

Hard Scattering in Hadron-Hadron Collisions: Physics and Anatomy

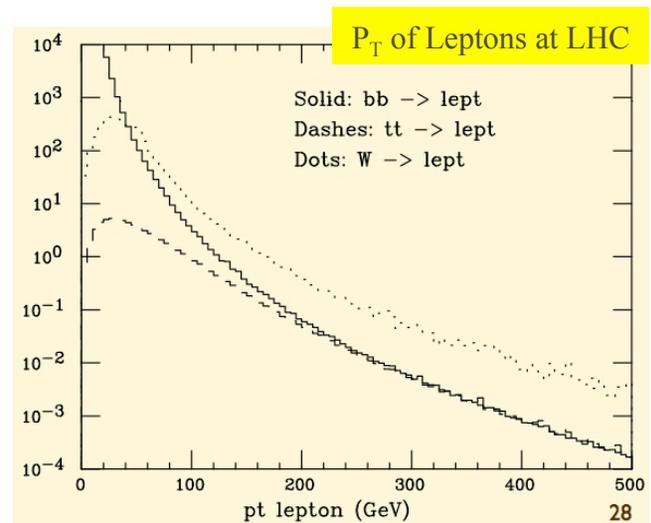
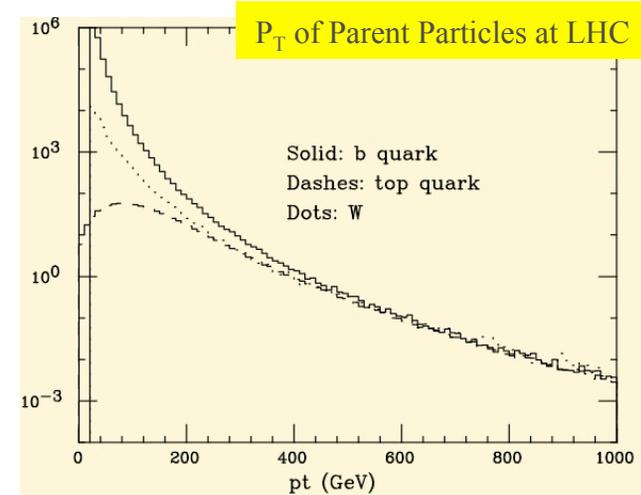
Section 5: Identification of Charged Leptons

1. Sources of leptons
2. ID techniques for electrons, muons and taus
3. Identification efficiencies
4. Background considerations
5. Example: Top quark decays to τ leptons

Sources of Leptons

- **In hadron-hadron collisions, leptons arise from**
 - Semileptonic decay of heavy quarks (t/b/c)
 - W and Z boson decay
 - Drell-Yan production
 - “Onia” production/decay
- **Various sources of backgrounds**
 - **Electrons**
 - > Photon conversions
 - > Misidentified jets
 - **Muons**
 - > Cosmic rays
 - > Decays-in-flight of hadrons
 - **Taus**
 - > Misidentified jets

$d\sigma/dpt$ (pb/5 GeV)

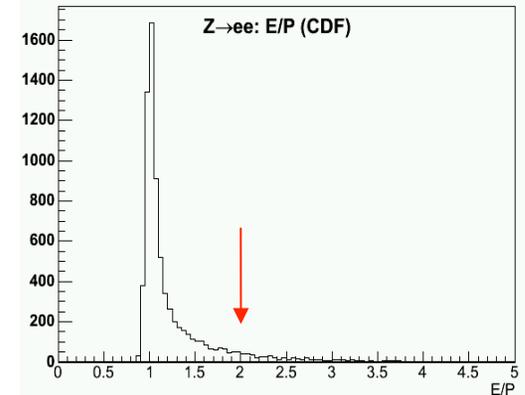
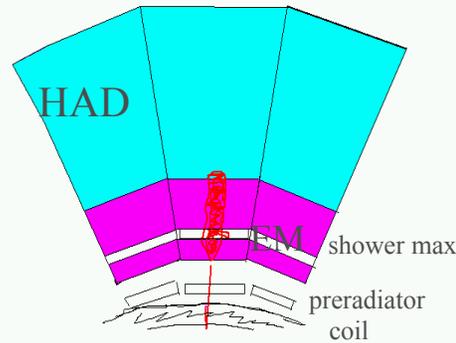


Courtesy of M. Mangano

Electron Identification Strategies

■ Identification makes use of

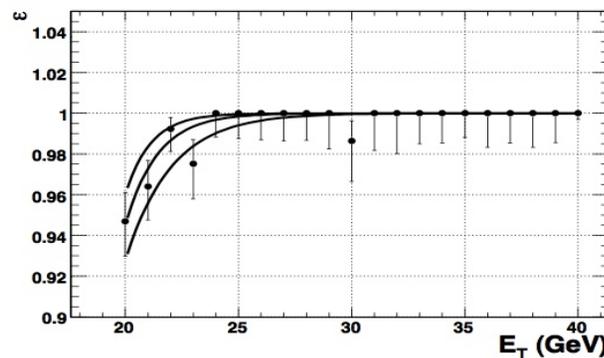
- **Calorimeter**
 - > Shower shape and location
- **Charged particle reconstruction**
 - > Position matching
 - > Energy vs Momentum
- **TRD and/or dEdX**
 - > TRD perhaps has the highest rejection power



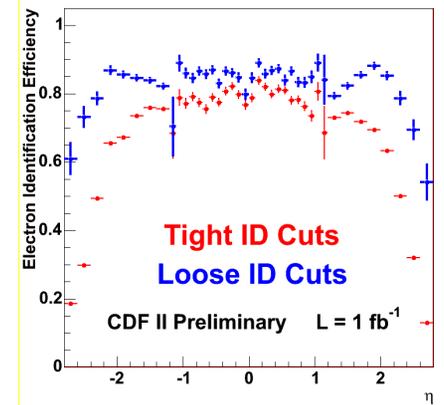
■ Strategy works well, but

- **Depends on a large number of ID variables**
 - > Have to be well-modelled
- **Requires "isolated" lepton candidates**
 - > Electrons from b/c decays difficult to reconstruct
- **Have correlation between tracks & calorimetry in trigger**

Trigger Efficiency from $Z \rightarrow e+e-$



ID Efficiency from $Z \rightarrow e+e-$



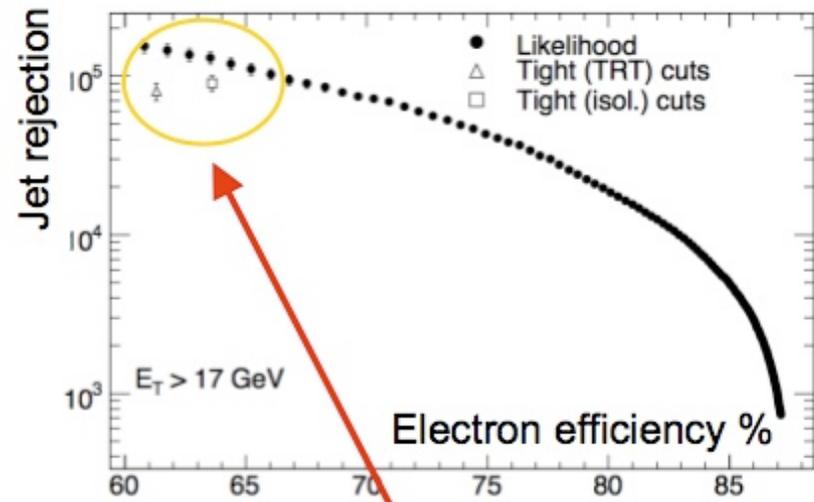
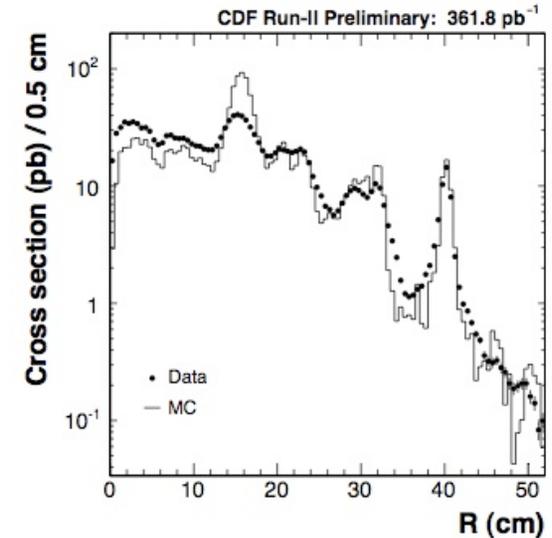
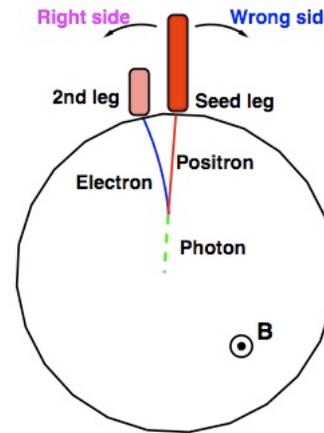
Backgrounds to Electrons

■ Backgrounds have to be measured

- **Conversions ($\gamma \rightarrow e^+e^-$)**
 - > Source of real electrons (about 30-40% of electrons above $P_T > 12 \text{ GeV}/c$)
 - Search for partner leg, or
 - No charged track
 - > Large background, but also a good control sample
- **Jets**
 - > π^+/π^0 overlap
 - Two pions overlap & mimic electron signature
 - > Charge-exchange
 - $\pi^+p \rightarrow \pi^0 n$ early in calorimeter

■ Can get to relatively pure samples

- $S/N > 10-100$, depending on process
- ATLAS/CMS expect to be able to do very well
 - > $Z \rightarrow e^+e^-$ provides excellent “standard candle”



Cut-based results vs likelihood

Performance of ATLAS

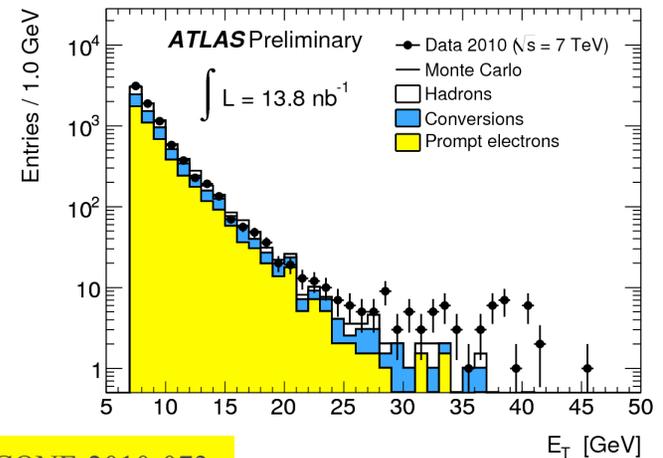
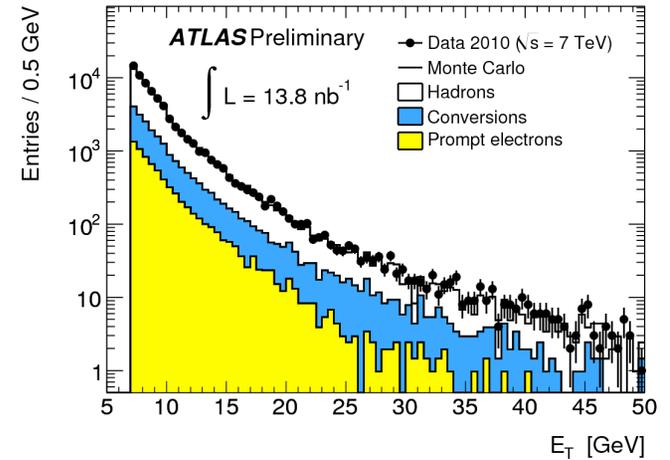
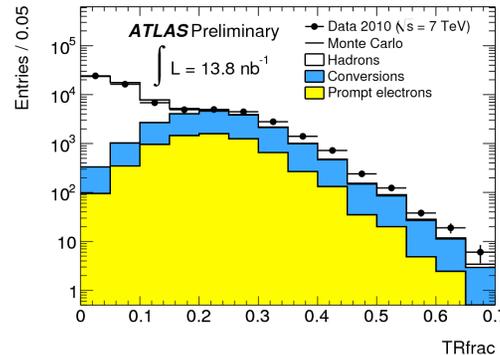
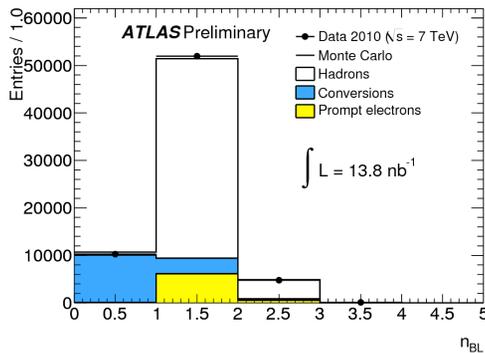
- **Developed sets of ID cuts that efficiently select electrons**
 - Key is to separate “prompt” electrons from
 - > Conversions ($\gamma \rightarrow e^+e^-$)
 - > Candidate from hadrons/jets
 - Use two variables
 - > Number of hits in pixel detector
 - Conversions typically have fewer
 - > Fraction of large pulse-height “hits” in TRT

- **Can then solve for the three components**

$$N = N^h + N^\gamma + N^Q$$

$$N_{TR} = N^h \epsilon_{TR}^h + N^\gamma \epsilon_{TR}^\gamma + N^Q \epsilon_{TR}^Q$$

$$N_{BL,TR} = N^h \epsilon_{BL}^h \epsilon_{TR}^h + N^\gamma \epsilon_{BL}^\gamma \epsilon_{TR}^\gamma + N^Q \epsilon_{BL}^Q \epsilon_{TR}^Q$$

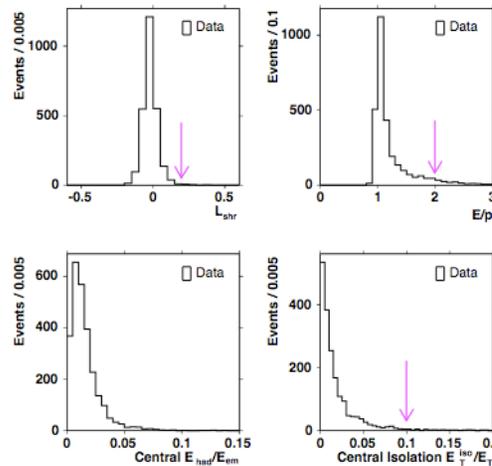


ATLAS-CONF-2010-073

Component	$h \rightarrow e$		$\gamma \rightarrow e$		$Q \rightarrow e$	
	Matrix	Likelihood	Matrix	Likelihood	Matrix	Likelihood
Fraction of electron candidates	65.2 ± 0.4	65.4 ± 0.3	19.8 ± 0.2	19.4 ± 0.2	15.0 ± 0.2	15.2 ± 0.2

Cut-Based Lepton ID Selections

- **Electron ID uses a large number of variables**
 - Traditionally, define selection criteria
 - Measure efficiencies of each cut in well-understood control sample
 - > Relax the cut and see how control sample responds



- **Likelihood techniques in principle more efficient**
 - But more difficult to understand in detail
 - Correlations are important to get right

Z Selection and Efficiency

- **Challenge is how to measure efficiencies & backgrounds**
 - Need to understand correlations between cuts
 - Multiple control samples are very helpful
 - Remember trigger also performs selection!

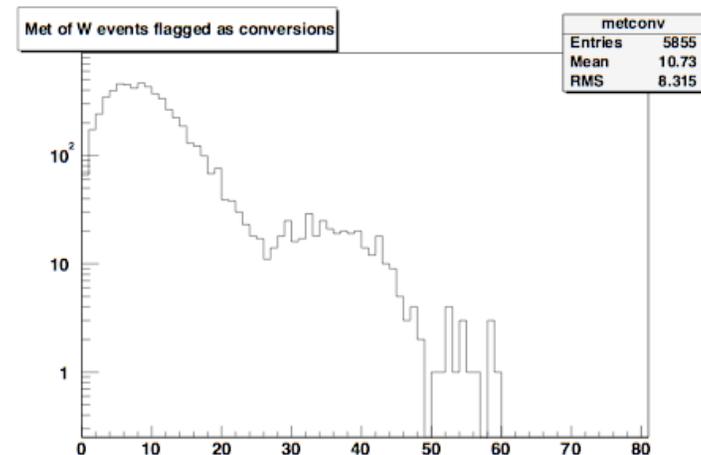
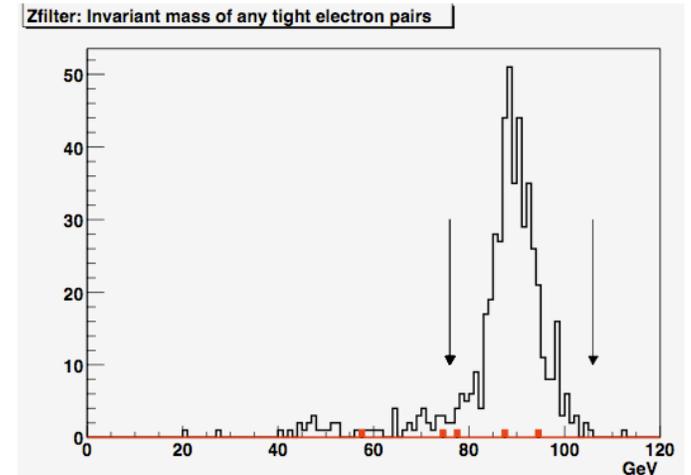
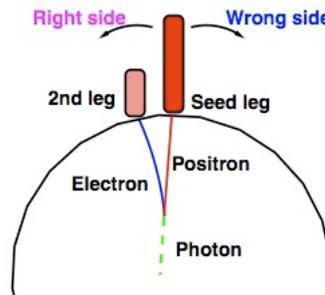
Selection Criteria	Number of Events	Net Acceptance
Total Events	507500	-
$ z_{vtx} < 60$ cm	490756	-
$66 \text{ GeV}/c^2 < M_{ee}(\text{Gen}) < 116 \text{ GeV}/c^2$	376523	-
Central EM Cluster	363994	0.9667 ± 0.0003
Calorimeter Fiducial Cuts	299530	0.7955 ± 0.0007
Electron Track $p_T > 10 \text{ GeV}/c$	252881	0.6716 ± 0.0008
EM Cluster $E_T > 25 \text{ GeV}$	186318	0.4948 ± 0.0008
Second EM cluster (Central or Plug)	176417	0.4685 ± 0.0008
Second Cluster Calorimeter Fiducial Cuts	146150	0.3882 ± 0.0008
Second Electron Track $p_T > 10 \text{ GeV}/c$ (Central)	138830	0.3687 ± 0.0008
Second EM Cluster $E_T > 25 \text{ GeV}$ (Central), 20 GeV (Plug)	125074	0.3322 ± 0.0008
Second EM Cluster $E_{had}/E_{em} < 0.125$ (Plug)	124881	0.3317 ± 0.0008
$66 \text{ GeV}/c^2 < M_{ee}(\text{Rec}) < 116 \text{ GeV}/c^2$	120575	0.3202 ± 0.0008
Opposite Charge (Central-Central)	119925	0.3185 ± 0.0008

Abulencia et al. (CDF), J. Phys G 34, 2457 (2007)

Example: Conversion Removal

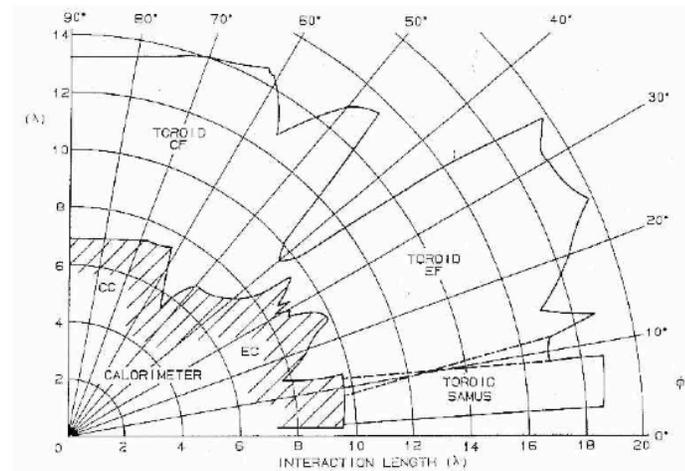
■ To identify conversions, CDF uses presence of 2nd track & SVX hits

- ~85% efficiency in identifying conversions in electron sample with $P_T > 9$ GeV/c
 - > Residual background depends on other cuts
- Significant “over-efficiency”
 - > Probability of misidentifying a prompt electron as γ
 - > Measure this using $Z \rightarrow e^+e^-$ decays
 - > Get between 5-10%, depending on details of algorithm
 - Measured to be $4.5 \pm 0.6\%$
- Check against W 's
 - > “Bump” at high MET are W s identified as conversions
 - > Gives a consistent answer



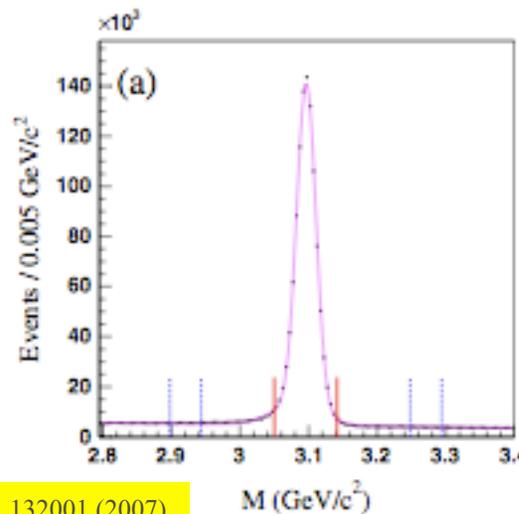
Muon Identification

- All techniques are based on highly-penetrating nature of γ
 - Have large amount of material ($>10 \lambda$)
 - > Require min-ionizing particle
 - Calorimeter energy deposition
 - Track particles before and after material
 - > Momentum analyze
 - Shown to be very effective
 - > High rejection factors, especially with isolation

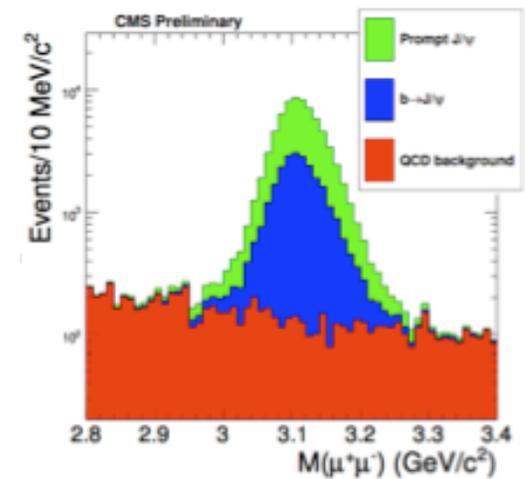


D0 Material Inventory vs Azimuth (quarter of detector)

- Backgrounds are primarily
 - Cosmic rays
 - Decay-in-flight for lower momentum candidates
 - Size of background depends critically on other requirements

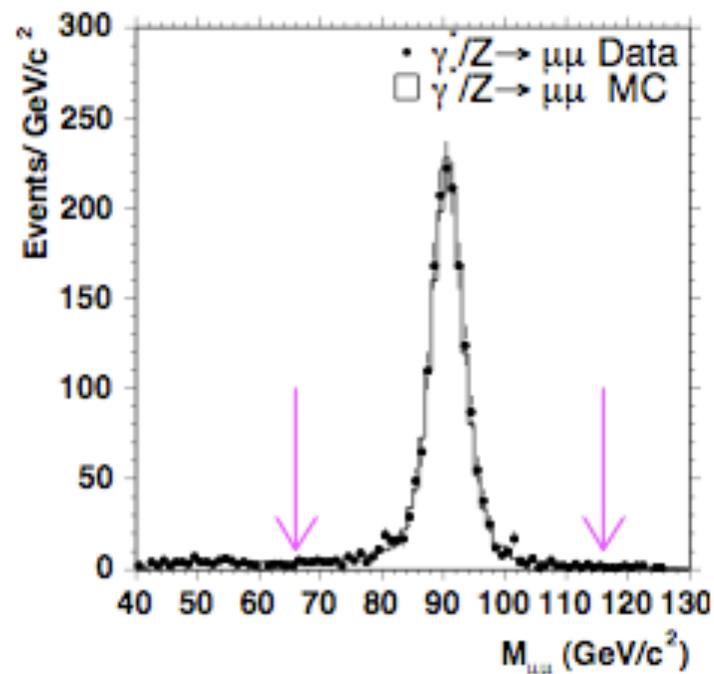


CDF, PRL 99, 132001 (2007)



Muon ID Efficiencies

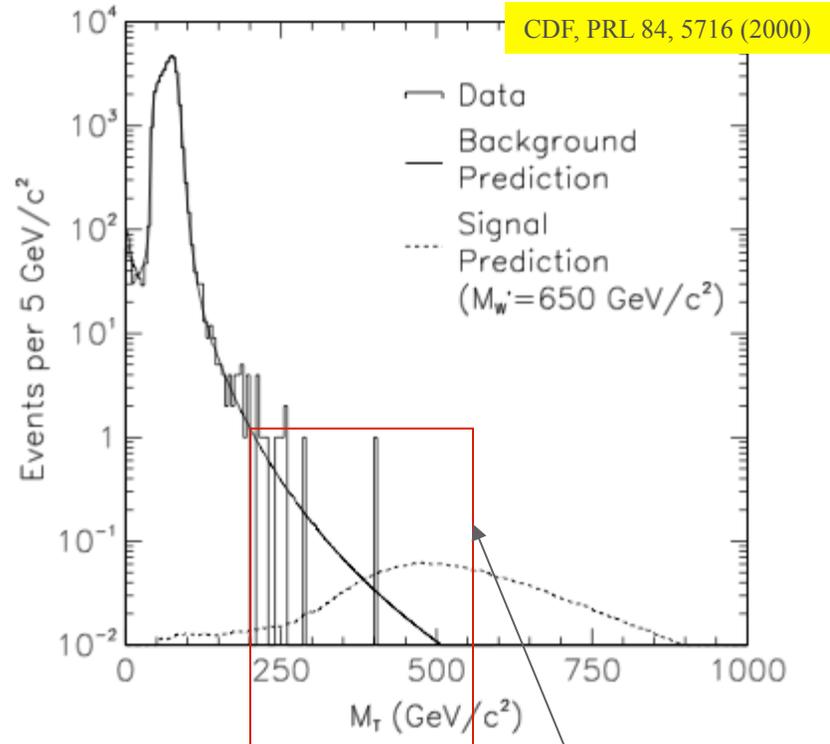
- **Efficiencies for high- P_T μ determined from $Z \rightarrow \mu^+ \mu^-$**
 - Select events requiring one μ candidate $P_T > 20$ GeV/c
 - Look at efficiency of reconstructing second leg
- **Can get MC/simulation to agree approximately**
 - Predicts 92.1% efficiency, but measure $88.6 \pm 0.9\%$
 - Rejection hard to quantify
 - > Key question is “rejection from what?”
 - In some sense, not relevant if one measures remnant background directly
 - > Limiting backgrounds are
 - Cosmic rays
 - QCD jets “punching through”



	data		MC	
No cuts applied	1153		28271	
Em Cut	1126	0.9766 ± 0.0044	27203	0.9622 ± 0.0011
Had Cut	1131	0.9809 ± 0.0040	27654	0.9782 ± 0.0009
Cot Cut	1128	0.9783 ± 0.0043	28226	0.9984 ± 0.0002
d0 Cut	1150	0.9974 ± 0.0015	28254	0.9994 ± 0.0001
isol Cut	1126	0.9766 ± 0.0045	27692	0.9795 ± 0.0008
dxemu Cut	1114	0.9662 ± 0.0053	28228	0.9985 ± 0.0002
all Cuts	1022	0.8864 ± 0.0093	26025	0.9206 ± 0.0016
all (w/o isol) Cuts	1044	0.9055 ± 0.0086	26523	0.9382 ± 0.0014

Backgrounds to Muons

- **Backgrounds depend on the physics process & other requirements**
 - Already see that dilepton signals are very clean
 - **Probably most difficult region is high momentum**
 - > Example is $W' \rightarrow \mu\nu_\mu$
 - Only high P_T object in detector is μ candidate
 - > Data comes from Run 1 with 100 pb^{-1}
- **Difficult to find a signal limited by backgrounds!**
 - Most backgrounds at high P_T are “intrinsic” -- ie., have a real μ



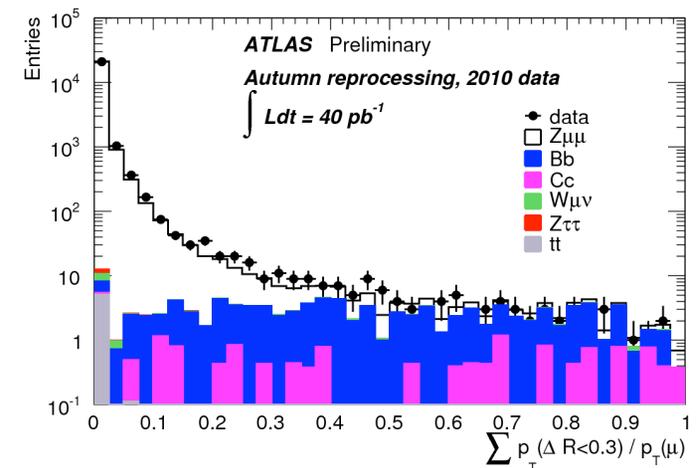
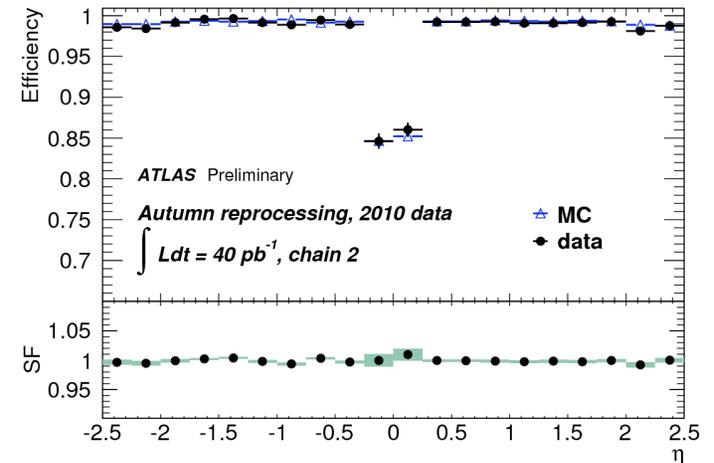
14 events $M_T > 200 \text{ GeV}/c^2$
and 12 expected (mostly W)

Muon Backgrounds at ATLAS

CDF, PRL 84, 5716 (2000)

- **ATLAS muon reconstruction is intrinsically cleaner**
 - **The primary background sources are hadrons decaying in flight**
 - > Become negligible at large p_T
 - **See this most clearly when looking at Z $\rightarrow \mu\mu$ decays**
 - > Very clean sample, with less than 1% background from non-m

- **Efficiency overall is $\sim 97\%$**
 - **Comes from a combined strategy of matching tracks in inner detector with muon spectrometer**
 - **This sample shows how effective “isolation” is in separating out the different sources**
 - > Heavy flavour decay
 - > Z and $t\bar{t}$ production



Comment on Isolation

- Isolation requirements on lepton candidates appear to be powerful tool.

- Why?

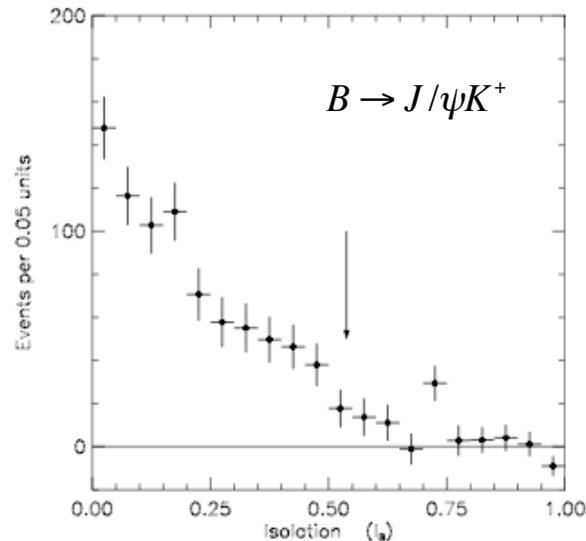
- Think about backgrounds:
 - > Jets faking leptons tend to be associated with additional particles
 - > Semileptonic decays of b/c jets also have associated energy
- On the other hand, leptons from W/Z decay are generally isolated

- But many forms of “isolation cuts”

- Some implicit
 - > Example: lepton ID criteria
- Some explicit
 - > Energy (or charged tracks) in a cone $\Delta R=0.2$ or $\Delta R=0.4$
 - Cut on ratio of E_T in cone to lepton candidate (10% typical)

- However, there are many ways to look at isolation

- Example comes from $B \rightarrow \psi(2S)\pi\pi$
- Form cone of $\Delta R=1.0$ around B candidate
 - > Sum up tracks not associated with B candidate
 - > Reject events with $I_B > 7/13$



$$I_B = \frac{\sum_{i \neq B}^R \vec{p}_i \cdot \vec{p}_B}{|\vec{p}_B|}$$

Tau Lepton Identification

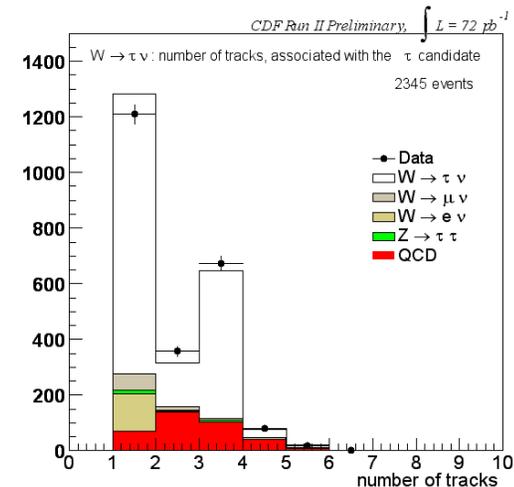
Tau Listing, 2008 PDG

■ Tau leptons difficult to identify

- Decay to either
 - > Leptonic final state ($\mu/e+\nu\nu$)
 - 37% of time
 - > Hadronic final states
 - 12% with single charged particle
 - 37% with h^- + neutral hadrons
- Look for low-multiplicity “jets”
 - > Work to reconstruct π^0
 - > Shower shape cuts to reduce QCD backgrounds
- Use track multiplicity to estimate observed yield
 - > 26 pb of $W \rightarrow \tau \nu_\tau$
 - Compare with 500 pb of $W \rightarrow e \nu_e$
 - Factor of x20 lower efficiency
 - > Purity also about x10 worse

■ Means that tau physics has been “poor” cousin to electrons & muons

Modes with one charged particle		
particle ⁻ ≥ 0 neutrals ≥ 0 $K^0_L \nu_\tau$	(“1-prong”)	(85.36 ± 0.08) %
particle ⁻ ≥ 0 neutrals ≥ 0 $K^0_L \nu_\tau$		(84.73 ± 0.08) %
$\mu^- \bar{\nu}_\mu \nu_\tau$	[g]	(17.36 ± 0.05) %
$\mu^- \nu_\mu \nu_\tau \gamma$	[e]	(3.6 ± 0.4) × 10 ⁻³
$e^- \nu_e \nu_\tau$	[g]	(17.85 ± 0.05) %
$e^- \bar{\nu}_e \nu_\tau \gamma$	[e]	(1.75 ± 0.18) %
$h^- \geq 0 K^0_L \nu_\tau$		(12.13 ± 0.07) %
$h^- \nu_\tau$		(11.60 ± 0.06) %
$\pi^- \nu_\tau$	[g]	(10.91 ± 0.07) %
$K^- \nu_\tau$	[g]	(6.95 ± 0.23) × 10 ⁻³
$h^- \geq 1$ neutrals ν_τ		(37.08 ± 0.11) %
$h^- \geq 1 \pi^0 \nu_\tau$ (ex. K^0)		(36.54 ± 0.11) %
$h^- \pi^0 \nu_\tau$		(25.95 ± 0.10) %
$\pi^- \pi^0 \nu_\tau$	[g]	(25.52 ± 0.10) %



Tau Lepton Reconstruction

■ Why is τ reconstruction so lousy?

- **Have at least one ν , sometimes several**
 - > Compromises energy measurement
 - > Reduces energy scale (and efficiency)
- **Reject decays to $l\nu_l\nu_\tau$**
 - > Background from leptons too large
- **Reliance on charged tracking information and π^0 reconstruction**
 - > Hit by BR and reconstruction efficiencies
- **Trigger is less efficient**
 - > Presence of ν in effect pushes up the minimum νP_T
 - > Work to add other information
 - τ + MET trigger
 - τ + lepton trigger
 - Help but don't solve the fundamental problem

■ Criteria for τ identification

- **1 charged track + evidence of π^0**
 - > Requires reconstruction of π^0 in EM calorimeter
 - > BR $\sim 1/3!$
 - **Look for “narrow” jet**
 - > Seed tower $E_T > 6$ GeV
 - > Seed track $P_T > 4.5$ GeV/c
 - > ≤ 6 towers with $E_T > 1$ GeV in cluster
 - > Overall efficiency of $\sim 50\%$
 - **A further “isolation” cut to reduce backgrounds from QCD jets**
 - > Typical cut: E_T in cone $R=0.4 < 10\%$ of τ candidate E_T
 - > About 60-70% efficient
- ## ■ Loss of $\times 10$ compared with e or μ
- **And backgrounds still high**

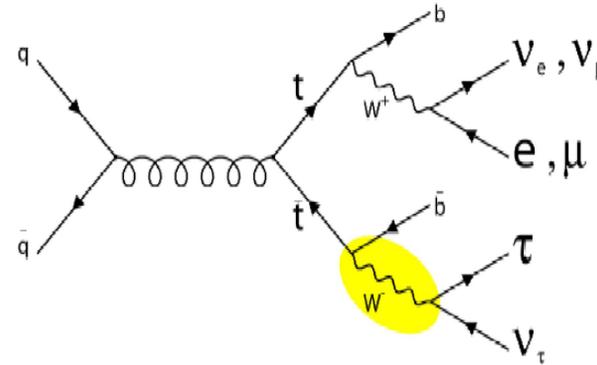
Example: Top decaying to $\tau\nu_\tau b$

- Top quark decays to τ lepton should be observable

- Also key signature for H^\pm

- Analysis strategy

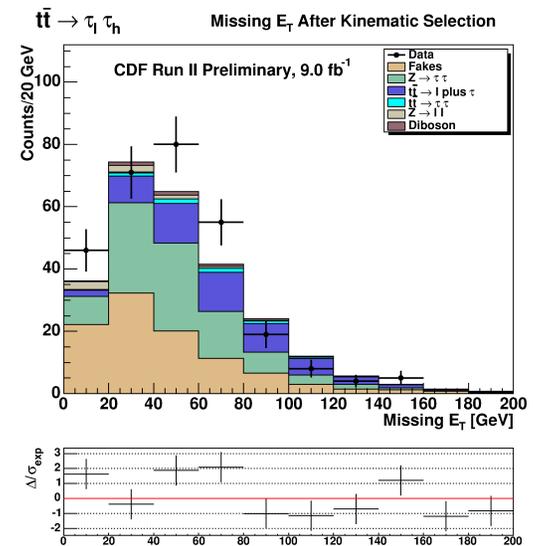
- Look for isolated e or μ
- Isolated τ candidate
- MET > GeV
- ≥ 2 jets
 - > Leading jet $E_T > 25$ GeV and 2nd jet $E_T > 15$ GeV
 - > Reduce $Z \rightarrow \tau\tau$
- Require significant energy in event
 - > $H_T > 205$ GeV



http://www-cdf.fnal.gov/physics/new/top/2012/tthar_taulen_xsec_9invf/Publicpage.html

- MET distribution for electron+ τ

- Kinematic cuts
- Require ≥ 2 jet



CDF Results

- **Backgrounds dominated by “fake” τ candidates**

- **To estimate, use dijet data**
 - > Create “fake matrix” that gives probability of jet passing τ criteria
 - > Have to be careful about “denominator”
 - Also correlations with rest of event
 - Primary background from W+jets

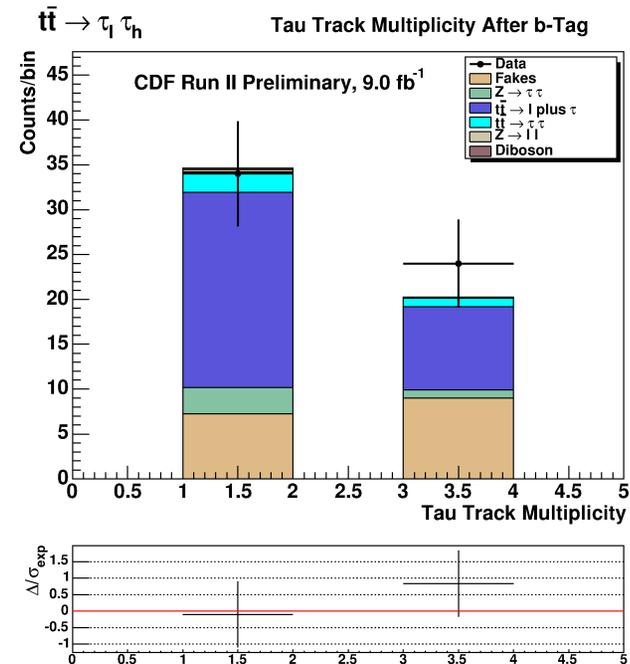
- **See 290 candidate events in 9 fb⁻¹**

- Expect 60 from top quark production

- **This is hard!**

- ee/e μ / $\mu\mu$ + 2 jets (1 b tag) has 80 candidate events with 2.8 fb⁻¹
 - > Estimate 4 background!
- Guess that ~8(?) of these are from $t\bar{t}$ $\rightarrow \tau\tau b\bar{b}$

	e+tau (events)	mu + tau (events)
Jet \rightarrow tau	65 \pm 14	36 \pm 8
Drell Yan	54 \pm 11	47 \pm 10
Top	33 \pm 3	26 \pm 3
WW	2.4 \pm 0.3	1.8 \pm 0.3
Total expected	154\pm20	110\pm14
Observed	175	115



LHC τ 's are not poor cousins

- Use similar techniques to separate τ candidate

- The width of the EM energy deposition
- The width of the charged track energy deposition
- The invariant mass of the charged tracks

- Can measure rejection rates from jets and electrons

- Get rejection rates of order 20-100
- With these, can see a clear $Z \rightarrow \tau\tau \rightarrow e\mu$ signal
 - > A little bit of a cheat, as it only looks for events with $25 < m_{e\mu} < 80 \text{ GeV}/c^2$

- A good start allowing one to build toward a full analysis
- Efficiencies only 10-20% that for electrons, muons

ATLAS-CONF-2011-045

