LHCb status and physics

a dedicated b physics experiment at CERN’s Large Hadron Collider to perform precision measurements of CP violation and rare decays

Olivier Schneider

Phenomenology club
Theory Division, CERN
June 13, 2002

Olivier.Schneider@iphe.unil.ch
# LHCb collaboration

O(500) participants from 45+3 institutes (Sept 2001)

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>France:</td>
<td>Annecy, Clermont-Ferrand, CPPM Marseille, LAL Orsay</td>
</tr>
<tr>
<td>Italy:</td>
<td>Bologna, Cagliari, Ferrara, Firenze, Frascati, Genoa, Milan, Univ. Rome I (La Sapienza), Univ. Rome II (Tor Vergata)</td>
</tr>
<tr>
<td>Netherlands:</td>
<td>NIKHEF</td>
</tr>
<tr>
<td>Spain:</td>
<td>Univ. Barcelona, Univ. Santiago de Compostela</td>
</tr>
<tr>
<td>Switzerland:</td>
<td>CERN, Univ. Lausanne, Univ. Zurich</td>
</tr>
<tr>
<td>Brazil:</td>
<td>UFRJ, CPBF</td>
</tr>
<tr>
<td>China:</td>
<td>IHEP (Beijing), Tsinghua Univ.</td>
</tr>
<tr>
<td>Russia:</td>
<td>BINP, INR, ITEP, IHEP, PNPI</td>
</tr>
<tr>
<td>Romania:</td>
<td>IFIN-HH (Bucharest)</td>
</tr>
<tr>
<td>Tech. ass:</td>
<td>Espoo-Vantaa Inst. Tech. (Finland), Geneva Engineering School (Switzerland), CEFET-RJ (Brazil)</td>
</tr>
</tbody>
</table>
LHCb’s physics goal

- Precision measurements of all parameters of the CKM matrix (in particular sides and angles of unitarity triangles)
  - high statistics
  - many different decay modes of $B^0$, $B_s$, ...
- Thorough test of CKM picture
  - Is Standard Model the only source of CP violation?
  - Is there new physics affecting b-hadron decays (Penguin loops) or B mixing (boxes, ...)?

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
= \begin{pmatrix}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\
-\lambda & 1-\lambda^2/2 & A\lambda^2 \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)

$$

$$V_{ub}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0$$

$$\arg V_{ub} = -\gamma$$
$$\arg V_{td} = -\beta$$

$$\arg V_{ts} = \pi + \delta\gamma$$

O. Schneider, June 13, 2002
Experimental results from

— Tevatron Run IIa: CDF + D0, each 2 fb\(^{-1}\)
— Asym. B factories: BABAR + Belle, each 300–500 fb\(^{-1}\)
— “Equivalent” to several \(10^8\) B mesons

Direct measurements of angles of unitarity triangle:

— \(\sigma(\sin(2\beta)) \approx 0.03\) from \(B^0 \to J/\psi K_S\) asymmetry
— no precise measurement of other angles

Knowledge on sides of unitarity triangle

\[
\begin{align*}
\sigma(|V_{cb}|) & \approx \text{few } \% \text{ error} \\
\sigma(|V_{ub}|) & \approx 5\text{-}10 \% \text{ error} \\
\sigma(|V_{td}|/|V_{ts}|) & \approx \text{few}-5 \% \text{ error} \\
\text{(assuming } & \Delta m_s < 40 \text{ ps}^{-1}) \end{align*}
\]

\[
\sin \left[ 2 \left( \tan^{-1} \left( \frac{\eta}{1-\rho} \right) \right) \right]
\]

indirectly known to < 0.03
CKM triangle in 5 years (SM)

- First stringent test of CKM ansatz!
  - Sides dominated by theoretical uncertainties
  - More statistics would improve $\sin(2\beta)$

\( \rho, \eta \)

- \( \rho^2 + \eta^2 \) from \( \frac{\Gamma(b \rightarrow u)}{\Gamma(b \rightarrow c)} \)
- \( (1-\rho)^2 + \eta^2 \) from \( \frac{\Delta m_d}{\Delta m_s} \)

… or CKM picture might already appear inconsistent …
A precise measurement of $\gamma$, independent of possible new physics in the mixing, is needed to get the true CKM parameters (and provide evidence for the new physics)

Assume:
- additional diagrams for B mixing due to new physics;
- SM tree decays unaffected.
Measuring CKM angle $\gamma$
(and possible new physics in B mixing)

$\Gamma(b \to u)/\Gamma(b \to c)$

$\eta^2 + \rho^2$

\[ \gamma - 2\delta \gamma_{\text{eff}} \quad \gamma \quad 2\delta \gamma_{\text{eff}} \]

\[ \gamma + 2\beta_{\text{eff}} \quad 2\beta_{\text{eff}} \]

\[ \Delta m_d = 2 \text{atan}(\eta/(1-\rho)) + \phi_{\text{new}} \]

SM values of $\eta$ and $\rho$

new physics parameters $r_{\text{new}}$ and $\phi_{\text{new}}$

Cannot be measured at current experiments
Need much higher statistics, including $B_s$ decays, and PID

LHCb!
**b production at LHC**

- **Huge cross section** (but large theoretical uncertainty on prediction!):
  - assume \( \sigma(pp \rightarrow b\bar{b}) = 500 \mu b \) at \( \sqrt{s} = 14 \text{ TeV} \)
  - strong angular correlation (\( b\bar{b} \) pair either forward or backward)

- **High luminosity**
  - LHC design: \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
  - LHCb choice to run at \( 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \)
    to get mostly events without pileup (single pp interactions)

- **All b hadron species produced**
  - \( B_u \) (40%), \( B_d \) (40%), \( B_s \) (10%), \( B_c \), and b-baryons (10%)

- **Large b-hadron momentum, hence boost**

- **Drawback: huge background**
  - non-bottom background: \( \sigma_{bb}/\sigma_{inelastic} \approx 0.6\% \)
  - bottom background (want to study channels with visible BR as low as \( 10^{-7} \))

---

**Main experimental issues:**
- trigger
- particle id. (e.g. \( K/\pi \) sep.)
- resolution (mass, proper time)
LHCb detector (side view, end 2001)

- Forward acceptance: $1.9 < \eta < 4.9$
- Trigger: sensitive to B final states with and without leptons
- Particle identification: RICH K/$\pi$ separation for $1 < p < 150$ GeV/c
- Vertexing (Si): $\sigma = 40$ fs (for $B_s \rightarrow D_s \pi$) $\sim 1/\Delta m_s$
Particle identification

LHCb K–π separation for true π

Extremely important for
many exclusive channel

Example:
clean up of $B^0 \rightarrow \pi^+\pi^-$ signal

### LHCb

- $B_d \rightarrow \pi\pi$
- $B_d \rightarrow \pi K$
- $B_s \rightarrow \pi K$
- $B_s \rightarrow K K$
- $\Lambda_b \rightarrow p K$
- $\Lambda_b \rightarrow p\pi$

### ATLAS

- $B \rightarrow h^+h^+$
- $B \rightarrow h^0h^0$
- $B_s$
- $\Lambda_b$
- Other $B_d$
- Signal

Events / 20 MeV/c^2

O. Schneider, June 13, 2002

LHCb status and physics
LHCb trigger scheme

40 MHz (12.4 MHz of inel. interactions)

**L0**
- Medium $p_T$ hadron, $\mu$, $e$, $\gamma$ + pileup veto
  - reduction $\sim 40$
  - (only $\sim 10$ from $p_T$ cut)
- Detached vertex + IP of $p_T$ candidate*
  - reduction $\sim 25$

* added since TP

**L1**
- Final state reconstruction
  - all detectors reduction $\sim 8 \times 25$

Efficiencies on signal events passing offline selection (TP)

<table>
<thead>
<tr>
<th></th>
<th>L0</th>
<th>L1</th>
<th>L2</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow J/\psi K_s$</td>
<td>0.88</td>
<td>0.50</td>
<td>0.81</td>
<td>0.36</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^-$</td>
<td>0.76</td>
<td>0.48</td>
<td>0.83</td>
<td>0.30</td>
</tr>
<tr>
<td>$B_s \rightarrow D_s^+ K^+$</td>
<td>0.54</td>
<td>0.56</td>
<td>0.92</td>
<td>0.28</td>
</tr>
</tbody>
</table>

O. Schneider, June 13, 2002

LHCb status and physics
**MC generation issues**

- **Track multiplicity and p$_T$ distributions:**
  - will affect the performance of the trigger
  - very important to have now realistic MC for signal and minimum bias events to assess trigger performance
  - using PYTHIA 6 with multi-parton interactions model tuned on track multiplicities observed at lower energy (SPS, Tevatron) in non-single diffractive events at $\eta \sim 0$

- How reliable are these predictions?

- Should we use also different generators/tuning? (Which ones?)
Progress in experiment design ...

LHCb Technical Proposal
Feb 1998

LHCb MAGNET Technical Design Report
Dec 1999

LHCb Calorimeters Technical Design Report
Sept 2000

LHCb RICH Technical Design Report
Sept 2000

LHCb Muon System Technical Design Report
May 2001

LHCb VELO Technical Design Report
May 2001

LHCb Outer Tracker Technical Design Report
Sept 2001

LHCb Online System Technical Design Report
Dec 2001

now under construction

O. Schneider, June 13, 2002
LHCb status and physics
Re-optimization

- Reducing secondary interactions (→ detector occupancy):
  - new beam pipe design: 25 mrad cone (Be?) + 10 mrad cone (Al-Be)

- Reducing material (→ γ conversion, Bremsstrahlung, and hadron absorption!)
  - hope to gain close to a factor 2
  - with new “LHCb-light” design

- Pattern recognition in the tracking
  - not addressed until outer tracker TDR (e.g. assumed perfect in TP)
  - effect on tracking design (long tracks, short tracks, ...)

- Improving L1 trigger performance
  - could be done if some rough momentum estimate was available for the L1 decision

<table>
<thead>
<tr>
<th>LHCb “heavy” (TDRs)</th>
<th>Radiation length (X₀)</th>
<th>Interaction length (λ₁)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex detector</td>
<td>19%</td>
<td>4%</td>
</tr>
<tr>
<td>RICH 1</td>
<td>14%</td>
<td>5%</td>
</tr>
<tr>
<td>9 tracking stations</td>
<td>27%</td>
<td>11%</td>
</tr>
<tr>
<td>Total (before RICH2)</td>
<td>60%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Re-optimized detector (side view)

To be described in a forthcoming TDR:

- New beam pipe, less stations in VELO, less material in RICH1
- Change in tracking philosophy: no stations in the magnet!
- Shielding wall removed: let B field extend in upstream region (→ need local shielding of RICH1 photodetectors)
- New (Si) tracking station TT1 in L1 trigger (also useful for $K_S$ finding)
Re-optimization of L1 trigger

Using VELO+TT1+B field (20% momentum resolution):
- require one or two large impact parameter tracks with minimum $p_T$

Big performance improvement:
- affects all hadronic channels ($B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow D_s K$, ...)
- efficiency for dimuon channels now > 90% (using L0 info at L1)

Since efficiency is high (and “steep curve”), might reduce L1 output rate
- need to optimize with L2

Trigger TDR foreseen early 2003

O. Schneider, June 13, 2002
LHCb status and physics
New tracking

- Abandon “continuous tracking à la HERAB”
- Several pattern recognition approaches under study
  - find tracks in VELO, extrapolate though magnet, and match with hits after the magnet (see figure)
  - finds tracks after magnet (seeding stations) and match with VELO tracks
  - find $K_S$ decaying outside VELO using TT1 hits
- Will reach typical efficiencies of 90% for “long tracks” (or more if from B decay), with reasonable ghost rate
Short term plans (for the rest of 2002)

- Finalize optimized detector design
- Tune reconstruction and trigger algorithms
- Generate MC new samples
- Re-assess reconstruction and trigger performance
- Update events yields and signal/background ratios for benchmark channels

Improvements will include:
- realistic design, including all material
- simulation of pileup and spillover
- new trigger algorithm & proper simulation of trigger
- full pattern recognition and reconstruction algorithms
- totally new software framework

Forthcoming TDRs
- inner tracker
- optimization/performance
- trigger

adding realism + real improvements!
### Event yields

- **Signal yields per year ($10^7$ s):**
  - triggered, reconstructed & selected
  - untagged

- **Flavour tagging (TP, 1998):**
  - only $b \to l$ and $b \to c \to s$
  - opposite side tags
  - simple ranking
  - 40% efficiency, 30% mistag

- **Large uncertainties:**
  - cross section, BRs
  - background estimates
  - lack of MC stat., assumptions, ...

- **Future:**
  - Get more solid (realistic) estimates by end 2002
  - Can then start/repeat more refined physics performance studies

### Table: Event yields per year ($10^7$ s)

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal yield</th>
<th>S/B</th>
<th>Useful for</th>
<th>Ref.</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \to J/\psi (\mu^+\mu^-) K_S$</td>
<td>73k</td>
<td>7</td>
<td>$\beta$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_d \to J/\psi (e^+e^-) K_S$</td>
<td>15k</td>
<td>2</td>
<td>$\beta$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_d \to D^*-(excl) \pi^+$</td>
<td>180k</td>
<td>6</td>
<td>$\gamma+2\beta$</td>
<td>PhD</td>
<td>2001</td>
</tr>
<tr>
<td>$B_d \to D^*-(incl) \pi^+$</td>
<td>1150k</td>
<td>4</td>
<td>$\gamma+2\beta$</td>
<td>PhD</td>
<td>2001</td>
</tr>
<tr>
<td>$B_s \to J/\psi (\mu^+\mu^-) \phi$</td>
<td>74k</td>
<td>30</td>
<td>$\delta\gamma$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_s \to D_s K$</td>
<td>6k</td>
<td>12</td>
<td>$\gamma-2\delta\gamma$</td>
<td>TP</td>
<td>1998</td>
</tr>
<tr>
<td>$B_d \to \pi^+\pi^-$</td>
<td>12k</td>
<td>&gt;1</td>
<td>$\alpha,\gamma$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_s \to K^+K^-$</td>
<td>12k</td>
<td></td>
<td>$\gamma$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_d \to \rho \pi$</td>
<td>3k</td>
<td></td>
<td>$\alpha$</td>
<td>YR</td>
<td>2000</td>
</tr>
<tr>
<td>$B_d \to D^0 K^{*0}$</td>
<td>0.4k</td>
<td>1</td>
<td>$\gamma$</td>
<td>TP</td>
<td>1998</td>
</tr>
<tr>
<td>$B_s \to D_s \pi^+$</td>
<td>86k</td>
<td>20</td>
<td>$\Delta m_s$</td>
<td>TP</td>
<td>1998</td>
</tr>
<tr>
<td>$B_d \to K^*0\gamma$</td>
<td>26k</td>
<td>1</td>
<td></td>
<td>TP</td>
<td>1998</td>
</tr>
<tr>
<td>$B_d \to K^*0\mu^+\mu^-$</td>
<td>8.6k</td>
<td>&gt;15</td>
<td></td>
<td>PhD</td>
<td>2002</td>
</tr>
<tr>
<td>$b \to s \mu^+\mu^-$</td>
<td>24k</td>
<td>8</td>
<td>$</td>
<td>V_{ts}/V_{td}</td>
<td>$</td>
</tr>
<tr>
<td>$b \to d \mu^+\mu^-$</td>
<td>0.5k</td>
<td>1.3</td>
<td>$</td>
<td>V_{ts}/V_{td}</td>
<td>$</td>
</tr>
<tr>
<td>$B_s \to \mu^+\mu^-$</td>
<td>16</td>
<td></td>
<td>$S/\sqrt{B}=3.5$</td>
<td>PhD</td>
<td>2002</td>
</tr>
</tbody>
</table>