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

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Warwick EPP Seminar

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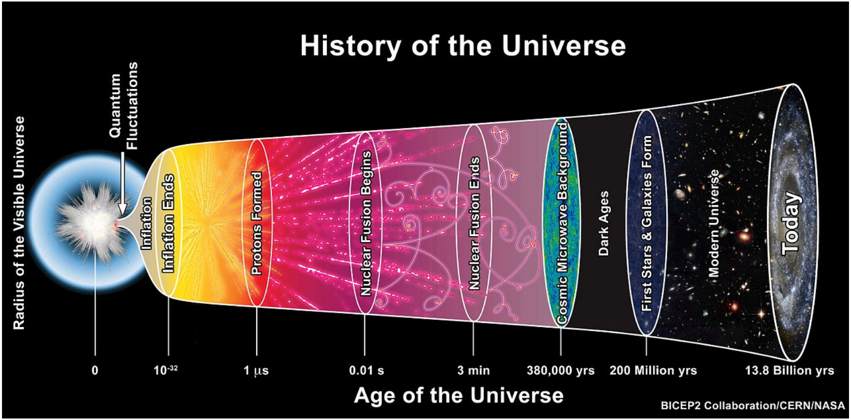
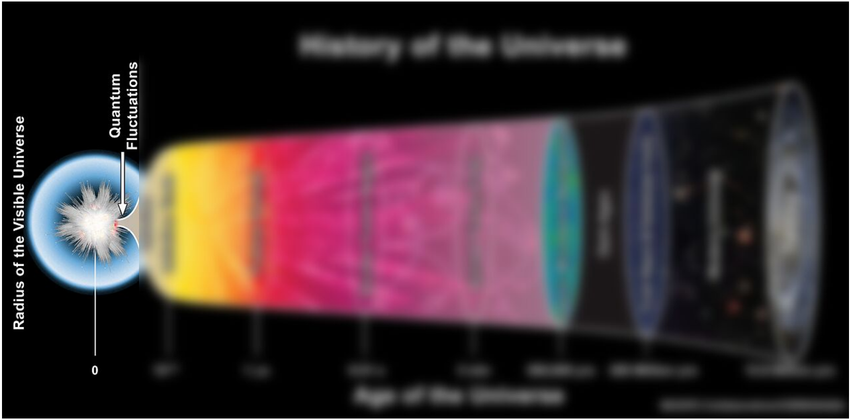
Introduction to CP violation

Big Bang and matter-antimatter asymmetry



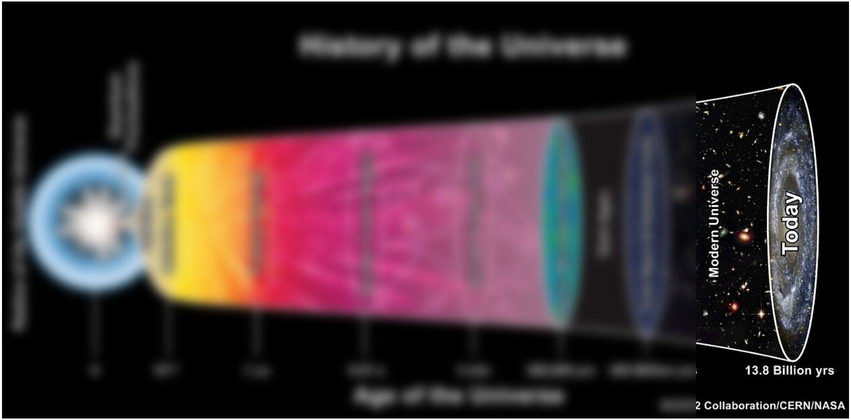
Where is the antimatter in the universe?

Big Bang and matter-antimatter asymmetry



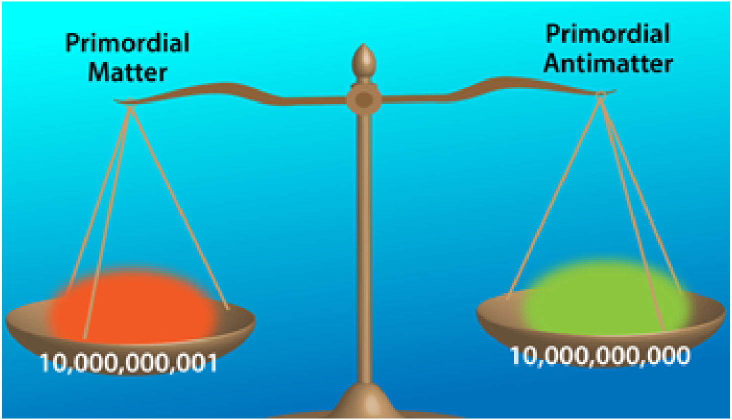
Initially equal amounts of matter and antimatter...

Big Bang and matter-antimatter asymmetry



... but today we only see matter!

Big Bang and matter-antimatter asymmetry



APS/Alan Stonebraker

The difference is very small...

Big Bang and matter-antimatter asymmetry

Quantum Diaries: "Why B physics? Why not A Physics?"

... but the effects we observe today are obviously huge!
How can we explain this?

CP violation

The Nobel Prize in Physics 1980

Photo from the Nobel Foundation archive.
James Watson Cronin
Prize share: 1/2

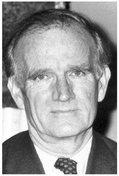


Photo from the Nobel Foundation archive.
Val Logsdon Fitch
Prize share: 1/2

The Nobel Prize in Physics 1980 was awarded jointly to James Watson Cronin and Val Logsdon Fitch "for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons"

- CP violation discovery in 1964
- Phys. Rev. Lett. **13**, 138
- Observed $K_L^0 \to \pi^+\pi^-$
- Since, CP violation has also been observed in the B, B_s and D systems

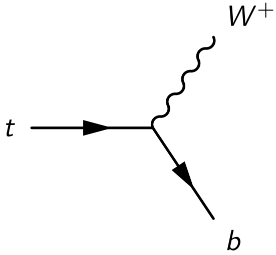
Can Standard Model CPV explain the matter-antimatter asymmetry?
Or, could it be physics beyond the SM?

The CKM matrix and the Unitary Triangle

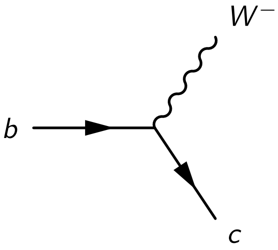
The CKM matrix and the Unitary Triangle

In SM, the charged current $W^{\pm}$ interactions couple (left-handed) up- and down-type quarks, given by

$$\frac{-g}{\sqrt{2}} \begin{bmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{bmatrix} \gamma^{\mu} W_{\mu} V_{\mathrm{CKM}} \begin{bmatrix} d_L \\ s_L \\ b_L \end{bmatrix} + \mathrm{h.c.}$$



(a) $t \to bW^+$



(b) $b \to cW^-$

The CKM matrix and the Unitary Triangle

The Cabbibo-Kobayashi-Maskawa matrix V_{CKM},

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

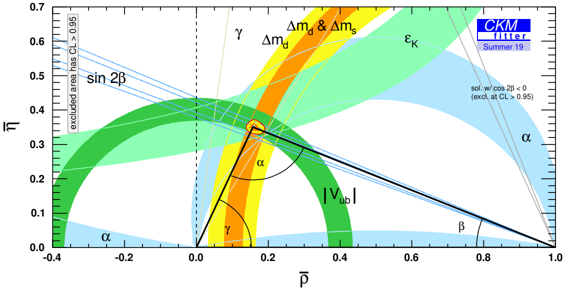
must be a unitary matrix: $V_{\mathrm{CKM}}^{\dagger} V_{\mathrm{CKM}} = I \implies$

$$V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

Represent this constraint as a triangle in the complex plane:
Unitary Triangle

The CKM matrix and the Unitary Triangle

- 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?

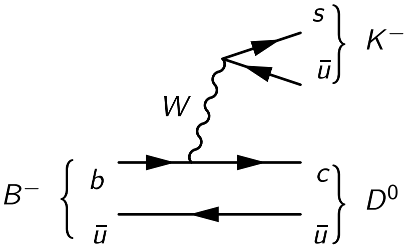


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

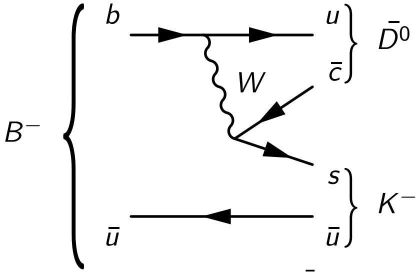
How to measure γ?

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 $\bar{D}^0$
- $b \to u\bar{c}s$ 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 $r_B \approx 0.1$

D decays to a CP eigenstate

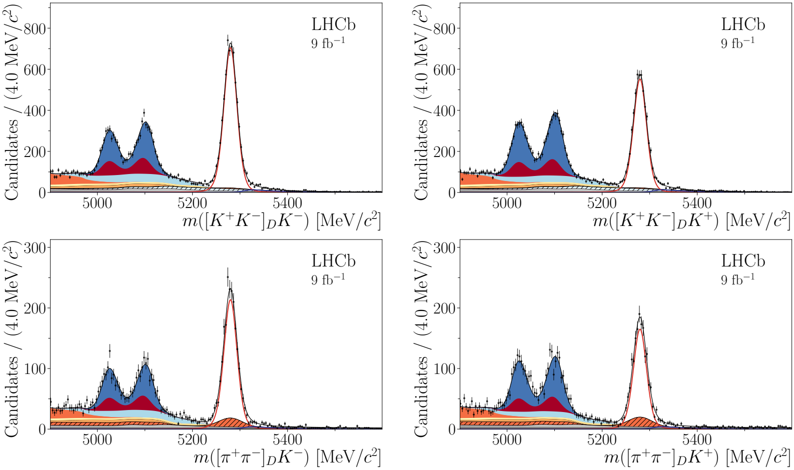
A well known strategy is to consider D decays to a CP eigenstate

For CP eigenstates, $\mathcal{A}_{D^0} = \mathcal{A}_{\bar{D}^0}$

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

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

D decays to a CP eigenstate



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In $B^\pm \to [h^+h^-]_D K^\pm$, we see significant CPV effects

Doubly Suppressed Cabbibo D decays

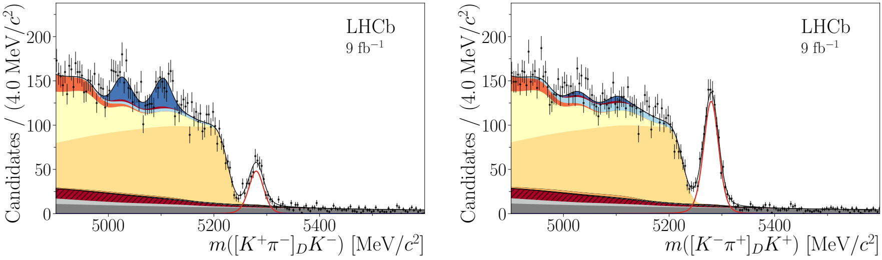
Can we enhance the interference effects?

Yes! Use a Doubly Suppressed Cabbibo decay: $\mathcal{A}_{D^0} = r_D e^{i\delta_D}\mathcal{A}_{\bar{D}^0}$

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

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

Doubly Suppressed Cabbibo D decays



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$B^\pm \to [K^\mp \pi^\pm]_D K^\pm$ has lower statistics, but a spectacular asymmetry!

Additionally, the partially reconstructed background has an equal but opposite asymmetry

The $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ decay mode

The $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ decay mode

The mode $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ has been proposed as a powerful channel for a measurement of γ

- $D \to K^+K^-\pi^+\pi^-$ has the best of both worlds:
  1. Singly Cabbibo Suppressed decay: Larger branching fraction
  2. Interference effects from over 25 resonance components

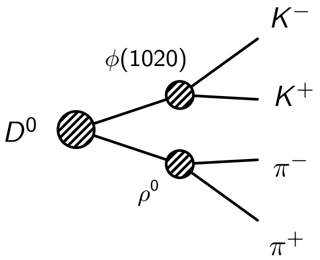
- Large interference effects in local regions of the 5D phase space

- First proposed by J. Rademacker and G. Wilkinson
  - Phys. Lett. **B647** (2007) 400
  - FOCUS amplitude model predicts a 14° precision with 1000 candidates

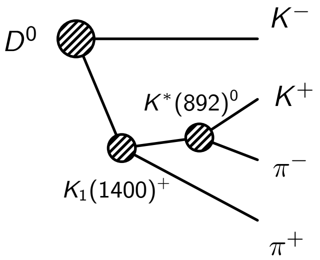
- State of the art amplitude analysis by LHCb:
  - JHEP **02** (2019) 126
  - Exploits the huge dataset of charm decays collected by LHCb

The $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ decay mode

Why do four-body decays have large local interferences?



$\phi(1020)(\to K^+K^-)\rho^0(\to \pi^+\pi^-)$



$K_1(1400)^+(\to K^*(892)^0(\to K^+\pi^-))K^-$

Many possible decay paths, in different phase space locations, contribute to the total decay amplitude...

The $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ decay mode

Amplitude	$\lvert c_k \rvert$	$\arg(c_k)$ [rad]	Fit fraction [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	1 (fixed)	0 (fixed)	$23.82 \pm 0.38 \pm 0.50$
$D^0 \to K_1(1400)^+K^-$	$0.614 \pm 0.011 \pm 0.031$	$1.05 \pm 0.02 \pm 0.05$	$19.08 \pm 0.60 \pm 1.46$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$0.282 \pm 0.004 \pm 0.008$	$-0.60 \pm 0.02 \pm 0.10$	$18.46 \pm 0.35 \pm 0.94$
$D^0 \to K_1(1270)^+K^-$	$0.452 \pm 0.011 \pm 0.017$	$2.02 \pm 0.03 \pm 0.05$	$18.05 \pm 0.52 \pm 0.98$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=0}$	$0.259 \pm 0.004 \pm 0.018$	$-0.27 \pm 0.02 \pm 0.03$	$9.18 \pm 0.21 \pm 0.28$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.359 \pm 0.036 \pm 0.624$	$0.44 \pm 0.02 \pm 0.03$	$6.61 \pm 0.15 \pm 0.37$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=1}$	$0.249 \pm 0.005 \pm 0.017$	$1.22 \pm 0.02 \pm 0.03$	$4.90 \pm 0.16 \pm 0.18$
$D^0 \to K_1(1270)^-K^+$	$0.220 \pm 0.006 \pm 0.011$	$2.09 \pm 0.03 \pm 0.07$	$4.29 \pm 0.18 \pm 0.41$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$0.120 \pm 0.003 \pm 0.018$	$-2.49 \pm 0.03 \pm 0.16$	$3.14 \pm 0.17 \pm 0.72$
$D^0 \to K_1(1400)^-K^+$	$0.236 \pm 0.008 \pm 0.018$	$0.04 \pm 0.04 \pm 0.09$	$2.82 \pm 0.19 \pm 0.39$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=0}$	$0.823 \pm 0.023 \pm 0.218$	$2.99 \pm 0.03 \pm 0.05$	$2.75 \pm 0.15 \pm 0.19$
$D^0 \to [\bar{K}^*(1680)^0K^*(892)^0]_{L=1}$	$1.009 \pm 0.022 \pm 0.276$	$-2.76 \pm 0.02 \pm 0.03$	$2.70 \pm 0.11 \pm 0.09$
$D^0 \to \bar{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$1.379 \pm 0.029 \pm 0.373$	$1.06 \pm 0.02 \pm 0.03$	$2.41 \pm 0.09 \pm 0.27$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$1.311 \pm 0.031 \pm 0.018$	$0.54 \pm 0.02 \pm 0.02$	$2.29 \pm 0.08 \pm 0.08$
$D^0 \to [K^*(892)^0\bar{K}^*(892)^0]_{L=2}$	$0.652 \pm 0.018 \pm 0.043$	$2.85 \pm 0.03 \pm 0.04$	$1.85 \pm 0.09 \pm 0.10$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$0.049 \pm 0.001 \pm 0.004$	$-1.71 \pm 0.04 \pm 0.37$	$1.49 \pm 0.09 \pm 0.33$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=1}$	$0.747 \pm 0.021 \pm 0.203$	$0.14 \pm 0.03 \pm 0.04$	$1.48 \pm 0.08 \pm 0.10$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$0.762 \pm 0.035 \pm 0.068$	$1.17 \pm 0.04 \pm 0.04$	$0.98 \pm 0.09 \pm 0.05$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.524 \pm 0.058 \pm 0.189$	$0.21 \pm 0.04 \pm 0.19$	$0.70 \pm 0.05 \pm 0.08$
$D^0 \to a_1(1260)^+\pi^-$	$0.189 \pm 0.011 \pm 0.042$	$-2.84 \pm 0.07 \pm 0.38$	$0.46 \pm 0.05 \pm 0.22$
$D^0 \to a_1(1260)^-\pi^+$	$0.188 \pm 0.014 \pm 0.031$	$0.18 \pm 0.06 \pm 0.43$	$0.45 \pm 0.06 \pm 0.16$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$0.160 \pm 0.011 \pm 0.005$	$0.28 \pm 0.07 \pm 0.03$	$0.43 \pm 0.05 \pm 0.03$
$D^0 \to [K^*(1680)^0\bar{K}^*(892)^0]_{L=2}$	$1.218 \pm 0.089 \pm 0.354$	$-2.44 \pm 0.08 \pm 0.15$	$0.33 \pm 0.05 \pm 0.06$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$0.195 \pm 0.015 \pm 0.035$	$2.95 \pm 0.08 \pm 0.29$	$0.27 \pm 0.04 \pm 0.05$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$1.388 \pm 0.095 \pm 0.257$	$1.71 \pm 0.06 \pm 0.37$	$0.18 \pm 0.02 \pm 0.07$
$D^0 \to [K^*(892)^0\bar{K}_2^*(1430)^0]_{L=1}$	$1.530 \pm 0.086 \pm 0.131$	$2.01 \pm 0.07 \pm 0.09$	$0.18 \pm 0.02 \pm 0.02$
		Sum of fit fractions	$129.32 \pm 1.09 \pm 2.38$
		χ^2/ndf	$9242/8121 = 1.14$

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... and I really mean a lot of resonances!

The $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ decay mode

Our equations suddenly become a lot more complicated

$\mathcal{A}_{D^0}(\Phi)$ now depends on a 5D phase space point Φ

Defining $\mathcal{A}_{\bar{D}^0} = r_D e^{i\delta_D}\mathcal{A}_{D^0}$, r_D and δ_D are now also functions of Φ!

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

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

The $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ decay mode

$r_D(\Phi)$ and $\delta_D(\Phi)$ can be predicted using the LHCb amplitude model

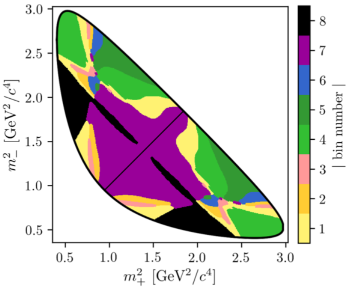
However, there are many reasons why we should **not** do this:

1. $r_D(\Phi)$ can be measured directly in data at LHCb
2. Amplitude models are just models, which may not reflect reality
3. In fact, the model is fitted to data that knows nothing about $\delta_D(\Phi)$
4. It is impossible to assign an objective error to a model!

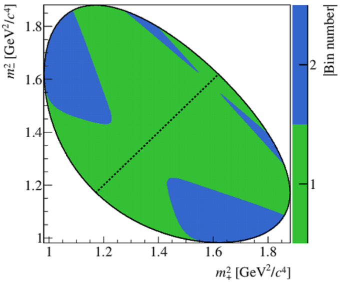
We wish to do a model independent measurement

Binned analysis of the $D \to K^+K^-\pi^+\pi^-$ mode

- Solution: Split phase space into <u>bins</u>, labelled by $i = 1, 2, \ldots$
- Study the CP asymmetry separately in each bin
- For the decays $D^0 \to K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$, the binning scheme may be visualised on a Dalitz plot

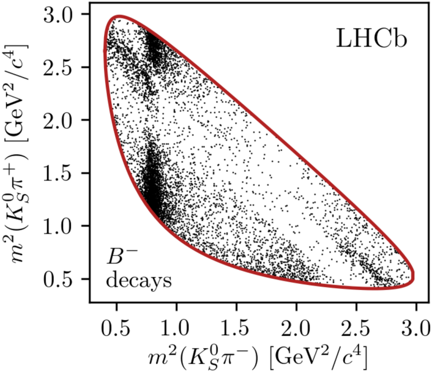


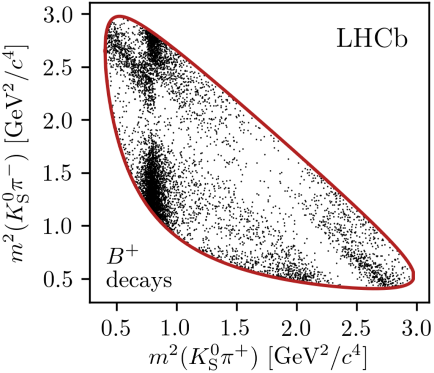
$K_S^0\pi^+\pi^-$



$K_S^0K^+K^-$

Binned analysis of the $D \to K^+K^-\pi^+\pi^-$ mode





$B^- \to [K_S^0\pi^+\pi^-]_D K^-$

$B^+ \to [K_S^0\pi^+\pi^-]_D K^+$

Can you find the asymmetries?

Back to rate equation:

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

Integrate rate over a local region Φ_i, which we call bin i:

$$N_i^- \propto F_i + r_B^2 \bar{F}_i + 2 r_B \sqrt{F_i \bar{F}_i} \big(\cos(\delta_B - \gamma) c_i - \sin(\delta_B - \gamma) s_i \big)$$

Amplitude averaged strong phase

$$c_i \equiv \frac{\int_i \mathrm{d}\Phi |\mathcal{A}_{D^0}||\mathcal{A}_{\bar{D}^0}| \cos(\delta_D(\Phi))}{\sqrt{\int \mathrm{d}\Phi |\mathcal{A}_{D^0}|^2 \int \mathrm{d}\Phi |\mathcal{A}_{\bar{D}^0}|^2}}$$

To "decouple" the interference effects in B^+ and B^-, define the CP violating observables

$$x_\pm \equiv r_B \cos(\delta_B \pm \gamma), \quad y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$$

Our final equation, which relates the CP observables to experimentally measured yields, is

$$N_i^- \propto F_i + r_B^2 \bar{F}_i + 2\sqrt{F_i \bar{F}_i}\left(x_- c_i - y_- s_i\right)$$

Amplitude averaged strong phase

$$c_i \equiv \frac{\int_i \mathrm{d}\Phi |\mathcal{A}_{D^0}||\mathcal{A}_{\bar{D}^0}|\cos(\delta_D(\Phi))}{\sqrt{\int \mathrm{d}\Phi |\mathcal{A}_{D^0}|^2 \int \mathrm{d}\Phi |\mathcal{A}_{\bar{D}^0}|^2}}$$

Binned analysis of the $D \to K^+K^-\pi^+\pi^-$ mode

Bin yield

$$N_i^- \propto F_i + r_B^2 \bar{F}_i + 2\sqrt{F_i \bar{F}_i}(x_- c_i - y_- s_i)$$

The strategy for measuring γ is now clear:

1. Measure bin yields $N_i^\pm$ in $B^\pm \to [K^+K^-\pi^+\pi^-]_D K^\pm$ decays
2. Do a likelihood maximisation to determine F_i, $\bar{F}_i$, c_i, s_i, $x_\pm$ and $y_\pm$
3. From $x_\pm$ and $y_\pm$, extract r_B, δ_B and γ
4. Publish new measurement of γ!

Strong phase input from charm factories

Unfortunately, it is unlikely that this fit will converge...

Sensitivity to c_i and s_i is very limited with current statistics

Strong phase input from charm factories

Unfortunately, it is unlikely that this fit will converge...
Sensitivity to c_i and s_i is very limited with current statistics

Instead, we can join forces with BESIII and measure c_i and s_i directly

LHCb + BESIII

This has never been done for $D^0 \to K^+K^-\pi^+\pi^-$
More on this later!

Constraining F_i with $B^\pm \to D\pi^\pm$

Constraining F_i with $B^\pm \to D\pi^\pm$

- The fractional bin yields F_i are yields in the absence of CP violation
- In principle we can measure these directly at both LHCb and BESIII

Four strategies:

1. Calculate from amplitude model
2. Measure in $B^- \to D^0\mu^-\bar{\nu_\mu}$ at LHCb
3. Measure with flavour tagged D^0 decays at BESIII
4. Measure in $B^\pm \to D\pi^\pm$

Constraining F_i with $B^\pm \to D\pi^\pm$

- The fractional bin yields F_i are yields in the abscence of CP violation
- In principle we can measure these directly at both LHCb and BESIII

Four strategies:

1. ~~Calculate from amplitude model~~ Avoid model dependence
2. Measure in $B^- \to D^0 \mu^- \bar{\nu_\mu}$ at LHCb
3. Measure with flavour tagged D^0 decays at BESIII
4. Measure in $B^\pm \to D\pi^\pm$

Constraining F_i with $B^\pm \to D\pi^\pm$

- The fractional bin yields F_i are yields in the abscence of CP violation
- In principle we can measure these directly at both LHCb and BESIII

Four strategies:

1. ~~Calculate from amplitude model~~ Avoid model dependence
2. ~~Measure in~~ $\cancel{B^- \to D^0\mu^-\bar{\nu}_\mu}$ ~~at LHCb~~ Different acceptance effects
3. ~~Measure with flavour tagged~~ $\cancel{D^0}$ ~~decays at BESIII~~
4. Measure in $B^\pm \to D\pi^\pm$

Constraining F_i with $B^\pm \to D\pi^\pm$

- The fractional bin yields F_i are yields in the absence of *CP* violation
- In principle we can measure these directly at both LHCb and BESIII

Four strategies:

1. ~~Calculate from amplitude model~~ Avoid model dependence
2. ~~Measure in $B^- \to D^0\mu^-\bar{\nu}_\mu$ at LHCb~~ Different acceptance effects
3. ~~Measure with flavour tagged D^0 decays at BESIII~~
4. Measure in $B^\pm \to D\pi^\pm$ Small CPV effects?

Constraining F_i with $B^\pm \to D\pi^\pm$

- The fractional bin yields F_i are yields in the absence of *CP* violation
- In principle we can measure these directly at both LHCb and BESIII

Four strategies:

1. ~~Calculate from amplitude model~~ Avoid model dependence
2. ~~Measure in $B^- \to D^0\mu^-\bar{\nu}_\mu$ at LHCb~~ Different acceptance effects
3. ~~Measure with flavour tagged D^0 decays at BESIII~~
4. Measure in $B^\pm \to D\pi^\pm$ Small CPV effects?

No problem, include $B^\pm \to D\pi^\pm$ as a signal channel

Constraining F_i with $B^{\pm} \to D\pi^{\pm}$

- $B^{\pm} \to D\pi^{\pm}$ has an identical topology to $B^{\pm} \to DK^{\pm}$
- CPV effects are highly suppressed because $r_B^{D\pi} \approx 0.005$
- Branching fraction more than 10 times larger
- As a signal channel, we add another 4 free parameters to our fit:
$$x_{\pm}^{D\pi} = r_B^{D\pi} \cos\left(\delta_B^{D\pi} - \gamma\right), \quad y_{\pm}^{D\pi} = r_B^{D\pi} \sin\left(\delta_B^{D\pi} - \gamma\right)$$

Constraining F_i with $B^{\pm} \to D\pi^{\pm}$

To avoid degeneracy, reduce this to 2 additional parameters using this parameterisation:

$$x_{\xi} = \mathrm{Re}(\xi), \quad y_{\xi} = \mathrm{Im}(\xi), \quad \xi = \frac{r_B^{D\pi} e^{i\delta_B^{D\pi}}}{r_B^{DK} e^{i\delta_B^{DK}}}$$

In summary:

1. Both $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ are signal channels, with $x_{\pm}^{DK}$, $y_{\pm}^{DK}$, x_{ξ} and y_{ξ} as CP observables
2. $B^{\pm} \to DK^{\pm}$ has lower statistics, but higher CPV effects
3. $B^{\pm} \to D\pi^{\pm}$ has higher statistics and constrain F_i in the fit, but sensitivity to CPV is limited

Binning scheme

Binning scheme

We need to split the phase space into bins

But how do we navigate through a 5D space? How do we decide on the bin boundaries?

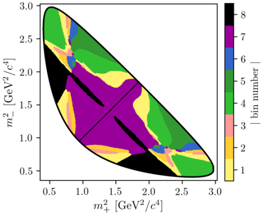
Let the amplitude model guide us!

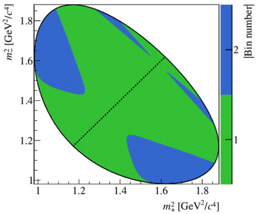
Binning scheme

Back to the amplitude averaged strong phase:

$$c_i \equiv \frac{\int_i \mathrm{d}\Phi |\mathcal{A}_{D^0}||\mathcal{A}_{\bar{D}^0}|\cos(\delta_D(\Phi))}{\sqrt{\int \mathrm{d}\Phi |\mathcal{A}_{D^0}|^2 \int \mathrm{d}\Phi |\mathcal{A}_{\bar{D}^0}|^2}}$$

- If the strong phase varies significantly within a bin, the interference effects will be diluted when integrating
- We need to group regions of similar strong phase into the same bin
- This was done for $K_S^0 h^+ h^-$, resulting in colourful "butterfly" plots



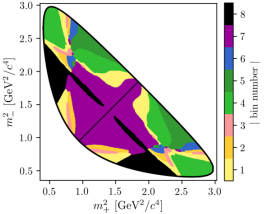


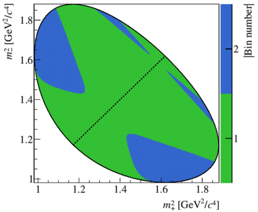
Binning scheme

Back to our yield formula:

$$N_i^- \propto F_i + r_B^2 \bar{F}_i + 2\sqrt{F_i \bar{F}_i}\left(x_- c_i - y_- s_i\right)$$

- In the charm system, CP is (approximately) conserved, so each D^0 decay has a corresponding identical CP conjugated decay
- Split each bin i into two "CP mirror bins", labelled by $\pm i$
- In $K_S^0 h^+ h^-$, this is indicated by the black symmetry line
- Under CP, $\delta_D \to -\delta_D$, so $c_i \to c_i$ and $s_i \to -s_i$





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 $B^\pm \to \bar{D}^0 K^\pm$

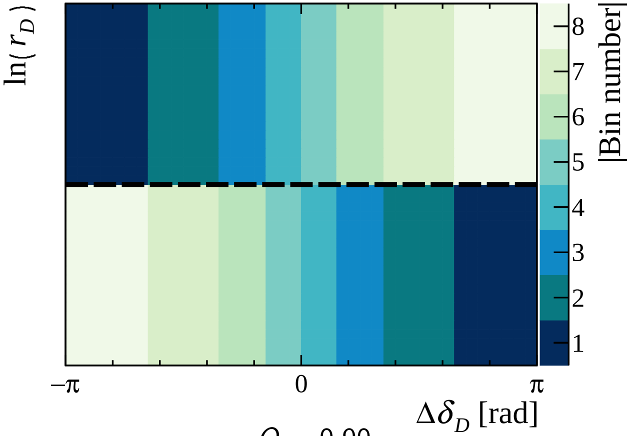
How to bin a 5-dimensional phase space?

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

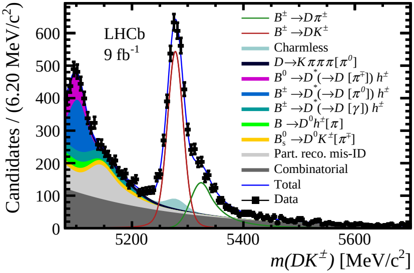
Mass fits and yield extraction

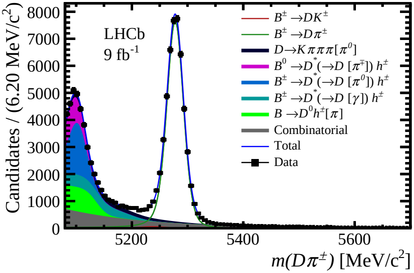
Mass fits and yield extraction

In the end, this analysis is a counting experiment

Counting strategy:

1. Perform a "global fit" of all $B^\pm$ candidates
2. Fix all shape parameters
3. Sort $B^\pm$ candidates by charge and bins
4. Perform a "CP fit" simultaneously, but only let bin yields float
5. From the bin yields, determine $x_\pm^{DK}$, $y_\pm^{DK}$, x_ξ and y_ξ





Signal yield:

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

CP fit setup

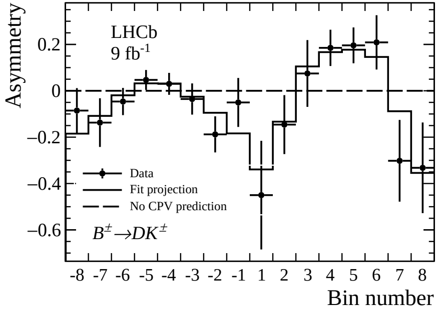
- No measurement of c_i and s_i available yet, use model predictions
- Fix mass shape from global fit
- Split by $B^{\pm}$ charge and D phase space bins (64 categories)

1. CP observables $x_{\pm}^{DK}$, $y_{\pm}^{DK}$ $x_{\xi}^{D\pi}$, $y_{\xi}^{D\pi}$ (6 parameters)
2. Fractional bin yields F_i (15 parameters)
3. Low mass and combinatorial background (128 parameters)
4. Yield normalisation (4 parameters)

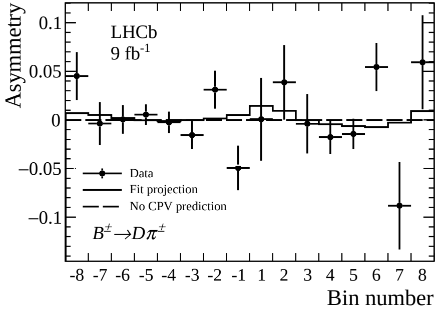
In total: 153 free parameters

CP fit results and γ

Fractional bin asymmetries



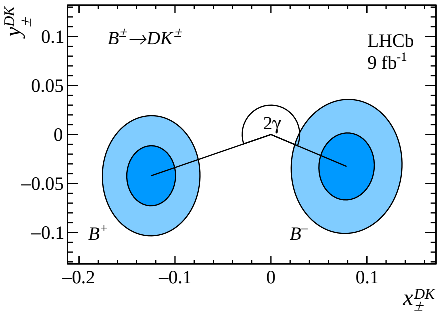
(a) $B^{\pm} \to DK^{\pm}$



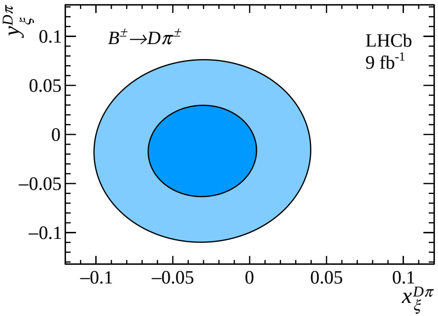
(b) $B^{\pm} \to D\pi^{\pm}$

- Useful cross check to compare measured bin asymmetries against bin asymmetries predicted by the fitted CP observables
- The $B^{\pm} \to DK^{\pm}$ mode show non-zero bin asymmetries, and the non-trivial distribution is driven by the change in strong phases across phase space

CP fit results



(a) $x_\pm^{DK}$ vs $y_\pm^{DK}$



(b) $x_\xi^{D\pi}$ vs $y_\xi^{D\pi}$

$$x_\pm^{DK} = r_B \cos(\delta_B \pm \gamma)$$
$$y_\pm^{DK} = r_B \sin(\delta_B \pm \gamma)$$

- The $B^\pm \to DK^\pm$ contours are distinct, indicating *CP* violation
- The $B^\pm \to D\pi^\pm$ mode has very low sensitivity to CP violation

We can interpret our CP observables in terms of the physics parameters γ, r_B^{DK}, δ_B^{DK}, $r_B^{D\pi}$, $\delta_B^{D\pi}$

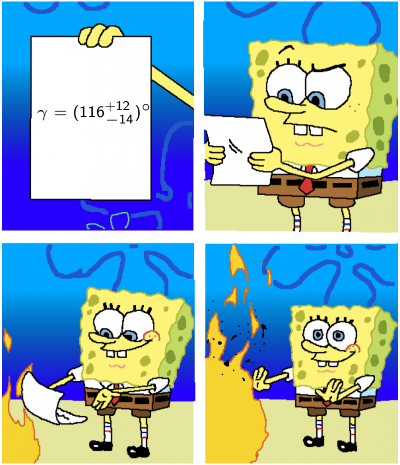
$$\begin{aligned}
\gamma &= (116^{+12}_{-14})^\circ, \\
\delta_B^{DK} &= (81^{+14}_{-13})^\circ, \\
r_B^{DK} &= 0.110^{+0.020}_{-0.020}, \\
\delta_B^{D\pi} &= (298^{+62}_{-118})^\circ, \\
r_B^{D\pi} &= 0.0041^{+0.0054}_{-0.0041},
\end{aligned}$$

However, the latest γ and charm combination result is:

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

What went wrong?!

Interpretation of γ



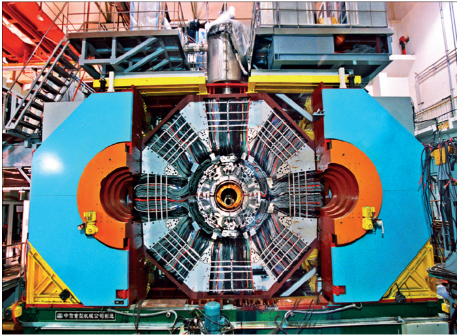
Do we trust the model predicted c_i and s_i, or their uncertainties? No!

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

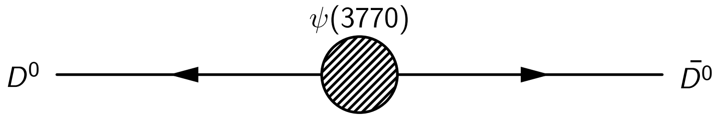
Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

- 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

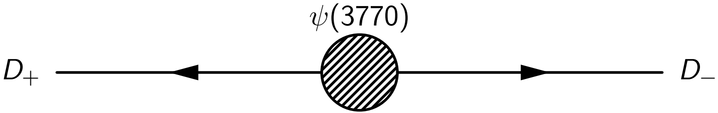


Strong phase analysis of $D^0 \to K^+K^-\pi^+\pi^-$ at BESIII

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



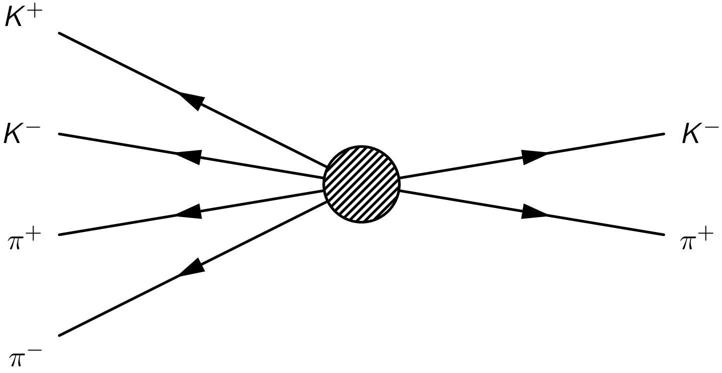
- Equivalently, we can consider D_+D_-
  - $D_\pm = \frac{1}{\sqrt{2}}(D^0 \pm \bar{D}^0)$ are CP eigenstates



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

Strong-phase in quantum correlated $D^0\bar{D}^0$ decays

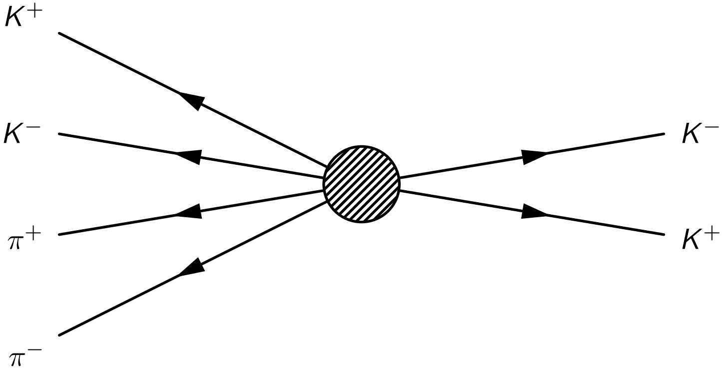
- Tag mode can be a flavour tag
  - $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K^-e^+\nu_e$



Flavour tags do not exhibit quantum correlation effects

Strong-phases in quantum correlated $D^0\bar{D}^0$ decays

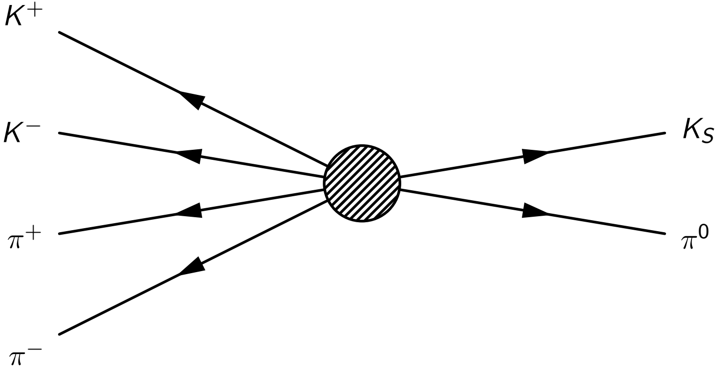
- Tag mode can be a CP even tag
  - KK, $\pi\pi$, $\pi\pi\pi^0$, $K_S\pi^0\pi^0$, $K_L\pi^0$, $K_L\omega$



$D \to K^+K^-$, which is CP even, forces $D \to K^+K^-\pi^+\pi^-$ to be CP odd

Strong-phase in quantum correlated $D^0\bar{D}^0$ decays

- Tag mode can be a CP odd tag
  - $K_S\pi^0$, $K_S\omega$, $K_S\eta$, $K_S\eta'$, $K_L\pi^0\pi^0$

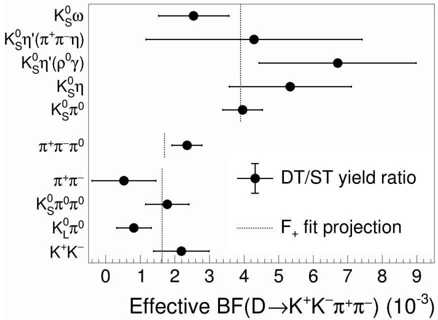


$D \to K_S^0\pi^0$, which is CP odd, forces $D \to K^+K^-\pi^+\pi^-$ to be CP even

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

Quantum correlation can modify the effective branching fraction:

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



arXiv:2212.06489

c_1 is the cosine of the strong phase, averaged over the whole 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

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

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

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

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,

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

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

into a binned ... ce analysis:

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

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

Work in progress!

1. F_i: Measure using ... 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

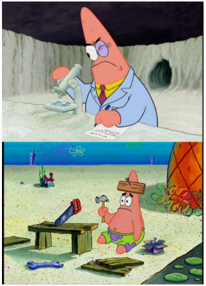
Summary and conclusion

1. I have presented a CPV study of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$

2. Multi-body decays, such as $D^0 \to K^+K^-\pi^+\pi^-$, have a great potential for measuring γ

3. The optimised binning scheme, developed with an amplitude model, successfully identified regions with large, local CP asymmetries

4. However, amplitude model predictions of δ_D <u>should not be trusted</u>



Making binning scheme with amplitude model

Predicting strong phases with amplitude model

Summary and conclusion

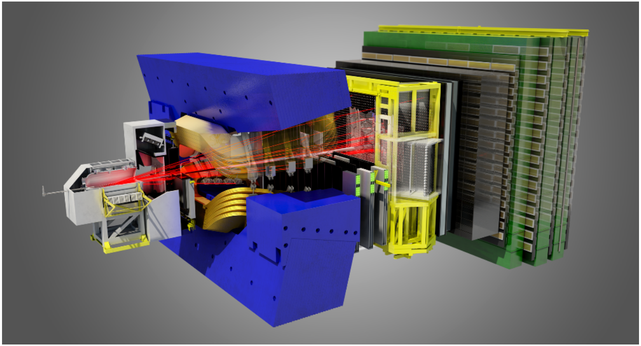
5. The fit results, using model predicted strong phases, were found to have a 3σ tension with the current LHCb combination
6. External inputs from charm factories, such as BESIII, are crucial to constrain charm strong phases
7. Combined, the LHCb and BESIII analyses will lead to the first model independent measurement of γ in this channel
8. Work is ongoing in similar four-body modes:
   - $D^0 \to \pi^+\pi^-\pi^+\pi^-$
   - $D^0 \to K_S^0\pi^+\pi^-\pi^0$

Thanks for your attention!

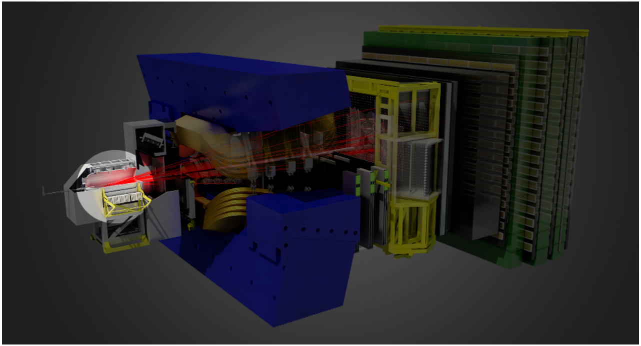
Backup slides

The LHCb detector

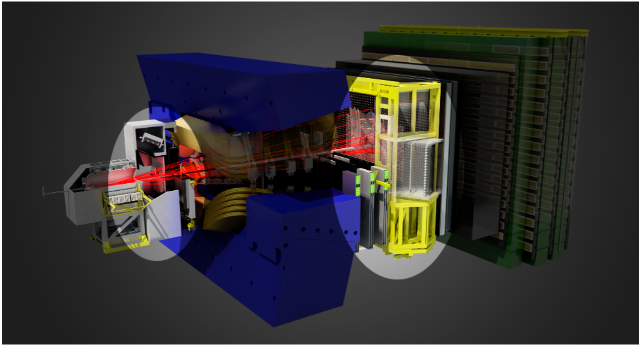
The LHCb detector



LHCb: A beauty experiment with a lot of charm



VELO: Vertex locator to reconstruct B and D vertices



RICH: Identify B and D daughter particles

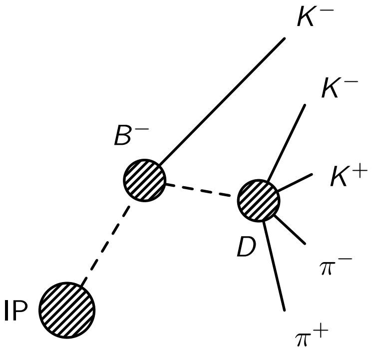
Event selection

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

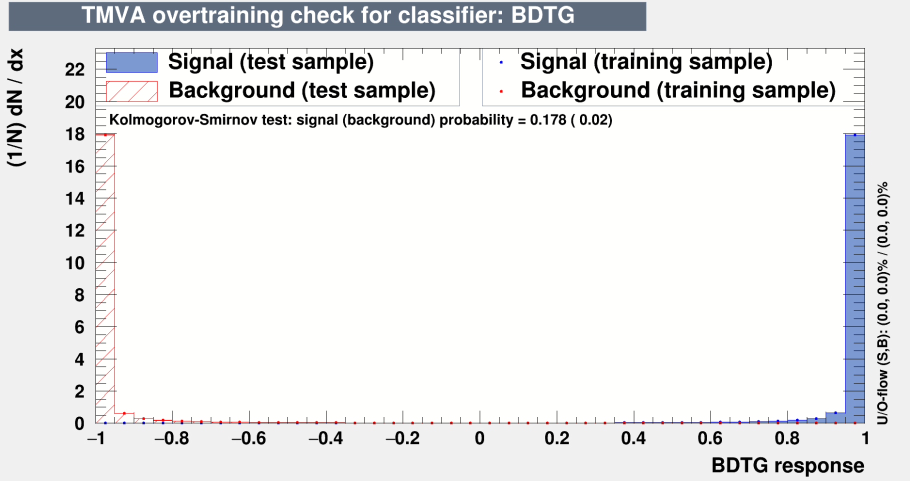
Boosted Decision Tree (BDT)

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

Final selection

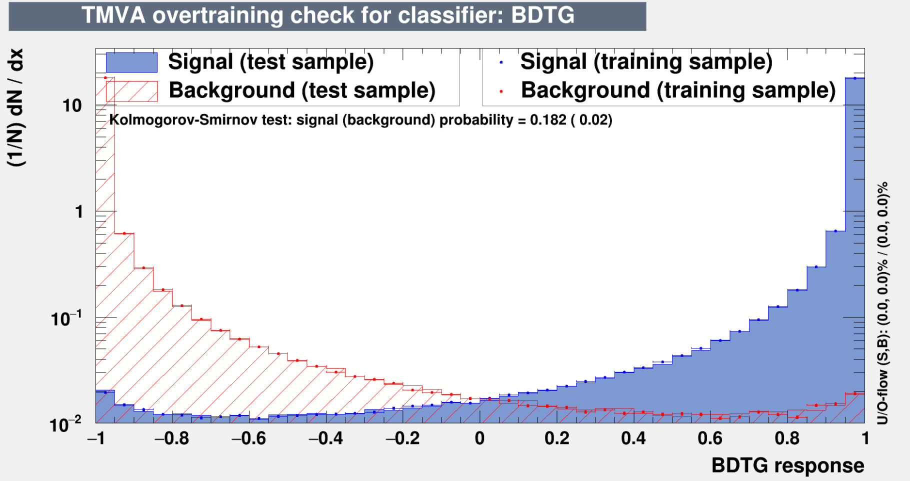
1. D Flight distance
2. Particle Identification of bachelor
3. K_S^0 veto

Event selection



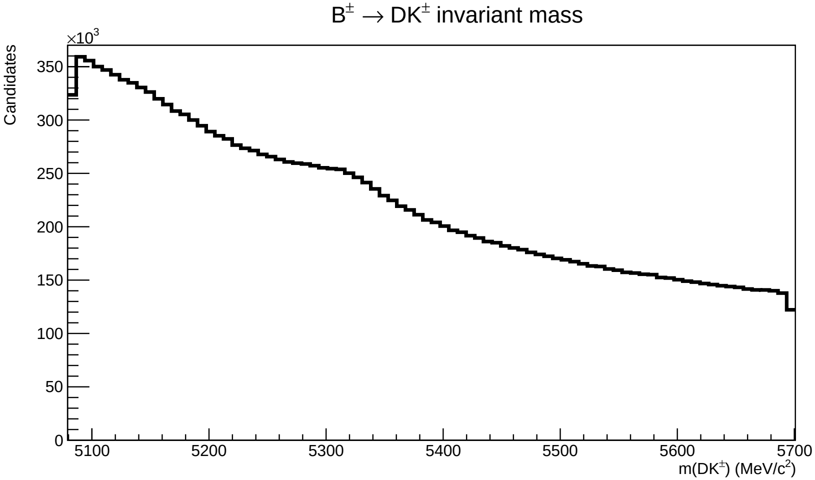
BDT is highly efficient at rejecting combinatorial background

Event selection



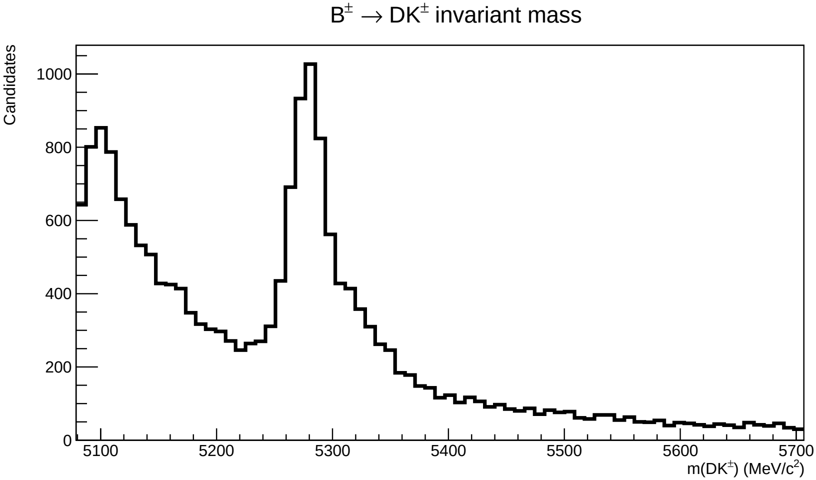
Very important, combinatorial background is large in multi-body decays

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!