Simple and Complex Objects: Strategies for Event Reconstruction at the LHC

Lecture II: Confronting the Standard Model

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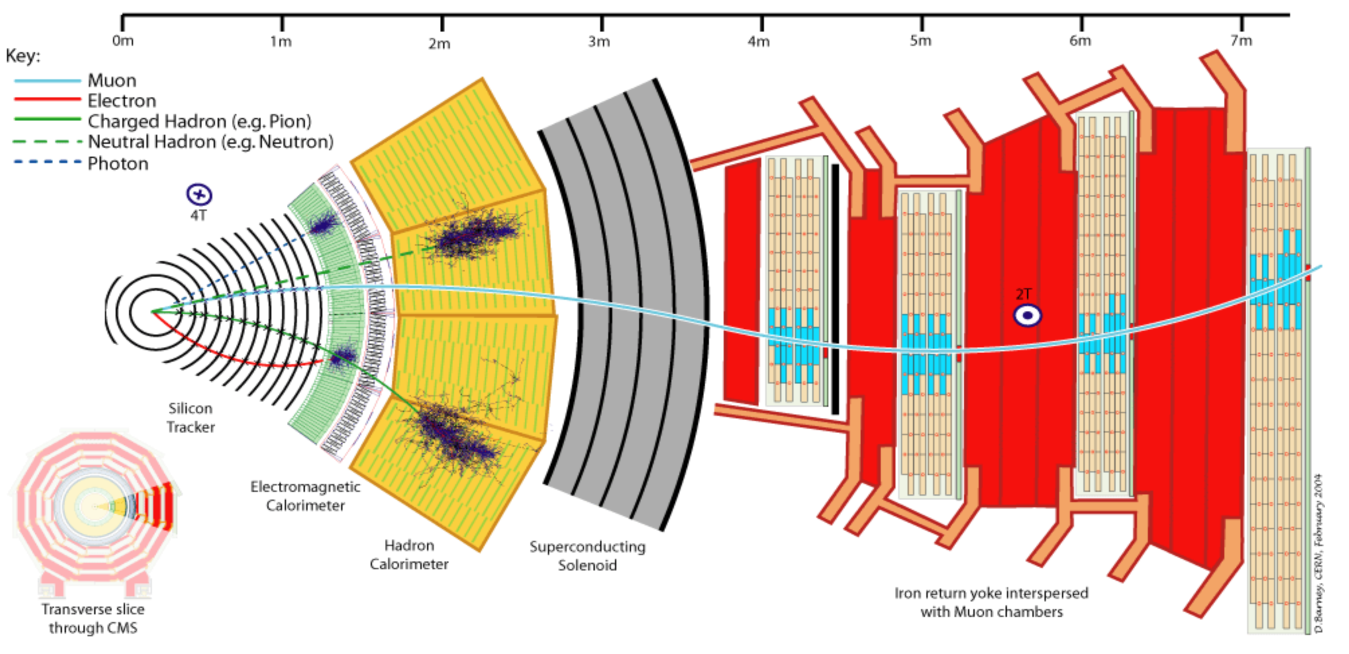
Outline

- Object Reconstruction Part 2
  - Charge Leptons: e, μ and τ
  - Neutrinos (and LSP)
- Finding W's and Z's
  - $Z \rightarrow ee, \ \mu\mu$
  - Lepton P_T spectrum
  - Transverse mass and W reconstruction

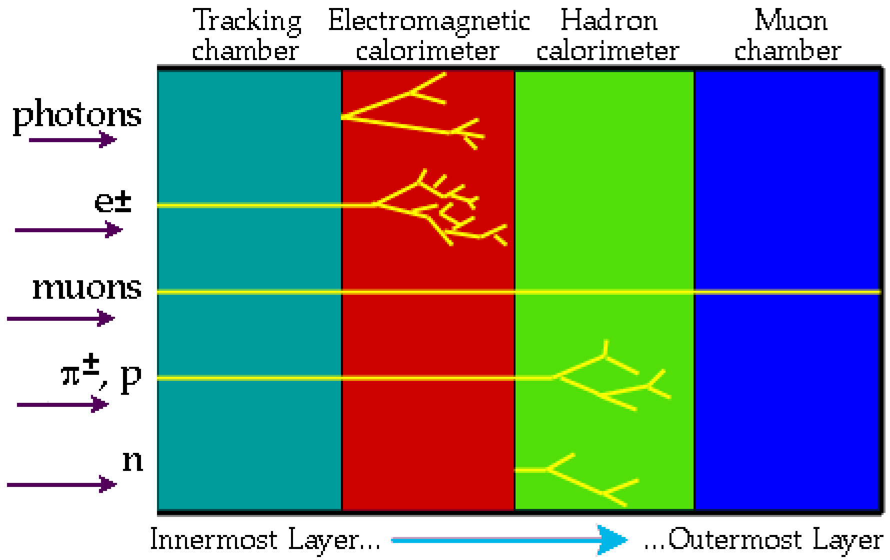
Where We Finished Yesterday: Lepton ID

- Must extract lepton signal from much larger jet bckgnd
- Requires correlation of information among detectors
- Selected based on properties of each lepton species



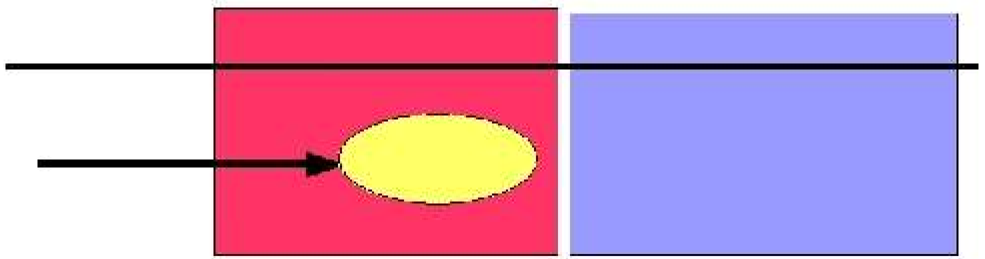
Object 3: Electron Reconstruction

- Electrons signature:
  - Energy Deposition in EM Calorimeter
  - Track pointing at the energy deposition and with momentum consistent with calorimeter energy
  - Little or no energy in hadron calorimeter

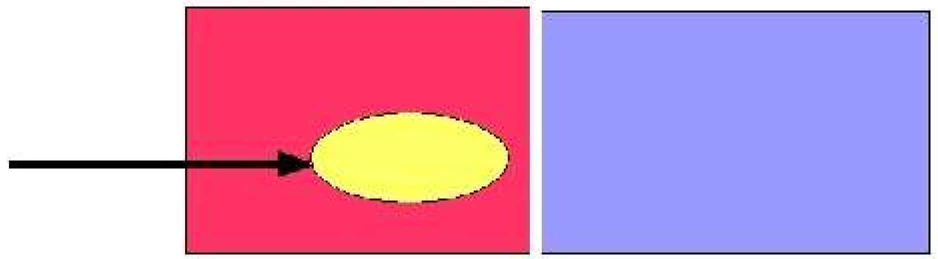


Backgrounds for Electron ID

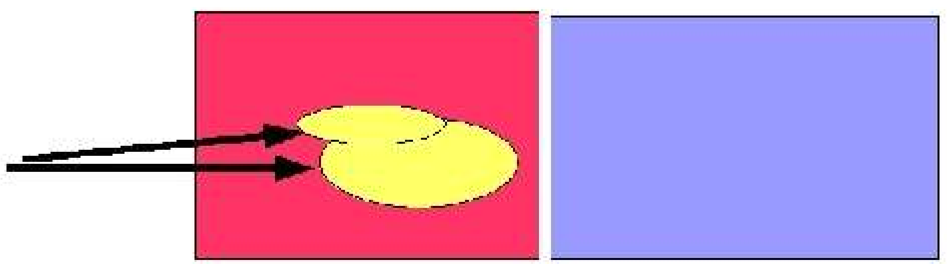
π^0 and non-interacting π^+



Early showering π^+



Photon Conversions

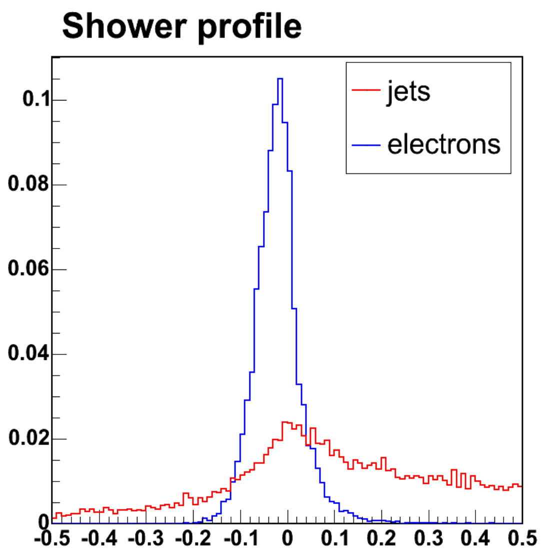


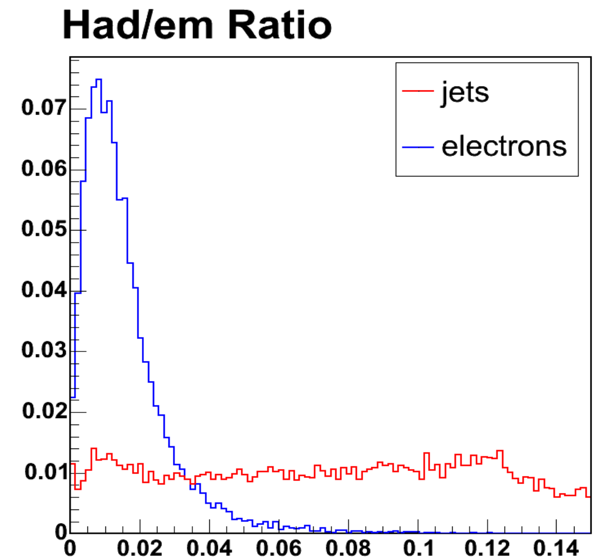
Electron ID: Rejection of Background (I)

Choice of variables depends on detector. Some possibilities:

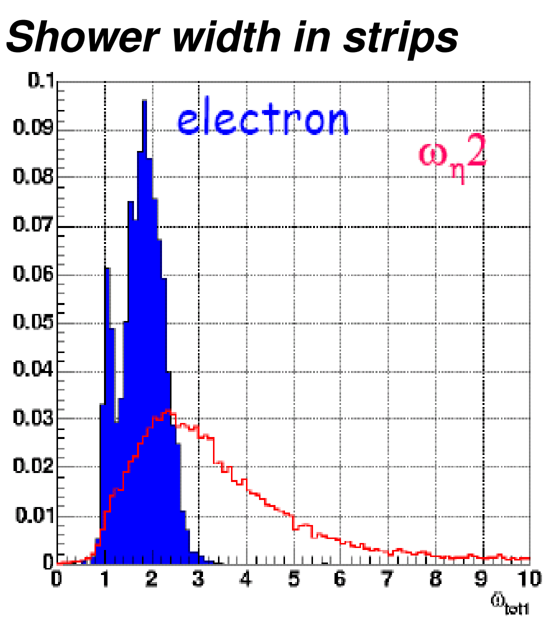
- Shower Shape Variables:
  - Longitudinal shape: ratio of energy in depth segments of calorimeter
  - Transverse shape: Hadron showers typically wider than electrons (also rejects π^0 π^+ overlap)
  - Had/EM: Expect very little energy deposit in HAD calorimeter

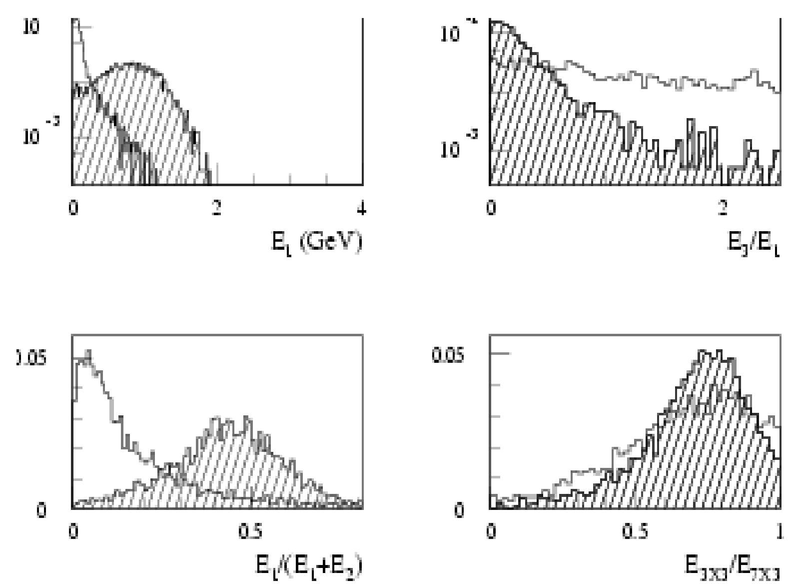
Shower Shape Distributions: Electrons Vs Jets





CDF





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Electron ID: Rejection of Background (II)

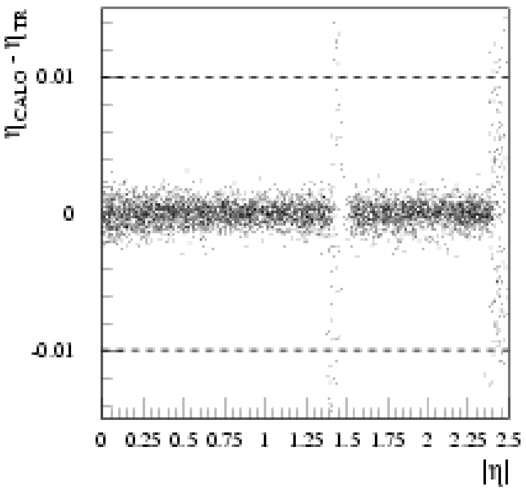
- Track-Shower Matching:
  - E/P: Ratio of energy in calorimeter to momentum in tracker
  - Pointing: Compare extrapolated position of track to position of EM cluster

Caution:

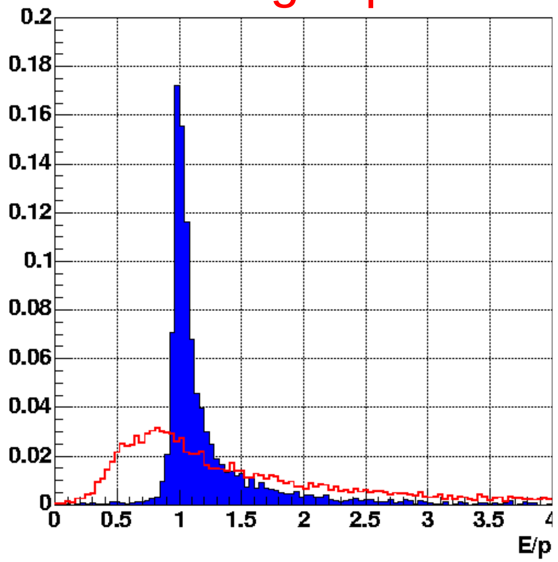
- Significant material in LHC trackers means electron bremstahlung
- Correct modeling of material distribution necessary both for defining selection criteria and for estimating efficiency

Matching Tracks and Calorimeter: Electrons vs Jets

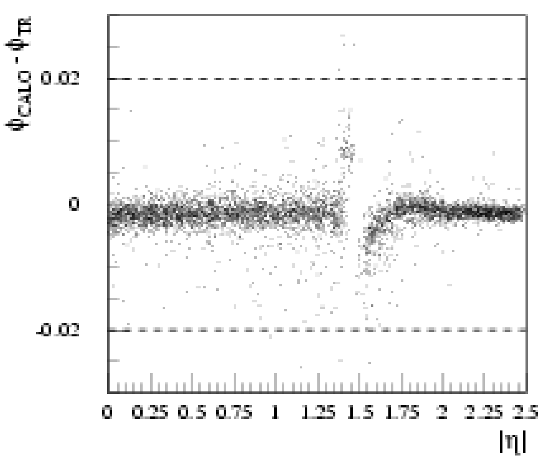
Matching in η



Matching E/p



Matching in ϕ



Electron ID: Rejection of Background (III)

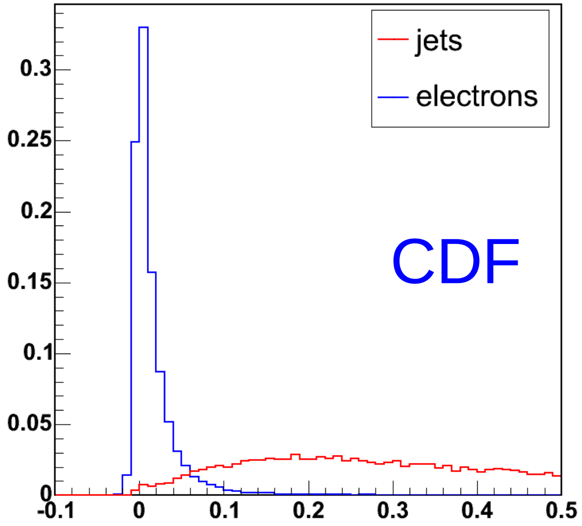
- Large amount of material also means photon conversions are an issue (photons from π^0)
  - Explicit removal of conversions:
    - Require hits in pixel layer (most of material outside this)
    - Look for second track from conversion: cut on reconstructed mass and angle

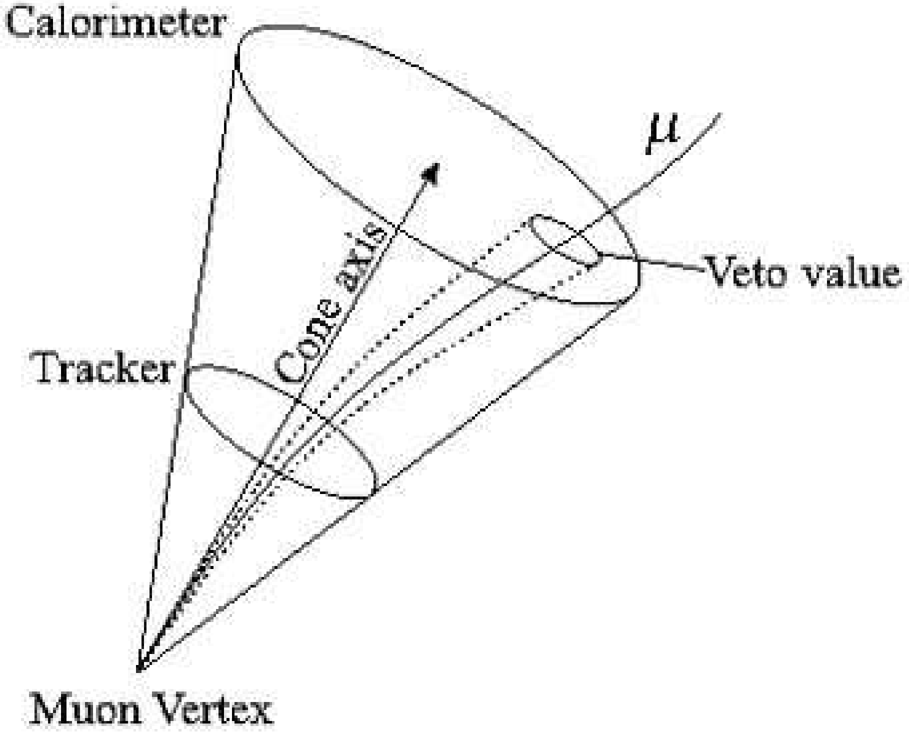
Electron ID: Rejection of Background (IV)

- Isolation:
  - Study ratio of energy in annulus round electron to enegy of electron
  - As noted above: Does not work for all physics processes
- Transitions Radiation and dE/dx:
  - CDF drift chamber measures dE/dx: sensitive to particle velocity: helps for low momentum e
  - Atlas tracker has TR function: Can require high energy deposition hit, at cost of efficiency

Lepton Isolation

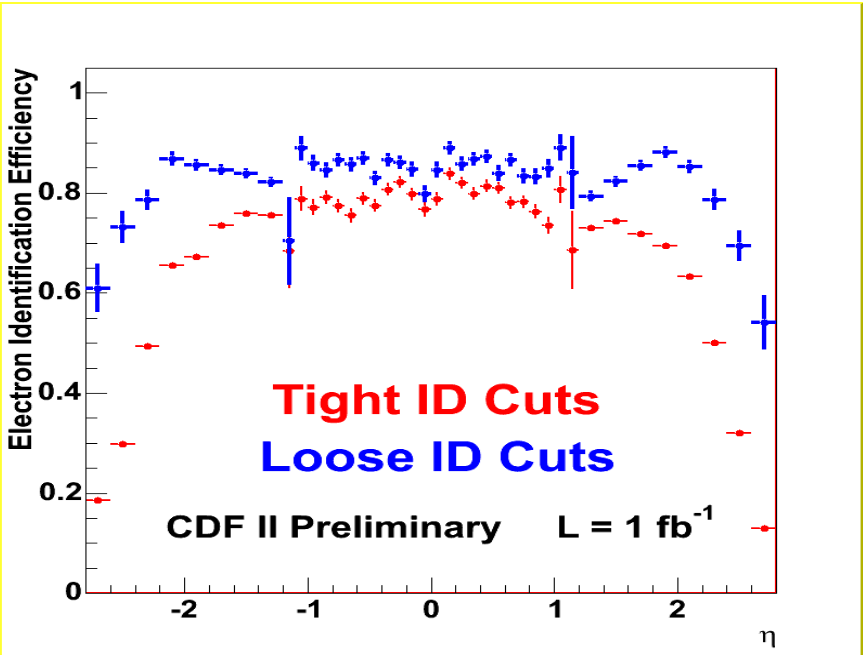
Calorimeter Isolation

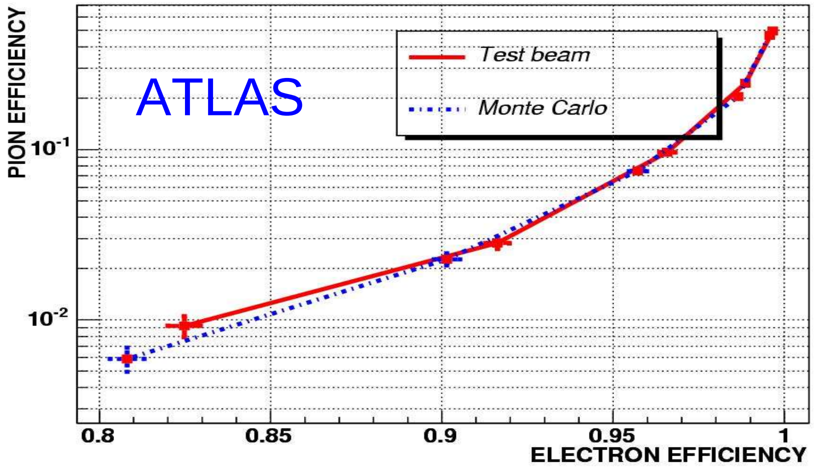




Efficiency of Electron Selection

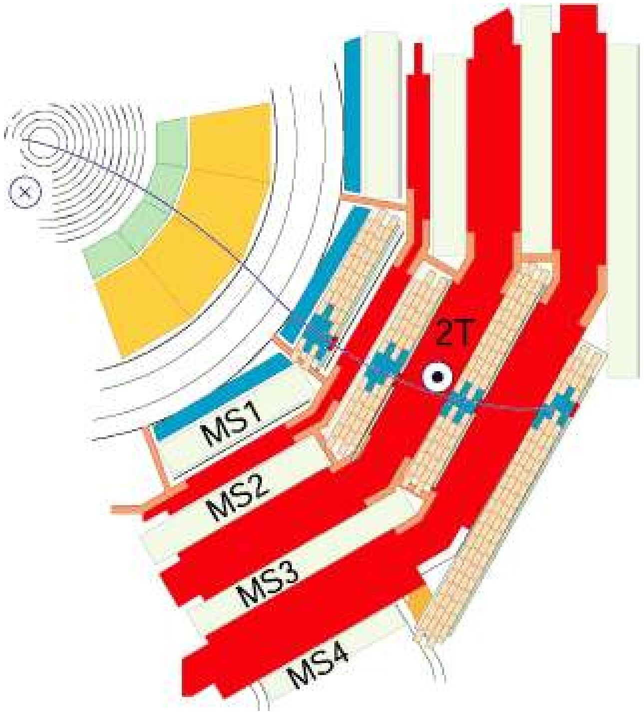
- Measure when possible using real data:
  - W from no-track trigger to measure tracking efficiency
  - Z with one tight electron and with loose selection
- Use simulation to extrapolate kinematics and correct for environmental issues (eg isolation)





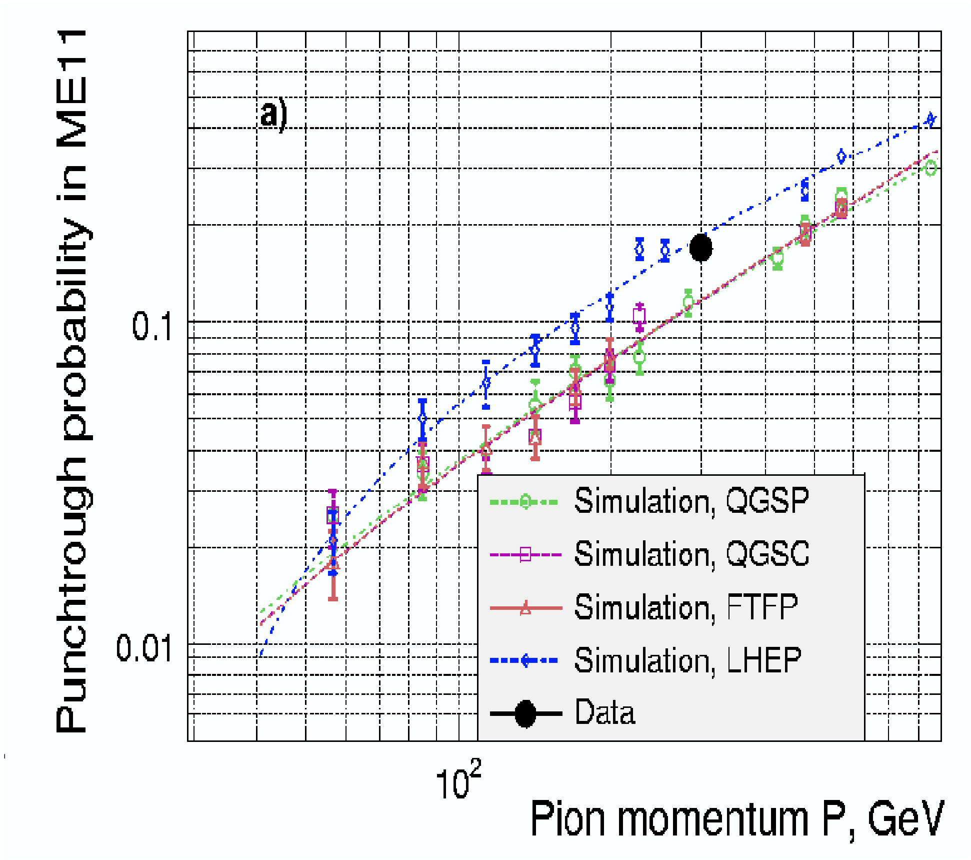
Object 4: Muon Reconstruction

- Muon signature:
  - Track passes through material in muon filter and is reconstructed in muon spectrometer
  - Min ionizing energy deposits in EM ad HAD Calorimeter
  - Track match between inner tracker and muon spectrometer



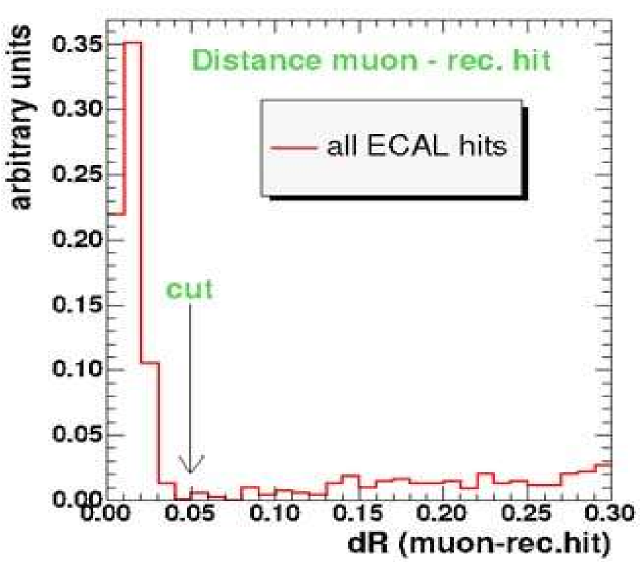
Backgrounds to Muon ID

- Decays in Flight: π and K decays inside jets
  - Fall steeply with P_T
  - Non-isolated
- Punchthrough
  - Probability rises with P_T
- Inner Detector track matched cavern background

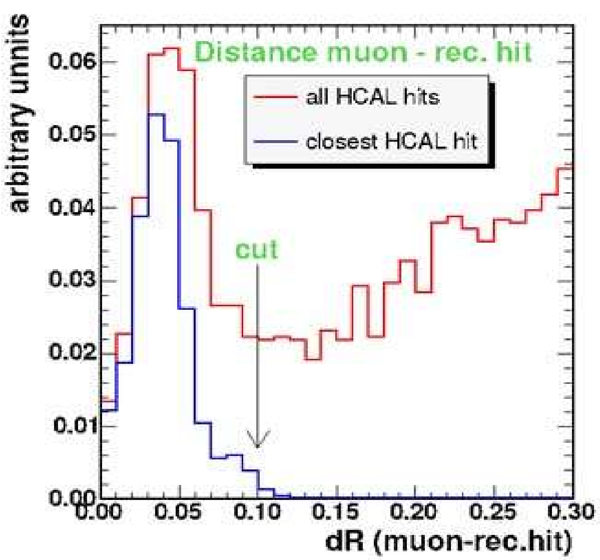


Muon ID: Rejection of Background

- Matching of track parameters between Inner Detector and Muon system powerful at high P_T
- Multiple scattering at low P_T limits resolution
- Verification of Min Ionizing energy in calorimeter

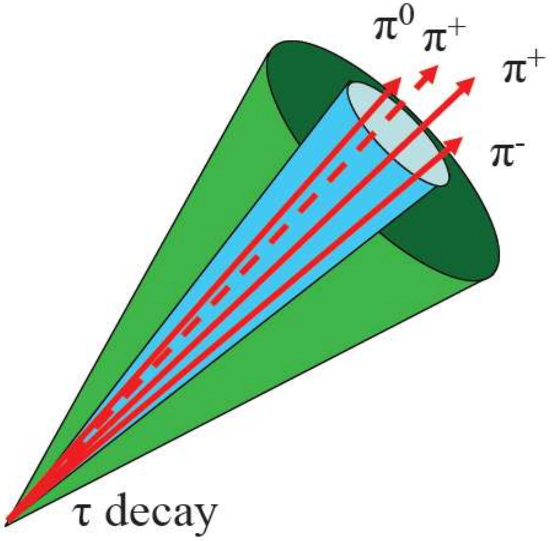


CMS



Object 5: Tau Reconstruction

- Unlike e and μ, τ decay to hadrons
- Look like narrow jets in calorimeter
- 1 or 3 charged tracks
- May have EM energy (π^0)



Tau Reconstruction

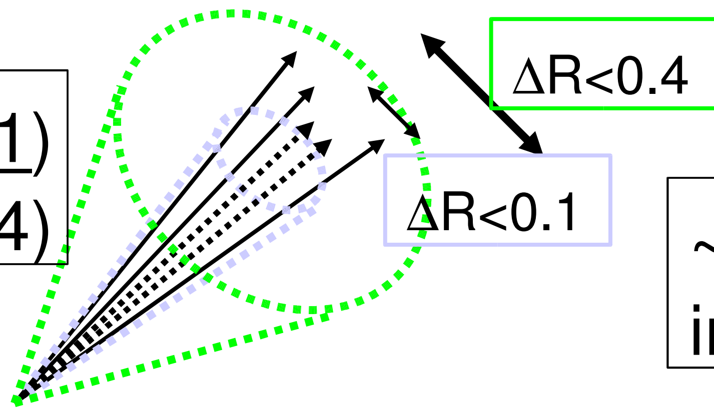
- Associate narrow jets in calorimeter with tracks
- Require
  - Low track multiplicity
  - Narrow calorimeter jet
  - Track and calorimeter isolation

Tau - Fraction of energy in ΔR<0.1

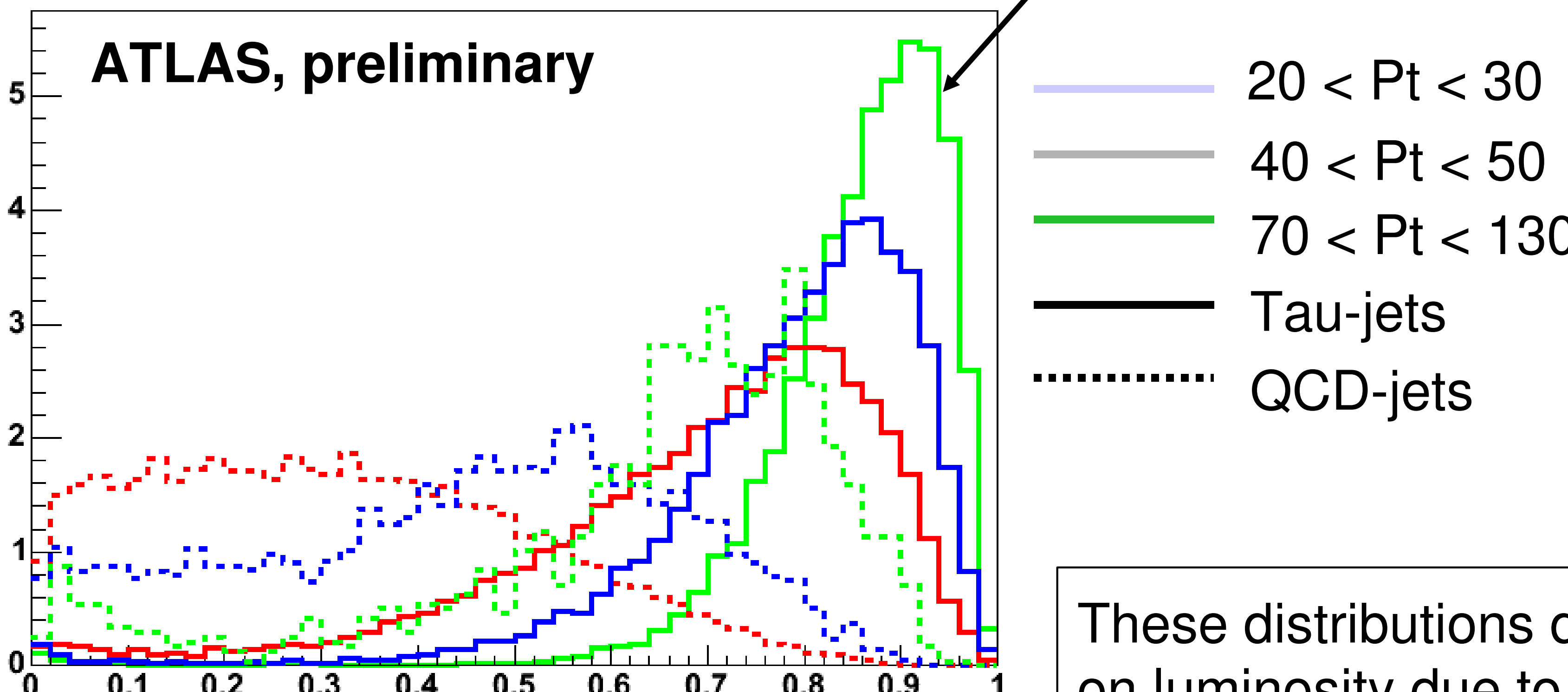
(transverse energy)

$$\frac{\Sigma E_T(\Delta R<0.1)}{\Sigma E_T(\Delta R<0.4)}$$

for tauID



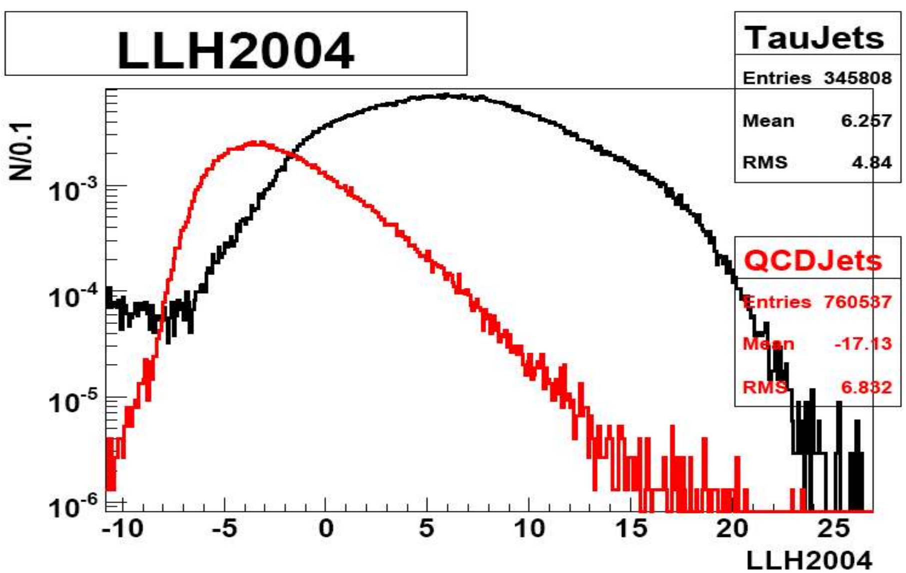
~90% of energy are deposited in ΔR<0.1. -> narrow jet



These distributions depend on luminosity due to the pile-up.

A Likelihood Approach to τ ID

- Construct variable that combines all cut variables
- Compare signal and bckgnd
- Can vary cut to get need rejection



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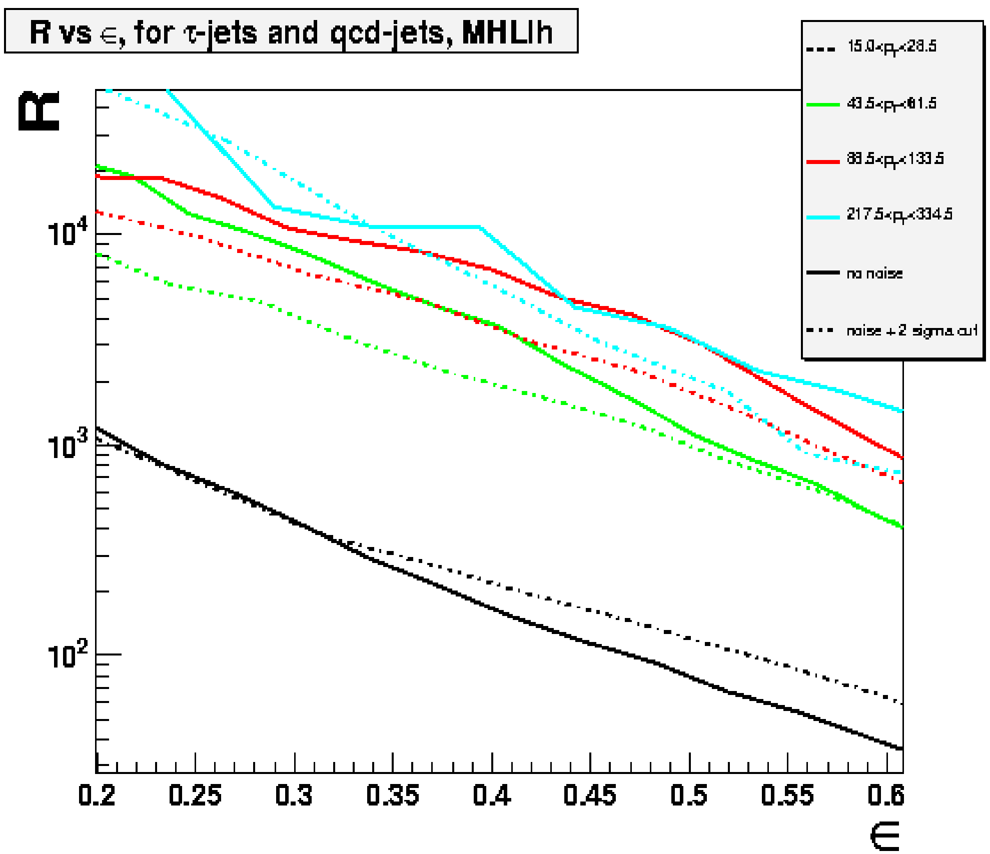
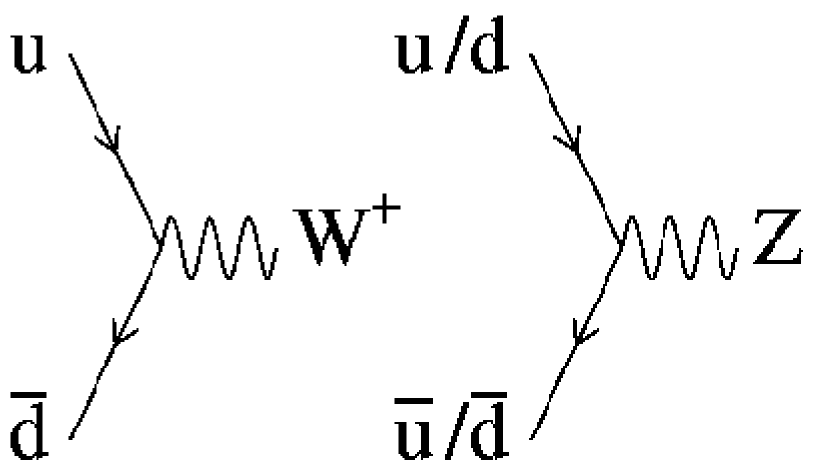


Production of W and Z Bosons

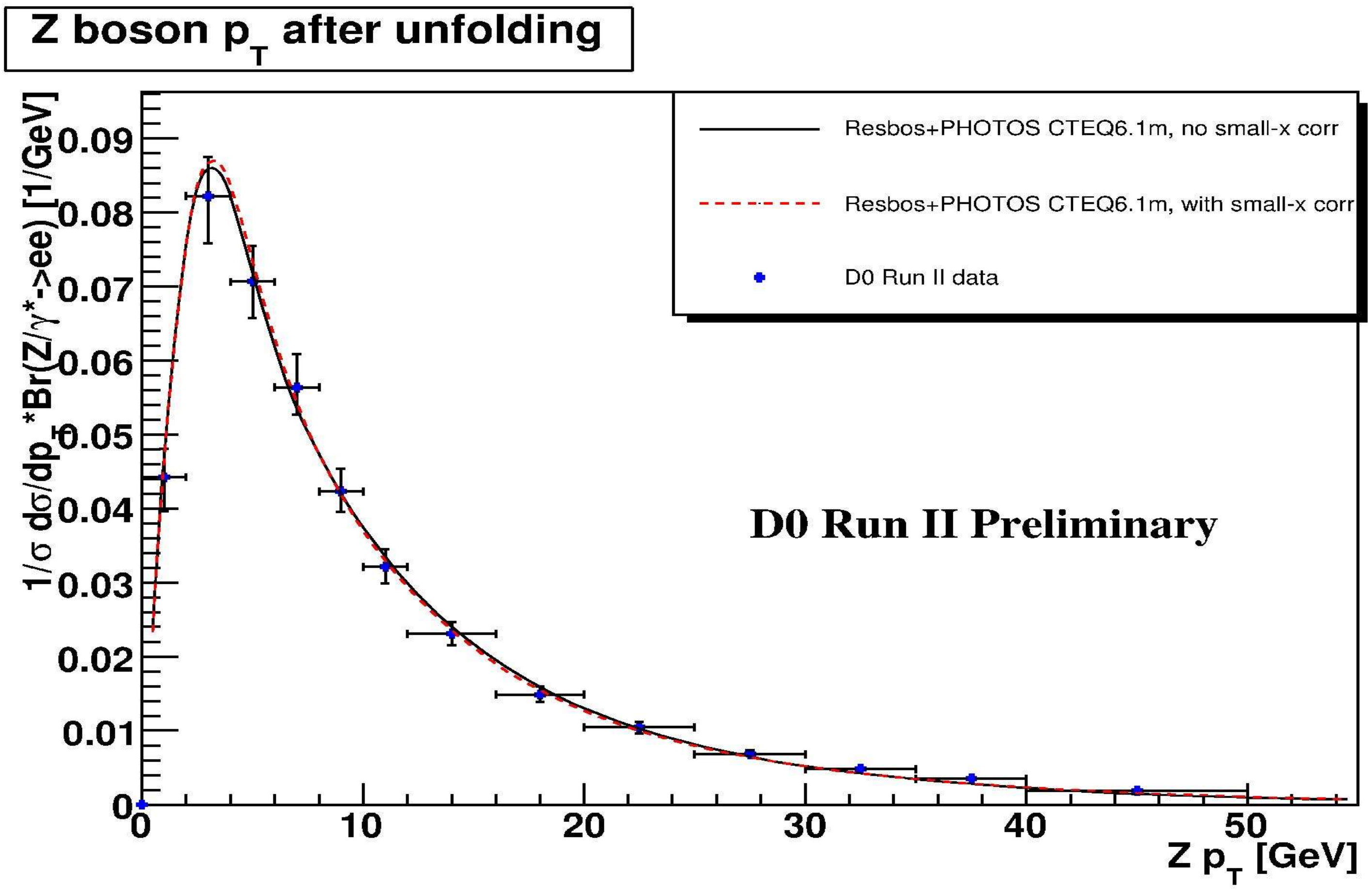
- Lowest order diagram: quark annihilation
- W and Z obtain P_T via initial state gluon emission



<u>Lowest order production:</u>

W and Z produced with 0 PT

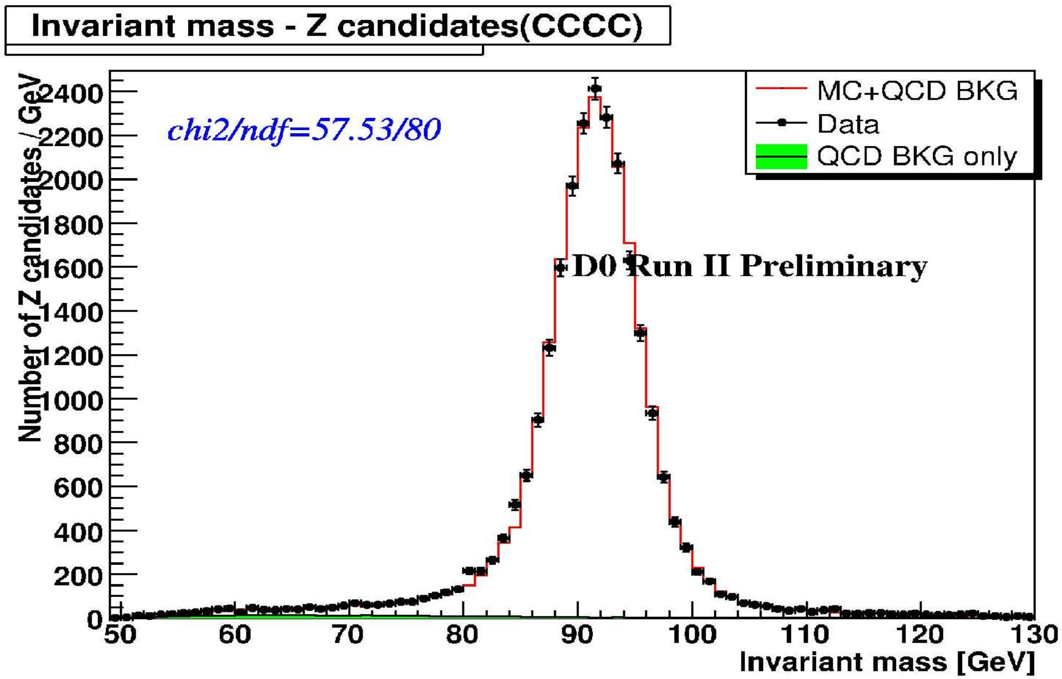
Full QCD Calculation: Boson P_T Remains Small



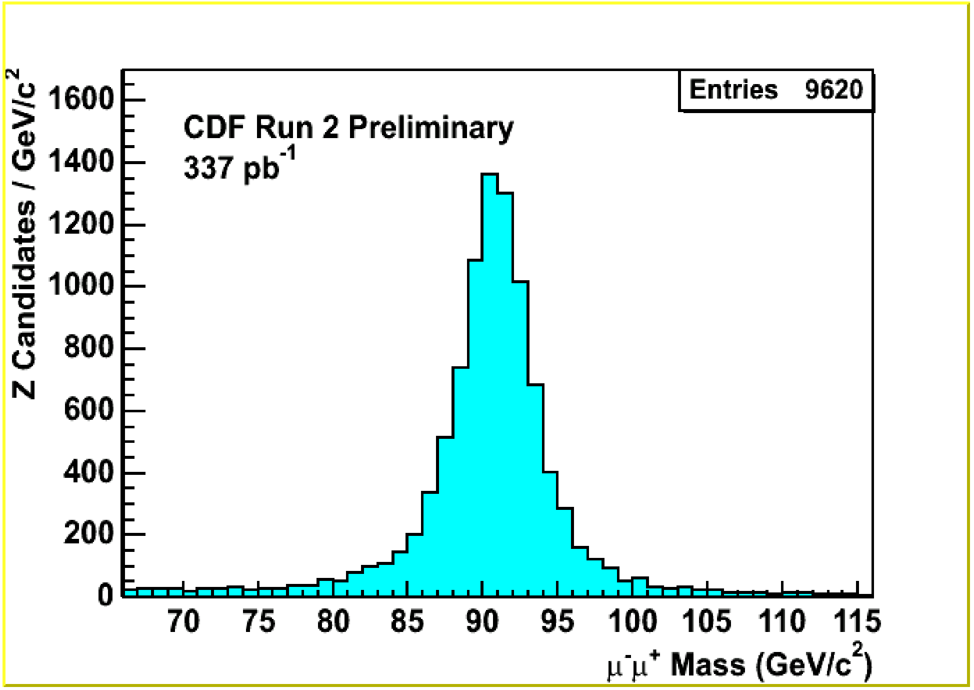
Distribution dominated by multiple soft gluon emission

Reconstruction of Z Bosons

- Limited to leptonic modes unless you trigger on b-jets
- Two high P_T leptons, nearly back-to-back in ϕ
- Reconstruction straightforward, background small



$Z \to ee$



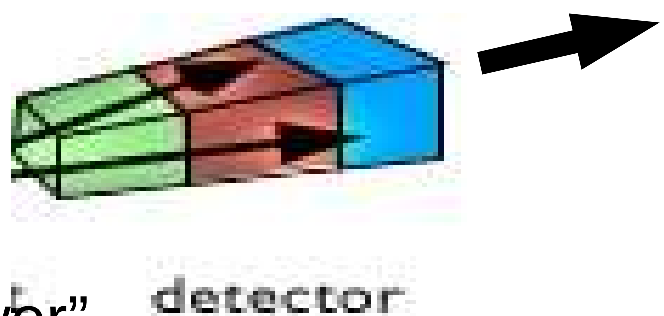
$Z \to \mu\mu$

Reconstruction of W Bosons

- Again, restricted to leptonic decays
- But here one of the nearly back-to-back leptons is a neutrino
- How do we “detect” a particle that does not interact in our detector?
- Same technique as we always use for ν: look for momentum imbalance and assign the missing momentum to the ν
- But in hadron colliders, limited to using only the 2 transverse components of the momentum

Object 6: Neutrino Reconstruction

- Use same technique as for jets
  - Create a grid of calorimeter towers
  - Treat each tower as a massless particle with momentum direction normal to the tower



Calorimeter “Tower”

Define $\not{E}_T$ (2 vector)

$$\begin{aligned}\not{E}_T &= -\sum_{\text{Towers}} E_{iT}\hat{n} \\ &= -\sum E_i \sin\theta_i \hat{n}\end{aligned}$$

Similarly total E_t

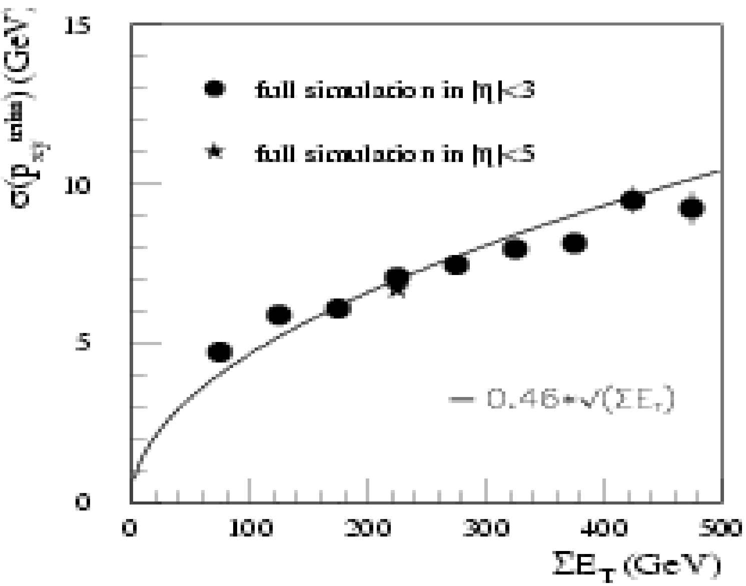
$$\begin{aligned}E_t &= \sum_{\text{Towers}} |E_{iT}| \\ &= \sum |E_i| \sin\theta_i\end{aligned}$$

Comments on Total and Missing E_T Resolution

- Calorimeter resolutions depend on energy deposition

$$\sigma_{\not{E}_T} \propto \sqrt{E_T}$$

- Measurement is also sensitive to detector imperfections (cracks) and noise
- Degrades with pile-up



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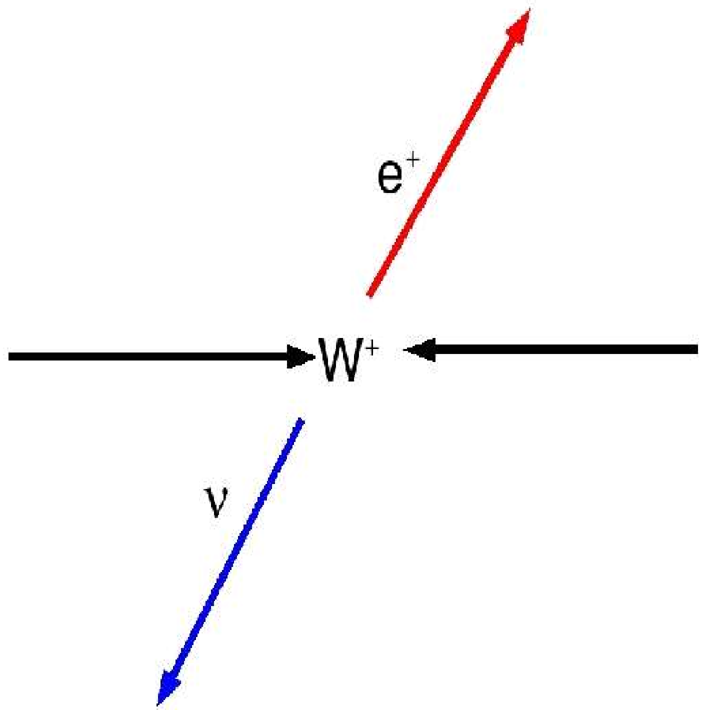
W Decay: Lepton P_T Distribution



(LO Calculation)

In CM frame, e and ν are back-to-back and balance p_T

$$p_T^2 = \frac{1}{4}\hat{s}\sin^2\theta$$

Changing variables from $\cos\theta$ to p_T means evaluating the Jacobean

$$\frac{d\cos\theta}{dp_T^2} = -\frac{2}{3}\left(1-4\frac{p_T^2}{\hat{s}}\right)^{\frac{1}{2}} = -\frac{2}{\hat{s}\cos\theta}$$

But we know

$$\frac{d\sigma}{dp_T^2} \propto (1+\cos\theta)^2$$

so

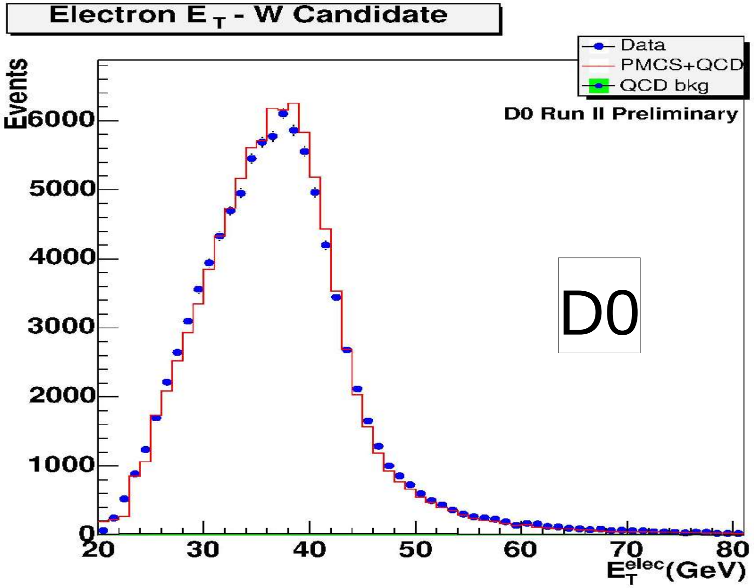
$$\frac{d\sigma}{dp_T^2} \propto \frac{1+\cos^2\theta}{\hat{s}\cos\theta} \propto \frac{2\left(1-2p_T^2/\hat{s}\right)}{\hat{s}\left(1-4p_T^2/\hat{s}\right)^{\frac{1}{2}}}$$

The Jacobean Peak

- Notice $$\frac{d\sigma}{dp_T} \propto \frac{1+\cos^2\theta}{cos\theta}$$

Diverges for $\theta = \pi/2$ $(p_T = \frac{\sqrt{s}}{2})$

- Divergence results from Jacobean factor in transformation to P_T
- Integration of Breit-Wigner over s removes singularity



HO corrections give W PT: Jacobean peak smeared but still present

Transverse Mass

- W P_T affect e and ν by same boost
- Define e-ν transverse mass:

$$m_T^2 = |p_T^\ell|^2 + |p_T^\nu|^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2$$

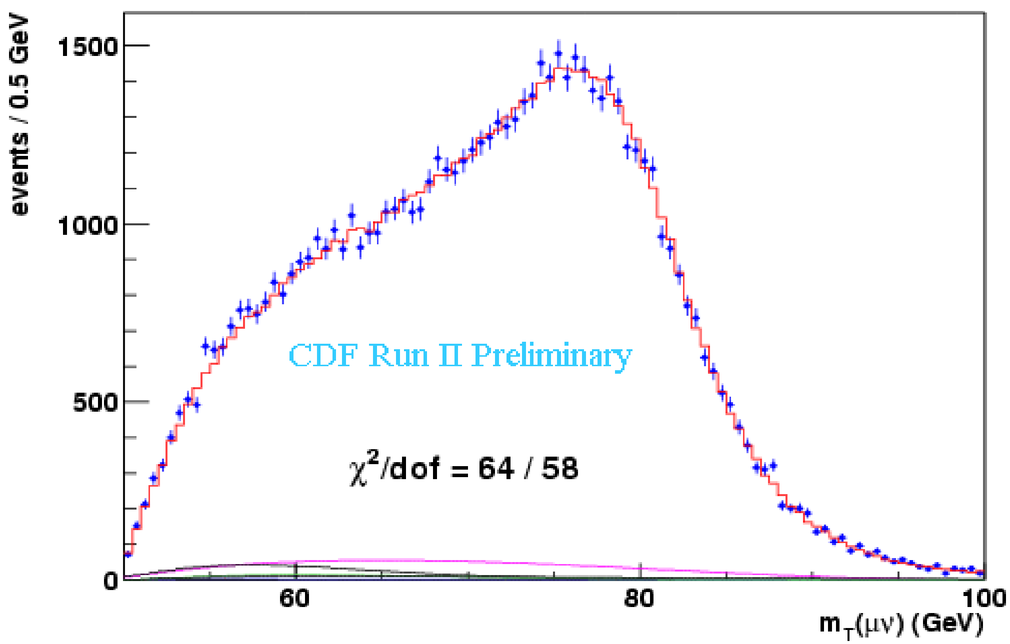
Note that for $P_T^W = 0$, $m_T = 2|p_T^\ell| = 2|p_T^\nu|$

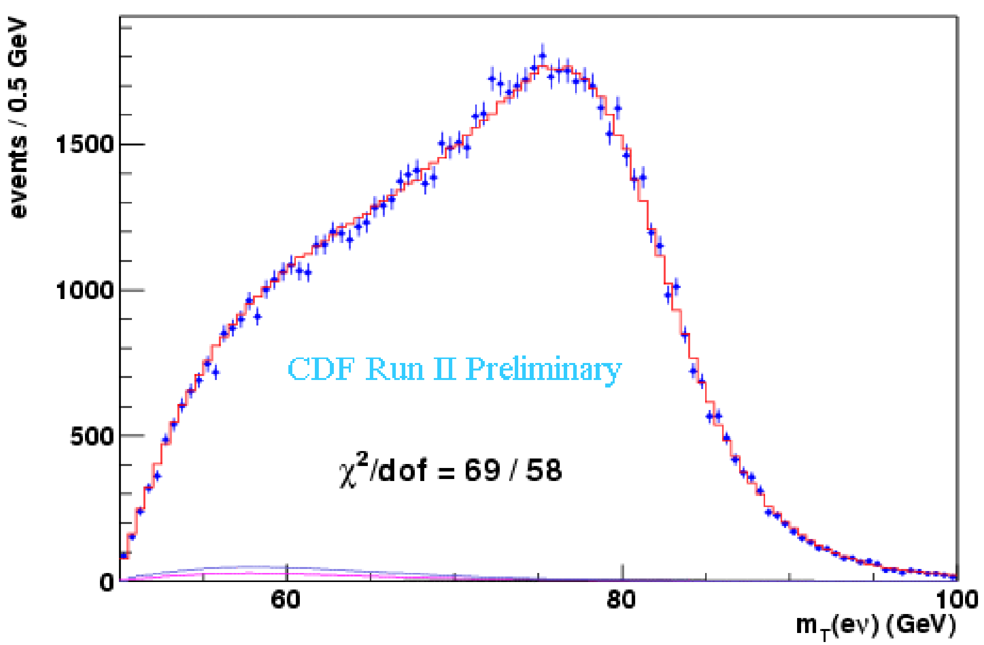
$$\frac{d\sigma}{dm_T^2} - 4\frac{d\sigma}{dp_T^2}$$

- m_T sensitive to transverse boosts only at second order
- But M_T is more sensitive to detector resolution than P_T of the lepton

Transverse Mass Distributions for W

- Background low in both e and μ channels
- Low theoretical uncertainties: better choice of variable than lepton P_T for measuring W mass





W Mass: Analysis Strategy

Use well measured Z to calibrate model of W

- Calibrate E or p scale using known resonances
- Measure lepton resolution using Z width
- Model recoil response using Z data
- Model P_T distribution from Z (theory to extrapolate to W)
- Likelihood fit to W mass
- Apply radiative corrections
- Evaluate systematics

Conclusions

- EW production can be cleanly separated from QCD background if leptons in the final state
- Reconstructed of isolated e, μ, τ and ν possible using a combination of variables from several detectors
- Non-isolated leptons more difficult

Next Time:

  - Top: b-jet tagging
  - Higgs: photons
  - SUSY: Everything together