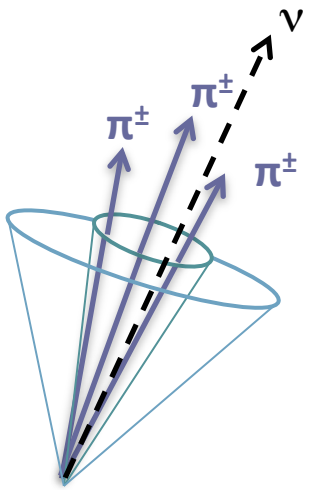
Taus at ATLAS

Davis
Thursday, April 7, 2011

Sarah Demers
Yale University

Outline

- ***BREIF* ATLAS Introduction**
- Taus at ATLAS
  - Reconstruction/Identification
  - Trigger
- Channels
  - W->τν
  - Z->ττ
  - H^+->τν
  - H->ττ
- Long-term outlook



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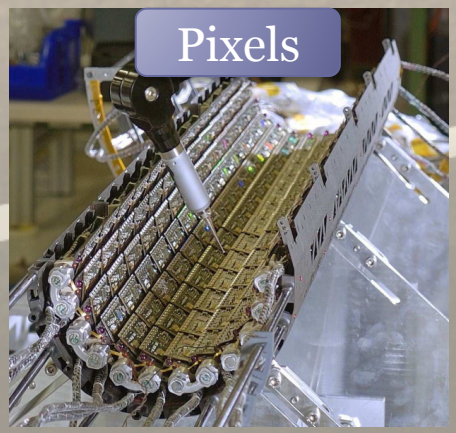
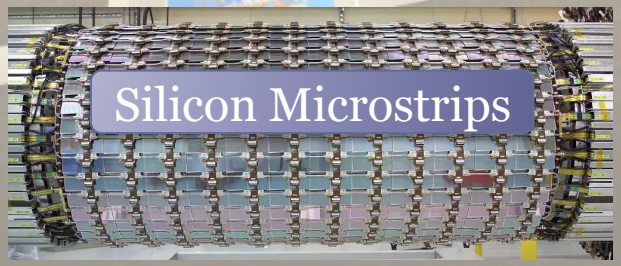
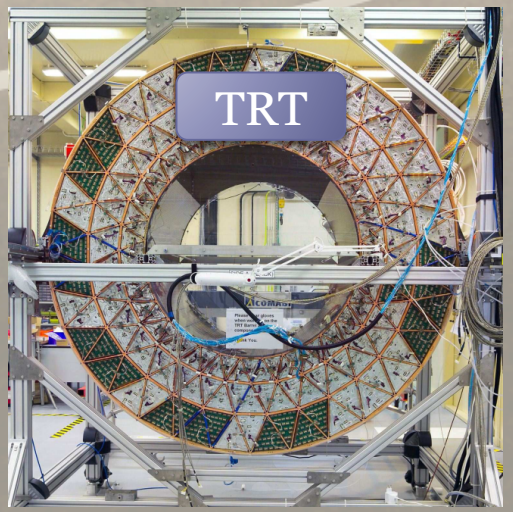
The ATLAS Detector at CERN's LHC

- **Tracking detectors** for momentum and charge (and in the case of the TRT) particle ID
- Sampling Calorimeters
- Trigger and Data Acquisition







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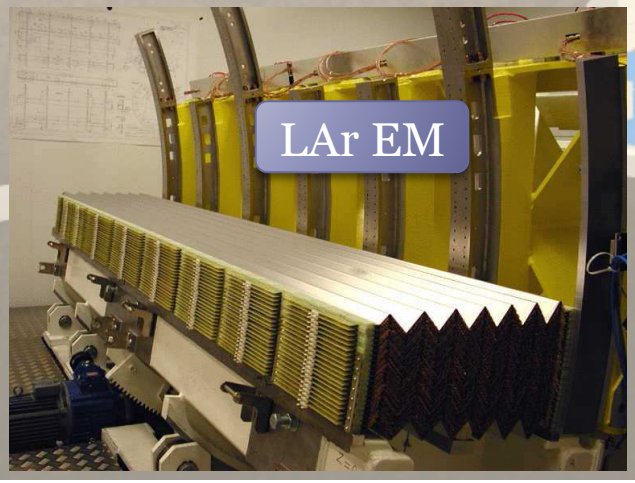
The ATLAS Detector at CERN's LHC

- Tracking detectors
- **Sampling Calorimeters** for energy deposits with fine granularity for shape discrimination
- Trigger and Data Acquisition



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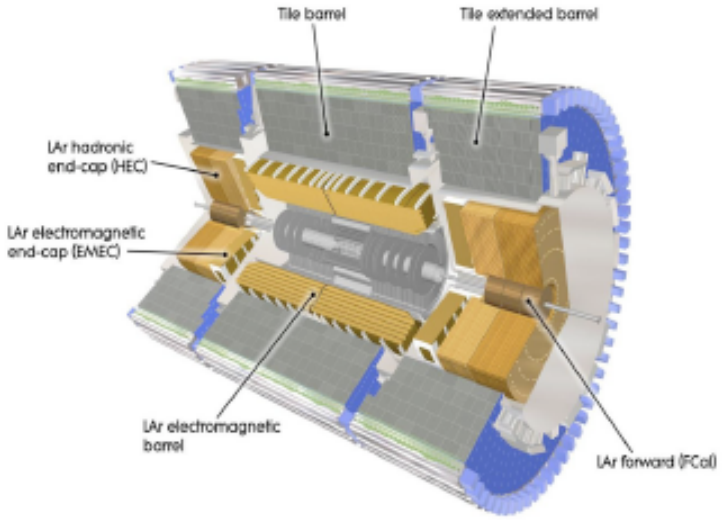
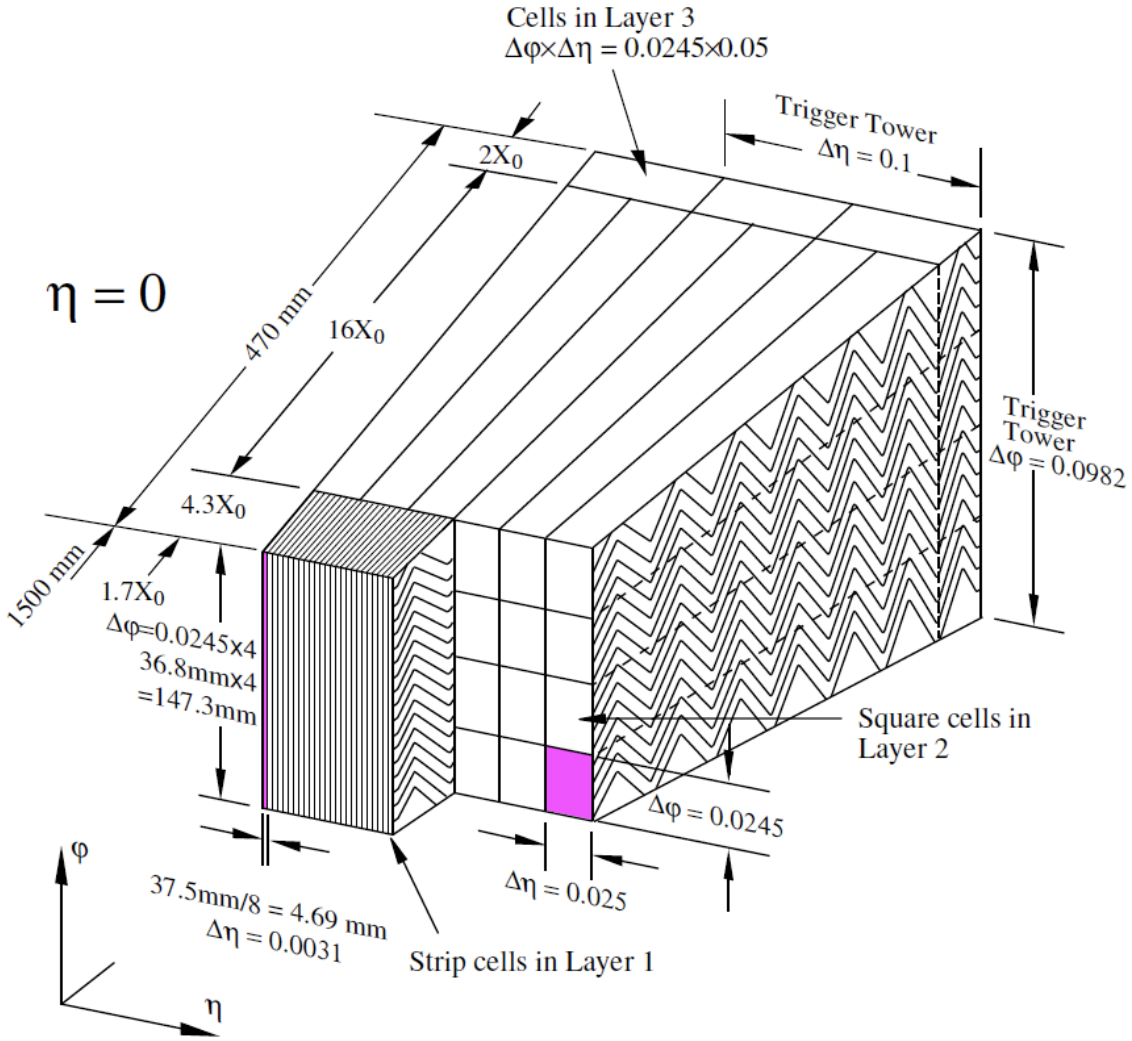
Calorimeters





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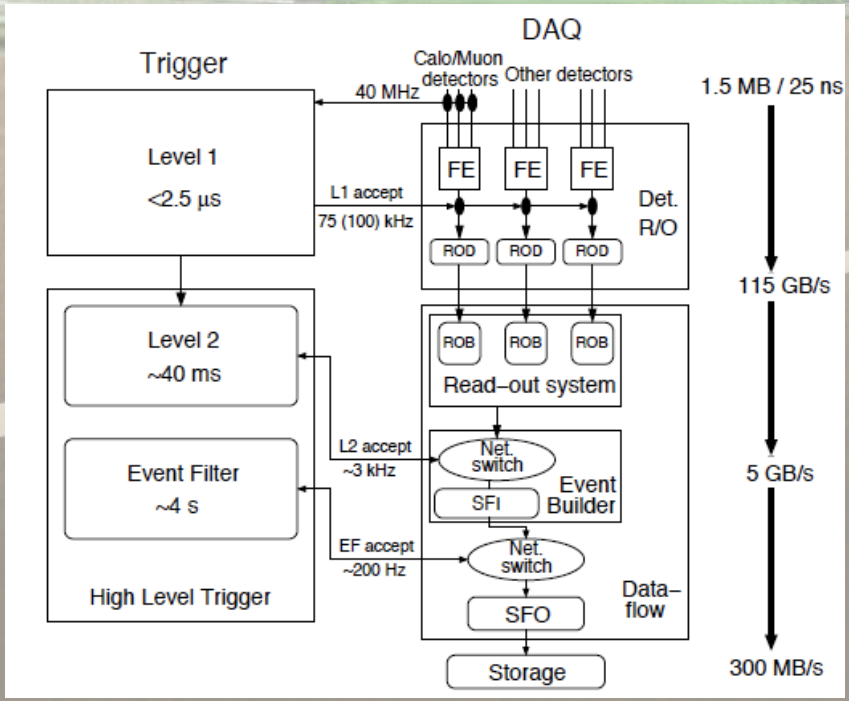
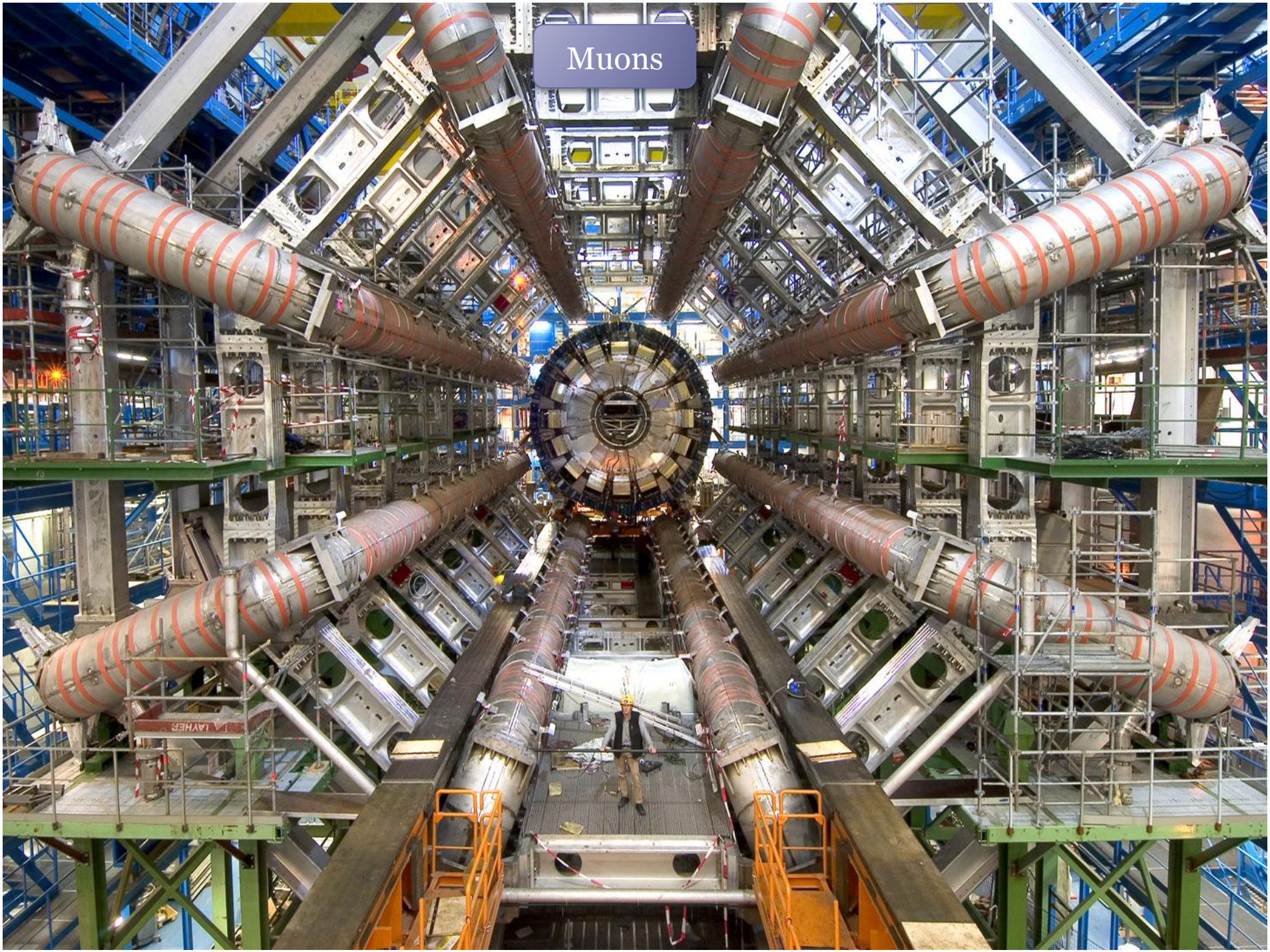
The ATLAS Detector at CERN's LHC

Trigger and Data Acquisition capable of handling 40 MHz interaction rate and writing out events at a rate of O(100 Hz)




Muons

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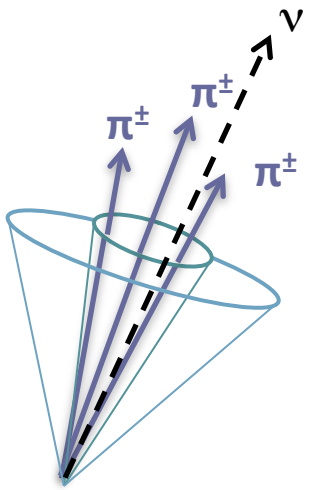

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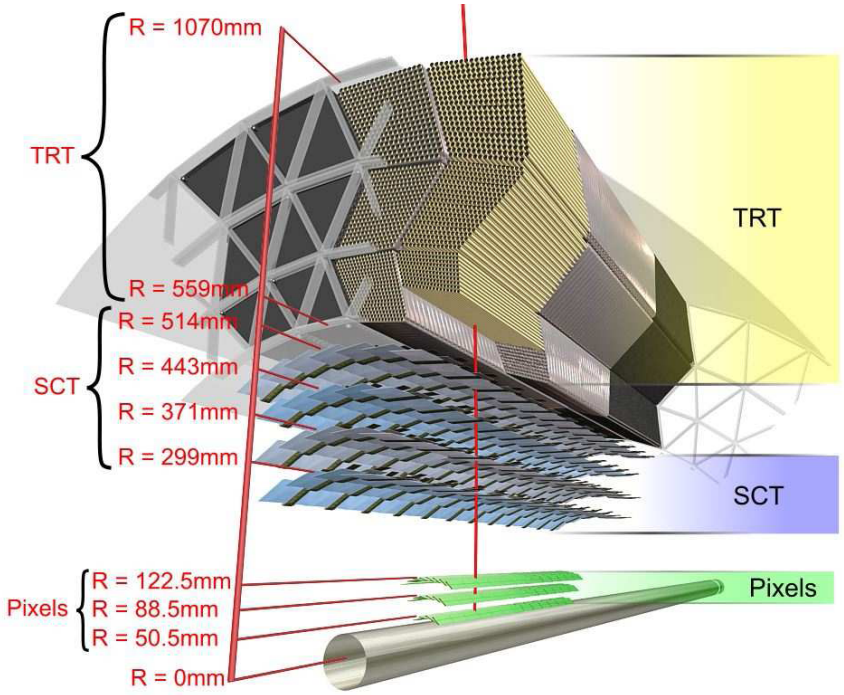
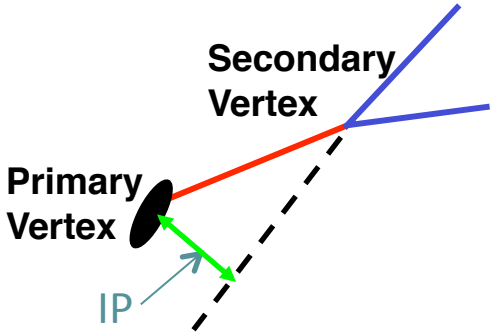
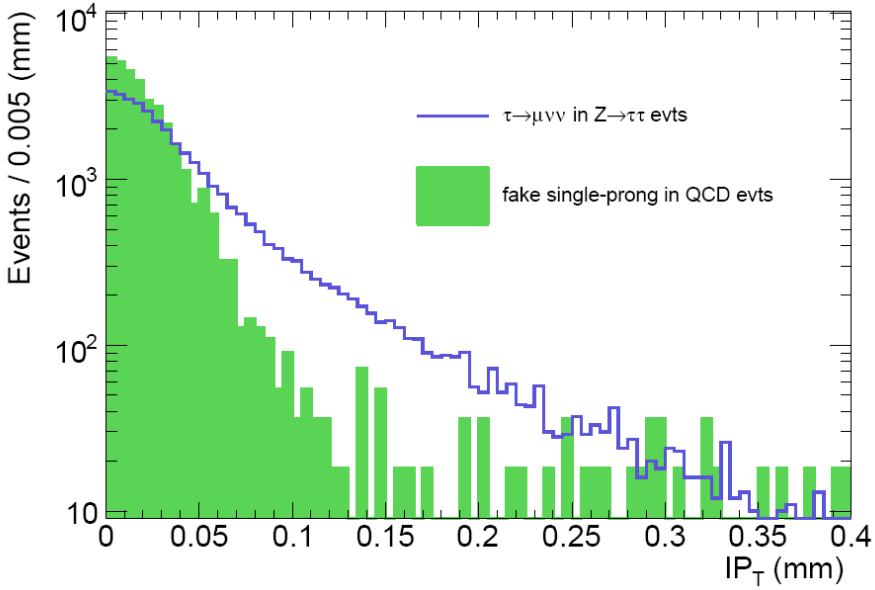
Using Impact Parameter







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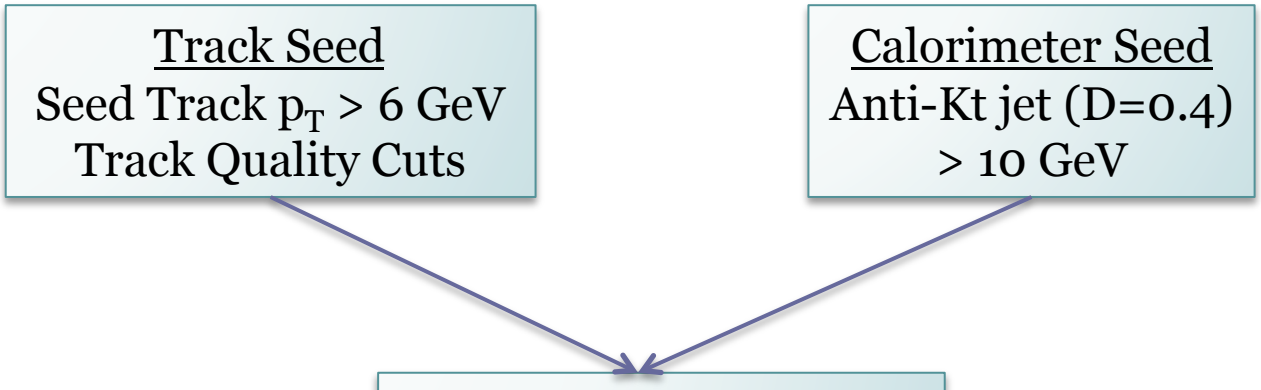
Tau Reconstruction



$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.2$$

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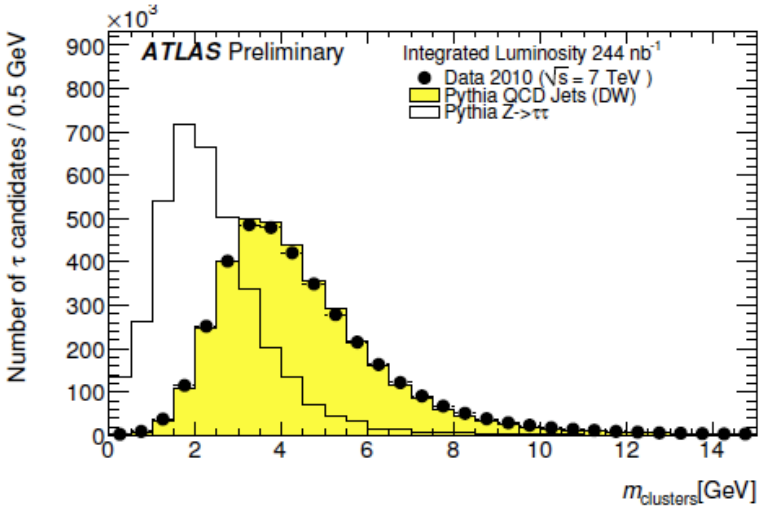
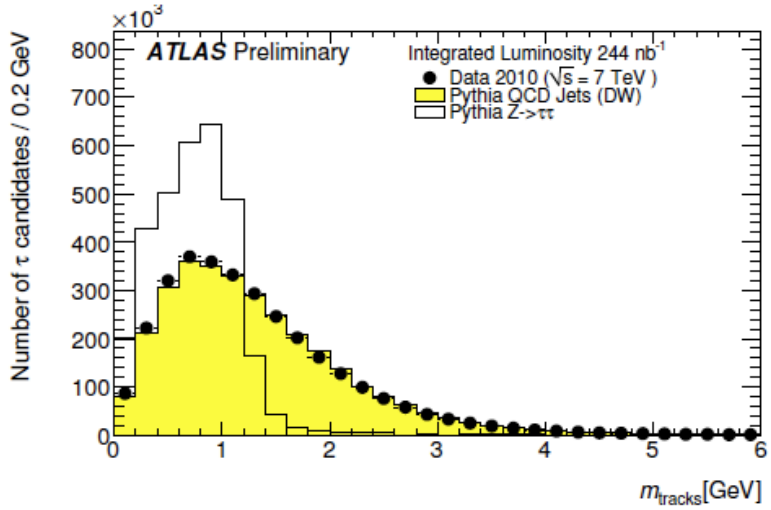
Tau Identification Variables (I)

- $m_{cluster}$
  - Invariant Mass from associated topoclusters
- m_{tracks}
  - Invariant Mass of track system





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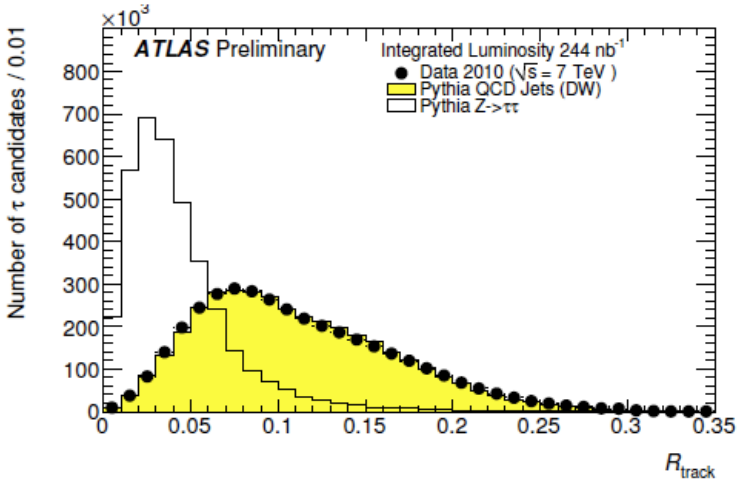
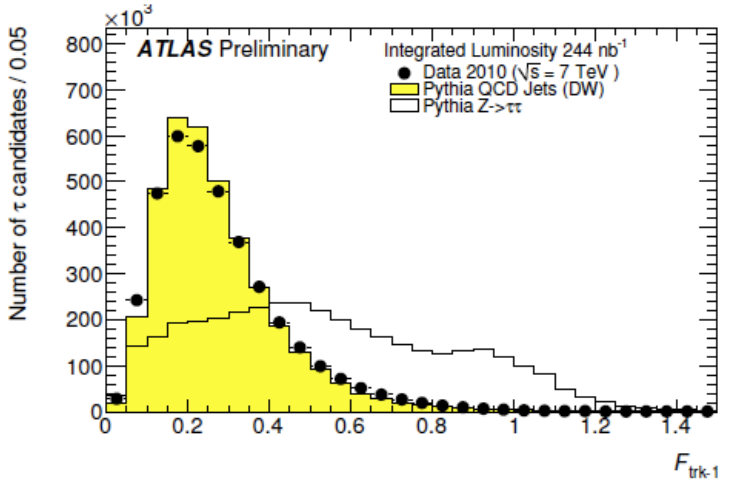
Tau Identification Variables (II)

- R_{track}
  - p_T weighted track width

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

- $F_{trk,1}$
  - Lead track p_T divided by total tau p_T





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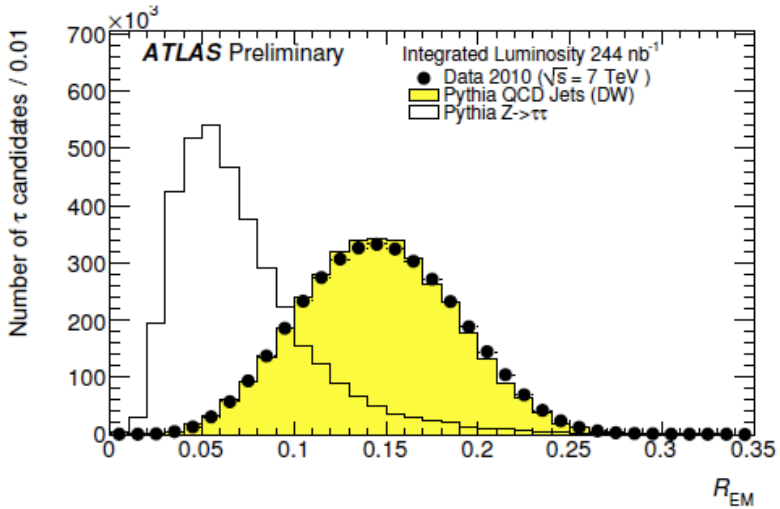
Tau Identification Variables (III)

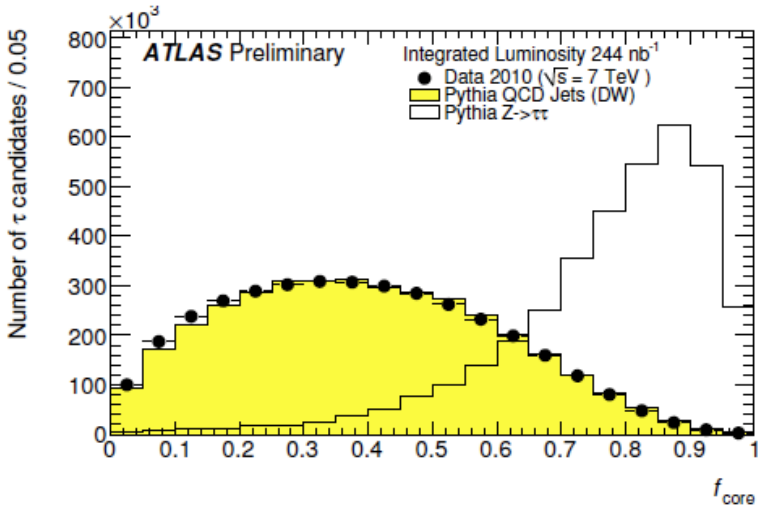
- R_{EM}
  - Transverse energy weighted width
  - "i" runs over cells in three EM calorimeter layers

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

- F_{core}
  - Fraction E_T in core region

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





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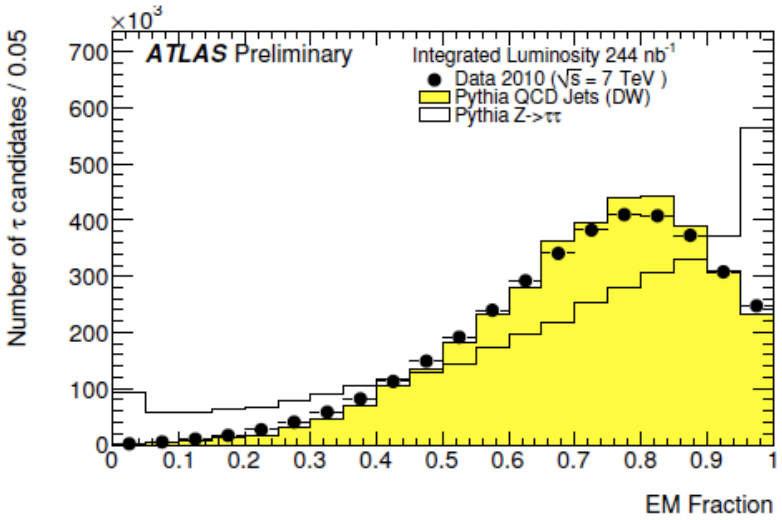
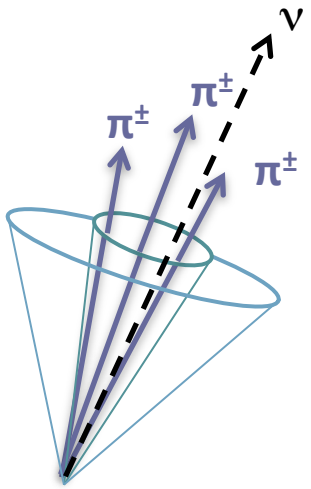
Tau Identification Variables (IV)

- f_{EM}
  - Fraction of energy deposited in the electromagnetic calorimeter
  - "i" runs over cells in EM Cal
  - "j" runs over cells in EM + HAD

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



2010 Tau Identification



Cut-Based

Likelihood

Boosted Decision Tree

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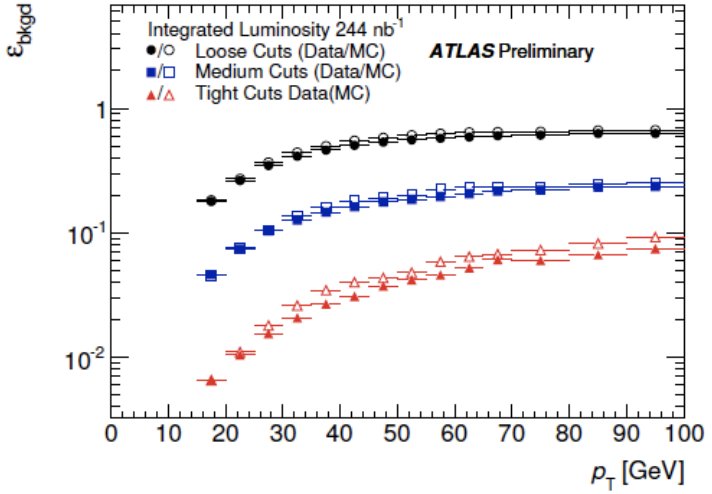
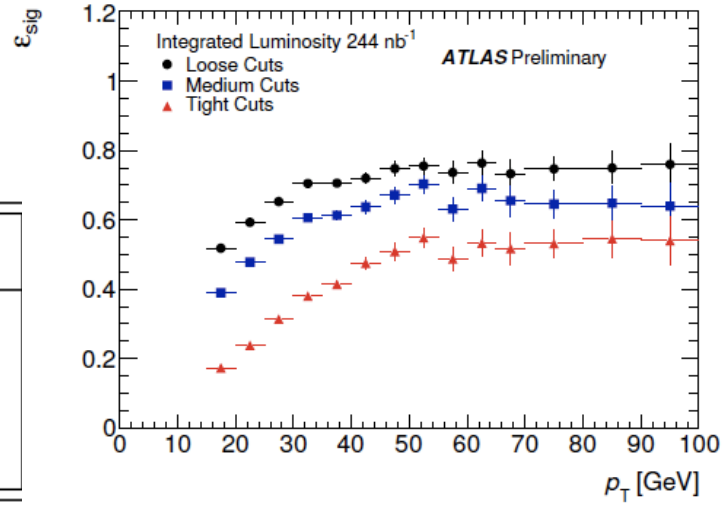
Tau Identification: Cut-Based

- Use three fairly uncorrelated variables
  - R_{EM}, R_{track}, $f_{trk,1}$
- Three levels
  - Loose: 60% efficiency
  - Medium: 50% efficiency
  - Tight: 30 % efficiency

Selection	ε_{bkgd} (data)	ε_{bkgd} (MC)
loose	$(3.2 \pm 0.2) \times 10^{-1}$	3.4×10^{-1}
medium	$(9.5 \pm 1.0) \times 10^{-2}$	9.9×10^{-2}
tight	$(1.6 \pm 0.3) \times 10^{-2}$	1.9×10^{-2}





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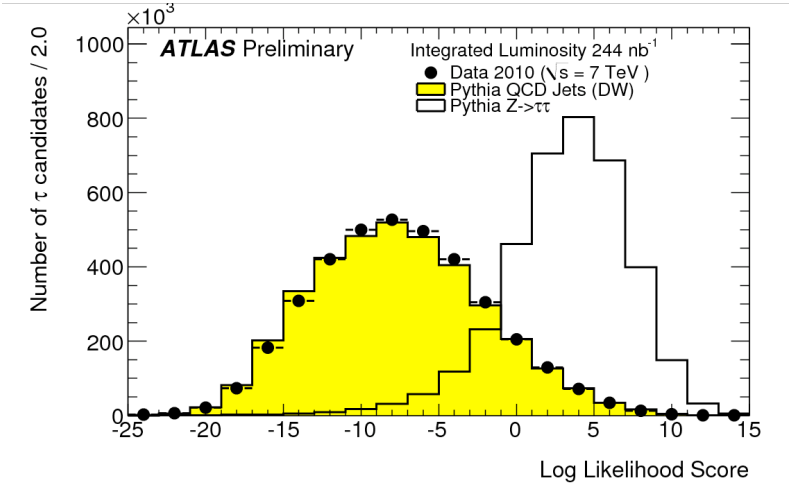
Tau Identification: Log Likelihood

- Uses six of the seven variables:
  - $m_{cluster}$, m_{track}, R_{track}, $f_{trk,l}$, R_{EM}, f_{EM}
- F_{core} was not used due to its high correlation with the other variables
- Training done in six p_T bins



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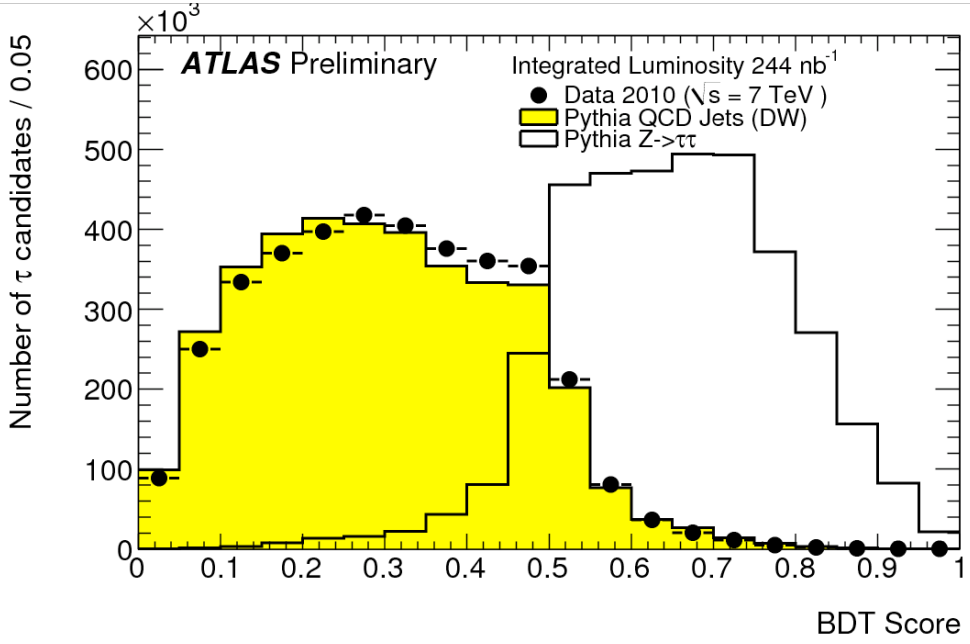
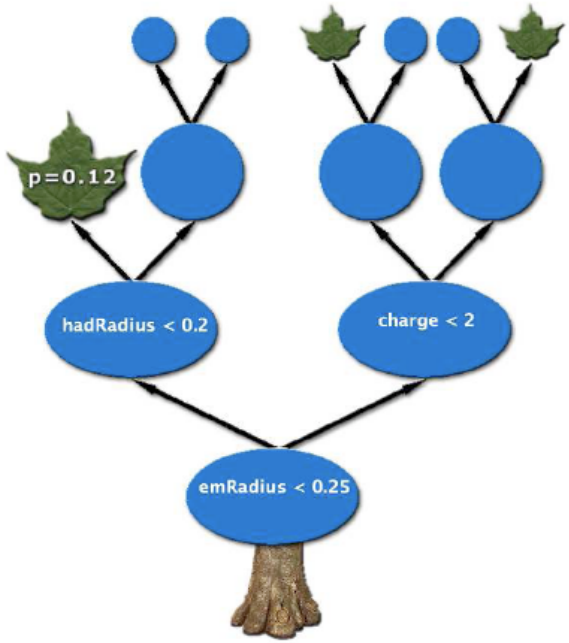
Tau Identification: Boosted Decision Tree

- Uses all seven ID variables:
  - $m_{cluster}$, m_{track}, R_{track}, $f_{trk,l}$, R_{EM}, f_{core}, f_{EM}





Thanks to J. Godfrey for image!

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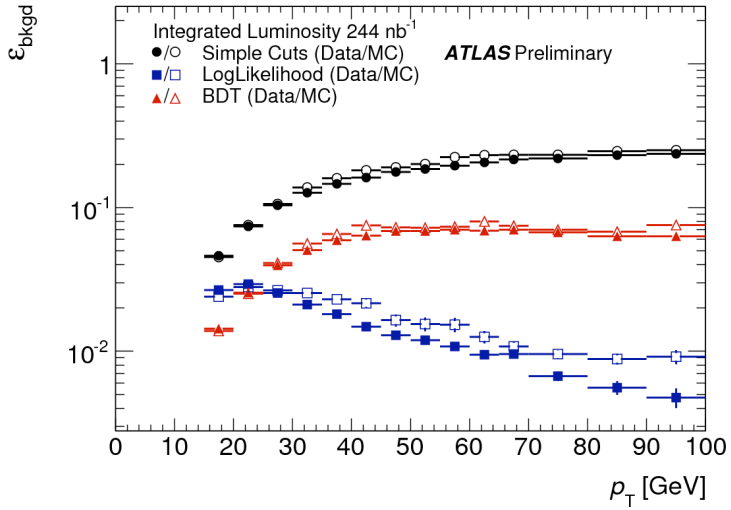
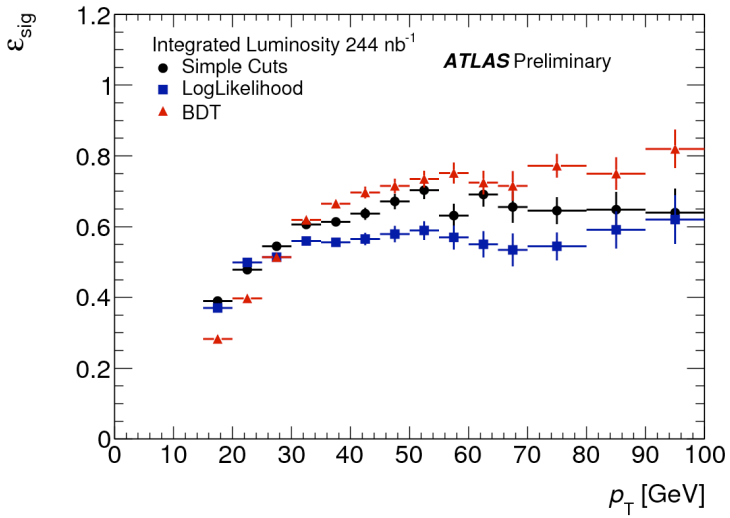
Performance Comparison

Simple Cut

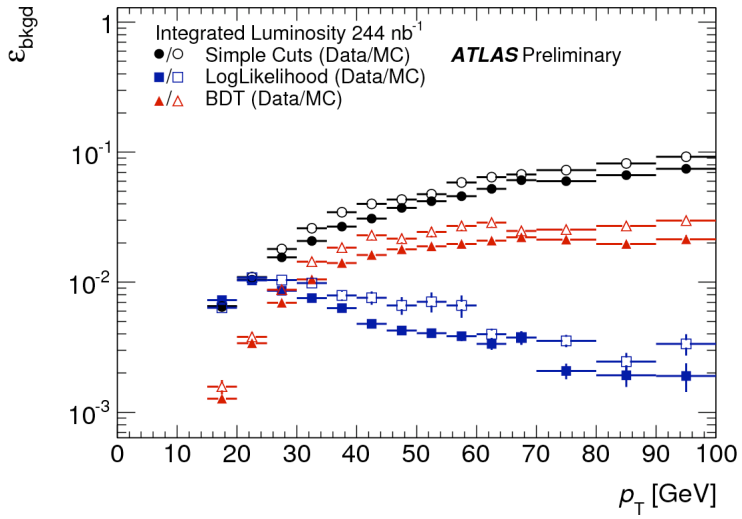
LL

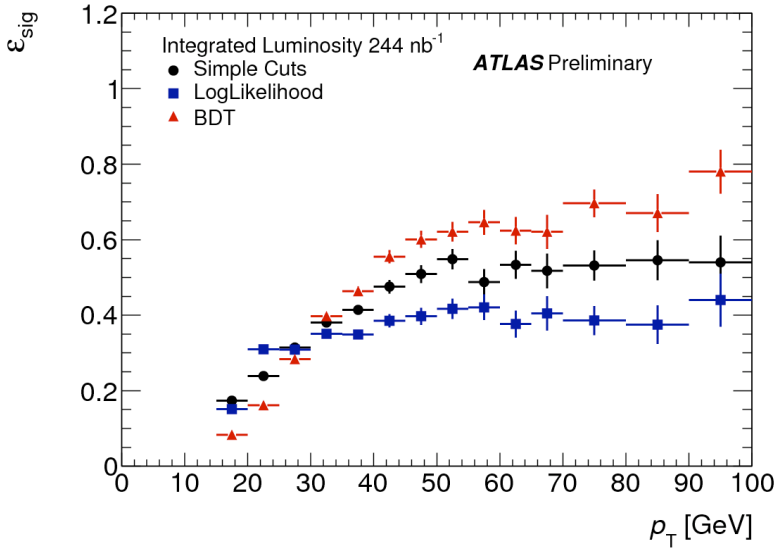
BDT





Medium Selection

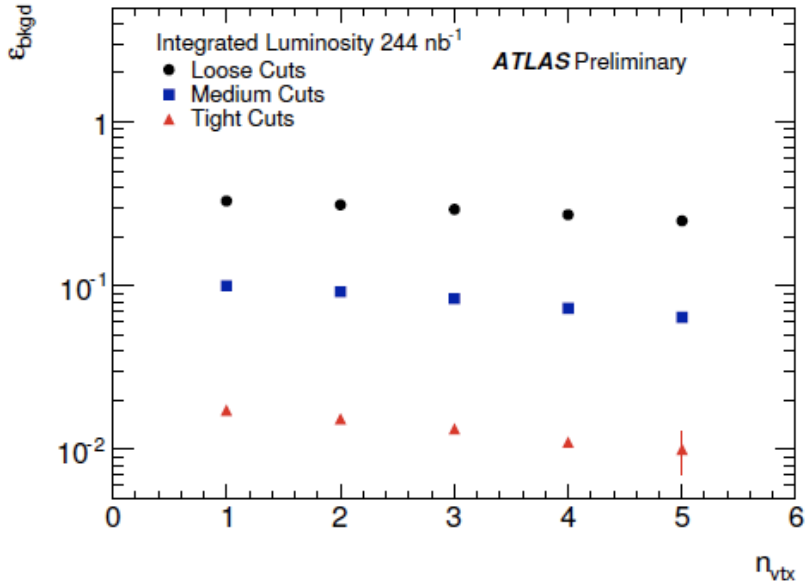




Tight Selection

Tau Identification: Future

- Some of the variables relied upon by the 2010 data are sensitive to pile-up so a re-optimization needs to be done as we move from a few pile-up events to ten.



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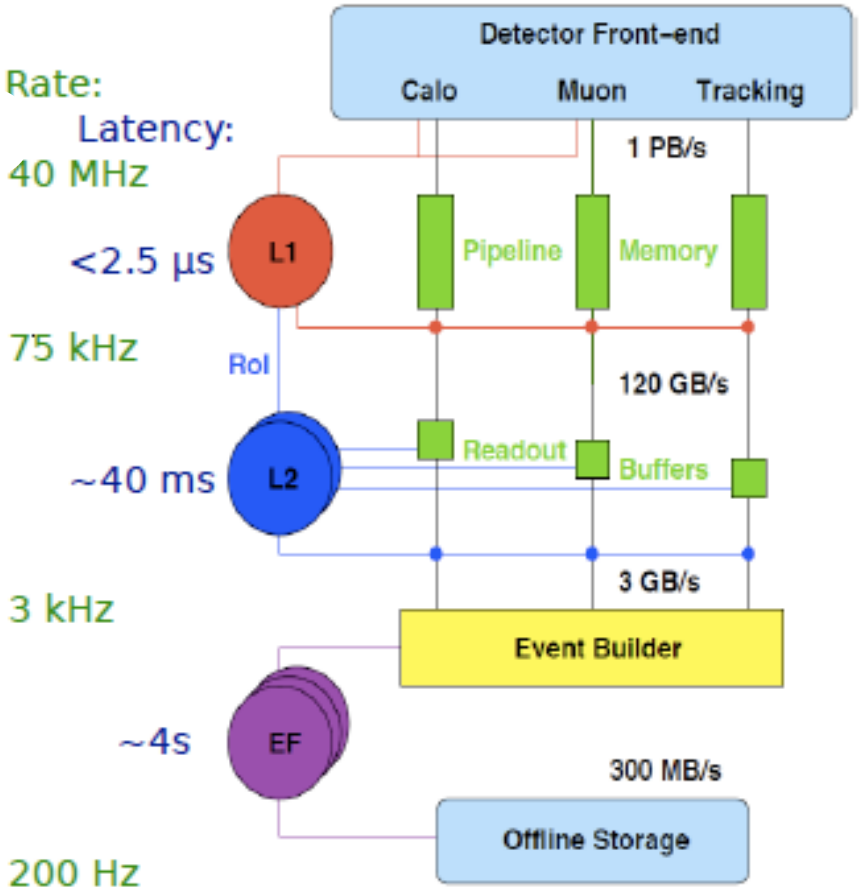
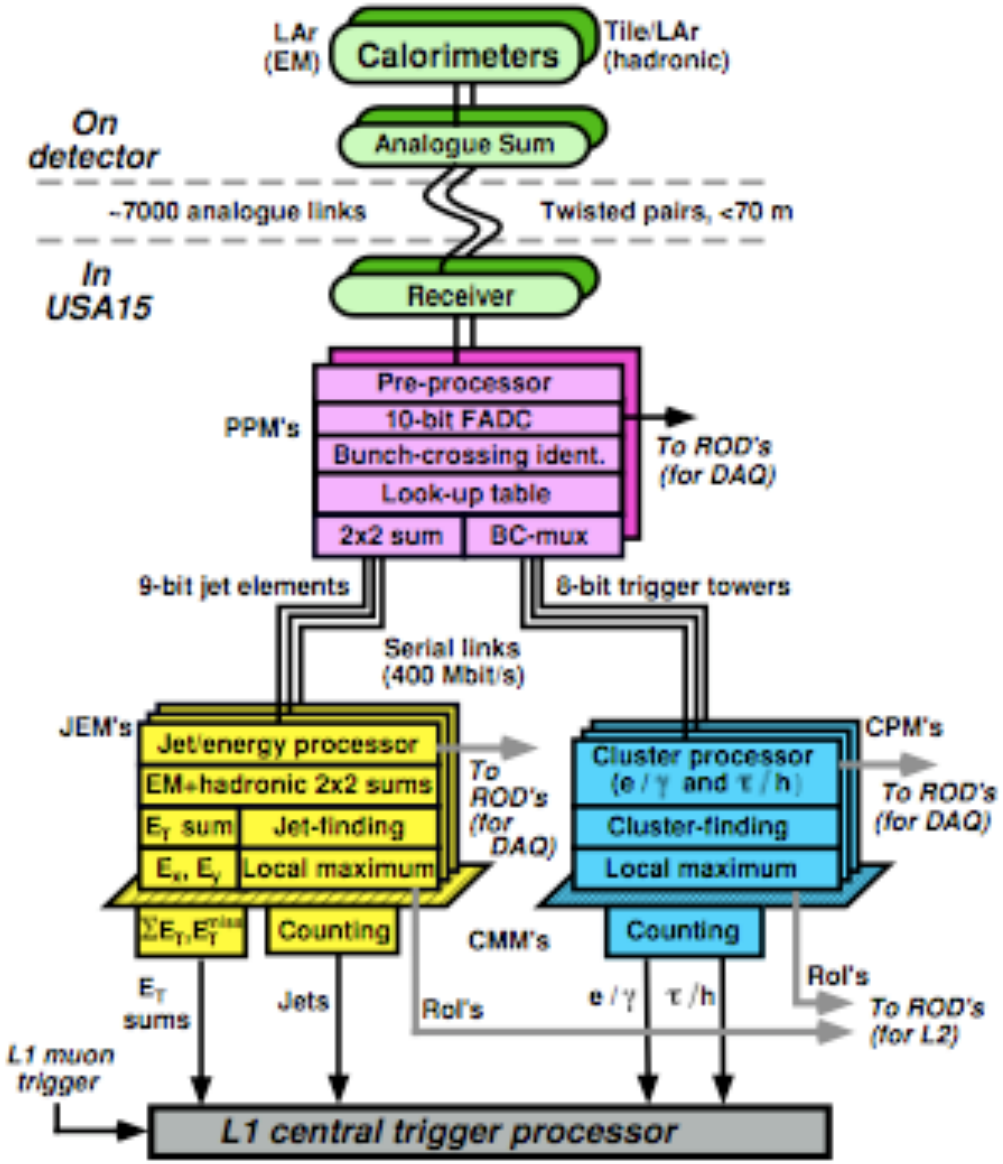
Tau Trigger

- Level 1
  - Hardware calorimeter trigger
  - Limited number of thresholds available
  - Tau energy + eta/phi passed to Level 2 (RoI)
- Level 2
  - Unpacks only the Region of Interest
  - Track and calorimeter variables
- Event Filter
  - Access to full event, but only uses tau RoI
  - Selection similar to offline is available



Level 1 Calo Trigger



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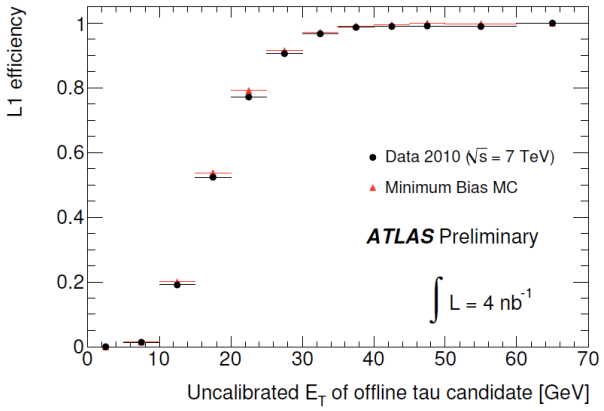
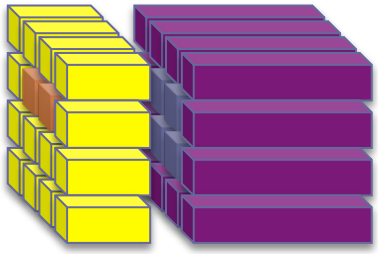
Level 1 Tau Trigger

5 GeV L1 Tau Trigger

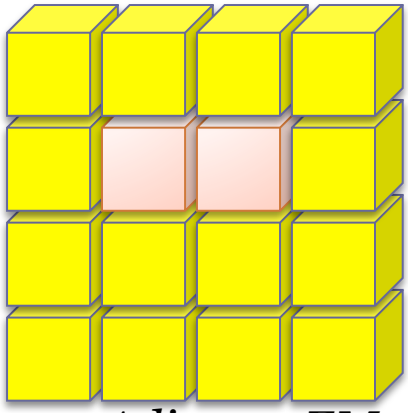


EM Trigger Towers



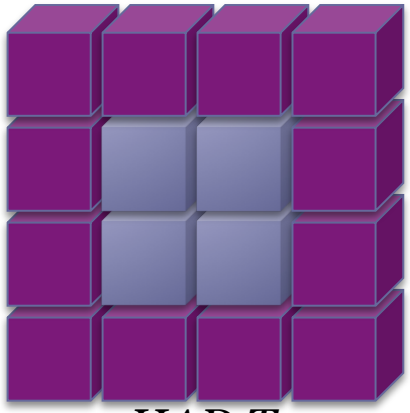
HAD Trigger Towers

Threshold Calculation =



2 Adjacent EM Trigger Towers

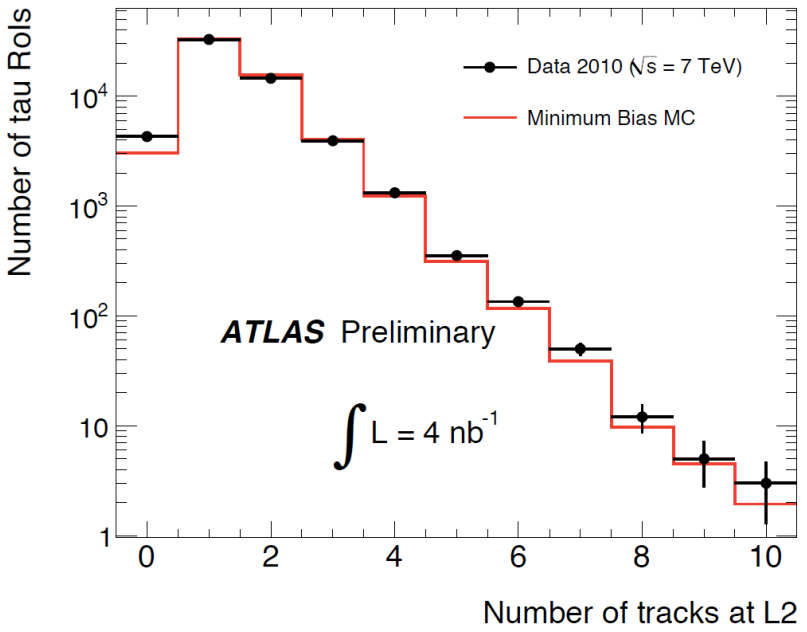
+

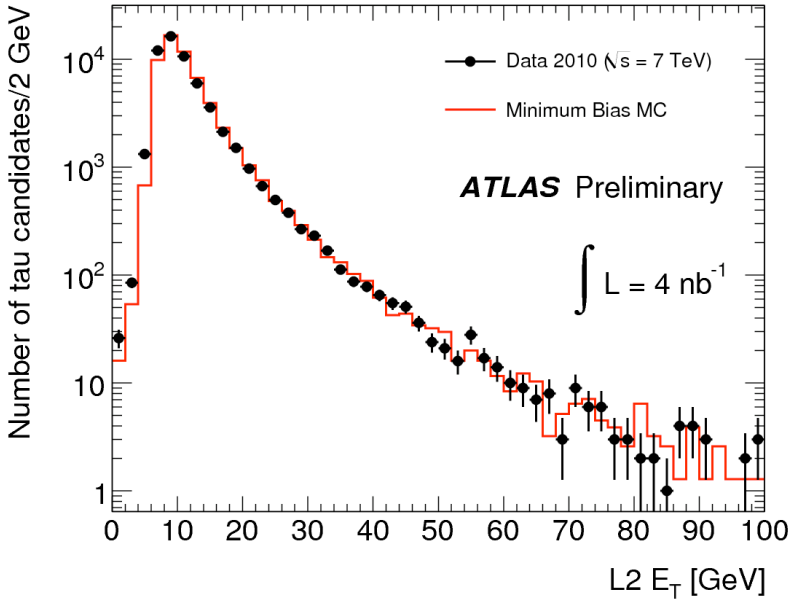


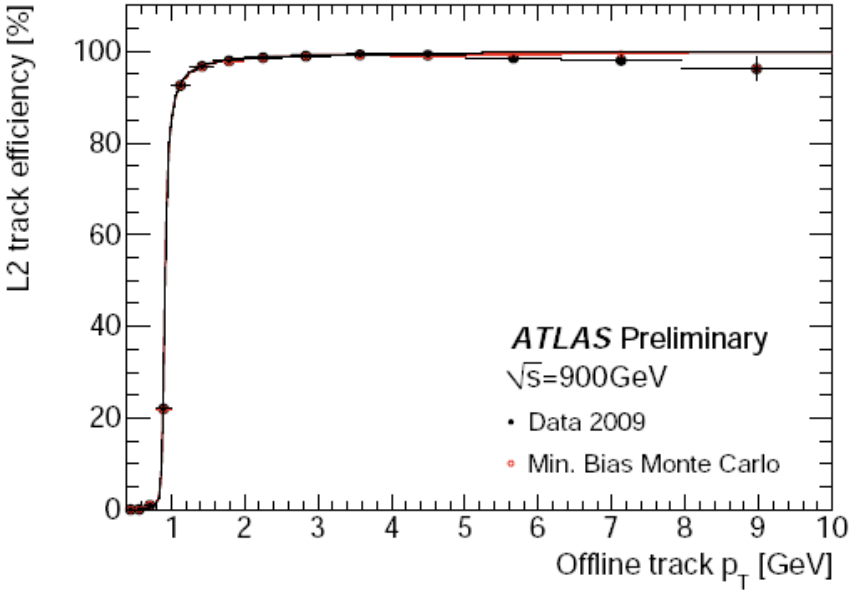
2x2 HAD Towers behind them

Level2 Trigger

- Only access to small fraction of data is available (a few percent) via L1 tau region of interest (RoI)
- Access to full calorimeter granularity is available

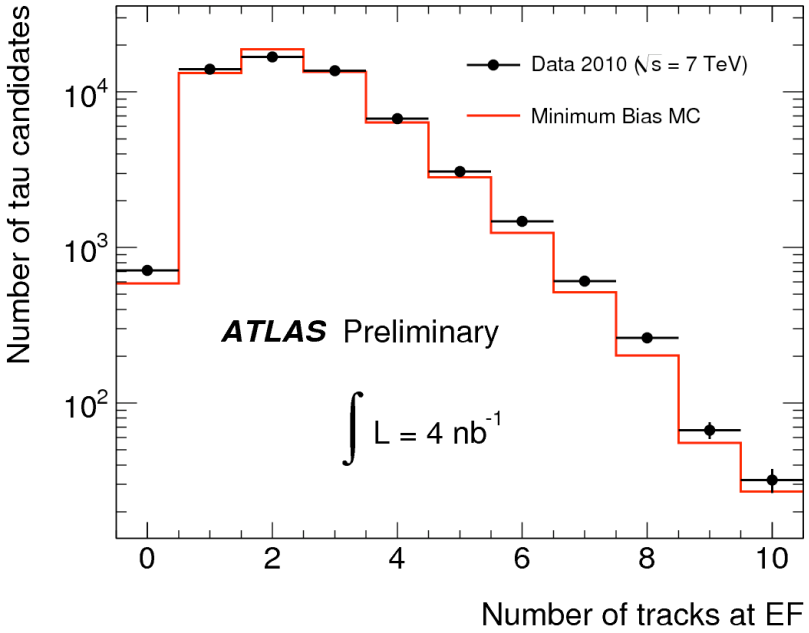


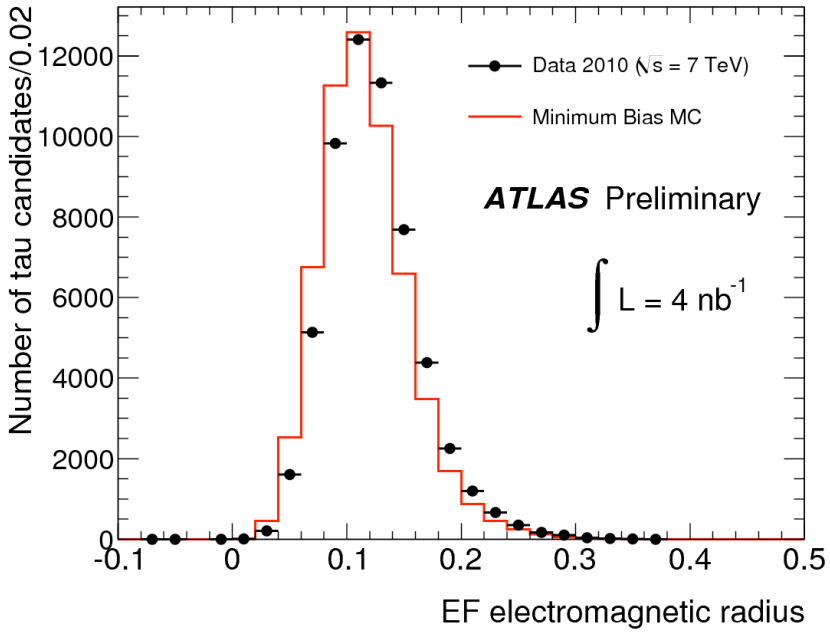




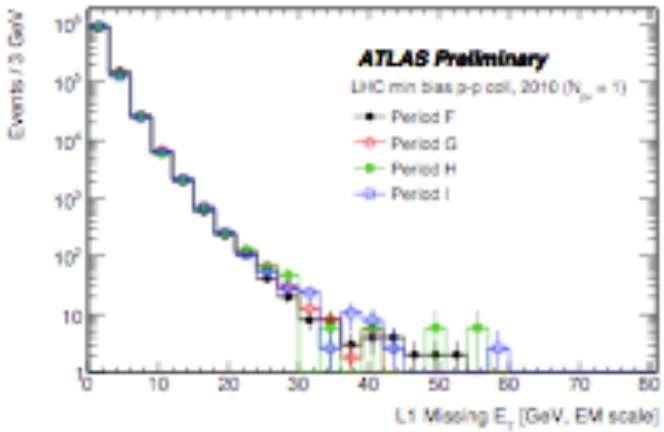
Event Filter (3rd Level Trigger)

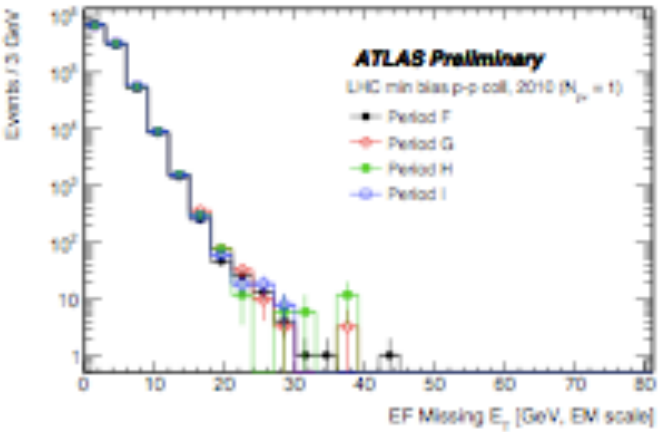
- EF has around 4 seconds per event
- R_{EM} comparison shown below with old MC tune



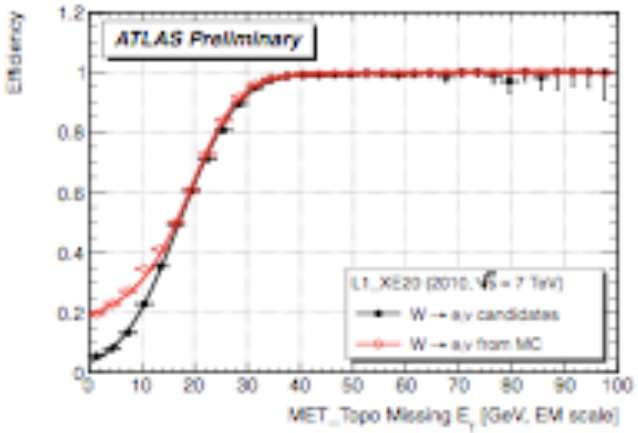


Level 1 Hardware Trigger: Missing E_T

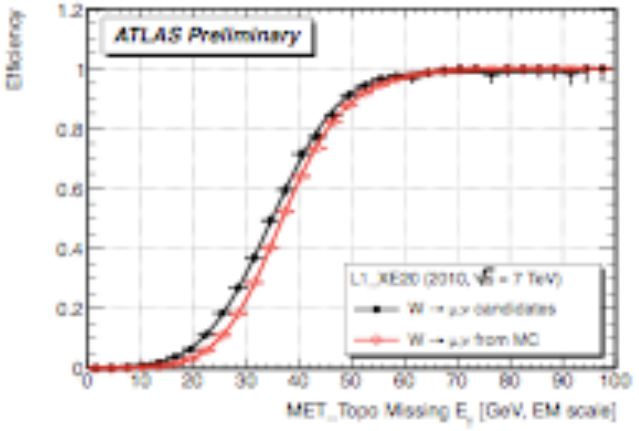




20 GeV Threshold
Efficiency from W->eν events



20 GeV Threshold
Efficiency from W->μν events



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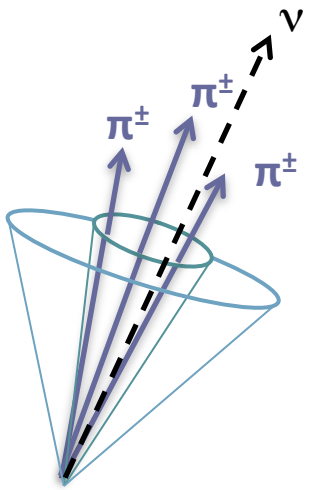
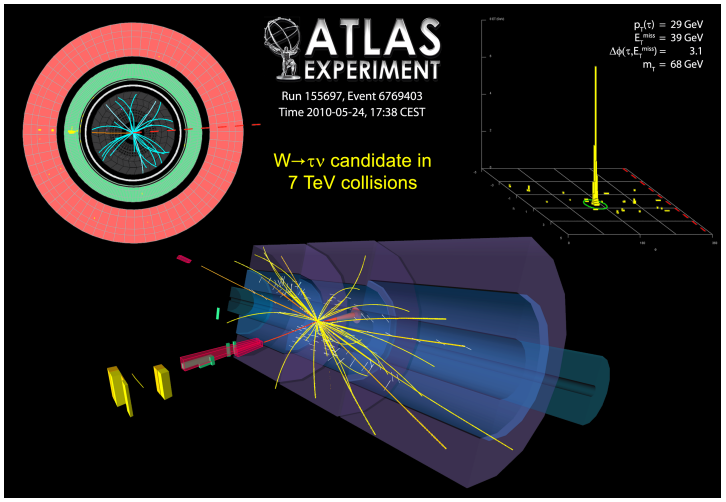


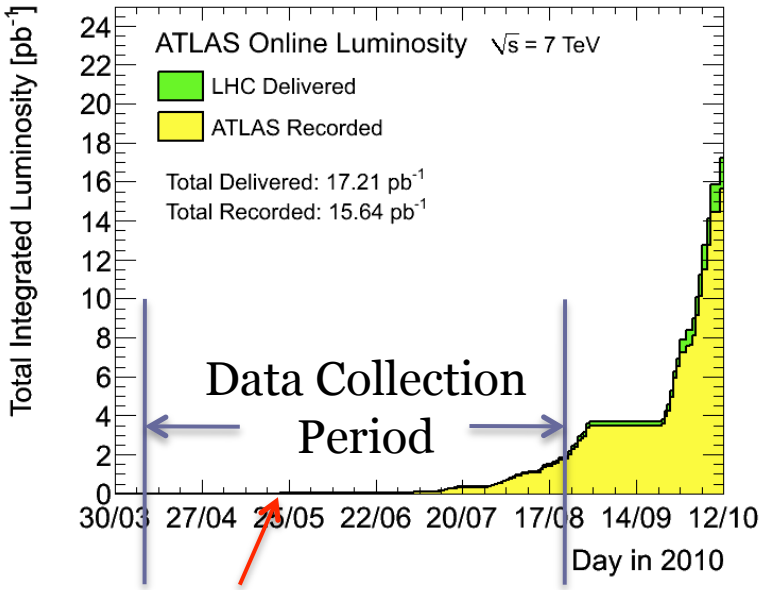
A Few Tau Channels

- **W->τν**
  - Exercise the trigger and early tau ID
- Z->ττ
  - Important benchmark channel
    - Practice for the SM Higgs?
  - Use for efficiency calculations
- H^+->τν
  - Hadronic tau decay mode
- MSSM H->ττ
  - One hadronic, one leptonic tau decay

W->τν

- W-τν Observation approved by ATLAS Collaboration: Nov 2010
- Dataset: 546 nb-1
- 78 events with excellent signal/background ratio

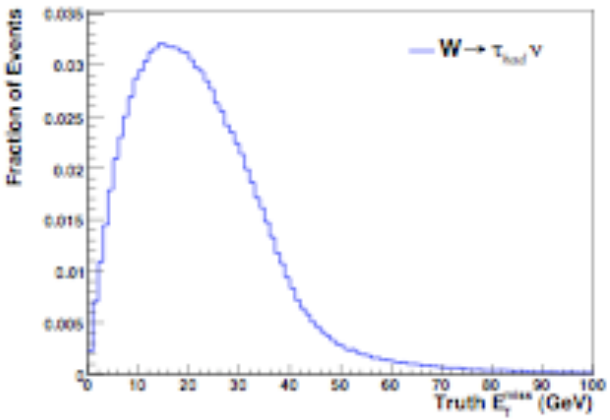


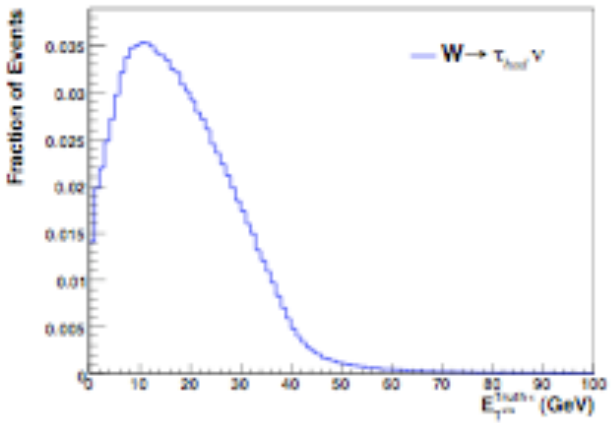


First W->τν candidate event
May 24, 2010

W-> τν

- W->τν production cross section at 7 TeV at NNLO is 10.46 nb
  - About ten times higher than the Z->ττ production
  - Orders of magnitude lower than QCD di-jet production





Relevant Analysis Cuts: Missing E_T > 30 GeV
tau p_T between 20 and 60 GeV

W->τν: Trigger

- There are only two objects in these events that we can use to control the trigger rate:
  - Missing transverse energy
  - Tau transverse energy
- Neither provide dramatic enough rate reduction, so the two need to be used in combination
- Keeping the rate low and measuring the trigger efficiency at the end of the day is challenging!
  - Particularly tricky: correlations between objects

>99% efficient after offline selection

Object	Cut
L1 Missing ET	5 GeV
L1 Tau	5 GeV
L2 Missing ET	5 GeV
L2 Tau (track)	6 GeV
EF Missing ET	15 GeV
EF Tau	-

W->τν: Offline Selection

- Tight Cut-based tau ID (30% efficient)
- Good data quality and cleaning cuts including
  - Primary vertex w/ 4 tracks p_T > 100 MeV
  - Jets cannot point toward Missing E_T
  - Objects cannot point toward overlap calo region (crack)
- Missing E_T > 30 GeV
- 20 GeV > tau candidate > 60 GeV
- Electron veto (loose electrons)
- Muon veto (combined muons)
- Missing ET significance > 6

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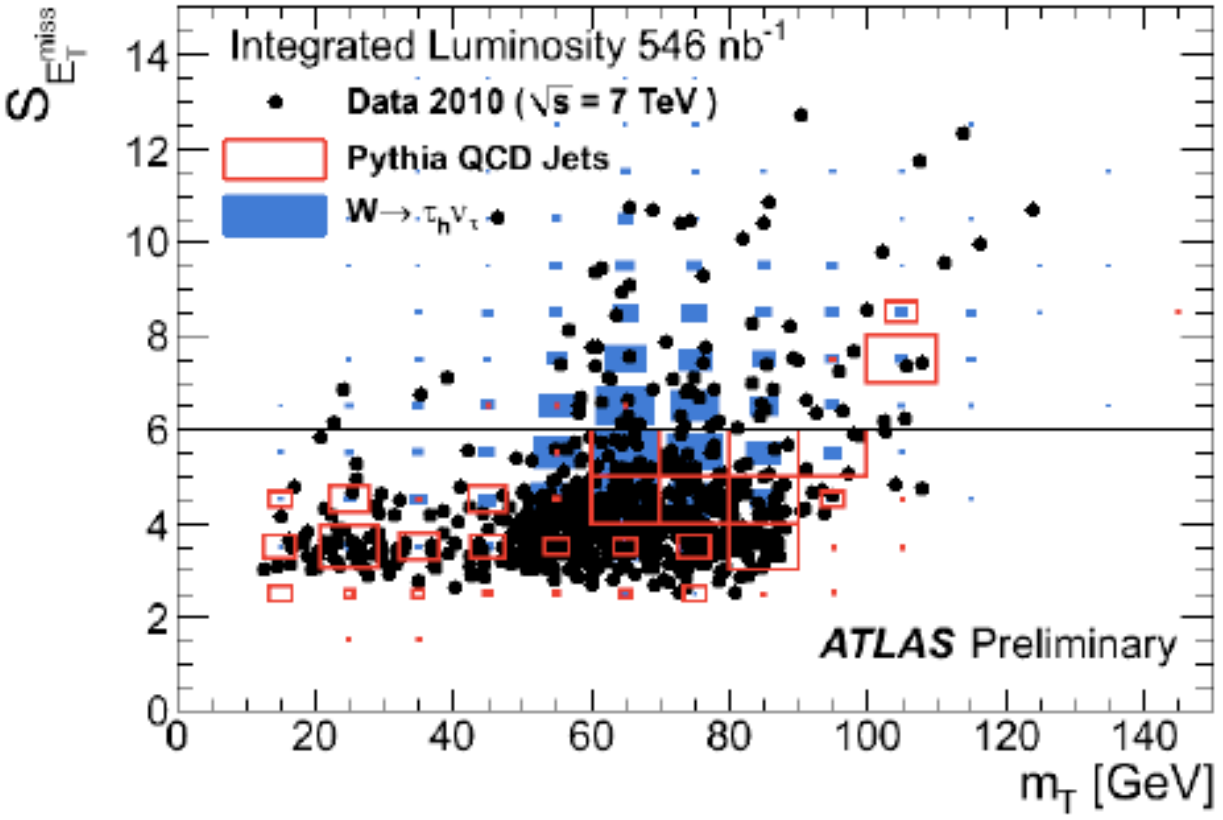
Missing E_T Significance

$$S_{E_T^{miss}} = \frac{E_T^{miss}}{0.5 \cdot \sqrt{\sum E_T}}$$



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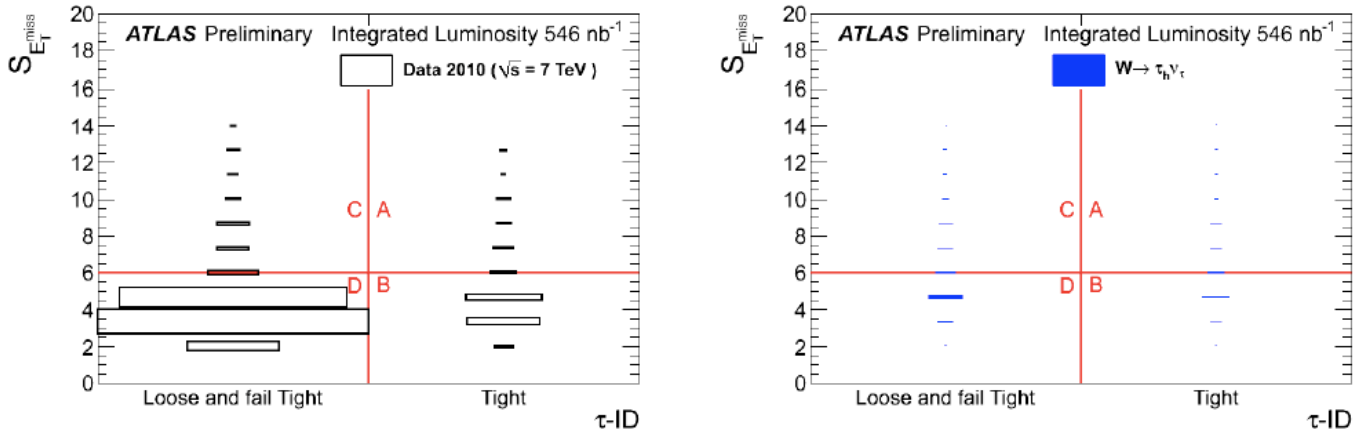
W->τν: Summary

	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



Estimated 11 QCD events in signal region (A)

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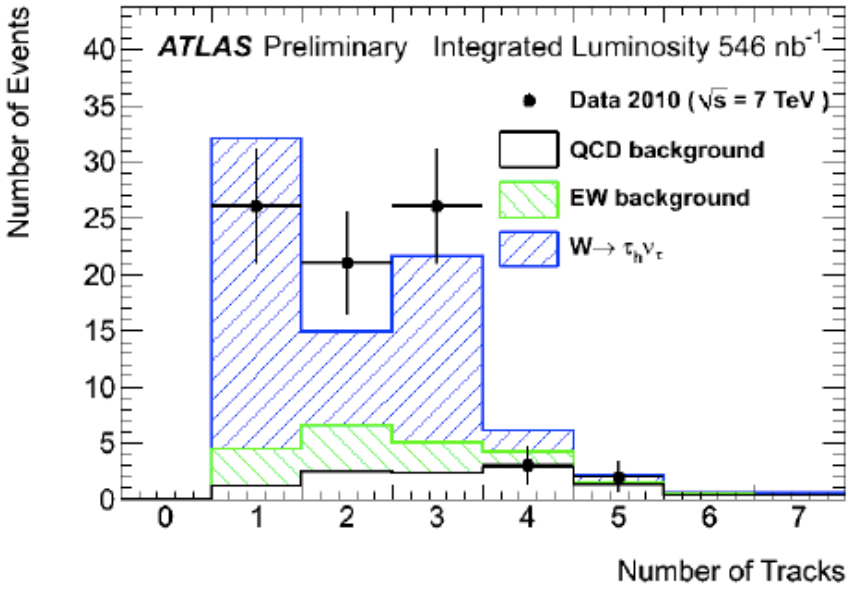
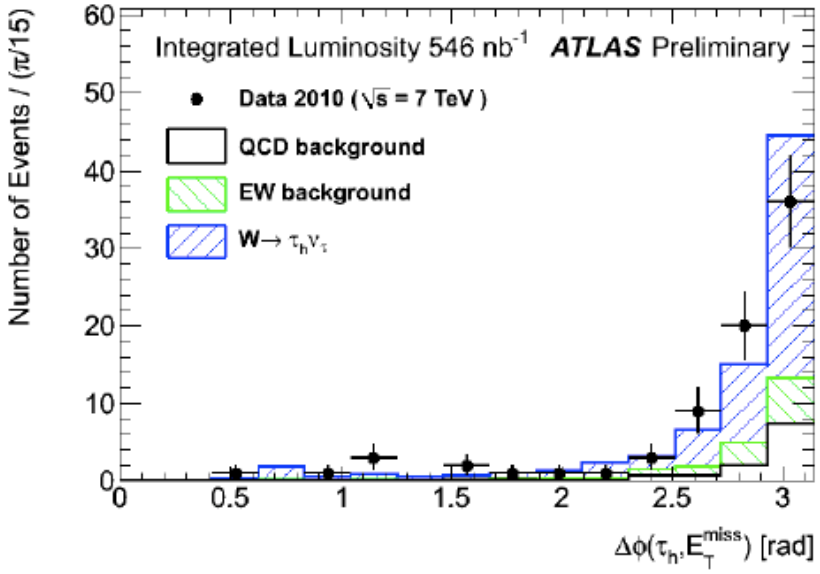
W->τν





A Few Tau Channels

- W->τν
  - Exercise the trigger and early tau ID
- **Z->ττ**
  - Important benchmark channel
    - Practice for the SM Higgs?
  - Use for efficiency calculations
- H^+->τν
  - Hadronic tau decay mode
- MSSM H->ττ
  - One hadronic, one leptonic tau decay

Z->ττ

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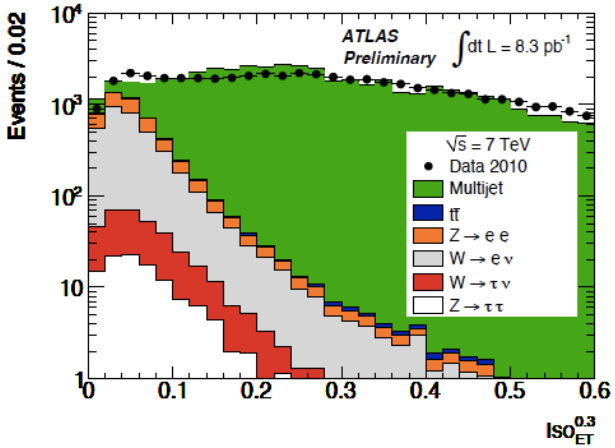
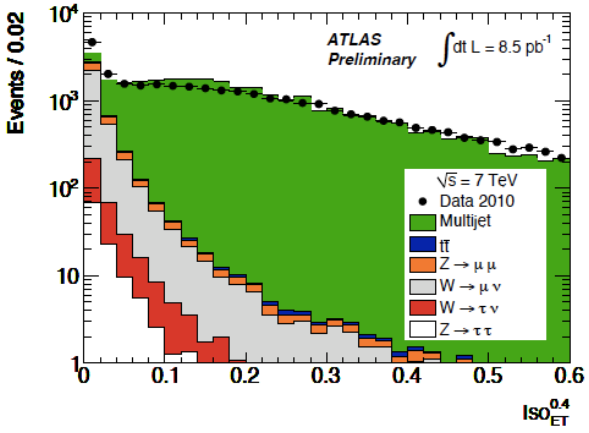
- Electron Channel: 8.3 pb^{-1}
- Trigger: 15 GeV electron (EF)
- Event Selection
  - 15 GeV tight electron
  - Track Isolation
    - Ratio in cone 0.4: <0.06
  - Calorimeter Isolation
    - Energy in annulus from 0.05 to 0.3 less than 0.1 GeV

- Muon Channel: 8.5 pb^{-1}
- Trigger: 10 GeV muon (EF)
- Event Selection
  - 15 GeV combined muon
  - Track Isolation
    - Ratio in cone 0.4: <0.06
  - Calorimeter Isolation
    - Energy in annulus from 0.05 to 0.4 less than 0.06 GeV





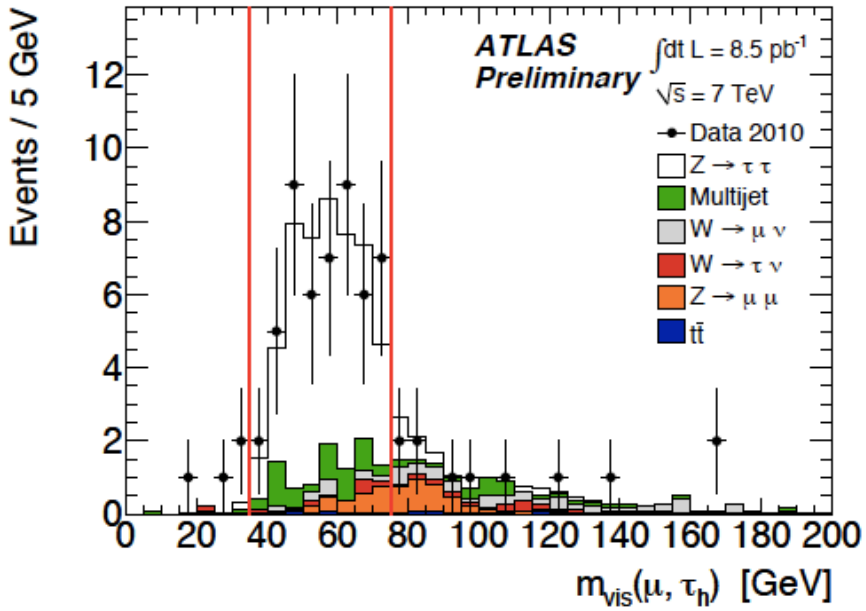
Z->ττ: Further event Selection

- Dilepton Veto
- W+jets reduction
- Visible mass between 35 and 75 GeV
- Opposite sign lepton and tau

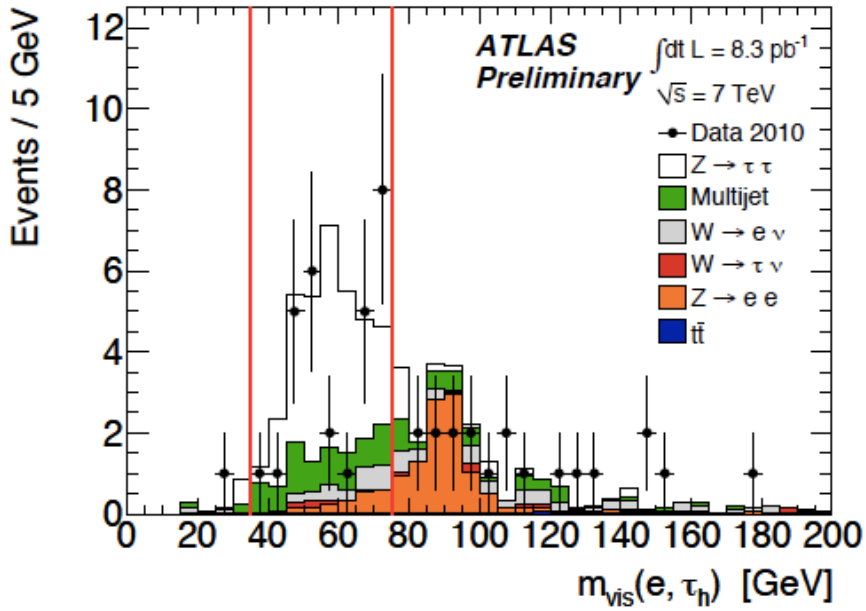
	Muon Channel (8.5 pb^{-1})	Electron Channel (8.3 pb^{-1})
Data (after all selections)	51	29
Total Estimated Background	9.9 ± 2.1	11.8 ± 1.7
Estimated Multijet Background	*5.2 ± 0.7(stat.) $\pm$ 0.7 (syst.)*	*6.8 ± 0.6(stat.) $\pm$ 0.7 (syst.)*
Estimated W, Z, $t\bar{t}$ Background	*4.7 ± 0.5(stat.) $\pm$ 1.5(syst.)*	*5.0 ± 0.6 (stat.) $\pm$ 1.4(syst.)*
Data (after background subtraction)	41.1 ± 7.1(stat.) $\pm$ 2.1(bkg. est.)	17.2 ± 5.4(stat.) $\pm$ 1.7(bkg. est.)
SM Signal Expectation	39.9 ± 1.8(stat.) $\pm$ 6.7(syst.)	24.5 ± 1.4(stat.) $\pm$ 7.9(syst.)

Z->ττ Visible Mass

Muon Channel



Electron Channel



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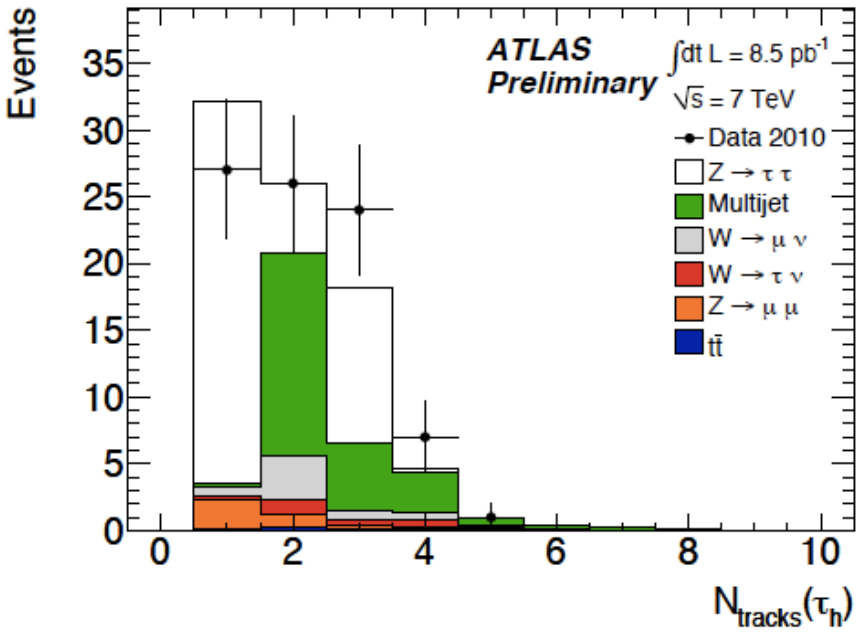
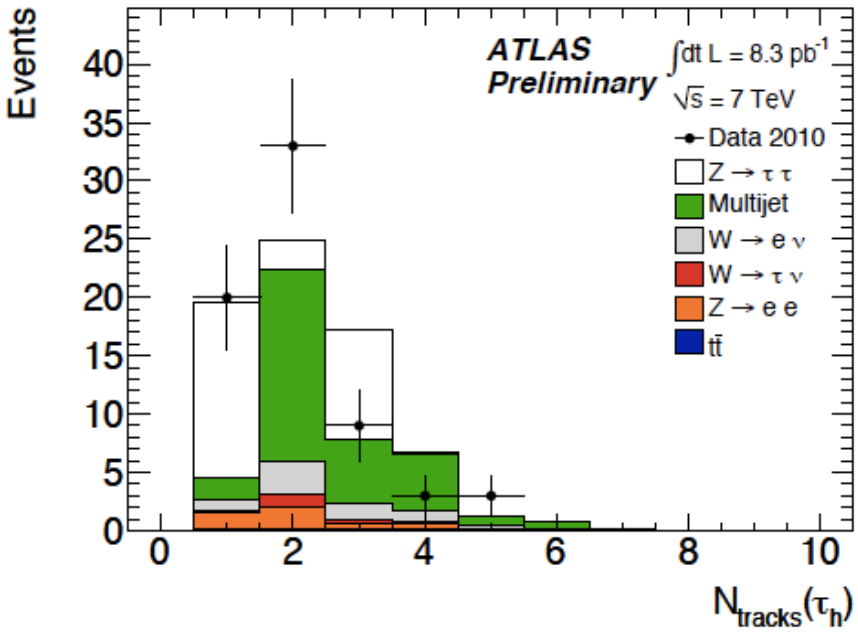
Z->ττ Track Multiplicity

Muon Channel



Electron Channel



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  - Exercise the trigger and early tau ID
- Z->ττ
  - Important benchmark channel
    - Practice for the SM Higgs?
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- **H^+->τν**
  - Hadronic tau decay mode
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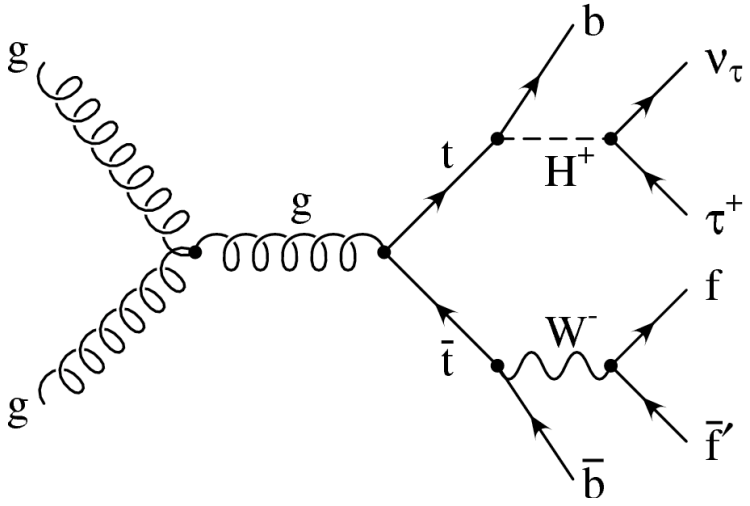
$H^+ \rightarrow \tau\nu$

Data-driven estimation of the background to charged Higgs boson searches using hadronically-decaying tau final states in ATLAS



$H^+ \rightarrow \tau\nu$

- Event selection:
  - 1 lepton (trigger-matched)
  - 1 τ jet with pT>20 GeV (opposite charge to lepton)
  - >= 2 jets, at least one of them b-tagged
  - E_T(sum)>200 GeV
  - E_T(miss)>200 GeV

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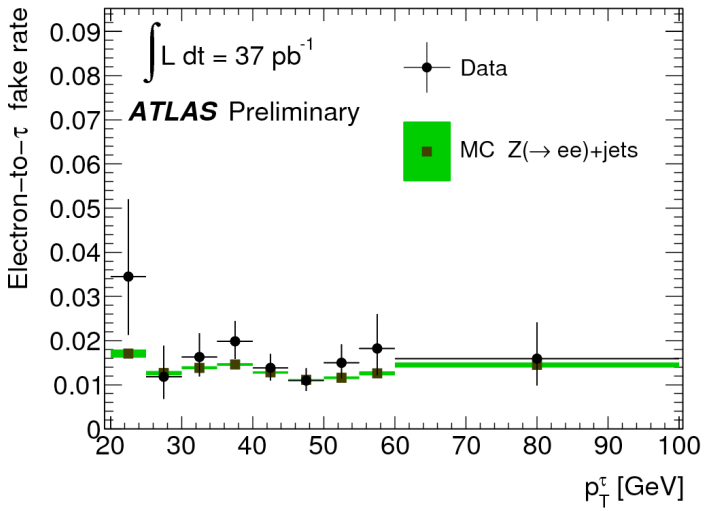
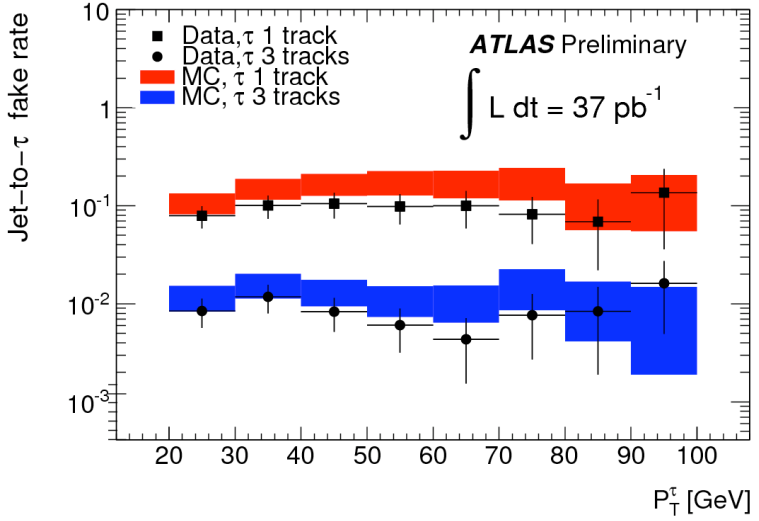
$H^+ \to \tau\nu$: Fake tau background

- Estimate of electron to tau fakes from Z->ee events
- Estimate of jet to tau fakes from γ+jet events





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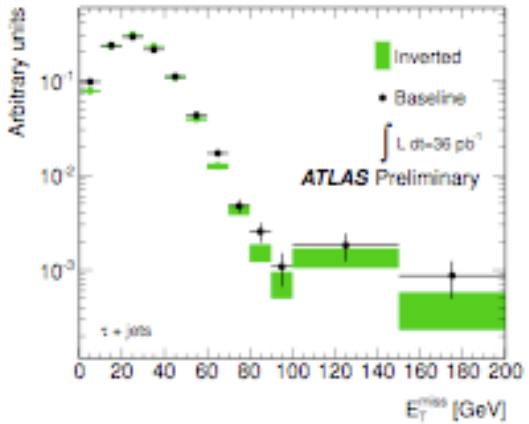
$H^+ \to \tau\nu$: QCD Background

- Assume the shape of the missing ET is the same in the signal region as it is in the "inverted" region
  - Require a loose tau, reject tight taus



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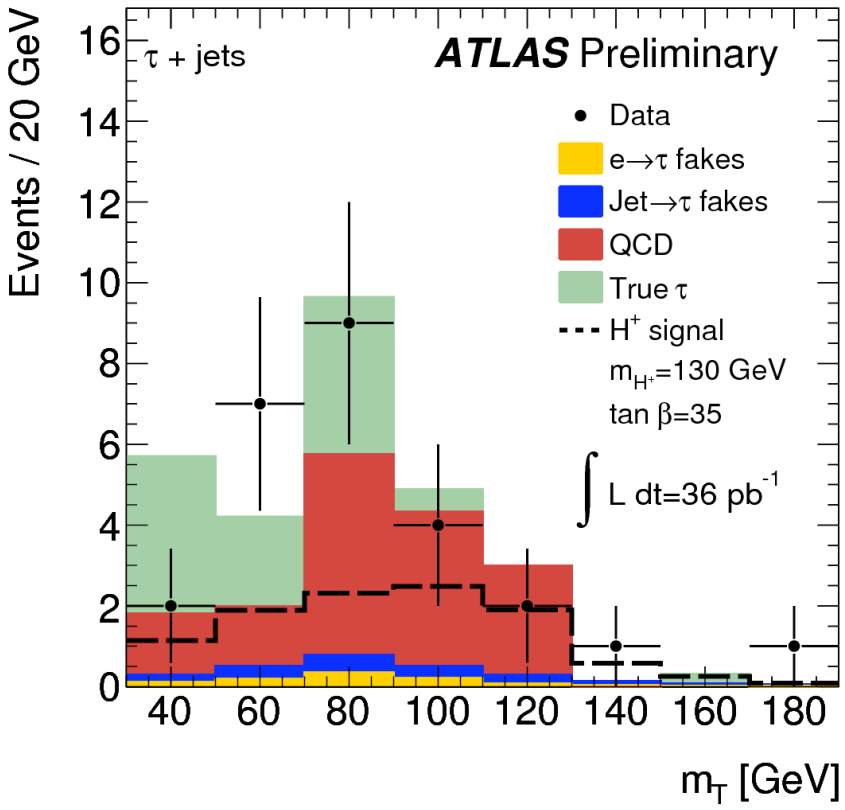
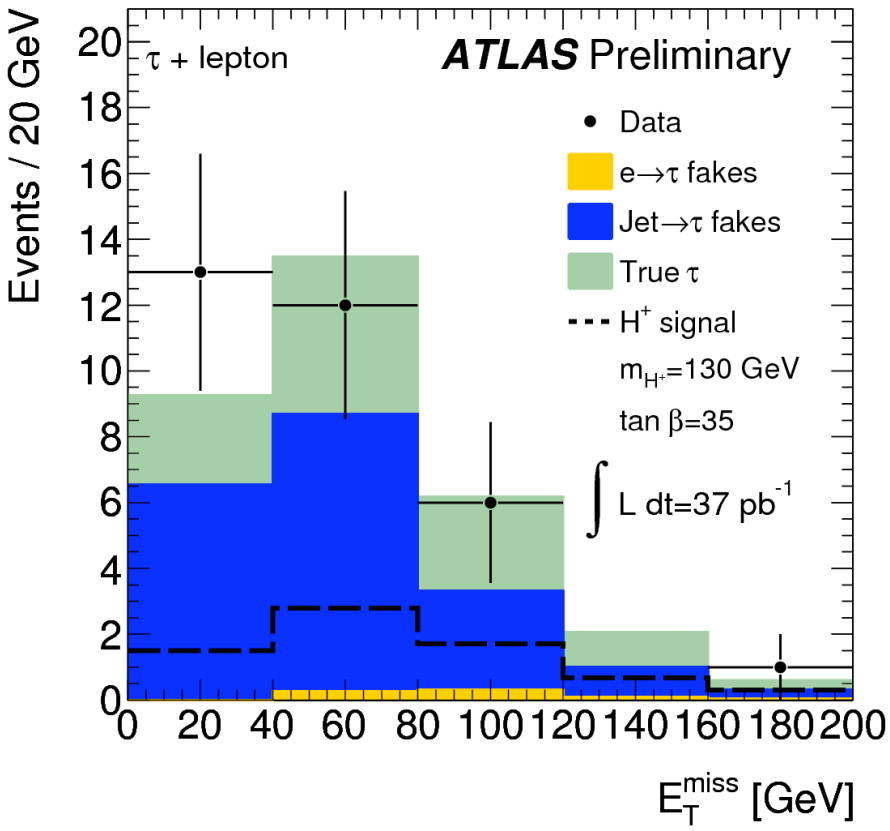
$H^+ \rightarrow \tau\nu$





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  - Use for efficiency calculations
- H^+->τν
  - Hadronic tau decay mode
- **MSSM H->ττ**
  - One hadronic, one leptonic tau decay

MSSM H->ττ

- Trigger:
  - Electron > 10 – 15 GeV (depending on inst lumi)
  - Muon > 10 – 13 GeV
- One lepton
  - Electron > 20 GeV
  - Muon > 15 GeV
- Hadronic tau p_T > 20 GeV
- Opposite sign lepton and tau
- Missing E_T > 20 GeV
- Transverse mass of lepton + MET < 30 GeV

MSSM H-> ττ

- QCD + W+Jets Background determination
  - Assume the shape of the visible mass (tt) spectrum is the same for SS and OS events
  - The ratio of SS to OS events is the same in the signal region as it is in a QCD-enhanced BG region

$$n_{\mathrm{OS}}^{Bkg}(m_{\mathrm{vis}}) = r_{\mathrm{QCD}} \cdot n_{\mathrm{SS}}^{\mathrm{QCD}}(m_{\mathrm{vis}}) + r_{W+\mathrm{jets}} \cdot n_{\mathrm{SS}}^{W+\mathrm{jets}}(m_{\mathrm{vis}}) + n_{\mathrm{OS}}^{Z+\mathrm{jets}}(m_{\mathrm{vis}}) + n_{\mathrm{OS}}^{\mathrm{other}}(m_{\mathrm{vis}})$$

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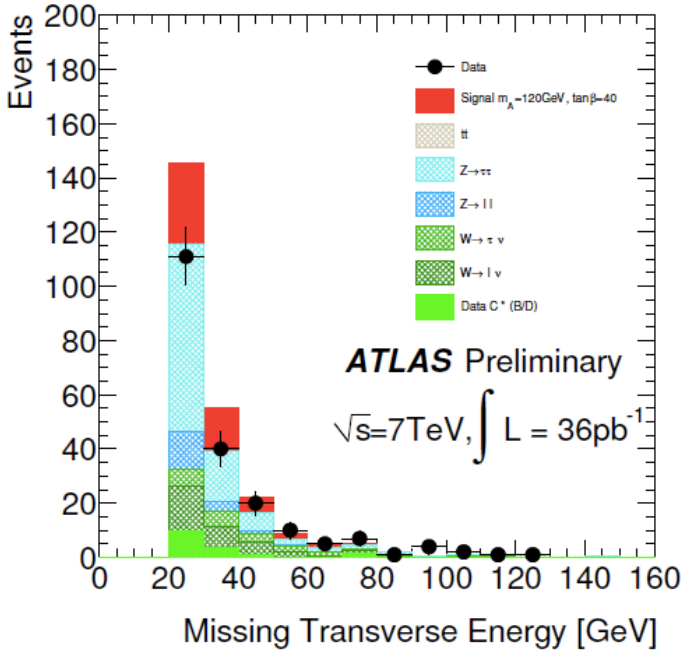
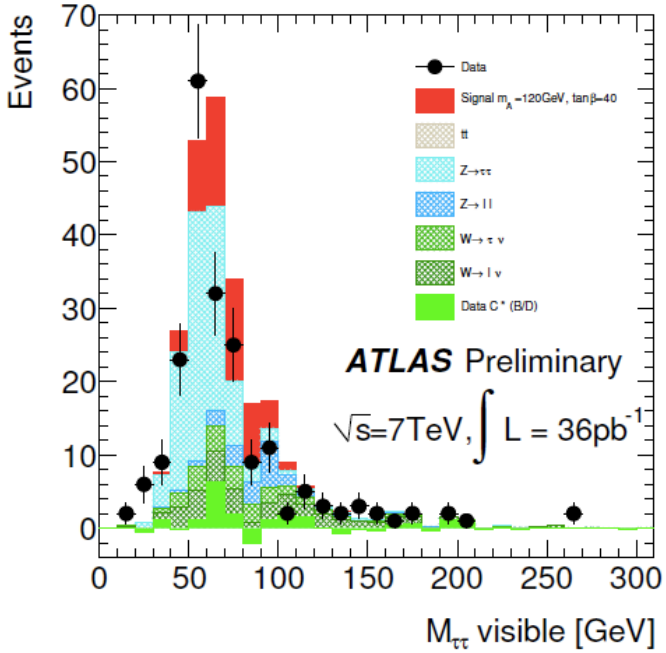
MSSM H-> ττ

- Alternate QCD Background determination

	Isolation	Inverted Isolation
OS	Signal region A	Control region B
SS	Control region C	Conrol region D

$$n_A^{QCD} = r_{B/D} \times (n_C^{data} - n_C^{non-QCD}) = 12.1 \pm 7.1$$





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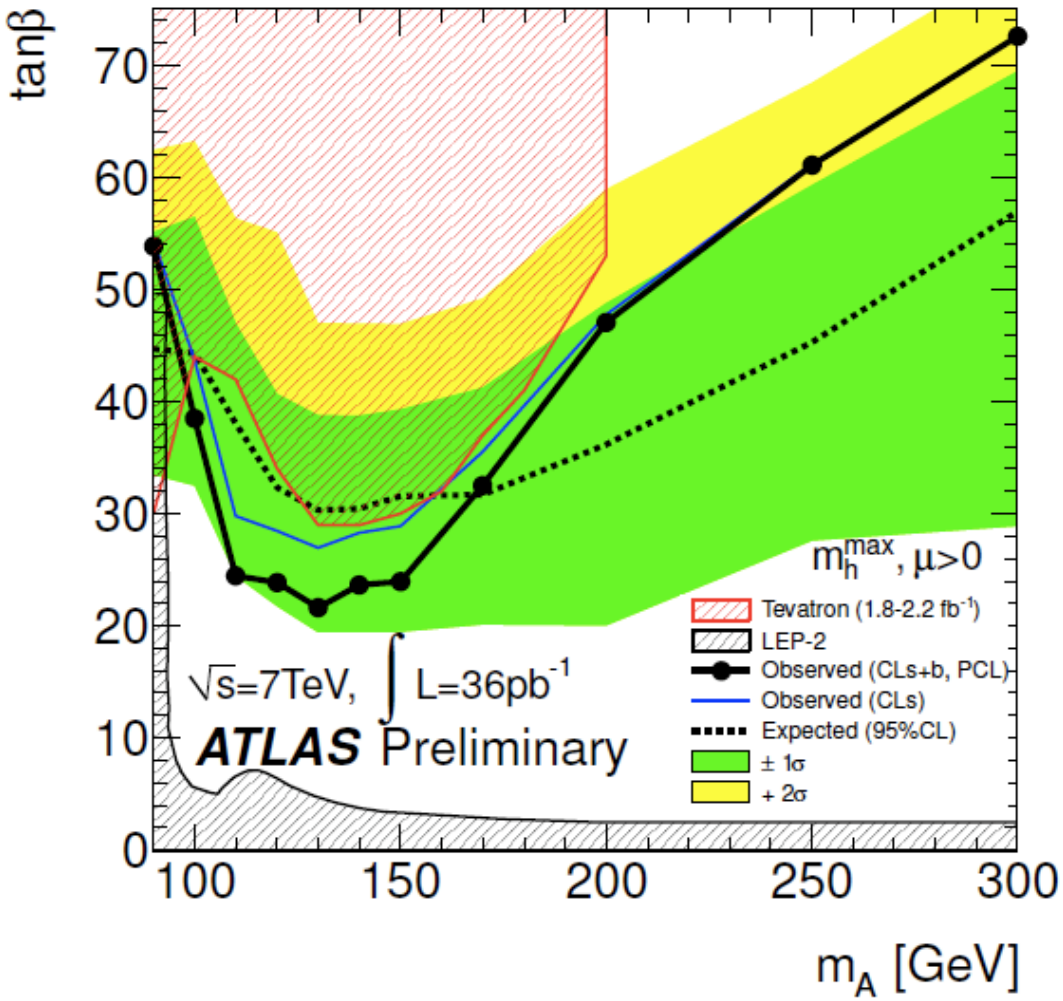
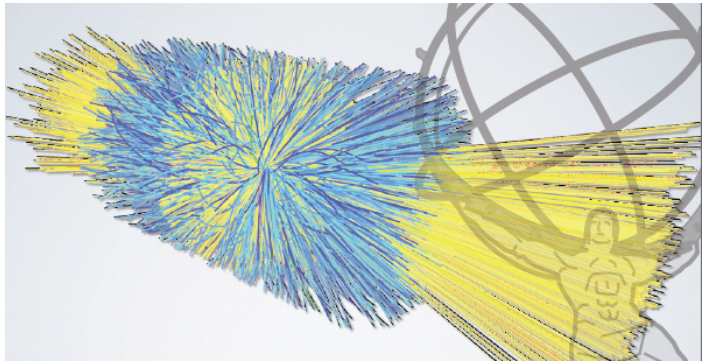
MSSM H -> ττ





Future Plans

- Phase I possibilities
  - Topology information in the trigger at Level 1?
  - New small FCAL?
- Phase II possibilities
  - New Inner Detector
  - Digital Calorimeter Readout (increased granularity for trigger as well)
  - Track trigger
    - RoI based or self-seeded?
    - maybe with a Level 0 + Level1?
- Simulation studies are ongoing to understand the physics requirements under shifting detector conditions
  - Peak luminosity of 5E34?
  - 50 ns bunch spacing?

Back-up

Event Selection for tau ID variable Data-MC Comparisons

- The leading tau in the event is not included, to remove trigger bias

- the Level 1 trigger requiring a τ trigger object passing a 5 GeV threshold [3] is satisfied,
- there are no "bad" jets in the event [4] caused by out-of-time cosmic events or sporadic noise effects in the calorimeters,
- at least one vertex reconstructed with more than four tracks is present,
- at least one τ candidate with $p_{\mathrm{T}} > 30$ GeV (fully calibrated, as described in Section 3) and $|\eta| < 2.5$, as well as another τ candidate with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$ (also fully calibrated). The two candidates are required to be separated by at least 2.7 radians in azimuth (the angle in the plane transverse to the beam pipe).

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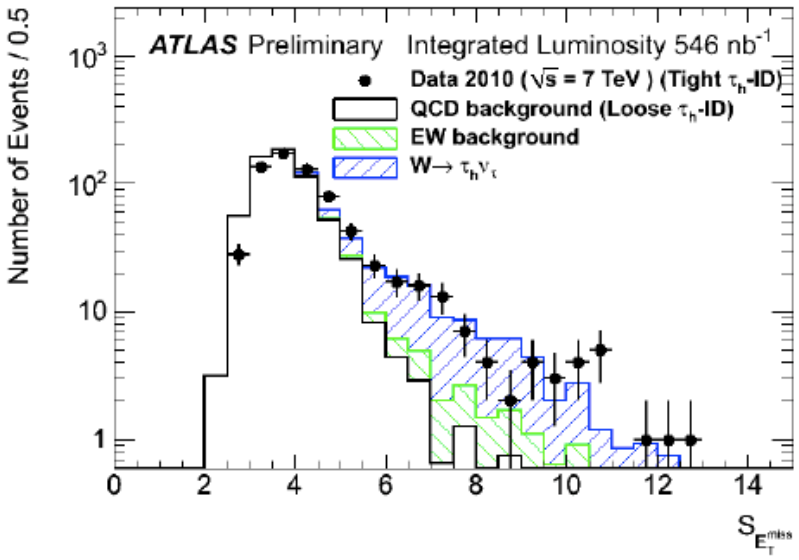
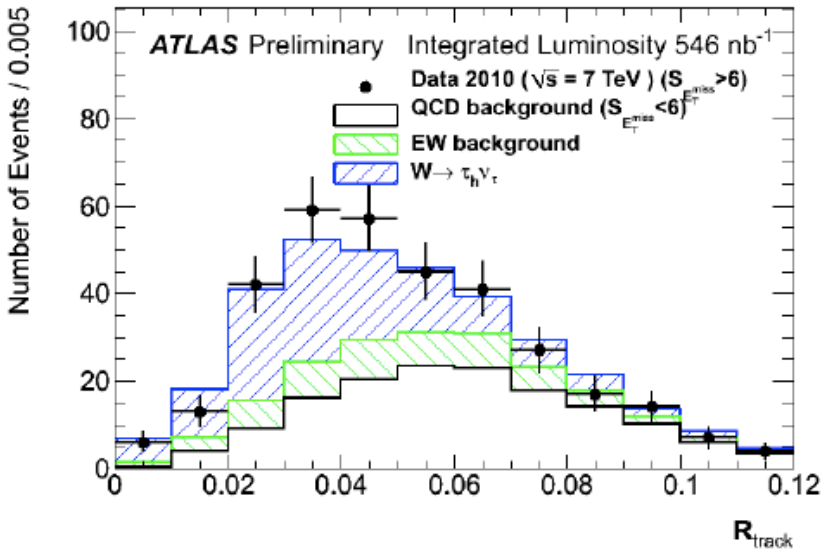
W->τν





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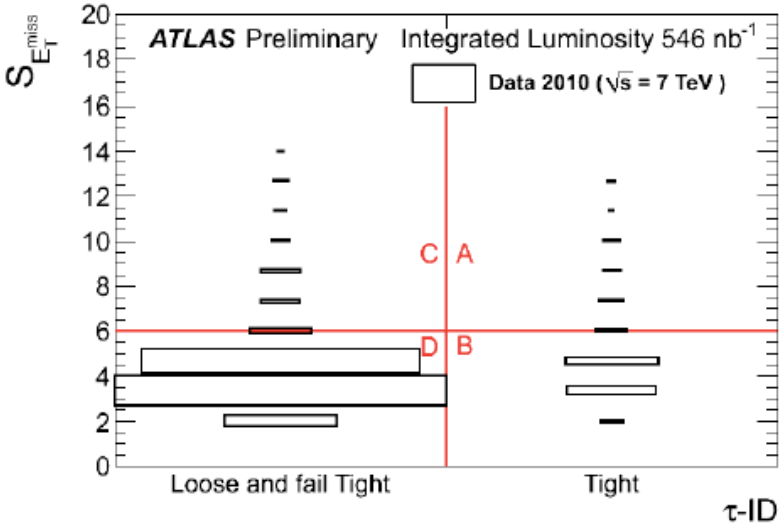
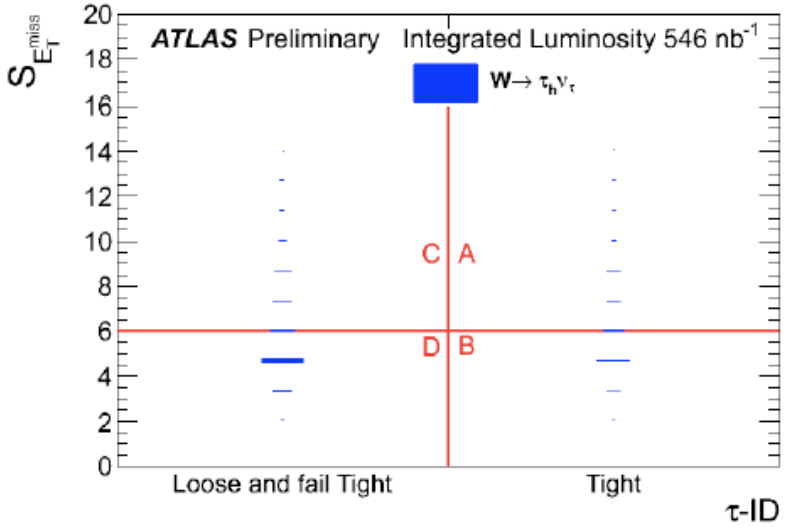
W->τν: Estimating QCD Background from Data

$$N^{A}_{QCD} = N^{B}N^{C}/N^{D}$$





$$c_i = \frac{N^{i}_{sig} + N^{i}_{EW}}{N^{A}_{sig} + N^{A}_{EW}}, \qquad i = B, C, D$$

Region	A	B	C	D
Data	78	607	254	7107
$W \rightarrow \tau_h \nu_\tau$	55.3±1.4	39.5±1.2	71.0±1.6	54.2±1.4
EW	11.8±0.4	6.5±0.2	44.5±0.7	22.1±0.5
c_i		0.69±0.02	1.72±0.05	1.14±0.03

W->τν: (Correct for Non-QCD in Control Regions)

$$N^{A}_{QCD} = (N^{B} - c_{B}(N^{A} - N^{A}_{QCD}))\frac{N^{C} - c_{C}(N^{A} - N^{A}_{QCD})}{N^{D} - c_{D}(N^{A} - N^{A}_{QCD})}$$

Estimated 11 QCD events in signal region (A)

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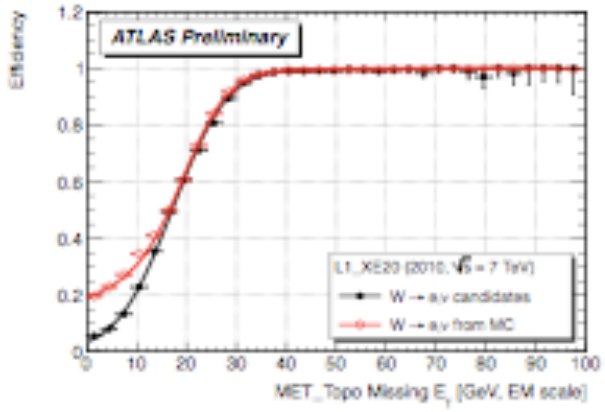
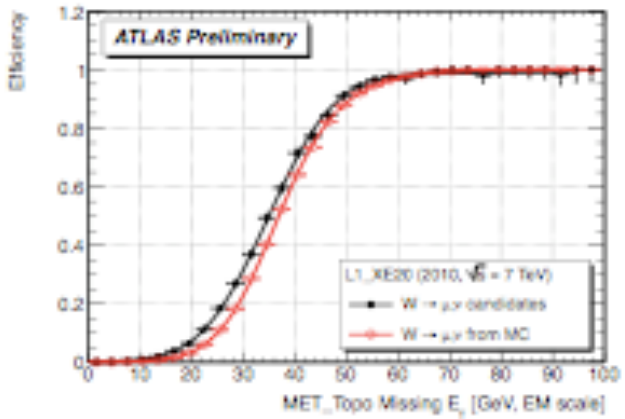
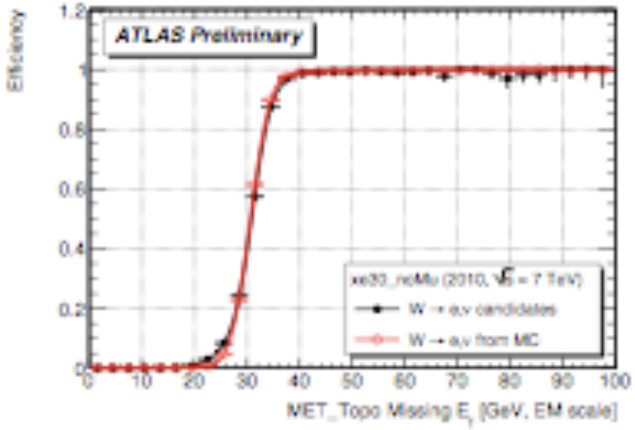
Trigger Summary

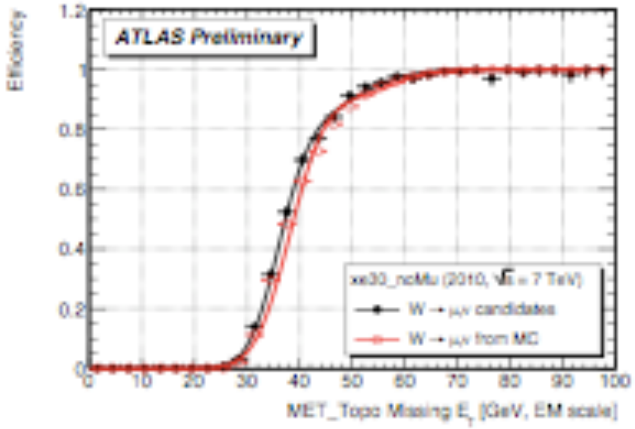
L1 20 GeV threshold efficiency from W->eν (top) W->μν (bottom) events





Event Filter Missing ET turn-on curves – very sharp!





Z->ττ Systematics

Systematic	Uncertainty	Multijets	W+jets	Z & $t\bar{t}$	$Z \to \tau\tau$
μ efficiency	2.7%	±0.03*	-	±0.07	±1.1
μ trigger efficiency	2.0%	±0.01*	-	±0.05	±0.8
μ isolation	1.6%	±0.01*	-	±0.04	±0.7
Jet τ fake rate	50%	±0.17*	-	±1.34	-
Energy scale	13% ($W \to \mu\nu$) / 16% ($W \to \tau\nu$)	±0.26*	±0.28	±0.40	±2.4
	6% (signal) / 13% (Z) / 21% ($t\bar{t}$)				
Pile-up re-weighting	0.5% (signal) / 0.58% ($t\bar{t}$)	±0.01*	-	±0.10	±0.2
	3.9% (Z)				
MC underlying event model	7%	±0.04*	-	-	±2.8
MC showering model	6%	±0.04*	-	-	±2.4
Luminosity	11%	±0.07*	-	±0.30	±4.4
Theoretical cross section	5% (Z)	±0.03*	-	±0.12	±2.0
	6% ($t\bar{t}$)	±0.01*	-	±0.02	-
W rescaling factor	8.8% in A, B	±0.04*	±0.17	-	-
	2.1% in C, D	-	-	-	-
Multijet est. (bkg subtraction)	-	±0.34	-	-	-
Multijet est. (method systematics)	-	±0.56	-	-	-
Total systematics	-	±0.66	±0.33	±1.44	±6.7

Z->tt W+Jets Reduction

- Angular, sum > -0.15:

$$\sum \cos\Delta\phi = \cos\left(\phi(\ell) - \phi(E_{\mathrm{T}}^{\mathrm{miss}})\right) + \cos\left(\phi(\tau_{\mathrm{h}}) - \phi(E_{\mathrm{T}}^{\mathrm{miss}})\right)$$

- Transverse Mass < 50 GeV:

$$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) = \sqrt{2\, p_{\mathrm{T}}(\ell) \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}}))}$$