



Probing the Higgs boson pair production through Vector Boson Fusion at the LHC in the ATLAS experiment

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1 Introduction

Large Hadron Collider

ATLAS Experiment

High-Luminosity LHC

Inner Tracker (ITk)

Why Study Higgs Pair Production?

Higgs Pair Production: $b\bar{b}\tau^+\tau^-$

2 Flavour tagging

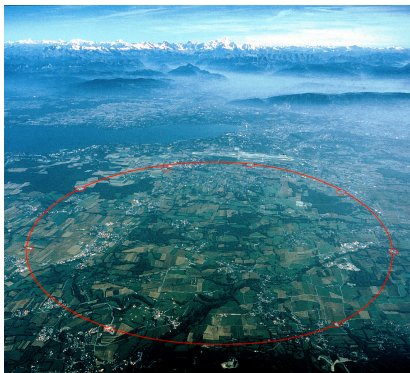
3 Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ channel.

Large Hadron Collider

- **Large Hadron Collider (LHC):** 27 km superconducting proton-proton collider at CERN.
- **Energy:** $\sqrt{s} = 13.6$ TeV in Run 3, probing the TeV scale.
- **Experiments:** ATLAS, CMS, ALICE and LHCb study SM physics and search for BSM phenomena.
- **Landmark result:** Higgs boson discovery in 2012 by ATLAS and CMS.

For proton-proton collisions:

- **Run 1 (2010-2012):** $\sqrt{s} = 7\text{-}8$ TeV,
 $\mathcal{L}_{\text{int}} \simeq 26 \text{ fb}^{-1}$
- **Run 2 (2015-2018):** $\sqrt{s} = 13$ TeV,
 $\mathcal{L}_{\text{int}} \simeq 147 \text{ fb}^{-1}$
- **Run 3 (2022-2026):** $\sqrt{s} = 13.6$ TeV,
 $\mathcal{L}_{\text{int}} \simeq 332 \text{ fb}^{-1}$

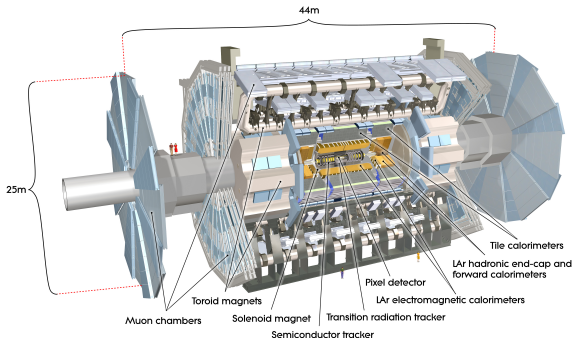


ATLAS Experiment

- **ATLAS:** A general-purpose detector at one of the LHC interaction points, located ~ 100 m underground.
- **Design:** Concentric tracking, calorimeter and muon systems provide near-complete coverage around the interaction point.
- **Physics programme:** Higgs boson, Standard Model precision measurements and searches for physics beyond the Standard Model.

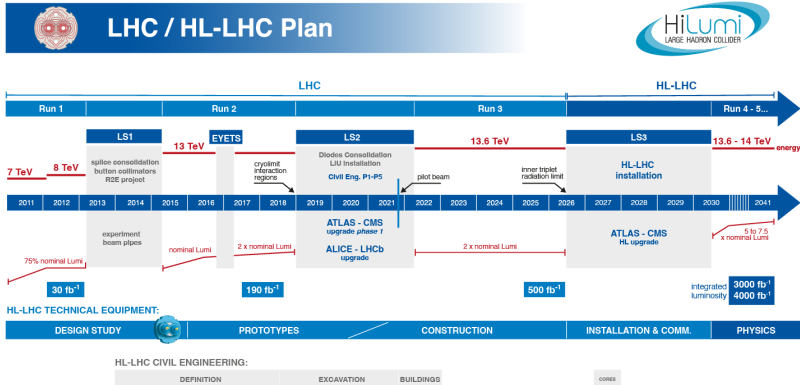
Main detector systems:

- **Inner Detector:**
Charged-particle tracking, vertex reconstruction.
- **Calorimeters:**
Energy measurements.
- **Muon Spectrometer:**
Precision reconstruction identification of muons.



High-Luminosity LHC

- **Goal:** Increase the LHC luminosity to significantly expand available statistics.
- **Instantaneous luminosity:** $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ vs $2.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in Run 3.
- **Integrated luminosity:** $\sim 3000 \text{ fb}^{-1}$ over ~ 10 years.
- **Collision energy:** $\sqrt{s} = 14 \text{ TeV}$.
- **Pile-up:** Up to $\langle \mu \rangle \sim 200$ interactions/crossing.
- These conditions require substantial upgrades to LHC and experiments.



Inner Tracker (ITk)

Designed to replace the current Inner Detector to provide precision tracking under HL-LHC conditions.

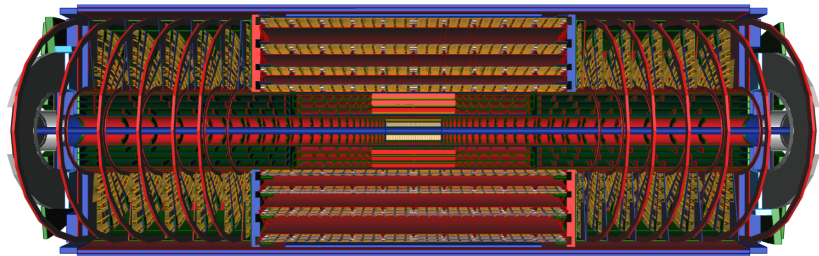
All-silicon tracker consisting of:

- Inner **Pixel Detector**: tracking up to $|\eta| = 4$.
- Outer **Strip Detector**: tracking up to $|\eta| = 2.7$.

Designed for high occupancy and radiation levels at HL-LHC.

Lightweight carbon-fibre structures with integrated CO₂ cooling.

Provides improved tracking performance.



Why Study Higgs Pair Production?

Higgs pair production directly probes the Higgs potential and provides sensitivity to deviations in Higgs self-interactions and Higgs-vector-boson couplings.

κ_λ - Higgs self-coupling

$$\lambda_{\text{SM}} = \frac{m_H^2}{2v^2}, \quad \kappa_\lambda = \frac{\lambda}{\lambda_{\text{SM}}}.$$

- Direct probe of Higgs potential.
- Modifies triangle contribution.
- Interferes with box contribution, affecting rate and kinematics.

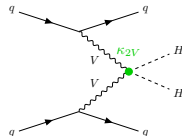
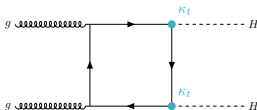
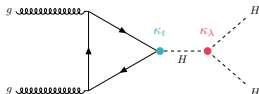
κ_{2V} - $VVHH$ coupling

$$g_{VVHH} = \kappa_{2V} g_{VVHH}^{\text{SM}}.$$

- Probes interaction of two Higgs bosons with vector bosons.
- Particularly relevant for VBF HH .
- Deviations can modify rates and kinematic distributions.

Relevant interactions

$$\mathcal{L}_{\text{int}} \supset -\kappa_\lambda \lambda_{\text{SM}} v H^3 + \kappa_{2V} \frac{m_V^2}{v^2} H^2 V_\mu V^\mu + \dots$$



Higgs Pair Production: $b\bar{b}\tau^+\tau^-$

Cross section for HH production

$$\sigma(pp \rightarrow HH) \sim 30\text{--}40 \text{ fb} \quad (\sqrt{s} = 14 \text{ TeV})$$

$\sim 10^3$ times rarer than single-Higgs production.

Many decay channels:

- $b\bar{b}b\bar{b}$
- $b\bar{b}\tau^+\tau^-$
- $b\bar{b}\gamma\gamma$
- And more...

Focus

$$HH \rightarrow b\bar{b}\tau^+\tau^-$$

Large branching fraction with manageable backgrounds; b -tagging and τ identification provide powerful analysis handles.

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

1 Introduction

2 Flavour tagging

- Jet reconstruction

- Introduction to flavour tagging

- GN2 flavour tagging algorithm

- Retraining GN2 for Run 4

- Flavour Discriminant

- ROC Curves

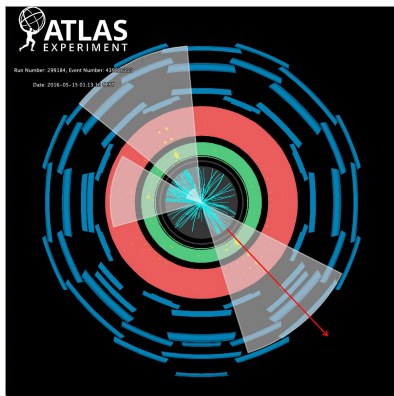
- Flavour Tagging vs $|\eta|$

- Efficiency Variations with Kinematics

- Summary

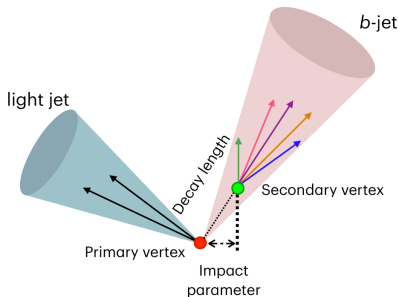
3 Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ channel.

- **What are jets?**
 - Collimated sprays of hadrons produced by the fragmentation and hadronization of quarks and gluons.
 - Reconstructed from energy deposits and charged-particle tracks in the detector.
- **Reconstruction:** Jets are clustered using the infrared- and collinear-safe anti- k_T algorithm.
- **Anti- k_T :** Objects are iteratively merged according to their transverse momenta and angular separation ΔR .
- **Jet radius:** Typically $R = 0.4$, producing approximately conical jets.



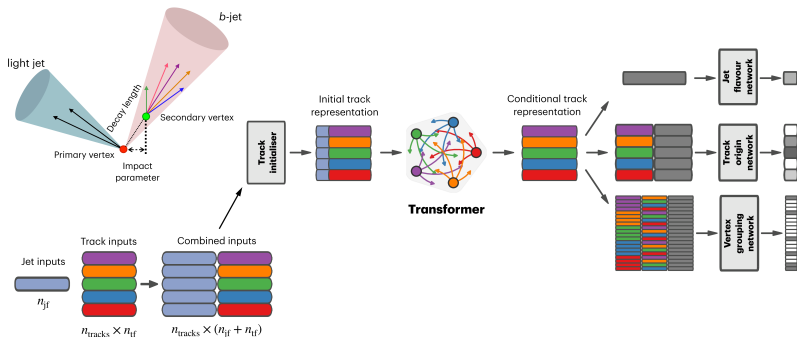
Introduction to flavour tagging

- **Goal:** Infer the flavour of the parton initiating a jet from its internal structure.
- ***b*-jets:** Jets originating from beauty hadrons, which have relatively long lifetimes ($\tau \simeq 1.5 \times 10^{-12}$ s).
- **Displaced decays:** *B* hadrons typically travel several mm before decaying, producing displaced tracks and secondary vertices.
- **Jet topology:** The presence of secondary vertices and large track impact parameters provides strong discrimination against light-flavour jets.
- **Flavour taggers:** Combine these kinematic and topological features to classify jets as *b*, *c*, τ or light-flavour jets.



GN2 flavour tagging algorithm

- **GN2** is a Transformer-based flavour tagging algorithm that directly processes jet and track information.
- Uses jet-level and track-level kinematic and tracking variables.
- In addition to jet flavour prediction, auxiliary tasks identify origins of tracks and whether track pairs share a common production vertex.
- At comparable b -jet efficiency, GN2 achieves substantially higher c -jet and light-jet rejection than its predecessors.



Retraining GN2 for Run 4

- **Changing detector conditions:** HL-LHC operation introduces $\sqrt{s} = 14 \text{ TeV}$, $\langle\mu\rangle \sim 200$ and a completely new **Inner Tracker (ITk)**.
- **Domain shift:** GN2 is trained on Run 2/3 simulation with the current ATLAS detector geometry. Its performance is not guaranteed to remain optimal with Run 4 detector conditions.

A training on Run 4 simulations is performed to assess the performance of the model at high-lumi conditions.

- **Run 4 training samples:** ~ 115 million simulated jets from $t\bar{t}$ (75%) and Z' (25%) samples, covering $p_T = (20, 250) \text{ GeV}$ and $p_T = (250, 6000) \text{ GeV}$.
- **Full detector simulation:** Events are processed through the Geant4 ATLAS simulation, including the Run 4 ITk geometry and high-pile-up conditions.
- **Training preparation:** Jets are rebalanced across flavour classes in (p_T, η) bins, input variables are normalized, and the dataset is split into 80% training, 10% validation and 10% evaluation.
- **Goal:** Obtain optimal flavour-tagging performance under the detector and collision conditions expected throughout the HL-LHC programme.

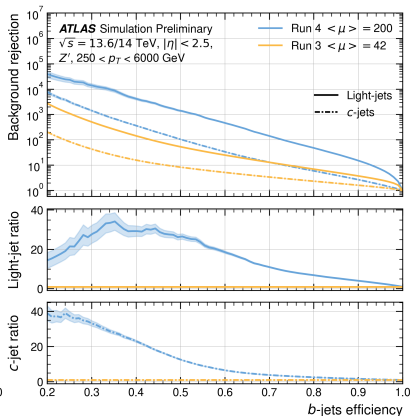
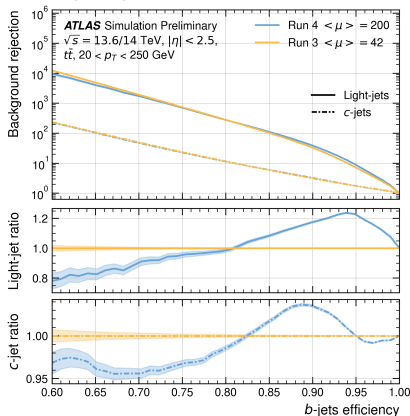
A flavour tagging discriminant is built from the scores provided by the model:

$$D_b = \log \left(\frac{p_b}{f_c p_c + f_\tau p_\tau + (1 - f_c - f_\tau) p_u} \right)$$

- p_b , p_c , p_τ and p_u are the GN2 classification scores for b , c , τ and light jets.
- f_c and f_τ : Relative fractions of backgrounds.
- The discriminant threshold defines the desired **b -jet tagging efficiency**.
- **Working point**: Fixed b -tagging efficiency ϵ_b by cutting on discriminant.
- **f_c optimisation**: Scan f_c and, for each value, determine the threshold giving the desired ϵ_b .
- Optimal value maximizes both c - and light-jet rejection: $f_c = 0.1$

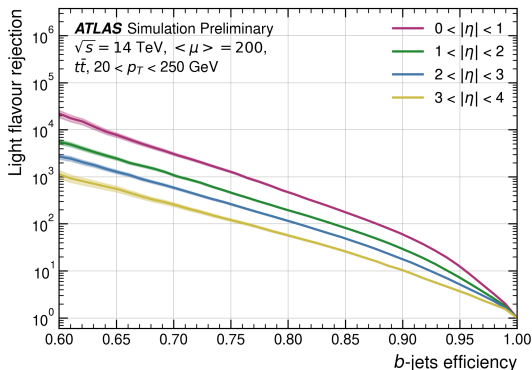
ROC Curves

- **ROC curve:** Characterizes performance of binary classifier by comparing signal efficiency with background rejection.
- For flavour tagging, b -jet efficiency ϵ_b compared against rejection of c - and light-flavour jets.
- Curves obtained by scanning threshold on flavour discriminant D_b .
- Compatible to Run 3 at low p_T , improvement up to $\times 40\%$ at high p_T .
- Improvement attributed primarily to **ITk**, with improved tracking efficiency and impact parameter resolution.



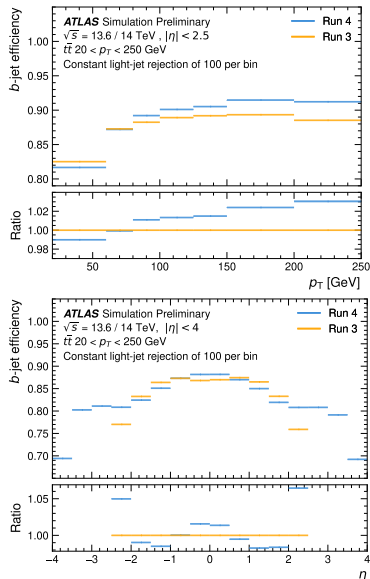
Flavour Tagging Performance vs $|\eta|$

- **Detector dependence:** ROC curves are evaluated in different $|\eta|$ regions to study spatial variations in tagging performance.
- **Central region:** Best performance is observed at low $|\eta|$, where tracking coverage and resolution are optimal.
- **Forward region:** Tagging performance degrades with increasing $|\eta|$.
- Largely driven by higher density of **passive material** in forward regions of ITk, degrading tracking performance.
- Despite reduced performance, flavour tagging at high $|\eta|$ is a significant **extension of Run 4 acceptance**, these regions are not accessible in Run 3.



Efficiency Variations with Kinematics

- **p_T dependence:** Compare b -tagging efficiency at a fixed light-jet rejection, of 100, in each p_T bin.
- Improved efficiency over most of p_T range, with a reduction at very low p_T .
- The low- p_T behaviour may be related to higher track- p_T thresholds in Run 4 $\rightarrow$ fewer associated tracks $\rightarrow$ less information for the tagger.
- **η dependence:** Run 4 maintains comparable central performance while extending flavour tagging to higher $|\eta|$.
- Performance decreases in most forward regions, consistent with reduced tracking performance of ITk at high $|\eta|$.



- **Motivation:** HL-LHC conditions introduce $\sqrt{s} = 14 \text{ TeV}$, $\langle \mu \rangle \sim 200$ and the new ITk detector, requiring dedicated retraining of GN2.
- **Run 4 GN2:** Trained on ~ 115 million fully simulated jets with Run 4 detector geometry and high-pile-up conditions.
- **Performance:** Compatible with Run 3 training at low p_T , with up $\sim 400\%$ improvements in background rejection high p_T .
- **Kinematic dependence:** Performance varies with both p_T and η ; the largest gains are observed at high p_T .
- **Forward region:** ITk extends flavour tagging to $|\eta| = 4$, but performance decreases at large $|\eta|$ due to increased passive material and degraded tracking.
- **Overall:** The Run 4 GN2 training provides reliable flavour discrimination while extending b -tagging coverage into previously inaccessible forward regions.

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3 Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ channel.

- Physics Objects
- Missing Mass Calculator
- Trigger Strategy
- Event Selection
- Signal and Control Regions
- Analysis Framework
- Optimisation of grid processing
- Background Modelling
- Fake- τ_{had} Backgrounds
- Multivariate Signal Extraction
- Signal Regions and Production Modes
- Classifier scores distributions
- Statistical Analysis
- Systematic Uncertainties
- ZZ and ZH results
- Sensitivity to HH
- Higgs Coupling Constraints
- HL-LHC Prospects
- Summary

- **Electrons and muons:** reconstructed and identified using standard ATLAS algorithms.
- **Jets:** Reconstructed with PFlow and calibrated to the particle energy scale.
- **b -jets:** Identified using **GN2** at the 85% b -tagging efficiency working point.
- τ_{had} : Identified with narrow, low-track-multiplicity signatures identified with dedicated RNNs.
- **Missing Transverse Energy (MET):** The transverse energy imbalance in a collision, arising when particles such as neutrinos or other weakly interacting states escape detection

Final states of $\tau\bar{\tau}$ pair:

$$\tau_{\text{lep}}\tau_{\text{had}}$$

One decay leptonically, the other hadronically.

$$\tau_{\text{had}}\tau_{\text{had}}$$

Both decay hadronically.

These are treated by the analysis as different channels.

- τ decays contain one or more neutrinos, which are not reconstructed by ATLAS
 $\Rightarrow$ the $\tau\bar{\tau}$ system is under-constrained.
- The system has **6–8 unknowns** but only **4 kinematic constraints**, including:

$$\vec{E}_T^{\text{miss}} = \vec{p}_{T,\nu_1} + \vec{p}_{T,\nu_2}, \quad m_\tau^2 = (p_{\text{vis}} + p_\nu)^2.$$

- **Missing Mass Calculator (MMC)**: adds probabilistic constraints from simulated ΔR distributions of visible and invisible decay products:

$$L = -\log[P(\Delta R_1, p_1) P(\Delta R_2, p_2)].$$

- Scans the neutrino phase space and selects the most probable $m_{\tau\bar{\tau}}$:

$$\begin{cases} (\phi_{\nu_1}, \phi_{\nu_2}) & \text{hadronic,} \\ (\phi_{\nu_1}, \phi_{\nu_2}, m_\nu) & \text{semi-leptonic,} \\ (\phi_{\nu_1}, \phi_{\nu_2}, m_{\nu_1}, m_{\nu_2}) & \text{fully leptonic.} \end{cases}$$

- **Performance**: unbiased mass reconstruction with $\sim 8\%$ – 13% resolution before detector effects, degrading to $\sim 16\%$ when detector resolution is included.

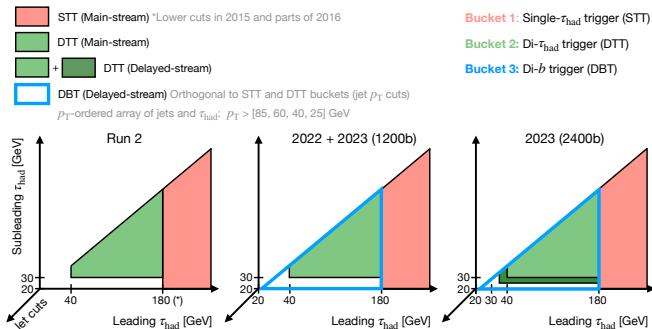
Trigger Strategy

$\tau_{\text{lep}} \tau_{\text{had}}$

- Single-lepton triggers.
- Thresholds and identification requirements evolve with the data-taking period.

$\tau_{\text{had}} \tau_{\text{had}}$

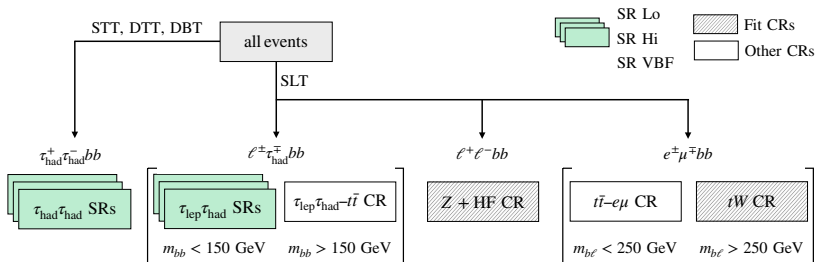
- Single- τ_{had} (STT).
- Di- τ_{had} (DTT), Requires two τ_{had} candidates at trigger level.
- Di- b -jet (DBT) Targets the $b\bar{b}$ jet signature, requiring two jets with b -tags.



- Two τ candidates with opposite electric charge.
- At least two central jets with $p_T > 45$ (20) GeV.
- One or two b -tagged jets using GN2 at the 85% working point.
- Reconstruct the di- τ system using visible kinematics and the **Missing Mass Calculator (MMC)**.
- Require $m_{\tau\tau}^{\text{vis}} > 40$ GeV and $m_{\tau\tau}^{\text{MMC}} > 60$ GeV.

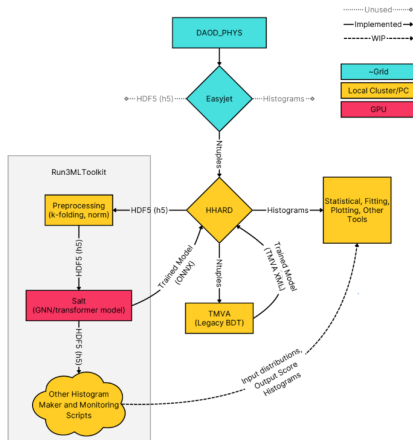
Signal and Control Regions

- Signal and control regions are defined using the reconstructed event topology.
- In the $\tau_{\text{lep}}\tau_{\text{had}}$ channel:
 - $m_{bb} < 150$ GeV defines the SR.
 - $m_{bb} > 150$ GeV provides a CR.
- Dedicated control regions constrain Z +**heavy flavour** and $t\bar{t}$ backgrounds.
- The $\tau_{\text{had}}\tau_{\text{had}}$ channel additionally uses 1-tag and 2-tag regions.



Analysis Framework

- **Athena:** common ATLAS framework for detector description, reconstruction, simulation and analysis algorithms.
- **EasyJet:** processes large datasets and applies trigger, object and event selections.
- Higher-level observables and systematic variations are computed during the EasyJet processing.
- Large-scale processing is performed on the **WLCG**.

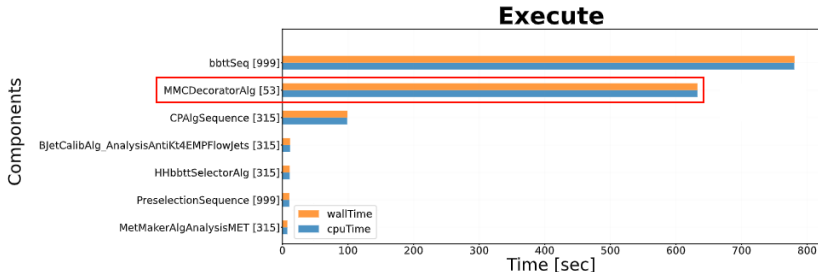


Optimisation of grid processing

- Full-data processing requires large-scale parallelisation; jobs are constrained by **CPU time, memory, and task throttling**.
- Task throttling: Single user submitting many tasks may find some put on hold to ensure fair distribution of resources.
- The MMC is a major computational bottleneck due to its multi-dimensional phase-space scan.

Processing optimisations:

- Split computationally expensive channels into separate jobs.
- Process control regions independently to free resources.
- Skip unnecessary MMC systematic variations in selected low-complexity events.
- Tune input size per dataset to balance **parallelism** against job throttling.
- Exclude computing sites with unsuitable resource constraints.



MMC optimisation reduced processing time by **60–70%**. Overall grid-processing success rate improved from $\sim 1\%$ to $\sim 98\%$.

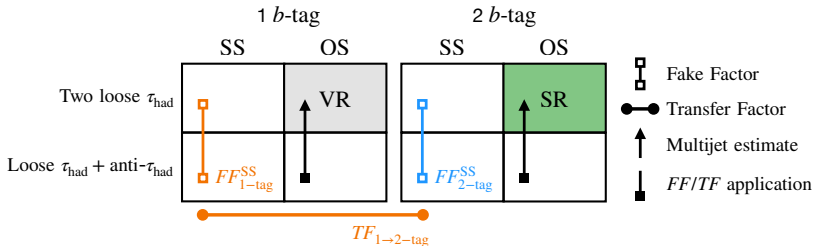
- The dominant backgrounds arise from processes producing real or misidentified τ leptons and b -jets.
- $t\bar{t}$: significant contribution in both τ channels.
- Z +**heavy flavour**: $Z + b\bar{b}$, $Z + bc$ and $Z + c\bar{c}$.
- Other backgrounds include single top, diboson and single-Higgs production.
- Backgrounds involving misidentified τ_{had} candidates require dedicated data-driven estimates.

Key challenge

Rare HH signal $\ll$ backgrounds from ordinary LHC processes.

Data-Driven Fake- τ_{had} Estimates

- Hadronic jets can be misidentified as τ_{had} candidates.
- Dedicated **anti- τ_{had}** candidates fail the loose τ identification.
- A **fake-factor (FF)** method relates anti- τ_{had} and identified τ_{had} candidates.
- In the $\tau_{\text{had}}\tau_{\text{had}}$ channel, transfer factors correct for differences between 1-tag and 2-tag regions.
- The method is applied separately to the STT, DTT and DBT trigger buckets.

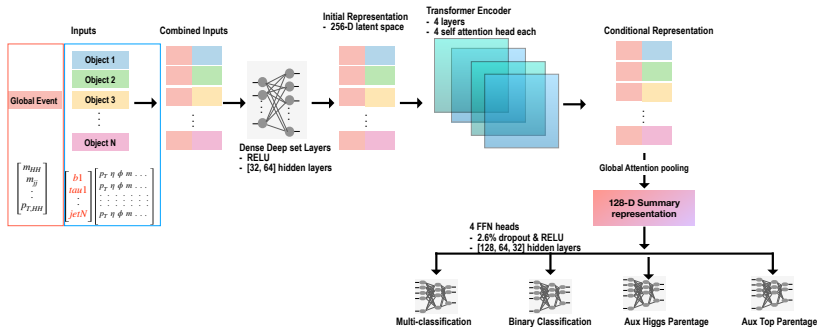


$$\text{STT/DTT} : FF_{1\text{-tag}}^{\text{SS, STT/DTT}} \cdot TF_{1\rightarrow 2\text{-tag}} \cdot \{e_{2\text{-tag, OS-AntiID, STT/DTT}, i}^{\text{Data-MC}}\}$$

$$\text{DBT} : FF_{2\text{-tag}}^{\text{SS, DBT}} \cdot \{e_{2\text{-tag, OS-AntiID, DBT}, i}^{\text{Data-MC}}\}$$

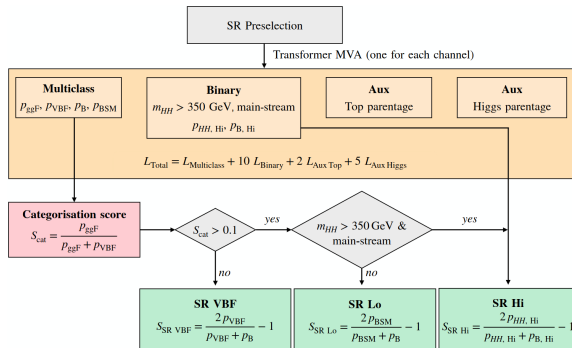
Multivariate Signal Extraction

- Signal and background are separated using **transformer-based deep neural networks**.
- Separate networks are trained for the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels.
- The networks combine **event-level** and **object-level** information.
- Multiple tasks are trained simultaneously:
 - multiclass signal/background classification,
 - dedicated high- m_{HH} ggF discrimination,
 - auxiliary classification tasks.
- The final MVA score provides the main discriminating observable for the statistical analysis.

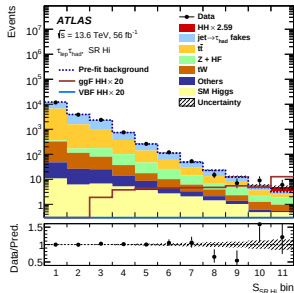
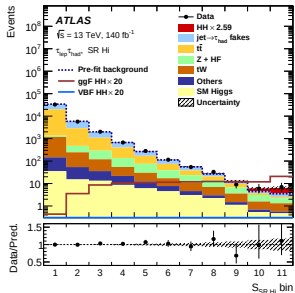
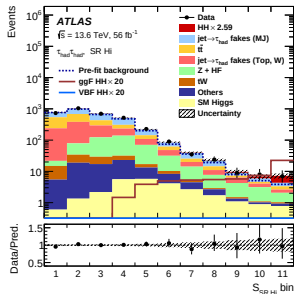
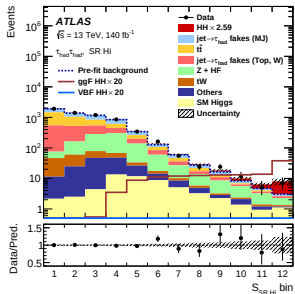


Signal Regions and Production Modes

- The MVA separates the signal according to both **production mechanism** and kinematic regime.
- ggF low- m_{HH}** : sensitive to the interference structure of the ggF amplitude.
- ggF high- m_{HH}** : targets the high-energy region with enhanced sensitivity to deviations from the SM.
- VBF**: probes Higgs-vector-boson interactions and is particularly sensitive to κ_{2V} .



Classifier scores distributions



- A **binned profile-likelihood fit** is performed.
- The MVA score distributions in the signal regions provide the primary discriminating information.
- The $Z+HF$ control region is included through the $m_{\ell\ell}$ distribution.
- The signal strength

$$\mu_{HH} = \frac{\sigma_{HH}}{\sigma_{HH}^{\text{SM}}}$$

scales the expected signal yield.

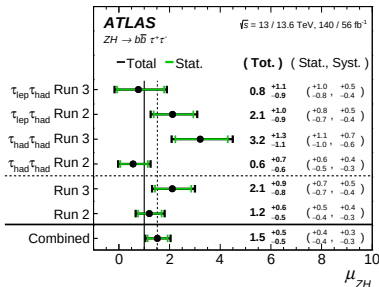
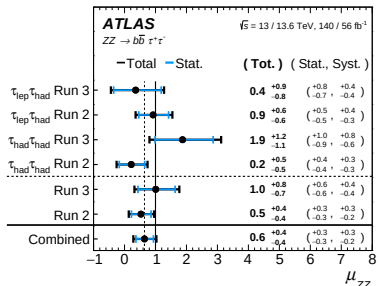
- Systematic uncertainties are incorporated through nuisance parameters and profiled in the fit.

$$\mathcal{L} = \prod_i \text{Pois}(N_i | \mu s_i + b_i) \times \mathcal{L}_{\text{aux}}$$

- The fit includes uncertainties affecting both **normalisation** and **shape**.
- **Experimental uncertainties**
 - luminosity,
 - pile-up modelling,
 - object reconstruction and identification,
 - b -tagging and τ identification.
- **Modelling uncertainties**
 - parton shower and radiation,
 - QCD scales,
 - PDFs and α_s ,
 - generator modelling.
- Data-driven backgrounds introduce additional uncertainties associated with fake-factor measurements.
- The leading uncertainties are propagated to the final MVA distributions and profiled in the fit.

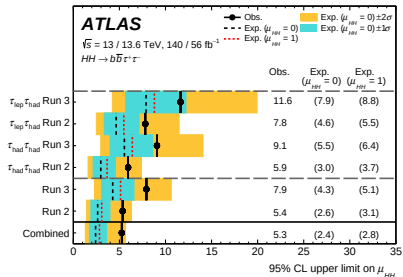
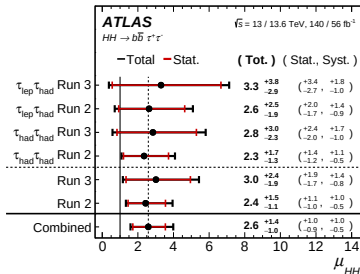
ZZ and ZH results

- Fitted signal strengths, μ , for ZZ (top) and ZH (bottom) processes.
- Results from combined fits to Run 2 and Run 3 data.
- Signal strengths fitted independently for each signal region and run period.
- ZZ observed (expected) significance at 1.8σ (2.7σ).
- ZH observed (expected) significance at 3.5σ (2.4σ).
- First evidence for** $ZH \rightarrow b\bar{b}\tau^+\tau^-$ process.



Sensitivity to HH

- Upper limits are evaluated using conditional $\mu = 0$ fits.
- Sensitivity is evaluated separately for
 - ggF,
 - VBF,
 - combined HH production.
- Combining Run 2 and Run 3 data improves the expected sensitivity.
- Gain comes from increased statistics (15%) and improved analysis strategy (25% – 30%).



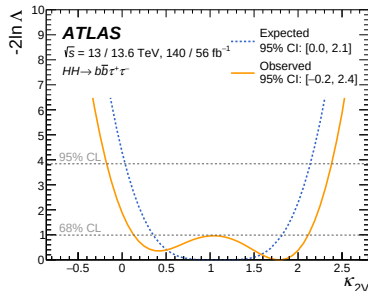
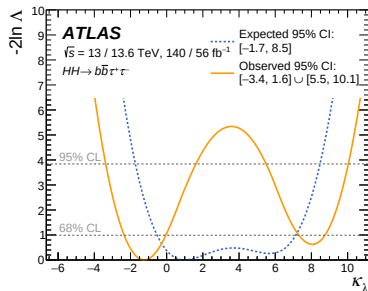
The HH signal strength μ_{HH} is observed to be $2.6^{+1.4}_{-1.0}$, with a significance of 2.6σ (expected 1.2σ) over the background-only hypothesis and 1.65σ from the SM prediction.

Higgs Coupling Constraints

- Used a combined 196 fb⁻¹ of Run 2 and Run 3 data.
- The analysis constrains both the Higgs self-coupling and the $VVHH$ coupling.
- Define

$$\kappa_\lambda = \frac{\lambda}{\lambda_{\text{SM}}}, \quad \kappa_{2V} = \frac{g_{VVHH}}{g_{VVHH}^{\text{SM}}}.$$

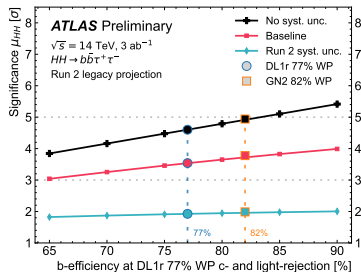
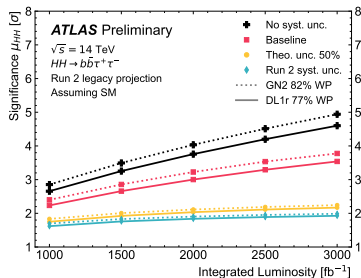
- Likelihood scans are performed separately for κ_λ and κ_{2V} .
- The two parameters affect different regions of the HH phase space.
- $\kappa_\lambda \in [-3.4, 1.6] \cup [5.5, 10.1]$ at 95% CL (assuming $\kappa_{2V} = 1$).
- $\kappa_{2V} \in [-0.2, 2.4]$ at 95% CL (assuming $\kappa_\lambda = 1$)
- Observed κ_λ constraint weaker than expected, primarily due to excess in fitted HH signal strength relative to SM prediction.



- The HL-LHC will provide up to

$$\mathcal{L}_{\text{int}} \simeq 3000 \text{ fb}^{-1}.$$

- The increased statistics are essential for overcoming the small HH production rate.
- Efficiency of b -tagging directly correlates to signal significance $\rightarrow$ maintaining FTAG performance vital for analyses.
- Projections indicate that the $HH \rightarrow b\bar{b}\tau^+\tau^-$ channel can reach a significance above 3σ .
- Projections based on lumi-scaled legacy Run 2 results have been surpassed by this analysis.
- Same projections predict a discovery significance of SM Higgs pair production of 4.26σ when the combination between all HH decay channels is considered.



- $HH \rightarrow b\bar{b}\tau^+\tau^-$ provides sensitivity to Higgs self-interactions through both ggF and VBF production.
- The analysis combines the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ final states.
- GN2 b -tagging and transformer-based multivariate classifiers provide the main handles for signal extraction.
- A profile-likelihood fit combines signal regions and control-region information while profiling systematic uncertainties.
- Run 2 + Run 3 data provide improved constraints on κ_λ and κ_{2V} .
- At the HL-LHC, increased luminosity and improved b -tagging performance offer the prospect of $> 3\sigma$ **sensitivity** in this channel.

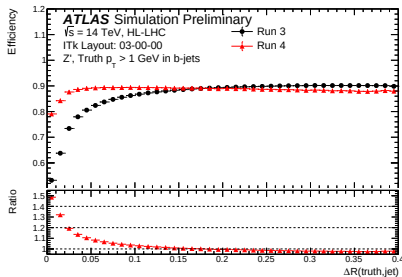
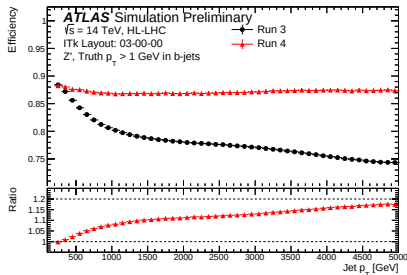
BACKUP

BACKUP: Detector Technologies

- **Tracking**
 - Silicon pixels and strips.
 - Straw-tube tracking.
- **Energy measurement**
 - Liquid-argon EM calorimetry.
 - Scintillator-based hadronic calorimetry.
- **Muon detection**
 - Precision drift-tube chambers.
 - Fast trigger chambers.
- **Magnetic fields**
 - Solenoid for inner tracking.
 - Toroidal magnets for muon momentum measurement.
- **Trigger system:**
 - Select events from ~ 40 MHz bunch-crossing rate.
 - Reduce event rate to $\mathcal{O}(1 \text{ kHz})$ for permanent storage.
- **Level-1 (L1) Trigger**
 - Custom hardware with fixed-latency processing.
 - Uses coarse information from calorimeters and muon trigger chambers.
 - Reduces rate to $\mathcal{O}(100 \text{ kHz})$.
- **High-Level Trigger (HLT)**
 - Software-based event reconstruction running on a computing farm.
 - Uses near-offline-quality detector information for refined event selection.

Selected events are written to permanent storage for offline reconstruction and analysis.

BACKUP: ITk Performance



Track reconstruction efficiency for charged particles with $p_T > 1$ GeV within b -jets in the Z' sample as a function of the jet p_T (left) and the ΔR separation between the particle and the jet (right).

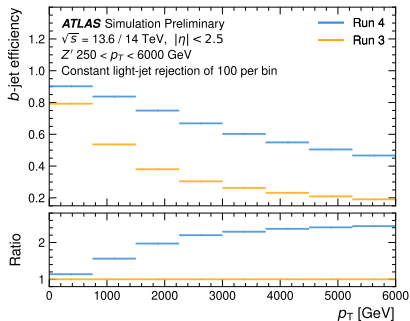
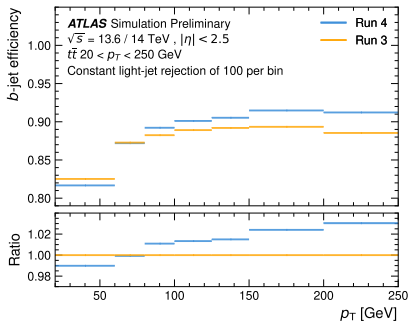
BACKUP: GN2 inputs

Jet variables	Description
p_T	Transverse momentum
η	Signed pseudorapidity
Track variables	Description
d_0	Closest distance from the track to the PV in the transverse plane
$z_0 \sin \theta$	Closest distance from the track to the PV in the longitudinal plane
$d\phi$	Azimuthal angle of the track, relative to the jet ϕ
$d\eta$	Pseudorapidity of the track, relative to the jet η
q/p	Ratio between the track charge and the momentum
$s(d_0)$	Lifetime signed transverse IP significance
$s(z_0 \sin \theta)$	Lifetime signed longitudinal IP significance
$\sigma(\phi)$	Uncertainty on ϕ
$\sigma(\theta)$	Uncertainty on θ
$\sigma(q/p)$	Uncertainty on q/p
nPixHits	Number of pixel hits
nSCTHits	Number of SCT / strip hits
nInnermostPixLayerHits	Number of innermost pixel layer hits
nNextToInnermostPixLayerHits	Number of next to innermost pixel layer hits
nInnermostPixLayerSharedHits	Number of innermost pixel layer shared hits
nInnermostPixLayerSplitHits	Number of innermost pixel layer split hits
nPixSharedHits	Number of pixel shared hits
nPixSplitHits	Number of pixel split hits
nSCTSharedHits	Number of SCT / strip shared hits

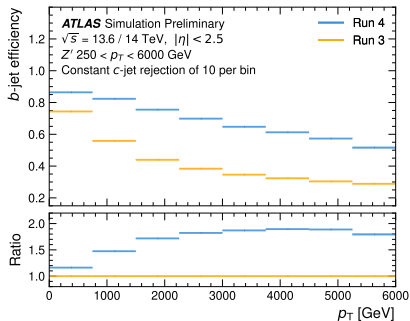
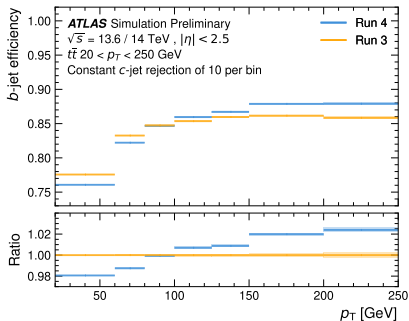
BACKUP: Run 4 track selections

Requirements	Run 3	Run 4		
	$ \eta < 2.5$	$ \eta < 2.0$	$2.0 < \eta < 2.6$	$2.6 < \eta < 4.0$
silicon hits	≥ 8	≥ 9	≥ 8	≥ 7
pixel hits	≥ 1	≥ 1	≥ 1	≥ 1
holes	≤ 2	≤ 2	≤ 2	≤ 2
p_T [MeV]	> 500	> 900	> 500	> 500
$ d_0 $ [mm]	< 3.5	< 2.0	< 2.0	< 3.5
$ z_0 \sin \theta $ [mm]	< 5.0	< 5.0	< 5.0	< 5.0

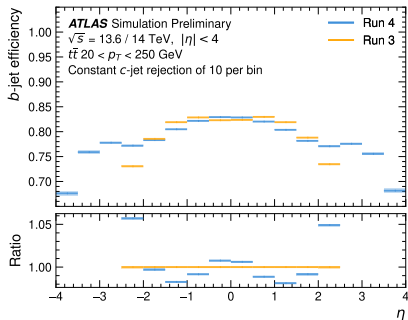
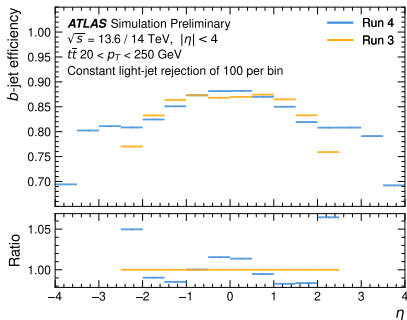
BACKUP: Performance vs p_T (light-jet)



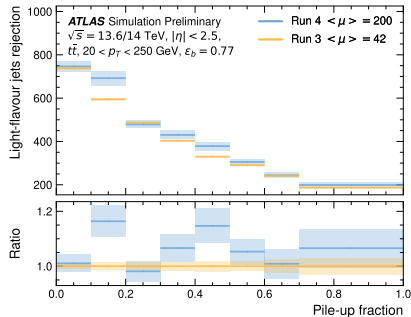
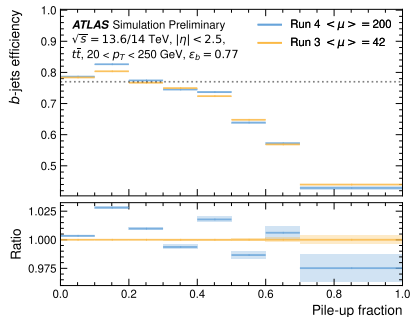
BACKUP: Performance vs p_T (c-jet)



BACKUP: Performance vs $|\eta|$

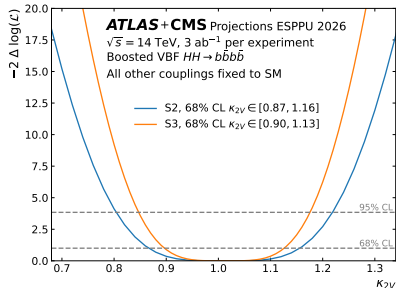
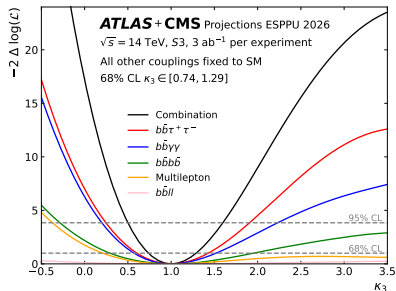


BACKUP: Robustness to PU

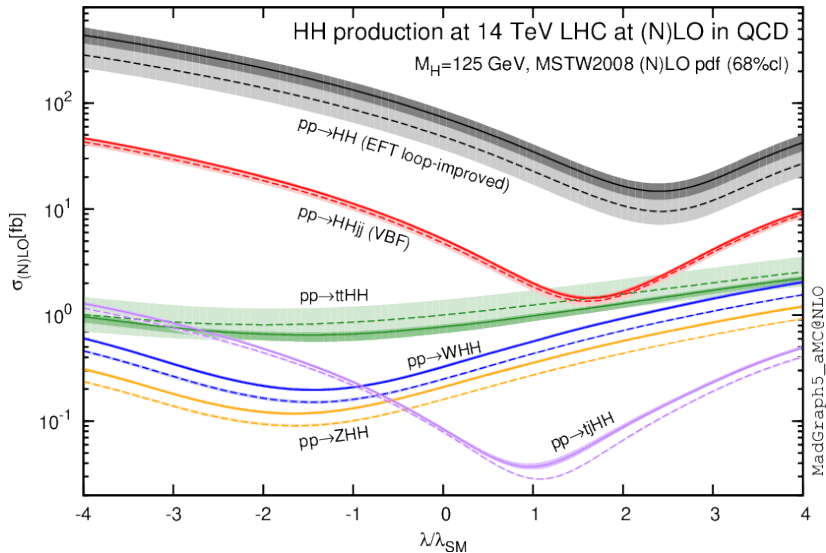


Efficiency of b -tagging (left) and light-jet rejection (right) as functions of the jet PU fraction.

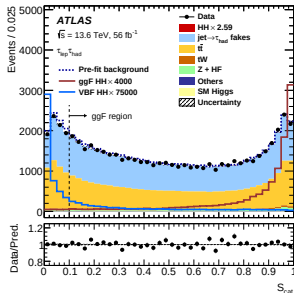
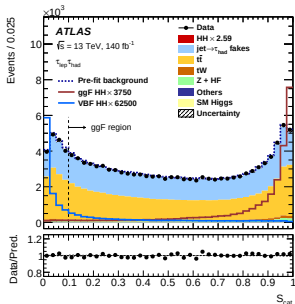
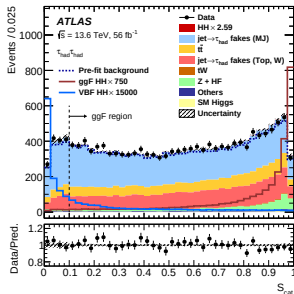
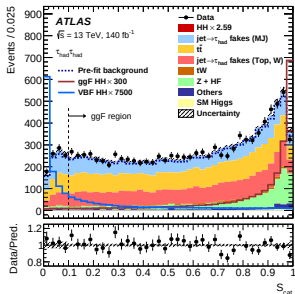
- Integrated luminosity:
 $\mathcal{L}_{\text{int}} = 3 \text{ ab}^{-1}$ per experiment
- Centre-of-mass energy: $\sqrt{s} = 14 \text{ TeV}$
- Expected HH observation: $> 7\sigma$
- Trilinear Higgs coupling:
 $\kappa_\lambda = 1^{+0.29}_{-0.26}$ (68% CL)
- Relative precision on κ_λ : $+29\%$
 -26%
- Longitudinal vector-boson scattering:
 $\delta\kappa_{2V} \simeq 13\%$



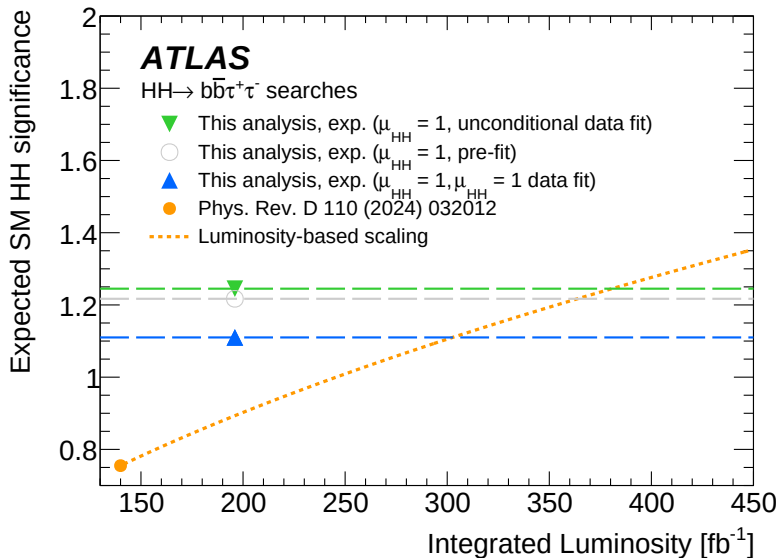
BACKUP: Di-Higgs cross section



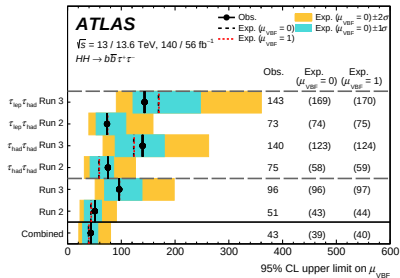
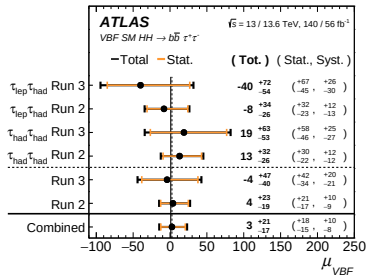
BACKUP: Classifier scores distributions



BACKUP: Improvements over previous round



BACKUP: VBF Results



Measured signal strength μ_{VBF} and associated 95% CL upper limits.

Combined $\mu_{VBF} = 3^{+21}_{-17}$. Observed upper limit at 43, expected 39 for $\mu_{VBF} = 0$ and 40 for $\mu_{VBF} = 1$.

CMS $b\bar{b}\tau^+\tau^-$ analysis:

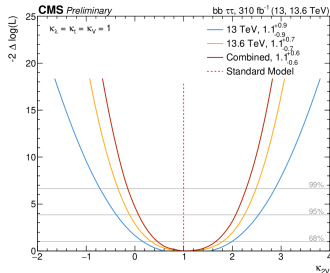
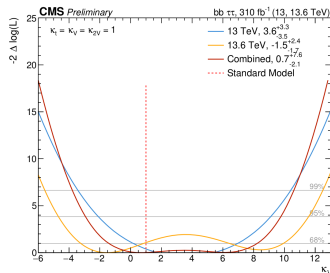
- Combined $\sqrt{s} = 13.6$ TeV (172 fb^{-1}),
 $\sqrt{s} = 13$ TeV (138 fb^{-1}).
- Observed (expected) 95% CL upper limits on μ_{HH} of 4.0 (3.0).
- Best fit $\mu_{HH} = 0.9^{+1.6}_{-1.4}$.
- Observed (expected) significance of 0.7σ (0.8σ) over background-only.
- Observed (expected) 95% CL limits on:

κ_λ :

$$-2.5 < \kappa_\lambda < 9.4 \quad (-1.5 < \kappa_\lambda < 8.4)$$

κ_{2V} :

$$0.02 < \kappa_{2V} < 2.1 \quad (-0.1 < \kappa_{2V} < 2.2)$$



- ATLAS: reanalysis of 140 fb^{-1} (Run 2) + 56 fb^{-1} (2022-2023 Run 3) data.
- CMS: 172 fb^{-1} (2022-2024 Run 3) data + comb. with 138 fb^{-1} Run 2 result.

ATLAS

- $\mu_{HH} = 2.6^{+1.4}_{-1.0}$
- Obs. (exp.) significance: 2.6σ (1.2σ)
- Obs. (exp.) 95% CL intervals:
 - $\kappa_{\lambda} \in [-3.4, 1.6] \cup [5.5, 10.1]$ ($[-1.7, 8.5]$)
 - $\kappa_{2V} \in [-0.2, 2.4]$ ($[0.0, 2.1]$)

CMS

- $\mu_{HH} = 0.9^{+1.6}_{-1.4}$
- Obs. (exp.) significance: 0.7σ (0.8σ)
- Obs. (exp.) 95% CL intervals:
 - $\kappa_{\lambda} \in [-2.5, 9.4]$ ($[-1.5, 8.4]$)
 - $\kappa_{2V} \in [0.02, 2.1]$ ($[-0.1, 2.5]$)

Where does this difference come from?

Hadronic τ :

ATLAS

Loose RNN ID: 85% efficiency on 1-prong τ_{had} and 75% on 3-prong τ_{had} .

CMS

DeepTauHad ID: Medium working point with 70% efficiency on true τ_{had} .

b-tagging:

ATLAS

GN2 at 85% b-efficiency.

CMS

UParT with 10% light-jet mis-tagging: 95% b-efficiency.

BACKUP: Signal extraction in ATLAS and CMS

ATLAS

Event representation

- Transformer-based event classifier
- Inputs encode reconstructed objects + event kinematics
- Dedicated GN2 b -tagging
- MMC reconstruction of $\tau\tau$

Multi-task learning

- Multiclass: ggF HH / VBF HH / background / BSM-like
- Binary high- m_{HH} HH/background classifier
- Auxiliary Higgs- and top-parentage tasks

Learned categorisation: $S_{\text{cat}} = \frac{p_{ggF}}{p_{ggF} + p_{\text{VBF}}}$

- $S_{\text{cat}} \rightarrow ggF$ -like vs. VBF-like
- ggF -like: split in m_{HH}
- **SR Hi, SR Lo, SR VBF**
- Final discriminant: classifier score in each SR

CMS

Event representation

- Particle-level inputs + high-level observables
- Lorentz Boost Network features
- Dedicated $\tau\tau$ mass regression
- Dedicated $H \rightarrow bb$ / boosted-object tagging

Dedicated DNN classifiers

- Separate classifiers $ggHH$ and $qqHH$.
- Optimised directly for signal/background separation
- Five-fold cross-validation + multiple trainings

Physics categorisation

- **VBF** topology
- **Boosted** topology
- **Resolved 2b**
- **Resolved 1b1j**
- Split $\tau_e\tau_h, \tau_\mu\tau_h, \tau_h\tau_h$

BACKUP: ATLAS $b\bar{b}\gamma\gamma$ results

ATLAS $HH \rightarrow b\bar{b}\gamma\gamma$ analysis:

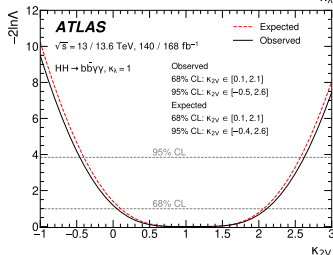
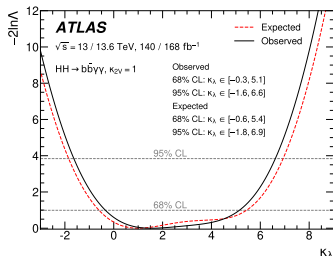
- Combined $\sqrt{s} = 13$ TeV (140 fb $^{-1}$), $\sqrt{s} = 13.6$ TeV (168 fb $^{-1}$).
- Observed (expected) 95% CL upper limits on μ_{HH} of 3.7 (2.6).
- Best fit $\mu_{HH} = 0.9^{+1.4}_{-1.1}$.
- Observed (expected) significance of 0.78σ (1.01σ) over background-only.
- Observed (expected) 95% CL limits on:

κ_λ :

$$-1.6 < \kappa_\lambda < 6.6 \quad (-1.8 < \kappa_\lambda < 6.9)$$

κ_{2V} :

$$-0.5 < \kappa_{2V} < 2.6 \quad (-0.4 < \kappa_{2V} < 2.6)$$



ATLAS $HH \rightarrow b\bar{b}b\bar{b}$ analysis:

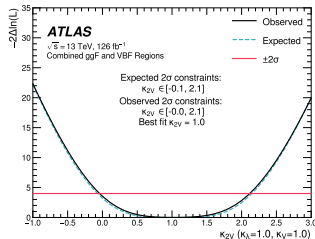
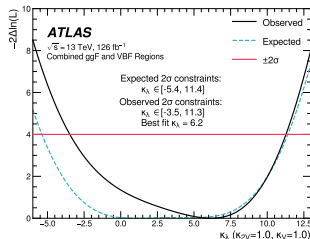
- $\sqrt{s} = 13$ TeV (126 fb $^{-1}$).
- Observed (expected) 95% CL upper limits on μ_{HH} of 5.4 (8.1).
- Observed (expected) 95% CL limits on:

κ_λ :

$$-3.5 < \kappa_\lambda < 11.3 \quad (-5.4 < \kappa_\lambda < 11.4)$$

κ_{2V} :

$$0.0 < \kappa_{2V} < 2.1 \quad (-0.1 < \kappa_{2V} < 2.1)$$



BACKUP: CMS Classifier

