Calibration of boosted $X \to b\bar{b}$ tagger in ATLAS

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On behalf of ATLAS DXbb calibration team

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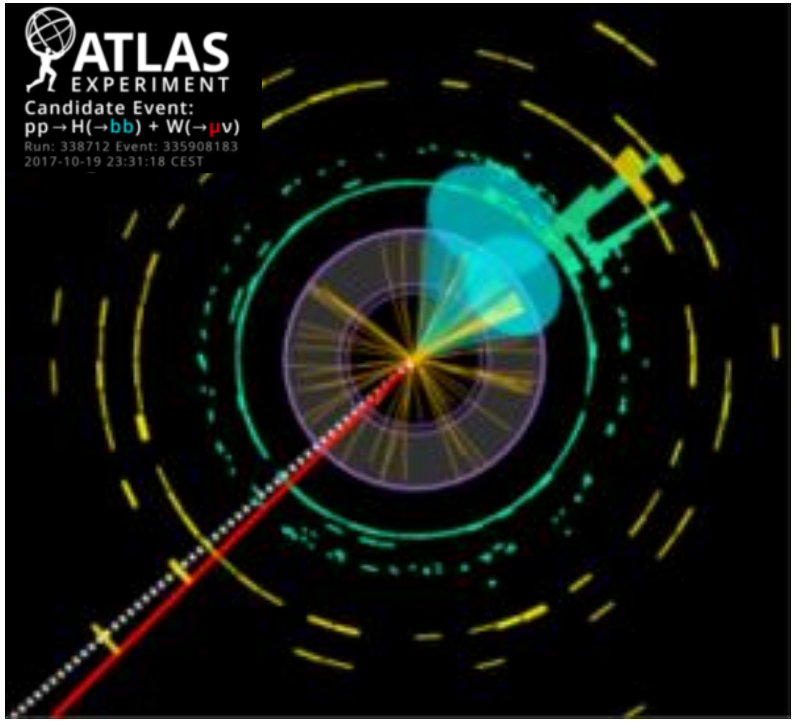
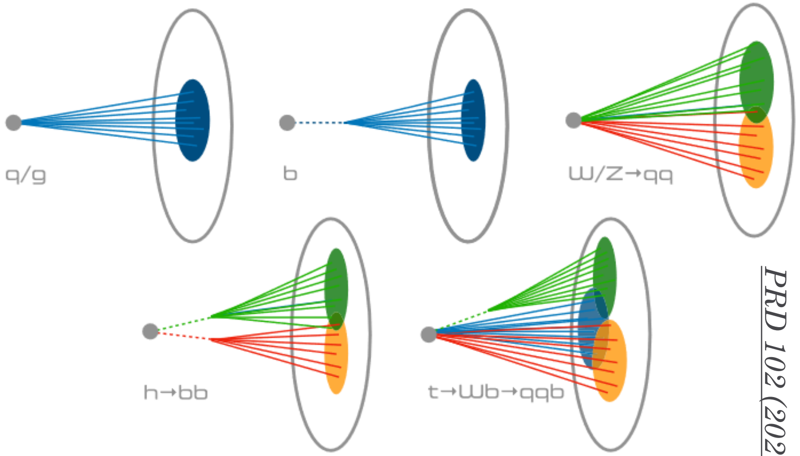
Introduction

- More interest in high transverse momentum region and boosted topologies especially $X \rightarrow b\bar{b}$ in HEP
- NN-based tagging method ***DXbb*** developed in ATLAS shows good performance
- **Series of calibration studied preparing for the application in physics analysis ← this talk**
- Active effort ongoing and promising future





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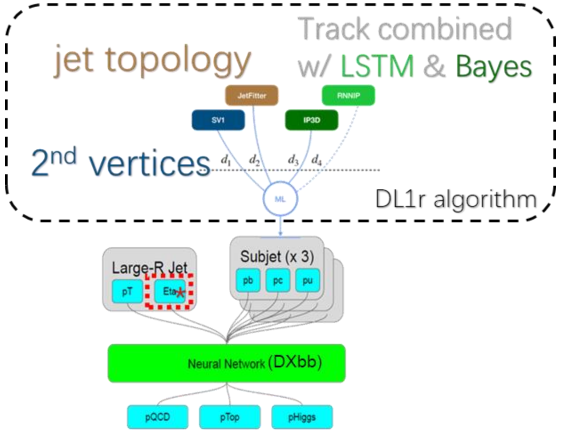
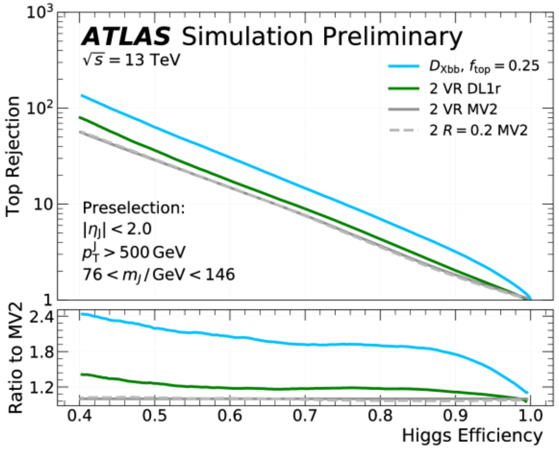
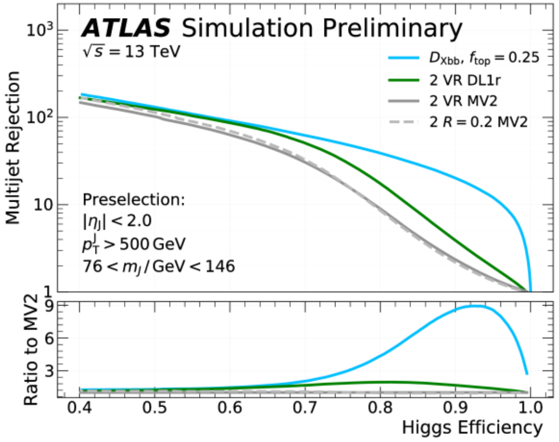
Boosted $X \rightarrow b\bar{b}$ tagging

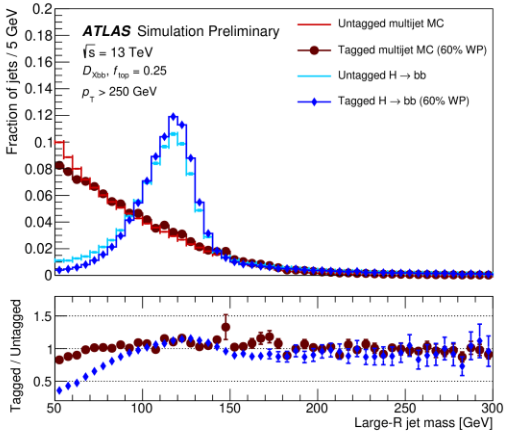
- Challenge for traditional method: highly boosted and collimated jets
- Especially with the heavy flavor like in the analysis of $VHbb$, $ggH \rightarrow bb$, WWW, $monoS(\rightarrow bb)$, $Y \rightarrow XH$
- ***DXbb*** uses large-Radius(R=1.0) jet and combines kinematics and information of track constitutes
- Good classification performance and mass decorrelation (ATL-PHYS-PUB-2020-019)

Dominant contribution from Tsinghua group CLHCP2020









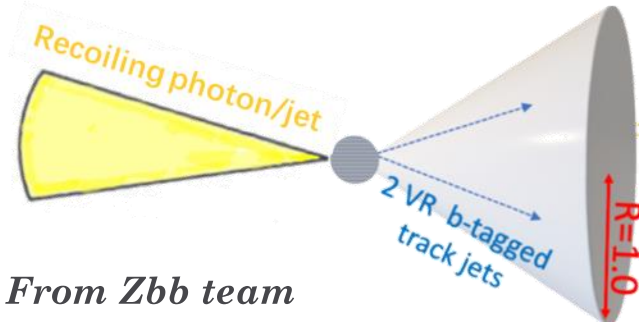
Calibration of $X \rightarrow b\bar{b}$ tagger

- Calibrated with full Run2 data and documented in the [ATL-PHYS-PUB-2021-035]

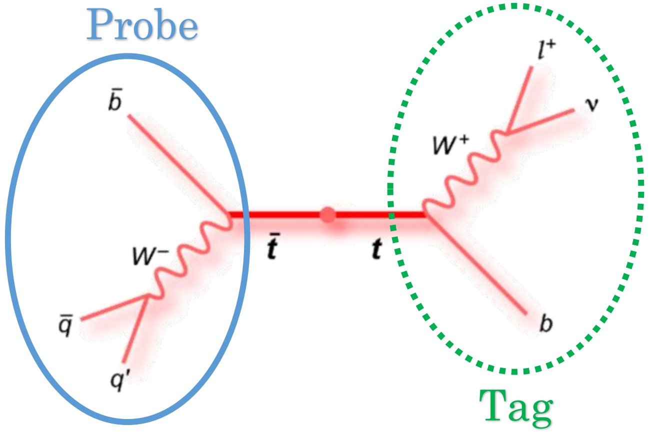
➢ $Z(\rightarrow b\bar{b}) + \gamma/jets$ calibration used for signal calibration

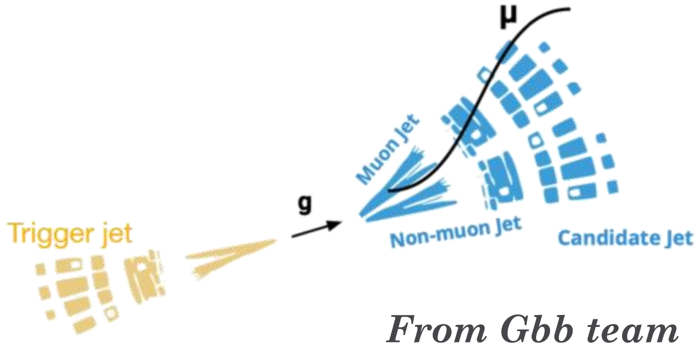
➢ Semi-leptonic $t\bar{t}$ calibration used for background calibration

➢ Gluon splitting calibration used for check of modelling



From Zbb team



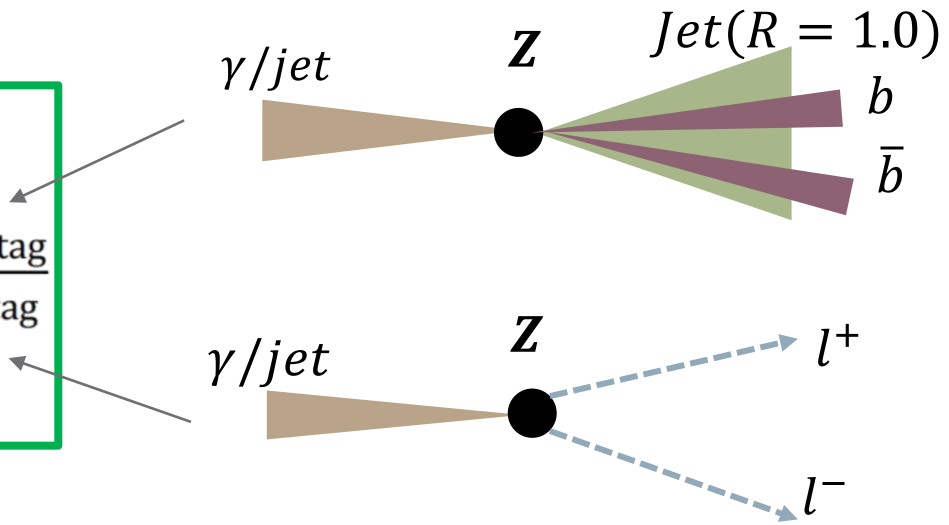


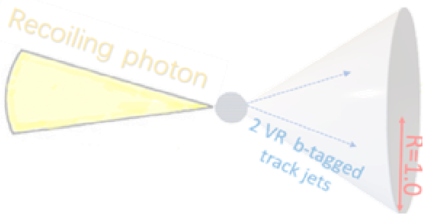
From Gbb team

Signal calibration: Overview

- $Z \rightarrow b\bar{b}$ process used for signal efficiency calibration with $p_T \in [200, 1000]$ GeV
- Recoiling photon or jet as trigger and Z peak provides good S/B
- Tagging efficiency($\boldsymbol{\epsilon}$) calibrated as the ratio of:
  - Post-tag correction from the $Z(\rightarrow b\bar{b}) + \gamma/jets$ process
  - Pre-tag correction from $Z(\rightarrow l^+l^-) + \gamma/jets$ at the same EWK/QCD accuracy as $Z(\rightarrow b\bar{b})$

$$\mathrm{SF} = \frac{\varepsilon^{\mathrm{data}}}{\varepsilon^{\mathrm{MC}}} = \frac{\dfrac{N^{\mathrm{data}}_{\mathrm{passed}}}{N^{\mathrm{data}}_{\mathrm{total}}}}{\dfrac{N^{\mathrm{MC}}_{\mathrm{passed}}}{N^{\mathrm{MC}}_{\mathrm{total}}}} = \frac{\dfrac{N^{\mathrm{data}}_{\mathrm{passed}}}{N^{\mathrm{MC}}_{\mathrm{passed}}}}{\dfrac{N^{\mathrm{data}}_{\mathrm{total}}}{N^{\mathrm{MC}}_{\mathrm{total}}}} = \frac{\mu_{\mathrm{post-tag}}}{\mu_{\mathrm{pre-tag}}}$$

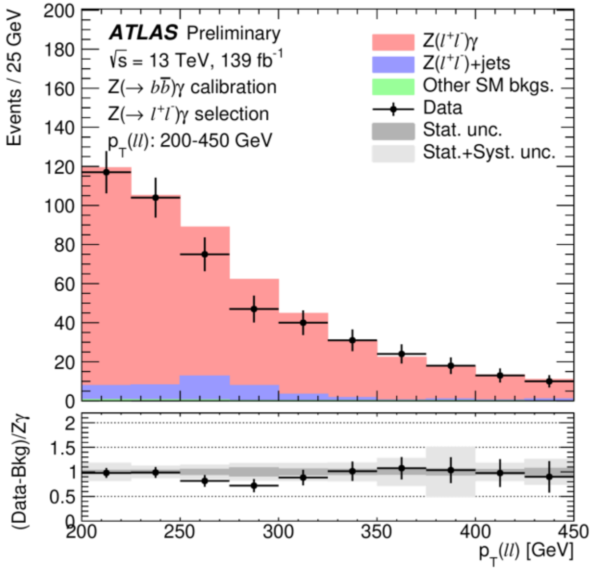


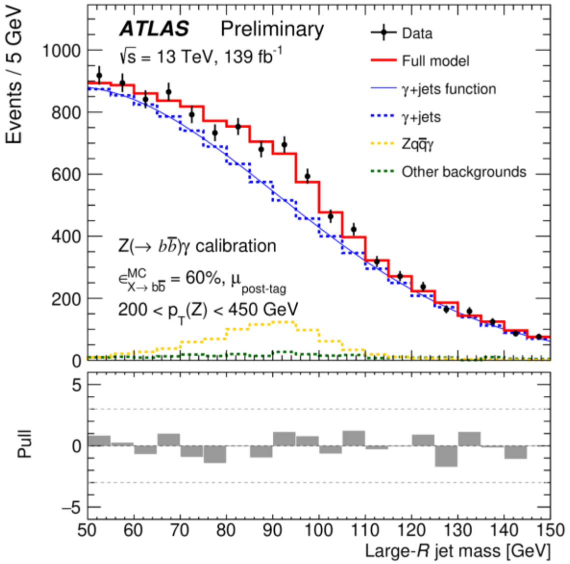


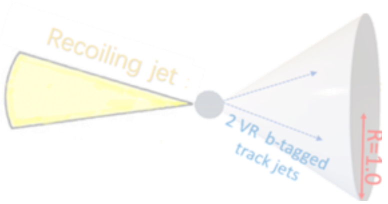
Signal calibration: $Z + \gamma$

- $Z + \gamma$ process used with p_T from 200GeV-450GeV
- Consistent photon trigger and similar selection for post-tag and pre-tag region
- Pre-tag: $Z(\rightarrow l^+l^-) + \gamma$ and dominant bkg $Z + jets(fake\ photon)$ from MC and good agreement with data
- Post-tag: $Z(\rightarrow b\bar{b}) + \gamma$ and other bkg ($W\gamma, t\bar{t}\gamma, fakes\ photon$) modelled using MC templates
- Dominant $\gamma + jets$ from exponentiated polynomial, validated by extra F-test and spurious signal test

	post-tag	pre-tag
Photon	$Single\ photon\ trigger\ , p_T > 200\ GeV$	
Z-candidate	$p_T \in [200{,}450\ GeV]$	
	$\geq 2\ tracks\ jets$ with $p_T > 7GeV$	$2\ same\ flavor\ leptons$ with $p_T > 20GeV$
	$m_J \in [50{,}150\ GeV]$	$m_{ll} \in [70{,}110\ GeV]$
	$\Delta R_{J,\gamma} > 1.0$ $2m_J/p_T < 1.0$	$OS\ in\ muon\ channel$ $lepton\ p_T\ balance$
Separation	$\Delta\phi_{Z,\gamma} > \pi/2$	



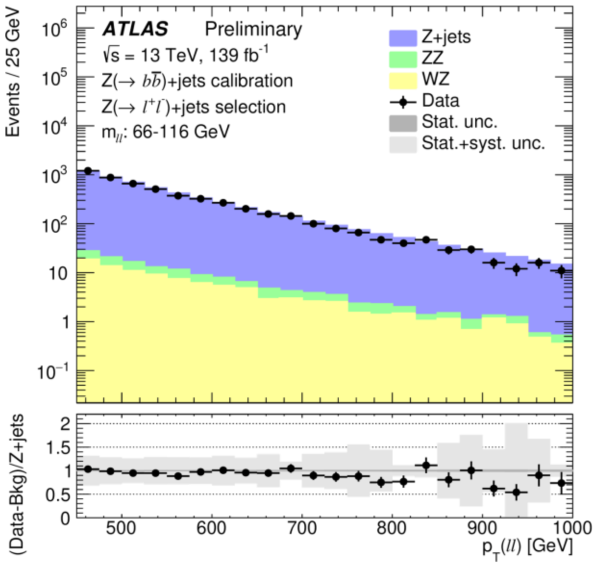


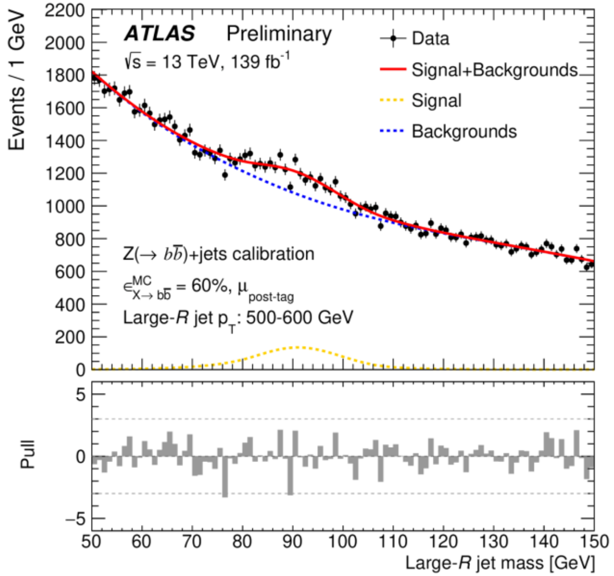


Signal calibration: $Z + jets$

- $Z + jets$ process used with p_T from 450GeV-1000GeV
- Jet or lepton trigger used and consistent selection for post-tag and pre-tag region
- Pre-tag: $Z(\rightarrow l^+l^-) + jets$ and dominant bkg $diboson(ZZ, WZ)$ from MC
- Post-tag: $Z(\rightarrow b\bar{b}) + jets$ and other bkg ($W + jets, t\bar{t}$) modelled using [Double-sided crystalball(DSCB)]
- Dominant multijet bkg modelled with (exponentiated) polynomial with different order in 3 p_T regions

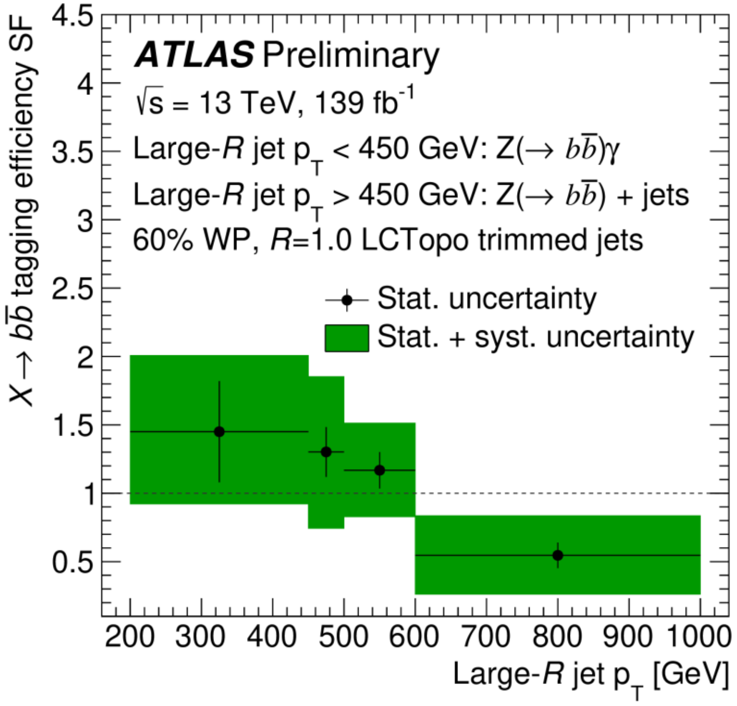
	post-tag	pre-tag
Trigger	$single\ large - R\ jet$	$single\ lepton\ trigger$
Z-candidate	$p_T \in [450, 1000\ GeV]$	
	$\geq 2\ tracks\ jets$ $with\ \ p_T > 7GeV$	$2\ electrons(muons)$ $with\ p_T > 25(27)GeV$
	$m_J \in [50{,}150\ GeV]$	$m_J \in [66{,}116\ GeV]$
Balance	$\Delta p_{T_{J,J}} < 0.15 \sum p_{T_J}$	$\Delta p_{T_{ll,J}} < 0.15 \sum p_{T_{ll/J}}$
	$\lvert\Delta y_{J,J}\rvert < 1.2$	$\lvert\Delta y_{ll,J}\rvert < 1.2$
	-	$\Delta p_{T_{l,l}} < 0.8 \sum p_{T_l}$
Extra	-	$p_{T_{ll}} > p_{T_J}$





Signal calibration: Result

- Correction of the tagging efficiency between $1.45^{+0.47}_{-0.45} \sim 0.55^{+0.23}_{-0.22}$
- Dominant uncertainties from statistical, fit model and signal modelling

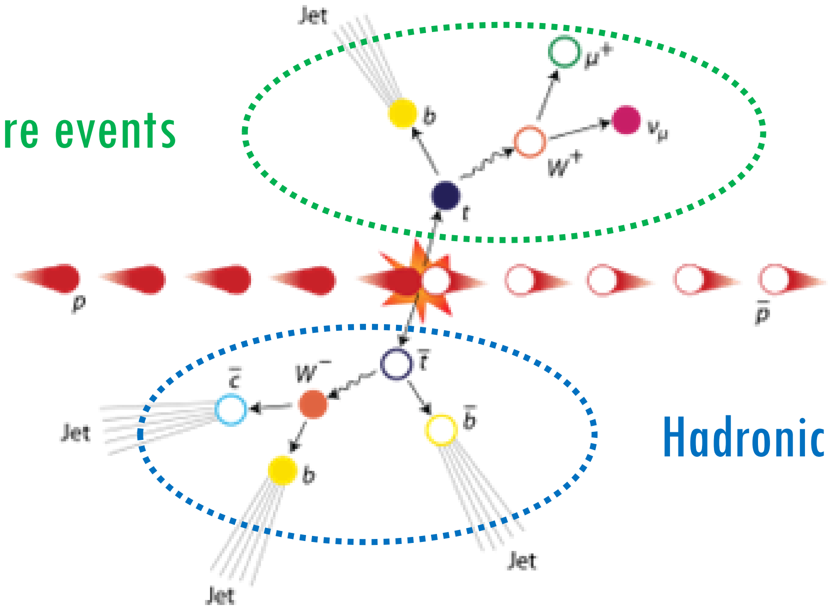


Calibration	$Z(\to b\bar{b})\gamma$	$Z(\to b\bar{b})$ + jets		
p_{T} [GeV]	200 – 450	450 – 500	500 – 600	600 – 1000
$\mu_{\mathrm{post-tag}}$	1.33	1.32	1.10	0.51
$\mu_{\mathrm{pre-tag}}$	0.92	1.01	0.94	0.93
SF	1.45	1.30	1.17	0.55
Uncertainties ($\pm\sigma$)				
Statistical	±0.37	±0.18	±0.13	±0.09
Z-boson 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	$< \pm0.01$	$< \pm0.01$
Total uncertainty	$^{+0.53}_{-0.56}$	$^{+0.55}_{-0.56}$	$^{+0.35}_{-0.34}$	$^{+0.29}_{-0.28}$

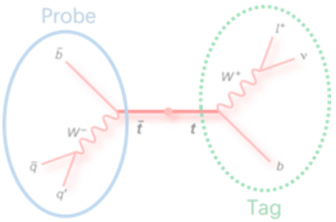
Background calibration: Overview

- Semi-leptonic $t\bar{t}$ used for background efficiency ($\epsilon_{mis-tag}$) calibration
- Clear signatures for selection and complex flavor composition
- Normalization and mis-tag efficiency corrected simultaneously of $p_T \in [300, 1000]$ GeV

Leptonic side: **tag** the pure events

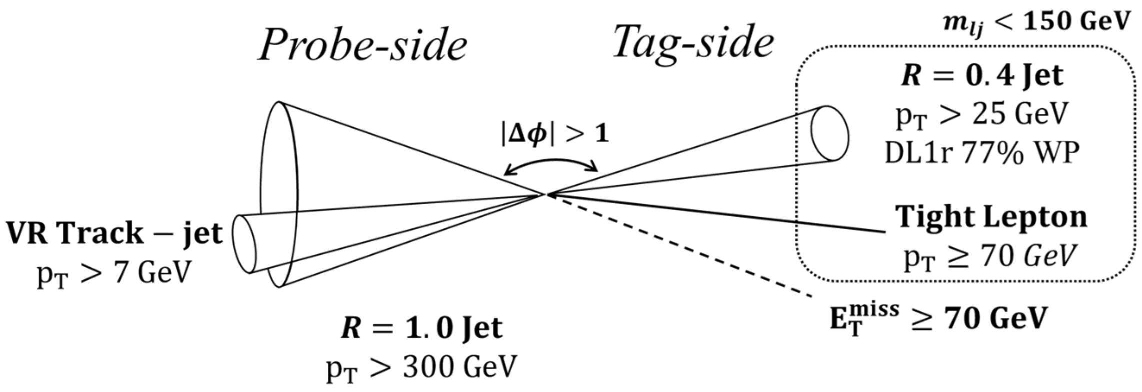


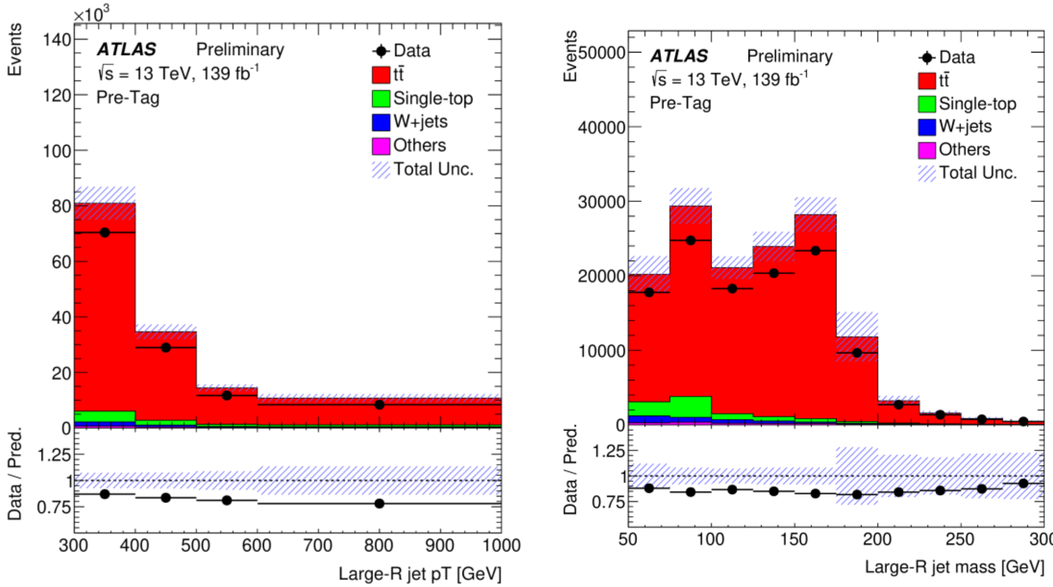
Hadronic side: **probe** the DXbb efficiency

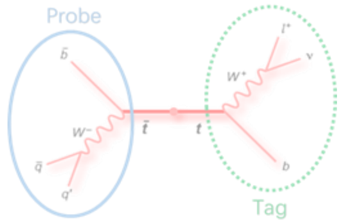


Background calibration: Event Selection

- Lepton trigger and requirement on leptonic side for pure $t\bar{t}$ events
- Dominant bkg $W + jets$ and tW highly suppressed using single-b-tagging and m_{lj} cut
- Hadronic decay top reconstructed as large-R jet with mass $\in$ [50, 300] GeV
- Over-estimation of $t\bar{t}$ simulation observed and corrected

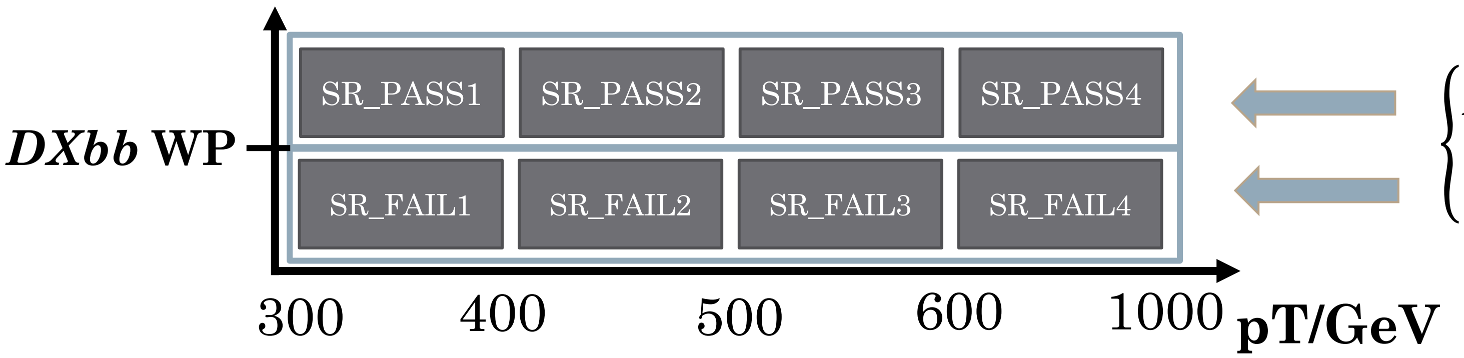






Background calibration: Methodology

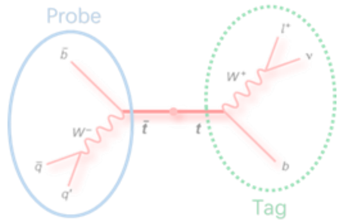
- $\epsilon_{mis-tag}$ correction (**SF**) extracted from fitting on mass
- $t\bar{t}$ normalization correction (**NF**) determined simultaneously
- Two sets of orthogonal regions (PASS/FAIL tagging) defined in 4 p_T bins
- Correlated with a priori ϵ^{MC} obtained from simulation samples



$$SF \equiv \frac{\epsilon^{data}}{\epsilon^{MC}}$$

$$\begin{cases} D_{pass} = NF * SF * S_{pass} + B_{pass} \\ D_{fail} = NF * SF' * S_{fail} + B_{fail} \end{cases}$$

$$SF' \equiv \frac{1 - \epsilon^{MC} * SF}{1 - \epsilon^{MC}}$$



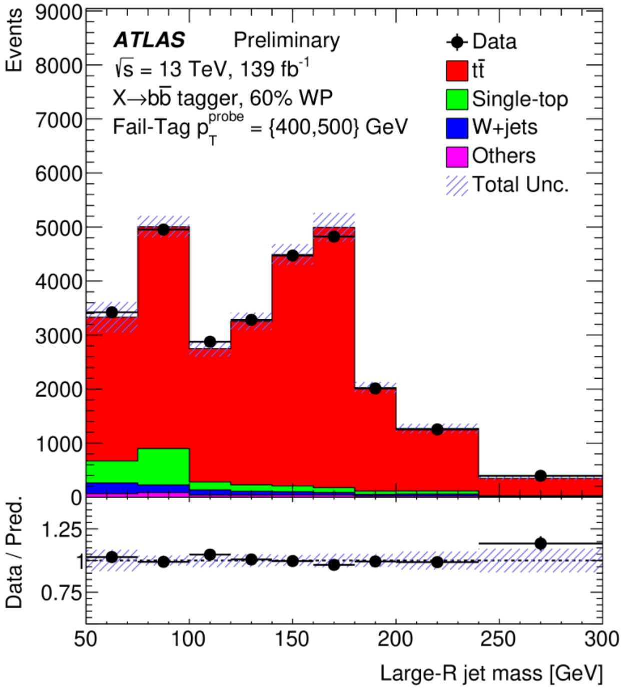
Background calibration: Systematics

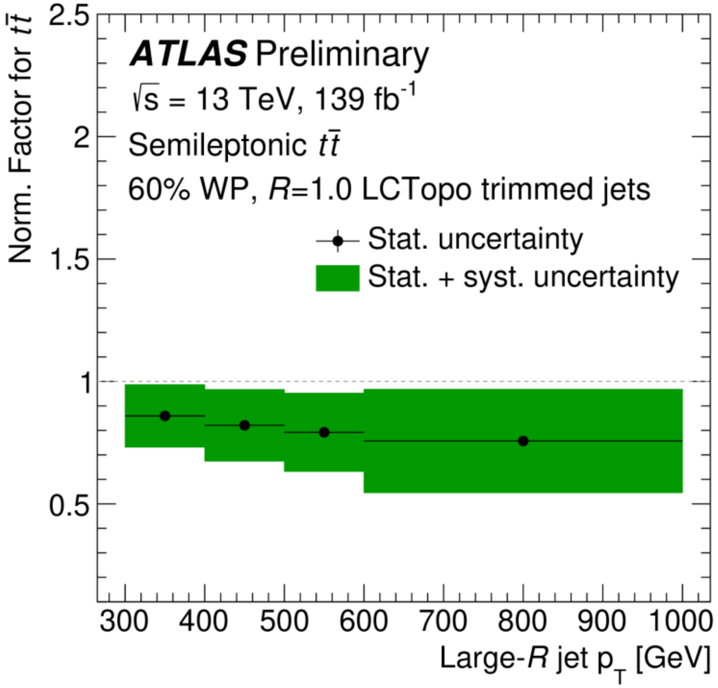
- Assessed with non-profiling method ($\sum\sigma^2$)
- Dominant from the modelling of ttbar, up to 15% in the high p_T region
- Different choice of generator and parton showering reflected in the priori ϵ^{MC}
- Residual uncertainty is under control

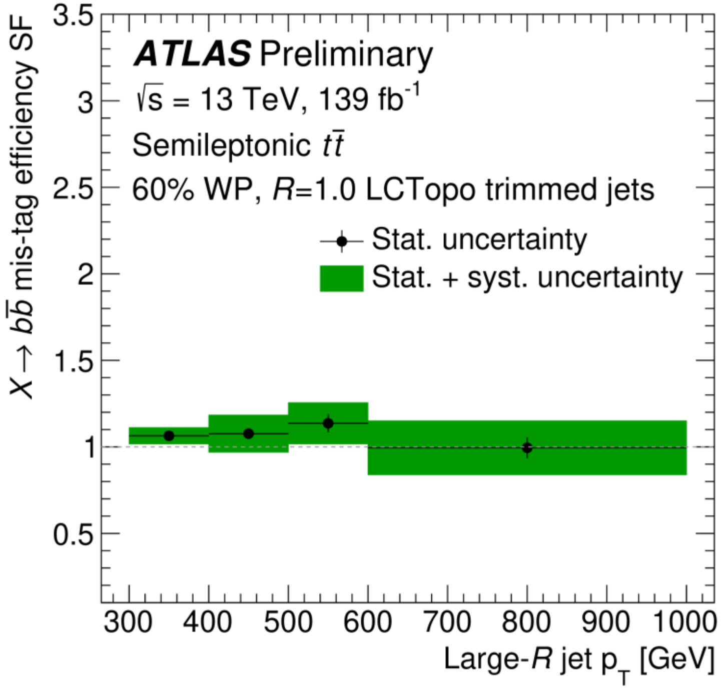
p_T [GeV]	300 – 400	400 – 500	500 – 600	600 – 1000
SF	1.06	1.08	1.14	0.99
Total unc.	0.045	0.10	0.11	0.16
Statistic unc.	0.018	0.029	0.046	0.06
Systematic unc.	0.041	0.095	0.095	0.15
$t\bar{t}$ modelling	0.039	0.094	0.088	0.14
$t\bar{t}$ PS	<0.001	0.002	0.003	0.002
$t\bar{t}$ FSR	0.022	0.075	0.036	0.093
$t\bar{t}$ 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

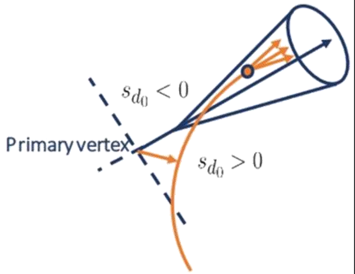
Background calibration: Results

- Good agreement between data and prediction after correction
- Normalization correction measured to be about 0.8 and over-estimation corrected
- SF measured to be 1.1 ± 0.12~1.0 ± 0.16 and compatible with unity within uncertainty





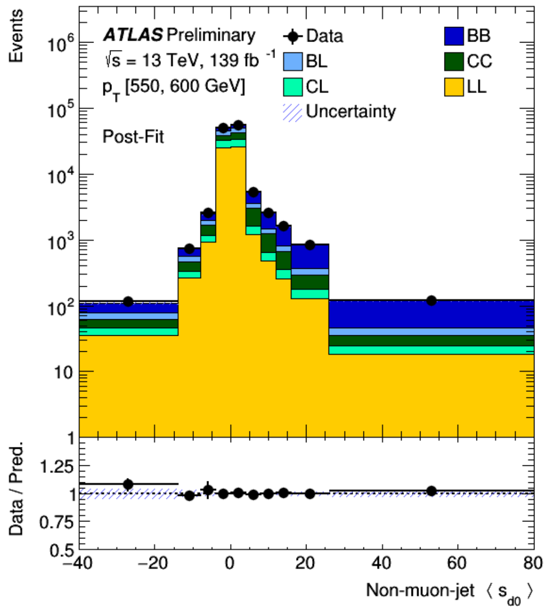


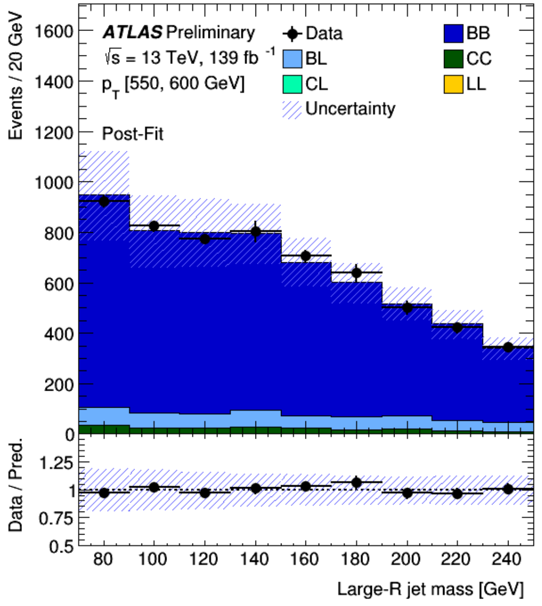


Check of MC Modelling with $g \rightarrow b\bar{b}$ process

- Multijet events used in the study of modelling of MC especially after tagging
- Flavor-sensitive variable $\langle sd_0 \rangle$ used as fitting discriminant to correct flavor fraction
- Good agreement is observed between data and prediction after flavor correction

Trigger	prescaled small-R jet (j_{recoil})
Primary Vertex	Highest p_T^2 sum of tracks
Track Jet	1 muon matched (j_{μ}^{trk}) & 1 non-muon matched ($j_{non-\mu}^{trk}$)
Large-R jet	$p_T > 500\ GeV$ $with\ \geq 1\ j_{muon}^{trk}$
Overlap Removal	$\Delta R_{j_{recoil}, j_{\mu}^{trk}} > 1.5$





Summary

- *NN*-based boosted $X \rightarrow b\bar{b}$ tagger $\boldsymbol{DXbb}$ developed in ATLAS is calibrated with full Run2 data and preparing for physics analysis (ATL-PHYS-PUB-2021-035)

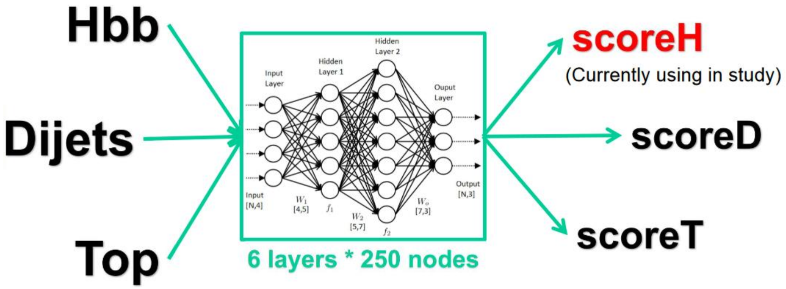
✓ Signal efficiency calibrated using $Z(\rightarrow b\bar{b}) + \gamma/jets$

✓ **Background efficiency ($\boldsymbol{\epsilon_{mis-tag}}$) calibrated using semi-leptonic $\boldsymbol{t\bar{t}}$ [my work]**

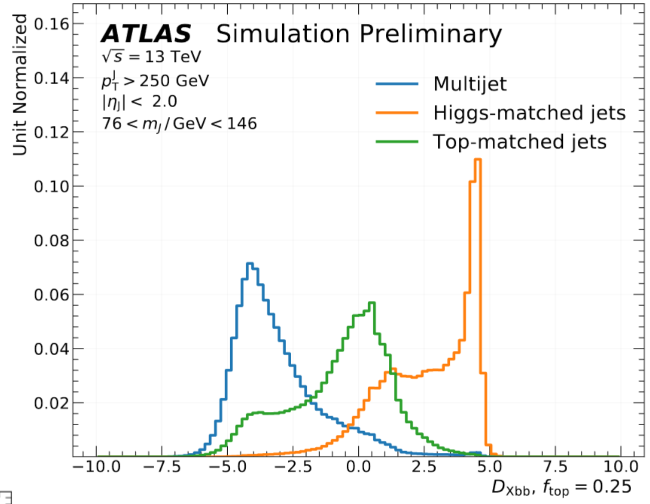
✓ Data and prediction agreement checked in the $multijets$ events

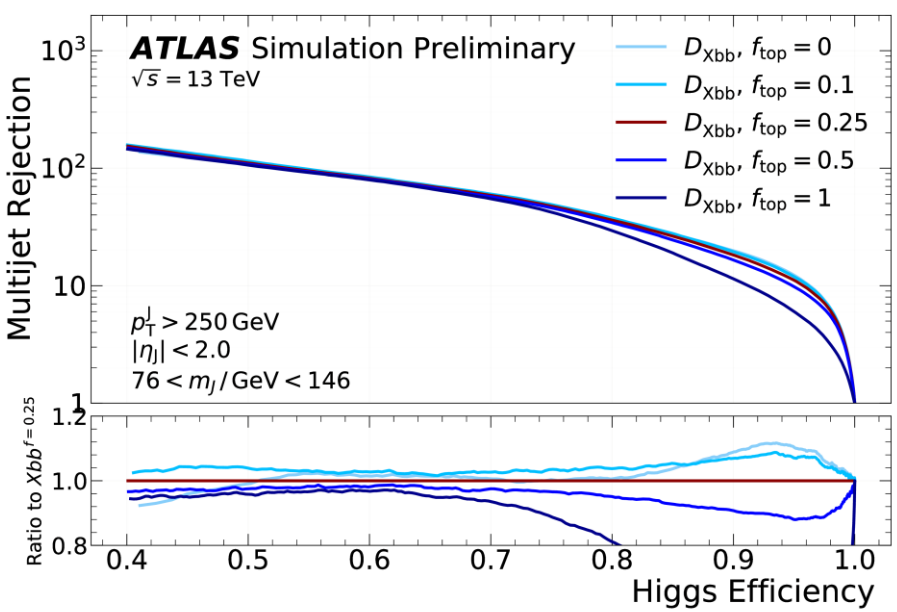
- Study and test of $\boldsymbol{DXbb}$ has been or is being performed in ongoing analyses
- Promising application (with updated recommendation) in the near future

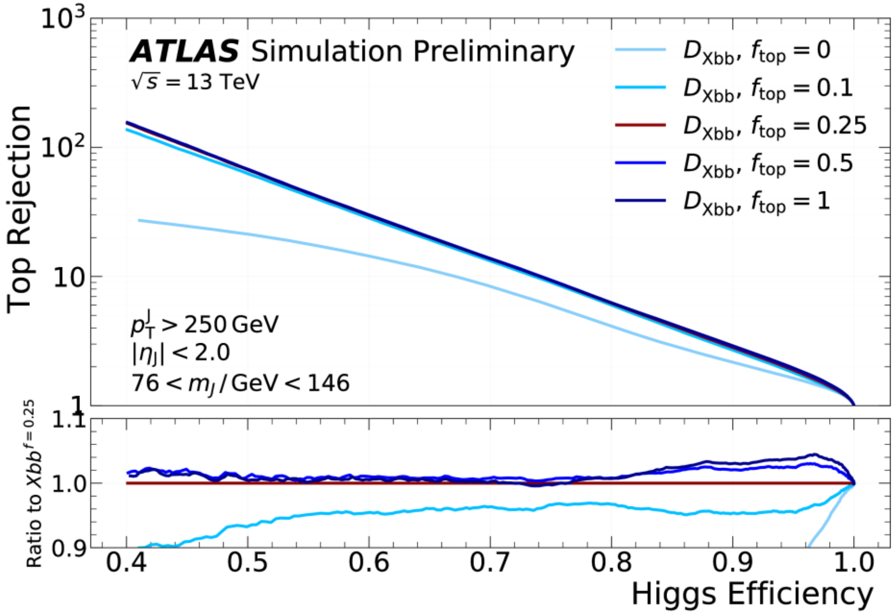
Backup: technical detail of DXbb

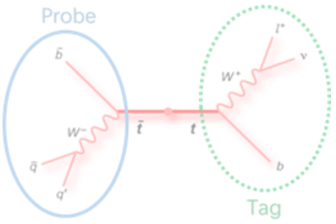


$$D = \ln\left(\frac{p_H}{(1-f_{top})p_{QCD} + f_{top}p_{top}}\right) \rightarrow$$



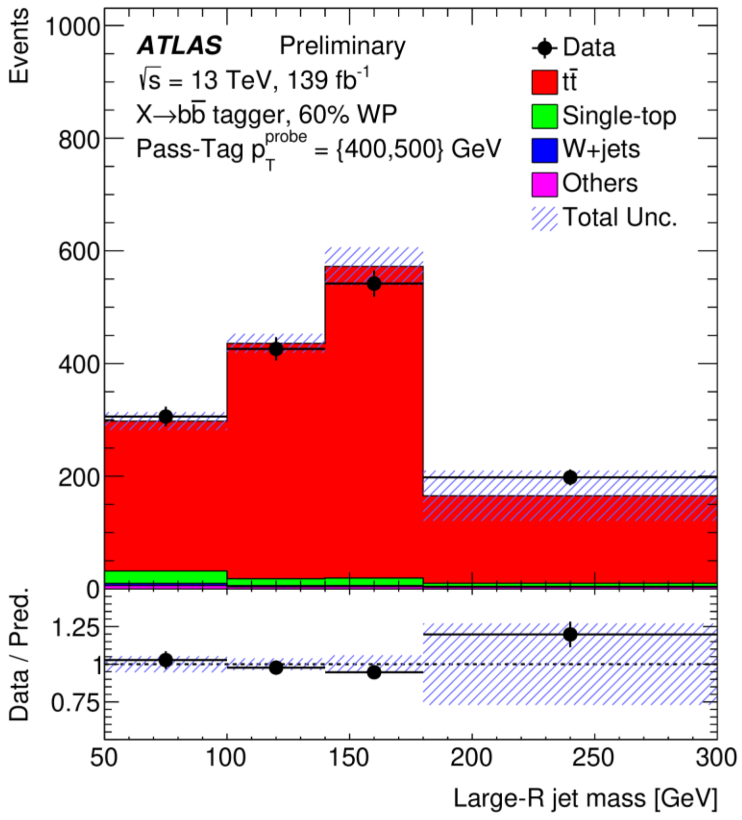


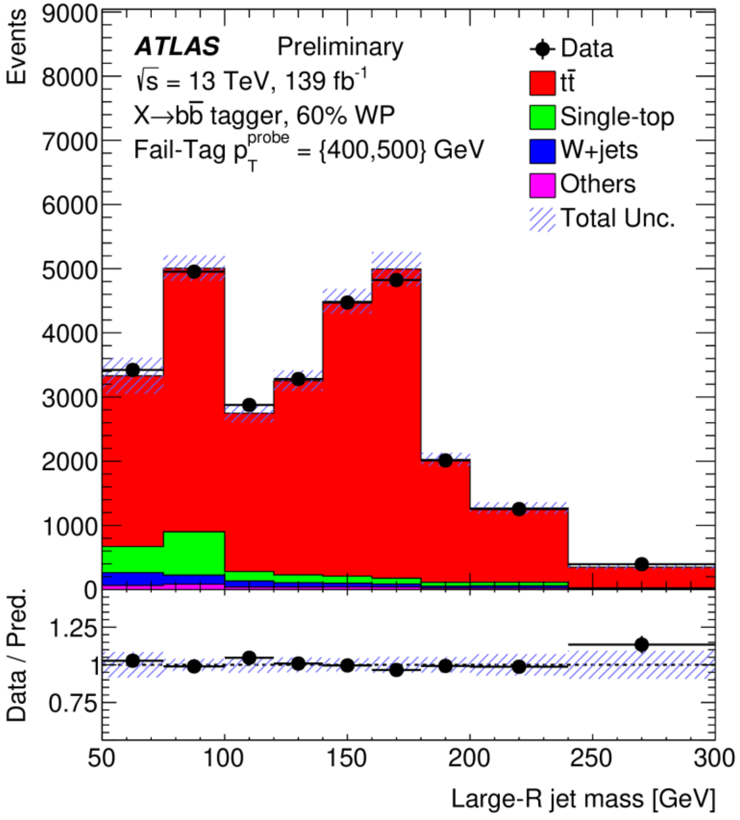


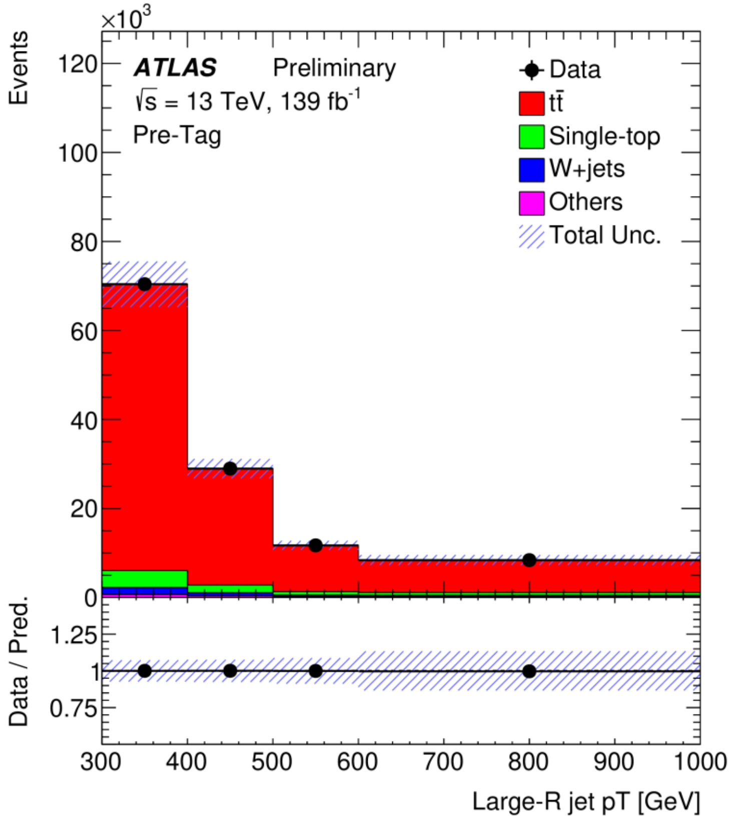


Background calibration: More results

- A good agreement is obtained between data and simulation after fitting (backups)







Functional form of dominant background in post-tag region of Z+γ/jets calibration

- Dominant background in $Z(\to b\bar{b}) + \gamma/jets$ are estimated parametrization and the functional form are optimized and validated by spurious signal test and F-test
  - Criterion of spurious signal test: $|S_{spur}| < 0.5\sigma_{others}, where\ S_{spur} \equiv S_{fitted} - S_{injected}$
  - Criterion of F-test: $p(F) > 0.05, where\ F \equiv \frac{\chi^2_{nom} - \chi^2_{alt}}{N_{par,alt} - N_{par,nom}} \Big/ \frac{\chi^2_{nom}}{N_{bins} - N_{par,nom}}$

- Dominant background in $Z(\to b\bar{b}) + \gamma$ calibration is $\gamma + jets$ and the optimal form found to be exponentiated polynomial with 2 parameters:

$$f_2(x) = a_0 \exp\left(\sum_{i=1}^{2} a_i x^i\right), x \equiv \frac{m_{Z\to b\bar{b}} - 100[GeV]}{50[GeV]}$$

- Parameters determined on side-band data with $m \in [50, 65\ GeV], [110, 150\ GeV]$

- Dominant background in $Z(\to b\bar{b}) + jets$ calibration is $multijets$ and the optimal form found to be (exponential) polynomial with different parameters in p_T :

$Z \to bb$ p_T bin	Optimal function
$450 \le p_T < 500$ GeV	$\sum_{i=0}^{3} a_i (\frac{m}{100[GeV]})^i$
$500 \le p_T < 600$ GeV	$\sum_{i=0}^{3} a_i (\frac{m}{100[GeV]})^i$
$600 \le p_T < 1000$ GeV	$a_0 \exp(\sum_{i=1}^{3} a_i (\frac{m}{100[GeV]})^i)$

- Parameters determined on side-band data with $m \in [50, 70\ GeV], [110, 150\ GeV]$