B-Physics at LHCb

XXXI International Meeting
On Fundamental Physics

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Many thanks to T. Nakada and O. Schneider for allowing me to recycle some of their transparencies.
Introduction

Why CP violation is an interesting phenomena?

Concept of symmetry is fundamental in our understanding of physical phenomena.

Violation of symmetries at low energies reflects what’s going on at higher energies. In general new physics will introduce new sources of CP violation.

Baryogenesis: Why the universe appears to be made of mostly matter? CP violation in the EW sector cannot explain the absence of antimatter. Something else must be going on.

Why we do not see CP violation in the strong interactions and we do see a very small effect in the EW sector? Could it be that the observed phenomena is indeed due to new physics?

The B-meson provides a laboratory where theoretical predictions can be precisely compared with experimental results.
Introduction

The world quest for CP violation in the B system

Primary Goal:
1) Carry a comprehensive study of CP violation in the b quark system
2) Test the consistency of the Standard Model in the CKM sector and probe the origin of CP violation
Introduction

When does one have CP violation?

when \( \Gamma(a \rightarrow c+b) \neq \Gamma(\bar{a} \rightarrow \bar{c}+\bar{b}) \) (\( x = \text{CP conjugate state} \))

How does one generate CP violation in the SM?

a) Get two amplitudes to interfere.
b) Get two relative phases between the two amplitudes.
c) Get one relative phase to change when going to the CP conjugate state, while the other does not change.

\[
\begin{align*}
\Gamma(a \rightarrow c+b) &= |\bar{A}_1|^2 + |\bar{A}_2|^2 + 2 \Re(\bar{A}_1 \bar{A}_2^*) \\
\Gamma(a \rightarrow c+b) &= |A_1|^2 + |A_2|^2 + 2 \Re(A_1 A_2^*)
\end{align*}
\]

In the SM for any process we have, \( |A_k| = |\bar{A}_k| \) \( \Rightarrow \) \( \Re(A_1 A_2^*) \neq \Re(\bar{A}_1 \bar{A}_2^*) \)

In the SM, only weak interactions do this. It does it via the quark flavor mixing mechanism. Hence it is a consequence of the quark mass generation mechanism.
CKM picture of CP violation

How are masses generated in the SM?

Before SU(2) symmetry breaking

\[ \sum_{j,k} \left[ Y_{j,k} \begin{pmatrix} u, d \end{pmatrix}_L H^+ u_R^k + Y'_{j,k} \begin{pmatrix} u, d \end{pmatrix}_L H d_R^k \right] + h.c. \]

After SU(2) symmetry breaking

\[ \sum_{j,k} \left[ Y_{j,k} \begin{pmatrix} u, d \end{pmatrix}_L \begin{pmatrix} v \sqrt{2} + \phi^0 \over \sqrt{2} \\ 0 \end{pmatrix} u_R^k + Y'_{j,k} \begin{pmatrix} u, d \end{pmatrix}_L \begin{pmatrix} 0 \\ v \sqrt{2} + \phi^0 \over \sqrt{2} \end{pmatrix} d_R^k \right] + h.c. \]

mass term: \[ m_{j,k} \overline{u}_L u_R^k + m'_{j,k} \overline{d}_L d_R^k \]

up quarks: \[ m_{j,k} = Y_{j,k} \overline{v} \over 2 \]

down quarks: \[ m'_{j,k} = Y'_{j,k} \overline{v} \over 2 \]

\( m \) is a matrix of complex numbers, in general not diagonal
**CKM picture of \( CP \) violation**

Quark fields used in the weak interactions are not the mass eigenstates

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

After diagonalization, using the convention \( u \equiv u^{\text{phys}} \), and

\[
d^{\text{phys}} \equiv \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
\]

1) Neutral currents unchanged
2) Charged currents are modified

\[
\left| V_{\text{CKM}} \right| = \begin{pmatrix}
0.974 & 0.220 & 0.0033 \pm 0.0008 \\
0.220 & 0.974 & 0.0395 \pm 0.0020 \\
0.0084 \pm 0.0020 & 0.038 \pm 0.004 & 0.999
\end{pmatrix}
\]
CKM picture of CP violation

Unitarity: $V^\dagger V = 1$

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

$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$

$\alpha = \arg \frac{-V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}$

$\gamma = \arg \frac{-V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}$

$\beta = \pi - \arg \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}}$

$\alpha + \beta + \gamma = \pi$
CKM picture of CP violation

\[ \alpha = \text{arg}\left( -\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right) \]

\[ \beta = \pi - \text{arg}\left( \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} \right) \]

\[ \gamma = \text{arg}\left( -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \right) \]

- invariant under quark phase redefinition -
**CKM picture of CP violation**

Far West

- $\alpha \iff \phi_2$
- $\beta \iff \phi_1$
- $\gamma \iff \phi_3$

Far East

If CKM is not unitary...

$$\alpha = \arg \left( -\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}} \right)$$

$$\beta = \pi - \arg \left( \frac{V_{tb}^* V_{td}}{V_{cb}^* V_{cd}} \right)$$

$$\gamma = \arg \left( -\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}} \right)$$

$\alpha + \beta + \gamma = \pi$ is still valid!

→ This is not a test of unitarity.
CKM picture of CP violation

CP violation measurements measure the angles (\(\beta\) and \(\gamma\)):

\[|\nu_{cb}|, |\nu_{ub}| \text{ and } |\nu_{td}| \text{ measurements define a triangle:}\]

\[\beta \neq \beta', \gamma \neq \gamma', \alpha \neq \alpha'\]
Using the Wolfenstein parameterisation $({\lambda, A, \rho, \eta})$

$$V = \begin{pmatrix}
1 - 0.5\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - 0.5\lambda^2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}$$
CKM picture of CP violation

2) \( V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0 \)

\[
\eta \lambda^2 \quad \beta' \quad \delta \gamma \\
\frac{V_{ub}^* V_{tb}}{A \lambda^3} \\
\frac{V_{us}^* V_{ts}}{A \lambda^3} \\
\rho \\
1 - \frac{\lambda^2}{2} + \rho \lambda^2
\]

\[
\gamma' + \delta \gamma = \gamma \\
\beta' - \delta \gamma = \beta
\]
CKM picture of CP violation

Some remarks:

\[ \arg V_{td} = -\beta \]
\[ \arg V_{ub} = -\gamma \]
\[ \arg V_{ts} = \delta \gamma + \pi \]

\[ \beta = \tan^{-1} \frac{\eta}{1-\rho} \left( 1 - \frac{\lambda^2}{2(1-\rho)} \right) \]
\[ \gamma = \tan^{-1} \frac{\eta}{\rho} \]
\[ \delta \gamma = \eta \lambda^2 \]

If we ignore the \( \lambda^2 \) correction, 1) and 2) are degenerate.
Measurements of the angles

$\bar{B} - B$ oscillation dispersive part: $M_{12}$

$$\Delta m = 2|M_{12}| \propto B_d f_d^2 |V_{td}|^2 |V_{tb}|^2$$

$$\arg M_{12} = \arg (V_{td} V_{tb})^2 + \pi = 2\beta + \pi$$

$$\Delta m_s = 2|M_{12}| \propto B_s f_s^2 |V_{ts}|^2 |V_{tb}|^2$$

$$\arg M_{12} = \arg (V_{ts} V_{tb})^2 + \pi = -2\delta \gamma + \pi$$
Measurements of the angles

\[ \Delta \Gamma = 2 |\Gamma_{12}| \]

\[ \frac{\Delta \Gamma}{\Delta m} = \frac{3\pi m_b^2}{2m_W^2 S(x_t)} \approx 5 \times 10^{-3} \]

\[ x_d = \frac{\Delta m}{\Gamma} = 0.75 \pm 0.02 \]

\[ x_s = \frac{\Delta m_s}{\Gamma_s} \approx O(20) \]

\[ \frac{\Delta \Gamma}{\Gamma} = \begin{cases} 
\sim 4 \times 10^{-3} & B_d \\
\sim 10^{-1} & B_s 
\end{cases} \]

\[ \arg \frac{M_{12}}{\Gamma_{12}} = \pi + \frac{8m_c^2}{3m_b^2} \eta \times \begin{cases} 
\frac{-1}{(1-\rho)^2 + \eta^2} & B_d \\
\Lambda^2 & B_s 
\end{cases} \approx \pi - 10^{-1} \]

\[ \approx \pi + 5 \times 10^{-3} \]
Measurements of the angles

The mass and decay width differences:

\[
m_{\text{heavy}} - m_{\text{light}} = \Delta m = -2|M_{12}| \times \cos (\arg M_{12}/\Gamma_{12})
\]

\[
\Gamma_{\text{heavy}} - \Gamma_{\text{light}} = \Delta \Gamma = 2|\Gamma_{12}| \times \cos (\arg M_{12}/\Gamma_{12})
\]

\[
\sim -1
\]

CP violation in the oscillation:

\[
d \equiv \text{Im} \left( \frac{\Gamma_{12}}{M_{12}} \right) = - \frac{\Delta \Gamma}{\Delta m} \sin (\arg M_{12}/\Gamma_{12})
\]

5×10^{-3}

\[
\frac{B_{t=0} \rightarrow B_t}{B_{t=0} \rightarrow \bar{B}_t} - \frac{B_{t=0} \rightarrow \bar{B}_t}{(B_{t=0} \rightarrow B_t) + (B_{t=0} \rightarrow \bar{B}_t)} = 2d < 10^{-3}
\]
Measurements of the angles

$M_{12} \propto e^{2i\beta}$

$b \rightarrow c + cs$: $V_{cb} V_{cs}^* \propto e^{i\theta}$

$J/\psi K_S$

$\bar{b} \rightarrow \bar{c} + \bar{cs}$: $V_{cb}^* V_{cs} \propto e^{i\theta}$

$\sin 2\beta \times \sin \Delta m t$

NB: penguin contribution

$b \rightarrow t \rightarrow s > b\rightarrow c \rightarrow s$

$V_{bt} V_{ts}^{*} \propto e^{-i\delta\gamma}$

$\frac{\delta\gamma}{\beta} \approx \lambda^2 = 0.05$  $\rightarrow$ effect should be less than a few %

Theoretically clean.
Measurements of the angles

\[ M_{12} \propto e^{2i\beta} \]

\[ b \to c+ud: \quad V_{cb} V_{cd}^* \propto e^{i\theta} \]

\[ \bar{B}^0 \to D^{(*)+} \pi^- \]

\[ \bar{b} \to \bar{u}+cd: \quad V_{ub}^* V_{cd} \propto e^{i\gamma} \]

\[ \sin 2\beta+\gamma \times \sin \Delta m t \]

No other diagram contribute to the process.

NB: strong phase

\[ b \to c+ud \text{ and } b \to u+cd \text{ may have a strong phase difference } \Delta! \]

\[ \bar{B}^0 \to D^{*+}\pi^- \text{ and } \bar{B}^0 \to D^{*-}\pi^+ \quad 2\beta+\gamma + \Delta \text{ and } 2\beta+\gamma - \Delta \]

Strong phase difference can be measured.

Theoretically VERY clean measurement.
Measurements of the angles

\[ \bar{B}_s^0 \rightarrow \bar{B}_s^0 \]

\[ b \rightarrow c + \bar{c}s: \quad V_{cb} V_{cs}^* \propto e^{i\theta_0} \]

\[ M_{12} \propto e^{-2i\delta_\gamma} \]

\[ \bar{B}_s^0 \rightarrow \bar{c} + c\bar{s}: \quad V_{cb}^* V_{cs} \propto e^{i\theta_0} \]

\[ \sin 2\delta_\gamma \times \sin \Delta mt \]

\[ \text{CP}(J/\psi) = +1, \quad \text{CP}(\phi) = +1 \]
\[ \text{CP}(J/\psi \phi) = (-1)^{L_{J/\psi-\phi}} \]

\[ L_{J/\psi-\phi} = 0, 1, 2 \]

\[ \rightarrow \text{fraction of } L_{J/\psi-\phi} = 1 \text{ needed: angular analysis or...} \]

\[ \text{CP}(J/\psi) = +1, \quad \text{CP}(\eta) = -1 \]
\[ \text{CP}(J/\psi \eta) = -(-1)^{L_{J/\psi-\eta}} = +1 \]

\[ L_{J/\psi-\eta} = 1 \]

24-28 February 2003

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Measurements of the angles

$\bar{B}_s^0 \rightarrow \bar{B}_s^0$  $b \rightarrow c+u{s}$: $V_{cb} V_{us}^* \propto e^{i0}$

$M_{12} \propto e^{-2i\delta \gamma}$  $B_s^0 \rightarrow D_s^+ K^-$

$\bar{b} \rightarrow \bar{u}+c{s}$: $V_{ub}^* V_{cs} \propto e^{i\gamma}$

$\sin 2\delta \gamma - \gamma \times \sin \Delta mt$

Strong phase: same as the $B_d \rightarrow D^* \pi$ case, i.e. measurable!

$\Delta \Gamma / \Gamma \approx 0.1 \rightarrow \cos 2\delta \gamma - \gamma \times \sinh \Delta \Gamma t$ measurable.

Theoretically VERY clean measurement.
**Measurements of the angles**

\[ B_d \rightarrow D^* \pi \]
\[ \approx \frac{A\lambda^2}{A\lambda^4 \sqrt{\rho^2 + \eta^2}} \approx 1/0.02 \]
small interference term 😞
\[ \frac{\Delta m}{\Gamma} \approx 1 \] 😊

\[ B_s \rightarrow D_s K \]
\[ \approx \frac{A\lambda^3}{A\lambda^3 \sqrt{\rho^2 + \eta^2}} \approx 0.4 \]
large interference term 😊
\[ \frac{\Delta m}{\Gamma} \approx 20 \] 😞

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**CP landscape in 2002**

**Success of the Standard Model and B factories current picture**

**CP asymmetry in** $B_d$ **and** $\bar{B}_d \rightarrow (\bar{c} \bar{c} \bar{s} d)$ **and** $(c \bar{c} s \bar{d})$

- $|V_{cb}|$ from $B \rightarrow H_c X$ decays $\rightarrow A$
- $|V_{ub}|$ from $B \rightarrow H_u L\nu$ decays $\rightarrow \rho^2 + \eta^2$

$B_d$-$B_d$ mixing, $\Delta m_d \rightarrow (1-\rho)^2 + \eta^2$
CP landscape in 2007

**Major improvements expected...**

**Theory:**

A better understanding of $B_d f_d^2 \rightarrow |V_{td} / V_{cb}|^2$ from $\Delta m(B_d)$

$$\sqrt{(1-\rho)^2 + \eta^2}$$

**Theory and more data:**

A better understanding of $b \rightarrow u, c^+ \ell \nu$ decays: $|V_{ub} / V_{cb}|$

$$\sqrt{\rho^2 + \eta^2}$$

**More data:**

More precision on $\sin 2\beta$: before hitting the penguin pollution from the $\Delta m(B_d) / \Delta m(B_s)$ measurement

$$\sqrt{(1 - \rho)^2 + \eta^2}$$
CP landscape in 2007

\( \sqrt{\rho^2 + \eta^2} \) : improved by a factor of 3

\( \sqrt{(1 - \rho)^2 + \eta^2} \) : improved by a factor of 4

\( \sin 2\beta \): ±0.01
How does new physics modifies the picture?

\[ M_{12} = M_{12}^{\text{SM}} + M_{12}^{\text{NP}} \]

\[ \Delta m \leftrightarrow |V_{td}|^2 \]

\[ \text{arg } M_{12} = 2\beta + \phi_{bd}^{\text{NP}} \]

CP asymmetry in \( B_d \rightarrow J/\psi K_S \) \[ \leftrightarrow \sin 2\beta \]
How does new physics modifies the picture?

$B_d$

$\bar{b} \quad \bar{t} \quad \bar{d} \quad b \quad t \quad d$

$\arg M_{12} = 2\beta + \phi_{bd}^{NP}$

$\text{CP asymmetry in } B_d \rightarrow J/\psi K_S \quad \leftrightarrow \sin (2\beta + \phi_{bd}^{NP})$

$\text{CP asymmetry in } B_d \rightarrow D^* \pi \quad \leftrightarrow \sin (2\beta + \gamma + \phi_{bd}^{NP})$

$B_s$

$\arg M_{12} = 2\delta\gamma + \phi_{bs}^{NP}$

$\text{CP asymmetry in } B_s \rightarrow J/\psi \phi \quad \leftrightarrow \sin (2\delta\gamma + \phi_{bs}^{NP})$

$\text{CP asymmetry in } B_s \rightarrow D_s K \quad \leftrightarrow \sin (2\delta\gamma + \gamma + \phi_{bs}^{NP})$

$\Rightarrow \gamma \text{ can be determined!}$
How does new physics modifies the picture?

~2007  BABAR, BELLE: $|V_{cb}|$, $|V_{ub}|$, $\Delta m_d$, $\sin 2\beta$,
       CDF (D0): $\Delta m_s$, $\sin 2\beta$,

Clean measurements of $\gamma$: $\pm 5^\circ$

Dedicated B experiments at LHC (and Tevatron)!!!
How does new physics modifies the picture?

\[ \frac{\Gamma(b \rightarrow u)}{\Gamma(b \rightarrow c)} \]

\[ \eta^2 + \rho^2 \]

\[ \begin{align*}
\text{CP asym. in } B_s & \rightarrow D_s^{+}K^- \\
\text{CP asym. in } B_s & \rightarrow D_s^{-}K^+ \\
\text{CP asym. in } B_s & \rightarrow J/\psi \phi \\
\text{CP asym. in } B_s & \rightarrow J/\psi \eta \\
\text{CP asym. in } B_d & \rightarrow D_s^{*+}\pi^- \\
\text{CP asym. in } B_d & \rightarrow D_s^{*-}\pi^+ \\
\text{CP asym. in } B_d & \rightarrow J/\psi K_S \\
\Delta m_d &
\end{align*} \]

\[ \begin{align*}
\gamma - 2\delta\gamma_{\text{eff}} & \\
2\delta\gamma_{\text{eff}} & \\
\gamma + 2\beta_{\text{eff}} & \\
2\beta_{\text{eff}} & = 2 \tan(\eta/(1-\rho)) + \phi_{\text{new}} \\
\eta^2 + (1-\rho)^2 + r_{\text{new}} &
\end{align*} \]

SM values of \( \eta \) and \( \rho \)

\[ \tan(\eta/\rho) \]

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

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How does new physics modify the picture?

Penguins could also be affected by new physics?

\[ V_{bt} V_{ts}^* \propto e^{-i\delta\gamma} \]

\[ A_{bs}^{NP} \propto e^{-i\phi_{pbs}^{NP}} \]

\[ B_d \rightarrow \phi K_s \]

\[ M_{12} \propto e^{i(2\beta+\phi_{pbs}^{NP})} \]

\[ B_s \rightarrow \phi \phi \]

\[ b \rightarrow s + \bar{s}s \]

\[ \bar{b} \rightarrow \bar{s}s \]

\[ B^0 \rightarrow B^0 \]

\[ B^0 \rightarrow \phi K_s \]

\[ \sin \theta \times \sin \Delta m_t \]
How does new physics modifies the picture?

Or look for very rare decays

\[ B_s \rightarrow \mu^+\mu^- \quad (BR \sim 2 \times 10^{-9}) \]

Challenging, but feasible at LHC !!!
Future experiments need to have:

- **High statistics** $B_d$ and $B_s$.

- **Trigger** sensitive to the final state with leptons and with **only hadrons**.

- **Good proper time resolution** for measuring the CP violating oscillation amplitudes of the $B_s$ meson.

- **Good $p/K/\mu/e$ separation** to reduce the background from both combinatorial and other $B$ meson decays.
  - **Kaon identification also useful for the flavour tag**-

- **Good momentum and vertex resolutions** to reduce background.
LHC experimental conditions
LHC as a B-factory
LHC as a B-factory

(dis)advantages of hadron colliders for B physics

😊 Large bottom production cross section
\[ \sigma_{bb} = 100-500 \, \mu b \text{ (for } \sqrt{s} = 2-14 \, \text{TeV)} \]

😊 All b hadrons produced
- \( B_u \) (40%), \( B_d \) (40%), \( B_s \) (10%), \( B_c \), and b-baryons (10%)

😊 Many primary particles to determine b production vertex

😊 Many particles not associated to b hadrons

😊 b hadron pairs don’t evolve coherently
- mixing dilutes tagging

😊 Triggering is an issue
\[ \frac{\sigma_{bb}}{\sigma_{inelastic}} = 0.2-0.6\% \text{ (for } \sqrt{s} = 2-14 \, \text{TeV)} \]

10^{12} bb / year
\[ @ \, 2 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1} \]

Y(4S) B factories:
\[ 10^7 \text{ B-B/year} @ \, 10^{33} \, \text{cm}^{-2}\text{s}^{-1} \]

Fixed target charm experiments:
\[ \frac{\sigma_{cc}}{\sigma_{inelastic}} \approx 0.1\% \]

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# LHC as a B-factory

**Hadron colliders (≥ 2007)**

<table>
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<th>Tevatron</th>
<th>LHC</th>
<th>@LHCb</th>
<th>@ATLAS/CMS</th>
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<td>14 TeV</td>
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<td>2×10^{32} 10^{33} (10^{34})</td>
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<td></td>
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<tr>
<td><strong>&lt;n_{inelastic pp interactions} / bx&gt;</strong></td>
<td>1.6</td>
<td>0.5 ~2 (20)</td>
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</table>

Cross sections not measured yet: large uncertainties
# LHC as a B-factory

## B physics’ future at hadron colliders

- **High p\_T central detectors**
  - **CDF+D0 @ Tevatron** → run II started
    - See talk from C. Paus
  - **ATLAS+CMS @ LHC** → ready in 2007
    - Construction well underway
    - Most B physics during LHC’s initial low luminosity period (10\(^33\))

- **(forward) detectors dedicated to B physics**
  - **LHCb @ LHC** → ready in 2007
    - Proposed and approved in 1998; construction started
    - Designed to do B physics at 2x10\(^{32}\) (even when ATLAS+CMS at 10\(^{34}\))
  - **BTeV @ Tevatron** → ready in 2007?
    - Proposed in 2000, more aggressive approach than LHCb (technology & funding)
    - approved (stage I) at FNAL, R&D phase; waiting for funding decision ...
LHC as a B-factory

Bunch crossing frequency: $\omega_{pp} = 40$ MHz, i.e. every 25 nsec

Number of $pp$ inelastic interactions in one bunch crossing $(\sigma_{\text{inelastic}} = 80$ mb$)$, 0, 1, 2 ...

One inelastic interaction per bunch crossing dominates.

- Reconstruction easier (final state and tag)
- Lower occupancies
- Lower radiation level
LHC as a B-factory

LHCb experiment: forward spectrometer (10-300 mrad)

Both b and \(\bar{b}\) are in the spectrometer.
Detector requirements

What do we measure? (an example)

pp interaction

b-hadron

$B_t = 0 \rightarrow \pi^+\pi^-$

flavour tag

proper time: $t$

primary vertex

B decay distance

B momentum

$K^-$
Detector requirements

Time dependent CP asymmetry

\[
\frac{\overline{B}^0_{t=0} \rightarrow \pi^+\pi^-(t) - B^0_{t=0} \rightarrow \pi^+\pi^-(t)}{\overline{B}^0_{t=0} \rightarrow \pi^+\pi^-(t) + B^0_{t=0} \rightarrow \pi^+\pi^-(t)}
\]

CP violating oscillation amplitudes are damped by

- proper time resolution
- good decay vertex resolution
- wrong flavour tag
- good momentum resolution
- background
- good particle identification
LHCb Detector