CPV in $B^{\pm} \to Dh^{\pm}$ Decays where $D \to K_S^0 h'^{+} h'^{-}$

A measurement of the CKM angle γ at LHCb and understanding the impact of neutral kaon CP violation

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UNIVERSITY OF OXFORD

First of all …

… many thanks to

Sneha Malde
Supervisor

Guy Wilkinson
Temp. supervisor

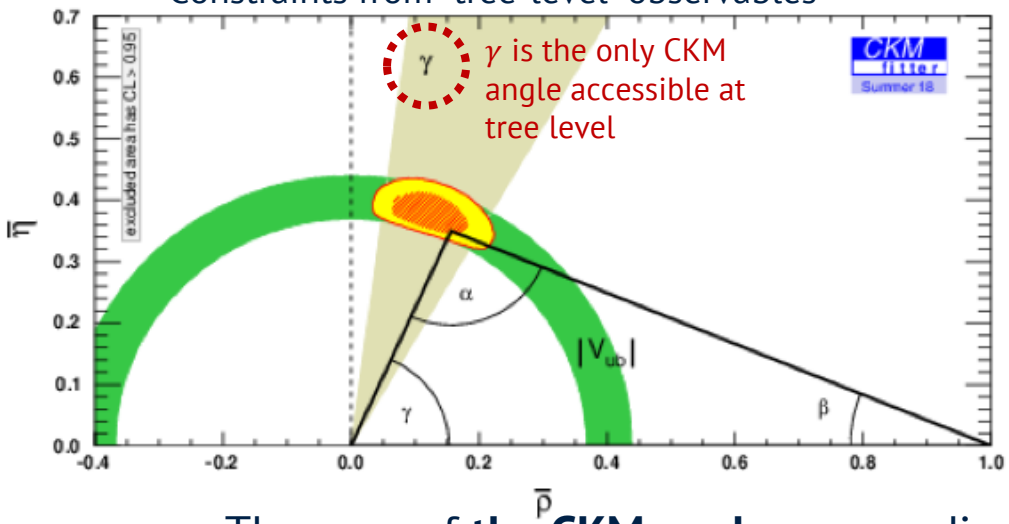
Nathan Jurik

… as well as to many *other colleagues, convenors, and fellow students, for invaluable help and inspiration throughout my time as a DPhil student*

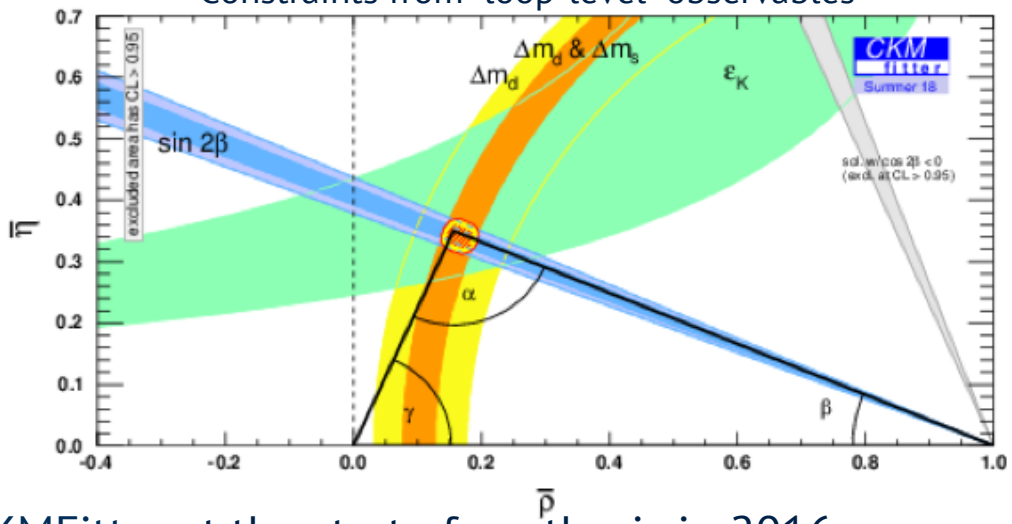
Is the Unitarity Triangle a triangle?

Crucial flavour physics goal: experimentally test consistency of the CKM mechanism by over-constraining parameters

Constraints from "tree-level" observables



Constraints from "loop-level" observables



The case of **the CKM angle γ** according to CKMFitter at the start of my thesis in 2016:

$$\gamma_{\text{direct}} = 72.1^{+5.4^\circ}_{-5.8}$$

= ?

$$\gamma_{\text{indirect}} = 65.33^{+0.96^\circ}_{-2.54}$$

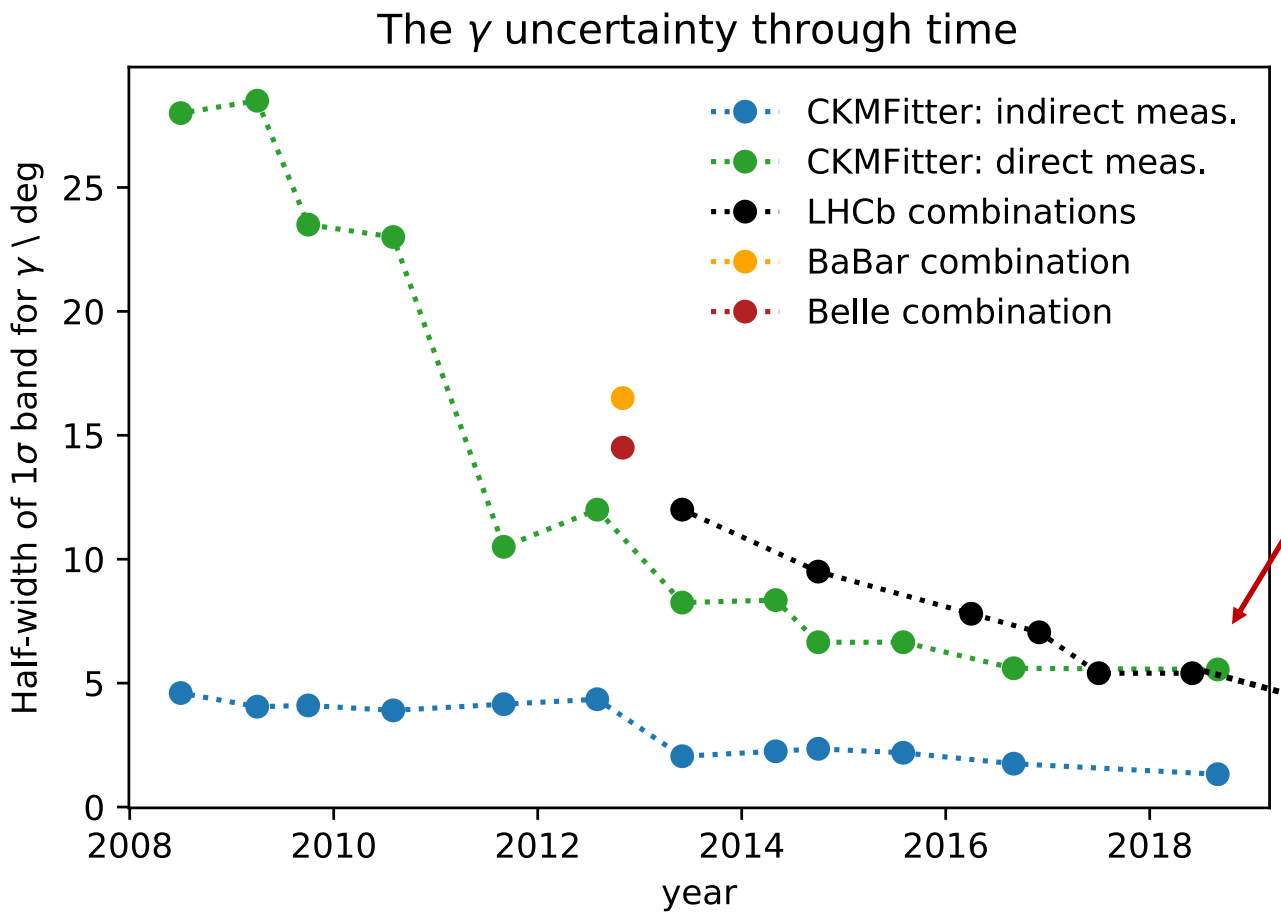
Measured in $B \to DK$ decays and friends

- Theoretically **clean**: $\delta\gamma_{\text{theory}}/\gamma \simeq 10^{-7}$
- **SM benchmark**: NP contributions to tree level process expected to be small

Indirect determination from other CKM parameters

- $\sin 2\beta$ from $B^0 \to J/\psi K_S^0$
- Δm_d and Δm_s from $B^0_{(s)}$ mixing
- ϵ_k from neutral kaon CPV measurements

LHCb has reduced the uncertainty on the CKM angle γ by a factor of 3



Two measurements of the thesis contributed to LHCb γ-combinations

$$\gamma_{\text{LHCb in 2021}} = 65.4^{+3.8^\circ}_{-4.2}$$

BaBar combination: [arXiv:1301.3283], Belle combination: [arXiv:1301.2033]. CKMFitter results: [CKMFitter.in2p3.fr]. Latest LHCb combination: [LHCb-PAPER-2021-033]

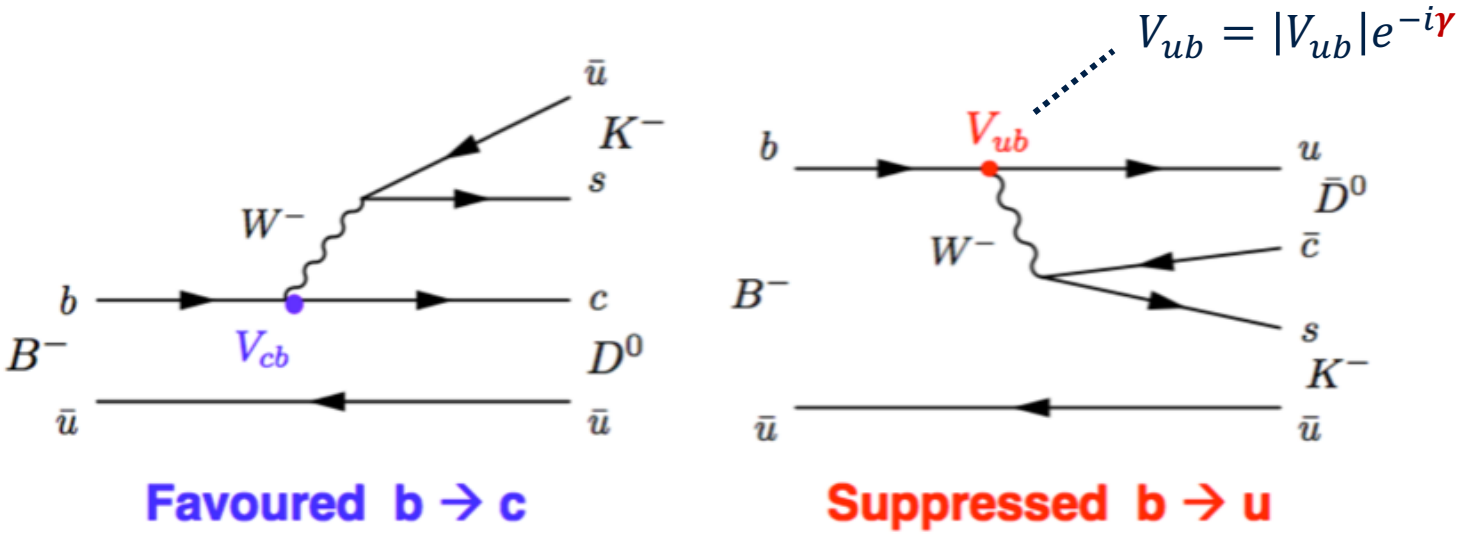
The main contributions of my thesis

- Two measurements of γ using $B^{\pm} \to Dh^{\pm}$ Decays where $D \to K_S^0 h'^{+} h'^{-}$
  - Using 2015+16 data *[LHCb-PAPER-2018-017]*
  - Update using full Run dataset *[LHCb-PAPER-2020-019]*
    - → Extended *and* simplified analysis
    - → Significant reduction in dominant systematic
    - → Most precise single measurement of γ

- A study of the impact of neutral kaon CPV and material interaction on the measurements above [JHEP08(2018)176]

- I also had the pleasure of working as a *RICH piquet*, and being both *PID liaison* and *Run 3 Stripping migration coordinator* for the B2OC working group

The canonical way to measure γ directly is to use $B^{\pm} \to DK^{\pm}$ decays



Access to γ via **interference between $b \to c$ and $b \to u$** transitions

- γ is the EW (CP-violating) phase between the $B^{\pm} \to D^0 K^{\pm}$ and $B^{\pm} \to \bar{D}^0 K^{\pm}$ amplitudes *(up to relative corrections of $O(\lambda^4) \simeq 2\times10^{-3}$)*

$$\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B \exp[i(\delta_B - \gamma)]$$

$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \bar{D}^0 K^+)} = r_B \exp[i(\delta_B + \gamma)]$$

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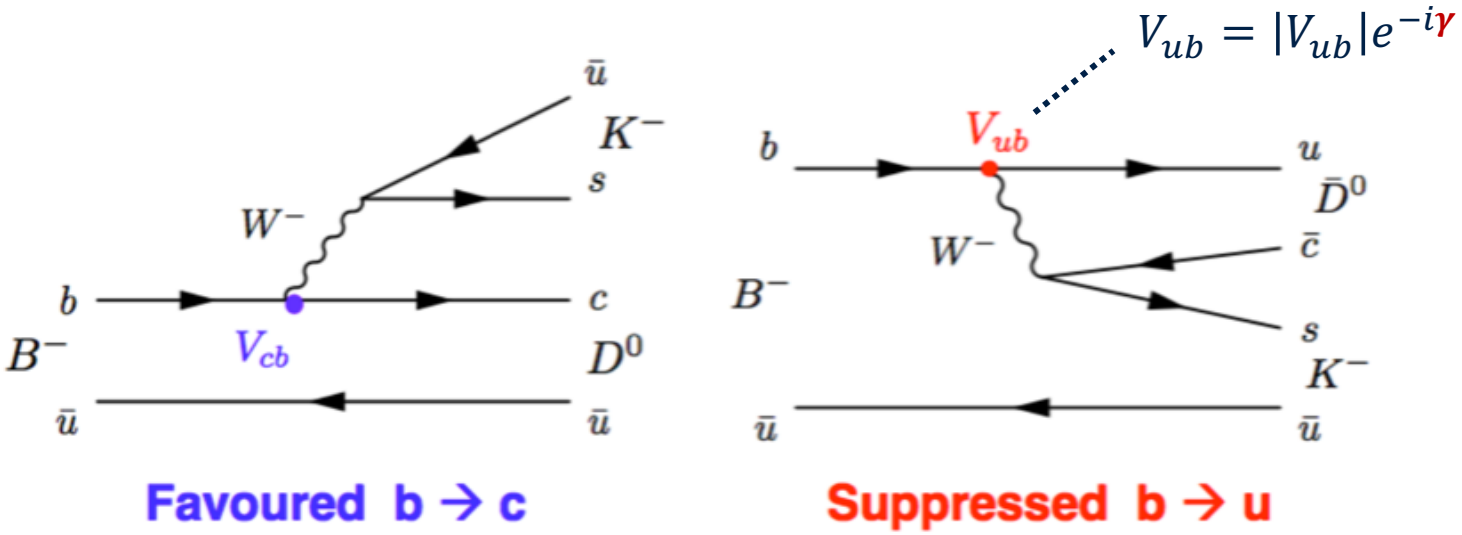

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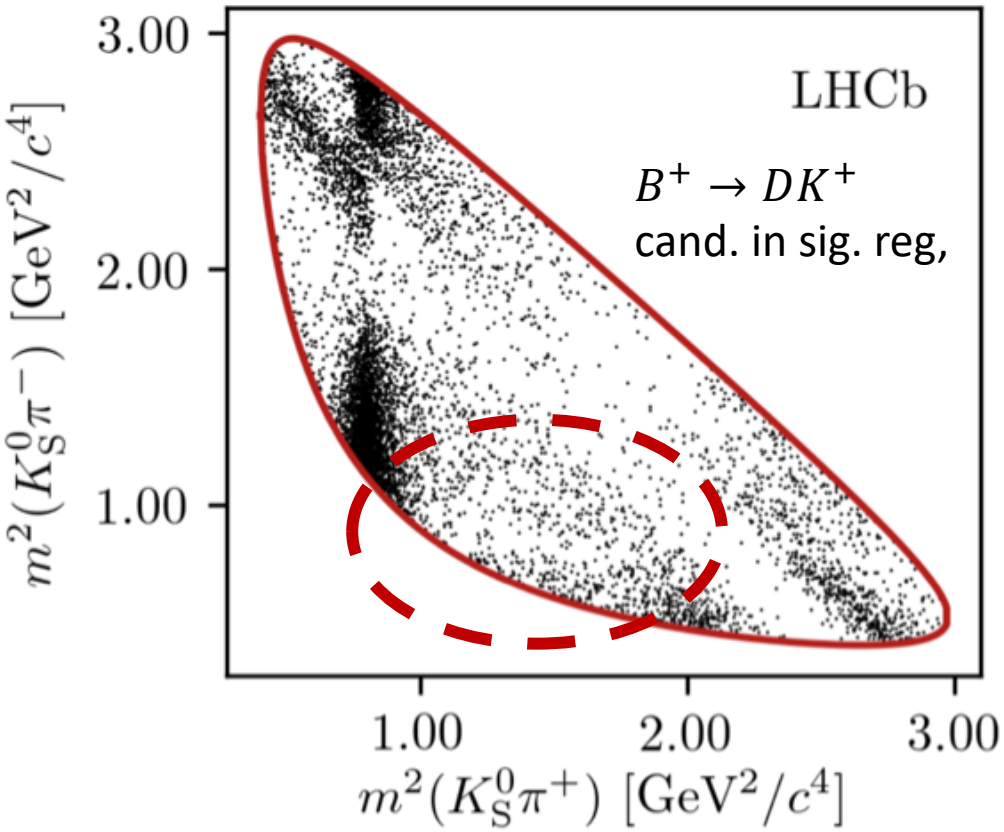
$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \bar{D}^0 K^+)} = r_B \exp[i(\delta_B + \gamma)]$$

With $\boldsymbol{D \to K_S^0 h^+ h^-}$ **final state**: interference $\propto \exp[\delta_B \pm \gamma + \Delta\delta_D(m^2_{K_S^0\pi^-}, m^2_{K_S^0\pi^+})]$

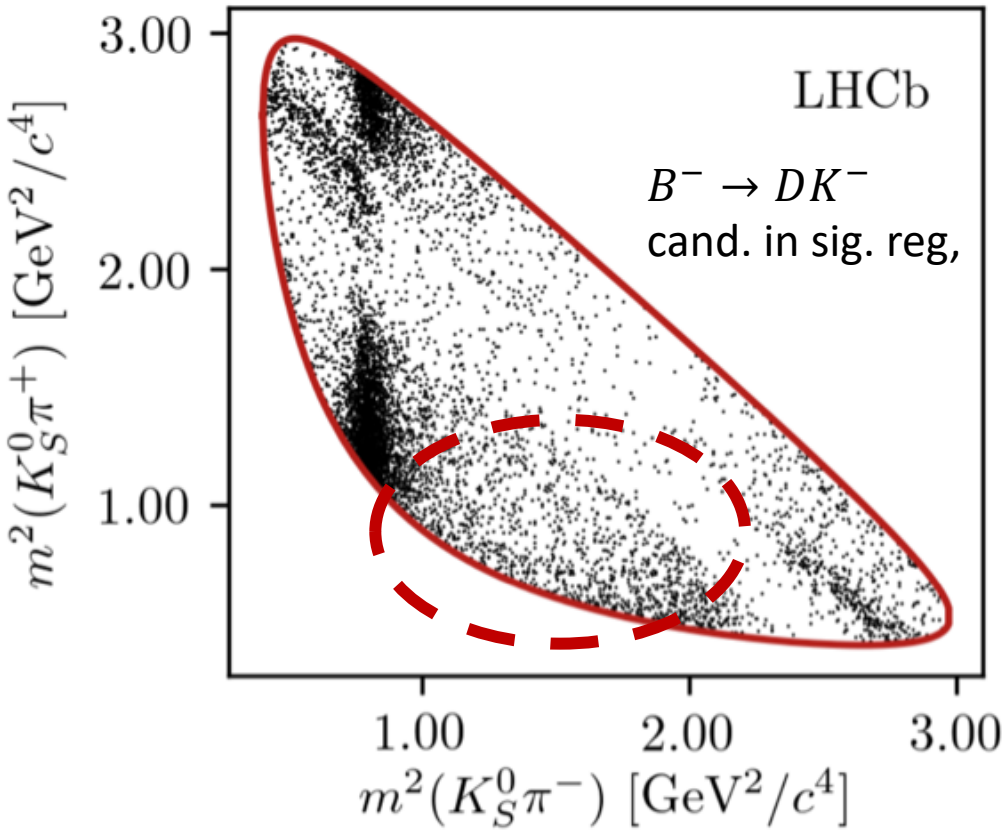
Phase-space dependent $\bar{D}^0 - D^0$ decay amplitude phase difference

In multi-body D final states the CP asymmetry varies over the D-decay phase space

Overall CP asymmetry **small** $\simeq$ **1**%



Large in *certain regions* of phase-space



The phase-space dependent asymmetry is key to the model-independent BPGGSZ method

Divide phase space of $D \to K_S^0 h^+ h^-$ decay into bins and measure yields in each

- Analysis is **independent of modelling** of D decay
- Sensitivity from **phase-space distribution**, not overall asymmetries
  → overall production/detection/K_S^0-CPV asymmetries have no impact

$$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + i y_\pm$$

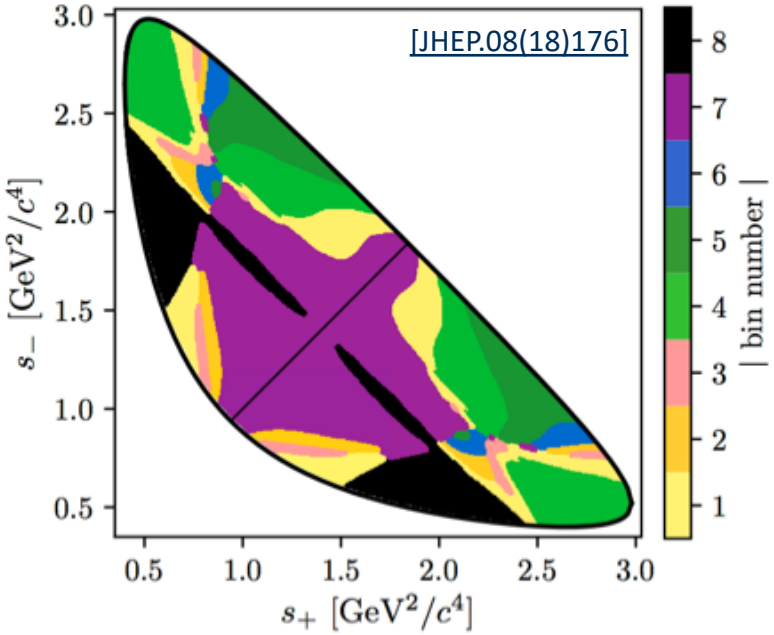
$$N_{\pm i}^- \propto F_{\pm i} + (x_\pm^2 + y_\pm^2) F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

F_i : Fractional yield of flavour tagged D^0 into bin i

Earlier analyses: measured in control channel: $\bar{B}^0 \to D^{*+}\mu^-\nu_\mu X$

c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

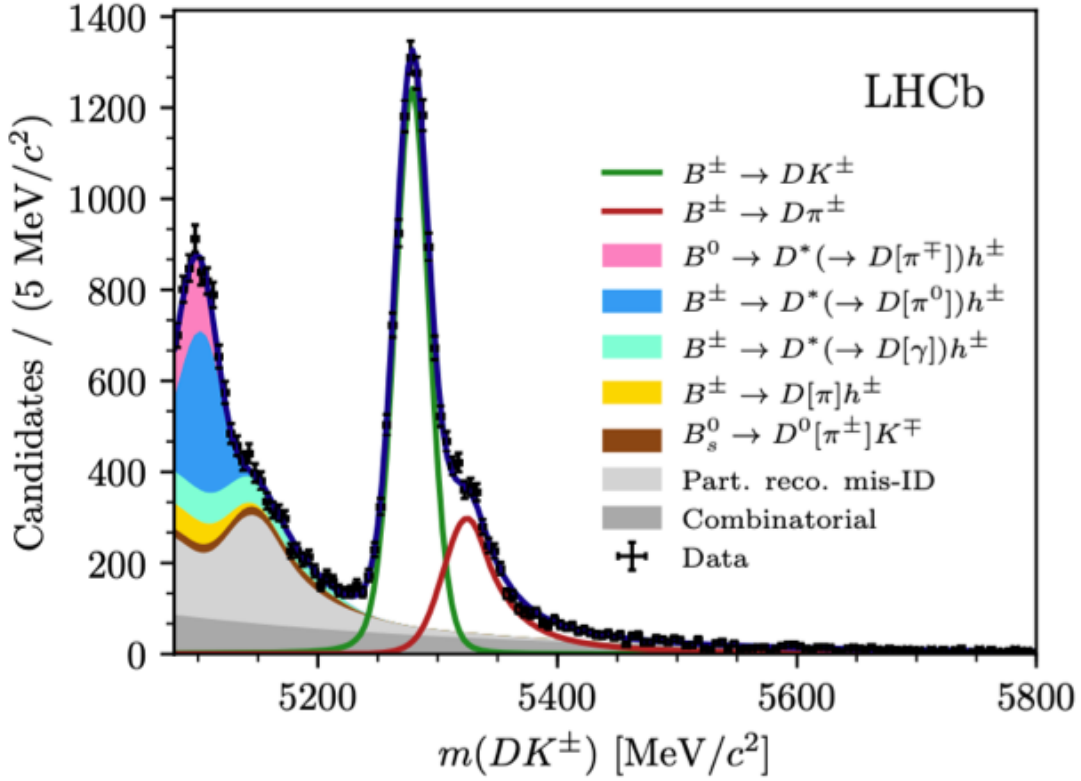
External input from CLEO-c/BESIII measurement

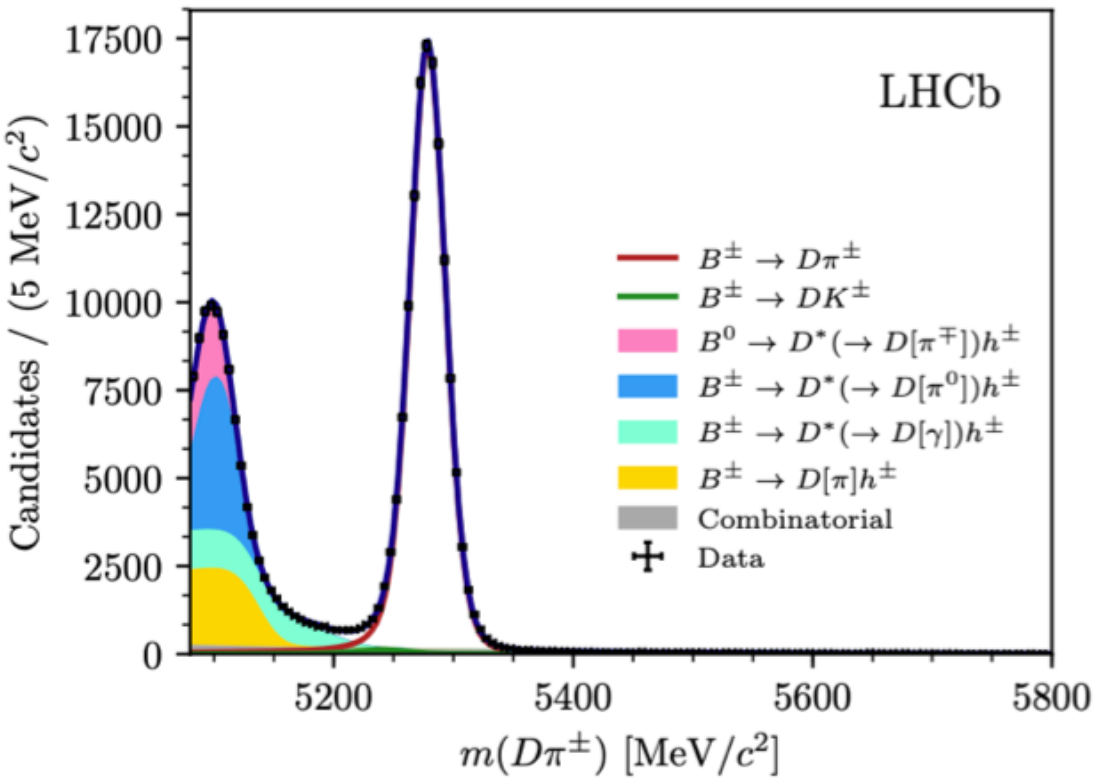


The fit employs a two-step mass fit procedure to fit results *(for selection details, see thesis ☺)*

Step 1: Fit B^+ and B^- together, combining all bins to determine shapes

Step 2: Split by charge and phase-space bin to determine $x_\pm$ and $y_\pm$

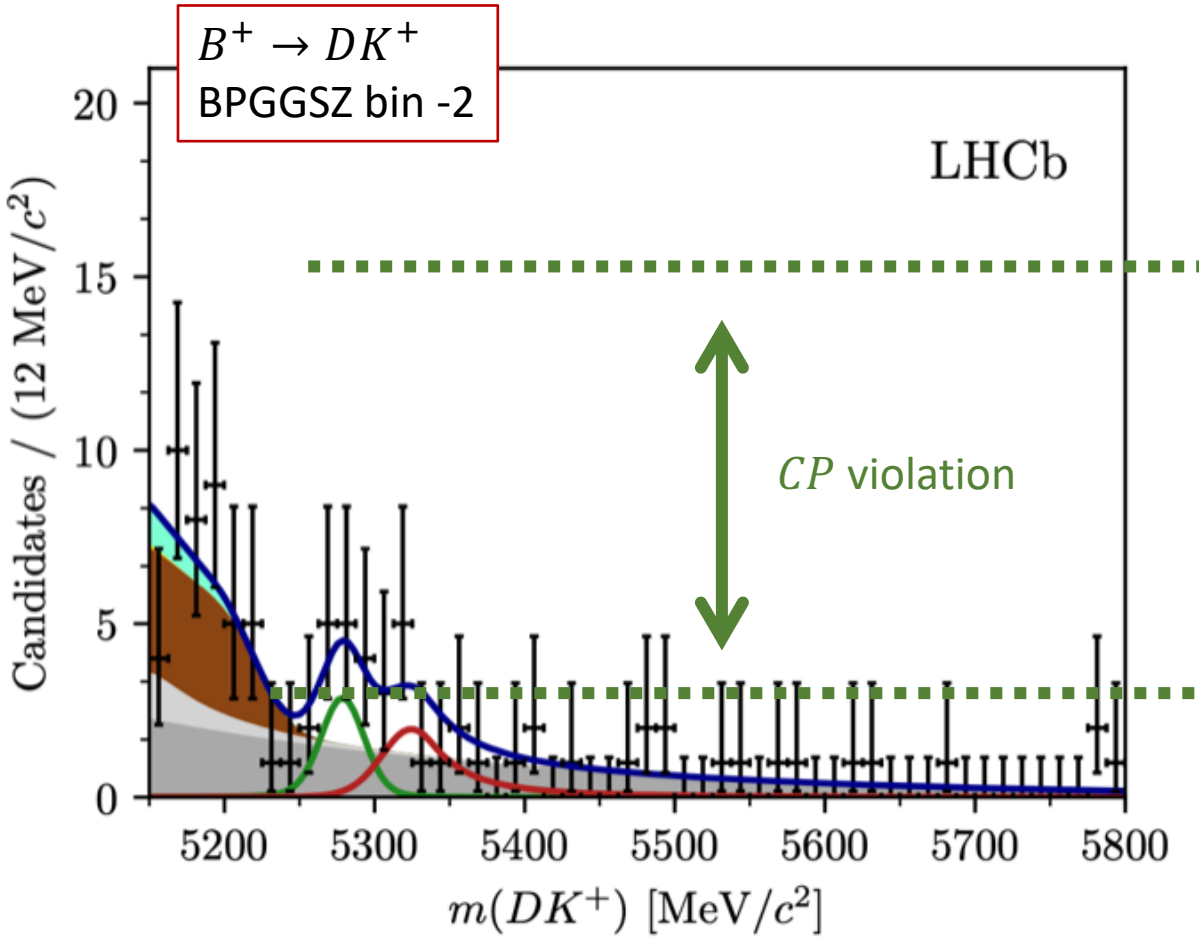


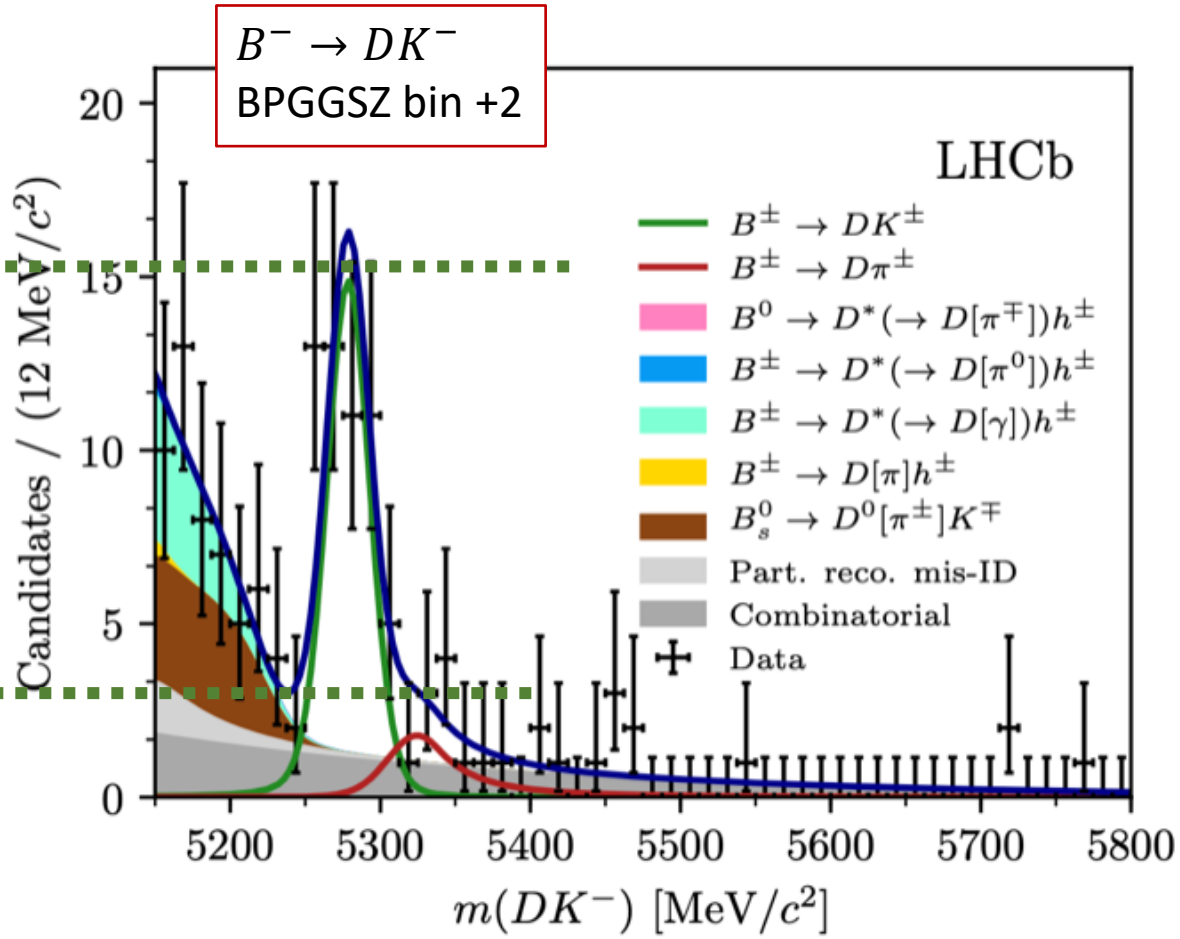


In model-independent BPGGSZ measurements the CP asymmetry is large in some bins

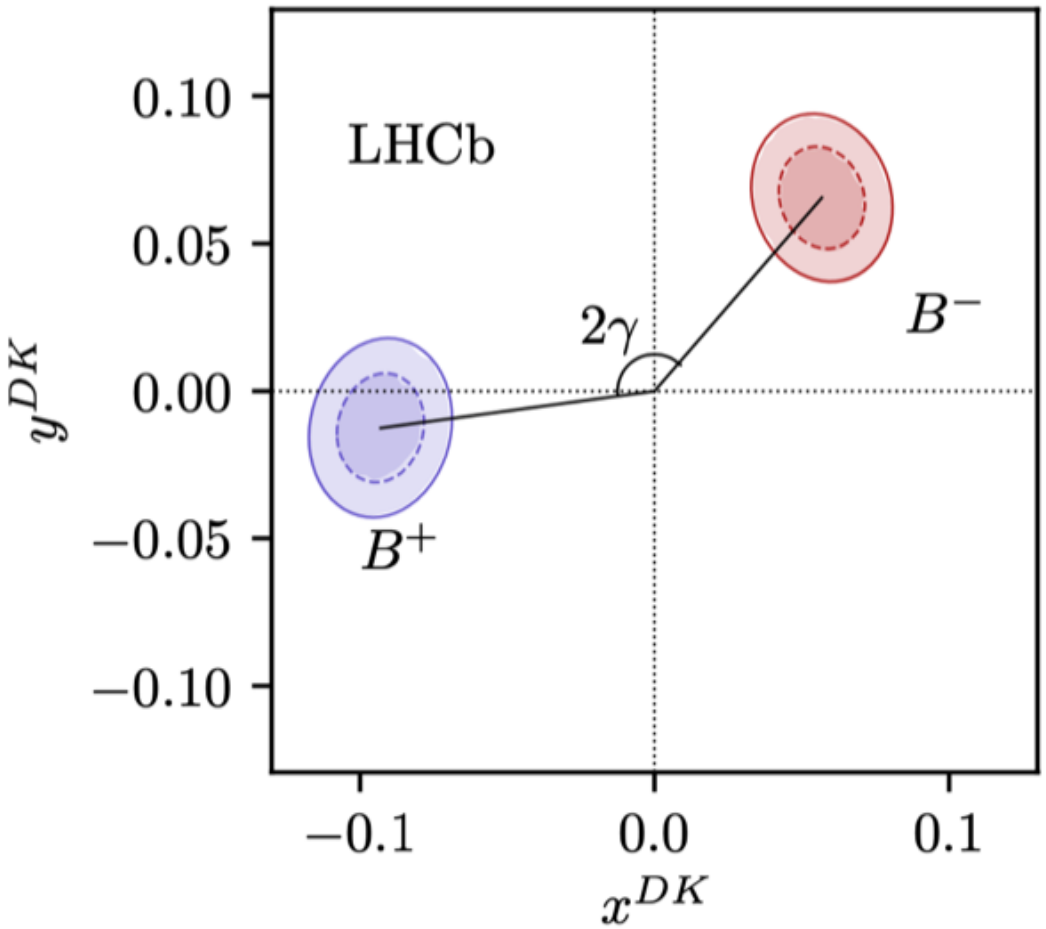
Overall CP asymmetry **small** $\simeq$ **1%**

Large in *certain BPGGSZ bins*

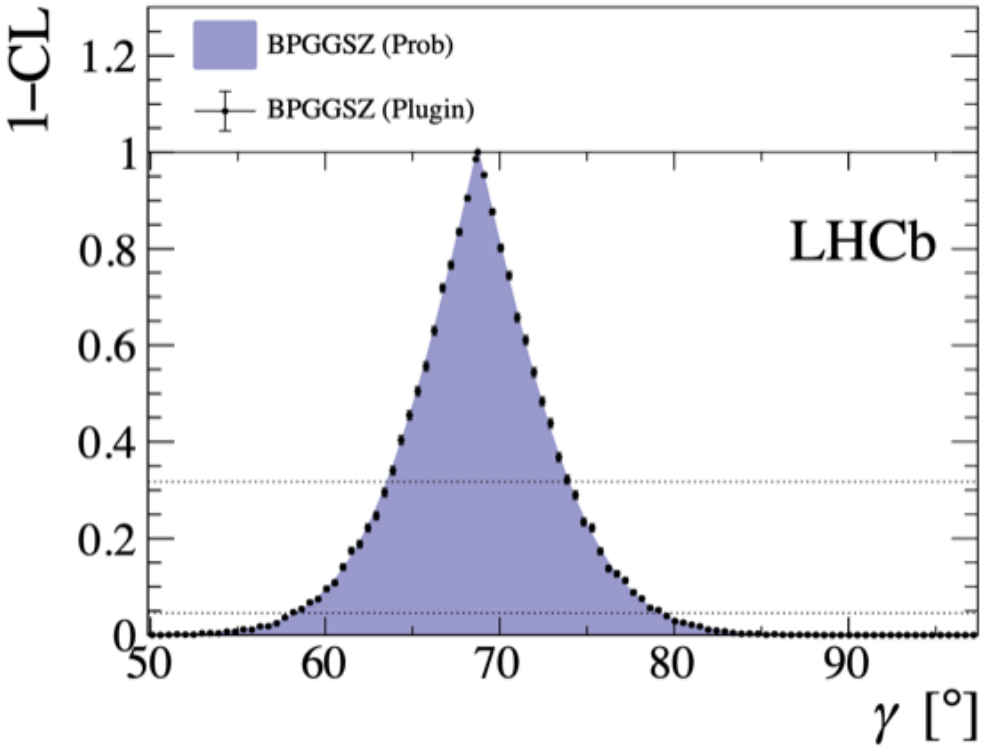




Run 1+2 data provided a γ measurement with precision comparable to the world average at the time



$$\gamma = (68.7^{+5.2}_{-5.1})^\circ$$



All sources of uncertainty were reduced compared to earlier measurements

Data: Run 1+15+16

$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$

Statistical uncertainty
In line with expectation due to increase in size of data set

Systematic uncertainty
Dominant systematic uncertainty **avoided** due to promotion of $B^\pm \to D\pi^\pm$ to signal channel

Uncertainty on external inputs
Improved knowledge of charm input due to BESIII measurement

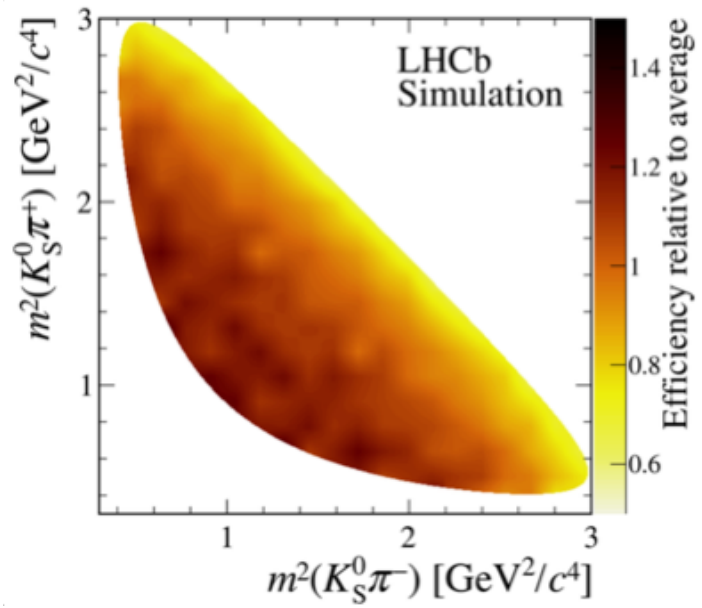
Data: Run 1+2

$$x_+ = (-9.3 \pm 1.0 \pm 0.2 \pm 0.2) \times 10^{-2}$$

Leading systematic uncertainty in earlier analyses was due to phase-space-dependent efficiency

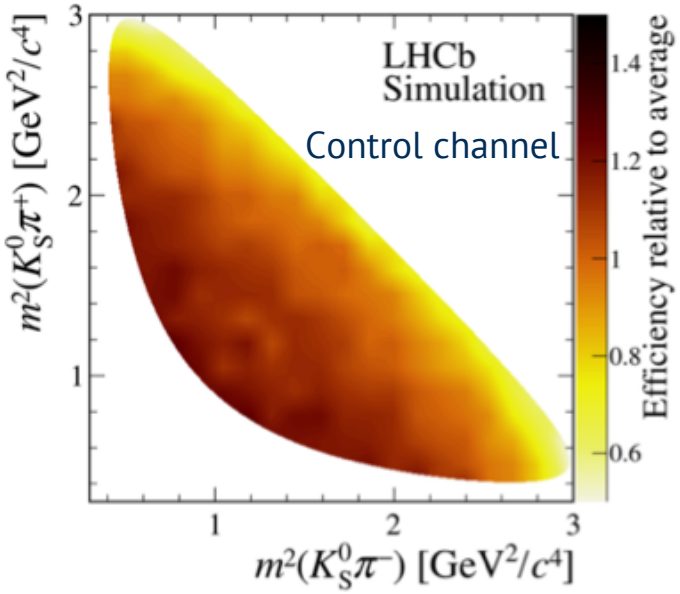
Leading systematic uncertainty in earlier analyses:

- Phase-space dependence of reconstruction efficiency must be taken into account
- Measured in $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\mu^-\nu_\mu X$ control channel
- There is an efficiency difference between signal and control channels, which must be adjusted for via MC



Dalitz-plot efficiency profiles expected to be very similar in $B \to DK$ and $B \to D\pi$

- $B \to D\pi$ must be included in analysis to control mis-ID bkg. under *all* circumstances
- Why was $B \to D\pi$ **not** used as efficiency control mode?



$B \to D\pi$ was not used as efficiency-control channel due to worries about impact of neutral kaon CPV

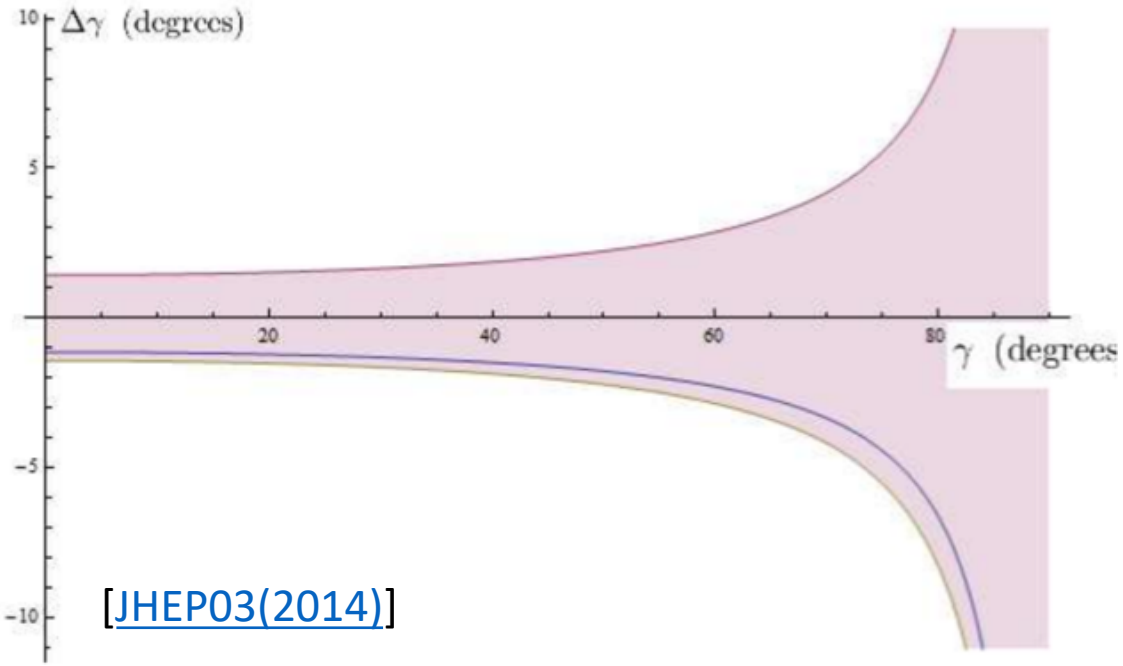
Why was $B \to D\pi$ **not** used as efficiency control mode?

a) Bias from non-zero CPV in $B \to D\pi$

b) Worries about effect of $\boldsymbol{K_S^0}$**-CPV in** $\boldsymbol{D\pi}$ if promoting to signal channel
→ Effect cf. [JHEP03(2014)]: $\Delta\gamma/\gamma = O(|\epsilon|/r_B)$

$|\epsilon|/r_B^{DK} \simeq 2\ \%$

$|\epsilon|/r_B^{D\pi} \simeq 40\ \%$



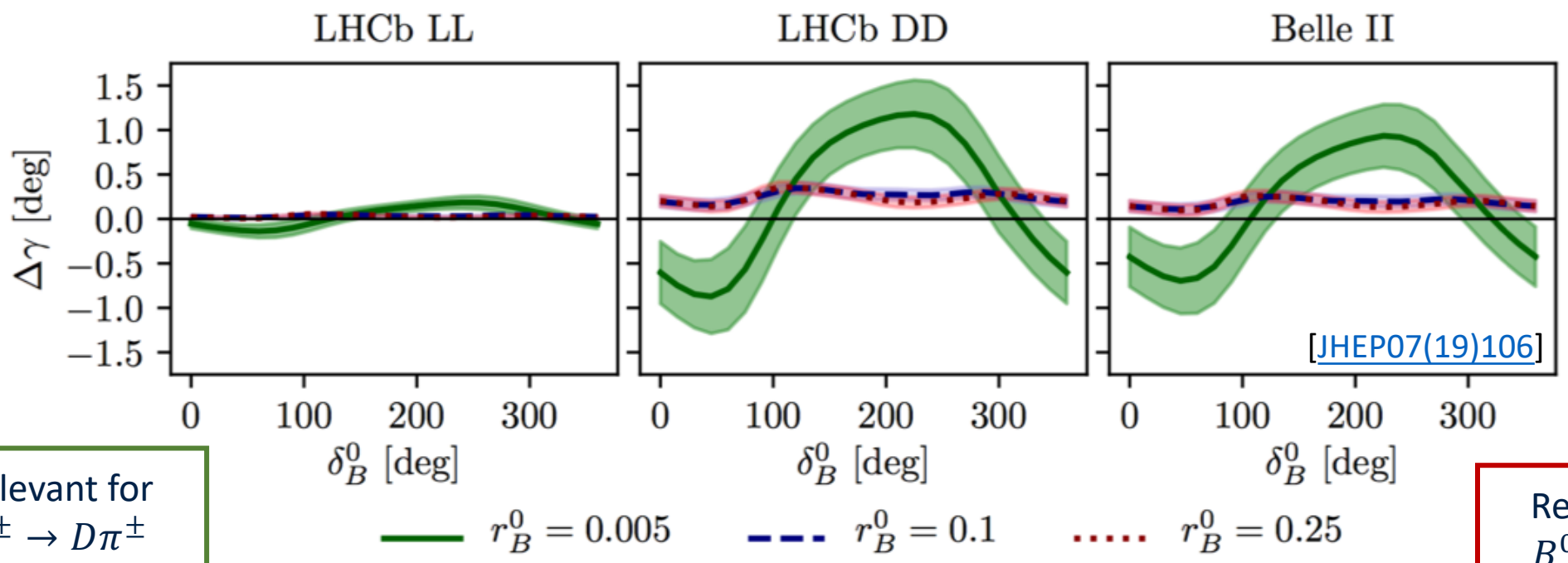
[JHEP03(2014)]

Impact of neutral kaon CPV and material interaction is negligible – also for $B \to D\pi$

Careful studies in thesis show effect to be $O(|\epsilon| \tan^2\theta_c / r_B)$ for BPGGSZ measurements (and *not* $O(|\epsilon|/r_B)$)

Reason: approach is based on *phase-space distribution*, not overall asymmetries

→ negligible compared to statistical uncertainties for both DK and $D\pi$ observables



Relevant for $B^\pm \to D\pi^\pm$

Relevant for $B^0 \to DK^{*0}$

Only two additional fit parameters are necessary to include $D\pi$ as signal channel

$$N^{-}_{\pm i} \propto F_{\pm i} + \left(x_{-}^{Dh^2} + y_{-}^{Dh^2}\right) F_{\mp i} + 2\sqrt{F_i F_{-i}}\left(x_{\pm}^{Dh} c_{\pm i} - y_{\pm}^{Dh} s_{\pm i}\right)$$

Bin-yield parameterisation used for both $DK^{\pm}$ and $D\pi^{\pm}$

The $D\pi$ CPV observables are parameterised using **two** nuisance parameters [1804.05597]

- Improved fit stability compared to introducing separate $(x_{\pm}, y_{\pm})$ for $D\pi$
- Information on γ from $D\pi$ channel enters via x^{DK}/y^{DK}, not via $\xi^{D\pi}$

$$\xi^{D\pi} = x_{\xi}^{D\pi} + i\, y_{\xi}^{D\pi} = \frac{r^{D\pi} e^{i\delta^{D\pi}}}{r^{DK} e^{i\delta^{DK}}}$$

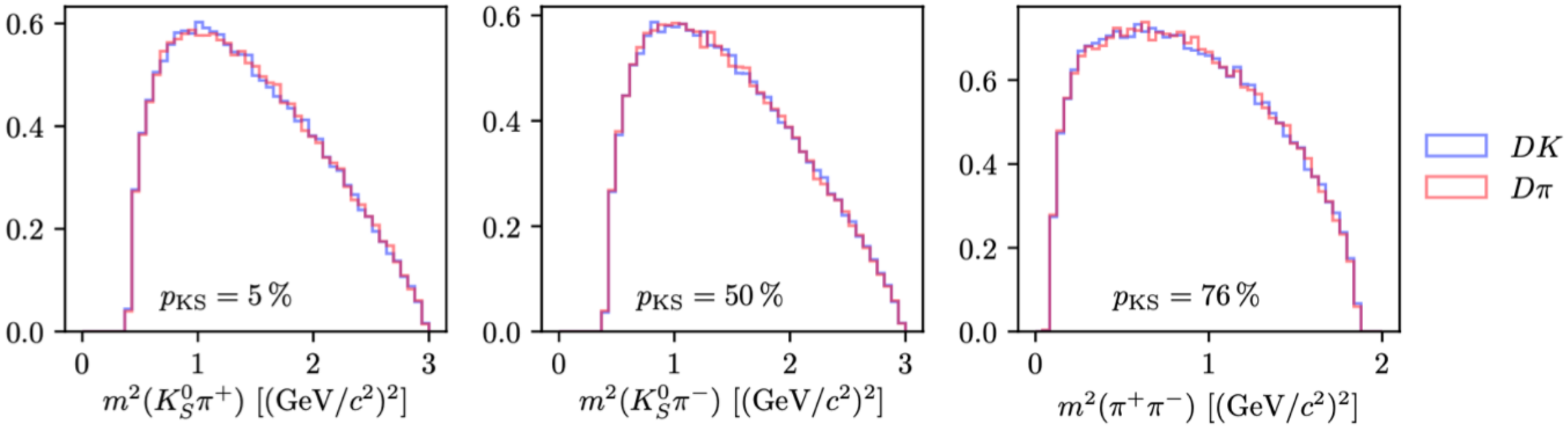
$$x_{\pm}^{D\pi} = x_{\xi}^{D\pi} x_{\pm}^{DK} - y_{\xi}^{D\pi} y_{\pm}^{DK}$$
$$y_{\pm}^{D\pi} = x_{\xi}^{D\pi} y_{\pm}^{DK} + y_{\xi}^{D\pi} x_{\pm}^{DK}$$

Large samples of simulated decays confirm identical efficiency profiles for DK and $D\pi$

Phase-space dependence of efficiency indistinguishable between $B \to DK$ and $D \to D\pi$, even with very large MC samples

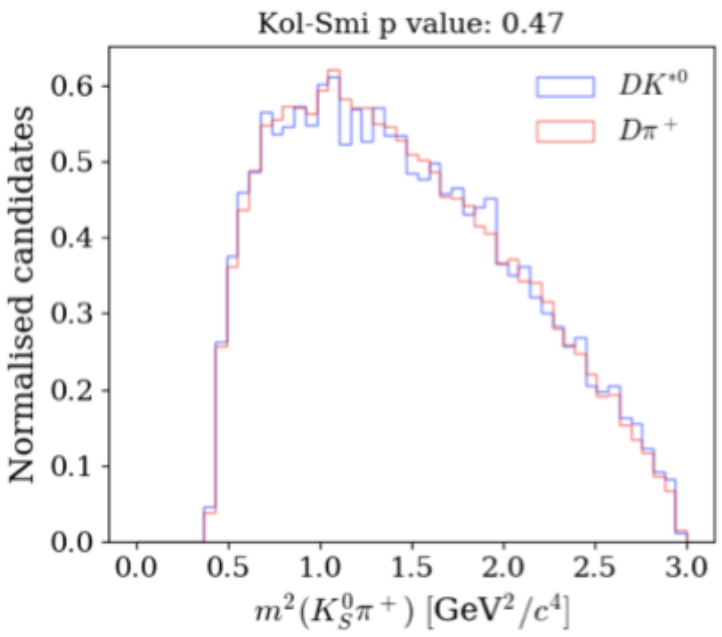
-> dominant systematic uncertainty from earlier analyses avoided

-> important in this measurement, essential with larger data samples



Approach and analysis code is proving useful in further analyses

- A number of related γ measurements are in preparation, using the measured F_i and/or the code base developed for the thesis:
  - Sneha working on $B^0 \to DK^{*0}$
  - Fidan will be working on $B^{\pm} \to DK^{*\pm}$
  - Martin working on $B \to D(\to K^+K^-\pi^+\pi^-)h$
  - Seophine working on a partially reconstructed $B \to D^*h^{\pm}$ analysis
  - *Very happy to hear that the results and analysis code continues to be useful*



Approach and analysis code is proving useful in further analyses

- **Belle + Belle II** have adopted the approach to a model-independent BPGGSZ measurement in $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ [arxiv: 2110.12125], obtaining $\gamma = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^{\circ}$
- **LHCb** has included the results in the latest γ-combination

$\gamma_{\text{LHCb in 2021}} = 65.4^{+3.8}_{-4.2}{}^{\circ}$

BPGGSZ mode key for precision on γ