Methods of Experimental Particle Physics

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Lecture #17
Today Lecture

• Particle Identification Summary

• Presentations:
  • D0 calorimeter by Jeff – delayed till next time
Important “Particles”

• Look at all known particles and consider their decay products
• There are not many options for what you can see in your detector:
  • Quarks and gluons fragment forming jets
    • One exception is top quark - it decays before fragmenting (mainly into a b-quark and a W-boson)
    • All jets look alike except b- and to some extent c-quarks as those can have a non-negligible life-time
      • Getting b’s is important for Higgs, top and many other studies - “tagging”
      • Also special cases, e.g. reconstruction of new hadronic bound states (excited mesons, baryons etc.) – here you often look inside jets and try to reconstruct individual particles
  • Photons:
    • Come from Higgs, from $\pi^0$’s, radiation etc.)
  • Leptons - mainly from W and Z decays
  • Invisible stuff (e.g. neutrinos)
Transverse Momentum and Pseudorapidity

- Full momentum of a reconstructed particle has $p_T$ and $p_z$ components
  - $p_z$ is not very meaningful because collisions are always “boosted”: proton momenta are balanced in z-direction but its not protons that collide, it’s partons, so the systems are not balanced in z

- Pseudorapidity:
  \[
  \eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right], \quad \eta = \frac{1}{2} \ln \left( \frac{|p| + p_L}{|p| - p_L} \right),
  \]

- Similar to rapidity:
  \[
  y = \frac{1}{2} \ln \left( \frac{E + p_L}{E - p_L} \right)
  \]

- Particle (or jet) distribution for QCD processes is about constant vs rapidity but not versus $\theta$
Leptons

- Excellent probe of electroweak processes (including Higgs)
  - Come from decays and interactions of gauge bosons and higgs
  - Relatively easy to recognize and reconstruct in many experimental analyses, large background suppression
    - Allows precision measurements important for understanding SM (top, W mass, Z cross section and asymmetry)
    - Many beyond SM new physics can be explored using lepton signatures
- Majority of experimental analyses at LHC heavily rely on leptons
  - Electroweak measurements (W, Z), top, higgs
  - Understanding SUSY, even if discovered in jets and missing energy channel, will require lepton channels
Leptons in Detector

• Reconstruction and ID explore basic properties of lepton interactions with matter as they pass through detector material
Muon Reconstruction 101

- Follow the muon through detector systems:
  - Track in the tracking device (charge)
    - Neutrals won’t (many backgrounds out)
  - Little energy deposit in calorimeter (MIP)
    - Backgrounds (pions) have more deposition
  - Muons reach muon system (unless too soft)
    - Most backgrounds never get there
  - Isolation (not much “stuff” around muon):
    - Not muon property, rather process feature
      - In many interesting processes muons are produced “by themselves”
      - Background “muons” almost always come from jets
- Depending on specific physics analysis, use different weights for each feature
  - A common definition often possible
CMS Muon System

- **Main components:** DT, CSC, RPC

- **Drift Tubes (DT):** barrel region (|\(\eta|\)<1.2)
  - 4 layers per superlayer; 2-3 superlayers per station
  - Precise measurement of position and momentum:
    - Offline: 250 – 100 \(\mu\)m; Online: \(~2\) mm

- **Cathode Strip Chambers (CSC):** endcaps (0.8<|\(\eta|\)<2.4)
  - 6 cathode/wire planes per chamber, 3.5 stations
  - Precise measurement of position and momentum:
    - Offline: 100 \(\mu\)m; Online \(~2\) mm

- **Resistive Parallel Plate Chambers (RPC):** barrel and endcaps
  - 1-2 PC per DT; 1 RPC per CSC
  - Good spatial and time resolution: \(~1\) cm; \(~2\) ns
CMS Muon Reconstruction

- Most straightforward approach: “Global Muon”
  - Reconstruct a track ("stub") in muon system
  - Link to a tracker track
- Works well above 5 GeV
  - Shoulders: barrel/endcap
- Can improve low $p_T$ side:
  - Recover tracker inefficiency
    - “Standalone muon” (stubs)
  - Get muons with fewer muon hits
    - “Tracker muon” (inside-out tracking + “compatibility”)
  - Recover muons that never made it to the muon system:
    - “Calo muons” (MIP-like track)
- Final candidate list combines all of the above
  - Can adjust purity and efficiency for specific analyses
Muon Momentum Reconstruction

- Standalone muon system resolution ~10%
  - Significant material in front of muon system makes it hard to do a lot better
  - Also not necessary as $p_T$ is always better measured by the tracker
- Generally, muon system’s task is to “recognize” muons, but there are exceptions:
  - Standalone muon momentum is used in the trigger at Level-1
    - 10% is good enough for that
  - Momentum reconstruction for very high momentum muons ($p_T>200$ GeV/c)
    - Larger lever arm of muon system helps
Electron Reconstruction 101

- Follow electron through detector systems:
  - Track in the tracking device (charge)
    - Neutrals won’t (many backgrounds out)
  - Most energy deposited in ECAL, very little in HCAL
    - Many backgrounds have more “even” deposition (charged hadrons)
  - Track momentum and energy deposited in ECAL should agree
    - For many backgrounds won’t be true
  - Narrow cluster in ECAL:
    - Backgrounds will be more spread out
  - Isolation (not much “stuff” around electron):
    - Not electron property, process dependent
      - In many interesting processes electrons are produced “by themselves”
      - Background “electrons” almost always come from jets
CMS ECAL Design

Homogenous Lead Tungstate (PbWO$_4$) Crystal Calorimeter + Pb-Si Preshower

Barrel (EB):
- 61200 crystals
- 36 Supermodules (SM), each 1700 crystals
- $|\eta| < 1.48$

Endcap (EE):
- 14648 crystals
- 4 Dees, SuperCrystals of 5x5 crystals
- $1.48 < |\eta| < 3.0$

Preshower (ES):
- Pb-Si
- 4 Dees
- 4300 Si strips
- $1.65 < |\eta| < 2.6$

Crystals are projective and positioned pointing slightly off the IP to avoid cracks.
Electron Reconstruction Challenges

• ECAL has excellent internal resolution
• Challenge is the “heavy” tracker
  • Many electrons will interact (brem) inside tracker (on average radiation is ~70% of energy)
    • Multiple clusters in ECAL
      • Spread in phi due to B-field
    • Standard tracking does not do a good job on “kinked” electrons
• More backgrounds as many photons (from $\pi^0$’s in jets) will convert:
  • Photons have >50% probability to convert into e+e- pair
  • Converted electron is a real electron
Electron Reconstruction

• SuperCluster algorithm:
  • Creates clusters (start with the seed) extending in phi (up to 17 crystals) and narrow in eta (5)
    • Designed to collect brem radiation
    • For reference, for a non-converted photon ~97% of energy in 5x5 crystals
  • Energy (position) from (weighted) crystal sum
• Similar approach in Endcap (multi5x5 algorithm)
Electrons: Association with Tracks

- Start with a loose match to tracker (pixel) seeds
- Extrapolate tracks inside-out to next layer
  - Use PDF defined from electron energy loss
- Keep up to three tracks at each step
- Final fit gives:
  - Track parameters in/out, energy loss, chi2
- Optimal final energy from comparison of ECAL and track measurements
Electron ID and Isolation

- Reconstruction should focus on high efficiency
  - Results in ~1 electron candidate per jet event
  - Need knobs to improve purity – ID
- Identification variables:
  - Had/EM, shower width in eta, quality of cluster-track matching
  - Cluster-track energy consistency: $E_{SC}/p_{in}$, $E_{seed}/p_{out}$ (when tracking understood in data)
- Isolation: similar to muons, large background reduction at relatively small loss to efficiency
  - A specific choice of selections is analysis dependent
Tau Lepton Reconstruction

- Tau is different from other leptons as it decays inside the detector:
  - $c\tau=87\ \mu$m
- Dominated by hadronic decays
  - Leptonic $B(\tau \rightarrow l\nu)\sim 17\%\ l=e,\mu$
  - Hadronic $B\sim 65\%$, main modes
    - $3/4$ with $\pi^\pm+N\pi^0$, $1/4\ 3\pi^\pm+N\pi^0$
- Hadronic tau looks like a generic QCD jet
  - Not good because jets are the main background
Hadronic Tau Reconstruction

• Explores tau/jet differences in fragmentation:
  • Taus: small number of relatively energetic and spatially close particles
  • Jets: more soft particles, spread out

• Uses Particle Flow, main steps:
  • Seed track with $p_T > 5$ GeV
  • Recent: seeding with neutral pions – noticeable improvement in efficiency

  ■ Form a cone of size $\Delta R = 0.15$ around the seed track
  ■ Everything inside the cone - tau constituents, outside (up to $\Delta R = 0.5$) – isolation region
  ■ Or look for combinations of pions and photons consistent with typical tau decay patterns

  ■ Energy is calculated from constituents
Reconstruction and ID: Fighting Jets

• After initial reduction in the number of candidates, some further cleanup:
  • Signal cone redefined:
    • Decrease cone size for energetic taus to reduce backgrounds
  • Correction for conversions:
    • Photon candidates consistent with being conversion electrons pulled from isolation into signal
  • Energy recalculated
  • Isolation variables defined:
    • Number of tracks (photons) in isolation cone above 1 GeV
      • Gives softer reduction, robust against UE effects and pile-up
    • Sum of transverse momenta for tracks and photons:
      • More aggressive
Photons

• That’s the main driver of significance in seeing Higgs at the LHC

• Very similar to electrons: photon is an electron without a track
  • That’s actually how you find them
  • Depending on the event topology can be isolated, i.e. photons from Higgs are isolated

• Can also reconstruct conversions – find two electrons consistent with having very small invariant mass coming from a common vertex where the photon converted
Heavy Flavor Tagging

- B-jets are special both in terms of physics and how they look:
  - Top quark decays to b and a W – can study tops
  - Higgs decay probability is proportional to the mass of a fermion – 90% of the time Higgs decays to b-jets
  - B-jets have “lifetime”:
    - B-quarks quickly hadronize forming typically mesons
  - B-hadrons are unstable (decay weakly, e.g. a b quark can decay into c and a virtual W), but lifetime is not negligible - potentially detectable
    - Note charm can given another decay vertex

[Diagram showing primary vertex and B flight axis]
Heavy Flavor Tagging

• B lifetime is of the order of ~1.5 ps
  • Then $c\tau \sim 0.5$ mm, for an energetic B-hadron the vertex can be a cm or few away from the collision point
    • This vertex will likely be still inside the beam-pipe, but you can detect such secondary vertex using tracks in the event that do not seem to originate in the IP

• You can guess that to do this well, one needs a good resolution for track trajectory determination near the beam line
  • Sub-mm precision, so we are talking some microns

\[ \lambda_B = 468 \pm 7 \text{(stat)} \pm 22 \text{(syst)} \mu m \]
Heavy Flavor Tagging

• Typical algorithms:
  • Reconstruct a secondary vertex well separated from the collision point
  • Identify and count tracks with large “impact parameter” relative to the interaction point
    • E.g. use how much off is the second or third most suspicious track is
  • “Soft lepton tagging”:
    • Virtual W from b->cW or from c->dW can give an electron or muon – look for leptons inside jets
Typical Analysis Flow

- In typical analyses, analyzers are trying to find or select a high purity sample of events of some specific type (say $H \rightarrow ZZ \rightarrow 4\mu$) using
  - “Standard” objects (e.g., muons in this case) as bricks in building a complete analysis
    - Sometimes one will want to modify the standard selections if there is a good reason for it, but generally “standard” selections have high efficiency and reasonable background suppression
  - Analysis-specific topological and kinematical selections:
    - These are done to reduce any remaining backgrounds by recognizing them or by exploring some kinematic variables that allow good discrimination of signal from background (for example the 4 muon mass for Higgs events will look like a narrow peak while for nonHiggs $pp \rightarrow ZZ \rightarrow 4\mu$ background events there will be no resonance-like peak
Next Time(s)

• Triggers at Hadron Collider Experiments
• Monte Carlo based simulations in HEP:
  • Event generators
    • Pythia (main example), Herwig, Madgraph
  • Detector simulation basics
    • GEANT program