LHC results on CP Violation

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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 $B \rightarrow 3h$
  • $V_{ub}$
The LHCb experiment

Forward spectrometer with very precise tracking and PID

- Decay time resolution ~40 fs (B→J/ψKK)
- Invariant mass resolution ~8 MeV (B→J/ψKK)
- 95% (K-π) ID efficiency for 5% fake rate

Efficient and flexible trigger

- ε ~80% B→J/ψX decays interesting for physics studies

Recorded luminosity: 3 fb⁻¹

1 fb⁻¹ at 7 TeV (2011)
2 fb⁻¹ at 8 TeV (2012)
>1 fb⁻¹ at 13 TeV (2015, 2016)
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\(^0\) inferred ten years before direct observation)
  - Kaon mixing
    (top-quark inferred 30 years before direct observation)
The LHCb experiment

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( you may also notice Earth’ radius was inferred indirectly 2.3k years before direct observation…)
What (and why) $\Phi_s$
\[ \Phi_s \text{ from } B_s \rightarrow J/\psi (\rightarrow \mu\mu) \text{ KK} \]

B\(_s\) mass eigenstates:

\[
\begin{align*}
|B_L^s\rangle &= p|B_s^s\rangle + q|\bar{B}_s^s\rangle \\
|B_H^s\rangle &= p|\bar{B}_s^s\rangle + q|B_s^s\rangle
\end{align*}
\]

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

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

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

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

SM prediction: \( Φ_s = -2 \arg \left( \frac{V_{cb}V_{cs}^*}{V_{tb}V_{ts}^*} \right) = -0.038 \pm 0.001 \) (*)

(*) Neglecting penguin contributions

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 to wino DM mAMSB best fit point

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
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 $B^+ \to J/\psi K^+$, $B_d \to D^{*+}\mu \nu$ and $B_s \to D_s^- \pi^+$.
$\Phi_s$ from $B_s \to J/\psi (\rightarrow \mu\mu) \, KK$

$\Phi_s (B_s \to J/\psi KK), \; 3 fb^{-1}$

-0.058$\pm$0.049$\pm$0.006 rad
**$\Phi_s$ from $B_s \to J/\psi (\rightarrow \mu\mu) \pi\pi$**

- 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 decaytime acceptance

\[ \phi_s (B_s \rightarrow J/\psi\pi\pi), \quad 3\text{fb}^{-1} = 0.075 \pm 0.067 \pm 0.008 \text{ rad} \]
**Φₚ (ATLAS/CMS)**

ATLAS and CMS also study $B_s \rightarrow J/\psi \, \phi \rightarrow \mu \mu K K$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lumi. (fb⁻¹)</th>
<th>14.3</th>
<th>19.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Gamma_s$ (ps⁻¹)</td>
<td>0.085±0.011±0.007</td>
<td>0.095±0.013±0.007</td>
<td></td>
</tr>
<tr>
<td>$\Phi_s$</td>
<td>-0.090±0.078±0.041</td>
<td>-0.075±0.097±0.031</td>
<td></td>
</tr>
</tbody>
</table>

**ΔΓₛ (World Average) = -0.033±0.033 rad**

**SM prediction: $Φ_s = -0.038±0.001^{(*)}$**
Prospects

Evidence/discovery of non-zero $\phi_s$

$5\sigma, 3\sigma$

New Physics claim in $\phi_s$

$5\sigma, 3\sigma$

SM

Bs $\rightarrow$ J/ψKK
Bs $\rightarrow$ J/ψKK + Bs $\rightarrow$ J/ψππ

~2016

~ end of Run-II

... and with LHCb upgrade the sensitivity can go below 0.01 rad
**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 $B_s \rightarrow J/\psi K^*$ and $B_d \rightarrow J/\psi \rho$ data.
Results dominated by $B_d \to J/\psi \rho$
The penguin contribution to $\phi_s$ is measured to be consistent with zero for all polarization states

\[
\delta_{\rho}^0 = 0.000_{-0.011}^{+0.009} \pm 0.004 \text{ rad}
\]

\[
\delta_{\rho}^\parallel = 0.001_{-0.014}^{+0.010} \pm 0.008 \text{ rad}
\]

\[
\delta_{\rho}^\perp = 0.003_{-0.014}^{+0.010} \pm 0.008 \text{ rad}
\]
Other CPV measurements
**\( \phi_s^{\Phi\Phi} from B_s \to \Phi\Phi \)**

\[
\phi_s^{\Phi\Phi} \equiv \arg \left( \frac{q A (B_s \to \Phi\Phi)}{p A (B_s \to \Phi\Phi)} \right)
\]

different quantity than the \( \Phi_s \) I presented at the beginning of my talk

SM expectation is \( \phi_s^{\Phi\Phi} < 0.02 \)

Also measured through time dependent angular analysis. We have analysed the full Run-I dataset:

\[
\phi_s^{\Phi\Phi} = -0.17 \pm 0.15 \pm 0.03
\]

In very good agreement with SM
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>$\gamma$ (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>PRD87(2013)05015</td>
<td>$70^{+18}_{-17}$</td>
</tr>
<tr>
<td>Belle</td>
<td>arXiv:1301.2033</td>
<td>$73^{+13}_{-15}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>LHCb-CONF-2016-001</td>
<td>$70.9^{+7.1}_{-8.5}$</td>
</tr>
</tbody>
</table>
**CPV in $B \rightarrow 3h$**

Study of CP asymmetries across the $B \rightarrow 3h$ Dalitz plane

Overall CP asymmetries are found to be significant

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

(3 fb\(^{-1}\))

On top of that, the asymmetries in some regions of the Dalitz plane are huge
$V_{ub}$ from semileptonic $\Lambda_b$ decays

\[
\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\mu^+\nu_\mu)}{\mathcal{B}(\Lambda_b^0 \rightarrow \Lambda_c^- \mu^-\nu_\mu)} |q^2 > 15 \text{ GeV}^2\rangle \cdot R_{FF} \\
\text{form factor ratio}
\text{5\% uncertainty on } |V_{ub}|$

$|V_{ub}| = (3.27 \pm 0.15_{\text{exp}} \pm 0.17_{\text{theory}} \pm 0.06_{|V_{cb}|}) \times 10^{-3}$
Conclusions

. Different CPV measurements from different types of decays and transitions @ LHC consistent with SM expectations

. $V_{ub}$ LHCb measurements from exclusive $\Lambda_{b}$ decays consistent with other exclusive results

. Good prospects for the LHCb upgrade!
Bone, you are hard…

… but I am patient…

source: google osso duro
Penguin pollution

Mainly two observables:

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

\[ f = \text{polarization state} \quad \text{Experimental input. Basically} \quad \frac{(BR \cdot f_f)_{J/\psi K^*}}{(BR \cdot f_f)_{J/\psi \phi}} \]

\[ A'_D = \frac{2a'_f \sin \theta'_f \sin \gamma}{1 - 2a'_f \cos \theta'_f \cos \gamma + a''_f} \]

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

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

\[ H' = \frac{\mathcal{A}_f}{\mathcal{A}_f'} \]

CKM angle

Experimental input. Basically (modulo lifetimes)

\[ \left( \frac{BR \cdot f_f}{f_{f'}} \right)_{J/\psi K^*} \]

Penguin pollution

\[ \tan \Delta \phi_f' = \frac{2\epsilon a_f \cos \theta_f' \sin \gamma + \epsilon^2 a_f^2 \sin 2\gamma}{1 + 2\epsilon a_f \cos \theta_f \cos \gamma + \epsilon^2 a_f^2 \cos 2\gamma}. \]

\[ \mathcal{A}_D = \frac{2a_f' \sin \theta_f' \sin \gamma}{1 - 2a_f' \cos \theta_f' \cos \gamma + a_f'^2}. \]

f = polarization state

\[ \text{SU}(3) \rightarrow a' = a, \theta' = \theta \]

Direct CP asymmetry (difference of yields)

\[ \text{...and plug here} \]
Mainly two observables:

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

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

\[
\left| \frac{A'_0}{A_0} \right|^2 = 0.42 \pm 0.27, \\
\left| \frac{A'_\parallel}{A_\parallel} \right|^2 = 0.70 \pm 0.29, \\
\left| \frac{A'_\perp}{A_\perp} \right|^2 = 0.38 \pm 0.16.
\]
Mainly two observables:

\[ H_f = \frac{1}{\epsilon} \left( \frac{A_f}{A'_f} \right)^2 \frac{\Gamma[f, t = 0]'}{\Gamma[f, t = 0]} = \frac{1 - 2a_f' \cos \theta_f' \cos \gamma + a_f''^2}{1 + 2\epsilon a_f' \cos \theta_f' \cos \gamma + \epsilon^2 a_f''^2} \]

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

Or maybe not so poorly?

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

arXiv:0810.4248

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:

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

… all consistent for the moment with CP conservation.
Apart from the wiggles, there are other terms in the pdf that have some sensitivity to $\Phi_s$: 

$$|A_0|^2(t) = |A_0|^2 e^{-T_s t} [\cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin (\Delta m t)],$$

$$|A_{\parallel}(t)|^2 = |A_{\parallel}|^2 e^{-T_s t} [\cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin (\Delta m t)],$$

$$|A_{\perp}(t)|^2 = |A_{\perp}|^2 e^{-T_s t} [\cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin (\Delta m t)],$$

$$\Re(A_{\parallel}(t) A_{\parallel}(t)) = |A_{\parallel}|^2 |A_{\parallel}| e^{-T_s t} \left(-\cos(\delta_{\parallel} - \delta_{\parallel}) \cos \phi_s \sin (\Delta m t) + \sin(\delta_{\parallel} - \delta_{\parallel}) \cos (\Delta m t) \right),$$

$$\Re(A_0(t) A_0(t)) = |A_0|^2 |A_0| e^{-T_s t} \left(-\cos(\delta_{\parallel} - \delta_0) \cos \phi_s \sin (\Delta m t) + \sin(\delta_{\parallel} - \delta_0) \cos (\Delta m t) \right),$$

$$\Re(A_{\perp}(t) A_{\perp}(t)) = |A_{\perp}|^2 |A_{\perp}| e^{-T_s t} \left(-\cos(\delta_{\perp} - \delta_{\perp}) \cos \phi_s \sin (\Delta m t) + \sin(\delta_{\perp} - \delta_{\perp}) \cos (\Delta m t) \right),$$

$$|A_s(t)|^2 = |A_s|^2 e^{-T_s t} [\cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin (\Delta m t)],$$

$$\Re(A_{s}(t) A_{s}(t)) = |A_{s}|^2 |A_{s}| e^{-T_s t} \left(-\sin(\delta_{\parallel} - \delta_0) \cos \phi_s \sin (\Delta m t) + \cos(\delta_0 - \delta_0) \cos (\Delta m t) \right),$$

$$\Re(A_{s}(t) A_{0}(t)) = |A_{s}|^2 |A_0| e^{-T_s t} \left(-\sin(\delta_{\parallel} - \delta_{\perp}) \cos \phi_s \sin (\Delta m t) + \cos(\delta_{\parallel} - \delta_{\perp}) \cos (\Delta m t) \right).$$
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 $\gamma$. 

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LHCb-PAPER-2014-041
The CKM angle $\gamma$

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

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

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

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