$D \to K^+K^-\pi^+\pi^-$ strong phase analysis and γ measurement at LHCb and BESIII

Martin Tat

Oxford LHCb

4th December 2023

Brief introduction to my PhD analysis

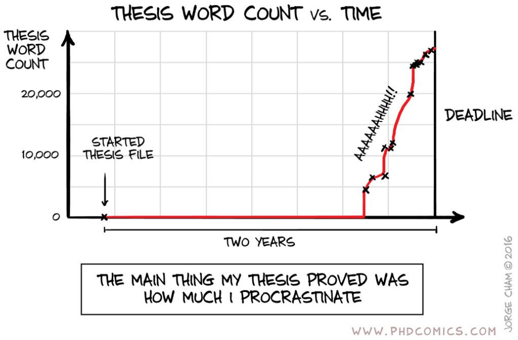
What's happened since my last update in June?

- Very busy summer! Many presentations, holiday, some analysis...
- Analysis: First strong-phase measurement of $D^0 \to K^+K^-\pi^+\pi^-$ in phase-space bins complete!
- Today: The combination of LHCb and BESIII, resulting in the first model-independent measurement of γ in this channel

Brief introduction to my PhD analysis

Status after 3 years:

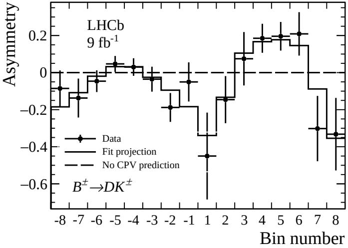
1. Final piece of my PhD analysis is coming together
2. Just started on analysis of November 2022 TORCH testbeam data
3. Will probably start writing PhD thesis next term



Recap of LHCb analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$

LHCb paper: A study of CP violation in the decays $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ $(h = K, \pi)$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$

- Binned model-dependent GGSZ analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$
- A 3σ tension: $\gamma = (116^{+12}_{-14})^{\circ}$



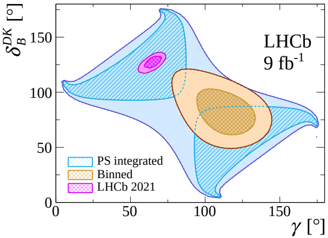


Figure 1: Left: $B^{\pm} \to DK^{\pm}$ bin asymmetries. Right: Interpretation of γ

Recap of LHCb analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$

Why is there a 3σ tension?

- $D^0 \to K^+K^-\pi^+\pi^-$ strong phases are from a model
- Model-independent inputs from BESIII are necessary
- It's been challenge to convince reviewers that γ is model dependent:

Recap of LHCb analysis of $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$

Why is there a 3σ tension?

- $D^0 \to K^+K^-\pi^+\pi^-$ strong phases are from a model
- Model-independent inputs from BESIII are necessary
- It's been challenge to convince reviewers that γ is model dependent:

" *If you plan to keep the model-dependent value of gamma in the paper, the interpretation part should contain more discussion on the model dependence.*" - EPJC referee 1

Why is there a 3σ tension?

- $D^0 \to K^+K^-\pi^+\pi^-$ strong phases are from a model
- Model-independent inputs from BESIII are necessary
- It's been challenge to convince reviewers that γ is model dependent:

" *If you plan to keep the model-dependent value of gamma in the paper, the interpretation part should contain more discussion on the model dependence.*" - EPJC referee 1

"*A general comment is that in (7 !!) different places [Abstract, Introduction (page 1)...] it is mentioned the same message: that the analysis is model-dependent...*" - EPJC referee 2

Brief summary of formalism

- Identical formalism to BPGGSZ analyses with $D^0 \to K_S^0 h^+ h^-$
- LHCb: Measure CP asymmetries in each bin
- BESIII: Measure the cosine (sine) of the strong-phase difference c_i (s_i)

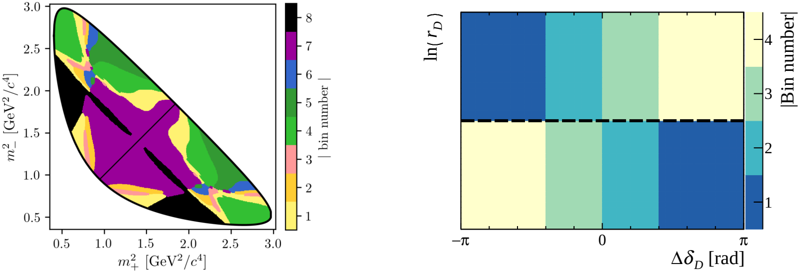
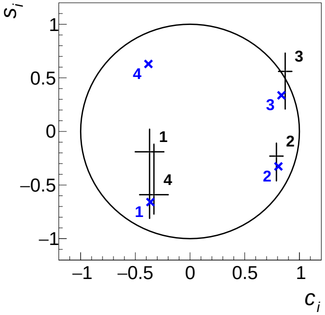


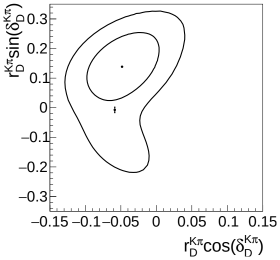
Figure 2: Left: Binning scheme of $D^0 \to K_S^0 \pi^+ \pi^-$, visualised on a Dalitz plot. Right: Analogous binning scheme for $D^0 \to K^+ K^- \pi^+ \pi^-$, where the 5D phase space is projected onto the model-predicted δ_D and r_D.

BESII c_i and s_i results

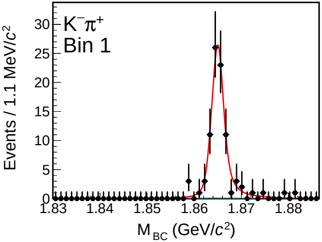
How to measure c_i and s_i? Sneha already introduced BESIII in last week's seminar!

1. Measure the double-tag yields
2. Tags with different CP content can enhance/suppress yields
3. Infer c_i and s_i in a large simultaneous fit of all 19 tag modes

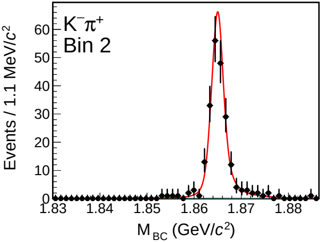




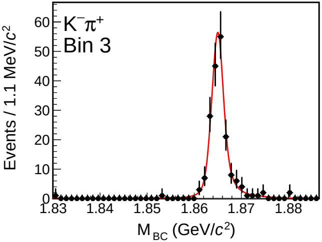
Double tag fit of $KK\pi\pi$ vs $K\pi$



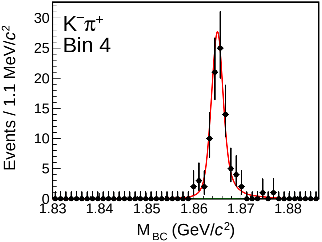
(a) Bin 1 yield: $84.5^{+9.8}_{-9.1}$



(b) Bin 2 yield: $211.2^{+15.4}_{-14.8}$

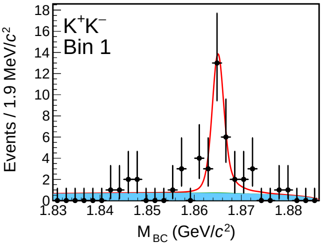


(c) Bin 3 yield: $181.0^{+14.0}_{-13.3}$

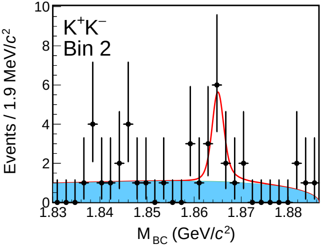


(d) Bin 4 yield: $88.6^{+9.7}_{-9.0}$

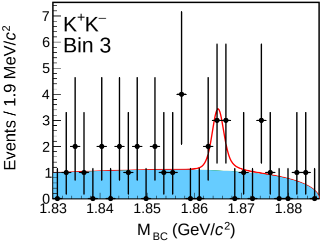
Double tag fit of $KK\pi\pi$ vs KK



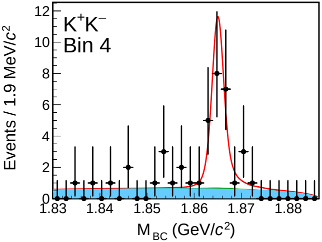
(a) Bin 1 yield: $25.3^{+6.2}_{-5.5}$



(b) Bin 2 yield: $8.8^{+4.0}_{-3.3}$

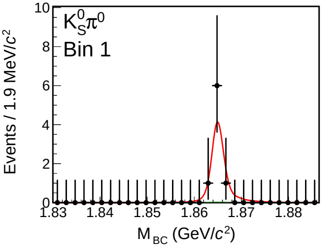


(c) Bin 3 yield: $4.5^{+3.3}_{-2.6}$

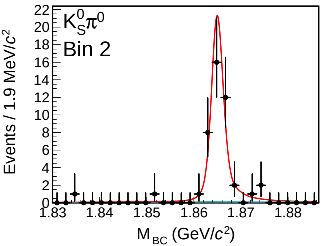


(d) Bin 4 yield: $21.1^{+5.5}_{-4.8}$

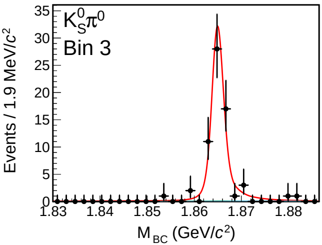
Double tag fit of $KK\pi\pi$ vs $K_S\pi^0$



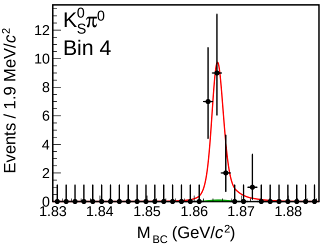
(a) Bin 1 yield: $7.9^{+3.1}_{-2.5}$



(b) Bin 2 yield: $40.4^{+6.8}_{-6.3}$



(c) Bin 3 yield: $61.1^{+8.3}_{-7.8}$



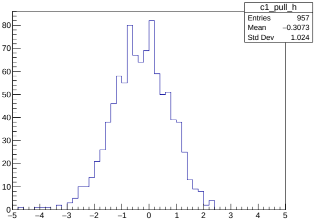
(d) Bin 4 yield: $18.3^{+4.5}_{-3.9}$

Toy studies

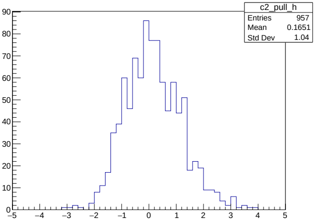
Can we trust the results? Let's do some toys!

1. Using model predictions of c_i and s_i, predict all DT yields
2. For each tag mode, generate 1000 toy datasets and fit DT yield
3. Run 1000 fits of c_i and s_i using fit results from toys
4. Plots pulls

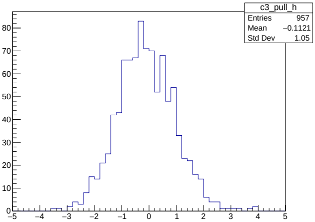
Toy studies



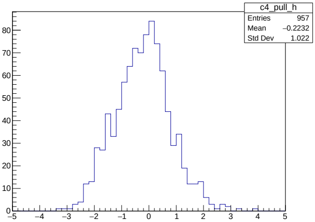
(a) c_1 pulls



(b) c_2 pulls

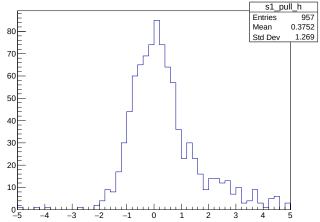


(c) c_3 pulls

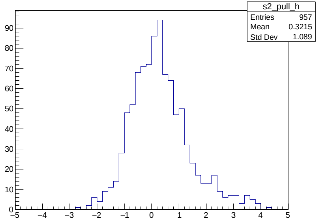


(d) c_4 pulls

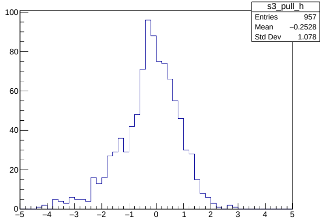
Toy studies



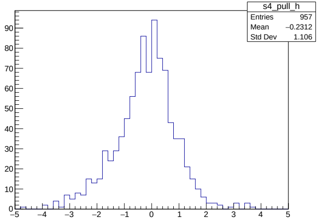
(a) s_1 pulls



(b) s_2 pulls



(c) s_3 pulls



(d) s_4 pulls

Toy studies

What do the toy fits tell us?

1. Small bias in c_i which can be corrected
2. s_i pulls are very asymmetric, and uncertainties are not very reliable

Toy studies

What do the toy fits tell us?

1. Small bias in c_i which can be corrected
2. s_i pulls are very asymmetric, and uncertainties are not very reliable

How do we determine reliable uncertainties for s_i?

What do we need?

- Assign correct uncertainties to non-Gaussian parameters
- Obtain a confidence interval with correct 68% coverage

Construction of confidence intervals

What do we need?

- Assign correct uncertainties to non-Gaussian parameters
- Obtain a confidence interval with correct 68% coverage

How do we achieve this?

- Feldman-Cousins method
- Also known as "Plugin" method in GammaCombo
- It's a "brute-force" approach to constructing a confidence interval

How to implement Feldman-Cousins method?

At each scan point of s_1, perform these fits to data:

1. Fit with all parameters floating, and save the log-likelihood χ^2
2. Fit with s_1 fixed to scan point, and save χ^2_{fix}
3. Calculate $\Delta\chi^2_{\mathrm{data}} = \chi^2_{\mathrm{fix}} - \chi^2$

We expect $\Delta\chi^2_{\mathrm{data}}$ to become large as we move away from best-fit value, but without direct knowledge of underlying PDF, we cannot determine any confidence intervals from this

Feldman-Cousins method

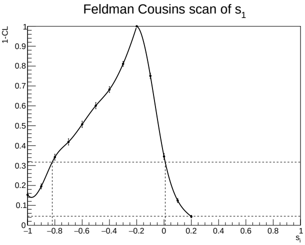
How to implement Feldman-Cousins method?

At each scan point of s_1, perform toy studies:

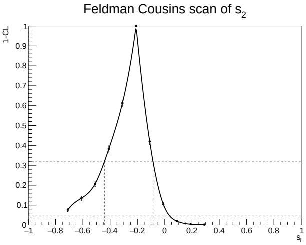
1. Fix s_1 to scan point and generate 1000 toys
2. Perform fits to each toy, with s_1 both floating and fixed
3. Calculate $\Delta\chi^2_{\mathrm{toy}}$

At each scan point, the fraction of toys with $\Delta\chi^2_{\mathrm{toy}} > \Delta\chi^2_{\mathrm{data}}$ is equal to $1 - \mathrm{CL}$, and the exact 68% confidence interval can then be obtained using an interpolation between points

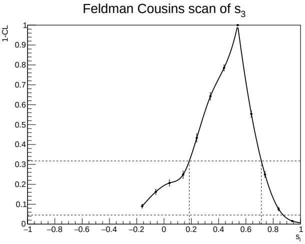
Toy studies



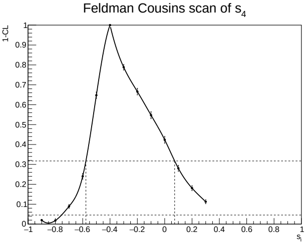
(a) s_1



(b) s_2

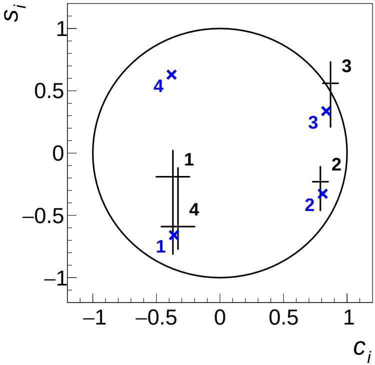


(c) s_3



(d) s_4

Fit results



$$c_1 = -0.37 \pm 0.13 \pm 0.01, \quad s_1 = -0.19^{+0.21}_{-0.62} \pm 0.04,$$
$$c_2 = 0.82 \pm 0.05 \pm 0.01, \quad s_2 = -0.23^{+0.12}_{-0.23} \pm 0.03,$$
$$c_3 = 0.86 \pm 0.05 \pm 0.01, \quad s_3 = 0.56^{+0.17}_{-0.35} \pm 0.06,$$
$$c_4 = -0.35 \pm 0.13 \pm 0.01, \quad s_4 = -0.59^{+0.47}_{-0.18} \pm 0.05,$$

BESIII paper

1. Paper was ready at the start of MT
2. Main result: c_i and s_i
3. Additional measurement: $D^0 \to K^+K^-\pi^+\pi^-$ branching fraction
4. Bonus measurement: Simultaneous determination of $\delta_D^{K\pi}$

Measurement of the strong-phase difference between D^0 and $\bar{D}^0 \to K^+K^-\pi^+\pi^-$ in bins of phase space

(Dated: 99th December 2023)

A first determination of the strong-phase difference between D^0 and $\bar{D}^0 \to K^+K^-\pi^+\pi^-$ in the decay $D^0 \to K^+K^-\pi^+\pi^-$ is performed using 7.91 fb^{-1} of $e^+e^- \to \psi(3770) \to D\bar{D}$ data collected by the BESIII detector. The measurements are made in four pairs of bins in phase space, which are chosen to provide optimal sensitivity to the angle γ of the Unitarity Triangle in $B^\pm \to DK^\pm$ decays. From these measurements, it follows that the *CP*-even fraction of the decay is $F_+ = 0.744 \pm 0.016_{\text{stat.}} \pm 0.008_{\text{syst.}}$. In addition, the branching fraction of $D^0 \to K^+K^-\pi^+\pi^-$ decays is measured to be $(2.76 \pm 0.05_{\text{stat.}} \pm 0.03_{\text{syst.}}) \times 10^{-3}$, which is significantly more precise than previous results obtained at other experiments.

I. INTRODUCTION

In the Standard Model (SM), all *CP*-violation phenomena in the quark sector can be described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2]. The unitarity nature of this matrix leads to a set of relations that may be represented as triangles in the complex plane. One of these representations, the so-called Unitarity Triangle (UT), has particular importance in flavor-physics studies as all its parameters may be conveniently measured in the decays of b hadrons [3].

In order to test the SM description of *CP* violation, it is important to verify that all measurements of the sides and angles of the UT are self consistent. In this task, measurements of the angle γ (sometimes denoted ϕ_3) $= \arg(-V_{us}V_{ub}^*/V_{cs}V_{cb}^*)$ are of particular importance, as they involve only tree-level processes, which are assumed to be dominated by SM contributions and have negligible theoretical uncertainties [4]. Hence, these measurements provide an important benchmark of the SM, which may be compared to indirect determinations of γ arising from measurements of other parameters of the UT that are more susceptible to any New Physics effects lying beyond our present knowledge.

The angle γ can be measured using $B^\pm \to DK^\pm$ decays, where D is a superposition

BESIII analysis review: a brief summary (paraphrased)

6th September 2023

BESIII analysis review: a brief summary (paraphrased)

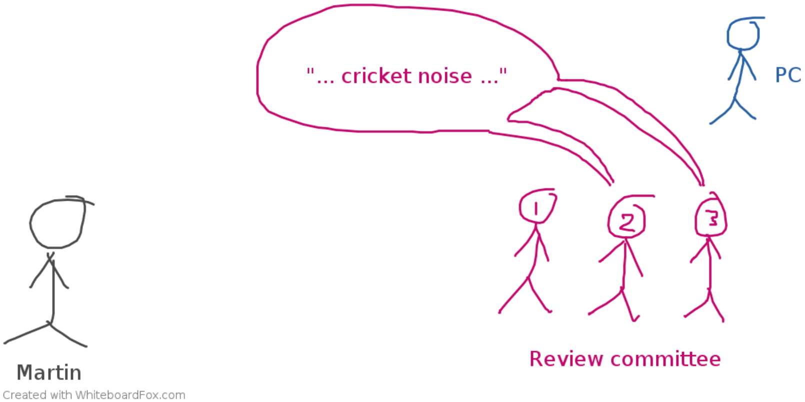
21st September 2023

BESIII analysis review: a brief summary (paraphrased)

22nd September 2023

BESIII analysis review: a brief summary (paraphrased)

22nd September 2023



BESIII analysis review: a brief summary (paraphrased)

30th September 2023

BESIII analysis review: a brief summary (paraphrased)

30th September 2023

BESIII analysis review: a brief summary (paraphrased)

10th October 2023

BESIII analysis review: a brief summary (paraphrased)

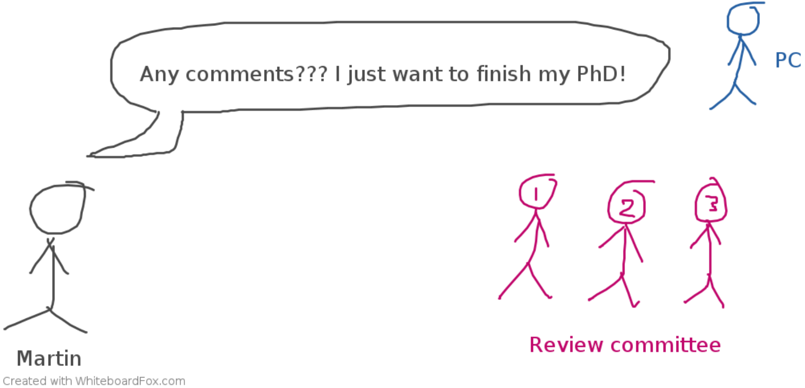
23rd October 2023

BESIII analysis review: a brief summary (paraphrased)

23rd October 2023

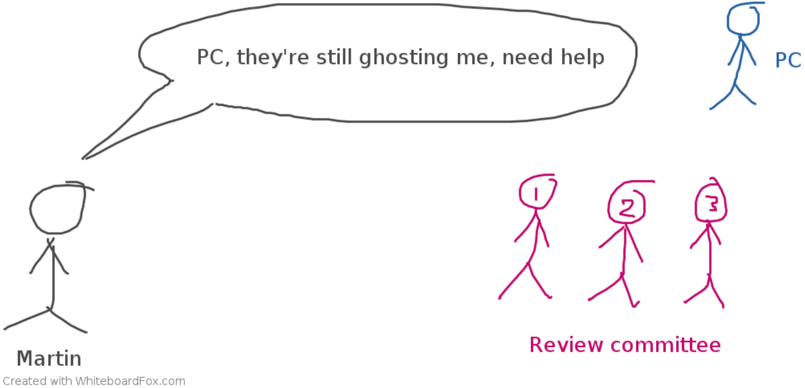
BESIII analysis review: a brief summary (paraphrased)

6th November 2023



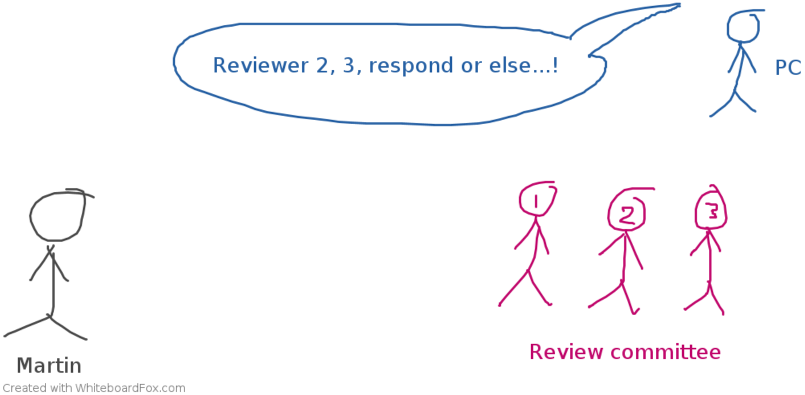
BESIII analysis review: a brief summary (paraphrased)

20th November 2023



BESIII analysis review: a brief summary (paraphrased)

20th November 2023



BESIII analysis review: a brief summary (paraphrased)

20th November 2023

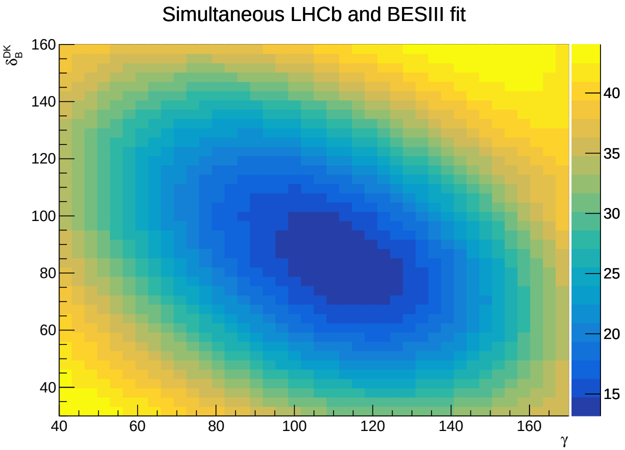
Combined BESIII and LHCb fit of γ

How to account for non-Gaussian s_i uncertainties in γ analysis?

1. Simultaneous fit of BESIII and LHCb data
2. Incorporate $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ bin yields into BESIII fit
3. Free parameters: γ, r_B, δ_B, F_i, c_i, s_i, K_i, etc

Long term plan: Make some likelihood code for c_i and s_i available

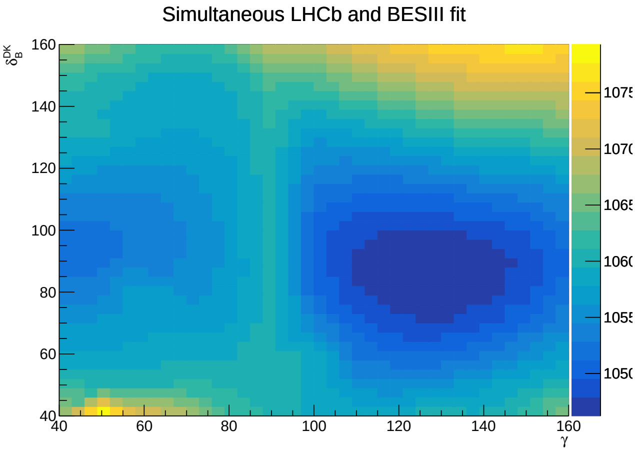
Cross check with model-dependent c_i and s_i:



$$\gamma = (112 \pm 13)^\circ \text{ as expected}$$

Combined BESIII and LHCb fit of γ

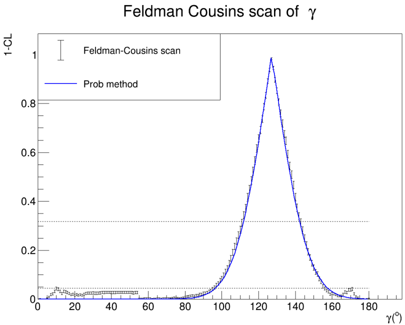
Then fit LHCb bin yields c_i and s_i simultaneously:



$\gamma = (127 \pm 15)^\circ$, what happened here?!

Combined BESIII and LHCb fit of γ

Confirm with Feldman-Cousins method:



- Good news: c_i and s_i systematic is smaller than expected!
- Bad news: Tension has now increased to 4σ!!!
- I have looked for bugs everywhere, any suggestions are welcome

Summary and conclusion

In summary:

1. BESIII analysis done, held up by deadweight in the review committee
2. Model-independent value of γ has a 4σ tension with LHCb combination, and I have no idea where the bug is

Next steps:

- Assist Warwick+Bristol groups with TORCH testbeam data
- Study PID separation with testbeam data
- Make a thesis writing plan