Correlated systematic uncertainties on the CKM angle γ

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on behalf of the LHCb collaboration

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Outline

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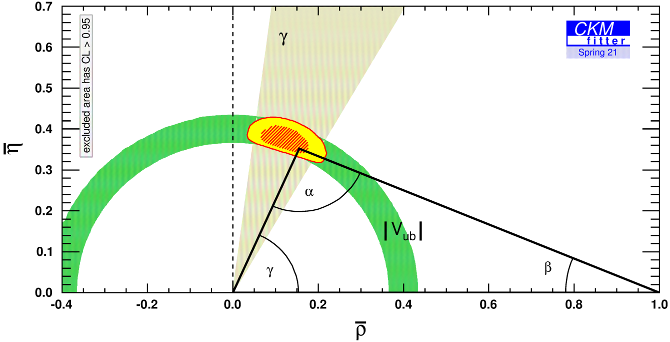
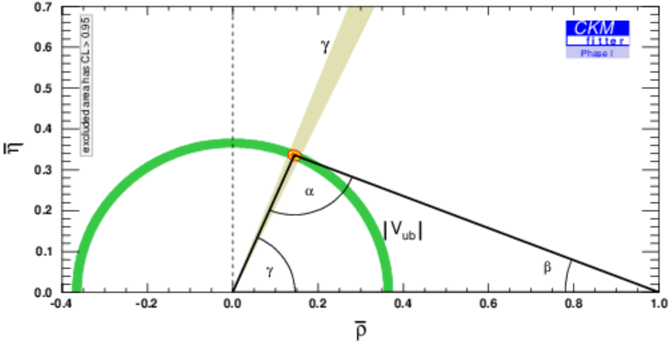
γ Overview: Where are we now?

- γ provides a theoretically clean unitarity test
- Access through interference of tree-level B decays

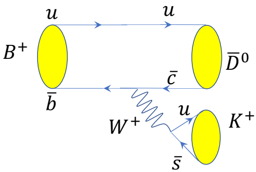


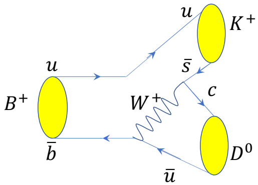
γ Overview: Where are going?

- By the end of Run4, expected uncertainty through direct measurements on γ is $\sim 1^\circ$, see arXiv:1812.07638



Golden Decay Channel: $B^+ \to DK^+$





- CPV through interference of $b \to c\bar{u}s$ and $b \to u\bar{c}s$
- Examine D decay modes common to D^0 and $\overline{D}^0$: Self Conjugate (GLW), CF/DCS (ADS), KK^* (GLS), $K^0_S h^+ h^-$ (BPGGSZ),
- Additional advantage: $B^+ \to D\pi^+$ decays, with similar decay topology and small effects from interference, can be used as normalisation channel.
- Sensitivity to γ achieved through:
  1. Flavour-dependant decay rates (B^- vs. B^+)
  2. Modulation of the flavour-integrated decay rate

Determination of γ by combining measurements

- Each γ analysis reports CPV observables, which are interpreted in combined analyses in terms of γ and:

  - Ratio of B amplitudes r_B
  - Strong phase between B amplitudes δ_B
  - Coherence factor R_B or κ_B of multibody B decays

  } From B measurements

  - Same set of parameters as above, but for D decays
  - Combinations of above , e.g. c_i, s_i in $K_S^0 hh$ or CP-even fractions F_+

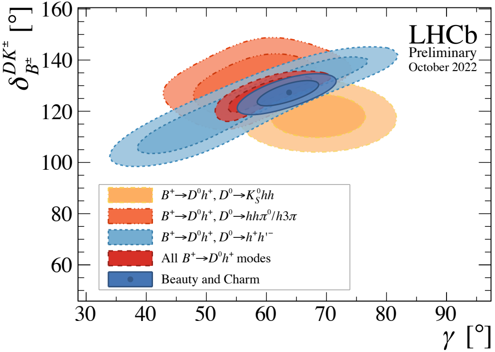
  } From external D measurements. BESIII/CLEO/LHCb

For examples, see LHCb Gamma Combinations, HFLAV, UTFit, CKMFitter

Where are we now?: Zooming In

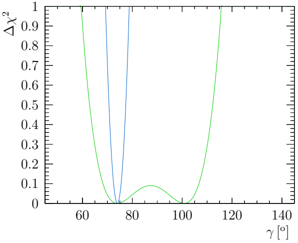
- LHCb average: $(63.8^{+3.5}_{-3.7})^\circ$, systematics contribute $\sim 1.4^\circ$
- Systematic contributions from strong phase inputs and LHCb are comparable

LHCb-CONF-2022-003



What's to come?

- Competitive sensitivites from combination of same D final states in $B^0 \to DK^+\pi^-$, $B^+ \to D^*K^+$, $B^+ \to DK^{*+}$, $\Lambda_b^0 \to DpK$, time-dependent $B_s^0 \to D_s^+K$
- Binned analysis of multi-body D final states, similar to LHCb $B^+ \to D[K\pi\pi\pi]K^+$ JHEP 07 (2023) 138



From $B^+ \to D[K\pi\pi\pi]K^+$ toy studies
PLB 802 (2020) 135188
With Binning
No Binning

See talks from K. Trabelsi, S. Stanislaus, Q. Fuhring, I. MacKay

Outline

Introduction

Correlated Uncertainties across CPV Observables

D^0 Hadronic Parameters

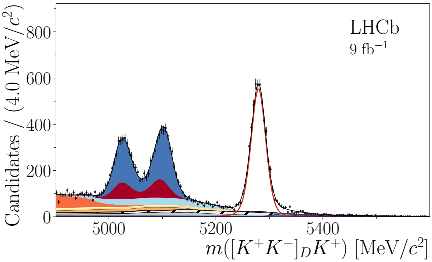
Concluding Remarks

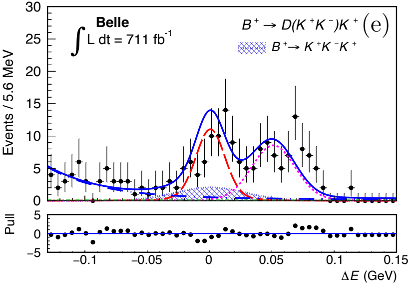
$B^+ \to D[ADS/GLW]K^+$

JHEP, 04 (2021) 081

arXiv:2308.05048

See talk by K. Trabelsi





- Experimental systematics dominated by charmless backgrounds, Λ_b^0, B_s^0 backgrounds (LHCb only)
- Charmless uncertainties decouple – determined from data

$B^+ \to D[ADS/GLW]K^+$

Systematic uncertainties from LHCb JHEP, 04 (2021) 081 relative to statistics

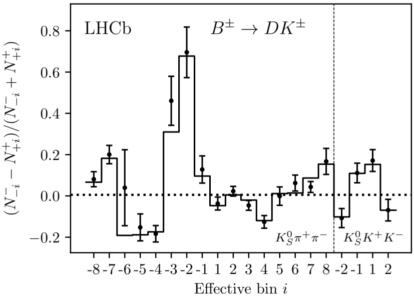
Observable	Total
A_K^{CP}	16
R^{CP}	109
$R_{K^-}^{\pi K}$	57
$R_{K^+}^{\pi K}$	53

- Experimental systematics dominated by charmless backgrounds, Λ_b^0, B_s^0 backgrounds (LHCb only)
- Charmless uncertainties decouple – determined from data
- Uncertainties should mostly scale with data, pending further analysis of backgrounds

$BPGGSZ$ Analyses

- Analysis measures binned yields in D phase-space, mostly insensitive to D uniform phase-space effects
- Fit to yields in all bins in terms of $x_{\pm} \equiv r_B \cos(\delta_B \pm \gamma)$, $y_{\pm} \equiv r_B \sin(\delta_B \pm \gamma)$, with c_i and s_i as inputs

JHEP. 2021, 169 (2021)



Measured asymmetries (points) vs. Predicted asymmetries (solid line)

$BPGGSZ$ Systematic Uncertainties

From LHCb JHEP. 2021, 169 (2021), in 10^{-2}

Source	$\sigma(x_-^{DK})$	$\sigma(y_-^{DK})$	$\sigma(x_+^{DK})$	$\sigma(y_+^{DK})$
Statistical	0.96	1.14	0.98	1.23
Strong-phase inputs	0.23	0.35	0.18	0.28
Total LHCb-related uncertainty	0.20	0.25	0.24	0.26
Total systematic uncertainty	0.31	0.43	0.30	0.38

- LHCb-related reducible with effort
- Correlations with BelleII negligible from JHEP 02 (2022) 063, except for strong-phase inputs

Some additional comments ...

- Correlated uncertainties between $B^+ \to DK^+$ exist due to some shared sources of background models, but are small enough to neglect for 1° precision
- Different B^+, B^0, B_s^0 measurements all have effectively decoupled systematics

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- Aside from strong-phase inputs, systematics decouple between BelleII and LHCb
- Reporting correlated uncertainties in binned analyses on CPV observables, e.g. BPGGSZ, will get administratively burdensome. Correlation matrices go like 6^N, where N is the number of published results.

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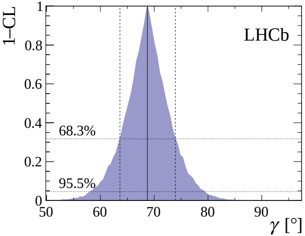
Strong Phase Impacts on γ

$B^+ \to D[K^0_S h^+ h^-]K^+$

LHCb, JHEP02 (2021), 169



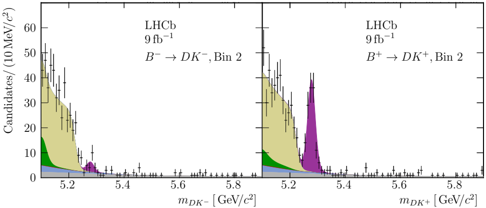
$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$$

from $\Delta c_i, \Delta s_i \sim \pm 1^\circ$

$B^+ \to D[K3\pi]K^+$

using $K3\pi$ binning

JHEP 07 (2023) 138



$$\gamma = \left(54.8^{+6.0\ +0.6\ +6.7}_{-5.8\ -0.6\ -4.7}\right)^\circ$$

from $\Delta R_D^{K3\pi}, \Delta\delta_D^{K3\pi} =^{+6.7}_{-4.7}$!

See talks from X. K. Zhou, Y. Gao

Correlated c_i, s_i uncertainties in BPGGSZ

- Correlations from shared c_i, s_i inputs between $B^+ \to D[K_S^0 hh]K^+$ and $B^0 \to D[K_S^0 hh]K^{*0}$ studied in arXiv:2309.05514
- Correlations very small!
- Correlations likely broken by different values of r_B, δ_B → sensitive to different parts of parameter space
- Variations will be made public for all future BPGGSZ analyses

	x_-^{DK}	x_+^{DK}	y_-^{DK}	y_+^{DK}
$x_+^{DK^{*0}}$	-0.02	0.06	-0.02	-0.02
$x_-^{DK^{*0}}$	0.00	-0.05	-0.01	0.04
$y_+^{DK^{*0}}$	-0.03	0.04	0.04	-0.05
$y_-^{DK^{*0}}$	0.01	0.01	-0.02	0.00

Looking to the future...

- New $\psi(3770)$ data sets at BESIII, useful for hadronic D measurements:
  - $\sim 8\text{fb}^{-1}$ taken at $\psi(3770)$ in 2022-2023 ready for analysis.
  - $\sim 20\text{fb}^{-1}$ at $\psi(3770)$ expected by the end of 2024.
- Compare to 3fb^{-1} of current data
- Measurement of hadronic D parameters look to still be stats. limited at BESIII with larger data,
- Dominating BESIII systematics likely scale with data (model/normalization related)
- Current precision on $\delta_D^{K\pi}$ comes from LHCb, although significant contributions to come from BESIII

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How do we report results?

- $D \to K_S^0 hh(\pi^0)$ analyses have c_i, s_i as inputs to CPV observables, $x^\pm$, $y^\pm$.
  - Updating with new c_i, s_i $\Rightarrow$ have to rerun fits
  - Moving forward, will publish raw yields in bins $\Rightarrow$ Reinterpretation at small cost of sensitivity, as in $B^+ \to D[KK\pi\pi]K^+$ EPJC83 547 (2023)

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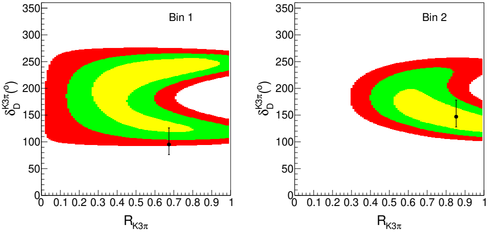
- Accounting for input uncertainties in binned $4h$ analyses non-trivial, e.g. full likelihood profile required in $B^+ \to D[K3\pi]K^+$

BESIII JHEP 05 (2021) 164



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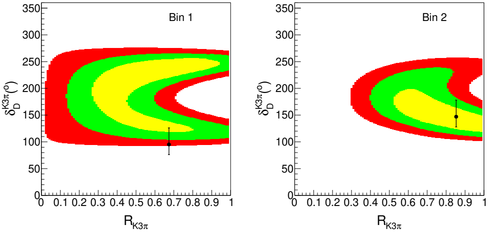

- Publish running with nuisance parameters for systematic uncertainties

In Summary

- Uncertainty on γ still statistically dominated, but current level of systematic uncertainty will limit future measurements ($\sim 1.4^{\circ}$)
- Different B decays introduce largely uncorrelated systematics
- Some correlations across LHCb BPGGSZ to be accounted for (work in progress)
- Uncertainties from LHCb/B factories largely uncorrelated, except strong phase inputs
- Uncertainties on D strong phases should scale with BESIII data
- $\sim\ 7x$ BESIII data sample for D strong phases by end of 2024
- Questions remain on how to best publish forward-compatible results

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Now for discussion...