	—	115%	275%	13%	—	32%	76%
$h \to Z\gamma$	25%	—	144%	—	18%	—	40%	—

Table 2. The estimated precision of CEPC and FCC-ee Higgs measurements. We gather the available estimations from refs. [1, 2, 86], while the missing ones (highlighted in green) are obtained from scaling with luminosity. See appendix B for more details. For $\sigma(e^+e^- \to \nu\bar{\nu}h)$, the precisions marked with a diamond $^\diamond$ are normalized to the cross section of the inclusive channel which includes both the WW fusion and $e^+e^- \to hZ, Z \to \nu\bar{\nu}$, while the unmarked precisions are normalized to the WW fusion process only. For the CEPC, the precision of the $\sigma(hZ) \times \mathrm{BR}(h \to b\bar{b})$ measurement (marked by a star *) reduces to 0.24% if one excludes the contribution from $e^+e^- \to hZ, Z \to \nu\bar{\nu}, h \to b\bar{b}$ to avoid double counting with $e^+e^- \to \nu\bar{\nu}h, h \to b\bar{b}$. The corresponding information is not available for the FCC-ee.

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Estimated precision @ linear colliders: ILC

	ILC										
	[250 GeV, 2 ab^{-1}]		[350 GeV, 200 fb^{-1}]		[500 GeV, 4 ab^{-1}]			[1 TeV, 1 ab^{-1}]		[1 TeV, 2.5 ab^{-1}]	
production	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$	$t\bar{t}h$
σ	0.71%	—	2.1%	—	1.1%	—	—	—	—	—	—
	$\sigma \times$ BR										
$h \to b\bar{b}$	0.42%	3.7%	1.7%	1.7%	0.64%	0.25%	9.9%	0.5%	6.0%	0.3%	3.8%
$h \to c\bar{c}$	2.9%	—	13%	17%	4.6%	2.2%	—	3.1%	—	2.0%	—
$h \to gg$	2.5%	—	9.4%	11%	3.9%	1.4%	—	2.3%	—	1.4%	—
$h \to \tau\tau$	1.1%	—	4.5%	24%	1.9%	3.2%	—	1.6%	—	1.0%	—
$h \to WW^*$	2.3%	—	8.7%	6.4%	3.3%	0.85%	—	3.1%	—	2.0%	—
$h \to ZZ^*$	6.7%	—	28%	22%	8.8%	2.9%	—	4.1%	—	2.6%	—
$h \to \gamma\gamma$	12%	—	44%	50%	12%	6.7%	—	8.5%	—	5.4%	—
$h \to \mu\mu$	25%	—	98%	180%	31%	25%	—	31%	—	20%	—
$h \to Z\gamma$	34%	—	145%	—	49%	—	—	—	—	—	—

Table 3. The estimated precision of ILC Higgs measurements. For the 250 GeV, 350 GeV and 500 GeV runs, all numbers are scaled from ref. [58] (table 13), except for $\sigma(hZ) \times \mathrm{BR}(h \to Z\gamma)$ which is scaled from the CEPC estimation. A beam polarization of $P(e^-, e^+) = (-0.8, +0.3)$ is assumed. The 1 TeV run is only included in figure 17 of appendix C, while the estimations are taken from ref. [59] which assumes a polarization of $P(e^-, e^+) = (-0.8, +0.2)$.

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Estimated precision @ linear colliders: CLIC

CLIC					
	[350 GeV, 500 fb^{-1}]		[1.4 TeV, 1.5 ab^{-1}]		[3 TeV, 2 ab^{-1}]
production	Zh	$\nu\bar{\nu}h$	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}h$
σ	1.6%	—	—	—	—
	$\sigma \times$ BR				
$h \to b\bar{b}$	0.84%	1.9%	0.4%	8.4%	0.3%
$h \to c\bar{c}$	10.3%	14.3%	6.1%	—	6.9%
$h \to gg$	4.5%	5.7%	5.0%	—	4.3%
$h \to \tau\tau$	6.2%	—	4.2%	—	4.4%
$h \to WW^*$	5.1%	—	1.0%	—	0.7%
$h \to ZZ^*$	—	—	5.6%	—	3.9%
$h \to \gamma\gamma$	—	—	15%	—	10%
$h \to \mu\mu$	—	—	38%	—	25%
$h \to Z\gamma$	—	—	42%	—	30%

Table 4. The estimated precision of CLIC Higgs measurements taken from ref. [60], which assumes unpolarized beams and considers only statistical uncertainties. In addition, we also include the estimations for $\sigma(hZ) \times \mathrm{BR}(h \to b\bar{b})$ at high energies in ref. [35], which are 3.3% (6.8%) at 1.4 TeV (3 TeV). We find the inclusion of the ZZ fusion ($e^+e^- \to e^+e^-h$) measurements to have little impact in our analysis.

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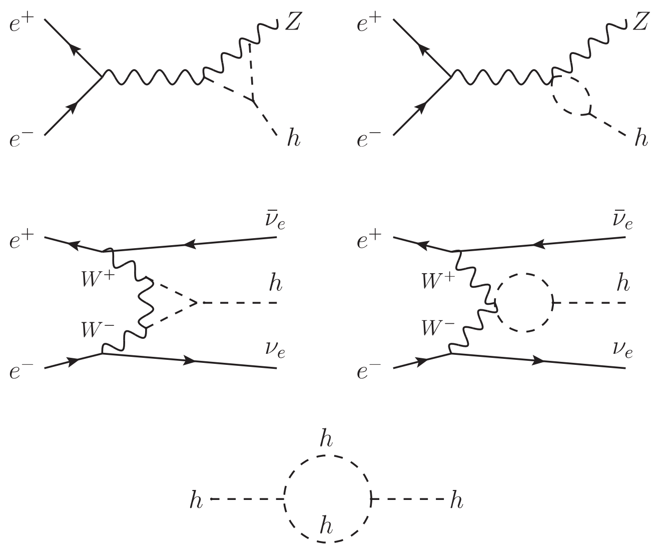
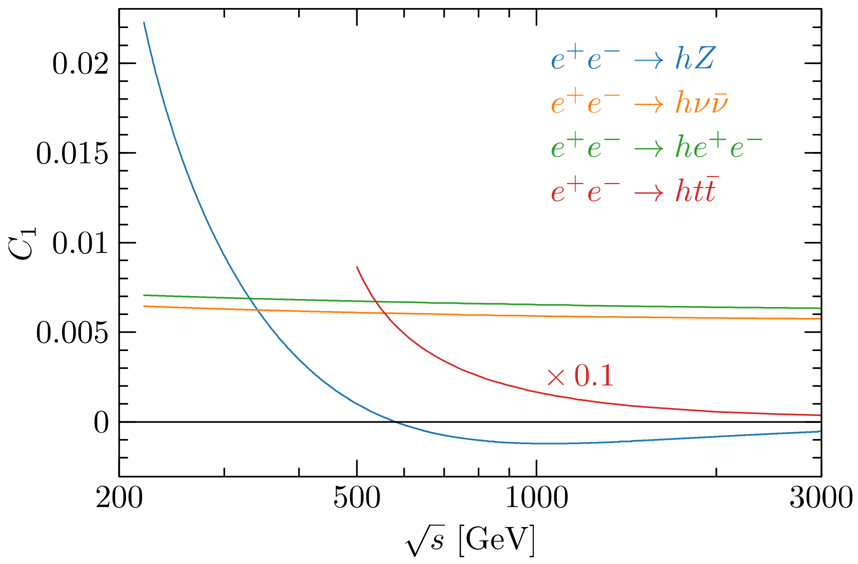
Low-energy lepton colliders





- 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

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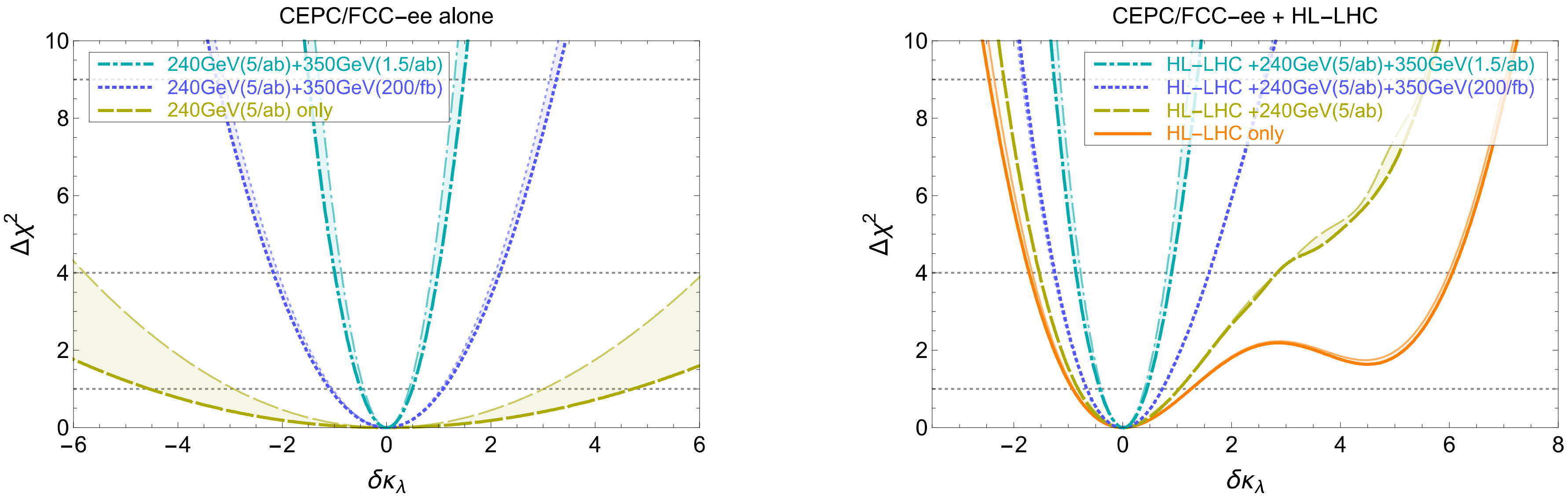
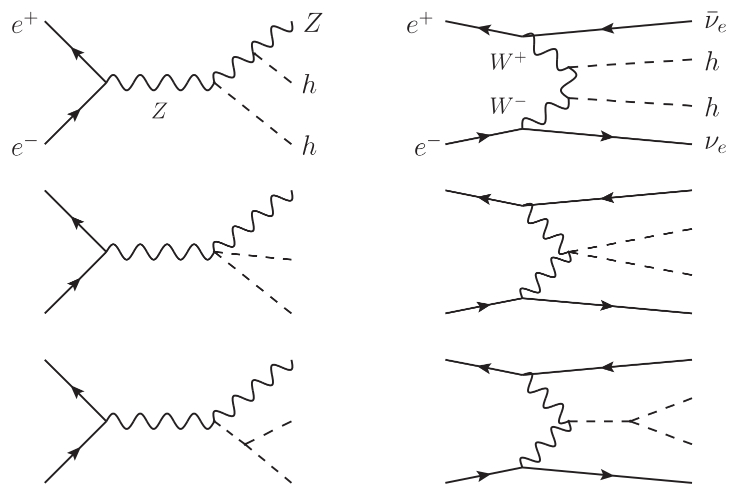
Low-energy lepton colliders

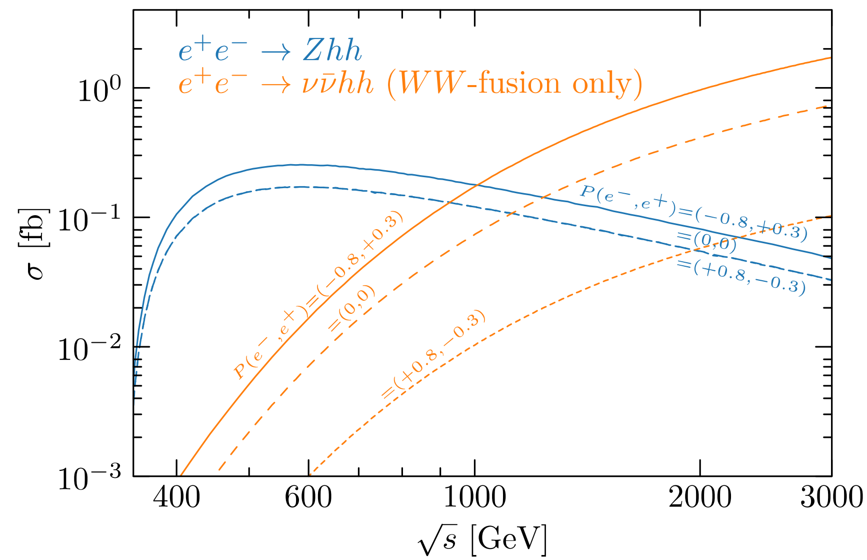


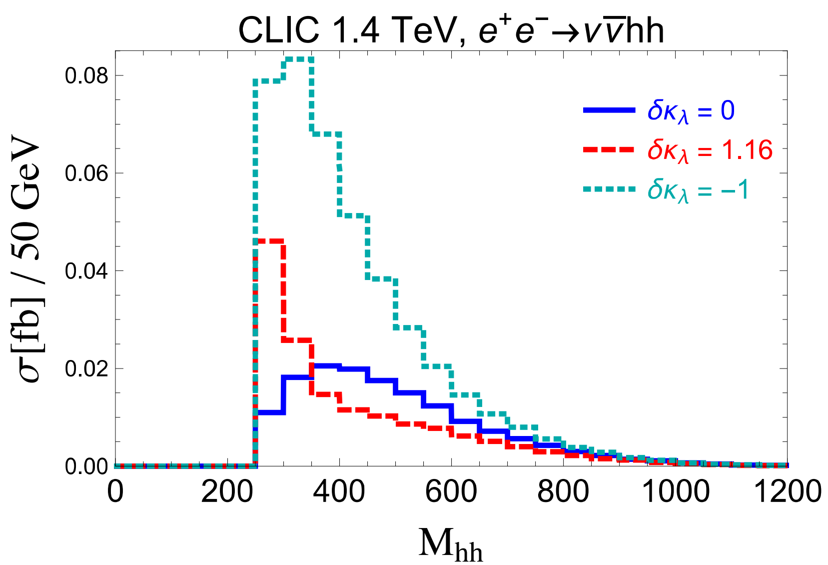
- shaded band reflects different assumptions on TGCs $\rightarrow$ large impact! global analysis needed to constrain single-Higgs deformations
- low-energy circular collider needs either combination with HL-LHC or 2 energy runs to set meaningful bounds

High-energy lepton colliders



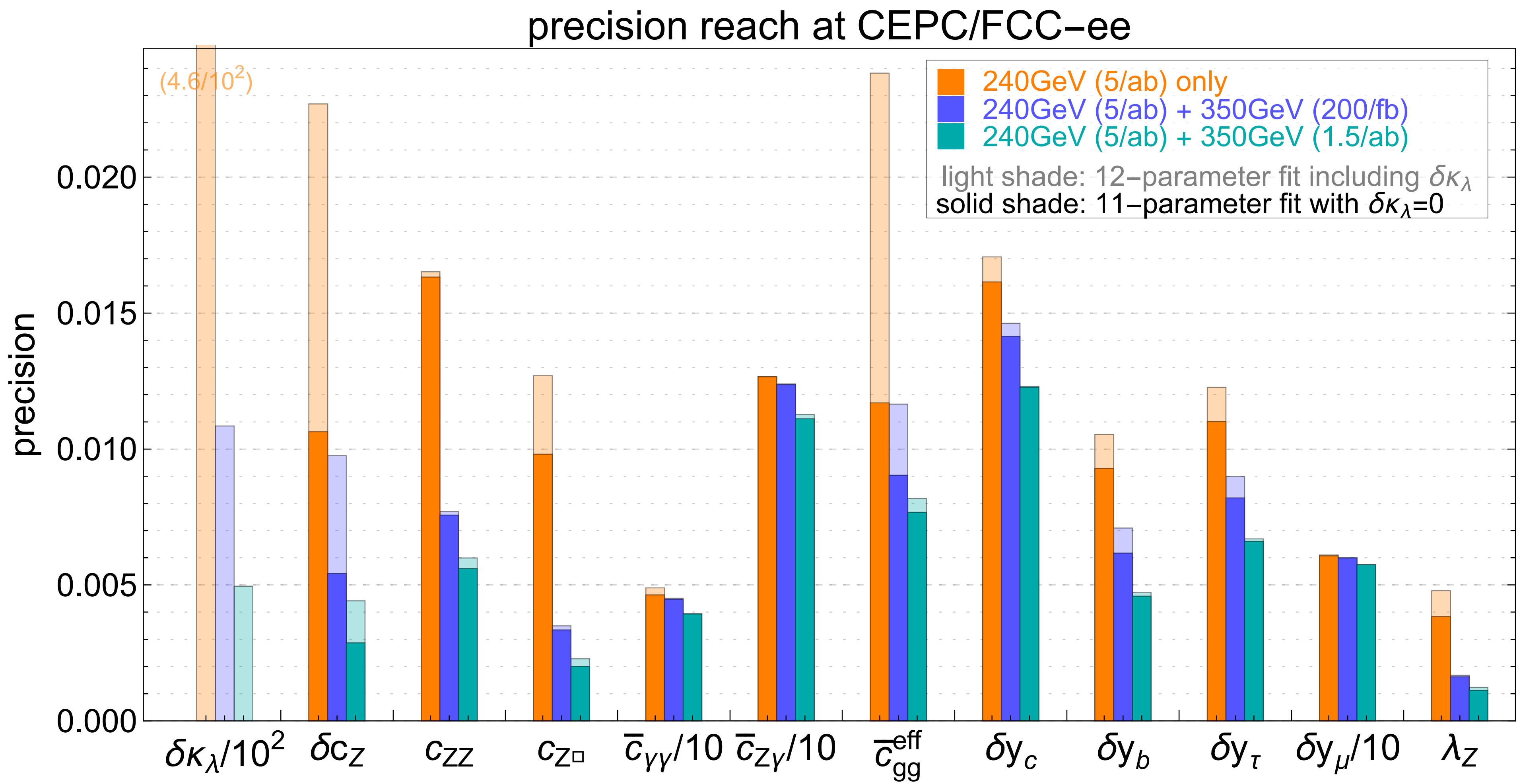
more sensitive to $\delta\kappa_\lambda>0$ more sensitive to $\delta\kappa_\lambda<0$





- 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 $\to$ILC runs at 500GeV and 1TeV maximize sensitivity

Impact on the other couplings



Impact on the other couplings