Performance of Tau Trigger and Tau Reconstruction in ATLAS in pp Collisions at $\sqrt{s}$=7 TeV

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Cracow Epiphany Conference
10-12 January 2010

Why are we interested in taus?

Tau leptons play an important role in ATLAS as they are „tools” in many areas

New physics phenomena

- Heavy lepton present in many final states of physics beyond the Standard Model
- Higgs bosons
- Supersymmetry (multilepton decays)
- Exotic scenarios

Standard Model

- But before testing new physics we need to understand our detector...
- ...and re-observe SM processes ($Z \rightarrow \tau\tau$, $W \rightarrow \tau\nu$, $t\bar{t} \rightarrow \tau + X$):
  - to demonstrate feasibility
  - to calibrate tau performance *(tau energy scale, missing energy scale, tau trigger and the reconstruction & identification efficiency)*
  - to understand backgrounds to new physics
  - interesting itself as first time at such high energy

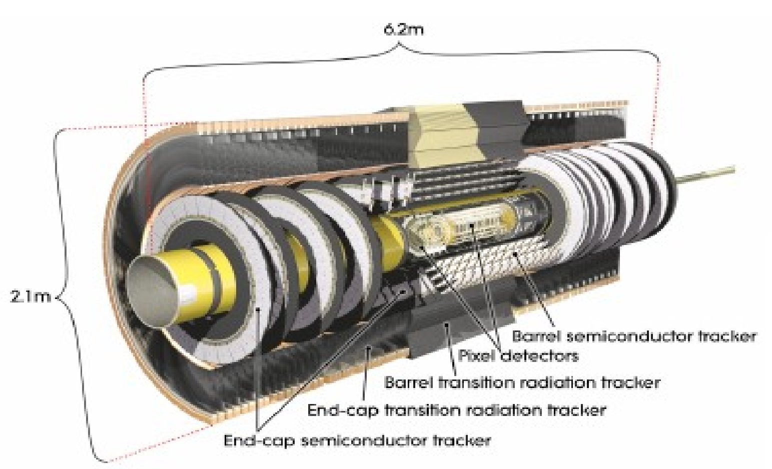
Hadronic tau lepton decays

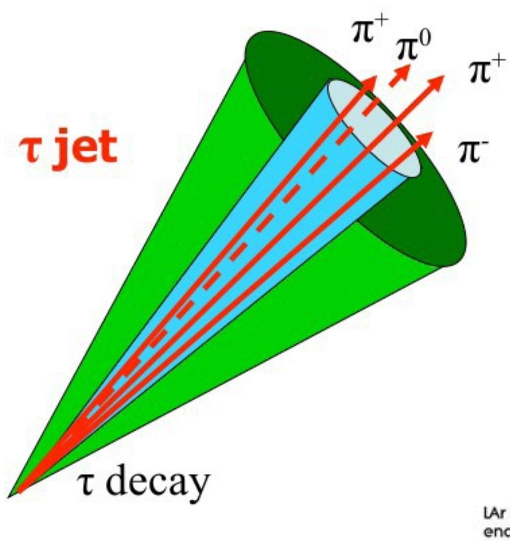
Leptonic decays: hard to distinguish from prompt e/μ (single track, short tau lifetime)
=> we concentrate on hadronic tau decays

Identifying hadronically decaying tau leptons requires good understanding of the detector performance, combining the calorimeter and tracking detectors.

Tracking

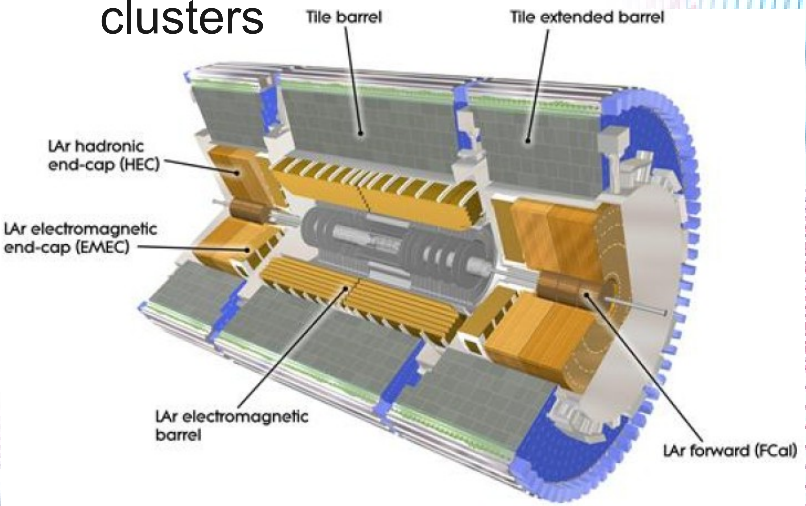
- Low track multiplicity (1 or 3 $\pi^{\pm}$)
- Collimated object and isolation from other tracks
- Modest but significant proper lifetime ($c\tau$ = 87.11 μm)
  -> displaced secondary vertex



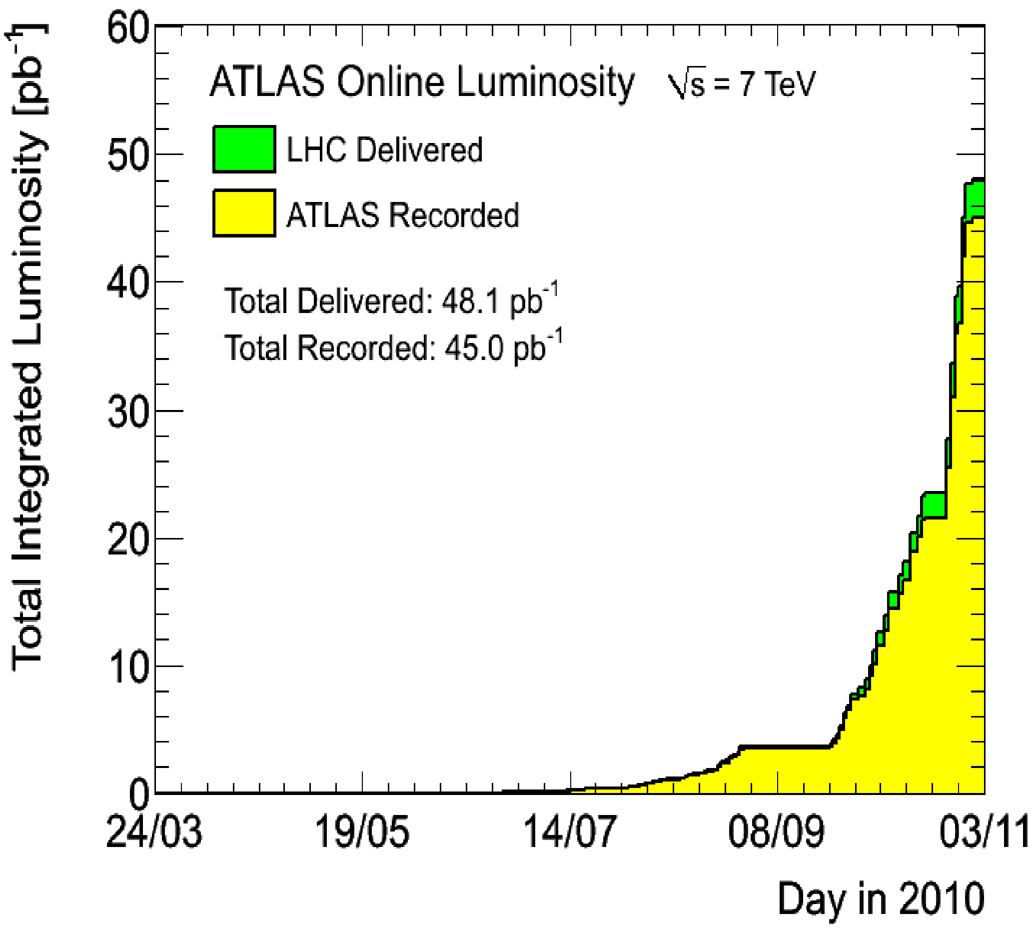


Calorimetry

- Collimated and isolated energy deposit (use shower shape)
- Strong EM component (π^0's in tau decays)
- Possibility to identify π^0 clusters



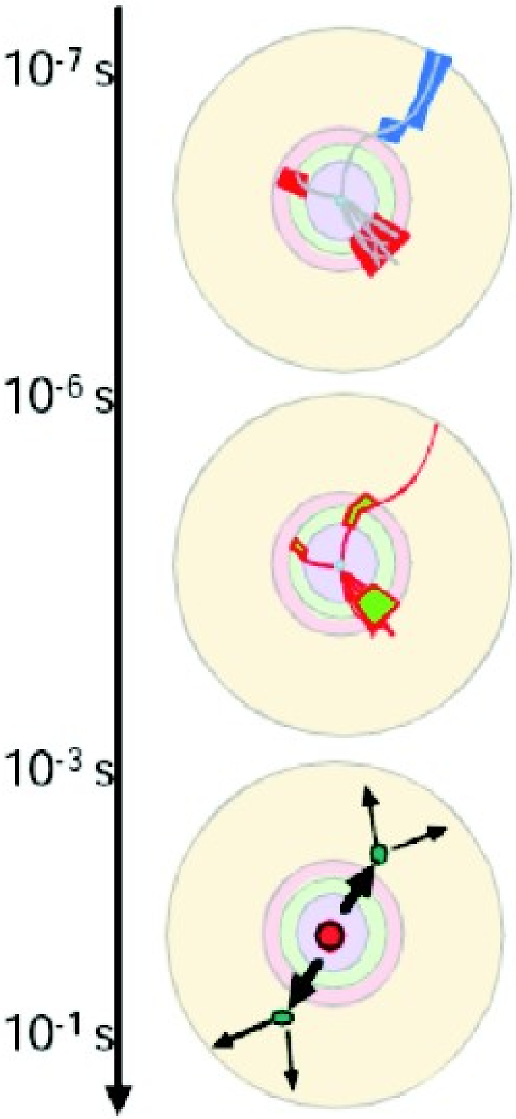
Data collected



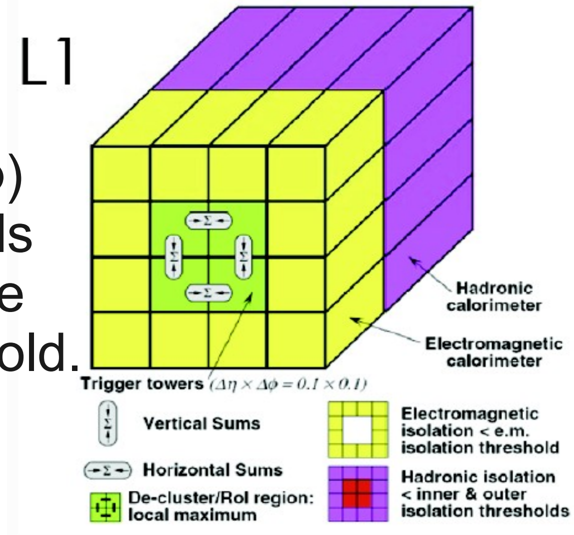
- ATLAS detector has recorded over 45 pb^{-1} of data
- But most of the results have been prepared with data taken up to mid-July 2010 ($L \approx 244\ nb^{-1}$ for performance plots and 546 nb^{-1} for $W \rightarrow \tau\nu$ analysis)
- Many studies ongoing to find taus coming from W and Z decays in full statistics of data

Stay tuned for new results!

Tau trigger



- **Level 1 (L1)** - finds regions of activity in the detector.
  - •Trigger Tower = 0.1 x 0.1(η x φ)
  - •Sum of several calorimeter cells
  - •Local maximum (0.2 x 0.2) core region should be above threshold.
  - •Simple, fast selection applied.



- **Level 2 (L2)** - track and calorimeter cell information is combined, tau dedicated selection on number of tracks, isolation and lateral shape in calorimeter is applied.
- **Event filter (EF)**
  - •Algorithm similar to offline reconstruction
  - •Calorimeter clusters with proper calibration and noise suppression
  - •Cut-based selection

Trigger menus

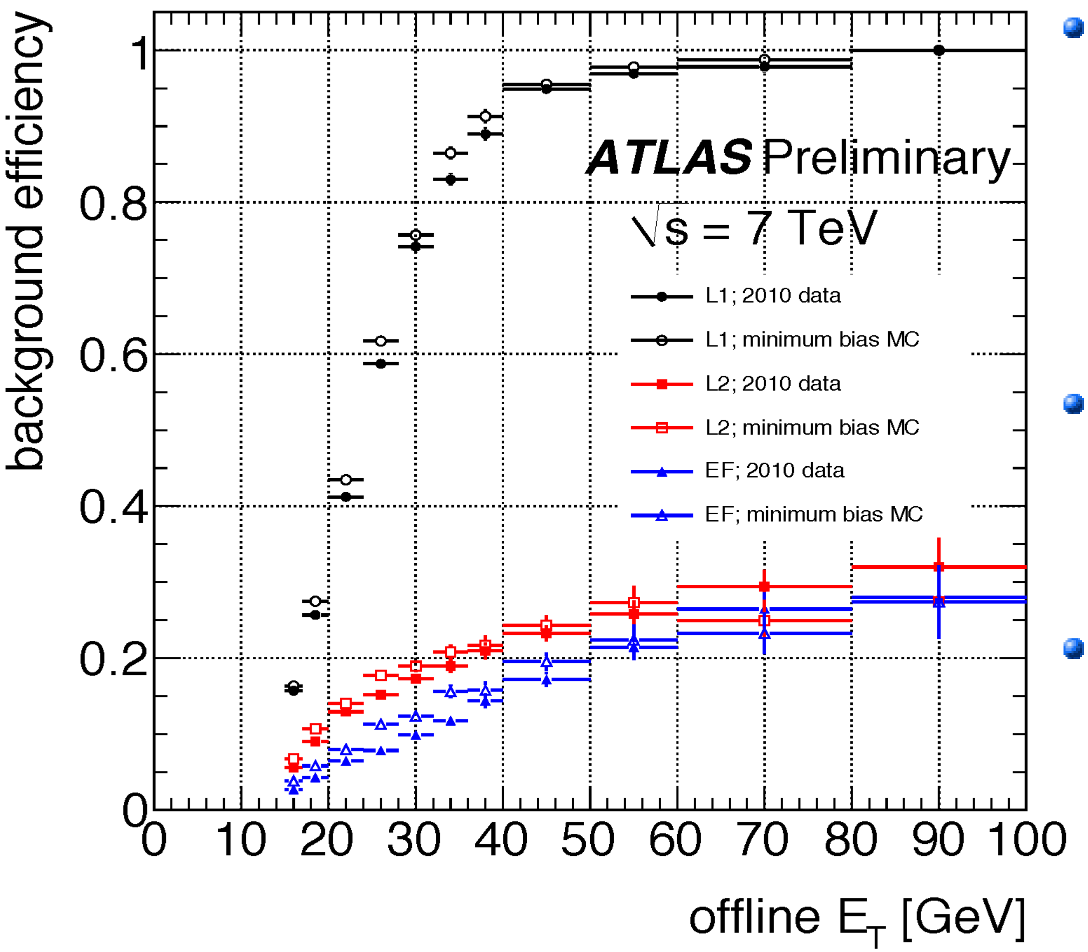
Primary triggers

- Single tau triggers with increasing energy thresholds and ID tightness.
  Used for heavy $H\rightarrow\tau\tau$, Z', $H^{\pm}\rightarrow\tau\nu$
- Ditau triggers for heavy resonances
- Combined triggers often required to reduce rates and to minimize trigger bias on tau object
  - tau+e/μ : $Z\rightarrow\tau\tau$, tt , $H\rightarrow\tau\tau$, SUSY
  - tau+$E_{T\ miss}$: $W\rightarrow\tau\nu$, $H^{\pm}\rightarrow\tau\nu$, SUSY
  - tau+(b)jets: tt , SUSY

Other triggers

- Monitoring: few events with no selection applied, to verify in each run that all detector components have optimal performance.
- Calibration: using single track triggers for single hadron calibration.

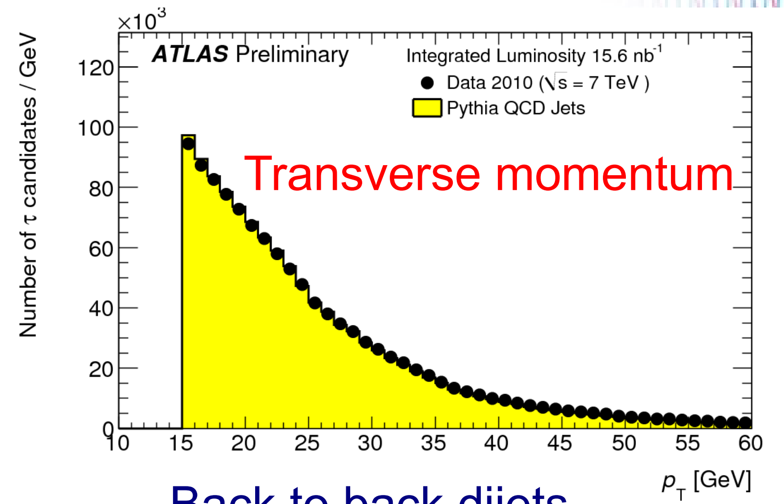
Trigger performance



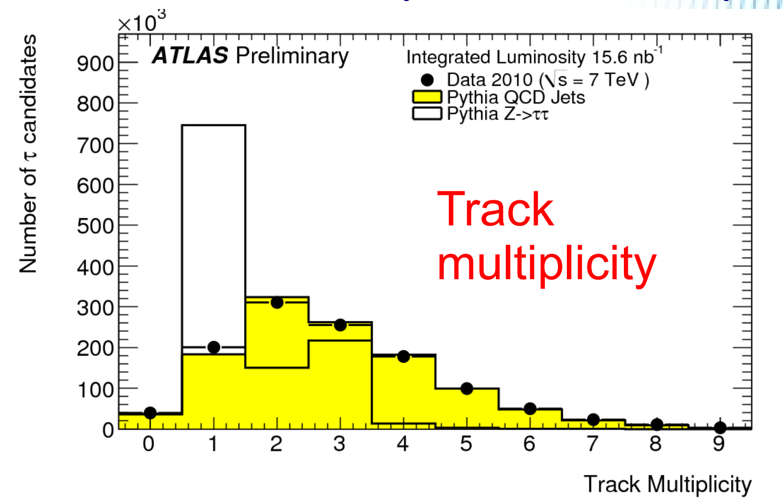
- Fraction of the background offline tau candidates passing L1, L2 and EF tau12_loose trigger as a function of the E_T of the offline tau candidate.
- Requirements for E_T are : > 5 GeV at L1, ≥ 7 GeV at L2 and ≥ 12 GeV at EF.
- Reasonable data-MC agreement.

Tau reconstruction

- **Both-seeded (track+calo) candidates**
  - Seed - tracks (pT > 6 GeV)
  - Tracks (pT > 1 GeV) in cone R < 0.2 added, define η,φ from tracks
  - Look for jet (anti-k_t algorithm with R = 0.4 on topological clusters) around track system (> 10 GeV, R < 0.2)
  - Reconstruct π^0 subclusters
  - E_T from energy flow algorithm (tracks + calo)
- **Calo-seeded only candidates**
  - Jet - seed
  - η,φ from calorimeter cluster barycentre
  - Looser-quality track selection
  - Calibrated calorimetric E_T



Back to back dijets
to select a pure QCD sample



Good agreement data - MC

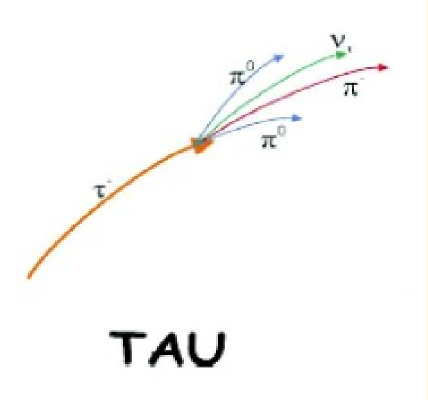
Tau Identification

Taus are difficult objects – we have to separate out a clean sample of taus from the overwhelming QCD jet rate!
We need dedicated identification algorithms, since reconstruction provides very little rejection against QCD jets.

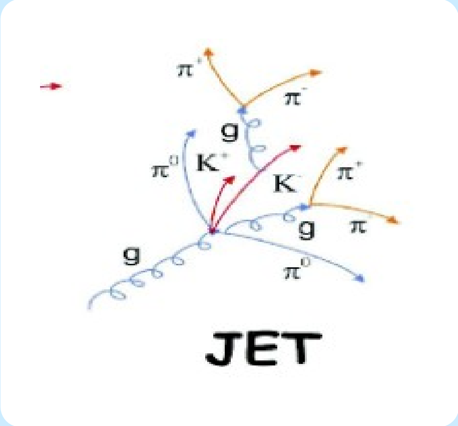
We need full power of input variables – selections based on simple cuts, boosted decision trees, and projective likelihood methods.

The identification variables need to be efficient and well understood.

For multivariate identification methods (BDT and Likelihood) and description of identification variables see the talk of A.Zemła.



- Narrow, collimated
- 1 or 3 tracks
- Can define isolation regions with low activity
- The leading track carries significant fraction of tau momentum



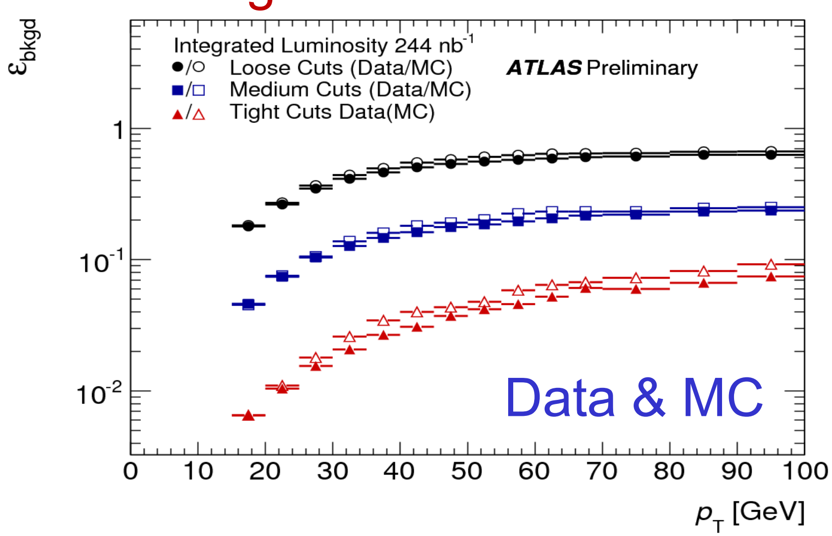
- wide
- can have many tracks
- isolation regions busy
- jet momenta spread over tracks

Cut-based efficiency and rejection

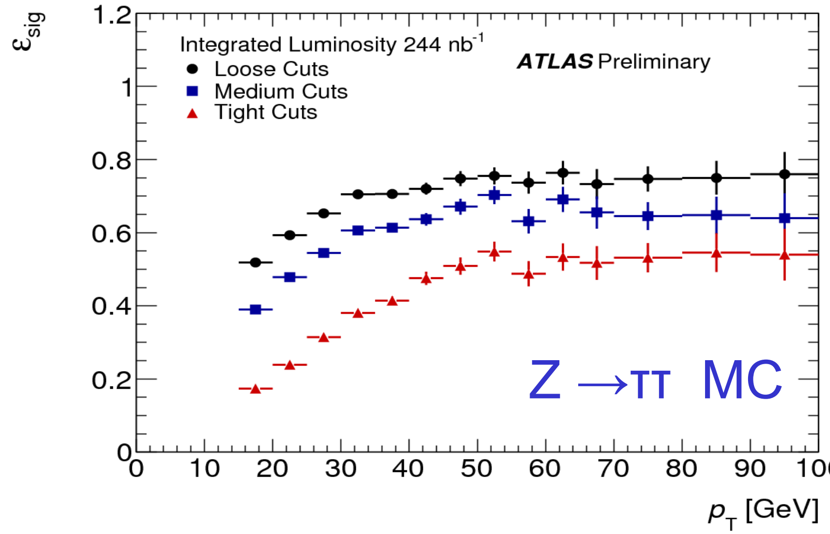
- The cut-based ID uses three variables: electromagnetic radius, track radius and leading track momentum fraction
- Three selections optimized to get signal efficiencies of 30% (tight), 50% (medium) and 60% (loose).
- Different cuts applied for tau candidates with $N_{track} = 1$ and $N_{track} \geq 2$.

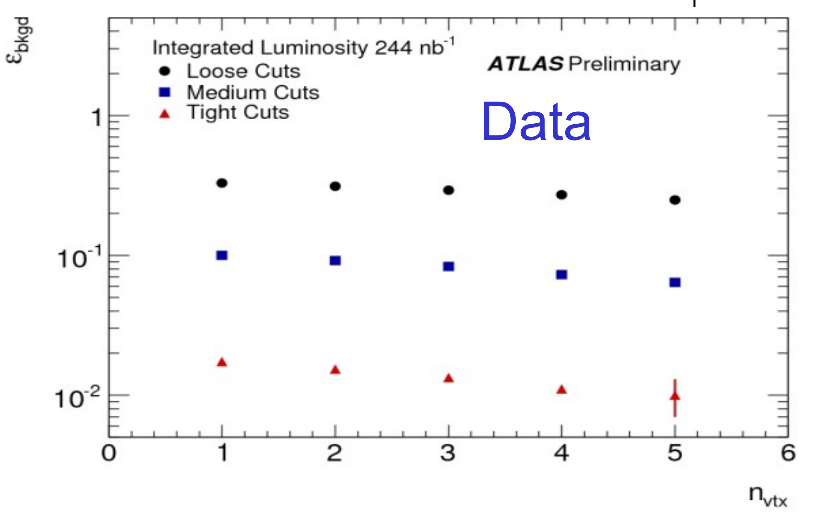
signal efficiency	$\varepsilon_{\rm sig} = \frac{N^{\tau}_{\rm pass,match}}{N^{\tau}_{\rm match}}$,
background efficiency	$\varepsilon_{\rm bkgd} = \frac{N^{\rm bkgd}_{\rm pass}}{N^{\rm bkgd}_{\rm total}}$,

Background efficiencies



Signal efficiencies



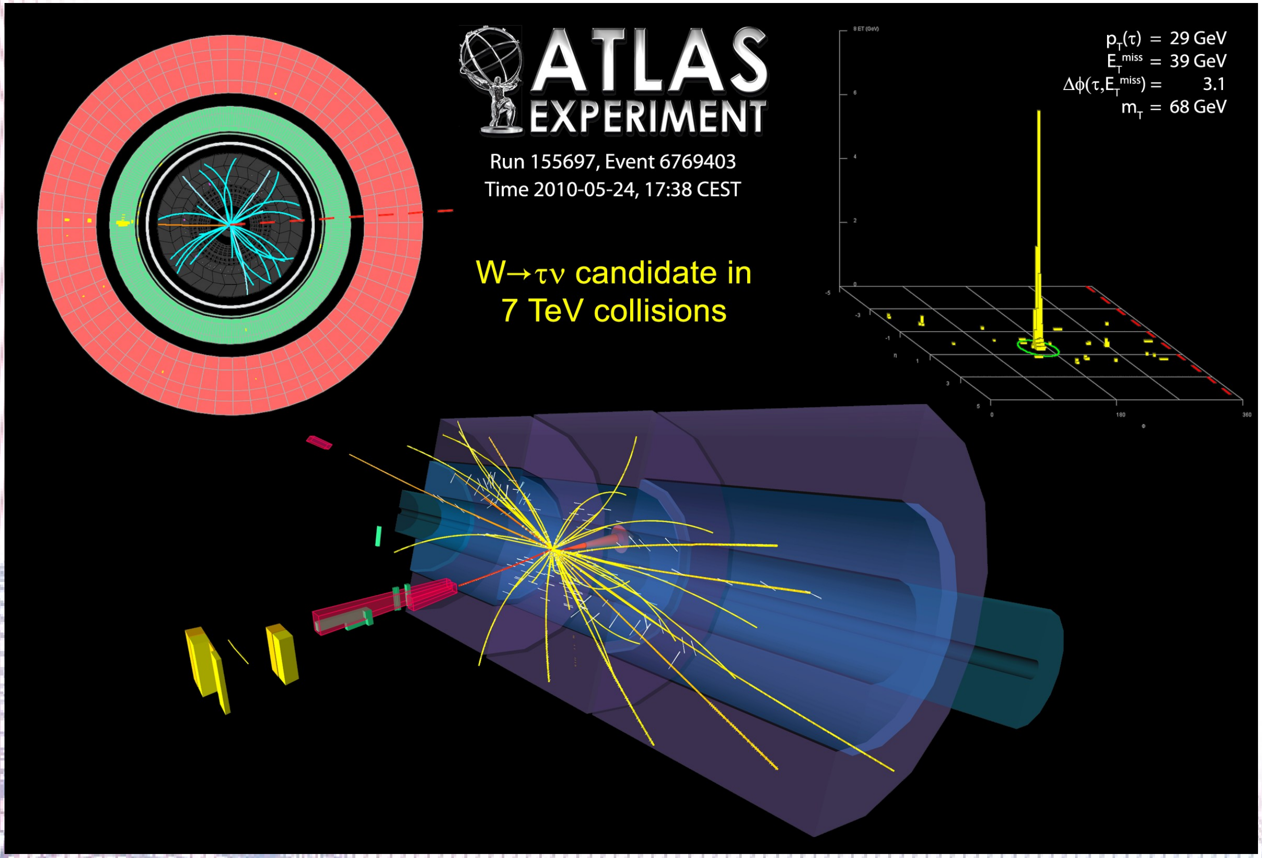


Background efficiencies as a function of the number of vertices => robustness of the simple cut ID against the presence of pile up.

Good agreement of MC and data

W→τ ν channel

- First observation of tau leptons in ATLAS !
    - cross-section: σ x BR = 10.46 x 103 pb, 10x larger than Z→ττ
- Very challenging channel due to lack of additional lepton like in Z channel and tau produced with low momenta
- Main Backgrounds: W→eυ, W→μυ, Z→ττ, Z→ee, top pairs, multi-jets
- Trigger: tau-lepton and the missing energy trigger
- Integrated luminosity 546 nb^{-1}



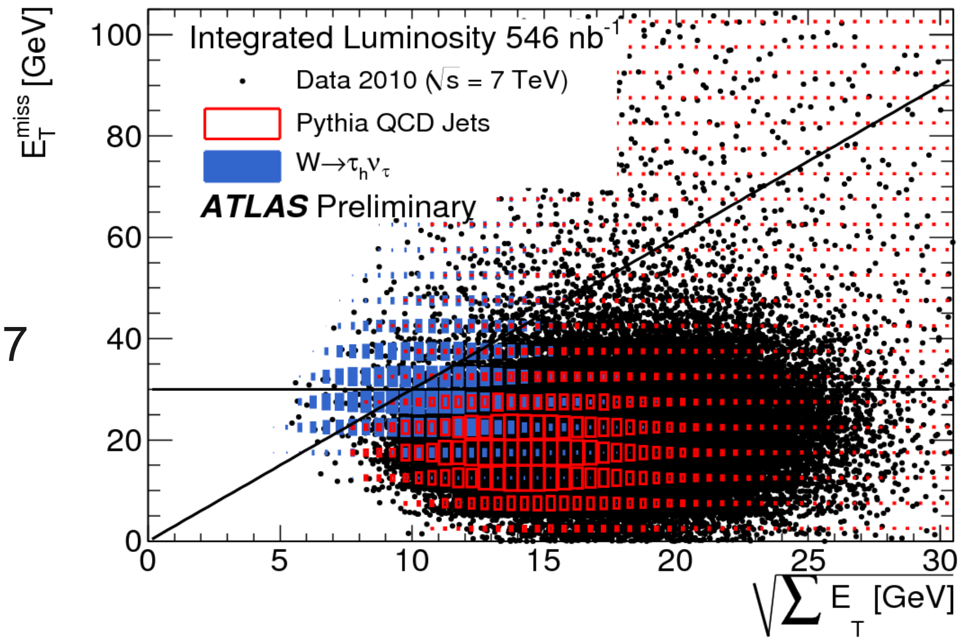
Event display of a W → τν candidate collected on 24.05.2010

First observed tau candidate in ATLAS

$W \to \tau\nu$ channel
event selection

Event selection:
- E_T^{miss}>30 GeV
- Electron and muon veto
- Both seeded, passing tight safe cuts ID
- 20 GeV<p_T<60 GeV and not in 1.3<|η|<1.7
- E_t^{miss} significance: $S(E_T^{miss}) = \frac{E_T^{miss}}{0.5 \cdot \sqrt{\sum E_T}}$

  (crucial for QCD suppression)



Distribution of events in the E_T^{miss} vs. $\sqrt{\sum E_T}$ plane after the trigger requirement for data, simulated signal events and QCD background.

78 events selected

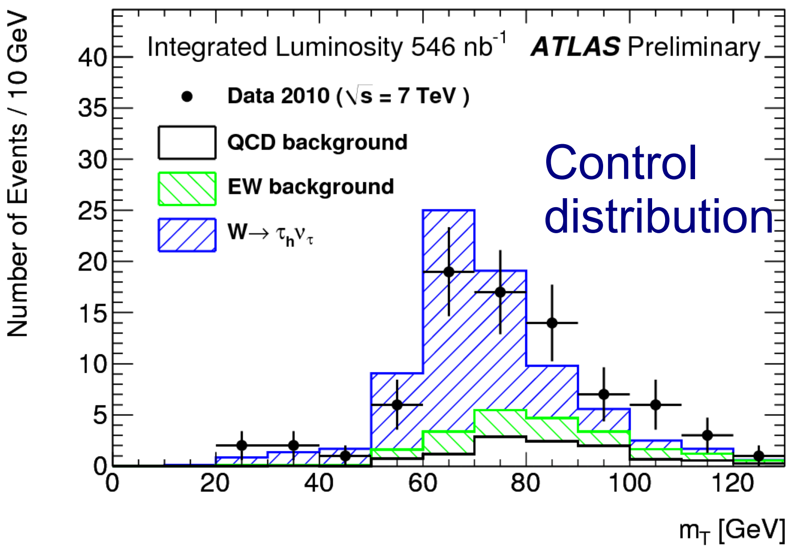
EW background, from MC:
11.8±0.4(stat)±3.7(syst)

Systematic uncertainties: lepton veto, MC model, tau energy scale

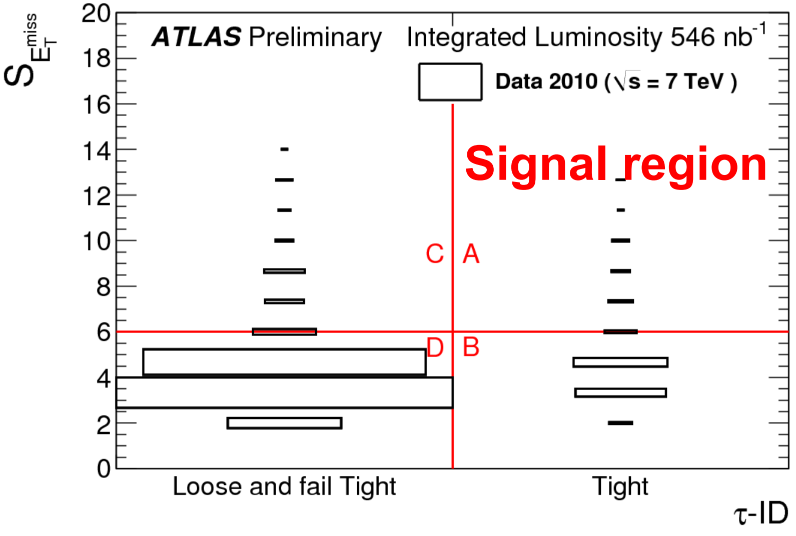
$W \to \tau\nu$ channel
QCD background estimation

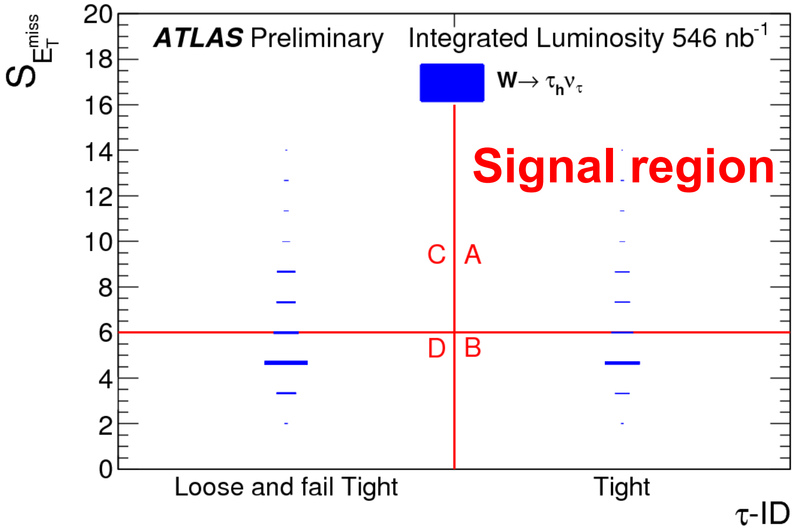
QCD background, estimated from data:
ABCD method: $N_A^{QCD} = N_B\, N_C / N_D$ (corrected for EW background)
11.1±2.3(stat)±3.2(syst)

Sources of systematic uncertainties: mostly correlation of $S(E_T^{miss})$ and tau ID



Distributions of the transverse mass for the data in signal region A, the scaled QCD background from control region C, and the contributions from signal and EW background in region A.





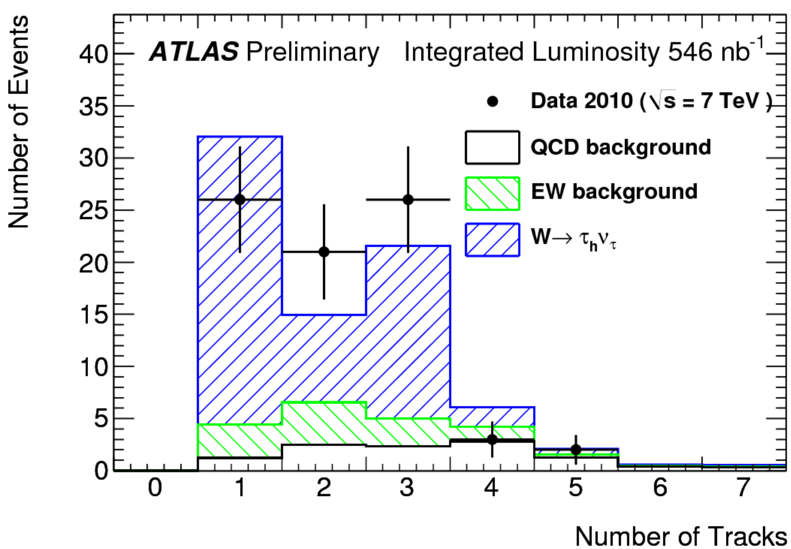
W→τν channel

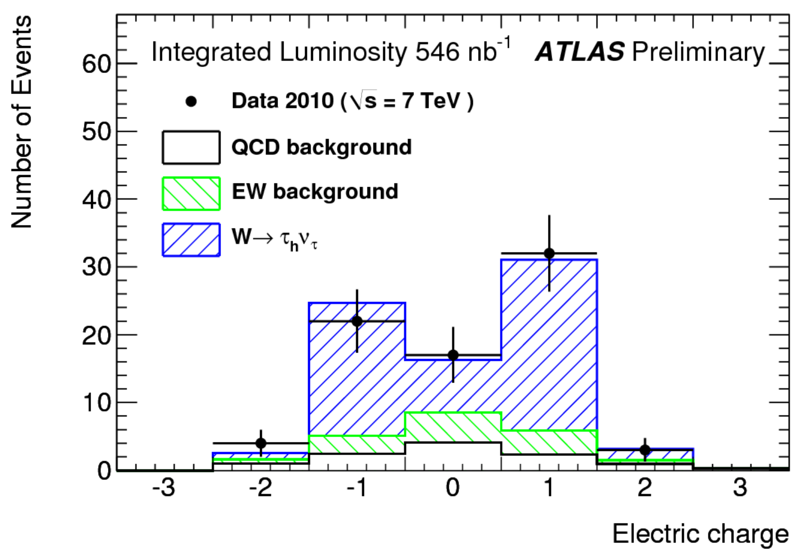
Standard Model W→τν decays observed

The excess of events and the shapes of control distributions compatible with Standard model:

- **Observed: 55.1±10.5(stat)±5.2(syst)**
- **Expected: 55.3±1.4(stat)±16.1(syst)**

Systematics for MC signal: tau energy scale, MC model, luminosity.





Distributions of number of tracks and electric charge for the data in signal region A, the scaled QCD background from control region C, and the contributions from signal and EW background in region A.

Z →τ(lep)τ(had) channel

Our golden channel for taus:

- One tau decays leptonically: use for trigger, QCD rejection
- Second tau decays hadronically, kept as unbiased as possible
- Allows to derive tau trigger efficiency, tau reconstruction and identification efficiency

Main Backgrounds:

W+jets, Z+jets, multi-jet production,

top pair production

Z->τ+τ-->μ+νντ-hν decay

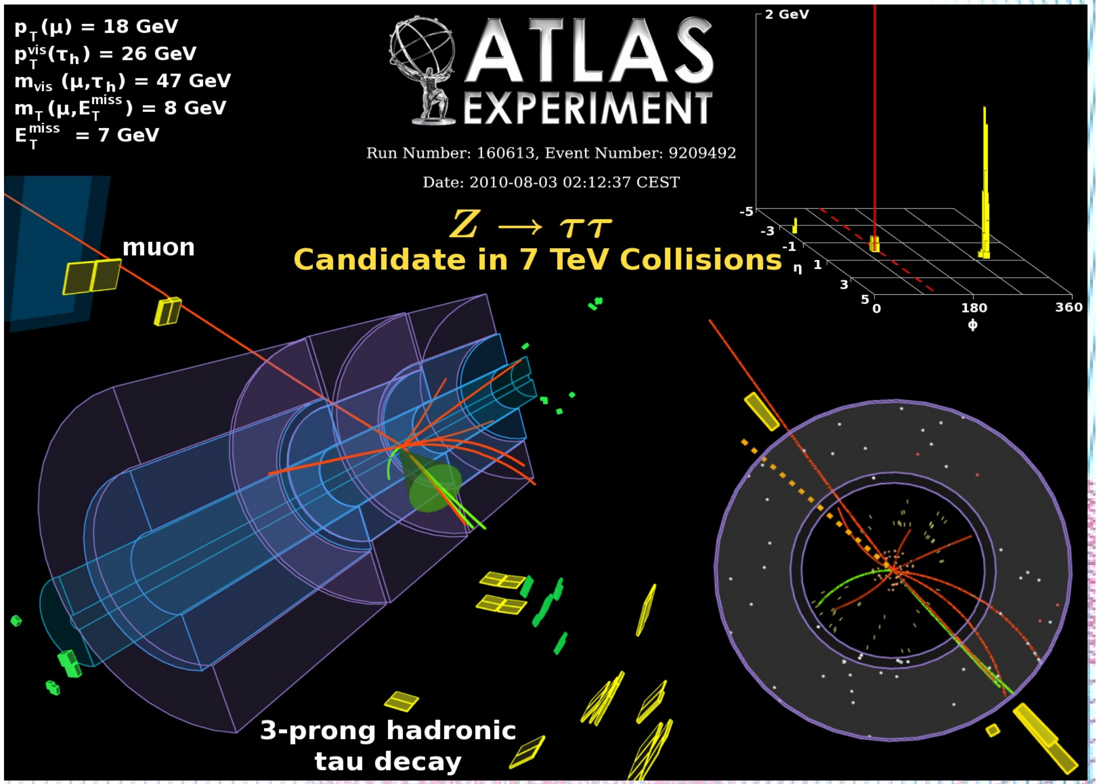
pT(μ) = 18 GeV
pTvis(τh) = 26 GeV
mvis(μ , τh) = 47 GeV
mT(μ , ETmiss) = 8 GeV
ETmiss = 7 GeV

Data analysis ongoing
First results soon!

Further use:

Visible mass distribution of the Z→ττ products - evaluation of the energy scale for taus

Invariant mass of Z→ττ products reconstructed using the missing energy information should peak at well measured Z mass. Peak of this distribution gives us a handle on the missing energy scale



Conclusions

- ATLAS has developed tau reconstruction and identification algorithms (robustness was a priority rather than optimal rejection).
- Good agreement between data and Monte Carlo predictions in all identification variables for background jets, as well as in fake rejection rates.
- On top of basic cut-based selection multivariate techniques developed and studied *(see talk of A. Zemła)*.
- Validated on real tau signal from $W \rightarrow \tau\nu$ and soon $Z \rightarrow \tau\tau$.

The ATLAS physics program with taus:

- SM channels (W, Z, top pairs) will provide invaluable feedback for the existing tau reconstruction and identification algorithms.
- Many exciting physics possibilities beyond the Standard Model that involve tau lepton final states (Higgs discovery?)

Backup slides

How to determine trigger efficiency from data?

Tag and probe method

Single tau trigger efficiency:
Using Z-> tau tau events (~ 500 events in 100 pb^{-1}) triggered by electron or muon single trigger +offline basic selection applied. Tau trigger (probe) efficiency measured on the opposite side of the (tag) trigger.

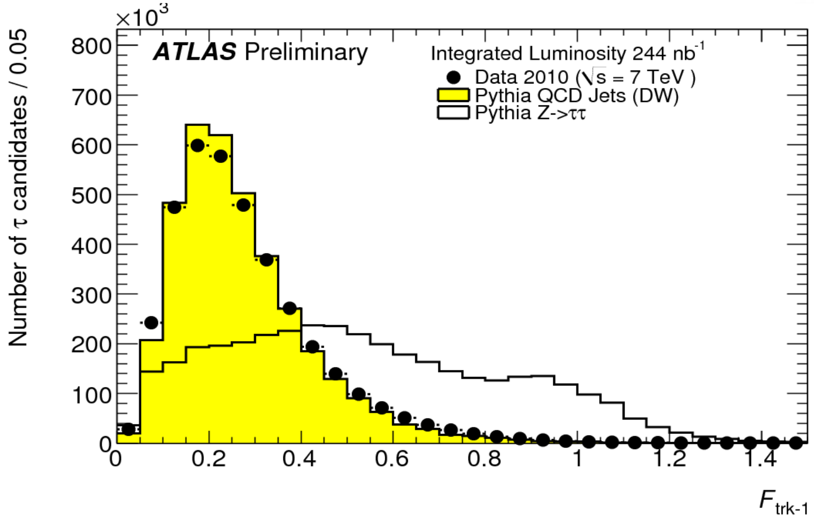
Combined tau+missing ET trigger :
Using ttbar events (~300 in 100 pb^{-1}), triggered by 4-jets trigger.

Bootstrap method

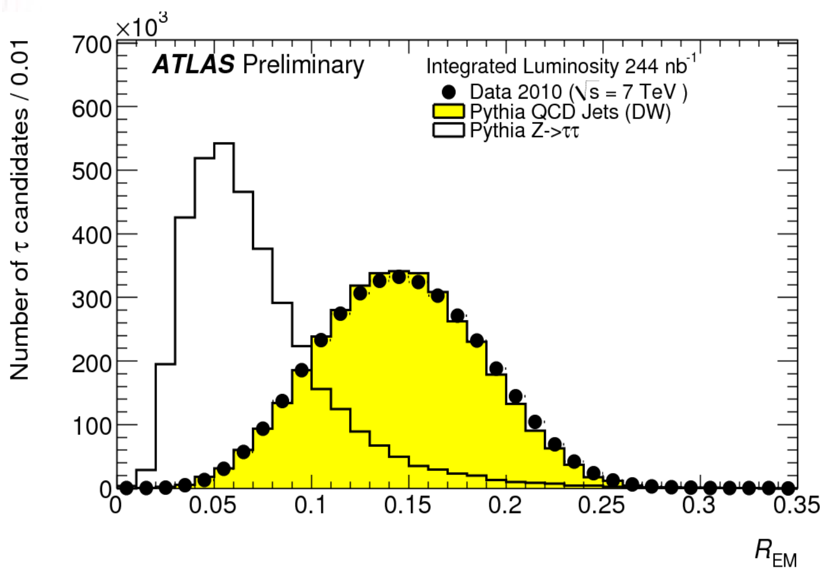
- Assume one can measure efficiency ε_A of trigger A.
- Then compute trigger B efficiency as $\varepsilon_B = \varepsilon_{B|A} x \varepsilon_A$ (if all events that trigger B also trigger A).
- Useful for higher p_T items.

Discriminating variables for cut-based id

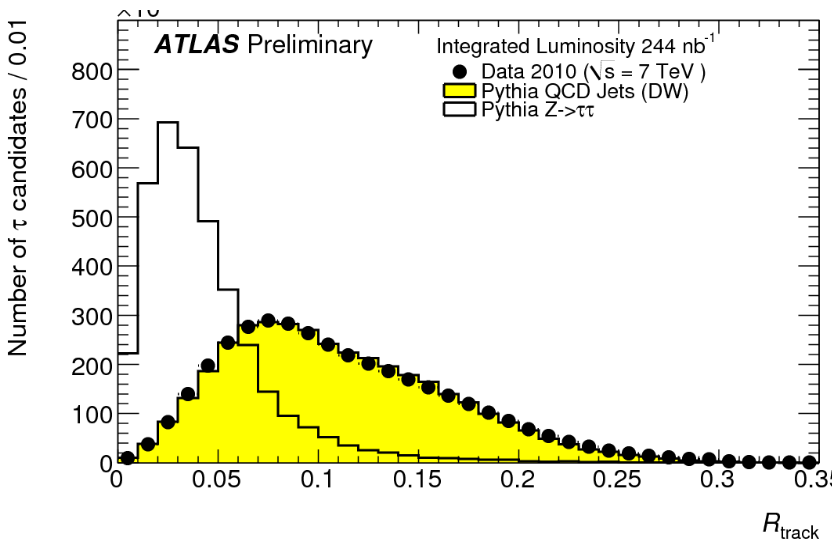
- Identification variables used for these methods have shown good tau/jet separation potential in MC studies
- For cut-based identification focus on only three well modeled, efficient and relatively uncorrelated variables



Leading track momentum fraction

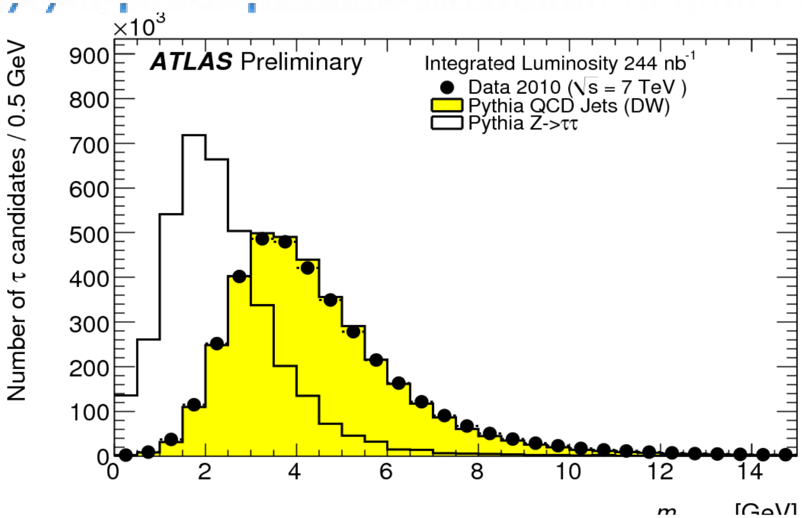


Electromagnetic radius: ET weighted shower width in EM Calo

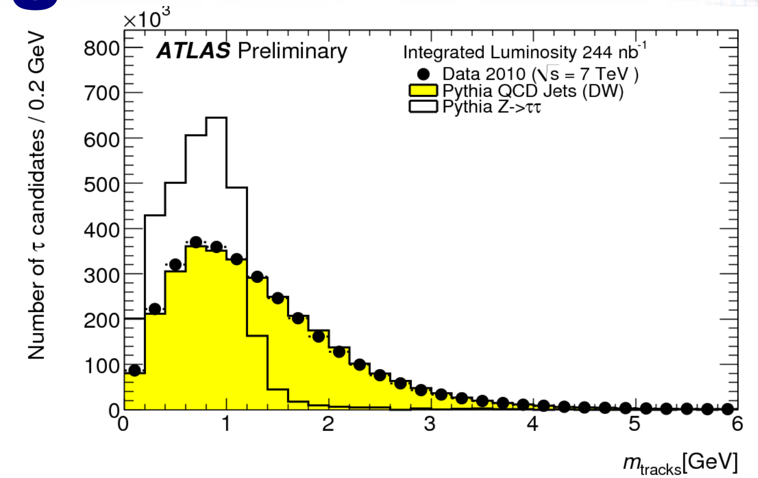


Track radius: pT weighted track width

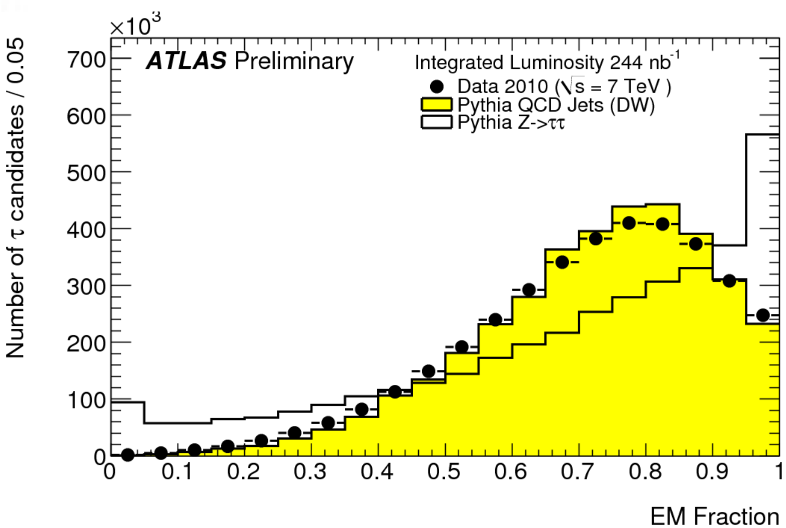
Other discriminating variables



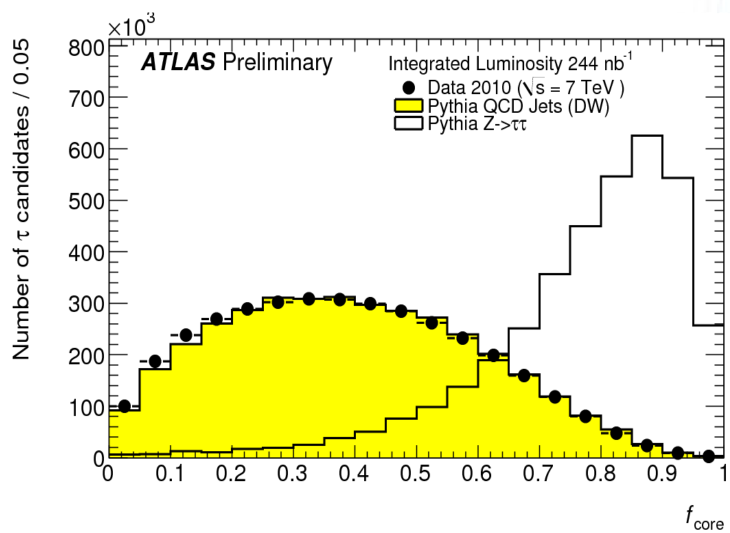
Cluster mass: Invariant mass computed from associated topological clusters



Track mass: Invariant mass of the track system

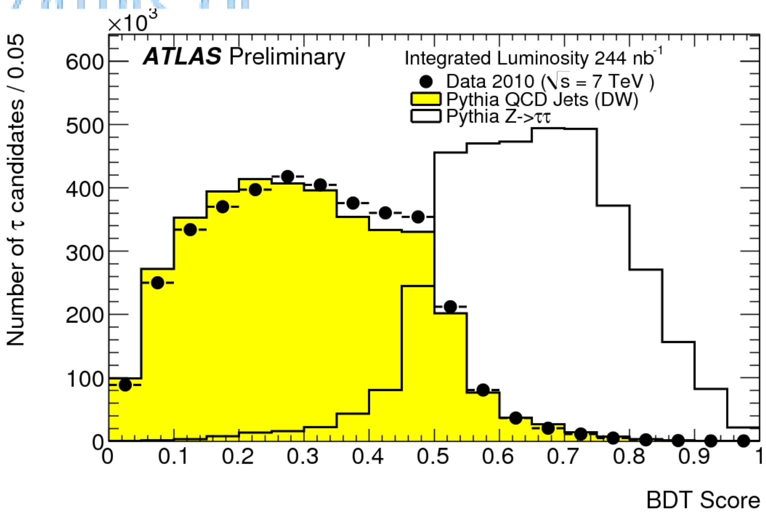


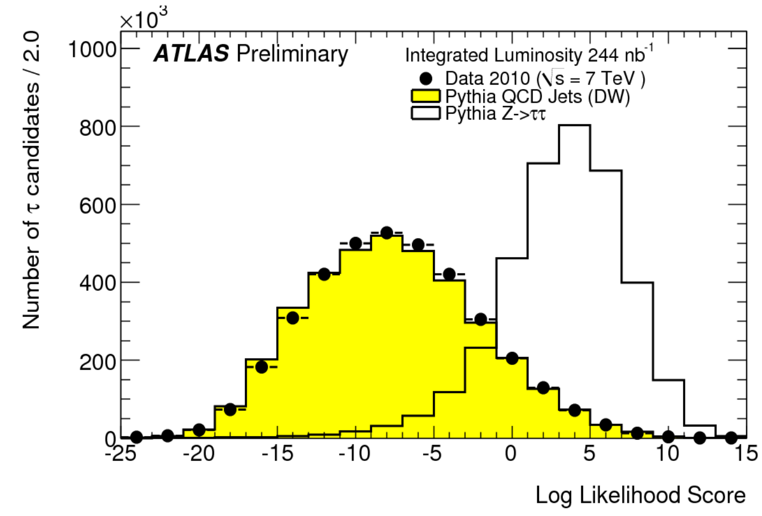
Electromagnetic fraction: fraction of calibrated ET deposited in EM Calo

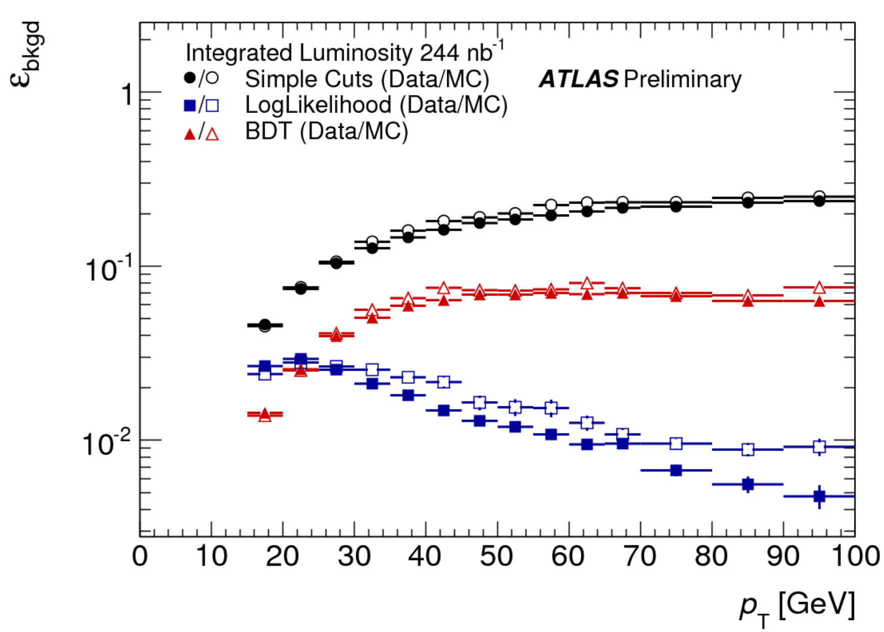


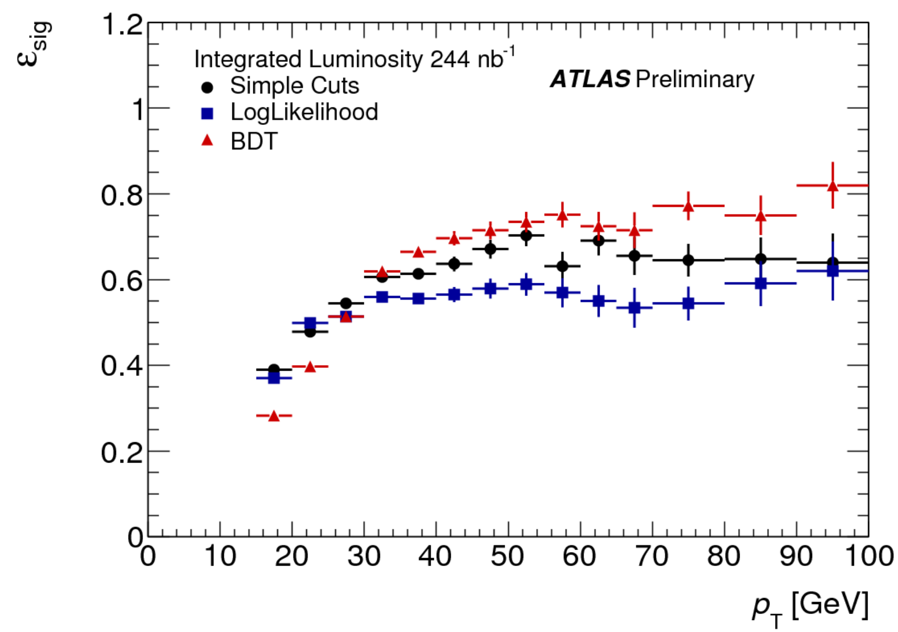
Core energy fraction: fraction of transverse energy in the core ($\Delta R<0.1$)

BDT and LL methods







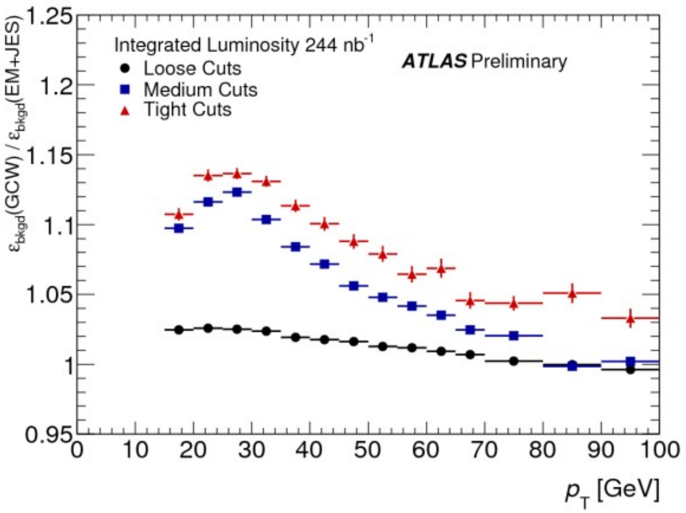


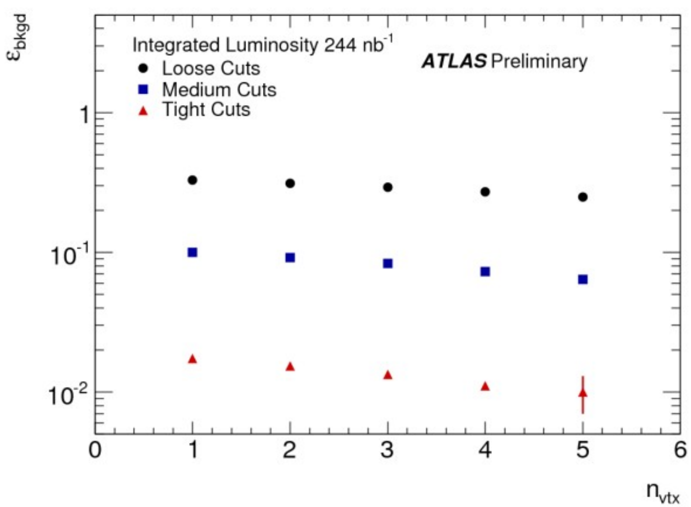
- Background eff. from Data/MC as function of reconstructed pT for medium selection
- Signal efficiency from Z → ττ MC as function of reconstructed pT for medium selection

Tau ID results and systematics

Two effects contribute to systematic uncertainties:

- The transverse momentum calibration: two calibration schemes compared:
  - Global cell energy-density weighting (GCW), ATLAS default
  - Simple *pT and η dependent calibration (EM+JES)*
- Pile-up effects since beam intensity has increased by a factor of 3 during the data taking period





Selection	$\varepsilon_{\mathrm{bkgd}}$ (data)	$\varepsilon_{\mathrm{bkgd}}$ (MC)	$\varepsilon'_{\mathrm{bkgd}}$ (data)	$\varepsilon'_{\mathrm{bkgd}}$ (MC)
loose	$(3.2 \pm 0.2) \times 10^{-1}$	3.4×10^{-1}	$(9.4 \pm 0.6) \times 10^{-2}$	10×10^{-2}
medium	$(9.5 \pm 1.0) \times 10^{-2}$	9.9×10^{-2}	$(3.1 \pm 0.4) \times 10^{-2}$	3.3×10^{-2}
tight	$(1.6 \pm 0.3) \times 10^{-2}$	1.9×10^{-2}	$(5.6 \pm 0.9) \times 10^{-3}$	6.8×10^{-3}

An alternative background efficiency, that requires in addition that candidates must have *ntrack = 1 or ntrack = 3,*

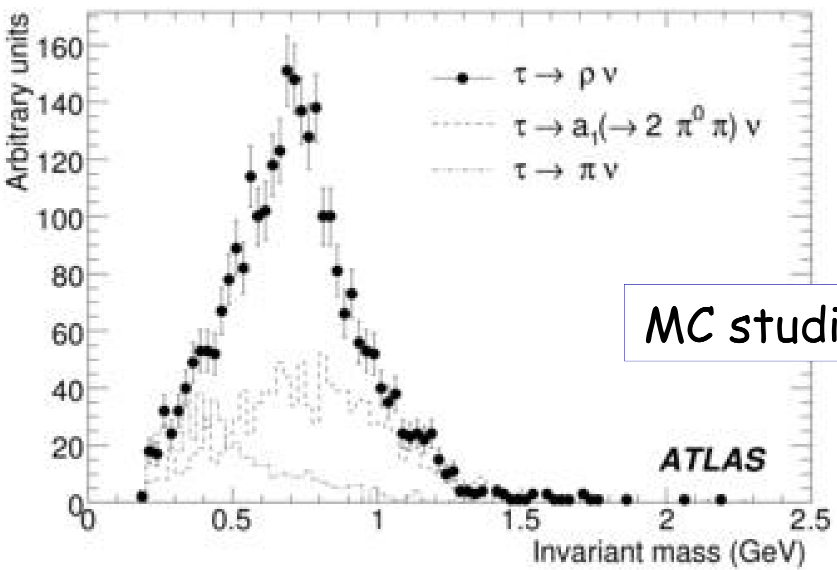
Reconstruction of π^0 subclusters

- High granularity of ATLAS electromagnetic calorimeter allows reconstruction of isolated subclusters from pi0s
- This allow to distinguish between different decay modes of tau leptons

Single prong candidates: fractions with zero, one and two or more reconstructed π^0 subclusters.

decay mode	no π^0 subclusters	1 π^0 subcluster	≥ 2 π^0 subclusters
all $\tau \to \text{had}\nu$	32%	35%	33%
$\tau \to \pi\nu$	65%	20%	15%
$\tau \to \rho\nu$	15%	50%	35%
$\tau \to a_1(\to 2\pi^0\pi)\nu$	9%	34%	57%

MC studies

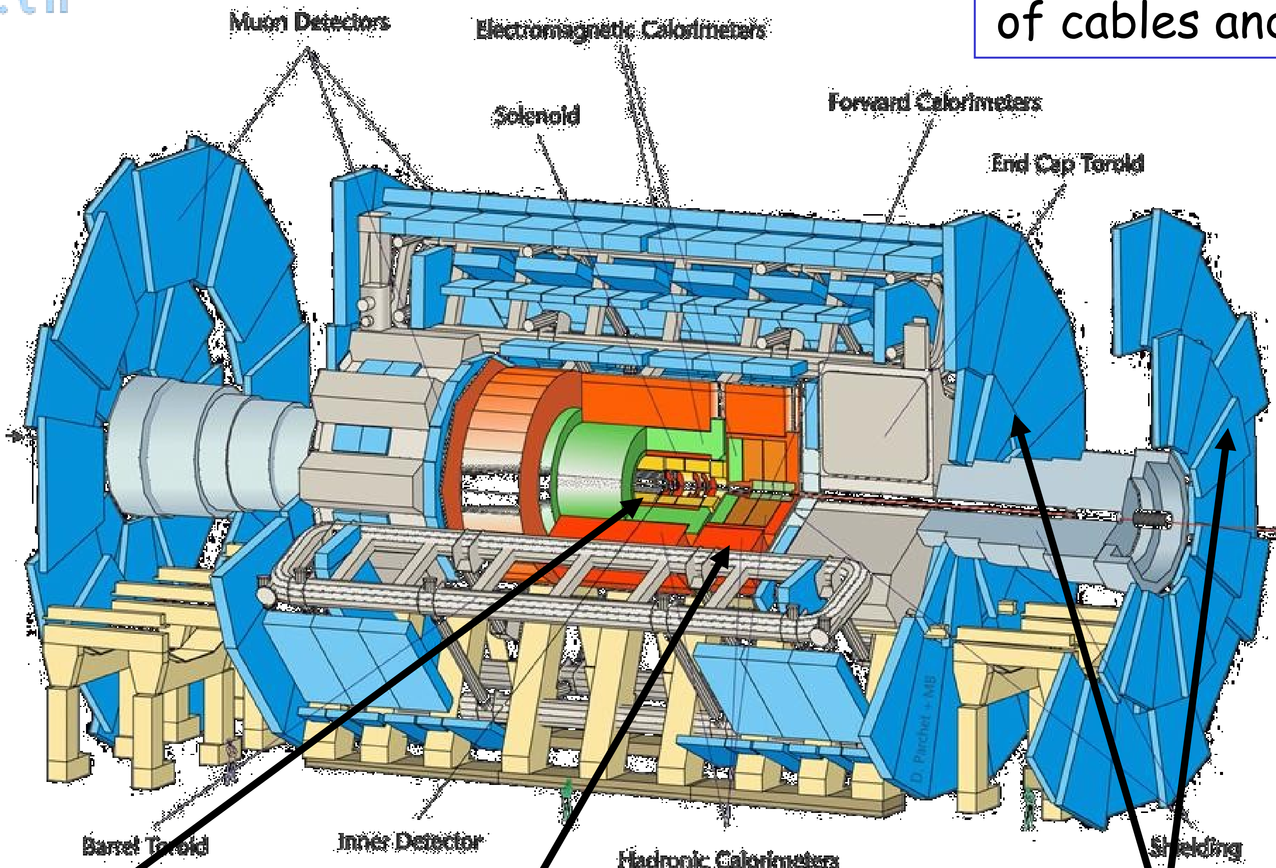


MC studies

The invariant mass of the visible decay products for hadronic single-prong $\tau \to \rho\nu$, $\tau \to a1\ (\to 2\ \pi^0\ \pi)\ \nu$, and $\tau \to \pi\nu$ decays using candidates from $W \to \tau\nu$ events with at least one $\pi0$ subcluster reconstructed

ATLAS – A Toroidal LHC ApparatuS

25m diameter, 46m long, weighing 7000T, with 3000km of cables and 108 channels



p 7TeV

p 7TeV

Tracking (|η|<2.5, B=2T):
- Silicon pixels and strips
- Transition Radiation Tracker

$\sigma/P_T = 0.05\%\ P_T + 1\%$
(2%@20GeV)
σ(d0)=15 um@20 GeV

Calorimetry (|η|<5)
EM : Pb-LAr
HAD: Fe/scintillator (central), Cu/W-LAr (fwd)

EM : $\sigma(E)/E = 10\%/\sqrt{E} + 0.7\%$

Hadron : $\sigma(E)/E = 50\%/\sqrt{E} + 3\%\ (\eta < 3)$

$\sigma(E)/E = 100\%/\sqrt{E} + 10\%\ (\eta > 3)$

Muon spectrometer (|η|<2.7, B=4T max)
Toroid magnet system with precision and trigger chambers

$\sigma/P_T = 2\text{-}7\%$

Tau/jet discriminating variables

Cluster mass: Invariant mass computed from associated topoclusters: m_{clusters}.

Track mass: Invariant mass of the track system: m_{tracks}.

Track radius: p_{T} weighted track width:

$$R_{\text{track}} = \frac{\sum_i^{\Delta R_i<0.2} p_{\text{T},i}\Delta R_i}{\sum_i^{\Delta R_i<0.2} p_{\text{T},i}},$$

where i runs over all tracks associated to the τ candidate, ΔR_i is defined relative to the τ jet seed axis and $p_{\text{T},i}$ is the track transverse momentum.

Leading track momentum fraction:

$$f_{\text{trk},1} = \frac{p_{\text{T},1}^{\text{track}}}{p_{\text{T}}^{\tau}},$$

where $p_{\text{T},1}^{\text{track}}$ is the transverse momentum of the leading track of the τ candidate and p_{T}^{τ} is the transverse momentum of the τ candidate.

Tau/jet discriminating variables

Electromagnetic radius: Transverse energy weighted shower width in the electromagnetic (EM) calorimeter:

$$R_{\mathrm{EM}} = \frac{\sum_i^{\Delta R_i<0.4} E_{\mathrm{T},i}^{\mathrm{EM}} \Delta R_i}{\sum_i^{\Delta R_i<0.4} E_{\mathrm{T},i}^{\mathrm{EM}}},$$

where i runs over cells in the first three layers of the EM calorimeter associated to the τ candidate, ΔR_i is defined relative to the τ jet seed axis and $E_{\mathrm{T},i}^{\mathrm{EM}}$ is the cell transverse energy.

Core energy fraction: Fraction of transverse energy in the core ($\Delta R < 0.1$) of the τ candidate:

$$f_{\mathrm{core}} = \frac{\sum_i^{\Delta R<0.1} E_{\mathrm{T},i}}{\sum_i^{\Delta R<0.4} E_{\mathrm{T},i}},$$

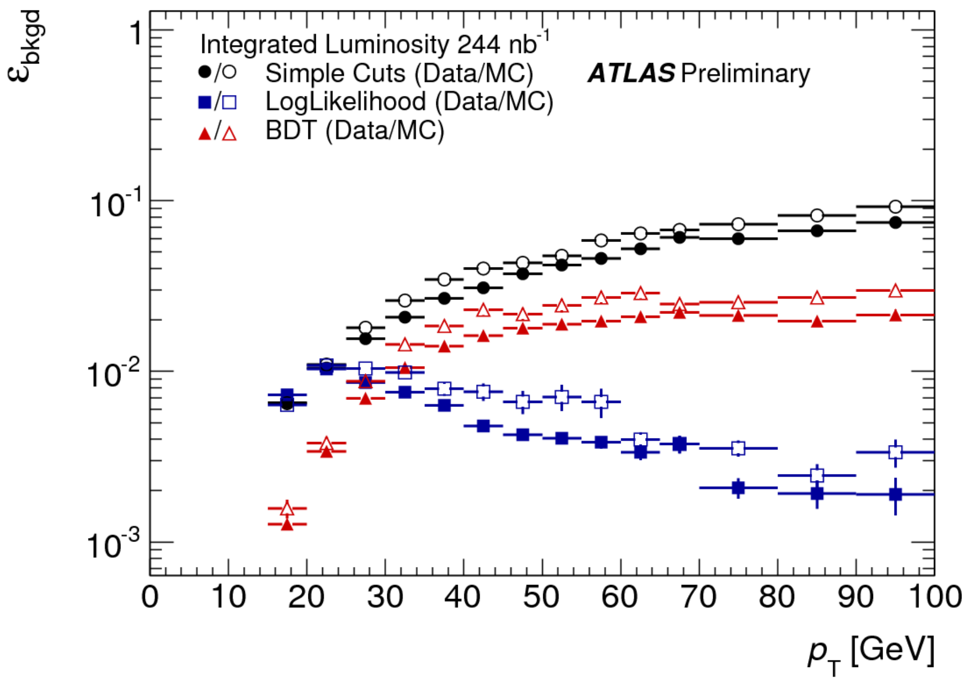
where i runs over all cells associated to the τ candidate within ΔR_i of the τ jet seed axis.

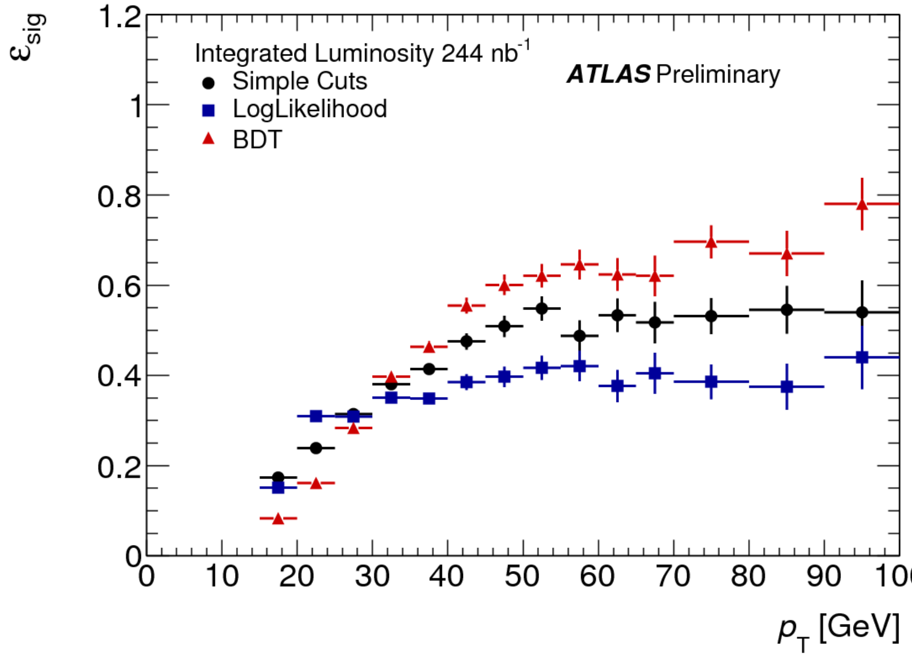
Electromagnetic fraction: Fraction of GCW calibrated transverse energy of the τ candidate deposited in the EM calorimeter:

$$f_{\mathrm{EM}} = \frac{\sum_i^{\Delta R_i<0.4} E_{\mathrm{T},i}^{\mathrm{GCW}}}{\sum_j^{\Delta R_i<0.4} E_{\mathrm{T},j}^{\mathrm{GCW}}},$$

where $E_{\mathrm{T},i}$ ($E_{\mathrm{T},j}$) is the GCW calibrated transverse energy deposited in cell i (j), and i runs over the cells in the first three layers of the EM calorimeter, while j runs over the cells in all layers of the calorimeter.

BDT and LL methods - tight

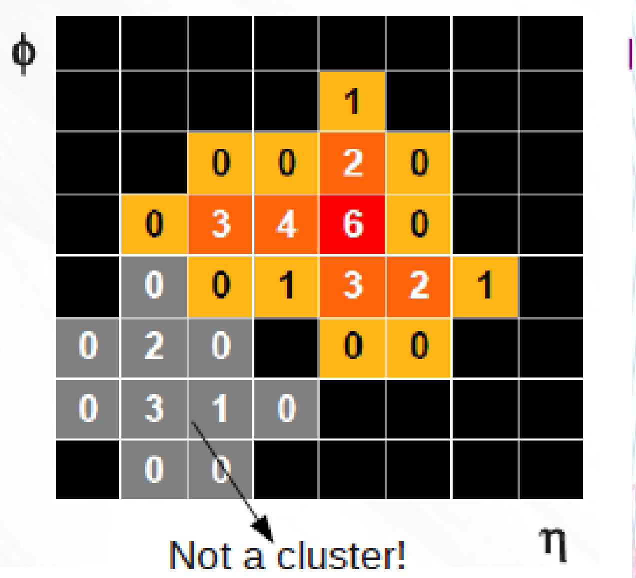




- Background eff. from Data/MC as function of reconstructed pT for tight selection
- Signal efficiency from $Z \rightarrow \tau\tau$ MC as function of reconstructed pT for tight selection

Topoclustering

- Topological Jet - cone algorithm run over TopoClusters
- Topological Cluster
  - group of calorimeter cells topologically
  - interconnected and selected by energy significance:
    - seed cell: |Ecell|> 4 sigma noise
    - neighbor cells: |Ecell|> 2 sigma
    - cells surrounding the cluster added
  - Tries somehow to match the shape of the shower.



- Details:
  - ATLAS Collaboration, *Calorimeter clustering algorithms: Description and performance,*

  ATL-LARG-PUB-2008-002 (2008).

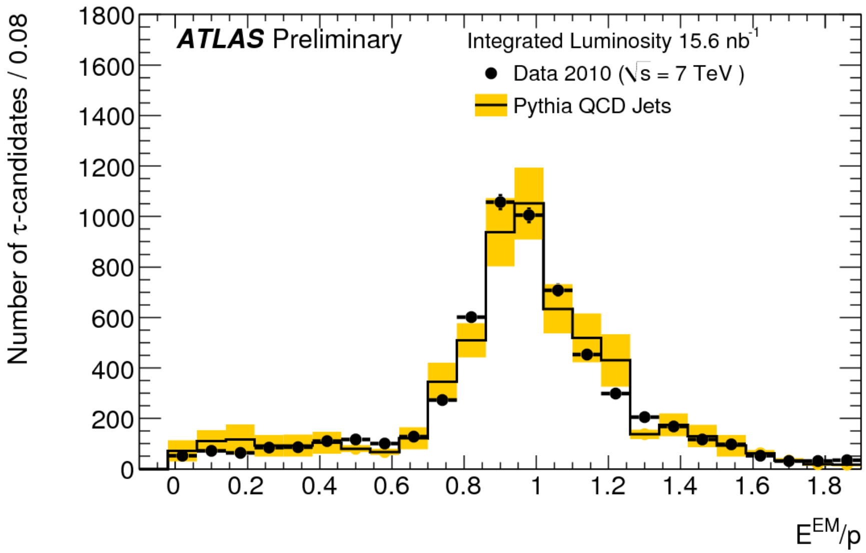
Photon conversion and π^0 identification

- **Photon conversions**
  Identify tracks from conversions in tau cone and remove them: minimizes electron contamination, improves charge and track multiplicity determination.

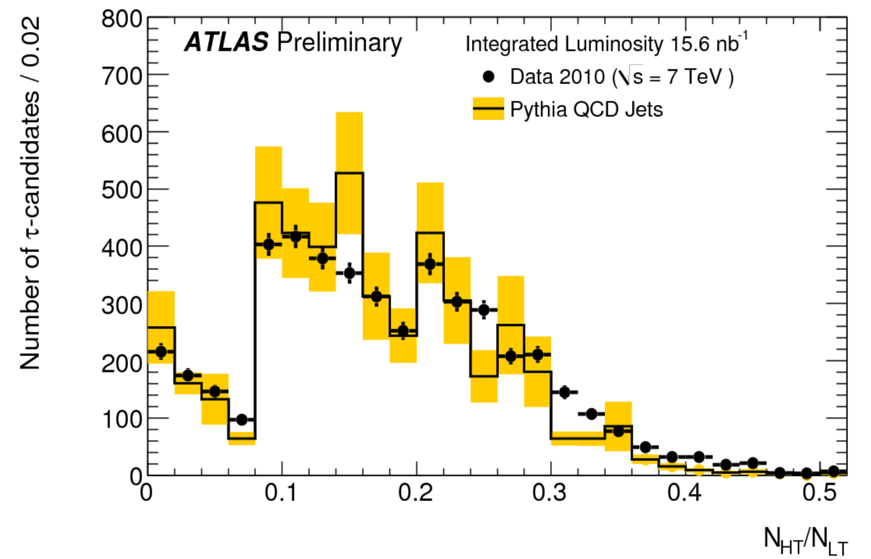
- **π^0 reconstruction**
  - Remove energy from charged pions
  - Find π^0 candidates in remaining EM energy
  - Allows identification of specific tau decays ($\pi^\pm$, $\rho^\pm$, a_1)

Electron veto

Narrow jet with few tracks => electrons are good tau candidates.
Use specific variables to reject electrons (two most important presented below)
From MC studies: rejection factor about 100 for a few percent loss in signal efficiency.



Ratio of EM energy in a narrow window around the impact cell to the leading track momentum for tau candidates identified as electrons by standard electron ID.



Ratio of high threshold to low threshold hits in the Transition Radiation Tracker for tau candidates identified as electrons by standard electron ID.

ATLAS EXPERIMENT
http://atlas.ch

W-> tau nu

Trigger – 99.7% effic MC
ET>5GeV at Level1
Track pT>6GeV and missing ET>5GeV at Level2
Missing ET>15 GeV at the Event Filter

	Data	$W \to \tau_h \nu_\tau$	$W \to e\nu_e$	$W \to \mu\nu_\mu$	$W \to \tau_\ell \nu_\tau$	$Z \to ee$	$Z \to \mu\mu$	$Z \to \tau\tau$
Trigger	986439	954.5±5.2	3560.7±3.4	521.4±1.6	296.5±2.8	75.3±0.2	59.7±0.2	115.1±0.7
QCD jets rejection	415951	728.3±4.7	2735.3±3.5	400.7±1.5	229.4±2.6	24.5±0.1	45.1±0.1	71.4±0.6
$E_T^{miss} > 30$ GeV	29686	411.5±3.8	1828.3±3.3	317.1±1.3	121.9±1.9	1.13±0.03	34.4±0.1	35.4±0.4
τ selection	2408	118.0±2.1	1482.0±3.1	26.6±0.4	34.4±1.0	0.59±0.02	3.24±0.04	11.9±0.3
Lepton rejection	685	94.8±1.9	6.7±0.2	4.9±0.2	2.3±0.3	<0.005	0.11±0.01	4.2±0.2
$S_{E_T^{miss}} > 6$	78	55.3±1.4	4.2±0.2	3.7±0.1	1.8±0.2		0.08±0.01	2.0±0.1

	signal	EW background	QCD background
Central values [events]	55.3	11.8	11.1
Statistical error [events]	±1.4	±0.4	±2.3
Systematic uncertainties			
Theoretical cross section	±5%	± 5%	–
Luminosity	±11	± 11%	–
Energy scale	±21%	±14%	–
Electron veto	–	±11%	–
Muon veto	–	±16%	–
Pile-up	±1	±0.2%	–
Monte Carlo model	±16%	±17%	–
QCD background estimation	–	–	±29%
Total systematic uncertainty [events]	±16.1	±3.7	±3.2

Data & event selection

Data
• collected with the ATLAS detector till mid of July 2010, corresponding to integrated luminosity 244 nb^{-1}
• no real tau leptons expected to be observed in this dataset but identification variables for QCD jets reconstructed as τ candidates can be compared to predictions from Monte Carlo simulations
MC
• di-jet Pythia samples with p_T of the outgoing partons in range 8-280 GeV

Event selection

- basic beam and data quality requirement for tracker and calorimeters
- the Level 1 trigger requiring a τ trigger object with $p_T > 5$ GeV
- cleaning for out-of-time cosmic events or sporadic noise effects in the calorimeters
- at least one vertex reconstructed with more than four tracks
- at least two τ candidates with $|\eta| < 2.5$ and one with $p_T > 30$ GeV and other with $p_T > 15$ GeV
- $\Delta\phi$ between two τ candidates to be at least 2.7 rad
  (ϕ - the angle in the plane transverse to the beam pipe).