Physics at LHCb

N. Serra on behalf of the LHCb Collaboration
Menu’

- CP Violation in Beauty
- CP violation in Charm
- Some Rare decays
Detector thought for doing b-hadron measurements:
Very good momentum resolution and particle ID.

Also very good for charm physics!
2011: 1.1 fb$^{-1}$
CP Violation in beauty

ANTIMATTER’S GONE MISSING...

WHEN DID THIS HAPPEN, SIR?

ABOUT IS BILLION YEARS AGO...

LOST-PROPERTY OFFICE

CERN
Unitarity triangles and CPV

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

where

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Imposing Unitarity

$$V^*_{ud} V_{cd} + V^*_{us} V_{cs} + V^*_{ub} V_{cb} = 0$$
$$V^*_{ud} V_{td} + V^*_{us} V_{ts} + V^*_{ub} V_{tb} = 0$$
$$V^*_{cd} V_{td} + V^*_{cs} V_{ts} + V^*_{cb} V_{tb} = 0$$
$$V_{ud} V^*_{us} + V_{cd} V^*_{cs} + V_{td} V^*_{ts} = 0$$
$$V_{ud} V^*_{ub} + V_{cd} V^*_{cb} + V_{td} V^*_{tb} = 0$$
$$V_{us} V^*_{ub} + V_{cs} V^*_{cb} + V_{ts} V^*_{tb} = 0$$

Unitarity Triangle

$$\beta_s$$ Triangle

Unitarity Triangle Matrix

P. F. Harrison, S. Dallison and W. G. Scott Phys Lett B 680 209 328

$$\begin{pmatrix} 1^\circ & 22^\circ & 157^\circ \\ 67^\circ & 90^\circ & 23^\circ \\ 112^\circ & 68^\circ & 0^\circ \end{pmatrix}$$

$$\frac{\phi_D}{2}$$
**CKM – matrix is measured very precisely.**
Great jobs done by B-factories and others,
Less constrained $\gamma$-angle: $\gamma = 68^{+13}_{-14}$  
*V. Niess (CKMFitter) EPS2011*

We can access $\gamma$ via the interference between $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$, 
e.g. with $B \rightarrow \bar{D}K$ and $B \rightarrow DK$ 
where $D$ and $\bar{D}$ decay to a common final state

$\gamma$ is the weak phase between $V_{cb}$ and $V_{ub}$

$V_{cb}V_{us}^*$
Color allowed

$V_{ub}V_{cs}^*$
Color suppressed
**CKM – matrix is measured very precisely.**

Great jobs done by B-factories and others,
Less constrained $\gamma$-angle:

\[ \gamma = 68^{+13}_{-14} \]  

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<table>
<thead>
<tr>
<th>$V_{cb}$</th>
<th>$V^*_{us}$</th>
<th>Color allowed</th>
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<tbody>
<tr>
<td>$V_{ub}$</td>
<td>$V^*_{cs}$</td>
<td>Color suppressed</td>
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</tbody>
</table>
GLW/ADS method


D. Atwood, I. Dunietz, A. Soni, PRL78, 3357 (1997)

\[ B^\pm \rightarrow D^0 K^\pm \]

\( CP \) eigenstate \( D^0 \rightarrow K^+ K^- \)

Cabibbo favoured \( D^0 \rightarrow K^- \pi^+ \)

Doubly cabibbo suppressed \( D^0 \rightarrow K^+ \pi^- \)

Time dependent analysis


\[ B_s \rightarrow D_s^+ K^- \]

\[ B^0 \rightarrow D^{(*)+} \pi^- \]

Dalitz analysis


A. Bondar, Proceedings of BINP Special Analysis Meeting on Dalitz Analysis

\[ B^\pm \rightarrow D^0 K^\pm \]

\[ D \rightarrow K_s^0 \pi \pi \]
2010 data (L = 35.5 pb$^{-1}$)

Ratio of branching fraction

$$\frac{BR(B^\pm \to DK^\pm)}{BR(B^\pm \to D\pi^\pm)}$$

$$R_{CF}^{K/\pi} = (6.30 \pm 0.38 \pm 0.40)\%$$
2010 data \((L = 35.5\text{ pb}^{-1})\)

Ratio of branching ratio \(\frac{BR(B^\pm \rightarrow DK^\pm)}{BR(B^\pm \rightarrow D\pi^\pm)}\)

\[R_{CP}^{K/\pi} = (9.31 \pm 1.89 \pm 0.53)\%\]
A_{CP^+} = \frac{\Gamma(B^+ \to D_{CP^+}^0 K^-) - \Gamma(B^+ \to D_{CP^+}^0 K^+)}{\Gamma(B^- \to D_{CP^+}^0 K^-) + \Gamma(B^- \to D_{CP^+}^0 K^+)} = \frac{\pm 2 r_B \sin \delta_B \sin \gamma}{1 + r_B^2 \pm 2 r_B \cos \delta_B \cos \gamma}

R_{CP^+} = \frac{\Gamma(B^- \to D_{CP^+}^0 K^-) + \Gamma(B^+ \to D_{CP^+}^0 K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos \delta_B \cos \gamma

LHCb: PRELIMINARY

R_{CP^+} = 1.48 \pm 0.31 \pm 0.12

A_{CP^+} = 0.07 \pm 0.18 \pm 0.07

HFAG averages including LHCb results

- Significant signal (4σ) for suppressed mode in 343/pb⁻¹.
- Data-driven methods for:
  - PID efficiency
  - Production and detection asymmetry
  - $B^\pm \rightarrow D(K\pi) \pi^\pm$ used as normalisation mode.
\[ R_{ADS} = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^- \pi^+]_D K^-) + \Gamma(B^+ \rightarrow [K^+ \pi^-]_D K^+)} = r_B^2 + r_D^2 + 2r_Br_D \cos \gamma \cos(\delta_B + \delta_D) \]

\[ A_{ADS} = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) - \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)} = \frac{2r_Br_D \sin \gamma \sin(\delta_B + \delta_D)}{R_{ADS}} \]

LHCb: PRELIMINARY

\[ R_{ADS}^{DK} = (1.66 \pm 0.39 \pm 0.24) \cdot 10^{-2} \]
\[ A_{ADS}^{DK} = -0.39 \pm 0.17 \pm 0.02 \]

World Average (HFAG):

\[ R_{ADS}^{DK} = (1.6 \pm 0.3) \cdot 10^{-2} \]
\[ A_{ADS}^{DK} = -0.58 \pm 0.21 \]

Large CP asymmetry, about 50%! 

HFAG average including LHCb results

D.Atwood,I.Dunietz,A.Soni,PRL78,3357(1997)
Other channels which have the similar quark level interference can in principle be added to the measurement of $\gamma$.

\[
\frac{BR(B^- \to D^0 K^- \pi^+ \pi^-)}{BR(B^- \to D^0 \pi^- \pi^+ \pi^-)} = (9.6 \pm 1.5 \pm 0.8) \cdot 10^{-2}
\]

\[
\frac{BR(\Lambda_b^0 \to D^0 pK^-)}{BR(\Lambda_b^0 \to D^0 p\pi^-)} = 0.112 \pm 0.019^{+0.011}_{-0.014}
\]
Another promising channel for the measurement of $\gamma$ are the decays $B^0 \rightarrow D K^{*0}$.

These modes are both color suppressed therefore it can exhibits an enhanced interference.

The yet unobserved CF decay $B_s \rightarrow D^0 K^*$ is a potentially dangerous background.

$$BR(\bar{B}_s^0 \rightarrow D^0 K^{*0}) = (4.72 \pm 1.07\text{(stat)} \pm 0.48\text{(syst)} \pm 0.37\text{($fs/\sqrt{fd}$)} \pm 0.74(BR)) \cdot 10^{-4}$$

Normalization with $B^0 \rightarrow D^0 \rho^0$

Measured by LHCb, see N. Tuning's talk
Both $b \to c$ and $b \to u$ diagrams are colour allowed.

Time dependent analysis required.

The first step is to observe the signal and measure the branching ratio.

\[
\mathcal{B}(B_s^0 \to D_s^{\mp} K^\pm) = (1.97 \pm 0.18 \text{ (stat.)} \pm 0.19 \text{ (syst.)} \pm 0.19 (f_s/f_d)) \times 10^{-4}
\]
The direct and mixing CP asymmetries in $B_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+K^-$ are related to the angle $\gamma$ (need to use U-spin symmetry).

R. Fleischer and R. Knegjens EPJ C71 (2011) 1532

Using U-spin symmetry and neglecting penguin annihilation and exchange topologies we expect $A_{CP}(B_s^0 \rightarrow \pi K) \sim A_{\pi \pi}^{\text{dir}}$. 
- $B^0 \rightarrow K\pi$ - the most precise single measurement and first $5\sigma$ observation at hadron machine!
- First evidence of CP-violation in $B^0_s \rightarrow K\pi$ decay!

LHCb: PRELIMINARY

$A_{CP}(B^0 \rightarrow K\pi) = -0.088 \pm 0.011 \pm 0.008$

$A_{CP}(B^0_s \rightarrow K\pi) = 0.27 \pm 0.08 \pm 0.02$

HFAG:

$A_{CP}(B^0 \rightarrow K^+\pi^-) = 0.098^{+0.012}_{-0.011}$
A measurement of the $B_s^0 \to K^+ K^-$ lifetime can be used to put constraints on NP to the $B_s^0$ mixing.

The LHCb Coll. arXiv:1111.0521v2

CDF Note 06-01-26

2010 data ($L = 37 \text{ pb}^{-1}$)

$$\tau_{LHCb} (B_s^0 \to K^+ K^-) = (1.44 \pm 0.10 \pm 0.01) \text{ ps}$$

$$\tau_{CDF} (B_s^0 \to K^+ K^-) = (1.53 \pm 0.18 \pm 0.02) \text{ ps}$$

$$\tau_{SM} (B_s^0 \to K^+ K^-) = (1.39 \pm 0.032) \text{ ps}$$

$$\tau_{HFAG} (B_s^0) = (1.48 \pm 0.02) \text{ ps}$$
See talk by W. Hulsbergen and talk by N. Tuning
Scalar triple products of momentum or spin vectors are T-odd, a real asymmetry implies CP asymmetry in (under CPT).

M. Gronau and J.L. Rosner arxiv:1107.1232

CDF measurement (arXiv:1107.4999)

\[ A_u = -0.007 \pm 0.064(stat) \pm 0.018(syst) \]
\[ A_v = -0.120 \pm 0.064(stat) \pm 0.016(syst) \]

LHCb: PRELIMINARY

\[ A_u = -0.064 \pm 0.057(stat) \pm 0.014(syst) \]
\[ A_v = -0.070 \pm 0.057(stat) \pm 0.014(syst) \]
CP Violation in charm
In the SM:

- Indirect CP violation in charm is expected to be small ($<10^{-3}$) and process independent.

- CP violation in the decay (different amplitude for a process and its conjugate) is process dependent:
  
  - Negligibly small for Cabibbo favoured processes
  - At the level of $10^{-3}$ possible for Cabibbo suppressed decays
The CP violation of the decays $D\to KK$ and $D\to \pi\pi$ is expected to be small $O(10^{-3})$ in the SM. New physics can contribute enhancing this asymmetry (depending on the model).

$$A_{CP} = \frac{\Gamma(D^0 \to hh) - \Gamma(D^0 \to \bar{hh})}{\Gamma(D^0 \to hh) + \Gamma(D^0 \to \bar{hh})} \approx a_{CP}^{dir}(hh) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

Direct CP asymmetry

Lifetime of the sample

CP asymmetry in the mixing

True $D^0$ lifetime

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) = [a_{CP}^{dir}(KK) - a_{CP}^{dir}(\pi\pi)] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind}$$

Using U-spin symmetry $A_{CP}(KK)$ and $A_{CP}(\pi\pi)$ are expected of similar size and opposite sign.
We need to know the flavour of the $D^0$. We use $D^0$ coming from $D^{*\pm}$.

\[
A_{raw} = \frac{N(D^{*+} \rightarrow D^0 (hh)\pi^+) - N(D^{*-} \rightarrow \bar{D}^0 (hh)\pi^-)}{N(D^{*+} \rightarrow D^0 (hh)\pi^+) + N(D^{*-} \rightarrow \bar{D}^0 (hh)\pi^-)} = A_{CP}(hh) + A_D(hh) + A_D(\pi_s) + A_P(D^*)
\]

$\Delta A_{CP}$ between KK and $\pi \pi$ is very robust:

- For decays in $h^+h^-$ (self-conjugate) of $D^0$ the term $A_D(hh)=0$
- The production asymmetry cancels out $A_P(D^*)=0$
- At first order also $A_D(\pi_s)$ cancels out

$\Delta A_{CP} \approx A_{RAW} (KK) - A_{RAW} (\pi \pi)$
We need to know the flavour of the $D^0$. We use $D^0$ coming from $D^{*\pm}$.

$$A_{raw} = \frac{N(D^{*+} \to D^0 (hh)\pi^+) - N(D^{*-} \to D^0 (hh)\pi^-)}{N(D^{*+} \to D^0 (hh)\pi^+) + N(D^{*-} \to D^0 (hh)\pi^-)} = A_{CP}(hh) + A_D(hh) + A_D(\pi_s) + A_P(D^*)$$

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$$\Delta A_{CP} \approx A_{RAW} (KK) - A_{RAW} (\pi \pi)$$
We need to know the flavour of the D⁰. We use D⁰ coming from D*±.

\[
A_{raw} = \frac{N(D^{*+} \to D^0 (hh)\pi^+) - N(D^{*-} \to \bar{D}^0 (hh)\pi^-)}{N(D^{*+} \to D^0 (hh)\pi^+) + N(D^{*-} \to \bar{D}^0 (hh)\pi^-)} = A_{CP}(hh) + A_D(hh) + A_D(\pi_s) + A_P(D^*)
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- At first order also \(A_D(\pi_s)\) cancels out

\[\Delta A_{CP} \approx A_{RAW} (KK) - A_{RAW} (\pi\pi)\]
CDF (arXiv:1111.5023v1)

HFAG result which includes the preliminary result by CDF

\[ a_{CP}(D^0 \rightarrow \pi\pi) = (0.22 \pm 0.24 \pm 0.11)\% \]

\[ a_{CP}(D^0 \rightarrow KK) = (-0.24 \pm 0.22 \pm 0.09)\% \]

\[ \Delta a_{CP} = (-0.46 \pm 0.31 \pm 0.12)\% \]

HFAG world average:

\[ a_{ind}^{CP} = (-0.023 \pm 0.232)\% \]

\[ \Delta a_{dir}^{CP} = (-0.447 \pm 0.270)\% \]

No evidence of CPV, but world average negative and 1.7 σ form zero.
• Divide data into kinematic bins of (pT of D*+, η of D*+, p of soft pion, left/right hemisphere) -- 54 bins

• split by magnet polarity (field pointing up, pointing down)

• split into two run groups (before & after technical stop)

• Fit final states $D^0 \rightarrow K^+ K^-$ and $\pi^+ \pi^-$ separately => 432 independent fits.

Fit to the $\delta m = m(D^0 \pi^+_s) - m(D^0) - m(\pi^-)$ with the model described in (LHCb-PUB-2009-031)

$D^*$ and $D^0$ are allowed to have different resolution

Consistency for $\Delta a_{CP}$ among individual fits $\chi^2/nDof = 211/215$

Example of Fit:
$D^0 \rightarrow KK$, First bin, first run block, Magnet Up
Cross Checks

- Electron and muon vetoes on the soft pion and on the D0 daughters
- Different kinematic binnings
- Stability of result vs time
- Toy MC studies of fit procedure, statistical errors
- Tightening of PID cuts on D0 daughters
- Tightening of kinematic cuts
- Variation with event track multiplicity
- Use of other signal, background lineshapes in the fit
- Use of alternative offline processing (skimming/stripping)
- Internal consistency between subsamples (splitting left/right, magnet up/down, etc)
- All variation within appropriate statistical/systematic uncertainties.

The result seems pretty stable against systematics!
\[ \Delta A_{\text{CP}} = (-0.82 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (sys)}) \% \]

Statistically compatible with world average (and CDF result)!
World First Evidence of CPV in charm (3.5 \sigma)!
Statistically dominated, eager to analyse more data!

Contribution from CPV suppressed by

\[ \frac{\Delta \langle t \rangle}{\tau} = \frac{\langle t_{KK} \rangle - \langle t_{\pi\pi} \rangle}{\tau} = (9.8 \pm 0.9)\% \]

therefore the main contribution is from direct CPV

Band drawn “by hand” not HFAG approved!
One place to look for NP contribution is $D^+ \rightarrow K^+ K^- \pi^+$. Use of Miranda method for ‘spotting’ CP asymmetries in the Dalitz plot.

**LHCb: 2010 dataset of 38 pb$^{-1}$**

Measurement very robust against bias:
1) Blind analysis
2) Run with two magnet polarities
3) Validation with ‘toy’ studies

No evidence of CPV in any binnings!


An important way to search for anomalous CP violation in charm mixing:

\[
A_T = \frac{\tau(D^0 \rightarrow K^+K^-) - \tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^+K^-) + \tau(D^0 \rightarrow K^+K^-)} \approx \left(\frac{A_m}{2}\right)y\cos \phi_D - x\sin \phi_D
\]

\[
y_{CP} = \frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^+\pi^-)} - 1 \approx y\cos \phi_D - x\sin \phi_D \left(\frac{A_m}{2}\right)
\]

- Need to know the flavor of the $D^0$, we use $D^{*+} \rightarrow D^0 \pi_s^+$.  
- Need to separate the contribution of charm coming from form B

Results obtained with a fraction of 2010 data, but LHCb has a large sample!
Rare decays
Evidence of $B_s \rightarrow \mu \mu$ at LHCb is possible between winter conference and the end of the running period at 7TeV.

For more details see the talk by Niels Tuning.
**Future steps for $B_d \to K^* \mu \mu$**:

- Measurement of the Zero-crossing of $A_{FB}$ in $B_d \to K^* \mu \mu$
- Isospin asymmetry in $B \to K(\ast) \mu \mu$
- Measurement of $A_T^2$ in $B_d \to K^* \mu \mu$
- Measurement of $A_T^2$ in $B_d \to K^{*} ee$
- Direct CPV in $B_d \to K^* \mu \mu$

*Theory predictions from C.Bobeth et al., arXiv:1105.0376v2 and reference therein*
Future steps for $B_d \rightarrow K^* \mu \mu$:
- Measurement of the Zero-crossing of $A_{FB}$ in $B_d \rightarrow K^* \mu \mu$
- Isospin asymmetry in $B \rightarrow K^{(*)} \mu \mu$
- Measurement of $A_T^2$ in $B_d \rightarrow K^* \mu \mu$
- Measurement of $A_T^2$ in $B_d \rightarrow K^{*} e e$
- Direct CPV in $B_d \rightarrow K^* \mu \mu$

Theory predictions from C. Bobeth et al., arXiv:1105.0376v2 and reference therein

For more details see the talk by Niels Tuning.
Future steps for $B_d \rightarrow K^* \mu \mu$:
- Measurement of the Zero-crossing of AFB in $B_d \rightarrow K^* \mu \mu$
- Isospin asymmetry in $B \rightarrow K(*) \mu \mu$
- **Measurement of $A_T^2$ in $B_d \rightarrow K^* \mu \mu$**
- Measurement of $A_T^2$ in $B_d \rightarrow K^{*}ee$
- Direct CPV in $B_d \rightarrow K^* \mu \mu$
In the SM photons are emitted almost completely left-handed polarized

\[ A_D \text{ is sensitive to fraction of right-handed photons (even for small } \Phi_s) \]

\[ (A_D \approx 0 \text{ in SM}) \]

Can be enhanced by NP with large Right-Handed currents.

Time evolution for an untagged sample of \( B_s \to \Phi \gamma \)

\[ R(t) \propto e^{-\Gamma_s t} \left\{ \cosh \left( \frac{\Delta \Gamma_s t}{2} \right) + A_D \sinh \left( \frac{\Delta \Gamma_s t}{2} \right) \right\} \]

Radiative decays at LHCb

**Future steps:** Direct CPV in $B_d \rightarrow K^* \gamma$, Measurement of baryon radiative decays, Photon Polarization in $B_s \rightarrow \phi \gamma$.

**SM expectation** $1.0 \pm 0.2$

$$\frac{\mathcal{B}(B^0 \rightarrow K^{*0} \gamma)}{\mathcal{B}(B_s^0 \rightarrow \phi \gamma)} = 1.52 \pm 0.14 \text{(stat)} \pm 0.10 \text{(syst)} \pm 0.12 (f_s/f_d)$$

What I did not cover in this talk

- Measurement of the BR(Bs → K*K*)
- Limits to LFV B⁺ → h⁻ μ⁺ μ⁺
- Measurement of mass of B resonances
- Measurement of excited B states
- Measurement on XYZ states
- Measurement on Bᶜ decays
- B production measurement
- Electroweak Physics
- ... and many more
Conclusions

- LHCb is over taking other experiments in several B-physics measurements
- World largest sample of exclusive B-decays
- Many propaedeutical measurements towards $\gamma$ (with Tree and Penguin) have been done
- LHCbeauty is also a nice “LHCcharm”:
  - We search in several decays for direct CPV
  - We also look for mixing induced CPV in $D^0$
  - **We have the world first evidence of CPV in charm in** $\Delta A_{\text{CP}} = A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi)$
- We have many measurements in rare decays that already severely constraint NP:
  - $\text{BR}(B_s \to \mu\mu)$
  - $A_{\text{FB}}$ in $B_d \to K^* \mu\mu$
- We are also studying radiative decays (e.g. $B_s \to \phi\gamma$)
- **MUCH MORE WILL BE COMING SOON, STAY TUNED!**
Backup slides
Unitarity Triangle

Measurement of the angles:

- $B \to \pi\pi$
- $\alpha \Rightarrow B \to \rho\rho$
- \( B \to \rho\pi \)
- \( B \to J / \psi K_s \)
- $\beta \Rightarrow B \to \phi K_s$
- \( B \to D^{(*)} D^{(*)} \)
- $\gamma \Rightarrow B \to D^{(*)}\pi$
- \( B \to DK \)

Sides:
- $V_{ud}$: $\beta$-decay
- $V_{us}$: $K$-decay
- $V_{cd}$: $v$-production of c's
- $V_{cs}$: B-decay
- $V_{ub}$: $B$-decay
- $V_{cb}$: $\Delta m$ in $B^0$-$\bar{B}^0$
- $V_{td}$: $\Delta m$ in $B^0$-$\bar{B}^0$

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]
Wolfenstein parameterization

\[ V^{CKM}_{\text{parameterization}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

⇒ Standard representation: \( s_i = \sin \vartheta_i \), \( c_i = \cos \vartheta_i \)

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
= \\
\begin{pmatrix}
c_{12}c_{13} & s_{12}c_{23} & s_{13}e^{i\delta} \\
-s_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{13}c_{13} \\
s_{13}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & s_{23}c_{13}
\end{pmatrix}
\]

Expanding as a function of the sin of Cabibbo angle:

\[
s_{12} = \lambda, \quad s_{13} \sin \delta_{13} = A \lambda^3 \eta, \quad s_{23} = A \lambda^2, \quad s_{13} \cos \delta_{13} = A \lambda^3 \rho
\]

\[
\begin{pmatrix}
1 - \frac{\lambda^2}{2} - \frac{\lambda^4}{8} \\
-\lambda - A^2 \lambda^5 (\rho + i \eta - \frac{1}{2}) \\
A \lambda^3 [1 - (\rho + i \eta)(1 - \frac{\lambda^2}{2})] - A \lambda^2 - A \lambda^4 (\rho + i \eta - \frac{1}{2}) \quad 1 - \frac{1}{2} A^2 \lambda^4
\end{pmatrix}
\]
\[ A(B^- \to D^0 K^-) = A_c e^{i\delta_c}, \quad A(B^- \to \bar{D}^0 K^-) = A_u e^{i(\delta_u - \gamma)} \]

\[ A(D^0 \to f) = A_f e^{i\delta_f} \quad \text{and} \quad A(\bar{D}^0 \to f) = A_f e^{i\delta_f} \quad f \text{ being a generic final state of D-meson.} \]

The \( \delta \)s are strong phases and \( \gamma \) is the weak phase, while \( A \) are real and positive

\[ A(B^- \to (f)_D K^-) = A_c A_f e^{i(\delta_c + \delta_f)} + A_u A_f e^{i(\delta_u + \delta_f - \gamma)} \]

\[ \Gamma(B^- \to (f)_D K^-) = A_c^2 A_f^2 \left( \frac{A_f^2}{A_f^2 + r_B^2 + 2r_B^2} \right) \frac{A_f}{A_f} \text{Re}(e^{i(\delta_u + \delta_f - \gamma)}) \]

where \( r_B = \frac{A_u}{A_c}, \quad \delta_B = \delta_u - \delta_c, \quad \delta_D = \delta_f - \delta_f \)
In the GLW method the D meson is reconstructed when it decays into a CP eigenstate (e.g. K K), therefore the \( \frac{A_f}{A_f^\perp} = 1, \delta_D = 0, \pi \) and CP=+1,-1 ⇒

\[
\Gamma(B^- \rightarrow [f_{CP \pm}, D^-] K^-) = A_C^2 A_{f_{CP \pm}}^2 (1 + r_B^2 \pm 2 r_B \cos(\delta_B - \gamma))
\]

We have:

\[
A_{CP \pm} = \frac{\Gamma(B^- \rightarrow D_{CP \pm}^0 K^-) - \Gamma(B^+ \rightarrow D_{CP \pm}^0 K^+)}{\Gamma(B^- \rightarrow D_{CP \pm}^0 K^-) + \Gamma(B^+ \rightarrow D_{CP \pm}^0 K^+)} = \frac{\pm 2 r_B \sin \delta_B \sin \gamma}{1 + r_B^2 \pm 2 r_B \cos \delta_B \cos \gamma}
\]

\[
R_{CP \pm} = \frac{\Gamma(B^- \rightarrow D_{CP \pm}^0 K^-) + \Gamma(B^+ \rightarrow D_{CP \pm}^0 K^+)}{2 \Gamma(B^- \rightarrow D^0 K^-)} = 1 + r_B^2 \pm 2 r_B \cos \delta_B \cos \gamma
\]
ADS method

In the ADS method it used the interference of 

\[ B^- \rightarrow D^0 K^- \] followed by doubly Cabibbo-suppressed \( D^0 \rightarrow K^+ \pi^- \)

and the suppressed \( B^- \rightarrow \bar{D}^0 K^- \) followed by the Cabibbo-allowed \( \bar{D}^0 \rightarrow K^+ \pi^- \).

\[ r_D = \frac{A(D^0 \rightarrow K^+ \pi^-)}{A(D^0 \rightarrow K^- \pi^+)} \]

Since \( r_D \sim 5\% \) and \( r \sim 10\% \) the interference can be quite large!

\[ R_{ADS} = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^- \pi^+]_D K^-) + \Gamma(B^+ \rightarrow [K^+ \pi^-]_D K^+)} = r_B^2 + r_D^2 + 2r_B r_D \cos \gamma \cos(\delta_B + \delta_D) \]

\[ A_{ADS} = \frac{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) - \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)}{\Gamma(B^- \rightarrow [K^+ \pi^-]_D K^-) + \Gamma(B^+ \rightarrow [K^- \pi^+]_D K^+)} = \frac{2r_B r_D \sin \gamma \sin(\delta_B + \delta_D)}{R_{ADS}} \]
Other ways of extracting $\Upsilon$

**GGSZ:**
In this method the $D^0$ is reconstructed when it decays in 3 bodies (e.g. $K_s^0 \pi \pi$).

\[ A_f e^{i\delta_f} = f(m_+^2, m_-^2) \]
\[ A_f e^{i\delta_f} = f(m_+^2, m_-^2) \]

\[ \Gamma(B^+ \to [K_s^0 \pi \pi], D K^+) \propto \left[ f(m_+^2, m_-^2) \right]^2 + r_B^2 \left[ f(m_+^2, m_-^2) \right]^2 + 2r_B \left[ f(m_+^2, m_-^2) \right] \left[ f(m_+^2, m_-^2) \right] \cos(\delta_B + \delta_D(m_+^2, m_-^2) + \gamma) \]

**$B_s \to D_s K$ (Time dependent CP asymmetry):**
The interference between the direct decay and the decay after mixing allows to access $\Upsilon$. The non-zero $\Delta \Gamma_s$ allows to include non tagged events in the analysis.

\[ \Gamma_{B_s^0 \to f}(t) = 2 \cdot |A_f|^2 (1 + |\lambda_f|^2) \frac{e^{-\Gamma_s t}}{2} \cdot \left( \cosh \frac{\Delta \Gamma_s t}{2} + D_f \sinh \frac{\Delta \Gamma_s t}{2} \right) \]
\[ \Gamma_{B_s^0 \to f}(t) = 2 \cdot |\bar{A}_f|^2 (1 + |\bar{\lambda}_f|^2) \frac{e^{-\Gamma_s t}}{2} \cdot \left( \cosh \frac{\Delta \Gamma_s t}{2} + D_f \sinh \frac{\Delta \Gamma_s t}{2} \right) \]

\[ \gamma + \phi_s = \frac{1}{2} [\arg(\bar{\lambda}_f) - \arg(\lambda_f)] \]
$\Upsilon$ with penguin

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Contributing diagrams</th>
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<tbody>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^-$</td>
<td>$T$, $P$, $PA$, $P_{EW}^C$, $E$</td>
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<td>$PA$, $E$</td>
</tr>
</tbody>
</table>

$$A_{K+K^-}^{dir} = -\frac{2\tilde{d}' \sin(\theta') \sin(\gamma)}{1 + 2\tilde{d}' \cos(\theta') \cos(\gamma) + \tilde{d}'^2}$$

$$A_{\pi^+\pi^-}^{dir} = \frac{2d \sin(\theta) \sin(\gamma)}{1 - 2d \cos(\theta) \cos(\gamma) + d^2}$$

$$A_{\pi^+\pi^-}^{mix} = -\frac{\sin(\phi_d + 2\gamma) - 2d \cos(\theta) \sin(\phi_d + \gamma) + d^2 \sin(\phi_d)}{1 - 2d \cos(\theta) \cos(\gamma) + d^2}$$

$$A_{K+K^-}^{mix} = -\frac{\sin(\phi_s + 2\gamma) + 2\tilde{d}' \cos(\theta') \sin(\phi_s + \gamma) + \tilde{d}'^2 \sin(\phi_s)}{1 + 2\tilde{d}' \cos(\theta') \cos(\gamma) + \tilde{d}'^2}$$
BR measurements:

\[ B^0 \rightarrow K^+ K^- \quad LHCb: 2011 \text{ data, } L=320 \text{ pb}^{-1} \]

\[ B_s \rightarrow \pi^+ \pi^- \]

\[ \text{BR}(B^0 \rightarrow K^+ K^-) = (0.13^{+0.06}_{-0.05} \text{ (stat)} \pm 0.07 \text{ (syst)}) \cdot 10^{-6} \]

\[ \text{BR}(B_s \rightarrow \pi^+ \pi^-) = (0.98^{+0.23}_{-0.19} \text{ (stat)} \pm 0.11 \text{ (syst)}) \cdot 10^{-6} \]

Using new LHCb result (LHCb-CONF-2011-34)

\[ f_s / f_d = 0.267^{+0.21}_{-0.20} \]
U-spin assumption

Using U-spin symmetry and neglecting penguin annihilation and exchange topologies we expect:

\[ C_{CP} = -A^{dir}_{\pi\pi} \]

\[ A_{CP}(B^0_s \rightarrow \pi^+ K^-) \approx A^{dir}_{\pi^+\pi^-} \]

\[ A_{CP}(B^0 \rightarrow K\pi) = A_{Raw} - A_\Delta = -0.088 \pm 0.011(stat) \pm 0.008(syst) \]

World Average: \( -0.098^{+0.012}_{-0.011} \)
2010 data (L = 35.5pb$^{-1}$)

Ratio of branching fraction

\[
R^{K/\pi}_{K_s0\pi\pi} = (12.0^{+6.0}_{-5.0} \pm 1.0)\% 
\]