Prospects for CP violation in LHCb

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Introduction

The LHCb experiment is dedicated to CP violation studies and rare decays search in $B$ sector

- Indirect search for New Physics: new particles can appear in loops
- Complementarity with ATLAS/CMS
- Rare decays: see talk for V. Egorychev

CP violation taken into account in the SM through CKM matrix:
- Lots of observables to over-constrain the model

⇒ Expect LHCb to play a leading role in the discovery of possible New Physics

This talk:
- review of LHCb’s expected sensitivities
Outline

CP violation primer

The LHCb detector

Mixing induced CP violation in $B^0_s$ mixing
  With $B^0_s \rightarrow J/\psi \phi$
  With $B^0_s \rightarrow \phi \phi$
  Calibration with $\sin(2\beta)$

$\gamma$ with tree level decays
  GLW and ADS: counting experiments
  Dalitz plot (GGSZ)
  Time dependent analysis

$\gamma$ in penguin decays

Conclusion
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CP violation in the Standard Model

The CKM matrix accounts for CP violation in the SM:

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

CP violation:

- an irreducible phase
- Unitary triangles with non-zero areas

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$
State of the Art

Precision on angles:

- $\alpha = \left(89.0^{+4.4}_{-4.2}\right)^\circ$
- $\beta = \left(21.07^{+0.90}_{-0.88}\right)^\circ$
- $\gamma = \left(70^{+27}_{-30}\right)^\circ$

Precision on apex:

- $\bar{\rho} = 0.139^{+0.025}_{-0.027}$
- $\bar{\eta} = 0.341^{+0.016}_{-0.015}$

Assuming SM valid $\Rightarrow$ estimate

$$\beta_s = \arg \left( - \frac{V_{ts}}{V^*_{tb}} \frac{V^*_{cs}}{V_{cb}} \right)$$

$$= 0.0360^{+0.0020}_{-0.0016} \text{ rad}$$
Probe of NP

- Direct searches look for NP with the presence of new particles
  - $H^+ \rightarrow t\bar{b}, Z' \rightarrow e^+e^-$, etc.

- Indirect searches look for NP in loop processes
  - neutral meson mixing

\[
\begin{align*}
&B^0_d, B^0_s \quad \text{?} & B^0_d, E^0_s \\
&\bar{d}, \bar{s} \quad \text{?} & \quad \text{?} \quad \bar{b}
\end{align*}
\]

- penguin decays

\[
\begin{align*}
&B \quad \text{?} & s, d \\
&g, Z, \gamma
\end{align*}
\]

$\Rightarrow$ NP changes value of couplings
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b production at LHC

- Total proton-proton inelastic cross section at 14 TeV: 102 mb
- Expected $b\overline{b}$ prod. cross section: 500 – 1000 $\mu$b (PYTHIA)
- Luminosity at LHCb: $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ $\Rightarrow$ dominated by single interactions
  - Integrated luminosity 2 fb$^{-1}$ for 1 nominal year
- $b$ quarks produced mainly in forward or backward direction, with both quarks in same direction
- Expect $10^{12}$ $b\overline{b}$ pairs per year
- All types of $b$ hadrons produced
Properties

- Precision on impact parameter: $\sigma(IP)/IP \approx 14 \mu m$
- Momentum resolution: $\delta(p)/p \approx 0.5\%$
  \[\Rightarrow\text{ resolution on proper time } \sigma(t) \approx 40 \text{ fs}\]
- Particle Identification: kaon ID eff. 88%, with pion mis-ID: 3%, effective separation range: $2 \rightarrow 100 \text{ GeV}$
- trigger: 2 levels
  - L0 (hardware): use VELO, CALO, MUON, 40 MHz $\rightarrow$ 1 MHz
    - Leptonic and hadronic trigger
  - HLT (software): use all sub-detectors, confirm L0 decision and reconstruction physical channels 1 MHz $\rightarrow$ 2 kHz
  \[\Rightarrow\text{ wide variety of signal channels available}\]
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In the $B_s^0 \rightarrow J/\psi \phi$ decays

$B_s^0 \rightarrow J/\psi \phi$

$B_s^0 \rightarrow B_s^0 \rightarrow J/\psi \phi$

$\Rightarrow$ Measured CP violating phase is $\phi_{J/\psi \phi} = -2\beta_s + \Phi^{NP}$

- $\Phi^{NP}$ is a possible New Physics phase
- penguin contribution in decay expected small and neglected
- Current status: $\phi_{J/\psi \phi} \in [-2.6, -1.94] \cup [-1.18, -0.54]$ rad at 68% CL (TeVatron EPS’09), $2\sigma$ from SM.

Difficulties: this decay is $P \rightarrow VV \Rightarrow$ angular analysis needed to disentangle CP components, $\Delta \Gamma_s \gg \Delta \Gamma_d$, $\Delta m_s \gg \Delta m_d$
Measurement

1. trigger and select the events: $117 \text{k events/2 fb}^{-1}$, $B/S \approx 2.1$
   CDF+D0: $\approx 5000 \text{ evts/5.6 fb}^{-1}$
2. measure their proper time: $\sigma(t) \approx 40 \text{ fs}$
3. measure the transversity angles of their decay products:
   distortions $< 10\%$
4. tag the initial flavour of the $B^0_s$: $\varepsilon_{\text{tag}} (1 - 2\omega)^2 \approx 6.2 \%$
5. fit $\phi_s^{J/\psi\phi}$, study model properties with fast Monte Carlo sim.
Sensitivity for 1 nominal year ($2 \text{ fb}^{-1}$) is $\sigma(\phi_\psi^{J/\psi}) \approx 0.03 \text{ rad}$

$\Rightarrow$ if measurement from TeVatron is correct, $5\sigma$ NP discovery with $0.2 \text{ fb}^{-1}$
In the $B_s^0 \to \phi\phi$ decays

Pure penguin decay:

Mixing phase due to $V_{ts}$ cancels: $\phi_s^{\phi\phi} = 0 + \delta^{pu-c} + \Phi^{NP}$

As $B_s^0 \to J/\psi\phi$, it is a $P \to VV$ decay $\Rightarrow$ angular analysis needed

Similar procedure as to $B_s^0 \to J/\psi\phi$

Parallel with $B_d^0 \to \phi K_{S}^0$ and $B_d^0 \to \eta' K_{S}^0$
Sensitivity to $\phi_s^{\phi\phi}$

- Yield = 6.2 k evts/2 fb$^{-1}$
  (with new BR measurement from CDF(HEP’09))
- B/S < 0.8
- $\sigma(\phi_s^{\phi\phi}) \approx 0.08$ for 2 fb$^{-1}$ and $\approx 0.04$ for 10 fb$^{-1}$
  - Current combined BaBar/Belle uncertainty on $S(\phi K_s^0) = 0.17$, on $S(\eta' K_s^0) \approx 0.07$
- can be used in addition to $\phi_s^{J/\psi \phi}$ to probe NP
Benchmark measurement: $\sin(2\beta)$ with $B_d^0 \rightarrow J/\psi K_S^0$

The measurement of $\sin(2\beta)$ is used for calibration:

- Similar trigger as to $B_s^0 \rightarrow J/\psi \phi$
- Selection procedure can share parts
- Tagging algorithm expected to behave identically
- Same tools used in both (except the angular analysis)
- Mostly same control channels

With $2 \text{fb}^{-1}$, the yield is expected to be $\sim 76 \text{k}$ events and the sensitivity $\sigma(\sin(2\beta)) \approx 0.02$, comparable to world average.
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Conclusion
\[ \gamma \text{ with tree dominated decays} \]

Time integrated analysis:
- Gronau, London, Wyler (GLW) and Atwood, Dunietz, Soni (ADS): counting experiments
- Dalitz plot analysis, also known as GGSZ (Giri, Grossman, Soffer and Zupan)

Time dependent analysis:
- Study of \( B_s^0 \rightarrow D_sK \) decays
GLW and ADS methods

- **GLW:** $B^+ \to D^0 K^+$ decays with $D^0$ decaying in CP eigenstates $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
- **ADS:** same, but with flavour specific $D$ decays: $D^0 \to K^+\pi^-$
- mix Cabibbo-allowed and Cabibbo-suppressed $D$ decays

Other similar decays like $B^0 \to D^0 K^{*0}$ also studied at LHCb, as well as multi-body decays $B^+ \to D(K^{\pm}\pi^\mp\pi^-\pi^+)K^+$
ADS/GLW: Method, yields and sensitivity

- Method: count how many events of each type are selected ⇒ use theoretical rates to extract $\gamma$
- Yield for $2 \text{ fb}^{-1}$ after L0 trigger:

<table>
<thead>
<tr>
<th></th>
<th>$B^+$</th>
<th>$B^0_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabibbo allowed</td>
<td>84 k</td>
<td>4 k</td>
</tr>
<tr>
<td>Cabibbo suppressed</td>
<td>1.6 k</td>
<td>360</td>
</tr>
<tr>
<td>B/S</td>
<td>0.6 – 3.2</td>
<td>0.2 – 13.5</td>
</tr>
</tbody>
</table>

See backup for details

- Sensitivity for $2 \text{ fb}^{-1}$:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma(\gamma) (^\circ)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^\pm \to DK^\pm$</td>
<td>13.8</td>
</tr>
<tr>
<td>$B^0 \to DK^*0$</td>
<td>5.2 – 12.7*</td>
</tr>
</tbody>
</table>

- compare to current world average sensitivity: $\sigma(\gamma) \approx 30^\circ$

*: Depends on $\delta_{B^0}$, not measured yet
Dalitz plot with $D \rightarrow K_S^0 \pi^+ \pi^-$

Study $B^\pm \rightarrow D(K_S^0 \pi^+ \pi^-)K^\pm$ decays:

- yield = 6800 evts/2 fb$^{-1}$
- $B/S < 1.1$

Sensitivity: $\sigma(\gamma)(°) = 9.8$ (Amplitude fit) – 12.8 (Binned fit) for 2 fb$^{-1}$

BaBar/Belle expected: $\sigma(\gamma) \approx 20°$
Time dependent analysis: $B^0_s \rightarrow D_s K$

Use LHCb's specific feature: separation $K - \pi$ with RICH detectors

- Yield: $6.2 \text{ fb}^{-1}$ and $B/S = 0.7$

- Sensitivity ($2 \text{ fb}^{-1}$): $\sigma(\gamma) = 10.3^\circ$

- Measured phase: $\gamma - 2\beta_s$
  - $\beta_s$ extracted from $B^0_s \rightarrow J/\psi \phi$
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\[ \gamma \text{ in loops with } B \to hh \]

Decay can occur through penguin process with non negligible contribution

Tree decay

\[ \bar{b} \rightarrow W^+ d(s) \rightarrow u \pi^+(K^+) \]

\[ B^0_d(B^0_s) \rightarrow \pi^-(K^-) d(s) \rightarrow d(s) d(s) \]

Penguin decay

\[ \bar{b} \rightarrow W^+ d(s) \rightarrow u \pi^+(K^+) \]

\[ B^0_d(B^0_s) \rightarrow \pi^-(K^-) d(s) \rightarrow d(s) d(s) \]

- Potentially sensitive to New physics
- Major advantage of LHCb: separation \( K - \pi \Rightarrow \) separate the different families
Sensitivity measurements

- Extract $\gamma$ through time dependent asymmetries

$$A_{CP}(t) = \frac{A_{\text{dir}} \cos(\Delta m t) + A_{\text{mix}} \sin(\Delta m t)}{\cosh(\Delta \Gamma t/2) + A_{\Delta \Gamma} \sinh(\Delta \Gamma t/2)}$$

- Reconstruction performance:

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield/2 fb$^{-1}$</th>
<th>B/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d^0 \to \pi^+\pi^-$</td>
<td>58.8 k</td>
<td>0.5</td>
</tr>
<tr>
<td>$B_s^0 \to K^+K^-$</td>
<td>71.9 k</td>
<td>0.07</td>
</tr>
</tbody>
</table>

- Sensitivity (2 fb$^{-1}$):

| $\sigma(A_{\text{dir}}^{\pi\pi})$ | 0.04 | $\sigma(A_{\text{dir}}^{KK})$ | 0.047 |
| $\sigma(A_{\text{mix}}^{\pi\pi})$ | 0.04 | $\sigma(A_{\text{mix}}^{KK})$ | 0.035 |

$\Rightarrow \sigma(\gamma) = 8^\circ$ assuming U-spin symmetry
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**CP violation primer**

**LHCb**

**Mixing**

**$B_s^0$ Mixing**

**$\gamma$ in trees**

**$\gamma$ in penguin**

**Conclusion**

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**Conclusion**
Conclusion

Summary of performance for 2 fb$^{-1}$:

- $B_s^0$ CP violation: $\sigma(\Phi_{J/\psi\phi}) \approx 0.03$ rad, $\sigma(\Phi_{\phi\phi}) \approx 0.08$ rad
  - 5$\sigma$ New Physics discovery with 0.2 fb$^{-1}$ if Tevatron value confirmed!
- $\gamma$ with trees: combined sensitivity is $\sigma(\gamma) = 4 - 5^\circ$
- $\gamma$ in penguin decays: $\sigma(\gamma) = 8^\circ$ assuming U-spin symmetry
  - Can be sensitive to NP in the first years
- $\alpha$ in $B \rightarrow (\rho\pi)^0$: $\sigma(\alpha) \approx 8^\circ$

$\Rightarrow$ Need data!
$\Rightarrow$ Long term measurements not mentioned here
Thanks!
Backups
**γ with trees: details of yields**

Yield for 2 fb$^{-1}$ after L0 trigger:

<table>
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<tr>
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<th>B/S</th>
</tr>
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<tbody>
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<td>$B^\pm \rightarrow D(K^\pm \pi^\mp)K^\pm$</td>
<td>84k</td>
<td>0.6</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(K^\mp \pi^\pm)K^\pm$</td>
<td>1.6k</td>
<td>0.6</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(K^+K^-)K^\pm$</td>
<td>8.5k</td>
<td>1.15</td>
</tr>
<tr>
<td>$B^\pm \rightarrow D(\pi^+\pi^-)K^\pm$</td>
<td>3k</td>
<td>3.2</td>
</tr>
</tbody>
</table>

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<tr>
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<td>$B^0 \rightarrow D(K^\pm \pi^\mp)K^*$</td>
<td>4k</td>
<td>~ 0.2</td>
</tr>
<tr>
<td>$B^0 \rightarrow D(K^\mp \pi^\pm)K^*$</td>
<td>360</td>
<td>~ 6</td>
</tr>
<tr>
<td>$B^0 \rightarrow D(K^+K^-)K^*$</td>
<td>340</td>
<td>&lt; 5 @90%CL</td>
</tr>
<tr>
<td>$B^0 \rightarrow D(\pi^+\pi^-)K^*$</td>
<td>120</td>
<td>~ 13.5</td>
</tr>
</tbody>
</table>
\[ \alpha \text{ with } B_d^0 \rightarrow (\rho \pi)^0 \]

Use time dependent Dalitz plot analysis:

- Yield: 14 k for 2 fb\(^{-1}\), \(B/S = 1\)
- Sensitivity: \(\sigma(\alpha) \approx 8^\circ\)
- No mention of \(B \rightarrow \rho\rho\) decays here