LHCb
Search for New Physics at a Hadron B Factory

CERN Colloquium
March 13, 2008
Tatsuya Nakada
CERN and EPFL
What is on the moon?
What is on the moon?

Of course going there...
What is on the moon?

Of course going there...

But you can study a lot from here before

And may be finding something new?
What is on the moon?

Of course going there...

But you can study a lot from here before

And may be finding something new?

Instruments can be improved and

We see far beyond the direct reach...

13 March 2008

CERN Colloquium

T. NAKADA 5/46
Excellent track record to probe high energy scale

Very suppressed \( K_L \rightarrow \mu^+\mu^- \)

\[ \begin{array}{c}
\bar{s} \\
d
\end{array} \xrightarrow{Z^0} \begin{array}{c}
\mu^+ \\
\mu^-
\end{array} \]

\[ \begin{array}{ccc}
\bar{s} & \bar{u} & W^+ \\
d & W^- & \nu_{\mu}
\end{array} \]

\[ \begin{array}{c}
\bar{s} \\
d
\end{array} \xrightarrow{Z^0} \begin{array}{c}
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d
\end{array} \xrightarrow{W^-} \begin{array}{c}
\mu^-
\end{array} \]
**Flavour Physics**

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+ \mu^-$  \Rightarrow  SU(2) doublet structure (GIM)

\[ \begin{align*}
\bar{s} & \quad \bar{u} \\
\bar{d} & \quad W^+ \\
& \quad W^- \\
\bar{s} & \quad \bar{u} \\
\bar{d} & \quad W^+ \\
& \quad W^- \\
\bar{s} & \quad \bar{c} \\
\bar{d} & \quad W^+ \\
& \quad W^- \\
\bar{s} & \quad \bar{c} \\
\bar{d} & \quad W^+ \\
& \quad W^- \\
& = 0 \text{ if } m_u = m_c
\end{align*} \]
Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+ \mu^-$  $\Rightarrow$ SU(2) doublet structure (GIM)

$\Delta m_K$ and $\text{Br}(K_L \rightarrow \mu^+ \mu^-)$
Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^-$

$\Delta m_K$ and $\text{Br}(K_L \rightarrow \mu^+\mu^-)$

$\Rightarrow$ SU(2) doublet structure (GIM)

$\Rightarrow$ charm mass $\sim 1.5$ GeV/$c^2$

$$ Br(K^0 \rightarrow \mu^+\mu^-) = F(m_c, \ldots) \quad \Delta m_K = G(m_c, \ldots) $$
Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+ \mu^-$ $\Rightarrow$ SU(2) doublet structure (GIM)

$\Delta m_K$ and $\text{Br}(K_L \rightarrow \mu^+ \mu^-)$ $\Rightarrow$ charm mass

CPV and very suppressed $B \rightarrow \mu^+ \mu^-$ $\Rightarrow$ third family

$\Delta m_B$ $\Rightarrow$ top mass

before observing directly $c$, $b$ or $t$
History of $m_t$

UA1, 1984

$W^+ \rightarrow t\ b$

$b/\nu \rightarrow b/\nu$

jet

jet

30~50 GeV/$c^2$

History of $m_t$

**UA1, 1984**

\[ W^+ \rightarrow t \ b \]

\[ b/\nu \rightarrow \text{jet} \]

\[ 30 \sim 50 \text{ GeV}/c^2 \]

*Phys. Lett. 147B (1984) 493*

**ARGUS, 1987**

\[ \gamma(4S) \rightarrow B_d^0 \overline{B_d^0} \]

\[ \rightarrow B_d^0 B_d^0 \text{ or } \overline{B_d^0} \overline{B_d^0} \]

\[ \rightarrow \ell^+ \ell^+ \text{ or } \ell^- \ell^- \]

\[ 24.8 \pm 7.6 \pm 3.8 \]

\[ \Delta m(B_d) \sim 100 \times \Delta m(K^0) \]


13 March 2008

CERN Colloquium

T. NAKADA 12/46
History of $m_t$

**UA1, 1984**

$W^+ \rightarrow t \; b$  
$\rightarrow b/\nu$  
jet

$W^+ \rightarrow t \; b$

**ARGUS, 1987**

$\gamma(4S) \rightarrow B_d^0 \overline{B_d^0}$  
$\rightarrow B_d^0 B_d^0$ or $\overline{B_d^0} \overline{B_d^0}$  
$\rightarrow \ell^+ \ell^+$ or $\ell^- \ell^-$  
$24.8 \pm 7.6 \pm 3.8$  
$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$

**LEP**

electroweak fit  
$150 \sim 210 \text{ GeV}/c^2$

**1995**

CDF  
$175 \pm 8 \pm 10 \text{ GeV}/c^2$

D0  
$199_{-21}^{+19} \pm 22 \text{ GeV}/c^2$


Flavour Physics

Excellent track record to probe high energy scale

Very suppressed $K_L \rightarrow \mu^+\mu^- \Rightarrow SU(2)$ doublet structure (GIM)

$\Delta m_K$ and $Br(K_L \rightarrow \mu^+\mu^-)$ $\Rightarrow$ charm mass

CPV and very suppressed $B \rightarrow \mu^+\mu^- \Rightarrow$ third family

$\Delta m_B$ $\Rightarrow$ top mass

and …

$\nu-\bar{\nu}$ oscillation $\Rightarrow$ may be heavy neutrinos?
Thoughts on Flavour Physics Experiments

General observation

Hadron machines have been “discovery” machines,
   e.g. charm, beauty, $W$, $Z$, and top

CP violation in the kaon system mainly studied at hadron machines
   plus some contribution from KLOE

Charm mesons have been successfully exploited by
   both fixed target hadron beams and $e^+e^-$ storage rings.
Fixed target charm experiments

Important breakthrough in the middle of 80’s:
large number of fully reconstructed D mesons
from the hadronic decays

using

Si micro-strip vertex detector and open trigger

\[
\frac{\sigma_{cc}}{\sigma_{inelastic}} \approx 10^{-3}
\]

Large amount of data processed by a custom made
microprocessor farm
An example: $D^0$ lifetime

200 GeV/c K and $\pi$ beam
ACCMOR 1987

Tagged photon beam
E691 1988

factor $\sim 50$ in statistics

Decay Time ($10^{-12}$ sec)
The latest generation of fixed target charm experiments

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<th>Beam</th>
<th>Statistics</th>
<th>Average $\sigma_t$</th>
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<tr>
<td>E791</td>
<td>500 GeV $\pi$</td>
<td>$10^5$</td>
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<tr>
<td>Focus</td>
<td>up to 300 GeV $\gamma$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Selex</td>
<td>600 GeV $\Sigma, \pi, p$</td>
<td>$10^4$</td>
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**Focus**

D$^0 \rightarrow K^-\pi^-$  119738 evts

D$^0 \rightarrow K^+K^-$  10331 evts
For many years, B meson study had been dominated by DORIS, CESR, VEPP and LEP, i.e. at e^+e^- machines.

Experiments at hadron machines, fixed target, were “limited”;

CERN: Beatrice FNAL:E866/E789/E772, E771

b cross section measurements (with large error bars)

→ simply not enough b’s and too small $\sigma_b/\sigma_{inelastic}$
There were some ideas to make B experiments at p\bar{p} colliders

**Bjorken at Tevatron**

**P. Schlein** at SppS and Tevatron

Large b\bar{b} cross section

Si vertex detector in Roman Pot

Forward spectrometer

(forward peaked b production)
Experiment not approved but a test run was made (1990)

at CERN SppS, 630 GeV, $L = 3 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$

NIM A317 (1991)28

rf-foil 1.5 mm from the beam (15 r.m.s.)
Si sensitive point 3.1 mm

DELPHI single sided silicon $\mu$-strip
detector + SVX chip

Beam position fill to fill variation less than 100$\mu$m

Vacuum
$5 \times 10^{-4}$ mb inside the rf-boxes
$5 \times 10^{-10}$ mb in the machine

A very clean running condition was observed, a pioneering work!
In the mean time, many ideas to build an $e^+e^-$ B meson “factory” at $\Upsilon(4S)$, starting with SIN in 1986 double ring with $L > 5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, symmetric energy

Upgraded to PSI Proposal (1988)

$L > 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

with modest asymmetric energy option

Discovery of $B\bar{B}$ mixing in 1887 made it possible to make a SM prediction for CPV for $B \rightarrow J/\psi K_S$ without knowing $m_t$: $\sim 0.4$ i.e. “large” (NB $f_B = 110 \text{ MeV}$ in those days)

$\rightarrow$ a concrete minimum “luminosity requirement”

i.e. $> 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
Many B factory ideas emerged: SLAC, DESY, Cornell, KEK, Novosibirsk, Italy, UCLA and CERN from standard storage rings with symmetric energy, with different energy asymmetries, linear collider, and to linear against circular…

European option has died with CERN-ISR option in 1990 CERN-YELLOW-90-02 →No European B opportunity except LEP running at Z^0

In US: competition between Cornell and SLAC
In Japan: water was slowly boiling
Then

First fully reconstructed $B$ meson at a hadron machine!
(largest number of reconstructed $B^\pm \rightarrow J/\psi K^\pm$ at that time)

$B$ physics with a hadron machine at high energy looks feasible!

$D0$ and $CDF$ then contributed a lot in lifetimes, CPV, and oscillations. ($B_s$ oscillation measurement is still unique)
Back to the European Front
Evian workshop EoI’s presentation, 1992

ECFA
European Committee for Future Accelerators

CERN
European Organization for Nuclear Research

Towards the LHC Experimental Programme
5-8 March 1992
Evian-les-Bains, France

LHC

NB: Approval of B factories at KEK and SLAC in 1993
Starting of data taking in 2000
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**General purpose high $p_T$ experiments**

**B experiments**
Evian workshop on EoI’s presentation, 1992
Four high $p_T$ experiments
Neutrino and Heavy Ion experiments
Three B physics experiments

- SM was not quantitatively tested for CPV
  main goals were
  CPV in $\rightarrow J/\psi K_S$, $\rightarrow \pi\pi$, $B_s$ oscillations
- three different approaches
  1) pp colliding mode in the forward direction
     COBEX
  2) extraction of p to a fixed target
     LHB
  3) internal gas jet as a fixed target
     GAJET

Followed by three LoI’s in 1993
COBEX
vertex and tracking detector, two magnets, RICH, E-cal, muon
first level topology trigger at low $L$ and $\mu p_T$ trigger at high $L$
large $\sqrt{s}$ → large $b\bar{b}$ cross section
LHB vertex and tracking detector, two magnets, RICH, E+H-cal, muon first level lepton (μ and e) $p_T$ trigger 😊large boost → charged Bs are visible in the vertex detector ($B^+\rightarrow\tau\nu$)

protons are extracted from the beam halo using a bent crystal dedicated experimental area, i.e. more flexibility
GAJET
vertex and tracking detector, single magnet, RICH, TRD, E+H-cal, muon
first level impact parameter and hadron-lepton $p_T$ trigger
small dimension of gas target $\rightarrow$ B production vertex a priori known

$r-\phi$ triplets
vertex detector
LHCC decisions
January 1994
In the subsequent discussion on B physics, the LHCC considered the case for a dedicated B experiment at the LHC, and agreed on a recommendation to be sent to the Director General for consideration by the Research Board.

June 1994
Decided not to approve any of the three experiments but to form one new collaboration to propose a new experiment based on the collider mode to exploit its large $b\bar{b}$ cross section with a convincing trigger strategy.

This appears to have been a correct decision, given the fact
1) B-factories and Tevatron are doing well
2) LHC is (much) later than originally thought
ARGUS group at DESY started to think about a fixed target experiment using HERA proton ring (920 GeV/c) and internal wire targets around the time of Evian workshop in 1992.

Approved in 1994 to compete with B-factories with \( \sigma(\sin 2\beta) = 0.13 \text{ y}^{-1} \)

Physics data taking started in 2001. Physics paper on production cross sections, but not CPV…

It was a quite tough job: \( \frac{\sigma_b}{\sigma_{\text{total}}} \approx 10^{-6} \)
Advantage of the LHC collider mode
Large $b$ cross section ($\sim 500 \mu b$)

Large $\sigma_{\bar{b}b} / \sigma_{\text{inelastic}} (> 10^{-3})$

at fixed target energies $10^{-6}$

$\approx \sigma_{\bar{c}c} / \sigma_{\text{inelastic}}$ at fixed target energies

Different $b$-hadrons ($B_u, B_d, B_s, B_c, \Lambda_b, \Sigma_b, \Xi_b$ etc.)

Many primary particles $\rightarrow$ well defined $b$ production vertex

To fight against combinatorial backgrounds:
vertexing, PID, and mass resolution
Open trigger a la charm fixed-target experiment is not an option at LHC
too high inelastic event rate
interesting decay modes are restricted

Trigger is crucial
At the first level
 inclusive signature: $p_T$ and displaced tracks/vertices
At the intermediate level
 semi-exclusive partial reconstruction
Finally
 exclusive reconstruction
A reminder of the forward geometry

Acceptance

Luminosity requirements

$L_t$ tuneable by adjusting final beam focusing
Choose $<L> \sim 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ (max. $\sim 5 \times 10^{32}$)

- Clean environment: $<n> \approx 0.5$
- Less radiation damage
- Will be available from “first” physics run

$p_T$ threshold for calo- and $\mu$-trigger can be set to few GeV/$c$ for high $b$ efficiency

pp interactions/crossing
LHCb Evolution

Letter of Intent for LHC-B, August 1995

- $x$-$y$ Si micro-strip detector
- Warm magnet
- Three RICH’s (aerogel + 2-gas) with HPD’s
- HERA-B tracking system
- Pre-shower, Shashlik+PbWO$_4$, Fe-Tilecal+Quarz-W
- CSC or Honeycomb or drift tube muon system

$L-1 $ $p_T$ 200 KHz
$L-2$ tracking + vertex 10 kHz
$L-3$ full reconstruction

RICH and HPD design
T. Ypsilantis

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Technical Proposal for LHCb, February 1998

Outer Tracker
$B_s$ oscillations and CPV
W. Ruckstuhl

What is different from LoI apart from $-B \rightarrow b$?

- Super conductive magnet
- $r$-$\phi$ strip Si vertex detector
- Two RICH's (still three radiators)
- No inner-part of calorimeters
- MRPC+MWPC muon system

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<tr>
<th>Level</th>
<th>Description</th>
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<tr>
<td>L-0</td>
<td>$p_T$</td>
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<tr>
<td>L-1</td>
<td>tracking + vertex</td>
<td>40 kHz</td>
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<td>L-2</td>
<td>vertex with $p$</td>
<td>5 kHz</td>
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<tr>
<td>L-3</td>
<td>full reconstruction</td>
<td>200 Hz</td>
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13 March 2008
Many changes in the mean time
Be conical beam pipe
Normal conductive magnet
All MWPC (with a little GEM) muon system
Straw chamber + Si tracking system
Greatly reduced tracking stations (nothing in the magnet)
All Si first tracking station
Two level trigger (1 MHz full readout after the first level to CPU farm)
Changes were motivated by:
  budgetary constraint (financial and material)
  technical feasibility
  physics flexibility

After TP, B physics has evolved a lot: major ones are…
  CPV in $B_d \to J/\psi K_{S,L}$ measured with $\sigma \approx 0.026$
  $\gamma(\phi_3)$ measured with $\sigma \approx 25^\circ$
  $B_s - \overline{B}_s$ oscillation frequency measured, better than one needs
i.e. KM model for CPV is now quantitatively tested

No major improvement of the B factory results expected from now on
  -BABAR end of run in April, Belle in 1~2 years-

Emphasis on the LHCb physics goal is shifting from
  Confirmation of CKM $\to$ Search for new physics
Some notable examples are...

NP search in $B_s$ where the effect could be still large

$B_s \rightarrow \mu^+\mu^-$

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

Probing Flavour Changing Neutral Current $b \rightarrow s$: deviation in

Phase = CP violation $B_s \rightarrow \phi\phi$  improvement over B factory $\phi K_S$

Lorentz structure = angular distribution or $\gamma$ polarization

$B_d \rightarrow K^*\mu^+\mu^-$  far larger statistics than B factory

CPV in $B_s \rightarrow \phi\gamma$  improvement over B factory $K^*(K_S\pi^0)\gamma$

from Standard Model predictions

FCN current in “up” type quark: NP effect different from “down” type

D: oscillations and CP violation down to the level of SM

much larger statistics than B factory

$\gamma$ from tree (only SM) and from tree + penguin (SM+NP): $\sigma_\gamma \approx 3^\circ$

much larger statistics than B factory
LHCb now close to being ready for physics
A lot of Monte Carlo events were generated and reconstructed.
Now we also have “properly” triggered cosmic events going through E-cal and H-cal
We are looking forward to see XX TeV pp collisions in our detector very soon!

Followed by finding out which one of the following exciting events we will have:
In 2014 at LHC

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Oh, no more space left…