Search for Higgs Boson Pairs in the bb$\tau\tau$ Final State with the ATLAS Experiment

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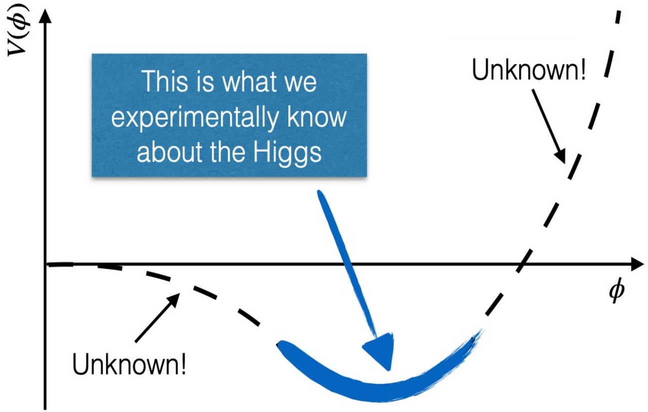
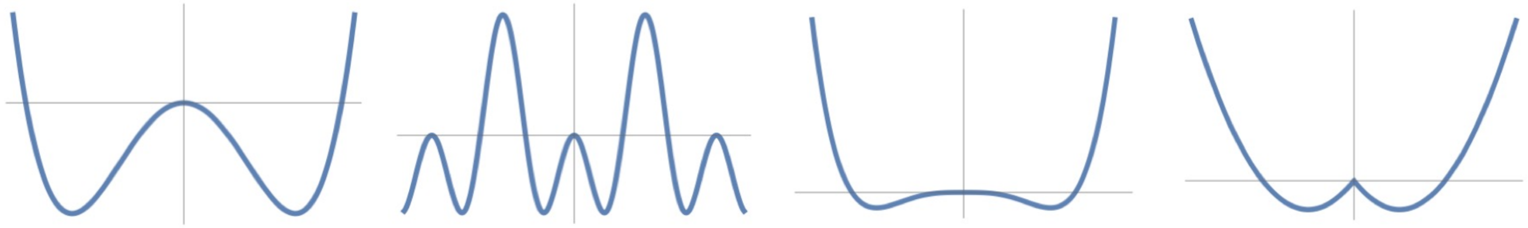
Higgs Discovery in 2012

Higgs Potential Not Determined Yet



- New physics (e.g. first order electroweak phase transition) can cause a significant deviation away from SM predicted Higgs potential
- Measurements of Higgs self-coupling can provide discrimination between different scenarios/models

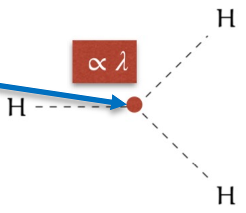


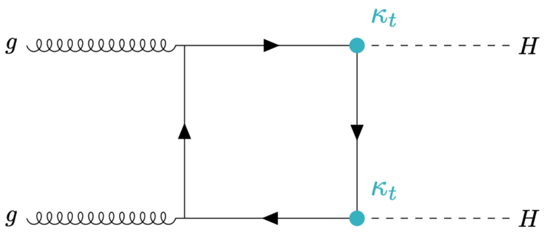
Landau-Ginzburg Higgs | Nambu-Goldstone Higgs | Coleman-Weinberg Higgs | Tadpole-Induced Higgs

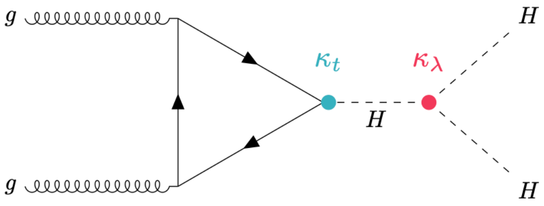
Ref: Phys. Rev. D 101, 075023 (2020)

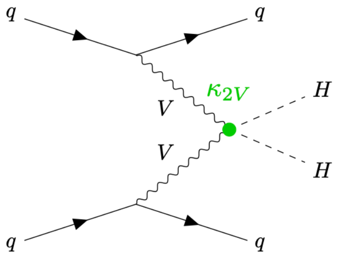
Higgs Self-coupling and HH Production

- 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})







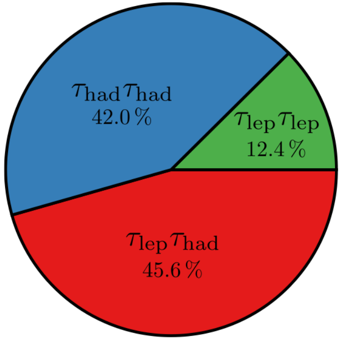


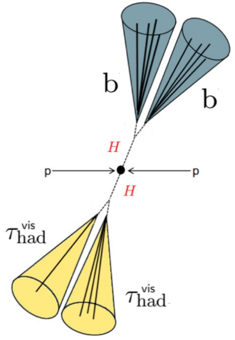
bb$\tau\tau$ Final State

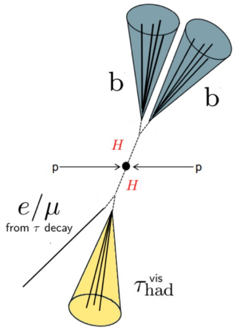
HH Branching Ratios

	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%

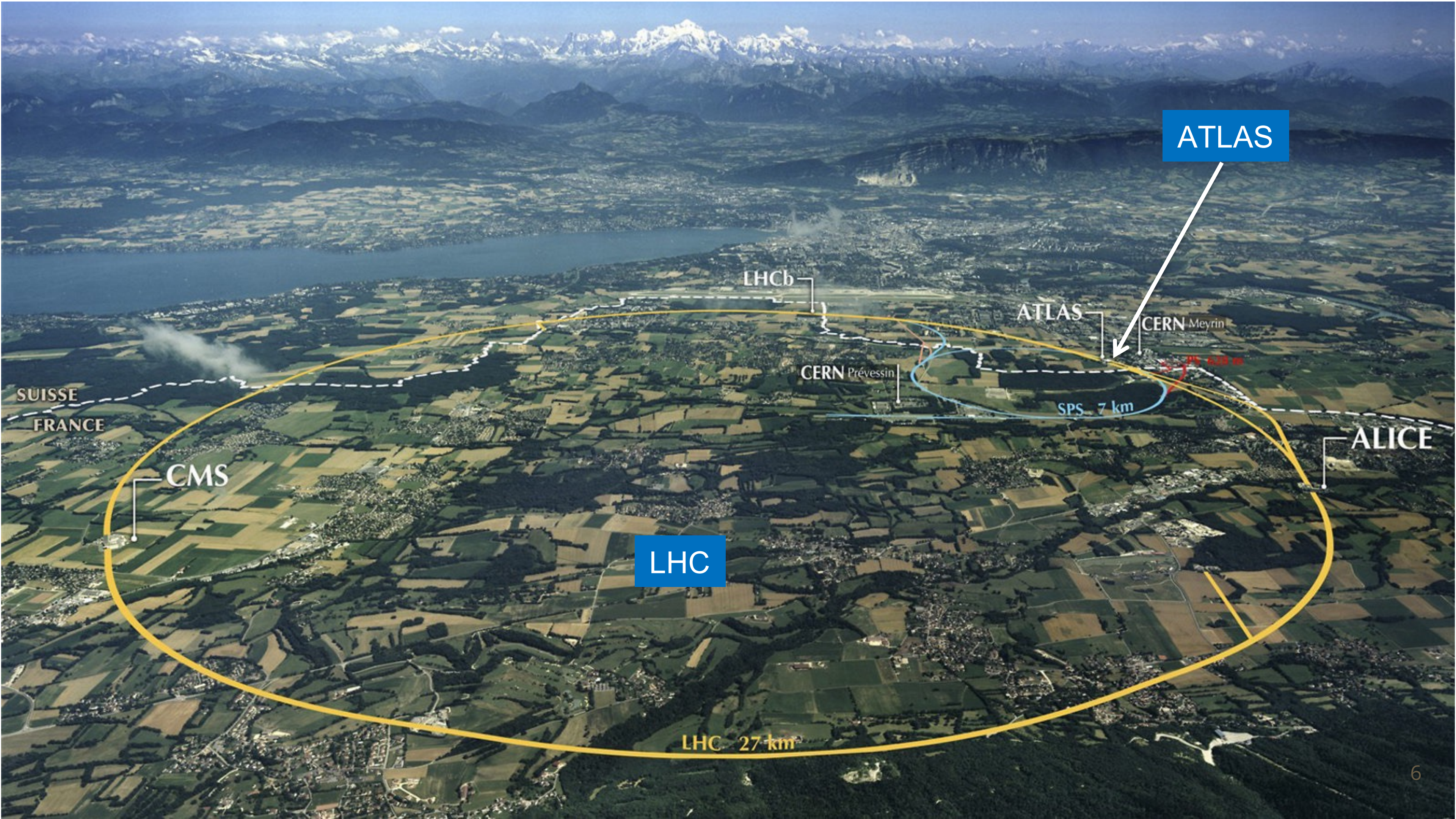
Di-τ Branching Ratios





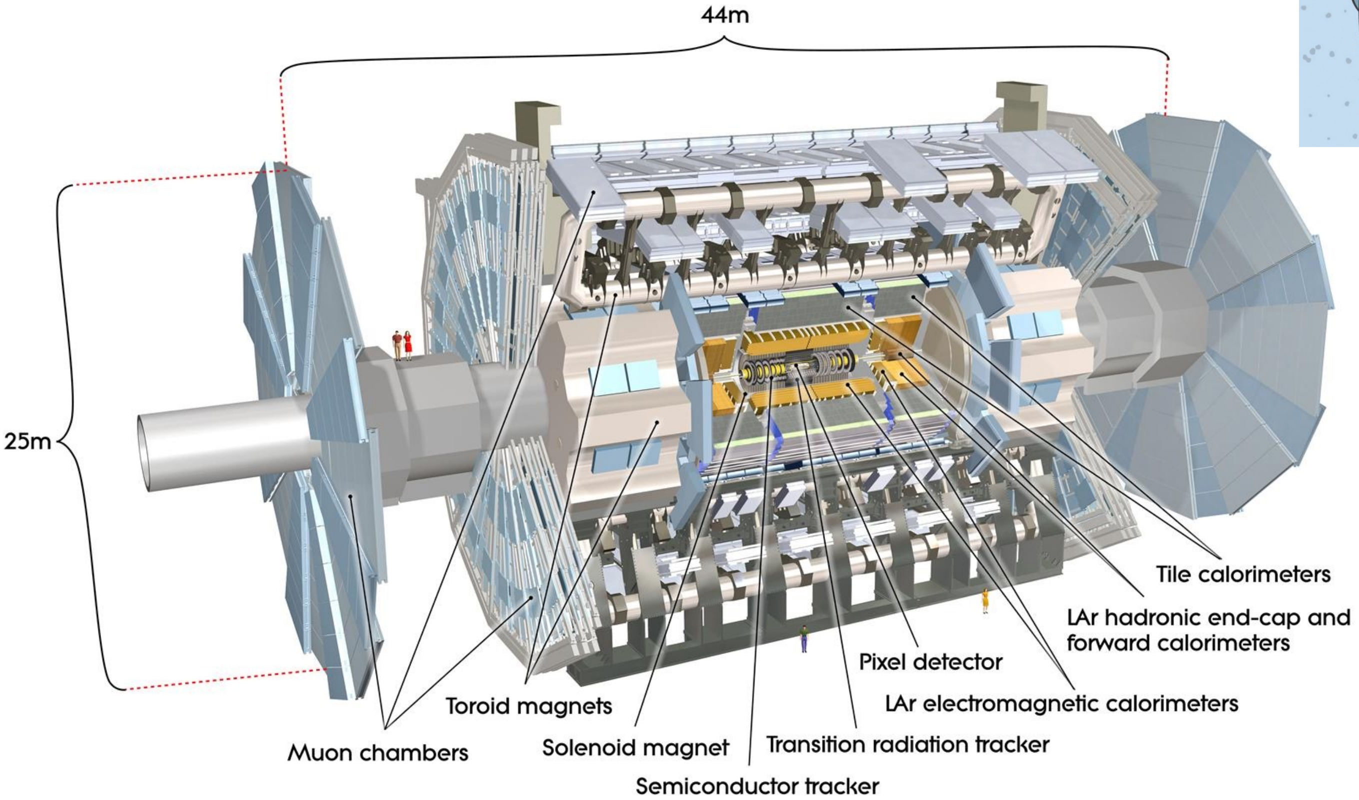


- bb$\tau\tau$: moderate BR, relatively clean signature
- Split into two channels depending on τ decay: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$



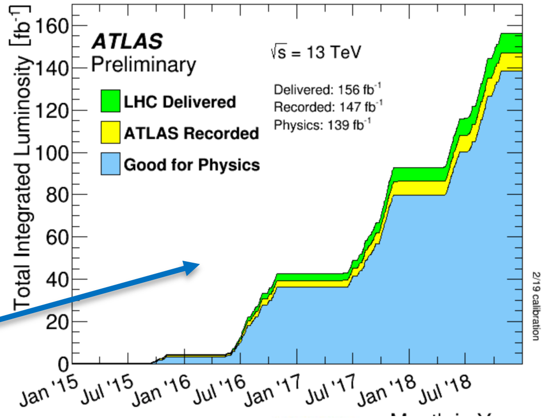
ATLAS
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC
LHC 27 km

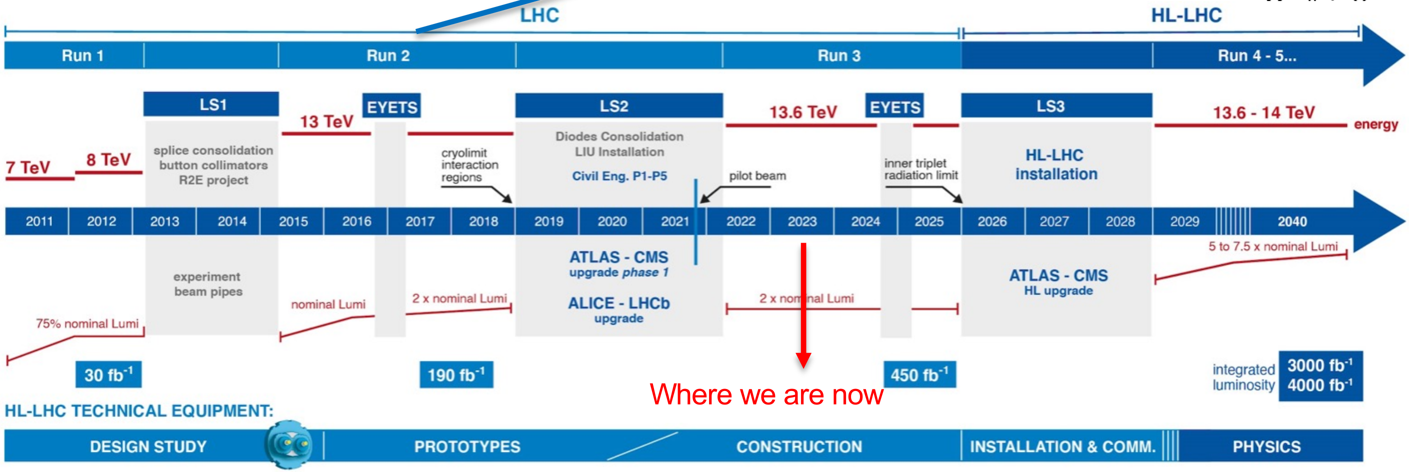
Our “Camara”: ATLAS Detector



Run 2 Dataset at ATLAS Experiment

- Great operation of the LHC and performance of ATLAS detector
- 139 fb^{-1} of 13 TeV pp collision data collected for physics by the ATLAS detector during the LHC Run 2





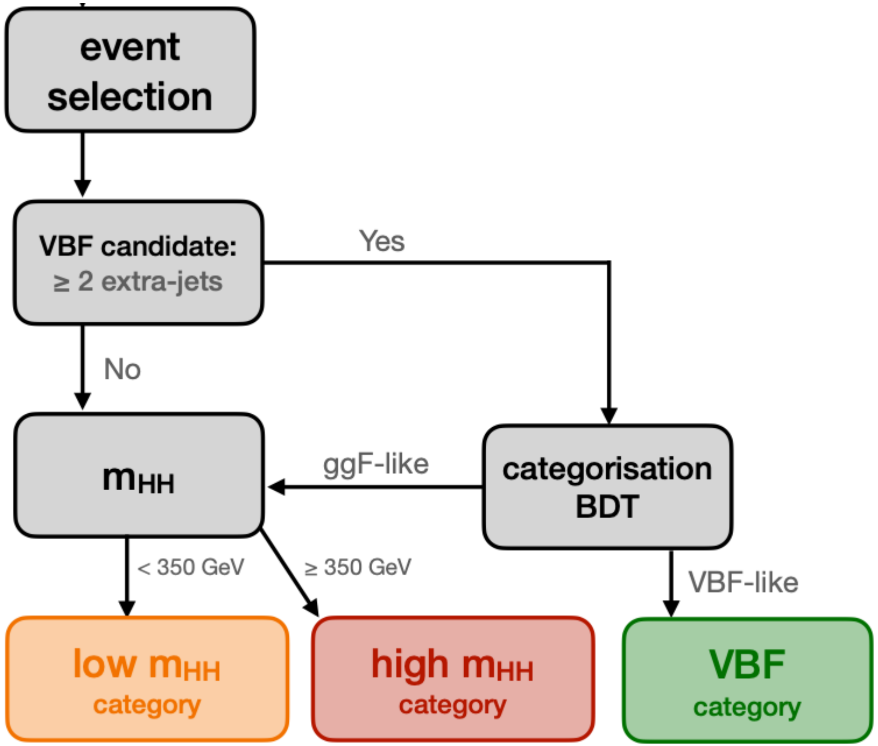
Event Selection for HH→bb$\tau\tau$

- Signal signature: two b-jets (DNN-based tagger, 77%) and $\tau_{had}\tau_{had}$/$\tau_{lep}\tau_{had}$ with opposite charge

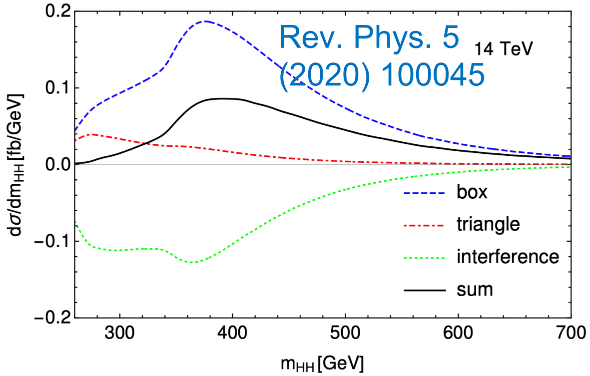
Signal region	Tau/Lepton	Trigger
$\tau_{had}\tau_{had}$	2 hadronic τ	Single or Di-tau Trigger (STT/DTT)
$\tau_{lep}\tau_{had}$ SLT	1 hadronic τ + 1 e/μ	Single lepton trigger (SLT)
$\tau_{lep}\tau_{had}$ LTT	1 hadronic τ + 1 e/μ	Lepton+tau trigger (LTT)

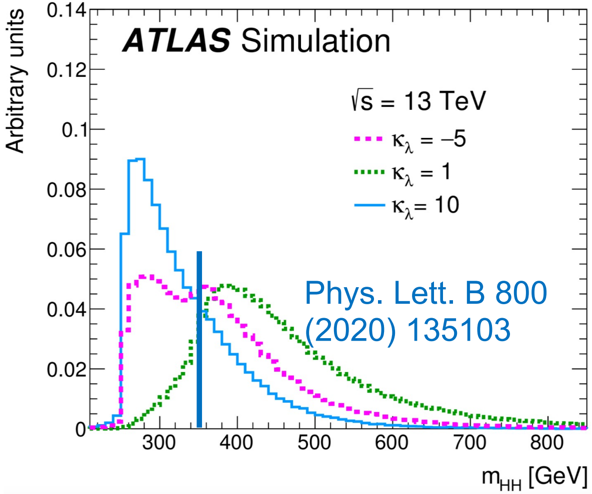
- Trigger-dependent thresholds on e/μ/τ_{had} and jets
- e/μ veto for $\tau_{had}\tau_{had}$; exactly 1 e/μ for $\tau_{lep}\tau_{had}$
- $m_{\tau\tau}^{MMC}$ > 60 GeV for all channels; m_{bb} < 150 GeV for $\tau_{lep}\tau_{had}$

Categorization Strategy



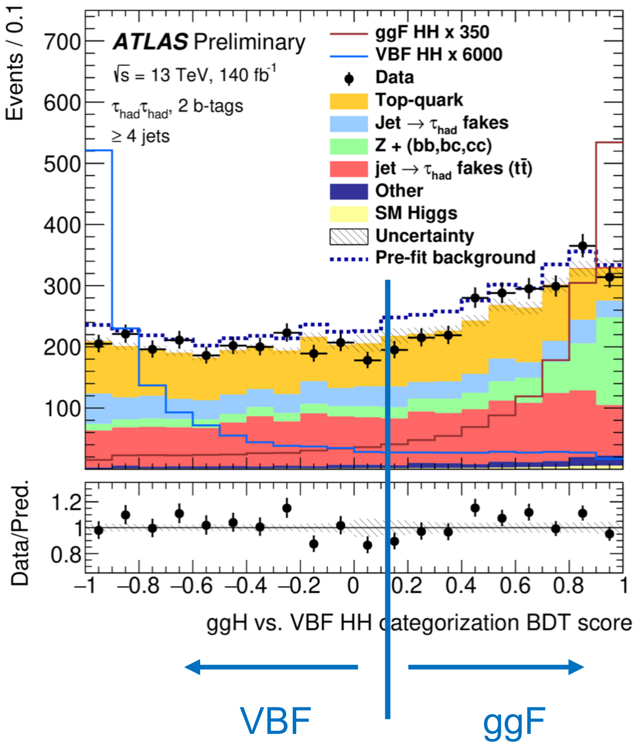
BDT trained on κ_λ=10 ggF signal vs bkg.	BDT trained on SM ggF signal vs bkg.	BDT trained on SM VBF signal vs bkg.





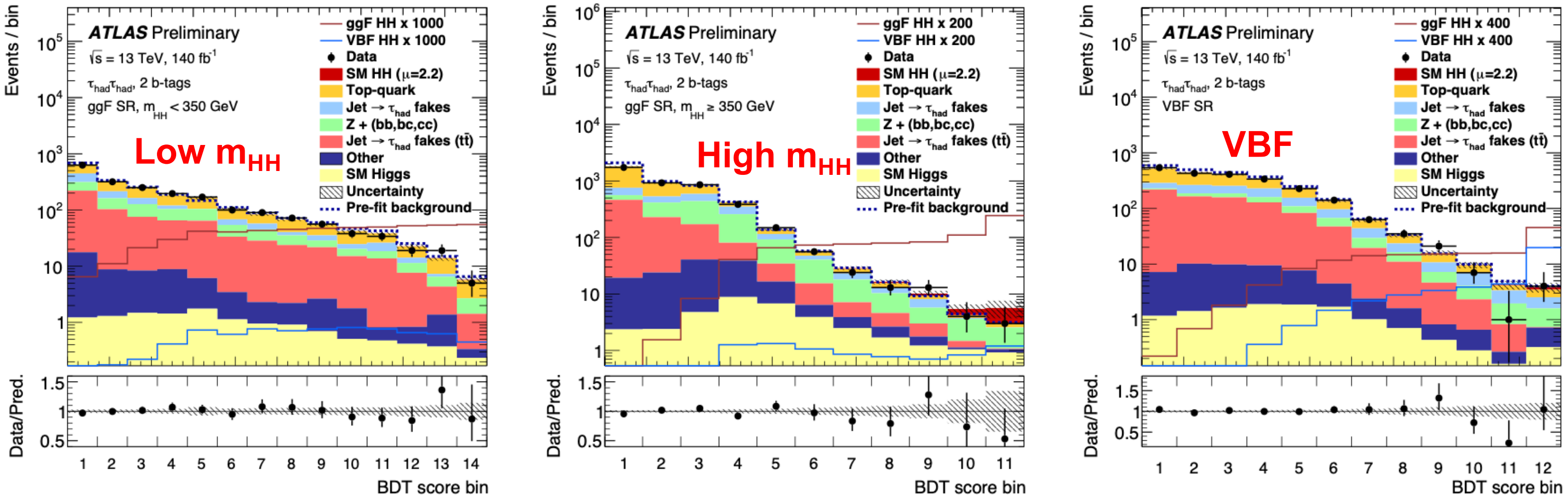
ggF vs VBF Categorization BDT

- BDT trained to separate ggF HH from VBF HH on events with 4 jets (two VBF-jet candidates + two H→bb)
- 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

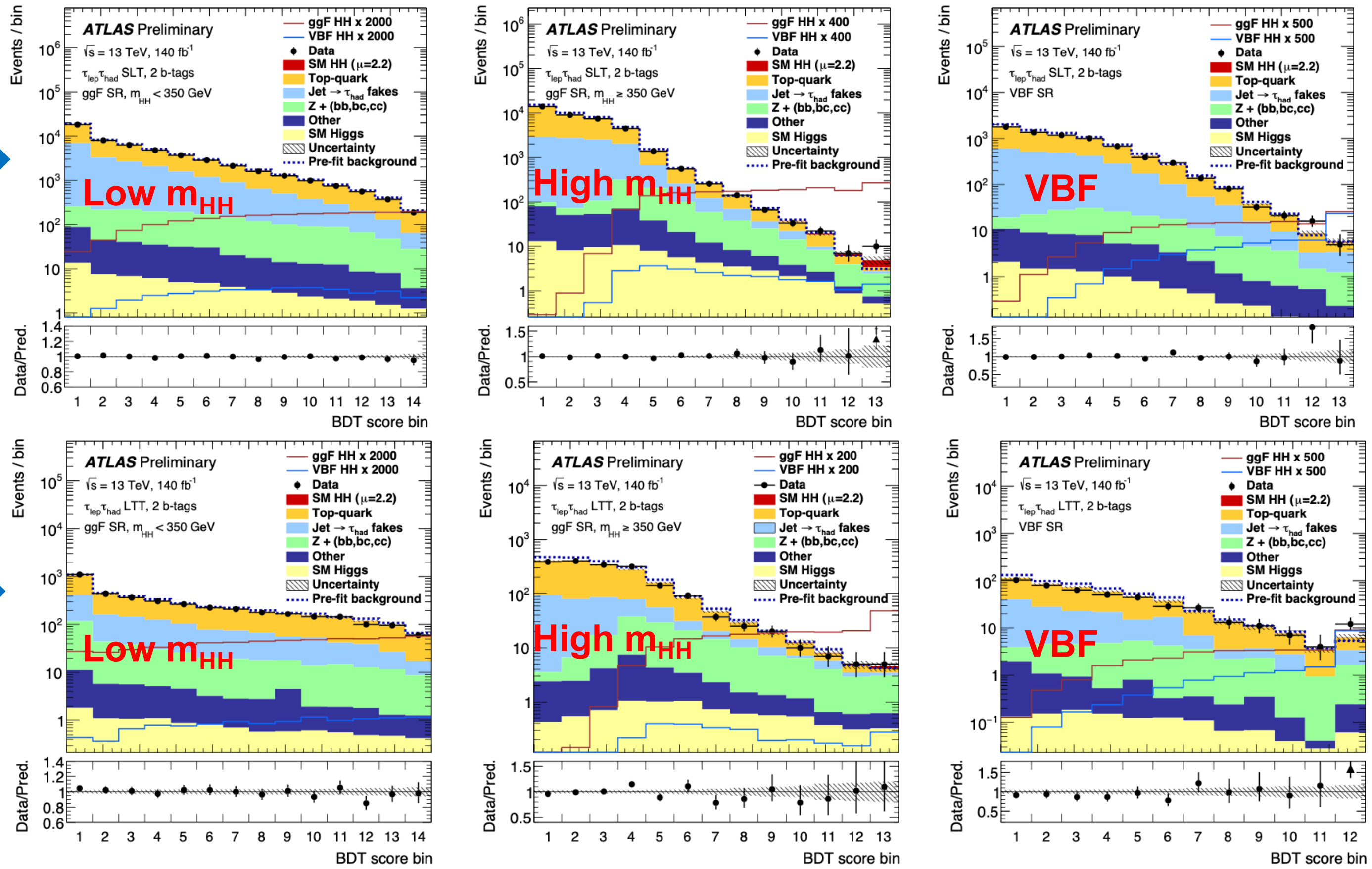
- In each SR, BDTs trained in low m_{HH}, high m_{HH} and VBF categories respectively and used as final discriminants
  - Input variables: m_{HH}, m_{bb}, $m_{\tau\tau}^{MMC}$, ΔR(b,b), ΔR(τ,τ), E_T^{miss}, etc



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

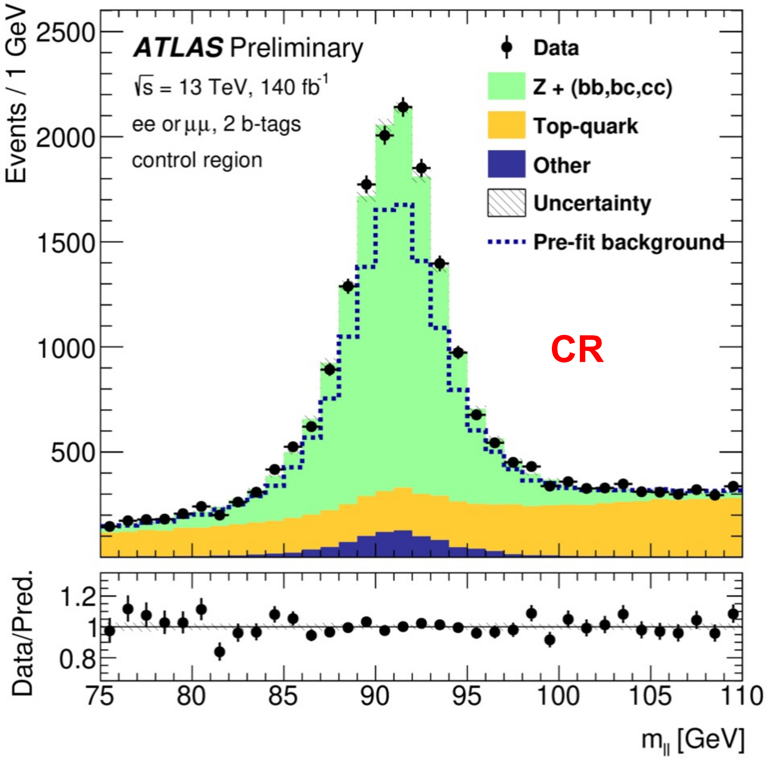
SLT

LTT



Background Estimation

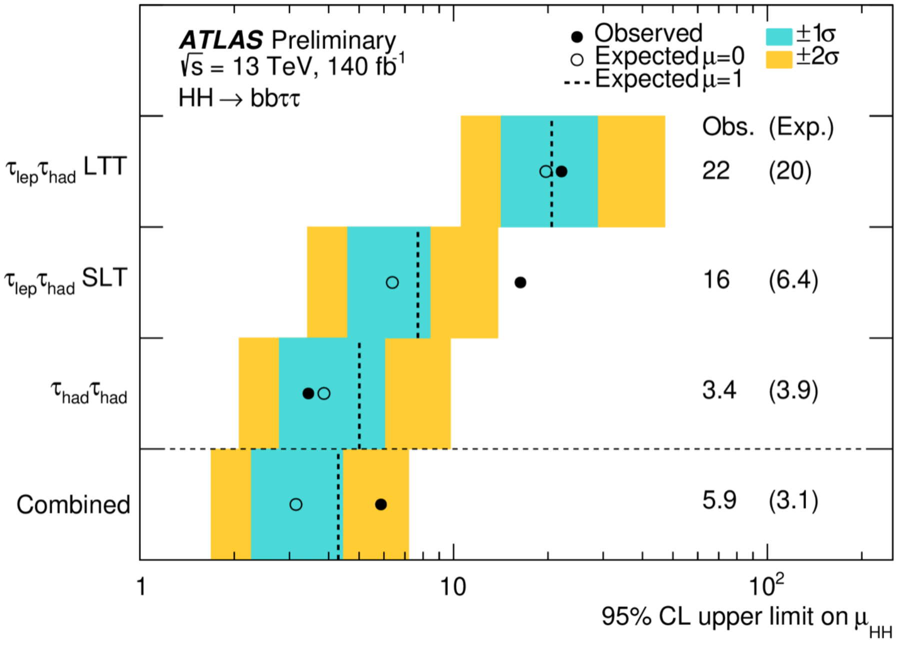
- ttbar and Z+heavy-flavor processes: shape from simulation, normalizations determined from the control region
- Single Higgs and other processes: estimated from simulation
- Jets → fake τ_{had} background: estimated with data-driven approach



Upper Limit on Non-resonant HH XS

ATLAS-CONF-2023-071

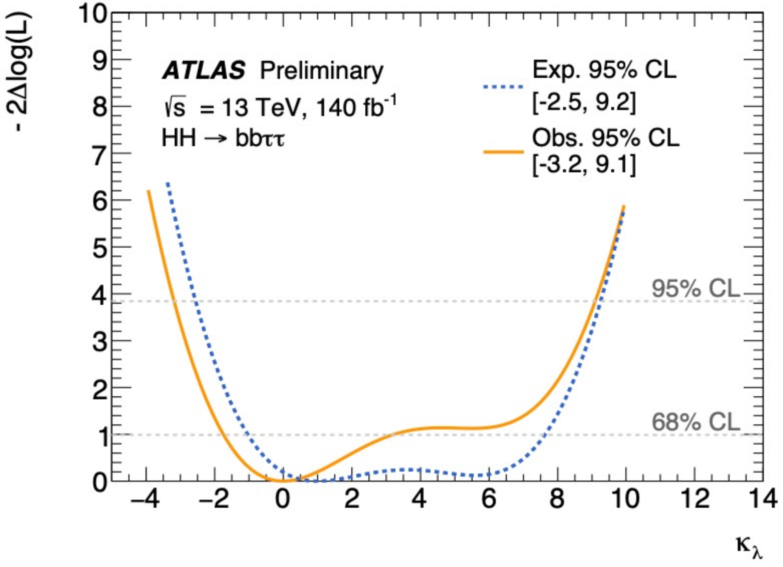
- No significant excess seen above the SM prediction (μ=1)
- Obs. (exp.) limit on HH XS is 5.9 (3.1) × σ_{SM}
  - ➢ The exp. limit represents the best constraint on HH XS in single channel
- Obs. limit higher than exp. due to a statistical fluctuation in the $\tau_{lep}\tau_{had}$ SLT high m_{HH} region

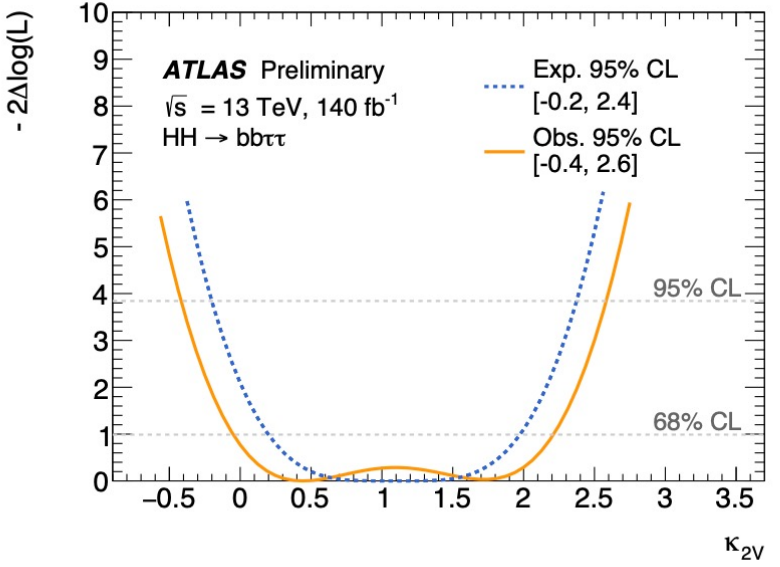


Major uncertainties coming from data/MC statistics as well as theory unc. on top and single Higgs processes

Constraints for κ_λ and κ_{2V}

ATLAS-CONF-2023-071





Obs. (exp.) constraint on κ_λ: $-3.2 \leq \kappa_\lambda \leq 9.1$ ($-2.5 \leq \kappa_\lambda \leq 9.2$)

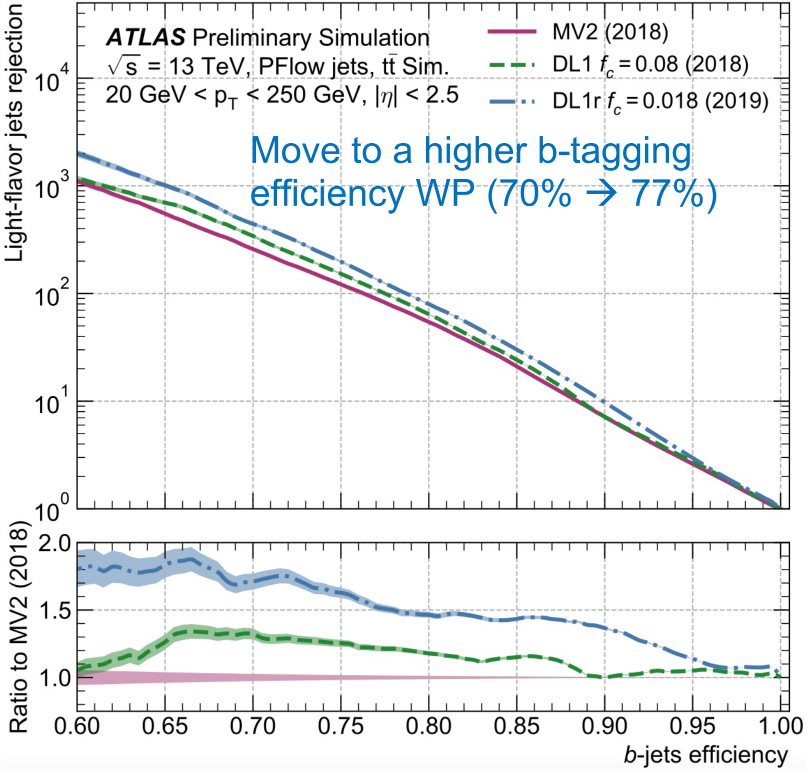
Obs. (exp.) constraint on κ_{2V}: $-0.4 \leq \kappa_\lambda \leq 2.6$ ($-0.2 \leq \kappa_\lambda \leq 2.4$)

Summary

- Presented the latest search for non-resonant HH→bb$\tau\tau$ based on the Run 2 dataset at ATLAS: no deviation from SM prediction seen
- Sensitive probe of HH production and Higgs self-coupling obtained: 20% improvement on expected limit on HH XS/signal strength w.r.t. previous publication (JHEP 07 (2023) 040)
- Run 3 and HL-LHC provide more room for exploring the Higgs potential and self-coupling!

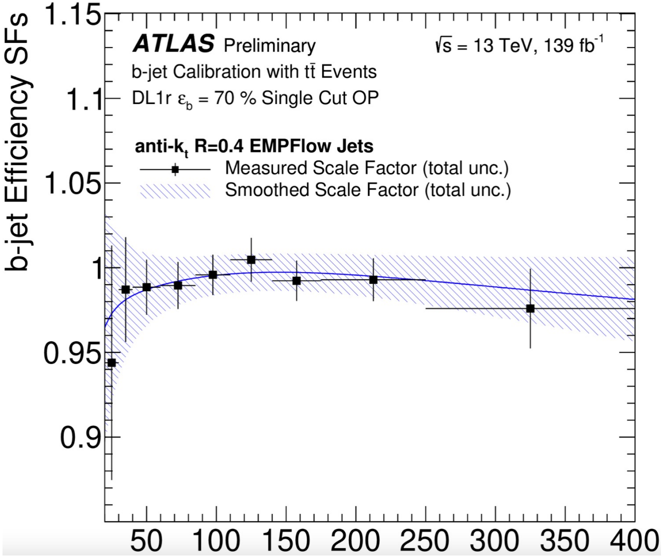
Backup

Flavor Tagging Improvement

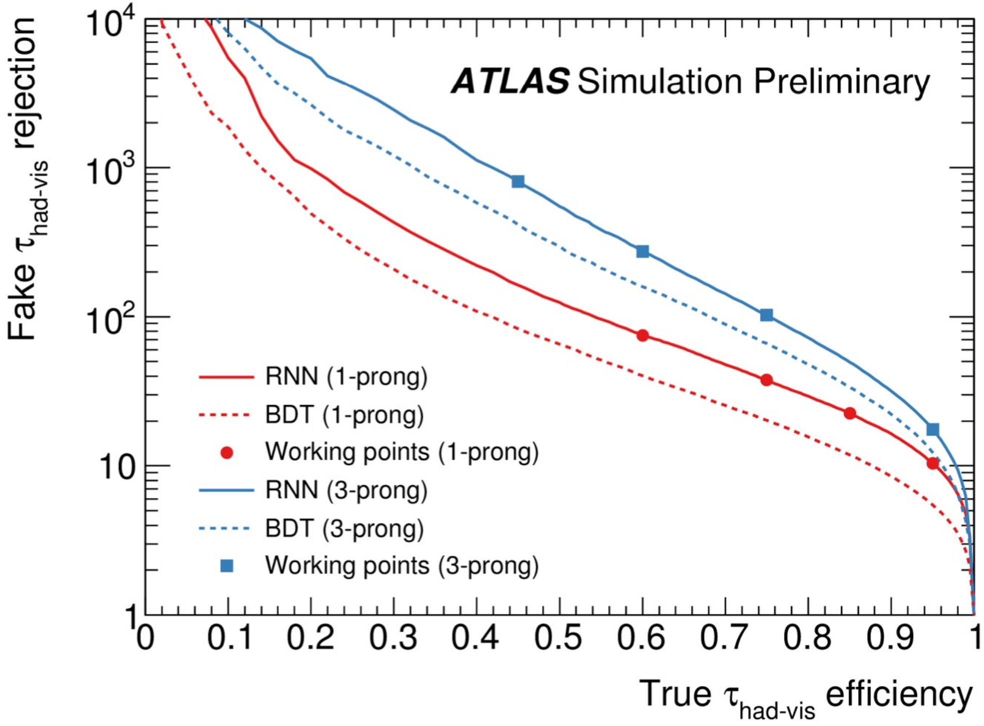


Move to a higher b-tagging efficiency WP (70% → 77%)

Likelihood-based calibration provides >2x reduction in uncertainties



τ Identification Improvement



RNN ID shows 2x improvement compared with BDT

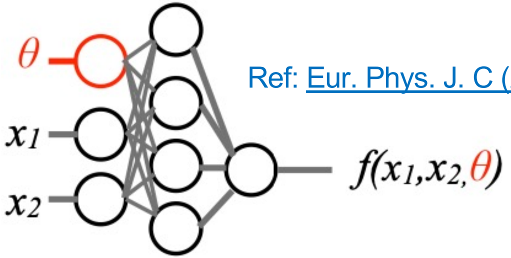
Moved from "medium" to "loose" WP

Per-tau efficiency:

1-prong: 75% → 85%

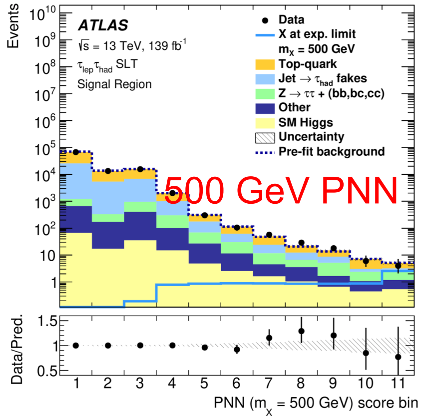
3-prong: 60% → 75%

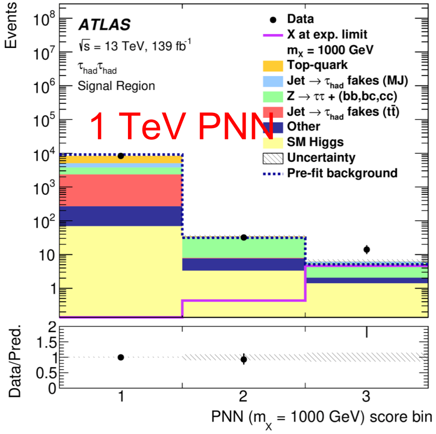
Resonant Signal Extraction



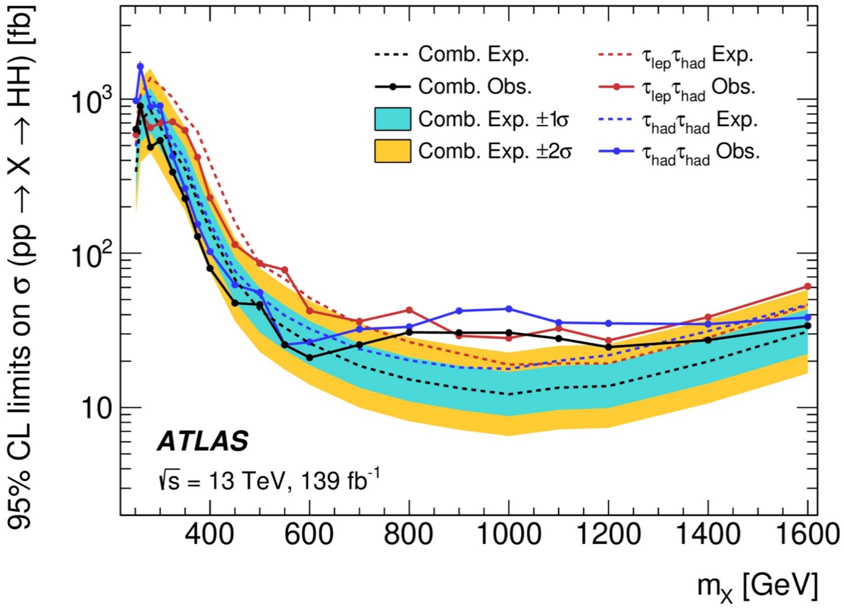
Ref: Eur. Phys. J. C (2016) 76:235

- Parametrized neural networks (PNN) used as discriminant
  - ➢ Parametrized in mass of scalar ($\theta = m_X$)
  - ➢ Training variables same as non-resonant
- It provides near-optimal sensitivity and continuity over the entire range



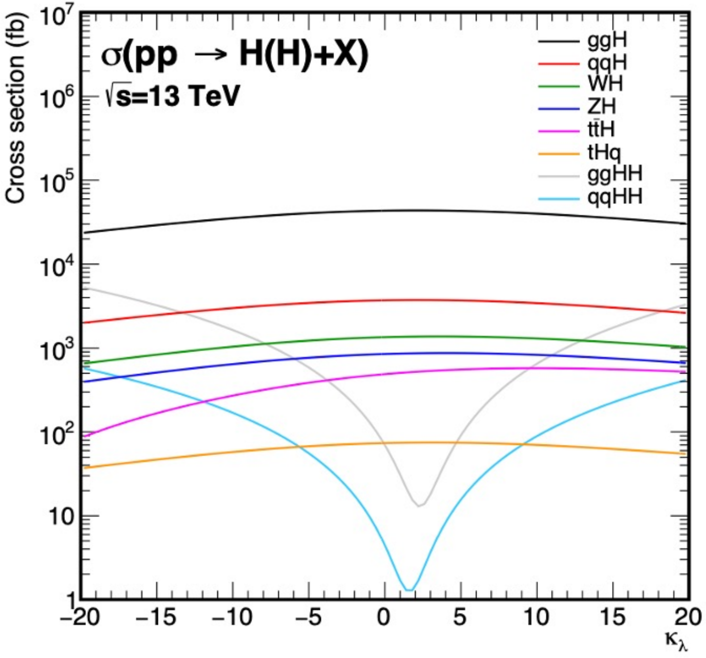


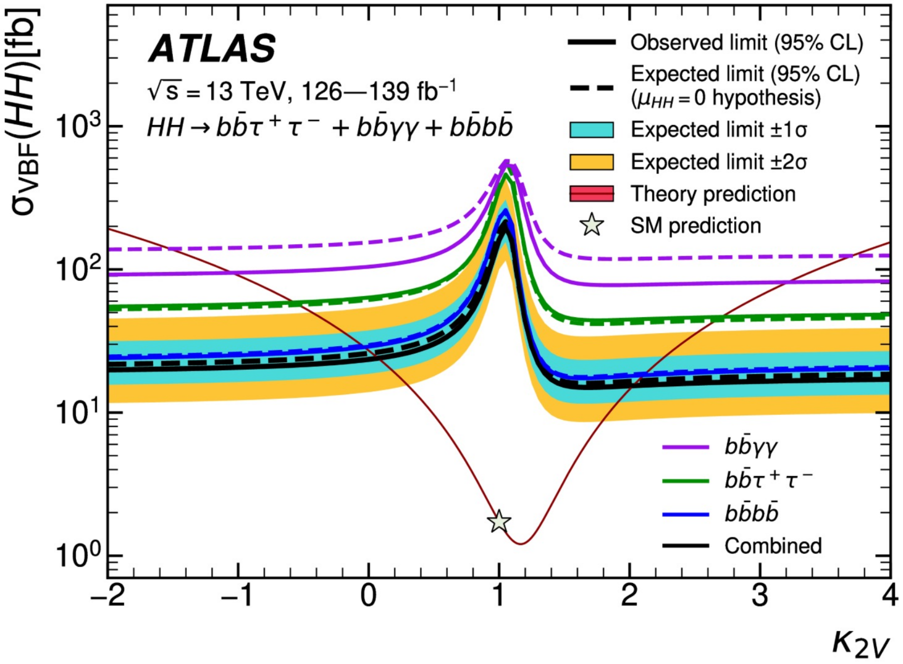
Resonant HH→bb$\tau\tau$ Results



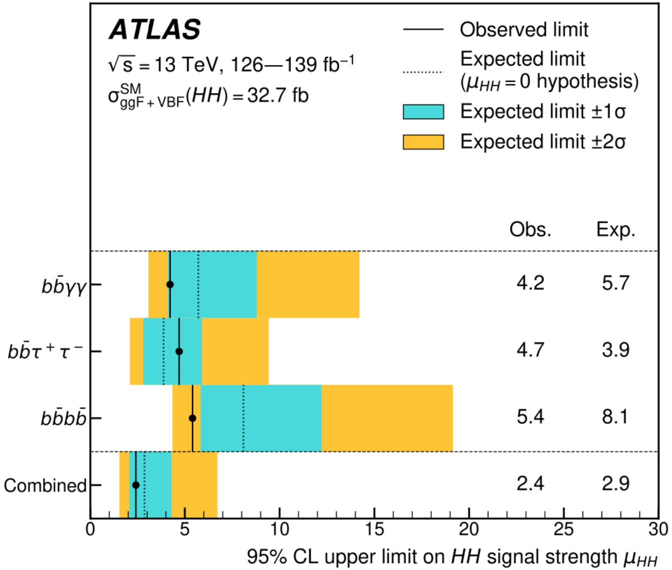
JHEP 07 (2023) 040

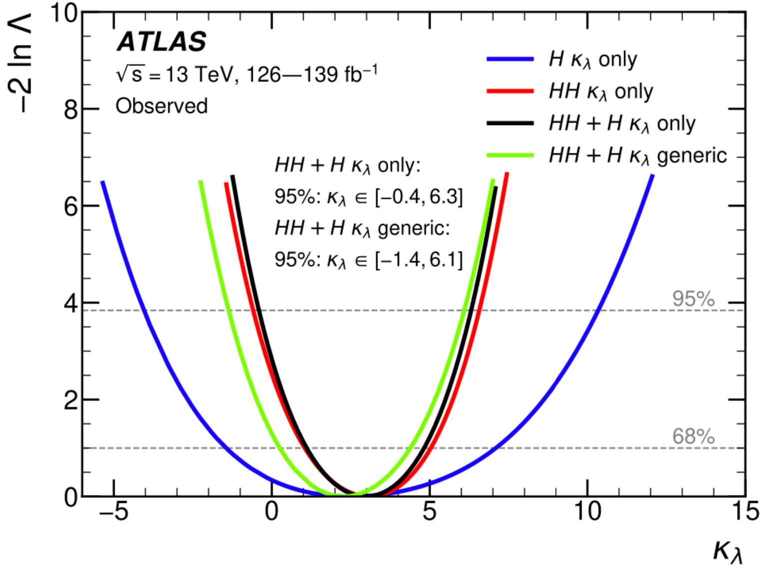
Obs. (exp.) upper limits: 920-23 fb (840-12 fb) depending on the mass region
Local (global) significance for 1 TeV is 3.0σ (2.0σ)


σ(pp → H(H)+X)
√s=13 TeV
Cross section (fb)
ggH
qqH
WH
ZH
tt̄H
tHq
ggHH
qqHH
κλ


ATLAS
√s = 13 TeV, 126—139 fb⁻¹
HH → bb̄τ⁺τ⁻ + bb̄γγ + bb̄bb̄
Observed limit (95% CL)
Expected limit (95% CL)
(μHH = 0 hypothesis)
Expected limit ±1σ
Expected limit ±2σ
Theory prediction
SM prediction
bb̄γγ
bb̄τ⁺τ⁻
bb̄bb̄
Combined
σVBF(HH)[fb]
κ2V

Results from HH+H Combination





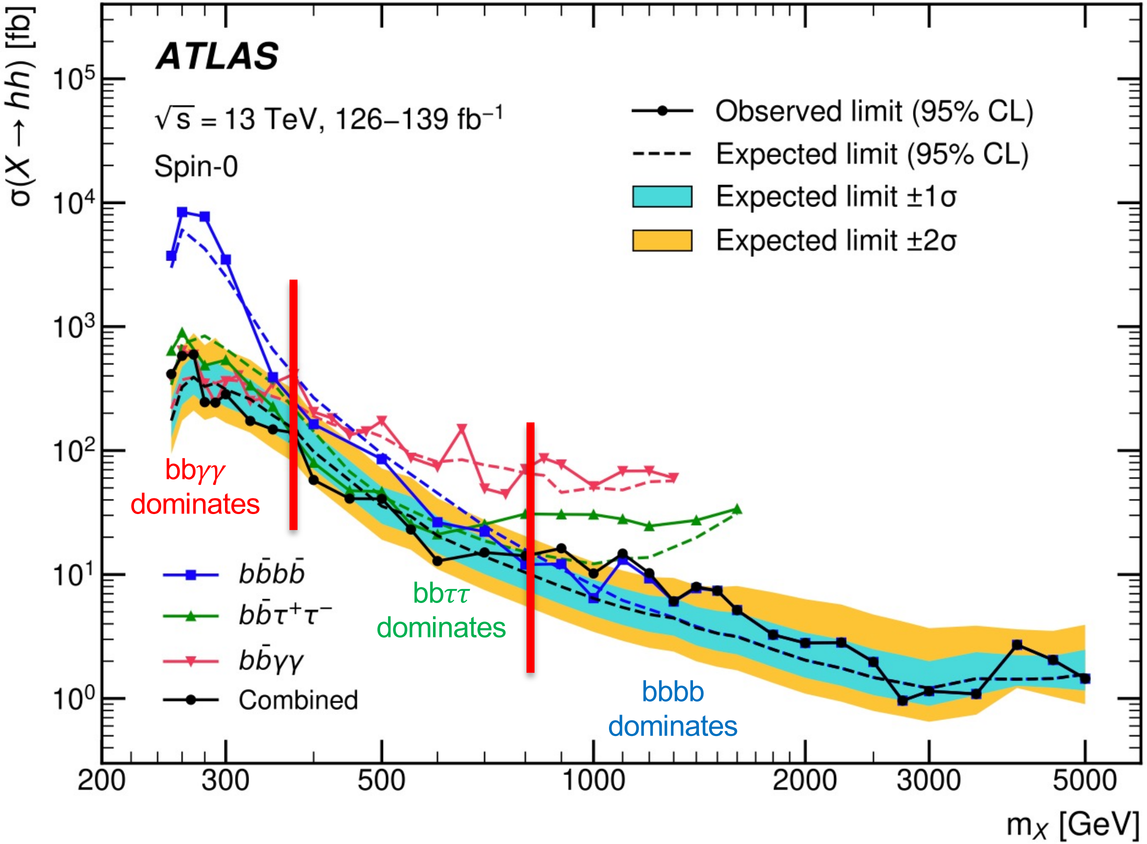
Obs. (exp.) limits: 2.4 (2.9) × σ_{SM}

Obs. (exp.) κ_λ constraint: $-0.4 \le \kappa_\lambda \le 6.3$ $(-1.9 \le \kappa_\lambda \le 7.6)$

The best constraints on HH signal strength and κ_λ to date

Phys. Lett. B 843 (2023) 137745

Resonant HH Combination Result



No statistically significant excess found, largest excess at 1.1 TeV: local (global) significance is 3.2σ (2.1σ)

arXiv:2311.15956 (submitted to PRL)

HL-LHC Projection

ATL-PHYS-PUB-2022-053

	Significance [σ]				Combined signal
Uncertainty scenario	$b\bar{b}\gamma\gamma$	$b\bar{b}\tau^+\tau^-$	$b\bar{b}b\bar{b}$	Combination	strength precision [%]
No syst. unc.	2.3	4.0	1.8	4.9	−21/+22
Baseline	2.2	2.8	0.99	3.4	−30/+33
Theoretical unc. halved	1.1	1.7	0.65	2.1	−47/+48
Run 2 syst. unc.	1.1	1.5	0.65	1.9	−53/+65

Uncertainty scenario	κ_λ 68% CI	κ_λ 95% CI
No syst. unc.	[0.7, 1.4]	[0.3, 1.9]
Baseline	[0.5, 1.6]	[0.0, 2.5]
Theoretical unc. halved	[0.3, 2.2]	[−0.3, 5.5]
Run 2 syst. unc.	[0.1, 2.4]	[−0.6, 5.6]

We Were Doing Better than Projection

Higgs Pair Production in the $H(\to \tau\tau)H(\to b\bar{b})$ channel at the High-Luminosity LHC

ATL-PHYS-PUB-2015-046

ing SM background and SM signal, we expect to set an upper limit of the cross section for the di-Higgs production of $4.3 \times \sigma(HH \to b\bar{b}\tau^+\tau^-)$ at 95% Confidence Level. Using an effective Lagrangian for the Higgs potential, and allowing its trilinear self-coupling to vary, we can project an exclusion of $\lambda_{HHH}/\lambda_{SM} \leq -4$ and $\lambda_{HHH}/\lambda_{SM} \geq 12$.

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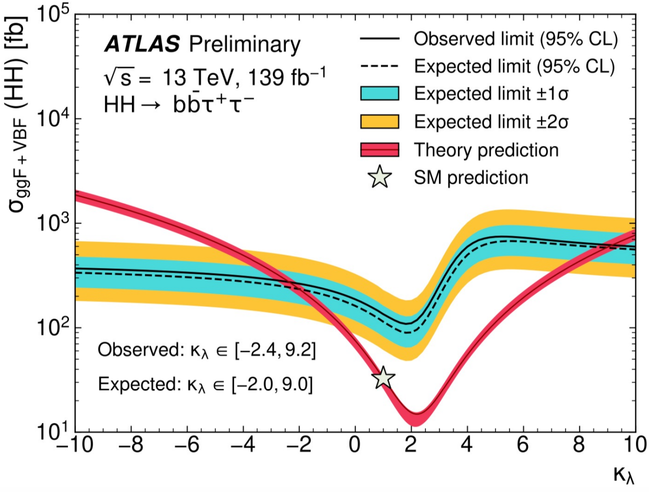

Obs. (exp.) limit on HH: 4.7 (3.9) × σ_{SM}
Obs. (exp.) κ_λ constraint: $-2.4 \leq \kappa_\lambda \leq 9.2$ ($-2.0 \leq \kappa_\lambda \leq 9.0$)
The HL-LHC projection (3 ab^{-1}) in 2015 was surpassed with just 139 fb^{-1} data