Input for γ measurements from BESIII

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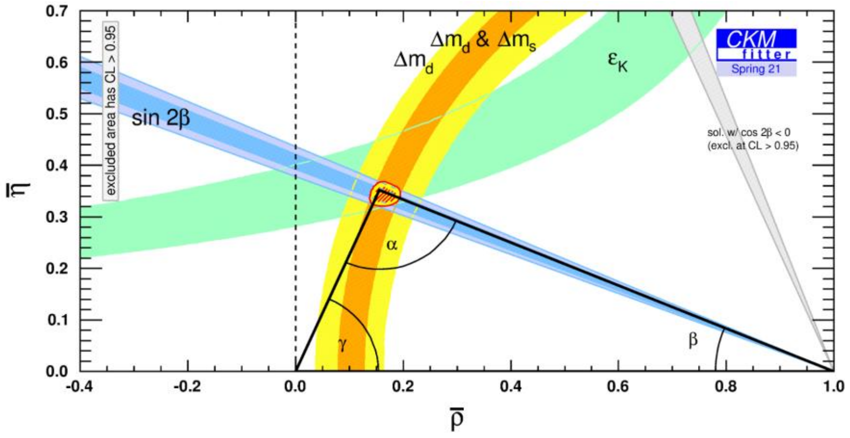
Outline

- Introduction
- Method to measure γ
- Latest γ results @ LHCb
- Joint measurement by LHCb & BESIII
- Future prospect of γ
- Summary

Why measure γ

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

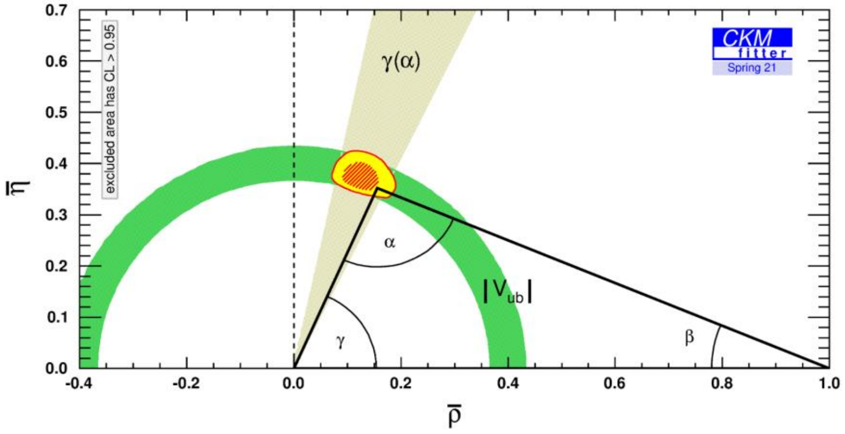
Indirect measurement



- Extrapolate γ from measurement of α and β
- Measured using loop-level decays: sensitivity to NP
- CKMFitter latest: $\gamma = (65.5^{+1.1}_{-2.7})^o$

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]*

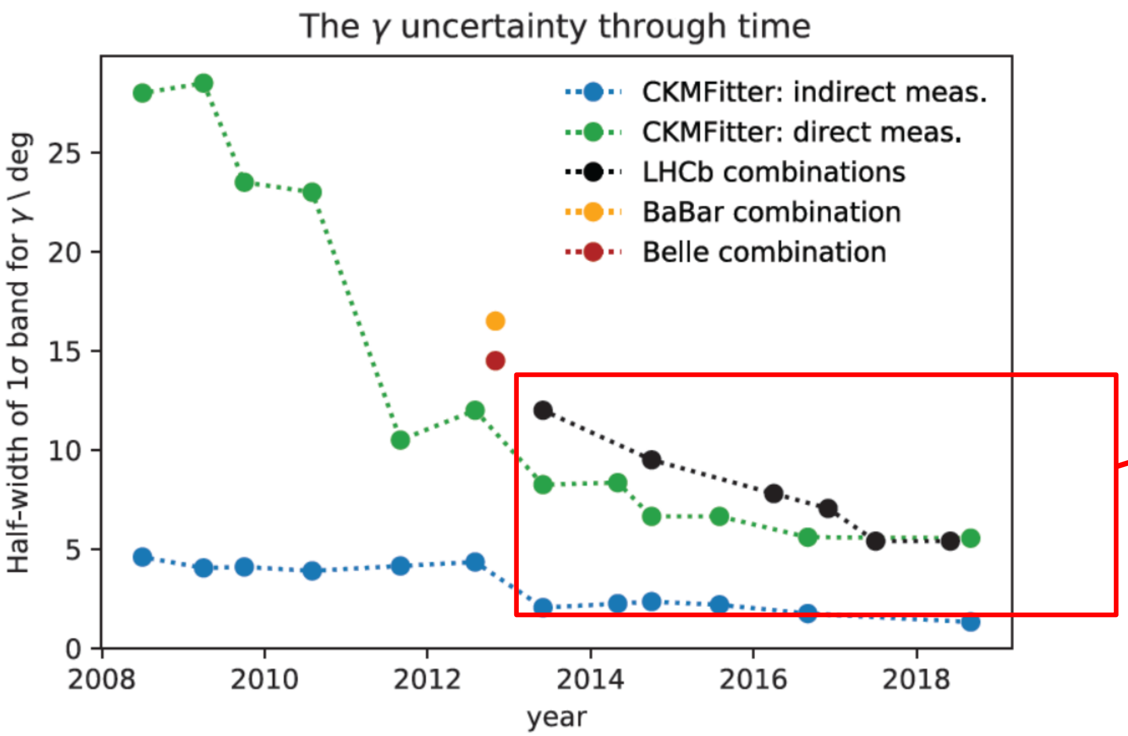
- Interference between favoured b→c and suppressed b→u decay amplitude

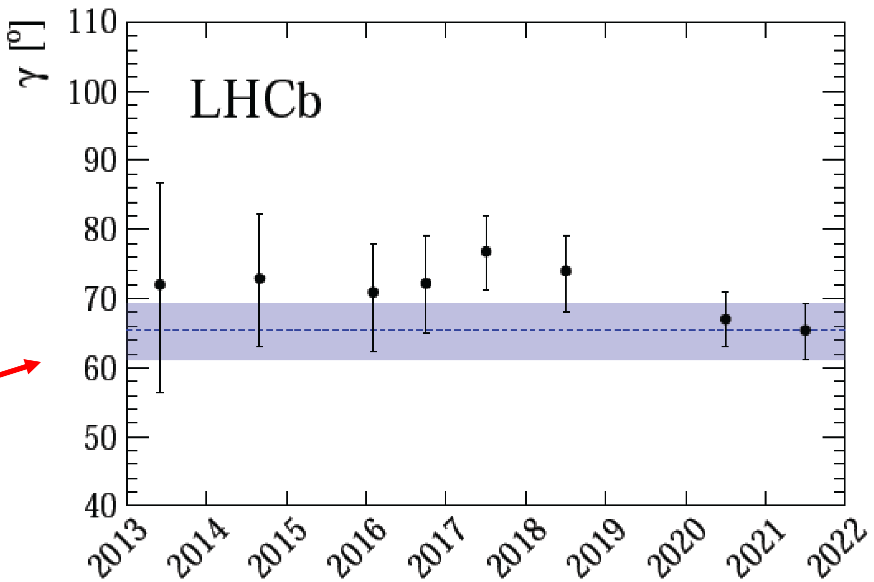
- Ideal decays: B→DK (clean background, large branching fraction)

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

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

Evolution of γ results



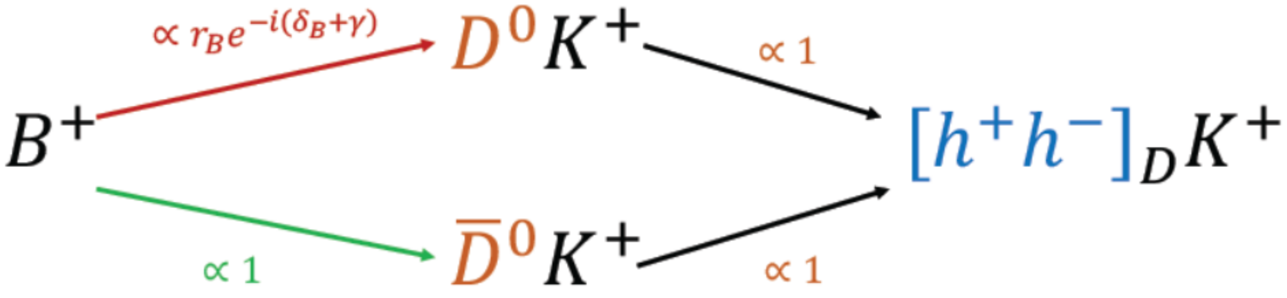


- LHCb dominates current world averages of direct γ measurements
- The focus of this talk:
  - Method to measure γ
  - LHCb latest results
  - Importance of the BESIII input

GLW method [1,2]

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

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



Changing flavours: sign of γ changes

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

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

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

$$A^{hh} = \frac{N(B^- \rightarrow [hh]_D K^-) - N(B^+ \rightarrow [hh]_D K^+)}{N(B^- \rightarrow [hh]_D K^-) + N(B^+ \rightarrow [hh]_D K^+)} = \frac{2r_B \sin\delta_B \sin\gamma}{R^{hh}}$$

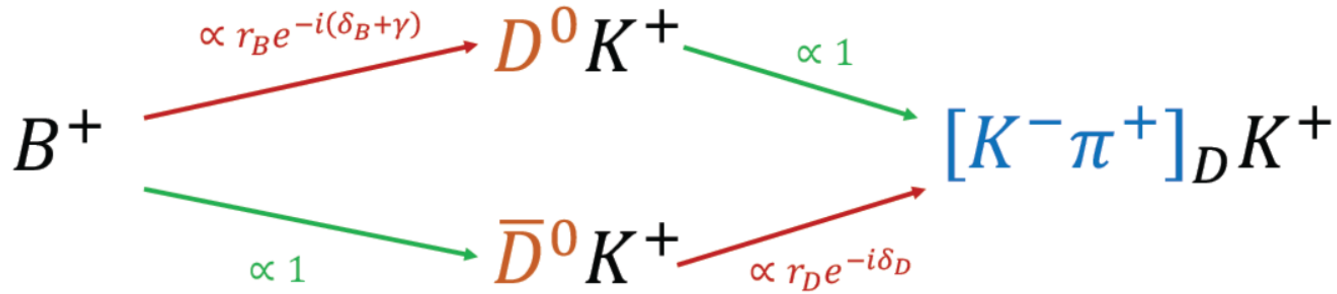
$$R^{hh} = \frac{N(B^- \rightarrow [hh]_D K^-) + N(B^+ \rightarrow [hh]_D K^+)}{N(B^- \rightarrow [K\pi]_D K^-) + N(B^+ \rightarrow [K\pi]_D K^+)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$

- Disadvantage:
  - Multiple solutions
  - Low statistic
  - Need input r_B/δ_B

[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

$$\Gamma(B^0 \to DK^{*0}) \propto r_D^2 + r_B^{DK^{*0}\,2} + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D + \gamma)$$
$$\Gamma(\bar{B}^0 \to D\bar{K}^{*0}) \propto r_D^2 + r_B^{DK^{*0}\,2} + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D - \gamma)$$

Need inputs from charm factory

- Disadvantage:
  - r_D is small
  - For $K n\pi$, coherence factor $\kappa_{Kn\pi}$ 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

- Golden mode: $D \rightarrow K_s\pi\pi/K_sKK$ (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° from BESIII input)

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

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

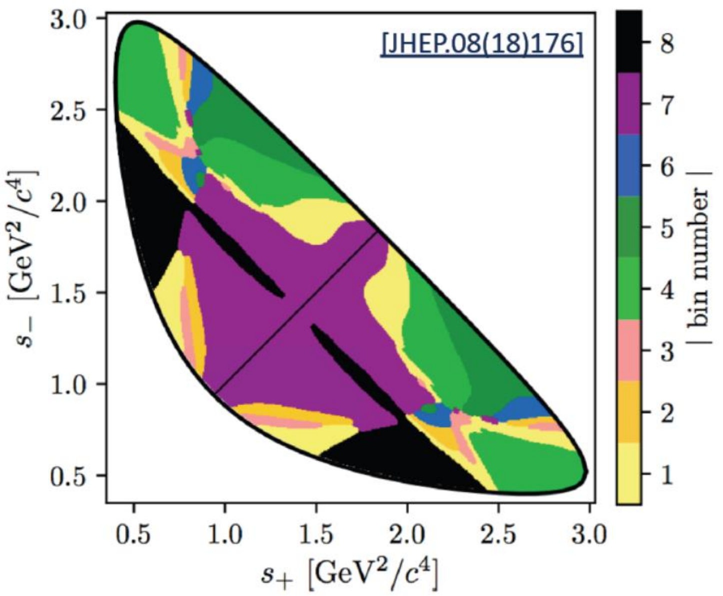
F_i : Fractional yield of flavour tagged D^0 into bin i

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

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

External input from CLEO-c measurement [1010.2817]

Superseded by BESIII



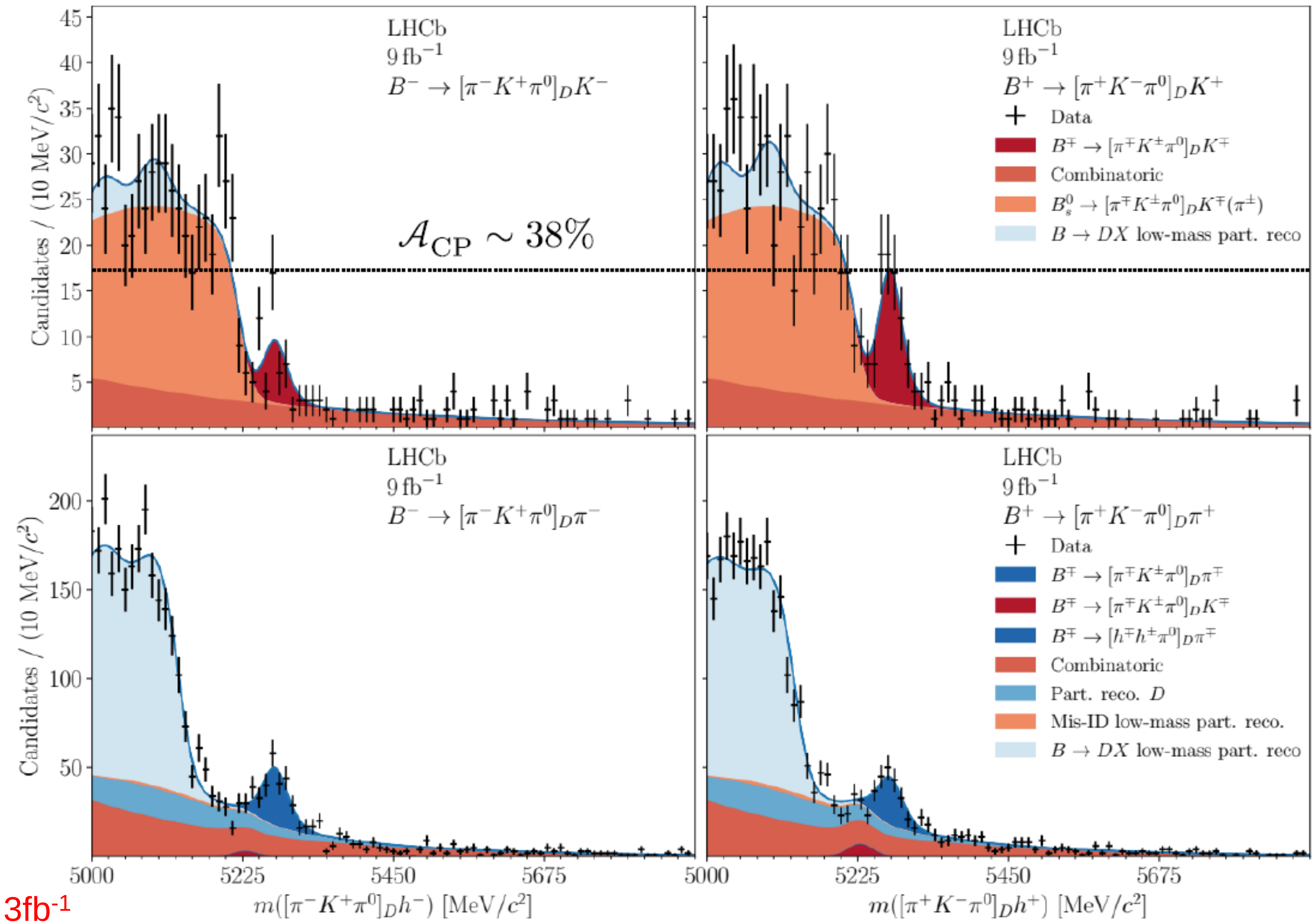
[1] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68 (2003) 054018

γ from $B^{\pm} \to D[h^{\pm}h'^{\mp}\pi^0]h^{\pm}$ decays

- GLW+ADS method
- π^0 reconstruction is challenge..
- Three D decays
  - $D \to K\pi\pi^0$(pictured)
  - $D \to \pi\pi\pi^0$
  - $D \to KK\pi^0$
- Two B decays
  - $B^+ \to DK^+$
  - $B^+ \to D\pi^+$
- Full Run 1&2 Data set

$$\gamma = (56^{+24}_{-19})^\circ, \quad \delta_B = (122^{+19}_{-23})^\circ, \quad r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$$

JHEP 07(2022) 099

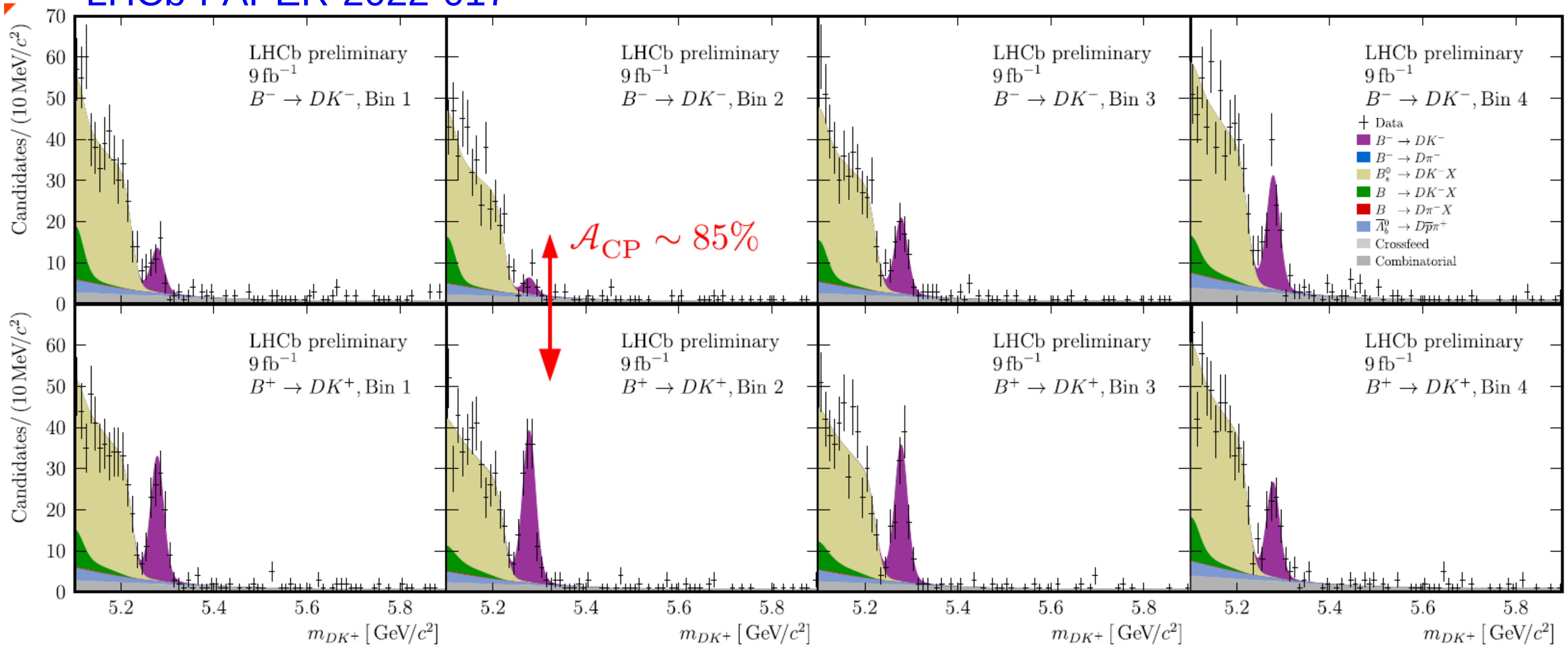


- Charm input
  - $r_D = 0.0441 \pm 0.0011$
  - $\delta_D = (196 \pm 11)^o$ — From BESIII 3fb^{-1}
  - $\kappa_D = 0.79 \pm 0.04$
  - $F_+^{\pi\pi\pi^0} = 0.973 \pm 0.017, F_+^{KK\pi^0} = 0.732 \pm 0.055$ — From CLEO-c 0.8fb^{-1}, soon updated by BESIII

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

- Measure observables in 4 bins of D-decay phase-space (*PLB 802(2020)135188*)

LHCb-PAPER-2022-017



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

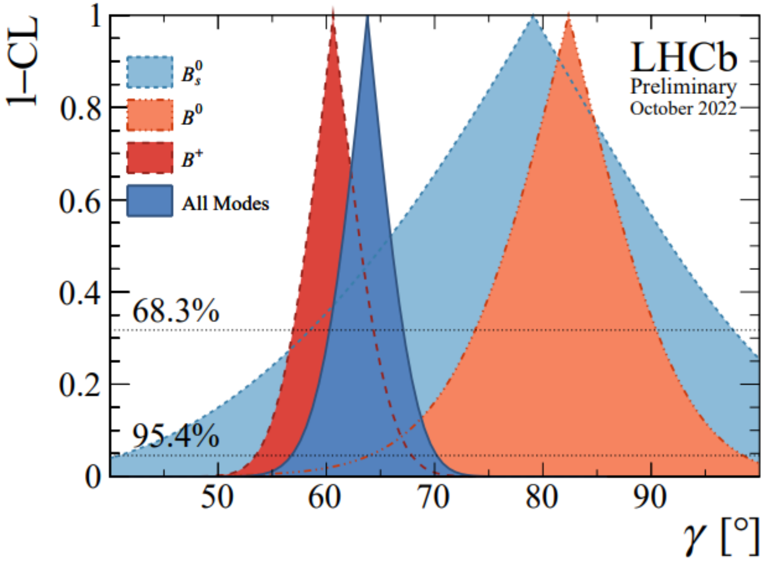
Comparable to golden mode!

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

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:

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



B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2	As before
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [14]
$D^0 \to h^+h^-$	ΔA_{CP}	[24, 40, 41]	Run 1&2	As before
$D^0 \to K^+K^-$	$A_{CP}(K^+K^-)$	[16, 24, 25]	Run 2	**New**
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[42]	Run 1	As before
$D^0 \to h^+h^-$	$y_{CP} - y_{CP}^{K^-\pi^+}$	[15]	Run 2	**New**
$D^0 \to h^+h^-$	ΔY	[43–46]	Run 1&2	As before
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[47]	Run 1	As before
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[48]	Run 1&2(*)	As before
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[49]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[50]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[51]	Run 1	As before
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[52]	Run 2	As before
$D^0 \to K^0_S\pi^+\pi^-$ (μ^- tag)	x_{CP}, y_{CP}, Δx, Δy	[17]	Run 2	**New**

LHCb-CONF-2022-003

Quantum correlated $D\bar{D}$ measurement

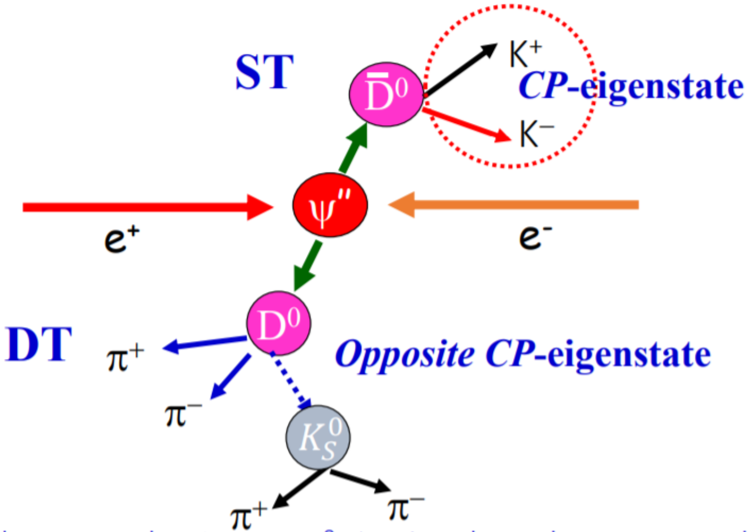
- $\psi(3770)$ is a spin -1 states, therefore the amplitude of $\psi(3770) \rightarrow D\bar{D}$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$ [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



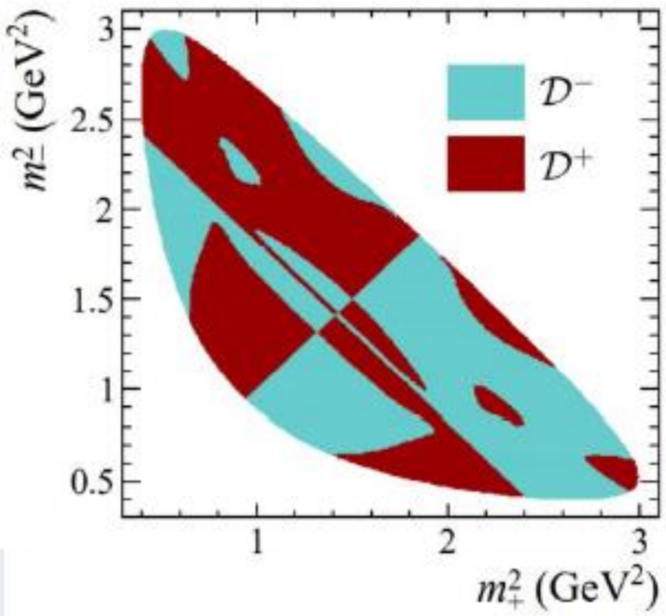
The DT mode K^+K^- *vs.* $K_S^0\pi^+\pi^-$ is selected as an example.

- ✓ 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	$K_S^0\pi^+\pi^-$

Unbinned model-independent method

- Basic idea: Bins → Events (Eur. Phys. J. C, 2018, 78(2))
  - Make most use of amplitude info in phase space
- Fourier expansion the amplitude by strong phase
  - Parameters definition similar to BPGGSZ method



- $\bar{a}_n^{B\pm} = \bar{h}_B\{a_n^{D\mp} + r_B^2 a_n^{D\pm} + 2[x_+ a_n^C \pm y_+ a_n^S]\}$
- $\bar{b}_n^{B\pm} = \bar{h}_B\{-b_n^{D\mp} + r_B^2 b_n^{D\pm} \pm 2[x_+ b_n^C - y_+ a_n^S]\}$
- $a_n^{B\pm} = h_B\{a_n^{D\pm} + r_B^2 a_n^{D\mp} + 2[x_- a_n^C \mp y_- a_n^S]\}$
- $b_n^{B\pm} = h_B\{b_n^{D\pm} - r_B^2 b_n^{D\mp} \pm 2[x_- b_n^C + y_- b_n^S]\}$
- $x_\pm = r_B \cos(\delta_B \pm \gamma)$
- $y_\pm = r_B \sin(\delta_B \pm \gamma)$

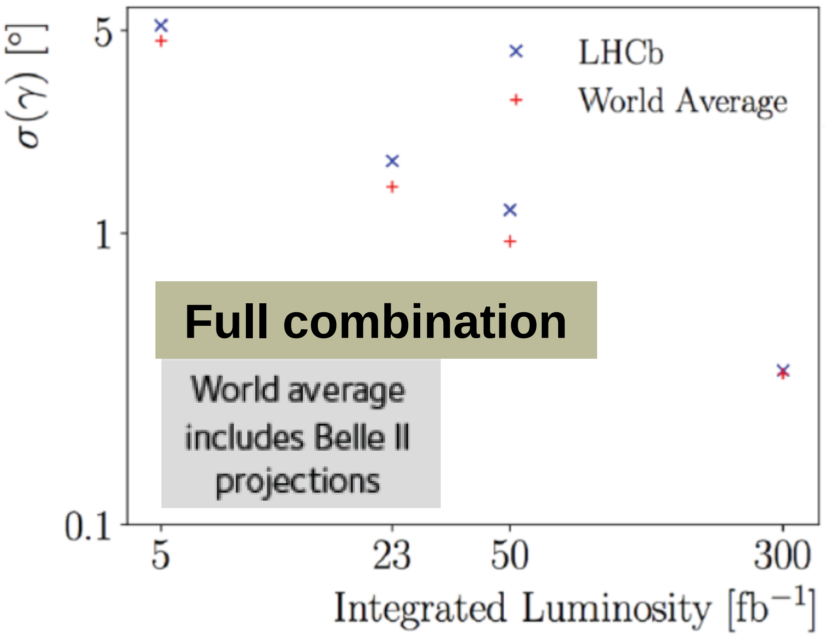
B sector

- $a'^{D\pm}_n = h_{D_f}\{a_n^{D\pm} + r_D^2 a_n^{D\mp} - 2R_D r_D[\cos(\delta_D) a_n^C \pm \sin(\delta_D)\, a_n^S]\}$
- $\lambda_{CP} = 2F_+ - 1$
- $a_n^{CP\pm} = h_{CP}[a_n^{D\pm} + a_n^{D\mp} - 2\lambda_{CP} a_n^C]$
- $a_{mn}^{DD\pm\pm} = h_{DD}[a_m^{D\pm} a_n^{D\mp} + a_m^{D\mp} a_n^{D\pm} - 2(a_m^C a_n^C \pm a_n^S a_m^S)]$

D sector

LHCb&BESIII joint analysis is ongoing

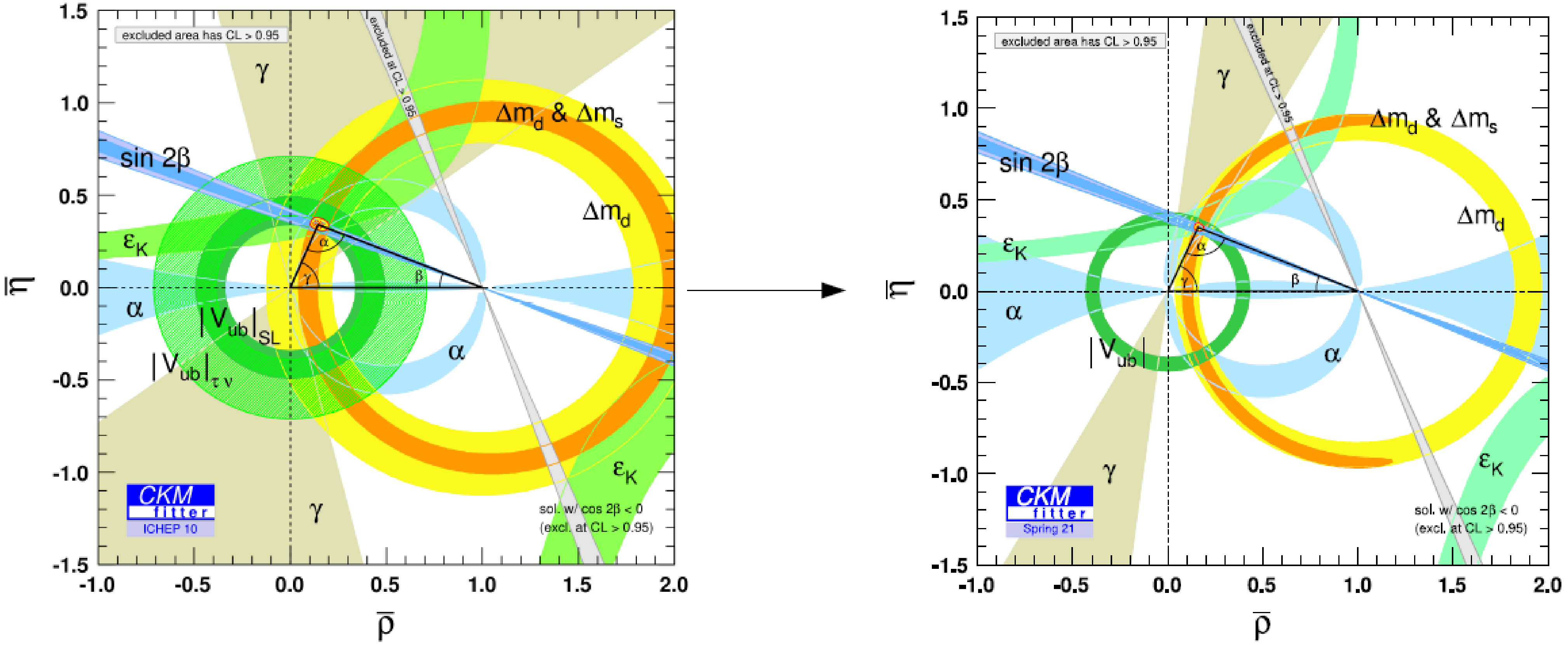
Future prospects for γ @ LHCb



- 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)

数据来源	收集/预期积分亮度	达成年份	B实验γ角精度
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°

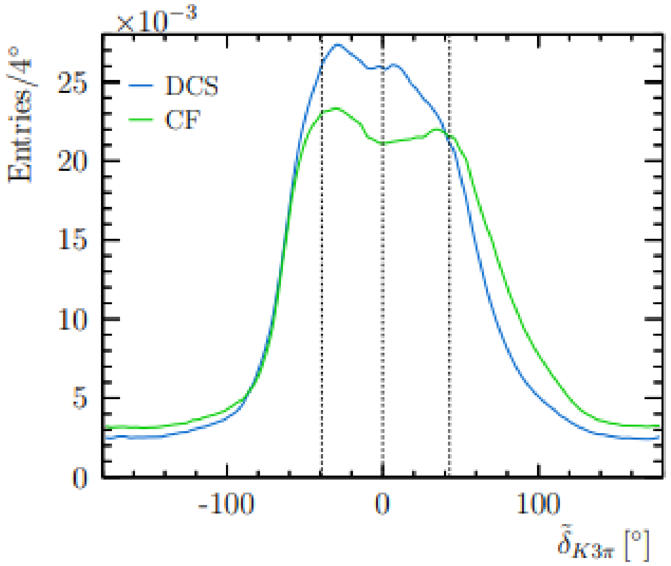
Summary



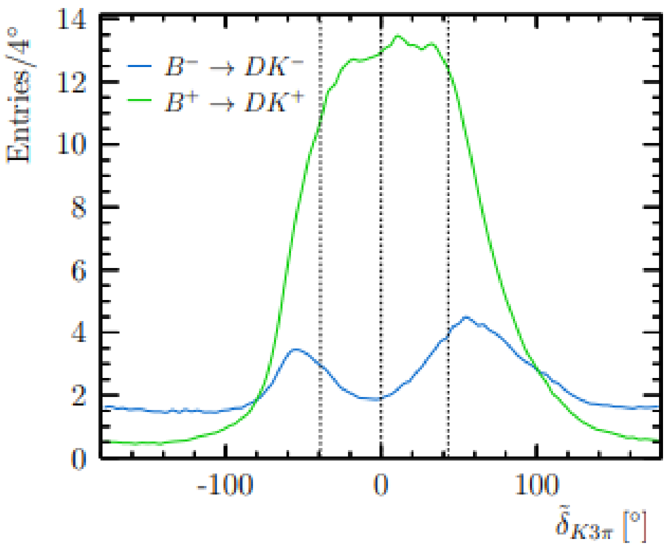
- 10 years of measurements have been game changing for flavor physics
- γ no longer the least precisely known of the weak phases!
- Now precision of < 4°, many more modes still to add!
- BESIII (STCF) will play important roles for the charm inputs

Thank you!

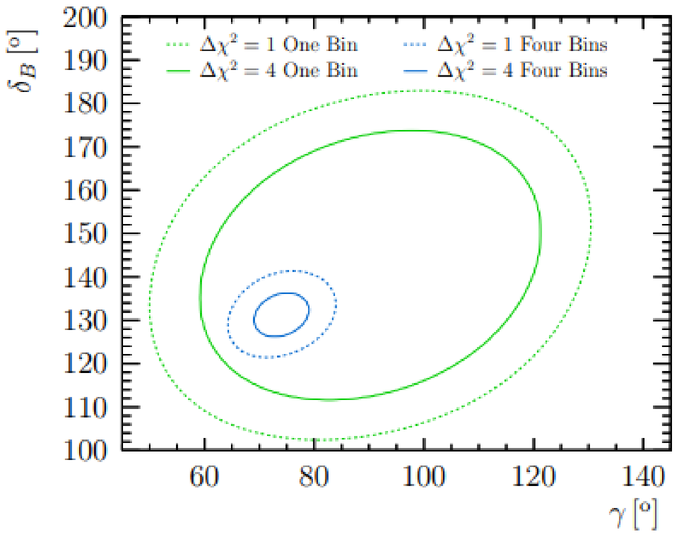
backup


$\times 10^{-3}$
Entries/4°
DCS
CF
$\tilde{\delta}_{K3\pi}$ [°]

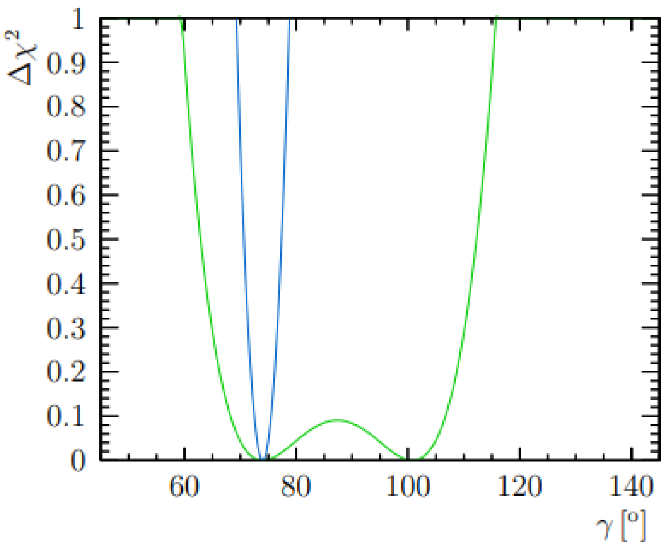
(a)


Entries/4°
$B^- \to DK^-$
$B^+ \to DK^+$
$\tilde{\delta}_{K3\pi}$ [°]

(b)


δ_B [°]
$\Delta\chi^2 = 1$ One Bin
$\Delta\chi^2 = 4$ One Bin
$\Delta\chi^2 = 1$ Four Bins
$\Delta\chi^2 = 4$ Four Bins
γ [°]

(a)


$\Delta\chi^2$
γ [°]

(b)

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