Input for γ measurements from BESIII

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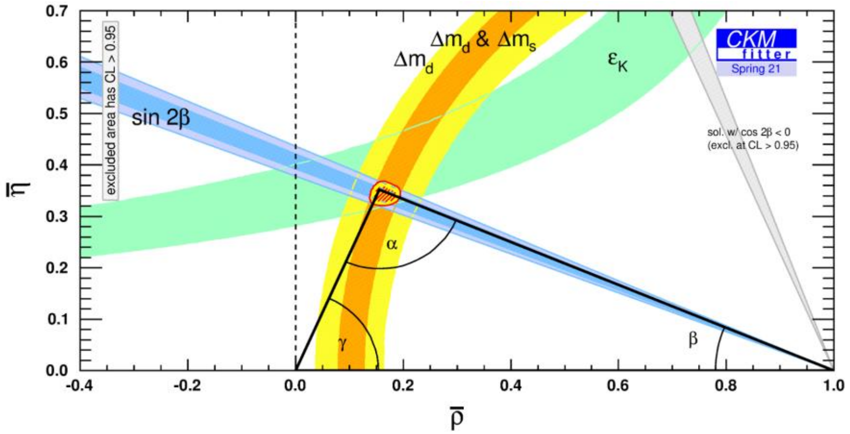
Outline

- Introduction
- Method to measure γ
- Recent strong parameters from BESIII
- Future prospect of γ
- Summary

Why measure γ

$$V_{\text{CKM}} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \longrightarrow \gamma = arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

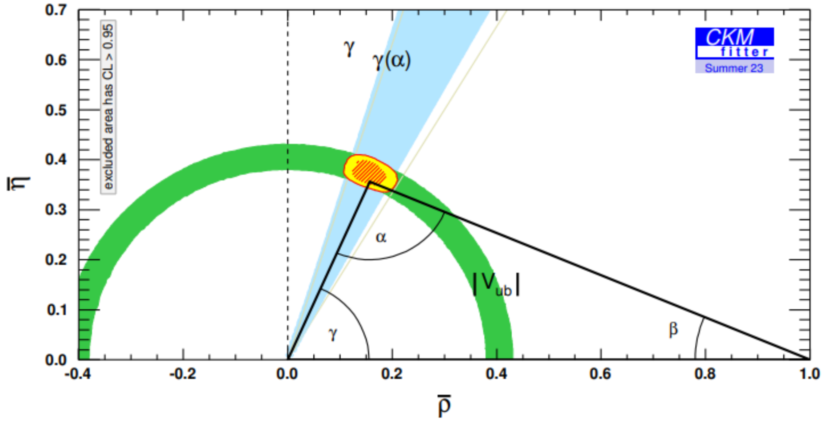
Indirect measurement



- Extrapolate γ from measurement of α and β
- Measured using loop-level decays: sensitivity to NP
- CKMFitter latest: $\gamma = (66.3^{+0.7}_{-1.9})^{o}$

Disagreement = New Physics!

Direct measurement



- Measure γ directly using tree-level decays
- Theoretically clean($\delta\gamma/\gamma < 10^{-7}$) [JHEP 1401(2014)051]
- HFLAV latest: $\gamma = (65.9^{+3.3}_{-3.5})^{o}$
- LHCb dominated: $\gamma = (63.8^{+3.5}_{-3.7})^{o}$ [LHCb-CONF-2022-003]

How to measure γ directly

- Interference between favoured b→c and suppressed b→u decay amplitude

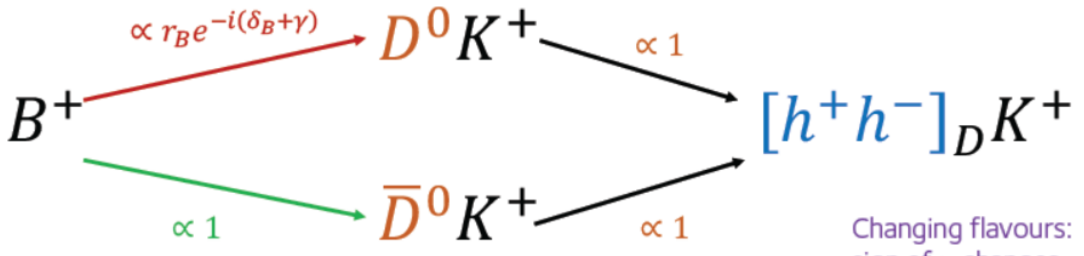
- Ideal decays: B→DK (clean background, large branching fraction)

$$A(b \to u)/A(b \to c) = r_B e^{i\delta_B \pm \gamma}$$

r_B = magnitude ratio (~0.1)
δ_B = strong-phase difference

GLW method [1,2]

- D CP-even final states such as D→K^+K^-,$\pi^+\pi^-$,$\pi^+\pi^-\pi^0$…



Changing flavours: sign of γ changes

$$A(B^+ \to [h^+h^-]_D K^+) \propto 1 + r_B e^{-i(\delta_B+\gamma)}$$
$$A(B^- \to [h^+h^-]_D K^-) \propto 1 + r_B e^{-i(\delta_B-\gamma)}$$

- Use the yields of B+ and B- to construct observables related to γ

$$A^f = \frac{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)}{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)} = \frac{2\kappa r_B sin\delta_B sin\gamma}{R^f}$$

$$R^f = \frac{N(B^- \to f_D K^-) - N(B^+ \to f_D K^+)}{N(B^- \to [K\pi]_D K^-) - N(B^+ \to [K\pi]_D K^+)} = 1 + r_B^2 + 2\kappa r_B cos\delta_B cos\gamma$$

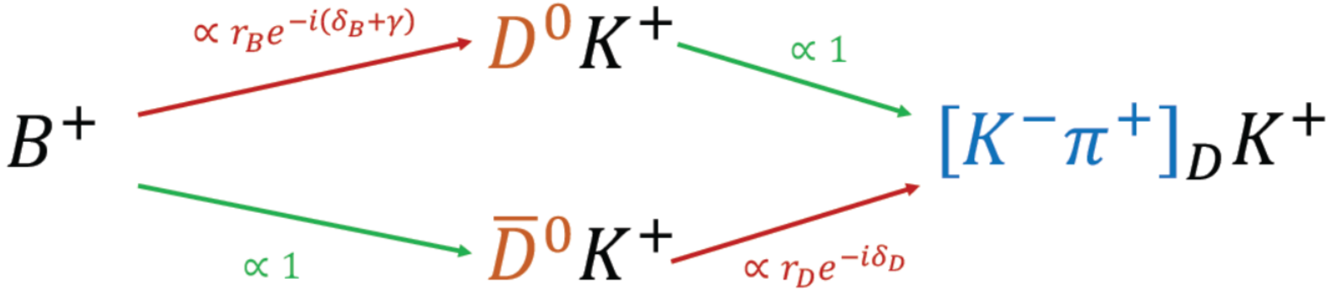
insert a factor of (κ=2F_+-1) before interference terms (F_+=CP even content), need charm input

Notice r_B/δ_B need input

[1] M. Gronau and D. Wyler, Phys. Lett. B265 (1991) 172
[2] M. Gronau and D. London, Phys. Lett. B253 (1991) 483

ADS method[1,2]

- Consider the Cabibbo-favored decay $D^0 \to K^-\pi^+$ and doubly-Cabibbo-suppressed decay $D^0 \to K^+\pi^-$



- r_B/δ_B can be obtained directly, but external input r_D/δ_D

$$\Gamma(B^\pm \to f_D K^\pm) \propto r_B^2 + r_D^2 + 2R_f r_B r_D cos(\delta_B + \delta_D \pm \gamma)$$
$$\Gamma\left(B^\pm \to \bar{f}_D K^\pm\right) \propto 1 + r_B^2 r_D^2 + 2R_f r_B r_D cos(\delta_B - \delta_D \pm \gamma)$$

Need inputs from charm factory

$$R_{K3\pi}e^{-i\delta_{K3\pi}} = \frac{\int A_{K^-3\pi}(x)A_{K^+3\pi}(x)dx}{A_{K^-3\pi}(x)A_{K^+3\pi}(x)}$$

- For K3π mode, coherence factor $R_{K3\pi}$ and $\delta_{K3\pi}$ averaged over phase space not good for whole space

[1] D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett. 78 (1997) 3257
[2] D. Atwood, I. Dunietz, and A. Soni , Phys. Rev. D63 (2001) 036005

Dalitz method[1]

- Golden mode: D→$K_s\pi\pi/K_sKK$ (large statistic, large r_D)
  - Model-dependent method (not used now)
  - Model-independent binned method (BPGGSZ method[1])
- Binned Dalitz plane according to δ_D, measure $B^{\pm}$ yields in each bins
  - Sensitivity from **phase-space distribution**, not overall asymmetries → not impacted by production/detection asymmetries
  - LHCb latest $\boldsymbol{K_s hh}$ result: $\gamma = (68.7^{+5.2}_{-5.1})^o$(uncertainty~1^o from BESIII input) *JHEP* ***02*** *(2021) 169*

$$r_B \exp[i(\delta_B \pm \gamma)] = x_\pm + iy_\pm$$

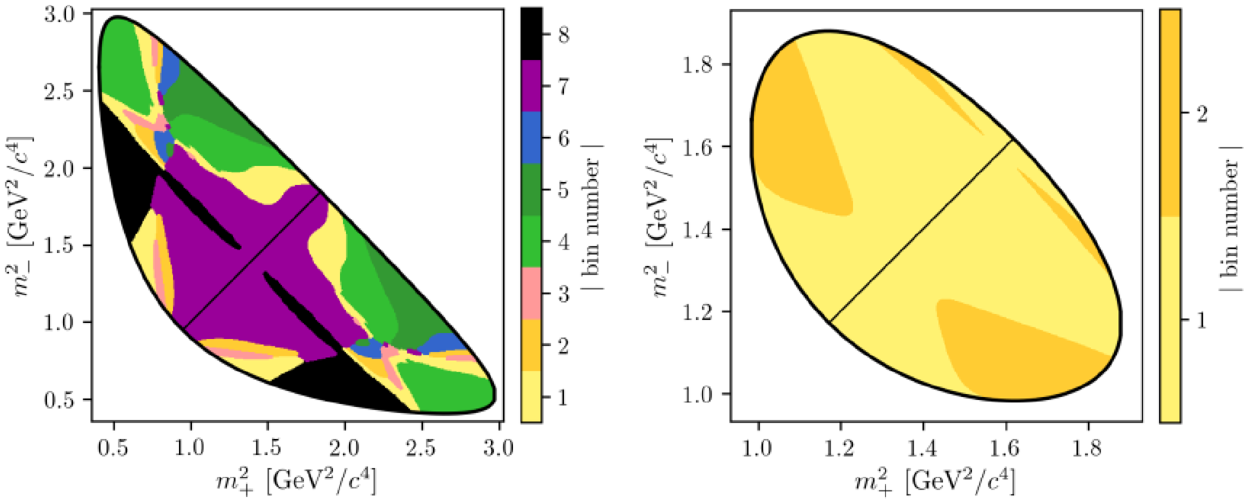
$$N^-_{\mp i} \propto F_{\pm i} + (x^2_- + y^2_-)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

F_i : Fractional yield of flavour tagged D^0 into bin i

Measured in control channel: $\bar{B}^0 \to D^{*+}\mu^-\nu_\mu X$

c_i/s_i : Strong phase difference of $D^0 - \bar{D}^0$ decays

External input from BESIII and CLEO-c



[1] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68 (2003) 054018

Quantum correlated $D\bar{D}$ measurement

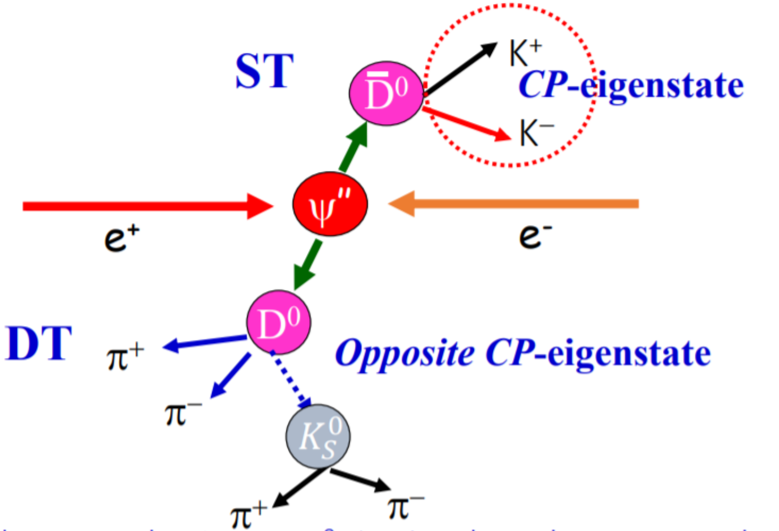
- $\psi(3770)$ is a spin -1 states, therefore the amplitude of $\psi(3770) \rightarrow D\bar{D}$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$ [anti-symmetric wave function]

The amplitude for two D mesons to decay to states *F* and *G* is [D. Atwood and A. Soni, PRD68, 033003 (2003)]:

$$\Gamma(F|G) = \Gamma_0\,[A_F^2\bar{A}_G^2 + \bar{A}_F^2 A_G^2 - 2R_F R_G A_F \bar{A}_F A_G \bar{A}_G \cos[\delta_D^F - \delta_D^G]]$$

The coherence factor κ_F and the strong phase difference δ_D can be extracted



The DT mode K^+K^- *vs.* $K_S^0\pi^+\pi^-$ is selected as an example.

- ✓ Single tag (ST) samples: decay products of only one D meson are reconstructed
- ✓ Double tag (DT) samples: decay products of both D mesons are reconstructed
- ✓ Some typical reconstructed D decay modes

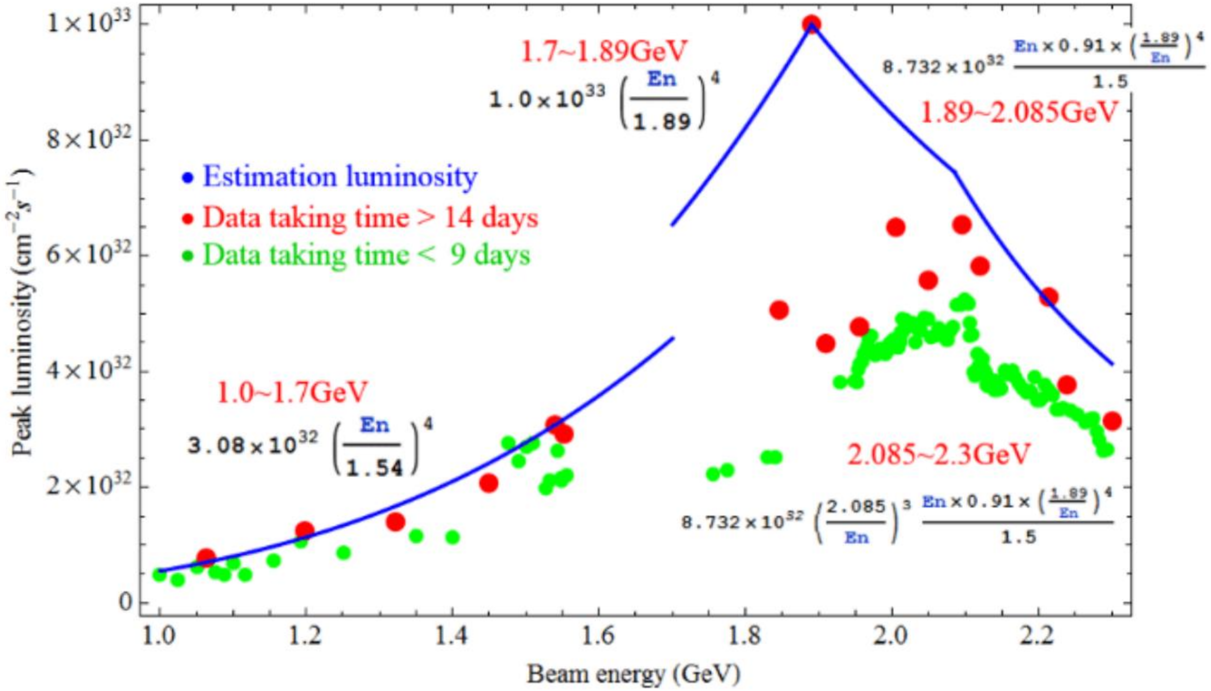
Tag group	
Flavor	$K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^+e^-\bar{\nu}_e$
CP-even	K^+K^-, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $\pi^+\pi^-\pi^0$
CP-odd	$K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_L^0\pi^0\pi^0$
Mixed-*CP*	$K_S^0\pi^+\pi^-$

The BESIII experiment

Key datasets for charm physics:

- ➙ 2010-2011: $2.9\,\mathrm{fb}^{-1}$ at $\psi(3770)$
- ● 2013-2019: $7.3\,\mathrm{fb}^{-1}$ of $D_s\bar{D}_s^*$
- ● 2020: $4.5\,\mathrm{fb}^{-1}$ of $\Lambda_c^+\bar{\Lambda}_c^-$
- ➙ 2021-2022: $5.0\,\mathrm{fb}^{-1}$ at $\psi(3770)$
- ➙ 2022-: $\sim 8\,\mathrm{fb}^{-1}$ at $\psi(3770)$

7.9 fb^{-1} $\psi(3770)$ data is ready for physics
20 fb^{-1} $\psi(3770)$ data will be obtained in 2024



BEPCII peak luminosity.

Threshold produced $\psi(3770)\to D\bar{D}$ provide a unique access to strong parameters information for γ measurement at LHCb/BelleII

Results in this talk

- Update measurement of $\delta_{K\pi}$ *EPJC **82** 1009 (2022)*
- $D \rightarrow K^-\pi^+\pi^-\pi^+/K^-\pi^+\pi^0$ strong parameters measurement *JHEP **5**(2021)164*
- $D \rightarrow \pi^+\pi^-\pi^+\pi^-$ F+ measurement *PRD **106** (2022) 092004*
- $D \rightarrow K^+K^-\pi^+\pi^-$ F+ measurement *PRD **107** (2023) 032009*
- $D \rightarrow K_S\pi^+\pi^-\pi^0$ F+ measurement *PRD **108** (2023) 032003*

Update measurement of $\delta_{K\pi}$

*EPJC **82** (2022)1009*

- Based on 2.9 fb^{-1} data
- More modes are used comparing to previous work (*PLB **734** (2014) 227*)
  - D→K_LX included (statistics improved a lot) →Independent determinations their BRS
  - D→$K_S/K_L\pi\pi$ included
- Asymmetry between CP-odd and CP-even eigenstate decays to Kπ: $\mathcal{A}_{K\pi} = \frac{-2r_D^{K\pi}\cos(\delta_{K\pi})+y}{1+(r_D^{K\pi})^2}$
- D→$K_S/K_L\pi\pi$ in bins: $Y_i \propto \left(K_i + (r_D^{K\pi})^2 K_{-i} - 2r_D^{K\pi}\sqrt{K_i K_{-i}}\left[c_i \cos\left(\delta_D^{K\pi}\right) - s_i \sin\left(\delta_D^{K\pi}\right)\right]\right)$

- Combine these modes:

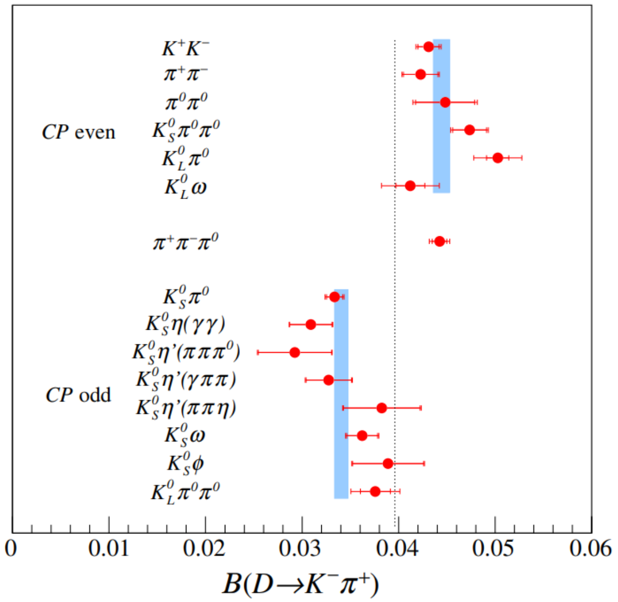
$$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$$

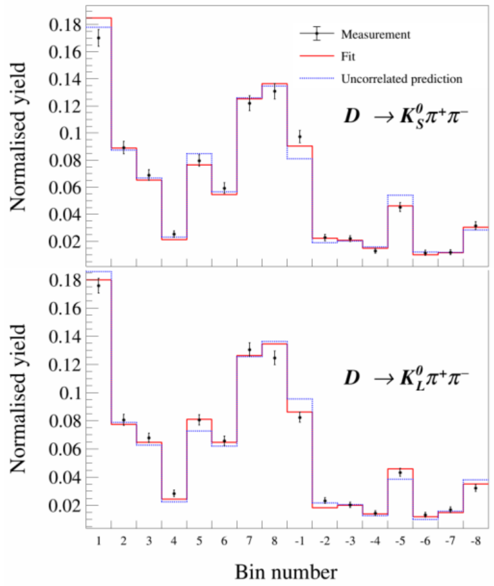
Used in latest LHCb γ fit (LHCb-CONF-2022-003)

- Also BRs:

$$\mathcal{B}(D^0 \to K_L^0\pi^0) = (0.97 \pm 0.03 \pm 0.02) \times 10^{-2}$$
$$\mathcal{B}(D^0 \to K_L^0\omega) = (1.09 \pm 0.06 \pm 0.03) \times 10^{-2}$$
$$\mathcal{B}(D^0 \to K_L^0\pi^0\pi^0) = (1.26 \pm 0.05 \pm 0.03) \times 10^{-2}$$

- Analysis with 8fb^{-1} data is ongoing

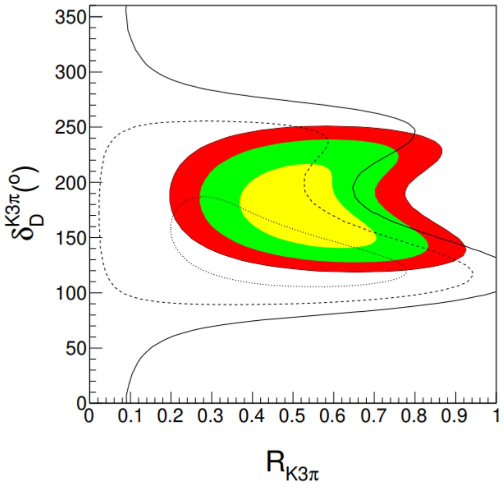


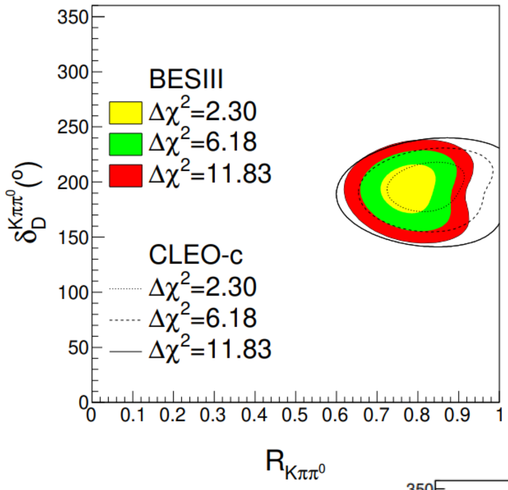


$D \to K^- \pi^+ \pi^- \pi^+ / K^- \pi^+ \pi^0$ strong parameters measurement

*JHEP **5**(2021)164*

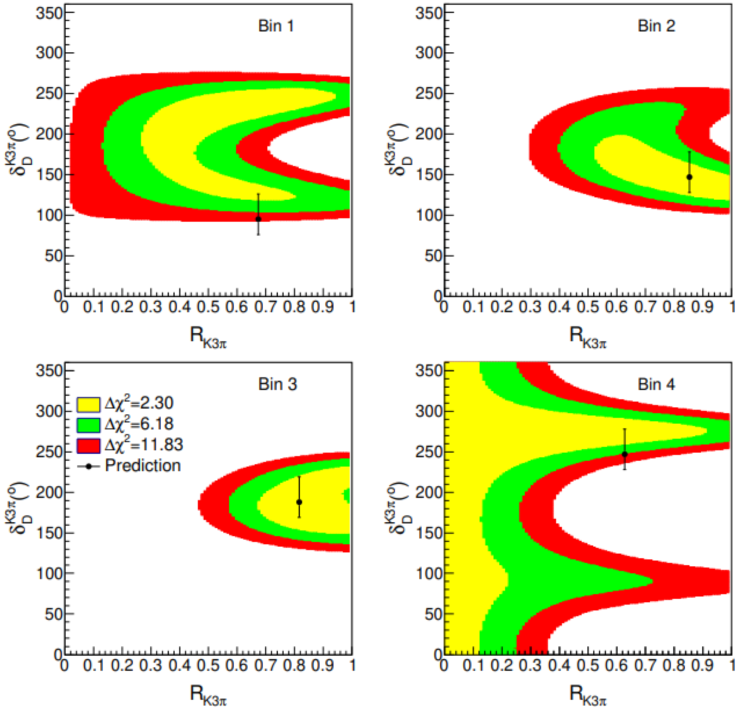
- Based on 2.9 fb^{-1} data
- Similar analysis strategy
  - CP tags
  - $D \to K_S/K_L \pi\pi$ included





- A binning scheme for $\delta_{K3\pi}$ (*PLB **802**(2020)135188*)
- Obtain corresponding $\delta_{K3\pi}$ and $R_{K3\pi}$

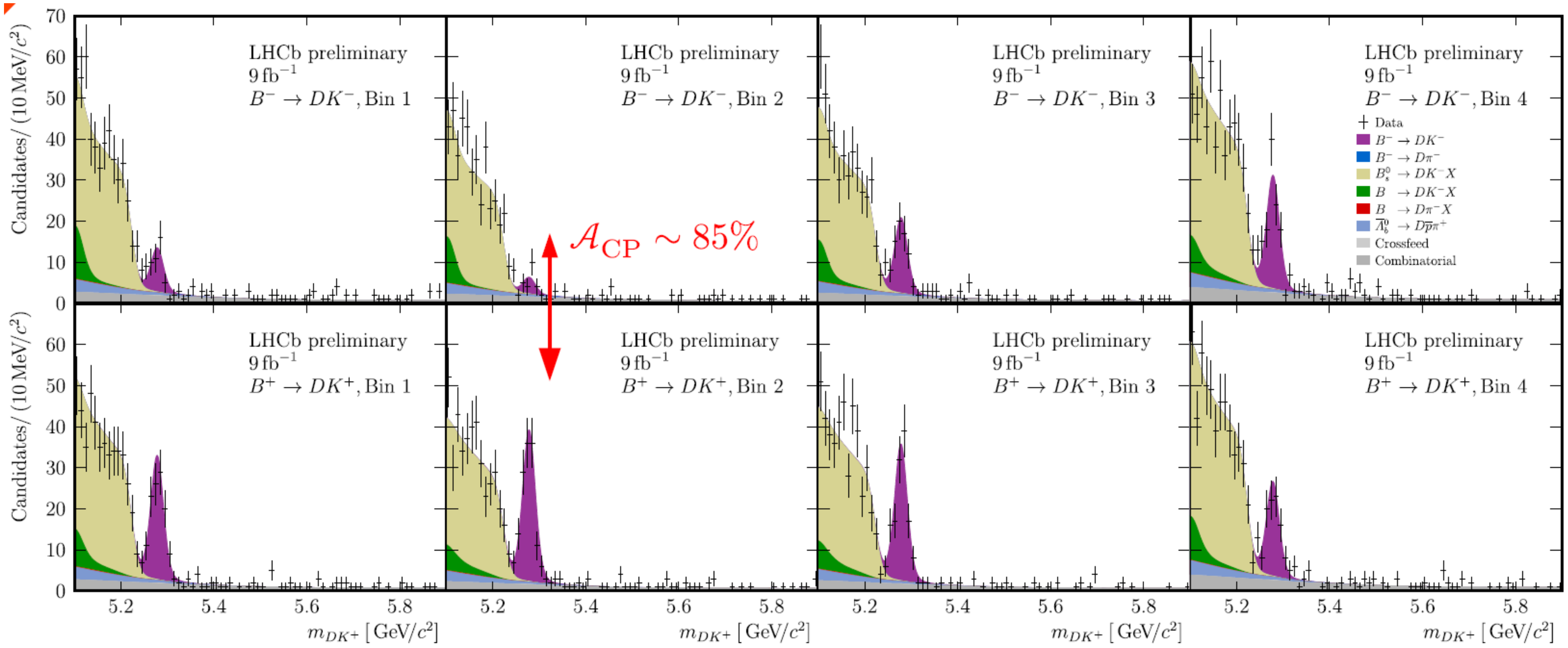
Parameter	Global fit	Binned fit			
		Bin 1	Bin 2	Bin 3	Bin 4
$R_{K3\pi}$	$0.52^{+0.12}_{-0.10}$	$0.58^{+0.25}_{-0.33}$	$0.78^{+0.50}_{-0.21}$	$0.85^{+0.15}_{-0.12}$	$0.45^{+0.33}_{-0.37}$
$\delta_D^{K3\pi}$	$(167^{+31}_{-19})^\circ$	$(131^{+124}_{-16})^\circ$	$(150^{+37}_{-39})^\circ$	$(176^{+57}_{-21})^\circ$	$(274^{+19}_{-30})^\circ$
$r_D^{K3\pi}$ $(\times 10^{-2})$	5.46 ± 0.09	$5.44^{+0.45}_{-0.14}$	$5.80^{+0.14}_{-0.13}$	$5.75^{+0.41}_{-0.14}$	$5.09^{+0.14}_{-0.14}$
$R_{K\pi\pi^0}$	0.78 ± 0.04	0.80 ± 0.04			
$\delta_D^{K\pi\pi^0}$	$(196^{+14}_{-15})^\circ$	$(200 \pm 11)^\circ$			
$r_D^{K\pi\pi^0}$ $(\times 10^{-2})$	4.40 ± 0.11	4.41 ± 0.11			



γ from $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ decays

- Large CPV observed in local bins!

JHEP ***07*** *(2023) 138*



$$\gamma = \left(54.8\,^{+6.0}_{-5.8}\,^{+0.6}_{-0.6}\,^{+6.7}_{-4.3}\right)^{\circ}$$

Comparable to golden mode!

Large expected improvement from incoming 20fb^{-1} of BESIII ψ(3770) data

D→π⁺π⁻π⁺π⁻ F⁺ measurement

*PRD **106** (2022) 092004*

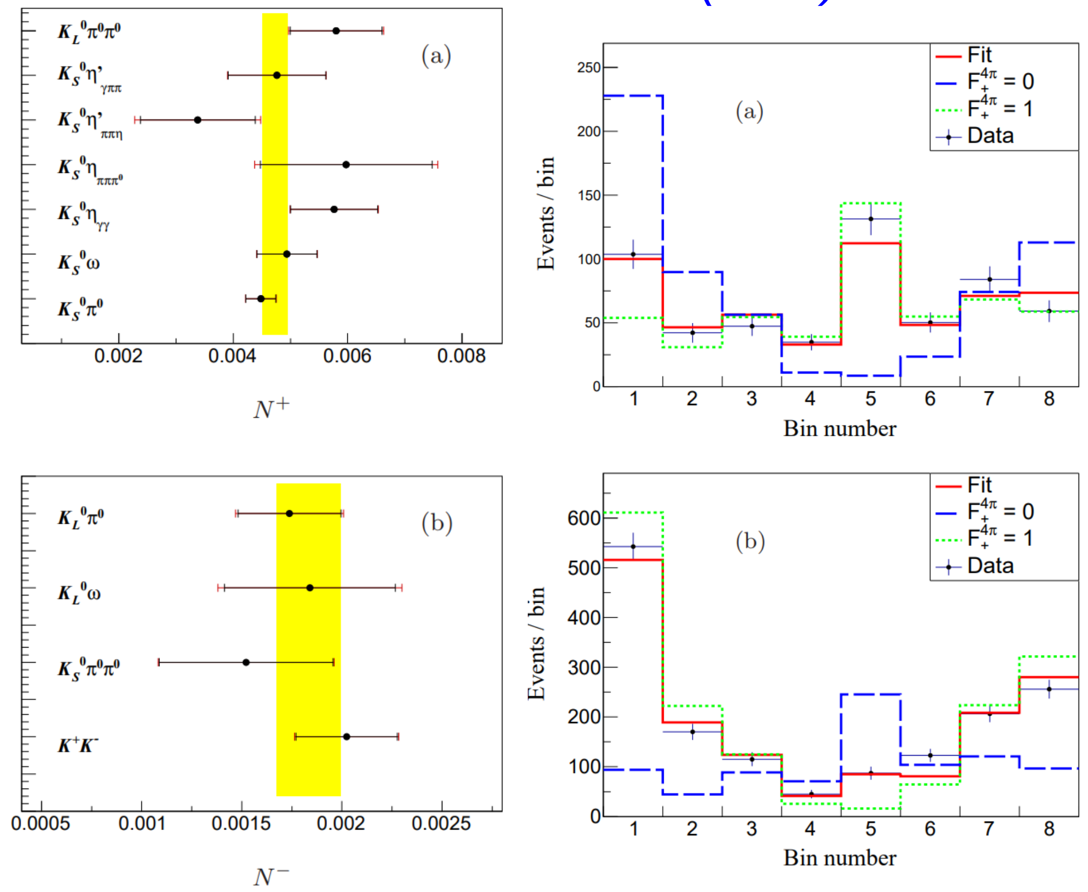
- Based on 2.9 fb^{-1} data
- Br(ππππ) = (7.56 ± 0.20)×10^{-3}
- Similar analysis strategy as previous
  - CP tags $\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} \propto 1 \mp (2F_+ - 1)$
  - $K_S/K_L\pi\pi$ included

$$M_i = h\left[K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}(2F_+ - 1)\right]$$

$$M_i' = h'\left[K_i' + K_{-i}' + 2c_i'\sqrt{K_i'K_{-i}'}(2F_+ - 1)\right]$$

- Combined: $F_+^{4\pi} = 0.735 \pm 0.015 \pm 0.005\,,$
- Consistent with previous results, but more precise
- This result is used for γ measurement in LHCb

*EPJC **83** (2023) 547*



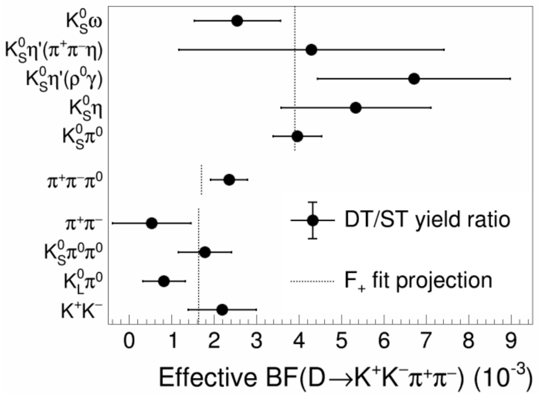
Tag modes	$F_+^{4\pi}$
CP eigenstates	0.721±0.019±0.007
$D \to \pi^+\pi^-\pi^0$	0.753±0.028±0.010
$D \to K^0_{S,L}\pi^+\pi^-$	0.754±0.031±0.009
Combination	0.735±0.015±0.005

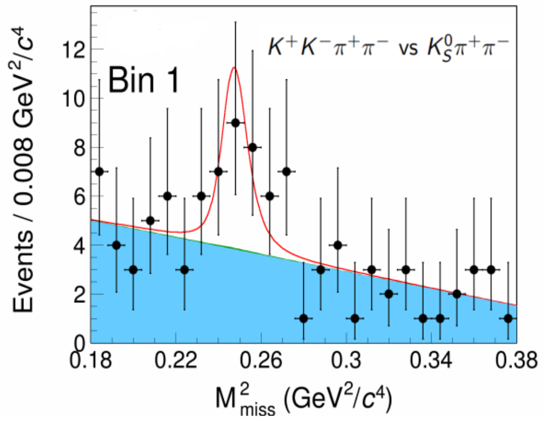
D→$K^+K^-\pi^+\pi^-$ F^+ measurement

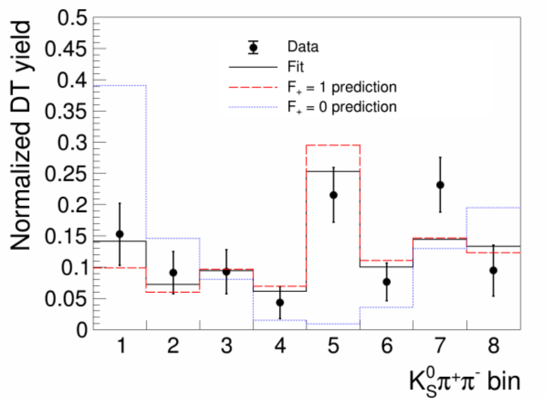
*PRD **107** (2023) 032009*

- Based on 2.9 fb^{-1} data
- $Br(KK\pi\pi) = (2.47 \pm 0.11)\times10^{-3}$
- Similar analysis strategy as previous
- Partial reconstruction method to improve statistics
- Finally: $F_+ = 0.730 \pm 0.037 \pm 0.021$
- This result is used for γ measurement in LHCb

*EPJC **83** (2023) 547*



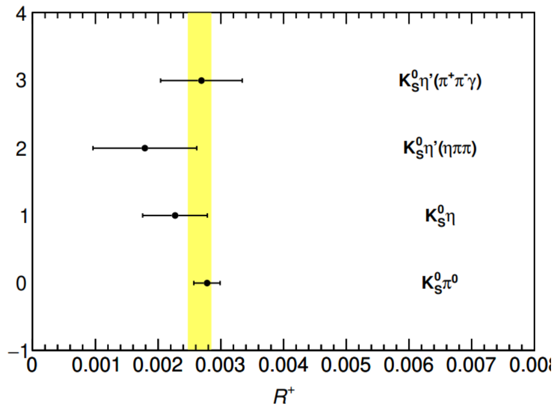


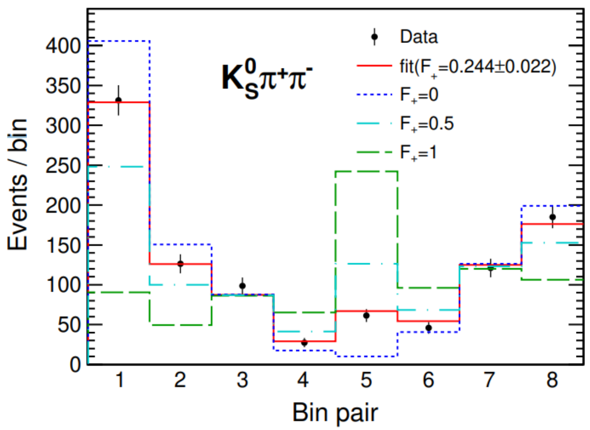


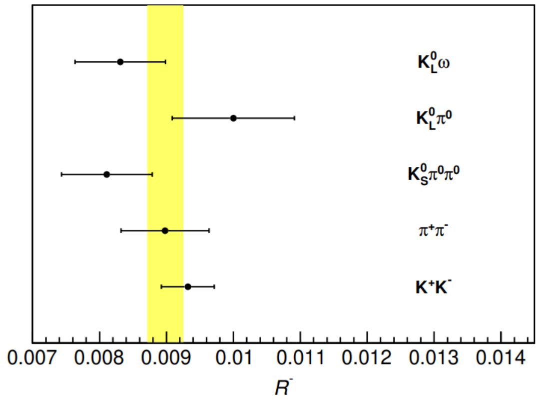
$D \rightarrow K_S\pi^+\pi^-\pi^0$ F^+ measurement

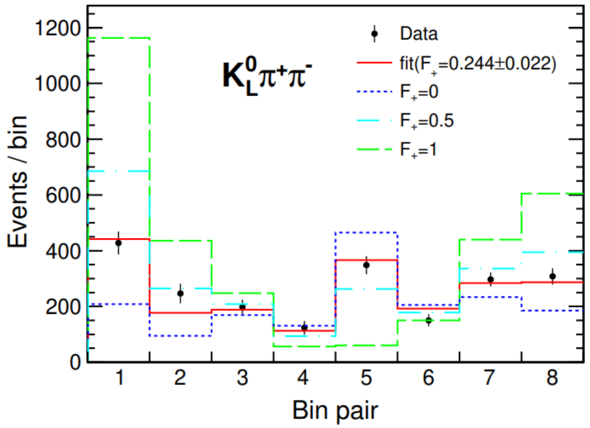
*PRD **108** (2023) 032003*

- Based on 2.9 fb^{-1} data
- $Br(K_S\pi^+\pi^-\pi^0) = (5.2 \pm 0.6)\%$
- Similar analysis strategy
- Consistent with CLEO-c's result, a factor 1.7 times more precise



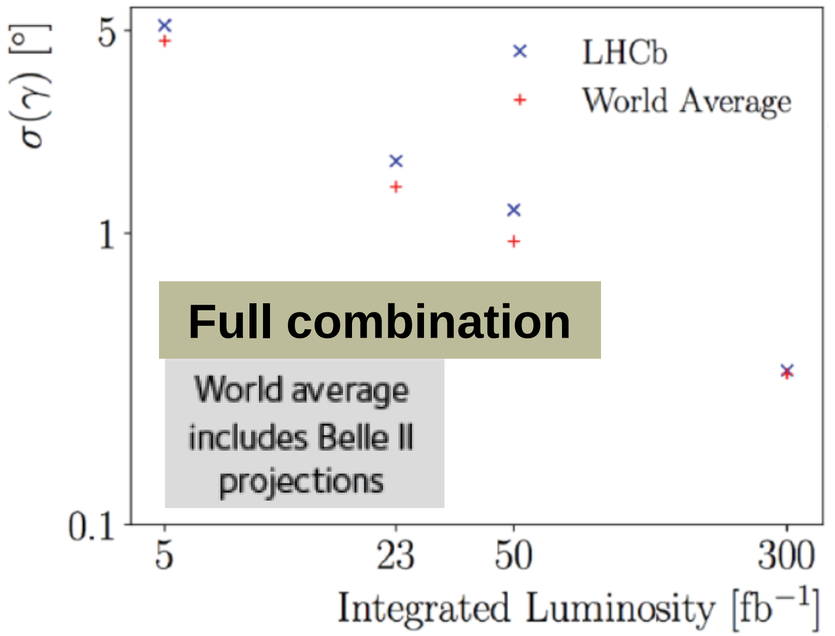






Method	F_+
CP-tag modes	$0.229 \pm 0.013 \pm 0.002$
$\pi^+\pi^-\pi^0$ tag mode	$0.227 \pm 0.014 \pm 0.003$
$\pi^+\pi^-\pi^+\pi^-$ tag mode	$0.227 \pm 0.016 \pm 0.003$
Self-tag modes	$0.244 \pm 0.019 \pm 0.002$
$K^0_{S,L}\pi^+\pi^-$	$0.244 \pm 0.021 \pm 0.006$
Combined	$0.235 \pm 0.010 \pm 0.002$

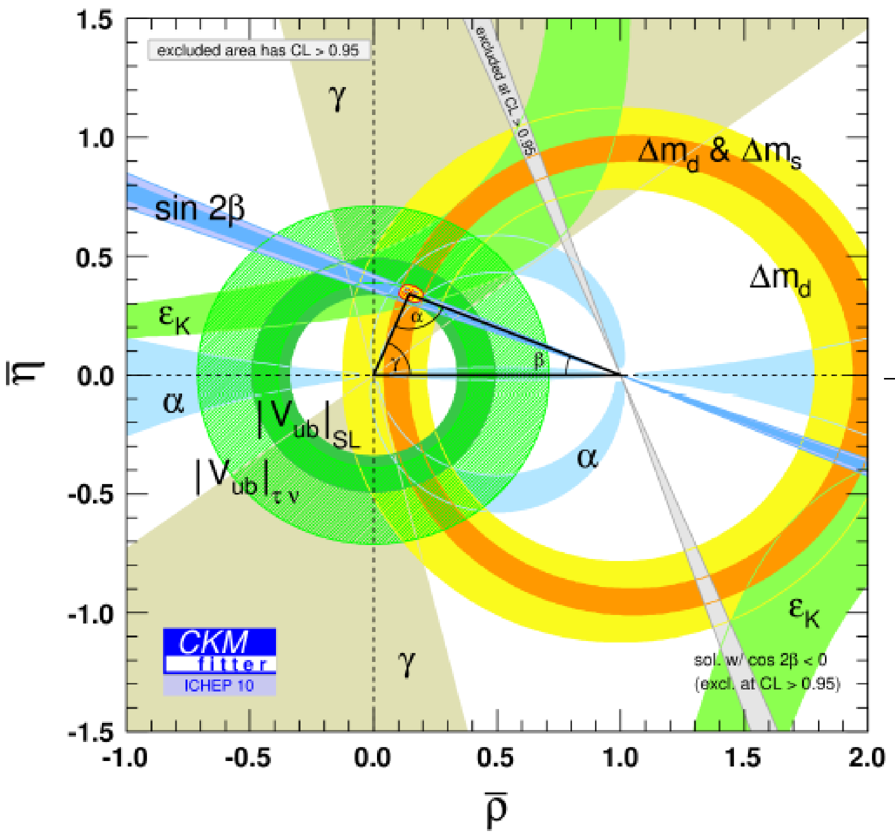
Future prospects for γ

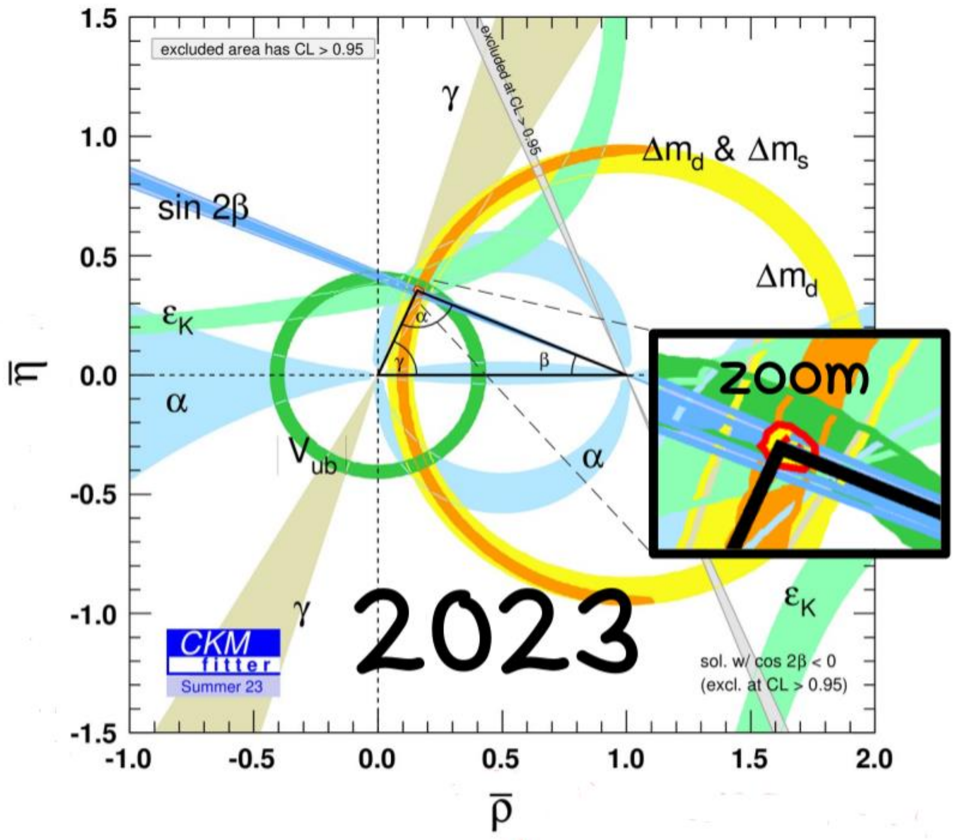


- Status now:
  - Error for γ is about 4°
  - BESIII contribute about 1°
- Around 2030
  - Less than 1° will be achieved
  - BESIII 20fb^{-1} data → improve the error to <0.5°
- (>)2035
  - LHCb upgradeII → sensitivity <0.4°
  - Need more charm factory data (STCF)

dataset	Int. Lum.	year	sensitivity
LHCb Run1 (7,8TeV)	3 fb^{-1}	2012	8°
LHCb Run2 (13TeV)	6 fb^{-1}	2018	4°
BelleII Run	50 ab^{-1}	2025	1-2°
LHCb upgrade (14TeV)	50 fb^{-1}	2030	<1°
LHCb upgradeII (14TeV)	200 fb^{-1}	(>)2035	<0.4°

Summary



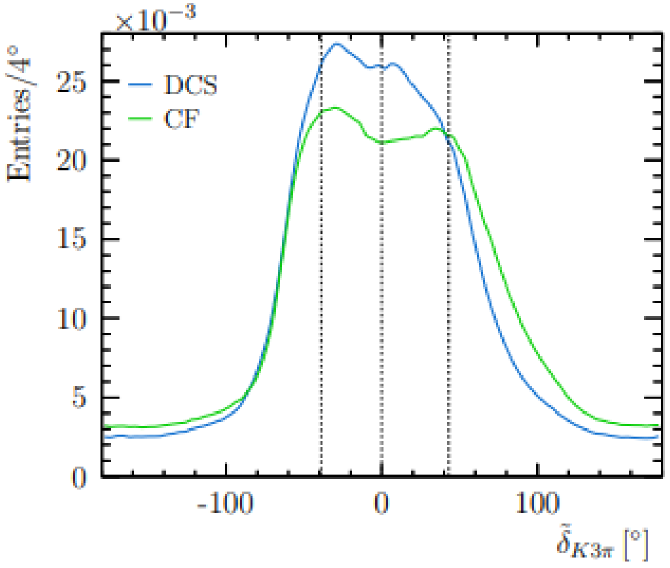


- 10 years of measurements have been game changing for flavor physics
- γ no longer the least precisely known of the weak phases!
- Now precision of < 4^{o}, many more modes still need to add!
- BESIII (STCF) will play important roles for the charm inputs

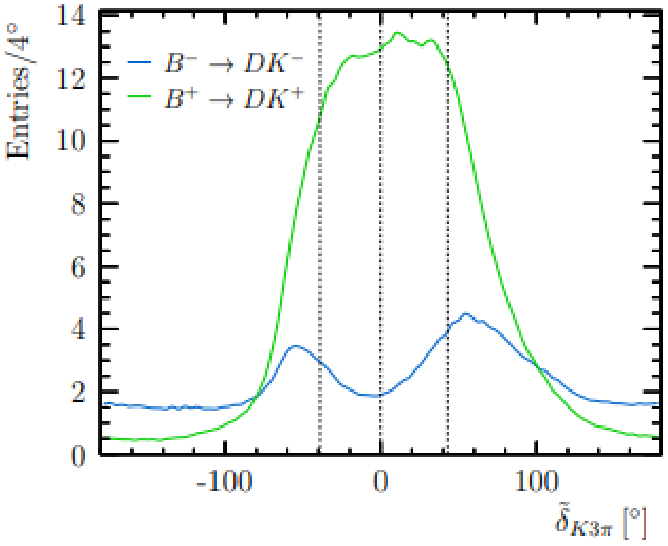
Thank you!

backup

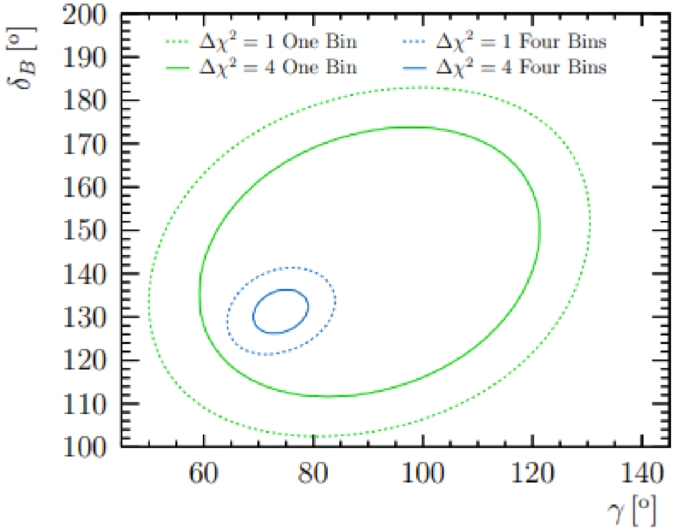
K3π binning scheme



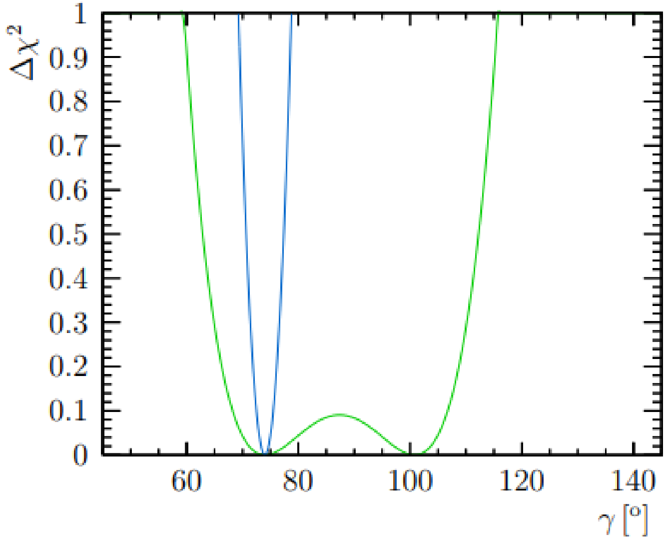
(a)



(b)



(a)

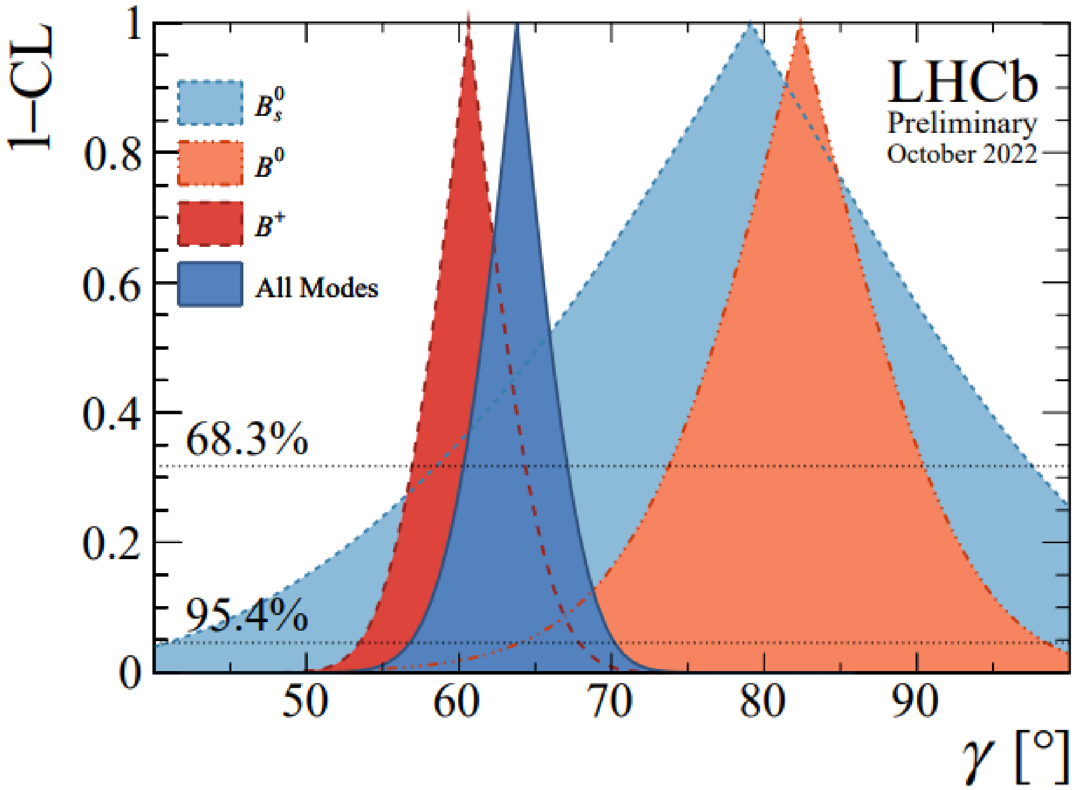


(b)

LHCb γ combination

- Best knowledge of γ comes from combination of many measurements
- Maximum likelihood fit
  - 173 observables
  - 52 free parameters
- Most precise determination of γ by a single experiment:

$$\gamma = (63.8^{+3.5}_{-3.7})^o$$



Input parameters

Decay	Parameters	Source	Ref.	Status since Ref. [14]
$B^\pm \to DK^{*\pm}$	$\kappa_{B^\pm}^{DK^{*\pm}}$	LHCb	[33]	As before
$B^0 \to DK^{*0}$	$\kappa_{B^0}^{DK^{*0}}$	LHCb	[53]	As before
$B^0 \to D^\mp\pi^\pm$	β	HFLAV	[13]	As before
$B_s^0 \to D_s^\mp K^\pm(\pi\pi)$	ϕ_s	HFLAV	[13]	As before
$D \to K^+\pi^-$	$\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$, $(r_D^{K\pi})^2$, x^2, y	CLEO-c	[27]	**New**
$D \to K^+\pi^-$	$A_{K\pi}$, $A_{K\pi}^{\pi\pi\pi^0}$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	BESIII	[28]	**New**
$D \to h^+h^-\pi^0$	$F_{\pi\pi\pi^0}^+$, $F_{KK\pi^0}^+$	CLEO-c	[54]	As before
$D \to \pi^+\pi^-\pi^+\pi^-$	$F_{4\pi}^+$	CLEO-c+BESIII	[26, 54]	**Updated**
$D \to K^+\pi^-\pi^0$	$r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	CLEO-c+LHCb+BESIII	[55–57]	As before
$D \to K^\pm\pi^\mp\pi^+\pi^-$	$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$	CLEO-c+LHCb+BESIII	[49, 55–57]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$, $\delta_D^{K_S^0K\pi}$, $\kappa_D^{K_S^0K\pi}$	CLEO	[58]	As before
$D \to K_S^0K^\pm\pi^\mp$	$r_D^{K_S^0K\pi}$	LHCb	[59]	As before