Performance of b-jet identification in ATLAS.

CMS Heavy flavour tagging workshop

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11 April 2018

HELMHOLTZ GEMEINSCHAFT

DESY

Disclaimer on the choice of topics

All ATLAS public results regarding Flavour Tagging are available here:
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- **a significant part of the b-tagging chain in ATLAS:**
  → flavour labeling, track association, identification algorithms, calibration.
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I will not cover* ...

- upgrade studies
- online b-tagging performance
- **c-tagging $\rightarrow$ see Andy C's talk** on "$H \rightarrow cc$ in ATLAS" this morning
- more generally, new developements with not yet public reference

*sorry in advance if your favorite topic is missing, I will do my best to answer questions

Why b-jet identification so important at the LHC?

- Identifying jets corresponding to a *b*-quark (*b*-tagging) is essential to many LHC data analysis
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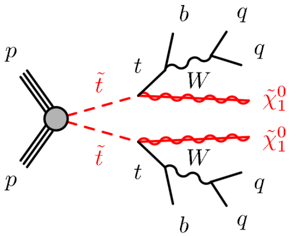
Top Physics / New Phenomena

→ top precision measurements

→ many searches, such as searches for stop pair production (SUSY)



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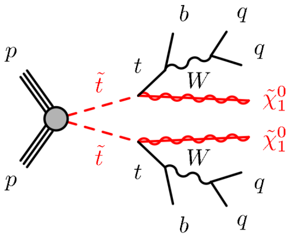
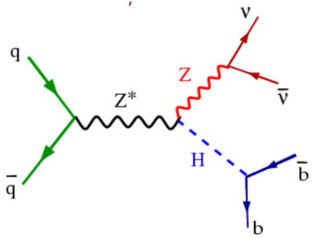


Higgs Physics

→ observation of $b\bar{b}$ decay mode

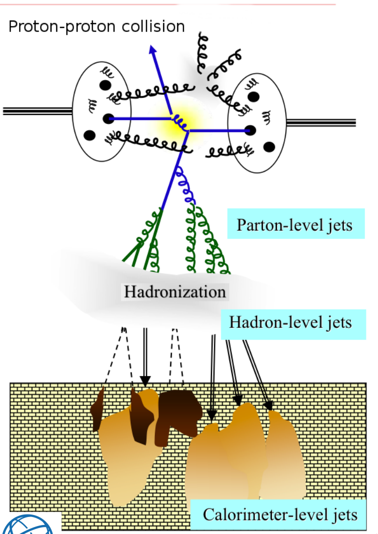
→ direct measurement of the top-Higgs coupling (ttH production)



1) Flavour labeling

– How do we define a b-jet, a c-jet and a "light-flavour"-jet in our simulated samples?

What’s a hadronic jet?



- Initial interacting partons determined from the Parton Density functions (PDFs)
- Perturbative QCD (matrix elements ME, parton shower PS), very small timescales $\rightarrow$ **coloured final state objects**
- Partons can be grouped together via a clustering algorithm $\rightarrow$ **definition of “parton-level” jets**

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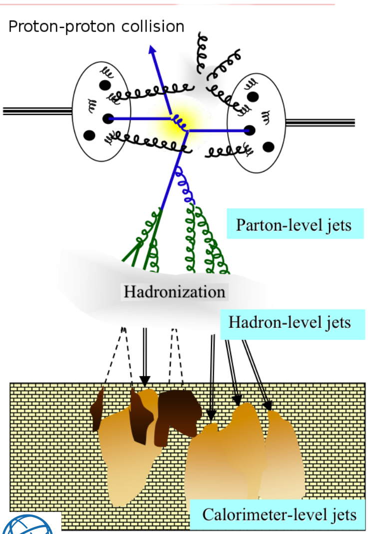

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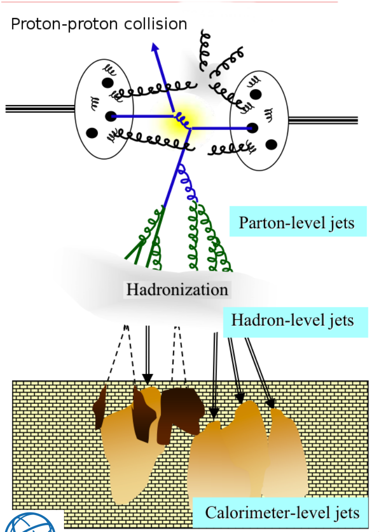

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- Parton $\rightarrow$ Hadrons (hadronization), other non-perturbative effects (underlying event) $\rightarrow$ **definition of "particle-level" jets**
- Experimentally, clustering based on **calorimeter energy deposits or inner detector tracks**

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– **definition of "including" is analysis dependent**, for flavour-tagging performance studies in ATLAS during Run 2 we use:

$$\boxed{\Delta R(\text{b-hadron, jet}) = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3}$$ **(priority to closest jet)**

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Wrapping up, in ATLAS simulation:

b-jets are jets including at least one *b*-hadron with $p_T > 5$ GeV

c-jets do not include *b*-hadrons but include at least one *c*-hadron with $p_T > 5$ GeV

τ-jets do not include *b*/*c*-hadrons but include at least one τ-lepton with $p_T > 5$ GeV

LF-jets ("light-flavour") are all the others

What about quark/gluon labeling?

A. Buckley, C. Pollard, arXiv:1507.00508 [hep-ph]

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Scheme	Generator	Jets	γ + jet	
		q/g	γ/g	q/g
Max-p_T	Pythia 8	0.39	15.4	9.5
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- **QCD-aware parton labeling:** k_T algorithm on partons + prompt lepton/γ vetoing proto-jet merging not compatible with a QCD/QED vertex

→ $k_T \sim$ "inversion of the QCD emission sequence"

→ **LO generators in good agreement**

k_T	Pythia 8	0.65	11.8	7.6
MPI off	Herwig++	0.68	11.2	8.0
	Sherpa	0.73	13.0	7.0

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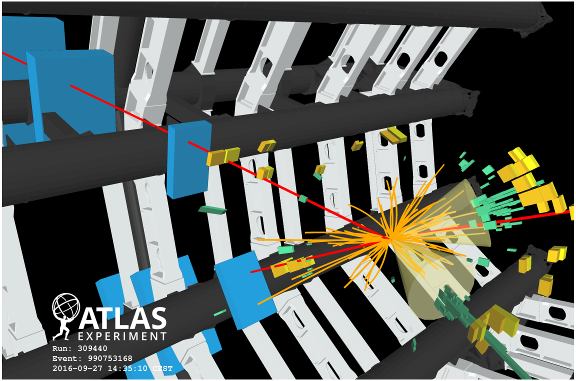
  $\rightarrow$ $k_T \sim$ "inversion of the QCD emission sequence"

  $\rightarrow$ **computation at various perturbative order (Sherpa) in good agreement**

ME	$N_{j3}/N_{j3}^{2\to2}$	Gluon frac.	Light quark frac.	Light parton frac.	Unlabelled frac.
$2\to2$	1.00	62.7%	27.0%	89.6%	2.3%
$2\to3$	1.59	56.4%	31.4%	88.3%	2.9%
$2\to4$	1.79	58.3%	31.9%	90.2%	2.6%

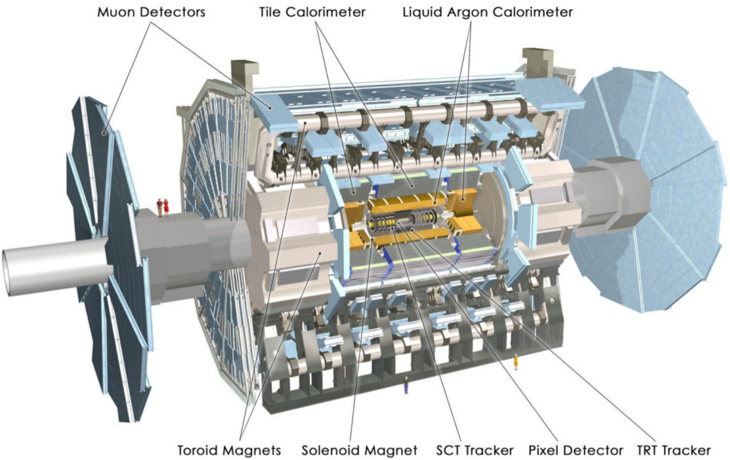
2) Jet-to-track association

- Which jet gets which tracks?



Candidate H → bb decay event with two b-jets and two muons recorded in 2016

Jets and track reconstruction in ATLAS



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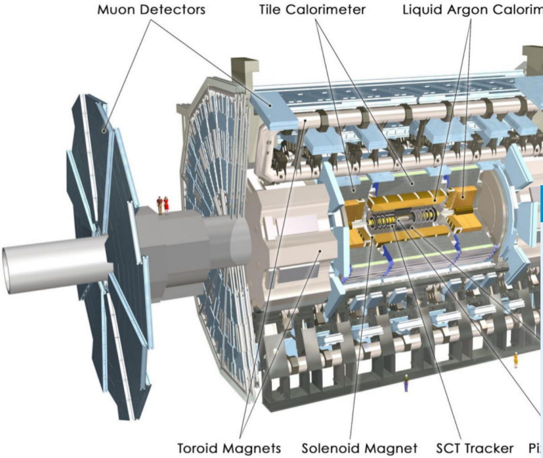

Inner detector

- $B = 2$ T
- Non-destructive detection of charged particles
- trajectories, p_T
- **primary (PV) and secondary vertices (SV) reconstruction**
- **track impact parameters**
- track momentum (angular) resolution decreases (increases) with p_T

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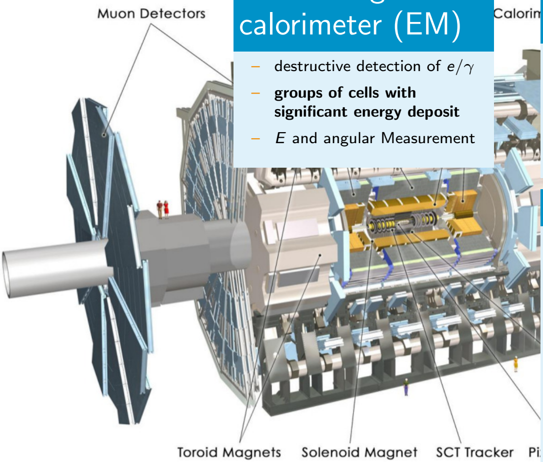

Electromagnetic calorimeter (EM)

- destructive detection of e/γ
- **groups of cells with significant energy deposit**
- E and angular Measurement

Hadronic calorimeter

- destructive detection of hadrons
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Jets and track reconstruction in ATLAS

Muon spectrometer

- $B = 0.5$ T (mean)
- muon detection
- **not included in the ATLAS most used b-tagging algo.**

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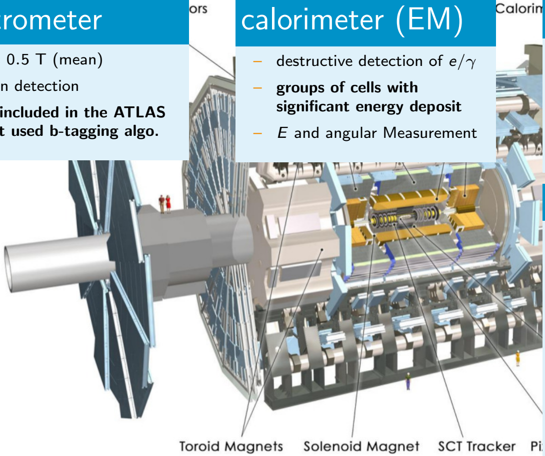

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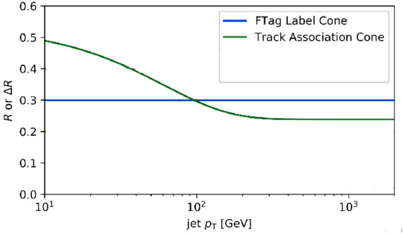
Track association algorithms

See ATL-PHYS-PUB-2017-010 for more details

– $R = 0.4$ anti-k_t calorimeter jets are the most common jets in ATLAS
  $\rightarrow$ **shrinking cone algorithm used to determine the tracks used for b-tagging**



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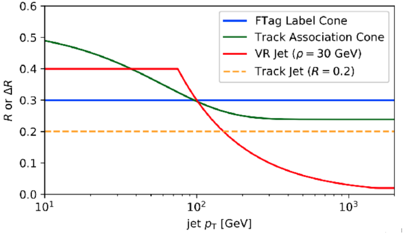

- Many recent activities studying anti-k_t jets based on tracks **(track jets)**
  $\rightarrow$ **primary use case: b-tagging in dense environment** (Top, Higgs, $X \rightarrow bb$)
  $\rightarrow$ studies include e.g. $R = 0.2$ and variable-R (shrinking cone) track jets

Subjet reconstruction with tracks

- Reconstruction of 1 large-R jet, **adequate constituent (subjet) reconstruction required to determine substructure accurately**
- Tracks have better angular resolution than calorimeter clusters
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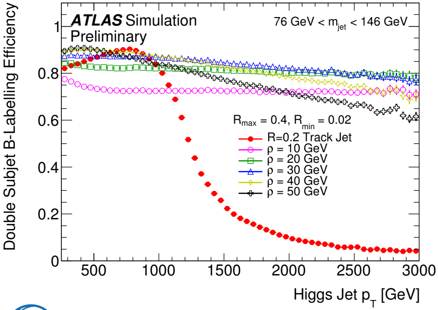
Probability to find 2 subjets truth-labeled as b



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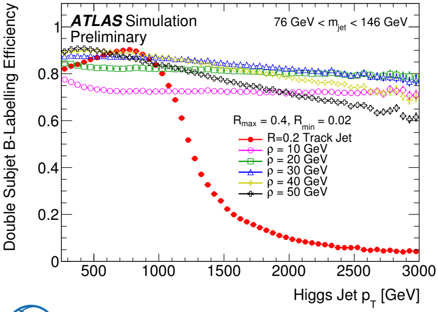
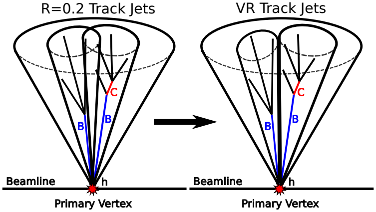


R=0.2 track jets vs Variable-R ($\sim \rho/p_T$)



- currently assessing b-tagging performance in data of such subjets
- other ideas also explored

3) b-jet identification algorithm

– **Properties of b-hadrons:**

1. **lifetime:**
   V_{cb} small, decay length $\sim 450\ \mu$m
2. **large mass:** few GeV
3. **high jet momentum fraction:** $\sim 80\%$
   due to b-fragmentation function
4. **high branching ratio to leptons:** $\sim 20\%$

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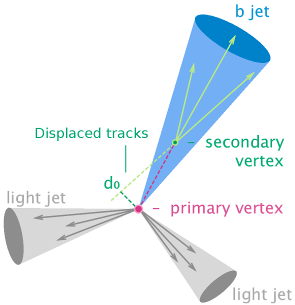

topology of *b*- and LF-jets

- **Experimental signatures of b-jets:**

  - presence of displaced tracks
  - presence of secondary vertices
    (B $\rightarrow$ C $\rightarrow$ light)
  - peculiar topology
    (more and higher energy tracks)
  - presence of electron and muon-in-jets
    (not used in nominal algorithms)

"Low-level" b-tagging algorithms in ATLAS

Impact parameter-based algorithm: IP2D/IP3D → **used at LEP/Tevatron**

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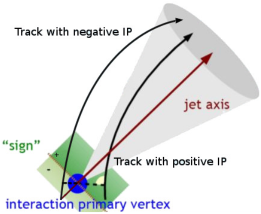

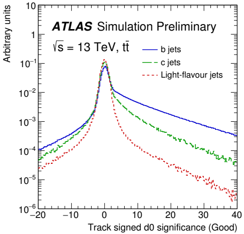

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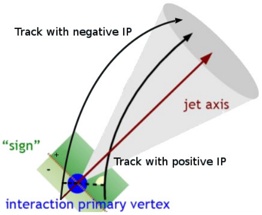

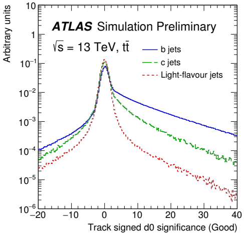

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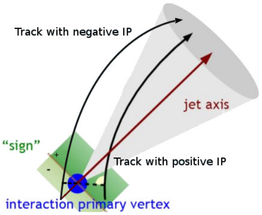
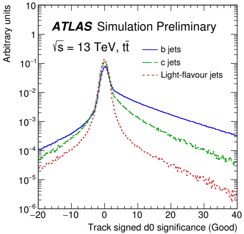
- **large positive tails for b and c-jets**

  → 14 track categories defined

  → log-likelihoods built **per jet** from associated tracks and *b*-, *c* and LF-jet IP templates





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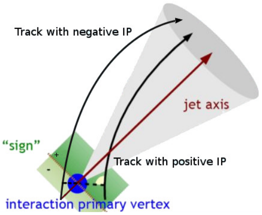
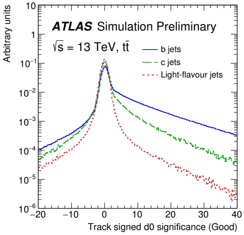


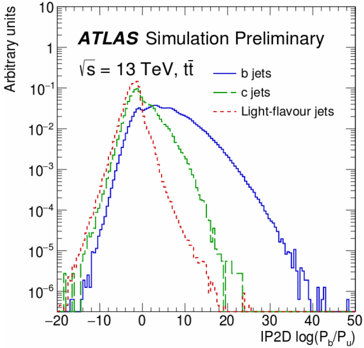


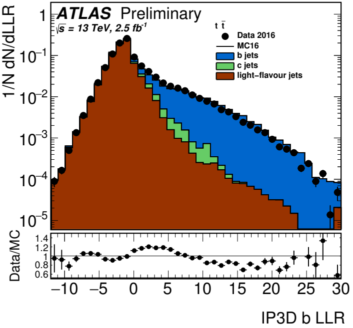
IP2D → 1D d_0 templates (x,y)
IP3D: → 2D (d_0,z_0) templates

IP2D/IP3D discriminants

see ATL-PHYS-PUB-2016-012 and ATL-PHYS-PUB-2017-013 for more details

$\log(P_b/P_u)$ log-likelihood discriminant for IP2D (left) and IP3D (right)





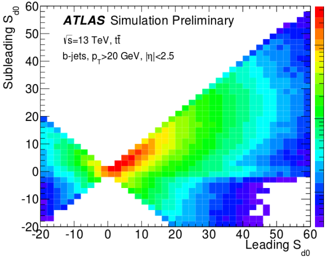
- $\log(P_c/P_u)$ and $\log(P_b/P_c)$ also defined, **total of 6 discriminants**
- **Advantage:** very inclusive, simple. **Drawback:** high sensitivity to jet axis and material interactions

New IP algorithm in ATLAS: RNNIP

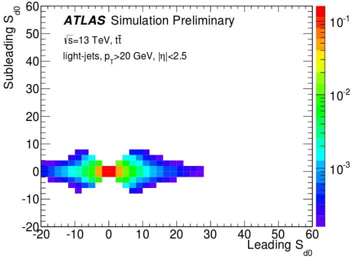
see ATL-PHYS-PUB-2017-003 and ATL-PHYS-PUB-2017-013 for more details

- **Track impact parameters are correlated if they originate from a common decay** (*b*-, *c*-hadrons), IP2D/IP3D likelihoods assume no correlation
- **New IP algorithm in ATLAS learning about the correlations** between tracks in *b*-, *c*- and LF-jets → RNNIP (based on a recurrent neural network)

track IP correlations in b-jets



no correlations for LF-jets



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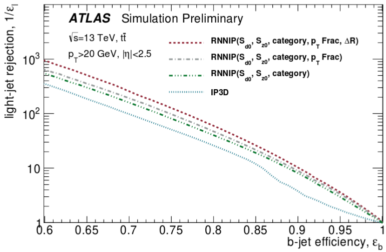
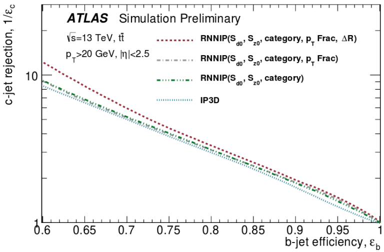
light rejection



c-rejection



- **RNNIP outperforms IP3D** if including only track category, d_0 and z_0 significance
- Performance increase if jet p_T fraction carried by track and ΔR(track, jet) added

New IP algorithm in ATLAS: RNNIP

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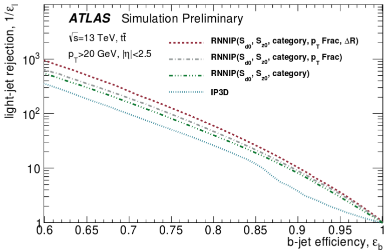

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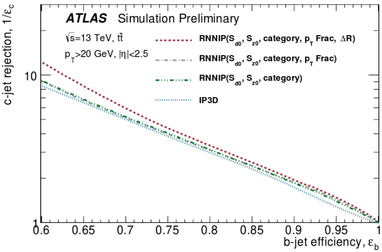

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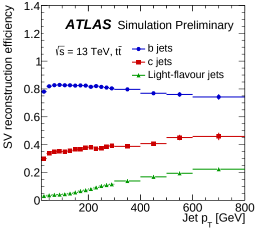
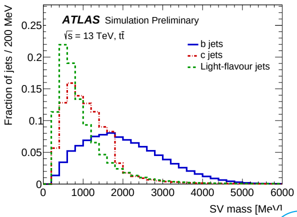
→ **studies assessing RNNIP performance in data in progress**

“Low-level” b-tagging algorithms in ATLAS

Inclusive secondary vertex (SV) reconstruction: SV1

- All track pairs within a jet are tested for a 2-track vertex hypothesis
- final fit includes all tracks from 2-trk vtx $\rightarrow$ 1 (or 0) “inclusive” vertex per jet





see *ATL-PHYS-PUB-2017-011*

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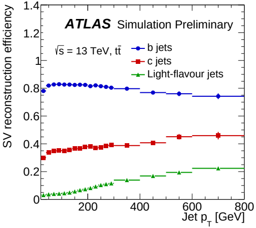

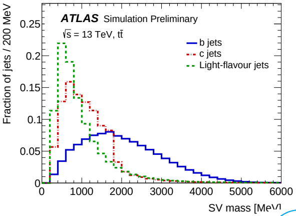

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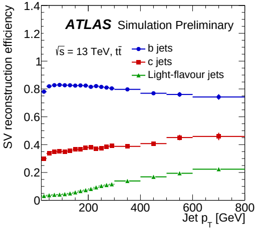

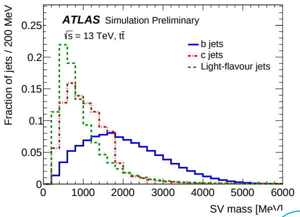

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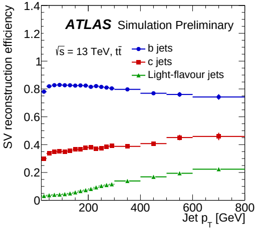

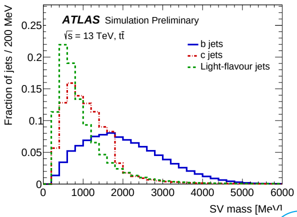

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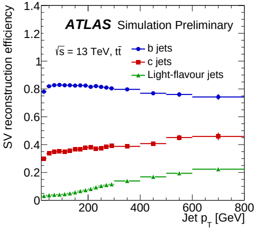
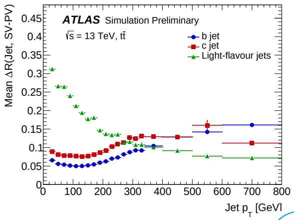




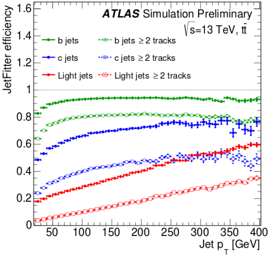
Interesting feature: mis-alignement of the jet and PV-SV axis at high p_T for HF-jets

see ATL-PHYS-PUB-2017-011

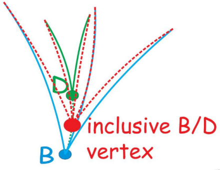
"Low-level" b-tagging algorithms in ATLAS

Decay chain multi-vertex reconstruction: JetFitter

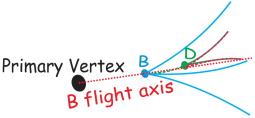
- J. Phys. Conf. Ser. 119 (2008) 03203
- exploits the topological structure of weak *b*- and *c*-hadron decays to reconstruct the full *b*-hadron decay chain
- *b*-hadron flight axis reconstructed using a Kalman filter



What SV1 does:



What JetFitter tries:

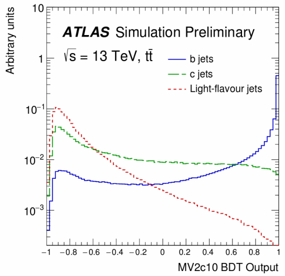


8 quantities reconstructed by JetFitter are used as discriminant

“High-level” b-tagging algorithm in ATLAS

$p_{\mathrm{T}}^{\mathrm{jet}} + \eta^{\mathrm{jet}}$ + 3 (IP2D/IP3D) + 8 (SV1) + 8 (JF) variables used as input to a boosted decision tree: **MV2 (multi-variate discriminant)**

- Algorithm learns how to identify *b*-jets, trained on **hybrid** simulated MC sample
- Provide a weight within [-1,1] telling you how likely the jet to be a *b*-jets



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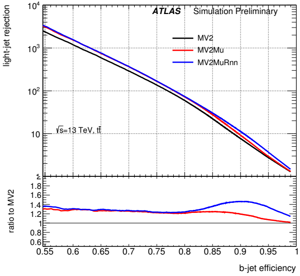
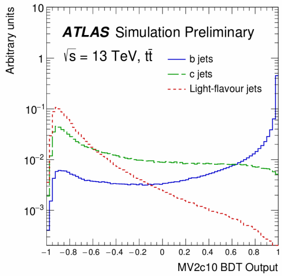
- Performance quantified in ROC curve: **signal efficiency vs background rejection**

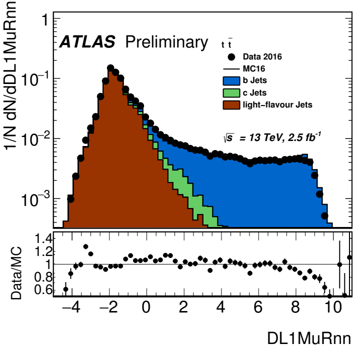




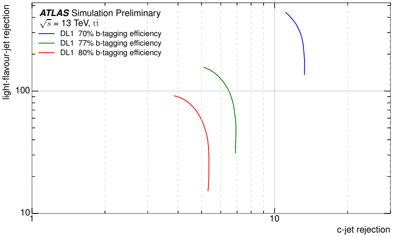
- **MV2,** main tagger used in run 2
- **MV2Mu** includes soft muon tagger output (see backup)
- **MV2MuRNN:** muons + RNNIP

New “high-level” tagger: DL1

- **New high-level tagger based on a deep recurrent neural network: DL1**
- fed with ∼ the same information than MV2, achieve similar performance
- **but higher technology:** combined RNNIP/DL1 training, tunable *c*-jet fraction in the background sample without retraining, etc, possible



DL1 iso b-tagging efficiency curves

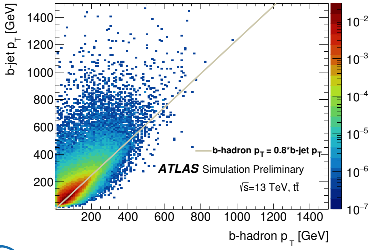


→ currently assessing DL1 *b*-tagging performance in data

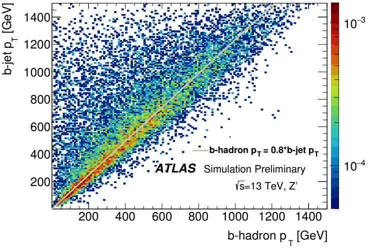
New "hybrid" training sample

- b-hadron p_T spectrum in $t\bar{t}$ intrinsically limited by $m_t \sim 175$ GeV
- for $p_T^{jet} > m_t$, jet clusters nearby hadronic activity, uncorrelated to the b-hadron (e.g. final state radiation) $\rightarrow$ $t\bar{t}$-based training may not be optimal
- Use of an hybrid sample: $t\bar{t}$ (b-hadron $p_T < 250$ GeV) and Z' (> 250 GeV)

$t\bar{t}$ simulated sample



Z′ simulated sample



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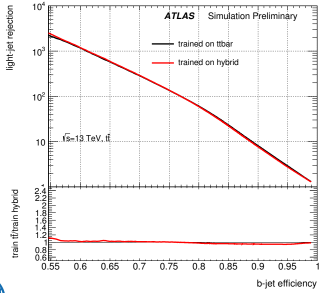
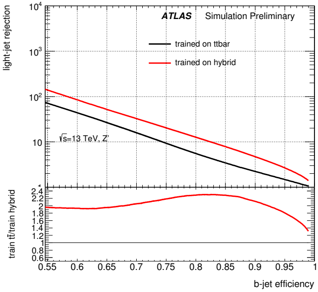
performance on $t\bar{t}$ sample unchanged



performance on Z' sample improved



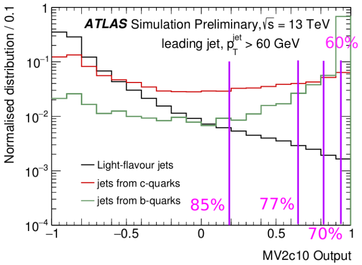
b-jet definition in collision data analysis

- **Tagger working points (WP) defined as a certain cut on the BDT output**

  → select a certain point on the ROC curves

- **"fixed-cut working points"**
  → constant cut value on the BDT output

- WP name gives b-efficiency observed in a $t\bar{t}$ simulated sample, ex: 85% WP



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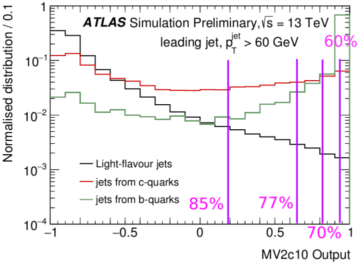

- Alternative *b*-jets definitions are available to physics analysers
  - "hybrid WP": fixed-cut at low jet p_T, flat-efficiency cut at high jet p_T
  - "pseudo-continuous calibration": 5 bins *b*-tagger output with correlations

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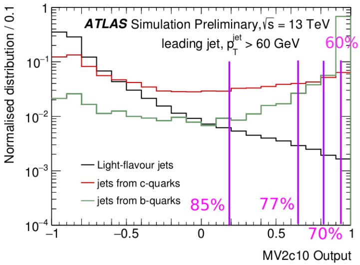

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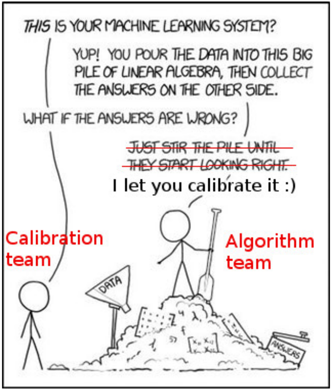
- **Strong reasons to believe performance in simulation and data differ**
  - **for signal (i.e. true b-jets): theory modeling effects.** Uncertainty in b-fragmentation function, underlying event, ..., also pileup, tracking in dense environment at high p_T, etc.
  - **for background (i.e. non-b jets): detector effects.** Non-perfect tracker geometry, dead pixels, fake tracks from random hits, material interactions, ..., also pileup, etc.

4) b-tagging performance in data

– also known as **“calibration”**



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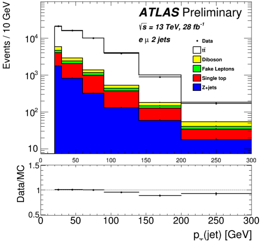
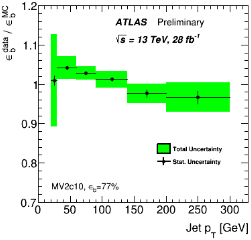
- use of opposite sign $e\mu$ + jets channel, $Z(\to ll)+$ jets background reduced
- exactly 2 jets required to limit combinatorics to bb, bl, lb, ll





see *FTAG-2016-003* (paper in preparation)

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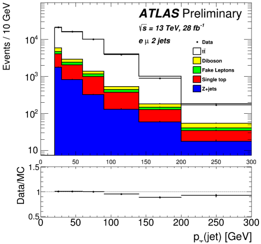
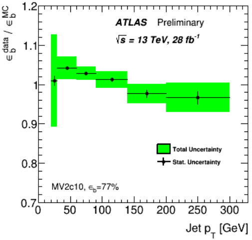
- flavour fractions and light mistag rate taken from simulation, **binned MV2 output for b-jets fitted from data (likelihood)**
- **data and MC compatible,** uncertainty: few %, dominated by $t\bar{t}$ modeling





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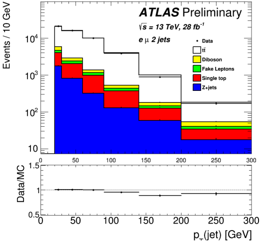

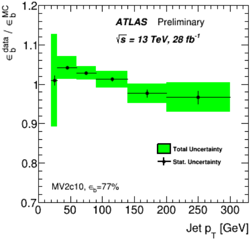

T&P $t\bar{t}$ di- and semi-leptonic and muon-in-jet analysis also performed

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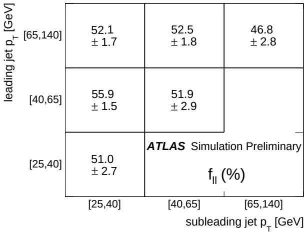

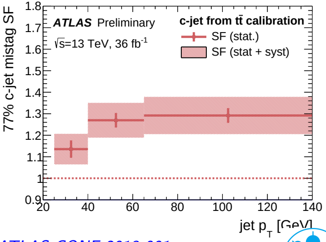

see ATLAS-CONF-2018-001

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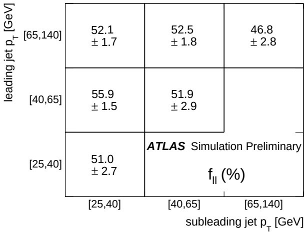
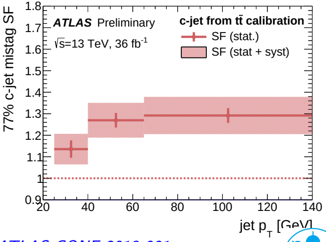
- 1 lepton + 4 jets (including 2 *b*-tagged jets), kinematic fit to reduce background
- fit of the 2 jets attributed to the *W* decay
- flavour fractions from simulation, use of calibration for *b*- and LF-jets, **binned MV2 output for c-jets fitted from data (likelihood)**
- **c-rejection in data lower than in MC** uncertainty 5-20 %, dominated by $t\bar{t}$ modeling





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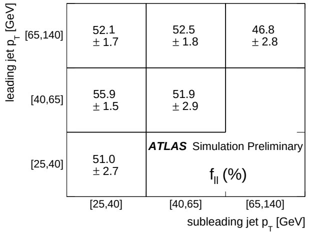
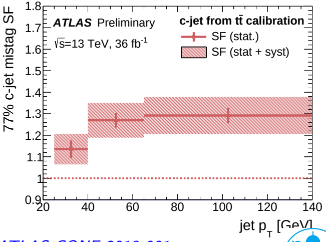
cut & count analysis based on $W + c$ events also performed





see *ATLAS-CONF-2018-001*

b-tagging efficiency measurements for light-jets (fake rate)

- sample of true light-jet **before and after** any tagging needed

- not achievable by regular di-jet selection: $\sim$ 2% (5%) b-(c-)jet bef tag ... x10 after.

b-tagging efficiency measurements for light-jets (fake rate)

- sample of true light-jet **before and after** any tagging needed
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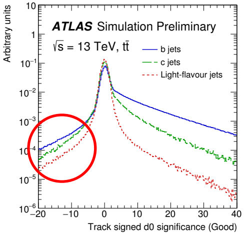
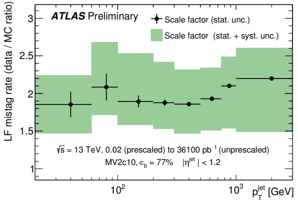
- use of a "flipped" tagger to calibrate **fakes from track resolution effects**





see *FTAG-2017-002*
(conference note in preparation)

b-tagging efficiency measurements for light-jets (fake rate)

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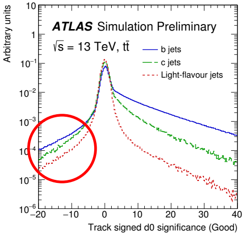

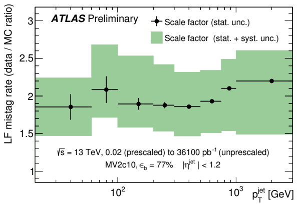

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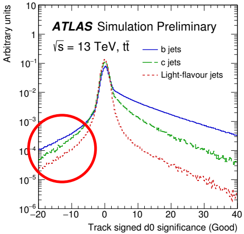

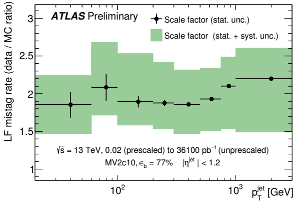

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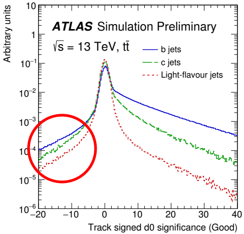
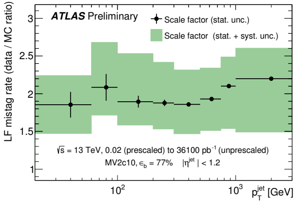
new bottom-up approach "adjusted-MC method" also performed





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Conclusion

- **b-tagging** is an essential tool for many key measurements at the LHC
- an overview of the latest algorithm developments and performance measurements performed by the ATLAS collaboration was presented

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  - complexity of the algorithms, limited "clean" data samples of *c*- and LF-jets
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  - nature of the fakes change with WP tightness (resolution $\rightarrow$ fake tracks)

- **many challenges, among them:**
  - b-tagging beyond the $t\bar{t}$ kinematic reach: algorithm & calibration
  - calibration of the LF-jets mistagged **not** because of track resolution effects

Performance of b-jet identification in ATLAS.

Back-up slides

Matthias Saimpert

DESY (Hamburg)

11 April 2018

QCD-aware parton labeling vertices

$$d_{ij}^{(n)} = \min\left(k_{T\,i}^{2n}, k_{T\,j}^{2n}\right)\Delta R_{ij}^2/R^2$$

$$D_{ij}^{(n)} = \begin{cases} d_{ij}^{(n)} & \text{if flavours QCD/QED compatible,} \\ \infty & \text{otherwise.} \end{cases}$$

k_t: $n = 1$, C/A: $n = 0$, anti-k_t: $n = -1$

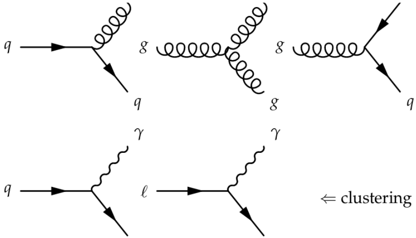


Figure 1: Feynman rule vertices used for QCD (and QED) aware jet clustering.

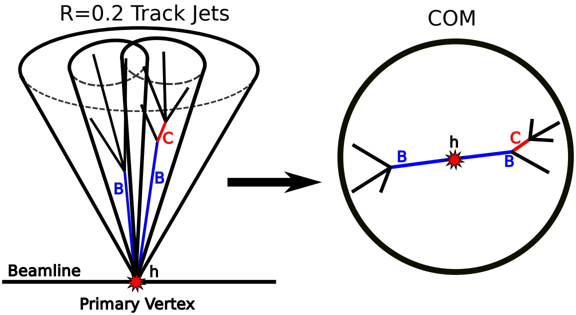
QCD-aware parton labeling with MPI on

MPI-quark particularly problematic since they can turn a gluon jet into a quark-jet

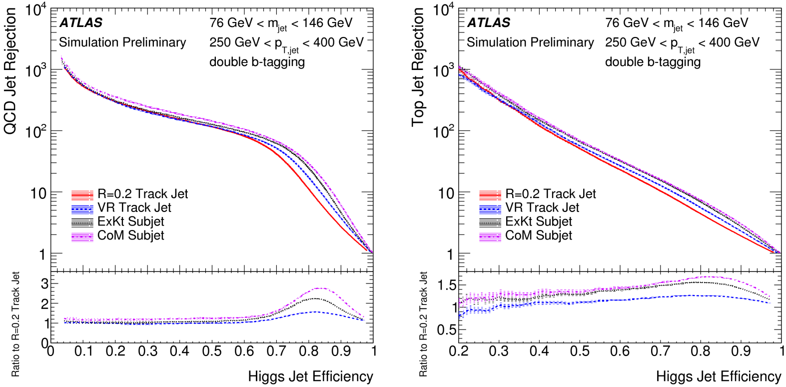
High discrepancy of Herwig++ MPI simulation with respect to the other generators

		Jets	$\gamma +$jet	
Scheme	Generator	q/g	γ/g	q/g
Max-p_T	Pythia 8	0.38	17.2	10.5
	Herwig++	0.33	7.7	4.8
	Sherpa	0.55	21.0	9.6
k_T	Pythia 8	0.80	10.4	8.2
	Herwig++	1.17	3.6	4.6
	Sherpa	0.85	10.5	7.5
anti-k_T	Pythia 8	0.79	10.2	8.3
	Herwig++	1.74	3.2	4.5
	Sherpa	0.86	10.2	7.5
Reclustered	Pythia 8	0.77	10.1	8.0
	Herwig++	1.36	3.5	4.8
	Sherpa	0.83	10.1	7.3

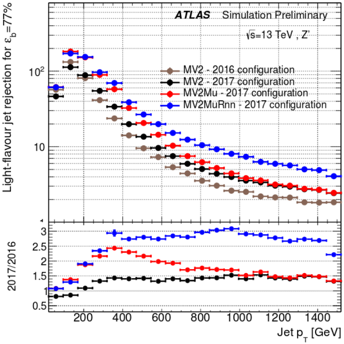
$X \to bb$ taggers: CoM sub-jets

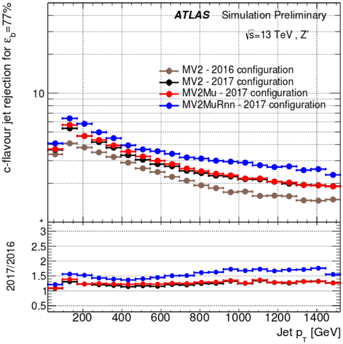


$X \to bb$ taggers: expected performance

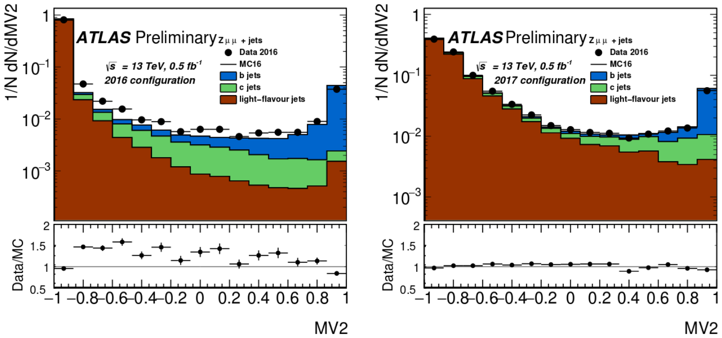


MV2 performance in 2016 and 2017 configuration





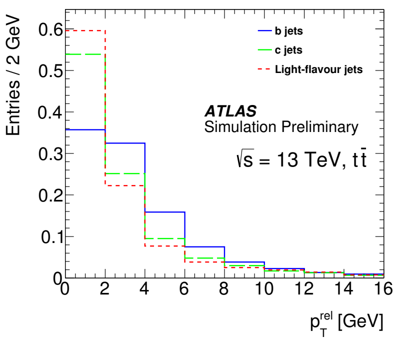
MV2 data/MC agreement with new ATLAS software (2017 configuration)

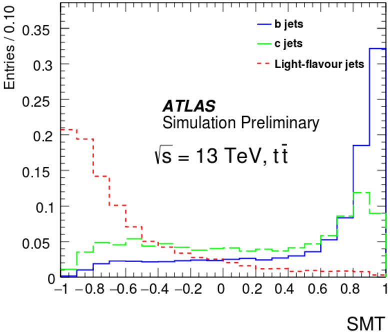


major improvements in tracking simulation in 2017 configuration
much better data/MC agreement before any calibration

Soft Muon Tagger in ATLAS

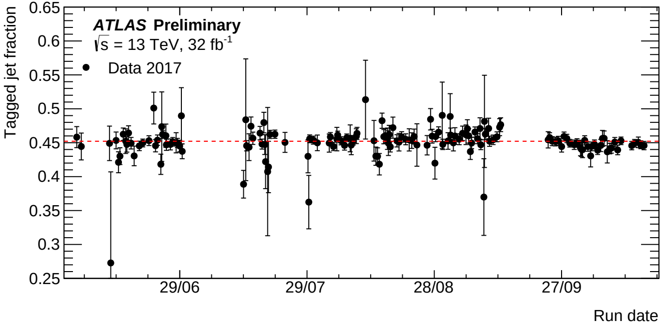
Boosted Decision Tree discriminant based on 6 observables developed for jets including a muon





Calibration of the light flavour background challenging (track resolution effect non-dominant)

b-tagging performance stability in 2017 (1)



b-tagging performance stability in 2017 (2)