中国科学院高能物理研究所
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ATLAS
EXPERIMENT

Combination of searches for Higgs boson pair production in ATLAS Run2

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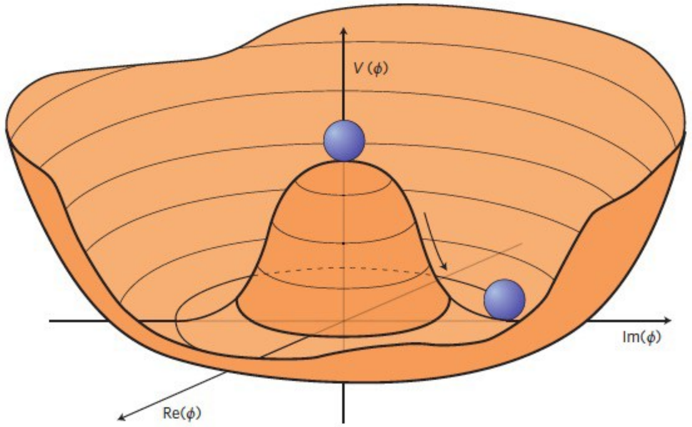
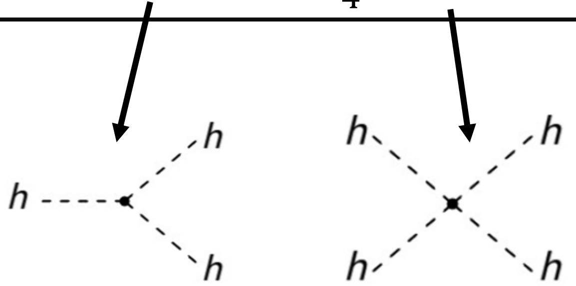
Motivation

- **Higgs potential is important to understand the mechanism of electroweak symmetry breaking**



The Higgs potential:

$$V(H) = \mathrm{V}_0 + \frac{1}{2}m_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4 + \cdots$$



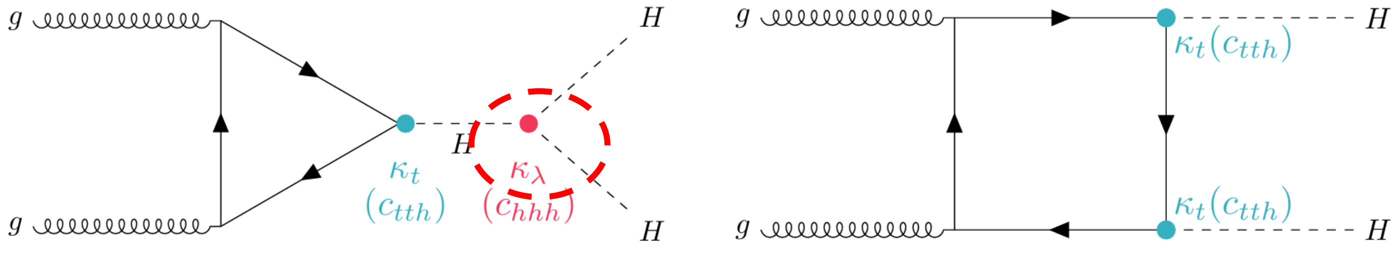
- **Properties of Higgs boson and its coupling to fermions and vector bosons have been scrutinized.**
  - No clear indications for new physics yet…
- **Self-interaction still not determined.**
  - Test SM and look for BSM

Di-Higgs production at LHC

coupling modifier:
$\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{SM}, \kappa_{2V}, \kappa_t \ldots\ldots$

➢ HH production via gluon-gluon fusion (ggF):

- accounts for more than 90% in the SM

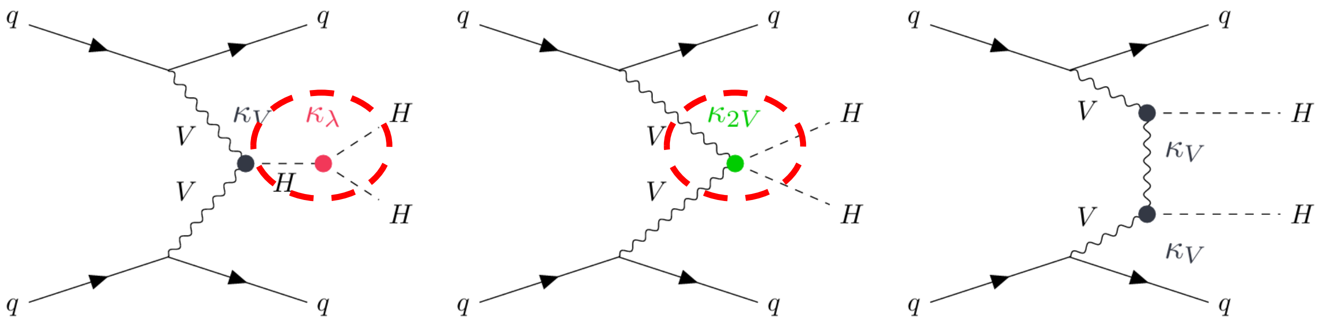


$$\sigma_{ggF}^{SM} = 31.05fb_{-23\%}^{+6\%}\left(scale + m_{top}\right) + 3.0\%(PDF + \alpha_s)$$

➢ HH production via vector-boson fusion (VBF):

- Advantage in κ_{2V} determination

Fucus on HH signal strength, κ_λ and κ_{2V}

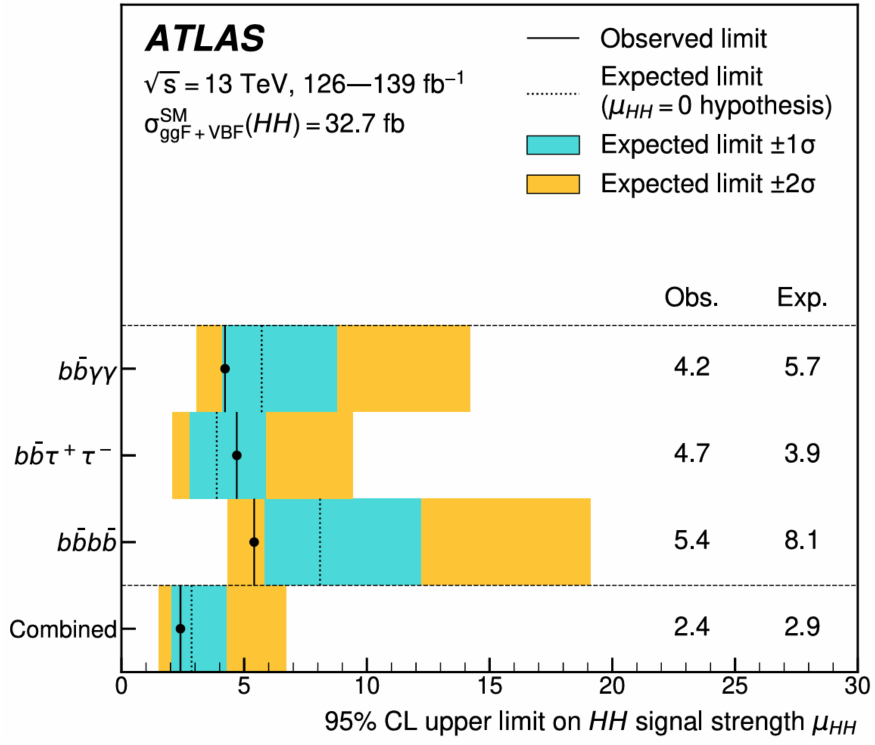


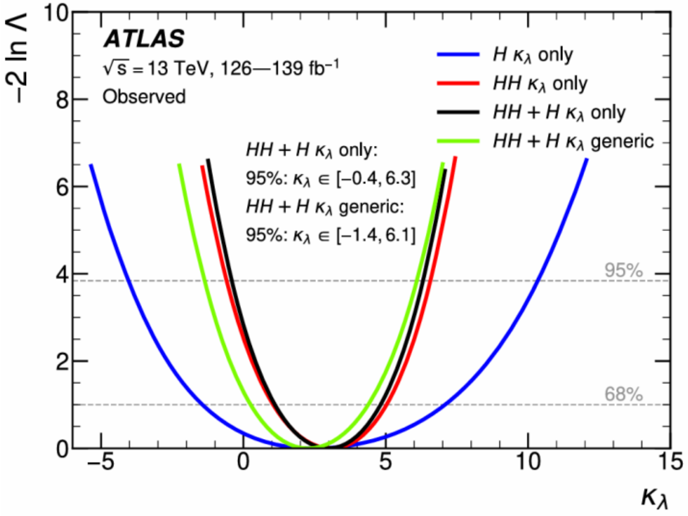
$$\sigma_{VBF}^{SM} = 1.73fb_{-0.04\%}^{+0.03\%}\left(scale + m_{top}\right) + 2.1\%(PDF + \alpha_s)$$

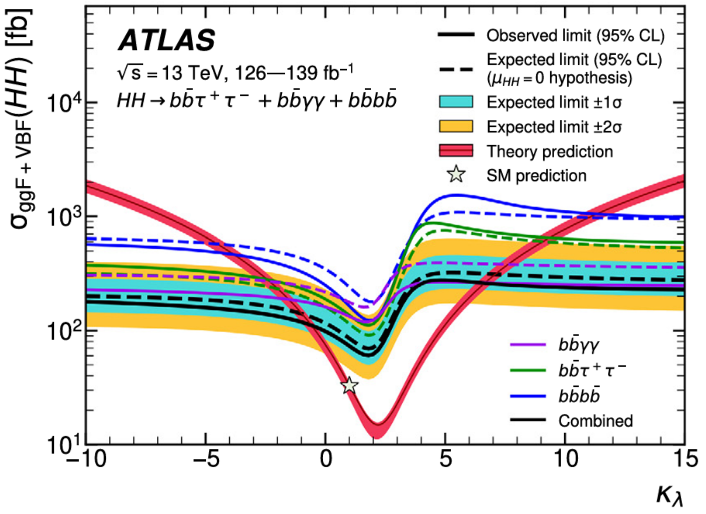
Previous HH+H combination publication

Phys. Lett. B (843) (2023) 137745

- **Previous HH+H combination considered the three most sensitive channels:**
  - $bbbb, bb\gamma\gamma, bb\tau\tau$
  - Single Higgs don't improve the accuracy but is helpful to constrain BSM model







Since previous publication:

- $bb\tau\tau$ and $bb\gamma\gamma$ have been re-optimized
- Boosted VBF $bbbb$ regime that provides better k2v constraint
- $bbll + E_T^{miss}$ and multi-lepton results available

Analyses Overview

- **Results from all 5 channels are combined to derive upper limits on signal strength and interpreted within the κ framework**
- **Accounts for about 50% of di-Higgs decay**
- **Overlap checks are performed across all channels**
  - Less than 1% overlaps in the signal regions, negligible

channel	BR	Lumi[fb^{-1}]	Paper(Draft)
$bbbb$	0.339	126(resolved) 140(boosted VBF)	PhysRevD.108.052003 arXiv.2404.17193
$bb\gamma\gamma$	2.6×10^{-3}	140	JHEP01(2024)066
$bb\tau\tau$	0.073	140	arXiv:2404.12660
$bbll + E_T^{miss}$	0.029	140	JHEP02(2024)037
multi-lepton	0.065	140	arXiv:2405.20040

Statistical model

- **Combined likelihood is the product of likelihoods from each channel**

$$\mathcal{L}(\mathcal{D},\mathcal{G}|\mu,\alpha)=\prod_{c\in\mathbb{C}}\mathrm{Pois}(n_c|\nu_c(\mu,\alpha))\prod_{e=1}^{n_c} f_c(x_{ce}|\mu,\alpha)\times\prod_{p\in\mathbb{S}} f_p(a_p|\alpha_p)$$

channel events Constrained NPs

- **The profile likelihood ratio is constructed as**

$$\tilde{\lambda}(\mu)=\begin{cases}\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\hat{\theta}}(0))} & \hat{\mu}<0,\\ \frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \hat{\mu}\geq 0.\end{cases}$$

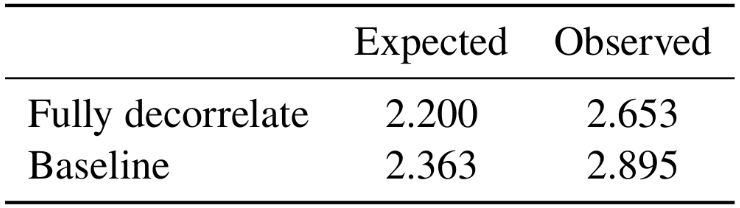
one-sided test statistics

- **The test statistics for limit setting is:**

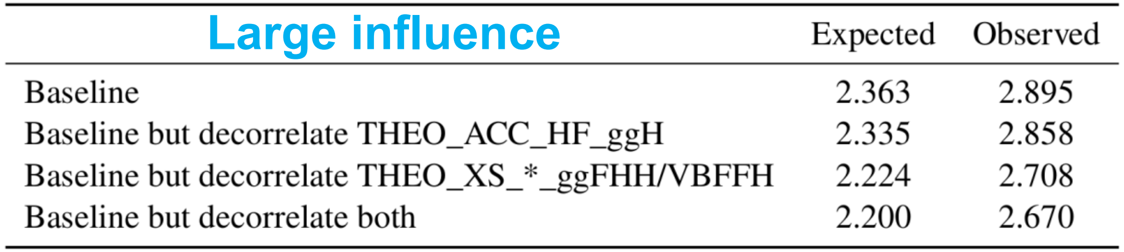
$$\tilde{q}_\mu=\begin{cases}-2\ln\tilde{\lambda}(\mu) & \hat{\mu}\leq\mu\\ 0 & \hat{\mu}>\mu\end{cases}=\begin{cases}-2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(0,\hat{\hat{\theta}}(0))} & \hat{\mu}<0,\\ -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu},\hat{\theta})} & 0\leq\hat{\mu}\leq\mu,\\ 0 & \hat{\mu}>\mu.\end{cases}$$

Systematic Uncertainties and Correlation

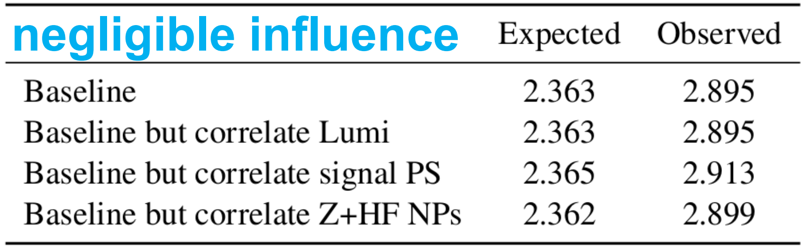
- **Nuisance parameters from the same systematic sources, ideally, should be correlated due to their expected similar impacts on the analysis**
  - Variations in calibrations or uncertainty models across different channels
  - NPs might be over-constrained in one analysis while showing shifts/pull in another → lead to improper final results
- **Correlation scheme (Baseline):**
  - Common systematic uncertainties sources are correlated
  - Over-constrained (<0.7σ) or strongly-pulled (>0.5σ), but rank top 20 NPs are decorrelated
- **Check on NP Correlation are performed**



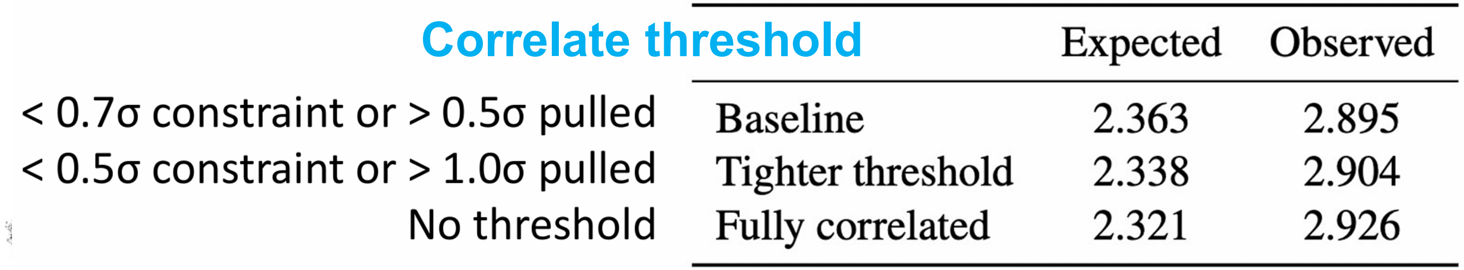
	Expected	Observed
Fully decorrelate	2.200	2.653
Baseline	2.363	2.895



Large influence	Expected	Observed
Baseline	2.363	2.895
Baseline but decorrelate THEO_ACC_HF_ggH	2.335	2.858
Baseline but decorrelate THEO_XS_*_ggFHH/VBFFH	2.224	2.708
Baseline but decorrelate both	2.200	2.670



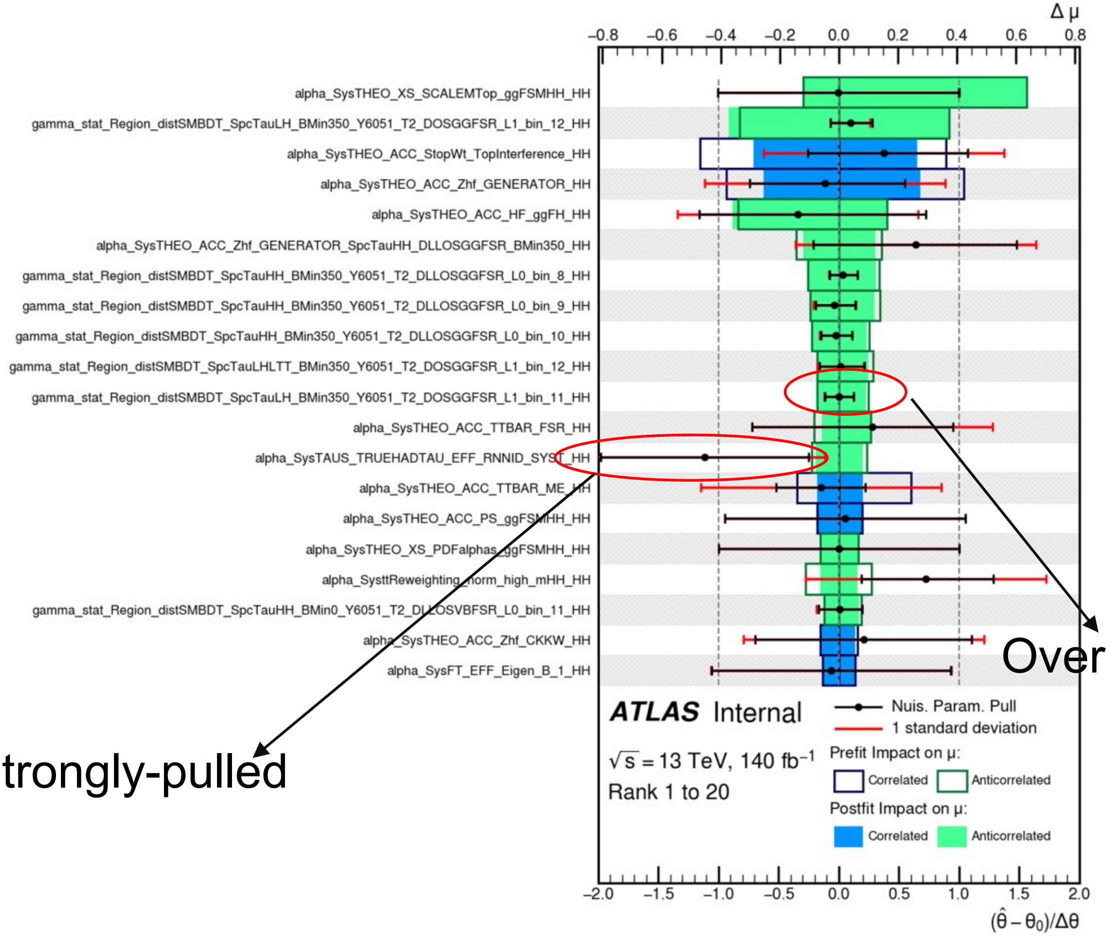
negligible influence	Expected	Observed
Baseline	2.363	2.895
Baseline but correlate Lumi	2.363	2.895
Baseline but correlate signal PS	2.365	2.913
Baseline but correlate Z+HF NPs	2.362	2.899



	Correlate threshold	Expected	Observed
< 0.7σ constraint or > 0.5σ pulled	Baseline	2.363	2.895
< 0.5σ constraint or > 1.0σ pulled	Tighter threshold	2.338	2.904
No threshold	Fully correlated	2.321	2.926

Ranking with Observed Data

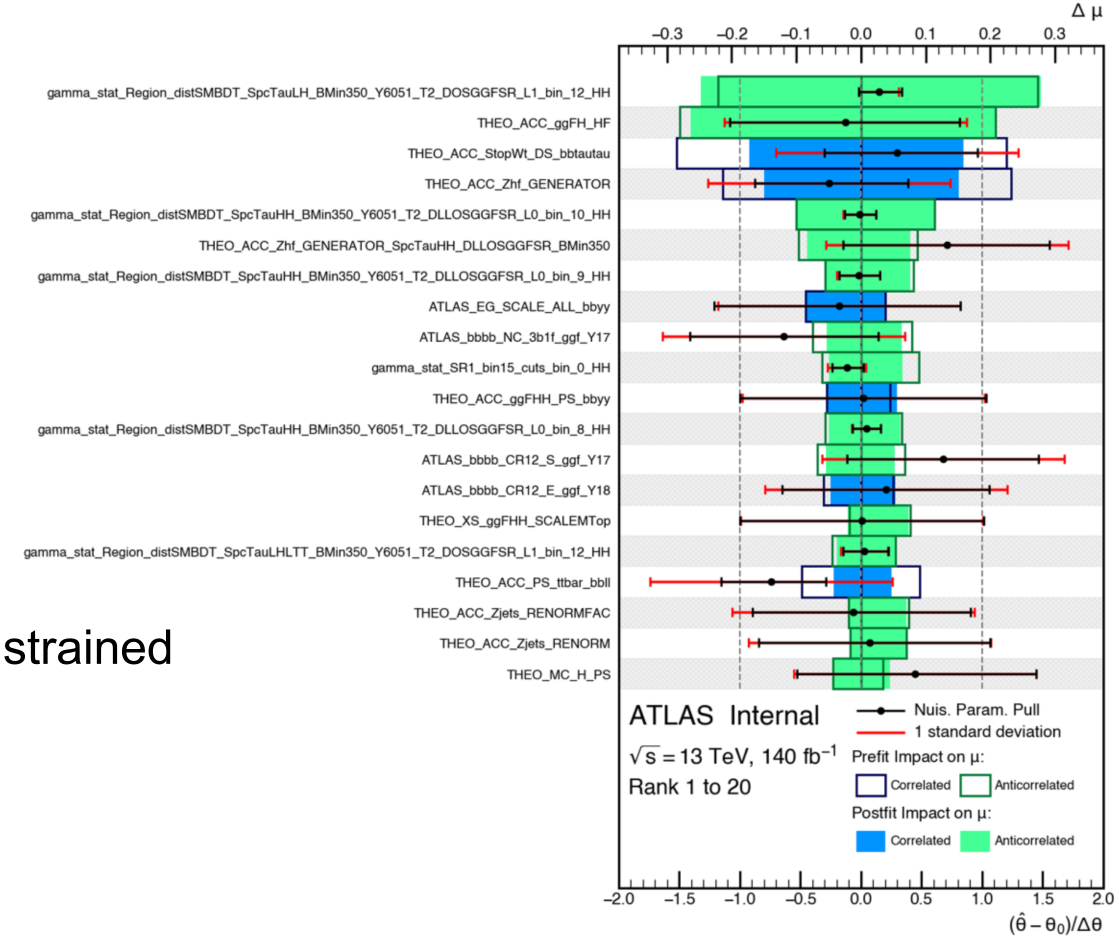
- **The ranking is consistent with the results reported in individual analysis (only show bbtautau here)**



Over constrained

strongly-pulled

Bbtautau Observed Data

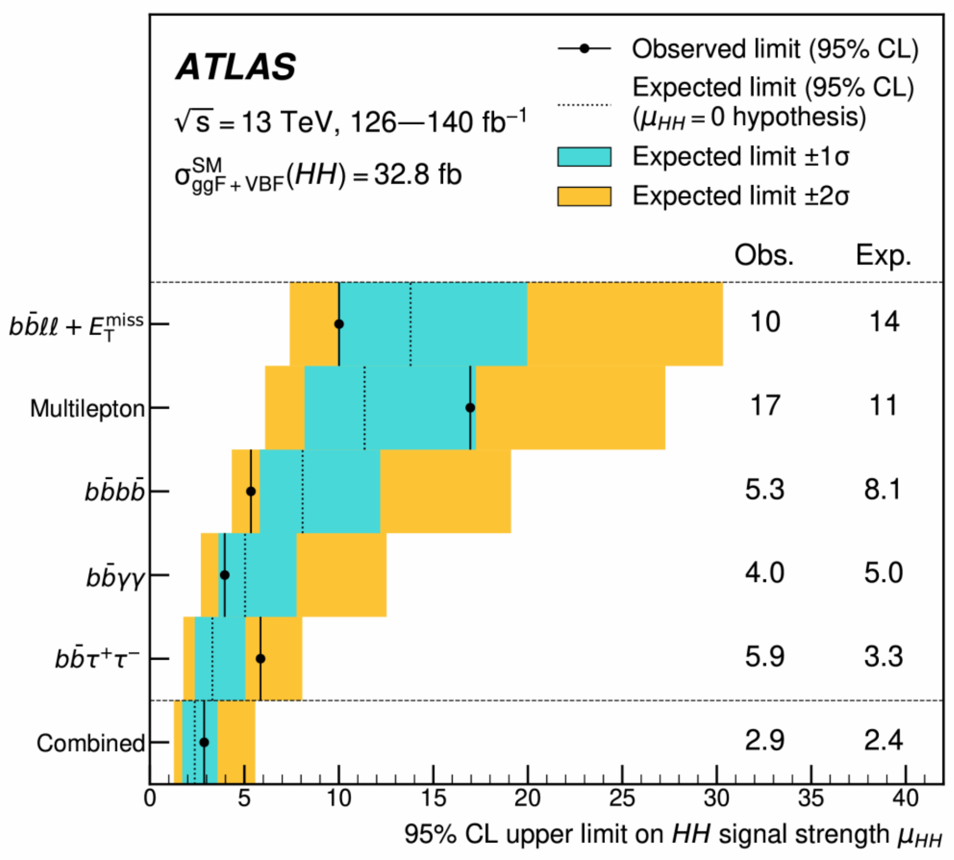


Combined observed data

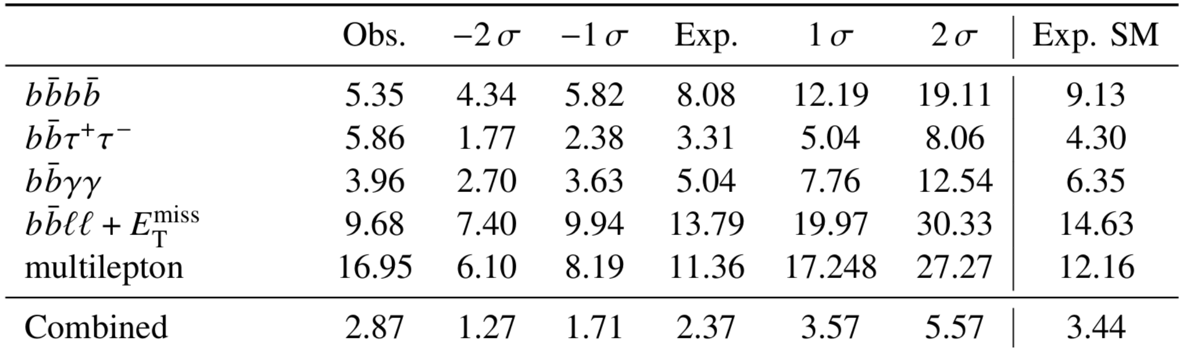
limit on HH signal strength

Exp: $\mu = 1.0^{+1.0}_{-0.9}(stat)^{+0.7}_{-0.5}(syst)$

Obs: $\mu = 0.5^{+0.9}_{-0.8}(stat)^{+0.7}_{-0.6}(syst)$



- **Obs. and exp. 95% CL upper limits on the SM HH signal strength in 5 channels and their combination**
- **All the limits obtained from individual channels agreed well with their paper**



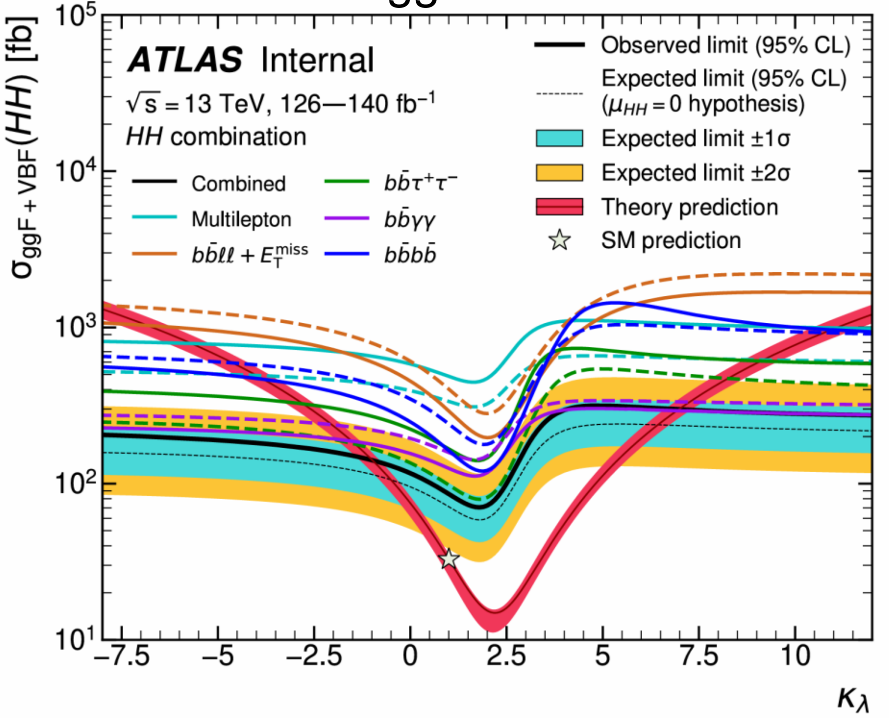
	Obs.	$-2\,\sigma$	$-1\,\sigma$	Exp.	$1\,\sigma$	$2\,\sigma$	Exp. SM
$b\bar{b}b\bar{b}$	5.35	4.34	5.82	8.08	12.19	19.11	9.13
$b\bar{b}\tau^+\tau^-$	5.86	1.77	2.38	3.31	5.04	8.06	4.30
$b\bar{b}\gamma\gamma$	3.96	2.70	3.63	5.04	7.76	12.54	6.35
$b\bar{b}\ell\ell + E_T^{miss}$	9.68	7.40	9.94	13.79	19.97	30.33	14.63
multilepton	16.95	6.10	8.19	11.36	17.248	27.27	12.16
Combined	2.87	1.27	1.71	2.37	3.57	5.57	3.44

- **Expected limits is improved by 19% with respect to previous result**
  - 4% from two new channels bbll and ML
  - 15% from improvements of the updated Legacy Run2 analysis

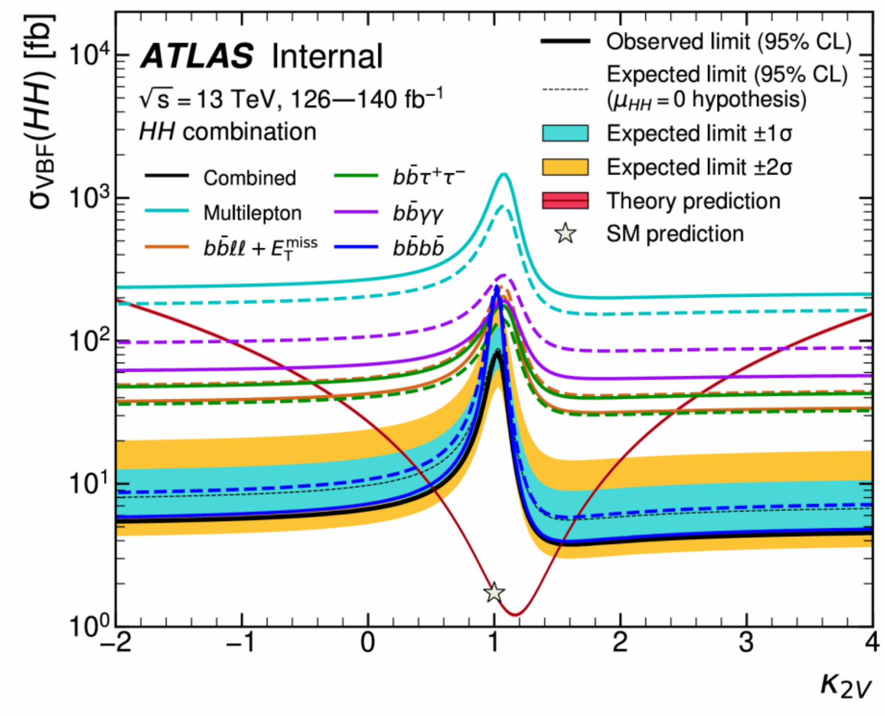
Xsec Limit vs κ-modifiers

- **An alternative and more intuitive statistical interapretation for 95% CL exclusion limits on the coupling κ-modifiers**
  - Compare with the theory prediction, the allowed
    - κ_λ range is obs.[-1.0,7.0],exp.[-0.5,6.4]
    - κ_{2V} range is obs.[0.5,1.5],exp.[0.4,1.6]

ggF + VBF

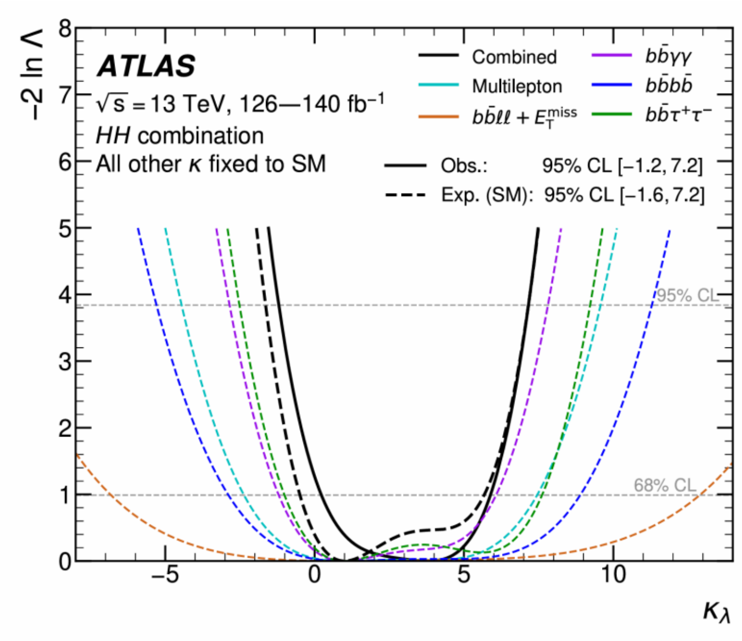


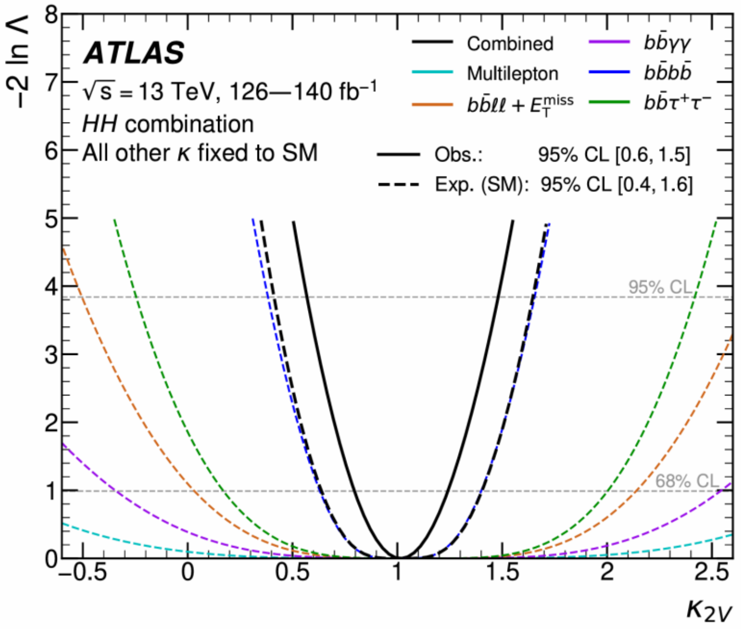
VBF (with ggF fixed to SM prediction)

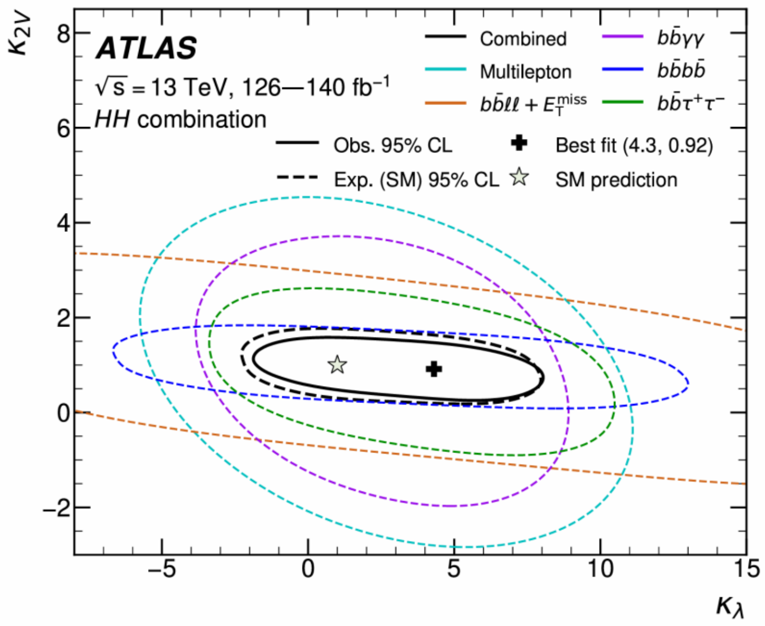


likelihood scan on κ_λ and κ_{2V}

- **The other κ parameters are fixed to the SM prediction for 1D scan**
  - The observed (expected) 95% CL interval is $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$), representing the best expected sensitivity to the Higgs boson self-coupling to date
  - The observed (expected) 95% CL interval is $0.6 < \kappa_{2V} < 1.5$ ($0.4 < \kappa_{2V} < 1.6$). The boosted VBF bbbb channel is most sensitive
- **To reduce model dependence, two-dimensional contours are also performed**







Summary

- **Searches for non-resonant di-Higgs production using latest Run 2 results in ATLAS**
  - Combine bbbb, bbtautau, bbyy, bbll and ML channels
- **Provides the best expected sensitivities to the HH production cross-section**
  - the upper limit on the production rate is 2.9 (2.4) times SM prediction for observed (expected) result
- **Provides the best expected sensitivities to the Higgs boson self-coupling**
  - The observed (expected) 95% CL interval is $-1.2 < \kappa_\lambda < 7.2$ ($-1.6 < \kappa_\lambda < 7.2$)
- **Results agree well with the SM predictions**

Additional slides

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