Charm mixing and *CP* violation at BESIII

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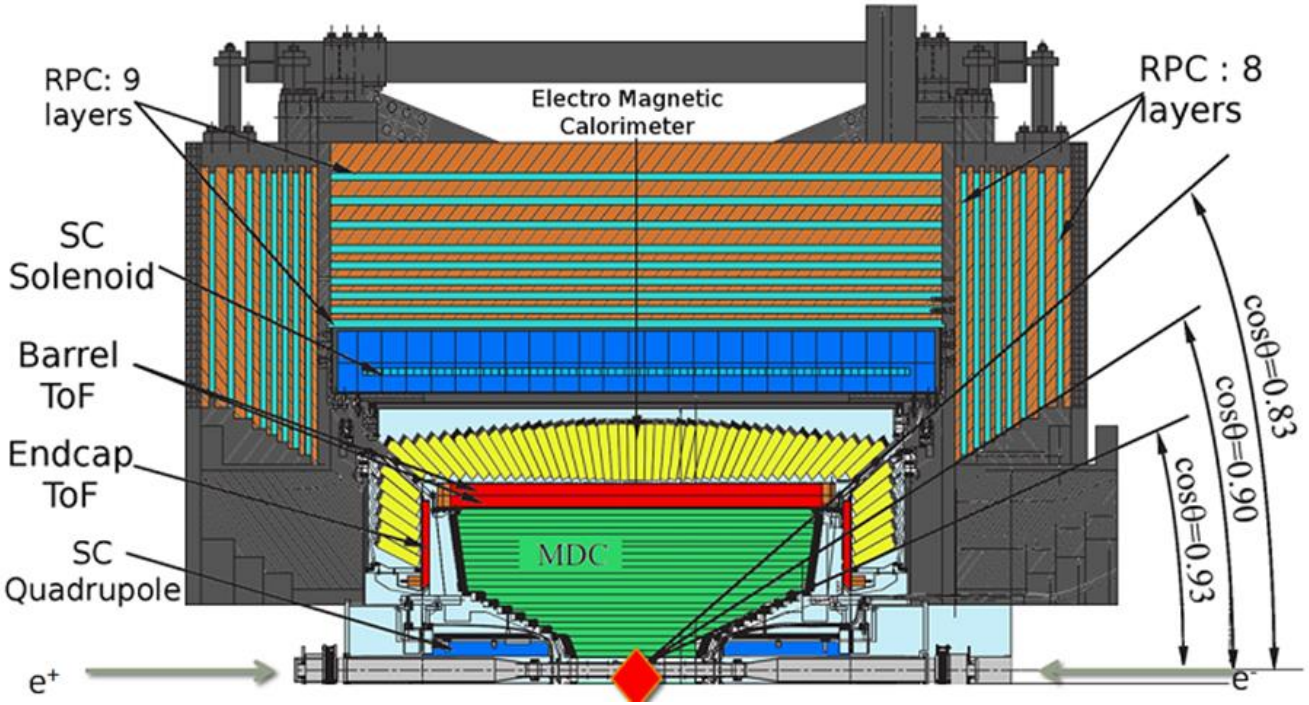
Outline

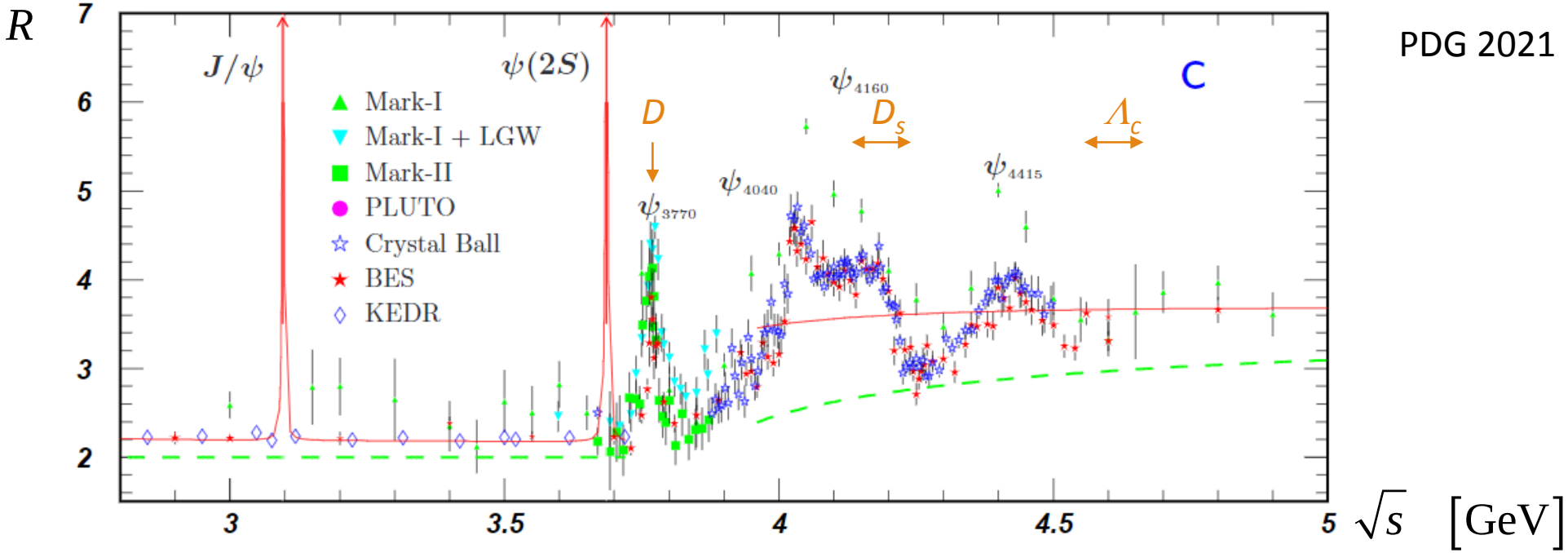
- BESIII
- The data samples and double-tagging
- Recent results
  - Direct *CP* violation
  - **Strong phases**
- Outlook

e^+e^- collisions at BEPCII between $\sqrt{s} = 2.0 - 4.7$ GeV

BESIII detector - NIM A **614**, 345 (2010)



BESIII charm data sets



PDG 2021

$\sqrt{s}$ (GeV)	Dominant processes of interest	Integrated luminosity (fb^{-1})
3.773	$\boldsymbol{e^+e^- \to \psi(3770) \to D^0\bar{D}^0/D^+D^-}$	**2.93**
4.178-4.226	$e^+e^- \to D_s^+D_s^{*-}, D_s^{*-} \to D_s^-\gamma$	6.32
4.60-4.70	$e^+e^- \to \Lambda_c\bar{\Lambda}_c$	4.48

The “single vs. double-tag” techniques

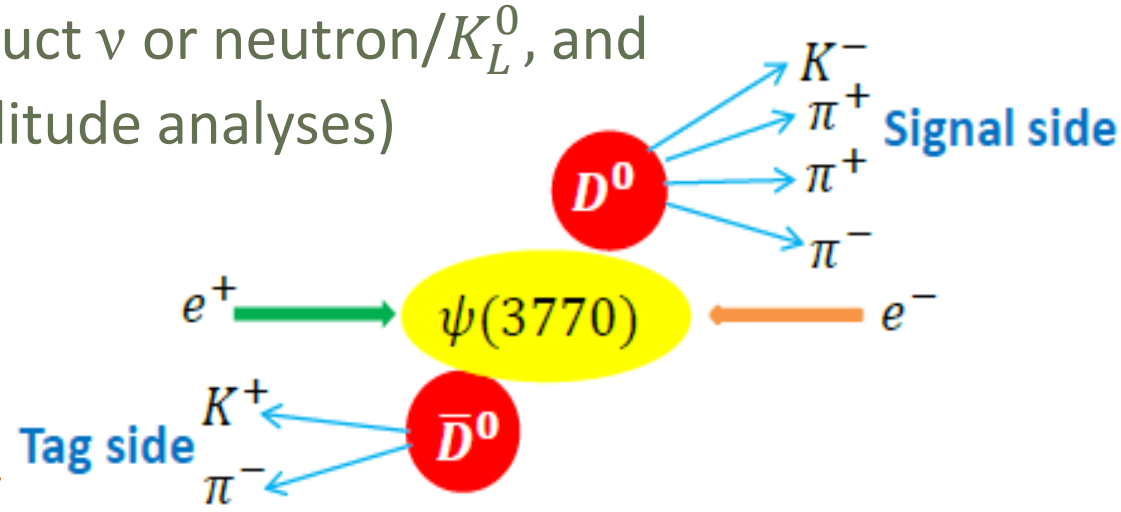
- Threshold production means that **no other** particles are produced along with the *DD*, *DD** and $\Lambda\Lambda$ pairs
- Full event reconstruction “double tag” possible

✓ Advantages

1. absolute branching fractions
2. full kinematic constraint to reconstruct ν or neutron/K_L^0, and
3. low backgrounds (i.e. good for amplitude analyses)

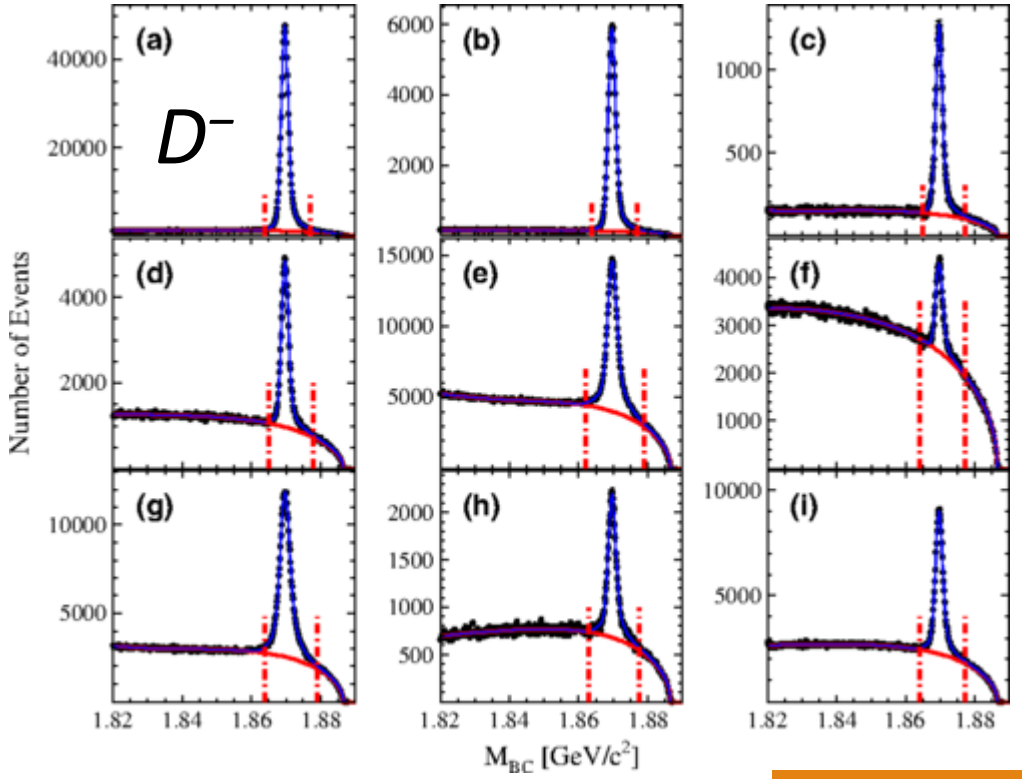
✗ Disadvantages

1. reduced reconstruction efficiency but still O(10%) c.f. FEI at Belle II
2. time-integrated measurements only



Single tag samples

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - \left|\vec{\mathbf{p}}_D\right|^2}$$



$(a)\ K^+\pi^-\pi^-$

$(b)\ K_S^0\pi^-$

$(c)\ K_S^0K^-$

$(d)\ K^+K^-\pi^-$

$(e)\ K^+\pi^-\pi^-\pi^0$

$(f)\ \pi^+\pi^-\pi^-$

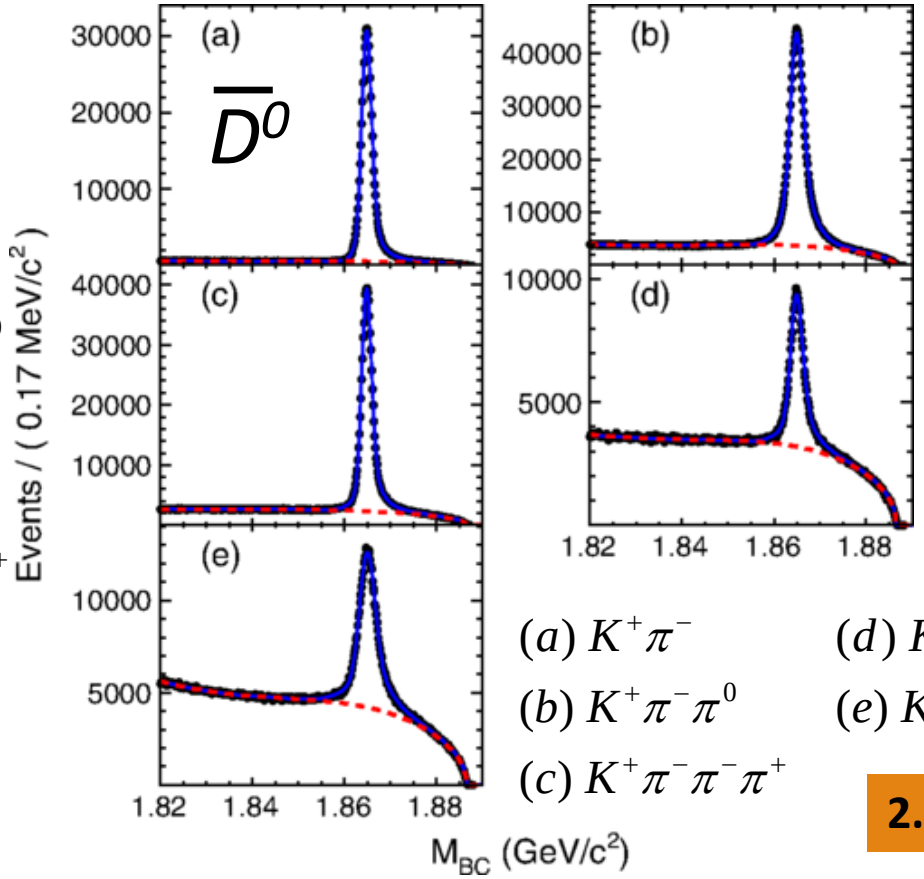
$(g)\ K_S^0\pi^-\pi^0$

$(h)\ K^+\pi^-\pi^-\pi^+$

$(i)\ K_S^0\pi^-\pi^+\pi^-$

1.7 million

Phys. Rev. D **89** (2014) 051104(R)



$(a)\ K^+\pi^-$

$(b)\ K^+\pi^-\pi^0$

$(c)\ K^+\pi^-\pi^-\pi^+$

$(d)\ K^+\pi^-\pi^-\pi^+\pi^0$

$(e)\ K^+\pi^-\pi^0\pi^0$

2.8 million

Phys. Rev. D **92** (2015) 072012

Direct CP violation at BESIII

- Direct CP violation observed at 10^{-3} level in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$
  - Sample of millions of flavour tagged events used [LHCb, PRL **122** (2019) 211803]
- In comparison **9300** flavour tagged $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ reconstructed from the BESIII $\psi(3770)$ sample - JHEP **05** (2021) 164
  - **Not competitive** unless there is a very big surprise in a specific decay
- Surprises happen e.g. doubly Cabibbo suppressed branching fraction for $D^+ \to K^+\pi^+\pi^-\pi^0$ [PRL **125** (2020) 14180]

$$B(D^+ \to K^+\pi^+\pi^-\pi^0) = (6.28 \pm 0.52) \times \tan^4\theta_C \times B(D^+ \to K^-\pi^+\pi^+\pi^0)$$

  - A_{CP} = -0.04 ± 0.06 (stat) $\pm$ 0.01 (syst)
- PRL **124** (2020) 241803: 14 branching fractions of 3- and 4-body D decays with an η
  - No significant A_{CP} observed - measured with 0.01 to 0.05 precision

So where does BESIII contribute?

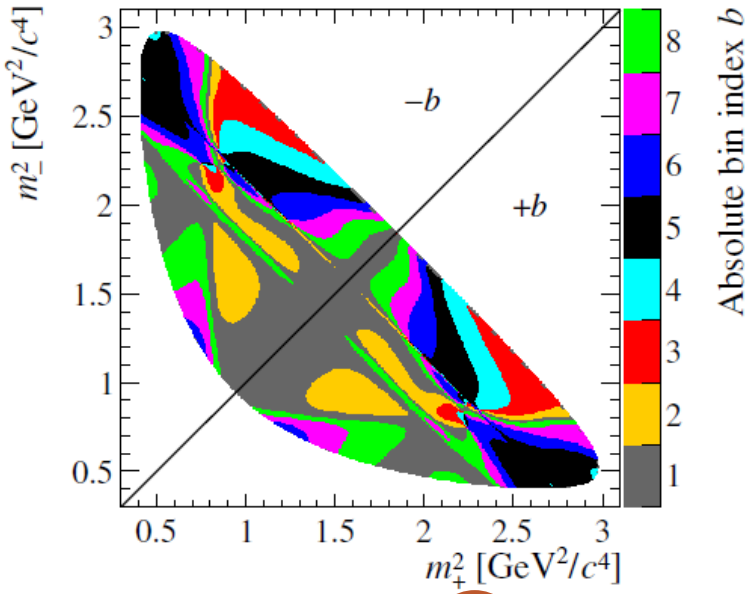
The major result in charm physics this year is the determination of the mass difference (x) between the D^0 eigenstates

- LHCb PRL **127** (2020) 111801

Measurement is decay-time (t) dependent in bins of the $D^0 \to K_S^0 \pi^+ \pi^-$ phase-space

- Independent of resolution, efficiency and amplitude modelling – A. di Canto et al. PRD **99** (2019) 111801

No direct CP



Ratio of D^0 (+) or $\bar{D}^0$ (–) events between b and $-b$ in j-th t bin

$$R_{bj}^{\pm} \approx \frac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}[X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t^2 \rangle_j}{4} |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}[X_b(z_{CP} \pm \Delta z)]}$$

$$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)$$

$$\left[|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle,\ x = (m_1 - m_2)/2\Gamma,\ y = (\Gamma_1 - \Gamma_2)/2\Gamma \right]$$

X_b is the amplitude-weighted strong-phase difference between bins b and –b – **external input from BESIII**

So where does BESIII contribute?

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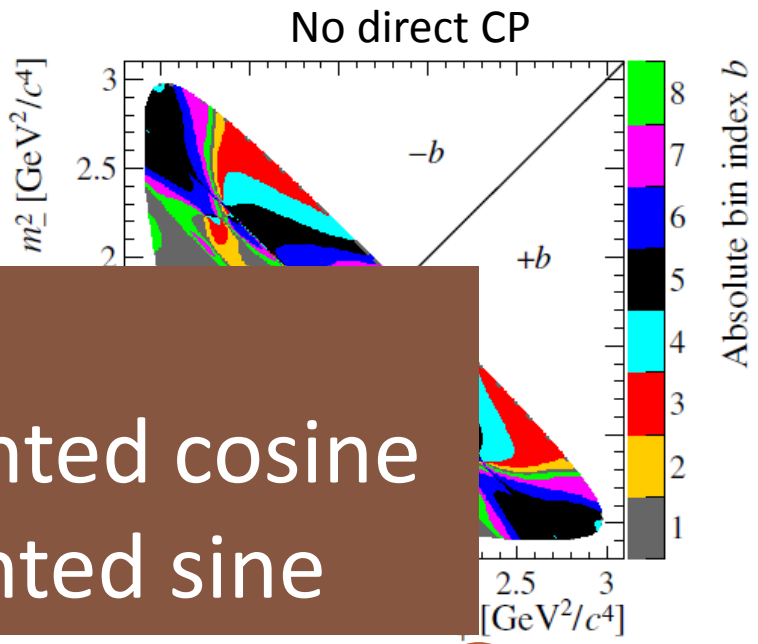
- LHCb PRL 1

Measureme
of the D^0 –

- Independe
modelling -



What we actually measure

$c_i = c_b \equiv \mathrm{Re}[X_b]$=amplitude-weighted cosine

$s_i = s_b \equiv \mathrm{Im}[X_b]$=amplitude-weighted sine

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Quantum correlated measurements

At the ψ (3770) neutral *D* pairs produced in quantum-entangled state:

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D^0\bar{D}^0 - \bar{D}^0 D^0\right]$$

$$e^+e^- \to \psi'' \to \tfrac{1}{\sqrt{2}}\left[D_{CP-}D_{CP+} - D_{CP+}D_{CP-}\right]$$

$$\text{where } D_{CP\pm} = \tfrac{1}{\sqrt{2}}\left[D^0 \pm \bar{D}^0\right]$$

Reconstruct one $D \to K_s\pi\pi$ and the other in a *CP* eigenstate such as KK, $K_s\pi^0$ then CP of the other is fixed

$$CP \pm \text{tagged yield in bin } i \propto K_i + K_{-i} \pm 2c_i\sqrt{K_iK_{-i}}$$

fractional D^0 yield in each bin

Also tag with $K_s\pi\pi$ tag

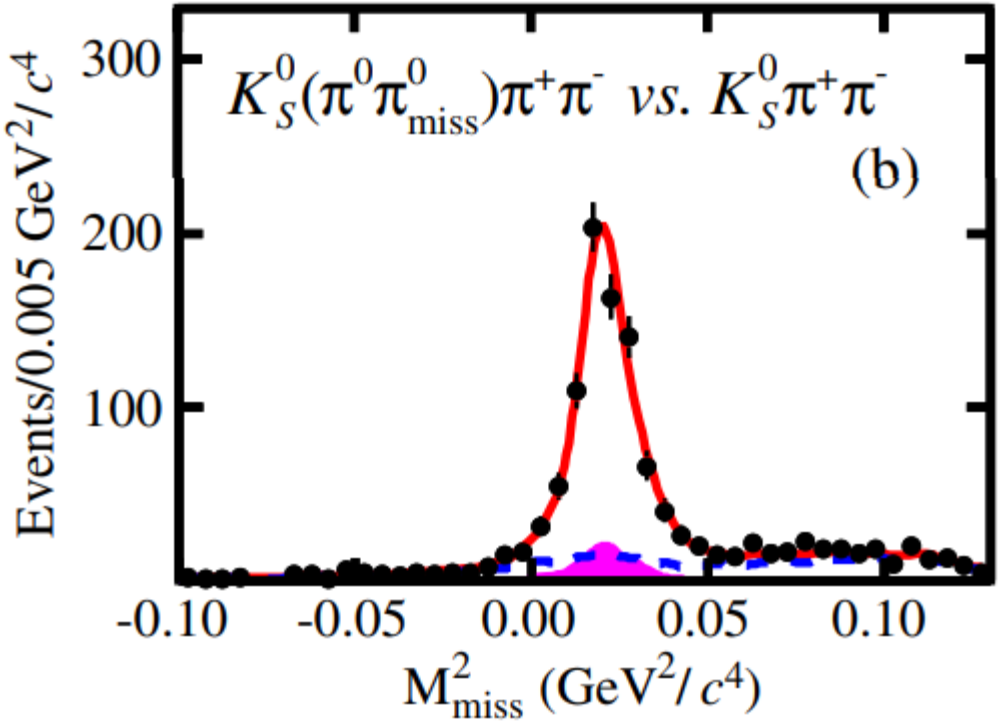
$$\text{Yield in bin } i \text{ tagged by bin } j \propto K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}\left(c_ic_j + s_is_j\right)$$

Yields

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

2.93 fb^{-1} of data compared with 0.82 fb^{-1} for CLEO – PRD **82** (2010) 112006

New final states: CP even $\pi^+\pi^-\pi^0$ and $K_S^0(\pi^0\pi^0)\pi^+\pi^-$ where one π^0 is not reconstructed



	$N_{DT}^{K_S^0\pi^+\pi^-}$	$N_{DT}^{K_L^0\pi^+\pi^-}$
CP-even tags		
K^+K^-	443 ± 22	1289 ± 41
$\pi^+\pi^-$	184 ± 14	531 ± 28
$K_S^0\pi^0\pi^0$	198 ± 16	612 ± 35
$\pi^+\pi^-\pi^0$	790 ± 31	2571 ± 74
$K_L^0\pi^0$	913 ± 41	
CP-odd tags		
$K_S^0\pi^0$	643 ± 26	861 ± 46
$K_S^0\eta_{\gamma\gamma}$	89 ± 10	105 ± 15
$K_S^0\eta_{\pi^+\pi^-\pi^0}$	23 ± 5	40 ± 9
$K_S^0\omega$	245 ± 17	321 ± 25
$K_S^0\eta'_{\pi^+\pi^-\eta}$	24 ± 6	38 ± 8
$K_S^0\eta'_{\gamma\pi^+\pi^-}$	81 ± 10	120 ± 14
$K_L^0\pi^0\pi^0$	620 ± 32	
Mixed-CP tags		
$K_S^0\pi^+\pi^-$	899 ± 31	3438 ± 72
$K_S^0\pi^+\pi^-_{miss}$	224 ± 17	
$K_S^0(\pi^0\pi^0_{miss})\pi^+\pi^-$	710 ± 34	

Results

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

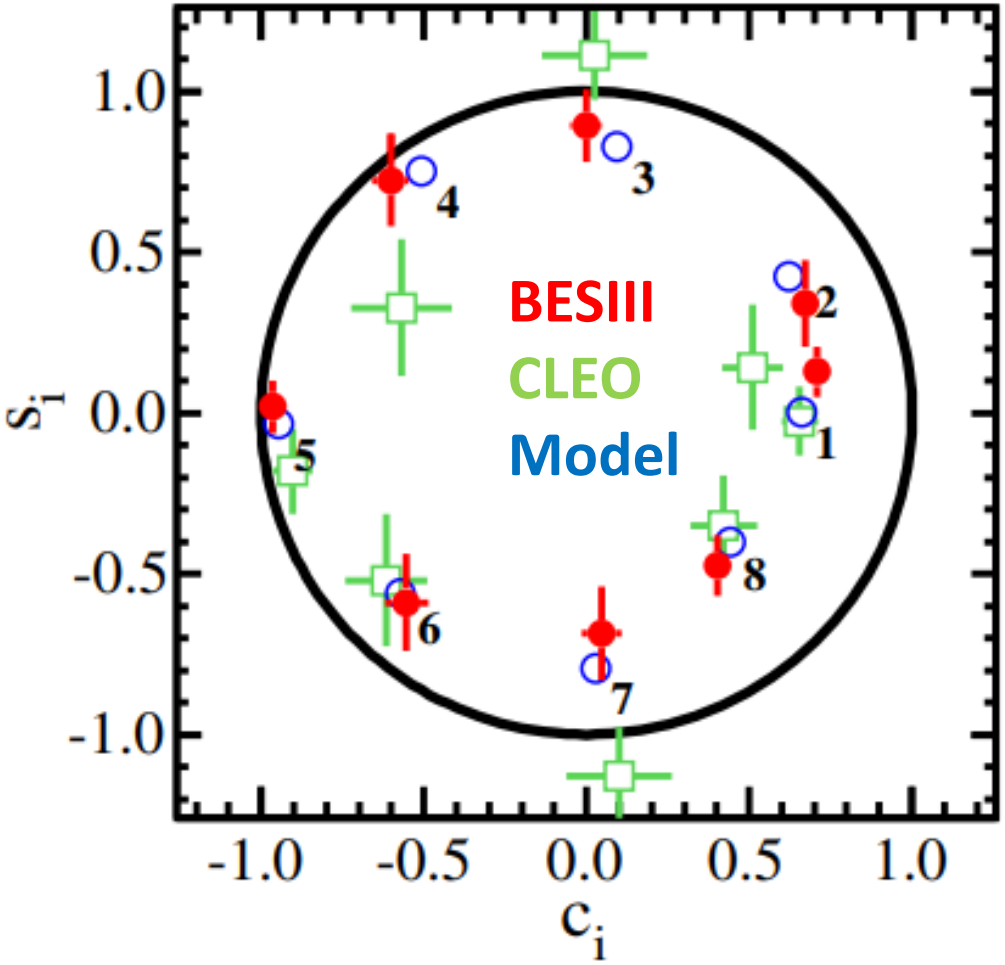
Three different binning schemes – some for γ measurements – see Xinyu Shan WG5

Use equal strong-phase binning - $\pi/4$ intervals

Fit binned quantum-correlated yields to extract c_i and s_i

	c_i	s_i
1	$0.708 \pm 0.020 \pm 0.009$	$0.128 \pm 0.076 \pm 0.017$
2	$0.671 \pm 0.035 \pm 0.016$	$0.341 \pm 0.134 \pm 0.015$
3	$0.001 \pm 0.047 \pm 0.019$	$0.893 \pm 0.112 \pm 0.020$
4	$-0.602 \pm 0.053 \pm 0.017$	$0.723 \pm 0.143 \pm 0.022$
5	$-0.965 \pm 0.019 \pm 0.013$	$0.020 \pm 0.081 \pm 0.009$
6	$-0.554 \pm 0.062 \pm 0.024$	$-0.589 \pm 0.147 \pm 0.031$
7	$0.046 \pm 0.057 \pm 0.023$	$-0.686 \pm 0.143 \pm 0.028$
8	$0.403 \pm 0.036 \pm 0.017$	$-0.474 \pm 0.091 \pm 0.027$

Statistically dominated



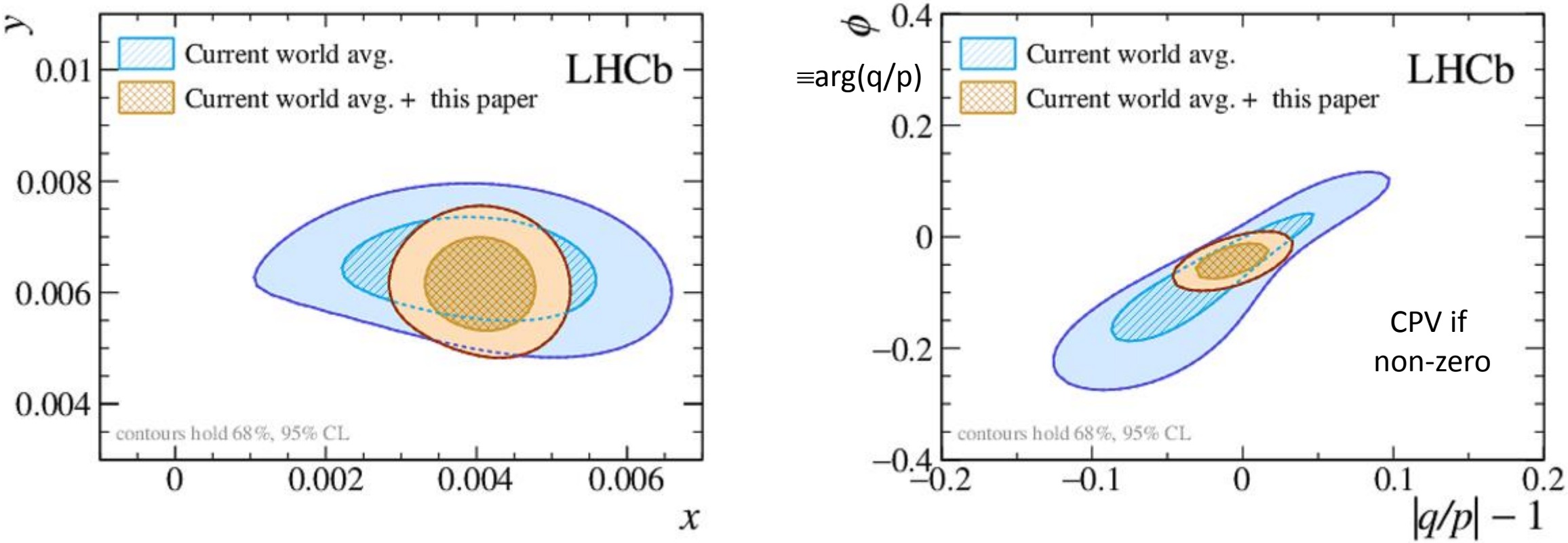
Systematic uncertainties - eye to the future

Uncertainty	c_5
K_i and K_i'	0.005
ST yields	0.004
MC statistics	0.001
DT peaking-background subtraction	0.005
DT yields	0.001
Momentum resolution	0.010
$D^0\bar{D}^0$ mixing	0.000
Total systematic	0.013
Statistical plus $K_L^0\pi^+\pi^-$ model	0.019
$K_L^0\pi^+\pi^-$ model alone	0.007
Total	0.023

1. Ignoring asymmetric bin-to-bin migration
   - can be mitigated by unfolding in the future
2. To leverage $D\to K_L\pi\pi$ we have to make assumptions related to the model and the size CF to DCS interference induced difference between $D\to K_L\pi\pi$ and $D\to K_S\pi\pi$
   - implemented a constraint hence appears in statistical uncertainty
   - potentially learn more from studying the $D\to K_L\pi\pi$ amplitude model
   - more weight to $D\to K_S\pi\pi$
3. Better understanding with more data

LHCb PRL **127** (2020) 111801

LHCb mixing and CP violation results



Systematic uncertainty related to c_i and s_i on these measurements are between 50% and 25% of the statistical uncertainty – will be limiting with LHCb upgrade data samples

Other BESIII measurements I

Other self-conjugate decays can be used in the same way for mixing as $D \to K_S \pi\pi$ and indirect CPV:

- $D \to K_S KK$ [PRD **102** (2020) 052008], $D \to K_S \pi\pi\pi^0$, $D \to 4\pi$ *and* $D \to 2K2\pi$ [in preparation]

<u>Wrong-sign mixing measurements</u>

In $D \to K\pi$ the measurements are $x' = x \cos \delta_{K\pi}$ and $y' = y \sin \delta_{K\pi}$ where

$$A_{DCS} / A_{CF} = (-) r_D \exp - i\delta_{K\pi}$$

BESIII measured $\cos \delta_{K\pi} = 1.02 \pm 0.13$ [PLB **734** (2014) 227] with eight CP tags

Many more tags in use now, including $D \to K_S \pi\pi$ that allows $\sin \delta_{K\pi}$ thus $\delta_{K\pi}$ [in preparation]

Power of better $\delta_{K\pi}$ knowledge shown in recent preprint [LHCb, arXiv:2110.02350] where y precision improved by 50% using $\delta_{K\pi}$ information from *B* decay

Other BESIII measurements II

$D \to K\pi\pi^0$ (14.4%) and $D \to K3\pi$ (8.2%) have larger branching fractions compared to $D \to K\pi$ (3.9%)

So despite the more difficult reconstruction and interpretation power to learn more about mixing

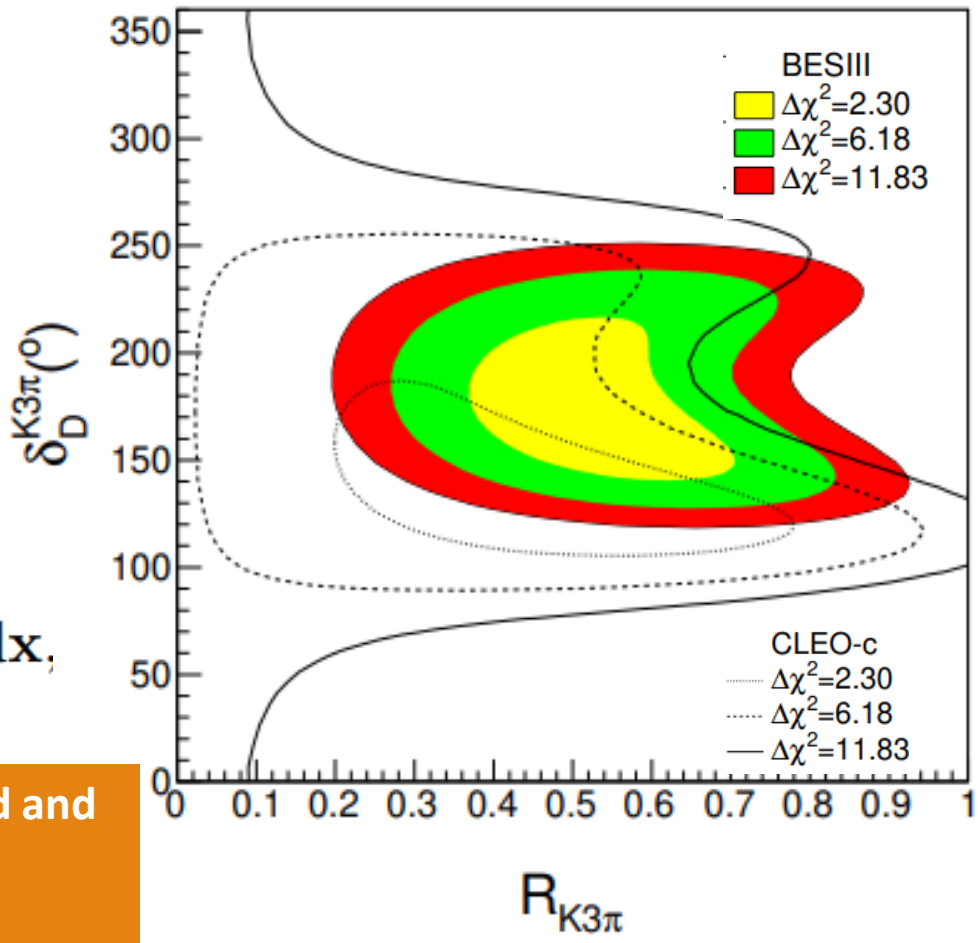
- $K\pi\pi^0$ [BaBar, PRL 103 (2009) 211801]
- $K3\pi$ [LHCb, PRL 116 (2016) 241801] – CLEO-c inputs

Improved measurements of the relevant parameters

$$R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^\star(\mathbf{x})\mathcal{A}_{\bar{S}}(\mathbf{x})\mathrm{d}\mathbf{x}}{A_S A_{\bar{S}}} \qquad A_S^2 = \int |\mathcal{A}_S(\mathbf{x})|^2 \mathrm{d}\mathbf{x},$$

coherence factor
0 (a lot of interference)
1 (quasi two-body)

JHEP 05 (2021) 164 with S=K3π (integrated and binned) and S=Kππ⁰ (integrated) – ready to use in new measurements



Conclusion and looking forward

Model-independent strong-phase parameters measured by BESIII essential for the improved determination of mixing and indirect CP violation parameters

Unique samples of threshold D, D_s and Λ decays can be searched for direct CP surprises, particularly in multibody modes with neutrals

Future Physics Programme at BESIII - Chin. Phys. C 44, 040001 (2020)

- 20 fb^{-1} at $\psi(3770)$ – run underway prior to BEPC upgrade in 2023

Improving c_i and s_i for charm mixing and indirect CP violation one of the primary motivators

Questions to the community

- binnings driven by γ measurements but would alternatives help charm measurements?
- are there modes we should be looking more closely at?