Results and Prospects from LHCb
PSROC2011 LHC Symposium
25 January - 27 January 2011, Taipei, Taiwan

Tatsuya NAKADA
Laboratory for High Energy Physics (LPHE)
Swiss Federal Institute of Technology Lausanne (EPFL)
Lausanne, Switzerland
Two general purpose experiments (ATLAS and CMS), one dedicated b-experiment (LHCb), and one dedicated heavy ion experiment (ALICE).
B Physics@Hadron machine

• b-qark first discovered by a hadron machine in 1977

S. Herb et al. in 1977@ FNAL
B Physics@Hadron machine

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• For many years, B physics had been dominated by the $e^+e^-$ machines: DORIS, CESR, VEPP, LEP, ...
  Tradition continued with PEP-II and KEKB
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- Experiments at hadron machines, i.e. fixed target, with “limited” results: CERN: Beatrice FNAL: E866/E789/E772, E771
  b cross section measurements (with large error bars) → simply not enough b’s and too small $\sigma_b/\sigma_{inelastic}$
  The last attempt being HERA-B
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- 1992 CDF reconstructed $B \rightarrow J/\psi K$
  B physics with a hadron machine at high energy looks feasible!
  D0 and CDF contributed a lot in lifetimes, CPV, and oscillations. (in particular for $B_s$)
New physics in $B_s$ @ hadron machine?

- CPV in $B_s \rightarrow J/\psi \phi$  time dependent CP asymmetry

$$\propto \sin \phi_{s}^{J/\psi \phi} \sin \Delta m t$$

68 % CL and 95% CL

- D0: 6.1 fb$^{-1}$
- CDF: 5.2 fb$^{-1}$

SM prediction
New physics in $B_s$ @ hadron machine?
CPV in $B_s-\overline{B}_s$ oscillations

$\text{Pr}(\overline{B}_s \rightarrow B_s) \neq \text{Pr}(B_s \rightarrow \overline{B}_s)$
New physics in $B_s \rightarrow \mu^+\mu^-$ hadron machine?

- $B_s \rightarrow \mu^+\mu^-$ GIM and helicity surpressed in the Standard Model.
- New physics can introduce large enhancement
- Current Tevatron observed limits still large

![Tevatron results graph](image)

- CDF
- D0

SM prediction
New physics in $B_d @ hadron$ machine?

- $A_{FB}$ in $B_d \rightarrow K^{*0}\mu^+\mu^-$
They are somehow related

CPV in $J/\psi\phi$

and $B_s - \overline{B}_s$ oscillation

$\propto \arg(M_{12})$

$B_s \rightarrow \mu\mu$

$B_d \rightarrow K^*\mu\mu$

\[
\begin{align*}
\bar{b} & \xrightarrow{W^+} t \xrightarrow{t} s & \bar{b} & \xrightarrow{W^+} t & \mu^+ \\
\bar{s} & \xrightarrow{W^-} b & \bar{s} & \xrightarrow{W^-} \nu & \mu^- \\
\end{align*}
\]
They are somehow related

CPV in $J/\psi\phi$

and $B_s - \bar{B}_s$ oscillation

$\propto \arg(M_{12})$

$B_s \rightarrow \mu\mu$

$B_d \rightarrow K^*\mu\mu$

and more related diagrams.
They are somehow related

CPV in $J/\psi\phi$

and $B_s - \bar{B}_s$ oscillation

$\propto \arg(M_{12})$

\[
\begin{array}{c}
\bar{b} \rightarrow W^+ \rightarrow t \rightarrow \bar{s} \rightarrow s \rightarrow b
\end{array}
\]

$B_s \rightarrow \mu\mu$

\[
\begin{array}{c}
\bar{b} \rightarrow W^+ \rightarrow t \rightarrow \nu \rightarrow \mu^+ \rightarrow s \rightarrow W^- \rightarrow \mu^-
\end{array}
\]

$B_d \rightarrow K^*\mu\mu$

\[
\begin{array}{c}
\bar{b} \rightarrow t \rightarrow \nu \rightarrow \mu^+ \rightarrow W^+ \rightarrow W^- \rightarrow s \rightarrow \mu^-
\end{array}
\]

All could contain loop of virtual New Particles.
More topics with hadron machines

• CP asymmetries in $B_u \to K^\pm \pi^0 \neq B_d \to K^\pm \pi^\mp$!
  – Experimentally established effect by Belle (Nature 2008)
  – Physics interpretation, Standard Model due to hadronic interaction effect or New Physics

• $C_{\pi\pi \neq 0}$?

• $\gamma$ from the tree = $\gamma$ from the loop?

  – Hadron machine: much more statistics
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• CP asymmetries in $b \rightarrow sX \neq b \rightarrow cX$?
  – Was a “suggestive” case for new physics…
\[ \sin(2\beta_{\text{eff}}) = \sin(2\phi_{1\text{eff}}) \]

<table>
<thead>
<tr>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b \to c\bar{c}s$</td>
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<tr>
<td>$\phi_{K^0}$</td>
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<tr>
<td>$\eta$, $K^0$</td>
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<td>$K_S$, $K_S$, $K^0_S$</td>
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<td>$\rho^0$, $K_S^0$</td>
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<td>$\omega$, $K_S^0$</td>
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<td>$f_{K^0}$, $K_S^0$</td>
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<td>$\pi^0$, $\pi^0$, $K^0_S$</td>
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<tr>
<td>$K^0$, $K^0$, $K^0_S$</td>
</tr>
</tbody>
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**Naïve average**

- $b \to q\bar{q}s$ | $0.53 \pm 0.05$

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**HFAG DPF/JPS 2006**

**PRELIMINARY**

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**HFAG CKM2008**

**PRELIMINARY**

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More topics with hadron machines

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• $C_{\pi\pi} \neq 0$? (CP violation in $B \rightarrow \pi^+\pi^-$ decay amplitudes)
\( \pi^+ \pi^- S_{CP} \) vs \( C_{CP} \)

- **BaBar**
- **Belle**
- **Average**

Contours give \(-2 \Delta \ln(L) = \Delta \chi^2 = 1\), corresponding to 60.7% CL for 2 dof
More topics with hadron machines

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• $\gamma$ from the tree = $\gamma$ from the loop?
$\Gamma(b \rightarrow uW)$

$\text{CPV}(B \rightarrow DK)$

2009 fit
More topics with hadron machines

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• $\gamma$ from the tree $= \gamma$ from the loop?
  – Hadron machine: much more statistics
LHCb Detector

Outer & Inner Tracker

Trigger Tracker

RICH-1

Vertex Locator

Magnet

Muon System

Calorimeters

RICH-2
Quick reminder for LHCb

LHCb is a forward spectrometer dedicated for flavour physics

Both $b$ and $\bar{b}$ are in the spectrometer.
Quick reminder for LHCb

Forward: $p_T$ threshold can be set low: $\rightarrow$ high $b$ efficiency

For triggering: $p > p_{\text{min}}$

- Muon: identification
- Hadron: energy resolution

$\sigma_E/E \approx \sqrt{70\%/E}$
Quick reminder for LHCb

Forward: $p_T$ threshold can be set low: $\rightarrow$ high b efficiency

For triggering: $p > p_{\text{min}}$

- muon: identification
- hadron: energy resolution

\[ p < p_{\text{min}} \rightarrow \text{Fe} \]
\[ p > p_{\text{min}} \rightarrow \]

\[ \frac{\sigma_E}{E} \approx \sqrt{70\%}/\sqrt{E} \]

central detector

\[ p \approx p_T > p_{\text{min}} \]

forward detector

\[ p \approx p_L > p_{\text{min}} \]
Quick reminder for LHCb

Can exploit low $p_T$ particles to trigger more b-hadron events

\[ \sigma_{bb} \text{ expected in pp collisions at } \sqrt{s} = 14 \text{ TeV: } 500 \mu \text{b} \]

\[ 5 \times 10^{11} \text{ } b\bar{b} \text{ pairs in } 10^7 \text{ s with } L = 10^{32} \text{ cm}^{-2} \text{s}^{-1} \]

First level trigger based on medium $p_T$ trigger (hardware)

- 40MHz → 1MHz
- readout@1 MHz to PC farm

Software trigger for the rest

- 1MHz → 2 kHz
- data logging@2 KHz for offline

Very flexible and efficient trigger
23rd November 2009

• First collisions took place at LHC
• 2009 run: \( \int L \, dt \approx 7 \, \mu \text{b}^{-1} \), at \( \sqrt{s} = 900 \, \text{GeV} \)

One of the first event

K_S^0 cross sections (PLB2010)
LHC running in 2010

• Since March 2010, running at $\sqrt{s} = 7$ TeV with a steady improvement in $\int L dt$ and very high DAQ efficiency

38 pb$^{-1}$ of data recorded 90% efficiency
σ_{b\bar{b}} measurements with very early data

b detection from \( b \rightarrow D^0(K^-\pi^+)\mu^-X \) (PLB 2010)

\[ \int L \, dt = 25 \text{ nb}^{-1} \text{ data} \]

Inclusive D:

Clean D signal with hadron PID
$\sigma_{b\bar{b}}$ measurements with very early data

b detection from $b \rightarrow D^0(K^-\pi^+)\mu^-X$

Inclusive D: dominated by the prompt production

IP(D from $b \rightarrow D$) > IP(prompt D)
σ_{bb} measurements with very early data

b detection from b\to D^0(K^−\pi^+)\mu^-X

Adding \mu with a right sign enhances D from b:
e.g. B^-\to D^0(\to K^-\pi^+)\mu^-X \ [B^-\to D^0(\to K^+\pi^-)\mu^-X only through DCSD]
σ_{b\bar{b}} measurements with very early data

b detection from b → D^0(K^-\pi^+)\mu^-X

Adding μ with a right sign enhances D from b:
e.g. B^− → D^0(→K^-\pi^+)\mu^-X [B^− → D^0(→K^+\pi^-)\mu^-X only through DCSD]

with right sign muons

with wrong sign muons
σ_{b\bar{b}} measurements with very early data

b detection from b→D^0(K^-\pi^+)\mu^-X
$\sigma_{b\bar{b}}$ measurements with very early data

b detection from $b \rightarrow J/\psi X$

Clean $\mu^+\mu^-$ mass distribution with $\int L \, dt = 14 \text{ nb}^{-1}$ data
$\sigma_{b\bar{b}}$ measurements with very early data

b detection from $b \rightarrow J/\psi X$

proper time distribution of $J/\psi$

![Diagram showing prompt $J/\psi$ and $J/\psi$ from b decay]
σ_{b\bar{b}} measurements with very early data

b detection from b→J/ψX

proper time distribution of J/ψ

negative proper time important for studying resolution
σ_{bb} measurements with very early data

b detection from b→J/ψX

proper time distribution of J/ψ

prompt J/ψ

J/ψ from b

with detector resolution

combinatorial background with prompt tracks and b tracks

negative proper time important for studying resolution
\( \sigma_{b\bar{b}} \) measurements with very early data

\( b \) detection from \( b \rightarrow J/\psi X \)

Proper time distribution with \( \int L \, dt = 14 \, \text{nb}^{-1} \) data

\( J/\psi \) with a long proper time due to \( b \)-hadron decays
$\sigma_{b\bar{b}}$ measurements with very early data
LHCb $\sigma_{b\bar{b}}$ from $b \rightarrow D^0 \mu X$ and $\rightarrow J/\psi X$

$\sigma_{b\bar{b}}$ in $4\pi = 292 \pm 15 \pm 43 \, \mu$b (with LEP $B_u/B_d/B_s/\Lambda_b$)

→agree with the Pythia used for the performance studies
Comments on 2010 running condition

- Most of the data at $\sqrt{s} = 7$ TeV with
  - $n_{p\text{-bunch}} \approx 10^{11}$ ↔ already nominal value
  - $\beta^* = 3.5$ m ↔ nominal 0.55 m for $10^{34}$ cm$^{-2}$s$^{-1}$
  - $n_{\text{bunch}} = \text{up to 344}$ ↔ nominal = 2808
  - $L \approx 1 \times 10^{32}$ cm$^{-2}$s$^{-1}$ ↔ nominal = $10^{34}$ cm$^{-2}$s$^{-1}$

\[\begin{array}{c|c}
\text{Peak Instantaneous Lumi over Time at 3.5 TeV} & 2010-12-08 06:00:04 \\
\hline
\end{array}\]

~1 month

Factor 100 increase in ~one month
Comments on 2010 running condition

- Most of the data at $\sqrt{s} = 7$ TeV at 80% of the LHCb nominal luminosity ($2 \times 10^{32}$) with 10% of bunches, i.e.
- > 6 times more pp interactions/bunch-crossing than designed

Multiple primary vertices
Higher track multiplicities
More difficult to trigger
More backgrounds

But the detector worked well as you will see now.
Prospect for $B \rightarrow hh$

- Particle identification is crucial
Prospect for $B \to hh$

No particle identification $\rightarrow$ any 2 hadrons!

$B^0 \to h^+ h^-$

large width
Prospect for $B \to hh$

No particle identification $\to$ any 2 hadrons!

$B_0 \to h^+ h^-$

particle identification of 2 Kaons

$B^0 \to h^+ h^-$

large width

$BR(B \to \pi^+ \pi^-) = 5 \times 10^{-6}$!

$B_d^0 \to \pi^+ \pi^-$

229±23 events in 35 pb$^{-1}$

particle identification of 1 $\pi$ and 1 $K$

$B_d^0 \to K \pi$ & $B_s^0 \to K \pi$

Expectations 2011:
LHCb: 6500 ev./fb$^{-1}$
Belle 1.5k

$B_s^0 \to K^+ K^-$

Belle 1.5k

(we will get as many $K\pi$ in <1 fb$^{-1}$ as Belle in 1000 fb$^{-1}$)
Prospect for B→hh

- Particle identification is crucial
- Promising signature in the raw charge asymmetries
Prospect for $B \to hh$

$B^0_d \to K \pi$ & $B^0_s \to K \pi$

$B^0_s/B^0_d$ yield = $(10.7 \pm 2.0)\%$,

$A_{CP}(B^0_d) = -0.134 \pm 0.041$

(HFAG: $-0.098 \pm 0.012$)

$A_{CP}(B^0_s) = 0.43 \pm 0.17$

(CDF: $0.39 \pm 0.15 \pm 0.08$ in $1 \text{ fb}^{-1}$)

- only raw asymmetries
- not accounted for production & detector asymmetries
- this is not a physics result yet!
Prospect for CPV in $B_s \rightarrow J/\psi \phi$

- First step is to observe $B^0 - \bar{B}^0$ oscillations

![Graph showing $B_d^0$ oscillation from $B_d^0 \rightarrow D^* \mu^+ \nu$ with asymmetry in tag, $\Delta m = 0.53 \pm 0.08 \times 10^{12} \text{ s}^{-1}$.](image)
Prospect for CPV in $B_s \rightarrow J/\psi \phi$

- First step is to observe $B^0 - \bar{B}^0$ oscillations
- Reconstruct $B^+ \rightarrow J/\psi K^+$ final states

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Prospect for CPV in $B_s \rightarrow J/\psi \phi$

- First step is to observe $B^0 - \bar{B}^0$ oscillations
- Reconstruct $B^+ \rightarrow J/\psi K^+$ final states
- Reconstruct $B^0 \rightarrow J/\psi K_S$ final states

![Graph showing mass distribution of $B^0 \rightarrow J/\psi K_S$ events.](image)
Prospect for CPV in $B_s \rightarrow J/\psi \phi$

- First step is to observe $B^0 - \bar{B}^0$ oscillations
- Reconstruct $B^+ \rightarrow J/\psi K^+$ final states
- Reconstruct $B^0 \rightarrow J/\psi K_S$ final states
- Reconstruct $B_s \rightarrow J/\psi \phi$ final states

![Graph showing invariant mass distribution with peaks at 5350 and 5400 MeV/c^2 with error bars and signal numbers.]

$LHCb$ Preliminary
$\sqrt{s} = 7$ TeV Data
$N_{\text{Signal}} = 877 \pm 31.59$
$\sigma_G = 7.28 \pm 0.24$ MeV/c^2

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- Reconstruct $B^+ \rightarrow J/\psi K^+$ final states
- Reconstruct $B^0 \rightarrow J/\psi K_S$ final states
- Reconstruct $B_s \rightarrow J/\psi \phi$ final states
- On going work:
  - $B_s \rightarrow \bar{B}_s$ oscillations
  - angular acceptance
  - fit model
  - etc.
  - and other final states,
    e.g. $B_s \rightarrow J/\psi f_0(980)$ observed (pure CP eigenstate)
Prospect for CPV in $B_s \rightarrow J/\psi \phi$

- Based on, measured b cross sections and $B_s \rightarrow J/\psi \phi$ reconstruction performance,
Prospect for $B_s \rightarrow \mu^+ \mu^-$

- Decays can be characterised by
  - Invariant mass
  - $B \rightarrow$ two-particle decay topology
  - Muon identification

- All can be studied by data:
  - Invariant mass and topology by $B \rightarrow \pi^+ \pi^-$ decays
  - Muon ID by $K_s \rightarrow \pi^+ \pi^-$, semileptonic decays, etc.
Background well described by MC

all the cuts are being tuned with a smaller sample
Prospect for $B_s \rightarrow \mu^+ \mu^-$
LHCb how about $B_d \rightarrow K^{*0} \mu^+ \mu^-$?

With 1 fb$^{-1}$ LHCb expects 1200 events

If the current BABAR and Belle results are correct, LHCb could exclude SM prediction with 4σ significance
Fantastic charm potential of LHCb

Initial flavour tagged $D^0$ decays: 34 pb$^{-1}$
$D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow K^+K^-$ and $\pi^+\pi^-$

97k for $\pi^+\pi^-$
31k for $\pi^+\pi^-$
(162k for $K^+\pi^-$)

Promising start for $D^0$ oscillation and CP violation studies
Current situation with $a_{SL}^s$?
LHCb how about $\alpha_{SL}^s$?

How to deal with
-possible $B_s^0/\bar{B}_s^0$ production asymmetry in pp 2$<\eta<$6
-controlling detection and background asymmetries to $<10^{-3}$
LHCb how about $a_{SL}^s$?

How to deal with
-possible $B_s^0/\bar{B}_s^0$ production asymmetry in pp $2<\eta<6$
-controlling detection and background asymmetries to $< 10^{-3}$

Inclusive muon pairs difficult to control systematic errors…
LHCb how about $a_{SL}^s$?

How to deal with
-possible $B_s^0/\overline{B}_s^0$ production asymmetry in $pp \ 2<\eta<6$
- controlling detection and background asymmetries to $<10^{-3}$

Inclusive muon pairs difficult to control systematic errors…

Time dependent $B_s$ decay asymmetry
$D_s^+(K^+K^-\pi^+)\pi^- \ vs \ D_s^-(K^+K^-\pi^+)\pi^+$
production or detection asymmetry from data
LHCb how about $a_{SL}^s$?

How to deal with
-possible $B_s^0/\overline{B}_s^0$ production asymmetry in pp 2<|$\eta$|<6
-controlling detection and background asymmetries to $<10^{-3}$

Inclusive muon pairs difficult to control systematic errors…

Time dependent $B_s$ decay asymmetry
$D_s^+(K^+K^-\pi^+)\pi^- \text{ vs } D_s^-(K^+K^-\pi^+)\pi^+$
production or detection asymmetry from data

$B_d$ and $B_s$ time depended CP asymmetries from the same final states: i.e.
$B_d \rightarrow D^+(K^+K^-\pi^+)\mu^-X - \text{ c.c. and } B_s \rightarrow D_s^+(K^+K^-\pi^+)\mu^-X - \text{ c.c.}$
difference depends only on $a_{SL}^s - a_{SL}^d$
LHCb how about $a^{s_{SL}}$?

$D^+ \to K^+K^-\pi^+$ and $D_s^+ \to K^+K^-\pi^+$
with 124 nb$^{-1}$ data
LHCb how about $a_{SL}^s$?

$D^+ \rightarrow K^+K^-\pi^+$ and $D_s^+ \rightarrow K^+K^-\pi^+$ with 124 nb$^{-1}$ data

Expected statistical errors on $\Delta_{SL} \equiv a_{SL}^s - a_{SL}^d$

$6.3 \times 10^{-4}$

with 1 fb$^{-1}$ of data

Systematic errors still to be investigated
LHCb how about $a_{SL}^s$?

LHCb expected performance with 1 fb$^{-1}$ data assuming $\Delta_{SL}(\text{LHCb measured}) = A_{SL}^b(\text{D0 now})$

![Graph showing $a_{SL}^s$ vs. $a_{SL}^d$ with data points and shaded regions](image-url)
B reconstruction in hadronic modes

- For $B_s$ oscillation studies
  \[ B_s \rightarrow D_s^+ (\phi \pi^+) \pi^- \]

- Benchmark channels for $\gamma$ studies
  \[ B^\pm \rightarrow D(K_S \pi^+ \pi^-) \pi^\pm \]
  \[ B^\pm \rightarrow D(K^+ \pi^\pm) K^\pm \]
And even radiative B decays

- with an ultimate goal to study CPV in $B_s \rightarrow \phi \gamma$
  photon polarization studies
Conclusions

- LHCb has started successful data taking at $\sqrt{s} = 7$ TeV, publishing physics results, including b physics.
- Majority of data collected were at close to the LHCb nominal luminosities, $\sim 10^{32}\text{cm}^{-2}\text{s}^{-1}$, but with almost one order of magnitude less number of bunches, resulting in many events with more than one pp interactions.
- However, LHCb detector could reconstruct clean B signals, due to excellent PID, momentum measurement and vertex determination even in those conditions.
- High event readout rate ($\sim 1$ MHz) followed by complete software based trigger allowed LHCb to follow the luminosity evolution effectively.
Conclusions

• We expect to collect 1 fb$^{-1}$ data in 2011, in a condition close to the nominal running, i.e. average pp interaction per bunch crossing of <1. (number of bunches will be steadily increased)

• Extrapolating the 2010 studies, with 1 fb$^{-1}$ data we expect to produce interesting results in $B_s \rightarrow \mu \mu$, CPV in $J/\psi\phi$, $B_s$ oscillations, $B_s \rightarrow K^\mp \pi^\pm$, $B_d \rightarrow \pi^+ \pi^-$, as well as many charm studies including $D_0$ oscillations and CP violation. If we continue to run in 2012, improved $\gamma$ measurements and $K^{*0}\mu^+\mu^-$ studies could emerge.

• Finally it gets exciting!
Now

\[ \Gamma(b \rightarrow uW) \]

\[ \text{CPV}(B \rightarrow DK) \]

2009 fit
May be a surprise!

LHCb with 10 fb$^{-1}$

$\Gamma(b \rightarrow uW)$

$\Gamma(B \rightarrow DK)$

2009 fit