Detectors: Electrons and Particle Id
[Lecture 12, March 16, 2009]
Organization

Project 1: Charged Track Multiplicity
• no hand-ins as of yet

Project 2: Upsilon Cross Section
• all material is on the Web
• is due April 9 (in 3.3 weeks)
• please, try to find a partner if you do not yet have one

CP Travel plans
• at MIT in the flesh Wednesday/Friday
• April 8 - May 13 as well: find alternative time for Apr 8
Lecture Outline

Electron Identification
  • electromagnetic calorimetry

Particle identification systems
  • dE/dx in drift chamber
  • TOF – Time-Of-Flight detectors
  • RICH – Ring Imaging CHERenkov detectors
  • DIRC – Detection of Internal Reflected Cherenkov light
Why Muons and Electrons?

Leptons

- rare in $pp$ (<1% of the tracks), often related to very interesting physics processes
- taus special case ($m = 1.777$ GeV, $c\tau = 87.11\ \mu$m)
  - decay well before they reach the silicon detector, lifetime more then a factor of five smaller then for $B$ mesons
  - can also produce hadrons in decay, more difficult to identify
  - always involve neutrino in decay (incomplete reconstruction)
- muons have very characteristic signature
  - penetrate the calorimetry, are detected in the muon chambers
  - leave minimally ionizing signature
- electrons have very characteristic signature
  - maximal ionization in tracking system
  - get absorbed completely in ECAL no signature in the HCAL
  - shower shape in ECAL is short and broad
Why Electrons/Photons at the LHC?

Physics opportunities

- very low Higgs masses (below 130 GeV): $H \rightarrow \gamma\gamma$
- most of other range: $H \rightarrow ZZ(*) \rightarrow e^+e^- (\mu^+\mu^-/e^+e^-)$
- $Z'$ decaying to $e^+e^-$ final state, masses as high as possible

Requirements for the ECAL at LHC

- excellent resolution over very large dynamic range
  - CMS decided for crystal calorimeter
  - high light output
- capable of dealing with dense particle distributions
  - dense material to quickly contain shower
  - fine granularity
- capable to resist high radiation, maintaining performance
  - material research necessary
Electron Signature: track + all energy in ECAL
- backgrounds: photons plus random track
- neutral pion: decays to 2 photons (shower shape)
Compare Electron and Muon Id

Muon identification
• by definition background is quite low
• few particles arrive in muon system: gold plated

Electron/Photon identification
• very large number of particles
• tracking essential (reject/select photons)
• electromagnetic calorimetry essential (reject neutral pions)
• hadron calorimetry essential (reject other hadrons)
• intrinsically more complex then muons but still very important
Higgs Mass Drives ECAL Design

Electroweak data
- Higgs < 144 GeV

Direct searches
- Higgs > 114 GeV

<table>
<thead>
<tr>
<th>H→γγ cuts</th>
<th>0.02758±0.00035</th>
</tr>
</thead>
<tbody>
<tr>
<td>H→γγ opt</td>
<td>0.02749±0.00012</td>
</tr>
<tr>
<td>H→ZZ→4l</td>
<td></td>
</tr>
<tr>
<td>H→WW→2l2ν</td>
<td></td>
</tr>
<tr>
<td>qqH, H→WW→lν</td>
<td></td>
</tr>
<tr>
<td>qqH, H→π→l+jet</td>
<td></td>
</tr>
<tr>
<td>qqH, H→γγ</td>
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</tbody>
</table>

Theory uncertainty
Δα\text{had}^{(5)} =

m_{\text{limit}} = 144 \text{ GeV}
ECAL Performance

Resolutions

• ECAL benchmark: mass resolution of $H \rightarrow yy$ process

$$\frac{\sigma_M}{M} = \frac{1}{2} \left( \frac{\sigma_{E_1}}{E_1} \oplus \frac{\sigma_{E_2}}{E_2} \oplus \frac{\sigma_{\theta}}{\tan \theta / 2} \right)$$

with $\oplus =$ quadr. sum

Components: energy and angular resolutions

• angular resolution can be achieved without too much problems: more about this later

• energy resolution more complex

$$\frac{\sigma_E}{E} = \left( \frac{a}{\sqrt{E}} \oplus b \oplus \frac{\sigma_N}{E} \right)$$

$a$ – stochastic proportionality factor

$b$ – constant term (calibration, non-uniformities etc.)

$\sigma_N$ – noise equivalent (electronics, pileup energy)

• $a<10\%$ difficult with sampling (pushes precise geometry)

• $a=2\%$ with active calorimeters (requires $b<0.5\%$, tricky)
**Higgs to gamma gamma**

The narrower the mass peak, the cleaner to separate.
Electromagnetic Calorimeters

Sampling calorimeters
- Atlas: liquid Argon, accordion geometry

Fully active calorimeters
- CMS: PbWO$_4$ crystal calorimeter
- more sensitive to radiation
- online laser monitoring system
- also called homogeneous
ECAL Layout in CMS

CMS choice

• crystal calorimeter: PbWO$_4$ (compact, fast, doable)
• PbWO$_4$ is optimal material, next page
• endcap has additional pre-shower: reject neutral pions as photon background
Crystal Comparison

Table 1.1: Comparison of properties of various crystals

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>BGO</th>
<th>CSI</th>
<th>BaF₂</th>
<th>CeF₃</th>
<th>PbWO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm³]</td>
<td>3.67</td>
<td>7.13</td>
<td>4.51</td>
<td>4.88</td>
<td>6.16</td>
<td>8.28</td>
</tr>
<tr>
<td>Radiation length [cm]</td>
<td>2.59</td>
<td>1.12</td>
<td>1.85</td>
<td>2.06</td>
<td>1.68</td>
<td>0.89</td>
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<tr>
<td>Interaction length [cm]</td>
<td>41.4</td>
<td>21.8</td>
<td>37.0</td>
<td>29.9</td>
<td>26.2</td>
<td>22.4</td>
</tr>
<tr>
<td>Molière radius [cm]</td>
<td>4.80</td>
<td>2.33</td>
<td>3.50</td>
<td>3.39</td>
<td>2.63</td>
<td>2.19</td>
</tr>
<tr>
<td>Light decay time [ns]</td>
<td>230</td>
<td>60</td>
<td>300</td>
<td>16</td>
<td>0.9</td>
<td>8</td>
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<td>5 (39%)</td>
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<td>15 (60%)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 (1%)</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.85</td>
<td>2.15</td>
<td>1.80</td>
<td>1.49</td>
<td>1.62</td>
<td>2.30</td>
</tr>
<tr>
<td>Maximum of emission [nm]</td>
<td>410</td>
<td>480</td>
<td>315</td>
<td>210</td>
<td>300</td>
<td>440</td>
</tr>
<tr>
<td>Temperature coefficient [%/°C]</td>
<td>~0</td>
<td>-1.6</td>
<td>-0.6</td>
<td>-2/0</td>
<td>0.14</td>
<td>-2</td>
</tr>
<tr>
<td>Relative light output</td>
<td>100</td>
<td>18</td>
<td>20</td>
<td>20/4</td>
<td>8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Moliere radius $R_M = 0.265 X_0 (Z+1.2)$

- 95% transverse shower contained in 2 $R_M$
Energy Loss in Trackers

Bethe Bloch

- depends on $\beta$ only
- given $dE/dx$ and momentum $p$ determines and $\beta$ thus the mass, $m$
- after mass correction: universal curve

How to measure?

- pulse height in tracker
- lots of corrections ...

\[
\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 Z \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{l^2} T_{\text{max}} - \beta^2 - \frac{\delta}{2} \right]
\]
**Time-Of-Flight Detectors**

**Principle**
- arrival depends on velocity
- $p + v: m$
CDF: Time-Of-Flight Detector

Characteristics of the system

- Scintillator Bars: 216 (1.7°)
- Radius: 140 cm
- Bar Cross Section: 4 x 4 cm²
- Bar Length Bar: 300 cm
- Coverage: |η| < 1
- Scintillator Material: Bicron–408
- Photomultipliers: Hamamatsu
- Readout of the Bars: two-sided
- Design Resolution: 100 ps

Hamamatsu photomultiplier

- Type: fine mesh, R7761
- Stages: 19
- Geometry: 1.5 inch diam.

PMT operates in 1.4 T B field
Bar Arrive at the Bore
Bar Unpacking
Inserting the Bar
And the Tracker still Fits
Particle Distinction with TOF

Number of tracks / 30 MeV

TOF mass in GeV, 0.5 GeV < p < 1.0 GeV
Cherenkov Light

Particle travels through material

- weak EM wave spreads: polarizing/de-polarizing effect
- slower than wave speed: waves never interfere
- faster than wave speed: they will interfere and create conic light under characteristic angle: \( \cos \theta_c = 1/\beta_n \)
Ring Imaging CHERENKOV Detectors

RHIC detectors

- particle velocity from the opening angle of light cone
- particle passes through proper type of material
- the light cone produces a ring image
- size of ring determines velocity
DIRC at BaBar Experiment

Detection of Internally Reflected Cherenkov light

- quartz bar is used to transport light under Cherenkov angle
- light ring in water tank
- size determines $\beta$
- high surface quality needed
- angle has to be retained
Conclusion

Electron/Photon reconstruction crucial at LHC
- very low Higgs masses drive the ECAL design
- $m_H$ below 130 GeV: $H \rightarrow \gamma\gamma$
- active calorimeter more precise then sampling type
- CMS and Atlas covers full Higgs range

Particle Id (mostly pion/kaon separation)
- $dE/dx$ in tracking (solid and gaseous)
- time of flight measurements
- Cherenkov light cone do determine velocity
  - Ring Imaging CHerenkov detectors: RICH
  - Detection of Internally reflected Cherenkov light: DIRC
Next Lecture

Analysis Tips Bottomonium Analysis....