Quantum Correlations of Neutral Charmed Mesons at the BESIII Experiment

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Outline

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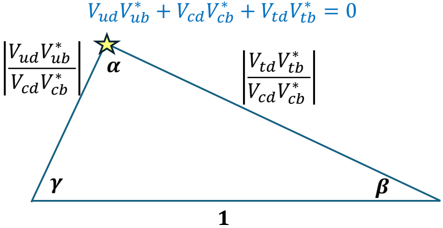
Quark Flavour Physics and CKM Unitarity

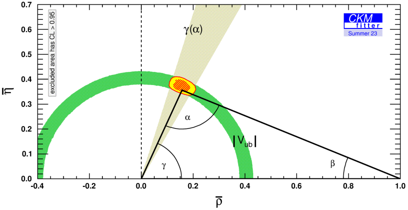
- Precision measurements of hadrons constrain new physics energy scales much higher than those achievable from direct searches with modern colliders (10^4 GeV–10^{10} GeV)
- One avenue is testing unitarity of Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix, which rigidly constrains quark flavour transitions in the SM.
- Can construct B-meson Unitarity Triangle from one such constraint

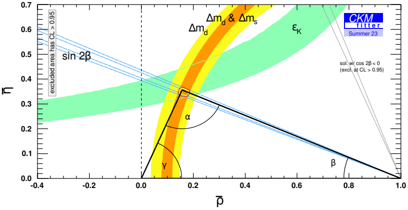
$$V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$



Unitarity Tests

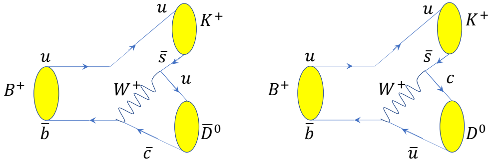
- Numerous measurements can constrain the Unitarity Triangle apex
- $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$, along with $\frac{|V_{ub}|}{|V_{cb}|}$, allows for a determination of the apex from processes that proceed through tree-level SM interactions.
- The apex can also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





Measuring γ

- γ: Interference of tree-level amplitudes of $B \to Dh$



$$\frac{\mathcal{A}(B\to D^0 h)}{\mathcal{A}(B\to \bar{D}^0 h)} = r_B r_D e^{i(\delta_B+\delta_D+\gamma)} \qquad \frac{\mathcal{A}(\bar{B}\to \bar{D}^0 h)}{\mathcal{A}(\bar{B}\to D^0 h)} = r_B r_D e^{i(\delta_B+\delta_D-\gamma)}$$

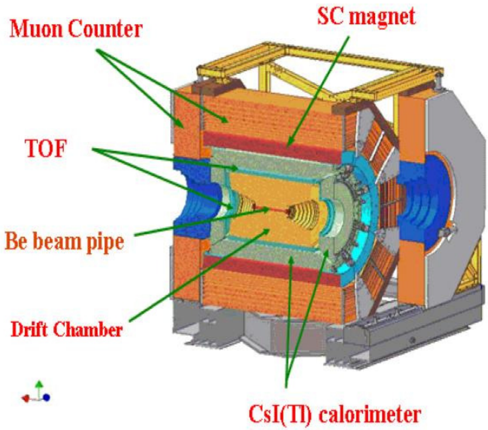
- Can determine γ with negligible theoretical uncertainty excluding tree-level new-physics[a], provided B and D amplitude parameters
- For given $B \to Dh$ process, can determine solution in (γ, r_B, δ_B) space through observations with D-decays of varying strong phases
- Similar relationship between parameters that characterise neutral charm-meson mixing and strong phases

[a] Brod and Zupan, JHEP 01 (2014) 051
Brod, Lenz, Tetlalmatzi-Xolocotzi, and Wiebusch, PRD 92 (2015) 033002

Beijing Electron-Positron Collider Mk. II (BEPCII)

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

Beijing Electron Spectrometer III (BESIII)



- Hermiticity: 93% of 4π
- Drift Chamber: $\sigma_p/p = 0.5\%$ at 1 GeV
- Time-of-Flight: $\sigma = 80$ ps
- EMC: $\sigma_E/E : 2.5\%$ at 1 GeV
- Superconducting Solenoid: 1T
- MUC: 9 layer RPC Muon System
- Some notable differences of charm decays at other experiments
  - Low boost $\Rightarrow$ (almost) no displaced vertices [Exceptions: $K_S^0 \to \pi\pi$ and $\Lambda \to p\pi$]
  - Momentum of final state particles in the lab frame: $50 - 1500$ MeV/c
  - $\sim 100\%$ trigger efficiency
  - Excellent e^+ ID, muons more challenging!

BESIII Physics Program

- In March 2025, BESIII published its 700th paper. Primary topics of interest:
  - Light Hadron Physics
    - e.g. Weak phases in double-strange baryons, *Nature* 606, 64-69 (2022)
  - R-value inputs to $g-2$
    - e.g. PRL 128, 062004 (2022)
  - Precision τ Physics
    - Projected uncertainty on τ mass $< 0.1\,\mathrm{M}e\mathrm{V}$
  - Charmonium and Exotic Hadron Spectroscopy
    - e.g. Discovery of $Z_c(3900)/\ T^b_{\psi 1}(3900)$ in 2013
  - **Open-Charm Physics: ($D^0(c\overline{u}), D^+(c\overline{d}), D_s^+(c\overline{s}), \Lambda_c^+(cdu), \ldots$)**

Outline

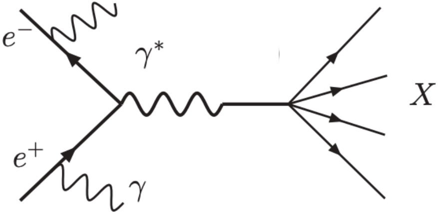
Introduction

Quantum Correlations in $e^+e^- \to \psi(3770)$

Correlations in $e^+e^- \to XDD$

Future Prospects & Summary

CP-symmetry induced correlations in $e^+e^- \to XD\bar{D}$



- $e^+e^- \to \gamma^* \to XD^0\bar{D}^0$ constrains the aggregate of final state particles to the C-eigenvalue of the photon, $C = -1$.
- If CP is a good symmetry in D^0 decays, then the D^0 and $\bar{D}^0$ decays must be correlated to state of definite CP.
- First published by Goldhaber and Rosner[a] with the first measurement from the CLEO collaboration[b] with data at $e^+e^- \to \psi(3770) \to D\bar{D}$ to measure δ_D in $D^0 \to K^-\pi^+$

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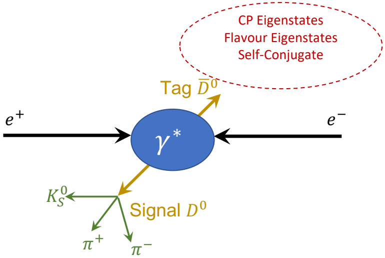
a M. Goldhaber and J. Rosner, PRD 15 (1977) 1254

b CLEO, PRD 80 (2008) 072001

Quantum Correlations at $\psi(3770)$



- In $e^+e^- \to \gamma^* \to D\overline{D}$, D^0 and $\overline{D}^0$ are constrained to $C = -1$:

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

- BESIII has collected 20.3 fb^{-1} at $E_{CM} = 3.773$ GeV:
  - 2.9 fb^{-1} in 2011
  - 17.4 fb^{-1} in 2022-2024

Quantum-Correlated Tag Decay Modes

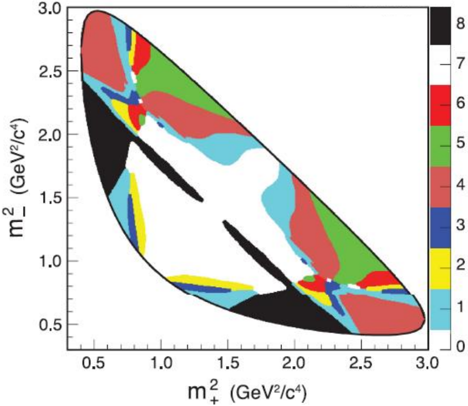
- Flavour Tags
  - $\overline{D}^0 \to K^+ e^- \nu$, is flavour-definite, so allow for a normalising determination of $P\left(D^0 \to X\right)$
  - Cabibbo-favoured decays, e.g. $\overline{D}^0 \to K^+\pi^-$, used as quasi-flavour tags
- CP Tags
  - $\overline{D}^0 \to \pi\pi, K^+K^-, K_S^0\pi^0$, etc. 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 tags with non-trivial phases needed to determine $\sin\left(\delta_D^X\right)$, e.g. $K_{S/L}^0\pi^+\pi^-$

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

- Using 7.9 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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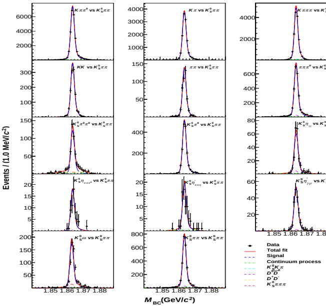
- 17 tag modes employed, yields determined with 2-D fits to $M_{\text{BC}} \equiv \sqrt{E^2_{\text{beam}} - p^2_D}$ or M^2_{miss}

JHEP 06 (2025) 086



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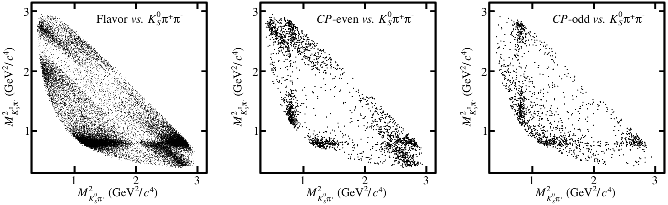
PRL 124, 241802 (2020) PRD 101, 112002, (2020)



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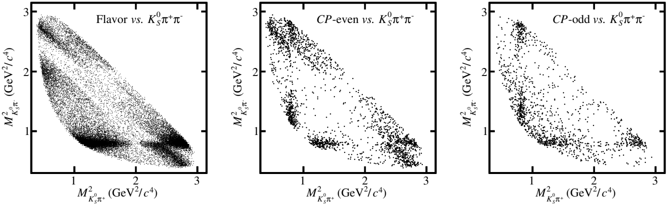
- In terms of fractional yields of flavour-tagged $K^0_S\pi^+\pi^- \equiv K_i$
- $K^0_S\pi^+\pi^-$ vs. CP tag: $M_i^\pm = h_{CP}\left(K_i + K_{-i} + 2c_i\sqrt{K_iK_{-i}}\right)$
- $K^0_S\pi^+\pi^-$ vs. $K^0_{S,L}\pi^+\pi^-$ tag:
  $M_{ij} = h_{DT}\left(K_iK_{-j} + K_{-i}K_j \mp \sqrt{K_iK_{-j}K_{-i}K_j}\,(c_ic_j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

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



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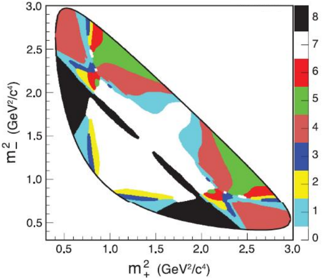
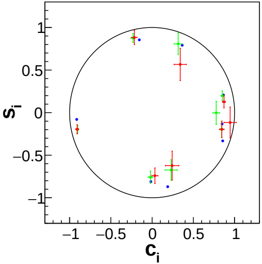




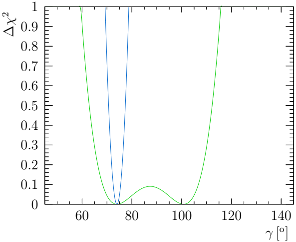
Binning schemes from
CLEO PRD 82,112006 (2010)

Green points are determined with c
Red points without constraints
Blue points are predictions from
BaBar and Belle,
PRD 98, 110212(2018)

Phases in $D^0 \to K^-\pi^+\pi^+\pi^-$

- Measurement of phase-space-averaged δ_D, coherence factors R, and amplitude ratios r_D with 2.9 fb^{-1}

4-bin binning scheme for $D^0 \to K^-\pi^+\pi^+\pi^-$ from T. Evans *et al.*, PLB 802 (2020) 135188 significantly improves sensitivity to γ



With Binning   No Binning

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JHEP 05 (2021) 164

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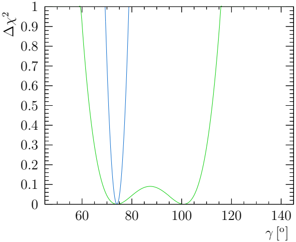

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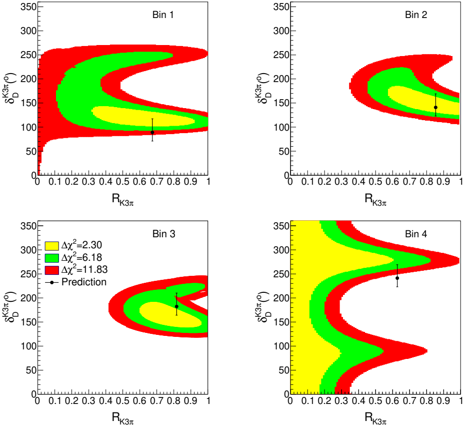


Strong phases in $D^0 \to K^+K^-\pi^+\pi^-$

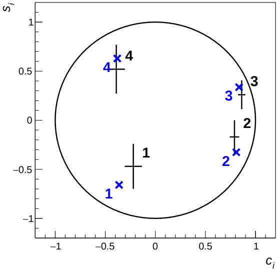
PRD 112 (2025) 012015

- Analysis of full 20.3 fb^{-1} sample @ $E_{\mathrm{CM}} = 3.773$ GeV
- Measurement of c_i/s_i in four bins of $D \to K^+K^-\pi^+\pi^-$ phase space:

$$c_i/s_i \propto \int d\Phi_i \, \mathcal{A}_D \bar{\mathcal{A}}_D \cos / \sin(\delta_D)$$

- Binning of 5-D phase-space optimised[c] for measurement of CKM angle γ
- Yields determined for $D\overline{D} \to K^+K^-\pi^+\pi^-$ vs:
  - 3 quasi-flavour tags $(K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-)$
  - 10 CP tags
  - $K^0_S\pi^+\pi^-$ and $K^0_L\pi^+\pi^-$
- Part. reco. $D \to K^+_{\mathrm{miss}}K^-\pi^+\pi^-$ also included

c_i/s_i from combined analysis of all yields
Compared to predictions from amp. model
Results employed in LHCb-PAPER-2025-019

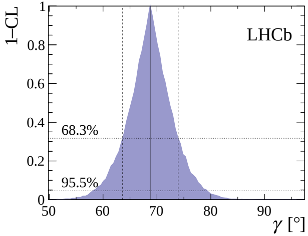


[c] LHCb, EPJC 83 (2023) 547

Impacts on beauty-sector CPV Measurements

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

LHCb, JHEP02 (2021), 169



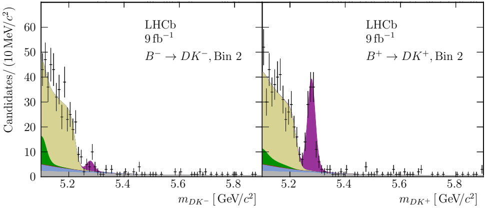
$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$$

from $\Delta\delta_D^{K_S^0 h^+ h^-} \sim \pm 1^\circ$

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

using $K3\pi$ binning

LHCb, JHEP 07 (2023) 138



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

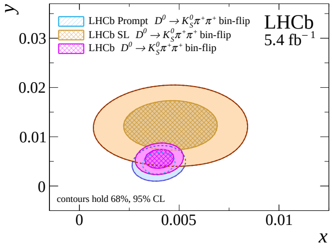
from $\Delta\delta_D^{K3\pi} =^{+6.7}_{-4.7}$!

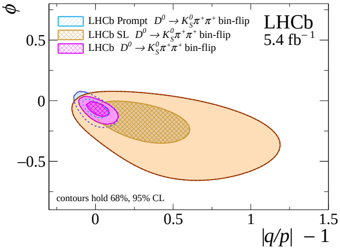
2025 LHCb Combination LHCb-CONF-2025-003:

$\gamma = (62.8 \pm 2.6)^\circ$, with $\sim 1^\circ$ uncertainty from BESIII inputs

Impacts on charm-sector CPV/Mixing Measurements

- LHCb average of $D \to K_S^0\pi^+\pi^-$ measurements from arXiv:2208.06512





$\Delta\delta_D^{K_S^0\pi^+\pi^-} \sim 50\%$ of total uncertainties on x_{CP}, y_{CP} and $\sim 15\%$ of total uncertainties on Δx and Δy

Major improvements to come with 20.3 fb^{-1} sample

Outline

Looking beyond $e^+e^- \to D\overline{D}$

- QC $D^0\overline{D}^0$ pairs should exist at higher energies from $e^+e^- \to XD\overline{D}$ with $C = (-1)^{n_\gamma+1}$ for X with n_γ photons.
- C-even constrained pairs have linear sensitivity to charm-mixing effects, enhanced $2\times$ relative to flavor-definite D mesons.

$$\frac{P([D^0\overline{D}^0]_C \to X_1X_2)}{P(D^0 \to X_1)P(\overline{D}^0 \to X_2)} = 1 + \left(r_D^{X_1} r_D^{X_2}\right)^2 + 2C r_D^{X_1} r_D^{X_2} \cos\left(\delta_D^{X_1} + \delta_D^{X_2}\right) + (1+C)\mathcal{O}(x,y)$$

- The simplest example is $e^+e^- \to D^{*0}\bar{D}^0 \to (\gamma/\pi^0)D^0\bar{D}^0$, and the recognition of prospects for probing the effects of charm mixing has been long-recognised in literature[a]
- Proposal for time-dependent studies of $c\bar{c} \to XD\overline{D}$ at the LHC/Belle II to probe T and CPT violation[b].

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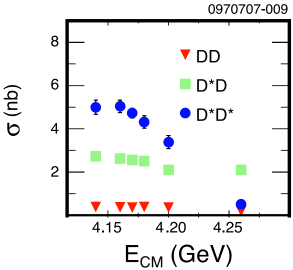
a See appendix for citations

b P. Naik, JHEP 03 (2023) 038

Correlations beyond $\psi(3770) \to D\overline{D}$

- BESIII has collected data at $E_{CM} = 4.13 - 4.23$ GeV, where $e^+e^- \to D^{*0}\bar{D}^0$ and $e^+e^- \to D^{*0}\bar{D}^{*0}$
- This produces numerous different possibilities for producing $D\overline{D}$:



	Final State	$D\overline{D}$ C
	$D\overline{D}$	-1
$D^*\overline{D}$	$\gamma D\overline{D}$	$+1$
	$\pi^0 D\overline{D}$	-1
$D^*\overline{D}^*$	$\pi^0\gamma D\overline{D}$	$+1$
	$\gamma\gamma D\overline{D}$	-1
	$\pi^0\pi^0 D\overline{D}$	-1
$D^{*+}D^{*-}$	$\pi^+\pi^- D^0\overline{D}^0$	0 (Uncorrelated)

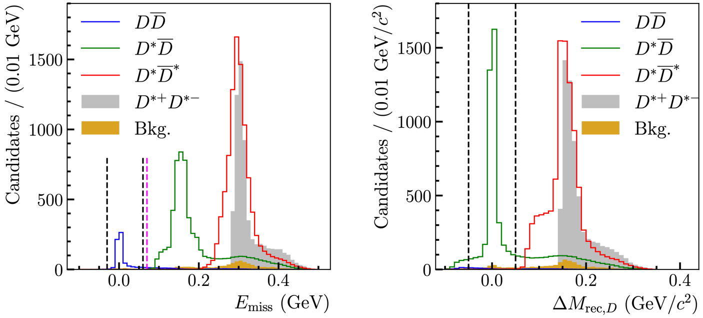
CLEO, PRD 80 (2008) 072001

Identifying $e^+e^- \to XD\overline{D}$

PRL 135 (2025) 171901 PRD 112 (2025) 072006

- Analysis of 7.3 fb^{-1} of data @ $E_{CM} = 4.13 - 4.23$ GeV
- Reconstruct only the $D\overline{D}$ pair
- Identify $D\overline{D}$ production mechanism with kinematic selection variables:

$$e^+e^- \to D\overline{D} \text{ \& } e^+e^- \to D^*\overline{D}$$



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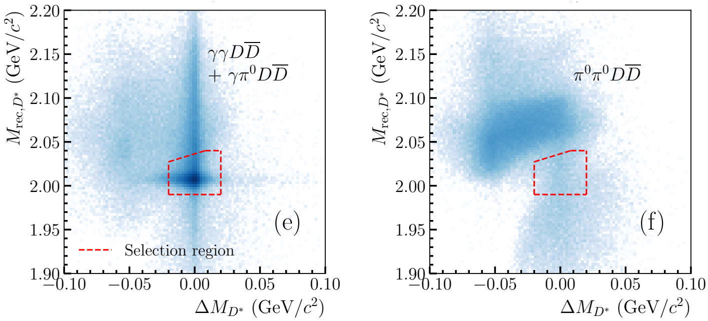
- For $D^*\overline{D}^*$ ID, reconstruct a $D^* \to \gamma D$ candidate and veto $D^{*+} \to \pi^+ D^0$

$e^+e^- \to D^*\overline{D}^*$



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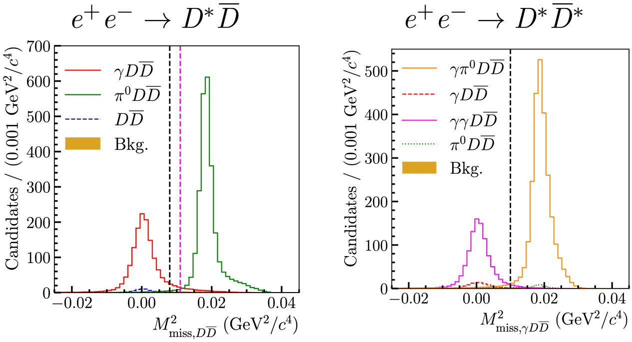
- For $D^*\overline{D}^*$ ID, reconstruct a $D^* \to \gamma D$ candidate and veto $D^{*+} \to \pi^+ D^0$
- Separate intermediate decays with missing-mass variables



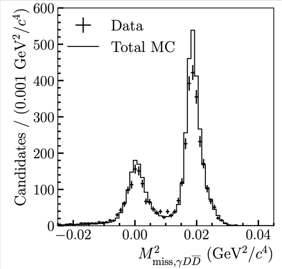
Measuring correlations in $e^+e^- \to XD\overline{D}$

PRL 135 (2025) 171901 PRD 112 (2025) 072006

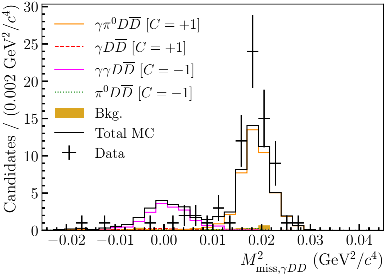
- Analysis of 7.3 fb^{-1} of data @ $E_{CM} = 4.13 - 4.23$ GeV
- Reconstruct $D\overline{D}$ pairs: Normalization $D\overline{D} \to K^-\pi^+$ vs. $K^+\pi^-$ and CP vs. CP final states: $D \to \pi^+\pi^-, K^+K^-, \pi^+\pi^-\pi^0$, and $K^0_S\pi^0$
- Sort into $e^+e^- \to XDD$ production hypotheses

$e^+e^- \to D^*\overline{D}^*$

$D\overline{D} \to K^+\pi^-$ vs. $K^-\pi^+$



$D\overline{D} \to K^0_S\pi^0$ vs. $K^0_S\pi^0$



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PRL 135 (2025) 171901 PRD 112 (2025) 072006

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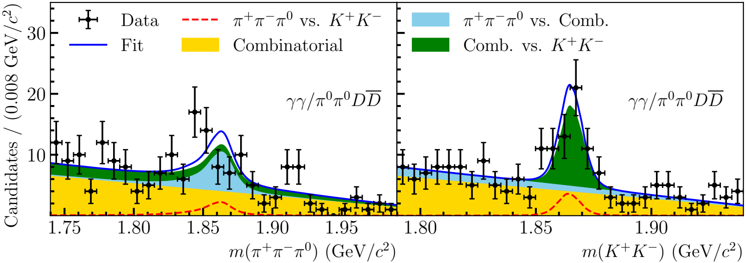
- Reconstruct $D\overline{D}$ pairs: Normalization $D\overline{D} \to K^-\pi^+$ vs. $K^+\pi^-$ and CP vs. CP final states: $D \to \pi^+\pi^-, K^+K^-, \pi^+\pi^-\pi^0$, and $K^0_S\pi^0$
- Sort into $e^+e^- \to XDD$ production hypotheses
- Fit to $M(D)$ vs.$M(\overline{D})$ to determine yields



Measuring correlations in $e^+e^- \to XD\overline{D}$

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- Account for efficiencies and production mechanism cross-feed

$$\vec{n}_{\text{true}} = \mathbf{A}^{-1}\vec{N}_{\text{meas.}}$$

$$\mathbf{A}_{ij} \equiv \text{prob. of prod. mech } i \text{ being identified as } j$$

		Identified as				
		$D\overline{D}$	$D^*\overline{D} \to \gamma D\overline{D}$	$D^*\overline{D} \to \pi^0 D\overline{D}$	$D^*\overline{D}^* \to \gamma\pi^0 D\overline{D}$	$D^*\overline{D}^* \to \gamma\gamma/\pi^0\pi^0 D\overline{D}$
True	$D\overline{D}$	32.45	2.98	0	0	0.07
	$D^*\overline{D} \to \gamma D\overline{D}$	0	25.44	1.57	0	1.94
	$D^*\overline{D} \to \pi^0 D\overline{D}$	0	0.40	30.06	0.55	0.50
	$D^*\overline{D}^* \to \gamma\pi^0 D\overline{D}$	0	0	0	25.23	1.04
	$D^*\overline{D}^* \to \gamma\gamma/\pi^0\pi^0 D\overline{D}$	0	0	0	0.25	8.83

(for $D \to K^+\pi^-$ vs. $K^-\pi^+$)

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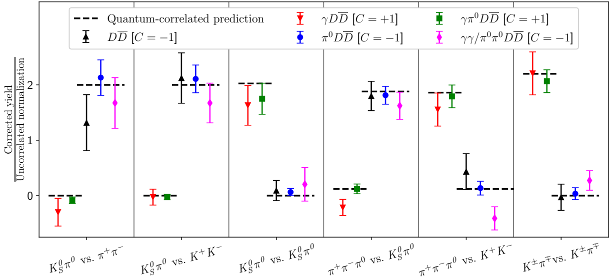
- Account for efficiencies and production mechanism cross-feed
- Compare corrected yields of $D\overline{D} \to$ CP vs. CP to normalization



Demonstration of correlations: ✓ Procedure verified for strong-phase measurements ✓

$\delta^D_{K\pi}$ with $e^+e^- \to XD\overline{D}$

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- Analysis of 7.3 fb^{-1} of data @ $E_{CM} = 4.13 - 4.23$ GeV
- With similar procedure, can measure $\delta_D^{K\pi}$ with $D\overline{D} \to K^+\pi^-$ vs. Y, where Y is a CP-eigenstate or $K^0_S\pi^+\pi^-$

$$\delta^D_{K\pi} = \left(192.8^{+11.0+1.9}_{-12.4-2.4}\right)^\circ$$

Compare to

$$\delta^D_{K\pi} = \left(187.6^{+8.9+5.4}_{-9.7-6.4}\right)^\circ$$

with 2.9 fb^{-1} @ $\psi(3770)$

- Higher stat. error per fb^{-1} due to exclusion of $D^*\overline{D}^* \to \pi^0\pi^0 D\overline{D}$ and part. reco. tags, e.g. $D \to K^0_L\pi^+\pi^-$
- Significantly reduced syst. error due to mixed C-even and C-odd sample.

$\delta^D_{K\pi}$ with $e^+e^- \to XD\overline{D}$

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BESIII combination
of 7.3 fb^{-1} of data @ $E_{CM} = 4.13 - 4.23$ GeV
and 2.9 fb^{-1} of data @ $E_{CM} = 3.77$ GeV:

$$\delta^D_{K\pi} = \left(189.2^{+6.9+3.4}_{-7.4-3.8}\right)^\circ$$

Outline

Introduction

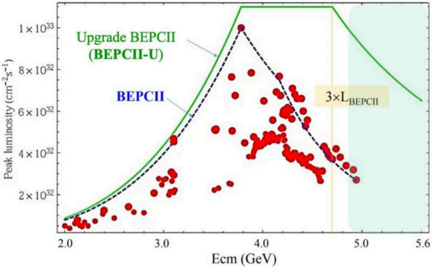
Quantum Correlations in $e^+e^- \to \psi(3770)$

Correlations in $e^+e^- \to XDD$

Future Prospects & Summary

Prospects for Strong Phase Measurments

- LHCb's stated goal is 1° uncertainty on γ
- New sample of $20.3\,\mathrm{fb}^{-1}$ at the $\psi(3770)$ is $\sim$7x larger than previous sample $\Rightarrow$ updated strong phase measurement will not limit γ uncertainty
- BEPCII Upgrade has been completed
  - Much higher instantaneous luminosity at $E_{CM} > 4$ GeV
  - Access to E_{CM} up to 5.6 GeV
  - Possibility of new samples of $e^+e^- \to XD\overline{D}$ to further improve



Further opportunities with quantum-correlated $D\overline{D}$ pairs

- Proposed Super-Tau Charm Factory[a] aims to collect $\mathcal{O}(\text{ab}^{-1})$ samples at open-charm pair-production thresholds
- With methods described in this talk[b], strong prospects for measurements of mixing and time-dependent CPV in D meson decays from purely hadronic final states, estimated with realistic efficiencies
- Previous estimates of sensitivity including some semileptonic modes[c] also show exciting prospects

	$x\ (10^{-4})$	$y\ (10^{-4})$	$\left\lvert\frac{q}{p}\right\rvert$ (%)	$\phi\ (^\circ)$
Hadronic $1\ \text{ab}^{-1}$	6.9	2.0	3.4	2.5
Semileptonic $1\ \text{ab}^{-1}$	6.0	6.1	1.7	1.7

a STCF CDR: https://arxiv.org/abs/2509.11522

b BESIII, PRL 135 (2025) 171901

c A. Bondar, A. Poluektov, and V. Vorobiev, PD **82** (2010) 034033.

Summary

- Quantum-correlated $D\overline{D}$ pairs at BESIII provide model-independent measurements of strong-phase parameters essential for CKM unitarity tests
- Strong-phase inputs from BESIII contribute $\sim 1^\circ$ uncertainty to LHCb's γ combination: $\gamma = (62.8 \pm 2.6)^\circ$
- New $20.3\,\text{fb}^{-1}$ sample at $\psi(3770)$ is ~7× larger than previous dataset ⇒ significant improvements forthcoming for $D \to K_S^0\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and other modes
- First demonstration of quantum correlations in $e^+e^- \to XD\bar{D}$ at $E_{\text{CM}} = 4.13$–$4.23\,\text{GeV}$, and observation of C-even correlated pairs
- BEPCII upgrade enables higher luminosity at $E_{\text{CM}} > 4\,\text{GeV}$, possibility for more $e^+e^- \to XDD$ data at BESIII
- Proposed Super Tau-Charm Facility would provide $\mathcal{O}(\text{ab}^{-1})$ samples opening new opportunities for charm mixing and CPV studies

Slide 20 References

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