CKM angle γ measurements at LHCb and expected inputs from BESIII

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22/08/2022

BESIII实验上粲强子、QCD及新物理研讨会

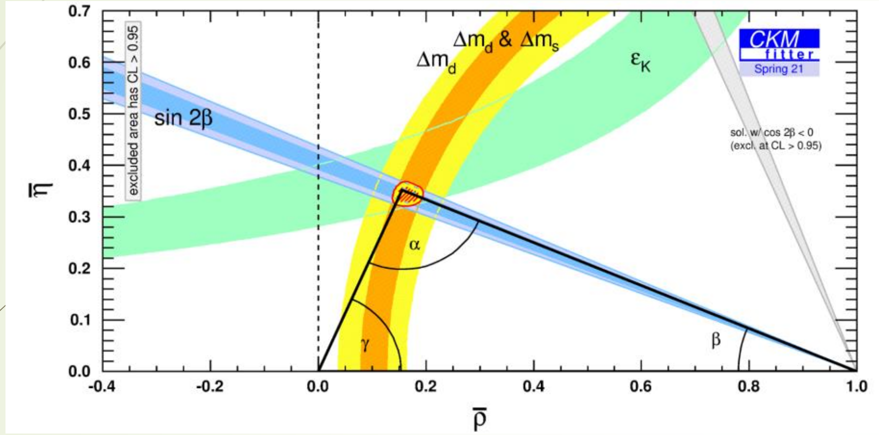
Outline

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

Why measure γ

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

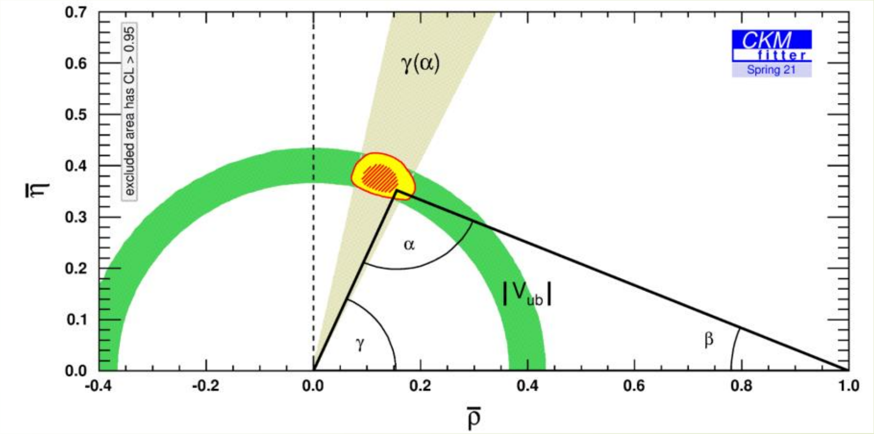
Indirect measurement



- 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!

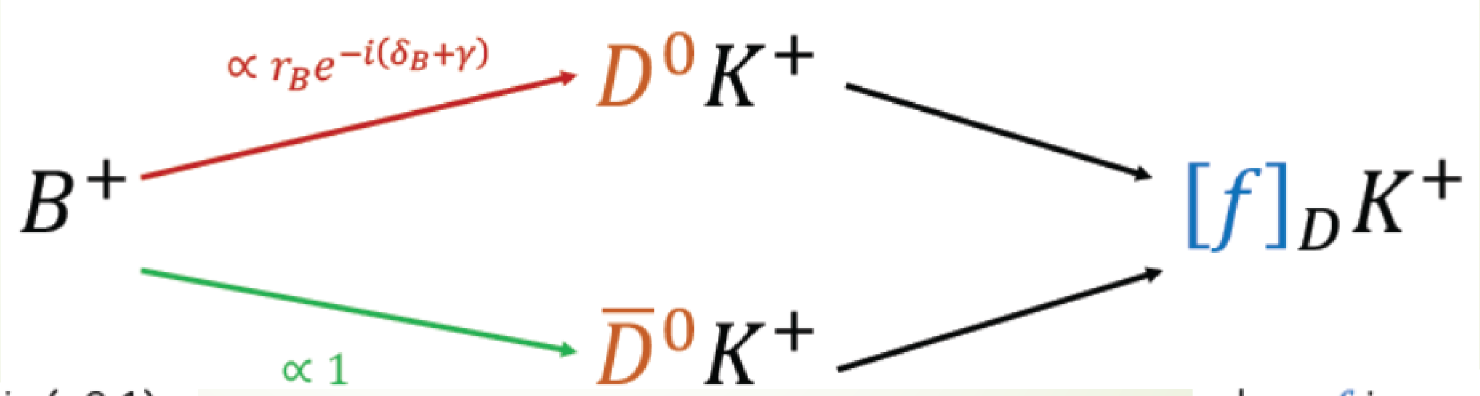
Direct measurement



- 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: $\gamma = (65.4^{+3.8}_{-4.2})^o$ *[JHEP 12(2021)141]*

How to measure γ directly

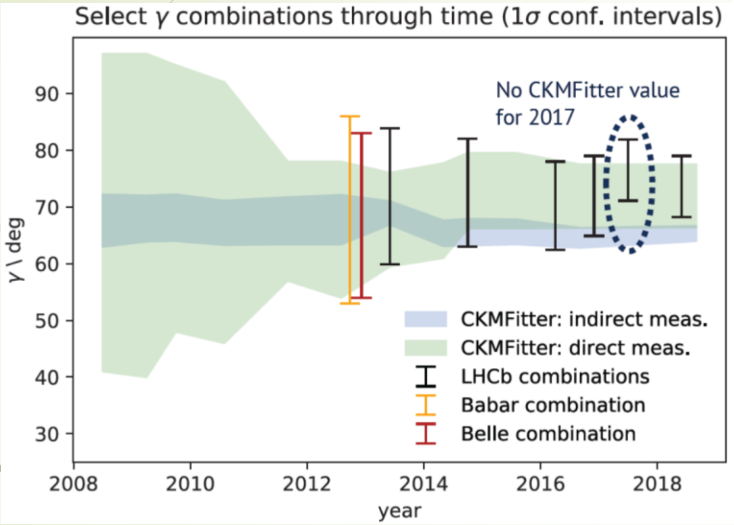
- Interference between favoured b→c and suppressed b→u decay amplitude
- Ideal decays: B→DK

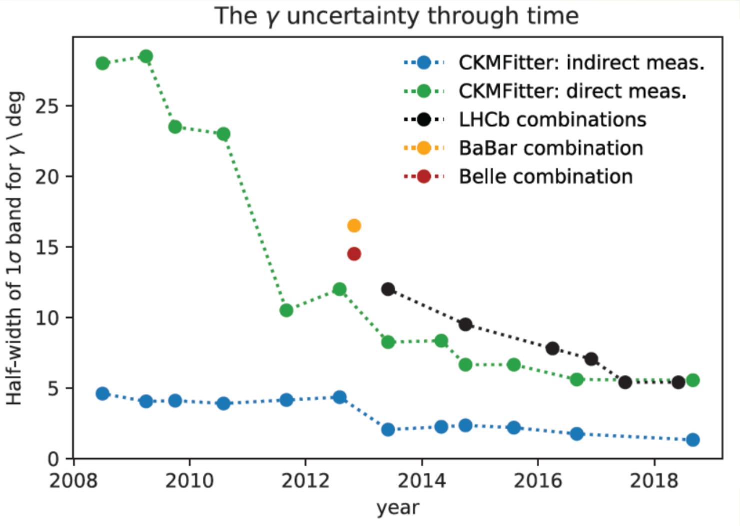


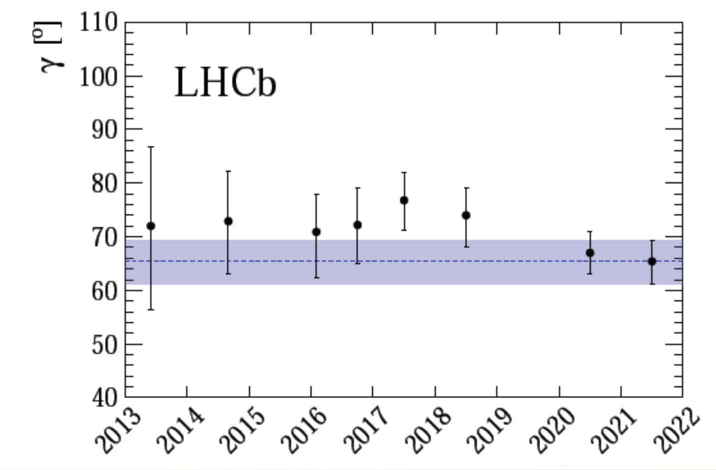
r_B = magnitude ratio (~0.1)
δ_B = strong-phase difference

where f is some final state accessible to both D^0 and $\bar{D}^0$

Evolution of γ results



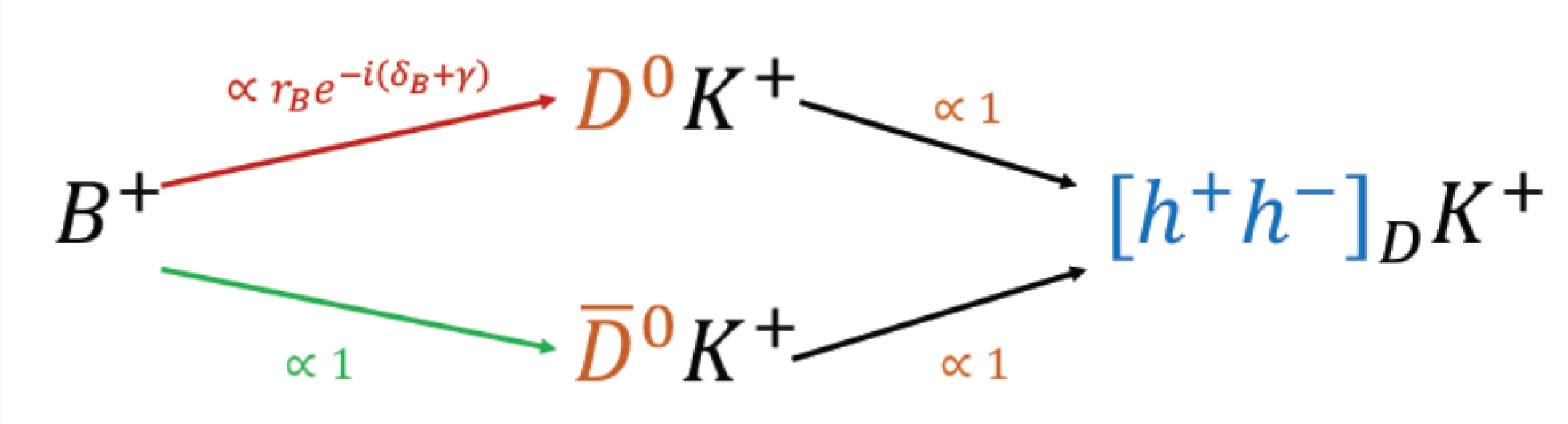




- LHCb dominates current world averages of direct γ measurements
- The focus of this talk:
  - LHCb latest results
  - The LHCb γ combination and a look towards the future

GLW method[1,2]

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



Changing flavours: sign of γ changes

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

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

GLW method

- Use the yields of B+ and B- to construct observables related to γ
- Asymmetry between flavors:

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

- Ratio of total yield w.r.t Cabibbo-favored decay $K\pi$

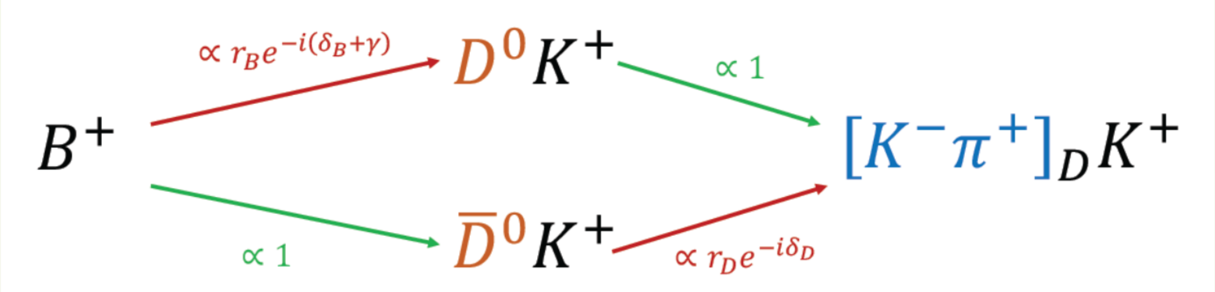
$$R^{hh}=\frac{N(B^-\to[hh]_DK^-)+N(B^+\to[hh]_DK^+)}{N(B^-\to[K\pi]_DK^-)+N(B^+\to[K\pi]_DK^+)}=1+r_B^2+2r_B\cos\delta_B\cos\gamma$$

- Can also use $D\to\pi^+\pi^-\pi^+\pi^-$: insert a factor of $(2F_+-1)$ before interference terms (F_+=CP even content = 0.769+-0.023[1])

[1] JHEP 01 (2018) 144

ADS method[1,2]

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



- Treat similarly to GLW, except the input D parameters r_D and δ_D
- Can also use $D \rightarrow K3\pi$, with a coherence factor $\kappa_{K3\pi}$, and $r_{K3\pi}$ and $\delta_{K3\pi}$ averaged over phase space

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

$$R_-^{\pi K} = \frac{\Gamma(\bar{B}^0 \to [\pi^- K^+]_D \bar{K}^{*0})}{\Gamma(\bar{B}^0 \to [K^-\pi^+]_D \bar{K}^{*0})}$$
$$R_+^{\pi K} = \frac{\Gamma(B^0 \to [\pi^+ K^-]_D K^{*0})}{\Gamma(B^0 \to [K^+\pi^-]_D K^{*0})}$$

$R_+^{\pi K} \neq R_-^{\pi K} \to CP$ violation!

Need inputs from charm factory

[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

BPGGSZ method[1]

- Divide the phase space of D→Ksh⁺h⁻ decays into bins and measure the yields of B⁺ and B⁻ in each
  - Analysis is **independent of modelling** of D decay
  - Sensitivity from **phase-space distribution**, not overall asymmetries → not impacted by production/detection asymmetries

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

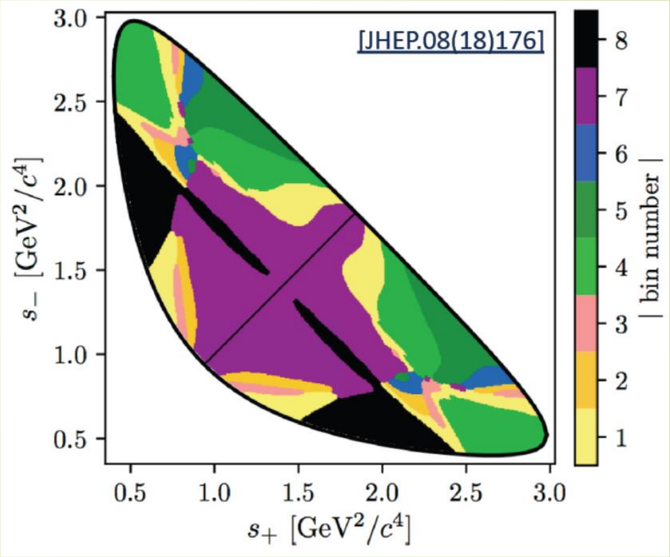
$$N^{-}_{\pm i} \propto F_{\pm i} + (x_\pm^2 + y_\pm^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} \mp y_\pm s_{\pm i})$$

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 CLEO-c measurement [1010.2817]

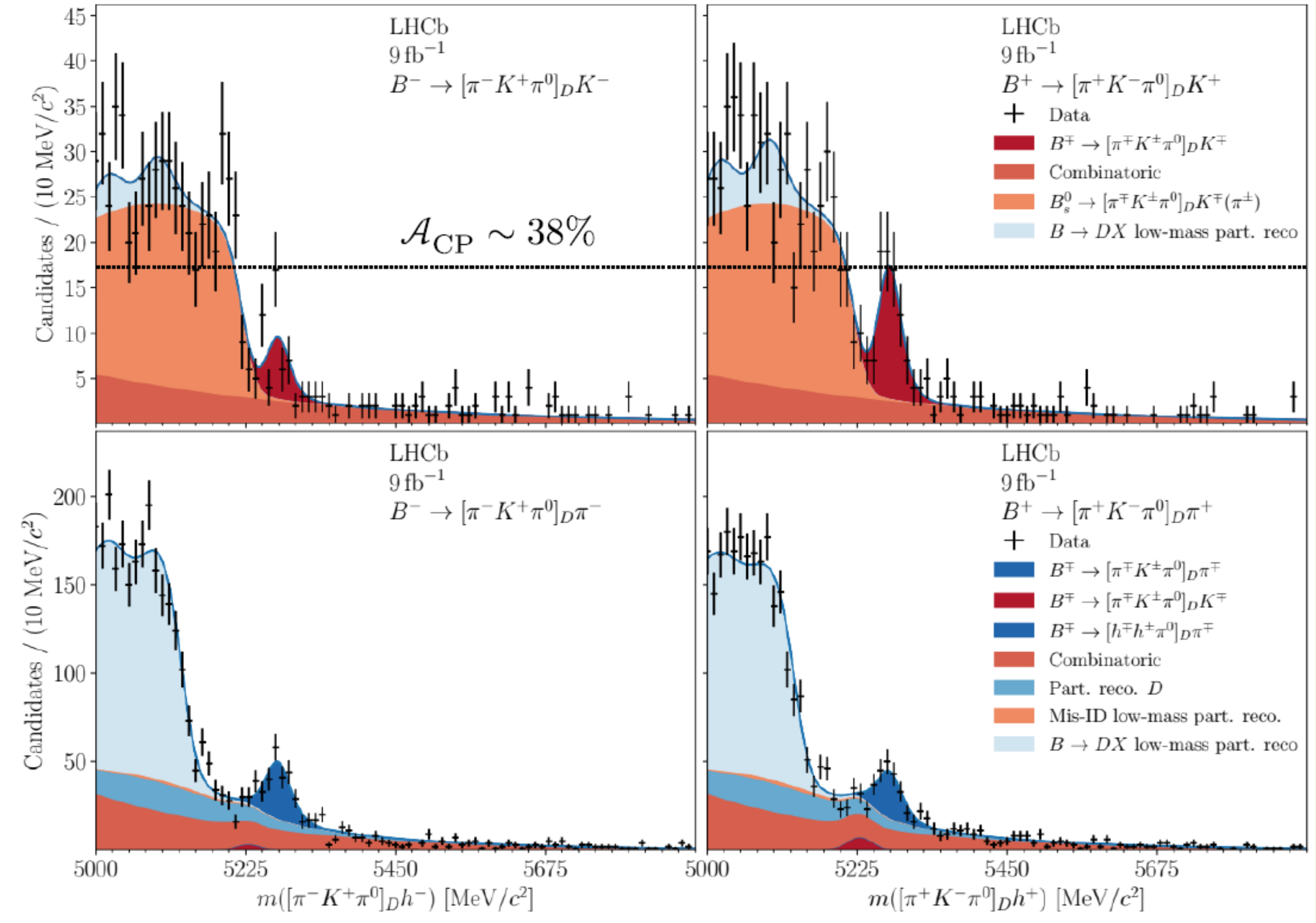


[1] A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68 (2003) 054018

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

- 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

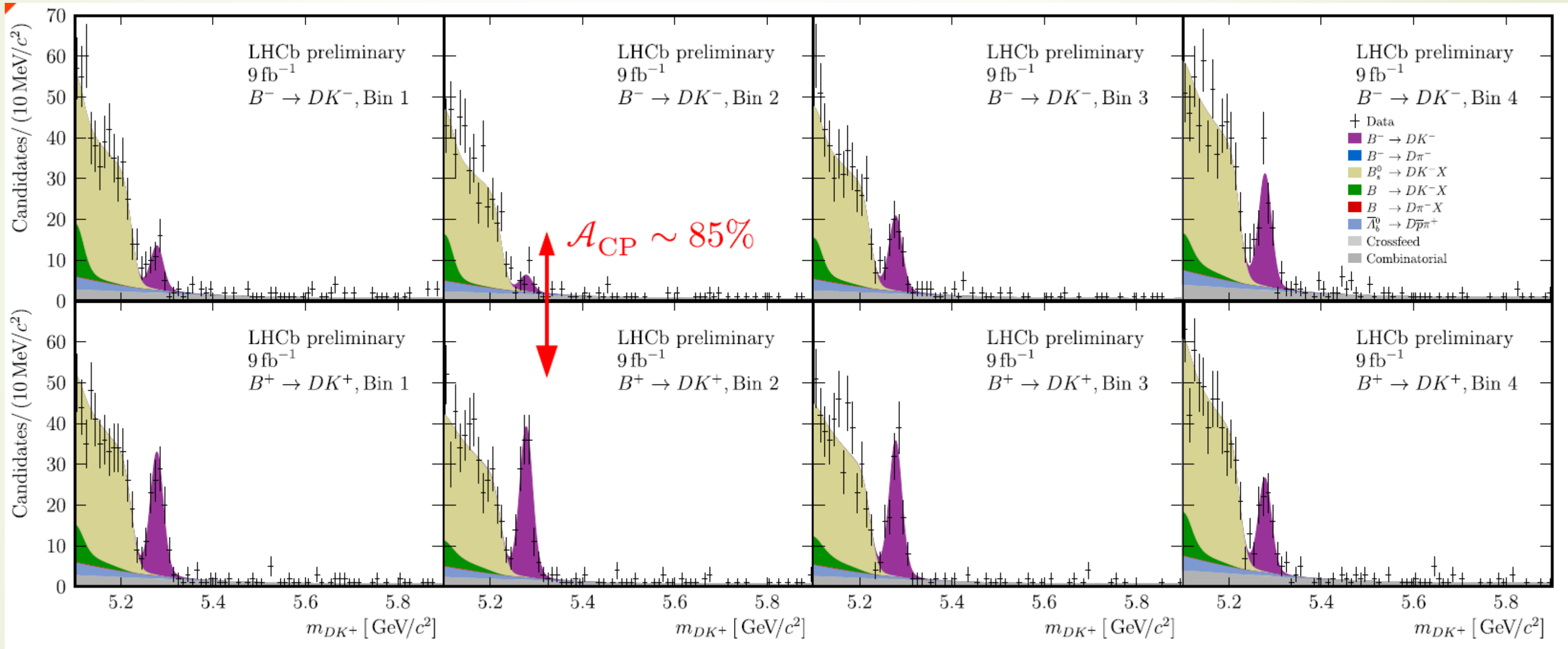
$$\begin{aligned}\gamma &= (56^{+24}_{-19})^\circ,\\ \delta_B &= (122^{+19}_{-23})^\circ,\\ r_B &= (9.3^{+1.0}_{-0.9}) \times 10^{-2}\end{aligned}$$



JHEP 07(2022) 099

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)



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

Large expected improvement from incoming 20fb^{-1} pf BESIII $\psi(3770)$ data

LHCb-PAPER-2022-017

LHCb γ combination [LHCb-CONF-2021-001]

- Best knowledge of γ comes from combination of many measurements

- Maximum likelihood fit
  - 151 observables
  - 52 free parameters

- Most precise determination of γ by a single experiment:

$$\boxed{\gamma = (65.4\,^{+3.8}_{-4.2})^\circ}$$

B decay	D decay	Data set
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	Run 1
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	Run 1&2
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	Run 1&2
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	Run 1&15/16
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1
$B^0 \to DK^{*0}$	$D \to h^+h^-$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^-\pi^+$	Run 1&15/16
$B^0 \to DK^{*0}$	$D \to K^0_S h^+h^-$	Run 1
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	Run 1
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	Run 1&2

NEW!

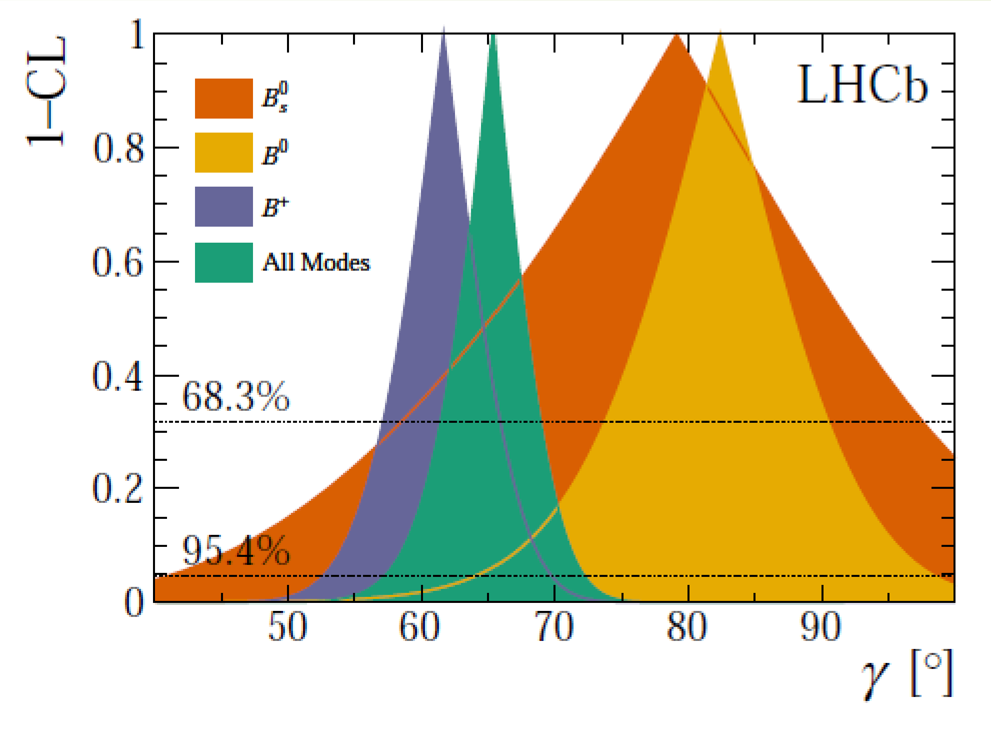
D decay	Observable(s)	Data set
$D^0 \to h^+h^-$	ΔA_{CP}	Run 1&2
$D^0 \to h^+h^-$	y_{CP}	Run 1
$D^0 \to h^+h^-$	ΔY	Run 1&2
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm, (x'^\pm)^2, y'^\pm$	Run 1&15/16
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	x, y	Run 1
$D^0 \to K^0_S\pi^+\pi^-$	$x_{CP}, y_{CP}, \Delta x, \Delta y$	Run 1&2

+ Critical input from BES-III (/CLEO-c) for D decay parameters

JHEP 12(2021)141

Results across different *B* decays

- Results are dominated by B+ decays
- New physics could lead to different results in different *B* decays
- Different *B* modes agree at 2σ level
- Different modes have different challenges and systematics:
  - Important to check consistency between modes



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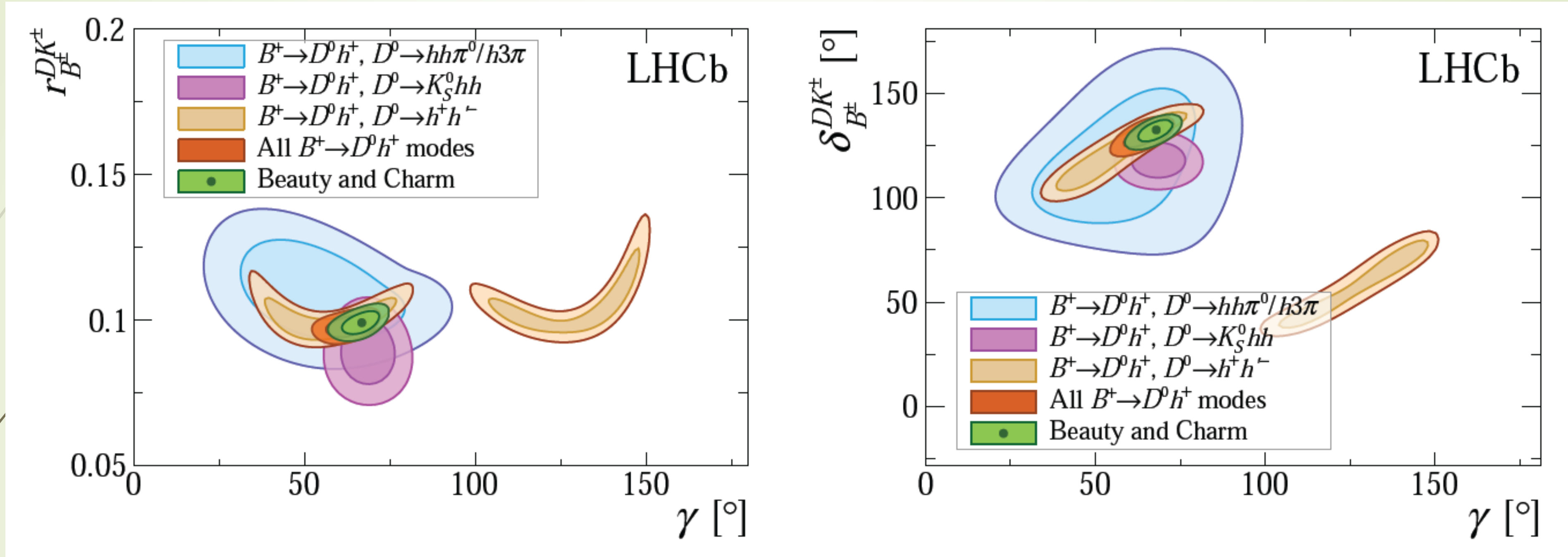
Results across different D decays

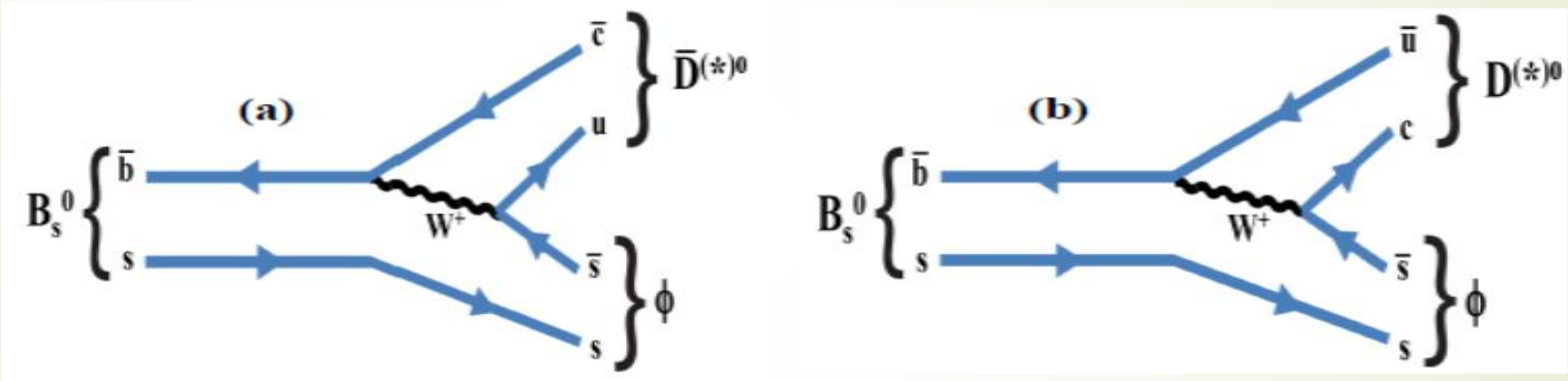


- ADS/GLW: several narrow solutions
- GGSZ: single, wider solution
- Analysing different modes serves as a useful cross-check: results have different sources of systematic uncertainty, but should agree

JHEP 12(2021)141

γ Measurement of $B_s^0 \to D^{(*)}\phi$ decays

- B_s result based on $B_s \to D_s K$ and $D_s K\pi\pi$ with large uncertainty
  - → Additional B_s will help improve the measurement precision



- By using expected event yields for 5 *D* sub-modes(3 flavor and 2 CP), we have shown that a precision on γ of about 8~19° with LHCb full data set
  - → Comparable to now combined B_s result: $\gamma = (79^{+21}_{-24})^o$

Chin. Phys. C 45 (2021) 2, 023003

Quantum correlated $D\bar{D}$ measurement

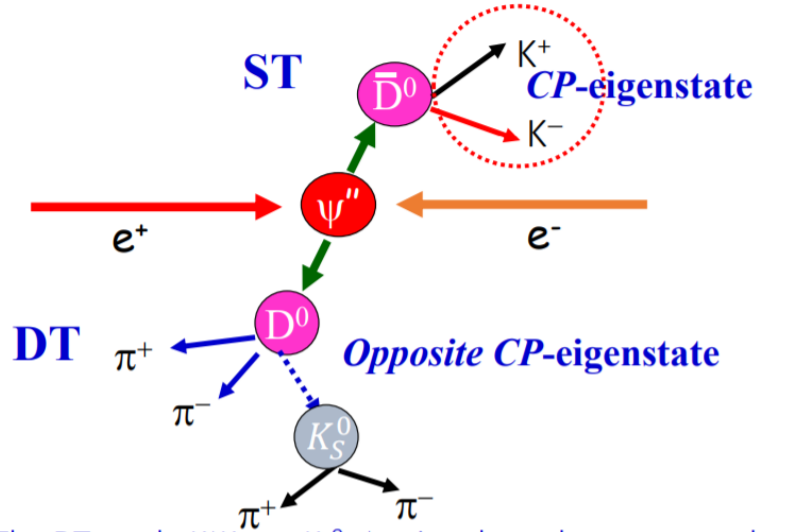
- $\psi(3770)$ is a spin -1 states, therefore the amplitude of $\psi(3770) \rightarrow D\bar{D}$:

$$(|D^0\rangle|\overline{D^0}\rangle - |\overline{D^0}\rangle|D^0\rangle)/\sqrt{2}$$ [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 R_F and the strong phase difference δ_D can be extracted



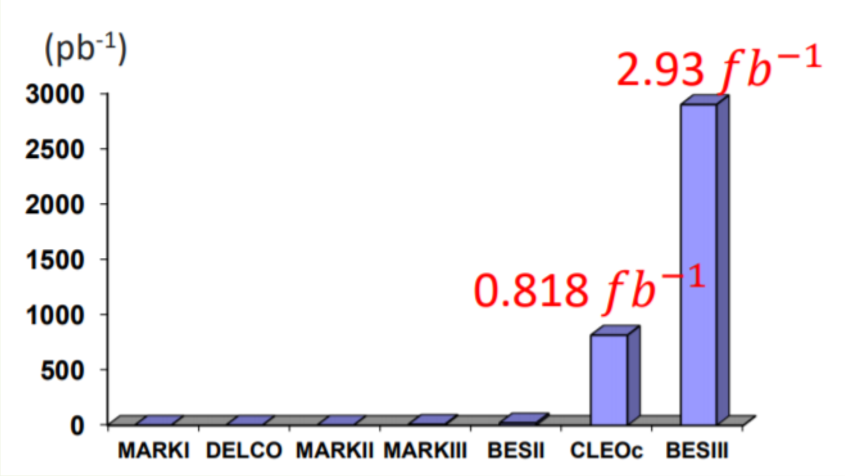
The DT mode K^+K^- *vs.* $K_S^0\pi^+\pi^-$ is selected as an example.

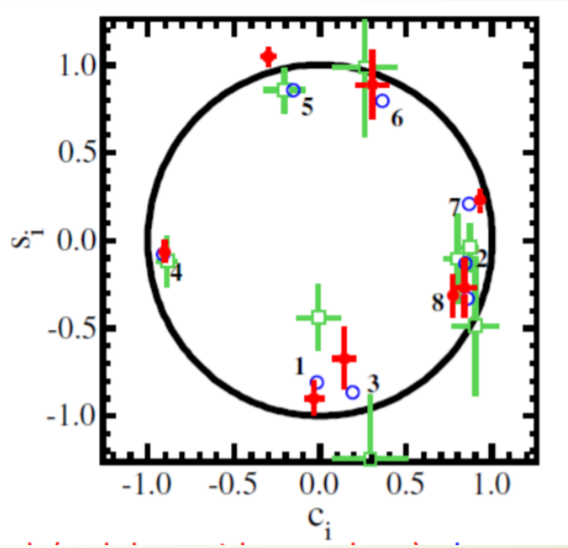
- ✓ Single tag (ST) samples:
  decay products of only one D meson are reconstructed
- ✓ Double tag (DT) samples:
  decay products of both D mesons are reconstructed
- ✓ Some typical reconstructed D decay modes

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	$K_S^0\pi^+\pi^-$

New BESIII strong phase inputs

- Measured using quantum-correlated DDbar meson pairs from $\Psi(3770)$ decays
- Current CLEO inputs contribute ~3.9° uncertainty to γ





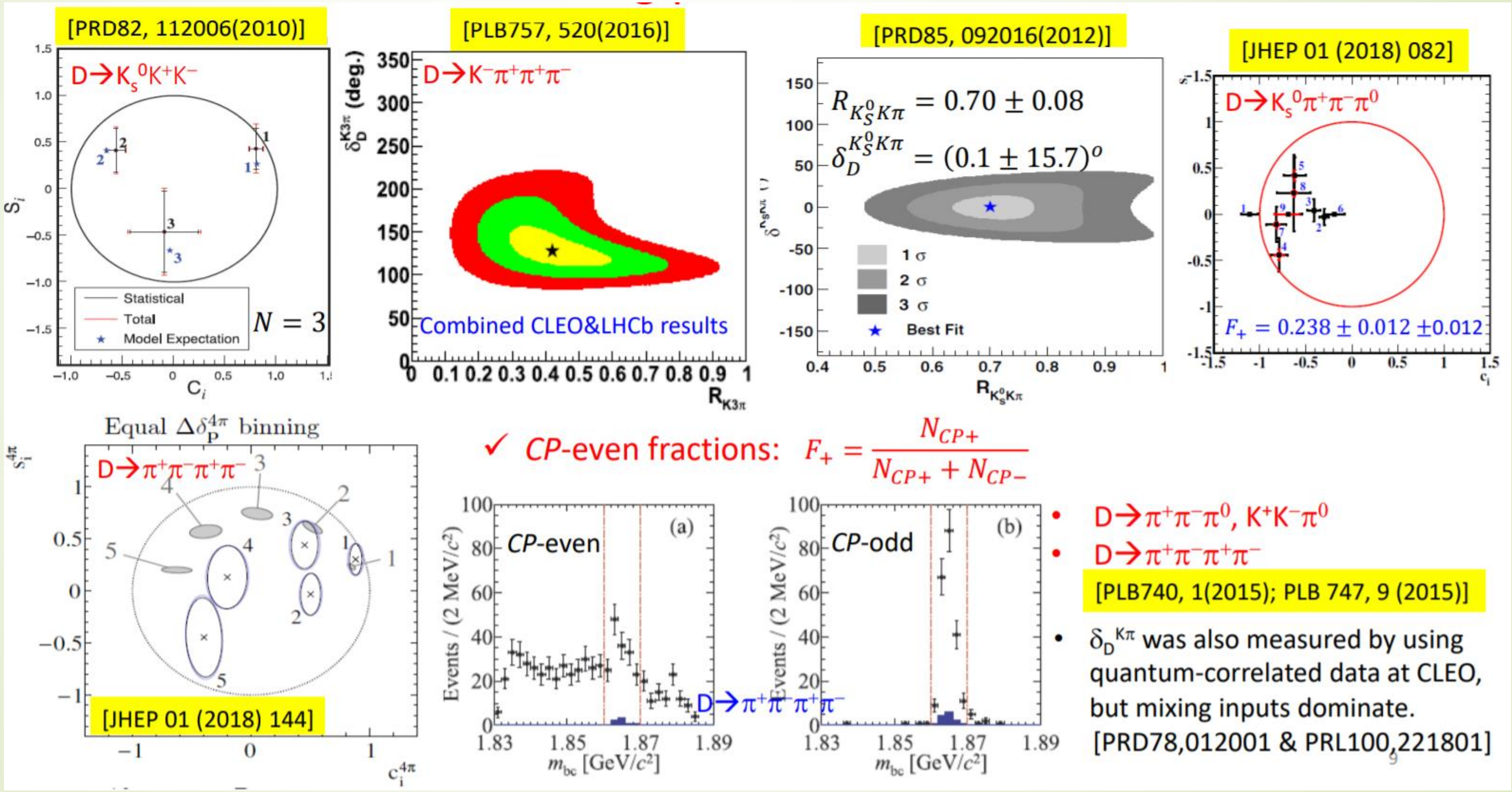
Model results
2010 CLEO results
2020 BESIII results

- New BESIII results:
  - On average,2.5(2.0)X more precise for ci(si) than CLEO
  - Expect associated uncertainty on γ to decrease by factor of 3

PRL124,241802(2020)

Other related measurements @ CLEO

BESIII intends to expand the programme performed at CLEO.



Improved BPGGSZ method

- Basic idea: Split events into bins
  - Make most use of amplitude info in phase space
- Observables
  - $p_D(z) = |A_D(z)|^2, \bar{p}_D(z) = |\bar{A}_D(z)|^2$ $\mathbf{z} \equiv (m_+^2, m_-^2)$
  - $p_B(z) \propto \bar{p}_D(z) + r_B^2 p_D(z) + 2[x\_C(z) + y\_S(z)]$

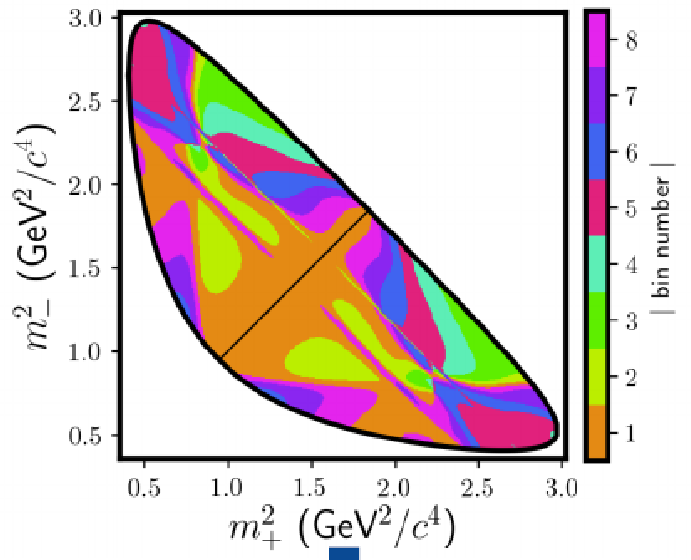
$$C(\mathbf{z}) = \mathrm{Re}\left[A_D^*(\mathbf{z})\overline{A}_D(\mathbf{z})\right] \quad S(\mathbf{z}) = \mathrm{Im}\left[A_D^*(\mathbf{z})\overline{A}_D(\mathbf{z})\right]$$

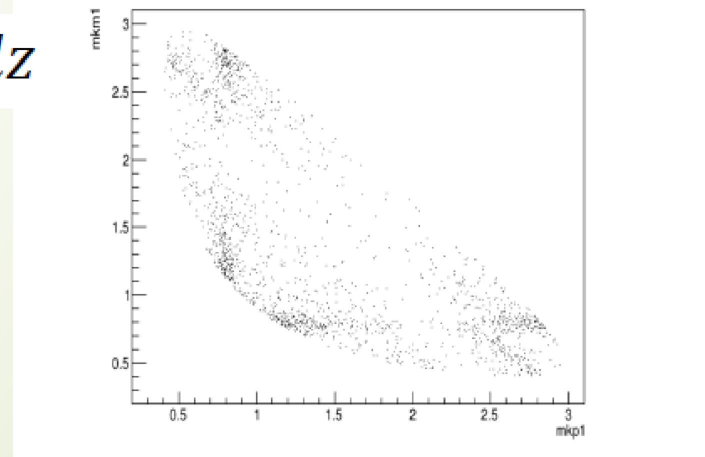
- Reform BPGGSZ method by $p(z) \to \int w(z)p(z)dz$
  - Binned BPGGSZ:

$$N_i = \int_D w_i(x)p_B(x)dx, \quad \boxed{w_i = \begin{cases} 1, \boldsymbol{D}_i \\ 0, \text{otherwise} \end{cases}}$$

  - Change w_i to Fourier coefficients: Bin → Point.

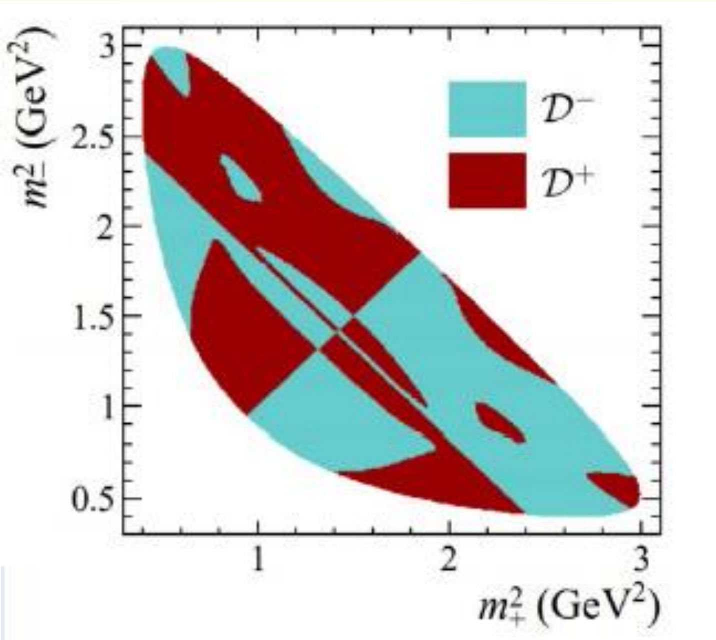
$$a_n^B = \int_D p_B(\phi)\cos(n\phi)\,d\phi$$





Eur. Phys. J. C, 2018, 78(2)

Analysis method



- Fourier coefficients:
  - $p^{\pm}(z) \to p^{\pm}(\phi) \to \frac{a_0^{\pm}}{2} + \sum_{n=1}^{M}[a_n^{\pm}\cos(n\phi) + b_n^{\pm}\sin(n\phi)]$
- Equations:

$$a_n^D = \frac{1}{\pi}\sum_{i=1}^{N_D}\cos(n\phi^i), \qquad b_n^D = \frac{1}{\pi}\sum_{i=1}^{N_D}\sin(n\phi^i).$$

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

B sector

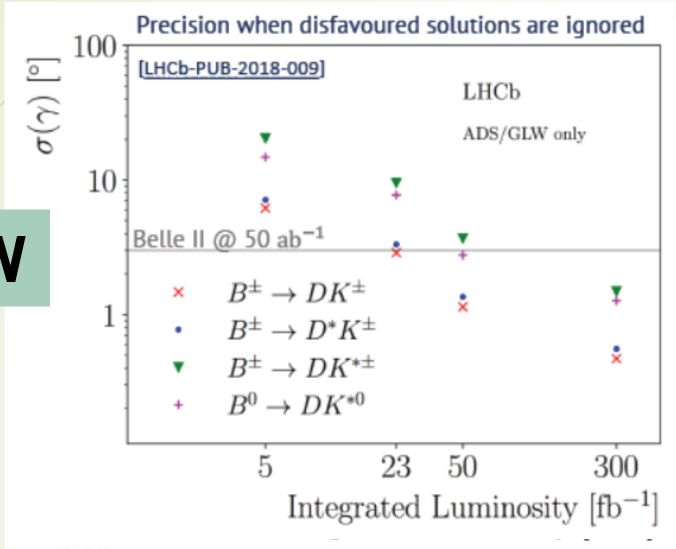
- $a'^{D\pm}_n = h_{D_f}\{a_n^{D\pm} + r_D^2 a_n^{D\mp} - 2R_D r_D[\cos(\delta_D)a_n^C \pm \sin(\delta_D)\, a_n^S]\}$
- $\lambda_{CP} = 2F_+ - 1$
- $a_n^{CP\pm} = h_{CP}[a_n^{D\pm} + a_n^{D\mp} - 2\lambda_{CP} a_n^C]$
- $a_{mn}^{DD\pm\pm} = h_{DD}[a_m^{D\pm} a_n^{D\mp} + a_m^{D\mp} a_n^{D\pm} - 2(a_m^C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

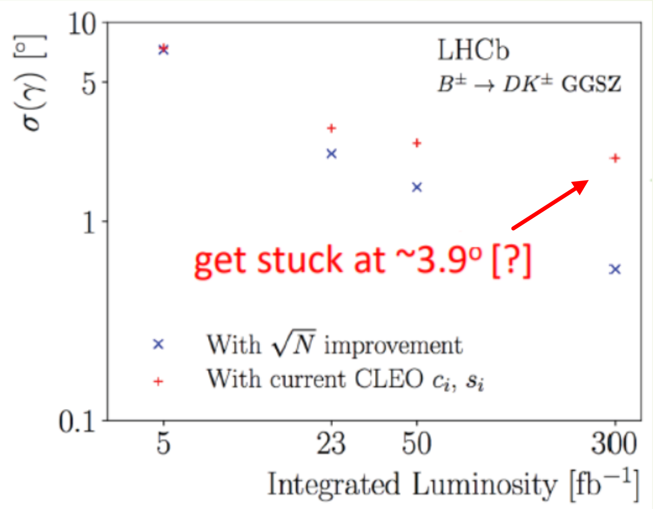
D sector

LHCb&BESIII joint analysis is ongoing

Future prospects for γ @ LHCb

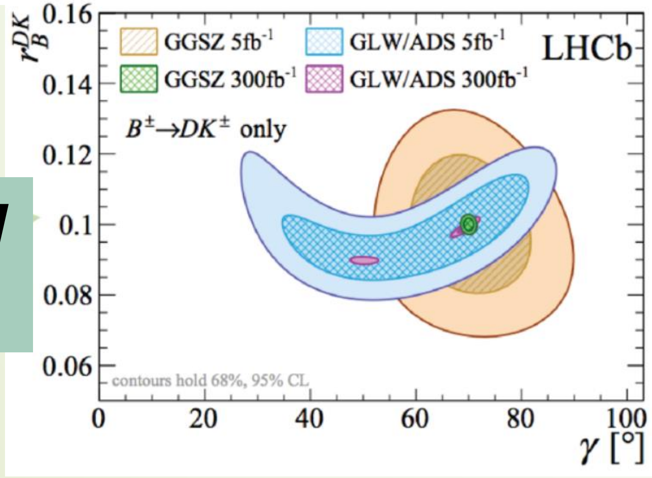
ADS/GLW

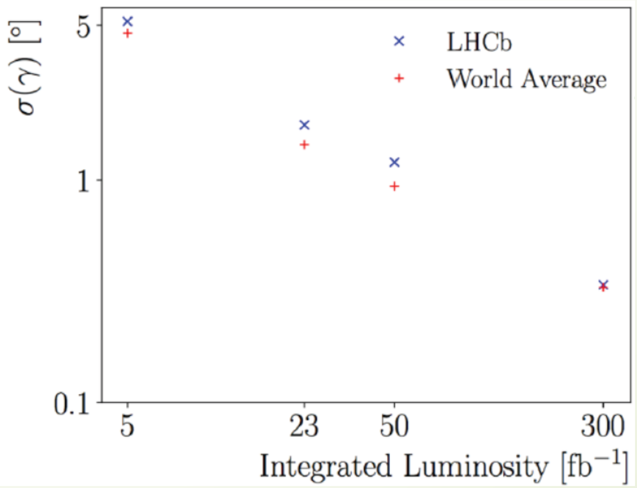




GGSZ

ADS/GLW & GGSZ



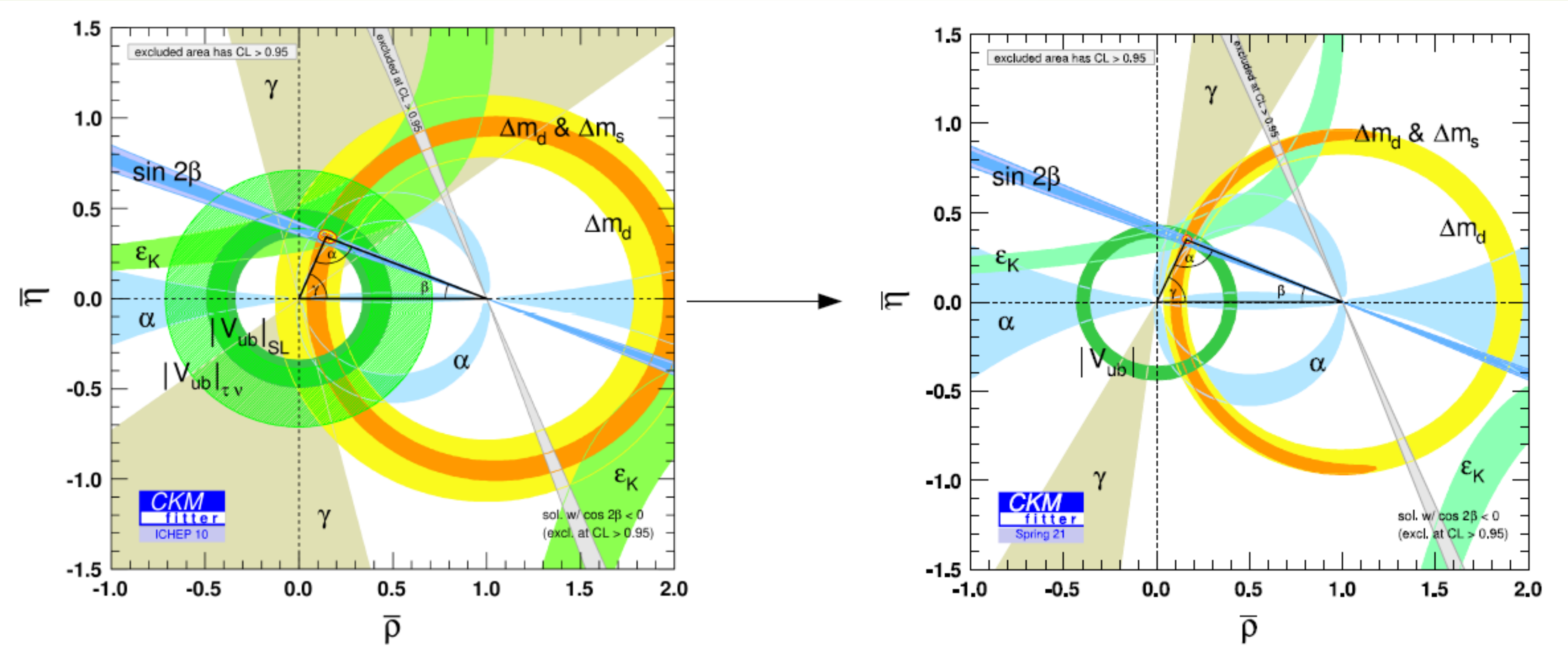


Full combination

World average includes Belle II projections

[LHCb-PUB-2018-009]

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

Toy study (LHCb+BESIII)

- Model
  - Signal D→$K_S\pi\pi$: BELLE 2010 model
  - Quantum-coherence Ddbar MC
- Signal & background yields: published paper
- Efficiency from signal MC

decay channel	signal yield	decay channel	signal yield
$B \to DK$	15k	$B \to D\pi$	221k
$K^0_S\pi\pi$ vs. quasi-flav.	23k	$K^0_L\pi\pi$ vs. quasi-flav.	41k
$K^0_S\pi\pi$ vs. $CP+$	2.5k	$K^0_L\pi\pi$ vs. $CP+$	5.0k
$K^0_S\pi\pi$ vs. $CP-$	1.7k	$K^0_L\pi\pi$ vs. $CP-$	1.5k
$K^0_S\pi\pi$ vs. $K^0_S\pi\pi$	1.8k	$K^0_L\pi\pi$ vs. $K^0_S\pi\pi$	3.4k

Toy test

- Test the precision under 4 methods by 1000 toy MC samples
  - BPGGSZ method
  - Model-dependent method
  - Fourier method with expansion order M=3
  - Fourier+Legendre method with expansion order M_F=2, M_L=2
  - Expansion order is limited by statistics
  - Efficiency and background are not included

- Test the γ precision: (input $\gamma(75^\circ)$, $\delta_B^{DK}(130^\circ)$, $\delta_B^{D\pi}(300^\circ)$, $r_B^{DK}(0.09)$, $r_B^{D\pi}(0.005)$.)

Method	$\gamma[^\circ]$	$\delta_B^{DK}[^\circ]$	$\delta_B^{D\pi}[^\circ]$	$r_B^{DK}[\times 10^{-2}]$	$r_B^{D\pi}[\times 10^{-3}]$
Unbinned MD	74.99 ± 3.77	130.02 ± 3.63	300 ± 17	8.96 ± 0.58	5.04 ± 1.52
Binned	74.95 ± 4.70	130.29 ± 5.59	300 ± 22	8.67 ± 0.76	4.91 ± 1.80
3rd Fourier	75.15 ± 4.23	130.04 ± 4.52	300 ± 21	8.99 ± 0.70	5.01 ± 1.80
2+2 Fourier + Legendre	75.07 ± 3.88	129.99 ± 4.28	300 ± 18	8.91 ± 0.63	5.01 ± 1.57
3rd Fourier (smear)	75.13 ± 4.23	130.45 ± 4.53	300 ± 21	8.98 ± 0.71	5.01 ± 1.80