Quantum-correlated studies in charm physics at BESIII

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Outline

- Introduction
- Quantum-correlated studies at BESIII
- Physics prospects
- Summary

Quantum correlated: phase input

- Relative D^0, $\overline{D}^0$ phases can show up:
  1. Quantum-correlated("EPR") D pairs @threshold: $\psi(3770)$
  2. $B \rightarrow DX$, with common D, $\overline{D}$ final states(for CKM γ)
  3. $D\overline{D}$ mixing
  - 1 is viewed as a source of information to be input for use by 2) & 3)

- Relevant datasets are CLEO-c(~$0.82 fb^{-1}$) and BESIII(~$2.92 fb^{-1}$)
  - Access to relative D^0, $\overline{D}^0$ strong phase differences
  - Can obtain model-independent results

CKM matrix

$$
\begin{pmatrix} u & c & t \end{pmatrix} \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}
$$

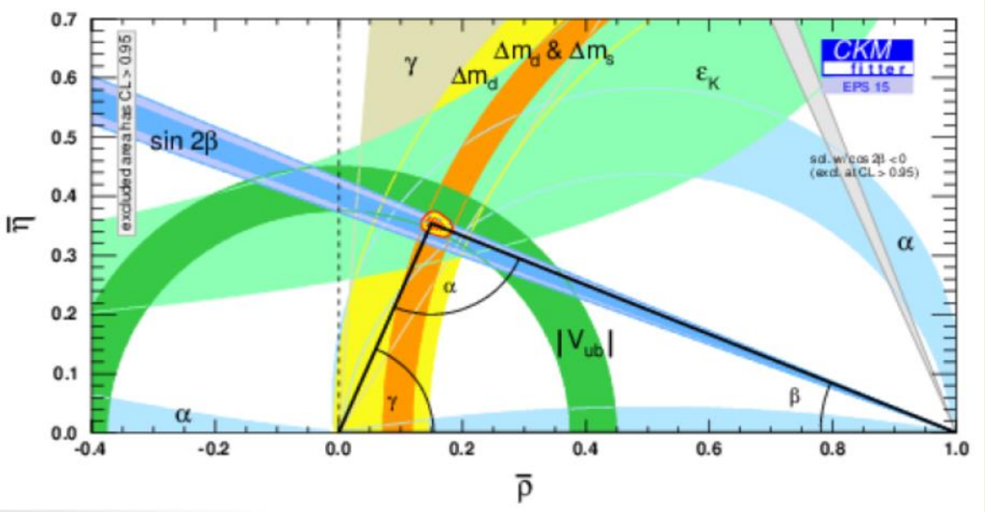
- 3X3 unitary complex matrix
  - 4 parameters
  - 3 mixing angle and 1 phase

$$
\begin{pmatrix} 1-\lambda^2/2 & \lambda & \boxed{A\lambda^3(\rho-i\eta)} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \boxed{A\lambda^3[1-(\rho-i\eta)]} & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)
$$

$$\lambda = \sin\theta_C$$

- $$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

- $$\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right) \equiv \phi_2,$$ $$\boxed{\alpha = (87.6^{+3.5}_{-3.3})^\circ}$$
  $$\beta = arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \equiv \phi_1,$$ $$\boxed{\sin 2\beta = 0.691 \pm 0.017}$$
  $$\gamma = arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right) \equiv \phi_3,$$ $$\boxed{\gamma = (73.2^{+6.3}_{-7.0})^\circ}$$



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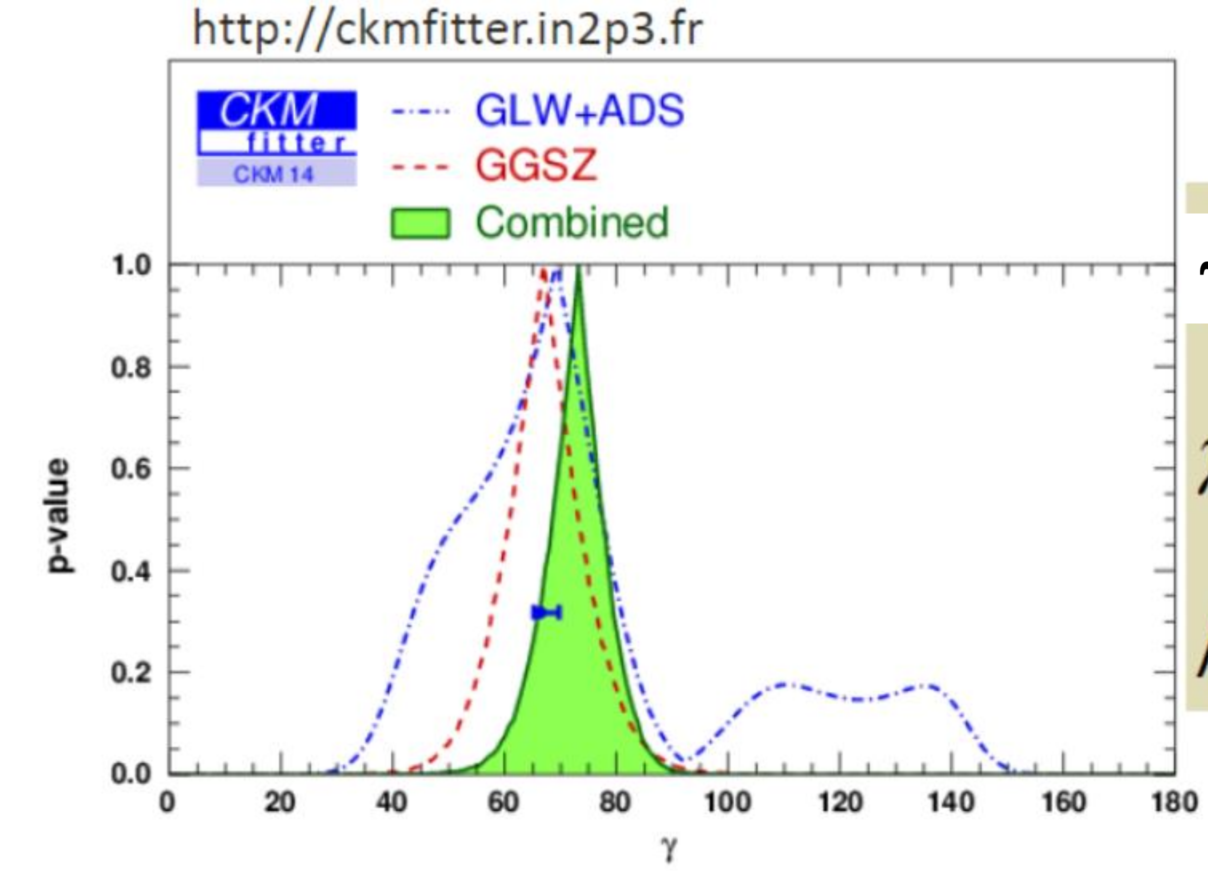
Large γ

NP could lead to 4º effects

PRD 92, 033002 (2015)



$\gamma_{\text{mearsured}} = (73.5^{+4.3}_{-5.0})^{\circ}$

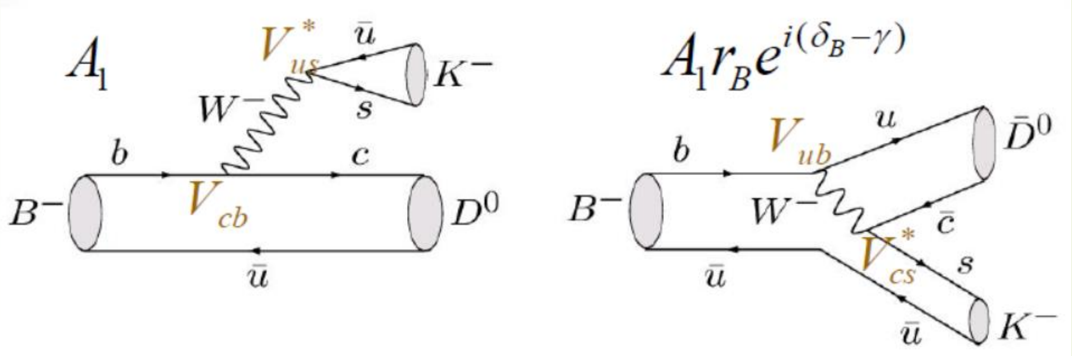
$$\gamma_{\text{predicted}} = \left(66.9^{+1.0}_{-3.7}\right)^{\circ}$$

$$\beta_{\text{measured}} = \left(21.50^{+0.75}_{-0.74}\right)^{\circ}$$

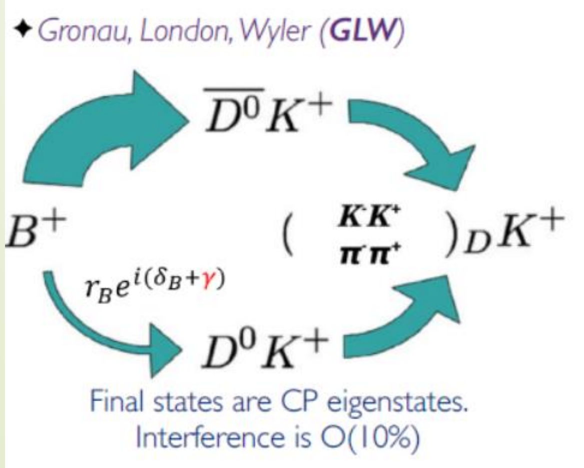
Principal experimental goal in CKM physics in the next decade is to reduce uncertainty to 1º

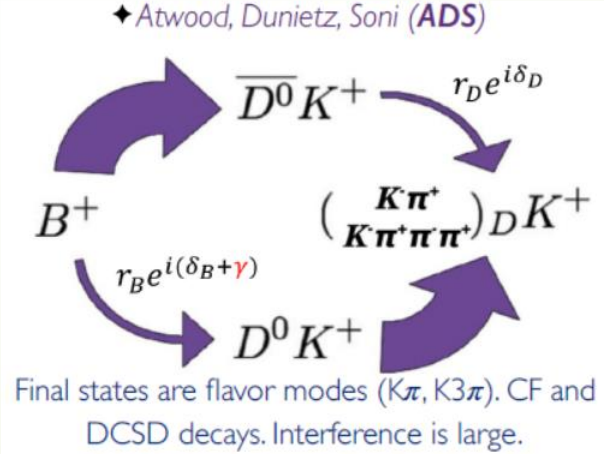
Determine γ by B→DK

- Usually use B→DK
  - Include B and D amplitudes, relative strong phase and γ

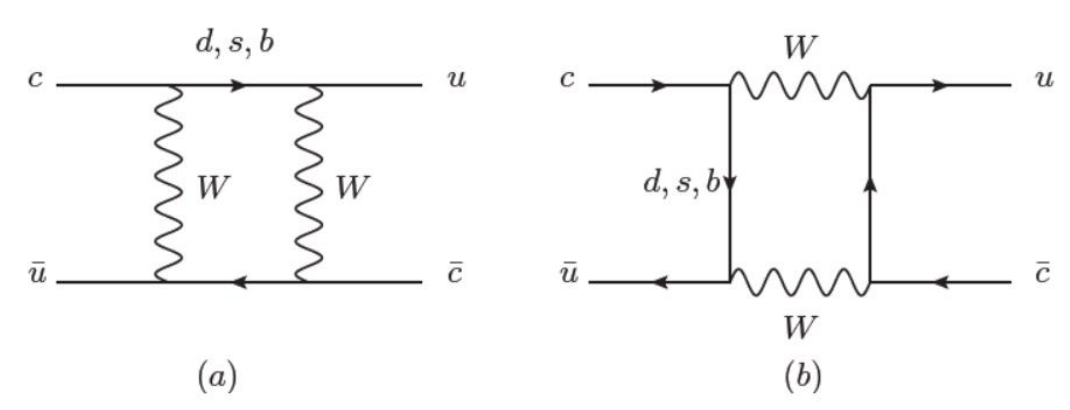


- 3 method
  - use K^+X^-($X^-=\pi^-, \pi^-\pi^0, \pi^-\pi^-\pi^+$) CF and DCS (ADS)
  - use CP-eigenstates (GLW)
  - use self-conjugate multi-body states: $K_sh^+h^-$ (Dalitz/GGSZ)

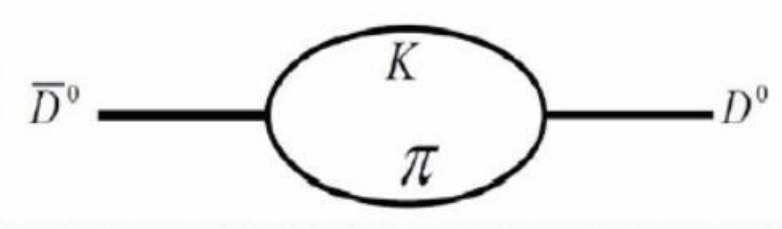




$D\bar{D}$ mixing



- Neutral D mixing parameter
  - $$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \qquad m = \frac{m_1 + m_2}{2},$$
    $$\Delta m = m_1 - m_2, \qquad \Delta\Gamma = \Gamma_1 - \Gamma_2,$$
    $$x = \frac{\Delta m}{\Gamma}, \qquad y = \frac{\Delta\Gamma}{2\Gamma}.$$
- In standard model, neutral D mixing is small
  - $\propto (V_{ui}V_{ci}^{*})(V_{uj}V_{cj}^{*})$, contribution from b is suppressed
  - Contribution from s and d is suppressed by GIM mechanism
  - Short-distance effect: $x \sim O(10^{-5})$, $y \sim O(10^{-7})$
- Long-distance effect
  - Enhanced to $x,y \sim O(10^{-3})$



Time dependent decay rates

$$\left|\frac{q}{p}\right| = R_m, \quad \frac{q}{p} = R_m e^{i\phi}$$

- D→f(example f=Kπ):
  - Define: $\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = -\sqrt{R}R_m e^{-i(\delta-\varphi)}$, $\lambda_{\bar{f}}^{-1} = \frac{p}{q}\frac{A_{\bar{f}}}{\bar{A}_{\bar{f}}} = -\sqrt{R}R_m^{-1} e^{-i(\delta+\varphi)}$
-

$$\begin{aligned}
\Gamma(D^0 \to K^+\pi^-) &\propto \left|\frac{q}{p}\right|^2 |\bar{A}_{\bar{f}}|^2 \left[|\lambda_{\bar{f}}^{-1}|^2 - yRe\lambda_{\bar{f}}^{-1} + xIm\lambda_{\bar{f}}^{-1}\right], \\
\Gamma(\bar{D}^0 \to K^-\pi^+) &\propto \left|\frac{p}{q}\right|^2 |A_f|^2 \left[|\lambda_f|^2 - yRe\lambda_f + xIm\lambda_f\right], \\
\Gamma(D^0 \to K^-\pi^+) &\propto |A_f|^2 \left[1 - yRe\lambda_f - xIm\lambda_f\right], \\
\Gamma(\bar{D}^0 \to K^+\pi^-) &\propto |\bar{A}_{\bar{f}}|^2 \left[1 - yRe\lambda_{\bar{f}}^{-1} - xIm\lambda_{\bar{f}}^{-1}\right], \\
\Gamma(D^0 \to K^+K^-) &\propto |A_{K^+K^-}|^2 \left[1 - R_m(y\cos\varphi - x\sin\varphi)\right], \\
\Gamma(\bar{D}^0 \to K^+K^-) &\propto |\bar{A}_{K^+K^-}|^2 \left[1 - R_m^{-1}(y\cos\varphi + x\sin\varphi)\right].
\end{aligned}$$

PDG16

Year	Exper.	y' (%)	x'^2 ($\times 10^{-3}$)
2014*†	Belle [14]	0.46±0.34	0.09±0.22
2013	LHCb [15]	0.48±0.10	0.055±0.049
2013	CDF [16]	0.43±0.43	0.08±0.18
2012*	LHCb [17]	0.72±0.24	−0.09±0.13
2007*	CDF [18]	0.85±0.76	−0.12±0.35
2007	BaBar [19]	0.97±0.44±0.31	−0.22±0.30±0.21

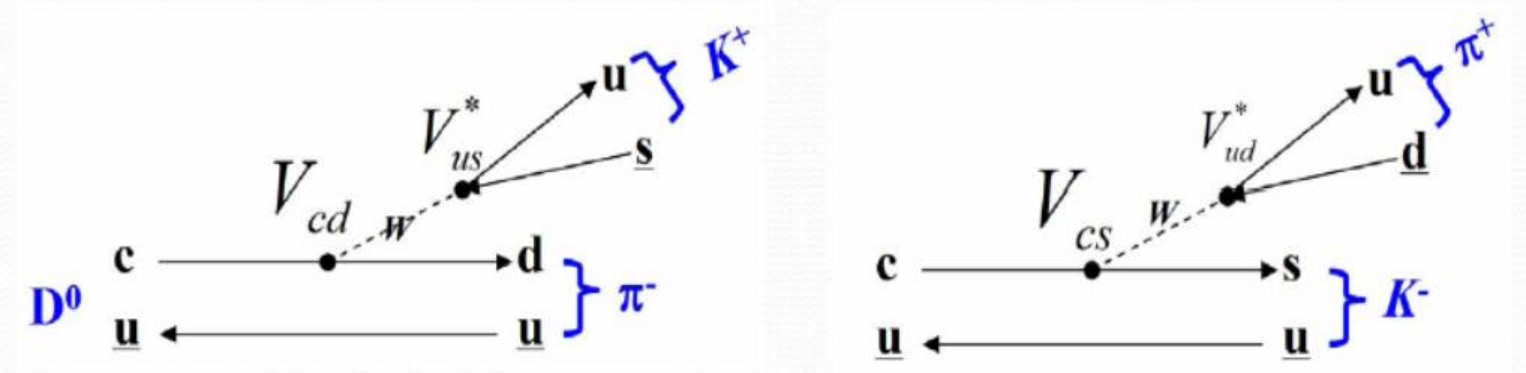
- Wrong sign(WS) progress $D^0 \to K^+\pi^-$ with time(if no CPV)

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R + \sqrt{R}y'\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right]$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

Relative strong phase

- $$\frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)} \equiv -r_D e^{-i\delta_D}$$



Doubly Cabibbo Suppressed (DCS) Cabibbo Favored (CF)

- Using the relevant dataset(BESIII & CLEO-c)
  - Reduce model-dep. of CKM γ from $B \to DK$
  - Rotate measured x', y' parameters to x, y

Time-intergrated decay rates

- No time dependent information at charm threshold
- Anti-sysmmetric wavefunction

$$\Gamma^2{}_{ij} = \left|\langle i|D^0\rangle\langle j|\bar{D}^0\rangle - \langle j|D^0\rangle\langle i|\bar{D}^0\rangle\right|^2$$

$$\psi(3770) \to [D^0\bar{D}^0 - \bar{D}^0 D^0]/\sqrt{2}$$

$$= -[D_{CP+}D_{CP-} - D_{CP-}D_{CP+}]/\sqrt{2}$$

$$D_{CP\pm} = [D^0 \pm \bar{D}^0]/\sqrt{2}$$

- Double tag rates:
  - $A_i^2 A_j^2[1 + r_i^2 r_j^2 - 2r_i r_j \cos(\delta_i+\delta_j)]$
  - CP tag: r=1.δ=0 or π; l± tag: r=0
- Single and Double tag rates

C-odd	f	$\bar{f}$	l^+	l^-	CP+	CP-
f	$R_M[1 + r_f^2(2 - z_f^2) + r_f^4]$					
$\bar{f}$	$1 + r_f^2(2 - z_f^2) + r_f^4$	$R_M[1 + r_f^2(2 - z_f^2) + r_f^4]$				
l^+	r_f^2	1	R_M			
l^-	1	r_f^2	1	R_M		
CP+	$1 + r_f(r_f + z_f)$	$1 + r_f(r_f + z_f)$	1	1	0	
CP-	$1 + r_f(r_f - z_f)$	$1 + r_f(r_f - z_f)$	1	1	4	0
Single Tag	$1 + r_f^2 - r_f z_f(A - y)$		1		$2[1 \pm (A - y)]$	

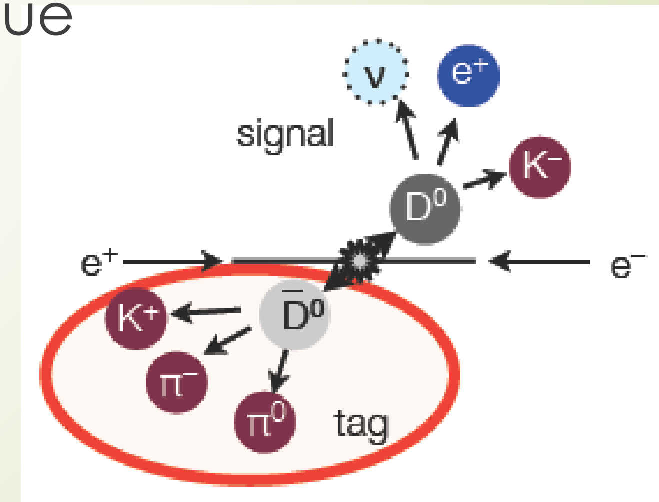
$$z_f \equiv 2\cos\delta_f\,, r_f \equiv \frac{A_{DCS}}{A_{CF}}, R_M \approx \frac{x^2+y^2}{2}$$

Double Tag (DT) techniques

- Threshold production at $\psi(3770)$
  - *D* generated in pair → $D^0\bar{D}^0$ and D^+D^-
  - 100% of beam energy converted to *D* pair (Clean environment, kinematic constrains)
  - Systematic uncertainties cancellations while applying double tag technique
  - Quantum Correlations and CP-tagging are unique
- Fully reconstruct about 15% of *D* decays

$$\Delta E = E_D - E_{\text{Beam}}$$

$$M_{\text{BC}} = \sqrt{E^2_{\text{Beam}} - p^2_D}$$



Decay modes

- Flavored:

Flavored semileptonic	$K^-e^+\nu$, $K^-\mu^+\nu$	Pure CF
Flavored hadronic	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi$-	CF + DCSD

- Self-Conjugate:

2-body CP eigenstate	K^-K^+, $\pi^+\pi^-$, ...	SCS
2-body CP eigenstate	$K_S\pi^0$, ...	CF + DCSD
Multi body	$K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^0$	SCS
Multi body	$K_Sh^+h^-$, $K_Lh^+h^-$	CF + DCSD

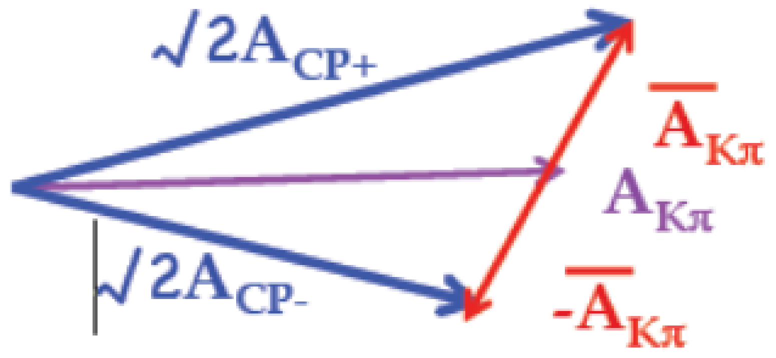
- Neither

$K_SK^-\pi^+$	SCS

Blue modes: used for γ **Green : future?** **Black: tag only**

D→Kπ strong phase

Simplified Picture: (simple = no mixing)



Amplitude triangle:

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

[DCSD enhanced for visibility !]

- D→Kπ vs D→CP

Complex ratio
DCSD/CF amplitude

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

- CP-tagged rate asymmetry relative to r·cosδ, straightforward analysis

$$\mathcal{A}_{CP} = [\,|A_{CP-}|^2 - |A_{CP+}|^2\,] \,/\, [\,|A_{CP-}|^2 + |A_{CP+}|^2\,] \quad \leftarrow \text{measure}$$

$$= r\cos\delta \quad (+\text{ D mixing corrections: } y, R_{WS}) \quad \leftarrow \text{extract}$$

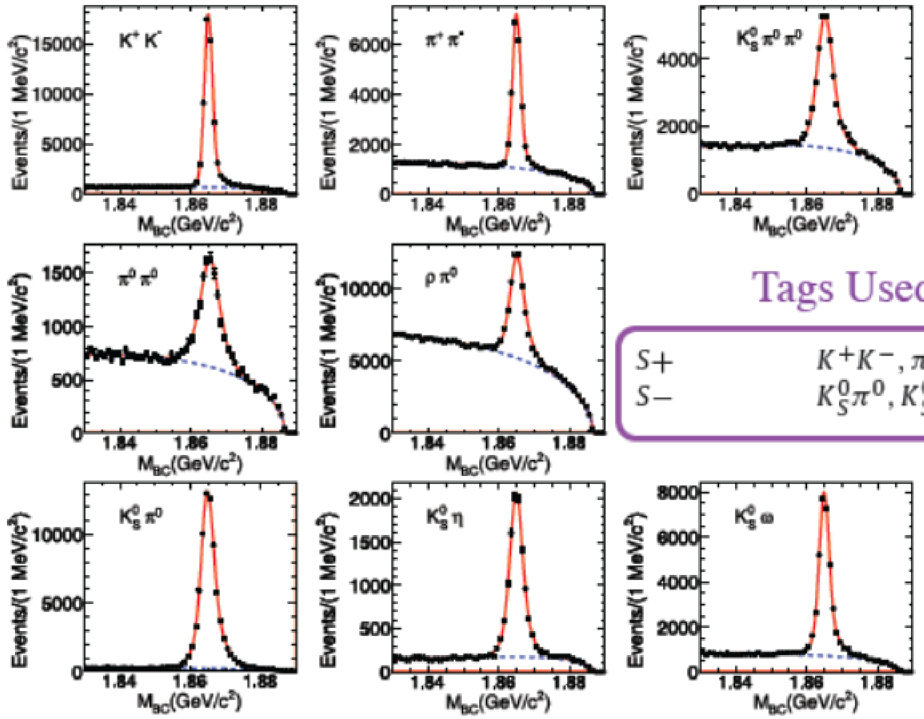
D→Kπ strong phase measurement

- 2.92fb[-1] data

$$\mathcal{A}^{CP}_{K\pi} \equiv \frac{\mathcal{B}_{D^{S-}\to K^-\pi^+} - \mathcal{B}_{D^{S+}\to K^-\pi^+}}{\mathcal{B}_{D^{S-}\to K^-\pi^+} + \mathcal{B}_{D^{S+}\to K^-\pi^+}}$$

- Direct result

$$A^{CP}_{K\pi} = (12.7 \pm 1.3 \pm 0.7)\%$$



Tags Used: 5 CP+, 3 CP-

$S+$	$K^+K^-, \pi^+\pi^-, K^0_S\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$
$S-$	$K^0_S\pi^0, K^0_S\eta, K^0_S\omega$

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

Using external inputs for $r_{K\pi}$, R_{WS}, y, we extract :

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

PLB 734, 227(2014)

D→Kπ strong phase measurement

- BESIII measurement(2.92fb^{-1}):

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

- CLEO-c measurement(0.82fb^{-1}):

$$\textit{without external inputs:} \quad \cos\delta = 0.81^{+0.22+0.07}_{-0.18-0.05},$$

$$\textit{with external inputs:} \quad \cos\delta = 1.15^{+0.19+0.00}_{-0.17-0.08};$$

- Agree with CLEO-c result of external inputs, CLEO-c use complex global fit
- HFLAV result: $\delta_{K\pi}^{\mathrm{HFAG}} = \left(11.8^{+\ 9.5}_{-14.7}\right)^{\circ}$ (do not use BESIII result)
  - I think they can directly use $A_{K\pi}^{CP}$
  - ADS method for extract γ

CLEO-c： PRD 86 112001(2012)
BESIII: PLB 734 227(2014)

Multi-body ADS

Mode	Branching Ratio
$K\pi$	3.89%
$K\pi\pi^0$	13.9%
$K3\pi$	8.1%

- D→Kππ⁰ and D→Kπππ can also be used
  - Large branching fractions than D→Kπ
- Need to account for the resonant substructure
- Atwood and Soni (PRD68,033003(2003)) show how to modify the usual ADS equations for this case

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

- $R_{K3\pi}$ ranges from
  - 1=coherent(dominated by a single mode) to
  - 0=incoherent(several significant components)

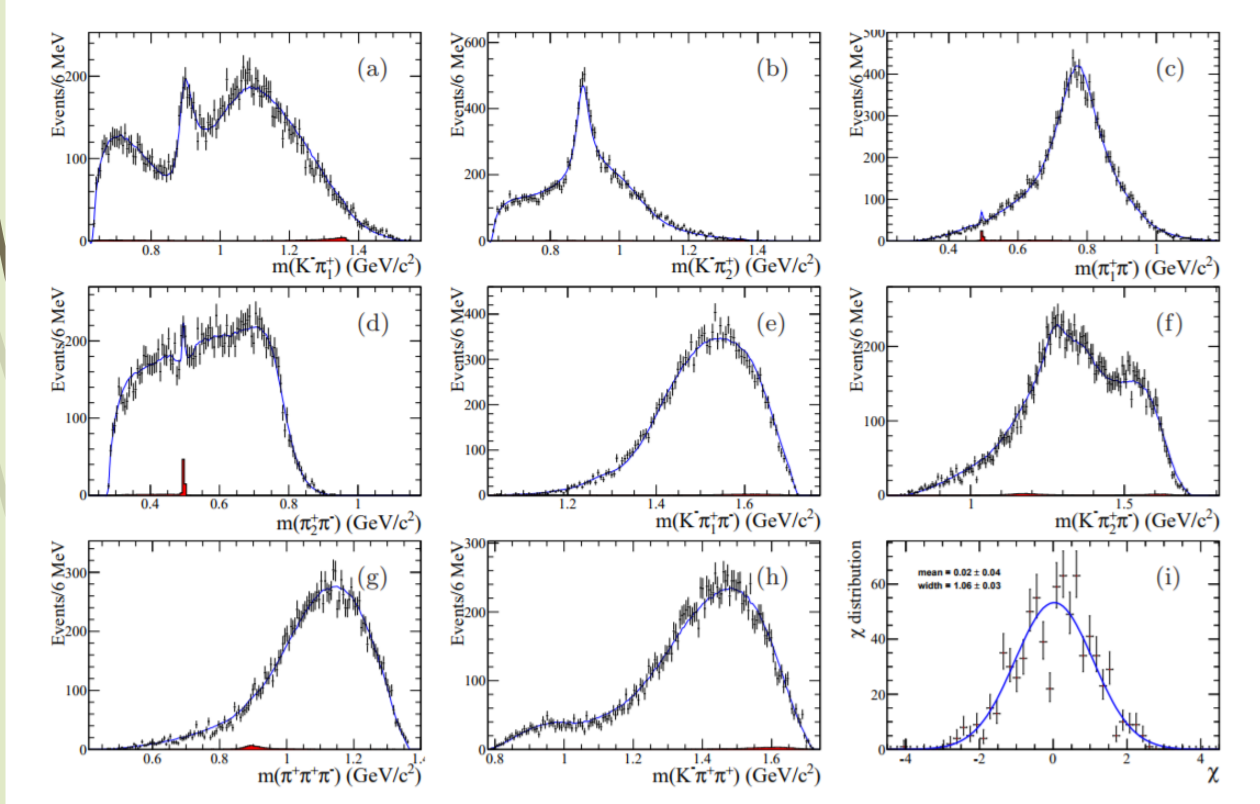
Need to find average strong phase

Amplitude analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$

PRD95(2017)072010

- Understanding the substructure
- strong phase measurement $\to \gamma$ measurement

Improve the absolute BF



Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0K^-)_A\pi^+,\ (\rho^0K^-)_A[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_P\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_{S-wave}\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_V\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_P\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_S$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_V\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_{S-wave}\pi^-)_A\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_S\pi^+)_A$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_S$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_V(\pi^+\pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_V$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_V(\pi^+\pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_T(\pi^+\pi^-)_S$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_{S-wave}(\pi^+\pi^-)_T$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

GGSZ method

- Total decay rate

$$\Gamma(B^{\pm} \to f(D^0)K^{\pm}) = A_B^2 A_f^2\left(r_D^2 + r_B^2 + 2r_D\, r_B\, \cos(\delta_B + \delta_D - \gamma)\right)$$

  - Substructure allows regions of $r_D \approx r_B$
  - Sizeable statistics
- Latest result:
  - Model dependent:
    - Babar: $\gamma=(68^{+15}_{-14}$+-4+-3)° PRL105,121801(2015)
    - Belle: $\gamma=(78^{+11}_{-12}$+-4+-9)° PRD81,112002(2010)
  - Model independent:
    - LHCb: $\gamma=(62^{+15}_{-14})$° JHEP1410,097(2014)

γ fit through GGSZ method

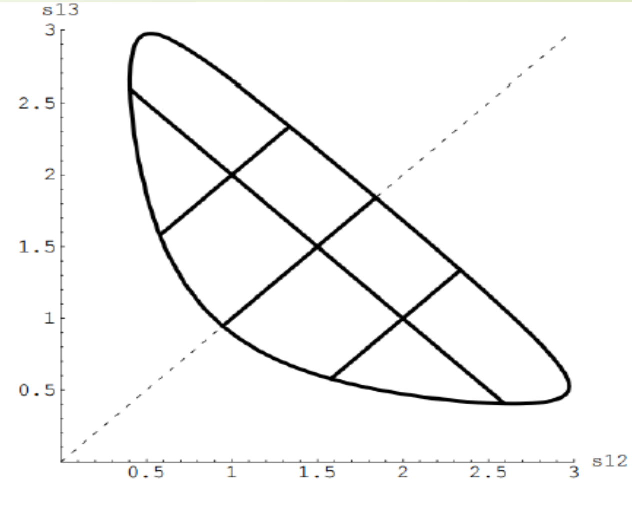
Binned decay rate:

$$\Gamma_i^{\pm} \equiv \int_i d\Gamma(B^{\pm} \to (K_S^0 \pi^- \pi^+)_D K^{\pm})$$
$$= T_i + r_B^2 T_{\bar{i}} \pm 2 r_B \sqrt{T_i T_{\bar{i}}} [\cos(\delta_B + \gamma) c_i - \sin(\delta_B + \gamma) s_i]$$

- T_i : Bin yield measured in flavor decays
- r_B : color suppression factor~0.1
- δ_B : strong phase of B decay
- c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively where $\Delta\delta_D$ is the difference between phase of D^0 and D^0

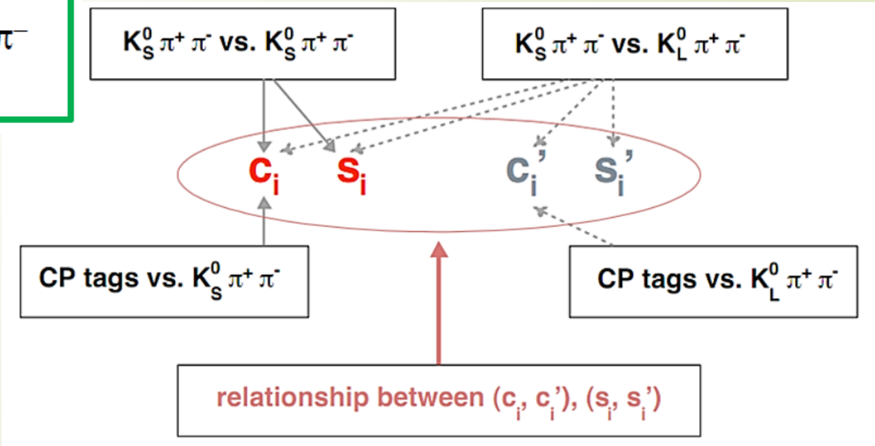
Measured at B-Factories

Through $D^0 \to K_S \pi^+ \pi^-$ analysis

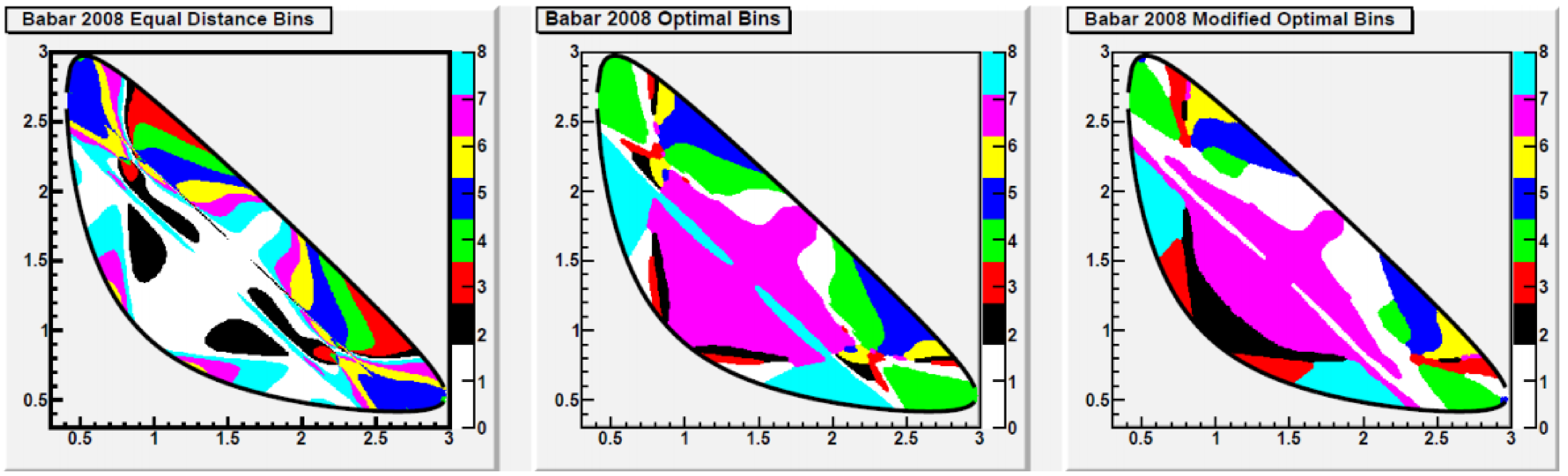


Mirrored binning over x=y makes it so $c_i = c_{-i}$ and $s_i = -s_{-i}$

- A relationship can be shown between Dalitz bin yields and c_i and s_i



Binning of D0→Ks$\pi^+\pi^-$ Dalitz plot



Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to γ. A secondary adjustment smooths binned areas smaller than detector resolution.

Similar to the "optimal binning" except the expected background is taken into account before optimizing for γ sensitivity.

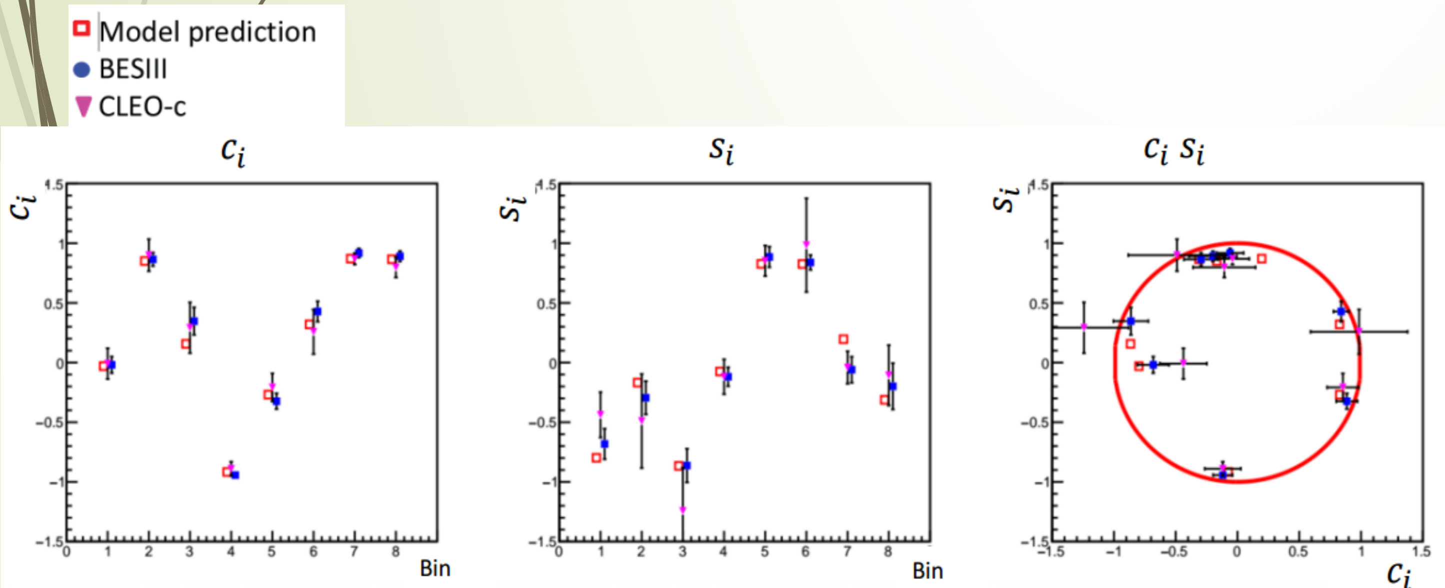
Preliminary result

$D^0/\bar{D}^0 \rightarrow K_S\pi^+\pi^-$ measurement at BESIII

Bins	c_i BES-III	c_i CLEO-c	s_i BES-III	s_i CLEO-c
1	0.066 ± 0.066	-0.009 ± 0.088	-0.843 ± 0.119	-0.438 ± 0.184
2	0.796 ± 0.061	0.900 ± 0.106	-0.357 ± 0.148	-0.490 ± 0.295
3	0.361 ± 0.125	0.292 ± 0.168	-0.962 ± 0.258	-1.243 ± 0.341
4	-0.985 ± 0.017	-0.890 ± 0.041	-0.090 ± 0.093	-0.119 ± 0.141
5	-0.278 ± 0.056	-0.208 ± 0.085	0.778 ± 0.092	0.853 ± 0.123
6	0.267 ± 0.119	0.258 ± 0.155	0.635 ± 0.293	0.984 ± 0.357
7	0.902 ± 0.017	0.869 ± 0.034	-0.018 ± 0.103	-0.041 ± 0.132
8	0.888 ± 0.036	0.798 ± 0.070	-0.301 ± 0.140	-0.107 ± 0.240

BESIII only statistical error **CLEO-c PRD82,112006**

- Consistent with CLEO-c, better stat. err
- Reduction of contribution to uncertainty of γ meas. of 40%(80% for 20fb^{-1})
- The uncertainty on γ from c_i,s_i contribution ~**2.6°**(**1.4°/0.9°** with 10/20 fb^{-1})



Measurement of y_{cp}

PLB744,339(2015)

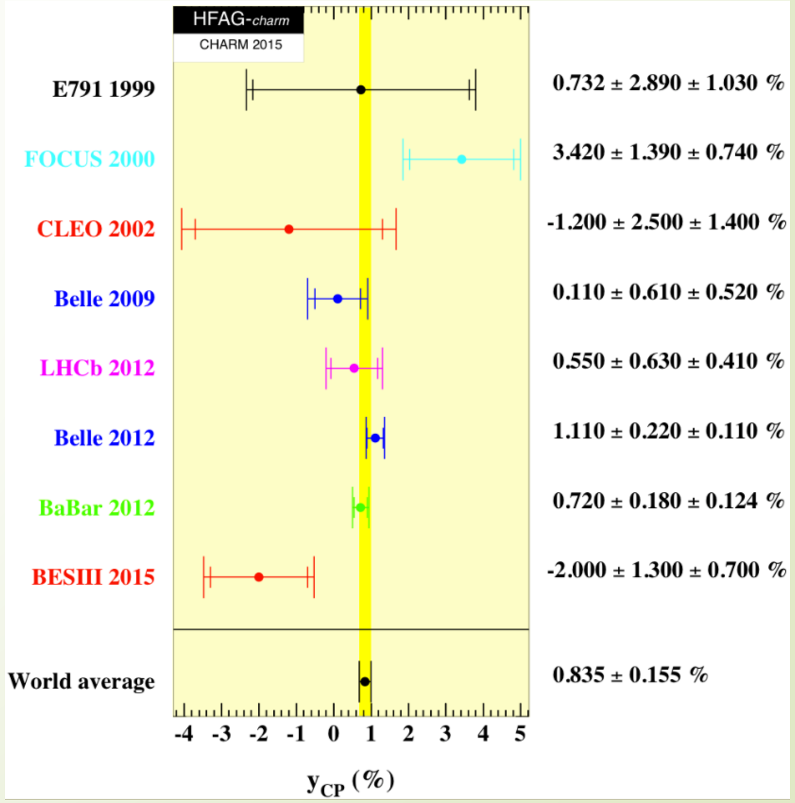
- In absence of direct CPV:

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

  - If no CPV, $y_{cp} = y$
- According to quantum-correlation:

$$y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}_{D_{CP-}\to l}}{\mathcal{B}_{D_{CP+}\to l}} - \frac{\mathcal{B}_{D_{CP+}\to l}}{\mathcal{B}_{D_{CP-}\to l}}\right)$$

- BESIII measured: $y_{CP} = (-2.0 \pm 1.3 \pm 0.7)\%$.
  - Need more data or global fit



$\pi^+\pi^-\pi^0$ & $K^+K^-\pi^0$ CP Fraction

PLB740,1(2015)

- CLEO-c "Legacy data" results
- CP fraction for a mixed –CP final state:

$$F_+ = N(CP+) / [\, N(CP+) + N(CP-) \,]$$

- If the CP-content is nearly pure, F_+ is near 1 or 0.

- Result(PLB740,1(2015) ~0.82fb^{-1}):

$$\pi^+\pi^-\pi^0: \quad F_+ = 0.968 \pm 0.017 \pm 0.006$$
$$K^+K^-\pi^0: \quad F_+ = 0.731 \pm 0.058 \pm 0.021$$

The three-pion mode is nearly pure:
acts *almost* like a CP-eigenstate

Analysis ongoing at BESIII

$\pi^+\pi^-\pi^+\pi^-$ CP Fraction & more

PLB747,9(2015)

- CLEO-c "Legacy data" results
- Use more complex non-CP-eigenstate tags

Results:

$\pi^+\pi^-\pi^+\pi^-$: $F_+ = 0.737 \pm 0.028$

The new tags can be used to update the previous modes

New $\pi^+\pi^-\pi^0$: $F_+ = 1.014 \pm 0.045 \pm 0.022$

Combined : $F_+ = 0.973 \pm 0.017$

New $K^+K^-\pi^0$: $F_+ = 0.734 \pm 0.106 \pm 0.054$

Combined : $F_+ = 0.732 \pm 0.055$

Analysis ongoing at BESIII

$K_S X$ vs $K_L X$ decay rate asymmetry

- The K_S & K_L wave-functions lead to net amplitudes that are sums and differences of the CF and DCSD amplitudes
  - Up to 10% effects, depending on a relative phase
- BESIII study $K_S\pi^0(\pi^0)$ and $K_L\pi^0(\pi^0)$ asymmetry

$$\mathcal{R}(D \to K^0_{S,L}\pi^0(\pi^0)) = \frac{\mathcal{B}(D \to K^0_S\pi^0(\pi^0)) - \mathcal{B}(D \to K^0_L\pi^0(\pi^0))}{\mathcal{B}(D \to K^0_S\pi^0(\pi^0)) + \mathcal{B}(D \to K^0_L\pi^0(\pi^0))}$$

  - While $\mathcal{B}_{\mathrm{sig}(CP\pm)} = \frac{1}{1 \mp C_f}\frac{N_{CF,CP\pm}/\epsilon}{N_{CF}}, \quad (C_f \equiv \frac{2r\cos\delta}{1+r^2})$
- Also can be used to extract y_{cp}

$$y_{CP} = \frac{\dfrac{N_{K^0_L\pi^0,Ke\nu}/\epsilon_{K^0_L\pi^0,Ke\nu}}{N_{K^0_L\pi^0}/\epsilon_{K^0_L\pi^0}} - \dfrac{N_{K^0_S\pi^0,Ke\nu}/\epsilon_{K^0_S\pi^0,Ke\nu}}{N_{K^0_S\pi^0}/\epsilon_{K^0_S\pi^0}}}{\dfrac{N_{K^0_L\pi^0,Ke\nu}/\epsilon_{K^0_L\pi^0,Ke\nu}}{N_{K^0_L\pi^0}/\epsilon_{K^0_L\pi^0}} + \dfrac{N_{K^0_S\pi^0,Ke\nu}/\epsilon_{K^0_S\pi^0,Ke\nu}}{N_{K^0_S\pi^0}/\epsilon_{K^0_S\pi^0}}}.$$

Preliminary result

K_SX vs K_LX decay rate asymmetry measurement

- Flavor tag use
  - $K\pi$, $K\pi\pi^0$, $K3\pi$

$$C_f = \frac{2r\cos\delta}{1+r^2}$$

	C_f (%)
$K^\pm\pi^\mp$	-12.39±1.79
$K^\pm\pi^\mp\pi^\mp\pi^\pm$	-8.73±1.62
$K^\pm\pi^\mp\pi^0$	-7.02±1.25

- $R(K_{SL}\pi^0)$ = (10.94+-1.24+-1.82)%
  - CLEO-c(~281pb^{-1}):**PRL100,091801(2008)**

$$R(D^0 \to K_{S,L}\pi^0) = 0.108 \pm 0.025 \pm 0.024$$

- $R(K_{SL}\pi^0\pi^0)$ = (-11.56+-1.95+-2.69)% (measured for first time)
  - $Br(K_L\pi^0\pi^0)$ = (1.280+-0.041+-0.059)% (measured for first time)
- $y_{CP} = (1.65 \pm 2.43(\mathrm{stat.}) \pm 0.56(\mathrm{sys.}))\%.$

Statistical limited, previous y_{cp}:

$$y_{CP} = (-2.0 \pm 1.3 \pm 0.7)\%.$$

More studies at BESIII

- KsKK
- $KK\pi\pi$
- $Ks\pi^0\eta(\omega,\eta')$
- $\omega\ \eta$ / $\eta\eta$ / $\eta'\pi^0$
- $KsK\pi$
- $\pi^0\pi^0\eta$ / $\pi^0\eta\eta$
- et al…

LHCb projections

Runs	Collected / Expected luminosity	Year attained	γ/ϕ_3 sensitivity
LHCb Run-1 [7, 8 TeV]	3 fb^{-1}	2012	8°
LHCb Run-2 [13 TeV]	5 fb^{-1}	2018	4°
Belle-II Run	50 ab^{-1}	2025	1.5°
LHCb phase-1 upgrade [14 TeV]	50 fb^{-1}	2030	$< 1^\circ$
LHCb phase-2 upgrade [14 TeV]	300 fb^{-1}	(>)2035	$< 0.4^\circ$

- If just consider GGSZ systematic uncertainty is $2{\sim}4^0$(CLEO-c)
  - Run I –$\sigma(\gamma) = 7^o$ -limited impact of strong phase measurements
  - Run II -$\sigma(\gamma) = 3.5^o$ -becomes significant
  - **Upgrade phase I $\sigma(\gamma)$ ~ strong phase uncertainty**

Prospects of BESIII

- Now 2.9fb^{-1}(3.5XCLEO-c)
- Preliminary result on c_i and s_i suggest ~2^0 increase in precision
- If an additional 10fb^{-1}(4Xdata) at BESIII, would lead to the strong phase errors being sub-leading at the end of the LHCb phase I upgrade
- **Without more data the knowledge of strong phases will limit the precision of γ**
- **Further if LHCb has a phase II upgrade the strong phase measurement would again be limiting**
- **LHCb-PUB-2016 suggests 15-20 fb^{-1}**
- **With 20fb^{-1} ψ(3770) data taken by BESIII**
  - $\Delta(\cos\delta_{K\pi}) \sim 5\%$
  - **Uncertainty on γ from c_i, s_i in $D \rightarrow K_S\pi\pi \sim 0.4^o$**

from LHCb-PUB-2016

Strong phases in D hadronic decays

	Decay mode	Quantity of interest	Comments
➢	$D \to K^0_S\pi^+\pi^-$ prel. release	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, δ	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, δ	Simple 2-3 bin scheme could be considered.
➢	$D \to K^0_S K^\pm\pi^\mp$	R, δ	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.
➡	$D \to K^\pm\pi^\mp$	δ	Of low priority due to good precision available through charm-mixing analyses.

Status at BESIII
- ➡ published
- ➢ under study
- ⇨ in plan

Summary

- **Unique access to strong phases & ability to extract model-independent results with charm at threshold (only BESIII now)**

- Interest of B physics for CKM γ measurement
- Interest of charm mixing study and searching for CPV

- **Future prospects are bright**
  - More precision, new modes, new variables

Thank you!

Backup

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

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

$K^-\pi^+$ only δ ; $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ have both R & δ

Multi-body Self-conjugate modes:
- If no CPV, only 2(n-1) isobar phases, not 2n-1
- Need threshold data only to avoid model dependence;
  - there is no "essential" D^0-D^{0bar} phase

4-body: more complicated angular momenta than 3-body

K_S modes: CF and DCSD give K^0, K^{0bar}, not K_S directly