Performance and calibration of boosted H(bb) tagging, including applications in physics analyses with ATLAS

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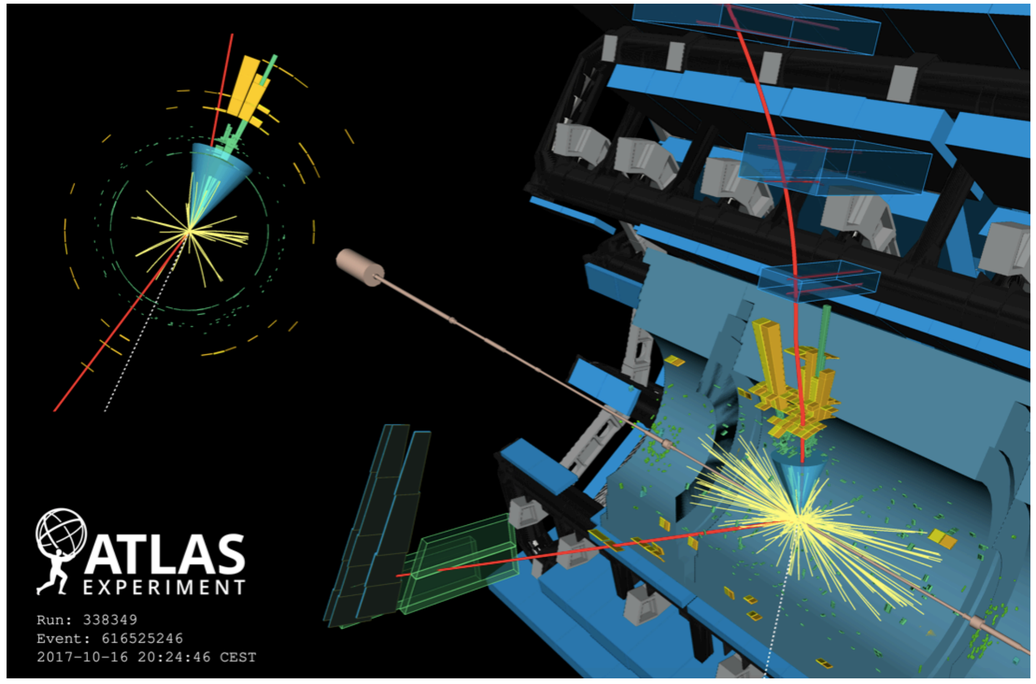
on behalf of ATLAS Collaboration

4th August

BOOST Online 2021

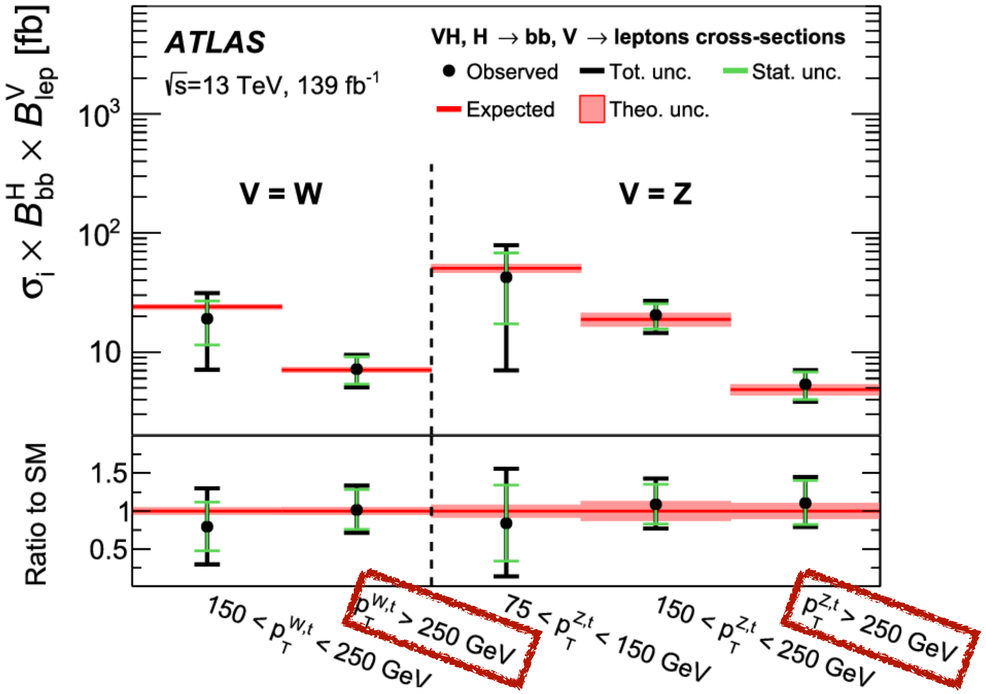


Event display of a boosted $H \to b\bar{b}$ candidate event
ATLAS-PHOTO-2020-006

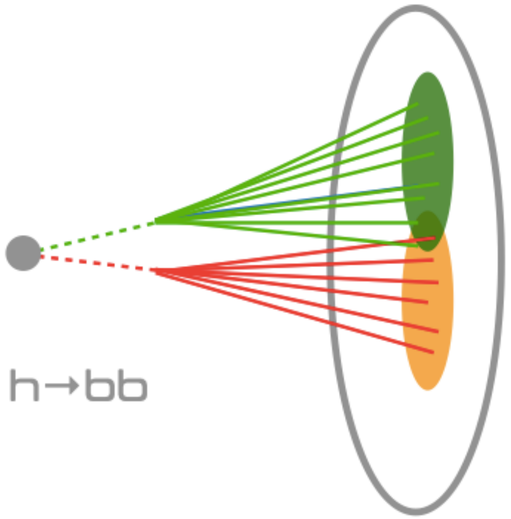
Introduction

- Resolved $H \to b\bar{b}$ tagging: two small-R (R=0.4) jets tagged as b-jet individually
- At high energies, decay products of b-hadrons highly collimated and statistics limited with resolved $H \to b\bar{b}$ tagging
- Boosted $H \to b\bar{b}$ tagging: (Calorimetric) large-R jets (R=1.0) and its associated (track) sub-jets used

SM studies with resolved $H \to b\bar{b}$ tagging



Eur. Phys. J. C 81, 178 (2021)



arXiv: 1909.12285

- Two methods and their applications:
  - Double-b-tagging method
  - Neural networks (NN-) based tagging techniques

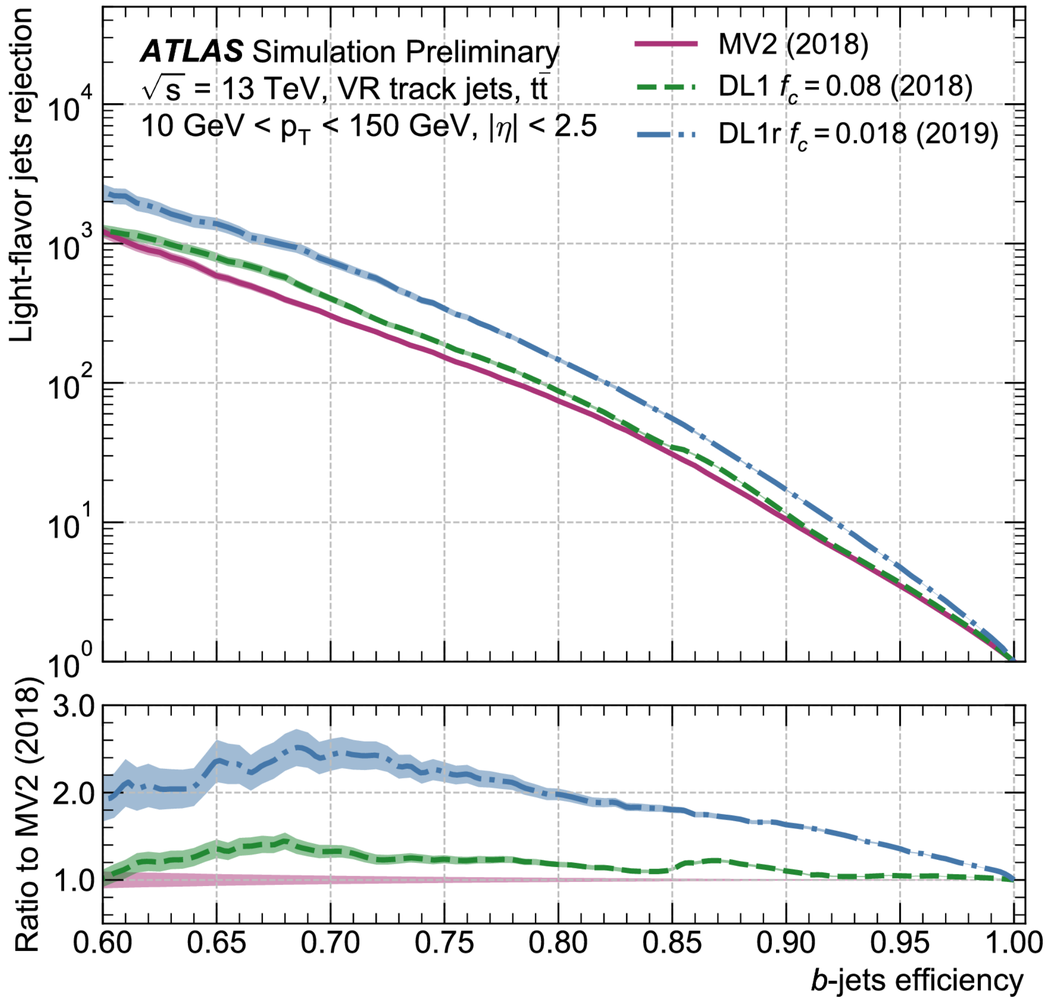
Double-b-tagging method

- Variable-Radius (VR) track jets (R shrinks vs p_T) used
- Most popular algorithms: MV2 (a single discriminant) and DL1r (three flavour probabilities)
- $H \to b\bar{b}$: large-R jets with 2 b-tagged ghost-associated VR track jets

- Performance and calibrations based on **isolated** VR track jets and jet flavours
  - No association requirement to large-R jets !!!
  - Efficiency and SFs measured based on b-jet (2L $t\bar{t}$), c-jet (1L $t\bar{t}$) and light-jet ($Z + jets$)
    FTAG-2019-003

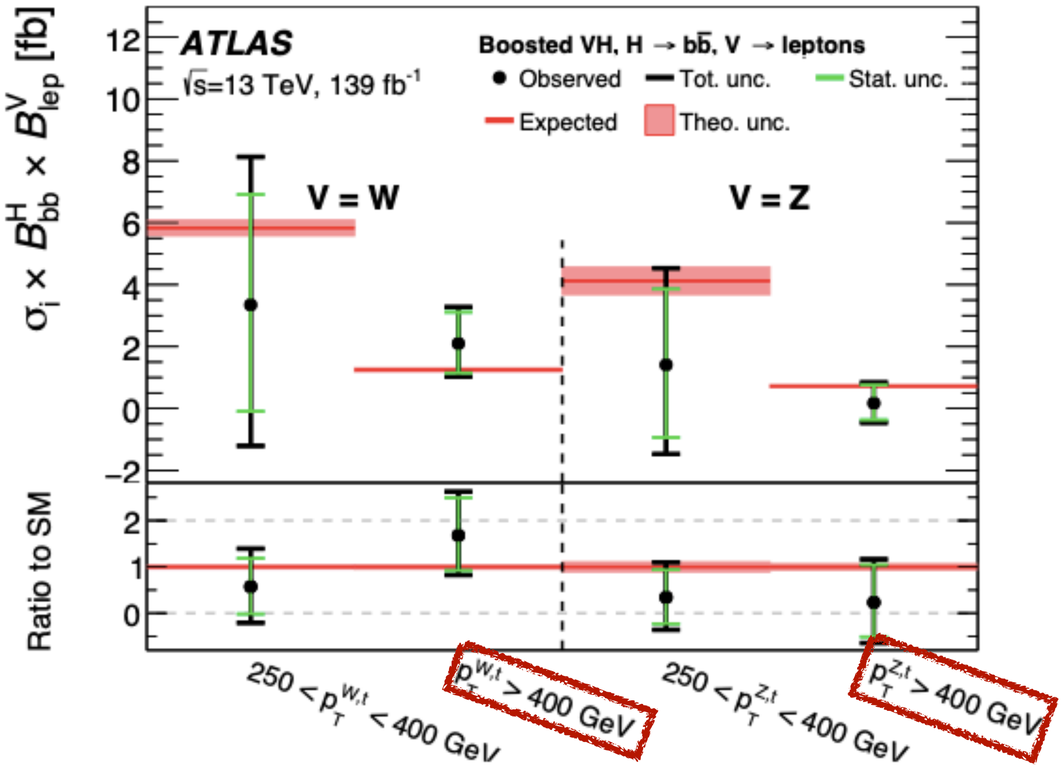
Data-to-simulation Scale Factor $SF = \frac{\epsilon^{data}}{\epsilon^{MC}}$

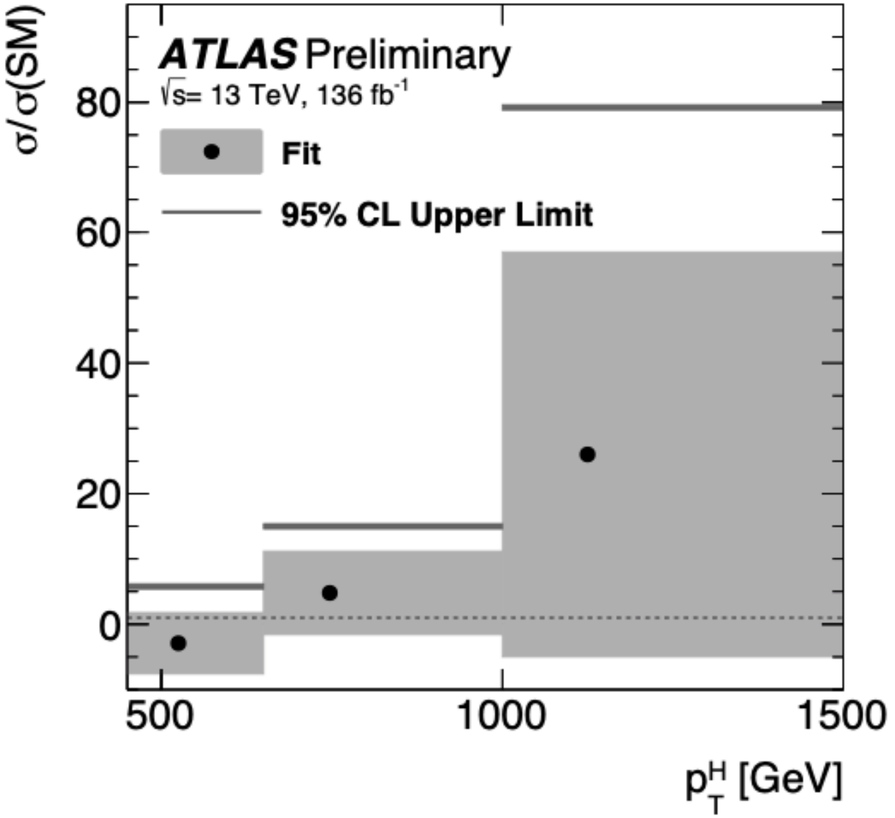
FTAG-2019-006



Double-b-tagging method

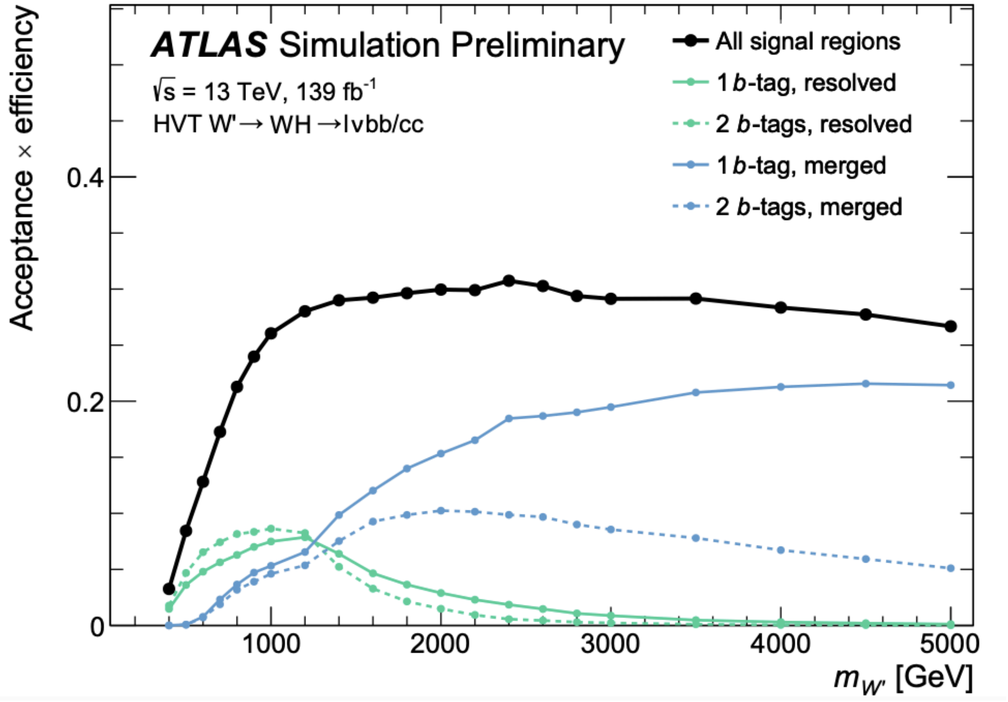
- For SM studies, more granularities added at high p_T regime compared to the resolved tagging
  - Left plot: Phys. Lett. B 816 (2021) 136204 (Semi-leptonic VH)
  - Right plot: ATLAS-CONF-2021-010 (Inclusive all hadronic $H \to b\bar{b}$)

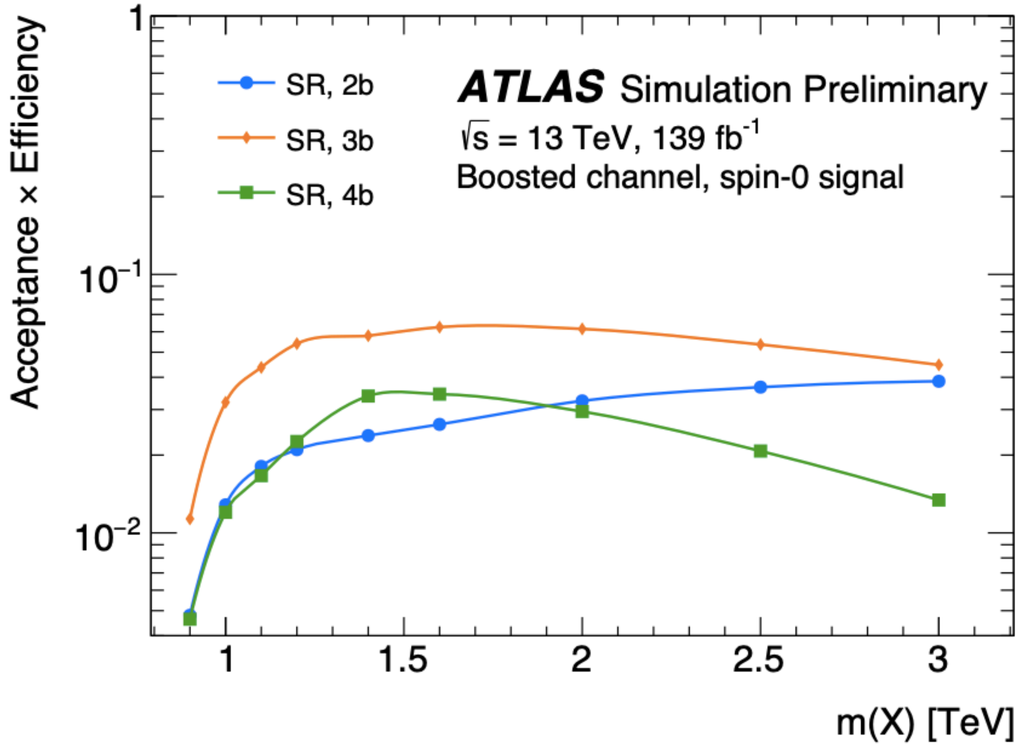




Double-b-tagging method

- For New Physics searches, 2 b-tagging good in heavy resonance mass range of 0.5-1.5 TeV but degraded at very high masses
  - Left plot: ATLAS-CONF-2021-026 ($qq \rightarrow W' \rightarrow WH \rightarrow l\nu b\bar{b}$)
  - Right plot: ATLAS-CONF-2021-035 ($gg \rightarrow X \rightarrow HH \rightarrow bb\bar{b}\bar{b}$)

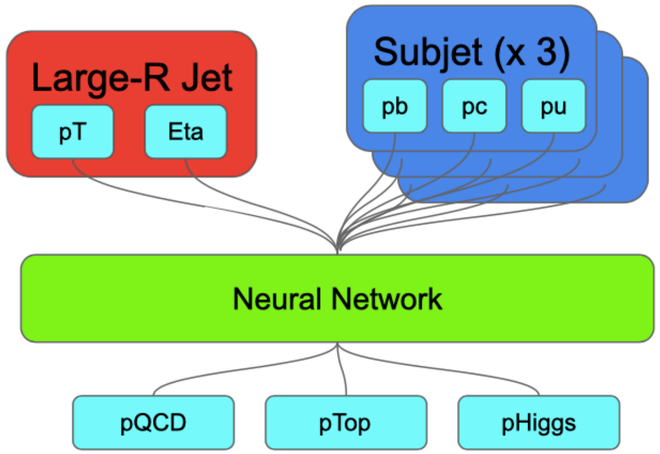


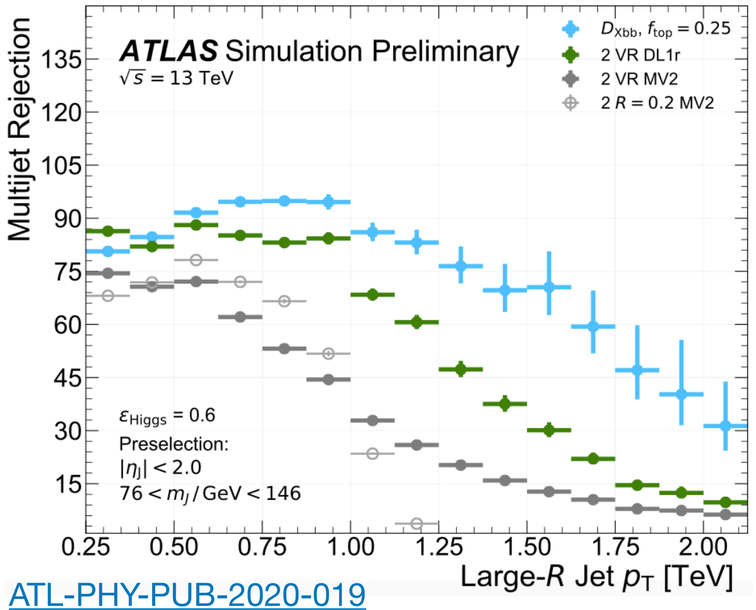


NN-based H(bb) tagging techniques

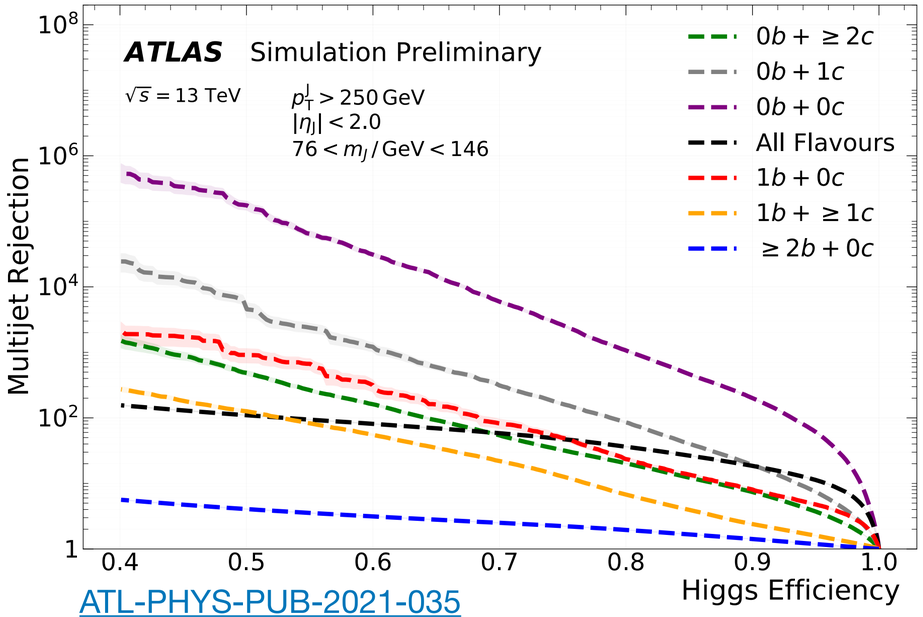
- NN-algorithm used to choose Higgs candidates in analyses
  - ATLAS-CONF-2020-058 ($t\bar{t}H(\rightarrow b\bar{b})$ production)
- $X \rightarrow b\bar{b}$ tagger
  - Better performance compared to 2 b-tagging method
  - Flavour-information based tagger
  - Dedicated topologies required in calibrations

$$D_{Xbb} = \ln \frac{p_{Higgs}}{f_{top} \cdot p_{top} + (1 - f_{top}) \cdot p_{multijet}}$$





ATL-PHY-PUB-2020-019

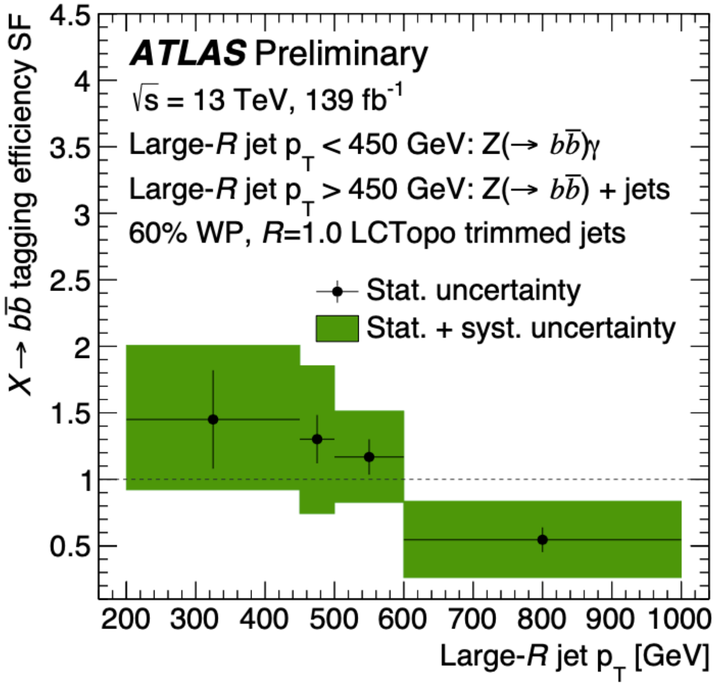


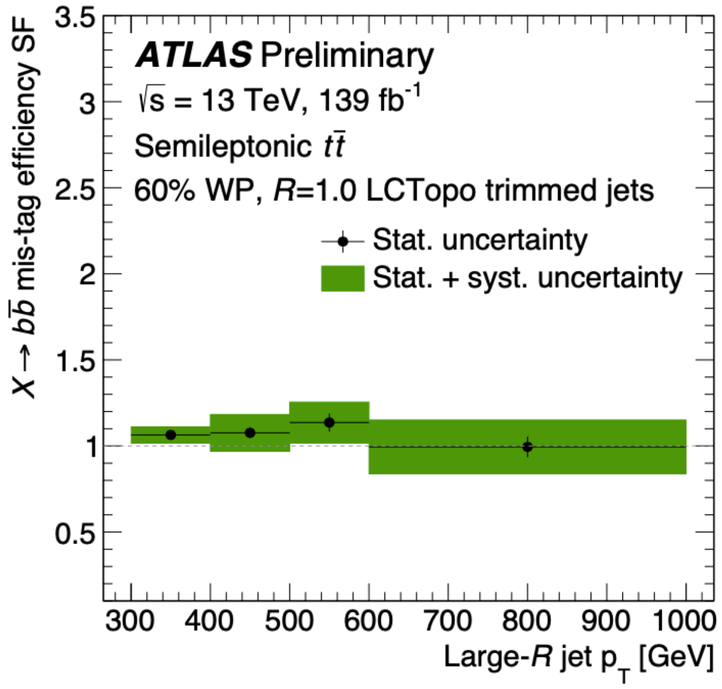
ATL-PHYS-PUB-2021-035

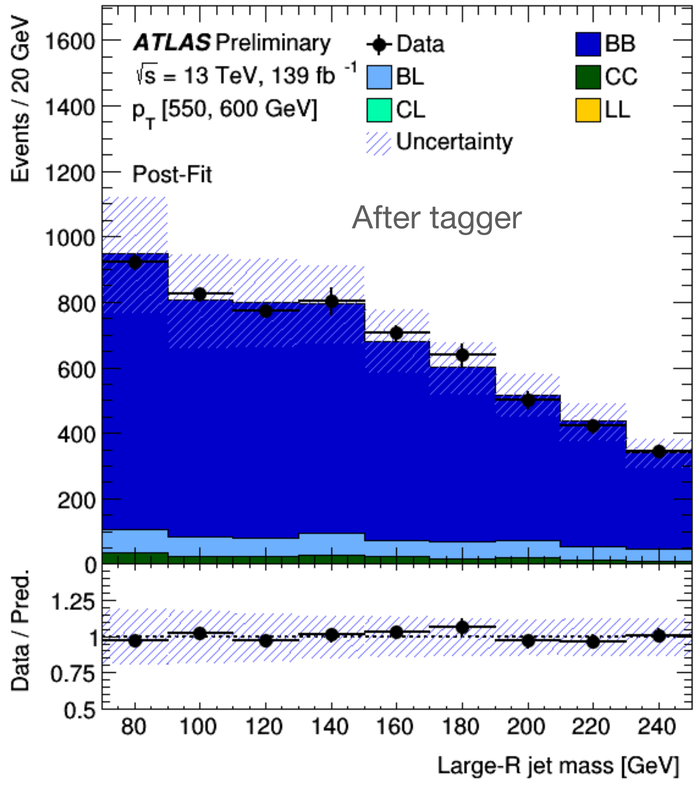
NN-based H(bb) tagging techniques

ATL-PHYS-PUB-2021-035

- $X \to b\bar{b}$ tagger
  - Calibrations (NEW!!!) based on large-R jet topologies with $\geq$ 2 VR track jets
    - (Left plot) $Z \to b\bar{b}$ signal efficiency SFs from $Z + jets$, $Z\gamma$
    - (Middle plot) Top mis-tag efficiency SFs from 1L $t\bar{t}$ using tag-and-probe method
    - (Right plot) Modelling checks with $g \to b\bar{b}$ events







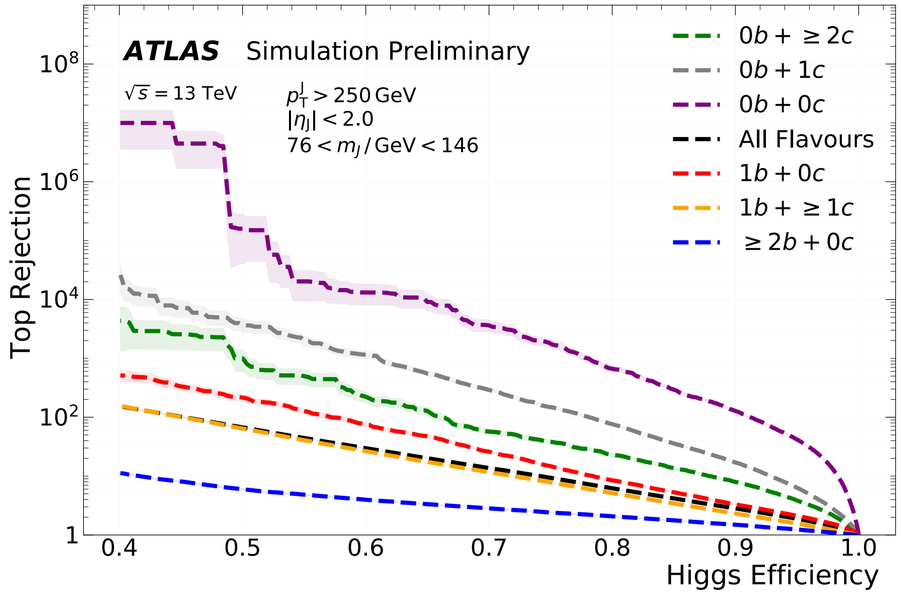
Summary

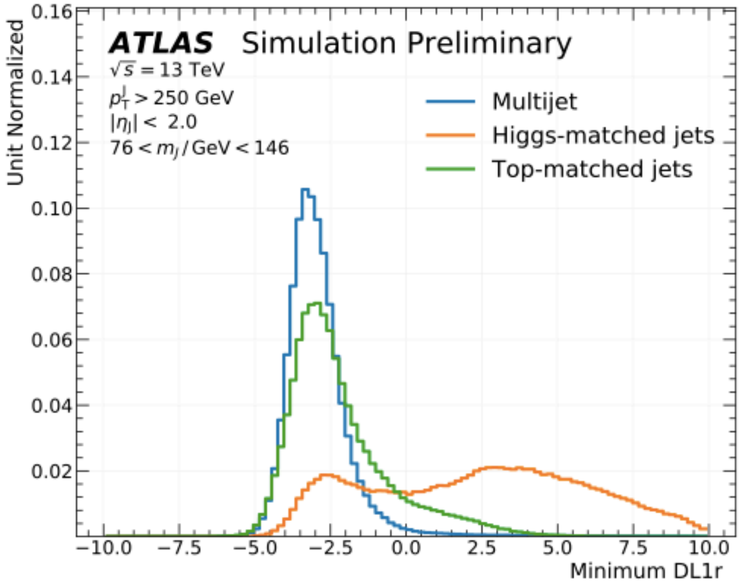
- Boosted $H \to b\bar{b}$ tagging is under very active development in ATLAS and very important for studies at high energies.
- Double-b-tagging method have been prevalently adopted in physics analyses and many interesting results published both in SM studies and in New Physics searches.
- Advanced techniques (e.g. NN-based) shows great promises in boosted $H \to b\bar{b}$ tagging.
- New calibration methods are reported for $X \to b\bar{b}$ tagger based on dedicated topologies and we're looking forward to its applications in physics analyses.

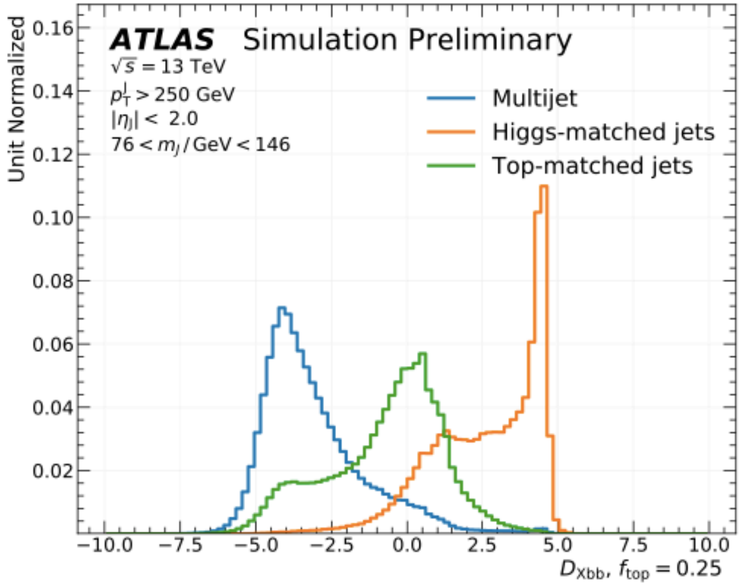
Backup

New $X \to b\bar{b}$ tagger

- Discriminant $D_{Xbb} = \ln \dfrac{p_{Higgs}}{f_{top} \cdot p_{top} + (1 - f_{top}) \cdot p_{multijet}}$
- Recommended $f_{top} = 0.25$
- 3 work points defined
  - 50%(3.13), 60%(2.55), 70%(1.92)

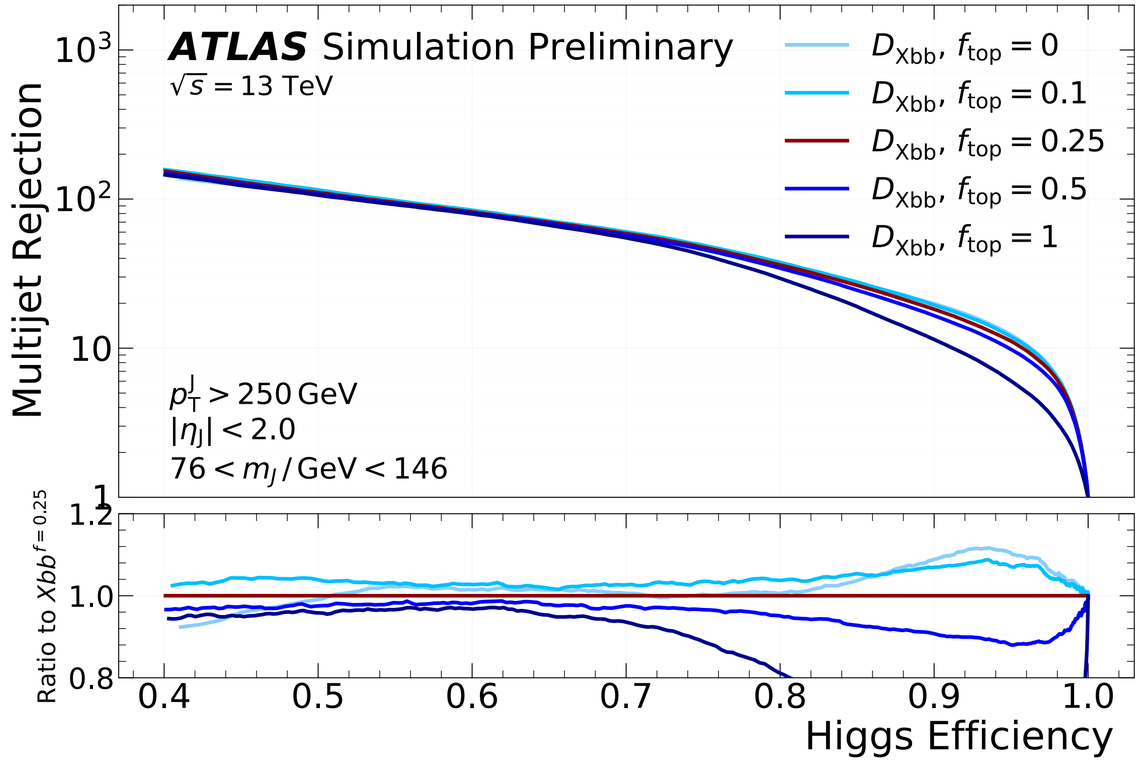


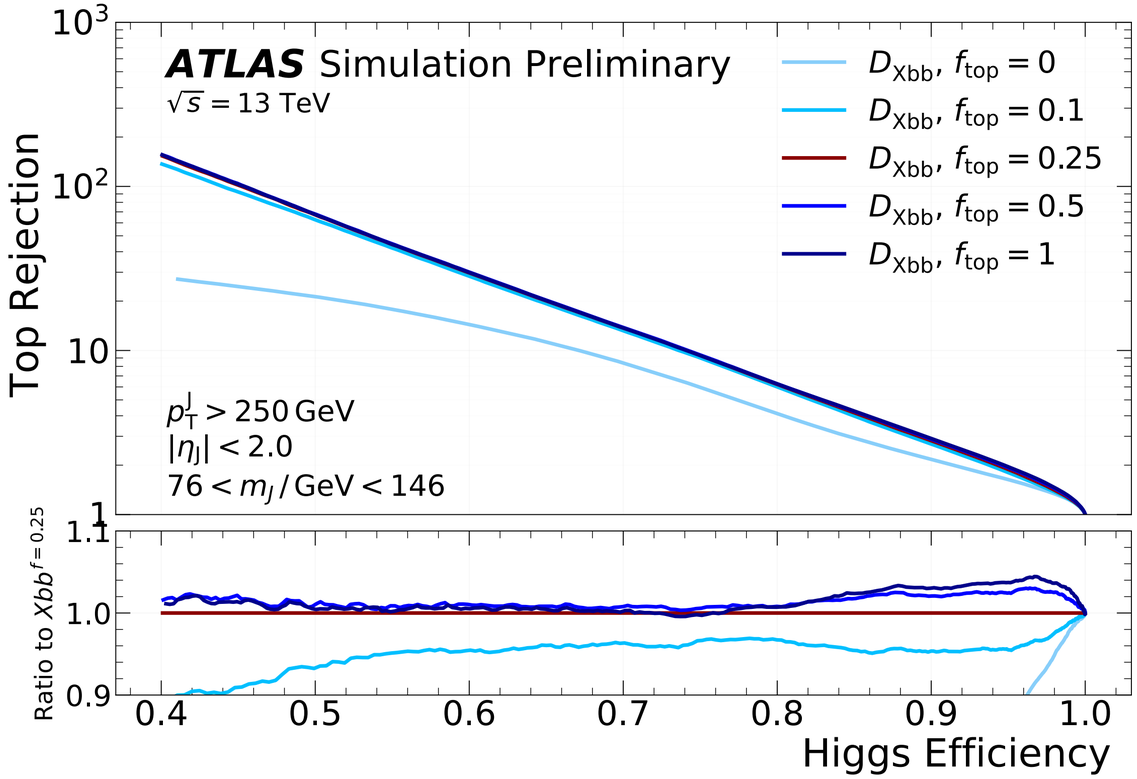




ATL-PHY-PUB-2020-019

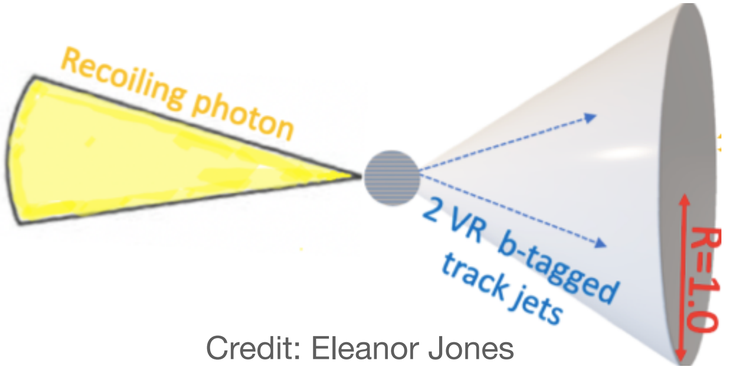
New $X \to b\bar{b}$ tagger





New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to b\bar{b})\gamma$ selections



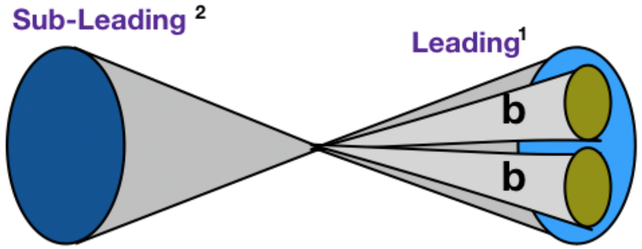
Credit: Eleanor Jones

- Photon triggers used
- At least one large-R jet with $200 < p_T < 450\ GeV,\ |\eta| < 2.0$
- Exactly one photon with $p_T > 200\ GeV$
- Remove large-R jets within $\Delta R < 1.0$ of the photon
- Z boson candidate:
  - large-R jets with $m > 50\ GeV, 2m/p_T < 1.0,$
  - $\Delta\phi(\text{jet}, \gamma) > \pi/2$
  - at least two ghost-associated VR track-jets with $p_T > 7\ GeV$
- Tagged event: Z boson candidate passing the $X \to b\bar{b}$ tagger at the 60% efficiency WP

New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to b\bar{b}) + jets$ selections

- Unprescaled single large-R jet triggers used
- At least two large-R jet with $p_T > 200\ GeV,\ |\eta| < 2.0$
- No electrons or muons with $p_T > 25\ GeV,\ |\eta| < 2.5$
- Z boson candidate:
  - the leading large-R jets with $p_T > 450\ GeV$
  - at least two ghost-associated VR track-jets with $p_T > 7\ GeV$
  - $\dfrac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}} < 0.15$ where $p_{\mathrm{T},1}$ and $p_{\mathrm{T},2}$ is the transverse momentum of the (sub)leading large-R jet
  - $|\Delta y_{1,2}| < 1.2$ rapidity difference of the leading and subleading large-R jet
- Tagged event: Z boson candidate passing the $X \to b\bar{b}$ tagger at the 60% efficiency WP

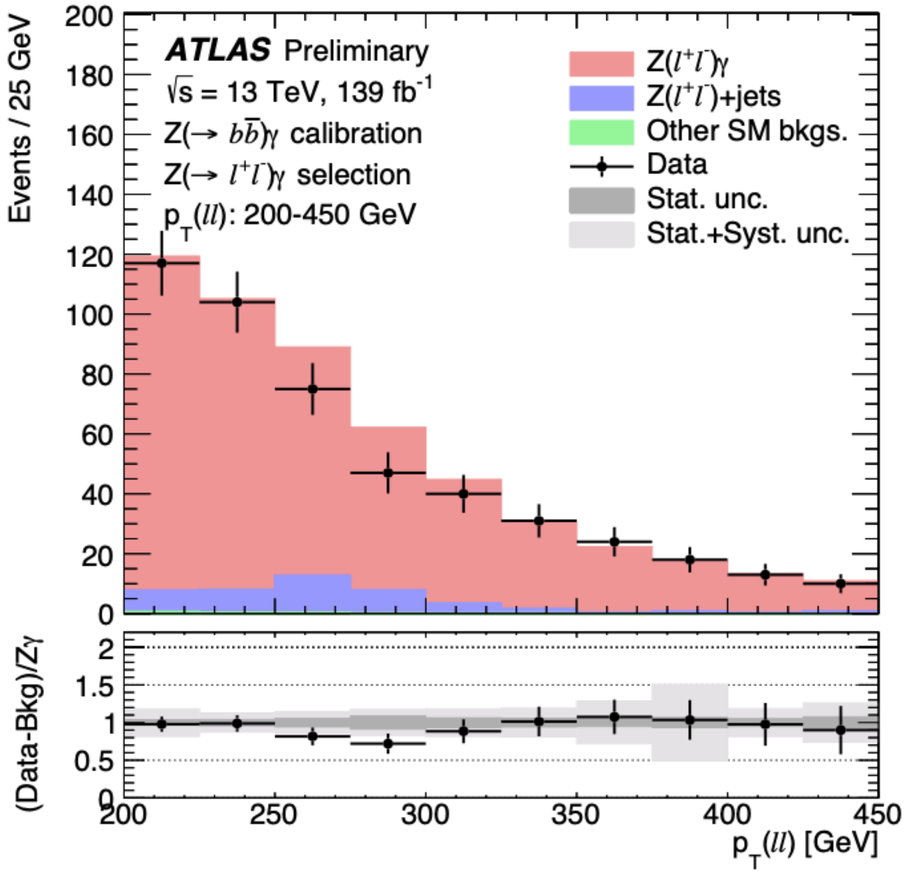


Credit: Shubham Bansal

New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to ll)\gamma$ selections

- Single-photon triggers used
- Two same flavour leptons with $p_T > 20\ GeV$
- Exactly one photon with $p_T > 200\ GeV$
- Opposite charge muons, no opposite charge requirement for electrons
- $\Delta\phi(ll, \gamma) > \pi/2$
- $(p_T^{l_1} - p_T^{l_2})/p_T^{ll} < 0.8$
- $200 < p_T^{ll} < 450\ GeV,\ 70 < m^{ll} < 110\ GeV$

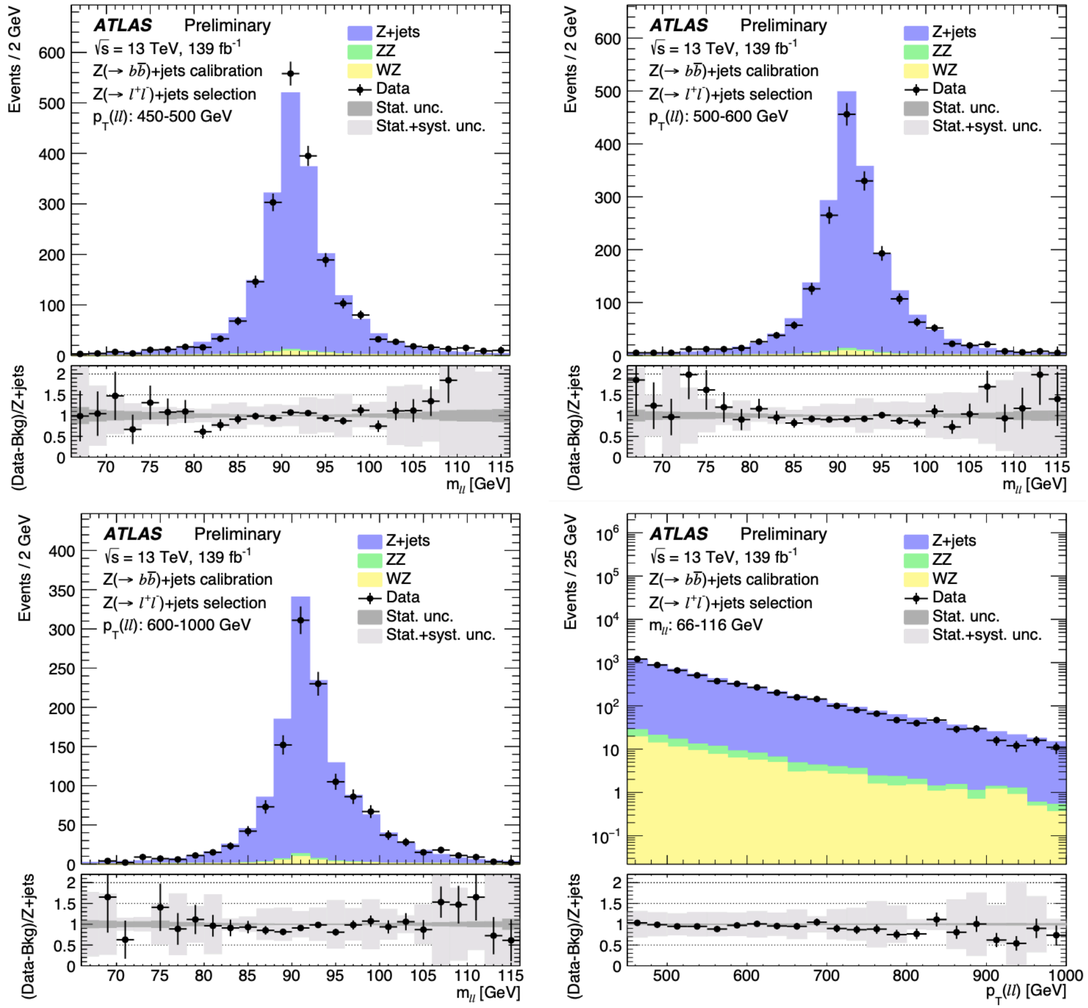


New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to ll) + jets$ selections

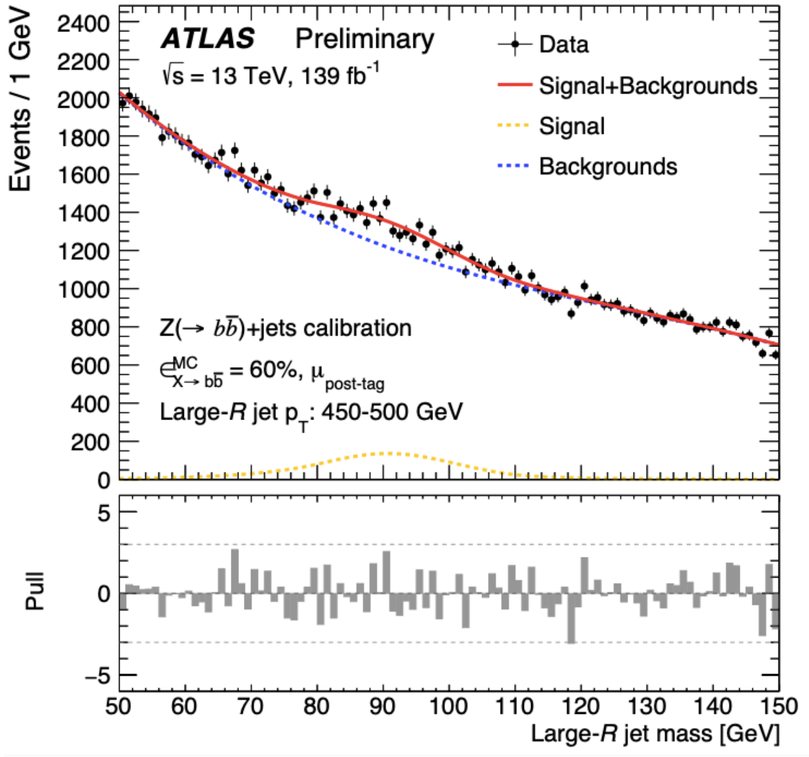
- Unprescaled single electron or muons triggers used
- At least one large-R jet with $p_T > 200\ GeV,\ |\eta| < 2.0$
- Two same flavour leptons with $p_T > 27(5)\ GeV$ for $\mu(e)$
- Opposite charge muons, no opposite charge requirement for electrons
- $(p_T^{l_1} - p_T^{l_2})/p_T^{ll} < 0.8$
- $p_T^{ll} > p_T^{\text{lead. jet}}, \quad \dfrac{p_{\mathrm{T}}^{ll} - p_{\mathrm{T}}^{\text{lead. jet}}}{p_{\mathrm{T}}^{ll} + p_{\mathrm{T}}^{\text{lead. jet}}} < 0.15,$

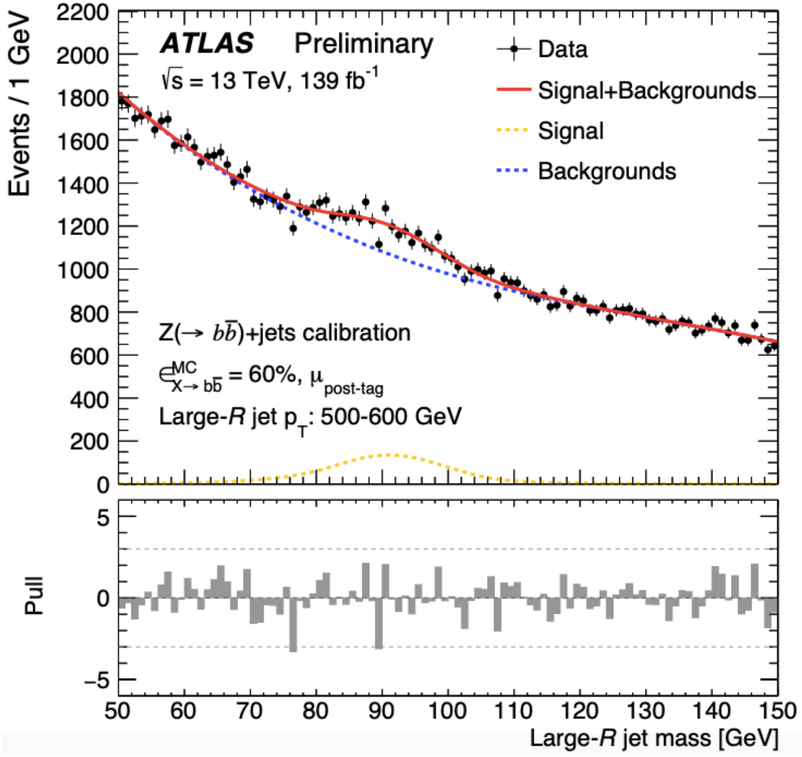
  $|\Delta y_{ll,lead.j}| < 1.2$
- $p_T^{ll} > 450\ GeV,\ 66 < m^{ll} < 116\ GeV$

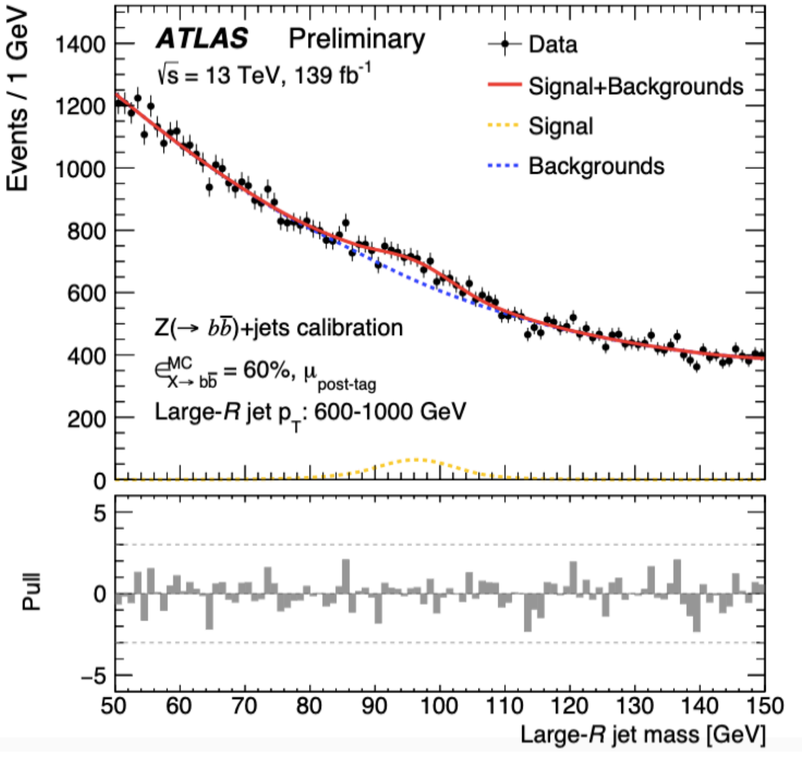


New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to b\bar{b}) + jets$ post-fit plots

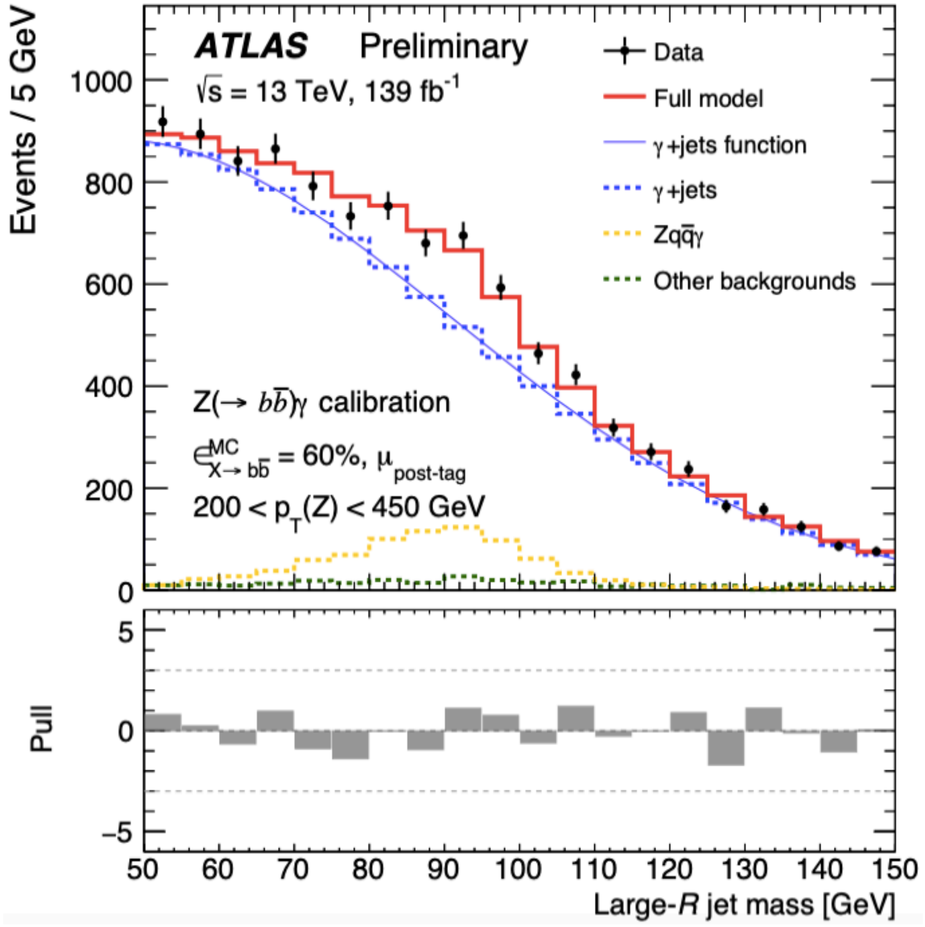






New $X \to b\bar{b}$ tagger: Signal efficiency calibration

$Z(\to b\bar{b})\gamma$ and $Z(\to b\bar{b}) + jets$ methods

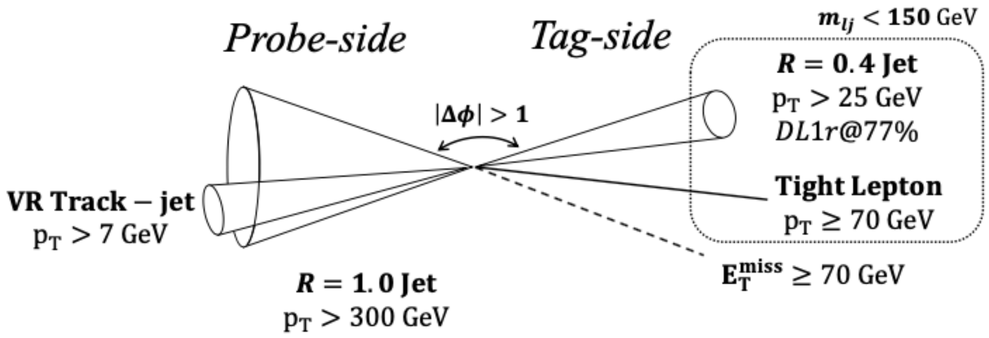


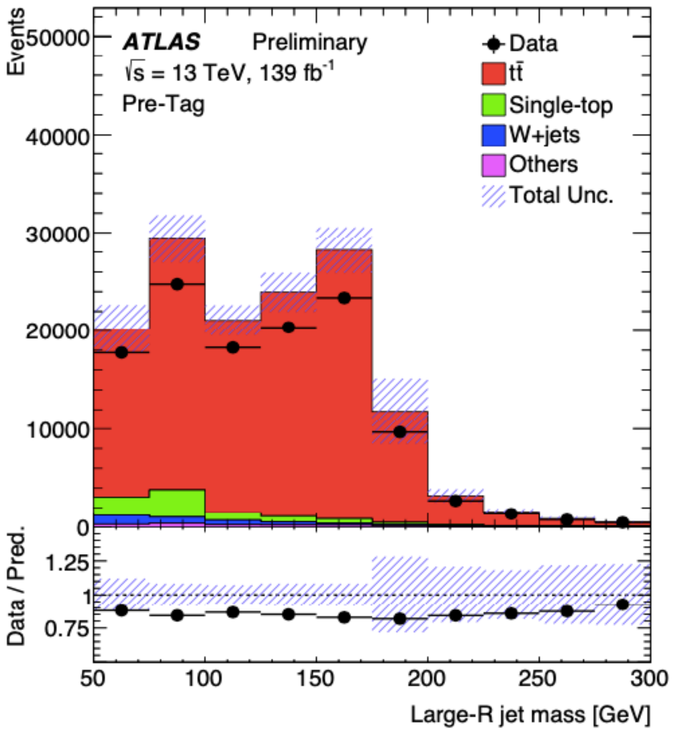
Calibration	$Z(\to b\bar{b})\gamma$	$Z(\to b\bar{b})$ + jets		
p_T [GeV]	200 – 450	450 – 500	500 – 600	600 – 1000
$\mu_{post-tag}$	1.33	1.32	1.10	0.51
$\mu_{pre-tag}$	0.92	1.01	0.94	0.93
SF	1.45	1.30	1.17	0.55
Uncertainties ($\pm\sigma$)				
Statistical	±0.37	±0.18	±0.13	±0.09
Z-boson modelling	$^{+0.24}_{-0.19}$	–	–	–
Z + jets modelling	–	$^{+0.21}_{-0.28}$	±0.15	±0.18
Fit model	0.14	0.39	0.22	0.16
Spurious signal	±0.26	±0.11	±0.07	±0.07
Other background modelling	±0.05	±0.03	±0.02	±0.01
Lepton & Photon related	±0.02	$^{+0.06}_{-0.07}$	$^{+0.06}_{-0.07}$	±0.03
Jet mass scale	±0.05	$^{+0.02}_{-0.01}$	±0.01	$^{+0.02}_{-0.01}$
Jet mass resolution	$^{+0.03}_{-0.02}$	$^{+0.22}_{-0.15}$	$^{+0.11}_{-0.09}$	$^{+0.09}_{-0.07}$
Jet energy scale	$^{+0.06}_{-0.07}$	±0.09	±0.09	±0.05
Others	$^{+0.14}_{-0.16}$	±0.01	< ±0.01	< ±0.01
Total uncertainty	$^{+0.53}_{-0.56}$	$^{+0.55}_{-0.56}$	$^{+0.35}_{-0.34}$	$^{+0.29}_{-0.28}$

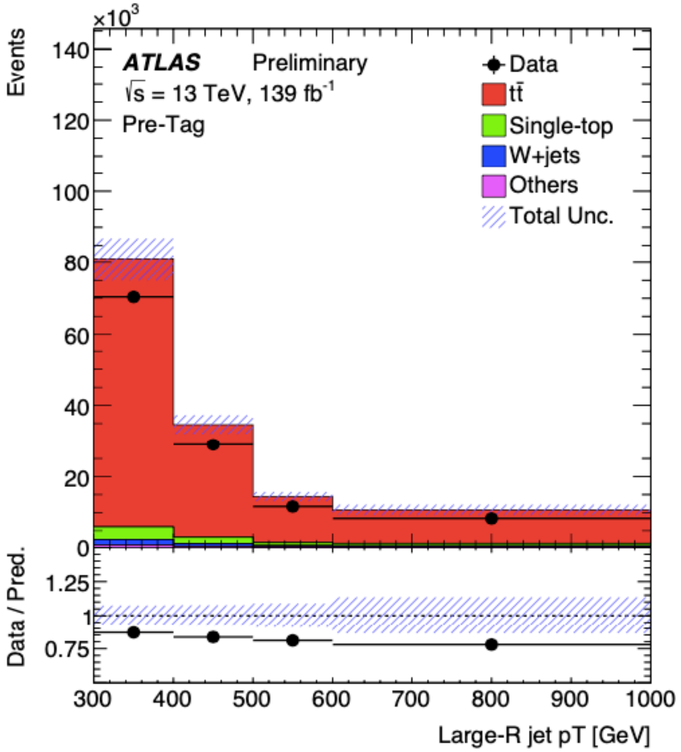
Table 3: Pre-tag ($\mu_{pre-tag}$) and post-tag ($\mu_{post-tag}$) signal strength and the resulting signal efficiency scale factors (SF) for the $X \to b\bar{b}$ tagger at 60% efficiency working point measured using the $Z \to b\bar{b}$ calibration methods. Systematic uncertainties on the scale factor measurement are listed as well. Not all uncertainties are relevant for both measurements.

New $X \to b\bar{b}$ tagger: Mis-tag rate calibration

1L $t\bar{t}$ method

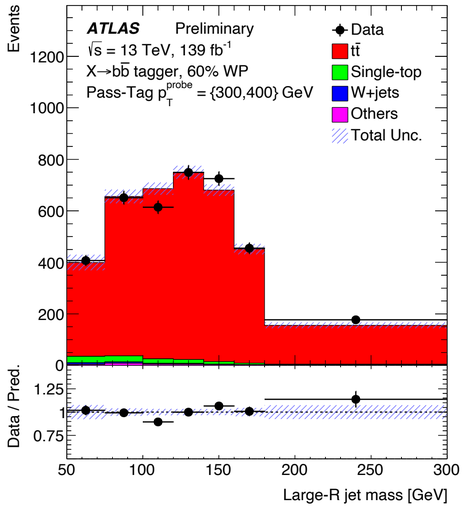


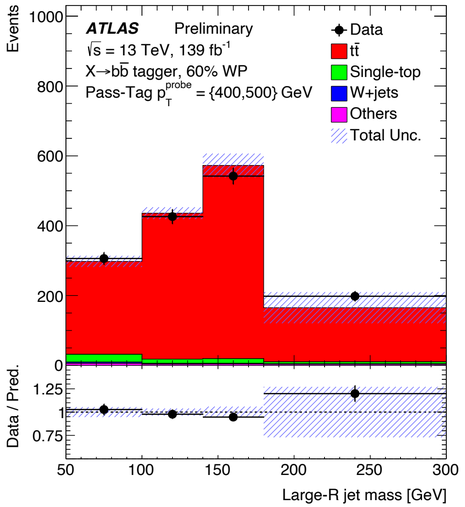


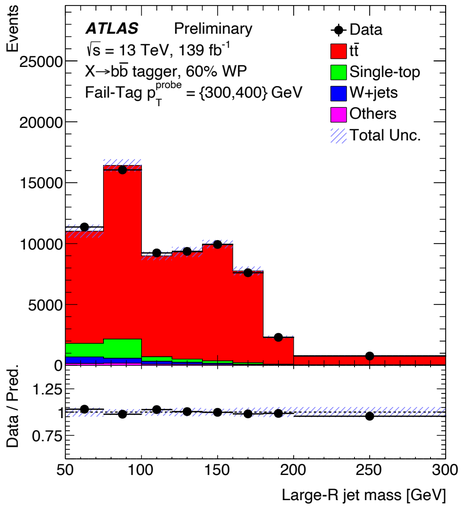


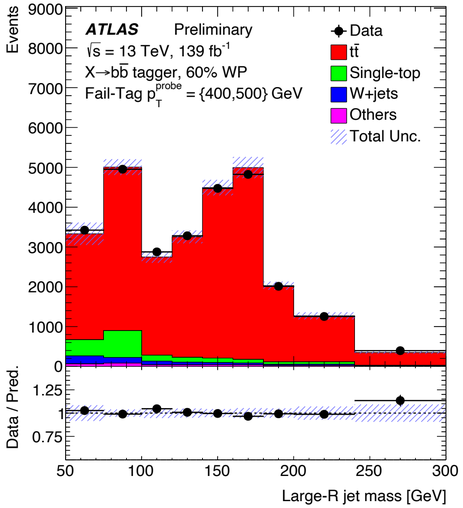
New $X \to b\bar{b}$ tagger: Mis-tag rate calibration

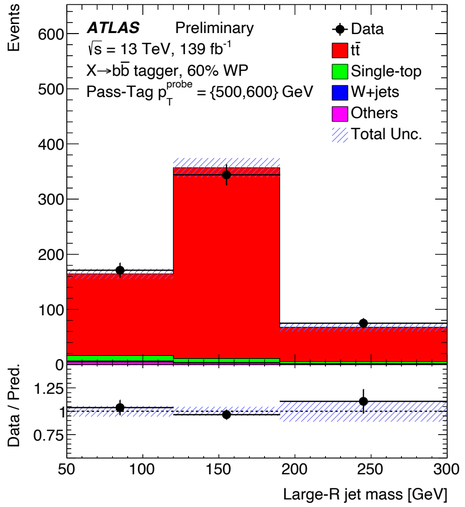
1L $t\bar{t}$ method (post-fit plot)

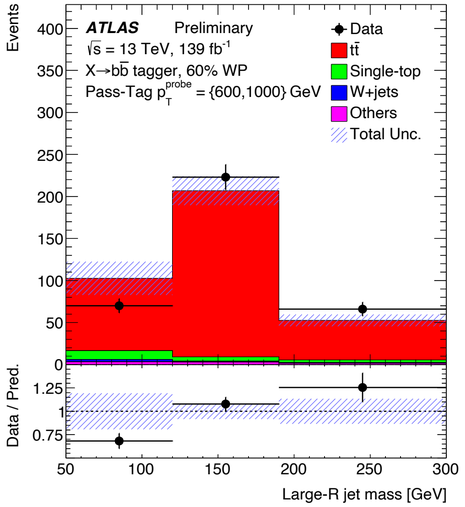


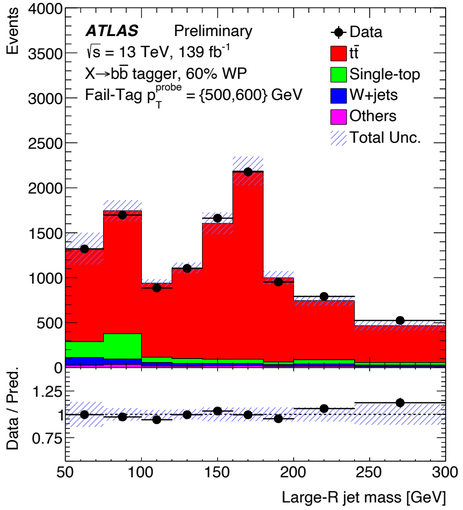


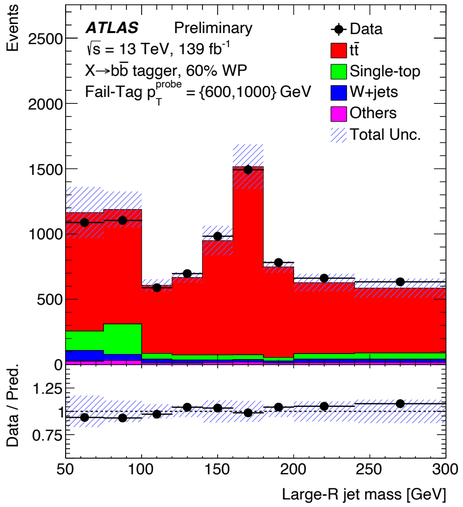


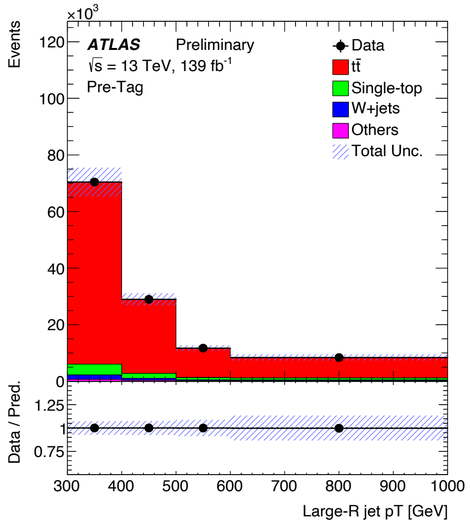












New $X \to b\bar{b}$ tagger: Mis-tag rate calibration

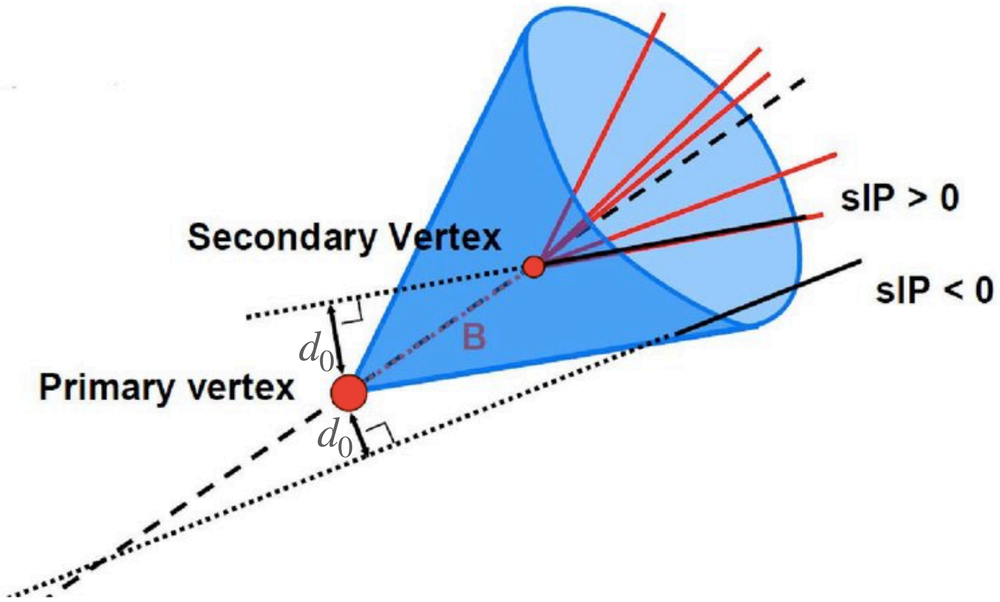
1L $t\bar{t}$ method

p_T [GeV]	300 – 400	400 – 500	500 – 600	600 – 1000
SF	1.06	1.08	1.14	0.99
Total unc.	0.045	0.10	0.11	0.16
Statistic unc.	0.018	0.029	0.046	0.06
Systematic unc.	0.041	0.095	0.095	0.15
$t\bar{t}$ modelling	0.039	0.094	0.088	0.14
$t\bar{t}$ PS	<0.001	0.002	0.003	0.002
$t\bar{t}$ FSR	0.022	0.075	0.036	0.093
$t\bar{t}$ ISR	0.031	0.055	0.078	0.11
$t\bar{t}$ generator	<0.001	<0.001	<0.001	<0.001
$t\bar{t}$ PDF	0.01	0.015	0.019	0.022
$t\bar{t}$ cross-section	–	<0.001	<0.001	<0.001
Single-top modelling	0.007	0.009	0.020	0.023
Single-top Wt DR vs DS	0.005	0.007	0.014	0.015
Single-top PS	<0.001	0.002	0.007	0.015
Single-top generator	0.004	–	0.011	0.002
Single-top cross-section	0.003	0.002	0.003	0.003
W + jets (scale, cross-section)	0.004	0.003	0.004	0.005
Small-R jet energy	0.008	0.011	0.022	0.016
Large-R jet energy and mass	0.004	0.008	0.014	0.008
Small-R jet Flavour tagging related	0.001	0.001	0.001	0.002
Others	0.003	0.004	0.004	0.006

Table 4: SF and the relative uncertainties in each p_T^{probe} bin for the $X \to b\bar{b}$ tagger at the 60% efficiency working point. The contributions from the sub-categories are added in quadrature.

New $X \to b\bar{b}$ tagger

$g \to b\bar{b}$ studies



Label	description
BB	At least two track-jets contain *b*-hadrons
BL	Exactly one track-jet contains *b*-hadrons
CC	No *b*-hadrons and at least two track-jets contain *c*-hadrons
CL	No *b*-hadrons and exactly one track-jets contains *c*-hadrons
LL	No track-jets contain *b*- or *c*-hadrons

Table 5: Flavour category labels and definitions used in the $g \to b\bar{b}$ calibration.

New $X \to b\bar{b}$ tagger

$g \to b\bar{b}$ studies

ATL-PHY-PUB-2020-019

Before $X \to b\bar{b}$ tagger

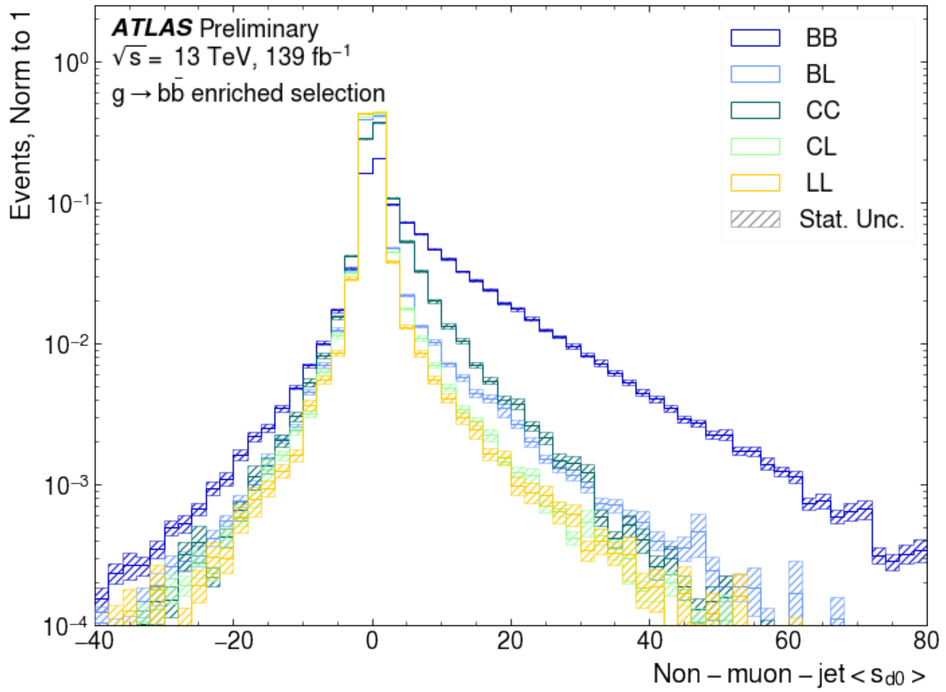
Category	Multijet	Top	Higgs
$\geq 2b$	0.022	0.019	0.922
$1b + \geq 1c$	0.005	0.221	0.007
$1b + 0c$	0.039	0.481	0.070
$0b + \geq 2c$	0.036	0.007	-
$0b + 1c$	0.098	0.109	-
$0b + 0c$	0.801	0.162	0.001
$= 1$ subjet	0.025	0.009	0.005
$= 2$ subjets	0.469	0.463	0.585
≥ 3 subjets	0.505	0.528	0.410

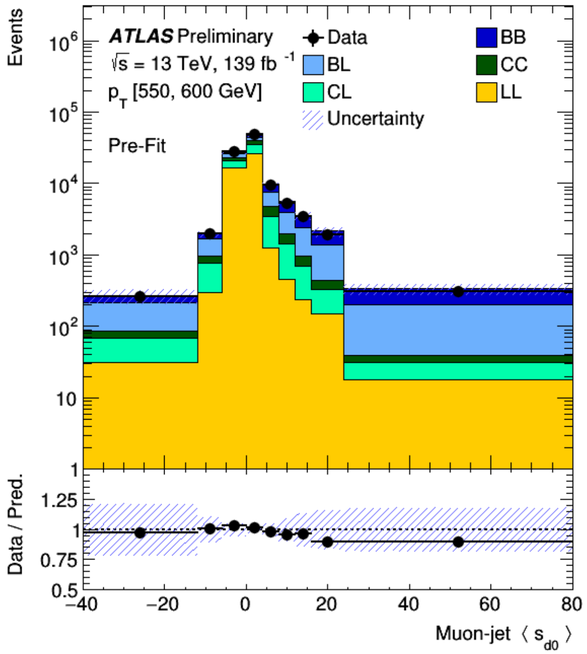
After $X \to b\bar{b}$ tagger (60%WP)

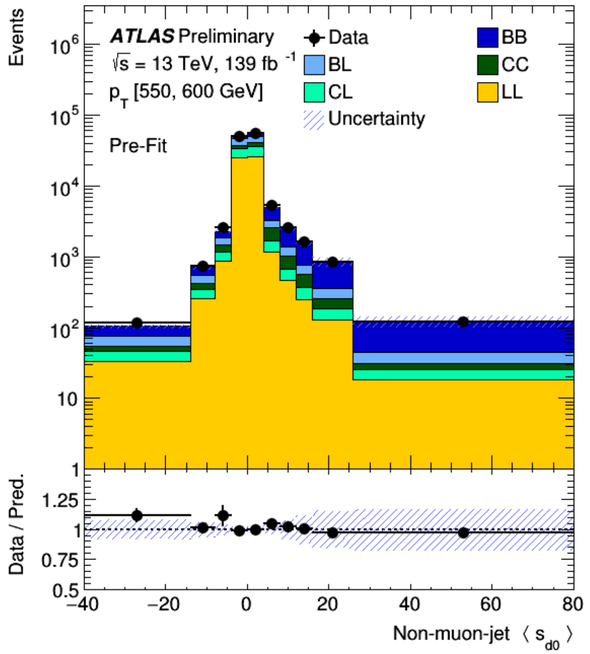
Category	Multijet	Top	Higgs
$\geq 2b$	0.871	0.229	0.997
$1b+ \geq 1c$	0.041	0.551	0.001
$1b + 0c$	0.046	0.216	0.002
$\geq 2c + 0b$	0.033	0.001	-
$1c + 0b$	0.008	0.003	-
$0b + 0c$	0.002	-	-

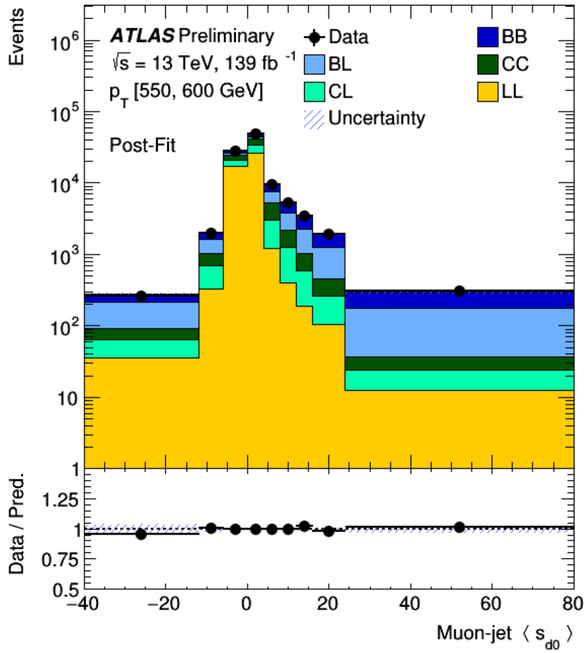
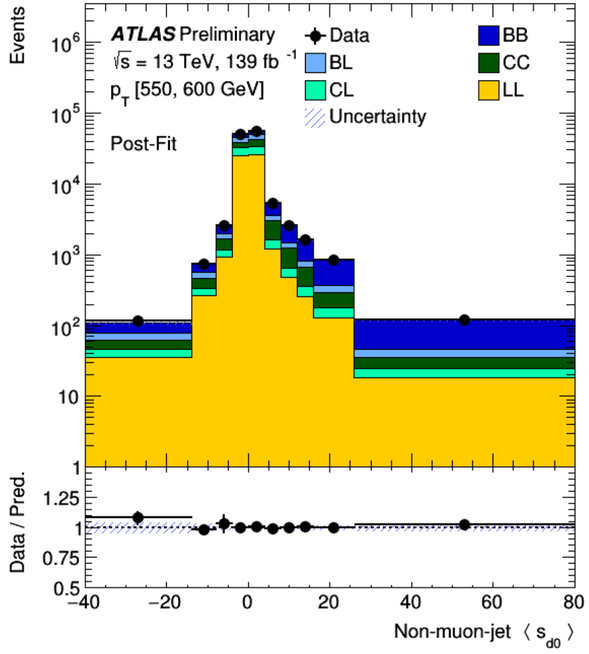
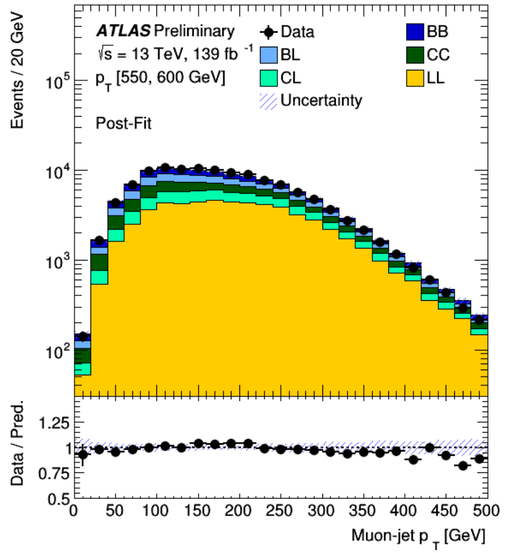
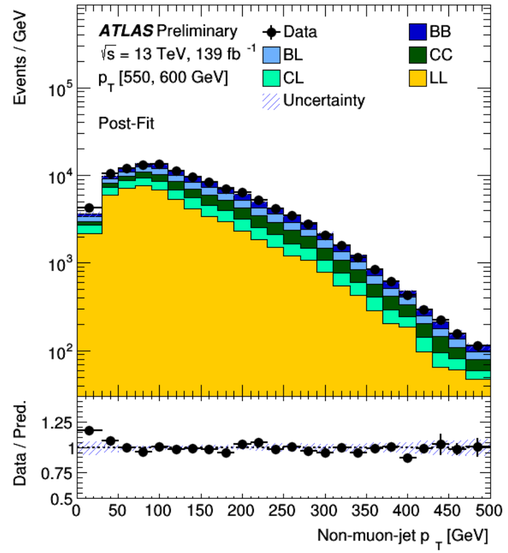
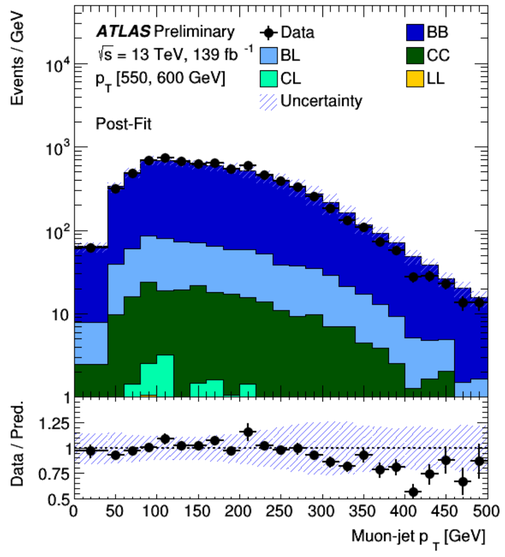
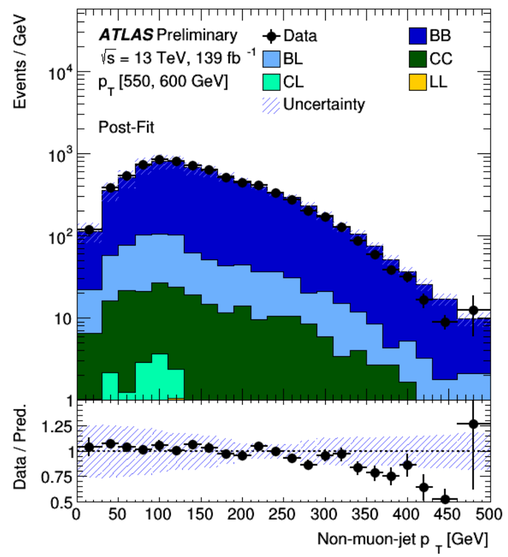
New $X \to b\bar{b}$ tagger

$g \to b\bar{b}$ studies







New $X \to b\bar{b}$ tagger

$g \to b\bar{b}$ studies