Performance of hadronic tau lepton reconstruction with ATLAS

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on behalf of the ATLAS collaboration

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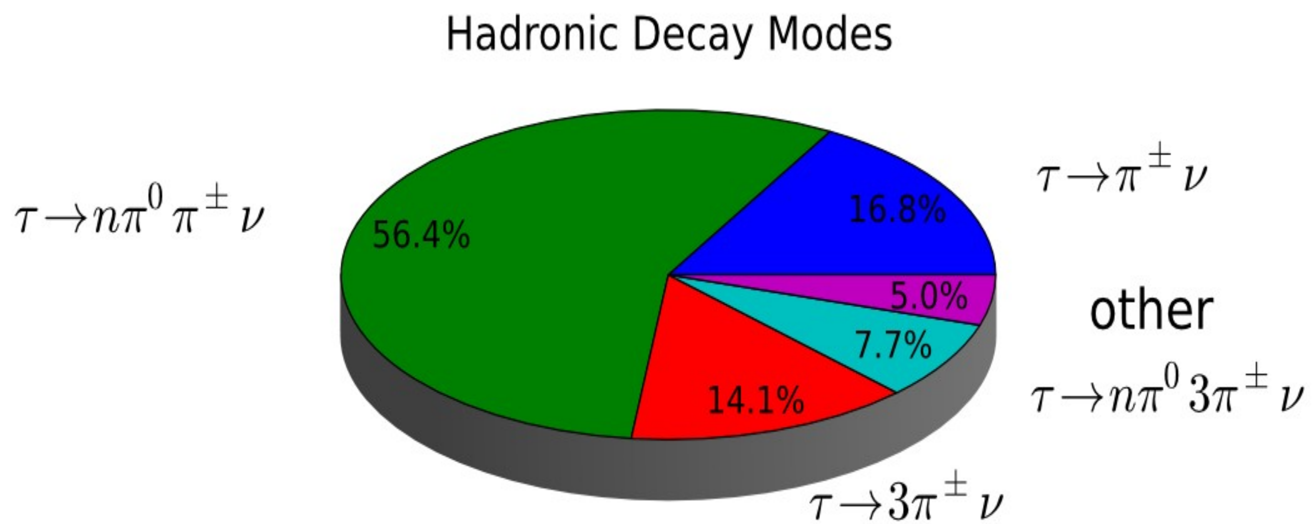
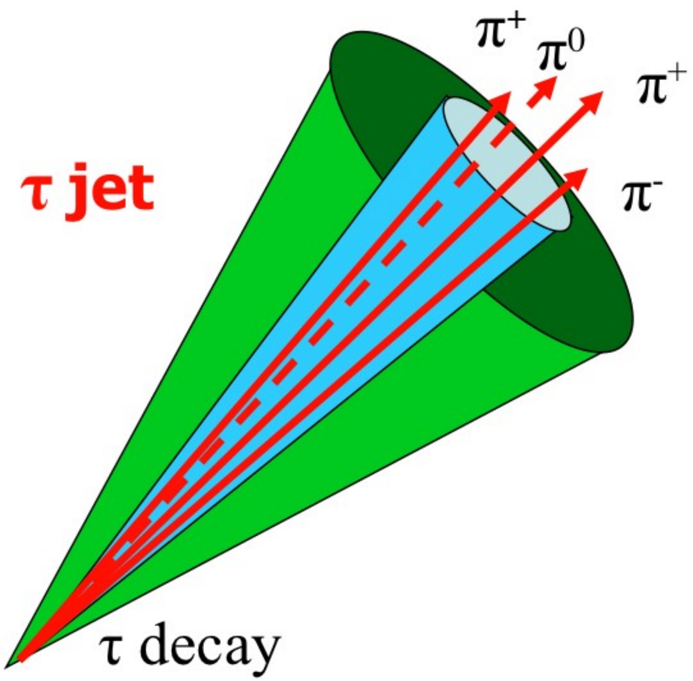
Tau Lepton Properties

Tau Lepton Properties
- m_τ = 1.78 GeV
- $c\tau$ = 87 μm
- BR($\tau \rightarrow l\nu\nu$) = 35.2%
- BR($\tau \rightarrow$hadrons) = 64.8%

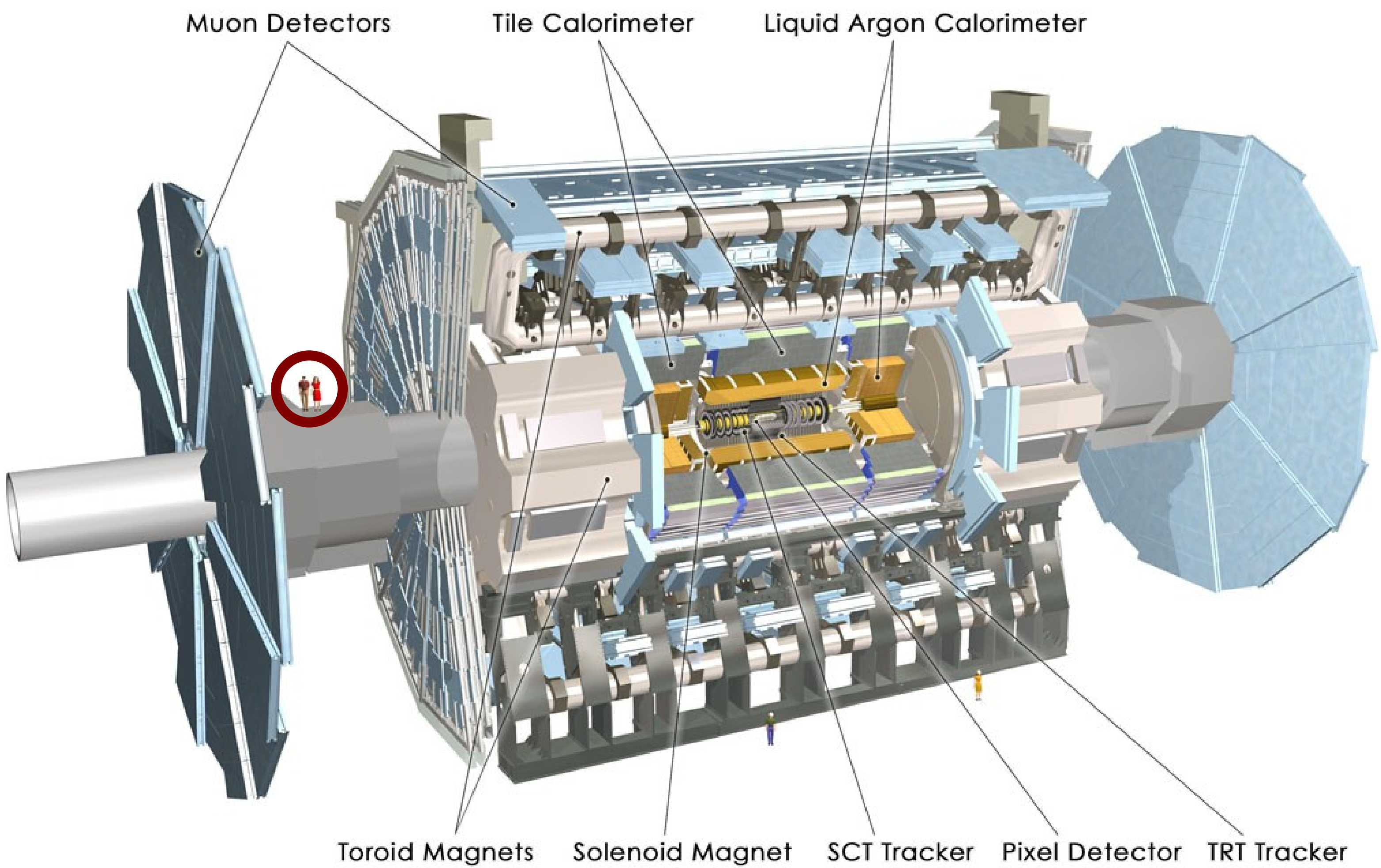




Typical detector signature
- one or three charged tracks
- collimated calorimeter energy deposits
- large leading track momentum fraction
- possible secondary vertex reconstruction

ATLAS Tau Physics Program
- Standard Model cross section measurements
- Higgs searches (SM and beyond)
- Searches for SUSY and exotica

ATLAS detector

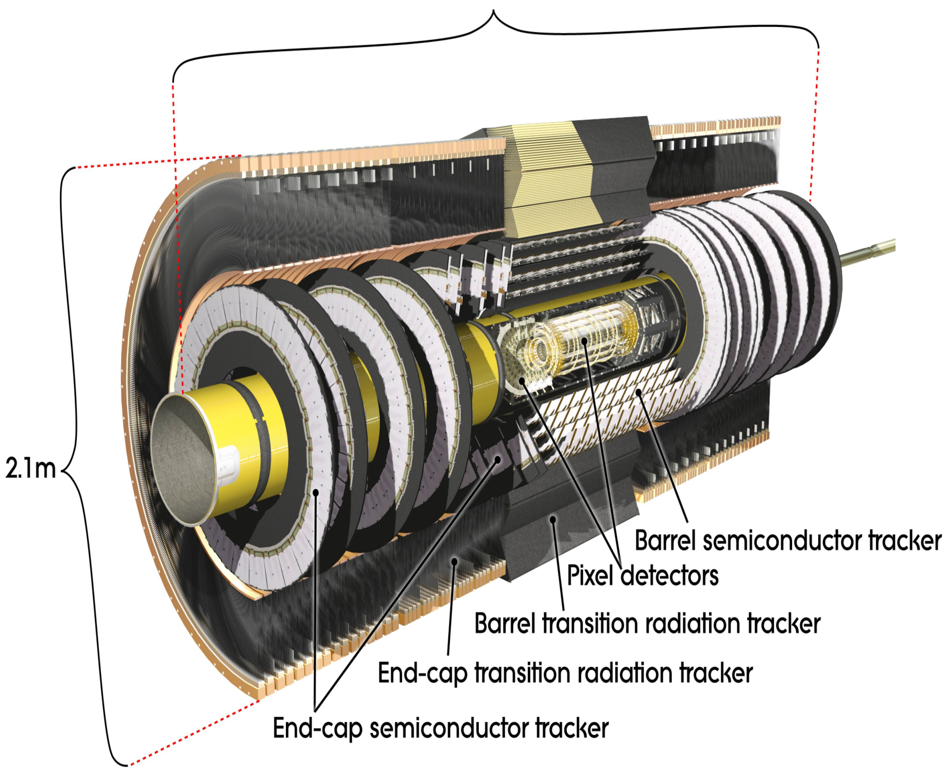


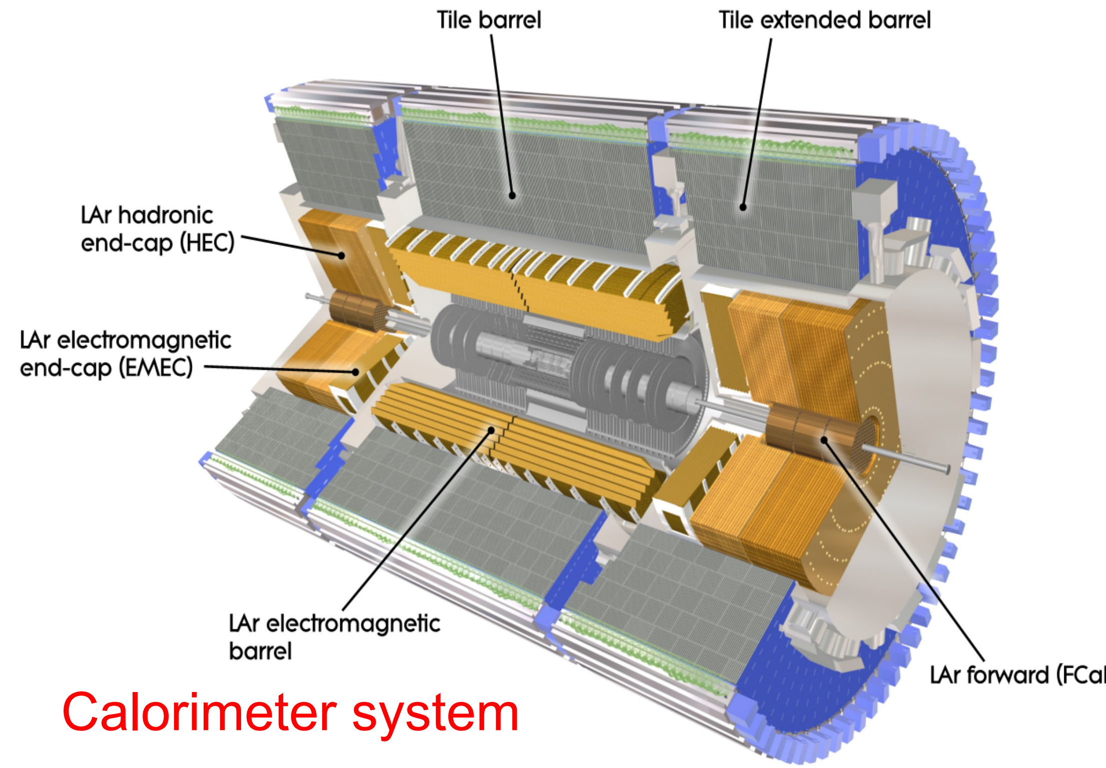
ATLAS detector:
- 44 m long, 25 m in diameter, 7000 tons
- Tracking system; EM calorimeter;
  hadronic calorimeter; muon spectrometer

ATLAS tracking & calorimeter

Tracking system

Pixel and SCT up to $|\eta| < 2.5$
TRT up to $|\eta| < 2.0$
(immersed in 2.0 T field)





Calorimeter system

Electromagnetic calorimeter up to $|\eta| < 3.2$
- with presampler up to $|\eta| < 1.8$

Hadronic calorimeter consists of
- Tile calorimeter up to $|\eta| < 1.7$
- Hadronic endcap for $1.5 < |\eta| < 3.2$

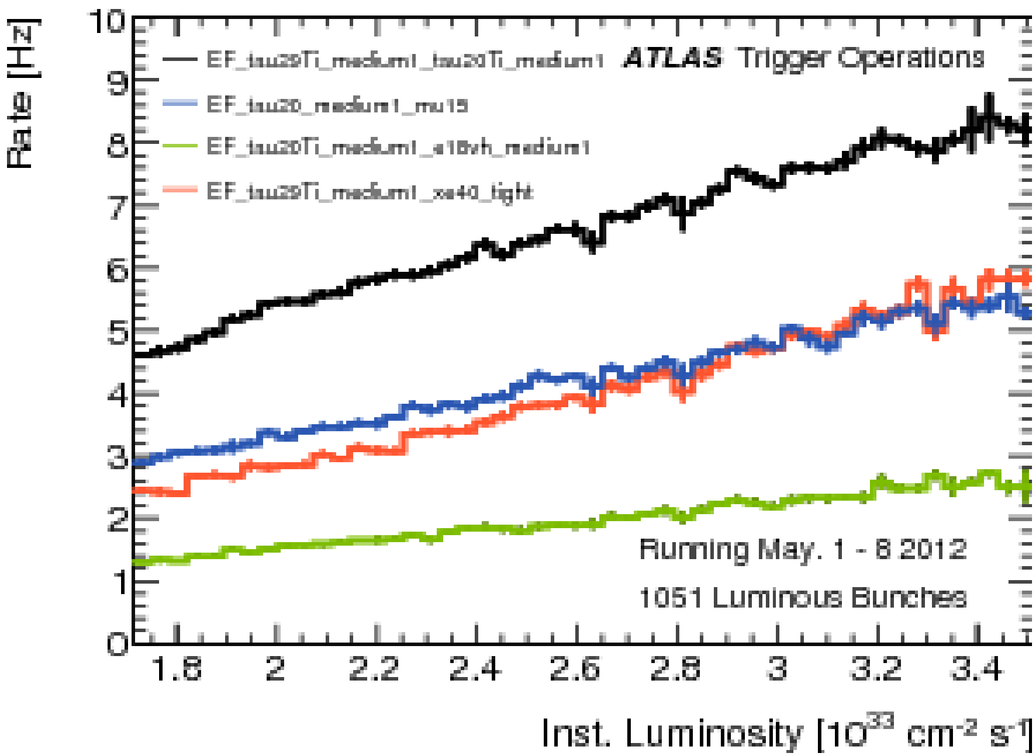
Forward calorimeter up to $|\eta| < 4.9$

Tau Trigger

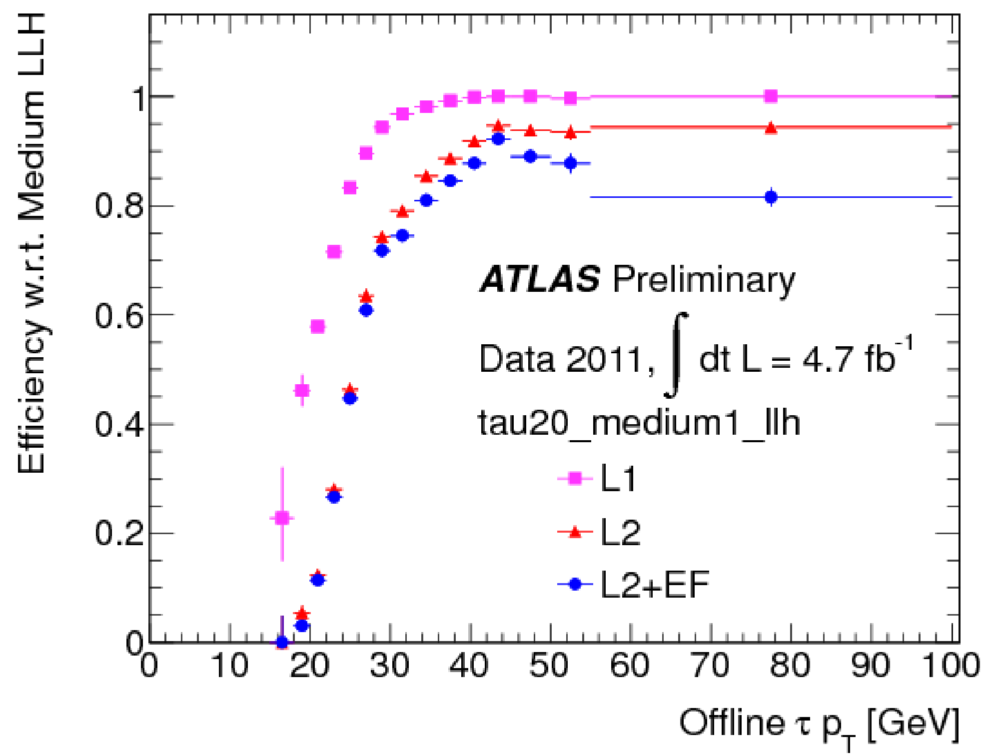
ATLAS trigger system – 3 levels:

- Level-1: hardware-based: only calorimeter towers serve as input
- Level-2, Event filter: computer farms: algorithms close to “offline”

Tau trigger rates wrt inst. luminosity

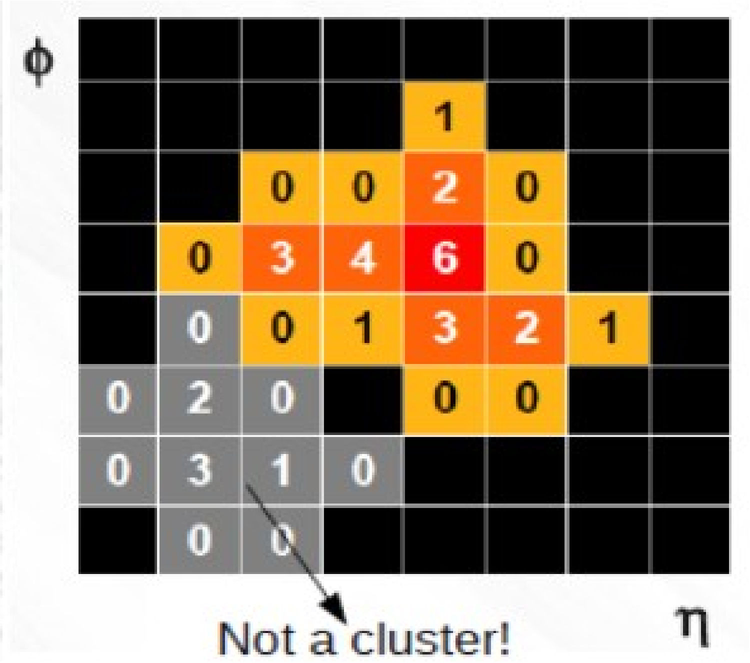


Expected tau trigger efficiency for 2012



Tau reconstruction

Tau candidates reconstructed from AntiKT jets (R=0.4) with ET>10 GeV built from topological clusters



Topological clustering is an algorithm that associates calorimeter cells into a cluster

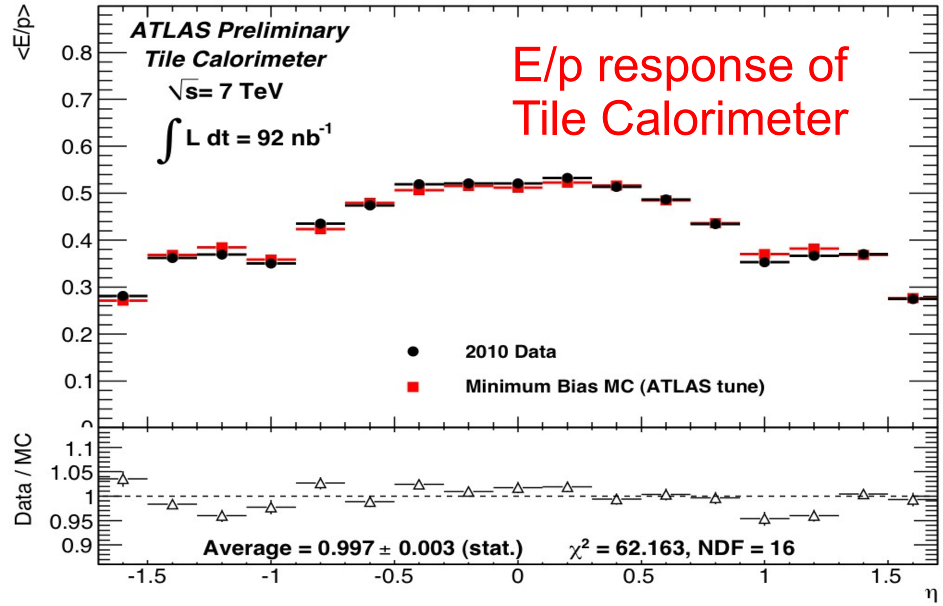
- Seed cells are used to form clusters with $E_{cell} > 4\sigma_{noise}$
- Neighbouring cells iteratively are added with $E_{cell} > 2\sigma_{noise}$
- Cells surrounding the cluster are added in a final step

During reconstruction, the tau four-momentum and various tracking and calorimeter (e.g. shower shape) variables are built.

Tau calibration

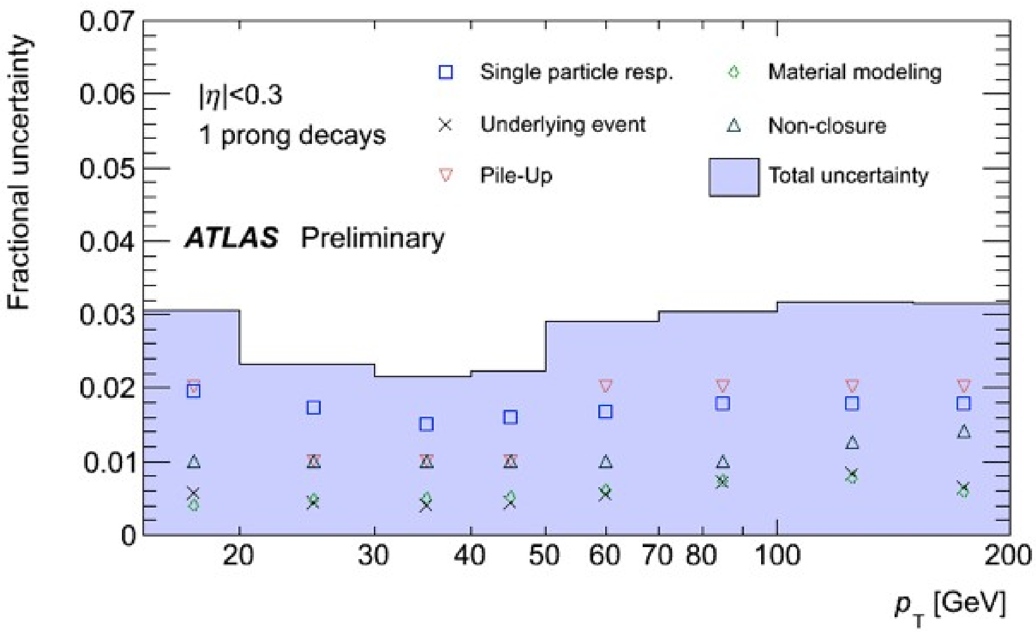
Energy calibration:

- uses local cluster-weighted scale of calorimeter clusters
  - =>weight is a function of the cluster energy, the cell energy density, energy around the cluster, ...
  - purpose: account for lower calorimeter response to hadrons
- further MC-based calibration to tau p_T scale

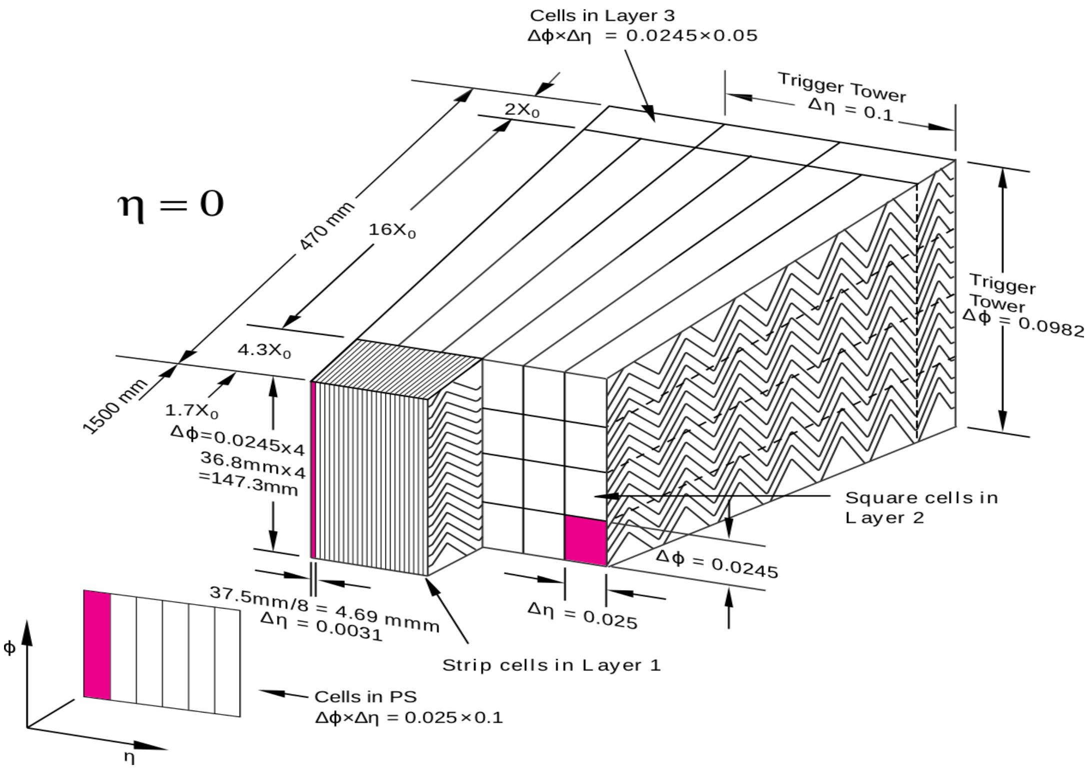


Uncertainties are evaluated by decomposing the energy scale and evaluating the uncertainty of each ingredient, e.g.

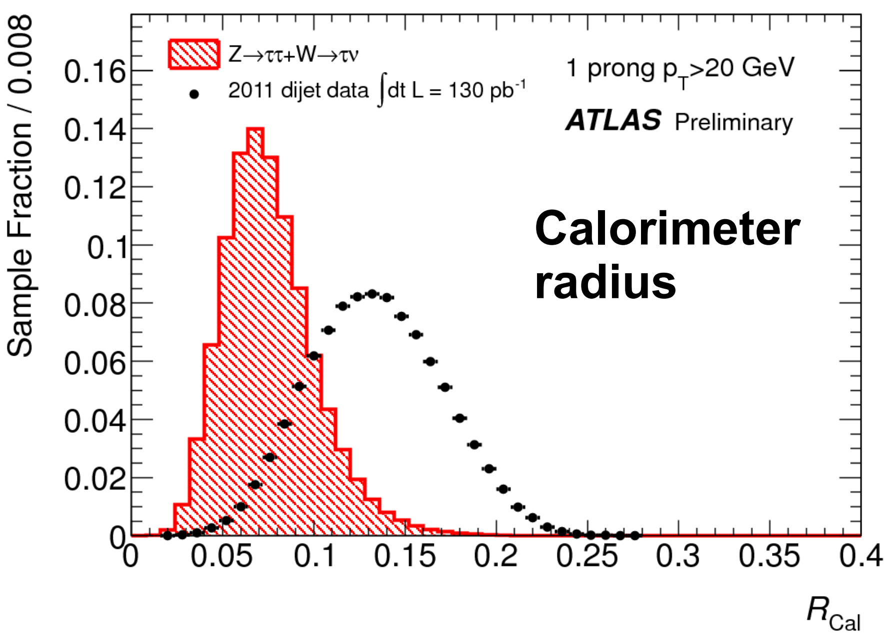
- single-particle response (=>test beam)
- E/p measurement (=>calo vs. tracking)
- Pile-up (=>simulation)



Calorimeter ID



Calorimeter granularity crucial for reconstructing the transverse energy shower profile of hadronic tau decays and jets



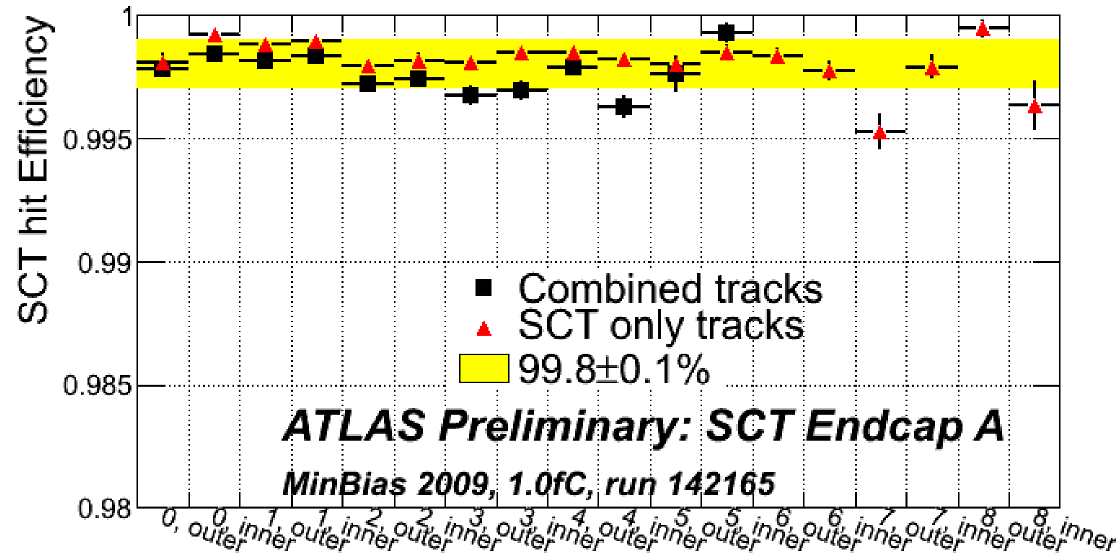
Key variables used in tau ID include:

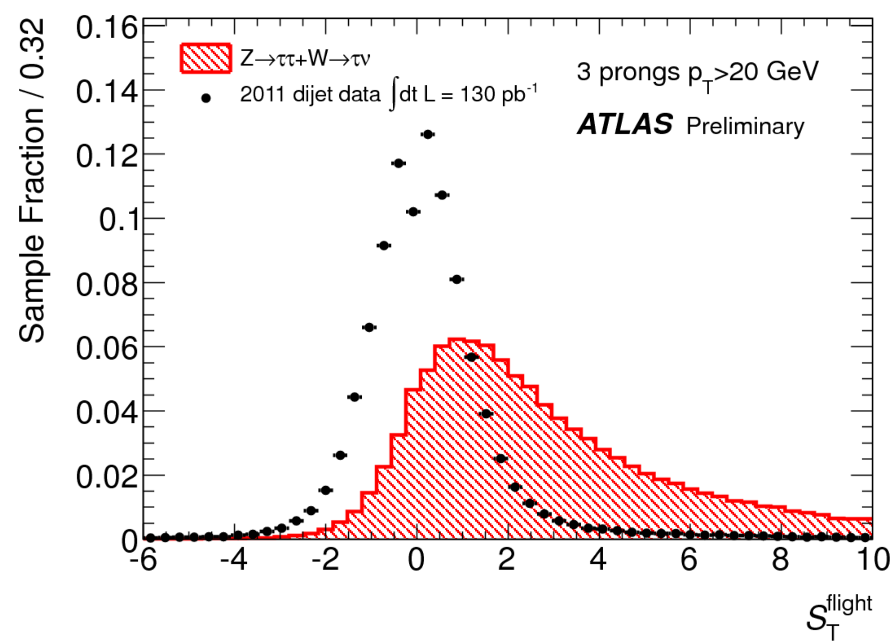
- R_{cal} : shower width in the EM calorimeter
- f_{core} : ΣE_T^{cells} (0.1) / ΣE_T^{cells} (0.4)
- $m_{clusters}$: mass of clusters

Tracks with p_T > 1 GeV and within $\Delta R<0.2$ are associated to the tau candidate

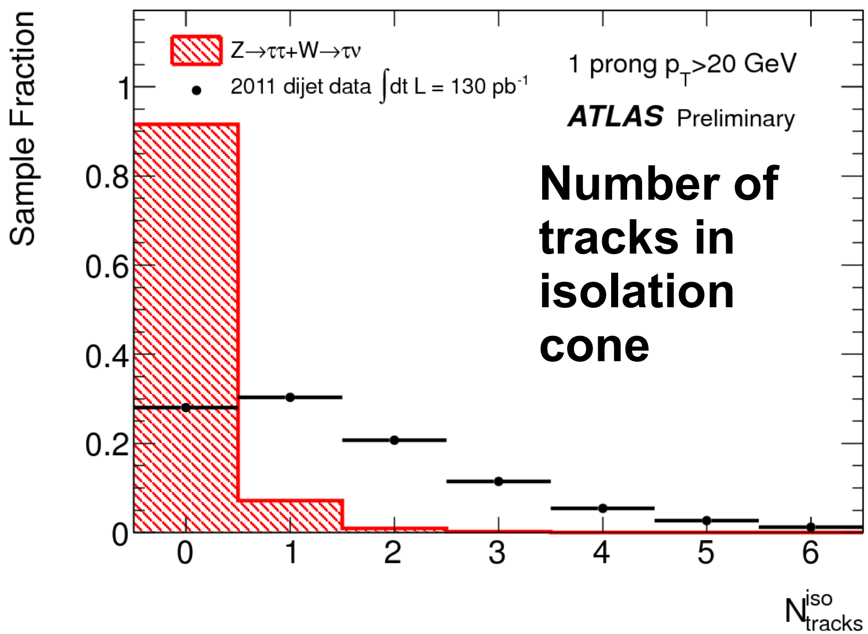
Key tracking variables for ID include:

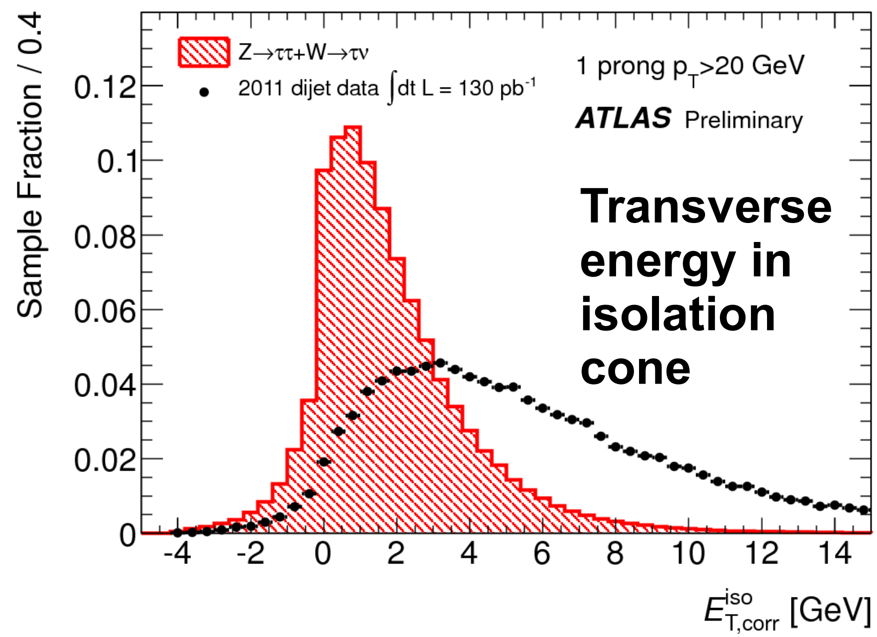
- m_{tracks} : mass of the track system
- R_{tracks} : average distance of tracks to je
- S_T^{flight} : secondary vertex flight path significance

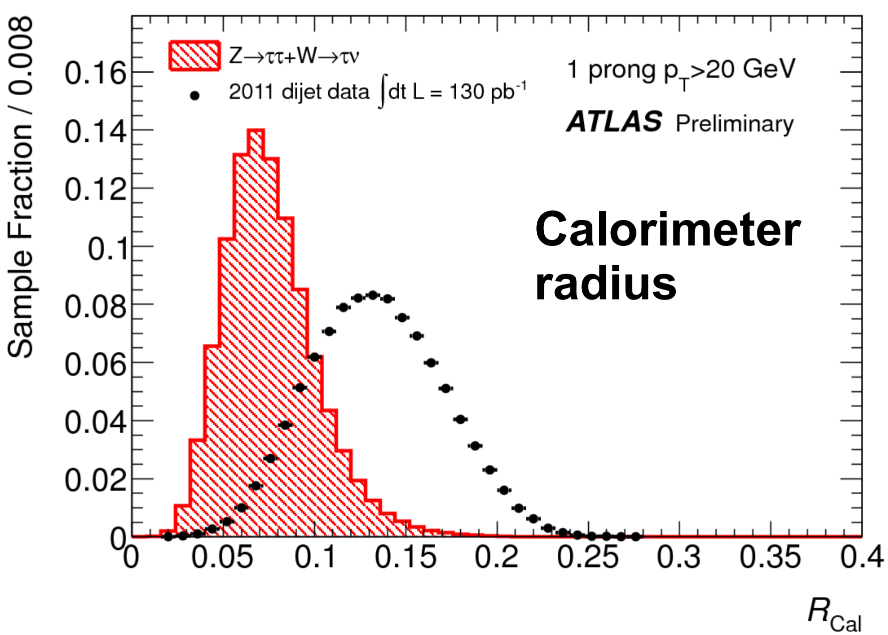


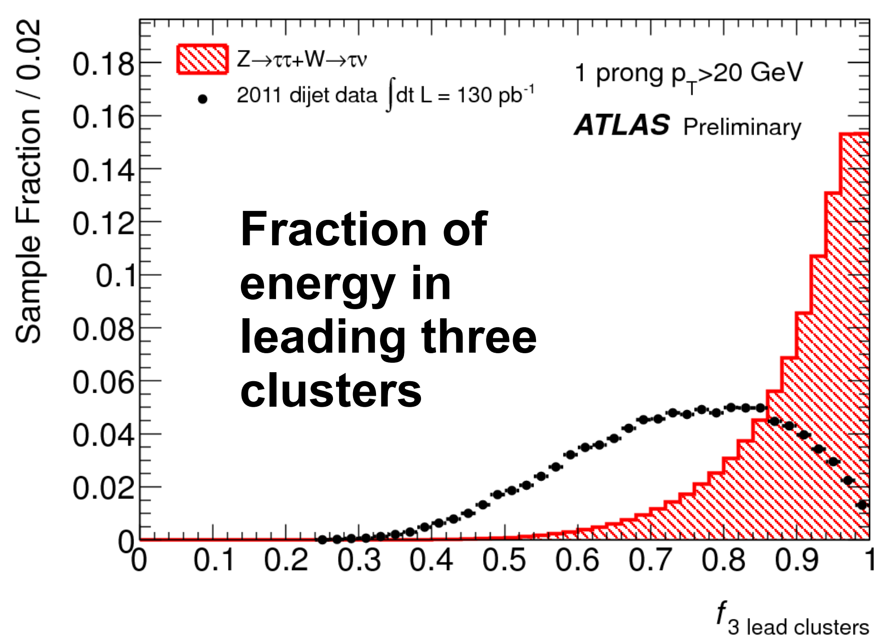


Selected Variables:
single-track tau ID

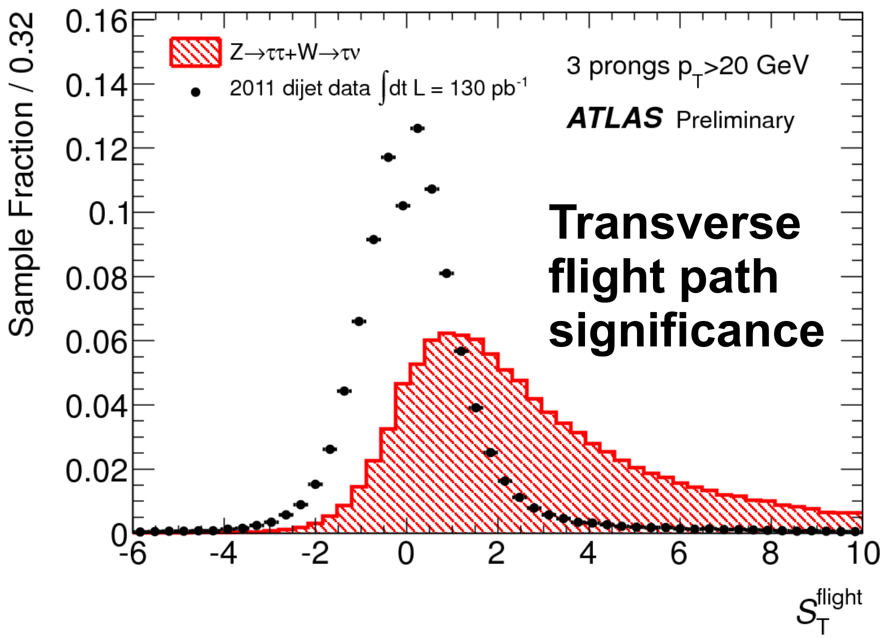


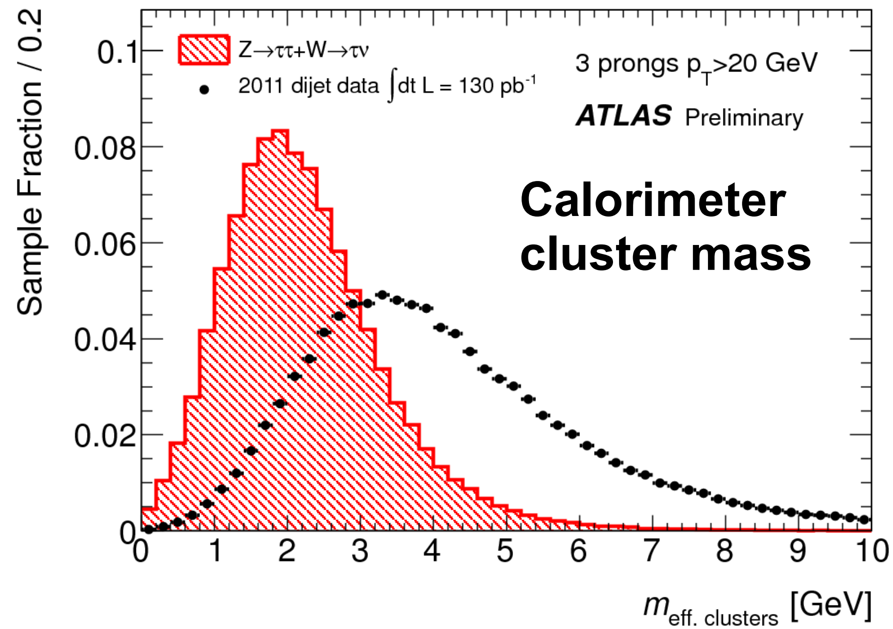


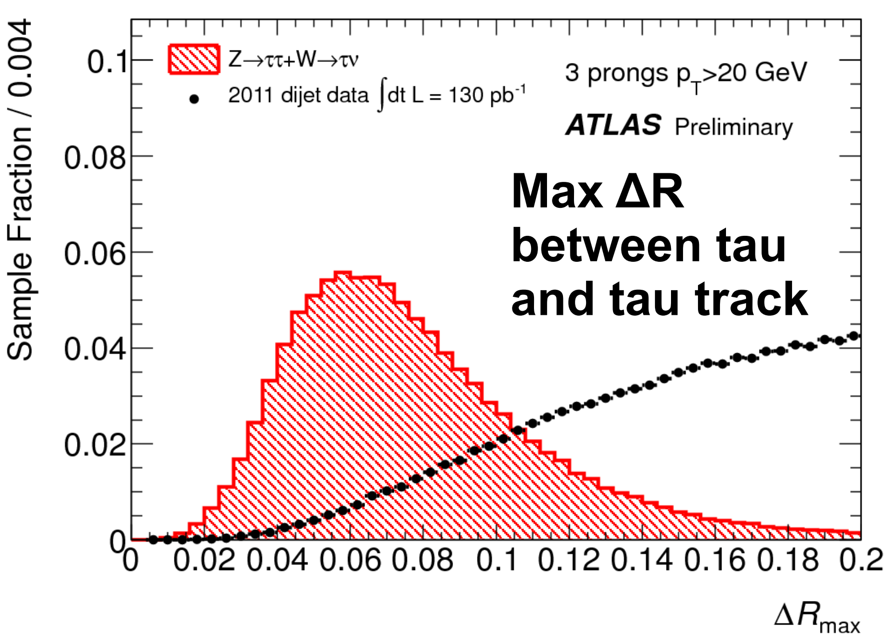


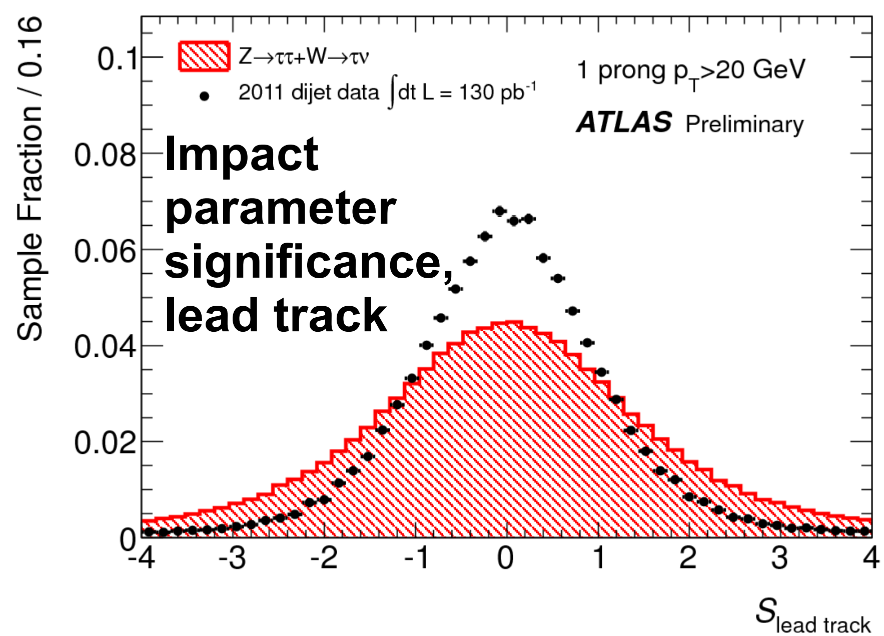


Selected Variables:
multi-track tau ID







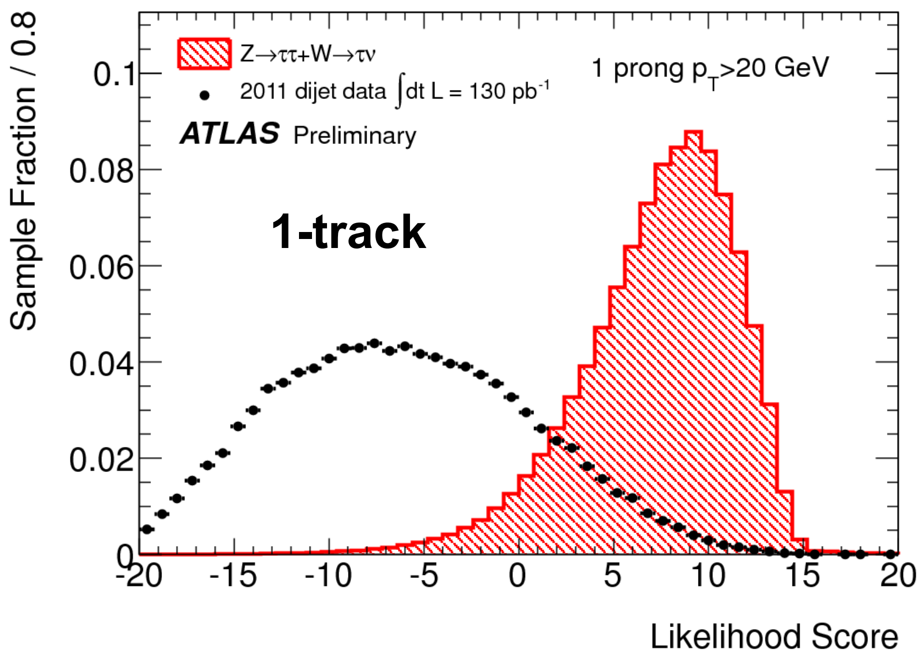


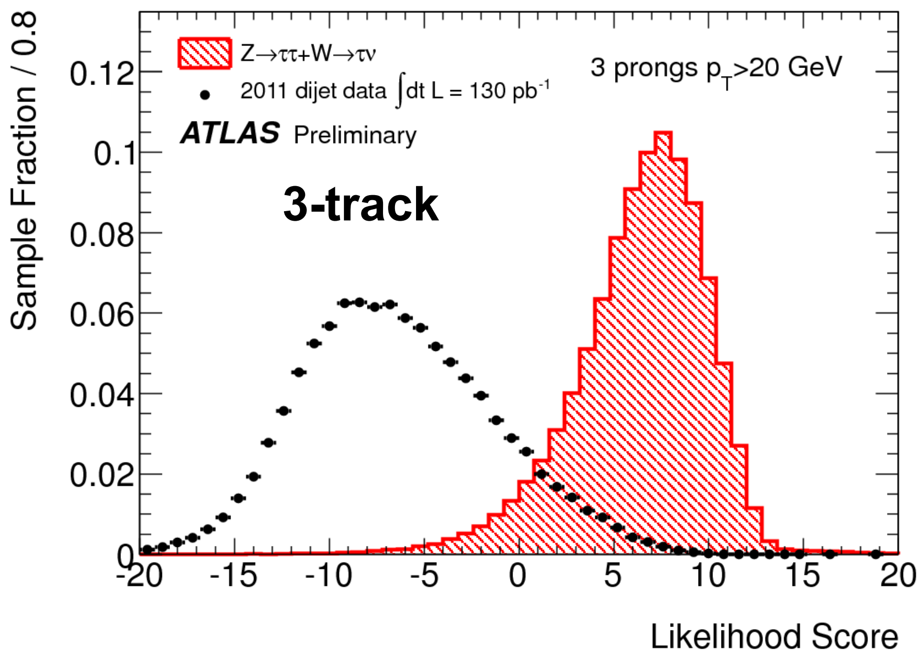
Tau ID: LLH

Variables are combined into multi-variate methods to increase discrimination power

Projective Likelihood

Likelihood ratio formed using signal (MC) and background (dijet data) probability distribution functions

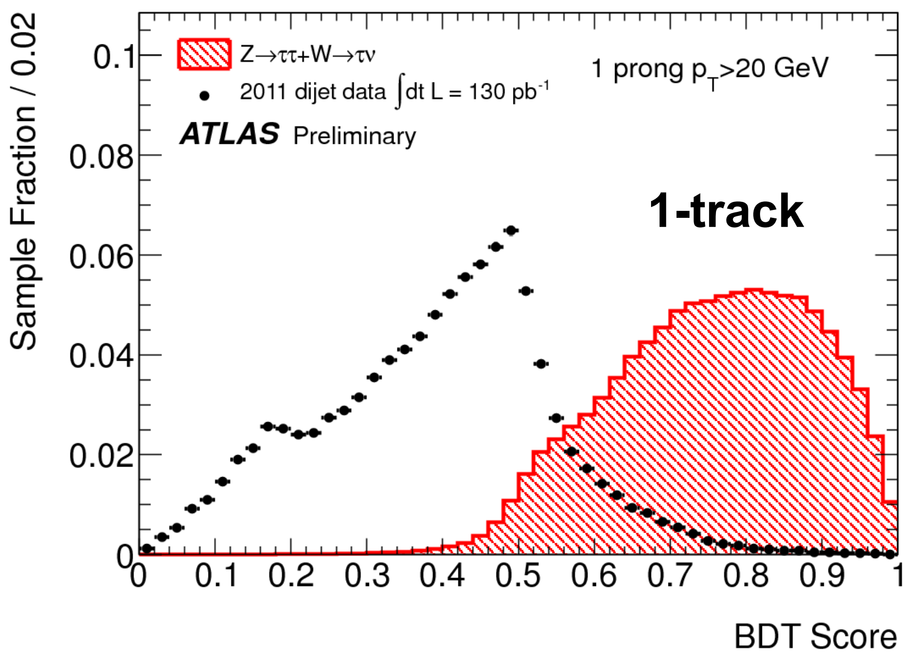


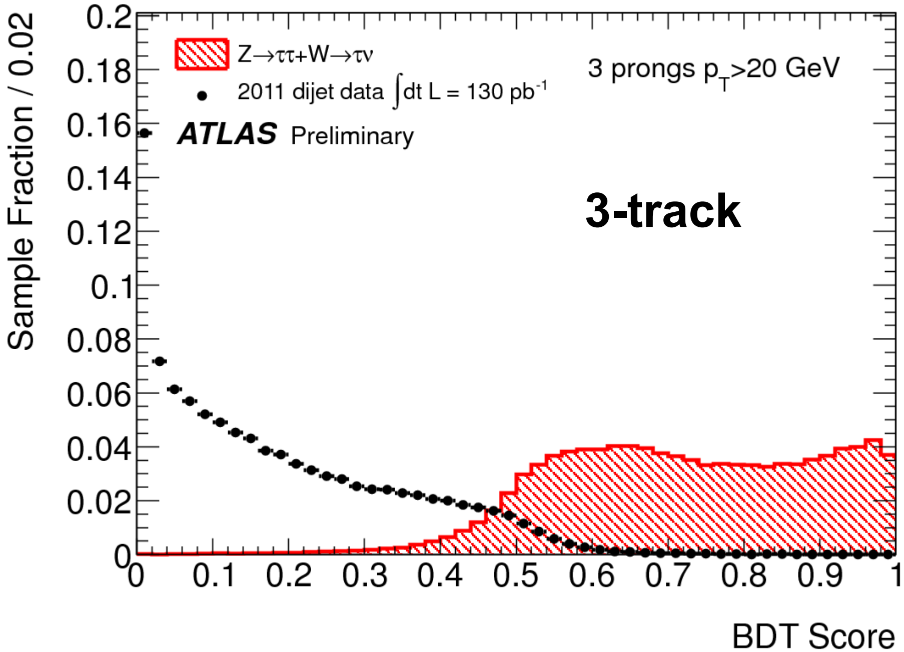


Tau ID: BDT

Boosted Decision Tree

uses information from multiple decision trees to form a weighted score for signal and background hypotheses

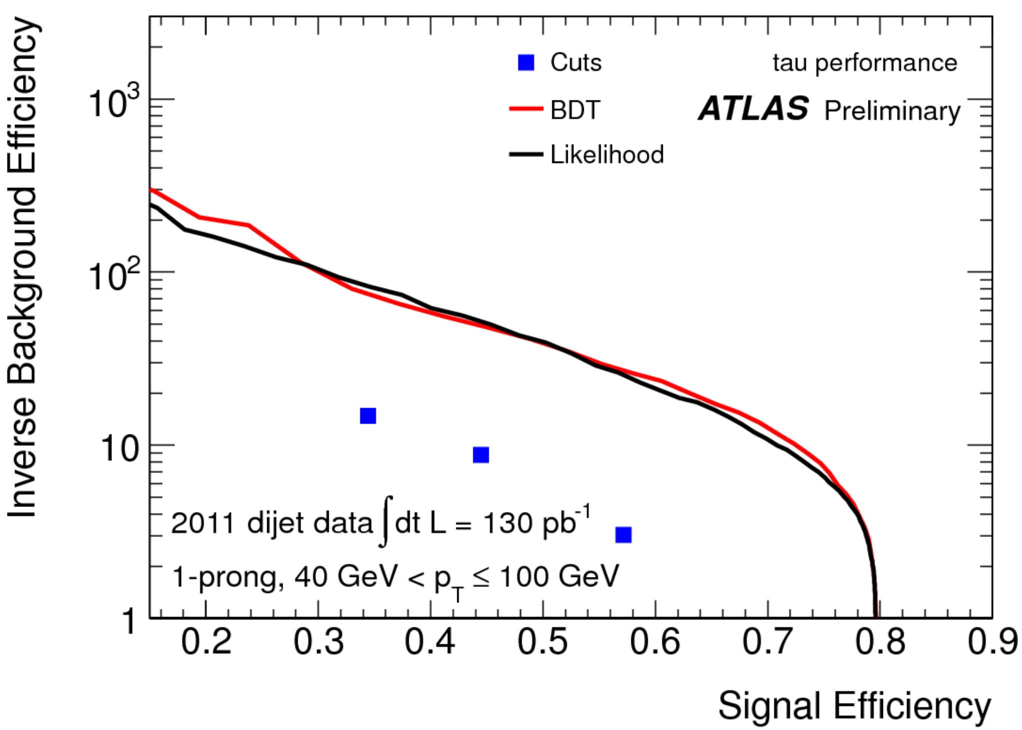


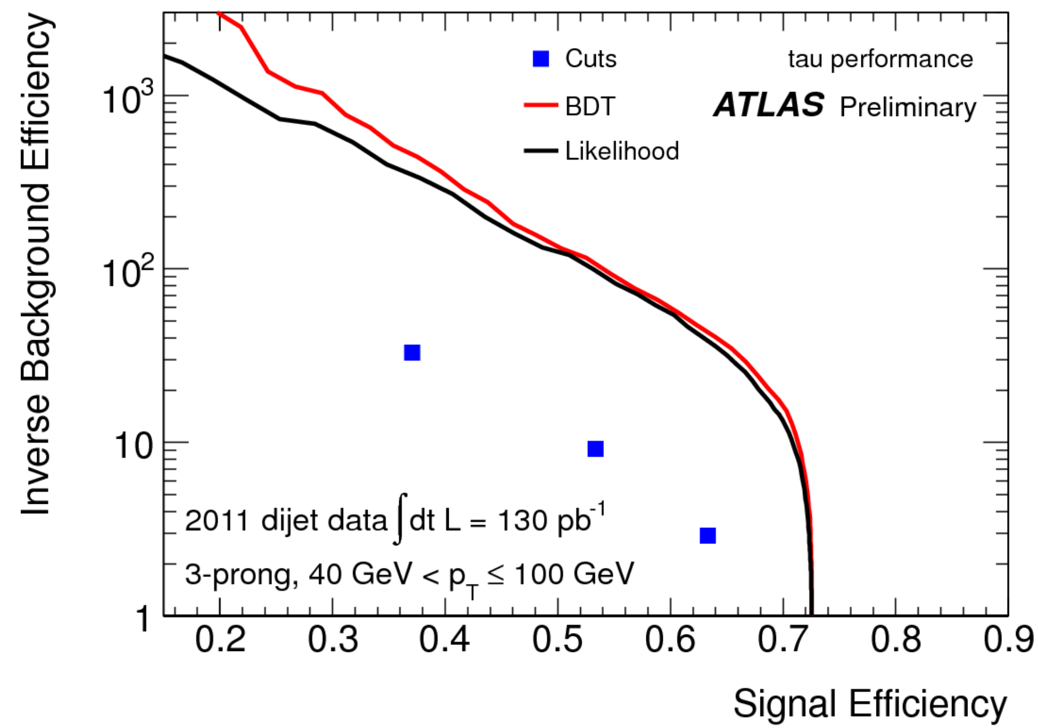


Tau ID performance

Signal efficiency from $W \to \tau\nu$
and $Z \to \tau\tau$ Monte Carlo samples

Rejection measured from
di-jet selection in data





$R = 1 / \varepsilon(\text{bkgd})$

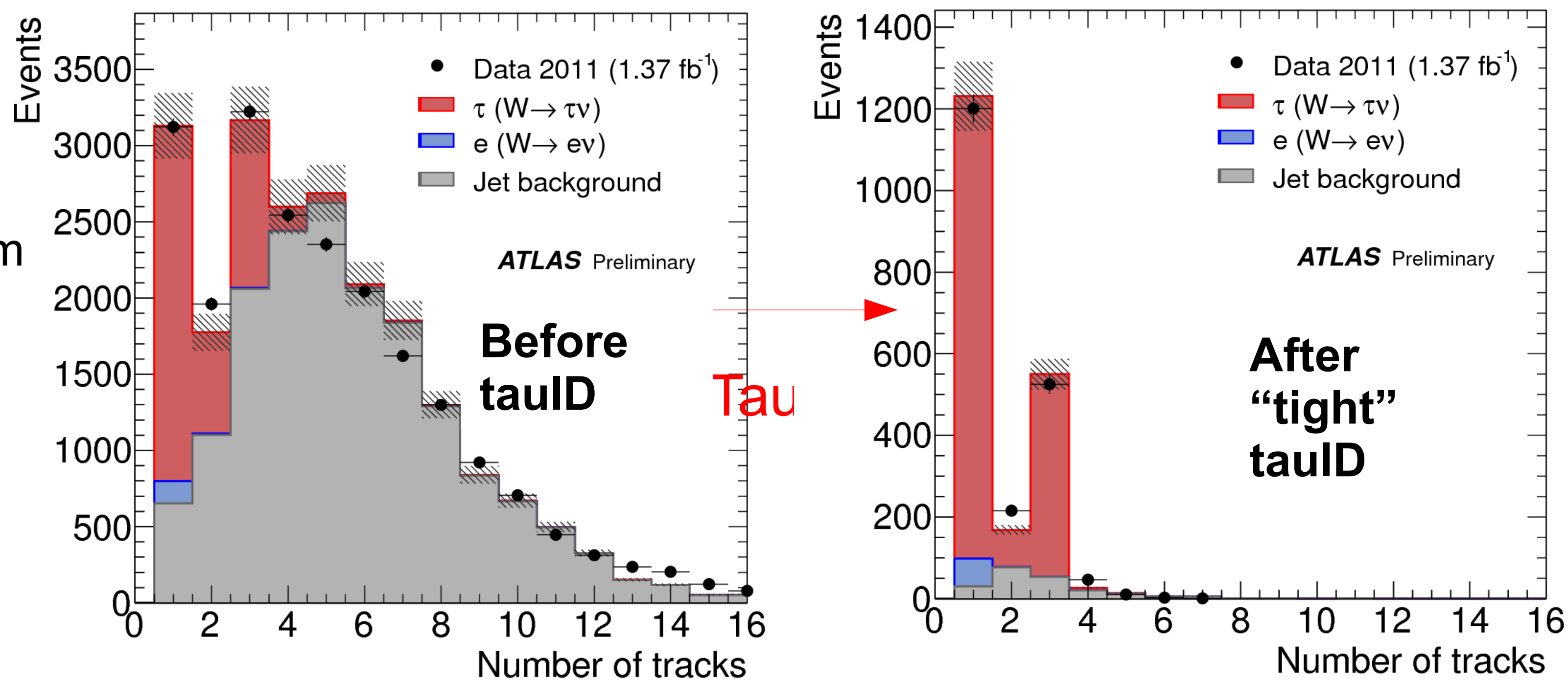
W→τν: Efficiency measurement

Tag & Probe method, using E_T^{miss} significance to tag events

The N_{trk} spectrum of tau leptons vs. jets fit to extract the $W \rightarrow \tau\nu$ fraction

multi-jet N_{trk} spectrum taken from low E_T^{miss} significance control region

Excellent agreement of data with MC efficiencies

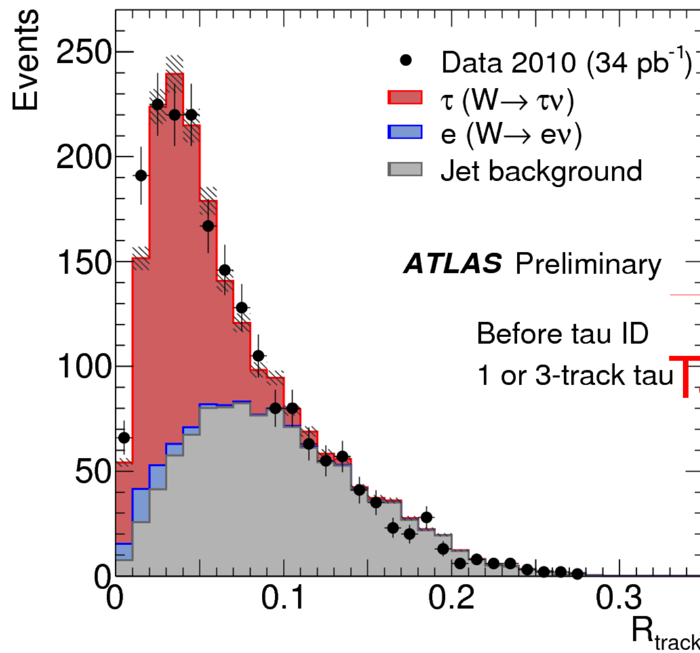


Cross-checked with cross section normalization method, normalizing $W \rightarrow \tau\nu$ to measured W cross-section in leptonic channels

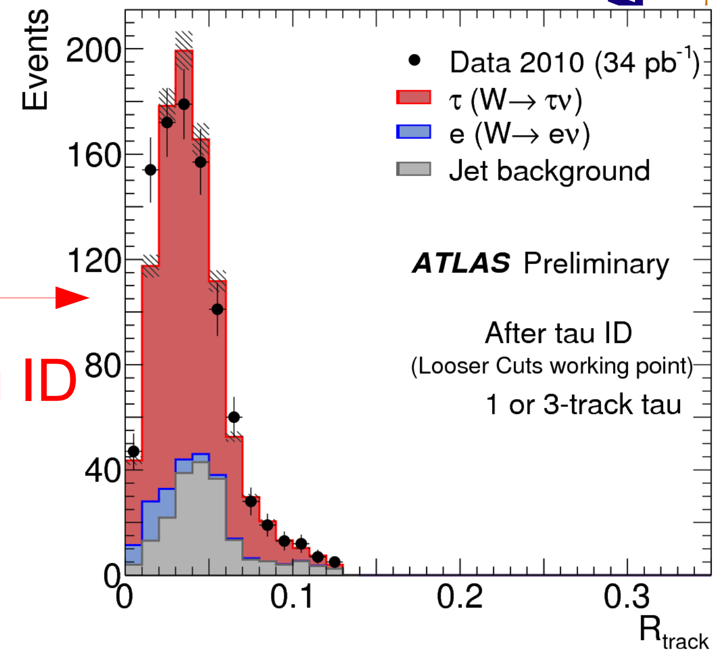
W→τν: Data vs MC control plots

Tag & Probe method

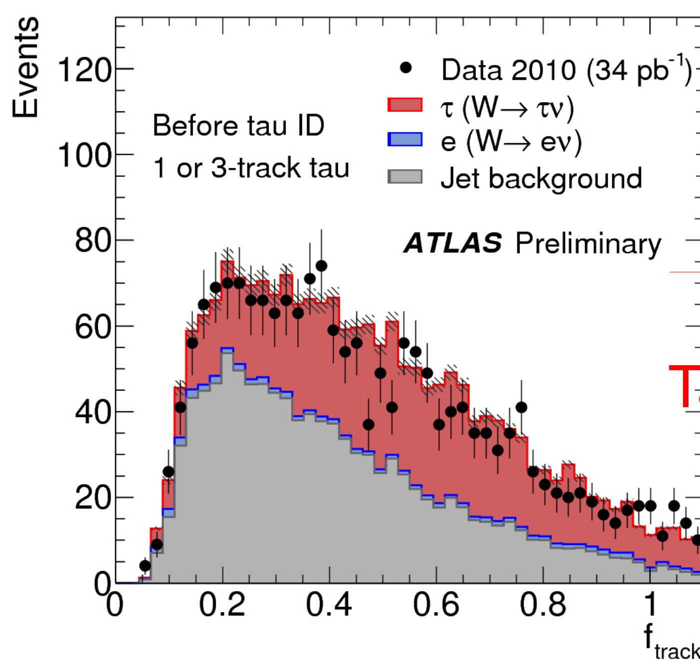
Track radius



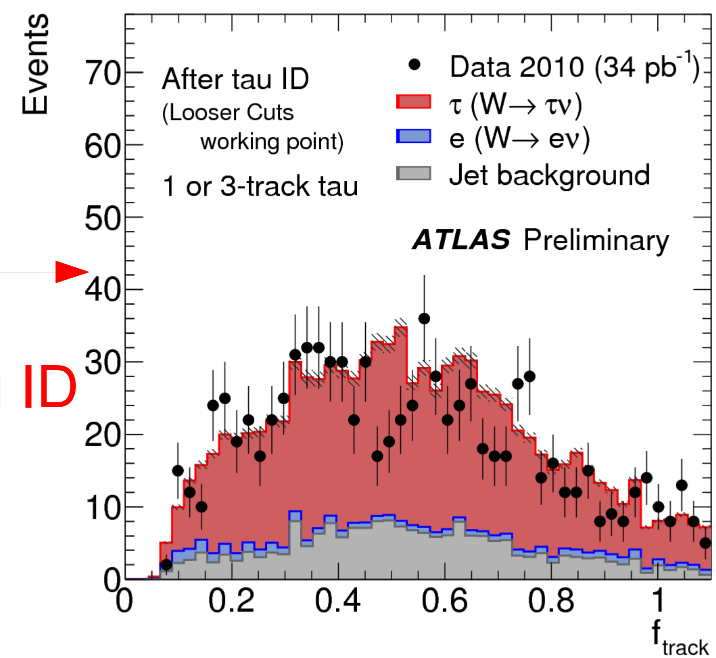
Tau ID



Leading track pT fraction



Tau ID

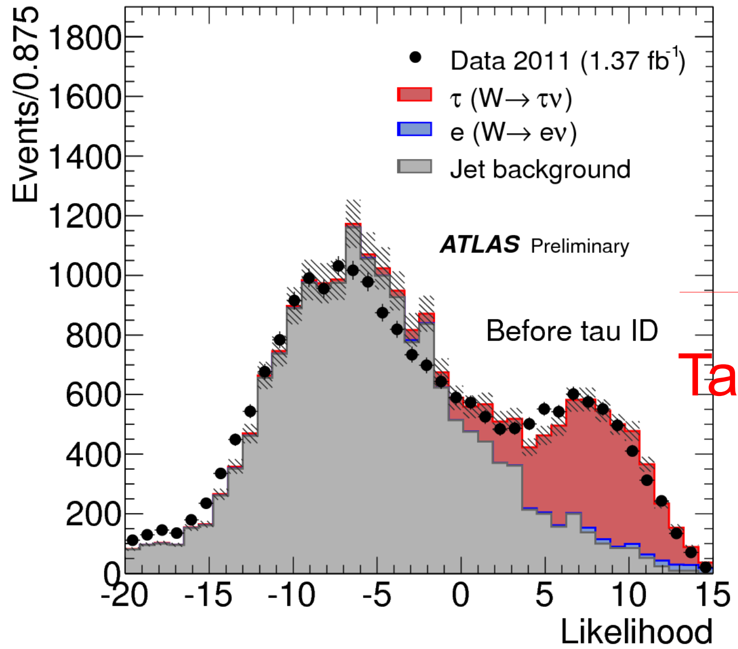


W→τν: Data vs MC control plots

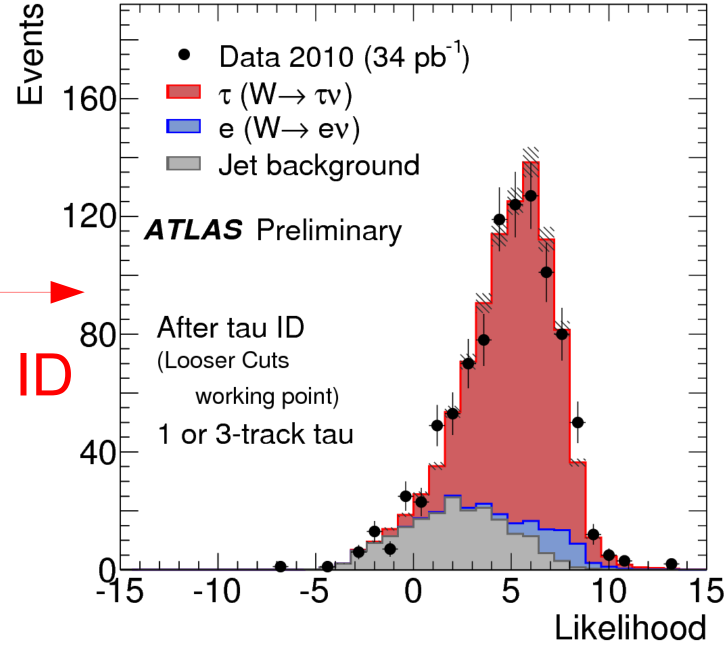
Tag & Probe method

Right: After cut-based Tau ID

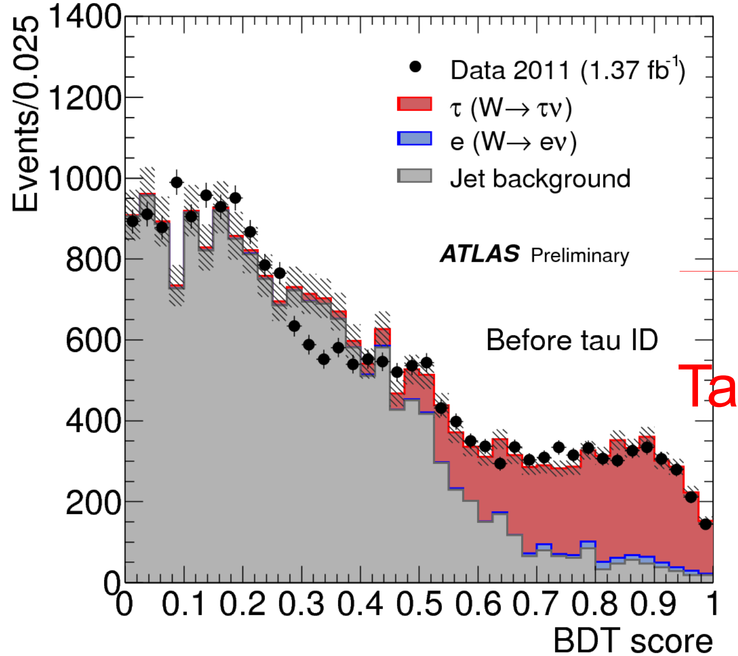
Likelihood



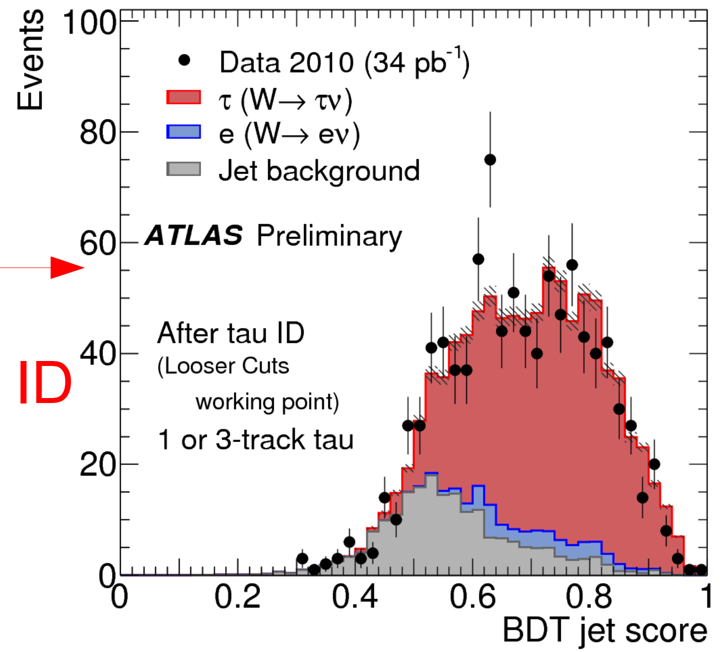
Tau ID



BDT



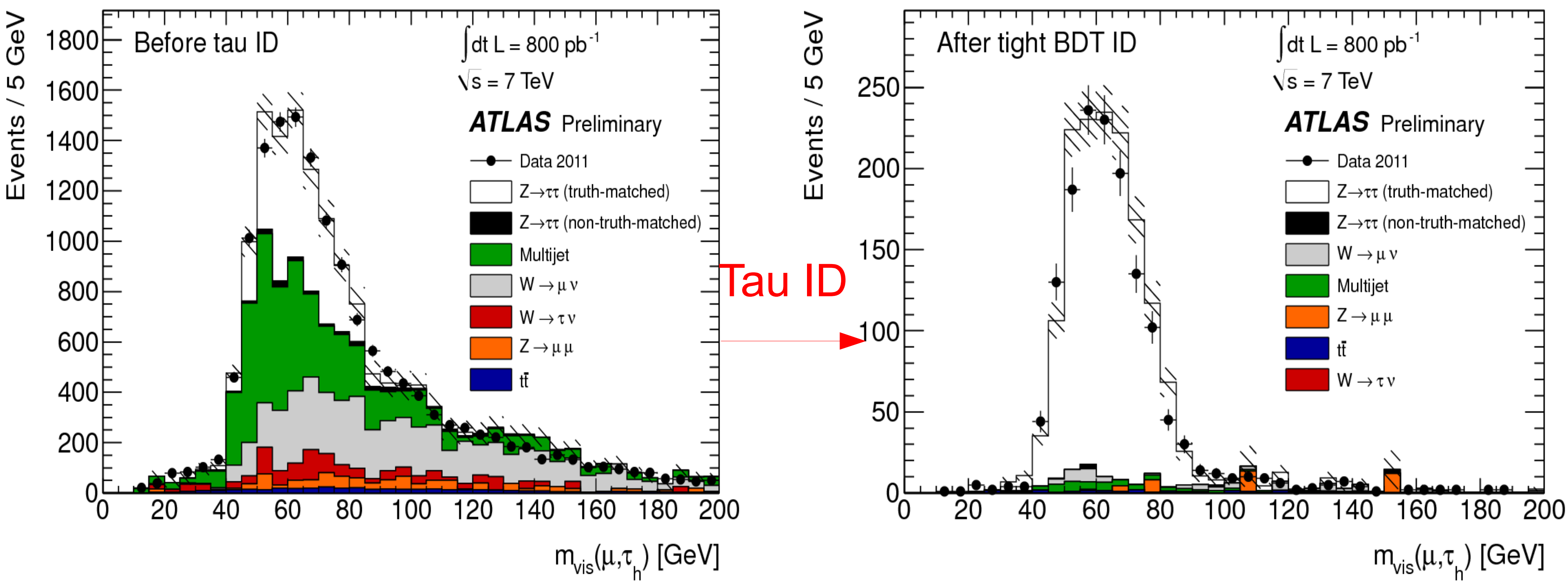
Tau ID



Z→ττ: Efficiency measurement

Using 800 pb^{-1}, tau identification efficiency studied in Z→ττ events where one tau decays via τ→μνν (tag), and the other decays hadronically (probe)

Very good agreement between MC and data.
(distribution of visible mass between muon-tau candidates shown)

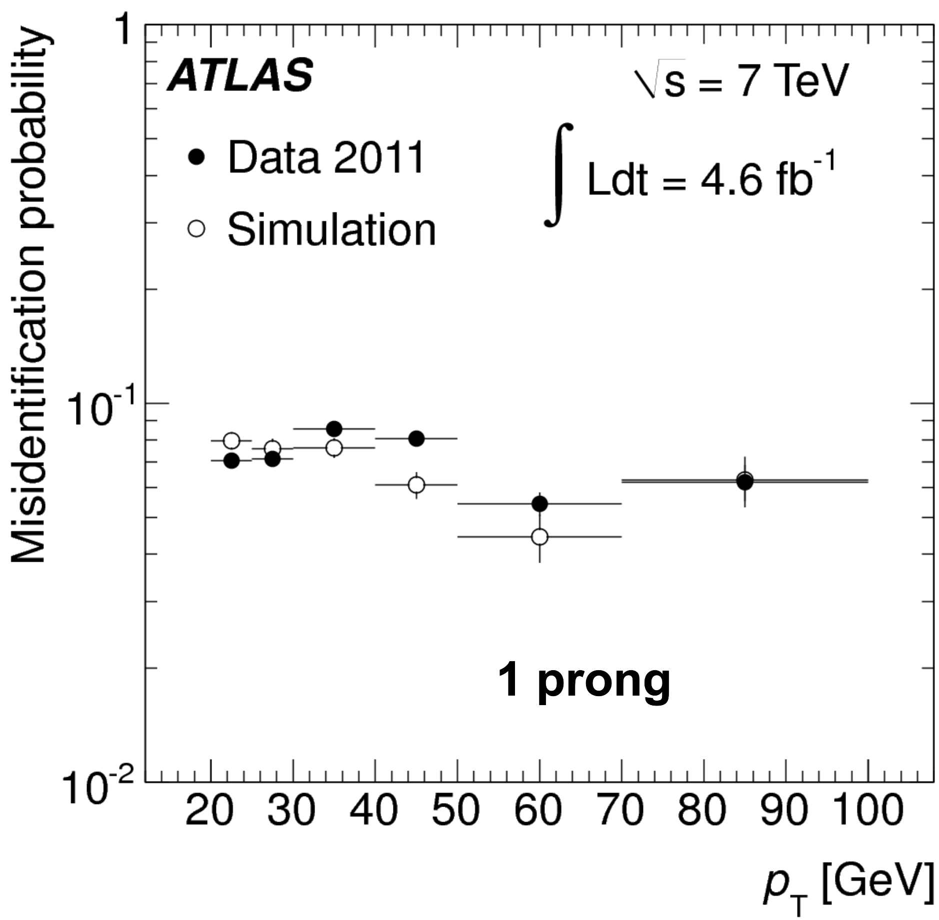


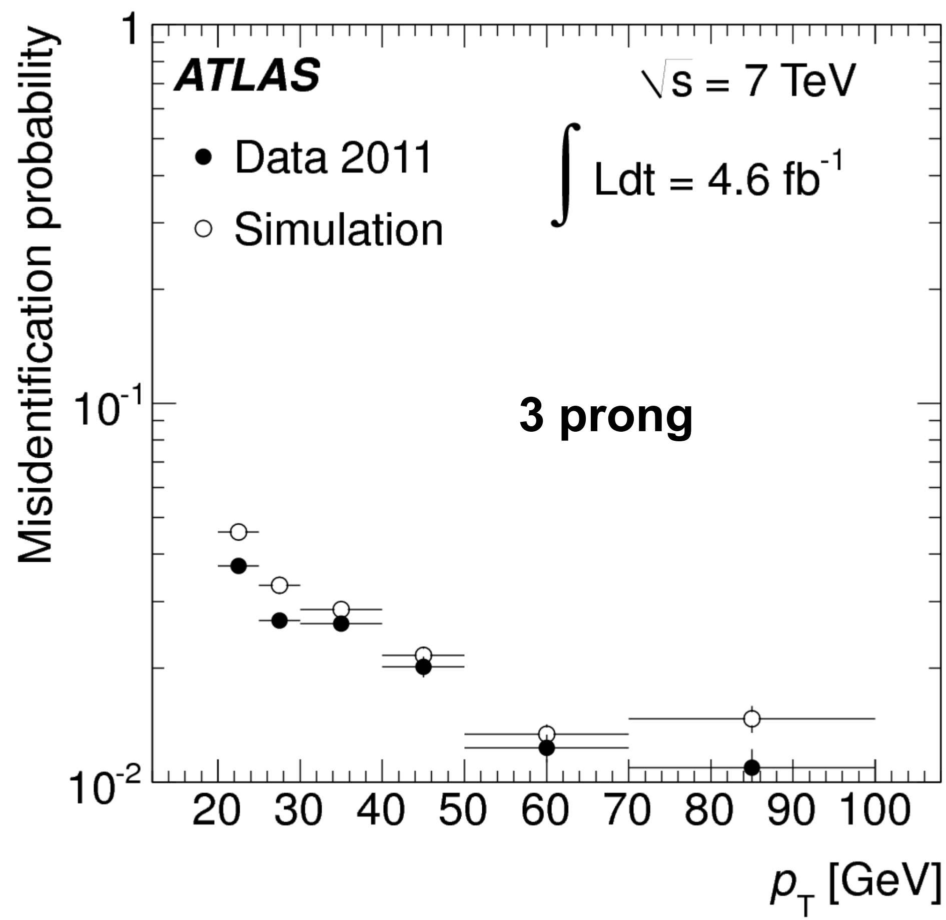
Tau misidentification probability

Tag & Probe method, W(lnu)+jets events, Tight LLH (signal efficiency ≈30%)

Probability for quark/gluon jets to be misidentified as tau jets

- with respect to all jets with 1 or 3 reconstructed tracks
- dominated by quark jets (from W+1 jet)





Summary and outlook

Summary

- good detector performance enables high performing tau identification
- identification variables and methods well understood
- efficiency measurements confirm accuracy of Monte Carlo predictions

Outlook

- tau reconstruction and identification algorithms still evolving
- continued optimization and investigation of tau substructure underway
- use data to continue to study ID efficiency, energy scale, and other properties
- lots to look forward to in the ATLAS tau physics program

References

ATLAS-CONF-2011-077
Reconstruction, Energy Calibration, and Identification of Hadronically Decaying Tau Leptons

ATLAS-CONF-2011-093
Measurement of Hadronic Tau Decay Identification Efficiency using $W \to \tau\nu$ Events

ATLAS-CONF-2011-152
Performance of the Reconstruction and Identification of Hadronic Tau Decays with ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauTriggerPublicResults
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionResults

Local Cluster Weighting

From: ATLAS-CONF-2010-053

Calorimeter cells in clusters are weighted according to the cluster energy and the cell energy density to account for the lower response of hadrons in the calorimeter

The cluster is weighted according to the energy measured around the cluster and the longitudinal depth of the barycentre of the cluster in the calorimeter to account for energy deposited but not contained within the cluster

The cluster is also weighted according to its energy and the fractional energy deposited in each calorimeter layer to account for energy deposited in the dead material and thus not measured by the calorimeter

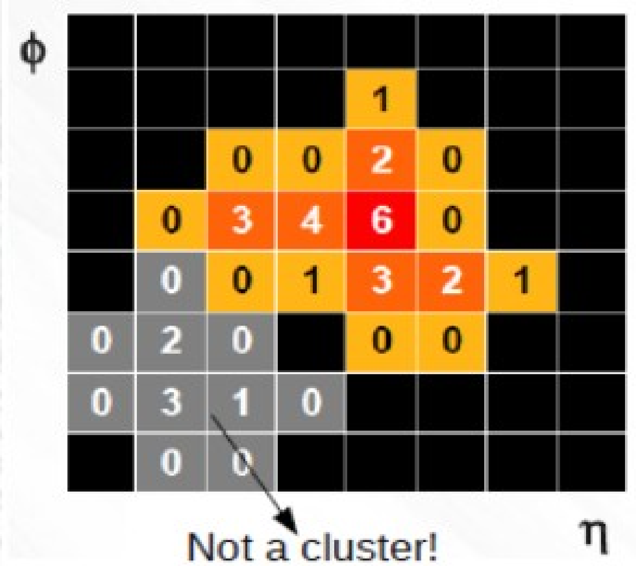
Topological Clustering

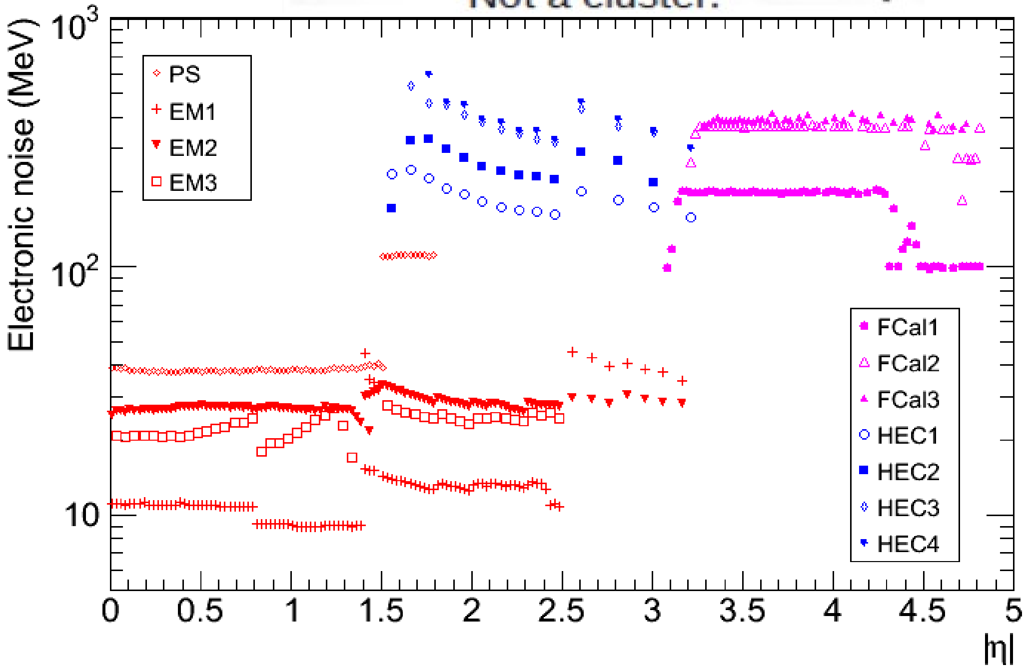
Topological clustering is an algorithm that associates calorimeter cells into a cluster

Seed cells are used to form clusters with $E_{cell} > 4\sigma_{noise}$

Neighbouring cells iteratively are added with $E_{cell} > 2\sigma_{noise}$

Cells surrounding the cluster are added in a final step





Variable	Eqn.	Jet discriminants						Electron discriminants	
		Cut		LLH		BDT		Cut	BDT
		1	m	1	m	1	m	1	1
R_{track}	11	•	•	•	•	•	•		•
f_{track}	12	•	•			•	•		•
f_{core}	13			•	•	•	•		•
$N_{\text{track}}^{\text{iso}}$		•	•	•		•	•		
R_{Cal}	14			•		•	•		
f_{iso}	15								•
$m_{\text{eff. clusters}}$	16					•	•		
m_{tracks}	18				•		•		
$S_{\text{T}}^{\text{flight}}$	19		•		•		•		
$S_{\text{lead track}}$	20					•	•		
$f_{\text{2 lead clusters}}$				•					
$f_{\text{3 lead clusters}}$						•	•		
ΔR_{max}					•		•		
f_{EM}	21								•
f_{HT}	22							•	•
$f_{\text{Had}}^{\text{track}}$	23							•	•
$E_{\text{T,max}}^{\text{strip}}$								•	•
$f_{\text{EM}}^{\text{track}}$	24							•	
R_{Had}	25								•
$E_{\text{T,corr}}^{\text{iso}}$	26	•	•						

Table 1: Complete list of variables used by the cut-based (Cut), likelihood-based (LLH) and boosted decision tree (BDT) jet discriminants, and the cut-based and BDT electron discriminants. The equation numbers refer to the variable definitions in Appendix A. The use of variables for the jet discriminants is defined separately for 1-prong (1) and multi-prong (m) candidates.

Track radius (R_{track}): the p_T weighted track width:

$$R_{\text{track}} = \frac{\sum_i^{\Delta R_i<0.4} p_{T,i}\,\Delta R_i}{\sum_i^{\Delta R_i<0.4} p_{T,i}}, \tag{11}$$

where i runs over all core and isolation tracks of the tau candidate, and $p_{T,i}$ is the track transverse momentum. Note that for candidates with only one track, R_{track} simplifies to the ΔR between the track and the tau candidate axis.

Leading track momentum fraction (f_{track}):

$$f_{\text{track}} = \frac{p_{T,1}^{\text{track}}}{p_T^{\tau}}, \tag{12}$$

where $p_{T,1}^{\text{track}}$ is the transverse momentum of the leading p_T core track and p_T^{τ} is the transverse momentum of the tau candidate, calibrated at the EM energy scale. Note that for candidates with one track, f_{track} is the fraction of the candidate's momentum attributed to the track, compared to the total momentum of the candidate, which can have contributions from the calorimeter deposits from π^0s and other neutrals.

Core energy fraction (f_{core}): the fraction of transverse energy within ($\Delta R < 0.1$) of the tau candidate:

$$f_{\text{core}} = \frac{\sum_{i\in\{\text{all}\}}^{\Delta R_i<0.1} E_{T,i}}{\sum_{j\in\{\text{all}\}}^{\Delta R_j<0.4} E_{T,j}}, \tag{13}$$

where i runs over all cells associated to the tau candidate within $\Delta R < 0.1$ and j runs over all cells in the wide cone. The calorimeter cells associated to a tau candidate are those which are clustered in the topological clusters that are constituents of the jet that seeded tau reconstruction. ΔR_i is defined between a calorimeter cell and the tau candidate axis. $E_{T,i}$ is the cell transverse energy, calibrated at the EM scale. Note that an unconventional definition of the core cone is used for f_{core}, as it provides better discrimination.

ID variables, cont.

Number of isolation tracks ($N^{\text{iso}}_{\text{track}}$): the number of tracks in the isolation annulus.

Calorimetric radius (R_{Cal}): the shower width in the electromagnetic and hadronic calorimeter weighted by the transverse energy of each calorimeter part.

$$R_{\text{Cal}} = \frac{\sum_{i \in \{\text{all}\}}^{\Delta R_i < 0.4} E_{\text{T},i} \, \Delta R_i}{\sum_{i \in \{\text{all}\}}^{\Delta R_i < 0.4} E_{\text{T},i}}, \qquad (14)$$

where i runs over cells in all layers of the EM and hadronic calorimeters. Only cells in the wide cone are considered.

Ring isolation (f_{iso}):

$$f_{\text{iso}} = \frac{\sum_{i \in \{\text{EM } 0-2\}}^{0.1 < \Delta R < 0.2} E_{\text{T},i}}{\sum_{j \in \{\text{EM } 0-2\}}^{\Delta R < 0.4} E_{\text{T},j}}, \qquad (15)$$

where i runs over cells in the first three layers of the EM calorimeter in the annulus $0.1 < \Delta R < 0.2$ around the tau candidate axis and j runs over EM cells in the wide cone.

Cluster mass ($m_{\text{eff. clusters}}$): the invariant mass computed from the constituent clusters of the seed jet, calibrated at the LC energy scale.

$$m_{\text{eff. clusters}} = \sqrt{\left(\sum_{\text{clusters}} E\right)^2 - \left(\sum_{\text{clusters}} \mathbf{p}\right)^2} \tag{16}$$

To minimise the effect of pileup, only the first N leading E_{T} clusters (effective clusters) are used in the calculation, defined as

$$N = \frac{(\sum_i E_{\mathrm{T}i})^2}{\sum_i E_{\mathrm{T}_i}^2}, \tag{17}$$

where i runs over all clusters associated to the tau candidate, and N is rounded up to the nearest integer.

Track mass (m_{tracks}): the invariant mass of the track system, where the tracks used for the invariant mass calculation use both core and isolation tracks:

$$m_{\text{tracks}} = \sqrt{\left(\sum_{\text{tracks}} E\right)^2 - \left(\sum_{\text{tracks}} \mathbf{p}\right)^2} \tag{18}$$

Transverse flight path significance ($S_{\mathrm{T}}^{\text{flight}}$): the decay length significance of the secondary vertex for multi-prong tau candidates in the transverse plane:

$$S_{\mathrm{T}}^{\text{flight}} = \frac{L_{\mathrm{T}}^{\text{flight}}}{\delta L_{\mathrm{T}}^{\text{flight}}}, \tag{19}$$

where $L_{\mathrm{T}}^{\text{flight}}$ is the reconstructed signed decay length, and $\delta L_{\mathrm{T}}^{\text{flight}}$ is its estimated uncertainty. Only core tracks are used for the secondary vertex fit.

ID variables, cont.

Leading track IP significance ($S_{\text{lead track}}$): the impact parameter significance of the leading track of the tau candidate:

$$S_{\text{lead track}} = \frac{d_0}{\delta d_0}, \tag{20}$$

where d_0 is the distance of closest approach of the track to the reconstructed primary vertex in the transverse plane, and δd_0 is its estimated uncertainty.

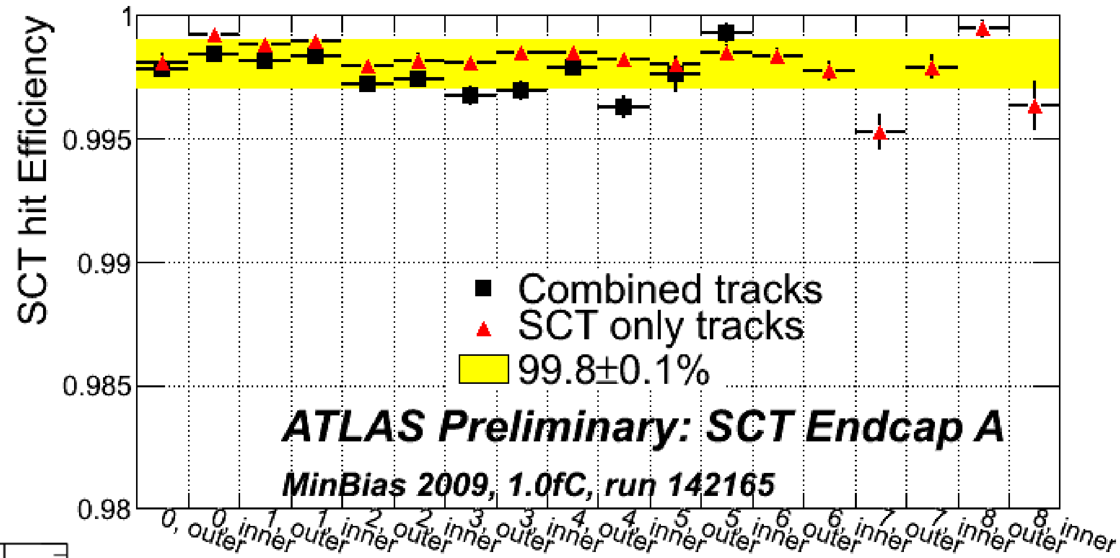
First 2(3) leading clusters energy ratio ($f_{2\text{ lead clusters}}$($f_{3\text{ lead clusters}}$)): the ratio of the energy of the first two (three) leading clusters (highest energy first) over the total energy of all clusters associated to the tau candidate.

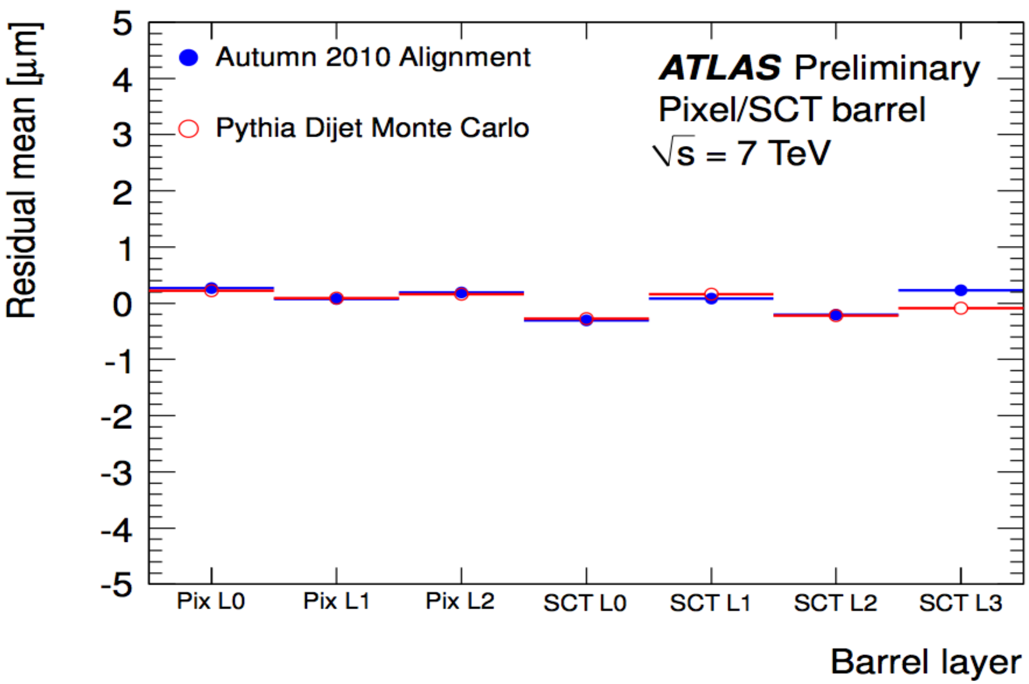
Maximum ΔR (ΔR_{max}): the maximal ΔR between a core track and the tau candidate axis.

Tracking Performance Plots

Track Quality Criteria for tau candidates

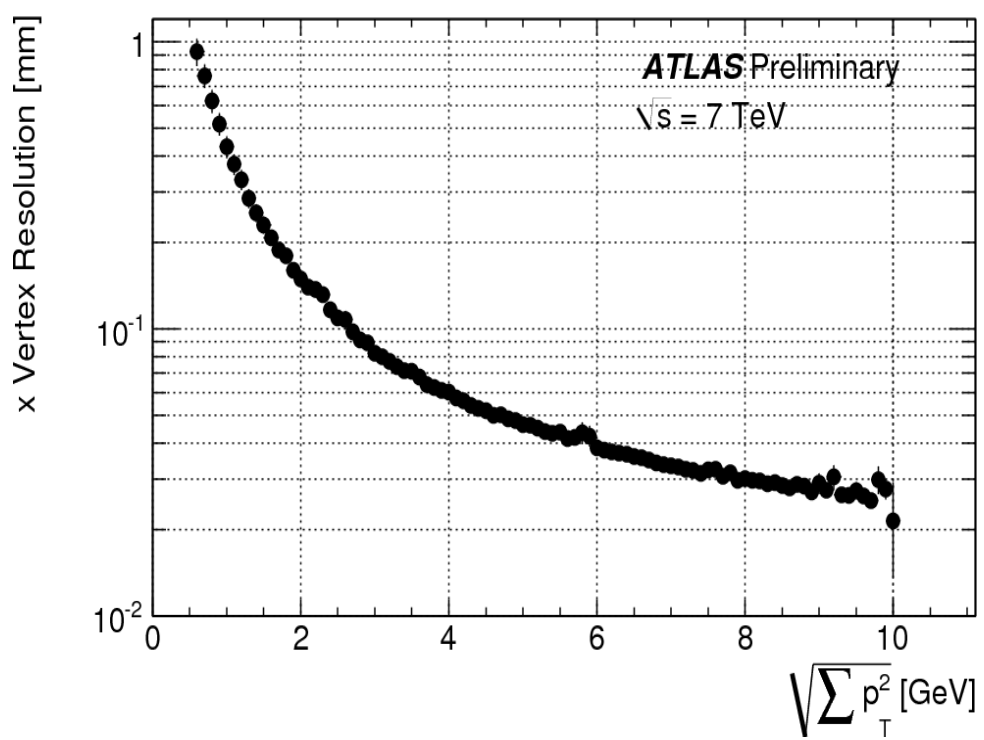
- $N_{pixel} \geq 2$
- $N_{pixel} + N_{SCT} \geq 7$
- $d_0 < 1.0$ mm
- $z_0 \sin(\theta) < 1.5$ mm
- b-layer hit (removed for 2011)

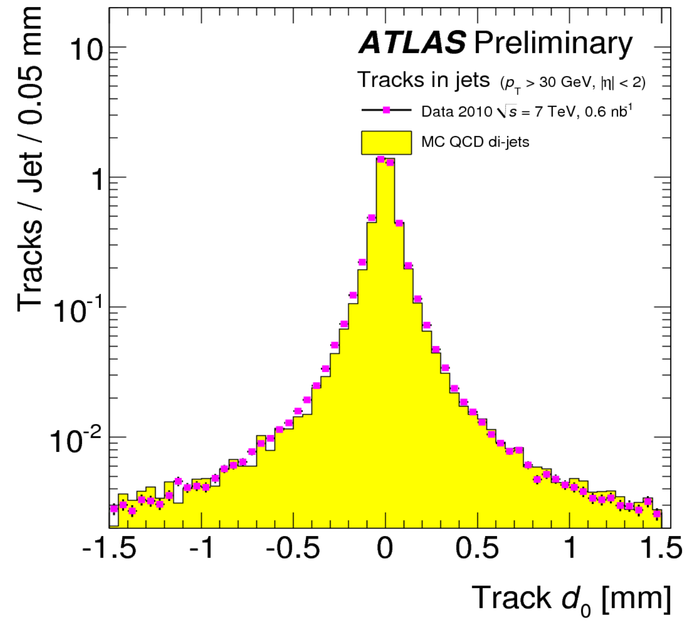


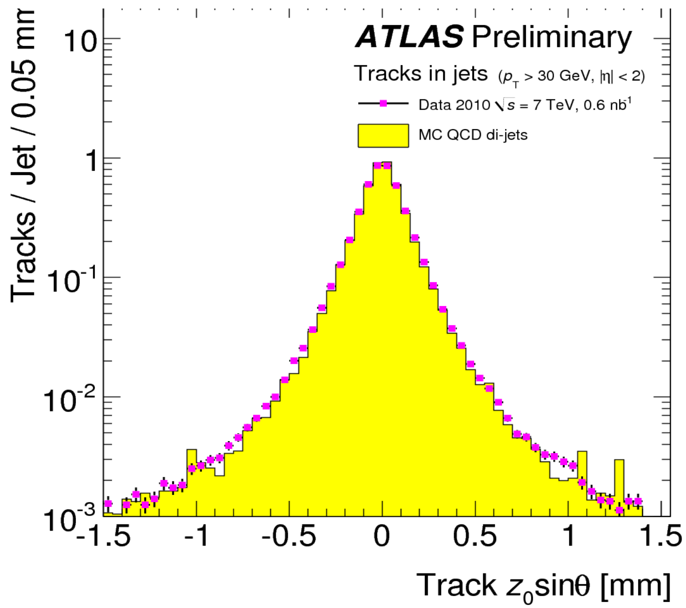


Resolution of tracking variables

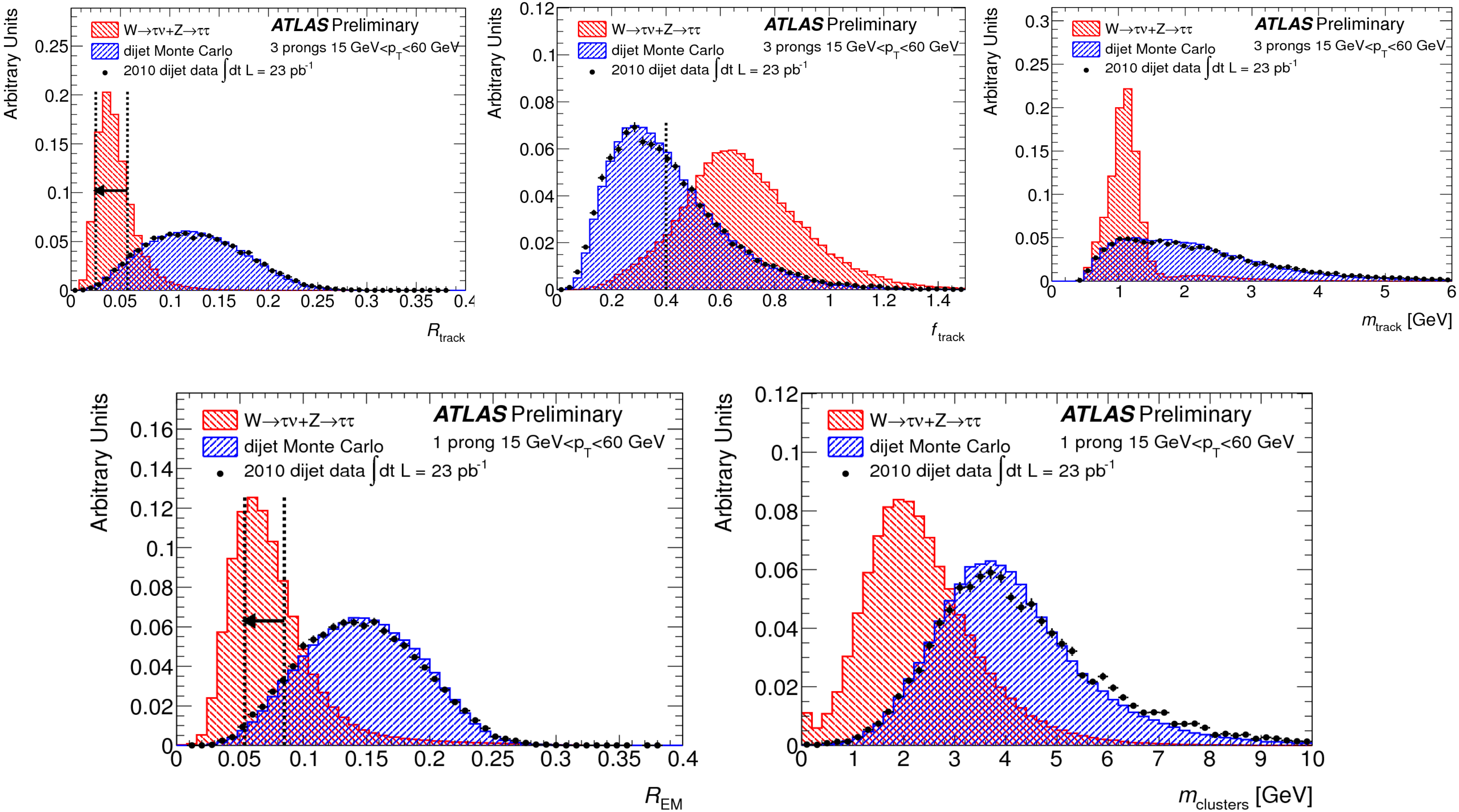
Good resolutions are necessary for precision tracking and secondary vertexing for tau candidates



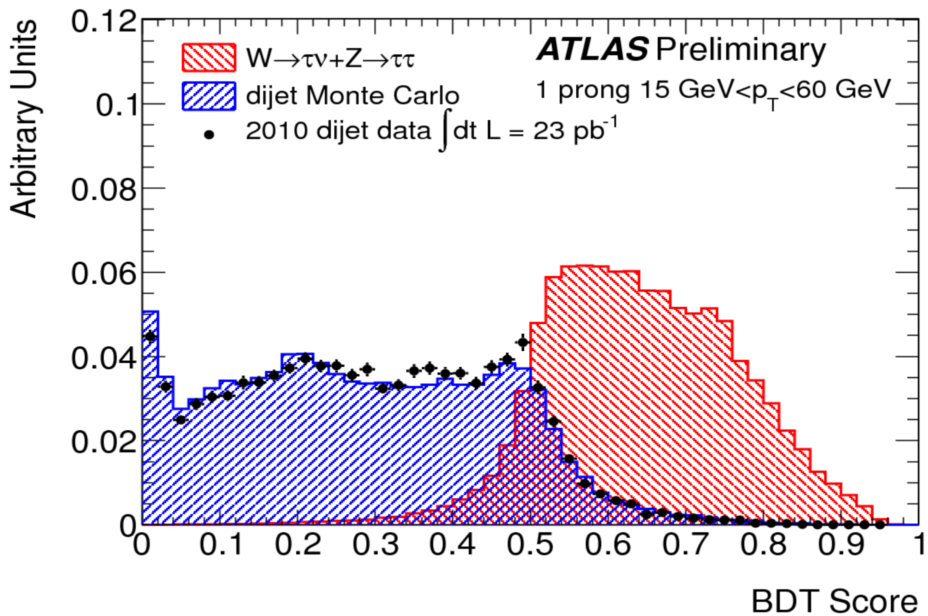




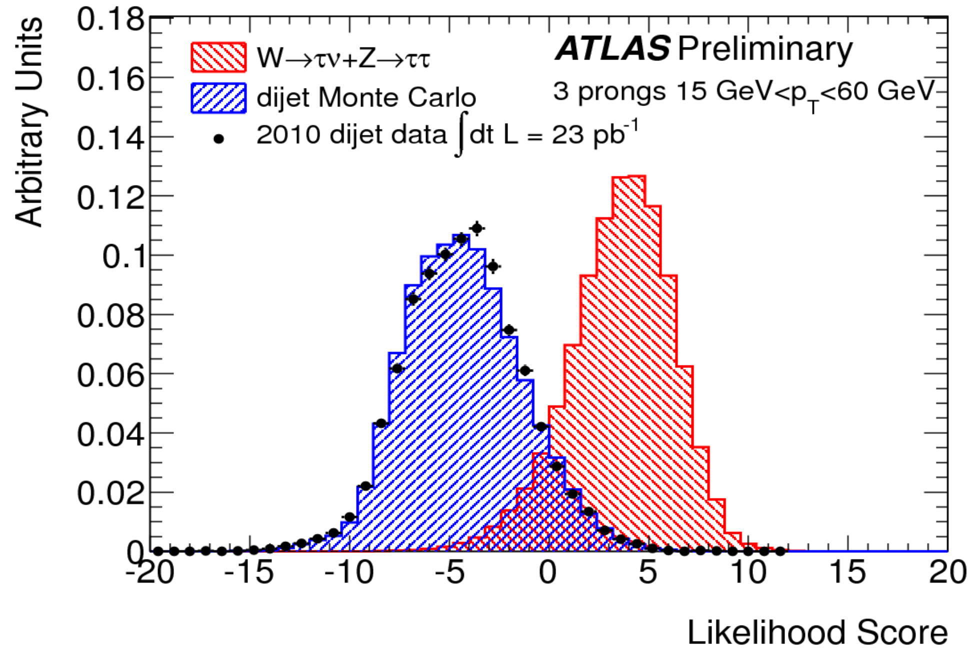
Other Tau ID Variables (2010)



LLH/BDT (2010)

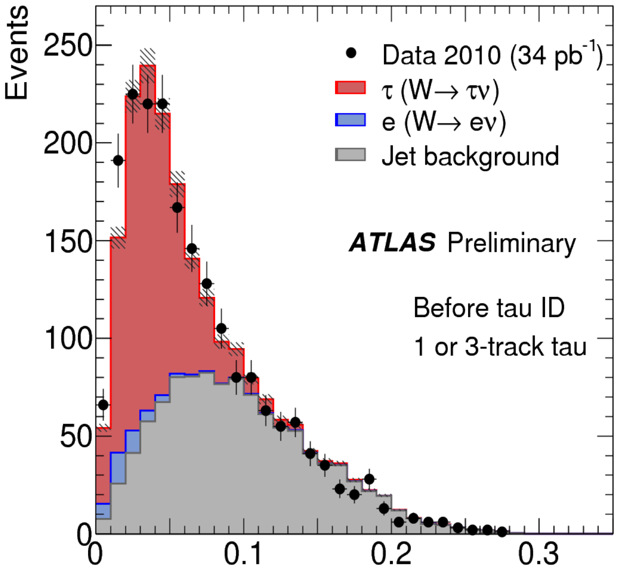


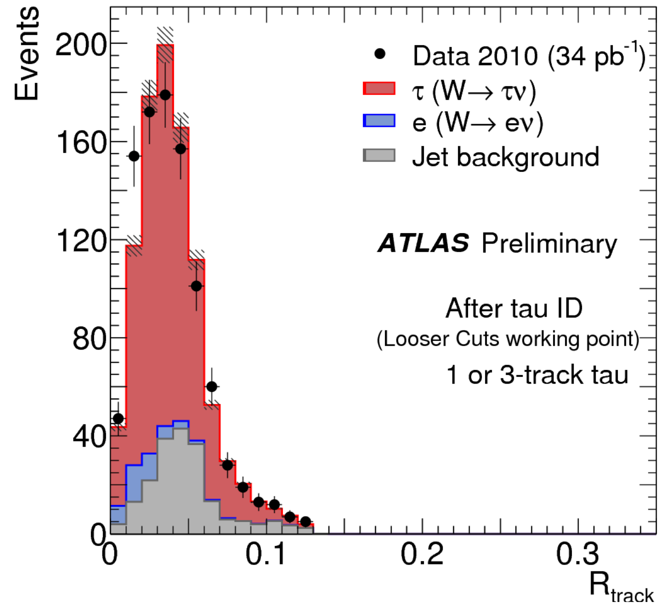
Arbitrary Units
W→τν+Z→ττ
dijet Monte Carlo
2010 dijet data ∫dt L = 23 pb-1
ATLAS Preliminary
1 prong 15 GeV<p_T<60 GeV
0.12
0.1
0.08
0.06
0.04
0.02
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
BDT Score

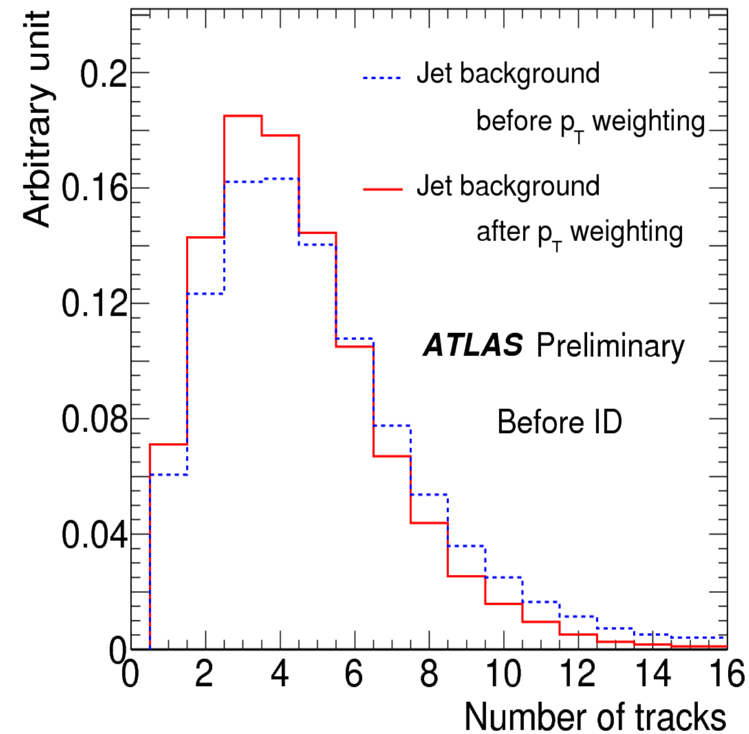


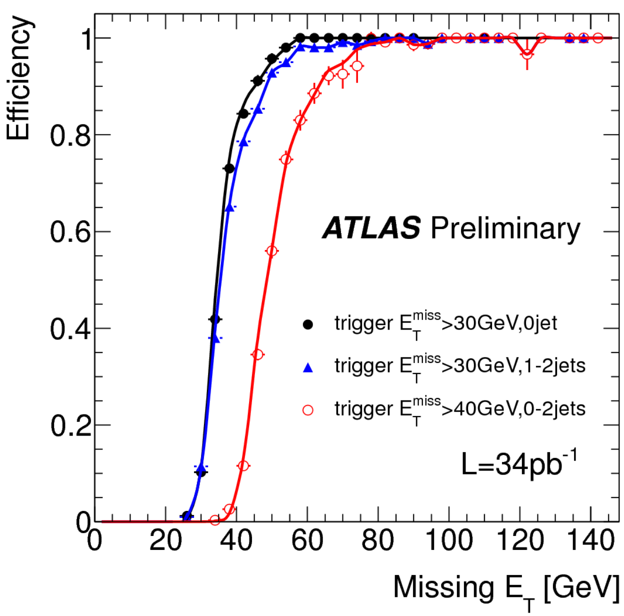
Arbitrary Units
W→τν+Z→ττ
dijet Monte Carlo
2010 dijet data ∫dt L = 23 pb-1
ATLAS Preliminary
3 prongs 15 GeV<p_T<60 GeV
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-20 -15 -10 -5 0 5 10 15 20
Likelihood Score

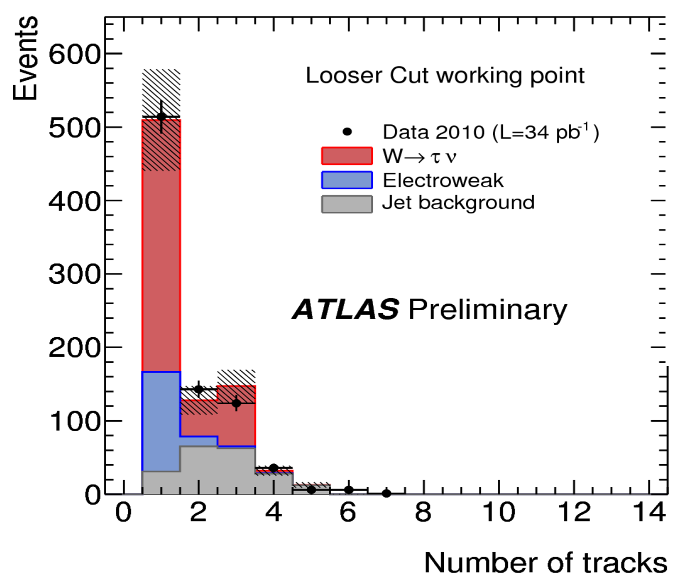
W→τν events (2010)



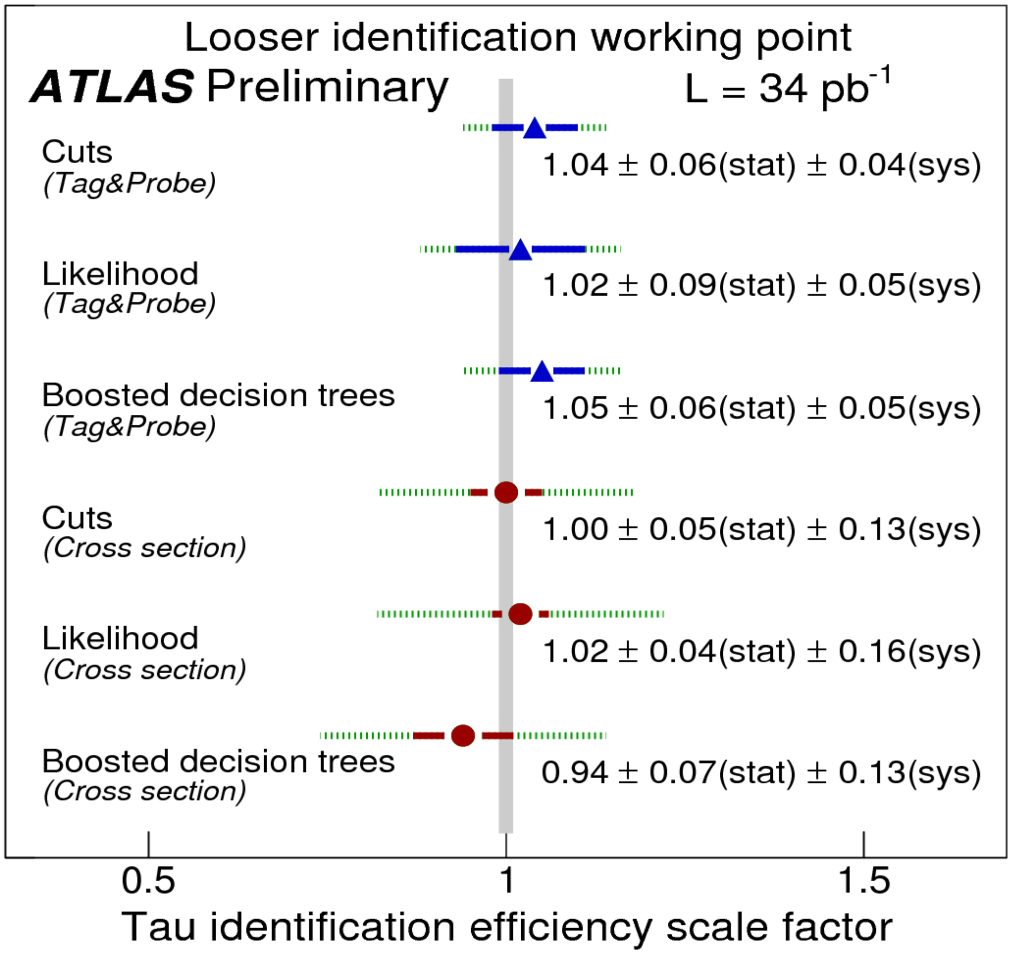








Systematic Uncertainties for W→τν Efficiency Measurement, 2010



~80% Efficiency

$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger	0.7%
Jet modelling (p_{T}-weighting)	0.4%
Jet modelling ($S_{E_{\mathrm{T}}^{\mathrm{miss}}}$)	0.6%
Electron misidentification	1.6%
Pileup condition	1.4%
Shower model	2.6%
Detector geometry	0.9%
Underlying event	1.3%
Total systematic uncertainty	3.7%

Jet modelling	1.1%
W cross-section	5.1%
Trigger efficiency	2.7%
Electron reconstruction	1.7%
Electron misidentification	4.8%
Tau energy scale	7.7%
Jet energy scale	0.1%
Electron energy scale	0.8%
Pileup	0.2%
Underlying event	6.8%
Total systematic uncertainty	12.9%

Efficiency with Z→ττ cross section normalization