Multibody D decays and their uses for B CP violation measurements including γ

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on behalf of

the LHCb collaboration

with material from BaBar, Belle (II), CLEO, BES III

Towards the Ultimate Precision in Flavour Physics

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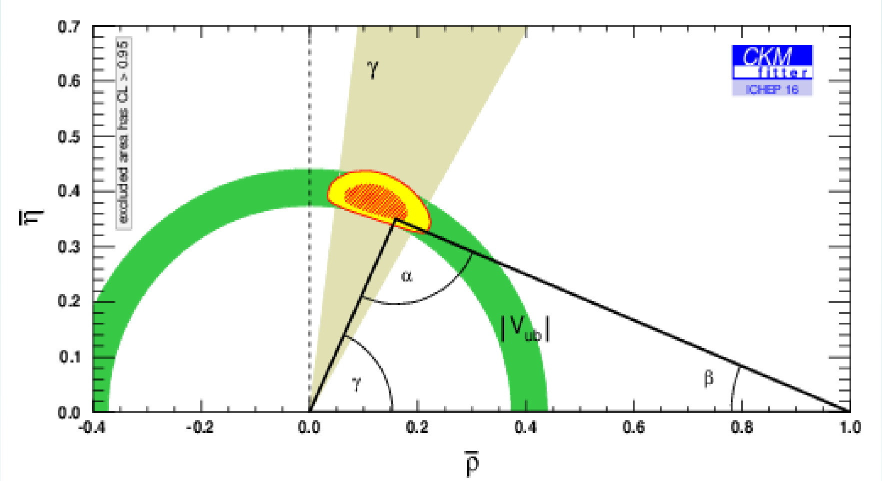
The Leverhulme Trust

CKM angle γ

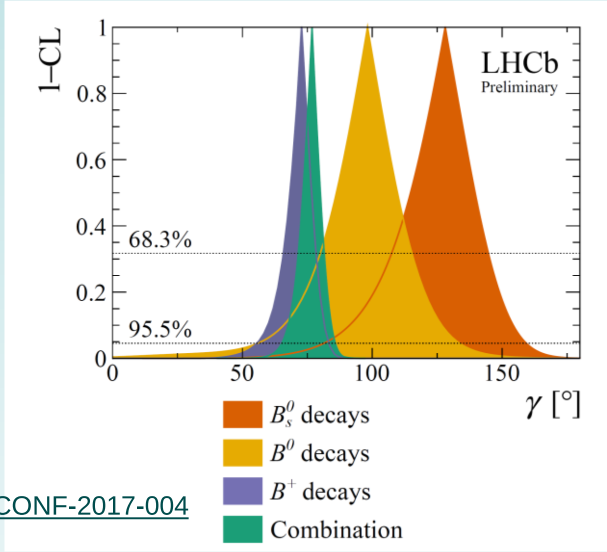
- Least well measured Unitarity Triangle angle
- Measure at tree level with $B \to DX$ decays



- Exploiting weak phase difference γ between V_{cb} and V_{ub}
- Theoretically clean but room for NP

JHEP 01 (2014) 051 PRD 92 033002 (2015)

- Experimentally more challenging
  - Small interference effects
  - Low branching fractions
  - Hadronic final states
- Combine many B decays and D decay final states to get best γ precision: see Matt Kenzie's talk for further details



LHCb-CONF-2017-004

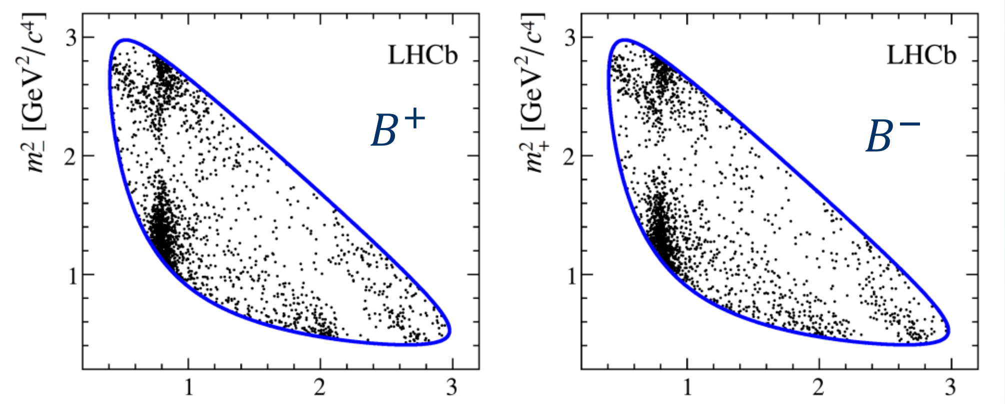
- Different methods for taking D part of decays into account
- Concentrate here on multibody D decays

GGSZ analysis of $B \to Dh, D \to K_S^0 h^+ h^-$

- Determine γ using amplitude analysis of D decay to three-body self-conjugate $K_S^0 \pi^+ \pi^-$ or $K_S^0 K^+ K^-$ final state PRD 68 054018 (2003) PRD 70 072003 (2004)
- One solution for γ in [0, π]
- Requires knowledge of $D \to K_S^0 h^+ h^-$ decay across phase space

$$A_{B^+} \propto \bar{A}_f + r_B e^{i(\delta_B + \gamma)} A_f$$

$$A_{B^-} \propto A_f + r_B e^{i(\delta_B - \gamma)} \bar{A}_f$$



JHEP 10 (2014) 097

- Two well-developed approaches to account for D part of decay

Model-dependent approach

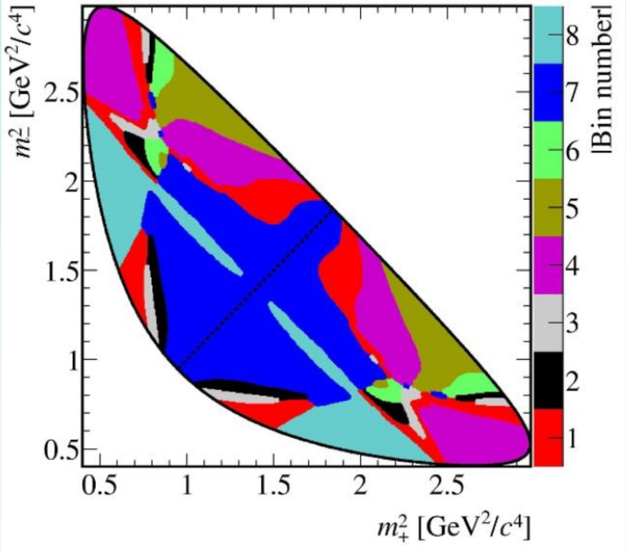
- Use model to describe amplitude of D decay over phase space PRD 81 112002 (2010) PRL 105 (2010) 121801 NPB 888 (2014) 169
- Unbinned
- At LHCb, dominating experimental systematics from background modelling, efficiency description over D decay phase space
- Systematic uncertainty from model choice:
  - Use large simulated signal samples
  - Vary resonance parameters, functional forms, formalism, add/remove resonances (21 changes at LHCb)
  - Depends on CP observable values
  - Belle: 9°, BaBar: 3°

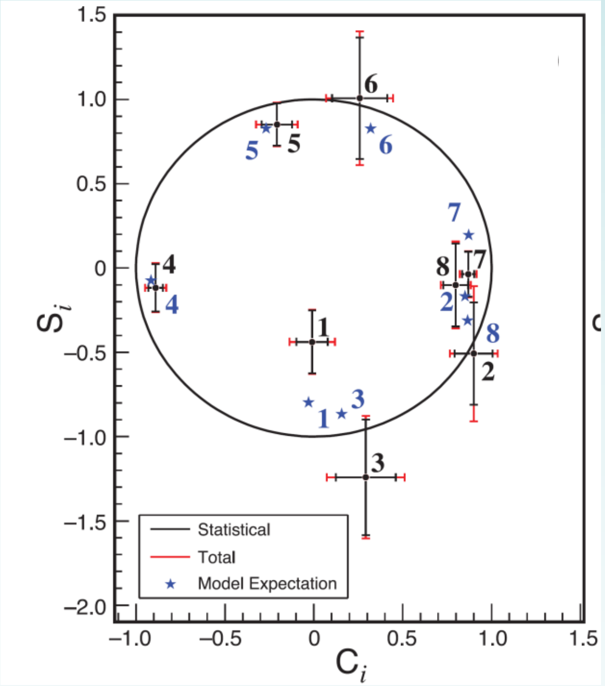
See Anton Poluektov's talk for ultimate limiting systematics

Model-independent binned approach

- Use quantum-correlated charm threshold data to measure $D^0 - \bar{D}^0$ strong phase difference δ_D in bins of D decay phase space
- Binning schemes optimised using model
  - "incorrect" model leads only to poorer sensitivity (no bias)

PRD 82 112006 (2010)
PRD 85 112014 (2012)
JHEP 10 (2014) 097





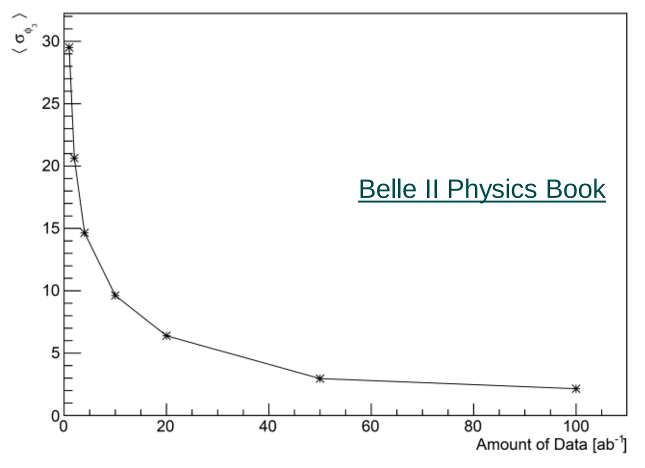
(c_i, s_i) are amplitude-weighted averages of $(\cos(\delta_D), \sin(\delta_D))$ over Dalitz bin i

- At LHCb, dominating experimental systematics from efficiency corrections over D decay phase space
- Systematic uncertainty from (c_i, s_i) inputs:
  - Sample values within their uncertainties, taking correlations into account, and repeat fit to data sample many times
  - Depends on CP observable values
  - Depends on binning scheme
  - Systematic can be split into a statistical part dependent on decay mode and data sample size, and an irreducible part (≡ infinite data sample) from inputs that can be determined with high statistics toy MC study

See Anton Poluektov's talk for ultimate limiting systematics

Future prospects

- $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$ most sensitive single analysis at Belle; the "Golden Mode"
- Belle II expect σ(γ) = 3° with 50 ab^{-1} using $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$ MI approach (CLEO-c inputs)

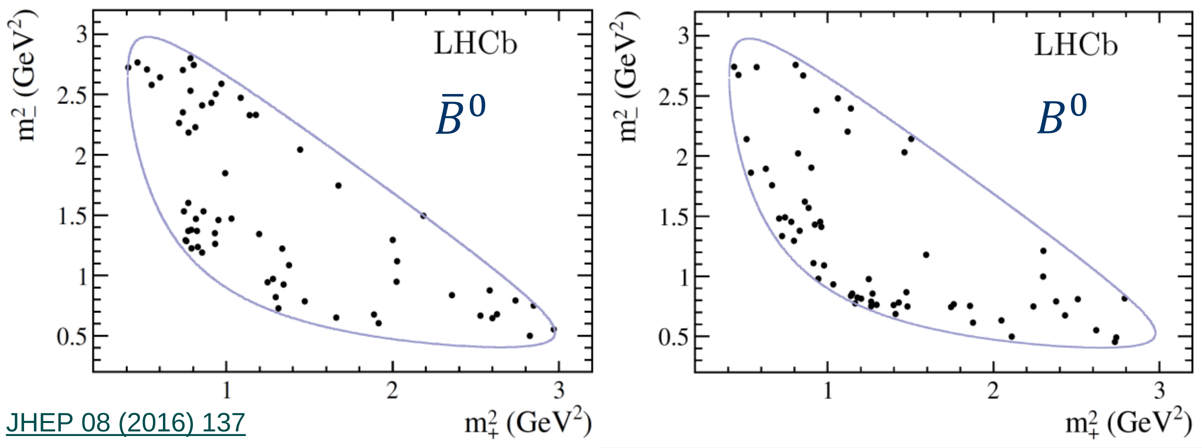


- Limiting uncertainty of 2-4° from CLEO-c (c_i, s_i)
  - dominant systematic during LHCb upgrade era LHCb-PUB-2016-025
- Measurements from BES III will be essential
  - See Guy Wilkinson's talk for further details

Other GGSZ decays

- MD and MI analyses using $B^{\pm} \to D^{*}K^{\pm}$, $B^{\pm} \to DK^{*\pm}$ and $B^{0} \to DK^{*0}$ decays also published by Belle, BaBar and LHCb

PRD 81 112002 (2010)
PRL 105 (2010) 121801
PRD 73 112009 (2006)
PTEP 2016 043C01
JHEP 06 (2016) 131



JHEP 08 (2016) 137

- How to combine model or (c_i, s_i) uncertainties for various measurements, taking cross-correlations into account?

Combining systematics from multiple B modes

- MD results: 100% correlation?
  - Belle and BaBar already combine results using same model in their MD papers PRD 81 112002 (2010) PRL 105 (2010) 121801
    - Belle treat systematics as uncorrelated, BaBar do not
  - BaBar also combines results in their γ combination PRD 87 052015 (2013)

- MI results:
  - If same binning scheme used, only need to consider cross-correlations for irreducible (pure (c_i, s_i)) part of systematics
  - Negligible with current statistics
  - In future, publish yield measurements as well as CP observables
    - Allows correlations to be taken into account and updates to inputs to be applied later

Different binnings/models?

Simultaneous fit to multiple B modes

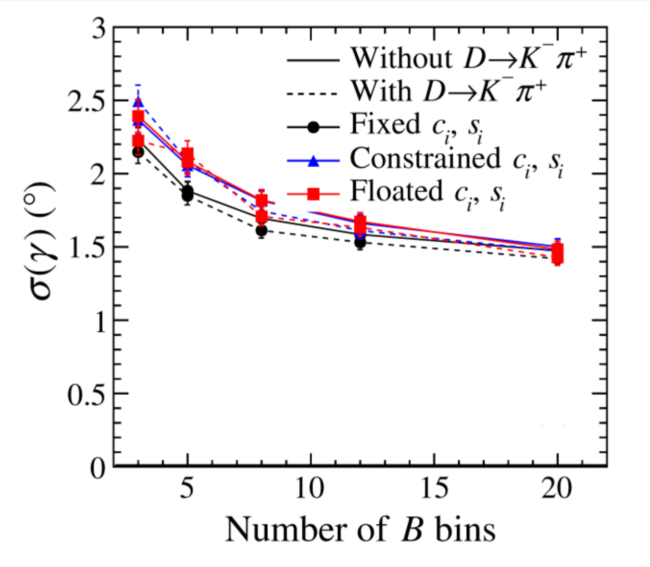
arXiv:1804.05597

- Possible to fit multiple B modes simultaneously to determine γ
  - Allows treatment of signal decays appearing as “backgrounds” in other decay modes
  - Common systematics can be determined simultaneously
  - Reduces number of independent parameters in the fit
  - Can be extended to include other D decays, time-dependent approaches
- Necessary to achieve ultimate precision?

Double Dalitz: $B^0 \to DK^+\pi^-, D \to K_S^0\pi^+\pi^-$

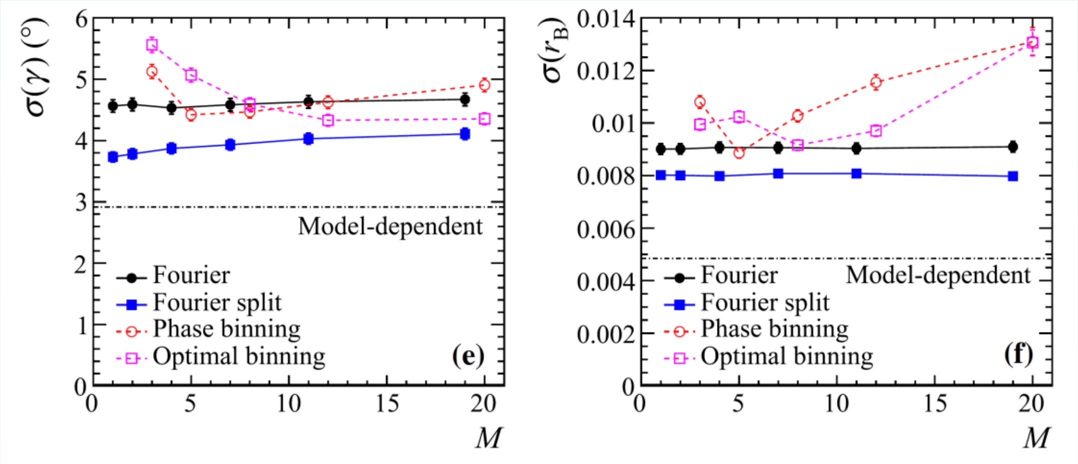
PRD 97 056002 (2018)

- Bin both B and D decay phase spaces
- Can easily extend to include other D decays
- Dangerous background: $\bar{B}_s^0 \to D^*K^+\pi^-$
  - Would not affect a Belle II analysis
- Analysis has some sensitivity to (c_i, s_i)
- As data sample increases, precision of (c_i, s_i) inputs becomes less important (opposite to $B^\pm \to DK^\pm$)
- Estimate LHCb $\sigma(\gamma)$ = 2° with 50 fb^{-1}
  - Belle II with 50 ab^{-1} factor of two worse?



Model-independent unbinned approach

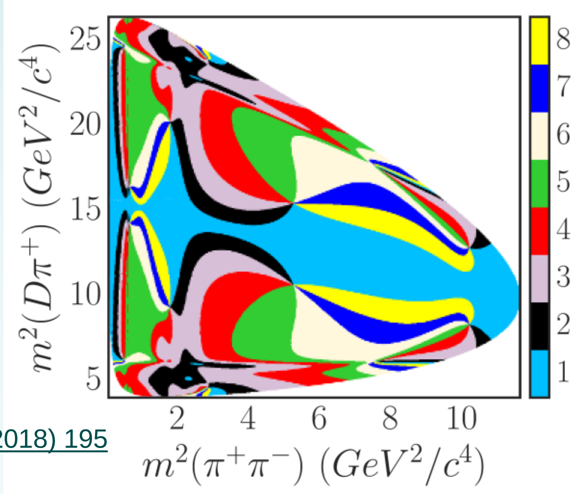
- Proposed alternative to MI binned approach EPJC (2018) 78:121
- Improve statistical sensitivity using Fourier analysis of strong phase difference distribution, rather than binning
- Demonstrated with $B^{\pm} \to DK^{\pm}, D \to K_S^0 \pi^+ \pi^-$ MC, but can be extended to other D decays, multibody B decays, time-dependent fits
- Greatest benefit in cases where quantum-correlated charm threshold data sample is small



Toy MC
(Q.C. sample
~0.1 of B sample)

Interlude: β

- $\sin(2\beta)$ well measured in $b \to c\bar{c}s$ transitions
- Can also measure $\sin(2\beta)$ and $\cos(2\beta)$ in $b \to c\bar{u}d$ transitions with time-dependent analysis of $B^0 \to Dh^0, D \to K_S^0\pi^+\pi^-$ PLB 624 (2005) 1
- Measurements made using D decay model PRL 97 (2006) 081801 PRL 99 (2007) 231802 BaBar+Belle prelim.
- Also by binning the D decay phase space and using CLEO-c (c_i, s_i) inputs PRD 94 052004 (2016)
- Model or (c_i, s_i) uncertainties dominant systematics
- New alternative: $B^0 \to D\pi^+\pi^-$, $D \to K_S^0\pi^+\pi^-$ and $D \to f_{CP}$
  - Bin B and D decay phase spaces
  - Estimate precision of a few degrees on β with LHCb upgrade/Belle II



JHEP 03 (2018) 195

Other multibody D decays for γ : ADS

- Modify $D \to$ 2-body ADS expressions with coherence factor and average strong phase difference
  - Considering decay phase space as a whole (or could use particular regions)
  - Determine from model or from Q.C. charm threshold data

$$\Gamma\left(B^{\mp} \to DK^{\mp}\right) \propto (r_B)^2 + (r_D)^2 + 2r_B r_D R cos(\delta_B + \delta_D \mp \gamma)$$

- $D \to K_S^0 K^+ \pi^-$
  - LHCb measurement using CLEO-c inputs PLB 733 (2014) 36 PRD 85 092016 (2012)
    - Dominant systematic: efficiency
  - LHCb amplitude model for $D \to K_S^0 K^+ \pi^-$ PRD 93 052018 (2016)

- $D \to K^+ \pi^- \pi^0$
  - BaBar, Belle and LHCb measurements using CLEO-c inputs PRD 88 091104(R) (2013) PRD 91 112014 (2015) PRD 80 031102(R) (2009) PRD 84 012002 (2011) PLB 731 (2014) 197 PRD 80 031105(R) (2009)
    - LHCb dominant systematics: background modelling, detector/interaction asymmetries
    - BaBar/Belle: backgrounds and modelling

- $D \to K^+ \pi^- \pi^+ \pi^-$
  - LHCb measurements using CLEO-c/LHCb D-mixing inputs PLB 760 (2016) 117 JHEP 11 (2017) 156 PRD 80 031105 (2009) PLB 757 (2016) 520 PRL 241801 (2016)
    - Dominant systematics: efficiency, background modelling
  - LHCb and BES III amplitude models for $D \to K^+ \pi^- \pi^+ \pi^-$ PRD 95 072010 (2017) arXiv:1712.08609
  - Proposal for MI binned method to determine γ JHEP 03 (2015) 169

Other multibody D decays for γ : self-conjugate decays

- Either modify $D \to$ 2-body GLW expressions with dilution factor parametrised by F_+ (fractional CP content)
  - Useful if D decay dominated by one CP eigenstate
  - Considering decay phase space as a whole (or could use particular regions)
  - Determine from model or from Q.C. charm threshold data

$$\Gamma\left(B^{\mp} \to DK^{\mp}\right) \propto 1 + (r_B)^2 + 2(2F_+ - 1)r_B cos(\delta_B \mp \gamma)$$

- Or perform GGSZ-style analysis
  - Useful if D decay not dominated by one CP eigenstate

- $D \to K^+K^-\pi^0, \pi^+\pi^-\pi^0$
  - BaBar $\pi^+\pi^-\pi^0$ measurement with amplitude model PRL 99 251801 (2007)
  - BaBar amplitude analysis of $D \to K^+K^-\pi^0$ PRD 76 011102(R) (2007)
  - LHCb measurements using CLEO-c F_+ PRD 91 112014 (2015) PLB 740 (2015) 1
    - Dominant systematics: efficiency, background modelling

- $D \to K_S^0\pi^+\pi^-\pi^0$
  - CLEO-c determinations of F_+ and (c_i, s_i) JHEP 01 (2018) 082

- $D \to \pi^+\pi^-\pi^+\pi^-$
  - LHCb measurements using CLEO-c determination of F_+
    - Dominant systematic: background modelling PLB 760 (2016) 117 PLB 747 (2015) 9 JHEP 11 (2017) 156
  - CLEO-c amplitude analyses of $D \to \pi^+\pi^-\pi^+\pi^-$ and $D \to K^+K^-\pi^+\pi^-$ JHEP 05 (2017) 143
  - CLEO-c determinations of (c_i, s_i) JHEP 01 (2018) 144

Conclusions

- Aiming for high precision on γ (and β)
  - 1° with LHCb upgrade
  - 1.5° with Belle II
- Multibody D decays have important role to play
- As statistics increase, careful handling of uncertainties from external inputs/models becomes essential
- May need to consider full D phase space analyses (unbinned/binned) to determine maximum amount of information
  - Lots to learn from $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$