Hadron Physics at LHCb

Thomas Ruf
for the LHCb Collaboration

- LHC and LHCb
- Detector Status
- Hadron Research Topics, Examples
Primary goal of the LHCb Experiment

- Search for New Physics contributions in decay amplitudes of $b$-hadrons

$$\begin{align*}
d &\to \text{W} & b \\
\bar{b} &\to \text{W} & \bar{d}
\end{align*}$$

- This requires
  - Detector with excellent vertex and charged particle identification capabilities
  - Sophisticated trigger algorithms to handle the high background rate

Free benefit

- Detector can also be used for studying Hadron Physics
  - Production cross sections in pp collisions at LHC energies
  - Properties of heavy hadrons, masses, lifetimes, decay channels
  - Studies of the new X,Y,Z states and search for other exotic particles

- Mainly a question of bandwidth, data storage and CPU time for reconstruction.
- For obvious reasons, LHCb main emphasis currently on core physics program
Location of the Experiment

Mont Blanc

Geneva

100m below surface

4.3km

LHCb  ATLAS  ALICE  CMS

10.9.2008  10:35:02  0ns

First circulating beam
What LHC has to offer

- Protons, 7 $\leftrightarrow$ 7 TeV
- Visible cross section: $\sim 63$ mb
- $b$-cross section: $\sim 0.5$ mb
- Charm cross section: $\sim 3.6$ mb
- $B_d/B_u/B_s/B_c/b$-baryons
  4 : 4 : 1 : 0.01 : 1
- Ultimate luminosity of LHC: $10^{34}$ cm$^{-2}$s$^{-1}$
  - $10^6$ b-hadrons/sec
    BUT $> 20$ interactions / x-ing
- LHCb prefers: $(2-3) \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - Mainly single interactions
  - Still $10^5$ b-hadrons per second
    and $7 \times 10^5$ charm-hadrons per second
  - Luminosity is tunable by adjusting beam focus
B meson average transverse momentum: $p_t \sim 5$ GeV/c

$\Rightarrow$ large boost

$\Rightarrow$ a forward single arm spectrometer can cover a large fraction of the phase space

Pythia production b-cross section

pseudorapidity range LHCb: $2<\eta<5$

$p_t$ thresholds for triggering: 1-2 GeV/c
LHCb Collaboration

700 people, 53 Institutes, 14 countries

http://LHCb.cern.ch
Detector Overview

Muon System
1368 MWPC + 24 GEM
Used in L0 trigger

Rich detectors
Cerenkov light
gas and aerogel

Magnet
Dipole, \( \int Bdl = 4Tm \)

Calorimeter System
Hadronic / Electromagnetic
Used in L0 trigger

Rich detectors
Cerenkov light
gas and aerogel

Magnet
Dipole, \( \int Bdl = 4Tm \)

Vertex Detector
Silicon strips

Tracking System
Straw tubes, silicon strips

pp collision Point

Beam 1

Beam 2
The Experimental Hall
Tracking in LHCb

Vertex reconstruction in vacuum
- Silicon strip detectors with $r$-$\phi$ geometry for fast online track reconstruction
- 2 halves, 21 stations, 7mm from beam, with 250$\mu$m Al foil between detector and beam vacuum
- Impact parameter resolution: $\sigma_{IP} = 14\mu m + 35\mu m/p_t [GeV/c]$

Downstream tracking:
- Silicon strip detector before, and mixture of silicon strip and drift tubes after magnet, $\Delta p/p \sim 0.4\%$
Hadrons, 2 Rich detectors

- Hybrid Photo Detectors (HPD)
  - Novel technology: Photocathodes ($\lambda \sim 200$-$600$ nm with Silicon pixel readout)
  - 3 radiators (aerogel, $C_4F_{10}$, CF$_4$) for $\pi$-K separation from 2-$100$ GeV/c

Muon ID

- $\mu$-misidentification probability: 
  ~1.5%, dominated by decays in flight
Global Performances

- Track efficiency in acceptance ~95%
- Momentum resolution $\Delta p/p \sim 0.4\%$
- Primary vertex resolution: $x/y \sim 10\, \mu m$, $z \sim 50\, \mu m$
- Impact Parameter resolution $\sigma_{IP} \sim 20\, \mu m$ for high-$p_t$ tracks
- B-Mass resolutions depending on final state topology 10-60 MeV/$c^2$
- Typical Lifetime resolution $\sim 40-60\, \text{fs}$
- Flavour Tagging:
  - $B_s: \varepsilon D^2 \sim 7\%$
  - $B_d: \varepsilon D^2 \sim 4\%$

LHCb Physics Studies are based on full GEANT4 MonteCarlo simulations including all known detector effects, material, noise, x-talk, spillover.
Trigger and DAQ

High Level Trigger: Software using offline reconstruction algorithms and tools

- Start with confirming L0 objects,
- reconstruct tracks in Velo to get primary vertices,
- find more high $p_t$ tracks and isolated secondary vertices to confirm b-decay topology
- $\varepsilon$(HLT) ~ 60-80%

<table>
<thead>
<tr>
<th></th>
<th>had</th>
<th>$\mu$</th>
<th>$\mu\mu$</th>
<th>$e^\pm$</th>
<th>$\gamma$</th>
<th>$\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T&gt;$ (GeV/c)</td>
<td>3.5</td>
<td>1.3</td>
<td>$\Sigma&gt;$1.5</td>
<td>2.6</td>
<td>2.3</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Hardware: Fixed latency of 4μs

Efficiencies: Muon (~90%), Hadron(~50%), Radiative(~70%)
First time synchronization and space alignment using Cosmics: only for big systems after magnet several weeks of running in 2008

Trigger: ECAL and HCAL in coincidence

Muon

Cosmics

Calo

OT+IT
Example: Time alignment of Muonstations

Hit raw time (ns)
First time synchronization and space alignment using
- Beam induced events, many particles, right geometry
  several shots, last September 10th beam1&2 passing through LHCb

Splashy event from lost particles
(not all tracks reconstructed...)

Side view
From a few hundred events with 2-3 tracks, first track based alignment:

- Module alignment precision is 5 μm for X and Y translation and 200 μrad for Z rotation

Resolution close to expectation:

\[
\text{line} = \frac{\text{pitch}}{\sqrt{12}} = \text{resolution for single strip clusters}
\]
MUON, CALO and RICH systems

- **Circulating beam1: right direction for LHCb**
- **Readout of consecutive triggers**
  - 8 events every 25 ns, slowest slow motion
    - (1s of film takes about 18 days to watch with 25 frames per second)
- **Splash events (hitting on collimator)**
- **Only a few hours ....**
Long running period of 11 month, aim for >0.3 fb\(^{-1}\) at 10 TeV cm energy (30% less bb)

End of July, cool down of last sector starts

September – October’09: Machine setup
   First collisions 2x2
   
   - increase bunches: 43x43, 156x156 bunches
   - 156x156: L=(0.5-1) x 10\(^{32}\) cm\(^{-2}\) s\(^{-1}\)
   - Eventually go to 50ns bunch spacing

November’10: Shutdown

Nominal year
   ATLAS/CMS: 10 fb\(^{-1}\)
   LHCb: 2 fb\(^{-1}\)
Hadron Physics Research Topics Examples

- Mbias events
- Dimuon physics
- $B_c$ Mass and Lifetime
- New X, Y, Z states
- Data Mining
- Luminosity Measurements

Unique pseudorapidity range
Early LHCb Physics using minimum bias data

1 bunch-bunch frequency: ~11kHz
Only interaction trigger required to get < 2kHz event rate at low luminosity

\( \frac{\sigma \cdot \varepsilon}{\sigma_{mb}} \)

10^8 minimum bias events, O(day) @ 2kHz

- Need to switch on trigger
- Prescale mbias events

\( N_{mb} \)
With $10^8$ minimum bias events

- Plenty of $K_S \to \pi\pi$ and $\Lambda \to p\pi$
  - 95% purity with kinematical and vertex cuts only
  - Clean and unbiased sample for PID studies, ~100k events
  - Measure differential distributions ($\eta$, $p_T$)
  - Strangeness studies:
    - Strange quarks are necessarily the result of the hadronization therefore strangeness probes the fragmentation in an unique way
    - Input to hadronization/fragmentation models
    - Baryon to meson ratios ($\Lambda/K_S$ vs $p_T$), ... many theoretical models that can be challenged in a unknown territory
    - $\Lambda / \Lambda$ ratio, ...
  - Systematics and not statistics will be the issue:
    - Acceptances, efficiencies, charge asymmetries

- Signal in 10k mbias events, few seconds @ $10^{31}$ cm$^{-2}$ s$^{-1}$
- $\Lambda \to p\pi$ events
  - ~ 40 mins @ $10^{31}$ cm$^{-2}$ s$^{-1}$
  - ~50k $\Lambda \to p\pi$ events

Thomas Ruf
GHP2009 Denver
LHCb can trigger very efficiently on muons:

- ~1s of running @ nom. luminosity
- $J/\psi$ reconstructed with low background, S/B = 4

$J/\psi \rightarrow \mu\mu$ production not fully understood:

- separate prompt $J/\psi$ from detached $b \rightarrow J/\psi$
  - $\sigma (pp \rightarrow J/\psi_{\text{prompt}} \rightarrow \mu\mu) = (3\pm1)\mu$b
  - $\sigma (pp \rightarrow b \rightarrow J/\psi \rightarrow \mu\mu) = \sim0.2\ \mu$b
  - expect 2M $J/\psi \rightarrow \mu\mu$ per 5 pb$^{-1}$
  - Efficiency depends on polarization, measure $\frac{d\sigma}{d(cos\theta)dp,d\eta}$

$\psi(2s) \rightarrow \mu\mu$

- measure the $\psi(2s)$ to $J/\psi$ production ratio, no luminosity measurement is needed.

$\chi_{c1,2} \rightarrow J/\psi \gamma$, $Y(1S) \rightarrow \mu\mu$, …
Expect: $\sigma(B_c) \sim 0.4 \mu b$ (10 × Tevatron)
- cleanest channel is $B_c^+ \to J/\psi \pi^+$
- BR is expected to be low (0.13%)
- Expect ~300 events for 1 fb$^{-1}$ with B/S ~ 1-2

$B_c^+$ mass measurement (1 fb$^{-1}$):
- Resolution: 17 MeV/c$^2$
- Expect: $\pm 1.7$ (stat) MeV/c$^2$
  - best measurement CDF: $\pm 2.9$ (stat.) $\pm 2.5$ (syst.) MeV/c$^2$

$B_c^+$ lifetime measurement (1 fb$^{-1}$):
- Expect: $\pm 27$ (stat.) fs
  - best measurement D0: $\pm 38$ (stat.) $\pm 32$ (sys.) fs

$B_c^+ \to J/\psi \mu^+\nu$ also under study for lifetime measurement,
- higher branching ratio, but missing neutrino
New X, Y, Z states

- **Proliferation of new states which do not fit into the quark model picture of hadrons: X(3872),... Y(4260),... Z(4430),...**
  - **X(3872):**
    - DD* molecule? $M(X)-M(D^*D) = +0.6$ MeV
    - diquark-antidiquark bound state: $[(cq) (cq)]_{S-wave}$, $J^{PC}=1^{++}$
  - **Y(4260):**
    - hybrid state: $(ccg)$? excluded by large isospin violation: decays in $\psi_{P}$ and $\psi_{\omega}$
    - diquark-antidiquark bound state: $[(cs) (cs)]_{P-wave}$, $J^{PC}=1^{−}$
    - molecular state, baryonium, ...

- **For the 4quark-model, more states expected**
  - Search for charged X states
  - Neutral partners of Z
New X, Y, Z states in LHCb

- Decay modes including high-mass di-muons, J/ψ, ψ(2S), Y(1S), ... have a high trigger efficiency:
  - LHCb can collect large samples, both prompt and from b:
    - e.g. $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \pi^+\pi^-$ : ~5000 decays / nominal year
    - Search for X,Y,Z states in the bb system via $Y(1S) \rightarrow \mu^+\mu^-$

- Study ongoing to determine $J^{PC}$ quantum numbers of X(3872), 1++ or 2-+
  - using $B^+ \rightarrow X(3872)(J/Ψρ) K^+$ and angular distributions of muons and pions
Inclusive single muon trigger, $B \rightarrow \mu X$

- $\sim 1$ kHz trigger rate with 50% b-purity
- Second b-hadron is almost trigger unbiased
- For free: flavour tag with $\varepsilon D^2 = 0.15$

Efficiency for decay products inside LHCb acceptance: (40-30)%

- $\rightarrow 1.5 \times 10^9$ events with fully contained b-hadron decay within one year (2 fb$^{-2}$)
- Equivalent to Belle and Babar total sample
- Contains all types of b-hadrons
Measurements of Luminosity

Method I, indirect measurements

- Normalize to reactions with known cross sections
  - \( pp \rightarrow pp + \mu^+\mu^- : \sigma = 70\text{pb} \) with < 1% theoretical error
    - \( \sim 5 \text{ events} / \text{pb}^{-1} \) or 10k events / nominal year
  - \( pp \rightarrow Z: < 5\% \) theoretical error (PDFs)
    - \( \sim 180 \text{ events} / \text{pb}^{-1} \) or 360k events / nominal year

Method II, direct measurements

- Van der Meer scan
  - Principle: Move beams and measure how the event rate changes => measure bunch shapes
  - Accuracy: \( \sim 20\% \) at the beginning, 5 -10% eventually ?

- Measure beam envelope with beam gas collisions
  - Principle: Reconstruct vertices of beam-gas events at the nominal interaction region => image the bunch shapes in X & Y
  - Accuracy: ultimately < 5%
The LHC produces huge amounts of known c,b-hadrons and yet unknown states

LHCb detector commissioning started with cosmics and beam induced events in 2008

Data processing and physics analysis being now exercised with MC data

LHCb was ready for first collisions in September 2008 and will be ready for the 2009/10 run.
The End
Backup Slides
Tracking Performance

\[ \int B dl = 4Tm \]

**Efficiency**

\(~ 95\%\)

**Momentum resolution**

\( \Delta p/p \sim 0.4\% \)

**Impact parameter**

\(~ 20\mu m\)
J/ψ Polarization

- **Polarization α**
  \[ \frac{d\sigma}{d \cos \theta} \sim 1 + \alpha \cos^2 \theta \]

  - Measurement complicated by LHCb acceptance
  - Fakes polarization
  - Eventually, need to measure
    \[ \frac{d\sigma}{d(\cos \theta) dp_t d\eta} \]

**Exercise:**

measure α from 30 nb\(^{-1}\) of inclusive J/ψ
(simulated α = 0, statistical errors only, using MC acceptance correction)
MC acceptance could be cross checked using unpolarized J/ψ from B → J/ψ K\(^+\)
Angular study of 
$B^+ \rightarrow X(3872)K^+$
$\rightarrow J/\psi \rho$

Studies on generator level, no detector simulation, no acceptance corrections!