Jets, Transverse Missing Energy and Tau Reconstruction in ATLAS

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on behalf of the ATLAS Collaboration

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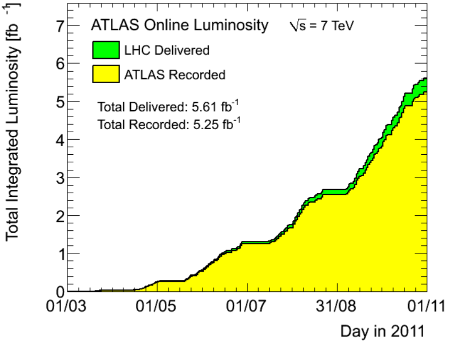
Introduction

- 2011 has been a fantastic year in terms of LHC and ATLAS performance.
- Data-taking efficiency for 2011 was 93.6%
- Increased from 6 interactions per bunch crossing to 12 and this may double again in 2012.
- Increasing pile-up presents many performance challenges.



Outline

1. Jet reconstruction performance
2. $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction performance
3. Tau reconstruction and identification performance

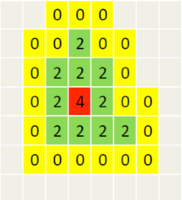
Jet Reconstruction Basics

ATLAS uses the anti-k_t algorithm with a distance parameter of $R = 0.4$ and $R = 0.6$.

Calorimeter jets

algorithm operates on calorimeter towers or topological clusters "topo-clusters":

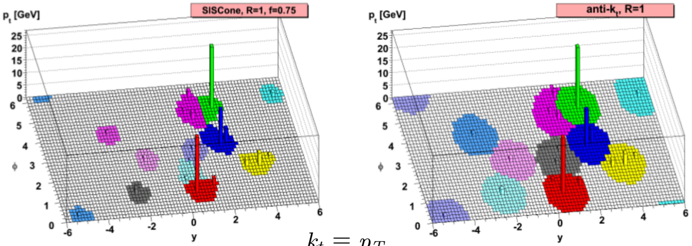
- **towers:**
  static $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ grid elements built from cells.
- **topo-clusters:**
  Start with cell with $S/N \geq 4$. Include neighbours iteratively with $S/N \geq 2$ and include neighbours beyond that.



Track Jets

- Use tracks ($p_T > 0.5$ GeV, $|\eta| < 2.5$, 6 pixel hits, $|d_0| < 1.5$ mm, $|z_0 \sin(\theta)| < 1.5$mm) originating from the primary hard-scattering vertex.
- Jets must contain at least two tracks and have $p_T > 3$ GeV.
- Calorimeter jets are then matched to track jets.
- Provides robustness against pile-up.

Matteo Cacciari *et al* JHEP04(2008)063



$k_t \equiv p_T$

1. Define distances between entities d_{ij} and between an entity and the beam d_{iB}:

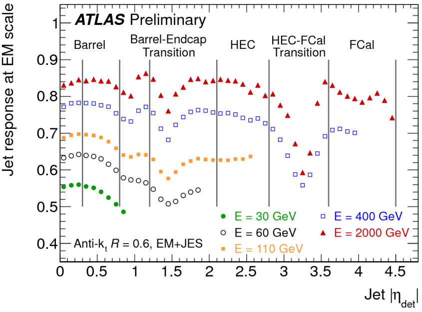
$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta y^2 + \Delta\phi^2}{R^2}; \quad d_{iB} = k_{ti}^{2p}; \quad p = \begin{cases} 1 & k_t \\ 0 & \text{Cambridge/Aachen} \\ -1 & \text{anti-}k_t \end{cases}$$

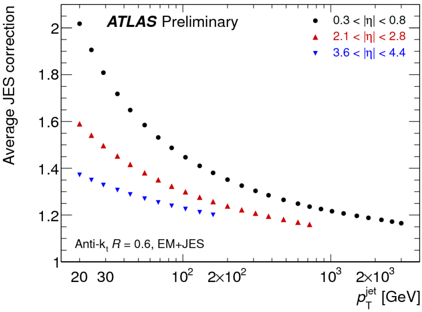
2. Compute all $\{d_{ij}, d_{iB}\}$ using proto-jets and clusters and let $d = \min(d_{ij}, d_{iB})$
   - if $d = d_{ij}$, combine jet i and jet j
   - if $d = d_{iB}$, define jet as a final jet
3. Continue until all jets are final

Soft-resilient jet boundaries $\rightarrow$ easier comparison with theory.

ATLAS calorimeters are non-compensating → derive correction factors from Monte Carlo simulation, in-situ techniques (photon/Z+jets, single particle E/p)

Correction factors are $\{p_T, \eta\}$-dependent





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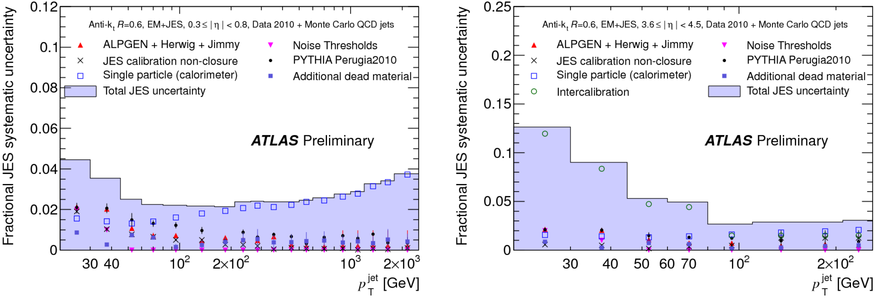

Uncertainties range from 2.5% for central jets up to 12% for forward jets

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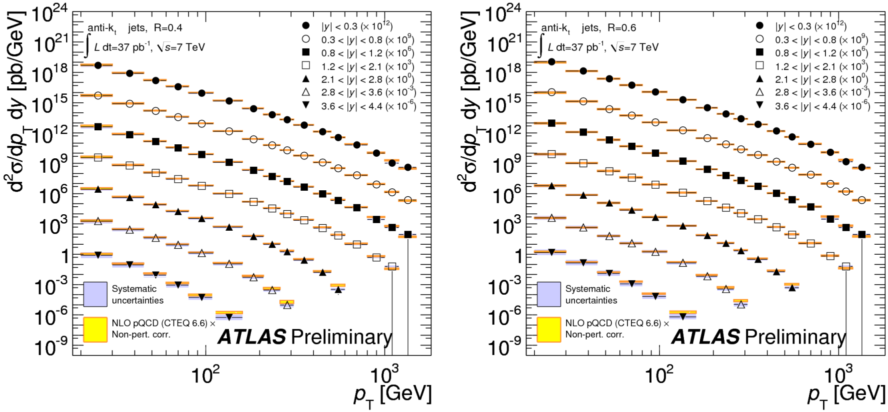

Inclusive jet cross-sections up to p_T of 1.5 TeV and $|\eta|$ of 4.4

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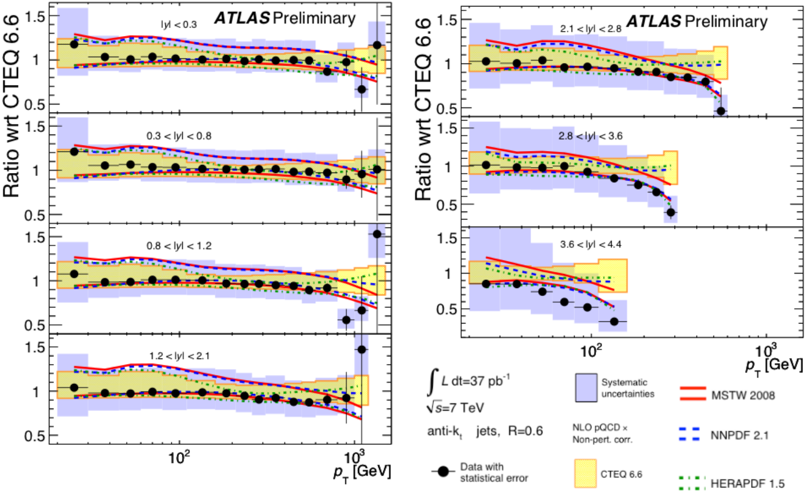
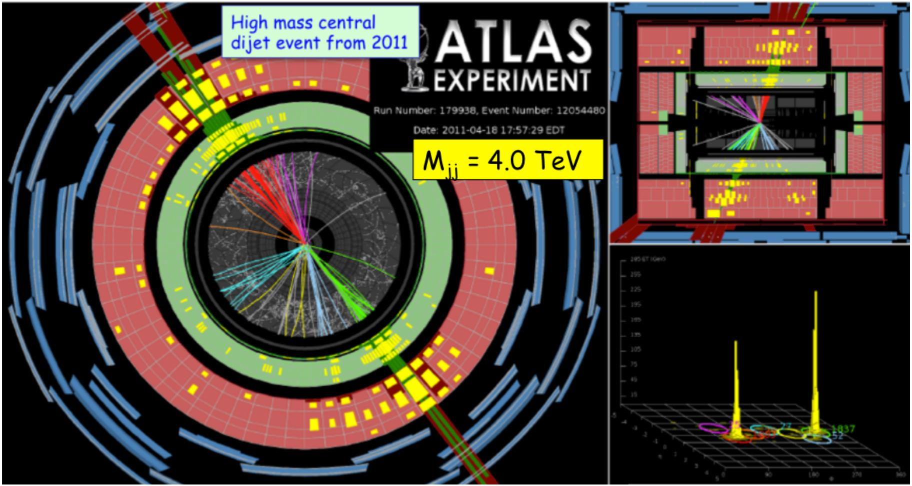


Good agreement within experimental uncertainties in 2010 data

Systematics should decrease in 2011 data with processes like gamma+jet



Highest-mass central dijet event collected during 2011, where the two leading jets have an invariant mass of 4.0 TeV. The two leading jets have $(p_T\ , \eta)$ of (1.8 TeV, 0.3) and (1.8 TeV, -0.5), respectively. $E_{\mathrm{T}}^{\mathrm{miss}} = 100$ GeV.

$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ Basics: Simple concept but complex treatment

The $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction includes contributions from energy deposits in the calorimeters and muons reconstructed in the muon spectrometer:

$$E_{x(y)}^{\mathsf{miss}} = E_{x(y)}^{\mathsf{miss,calo}} + E_{x(y)}^{\mathsf{miss},\mu}$$

$$E_{x(y)}^{\mathrm{miss,calo}} = E_{x(y)}^{\mathrm{miss},e} + E_{x(y)}^{\mathrm{miss},\gamma} + E_{x(y)}^{\mathrm{miss},\tau} + E_{x(y)}^{\mathrm{miss,jets}}$$

$$+E_{x(y)}^{\mathrm{miss,softjets}} + (E_{x(y)}^{\mathrm{miss,calo},\mu}) + E_{x(y)}^{\mathrm{miss,CellOut}}$$

each term is calculated from the calibrated cell energies in the corresponding objects:

$$E_x^{\mathrm{miss,term}} = -\sum_{i=1}^{N_{\mathrm{cell}}^{\mathrm{term}}} E_i \sin\theta_i \cos\phi_i \qquad E_y^{\mathrm{miss,term}} = -\sum_{i=1}^{N_{\mathrm{cell}}^{\mathrm{term}}} E_i \sin\theta_i \sin\phi_i$$

$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$ is then:

$$\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}} = \sqrt{(E_x^{\mathsf{miss}})^2 + (E_y^{\mathsf{miss}})^2}, \qquad \phi^{\mathsf{miss}} = \arctan(E_y^{\mathsf{miss}}, E_x^{\mathsf{miss}})$$

Low p_T particles missed by the calorimeter are recovered by also including low p_T tracks. Muons reconstructed from the inner detector are used to recover muons in regions not covered by the muon spectrometer

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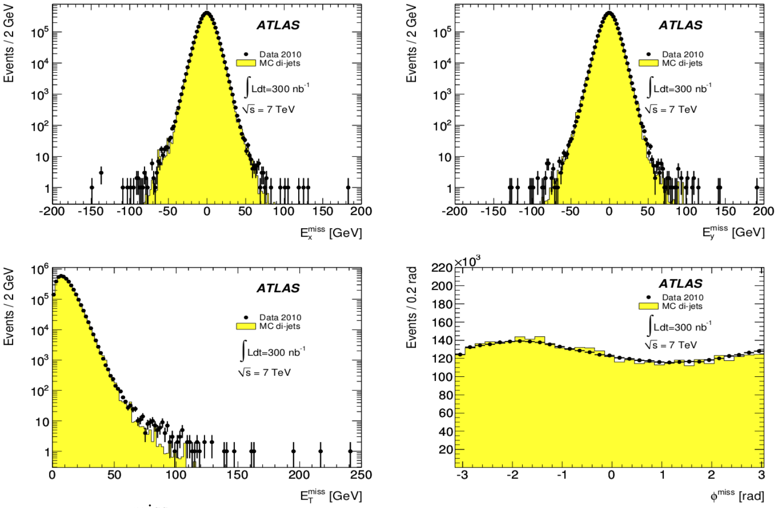

E_T^{miss} as measured in the data sample of di-jet events.
Monte Carlo simulation expectation normalized to data.

E_T^{miss} Performance

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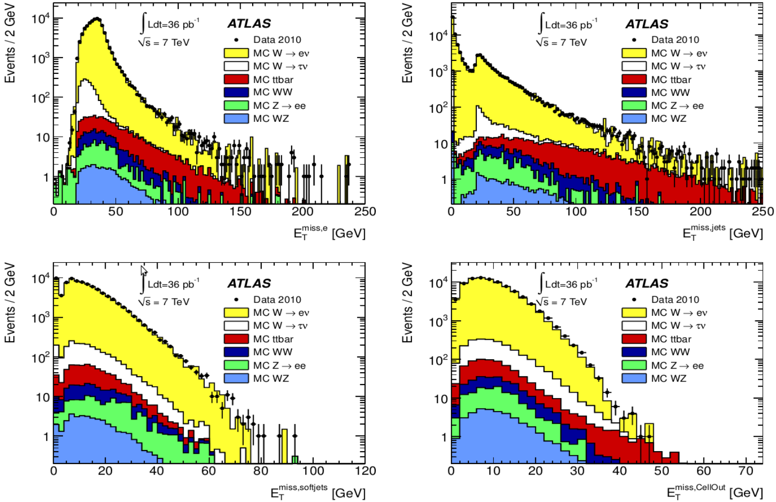

topoclusters in electrons (top left), jets with $p_T > 20$ GeV (top right), jets with $p_T < 20$ GeV (bottom left), from outside reco objects (bottom right) for data.

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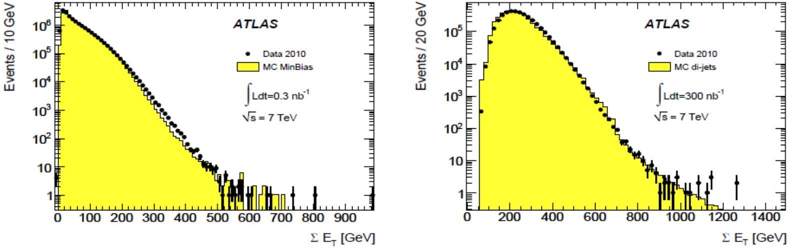

$\sum E_{\mathrm{T}}$ in PYTHIA6 minbias (left) and di-jets (right) events.
Some difference between data and MC dependent on soft-physics models.

Using $Z \to ll$ event topology, define the axis in the transverse plane (Z direction):

$$\boldsymbol{A}_\mathbf{Z} = (\ \boldsymbol{p}_\mathbf{T}^{\ell^+} + \ \boldsymbol{p}_\mathbf{T}^{\ell^-})/| \boldsymbol{p}_\mathbf{T}^{\ell^+} + \boldsymbol{p}_\mathbf{T}^{\ell^-} |$$

$\boldsymbol{E}_\mathrm{T}^\mathrm{miss}$ projected on this axis is sensitive to detector resolution and biases.

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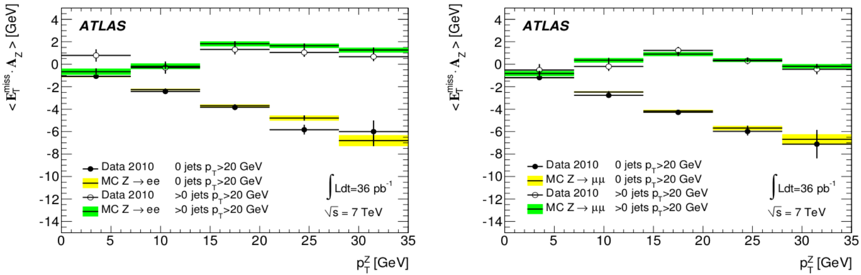


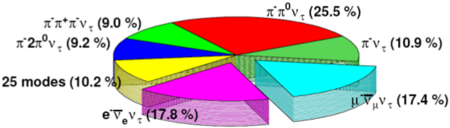
Mean value of $\boldsymbol{E}_\mathrm{T}^\mathrm{miss} \cdot \boldsymbol{A}_\mathbf{Z}$ as a function of p_T^Z requiring either zero jets with $p_\mathrm{T} > 20$ GeV or at least 1 jet with $p_\mathrm{T} > 20$ GeV in the event for $Z \to ee$ (left) and $Z \to \mu\mu$ (right).

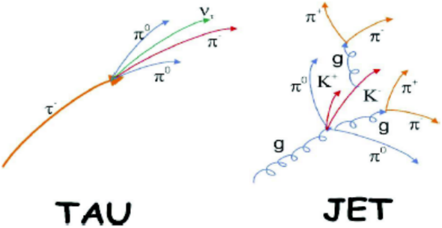
Small negative bias in both channels reproduced by MC simulation.
p_T **of lepton system overestimated or hadronic recoil is underestimated.**

Tau Basics

τ Characteristics

- $m_\tau = 1.8$ GeV
- Lifetime: $c\tau = 87\mu$m
- 65% of taus decay hadronically
- Hadronic decays are mostly collimated collections of neutral and 1 or 3 charged pions ("prongs"). There are also rare modes involving kaons.





Experimentally, taus are characterized by:

- the low number of tracks (prongs),
- a leading track and a displaced secondary vertex
- narrow jet with a relatively large EM component (1-prong) from $\pi^0 \to \gamma\gamma$,

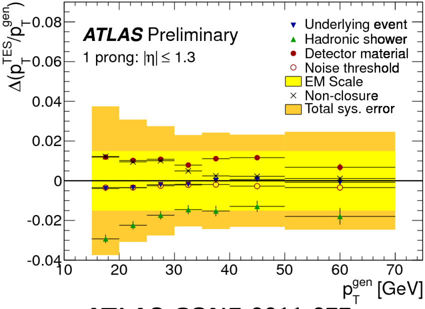
Requires good performance from the ATLAS calorimeters and tracking systems

ATLAS only attempts to reconstruct taus which decay hadronically.

Tau Reconstruction

- Tau candidates are seeded by calorimeter anti-k_t $R = 0.4$ jets of topoclusters
- For each candidate, tracks within $\Delta R < 0.2$ around the axis of the jet seed (the "core region") are associated to the candidate if they have $p_T > 1$ GeV and if they pass quality criteria:
  - at least 2 pixel hits
  - sum of pixel hits and SCT hits is at least 7
  - $|d_0| < 1.0$ mm and $|z_0 \sin(\theta)| < 1.5$ mm

- particular mix of pions
- calibrated independently of the jet energy scale.
- A $\{p_T, \eta\}$-dependent correction is applied on top of the energy of the topoclusters.
- Tau candidates are still easily faked by QCD processes and electrons.
- **identification is required to reject the vast background.**



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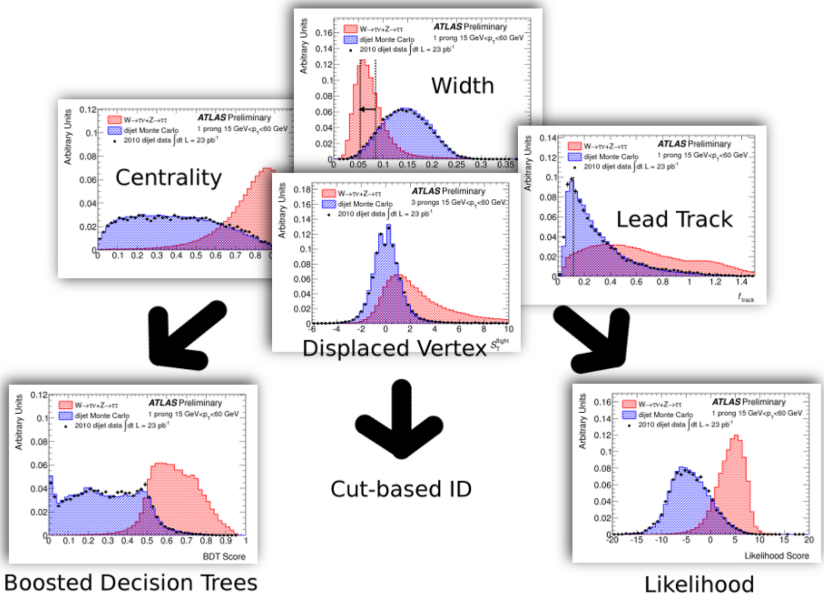
Tau Identification



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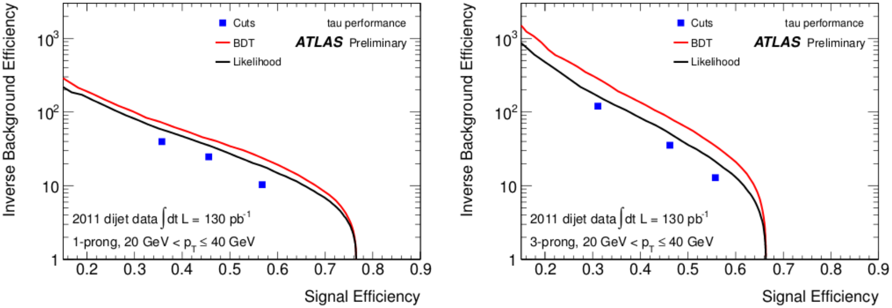

Performance of the tau identification techniques on 1-prong (left) and 3-prong candidates using a di-jet selection in data and simulated $Z \to \tau\tau$ and $W \to \tau\nu$ events.

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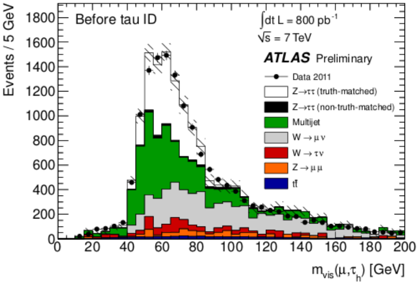

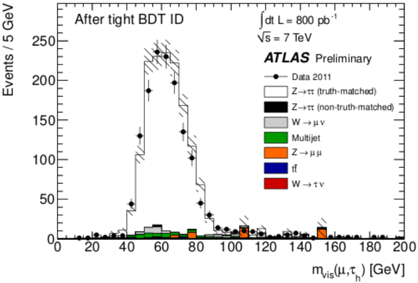

The invariant mass of the visible decay products from a $Z \to \tau\tau$ selection before (left) and after (right) tau identification:

Identification Efficiency in Data: $W \to \tau + \nu$

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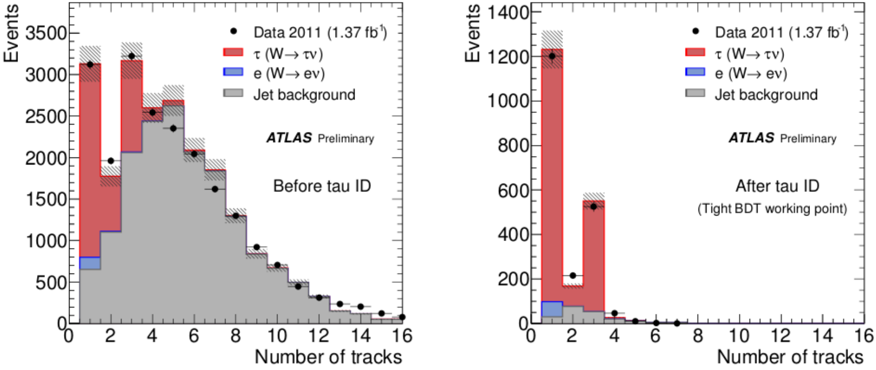

Track multiplicity distributions before tau identification (left) and after a tight boosted decision tree identification (right).

Number of real taus in data is estimated by fitting to these track distributions.

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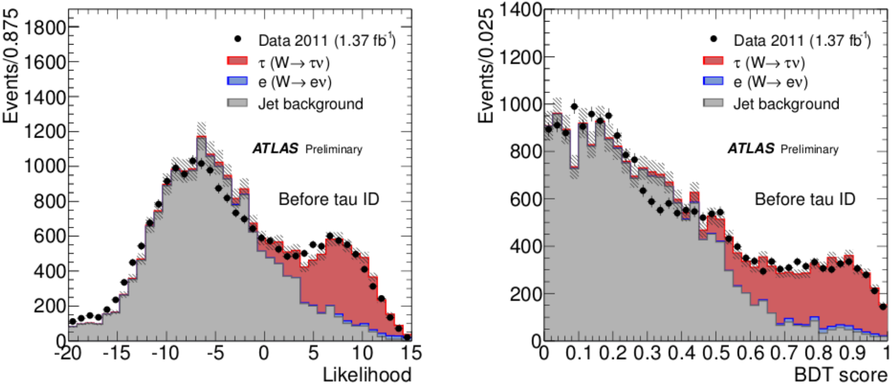

Likelihood (left) and boosted decision trees (right)
Using the track distribution fits we can determine
the efficiency after a given cut on identification scores.

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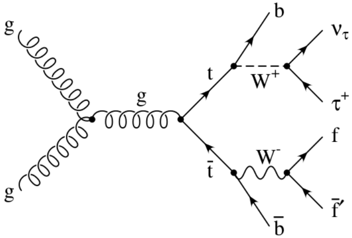
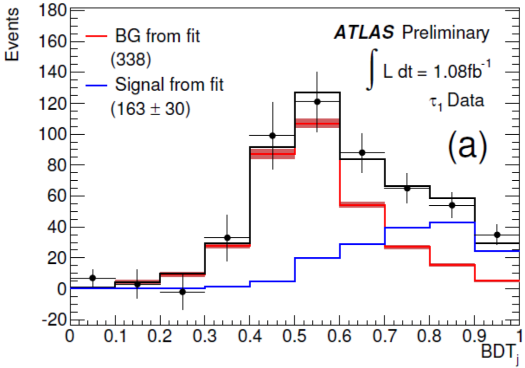
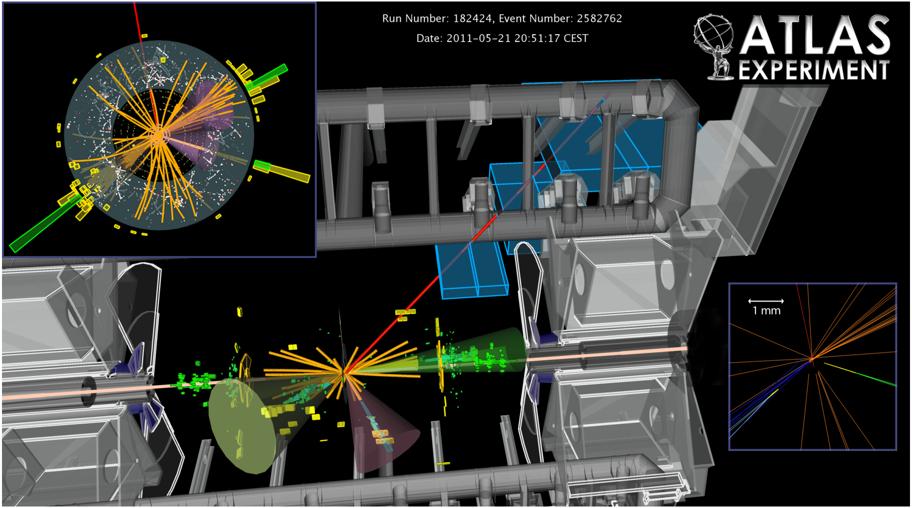




OS-SS boosted decision tree output for 1-prong tau candidates after a $t\bar{t} \rightarrow \mu + \tau$ selection. Normlizations are derived from a fit to the data and are shown as blue (signal), red (background), and black (total).



$t\bar{t} \to \tau + \mu$ candidate.

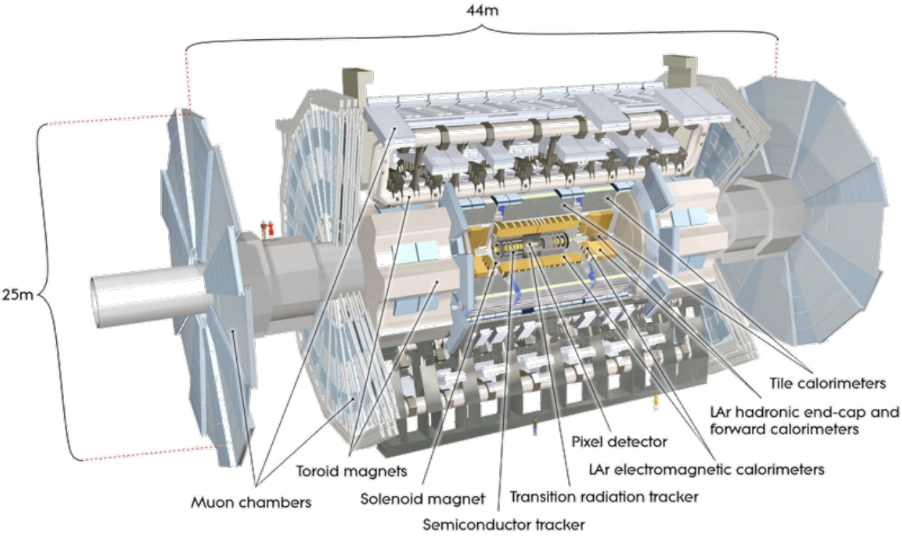
Summary

- Jet reconstruction:
  - uncertainty on energy scale 2.5% for central jets up to 12% for forward jets.
  - inclusive jet cross-sections have been measured up to p_T of 1.5TeV and $|\eta|$ of 4.4 with excellent agreement between data and Monte Carlo simulation
- $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$reconstruction:
  - Monte Carlo simulation agrees well with data
  - The $\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}$projected along the Z direction shows some bias
  - Improvements are needed in the calibration of low-p_T objects
- Tau reconstruction and identification in ATLAS has been performing well:
  - Efficiencies and mis-identification have been measured in data
  - Many physics results involving taus have been released by ATLAS. These include SM measurements and searches for new physics.
  - Much effort will be devoted to further improvements and making tau candidates more robust against pile-up in the near future

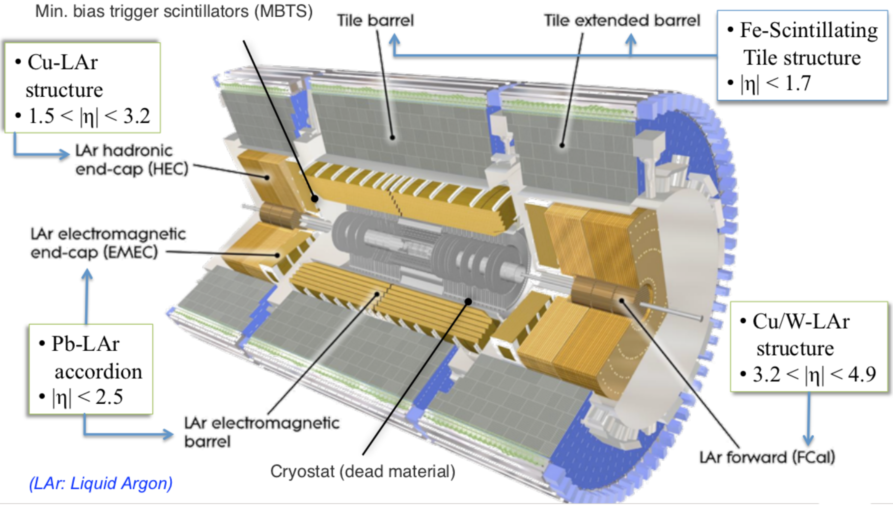
Stay tuned for exciting ATLAS results to come from 2011's 5 fb^{-1}!

Backup

The ATLAS Detector

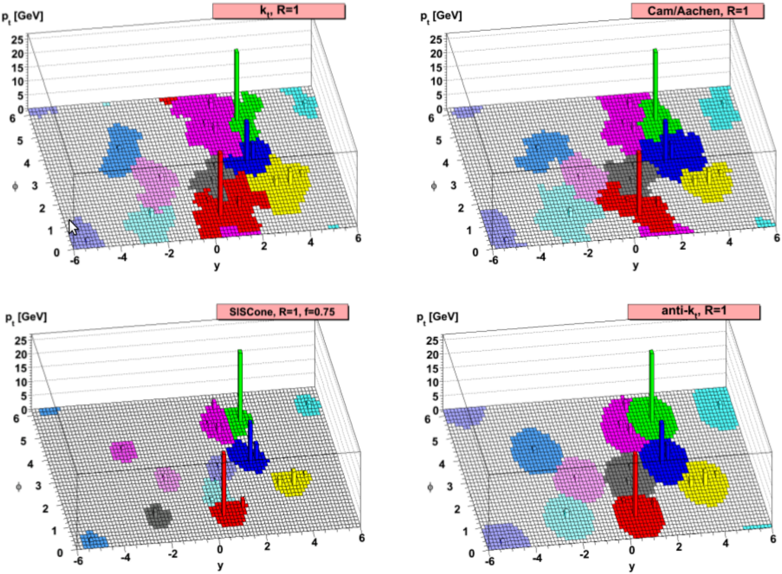


The ATLAS Calorimeters



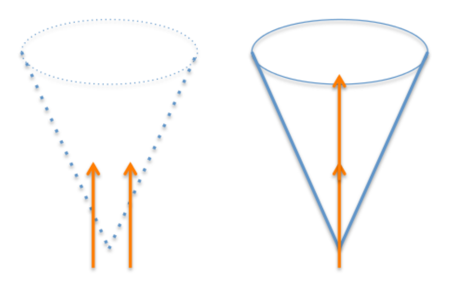
(LAr: Liquid Argon)

The Anti-k_t Jet-Clustering Algorithm



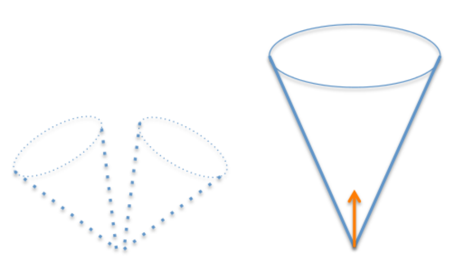
Collinear/Infrared Safety

Collinear Safe



Jet algorithm output is the same if energy of a particle is split between two collinear particles

Infrared Safe



Jet algorithm output is stable against the addition of soft particles

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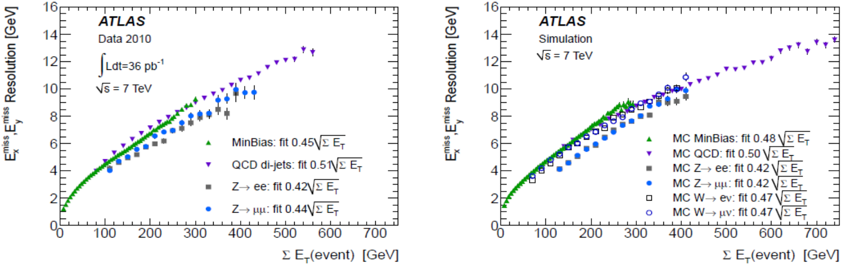

Fig. 15. *E_x^{miss} and E_y^{miss} resolution as a function of the total transverse energy in the event calculated by summing the p_{T} of muons and the total transverse energy in the calorimeter in data at $\sqrt{s}$ = 7 TeV (left) and MC (right). The resolution of the two $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ components is fitted with a function $\sigma = k \cdot \sqrt{\Sigma E_{\mathrm{T}}}$ and the fitted values of the parameter k, expressed in GeV$^{1/2}$, are reported in the figure.*

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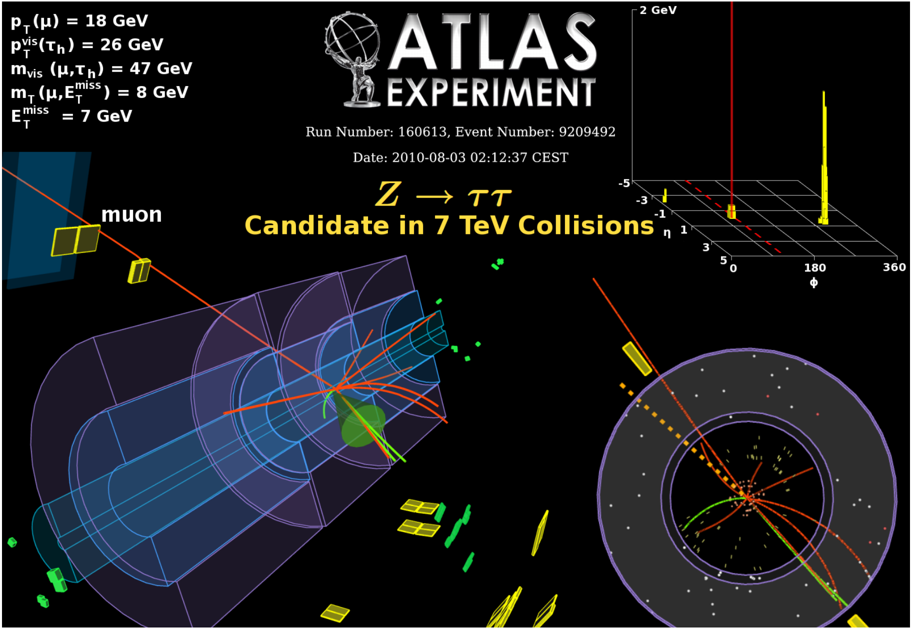
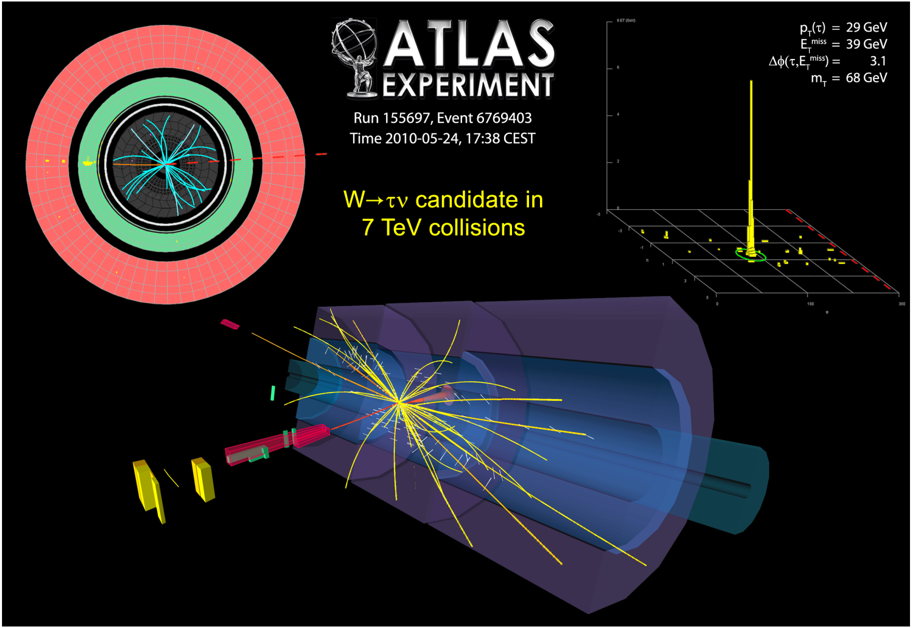
ID method	Tau ID efficiency	Jet mis-ID probability	MC correction factor
CUT Loose	0.87 ± 0.02 ± 0.02	0.221 ± 0.008	0.98 ± 0.03 ± 0.02
CUT Medium	0.79 ± 0.02 ± 0.03	0.081 ± 0.007	1.10 ± 0.03 ± 0.04
CUT Tight	0.65 ± 0.02 ± 0.03	0.025 ± 0.006	1.21 ± 0.02 ± 0.06
LLH Loose	0.70 ± 0.02 ± 0.02	0.085 ± 0.008	0.92 ± 0.03 ± 0.03
LLH Medium	0.46 ± 0.02 ± 0.03	0.046 ± 0.006	0.85 ± 0.03 ± 0.06
LLH Tight	0.27 ± 0.01 ± 0.02	0.021 ± 0.004	0.87 ± 0.02 ± 0.05
BDT Loose	0.81 ± 0.02 ± 0.03	0.085 ± 0.008	0.99 ± 0.03 ± 0.03
BDT Medium	0.63 ± 0.02 ± 0.03	0.029 ± 0.006	1.06 ± 0.02 ± 0.05
BDT Tight	0.42 ± 0.01 ± 0.03	0.012 ± 0.004	1.02 ± 0.02 ± 0.07

Table 7: Tau ID efficiency, QCD jet mis-identification probability and MC correction factor (12) for the Tau ID measured from data using the $W \to \tau\nu$ tag and probe method. For the ID efficiency and the correction factor, the statistical uncertainty is given first and the systematic uncertainty is given second. For the jet mis-identification probability, the statistical uncertainty is given.

Tau Identification: $Z \to \tau + \tau$




ATLAS EXPERIMENT
Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST
W→τν candidate in 7 TeV collisions
p_T(τ) = 29 GeV
E_T^miss = 39 GeV
Δφ(τ,E_T^miss) = 3.1
m_T = 68 GeV

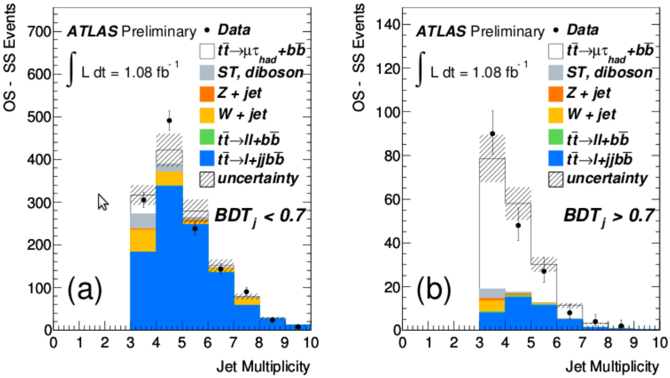
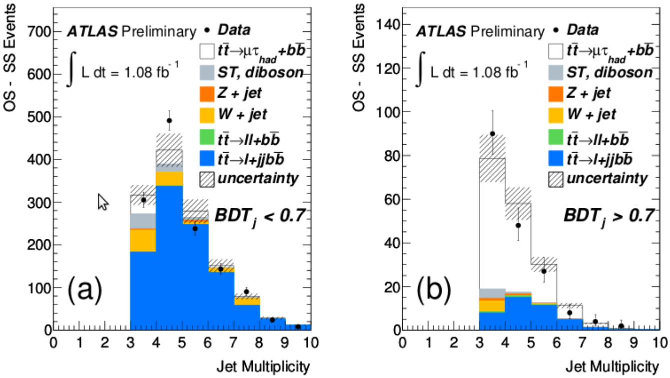


Figure 7: Number of jets distributions for OS-SS events after the b−tagging selection. The solid circles indicate data and the histograms indicate the expected signal and backgrounds from MC. The normalization of the expected signal and the backgrounds are based on the fit result. The fraction of each background is estimated from MC. (a) $BDT_j < 0.7$, (b) $BDT_j > 0.7$.



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