Improved analysis of non-resonant Higgs boson pair production in the bb$\tau\tau$ final state with the ATLAS detector

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Outline

- **Higgs self-coupling and HH production at the LHC**
- **Run 2 + partial Run 3 ATLAS HH → bb$\tau\tau$ Analysis Strategy**
  - Trigger strategy, *b*-tagging, event selection
  - Control and Signal regions
  - Event classification
- **Results**
  - HH signal strength and significance
  - Constraints on κ_λ and κ_{2V}
- **Outlook**
  - Trigger and detector upgrades
  - ATLAS HH → bb$\tau\tau$ projections
- **Conclusions**

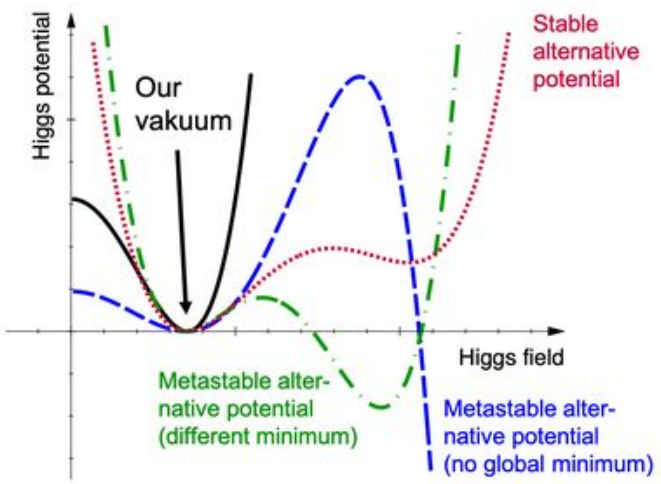
Higgs Self-coupling: A Portal to New Physics

- **Higgs Mechanism of the Electroweak Symmetry Breaking**
  - Explains the origin of vector boson masses
  - Provides mass to fermions through Yukawa couplings
  - **Higgs potential shape free parameter → unknown**

See johannes' talk: Precise predictions of λ

- **Higgs Potential Shape and Universe stability**
  - Crucial to understanding the nature of the Higgs field
  - Accessible with the measurements of the Higgs self-coupling (λ)

Higgs potential shape



$$\mathscr{L}_{\text{h-coupling}} = \kappa_V \left[\frac{g^2}{4}(v+h)^2 W_\mu^+ W^{\mu-} + \frac{g^2+g'^2}{8}(v+h)^2 Z_\mu Z^\mu \right]$$

$$-\sum_f \kappa_f \frac{m_f}{v} \bar{\psi}_f \psi_f (v+h)$$

$$-\frac{1}{2} m_h^2 h^2 - \kappa_\lambda \lambda_{\text{SM}} v h^3 - \frac{\kappa_{\lambda_4} \lambda_{\text{SM}}}{4} h^4 .$$

→ V(h)

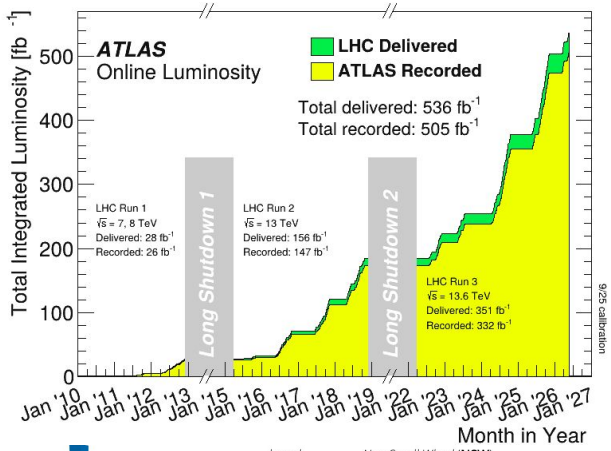
Kappa framework

$$\kappa_\lambda = \frac{\lambda}{\lambda^{SM}}$$

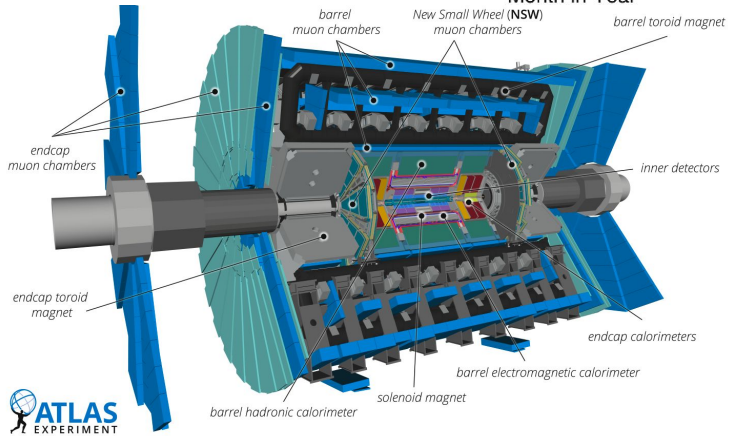
Accessible at the LHC (13.6 TeV)

LHC: A Necessary Framework for HH Studies

- **The Large Hadron collider (LHC)**
  - **pp** (and heavy ions) collisions
    - Run 2: $\sqrt{s}$ =13 TeV (L_{int} = 156 fb^{-1})
    - Run 3: $\sqrt{s}$ =13.6 TeV (L_{int} = 351 fb^{-1})



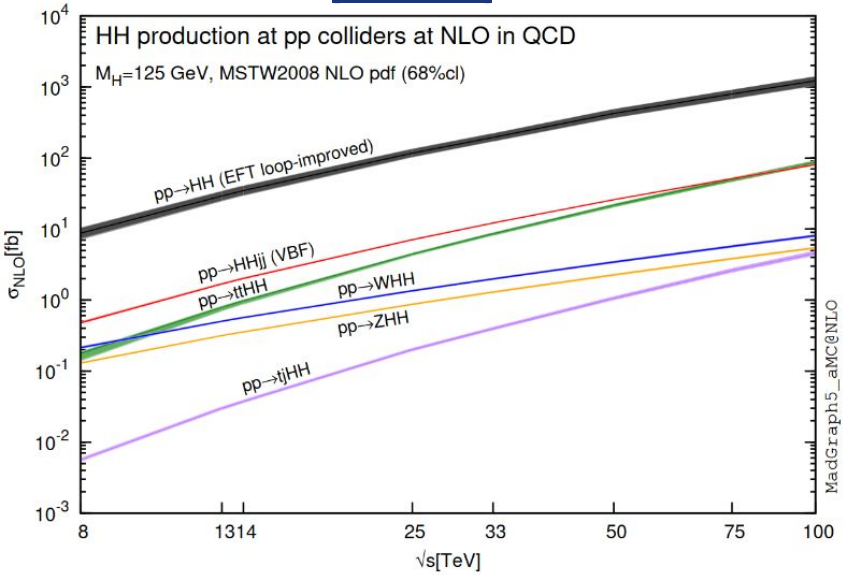
- **ATLAS: a general purpose detector**
  - **Inner detector**: Charged-particle tracking and vertexing
  - **Sampling calorimeters**: Energy measurement
  - **Muon Spectrometer**:
    - μ identification & momentum measurement
  - **Two-level trigger system**:
    - L1: hardware-based → calorimeter & muon information
    - HLT: software-based → object reconstruction and event selection



HH Production at LHC

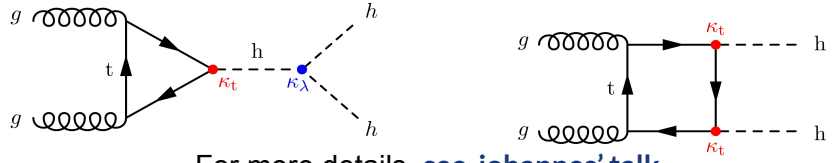
- **Di-Higgs boson production at the LHC**

[1401.7340]



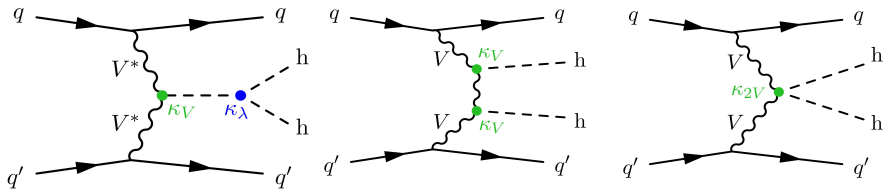
- Dominated by ggF (~34 fb at $\sqrt{s}$ = 13.6 TeV)
- Followed by VBF (~1.9 fb at $\sqrt{s}$ = 13.6 TeV)

- **ggF→ HH occurs mostly via:**
  - top-box and triangle diagrams, which interfere destructively
  - Triangle diagram depends on λ



For more details, see johannes' talk

- **VBF→ HH production:**
  - Contribute additionally via three maidiagrams
  - Access to ***K***_λ, ***K***_V and ***K***_2V

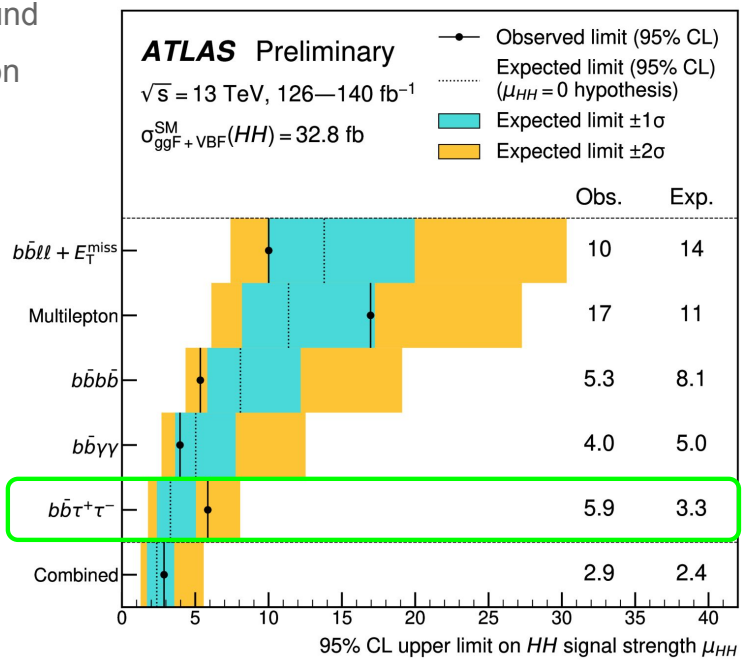


ATLAS HH Search

- **ATLAS searches for HH in multiple final states**
  - **bbbb**: Largest BR, but large QCD background
  - **bbγγ**: Small BR, but excellent mass resolution and low background
  - **bb$\tau\tau$**: Significant BR and good signal-to-background discrimination
    - Among the **most sensitive** HH search **channels**

	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%

[2406.09971]



Run 2 + Partial Run 3 HH → bb$\tau\tau$ Analysis

[2607.26879]

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: EPJC

CERN-EP-2026-227

30th July 2026

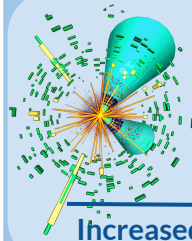
Improved analysis of non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state with 196 fb^{-1} of data collected at $\sqrt{s}$ = 13 TeV and 13.6 TeV with the ATLAS detector

The ATLAS Collaboration

A search for non-resonant Higgs boson pair production (HH) in the $b\bar{b}\tau^+\tau^-$ final state is performed using 140 fb^{-1} and 56 fb^{-1} of proton–proton collision data at centre-of-mass energies of $\sqrt{s}$ = 13 TeV and 13.6 TeV, respectively, recorded by the ATLAS detector during 2015–2023 at the CERN Large Hadron Collider. Relative to the previous ATLAS searches in the same final state, the analysis benefits from the additional dataset collected at 13.6 TeV and from improvements in both event reconstruction and analysis techniques. The Higgs boson pair production cross-section divided by the Standard Model (SM) prediction is found to be $\mu_{HH} = 2.6^{+1.4}_{-1.0}$, consistent with the SM expectation. This corresponds to an observed (expected) significance of 2.6 (1.2) standard deviations over the background-only hypothesis of no HH production and 1.65 standard deviations with respect to the SM prediction. Under the assumption that all other Higgs boson couplings take their SM values, the observed (expected) 95% confidence level interval for the Higgs boson self-coupling modifier is found to be $\kappa_\lambda \in [-3.4, 1.6] \cup [5.5, 10.1]$ ($\kappa_\lambda \in [-1.7, 8.5]$). As a validation of the analysis strategy, measurements of the ZH and ZZ processes are performed in the same final state using the same event selection, yielding observed (expected) significances of 3.5 (2.4) and 1.8 (2.7) standard deviations, respectively, relative to the background-only prediction.

arXiv:2607.26879v1 [hep-ex] 29 Jul 2026

Increased Dataset and Trigger Acceptance

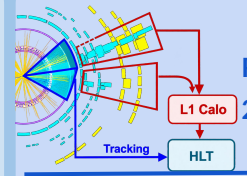


Run 2 (2015–2018): 140 fb^{-1}

Run 3 (2022–2023): 56 fb^{-1}

Total: 196 fb^{-1}

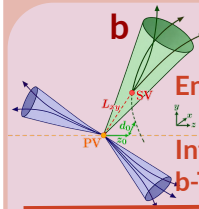
Increased Statistical Power



Run 2 τ-Triggers + 2b2j Triggers

Improved Signal Acceptance

Improved Flavour Tagging and Event Classification



End-to-End Offline GN2

Introduction of Online b-Tagging

Improved b-Jet Identification

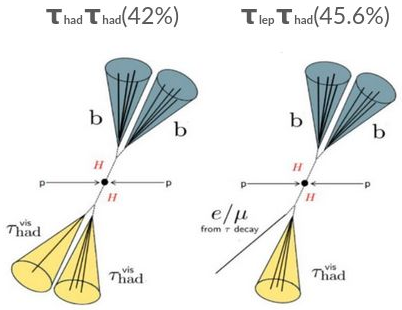


BDT → Graph Transformer

Enhanced Signal–Background Discrimination

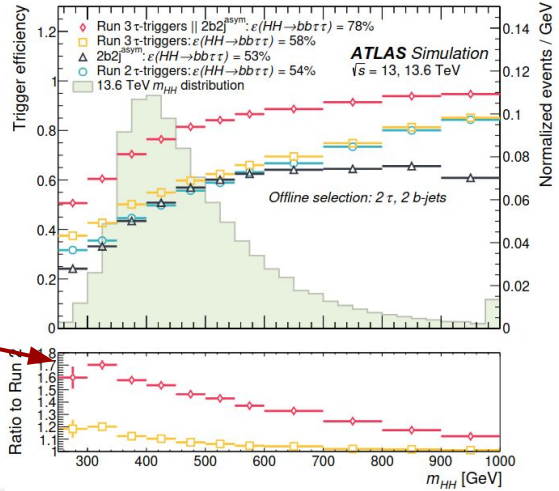
Run 3 Trigger Strategy

- **$\tau_{lep}\tau_{had}$: one leptonic and one hadronic τ decay**
  - Single-lepton triggers (SLT) : 20-80 GeV



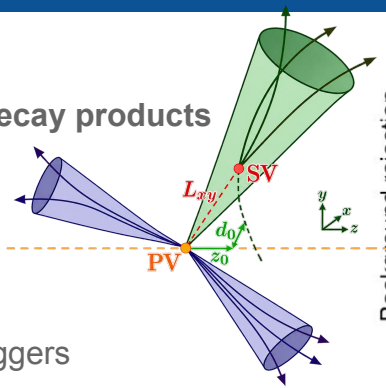
- **$\tau_{had}\tau_{had}$: both τ leptons decay hadronically**
  - τ triggers modeled as in Run 2 analysis
    - **Single-τ (STT) :** high pT τ (160 GeV)
    - **Di-τ (DTT):** 2 low pT τ (40, 25 GeV) + 4 L1 jets or $\Delta R(\tau,\tau) < 2.5$
  - Run 3 introduced dedicated b-jet triggers
    - **2b2j triggers (DBT):** multi-jet with ≥ 2 b-tagged jets
  - Combining τ and b-jet triggers Improves signal acceptance

[2501.11420]

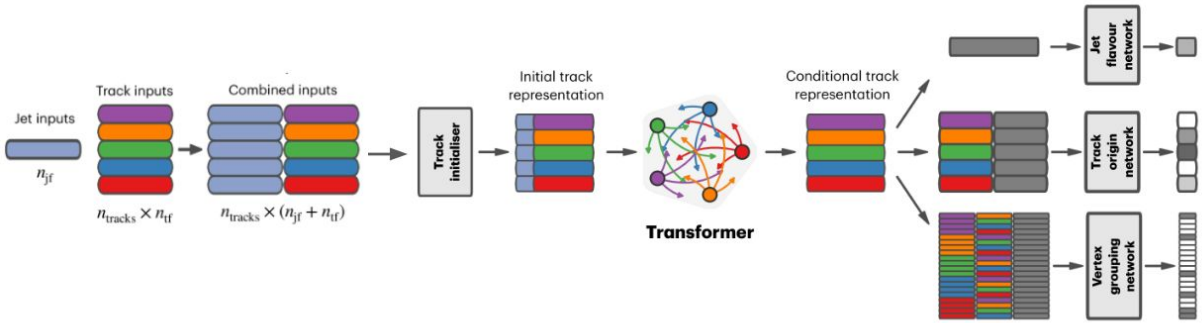


ATLAS b-tagging

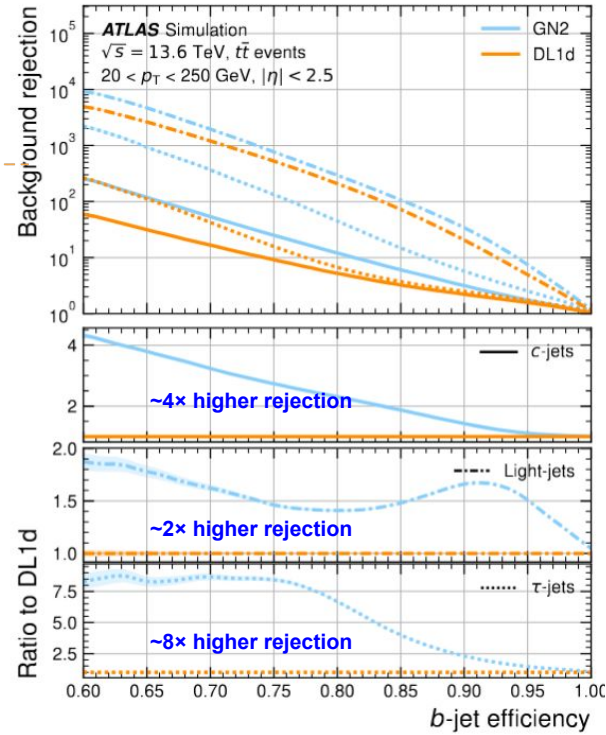
- **Identification of jet originating from b-hadron**
  - Exploits the **long b-hadron lifetime** (~1.5 ps) and **decay products**
    - **Displaced Secondary Vertices**
    - **Track impact parameters (d_0 and z_0)**



  - Run 3: **End-to-end Graph Neural Network** (GN) taggers
    - **Input**: Jet and track information
    - **Output**: Jet-flavour probabilities, combined into a discriminant → **WP**



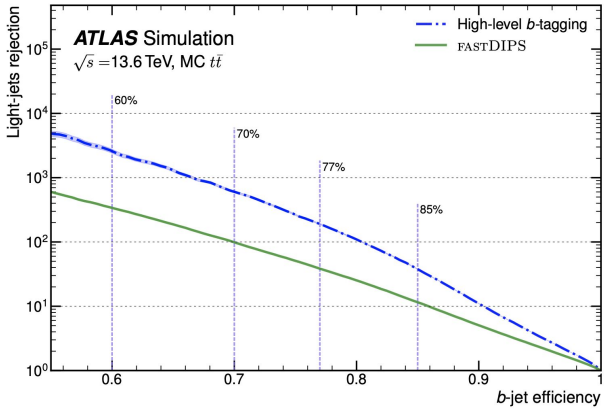
[2505.19689]



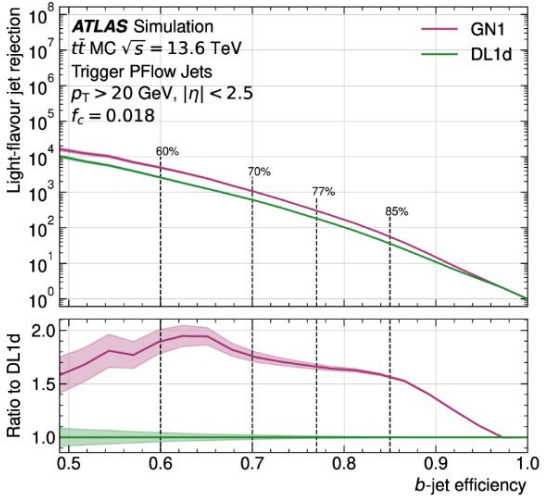
Online b-tagging

- **Online b-tagging has 2 step process:**
  - Preselection with Fast Tracker and DIPS
    - EMTopo jets
    - Early rejection to reduce rate and CPU
  - Full FTF scan for Particle-flow jets
  - Precision b-tagging (DL1d, GN1)
    - Full tracking reconstruction
    - DL1d (2022) Two-stage architecture: Low-level (PV, SVs, IPs) → High-level
    - GN1 (2023) and GN2 (2024)

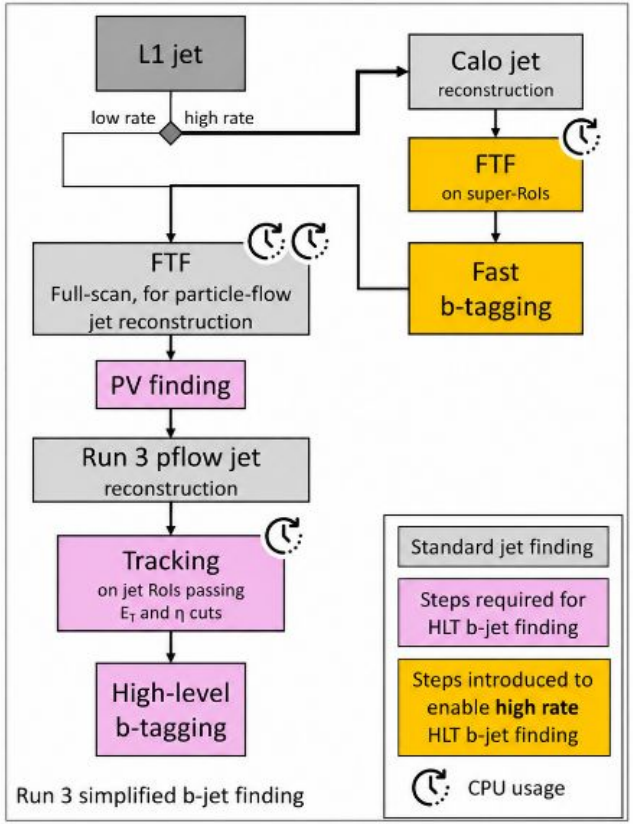
[2306.09738]



[2501.11420]

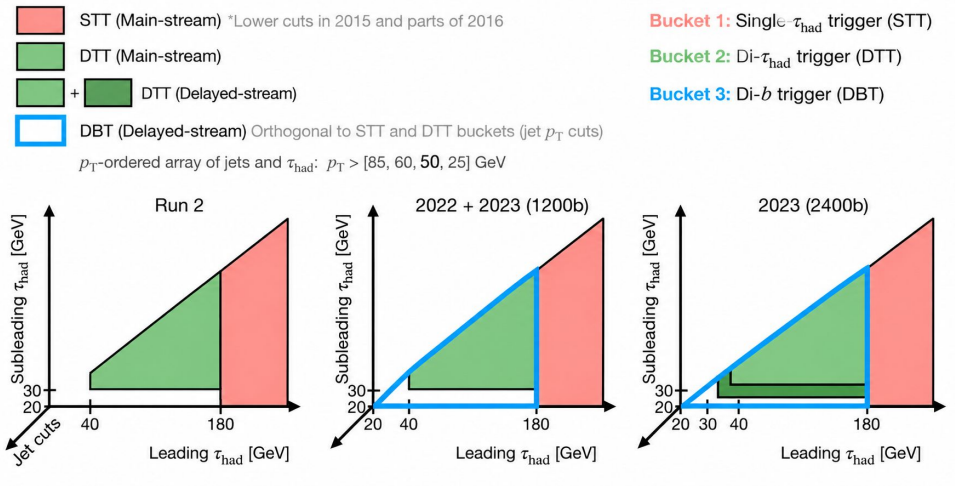


Run 3 Workflow [2306.09738]



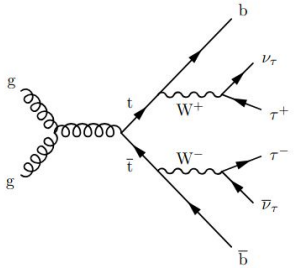
Event Selection

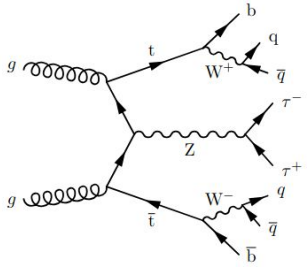
- **Pre-selection**
  - 2 offline jets: pT > [45, 20] GeV, |η| < 2.5
  - ≥1 b-tagged (**GN2**, 85% WP)
  - Di-τ system |η| < 2.5
    - Visible invariant mass $m_{\tau\tau}^{vis}$ > 40 GeV,
    - Missing mass calculator $m_{\tau\tau}^{MMc}$ > 60 GeV
- **Signal Region**
  - **2 b-tagged** jets and **2 opposite-sign** τ
  - $\tau_{lep}\tau_{had}$: 40 < m_{bb} < 150 GeV
  - $\tau_{had}\tau_{had}$: 40 < m_{bb} < 210 GeV
- **Orthogonal trigger bucketing ($\tau_{had}\tau_{had}$)**
  - **3 exclusive signal regions**
    - **STT→DTT→DBT**

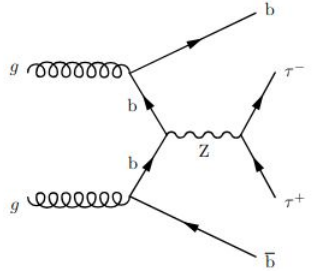


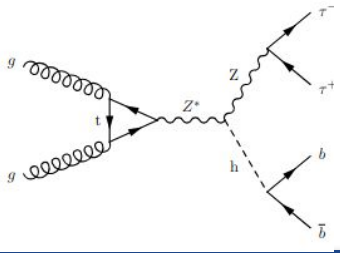
Backgrounds

- **Top-quark backgrounds**
  - tt: **Dominant background** in both channels
  - tW: **Important in $\tau_{lep}\tau_{had}$**
- **V + jets and Diboson**
  - Z + jets: **Dominated by Z→ $\tau\tau$**
  - ZZ: Dominant diboson contribution; **similar topology to HH**
- **Single-Higgs boson**
  - **Subdominant background**, dominated by ttH, followed by ZH and ggH + HF
- **Multijet production → very large cross-section**
  - **Strongly suppressed in $\tau_{lep}\tau_{had}$**
  - **Significant in $\tau_{had}\tau_{had}$** due to jets misidentified as τ_{had} (fake-τ_{had})
    - **Estimated using a data-driven method**



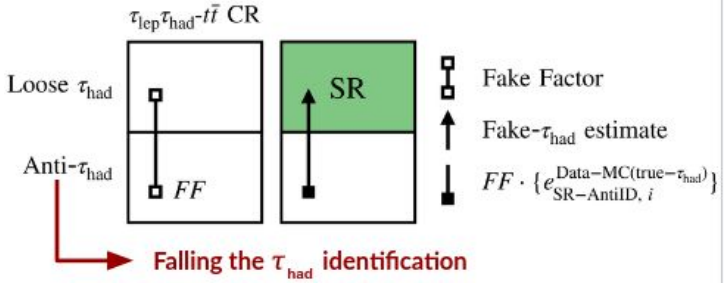




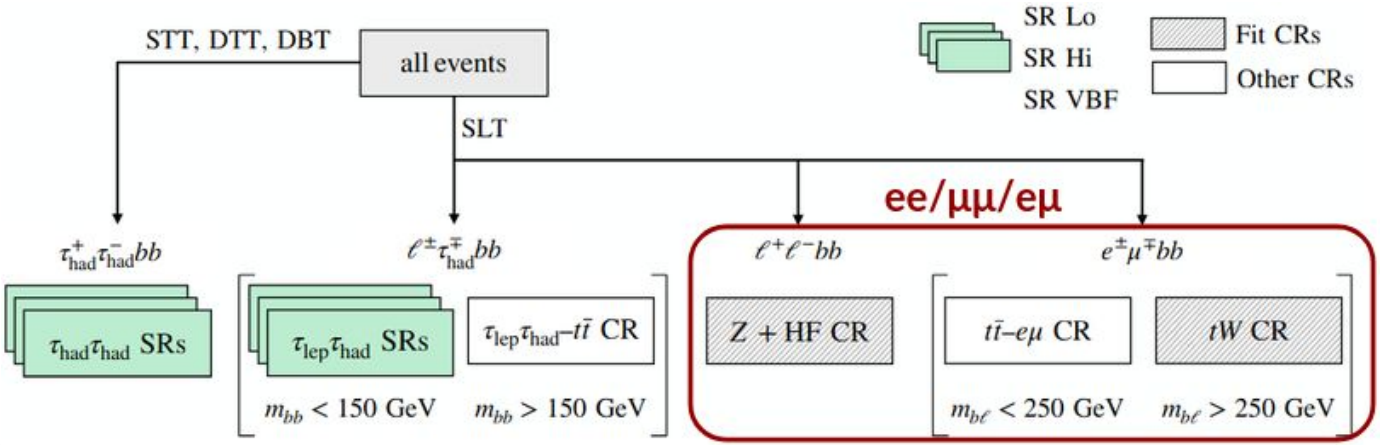


Analysis Control Regions

- **In addition to SRs, dedicated CRs are defined**
  - Inverted SR requirements: constrain the main backgrounds
- **Fake-τ_{had} and multijet backgrounds**
  - $\tau_{lep}\tau_{had}$-tt CR: **data-driven** fake-τ_{had} estimation using Fake Factor (FF)
  - $\tau_{had}\tau_{had}$ SS CR: Multijet estimation using FF
  - Fake-τ_{had}-SF CR: Correction of fake-τ_{had} events in $\tau_{had}\tau_{had}$ channel



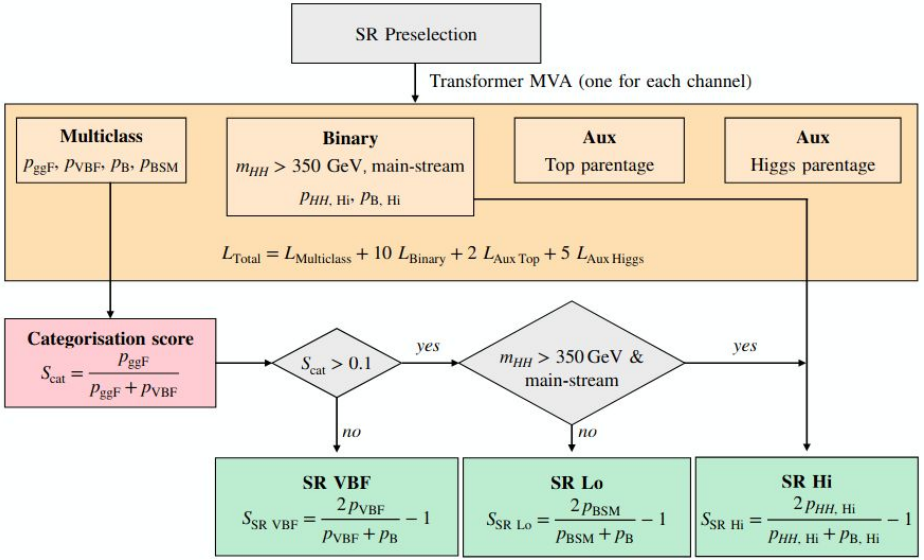
- **Dilepton CRs (ee/μμ/eμ):** Constrain Z + heavy flavour, tt, and tW backgrounds

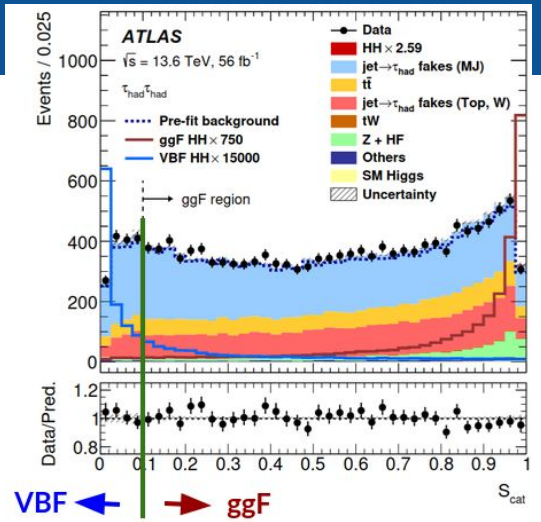


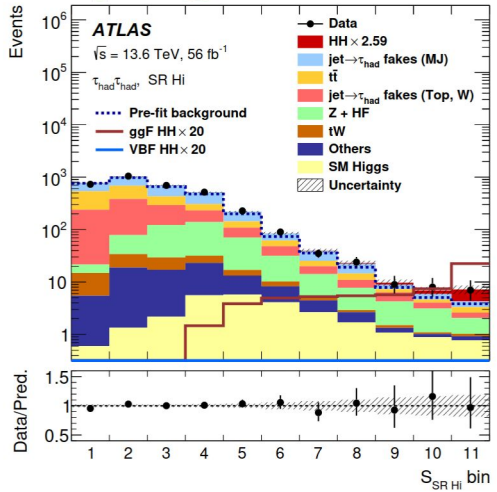
Event Categorization

- **Multivariate Analysis (MVA) for signal–background discrimination**
  - Combines multiple kinematic and event-level observables
  - Transformer based on GN2
  - Separate models for $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$:
    - Same architecture and training strategy

MVA Classifiers



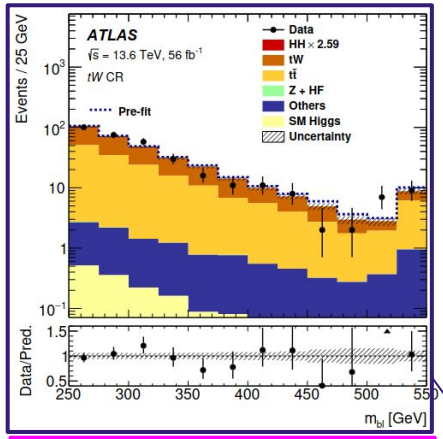


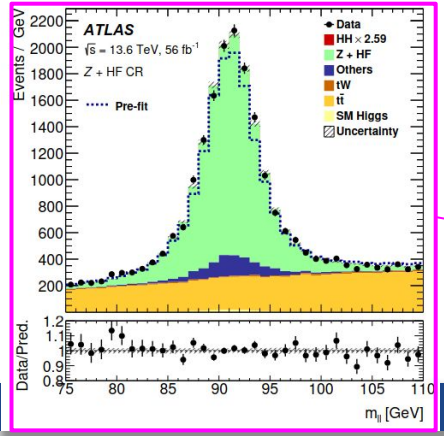


[2607.26879]

HH → bbττ Analysis: Statistical Inference

- Results are obtained from a simultaneous binned profile-likelihood fit to the MVA distributions





Fit Inputs

SRs

12 bined classification score dist.

ggF: $S_{SR,\,Hi}$

ggF: $S_{SR,\,Lo}$

VBF: $S_{SR,\,VBF}$

CRs

4 bined classification score dist

tW: m_{bl}

Z+HF: m_{ll}

Simultaneous Fit

$$\mathcal{L}(\mu,\vec{\theta},\vec{\gamma}) = \prod_{i\in \text{bins}} \text{Pois}\left(N_i \,|\, \mu s_i(\vec{\theta}) + \gamma_i b_i(\vec{\theta})\right) \mathcal{L}_{\text{aux}}(\vec{\theta})\, \mathcal{L}_{\text{bkg,stat}}(\vec{\gamma})$$

Poisson Terms

Event counts in each bin

Sys. Unc.

Nuisance parameters and auxiliary constraints

B Stat.

Template statistical uncertainties

Outputs

Signal strengths: μ_{hh}, and μ_{ggF}, μ_{VBF}

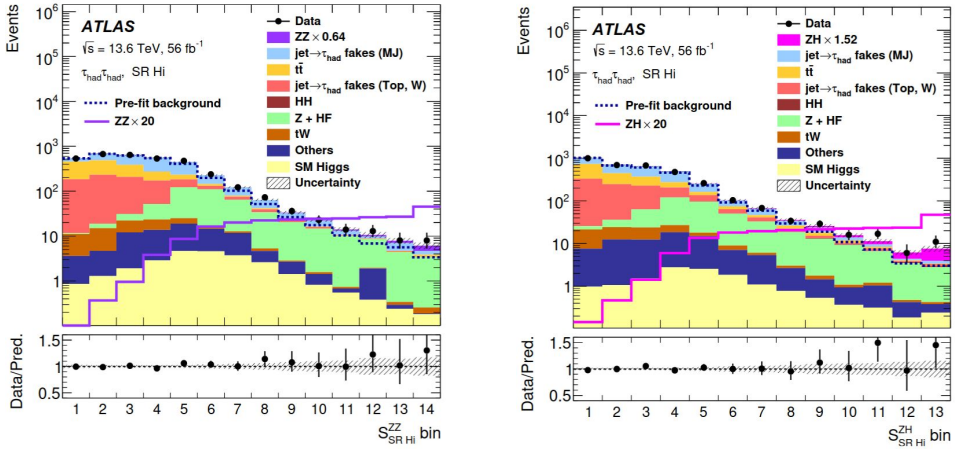
Coupling scans: κ_λ and κ_{2V}

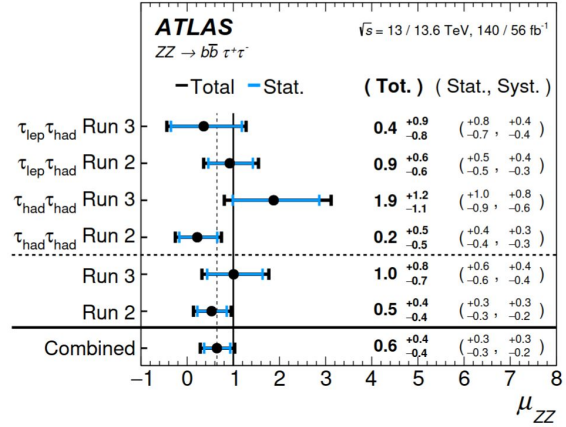
Observed/Expected limits

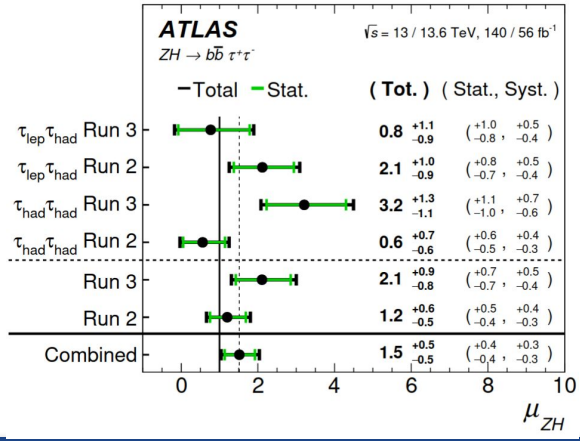
Auxiliary ZZ and ZH Measurements

- **Analysis strategy validation**
  - ZZ→ bb$\tau\tau$ and Zh→ bb$\tau\tau$ measurements before extracting μ_{hh}
  - Same analysis strategy as HH, with dedicated signal discriminants:
    - $S_{SR,\,Hi}$ replaced by $S_{SR,\,Hi}(ZZ)$ or $S_{SR,\,Hi}(Zh)$

[2607.26879]

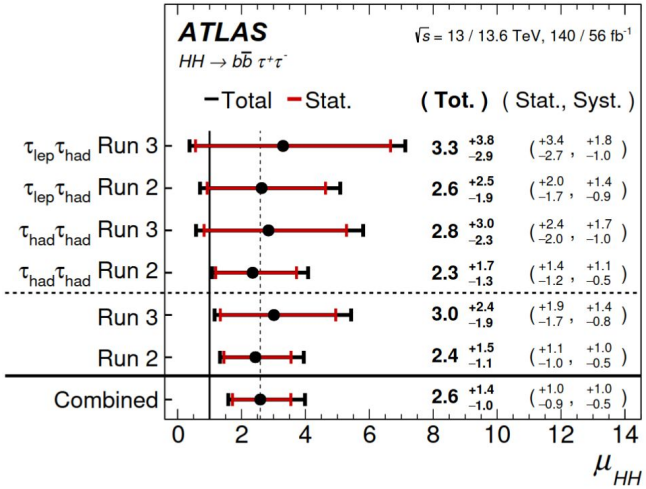




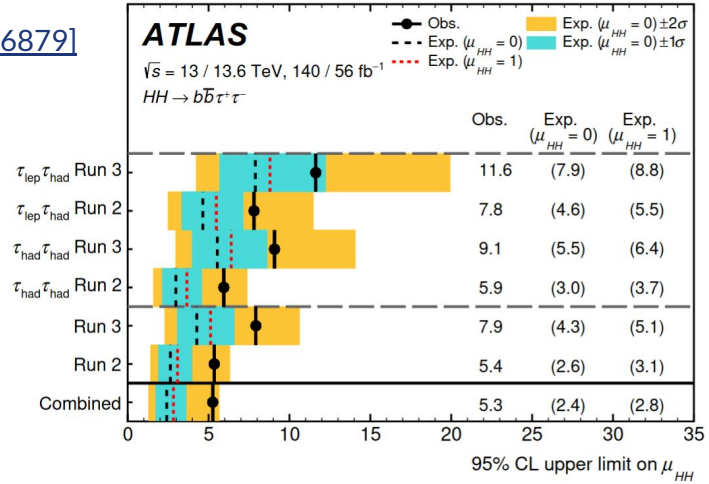


- **Observed (expected) Significance:**
  - **ZZ→ bb$\tau\tau$: 1.8 (2.7) σ**
  - **Zh→ bb$\tau\tau$: 3.5 (2.4) σ, First evidence of Zh production in this final state**

HH Signal Strength



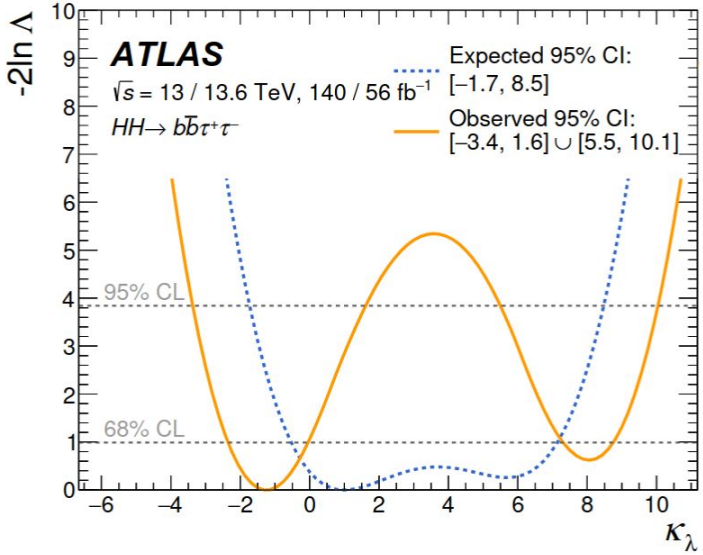
[2607.26879]



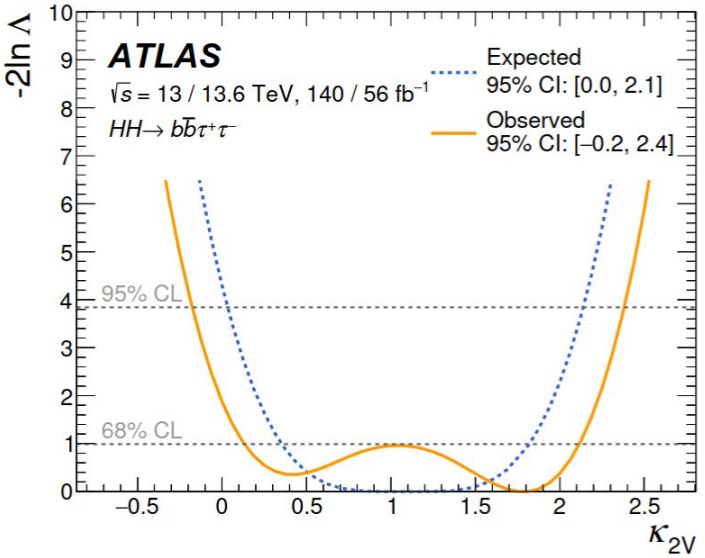
- **Signal strength measurement**
  - **Combined signal strength**: $\mu_{hh} = 2.6^{+1.0}_{-0.9}\,(\text{stat.})^{+1.0}_{-0.5}\,(\text{syst.})$
  - Compatible with the SM prediction at **1.65σ**
- **Background-only hypothesis**
  - Observed (expected) **significance: 2.6σ (1.2σ)**
- **Upper limits at 95% CL:** Observed (expected) μ_{hh} < 5.3 (2.4)

- **Leading systematic uncertainties**
  - ggF HH theory modelling
  - ggH + HF modelling
  - tt–tW interference modelling
  - Limited statistics in background templates

Coupling Measurements



[2607.26879]



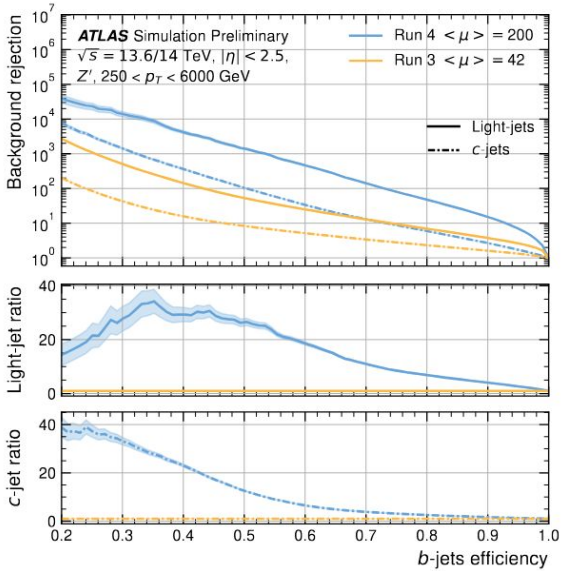
- **Higgs self-coupling modifier κ_λ**
  - Observed (expected) constraints at 95% CL:

$$\kappa_\lambda \in [-3.4, 1.6] \cup [5.5, 10.1] \ ([-1.7, 8.5])$$

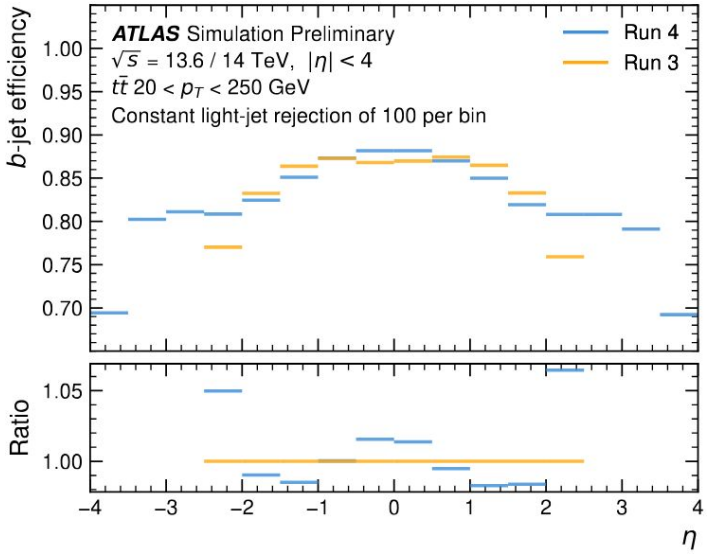
- **Higgs–vector boson coupling modifier κ_{2V}**
  - Observed (expected) constraints at 95% CL:

$$\kappa_{2V} \in [-0.2, 2.4] \ ([0.0, 2.1])$$

HH → bbττ: Trigger and b-tagging Prospects



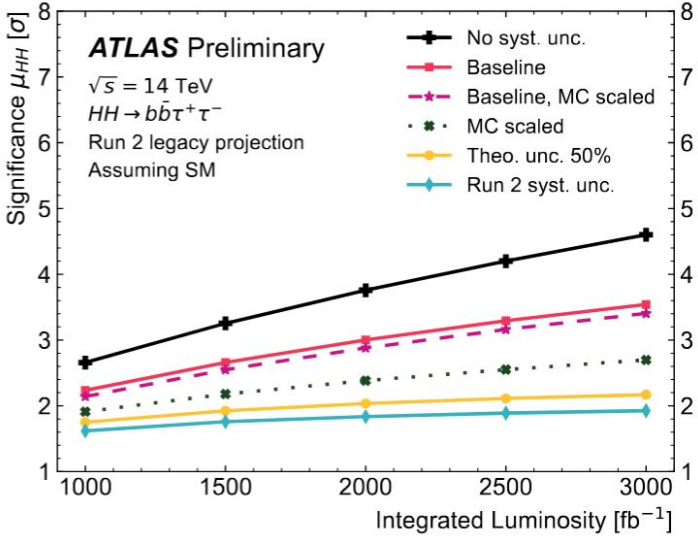
[2306.09738]



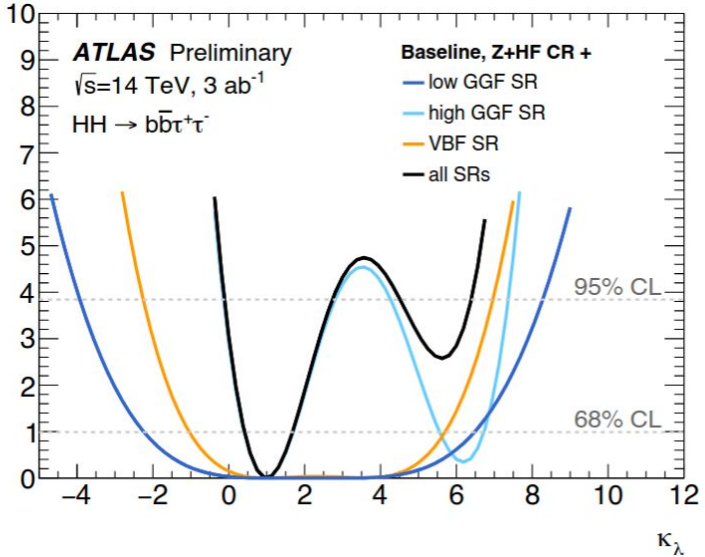
- **New bτ triggers (BTT)**
  - Improved signal acceptance compared with DBT
  - Expected gain in HH sensitivity

- **HL-LHC Detector Upgrades**
  - Improved object reconstruction and identification
  - Extended tracking (ITK) coverage: |η| < 2.5 → |η| < 4
- **GN2 b-tagging Prospects with ITk**
  - **Up to 40× higher light- and c-jet rejection** at high pT
  - **Up to ~5% higher b-tagging efficiency** in the forward region

HL-LHC Projection: Significance and Coupling



[2025-001]



- **HL-LHC extrapolation (3000 fb⁻¹, 14 TeV)**
  - Assuming Run 2 analysis strategy and detector performance
  - Signal and Background yields: Luminosity scaling
  - Process SFs: Cross-section 13 → 14 TeV
  - Different systematic uncertainty scenarios

- **Expected HH significance at 3000 fb⁻¹**
  - Baseline: 3.5σ
- **Expected κ_λ constraints (95% CL)**
  - Basline: $\kappa_\lambda \in [-0.1, 2.7] \cup [4.5, 6.4]$

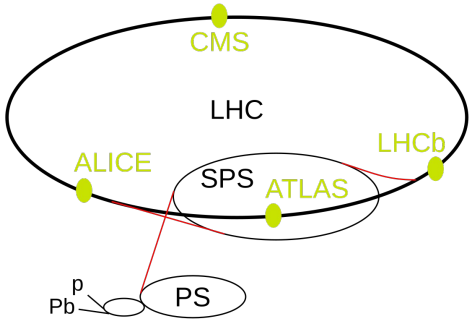
Conclusion

- **Improved HH → bb$\tau\tau$ analysis** [2607.26879]
  - Search for non-resonant Higgs boson pair production
    - Using 196 fb^{-1} of Run 2 and partial Run 3 data
  - Usage of online b-tagging
  - Improved trigger acceptance, offline GN2 b-tagging, and event categorization
- **HH Search Results**
  - Observed (expected) significance: 2.6σ (1.2σ)
  - 95% CL upper limit: $\mu_{hh} < 5.3$ (2.4)
- **Prospects for the HL-LHC**
  - New bτ triggers and upgraded tracking and b-tagging capabilities
  - Expected significance: ~3.5σ at 3000 fb^{-1} under the baseline extrapolation

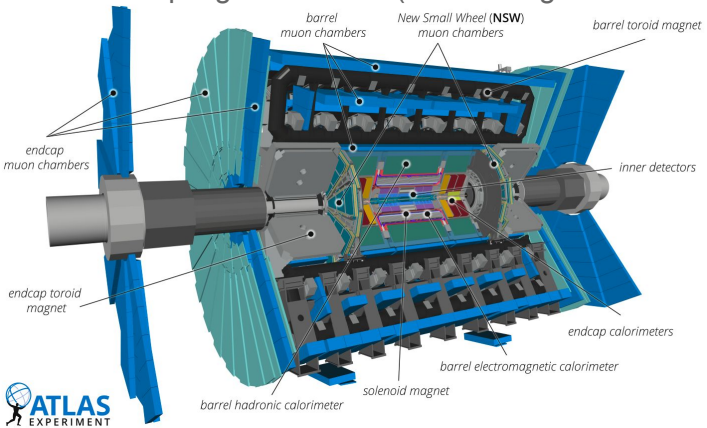
Backup

LHC: A Necessary Framework for HH Studies

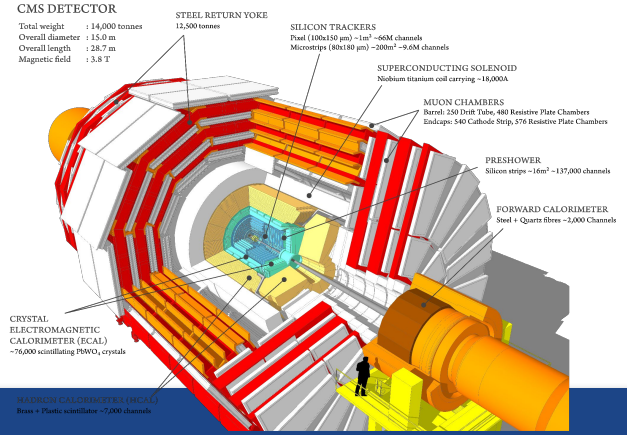
- **The Large Hadron collider (LHC):**
  - **In Run 3 → pp** collisions at **13.6 TeV**
  - **4 interaction points**: **ATLAS, CMS, LHCb, ALICE**
  - **ATLAS** and **CMS**:
    - General-Purpose experiments: Optimized for **Higgs**, top quark, **BSM** searches
    - **Two-level trigger system**



- **ATLAS Detector**
  - Silicon + transition radiation tracker
  - 2 magnet systems
  - Sampling calorimeter (Electromagnetic and Tile)

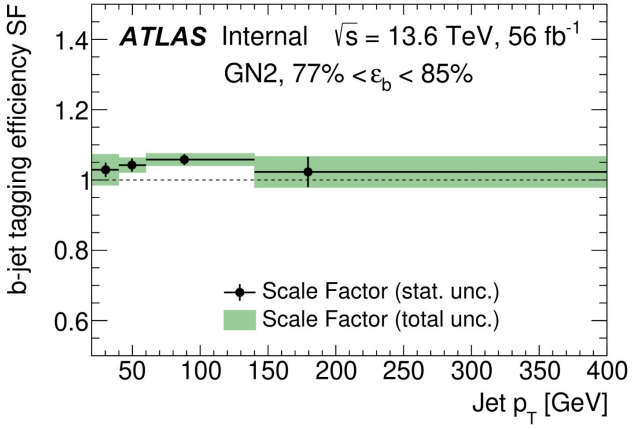


- **CMS Detector**
  - All silicon tracker
  - 1 magnet system
  - Homogeneous crystal Electromagnetic calorimeter

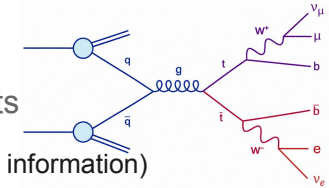


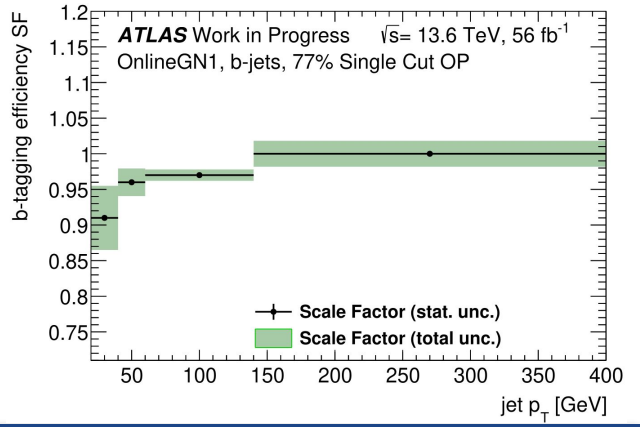
ATLAS b-tagging Calibration

- **Jet scale factor (SF)**
  - Corrects MC–data b-tagging efficiency discrepancies: $SF = \frac{\varepsilon_b^{\text{Data}}}{\varepsilon_b^{\text{MC}}}$
  - Depends on jet flavor, pT, η and b-tag score
  - Online+offline b-tagging combined SF
    - Final event weight : $SF_{\text{event}} = \prod_i^{N_{\text{jets}}} SF_i$



- **b-tagging calibration extraction**
  - Efficiency derivation is f performed with tt bar events
    - Single-lepton triggers + b-jet trigger (only for tagging information)
    - Offline opposite-charge dilepton pair + ≥ 2 jets
  - b-tagging efficiencies measured in data and MC
    - Same strategy for offline and online



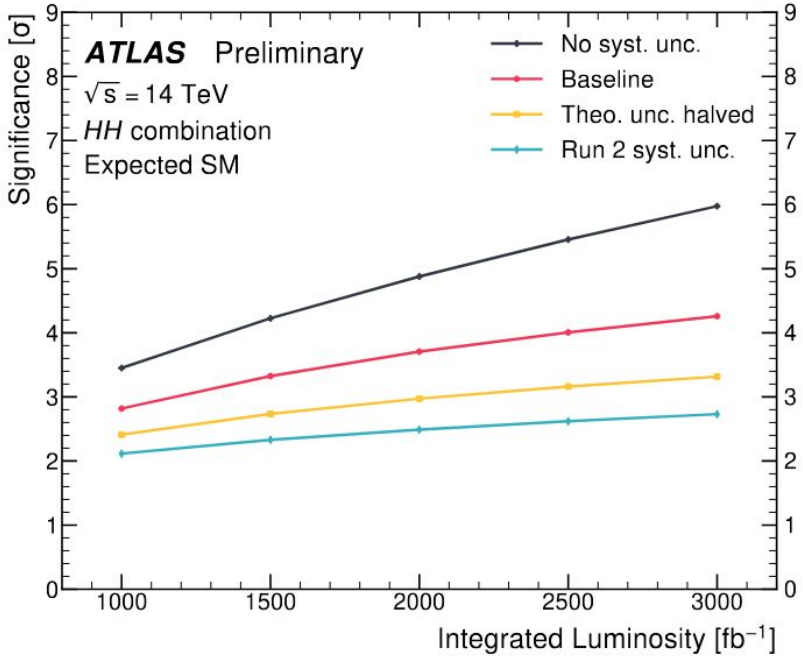


ATLAS Combined HL-LHC Projection: Significance

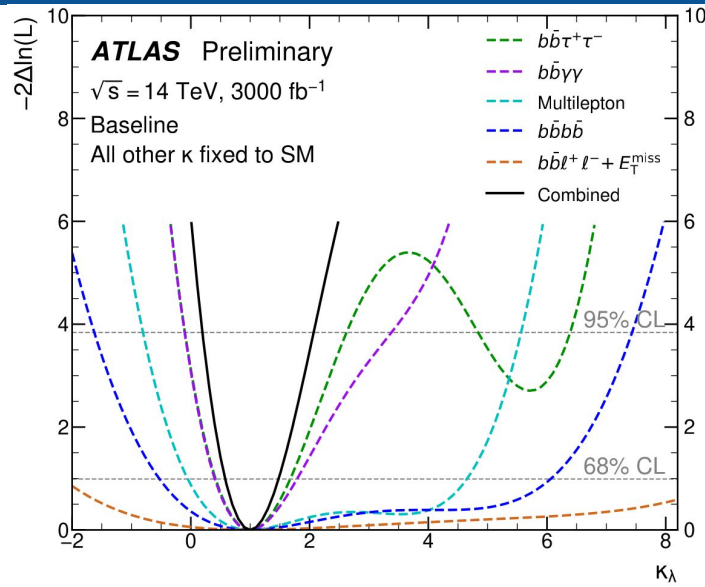
- **ATLAS HH combination for HL-LHC extrapolation**
  - Using bbγγ, bbττ, bbbb, bb$\ell^+\ell^-$ + E$^{miss}_{T}$ and boosted VBF
  - Extrapolation from Run 2 to $\sqrt{s}$ = 14 TeV and 3000 fb^{-1}

- **Expected SM HH significance**
  - Baseline scenario: 4.26σ
  - No systematic uncertainties: 5.98σ
  - Sensitivity strongly depends on the assumed systematic uncertainties

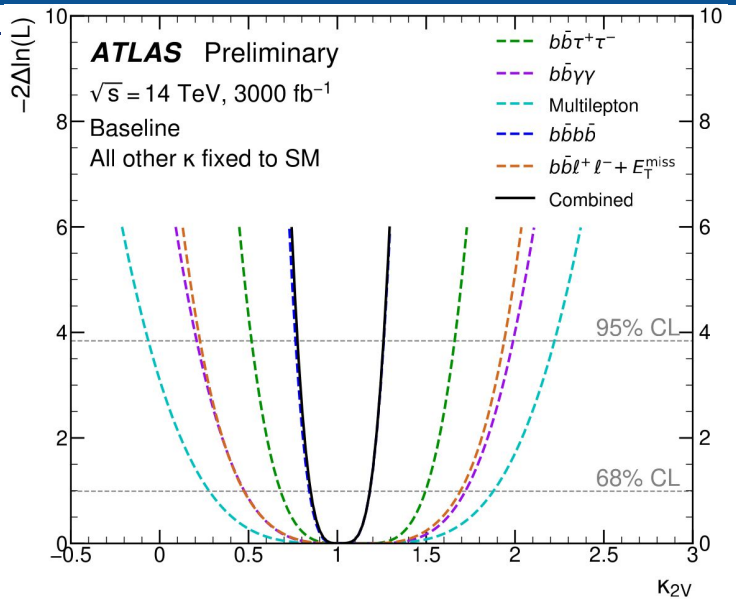
ATL-PHYS-PUB-2025-006



ATLAS Combined HL-LHC Projection: Coupling

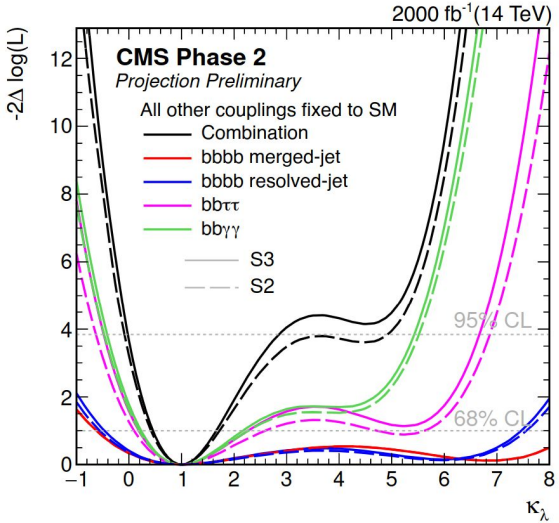


ATL-PHYS-PUB-2025-006

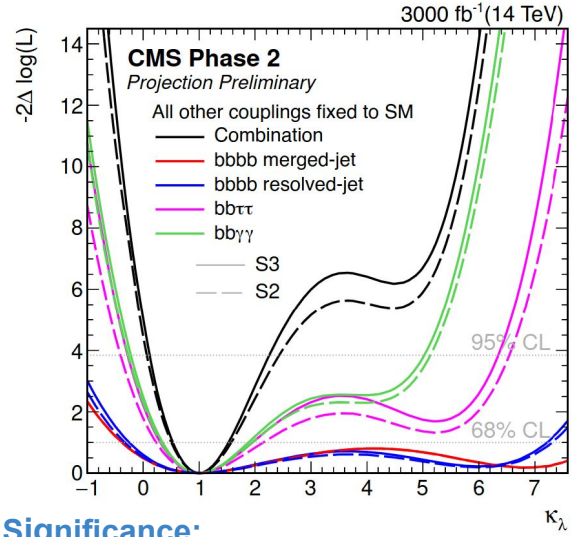


- **Coupling constraints**
  - One-dimensional likelihood scans
  - All other coupling modifiers fixed to their SM values
- **Higgs self-coupling: κ_λ = 1.0 (+0.48, -0.43)**
- **Vector-boson coupling: κ_{2V} = 1.0 (+0.18, -0.15)**

CMS HL-LHC Projection: Coupling



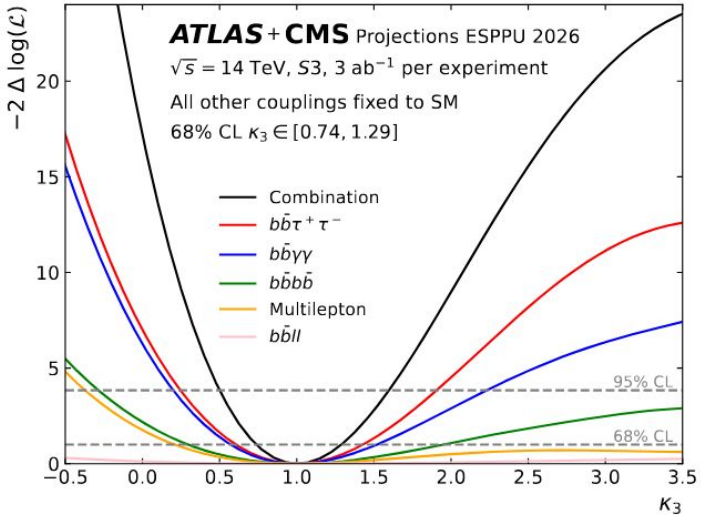
CMS-NOTE-2025-006



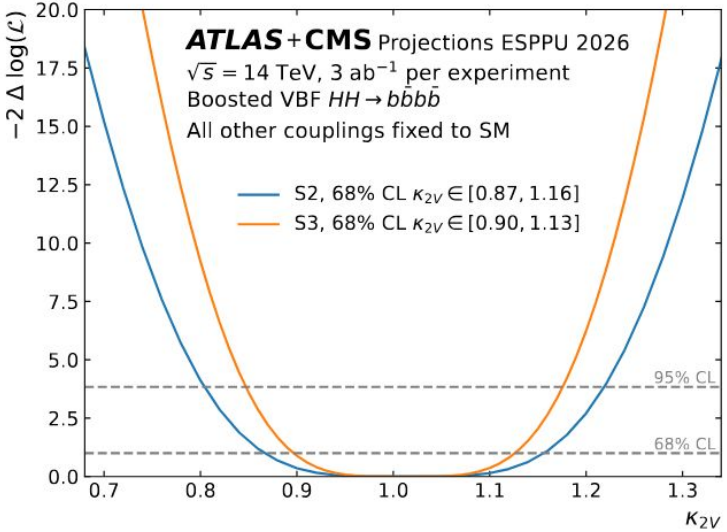
- **Run 2 analyses extrapolated to the HL-LHC**
  - Using bbγγ, bbττ and bbbb (resolved and merged)
  - 2000–3000 fb^{-1} at $\sqrt{s}$ = 14 TeV
- **Two uncertainty scenarios:**
  - S2: Run 2 object-identification performance
  - S3: Improved object-identification performance

- **Expected Significance:**
  - 2000 fb^{-1}: 3.5σ (S2) / 3.7σ (S3)
  - 3000 fb^{-1}: 4.2σ (S2) / 4.5σ (S3)
- **Higgs self-coupling (κ_λ)**
  - Expected relative precision: ~50% at 68% CL (3000 fb^{-1})
  - Sensitivity mainly driven by bbγγ and bbττ

ATLAS + CMS HL-LHC Projection: Coupling



[2504.00672]



- **Combined ATLAS and CMS projections**
  - Using bbγγ, bbττ, bbbb, bb$\ell^+\ell^-$ + E^{miss} and boosted VBF
  - Extrapolation from Run 2 to √s = 14 TeV and 3000 fb^{-1}
- **Expected κ_λ constraints (68% CL)**
  - S3: $\kappa_\lambda \in [0.74, 1.29]$

- **Expected κ_{2V} constraints (68% CL)**
  - S2: $\kappa_{2V} \in [0.87, 1.16]$
  - S3: $\kappa_{2V} \in [0.90, 1.13]$
- **Combined expected significance**
  - S2: 7.2σ and S3: 7.6σ