CP Violation Prospects at the LHC

- CPV Introduction
  - The CKM-matrix
  - Unitarity Triangle(s)
  - Selected B-factory measurements
- B’s at the LHC
  - $b\bar{b}$ production at the LHC
  - Experiments at the LHC
  - LHCb in detail
    - Tracking environment and detectors
    - Vertex detector and proper time resolution
    - Particle identification
    - Calorimetry
    - Triggering
    - Expected event yields
- Expected performance illustration
- Conclusions
CP Violation

- Charge conjugation: particle → anti-particle
- Parity: reflection in the origin of the space coordinates of a particle.

*CP violation distinguishes matter from anti-matter: baryogenesis.*

The CPV in the standard model too small to explain our existence:

- Leptogenesis? Since $\nu$’s have mass, they mix and they will probably have CPV.
- New physics → new source(s) of CPV

Studying CPV can reveal new physics, beyond the reach of “direct searches”.

The observation of CPV in the K-system, led Kobayashi and Maskawa to the prediction of the third generation. Hence....

But: no smoking gun....
The Cabibbo-Kobayashi-Maskawa Matrix

CKM-matrix describes the charged current interactions of quarks: $\rightarrow$ couplings of $W^+$-boson to up-down quark pairs:

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

The matrix can be parametrized with four independent parameters, including one phase, which introduces CP violation.

Wolfenstein parametrization: $\lambda (= \sin \theta_{\text{Cabibbo}}), A, \rho$ and $\eta$ parameters.

$$ V \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3 (1 - \rho - i \eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V, $$

$\delta V$ contains $\lambda^{\geq 4}$ terms

There are nine unitarity relations in the matrix: $\rightarrow$ triangles.
Two “most relevant” unitarity relations:

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
\[ V_{tb}V_{ub}^* + V_{ts}V_{us}^* + V_{td}V_{ud}^* = 0 \]
Triangle without CPV \(_{\text{B-system}}\)

- \(|V_{ud}|\) and \(|V_{cs}|\) from nuclear \(\beta\)-decay and \(K \rightarrow \pi l \nu\) resp: fixes \(\lambda\).
- \(|V_{ub}|\) and \(|V_{cb}|\): from tree diagram B-decays at LEP/CLEO: fixes \(A\).
- \(\Delta m_d\): dominated by B-factories \((0.503 \pm 0.006 \text{ ps}^{-1})\), but dominated by theoretical uncertainty.
- \(\Delta m_s\): lower limit only (LEP, SLD), if measured (Tevatron?, but LHC for certain) will reduce theory contribution to error significantly.
- \(\epsilon_K\): CPV in \(K \rightarrow \pi \pi\).

Fit tip if the triangle \([\bar{\eta}, \bar{\rho}]\), and extract prediction:

\[
\sin 2\beta = 0.695 \pm 0.055
\]

\(\sin 2\beta\) can be measured in CPV in the B-system....
The **Golden Channel**: $B_d \rightarrow J/\psi K_S^0$

In general (with some approximations though):

$$\frac{\Gamma_{\bar{B} \rightarrow f}(t) - \Gamma_{B \rightarrow f}(t)}{\Gamma_{\bar{B} \rightarrow f}(t) + \Gamma_{B \rightarrow f}(t)} =$$

$$= A^{\text{dir}}_f \cos(\Delta m t) + A^{\text{mix}}_f \sin(\Delta m t)$$

\[ \text{J}/\psi \]

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

\[ w^- \]

\[ c \rightarrow t \]

\[ \bar{c} \]

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

\[ \bar{d} \rightarrow \bar{B} \]

\[ d \rightarrow \bar{d} \]

\[ K_S \]

\[ \bar{t} \]

- Theoretically "clean" case:
  - Small penguin with a phase close to tree
  - Standard Model expectations are: $A^{\text{dir}} = 0$ and $A^{\text{mix}} = \sin(2 \beta)$

- Experimentally: nature has been 'kind' to us
  - $BR \ B_d \rightarrow J/\psi (\mu \mu) K_S^0 (\pi^+ \pi^-) = 2.10^{-5}$.
  - Two resonances: good Signal/Background
Extract $\sin(2\beta)$ at B-factories

- Asymmetric $e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$
- $B^0\bar{B}^0$-pair evolves coherently, hence have opposite flavour at decay $\rightarrow$ tagging.
- Measure $\frac{N_{B^0} - N_{\bar{B}^0}}{N_{B^0} + N_{\bar{B}^0}}$ as a function of $\tau$.
- Likelihood fit to extract $A^{\text{mix}}$ and $A^{\text{dir}}$

\[
\tau = \Delta z \beta \gamma
\]

B-Factories

<table>
<thead>
<tr>
<th>$\int L dt$ (2003)</th>
<th>KEKB</th>
<th>PEP II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\int L dt$ on peak</td>
<td>158 fb$^{-1}$</td>
<td>131 fb$^{-1}$</td>
</tr>
<tr>
<td>Detectors</td>
<td>140 fb$^{-1}$</td>
<td>113 fb$^{-1}$</td>
</tr>
<tr>
<td>Nr $B\bar{B}$-pairs</td>
<td>$152 \times 10^6$</td>
<td>$123 \times 10^6$</td>
</tr>
<tr>
<td>Belle</td>
<td>152 $\times 10^6$</td>
<td>123 $\times 10^6$</td>
</tr>
<tr>
<td>Babar</td>
<td>152 $\times 10^6$</td>
<td>123 $\times 10^6$</td>
</tr>
</tbody>
</table>
Belle Detector

- SC solenoid 1.5T
- CsI(Tl) 16$X_0$
- TOF counter
- 8GeV $e^-$
- 3.5GeV $e^+$
- Aerogel Cherenkov cnt. n=1.015~1.030
- Tracking + dE/dx small cell + He/C$_2$H$_5$
- Si vtx. det. 3 lyr. DSSD
- $\mu / K_L$ detection 14/15 lyr. RPC+Fe

The BaBar Detector

- Superconducting Coil (1.5T)
- Silicon Vertex Tracker (SVT)[5 layers]
- e$^+$ (3 GeV)
- e$^-$ (9 GeV)
- Drift Chamber [40 stereo lyr] (DCH)
- CsI(Tl) Calorimeter (EMC) [6580 crystals]
- Instrumented Flux Return (IFR) [Iron interleaved with RPCs]
Extract \( \sin(2\beta) \) at B-factories

\[ \sqrt{(E_{CM}/2)^2 - (p_{J/\psi} + p_{K_S})^2} \]

Belle(2003): \( \sin(2\beta) = 0.733 \pm 0.057 \pm 0.028 \)

Babbar(2002): \( \sin(2\beta) = 0.741 \pm 0.067 \pm 0.033 \)

CKM-fit prediction: \( \sin(2\beta) = 0.695 \pm 0.055 \)

Excellent agreement!
Conclusion:

● KM mechanism can explain the CPV in flavour changing processes!

● CPV in B-system better constraint than any other observable.

But:

● Coincidence? A combination of SM contribution and new physics?

Bottom line:

● Need to check CPV in many B-decays.

● Especially look for decays sensitive to new physics.
New Physics Searches in Rare B-decays

Theoretically cleanest example: $\phi K_S$

In the Standard Model:

$$\sin(2\beta)_{K_S} = \sin(2\beta)_{\phi K_S}$$

But the hope is that CPV probes other penguin diagram with new particles in their loop (squarks and gluinos?).

Experimentally:

$$\text{BR}(B \rightarrow \phi(K^+K^-)K_S(\pi^+\pi^-) = 1.4 \times 10^{-6}).$$

Compare: $J/\psi(\mu\mu)K_S$: $20 \times 10^{-6}$. 
Experiments and $\phi K_s$

Belle: $\sin(2\beta)_{\phi K_s} = -0.96 \pm 0.50^{+0.09}_{-0.11}$

Babar $\sin(2\beta)_{\phi K_s} = +0.45 \pm 0.43 \pm 0.07$

World average: $\sin(2\beta)_{\psi K_s} = +0.736 \pm 0.049$
Comparison of Tree/Penguin Measurements

Charmonium Modes

- OPAL 98
  $3.2^{+1.3}_{-2.6} \pm 0.5$
- ALEPH 00
  $0.84^{+0.82}_{-1.04} \pm 0.16$
- CDF 00
  $0.79 \pm 0.44$
- BABAR 02
  $0.741 \pm 0.067 \pm 0.034$
- Belle 03
  $0.733 \pm 0.057 \pm 0.028$

Average (charmonium)

$0.736 \pm 0.049$

- BABAR 03
  $0.45 \pm 0.43 \pm 0.07$
- Belle 03
  $-0.96 \pm 0.5 \pm 0.09$

$\phi K_S$

- BABAR 03
  $0.02 \pm 0.34 \pm 0.03$
- Belle 03
  $0.43 \pm 0.27 \pm 0.05$

$\eta K_S$

- BABAR 03
  $0.51 \pm 0.26 \pm 0.05$
- Belle 03
  $0.51 \pm 0.26 \pm 0.05$

Average (s penguin)

$0.24 \pm 0.15$

Average (All)

$0.695 \pm 0.047$

Based on $\sim 250 \text{ fb}^{-1}$ (Babar+Belle)

Expected: $\sim 1000 \text{ fb}^{-1}$ in 2006

(LHC starts in 2007!)
What about $\alpha$ and $\gamma$?

- Constraints from CKM fit “weak”: while $\Delta \beta \sim \pm 3^\circ$, $\Delta \alpha(\gamma) \sim \pm 20^\circ$
- no golden channels accessible to B-factories.

But fruitful ground to check deviations from Standard Model:

- Do the angles agree with CKM-fit ranges?
- $\alpha + \beta + \gamma = \pi$?

To probe $\alpha$ take a charmless CP eigenstate:

![Diagram showing particle interactions](image)

- $P/T \sim 0.3$ from $\text{BR}(\pi^+\pi^-/K\pi)$.
- $P&T$ not the same weak phase!

Large penguin effects (in $B_d$-decays), hence:

Measurements + symmetries + theory $\rightarrow \alpha, \gamma$
**CPV in** \( B \rightarrow \pi\pi \) (BR=5×10^{-6})

Belle and Babar reconstruct ~ 200 \( \pi^+\pi^- \):

![Graphs showing CPV in B → ππ](image)

**Extracted asymmetries:**

<table>
<thead>
<tr>
<th>( fL )</th>
<th>Babar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \int A^{\text{mix}} )</td>
<td>113 fb(^{-1})</td>
<td>78 fb(^{-1})</td>
</tr>
<tr>
<td>( \int A^{\text{dir}} )</td>
<td>( -0.40 \pm 0.22 \pm 0.03 )</td>
<td>( -1.23 \pm 0.41^{+0.08}_{-0.07} )</td>
</tr>
<tr>
<td>( \int A^{\text{dir}} )</td>
<td>0.19 ( \pm 0.19 \pm 0.05 )</td>
<td>0.77 ( \pm 0.27 \pm 0.08 )</td>
</tr>
</tbody>
</table>

- \( A^{\text{mix}} \& A^{\text{dir}} \rightarrow \sin(2\alpha_{\text{eff}}) \): \( \Delta \alpha = \alpha_{\text{eff}} - \alpha \)
- New measurement of BR(\( B \rightarrow \pi^0\pi^0 \)): \( |\Delta \alpha| < 48^\circ \), hence not constraining...
Full Isospin Analysis to Constrain $\Delta \alpha$

Use Babar central values, increase statistics...

Even with 2000 fb$^{-1}$ $\Delta \alpha$ cannot be pinned down!
What will we know in <2007?

Babar and Belle together will have accumulated \( \sim 1000 \text{ fb}^{-1} \), hence roughly \( 10^9 \, b\bar{b} \)-pairs:

- \( \sin(2\beta) \) will be know to \( \sim 0.025 \) from \( J/\psi K_S \).

  But probably not even enough increase in statistics to reconcile \( \phi K_S \) discrepancy between two experiments, let alone establish a signal for new physics.

- \( \alpha, \gamma \): No precise measurement of either of these angles.

What is needed?

Increase Statistics
AND
Study ALL B-hadrons

The Large Hadron Collider allows both.
$b\bar{b}$ production at the LHC

CDF&D0 @ 1.8 TeV

PYTHIA at 14 TeV predicts $\sigma_{b\bar{b}} = 633 \, \mu b$, with flat $\eta$-distribution up to $\eta = 4 - 5$ (down to $\sim 15$ mrad).

But also need to “tag” the $b$-flavour:

$\eta$-B(signal) with decay products in LHCb
Comparison B-factory \Leftrightarrow \text{LHC}

- \( L \times \sigma(b\bar{b}) \) 10000 times larger at LHC(b).
- At LHC produce also \( B_s, B_c \) and baryons.
- \( \sigma(b\bar{b})/\sigma_{\text{total}} = 30 \times \) larger at the LHC.
- LHC: radiation damage issues.
- Tagging at LHC more diluted: more particles and \( b\bar{b} \)-pairs do not evolve coherently.
LHC B-Physics Experiments

- High $p_T$ central detectors: ATLAS and CMS
  - Coverage $-2.5 < \eta < 2.5$
  - Optimized for “direct searches” of Higgs and SuSy.
  - During LHC startup phase
    $(L \sim 10^{33}\text{cm}^{-2}\text{s}^{-1})$ can trigger on “low” $p_T$ leptons.
  - No $\pi/K/p$ identification.

- Dedicated B-physics experiment: LHCb
  - Coverage $1.9 < \eta < 4.9$
  - Optimized for low $p_T$ physics
  - Beam optics allow running at
    $L \sim 2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$, even when
    Atlas/CMS run at $L \sim 10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - RICHes for PID
  - Dedicated B-trigger including hadrons.
Compact Muon Solenoid

Si micro-strip Tracker
210 m$^2$ of 320-500 $\mu$m thick Si
$10^7$ electronic channels

Pixels: $(44 < \text{Radius} < 102 \text{ mm})$
Pixel size: $150 \times 150 \mu$m
$\sim 12 \mu$m resolution in $r\phi$
$45 \times 10^6$ electronic channels
Three barrel layers (2 at startup?)
• Pixels (5< Radius < 13 cm): 50 × 300 μm
• Three barrel pixel layers, 2 m², again 2 at startup?
• 80×10⁶ channels
• ∼ 12 μm resolution in rφ
• Si-strips: 65 m², 6 × 10⁶ channels
VELO: Si-vertex detector.

Two RICH detectors to separate $\pi/K/p$

Dipole magnet: 4 Tm.

Trigger Tracker: Si-planes for tracking.

T1-T3: Tracking stations, Straws/Si.

M1-M5: MWP Muon Chambers.

Calorimetry: Scintillating Pad detector (SPD), Pre-Shower (PS), ECAL and HCAL.

and the Trigger and DAQ
LHCb Trigger/DAQ Overview

Pile-Up Trigger

Calorimeter Trigger
1 e, 1 γ, 1 π₀
1 hadron, Σ E_T
SPD-multiplicity

Muon Trigger
≤ 2 µ

Level-0 decision unit

To FE

Readout Supervisor
buffers: 160 events
timing & fast control

40 MHz → LEVEL-0 → 1 MHz

CPU farm L1 & HLT

buffers: 58254 events

LEVEL-1 → 40 kHz

HLT → 200 Hz

All DATA

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40 MHz, but 30 MHz of x-ings with $p \rightarrow \bar{p}$

- LHCb runs at $L=2 \times 10^{32}$ cm$^{-2}$s$^{-1}$.
- $\sigma_{\text{pp}}^{\text{visible}} \sim 60$ mb: $\rightarrow \sim 10$ MHz of “visible” x-ings.
- Pile-Up, multiplicity: rate to $\sim 8$ MHz
- L0 highest $E_T$, $\mu, e, \gamma, \pi^0$ and $h$: $\rightarrow 1$ MHz
- L1$\rightarrow 40$ kHz: finite lifetime and $p_T$
- HLT$\rightarrow \sim 200$ kHz using “all” info.
A Typical B-event in LHCb

- 26 “long” tracks
- 26 “VELO” tracks
- 11 “upstream” tracks
- 4 “downstream” tracks
Tracking Stations

- Beryllium conical beam-pipe to avoid too many secondaries.
- $3 \times 8$ layers of 5 mm $\varnothing$, 5 m long, straws, $0^\circ$, $5^\circ$ stereo.
- 200 $\mu$m pitch Silicon, $0^\circ$, $5^\circ$ stereo. $\sim 14 \text{ m}^2$ of Si.
Tracking in LHCb

Red = measurements (hits)
Blue = all reconstructed tracks

$K_S$ reconstruction

After VELO

In VELO

$B_s \to D_s K$

$m_{B_s} = 5.37 \text{ GeV}/c^2$
$\sigma_{B_s} = 13.8 \text{ MeV}/c^2$

$m_{B_s} = 5.42 \text{ GeV}/c^2$
$\sigma_{B_s} = 24.0 \text{ MeV}/c^2$
LHCb VELO

VELO “tasks”:
- Provide precise tracking close to the B-vertex
- Stand-alone tracking capability
- Contribute to L1 and HLT triggers

- VELO: 220\(\mu\)m thick Si, 40 – 100 \(\mu\)m pitch, 170k channels, 0.23 m\(^2\) of Si,
- Each station is a sandwich of a R and \(\Phi\)-sensor.
- \(\Phi\)-sensors have a 10-20° stereo angle.
- Sensitive Si-area: 8 mm from LHC beams
- But: during LHC injection 3 cm away from beam.
- VELO on XY-table to centre on beam-line.

Critical issues: Roman-pot mounting, radiation damage.
VELO roles

VELO: two halves in a “Roman-pot”.

- Retractable by 3 cm left/right.
- Separated from LHC vacuum by 250 $\mu$m AlMg$_3$ corrugated foil.
Radiation damage

- Close to beam: 
  \( \sim 10^{14} \text{ n/cm}^2/\text{year} \)
- Dislocations in Si-cristal
- \(< 0^\circ \text{ C} \)
  to freeze damage
- Survives 3-4 years
- Hence: replace (but small surface area)
Working at the LHC (7 TeV beams!), still see multiple scattering effects!.
But for “most” B-tracks: $20 - 40 \ \mu$m impact parameter resolution
Typical B-vertex resolution $40 \ \text{fs} \ (\tau_B = 1.5 \ \text{ps})$, hence:
LHCb $\Delta m_s$ sensitivity

One year of running ($10^7$ s): $\Delta m_s$ from $44 \, k \, B_s \rightarrow D_s \pi$

$\Delta m_s = 15 \, \text{ps}^{-1}$

$\Delta m_s = 25 \, \text{ps}^{-1}$

CMK-fit: expect $\sim 20 \, \text{ps}^{-1}$
ATLAS & CMS $\Delta m_s$ sensitivity

One year at $L = 10^{33}\text{cm}^{-2}\text{s}^{-1}$

- Atlas
  - Tagged events/year: few k
  - Proper time resolution: $\sim 70\text{ps}^{-1}$
- CMS:
  - Tagged events/year: few k
  - Proper time resolution: $\sim 65\text{ps}^{-1}$
LHCb Particle Identification

What is the relevant momentum range?

(a) $B \rightarrow \pi\pi$ decay

(b) tagging kaons

RICH1

RICH2

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Photon Detections and Ring reconstruction

- cover 2.6 m$^2$ with segmented photon detectors
- Typical resolution required corresponds to pads of 2.5 $\times$ 2.5 mm$^2$
- Hybrid Photon Detectors (Si-pixel detectors encapsulated in photo-tube), or
- Multi-anode Photo Multipliers

Rings obtained with “global” likelihood fit using all reconstructed tracks.
$\pi/K$ Separation

LHCb

No RICH

Mass resolution:
LHCb: 17 MeV
ATLAS: 70 MeV

with RICH

ATLAS (no PID!)
Calorimetry

- Scintillating Pad Detector: 5984 cells Level-0 Trigger.
- Preshower: scintillator, 5984 cells, 2.5 $X_0$
- Electromagnetic-Cal.: shashlik, 5984 cells, 25 $X_0$
  \[ \frac{\sigma_E}{E} = \frac{9.5\%}{\sqrt{E}} \oplus 1\% \]
- Hadron-Cal.: iron/scintillating tiles, 1468 cells, 5.6$\lambda_I$
  Level-0 Trigger.
  \[ \frac{\sigma_E}{E} = 80\% \]
  Cell-size from
  \[ 4 \times 4 \rightarrow 26 \times 26 \text{ cm}^2 \]
Calorimetry Performance

Note:
only air in B-field:

\[ J/\psi \to ee \]

\[ \pi^0 \to \gamma\gamma \]

\[ B^0 \to K^*\gamma \]

\[ B^0 \to K^*\pi^0 \]
Muon System

Look for straight lines in pads in the $\mu$-chambers

- Technology: MWPC, projective in $Y$ for L0-trigger.
- 120k pads and strips. Eff $> 99\%$ by $\text{AND}$ or 2 layers per station.
- Combined strips $\rightarrow$ 26k pads. Size: $1 \times 2.5$ cm$^2$ (M1-inner) to $16 \times 20$ cm$^2$ (M5-outer)
Muon Performance

Efficiency (%) vs. Momentum (GeV/c)

- $\mu \rightarrow \mu$

- $\pi \rightarrow \mu$

Pion misid rate (%) at e

$J/\psi \rightarrow \mu\mu$
Triggering on B’s @ LHC

ATLAS & CMS:
- Only lepton triggers to reduce 40 MHz rate to 50-100 kHz.
- Need to apply “large” $p_T$ cuts: $> 6 - 7$ GeV.
- Physics: yields large statistics in B-decays involving $J/\psi$ and rare decays like $B_s \to \mu\mu$. Or trigger on tagging lepton.
- From 50 kHz → “Hz”:
  - ATLAS: FOI search to confirm L1 $\mu$ trigger, define cones of interest (and PV, pile-up) to look for hadrons.
  - CMS: CPU farm with full detector information.
    Algorithms: similar strategy.

LHCb three trigger levels:
- L0 $\mu$&e&$\gamma$ and HADRON trigger
- L1 Input rate: 1 MHz: “full” tracking in VELO + rough momentum
- HLT Input rate: 40 kHz: “off-line” quality tracking

One year ($10^7$ s):

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>$10^{33}$</td>
<td>$10^{33}$</td>
<td>$2 \times 10^{32}$</td>
</tr>
<tr>
<td>$J/\psi(\mu\mu)\phi$</td>
<td>~100 k</td>
<td>84 k</td>
<td>100 k</td>
</tr>
<tr>
<td>$D_s\pi+$tagged</td>
<td>few k</td>
<td>few k</td>
<td>44 k</td>
</tr>
</tbody>
</table>
LHCb-L0: Special Complex Events

Veto

LHCb uses combination of detecting Pile-Up and charged track multiplicity to Veto these events:

Pile-Up veto

No Pile-Up veto
LHCb-L1: tracking @ 1 MHz event rate

- Reconstruct all tracks in VELO: 1 event/μs, 1000 CPUs: 1 ms/event.
- 45° sectors: busy event “slice”:

- Determine primary vertex using all VELO tracks
- Add momentum to “large impact” tracks using TT:
LHCb L1-Performance

Using L0-muons:

Select hadronic channels with combined impact/$p_T$ cut:

- $B_d \rightarrow \pi^+\pi$
- $B_s \rightarrow D_K$

![Graphs showing hadronic channels with combined impact/$p_T$ cut](image)
Expected Trigger Performance
Normalized to off-line selected events

<table>
<thead>
<tr>
<th></th>
<th>Efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi\pi$</td>
<td></td>
</tr>
<tr>
<td>$K\pi$</td>
<td></td>
</tr>
<tr>
<td>$KK$</td>
<td></td>
</tr>
<tr>
<td>$D_sK$</td>
<td></td>
</tr>
<tr>
<td>$D^*\pi$</td>
<td></td>
</tr>
<tr>
<td>$DK^*$</td>
<td></td>
</tr>
<tr>
<td>$\eta_{c}\phi$</td>
<td></td>
</tr>
<tr>
<td>$\phi\phi$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi(\mu\mu)K_s$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi(\mu\mu)\phi$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi(\mu\mu)K$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi(\mu\mu)\eta(\gamma\gamma)$</td>
<td></td>
</tr>
<tr>
<td>$\mu\muK^*$</td>
<td></td>
</tr>
<tr>
<td>$J/\psi(ee)K_s$</td>
<td></td>
</tr>
<tr>
<td>$\pi\pi\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$K^*\gamma$</td>
<td></td>
</tr>
</tbody>
</table>

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LHCb: Expected Event Yield

Yield/year x 1000

- \pi\pi
- K\pi
- KK
- D_sK
- D^*\pi
- DK^*
- \eta_c\phi
- \phi\phi
- J/\psi(\mu\mu)K_s
- J/\psi(\mu\mu)\phi
- J/\psi(\mu\mu)K^*
- J/\psi(\mu\mu)K^+
- J/\psi(\mu\mu)\eta(\gamma\gamma)
- \mu\muK^*
- J/\psi(ee)K_s
- \pi\pi\pi^0
- K^*\gamma
Compare to B-factories?

Yield comparison, after trigger/background rejection:

<table>
<thead>
<tr>
<th>channel</th>
<th>B-factory ≤ 2003</th>
<th>LHCb (1 year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_S$</td>
<td>2000</td>
<td>220,000</td>
</tr>
<tr>
<td>$\pi \pi$</td>
<td>200</td>
<td>26,000</td>
</tr>
<tr>
<td>$\phi K_S$</td>
<td>60</td>
<td>1000</td>
</tr>
</tbody>
</table>

And LHCb has large yields in many interesting $B_s$ decays...

But comparison is “not fare”, need to include the tagging and Signal/Background.

<table>
<thead>
<tr>
<th>$\epsilon_{\text{tagging}}(1 - 2\omega)^2$</th>
<th>B-factory</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d$</td>
<td>28%</td>
<td>4%</td>
</tr>
<tr>
<td>$B_s$</td>
<td>-</td>
<td>6%</td>
</tr>
</tbody>
</table>

Hence B-factory (B’s evolve coherently, no “spectator” background) a factor 7 better.

On top of that at LHC more background, typically: $B/S \sim 1$, looses a factor $\sim \sqrt{2}$ in sensitivity:

Bottom line: loose a factor 10 in sensitivity at LHCb compared to B-factories per event. Hence effective yields comparison looks like

<table>
<thead>
<tr>
<th>channel</th>
<th>B-factory ≤ 2003</th>
<th>LHCb (1 year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K_S$</td>
<td>560</td>
<td>6200</td>
</tr>
<tr>
<td>$\pi \pi$</td>
<td>56</td>
<td>740</td>
</tr>
<tr>
<td>$\phi K_S$</td>
<td>17</td>
<td>30</td>
</tr>
</tbody>
</table>
Example: LHCb precision on $\gamma$
(in one year):

- $5.4k \, B_s \rightarrow D_s^{\pm}K^{\mp}$ combined with $100k \, B_s \rightarrow J/\psi(\mu\mu)\phi(K^+K^-)$ will yield theoretically clean measurement with $\sigma(\gamma) = 14 - 15^\circ$.

- $26k \, B^0 \rightarrow \pi^+\pi^-$ and $37k \, B_s \rightarrow K^+K^-$, combined with $216k \, B^0 \rightarrow J/\psi(\mu\mu)K_S$ and $100k \, B_s \rightarrow J/\psi(\mu\mu)\phi(K^+K^-)$ allows $\sigma(\gamma) = 4 - 6^\circ$ assuming U-spin symmetry.

- $3.4k \, B^0 \rightarrow D^-0(K\pi)K^*$ and $600 \, B^0 \rightarrow D_{CP}(K^+K^-)K^*$ gives $\sigma(\gamma) = 7 - 8^\circ$.

LHCb will run for at least 10 years: hence eventually $\sigma(\gamma) < $ few degrees in at least three independent ways!

How could new physics manifest itself?
New Physics?

Lemma: there are more NP-models than theoreticians... But suppose in 2008 LHCb measures $\gamma$ to be:

- Before 2007: $\Delta m$ is thought to measure $V_{td}$
- But in 2008 we find $\gamma$, which really measured $[\bar{\eta}, \bar{\rho}]$.
- Conclusion: NP in $B^0 - \bar{B}^0$ oscillations.

Bottom line:
extract CKM and NP contributions by measuring CPV in many decays.
Conclusions

- The first generation CPV experiments at the B-factories have achieved precise measurements already.
- However, to look beyond the SM predictions, need $B_s$ and larger statistics.
- The LHC offers large statistics, and all B-flavours, at an “experimental” cost.
- ATLAS and CMS can contribute to channels with leptons in the final state at the start-up luminosities of the LHC.
- LHCb is “made to measure” to exploit CPV in the B-system by:
  - a dedicated trigger,
  - excellent proper time resolution,
  - good tracking,
  - ability to reconstruct and identify charged and neutral hadrons, muons, electrons and photons,
  - acceptable background rejection, and
  - adequate flavour tagging.

LHC and its experiments under construction. First collision expected on April 1, 2007 First hints of NP: Caxambu October 2007?