LHCb status and physics

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B-physics

• Direct searches at LHC will likely reveal new degrees of freedom responsible for electroweak symmetry breaking.
• Direct observations of new particles at LHC unlikely to resolve the flavor puzzles.
• B-decays are sensitive to new particles and their flavor structure via virtual contributions in loop diagrams.
• On-going B-physics experiments already constrain NP scenarios.
• Improving precision of existing measurements and enabling new measurements, especially in $B_s$ decays, are of fundamental importance.
• For a long time $e^+e^-$ experiments carried the ball in B-physics domain.
• Recent measurement of $B_s - \overline{B}_s$ oscillation frequency by CDF (and D0) and its impact on NP constraints illustrates mostly untapped potential of hadron colliders for B-physics.
• LHCb is the first dedicated B-physics experiment at a hadronic collider.
LHCb Collaboration

14 countries
48 institutions
~600 people
The Forward Direction

• In the forward region the $b\bar{b}$ production cross-section is large:
  – At $\mathcal{L}=2\times10^{32}/\text{cm}^2\text{s}$, we get $10^{12}$ $B$ hadrons in $10^7$ sec
  – Limited solid angle $\rightarrow$ Limited cost (75 MCHF)

• The hadrons containing the $b$ & $\bar{b}$ quarks are both likely to be in the acceptance (flavor tagging!)

• $B$’s are moving with considerable momentum $\sim50$ GeV, thus minimizing multiple scattering:
  – Background rejection via detached vertex
  – Improved decay time resolution

• Compared to Tevatron:
  – $\sim5 \times \sigma_{bb}$; $\sim3 \times \sigma_{bb}/\sigma_{\text{inelastic}}$
  – Dedicated large bandwidth triggers (2000 Hz) and excellent hadron ID
The LHCb Detector

- Vertexing
- Tracking
- Hadron Identification
- Hadron triggering
- Muon Detector
- Calorimeters
- RICH1
- RICH2
- Proton beam interactions
- Cavern wall
- Interaction region
- Proton beam
- 250 mrad
- 15 mrad
L0 Trigger

- **Hardware trigger** (customs boards) with 4 μs latency
- Reduces 10 MHz inelastic collision rate to 1 MHz:
  - \( P_{t_{\mu_1}} \) + \( P_{t_{\mu_2}} \) > 1.3 GeV
  - \( E_{t_e} > 2.8 \text{ GeV} \)  \( E_{t_{\gamma}} > 2.6 \text{ GeV} \)  \( E_{t_{\pi^0}} > 4.0 \text{ GeV} \)
  - \( E_{t_{\pi,K,p}} > 3.6 \text{ GeV} \)

**Pile-up veto:**
Remove bunch crossings with too many beam-beam interactions (not applied to \( \mu \)-trigger)
DAQ Farm

- **Common Front End readout board**
  - Performs zero suppression
  - Event formatting for DAQ

- **Single Core Router:**
  - 1MHz input event rate
  - Total throughput: 50 GB/s

- **Event Filtering Farm**
  - ~1800 computer boxes (multicore)
  - Up to 44 boxes/rack
  - Executing High Level Triggers code
  - 2kHz data logging rate (~0.25 GB/s)

Force10 E1200, 1260 GbE ports
High Level Triggers

Trigger Tracker (TT):
- Fringe magnetic field
- Select high $p_T$ tracks

Tracking stations (T):
- Full magnetic field
- Refined $p_T$ selection
- Create secondary vertices

Muon stations:
- Full magnetic field
  - $p_T/p \sim 20\%$ standalone (L0)
  - $p_T/p \sim 5\%$ matched with Velo tracks

VELO:
- $r\phi$ strip geometry
- No magnetic field
- Reconstruct Primary Vertex
- Select large Impact Parameter tracks

All tracks
- $\sim 1\ ms$

High IP tracks
- $\sim 0.5\ ms$

High IP, $p_T$ or muon tracks
- $\sim 8\ ms$

<table>
<thead>
<tr>
<th>Rate</th>
<th>Trigger Type</th>
<th>Physics Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive $B$ ($B \rightarrow hh, D_{s} h, \ldots$) ($\pm 0.5$ GeV on $M_{B}$)</td>
<td>Targeted signals</td>
</tr>
<tr>
<td>600 Hz</td>
<td>Dimuon ($M_{\mu\mu} &gt; 2.5$ GeV)</td>
<td>$J/\psi$, $b \rightarrow J/\psi X$</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Single muon ($p_T &gt; 3$ GeV, $IP &gt; 3\sigma$)</td>
<td>data mining (other $B$)</td>
</tr>
<tr>
<td>300 Hz</td>
<td>Inclusive $D^* \rightarrow \pi D^0 \rightarrow \pi(K\pi)$ ($p_T &gt; 2$ GeV, $IP &gt; 5\sigma$, $\Delta m &lt; 10$ MeV)</td>
<td>Charm, PID calibrations</td>
</tr>
</tbody>
</table>

2000 Hz Total
Detector Status - VELO

21 stations
- R and $\phi$ layer each
- $n^+n$ type
- 2048 strips/sensor
- Strip pitch varies from $40\mu m$ to $100\mu m$

RF foil (0.3 mm Al)
Silicon Sensors

3 cm separation
Interaction point

Pile-up Veto ($r$ strips)
Detector halves retractable for injection

Beetle readout chips

Production about half done.

Successful test beam (Nov.06)
Trigger Tracker

2 double-layers:
   1 layer with stereo strips
Silicon microstrip sensors
   500µm thick
   ~200µm readout pitch

- Production is finished.
- Super-module assembly is in progress.
Tracking Stations

**Inner Tracker:**
- 2% of area
- 20% of tracks
- Silicon strips
  - 11 cm long
  - 200 μm pitch
  - 320-410 μm thick

**Outer Tracker:**
- 4 double-layers of Kapton/Al straws
- Production of modules and frames finished
- Installation in progress

- Sensor-module production finished
- Assembly of boxes in progress
Expected tracking performance

Impact parameter resolution

$\delta IP = 14 \mu m + 35 \mu m / p_T$

- For typical B decay modes:
  - Vertex resolution:
    - $\sim 10 \mu m$ in x,y; $\sim 100 \mu m$ in z
  - Proper time resolution: $\sim 40$ fs
  - B Mass resolution $\sim 15$ MeV
RICH detectors

Aerogel: 2 - ~10 GeV
C$_4$F$_{10}$: 10 - ~60 GeV
CF$_4$: 16 - ~100 GeV

Efficient K/$\pi$ separation up to 100 GeV
Helps e.g. tagging effectiveness: $\varepsilon D^2 \sim 7.5\% (4.3\%)$ for $B_s (B_d)$

<table>
<thead>
<tr>
<th>(For $B_s$)</th>
<th>$\mu^\pm$</th>
<th>$e^\pm$</th>
<th>$K^\pm$ same</th>
<th>$K^\pm$ opp</th>
<th>Jet charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon D^2(%)$</td>
<td>1.5</td>
<td>0.7</td>
<td>3.1</td>
<td>2.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

- Novel photo-detector: HPDs with built in readout chip. Production almost complete.
- Successful test beam of full readout chain in Sept.06.
- RICH2 in place. HPDs are being installed.
- RICH1 gas enclosure installed. Flat mirrors ready. Spherical mirrors fabricated, to be coated in February.

Kaon ID: ~88%  
Pion miss-ID: 3%
Calorimeters

- All calorimeter modules installed (SPD/PS recently)
- Production/installation of readout electronics ongoing.
Muon system

- MWPCs and GEMs produced.
- Full readout chain with MWPCs and 3-GEMs checked at the test beam.
- Installation in progress.
Measurement of CPV in $B_s$ mixing

- $B_s$-$\bar{B}_s$ mixing measured by CDF
  - theoretical uncertainties limit constraints on NP
- Need to measure CP violating mixing phase in $B_s$ decays ($\phi_s$):
  - SM contribution and theoretical uncertainties are small

Huge increase in sensitivity to New Physics!
Measurement of $\text{BR}(B_S \rightarrow \mu^+\mu^-)$

<table>
<thead>
<tr>
<th>Integrated Luminosity (fb$^{-1}$)</th>
<th>BR ($\times 10^{-9}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>0.1</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>0.2</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>0.3</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>0.4</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>0.5</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>0.6</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

- **Expected CDF+D0 Limit**
- **Bkg: $b \rightarrow \mu^- X$ & $\bar{b} \rightarrow \mu^+ X$**
- **SM prediction**
- **Uncertainty in bkg prediction**

**LHCb Sensitivity (signal+bkg is observed)**

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<tr>
<th>Integrated Luminosity (fb$^{-1}$)</th>
<th>BR ($\times 10^{-9}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$5\sigma$</td>
</tr>
<tr>
<td>1</td>
<td>$3\sigma$</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
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<tr>
<td>7</td>
<td></td>
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<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

- **Sensitive probe for NP:**
  - SM contribution and theoretical uncertainties are small
  - Many NP scenarios predict much larger BR (e.g. in large tan$\beta$ SUSY).
- **LHCb 2 fb$^{-1}$ (1 year at nominal luminosity):**
  - 17 SM events
Forward-Backward Asymmetry in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Zero point $s_0$ is a sensitive probe for NP
- LHCb estimates
  - Yield: 7700 events/2 fb$^{-1}$
  - $B/S = 0.4 \pm 0.1$
  - In 2 fb$^{-1}$ (10 fb$^{-1}$) measure $s_0$ to $\pm 0.5$ ($\pm 0.3$) GeV$^2$
Neutral Reconstruction

- Mass resolution $\sigma = \sim 10 \ (15)$ MeV resolved (merged) $\pi^0$
- Example: time dependent Dalitz Plot analysis ala’ Snyder & Quinn for $B^0 \rightarrow \rho \pi \rightarrow \pi^+ \pi^- \pi^0$
- 14K signal events in 2 fb$^{-1}$ with B/S<0.8, yielding $\sigma(\alpha) = 10^\circ$
### LHCb Sensitivities with 2 fb^{-1}

#### Subset of studied modes

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>B/S</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
<td>( B_s \to D_s^{-} K^{-} )</td>
<td>5.4k</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td></td>
<td>( B_d \to \pi^+ \pi^- )</td>
<td>36k</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>( B_s \to K^+ K^- )</td>
<td>36k</td>
<td>&lt; 0.06</td>
</tr>
<tr>
<td></td>
<td>( B_d \to D^0 (K\pi, KK) K^{*0} )</td>
<td>3.4 k, 0.5 k, 0.6 k</td>
<td>&lt; 0.3, &lt; 1.7, ( &lt; 1.4 )</td>
</tr>
<tr>
<td></td>
<td>( B^- \to D^0 (K^-\pi^+, K^+ \pi^-) K^- )</td>
<td>28k, 0.5k</td>
<td>0.6, 4.3</td>
</tr>
<tr>
<td></td>
<td>( B^- \to D^0 (K^-K^+ \pi^+, \pi^+ \pi^-) K^- )</td>
<td>4.3 k</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>( B^- \to D^0 (K_S \pi^+ \pi^-) K^- )</td>
<td>1.5 - 5k</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>( B_d \to \pi^+ \pi^- \pi^0 )</td>
<td>14k</td>
<td>&lt; 0.8</td>
</tr>
<tr>
<td></td>
<td>( B \to \rho^+ \rho^0, \rho^+ \rho^-, \rho^0 \rho^0 )</td>
<td>9k, 2k, 1k</td>
<td>1, 5, &lt; 4</td>
</tr>
<tr>
<td>( \beta )</td>
<td>( B_d \to J/\psi (\mu \mu) K_S )</td>
<td>216k</td>
<td>0.8</td>
</tr>
<tr>
<td>( \Delta m_s )</td>
<td>( B_s \to D_s^{-} \pi^+ )</td>
<td>80k</td>
<td>0.3</td>
</tr>
<tr>
<td>( \phi_s )</td>
<td>( B_s \to J/\psi (\mu \mu) \phi )</td>
<td>131k</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Rare decays</strong></td>
<td>( B_s \to \mu^+ \mu^- )</td>
<td>17</td>
<td>&lt; 5.7</td>
</tr>
<tr>
<td></td>
<td>( B_d \to K^{*0} \mu^+ \mu^- )</td>
<td>7.7 k</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>( B_d \to K^{*0} \gamma )</td>
<td>35k</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>( B_s \to \phi \gamma )</td>
<td>9.3 k</td>
<td>&lt; 2.4</td>
</tr>
<tr>
<td><strong>charm</strong></td>
<td>( D^{*+} \to D^0 (K^- \pi^+) \pi^+ )</td>
<td>100 M</td>
<td></td>
</tr>
</tbody>
</table>

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*Note: The table contains a subset of studied modes, focusing on specific decay channels with measured yields, branching ratios, and precision metrics.*
Road Ahead

• 2007
  – Complete installation before machine closes in Aug
  – Commissioning of the detector, including a 450 GeV pilot run in Nov/Dec

• 2008
  – Commissioning of trigger on initial 7 TeV data
  – ~0.5 fb\(^{-1}\) of physics data:
    • Initial B physics: e.g. b-hadron lifetimes, \(\Delta m_s\), sin 2\(\beta\), etc.,
    • Probe large NP contributions in \(B_s\) sector by reaching sensitivity equal the SM predictions:
      – \(\sigma_{\phi_s} = 0.04\) rad vs SM prediction \(\phi_s = -0.04\) rad
      – \(BR(B_S \rightarrow \mu^+\mu^-) < SM-Br\) (90% CL) (SM-Br\(\sim 3 \times 10^{-9}\))

• 2009–(2013?)
  – Massive data taking: 5-10 fb\(^{-1}\) @ 2\(\times 10^{32}\) cm\(^{-2}\)s\(^{-1}\)
    • Observe SM signals for \(\phi_s\) and \(B_S \rightarrow \mu^+\mu^-\);
      probe/observe smaller NP contributions
    • Significant improvement in \(\alpha, \beta, \gamma\) measurements
    • Many other results
LHCb-II?

- Luminosity is tunable in LHCb area by adjusting beam focus, much smaller than the LHC design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$

- Present LHCb detector:
  - Designed to run at $2\times10^{32}$ cm$^{-2}$s$^{-1}$ to limit number of interactions per bunch crossing ($n$):
    - Smaller occupancies, less confusion
    - Little pile-up ($n=0.5$)
    - Less radiation damage
  - Detectors can operate up to $5\times10^{32}$ cm$^{-2}$s$^{-1}$:
    - Only channels with muons benefit from cranking up luminosity
  - Many important measurements will be statistics limited in 10 fb$^{-1}$

- Upgraded LHCb detector?
  - Aim to run at $\sim2\times10^{33}$ cm$^{-2}$s$^{-1}$ ($n=4$) for ~5 years and collect 100 fb$^{-1}$
  - Does not require Super-LHC luminosity upgrade (but it is compatible with it)
  - Need radiation hard vertex detector and detached vertex trigger in L0
  - LHCb Upgrade Workshop Jan 11-12, 2007, Edinburgh (see http://www.nesc.ac.uk/esi/events/729/)
Conclusions

• LHCb is the first dedicated B-physics experiment at a hadronic collider:
  – New level of sensitivity to New Physics via loop processes, especially in $B_s$ decays
  – Complementary character to direct searches for NP at LHC by ATLAS and CMS:
    • if new particles (beyond SM Higgs) are observed in direct searches, LHCb will reveal (positive signals) or constrain (non-observations) their flavor structure
    • sensitivity of LHCb to certain NP scenarios reaches to mass scales beyond directly reachable at LHC (positive signals may establish new mass scales to be reached)

• LHCb is on schedule for a pilot run in late 2007 and first data in 2008

• LHCb is starting to think about upgrades to take advantage of high design luminosity of LHC and statistical limitation of many important measurements