Model independent measurement of the CKM angle γ with $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ at LHCb and BESIII

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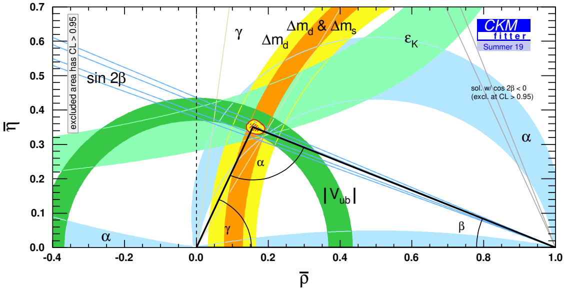
Introduction to γ and CP violation

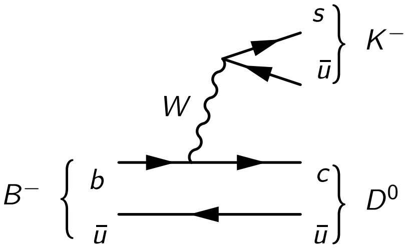
Introduction to γ and *CP* violation

- 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 α, β measurements: Is the Unitary Triangle a triangle?

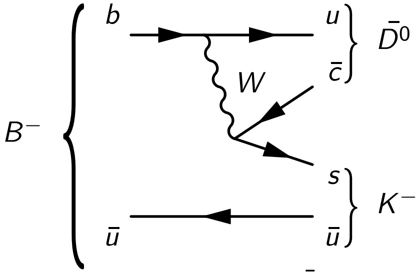


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

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 $\bar{D}^0$
- $b \to u\bar{c}s$ and $b \to c\bar{u}s$ interference $\to$ Sensitivity to γ

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

- The magnitude of interference effects governed by $r_B \approx 0.1$

Sensitivity through interference

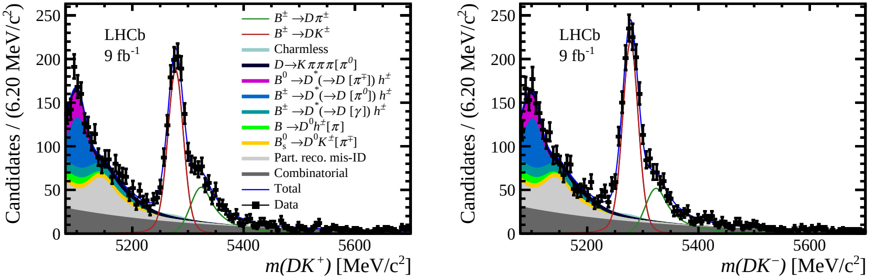
Phase space integrated analysis: Compare yields of B^+ and B^-

Interference depends on γ, diluted by κ when integrated over phase space

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

$$|\mathcal{A}(B^-)|^2 \propto 1 + r_B^2 + 2 r_B \kappa \cos(\delta_B - \gamma)$$

First look at $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$



arXiv:2301.10328

Measuring the $B^\pm \to DK^\pm$ asymmetry $\mathcal{A}$ provide useful constraints on γ, but with some caveats:

1. Interference effects are diluted by a factor $\kappa = 0.46 \pm 0.08$
   - Phys. Rev. D **107**, 032009
2. Four-fold degeneracy:
   - $(\gamma, \delta_B) \to (\delta_B, \gamma)$
   - $(\gamma, \delta_B) \to (\pi - \gamma, \pi - \delta_B)$

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

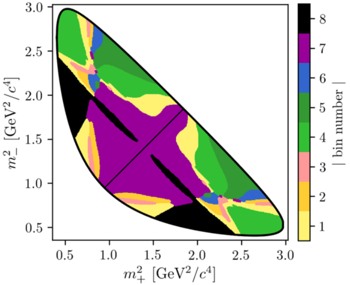
Phase space binned analysis of $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

Our aim: First binned model independent measurement of γ in $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$

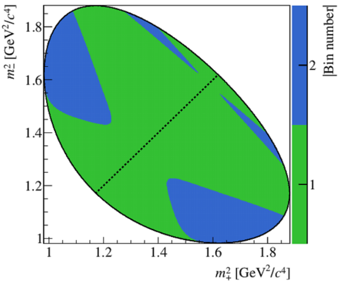
- Model dependent measurement first proposed in 2007
  - Phys. Lett. **B647** (2007) 400 by J. Rademacker and G. Wilkinson
  - FOCUS amplitude model: 14° precision with 1000 candidates
- State of the art amplitude analysis by LHCb:
  - JHEP **02** (2019) 126
  - Exploits the huge dataset of charm decays collected by LHCb
  - Useful for understanding the 5-dimensional phase space
- Use LHCb model to identify regions with large asymmetries
  - Place regions with similar asymmetries together in bins

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

- Analogous to the decays $D^0 \to K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$, where the binning scheme may be visualised on a Dalitz plot



$K_S^0\pi^+\pi^-$



$K_S^0K^+K^-$

- The strong phase δ_D varies across phase space, leading to different asymmetries in each bin
- The amplitude-averaged cosine and sine of δ_D, c_i and s_i, are measured directly in each bin at charm factories

Binning scheme

Binning scheme

A binning scheme must satisfy the following:

- Minimal dilution of strong phases when integrating over bins
- Enhance interference between $B^\pm \to D^0 K^\pm$ and $B^\pm \to \bar{D}^0 K^\pm$

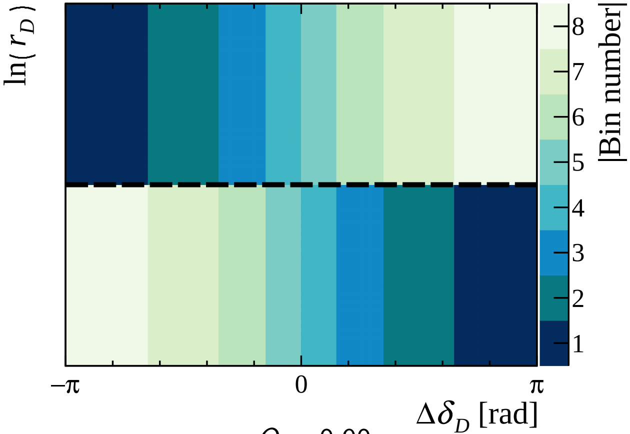
How to bin a 5-dimensional phase space?

1. For each $B^\pm$ candidate, use the amplitude model to calculate

$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

2. Split δ_D into uniformly spaced bins
3. Use the symmetry line $r_D = 1$ to separate bin $+i$ from $-i$
4. Optimise the binning scheme by adjusting the bin boundaries in δ_D

Binning scheme

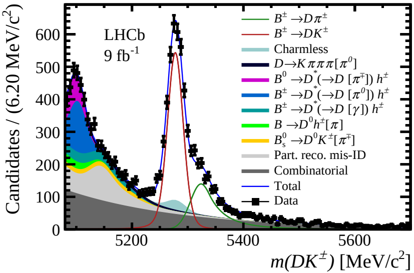


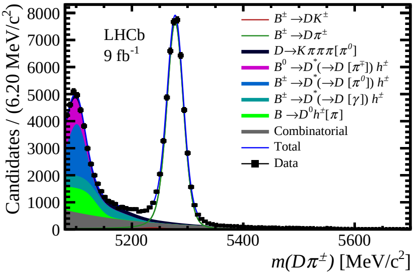
$Q = 0.90$

Bins $i < 0$ on top, $i > 0$ below

Mass fits, CP fit and γ

Global invariant mass fit: Fit everything to understand mass shapes and background yields





Signal yield:

$$B^\pm \to DK^\pm: \quad 3026 \pm 38$$
$$B^\pm \to D\pi^\pm: \quad 44\,349 \pm 218$$

Interpretation of γ

CP fit: Simultaneously fit bin yields and determine physics parameters, using model predictions of c_i and s_i:

$$\begin{aligned}
\gamma &= (116^{+12}_{-14})^\circ, \\
\delta_B^{DK} &= (81^{+14}_{-13})^\circ, \\
r_B^{DK} &= 0.110^{+0.020}_{-0.020}, \\
\delta_B^{D\pi} &= (298^{+62}_{-118})^\circ, \\
r_B^{D\pi} &= 0.0041^{+0.0054}_{-0.0041},
\end{aligned}$$

However, the latest γ and charm combination result is:

$$\gamma = (63.8^{+3.5}_{-3.7})^\circ$$

What went wrong?!

Do we trust the model predicted c_i and s_i, or their uncertainties?

Interpretation of γ

There are several reasons why amplitude models cannot be trusted

1. Amplitude models are just models, which may not reflect reality
2. In fact, the model is fitted to data that knows nothing about δ_D
3. It is impossible to assign an objective error to a model!

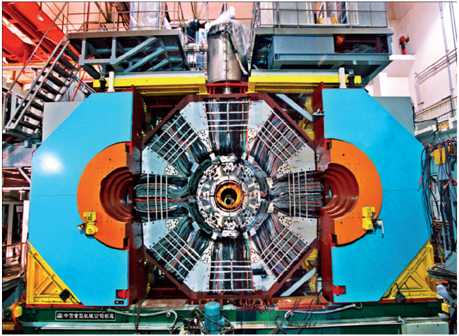
We wish to do a model independent measurement

Let's go and measure c_i and s_i at BESIII!

Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

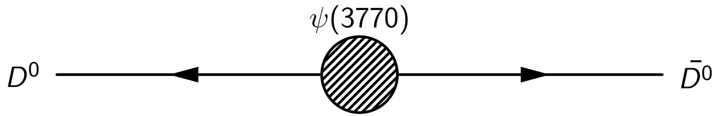
Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

- BESIII: Beijing Spectrometer III, a detector at the Beijing Electron-Positron Collider II, located at IHEP
- e^+e^- collider at the $\psi(3770) \to D^0\bar{D}^0$ threshold
  - 2010-2011: 3 fb^{-1}
  - 2022: 5 fb^{-1}
  - Expect 20 fb^{-1} in total by end of 2024

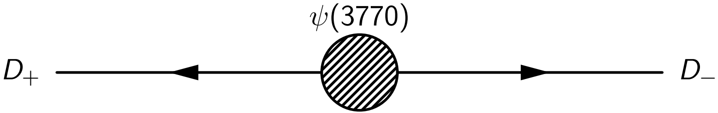


Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

- Double-tag analysis: Reconstruct signal ($KK\pi\pi$) and tag mode
- $D^0\bar{D}^0$ pair is quantum correlated



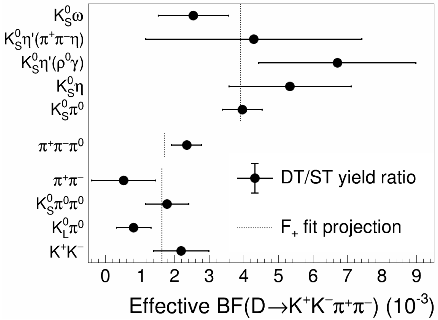
- Equivalently, we can consider D_+D_-
  - $D_\pm = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$ are CP eigenstates



The DD pair is quantum correlated, spooky action at a distance!

Quantum correlation: The CP content of the tag can modify the effective branching fraction:

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)\left(1 \pm c_1\right)$$



Phys. Rev. D **107**, 032009

c_1 is the cosine of the strong phase, averaged over the <u>whole</u> phase space

Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

Our next task is to change the phase space inclusive analysis,

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi) \quad \text{(flavour tag)}$$
$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)(1 \pm c_1) \quad \text{(CP tag)}$$

into a binned phase space analysis:

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)F_i \quad \text{(flavour tag)}$$
$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi)\left(F_i + \bar{F}_i \pm 2\sqrt{F_i\bar{F}_i}c_i\right) \quad \text{(CP tag)}$$

1. F_i: Measure using flavour tags
2. c_i: Determine from asymmetry of CP even and odd tags
3. s_i: Analogous to c_i, but requires binning of tag mode

Our next task is to change the phase space inclusive analysis,

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi\pi) \quad (\text{f[illegible]s})$$

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK\pi \text{[illegible]}) \quad (\text{CP tag})$$

into a binned [illegible]ce analysis:

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \to KK \text{[illegible]}) \quad (\text{[illegible]lavour tag})$$

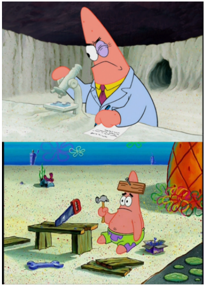
$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(D^0 \text{[illegible]})(F_i + \bar{F}_i \pm 2\sqrt{F_i\bar{F}_i c_i}) \quad (\text{CP tag})$$

Work in progress!

1. F_i: Measure using [illegible]our tags
2. c_i: Determine from asymmetry of *CP* even and odd tags
3. s_i: Analogous to c_i, but requires binning of tag mode

Summary and conclusion

1. I have presented the first model-independent measurement of γ using $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$
2. The optimised binning scheme, developed with an amplitude model, successfully identified regions with large, local CP asymmetries
3. However, amplitude model predictions of δ_D <u>should not be trusted</u>
4. LHCb analysis has 3σ tension with world average



Making binning scheme with amplitude model

Predicting strong phases with amplitude model

5. External inputs from charm factories, such as BESIII, are crucial to eliminate biases due to modelling

Thanks for your attention!

Backup slides

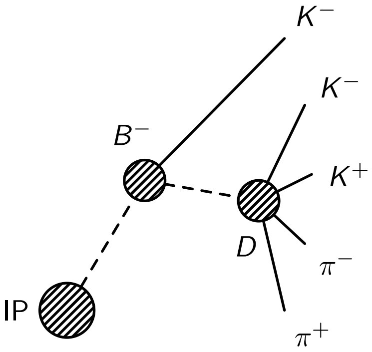
Event selection

Event selection

Decay topology

Look for:

1. 5 charged tracks
2. Displaced B vertex
3. 1 bachelor track with good PID information
4. Displaced D vertex with invariant mass within 25 MeV of the D^0 mass



Event selection

Offline selection has 3 stages

Initial cuts:

1. Invariant D and B mass cuts
2. Momentum and RICH requirements

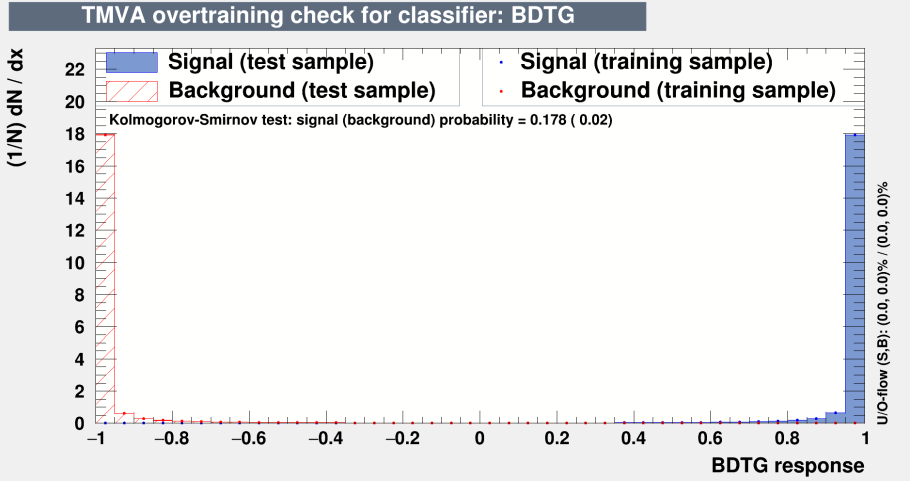
Boosted Decision Tree (BDT)

- Signal sample: Simulation samples
- Background sample: Upper B mass sideband
- 28 variables describing kinematics, impact parameters, vertex quality

Final selection

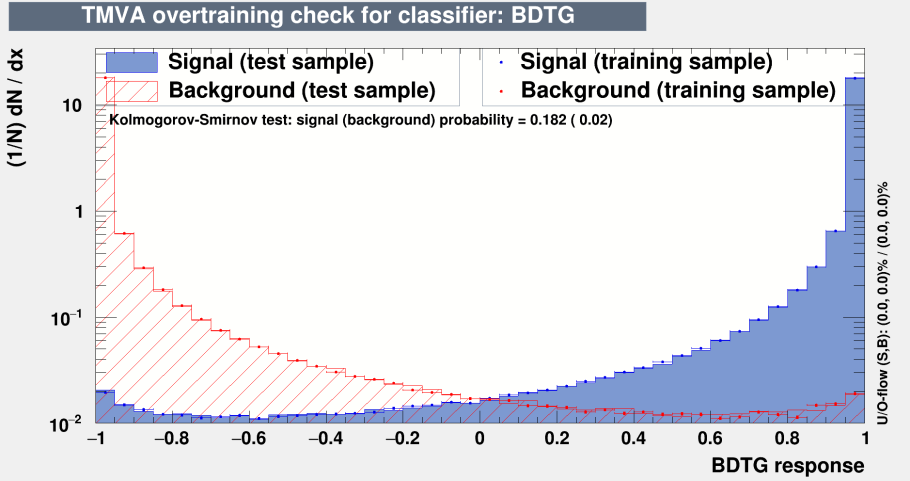
1. D Flight distance
2. Particle Identification of bachelor
3. K_S^0 veto

Event selection



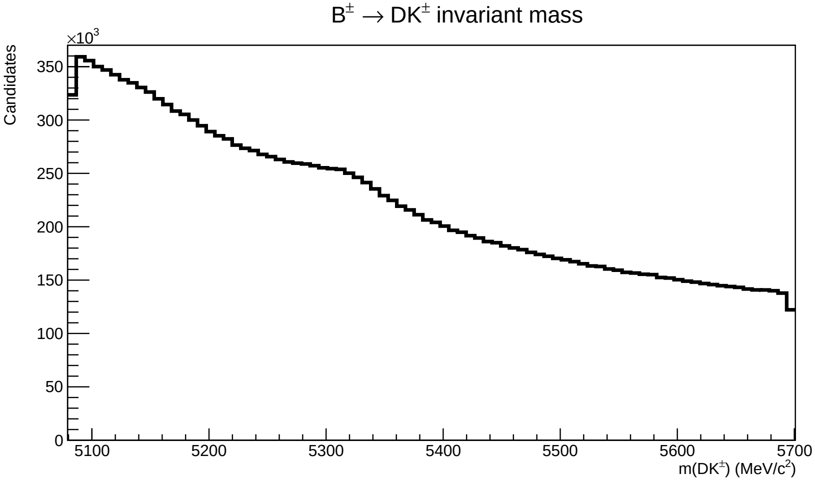
BDT is highly efficient at rejecting combinatorial background

Event selection



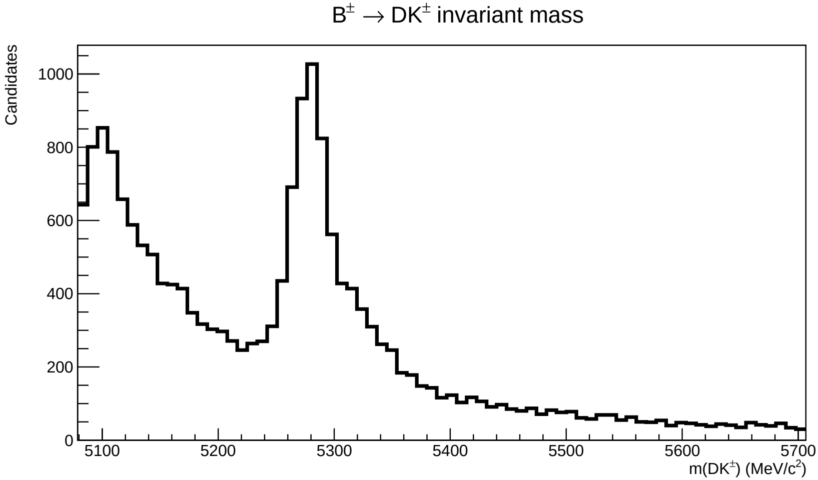
Very important, combinatorial background is large in multi-body decays

Event selection



The invariant B mass, after online selection, show no visible signal...

Event selection



... but the BDT does a great job cleaning this up!