Recent progress on the CKM angle γ and Quantum-Correlated $D^0\overline{D}^0$ pairs

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Outline

Introduction

Quantum-correlated $D^0\overline{D}^0$ pairs and D^0 Hadronic Parameters

Measuring γ at LHCb

LHCb γ + Charm Combination

Future Prospects & Summary

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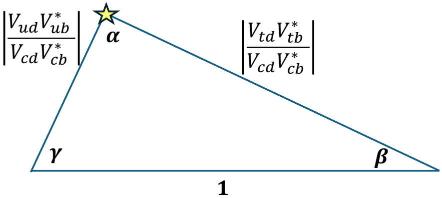
Future Prospects & Summary

The CKM Unitarity Triangle(s)

- The Cabibbo-Kobayashi-Maskawa (CKM) matrix defines the probability of flavour transitions in weak interactions of quarks.
- SM predicts this matrix to be unitary $\Rightarrow$ cannot predict individual elements, but does provide a system of constraints!
- Can construct B-meson Unitarity Triangle from one such constraint

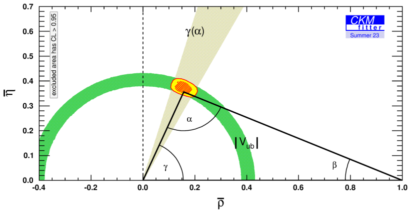
$$V_{\mathsf{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

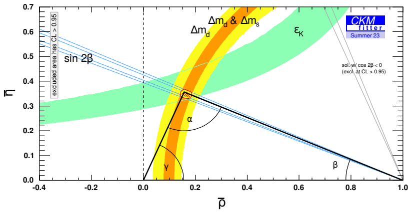
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



Unitarity tests as new physics probes

- Numerous measurements can constrain the Unitarity Triangle apex
- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$, along with $\frac{|V_{ub}|}{|V_{cb}|}$, allows for a determination of the apex from processes that proceed through tree-level SM interactions.





Unitarity tests as new physics probes

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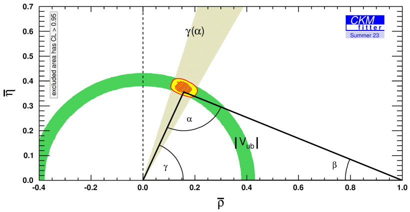
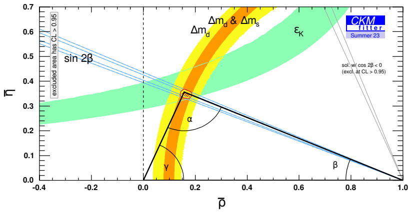
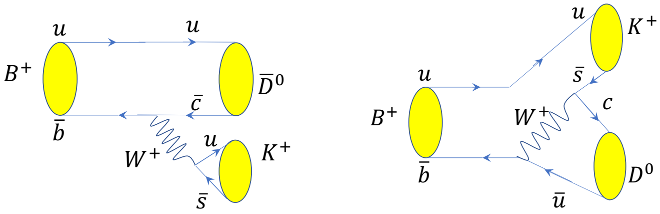
- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$, along with $\frac{|V_{ub}|}{|V_{cb}|}$, allows for a determination of the apex from processes that proceed through tree-level SM interactions.
- The apex can also be determined from loop-level observables
- Difference between the two gives strong evidence for new physics entering at loop-level!
- Tree-level determination, especially γ, provides limiting uncertainty



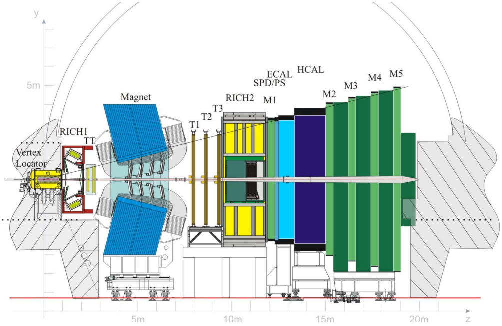


γ Golden Decay Channel: $B^+ \to DK^+$



- CP violation (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 $\overline{D}^0$:
- This interference induces:
  1. Flavour-dependent decay rates ($B^- \to DK^-$ vs. $B^+ \to DK^+$)
  2. Modulation of the flavour-integrated decay rate ($B^\pm \to DK^\pm$ branching fraction depends on D decay!)
- Interference effects depend on γ, B-decay and D-decay hadronic parameters
- Need samples of B mesons (LHCb/BelleII) and and D^0 mesons (BESIII) for optimal measurements

The LHCb Detector and Datasets



- Single-arm forward spectrometer designed for analysis of beauty and charm hadrons produced in LHC pp collisions
- $2 < \eta < 5$ (40% of heavy quark production)
- $\sigma_{\text{Vtx}} : \left(15 + \frac{29}{p_T/\text{GeV}}\right) \mu\text{m}$
- Excellent $K^{\pm}/\pi^{\pm}$ separation

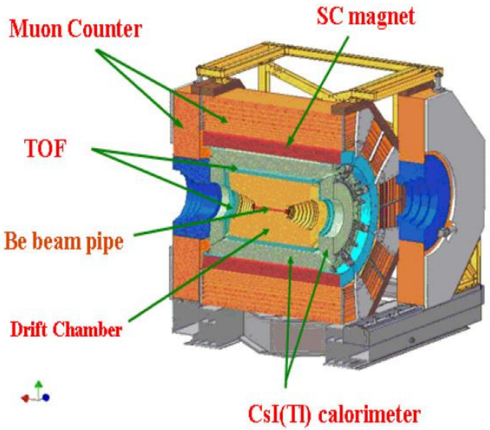
- LHC Run 1 (2011-2012): 3.0 fb^{-1} at 7 TeV and 8 TeV
- LHC Run 2 (2015-2018): 6.0 fb^{-1} at 13 TeV

Beijing Electron-Positron Collider Mk. II (BEPCII)

- Symmetric e^+e^- collider
- Diameter of storage rings: $\sim$ 75 m (LHC: $\sim$ 8 km)
- E_{CM}: $2 - 5$ GeV

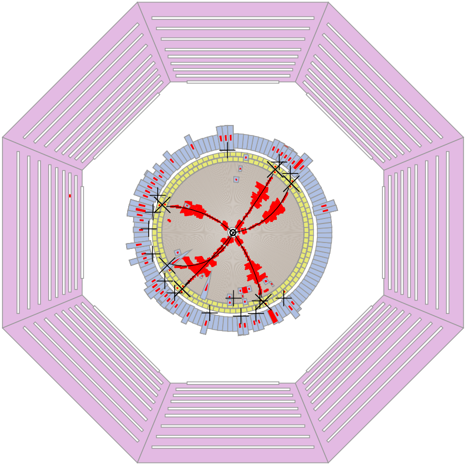
- Construction Phase from 2004-2008
  - Upgrade from BEPC and BESII
- First Data Taking in 2009
- ~600 members representing 85 institutions from 17 countries

Beijing Electron Spectrometer III (BESIII)



- "Onion"-style detector designed for studies of charm hadrons
- Hermiticity: 93% of 4π
- Gaseous Drift Chamber for tracking charged particles: $\frac{\sigma_p}{p} \sim 0.5\%$
- Time-of-Flight system for particle identifcation: $\sigma_{TOF} = 80$ ps
- Calorimeter for e^- identifcation and neutral particle reconstruction: $\sigma_E/E \sim 2.5\%$
- Some notable differences with a typical LHC experiment:
  - Low boost $\Rightarrow$ (almost) no displaced vertices
  - Momentum of final state particles in the lab frame: $50 - 1500$ MeV$/c$
  - e^+e^- leads to very clean environments
  - $\sim 100\%$ trigger efficiency

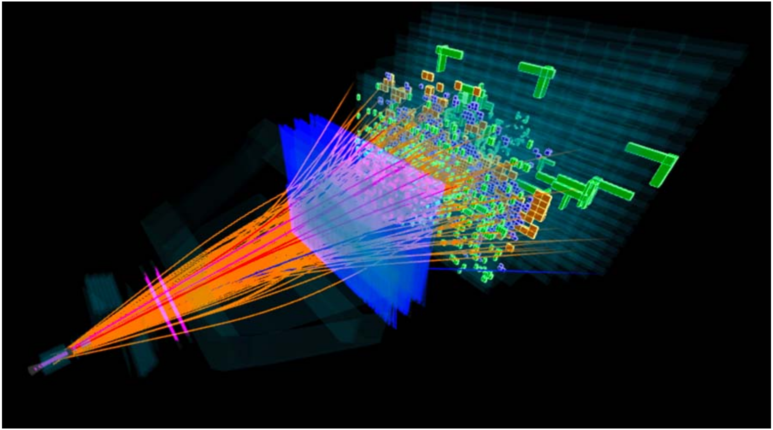
BESIII Event Reconstruction



Simulated $D_s^{*+} D_s^-$ event

LHCb Event Reconstruction

- Each orange curve is a charged track!



Heavy Ion Collision event

Outline

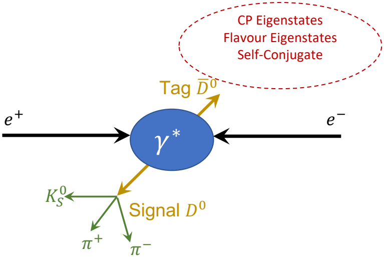
D^0 Hadronic Parameters

- $B \to D^0 h$ CPV observables, and thus determination of γ depend on D^0 decay parameters

$$\Gamma\left(\overline{B} \to D\overline{K}\right) - \Gamma\left(B \to DK\right) \propto r_B^{DK} R_D^X r_D^X \sin\left(\delta_B^{DK} + \delta_D^X\right) \sin\gamma$$

  - Ratio of $D^0 \to X$ and $\overline{D}^0 \to X$ amplitudes $r_D^X \equiv \left|\frac{\overline{A}}{A}\right|$
  - Strong phase between amplitudes δ_D^X
  - Coherence factor R_D^X of multibody D^0 decays,
    $R_D^X e^{-i\delta_D^X} \equiv \int A(\mathbf{x})\overline{A}(\mathbf{x})d\mathbf{x} / \sqrt{\int |A(\mathbf{x})|^2 d\mathbf{x} \int |\overline{A}(\mathbf{x})|^2 d\mathbf{x}}$

Quantum Correlated $D^0\overline{D}^0$ pairs @ BESIII



- Production through virtual photon constrains $D\overline{D}$ state to be $\mathcal{C}$-odd
- BESIII collects data the $D\overline{D}$ threshold, so it is guaranteed that there are no other particles in the final state
- $\mathcal{C}$ constraint correlates D^0 and $\overline{D}^0$ decays to have opposite CP :

$$\frac{P(D^0\overline{D}^0 \to X_1 X_2)}{P(D^0 \to X_1)P(\overline{D}^0 \to X_2)} = 1+\left(r_D^{X_1} r_D^{X_2}\right)^2 - 2r_D^{X_1} r_D^{X_2} R_D^{X_1} R_D^{X_2} \cos\left(\delta_D^{X_1} + \delta_D^{X_2}\right)$$

Quantum Correlated Tag Decay Modes

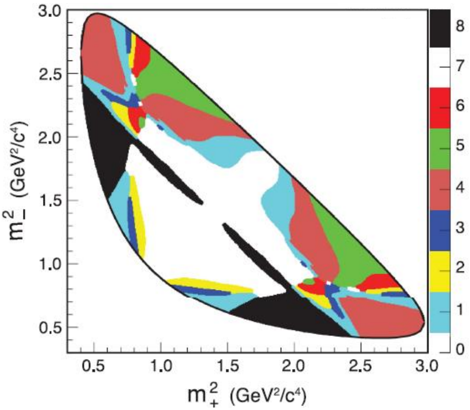
- Flavour Tags
  - $\overline{D}^0 \to K^+ e^- \nu$, is flavour-definite, so allow for a normalising determination of $P\left(D^0 \to X\right)$
  - Cabibbo-favoured decays, e.g. $\overline{D}^0 \to K^+\pi^-$, used as quasi-flavour tags
- CP Tags
  - $\overline{D}^0 \to \pi\pi, K^+K^-, K_S^0\pi^0$, etc. are CP-eigenstates (neglecting $\mathcal{O}(10^{-3})$ CP violation)
  - $\overline{D}^0 \to \pi^+\pi^-\pi^0$ has high coherence ($R_D^{\pi\pi\pi^0} \approx 95\%$), so it can be treated as an approximate CP eigenstate.

$$\frac{P(D^0\overline{D}^0 \to X k_{CP})}{P(D^0 \to X)P(\overline{D}^0 \to k_{CP})} = 1 + \left(r_D^X\right)^2 \mp 2R_D^{k_{CP}} r_D^X R_D^X \cos\left(\delta_D^X\right)$$

- Note that other CP-indefinite tags needed to determine $\sin\left(\delta_D^X\right)$

Strong Phases in $D^0 \to K^0_{S,L}\pi^+\pi^-$

- Using 2.93 fb^{-1} of data @ $E_{CM} = 3.773$ GeV
- Measurement of $D^0/\overline{D}^0 \to K^0_S\pi^+\pi^-$ strong phase parameters $c_i\,[s_i] \equiv$ amplitude-weighted $\cos\,[\sin]\,\delta_D$ in phase-space bin i
- Phase space described by $m_\pm \equiv m\left(K^0\pi^\pm\right)$



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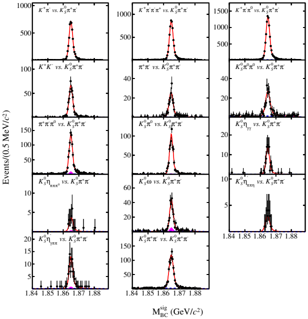
- 17 tag modes employed, yields determined with 2-D fits to $M_{\text{BC}} \equiv \sqrt{E^2_{\text{beam}} - p^2_D}$ or M^2_{miss}

PRL 124, 241802 (2020), PRD 101, 112002, (2020)



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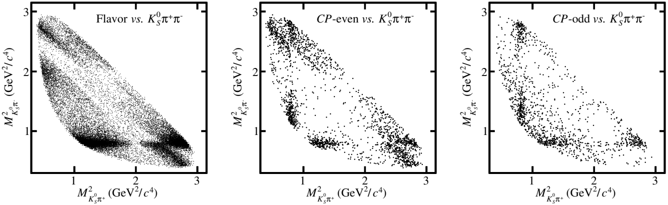
- In terms of fractional yields of flavour-tagged $K^0_S\pi^+\pi^- \equiv K_i$
- $K^0_S\pi^+\pi^-$ vs. CP tag: $M_i^\pm = h_{CP}\left(K_i + K_{-i} + 2c_i\sqrt{K_iK_{-i}}\right)$
- $K^0_S\pi^+\pi^-$ vs. $K^0_{S,L}\pi^+\pi^-$ tag:
  $M_{ij} = h_{DT}\left(K_iK_{-j} + K_{-i}K_j \mp \sqrt{K_iK_{-j}K_{-i}K_j}\,(c_ic_j + s_is_j)\right)$

PRL 124, 241802 (2020) PRD 101, 112002, (2020)



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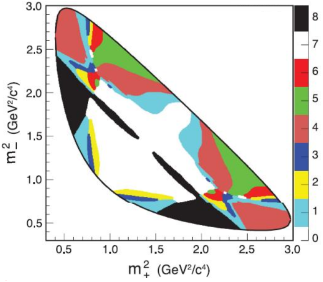

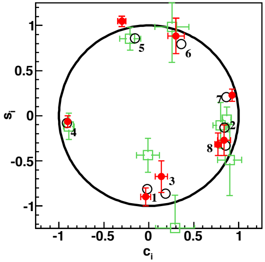

Binning schemes from
CLEO PRD 82,112006 (2010)
PRL 124, 241802 (2020)
PRD 101, 112002, (2020)

Circles are predictions from
BaBar and Belle,
PRD 98, 110212(2018)

Outline

Measuring γ: Different D decay channels

- Different D decay channels provide complementary sensitivity to gamma and samples with uncorrelated statistical and systematic uncertainties:
  - $D \to$ multibody[1] $K^0_S\pi^+\pi^-/D \to K_S K^+ K^-$:
    - Hadronic parameters vary significantly across D phase space
    - CPV observables $B \to Dh$ interference effects across the D phase space and increased sensitivity to γ
  - $D \to$ Cabibbo-favoured/suppressed decays[2], e.g. $D^0 \to K^-\pi^+$:
    - Amplitude ratios r_D measured to high precision, but not strong phases
  - $D \to$ (quasi)-CP eigenstates[3], e.g. $D^0 \to K^-K^+$:
    - Two-body decays trivially have $r_D = 1$, $\delta_D = 0, \pi$
    - Multi-body decays require a coherence-factor correction determined from $D^0\overline{D}^0$ data
  - Multi-body decays, e.g. $D \to K^-\pi^+\pi^+\pi^-$, also benefit greatly from phase-space dependent analysis

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Bondar and Poluektov, EPJC 47 (2006) 347; Giri, Grossman, Soffer, and Zupan PRD 68 (2003) 054018

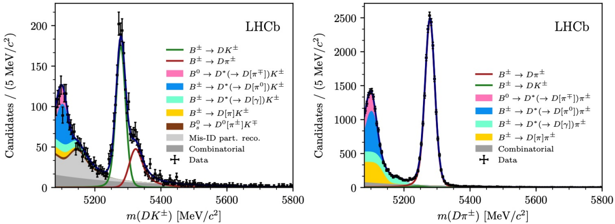
Atwood, Dunietz, Soni, PRD63 (2001) 036005

Gronau and Wyler, PLB265 (1991) 172;Gronau and London, LB253 (1991) 483

γ from $B^{\pm} \to Dh^{\pm}$, $D \to K_S^0 h^+ h^-$

- Using full LHCb Run 1+ Run 2 dataset, analysing $K_S^0\pi^+\pi^-$ & $K_S^0 K^+ K^-$
- $B^{\pm} \to DK^{\pm}$ has amplitude ratio $r_B^{DK} \sim 0.1 \Rightarrow$ large interference effects
- $B^{\pm} \to D\pi^{\pm}$ has $r_B^{D\pi} \sim 0.05 \Rightarrow$ small interference effects, good control channel for detection and production asymmetries

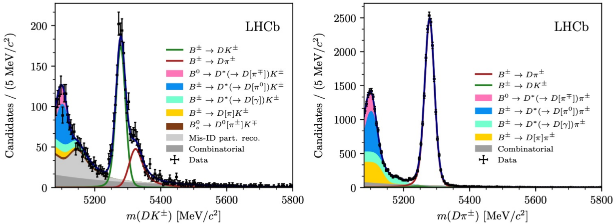
LHCb, JHEP 2021, 169 (2021)



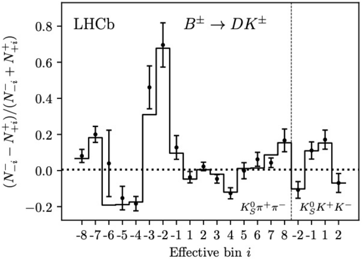
γ from $B^{\pm} \to Dh^{\pm}$, $D \to K_S^0 h^+ h^-$

- Using full LHCb Run 1+ Run 2 dataset, analysing $K_S^0\pi^+\pi^-$ & $K_S^0 K^+ K^-$
- Perform simultaneous fit of invariant masses for $B \to DK / B \to D\pi$ to determine CPV observables $r_B^{DK}\cos\left(\delta_B^{DK} \pm \gamma\right)$ and $r_B^{DK}\sin\left(\delta_B^{DK} \pm \gamma\right)$ and related $B \to D\pi$ observables
- Sample is split by B-decay, B-charge, D-decay, K_S^0 decay category (before/after LHCb magnet), and phase-space bin (160 subsamples total!)
- Strong phase inputs fixed in fit from BESIII measurements

LHCb, JHEP 2021, 169 (2021)



γ from $B^\pm \to Dh^\pm$, $D \to K^0_S h^+ h^-$



- $r_B^{DK}\cos\left(\delta_B^{DK} \pm \gamma\right)$ and $r_B^{DK}\sin\left(\delta_B^{DK} \pm \gamma\right)$, and $B \to D\pi$ observables can be analysed in turn to determine r_B^{DK}, δ_B^{DK} and γ

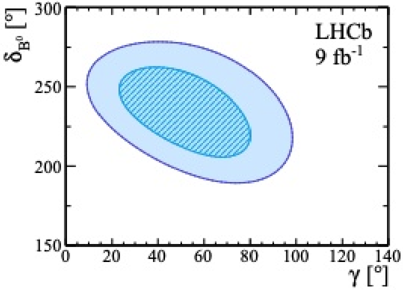
$$r_B^{DK} = 0.0904^{+0.0077}_{-0.0075} \qquad \delta_B^{DK} = \left(118.3^{+5.5}_{-5.6}\right)^\circ \qquad \gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$$

- Most precise determination of γ from any single measurement
- $\sim 1^\circ$ uncertainty from BESIII inputs, similar size for LHCb systematics $\Rightarrow$ stastical uncertainty dominates

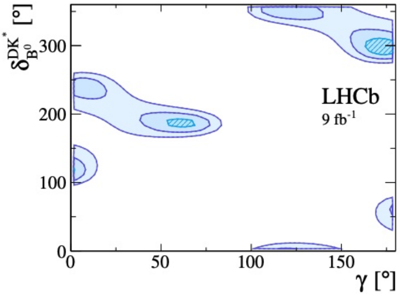
LHCb, JHEP 2021, 169 (2021)

γ from $B^0 \to DK^{*0}$

- $B^0 \to DK^*(892)^0$ has smaller branching fraction than $B^+ \to DK^+$, but larger amplitude ratio $r_{B^0}^{DK^*} \sim 0.250$, and so gives competitive sensitivity.
- Run1 + Run2 analysis of $B^0 \to DK^*(892)^0$ with $D \to K_S^0 h^+ h^-$ final states determined $\gamma = \left(49^{+22}_{-19}\right)^\circ$ [LHCb, EPJC 84, 206 (2024)]
- Run1 + Run2 measurement with $D \to K^+K^-, \pi^+\pi^-(\pi^+\pi^-)$, and $K^-\pi^+(\pi^+\pi^-)$ also published [LHCb, JHEP 2024, 25 (2024)]



$K_S^0 h^+ h^-$

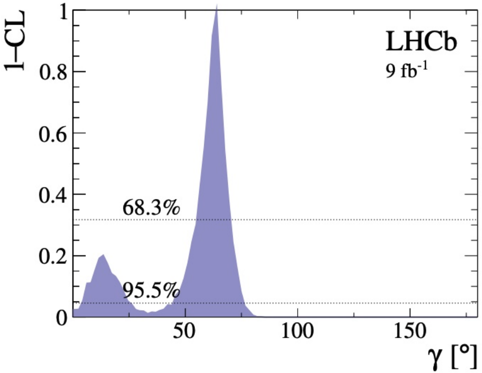


Two and Four-body

γ from $B^0 \to DK^{*0}$

- $B^0 \to DK^*(892)^0$ has smaller branching fraction than $B^+ \to DK^+$, but larger amplitude ratio $r_{B^0}^{DK^*} \sim 0.250$, and so gives competitive sensitivity.
- Combination of all modes (partially) resolves the degeneracy, with preferred solution $\gamma = (63.2^{+6.9}_{-8.1})^\circ$

$B \to DK^{*0}$ combined



Outline

Determination of γ by combining measurements

- Each γ analysis reports CPV observables, which are interpreted in combination 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_+

  } Primarily from external D measurements BESIII/CLEO/LHCb

- Many groups deliver combinations of γ observables: CKMFitter, HFLAV, UTFit, Belle+BelleII, etc.
- LHCb combination uses a frequentist implementation through the GammaCombo package, see PLB 726 (2013) 151 for details on the formalism

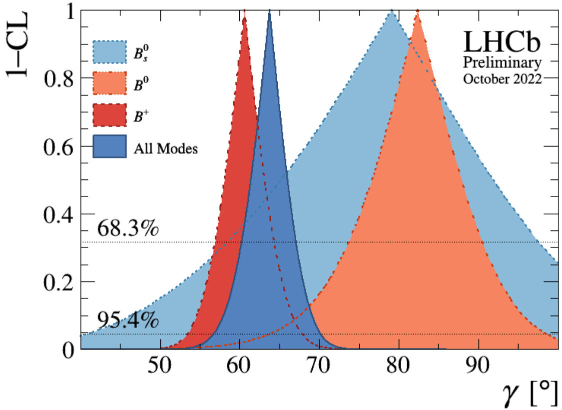
Why combine with charm mixing?

$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$$

$$x \equiv (m_1 - m_2)/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$$

- Charm mixing measurements depend on same set of D hadronic parameters as γ measurements from $B \to Dh$
- Interpretation of $B \to Dh$ measurements requires corrections due charm mixing
- $B \to D[K\pi]h$ measurements sensitive to $\delta_D^{K\pi}/r_D^{K\pi} \Rightarrow$ improve precision on y measurements from $D \to K\pi$ decays
- First LHCb γ + charm mixing combination JHEP 12 (2021) 141, direct charm CPV observables added in LHCb-CONF-2022-003

Results of 2022 LHCb combination



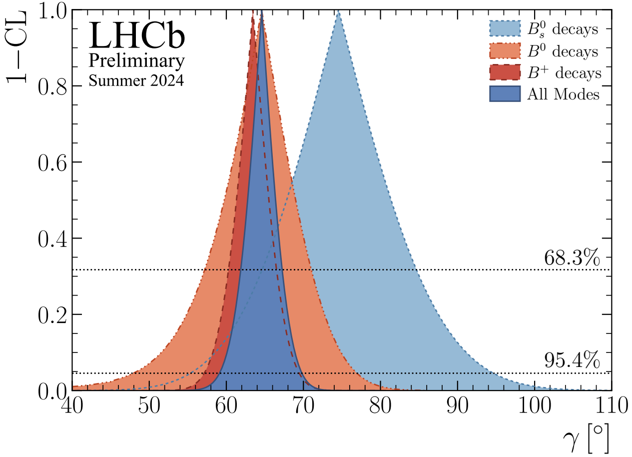
$$\gamma = \left(63.8^{+3.5}_{-3.7}\right)^\circ$$

B_s^0 only with Run1 data, and B^0 with partial Run2 data

A family of γ measurements in 2024

- LHCb has now published analyses of many B and D decay channels with Run1 and Run2 data including:
  - $B^+ \to DK^+$
  - $B^+ \to D^*K^+$(new)
  - $B^+ \to DK^{*+}$ (new)
  - $B^0 \to DK^{*0}$ (updated from partial Run2 in 2024)
  - $B_s^0 \to D_s^+K^+$ (updated from Run1 only in 2024)
- Different B decays give complementary sensitivity with largely uncorrelated uncertainties
- First opportunity to compare results across B decays with full Run1+Run2 dataset
- 2024 combination includes 198 input observables to determine 53 free parameters

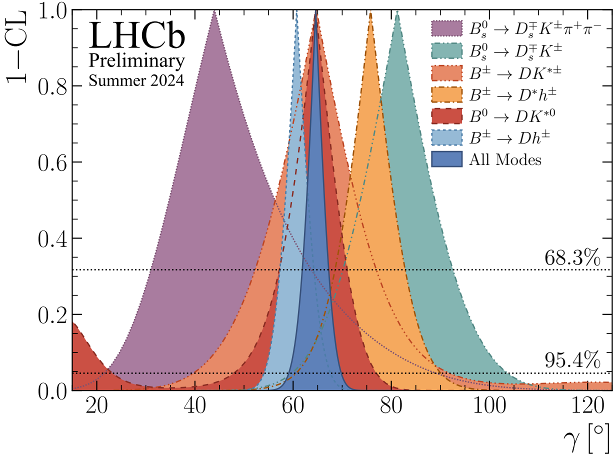
Results of the 2024 combination: γ by B flavour



$$\gamma = (64.6 \pm 2.8)^\circ$$

Goodness of fit $= 20.8\%$ from χ^2

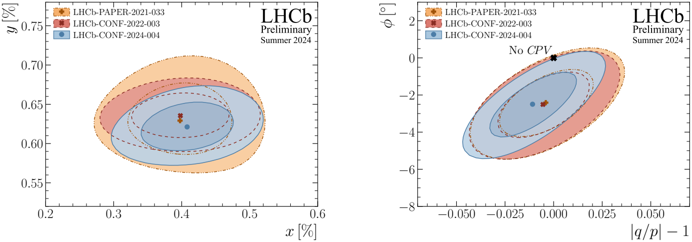
Results of the 2024 combination: γ by decay channel



- Now have distinct solutions in eight separate decay channels

Results of the 2024 combination: Charm results

- Since 2022 combination, new measurements of mixing in $D^0 \to K^-\pi^+$ and $\pi^+\pi^-\pi^0$ decays



- CPV in D-mixing just outside of 95% C.L.
- From LHCb combination $\delta_D^{K\pi} = \left(191.6^{+2.5}_{-2.4}\right)^\circ$, significantly more precise than best current BESIII measurement

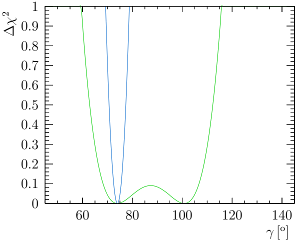
Outline

γ prospects: Prospects for Multibody D-decays

- Phase-space dependent analysis of multi-body final states greatly improves sensitivity to γ, as demonstrated in 2023 LHCb measurement of $B^+ \to DK^+$, $D \to K^-\pi^+\pi^+\pi^-$
- Both BESIII and LHCb data essential to deliver meaningful precision
- Results to come from with other $D \to$ multi-body final states

$B^+ \to DK^+$, $D \to K^-\pi^+\pi^+\pi^-$ LHCb, JHEP 07 (2023), 138

γ sensitivity



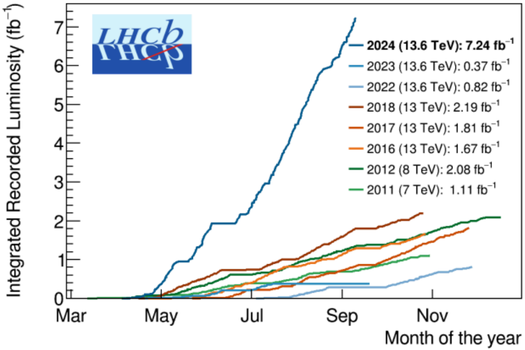
PS-Integrated PS-dependent

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

From BESIII $\delta_D^{K3\pi} =^{+6.7^\circ}_{-4.7^\circ}$

γ prospects: New data at LHCb and BESIII

- Run 3 is well underway, and LHCb has already collected a data sample larger than the Run 2 sample. Fantastic prospects for the full Run3 sample.
- BESIII has collected ~ 20 fb^{-1} at the $D^0\overline{D}^0$ production threshold, roughly $7\times$ larger than the previous sample.



New avenues for quantum-correlated $D^0\overline{D}^0$ measurements

- $\mathcal{C}$-odd constraint still applies to $e^+e^- \to XD^0\overline{D}^0$
- If X is a $\mathcal{C}$-odd eigenstate (e.g. γ), $D^0\overline{D}^0$ system should be constrained to be C-even : Predicted but never observed
- Correlations in C-even decays have different dependencies on hadronic parameters – measurements in both C-even and C-odd samples allow for reduced systematic uncertainties from future measurements
- C-even decays also have linear sensitivity to D-mixing terms[4]
  $\Rightarrow$ possibility for time-independent measurements of mixing from e^+e^- data
- Preliminary studies with BESIII $D^{*0}\overline{D}^0$ and $D^{*0}\overline{D}^{*0}$ data ongoing

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Bondar, Poluektov, Vorobiev, PRD 82 (2010) 034033

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- Possibility for measurements of CPV in decay from QC data?
  $P([D^0\overline{D}^0]_{\mathcal{C}-\text{odd}} \to \pi^+\pi^-\pi^+\pi^-) \sim \mathcal{B}(D^0 \to \pi^+\pi^-)^2 \times a^d_{\pi^+\pi^-} \sim 5 \times 10^{-9}$
  Compare to $\sim 10^8$ $D^0\overline{D}^0$ events in current data.
- Could be expanded with other QC-forbidden decays, e.g. $\pi^+\pi^-K^+K^-$
- Unique opportunities with missing/neutral particles e.g. $D^0 \to K^0_L\pi^0$, $D^0 \to \pi^0\pi^0$

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Summary

- Unitarity tests provide opportunity to search for new physics entering at loop level – searches currently limited by CKM angle γ
- Physics programs of BESIII linked to LHCb measurements of γ through quantum-correlated $D^0\overline{D}^0$ pairs
- 2024 Average of all available LHCb and BESIII measurements determines $\gamma = (64.6 \pm 2.8)^\circ$ $\sim 0.7^\circ$ improvement over 2023 global average
  - Consistent determination of γ from B^+, B^0, and B_s^0 decays
- Strong prospects for further improvement with Run 2 data, and fantastic prospects from Run 3 data and new BESIII datasets
  - Uncertainty on $\frac{|V_{ub}|}{|V_{cb}|}$ could soon be a limiting uncertainty
- Quantum-correlated $D^0\overline{D}^0$ pairs present unique opportunities for measurements of D^0 mixing and CPV

BACKUPS