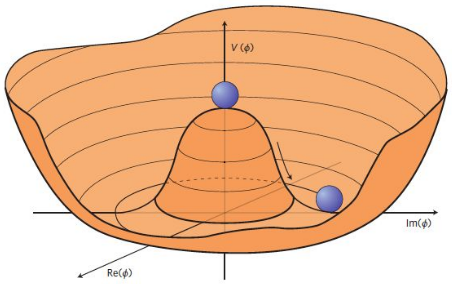
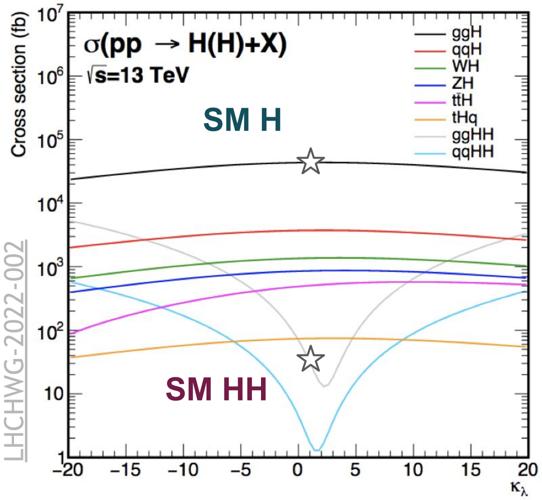
$X \to SH \to b\bar{b}b\bar{b}$ search in the boosted regime in ATLAS

Marta Lanzac Berrocal (IFIC, CSIC-UV)

XL Reunión Bienal de la Real Sociedad Española de Física, Sevilla, 20-24 Julio 2026

Higgs boson potential



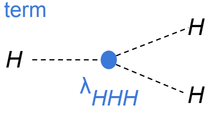


- The Higgs boson potential remains partially unconstrained:

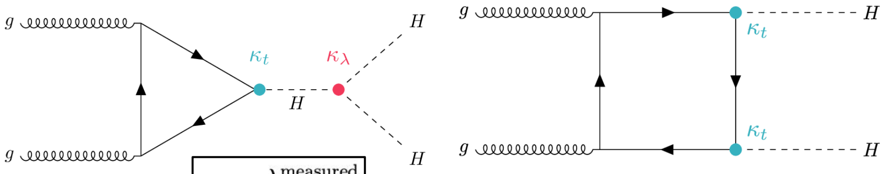
Higgs boson mass term — Trilinear self interaction term

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \longrightarrow V_H = \frac{1}{2}m_H H^2 + \lambda v H^3 + \ldots$$

Electroweak symmetry breaking



- Measuring **Higgs boson pair production (HH)** is the only direct probe of the Higgs boson self-coupling (λ_{HHH})



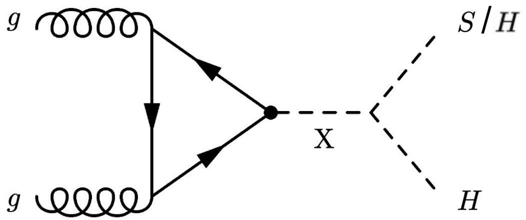
$$\kappa_\lambda = \frac{\lambda_{HHH}^{\text{measured}}}{\lambda_{HHH}^{\text{SM}}}$$

- In the Standard Model, the HH production is rare (σ_{SM} ≈ 33 fb at √s = 13 TeV)
- **No observation yet** - expected to be observed at the HL-LHC

Beyond the Standard Model Theories in Higgs Physics

- **Non-resonant production (pp → HH)** enhancements can arise from:
  - **Loop corrections** involving new particles
  - **Anomalous coupling** between the Higgs boson and SM particles
  - **Modified Higgs potential,** affecting the trilinear self-coupling (λ_{HHH})

- **Resonant production (pp → X → HH / SH)** motivated by different BSM theories:
  - **TRSM** (Two Real Singlet Model)**:**
    → adds two CP even neutral bosons alongside the SM Higgs
  - **2HDM** (Two Higgs-Doublet Model):
    → two new Higgs doublets; e.g. CP-conserving: 1 lighter and 1 heavier (wrt. to the SM Higgs boson) CP-even scalar
  - **NMSSM** (Next-to-Minimal Supersymmetric Standard Model): 2HDM+S model
    → multiple charged and neutral scalars
    → less constrained than the pMSSM



H: SM Higgs (m = 125 GeV)
S: additional scalar

Signal topologies and phase space in $X \to SH \to 4b$

Resonant HH searches in the 4b final state have similar characteristics as in the non-resonant case:

- Main advantage: **largest branching ratio**
- Challenges: complex **QCD multijet background estimation**

Mass coverage and regimes:

- Full analysis scan: $\mathbf{m_X \in [300, 6000]}$ **GeV**, $\mathbf{m_S \in [70, 5000]}$ **GeV**
- Phase space divided by topology:

Resolved

4 small-R jets: R=0.4

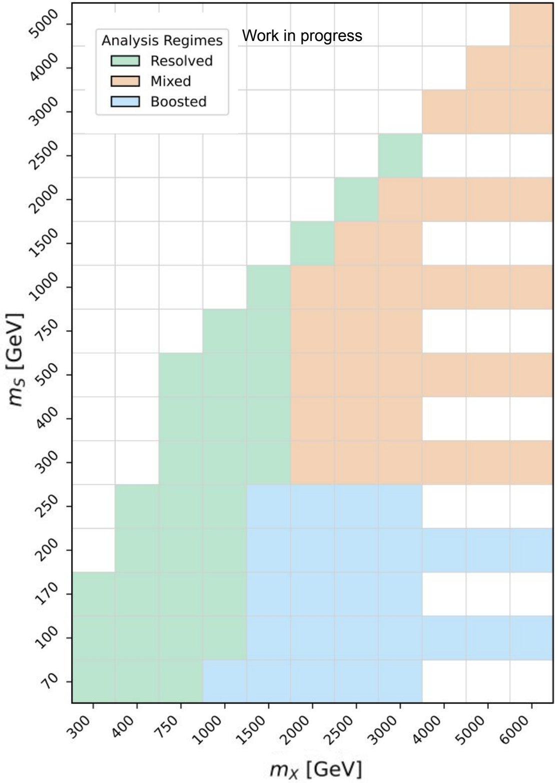
Mixed

2 small-R jets: R=0.4
1 large-R jet: R=1.0

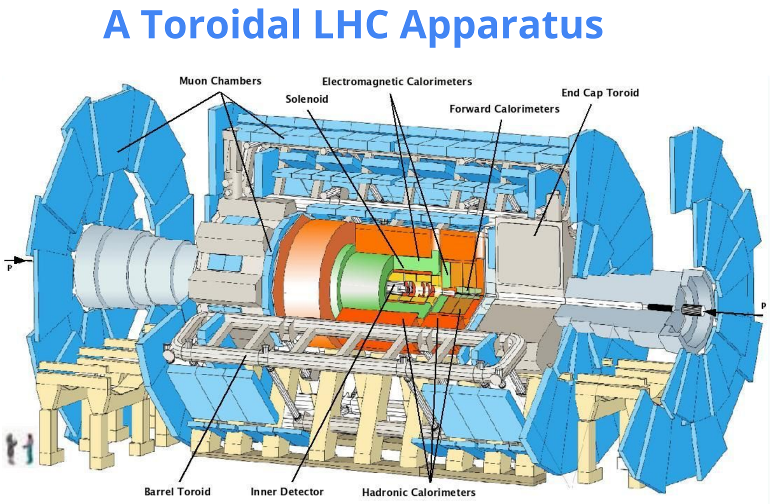
Boosted

2 large-R jets: R=1.0

In this talk we will focus on the **boosted regime**



The ATLAS detector



arXiv:2305.16623, JINST 19 (2024)

- General purpose detector composed of various components (sub-detectors) in layers to reconstruct fundamental particles and investigate SM and beyond SM processes
- Designed to **reconstruct complex final states** at very high energies:
  - Cover nearly the full solid angle (≈4π coverage)
  - Capable of **measuring** particles from **low to multi-TeV** scales
- Sub-detectors:
  - **Inner Detector** (tracking, $|\eta| < 2.5$)
  - **Solenoid** (2 T)
  - **EM + Hadronic Calorimeters**
  - **Muon Spectrometer**
  - held together by the barrel + end-cap **toroid magnets** shown in blue

Relevant for boosted SH4b analysis:

- large-R jets are reconstructed from **combined calorimeter + tracking information**
- large-R jets measure in $|\eta| < 2.0$: this is what lets a single large-R jet capture a fully merged $H \to b\bar{b}$ or $S \to b\bar{b}$ decay

Trigger strategy

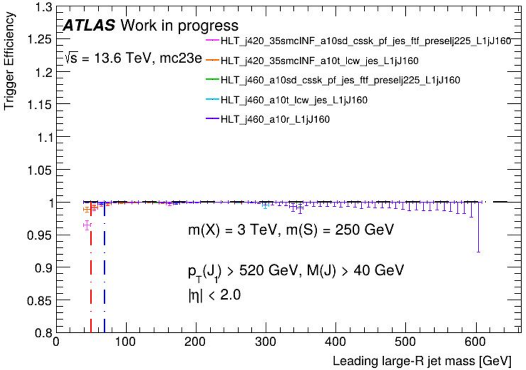
- Only large-R jet triggers are used in the boosted channel
  - A single unprescaled large-R jet trigger gives maximum efficiency, since the boosted analysis lives at high p_T ([500, 3000] GeV)

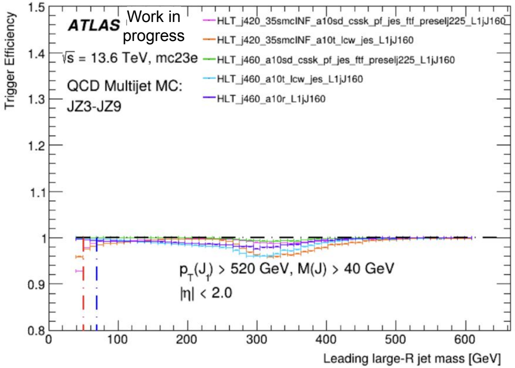
- **Run 3 triggers:**
  - 2022-2023 nominal: `HLT_j460_a10sd_cssk_pf_jes_ftf_preselj225_L1J100`
    1. best-performing single large-R jet trigger tested
    2. ~1% dip observed in the efficiency as a function of the jet mass in the 280–400 GeV range

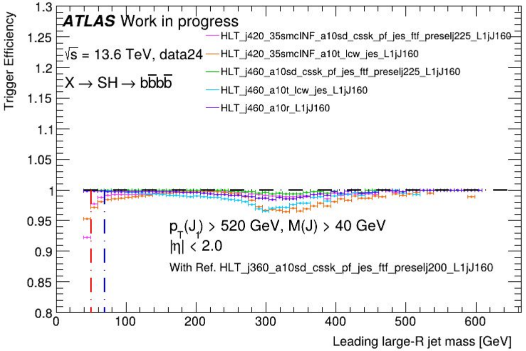
  - 2024: `HLT_j460_a10sd_cssk_pf_jes_ftf_preselj225_L1jJ160`
    1. same p_T threshold and soft-drop algorithm, but L1 seed based on the Phase-II Level-1 Calorimeter trigger system
    2. same ~1% dip present

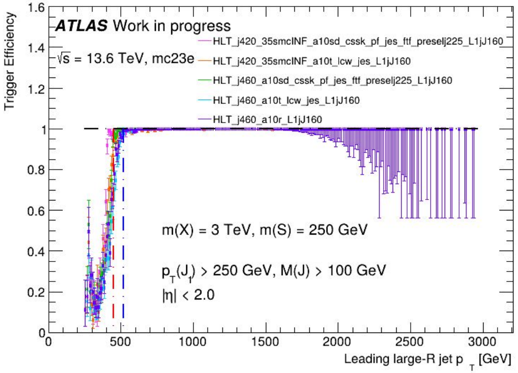
- Offline kinematic thresholds ensure full trigger efficiency:
  leading jet $p_T(J1) > 520$ GeV, both jets $m(J) > 50$ GeV

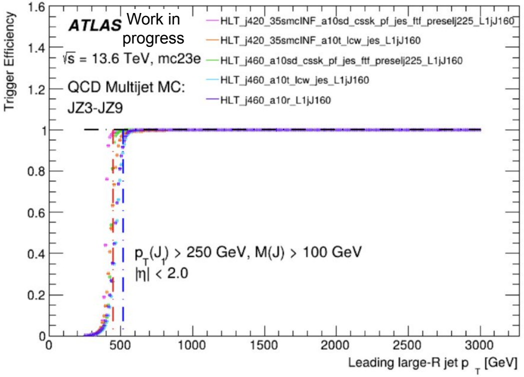
Trigger efficiency

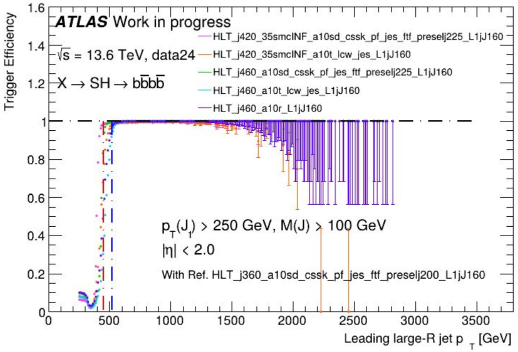






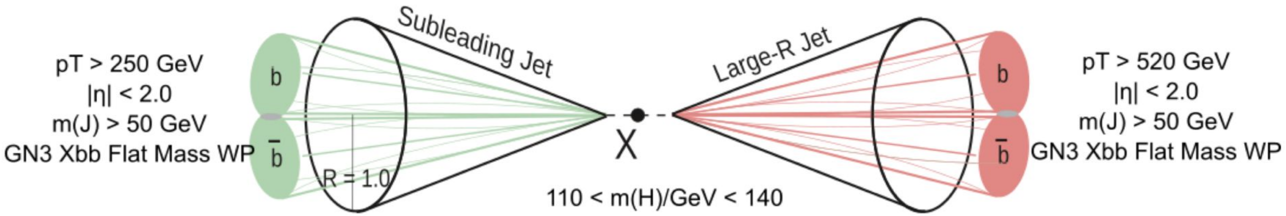






Turn-on at p_T= 520 GeV, consistent in signal MC, background MC and data

Event selection



Offline selection:

- ≥ 2 large-R jets reconstructed using the anti-k_t algorithm with R=1.0:
    - all required |η| < 2.0 and 40 < M(J) < 600 GeV
    - leading jet $p_T(J1)$ > 520 GeV
    - sub-leading jet $p_T(J2)$ > 250 GeV
    - both jets bb-tagged with GN3XPV01 @ 70% Hbb efficiency

Kinematic regions:

- ***Signal Region (SR):*** $m_H \in$ [110, 140] GeV
- ***Near sidebands (NSB):*** $m_H \in$ [90, 110] && [140, 170] GeV
- ***Far sidebands (FSB):*** $m_H \in$ [70, 90] && [170, 220] GeV

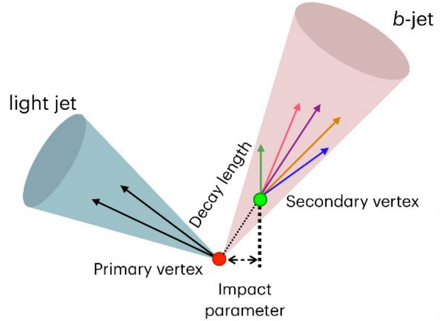
H/S assignment:

- if one candidate mass falls in m_H window:
    - this is assigned as H
    - the other becomes S
- if both candidates mass fall in m_H window:
    - random assignment

Flavour tagging: GN3X

- Flavour Tagging is a way of estimating the origin or content of a jet
  → Needed in our case to identify b-jets

- It exploits the peculiar topological features of b-hadron decays: displaced tracks, high mass secondary vertex

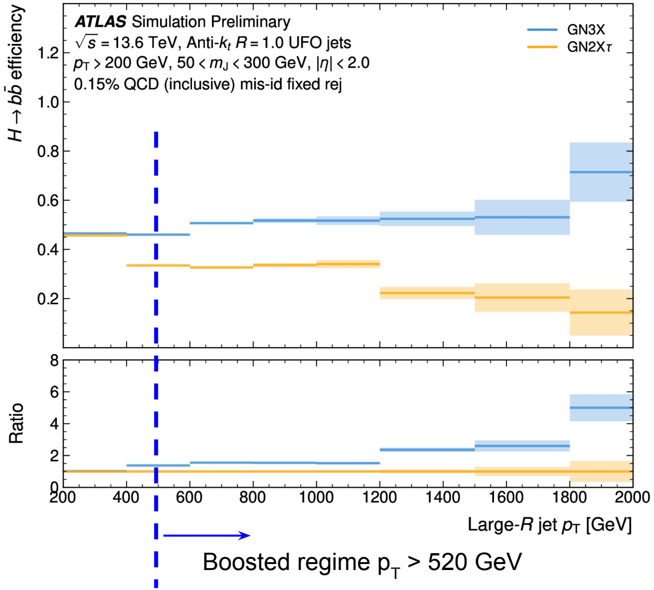


Previous Xbb taggers:

- DL1r (Run 2):
  - re-clusters the large-R jet into ≤ 3 small-R sub-jets, tags each independently and only combine its scores
    → misses fine-grained substructure correlations
- GN2X:
  - transformer trained directly on all tracks in the large-R jet, learning one unified representation instead of combining independent sub-jet scores
    → separated taggers for $H \to b\bar{b}/c\bar{c}/\tau\tau$

Newer Xbb tagger: **GN3X**:

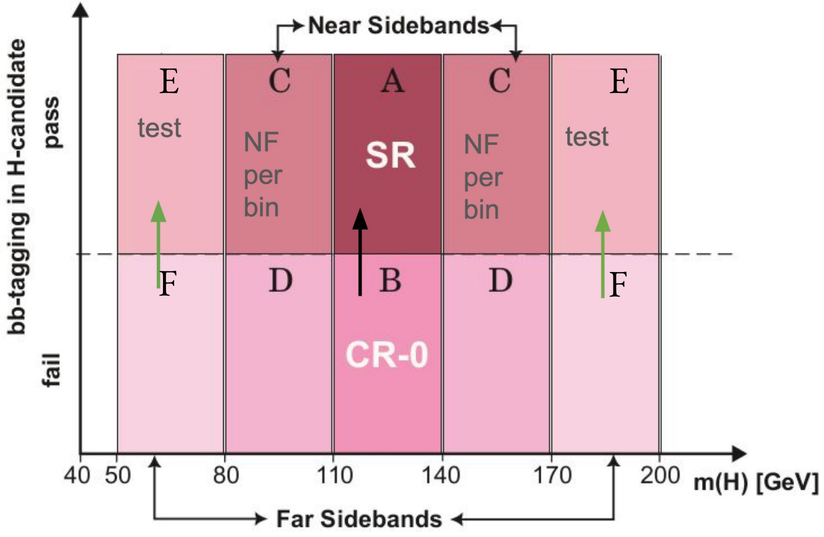
- Single unified model covering all three decay channels, via architectural upgrades, larger training samples, and more granular jet-class definitions
- **At 70% $H \to b\bar{b}$ efficiency**, GN3X achieves ~25% higher inclusive QCD jet rejection than GN2Xτ



Analysis regions & background estimation

Regions are defined in the 2D plane of the H candidate mass x bb-tagging outcome of the H candidate

→ S candidate is always required to pass bb-tagging



A - Signal region
B - Control region
C/D - Near sidebands
E/F - Far sidebands

Background composition:

- Small backgrounds: $t\bar{t}$, Zbb+jets and single Hbb → modeled with MC samples
- Dominant background: QCD multijet → based on **data-driven** techniques

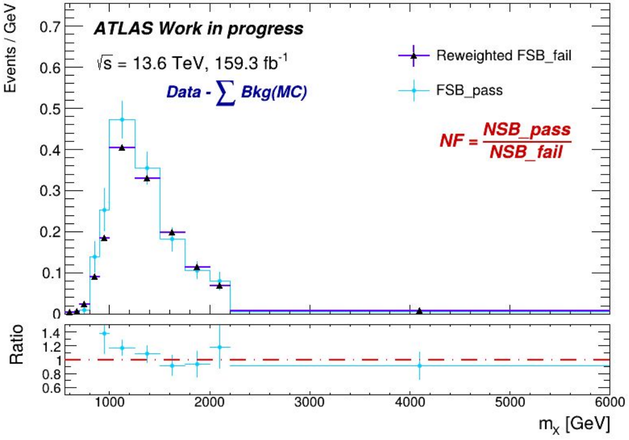
ABCD method:

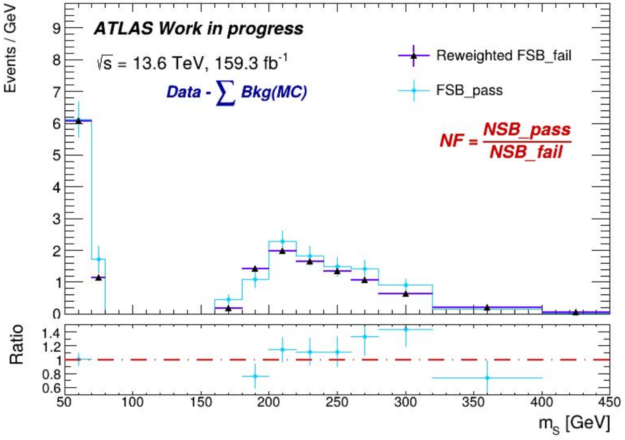
- Normalization Factor (NF) extracted from the NSB region:

$$\frac{\text{SR}}{\text{CR-0}} = \frac{\text{NSB\_passed}}{\text{NSB\_failed}} \Rightarrow \text{SR} = \text{CR-0} \cdot \frac{\text{NSB\_passed}}{\text{NSB\_failed}}$$

- FSBs are used as the validation regions:
    - The NF is used to normalize the F region
    - m_X distribution compared between the normalized F region and the E region

Background estimation: QCD multijet estimation



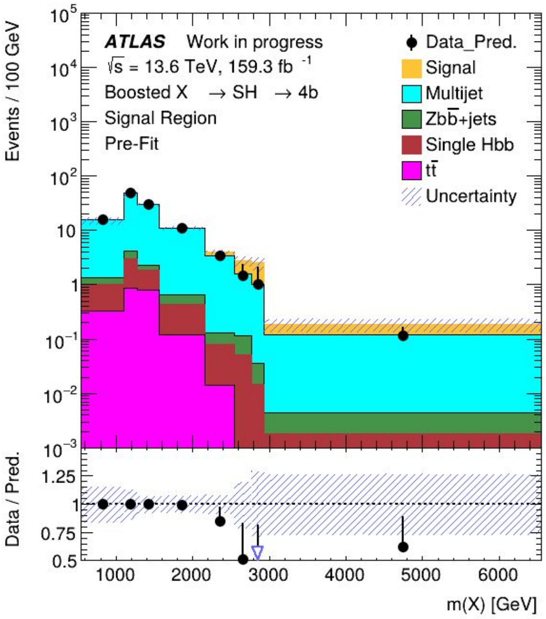


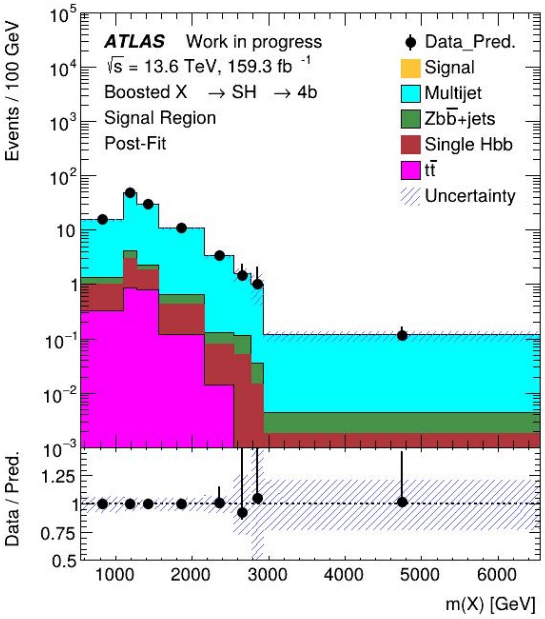
	QCD Multijet MC (old ntuple)				**Data - $t\bar{t}$ (new ntuple)**	
NF_NSB	0.00768 ± 0.00033				0.009821 ± 0.00035	
Regions	SR	reweighted CR-0	FSB_pass	reweighted FSB_fail	FSB_pass	reweighted FSB_fail
Event yield	406.88960	373.76972	269.44226	251.52685	560.82187	536.70566
Ratio (reweighted_fail/pass)	0.91860		0.93351		0.95721	
Relative comparison [%]	-8.2		-6.6		-4.3 (-12 for 0.3% flat mass WP)	

- The normalized FSB_fail distribution is compared to the observed FSB_pass distribution across the full m_X range
- From the ratio plot: an additional shape uncertainty is assigned for the background estimation

Signal region: prefit and postfit m_X distribution

Prefit and postfit distributions for (m_X, m_S) = (3000, 250) GeV:



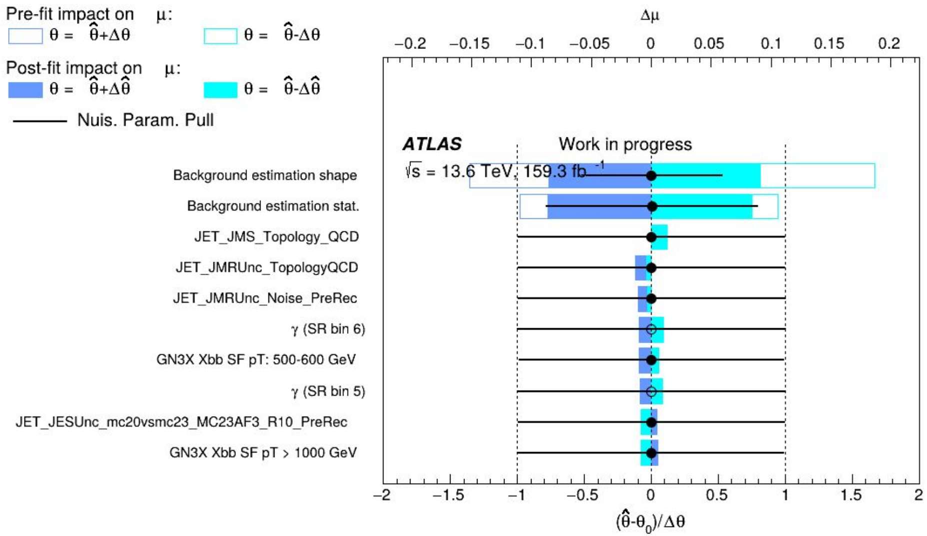


- Multijet (data-driven) dominates the background composition
- Small contributions from tt̄, Zbb+jets, single Hbb
- Ratio panel shows agreement between predicted background and data (Asimov predicted data)

Systematic uncertainties

Systematic sources considered in the fit and their impact on μ for (m_X, m_S) = (3000, 250) GeV:

Systematic source	Type	Affected processes	Correlation
Template Statistics (γ)	Shape	All	Uncorrelated (per m_X bin)
Background modeling			
Background estimation	Norm + Shape	Multijet	Uncorrelated
Experimental			
Luminosity	Norm	All (except Multijet)	Correlated
Pile-up	Norm + Shape	Signal, $t\bar{t}$, Z + jets, ZH	Correlated
JES (31 NP), JER (14 NP) JMS (27 NP), JMR (14 NP)	Norm + Shape	Signal, $t\bar{t}$, Z + jets, ZH	Split by NP, correlated across the processes
AF3 vs FS jet (4 NP)	Norm + Shape	Signal	Split by NP, uncorrelated
Flavour-tagging			
GN3X signal eff. SF (5 NP)	Norm + Shape	Signal, Z + jets, $H \to b\bar{b}$	Uncorrelated per p_T bin, correlated across the processes
GN3X mis-tag eff. SF (6 NP)	Norm + Shape	$t\bar{t}$	Uncorrelated per p_T bin
Theoretical			
PDF + α_s	Norm + Shape	$t\bar{t}$, ZH	Uncorrelated
Scale envelope (μ_R, μ_F)	Norm + Shape	$t\bar{t}$, ZH	Uncorrelated
Parton Shower (PS)	Norm + Shape	Signal	Uncorrelated
MC modeling	Norm	All (except Multijet)	Uncorrelated



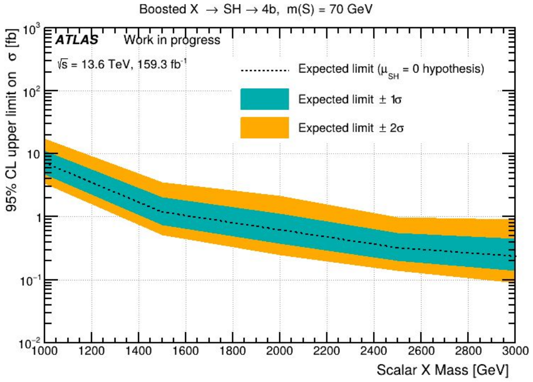
- Data-driven method: normalization + shape uncertainty
- Detector uncertainties: large-R jet calibration and Xbb tagging Scale Factor (SF)

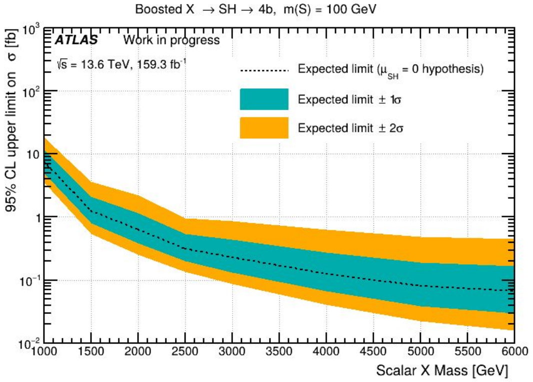
- At low mass, background estimation normalization and shape uncertainties dominate, followed by GN3X Xbb SF
- Same pattern for medium and high masses, having Jet Mass Scale (JMS) and Resolution (JMR) uncertainties more impact than the Jet Energy Scale (JES)

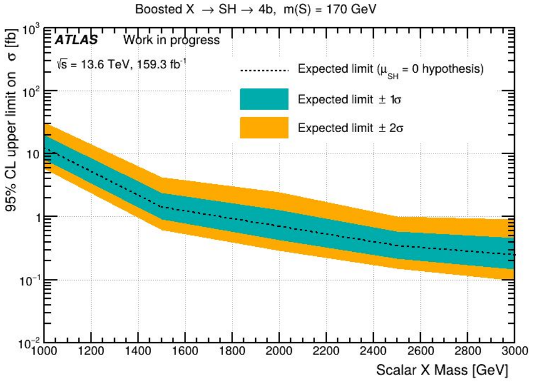
GN3XPV01 tagging SFs: preliminary, official FTAG calibration pending (~2026).

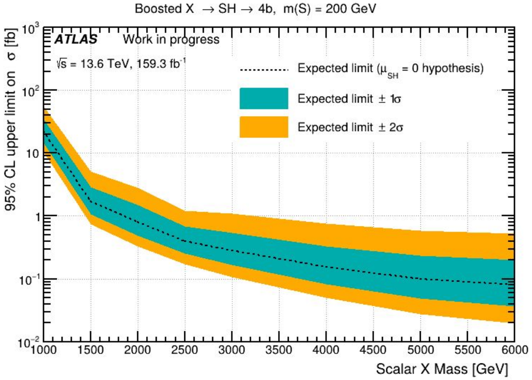
Results

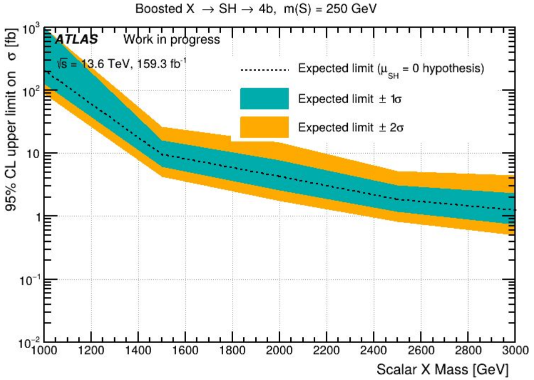
- Expected 95% CL upper limits on σ(X→SH→4b): from ~7.5 fb to ~0.05 fb across $m_X \in [1, 6]$ TeV at fixed m_S = 100 GeV, with best sensitivity at high m_X
- At (m_X, m_S) = (1000, 250) GeV the limit is comparatively weak (these candidates are not sufficiently boosted at that mass splitting)
- These are expected-only limits (background-only Asimov fit) — the analysis is still blinded in the SR











Summary

$X \rightarrow SH \rightarrow 4b$ search in the boosted topology, partial Run 3 dataset:

- **First result** from a dedicated boosted-topology search for $X \rightarrow SH \rightarrow 4b$ in ATLAS: H and S reconstructed from two double-b-tagged large-R jets
- Uses 159.3 fb^{-1} of $\sqrt{s}$ = 13.6 TeV pp collision data (2022–2024)
- Simplified single-trigger strategy compared to resolved/mixed: one large-R jet trigger suffices given the high-p_T topology
- Background estimation is fully data-driven (ABCD method on H-candidate mass sidebands)

Results:

- No excess observed, 95% CL expected upper limits set on $\sigma(X\rightarrow SH\rightarrow 4b)$ across $m_X \in [1, 6]$ TeV, mS $\in [70, 250]$ GeV
- Best expected sensitivity (~0.05 fb) at high m_X, low m_S

Status:

- Next steps: combine Run 2 + partial Run 3
- Paper in preparation