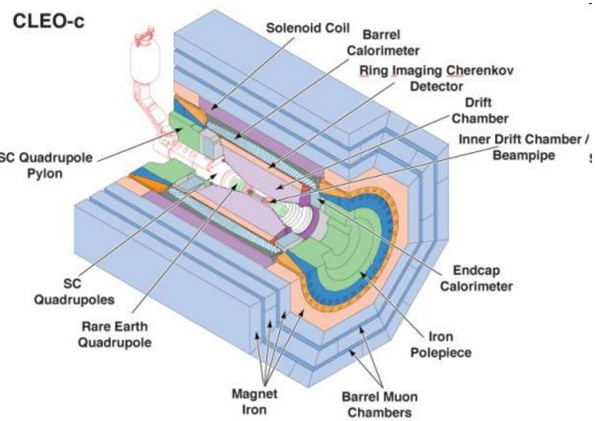
Measurements using quantum-correlated charm mesons



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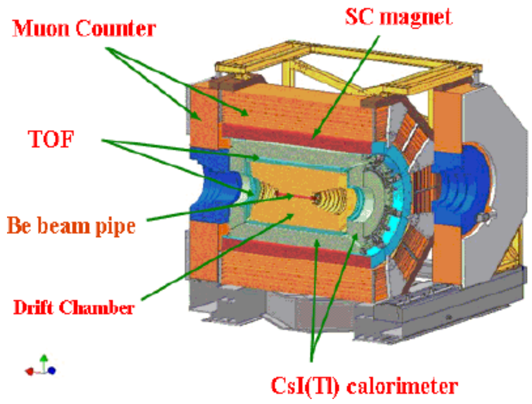


Outline

- Introduction
- Experimental results
  - $D^0 \to K^+\pi^-$ (CLEO-c & BESIII)
  - $D^0 \to K_s^0\pi^+\pi^-$ (CLEO-c)
  - $D^0 \to K_s^0 K^+\pi^-$ and $D^0 \to K_s^0 K^-\pi^+$ (CLEO-c)
  - $D^0 \to K^-\pi^+\pi^0$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ (CLEO-c)
  - y_{CP} measurements (BESIII)
- Summary and prospect

See Xiaorui Lu's talk for details of related BESIII analyses.

Charm facilities

- Hadron colliders (huge cross-section, energy boost)
  - Tevetron (CDF, D0)
  - LHC (LHCb, CMS, ATLAS)
- e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - B-factories (Belle, BaBar)
  - Threshold production (CLEOc, BESIII)
    - Quantum Correlations (QC) and CP-tagging are unique
    - Only D meson pairs, no extra CM Energy for pions
    - Lots of systematic uncertainties cancellation while applying double tag technique

Quantum Correlations at the ψ(3770)

- $e^+e^- \to \psi(3770) \to D\bar{D}$: Pure $J^{PC} = 1^{--}$ initial state

  ψ(3770) : spin=1, $c\bar{c}$ bound state, Mass: 3.773 GeV

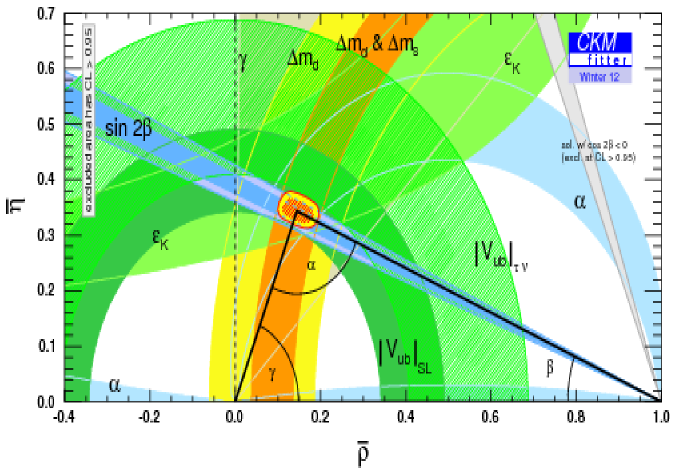
  D^0 : spin=0, Mass: 1.864 GeV

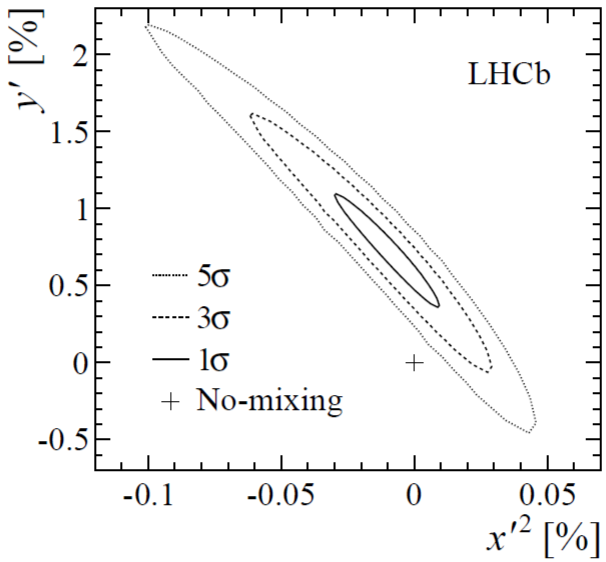
  $\Rightarrow$ D mesons created ≈ at rest in CM

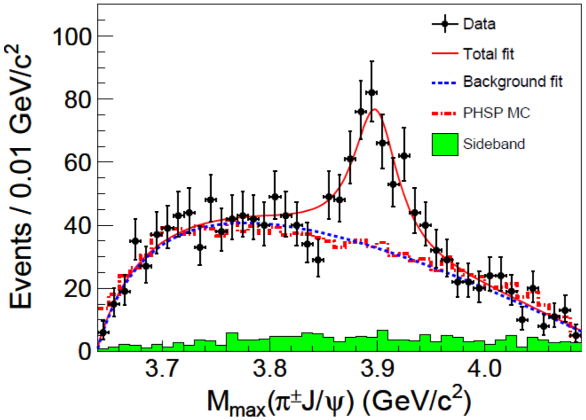
  $\Rightarrow$ $D\bar{D}$ orbit angular momentum L=1
- A typical entangled 2-state system
  - L=1 and Bose statistics $\Rightarrow$ $D\bar{D}$ state anti-symmetric
  - $|\alpha\rangle = \frac{1}{\sqrt{2}}\left(|D^0(p)\rangle|\overline{D^0}(-p)\rangle - |\overline{D^0}(p)\rangle|D^0(-p)\rangle\right)$

    $\Rightarrow$ D^0D^0 and $\overline{D^0D^0}$ are prohibited
  - At any time until one D decays : one D^0 and one $\overline{D^0}$
- Similar to CP eigenstates $|D_{CP\pm}\rangle = \left(|D^0\rangle \pm |\overline{D^0}\rangle\right)/\sqrt{2}$, assuming no CPV:
  - $|\alpha\rangle = \frac{1}{\sqrt{2}}\left(|D_{CP+}(p)\rangle|D_{CP-}(-p)\rangle - |D_{CP-}(p)\rangle|D_{CP+}(-p)\rangle\right)$
  - At any time one D_{CP+} , one D_{CP-}

QC inputs for Charm Physics







Precision CKM test

Charm Mixing & CP violation

(XYZ) Charm spectroscopy

- inputs from Quantum Correlated (QC) $\psi(3770)\to D\bar{D}$ decays
  - (Averaged)Strong phase difference: δ_D
  - Coherent factors: R_D
  - (Averaged)Strong phase in Dalitz bins: c_i, s_i
- *B* factories, LHCb, Super *B* factories are the customers

δ and γ/ϕ_3 input

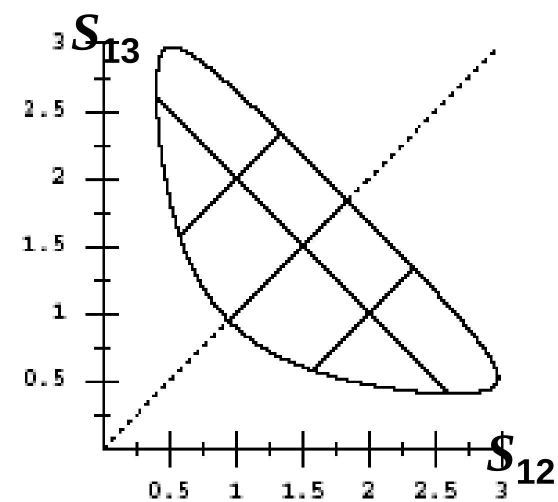
- D hadronic parameters for a final state f : $\frac{A(\bar{D}^0\to f)}{A(D^0\to f)} \equiv -r_D e^{-i\delta_D}$
- Charm mixing parameters: $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$
  - Time-dependent WS $D^0 \to K^+\pi^-$ rate ⇒ $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} = (0.72 \pm 0.24)\%$ (LHCb 2012)
  - $\delta_{K\pi}$: QC measurements from Charm factory
- γ/ϕ_3 measurements from $B\to D^0 K$
  - $b\to u$: $\gamma/\phi_3 = \arg V^*_{ub}$
  - most sensitive method to constrain γ/ϕ_3 at present
  - GLW method (Gronau & London, PLB253, 483 (1991); Gronau & Wyler, PLB265, 172 (1991))
  - ADS method (Atwood, Dunetz & Soni, PRL78, 3257 (1997); PRD63, 036005 (2001))
  - GGSZ (Dalitz) method (Giri, Grossman, Soffer & Zupan, PRD68, 054018 (2003))
- GLW and ADS methods in $B\to D^0 K$
  - D^0 to doubly Cabibbo suppressed decays $K^+\pi^-$, $K^+\pi^-\pi^0$
  - Decay rates:

$$\Gamma\left(B^\pm \to (f)_D K^\pm\right) \propto r_B^2 + r_D^2 + 2r_B r_D \cos\left(\delta_B + \delta_D \pm \phi_3\right)$$

  - r_D, δ_D : QC measurements from Charm factory
  - (r_B, δ_B, ϕ_3) 3 unknowns, 4 measurements

c_i, s_i for γ/ϕ_3 measurements

- **GGSZ (Dalitz) method in $B \to D^0 K$**
  - Most powerful method nowadays
  - D^0 to 3-body decays $K_S\pi^+\pi^-$, $K_SK^+K^-$,…
  - Partition the Dalitz plot to 2k bins
  - B Signal yields in i[th] Dalitz bin



$B^\pm \to DK^\pm$ yields

from flav.-tagged D→Ksππ

extracted from fit to the B$^\pm$ yields

QC measurements from Charm factories

$$N_i^\pm = h_B\left[K_{\pm i} + r_b^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}(x_\pm c_i \pm y_\pm s_i)\right]$$

- **Averaged phases in each bin: c_i, s_i** (Giri et. al. PRD68, 054018 (2003))

$$A_D(s_{12}, s_{13}) \equiv A_{12,13} e^{i\delta_{12,13}} \equiv A(D^0 \to K_s^0(p_1)\pi^-(p_2)\pi^+(p_3))$$
$$= A(\overline{D^0} \to K_s^0(p_1)\pi^+(p_2)\pi^-(p_3))$$

$$s_{12} \equiv m^2_{K_s\pi^-}, s_{13} \equiv m^2_{K_s\pi^+}$$

$$c_i \equiv \int_i dp A_{12,13} A_{13,12} \cos(\delta_{12,13} - \delta_{13,12})$$

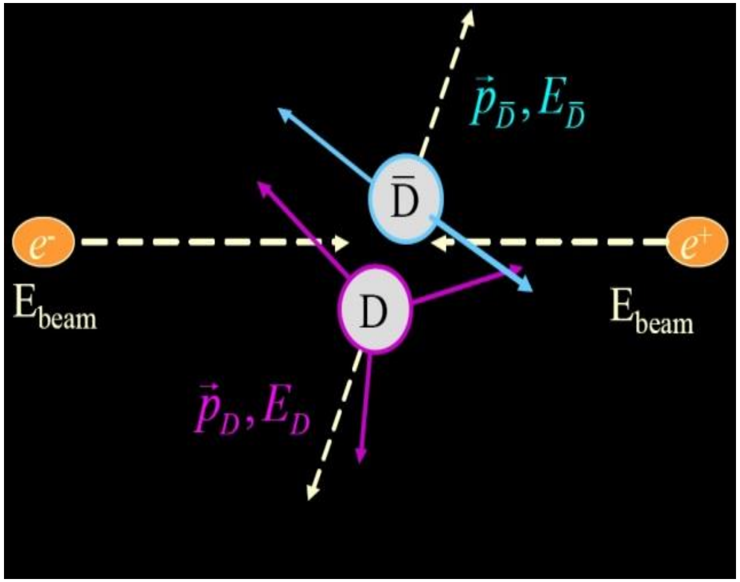
$$s_i \equiv \int_i dp A_{12,13} A_{13,12} \sin(\delta_{12,13} - \delta_{13,12})$$

$$T_i \equiv \int_i dp A^2_{12,13}$$

Charm tagging at the ψ(3770)

$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

- Pure $D\bar{D}$ final state, no additional particles ($E_D = E_{beam}$).
- Low multiplicity ~ 5-6 charged particles / event
- More kinematical constrains to reconstruct decay channels with ν



- Single Tag (ST)
  - Reconstruct one *D* meson
- Double Tag (DT)
  - Tag one *D* meson in a selected *tag mode*. Study the other *D* (*signal D*).
- Flavor Tag
  - Tag the flavor of D^0 or $\overline{D^0}$
- CP tag (CP±)
  - Tag the CP eigenstate: D_{CP+} or D_{CP-}

Time-integrated decay rates

- No time dependent information at Charm threshold
- Anti-symmetric wavefuction:

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

- Double tag rates:

$$A_i^2 A_j^2\left[1 + r_i^2 r_j^2 - 2r_i r_j \cos(\delta_i + \delta_j)\right]$$

  - CP tag: r=1, δ=0 or π; $l^{\pm}$ tag: r=0
- Single and Double tag rates
  - $z_f \equiv 2\cos\delta_f$, $r_f \equiv \frac{A_{DCS}}{A_{CF}}$, $R_M \approx \frac{x^2+y^2}{2}$

Selected references:

Goldhaber and Rosner, PRD 15, 1254 (1977)

Bigi and Sanda, PLB 171, 320 (1986)

Xing, PRD 55, 196 (1997)

Gronau, Grossman, Rosner, PLB 508, 37 (2001)

Atwood and Petrov, PRD 71, 054032 (2005)

Asner and Sun, PRD 73, 034024 (2006);PRD 77, 019901(E) (2008)

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

Analysis techniques

Quantum Correlated topics

- **Mixing (x^2+y^2):$D\overline{D} \rightarrow (K^-l^+\nu)^2, (K^-\pi^+)^2$**
- **Strong phase $\cos\delta$: Double Tag Events: $K^-\pi^+$ vs $CP\pm$**
- **Charm Mixing (y_{CP}): Flavor Tag vs $CP\pm$**
- **DCS: Wrong sign decays $K^-\pi^+$ vs $K^-l^+\nu$**
- **Strong phase c_i, s_i (Dalitz) : $K_S\pi^+\pi^-$ vs $CP\pm$; $K_S\pi^+\pi^-$ vs Flavor Tag; $K_S\pi^+\pi^-$ vs $K_{S,L}\pi^+\pi^-$**
- **Typical Kinematic variables for full reconstruction**
  - **Energy difference & Beam Constrained mass**

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

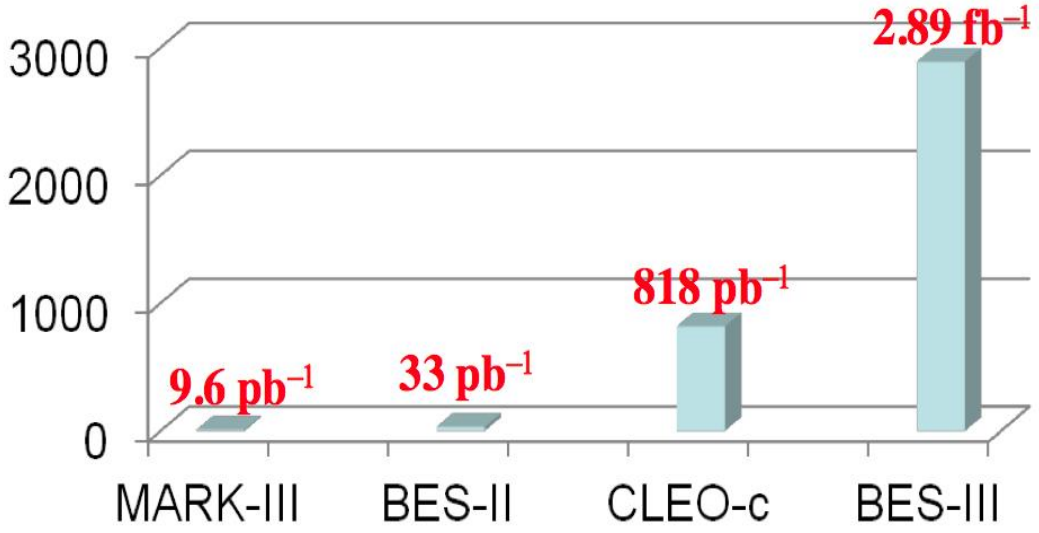
$$M_{\mathrm{BC}} = \sqrt{E^2{}_{\mathrm{Beam}} - \vec{p}^2{}_D}$$

Global fit method

- **Combined analysis to extract mixing parameters, DCS, strong phase plus charm hadronic branching fractions**

Data samples @ charm threshold

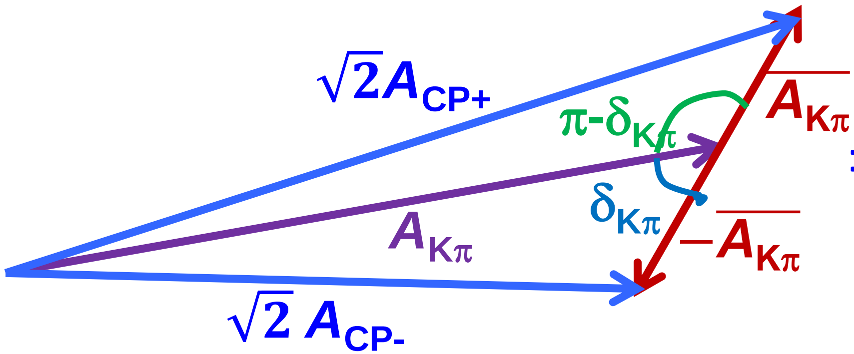
- CLEO-c: 818 pb^{-1} @ ψ(3770)
- BESIII: 2.9 fb^{-1} (~3.5 x CLEO-c data) @ψ(3770)



$\delta_{K\pi}$ in $D \to K\pi$ (BESIII: 2.9 fb^{-1})

A simple picture: $$\frac{\langle K\pi|\overline{D^0}\rangle}{\langle K\pi|D^0\rangle} \equiv \frac{\overline{A}_{K\pi}}{A_{K\pi}} \equiv r_{K\pi}e^{i\delta_{K\pi}}$$

$$\langle K\pi|D_{CP\pm}\rangle = (\langle K\pi|D^0\rangle \pm \langle K\pi|\overline{D^0}\rangle)/\sqrt{2} \Rightarrow \sqrt{2}A_{CP\pm} = A_{K\pi} \pm \overline{A}_{K\pi}$$



$$\Rightarrow 2r_{K\pi}\cdot\cos\delta_{K\pi} \approx A_{CP\to K\pi} \equiv \frac{|A_{CP-}|^2 - |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2}$$

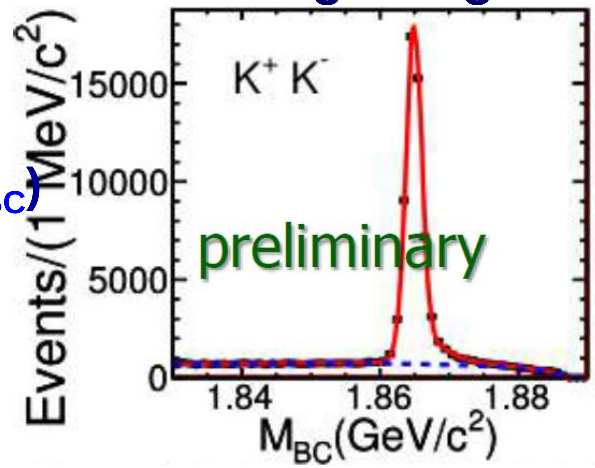
$$= \frac{Br(D_{CP-}\to K\pi) - Br(D_{CP+}\to K\pi)}{Br(D_{CP-}\to K\pi) + Br(D_{CP+}\to K\pi)}$$

- **Measuring $\delta_{K\pi}$ from rate differences if using external $r_{K\pi}$**
- **Reconstructed modes:**
  - **Flavor tags:** $K^-\pi^+$, $K^+\pi^-$
  - **CP+ tags (5 modes):** K^-K^+, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
  - **CP- tags (3 modes):** $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$

$\delta_{K\pi}$ in $D \to K\pi$ (BESIII: 2.9 fb^{-1})

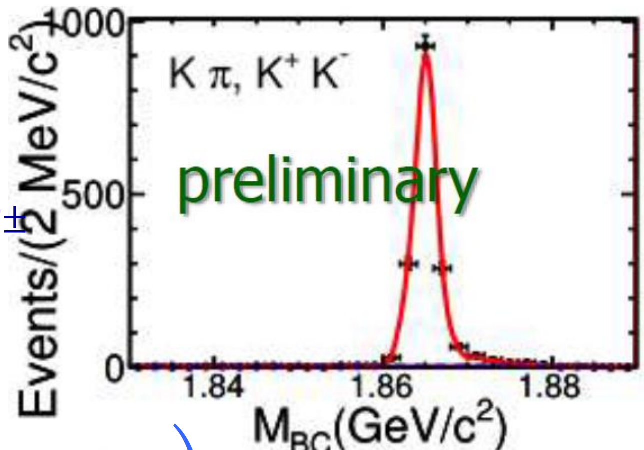
- Signal reconstruction:
  - Single Tag (ST): CP tags
  - Double Tag (DT) : Kπ + CP Tag
  - Kinematic variable: Beam Constrained Mass (M_{BC})
  - Singal shape: σ⊗MC-truth
  - Background shape: ARGUS function

Single Tags



- $$Br(D_{CP\pm} \to K\pi) = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}$$
  - $n_{K\pi,CP\pm}$ and $n_{CP\pm}$ are event yields for DT and ST from M_{BC} fit
  - $\varepsilon_{K\pi,CP\pm}$ and $\varepsilon_{CP\pm}$ are detection efficiencies of DT and ST from MC simulation
  - Most systematics cancelled for ratio $\varepsilon_{CP\pm}/\ \varepsilon_{K\pi,CP\pm}$

Double Tags



BES III preliminary:

$$A_{CP\to K\pi} = \left(12.77 \pm 1.31(\text{Stat.})\ {}^{+0.33}_{-0.31}(\text{sys.})\right)\%$$

$\delta_{K\pi}$ in $D \to K\pi$ (BESIII: 2.9 fb^{-1})

- If we don't ignore the mixing effect
- $2r_{K\pi}\cos\delta_{K\pi} + y = (1 + R_{WS}) \cdot A_{CP\to K\pi}$
  - $R_{WS} \equiv \frac{\Gamma(D^0\to K^+\pi^-)}{\Gamma(D^0\to K^-\pi^+)} = r_{K\pi}^2 + r_{K\pi}y' + \frac{(x^2+y^2)}{2}$
- External inputs from HFAG2013 and PDG
  - $r_{K\pi}^2 = 0.347 \pm 0.006\%$,
  - $y = 0.66 \pm 0.09\%$,
  - $R_{WS} = 0.380 \pm 0.005\%$
- **BESIII preliminary results:**

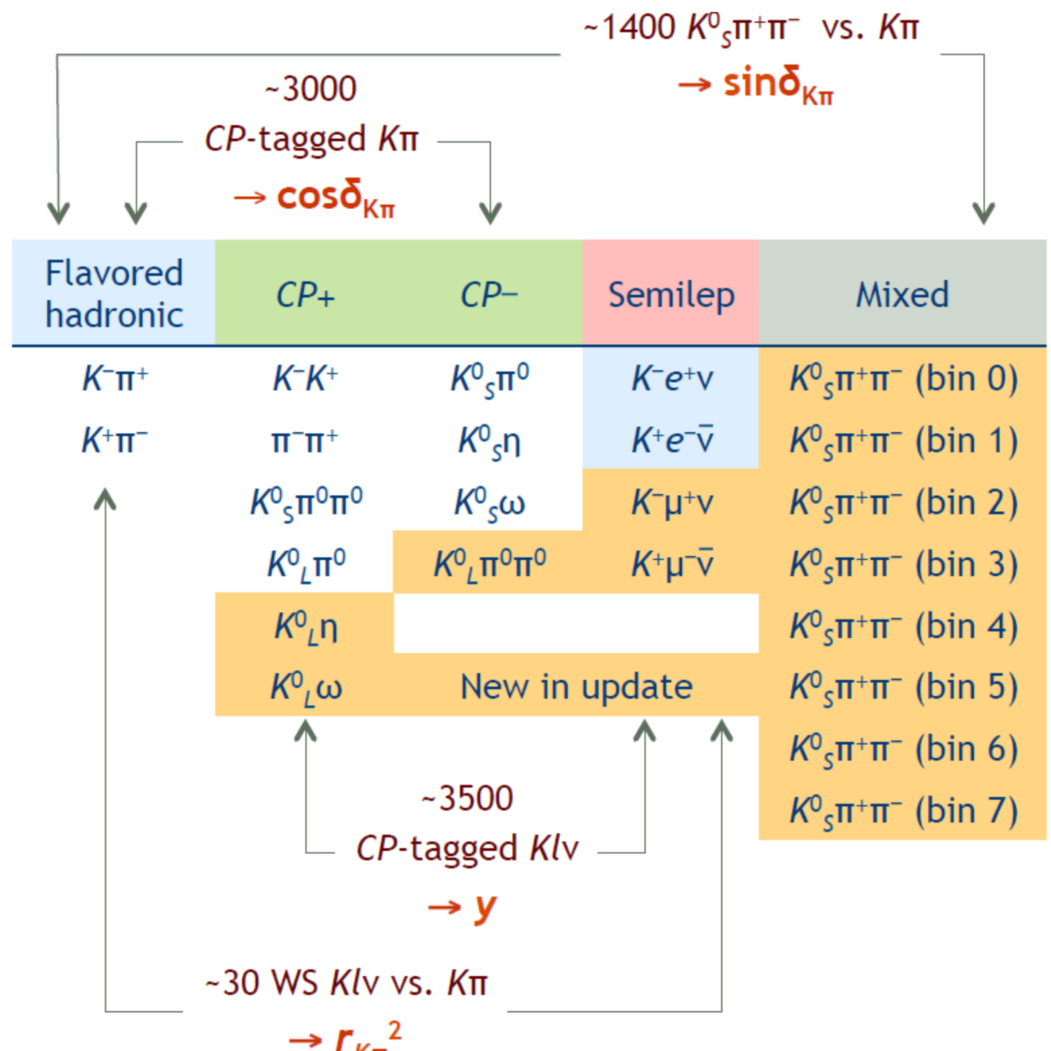
  $\cos\delta_{K\pi} = 1.03 \pm 0.12 \pm 0.04 \pm 0.01$

  (Uncertainty is dominated by the statistical error.)

updated δ in $D \to K\pi$ (CLEO-c: 818 pb^{-1})

PRD86,112001(2012)

- **Previous results in 2008**
  - $\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$
  - PRL 100, 221801 (2008) / PRD 78, 012001 (2008)
  - **Global fit** for hadronic and semileptonic branching fractions, mixing and DCS parameters to extract δ
- **Updated results**
  - full CLEO-c dataset: 818 pb^{-1}
  - Additional final states
  - Single tags for all fully-reconstructed modes except $K^0_S\pi^+\pi^-$
  - Double tags for almost all combinations of modes.
    - At most one missing particle (K^0_L or ν). (Except for $Ke\nu$ vs. $K^0_L\pi^0$ (2 missing particles))
  - 261 yield measurements
    - $K^0_S\pi^+\pi^-$ from PRD 80,032002 (2009)



Courtesy of Werner Sun, CKM2012

updated δ in $D \to K\pi$ (CLEO-c: 818 pb^{-1})

PRD86,112001(2012)

- Fit has 51 parameters :
  - N_{DD} + 21 BFs + 24 amplitudes & phases for $K_S\pi^+\pi^-$ + 5 $K\pi$ and mixing parameters
- Statistical errors on y and $r_{K\pi}\cos\delta_{K\pi}$ 3x smaller than 2008 analysis (standard fit)
  - First direct measurements of $r^2_{K\pi}$ and $\sin\delta_{K\pi}$
  - When used to average y and y', improves overall precision by 12%.
- $\sin\delta_{K\pi}$ sign ambiguity in standard fit
- All measurements are statistics-limited

Parameter	HFAG 2010 CLEO 2008	Fit: no ext. meas. (standard)	Fit: w/ ext. y, x, y' (extended)	
y (10^{-2})	0.79 ± 0.13	$4.2 \pm 2.0 \pm 1.0$	**0.636 ± 0.114**	Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$
x^2 (10^{-3})	0.037 ± 0.024	$0.6 \pm 2.3 \pm 1.1$	0.022 ± 0.023	
$r_{K\pi}^2$ (10^{-3})	3.32 ± 0.08	$5.33 \pm 1.07 \pm 0.45$	3.33 ± 0.08	
$\cos\delta_{K\pi}$	1.10 ± 0.36	**$0.81^{+0.22}_{-0.18}{}^{+0.07}_{-0.05}$**	**$1.15^{+0.19}_{-0.17}{}^{+0}_{-0.08}$**	2.5σ diff. due to fluctuations in r^2 and y, correlated with $\cos\delta_{K\pi}$
$\sin\delta_{K\pi}$	---	**$-0.01 \pm 0.41 \pm 0.04$**	**$0.56^{+0.32}_{-0.31}{}^{+0.21}_{-0.20}$**	
$\delta_{K\pi}$ (°) [derived]	$22^{+11}_{-12}{}^{+9}_{-11}$	$10^{+28}_{-53}{}^{+13}_{-0}$	18^{+11}_{-17}	

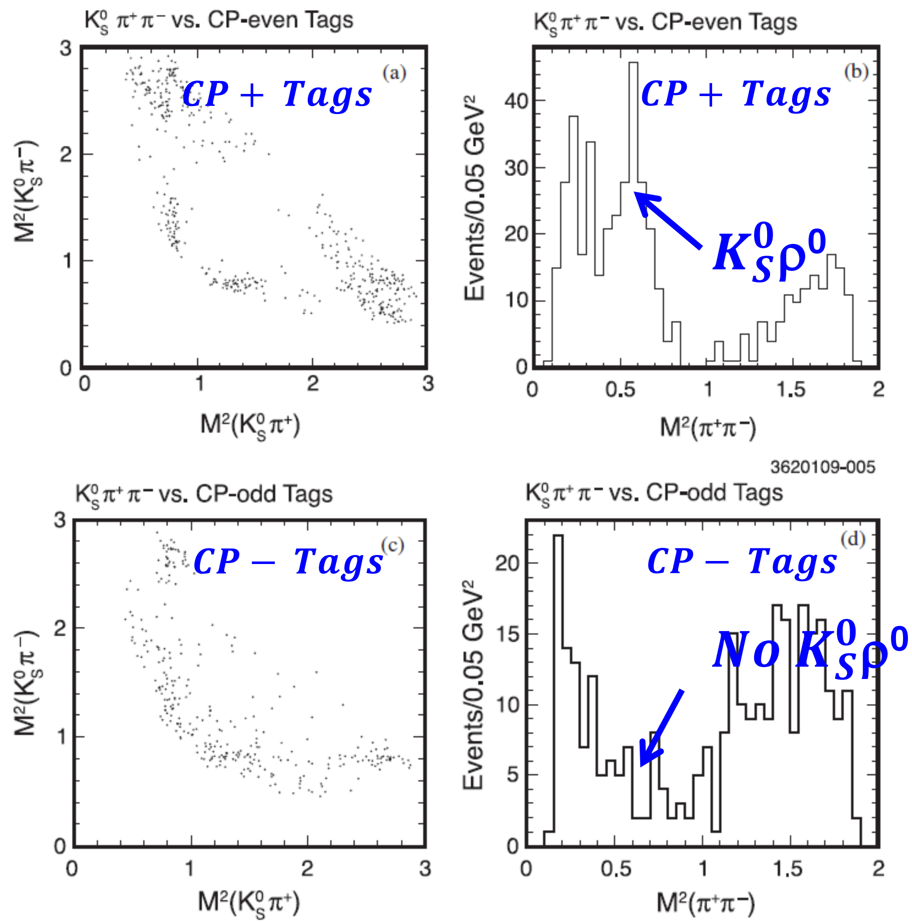
Courtesy of Werner Sun, CKM2012

$D^0 \to K_{S,L} h^+ h^-$ (CLEO-c: 818 pb^{-1})

PRD80,032002(2009) ;PRD82,112006(2010)

- Motivation: extract c_i, s_i for γ/ϕ_3 customers
- Decay modes:
  - $D^0 \to K_{S,L}\pi^+\pi^-$
  - $D^0 \to K_{S,L}K^+K^-$
- Dalitz analysis (divided into 8 bins)
- Tagged modes:
  - Flavor tags: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-e^+\nu$
  - CP+ tags: K^-K^+, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$
  - CP- tags: $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$
  - $K_S^0\pi^+\pi^-$ tags

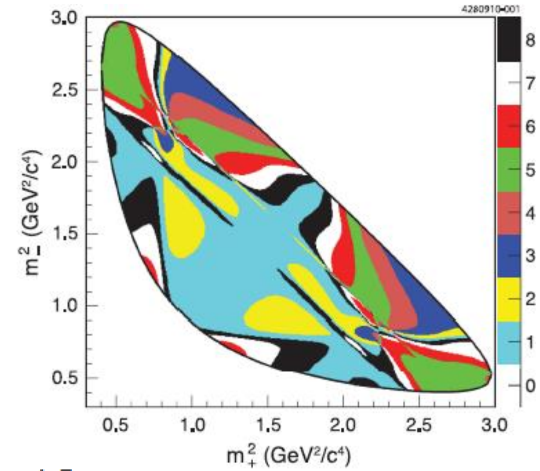
QC ⇒ "CP eigenstates filter" ⇒ Clear differences in Dalitz plots for CP+ and CP- tags

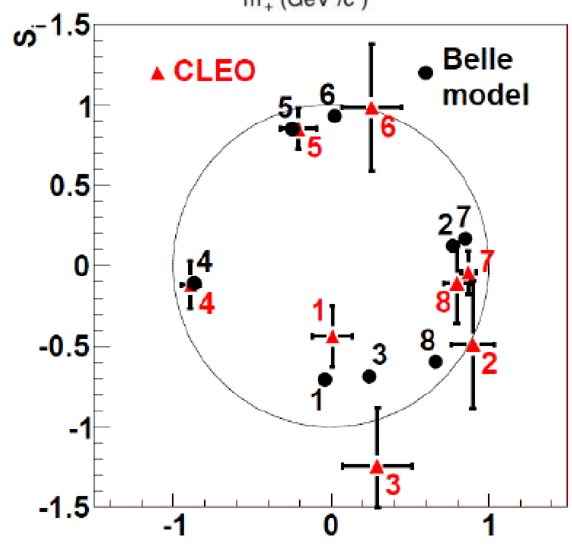


$D^0 \to K_{S,L} h^+ h^-$ (CLEO-c: 818 pb^{-1})

PRD82,112006(2010)

- **Model-independent measurement of γ/ϕ_3**
  - $K_S^0\pi^+\pi^-$ mode proposed by Giri et. al. PRD68, 054018(2003);
  - Pioneered by Belle, Bondar& Poluektov EPJ C 47, 347 (2006); EPJ C 55, 51 (2008)
- **Updated results: PRD82,112006(2010)**
- **Choice of binning is optimized for precision (Compare CLEO-c measurement with Belle model)**
- **Toy MC ⇒ Model uncertainty in γ/ϕ_3 measurement reduced from ~7° to 1.7°**
- **Belle used CLEO-c c_i, s_i as input**
- **uncertainty in c_i, s_i can be further reduced at BESIII**





a polar-to-Cartesian re-mapping of previous δ in each bin: $c_i^2 + s_i^2 = 1$

$B^\pm \to DK^\pm$ yields

from flav.-tagged D→Ksππ

extracted from fit to the $B^\pm$ yields

measured by CLEO [PRD82, 112006 (2010)]

$$N_i^{\pm} = h_B\left[K_{\pm i} + r_b^2 K_{\mp i} + 2\sqrt{K_i K_{-i}}\left(x_\pm c_i \pm y_\pm s_i\right)\right]$$

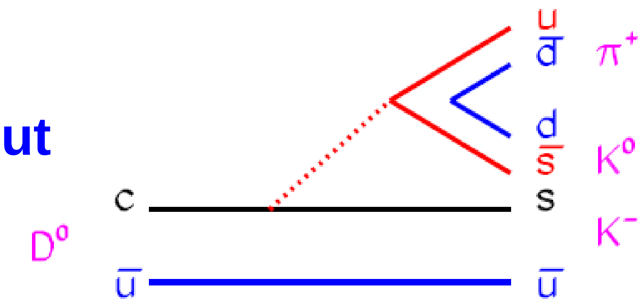
$$\gamma = \left(77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3\right)^\circ$$

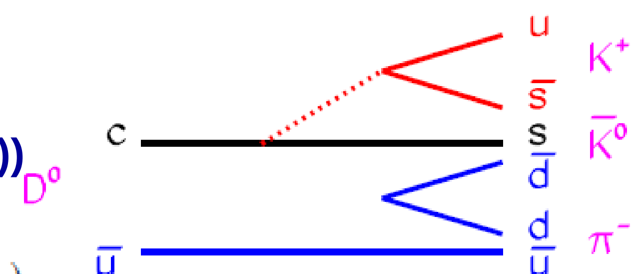
stat exp sys c_i,s_i error

$D^0 \to K_S K^+ \pi^-$ and $D^0 \to K_S K^- \pi^+$ (CLEO-c: 818 pb^{-1})

PRD85, 092016 (2012)

- **Non-flavored, non-self-conjugate modes (Singly-Cabibbo-supressed)**
- **Motivations**
  - **Coherence factors & Strong phases ⇒ input for γ/ϕ_3 measurements**
  - **"Generic" Dalitz analysis ⇒ resonant substructures, BFs of two modes**
    - **CLEOIII continuum charm w/ D* tag**
    - **CLEO-c with flavor tags**
  - **Time-dependent study ⇒ Charm mixing & CPV (Malde & Wilkinson, Phys. Lett. B701, 353 (2011))**





- **Formalism (Dalitz case)**

$$\Gamma(B^{\mp} \to D(K^{\pm}\pi^{\mp})K^{\mp}) \propto (r_B)^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \times \cos(\delta_B + \delta_D^{K\pi} \mp \gamma),$$

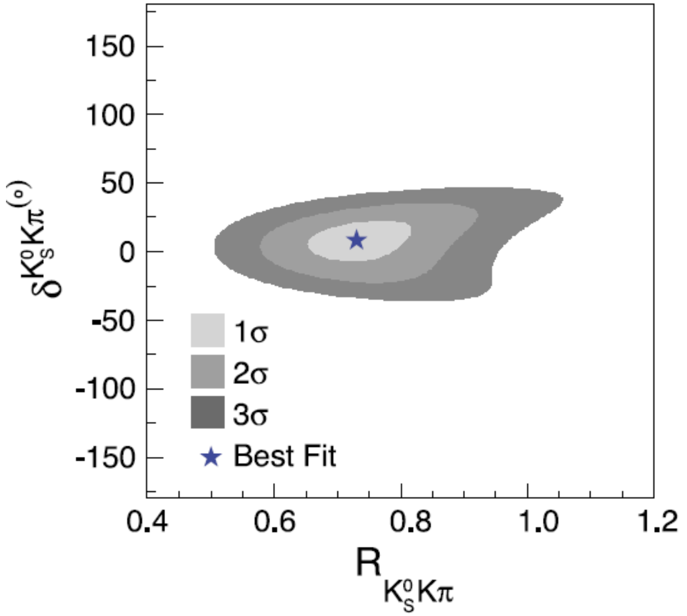
$$\Gamma(B^{\mp} \to D(K^0_S K^{\pm}\pi^{\mp})K^{\mp}) \propto (r_B)^2 + (r_D^{K^0_S K\pi})^2 + 2 r_B r_D^{K^0_S K\pi} \boxed{R_{K^0_S K\pi}} \cos(\delta_B + \delta_D^{K^0_S K\pi} \mp \gamma),$$

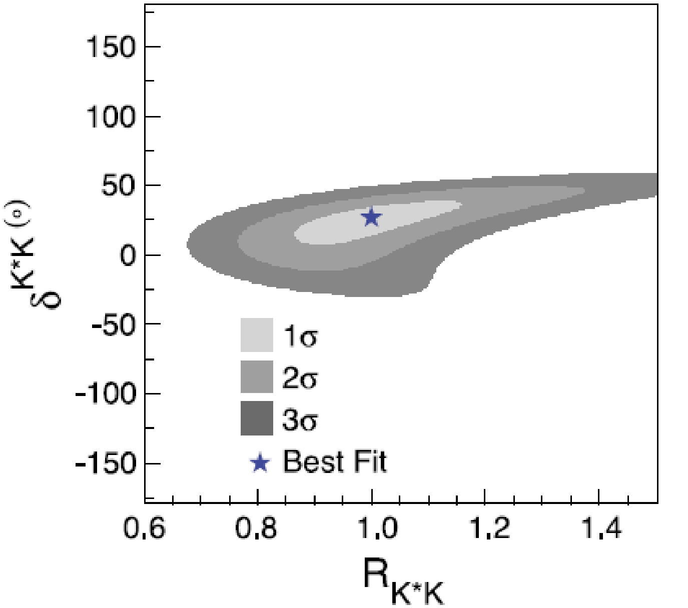
$$R_{K^0_S K\pi} e^{-i\delta_{K^0_S K\pi}} = \frac{\int \mathcal{A}_{K^0_S K^- \pi^+}(m^2_{K^0_S K}, m^2_{K\pi}) \mathcal{A}_{K^0_S K^+ \pi^-}(m^2_{K^0_S K}, m^2_{K\pi}) dm^2_{K^0_S K} dm^2_{K\pi}}{A_{K^0_S K^- \pi^+} A_{K^0_S K^+ \pi^-}} \qquad r_D^{K^0_S K\pi} = \frac{A_{K^0_S K^+ \pi^-}}{A_{K^0_S K^- \pi^+}}$$

- **Coherence factor R can be [0, 1]**
  - **One state dominant ⇒ R~1**

$D^0 \to K_S K^+ \pi^-$ and $D^0 \to K_S K^- \pi^+$ (CLEO-c: 818 pb^{-1})

- PRD85, 092016 (2012)
- Coherence Factor Analysis:
  - Data sample: CLEO-c with CP-tags
- Tagged modes:
  - Flavor tags: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
  - CP+ tags: K^-K^+, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $K_L^0\eta$, $K_L^0\omega$, $K_L^0\eta'$
  - CP- tags: $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_L^0\pi^0\pi^0$
  - Mixed CP tags: $K_S^0\pi^+\pi^-$, $K_L^0\pi^+\pi^-$
- Results in full Dalitz plot region:
  - $R = 0.73 \pm 0.08$
  - $\delta = (8.3 \pm 15.2)^o$
- Results for a restricted region (±100 MeV around $K^*(892)^+$):
  - $R = 1.00 \pm 0.16$
  - $\delta = (26.5 \pm 15.8)^o$





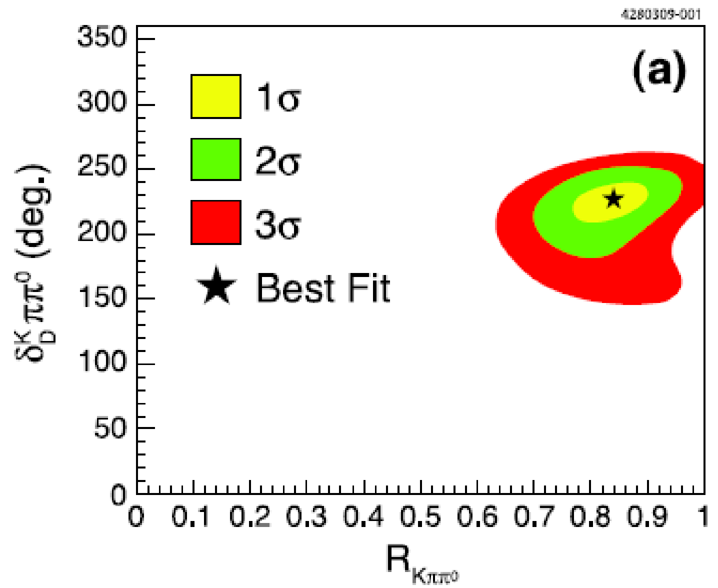
$D\to K\pi\pi^0$ and $D\to K3\pi$ (CLEO-c: 818 pb^{-1})

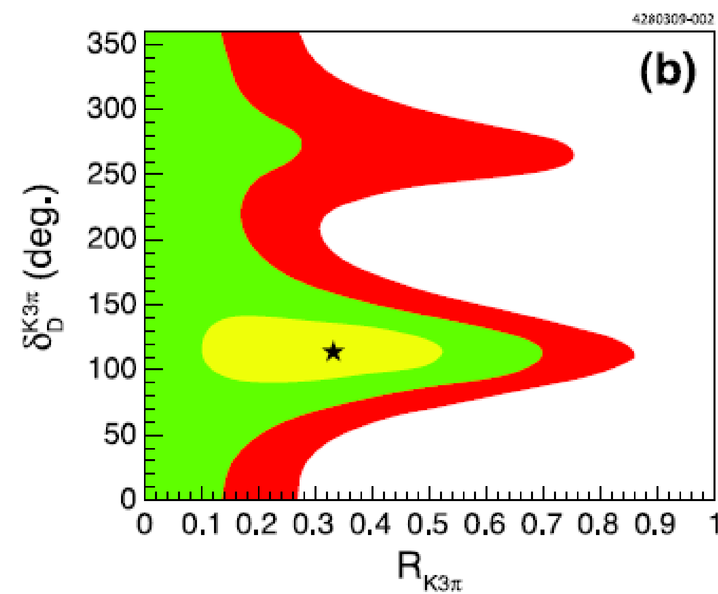
PRD80, 031105(R) (2009)

- **Motivation**
  - Coherence factors & Strong phases $\Rightarrow$ input for γ/ϕ_3 measurements
- **Formalism (Dalitz case: similar to $D^0\to K_S K\pi$)**

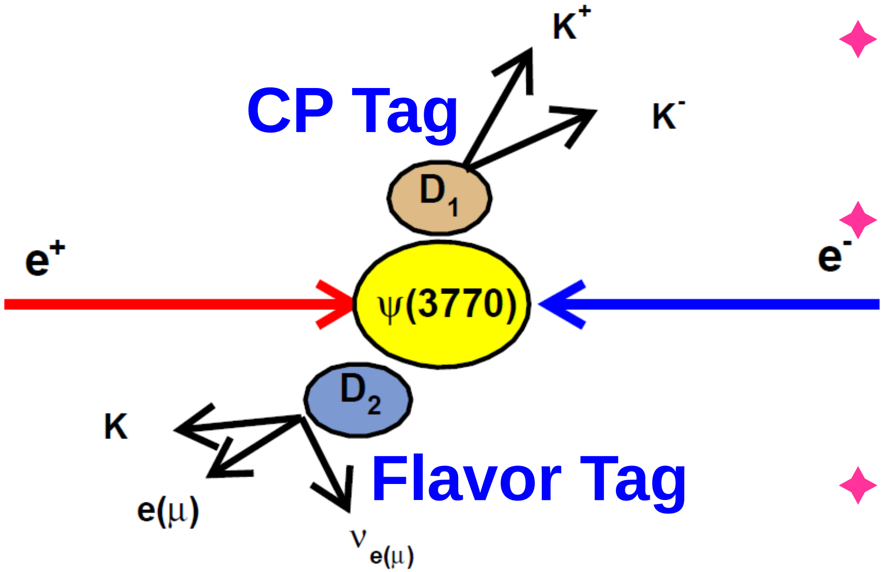
$$R_{K\pi\pi^0} e^{-i\delta_D^{K\pi\pi^0}} = \frac{\int \mathcal{A}_{K^-\pi^+\pi^0}(\mathbf{x})\mathcal{A}_{K^+\pi^-\pi^0}(\mathbf{x})d\mathbf{x}}{A_{K^-\pi^+\pi^0}A_{K^+\pi^-\pi^0}} \qquad r_D^{K\pi\pi^0} = \frac{A_{K^+\pi^-\pi^0}}{A_{K^-\pi^+\pi^0}}$$

- **Tagged modes:**
  - Flavor tags: $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
  - CP+ tags: K^-K^+, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$
  - CP- tags: $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, $K^0_S\phi$
- **First determination of $R_{K\pi\pi0}$, $R_{K3\pi}$, $\delta_D^{K\pi\pi0}$, $\delta_D^{K3\pi}$**
- **$D\to K\pi\pi^0$: Large R $\Rightarrow$ Significant coherence**
- **$D\to K3\pi$: R ~ 0.3, No significant coherence**
  - LHCb time dependent analysis $\Rightarrow$ Constrain R and δ (See Sam Harnew's talk in 9/1)





y_{CP} measurement (BESIII: 2.9 fb^{-1})



- Single Tag decay rate (CP tags)
  - $\Gamma_{CP\pm} \propto 2|A_{CP\pm}|^2(1 \mp y)$
- Double Tag decay rate (Flavor tags + CP tags)
  - $\Gamma_{l;CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$
- Neglect term y^2 or higher order
  - $y_{CP} \approx \frac{1}{4}\left(\frac{\Gamma_{l;CP+}\Gamma_{CP-}}{\Gamma_{l;CP-}\Gamma_{CP+}} - \frac{\Gamma_{l;CP-}\Gamma_{CP+}}{\Gamma_{l;CP+}\Gamma_{CP-}}\right)$

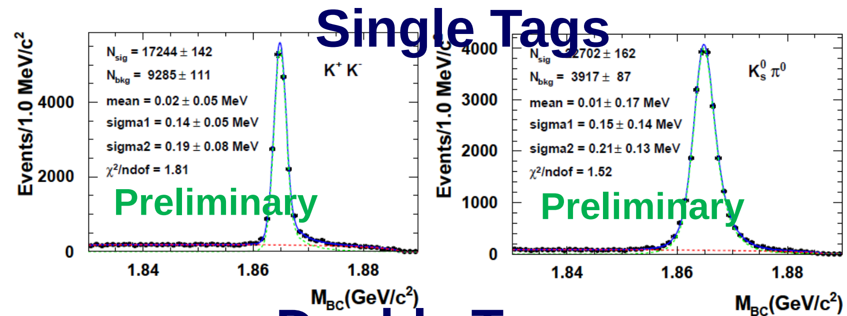
- **Reconstructed modes:**
  - Flavor tags: $Ke\nu_e$, $K\mu\nu_\mu$
  - CP+ tags (3 modes): K^-K^+, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$,
  - CP- tags (3 modes): $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$

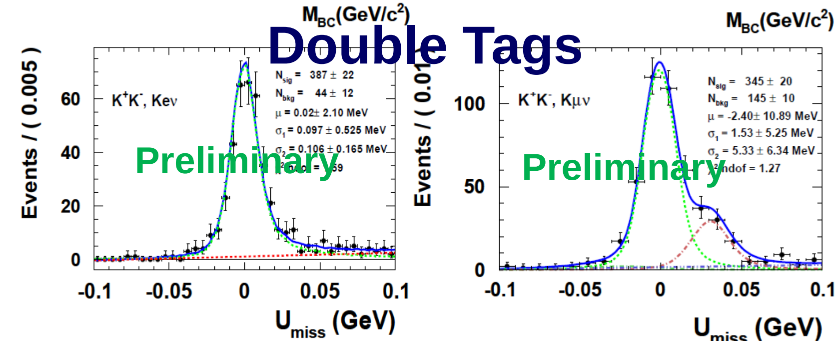
y_{CP} measurement (BESIII: 2.9 fb^{-1})

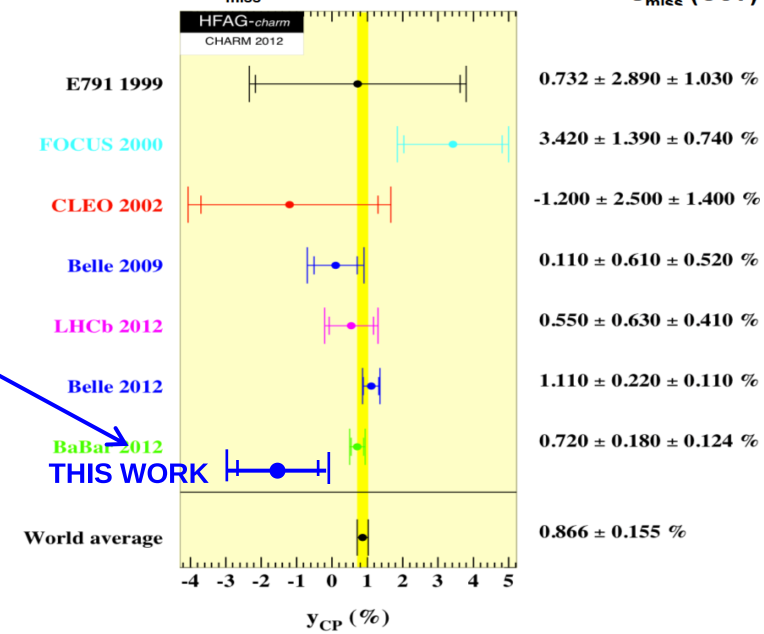
- **Signal reconstruction:**
  - **Single tag yields extraction:**
    - Singal shape: $\sigma \otimes$MC-truth
    - Background: ARGUS function
    - Kinematic variable: M_{BC}
  - **Double tag yields extraction:**
    - Singal shape: $\sigma \otimes$MC-truth
    - Background: Polynomial
    - $K\pi\pi^0$ background shape from data
    - Kinematic variable:

      $U_{miss} = E_{miss} - |\vec{P}_{miss}|$ (≈0 for signals)
- **BESIII preliminary results:**

  $$y_{CP} = (-1.6 \pm 1.3 \pm 0.6)\%$$
- **Most precise measurement with QC charm mesons**
- **In the limit of no CP violation: $y_{CP} = y$**







Summary and prospect

- Quantum Correlated measurements from CLEO-c played very important role on improving the precision of γ/ϕ_3 and D mixing parameters
  - When used to average y and y', improves overall precision by 12%.
  - For Belle analysis, theoretical model uncertainty of γ/ϕ_3 reduced to 4.2^o by using CLEO-c strong D phase input.
  - CLEO-c have stopped data taking, and most QC results are statistics limited.
- BESIII have shown first QC results, and released the most precise $\cos\delta_{K\pi}$ measurement. Many more QC analyses are undergoing.
- The simultaneous fitting package has been developed in BESIII. The package will be applied on $\delta_{K\pi}$ and y_{CP} measurement.
- Possible extensions: C-even (C=+1) Quntum Correlated Analysis $D^0\overline{D}^0\gamma$, $D^0\overline{D}^0\pi^0$from higher-energy data?
- Thanks to CLEO-c and BESIII colleagues.

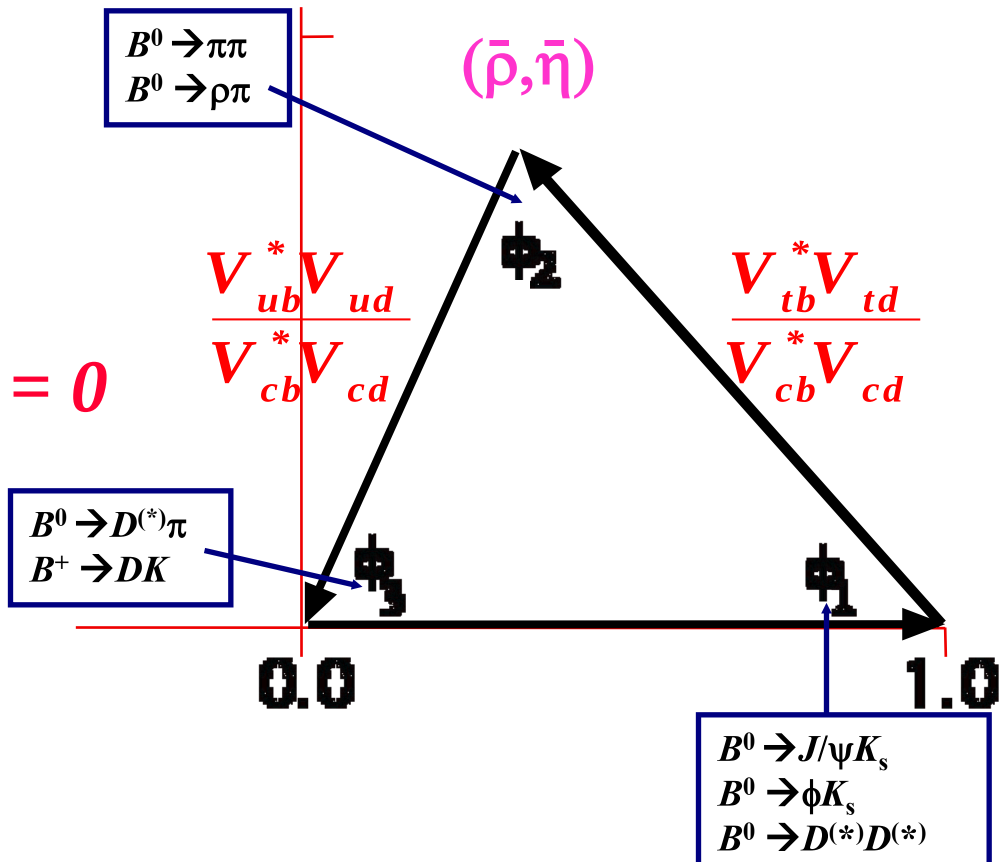
Backup slides

Unitarity Triangle

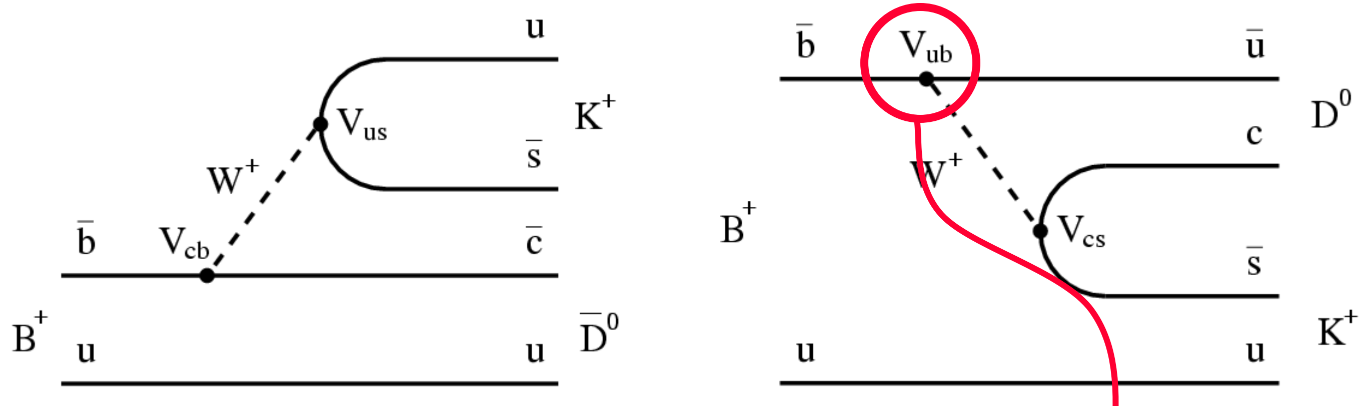
$$V^{+}V = I \Rightarrow \begin{pmatrix} V_{ud}^{*} & V_{cd}^{*} & V_{td}^{*} \\ V_{us}^{*} & V_{cs}^{*} & V_{ts}^{*} \\ V_{ub}^{*} & V_{cb}^{*} & V_{tb}^{*} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

(B system)



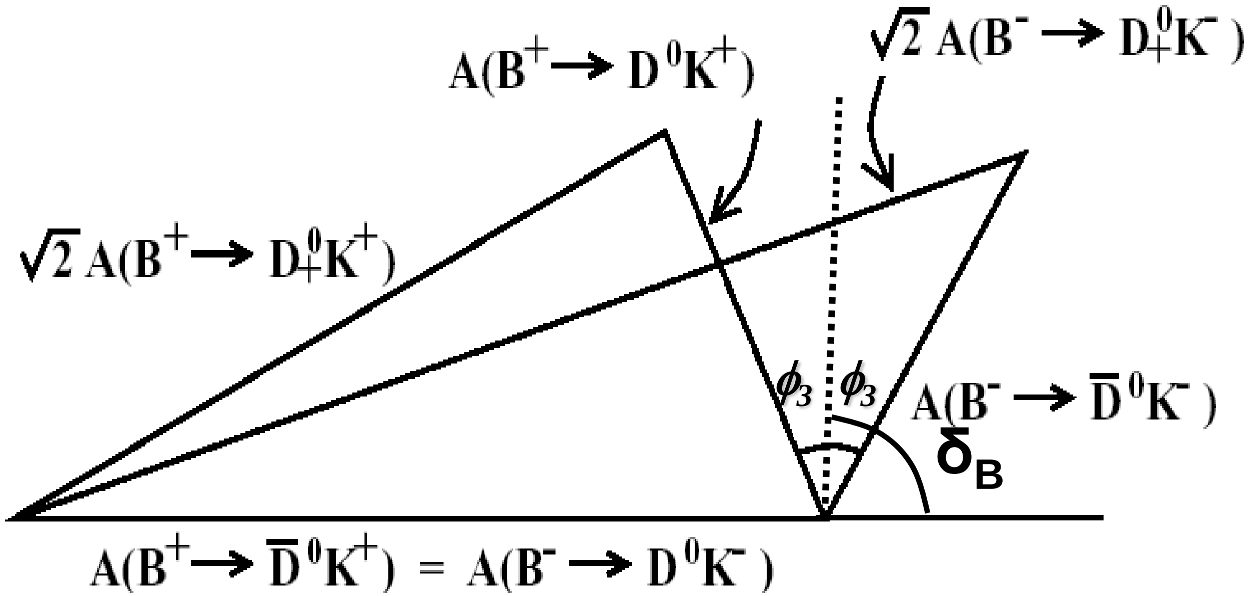
ϕ_3 from $B^- \to D^0 K^-$



$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D^0} K^+)} \equiv r_B e^{i(\delta_B + \phi_3)}$$

- No hadronic uncertainty
- Methods
  - Gronau-Wyler original method
  - Atwood-Dunietz-Soni Method
  - Dalitz method
- Problem: statistics

Gronau-Wyler original method



Theoretically clean

Experimentally challenging

- **Hadronic *D* decay modes: hard for *D* flavor tagging**
- **Semi-leptonic *D* decays : Background too high**
- ***CP* eigenstate decays of *D*: small Branching ratio**

Atwood-Dunietz-Soni Method

Use interference between

$B^+ \rightarrow DK^+$ and $B^+ \rightarrow D\overline{K^+}$ follows by D $(\overline{D}) \rightarrow$

To get a , we need

Double Cabibbo Suppression (DCS): $= K^+ \pi^-$, $K^+ K^-$

K - $\overline{K}$ mixing: $= K_S\pi^0$, $K_S\pi^+\pi^-$

D hadronic parameters:

$$\frac{A_{DCS}(D^0 \rightarrow f)}{A_{CA}(\overline{D^0} \rightarrow f)} \equiv r_D e^{i\delta_D}$$

Decay rates:

$$\Gamma\left(B^{\pm} \rightarrow (f)_D K^{\pm}\right) \propto r_B^2 + r_D^2 + 2 r_B r_D \cos\left(\delta_B + \delta_D \pm \phi_3\right)$$

r_D, δ_D :measured from Charm factory (see next slides)

(r_B, δ_B, ϕ_3) 3 unknowns, 4 measurements $\Rightarrow$ ϕ_3

δ_D from Charm-factory

- Get r_D from the large tagged *D* decay samples (B-factory or Charm factory (CLEO-c sensitivity: ~0.05 from 3fb^{-1}))
- $\delta_D \Leftarrow$ Charm factory on $\psi(3770)$ accurately measured (Soffer hep-ex/9801018)
  - Reconstruct Double Tags: *CP* and *f*
    - *CP*+: $K^+ K^-$, $\pi^+ \pi^-$, $K_s \pi^0 \pi^0$
    - *CP*- : $K_s \pi^0$, $K_s \omega$, $K_s \phi$
  - Asymmetry in *CP*+ and *CP*- of *D* decays:

$$A \equiv \frac{Br(D_{cp+} \to f) - Br(D_{cp-} \to f)}{Br(D_{cp+} \to f) + Br(D_{cp-} \to f)}$$

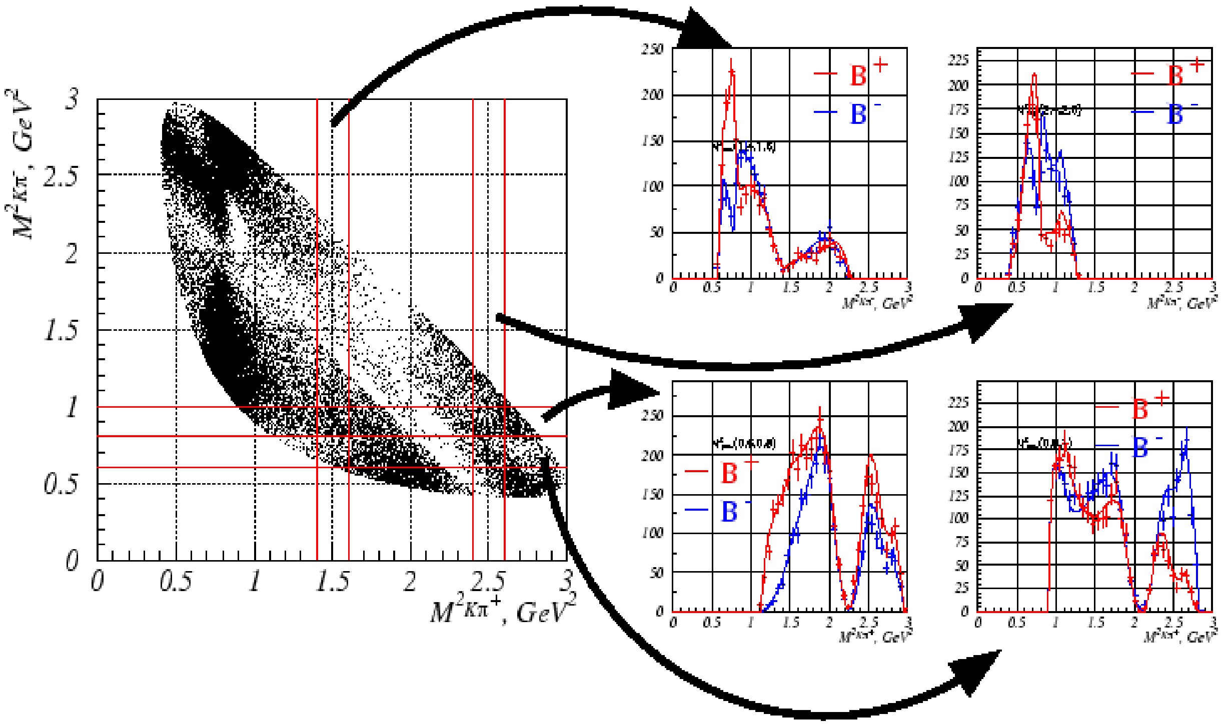
  - Input $R_D = r_D^2$ from PDG

$$\cos \delta_D = \frac{A}{2\sqrt{R_D}}$$

  - BESIII sensitivity: <0.06 from 10fb^{-1} for $\cos\delta_D$

Dalitz method

- Three body *D* decays: $K_S\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K_S K^+K^-$…
- Effect of *D* – $\bar{D}$ *interference*



Most sensitive regions on the Dalitz plot ($\delta = 0^o$, $\phi_3 = 70^o$).
5×10^4 detected events (equiv. $\int L \sim 50$ ab^{-1}).

Formalism (Giri,Grossman,Soffer,Zupan)

- $B^{\pm} \to (K_S\pi^+\pi^-)_D K^{\pm}$ **(hep-ph/0303187)**
- ***D* hadronic parameters**

$$A_D(s_{12}, s_{13}) \equiv A_{12,13} e^{i\delta_{12,13}} \equiv A(D^0 \to K_s^0(p_1)\pi^-(p_2)\pi^+(p_3))$$

$$s_{12} \equiv m^2_{K_s\pi^-}, s_{13} \equiv m^2_{K_s\pi^+}$$

$$= A(\overline{D^0} \to K_s^0(p_1)\pi^+(p_2)\pi^-(p_3))$$

- **Partition the Dalitz plot to *2k* bins**
- **Label bins below symmetry axis *i*, above axis $\bar{i}$**

$$c_i \equiv \int_i dp A_{12,13} A_{13,12} \cos(\delta_{12,13} - \delta_{13,12})$$

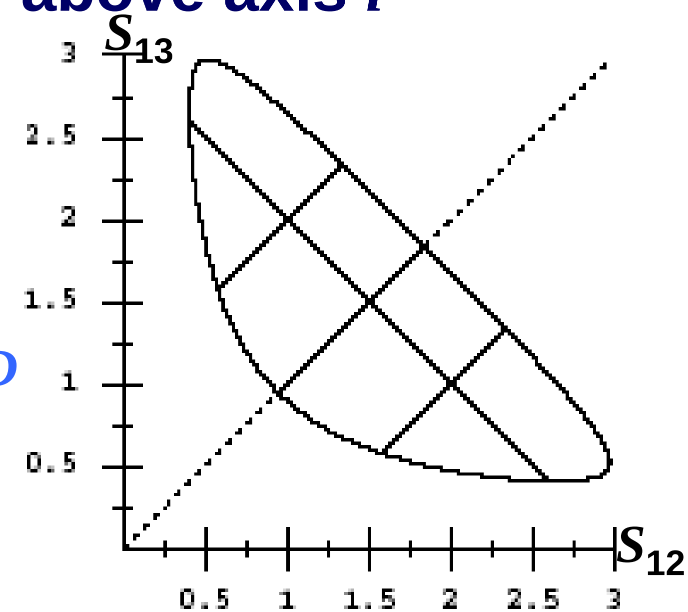
unknown

$$s_i \equiv \int_i dp A_{12,13} A_{13,12} \sin(\delta_{12,13} - \delta_{13,12})$$

Measurable from tagged *D*

$$T_i \equiv \int_i dp A^2_{12,13}$$

$$c_{\bar{i}} = c_i, s_{\bar{i}} = -s_i$$



ϕ_3 extraction

- $2k$ bins × $2(B$ modes$)$ = $4k$ equations
- For the i^{th} bin:

$$\hat{\Gamma}_i^- \equiv \int_i d\hat{\Gamma}(B^- \to (K_s^0\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{\bar{i}} + 2r_B\left[\cos(\delta_B - \varphi_3)c_i + \sin(\delta_B - \varphi_3)s_i\right]$$

$$\hat{\Gamma}_{\bar{i}}^- \equiv \int_{\bar{i}} d\hat{\Gamma}(B^- \to (K_s^0\pi^-\pi^+)_D K^-) = T_{\bar{i}} + r_B^2 T_i + 2r_B\left[\cos(\delta_B - \varphi_3)c_i - \sin(\delta_B - \varphi_3)s_i\right]$$

$$\hat{\Gamma}_i^+ \equiv \int_i d\hat{\Gamma}(B^+ \to (K_s^0\pi^-\pi^+)_D K^-) = T_{\bar{i}} + r_B^2 T_i + 2r_B\left[\cos(\delta_B + \varphi_3)c_i - \sin(\delta_B + \varphi_3)s_i\right]$$

$$\hat{\Gamma}_{\bar{i}}^+ \equiv \int_{\bar{i}} d\hat{\Gamma}(B^+ \to (K_s^0\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{\bar{i}} + 2r_B\left[\cos(\delta_B + \varphi_3)c_i + \sin(\delta_B + \varphi_3)s_i\right]$$

- $2k+3$ unknowns: c_i, s_i, r_B, δ_B, $\phi_3 \Leftarrow$ Solvable for $k\geq 2$
- Belle results from Dalitz method in 2005:

$$\phi_3 = 68^o{}^{+14^o}_{-15^o} \pm 13^o \pm 11^o$$

D Decay model Systematic Uncertainty

c_i ,s_i from Charm-factory

- D double tag: ($K_S\pi^+\pi^-$ vs General state: g)

$$\Gamma_{i,j} \propto T_i T_{\bar{j}}^g + T_{\bar{i}} T_j^g - 2(c_i c_j^g + s_i s_j^g)$$

- If g= $K_S\pi^+\pi^-$ and j=i ⇒ $c^2_i + s^2_i$

$$\Gamma_{i,i} \propto 2T_i T_{\bar{i}} - 2(c_i^2 + s_i^2)$$

- If g=$CP\pm$ ⇒ $s^g_j=0$, $T^g_j = T^g_{\bar{j}} = \pm c^g_j$ ⇒ c_i

$$\Gamma_i \propto T_i + T_{\bar{i}} \pm 2c_i$$

- Belle studied relationship between systematic error on ϕ_3 and # of CP tagged $K_S\pi^+\pi^-$ events in Charm factory (BESIII)
    - 2000 CP+ and CP- tagged events ⇒ $\delta\phi_3$ (sys)~ 1º -2º