Recent LHCb results on CP Violation

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(on behalf of LHCb collaboration)
**Introduction**

- The LHCb experiment
  - Detector
  - Indirect searches for New Physics
- Measurement of $\phi_s$
  - Introduction
  - Results / status
  - Prospects
- Other CPV measurements
  - The CKM angle $\gamma$
  - $\phi_s^{\Phi\Phi}$ from $B_s \rightarrow \Phi\Phi$
  - CPV in $B \rightarrow 3h$
  - CPV in charm
The LHCb experiment

Forward spectrometer with very precise tracking and PID

- Decay time resolution ~40 fs ($B \rightarrow J/\psi KK$)
- Invariant mass resolution ~8 MeV ($B \rightarrow J/\psi KK$)
- 95% (K-π) ID efficiency for 5% fake rate

Efficient and flexible trigger
  $\varepsilon \sim 80\%$ $B \rightarrow J/\psi X$ decays interesting for physics studies

Recorded luminosity: 3 fb$^{-1}$

1 fb$^{-1}$ at 7 TeV (2011)
2 fb$^{-1}$ at 8 TeV (2012)

Also, took 13nb$^{-1}$ of pA data
The LHCb experiment

• The LHCb physics program focuses mostly on CP violation and rare decays

• Both correspond to indirect searches for New Physics (i.e., new particles),

• Indirect approach has been very successful in the past

  • Neutral Currents
    (Z⁰ inferred ten years before direct observation)

  • Kaon mixing
    (top-quark inferred 30 years before direct observation)
The LHCb experiment

- The **LHCb physics program** focuses mostly on CP violation and rare decays.
- Both correspond to **indirect searches for New Physics** (i.e., new particles).
- Indirect approach has been very successful in the past:
  - Neutral Currents
    
    \[ Z^0 \text{ inferred ten years before direct observation} \]
  - Kaon mixing
    
    \[ \text{top-quark inferred 30 years before direct observation} \]

( you may also notice Earth’ radius was inferred indirectly 2.3k years before direct observation…)

~2.3 K years till the direct observation...

Ερατοσθένης
What (and why) $\Phi_s$
$\Phi_s$ from $B_s \to J/\psi (\rightarrow \mu\mu) KK$

**B_s mass eigenstates:**

\[
|B_s^+\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle \\
|B_s^-\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle
\]

- $q/p$: complex number. $|q/p| \neq 1 \Rightarrow$ CPV in mixing
- $A_f, \bar{A}_f$ complex amplitudes. $|A_f/\bar{A}_f| \neq 1 \Rightarrow$ CPV in decay

Even if not CPV in mixing or decay, you can generate CPV in the interference if

\[
\sin(\Phi_s) \equiv \sin\left(-\text{arg}\left(\frac{q A_f}{p \bar{A}_f}\right)\right) \neq 0
\]

Main (but not only) experimental signature of a non-zero $\Phi_s$: it generates **wiggles** in the time-dependent angular distribution of the $B_s \to J/\psi \phi \rightarrow \mu\mu KK$ final state particles. The frequency of the (potential) wiggles is known: $\Delta m_s$. 
$\Phi_s : \text{Standard Model and New Physics sensitivity}$

**SM prediction:** $\Phi_s = -2 \arg \left( -\frac{V_{cb} V_{cs}^*}{V_{tb} V_{ts}^*} \right) = -0.036 \pm 0.002^{(*)}$

It is very precise, and sensitive to Physics Beyond the SM, specially to non-MFV New physics .... which is accessible even if the NP is at a high scales

→ Illustrative (brute force) test: calculate non-MFV SUSY contributions setting all particle masses $\sim 10$ TeV

(*)Neglecting penguin contributions. Work is ongoing to confirm/reject such assumption

Warning: at this point of course interplay with other low Energy observables is important

Those potential effects are within reach of current experimental precision!
Results and prospects
Φ_s from B_s → J/ψ (μμ) KK

Analysis strategy: Fit the time dependent angular distribution, considering experimental effects:

- **Background**: Events are weighted according to position in J/ψKK mass spectrum.

- Angular distributions are distorted on data because of **non-flat angular acceptance**. Simulation (weighted according to kinematics seen on data) is used to correct for this.

- **Lifetime acceptance**: Samples from different trigger lines are used to unfold trigger biases. Simulation is used for selection/reconstruction biases.
**$\Phi_s$ from $B_s \rightarrow J/\psi (\rightarrow \mu\mu) K K$**

Analysis strategy: Fit the time dependent angular distribution, considering experimental effects:

- **Lifetime resolution**: Non-perfect time resolution (45 fs, still much smaller than oscillation period, 350 fs) convolved with the pdf. Main effect is a ~25% dilution of the amplitude of the wiggles. Measured on data using prompt $J/\psi$ events.

- **Flavour tagging**: The initial flavour of the $B_s$ is determined either by a muon/kaon from the other $B$, and/or by a kaon from the fragmentation. The performance of these taggers is calibrated with control samples such as $B^+ \rightarrow J/\psi K^+$, $B_d \rightarrow D^{*+} \mu\nu$ and $B_s \rightarrow D_s^- \pi^+$.
\( \Phi_s \) from \( B_s \to J/\psi (\rightarrow \mu\mu) \) KK

\( \phi_s (B_s \to J/\psi KK), \ 1 \text{ fb}^{-1} = 0.07 \pm 0.09 \pm 0.01 \text{ rad} \)

3 fb\(^{-1}\) update will come soon. Expected statistical uncertainty is 50 mrad!
\( \Phi_s \) from \( B_s \to J/\psi (\not\!\!\!\!\!\!\!\!\!\mu\mu) \pi\pi 

- Similar analysis methodology than \( B_s \to J/\psi KK \). Some differences:
  - Deal with several \( \pi^+\pi^- \) resonances (implies a time dependent Dalitz analysis)
  - Almost no sensitivity to \( \Delta \Gamma_s \rightarrow \) less sensitive to decay time acceptance
\( \Phi_s \) from \( B_s \to J/\psi (\not\mu\mu) \pi\pi \\

\( \phi_s (B_s \to J/\psi\pi\pi), \ 3\text{fb}^{-1} = 0.075\pm0.067\pm0.008 \text{ rad} \)

0.070\pm0.068\pm0.008 \text{ rad allowing } |\lambda| \text{ to vary}

This is currently world best measurement, until the 3 \( \text{fb}^{-1} \) \( B_s \to J/\psi\K\K \) comes out

Combined with \( B_s \to J/\psi\K\K \) (1 \( \text{fb}^{-1} \))

\( \Phi_s = 0.070\pm0.055 \text{ radians} \)

Compatible within two sigma with SM (i.e, excluded at 95% CL) : -0.036\pm0.002
\( \Phi_s \) from \( B_s \to J/\psi (\tau \mu \mu) \pi \pi 

\( \phi_s (B_s \to J/\psi \pi \pi) \), \( 3 \text{fb}^{-1} = 0.075 \pm 0.067 \pm 0.008 \text{ rad} \)

\( 0.070 \pm 0.068 \pm 0.008 \text{ rad allowing } |\lambda| \text{ to vary} \)

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\(-0.036 \pm 0.002\)

Points consistent with no significant NP in \( \Delta m_s \)

Precision will go further to \( \sim 0.04 \) once Bs \( \to J/\psi KK \) is out
$\Phi_s$ (ATLAS/CMS)

ATLAS and CMS also study $B_s \to J/\psi \phi \to \mu \mu KK$

<table>
<thead>
<tr>
<th>Experiment</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumi. (fb⁻¹)</td>
<td>4.9</td>
<td>20.0</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ (ps⁻¹)</td>
<td>0.053±0.021±0.010</td>
<td>0.096±0.014±0.007</td>
</tr>
<tr>
<td>$\Phi_s$</td>
<td>0.12±0.25±0.05</td>
<td>-0.03±0.11±0.03</td>
</tr>
</tbody>
</table>

HFAF private/unofficial combination yields

- LHCb: $0.070 \pm 0.055$ rad
- LHC: $0.054 \pm 0.049$ rad
- World: $0.038 \pm 0.048$ rad
Prospects

Evidence/discovery of non-zero \( \phi_s \)

New Physics claim in \( \phi_s \) below \( 5\sigma, 3\sigma \)

~2016

~ end of Run-II

... and with LHCb upgrade the sensitivity can go below 0.01 rad
Other CPV measurements
The CKM angle $\gamma$

- The precision of the SM prediction is very high, $\delta \gamma / \gamma \sim 10^{-7}$ (JHEP 1401(2014)051)

- Comparison between different measurements (specially those from tree-level decays with loop-level decays) can be used to test SM/NP

<table>
<thead>
<tr>
<th>Experiment</th>
<th>ref</th>
<th>$\gamma (\circ)$</th>
<th>CKM fitter (from global fit): 66.5$^{+1.3}_{-2.5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>PRD87(2013)05015</td>
<td>$69 \pm 17$</td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>arXiv:1301.2033</td>
<td>$68 \pm 15$</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>LHCb-CONF-2013-006</td>
<td>$67 \pm 12$</td>
<td></td>
</tr>
</tbody>
</table>
The CKM angle $\gamma$

- $B^\pm \to DK^\pm$, full Run-I dataset

Measured by comparing the Dalitz plot of the $D$ decays between $D$’s from $B^+$ and $D$’s from $B^-$. 

\[
A_+(m_+^2, m_-^2) \equiv \overline{A}(m_+^2, m_-^2) + r_B e^{i(\delta + \gamma)} A(m_+^2, m_-^2) \\
A_-(m_+^2, m_-^2) \equiv A(m_+^2, m_-^2) + r_B e^{i(\delta - \gamma)} \overline{A}(m_+^2, m_-^2)
\]

The $(m_+^2, m_-^2)$ Dalitz planes are binned in a non-trivial way in order to maximize sensitivity to $\gamma$. 

LHCb-PAPER-2014-041

Binning scheme
The CKM angle $\gamma$

$A_+ (m_+^2, m_-^2) \equiv \overline{A}(m_+^2, m_-^2) + r_B e^{i(\delta + \gamma)} A(m_+^2, m_-^2)$

$A_- (m_+^2, m_-^2) \equiv A(m_+^2, m_-^2) + r_B e^{i(\delta - \gamma)} \overline{A}(m_+^2, m_-^2)$

Detector efficiency modelled with data from $B \rightarrow D^* \mu \nu$

$\gamma = (62^{+15}_{-14})^\circ$ (modulo 180°)

Other LHCb measurements of $\gamma$ from tree level decays:

$B \rightarrow DK$, different methodology, 1fb$^{-1}$ (arXiv:1407.6211 [hep-ex])

$Bs \rightarrow DsK$ 1fb$^{-1}$ (arXiv:1407.6127 [hep-ex]):

$\gamma = (84^{+49}_{-42})^\circ$

$\gamma = (115^{+28}_{-43})^\circ$
\( \phi_{s\phi} \) from \( B_s \to \phi\phi \\

\[
\phi_{s\phi} \equiv \text{arg} \left( \frac{q A (B_s \to \phi\phi)}{p A (B_s \to \phi\phi)} \right)
\]

different quantity than the \( \Phi \)s I presented at the beginning of my talk
SM expectation is \( \phi_{s\phi} < 0.02 \)

Also measured through time dependent angular analysis. We have analysed the full 3 fb\(^{-1}\) dataset:

\[
\phi_{s\phi} = -0.17 \pm 0.15 \pm 0.03
\]

In very good agreement with SM
CPV in $B \rightarrow 3h$

Study of CP asymmetries across the $B \rightarrow 3h$ Dalitz plane
Overall CP asymmetries are found to be significant

Overall CP asymmetries are found to be significant
On top of that, the asymmetries in some regions of the Dalitz plane are huge

$A_{CP}(B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}) = +0.025 \pm 0.004 \text{ (stat)} \pm 0.004 \text{ (syst)} \pm 0.007 (J/\psi K^{\pm})$, 
$A_{CP}(B^{\pm} \rightarrow K^{\pm}K^{+}K^{-}) = -0.036 \pm 0.004 \text{ (stat)} \pm 0.002 \text{ (syst)} \pm 0.007 (J/\psi K^{\pm})$, 
$A_{CP}(B^{\pm} \rightarrow \pi^{\pm}\pi^{+}\pi^{-}) = +0.058 \pm 0.008 \text{ (stat)} \pm 0.009 \text{ (syst)} \pm 0.007 (J/\psi K^{\pm})$, 
$A_{CP}(B^{\pm} \rightarrow \pi^{\pm}K^{+}K^{-}) = -0.123 \pm 0.017 \text{ (stat)} \pm 0.012 \text{ (syst)} \pm 0.007 (J/\psi K^{\pm})$, 

(3 fb$^{-1}$)
**CPV in charm**

\[
A_{CP} \equiv \frac{N(D^0 \rightarrow h^- h^+) - N(\bar{D}^0 \rightarrow h^- h^+)}{N(D^0 \rightarrow h^- h^+) + N(\bar{D}^0 \rightarrow h^- h^+)}
\]

\[
\Delta A_{CP} = A_{CP}(K^+ K^-) - A_{CP}(\pi^+ \pi^-)
\]

\[
\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08) \%
\]

arxiv:1405.2797

Other recent studies of CPV in charm:

\[D_{(s)^+} \rightarrow K_S h^+ \text{ (arXiv: 1406.2624)}\]
\[D^+ \rightarrow \pi^+ \pi^- \pi^+ \text{ PLB 728 (2014) 585}\]
\[D^0 \rightarrow K^+ K^- \pi^+ \pi^- \text{ (LHCb-PAPER-2014-046)}\]

… all consistent for the moment with CP conservation.
Conclusions

- Flavour physics measurements are sensitive to New Physics even if the scale is higher than several TeV
- Current LHCb combined value of $\phi_s$ is $0.070\pm0.055$ rad, $2\sigma$ within SM prediction
- Stay tuned for update, where the overall uncertainty will reduce to $\sim0.04$
- Latest measurements of $\gamma$ from tree decays, $\phi_s^{\phi\phi}$ and CPV in $B\to3h$ have been presented
- No evidence of CP violation in charm decays up to now
ευχαριστώ
$\Phi_s$ from $B_s \to J/\psi (\phi \mu \mu) \pi \pi$

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\phi_s$ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay time acceptance</td>
<td>±0.6</td>
</tr>
<tr>
<td>Mass acceptance</td>
<td>±0.3</td>
</tr>
<tr>
<td>Background time PDF</td>
<td>±0.2</td>
</tr>
<tr>
<td>Background mass distribution PDF</td>
<td>±0.6</td>
</tr>
<tr>
<td>Resonance model</td>
<td>±6.0</td>
</tr>
<tr>
<td>Resonance parameters</td>
<td>±0.7</td>
</tr>
<tr>
<td>Other fixed parameters</td>
<td>±0.4</td>
</tr>
<tr>
<td>Production asymmetry</td>
<td>±5.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>±8.4</strong></td>
</tr>
</tbody>
</table>
\[ \Phi_s \text{ from } B_s \rightarrow J/\psi (\rightarrow \mu\mu) \text{ KK} \]

| Source                                      | \( \Gamma_s \) \text{ [ps}^{-1}] | \( \Delta \Gamma_s \) \text{ [ps}^{-1}] | \( |A_\perp|^2 \) | \( |A_0|^2 \) | \( \delta_\parallel \) \text{ [rad]} | \( \delta_\perp \) \text{ [rad]} | \( \phi_s \) \text{ [rad]} | \( |\lambda| \) |
|---------------------------------------------|-----------------------------------|------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Stat. uncertainty                           | 0.0048                           | 0.016                                    | 0.0086          | 0.0061          | \( +0.13 \) \text{ [rad]} | \( -0.21 \) \text{ [rad]} | 0.091           | 0.031           |
| Background subtraction                      | 0.0041                           | 0.002                                    | 0.0031          | 0.0001          | 0.03             | 0.02             | 0.003           | 0.003           |
| \( B^0 \rightarrow J/\psi K^{*0} \) background | –                                | 0.001                                    | 0.0030          | 0.0001          | 0.01             | 0.02             | 0.004           | 0.005           |
| Ang. acc. reweighting                       | 0.0007                           | –                                        | 0.0052          | 0.0091          | 0.07             | 0.05             | 0.003           | 0.020           |
| Ang. acc. statistical                       | 0.0002                           | –                                        | 0.0020          | 0.0010          | 0.03             | 0.04             | 0.007           | 0.006           |
| Lower decay time acc. model                 | 0.0023                           | 0.002                                    | –               | –               | –               | –               | –               | –               |
| Upper decay time acc. model                 | 0.0040                           | –                                        | –               | –               | –               | –               | –               | –               |
| Length and mom. scales                      | 0.0002                           | –                                        | –               | –               | –               | –               | –               | –               |
| Fit bias                                    | –                                | –                                        | –               | –               | –               | –               | –               | –               |
| Decay time resolution offset                | –                                | –                                        | 0.0010          | –               | –               | 0.04             | 0.006           | –               |
| Quadratic sum of syst.                     | 0.0063                           | 0.003                                    | 0.0064          | 0.0097          | 0.08             | 0.08             | 0.011           | 0.022           |
| Total uncertainties                         | 0.0079                           | 0.016                                    | 0.0107          | 0.0114          | \( +0.15 \) \text{ [rad]} | \( -0.23 \) \text{ [rad]} | 0.092           | 0.038           |
Mainly two observables:

$$F(|V_{us}|) = \frac{1}{\epsilon} \left| \frac{\mathcal{A}_f}{\mathcal{A}'_f} \right|^2 \frac{\Gamma[f, t = 0]'}{\Gamma[f, t = 0]} = \frac{1 - 2a'_f \cos \theta'_f \cos \gamma + a'^2_f}{1 + 2\epsilon a'_f \cos \theta'_f \cos \gamma + \epsilon^2 a'^2_f}$$

$penguin$ stuff

$f =$ polarization state

Experimental input. Basically

$\frac{(BR \cdot f_f)_{J/\psi K^*}}{(BR \cdot f_f)_{J/\psi \phi}}$

Direct CP asymmetry (difference of yields)
Mainly two observables:

$$F(|V_{us}|) = \frac{1}{\epsilon} \frac{\mathcal{A}_f}{\mathcal{A}_f'} \frac{\Gamma[f, t = 0]'}{\Gamma[f, t = 0]} = \frac{1 - 2a_f' \cos \theta_f' \cos \gamma + a_f'^2}{1 + 2\epsilon a_f \cos \theta_f' \cos \gamma + \epsilon^2 a_f'^2}$$

$penguin stuff$

Experimental input. Basically

$\left( \frac{BR \cdot f_f}{BR \cdot f_{K^*}} \right)_{J/\psi K^*}$

$SU(3) \rightarrow a' = a, \theta' = \theta$

Direct CP asymmetry (difference of yields)

$$A_D^f = \frac{2a_f' \sin \theta_f' \sin \gamma}{1 - 2a_f' \cos \theta_f' \cos \gamma + a_f'^2}$$

$$\tan \Delta \phi_s = \frac{2\epsilon a_f \cos \theta_f \sin \gamma + \epsilon^2 a_f'^2 \sin 2\gamma}{1 + 2\epsilon a_f \cos \theta_f' \cos \gamma + \epsilon^2 a_f'^2 \cos 2\gamma}$$

...and plug here

arXiv:0810.4248
Mainly two observables:

\[ H_f \equiv \left( \frac{A_f'}{A_f'} \right)^2 \frac{\Gamma[f, t = 0]'}{\Gamma[f, t = 0]} = \frac{1 - 2a'_f \cos \theta'_f \cos \gamma + a'^2_f}{1 + 2e a'_f \cos \theta'_f \cos \gamma + e^2 a'^2_f} \]

This other stuff are SU(3) breaking effects which are currently poorly known.

\[
\begin{align*}
\left| \frac{A_0'}{A_0} \right|^2 &= 0.42 \pm 0.27, \\
\left| \frac{A_\parallel'}{A_\parallel} \right|^2 &= 0.70 \pm 0.29, \\
\left| \frac{A_{\perp}'}{A_{\perp}} \right|^2 &= 0.38 \pm 0.16.
\end{align*}
\]
Mainly two observables:

\[ H_f = \frac{1}{\epsilon} \left| \frac{A_f'}{A'_f} \right|^2 \frac{\Gamma[f, t = 0]}{\Gamma[f, t = 0]} = \frac{1 - 2a'_f \cos \theta'_f \cos \gamma + a^2_f}{1 + 2\epsilon a'_f \cos \theta'_f \cos \gamma + \epsilon^2 a^2_f} \]

This other stuff are SU(3) breaking effects which are currently poorly known

Or maybe not so poorly?

\[ \left| \frac{A_0'}{A_0} \right|^2 = 0.42 \pm 0.27, \]
\[ \left| \frac{A_\parallel'}{A_\parallel} \right|^2 = 0.70 \pm 0.29, \]
\[ \left| \frac{A_\perp'}{A_\perp} \right|^2 = 0.38 \pm 0.16. \]
**Penguin pollution**

- Penguin contributions to $\Phi_s$, are usually neglected because they are doubly Cabibbo suppressed.

- However, these contributions cannot be calculated reliably from QCD

- S. Faller, R. Fleischer, T. Mannel arXiv:0810.4248 [hep-ph] propose a method to calculate the penguin pollution to $\Phi_s$ by analyzing $B_s \to J/\psi K^*$ and $B_d \to J/\psi \rho$ data

Source: google penguin pollution
\( \Phi_s \) from \( B_s \rightarrow J/\psi (\rightarrow \mu\mu) \) KK

Apart from the wiggles, there are other terms in the pdf that have some sensitivity to \( \Phi_s \):