Strong-phase results from quantum-correlated $D^0\overline{D}^0$ events

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on behalf of the BESIII Collaboration

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Outline

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Motivations

- Strong phases between $D^0/\overline{D}^0$ decays to the same final state are essential inputs to determining
  - the CKM angle γ/ϕ_3:

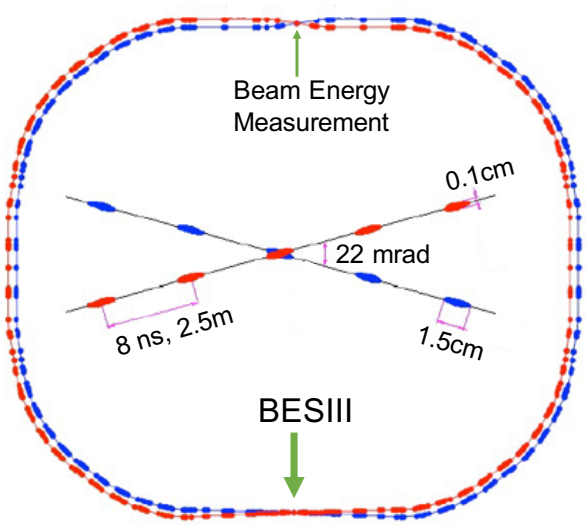
    $$\mathcal{A}_{B\to DK,D\to X} = \mathcal{A}_{B\to DK,D\to X}(r_B^{DK}, \delta_B^{DK}, r_D^X, \delta_D^X, \gamma)$$

    where r gives the ratio of decay amplitudes and δ gives the relative strong phase between the meson and antimeson
    - Current projection from Upgrade I at LHCb estimates a statistical uncertainty on γ of $\sim 1^\circ$
      $\Rightarrow$ current measurements of strong phase inputs will dominate γ uncertainty!
  - CP violation/mixing in D^0
- While models of D^0 strong phases exist, systematic uncertainties are too large to use in CPV analyses $\Rightarrow$ direct measurements are the only option

BESIII Experiment

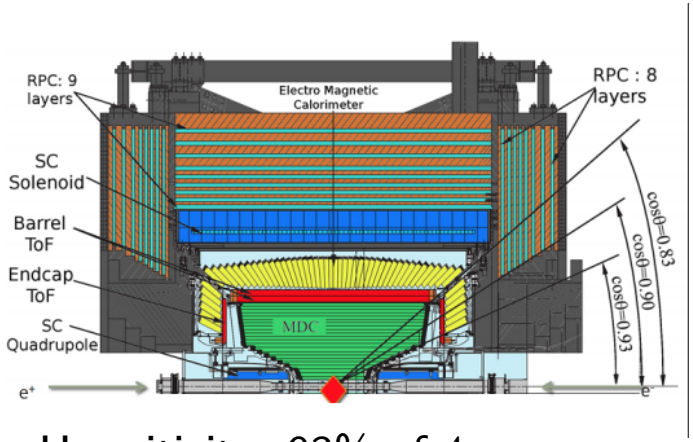
BESIII Experiment

BEPCII



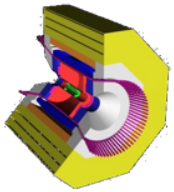
- Two ring symmetric e^+e^- collider
- Circumference: 240 m
- Design Luminosity: 10^{33} cm^{-2}s^{-1} Achieved Apr. 2016
- $\sqrt{s}$: $2-5$ GeV
- Beam Crossing Angle: 22 mrad

BESIII



- Hermiticity: 93% of 4π
- MDC: $\sigma_p/p = 0.5\%$ at 1 GeV
- ToF: $\sigma = 80$ ps
- EMC: σ_E/E : 2.5% at 1 GeV
- Superconducting Solenoid: 1T
- 9 layer RPC Muon System
- More detail in D.M. Asner *et al.*, Int. J. Mod. Phys. A 24, 1 (2009)

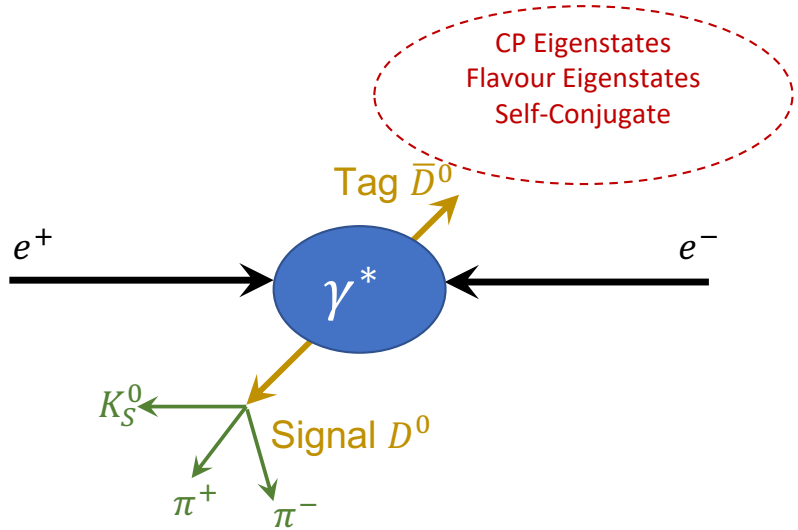
Datasets

CLEO-c  BESIII

- CLEO-c: Data collected until 2008
  - $D^{+(0)}$ 0.82 fb^{-1} @ $E_{cm} = 3.77$ GeV.
- BESIII
  - $D^{+(0)}$ 2.93 fb^{-1} @ $E_{cm} = 3.773$ GeV. Collected in 2011

Spoiler alert: More BESIII data being collected/analysed.

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



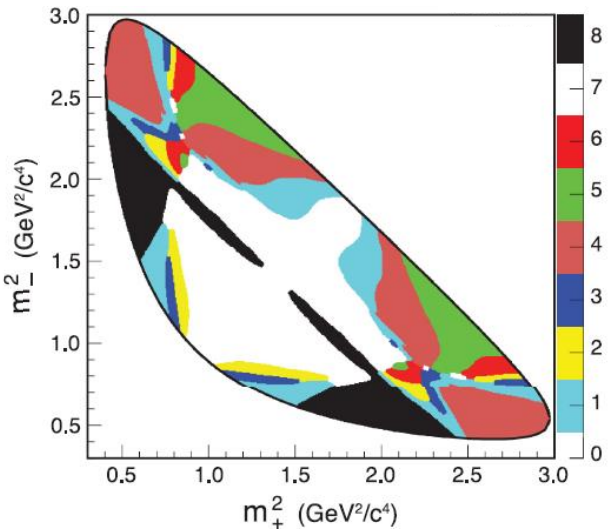
- Production through virtual photon constrains $D\overline{D}$ state to be CP-odd
- BESIII has large sample at the $D\overline{D}$ threshold, so it is guaranteed that there are no other particles in the final state
- CP constraint correlates D and $\overline{D}$ final states
- Can leverage this to measure D strong phases and CP-content of final states.

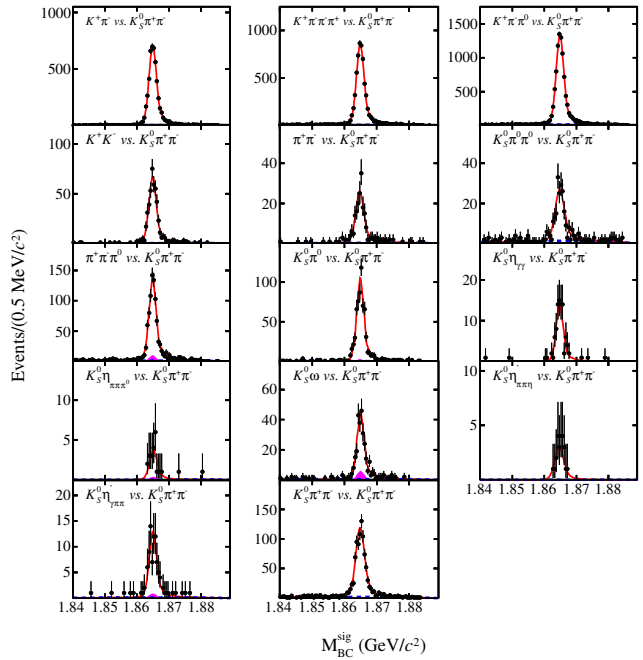
Outline

$D^0 \to K^0_S \pi^+ \pi^-$

- Measurement of $D^0/\overline{D}^0 \to K^0\pi^+\pi^-$ strong phase parameters $c_i\,[s_i] \equiv$ amplitude-weighted $\cos\,[\sin]\,\Delta\delta_D$ in phase-space bin i
- Phase space described by $m_\pm \equiv m\left(K^0\pi^\pm\right)$
- 17 tag modes employed, yields determined with 2-D fits to $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam} - p^2_D}$

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





Binning scheme from CLEO PRD 82,112006 (2010)

$D^0 \to K^0_S \pi^+ \pi^-$

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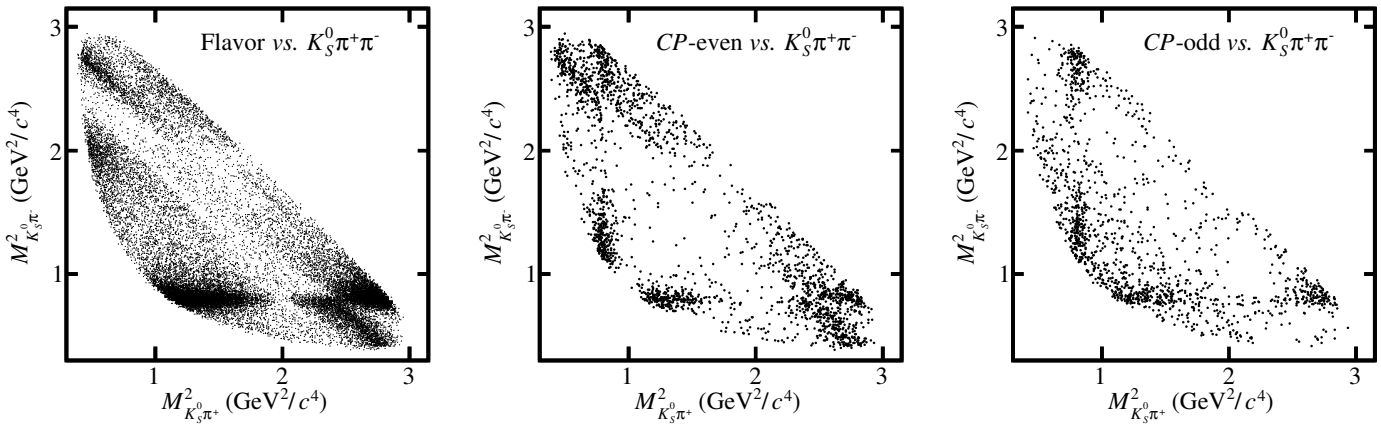
- Phase space described by $m_\pm \equiv m\left(K^0\pi^\pm\right)$
- In terms of fractional yields of flavour-tagged $K^0_S\pi^+\pi^- \equiv K_i$
- $K^0_S\pi^+\pi^-$ vs. CP tag: $M^\pm_i = h_{CP}\left(K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}\right)$
- $K^0_S\pi^+\pi^-$ vs. $K^0_{S,L}\pi^+\pi^-$ tag:
  $M_{ij}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

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



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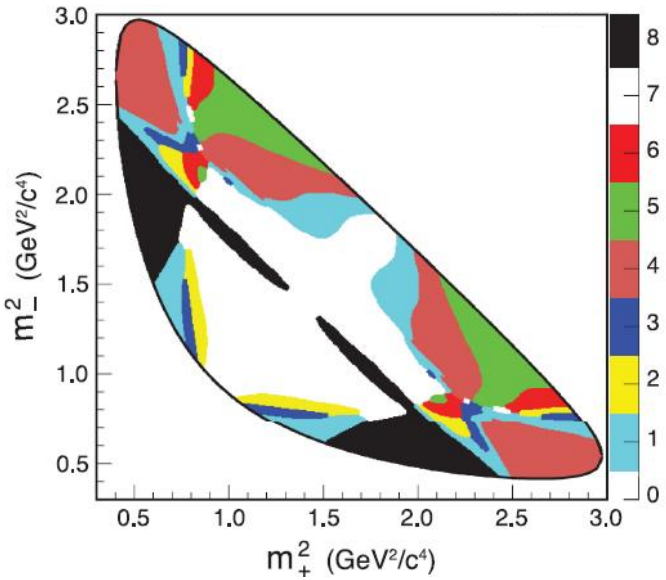
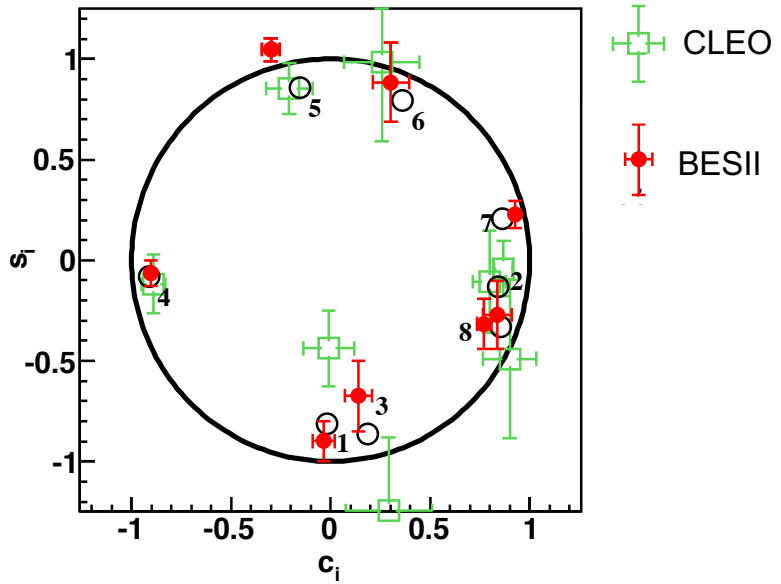


Binning scheme from CLEO PRD 82,112006 (2010)



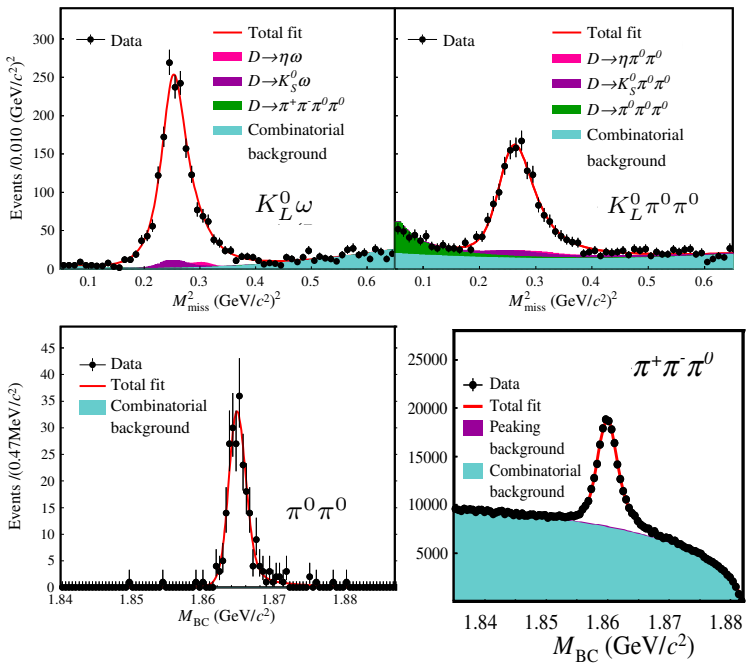
PRL 124, 241802 (2020)
PRD 101, 112002, (2020)

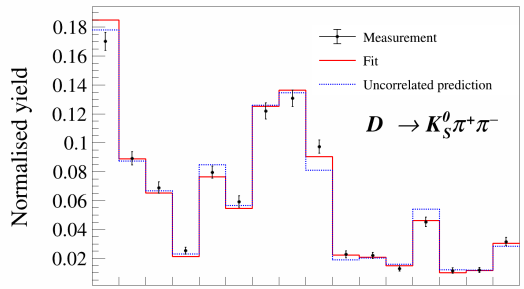
Circles are predictions from BaBar and Belle, PRD 98, 110212(2018)

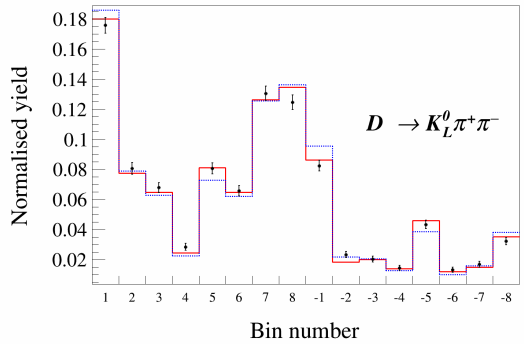
$D^0 \to K^-\pi^+$

- Updated measurement of $D^0/\overline{D}^0 \to K^-\pi^+$ strong phase defined by $r_D^{K\pi} e^{-i\delta_D^{K\pi}} = \frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle}$ from PLB 734 (2014)227-233
- Many new tag modes included, including partially reconstructed K^0_L modes

Eur. Phys. J. C 82, 1009 (2022)







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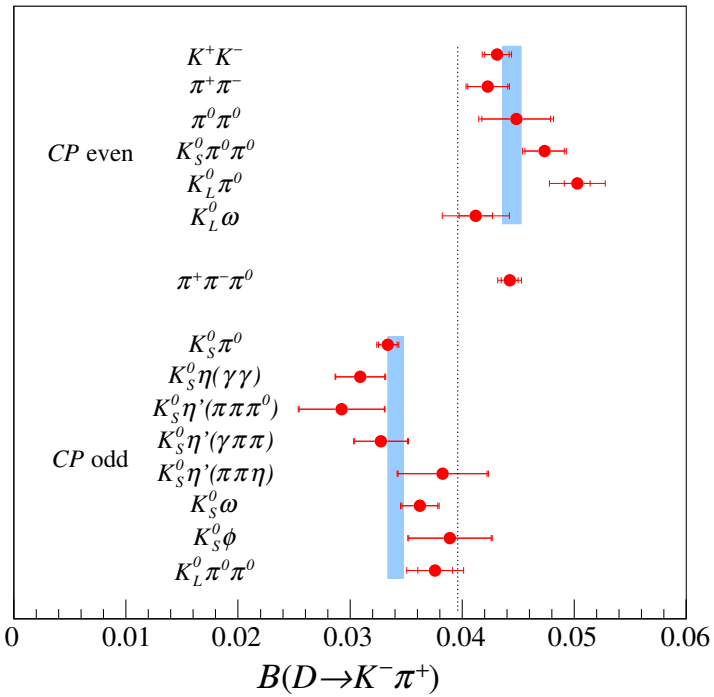


- $\delta_D^{K\pi} = \left(187.6^{+8.9\,+5.4}_{-9.7\,-6.4}\right)^\circ$
- Most precise measurement from QC $D\overline{D}$
- B factories have sensitivity, but as a nuisance parameter: $\delta_D^{K\pi} = \left(192.1^{+3.7}_{-4.0}\right)$ from LHCb, Phys. Rev. D 105 (2022), 092013

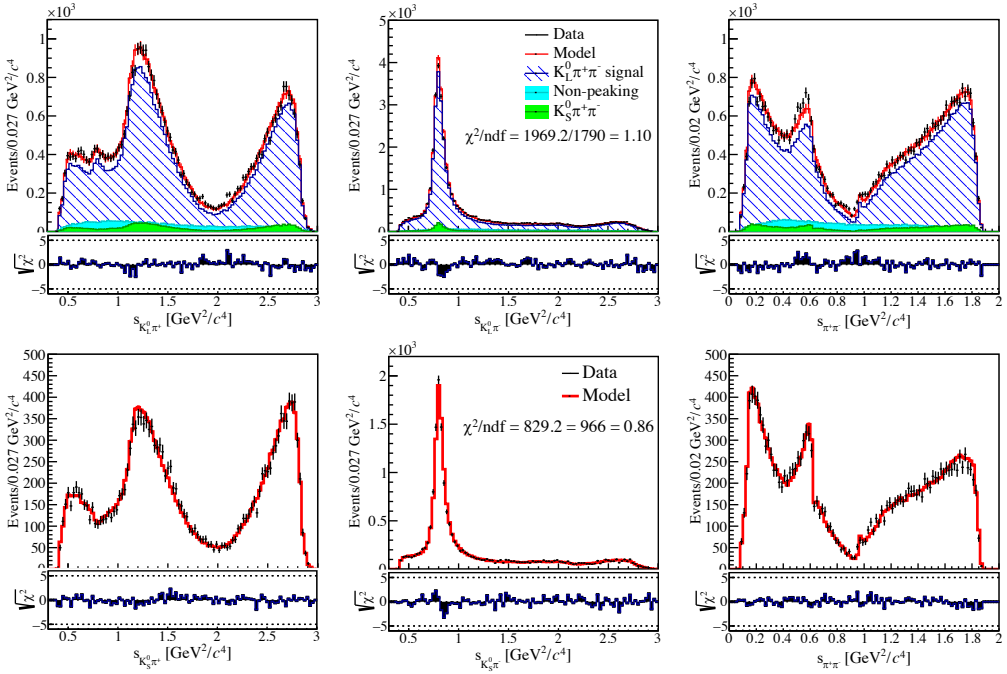
$D^0 \to K^0_L \pi^+ \pi^-$

- U-spin breaking effects between $D^0 \to K^0_L \pi^+ \pi^-$ and $D^0 \to K^0_S \pi^+ \pi^-$ amplitudes where $D^0 \to K_L k_{CP}, k_{CP} \to \pi\pi$ quantified by $\hat{\rho}_{k_{CP}}$:

$$\Gamma\left(D^0 \to K^0_L \left(\pi^+\pi^-\right)_{k_{CP}}\right) / \Gamma\left(D^0 \to K^0_S \left(\pi^+\pi^-\right)_{k_{CP}}\right) \approx 1 - 2\tan^2\theta_C \hat{\rho}_{k_{CP}}$$

- $\hat{\rho}_{k_{CP}}$'s determined for first time in $D^0 \to K^0_L \pi^+ \pi^-$ amplitude fit

arXiv:2212.09048



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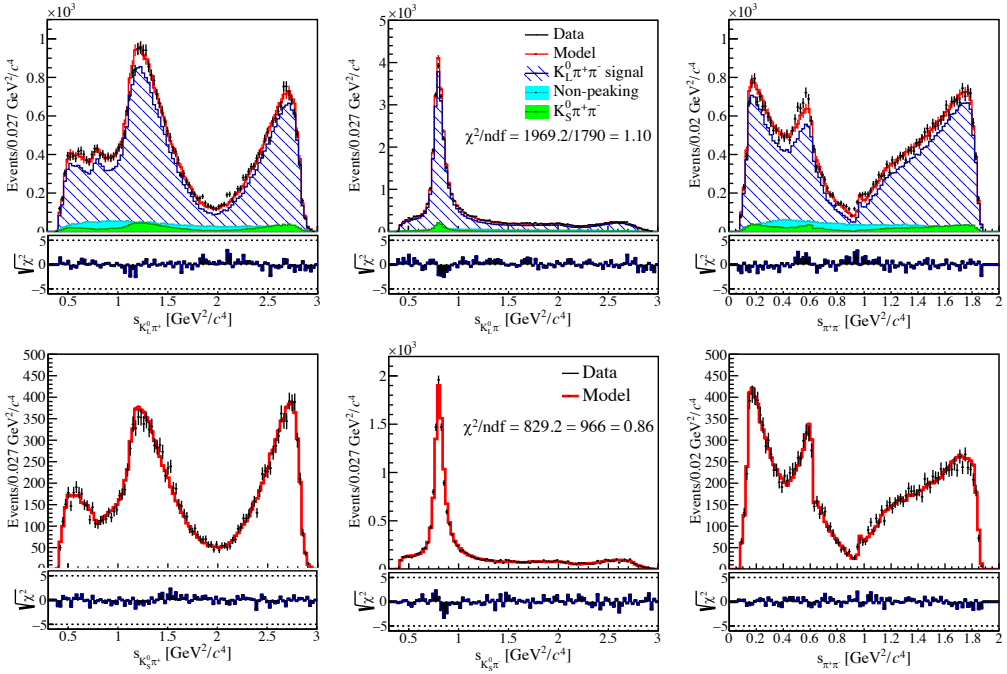
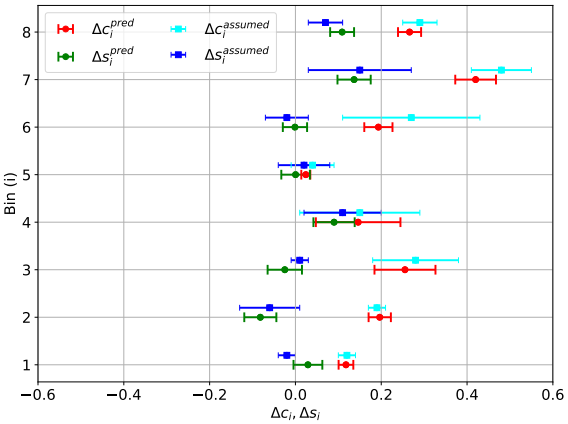


- Provides constraints of systematics on future strong phases measurements in $D^0 \to K^0_S \pi^+ \pi^-$ PRD 101, 112002, (2020)

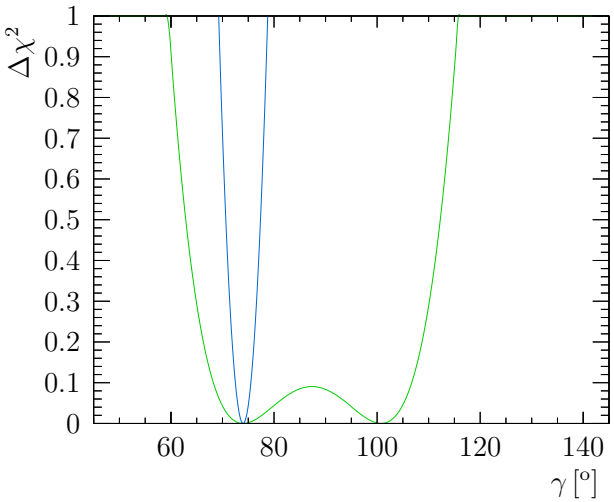


Outline

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

- Measurement of phase-space-averaged δ_D, coherence factors R, and amplitude ratios r_D

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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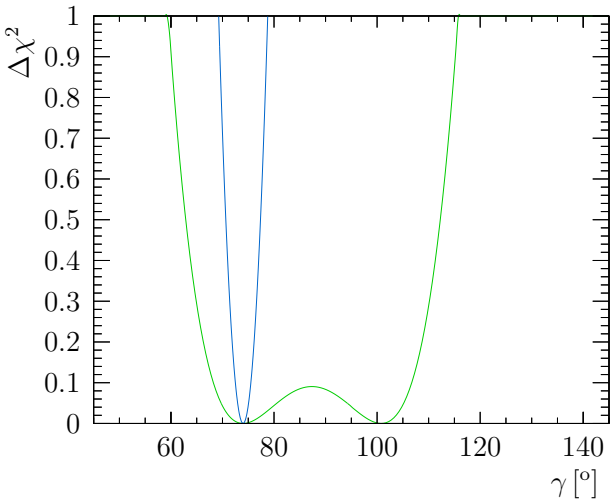

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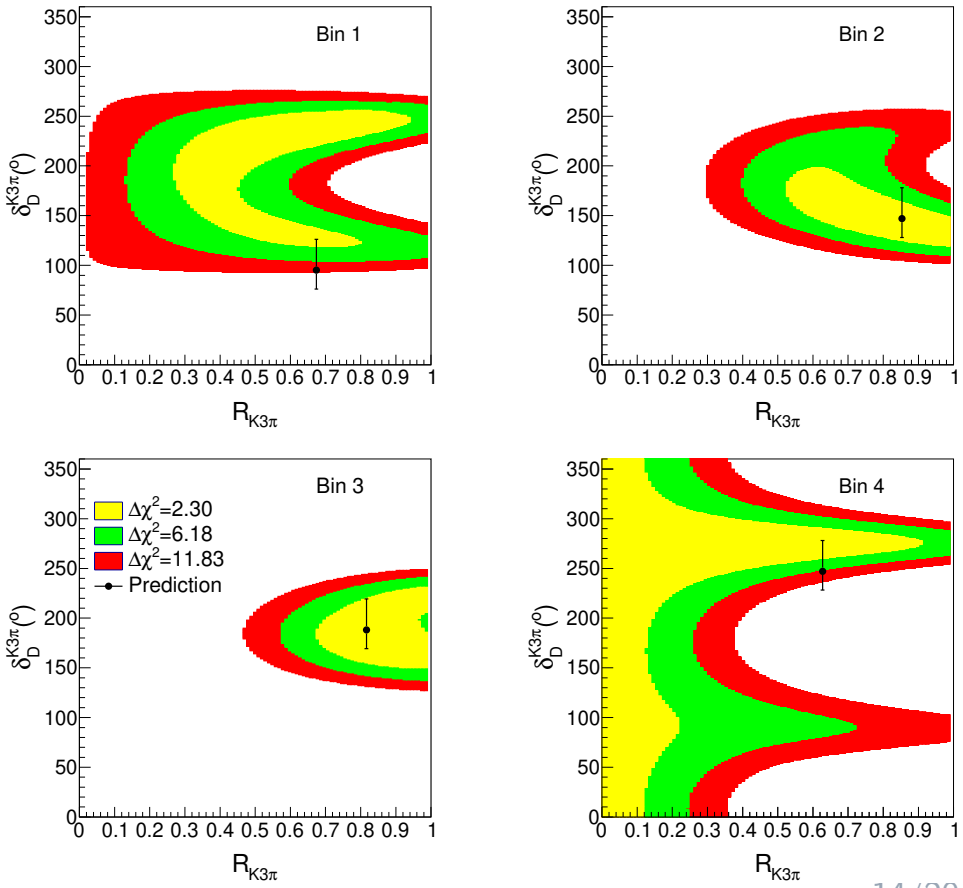
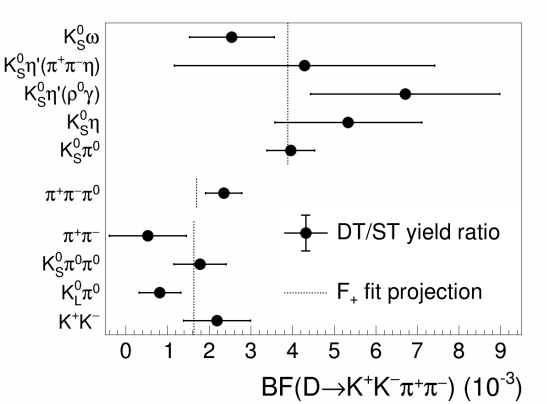
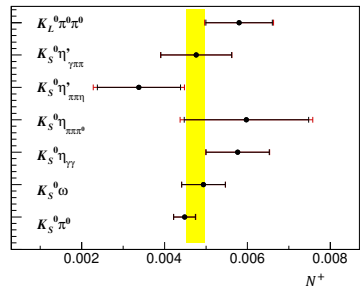


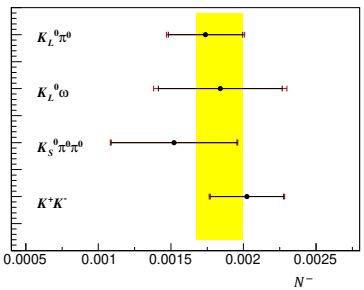
CP content of $D \to 4h$

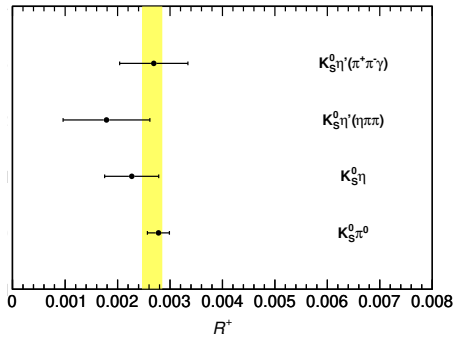
- CP-even fractions F^+ of $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$, and $D^0 \to K^0_S\pi^+\pi^-\pi^0$ recently measured

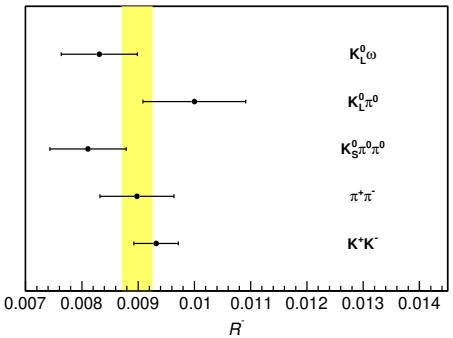
$K^+K^-\pi^+\pi^-$	$\pi^+\pi^-\pi^+\pi^-$	$K^0_S\pi^+\pi^-\pi^0$
PRD 107, 032009 (2023)	PRD 106, 092004 (2022)	arXiv:2305.03975











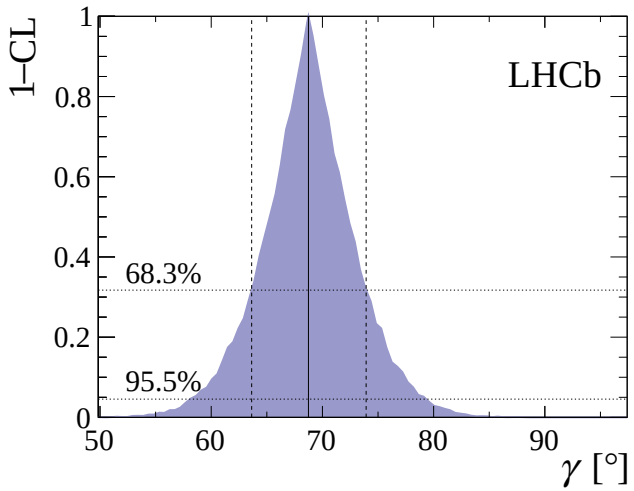
$F_+ = 0.730 \pm 0.037 \pm 0.021$ $F_+ = 0.753 \pm 0.028 \pm 0.010$ $F_+ = 0.235 \pm 0.010 \pm 0.002$

Outline

Impacts on beauty-sector CPV Measurements

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

LHCb, JHEP02 (2021), 169



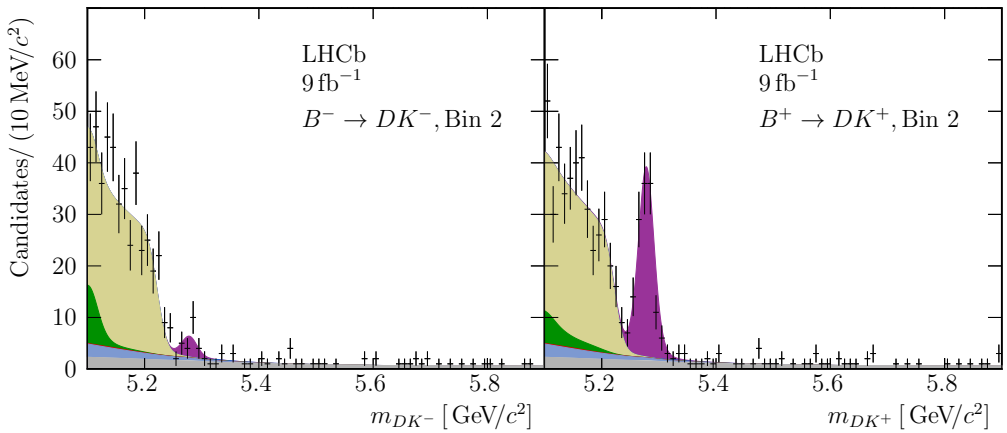
$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^\circ$

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

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

using $K3\pi$ binning

LHCb-PAPER-2022-017



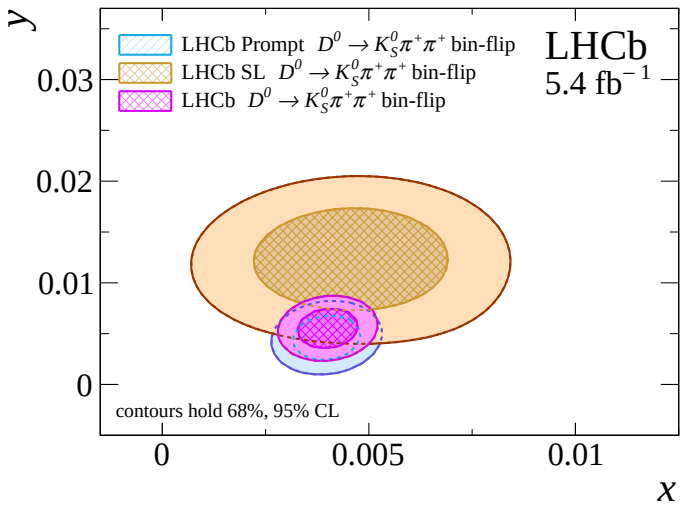
$\gamma = \left(54.8^{+6.0\,+0.6\,+6.7}_{-5.8\,-0.6\,-4.7}\right)^\circ$

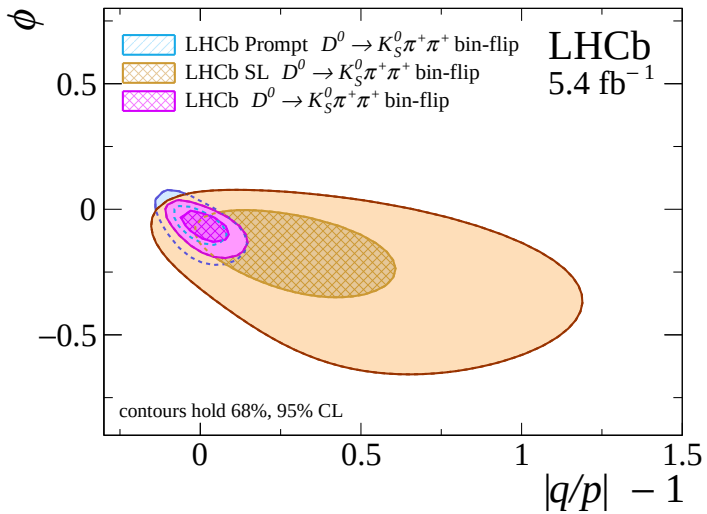
from $\Delta\delta_D^{K3\pi} =^{+6.7}_{-4.7}$!

See talk from M. Tat

Impacts on charm-sector CPV/Mixing Measurements

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





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

See talk from D. Mitzel

Looking to the future...

- LHCb aims to reduce uncertainty on γ and charm CPV parameters by 4x, and Belle II is amassing luminosity
  - Uncertainties on $D^0 \to K^0_S h^+ h^-, K3\pi$, etc. strong phases need to reduce to not dominate uncertainties!
  - More quantum correlated $D\overline{D}$ data allows for refined analysis of $D^0 \to$ multibody decays (e.g. precision of $K3\pi$)
- New $\psi(3770)$ data sets at BESIII:
  - $\sim 9\text{fb}^{-1}$ taken at $\psi(3770)$ in 2022-2023.
  - $\sim 21\text{fb}^{-1}$ at $\psi(3770)$ expected by the end of 2024.
- Super τ-Charm Factory (STCF) plans for ~ 100x the sample size of BESIII: see CDR at arXiv:2303.15790.

Conclusions

- Model-independent measurements of D^0 strong phases are necessary inputs to beauty and charm CPV measurements
- D^0 inputs currently contribute sub-dominant uncertainties to γ and charm CPV parameters, but further precision is needed for LHCb's Run 3 and data from Belle II
- Significantly more data collection underway @ $\psi(3770)$ in the near future @ BESIII, which will provide necessary precision on previous results and prospects for novel CPV analyses of multibody D^0 decay modes
- More detail on future prospects in BESIII white paper: Chin. Phys. C 44, 040001 (2020)

Thanks for your attention!