Search of Higgs Boson Pair Production in the $bb\tau\tau$ Final State using b-jet triggers with the ATLAS Detector at the LHC

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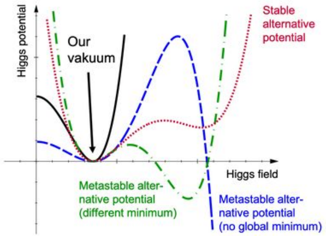
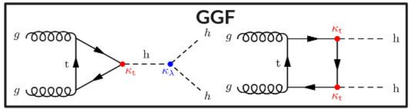
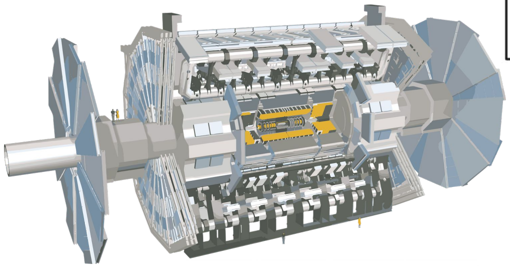
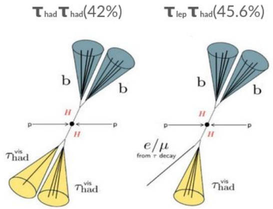
Outline

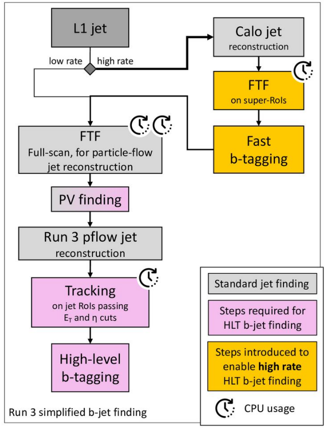
- **Higgs Self-coupling: A Portal to New Physics**
- **The ATLAS Experiment**
- **HH Production at the LHC**
- **HH → bb$\tau\tau$ Analysis**
  - b-tagging and trigger strategy
  - Reconstruction and event categorisation
- **b-jet trigger in bb$\tau\tau$ Analysis**
  - Trigger calibration and b-tagging Scale Factors
  - Impact of combined SFs
- **Conclusions and Outlook**











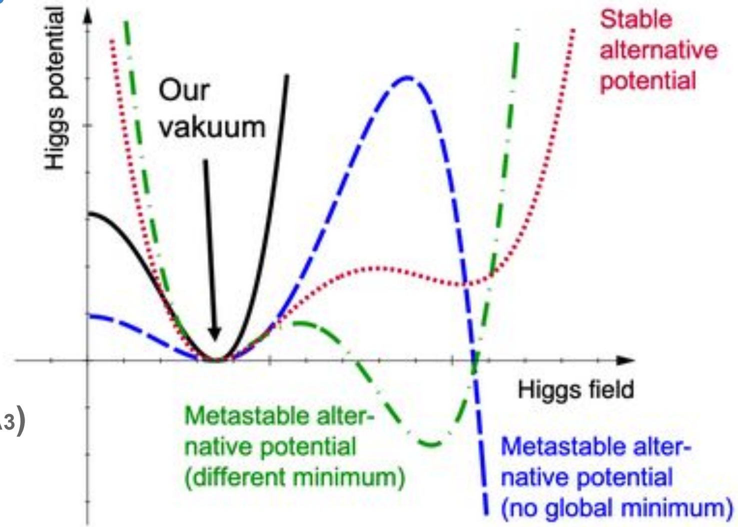
Higgs Self-coupling: A Portal to New Physics

Higgs potential shape

- **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**

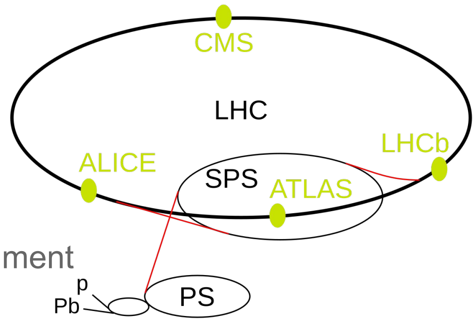
- **Higgs Potential Shape and Universe stability**
  - Crucial to understanding the nature of the Higgs field
  - Accessible with the measurements of the Higgs self-coupling (**λ_3**)

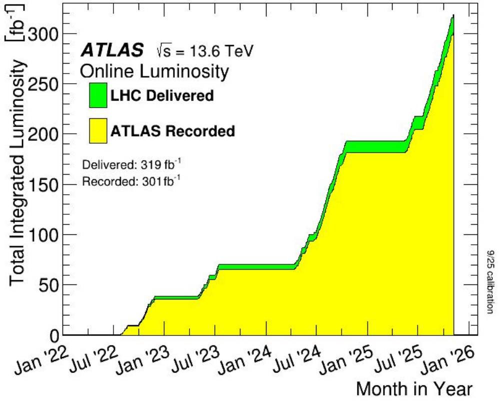
$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \frac{1}{4}\lambda_4 v H^4$$



ATLAS Detector: A Necessary Framework for HH Studies

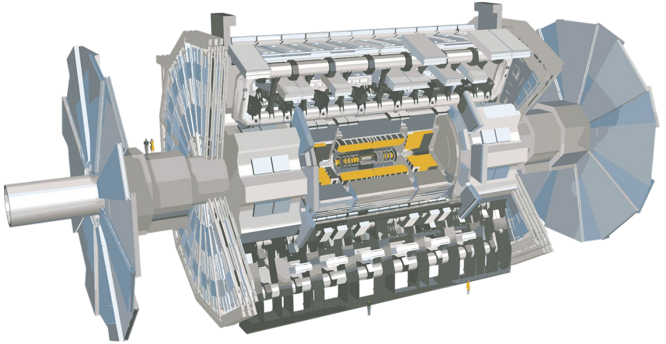
- **The Large Hadron collider (LHC):**
  - **In Run 3** → **pp** collisions at **13.6 TeV**
  - **4 interaction points**, each hosting a experiment
    - ATLAS, CMS, LHCb, ALICE





- **ATLAS: A General-Purpose Experiment**
  - Optimized for Higgs, top quark, beyond the SM searches
    - **Inner Tracker** (particles ID, vertex impact parameter)
    - **Calorimeter** (energy measurement)
    - **Muon Spectrometer**
    - **Two-level trigger system:**
      - **L1**: Hardware-based → fast calorimeter and muon information
      - **High Level Trigger (HLT)**: software-based → refined reconstruction

ATLAS Detector

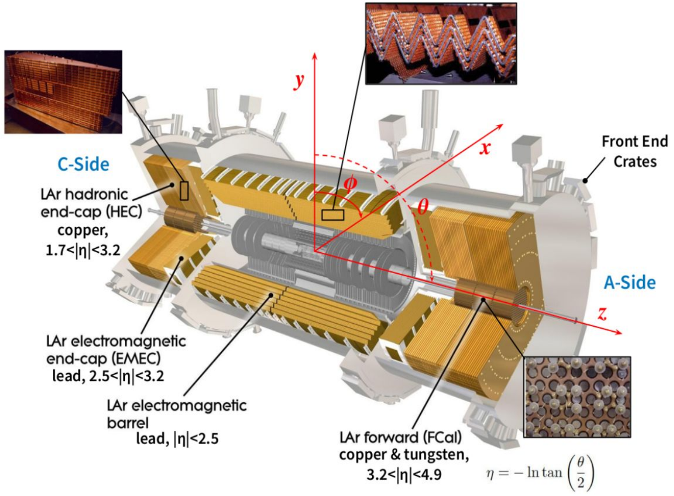


ATLAS Detector: Liquid Argon calorimeter

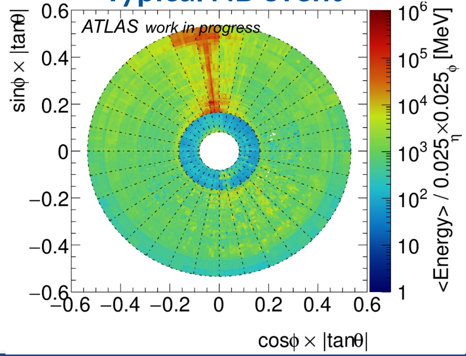
- **Liquid Argon calorimeter (LAr):**
  - **Sampling calorimeter** for e/γ, jets energy measurement
  - **Key component** of the **L1 trigger**
    - Reduces event rate **40 MHz → 100 kHz**
    - Maintains efficiency for **key physics signals**

- **Affected by Coherent Noise since Run 1:**
  - **Fake physics signals** → Increases event rates
    - Noise Bursts (NB): sudden correlated signals in time and space

- **First-year work: LAr Noise Burst Mitigation Measures**



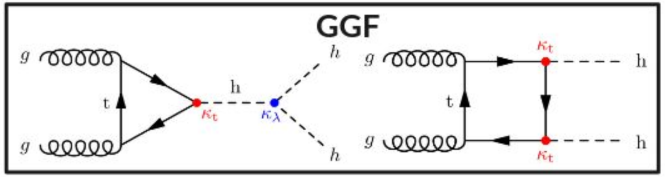
Typical NB event



HH Production at the LHC

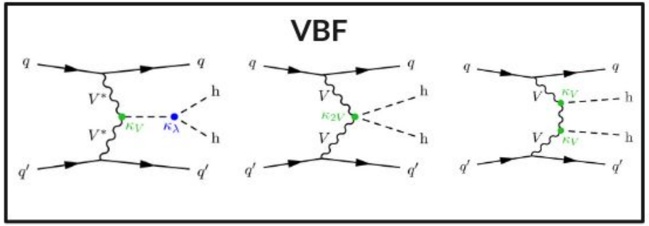
- **At the LHC, HH production mainly occurs through ggf:**
  - Two main contributions:
    - **Triangle diagram**: proportional to the trilinear Higgs self-coupling (λhhh)
    - **Top box diagram**: interferes destructively with the triangle
  - Sensitive to κ_λ and κ_t, defined at LO
    - To parameterise cross sections in terms of coupling modifiers

$$\kappa_\lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}}$$



σ(13.6 TeV)~34.1 fb

- **Additionally, VBF contributes through three distinct diagrams**
  - Involving **electroweak boson exchange**
  - Sensitive to κ_{2V}

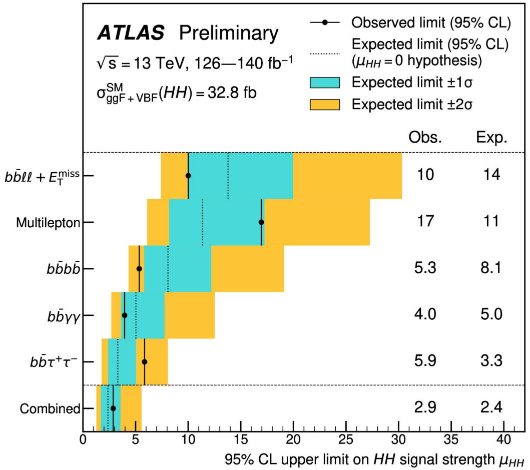


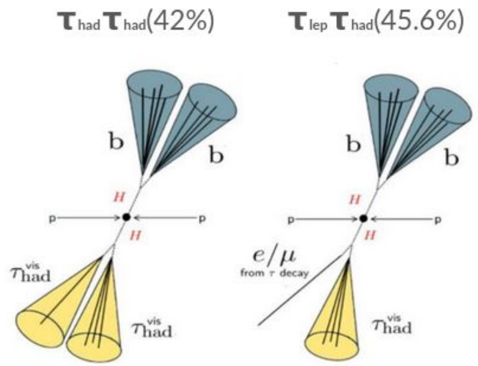
σ(13.6 TeV)~1.87 fb

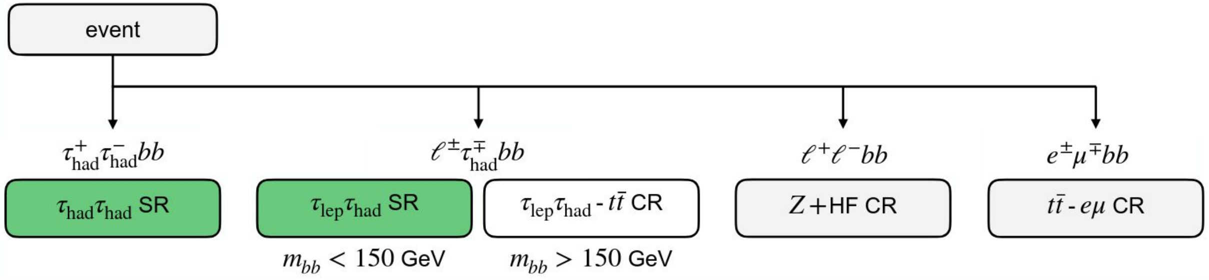
HH → bb$\tau\tau$ Analysis

- **The second part of my thesis focuses on the HH studies in the bb$\tau\tau$ final state, one of the key channels to measure the λ_{hhh}**
  - Reasonably large BR (7.3%)
  - Manageable backgrounds

- **Signal and Control Regions are defined to maximise sensitivity:**
  - SRs based on two final states
    - **τhadτhad** (***HadHad)*** and **τlepτhad** (***LepHad)***
  - Several CRs to constraint and validate instrumental and physics backgrounds





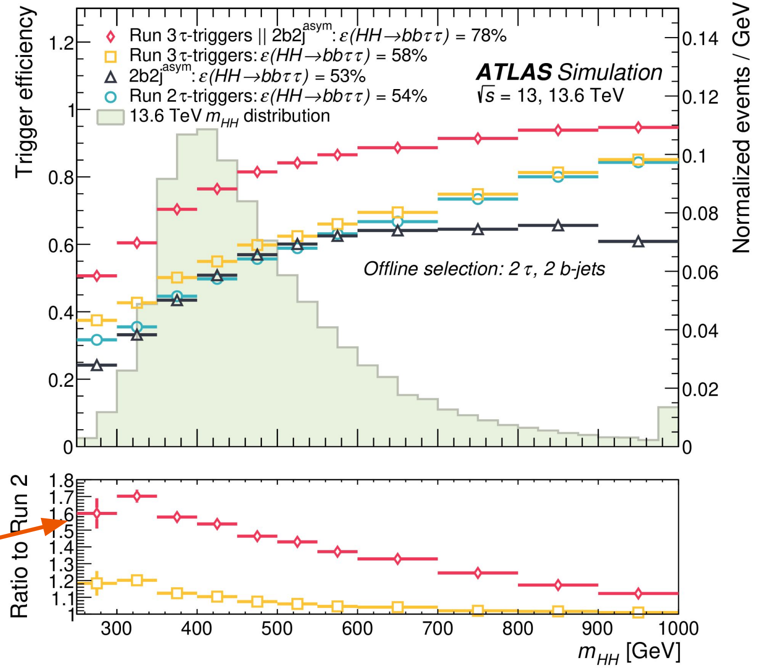


HH → bbττ Analysis strategy

- **Reconstruction of bb and $\tau\tau$ systems:**
  - Likelihood mass reconstruction → better accuracy
- **Event categorisation**
  - Categories built from m_{HH} (low/high) and production mode (ggF / VBF)
  - Transformer outputs used as final SR discriminants
- **NEW for Run 3 : b-jet triggers**
  - Hadronic triggers improve bb$\tau\tau$ acceptance by >40%
  - Dataset: Run 2 (140 fb^{-1}) + partial Run 3 (56 fb^{-1})

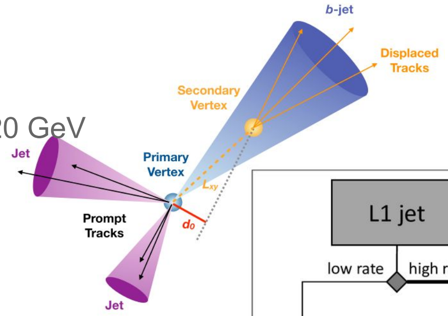
Run 3 HH b-jet triggers

Type	L1 threshold E_T [GeV]	HLT preselection p_T [GeV]	HLT preselection b-tag	HLT selection p_T [GeV]	HLT selection b-tag
3b1j^{asym}	j: 1×45, $\|\eta\|<2.1$ 2×15, $\|\eta\|<2.5$	4×20	$2\times b$, $\varepsilon=85\%$	1×80 1×55 1×28 1×20	$3\times b$, $\varepsilon=82\%$
2b2j^{asym}(*)	j: 1×45, $\|\eta\|<2.1$ 2×15, $\|\eta\|<2.5$	4×20	$2\times b$, $\varepsilon=85\%$	1×80 1×55 1×28 1×20	$2\times b$, $\varepsilon=77\%$
μ+2b2j^{asym}(*)	j: 1×20 1×15 μ: 1×8 (p_T)	4×20	$2\times b$, $\varepsilon=85\%$	1×80 1×55 1×28 1×20	$2\times b$, $\varepsilon=77\%$

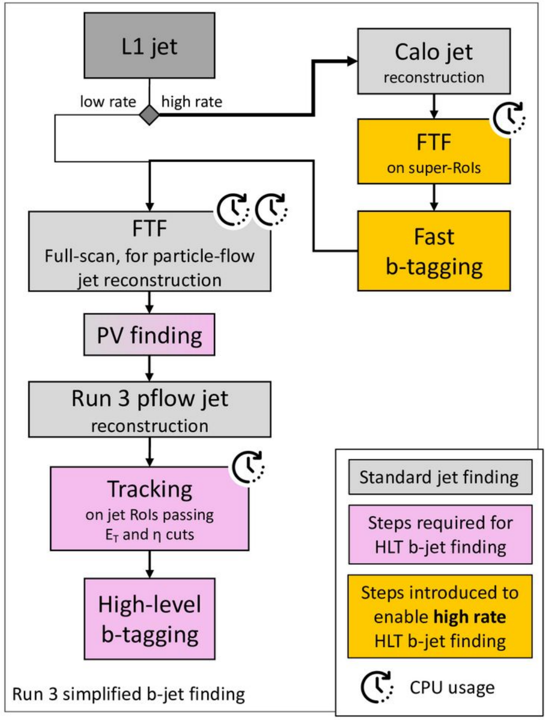


Run 3 b-jet Tagging at Trigger Level

- **B-hadron identification:**
  - Long lifetime: ~2 mm decay length in the inner tracker for pt > 20 GeV
  - Large impact parameter of displaced tracks
    - Transverse (d0): ~7–10 µm for tracks (pt > 20 GeV)
  - Displaced secondary vertex reconstructed from multiple tracks



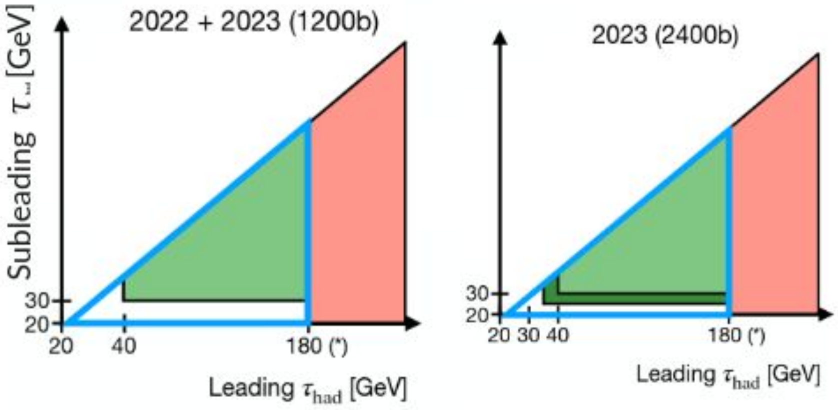
- **b-tagging at ATLAS is performed in two steps**
  - Fast b-tagging pre-selection
    - Fast Track Finder (FTF) ⟶ No further reconstruction
    - Loose b-tagging used for rate reduction
  - Precision b-tagging
    - FTF Full scan for high tracking efficiency
    - Particle flow for better resolution at low pt
    - High level b-tagging based on neural networks
      - **DL1d (2022)** and **GN1 (2023)**



HH → bb$\tau\tau$: Trigger aware SR definition

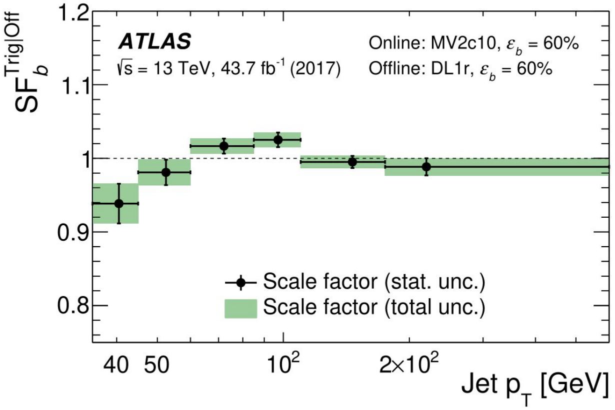
- ***LepHad* → Based on single-lepton triggers (SLT):**
  - Single-e and single-μ triggers
- ***HadHad* → Orthogonal trigger buckets: set of same type triggers**
  - single-τ triggers (**STT**)
  - di-τ triggers main and delayed streams (**DTT**)
  - di-b triggers delayed stream (**DBT**) → **NEW in Run 3**

τ_{had} selection within Buckets

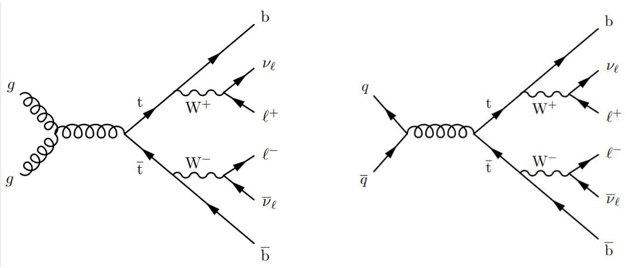


b-jet Triggers: Calibration

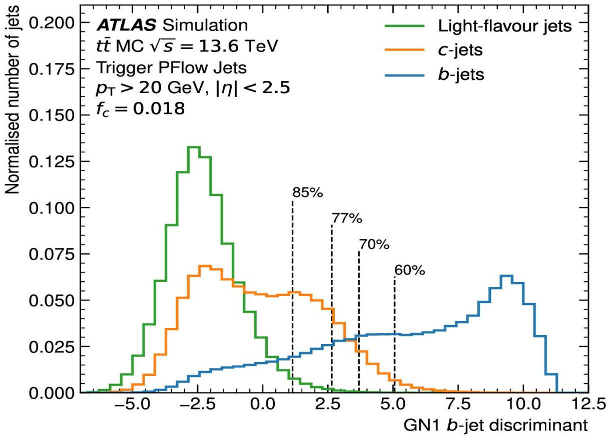
- **b-tagging Scale Factor (SF) corrects the MC jet tagging efficiency to reproduce that of the data**
  - Calculated as: $\mathrm{SF}^{\mathrm{jet}} = \frac{p^{\mathrm{jet}}_{\mathrm{data}}}{p^{\mathrm{jet}}_{\mathrm{MC}}}$
  - Depends on jet flavor, pT, η and b-tag score
  - Stored in Calibration Data Interface (CDI)



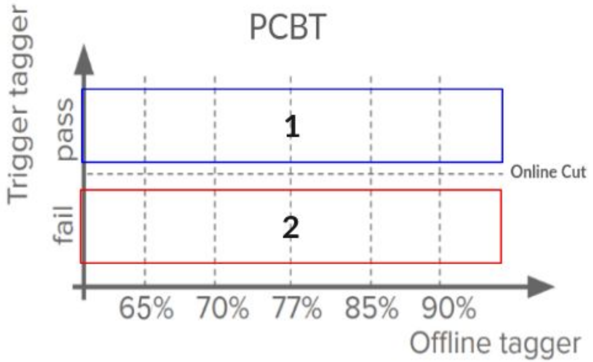
- **Calibration are derived in ttbar events**
  - **Pure b-jets samples** (BR(t→Wb) ≈ 100%)
    - Offline selection: e or μ with opposite-sign charge
      - Suppress W/Z background
  - Taggers categorized by working points (65%, 70%, 77%, 85%, 90%, 100%)
  - Maximum-likelihood fit extracts online b-tagging efficiency vs jet pT



b-jet Triggers + Offline b-tagging Scale Factor



- **b-jet triggers are always used in association with offline b-tagging:**
  - Online tagging fixed working point → cut on b-tag weight
  - Offline tagging uses **Pseudo-Continuous B-Tagging** (PCBT)
    - Whole b-tagging spectrum is used → no cut.
  - Adds complexity to the calibration strategy
    - Combined SF estimation in efficiency bins



- **Efficiency and inefficiency SFs according to region:**
  - Region 1 → Trig Eff: Region 2 → Trig InEff:

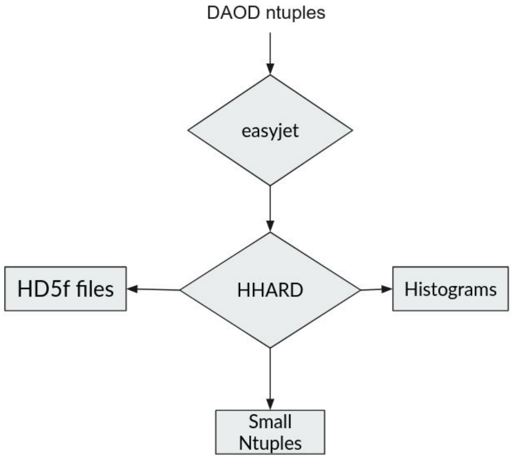
$$SF = \frac{\mathcal{P}(\text{off}|\text{trig})_{\text{data}}\,\mathcal{P}(\text{trig})_{\text{data}}}{\mathcal{P}(\text{off}|\text{trig})_{\text{MC}}\,\mathcal{P}(\text{trig})_{\text{MC}}}$$

$$SF = \frac{\mathcal{P}(\text{off})_{\text{data}} - \mathcal{P}(\text{off}|\text{trig})_{\text{data}}\,\mathcal{P}(\text{trig})_{\text{data}}}{\mathcal{P}(\text{off})_{\text{MC}} - \mathcal{P}(\text{off}|\text{trig})_{\text{MC}}\,\mathcal{P}(\text{trig})_{\text{MC}}}$$

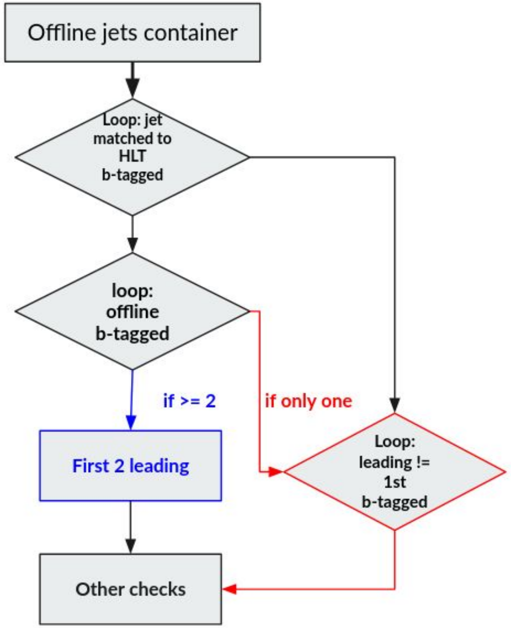
FTag Tool: A Calibration Interface

- **The Flavour Tagging tool (FTag) performs the matching and computes the combined SFs within the Athena software**
  - Selects offline jet matched to the HLT b-tagged and estimate the SF
  - Used by analysis software (Easyjet + HHARD) for DBT analysis bucket

Analysis workflow



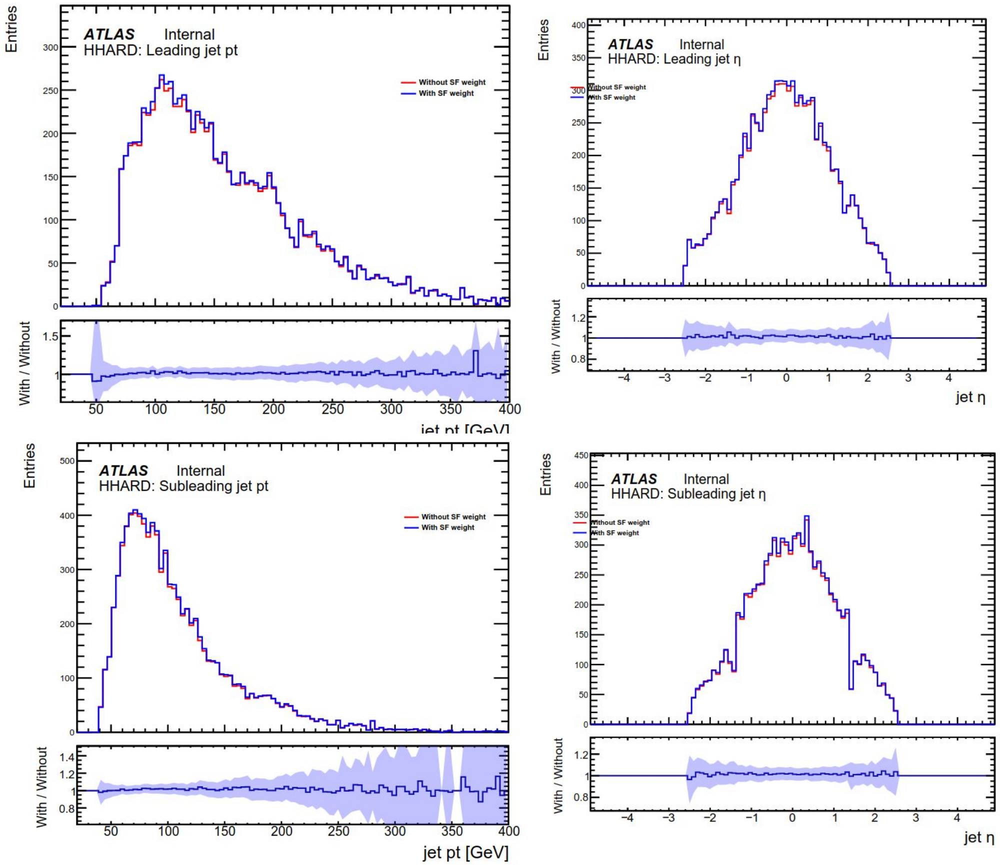
DBT matching stage



Impact of b-jet Trigger SFs

- **The final event selection is performed in HHARD, applies all MC corrections**
  - Calibration of b-jet, taus, pile-up,...

- **Comparison with and without b-jet trigger SFs shows:**
  - No significant distortion in the leading/subleading jet pt and η distributions
    - compatible with precision of the SF measurement



Conclusion

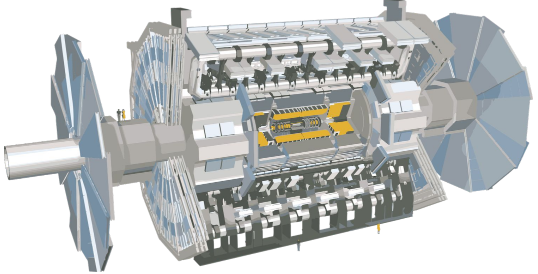
- **HH $\rightarrow$ bb$\tau\tau$ as a key channel for measurement of the Higgs self coupling**
  - Provides an optimal balance between branching ratio and background control
  - Thanks to the outstanding performance ATLAS could set UL at 95% CL of 2.9 SM
- **Current work focus on the Run 3 b-jet triggers in the HH $\rightarrow$ bb$\tau\tau$ analysis**
  - Integration of HLT b-tagging in hadhad categories leads to an acceptance gain of over 40%
  - Full calibration chain implemented, including combined Scale Factors via the FTag framework
- **Current status & outlook**
  - Validation of b-jet trigger SFs and final estimation of impact on sensitivity in data is ongoing
  - Updated HH bb$\tau\tau$ publication will include for thee first time b-jet triggers categories

Backup

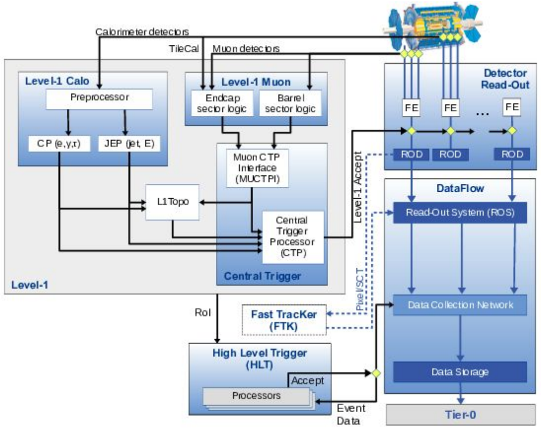
ATLAS Detector: A Necessary Framework for HH Studies

- ## The Large Hadron collider (LHC):
  - **pp** collisions at **13.6 TeV (Run 3)**
  - **4 interaction points**, each hosting a experiment
    - ATLAS, CMS, LHCb, ALICE

ATLAS Detector

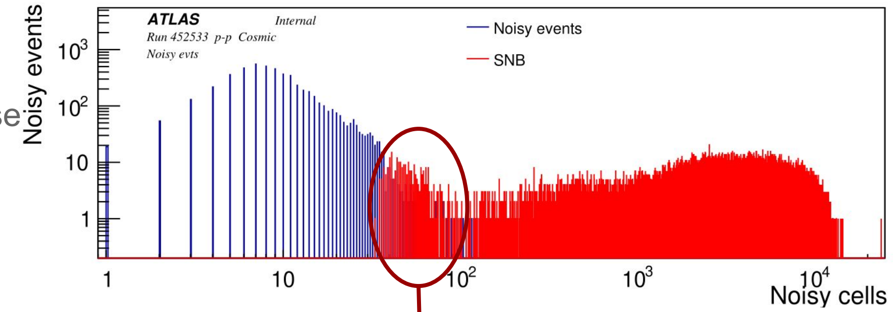


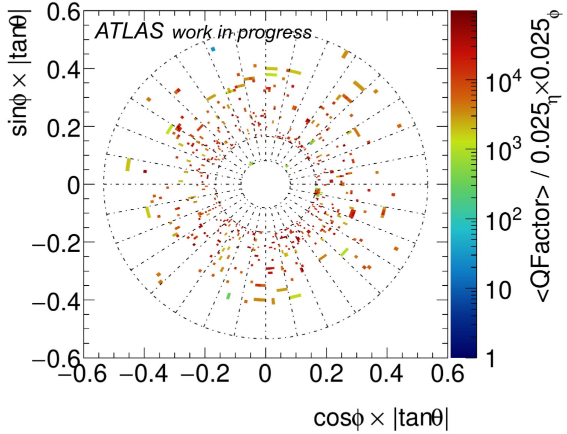
- ## ATLAS: A General-Purpose Experiment
  - Wide range of physics process → Including **HH production**
  - Consists of:
    - **Trackers** (particles ID, vertex impact parameter)
    - **Calorimeters** (energy measurement)
  - Efficient event selection relies on the two-level trigger system:
    - **L1** Trigger: Hardware-based → fast calorimeter and muon information
    - **High Level Trigger (HLT)**: software-based → refined reconstruction



Liquid Argon Calorimeter: Noise Burst Identification

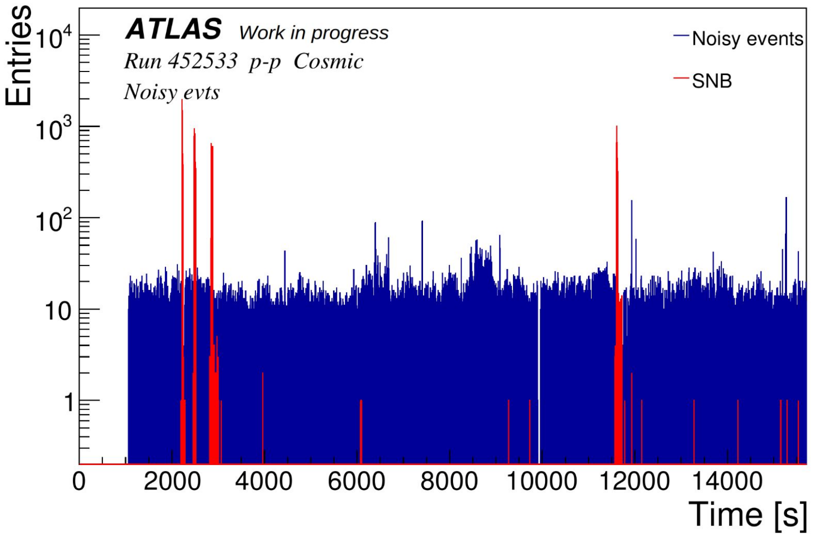
- **NB usual identification and characterization:**
  - Noisy event: ≥1 cell with E > 3σ above the electronic noise
  - Identified by event-by-event criteria, using:
    - Noisy cells Q thresholds, Energy and affected FEBs
  - Flags for Noise Bursts:
    - Standard Flag (SNB): ≥5 FEBs with >30 channels having Q > 4000
    - Saturated Flag: ≥20 channels with |E| > 1 GeV and Q saturated (65535)

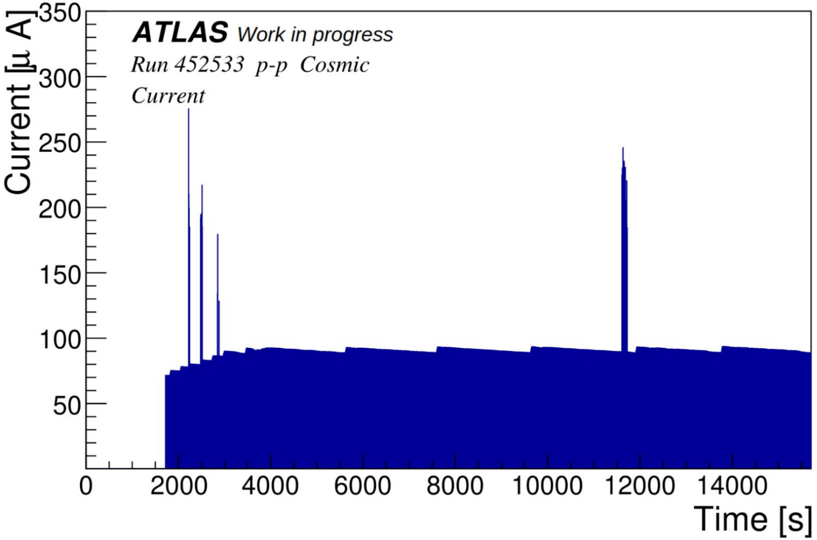




- **Inconsistencies in the SNB Flag:**
  - Events with few noisy cells can still trigger SNB (lack of spatial coherence)
  - Two multiplicity regimes
    - Electronic noise vs true Noise Bursts
    - Overlap between the two → ambiguity in NB classification

Liquid Argon Calorimeter: Noise Burst vs HV Current Spike

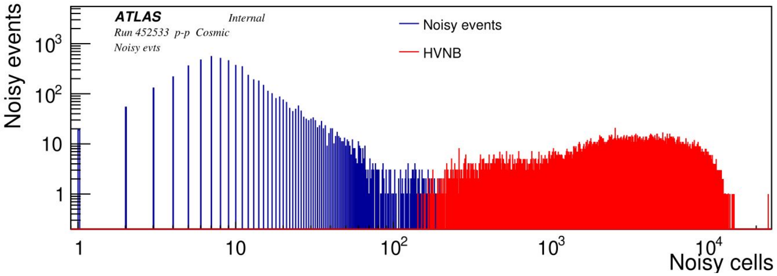




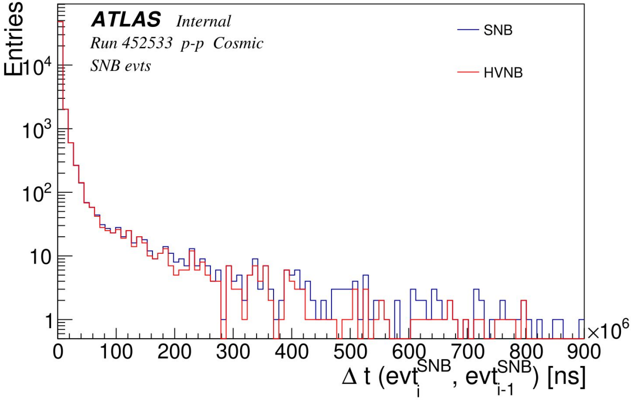
- **Correlation observed between Noise Bursts (NB) and HV current spikes**

Liquid Argon Calorimeter: HV Noise Burst

- **HV-based flag (HVNB):**
  - Groups HV lines (>10 cells)
  - Fraction of noisy cells (Mr) with Q > 4000 within group
  - Event flagged as HVNB if:
    - ≥3 HV groups with Mr>24% in one partition

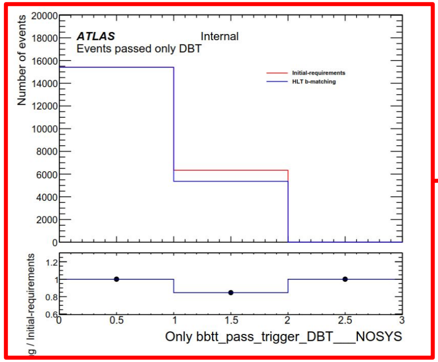


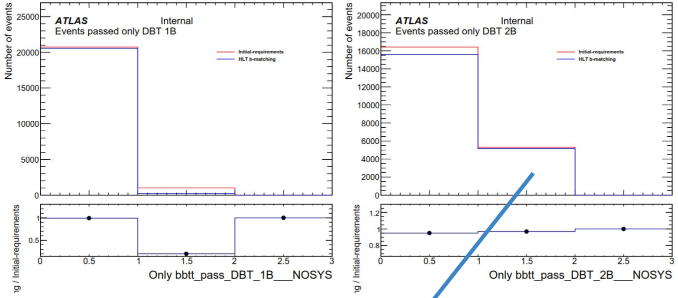
- **NB candidate and Window Veto:**
  - ≥2 events flagged SNB or HVNB with separation $\Delta t < \delta t_{(c)}/2$ are clustered into one NB event
  - Candidate extended by δt_veto = δtc/2 to catch nearby bursts
  - Events inside veto windows are rejected



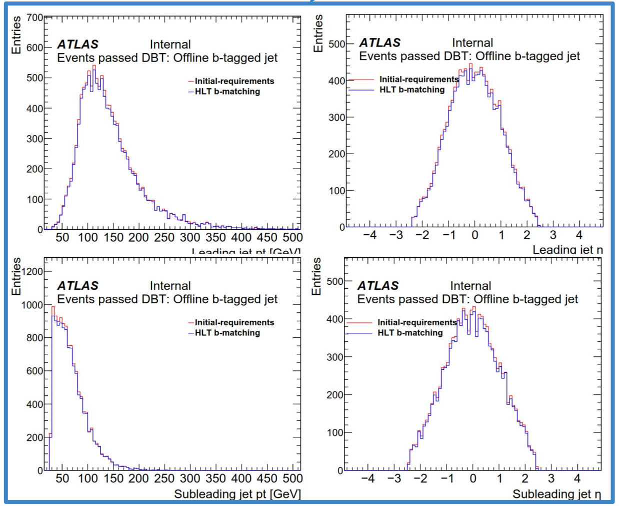
- **HV-based method:**
  - Higher veto efficiency
  - Fewer false positives → removes events far from true NB peaks

easyjet: DBT Bucket Selection





- **With the updated requirements, a reduction of ~5% of events is observed compared to the initial selection:**
  - Events with 1 offline b-tagging pass_DBT_1B ~4.1 %
  - Events with 2 offline b-tagging pass_DBT_2B ~0.9 %



- **Trigger matching has no impact on events with two offline b-tags that satisfy the 2bjj trigger**