LHCb status report

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On behalf of the LHCb collaboration
LHCb detector: New Physics in the forward region

Search for New Physics by studying rare processes and precision CP violation measurements in B and D sectors

- Good vertexing
  - Measure $B_d$ and $B_s$ oscillations, reject prompt background
- Particle identification
  - Flavour tagging, misID background
- Calorimetry
  - Reconstruction of neutral particles ($\gamma, \pi^0$)
- Efficient trigger, including hadronic modes
Very successful data taking in 2011 (thanks to the LHC crew!)

Instantaneous luminosity:
- levelled at \((3-3.5) \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
- higher than design \(2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)

91% data taking efficiency

1.2 fb\(^{-1}\) delivered by LHC

1.04 fb\(^{-1}\) of analysis-quality data
Vertexing

- Typical primary vertex resolution (with 30 tracks):
  - $\sigma_{x,y} = 12 \, \mu\text{m}$
  - $\sigma_z = 65 \, \mu\text{m}$
- Decay time resolution: 40-50 fs

Hadronic vertices reconstructed in VELO used for “tomography” (check of MC description)

$\sigma_t = 50$ fs for prompt J/$\psi$
Tracking and calorimetry

Momentum resolution:
$\delta p/p = 0.35 \div 0.55\%$

ECAL: $\sigma_E/E = 10\%\sqrt{E} \otimes 1\%$
HCAL: $\sigma_E/E = 80\%\sqrt{E} \otimes 10\%$

Two-body invariant mass resolution:
$\sigma(\mu\mu) = 15\text{ MeV}/c^2$ at $J/\psi$
$\sigma(\mu\mu) = 45\text{ MeV}/c^2$ at $\Upsilon(1S)$

Momentum scale calibrated to 0.5 per mille precision.

A number of world-best $b$ meson and baryon mass measurements, systematic error $\sim 0.2\text{ MeV}/c^2$. 

$\chi_{c1}, \chi_{c2} \rightarrow J/\psi \gamma$

$B^0 \rightarrow K^*\gamma$
Particle identification

Two RICH detectors with aerogel and C$_4$F$_{10}$ radiators, π/K/p separation in the momentum range 3-100 GeV/c

New gas-tight aerogel box is installed in January 2012, to prevent aerogel degradation due to C$_4$F$_{10}$ filling.
Flavour tagging

Use information from
- Opposite side:
  Charge of kaon, muon, electron, charge of tracks from the secondary vertex
- Same side:
  Charge of associated track

Tagging performance calibrated on data: $B \rightarrow J/\psi K$ sample

Flavour tagging performance in $B_S \rightarrow J/\psi \phi$ analysis (opposite-side taggers only):

<table>
<thead>
<tr>
<th>Mistag probability $\omega$</th>
<th>$(36.81 \pm 0.18 \pm 0.74)%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tagging efficiency $\varepsilon_{\text{tag}}$</td>
<td>$(32.99 \pm 0.33)%$</td>
</tr>
<tr>
<td>Tagging power $\varepsilon_{\text{tag}} (1-2\omega)^2$</td>
<td>$(2.29 \pm 0.07 \pm 0.26)%$</td>
</tr>
</tbody>
</table>
Trigger in 2011

L0: Hardware trigger
   Require a high-$p_T$ particle

HLT: Two-level software trigger
    Trigger farm (26k cores)
    HLT1: Require high-$p_T$ displaced track
    HLT2: Full reconstruction

Typical overall efficiency:
   Dimuon: 80%, Hadronic: 30%

In 2011, run with 50% higher output rate than designed (2 kHz → 3 kHz), limited by CPU for reconstruction and by disk storage

**HLT Output Rate (Hz)**

- Other physics lines
- charm
- Muons
- hadron

Storage: event size ~50kB
Main physics results with 2011 dataset

Many results with 2011 dataset reported at winter conferences

- Roadmap measurements...
  - Tree-level determination of $\gamma$
  - CPV in charmless two-body B decays
  - $\beta_s$ measurement in $B_s \rightarrow J/\psi \phi$
  - Search for $B_s \rightarrow \mu \mu$
  - Angular analysis of $B^0 \rightarrow K^* \mu \mu$
  - Radiative B decays

- ... and beyond:
  - CP violation in charm
  - Other rare decays: $D \rightarrow \mu \mu$, $B_s \rightarrow \mu \mu \mu \mu$, $B_s \rightarrow \phi \mu \mu$, $B^+ \rightarrow \pi^+ \mu \mu$
  - $\beta_s$ measurement in $B_s \rightarrow J/\psi \pi \pi$
  - First observations in hadronic B decays
  - Studies of exotic states (X,Y,Z)

Will concentrate on most recent results with full 2011 dataset.

Many interesting results not covered:
- Soft QCD
- Electroweak physics
- Heavy flavour production and spectroscopy

To be reported at DIS next week
Rare decays: $B_s \rightarrow \mu^+\mu^-$

One of the most sensitive probes of New Physics

- **Standard Model:** FCNC, helicity suppressed:
  $$\text{Br}(\text{SM}) = (3.2 \pm 0.2) \times 10^{-9}$$

- Can be enhanced in NP models.

  **MSSM:**
  $$\text{BR} \propto \left( C_{S,P}^{\text{MSSM}} \right)^2 \propto \frac{\tan^6 \beta}{M_A^4}$$

- **Use two variables**
  - $\mu^+\mu^-$ invariant mass
  - BDT based on variables that select good-quality secondary vertex, well-separated from the PV

- Results in 2D bins, BDT vs. mass

1 fb$^{-1}$, LHCb-PAPER-2012-007
Rare decays: $B_s \rightarrow \mu^+\mu^-$

$1 \text{ fb}^{-1}$, LHCb-PAPER-2012-007
Rare decays: $B_S \rightarrow \mu^+\mu^-$

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>CMS</th>
<th>Atlas</th>
<th>LHCb</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (fb$^{-1}$)</td>
<td>10</td>
<td>4.9</td>
<td>2.4</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>$\text{Br}(B_d \rightarrow \mu^+\mu^-)$ 95% CL (x10$^{-9}$)</td>
<td>4.6</td>
<td>1.8</td>
<td></td>
<td>1.03</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>$\text{Br}(B_S \rightarrow \mu^+\mu^-)$ 95% CL (x10$^{-9}$)</td>
<td>31</td>
<td>7.7</td>
<td>22</td>
<td>4.5</td>
<td>3.2 ± 0.2</td>
</tr>
<tr>
<td>Central value (x10$^{-9}$)</td>
<td>13$^{+9}_{-7}$</td>
<td>7.7</td>
<td></td>
<td>4.5</td>
<td>3.2 ± 0.2</td>
</tr>
</tbody>
</table>

1 fb$^{-1}$, LHCb-PAPER-2012-007

95% $B_S \rightarrow \mu^+\mu^-$ upper limit already close to Standard Model value.
Rare decays: $B_S \rightarrow \mu^+\mu^-$


Implications of LHCb result on SUSY parameters (with $\tan \beta = 50$)

TeV-scale SUSY with large $\tan \beta$ is practically excluded

NP that reduces $B_S \rightarrow \mu^+\mu^-$ amplitude already discussed by theorists.
Rare decays: $B^0 \rightarrow K^* \mu^+ \mu^-$

FCNC process, can be affected by presence of NP.

Measure angular distributions as functions of $q^2 = m^2(\mu\mu)$.

$K^*$ polarization $F_L$, forward-backward asymmetry $A_{FB}$.

$q^2$ where $A_{FB} = 0$ is well predicted in SM:

$q^2 (A_{FB} = 0) = (4 - 4.3) \text{ GeV}^2/c^4$

First measurement of zero crossing point:

$q^2 (A_{FB} = 0) = 4.9^{+1.1}_{-1.3} \text{ GeV}^2/c^4$

900±34 events
Rare decays: $B^+ \rightarrow \pi^+ \mu^+ \mu^-$

$b \rightarrow d\ell\ell$ transition,

SM prediction:

$$\text{Br} = (1.96 \pm 0.21) \times 10^{-8}$$

x25 smaller than $B^+ \rightarrow K^+ \mu^+ \mu^-$

(misID is a challenge)

25±6 signal events, 5.2σ significance

First observation of $b \rightarrow d\ell\ell$ transition,

$$\text{Br}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) = (2.4 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-8}$$

In a good agreement with SM prediction

The rarest B decay ever observed
**CP violation: $B^{\pm} \rightarrow DK^{\pm}$**

Access CKM phase $\gamma$ through interference of $V_{cb} V_{us}^*$ and $V_{cs} V_{ud}^*$ amplitudes.

Tree-level measurement, SM reference. Theoretically clean, experimentally challenging

- GLW mode: $D \rightarrow KK, \pi\pi$
- ADS mode: fav. $B \rightarrow DK$, sup. $D \rightarrow K\pi$
  
and sup. $B \rightarrow DK$, fav. $D \rightarrow K\pi$

5.8$\sigma$ observation of CP violation in the combination of $B \rightarrow D(hh)K$ modes

1 fb$^{-1}$, LHCb-PAPER-2012-001
**CP violation: \( B^\pm \rightarrow DK^\pm \)**

Measured observables, e.g. asymmetries, depend on \( \gamma \) as well as other unknown parameters:

\[
A_{CP\pm} = \frac{\pm 2r_B \sin \delta_B \sin \gamma}{1 + r_B^2 \pm 2r_B \cos \delta_B \cos \gamma}, \quad A_{ADS} = \frac{2r_B r_D \sin(\delta_B + \delta_D) \sin \gamma}{r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos \gamma}
\]

Measurement of \( \gamma \) in \( B \rightarrow DK, D \rightarrow \text{hh} \) modes alone suffers from ambiguities. Combination with other modes is required to constrain \( \gamma \):

\( B \rightarrow D(K_s \text{hh})K, B \rightarrow D(hh)K\pi\pi, B^0 \rightarrow DK\pi, B_S \rightarrow D\phi \), etc.
CP violation: $B^0 \rightarrow \pi\pi$, $B_S \rightarrow KK$

Time-dependent CP violation:

$$A_{CP}(t) = \frac{\Gamma_{\bar{B} \rightarrow f}(t) - \Gamma_{B \rightarrow f}(t)}{\Gamma_{\bar{B} \rightarrow f}(t) + \Gamma_{B \rightarrow f}(t)} = \frac{A_{dir} \cos(\Delta M t) + A_{mix} \sin(\Delta M t)}{\cosh(\Delta \Gamma t) - A_{\Delta \Gamma} \sinh(\Delta \Gamma t)}$$

Invoking U-spin symmetry, can constrain CKM phase $\gamma$ by analysing $B^0 \rightarrow \pi\pi$ and $B_S \rightarrow KK$ decays

LHCb Preliminary
$\sqrt{s} = 7$ TeV Data

$B^0 \rightarrow \pi\pi$
5359$\pm$96 events

LHCb Preliminary
$\sqrt{s} = 7$ TeV Data

$B_S \rightarrow KK$
7155$\pm$97 events

0.69 fb$^{-1}$, LHCb-CONF-2012-007
CP violation: $B^0 \rightarrow \pi\pi$, $B_s \rightarrow KK$

$A^\text{dir}_{\pi\pi} = 0.11 \pm 0.21 \pm 0.03$

$A^\text{mix}_{\pi\pi} = -0.56 \pm 0.17 \pm 0.03$

$A^\text{dir}_{KK} = 0.02 \pm 0.18 \pm 0.04$

$A^\text{mix}_{KK} = 0.17 \pm 0.18 \pm 0.05$

0.69 fb$^{-1}$, LHCb-CONF-2012-007
CP violation: $B_s \rightarrow J/\psi \, \phi$

Interference of $B_s \rightarrow J/\psi \phi$ decays with and without mixing

In SM, small phase difference:

$$\phi_s = -0.036 \pm 0.002$$

Measurement involves a number of advanced analysis techniques:

- Flavour tagging to identify the initial $B_s$ flavour
- Decay time measurement to measure oscillations
- Angular analysis to distinguish between CP-odd and CP-even states ($P \rightarrow VV$ decay)
CP violation: \( B_S \rightarrow J/\psi \phi \)

\[ \Delta \Gamma_s = 0.116 \pm 0.018 \pm 0.006 \text{ ps}^{-1} \]

\[ \phi_s = -0.001 \pm 0.101 \pm 0.027 \]

Similar measurement in \( B_S \rightarrow J/\psi \pi^+ \pi^- \)

\[ \phi_s = -0.02 \pm 0.17 \pm 0.02 \]

Combined result: \( \phi_s = -0.002 \pm 0.083 \pm 0.027 \)
Some new observations: $B \to \bar{D}D$

$\text{Br}(B_s \to \bar{D}_sD_s)/\text{Br}(B^0 \to \bar{D}_sD_s) = 0.048 \pm 0.008 \pm 0.004$
Significance: 10σ

$\text{Br}(B_s \to D^+D^-)/\text{Br}(B^0 \to D^+D^-) = 1.00 \pm 0.18 \pm 0.09$
Significance: 10σ

$\text{Br}(B_s \to D^0\bar{D}^0)/\text{Br}(B^- \to D^0\bar{D}^0) = 0.015 \pm 0.004 \pm 0.002$
Significance: 5.4σ
More new observations: \( B_c \rightarrow J/\psi \pi^+\pi^-\pi^+\pi^+ \)

- \( \text{Br} \) consistent with QCD sum rules
- Multibody dynamics is studied:

\[
\frac{BR(B_c^\pm \rightarrow J/\psi 3\pi^\pm)}{BR(B^\pm \rightarrow J/\psi \pi^\pm)} = 2.41 \pm 0.30_{\text{stat}} \pm 0.33_{\text{syst}}
\]

0.8 fb\(^{-1}\), LHCb-PAPER-2011-044

\( N = 135 \pm 14 \)

\( N = 414 \pm 25 \)

Dominated by \( B_c^+ \rightarrow J/\psi \ a_1^+ \), \( a_1^+ \rightarrow \rho^0 \pi^+ \).
Charm physics

- CP violation in charm:
  
  Evidence for direct CPV in $D \rightarrow hh$
  
  $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$
  
  $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$

  Recent confirmation by CDF
  
  More charm CPV studies to come...

- Rare charm decays:
  
  Search for $D \rightarrow \mu\mu$

  $0.9 \text{ fb}^{-1}$, LHCb-CONF-2012-005

  Use tagged $D$ from $D^* \rightarrow D\pi$

  $B(D^0 \rightarrow \mu^+\mu^-) < 1.3 \times 10^{-8}$ at 95% CL
Preparation for 2012

• Bunch energy increases to 4 TeV
  Will run at \(4 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}\) ⇒ expect 25% increase in \(b\bar{b}\) rate

• Better control of systematics:
  ▪ Introduce vertical external crossing angle (instead of horizontal one), to ensure that the crossing angle is the same for both polarities.
  ▪ For better control of detector asymmetries, need to change magnet polarity frequently to follow change in running conditions. Compromise with LHC: run with 3 polarity switches between technical stops (flip every 1.5 weeks).

• Aim is to collect 1.5 fb\(^{-1}\) in 2012.

• Aim to take as much data as possible before long shutdown: increase trigger rate from 3 kHz (2011) ⇒ 4.5 kHz
Trigger improvements for 2012

- Trigger has to cope with the increased rate due to luminosity and beam energy increase.
- HLT farm will increase by 10% (1200 additional cores)
- Deferred trigger:
  - The whole farm is idle between fills
  - Instead:
    - Buffer L0-filtered events to local disks (200 Gbytes/node is available)
    - Run HLT on buffered data between fills
    - Equivalent to 10%-20% gain in CPU
- Improvements in tracking and vertexing performance
  - Downstream tracking in trigger (tracks with no hits in VELO: $K_S, \Lambda$)
    - Gain a factor of 3.5 for $D \rightarrow K_S \pi^+\pi^-$: golden mode for mixing and CPV in charm
- Increased physics rate is challenging for data storage:
  - Bandwidth for analysis skims for 2012 is limited by available storage: ~35 Mbytes/sec.
  - A lot of effort to stay within this bandwidth: data compression, event size reduction, tighter selections.
LHCb upgrade: physics programme

LHCb will run in its current configuration until the end of 2017, expect to take 5-7 fb\(^{-1}\).
There is a rich physics programme for integrated luminosities up to 50 fb\(^{-1}\).

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb (5 fb(^{-1}))</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluonic penguin</td>
<td>(S(B_s \to \phi\phi))</td>
<td>-</td>
<td>0.08</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>(S(B_s \to K^{*0}K^{*0}))</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>(S(B^0 \to \phi K_S^0))</td>
<td>0.17</td>
<td>0.15</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>(B_s) mixing</td>
<td>(2\beta_s \ (B_s \to J/\psi\phi))</td>
<td>0.35</td>
<td>0.019</td>
<td>0.006</td>
<td>(~ 0.003)</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>(S(B_s \to \phi\gamma))</td>
<td>-</td>
<td>0.07</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>(A^{\tau_s}_s(B_s \to \phi\gamma))</td>
<td>-</td>
<td>0.14</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>E/W penguin</td>
<td>(A_T^{(2)}(B^0 \to K^{*0}\mu^+\mu^-))</td>
<td>-</td>
<td>0.14</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>(s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-))</td>
<td>-</td>
<td>4%</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>(B(B_s \to \mu^+\mu^-))</td>
<td>-</td>
<td>30%</td>
<td>8%</td>
<td>&lt; 10%</td>
</tr>
<tr>
<td></td>
<td>(B(B_s \to \mu^+\mu^-)/\bar{B}(B_s \to \mu^+\mu^-))</td>
<td>-</td>
<td>-</td>
<td>(~ 35%)</td>
<td>(~ 5%)</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>(\gamma \ (B \to D^{(<em>)}K^{(</em>)}))</td>
<td>(~ 20^\circ)</td>
<td>(~ 4^\circ)</td>
<td>0.9(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>(\gamma \ (B_s \to D_s K))</td>
<td>-</td>
<td>(~ 7^\circ)</td>
<td>1.5(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta \ (B^0 \to J/\psi K^0))</td>
<td>1(^\circ)</td>
<td>-</td>
<td>0.2(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm CPV</td>
<td>(A_{T})</td>
<td>2.5 \times 10^{-3}</td>
<td>2 \times 10^{-4}</td>
<td>4 \times 10^{-3}</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>(A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi))</td>
<td>4.3 \times 10^{-3}</td>
<td>4 \times 10^{-4}</td>
<td>8 \times 10^{-5}</td>
<td>-</td>
</tr>
</tbody>
</table>

Framework TDR to be submitted to LHCC in June 2012 (schedule, cost and resources for the upgrade) together with an update of physics performance based on real data.
LHCb upgrade: detector modifications

- Need to read out at full 40 MHz speed to gain from increased luminosity.
- Fully software trigger running at 40 MHz.
- Aim to increase the rate for muonic channels by x5, hadronic by x10 wrt. current setup.

Subsystems TDRs to be ready by the end of 2013
Conclusion

- A lot of interesting results in heavy flavour physics obtained by LHCb.
  - Thanks to the excellent performance of the machine and detector.
- Most roadmap measurements updated with 1 fb$^{-1}$ and reported at winter conferences.
  - Expanding our physics programme beyond the roadmap: prepare for exciting new results already this spring and summer.
- All results are well consistent with SM so far.
  - Except for CP violation in charm, which may (or may not) be the evidence of NP.
- 44 papers submitted to journals, 73 conference papers.
  - 120% more than December LHCC.
- Looking forward to continue:
  - Trigger improvements in 2012, aim to collect 1.5 fb$^{-1}$ with increased trigger efficiency, especially for charm decays.
  - Upgrade programme aiming at 50 fb$^{-1}$.
Backup
CP violation: $B^0 \rightarrow K^*\gamma$

SM prediction for CP asymmetry:
$$A_{CP} = -0.0061 \pm 0.0043$$
Smaller theoretical uncertainty than in $Br$.

Measured CP asymmetry:
$$A_{CP}(B^0 \rightarrow K^*\gamma) = +0.008 \pm 0.017\text{(stat)} \pm 0.009\text{(syst)}$$
Non-observations: $X(4140)$

- $X(4140) \rightarrow J/\psi \phi$ observed by CDF in $B \rightarrow J/\psi \phi K$
  - $19 \pm 6 \text{(stat)} \pm 3 \text{(syst)}$ events at $M = 4143.4^{+2.9}_{-3.0} \pm 0.6$ MeV/c$^2$
  - $22 \pm 8$ events ($3.1 \sigma$) at $M=4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV/c$^2$
- $X(4140)$ not confirmed by LHCb:
  - $7 \pm 5$ events
  - $0.6 \pm 7$ events

0.37 fb$^{-1}$, LHCb-PAPER-2011-033
CP violation: $B^{(S)} \rightarrow K\pi$

$A_{CP}(B^{0} \rightarrow K\pi) = -0.088 \pm 0.011\text{ (stat)} \pm 0.008\text{ (syst)}$

$A_{CP}(B_{s}^{0} \rightarrow K\pi) = 0.27 \pm 0.08\text{ (stat)} \pm 0.02\text{ (syst)}$