Strong Phase at BESIII

Xiaokang Zhou
(for the BESIII Collaboration)
Graduate University of Chinese Academy of Sciences

Workshop on charm physics at threshold
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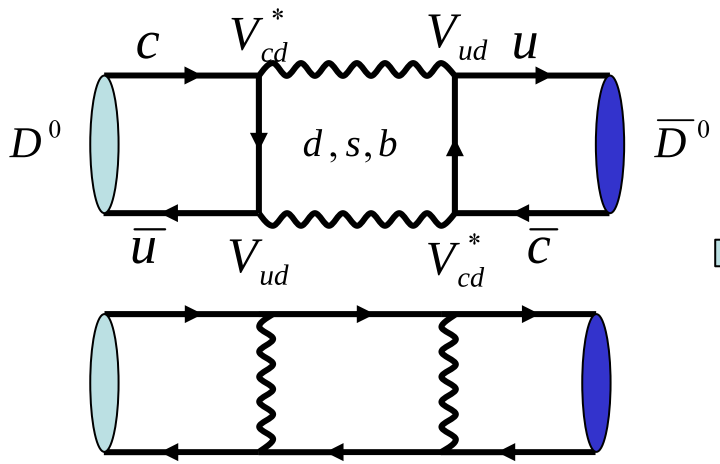
Outline

- **Introduction**
- **BEPCII and BESIII Experiment**
- **Data Analysis**
- **Summary**

Introduction

- Mixing in neutral-D system → severely suppressed by the GIM mechanisms ($\Delta s=0$ for neutral weak current)



$$D^0 \rightleftharpoons \overline{D}^0$$

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle \rightarrow \mu_1 = m_1 - \frac{i}{2}\Gamma_1$$

$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle \rightarrow \mu_2 = m_2 - \frac{i}{2}\Gamma_2$$

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_2 - m_1}{\Gamma}$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

mixing parameter

$$\Gamma = \Gamma_1 + \Gamma_2$$

$$|D^0_{phys}(t)\rangle = g_+(t)|D^0\rangle - \frac{q}{p} g_-(t)|\overline{D}^0\rangle$$

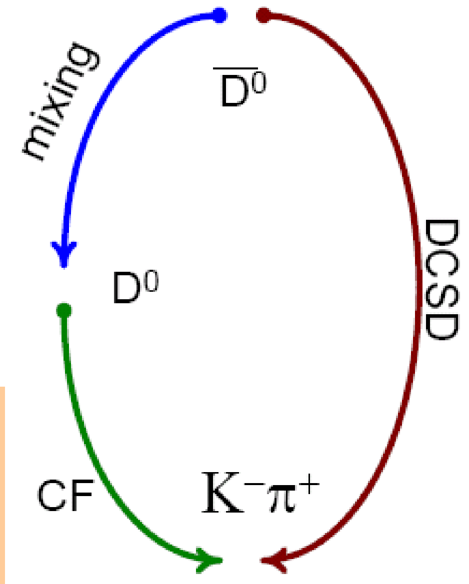
$$|\overline{D}^0_{phys}(t)\rangle = g_+(t)|\overline{D}^0\rangle - \frac{p}{q} g_-(t)|D^0\rangle$$

$$g_\pm(t) \equiv \frac{1}{2}\left(e^{-i(m_2 - \frac{i}{2}\Gamma_2)t} \pm e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}\right)$$

Neutral-D Mixing

$$\frac{d\Gamma[\overline{D}^0_{phys}(t)\to K^-\pi^+]/dt}{e^{-\Gamma t}N_f}=\left|\frac{p}{q}A_{K^-\pi^+}\right|^2\{R_D^+-\sqrt{R_D^+}y'_+(\Gamma t)+\frac{x'^2_++y'^2_+}{4}(\Gamma t)^2\}$$

$$\frac{d\Gamma[D^0_{phys}(t)\to K^+\pi^-]/dt}{e^{-\Gamma t}N_f}=\left|\frac{q}{p}\overline{A}_{K^+\pi^-}\right|^2\{R_D^--\sqrt{R_D^-}y'_-(\Gamma t)+\frac{x'^2_-+y'^2_-}{4}(\Gamma t)^2\}$$



parameters: A_D A_M ϕ δ R_D x y

$$R_D^+=\frac{(1+A_M)^2}{(1+A_D)^2}R_D,\quad R_D^-=\frac{(1+A_D)^2}{(1+A_M)^2}R_D$$

$$x'_\pm=x\cos(\delta\pm\phi)+y\sin(\delta\pm\phi)$$

$$y'_\pm=y\cos(\delta\pm\phi)-x\sin(\delta\pm\phi)$$

CPV

$A_D\neq 0$ direct CPV (decay)

$A_M\neq 0$ indirect CPV (mixing)

$\phi\neq 0$ CP violation in the interference between decays with/without mixing

When assuming no CPV (here f=Kπ):

Define:

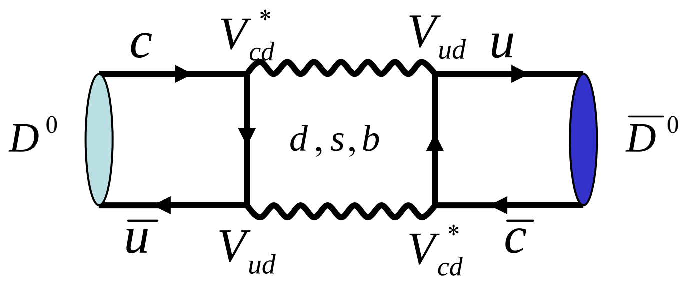
$$\frac{\langle f\,|\,\overline{D}\rangle_{DCS}}{\langle f\,|\,D\rangle_{CF}}\equiv\sqrt{R_D}\cdot e^{-i\delta}$$

$$R_D\equiv\left|\frac{\langle f\,|\,\overline{D}\rangle_{DCS}}{\langle f\,|\,D\rangle_{CF}}\right|^2$$

δ is very important for study mixing and CPV!

Neutral-D Mixing and CP Violation

- Standard Model： mixing and CPV can't be observed nowadays

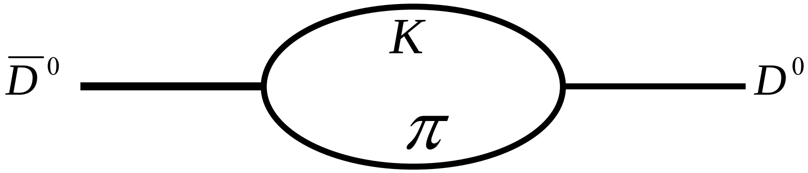


D^0—$\overline{D}^0$ mixing $\propto |V_{cb}V_{ub}^*|^2$ ~trivial

- B-factory (Belle/BaBar/CDF) combined result： >10 σ mixing， no CPV

- Long Distance + New Physics： enhance the effect, perhaps would be observed

Long-Distance effects



$\pi\pi,\ KK,\ K\pi\pi,\ K\pi\pi\pi,\ K\pi\pi\pi\pi,\ etc.$

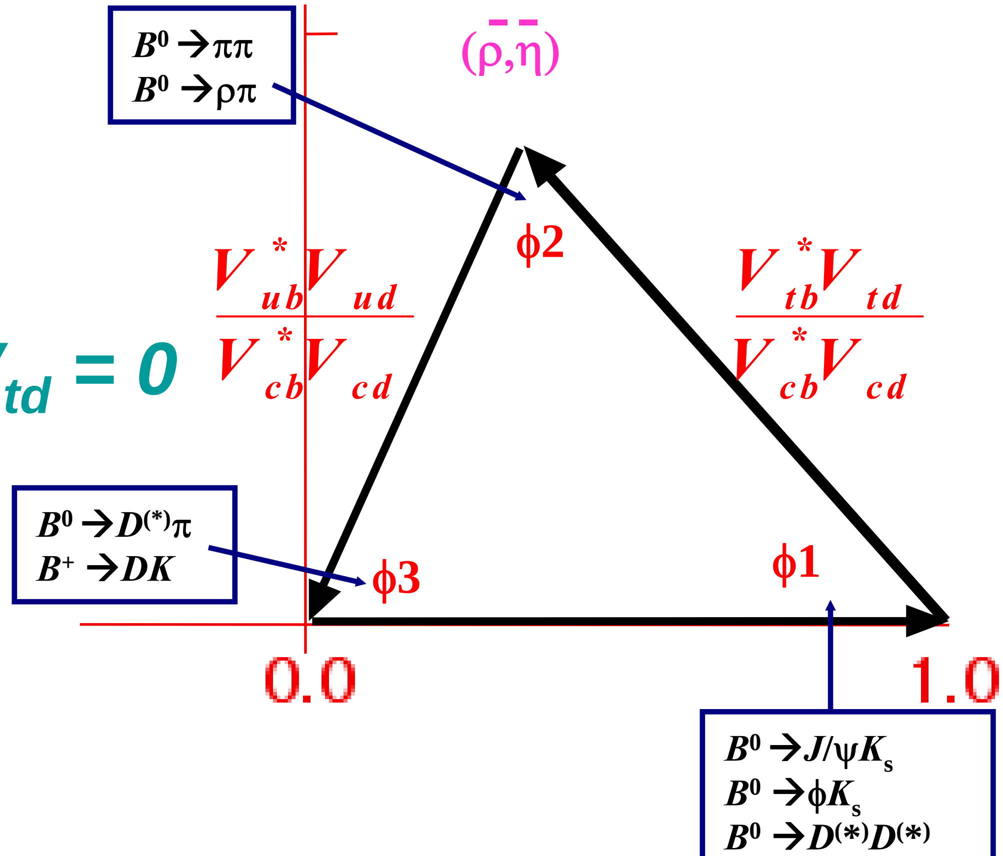
Studying Mixing and CPV help to find New Physics!

Unitarity Triangle

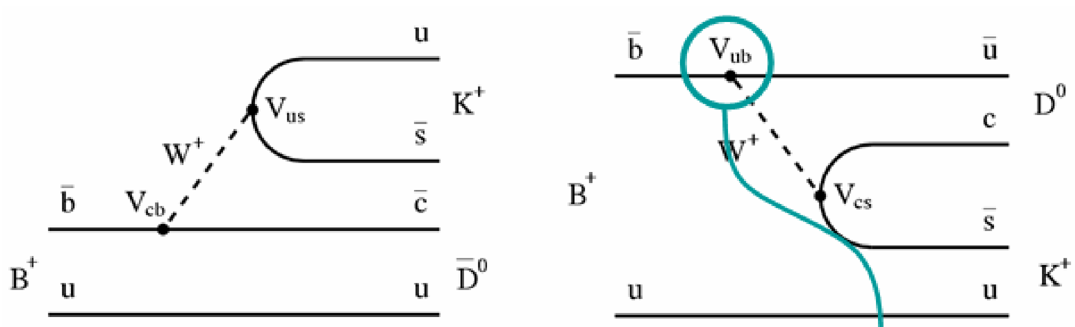
$$V^{+}V = I \Rightarrow \begin{pmatrix} V_{ud}^{*} & V_{cd}^{*} & V_{td}^{*} \\ V_{us}^{*} & V_{cs}^{*} & V_{ts}^{*} \\ V_{ub}^{*} & V_{cb}^{*} & V_{tb}^{*} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix}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

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

(B system)



Measure ϕ_3/γ in B-factory



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

- *D* hadronic parameters:

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

- Decay rates: $\Gamma\left(B^\pm \to (f)_D K^\pm\right) \propto r_B^2 + r_D^2 + 2 r_B r_D \cos\left(\delta_B + \delta_D \pm \phi_3\right)$
- r_D, δ_D :measured from BESIII
- (r_B, δ_B, ϕ_3) 3 unknowns, 4 measurements $\Rightarrow$ ϕ_3

Belle results from Dalitz method in 2010:

$$\phi_3 = 78.4^{o}{}^{+10.8^o}_{-11.6^o} \pm 3.6^o \pm 8.9^o$$

D Decay model Systematic Uncertainty

BESIII contribution $\Rightarrow$ δ ϕ_3 (from D)~ 1º -2º

Threshold Charm Production

- BESIII:

  $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D^0}/D^+D^-$(clean D sample)
- $\psi(3770)$: spin=1, cc bound state, Mass: 3.771 GeV

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

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

$\Rightarrow$ $D\overline{D}$ orbit angular momentum L=1

$\Rightarrow$ Ratio of signal to background is optimum

$\Rightarrow$ Lots of systematic uncertainties cancellation while applying double tag method

Quantum Coherence

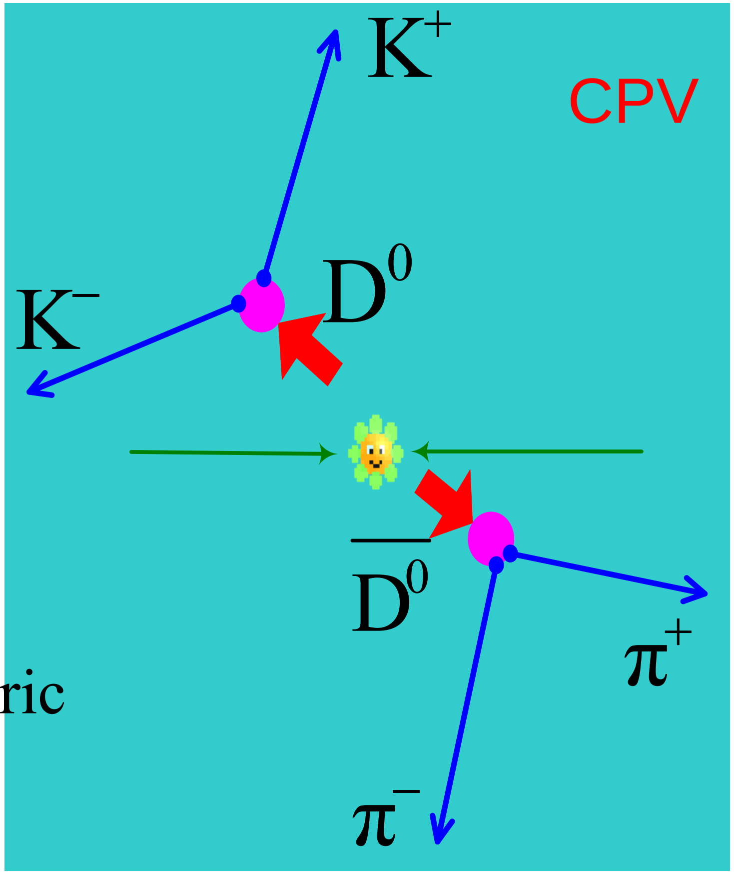
Suppose Both D^0 decay to CP eigenstate f_1 and f_2.

For the decay of $\psi'' \rightarrow f_1 f_2$

$CP(f_1 f_2) = CP(f_1) CP(f_2) (-1)^L = -$

$CP(\psi'') = +$

Thus if a final state such as (*KK*)(ππ) observed, we immediately have evidence of CP violation



Bose statistics $\Rightarrow D^0\bar{D}^0$ state anti-symmetric

$$|\alpha\rangle = \frac{1}{\sqrt{2}}\left(\left|D^0(1)\right\rangle\left|\overline{D^0}(2)\right\rangle - \left|\overline{D^0}(1)\right\rangle\left|D^0(2)\right\rangle\right)$$

$\Rightarrow D^0D^0$ and $\overline{D^0D^0}$ are prohibited(if no mixing)

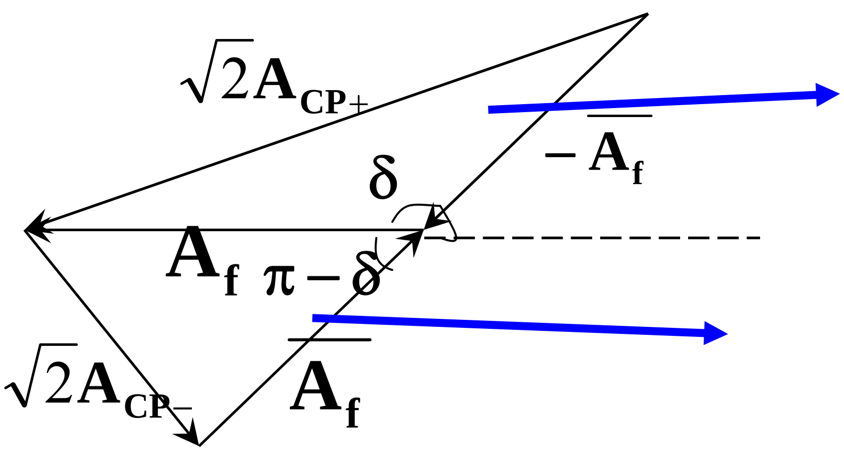
At any time : one D^0 one $\bar{D}^0$ until one D decays

Measure δ

CP eigenstate: $|D^{CP\pm}\rangle = \frac{1}{\sqrt{2}}(|D^0\rangle \pm |\overline{D^0}\rangle)$

$$\langle f|D^{CP\pm}\rangle = \frac{1}{\sqrt{2}}(\langle f|D^0\rangle \pm \langle f|\overline{D^0}\rangle) \Rightarrow \sqrt{2}A_{CP\pm} = A_f \pm \overline{A_f}$$

Construct:

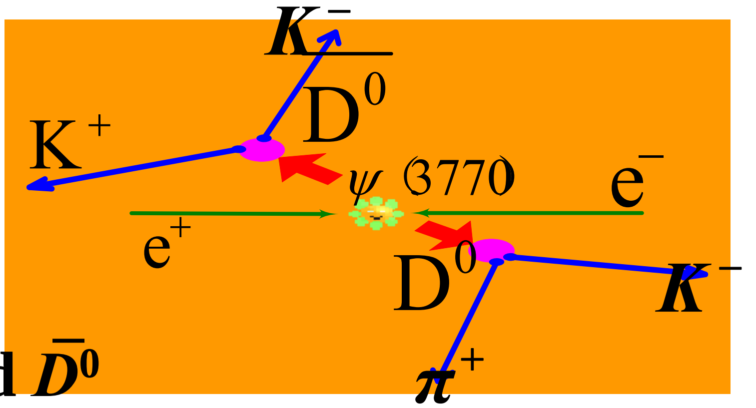


$$\cos\delta = \frac{|A_f|^2 + |\overline{A_f}|^2 - |\sqrt{2}A_{CP+}|^2}{2\cdot|A_f|\cdot|\overline{A_f}|}$$

$$\cos(\pi-\delta) = \frac{|A_f|^2 + |\overline{A_f}|^2 - |\sqrt{2}A_{CP-}|^2}{2\cdot|A_f|\cdot|\overline{A_f}|}$$

$$2\sqrt{R_D}\cdot\cos\delta \approx \frac{|A_{CP-}|^2 - |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2} = \frac{Br(D^{CP-}\to f) - Br(D^{CP+}\to f)}{Br(D^{CP-}\to f) + Br(D^{CP+}\to f)}$$

Single Tag and Double Tag



- **Single tag(ST): fully reconstruct one *D***

$$N_f = N_{D\bar{D}} \cdot Br(D^0 \to f) \cdot \varepsilon_f ,$$

$$N_{CP} = 2N_{D\bar{D}} \cdot Br(D^0 \to CP) \cdot \varepsilon_{CP}$$

- **Double tag(DT): reconstruct both D^0 and $\bar{D}^0$**

$$N_{f,CP^\pm} = 2N_{D\bar{D}} \cdot Br(D^0 \to CP\mp) \cdot Br(D^{CP\pm} \to f) \cdot \varepsilon_{f,CP^\pm}$$

$$\Rightarrow Br(D^{CP\pm} \to f) = \frac{N_{f,CP^\pm} \times \varepsilon_{CP^\pm}}{N_{CP^\pm} \times \varepsilon_{f,CP^\pm}}$$

- **CP channels：**

✓ **cp+**

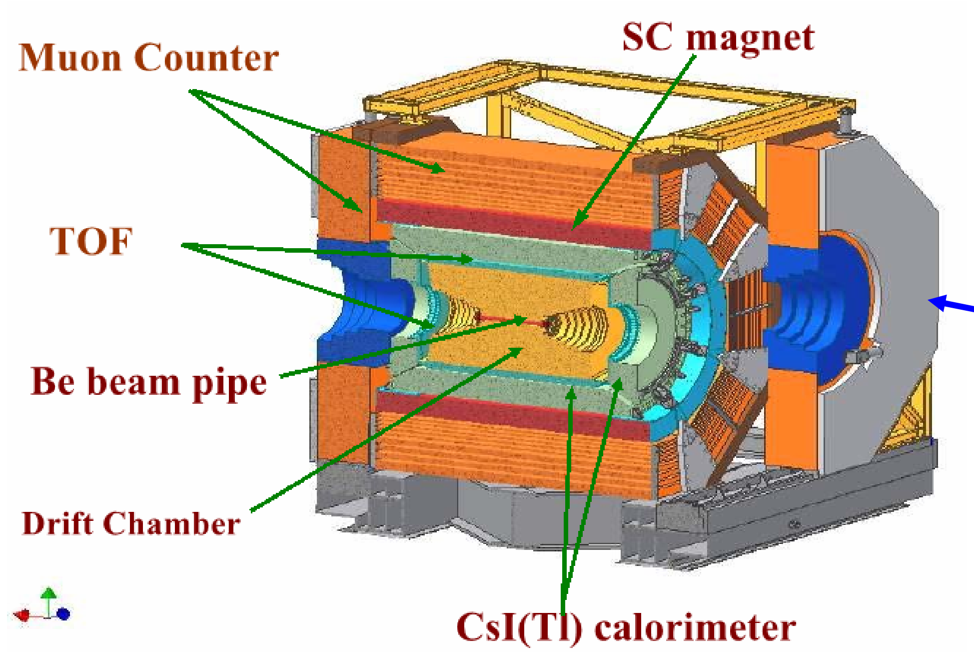
- **K-K+ (3.94+/-0.07) ·10^{-3}**
- π–π+ (1.397+/–0.026) ·**10^{-3}**
- $K_s^0\pi^0\pi^0$ (8.3+/–0.6) ·10^{-3}
- $K_L^0\pi^0$ (10.0+/–0.7) ·10^{-3}

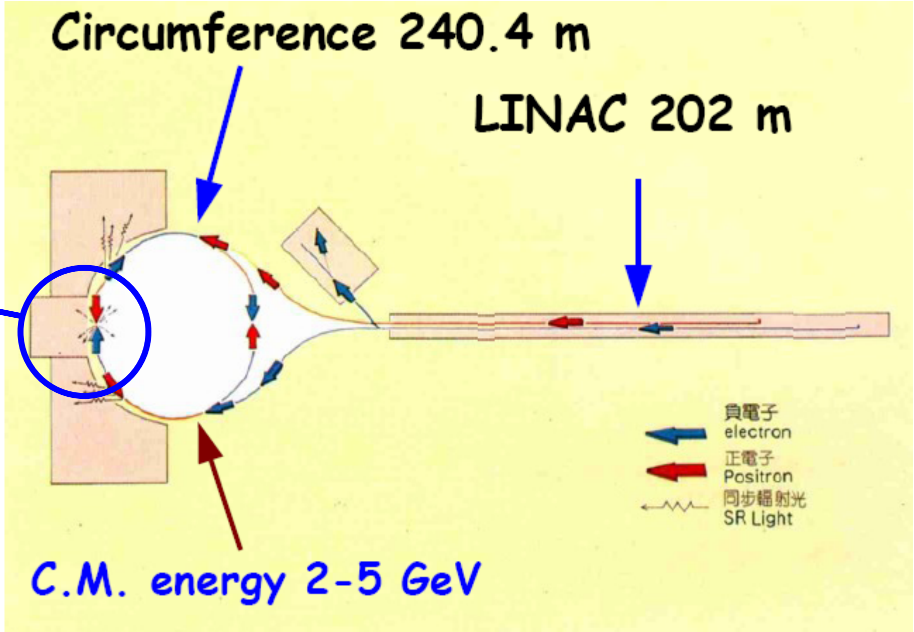
✓ **cp-**

- $K_s^0\pi^0$ (1.22+/–0.05)%
- $K_s^0\eta$ **(4.29+/-0.27) ·10^{-3}**
- $K_s^0\omega$ (1.11+/–0.06)%

BESIII and BEPCII

Beijing Spectrometers III | **Beijing Electron Positron Collider II**



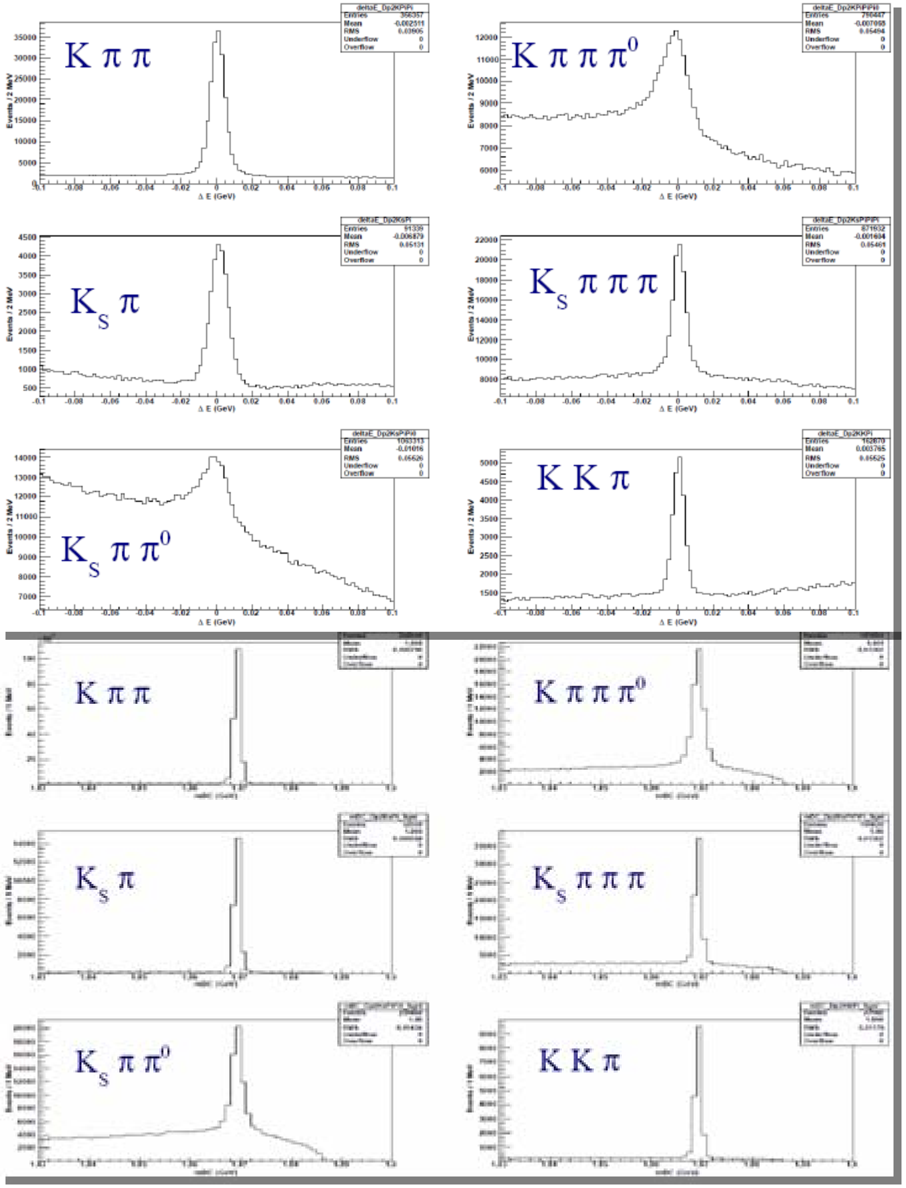


Charm Data at BESIII

- data:
  - $\Psi(3770)$
    - 1st round: 2010.01 - 2010.06(**0.929 fb^{-1}**)
    - 2nd round: 2010.12 - 2011.05(**1.922 fb^{-1}**)
  - $\Psi(4040)$
    - 2011.05 – 2011.06(**0.477 fb^{-1}**)
- MC:
  - $\Psi(3770)$: 105.6M $D\bar{D}$ inclusive MC
  - $\Psi(4040)$: ~1fb^{-1}

DTag Package at BESIII

- Base on BesDchain package, focus on charm reconstruction
- Easy for single tag, double tag and CP tag
- Including:34 D^0,23 D^+ and 25 D_S decay channels
- Monte Carlo and data tests agree well as expected



DTag Status

- With the 1st round of $\psi(3770)$ data(~929pb-1)

Modes	Yields	Effs(%)*	CLEO-c's effs(%)#
$K\pi$	**149,085**	**60.83+/-0.10**	**65.32**
$K\pi\pi^0$	**300,706**	**32.75+/-0.05**	**35.15**
$K\pi\pi\pi$	**190,667**	**39.70+/-0.07**	**45.55**
$K\pi\pi$	**213,944**	**48.99+/-0.07**	**55.42**
$K\pi\pi\pi^0$	**66,344**	**25.01+/-0.09**	**27.39**
$Ks\pi$	**28,763**	**50.33+/-0.25**	**51.10**
$Ks\pi\pi^0$	**66,438**	**26.49+/-0.09**	**28.74**
$Ks\pi\pi\pi$	**36,311**	**31.46+/-0.10**	**43.58**
$KK\pi$	**17,682**	**40.34+/-0.21**	**42.07**

*:the efficiencies do not include the branch fractions of $Ks\rightarrow\pi+\pi-$, $\pi^0\rightarrow\gamma\gamma$

#:from **PRD 80, 032005 (2009)**

The efficiencies are lower than CLEO-c

Singly Tag CP Channels

- 2 kinematics variables used:

$$\Delta E = E_{tag} - E_{beam}$$

$$m_{BC} = \sqrt{E_{beam}^2 - P_{tag}^2}$$

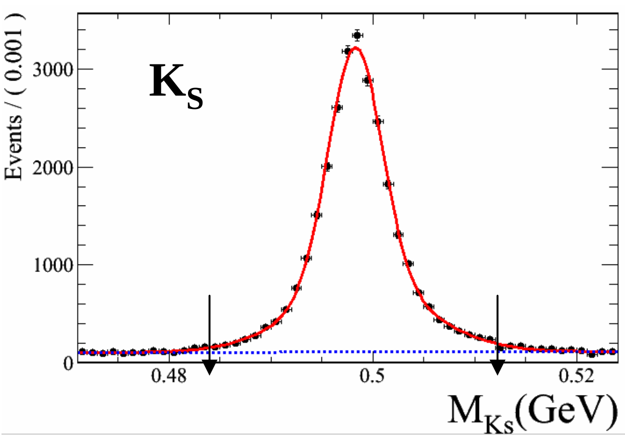
If multiple candidates are present in the same tag mode, one candidate per tag with the smallest |ΔE| is chosen.

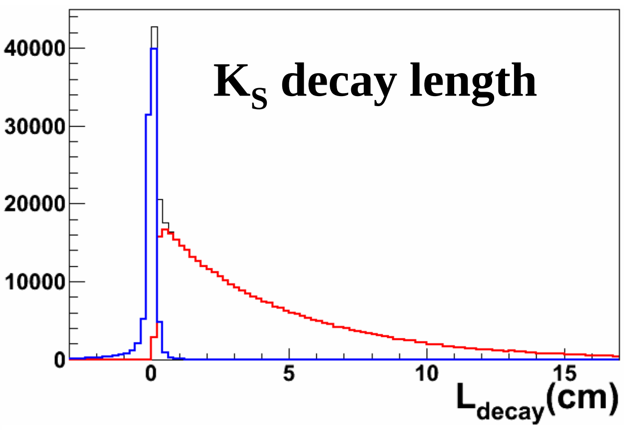
get ST yields by fitting m_{BC} with mode-dependent requirements on ΔE

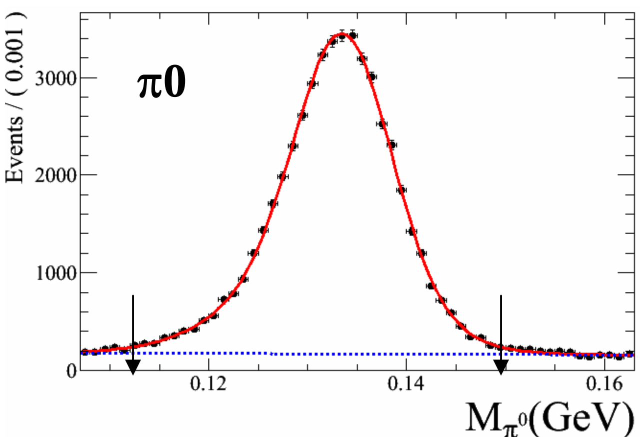
Modes	Requirement (GeV)
D→KK	$-0.025<\Delta E<0.025$
D→ππ	$-0.032<\Delta E<0.032$
D→$K_S\pi^0$	$-0.071<\Delta E<0.045$
D→$K_S\eta$	$-0.045<\Delta E<0.045$

Reconstruction Details

- **K/π separate**
- **K_S:** 2 pions form Ks candidate
  - mass of candidate within 3σ of Ks mass
  - 2 pions have the same vertex
  - candidate has a significant decay length
- **π^0/η:** 2 photons form π^0/η
  - mass of candidate within 3σ of π^0/η mass
  - 1C kinematic fit







Suppress Bhabhas and Cosmic Rays

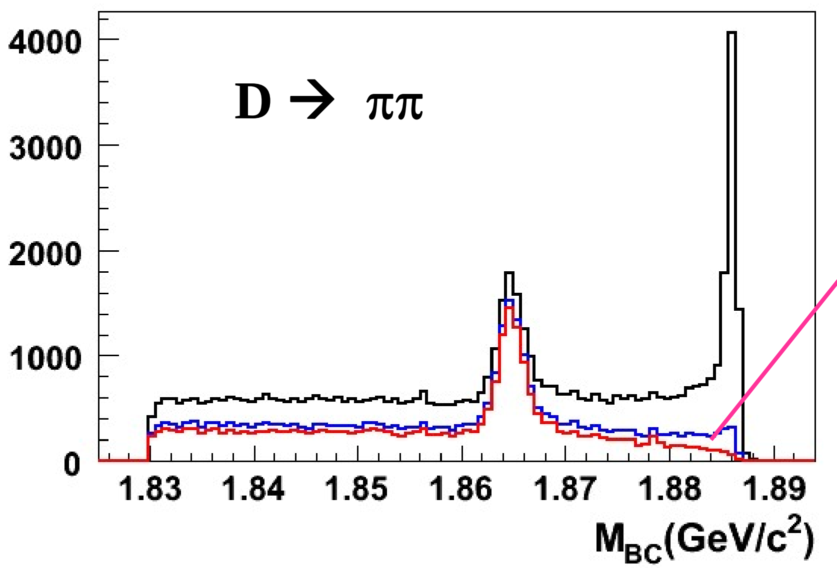
Used in 2-tracks-events such as KK,ππ and Kπ single tags:

- e/μ Identification
- TOF response time of the 2 tracks should be similar
- **An addition requirement**:
  - require there is at least one additional unassociated shower in EMC above 50MeV and more than 20 degree away from 2 signal tracks

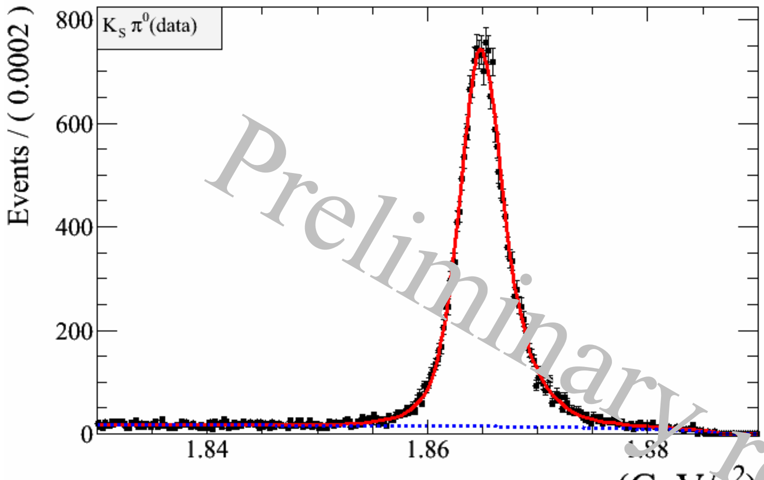
Black: preliminary result

Blue: standard cut

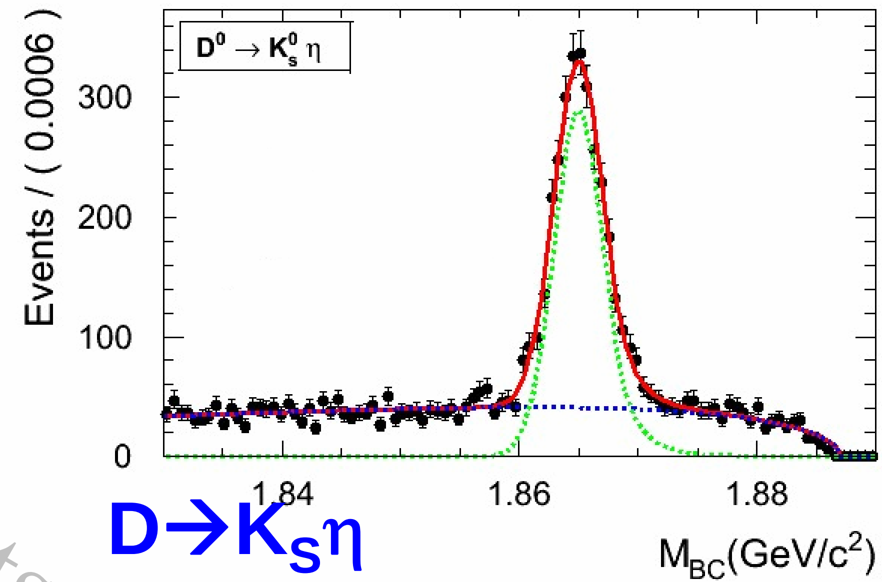
Red: additional cut



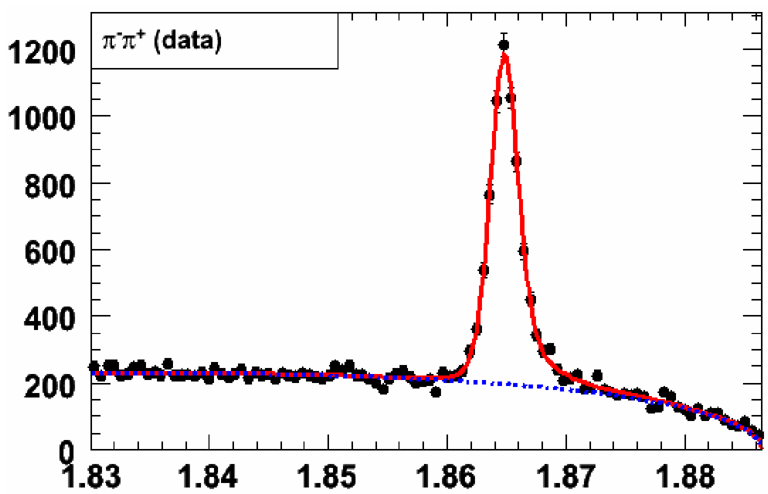
MC shape ⊗ gauss(sig) + Argus(bg)



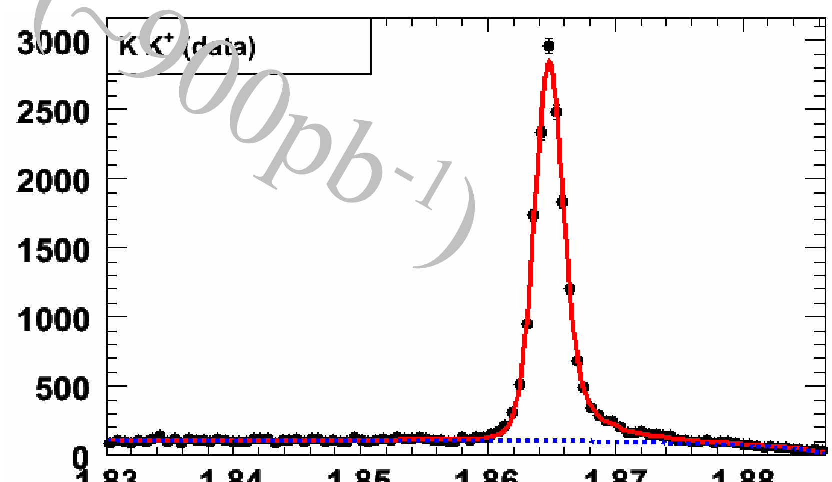
$D \rightarrow K_S\pi^0$



$D \rightarrow K_S\eta$



$D \rightarrow \pi\pi$



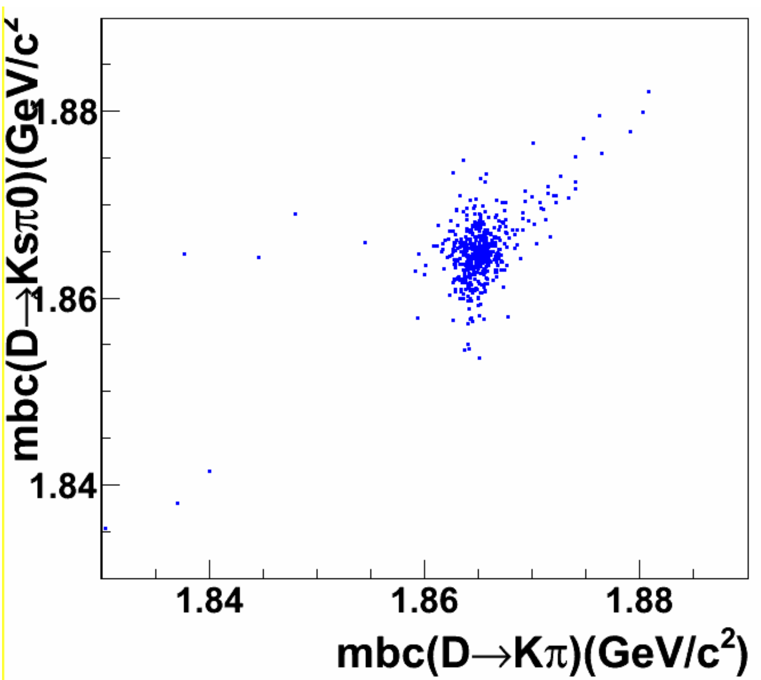
$D \rightarrow KK$

Preliminary results (~900pb-1)

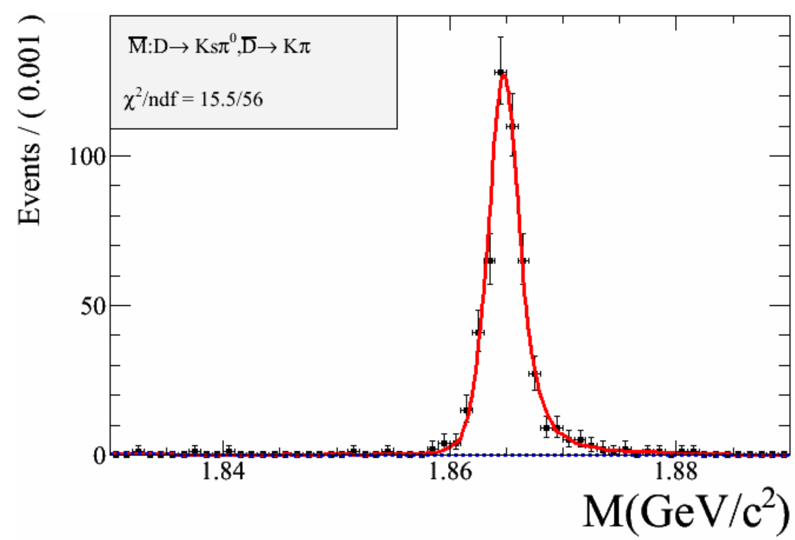
Doubly Tag $D\bar{D}$ Decay

- We form DTs by combining two ST candidates passing the selection criteria. If multiple candidates, we choose one per mode per event with M closest to measured D mass, where:

$$M \equiv [m_{BC}(D^0) + m_{BC}(\overline{D^0})]/2$$



get DT yields by fitting M with combine requirements on 2 D mesons



Efficiencies from MC

Modes	Effs*(%)	
	BESIII	CLEO-c#
$D \to K^-K^+$, $D \to K\pi$	**37.92+/-0.12**	**35.8+/-0.6**
$D \to \pi^-\pi^+$, $D \to K\pi$	**41.23+/-0.12**	**46.3+/-1.1**
$D \to K_S\pi^0$, $D \to K\pi$	**17.69+/-0.05**	**18.5+/-0.3**
$D \to K_S\pi^0$, $D \to K\pi$	**5.97+/-0.06**	**6.05+/-0.3**
$D \to K\pi$	**61.33+/-0.18**	**64.70+/-0.04**
$D \to K^-K^+$	**58.39+/-0.20**	**57.25+/-0.09**
$D \to \pi^-\pi^+$	**63.10+/-0.21**	**72.92+/-0.13**
$D \to K_S\pi^0$	**26.17+/-0.08**	**29.73+/-0.05**
$D \to K_S\eta$	**8.68+/-0.07**	**10.34+/-0.06**

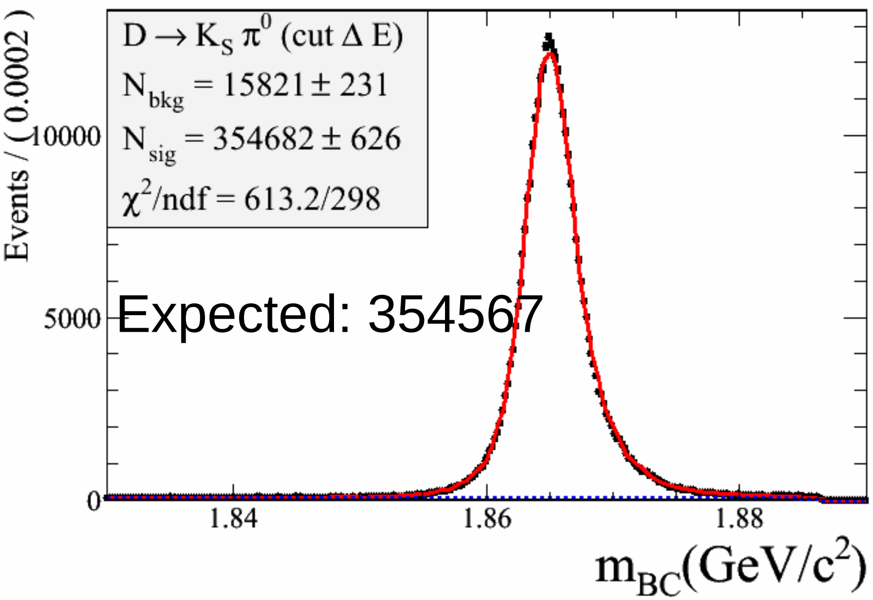
*:the efficiencies include the branch fractions of $K_S \to \pi+\pi-$, $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$

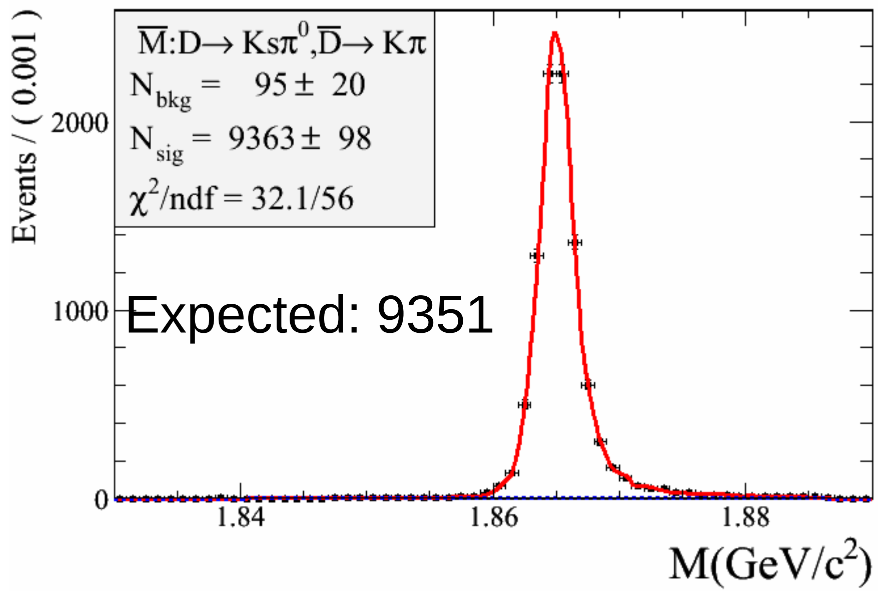
#:from **PRD 78, 012001 (2008)**

Most of the efficiencies are lower than CLEO-c

Input/Output Check

In MC, there is no δ, cosδ equals to **0**





We get Br(CP+→Kπ) : (3.902+/-0.04)%

Br(CP–→Kπ) : (3.93+/-0.08)%

Input: (3.89+/-0.05)%

So,

$$2\sqrt{R_D} \cdot \cos\delta = (0.36 \pm 1.14) \cdot 10^{-4}$$

The I/O result agrees well!

Statistical Sensitivity

- Using **~0.9fb^{-1}** data, we get

$$2\sqrt{R_D}\cdot\cos\delta = (XXX \pm 3.125(stat.))\%$$

If using HFAG 2010 average of R_D, that is (3.37+/-0.09) ‰,we got:

$$\cos\delta = 0.XXX \pm 0.270(stat.)$$

The result is still need to be optimize. The statistics error is comparable to CLEO-c

Systematic Errors Study

- Sources of systematic uncertainties:
  - Track finding
  - K/π PID
  - K_S, π^0/η finding
  - lepton veto (for $K\pi$, KK, $\pi\pi$)
  - ΔE requirement
  - Signal/background shape
  - FSR/ISR

Different modes have different sys. errors about ΔE, FSR..
We will show it in next page

Systematic Uncertainties

	ΔE(%)	Lepton veto(%)	FSR(%)	Other(%)
$K\pi$	**2.0**	**0.5**	**1.1**	**<1 (tracking)** **<1 (PID)**
KK	**2.0**	**0.4**	**0.3**	
$\pi\pi$	**2.7**	**0.6**	**1.5**	
$K_S\pi^0$	**1.3**	**--**	**--**	**7.6 (K_S)** **3 (η/π^0)**
$K_S\eta$	**2.9**	**--**	**--**	

Parts of the sys. errs are given for STs; for DT on mode {A,B} for ST uncertainties of α on mode A and β on mode B, we got (except correlated): $\sqrt{\alpha^2+\beta^2}$

The study of systematic errors is ongoing

Summary and Next-to-do

- Due to large statistics of $D\bar{D}$ data, BESIII will contribute a lot to charm physics!
- With first round of $\Psi(3770)$ data, we study the Strong Phase Difference, and statistic error is comparable to CLEO-c:

$$2\sqrt{R_D}\times\cos\delta = (XXX \pm 3.125(stat.) \pm (sys.))\%$$

- Further studies need to be done in:
  - Optimize cuts and fits
  - Systematic errors study
  - Use all of the $\Psi(3770)$ data
  - Maybe more CP decay modes($K_S\omega$,$K_L\pi^0$ etc.) can be include to increase statistics

Thank you!

Backup

Details on Formalism

$$\cos\delta = \frac{|A_f|^2 + |\overline{A_f}|^2 - |\sqrt{2}A_{CP+}|^2}{2\cdot|A_f|\cdot|\overline{A_f}|},$$

$$\cos(\pi-\delta) = \frac{|A_f|^2 + |\overline{A_f}|^2 - |\sqrt{2}A_{CP-}|^2}{2\cdot|A_f|\cdot|\overline{A_f}|}$$

$$\Rightarrow |A_f|^2 + |\overline{A_f}|^2 = |A_{CP+}|^2 + |A_{CP-}|^2$$

$$\therefore \cos\delta = -\frac{|A_{CP-}|^2 - |A_{CP+}|^2}{2\cdot|A_f|^2\cdot\frac{|\overline{A_f}|}{|A_f|}}$$

$$\Rightarrow 2\sqrt{R_D}\cos\delta = -\frac{|A_{CP-}|^2 - |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2}\cdot\left(1+\frac{|\overline{A_f}|^2}{|A_f|^2}\right)$$

Result from CLEO-c

- CLEO-c use different method, and got:

$$\cos\delta = 1.10 \pm 0.35 \pm 0.07$$

This result is from 281pb-1. They use more CP decay channels