Strong-phase inputs for CPV measurements at LHCb and Belle II

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HQL2021, Warwick, 14/09/2021

Outline

Strong-phase inputs for γ measurement

Strong-phase measurements at BESIII

- $D \to K\pi\pi\pi/K\pi\pi^0$ [JHEP 05 (2021) 164]
- $D \to K\pi$ [PLB 05, 071 (2014)]
- $D \to K^0_S h^+ h^-$ [PRD 101 (2020) 112002; PRD 102 (2020) 052008]

Strong-phase inputs for indirect charm CPV

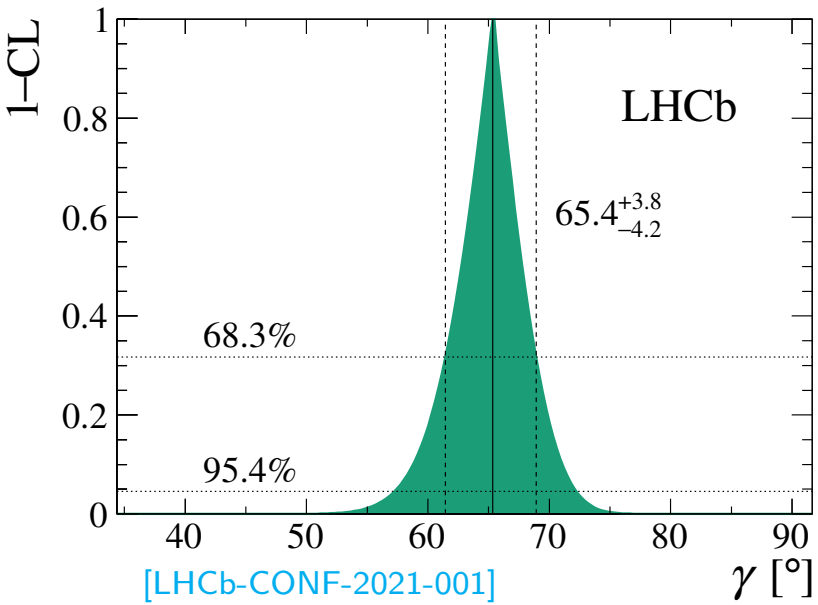
Future prospects at BESIII

Summary

Strong-phase inputs for γ measurement

- CKM matrix, only source of CP violation in the SM
- CKM angles are large ($\mathcal{O}(1)$) in the b sector $\Rightarrow$ direct CP violation

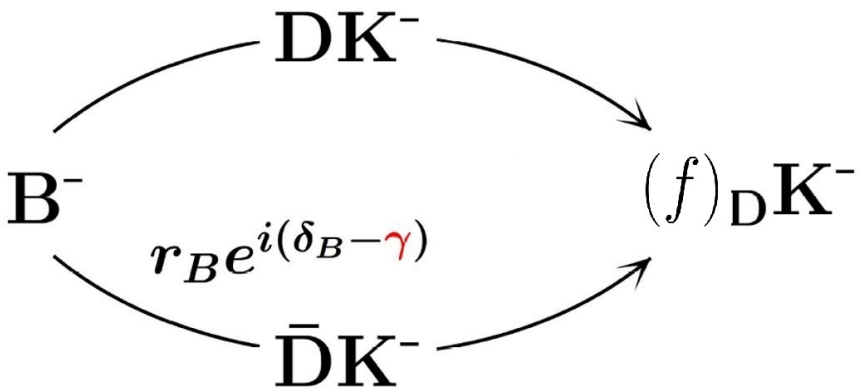
LHCb combination



[LHCb-CONF-2021-001]

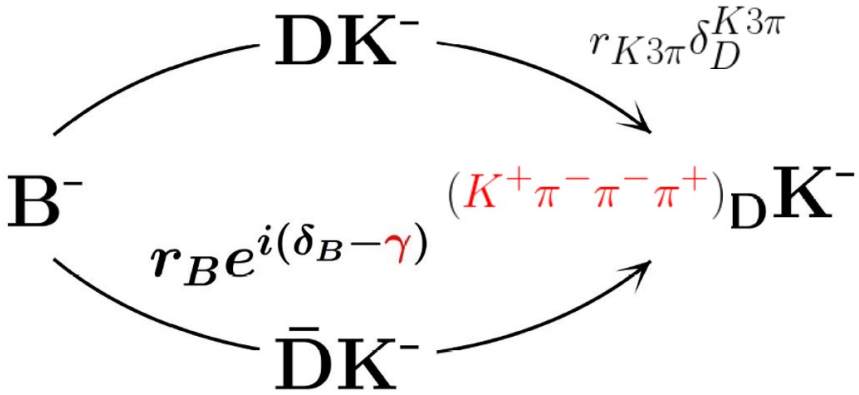
- Determined in tree-level B decays, eg. $B \to DK$
- No interference from NP effects
- Large experimental uncertainties
  - Statistics, systematics
  - External inputs

Strong-phase inputs for γ measurement



- Measurement of the interference between the two paths depends on the B and D decay parameters $\Rightarrow$ External inputs of strong phase and associated parameters in D decays
- Allow extracting γ using different D decays:
  - DCS decays (eg. $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$): "ADS" [PRL 78 (1997) 3257; PRD 63 (2001) 036005] $\Rightarrow \delta_D$, R_f
  - Self-conjugate decays (eg. $K^0_S h^+ h^-$): "BPGGSZ" [PRD 68 (2003) 054018; PRD 67 (2003) 071301; A. Bondar] $\Rightarrow c_i$, s_i
  - (Quasi-)CP eigenstates (eg. h^+h^-): "GLW" [PLB 265 (1991) 172; PLB 253 (1991) 483] $\Rightarrow$ CP fraction F^+ ; Others...

ADS method with multi-body D decays



- Both DCS and CF processes contribute to $B^{\mp} \to (K^{\pm}3\pi)_D K^{\mp}$
- Phase-space integrated decay rate

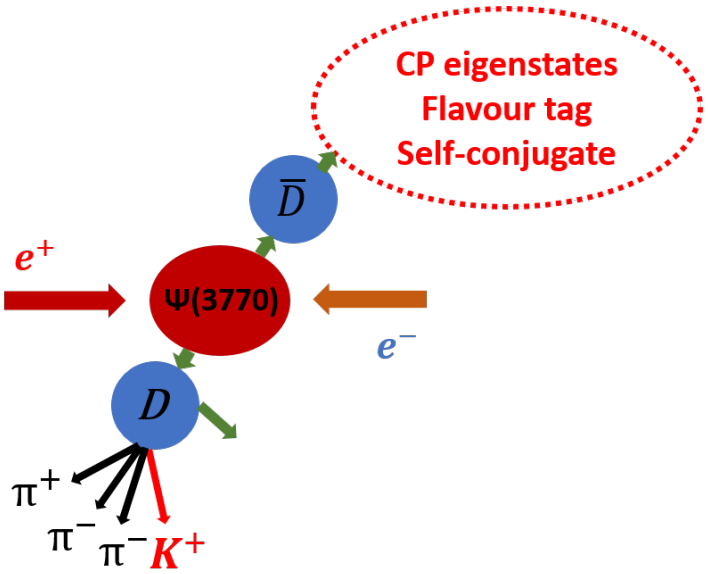
$$\Gamma(B^{\mp} \to (K^{\pm}3\pi)_D K^{\mp}) \propto r_{K3\pi}^2 + r_B^2 + 2r_B R_{K3\pi} r_{K3\pi} \cos(\delta_B \pm \gamma - \delta_D^{K3\pi})$$

- $R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^*(\mathbf{x})\mathcal{A}_{\bar{S}}(\mathbf{x})\mathrm{d}\mathbf{x}}{A_S A_{\bar{S}}}$, coherence factor and strong phase
- R indicates the intermediate resonances, $0 < R < 1$ for $K3\pi$ and $K\pi\pi^0$, $R = 1$ for $K\pi$

Strong-phase measurement with QC $D\bar{D}$

- Quantum correlated C-odd $D\bar{D}$ produced at BESIII

$$e^+e^- \to \psi(3770) \to D\bar{D}$$



- $\int dt\mathcal{L} = 2.93\ \mathrm{fb}^{-1}$
- 10597,000 neutral $D\bar{D}$
  [CPC 42 (2018) 083001]
- "Double-tag" method: reconstruct both $D\&\bar{D}$
- $M_{\mathrm{BC}} = \sqrt{\mathrm{E}^2_{\mathrm{beam}}/c^4 - |\mathbf{p}^2_{\bar{D}}|/c^2}$
- $\Delta\mathrm{E} = \mathrm{E}_D - \mathrm{E}_{\mathrm{beam}}$

- Compare the double tag yields w/w.o. quantum correlation

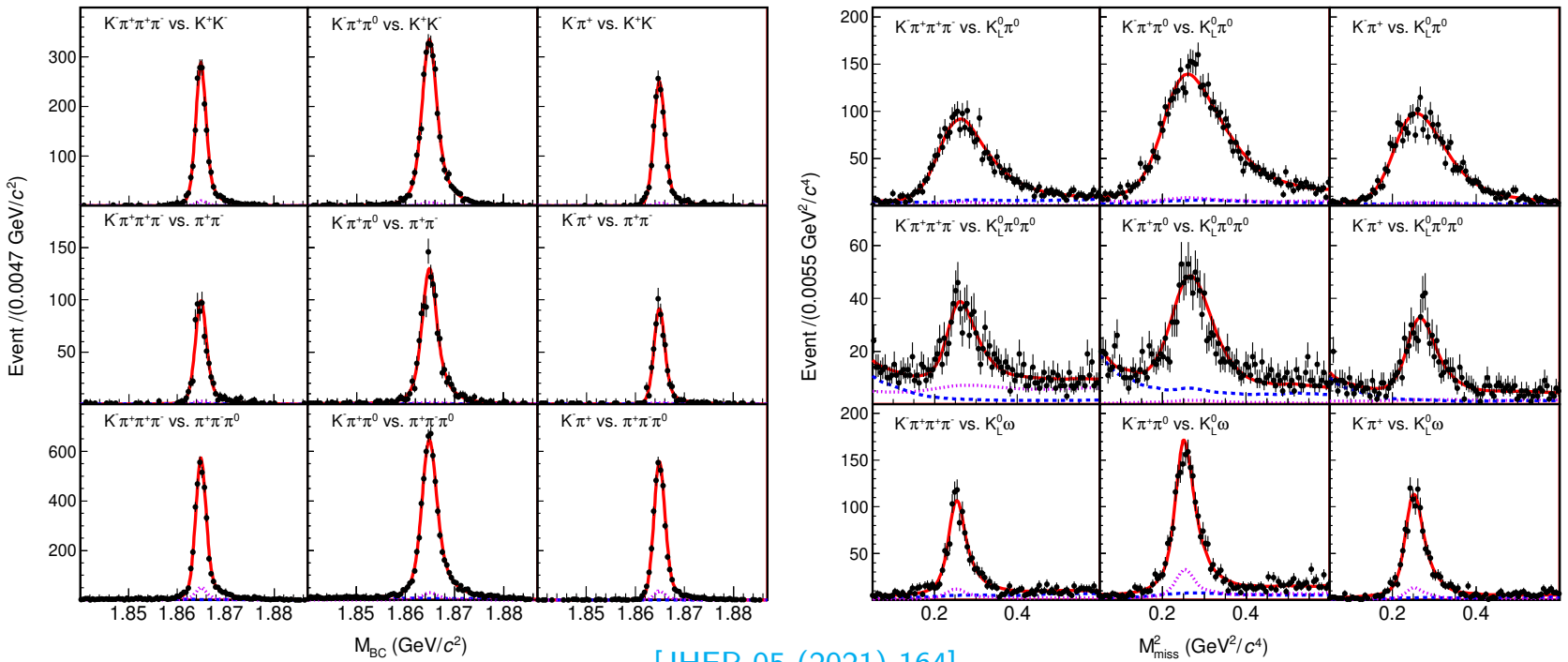
$$\Gamma_{\mathrm{QC}}(S|T) = \Gamma_0 A_S^2 A_T^2 \left[(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos\left(\delta_D^T - \delta_D^S\right)\right]$$
$$\Gamma(ST) = \Gamma_0 A_S^2 A_T^2 \left[(r_D^S)^2 + (r_D^T)^2\right]$$

Double tag events

- Example fits to double tag events

Fully reconstructed CP modes

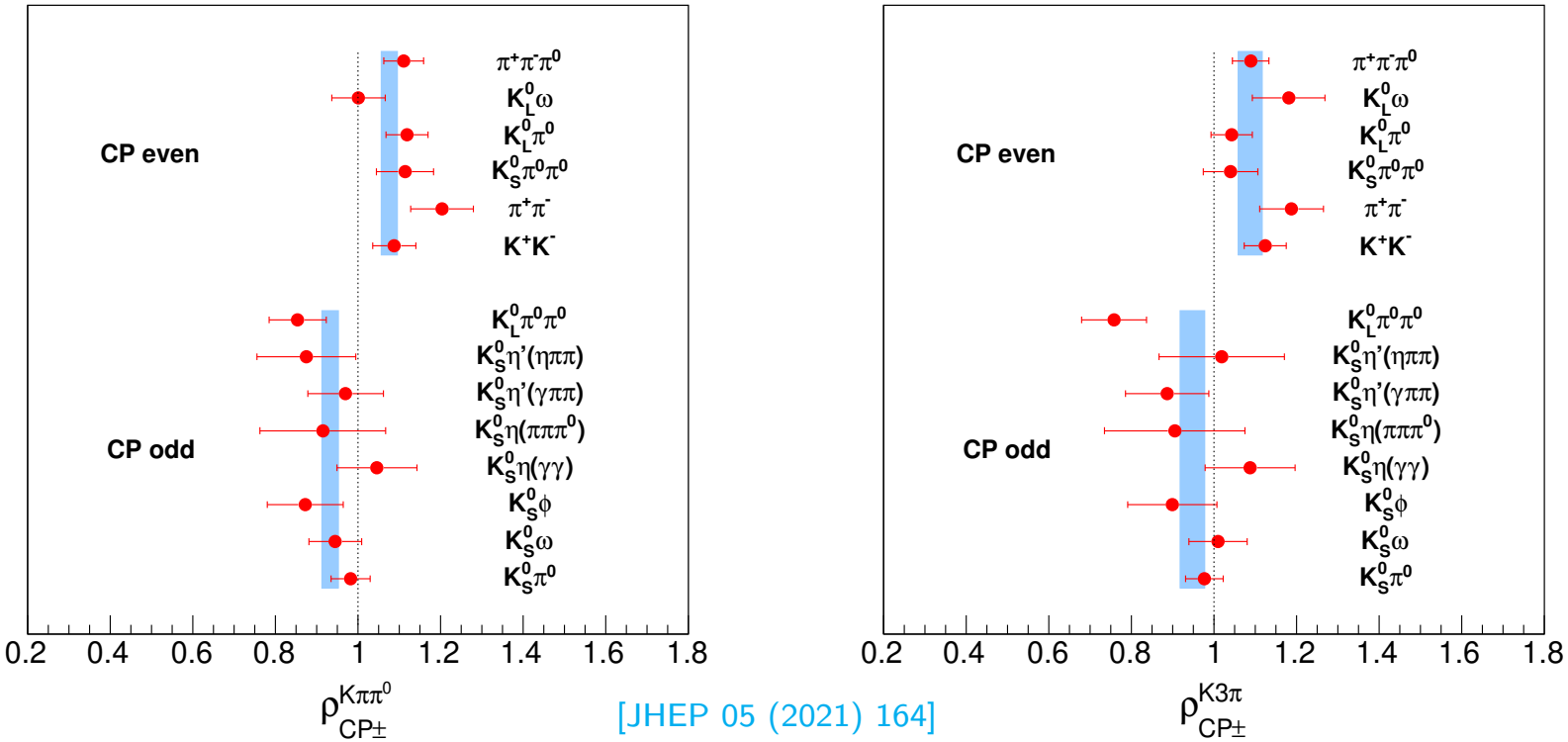
K^0_L modes



[JHEP 05 (2021) 164]

- Clean background in fully reconstructed events
- K^0_L can be reconstructed with the missing mass $M^2_{\rm miss}$ recoiled against the tagged D and particles in the signal side

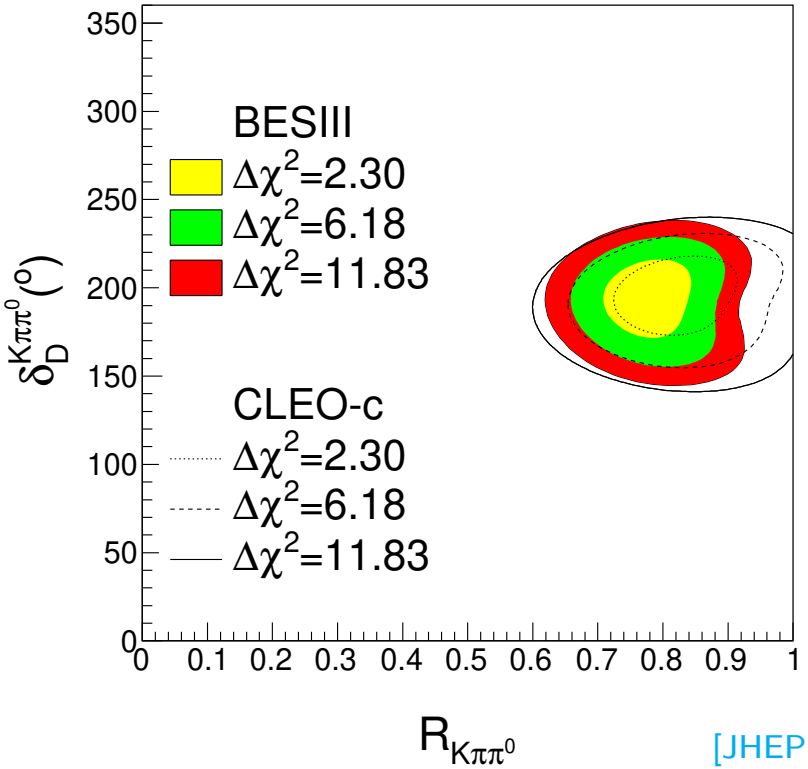
CP observables



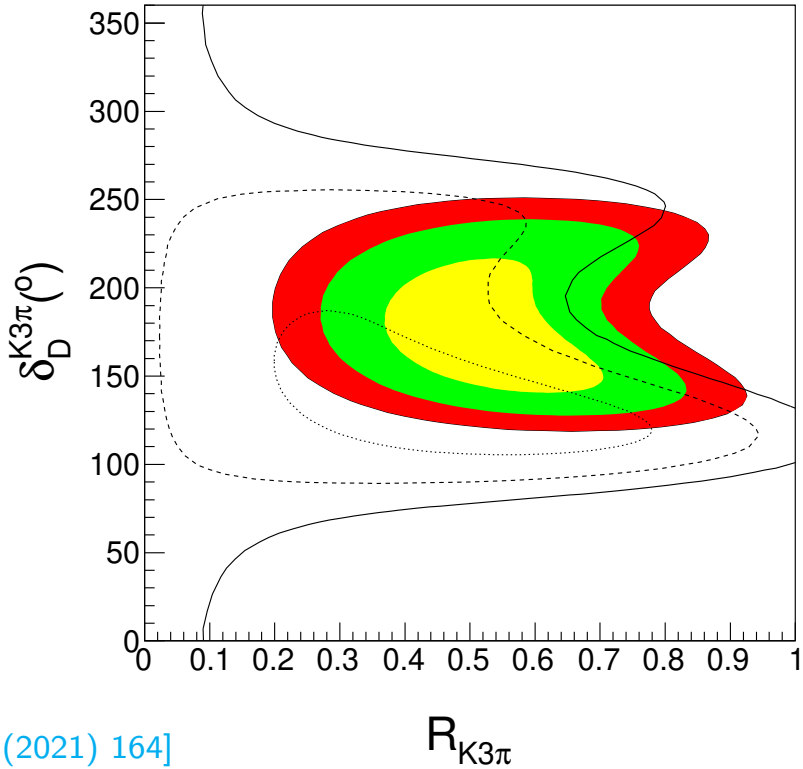
[JHEP 05 (2021) 164]

- ρ_{CP}, the ratio of background-subtracted and efficiency-corrected yields and expectations w.o. QC, differ from 1
- Other tags also contribute: Like-sign flavour tags (eg. $K^+3\pi$ vs $K^+3\pi$); $K^0_S\pi^+\pi^-$ tag (phase variations over Dalitz plane)

Strong-phase difference and coherence factor



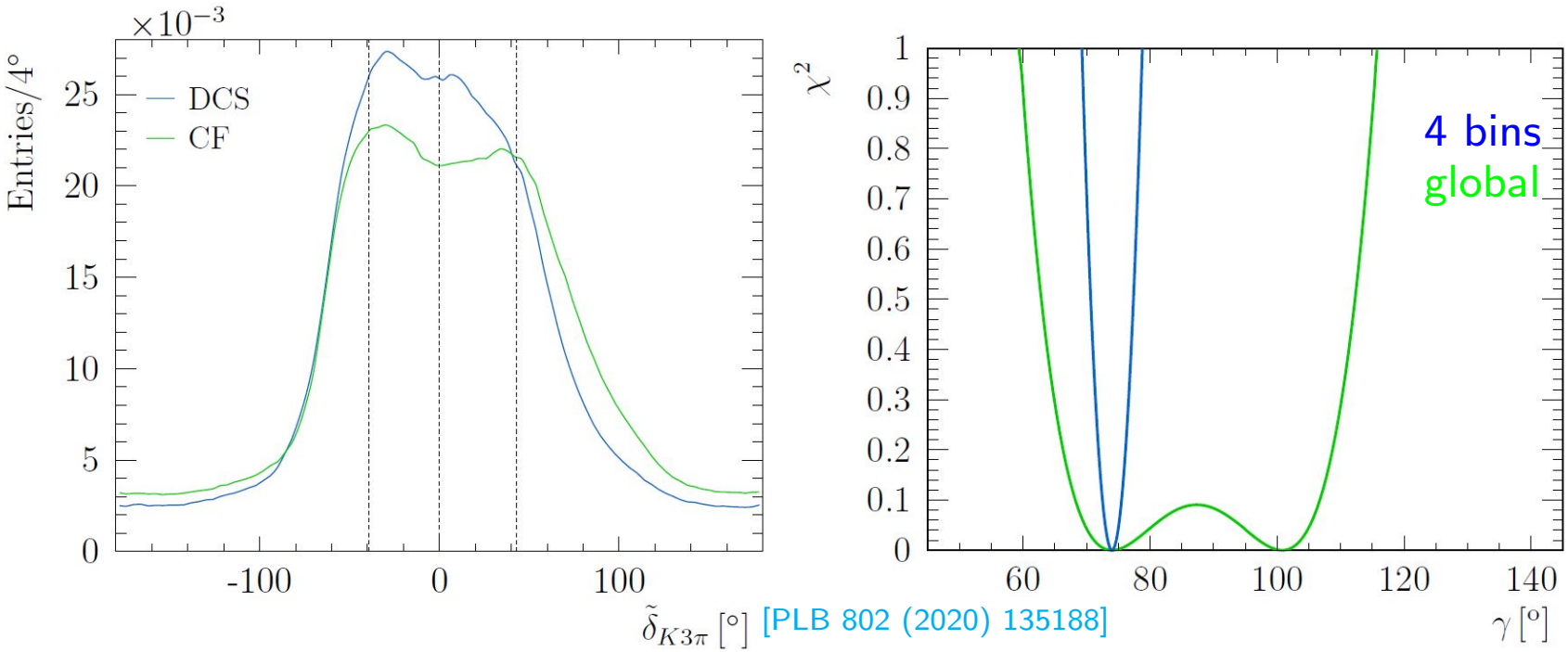
[JHEP 05 (2021) 164]



- Average δ_D and R in the whole phase space in $K3\pi$ and $K\pi\pi^0$
- Significant improvement compared to CLEO-c results [PLB 757 (2016) 520]

Binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$

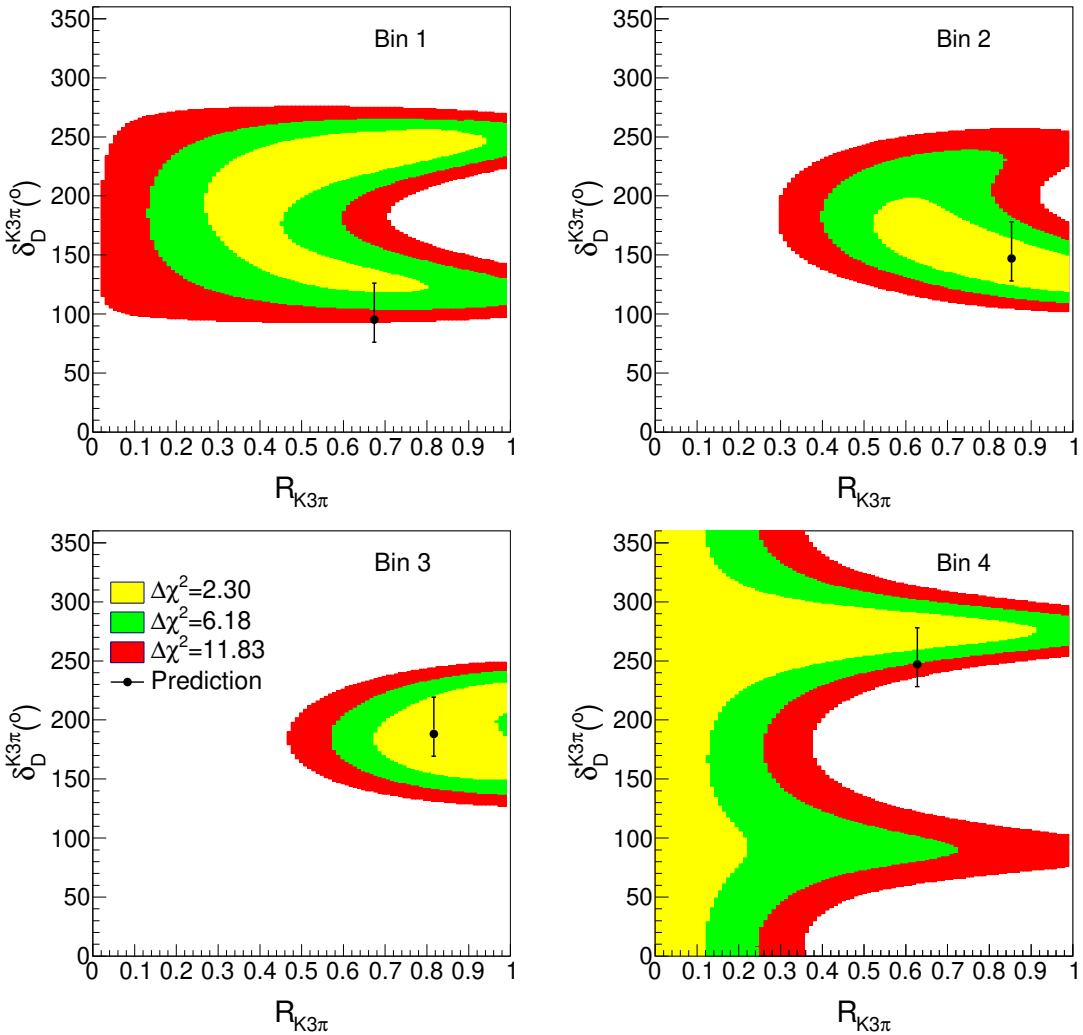
- $D \to K3\pi$ is rich of resonances, $\delta_D^{K3\pi}$ varies in phase space regions
- Sensitivity on γ can be improved measuring it in $D \to K3\pi$ bins



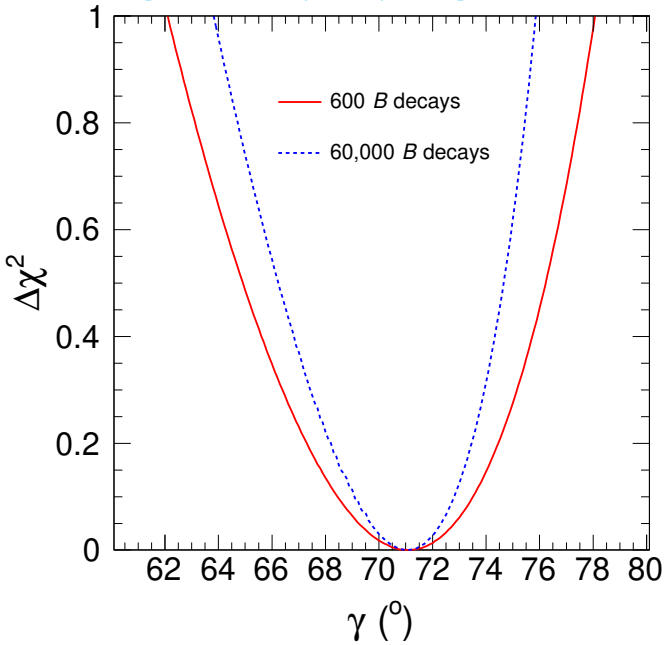
[PLB 802 (2020) 135188]

- Model-independent measurement, only binning method depends on the DCS and CF model of $D \to K3\pi$ [EPJC 78 (2018) 443]

Results of binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$



[JHEP 05 (2021) 164]



- $\delta_{\rm LHCb}^{\rm Run1\&2} = (^{+7}_{-9})^\circ$
- $(^{+5}_{-7})^\circ$ comes from BESIII
- $\delta_{\rm LHCb}^{K^0_S\pi\pi} \sim 5^\circ$ [JHEP 02 (2021) 169]

- Significant improvement compared to CLEO-c results [PLB 802 (2020) 135188]

Determination of $\cos\delta_D^{K\pi}$ at BESIII

- $\mathcal{A}_{K\pi}^{CP} = \frac{2r_D^{K\pi}\cos\delta_{K\pi}+y}{1+R_{\rm WS}} = \frac{\mathcal{B}_{D^S-\to K^-\pi^+} - \mathcal{B}_{D^S+\to K^-\pi^+}}{\mathcal{B}_{D^S-\to K^-\pi^+} + \mathcal{B}_{D^S-\to K^-\pi^+}}$

- CP tagged $K\pi$ events

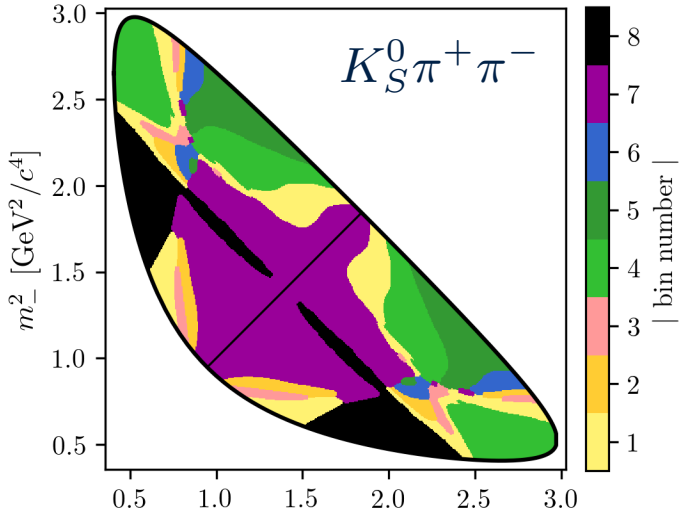
DT mode	$n_{K\pi,S\pm}$
$K\pi,\ K^+K^-$	1671 ± 41
$K\pi,\ \pi^+\pi^-$	610 ± 25
$K\pi,\ K_S^0\pi^0\pi^0$	806 ± 29
$K\pi,\ \pi^0\pi^0$	213 ± 14
$K\pi,\ \rho\pi^0$	1240 ± 35
$K\pi,\ K_S^0\pi^0$	1689 ± 41
$K\pi,\ K_S^0\eta$	230 ± 15
$K\pi,\ K_S^0\omega$	747 ± 27

[PLB 05, 071 (2014)]

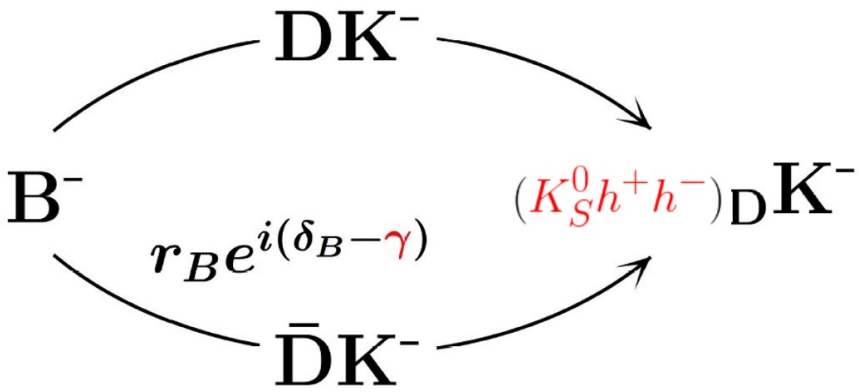
- $\cos\delta_{K\pi} = 1.02\pm0.11\pm0.06\pm0.01$
- $\cos\delta_{K\pi} = 0.81^{+0.22+0.07}_{-0.18-0.05}$ [CLEO-c, PRD 86 (2012) 112001]
- $\delta_{K\pi} = (187.2^{+7.9}_{-9.2})^\circ$ [HFLAV, summer2021]

- Future prospects: explore how much could be gained for $\delta_{K\pi}$ by including other CP tags and $K_S^0h^+h^-$ tags with binned method

Phase-difference parameters in $D \to K^0_S h^+ h^-$



"optimal binning"
[JHEP 02 (2021) 169]



- Divide $D \to K^0_S\pi^+\pi^-$ Dalitz plot into bins $\Rightarrow$ full potential to γ measurement
- Binned $B \to DK$ yields:

$$N^{\pm}_{+i} = h_{B^\pm}\left[F_{\mp i} + \left((x^{DK}_\pm)^2 + (y^{DK}_\pm)^2\right) F_{\pm i} + 2\sqrt{F_i F_{-i}}(x^{DK}_\pm c_i \mp y^{DK}_\pm s_i)\right]$$

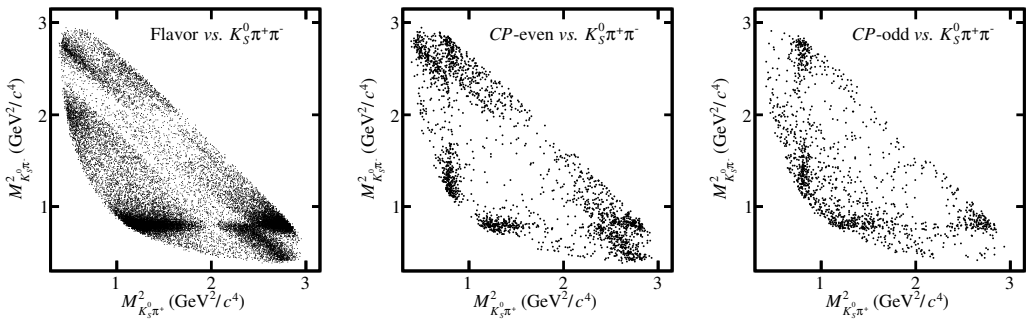
$$(x_\pm = r_B\cos(\delta_B \pm \gamma), y_\pm = r_B \sin(\delta_B \pm \gamma))$$

- Require input of the bin-averaged strong-phase parameters $c_i = \cos(\Delta\delta_D)$, $s_i = \sin(\Delta\delta_D)$

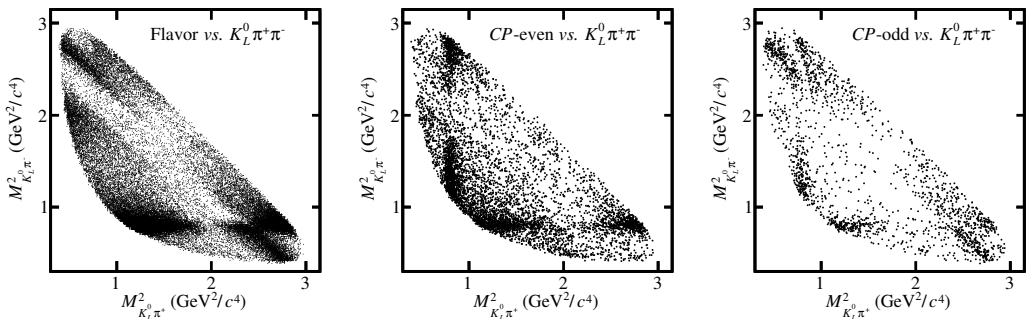
Measurement of c_i and s_i in $D \to K^0_S h^+ h^-$

- CP tags (eg. $\pi\pi\pi^0$, $K^0_S\pi^0$): different behaviour in Dalitz plot for CP-even/odd events $\Rightarrow c_i$
- Self tags (tagged by itself) $\Rightarrow c_i,\ s_i$
- $K^0_S h'^+ h'^-/K^0_L h^{(\prime)+} h^{(\prime)-}$ tags $\Rightarrow c_i,\ s_i$ and $c'_i,\ s'_i$

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



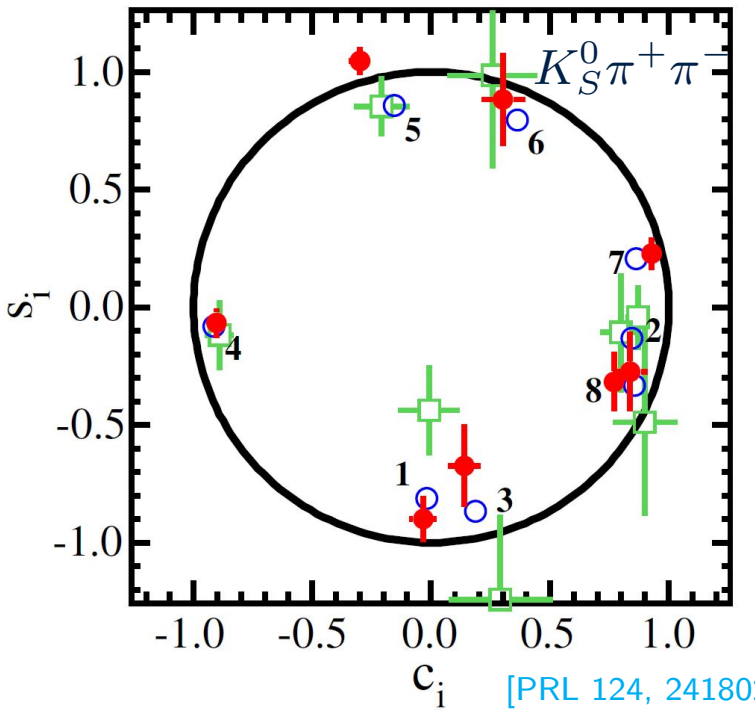
$K^0_L\pi^+\pi^-$



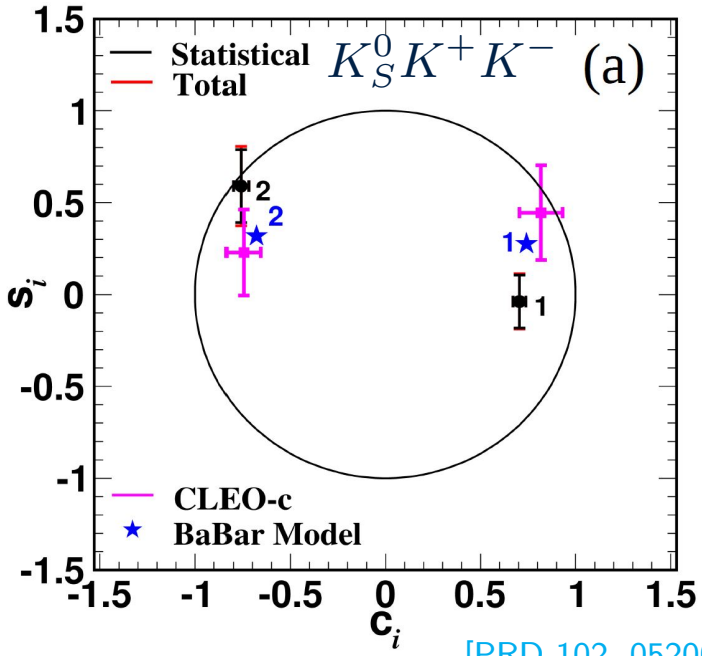
[PRD 101, 112002 (2020)]

Results of c_i and s_i at BESIII

- Global analysis of the flavour, CP and self-tagged $K^0_S h^+ h^-$ events
- $K^0_S K^+ K^-$ is similarly studied with 2 bins due to low statistics



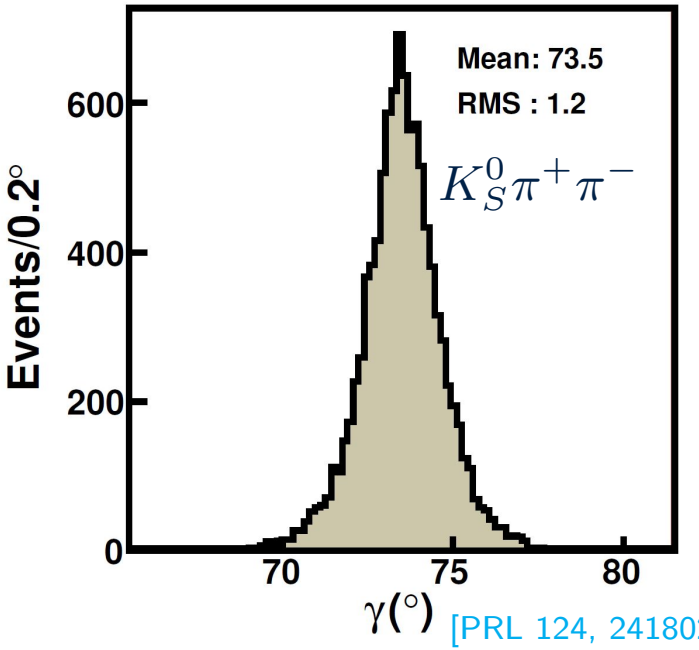
[PRL 124, 241802 (2020)]
[PRD 101, 112002 (2020)]



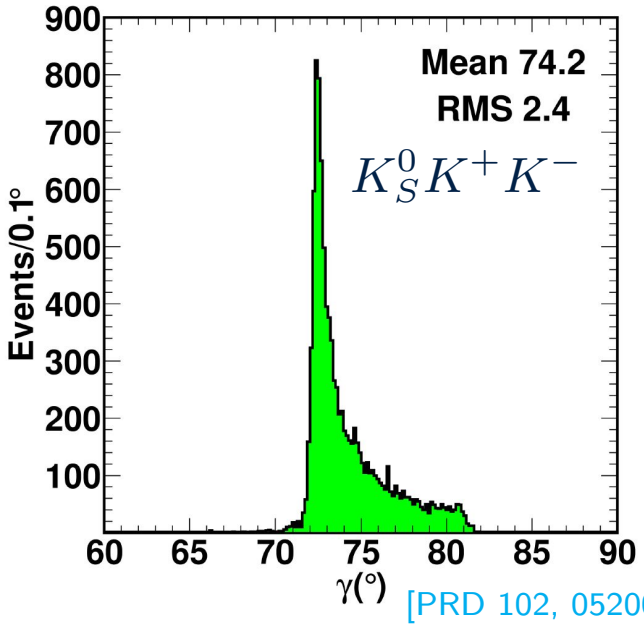
[PRD 102, 052008 (2020)]

- Significant improvement compared to CLEO-c measurements
- Results with more binning methods can be found in the publications

Impact on γ measurement



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

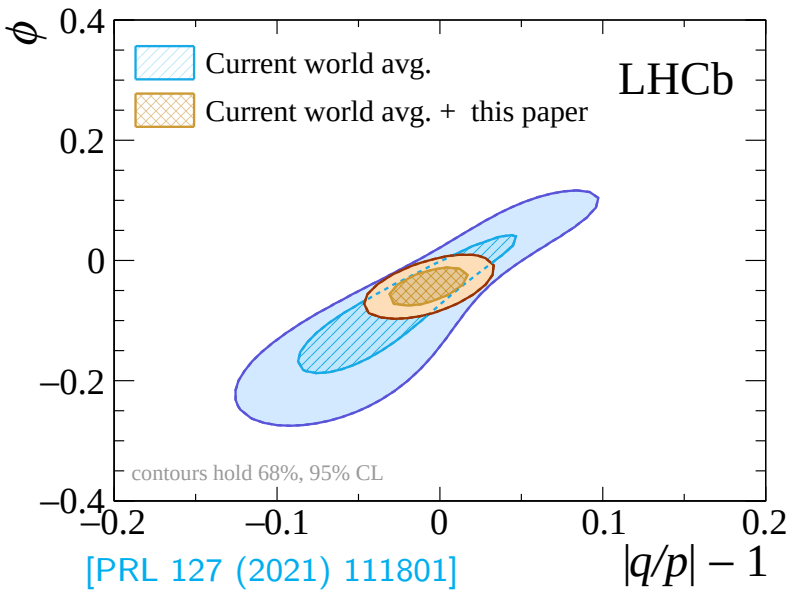


[PRD 102, 052008 (2020)]

- Improvement of the γ sensitivity with only CLEO-c inputs $\sim 3^\circ$ [PRD 82, 112006 (2010)]
- BESIII uncertainty of $K^0_S\pi^+\pi^-$ contributes around 1° to the latest LHCb measurement, leading to the best single measurement of γ (5°) [JHEP 02 (2021) 169]

Strong-phase inputs for CPV in charm decays

- Indirect CP violation due to charm mixing and interference of mixing and decay
- Non-vanishing ϕ and $|q/p| - 1$ leads to observation



[PRL 127 (2021) 111801]

- $D \to K^0_S \pi^+ \pi^-$
- Not observed yet but significantly constrained
- c_i, s_i input from BESIII
  contributes to non-negligible systematics
- Other strong-phase measurements could contribute as inputs to charm mixing and CPV studies

  [PRD 99 (2019) 012007; PRD 91 (2015) 094032]

  [PLB 701 (2011) 353]

Strong-phase inputs for γ measurement

Strong-phase measurements at BESIII

$D \to K\pi\pi\pi/K\pi\pi^0$ [JHEP 05 (2021) 164]

$D \to K\pi$ [PLB 05, 071 (2014)]

$D \to K^0_S h^+ h^-$ [PRD 101 (2020) 112002; PRD 102 (2020) 052008]

Strong-phase inputs for indirect charm CPV

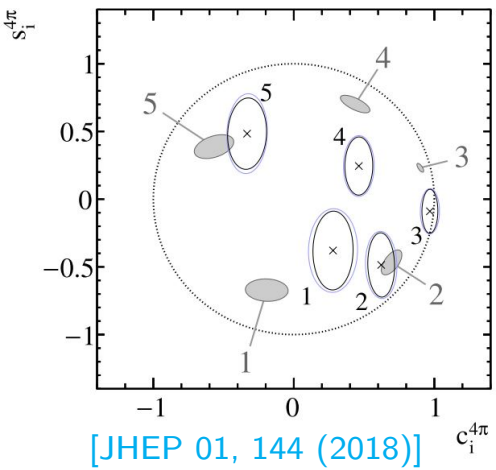
Future prospects at BESIII

Summary

Other decays measured by CLEO-c

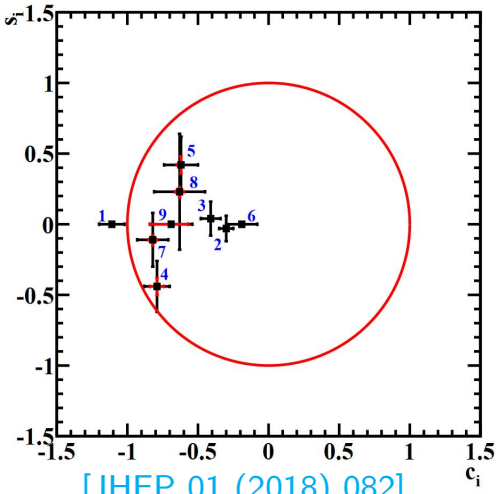
- 0.818 fb^{-1} $\psi(3770)$ CLEO-c data, BESIII can provide improved measurements with about 3.5 times data

c_i, s_i in $\pi^+\pi^-\pi^+\pi^-$



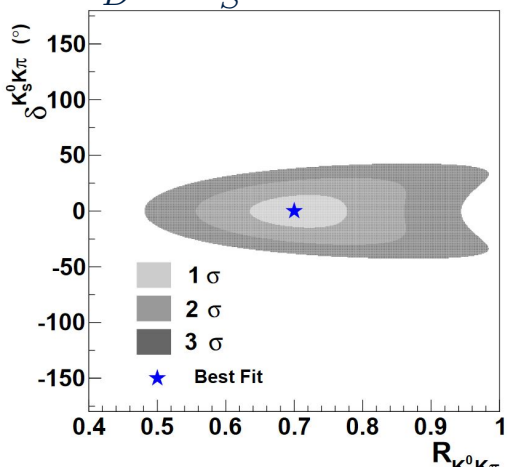
[JHEP 01, 144 (2018)]

c_i, s_i in $K^0_S\pi^+\pi^-\pi^0$



[JHEP 01 (2018) 082]

δ_D in $K^0_S K\pi$



[PRD 85, 092016 (2012)]

- Improvement in $K^0_S\pi^+\pi^-\pi^0$ shall be of interest for Belle II as its $\mathcal{B}$ reaches $(5.2 \pm 0.6)\%$ and it's challenging in LHCb

Future prospects at BESIII

	Decay mode	Quantity of interest
✓	$D \to K^0_S\pi^+\pi^-$	c_i and s_i
✓	$D \to K^0_S K^+ K^-$	c_i and s_i
✓	$D \to K^\pm\pi^\mp\pi^+\pi^-$	R, δ
	$D \to K^+K^-\pi^+\pi^-$	c_i and s_i
	$D \to \pi^+\pi^-\pi^+\pi^-$	F_+ or c_i and s_i
✓	$D \to K^\pm\pi^\mp\pi^0$	R, δ
	$D \to K^0_S K^\pm\pi^\mp$	R, δ
	$D \to \pi^+\pi^-\pi^0$	F_+
	$D \to K^0_S\pi^+\pi^-\pi^0$	F_+ or c_i and s_i
	$D \to K^+K^-\pi^0$	F_+
✓	$D \to K^\pm\pi^\mp$	δ

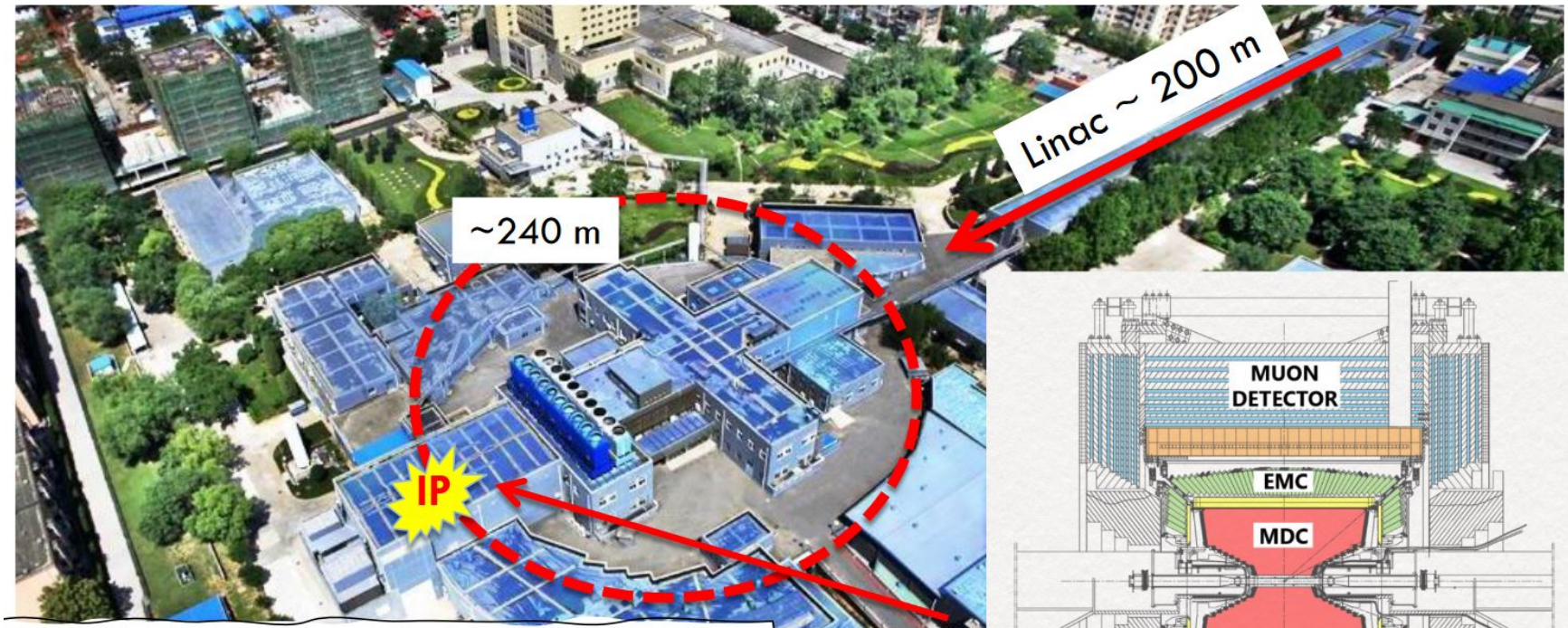
- Limited by statistics:
  - $\pi^+\pi^-\pi^+\pi^-$
  - $K^+K^-\pi^+\pi^-$
- Inputs for Belle II (challenging for LHCb):
  - $K^0_S\pi^+\pi^-\pi^0$
  - $K\pi\pi^0$
  - $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$

Summary

- BESIII provides unique quantum correlated $D\bar{D}$ data to measure the strong-phase parameters in D decays as inputs to LHCb and Belle II for
  - CKM angle γ measurement in the b sector
  - Indirect CP violation and mixing in neutral D meson decays
- Decays have been studied at BESIII:
  - $K^0_S h^+ h^-$, $K3\pi$, $K\pi\pi^0$, $K\pi$
- 20 fb^{-1} $\psi(3770)$ data at BESIII in the near future [CPC 44, 040001 (2020)]
  - Improve the current measurement, eg. c_i , s_i and $\delta_D^{K3\pi}$ and $R_{K3\pi}$
  - Low statistics decays, eg. $\pi^+\pi^-\pi^+\pi^+$, $K^+K^-\pi^+\pi^+$

Thanks!

Back-up: BEPCII



2004: started BEPCII/BESIII construction

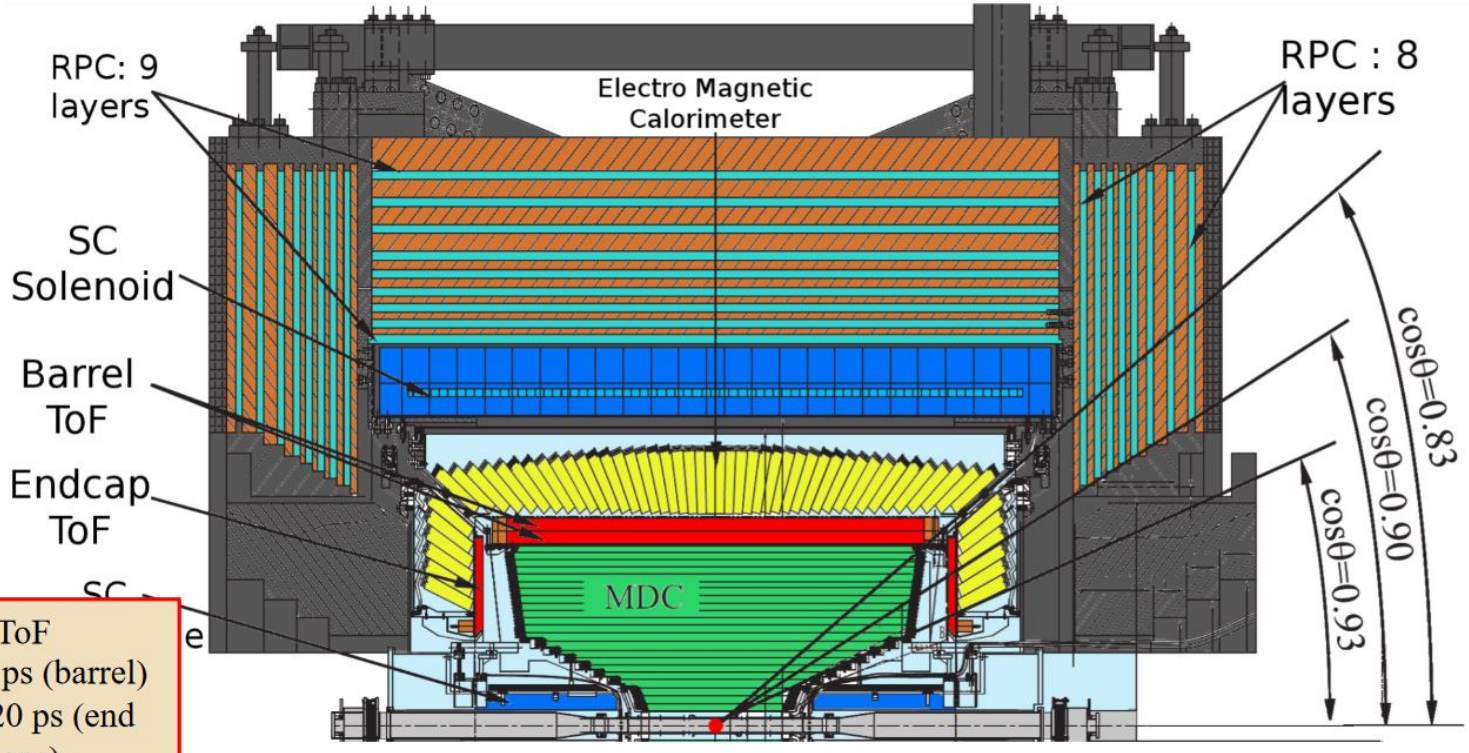
- ✓ Double rings
- ✓ Beam energy: 1-~~2.3~~ 2.45 GeV
- ✓ Design luminosity: 1×10^{33} $cm^{-2}s^{-1}$ @ $\psi(3770)$, achieved in 2016

2009 – today: BESIII physics runs

[ISABELLA Charm20]

Back-up: BESIII

Nucl. Instr. Meth. A614, 345 (2010)



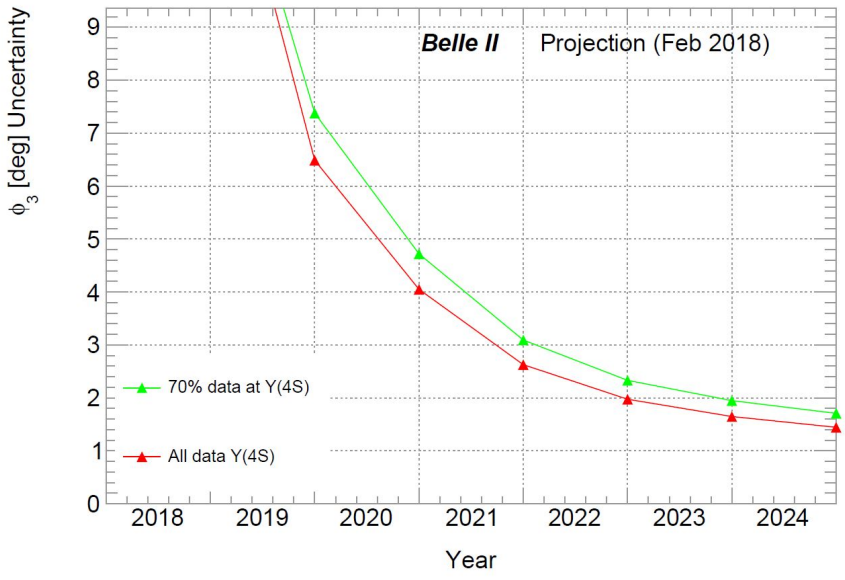
ToF
σ_t ~ 90 ps (barrel)
σ_t ~ 120 ps (end caps)

Drift Chamber
$\sigma_{r\phi}$ ~ 130 μm (single wire)
σ_{pt}/p_t ~ 0.5 % @ 1 GeV

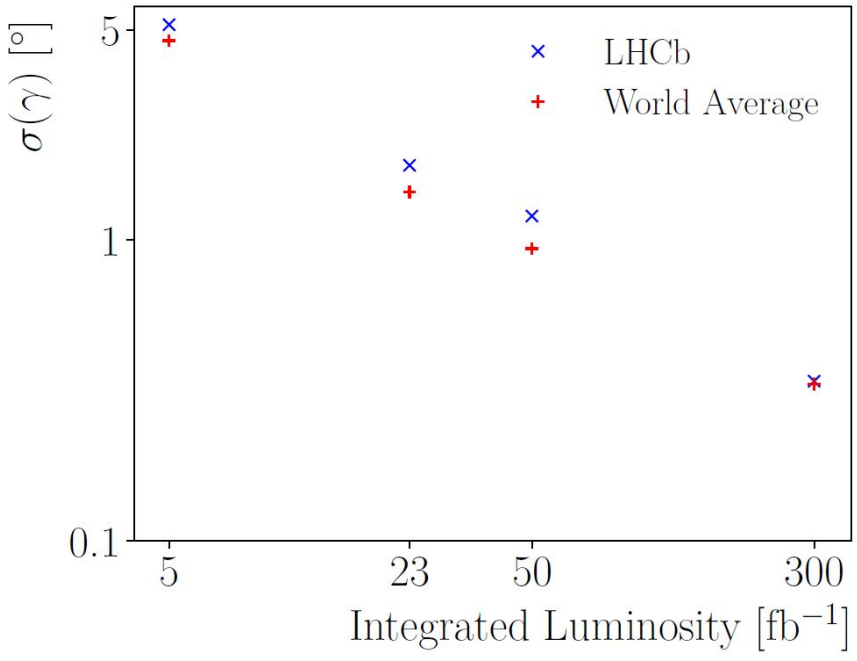
Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
σ_{xy} ~ (6 mm)/$E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi$=93%

Back-up: γ sensitivity at LHCb and Belle II

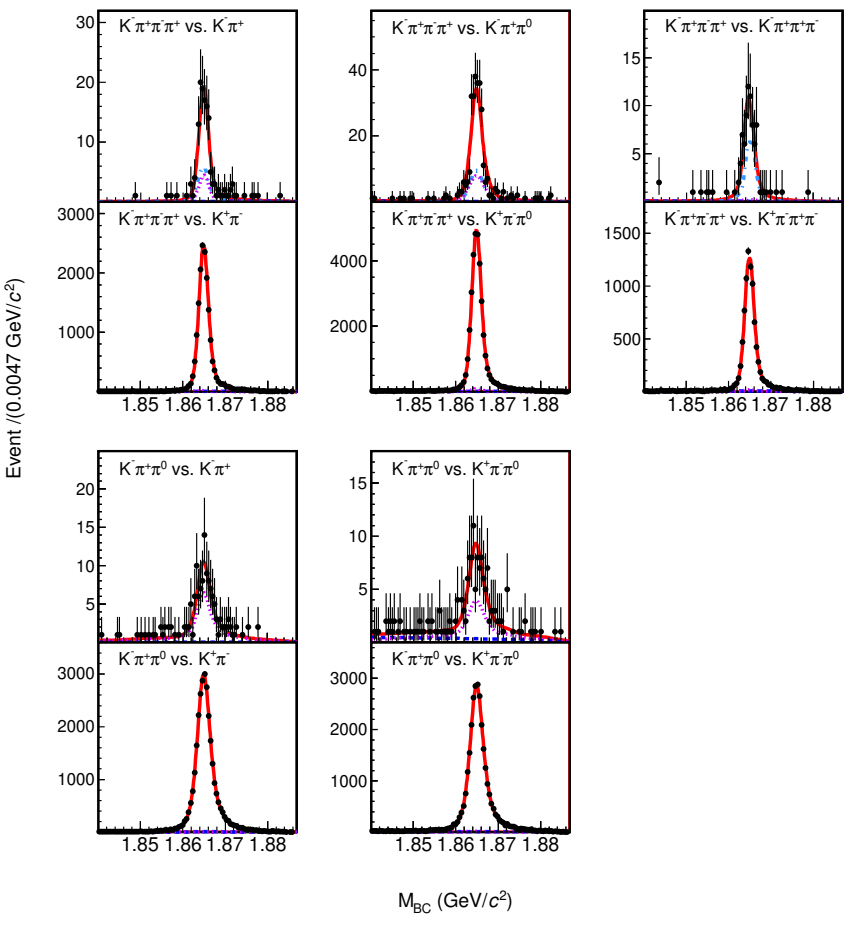


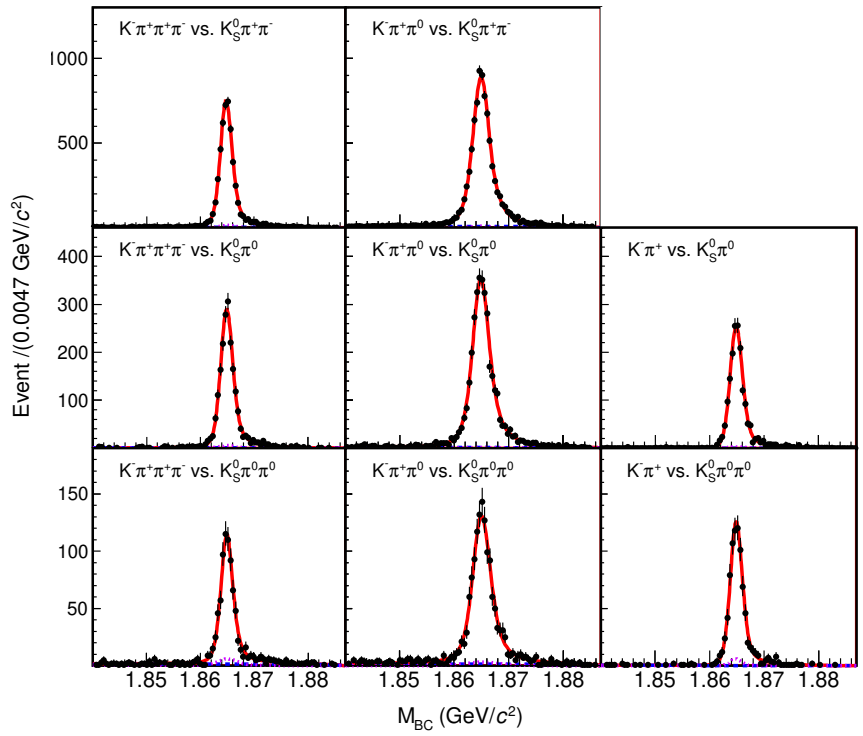
[arXiv: 1808.10567]



[arXiv:1808.08865]

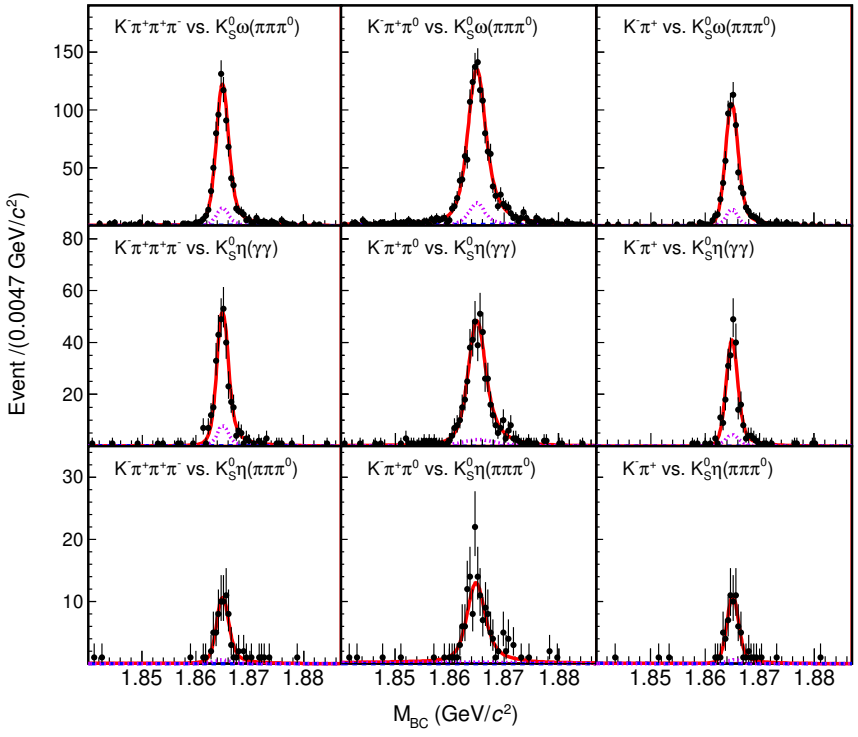
Back-up: $K3\pi/K\pi\pi^0$ DT modes

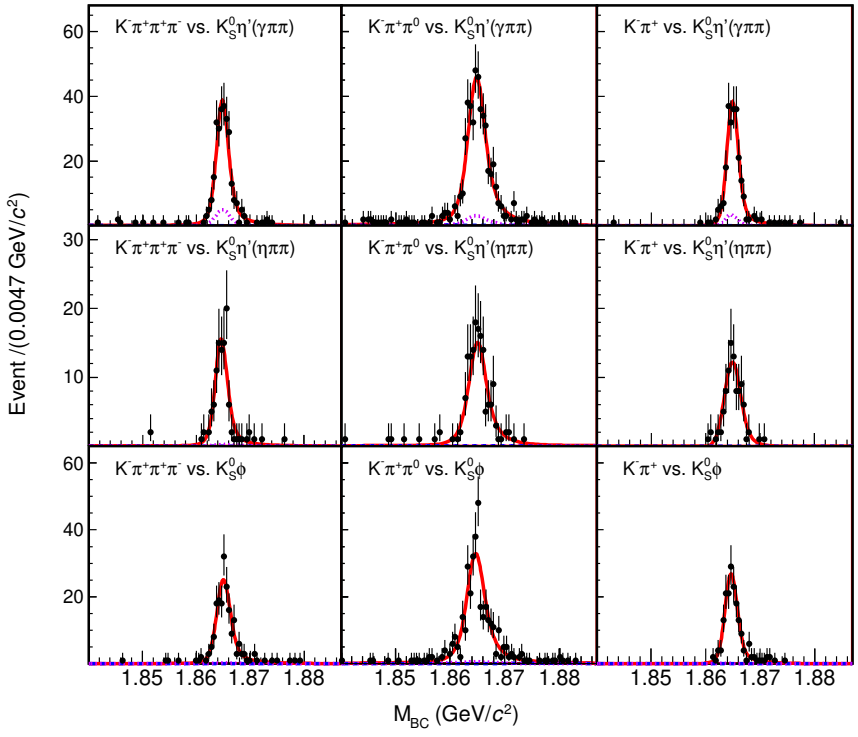




[JHEP 05 (2021) 164]

Back-up: $K3\pi/K\pi\pi^0$ DT modes





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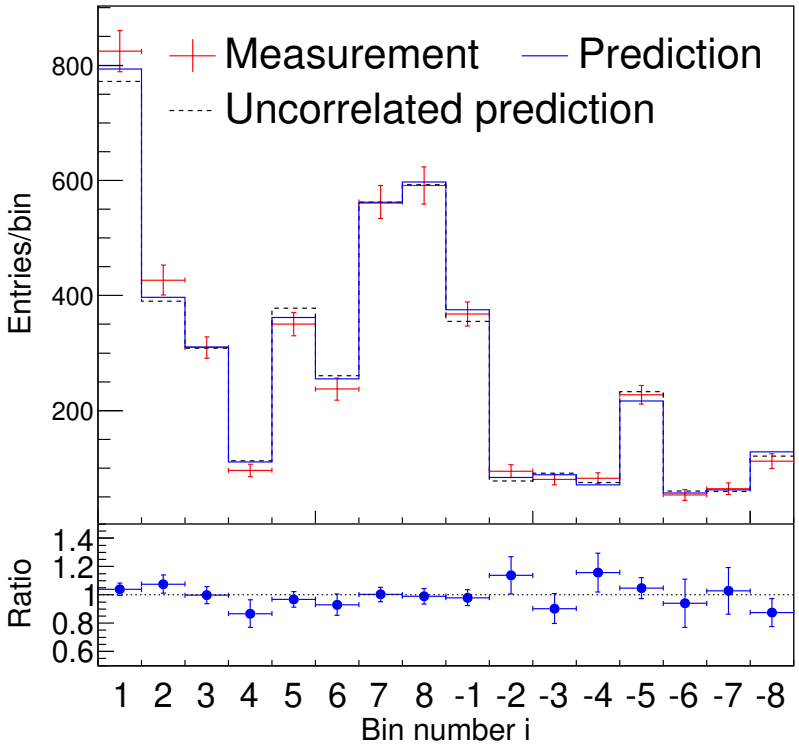
Back-up: $K^0_S\pi^+\pi^-$ tag for $K3\pi/K\pi\pi^0$



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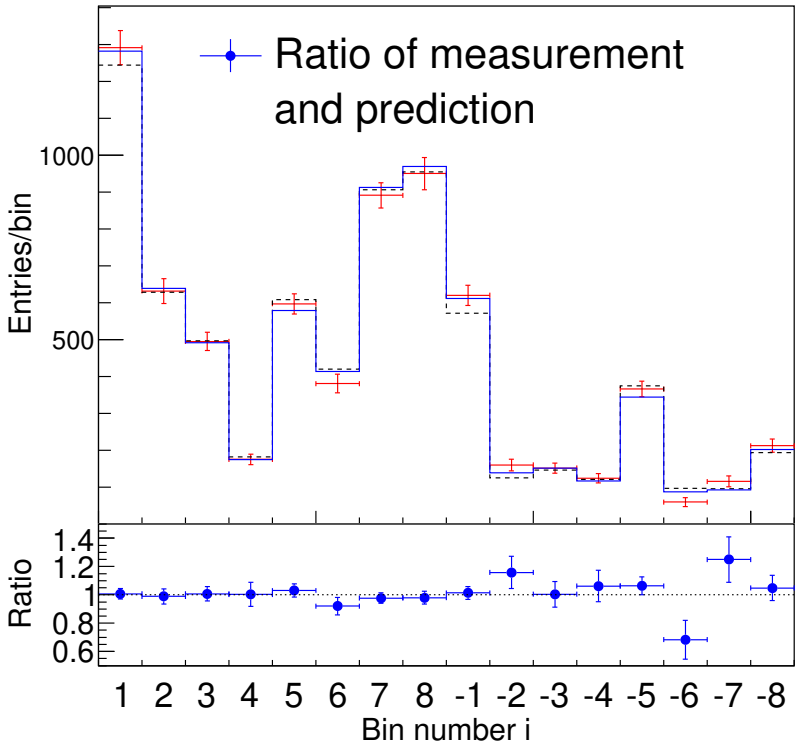
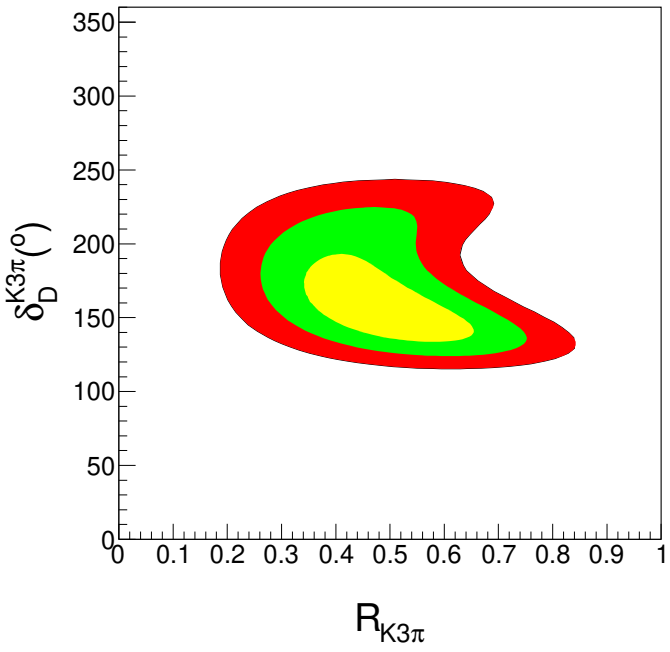
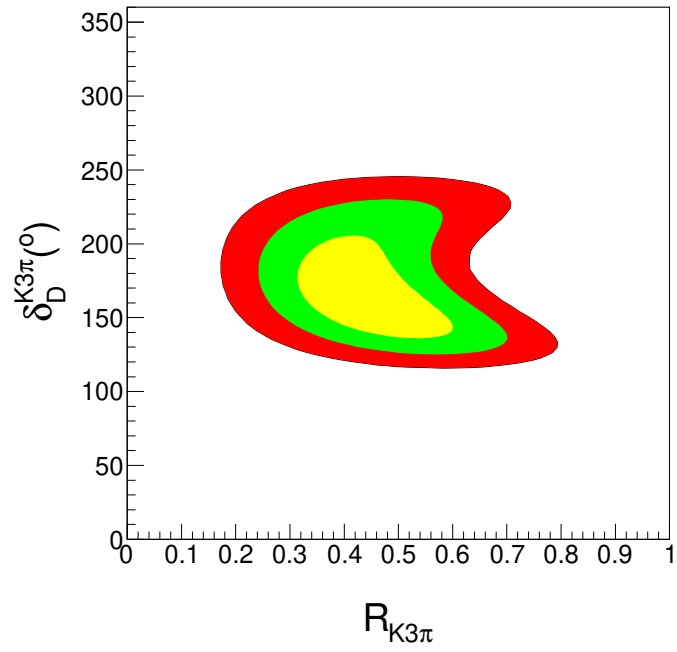
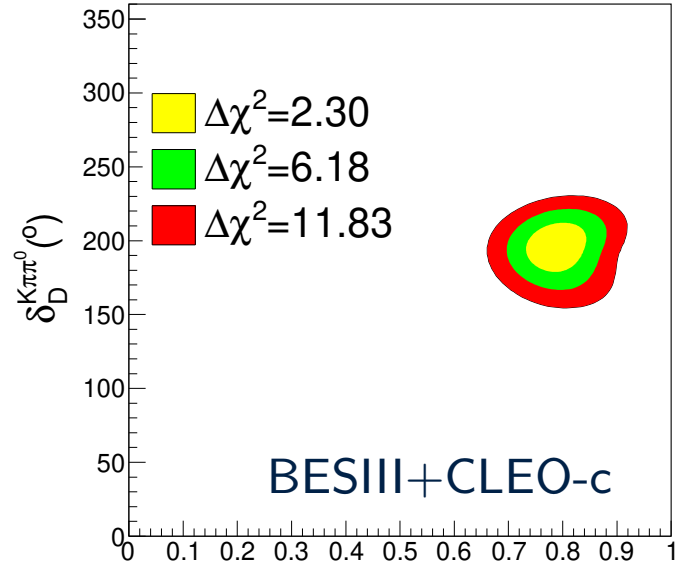
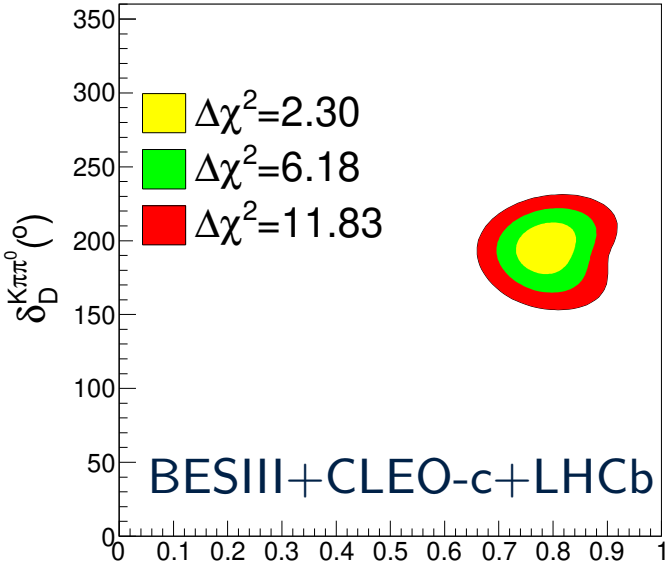


Back-up: Combination of $\delta_D^{K3\pi}$ and $R_{K3\pi}$

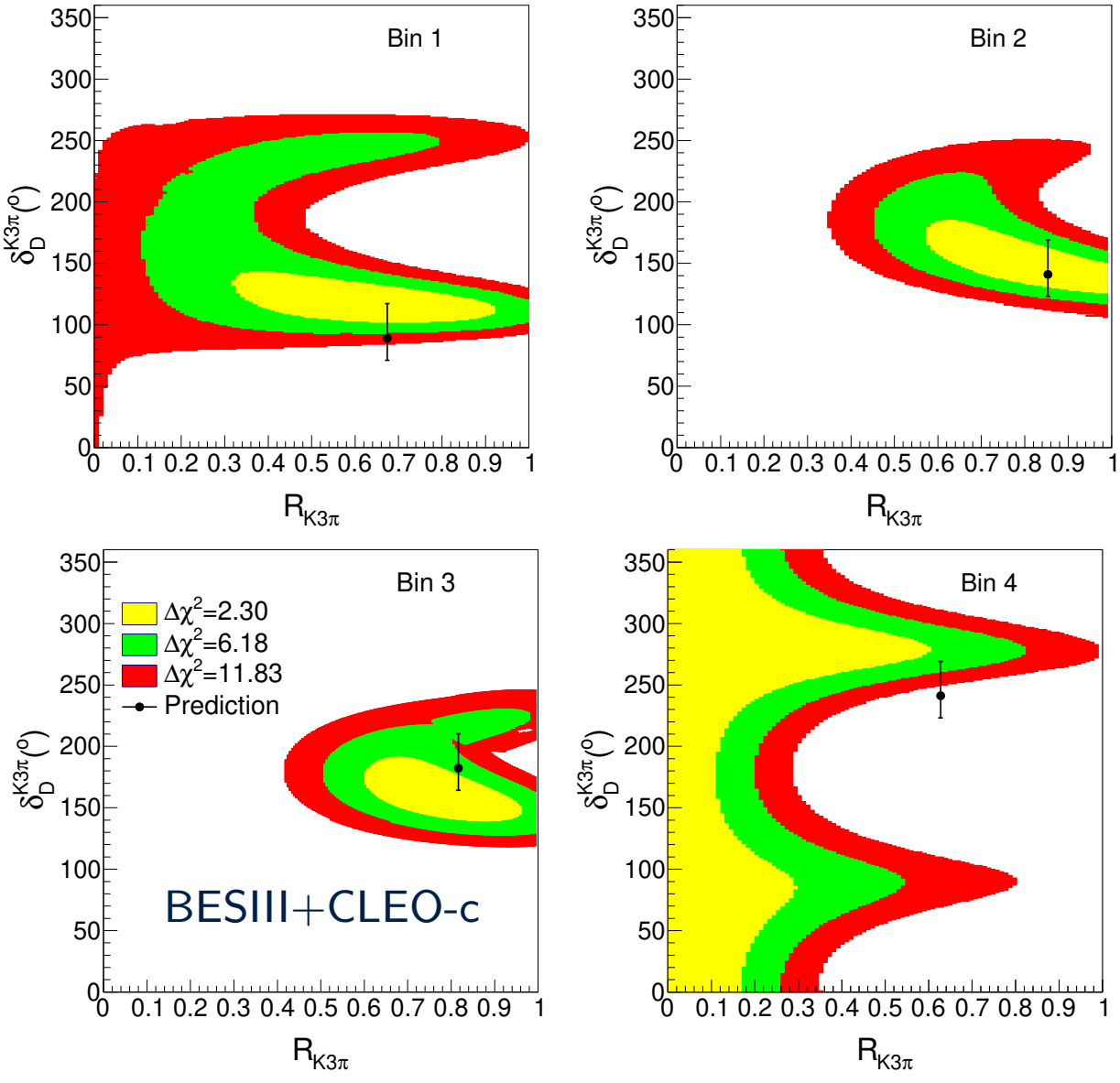








Back-up: Combination of binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$



Back-up: Determination of CP fraction at CLEO-c

- (Quasi)CP tags: $M(f|g) = \mathcal{Z}\mathcal{B}_f\mathcal{B}_g\left[1-(2F_+^f-1)(2F_+^g-1)\right]$
- $K^0_{S,L}\pi^+\pi^-$ tags: $M_i = h\left[K_i + K_{-i} - (2F_+ - 1)2c_i\sqrt{K_iK_{-i}}\right]$
- [PLB 05, 043 (2015)]
- Input to γ measurement [PRD 91, 112014 (2015)]

Tag	$F_+^{\pi^+\pi^-\pi^0}$	$F_+^{K^+K^-\pi^0}$	$F_+^{\pi^+\pi^-\pi^+\pi^-}$
CP eigenstates	$0.968(17)(6)$	$0.731(58)(21)$	$0.754(31)(21)$
$K^0_{S,L}\pi^+\pi^-$	$1.014(45)(22)$	$0.734(106)(54)$	$0.737(49)(24)$
$\pi^+\pi^-\pi^0$	-	-	$0.695(50)(21)$
Combined	0.973 ± 0.017	0.732 ± 0.055	0.737 ± 0.028

- BESIII data can improve these measurements