Overview of the week

• Today: an introduction to collider experiments
• Tomorrow: Breit-Wigner and Angular momentum
• Friday: Rotations and symmetry
Collider experiments

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Collider physics

• Introduction

• Some $e^+e^-$ collider physics
  – $R(e^+e^-\rightarrow\text{hadrons}/e^+e^-\rightarrow\mu^-\mu^+)$
  – The Breit-Wigner cross section
  – $Z^0$ and $W$ at LEP

• Hadronic machines
  – Total cross sections
  – Hard and soft collisions
  – Triggers
  – An example: LHCb
Why collide?

- Total centre-of-mass energy for proton beam on a fixed H target (p-p collision):
  \[ s_{\text{FIXED}} = (E_{p}^{\text{LAB}} + m_{p})^2 - p^2 = 2m_{p}^2 + 2m_{p}E_{p} \]
- Same beam energy but p and p colliding in lab frame
  \[ s_{\text{CM}} = 4E_{p}^2 \]
- The ratio:
  \[ \sqrt{\frac{s_{\text{CM}}}{s_{\text{Fixed}}}} \approx \sqrt{\frac{2E_{p}}{m_{p}}} \text{ when } m_{p} \ll E_{p}. \]
  \[ \approx 120 \text{ for 7 TeV protons} \]
- Physics beyond the Standard Model lives at high mass therefore require highest energy possible
- Some other advantages (of many)
  - Focussed high intensity e^+e^- collisions-clean with a tunable CoM energy
  - 4\pi detectors
  - Recycle bunches
Types of collider

• e+e-
  – LEP, CERN, Switzerland-(Electroweak physics) \( \sqrt{s} = 90-200 \text{ GeV} \)
  – PEP-II, SLAC, US and KEK-B, KEK, Japan – B factories \( \sqrt{s} = m(\Upsilon(4s)) \)
  – DAFNE, Frascati, Italy-K factory \( \sqrt{s} = m(\phi) \)
  – CESR, Cornell, US-Charm and B factory
  – VEPP, Novisibirk, Russia and BES, Beijing, China– light meson spectroscopy
  – SLC, SLAC, US - \( \sqrt{s} = 90 \text{ GeV} \) (Linear collider)
  – ILC,??? - \( \sqrt{s} = 500-1 \text{ TeV} \)

• ep
  – HERA, DESY-Deep Inelastic Scattering

• proton - antiproton:
  – SppS, CERN-Discovery of W and Z
  – Tevatron, Fermilab-Current energy frontier machine \( \sqrt{s} \approx 1.8 \text{ TeV} \)

• pp
  – LHC, CERN- \( \sqrt{s} = 14 \text{ TeV} \) (starts 2007)

• Heavy Ion (Au-Au) Collisions
  – RHIC, Brookhaven, US and LHC -Quark-Gluon Plasma
The total $e^+e^-\rightarrow$hadron cross section

- $e^+e^-\rightarrow$qq→hadrons – no free quarks
- The quark level process can be compared to $e^+e^-\rightarrow\mu^-\mu^+$
- $\sigma(e^+e^-\rightarrow\mu^-\mu^+) = 4\pi\alpha^2/3s \approx (88\ nb)/s$ for $\sqrt{s}<<M_Z$
- You will calculate this during the C4 course
  - Matrix element $\propto$ propagator$^2 \propto 1/s^2$
  - Density of final states $\propto s$
\[
R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \quad \text{Calculated}
\]

\begin{align*}
R &= n_c \sum Q_q^2, \text{ where } n_c \text{ is the number of colours and } Q_q \text{ are the charges of the quarks produced.} \\
\text{Below charm threshold: } & R = n_c \sum_{q=u,d,s} Q_q^2 = \frac{2}{3} n_c \quad \text{Above bottom threshold: } R = n_c \sum_{q=u,d,s,c,b} Q_q^2 = \frac{49}{9} n_c \\
n_c = 3 \text{ is consistent with the data}
\end{align*}
LEP and the Z0

- Experiments at the LEP collider performed precise measurements of the total cross section near the
- One of several important results is that the resonance is compatible with only 3 neutrinos within the Standard Model
- Also, measurements are precise enough to probe loop effects
  - Indirectly constrain new physics and mass of the Standard Model Higgs boson
LEP and the W

- LEP also ran at energy above threshold for WW production
- Measured cross sections and W mass
- W mass important constraint on Higgs boson

\[ \sqrt{s} \text{ (GeV)} \]

\[ \sigma_{WW} \text{ (pb)} \]

\[ m_H \text{ [GeV]} \]

\[ m_t \text{ [GeV]} \]

\[ 68\% \text{ CL} \]
Multiplicity measurements

- Test and tune models of hadronisation
- Operates in a non-perturbative regime which is very hard/impossible to calculate
- At $Z^0$ multiplicity of different types of mesons is:

<table>
<thead>
<tr>
<th>Meson</th>
<th>$\langle \text{Multiplicity} \rangle$/event</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm$</td>
<td>16.99±0.27</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>9.42±0.32</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>2.242±0.063</td>
</tr>
<tr>
<td>$K^0$</td>
<td>2.049±0.026</td>
</tr>
<tr>
<td>$D^\pm$</td>
<td>0.175±0.016</td>
</tr>
<tr>
<td>$D^0$</td>
<td>0.454±0.030</td>
</tr>
<tr>
<td>$B^\pm/B^0$</td>
<td>0.165±0.026</td>
</tr>
</tbody>
</table>
Hadron machines-cross sections

• **Proton-proton** cross sections
  – 10s of mb compared to nb in $e^+e^-$
  – resonance structure at low centre-of-mass energies over falling cross section
  – no purely elastic ($\bar{p}p \rightarrow \bar{p}p$) regime in $\bar{p}p$ collisions-annihilation
  – raising smoothly above $\sqrt{s} \sim 10$ GeV
    • parton-parton collisions, in particular gluon gluon collisions
    • $\bar{p}$ and $p$ the same

• **Pion-proton** cross section
  – Elastic $\Delta$ resonances at low momentum
  – Same smooth behaviour and magnitude at higher energies
Hard and soft collisions

- Hard scattering of partons within proton and (anti)proton yield two high transverse momentum (component perpendicular to beam direction) partons.
- Heavy intermediate states or high momentum transfer high $Q^2$
  - Drell Yan production of $Z^0/\gamma$ which then decays to a $q$ anti-$q$ pair
  - gluon gluon fusion to produce bottom or top quarks ($m_t\sim 175$ GeV/c)
- The remains of the breakup of the proton and antiproton form the underlying event (unlikely to have high $p_t$)
- Initial and final state radiation of gluons or photons contribute to the hard-scattering process
Hard and soft collisions

- Soft collisions: $\sigma \propto \exp(-a p_t)$
- Hard collisions: $\sigma \propto 1/p_t^4$
  - Dependence similar to Rutherford scattering
- Hard collisions a tiny piece of the total cross section
- Typical $p_t$:
  - Hard greater than $\sim 3$ GeV/c
  - Softer $\sim 0.3$ GeV/c
- QCD models used in simulations of proton-(anti)proton collisions tuned on data
  - Events selected in well understood regions of experiments with high efficiency for finding all tracks
  - Central or low rapidity
  - Pseudorapidity $\eta = -\ln \tan (\theta/2)$
Triggering at hadron colliders

• At hadron machines:
  – # of interesting events/# of bunch crossings<<1
  – interesting events are all hard, high transverse momentum
• Bunch crossings happen at a rate of 40 MHz at LHC
• Hardware limitations mean you cannot store all events to analyse at your leisure later
  – Can only write at O(1 kHz) to disk
  – Limited storage space: each event 100 kbytes. (LHCb will have $40 \times 10^{13}$ events/year
  – Limited CPU time for offline analysis
• Need to select/trigger interesting events in real time
• Rough analysis performed using a limited set of detectors components to make the decision whether to keep or discard an event
Example: LHCb

- LHC experiment to collect large samples of events that contain bottom quarks
- Study CP violation – the difference between matter and antimatter

Precise tracking, vertexing, impact parameters

Momentum measurement

Particle ID

Electron, photon and hadron calorimetry

Muon identification

C4 option 15
Simulated LHCb events
LHCb trigger architecture

- Several stages (‘levels’) of the trigger with more complex and hence slower algorithms are run sequential
- If an event fails at any stage it is rejected
- Outline of the stages
  1. Select single beam interactions at a rate of 10 MHz – suppression by a factor of 4
  2. On detector electronics perform first signal processing. There is a 4μs (160 clock periods) fixed wait (‘latency’) for decision. All data collected in this period is stored in on-detector electronics (‘pipelines’). Accept rate 1 MHz – suppression by a further factor of 10.
  3. All data transferred via fibre optic cables to a ‘counting room’ 100 m away from the detector, which has far less radiation than around the detector. (Electronics simpler and cheaper.) This room is equipped with hundreds of CPUs, which perform the first coarse analysis in 1 ms on average (max 50 ms) with an accept rate of 40 kHz – suppression by a factor of 25.
  4. More dedicated algorithms run for specific (‘exclusive’) decay modes and inclusive channels of interest. For example: $B^0 \rightarrow h^+h^-$ ($h=\pi,K$), $B_s \rightarrow D_s \pi$, inclusive $J/\psi$ ($pp \rightarrow J/\psi + X$) and inclusive $D^*$ ($pp \rightarrow B + X, B \rightarrow D^* + X$). Variable time for decision. Events written to disk for offline analysis at ~2 kHz – suppression by a factor of 20.
LHCb trigger algorithms

• Single beam crossings
  – 30 MHz bunch crossings – empty spots in comparison to general purpose LHC experiments (Atlas/CMS)
  – 2D primary vertex finding – each primary vertex corresponds to a pp interaction

• On-detector 1st level:
  – Recognise high transverse momentum $\mu^\pm$, $e^\pm$, $\gamma$ and hadrons in muon system and calorimeters. Signature of a hard scatter producing a $b$ quark.

• Off-detector 2nd level:
  – 3D reconstruction of primary vertices using the vertex detector
  – B decays have a relatively long lifetime of 1.2 ps, so they fly some distance ($c\tau=360 \, \mu$m) from primary vertex.
  – Therefore, identify tracks with large ‘impact parameter’ (originated from a decay some distance from the primary)
  – Make crude transverse momentum measurement of these tracks to remove fakes from multiple scattering and hadronic interactions in detector material. Uses first tracking station and vertex detector only.
  – Associate with 1st level $\mu^\pm$, $e^\pm$, $\gamma$ and hadrons.

• Off-detector 3rd level:
  – All subsystems data available for reconstruction, including hadron ID.
  – Reconstruction of tracks for precise momentum measurement
  – Pion and kaon ID

• 2nd and 3rd stages are C++ algorithms which are easy to evolve over time. Only 1st level fixed when building the experiment.
Summary

• Different types of collider main tool for high-energy physics experiments
• $e^+e^-$: the importance of R and electroweak physics at LEP
• Hadron-hadron: large cross-sections, but complex events
  – Hard vs soft
• How to trigger