Probing the Higgs self coupling via single Higgs production at the LHC

based on arXiv:1607.04251

in collaboration with G. Degrassi, P.P. Giardino and F. Maltoni

Davide Pagani

Higgs Couplings 2016
SLAC
11-11-2016

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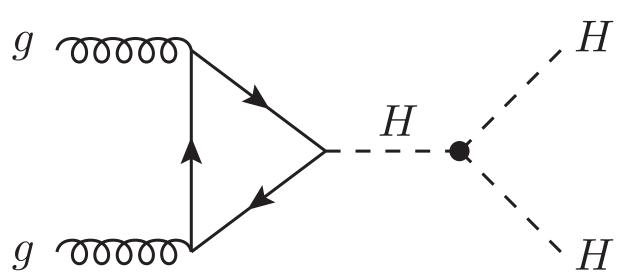
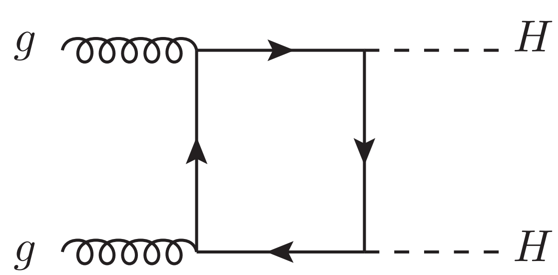
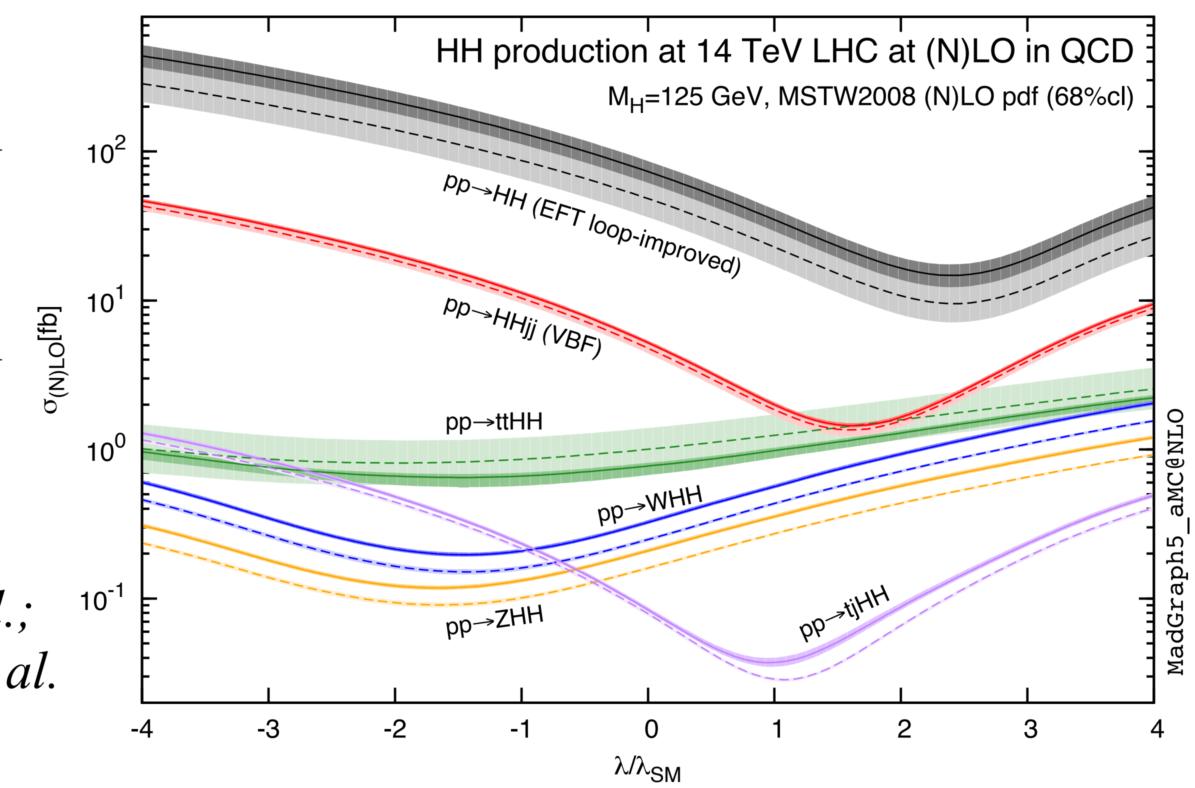
Standard Answer: you need to produce **at least two** Higgs!

$$\lambda \equiv \kappa_\lambda \lambda^{\rm SM}$$





Frederix et al. '14



Pheno studies on LHC constraints for κ_λ:

Baur et al. '03. Baglio et al.; Papaefstathiou et al. '12. Barger et al.; Yao '13. de Lima et al.; Englert et al.; Liu and Zhang; Wardrope et al. '14. Azatov et al.; Behr et al.; Cao et al.; Dolan et al.; Lu et al. '15.

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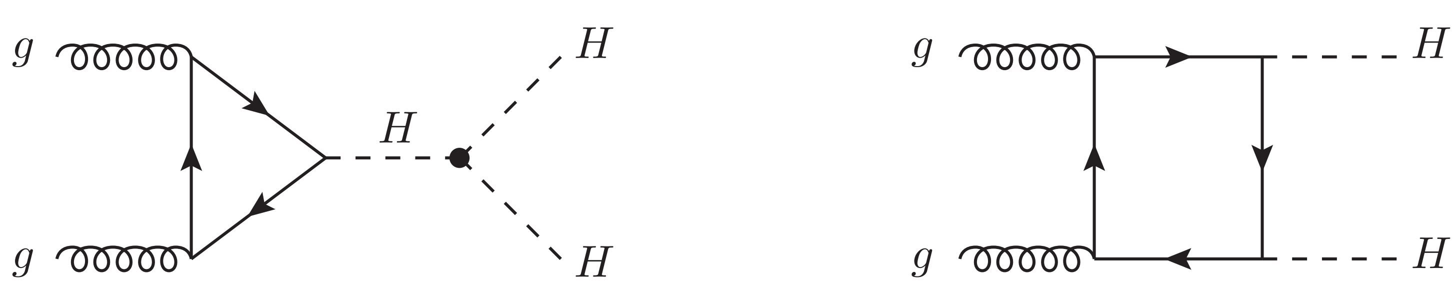

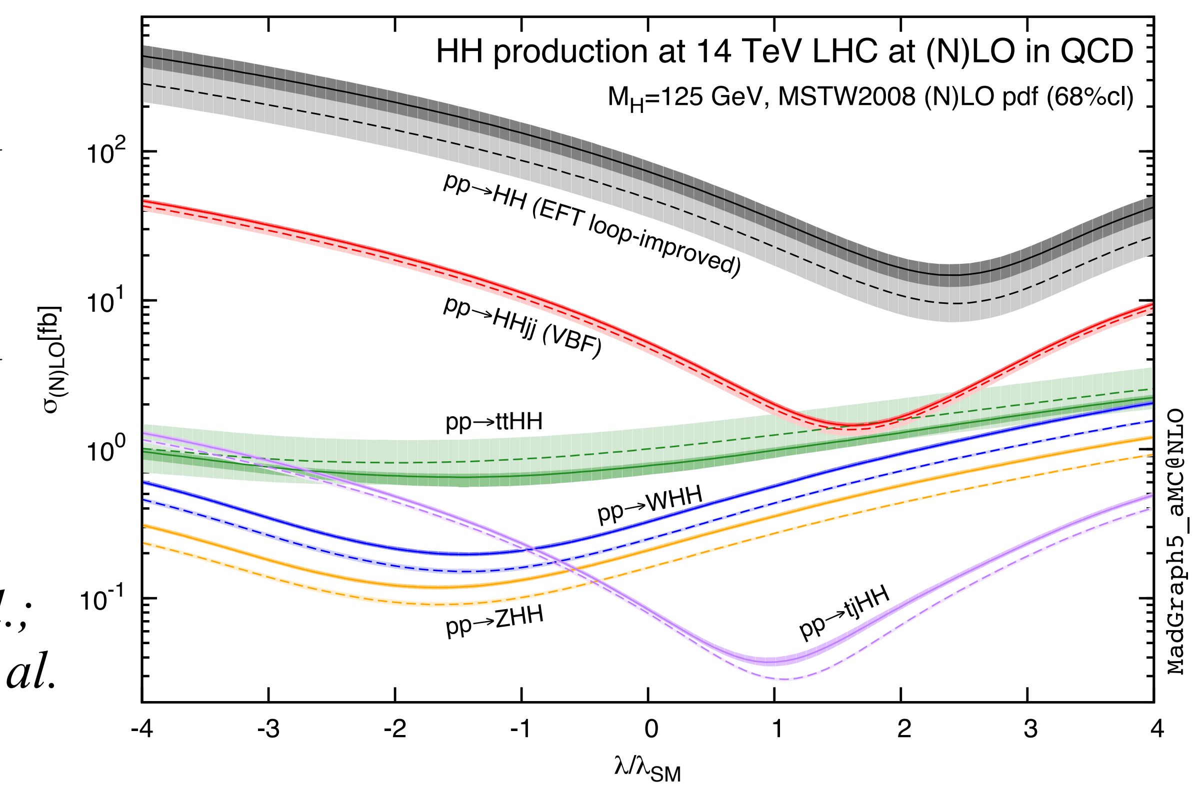

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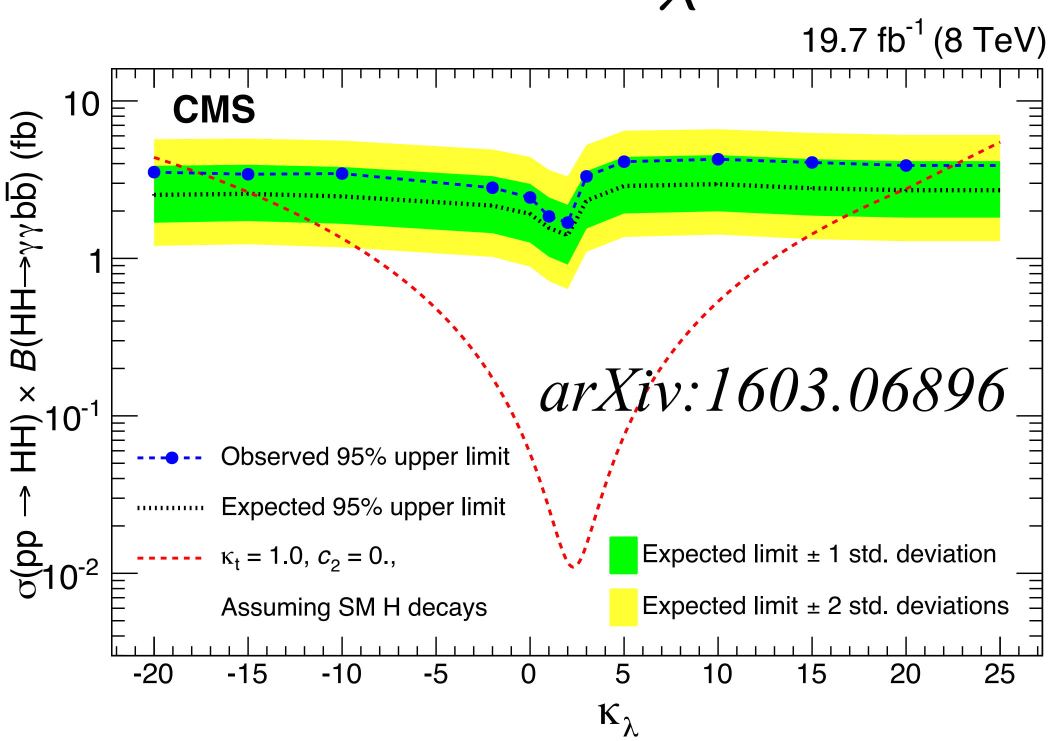

We can exclude only κ_λ in the range

$(-\infty, -17.5] \cup [22.5, \infty)$ *arXiv:1603.06896*

And the best ***experimental*** estimate for 3000 fb^{-1} ($b\bar{b}\gamma\gamma$) are:

$(-\infty, -1.3] \cup [8.7, \infty)$ *ATL-PHYS-PUB-2014-019*

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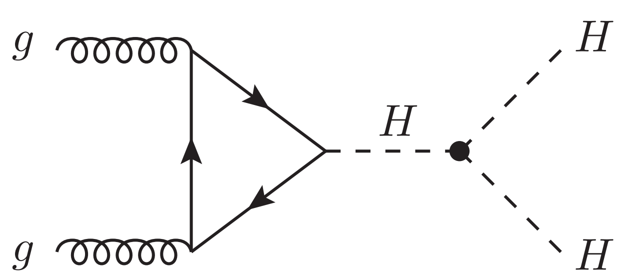

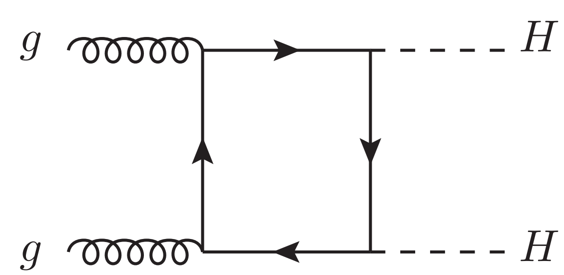

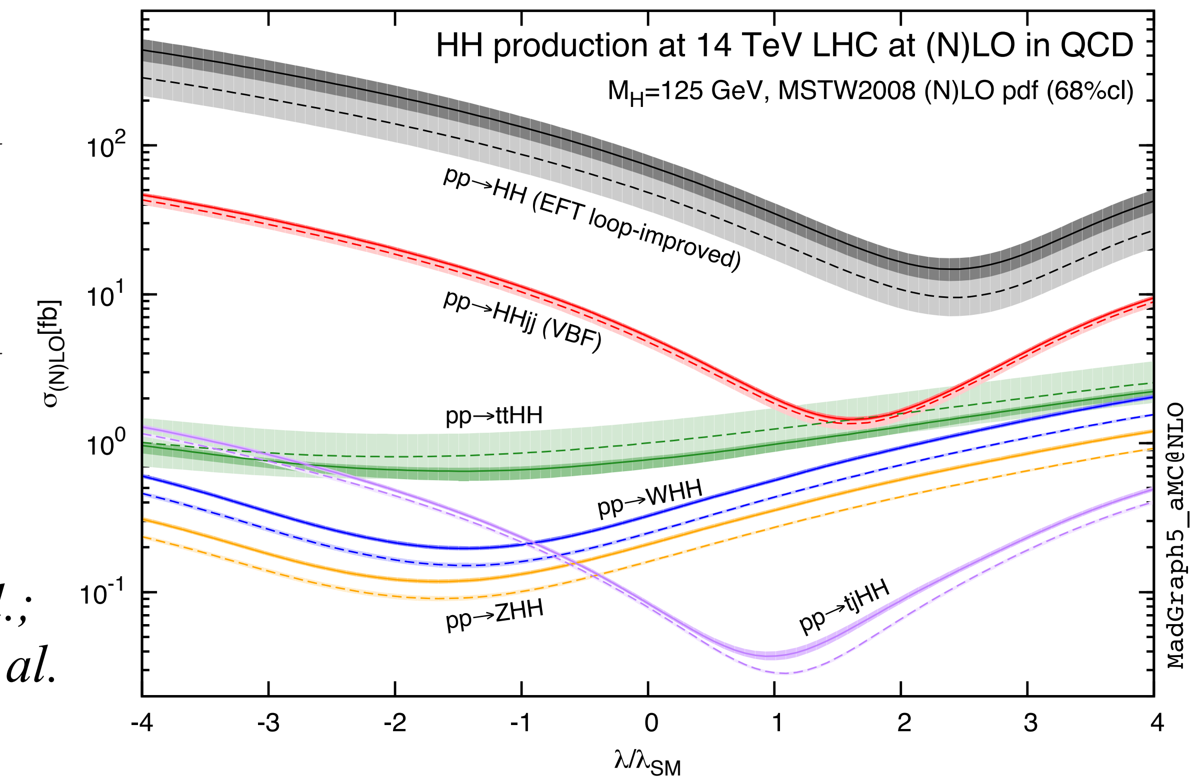

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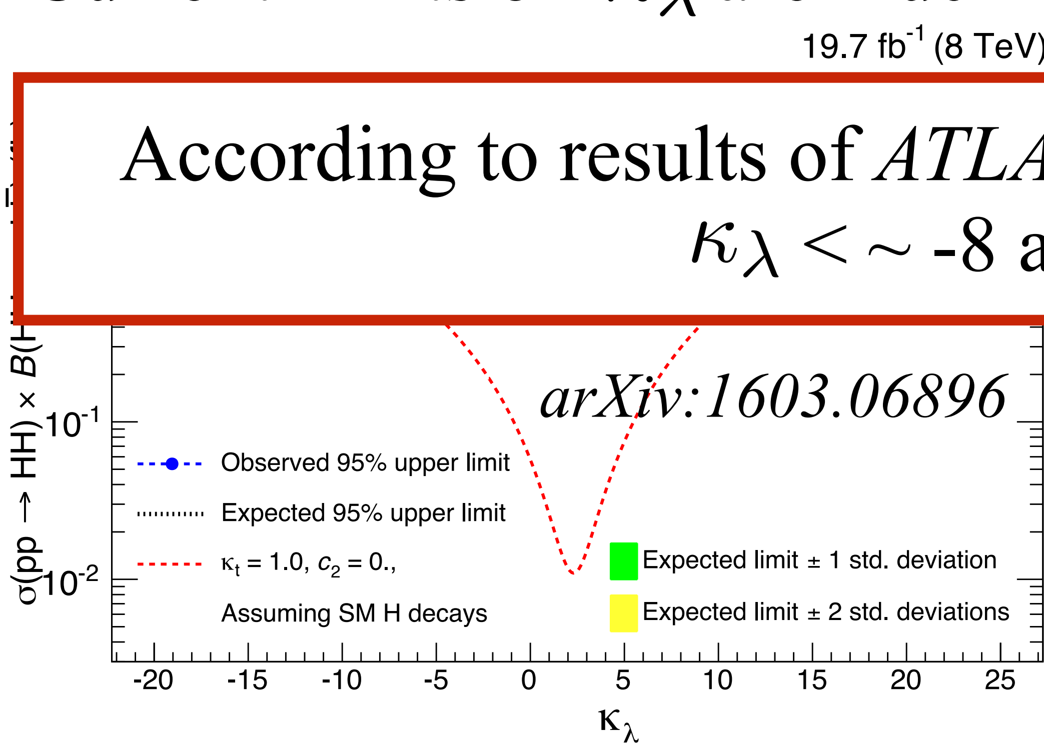
Current limits on κ_λ are much weaker than those on the other kappas. ($\kappa_t = 1$)

According to results of *ATLAS-CONF-2016-049* (4b final state at 13 TeV)
$\kappa_\lambda < \sim -8$ and $\kappa_\lambda > \sim 12$ are excluded



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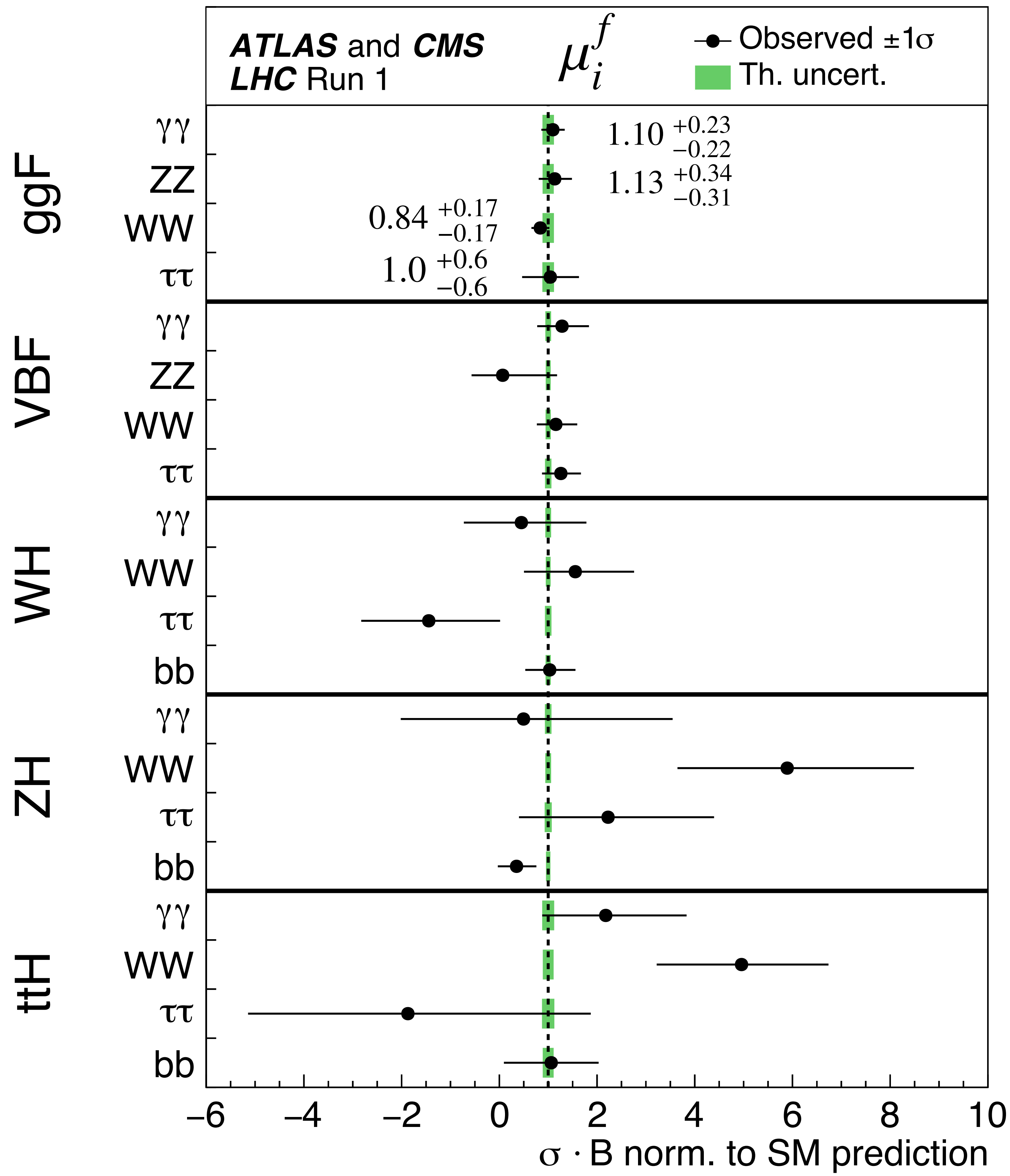
Single-Higgs production is measured NOW: μ_i^f



LHC 8-TeV data for most of the **single-Higgs** production+decay channels have been exploited for a combined determination of the various signal strengths μ_i^f.

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} \qquad \mu^f = \frac{{\rm B}^f}{({\rm B}^f)_{\rm SM}}$$

$$\mu_i^f = \frac{\sigma_i \cdot {\rm B}^f}{(\sigma_i)_{\rm SM} \cdot ({\rm B}^f)_{\rm SM}} = \mu_i \cdot \mu^f$$

Atlas and CMS: JHEP 1608 (2016) 045, arXiv:1606.02266

See talk of Stefan Guindon

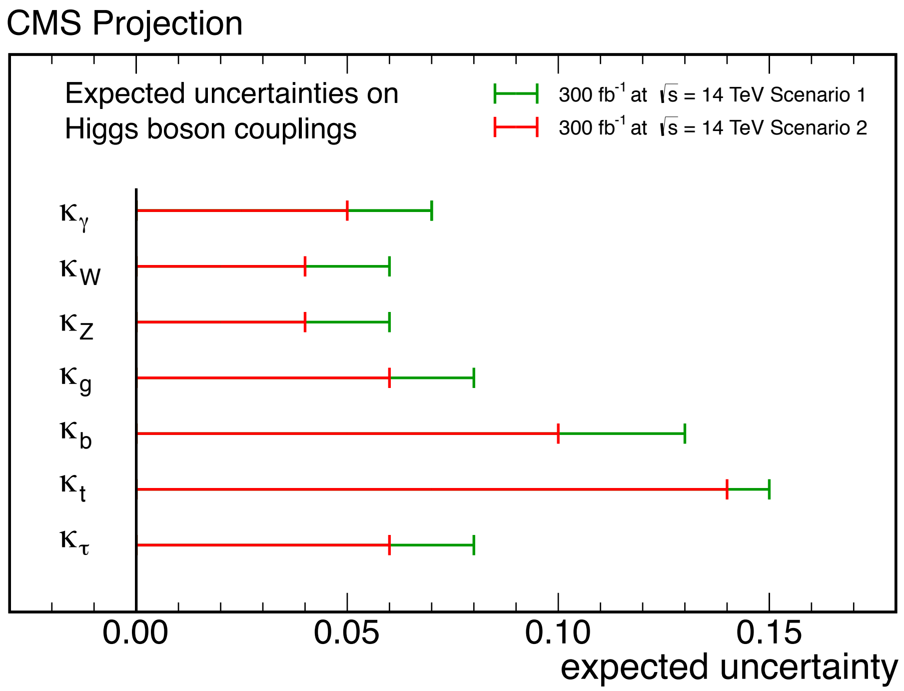
… and more precisely in the future

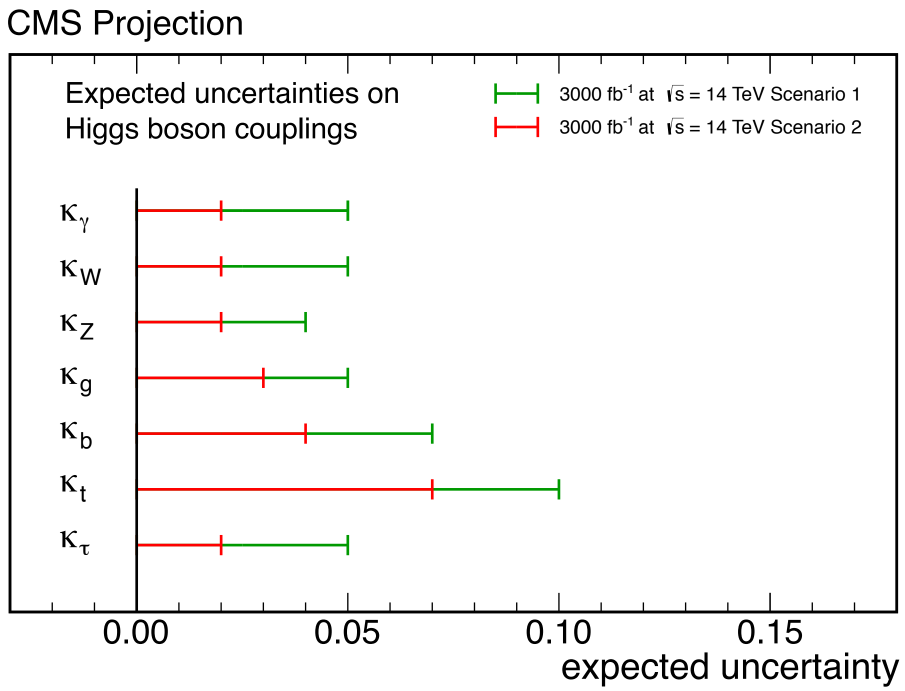
3000 fb^{-1} :

Observable	ATLAS-HL	CMS-HL-1	CMS-HL-2
$\sigma(gg) \cdot BR(\gamma\gamma)$	$5 \oplus 19$	$4 \oplus 12.3$	$0.9 \oplus 6.2$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$15 \oplus 15$	$10 \oplus 2.4$	$4.4 \oplus 1.2$
$\sigma(gg) \cdot BR(WW)$	$5 \oplus 18$	$6 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW) \cdot BR(WW)$	$9 \oplus 8$	$24 \oplus 2.4$	$8.9 \oplus 1.2$
$\sigma(gg) \cdot BR(ZZ)$	$4 \oplus 11$	$4 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW) \cdot BR(ZZ)$	$16 \oplus 13$	$7 \oplus 12.3$	$1.9 \oplus 6.2$
$\sigma(WW) \cdot BR(\tau\tau)$	$12 \oplus 15$	$8 \oplus 2.4$	$2.8 \oplus 1.2$
$\sigma(Wh) \cdot BR(b\bar{b})$	—	$8 \oplus 3.8$	$4.4 \oplus 1.7$
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	—	$35 \oplus 11.7$	$16 \oplus 5.9$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$17 \oplus 12$	$28 \oplus 11.7$	$12 \oplus 5.9$
$\sigma(Zh) \cdot BR(invis)$	—	$10 \oplus 4.3$	$3.5 \oplus 2.2$

Predicted precision on the signal strengths μ_i^f

Peskin, arXiv:1312.4974





κ_j

CMS, arXiv:1307.7135

Predicted precision on the coupling modifiers κ_j

An additional and complementary strategy for the determination (at the LHC) of the Higgs self coupling would be desirable!

We can exploit at the LHC the
"High Precision for Hard Processes"

HP^2

It is time for something new

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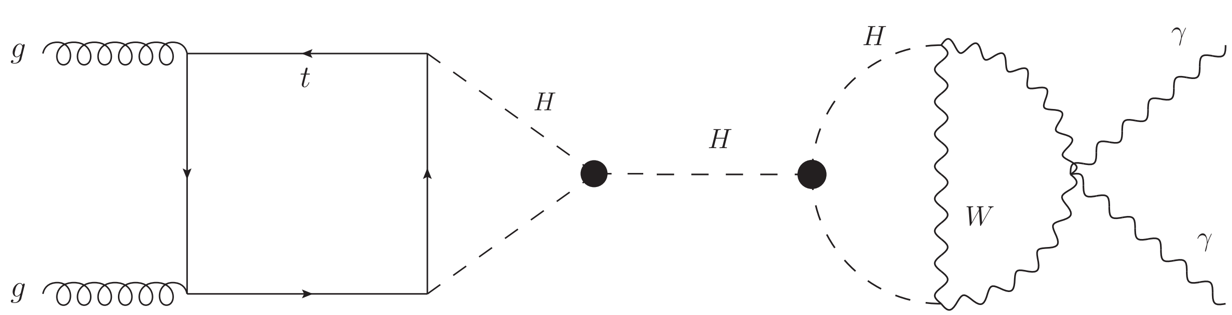
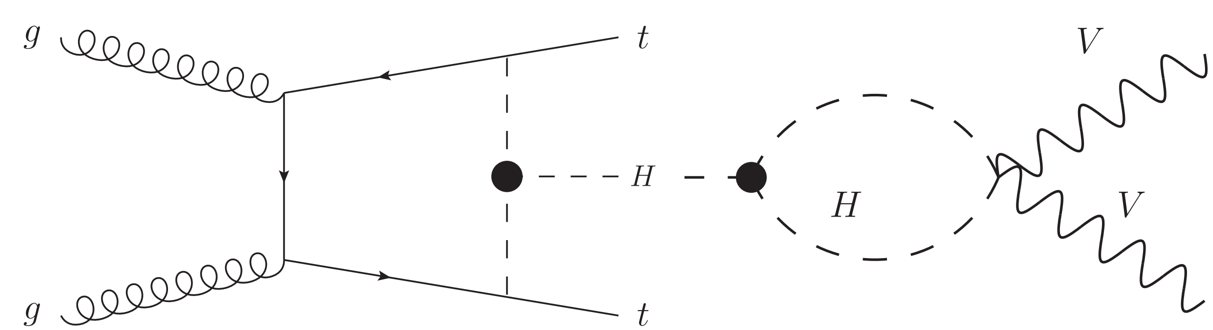
and ***probe*** the quantum effects (NLO EW) induced by the triple Higgs self coupling on single Higgs production and decay modes.





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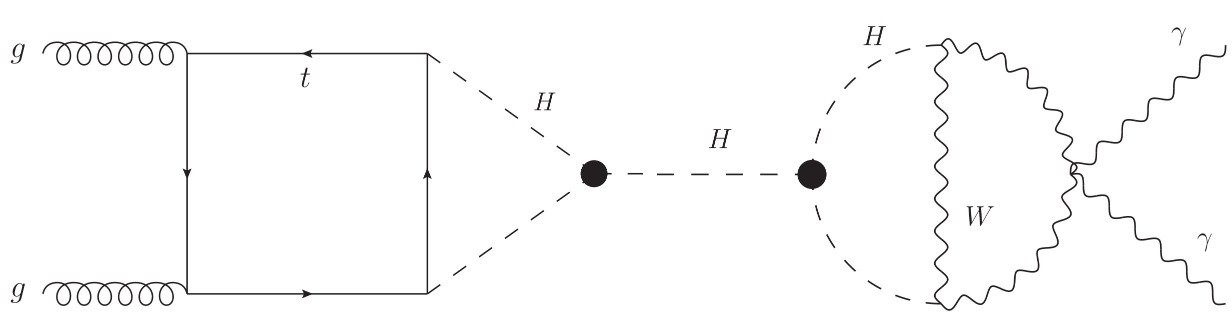

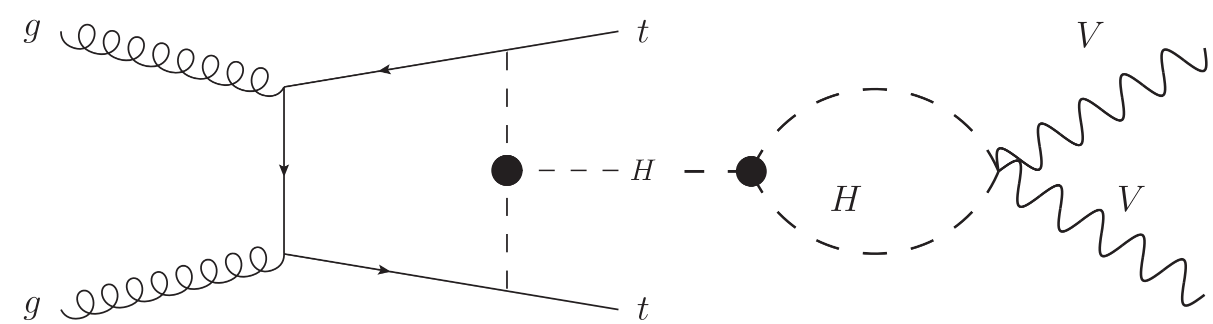

All the single Higgs production and decay processes are affected by an anomalous trilinear Higgs self coupling, parametrized by κ_λ.

All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

Calculation framework

We assume that New Physics induces only a modification in the Higgs potential, rescaling the trilinear coupling by a factor κ_λ

SM

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

$$m_H^2 = 2\lambda v^2, \lambda_3^{\rm SM} = \lambda, \lambda_4^{\rm SM} = \lambda/4$$

→

New Physics

$$V_{H^3} = \lambda_3 \, v \, H^3 \equiv \kappa_\lambda \lambda_3^{\rm SM} \, v \, H^3$$

Equivalently, the calculation is valid also for NP scenarios where effects from anomalous HVV and Hff interactions are smaller than those induced by κ_λ.

The calculation can also be understood as the sensitivity of the single-Higgs production on the parameter κ_λ in the kappa framework with $1 = \kappa_F = \kappa_V$.

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Equivalent study for only ZH production at e+e- collider in *McCullough '14*

Similar studies in EFT approach for only gluon-fusion with decays into photons in *Gorbahn, Haisch '16,* and for VBF+VH in *Bizon, Gorbahn, Haisch, Zanderighi '16*

The Master Formula

The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

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

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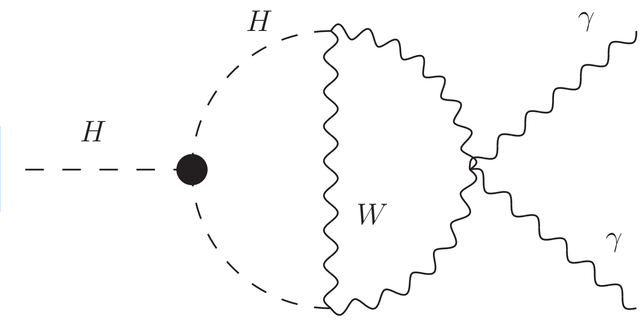
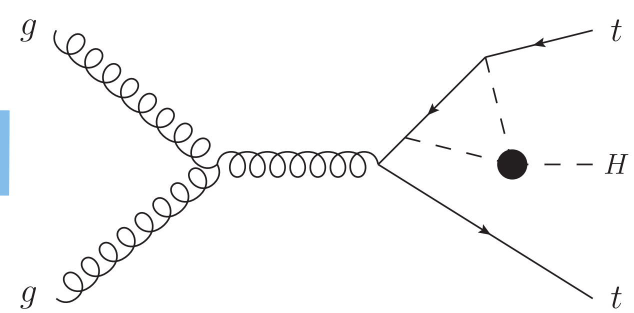


$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

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



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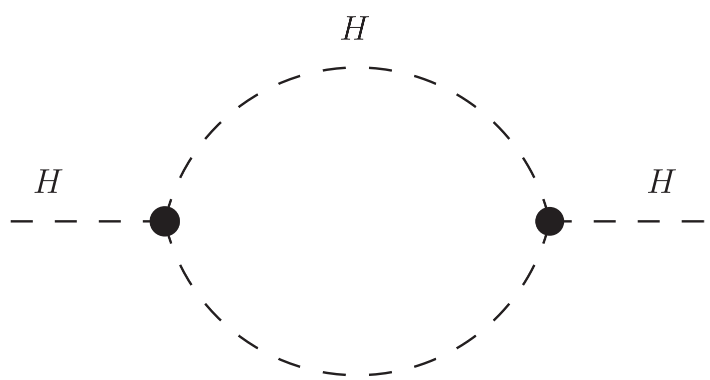
$$\Sigma_{\rm NLO} = \boxed{Z_H}\, \Sigma_{\rm LO}\, (1 + \kappa_\lambda C_1)$$

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



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

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

The Master Formula

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

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

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

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

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

NLO EW and anomalous couplings

If we modify a SM coupling via $c_i^{\mathrm{SM}} \to c_i \equiv \kappa_i c_i^{\mathrm{SM}}$, do higher-order computations ***remain in general finite*** (UV cancellation)? **NO**

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Exceptions

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Standard "kappa framework"
(No EW corrections possible)

Sensitivity of ttbar production on κ_t
(NLO EW effect)

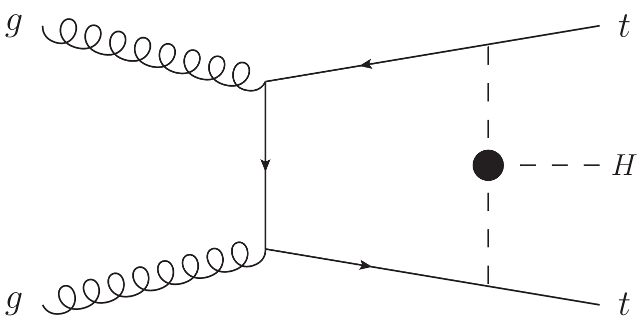
Kühn et al. '13; Beneke et al. '15

Double Higgs dependence on κ_λ
(No EW corrections possible)

Sensitivity of single Higgs production on κ_λ
(NLO EW effect)

Calculation of C_1 coefficients

1 Loop Case : *FeynArts, FormCalc, Feyncalc*



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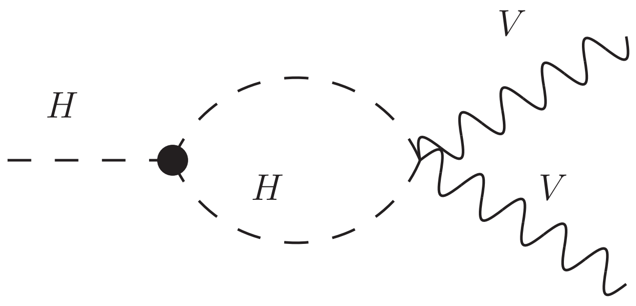

decay and HV, VBF

Cannot be expressed via

κ_t κ_Z, κ_W

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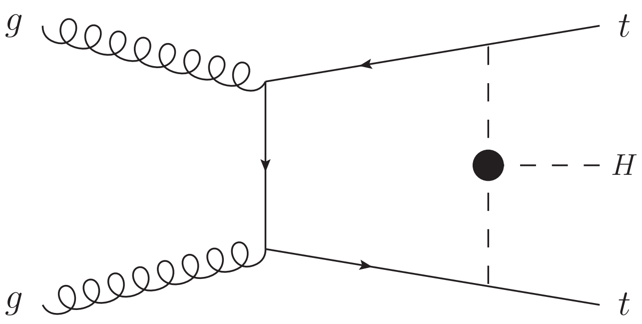

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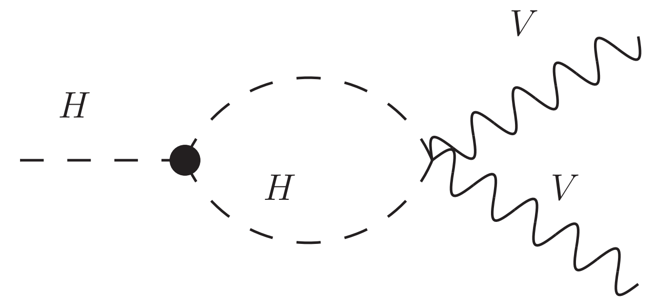

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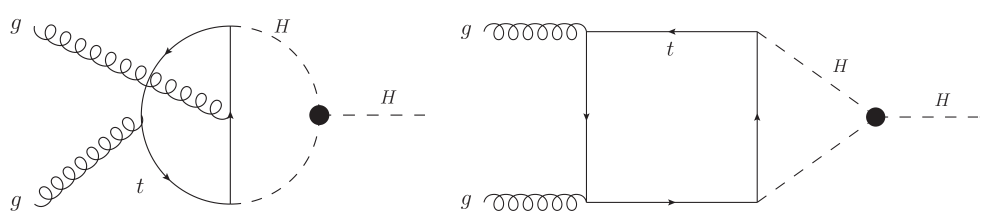
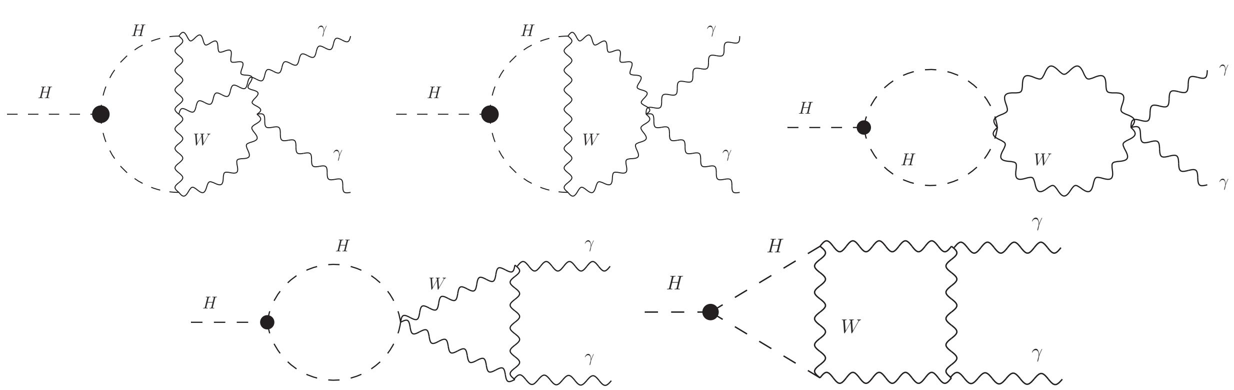
2 Loop Case : *FeynArts and expansions*



ggF

Large top-mass expansion with terms up to $\mathcal{O}(m_H^6/m_t^6)$



$H \to \gamma\gamma$

Taylor expansion in $q^2/(4m_W^2)$, $q^2/(4m_H^2)$ up to $\mathcal{O}(q^6/m^6)$

Calculation performed in unitary gauge in order to identify genuine λ_3-dependence and keep only kinematic m_H-dependence

Numerical results

universal

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

Process and kinetic dependent

$C_2 = -9.514 \cdot 10^{-4}$ for $\kappa_\lambda = \pm 20$ $\qquad$ $C_2 = -1.536 \cdot 10^{-3}$ for $\kappa_\lambda = 1$

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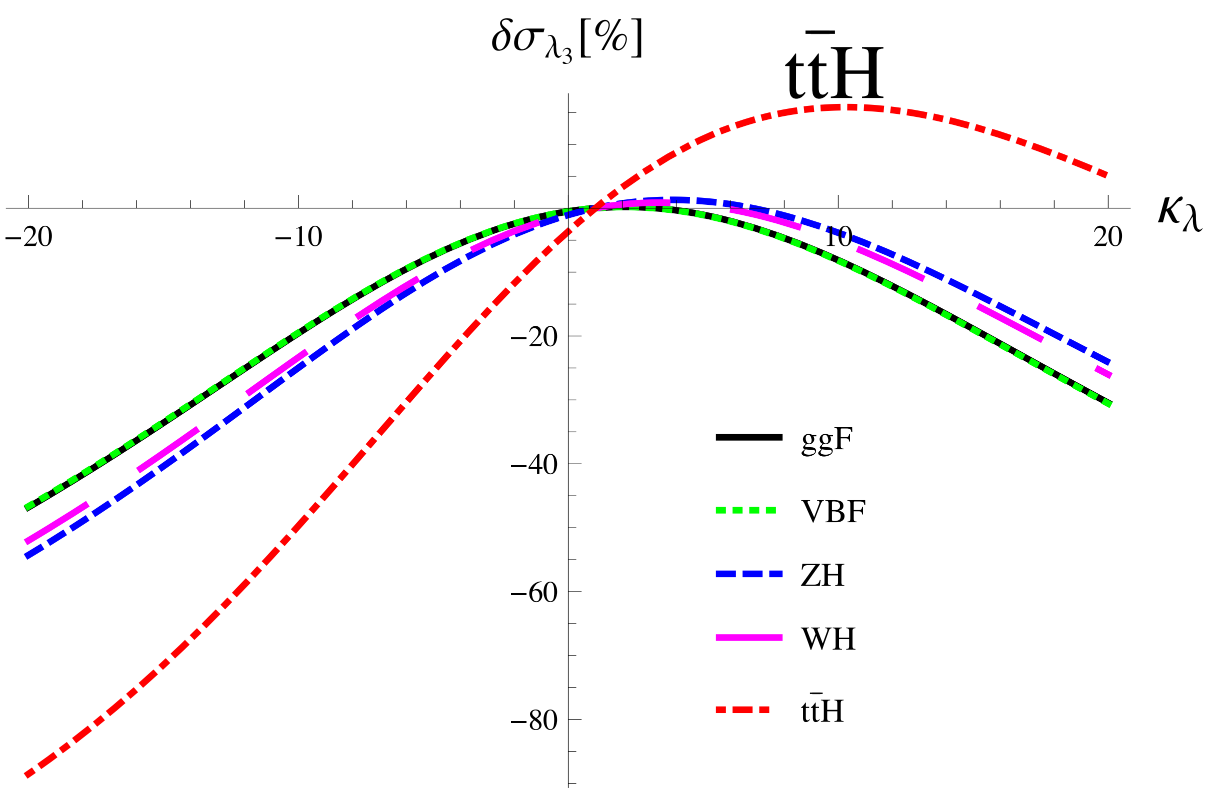
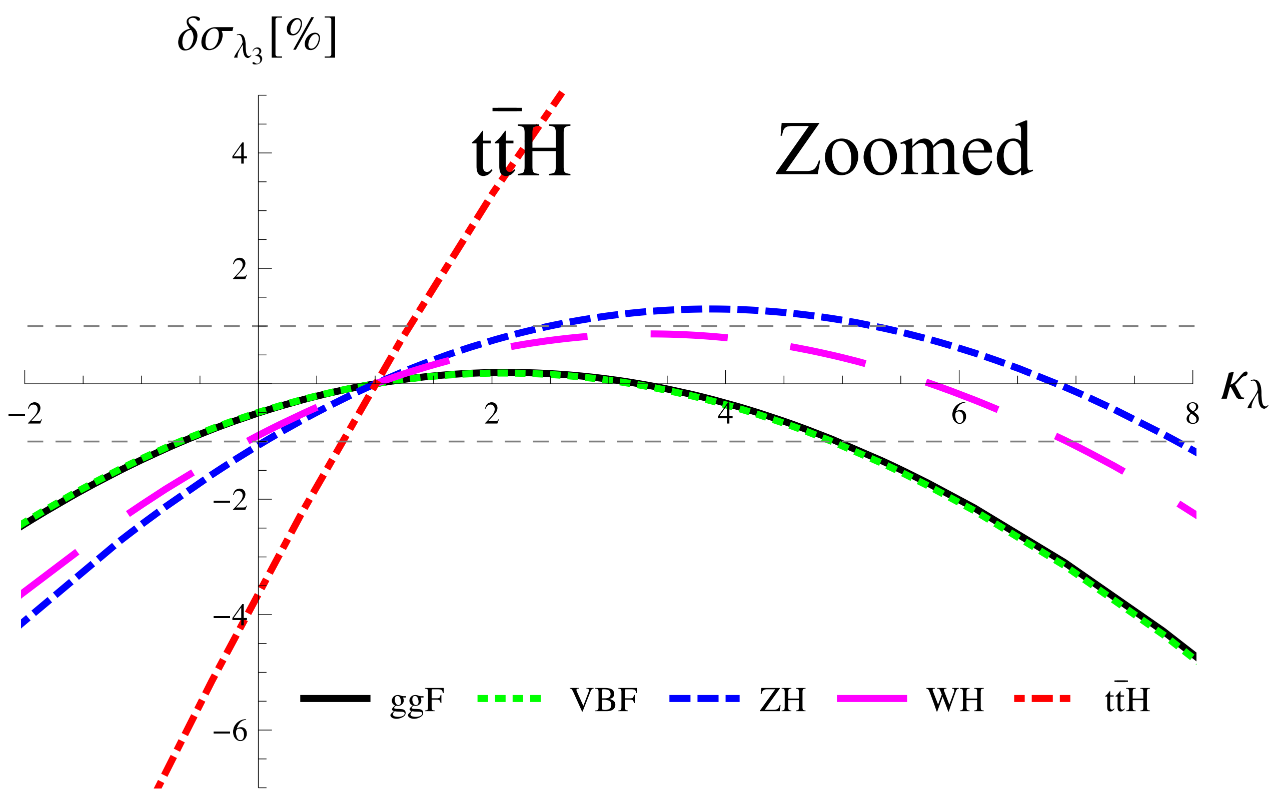
Production: $\delta\sigma_{\lambda_3}$

$C_1^\sigma[\%]$	ggF	VBF	WH	ZH	$t\bar{t}H$
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51





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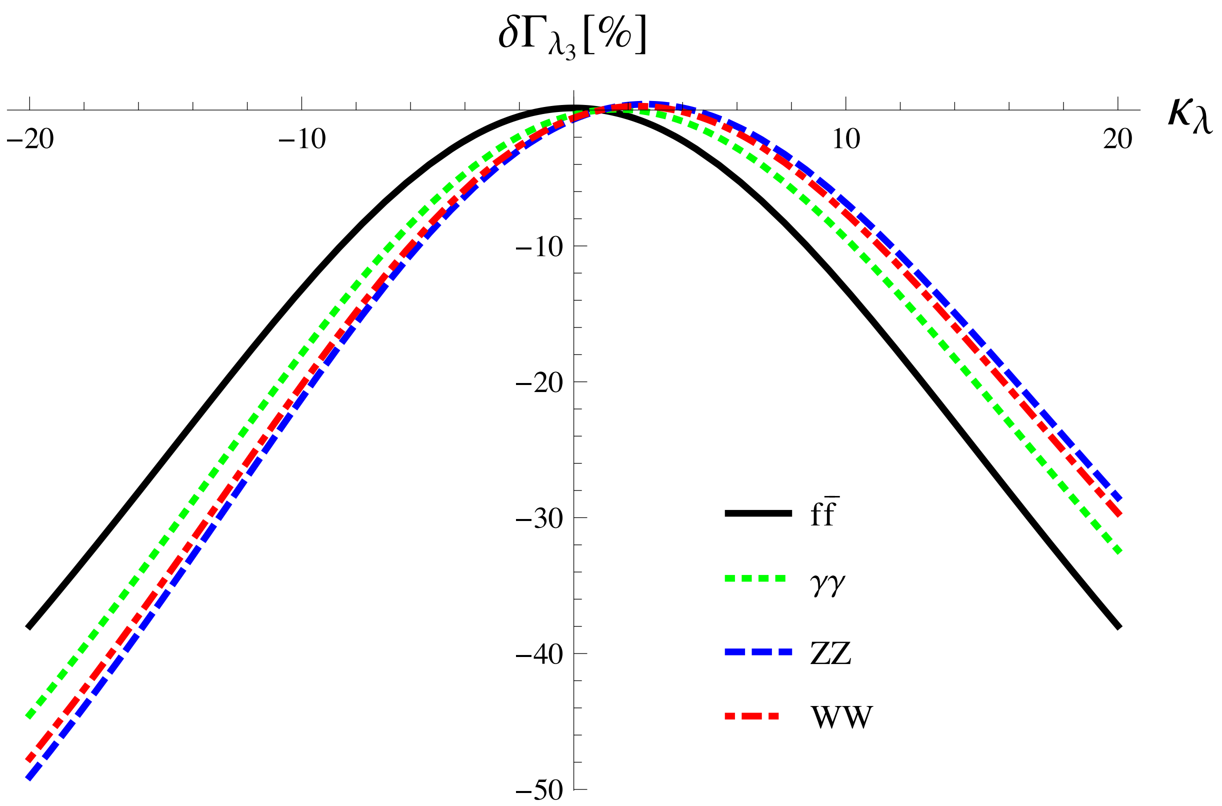
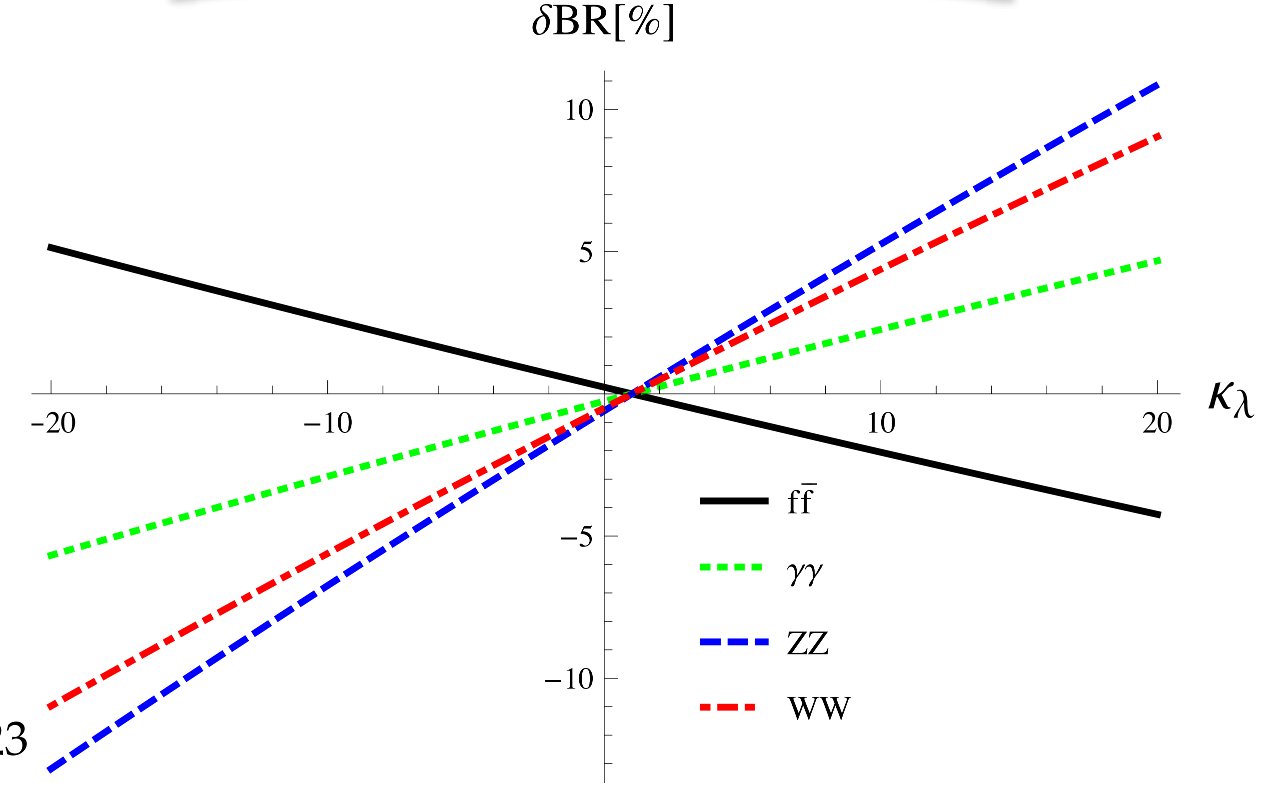
Decay: $\delta\Gamma_{\lambda_3}$ and $\delta{\rm BR}_{\lambda_3}$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$\delta{\rm BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1) C_1^{\Gamma_{\rm tot}}}$$





Predictions for signal strengths

$i \to H \to f$ ⇒ $\mu_i^f \equiv \mu_i \times \mu^f$

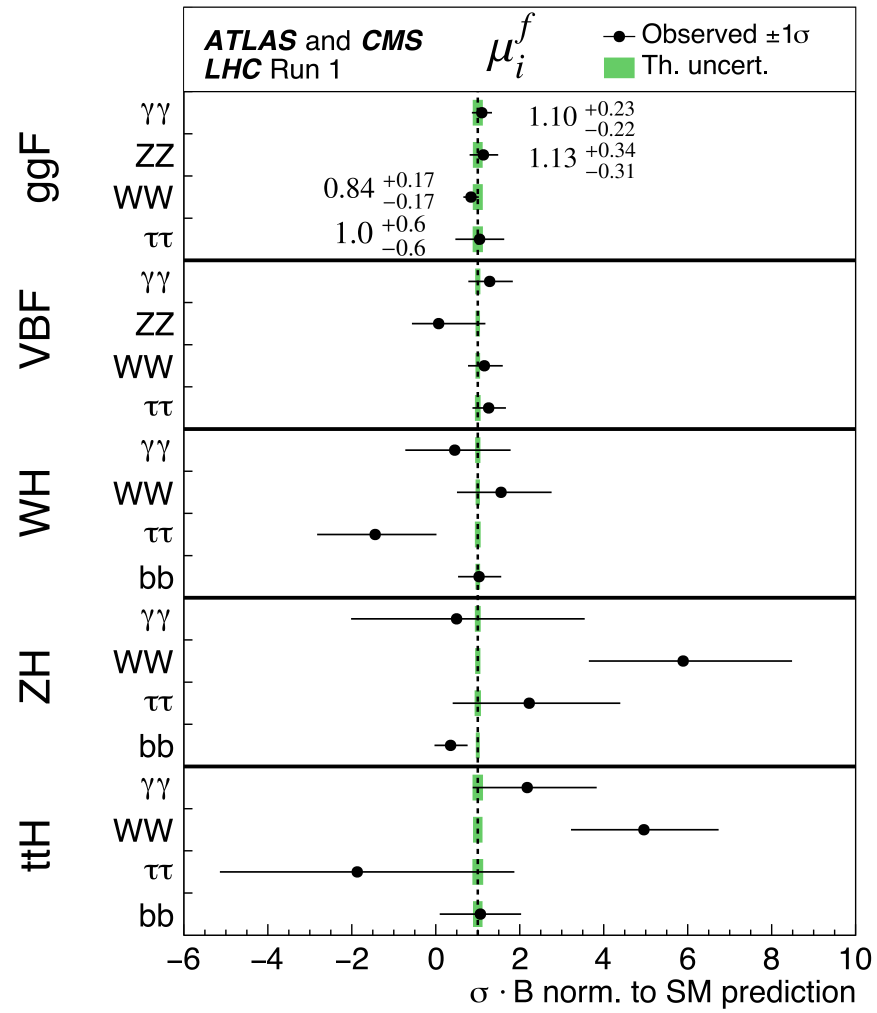
$$\begin{aligned} \mu_i &= 1 + \delta\sigma_{\lambda_3}(i) \\ \mu^f &= 1 + \delta\mathrm{BR}_{\lambda_3}(f) \end{aligned}$$

Predictions for signal strengths

$$i \to H \to f \quad \Rightarrow \quad \mu_i^f \equiv \mu_i \times \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$
$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

Determination of signal strengths μ_i^f



LHC 8-TeV data for most of the **single-Higgs** production+decay channels have been exploited for a combined determination of the various signal strengths μ_i^f.

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \qquad \mu^f = \frac{\mathrm{B}^f}{(\mathrm{B}^f)_{\mathrm{SM}}}$$

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

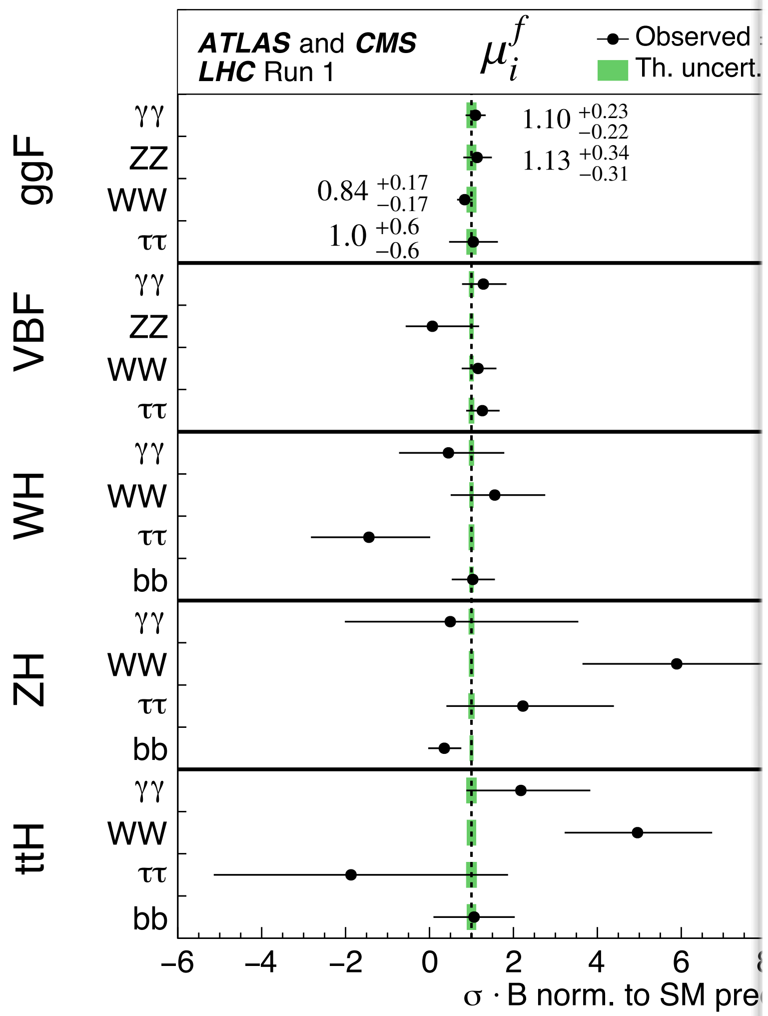
Atlas and CMS: JHEP 1608 (2016) 045, arXiv:1606.02266

Predictions for signal strengths

$$i \to H \to f \quad \Rightarrow \quad \mu_i^f \equiv \mu_i \times \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$
$$\mu^f = 1 + \delta\mathrm{BR}_{\lambda_3}(f)$$

Determination of signal strengths μ_i^f



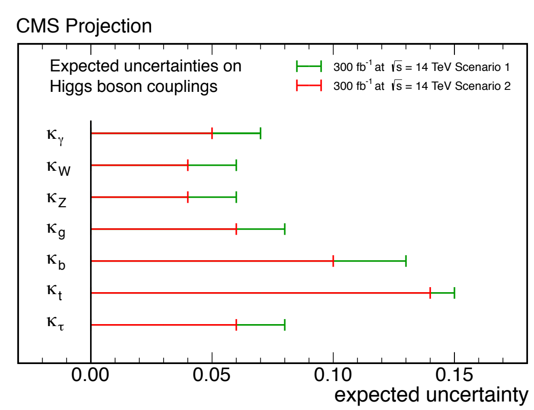
And the prospect for the future

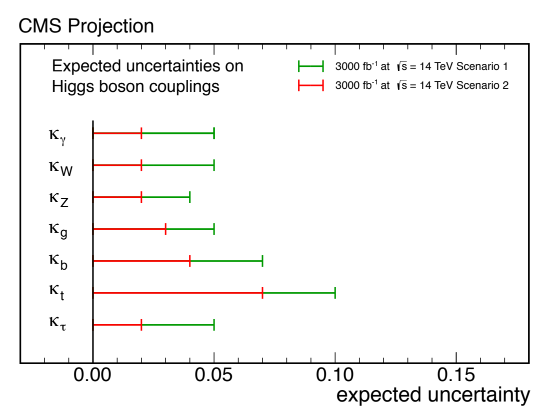
3000 fb^{-1} :

Observable	ATLAS-HL	CMS-HL-1	CMS-HL-2
$\sigma(gg)\cdot BR(\gamma\gamma)$	5 ⊕ 19	4 ⊕ 12.3	0.9 ⊕ 6.2
$\sigma(WW)\cdot BR(\gamma\gamma)$	15 ⊕ 15	10 ⊕ 2.4	4.4 ⊕1.2
$\sigma(gg)\cdot BR(WW)$	5 ⊕ 18	6 ⊕12.3	1.6 ⊕ 6.2
$\sigma(WW)\cdot BR(WW)$	9 ⊕ 8	24 ⊕ 2.4	8.9 ⊕ 1.2
$\sigma(gg)\cdot BR(ZZ)$	4 ⊕ 11	4 ⊕ 12.3	1.6 ⊕ 6.2
$\sigma(WW)\cdot BR(ZZ)$	16 ⊕ 13	7 ⊕ 12.3	1.9 ⊕ 6.2
$\sigma(WW)\cdot BR(\tau\tau)$	12 ⊕ 15	8 ⊕ 2.4	2.8 ⊕ 1.2
$\sigma(Wh)\cdot BR(b\bar{b})$	—	8 ⊕ 3.8	4.4 ⊕ 1.7
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	—	35 ⊕ 11.7	16 ⊕ 5.9
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	17 ⊕ 12	28 ⊕ 11.7	12 ⊕ 5.9
$\sigma(Zh)\cdot BR(invis)$	—	10 ⊕ 4.3	3.5 ⊕ 2.2

Predicted precision on the signal strengths μ_i^f

Peskin, arXiv:1312.4974





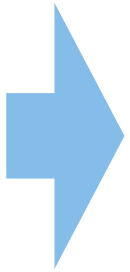
CMS, arXiv:1307.0135

Predicted precision on the coupling modifiers κ_j

7

Predictions for signal strengths

$$i \to H \to f$$

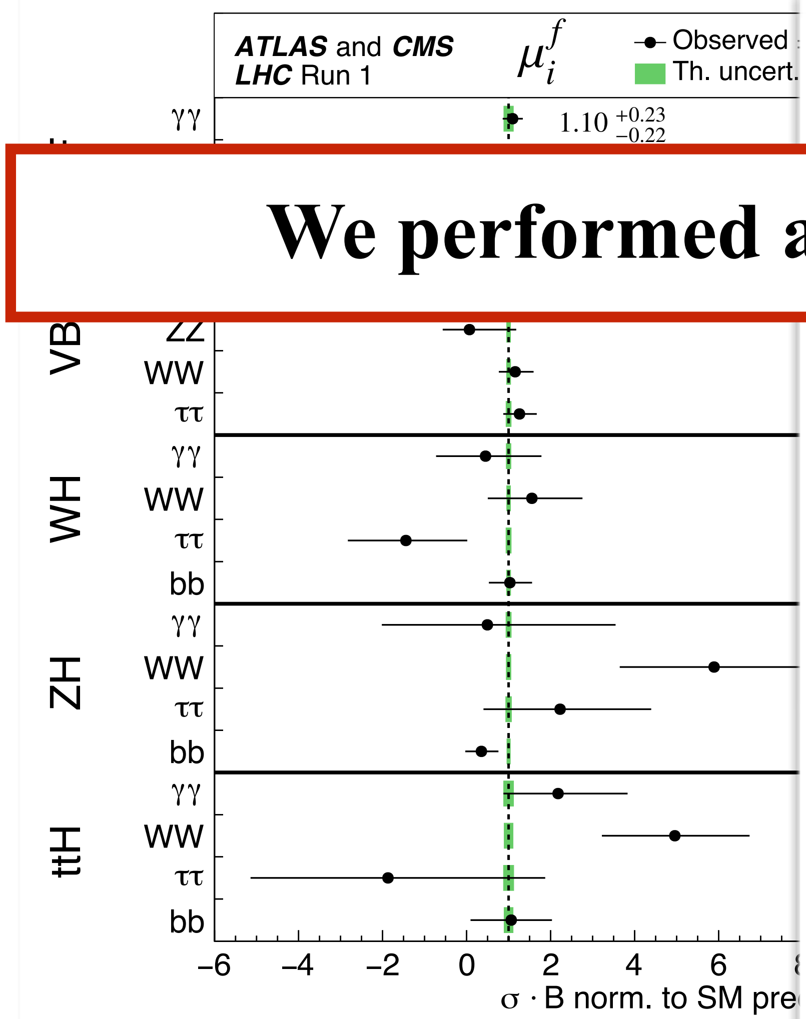


$$\mu_i^f \equiv \mu_i \times \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$

$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$

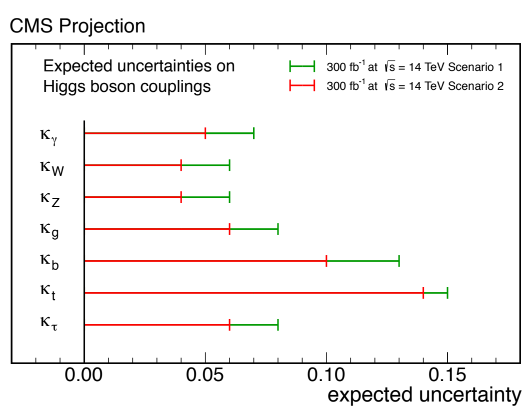
Determination of signal strengths μ_i^f

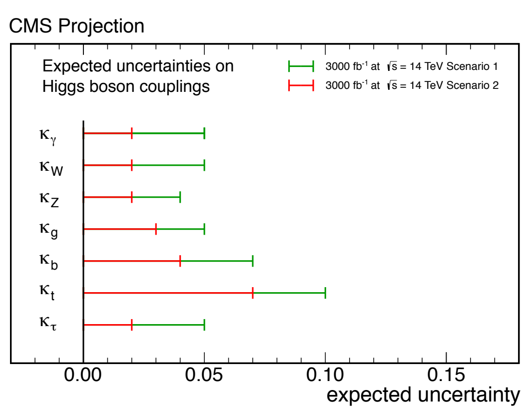


And the prospect for the future

$\sigma(gg)\cdot BR(ZZ)$	$4 \oplus 11$	$4 \oplus 12.3$	$1.6 \oplus 6.2$
$\sigma(WW)\cdot BR(ZZ)$	$16 \oplus 13$	$7 \oplus 12.3$	$1.9 \oplus 6.2$
$\sigma(WW)\cdot BR(\tau\tau)$	$12 \oplus 15$	$8 \oplus 2.4$	$2.8 \oplus 1.2$
$\sigma(Wh)\cdot BR(b\bar{b})$	—	$8 \oplus 3.8$	$4.4 \oplus 1.7$
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	—	$35 \oplus 11.7$	$16 \oplus 5.9$
$\sigma(t\bar{t}h)\cdot BR(\gamma\gamma)$	$17 \oplus 12$	$28 \oplus 11.7$	$12 \oplus 5.9$
$\sigma(Zh)\cdot BR(invis)$	—	$10 \oplus 4.3$	$3.5 \oplus 2.2$

Peskin, arXiv:1312.4974





CMS, arXiv:1307.0135

Predicted precision on the coupling modifiers κ_j

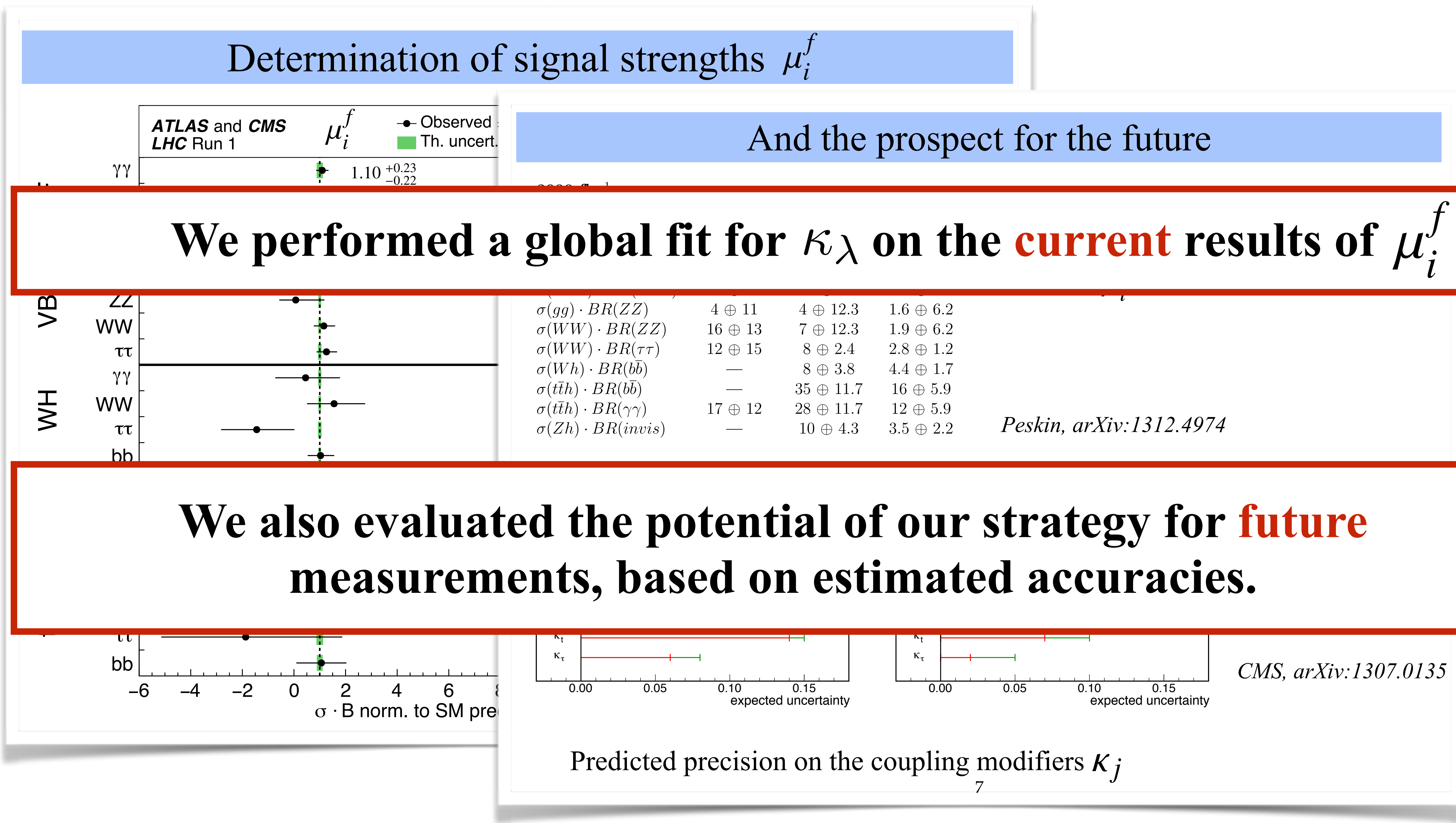
7

We performed a global fit for κ_λ on the current results of μ_i^f

Predictions for signal strengths

$$i \to H \to f \quad \Rightarrow \quad \mu_i^f \equiv \mu_i \times \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$
$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$



We performed a global fit for κ_λ on the current results of μ_i^f

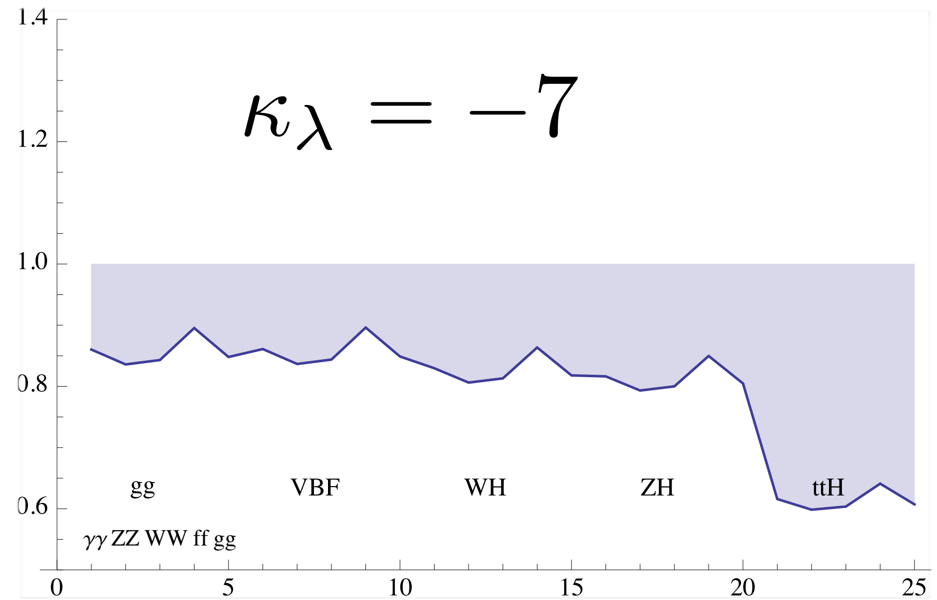
We also evaluated the potential of our strategy for future measurements, based on estimated accuracies.

Fit procedure

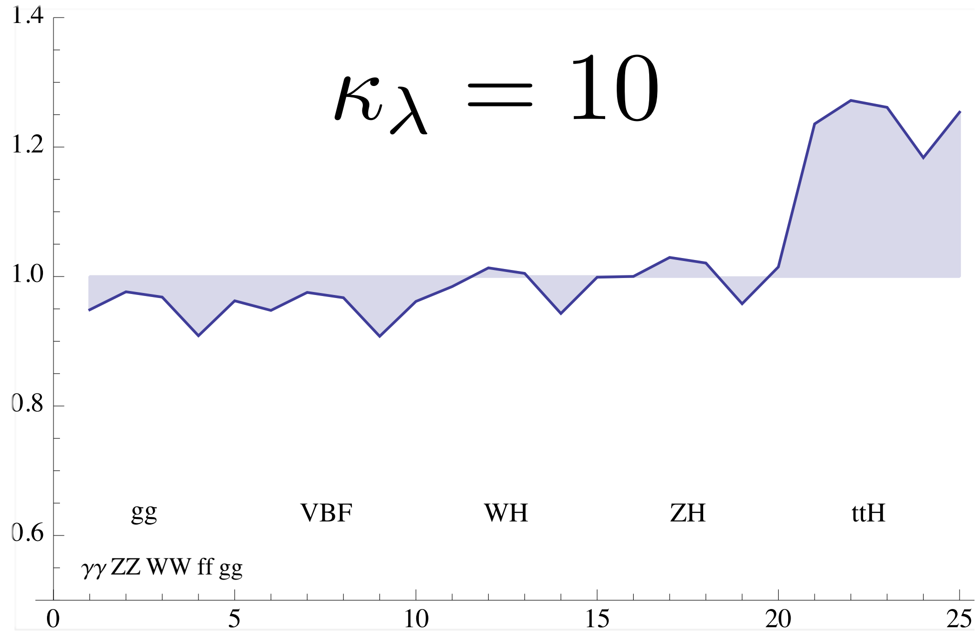
Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$

Fit procedure

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



$\mu_i^f(\kappa_\lambda)$



Fit procedure

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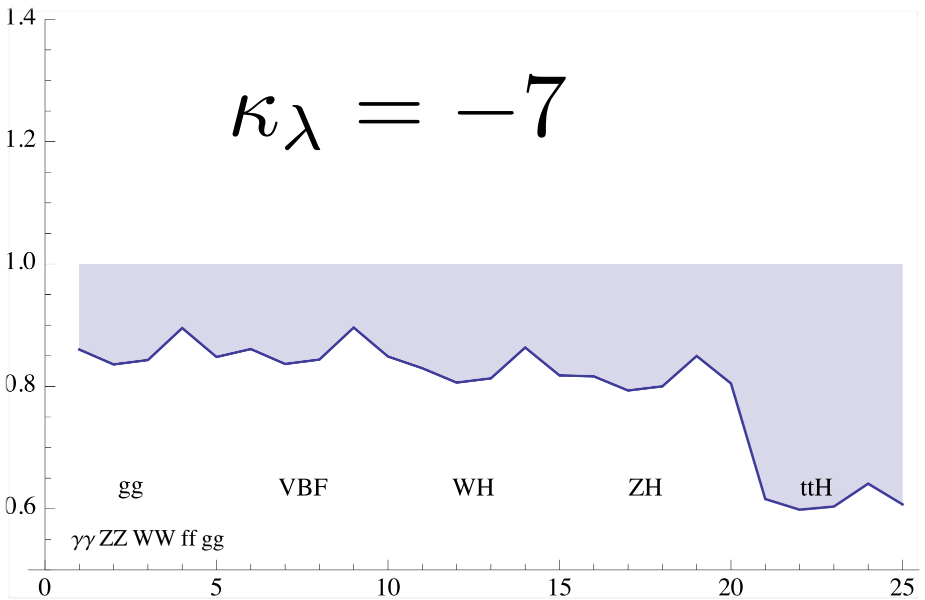
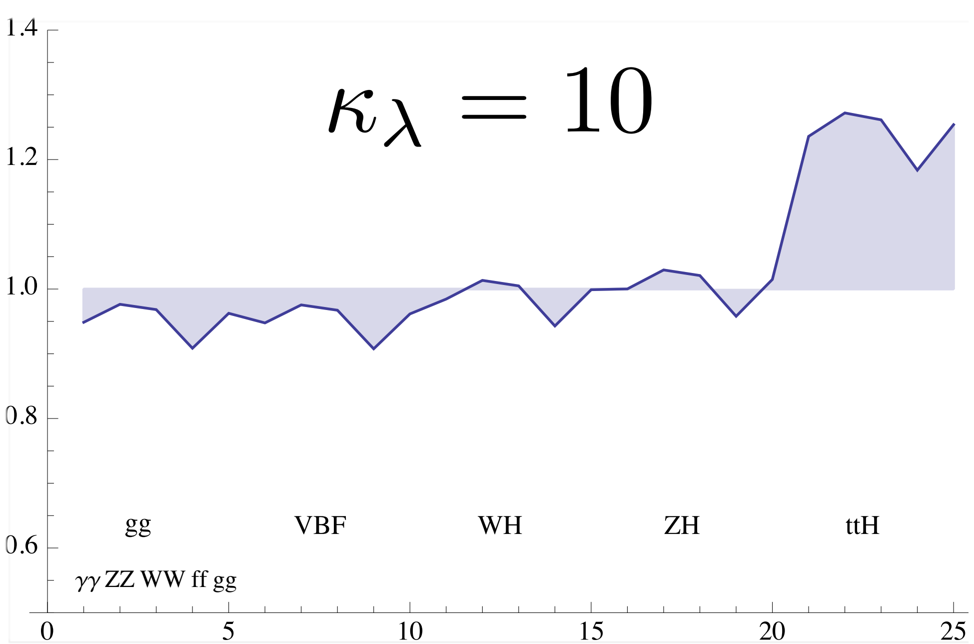
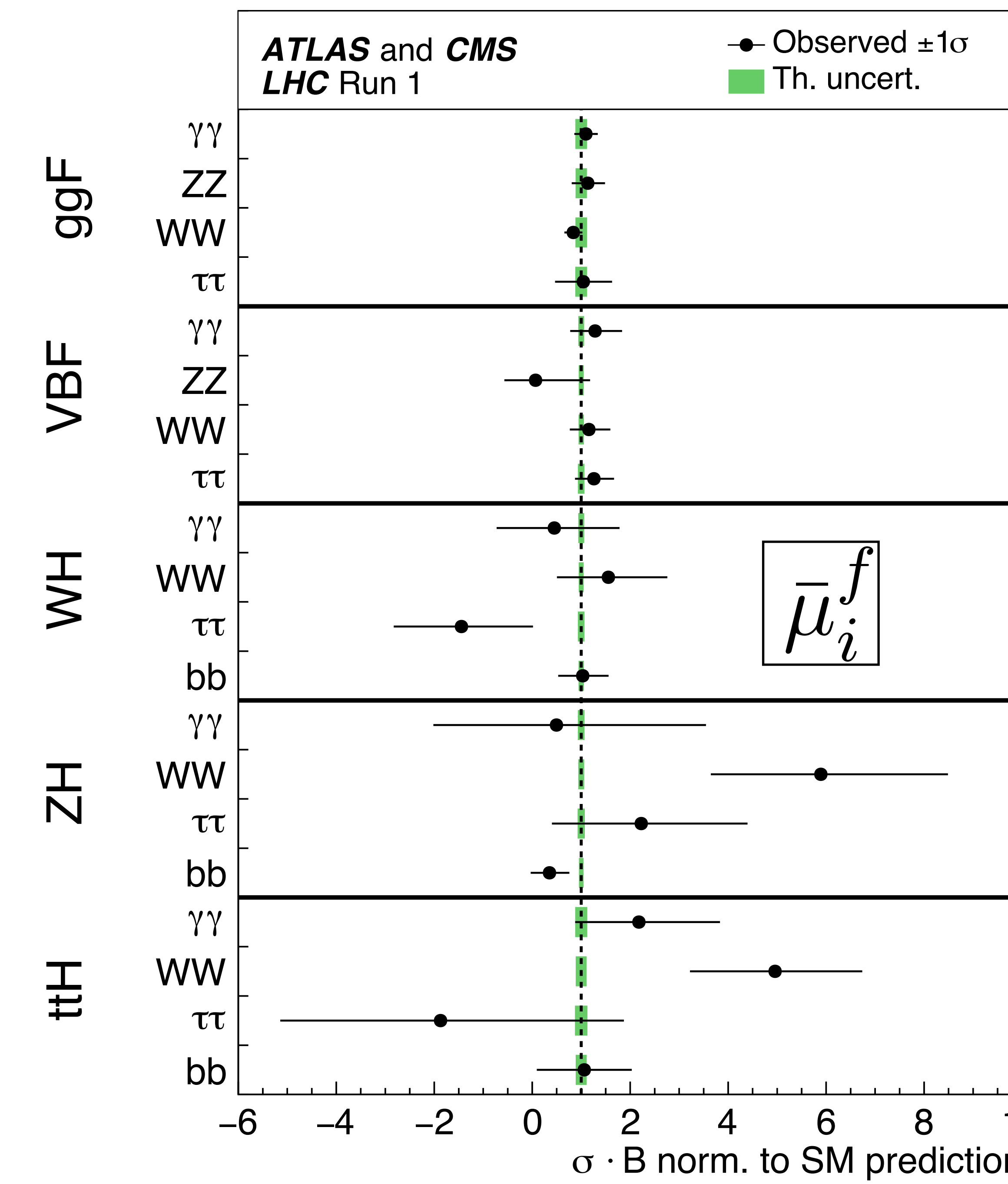




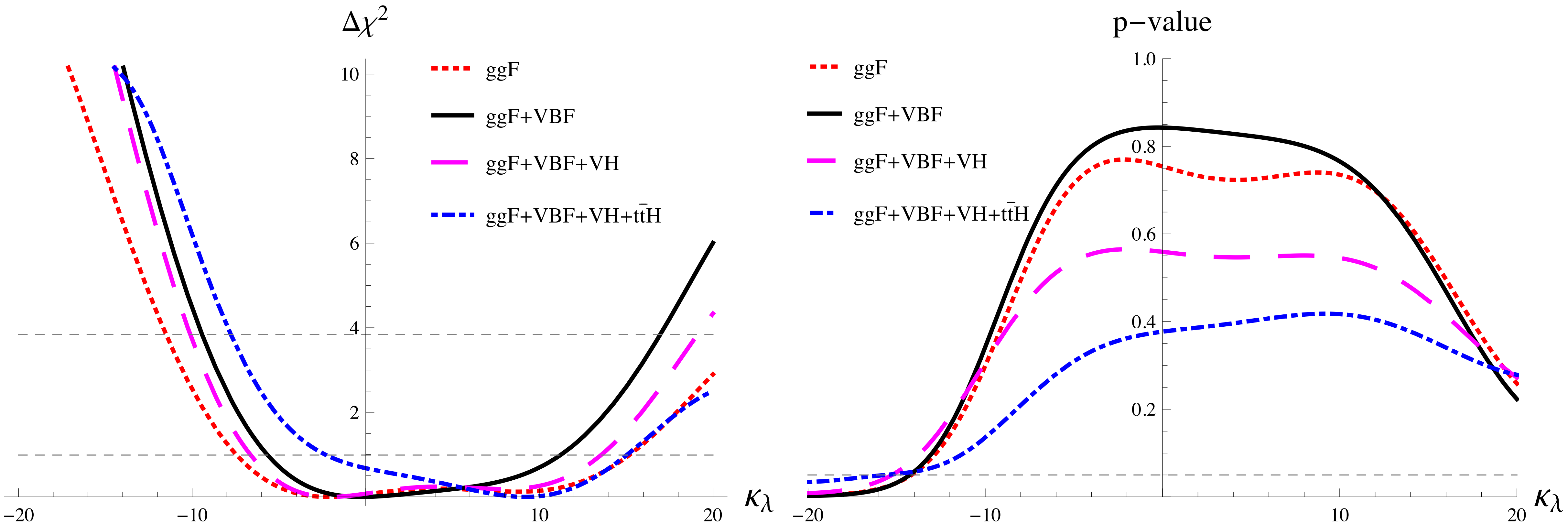
$$\mu_i^f(\kappa_\lambda)$$



$$\bar{\mu}_i^f$$

Results for present data

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



P_2: ggF+VBF ➡ $\kappa_\lambda^{\text{best}} = -0.24\,, \quad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \quad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

$p\text{-value}(\kappa_\lambda) = 1 - F_{\chi^2_{(n)}}(\chi^2(\kappa_\lambda))$ ➡ $\kappa_\lambda < -14.3$ Excluded at more than 2σ

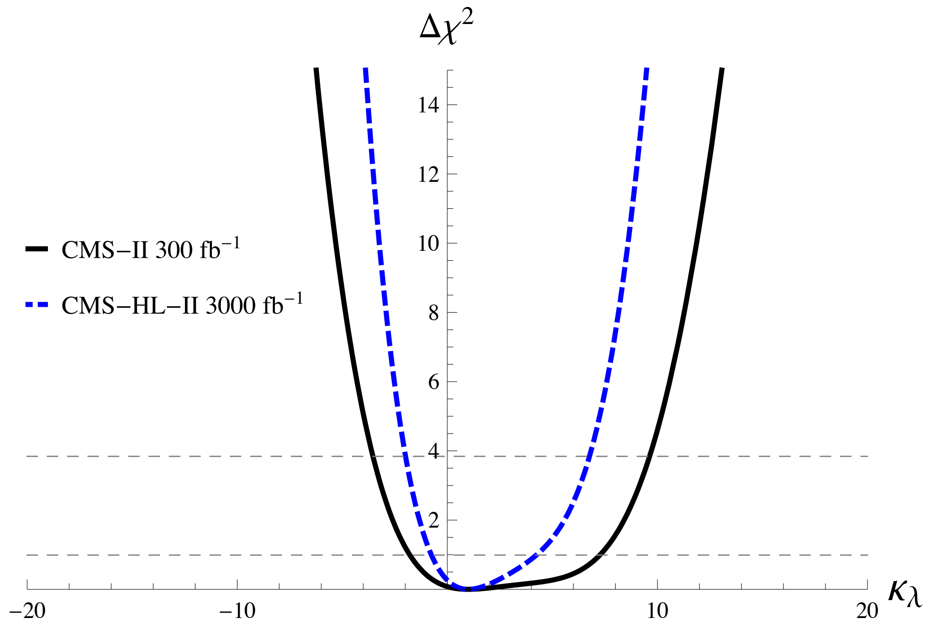
Results for the future

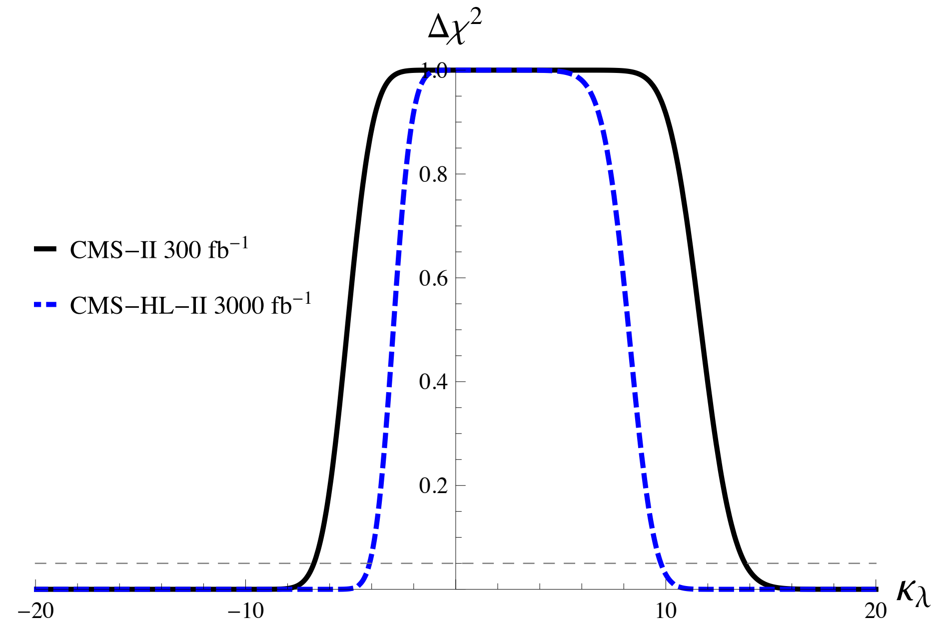
Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$

Exercise 0:

$\bar{\mu}_i^f = 1$

$\kappa_\lambda^{\text{best}} = 1$





"CMS-II" (300 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-1.8, 7.3]\,, \quad \kappa_\lambda^{2\sigma} = [-3.5, 9.6]\,, \quad \kappa_\lambda^{p>0.05} = [-6.7, 13.8]$$

"CMS-HL-II" (3000 fb^{-1})

$$\kappa_\lambda^{1\sigma} = [-0.7, 4.2]\,, \quad \kappa_\lambda^{2\sigma} = [-2.0, 6.8]\,, \quad \kappa_\lambda^{p>0.05} = [-4.1, 9.8]$$

Results for the future

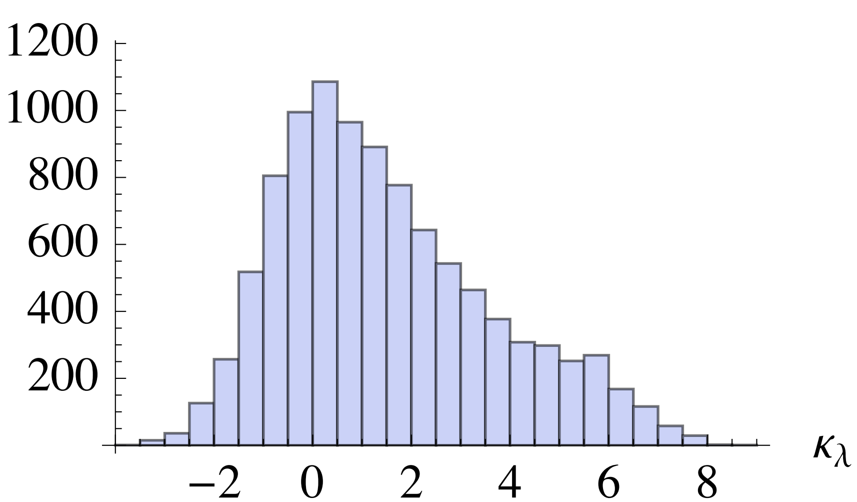
Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$

Assuming SM, we study the statistical distributions of $\kappa_\lambda^{\text{best}}$ and and the extremes of $\kappa_\lambda^{1\sigma}$, $\kappa_\lambda^{2\sigma}$ and $\kappa_\lambda^{p>0.05}$.

We generate n = 10000 pseudo experiments $\{\bar{\mu}_i^f\}$, with a Gaussian distribution centered around 1 and with σ given by the exp error.

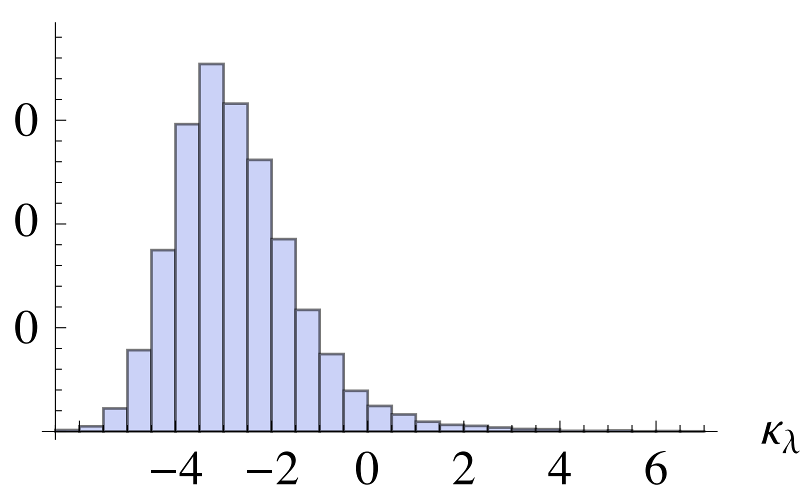
"CMS-HL-II" (3000 fb^{-1})

1) Mean=1.51, Med.=1.11



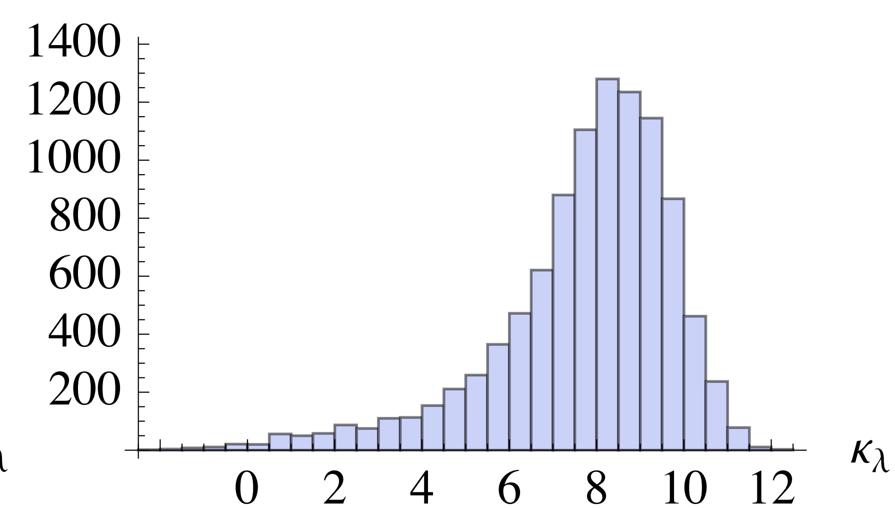
$\kappa_\lambda^{\text{best}}$

6) Mean=−2.71, Med.=−2.90



$p > 0.05$ region lower limit

7) Mean=7.73, Med.=8.13



$p > 0.05$ region upper

Results for the future

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

Assuming SM, we study the statistical distributions of $\kappa_\lambda^{\rm best}$ and and the extremes of $\kappa_\lambda^{1\sigma}$, $\kappa_\lambda^{2\sigma}$ and $\kappa_\lambda^{p>0.05}$.

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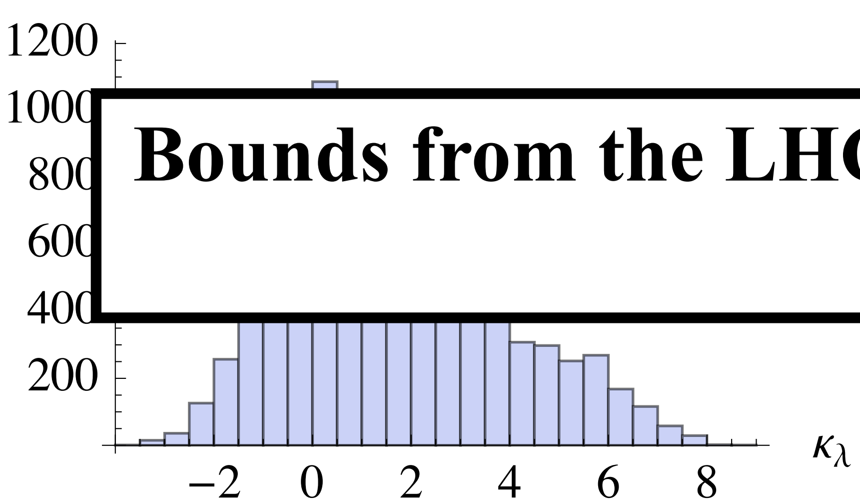
“CMS-HL-II” (3000 fb^{-1})

1) Mean=1.51, Med.=1.11



$\kappa_\lambda^{\rm best}$

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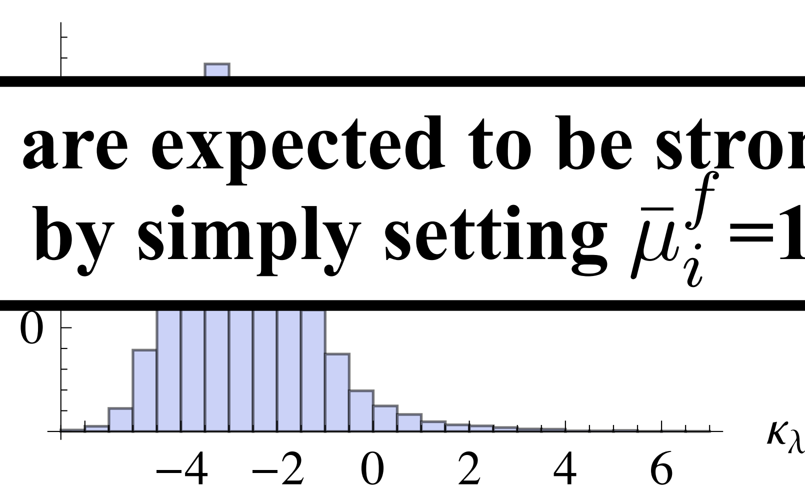
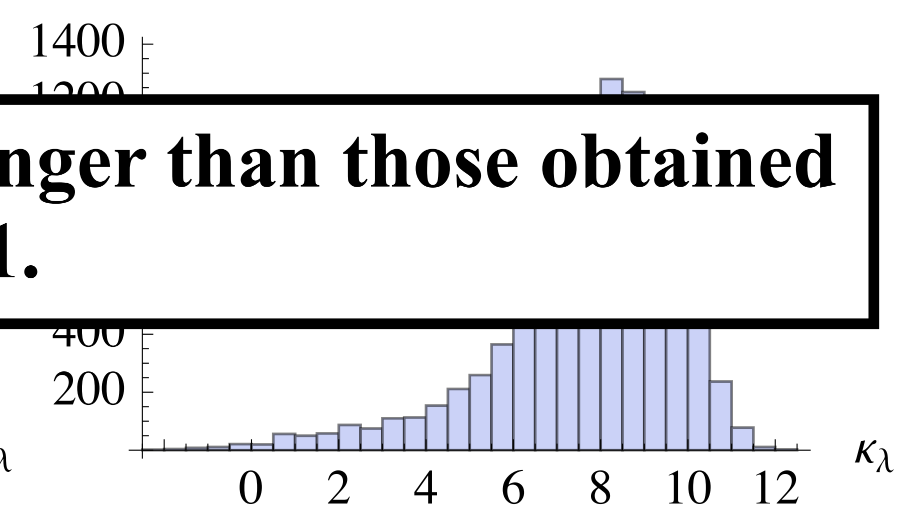


$p > 0.05$ region lower limit

7) Mean=7.73, Med.=8.13



$p > 0.05$ region upper

Bounds from the LHC are expected to be stronger than those obtained by simply setting $\bar{\mu}_i^f$=1.

C1: kinematic dependence

$C_1^\sigma[\%]$	25 GeV	50 GeV	100 GeV	200 GeV	500 GeV
WH	1.71 (0.11)	1.56 (0.34)	1.29 (0.72)	1.09 (0.94)	1.03 (0.99)
ZH	2.00 (0.10)	1.83 (0.33)	1.50 (0.71)	1.26 (0.94)	1.19 (0.99)
$t\bar{t}H$	5.44 (0.04)	5.14 (0.17)	4.66 (0.48)	3.95 (0.84)	3.54 (0.99)

$$p_T(H) < p_{T,\mathrm{cut}}$$

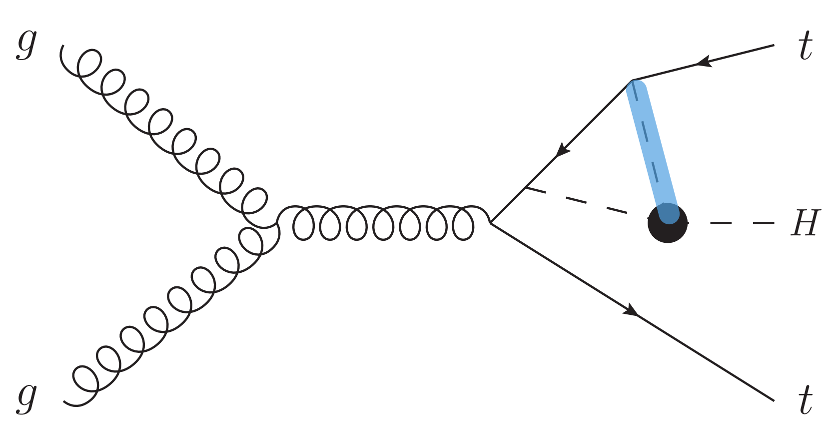
Table 3: C_1^σ at 13 TeV obtained by imposing the cut $p_T(H) < p_{T,\mathrm{cut}}$, for several values of $p_{T,\mathrm{cut}}$. In parentheses the fraction of events left after the quoted cut is applied.

$C_1^\sigma[\%]$	1.1	1.2	1.5	2	3
WH	1.78 (0.17)	1.60 (0.36)	1.32 (0.70)	1.15 (0.89)	1.06 (0.97)
ZH	2.08 (0.19)	1.86 (0.38)	1.51 (0.72)	1.31 (0.90)	1.22 (0.98)
$t\bar{t}H$	8.57 (0.02)	7.02 (0.10)	5.11 (0.43)	4.12 (0.76)	3.64 (0.94)

$$m_{\mathrm{tot}} < K \cdot m_{\mathrm{thr}}$$

Table 4: C_1^σ at 13 TeV obtained by imposing the cut $m_{\mathrm{tot}} < K \cdot m_{\mathrm{thr}}$, for several values of K. In parentheses the fraction of events left after the quoted cut is applied.

Contributions to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement at the threshold.



Conclusion

We proposed an **alternative method** for the determination of the trilinear Higgs **self coupling** λ_3, which relies on the effects that **loops** featuring λ_3 would imprint on **single Higgs production** channels at the **LHC**.

We have calculated the contributions arising **at NLO** on **all the** phenomenologically relevant **single Higgs production** (ggF, VBF, WH, ZH, ttH) **and decay** ($\gamma\gamma$, WW*/ZZ* $\rightarrow$ 4f, bb, $\tau\tau$) modes at the LHC

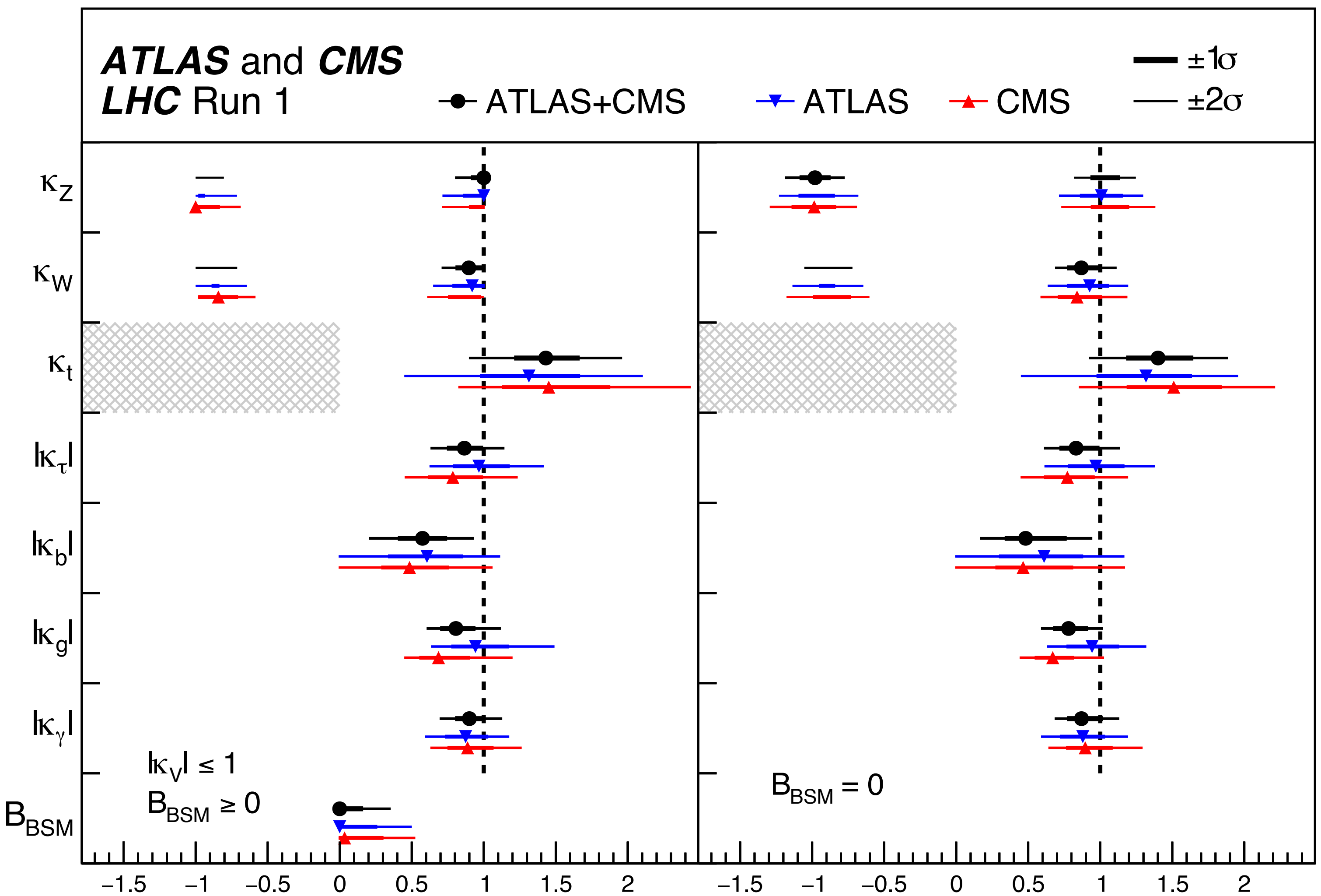
We have then estimated the sensitivity to the trilinear coupling via a **one-parameter fit** to the complete set of single Higgs inclusive measurements at the LHC 8 TeV. The **bounds** obtained are found to be **competitive with** the current **ones** obtained from **Higgs pair production**

We have also estimated the constraints that can be obtained at the end of the current **Run II and also at HL**. The determination of λ_3 with this strategy is **also in this case competitive** with the results from double Higgs production.

EXTRA SLIDES

From the signal strengths μ_i^f to the coupling modifiers κ_j

The “kappa framework”: $\kappa_j^2 = \sigma_j/\sigma_j^{SM}$ $\kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$



$[-1.08, -0.88] \cup$
$[0.94, 1.13]$

$[0.78, 1.00]$

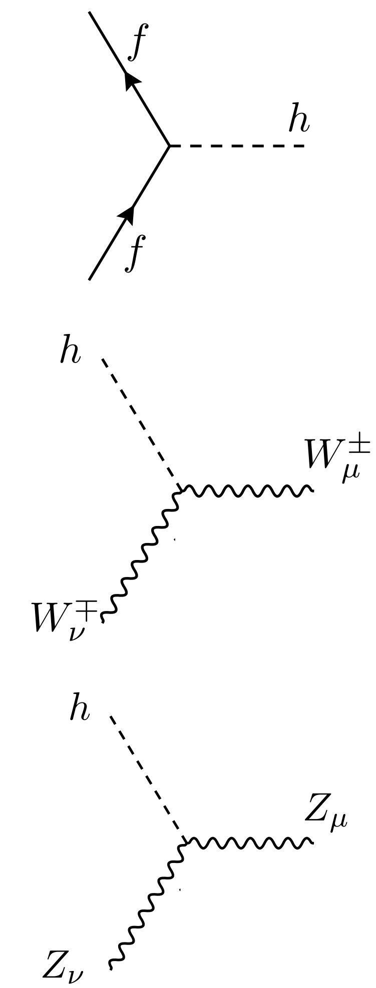
$1.40^{+0.24}_{-0.21}$

$0.84^{+0.15}_{-0.11}$

$0.49^{+0.27}_{-0.15}$

$0.78^{+0.13}_{-0.10}$

$0.87^{+0.14}_{-0.09}$



κ_F

κ_W

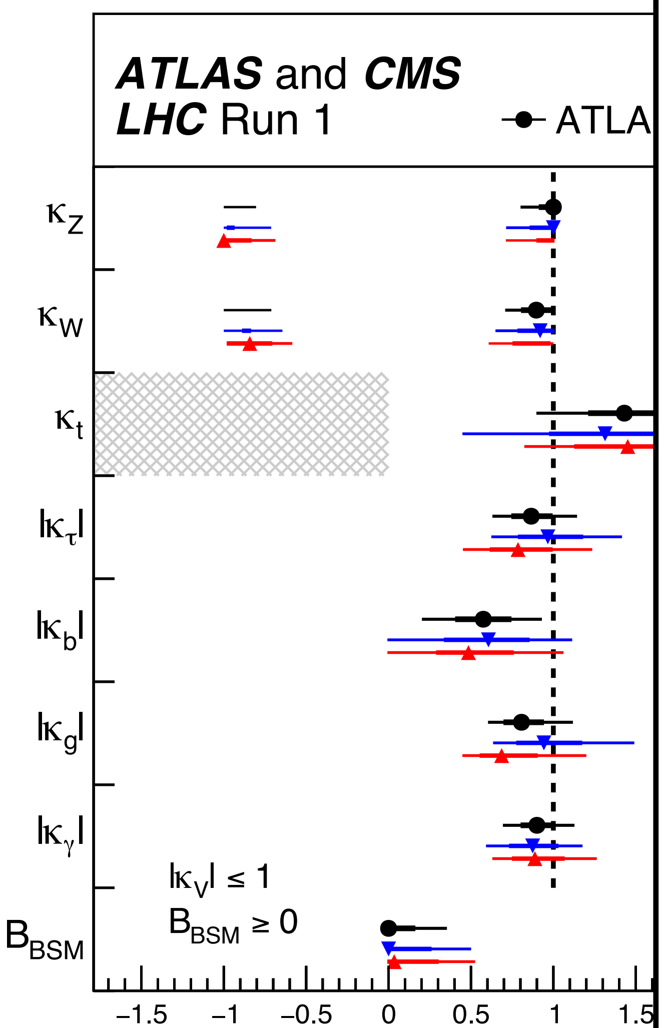
κ_Z

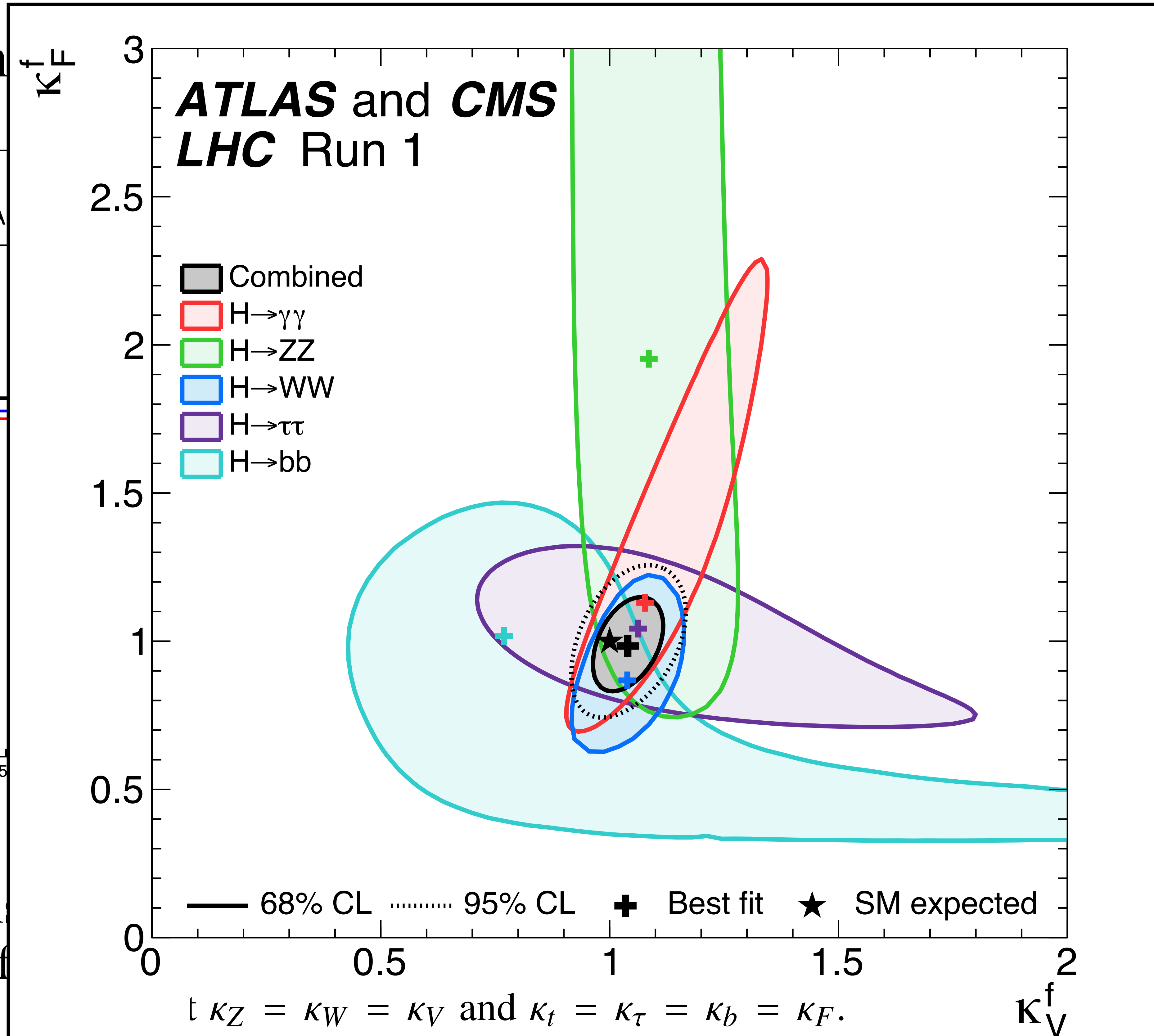
Several assumptions can be made on the relations among the different κ_j and they strongly affect the values extracted!

See talk of Stefan Guindon

From the signal strengths μ_i^f to the coupling modifiers κ_j

The “kappa fram





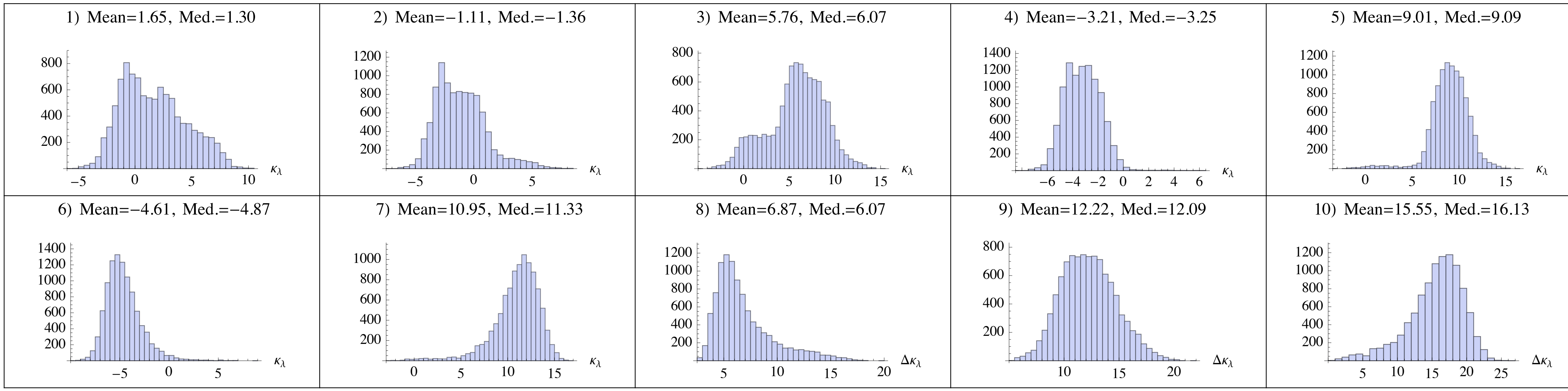
Several assumption

and they strongly af

t $\kappa_Z = \kappa_W = \kappa_V$ and $\kappa_t = \kappa_\tau = \kappa_b = \kappa_F$.

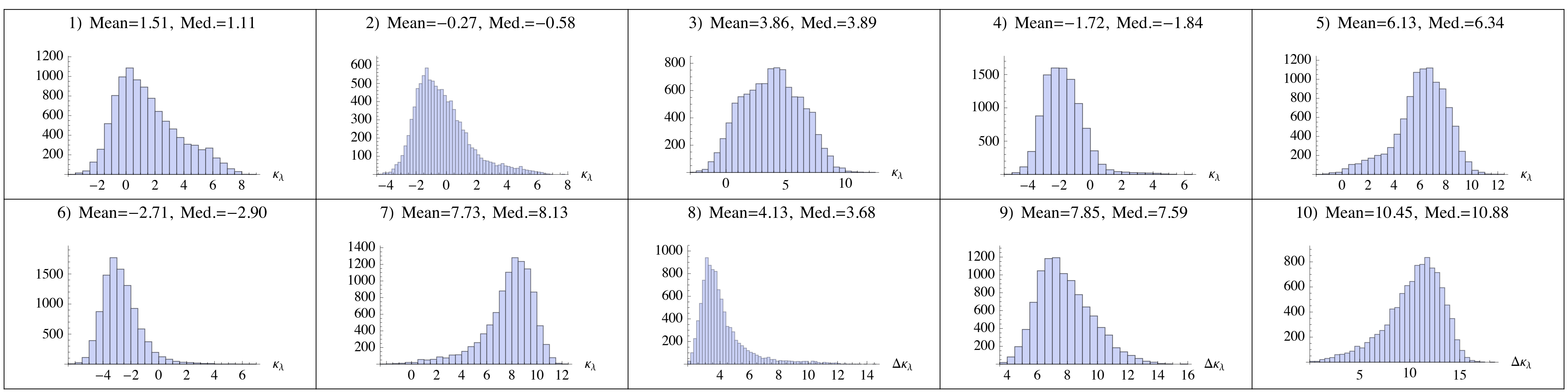
Results for the future

“CMS-II” (300 fb^{-1})



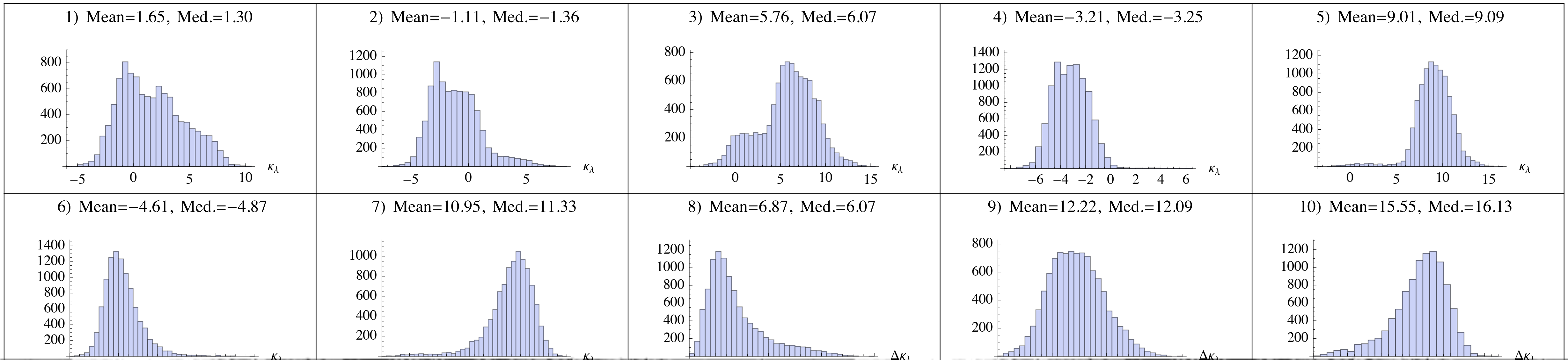
1) best values, 2) 1σ region lower limit, 3) 1σ region upper limit, 4) 2σ region lower limit, 5) 2σ region upper limit, 6) p > 0.05 region lower limit, 7) p > 0.05 region upper limit, 8) 1σ region width, 9) 2σ region width, 10) p > 0.05 region width.

“CMS-HL-II” (3000 fb^{-1})



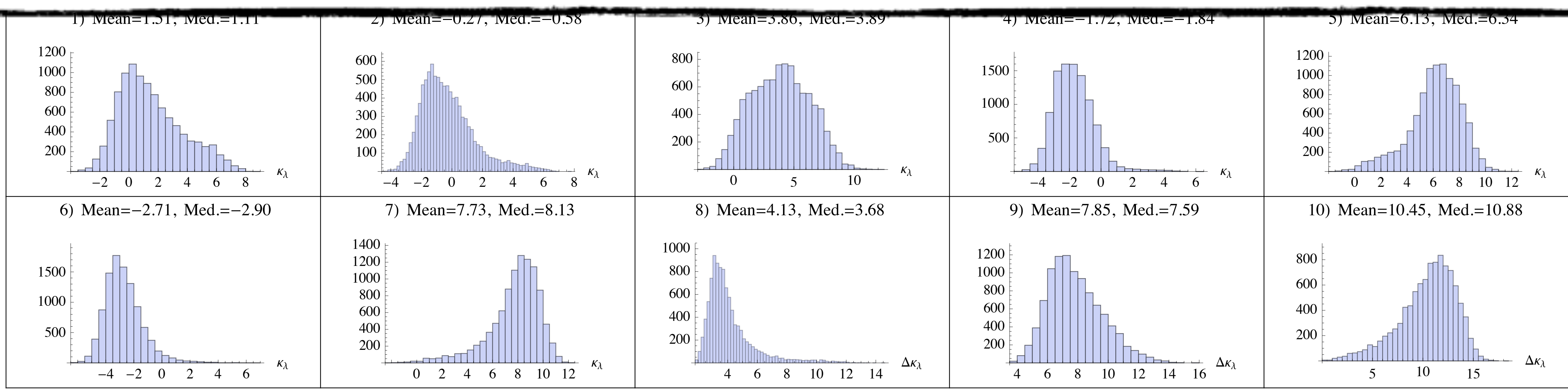
Results for the future

"CMS-II" $(300\ \mathrm{fb}^{-1})$



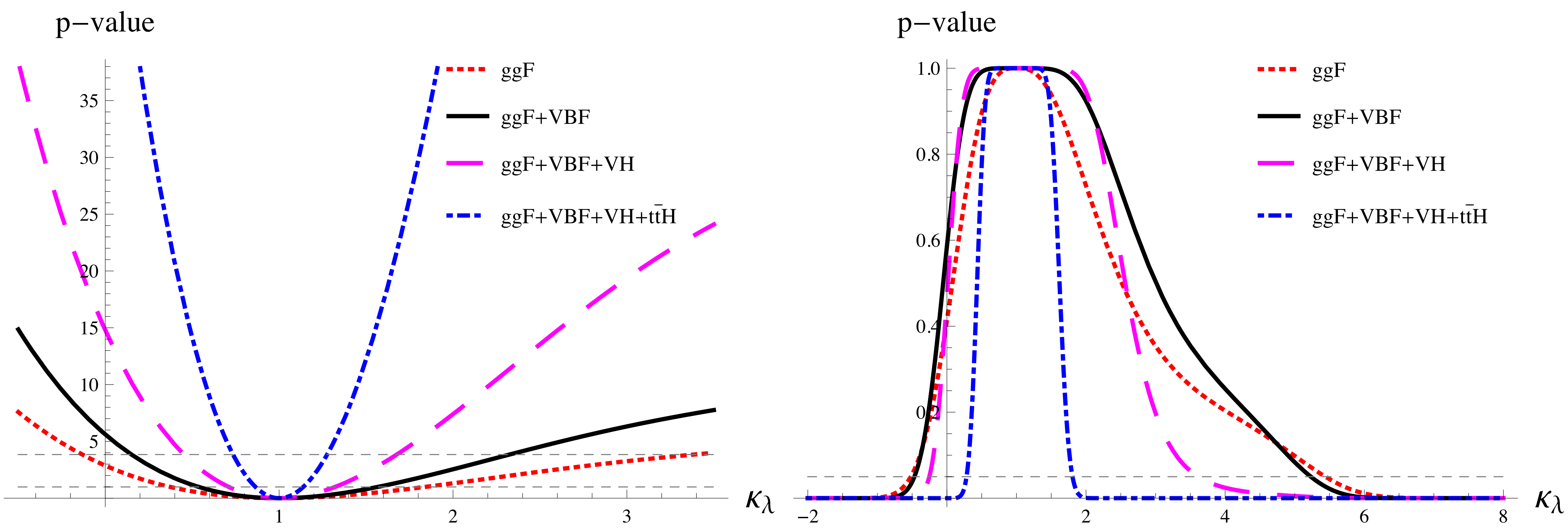
Bounds from the LHC are expected to be stronger than those obtained by simply setting $\bar{\mu}_i^f$=1.

"CMS-HL-II" $(3000\ \mathrm{fb}^{-1})$



Exercise: 1% errors

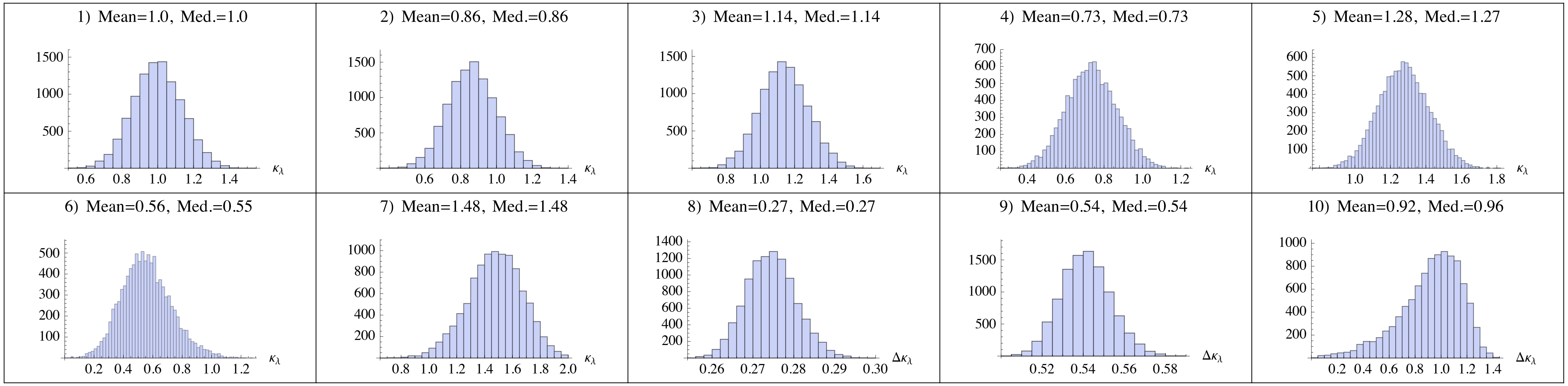
Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



$$\kappa_\lambda^{1\sigma} = [0.86, 1.14]\,, \qquad \kappa_\lambda^{2\sigma} = [0.74, 1.28]\,, \qquad \kappa_\lambda^{p>0.05} = [0.28, 1.80]$$

The ttH process strongly improves (as expected) the determination of κ_λ.
The statistical analysis suggests also in this case the possibility of obtaining stronger bounds.

Exercise: 1% errors



1) best values, 2) 1σ region lower limit, 3) 1σ region upper limit, 4) 2σ region lower limit, 5) 2σ region upper limit, 6) $p > 0.05$ region lower limit, 7) $p > 0.05$ region upper limit, 8) 1σ region width, 9) 2σ region width, 10) $p > 0.05$ region width.