Higgs trilinear coupling from single Higgs observables

Marc Riembau
11th Dec 2018

Based on:
Degrassi, Giardino, Maltoni, Pagani; 1607.04251
DiVita, Grojean, Panico, MR, Vantalon; 1704.01953
DiVita, Durieux, Gorjean, Gu, Liu, Panico, MR, Vantalon; 1704.01953

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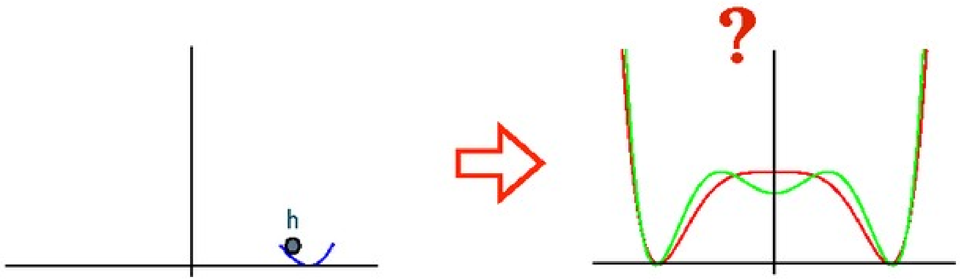
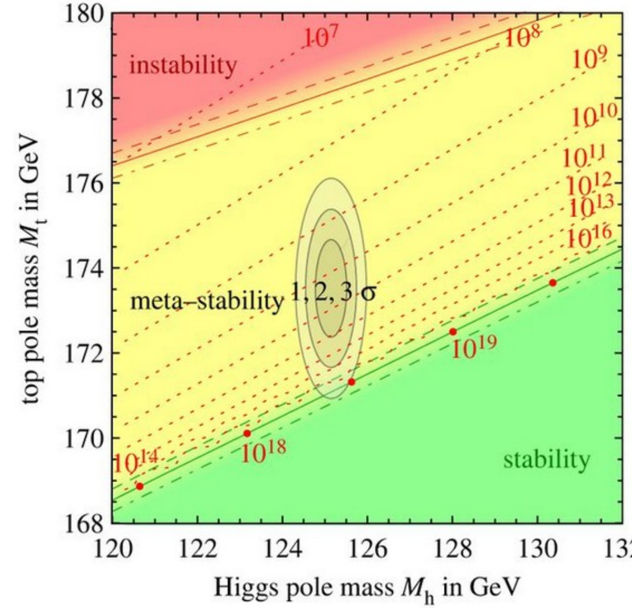
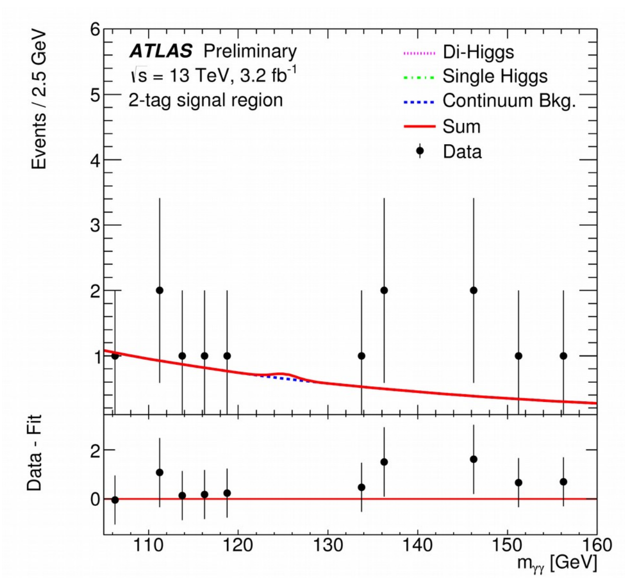
The multifaced relevance of the Higgs self-coupling



arXiv: 1511.06495

arXiv: 1205.6497





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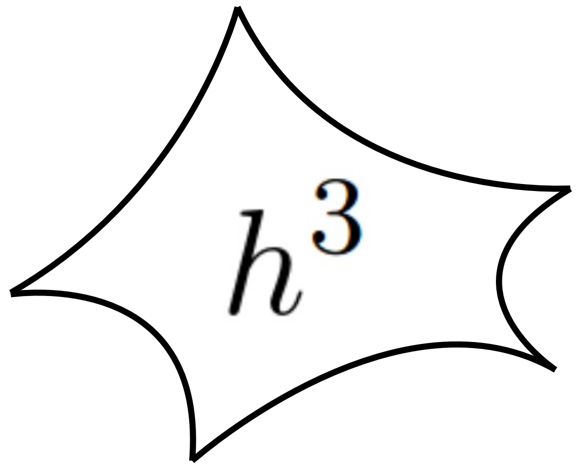
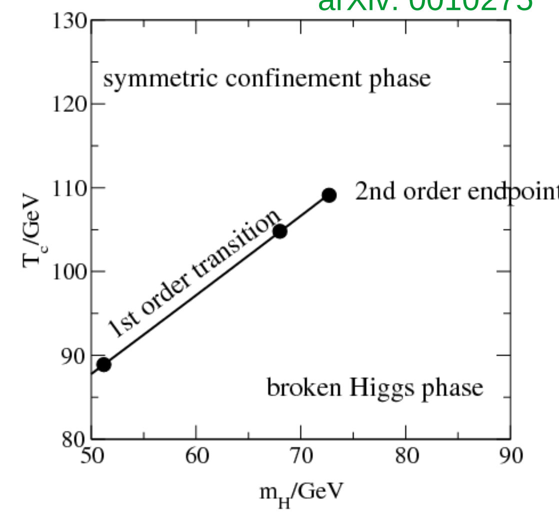
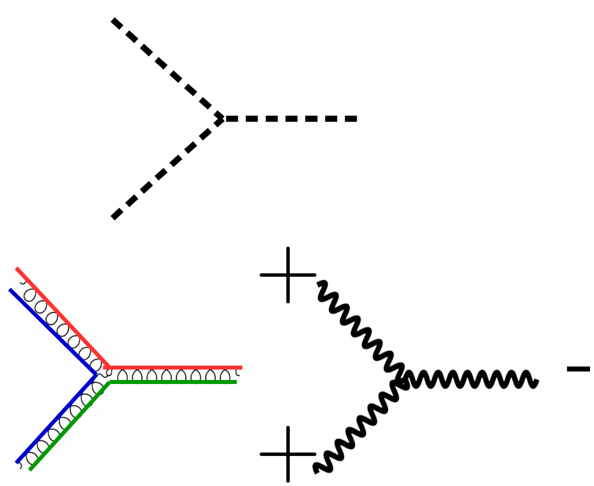


arXiv: 0010275

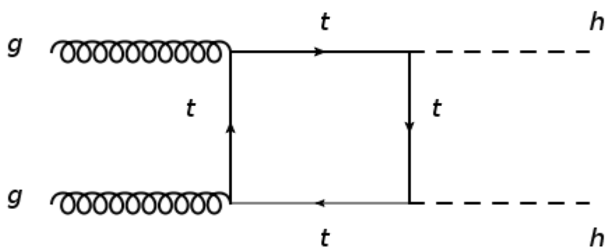


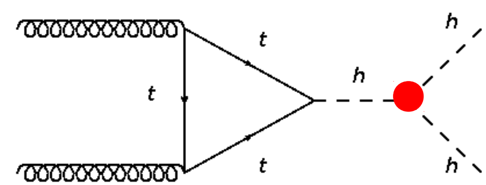


Double Higgs production at LHC

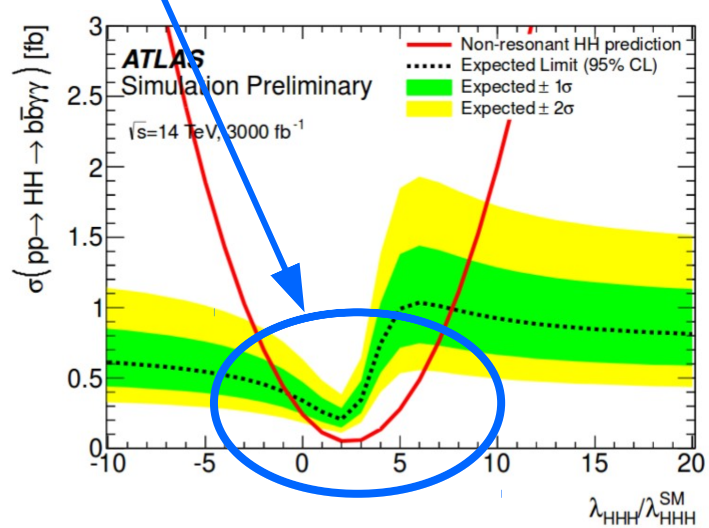
Small production rate times a small visible branching ratio:

$$\frac{\sigma(pp \to hh)}{\sigma(pp \to h)} \sim 10^{-3} \qquad \mathrm{Br}(h \to b\bar{b}) \times \mathrm{Br}(h \to \gamma\gamma) \sim 60\% \times 0.1\%$$





destructive interference



ATL-PHYS_PUB_2017-001

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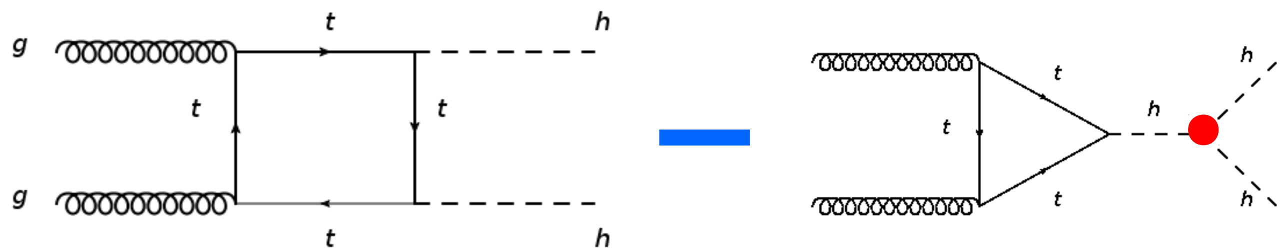

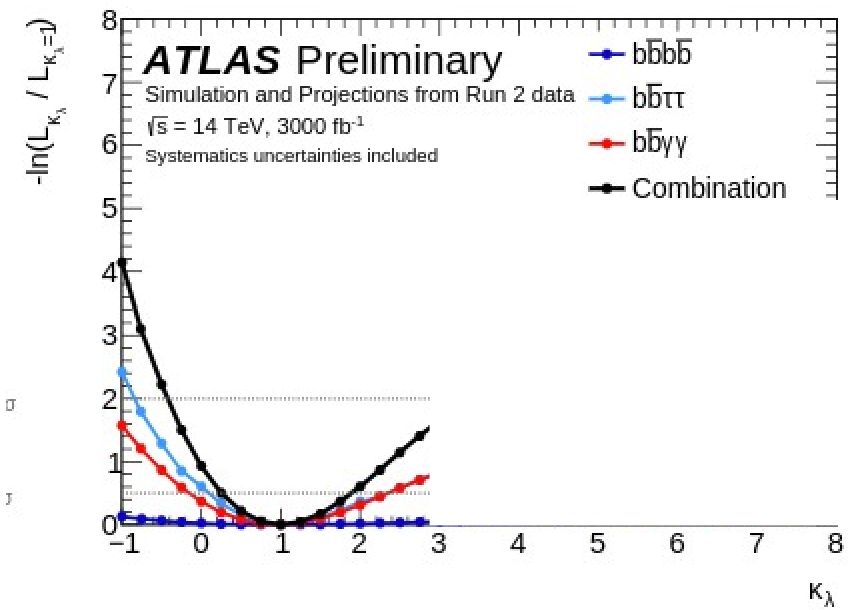

HL-LHC @ 3 ab^{-1}, 95% CL

$$\kappa_\lambda \in \sim [-0.5, 3]\,?$$

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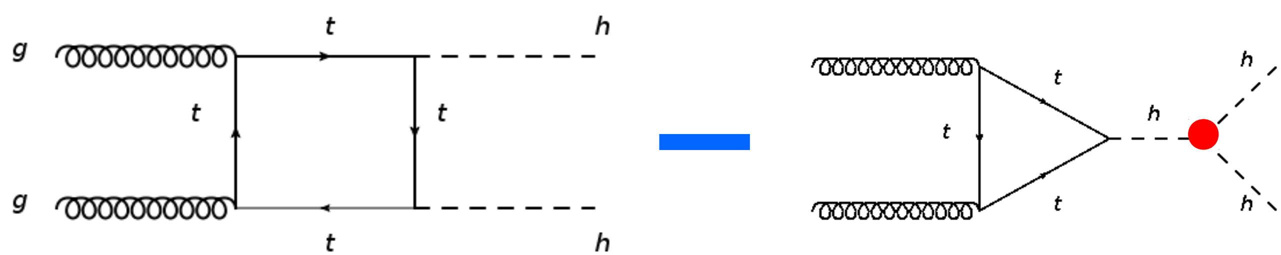
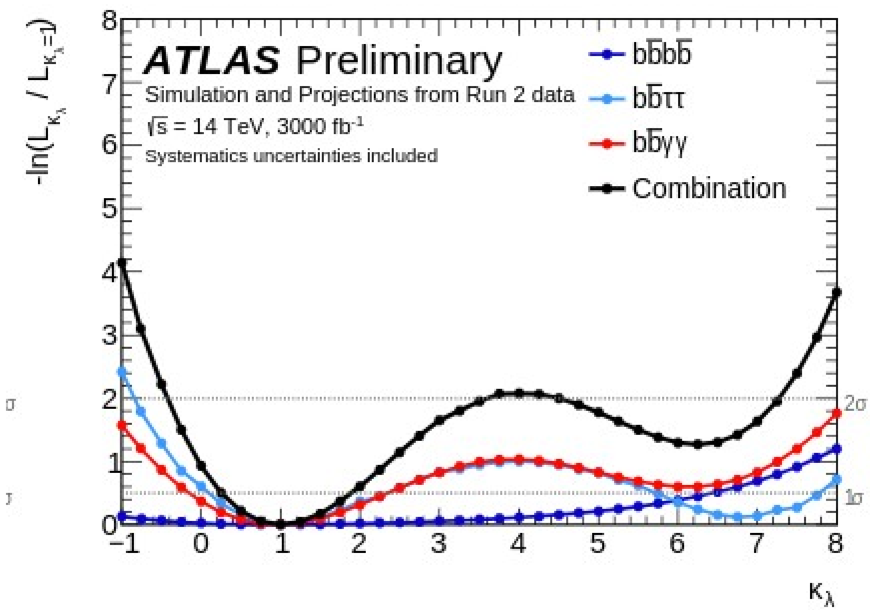




HL-LHC @ 3 ab^{-1}, 95% CL

$$\kappa_\lambda \in\sim [-0.5, 3]\,?$$

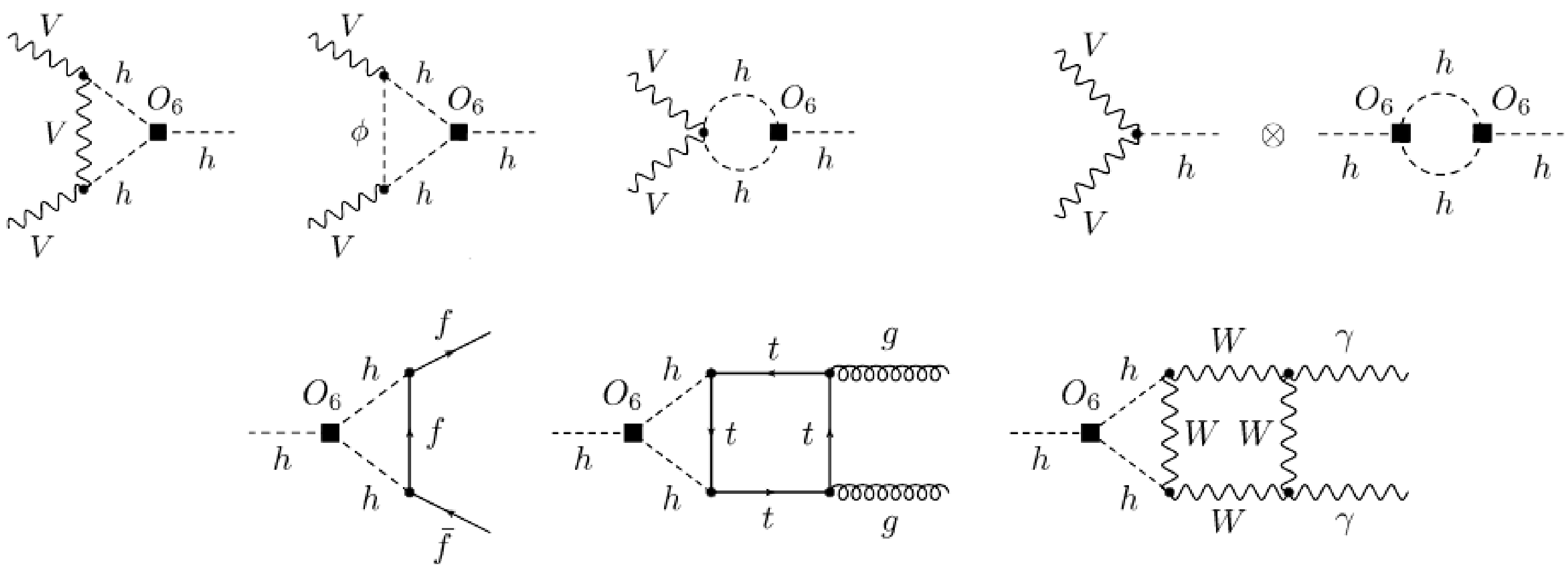
7!

Large and negative interference spoils sensitivity

Higgs self-coupling from single Higgs processes

Given the loose constraints from double Higgs production, perhaps single Higgs processes can help

McCullough, 1312.3322
Gorbahn, Haisch 1607.03773
Degrassi, et al. 1607.04251
Bizon, et al. 1610.05771



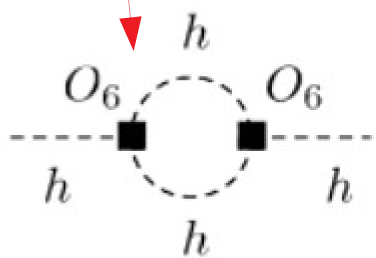
Higgs self-coupling from single Higgs processes

$$\mu_i^f \equiv \mu_i \times \mu^f = \frac{\sigma(i)}{\sigma^{\rm SM}(i)} \times \frac{{\rm BR}(f)}{{\rm BR}^{\rm SM}(f)}$$

$$\mu_i = 1 + (\kappa_3 - 1)\, C_1^\sigma + \left(\kappa_3^2 - 1\right) \delta Z_H \qquad \mu^f = 1 + (\kappa_3 - 1)\, (C_1^\Gamma - C_1^{\Gamma_{\rm tot}})$$

Universal factor

Process specific



Process specific

C_1^σ [%]	ggF	VBF	WH	ZH	ttH	tHj
13 TeV	0.66	0.64	1.03	1.19	3.51	0.91
14 TeV	0.66	0.64	1.03	1.18	3.47	0.89
27 TeV	0.66	0.62	1.01	1.16	3.20	0.79

C_1^Γ [%]	$\gamma\gamma$	ZZ	WW	gg
on-shell H	0.49	0.83	0.73	0.66

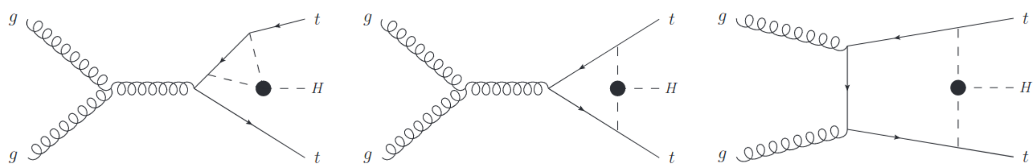
13 TeV

$p_T(H)$ [GeV]	$[0, 25]$	$[25, 50]$	$[50, 100]$	$[100, 200]$	$[200, 500]$	> 500
VBF	0.97	0.88	0.73	0.58	0.45	0.29
ZH	2.00	1.75	1.21	0.51	0.01	-0.10
WH	1.70	1.49	1.04	0.44	0.01	-0.09
$t\bar{t}H$	5.31	5.07	4.38	3.00	1.27	0.17
tHj	1.23	1.18	1.02	0.74	0.33	-0.06

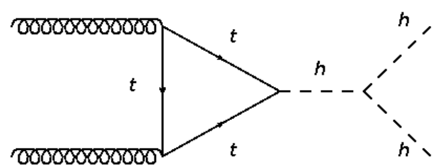
Degrassi, Giardino, Maltoni, Pagani; 1607.04251
Maltoni, Pagani, Shivaji, Zhao; 1709.08649

Higgs self-coupling in tth vs double Higgs

«Looking for loop effects in tth» sounds bad,
but there is a better perspective:



→ 3.5%



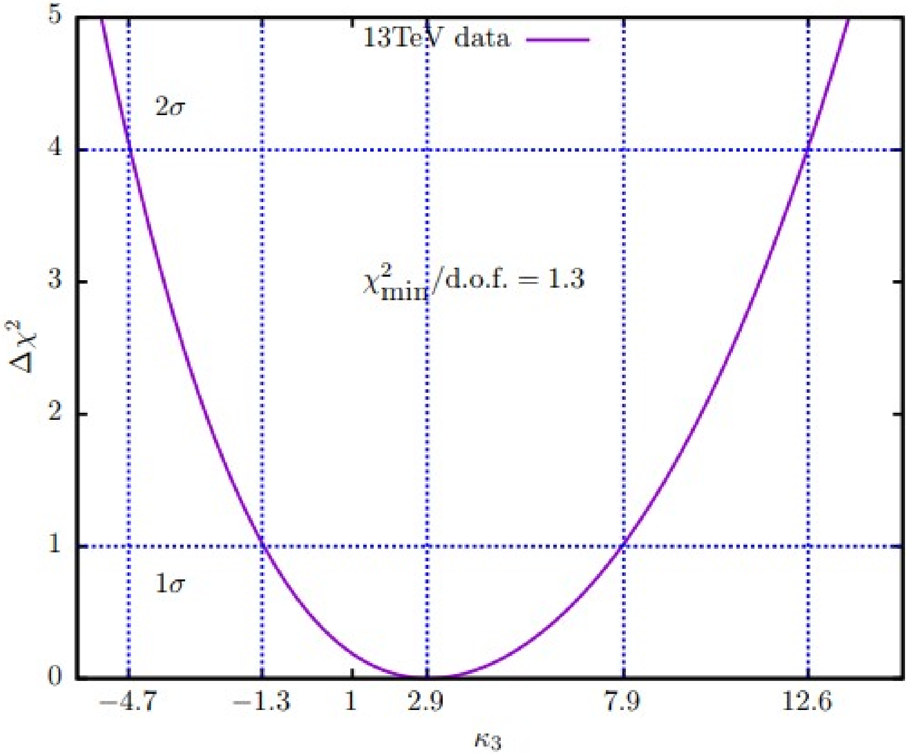
→ 40%

$$\frac{1}{\sigma}\frac{d\sigma}{d\kappa_\lambda}\bigg|_{\kappa_\lambda=1}$$

Rule of thumb:

$$\frac{\text{precision of tth} \times 10}{\text{precision of di-Higgs}} = \frac{\text{constraint on trilinear from tth}}{\text{constraint on trilinear from di-Higgs}}$$

Minimization of
$$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



plot done by Xiaoran Zhao

based on CMS-HIG-17-031

$$\kappa_\lambda^{\rm best} = 2.9\,, \qquad \kappa_\lambda^{1\sigma} = [-1.3, 7.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-4.7, 12.6]$$

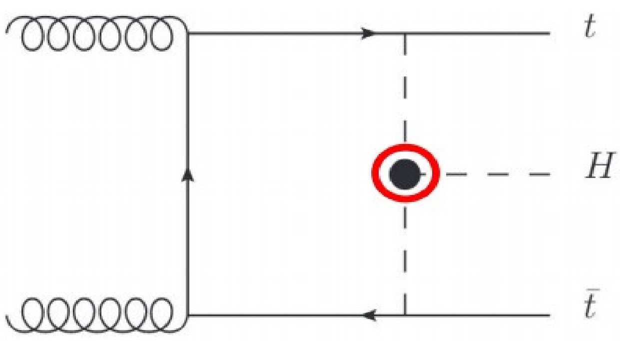
EXP double Higgs:

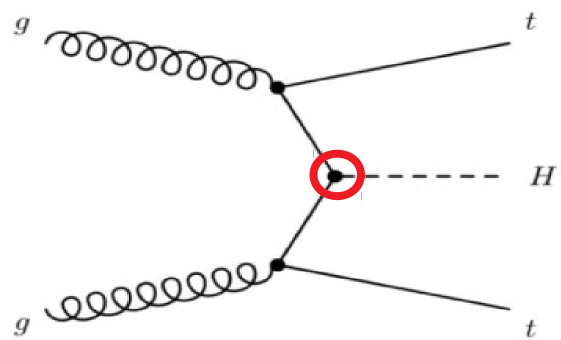
- ATLAS: $-5.0<\kappa_\lambda<12.1$
- CMS: $-11.8<\kappa_\lambda<18.8$

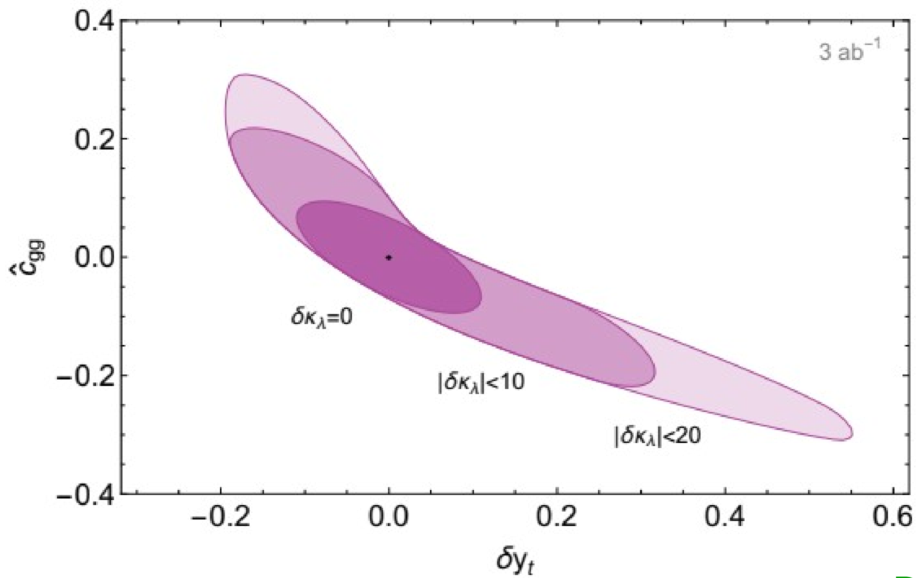
Slide by Davide Pagani, Higgs Couplings ‘18, Tokyo

Correlations of inclusive observables...

Imagine tth is measured to be different from SM...
who is the responsible?







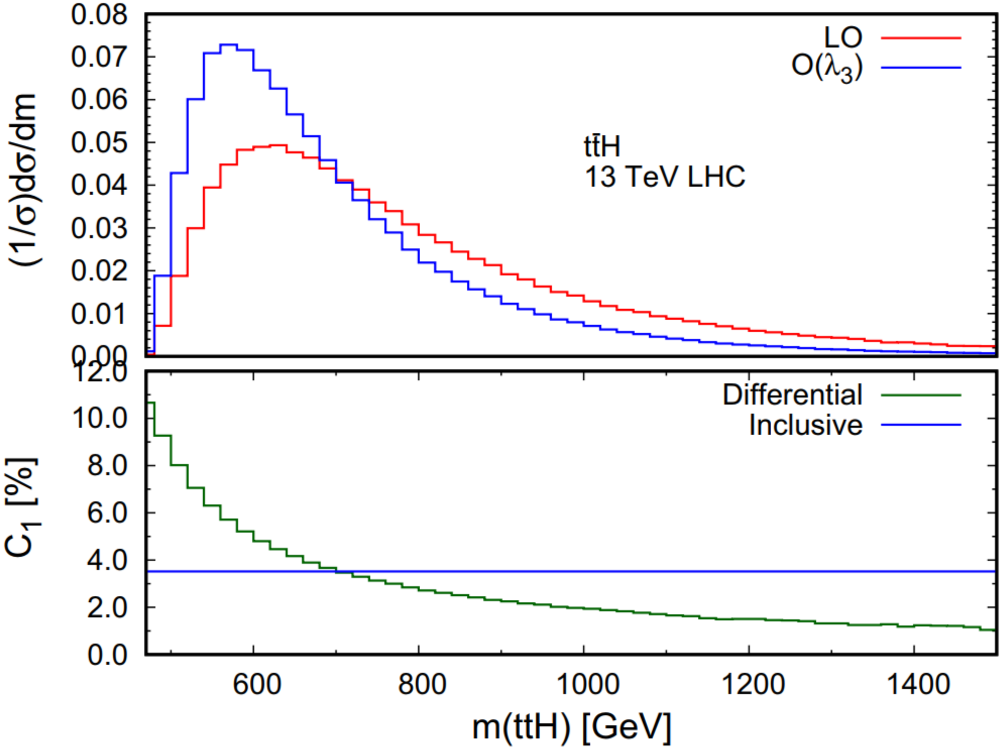
Large trilinear affects precision on single Higgs parameters, and vice versa

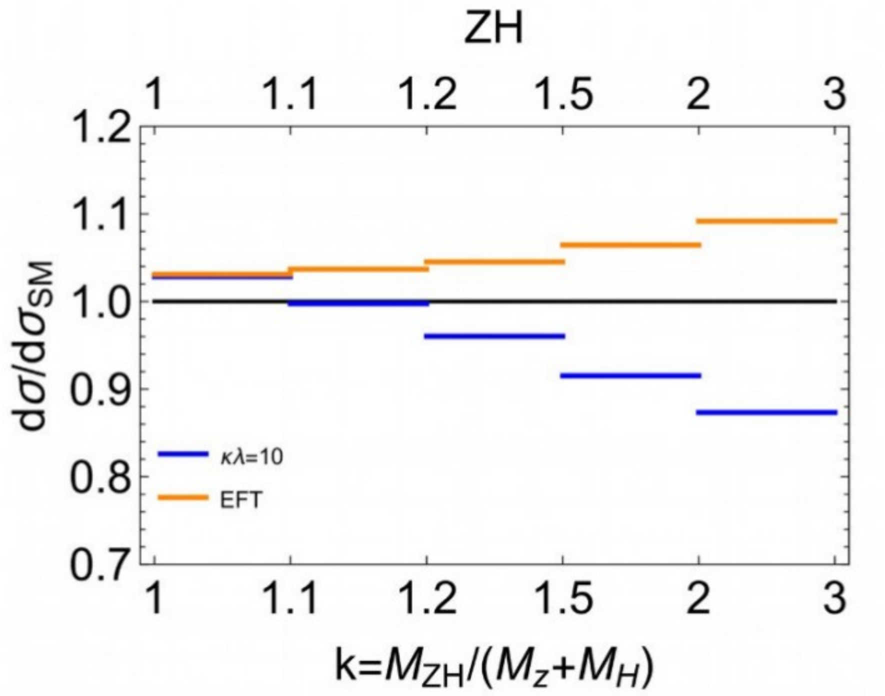
DiVita, Grojean, Panico, MR, Vantalon; 1704.01953

... and the need for differential information

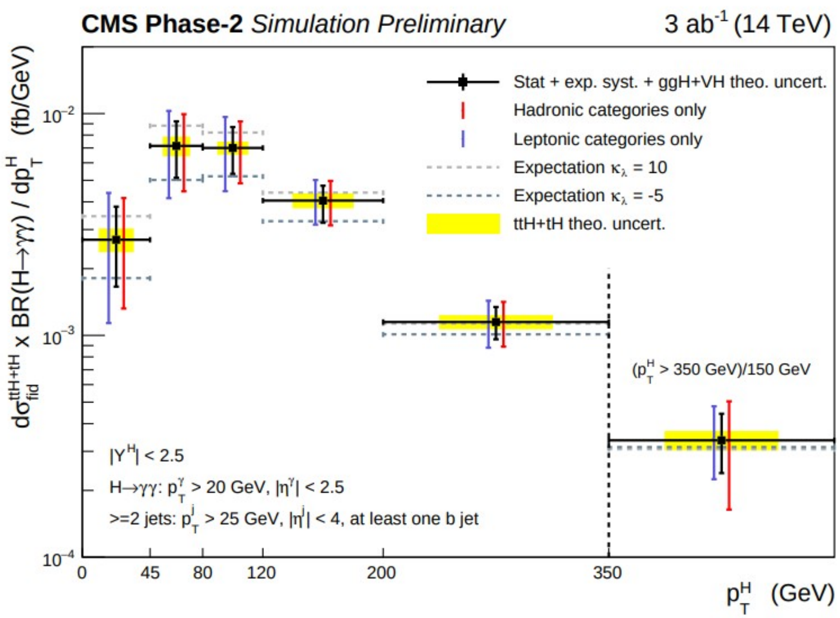
EFT operators tend to show – larger effects at large invariant masses
– global rescalings of the distribution

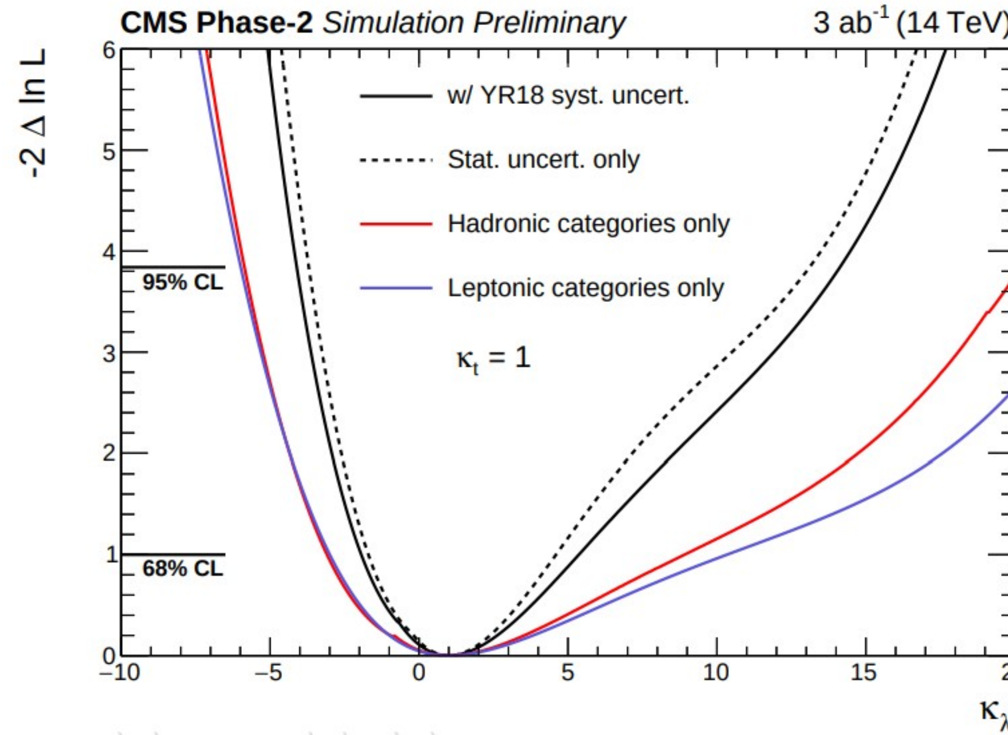
Higgs self-coupling deforms the distribution nontrivially.





Maltoni, Pagani, Shivaji, Zhao; 1709.08649





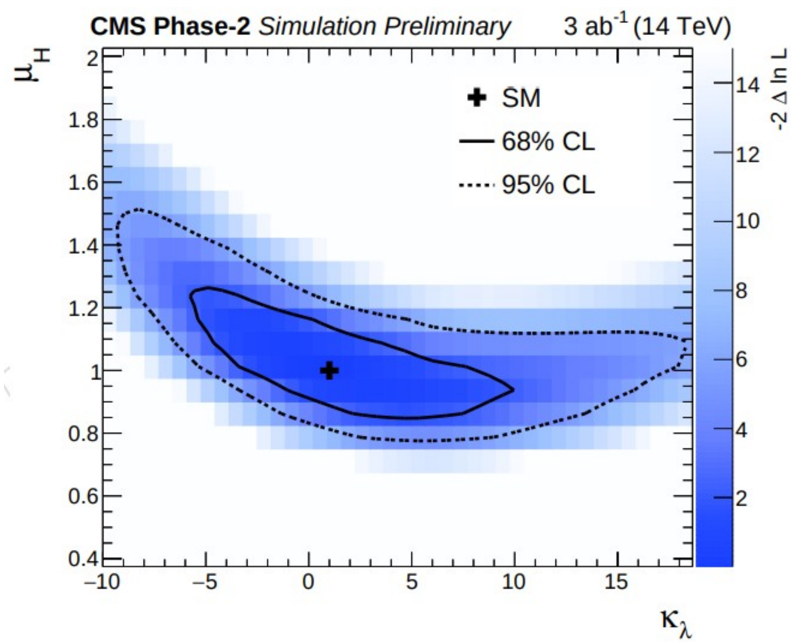


Figure 42: Results of the likelihood scan in κ_λ. The individual contributions of the statistical and systematic uncertainties are disentangled by performing a likelihood scan with all systematics removed. The observed deviation from the statistical uncertainty only curve is driven by the theoretical systematic uncertainties in the Higgs boson production yields. Additionally, the contributions from the hadronic and leptonic channels have been separated, shown in red and purple respectively.

First CMS study on tth!

CMS PAS FTR-18-020

Global fit

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

7+2+1 independent parameters: $\delta c_z\,,\ c_{zz}\,,\ c_{z\Box}\,,\ \hat{c}_{z\gamma}\,,\ \hat{c}_{\gamma\gamma}\,,\ \hat{c}_{gg}\,,\ \delta y_t\,,\ \delta y_b\,,\ \delta y_\tau\,,\ \kappa_\lambda\,.$

$$\begin{aligned}
\delta c_w &= \delta c_z\,,\\
c_{ww} &= c_{zz} + 2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma} + \frac{g'^4}{\pi^2(g^2+g'^2)^2}\hat{c}_{\gamma\gamma}\,,\\
c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{\gamma\gamma} - (g^2-g'^2)\frac{g'^2}{\pi^2(g^2+g'^2)}\hat{c}_{z\gamma}\right],\\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + (g^2+g'^2)\,c_{zz} - \frac{e^2}{\pi^2}\hat{c}_{\gamma\gamma} - \frac{g^2-g'^2}{\pi^2}\hat{c}_{z\gamma}\right],\\
\hat{c}^{(2)}_{gg} &= \hat{c}_{gg}\,,\\
\delta y_f^{(2)} &= 3\delta y_f - \delta c_z\,.
\end{aligned}$$

relations at dimension 6

$$\begin{aligned}
\delta g_{1,z} &= \frac{g'^2}{2(g^2-g'^2)}\left[\hat{c}_{\gamma\gamma}\frac{e^2}{\pi^2} + \hat{c}_{z\gamma}\frac{g^2-g'^2}{\pi^2} - c_{zz}\,(g^2+g'^2) - c_{z\Box}\frac{g^2}{g'^2}\,(g^2+g'^2)\right],\\
\delta\kappa_\gamma &= -\frac{g^2}{2(g^2+g'^2)}\left[\hat{c}_{\gamma\gamma}\frac{e^2}{\pi^2} + \hat{c}_{z\gamma}\frac{g^2-g'^2}{\pi^2} - c_{zz}(g^2+g'^2)\right],
\end{aligned}$$

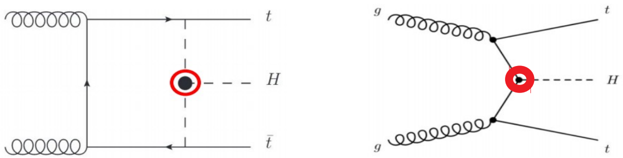
measured in diboson

Global fit

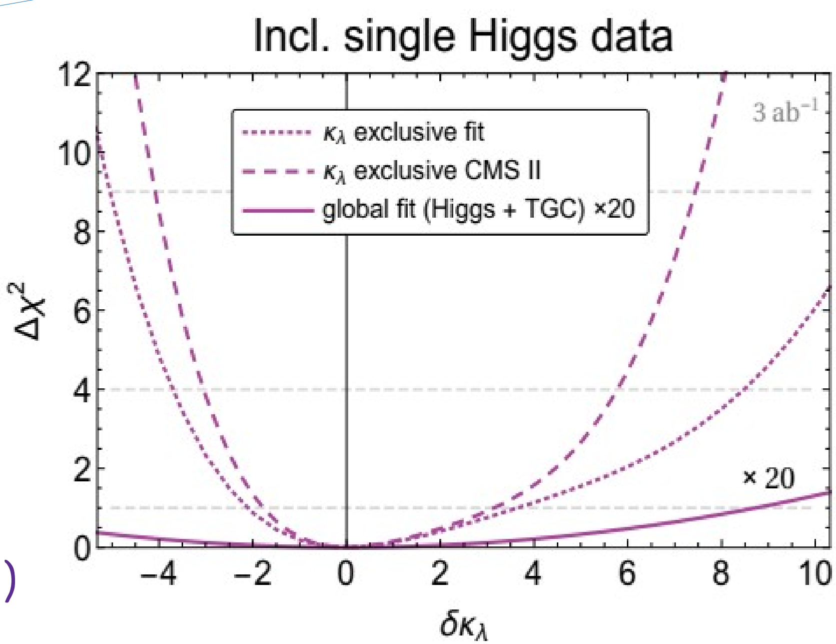
https://twikiai06.cern.ch/twiki/bin/view/LHCPhysics/GuidelinesCouplingProjections2018

Signal strength per production x decay mode

L = 3000 fb-1		Expected uncertainty [%]				
POI	Scenario	Total	Stat	SigTh	BkgTh	Expt
$\mu_{ggH}^{\gamma\gamma}$	S1	7.1	1.9	5.8	1.0	3.3
	S2	4.2	1.9	3.1	0.9	2.1
μ_{ggH}^{ZZ}	S1	6.6	2.1	5.4	1.7	2.7
	S2	4.0	2.1	2.8	0.7	1.8
μ_{ggH}^{WW}	S1	6.6	1.2	6.2	1.0	1.5
	S2	3.7	1.2	3.1	0.9	1.2
$\mu_{ggH}^{\tau\tau}$	S1	8.1	2.6	6.6	1.7	3.5
	S2	5.5	2.6	3.9	0.7	2.9
μ_{ggH}^{bb}	S1	34.0	20.6	23.5	3.2	10.0
	S2	24.7	20.6	12.2	1.5	2.6
$\mu_{ggH}^{\mu\mu}$	S1	16.6	13.4	5.5	1.9	8.0
	S2	13.8	13.4	3.2	0.6	2.0



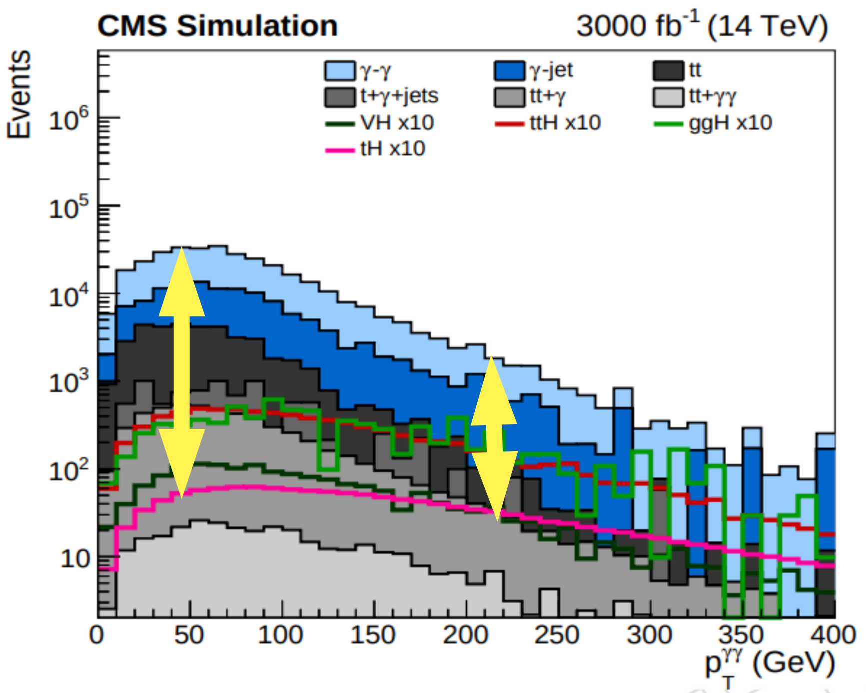
$$\chi^2 = \sum \frac{(1-\mu(\kappa_\lambda))^2}{\sigma^2}$$



(plot done with old projections...)

Global fit

- Differential uncertainties:
  - › Just rescaling uncertainties for cross section in each bin overestimates the reach:

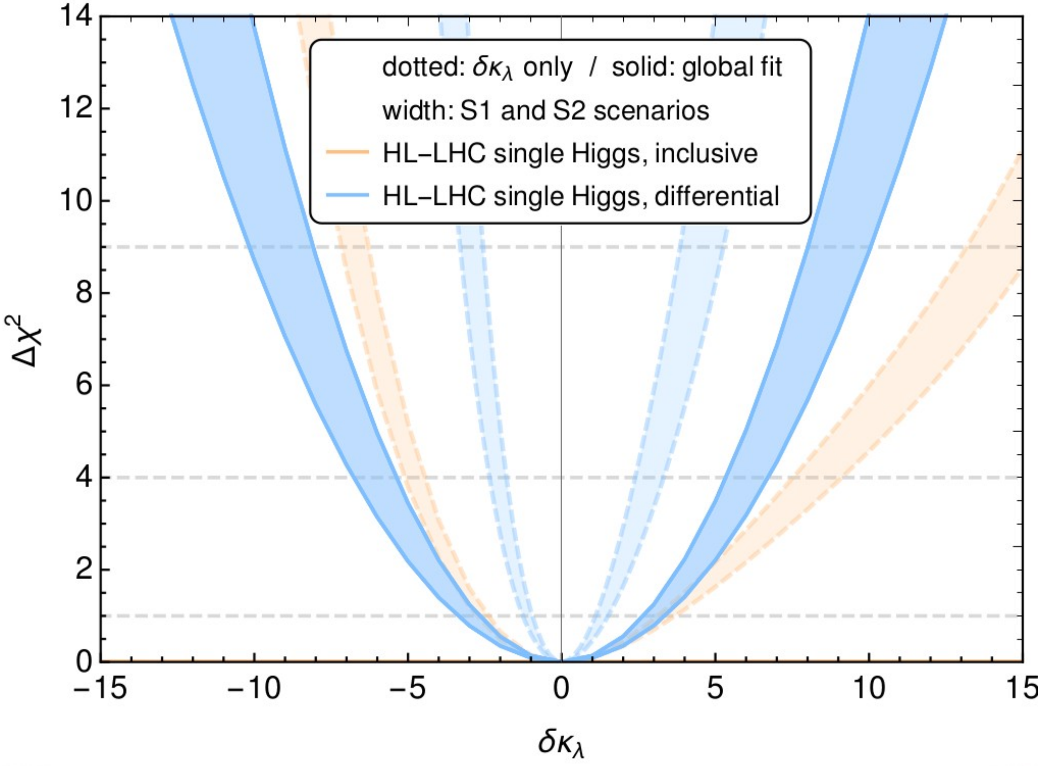


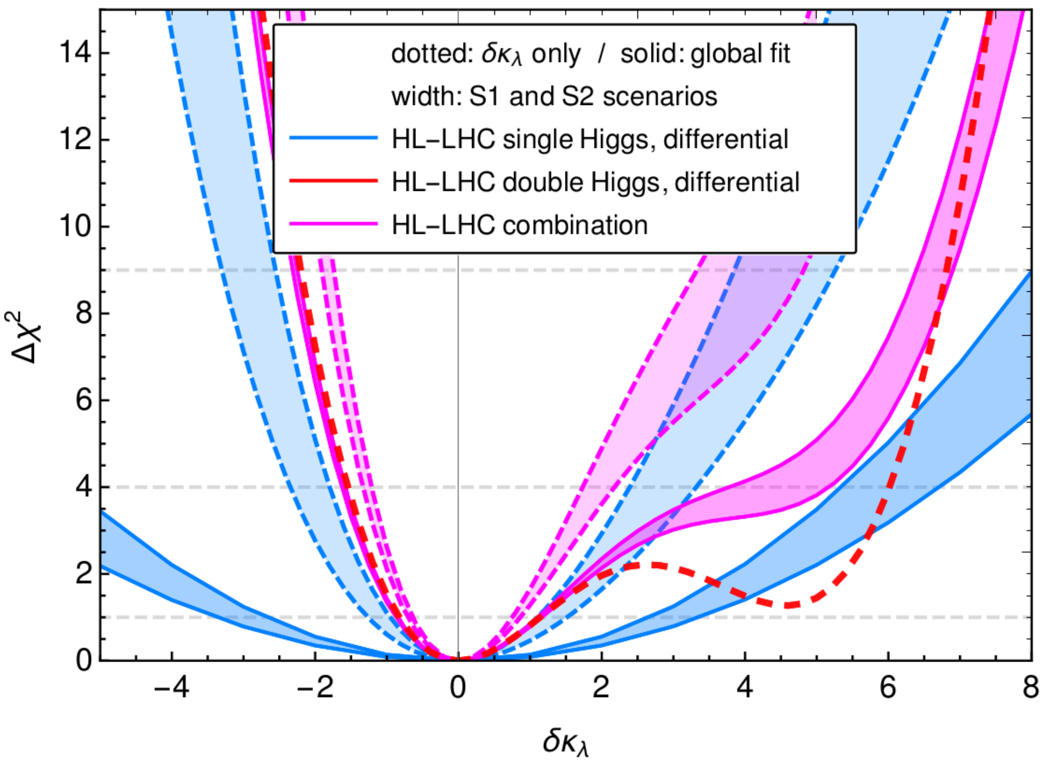
p_T^H bin [GeV]	$\mu \pm \sigma_\mu = \mu \pm \sigma_\mu^{\rm stat} \pm \sigma_\mu^{\rm syst.}$
[0,45]	$1.00^{+0.410}_{-0.385} = 1.00^{+0.408}_{-0.385}{}^{+0.043}_{-0.018}$
[45,80]	$1.00^{+0.290}_{-0.281} = 1.00^{+0.289}_{-0.281}{}^{+0.032}_{-0.018}$
[80,120]	$1.00^{+0.243}_{-0.236} = 1.00^{+0.241}_{-0.235}{}^{+0.030}_{-0.021}$
[120,200]	$1.00^{+0.168}_{-0.206} = 1.00^{+0.164}_{-0.204}{}^{+0.033}_{-0.030}$
[200,350]	$1.00^{+0.172}_{-0.168} = 1.00^{+0.163}_{-0.159}{}^{+0.053}_{-0.052}$
[350,∞]	$1.00^{+0.334}_{-0.304} = 1.00^{+0.303}_{-0.275}{}^{+0.141}_{-0.130}$

- Background is larger at threshold, just where sensitivity to trilinear is larger.

Global fits using extrapolations of inclusive uncertainties to differential level must take this into account!

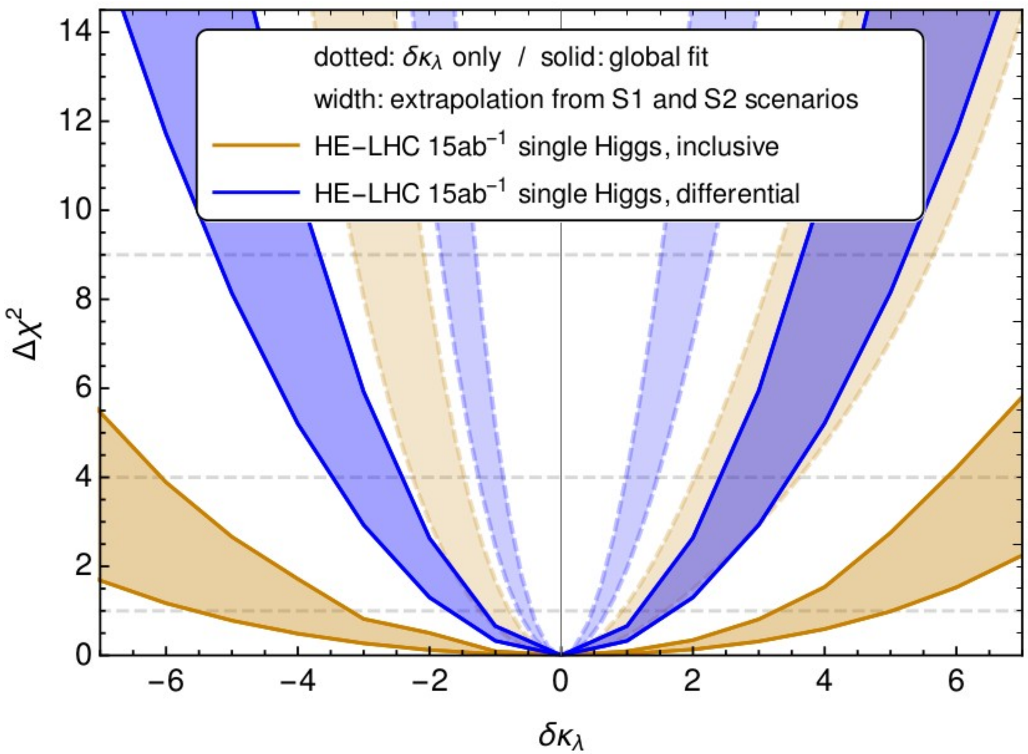
Results at HL-LHC

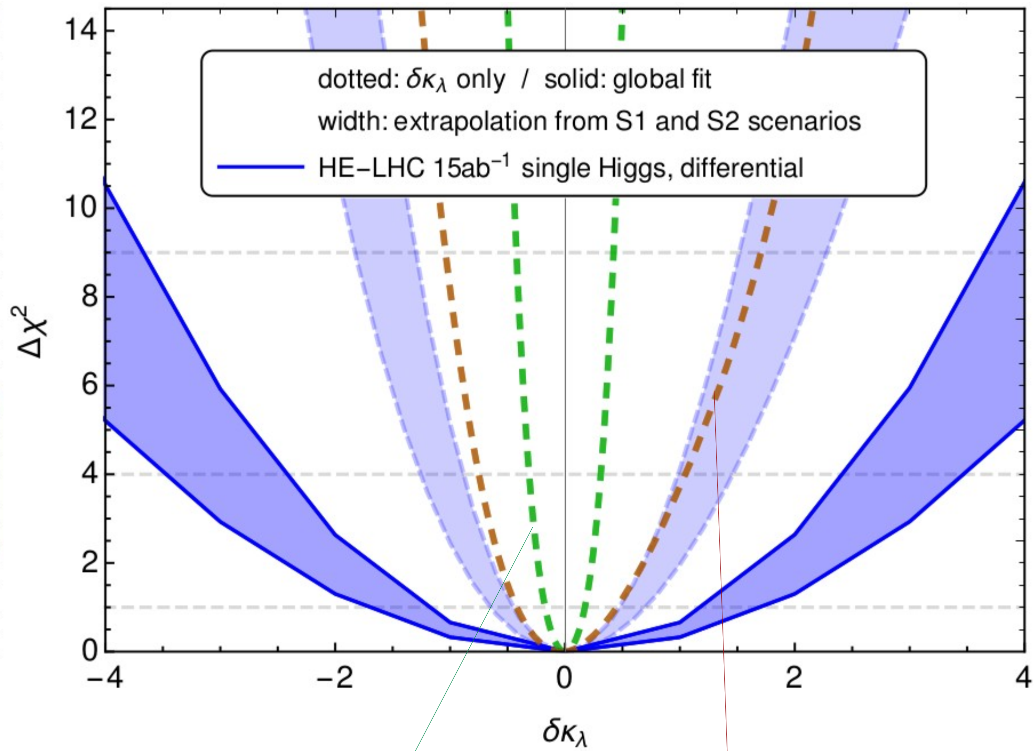




- Differential information is crucial
- Differences between S1 and S2 scenarios: not limited by statistics
- Complementary with double Higgs production

Results at HL-LHC





Homiller, Meade; **1811.02572**

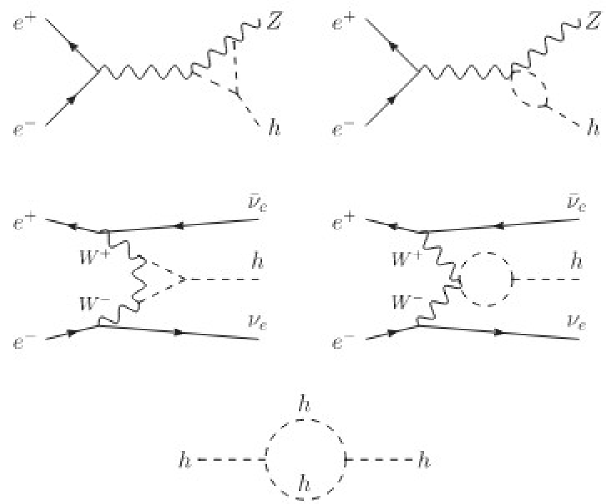
Goncalves, Han, Kling, Plehn, Takeuchi; **1802.04319**

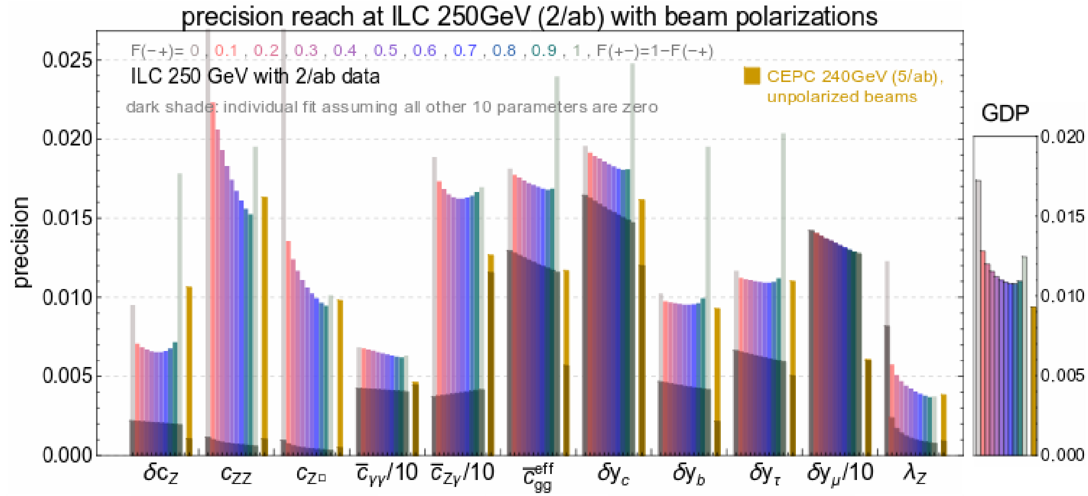
- Single Higgs production constrains trilinear between −3 and 3 even in a global fit!
- Double Higgs production gives much stronger constraints.

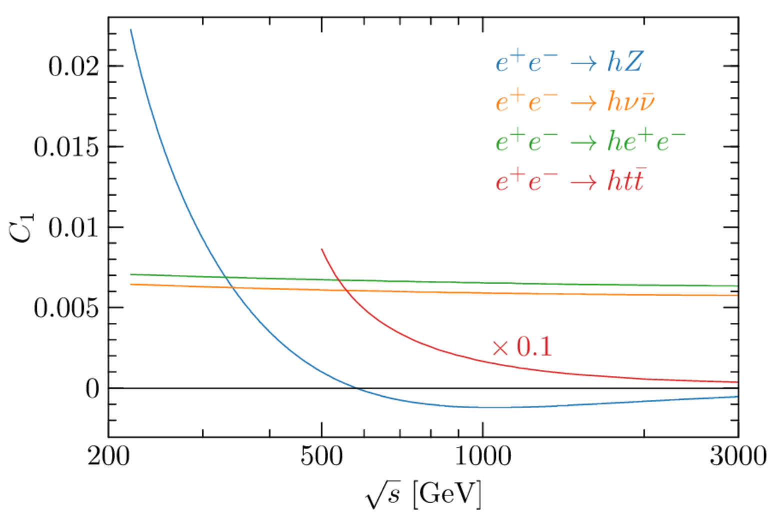
Higgs self-coupling at lepton colliders

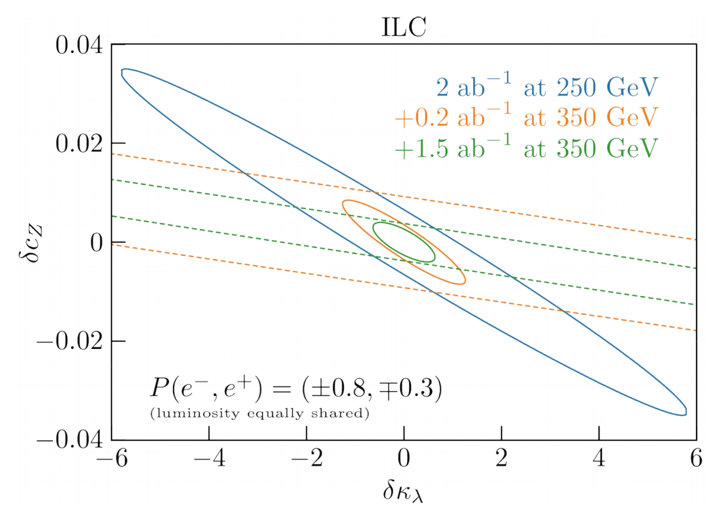
This program benefits from the high precision machines

arXiv:1704.02333

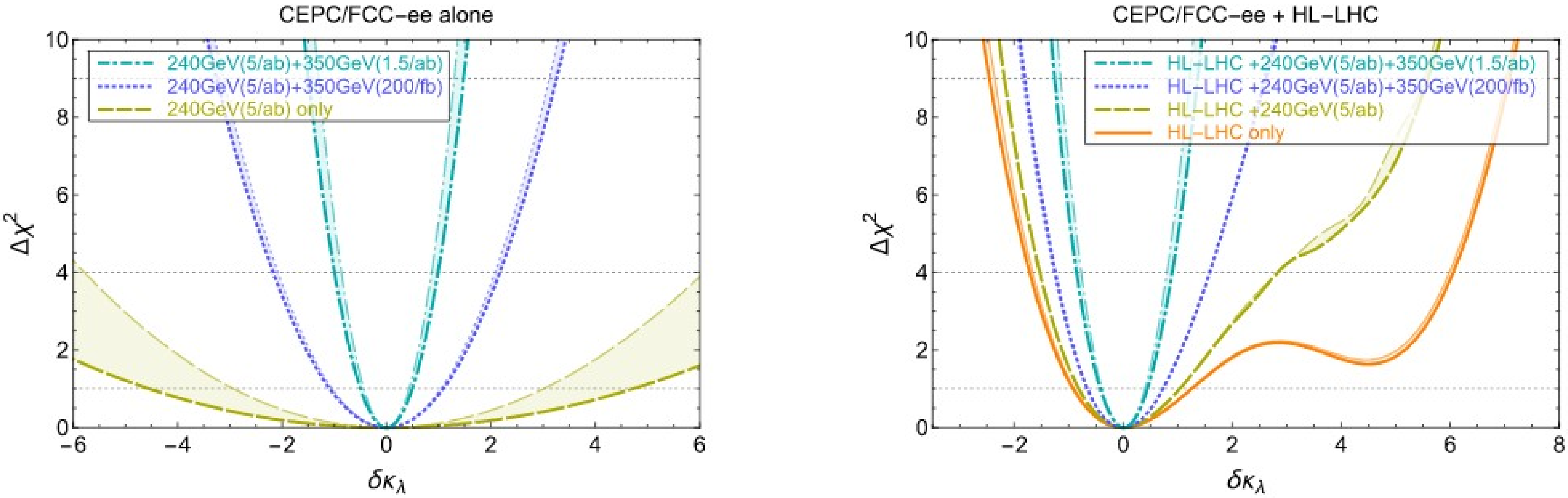






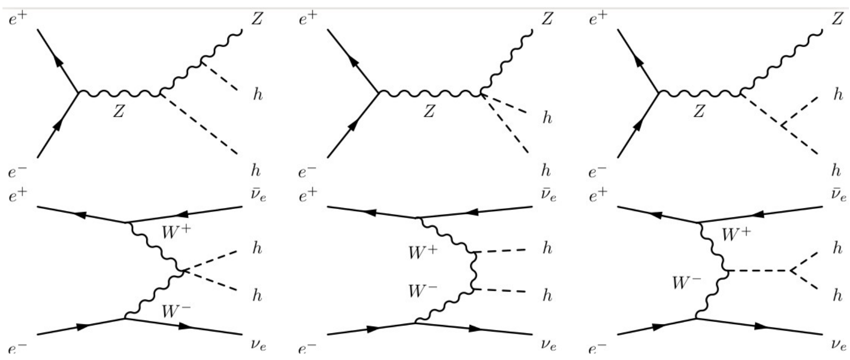


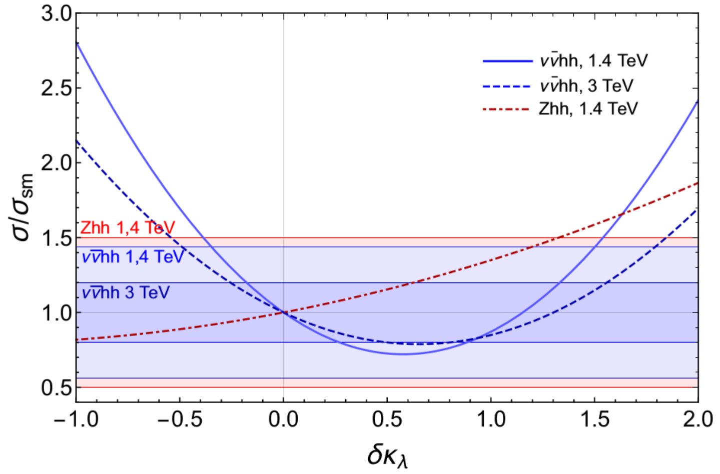
Higgs self-coupling at lepton colliders

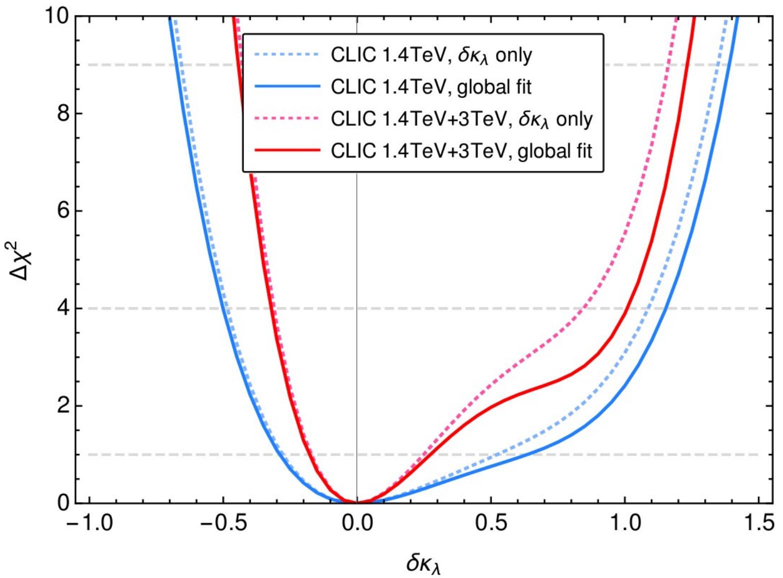


- Low energy lepton colliders set strong constraints on the self-coupling, even running below di-Higgs threshold.
- No self-coupling can be excluded at 95%CL!

Higgs self-coupling at high energy lepton colliders

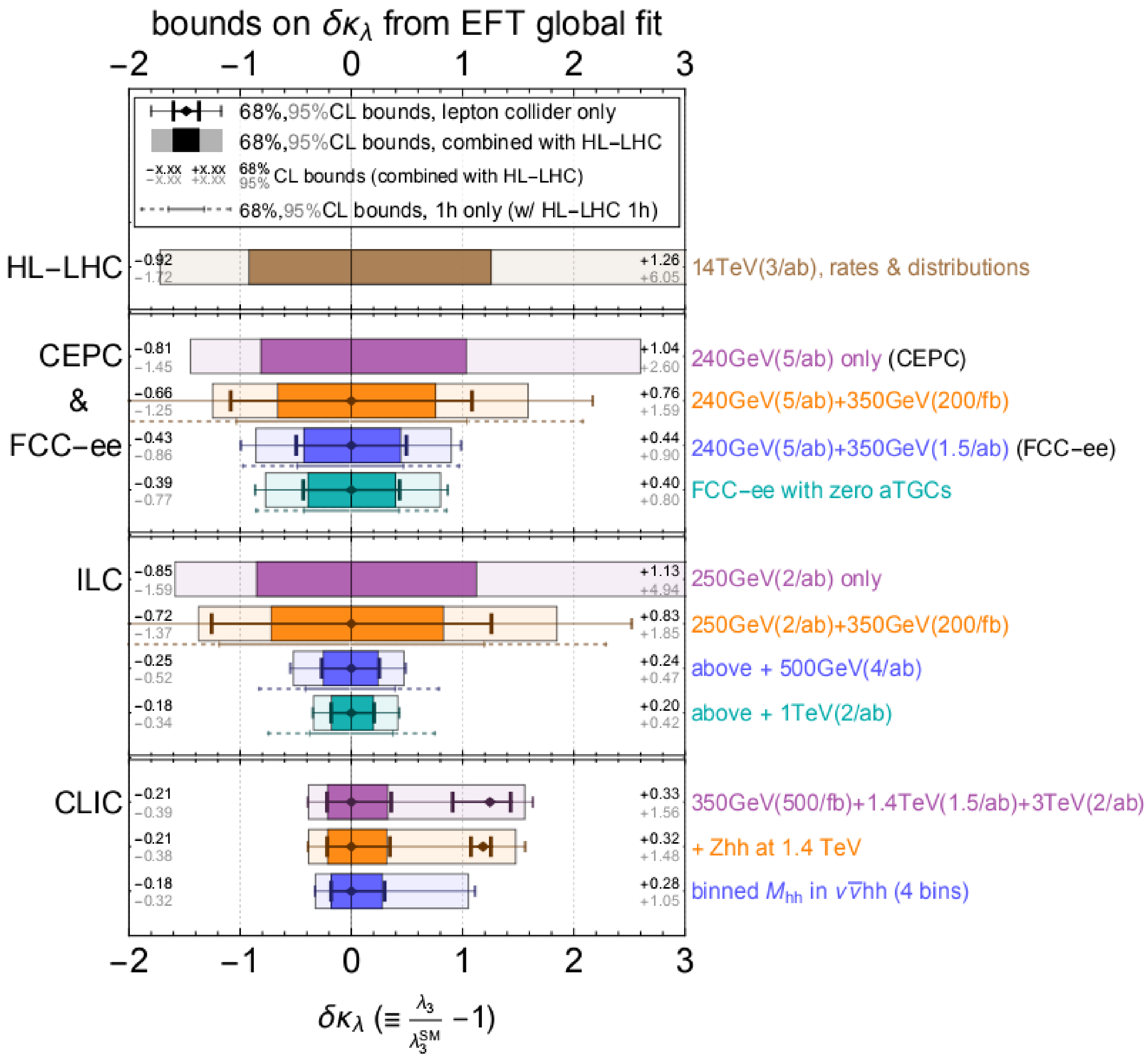






- At high energy lepton colliders, if kinematically allowed di-Higgs dominates the constraints.

Summary



bounds on $\delta\kappa_\lambda$ from EFT global fit
68%,95%CL bounds, lepton collider only
68%,95%CL bounds, combined with HL-LHC
68% 95% CL bounds (combined with HL-LHC)
68%,95%CL bounds, 1h only (w/ HL-LHC 1h)
HL-LHC
14TeV(3/ab), rates & distributions
-0.92 -1.72 +1.26 +6.05
CEPC & FCC-ee
240GeV(5/ab) only (CEPC)
-0.81 -1.45 +1.04 +2.60
240GeV(5/ab)+350GeV(200/fb)
-0.66 -1.25 +0.76 +1.59
240GeV(5/ab)+350GeV(1.5/ab) (FCC-ee)
-0.43 -0.86 +0.44 +0.90
FCC-ee with zero aTGCs
-0.39 -0.77 +0.40 +0.80
ILC
250GeV(2/ab) only
-0.85 -1.59 +1.13 +4.94
250GeV(2/ab)+350GeV(200/fb)
-0.72 -1.37 +0.83 +1.85
above + 500GeV(4/ab)
-0.25 -0.52 +0.24 +0.47
above + 1TeV(2/ab)
-0.18 -0.34 +0.20 +0.42
CLIC
350GeV(500/fb)+1.4TeV(1.5/ab)+3TeV(2/ab)
-0.21 -0.39 +0.33 +1.56
+ Zhh at 1.4 TeV
-0.21 -0.38 +0.32 +1.48
binned M_{hh} in $\nu\bar{\nu}hh$ (4 bins)
-0.18 -0.32 +0.28 +1.05
$\delta\kappa_\lambda \left(\equiv \frac{\lambda_3}{\lambda_3^{SM}} - 1\right)$

A few items for discussion...

- Some diff. distributions will get an amazing precision,

ATLAS											
$p_T{}^H$ [GeV]	0-10	10-15	15-20	20-30	30-45	45-60	60-80	80-120	120-200	200-350	350-1000
$H \to \gamma\gamma$	5.3%	4.6%		4.9%	4.7%	5.4%	5.7%	4.9%	4.2%	5.1%	8.7%
$H \to ZZ$	8.3%	7.6%	8.3%	6.3%	5.7%	6.2%	6.3%	5.7%	6.4%	13.1%	23.2%
Combination	4.5%	3.8%		3.9%	3.6%	4.1%	4.2%	3.7%	3.5%	4.5%	8.2%

CMS									
$p_T{}^H$ [GeV]	0-15	15-30	30-45	45-80	80-120	120-200	200-350	350-600	600-∞
$H \to \gamma\gamma$	5.1%	4.6%	5.1%	4.8%	4.9%	4.5%	5.1%	8.6%	32.2%
$H \to ZZ$	5.4%	4.8%	4.1%		4.7%		9.1%		
$H \to bb$	none							31.4%	36.8%
Combination	3.7%	3.3%	4.2%	3.7%	4.0%	3.8%	4.4%	8.0%	24.5%

Table 26: Relative uncertainties on the projected $p_T{}^H$ spectrum measurements by ATLAS and CMS under S2 at 3000 fb^{-1}.

there seems to be room for improvement.

- Different from *traditional* EFT dimension 6 effects, since they show up at large invariant masses, while here the crucial aspect is high precision near threshold.

- Current theory fit for tth is validated with CMS projections for tth, but the rest are not... need for more experimental studies!