Measurements of the CKM angle γ from $B^0 \to DK^+\pi^-$ decays with LHCb

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Outline

- CKM angle γ
- Measuring γ with 2-body D final states (GLW, ADS)
- Use of 3-body decay of D, BPGGSZ method
- γ with two 3-body decays: B Dalitz and D Dalitz, Double Dalitz method
- Ongoing work at the LHCb

The Cabbibo-Kobayashi-Maskawa (CKM) matrix

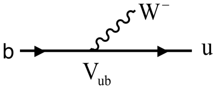
CKM matrix

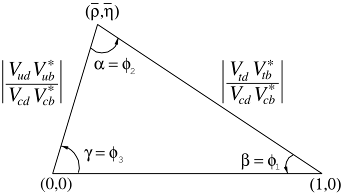
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- It describes the mixing between the three generations of quarks in the Standard Model
- V_{ij} corresponds to the transition amplitude from quark j to quark i.
- The CKM matrix is unitary and thus leads to the following relation:

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

- This equation can be graphically represented on the complex plane.



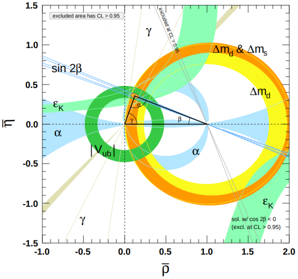


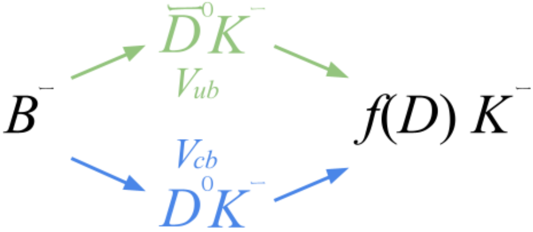
The angle γ of the unitarity triangle

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

- The only CKM parameter which can be measured using a tree-level decay alone
  - The theoretical uncertainty is very small: $\delta\gamma/\gamma \sim 10^{-7}$ [1]
- Precise measurement could give a hint to New Physics
- The latest value: $\gamma = (66.2^{+3.3}_{-3.5})^\circ$ (direct measurement with LHCb [2])

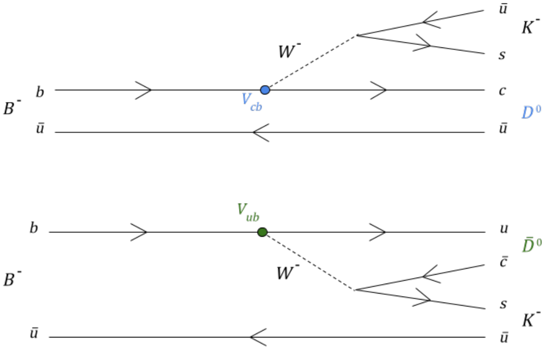
  $\gamma = (65.5^{+1.1}_{-2.7})^\circ$ (from other constraints)





- A typical channel to measure γ is $B^{\pm} \to DK^{\pm}$, where D can be either D^0 or $\overline{D}^0$
- The final state f should be accessible from both D^0 and $\overline{D}^0$
- Interference between $b \to cus$ and $b \to ucs$

- Feynman diagrams of the favoured and suppressed decays



- Favoured $b \rightarrow c$ and suppressed $b \rightarrow u$
- Note $V_{cb} \sim 10V_{ub}$
- Suppressed even further by the colour suppression

D decay to CP eigenstates (GLW)

- Consider D final states which are CP eigenstates such as $D \to \pi^+\pi^-$ or $D \to K^+K^-$ [3][4]
- The CP asymmetry can be defined as the decay rate between B^+ and B^-

Amplitude to the final state f_{CP}

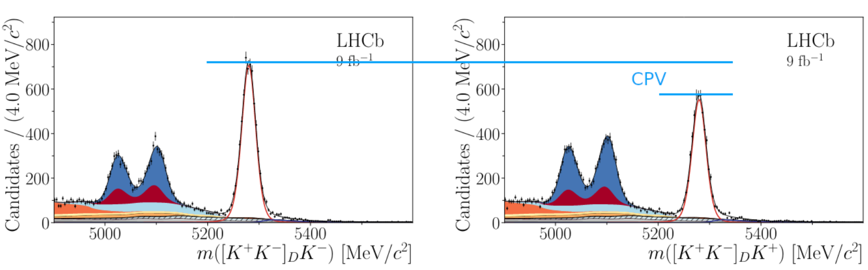
$$A_{B^\pm} = |F|e^{i(\delta_F \pm \phi_F)} + |S|e^{i(\delta_S \pm \phi_S)}$$

$$\begin{aligned}\mathcal{A}_{CP} &= \frac{|A_{B^-}|^2 - |A_{B^+}|^2}{|A_{B^-}|^2 + |A_{B^+}|^2} \\ &= \frac{2|F||S|\sin(\delta_F - \delta_S)\sin(\phi_F - \phi_S)}{|F|^2 + |S|^2 + 2|F||S|\cos(\delta_F - \delta_S)\cos(\phi_F - \phi_S)} \\ &= \frac{\pm 2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma}\end{aligned}$$

- $r_B = |S|/|F|$: ratio between favoured and suppressed
- $\delta_B = \delta_F - \delta_S$: strong phase difference
- $\gamma = \phi_F - \phi_S$: weak phase difference

GLW with LHCb

- Analysis with $D \to K^+K^-$ and $D \to \pi^+\pi^-$ [5]
- CP violation can be clearly seen



$$\mathcal{A}_{CP}^{KK} = \frac{\Gamma(B^- \to [K^+K^-]_D K^-) - \Gamma(B^+ \to [K^+K^-]_D K^+)}{\Gamma(B^- \to [K^+K^-]_D K^-) + \Gamma(B^+ \to [K^+K^-]_D K^+)}$$
$$= 0.136 \pm 0.009 \pm 0.001$$

CF and DCS decays (ADS)

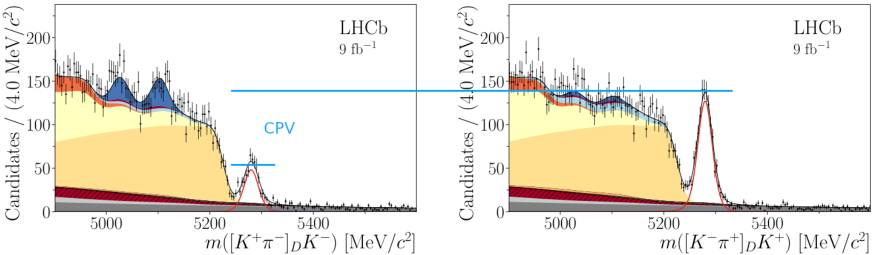
- 2-body final state such as $D \to K^{\pm}\pi^{\mp}$, $D \to \pi^{\pm}K^{\mp}$ [6][7]
  - Cabibbo Favoured (CF): $D^0 \to K^+\pi^-$
  - Doubly Cabibbo Suppressed (DCS): $\overline{D}^0 \to K^+\pi^-$
- CP asymmetry can be written as

$$\mathcal{A}_{ADS} = \frac{2r_D r_B \sin\delta_B + \delta_D sin\gamma}{r_D^2 + r_B^2 + 2r_B r_D \cos\left(\delta_B + \delta_D\right)\cos\gamma}$$

  - r_D: ratio of magnitudes for D^0 and $\overline{D}^0$ decay to f
  - δ_D : phase difference for D^0 and $\overline{D}^0$ decay to f
  - can retrieve the expression for GLW with $r_D = 1$ and $\delta_D = 0$

ADS with LHCb

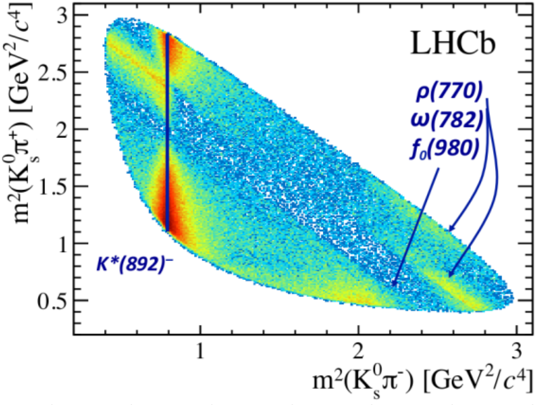
- Larger CP violation has been observed for $B^- \to [K^+\pi^-]_D K^-$ [5]
  - interference between (fav. B and sup. D) and (sup. B and fav. D)



$$\mathcal{A}_{ADS}^{\pi K} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)}$$
$$= -0.451 \pm 0.026$$

Self-conjugated 3-body decay of D (BPGGSZ method)

- 3-body decay of D can be used [8] [9]
- For example, $B^{\pm} \to DK^{\pm}$, $D \to K_S^0\pi^+\pi^-$
- The sensitivity to γ is enhanced thanks to the resonances in $D \to K_S^0\pi^+\pi^-$
  - Cabibbo suppressed $D \to K_S^0\rho$
  - Doubly Cabibbo suppressed $D \to K^{*+}\pi^-$



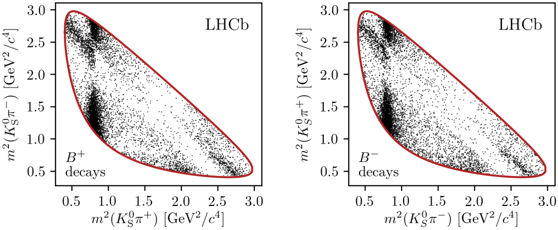
- The amplitude of $B^{\pm} \to DK^{\pm}$, $D \to K^0_{\rm S}\pi^+\pi^-$ can be written as

$$A \propto \overline{A}_D + r_B e^{i(\delta_B+\gamma)} A_D$$

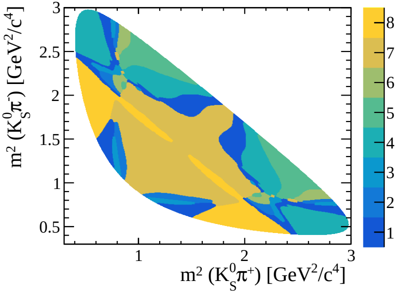
- r_B: ratio of the suppressed to the favoured decays
- δ_B: strong phase difference between the suppressed and favoured decays
- δ_D: strong phase difference between D^0 $(\overline{D}^0) \to f$

Partial width as a function of the position on the Dalitz plane

$$d\Gamma_{B^{\pm}\to DK^{\pm}}(x) = \overline{A}_D^2 + r_B A_D^2 + 2\overline{A}_D A_D[r_B\cos(\delta_B \pm \gamma)\cos\delta_D + r_B\sin(\delta_B \pm \gamma)\sin\delta_D]$$



$B^+ \to DK^+$ $\quad$ $B^- \to DK^-$



- Binned D Dalitz method is model-independent
- Binning scheme is chosen to maximise sensitivity to γ [10]
- Run 1+2 analysis has measured $\gamma = (68.7^{+5.2}_{-5.1})^\circ$, which is the most precise measurement of γ from a single analysis [11]

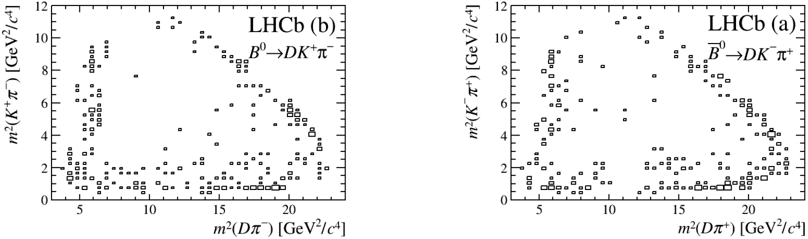
Number of events in bin *i*

$$N^{+}_{\pm i} = h_{B+}[K_{\mp i} + (x_+^2 + y_+^2)K_{\pm i} + 2\sqrt{K_i K_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})]$$

$$N^{-}_{\pm i} = h_{B-}[K_{\pm i} + (x_-^2 + y_-^2)K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_- c_{\pm i} - y_- s_{\pm i})]$$

- $x_\pm = r_B \cos(\delta_B \pm \gamma)$
- $h_{B\pm}$: normalisation factor,
- $K_{+(-)i}$: fraction of D^0 ($\overline{D}^0$) $\to f$ in bin i, estimated using $B^\pm \to D\pi^\pm$ control mode
- $y_\pm = r_B \sin(\delta_B \pm \gamma)$
- $c_{\pm i}, s_{\pm i}$: sine and cosine of the strong phase difference between D^0 ($\overline{D}^0$) $\to f$, taken from CLEO and BESIII

- We can include the entire phase space of $B^0 \to DK^+\pi^-$
- Having different resonances can give additional sensitivity to γ
  - $B^0 \to DK_0^*(1430)^0$
  - $B^0 \to DK_2^*(1430)^0$
  - $B^0 \to D_2^*(2460)^- K^+$
- Simultaneously use B Dalitz and D Dalitz $\to$ Double Dalitz [12] [13]



B Dalitz plot [14]

- The amplitude of $B^0 \to DK^+\pi^-$, $D \to K^0_S\pi^+\pi^-$ can be written as

$$A \propto \overline{A}_B \overline{A}_D + e^{i\gamma} A_B A_D$$

- $A_B(\overline{A}_B)$: amplitude of $B^0 \to D^0(\overline{D}^0)K^+\pi^-$
- $A_D(\overline{A}_D)$: amplitude of $D^0(\overline{D}^0) \to f$

Partial width as a function of the position on the Double Dalitz plane

$$d\Gamma_{B^0\to DK^+\pi^-}(x) = \overline{A}_B^2 \overline{A}_D^2 + A_B^2 A_D^2 + 2\overline{A}_B \overline{A}_D A_B A_D \\ [(\cos\delta_B \cos\delta_D - \sin\delta_B \sin\delta_D)\cos\gamma - (\cos\delta_B \sin\delta_D - \sin\delta_B \cos\delta_D)\sin\gamma]$$

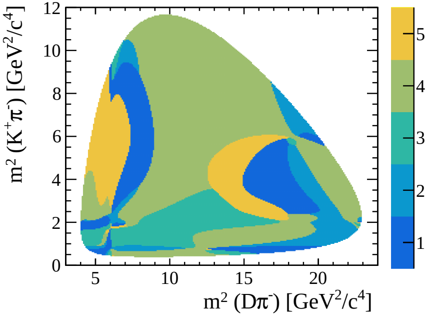
Number of events in each bin for $B^0 \to DK^+\pi^-$ (for $\overline{B}^0$ $\gamma \to -\gamma$)

$$N_{\alpha i} = h\left\{\bar{\kappa}_\alpha K_{-i} + \kappa_\alpha K_{+i} + 2\sqrt{\kappa_\alpha K_{+i}\bar{\kappa}_\alpha K_{-i}}\left[(\chi_\alpha c_i - \sigma_\alpha s_i)\cos\gamma - (\chi_\alpha s_i + \sigma_\alpha c_i)\sin\gamma\right]\right\} \quad (1)$$

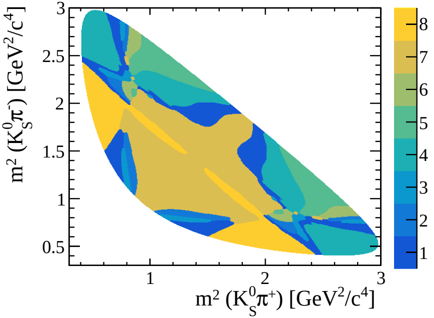
- α for B Dalitz bin, i for D Dalitz bin
- κ_α ($\bar{\kappa}_\alpha$) fraction of $B^0 \to D^0(\overline{D}^0)K^+\pi^-$ in each bin α
- χ_α, σ_α cosine and sine of strong phase difference between $B^0 \to D^0(\overline{D}^0)K^+\pi^-$ in each bin α
- $K_{+(-)i}$ fraction of D^0 ($\overline{D}^0$) $\to f$ in bin i
- c_i, s_i cosine and sine of strong phase difference between D^0 ($\overline{D}^0$) $\to f$
- h overall normalisation factor
- $\kappa_\alpha, \bar{\kappa}_\alpha, \chi_\alpha, \sigma_\alpha$ **are shared across all decay modes and float in the fit**
  - additional decay modes improve precision to these parameters

Binned Double Dalitz

- The binning scheme is based on B^0 and D Dalitz planes from [13], [10]
- A single three–body B (D) decay results in 2×5 (2×8) bins.
- A Double Dalitz decay results in $2 \times 5 \times 16 = 160$ bins
- For 160 observables we have 23 free parameters
- $B^0 \to (D \to K_S^0 K^+ K^-) K^+ \pi^-$ can also be used with a suitable D Dalitz binning



B Dalitz Plane [13]



D Dalitz Plane [10]

Additional Decays

- We could add other decays in addition to 3-body D final states
- $D \to K^+\pi^-$
  - the favoured control mode with low sensitivity to γ
  - but a high statistics provides sensitivity to the B phase space parameters
  - it adds 10 observables:

$$N_\alpha = h\left\{\bar{\kappa}_\alpha + r_D^2\kappa_\alpha + 2\sqrt{\kappa_\alpha\bar{\kappa}_\alpha}\left[(\chi_\alpha\cos(\gamma-\delta_D) - \sigma_\alpha\sin(\gamma-\delta_D)\right]\right\}$$

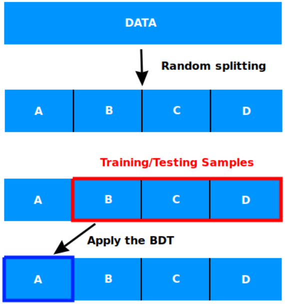
- $D \to K^-\pi^+$
  - less sensitive compared to $B^+ \to DK^+$ because r_B is larger
  - also have to manage the $B_s^0 \to D^{(*)}K^-\pi^+$ background
- $D \to K^+K^-, \pi^+\pi^-$
- $D \to \pi^+\pi^-\pi^+\pi^-, K^+\pi^-\pi^+\pi^-, K^-\pi^+\pi^+\pi^-$
  - for $K3\pi$ modes binning can be used [15]
- In principle, we could add more (e.g. $D \to h^+h^-\pi^0$)

Extraction of γ

- First we need to remove background
  - Trigger and stripping requirement
  - Boosted Decision Tree to remove combinatorial background
  - Particle identification requirement particularly against $B^0 \to D\pi^+\pi^-$
  - and so on
- We fit the B^0 invariant mass globally rather than fit for each of 160 bins
- To get $N_{\alpha,i}$, we need to subtract the number of background
- For partially reconstructed background or mis-ID background we can use `Laura++` and ongoing $B^0 \to D^* K^+\pi^-$, $B_s^0 \to D^* K^-\pi^+$ analysis to get the distribution in Dalitz space
- Then finally obtain the value of γ using 1

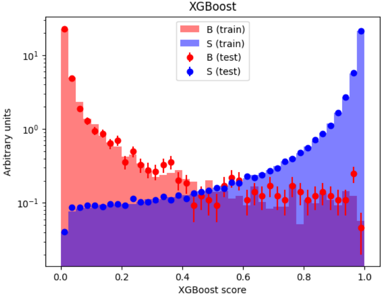
Boosted Decision Tree

- BDT with `XGBoost` to suppress combinatorials [16]
- The k-fold cross BDT method with $k = 4$ is exploited
- It allows us to use events in the fitting region for training a BDT
- We apply PID cuts on the companion particles before the training

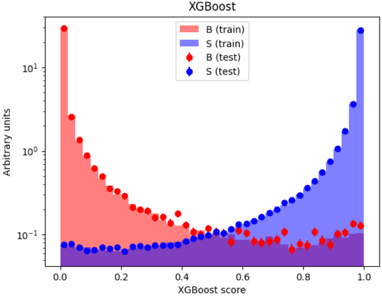


Training/Testing sample comparison

- Good agreement between the training and testing samples
- No significant overtraining
- Good separation between signal and background



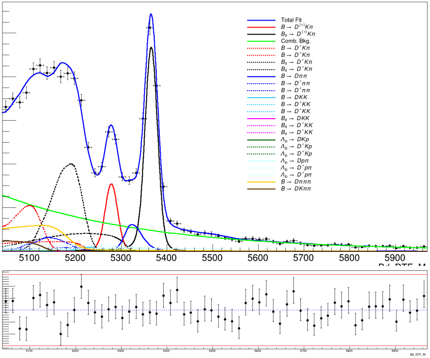
$D \to K_S^0 \pi^+ \pi^-$ DD Run1

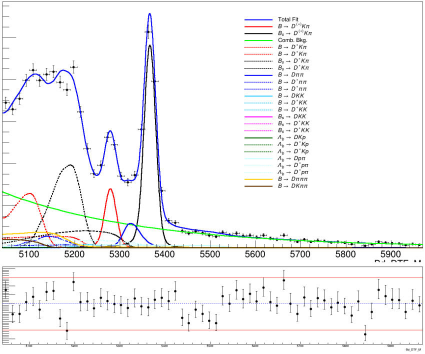


$D \to K_S^0 \pi^+ \pi^-$ DD Run 2

Mass fit

- We perform an unbinned fit to the mass distribution of B^0 and $\overline{B}^0$
- The fit is done globally (per bin) to avoid too few entries
- Need to model quite a few categories of background
- The signal peak can be clearly seen





What's next?

Number of events in bin (α, i)

$$\mu_{\alpha,i} = N_{\alpha,i} + \sum_{b \in \mathcal{B}} f^{b}_{\alpha,i} y_b,$$

- Raw number of events in each bin $\mu_{\alpha,i}$ contains background
- Need a background distribution model to estimate the yields in each bin
  - The result from $B^0 \to D^* K^+ \pi^-$, $B^0_s \to D^* K^- \pi^+$ analysis [17] are used as input
  - `Laura++` [18] is used for the other modes to obtain the model
- Then the population equations can be fitted to obtain γ

Summary

- Double Dalitz method with $B^0 \to DK^+\pi^-$, $D \to K^0_{\rm S}h^+h^-$ is a promising way to measure γ
- Including decays as $D \to h^+h^-$ or $D \to h^+h^-h^+h^-$ further improves sensitivity to γ
- The analysis is still ongoing with LHCb and getting closer to the end
- This analysis alone aims to achieve $\sigma(\gamma) \sim 5^\circ$ with Run 1+2 data

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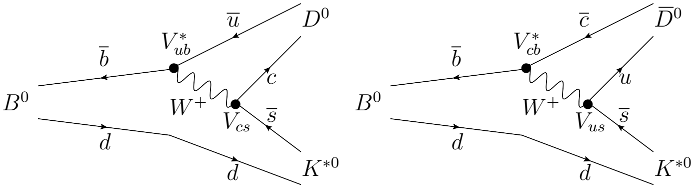
BACK UP

Measurement of γ with $B^0 \to DK^{*0}$



- The branching fraction is small ($\sim 5 \times 10^{-5}$)
- However, $r_B \sim 0.3$ which provides larger interference than $B^{\pm} \to DK^{\pm}$ (~ 0.1)
- Model-independent BPGGSZ analysis has been done for Run 1 [19]
- Run 1+2 analysis is ongoing

Decay Summary

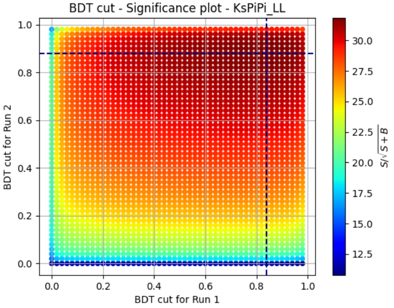
Expected number of events in each bin (α for B bin, i for D bin) for $B^0 \to DK^+\pi^-$ (to get $\overline{B}^0$ then $\gamma \to -\gamma$)

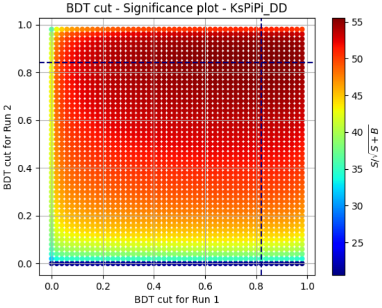
$$N_{\alpha i} = h\left\{\bar{\kappa}_\alpha K_{+i} + \kappa_\alpha K_{-i} + 2\kappa_D\sqrt{\kappa_\alpha K_{+i}\bar{\kappa}_\alpha K_{-i}}\left[(\chi_\alpha c_i - \sigma_\alpha s_i)\cos\gamma - (\chi_\alpha s_i + \sigma_\alpha c_i \sin\gamma\right]\right\}$$

Decay	Parameters	Observables
$D \to K_s^0\pi^+\pi^-$	$K_{\pm i}$ from $B^+ \to Dh^+$ BPGGSZ[20]	160
	c_i, s_i from CLEO+BES-III[21], $\kappa_D = 1$	
$D \to K_s^0 K^+K^-$	$K_{\pm i}$ from $B^+ \to Dh^+$ BPGGSZ[20]	40
	c_i, s_i from CLEO+BES-III[22], $\kappa_D = 1$	
$D \to K^+\pi^-$	$K_{+i} = 1,\ K_{-i} = r_D^2,\ c_i, s_i = \cos,\sin(-\delta_D),\ \kappa_D = 1$	10
$D \to K^-\pi^+$	$K_{+i} = r_D^2,\ K_{-i} = 1,\ c_i, s_i = \cos,\sin(\delta_D),\ \kappa_D = 1$	10
$D \to h^+h^-$	$K_{+i} = 1,\ K_{-i} = 1,\ c_i = 1,\ s_i = 0,\ \kappa_D = 1$	10
$D \to K^+\pi^-\pi^0$	$K_{+i} = 1,\ K_{-i} = r_D^2,\ c_i, s_i = \cos,\sin(-\delta_D),\ \kappa_D$	10
$D \to K^-\pi^+\pi^0$	$K_{+i} = r_D^2,\ \kappa_D,\ K_{-i} = 1,\ c_i, s_i = \cos,\sin(\delta_D),\ \kappa_D$	10
$D \to h^+h^-\pi^0$	$K_{+i} = 1,\ K_{-i} = 1,\ c_i = 1,\ s_i = 0,\ \kappa_D = (2F^+ - 1)$	10
$D \to K^-\pi^+\pi^+\pi^-$	$K_{\pm i}$ from $B^+ \to Dh^+$ BPGGSZ	80
	c_i, s_i from CLEO+BES-III, $\kappa_D = 1$	
$D \to \pi^+\pi^-\pi^+\pi^-$	$K_{+i} = 1,\ K_{-i} = 1,\ c_i = 1,\ s_i = 0,\ \kappa_D = (2F^+ - 1)$	10

Optimising the BDT cut

- We optimise the BDT cut by maximising the figure of merit $S/\sqrt{S+B}$, where S and B are the sum of signal and background around B^0 mass for both Runs
- The initial values of S and B are extracted from a simplified B^0 mass fit
- The FOM is then evaluated at each working point from the efficiency
- We set the cut at 0.85 for both Runs





Boosted Decision Tree

- Signal: truth-matched MC 11, 12, 15, 16, 17, 18 (proportional to the luminosity)
- Background: Run 1 and Run 2 data, $m_{B^0} > 5.5$ GeV
- The samples are treated separately for Run 1 and Run 2
- We split the D decay modes into categories of topology rather than training a BDT for each mode
- BDTs for each of the following categories and for each Run:
  1. KsHH LL with $D \to K^0_\mathrm{S}\pi^+\pi^-$ LL
  2. KsHH DD with $D \to K^0_\mathrm{S}\pi^+\pi^-$ DD
  3. HH with $D \to K^+K^-$
  4. HHHH with $D \to \pi^+\pi^-\pi^+\pi^-$
     - Last two are for additional decay modes
- We checked using different BDTs for each D final state does not improve performance

Combination of LHCb measurements

LHCb-CONF-2022-003

- $\gamma = (63.8^{+3.5}_{-3.7})^\circ$, $x_D = (0.398^{+0.050}_{-0.049})\%$, $y_D = (0.636^{+0.020}_{-0.019})\%$

  * Improvements about 10% on γ ($\sim$ 1 year data-taking), 6% on x_D and 38% on y_D

  \- $\gamma_{\rm UTFit} = (65.8 \pm 2.2)^\circ$, $\gamma_{\rm CKMFitter} = (65.5^{+1.1}_{-2.7})^\circ$
- Tension between different B categories remains ($\sim 2\sigma$)