Constraining the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $\sqrt{s}$ = 13 TeV

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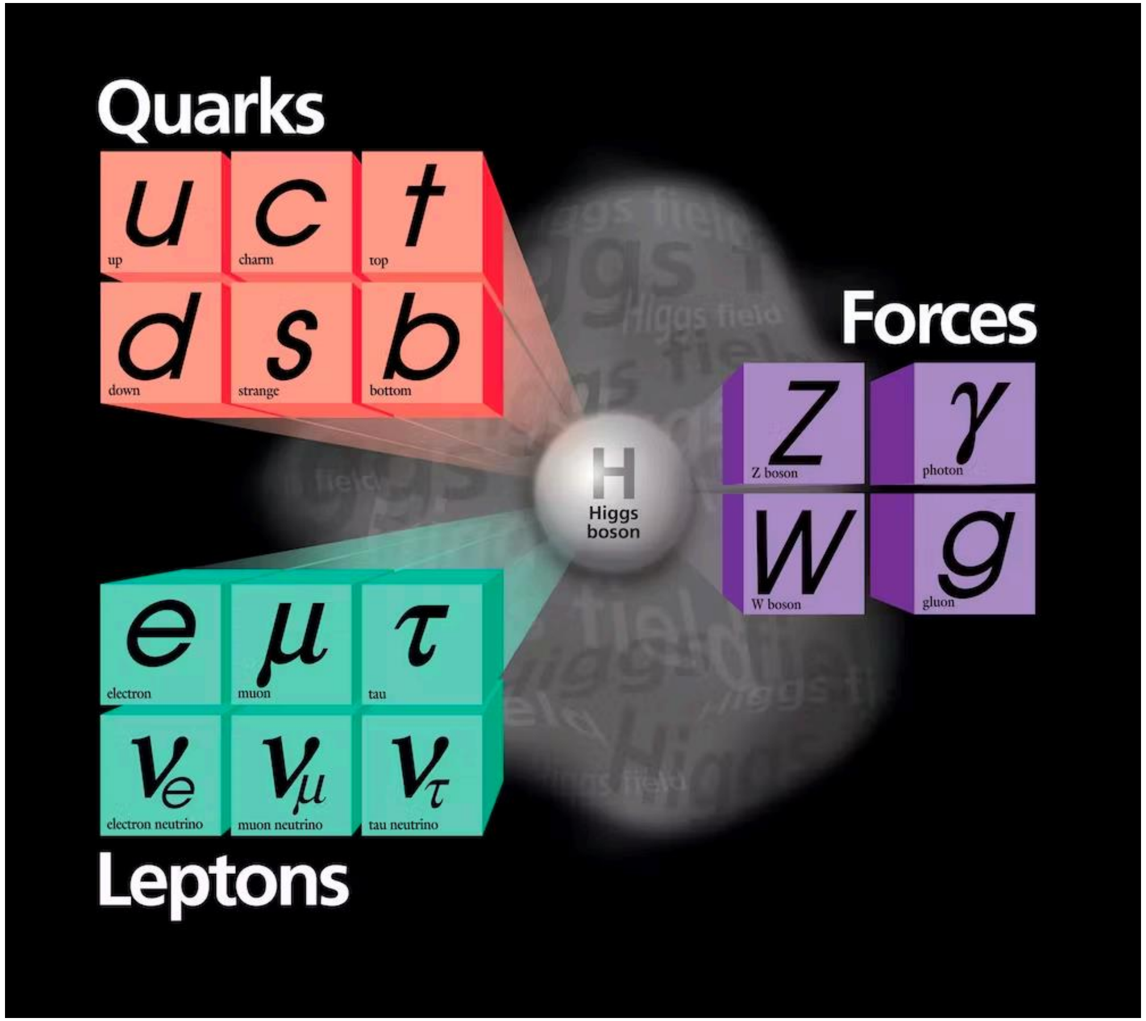
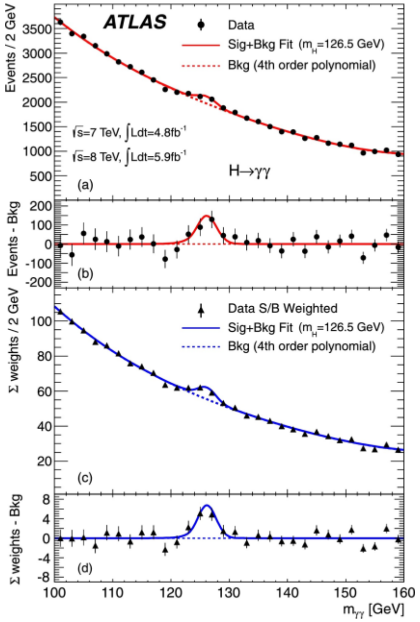
ATLAS EXPERIMENT

Higgs boson

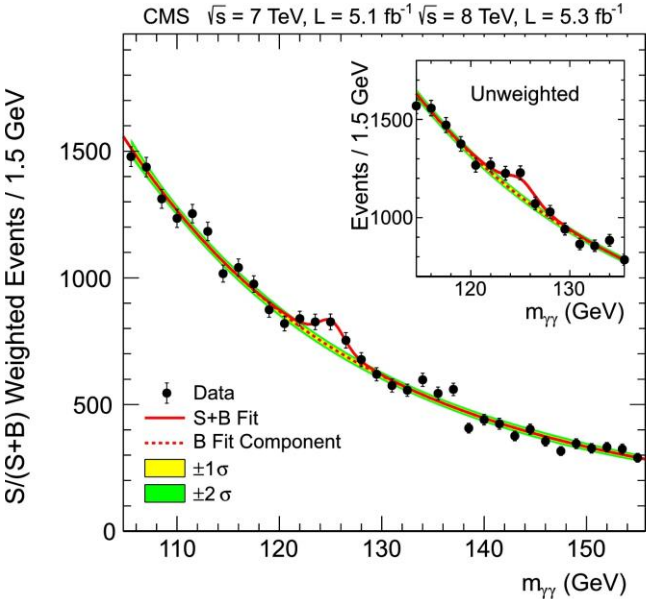


- SM predicts a scalar boson, **Higgs boson**, that gives mass to elementary particles through the spontaneous **EW symmetry breaking** and **Yukawa couplings**
- Higgs boson is discovered by ATLAS and CMS experiment at July 4th, 2012
- **A new era of particle physics!**

Phys. Lett. B716 (2012) 1-29



Phys. Lett. B716 (2012) 30-61

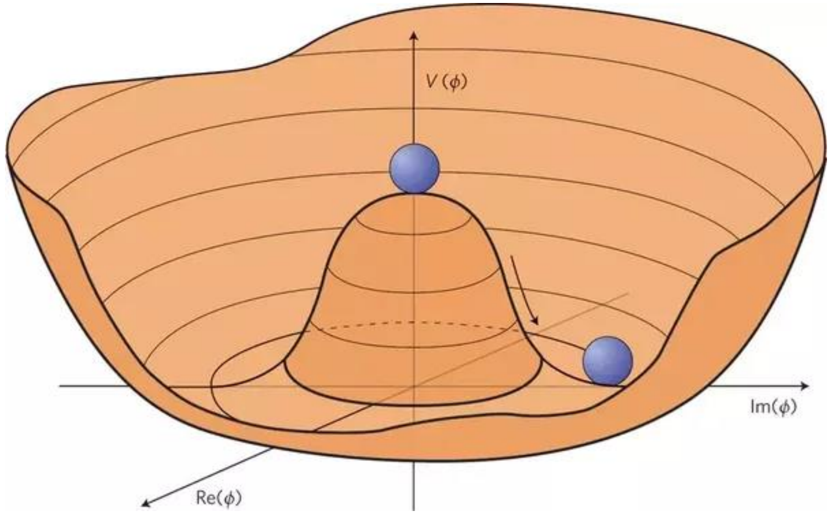


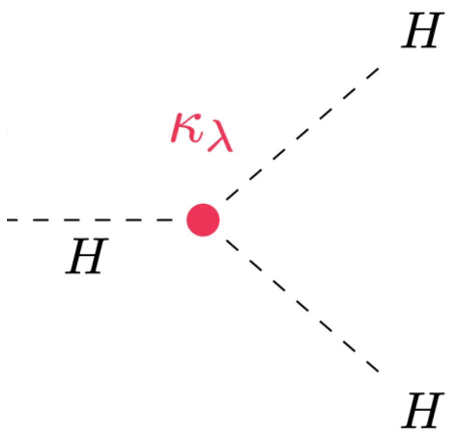
Higgs potential and Higgs boson self coupling

- Higgs at 10: interaction with the fermions and vector bosons are precisely studied in Nature 607, 52–59 (2022)
- Higgs self-interaction is also crucial and not discovered by experiment
- Higgs potential shape completely determines the properties of the scalar sector
  - $V(h) = -\mu^2\phi^2 + \lambda\phi^4$
  - $V(h) = \frac{m_h^2}{2}h^2 + \lambda v h^3 + \cdots$

$$\lambda_{hhh} = \frac{m_h^2}{2v^2}$$

- Higgs boson self coupling $\lambda = \sim 0.13$ in SM prediction
- $\kappa_\lambda \equiv \kappa_3 \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$ introduced to define the deviation of λ from the SM

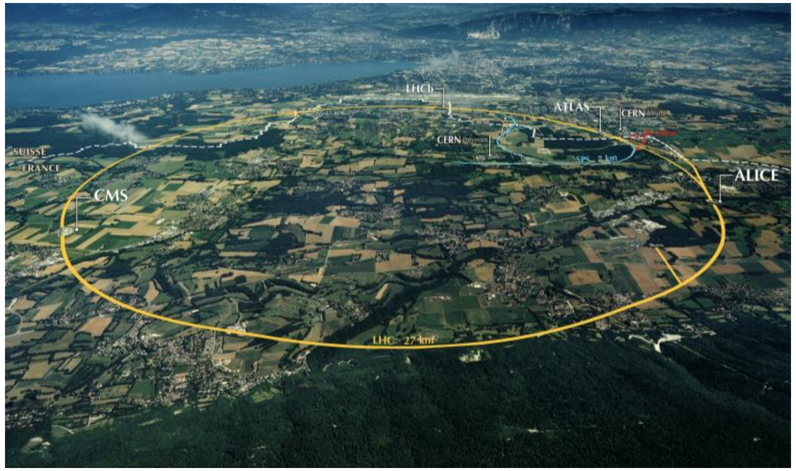




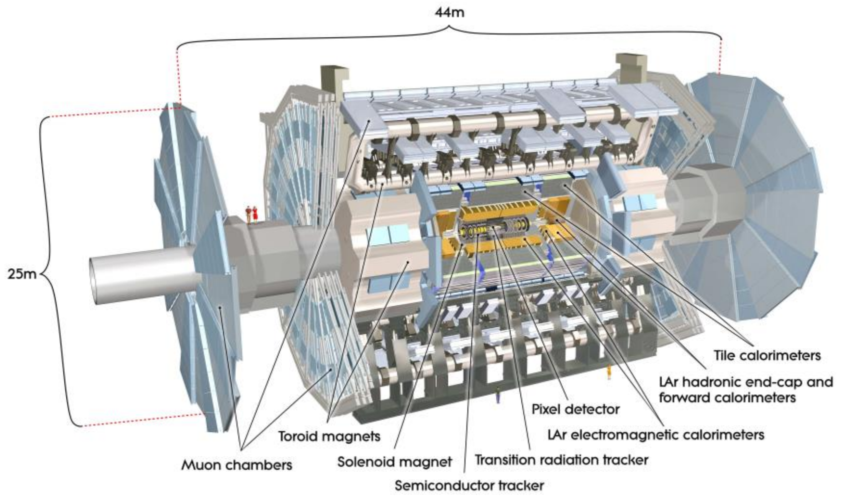
One of the targets of HL-LHC

Large Hadron Collider (LHC) and ATLAS detector

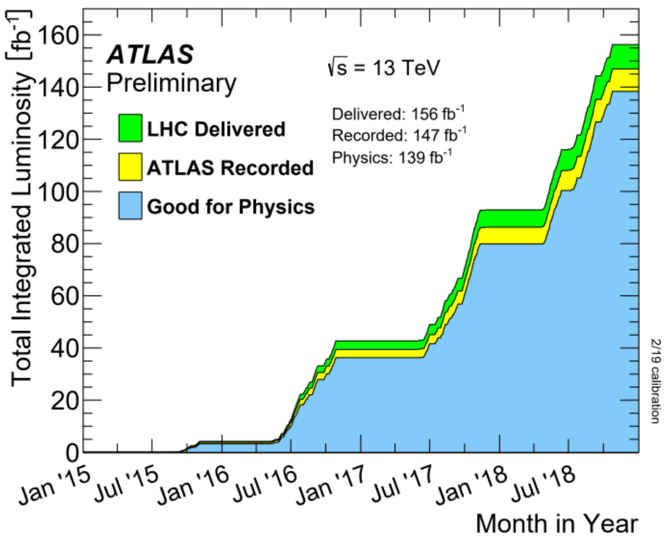
Picture of LHC



Structure of ATLAS



Luminosity of ATLAS Run 2



- The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator
- ATLAS is the largest general purpose particle detector for recording final states of pp collisions
- 10 years later after the discovery, **~9 million Higgs** are predicted to be produced (0.3% are accessible) in Run 2, 30 times more than the time of discovery due to higher integrated luminosity (**~139 fb^{-1}**), higher energy (**~8 TeV - 13 TeV**)
- Studying Higgs coupling properties by combing Run 2 analyses to celebrate the 10th anniversary of the Higgs discovery!

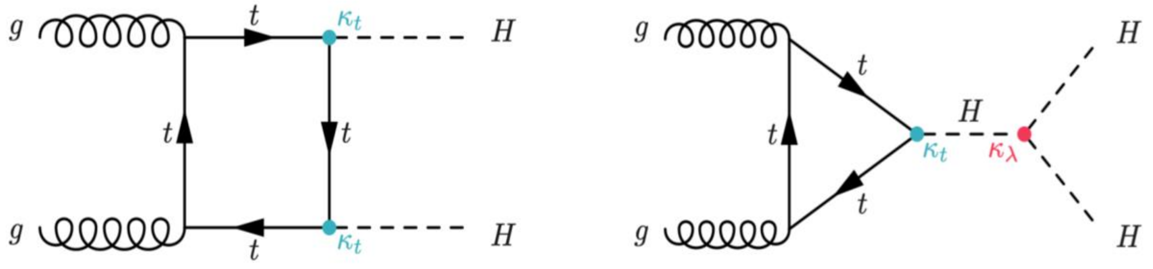
DOUBLE-HIGGS COMBINATION

Higgs boson pair production

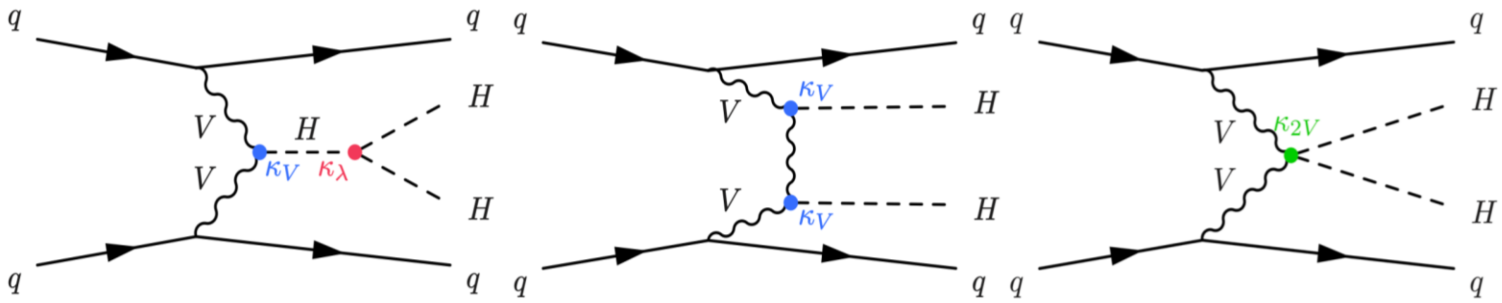
Higgs boson pair (HH) production allows to probe directly the Higgs boson self-interaction

Non-resonant pairs of Higgs bosons (HH) arise from several diagrams, some of which interfere destructively. Very small cross-sections!

Gluon-gluon fusion: $\sigma_{ggF}^{SM} \simeq 31$ fb [13 TeV].



Vector-boson fusion: $\sigma_{VBF}^{SM} \simeq 1.7$ fb [13 TeV].



Other production modes (e.g. VHH, $ttHH$) have even smaller cross-sections.

HH decays and search channels

- **Combine 3 most sensitive channels** (no single ”golden” channel)
- $bbbb$ (ATLAS-CONF-2022-035)
  - Highest branching ratio, but large multi-jet background!
  - Mostly probes large m_{HH} ⇒ sensitivity to HH events with large p_T^H
- $bb\tau\tau$ (ATLAS-CONF-2021-030)
  - Intermediate branching ratio, but clean final state with moderate backgrounds!
- $bb\gamma\gamma$ (Phys. Rev. D 106, 052001)
  - Tiny branching ratio, but very clean signature: excellent $m_{\gamma\gamma}$ resolution and small backgrounds!
  - Enhanced sensitivity at low m_{HH}, hence sensitive to the Higgs boson self-interaction.

Multitude of Higgs boson decay modes ⇒ $\mathcal{O}$(multitude^2) of HH search channels, each with specific experimental challenges and sensitivity reach.

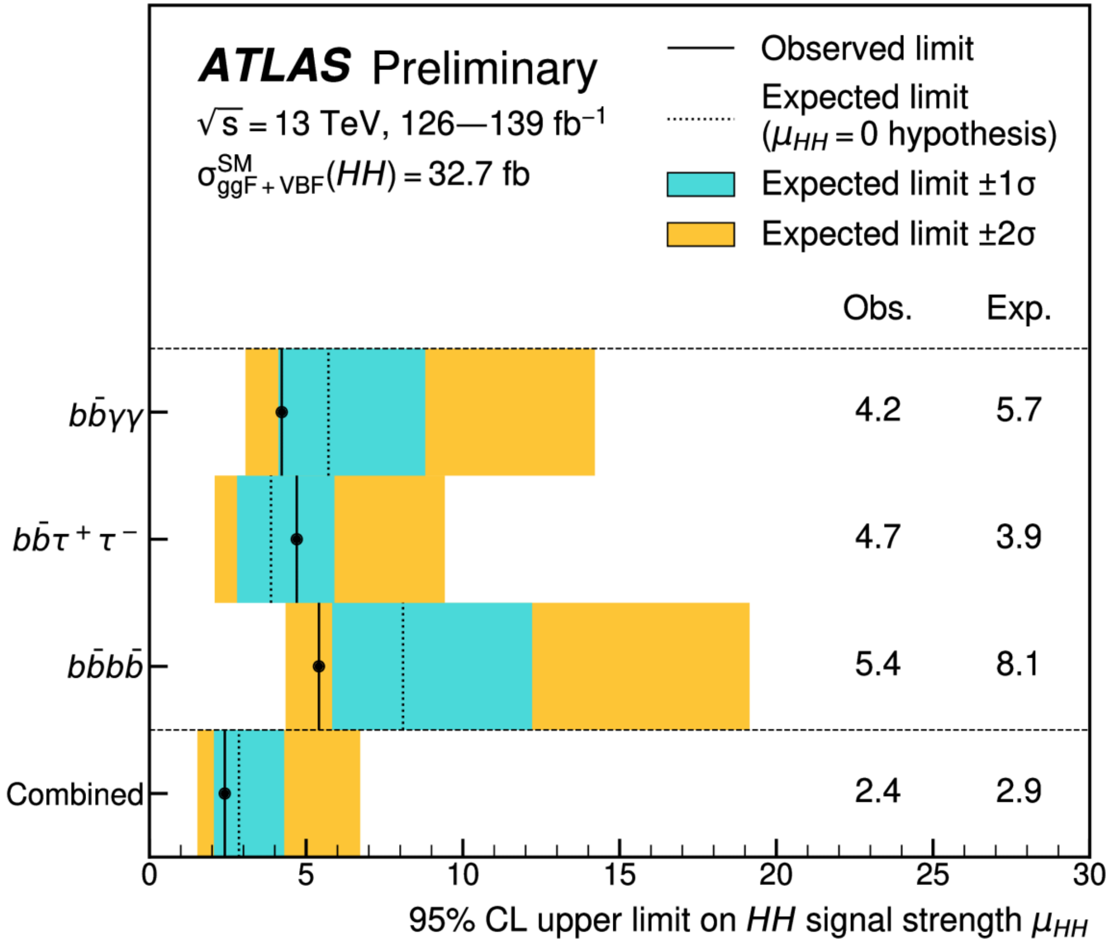
Branching ratio of HH decay mode

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH combined results: signal strength

- Overlaps among 3 analyses are negligible
- Upper limits of HH XS are measured

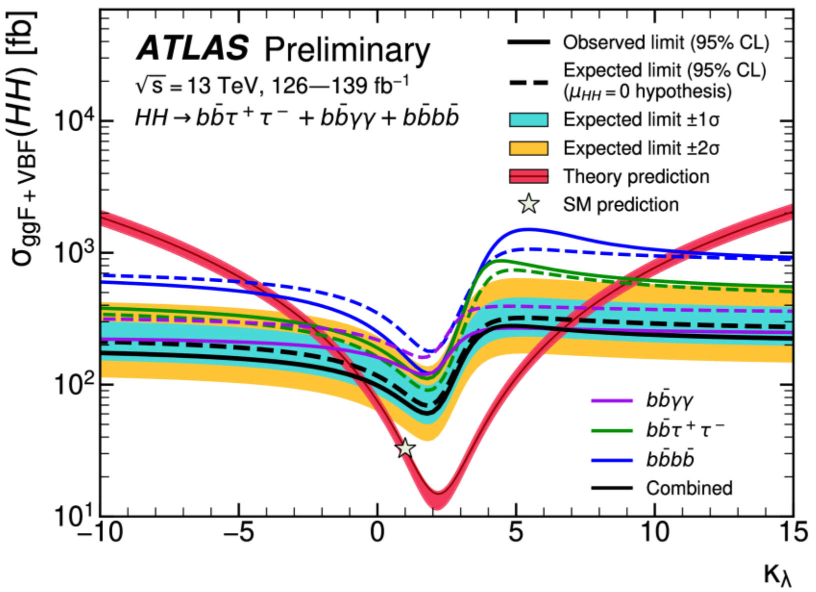
arXiv:2211.01216 [hep-ex]

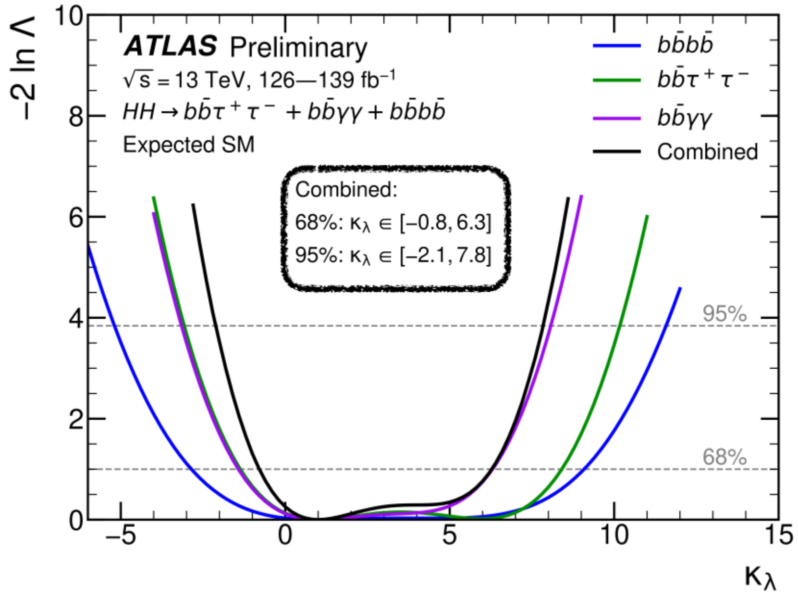


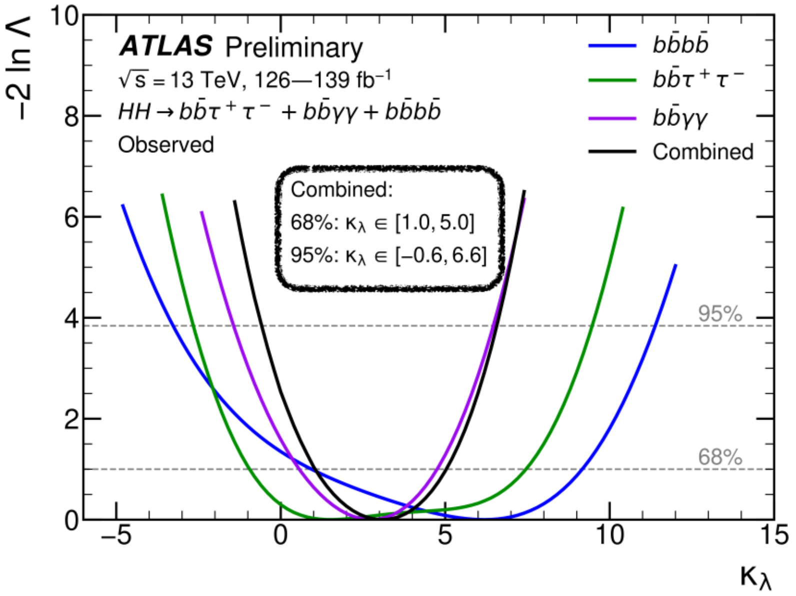
- $\mu_{HH} \equiv \frac{\sigma_{ggF+VBF}}{\sigma^{SM}_{ggF+VBF}} = -0.7 \pm 1.2, \mathrm{p_{SM}} = 20\%$
- Upper limit of σ_{HH} at 95% CL: 73 fb (85 fb)
- Compare to 36 fb^{-1} ATLAS HH combination [Phys. Lett. B 800 (2020) 135103]
  - **3.4 times better** exp. upper limit
  - Additional VBF mode; Better particle reconstruction algorithms; Greater number of simulated events; Better analysis strategies; Improved theory predictions

HH combined results: $\boldsymbol{\kappa_\lambda}$

arXiv:2211.01216 [hep-ex]





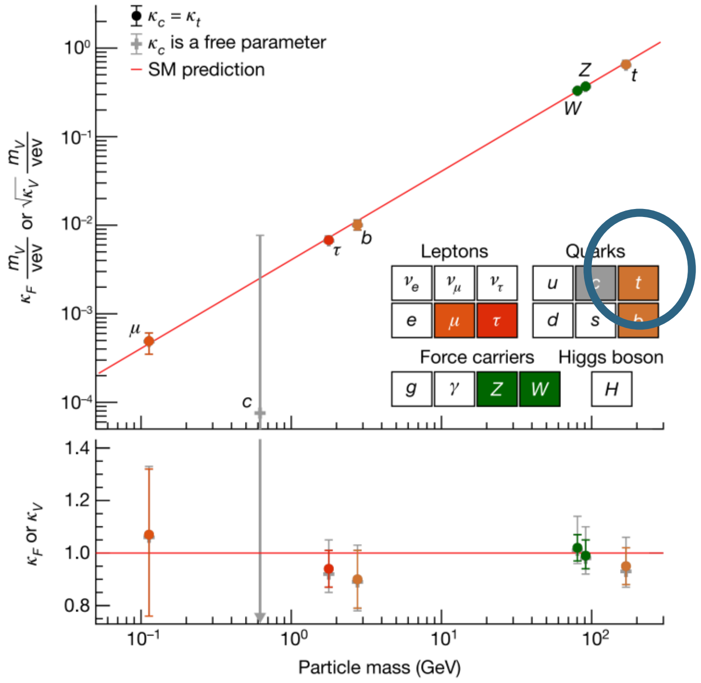


- Shape of $\boldsymbol{\sigma_{HH}(\kappa_\lambda)}$ exclusion limit is determined by $A \times \epsilon$ and kinematic dependence on $\boldsymbol{\kappa_\lambda}$
- Most sensitive: $bb\gamma\gamma$ due to low m_{HH}
- 2.4 times better κ_λ limit than 36 fb^{-1} ATLAS HH combination

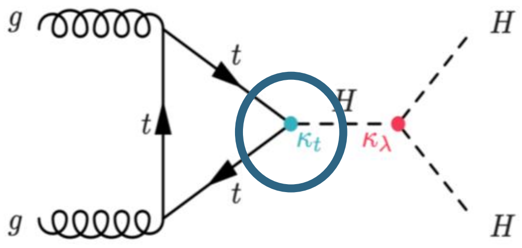
SINGLE-/DOUBLE-HIGGS COMBINATION

Context of the measurement

- κ_λ-only model: κ_λ is the only source of physics beyond SM, higher precision on κ_λ
- Generic model: κ_λ, κ_V, κ_t, κ_b, κ_τ all included for the source of physics beyond SM, less model dependence



[Nature 607, 52–59 (2022)]



- With the introduce of single-Higgs production modes
- the other κ assumptions are well constrained
- without losing too much κ_λ sensitivity

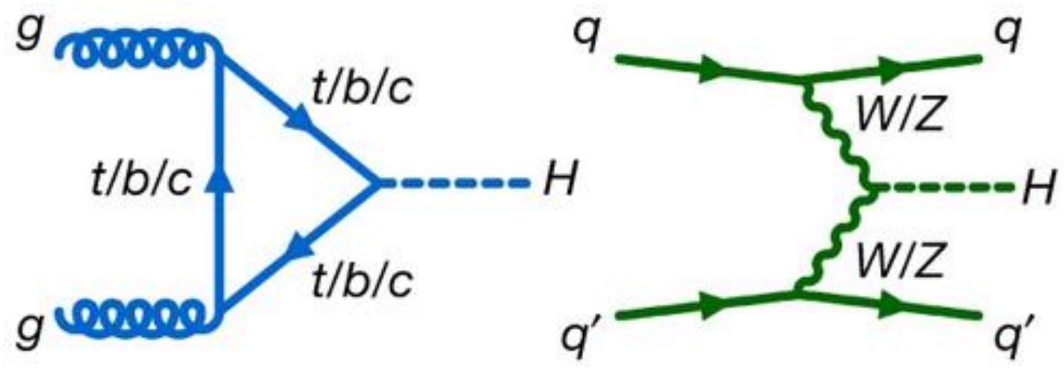
κ_λ interpretation on single Higgs channel

- Single Higgs boson processes do not depend on κ_λ at LO
- However, **NLO electroweak loops** allow κ_λ to affect single Higgs boson **production** and **decay** modes

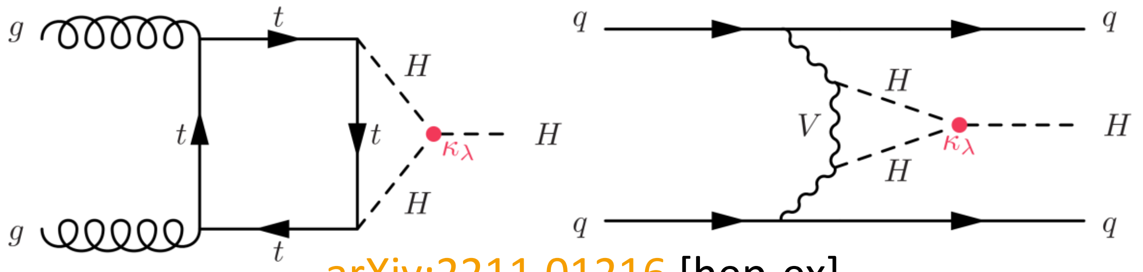
LO

NLO

Production mode

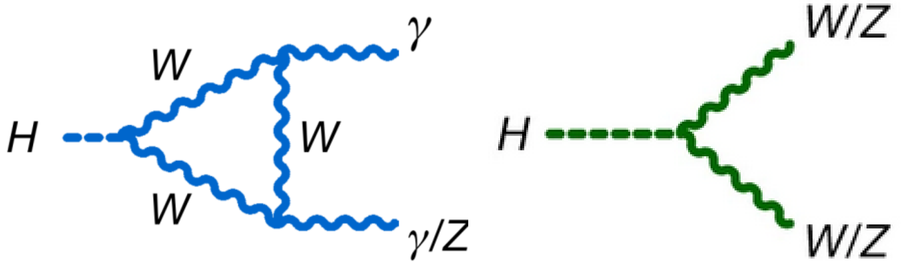


Nature 607, 52–59 (2022)

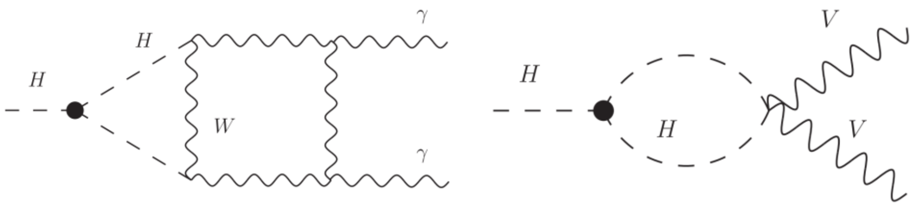


arXiv:2211.01216 [hep-ex]

Decay mode

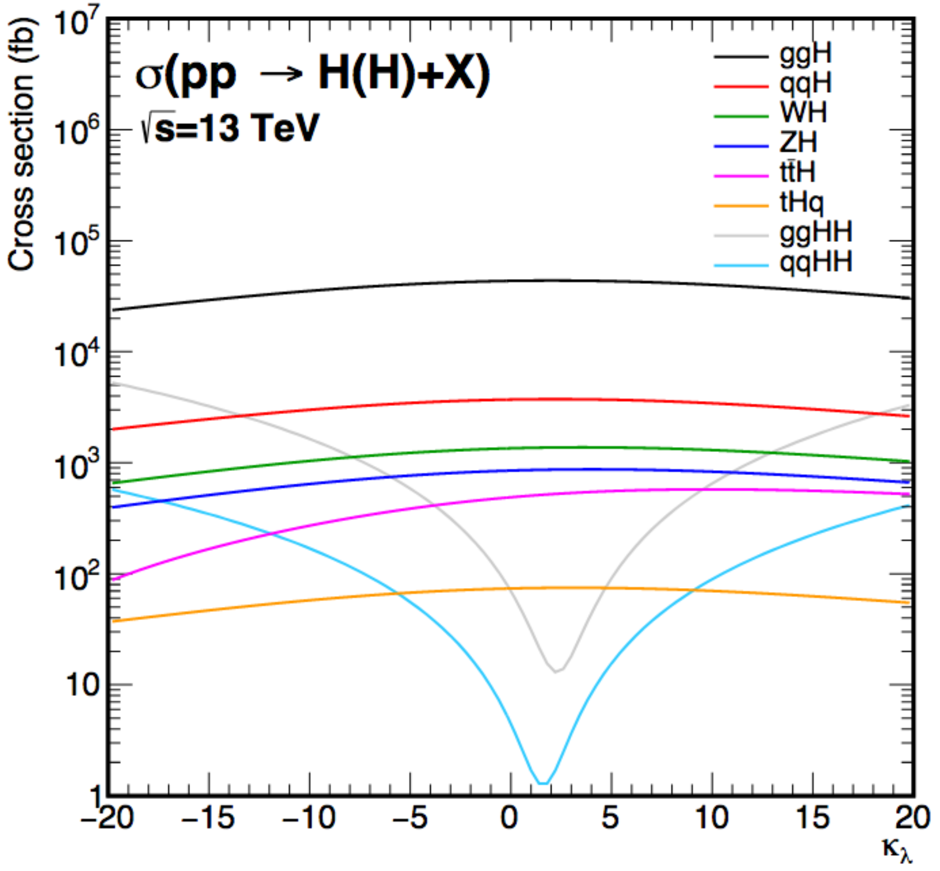


Nature 607, 52–59 (2022)

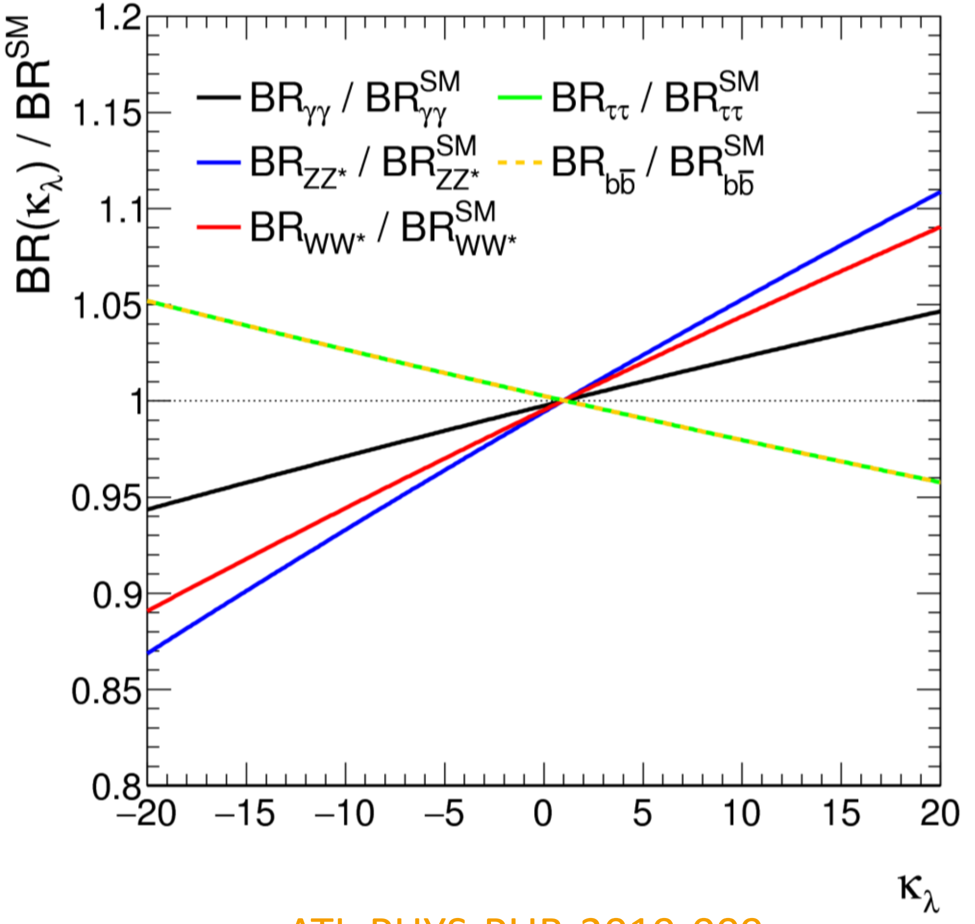


JHEP 1612, 080 (2016)

Impacts on Higgs production and decay



LHCHWG-2022-02



ATL-PHYS-PUB-2019-009

Combine with single Higgs

arXiv:2211.01216 [hep-ex]

- Combine single- and double-Higgs to have more stringent constraints on κ_λ
- Comprehensive combination to relax assumptions on other Higgs couplings (κ_t, κ_V, etc.)

Channel	Integrated luminosity (fb^{-1})
$HH \to b\bar{b}\gamma\gamma$	139
$HH \to b\bar{b}\tau\bar{\tau}$	139
$HH \to b\bar{b}b\bar{b}$	126
$H \to \gamma\gamma$	139
$H \to ZZ^* \to 4\ell$	139
$H \to \tau^+\tau^-$	139
$H \to WW^* \to e\nu\mu\nu$ (ggF,VBF)	139
$H \to b\bar{b}$ (VH)	139
$H \to b\bar{b}$ (VBF)	126
$H \to b\bar{b}$ $(t\bar{t}H)$	139

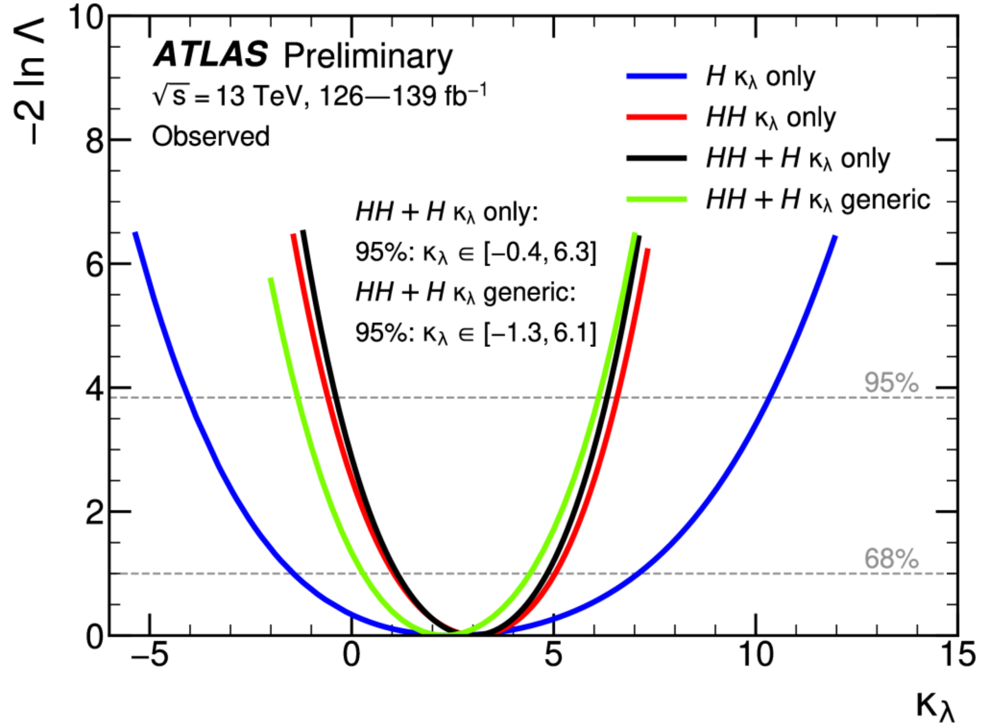
- Overlaps are mostly negligible between single-Higgs and double-Higgs
- Except 4% $HH \to bb\tau\tau$ SR events overlapping with $ttH, H \to \tau\tau$
  - Remove $ttH, H \to \tau\tau$ categories (low sensitivity to κ_λ) in combination

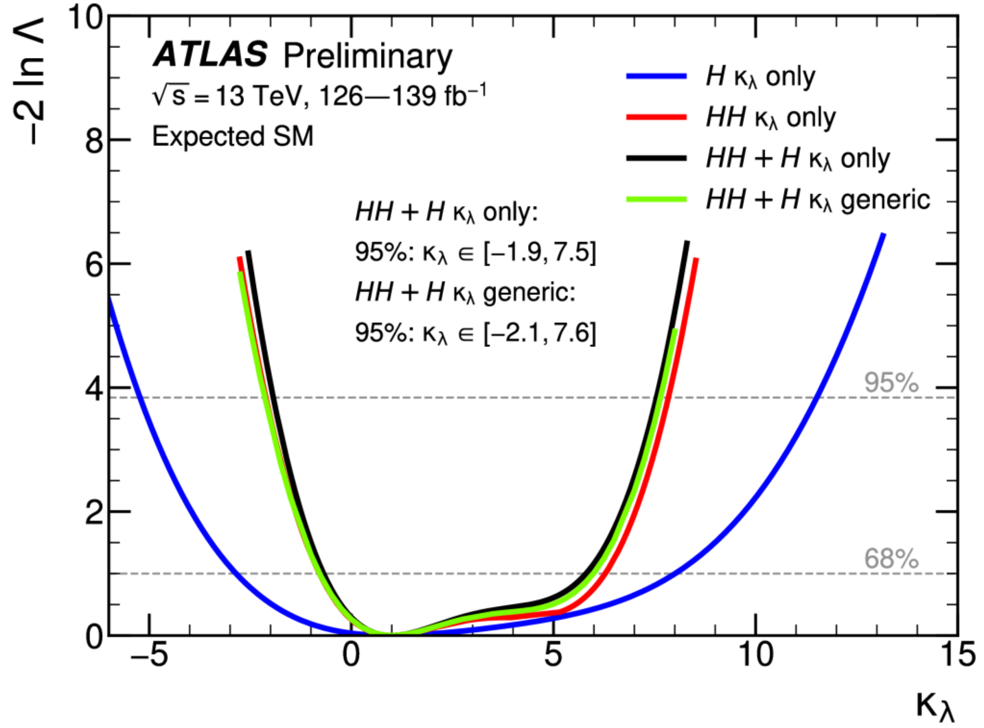
HH+H: constraints on κ_λ

arXiv:2211.01216 [hep-ex]

- Di-Higgs has much stronger constraining power than Single-Higgs
- However, it helps to remove assumptions on other kappa

Observed and expected value of the test statistics $(-2\ \ln\Lambda)$ for κ_λ





HH+H: results from κ_λ likelihood scans

- Di-Higgs has much stronger constraining power than Single-Higgs
  - Marginal contribution from single H, ~5%
- However, it helps to remove assumptions on other kappa

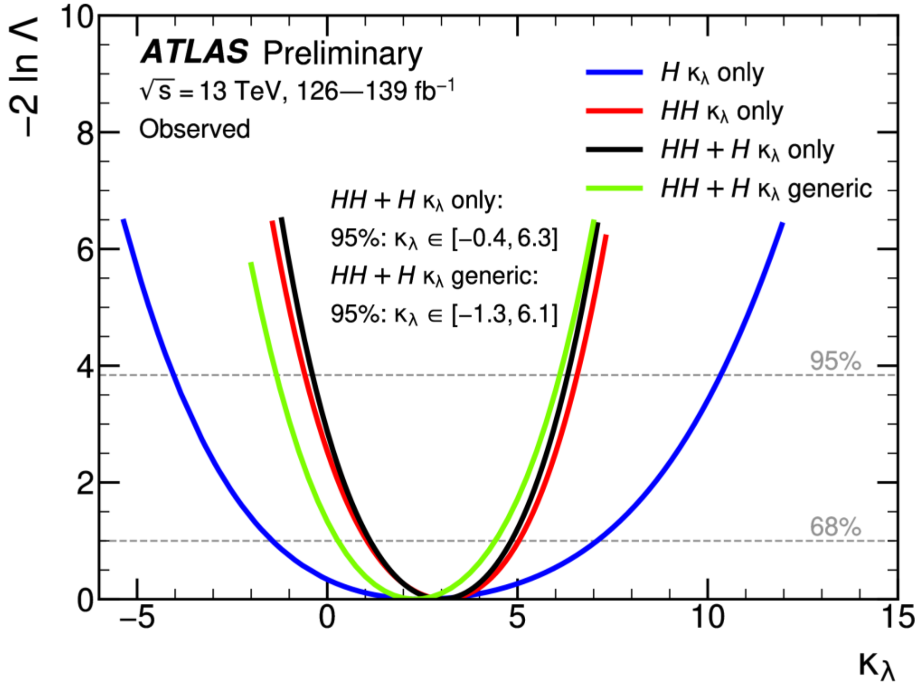
Observed value and 95% CL limits of κ_λ

arXiv:2211.01216 [hep-ex]

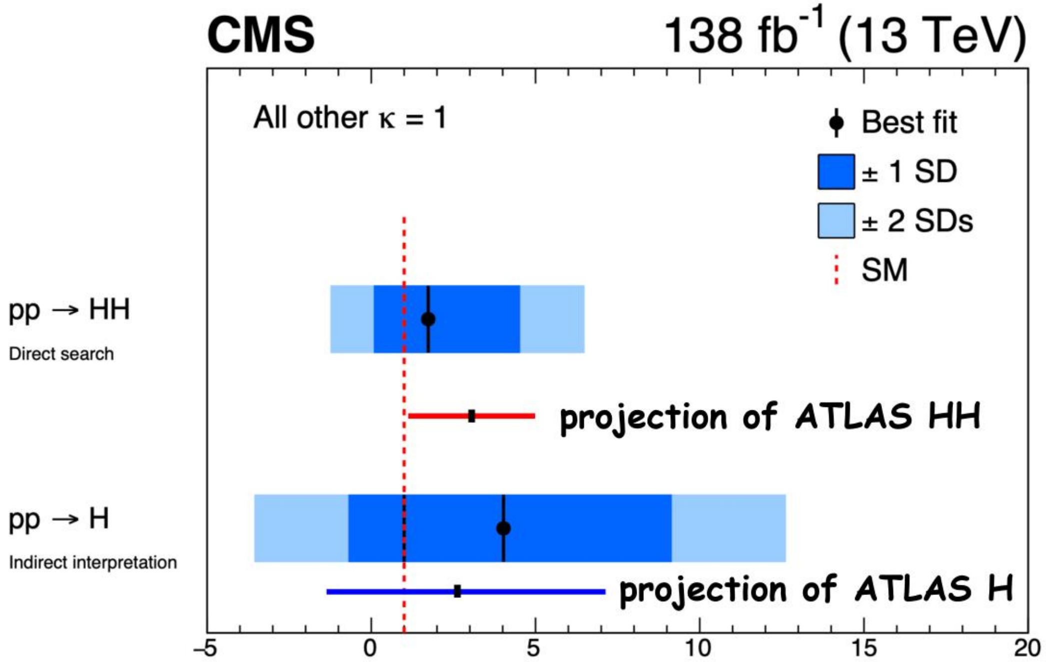
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.5$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t, κ_V, κ_b, κ_τ floating	$-1.3 < \kappa_\lambda < 6.1$	$-2.1 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

Comparison with CMS results

- Self coupling measurement results also published by CMS collaboration



arXiv:2211.01216 [hep-ex]



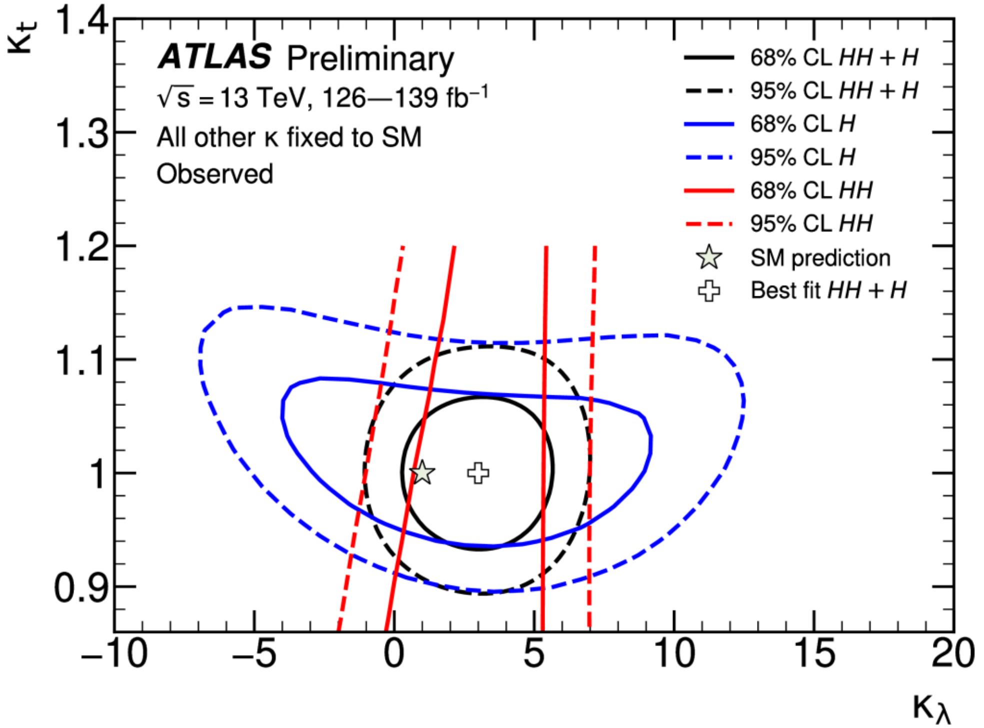
Nature 607, 60–568 (2022)

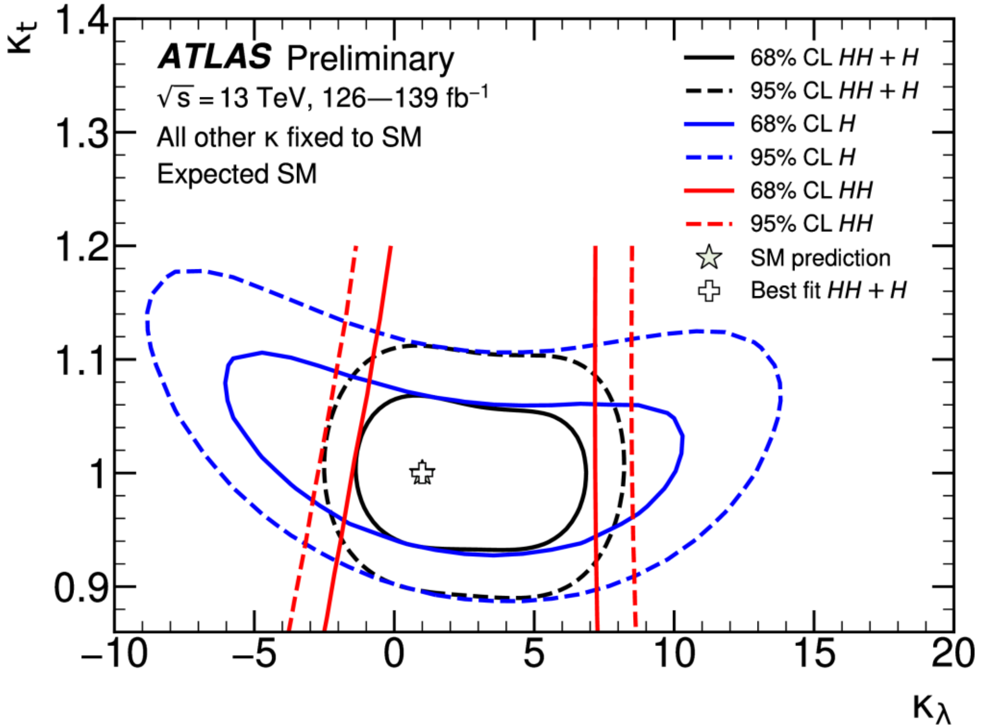
Compatible with observed κ_λ limits from CMS!

HH+H: constraints on κ_λ versus κ_t

arXiv:2211.01216 [hep-ex]

Observed and expected constraints in the κ_λ–κ_t plane from single-Higgs, double-Higgs and their combination





- HH only can't constrain κ_t, κ_λ simultaneously
  - κ_t, κ_λ almost fully correlated in ggF HH XS interpretation
- With single-Higgs, assumption on κ_t can be relaxed without losing κ_λ sensitivity

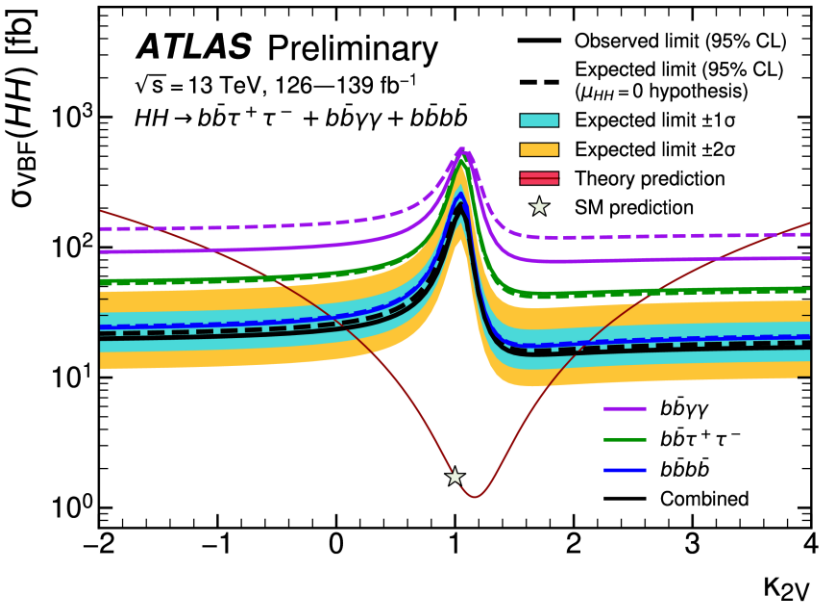
Summary

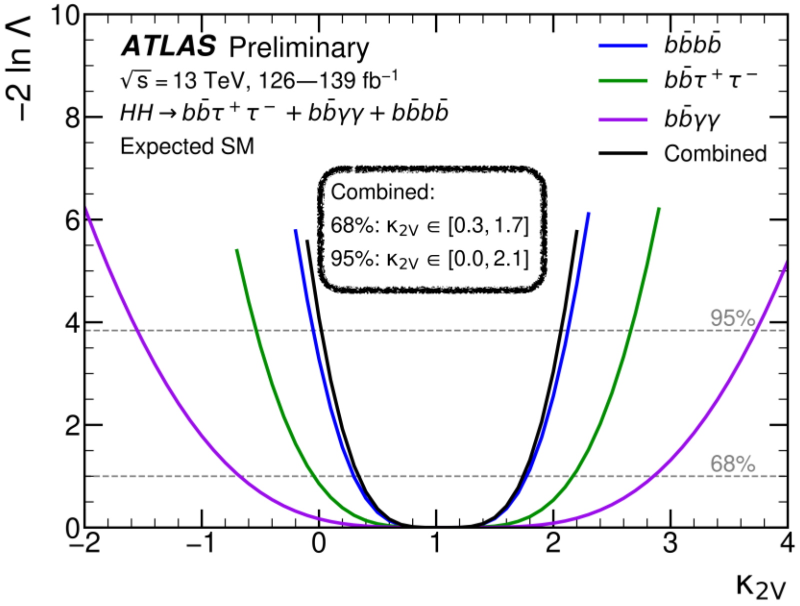
- Elusive non-resonant pairs of Higgs bosons are the prime experimental signature of the Higgs boson self-interaction
- Di-Higgs only results are included as it is done for the first time using full Run 2 data
- Electroweak corrections in single-H processes provide additional sensitivity to the Higgs boson self-interaction
- A combination of single- and double-Higgs full Run 2 analyses is presented to provide the most constraint results on the Higgs self-coupling to date
  - At 68% C.L., the observed (expected) allowed interval of κ_λ: [-0.4, 6.3] ([-1.9, 7.5])
- Results were published in July 4, 10 year Higgs Symposium and already submitted to PLB (arXiv:2211.01216 [hep-ex])
- Stay tuned for better results from LHC Run3 and HL-LHC results!

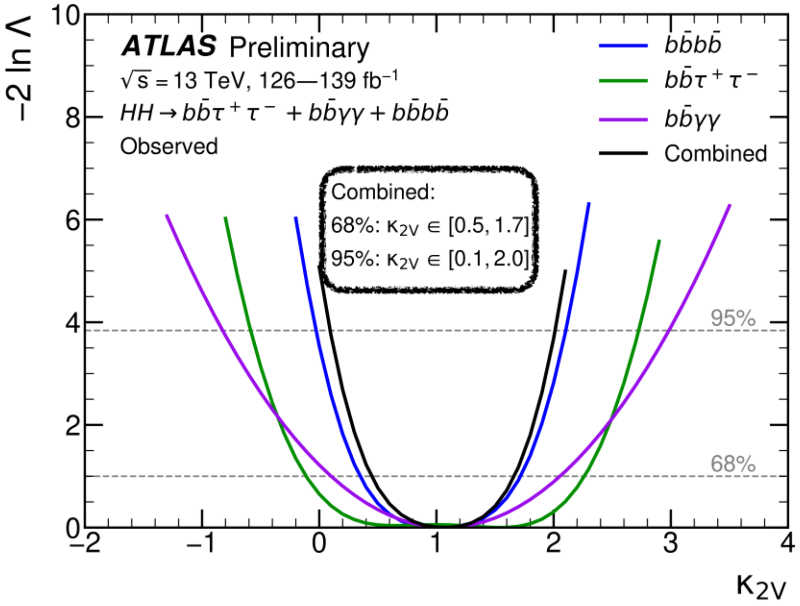
Backup

HH combined results: κ_{2V}

arXiv:2211.01216 [hep-ex]



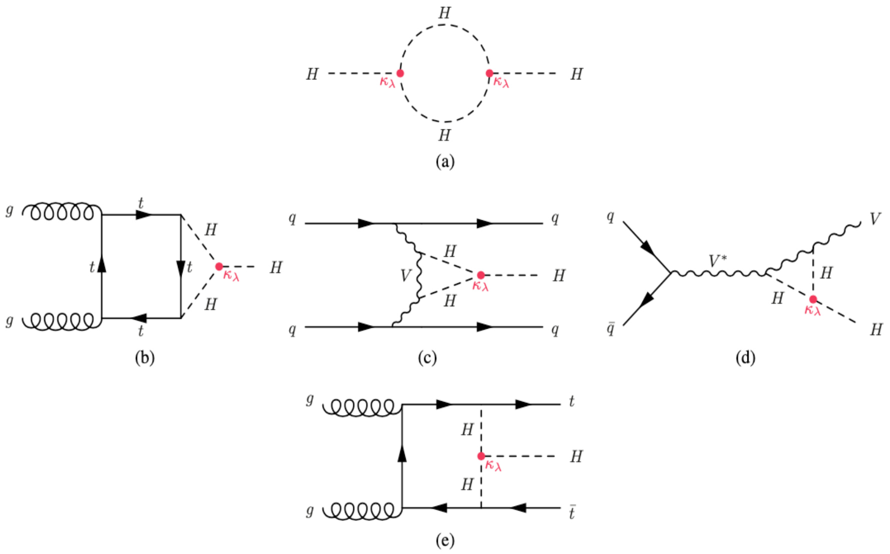




- VBF is sensitive to $HHVV$ interaction, constrain κ_{2V} **first time** in combination
- **Tight m_{HH}** is more sensitive to κ_{2V}, $bbbb$ contributes most
- Only include **resolved $bbbb$** final states, expect higher significance in boosted case
  - ($\kappa_{2V} \in [0.62, 1.41]$ at 95% CL in boosted $bbbb$ in CMS, exclude $\kappa_{2V} = 0$ at 6.3σ)

κ_λ parametrisation in single Higgs

- κ_λ contributes to NLO EW correction to Higgs production and decay



$$\mu_{if}(\kappa_\lambda) = \mu_i(\kappa_\lambda) \times \mu_f(\kappa_\lambda) \equiv \frac{\sigma_i(\kappa_\lambda)}{\sigma_{\mathrm{SM},i}} \times \frac{\mathrm{BR}_f(\kappa_\lambda)}{\mathrm{BR}_{\mathrm{SM},f}}$$

Production

$$\mu_i(\kappa_\lambda, \kappa_i) = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}} = Z_H^{\mathrm{BSM}}(\kappa_\lambda)\left[\kappa_i^2 + \frac{(\kappa_\lambda - 1)C_1^i}{K_{\mathrm{EW}}^i}\right]$$

Decay

$$\mu_f(\kappa_\lambda, \kappa_f) = \frac{\mathrm{BR}_f^{\mathrm{BSM}}}{\mathrm{BR}_f^{SM}} = \frac{\kappa_f^2 + (\kappa_\lambda - 1)C_1^f}{\sum_j \mathrm{BR}_j^{\mathrm{SM}}\left[\kappa_j^2 + (\kappa_\lambda - 1)C_1^j\right]}$$

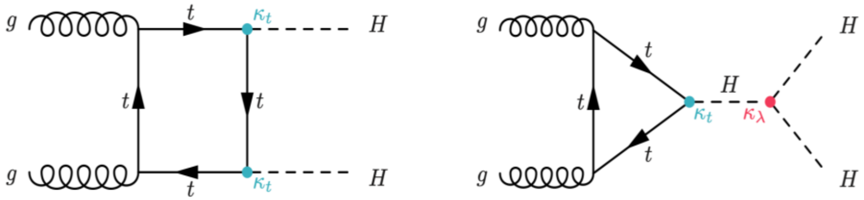
- C_1^i and K_{EW}^i values are taken from LHCHWG-2022-02
- STXS 1.2 differential values applied to Hjj, V(let)H, ttH; inclusive values applied to ggH, tHj; no values available for tHW, bbH and ggZH
- Uncertainties on these values are not considered and are expected to be negligible
- Acc x eff assumed to be constant wrt κ_λ in each STXS bin
- κ_i is parametrized in terms of $\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$

Single H workspace parametrized as a function of $\kappa_\lambda, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau$

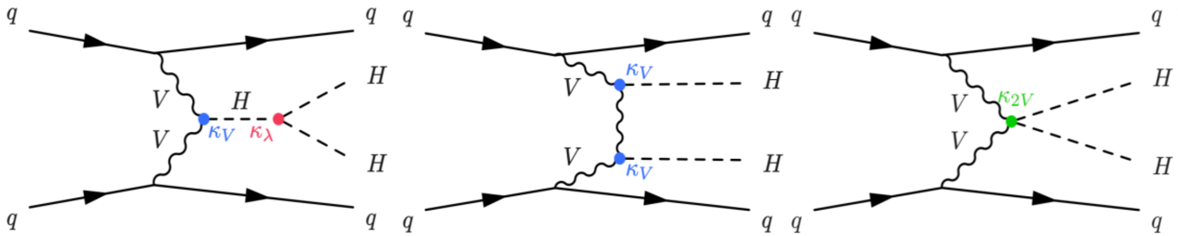
κ_λ parametrization in di-Higgs

Di-Higgs production diagrams

$31.0^{+2.1}_{-7.2}$ fb



1.72 ± 0.04 fb



- Di-Higgs decay is parametrized the same way as for single H
- Single Higgs background is parametrized the same way as for single H

- Di-Higgs production is directly sensitive to κ_λ at LO in EW

$$\sigma_{ggF}(\kappa_t, \kappa_\lambda) \propto |\kappa_t^2 \mathcal{A}_1 + \kappa_t \kappa_\lambda \mathcal{A}_2|^2$$

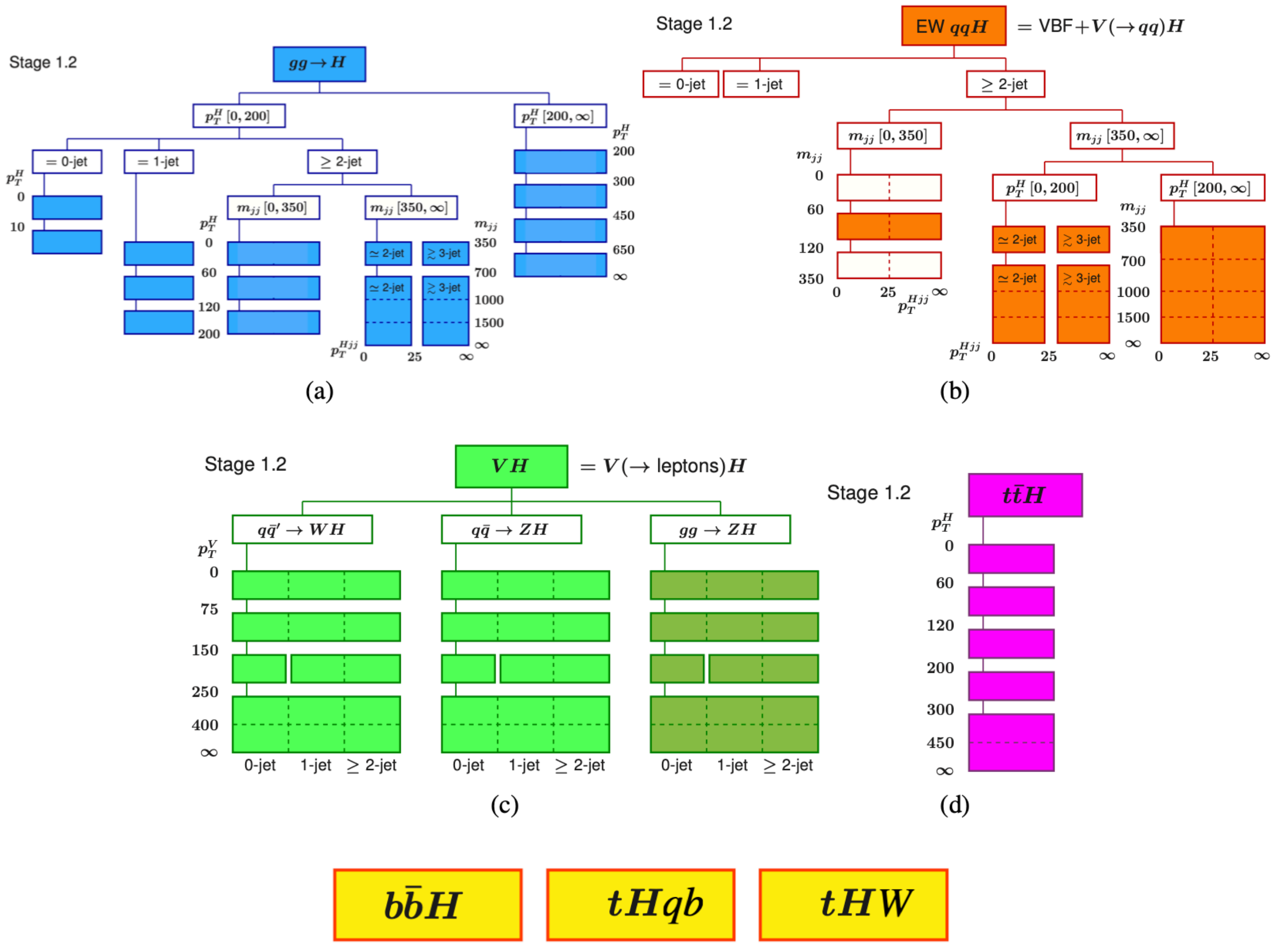
- $|\mathcal{A}_1|^2$, $|\mathcal{A}_2|^2$, $|\mathcal{A}_1\mathcal{A}_2|$ determined by reweighting three ggF signal samples at reconstruction level

$$\sigma_{VBF}(\kappa_\lambda, \kappa_V, \kappa_{2V}) \propto \left|\kappa_\lambda \kappa_V \mathcal{A}_1 + \kappa_V^2 \mathcal{A}_2 + \kappa_{2V} \mathcal{A}_3\right|^2$$

- $|\mathcal{A}_1|^2$, $|\mathcal{A}_2|^2$, $|\mathcal{A}_3|^2$, $|\mathcal{A}_1\mathcal{A}_2|$, $|\mathcal{A}_2\mathcal{A}_3|$, $|\mathcal{A}_1\mathcal{A}_3|$ are determined by reweighting six VBF signal samples at reconstruction level

Double H workspace parametrized as a function of κ_λ, κ_{2V}, κ_V, κ_t, κ_b, κ_τ

Single Higgs parametrization with STXS



(a) (b) (c) (d)