# Strong-phase measurement of D decays at BESIII

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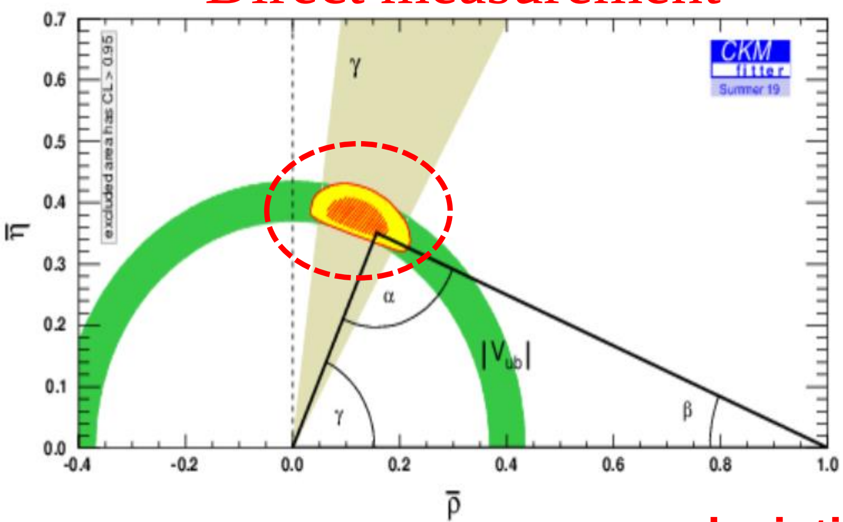
# Outline

- **Strong-phase measurements at BESIII**
  - $D \rightarrow K_{S/L} h^+ h^-$ ($h = \pi$, K)
  - $D \rightarrow K\pi\pi^0$, $K\pi\pi\pi$
  - $D \rightarrow K\pi$
- **Summary**

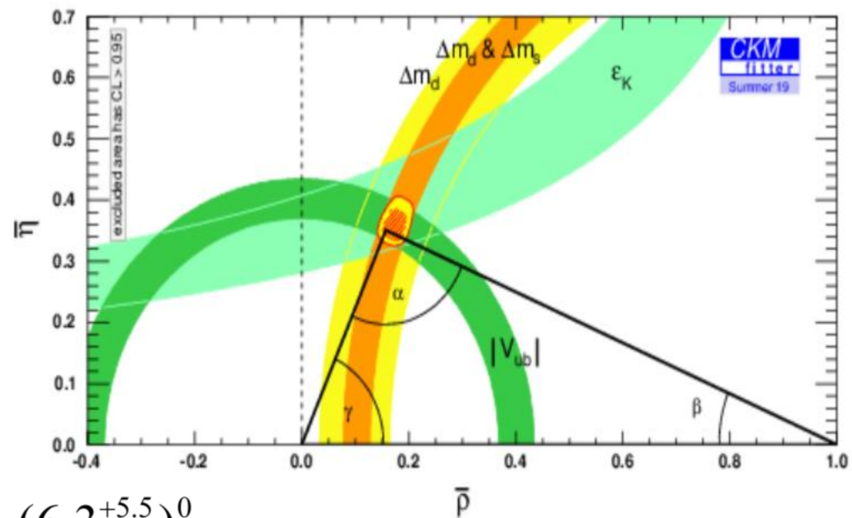
# Measurements of strong-phase parameters

- Phase angle $\gamma/\phi_3$ is the only CKM angle that can be measured in tree-level processes, in which the contribution of non-SM effects is expected to be small [JHEP 01(2014)051].
- Measurement of $\gamma$ provides a benchmark of the SM with negligible theoretical uncertainty.

Direct measurement




CKM fitter




$(72.1^{+5.4}_{-5.7})^0$

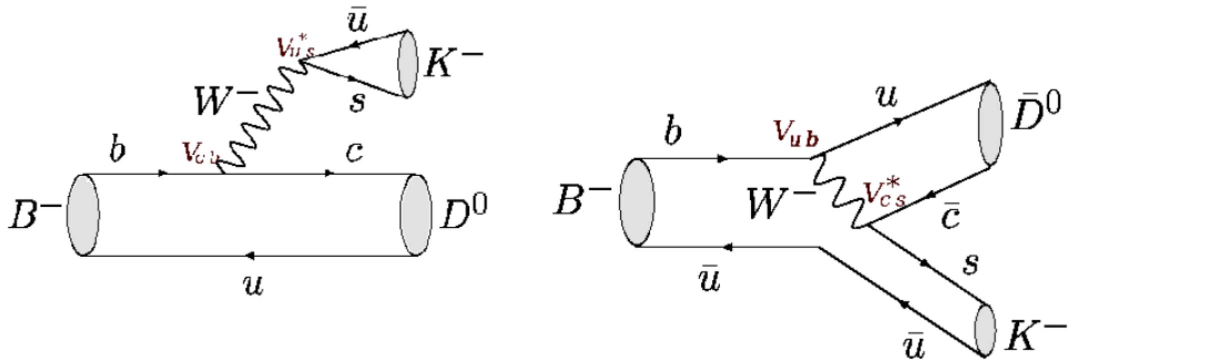
**deviation:** $(6.3^{+5.5}_{-5.8})^0$

$(65.8^{+0.9}_{-1.3})^0$

- An improved knowledge of the measurement of $\gamma$ (precision: $\sim 1^{o}$, $>5\sigma$) is important to further test the SM and probe for new physics.

# Measurements of strong-phase parameters

- Phase angle $\gamma/\phi_3$ can be measured by studying the interference between $B^- \to D^0 K^-$ and $B^- \to \bar{D}^0 K^-$.




$$A(B^- \to D^0 K^-) = A_B A_D \qquad A(B^- \to \bar{D}^0 K^-) = A_B r_B e^{i(\delta_B - \gamma)} A_{\bar{D}}$$

*where $r_B$ is ratio of suppressed to favored amplitudes, $\delta_B$ is the strong-phase difference between the favoured and suppressed amplitudes.*

- Generally, three methods were proposed to measure $\gamma/\phi_3$:
  - ✓ GLW [1]: via $D^0 \to$ CP eigenstate, $K^+K^-$, $\pi^+\pi^-$, $K_S^0\pi^0$ etc.
  - ✓ ADS [2]: via $D^0 \to$ CF and DCS, such as $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$ etc.
  - ✓ GGSZ [3]: via with $D^0 \to$ Multi-body self-conjugate decays, $K_s^0\pi^+\pi^-$ etc.

} strong-phase parameters are key inputs.


*[1] M. **G**ronau, D. **L**ondon, Phys. Lett. B 253, 483 (1991); M. Gronau, D. **W**yler, Phys. Lett. B 265, 172 (1991).*
*[2] D. **A**twood, I. **D**unietz and A. **S**oni, Phys. Rev. Lett. 78, 3257 (1997).*
*[3] A. **G**iri, Y. **G**rossman, A. **S**offer and J. **Z**upan, Phys. Rev. D 68, 054018 (2003).*

- **ADS approach** [D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78, 3257 (1997) ] :

  $B^- \to DK^-$ with $D \to Kn\pi$, such as: $D \to K\pi\pi\pi$, $K\pi\pi^0$ etc.

$$\Gamma\left(B^- \to (K^+3\pi)_D K^-\right) \propto r_B^2 + \left(r_D^{K3\pi}\right)^2 + 2R_{K3\pi} r_B r_D^{K3\pi} \cdot \cos\left(\delta_B + \delta_D^{K3\pi} - \gamma\right)$$

  where $R_{K3\pi}$ is coherence factor, and $\delta_D^{K3\pi}$ is averaged strong-phase difference.

- **GGSZ approach** [A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68, 054018] :

  $B^- \to DK^-$ with $D \to$ Multi-body self-conjugate decays, $K_{s/L}^0\pi^+\pi^-$, $K_{s/L}^0K^+K^-$ etc.

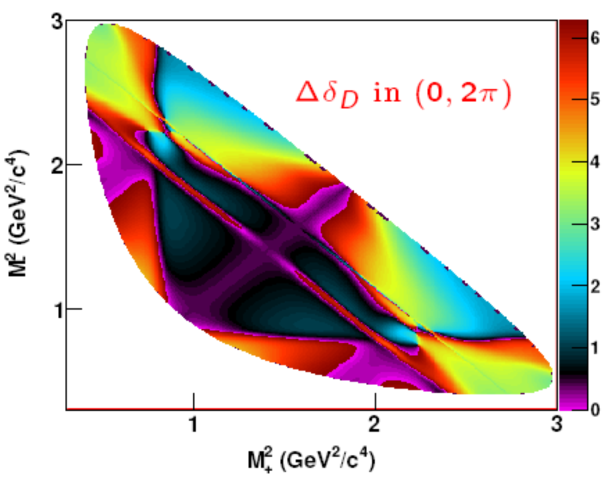
  Amplitude:
$$d\Gamma(B^\pm \to \tilde{D}^0 K^\pm) = |f_D(m_\pm^2, m_\mp^2)|^2 + r_B^2 |f_D(m_\mp^2, m_\pm^2)|^2 + 2r_B |f_D(m_\pm^2, m_\mp^2)||f_D(m_\mp^2, m_\pm^2)| \times [cos\Delta\delta_D cos(\delta_B \pm \phi_3) + [sin\Delta\delta_D sin(\delta_B \pm \phi_3)],$$

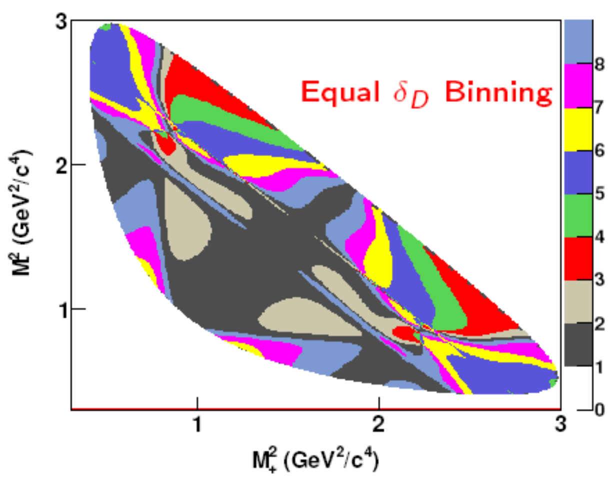
$$c_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \cos[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$
$$s_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i |f_D(m_+^2, m_-^2)||f_D(m_-^2, m_+^2)| \sin[\Delta\delta_D(m_+^2, m_-^2)] dm_+^2 dm_-^2$$

*strong-phase difference:*
$$\Delta\delta_D = \delta_D(m_+^2, m_-^2) - \delta_D(m_-^2, m_+^2)$$

where $c_i$ and $s_i$ are the amplitude-weighted averages of $\cos\Delta\delta_D$ and $\sin\Delta\delta_D$ over each Dalitz-plot bin.

- Equal $\Delta\delta_D$ binning scheme (N=8): $2\pi(i - 3/2)/\mathcal{N} < \Delta\delta_D(m_+^2, m_-^2) < 2\pi(i - 1/2)/\mathcal{N}$



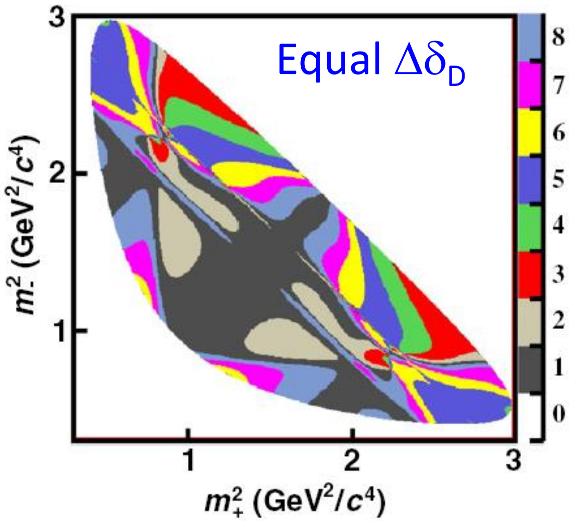




*The strong-phase difference ($\Delta\delta_D$) calculated based on "Babar 2008" Model.*
Phys. Rev. D 78, 034023 (2008)

Model-indenpendent: Bondar and Poluektov [EPJC47, 347(2006), EPJC55, 51(2008)].

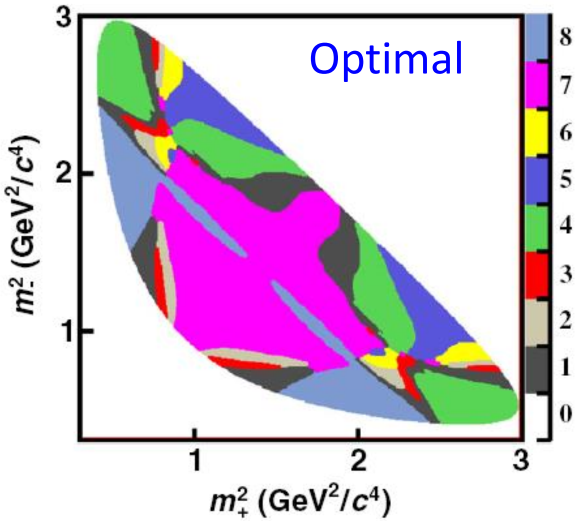
# Strong-phase parameters in $D \to K_S^0\pi^+\pi^-$

## ❑ Three typical binning schemes [Phys. Rev. D 82, 112006 (2010)]



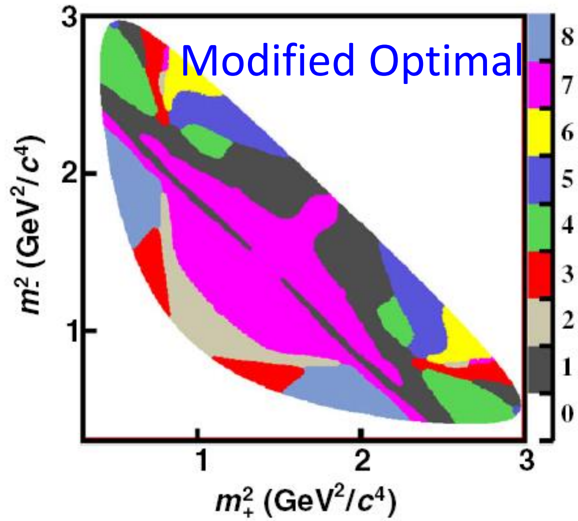

**DD-mixing[1], β measurements[2]**

[minimum variation in $\Delta\delta_D$]




**γ measurements[3,4]**

[Optimized sensitivity, no background included]




**γ in Low yields**

[Optimization including backgrounds]

- ✓ "BaBar K-matrix" $D^0 \to K_s^0\pi^+\pi^-$ model as in Ref. [Phys. Rev. D 78, 034023 (2008)].
- ✓ It should be noted that although the choice of binning is model-dependent, however, a poor choice of model results only in a loss of precision, instead of bias in measuring $\gamma/\phi_3$.


[1] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122, 231802 (2019); JHEP 04(2016) 033.
[2] V. Vorobyev et al. (Belle Collaboration), Phys. Rev. D 94, 052004 (2016).
[3] R. Aaij et al. (LHCb Collaboration), Phys. Lett. B 718, 43 (2012); JHEP 10 (2014) 097; JHEP 06 (2016) 131; JHEP 08 (2018) 176.
[4] H. Aihara et al. (Belle Collaboration), Phys. Rev. D 85, 112014 (2012).

# The Quantum Correlated $D\bar{D}$ meson pairs

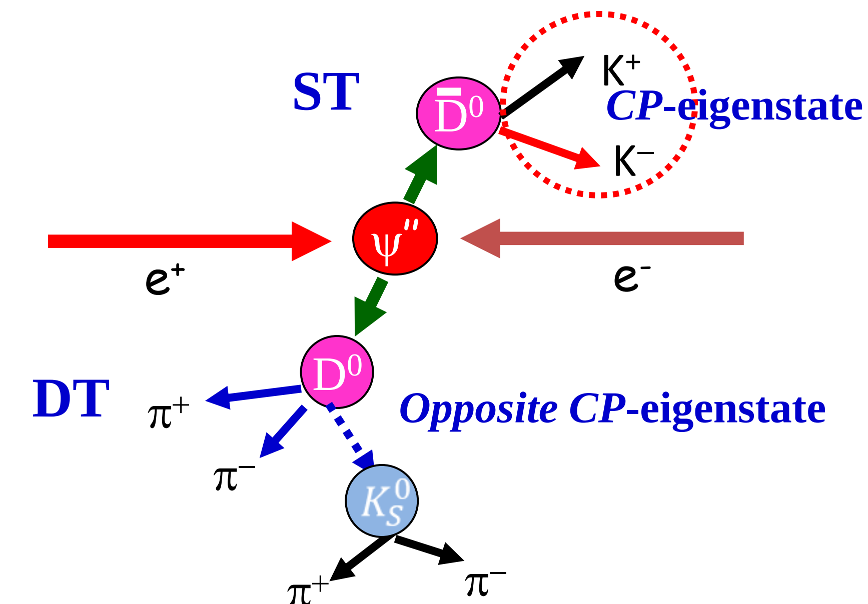
- ψ(3770) is a spin –1 state and therefore the amplitude of ψ(3770)→$D^0\bar{D}^0$:

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

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

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

- Hence, the coherence factors $R_F$, the strong-phase difference $\delta_D{}^F$, can be extracted based on the study of the quantum correlated DD meson pairs.




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**

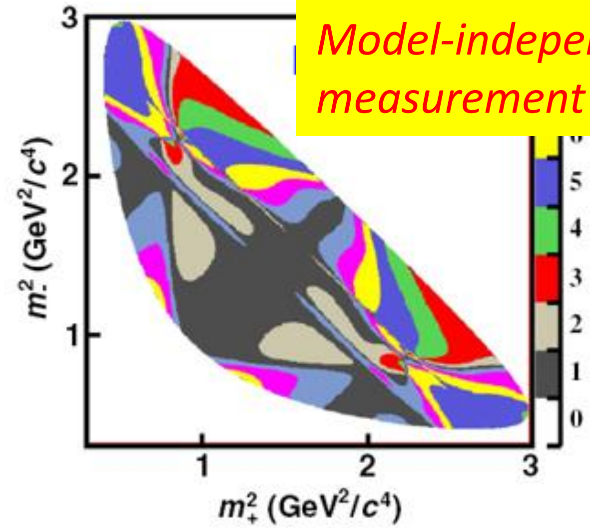
| Tag group | |
|---|---|
| Flavor | $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^+e^-\bar{\nu}_e$ |
| $CP$-even | $K^+K^-$, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $\pi^+\pi^-\pi^0$ |
| $CP$-odd | $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_L^0\pi^0\pi^0$ |
| Mixed-$CP$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

- ✓ **Expected events for $K_S\pi^+\pi^-$ .vs. CP-eigenstate:**

$$f_{CP\pm} = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \pm f_D(m_-^2, m_+^2)]$$

$$M_i^{\pm} = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i})$$

# Strong-phase parameters ($c_i$, $s_i$) in $D \rightarrow K_S^0\pi^+\pi^-$




*Model-independent measurement*

- For CP-tagged $K_s^0\pi^+\pi^-$, the amplitude:

$$f_{CP\pm} = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \pm f_D(m_-^2, m_+^2)]$$

*The expected number of events in DP bins:*

$$M_i^{\pm} = \frac{S^{\pm}}{2S_f}(K_i \pm 2c_i\sqrt{K_iK_{-i}} + K_{-i}) \text{ for } D^0 \to K_S^0\pi^+\pi^-$$

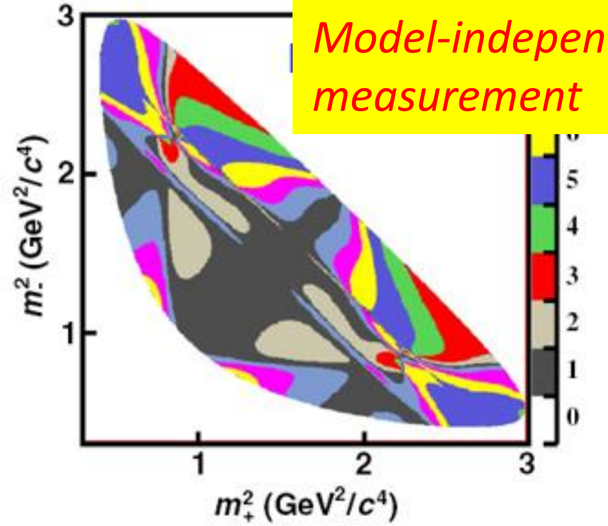
- For $K_s^0\pi^+\pi^-$ .vs. $K_s^0\pi^+\pi^-$, its amplitude is expressed by:

$$f(m_+^2, m_-^2, m_+'^2, m_-'^2) = \frac{f_D(m_+^2, m_-^2)f_D(m_-'^2, m_+'^2) - f_D(m_+'^2, m_-'^2)f_D(m_-^2, m_+^2)}{\sqrt{2}}$$

*The expected number of events in DP bins:*

$$M_{ij}^{\pm} = \frac{N_{D\bar{D}}}{2S_f^2}(K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(c_ic_j + s_is_j))$$

# Strong-phase parameters ($c'_i$, $s'_i$) in $D \to K_L^0\pi^+\pi^-$




*Model-independent measurement*

- For CP-tagged $K_L^0\pi^+\pi^-$, the amplitude:

$$f_{CP\pm} = \frac{1}{\sqrt{2}}[f_D(m_+^2, m_-^2) \mp f_D(m_-^2, m_+^2)]$$

The expected number of events in DP bins:

$$\Rightarrow \quad M_i'^{\pm} = \frac{S^{\pm}}{2S_f}(K_i' \mp 2c_i'\sqrt{K_i'K_{-i}'} + K_{-i}') \text{ for } D^0 \to K_L^0\pi^+\pi^-$$

- For $K_S^0\pi^+\pi^-$ .vs. $K_L^0\pi^+\pi^-$, its amplitude is expressed by:

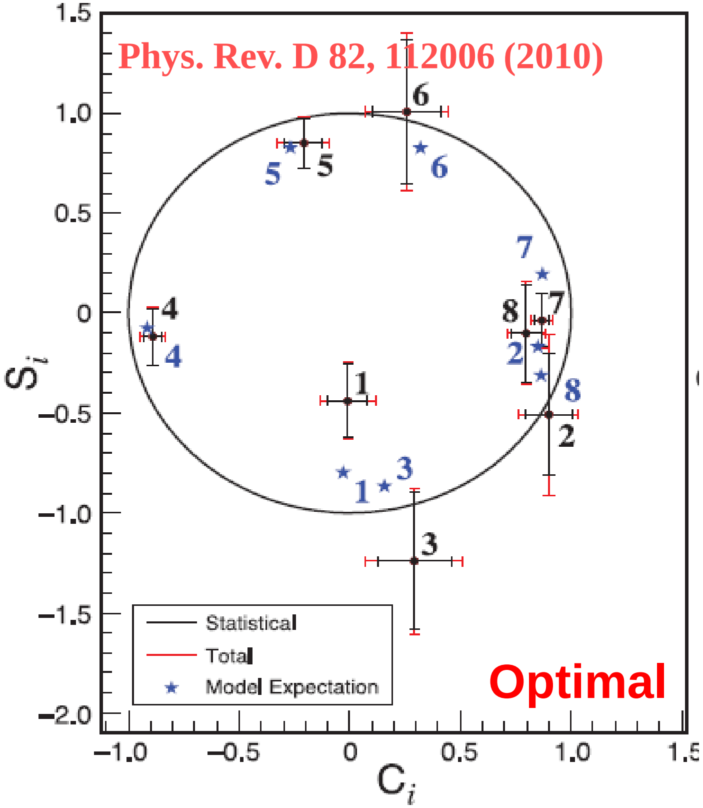
$$f(m_+^2, m_-^2, m_+'^2, m_-'^2) = \frac{f_D(m_+^2, m_-^2)f_D(m_-'^2, m_+'^2) + f_D(m_+'^2, m_-'^2)f_D(m_-^2, m_+^2)}{\sqrt{2}}$$

The expected number of events in DP bins:

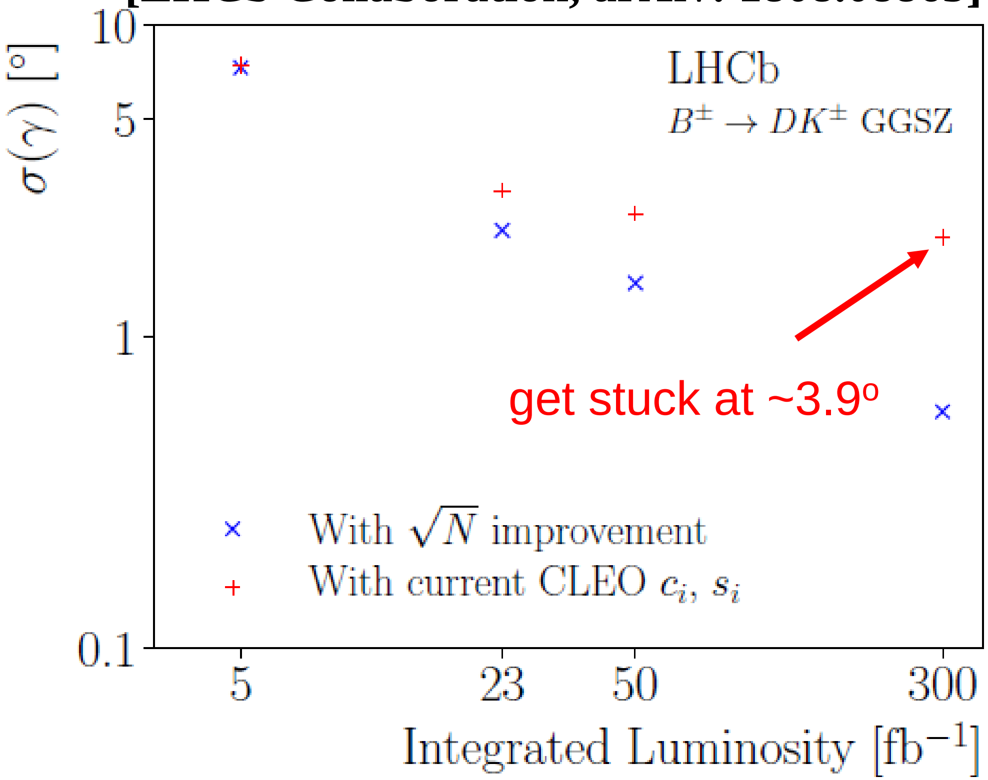
$$\Rightarrow \quad M_{ij}'^{\pm} = \frac{N_{D\bar{D}}}{2S_f^2}(K_iK_{-j}' + K_{-i}K_j' + 2\sqrt{K_iK_{-j}'K_{-i}K_j'}(c_ic_j' + s_is_j'))$$

# Strong-phase parameters in $D \rightarrow K_S^0 \pi^+ \pi^-$

✓ **Results of $c_i$ and $s_i$ in optimal binning from CLEO experiments.**




**[LHCb Collaboration, arXiv: 1808.08865]**




✓ The systematic uncertainty in measurement of $\gamma$ due to the input of strong-phase parameters is 3.9° for optimal binning. The overall sensitivity of $\gamma$ is systematically limited to ~3.9° for model-independent GGSZ approach.

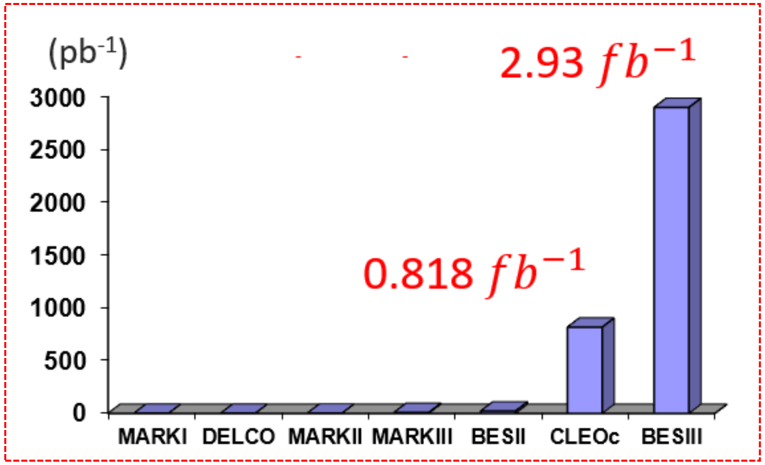
✓ *Therefore, improved measurements in $c_i$ & $s_i$ from BESIII are essential for degree-level precision of measuring $\gamma$ via model-independent GGSZ approach.*

# $\psi(3770)\rightarrow D^0\bar{D}^0$ samples at BESIII

- BESIII is the only machine running at $\tau$-charm energy region. The quantum-correlated studies are key to constrain the $\gamma/\phi_3$ measurement at LHCb upgrades 1(2) and Belle II experiments.

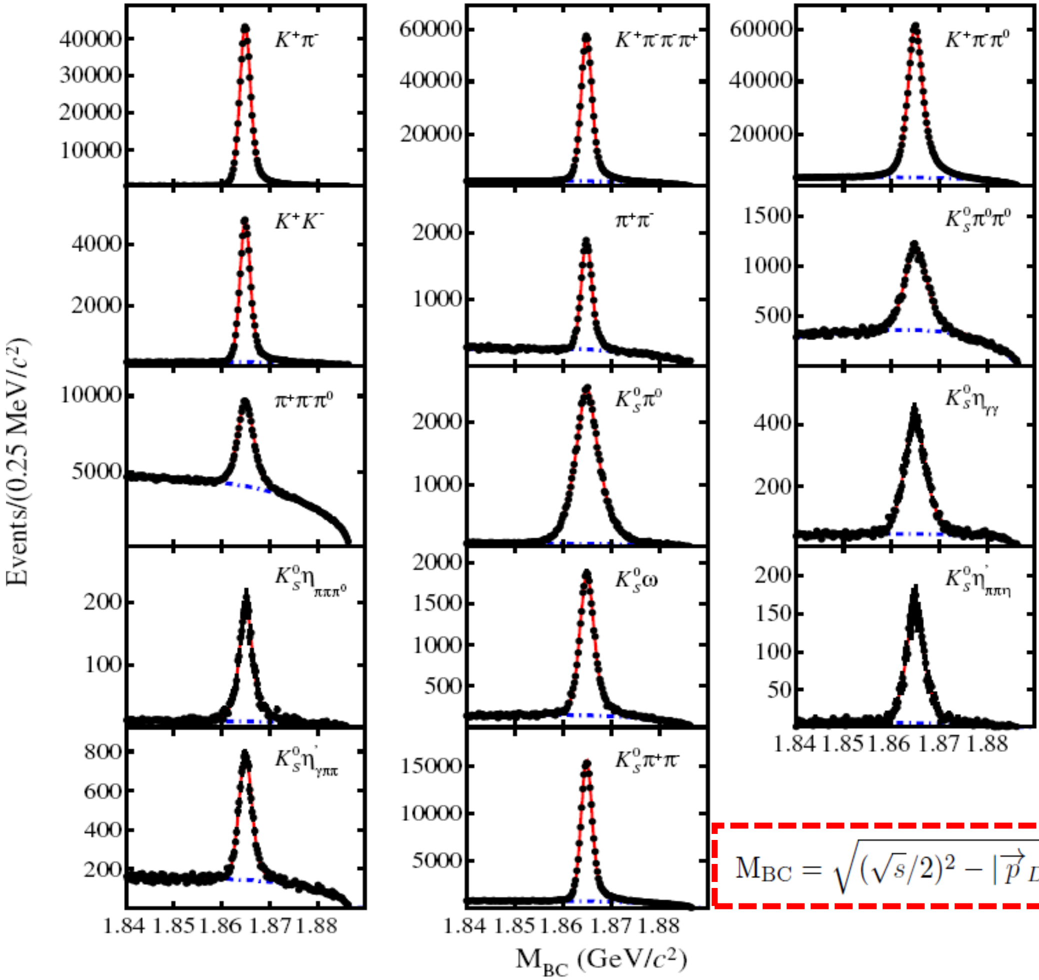
**2.93/fb @ 3.773 GeV**

The largest $\psi(3770)$ data sample




✓ Good performance of BESIII detector: high tracking & PID efficiencies; high purity samples.

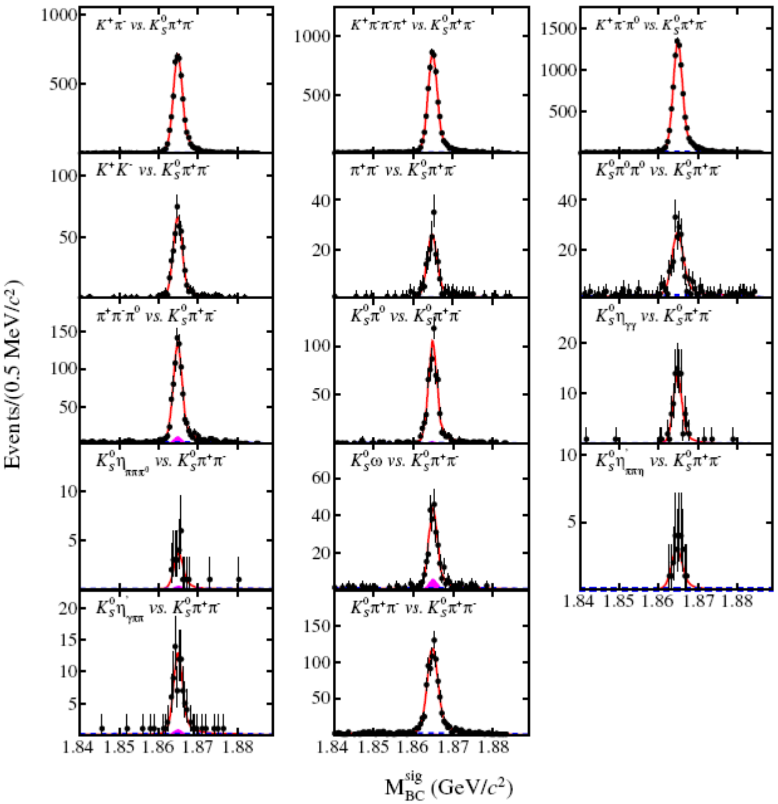
**beam-constrained mass distributions in data**

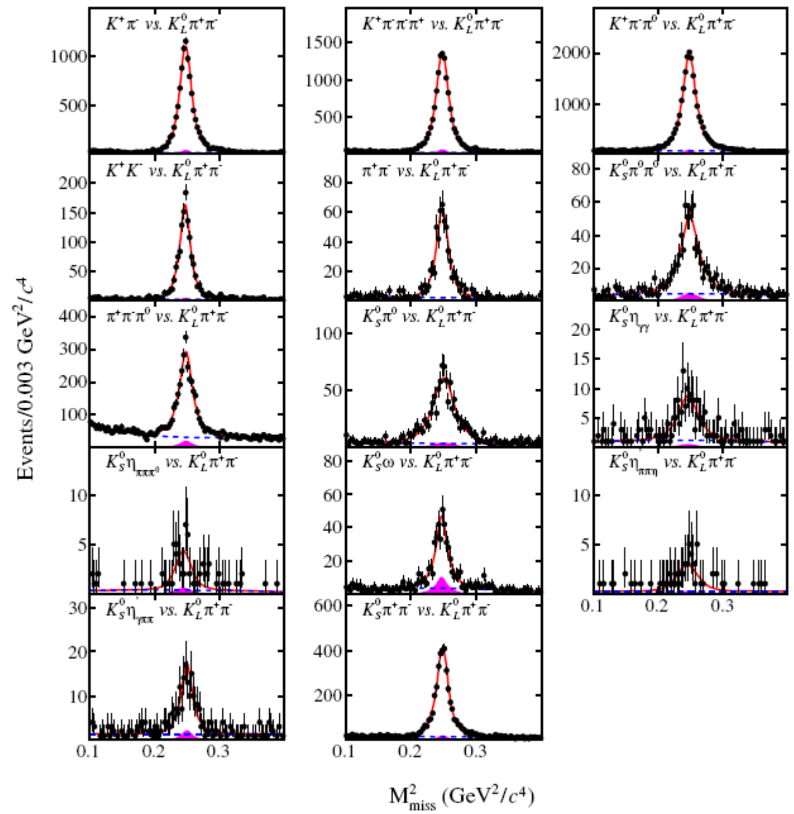


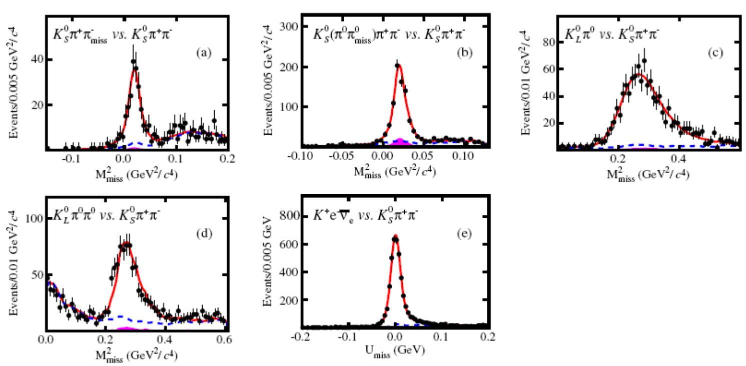

$$M_{BC} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_{D_{tag}}|^2}$$

Phys. Rev. Lett. 124, 241802(2020)
Phys. Rev. D 101, 112002(2020)

# DT events for $D \rightarrow K_{S/L}^{0}\pi^{+}\pi^{-}$ in data




*DT events at BESIII:*

$CP-eigenstate\ vs. K_S^0\pi^+\pi^-$: 5.3× CLEO

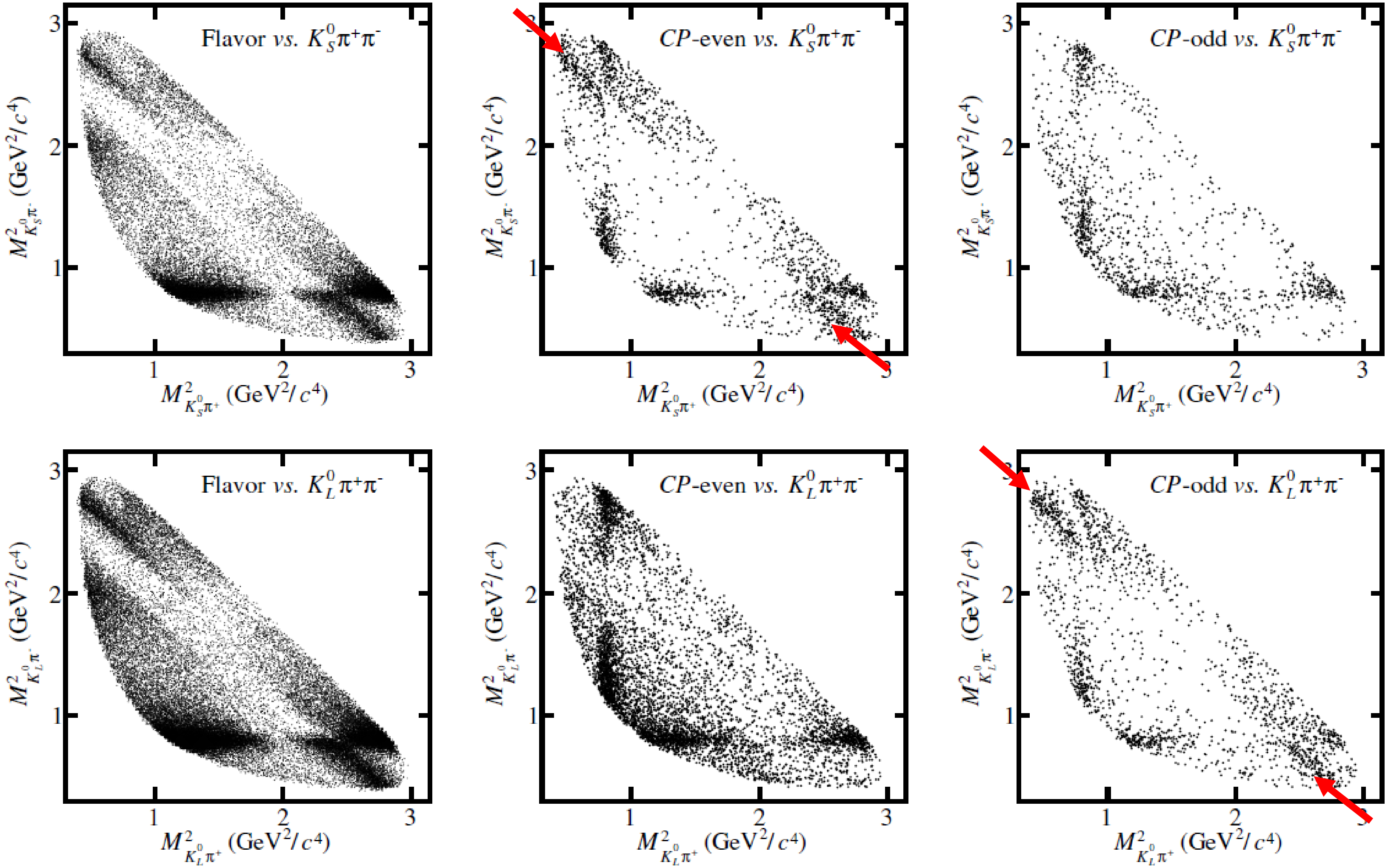
$CP-eigenstate\ vs. K_L^0\pi^+\pi^-$: 9.2× CLEO

$K_S^0\pi^+\pi^-\ vs. K_S^0\pi^+\pi^-$: 3.9× CLEO

$K_L^0\pi^+\pi^-\ vs. K_S^0\pi^+\pi^-$ : 2.9× CLEO

# Dalitz plots for D→$K_{S/L}\pi^+\pi^-$ observed in data

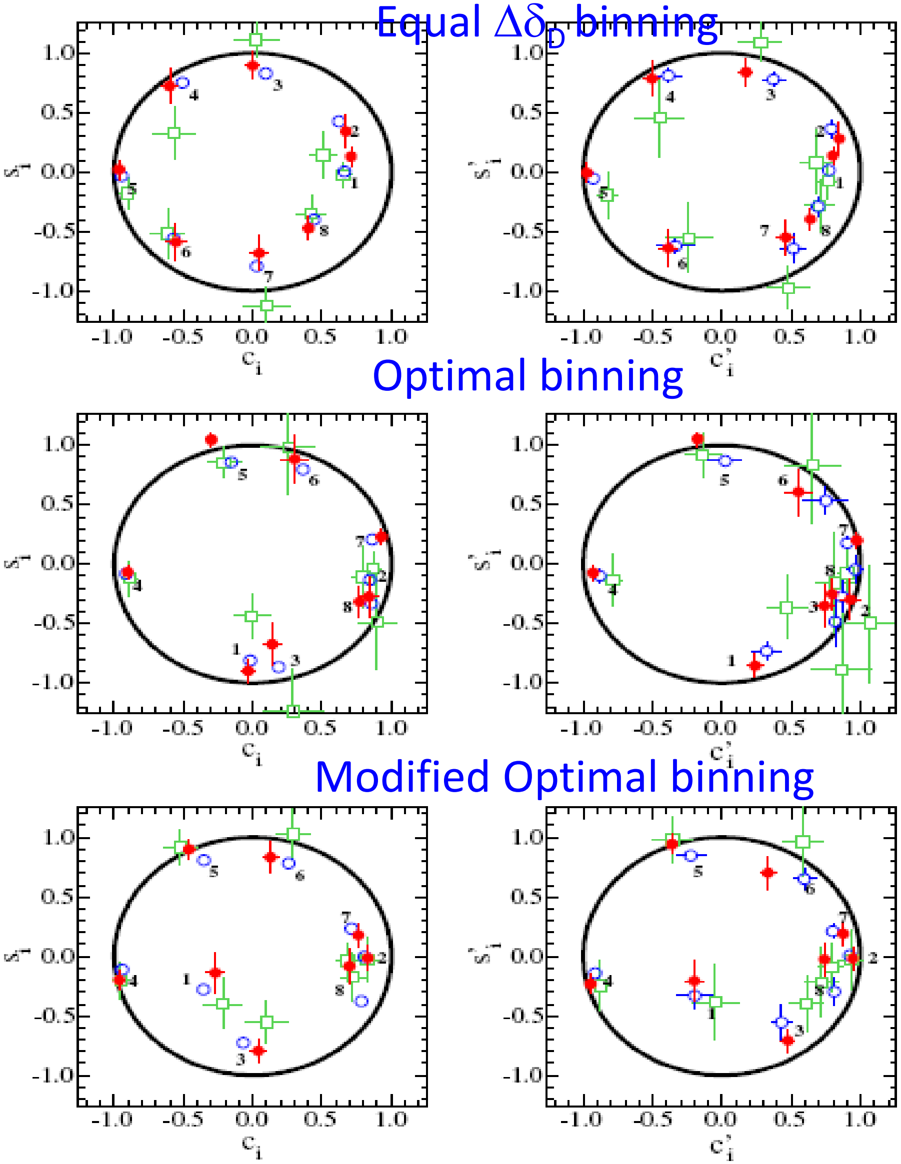
- Effect of quantum correlation is immediately seen in Dalitz plots.



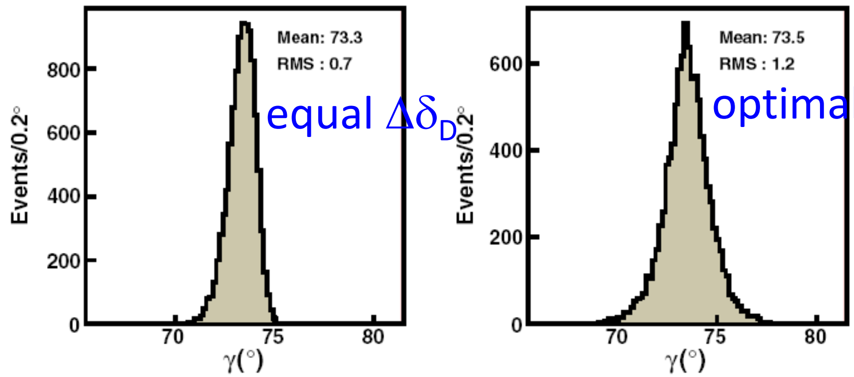

The CP-odd component $K_S^0\rho(770)^0$ is visible in CP-even tagged $K_S^0\pi^+\pi^-$ decays, but is absent in CP-odd tagged $K_S^0\pi^+\pi^-$ decays.

# The strong-phase parameters ($c_i^{(\prime)}$, $s_i^{(\prime)}$) in $D \rightarrow K_{S/L}^0\pi^+\pi^-$

✓ The $c_i^{(\prime)}$ and $s_i^{(\prime)}$ measured in this work, the expected results and the CLEO results.




✓ The expected uncertainty for $\gamma$ with $B^- \rightarrow DK^-$, $D \rightarrow K_S^0\pi^+\pi^-$.




Phys. Rev. Lett. 124, 241802(2020)
Phys. Rev. D 101, 112002(2020)

✓ On average a factor of ~2.5 (2.0) more precise for $c_i$ ($s_i$) and ~2.8 (2.2) more precise for $c'_i$ ($s'_i$) than CLEO.

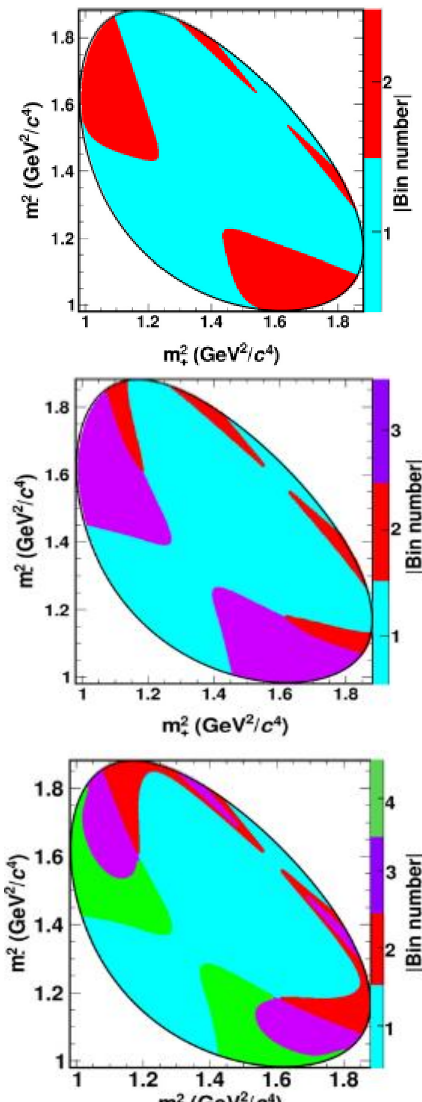
✓ The associated uncertainty on $\gamma/\phi_3$ is expected to be roughly a factor of three smaller than that from CLEO analysis.

✓ The improved precision on $c'_i$ and $s'_i$ are important for Belle-II in $\gamma/\phi_3$ measurement with $B^- \rightarrow DK^-$, $D \rightarrow K_L^0\pi^+\pi^-$.

# The strong-phase parameters in D→$K_{S/L}^0K^+K^-$

[Phys. Rev. D 102, 152008(2020)]

Equal $\Delta\delta_D$ binning [PRD78,034023(2008)]

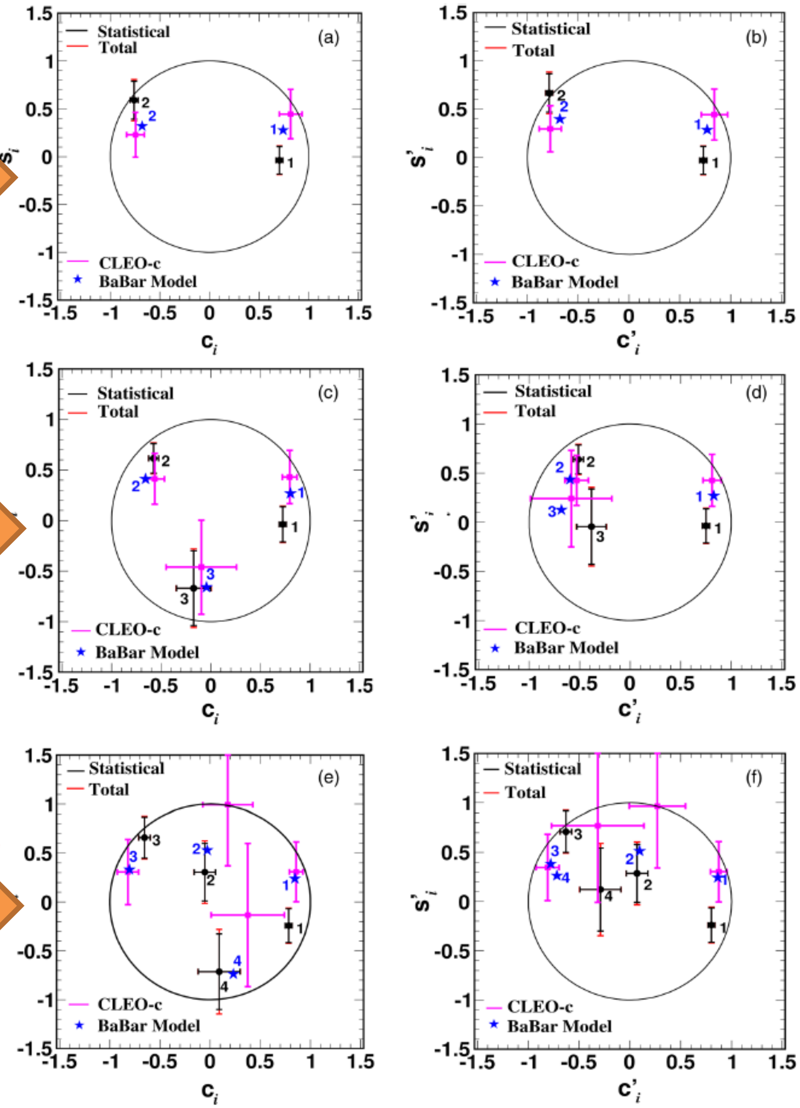



$N = 2$

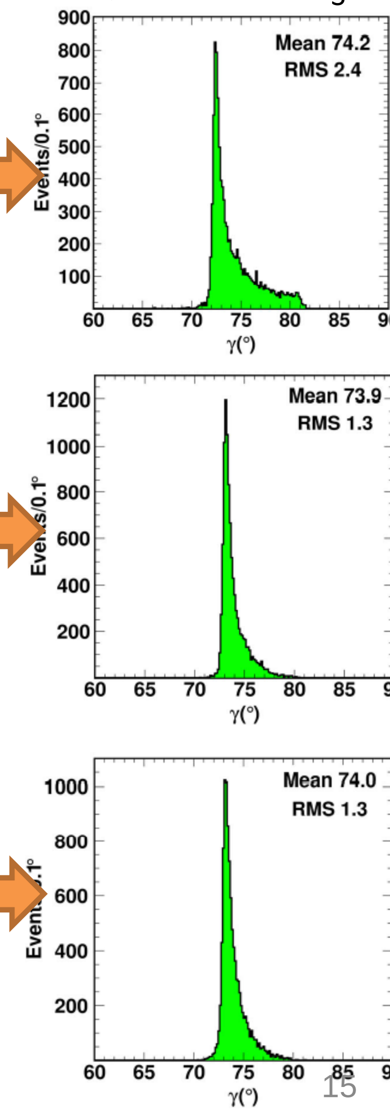
$N = 3$

$N = 4$

Strong-phase parameters $[c_i^{(')}, s_i^{(')}]$ measured in data

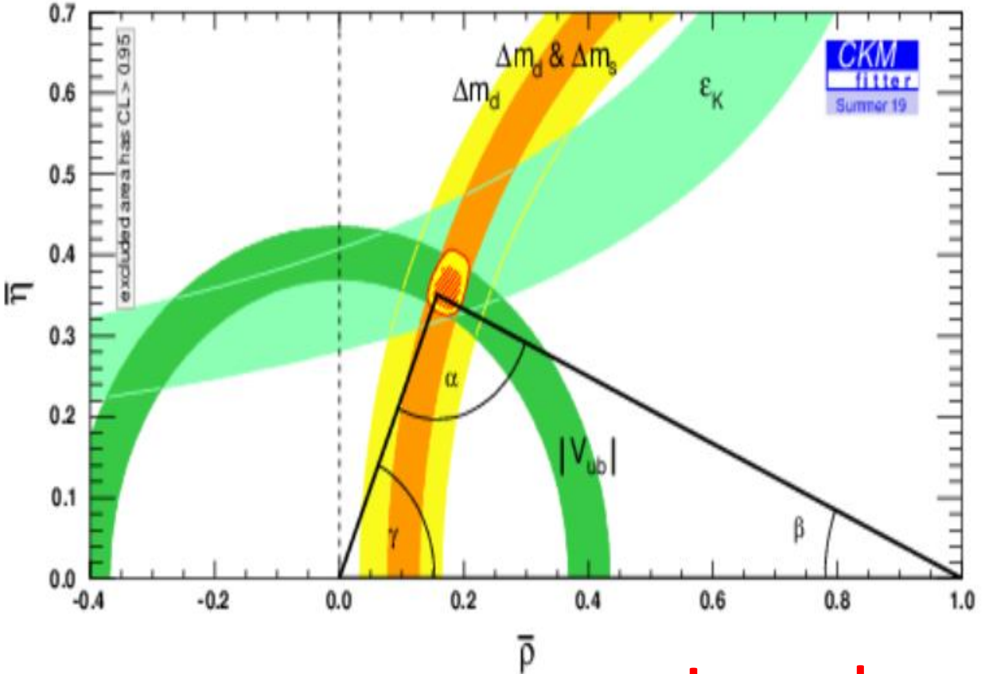



expected uncertainties on $\gamma$ by $B^-$→$DK^-$, with D→$K_SK^+K^-$

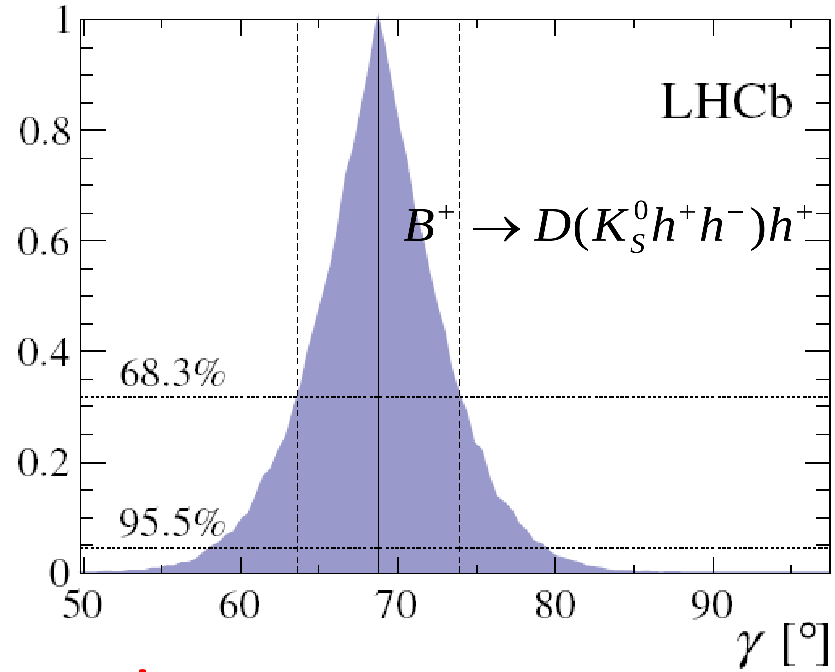


# $\gamma/\phi_3$ measurements with inputs of strong-phase parameters from $D \rightarrow K_S^0 h^+ h^-$

CKM fitter




JHEP02(2021)169




**In good agreement**

Indirect: $(65.8^{+0.9}_{-1.3})^0$ ⟷ $\gamma/\phi_3 = (68.7^{+5.2}_{-5.1})^o$

The uncertainty from strong phases is roughly 1°, which is significantly improved.

- Previous LHCb result, $\gamma=(80 \pm 10)^o$ [JHEP08(2018)176] with CLEO inputs.

# Measurements of coherence factors in $D \to K^-\pi^+\pi^+\pi^-$ and $D \to K^-\pi^+\pi^0$

[JHEP05(2021)164]

- For $D \to K^- n\pi$, the coherence factor $R_S$, the amplitude ratio $r_D$ and strong-phase difference $\delta_D$ between the CF and DCS amplitude averaged over phase space:

$$R_S e^{-i\delta_D^S} = \frac{\int \mathcal{A}_S^*(\mathrm{x})\mathcal{A}_{\bar{S}}(\mathrm{x})\mathrm{dx}}{A_S A_{\bar{S}}} \quad \text{and} \quad r_D^S = A_{\bar{S}}/A_S$$

*$A(s)$ is the decay amplitude of $D \to K^- n\pi$.*

- The amplitude for two D mesons decay to states S(single tag) and T(double tag):

$$\Gamma(S|T) = A_S^2 A_T^2 \left[(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos(\delta_D^T - \delta_D^S)\right]$$

| | | |
|---|---|---|
| Flavour | Like sign | $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^0$, $K^-\pi^+$ |
| | Opposite sign | $K^+\pi^-\pi^-\pi^+$, $K^+\pi^-\pi^0$, $K^+\pi^-$ |
| $CP$ | Even | $K^+K^-$, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $K_L^0\omega$, $\pi^+\pi^-\pi^0$ |
| | Odd | $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_S^0\phi$, $K_L^0\pi^0\pi^0$ |
| Self-conjugate | | $K_S^0\pi^+\pi^-$ |

✓ *For CP tags:* $\Gamma(S|CP) = A_S^2 A_{CP}^2 \left(1 + (r_D^S)^2 - 2\lambda R_S r_D^S \cos\delta_D^S\right)$

✓ *For Like-sign tags:* $\Gamma(S|S) = A_S^2 A_{\bar{S}}^2 \left[1 - R_S^2\right]$

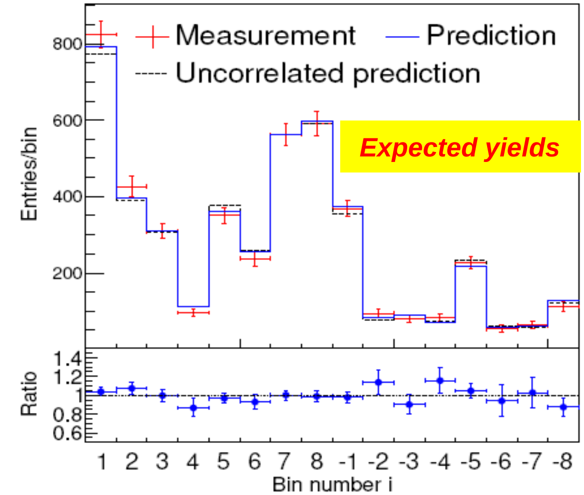
✓ *For Like-sign tags:* $Y_i^S = H\left(K_i + \left(r_D^S\right)^2 K_{-i} - 2r_D^S R_S \sqrt{K_i K_{-i}}\left[c_i \cos\delta_D^S - s_i \sin\delta_D^S\right]\right)$

# Measurements of coherence factors in $D \to K^-\pi^+\pi^+\pi^-$ and $D \to K^-\pi^+\pi^0$

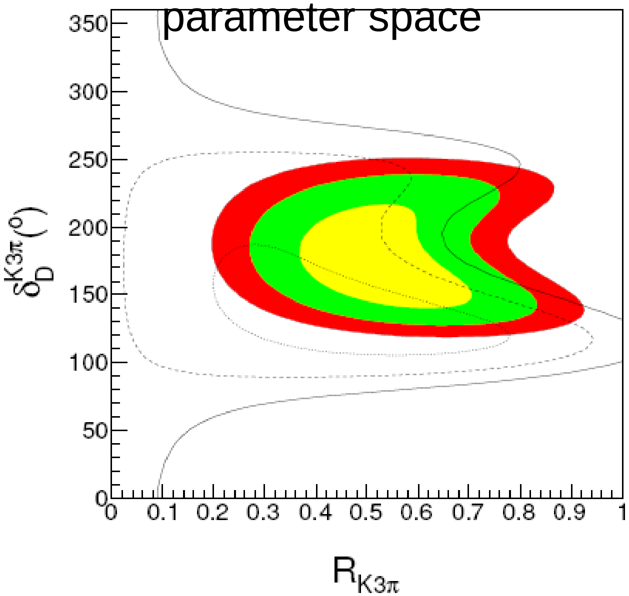
[JHEP05(2021)164]

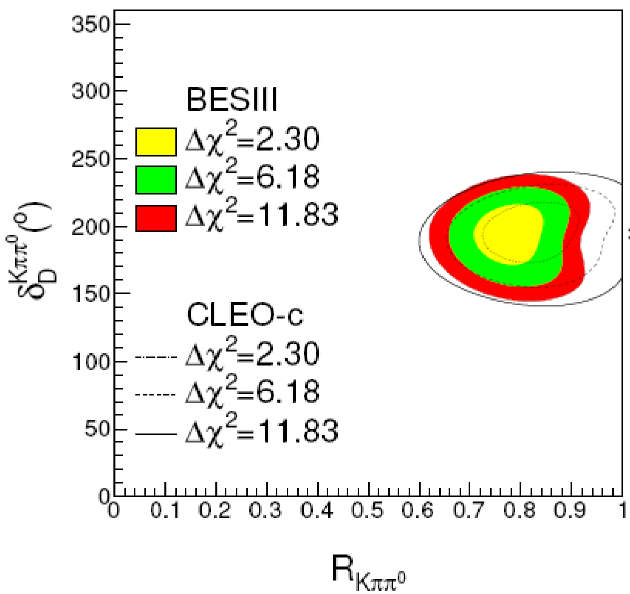
- Fitted central values for strong-phase parameters.

| Parameter | Global fit | Binned fit | | | |
|---|---|---|---|---|---|
| | | Bin 1 | Bin 2 | Bin 3 | Bin 4 |
| $R_{K3\pi}$ | $0.52^{+0.12}_{-0.10}$ | $0.58^{+0.25}_{-0.33}$ | $0.78^{+0.50}_{-0.21}$ | $0.85^{+0.15}_{-0.12}$ | $0.45^{+0.33}_{-0.37}$ |
| $\delta_D^{K3\pi}$ | $\left(167^{+31}_{-19}\right)^\circ$ | $\left(131^{+124}_{-16}\right)^\circ$ | $\left(150^{+37}_{-39}\right)^\circ$ | $\left(176^{+57}_{-21}\right)^\circ$ | $\left(274^{+19}_{-30}\right)^\circ$ |
| $r_D^{K3\pi}$ $(\times 10^{-2})$ | $5.46\pm0.09$ | $5.44^{+0.45}_{-0.14}$ | $5.80^{+0.14}_{-0.13}$ | $5.75^{+0.41}_{-0.14}$ | $5.09^{+0.14}_{-0.14}$ |
| $R_{K\pi\pi^0}$ | $0.78\pm0.04$ | $0.80\pm0.04$ | | | |
| $\delta_D^{K\pi\pi^0}$ | $\left(196^{+14}_{-15}\right)^\circ$ | $(200\pm11)^\circ$ | | | |
| $r_D^{K\pi\pi^0}$ $(\times 10^{-2})$ | $4.40\pm0.11$ | $4.41\pm0.11$ | | | |

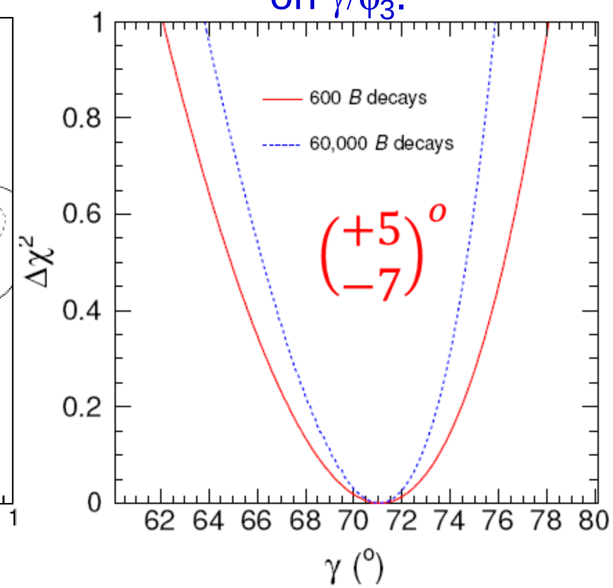



- ✓ Scans of $\Delta\chi^2$ in the global ($R^{K3\pi}$, $\delta_D^{K3\pi}$) and ($R_{K\pi\pi0}$, $\delta_D^{K\pi\pi0}$) parameter space



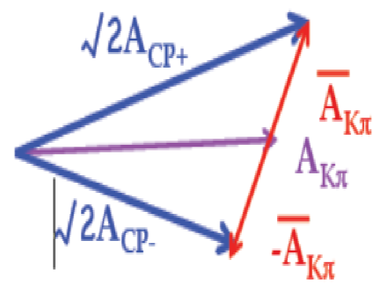




- ✓ Expected uncertainty on $\gamma/\phi_3$.



# Strong phase difference ($\delta$) of $D \rightarrow K^-\pi^+$

Simplified Picture: ( simple = no mixing )




Amplitude triangle:

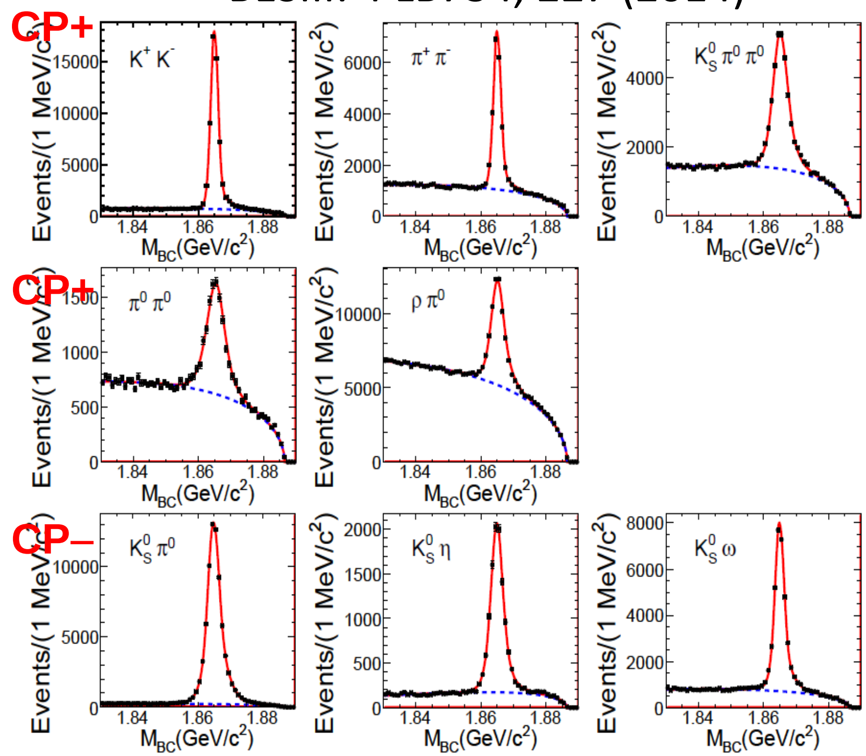
$CP_{\pm} = CF \pm DCSD$

[ DCSD enhanced for visibility ! ]

Complex ratio DCSD/CF amplitude

$$\frac{\langle K^-\pi^+|\bar{D}^0\rangle}{\langle K^-\pi^+|D^0\rangle} = -re^{-i\delta_{K\pi}}$$

BESIII: PLB734, 227 (2014)




$$A_{K\pi}^{CP} = \frac{B_{D^{CP-}\to K^-\pi^+} - B_{D^{CP+}\to K^-\pi^+}}{B_{D^{CP-}\to K^-\pi^+} + B_{D^{CP+}\to K^-\pi^+}} = (12.7 \pm 1.3 \pm 0.7)\%$$

$$2r\cos\delta_{K\pi} + y = (1 + R_{WS})A_{K\pi}^{CP}$$

**With external inputs (r, y, $R_{WS}$) and $A_{K\pi}$:**

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

**CLEO-c: PRD86, 112001 (2012)**

$$\cos\delta_{K\pi}^{\text{wihtout input}} = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\cos\delta_{K\pi}^{\text{with input}} = 1.15^{+0.19+0.00}_{-0.17-0.08}$$

**Benefit ADS method of extracting $\gamma$**

# Other topics: $y_{cp}$

**CP eigenstates of D:**

$$|D_{CP+}\rangle \equiv \frac{|D^0\rangle + |\overline{D}^0\rangle}{\sqrt{2}}, \quad |D_{CP-}\rangle \equiv \frac{|D^0\rangle - |\overline{D}^0\rangle}{\sqrt{2}}$$

**If no direct CPV, the difference of effective lifetimes between CP and flavor eigenstates:**

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$y = \Delta\Gamma/2\Gamma, \quad |D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \quad \phi = \arg(q/p)$$

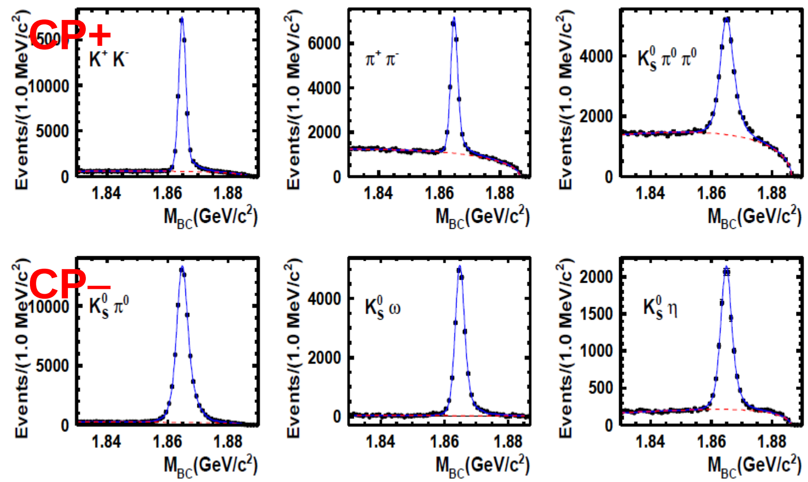
**If no CPV, $\phi$=0 and |p/q|=1: $y_{CP}=y$**

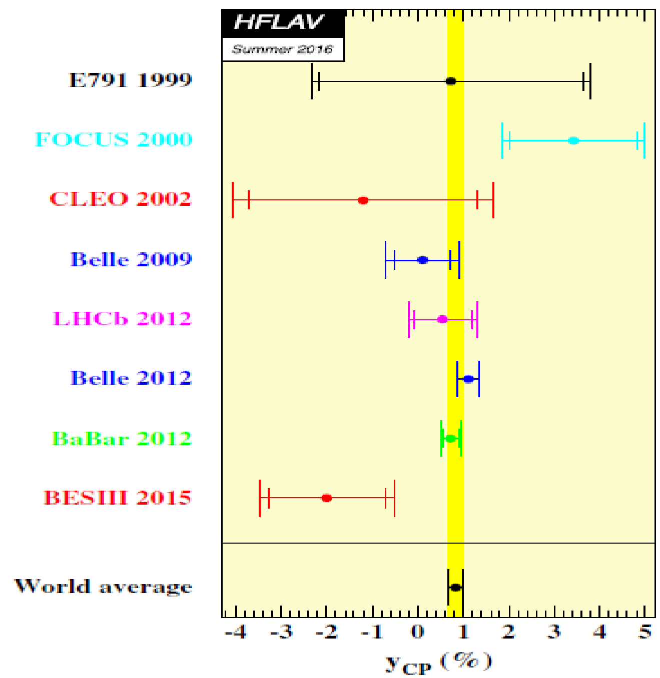
**Measurements with $D\rightarrow Ke\nu$ & $K\mu\nu$**

$$y_{CP} \approx \frac{1}{4}\left(\frac{B_{D^{CP-}\rightarrow Kl\nu}}{B_{D^{CP+}\rightarrow Kl\nu}} - \frac{B_{D^{CP+}\rightarrow Kl\nu}}{B_{D^{CP-}\rightarrow Kl\nu}}\right) = (-2.0 \pm 1.3 \pm 0.7)\%$$

**Need more data or global fit**

BESIII, PLB744,339(2015)



# Desirable Quantum Correlated measurements

LHCb-PUB-2016

- Uncertainty of strong-phase inputs from CLEO-c contribute ~2$^0$ to $\gamma$, and will be comparable with the experimental systematic uncertainty at LHCb RUN2

- BESIII is only machine running at $\tau$-charm energy region. Related QC studies are key to constrain the $\gamma$ measurement at LHCb upgrades 1(2)

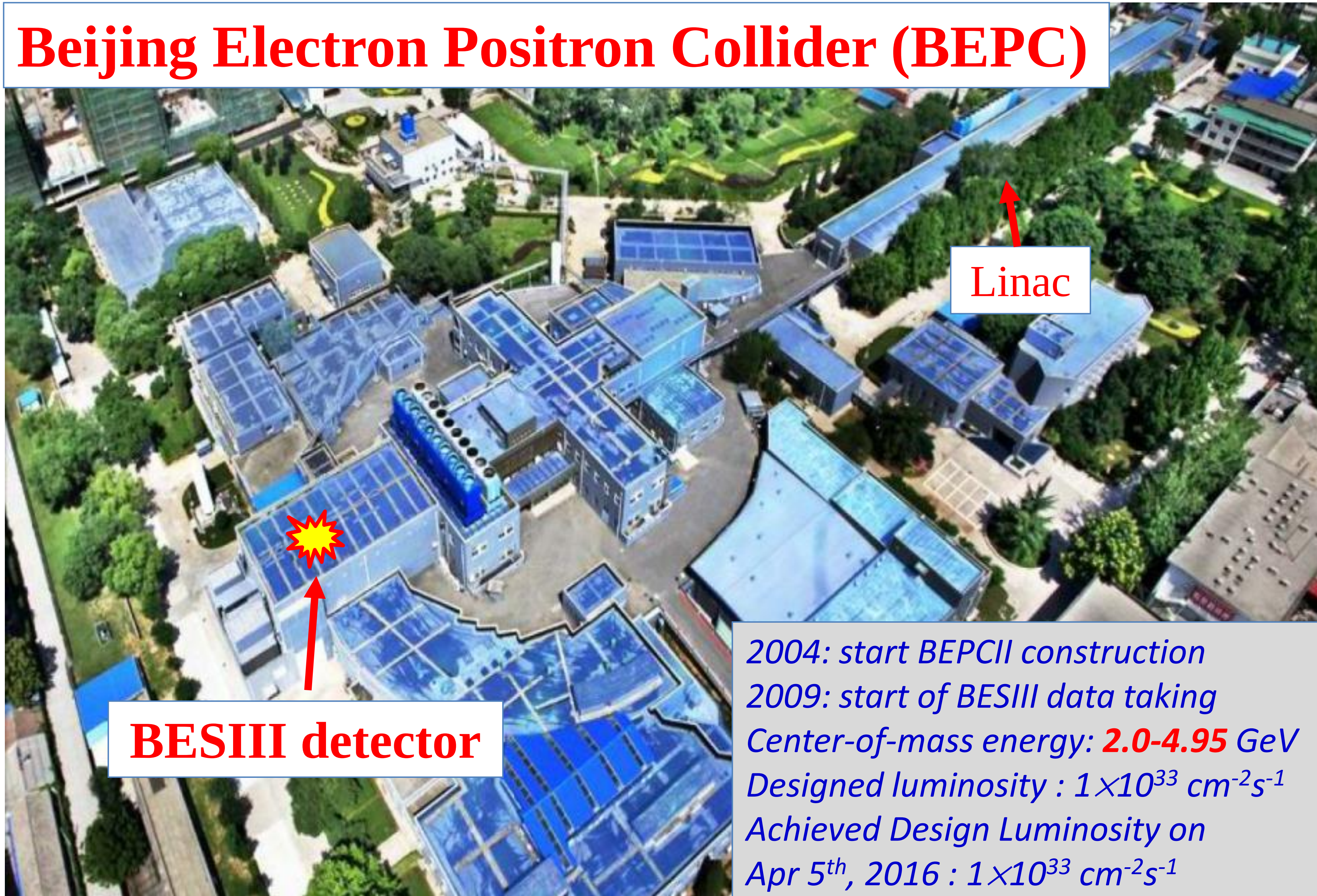
| Decay mode | Quantity of interest | Comments |
|---|---|---|
| $D \to K^0_S\pi^+\pi^-$ | $c_i$ and $s_i$ √ | Binning schemes as those used in the CLEO-c analysis. With future, very large $\psi(3770)$data sets, it might be worthwhile to explore alternative binning. |
| $D \to K^0_S K^+K^-$ | $c_i$ and $s_i$ √ | Binning schemes as those used in the CLEO-c analysis. With future, very large $\psi(3770)$data sets, it might be worthwhile to explore alternative binning. |
| $D \to K^\pm\pi^\mp\pi^+\pi^-$ | $R$, $\delta$ √ | In bins guided by amplitude models, currently under development by LHCb. |
| $D \to K^+K^-\pi^+\pi^-$ | $c_i$ and $s_i$ | Binning scheme can be guided by the CLEO model [18] or potentially an improved model from LHCb in the future. |
| $D \to \pi^+\pi^-\pi^+\pi^-$ | $F_+$ or $c_i$ and $s_i$ | Unbinned measurement of $F_+$. Measurements of $F_+$ in bins or $c_i$ and $s_i$ in bins could be explored. |
| $D \to K^\pm\pi^\mp\pi^0$ | $R$, $\delta$ √ | Simple 2-3 bin scheme could be considered. |
| $D \to K^0_S K^\pm\pi^\mp$ | $R$, $\delta$ | Simple 2 bin scheme where one bin encloses the $K^*$ resonance. |
| $D \to \pi^+\pi^-\pi^0$ | $F_+$ | No binning required as $F_+ \sim 1$. |
| $D \to K^0_S\pi^+\pi^-\pi^0$ | $F_+$ and $c_i$ and $s_i$ | Unbinned measurement of $F_+$ required. Additional measurements of $F_+$ or $c_i$ and $s_i$ in bins could be explored. |
| $D \to K^+K^-\pi^0$ | $F_+$ | Unbinned measurement required. Extensions to binned measurements of either $F_+$ or $c_i$ and $s_i$ possible. |
| $D \to K^\pm\pi^\mp$ | $\delta$ | Of low priority due to good precision available through charm-mixing analyses. |

# Summary

- BESIII had collected the largest data samples for study of charmed hadrons, including $D^0$, $D^+$, $D_s^+$ and $\Lambda_c^+$ etc.
- A range of important and unique results had been published in recent years.
- BESIII will collected more 17/fb data at $\psi(3770)$ resonance peak. The constraint on $\gamma$ from strong phases is expected to be <0.5%.
- More important results are expected in charmed hadron decays at BESIII.

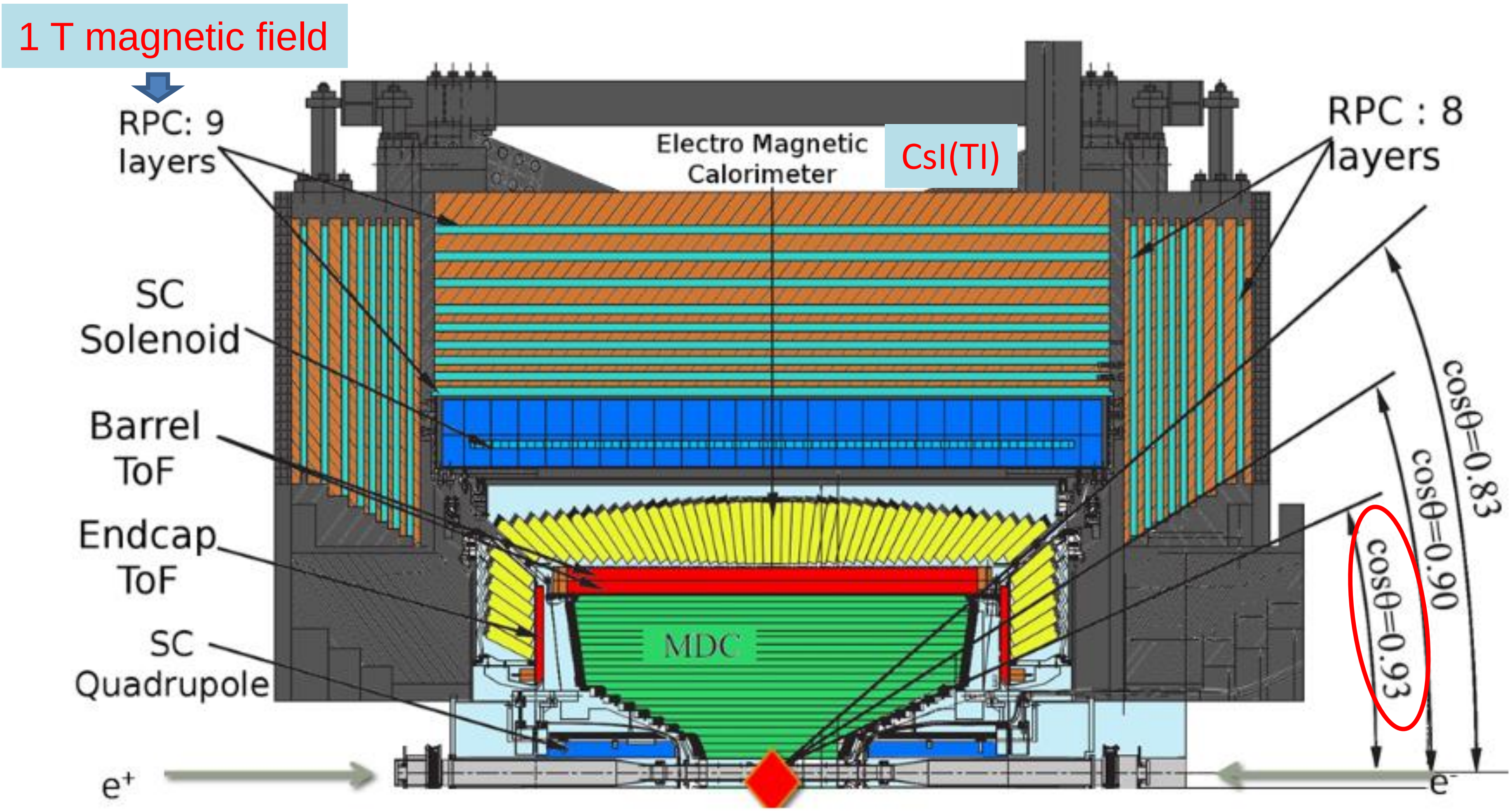
# Thanks!

# Beijing Electron Positron Collider (BEPC)




*2004: start BEPCII construction*
*2009: start of BESIII data taking*
*Center-of-mass energy: **2.0-4.95** GeV*
*Designed luminosity : $1\times10^{33}$ $cm^{-2}s^{-1}$*
*Achieved Design Luminosity on*
*Apr $5^{th}$, 2016 : $1\times10^{33}$ $cm^{-2}s^{-1}$*

# BESIII Detector




- MDC:
  - σp/p: 0.5%@1GeV/c
  - $\sigma_{dE/dx}$: 6% for electrons
- TOF:
  - $\sigma_T$: 68 ps (Barrel)
  - 110 ps (Endcap)
- EMC:
  - σE/√E: 2.5(5.0)%@1GeV for barrel(endcap)

# BESIII Collaboration

## Europe (17)

Germany: Bochum Ruhr Univ., GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg Univ. of Mainz, Justus-Liebig-Univ. Giessen, Univ. of Münster, Univ. of Giessen; Russia: Budker Institute of Nuclear Physics, Joint Institute for Nuclear Research; Italy: Ferrara Univ., INFN Laboratori Nazionali di Frascati, Univ. of Turin; The Netherlands : KVI-CART Univ. of Groningen; Sweden: Uppsala Univ.,

Turkey: *Turkish Accelerator Center Particle Factory Group; UK: Univ. of Oxford, Univ. of Manchester.*

## USA (5)

Carnegie Mellon Univ.,

Indiana Univ.,

Univ. of Hawaii,

Univ. of Minnesota,

Univ. of Rochester,

## Others In ASIA(9)

COMSATS Institute of Information Technology, Pakistan,

Indian Institute of Technology, Madras, India

Institute of Physics and Technology Mongolia,

Seoul National Univ., Korea,

Tokyo University, Japan

Univ. of Punjab, Pakistan

*Suranaree Univ. of Technology, Thailand*

*University of Lahore, Pakistan*

## South America (1)

University of Tarapaca

## China (48)

IHEP, Beihang Univ.,

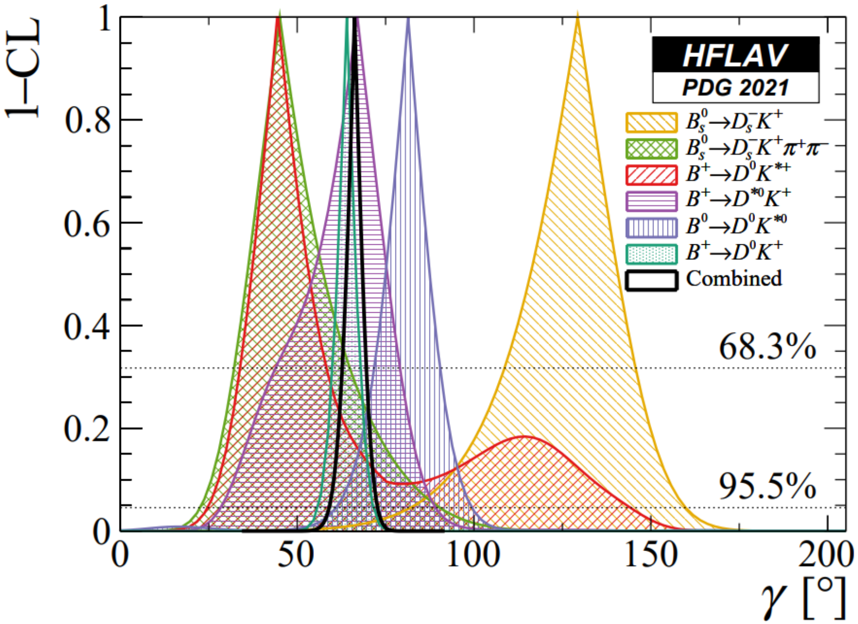
*Beijing Institute of Petrochemical Technology*,

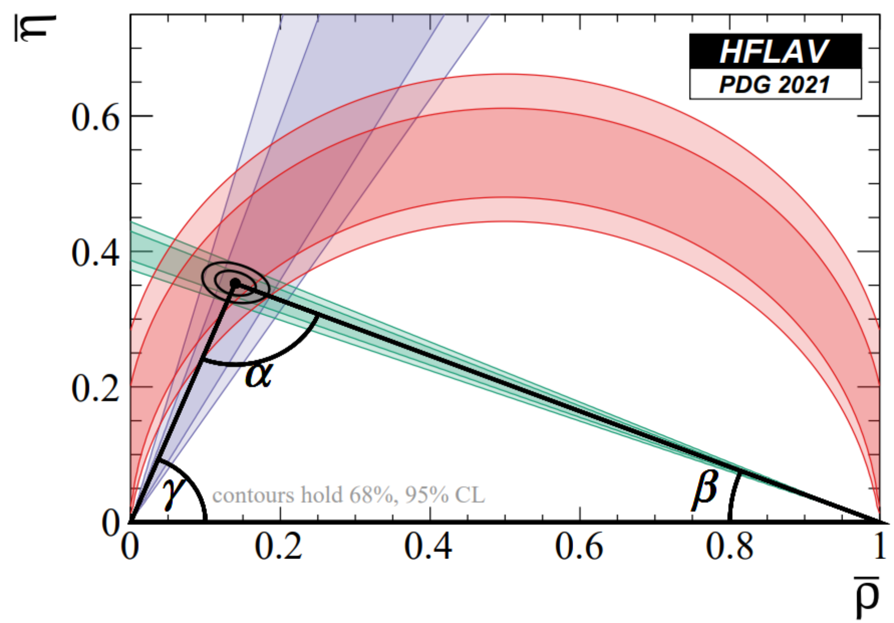
CCAST, Fudan Univ., Guangxi Normal Univ., Guangxi Univ., Hangzhou Normal Univ., Henan Normal Univ., Henan Univ. of Science and Technology, Huazhong Normal Univ., Huangshan College, Hunan Univ., Hunan Univ., Hunan Normal Univ., Institute of modern Physics, Jilin Univ., Lanzhou Univ., Liaoning Normal Univ., Liaoning Univ., Nanjing Normal Univ., Nanjing Univ., Nankai Univ., Peking Univ., Qufu Normal Univ., North China Electric Power Univ., Shanxi Univ., Shanxi Normal Univ., Shandong Normal Univ., Shandong Univ., Shanghai Jiao Tong Univ., Soochow Univ., South China Normal Univ., Southeast Univ., Sun Yat-Sen Univ., Tsinghua Univ., Univ. of Chinese Academy of Sciences ,

Univ. of Jinan, Univ. of Science and Technology of China, Univ. of Sciences and Technology Liaoning, Univ. of South China, Wuhan Univ., Xinyang Normal Univ., Zhejiang Univ., Zhengzhou Univ.

BESIII: ~500 members from 80 institutes in 17 countries.

# The latest world averages of the CKM Unitarity Triangle Angles




$$\gamma/\phi_3 = (66.2^{+3.4}_{-3.6})^o$$

$$\beta/\phi_1 = (22.2 \pm 0.7)^o$$

$$\alpha/\phi_2 = (85.2^{+4.8}_{-4.3})^o$$

$$\alpha + \beta + \gamma = (173.6^{+5.9}_{-5.6})^o$$

## For B→D($K_S^0\pi^+\pi^-$)K decays, the relations are followed:

Assuming *k* bins in DP,
4*k* relations and 2*k*+3 unknowns;
The bin number: *k*≥2;

✓ bin +i:

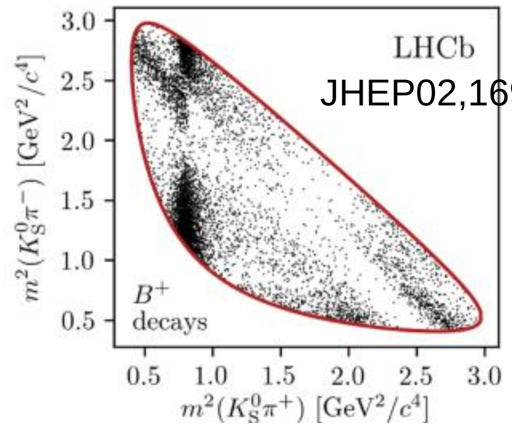
$$\hat{\Gamma}_i^- \equiv \int_i d\hat{\Gamma}(B^- \to (K_S\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{\bar{i}} + 2r_B[\cos(\delta_B - \gamma)c_i + \sin(\delta_B - \gamma)s_i],$$

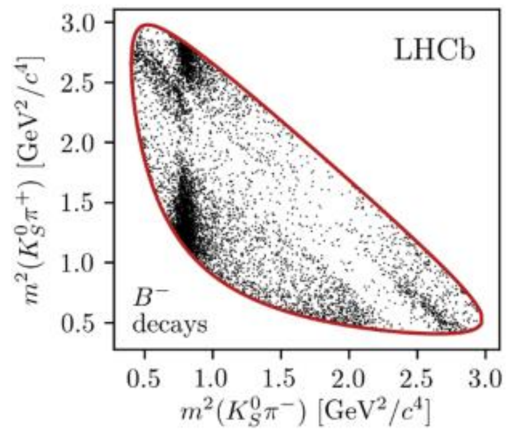
$$\hat{\Gamma}_i^+ \equiv \int_i d\hat{\Gamma}(B^+ \to (K_S\pi^-\pi^+)_D K^+) = T_{\bar{i}} + r_B^2 T_i + 2r_B[\cos(\delta_B + \gamma)c_i - \sin(\delta_B + \gamma)s_i],$$

✓ bin –i:

$$\hat{\Gamma}_{\bar{i}}^- \equiv \int_{\bar{i}} d\hat{\Gamma}(B^- \to (K_S\pi^-\pi^+)_D K^-) = T_{\bar{i}} + r_B^2 T_i + 2r_B[\cos(\delta_B - \gamma)c_i - \sin(\delta_B - \gamma)s_i],$$

$$\hat{\Gamma}_{\bar{i}}^+ \equiv \int_{\bar{i}} d\hat{\Gamma}(B^+ \to (K_S\pi^-\pi^+)_D K^+) = T_i + r_B^2 T_{\bar{i}} + 2r_B[\cos(\delta_B + \gamma)c_i + \sin(\delta_B + \gamma)s_i].$$

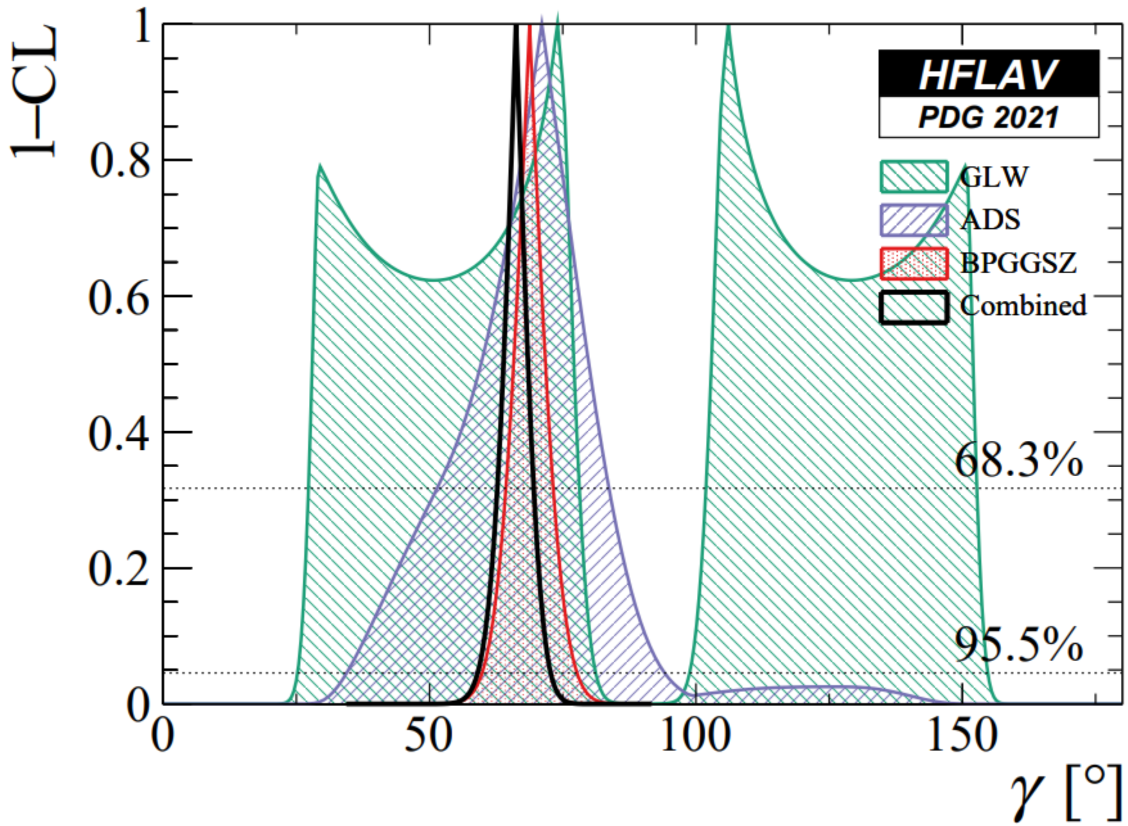



**Charm inputs ($c_i$ and $s_i$) are essential to constrain the γ measurement!**

- ❑ $D \to K_S^0 \pi^+ \pi^-$ is the most important channel to measure strong-phases
- ❑ The $(c_i, s_i)$ measured in $D \to K_S^0 \pi^+ \pi^-$ also provide critical inputs of measuring strong-phase in other D decays.
  - ✓ GLW [1]: via $D^0 \to$ CP eigenstate, $K^+K^-$, $\pi^+\pi^-$, $K_S^0\pi^0$ etc.
  - ✓ ADS [2]: via $D^0 \to$ CF and DCS, such as $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K_S^0 K\pi$, etc.
  - ✓ GGSZ [3]: via with $D^0 \to$ Multi-body self-conjugate decays, $K_s^0\pi^+\pi^-$ , $K_s^0 K^+K^-$ etc.

No strong-phase input for $\gamma$ measurements for GLW.




The precision of $\gamma$ measurement from three methods.