Expected physics performance of the LHCb experiment

Olivier Leroy, on behalf of the LHCb collaboration

CPPM (IN2P3-CNRS et Université de la Méditerranée), Marseille, France
LHCb is a dedicated *B physics precision* experiment at LHC to study *CP violation and rare decays*

- Standard Model CP violation described by single complex phase in the unitarity CKM matrix
- LHCb precision $\Rightarrow$ 2 Unitarity Triangles
- $b$ meson sector is a place where theoretical predictions can be precisely compared with experimental results
- We will over constrain the Unitarity Triangles and search for new physics

New particles ?

New particles ?
LHCb Physics program

- $B_s$ oscillation frequency, phase and $\Delta \Gamma_s$
  - $B_s \rightarrow D_s \pi, J/\Psi \Phi, J/\Psi \eta, \eta_c \Phi$
- $\alpha$ from $B_d \rightarrow \pi^0 \pi^- \pi^+$
- $\beta$ with $B_d \rightarrow J/\psi K_S$ as a proof of principle
  - And $\beta$ from $b \rightarrow s$ penguin
- $\gamma$ in various channels, differing sensitivity to new physics:
  - Time-dependent CP asymmetry of $B_s \rightarrow D_s^- K^+$ and $D_s^+ K^-$
  - Time dependent CP asymmetries of $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+ K^-$
  - Comparison of decay rates in the $B_d \rightarrow D^0(K^+ \pi^-, K^- \pi^+, K^+ K^-) K^*0$ system
  - Comparison of decay rates in the $B^- \rightarrow D^0(K^+ \pi^-, K^- \pi^+ \pi^+ \pi^-) K^- K^*$ system
  - Dalitz analysis of $B^- \rightarrow D^0(K_S \pi^\mp \pi^\mp) K^-$ and $B_d \rightarrow D^0(K_S \pi^\mp \pi^\mp) K^*0$
- Rare decays
  - Radiative penguin $B_d \rightarrow K^* \gamma, B_s \rightarrow \Phi \gamma, B_d \rightarrow \omega \gamma$
  - Electroweak penguin $B_d \rightarrow K^{*0} \mu^+ \mu^-$
  - Gluonic penguin $B_s \rightarrow \Phi \Phi, B_d \rightarrow \Phi K_s$
  - Rare box diagram $B_s \rightarrow \mu^+ \mu^-$
- $B_c$, $b$-baryon physics + unexpected!
LHCb Physics program (in 12 minutes !)

✧ Bs oscillation frequency, phase and ΔΓs
  ■ Bs → Dsπ, J/ΨΦ, J/Ψη, ηcΦ

✧ α from Bd → π0π−π+

✧ β with Bd → J/ψ Ks as a proof of principle
  ■ And β from b → s penguin

✧ γ in various channels, differing sensitivity to new physics:
  ■ Time-dependent CP asymmetry of Bs → Ds−K+ and Ds+K−
  ■ Comparison of asymmetries of Bd → π+π− and Bs → K+K−
  ■ Comparison of decay rates in the Bd → D0(K+π−,K+π−,K+π−)K*0 system
  ■ Comparison of decay rates in the B− → D0(K+π−,K+π−π−π−,π−π+)K− system
  ■ Dalitz analysis of B− → D0(KSπ−π+)K− and Bd → D0(KSπ−π+)K*0

✧ Rare decays
  ■ Radiative penguin Bd → K* γ, Bs → Φ γ, Bd → ωγ
  ■ Electroweak penguin Bd → K*0 μ+μ−
  ■ Gluonic penguin Bs → ΦΦ, Bd → ΦKs
  ■ Rare box diagram Bs → μ+μ−

✧ Bc , b-baryon physics + unexpected !
Typical B event in LHCb

Monte-Carlo Simulation

- Pythia 6.2, EvtGen, Geant, full detector simulation, reconstruction
- 40M $b\bar{b}$ and 70M min. bias events for detailed background studies

Proper time of B decay: $t = mL/p$

Flavour tagging:
- tags = $e$, $\mu$, $K$, vertex charge ("opposite side"), and $\pi/K$ ("same side")
- Neural Net to combine all information

<table>
<thead>
<tr>
<th>$\varepsilon(1-2\omega)^2$</th>
<th>$B_d$</th>
<th>$B_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4%-5%</td>
<td>7%-9%</td>
</tr>
</tbody>
</table>

Primary vertex:
- Many tracks
- $\sigma_{xy} = 8 \mu m$
- $\sigma_z = 44 \mu m$

L~9 mm

LHCb

Lake Louise Winter Institute

February 22, 2006
**B_s oscillation frequency: \( \Delta m_s \)**

- Needed for the observation of time dependent CP asymmetries with B_s decays
- Use \( B_s \rightarrow D_s^{-}\pi^+ \)
- If \( \Delta m_s = 20 \text{ ps}^{-1} \)

\[ \sigma(\Delta m_s) = 0.01 \text{ ps}^{-1} \]

with 2fb\(^{-1}\) (1 year)

- Can observe \( >5\sigma \) oscillation signal if \( \Delta m_s < 68 \text{ ps}^{-1} \)

well beyond SM prediction (~20 ps\(^{-1}\))
**B_s mixing phase \( \phi_s \)**

- CP asymmetry arises from interference of 
  \( B_s \rightarrow J/\psi \phi \) and \( B_s \rightarrow B_s \rightarrow J/\psi \phi \rightarrow \) measures the phase of \( B_s \) mixing, \( \phi_s \)
- \( B_s \) counterpart of the golden mode \( B_d \rightarrow J/\psi K_S \)
- Final state is admixture of CP-even and odd contributions → angular analysis of decay products required
- \( \phi_s \) can also be extracted from pure CP eigenstates: \( J/\psi \eta(\gamma \gamma, \pi^+ \pi^- \pi^0), \eta_c \phi \)
  - Much lower stats, but no need for angular analysis
- All mode combined after 5 years: \( \sigma(\phi_s) = 0.013 \text{ rad with } 10 \text{ fb}^{-1} \)

- In Standard Model, \( \phi_s = -2 \chi = -0.036 \pm 0.003 \) (CKM fitter)
- \( \phi_s \) could be significantly larger if New Physics...

<table>
<thead>
<tr>
<th>Channels</th>
<th>( \sigma(\phi_s) ) [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s^0 \rightarrow J/\psi \eta(\gamma \gamma) )</td>
<td>0.112</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow J/\psi \eta(\pi^+ \pi^- \pi^0) )</td>
<td>0.148</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow \eta_c \phi )</td>
<td>0.106</td>
</tr>
<tr>
<td>Combined three pure CP eigenstates channels</td>
<td>0.068</td>
</tr>
<tr>
<td>( B_s^0 \rightarrow J/\psi \phi )</td>
<td>0.031</td>
</tr>
<tr>
<td>Combined all four CP eigenstates channels</td>
<td>0.028</td>
</tr>
</tbody>
</table>

(2 \text{ fb}^{-1})
Angle $\alpha$ from $B_d \rightarrow \pi^0\pi^-\pi^+$ decays

- Dalitz plot analysis (Quinn Snyder method)
  - $B_d \rightarrow \pi^0\pi^-\pi^+$ selection based on multivariate analysis
  - Use resolved and merged $\pi^0$
  - Expect 14k events per year, $B(bb)/S < 1$

- Toy MC study:
  - 11-parameter likelihood fits performed in time-dependent Dalitz space
  - $B/S = 0.8$ (flat and resonant bkg)

$\sigma(\alpha) \sim 10^\circ$ with $2fb^{-1}$

$\alpha_{\text{gen}} = 106^\circ$
Angle $\gamma$ from $B_s \rightarrow D_s^{-} K^+$

- Interference between 2 tree diagrams
- Measure $\gamma + \phi_s$ from time-dependent rates of $B_s \rightarrow D_s^{-} K^+$ and $B_s \rightarrow D_s^{+} K^-$ decays and their CP-conjugates:
  - Mistag extracted from $B_s \rightarrow D_s^{-} \pi^+$ sample
  - Subtract $\phi_s$ measured with $B_s \rightarrow J/\psi \phi$

With 2 fb$^{-1}$, if $\Delta m_s = 20$ ps$^{-1}$, $\Delta \Gamma_s/\Gamma_s = 0.1$, $55 < \gamma < 105$ deg, $-20 < \Delta_{T1/T2} < 20$ deg:

$\sigma(\gamma) \approx 14^\circ$

No theoretical uncertainty; insensitive to new physics in $B_s$ mixing

After 5 years of data
Angle $\gamma$ from $B^- \rightarrow DK^-$

- Both $D^0$ and $\bar{D}^0$ decay to $K^+\pi^-$:
  
  $B^- \rightarrow D^0 K^-$ (colour favoured) then:
  
  \[ D^0 \left\{ \begin{array}{c} c \\ \bar{u} \end{array} \right\} \rightarrow \begin{array}{c} u \\ \bar{s} \end{array} K^+ \]
  
  Doubly Cabbibo suppressed

  $B^- \rightarrow \bar{D}^0 K^-$ (colour suppressed) then:
  
  \[ \bar{D}^0 \left\{ \begin{array}{c} \bar{c} \\ u \end{array} \right\} \rightarrow \begin{array}{c} d \\ u \end{array} \pi^- \]
  
  Cabbibo favoured

- For these decays the reversed suppression of the $D$ decays relative to the $B$ decays results in similar amplitudes $\rightarrow$ big interference effects

- Counting experiment (no need tagging nor proper time)

- Interference depends on 5 parameters:
  
  - From the $B$ decays $\gamma, r_B$ and $\delta_B$
  - $r_{D^{K\pi}}$ - the ratio in magnitude of two $D$ decay processes
    - Well measured (PDG value 0.060)
  - $\delta_{D^{K\pi}}$ - a CP conserving strong phase difference
Measure the following rates:

\[ \Gamma(B^- \rightarrow (K^-\pi^+)_D K^-) \propto 1 + (r_B r_{D}^{K\pi})^2 + 2 r_B r_{D}^{K\pi} \cos(\delta_B - \delta_{D}^{K\pi} - \gamma) \quad (1) \quad 60k \]

\[ \Gamma(B^- \rightarrow (K^+\pi^-)_D K^-) \propto r_B^2 + (r_{D}^{K\pi})^2 + 2 r_B r_{D}^{K\pi} \cos(\delta_B + \delta_{D}^{K\pi} - \gamma) \quad (2) \quad 2k \]

\[ \Gamma(B^+ \rightarrow (K^+\pi^-)_D K^+) \propto 1 + (r_B r_{D}^{K\pi})^2 + 2 r_B r_{D}^{K\pi} \cos(\delta_B - \delta_{D}^{K\pi} + \gamma) \quad (3) \quad 60k \]

\[ \Gamma(B^+ \rightarrow (K^-\pi^+)_D K^+) \propto r_B^2 + (r_{D}^{K\pi})^2 + 2 r_B r_{D}^{K\pi} \cos(\delta_B + \delta_{D}^{K\pi} + \gamma) \quad (4) \quad 2k \]

Two rates are favoured (1) and (3)

Two rates are suppressed (2) and (4)

- but have \( O(1) \) interference effects as \( r_B \sim r_D \)
- so particularly sensitive to \( \delta_{D}^{K\pi} \) and \( \gamma \)
- \( \sim 50 \) times more statistics than current b-factories!

Taking the relative rates have more unknowns than equations

- need information from other decays
  - e.g. \( D \rightarrow K\pi\pi\pi \) or the CP eigenstates \( KK, \pi\pi \) (\( r_{D}^{KK}=1, \delta_{D}^{KK}=0 \))
Toy MC estimate of $\sigma(\gamma)$ from $B^{-}\rightarrow DK^{-}$

- Inputs $\gamma=60^\circ$, $\delta_B=130^\circ$, $r_B=0.15$
- Fit: $r_B$, $\delta_B$, $\delta_D K\pi$, $\delta_D K^3\pi$ and $\gamma$
- No background
  $\Rightarrow \sigma(\gamma)\sim 3.9^\circ$

- Adding background:

  \[
  \begin{array}{c|ccccc}
  & B/S & \pi K, & KK, & \pi \pi \\
  \hline
  0 & 3.9^\circ & 4.0^\circ & 4.0^\circ & 4.1^\circ \\
  B/S & 1 & 4.6^\circ & 4.8^\circ & 4.8^\circ & 5.0^\circ \\
  K\pi\pi\pi & 2 & 5.0^\circ & 5.1^\circ & 5.3^\circ & 5.5^\circ \\
  & 5 & 5.6^\circ & 5.9^\circ & 6.0^\circ & 6.3^\circ \\
  \end{array}
  \]

$\sigma(\gamma) \approx 5^\circ$ with 2 fb$^{-1}$

- $K\pi\pi\pi$ selection studies underway
Rare decays: $A_{FB}$ in $B_d \rightarrow K^{*0} \mu^+ \mu^-$

- Forward-backward asymmetry $A_{FB}(s)$ in the $\mu\mu$ rest-frame is sensitive probe of New Physics
- Suppressed decays, SM BR $\sim 10^{-6}$
- 4400 $B_d \rightarrow K^{*0} \mu^+ \mu^-$ events/2fb$^{-1}$, B/S<2.6
- With 10fb$^{-1}$: zero of $A_{FB}(s)$ located to $\pm 0.53$ GeV$^2$ → determine $C_7^{\text{eff}}/C_9^{\text{eff}}$ with 13% error (in SM)

hep-ph/0003238
### LHCb performance with 2fb⁻¹ (1 year)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield*</th>
<th>Bbb/S</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow D_sK$</td>
<td>5.4k</td>
<td>&lt;1</td>
<td>$\sigma(\gamma) \approx 14^\circ$</td>
</tr>
<tr>
<td>$B_d \rightarrow \pi\pi$</td>
<td>26k</td>
<td>&lt;0.7</td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow KK$</td>
<td>37k</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow D^0(K^-\pi^+)K^0$</td>
<td>0.5k</td>
<td>&lt;0.3</td>
<td>Fleischer $\sigma(\gamma) \approx 6^\circ$</td>
</tr>
<tr>
<td>$B_d \rightarrow D^0(K^-\pi^-)K^0$</td>
<td>2.4k</td>
<td>&lt;2</td>
<td>GLW+D $\sigma(\gamma) \approx 8^\circ$</td>
</tr>
<tr>
<td>$B_d \rightarrow D_{CP}(K^+K^-)K^0$</td>
<td>0.6k</td>
<td>&lt;0.3</td>
<td>ADS $\sigma(\gamma) \approx 5^\circ$</td>
</tr>
<tr>
<td>$B^- \rightarrow D^0(K^-\pi^+)K^-$</td>
<td>60k</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$B^- \rightarrow D^0(K^-\pi^-)K^-$</td>
<td>2k</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>$\alpha$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow \pi^0\pi^-\pi^+$</td>
<td>14k</td>
<td>0.8</td>
<td>Snyder Quinn $\sigma(\alpha) \approx 10^\circ$</td>
</tr>
<tr>
<td>$\phi_s$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow J/\Psi\Phi$</td>
<td>125k</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow J/\Psi\eta$</td>
<td>12k</td>
<td>2-3</td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow \eta_c\Phi$</td>
<td>3k</td>
<td>0.7</td>
<td>$\sigma(\phi_s) \approx 2^\circ$</td>
</tr>
<tr>
<td>$\Delta m_s$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_s \rightarrow D_s\pi$</td>
<td>80k</td>
<td>0.3</td>
<td>$\Delta m_s$ up to 68 ps⁻¹</td>
</tr>
<tr>
<td>$\beta$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow J/\Psi K_S$</td>
<td>216k</td>
<td>0.8</td>
<td>$\sigma(\sin2\beta) \approx 0.022$</td>
</tr>
<tr>
<td>rare decays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B_d \rightarrow K^*\mu^+\mu^-$</td>
<td>4.4k</td>
<td>&lt;2.6</td>
<td>$C_7^{eff}/C_9^{eff}$ with 13% error</td>
</tr>
<tr>
<td>$B_s \rightarrow \mu^+\mu^-$</td>
<td>17</td>
<td>&lt;5.7</td>
<td>NP search</td>
</tr>
<tr>
<td>$B_d \rightarrow K^*\gamma$</td>
<td>35k</td>
<td>&lt;0.7</td>
<td>$\sigma(A_{CP}^{dir}) \approx 0.01$</td>
</tr>
</tbody>
</table>

**+Bc + b-baryons + many other modes**

(*) Untagged annual yields after L0xL1 trigger stat. only; we work hard on systematics
Conclusions

✧ LHCb will give unprecedented statistics for B decays, including access to the $B_s$, $B_c$ and b-baryons, unavailable to the B factories

✧ $B_s$-$\bar{B_s}$ oscillations will be measured precisely

\begin{align*}
&\text{> } 5\sigma \text{ for } \Delta m_s \text{ up to } 68 \text{ ps}^{-1} \\
&\sigma (\Delta m_s) \sim 0.01 \text{ ps}^{-1}
\end{align*}

\begin{align*}
\text{with } 2 \text{ fb}^{-1}
\end{align*}

✧ Many measurements of rare decays and CP asymmetries will be performed

\begin{align*}
&\sigma (\alpha) \sim 10^\circ \\
&\sigma (\phi_s) \sim 2^\circ \\
&\sigma (\gamma) \sim 5^\circ
\end{align*}

\begin{align*}
\text{with } 2 \text{ fb}^{-1}
\end{align*}

✧ CP angles determined via channels with different sensitivity to new physics → detailed test of the CKM description of the quark sector

LHCb offers an excellent opportunity to spot New Physics signals beyond Standard Model and will be ready in 2007
Backup slides
**Trigger overview**

40 MHz

**Level-0:**
- \( p_T \) of \( \mu, e, h, \gamma \)

1 MHz

**HLT:**
- Confirm level-0
- \( \mu, e, h, \gamma \) alley
- Inclusive/exclusive selections

2 kHz output to tape

**Calorimeter**
- Muon system
- Pile-up system

**Full detector information**

- **Level-0:** custom hardware
- **HLT:** CPU farm
## Trigger Output

<table>
<thead>
<tr>
<th>Output rate</th>
<th>Trigger Type</th>
<th>Physics Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive B candidates</td>
<td>Specific final states</td>
</tr>
<tr>
<td>600 Hz</td>
<td>High Mass di-muons</td>
<td>$J/\psi$, $b \rightarrow J/\psi X$</td>
</tr>
<tr>
<td>300 Hz</td>
<td>D* Candidates</td>
<td>Charm, calibrations</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Inclusive b (e.g. $b \rightarrow \mu$)</td>
<td>B data mining</td>
</tr>
</tbody>
</table>

- Rough guess at present (split between streams still to be determined)
- Large inclusive streams to be used to control calibration and systematics (trigger, tracking, PID, tagging)
Flavour tagging

- **Current tagging performance:**
  - Tags: e, μ, K, vertex charge (“opposite side”), and π/K (“same side”)
  - A neural net is used to combine all information
    - Without PID, εD² = 2.8% from vertex/jet charge only
  - First studies to use protons in tagging

- **Mistag rate will be measured from data:**
  - Many control channels under study:
    - B⁺ → J/ψ(μμ)K⁺, D⁰π⁺, D⁰μ⁺ν
    - B⁰ → J/ψ(μμ)K*⁰, D*⁻μ⁺ν
    - Bₛ → Dₛ⁻π⁺, Dₛ⁻μ⁺ν
    - Several Mevts/year (after trigger+reco+sel)
    - Measure opposite side mistag in B⁺ samples
    - Extract mistag from B⁰ oscillation amplitude
  - High yields and good S/B also for semileptonic decays, improving statistics on control channels

<table>
<thead>
<tr>
<th>εD² (in MC)</th>
<th>B⁰</th>
<th>4%-5%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bₛ</td>
<td>7%-10%</td>
</tr>
</tbody>
</table>

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\[ B⁰ \rightarrow D*\mu\nu \]

~3 hours of data-taking
**Highlights: Flavour tagging WG (2)**

- **Classification in trigger sub-samples (TIS/TOS) and p_T(signal) re-weighting:**
  - **Aim:** use in CP channels the mistag measured in control samples
  - In full MC, mistag for signal and re-weighted control channels agree in each trigger sub-sample

- **Mistag for same-side kaons:**
  - Can be extracted using double-tag technique:
    - \( w_{SS} = \text{mistag rate of same-side tags} \)
    - \( w_{OS} = \text{mistag rate of opposite-side tags} \)
    - \( F = \text{fraction of events where SS and OS tags agree} \)
    
      \[
      w_{SS} = \frac{1 - w_{OS} - F}{1 - 2w_{OS}}
      \]

- Using \( B_s \to D_s \pi \) sample only to measure \( F \), and assuming \( w_{OS} \) known to 2% (relative)

  \[
  \Rightarrow \sigma_{\text{stat}}(w_{SS})/w_{SS} < 5\% \text{ after 1 year (= 2fb}^{-1})
  \]