Status and expected physics performance of the LHCb experiment

Olivier Schneider

Contents

- Short introduction to hadronic flavour physics and CP violation
  - Present status and motivation

- LHCb detector:
  - Requirements & design
  - Construction status
  - Expected performance

- LHCb physics:
  - Expected sensitivity for a few selected key measurements
Standard Model (SM) of particles

- Matter is made of fermions (spin 1/2)
- Each fermion has an anti-matter partner

<table>
<thead>
<tr>
<th>Leptons</th>
<th>electron e</th>
<th>muon μ</th>
<th>tau τ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>neutrino ν_e</td>
<td>neutrino ν_μ</td>
<td>neutrino ν_τ</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quarks</th>
<th>up u</th>
<th>charm c</th>
<th>top t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>down d</td>
<td>strange s</td>
<td>bottom b</td>
</tr>
</tbody>
</table>

- Quarks only appear in colourless combinations (=hadrons):

- Forces are described as exchanges of bosons (e.g. photon for e.m. interaction, \( W^\pm \) and \( Z^0 \) for the weak interaction)

Feynman diagram

- CP violation in the Standard Model (SM)

- Higgs field (yet to be discovered !) generates mass of particles

- Quark mass eigenstates are different from weak eigenstates
  → quark mixing matrix (Cabibbo, Kobayashi, Maskawa)

\[
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix}
\]

- Different mixing matrix for quarks and anti-quarks \( \Rightarrow \) CP violation
CP violation in the Standard Model (SM)

- **CKM matrix:**
  - complex and unitary
  - 4 parameters (e.g., 3 angles and 1 phase)
  - responsible for CP violation

\[
V_{\text{CKM}} = \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\Rightarrow V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0
\]

- 6 unitarity triangles
- most sensitive experimental tests on the two unsquashed triangles, with transitions involving b quarks

- \( B^0, B^0 \) decays and \( B^+_{s}, B^0_{s} \) decays most suitable to study CP violation

- **“Unitarity triangle”** (area \( \propto \) CP violation)

Wolfenstein parametrization

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

Wolfenstein parameters:
- \( \lambda = 0.2272 \pm 0.0010 \) (well known)
- \( A = 0.809 \pm 0.014 \) (well known)
- \( \rho \)
- \( \eta \) (CPV due to \( \eta \neq 0 \))

- \( \bar{\eta} = (1 - \lambda^2 / 2)\eta \)

- \( \text{arg}(V_{td}) = -\beta \)
- \( \text{arg}(V_{ub}) = -\gamma \)
- \( \text{arg}(V_{cb}) = 0 \)
Unitarity triangle from the sides

B decays at tree level

\[ \begin{align*}
W^- & \quad V_{cb}, V_{ub} \\
\text{Rates} & \propto |V_{cb}|^2 \text{ or } |V_{ub}|^2 \\
& \Rightarrow |V_{ub}|/|V_{cb}| \text{ ratio} \\
& \Rightarrow \text{length of left side}
\end{align*} \]

B\(^0\)–\(\bar{B}\)^0 mixing (box diagrams dominated by virtual top quarks)

\[ \begin{align*}
& \{ B^0, \bar{B}^0 \} \\
& \Rightarrow |V_{td}|/|V_{cb}| \text{ ratio} \\
& \Rightarrow \text{length of right side}
\end{align*} \]

Unitarity triangle from the angles

- First measurements of CP-violating processes in K and B decays:
  - \( \epsilon_K \) CPV in K sector (discovered in 1964)
  - \( \sin(2\beta) \) CPV in B sector (discovered in 2001) \( \leftarrow \) main initial goal of B factories!

- Today, can measure all angles with B decays:
  - \( \sin(2\beta) \) from \( B^0 \to (cc)K_{S,L} \)
    * interference of \( b \to c \) amplitude with \( B^0\)-\( B^0 \) mixing
  - \( \alpha \) (or \( \beta+\gamma \)) from \( B \to \pi\pi, \rho\rho, \rho\pi \)
    * interference of \( b \to u \) amplitude with \( B^0\)-\( B^0 \) mixing
  - \( \gamma \) from \( B \to D^{(*)}K \)
    * interference of \( b \to c \) and \( b \to u \) amplitudes
Consistency of CKM picture

- Measure unitarity triangle from CP-violating processes (angles + $\varepsilon_K$)
- Compare with result from CP-conserving processes (sides)
  - Slight tension between $|V_{ub}|$ and $\sin(2\beta)$:
    - would need more precise data but, for the time being …
  
  **Test passed successfully!**

Does the SM give a coherent description of CP violation?
What are the alternatives to CKM?

How accurate is the CKM picture?
Are there “corrections” to it?

Motivation for continuing the game

- SM cannot be the ultimate theory
  - Too many free parameters (quark and lepton masses and mixing angles)
    → pattern must be governed by a hidden mechanism yet to be discovered
  - SM believed to be a low-energy effective theory of a more fundamental theory at a higher energy scale $\Lambda$, expected to be in the TeV region

- How can New Physics (NP) be discovered and studied?
  - NP models (= extensions of the SM) introduce new particles, dynamics, symmetries, … at the higher scale $\Lambda \sim$ TeV. These new particles could
    - be produced and observed as real particles at energy frontier machines (LHC, linear collider)
    - appear as virtual particles in loop processes, leading to observable deviations from the pure SM expectations in flavour physics and CP violation

The TeV scale is accessible at future planned experiments → must continue
The “direct” and “indirect” approaches are complementary!
Strengths of indirect approach

- Can in principle access higher scales and therefore see effect earlier:
  - Third quark family inferred by Kobayashi and Maskawa (1973) to explain small CP violation measured in kaon mixing (1964), but only directly observed in 1977 (b) and 1995 (t)
  - Neutral currents ($\nu+N \rightarrow \nu+N$) discovered in 1973, but real Z discovered in 1983

- Can in principle access the phases of the new couplings:
  - NP at TeV scale needs to have a “flavour structure” to provide the suppression mechanism for already observed FCNC processes → once NP is discovered, it is important to measure this structure (including new phases)

\[ \Delta m_s = \Delta m_s^{\text{SM}} \propto |V_{ts}^2|, \]
\[ \phi_s = \phi_s^{\text{SM}} = -\arg(V_{ts}^2) = -2\lambda \eta^2 \]

New Physics

New physics and baryogenesis

- Our Universe displays obvious baryon number asymmetry (i.e. matter-antimatter asymmetry)
  - No anti-helium (or heavier anti-nuclei) detected in outer space
  - No annihilation $\gamma$ rays seen in from outer space

- Evolution from symmetric situation at Big Bang (or after inflation) requires a number of conditions:
  - Baryon number violation
  - C and CP violation
  - Thermal non-equilibrium
  - Sakharov’s conditions (1967)
  - EW B violation at high T (sphaleron)
  - Weak interaction, non trivial CKM phase
  - 1st-order phase transition in early universe

- Problems:
  - SM Higgs too heavy to produce 1st order transition → other scalars must exist
  - SM CP violation far too small → other sources of CP violation must exist

Baryogenesis seems to call for physics and CP violation beyond the SM

(NB: almost every extension to the SM implies new sources of CP violation)
NP-free triangle

- Unitarity triangle determined only from measurements of tree processes (assumed to be free from NP):
  - $|V_{ub}|$, from $b \to u$ rate
  - $\gamma = -\arg(V_{td})$ from $B \to D(*)K$

- This is indeed what we know about the CKM matrix if we suspect New Physics might exist in loop processes
  - It is essential to improve the precision on $\gamma$ from tree decays.

Search strategies for NP

- Measure FCNC transitions where NP may show up as a relatively large contribution, especially in $b \to s$ transitions which are poorly constrained by existing data:
  - $B_s$ oscillations ($\Delta m$) and $B_s$ mixing phase ($\phi_s$)
  - $b \to s\gamma$, $b \to s l^+ l^-$, $B_{(s)} \to \mu\mu$
  - Also: rare $K$ and $D$ decays, $D^0$ mixing

- Improve measurement precision of CKM elements
  - Compare two measurements of the same quantity, one which is insensitive and another one which is sensitive to NP:
    - $\sin(2\beta)$ from $B^0 \to J/\psi K_S$ and $\sin(2\beta)$ from $B^0 \to \phi K_S$
    - $\gamma$ from $B_{(s)} \to D_{(s)} K$ and $\gamma$ from $B^0 \to \pi^+ \pi^-$ and $B_s \to K^+ K^-$
  - Measure all angles and sides in many different ways
    - any inconsistency will be a sign of new physics

Single measurements with NP discovery potential

Precision CKM metrology, including NP-free determinations of angle $\gamma$
Higher $\lambda$-orders in CKM: angle $\chi$

$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2 / 2 & \lambda & \alpha \\ -\lambda & 1 - \lambda^2 / 2 & \beta \\ \lambda \epsilon (1 - \rho - i \eta) & -\lambda \epsilon & \gamma \end{pmatrix} + \begin{pmatrix} \epsilon \lambda^4 (1/2 - \rho - i \eta) & 0 & 0 \\ -\epsilon \lambda^4 (1 + 4 \lambda^2) / 8 & \epsilon \lambda^2 (\rho + i \eta) & 0 \\ -\epsilon \lambda^2 (1/2 - \rho - i \eta) & -\epsilon \lambda^2 \lambda^4 / 2 & 0 \end{pmatrix} + O(\lambda^6)$

$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0 \quad \leftarrow \text{keep terms up to } O(\lambda^2) \quad \rightarrow \quad V_{tb} V_{ub}^* + V_{ts} V_{us}^* + V_{td} V_{ud}^* = 0$

$\text{arg}(V_{ub}) = -\gamma, \quad \text{arg}(V_{td}) = -\beta, \quad \text{arg}(V_{ts}) = \chi + \pi$

B physics at LHC: (dis)advantages

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$</th>
<th>$pp \rightarrow b\bar{b}X$ ($\sqrt{s} = 14 \text{ TeV}, \Delta t_{\text{bunch}} = 25 \text{ ns}$)</th>
<th>LHC (LHCb–ATLAS/CMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production $\sigma_{bb}$</td>
<td>1 nb</td>
<td>~500 $\mu$b</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>Typical $bb$ rate</td>
<td>10 Hz</td>
<td>100–1000 kHz</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>$b\bar{b}$ purity</td>
<td>$\sim 1/4$</td>
<td>$\sigma_{bb}/\sigma_{\text{inel}} = 0.6%$</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>Pileup</td>
<td>0</td>
<td>0.5–5</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>$b$-hadron types</td>
<td>$B^+B^-$ (50%) $B^0\bar{B}^0$ (50%)</td>
<td>$B^+$ (40%), $B^0$ (40%), $B_c$ (10%) $B_c$ (&lt; 0.1%), b-baryons (10%)</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>$b$-hadron boost</td>
<td>Small</td>
<td>Large (decay vertexes well separated)</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>Production vertex</td>
<td>Not reconstructed</td>
<td>Reconstructed (many tracks)</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>Neutral B mixing</td>
<td>Coherent $B^0\bar{B}^0$ pair mixing</td>
<td>Incoherent $B^0$ and $B_c$ mixing (extra flavour-tagging dilution)</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
<tr>
<td>Event structure</td>
<td>$B\bar{B}$ pair alone</td>
<td>Many particles not associated with the two $b$ hadrons</td>
<td>$\scriptstyle \Upsilon(4S)$</td>
</tr>
</tbody>
</table>
LHCb = Large Hadron Collider beauty experiment

- LHCb designed to maximize B acceptance (within cost and space constraints)
  - moderate-pT triggers
  - forward spectrometer, 1.9 < $\eta$ < 4.9 or 15<0<300 mrad
    - more b hadrons produced at low angles
    - single arm OK since $bb$ pairs produced correlated in space

- Detector requirements:
  - Flexible and efficient trigger
    - final states with leptons
    - fully hadronic final states
  - Good mass resolution
  - Particle identification (p/K/$\pi$/\mu/e)
  - Excellent vertexing capabilities and proper-time resolution

Pythia production cross section

Detector requirements:

- ATLAS/CMS
- LHCb

- $\eta$ of B-hadron
- $p_T$ of B-hadron

- $bb$ correlation

Luminosity and pileup

- LHC machine, pp collisions at $\sqrt{s} = 14$ TeV:
  - design luminosity = $L = 10^{34}$ cm$^{-2}$s$^{-1}$, bunch crossing rate = 40 MHz
  - average non-empty bunch crossing rate = $f = 30$–32 MHz
  - Pileup:
    - $n =$ number of inelastic pp interactions occurring in the same bunch crossing
    - Poisson distribution with mean $<n> = L \sigma_{inel}/f$, with $\sigma_{inel} = 80$ mb
    - $<n> = 25$ at $10^{34}$ cm$^{-2}$s$^{-1}$ → not good for B physics

- At LHCb:
  - $L$ tuneable by adjusting final beam focusing
  - Choose to run at $<L> \sim 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ (max. $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$)
    - Clean environment: $<n> = 0.5$
    - Less radiation damage
    - Will be available from “first” physics run
  - In one “nominal year” = $10^7$ s:
    - 2 fb$^{-1}$ of data
    - $10^{12}$ $bb$ pairs produced

- LHCb

- $n=0$
- $n=1$

- Probability

- Luminosity [cm$^{-2}$ s$^{-1}$]
LHCb spectrometer

- VELO: Vertex Locator (around interaction point)
- TT, T1, T2, T3: Tracking stations
- RICH1-2: Ring Imaging Cherenkov detectors
- ECAL, HCAL: Calorimeters
- M1–M5: Muon stations

Vertex LOcator

- 21 stations (=42 Si disks):
  - each disk measures r or φ
  - 300 µm thick sensors
  - short strips, 40–100 µm pitch
- 2 additional disks for “pileup” system
  - each measures r only

- Radiation hardness
  - Active Si 8 mm from beam where ~10^{14} n_{eq}/cm²/year is expected
- Analogue readout
  - Beetle chip, ~180 k channels

Module production starting
**Vertex LOcator**

- Si disks in secondary vacuum system like a Roman pot
  - separated from primary machine vacuum with thin Al foil (RF shield)
- Complex mechanics to allow retraction during injection

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O. Schneider, May 11, 2006
Seminar on LHCb at University of Basel
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**Ring Imaging Cherenkov detectors**

- Two RICH detectors with three radiators for particle identification:
  - RICH1: aerogel \((n=1.03, 2-10 \text{ GeV/c})\) and \(C_4F_{10}\) gas \((n=1.0014, 10-60 \text{ GeV/c})\)
  - RICH2: \(CF_4\) gas \((n=1.0005, 16-100 \text{ GeV/c})\)

```
\[ \cos \theta_C = \frac{1}{\beta n} \]
```

Reconstruct up to two concentric rings per track on the photon-detector plane \(\theta_{C1}, \theta_{C2}\)

```
Arrived at CERN, ready for installation
```

```
O. Schneider, May 11, 2006
Seminar on LHCb at University of Basel
```
Hybrid photon detectors

- Novel photon detectors, developed for LHCb RICH1 and RICH2 systems
  - ~500 tubes, with 1024 pixels each
  - 2.5 x 2.5 mm² granularity → σ(θ)=0.6 mrad (RICH1)

Test beam results

C₄F₁₀ ring

~1/3 of the tubes delivered so far

Tracking system

Trigger Tracker
(together with VELO, measures track pₜ for trigger)

500 µm Si, 183 µm pitch
2+2 layers:
  x, u, (30 cm gap), v, x

Warm dipole magnet

T1 T2 T3

OT T1 to T3

Outer Tracker

Inner Tracker

4-sensor ladder 3-sensor ladder

All Si sensors and hybrids in hand, module production on-going
Inner tracker

- High track-multiplicity region close to the beam pipe:
  - Area: IT=2%, OT=98%
  - Tracks: IT=20%, OT=80%

- Si-strip detectors:
  - arranged in 4 boxes/station around beam pipe
  - 4 Si planes (xuvx) per box
  - 198 µm pitch, ~130k channels
  - Beetle readout chips with analog pipeline (L0 buffer, 4 µs)

Outer tracker

- 3 stations each made of 4 double-layers of Kapton/Al straws glued together to form modules
  - Production completed
Installation in progress …

Installation planned to be finished in 2006, global commissioning in first half of 2007

LHCb at Point 8

Access shaft
LHC tunnel
Electronics (TELL1 boards) + CPU farm
Interaction point
Detectors can be moved away from beam line for access
Shielding wall

Seminar on LHCb at University of Basel
O. Schneider, May 11, 2006
Common readout board (TELL1)

- Pre-processor FPGA
- Optical or analog interfaces
- Optical or analog interfaces
- Credit-card PC
- Gigabit ethernet interface
- Sync & link FPGA
- 2 kHz storage
- to HLT
- 1 MHz
- L0 “yes”
- Font-end (on-detector) electronics
- L0 “yes”
- Experiment control system
- clock
- CPU farm (~2000)

Trigger overview

- Software trigger (farm of ~1000 dual CPUs)
  - Current implementation in 2 stages (may/will change)
  - 1st stage: ~1 ms → 40 kHz
    - Fast partial reconstruction (using VELO, TT and L0 objects)
    - Tracks with minimum $p_T$ and impact parameter + (di)muon
  - 2nd stage: ~ 10 ms
    - Generic selection → 10 kHz
    - Full reconstruction and specific exclusive or inclusive selections
- Hardware trigger (custom electronics)
  - Fully synchronized (40 MHz), 4 µs fixed latency
  - “High $p_T$” µ, µµ, e, γ and hadron + pileup info
    (e.g. $p_T(\mu) > 1.3$ GeV/c)

- L0
  - 1 MHz (full detector readout, 40 kB/evt)
- HLT
  - ≤ 2 kHz (storage)

Use info from:
- full detector
  (only limitation is CPU time)
- muon system
- calorimeters
- pileup system
  (two Si disks behind VELO)
Expected trigger performance

- **Algorithms:**
  - L0 mature, within time budget
  - HLT under development
    (prototype available within time budget for a limited set of channels)

- **L0*HLT efficiencies:**
  - Determined using detailed MC simulation
  - Typically 30%–80% for offline-selected signal events, depending on channel

- **HLT output rates:**
  - 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)

<table>
<thead>
<tr>
<th>Output rate</th>
<th>Event type</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive B candidates</td>
<td>B (core program)</td>
</tr>
<tr>
<td>600 Hz</td>
<td>High mass di-muons</td>
<td>J/ψ, b→J/ψX (unbiased)</td>
</tr>
<tr>
<td>300 Hz</td>
<td>D* candidates</td>
<td>Charm</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Inclusive b (e.g. b→μ)</td>
<td>B (data mining)</td>
</tr>
</tbody>
</table>

Expected tracking performance

- **High multiplicity environment:**
  - In a bb event, ~30 charged particles traverse the whole spectrometer

- **Full pattern recognition implemented:**
  - Track finding efficiency > 95% for long tracks from B decays
    (only 4% ghosts for p_T > 0.5 GeV/c)
  - K_S→π⁺π⁻ reconstruction 75% efficient for decay in the VELO, lower otherwise
Expected tracking resolutions

- **Average B-decay track resolutions:**
  - Impact parameter: ~30 μm
  - Momentum: ~0.4%

- **Typical B resolutions:**
  - Proper time: ~40 fs
  - Mass: 8–18 MeV/c²

<table>
<thead>
<tr>
<th></th>
<th>Mass resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_s \to \mu\mu)</td>
<td>18 MeV/c²</td>
</tr>
<tr>
<td>(B_s \to D_s \pi)</td>
<td>14 MeV/c²</td>
</tr>
<tr>
<td>(B_s \to J/\psi \phi)</td>
<td>16 MeV/c²</td>
</tr>
<tr>
<td>(B_s \to J/\psi \phi)</td>
<td>8 MeV/c² *</td>
</tr>
</tbody>
</table>

* with J/ψ mass constraint

Good proper time resolution essential for time-dependent \(B_s\) measurements!

(CDF, ATLAS, CMS have ~100 fs)

Particle ID performance

- **Average efficiency:**
  - \(K\) id = 88%
  - \(\pi\) mis-id = 3%

- **Good K/π separation in 2–100 GeV/c range**
  - Low momentum
    - kaon tagging
  - High momentum
    - clean separation of the different \(B_s\)→hh modes

- **Unique at hadron colliders!**
Flavour tagging

- Several tags:
  - Performance assessed on full MC, after trigger and reconstruction
  - Kaon tags are the most powerful, e.g. opposite K (from b\rightarrow c\rightarrow s)
  - All tags combined with neural network

- Compare with:
  - CDF achieved \sim 5% for B_s in Run II
  - B factories achieved \sim 30% for B^0 (coherent BB pair, no extra tracks)

<table>
<thead>
<tr>
<th>Tag</th>
<th>\epsilon D^2 = \epsilon (1-2w)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite \mu</td>
<td>0.7%–1.8%</td>
</tr>
<tr>
<td>Opposite e</td>
<td>0.4%–0.6%</td>
</tr>
<tr>
<td>Opposite K</td>
<td>1.6%–2.4%</td>
</tr>
<tr>
<td>Opposite Q_{vtx}</td>
<td>0.9%–1.3%</td>
</tr>
<tr>
<td>Same side \pi (B^0)</td>
<td>0.8%–1.0%</td>
</tr>
<tr>
<td>Same side K (B_s)</td>
<td>2.7%–3.3%</td>
</tr>
<tr>
<td>Combined (B^0)</td>
<td>4%–5%</td>
</tr>
<tr>
<td>Combined (B_s)</td>
<td>7%–9%</td>
</tr>
</tbody>
</table>

\[ D_2 = (1 - 2w)^2 \]

Expected to be one of the first CP measurements:

- Demonstrate tagging performance and ability for CP physics
- Tagging systematics:
  - Extract tagging performance from control channels (e.g. B^+ \rightarrow J/\psi K^+ and B^0 \rightarrow J/\psi K^{*0} in this case)
  - Tagging performance depends on how event is triggered (e.g. on signal or on rest of the event)
- Sensitivity:
  - Expect \sim 240k signal events/year
  \[ \sigma_{stat}(\sin(2\beta)) \sim 0.02 \]
  - Can also push further the search for direct CP violating term \sim \cos(\Delta m_d t)

\[ A_{CP}(t) = \frac{N(B^0 \rightarrow J/\psi K_s) - N(B^0 \rightarrow J/\psi K_s)}{N(B^0 \rightarrow J/\psi K_s) + N(B^0 \rightarrow J/\psi K_s)} \]

\[ A_{CP}^{true}(t) = \sin(2\beta) \sin(\Delta m_d t) \]

\[ A_{CP}(t) = (\text{background subtracted}) \]
**B_s mixing**

- **B_s oscillations observed recently by CDF**
  - ~3σ effect at ~17.5 ps⁻¹ (compatible with SM)

- **Oscillation frequency Δm_s can be measured in early phase of LHCb (< 0.2 fb⁻¹)**
  - Expect ~ 80k B_s → D_s⁻π⁺ events per year (2 fb⁻¹)
  - Average σ_t ~ 40 fs
  - S/B ~ 3 (derived from 10⁷ fully simulated inclusive bb events)
  - Systematics will dominate (τ scale)

- **Important step towards:**
  - time-dependent analyses with B_s decays
  - measurement of other mixing parameters, e.g. mixing phase or CP violation in mixing

---

**φ_s from B_s → J/ψφ, ...**

- **B_s → J/ψφ** is the B_s counterpart of B^0 → J/ψ K_S:
  - B_s mixing phase φ_s is very small in SM:
    - φ_s = -2χ = -arg(V_{ts}^2) = -2λη^2 = -0.036 ± 0.003 (CKMfitter)
    - Could be much larger if New Physics runs in the box
  - J/ψφ final state contains two vectors:
    - Angular analysis needed to separate CP-even and CP-odd contributions
  - Expect 125k B_s → J/ψφ signal events/year (before tagging), S/B_{bb} > 3

- **Add also pure CP final states** such as J/ψη, J/ψη', η_cφ
  - No angular analysis needed, but smaller statistics

- **Sensitivity (at Δm_s = 20 ps⁻¹):**
  - dominated by J/ψφ
  - All modes combined, after 5 years (10 fb⁻¹)
  \[ \sigma_{\text{stat}}(φ_s) \sim 0.013 \]
  - systematics need to be tackled
**B^0 \rightarrow K^{*0}\mu^+\mu^-**

- Suppressed loop decay, SM BR $\sim 10^{-6}$
- Forward-backward asymmetry $A_{FB}(s)$ in the $\mu\mu$ rest-frame is a sensitive probe of New Physics:
  - Predicted zero of $A_{FB}(s)$ depends on Wilson coefficients $C_7^{\text{eff}}/C_9^{\text{eff}}$

**Sensitivity**

- 4400 signal events/2fb$^{-1}$, S/B > 0.4
- After 5 years:
  - Zero of $A_{FB}(s)$ located to $\pm 0.53$ GeV$^2$
  - Determine $C_7^{\text{eff}}/C_9^{\text{eff}}$ with 13% error (SM)

**Bs \rightarrow \mu^+\mu^-**

- Very rare loop decay, sensitive to new physics:
  - BR $\sim 3.5 \times 10^{-9}$ in SM, can be strongly enhanced in SUSY
  - Current limit from Tevatron (CDF+D0): $1.5 \times 10^{-7}$ at 95% CL
- LHC should have prospect for significant measurement, but difficult to get reliable estimate of expected background:
  - **LHCb**: Full simulation: 10M inclusive $bb$ events + 10M $bb\rightarrow\mu\mu$ events (all rejected)
  - **ATLAS**: 80k $bb\rightarrow\mu\mu$ events with generator cuts, efficiency assuming cut factorization
  - **CMS**: 10k $bb\rightarrow\mu\mu$ events with generator cuts, trigger simulated at generator level, efficiency assuming cut factorization

<table>
<thead>
<tr>
<th></th>
<th>1 year</th>
<th>$B^s \rightarrow \mu^+\mu^-$ signal (SM)</th>
<th>$b\rightarrow\mu$, $b\rightarrow\mu$ background</th>
<th>Inclusive $bb$ background</th>
<th>All backgrounds</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHCb</strong></td>
<td>2 fb$^{-1}$</td>
<td>17</td>
<td>$&lt;100$</td>
<td>$&lt;7500$</td>
<td></td>
</tr>
<tr>
<td><strong>ATLAS</strong></td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>$&lt;20$</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CMS (1999)</strong></td>
<td>10 fb$^{-1}$</td>
<td>7</td>
<td>$&lt;1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Two tree decays ($b \to c$ and $b \to u$), which interfere via $B_s$ mixing:

- can determine $\phi_s + \gamma$, hence $\gamma$ in a very clean way
- similar to $2\beta + \gamma$ extraction with $B^0 \to D^+\pi$, but with the advantage that the two decay amplitudes are similar ($\sim \lambda^3$) and that their ratio can be extracted from data

Expect 5400 signal events/year

$S/B_{bb} > 1$ at 90% CL (estimated from one MC $bb$ events after cuts, not shown here)

Fit the 4 tagged time-dependent rates:

- Extract $\phi_s + \gamma$, strong phase difference $\Delta$, amplitude ratio
- $B_s \to D_s\pi$ also used in the fit to constrain other parameters (mistag rate, $\Delta m_s$, $\Delta \Gamma_s$ ...)

$\sigma(\gamma) \sim 14^\circ$ in one year (if $\Delta m_s = 20$ ps$^{-1}$)

- expected to be statistically limited
\( \gamma \) from \( B^0 \to D^0 K^{*0} \)

- Dunietz variant of Gronau-Wyler method
  - Two colour-suppressed diagrams with \(|A_2/A_1| \sim 0.4\) interfering via D\(^0\) mixing

\[
\begin{align*}
B^0 \to & \{ \begin{array}{c} \bar{b} \\ d \end{array} \} D^0 \{ \begin{array}{c} \bar{c} \\ u \end{array} \} K^{*0} \\
B^0 \to & \{ \begin{array}{c} \bar{b} \\ d \end{array} \} D^0 \{ \begin{array}{c} \bar{u} \\ c \end{array} \} K^{*0}
\end{align*}
\]

\( A_1 = \bar{A}_1 \)

\( A_2 = A_2 e^{-2i\gamma} \)

\[
A_1 = A(B^0 \to \bar{D}^0 K^{*0}); \ b \to c \ transition, \ phase \ 0 \\
A_2 = A(B^0 \to D^0 K^{*0}); \ b \to u \ transition, \ phase \ \Delta + \gamma \\
A_3 = \sqrt{2} A(B^0 \to D_{cp} K^{*0}) = A_1 + A_2, \ because \ D_{cp} = (\bar{D}^0 + D^0)/\sqrt{2}
\]

- Measure 6 decay rates (self-tagged + time-integrated):
  - LHCb expectations for 2 fb\(^{-1}\) (\(\gamma = 65^\circ, \Delta = 0\))

<table>
<thead>
<tr>
<th>Mode (+ cc)</th>
<th>Yield</th>
<th>S/B_{bb} (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \to \bar{D}^0 (K^+ \pi^-) K^{*0} )</td>
<td>3.4k</td>
<td>( &gt; 2 )</td>
</tr>
<tr>
<td>( B^0 \to D^0 (K^- \pi^+) K^{*0} )</td>
<td>0.5k</td>
<td>( &gt; 0.3 )</td>
</tr>
<tr>
<td>( B^0 \to D^0_{cp} (K^+ K^-) K^{*0} )</td>
<td>0.6k</td>
<td>( &gt; 0.3 )</td>
</tr>
</tbody>
</table>

\( \to \sigma(\gamma) \sim 8^\circ \) in one year

\( \gamma \) from \( B^\pm \to D K^\pm \)

- New proposed clean measurement of \( \gamma \) for LHCb, based on ADS (Atwood, Dunietz, Soni) method:
  - Measure the relative rates of \( B^- \to D^- K^- \) and \( B^+ \to D^+ K^+ \) decays with neutral D’s observed in final states such as:
    - \( K^- \pi^+ \) and \( K^+ \pi^- \), \( K^- \pi^+ \pi^+ \) and \( K^+ \pi^- \pi^- \), \( K^+ K^- \)
  - These depend on:
    - Relative magnitude, weak phase and strong phase between \( B^- \to D^0 K^- \) and \( B^- \to \bar{D}^0 K^- \)
    - Relative magnitudes (known) and strong phases between \( D^0 \to K^- \pi^+ \) and \( \bar{D}^0 \to K^- \pi^+ \), and between \( D^0 \to K^- \pi^+ \pi^+ \) and \( \bar{D}^0 \to K^- \pi^+ \pi^+ \)
  - Can solve for all unknowns, including the weak phase \( \gamma \)

- Candidate for LHCb’s statistically most precise determination of \( \gamma \)
  - \( \sigma(\gamma) \sim 5^\circ \) in one year
\[ \gamma \text{ from } B^0 \to \pi^+\pi^- \text{ and } B_s \to K^+K^- \]

- **For each mode**, measure time-dependent CP asymmetry:
  \[ A_{\text{CP}}(t) = A_{\text{dir}} \cos(\Delta m t) + A_{\text{mix}} \sin(\Delta m t) \]
  - \( A_{\text{dir}} \) and \( A_{\text{mix}} \) depend on mixing phase, angle \( \gamma \), and ratio of penguin to tree amplitudes = \( d e^{i\theta} \)

- **Exploit U-spin symmetry (Fleischer):**
  - Assume \( d_{\pi\pi} = d_{KK} \) and \( \theta_{\pi\pi} = \theta_{KK} \)
  - 4 measurements and 3 unknowns (taking mixing phases from other modes) → can solve for \( \gamma \)

- **LHCb expectations (one year):**
  - 26k \( B^0 \to \pi^+\pi^- \) → \( \sigma(\gamma) \sim 5^\circ \)
  - 37k \( B_s \to K^+K^- \)
    - Uncertainty from U-spin assumption
    - Sensitive to new physics in penguins

- **Conclusion**
  - The hadronic flavour sector will surely contribute significantly to the overall LHC effort to find and study physics beyond the SM
  - **LHCb:**
    - can chase New Physics in loop B decays
      - A few superb (highly-sensitive) \( b \to s \) observables are accessible:
        - \( B_s \) mixing parameters, exclusive \( b \to s\mu\mu, B_{ud} \to \mu\mu \)
        - Large NP phase space can already be covered with the first year of data
    - can significantly improve precision on CKM angles
      - Several \( \gamma \) measurements from tree decays only: \( \sigma_{\text{stat}}(\gamma) \sim 2.5^\circ \) in 5 years (10 fb\(^{-1}\))
      - May reveal inconsistencies with other/indirect measurements
    - is aiming for complete detector at end of 2006, ready to exploit nominal luminosity from day 1
    - is looking forward to first collisions in 2007