



Latest results on CPV in B and D decays at LHCb

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On behalf of the LHCb Collaboration

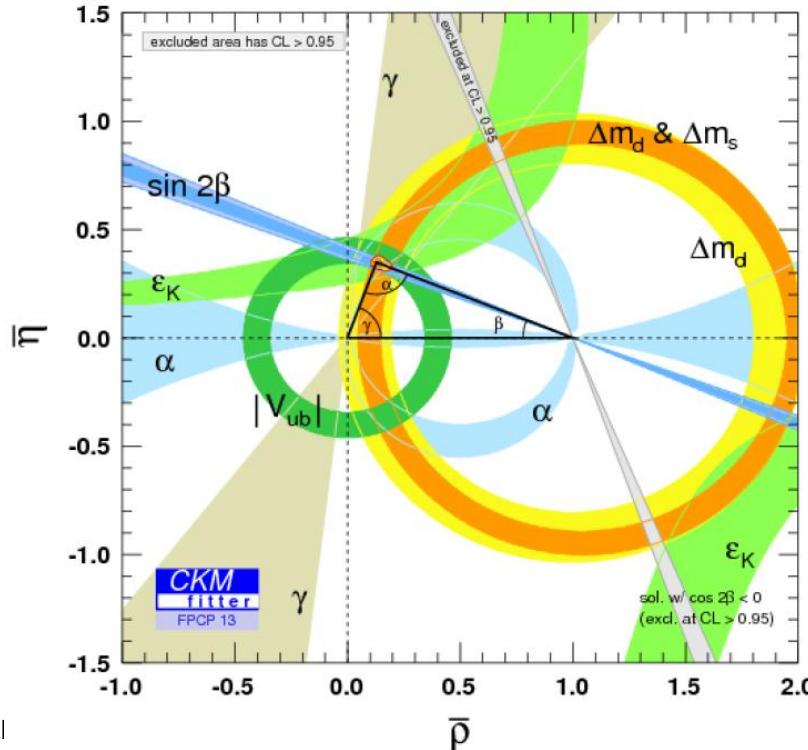
Outline

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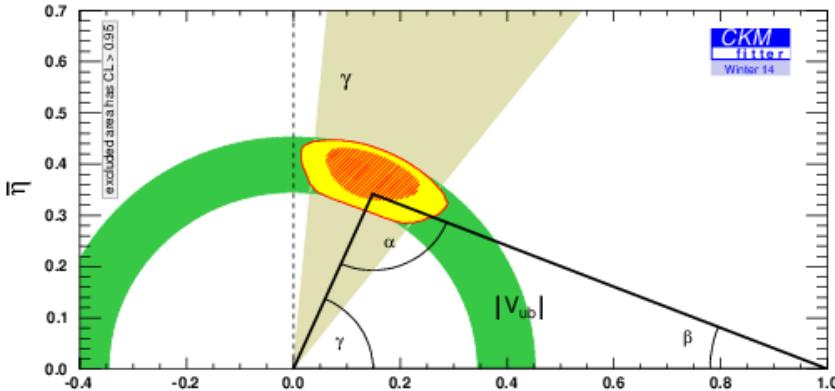
Introduction

- CKM matrix parameterizes quark couplings
- The matrix has one complex phase that results in CP violation (CPV)
- Various methods can measure CPV independently – elegant way to test Standard Model (SM)
- The size of CPV can be represented by the size of the unitarity triangle
- γ is the least well known angle

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



γ measurements



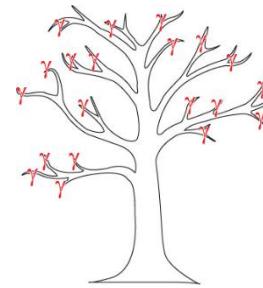
$$\gamma = -\arg \left(\frac{\bar{V}_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right)$$

Direct measurements: $70.0^{+7.7}_{-9.9}$

Combined precision from global CKM fit: $66.5^{+1.3}_{-2.5}$

- ▶ γ is the only angle accessible in tree decays
 - time-integrated methods: $B \rightarrow D h$ measurements (ADS/GLW and GGSZ)
 - time-dependent methods: $B_s \rightarrow D_s K$
- ▶ Can also be accessed through loop level transitions: $B_{(s)} \rightarrow \pi\pi(KK)$, (see Jan's talk)
- ▶ By looking at the difference on γ measured with and without penguin contributions we can get sensitivity to New Physics (NP)

γ from trees



- ▶ time-integrated measurement methods ($B \rightarrow D\gamma$)
 - GLW – use D mesons decaying to CP eigenstates e.g.: $D \rightarrow K\bar{K}$ and $D \rightarrow \pi\pi$
 - ADS – use anti- $D^0 \rightarrow K^-\pi^+$ for $b \rightarrow u$ transitions (Cabibbo allowed) and $D^0 \rightarrow K^+\pi^-$ (Doubly Cabibbo Suppressed) for $b \rightarrow c$ transitions. One has to know strong phases from D decays.
 - GGSZ/Dalitz – use self-conjugate 3-body final states of the D to be resolved in the Dalitz plane. $D^0 \rightarrow K_s \pi\pi$. So far the most precise gamma determination.
- ▶ time-dependent measurement methods, e.g. $B_s \rightarrow D_s K$
 - Aleksan, Dunietz, Kayser [Z. Phys. C, 54 (1992), p. 653], Fleischer [arXiv:hep-ph/0304027v2]

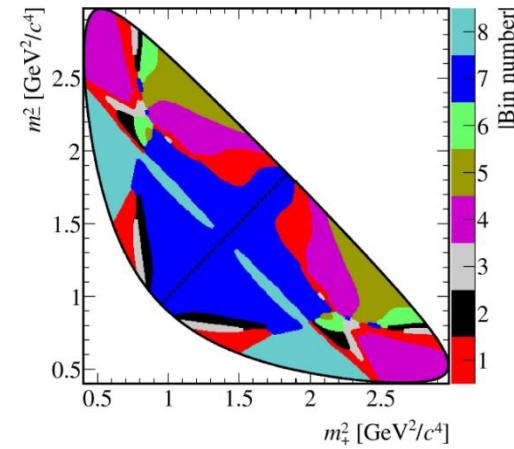
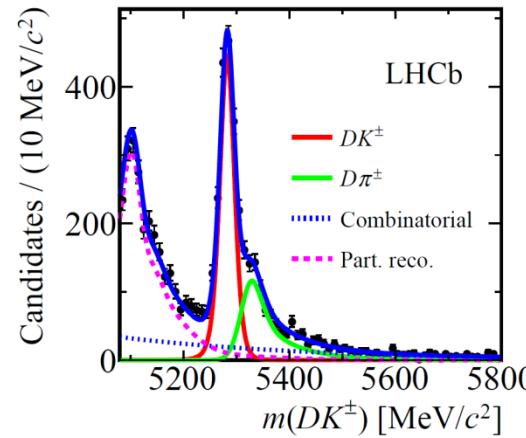
GGSZ analysis at LHCb

- Model independent $B^\pm \rightarrow D(K_0^0 h^+ h^-) K^\pm$ analysis (LHCb-PAPER-2014-041)
 - D strong phase variation measured by CLEO-c in a particular binning scheme
 - Count the number of events in region of Dalitz plot

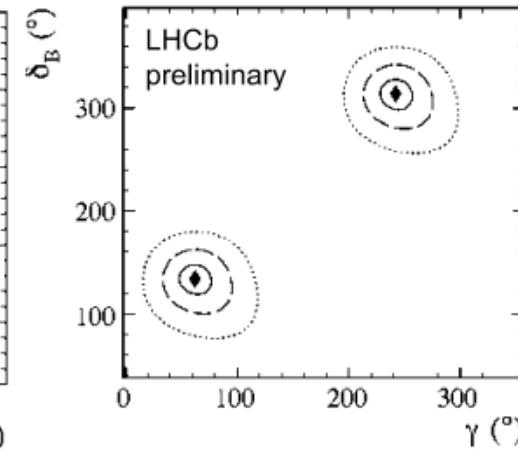
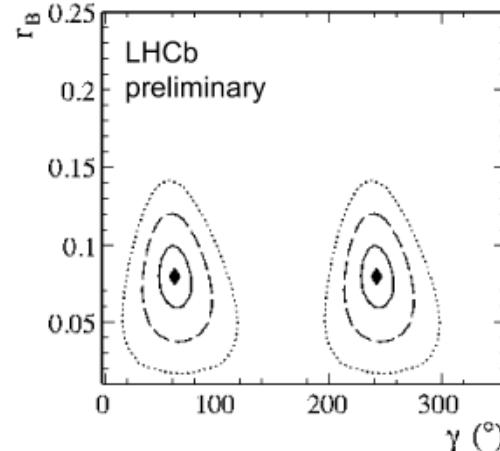
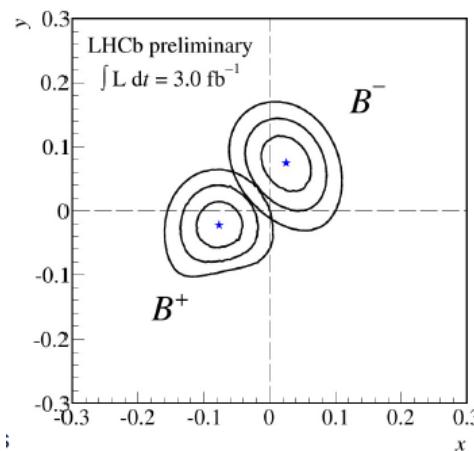
$$N_i^\pm = h \left(K_{\pm i} + r_B^2 K_{\mp i} + 2\sqrt{K_i K_{-i}} [x_\pm c_i \pm y_\pm s_i] \right)$$

D from B^\pm events in bin i of Dalitz plot
Fraction of events in bin for pure D^0 sample with the efficiency profile of signal
 $x_\pm = r_B \cos(\delta_B \pm \gamma)$
 $y_\pm = r_B \sin(\delta_B \pm \gamma)$

- K_i are inputs from other LHCb decays – use $B^0 \rightarrow D^{*+} \mu^- \nu$, $D^{*+} \rightarrow D^0 \pi^+$
 - Simultaneous mass fit in all bins for x_\pm , y_\pm
 - Combined 3 fb^{-1}



GGSZ analysis at LHCb



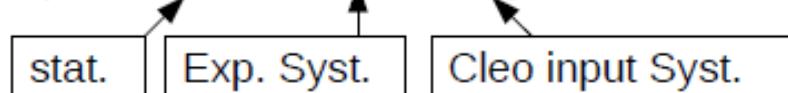
Contours correspond to 39.3%, 86.5% 98.9% CL

$$x_+ = (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2}$$

$$x_- = (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2}$$

$$y_+ = (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2}$$

$$y_- = (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2}$$



$$r_B = 0.080^{+0.019}_{-0.021}$$

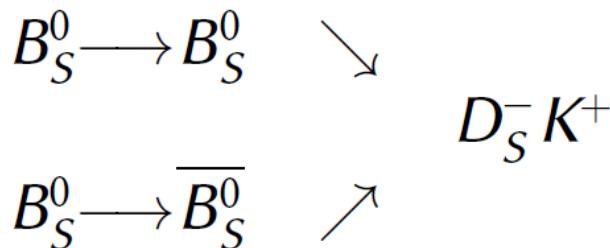
$$\gamma = (62^{+15})^\circ$$

$$\delta_B = (134^{+14})^\circ$$

► One 3fb^{-1} LHCb measurement as good as B factories or 1fb^{-1} combination of LHCb!

- BaBar [arXiv:1301.3283]: $\gamma = (69^{+17}_{-16})^\circ$
- Belle [arXiv:1301.2033]: $\gamma = (68^{+15}_{-14})^\circ$,
- 1fb^{-1} LHCb combination [arXiv:1305.2050v3] : $\gamma = (72^{+15}_{-16})^\circ$,

Time-dependent $B_s \rightarrow D_s K$



- ▶ Interference between decays with and without mixing
- ▶ Not colour-suppressed

▶ Four interfering decay amplitudes:

$$\begin{aligned} \frac{d\Gamma_{B_S^0 \rightarrow f}(t)}{dt e^{-\Gamma t}} &\sim |A_f|^2 (1 + |\lambda_f|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) + C_f \cos(\Delta m t) - S_f \sin(\Delta m t) \right) \\ \frac{d\Gamma_{\bar{B}_S^0 \rightarrow f}(t)}{dt e^{-\Gamma t}} &\sim |A_f|^2 \left| \frac{p}{q} \right|^2 (1 + |\lambda_f|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) - C_f \cos(\Delta m t) + S_f \sin(\Delta m t) \right) \\ \frac{d\Gamma_{\bar{B}_S^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma t}} &\sim |\bar{A}_{\bar{f}}|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\bar{f}}^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) - C_{\bar{f}} \cos(\Delta m t) + S_{\bar{f}} \sin(\Delta m t) \right) \\ \frac{d\Gamma_{B_S^0 \rightarrow \bar{f}}(t)}{dt e^{-\Gamma t}} &\sim |\bar{A}_{\bar{f}}|^2 \left| \frac{q}{p} \right|^2 (1 + |\bar{\lambda}_{\bar{f}}|^2) \left(\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A_{\bar{f}}^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma t}{2}\right) + C_{\bar{f}} \cos(\Delta m t) - S_{\bar{f}} \sin(\Delta m t) \right) \end{aligned}$$

Observables:

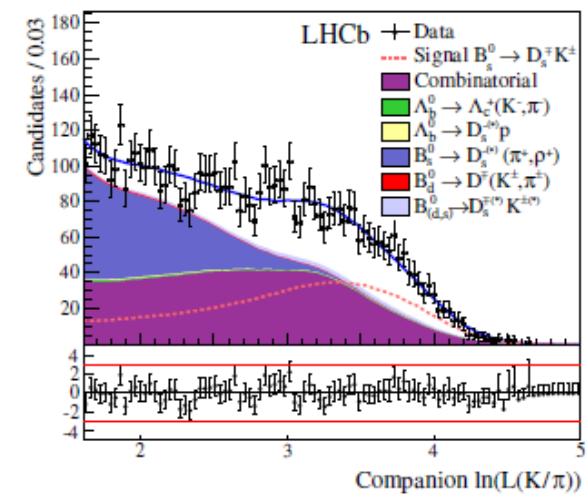
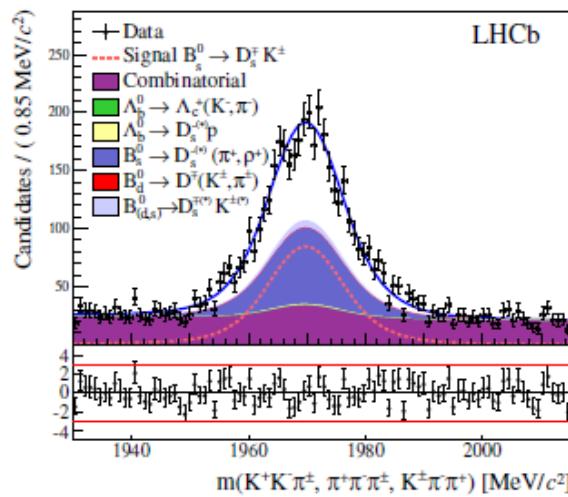
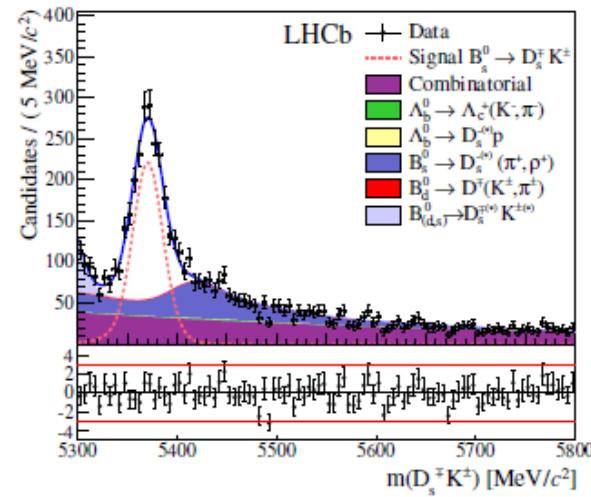
$$C_f = \frac{1 - r_{D_s K}^2}{1 + r_{D_s K}^2},$$

$$A_f^{\Delta\Gamma} = \frac{2r_{D_s K} \cos(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{2r_{D_s K} \cos(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s K}^2},$$

$$S_f = \frac{2r_{D_s K} \sin(\delta - (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}, \quad S_{\bar{f}} = \frac{2r_{D_s K} \sin(\delta + (\gamma - 2\beta_s))}{1 + r_{D_s K}^2}.$$

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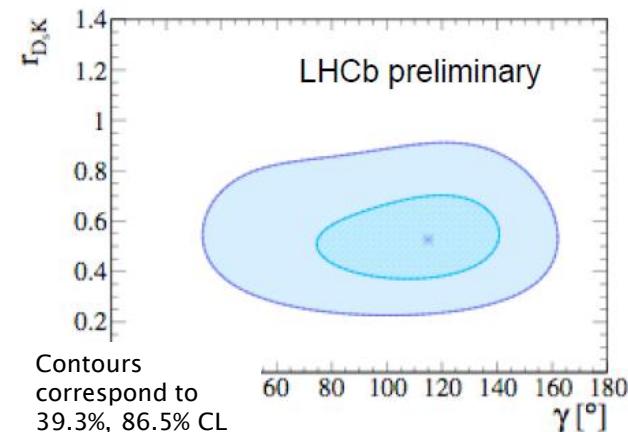
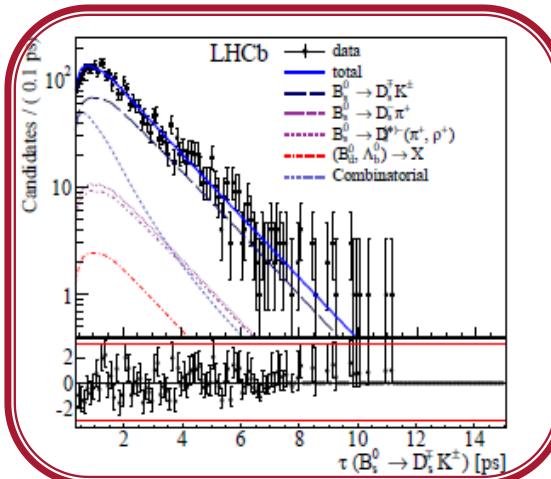
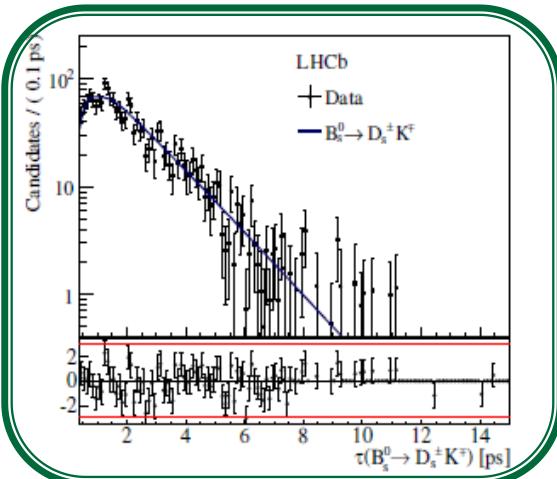
Time-dependent $B_s \rightarrow D_s K$



- ▶ Two independent approaches:
 - sFit: Using 3D fit in $m(B)$, $m(D)$, particle identification (PID) of the bachelor particle to produce sWeights and subtract the background. Fitting time dependent model to signal only
 - cFit: Using 4D model (with additional time variable) to describe data sample. Requires full description of backgrounds in time.

[LHCb-PAPER-2014-038](#)

Time-dependent $B_s \rightarrow D_s K$



| Parameter | sFit fitted value |
|------------------------------|---------------------------|
| C_f | $0.52 \pm 0.25 \pm 0.04$ |
| $A_f^{\Delta\Gamma}$ | $0.29 \pm 0.42 \pm 0.17$ |
| $A_{\bar{f}}^{\Delta\Gamma}$ | $0.14 \pm 0.41 \pm 0.18$ |
| S_f | $-0.90 \pm 0.31 \pm 0.06$ |
| $S_{\bar{f}}$ | $-0.36 \pm 0.34 \pm 0.06$ |

| Parameter | cFit fitted value |
|------------------------------|---------------------------|
| C_f | $0.53 \pm 0.25 \pm 0.04$ |
| $A_f^{\Delta\Gamma}$ | $0.37 \pm 0.42 \pm 0.20$ |
| $A_{\bar{f}}^{\Delta\Gamma}$ | $0.20 \pm 0.41 \pm 0.20$ |
| S_f | $-1.09 \pm 0.33 \pm 0.08$ |
| $S_{\bar{f}}$ | $-0.36 \pm 0.34 \pm 0.08$ |

$$\gamma = (115^{+28}_{-43})^\circ$$

$$r_{D_s K} = (0.53^{+0.17}_{-0.16})$$

$$\delta_{D_s K} = (3^{+19}_{-20})^\circ$$

- ▶ First measurement from $B_s \rightarrow D_s K$
- ▶ Only 1 fb^{-1} used

[LHCb-PAPER-2014-038](#)

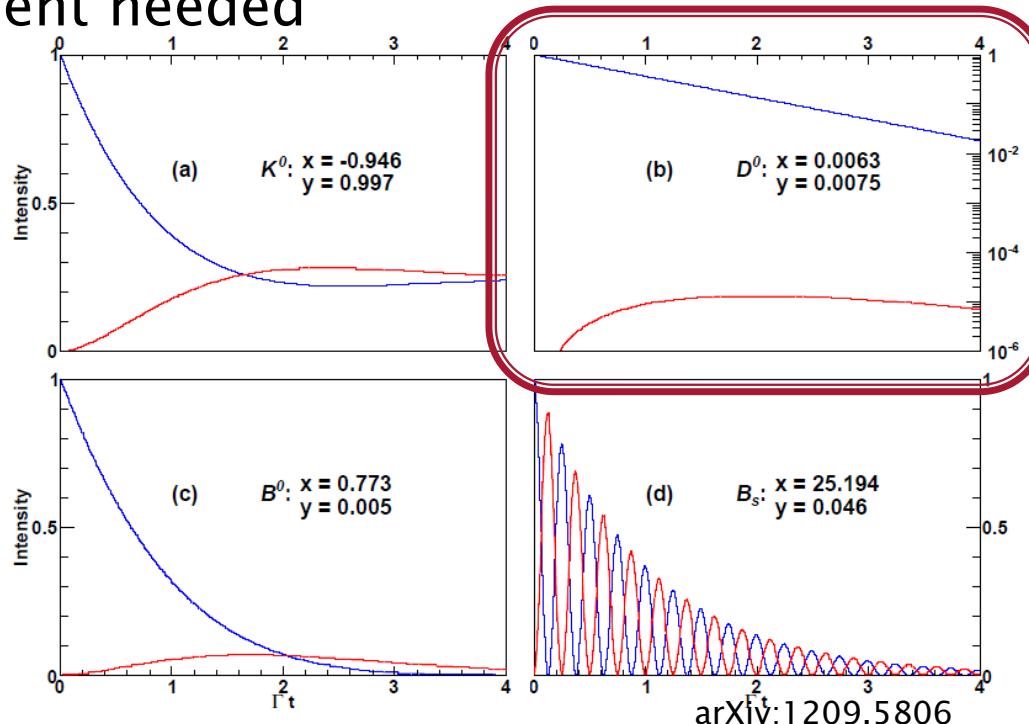
CPV in charm sector

► Predictions

- Two parameters describes mixing: $x = \Delta m / \Gamma$ and $y = \Delta \Gamma / 2\Gamma$
- very small x, y ($|x|, |y| < 10^{-2}$) in charm sector, therefore mixing is very slow
- Small CPV($< 10^{-3}$)
- Very precise measurement needed

► Motivations:

- New Physics can enhance the CPV effects
- No evidence of CPV in charm sector discovered



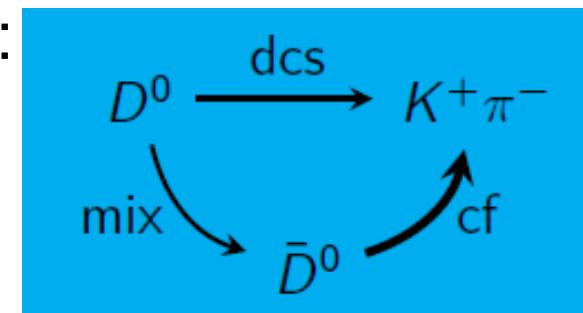
arXiv:1209.5806

Mixing in $D^0 \rightarrow K^- \pi^+$

- Measure the time dependent ratio between Right Sign and Wrong Sign decays:

$$R(t) = \frac{N(D^0 \rightarrow K^+ \pi^-)}{N(D^0 \rightarrow K^- \pi^+)}$$

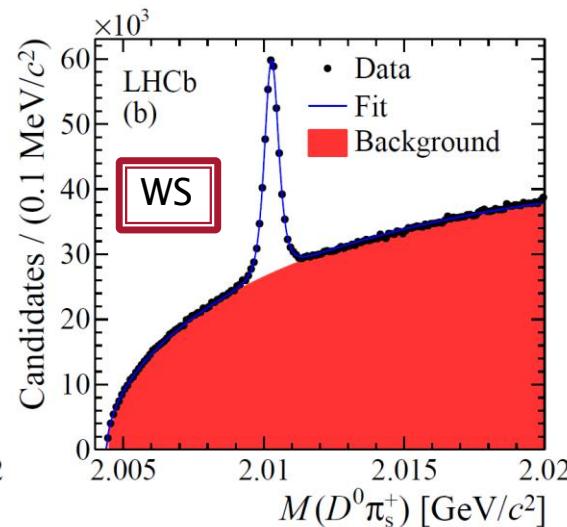
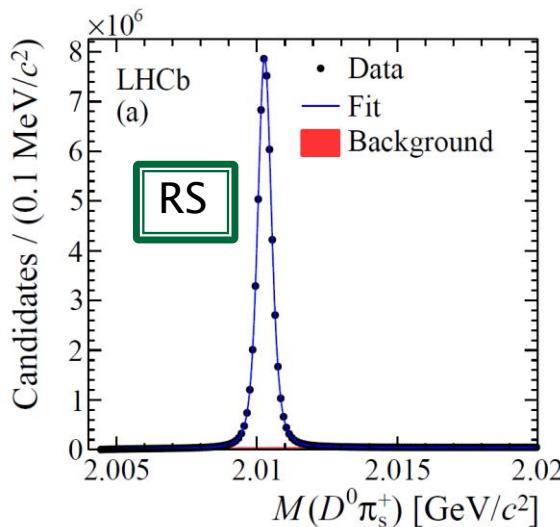
$$R(t) \approx R_D + \sqrt{R_D} y' \left(\frac{t}{\tau} \right) + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau} \right)^2$$



Ratio between DCS/CF

The interference of DCS and mixed decay

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

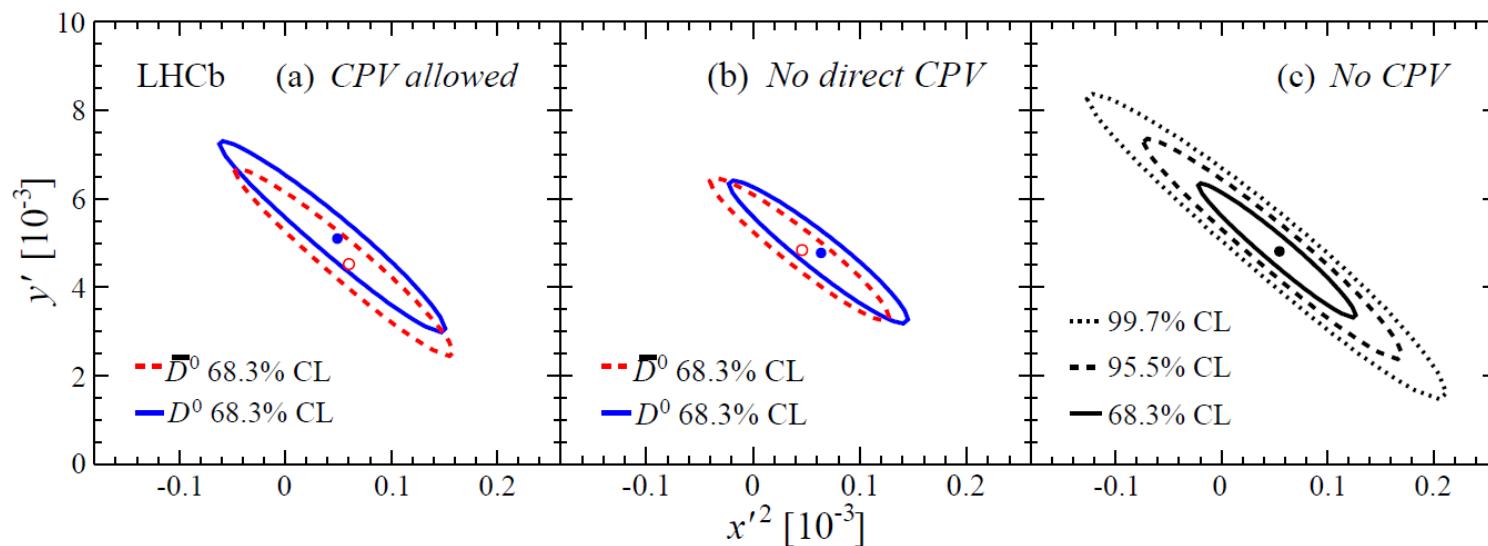


DCS – Doubly Cabibbo Suppressed

CF – Cabibbo Favoured

- Analysis uses 3 fb^{-1} of data
- Huge samples of D candidates: **230k WS** and **54M RS**

Mixing in $D^0 \rightarrow K^- \pi^+$



| Parameter | Value |
|---|-----------------------------|
| Direct and indirect <i>CP</i> violation | |
| $R_D^+ [10^{-3}]$ | $3.545 \pm 0.082 \pm 0.048$ |
| $y'^+ [10^{-3}]$ | $5.1 \pm 1.2 \pm 0.7$ |
| $x'^{2+} [10^{-5}]$ | $4.9 \pm 6.0 \pm 3.6$ |
| $R_D^- [10^{-3}]$ | $3.591 \pm 0.081 \pm 0.048$ |
| $y'^- [10^{-3}]$ | $4.5 \pm 1.2 \pm 0.7$ |
| $x'^{2-} [10^{-5}]$ | $6.0 \pm 5.8 \pm 3.6$ |
| χ^2/ndf | 85.9/98 |

| Parameter | Value |
|-------------------------------|-----------------------------|
| No direct <i>CP</i> violation | |
| $R_D [10^{-3}]$ | $3.568 \pm 0.058 \pm 0.033$ |
| $y'^+ [10^{-3}]$ | $4.8 \pm 0.9 \pm 0.6$ |
| $x'^{2+} [10^{-5}]$ | $6.4 \pm 4.7 \pm 3.0$ |
| $y'^- [10^{-3}]$ | $4.8 \pm 0.9 \pm 0.6$ |
| $x'^{2-} [10^{-5}]$ | $4.6 \pm 4.6 \pm 3.0$ |
| χ^2/ndf | 86.0/99 |

| Parameter | Value |
|------------------------|-----------------------------|
| No <i>CP</i> violation | |
| $R_D [10^{-3}]$ | $3.568 \pm 0.058 \pm 0.033$ |
| $y' [10^{-3}]$ | $4.8 \pm 0.8 \pm 0.5$ |
| $x'^2 [10^{-5}]$ | $5.5 \pm 4.2 \pm 2.6$ |
| χ^2/ndf | 86.4/101 |

- ▶ Results consisted with No CPV
- ▶ The most precise charm mixing measurement

Time-integrated CPV

- ▶ Using $D^0 \rightarrow \pi^-\pi^+$ and $D^0 \rightarrow K^-K^+$ decays to measure an asymmetry:

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow h^-h^+) - \Gamma(\bar{D}^0 \rightarrow h^-h^+)}{\Gamma(D^0 \rightarrow h^-h^+) + \Gamma(\bar{D}^0 \rightarrow h^-h^+)}$$

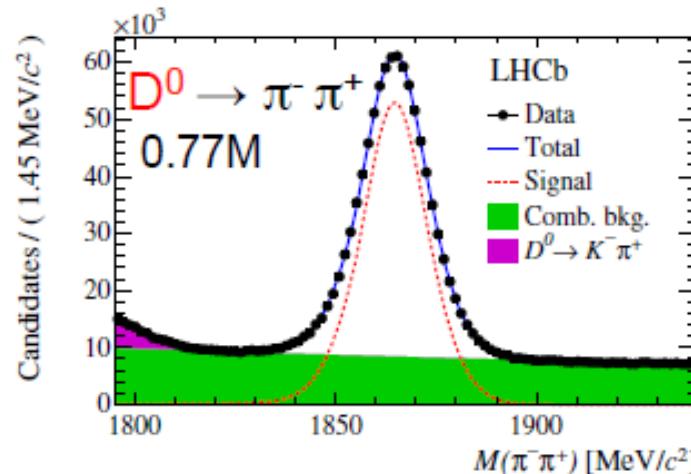
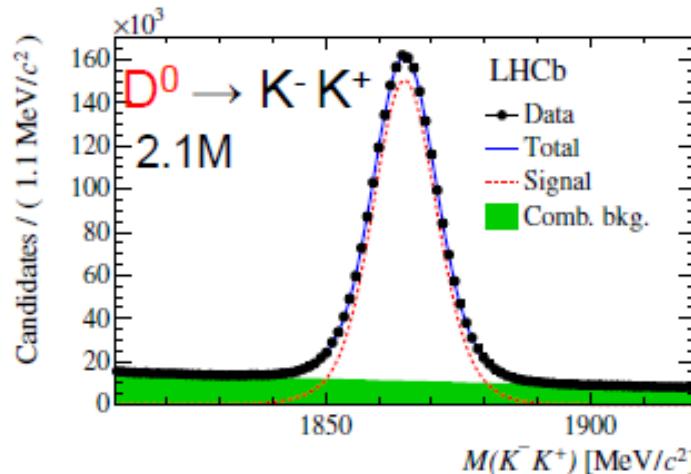
- ▶ Measured raw asymmetry includes not only CP dependent part but also detector effects and production asymmetry:

$$A_{RAW}(f) = A_{CP}(f) + A_{DET} + A_{Prod}$$

- ▶ Taking the difference cancels detection and production asymmetries:

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

Time-integrated CPV



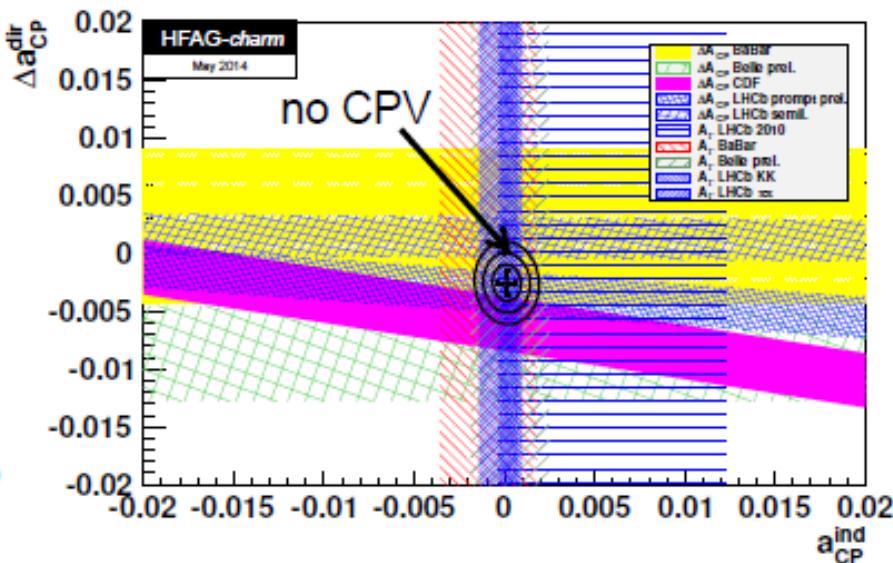
$$\Delta A_{CP} = (0.14 \pm 0.15 \pm 0.10)\%$$

- Using 3fb^{-1} of data
- Exact CP asymmetries using combination of Cabibbo Favoured modes where CP asymmetry is not expected:

$$A_{CP}(K^+K^-) = (-0.06 \pm 0.15 \pm 0.10)\%$$

$$A_{CP}(\pi^+\pi^-) = (-0.20 \pm 0.19 \pm 0.10)\%$$

- No CP violation observed



Summary

- ▶ GGSZ with 3fb^{-1} has improved the gamma precision
- ▶ Other $B \rightarrow D\gamma$ analysis will soon follow with update to full 2011+2012 samples
- ▶ Next LHCb γ combination on the way

- ▶ LHCb has provided the most precise D mixing measurement
- ▶ LHCb established new limits on direct CPV and CPV in mixing of D mesons
- ▶ Sensitivity to charm CPV will be more exciting with more data provided in run2 of the LHC



AGH



Thank You!



AGH



Backup

▶ ADS/GLW

- $B^- \rightarrow D^0 h^-$, ($h = \pi, K$), $D^0 \rightarrow hh$ ([arxiv:1203.3662](https://arxiv.org/abs/1203.3662))
- $B^- \rightarrow D^0 h^-$, ($h = \pi, K$), $D^0 \rightarrow K\pi\pi\pi$ ([arxiv:1303.4646](https://arxiv.org/abs/1303.4646))
- $B^0 \rightarrow D^0 K^{*0}$, $D^0 \rightarrow hh$ ([arxiv:1212.5205](https://arxiv.org/abs/1212.5205))
- $B^- \rightarrow D^0 K^-\pi^+\pi^-$, ($h = \pi, K$), $D^0 \rightarrow hh$ ([LHCb-CONF-2012-021](#))

▶ GGSZ

- $B^- \rightarrow D^0 K^-$, $D^0 \rightarrow K_s^0 h^+ h^-$, ($h = \pi, K$) ([arxiv:1203.3662](https://arxiv.org/abs/1203.3662))

▶ Time-dependent

- $B_s \rightarrow D_s K$ ([LHCb-PAPER-2014-038](#))

Current charm analyses

- ▶ D^0 mixing – [PRL 111 \(2013\) 251801](#)
- ▶ A_Γ asymmetry – [PRL 112 \(2014\) 041801](#)
- ▶ Direct CPV in $D^+ \rightarrow K_s^0 K^+$ and $D_s^+ \rightarrow K_s^0 \pi^+ -$
[arXiv:1406.2624](#)
- ▶ Time integrated CPV in $D^0 \rightarrow K^+ K^-$ and
 $D^0 \rightarrow \pi^+ \pi^-$ – [arXiv:1405.2797](#)
- ▶ CPV in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ LHCb-PAPER-2014-046

LHCb upgrade

Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved by the LHCb upgrade experiment. Systematic uncertainties are expected to be non-negligible for the most precise sensitivities do not include new results presented at ICHEP 2012 or CKM 2012.

EPJ C73 (2013)2373

| Type | Observable | Current precision | LHCb 2018 | Upgrade (50 fb^{-1}) | Theory uncertainty |
|---------------------------|---|---------------------------------------|-----------------------|----------------------------------|-----------------------|
| B_s^0 mixing | $2\beta_s (B_s^0 \rightarrow J/\psi \phi)$ | 0.10 [138] | 0.025 | 0.008 | ~ 0.003 |
| | $2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$ | 0.17 [214] | 0.045 | 0.014 | ~ 0.01 |
| | a_d^s | 6.4×10^{-3} [43] | 0.6×10^{-3} | 0.2×10^{-3} | 0.03×10^{-3} |
| Gluonic penguins | $2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\phi)$ | — | 0.17 | 0.03 | 0.02 |
| | $2\beta_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$ | — | 0.13 | 0.02 | < 0.02 |
| | $2\beta_s^{\text{eff}}(B^0 \rightarrow \phi K_S^0)$ | 0.17 [43] | 0.30 | 0.05 | 0.02 |
| Right-handed currents | $2\beta_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$ | — | 0.09 | 0.02 | < 0.01 |
| | $\tau^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$ | — | 5 % | 1 % | 0.2 % |
| Electroweak penguins | $S_3(B^0 \rightarrow K^{*0}\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$ | 0.08 [67] | 0.025 | 0.008 | 0.02 |
| | $s_0 A_{\text{FB}}(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ | 25 % [67] | 6 % | 2 % | 7 % |
| | $A_1(K\mu^+\mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$ | 0.25 [76] | 0.08 | 0.025 | ~ 0.02 |
| | $\mathcal{B}(B^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)$ | 25 % [85] | 8 % | 2.5 % | $\sim 10\%$ |
| Higgs | $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ | 1.5×10^{-9} [13] | 0.5×10^{-9} | 0.15×10^{-9} | 0.3×10^{-9} |
| Penguins | $\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ | — | ~ 100 % | ~ 35 % | ~ 5 % |
| Unitarity triangle angles | $\gamma (B \rightarrow D^{(*)}K^{(*)})$ | $\sim 10\text{--}12^\circ$ [244, 258] | 4° | 0.9° | negligible |
| | $\gamma (B_s^0 \rightarrow D_s K)$ | — | 11° | 2.0° | negligible |
| | $\beta (B^0 \rightarrow J/\psi K^0)$ | 0.8° [43] | 0.6° | 0.2° | negligible |
| Charm | A_T | 2.3×10^{-3} [43] | 0.40×10^{-3} | 0.07×10^{-3} | — |
| CP violation | ΔA_{CP} | 2.1×10^{-3} [18] | 0.65×10^{-3} | 0.12×10^{-3} | — |