Observation of W and Z Boson Production at 7 TeV with the ATLAS Experiment

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Physics at LHC

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The rediscovery of the W/Z Bosons

@ 7 TeV

$$\sigma^{\mathrm{NNLO}}_{\mathbf{W}\to\ell\nu} = \mathbf{10.45}\ \mathrm{nb} \qquad \sigma^{\mathrm{NNLO}}_{\mathbf{Z}/\gamma^*\to\ell\ell} = \mathbf{0.989}\ \mathrm{nb}$$

FEWZ, MSTW2008

~3% uncertainty

- Goals:
  - Detector commissioning and explore its capabilities
  - Establish analysis for $\sigma_{W,Z}$ measurement at 7 TeV
    - Stringent test of QCD
    - Constraints parton distribution functions
  - First step towards possible discoveries in high-p_T physics

$pp \to W + X$

- $e\,\nu$
- $\mu\,\nu$

$pp \to Z + X$

- ee
- $\mu\,\mu$

Data Sample

- Data Collected from March to May 2010

$\mathcal{L}$	Channel	
	Electron	Muon
W	6.7 nb^{-1}	6.4 nb^{-1}
Z	6.7 nb^{-1}	7.9 nb^{-1}

Luminosity uncertainty: 20%

Stable beams
Good quality data

Z →μμ analysis does not require calorimeters

Level 1 Hardware triggers

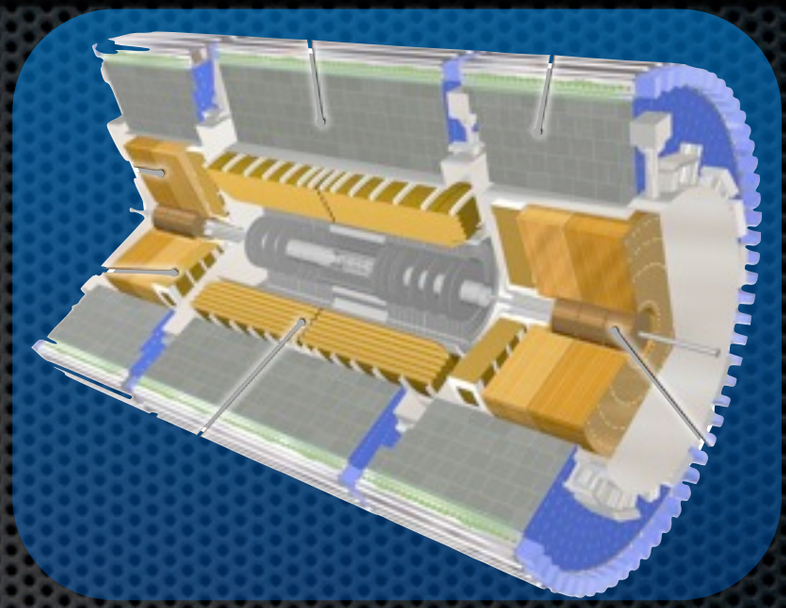
		Number of events
Electron	EM calorimeter (threshold ~ 2 GeV), $\|\eta\| < 2.5$	1.2×10^7
Muon	Open road - no p_T requirement, $\|\eta\| < 2.4$	2.8×10^5

- Monte carlo samples:
  - Pythia 6.4, MRST LO pdfs, GEANT 4
  - Signal: corrected to NNLO cross section
  - Background: measured in data or normalized to σ (details later)

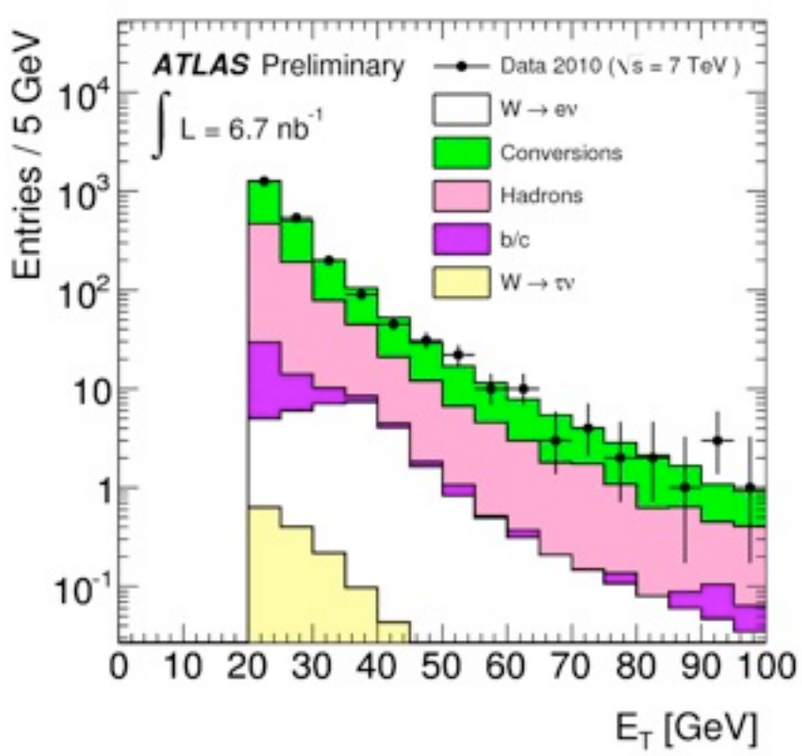
Electron Preselection

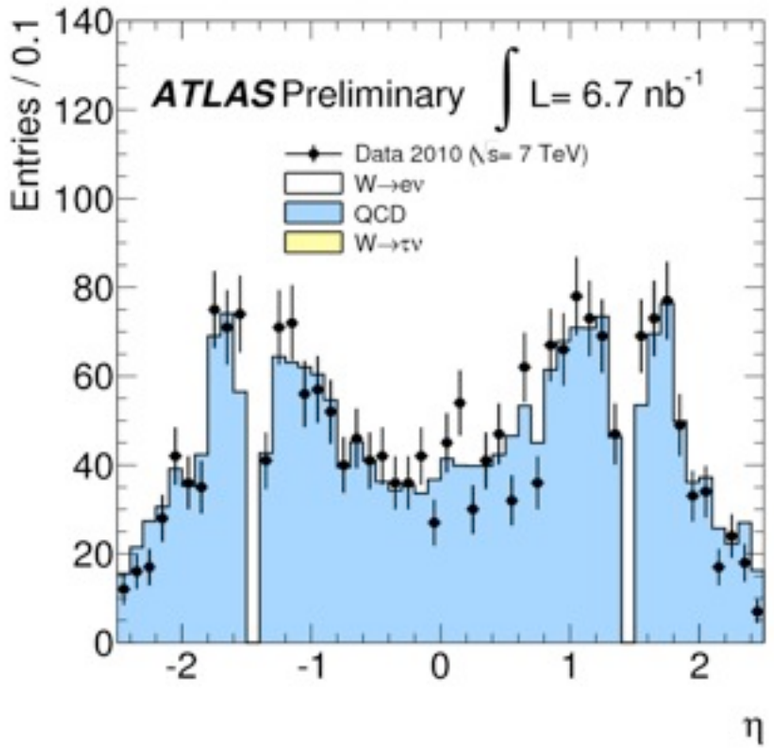
- One PV with ≥ 3 tracks
- At least one Loose Electron
  - Cluster-E_T > 20 GeV, $|\eta|$ < 2.47
  - Excluding region
    - 1.37 < $|\eta|$ < 1.52

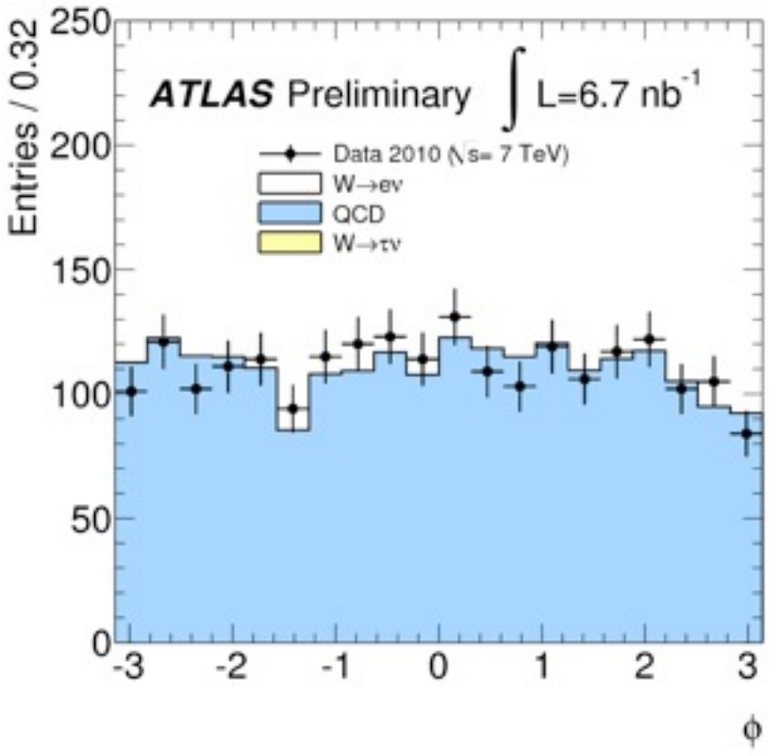
Loose Electron:
ID track matching an EM calo cluster
Selected on shower shape on 2nd calo layer and energy leakage into hadronic calo
ε=94%, Rejection factor = 1100



Good agreement with MC shapes
- MC cross section higher by ~2.2
- Normalized to total data events

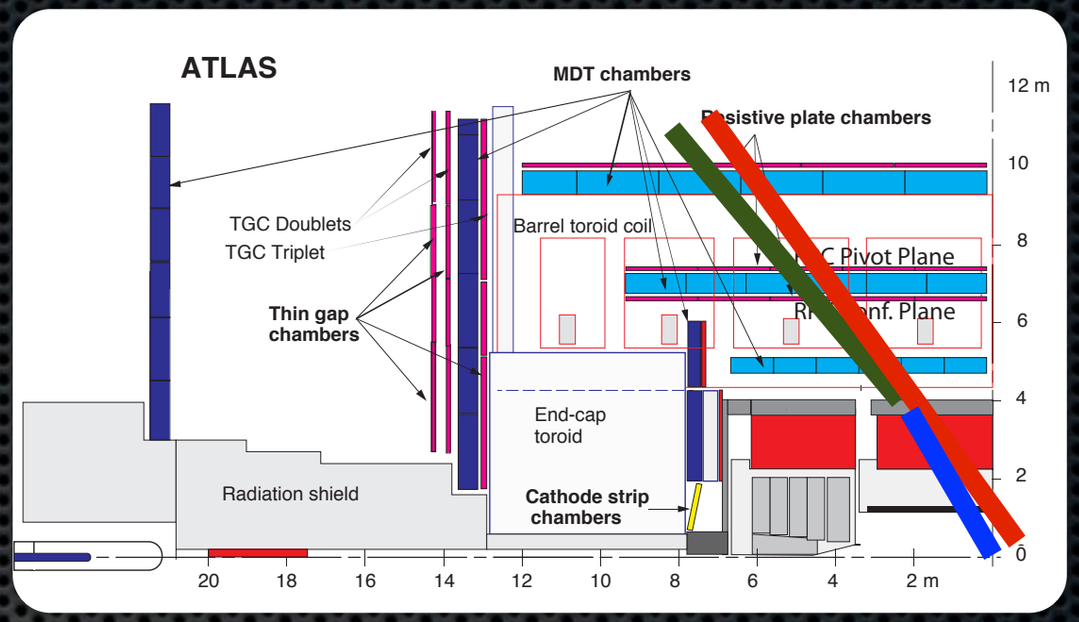




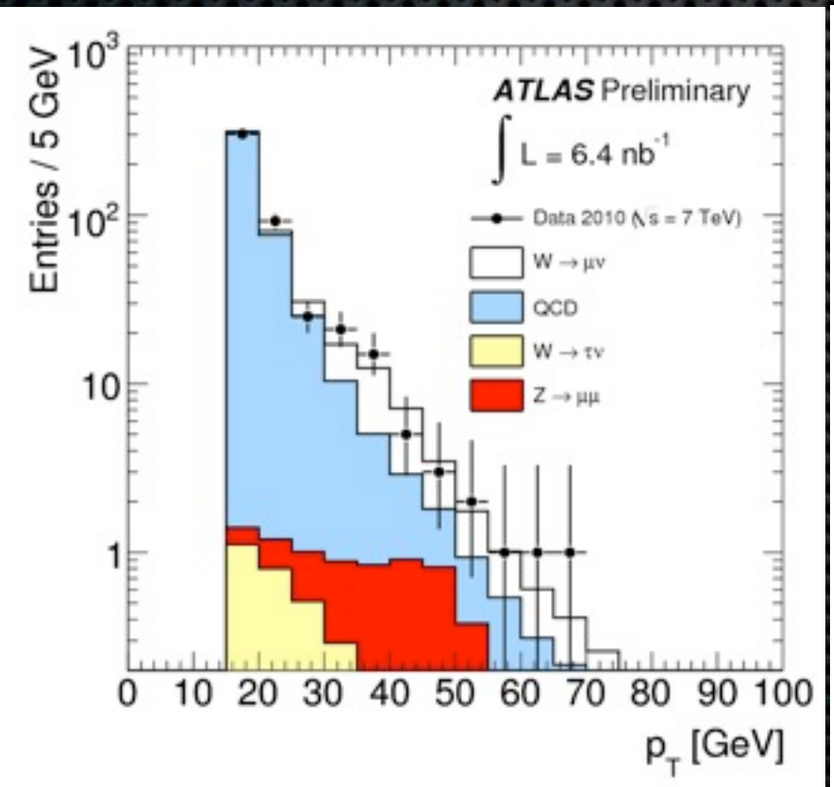


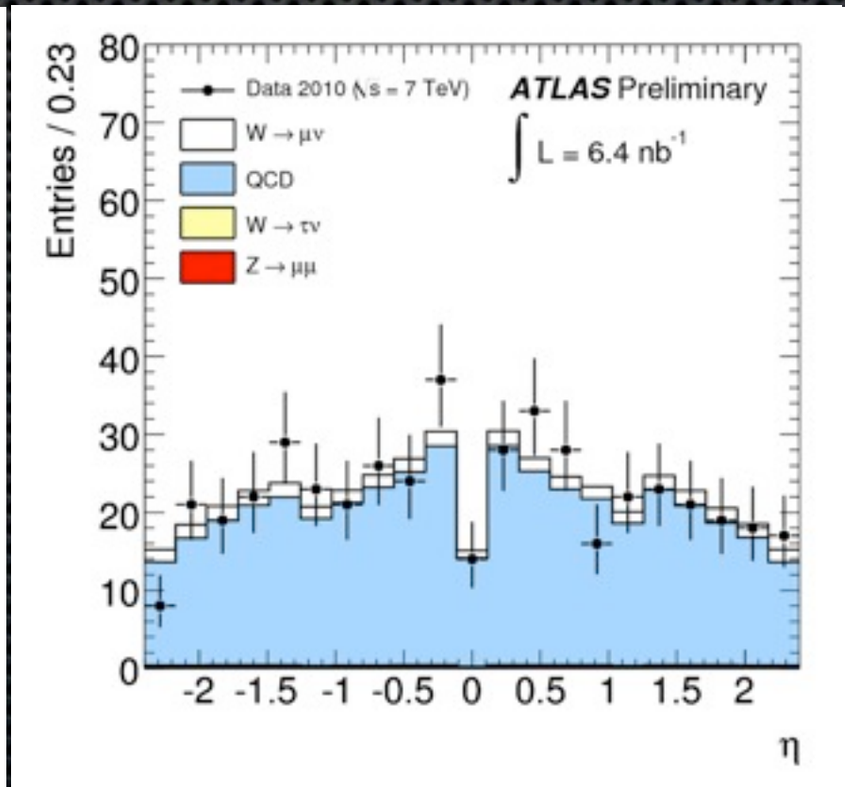
Muon Preselection

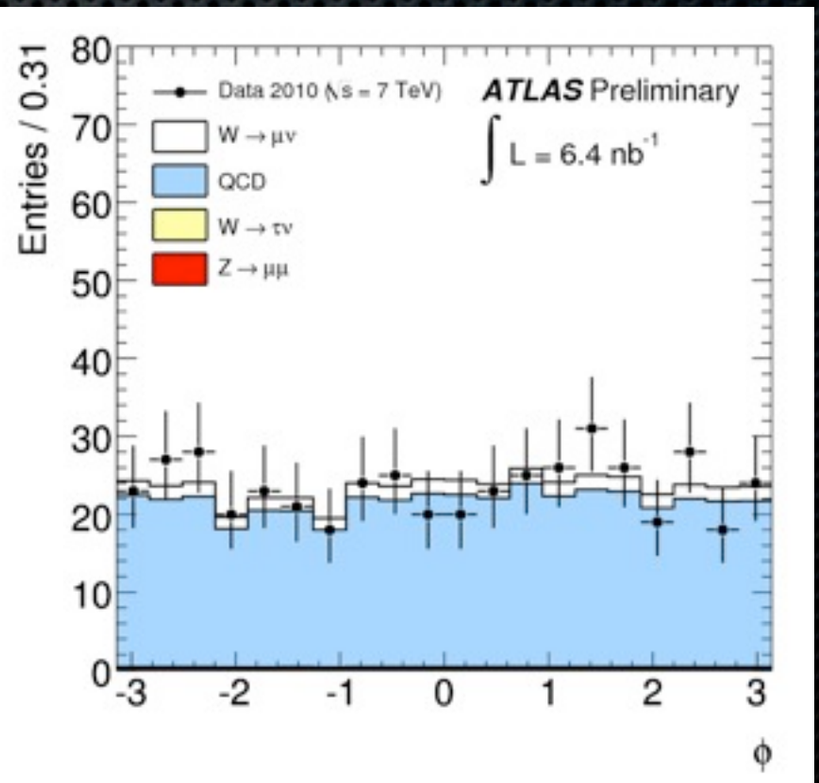
- One PV with ≥ 3 tracks, $|Z_{PV}| < 15$ cm
- At least one combined muon
  - $P_T > 15$ GeV, $|\eta| < 2.4$
  - Muon Spectrometer $P_T(MS) > 10$ GeV
    - Reduces decays-in-flight
  - $|P_T(MS) - P_T(ID)| < 15$ GeV
    - Removes bad track matches
  - $|Z_{track} - Z_{PV}| < 1$ cm
    - Removes cosmic events



Good agreement with MC shapes
- MC cross section higher by ~1.9
- Normalized to total data events

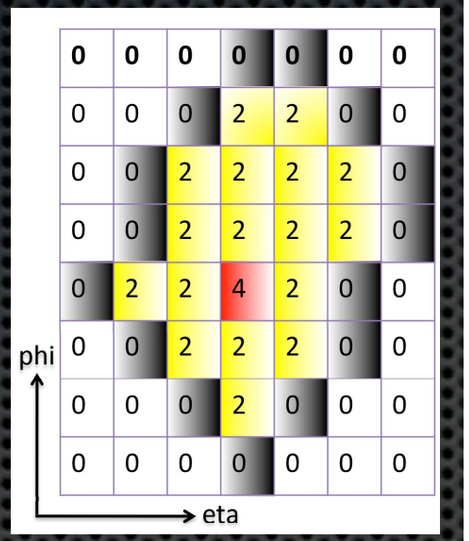






Missing Transverse Energy

- Calorimeter Missing Energy
  - Topological clusters
    - Seeded by cell with $|E| > 4\ \sigma_{noise}$
  - Electromagnetic scale
    - No correction for different calorimeter response to photons, electrons or hadrons

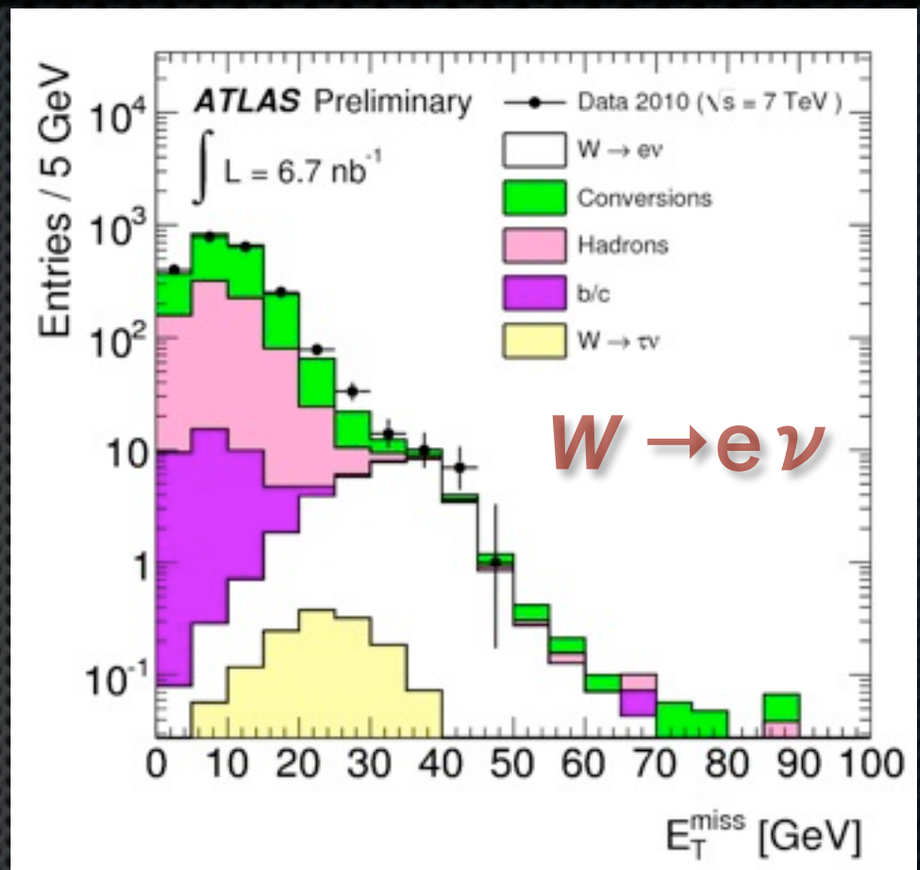


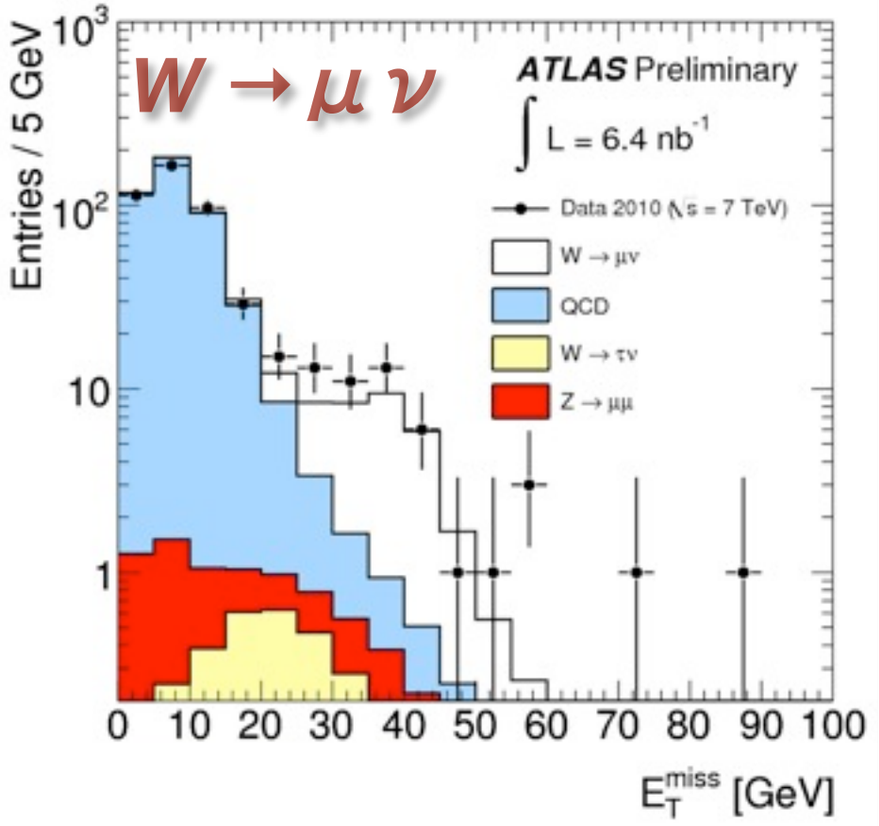
- $W \rightarrow e\nu$ selection:

$$E_T^{miss,e} = E_T^{miss,calo} = -\sum_i E_{x,y}$$

- $W \rightarrow \mu\nu$ selection:

$$E_T^{miss,\mu} = E_T^{miss,calo} - p_T^{\mu}$$



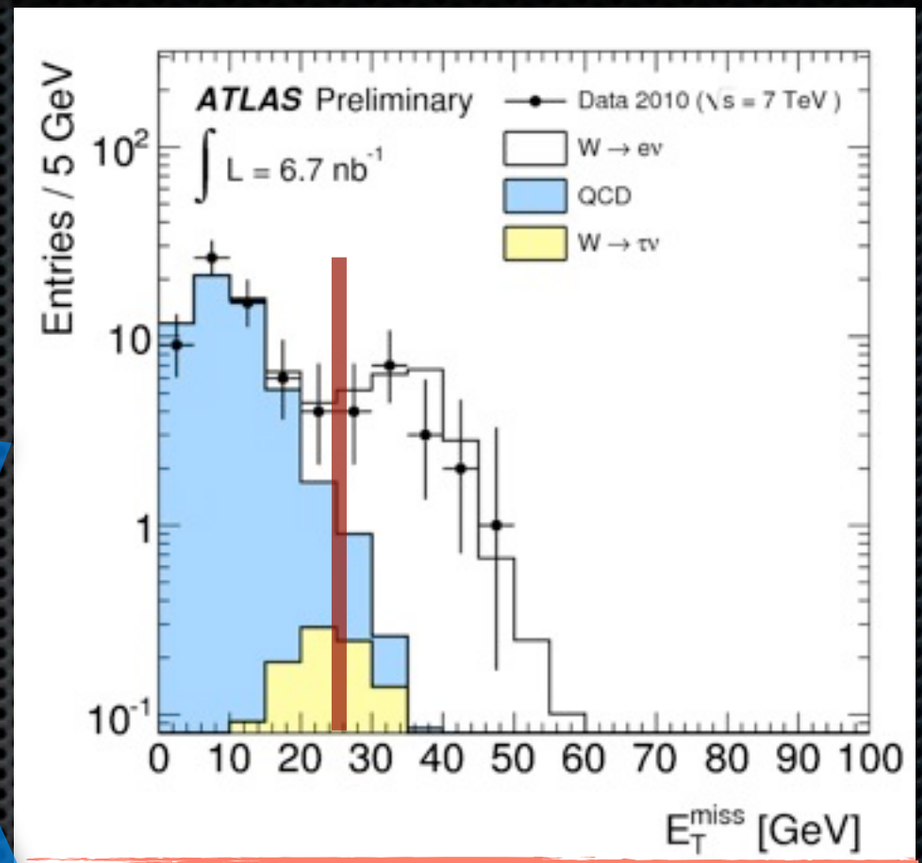


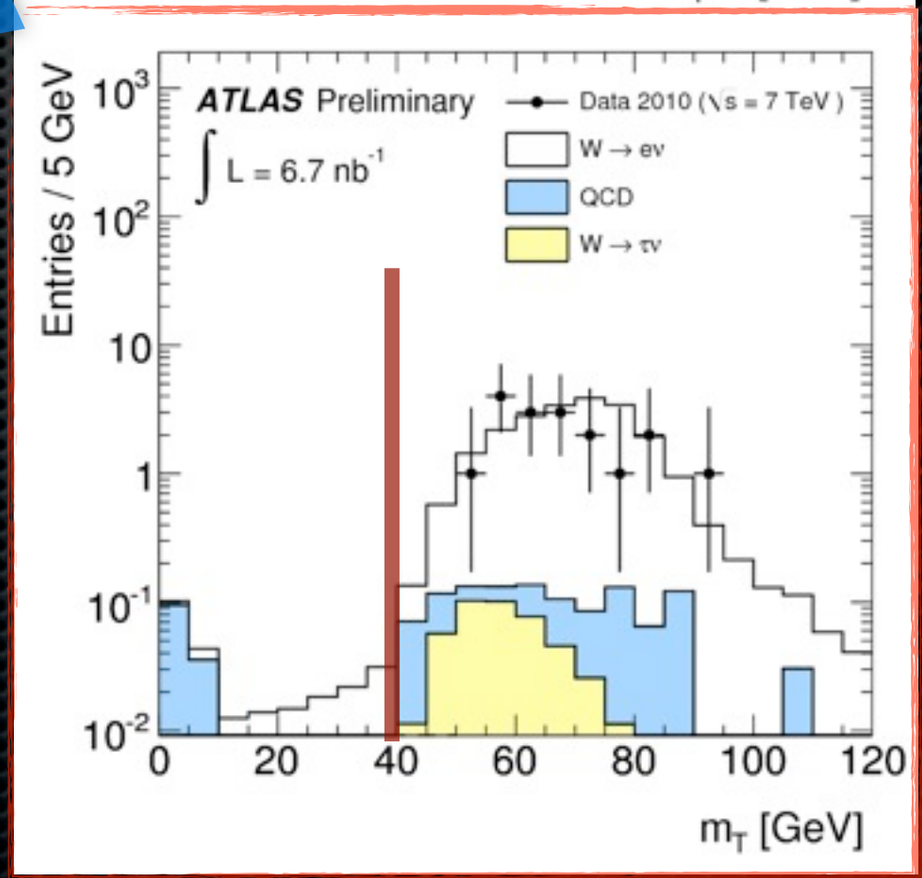
W Candidates in the Electron Channel

Requirement	Number of events
Triggered	1.2×10^7
Preselection	2.2×10^3
Tight electron	77
E_T^{miss} > 25 GeV	17
M_T > 40 GeV	17

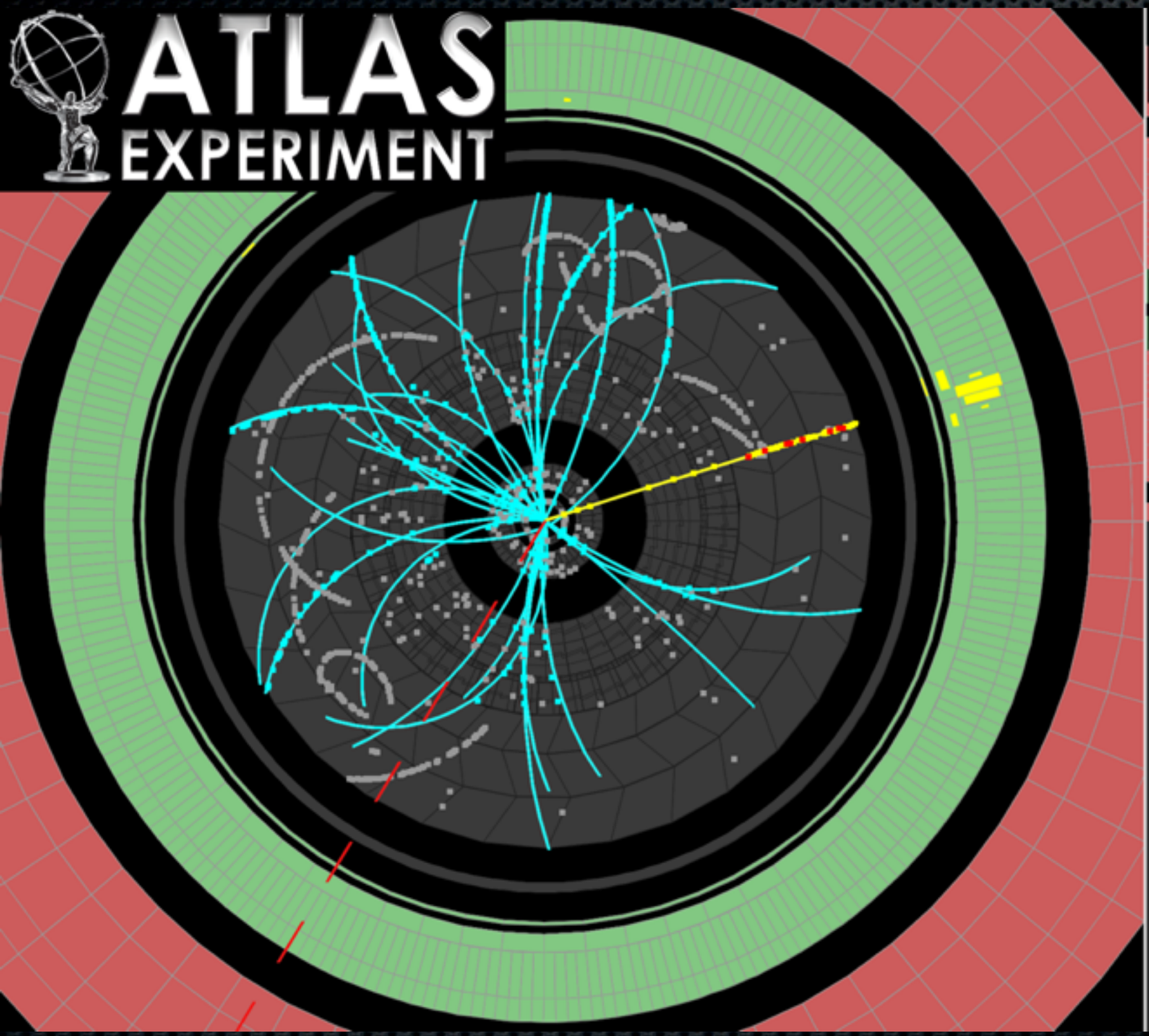
Tight Electron:
TRT high-threshold hits
Cluster E/p
Conversion veto, detailed shower shapes, impact parameter requirement
ε=72%, Rejection factor = 92000

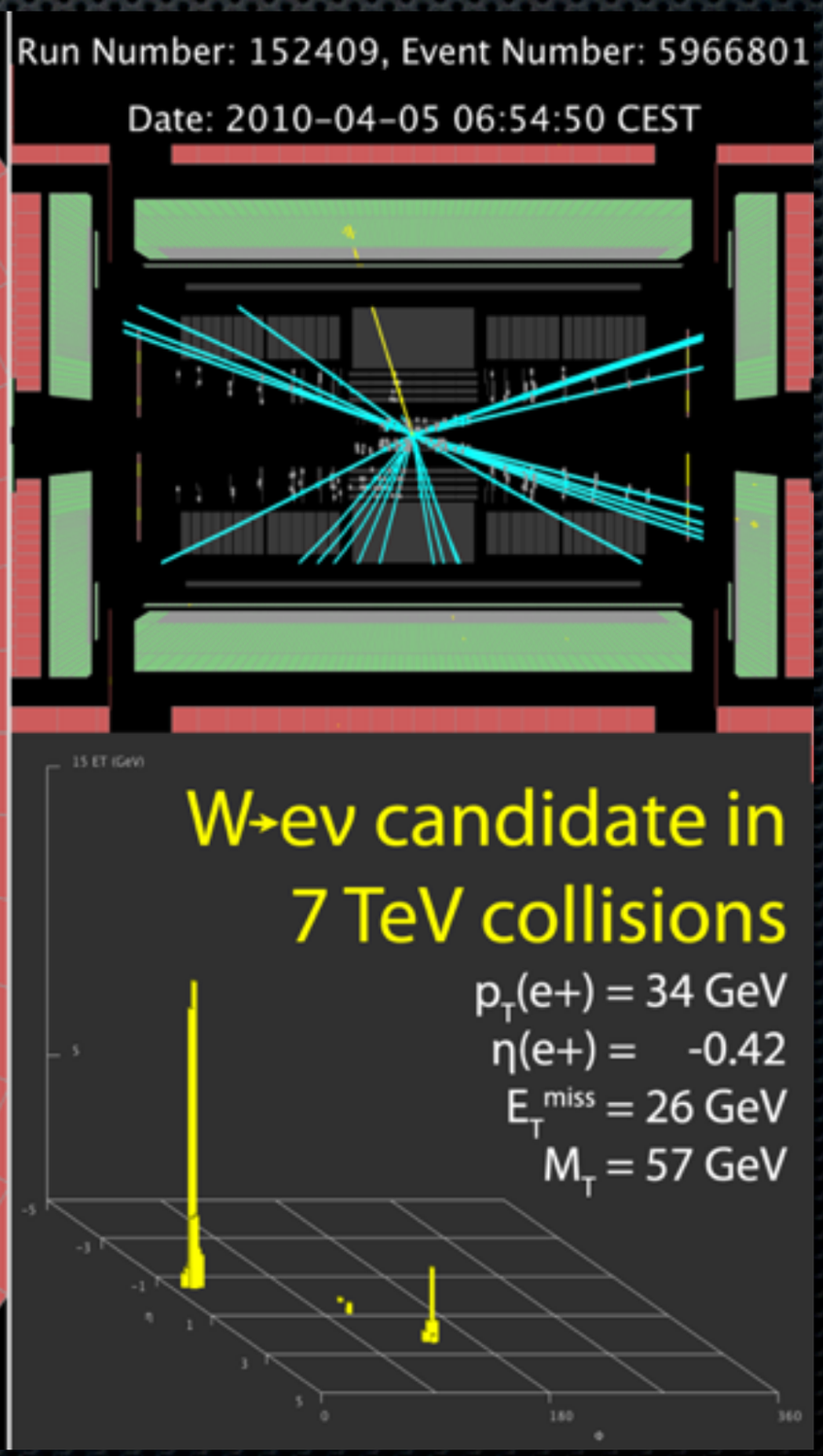
QCD background scaled to measurement in data





$W \rightarrow e\nu$ Candidate Event





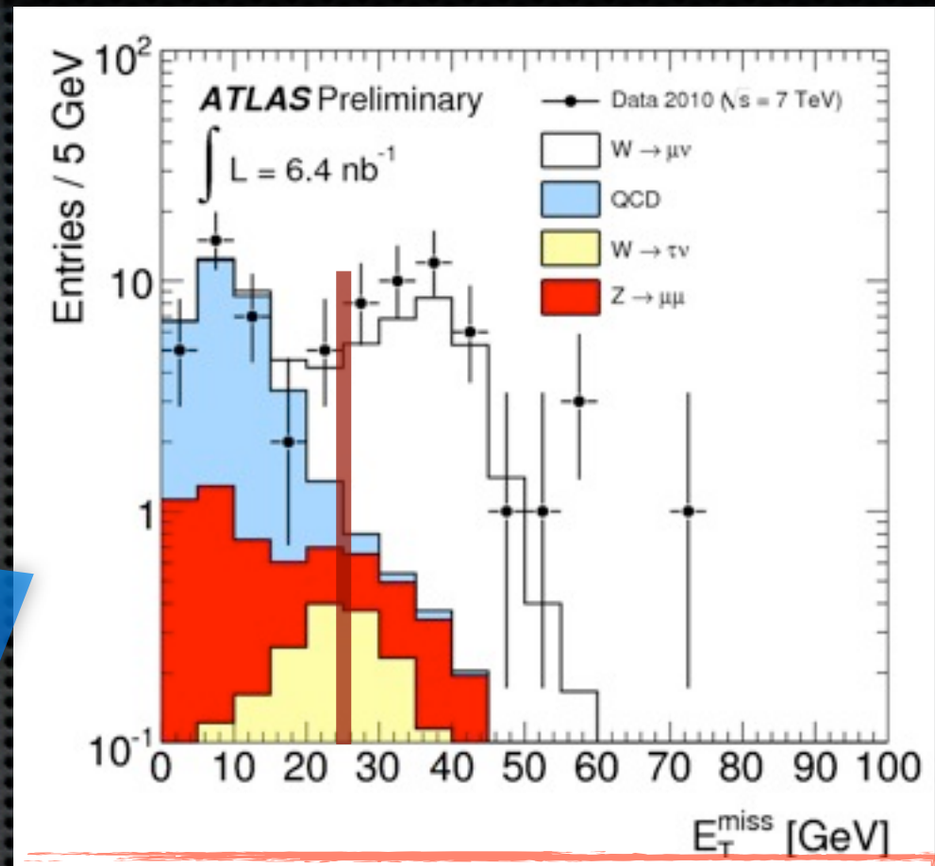
W Candidates in the Muon Channel

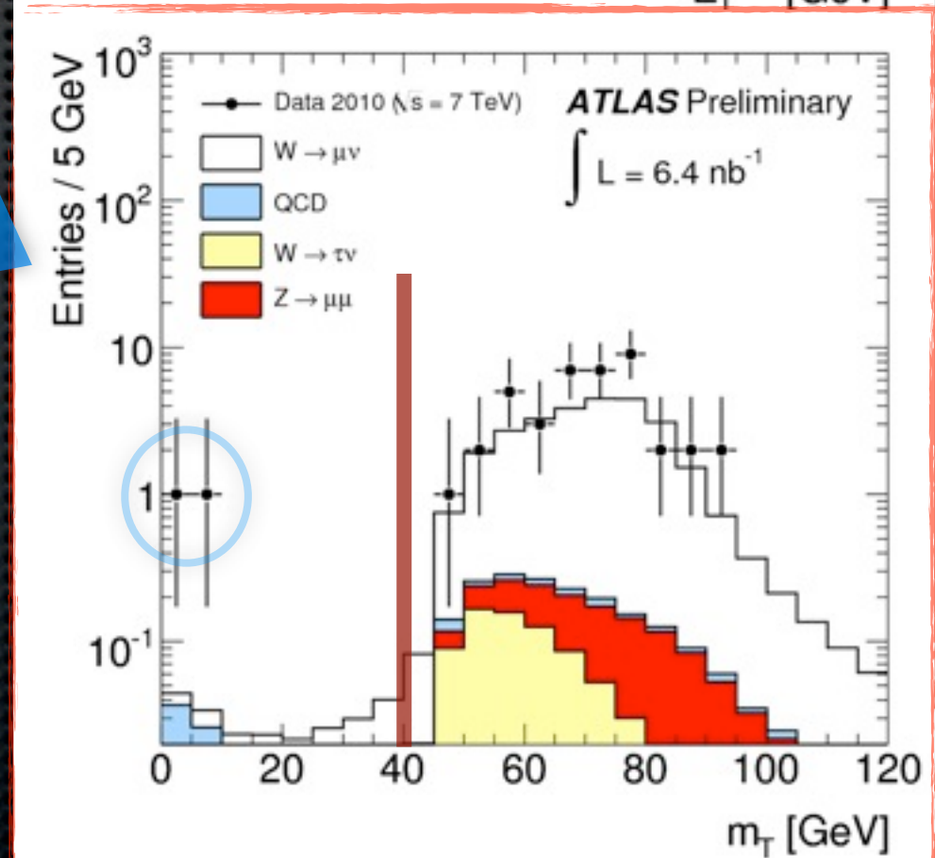
Requirement	Number of events
Triggered	2.8×10^5
Preselection	534
$P_T > 20$ GeV	166
Track Isolation	76
$E_T^{miss} > 25$ GeV	42
$M_T > 40$ GeV	40

Track Isolation:
$\sum p_T$ (cone = 0.4)/ $p_T^{\mu} < 0.2$

99% efficient
87% bkg rejection

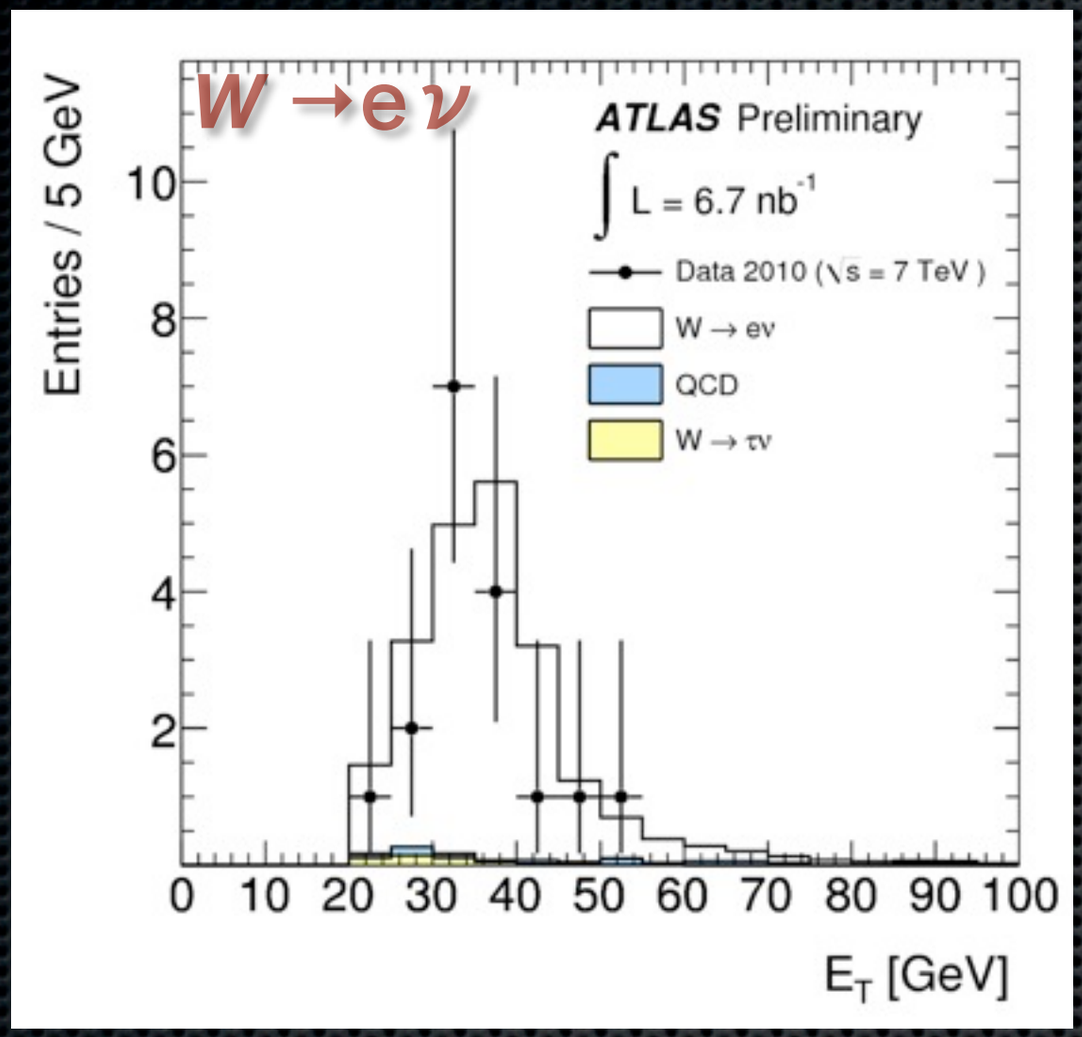
QCD background scaled to measurement in data





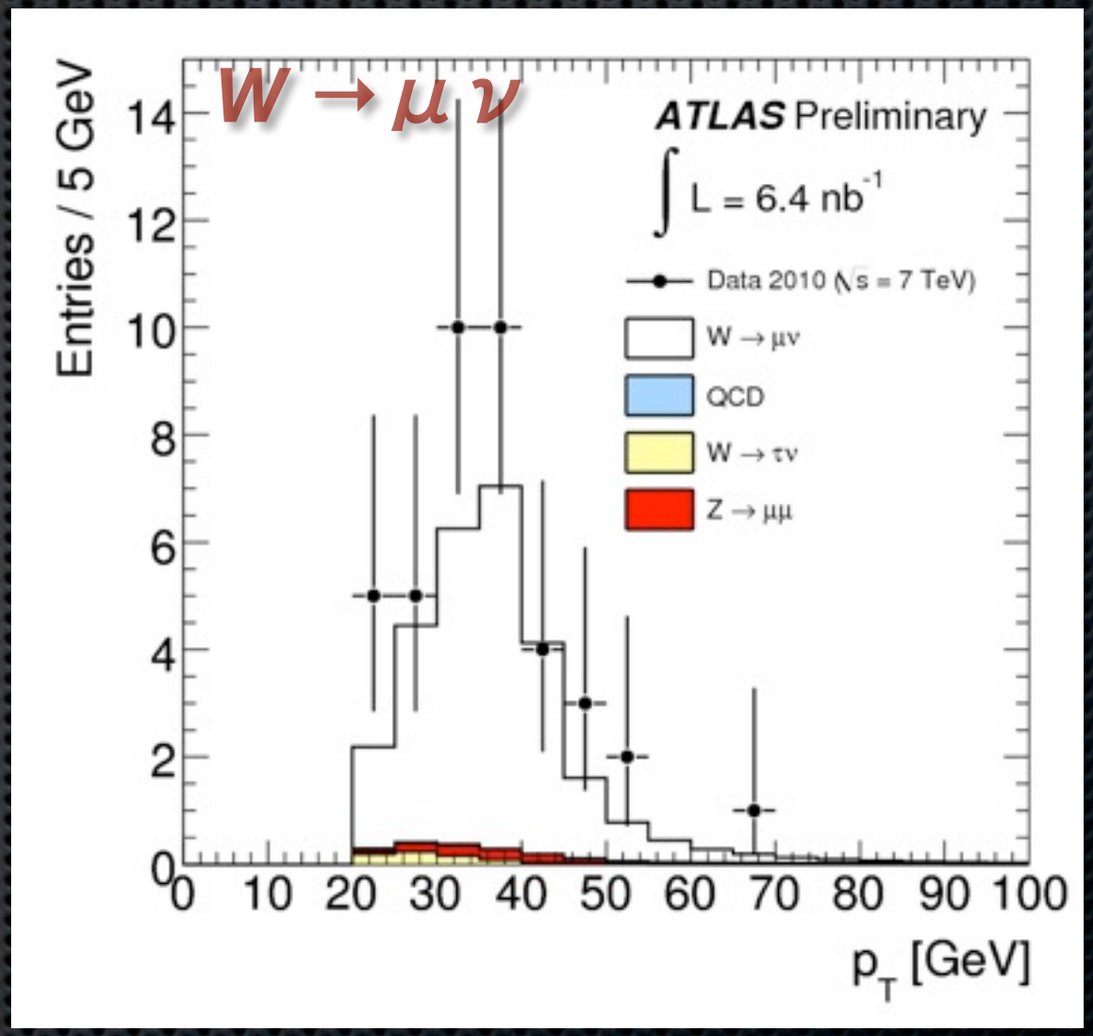
Properties of the W Boson Candidates

Electron Transverse Energy



17 Candidates
- 11 e^+
- 6 e^-

Muon Transverse Momentum

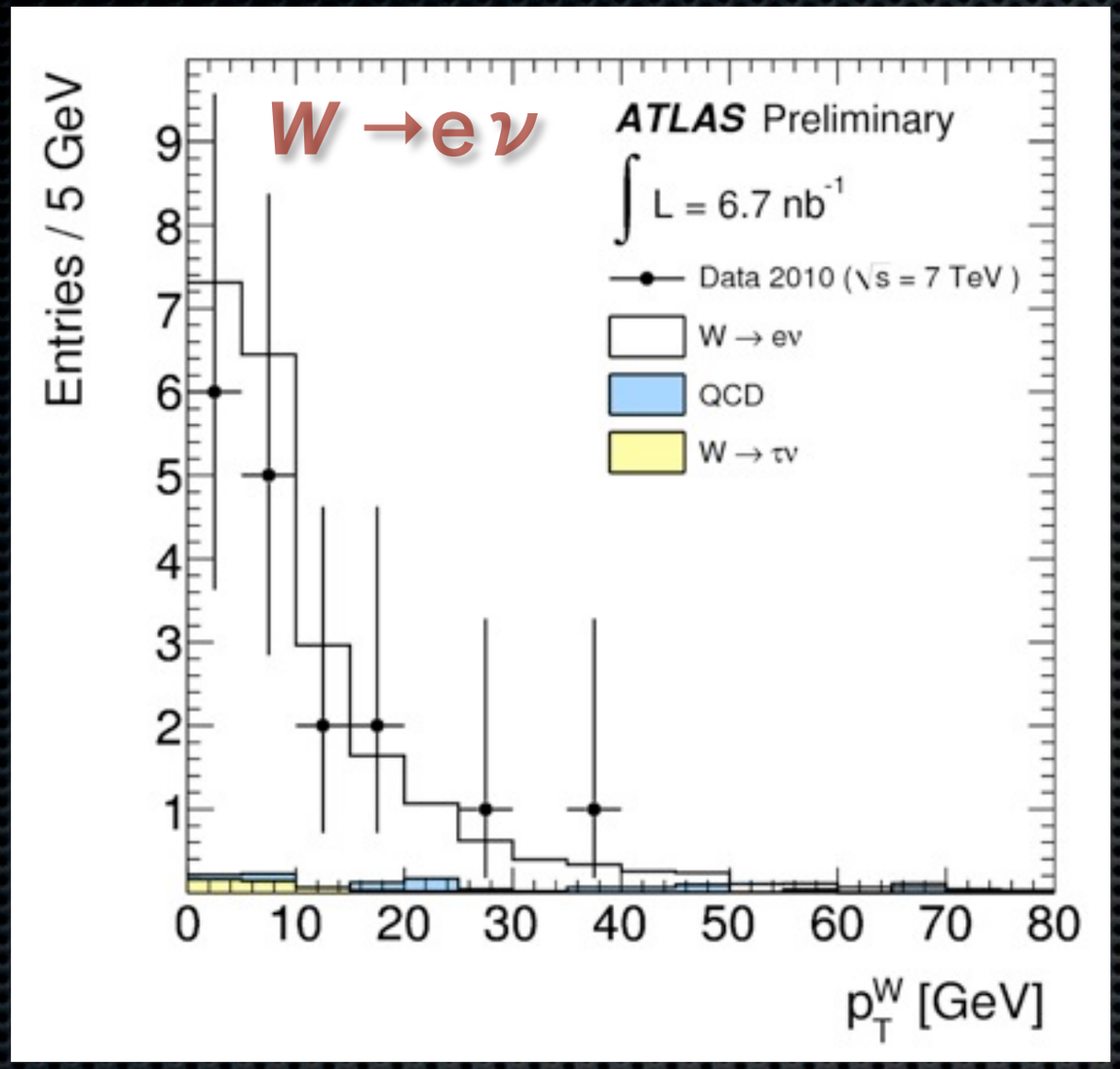


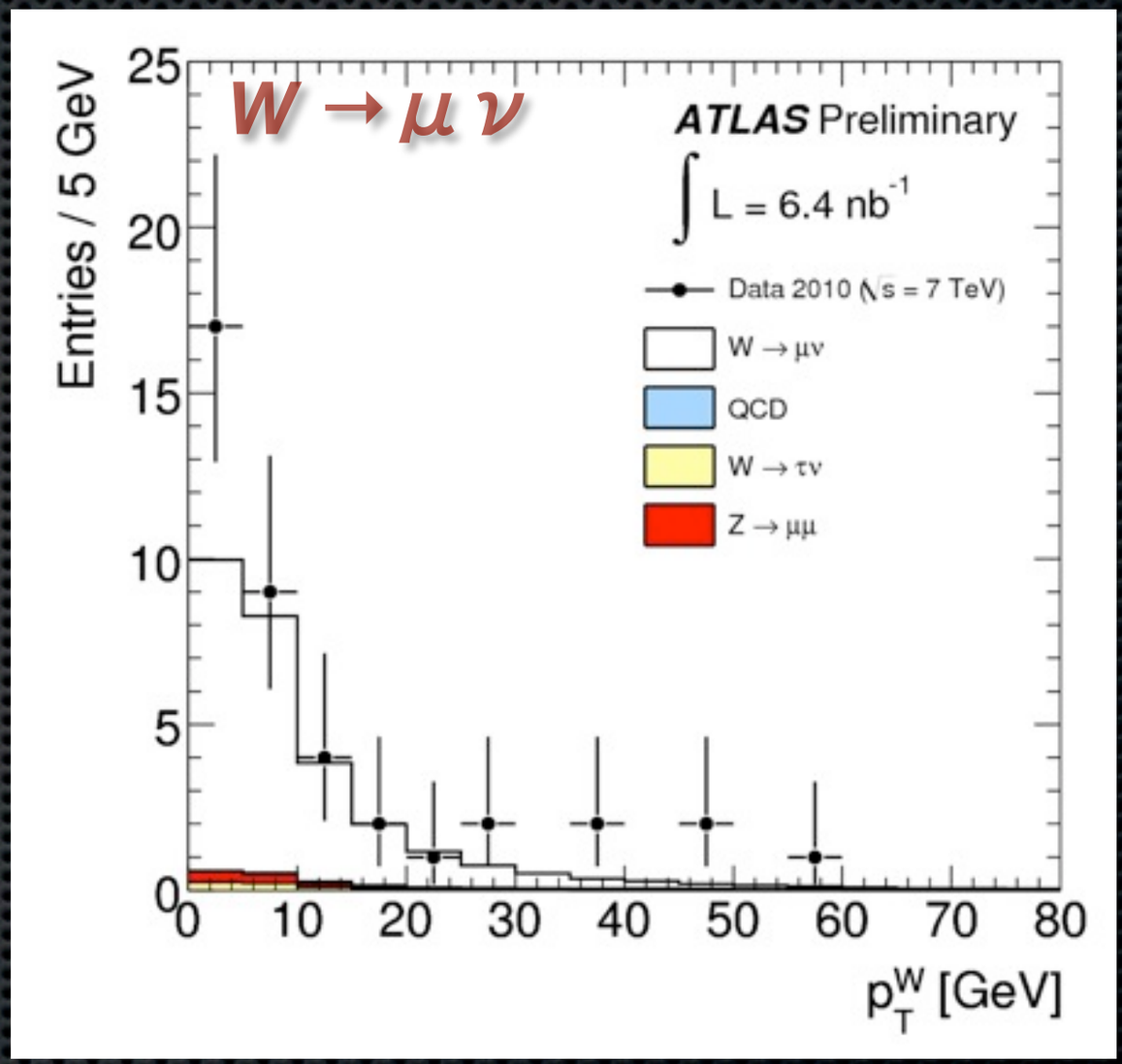
40 Candidates
- 25 μ^+
- 15 μ^-

SM NNLO prediction W^+/W^- ~1.4

Properties of the W Boson Candidates

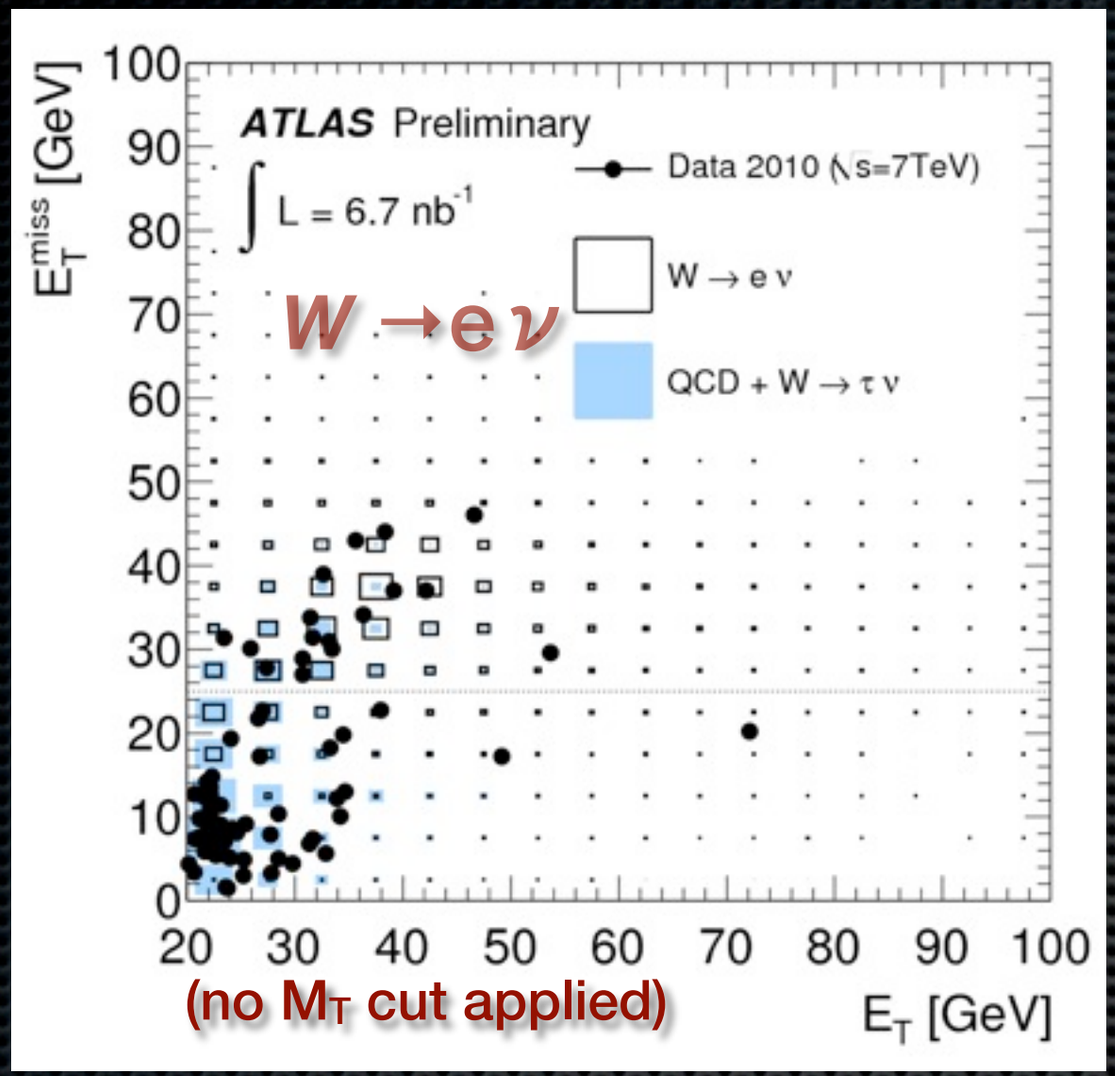
Transverse Momentum of the W boson

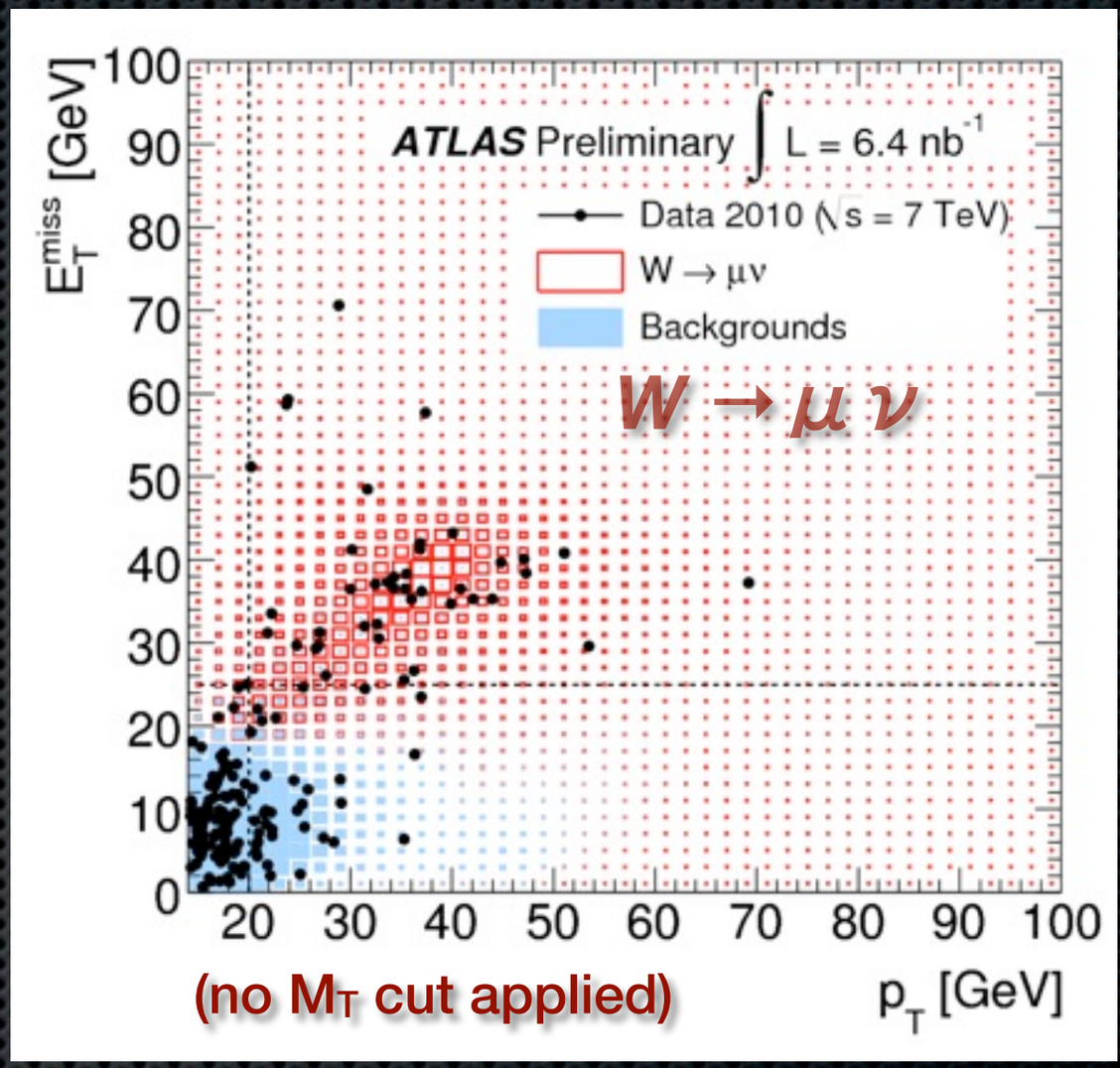




- Small excess of high-p_T W bosons in muon channel
  - 8 events with jets
    - W+ jets events
    - QCD background

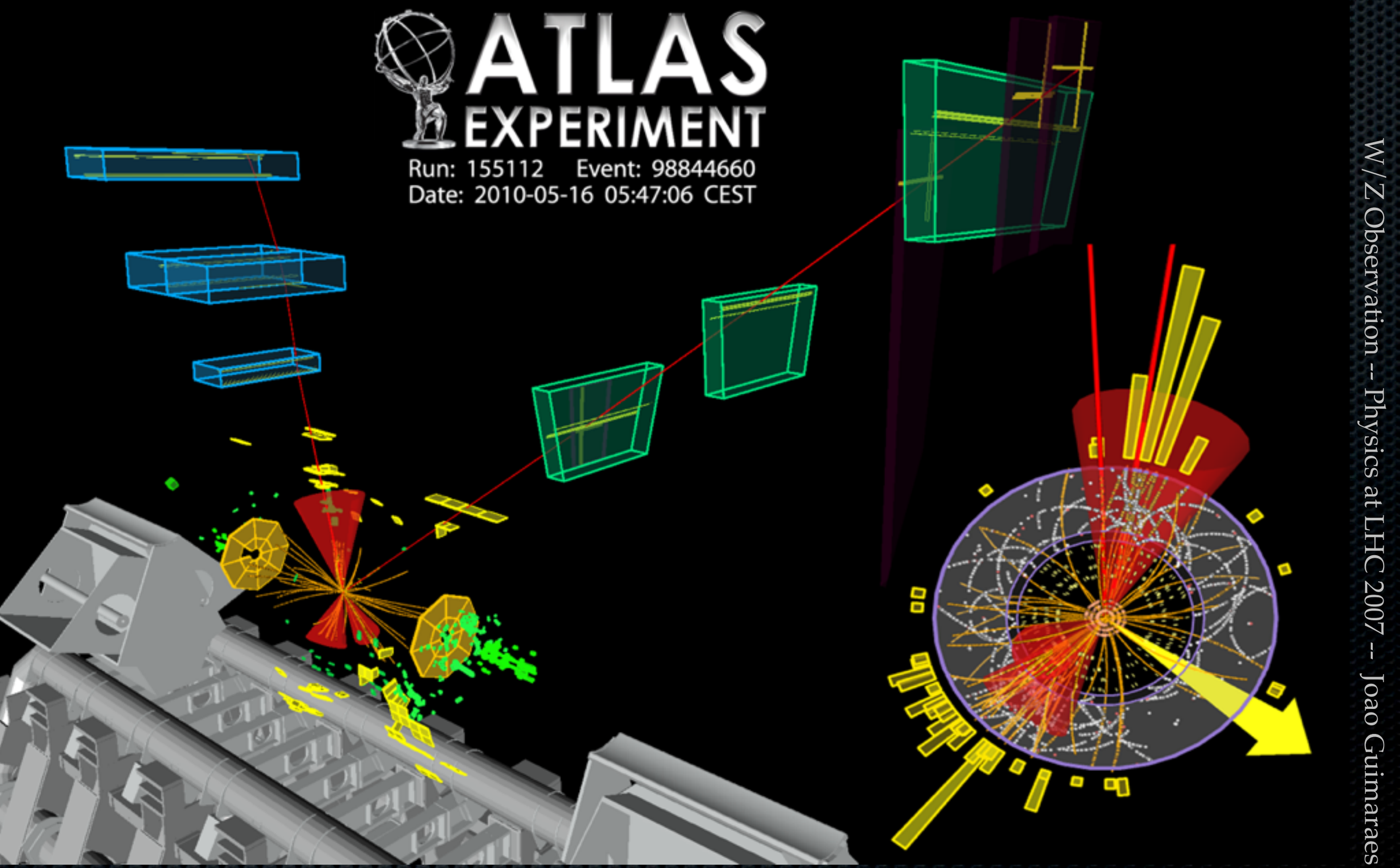
Properties of the W Boson Candidates





- High-p_T *W* candidates in muon channel
  - All muons are well isolated and consistent with the *W* boson hypothesis
- All final events inspected:
  - Lepton reconstruction quality
  - Event topology
  - Timing tests in TRT, Calorimeters and MDT ==> inconsistent with cosmics

$W \to \mu\,\nu$ Candidate Event with 3 Jets



Background Estimation: Electron Channel

QCD background

Heavy-quark decays, conversions
and hadrons faking electrons

Data driven estimation:

Calorimeter Isolation
$\sum E$ (cone = 0.3)/ E_T^e

Templates from MC

Binned maximum likelihood fit

Little statistics {

Use medium electrons

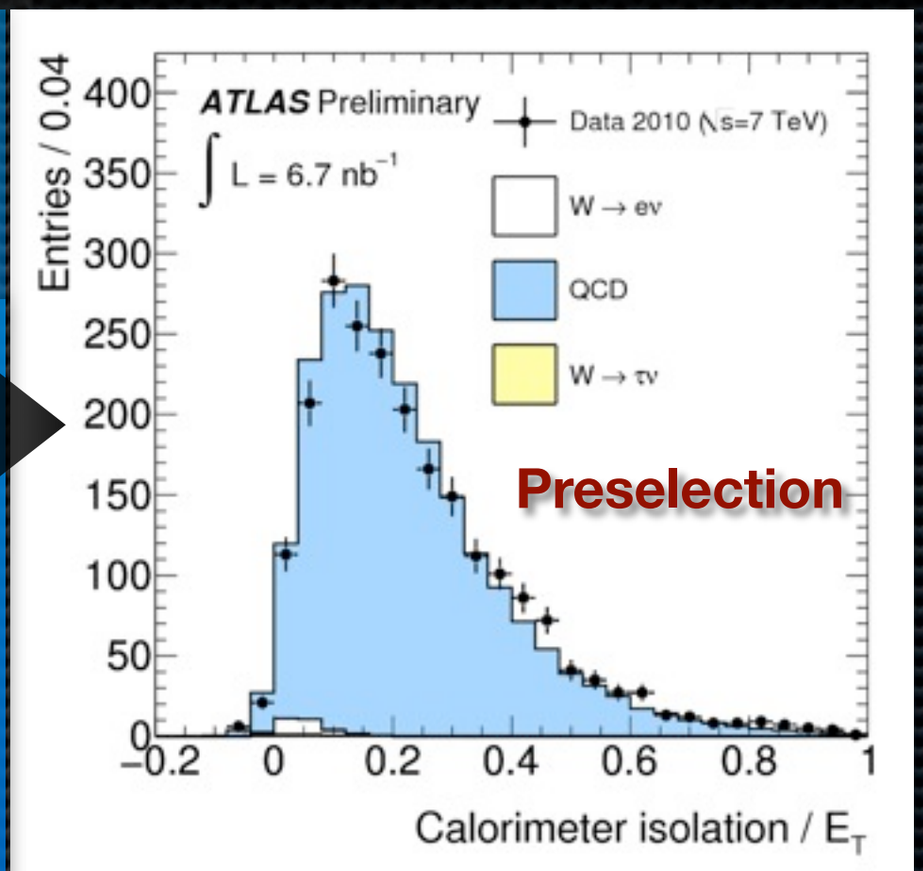
Scale to expectations for tight electrons (4.9 ± 1.0)

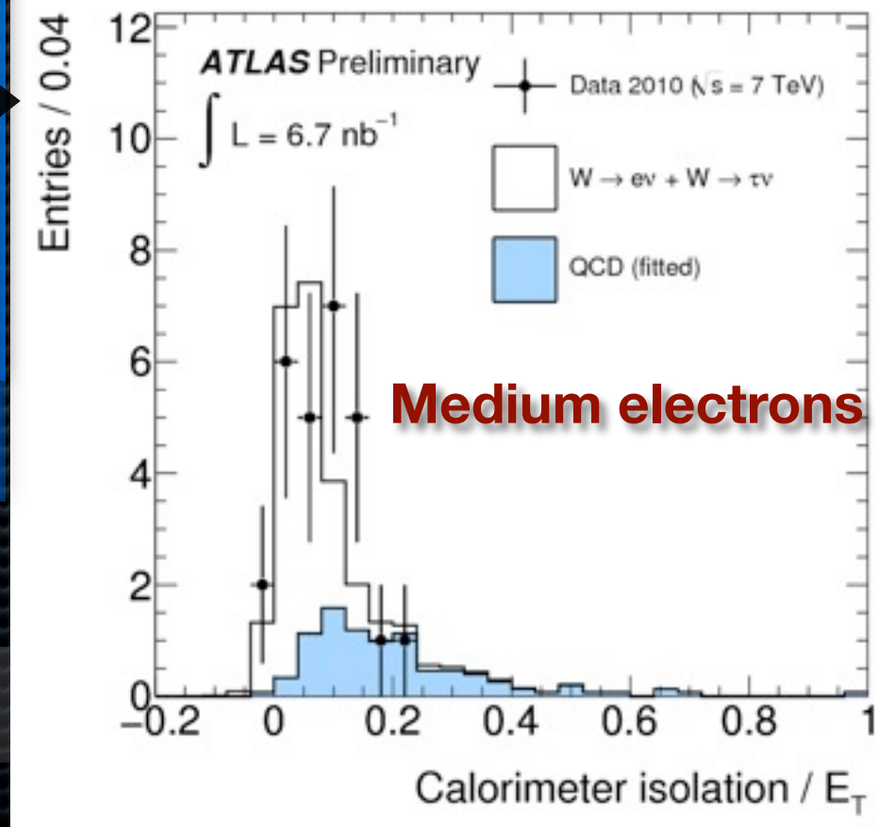
N_{QCD} = 2.0 ± 1.2(stat) ± 0.4 (syst)

Other backgrounds

$W \rightarrow \tau\ \nu$: 0.4 events

$Z \rightarrow$ee small





Background Estimation: Muon Channel

QCD background

Heavy-quark decays, decays in flight and hadrons punch-through

Data driven estimation: Assume -- Track isolation and missing E_T not correlated

$$N_D^{QCD} = N_C \times \frac{N_B}{N_A}$$

Remove EW+SGN

1.3±1.2 evts

Apply M_T cut

$N_{QCD} = 1.0 \pm 0.5\ (stat) \pm 0.7\ (syst)$

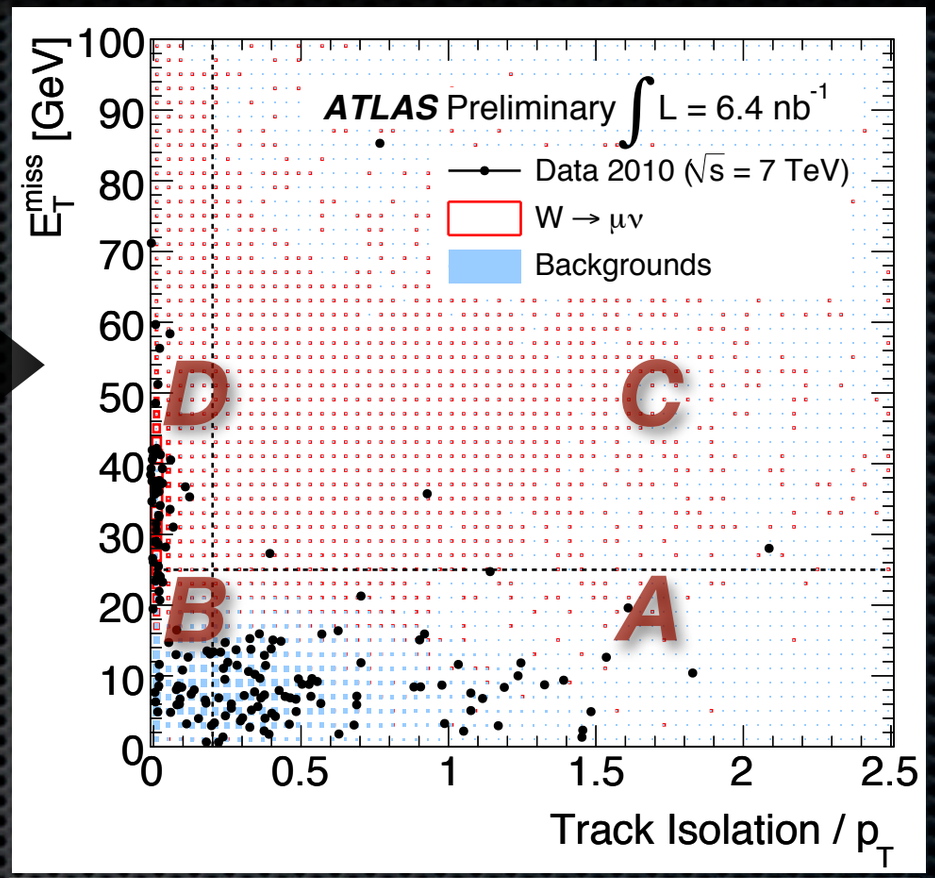
Cross check

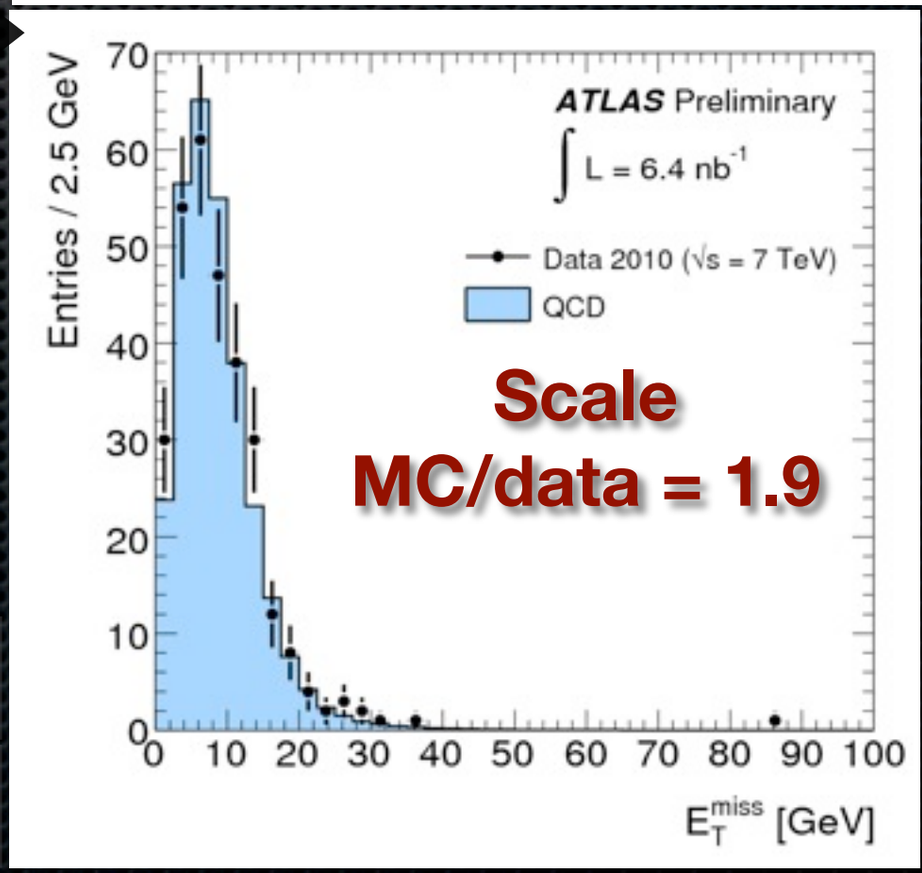
Use non-isolated control sample

Scale QCD MC to data

Apply to isolated muon data

$N_{QCD} = 0.2 \pm 0.1\ (stat)$





Other backgrounds

$Z \to \mu\,\mu$: 1.0 events	tt : 0.08 events
$W \to \tau\,\nu$: 0.7 events	$Z \to \tau\,\tau$: 0.03 events

Summary

Systematic Uncertainties	$W \to e\nu$	$W \to \mu\nu$
Lepton Identification	5%	10%
Trigger	small	7%
Momentum Resolution	--	5%
E_T^{miss}	5%	
Theoretical σ + pdf	4%	4%

e: Data/MC comparisons
μ: Cosmic ray data

e: $\varepsilon_{trigger}$ ~ 100%
μ: $\varepsilon_{trigger}$ ~ 85% in data

e: Choice of E_T^{miss}
μ: Cosmic ray data

	$W \to e\nu$	$W \to \mu\nu$
Signal	20.7 ± 1.7 (syst) ± 4.1 (lumi)	25.9 ± 3.6 (syst) ± 5.2 (lumi)
Bkg	2.4 ± 1.2 (stat) ± 0.4 (syst) ± 0.5 (lumi)	2.8 ± 0.5 (stat) ± 0.8 (syst) ± 0.6 (lumi)
Expected	23.1 ± 1.2 (stat) ± 1.7 (syst) ± 4.6 (lumi)	28.7 ± 0.5 (stat) ± 3.9 (syst) ± 5.7 (lumi)
Observed	17	40

Stat error due to data-driven background estimation

Observation of the Z boson

Observation of the Z Boson

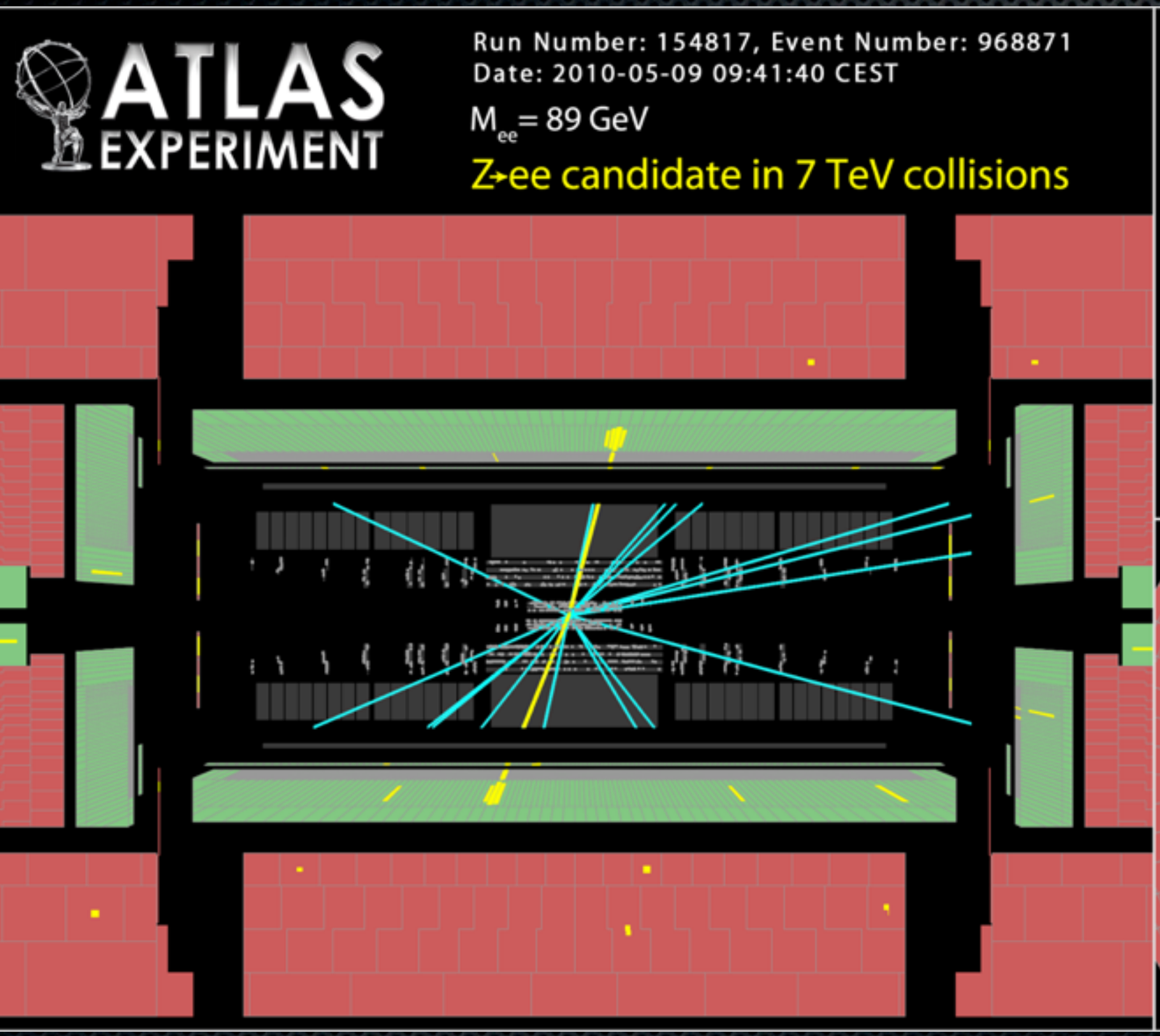
Executed full analysis

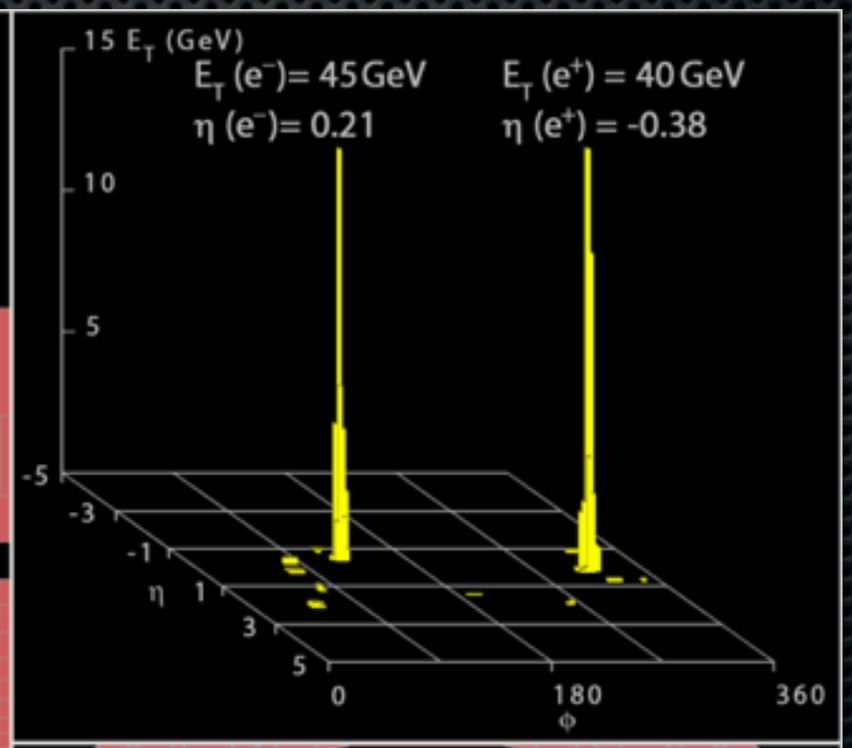
Selection	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$
Looser Lepton Identification	Medium electron	$P_T(2) > 15$ GeV, $\|\eta\| < 2.5$
Opposite Lepton Charge	✔	✔
	80 GeV < m_{ll} < 100 GeV	

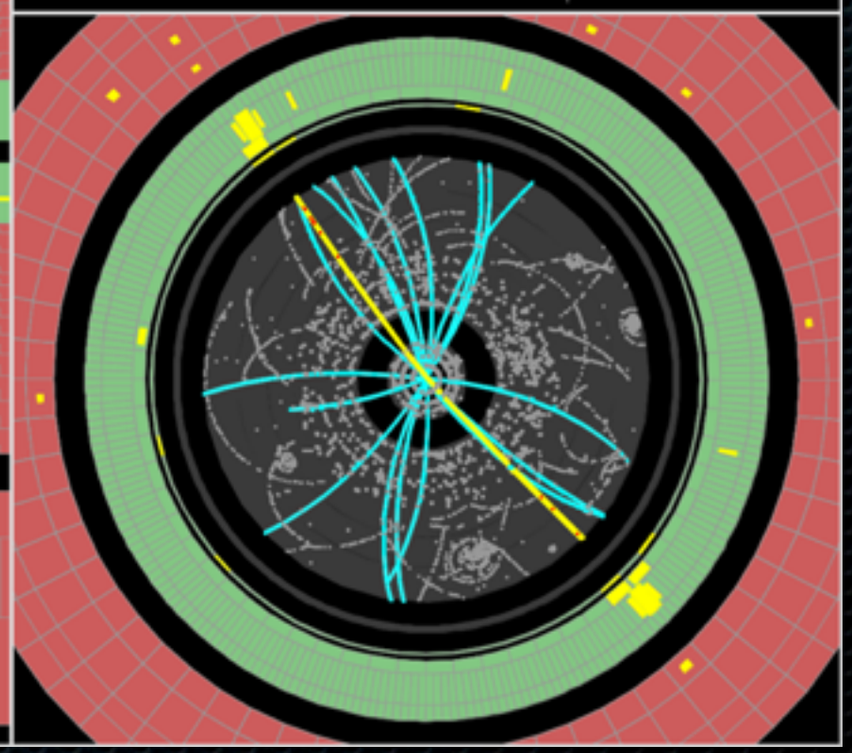
	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$
Signal	1.6 ± 0.1 (syst) ± 0.3 (lumi)	3.2 ± 0.7 (syst) ± 0.6 (lumi)
Bkg	0.01	(2.1 ± 0.8 (syst) ± 0.4 (lumi)) x 10^{-4}
Observed	**1**	**2**
Mass reconstructed	**91.4 GeV**	**87.6 GeV** **80.2 GeV**

Systematic uncertainties similar to the W analysis but taking into account correlations between leptons

The First Z Boson in the Electron Channel



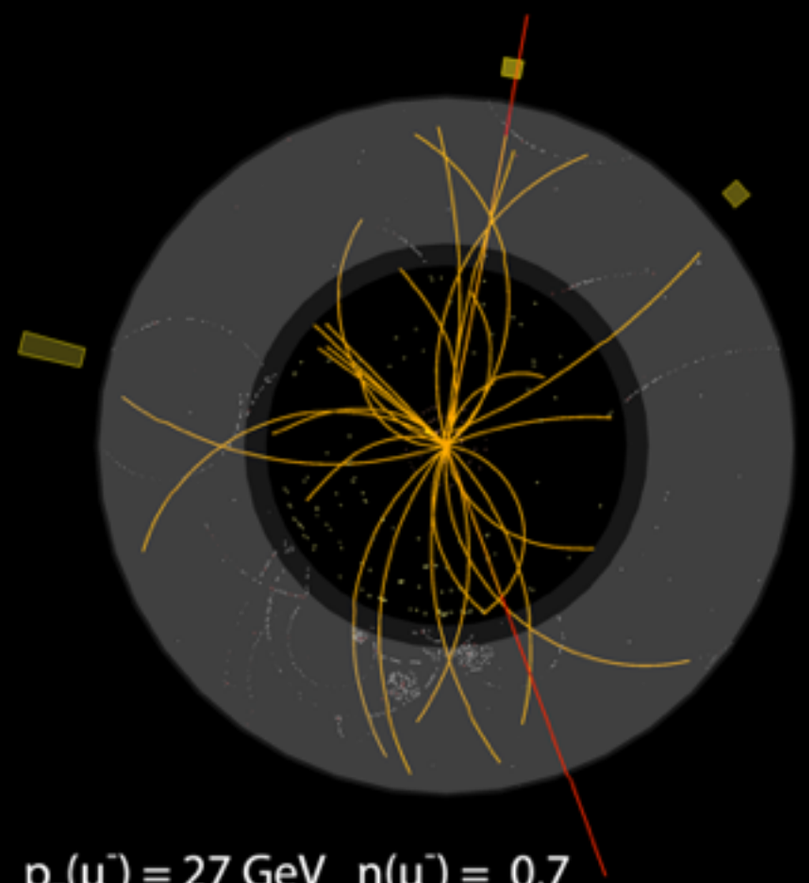




The First Z Boson in the Muon Channel

ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV

Z→μμ candidate
in 7 TeV collisions

Conclusions

- $W \rightarrow \mu \nu$ and $W \rightarrow e \nu$ have been observed in ATLAS

Observed	57 events
Expected	51.8 events

  - Individual results are consistent with Standard Model expectations
    - Small excess of events is observed in the muon channel
    - Data has been scrutinized and so far there is no evidence of problems
- Z boson events have been observed in both channels

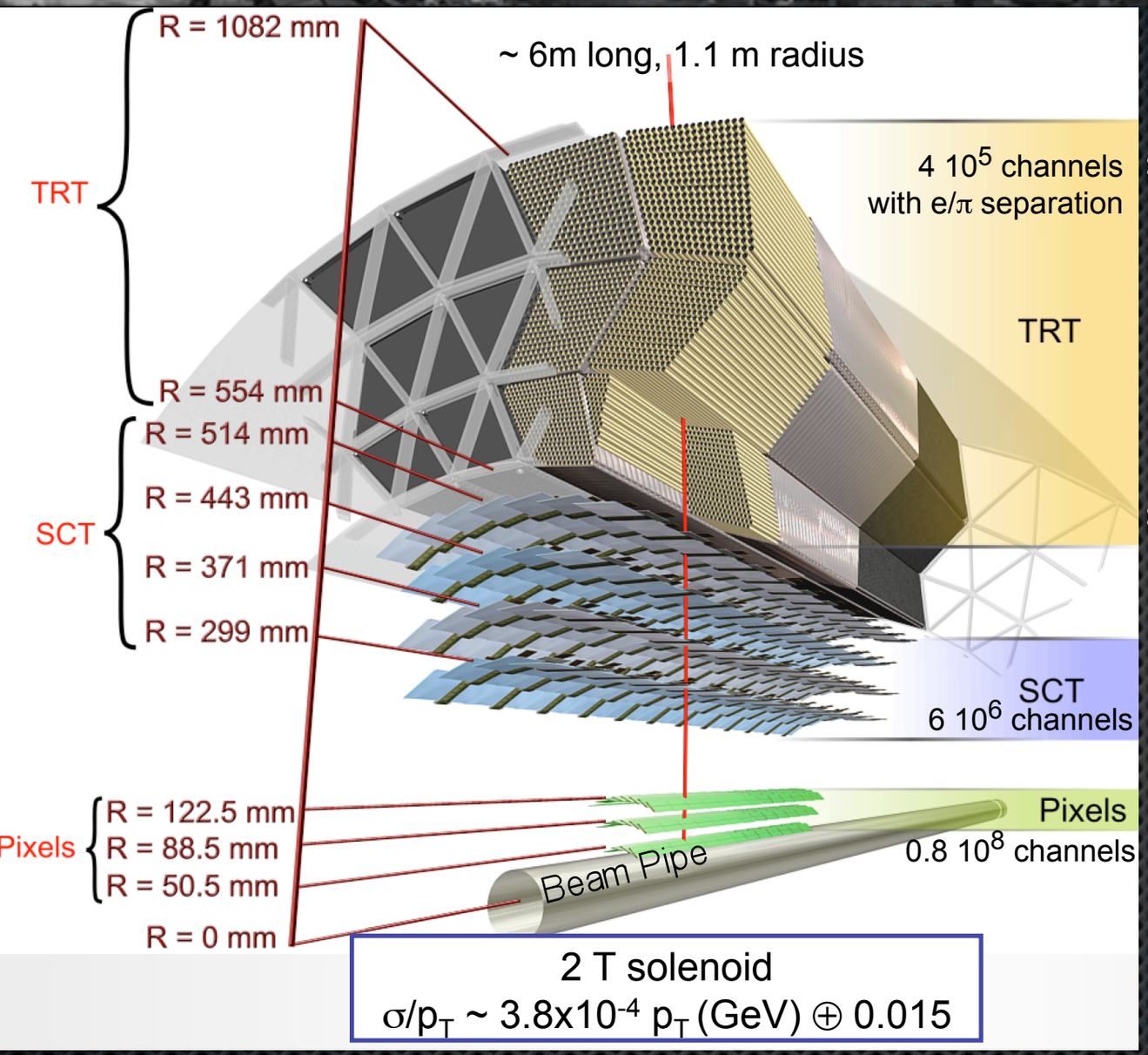
Observed	3 events
Expected	4.8 events

- Work well advanced towards cross section measurements

We eagerly await the addition of more data

Backup Slides

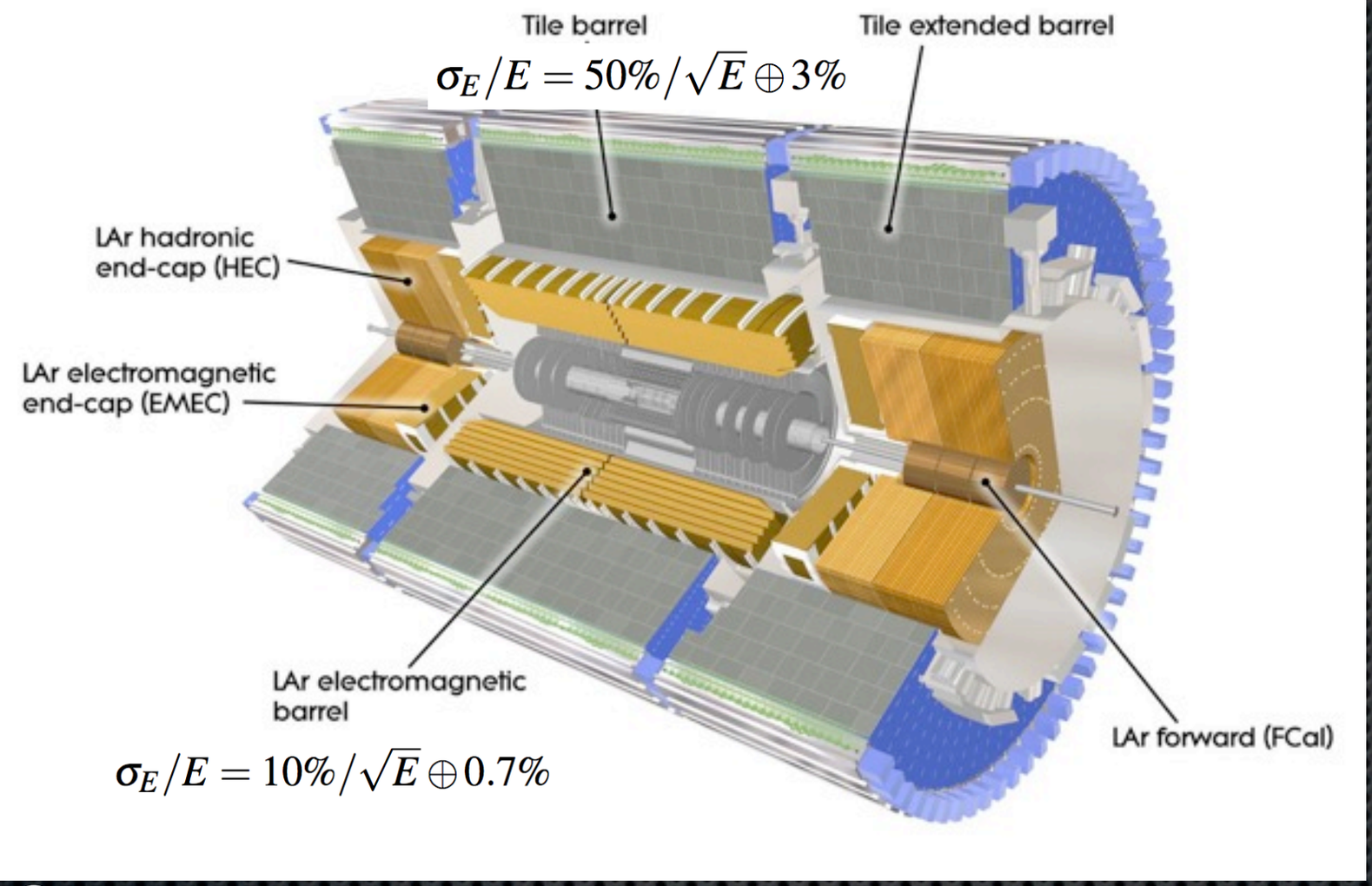
ATLAS Tracking Detectors (ID)



ID Coverage

- SCT + Pixels
  - $|\eta| < 2.5$
  - Pixels: 3 points
  - SCT: 4 points
- TRT
  - $|\eta| < 2$
  - ~ 30 hits/track
  - Discriminates between electrons and pions over energy range between 1 and 200 GeV using transition radiation (TR) in foils and fibres.
  - Two thresholds:
    - The lower registers minimum-ionising particles
    - The higher intended for transition radiation (TR) photon interactions

Electron reconstruction



Coverage:

- LAr electromagnetic calorimeter:
  - Barrel: $|\eta| < 1.475$
  - Endcap: $1.375 < |\eta| < 3.2$
- Hadronic calorimeter
  - Tile calorimeter: $|\eta| < 1.7$
  - LAr endcap calorimeter: $1.5 < |\eta| < 3.2$

= Electrons =

Loose:

- EM shower in second layer of calorimeter

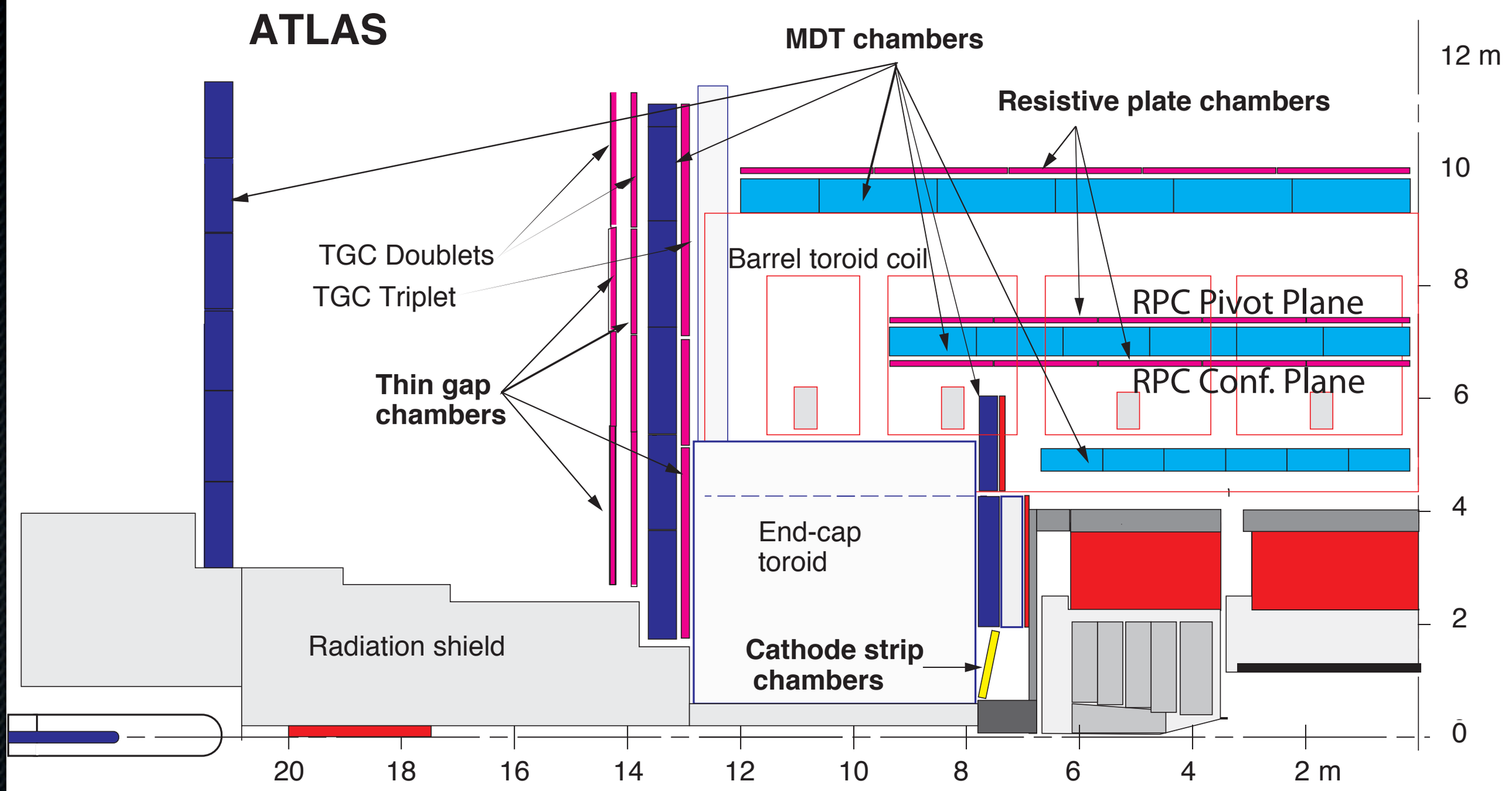
Medium:

- Include first layer of calorimeter
- Cluster-track matching

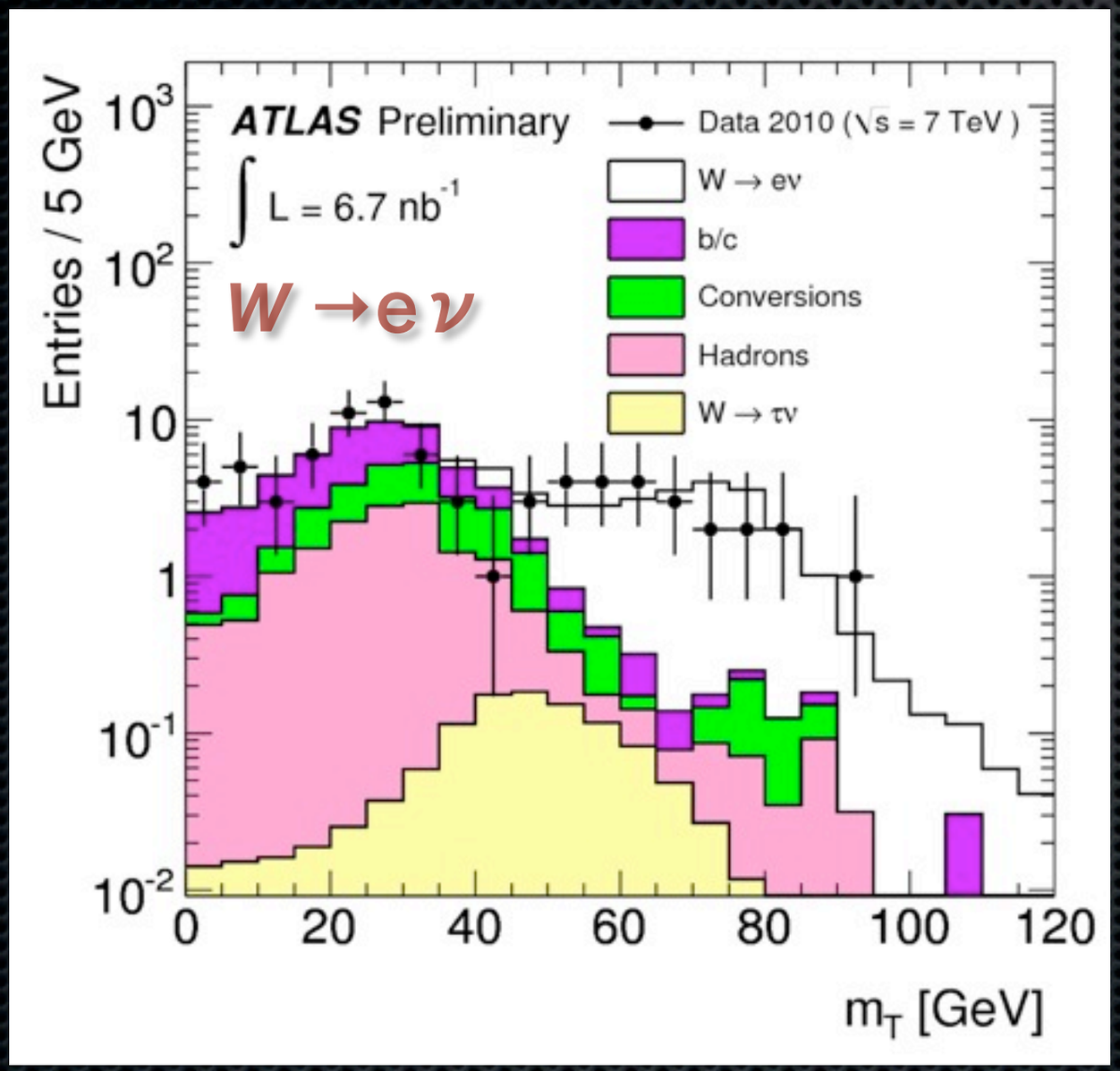
Tight:

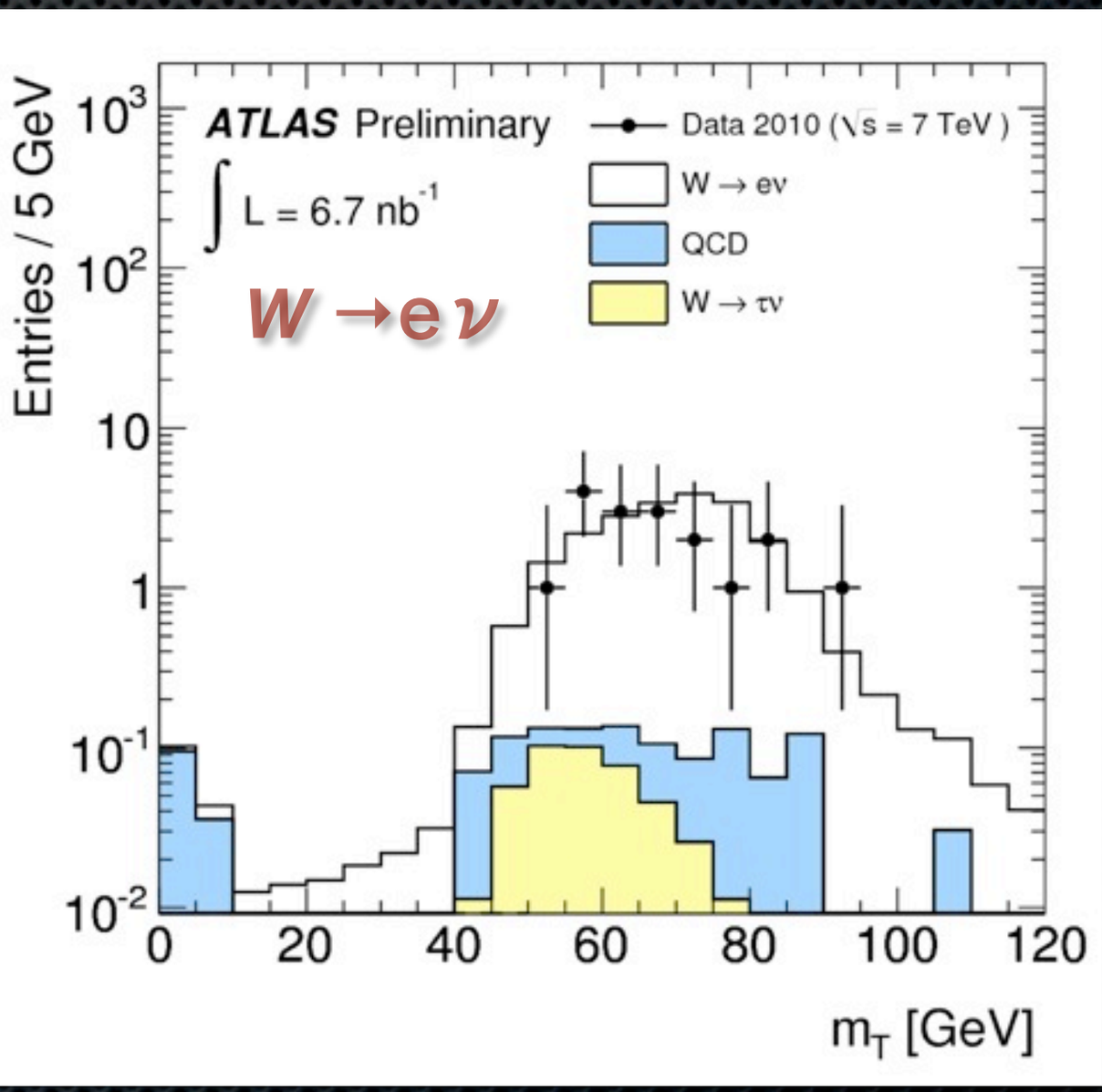
- Includes TRT information
- Includes pixels
- Further removes contamination from conversion and hadrons

The Muon Spectrometer

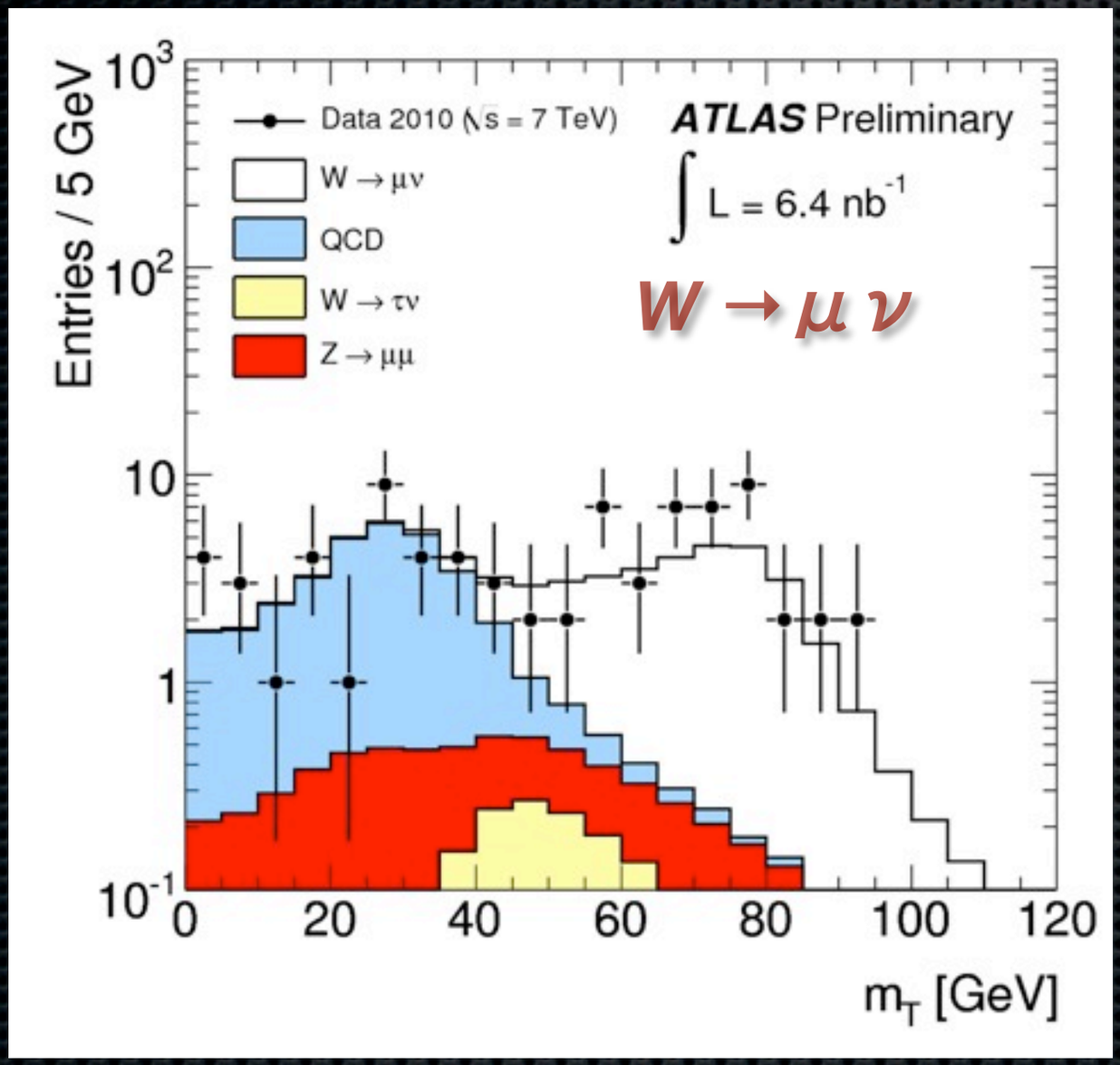


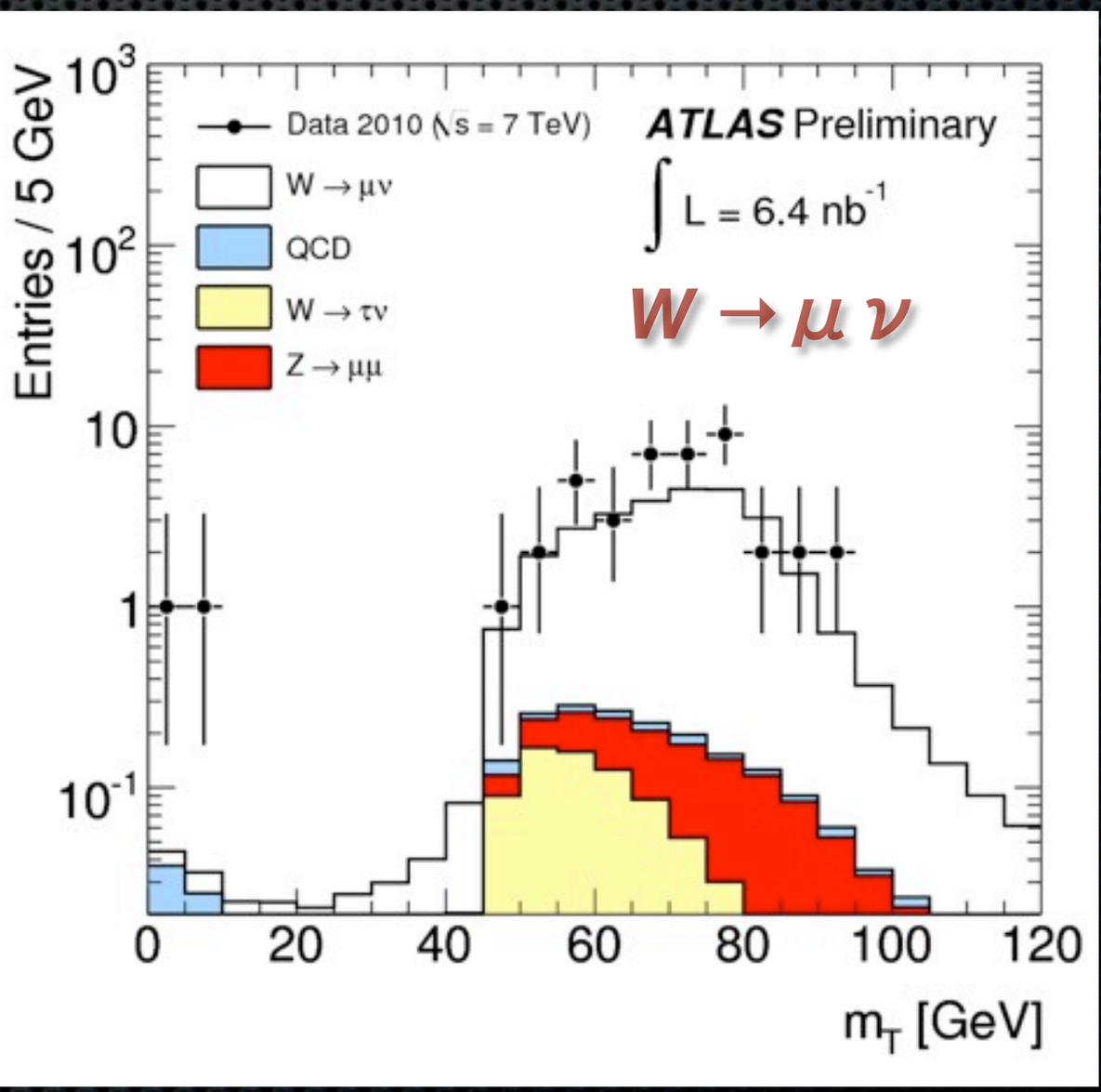
Transverse Mass for Electron Candidates



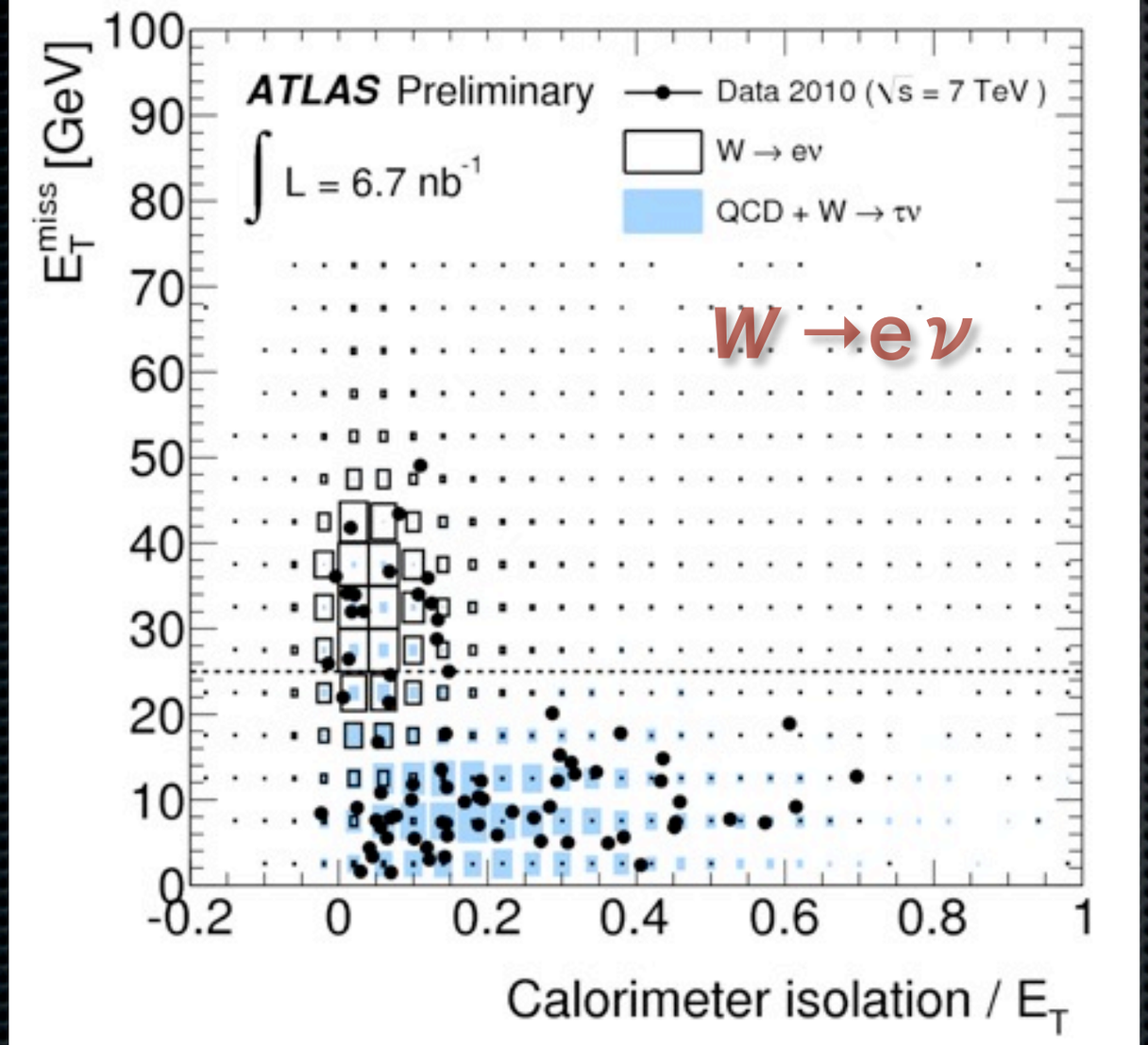


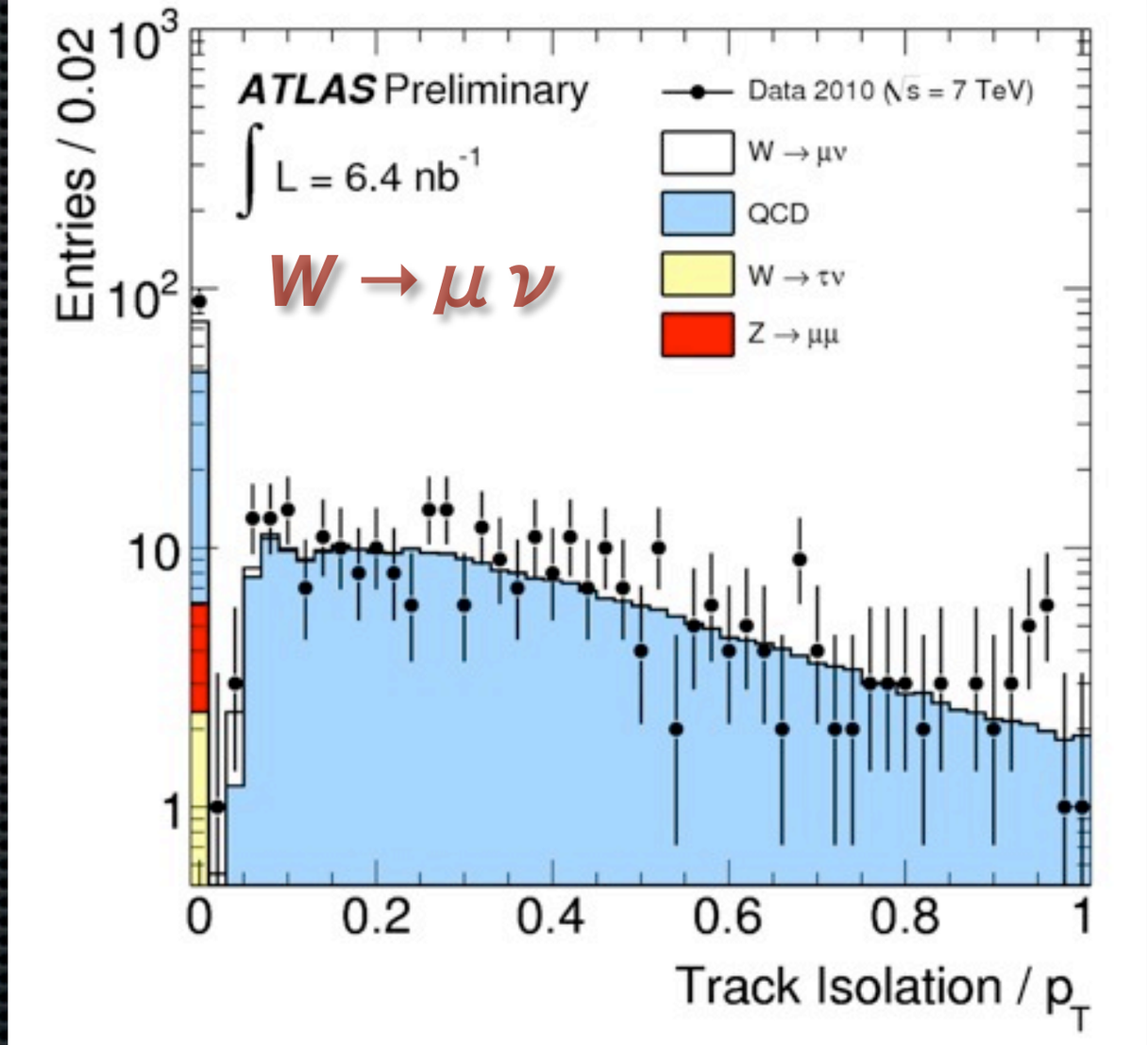
Transverse Mass for Muon Candidates





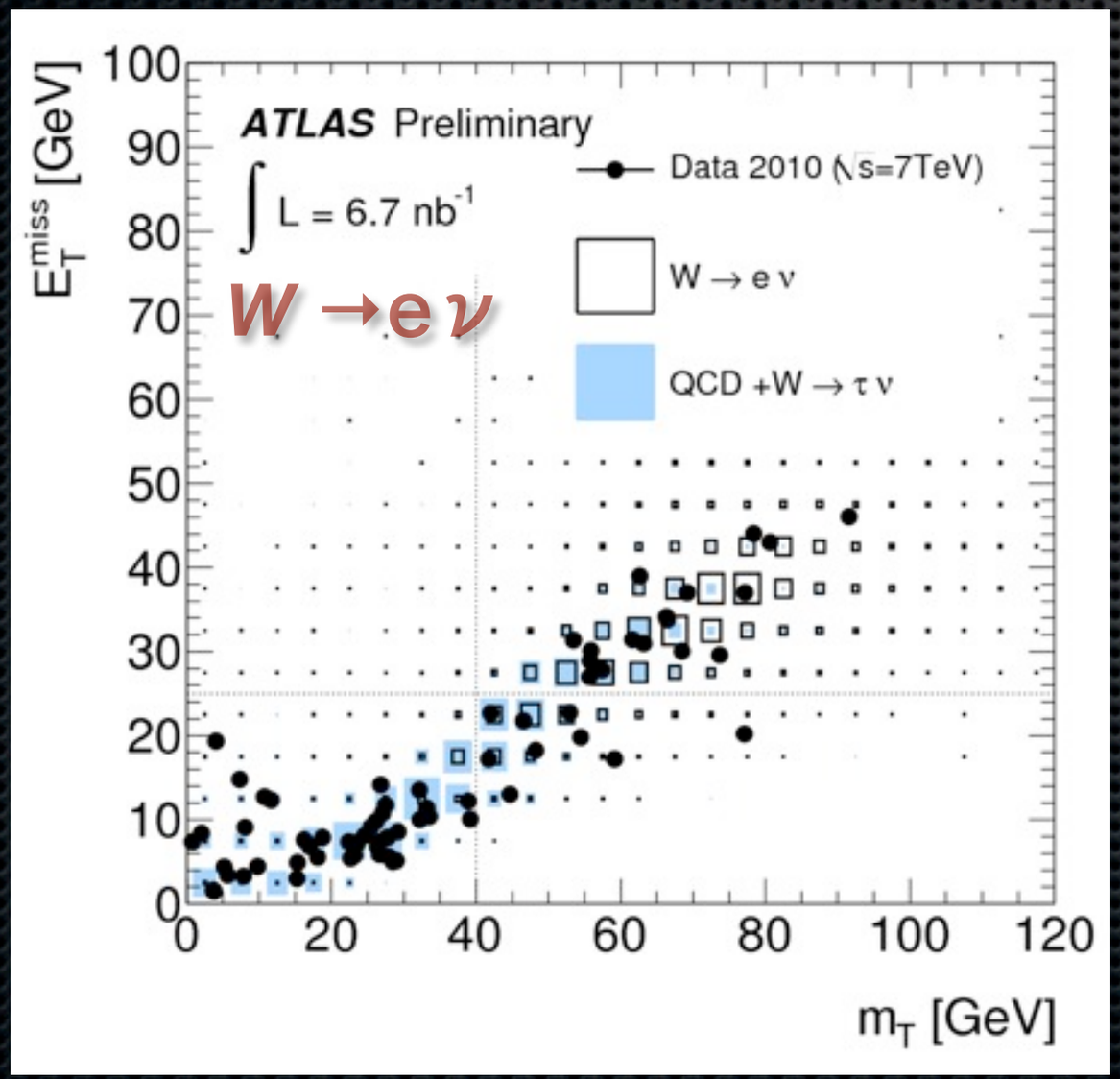
Isolation variables

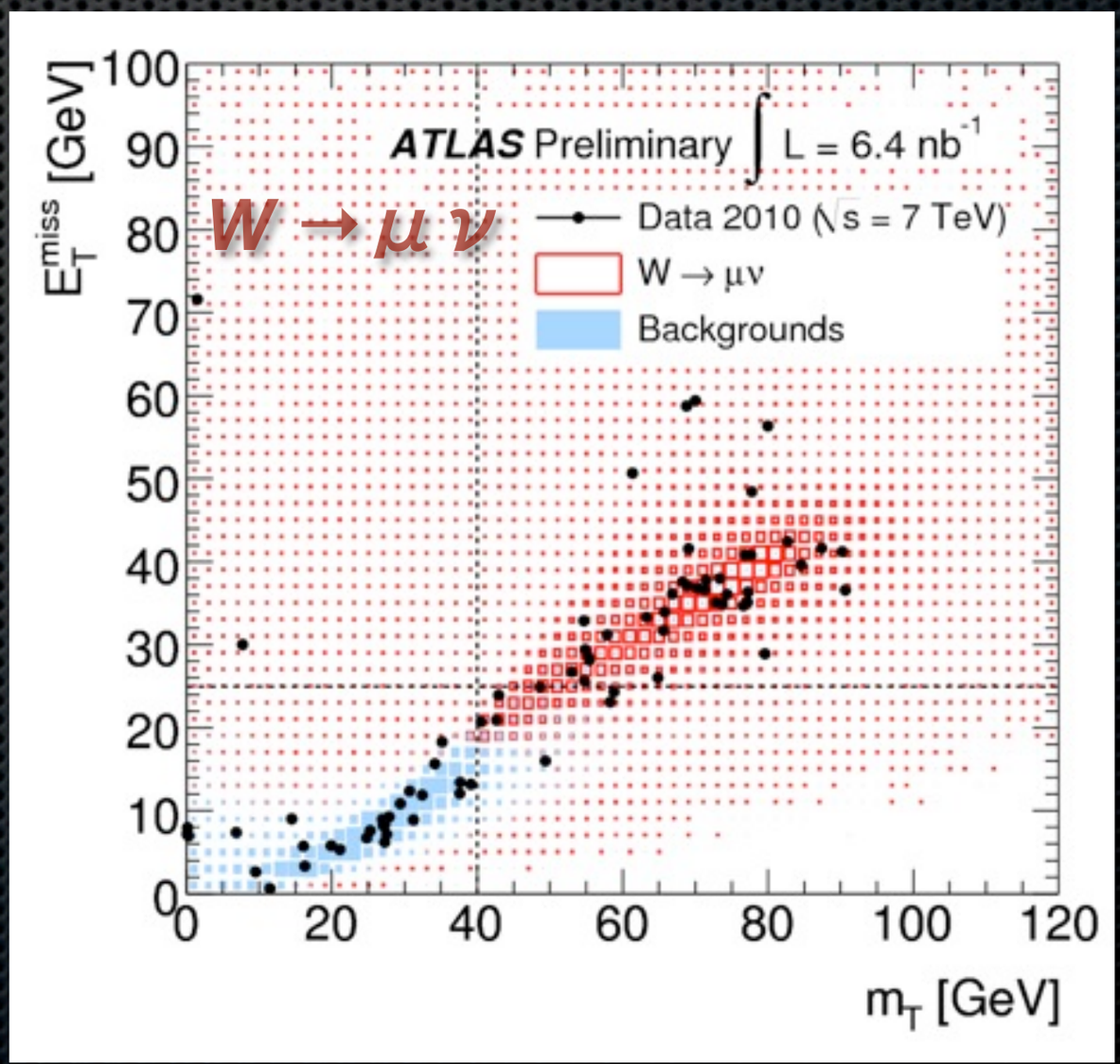




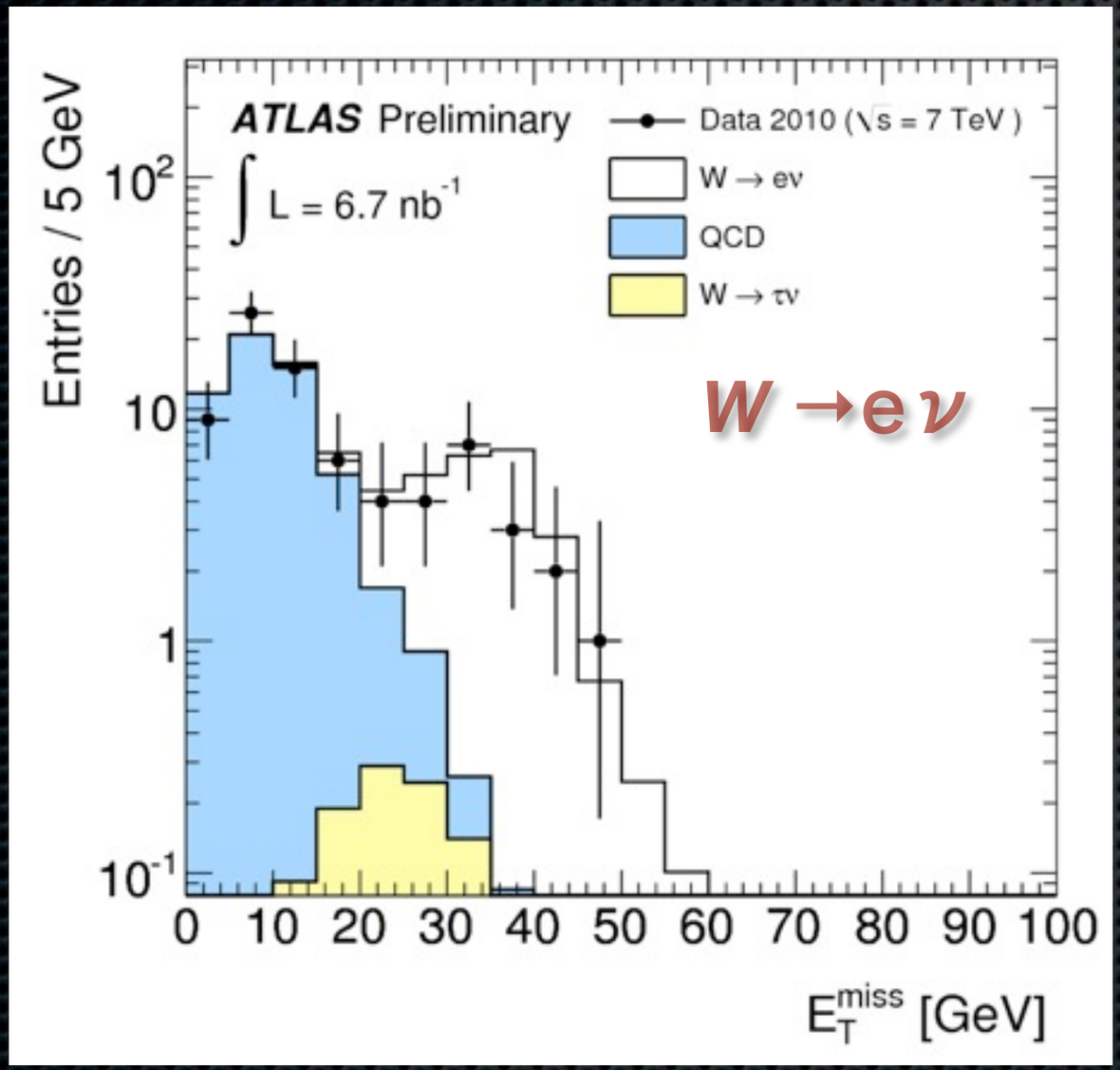
Properties of the W Boson Candidates

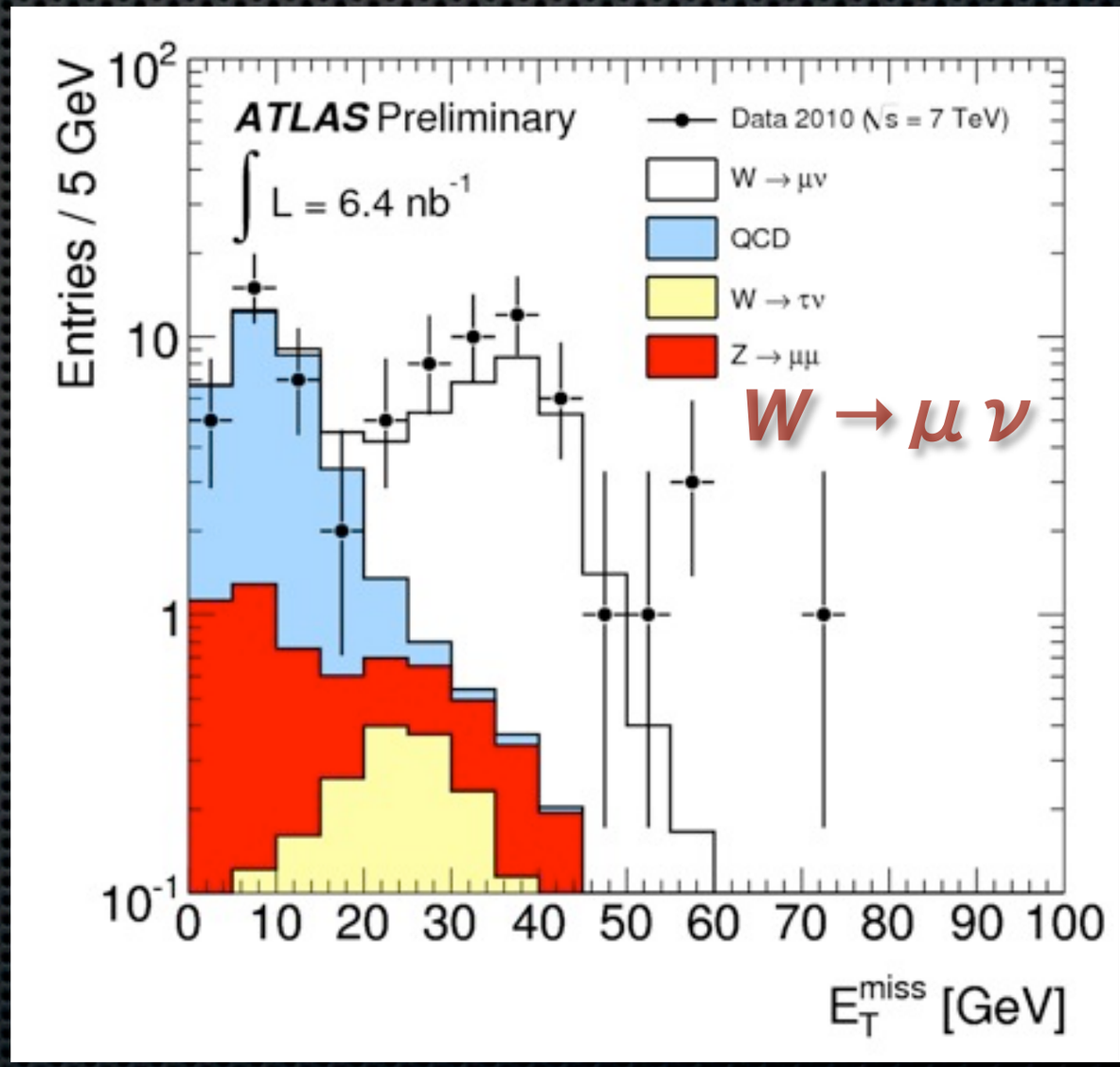
- Outliers in muon channel checked for a diverse set of problems
  - All muons are well isolated and consistent with the W boson hypothesis
    - Possibility of extra QCD background is not ruled out
- All events passed timing tests (in TRT, Calorimeters and MDT) showing they are inconsistent with being from cosmic



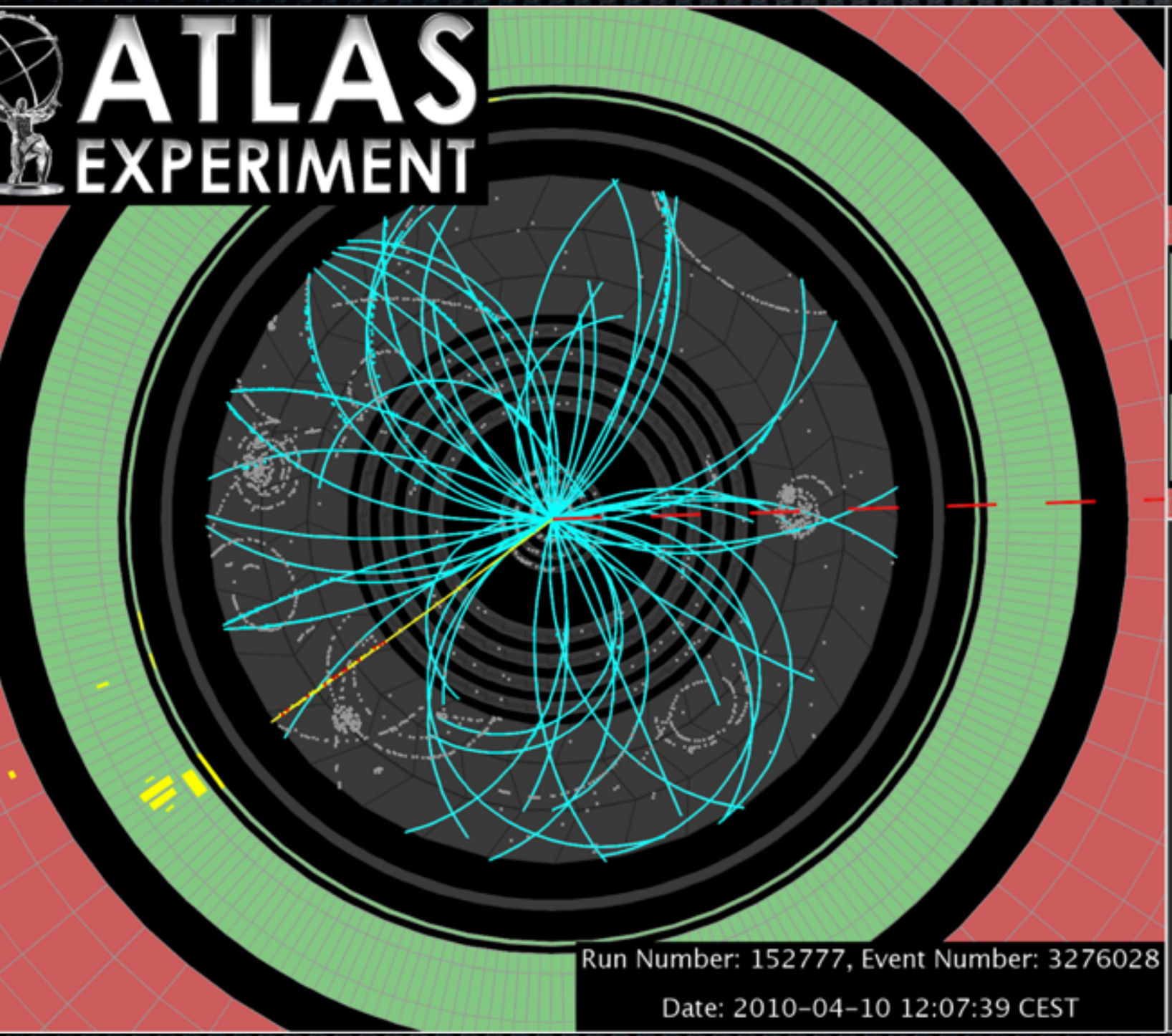


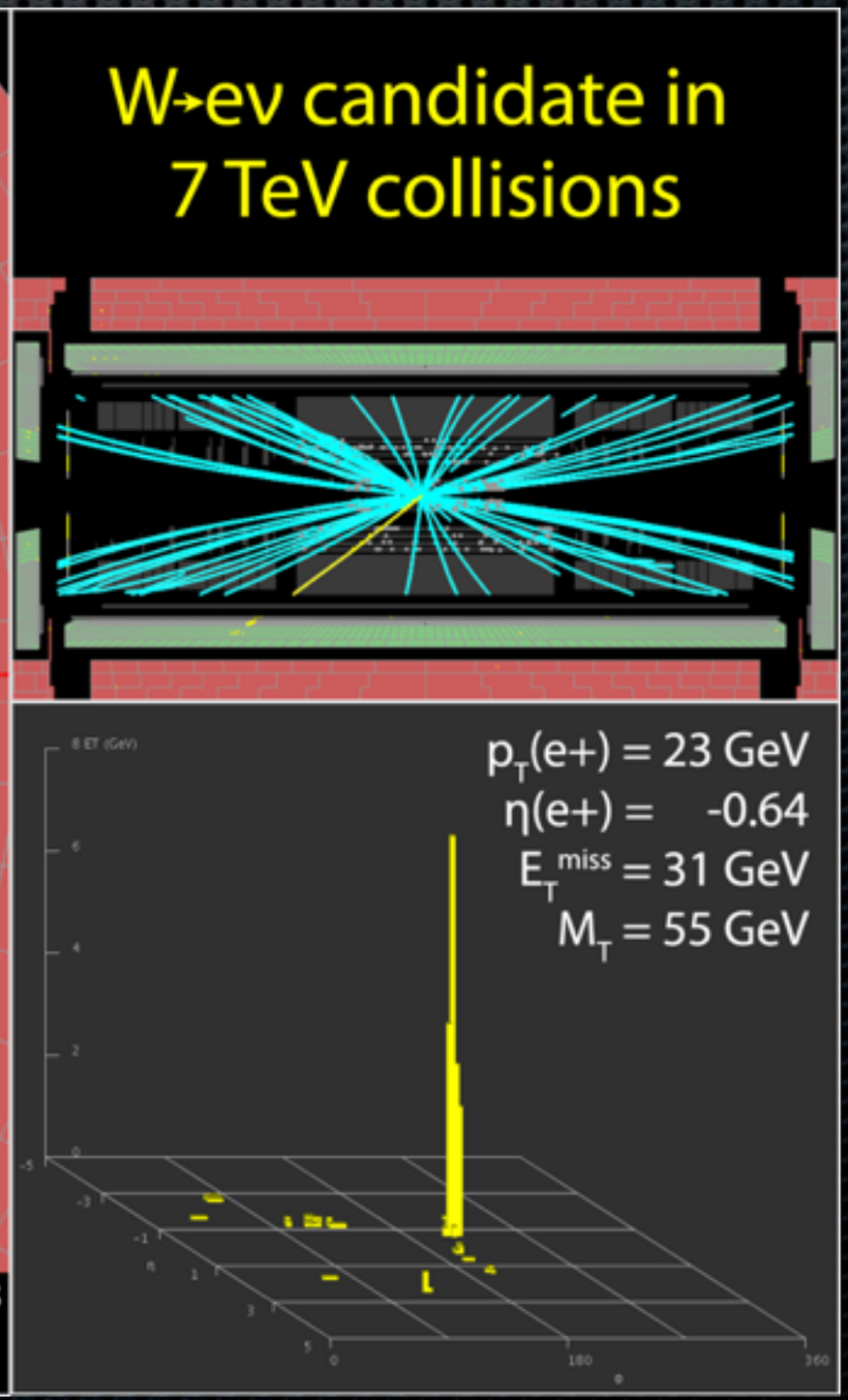
Missing Energy Prior to Transverse Mass Cut





$W \rightarrow e\nu$ Candidate Event

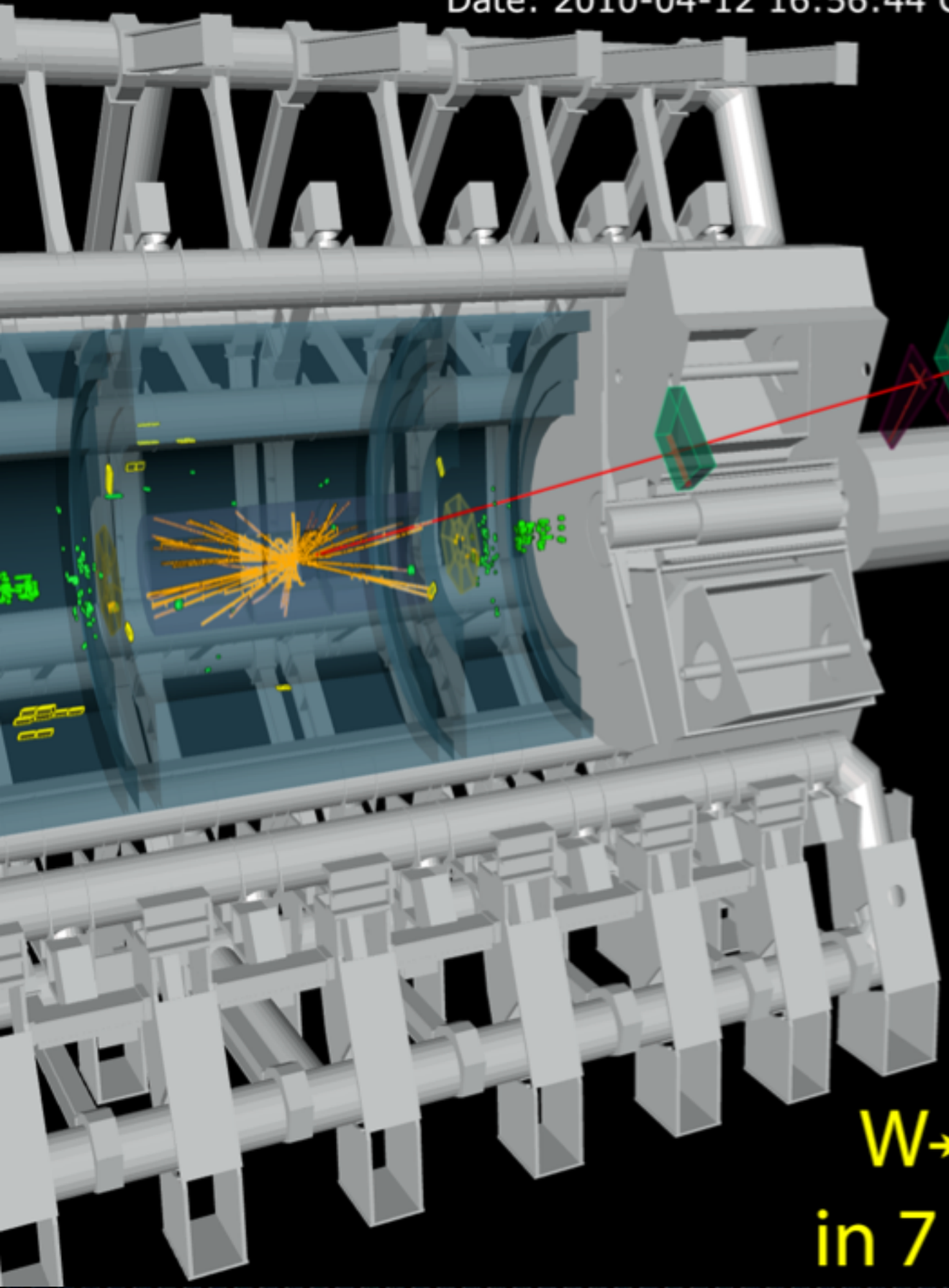


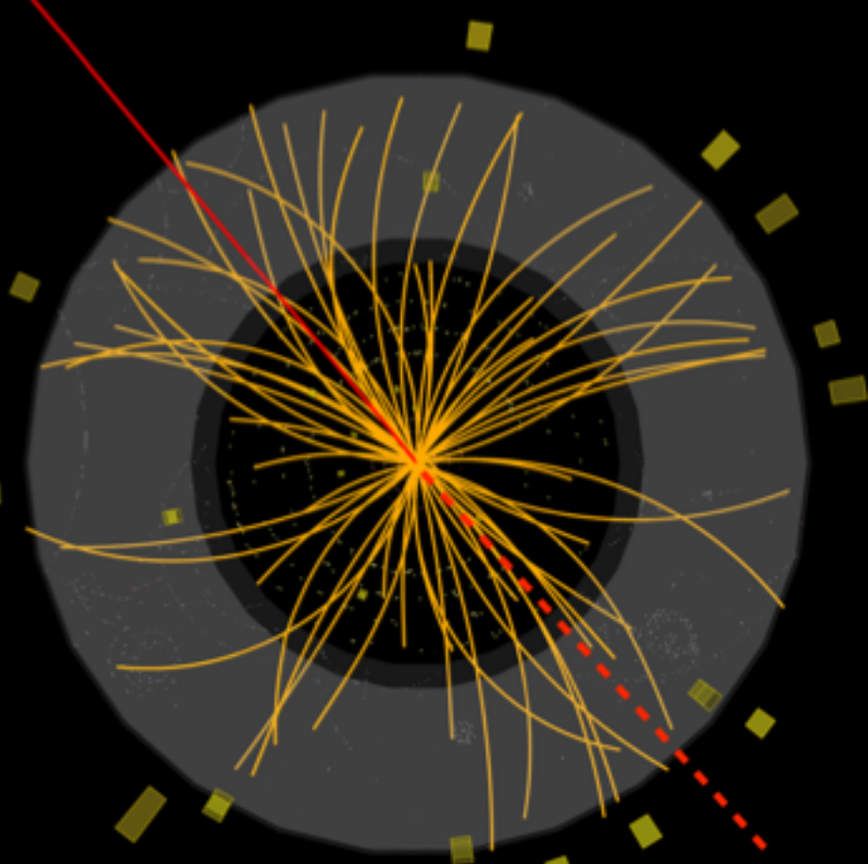


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST

ATLAS EXPERIMENT

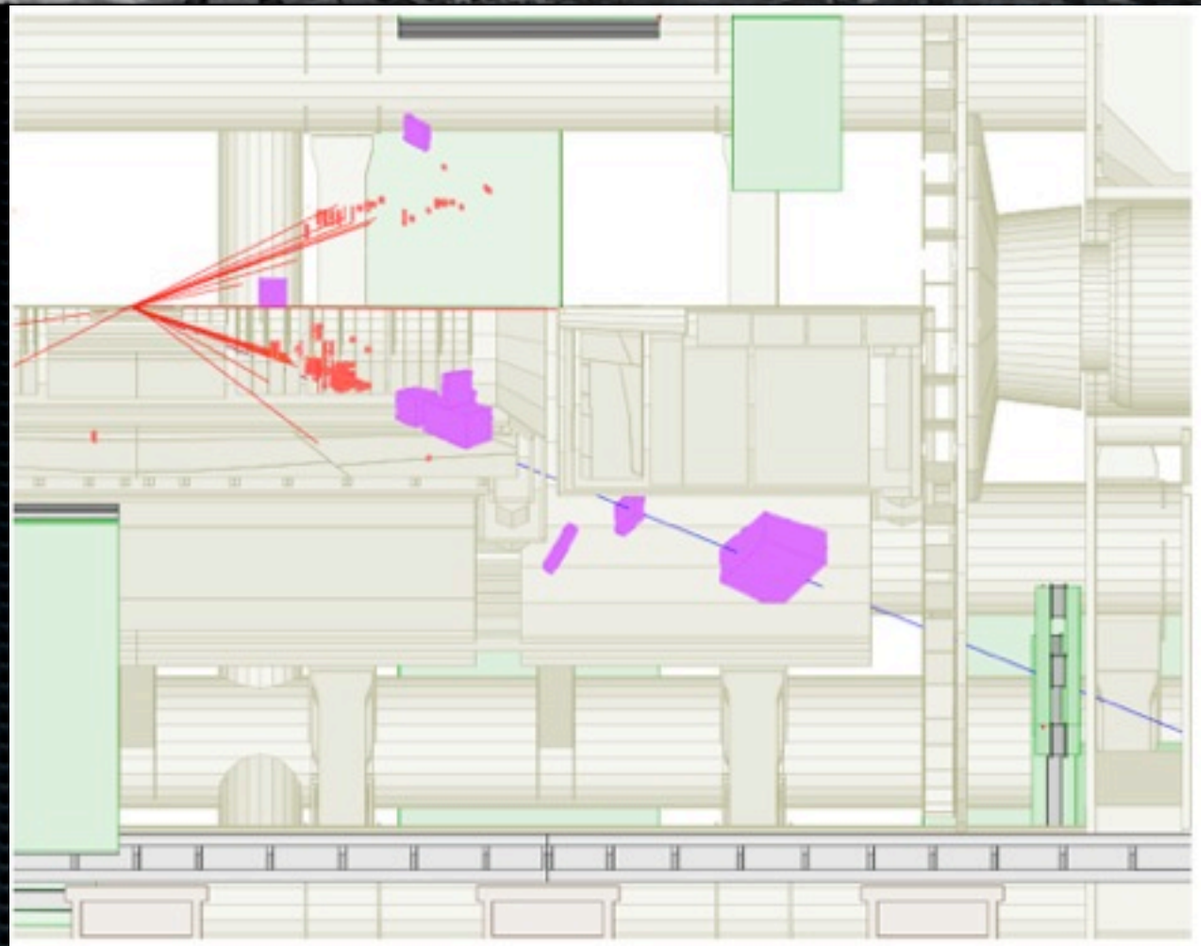
$p_T(\mu\text{-}) = 40$ GeV
$\eta(\mu\text{-}) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV

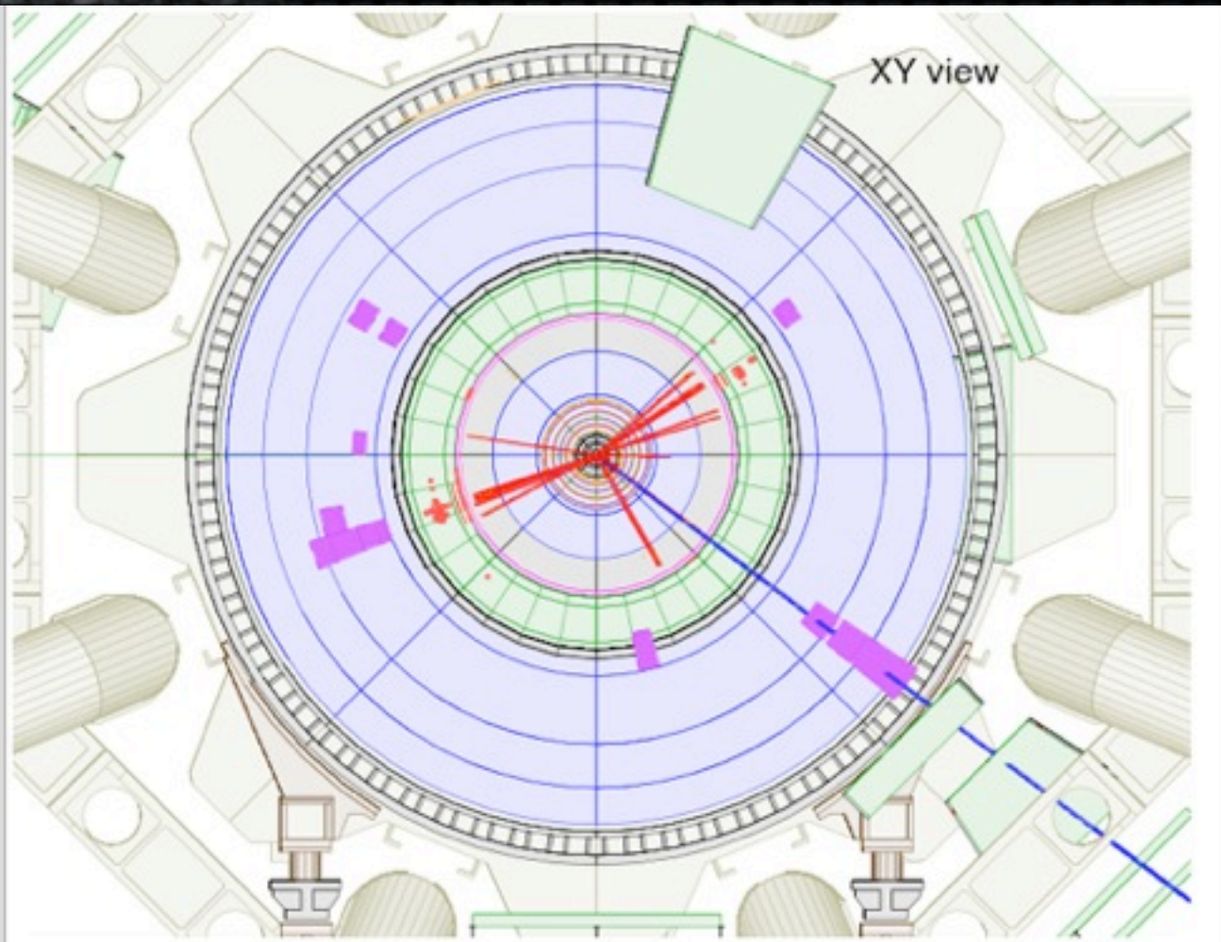


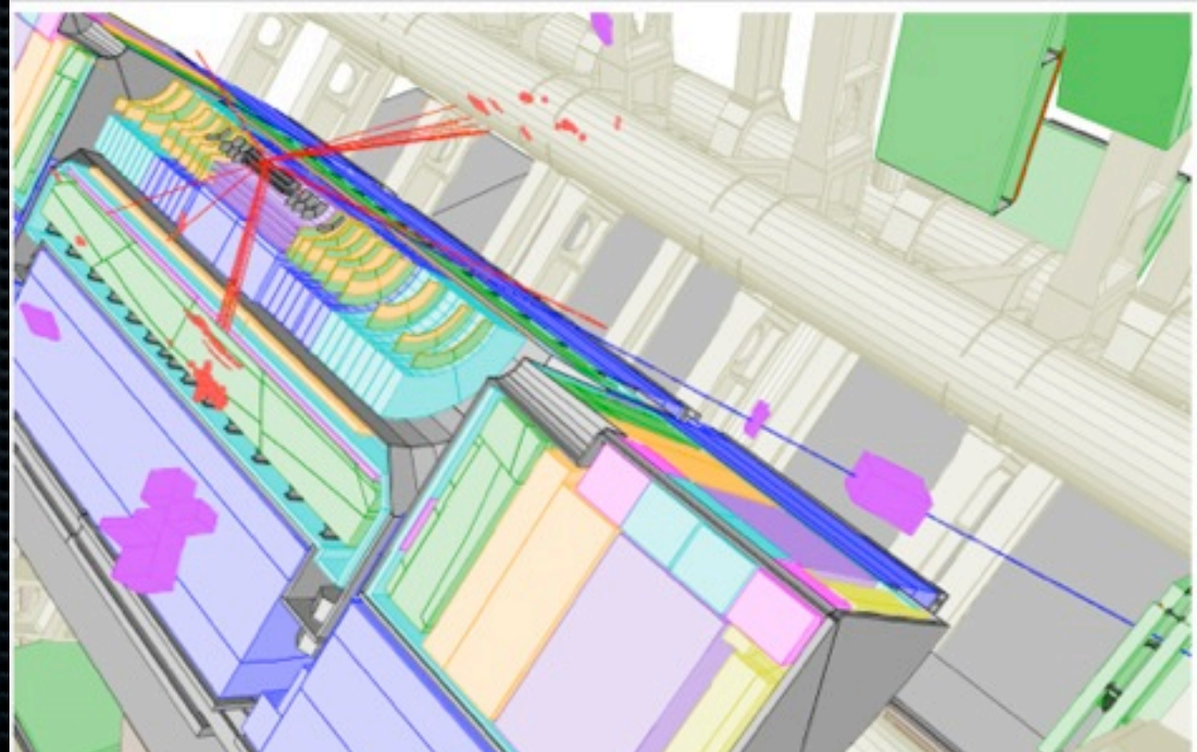


W→μν candidate
in 7 TeV collisions

$W \to \mu\, \nu$ Candidate Event with Di-jets

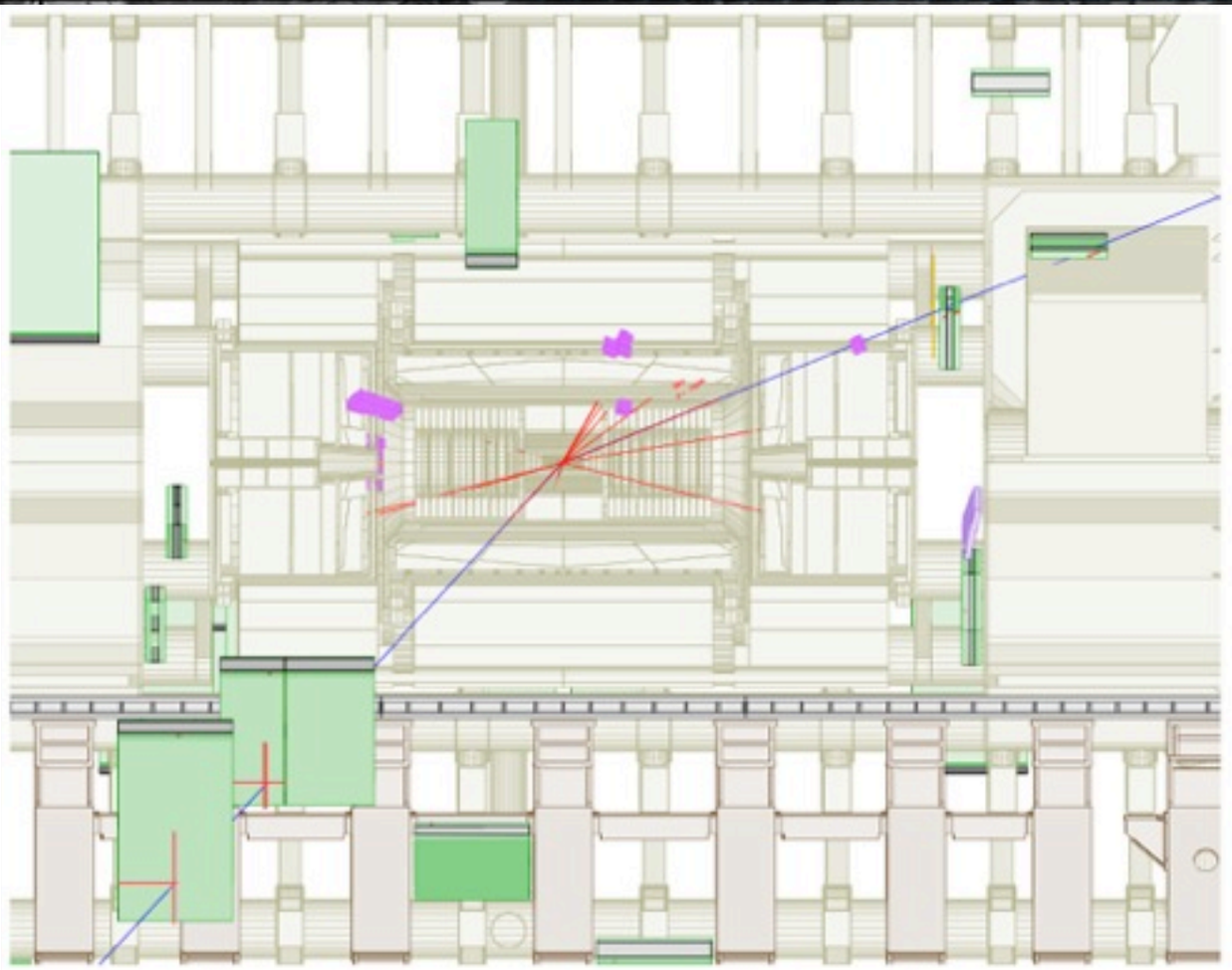


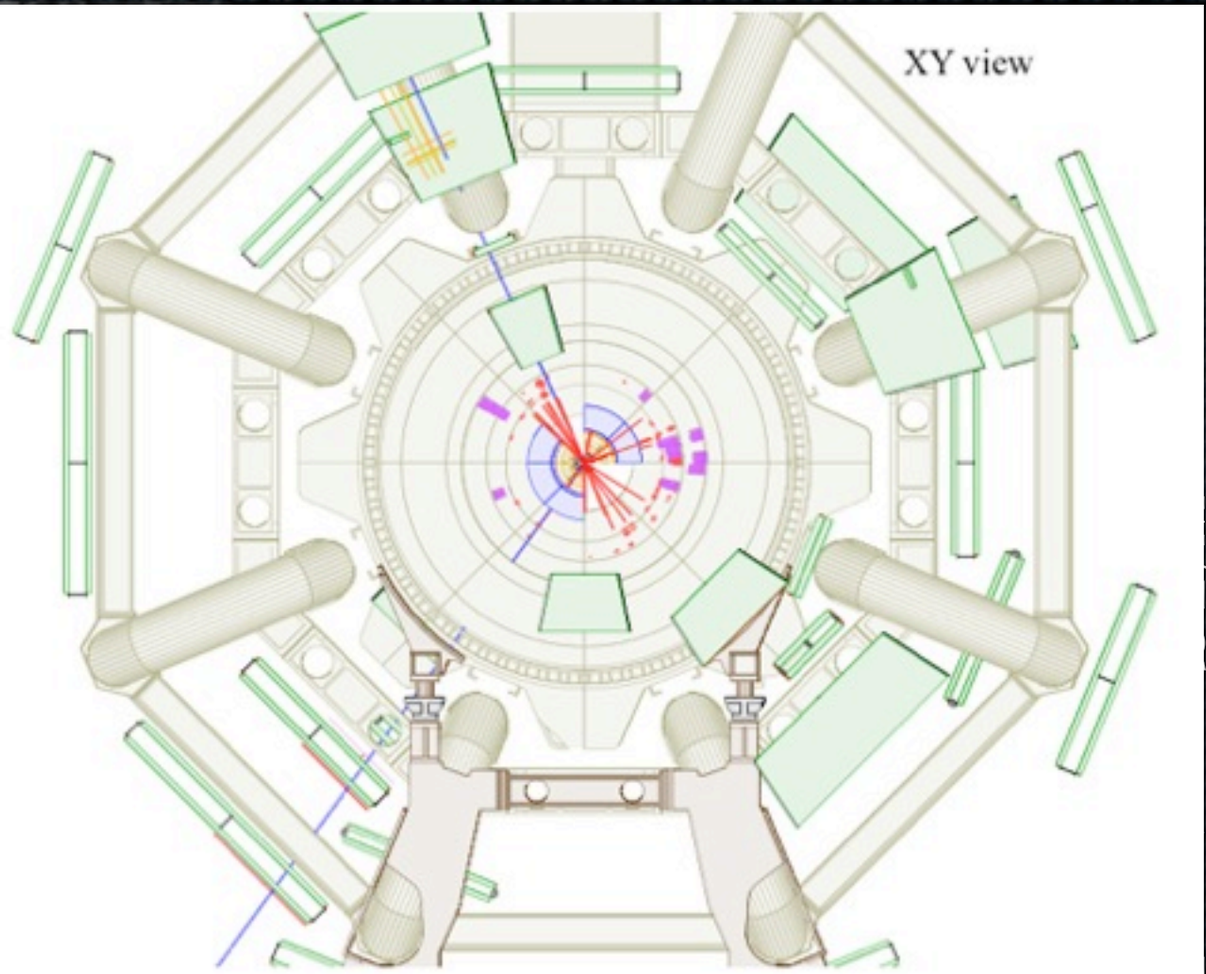


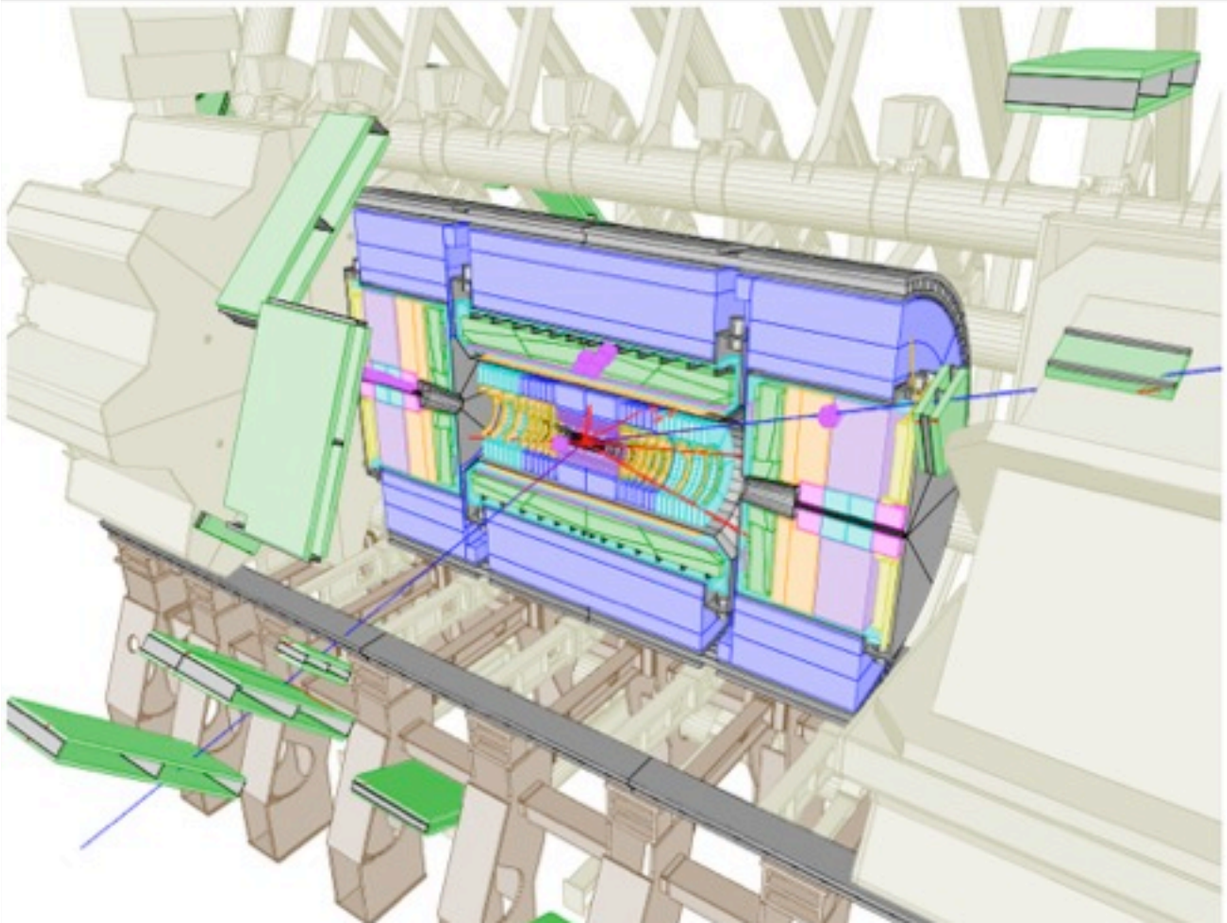


W->μν candidate in 7 TeV collisions

run#: 155112, event#:44298790
W_{MT} = 90 GeV, pT = 56 GeV
MET = 36 GeV
-Lepton:
pT(μ+) = 69 GeV, η = -1.19, ϕ = -2.5
-Jets:
jet 0 pt = 90 GeV, η = -0.87
jet 1 pt = 36 GeV, η = -1.09
sumEt = 170 GeV







Z->μμ candidate in 7 TeV collisions

run#: 1551127 event#: 79831531

Z: Minv = 80 GeV, Pt= 26 GeV

Pt(μ+) = 28 GeV, η = 0.69

Pt(μ -) = 21 GeV, η = 1.55

ATLAS