Update of γ in $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ with external strong-phase inputs

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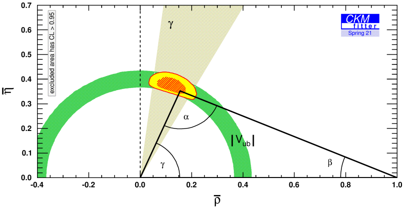
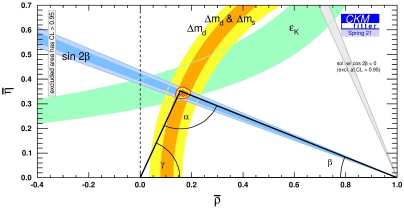
Introduction to γ and *CP* violation

- CPV in SM is described by the Unitary Triangle, with angles α, β, γ
- The angle $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is very important:
  1. Negligible theoretical uncertainties: Ideal SM benchmark
  2. Accessible at tree level: Indirectly probe New Physics that enter loops
  3. Compare with a global CKM fit: Is the Unitary Triangle a triangle?



(a) Tree level: $\gamma = \left(72.1^{+5.4}_{-5.7}\right)^\circ$

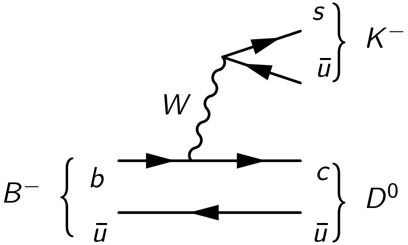


(b) Loop level: $\gamma = \left(65.5^{+1.1}_{-2.7}\right)^\circ$

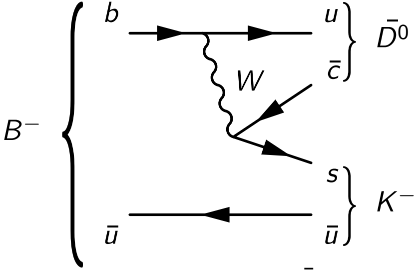
CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at: http://ckmfitter.in2p3.fr

Sensitivity through interference

Measure γ through interference effects in $B^\pm \to DK^\pm$



Favoured $B^- \to D^0 K^-$



Suppressed $B^- \to \bar{D}^0 K^-$

- Superposition of D^0 and $\bar{D}^0$
  - Consider $D^0/\bar{D}^0$ decays to the same final state, such as $D \to K^+K^-$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

$$\mathcal{A}(B^-) = \mathcal{A}_B\left(\mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)}\mathcal{A}_{\bar{D}^0}\right)$$
$$\mathcal{A}(B^+) = \mathcal{A}_B\left(\mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)}\mathcal{A}_{D^0}\right)$$

Multi-body D decays

This talk: Discuss $D \to K^+K^-\pi^+\pi^-$, where interference effects vary across phase space

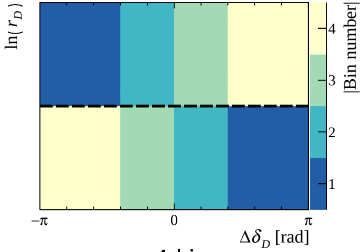
- Strong-phase difference δ_D is a function of phase space
- Compare yields of B^+ and B^- and determine the asymmetry <u>in local phase space regions</u>

$$
\begin{tikzcd}
 & D^0K^- \arrow[dr, bend left, "\mathcal{A}_{D^0}(\Phi)"] & \\
B^- \arrow[ur, bend left, "\mathcal{A}_B"] \arrow[dr, bend right, "\mathcal{A}_B r_B e^{i(\delta_B-\gamma)}"'] & & DK^- \\
 & \bar{D}^0K^- \arrow[ur, bend right, "\mathcal{A}_{\bar{D}^0}(\Phi)"'] &
\end{tikzcd}
$$

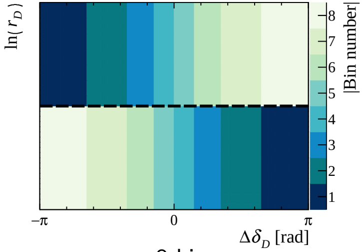
$$
\begin{aligned}
|\mathcal{A}(B^-)|^2 \propto\ & |\mathcal{A}_{D^0}(\Phi)|^2 + r_B^2|\mathcal{A}_{\bar{D}^0}(\Phi)|^2 \\
& + 2r_B|\mathcal{A}_{D^0}(\Phi)||\mathcal{A}_{\bar{D}^0}(\Phi)|\cos(\delta_B - \gamma + \delta_D)
\end{aligned}
$$

Multi-body D decays

- Interpretation of γ from the multi-body charm decays require external inputs of the charm strong-phase differences
- Measure model-independent strong-phases at a charm factory, such as BESIII, using an optimised binning scheme



4 bins



8 bins

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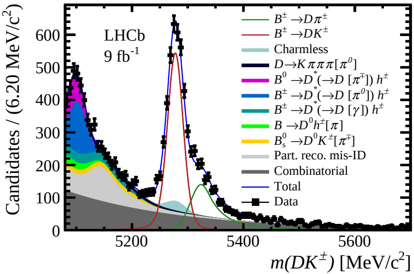
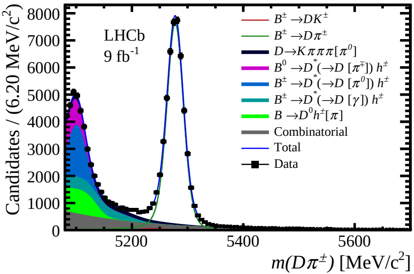
Phase-space binned $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

Fully charged final state $\implies$ Highly suitable for LHCb





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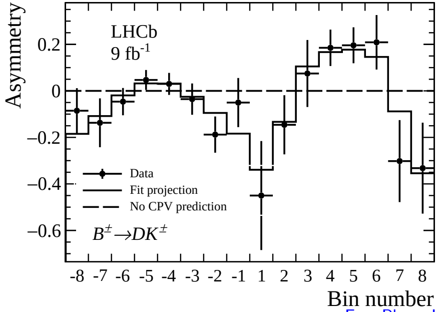
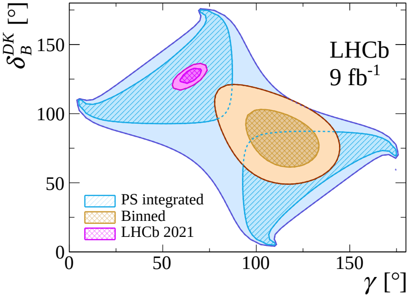
- $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ signal yield:
  - $B^\pm \to DK^\pm$: 3026 ± 38
  - $B^\pm \to D\pi^\pm$: 44349 ± 218

Phase-space binned $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

From the phase-space binned asymmetries, we obtain:

$$\gamma = (116^{+12}_{-14})^\circ$$





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How will this evolve with model-independent BESIII inputs?

Reminder of formalism

Key free parameters in the fit:

- γ (obviously)
- r_B, δ_B: Hadronic parameters of $B^\pm \to DK^\pm$
- c_i, s_i: Charm strong-phase parameters

$B^\pm \to DK^\pm$ yield in bin i

$$\hat{N}^\pm_{\pm i} = h_{B^\pm}\left(F_i + r_B^2 F_{+i} + 2r_B\sqrt{F_+F_{-i}}\left(\cos(\delta_B \pm \gamma)c_i - \sin(\delta_B \pm \gamma)s_i\right)\right)$$

In principle straightforward: Fit $B^\pm$ yields and extract γ

Reduce binning to 2×4 bins to accommodate BESIII statistics:
Current analysis uses $8\,\mathrm{fb}^{-1}$ at $\psi(3770)$, expect $20\,\mathrm{fb}^{-1}$ in the near future

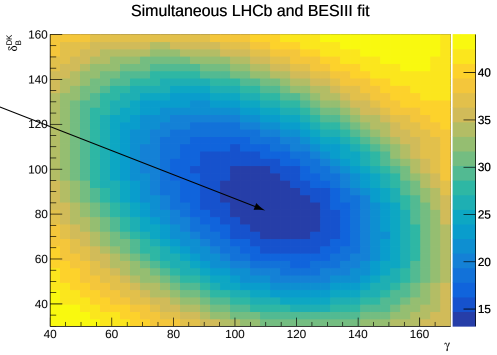
Cross check: Model-dependent fit of γ

Construct log-likelihood function using $B^\pm \to DK^\pm$ yields and model-predicted c_i and s_i:

$$\mathcal{L} = \frac{1}{2}\sum_i \left(\frac{N_i - \hat{N}_i}{\sigma_i}\right)^2$$

Fit result:
$\gamma = (112 \pm 13)^\circ$

Consistent with 2×8 bins ✓

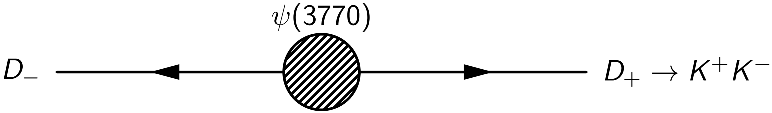


Strong-phase measurement at charm factories

Quick digression: Charm factories 101

Consider charm production at threshold: $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$

- $\psi(3770) \to D^0\bar{D}^0$ decay conserves $\mathcal{C} = -1$



- If, for example, the tag is CP-even, $D_+ \to K^+K^-$, the other D meson is forced into an CP-odd state

Quick digression: Charm factories 101

Consider charm production at threshold: $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$

- CP-odd wave function and decay rate:

$$\mathcal{A}(D_-) = \mathcal{A}(D^0) - \mathcal{A}(\bar{D}^0) \implies$$

$$|\mathcal{A}(D_-)|^2 = |\mathcal{A}(D^0)|^2 + |\mathcal{A}(\bar{D}^0)|^2 - 2|\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)|\cos(\delta_D)$$

With CP tags, one can directly access $\cos(\delta_D)$

Quick digression: Charm factories 101

CP tags

$$N_i \propto K_i + K_{-i} \mp 2\sqrt{K_i K_{-i}} c_i$$

Self-conjugate multi-body tags

$$N_{ij} \propto K_i K'_{-j} + K_{-i} K'_j - 2\sqrt{K_i K_{-i} K'_j K'_{-j}} (c_i c'_j + s_i s'_j)$$

1. More than 10 different CP tags $\implies$ Can measure c_i precisely
2. Only $D \to K^0_S h^+ h^-$ tag is sensitive to s_i $\implies$ Worse s_i precision

Simultaneous fit of LHCb and BESIII bin yields

To include the effect of c_i and s_i from the BESIII measurement, perform a simultaneous fit:

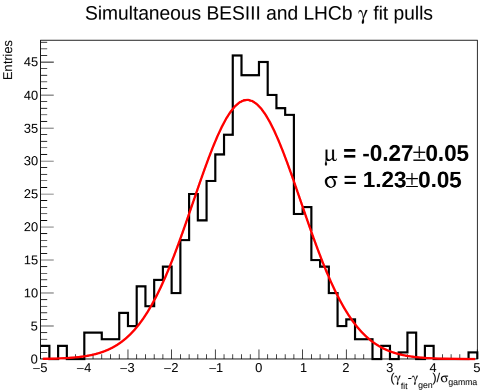
$$\mathcal{L} = \frac{1}{2}\sum_i \left(\frac{N_i - \hat{N}_i}{\sigma_i}\right)^2 + \mathcal{L}_{BESIII}$$

Why not simply assign a systematic uncertainty?

1. Contribution of γ uncertainty from BESIII could be large, and may move the central value of γ
2. Uncertainties of s_i are expected to be very non-Gaussian, which could propagate into non-Gaussian uncertainties of γ

Simultaneous fit of LHCb and BESIII bin yields

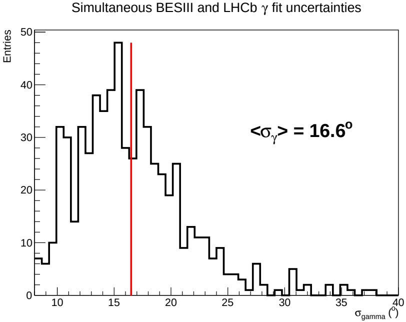
Run toys using expected BESIII yields and bin yields from $B^{\pm} \to [K^{+}K^{-}\pi^{+}\pi^{-}]_{D}h^{\pm}$ paper:



Stable fit with minimal bias and small undercoverage

Simultaneous fit of LHCb and BESIII bin yields

Study expected γ uncertainty, after correcting for coverage:

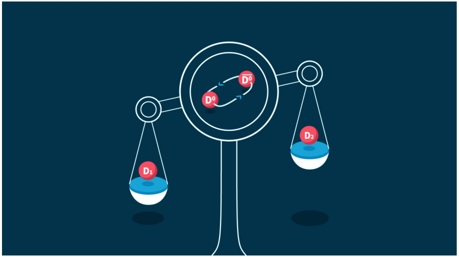


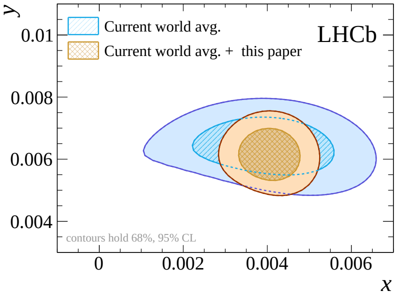
Conclusion from toy studies:

1. Well behaved fit, with expected sensitivity of $\sigma(\gamma) = 16.6^\circ$
2. Only small corrections to bias and coverage required
3. Will update γ result once BESIII measurement is released

Charm mixing studies with multi-body decays

The non-zero mass difference between D^0 and $\bar{D}^0$ was measured using the multi-body decay $D \to K_S^0\pi^+\pi^-$





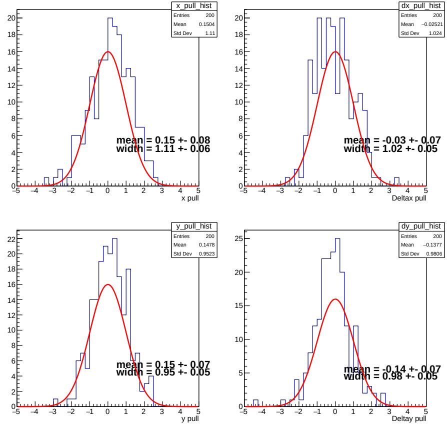
Phys. Rev. Lett **127**, 111801 (2021)

Charm strong-phase differences were crucial for this measurement!

Ongoing charm mixing study of $D \to h^+h^-\pi^+\pi^-$

by Jairus Tristan Patoc

- Prompt $D^{*+} \to D^0\pi^+$ sample
- Study $D^0 \to h^+h^-\pi^+\pi^-$
- Run 2 ($6\,\mathrm{fb}^{-1}$)
- Expected yields are
  - $K^+K^-\pi^+\pi^-$: 4 million
  - $\pi^+\pi^-\pi^+\pi^-$: 12 million
- Current work:
  1. Sensitivity and bias studies
  2. Optimised selection



Charm mixing studies with multi-body decays

Mixing equations depend on x and y, but also c_i and s_i:

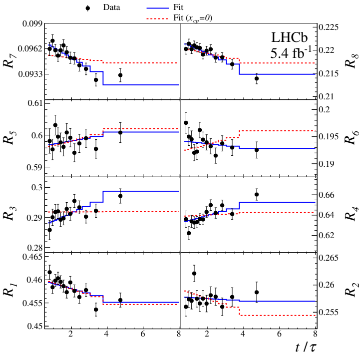
1. Charm mixing equations

$$N_{D^0}(+i, \langle t\rangle_j) = K_{+i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j(yc_i + xs_i)$$
$$N_{D^0}(-i, \langle t\rangle_j) = K_{-i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j(yc_i - xs_i)$$

1. Fit the mixing equations
2. Fit the ratio of mixing equations

2. Charm mixing ratio (bin-flip)

$$R_i = \frac{K_{+i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j(yc_i + xs_i)}{K_{-i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j(yc_i - xs_i)}$$



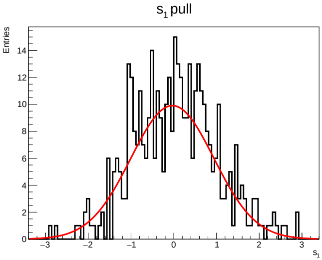
Charm mixing studies with multi-body decays

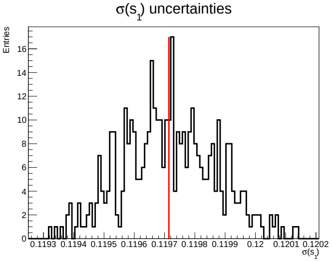
Alternative strategy: Fix x and y, and measure c_i and s_i

1. Charm mixing equations

$$N_{D^0}(+i, \langle t \rangle_j) = K_{+i} - \sqrt{K_{+i}K_{-i}}\langle t \rangle_j (yc_i + xs_i)$$
$$N_{D^0}(-i, \langle t \rangle_j) = K_{-i} - \sqrt{K_{+i}K_{-i}}\langle t \rangle_j (yc_i - xs_i)$$

- Two independent equations per bin, two observables per bin
- Similar statistical sensitivity to c_i and s_i, in contrast to BESIII



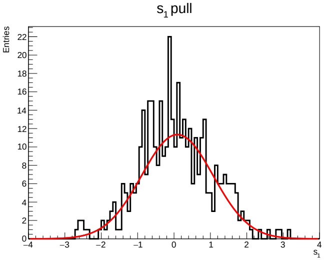


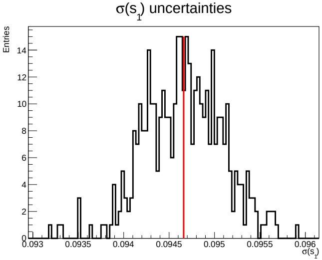
Can also use bin-flip method to fit s_i, but c_i must be fixed

2. Charm mixing ratio (bin-flip)

$$R_i = \frac{K_{+i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j (yc_i + xs_i)}{K_{-i} - \sqrt{K_{+i}K_{-i}}\langle t\rangle_j (yc_i - xs_i)}$$

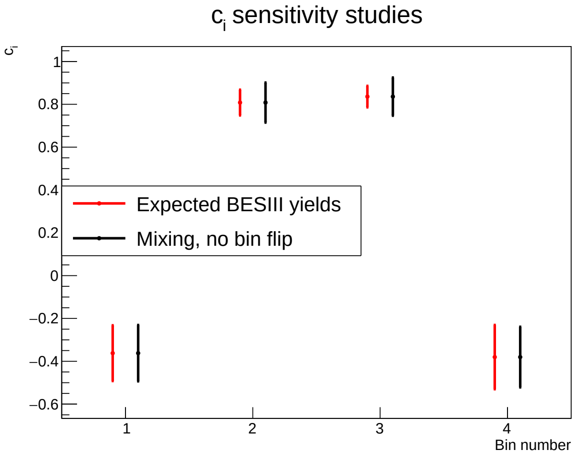
- Only one independent equation per bin
- Sensitivity found to be similar to fitting mixing equations directly





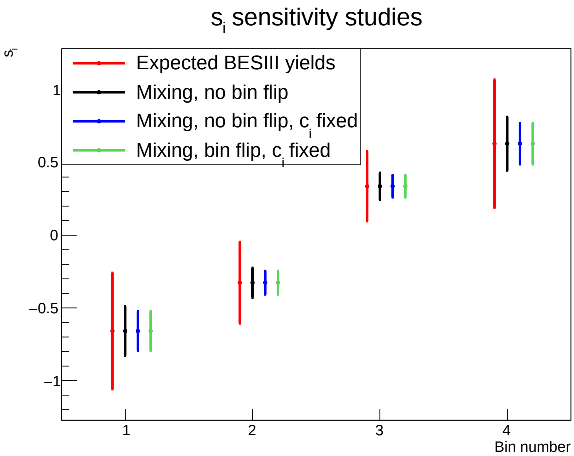
Charm mixing studies with multi-body decays

Sensitivity to c_i: Similar between BESIII and charm mixing at LHCb



- BESIII yields equivalent to $8\,\text{fb}^{-1}$ of $\psi(3770)$
- 4 million $D \to K^+K^-\pi^+\pi^-$ candidates in mixing analysis

Sensitivity to s_i: Significant improvements expected!



- BESIII yields equivalent to $8\,\mathrm{fb}^{-1}$ of $\psi(3770)$
- 4 million $D \to K^+K^-\pi^+\pi^-$ candidates in mixing analysis

Summary and future prospects

Summary:

1. Measurement of γ in $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ is ready to be combined with **model-independent** strong-phase inputs

2. BESIII strong-phase inputs can be further constrained using charm-mixing measurements at LHCb, and provide comparable sensitivity to s_i

Summary and future prospects

Future prospects:

1. Measurement is still statistically limited, and will be significantly improved with LHCb Upgrade I
2. Additional BESIII data and charm-mixing measurements from LHCb will bring strong-phase systematics down further
3. Can extend this strategy to many more four-body modes
   - Studies of $D \to \pi^+\pi^-\pi^+\pi^-$ show similar results

Thanks for your attention!