LHC Experiments:
Physics of Particle Detectors

Jason Nielsen
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz

Theoretical Advanced Studies Institute
Boulder, Colorado
June 2010
Goals of Particle Detection

- Measure 4-vector of each particle
  - \((P_x, P_y, P_z, m)\) or \((P_x, P_y, P_z, E)\) or \((P_t, \eta, \phi, E)\)
- Relativistic momentum measured in B field
- Lab frame velocity measured with timing
- Particle type measured with energy loss
- Scalar energy measured with shower of large cross section interactions

- Two kinds of measurements:
  - Non-destructive measurements
  - Destructive measurements
Large Cross-Section Particle Interactions

• Need some interaction to see the particles’ passage, preferably a lot to reach electronics threshold
  – Electromagnetic interaction at short range
  – Strong/nuclear interaction in high-A material

• Interesting to note the following contrasts for particle interactions: \((\hbar c)^2 = 0.4(\text{GeV})^2 \text{mb}\)

<table>
<thead>
<tr>
<th></th>
<th>Radius</th>
<th>Cross Section</th>
<th>Energy Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms</td>
<td>1 Å</td>
<td>(10^8) barn</td>
<td>eV</td>
</tr>
<tr>
<td>Nucleons</td>
<td>1 fm</td>
<td>(10^{-2}) barn</td>
<td>GeV</td>
</tr>
</tbody>
</table>
Charged Particle Spectrometer

• Lorentz force gives rise to helix
• Transverse momentum inversely proportional to sagitta:
  \[ s = \frac{0.3}{8} \frac{L^2 B}{p_T} \]
  – 2 mm in CMS (B=4, L=1.1)
• Goal on momentum resolution translates to sagitta resolution
  – ATLAS: 10% on 1 TeV muon requires 50 µm resolution on sagitta measurement
Electromagnetic Interaction

- Elastic scattering off charge centers: “multiple scattering”
  - Increases with material: \( \langle \theta^2_{\text{MS}} \rangle = N \langle \theta^2 \rangle \)
  - The kick from MS is roughly 21 MeV per rad. length

- Energy loss through ionization: “dE/dx” or “Bethe-Bloch”
  \[
  \frac{dE}{d(\rho x)} \sim \left( \frac{N_A Z}{A} \right) \left( \frac{\alpha^2 \hbar}{m_e c} \right) \left( \frac{1}{\beta^2} \right) \ln() \]

- Minimum ionizing particle energy loss: 1.5 MeV/(g/cm^2)
  - Muons, other charged weak relativistic particles
Energy Loss Plot for Different Particles

Review of Particle Properties
(pdg.lbl.gov)
Charged Particle Detectors

- Current generation use controlled electric fields to collect ionization electrons and cations
- Original drift tube geometry still used in muon detectors, straw tube systems
- Exact knowledge of drift time allows sub-volume resolution if $t_0$ is calibrated
- Intrinsic resolution limited by placement resolution and charge cloud diffusion

$$E(r) \sim \frac{V_0}{r}$$
Solid-State Charged Particle Detectors

- Larger ionization energy loss than in gaseous media
  - In silicon, roughly 400 keV per mm traversed
- Lithographic patterning allows fine segmentation: 50 µm
- Charges drift under applied electric field to strip or pixel elements
- No amplification of charge ("unity gain")
- Crystal defects can trap charge carrier in bulk
Electronic Readout of Tracking Detectors

• Electron-hole pair creation requires 3.6 eV
  – Total charge expected in 300μm detector is 5 fC, fed to low-noise analog preamplifier
  – A “hit” is $X \sigma$ (noise) above dark threshold, where $\sigma$ can change with time as detector ages

• “Binary” readout vs “Time Over Threshold”: cost vs spatial and charge resolutions
Particle Type Identification

- Measure $\gamma$ or $\beta$ and use $E=\gamma m$ to determine mass/type
  - Energy loss ($dE/dx$) as measured by ToT electronics
  - Direct timing measurements of velocity
  - Transition radiation / Cherenkov radiation
Calorimeter Showers: EM vs strong

- EM interactions: Bremsstrahlung and pair production
  - Bremsstrahlung \( E(x) = E(0)e^{-\rho x/X_0} \)
  - Pair production cross section similar \( \sigma_{\text{pair}} = \frac{7}{9}\sigma_B \)
- EM cascade continues until critical energy (ionization)
  - Exponential branching, then pinching down at end
- Hadronic showers are nuclear interactions with multiplicities that scale with incident particle energy
Calorimeter Energy Resolution

- Critical energy: energy loss through ionization and pair production are equal
- “Shower maximum” has many particles just above $E_c$
  - Proportional to total number of particles in shower
  - $N_{\text{max}} \sim E/E_c$, even though this is a random process

- Energy resolution $\frac{dE}{E} \sim \frac{dN}{N} \sim \frac{1}{\sqrt{E}}$
  - ATLAS: $\sigma(E)/E = 10%/\sqrt{E}$
  - CMS: $\sigma(E)/E = 2.7%/\sqrt{E}$
Calorimeter vs Tracker Resolution

ATLAS resolutions

- Tracking
- EM calo
- Hadr calo

\[ \frac{\sigma}{p_T} \] vs \[ p_T \] (GeV/c)
Muon Detection

• Standalone spectrometer or integrated muon chambers
  – Well-mapped large-volume high magnetic field
  – Precision hits for sagitta measurement
  – Precision timing for long flight distances (ATLAS)
  – Link with inner tracker reconstruction

• Muon chambers lie beyond 20 interaction lengths of material
• Muon MIPs deposit few GeV in hadronic calorimeter
Missing Energy Reconstruction

- Vector quantity: assume zero total transverse momentum
- Hermetic calorimeters account for charged & neutral
  - Apply corrections for response to muons, jets

- Etmiss resolution

\[ \sigma = 0.57 \sqrt{E} \text{ (GeV)} \]

(confirmed early data)
Tracking of Charged Particles

• Dual challenges for tracking algorithms:
  – Pattern recognition in 1% occupancy subsystems
  – Precision track fitting to recover 4-momentum
• ATLAS and CMS begin with pixel detectors and build segments moving out (except for “backtracking”)
  – Define “search road” for next layers’ hits
• Expect helical trajectory in solenoidal field (if no dE/dx)
  – $\chi^2$ fit to helix with 5 parameters
• Kalman filter accounts for energy loss in each detector layer, adjusting search road and fit simultaneously
Event Before Tracking Algorithm
Event After Tracking Algorithm
Limitations of Tracking and Some Solutions

• Algorithms require low occupancy $O(1\%)$ to avoid fakes
  – Detectors designed to meet this requirement, even in most dense environments like boosted jets

• Kinks in track may fool pattern recognition algorithm
  – Bremsstrahlung effects, other material interactions
  – May be solved by connecting two segments, but usually does not affect electron 4-mom reconstruction

• Converted photons do not produce tracks until outside of the pixel detectors, so track “seed” is not found
  – Employ “back-tracking” techniques seeded by calorimeter deposits for initial 4-momentum estimate
Conversions, Bremsstrahlung, “Tridents”

• Large amount of material in LHC experiments
  – Momentum conservation dictates $e^+e^-$ kinematics

• Charged particles radiate

• “Trident”: Bremsstrahlung followed by conversion
  – Possibility to mismatch $e^+e^-$ pair and misidentify electron as converted photon

\[
\begin{align*}
&\begin{array}{c}
e^+ \\
\gamma
\end{array} & \begin{array}{c}
e^- \\
\gamma
\end{array} & \begin{array}{c}
\gamma \\
e^-
\end{array} & \begin{array}{c}
\gamma \\
e^-
\end{array} & \begin{array}{c}
e^+ \\
\gamma
\end{array} & \begin{array}{c}
e^- \\
\gamma
\end{array}
\end{align*}
\]
Other Detector Backgrounds (Fakes)

• Distinguished from “physics backgrounds”:
  - $\pi^0$ decays to $\gamma\gamma$, muon decays to $e\nu\nu$

• Even large cross section processes do not have to happen
  - $\pi$ mesons “punch through” many interaction lengths into muon chambers

• Simple algorithms can confuse similar signatures
  - Jet algorithm in calorimeter gathers electron energy
  - Losing an electron’s track makes it look like a photon
Exotic Particle Signatures: CHAMPS

- CHarged MAssive Particles in any theory beyond SM (understood to be stable particles on scale of detector)
- High mass implies low velocity trajectories
  - Large energy loss through ionization ($\beta$-2)
  - Possibly slow ($\beta<0.7$) enough to be out-of-time with other, relativistic particles in the same hard scatter
  - No EM showering (brem m$^{-4}$)
- CHAMPS may stop in middle of detector, depending on initial momentum
- Doubly-charged particles (long-lived H$^{++}$) have 4x ionization energy in the tracking detectors
Exotic Particle Signatures: R-hadrons

• Stable Massive Particles with heavy colored particles, especially meta-stable gluinos – \( \tilde{g}q\bar{q}; \tilde{g}qqq \)
  – Heavy gluino is a spectator to the quark interactions
  – Expect signature similar to CHAMPs

• Most striking signature is charge flipping (charge/neutral) between inner detector and muon detectors

• Precise interactions are still under study for LHC
Exotic Signatures: Non-Pointing Photons

- Long-lived neutralinos decay to photon + gravitino $\gamma\tilde{G}$
  - Typical $c\tau$ is $O(1 \text{ m})$; photons appear displaced
  - Not contained in projective tower

- Measure lifetime of neutralino via photon
  - Converted photon in tracker
  - Angle in EM calorimeter
  - Kinematics

- Very long-lived neutralinos look like missing energy
Exotic Signatures: Stopped Gluinos

• Special case of low-\(\beta\) R-hadrons that stop in the detector
  – Most probable stopping points shown below

  – Decay can be seconds to weeks later than production

• Signature: displaced decay is a calorimeter signal out of time with LHC collisions (vetoed by beam monitors)
Exotic Signatures: Quirks

- New strong interaction at energy < 1 TeV
- Infracolor “string” connecting quirks cannot break easily
- Experimental signature of quirk-antiquirk pair depends on physics scale, length of string

- Mesoscopic string: appears as single particle with 2q
- Macroscopic string: quirks on end of string spiral through detector in unique pattern

Kang & Luty 0805.4642

Fig. 5. Anomalous tracks from quirks with macroscopic strings.