b-tagging performance in ATLAS

Berkeley Workshop on
Physics Opportunities with the First LHC Data

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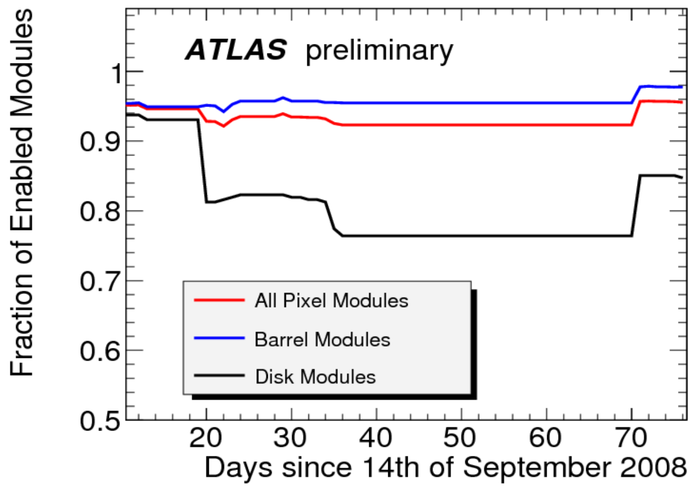
On behalf of the ATLAS Collaboration

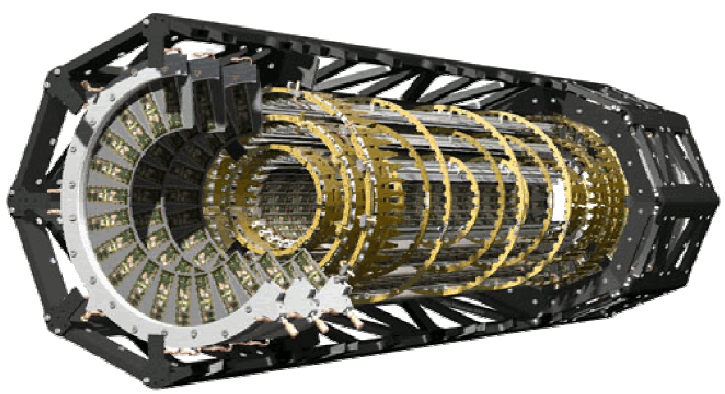
Introduction

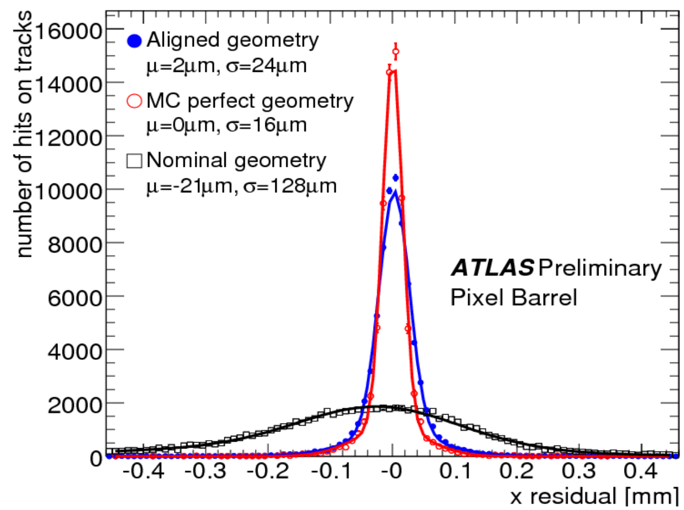
- *b*-tagging is critical to achieve the primary physics goals of the ATLAS experiment:
  - Heavy flavor cross section measurements, top physics, Higgs, SUSY, and many other physics channels require *b*-tagging.
- The readiness of the *b*-tagging depends on the readiness of the inner detector, especially the Pixel detector:
  - Good alignment is needed.
  - The current status looks good: *b*-tagging should quickly be ready for physics.
- Outline:
  - Status of the Pixel detector.
  - Overview on *b*-tagging algorithms and their performance.
  - Commissioning of early data taggers: JetProb
  - Measurement of the *b*-tagging performance on data.
  - Conclusion.

Status of the Pixel Detector

- Pixel Calibration with cosmic tracks:
  - Fraction of disabled modules: 4.2%
  - Hit on track efficiency: >99.8%
  - The fraction of masked noisy pixels is well below 0.02%
  - Occupancy after masking noisy pixels: $\sim 10^{-10}$
  - Hit resolution with preliminary aligned geometry: 24µm
- Better alignment is expected to be achieved with the first data.







Overview on *b*-tagging Algorithms

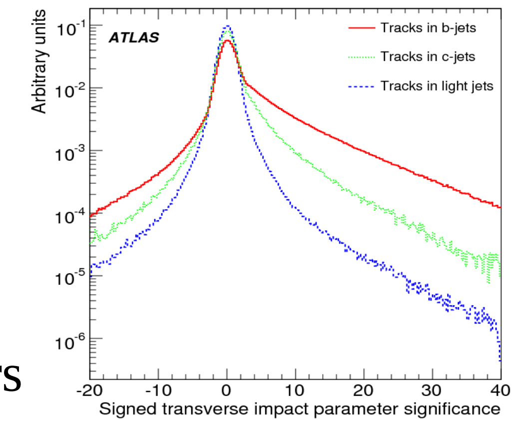
Spatial tagging (or life-time tagging):

⇒ B hadrons have a significant flight path length:

E(B) ~ 50 GeV ⇒ L ~ 5 mm

⇒ Secondary vertex in jets.

⇒ Tracks with high positive impact parameter.



Soft lepton tagging: Useful to commission other taggers

⇒ Low p_T electron/muon from B/D decay.

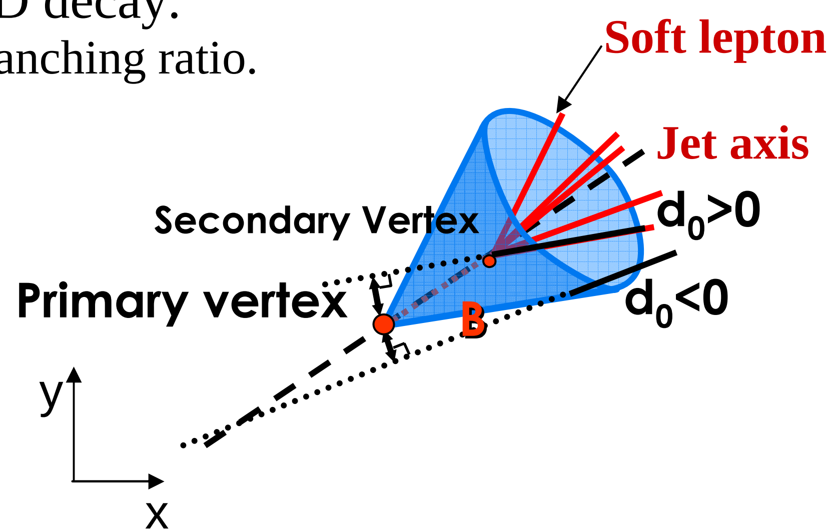
⇒ Efficiency limited by (B/D → ℓ) branching ratio.

Key ingredients:

⇒ Tracking / Inner (esp. Pixel) detector: IP resolution, SV, PV.

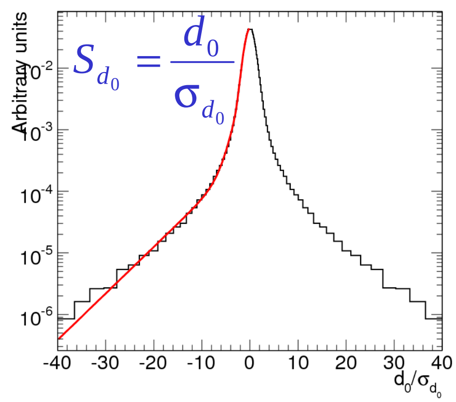
⇒ Jets: Jet Axis.

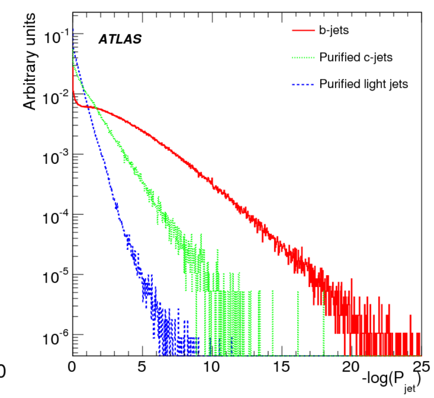
⇒ Leptons.



Early data taggers

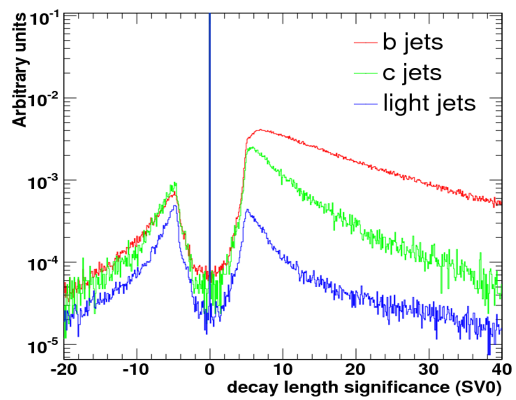
- Track Counting
  - Simply counts the tracks with high impact parameter.
- Simple IP based: JetProb
  - Based on IP distribution for prompt tracks.
  - This distribution can easily be extracted from data:
    - Measure distribution of negative IP in minimum bias events
  - Performance is mostly sensitive to fake tracks.



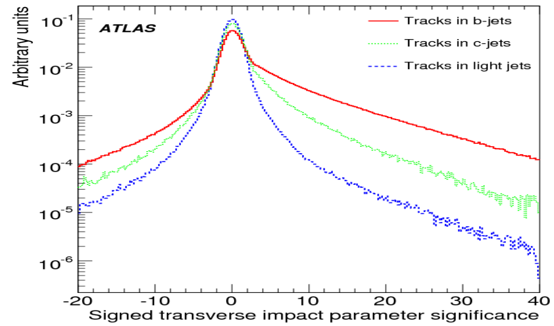


$$P(jet) = \Pi \cdot \sum_{i=0}^{N_{trk}} \frac{-\ln(\Pi)^i}{i!} \quad where \quad \Pi = \prod_{i \in jet} \int_{S_i}^{+\infty} f(S)dS$$

- Simple SV based: SV0
  - Fits the secondary vertex and returns the significance of the decay length of the secondary vertex.
  - Less sensitive to fake tracks but more sensitive to resolution.

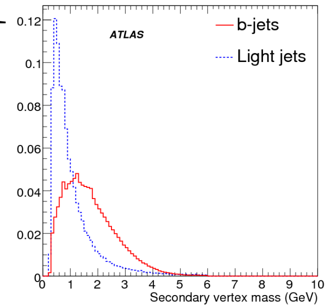


Likelihood taggers



- IP based taggers:
  - IP2D: only transverse IP
  - IP3D: also longitudinal IP
  - Use separate distributions for *b* and light jets:
    - More powerful than JetProb
    - More difficult to calibrate on data.
- SV based tagger: SV1
  - Mass
  - Energy fraction
  - Number of 2-track Vertices.

M



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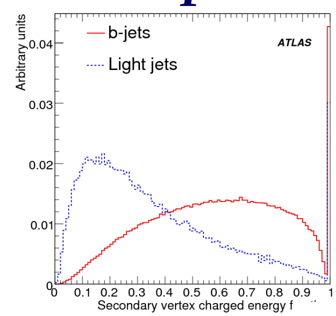

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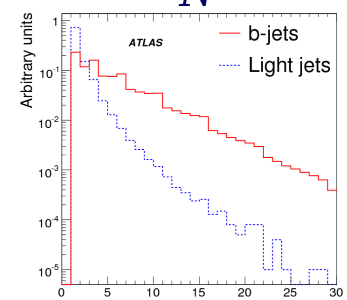
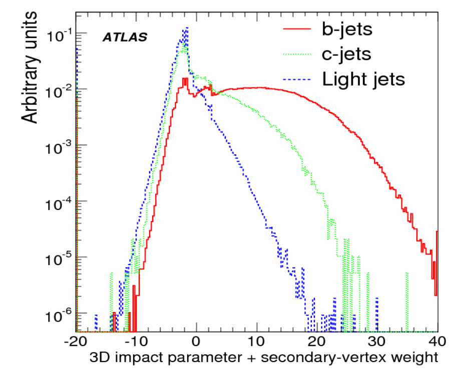


- JetFitter:
  - Uses a Kalman fitter to explicitly fit the B→D→X decay chain.

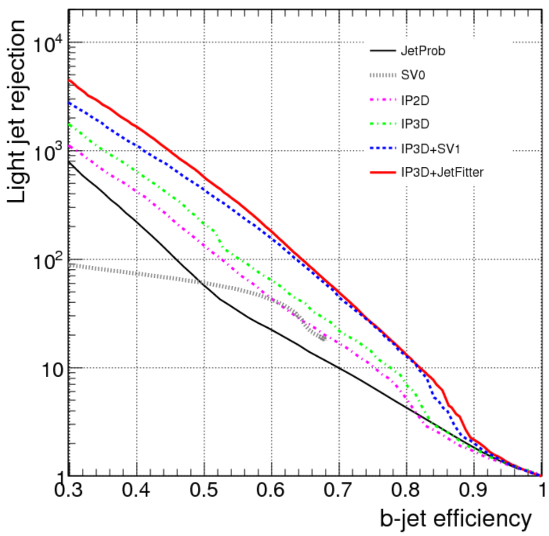


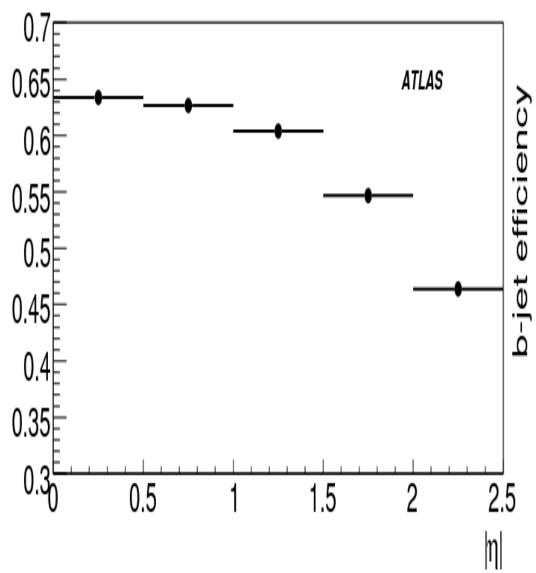
- Combined IP3D+SV1:

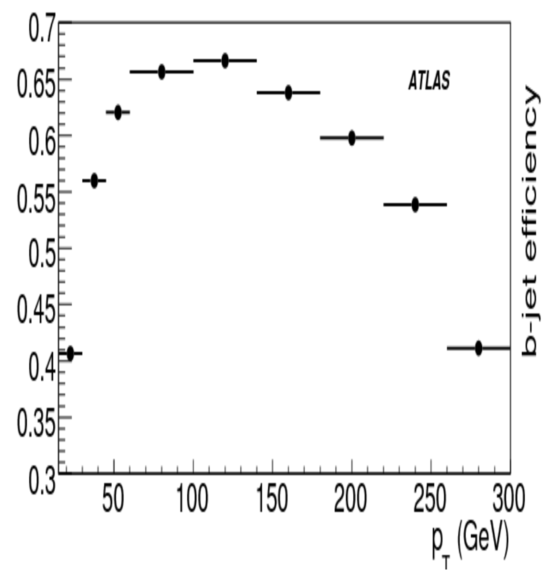
$$W_{jet} = W_{tracks} + W_{vertex} = \sum_{i=1}^{N_{trk}} \ln\frac{b(S_i)}{u(S_i)} + \ln\frac{b(M,F,N)}{u(M,F,N)}$$

Overview on *b*-tagging performance

- Strong dependence on kinematics:
  - Low p_T and high $|\eta|$: Multiple scattering and material interactions
  - High p_T: collimated tracks $\Rightarrow$ Pattern recognition issues
  - High p_T: ‘late’ B decay ($p_T \sim 200$ GeV, ~8% of B’s decay after the B-Layer)
- Shown for *ttbar* events:
  - Light jet rejection as function of tagging efficiency for different taggers.
  - *b*-jet efficiency or IP3D+SV1 at a fixed cut (w>4) as function of p_T and $|\eta|$.



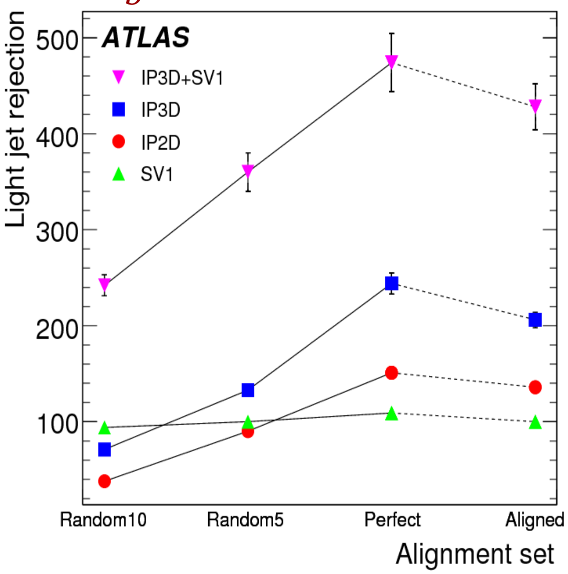




Effect of alignment and inner detector material.

- Detailed studies were performed to estimate the impact of residual misalignment:
  - 4 scenarios were studied (details on backup slide):
    - Perfect: no residual misalignment.
    - Random10: 10 μm in *x* and 30 μm in *y* and *z*.
    - Random5: 5 μm in *x* and 15 μm in *y* and *z*.
    - Aligned: standard alignment procedure applied.
  - 15% loss in rejection for IP based taggers when alignment procedure is applied with respect to perfect re-alignment.
  - Secondary vertex reconstruction is not so sensitive to residual misalignment.

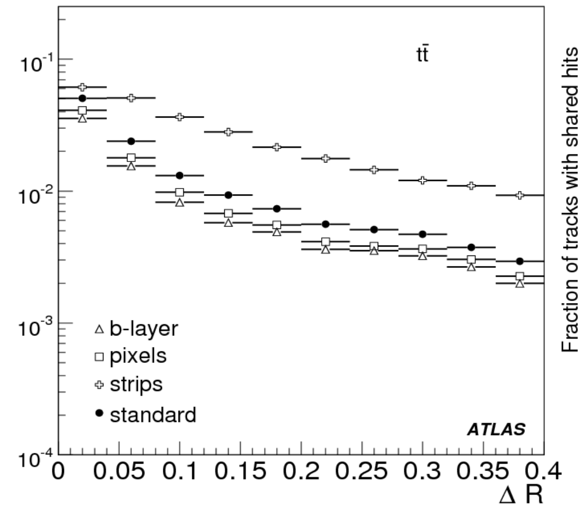
$\varepsilon_b = 50\%$

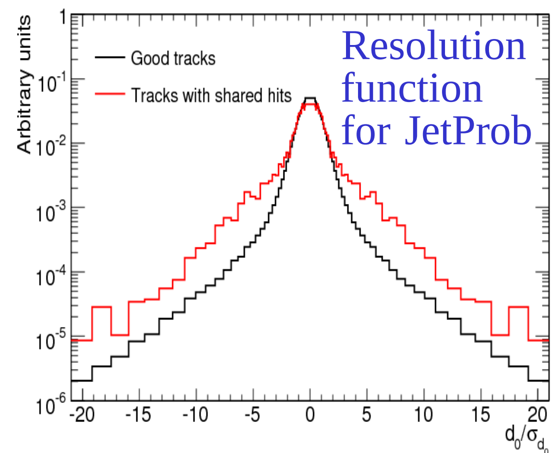


- Studies were also performed to show the impact of material in the inner detector:
  - Degradation in performance of ~15% was observed when adding ~$0.02X_0$ (~10%) of material in the silicon (SCT+Pixels) regions.
  - Degradation in performance can be attributed to worse IP resolution and increase in the rate of secondary tracks from nuclear interactions.

Effect of tracking performance and tuning

- Several studies are currently in progress in order to understand the correlation between *b*-tagging and tracking performance:
  - Impact parameter taggers performance depends on the track fake rate.
  - Secondary vertex performance depends on resolution and error matrix calculation.
  - Example: Tracks with shared hits:
    - *"Shared"*: At least 1 shared hit in Pixel or 2 in SCT.
    - About 7% of tracks are identified as *"Shared"* in *ttbar* events.
    - Define track categories: Use different calibrations for tracks with or without shared hits.
    - ➔Gained ~10 – 15% at 50% efficiency.



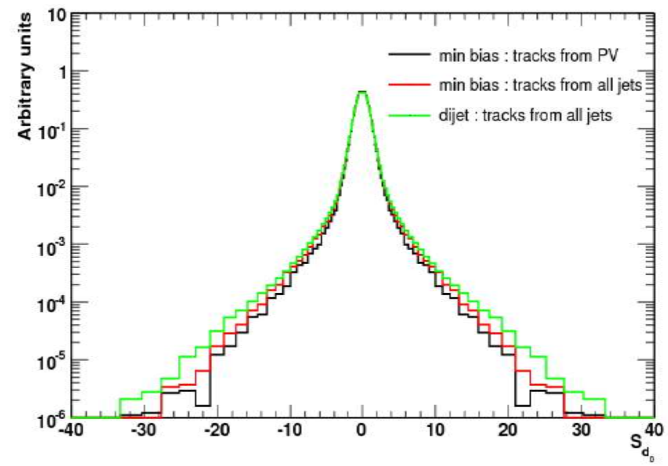


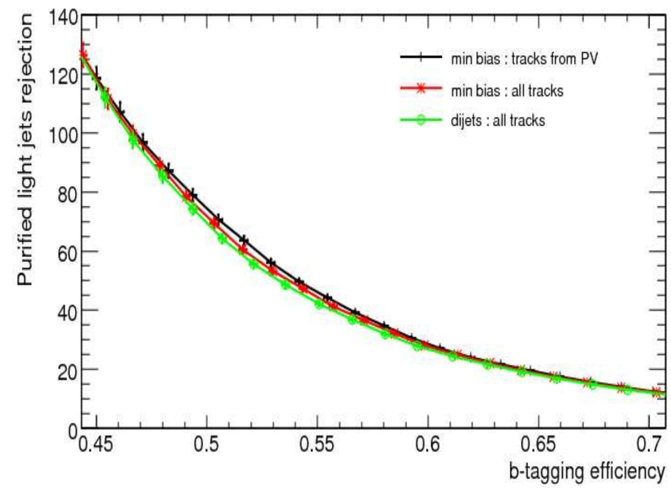
JetProb tested on *ttbar* events	ε_b = 50%	ε_b = 60%
No track categories	65.9 ± 1.5	26.6 ± 0.4
Special calibration for *"Shared"*	71.8 ± 1.8	27.7 ± 0.4

JetProb commissioning

- Extracting resolution function from data:
  - Performance depends on the resolution function.
  - Ideally use tracks from primary vertex
  - On data:
    - Use minimum bias events
    - Simple selection: ($p_T > 15$ GeV & $|\eta| < 2.5$)
    - Calibrate using tracks with negative impact parameter from all selected jets
- Shown: two different calibrations:
  - Measured on di-jet events (1.5 M).
  - Measured on minimum bias events (2.5 M).
  - Ideal: using only tracks from PV
- Tested on *ttbar* events:

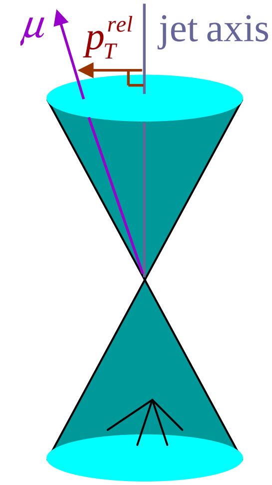
Used calibration	$\varepsilon_b = 50\%$	$\varepsilon_b = 60\%$
Measured on di-jets	69.6 ± 1.7	26.9 ± 0.4
Measured on min. bias	71.8 ± 1.8	27.7 ± 0.4
Ideal: tracks from PV	74.4 ± 1.9	28.5 ± 0.4

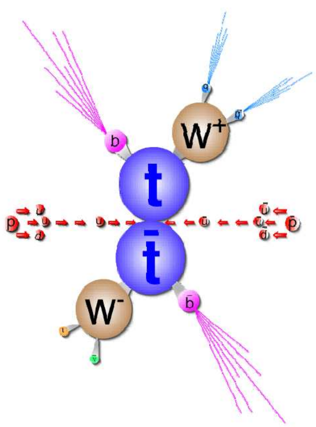




b-tagging calibration on data

- Measuring the *b*-tagging efficiency on data:
  - Using QCD jet events (50-100 pb^{-1}):
    - p_T^{rel} method: uses the p_T^{rel} of muons in jets as a discriminating variable to estimate the fraction of *b*-jets in a sample before and after the tagging.
    - System 8: uses two samples with different *b*-fraction and two uncorrelated taggers to solve a system of 8 non-linear equations.
    - Both methods work only at low p_T ($p_T < 80$ GeV).





  - Using *ttbar* events (100-200 pb^{-1}):
    - Tag Counting: count the number of events with *n* tagged jets and fit both *b*-tagging efficiency and *ttbar* cross-section
    - Extracting a *b*-jet sample: by fully reconstructing the *ttbar* decay chain and applying tight selection.
  - Results are available for 14 TeV analysis:
    - Currently re-optimizing the analysis to work at 10 TeV
    - Will need more luminosity for the *ttbar* analysis.
- Analysis to measure the *b*-tagging fake rate is currently in progress.

Conclusion

- The *b*-tagging will quickly be ready for physics analysis:
  - The detector is in good shape.
  - Expect to quickly reach the needed alignment.
- Large variety of taggers available:
  - Performance:
    - Ranges from Rej=30 to 150 @ 60% efficiency
    - Expect to achieve Rej=100 for ε_b=70% with latest improvements.
  - Start commissioning simple taggers with the first data:
    - Track counting, JetProb and SV0.
  - Efforts are now focused on understanding the sensitivity of *b*-tagging to tracking performance and tuning.
- *b*-tagging performance measurement on data:
  - Measuring efficiency with complementary methods:
    - On QCD events: Will quickly reach enough statistics and become dominated by systematics.
    - On *ttbar* events: Need more statistics but more reliable at high p_T.
  - Extracting pure *b*-jet sample is also useful to extract reference histograms for likelihood taggers.
  - Efforts are now ongoing on mistag rate measurements techniques.

Backup slides

Residual misalignment sets

- Simulation:
  - Large misalignments were introduced at simulation level.
  - Alignment corrections should be introduced at reconstruction level.
- Perfect alignment:
  - This is the ideal case were the reconstruction uses the same alignment as for the simulation: ➔ No residual misalignment.
- Two sets of known residual misalignments: Random10 – Random5:
  - These are hand-made alignment that takes the misalignment sets used for simulation and randomly shift the positions by small amounts (see tables below).
- Real Alignment:
  - This uses an alignment set produced using the actual track based alignment algorithms developed for ATLAS.

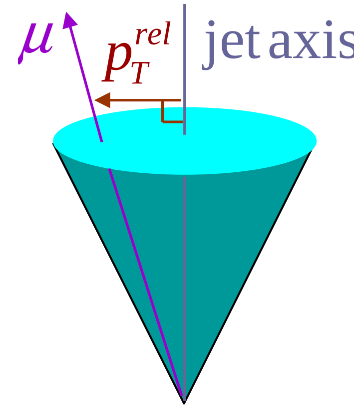
Random 10						
Level	x	y	z	RotX	RotY	RotZ
Module	10	30	30	0.3	0.5	0.2
Layer	10	10	15	0.05	0.05	0.1
Disk	10	10	30	0.2	0.2	0.1
Whole Pixel	10	10	15	0.1	0.1	0.1

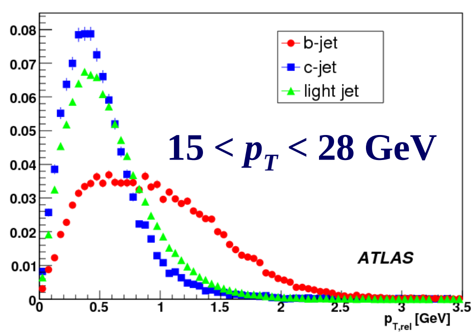
Random 5						
Level	x	y	z	RotX	RotY	RotZ
Module	5	5	15	0.15	0.3	0.1
Layer	7	7	10	0.02	0.02	0.05
Disk	7	7	20	0.1	0.1	0.05
Whole Pixel	7	7	10	0.05	0.05	0.05

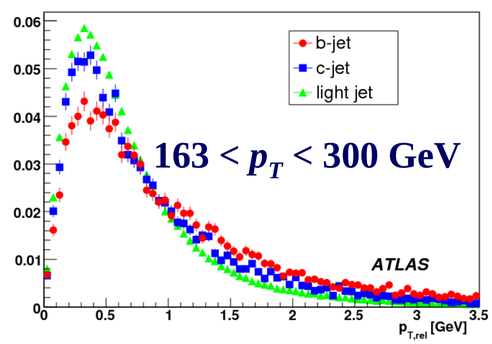
Random misalignment was generated with a Gaussian distributions with σ as tabulated: Shifts are in μm and rotations in mrad.

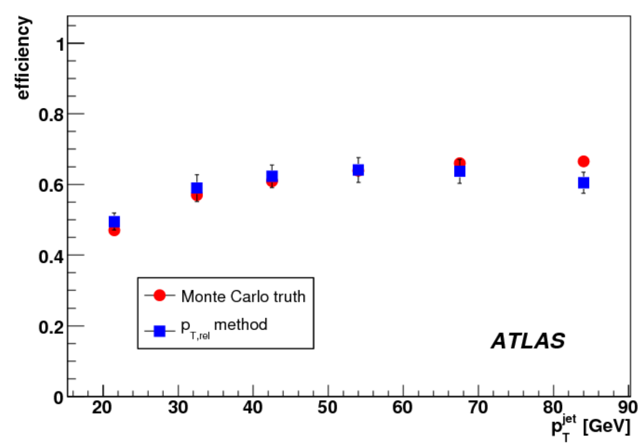
b-tagging calibration using QCD jet events: p_T^{rel}

- Uses the p_T^{rel} distribution of muons in jets as a discriminating variable.
- Fit the fraction of b, c and light jets that reproduces the inclusive distribution of p_T^{rel} before and after b-tagging and compute b-tagging efficiency.
- The method fails at high p_T (p_T > 80 GeV) as the p_T^{rel} distribution of a muon in b-jets looks similar to the one in c and light jets.
- Precision at 100 pb^{-1} :
  - Statistical: below 1%
  - Systematic: Controllable at the level of 6%.





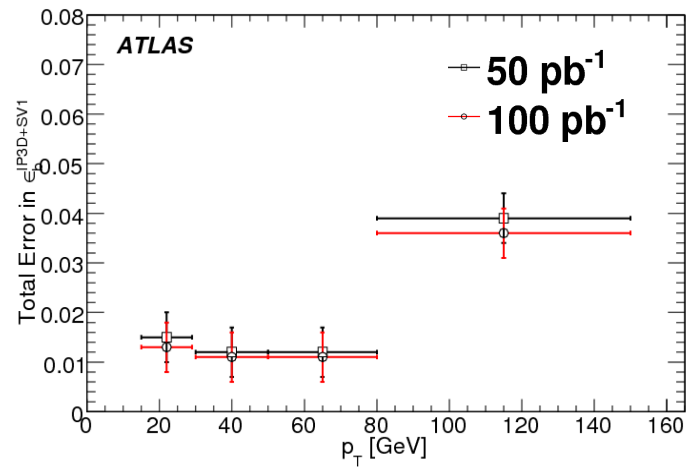




b-tagging calibration using QCD jet events: System 8

- Use two uncorrelated taggers:
  - Soft muon tagger.
  - Lifetime tagger.
- Use two samples with different flavor contents:
  - *n* sample: jets containing muons.
  - *p* sample: subset of the *n* sample where the muon tagged jet is required to have a back-to-back lifetime tagged jet.
- Measure on each sample the number of jets before tagging and the number of jets tagged by each and by both taggers.
- Solve a system of 8 non-linear equations involving 8 unknown quantities including *b*-tagging efficiency.
  - Correlation between taggers and biases between *n* and *p* samples are taken from MC.
  - The accuracy with which MC can reproduce these parameters is included as a systematic.
- The method is valid up to p_T = 80 GeV.

$$
\begin{aligned}
n &= n_b + n_{cl} \\
p &= p_b + p_{cl} \\
n^{LT} &= \epsilon_b^{LT}\, n_b + \epsilon_{cl}^{LT}\, n_{cl} \\
p^{LT} &= \alpha_6\, \epsilon_b^{LT}\, p_b + \alpha_4\, \epsilon_{cl}^{LT}\, p_{cl} \\
n^{SMT} &= \epsilon_b^{SMT}\, n_b + \epsilon_{cl}^{SMT}\, n_{cl} \\
p^{SMT} &= \alpha_5\, \epsilon_b^{SMT}\, p_b + \alpha_3\, \epsilon_{cl}^{SMT}\, p_{cl} \\
n^{both} &= \alpha_1\, \epsilon_b^{LT}\, \epsilon_b^{SMT}\, n_b + \alpha_2\, \epsilon_{cl}^{LT}\, \epsilon_{cl}^{SMT}\, n_{cl} \\
p^{both} &= \alpha_1\, \alpha_5\, \alpha_6\, \epsilon_b^{LT}\, \epsilon_b^{SMT}\, p_b + \alpha_2\, \alpha_3\, \alpha_4\, \epsilon_{cl}^{LT}\, \epsilon_{cl}^{SMT}\, p_{cl}
\end{aligned}
$$



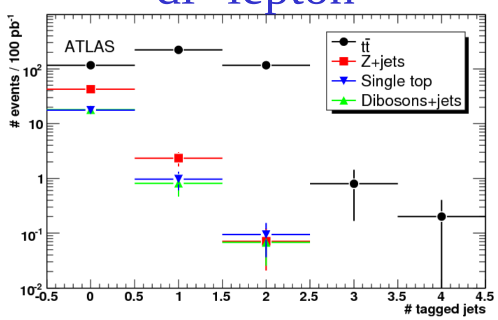
b-tagging calibration using *ttbar* events

- Tag counting method:
  - Select *ttbar* events in either lepton+jets or di-lepton channels.
  - Count the number N_{nb} of events with a given number n_b of tagged jets.
  - Ideal world:

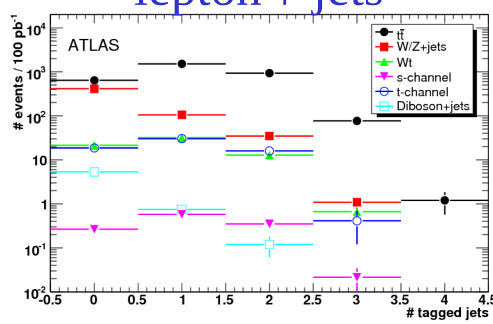
$$N_{1b} = 2N\varepsilon_b(1-\varepsilon_b)$$

$$N_{2b} = N\varepsilon_b^2$$

di - lepton



lepton + jets



  - In reality:
    - ➔ Flavor contents have to be estimated on MC:
      - Presence of *b*-tagged light and c jets and also *b*-jets from gluon radiation.
      - *b*-jets reconstruction and selection efficiency has to be taken into account.
    - ➔ Light jets mistag rate measured elsewhere or input from MC.
    - Fit at the same time: *b*-tagging efficiency and *ttbar* cross section.
  - Results (100 pb^{-1} lepton+jets):
    - Systematic uncertainties well understood.
    - Precision on *b*-tagging efficiency: ± 2.7% (stat) ± 3.4% (sys)
    - Precision on *ttbar* cross section: ± 2.4% (stat) $^{+12.7\%}_{-14.7\%}$ (sys) ± 5% (lumi)

b-tagging calibration on *ttbar* events

- Extracting a *b*-jet sample:
  - Three methods to overcome combinatorial background:
    - Topological: using invariant masses.
    - Likelihood: exploiting masses and angular correlations.
    - Kinematic fit: minimizing χ^2.
  - All three methods require background subtraction.
  - Performance:
    - Purity of the *b*-jet sample: up to 80% with an estimated purity of 98% after background subtraction.
    - Precision on ε_b at 200 pb^{-1}: from 5% to 8%
  - The method can also be used to extract *b*-jet reference distributions for likelihood taggers:
    - Multidimensional histograms are problematic and require huge statistics.