Evidence for H→μμ and Search for HH→bb$\tau\tau$ at ATLAS Experiment

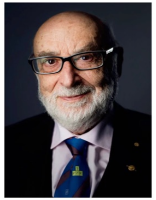
刘彦麟
山东大学

中国物理学会高能物理分会第十二届全国会员代表大会
2026年7月13日-19日

Physics Motivation

High-energy frontier: Higgs physics is one of the primary goals at the LHC

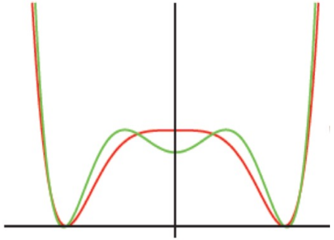
Higgs discovery in 2012



© Nobel Media AB. Photo: A. Mahmoud
François Englert
Prize share: 1/2

© Nobel Media AB. Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

Higgs potential like Mexican hat?



Vacuum stable? Metastable?

Key questions after Higgs discovery

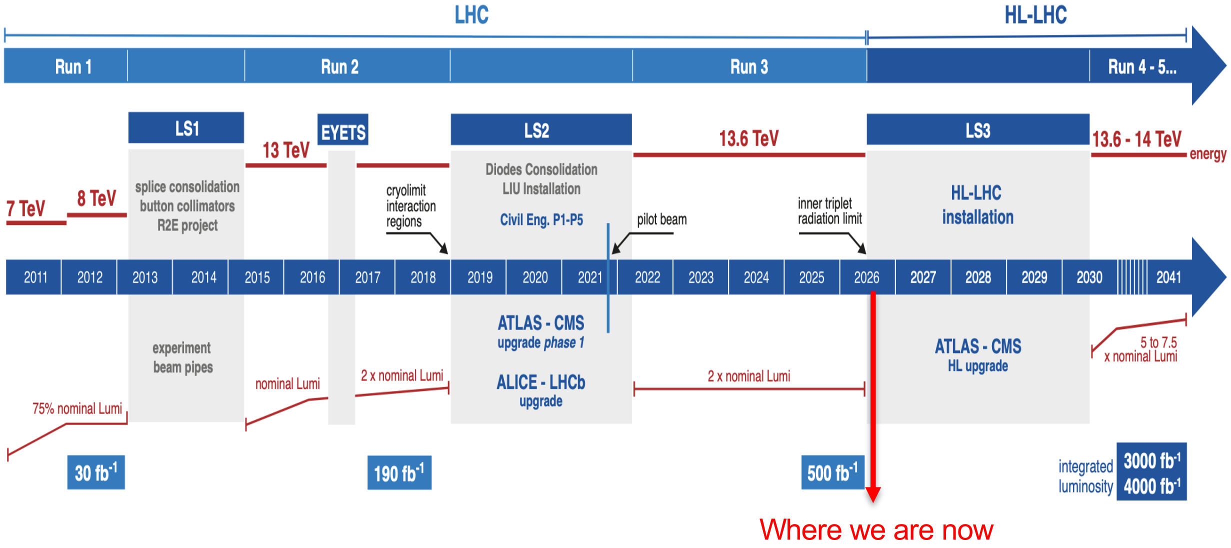
Origin of fermion masses? → 1. Higgs Yukawa couplings

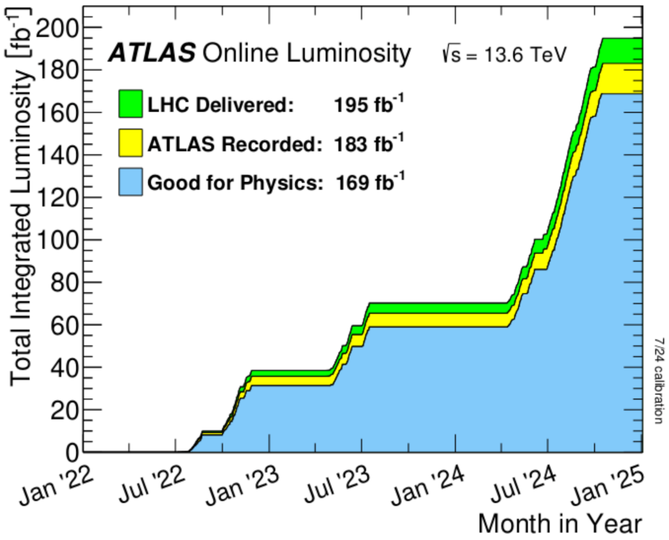
Higgs potential? → 2. Higgs self-coupling

Outline of My Talk Today

- 1. H→μμ: Higgs Yukawa coupling to 2nd generation fermion
- 2. HH→bb$\tau\tau$: Higgs self-coupling

Run-2 and Run-3 Datasets

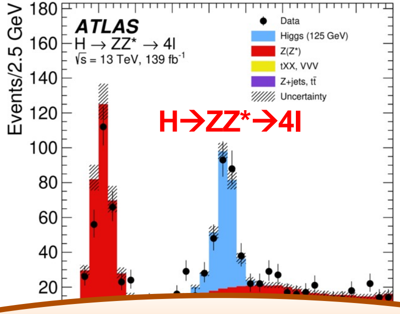


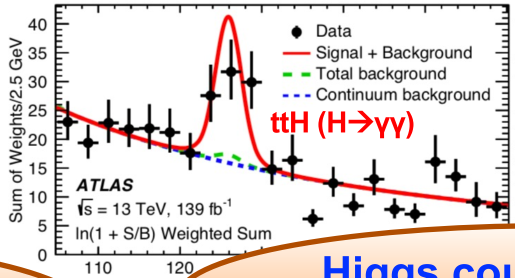


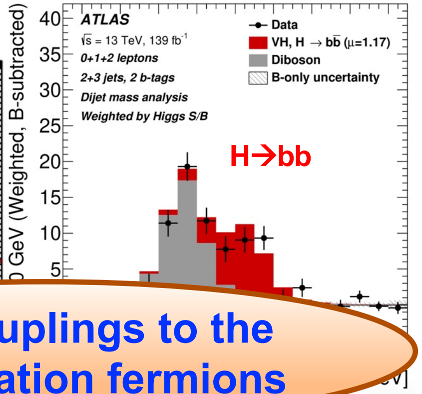
- During Run-2, 140 fb^{-1} (13 TeV) data collected for physics
- From 2022-2024 (partial Run-3), ~165 fb^{-1} (13.6 TeV) data for physics

Search for $H \rightarrow \mu\mu$

Higgs Couplings to Massive Particles (>5σ)

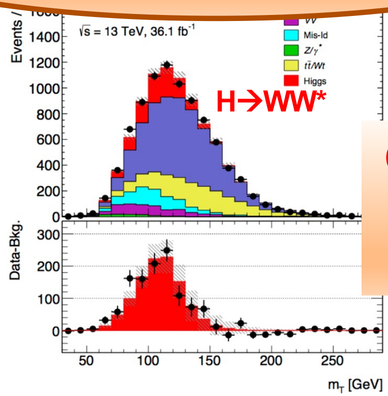


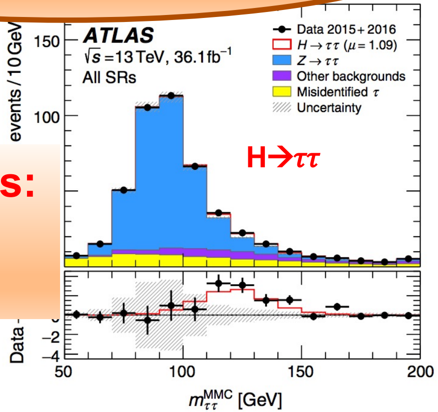




Higgs coupling to
massive gauge bosons

Higgs couplings to the
3rd generation fermions

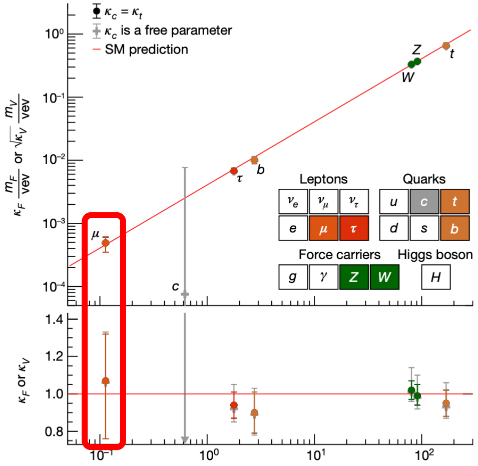


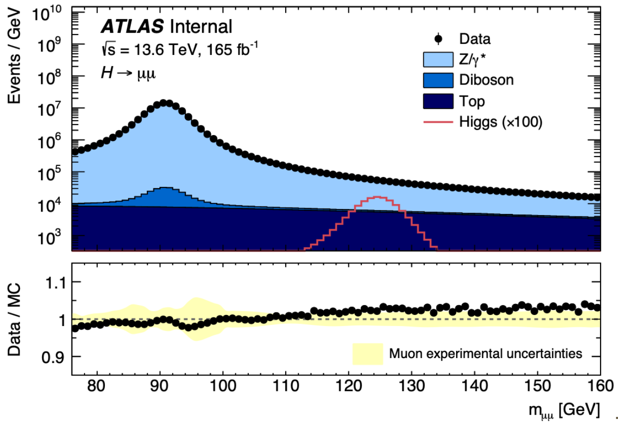


One of the next big milestones:
Higgs couplings to the 2nd
generation fermions

Introduction

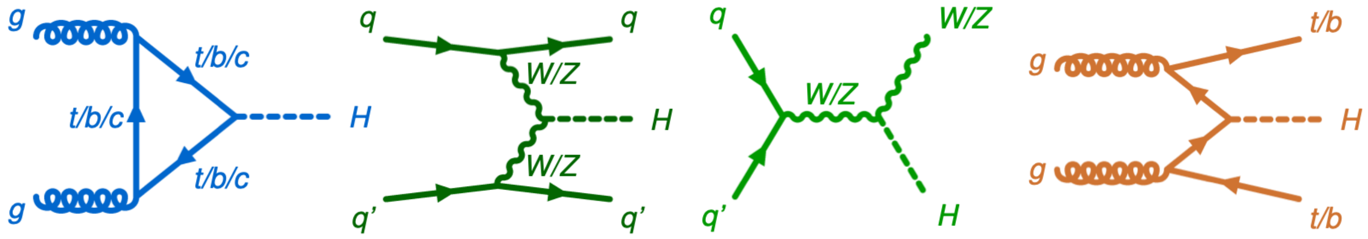
- H→μμ: most promising channel to explore Yukawa coupling to 2nd generation fermions
- Major challenge: low BR and large irreducible bkg. from Drell-Yan, S/B at ~0.1%
- Run-2 analysis: obs. (exp.) significance is 2.0σ (1.7σ)
- Latest analysis based on partial Run-3 (165 fb^{-1}), then combined with full Run-2 (140 fb^{-1}) analysis





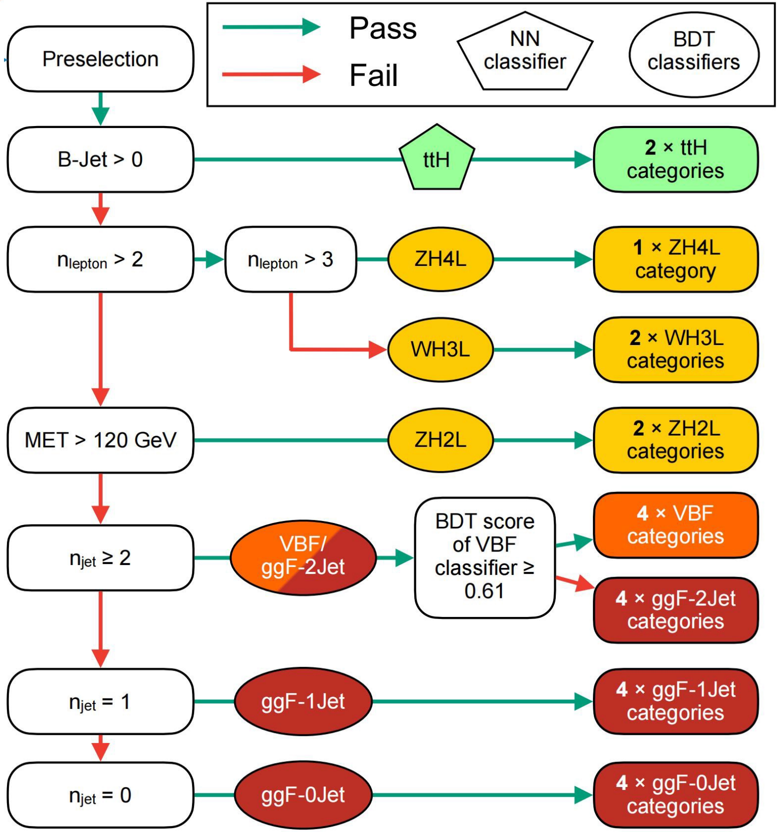
Overview of Analysis Methodology

- Signal signatures: two isolated muons with opposite charge
- MVA-based categorization developed to enhance the sensitivity
  - ➢ Driven by the four major production modes
  - ➢ 23 exclusive categories in the order of ttH→VH→VBF→ggF



- Data driven approach used for bkg. estimation
- S+B PDF used to fit the observed $m_{\mu\mu}$ spectra simultaneously in all the categories to derive the final results
  - ➢ Sig. and bkg. modeled by analytic functions

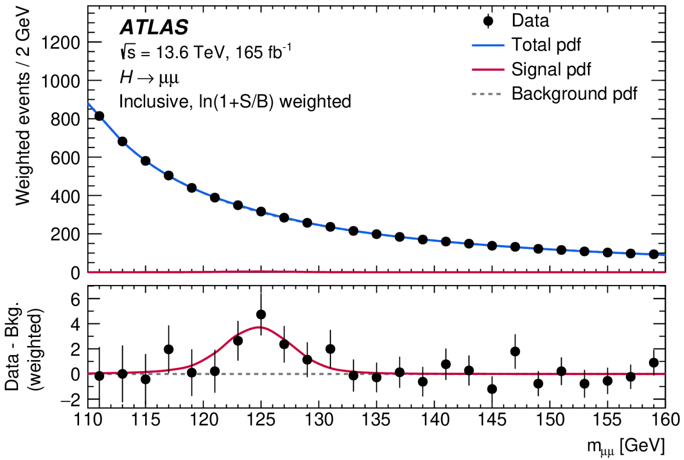
Event Categorization

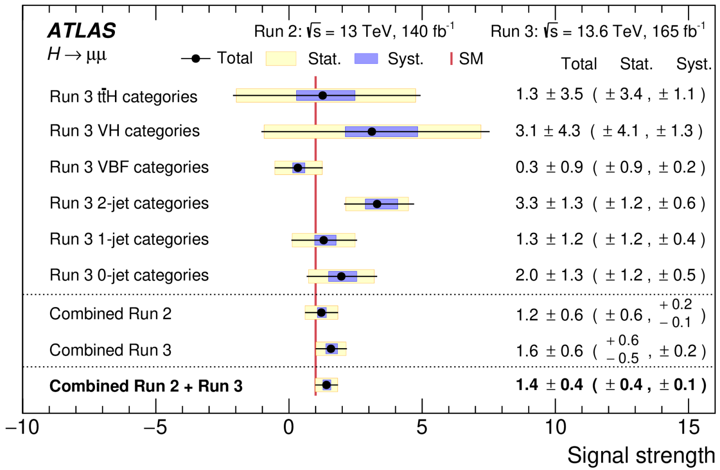


Category	Data	S	B	$S/\sqrt{B}$	S/B [%]
$t\bar{t}H$-High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$-Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very Low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1 399	31 ± 12	$1\,367 \pm 25$	0.84	2.3
2-jet Medium	5 657	69 ± 26	$5\,560 \pm 50$	0.92	1.2
2-jet Low	17 684	110 ± 40	$17\,300 \pm 70$	0.87	0.7
2-jet Very Low	35 147	110 ± 40	$35\,160 \pm 140$	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7 166	80 ± 30	$7\,140 \pm 70$	0.95	1.1
1-jet Low	31 761	180 ± 70	$31\,510 \pm 120$	1.00	0.6
1-jet Very Low	73 578	200 ± 80	$73\,330 \pm 200$	0.75	0.3
0-jet High	19 445	120 ± 50	$19\,260 \pm 90$	0.89	0.6
0-jet Medium	50 742	200 ± 80	$50\,830 \pm 190$	0.90	0.4
0-jet Low	94 032	240 ± 90	$93\,770 \pm 210$	0.78	0.3
0-jet Very Low	136 762	170 ± 60	$136\,510 \pm 290$	0.47	0.1

Results for H→μμ

- A simultaneous maximum-likelihood fit performed to the observed $m_{\mu\mu}$ spectra in 23 categories
- Run-3 data only: obs. (exp.) significance is 2.8σ (1.8σ), μ = 1.6 ± 0.6
- Run-2 and Run-3: obs. (exp.) significance is 3.4σ (2.5σ), μ = 1.4 ± 0.4
- Evidence of Yukawa coupling to 2nd generation fermions at ATLAS!

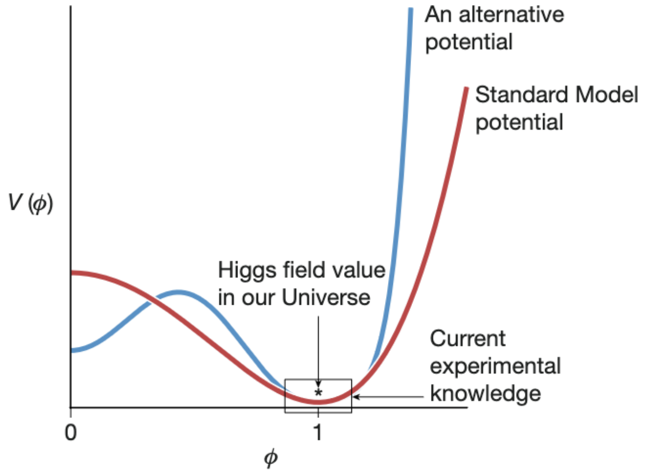




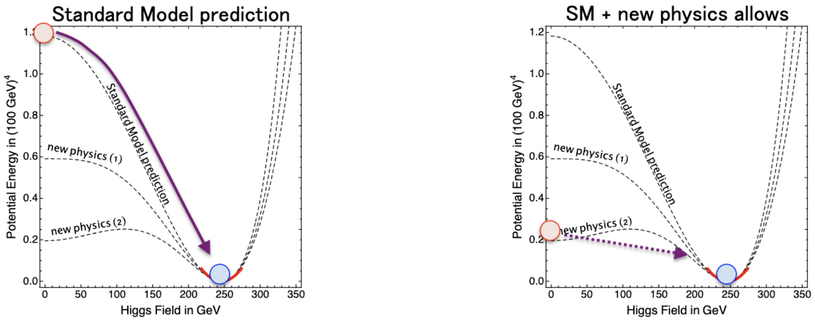
Phys. Rev. Lett. 135 (2025) 231802 (Editors' suggestion)

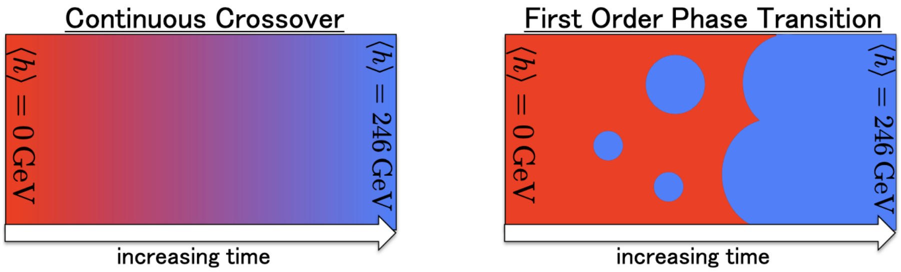
HH→bb$\tau\tau$

Higgs Potential Not Determined Yet



Ref: Nature 607, 41–47 (2022)



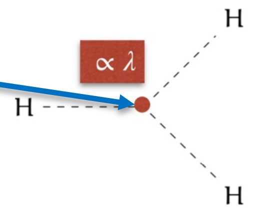


From L. Wang

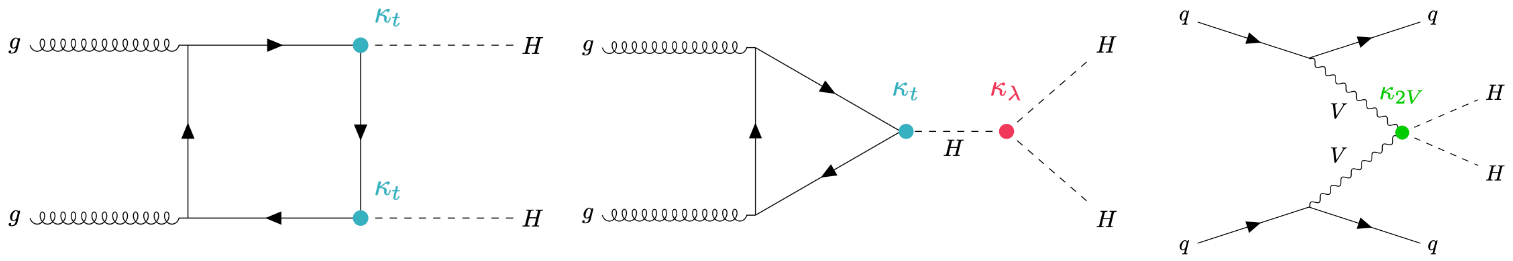
- New physics (e.g. 1st order EW phase transition) can cause a significant deviation from SM
- Measurements of Higgs self-coupling can provide discrimination between different scenarios

Higgs Self-coupling and HH Production

- Higgs potential: $V(h) = \frac{1}{4}\lambda h^4 + \lambda v h^3 + \lambda v^2 h^2$
  - ➢ In SM, $\lambda \approx 0.13$ give $m_H \approx 125$ GeV
- HH productions provide directly access to Higgs self-coupling κ_λ ($\lambda_{HHH}/\lambda_{SM}$)



- SM non-resonant HH: σ_{HH}^{ggF} = 31.05 fb, σ_{HH}^{VBF} = 1.72 fb
  - ➢ Direct access to κ_λ and Higgs potential
  - ➢ VBF: unique process to probe HHVV coupling (κ_{2V})

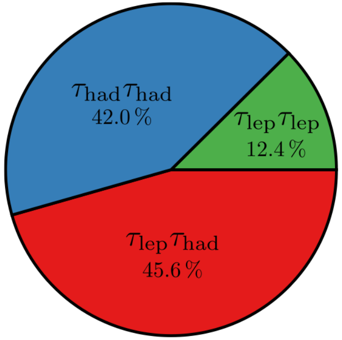


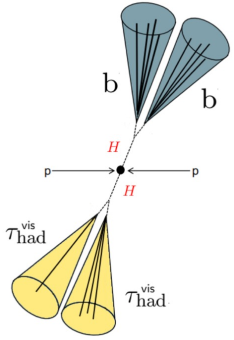
$bb\tau\tau$ Final State

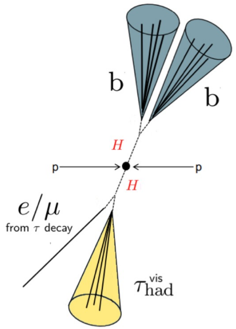
HH Branching Ratios

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39 %		
ZZ	3.1%	1.2%	0.34 %	0.076 %	
$\gamma\gamma$	0.26 %	0.10 %	0.029 %	0.013 %	0.0053%

Di-τ Branching Ratios

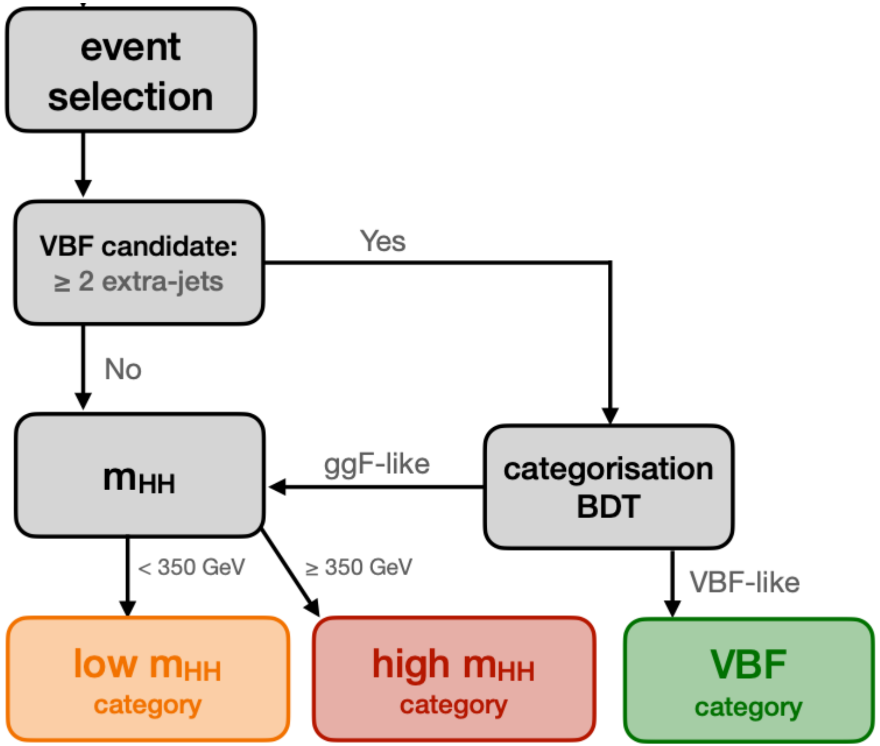




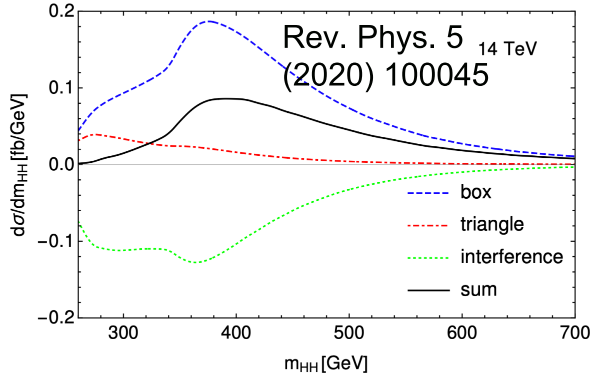


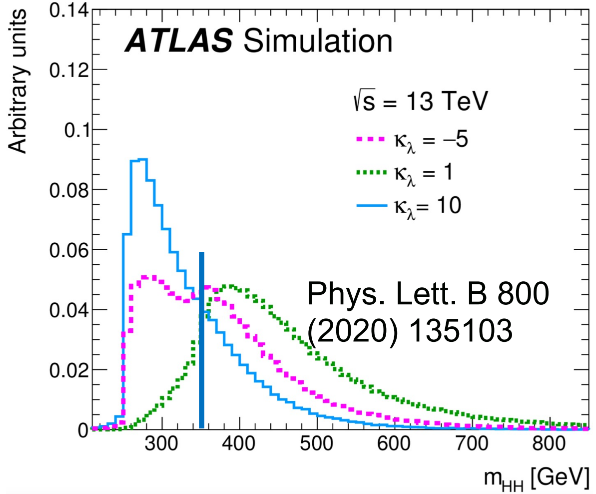
- $bb\tau\tau$: moderate BR, relatively clean signature
- Split into two channels depending on τ decay: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$
- Analysis performed base on full Run-2 dataset (140 fb^{-1})

Categorization Strategy



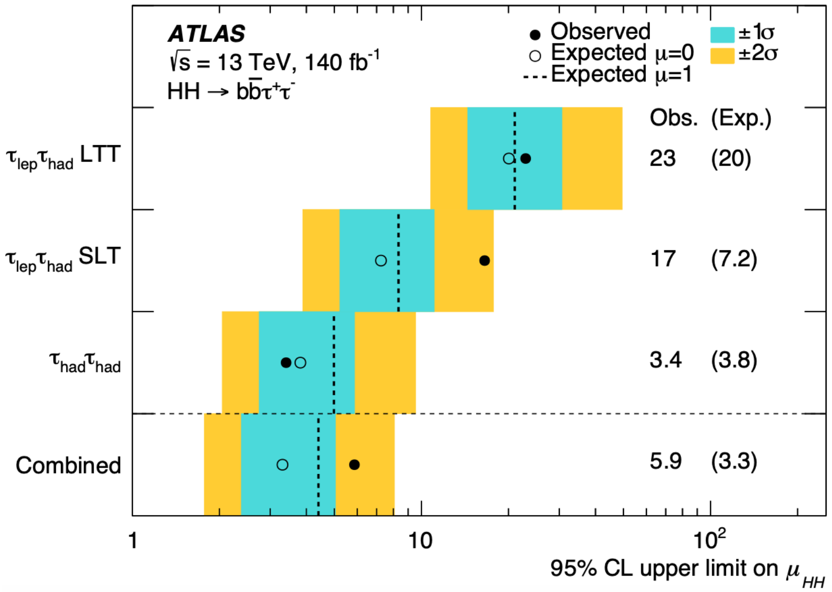
BDT trained on κ_λ=10 ggF signal vs bkg.	BDT trained on SM ggF signal vs bkg.	BDT trained on SM VBF signal vs bkg.

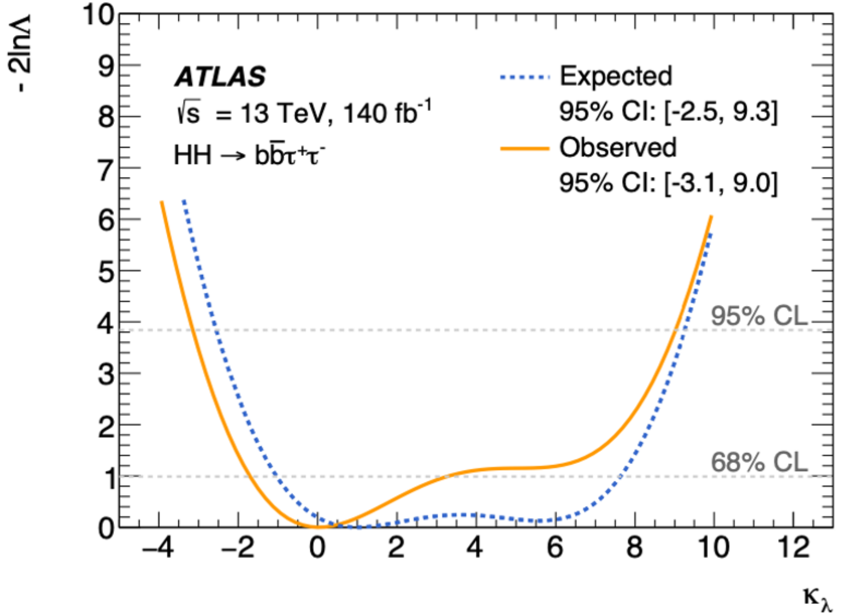




Results for HH→bb$\tau\tau$

Phys. Rev. D 110 (2024) 032012



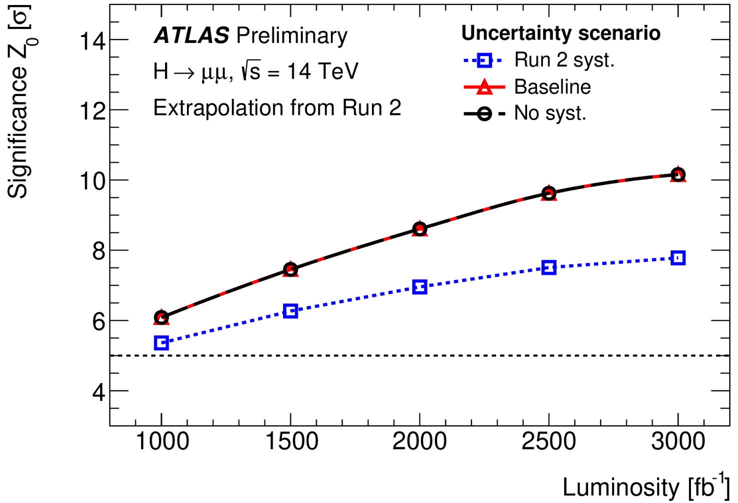


Obs. (exp.) limit on HH XS: 5.9 (3.3) × σ_{SM}
The exp. limit represents the best constraint on HH XS in single channel during Run-2

Obs. (exp.) constraint on κ_λ: $-3.1 \leq \kappa_\lambda \leq 9.0$ ($-2.5 \leq \kappa_\lambda \leq 9.3$)

HL-LHC Projection

ATL-PHYS-PUB-2025-014



ATL-PHYS-PUB-2024-016

L_{int} = 3000 fb^{-1}	$b\bar{b}\tau_{lep}\tau_{had}$	$b\bar{b}\tau_{had}\tau_{had}$	Combination
No syst. unc.	2.3	4.0	4.6
Baseline	1.8	3.1	3.5
Baseline with MC luminosity scaled	1.7	3.0	3.4
MC luminosity scaled	1.6	2.4	2.7
Theoretical unc. halved	1.0	1.9	2.2
Run 2 syst. unc.	0.9	1.8	1.9

Projection performed based on Run-2 analysis strategy
Precision for κ_μ and κ_λ can reach 3% and <30% with 3000 fb^{-1} data with combination of ATLAS and CMS arXiv:2504.00672

Summary

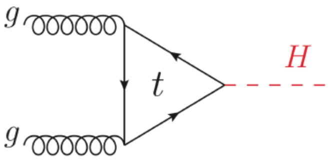
- Presented the latest studies for H→μμ and HH→$bb\tau\tau$ at the ATLAS experiment
  - ➢ Evidence of Higgs Yukawa coupling to muons at ATLAS
  - ➢ Stringent constraints set on HH cross section and Higgs self-coupling

- Full Run-3 and future HL-LHC datasets provide more room for exploring the Higgs boson Yukawa couplings and self-coupling. Stay tuned!

Backup

Higgs Production and Decay at LHC

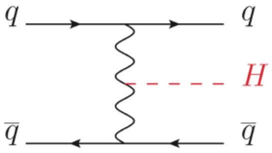
ggF



Gluon fusion process

~8 M events produced

VBF

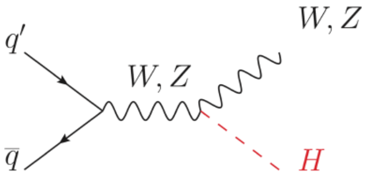


Vector Boson Fusion

Two forward jets and a large rapidity gap

~600 k events produced

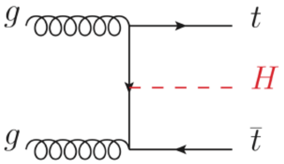
VH



W and Z Associated Production

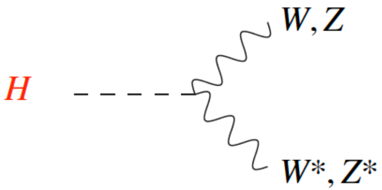
~400 k events produced

ttH



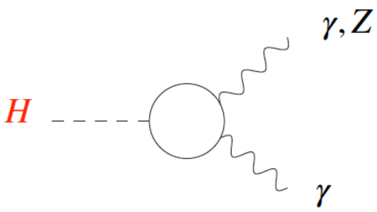
Top Assoc. Prod.

~80 k evts produced



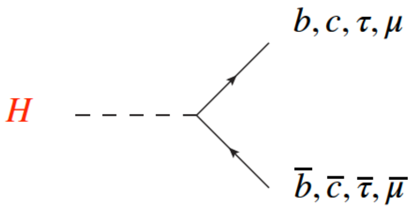
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\boxed{\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%}$

Event Selection

- Single muon triggers (24 or 50 GeV) with matching
- 23 exclusive categories in the order of ttH→VH→VBF→ggF

	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\lvert\eta\rvert < 2.5$, $p_T^{lead} > 27$ GeV, $p_T^{sublead} > 15$ GeV
Fit region	$m_{\mu\mu} = 110 - 160$ GeV
Jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_T > 30$ GeV and $2.4 < \lvert\eta\rvert < 4.5$
b-tagged jets	$p_T > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_T > 30$ GeV and $2.4 < \lvert\eta\rvert < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b-jet
VH 4-lepton category	Exactly two additional e or μ with $p_T > 8$ GeV, 5 GeV (μ) / 7 GeV (e), no b-jets
VH 3-lepton categories	Exactly one additional e or μ with $p_T > 15$ GeV, no b-jets
VH 2-lepton categories	No additional lepton, no b-jets, $E_T^{miss} > 120$ GeV
VBF and ggF categories	No additional lepton, no b-jets, $E_T^{miss} < 120$ GeV

Event Selection for HH→bb$\tau\tau$

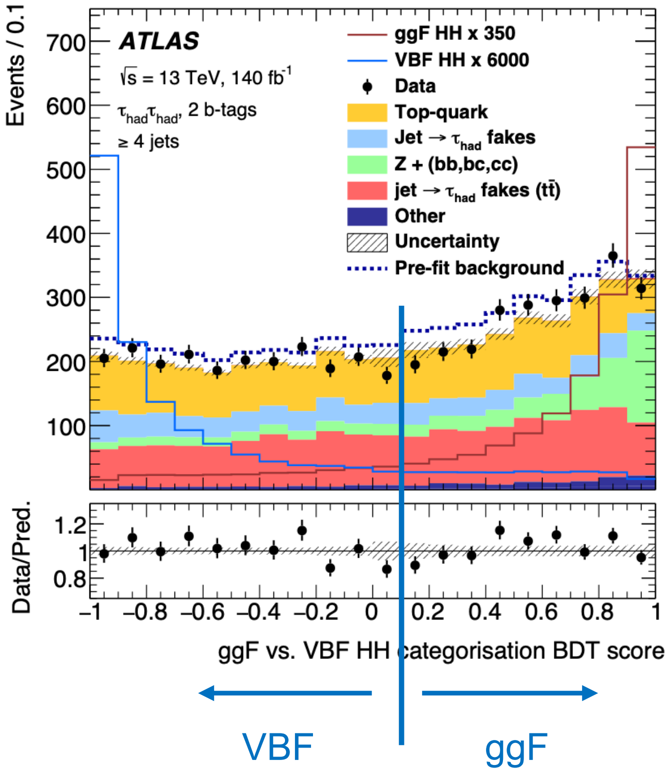
- Signal signature: two b-jets and $\tau_{\rm had}\tau_{\rm had}$/$\tau_{\rm lep}\tau_{\rm had}$ with opposite charge

Signal region	Tau/Lepton	Trigger
$\tau_{\rm had}\tau_{\rm had}$	2 hadronic τ	Single or Di-tau Trigger (STT/DTT)
$\tau_{\rm lep}\tau_{\rm had}$ SLT	1 hadronic τ + 1 e/μ	Single lepton trigger (SLT)
$\tau_{\rm lep}\tau_{\rm had}$ LTT	1 hadronic τ + 1 e/μ	Lepton+tau trigger (LTT)

- e/μ veto for $\tau_{\rm had}\tau_{\rm had}$; exactly 1 e/μ for $\tau_{\rm lep}\tau_{\rm had}$
- $m_{\tau\tau}^{MMC}$ > 60 GeV for all channels; m_{bb} < 150 GeV for $\tau_{\rm lep}\tau_{\rm had}$
- Major background: ttbar, Z+heavy-flavor jets, jets → $\tau_{\rm had}$ fakes, etc

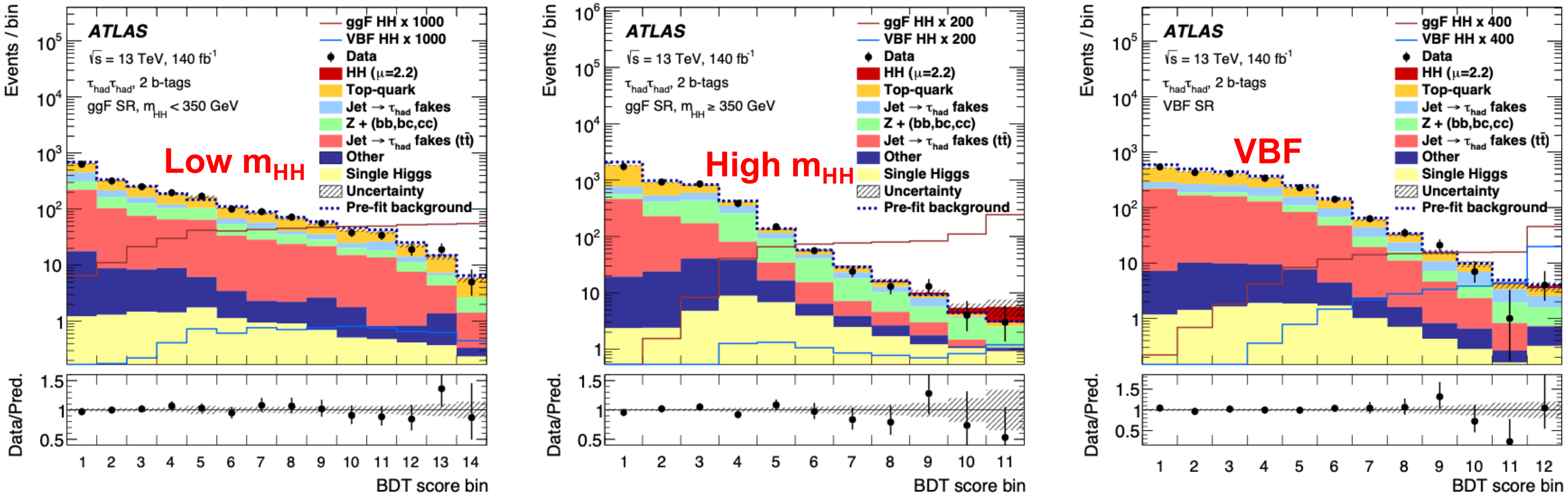
ggF vs VBF Categorization BDT

- BDT trained to separate ggF HH from VBF HH on events with 4 jets (two VBF-jet candidates + two b-jets)
- Input variables: m_{jj}^{VBF}, ΔR_{jj}^{VBF}, $\eta_{j1}\times\eta_{j2}$, etc
- BDT cuts optimized in each SR to achieve the best limit on HH as well as constraint for κ_λ and κ_{2V}



Discriminant BDTs

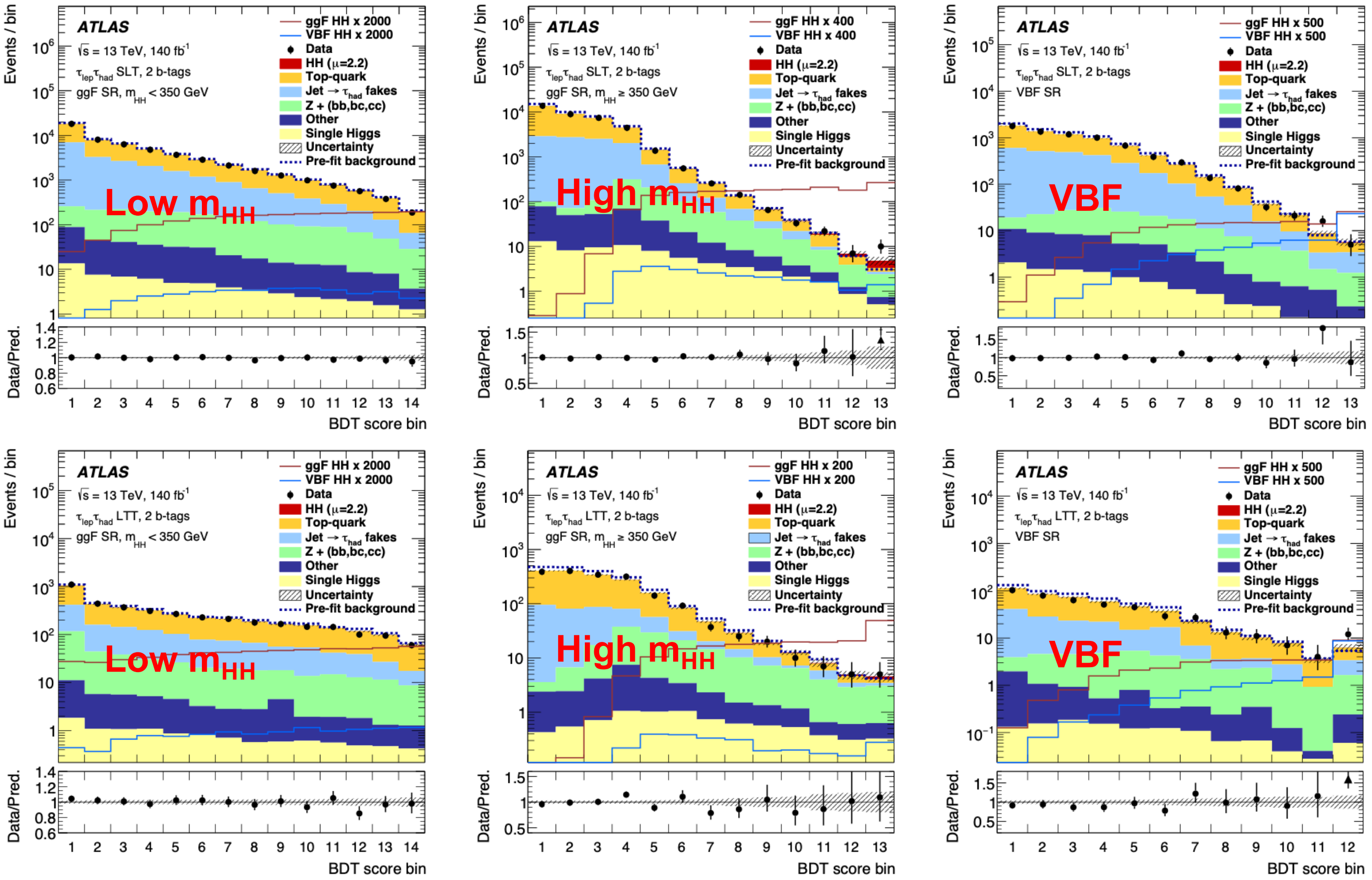
- In each SR, BDTs trained in low m_{HH}, high m_{HH} and VBF categories respectively and used as final discriminants
  - Input variables: m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, ΔR(b,b), ΔR(τ,τ), E_T^{miss}, etc



Discriminant BDTs in $\tau_{lep}\tau_{had}$

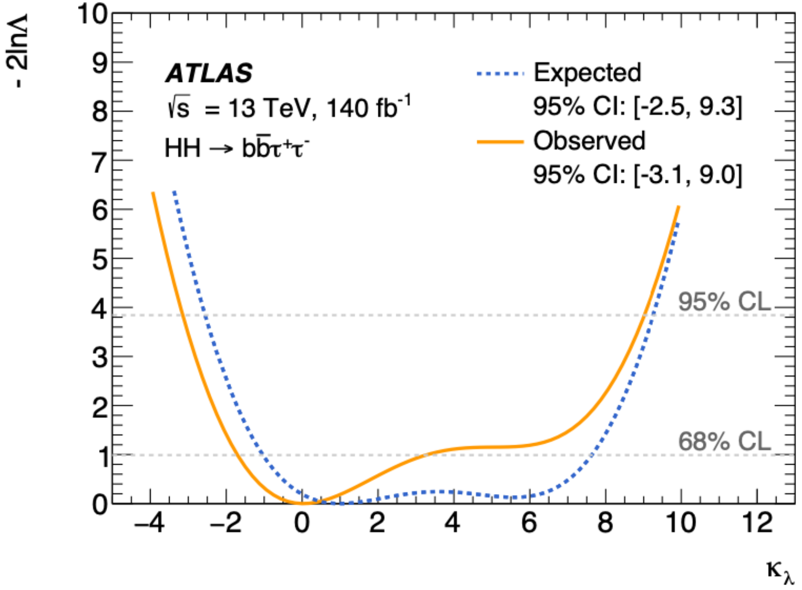
SLT

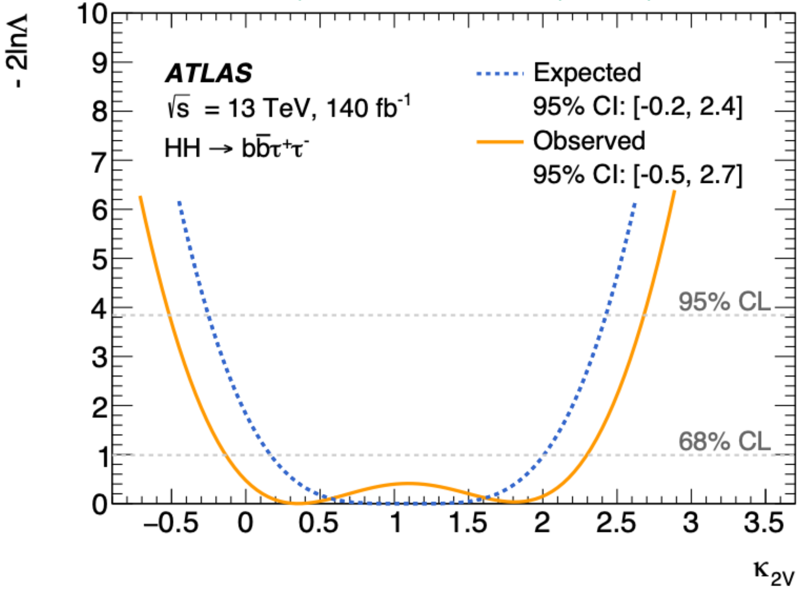
LTT



Constraints for κ_λ and κ_{2V}

Phys. Rev. D 110 (2024) 032012

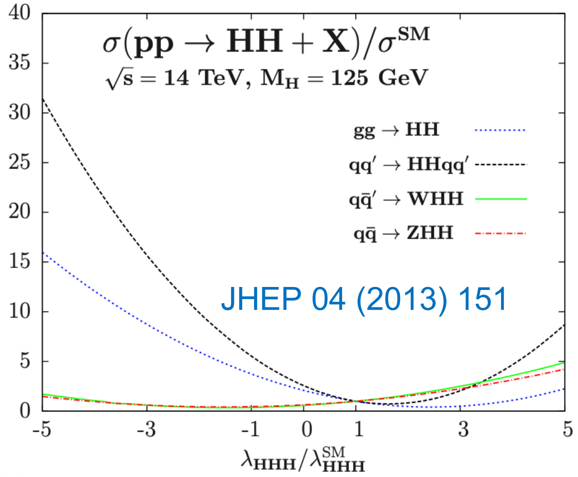




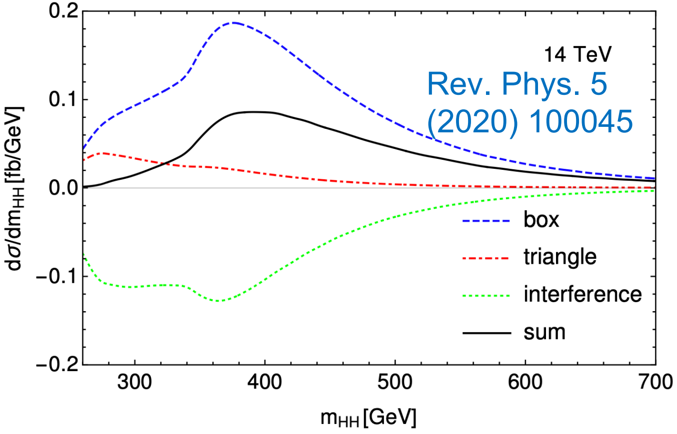
Obs. (exp.) constraint on κ_λ: $-3.1 \leq \kappa_\lambda \leq 9.0$ ($-2.5 \leq \kappa_\lambda \leq 9.3$)

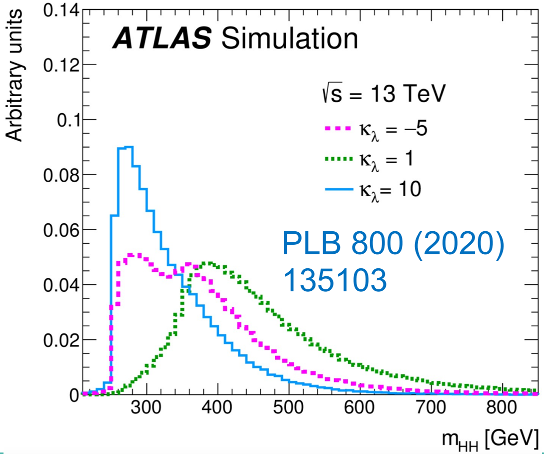
Obs. (exp.) constraint on κ_{2V}: $-0.5 \leq \kappa_\lambda \leq 2.7$ ($-0.2 \leq \kappa_\lambda \leq 2.4$)

Anomalous κ_λ Impact on HH Processes

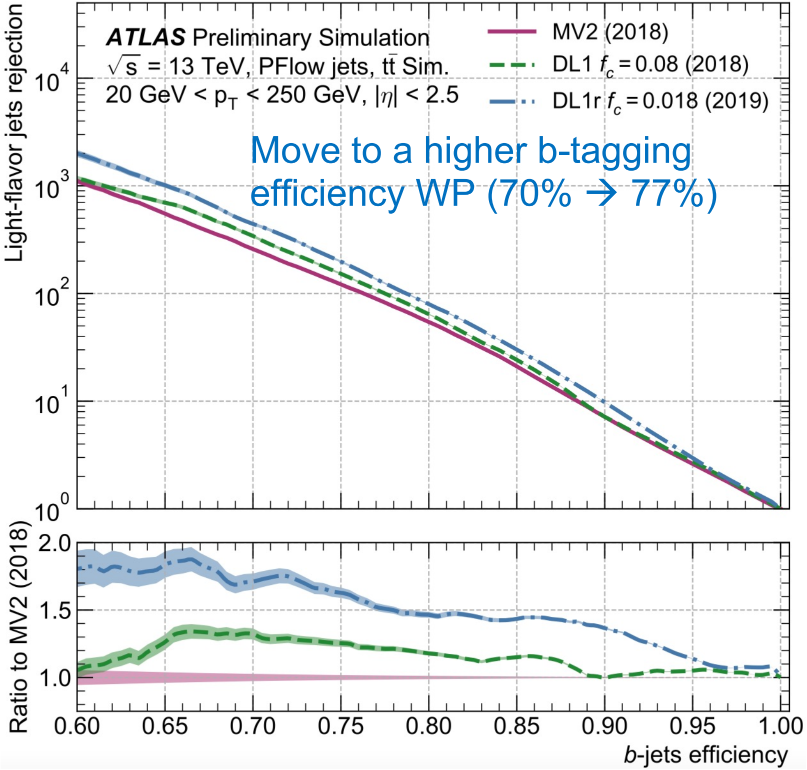


Anomalous κ_λ would result in enhanced HH cross section and modified kinematics of the process due to different contributions and interference of diagrams





Flavor Tagging Improvement



Move to a higher b-tagging efficiency WP (70% → 77%)

Likelihood-based calibration provides >2x reduction in uncertainties