Strong phase in $D^0\to K\pi$ decay and y_{CP} measurement at BESIII

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Introduction

The mixing parameters describes the magnitude of DDbar mixing

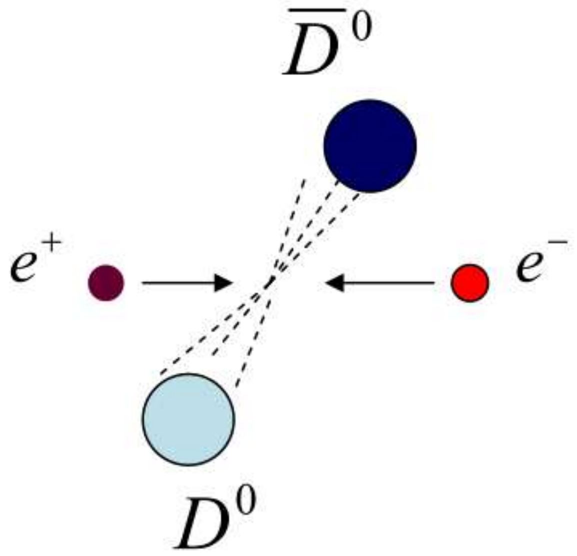
$$x = 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \qquad y = \frac{\mathit{\Gamma}_1 - \mathit{\Gamma}_2}{\mathit{\Gamma}_1 + \mathit{\Gamma}_2}$$

where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the neutral *D* meson mass eigenstates.

- ✓ DDbar mixing is highly suppressed by the GIM mechanism and by the CKM matrix elements within the Standard Model
- ✓ Observation of DDbar mixing by LHCb
- ✓ Improving the constraints on the charm mixing parameters is important for testing the SM, such as long-distance effect
- ✓ In addition, strong phase is an important ingredient for (over-)constraining the CKM unitary triangle, which is an crucial for searching for new physics

Production at threshold

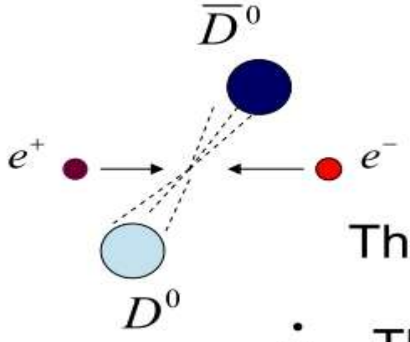
- **Threshold production at 3.773 GeV**
- **Double Tag techniques: (partial-)reconstruct both *D* mesons**
- **Charm events at threshold are very clean and unique in studying *D* decays**



- Quantum correlation of two *D* mesons
- Very clean environment with little to no non-*DDbar* background
- Lots of systematic uncertainties uncertainties cancel when applying double tag method

The decay rate of a correlated state

For a physical process producing $D^0\,\overline{D}^0$ such as



$$e^+e^- \to \psi(3770) \to D^0\overline{D}^0$$

The $D^0\,\overline{D}^0$ pair will be a quantum-correlated state

The quantum number of $\psi(3770)$ is $J^{PC} = 1^{--}$

$\therefore$ The C number of $D^0\,\overline{D}^0$ pair in this process is $C = -$

For a correlated state with $C = -$

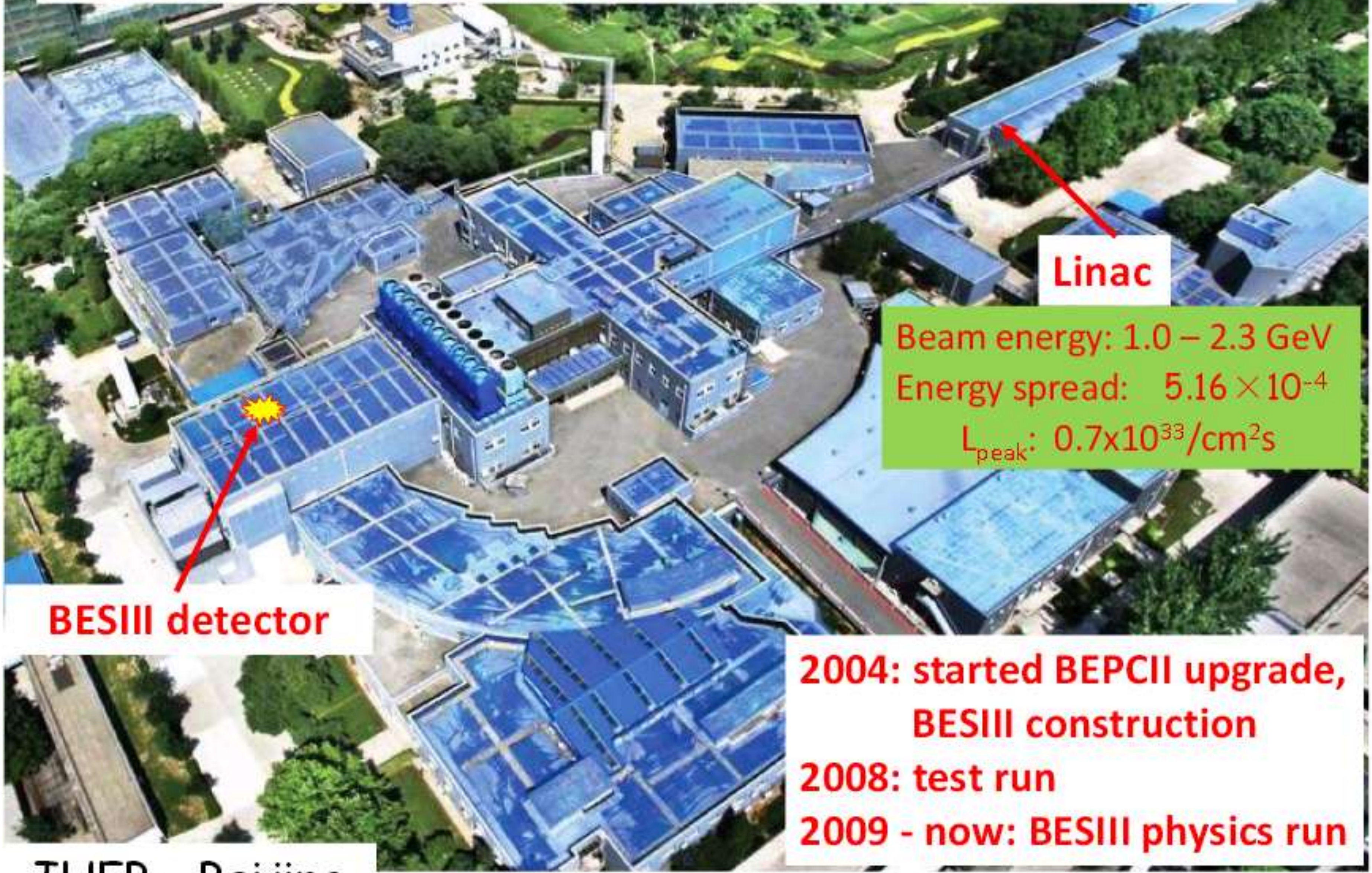
$$\psi_- = \frac{1}{\sqrt{2}}(|D^0\rangle|\overline{D}^0\rangle - |\overline{D}^0\rangle|D^0\rangle)$$

$$\hat{C}|D^0\rangle = |\overline{D}^0\rangle$$
$$\hat{C}|\overline{D}^0\rangle = |D^0\rangle$$

Taking advantage the quantum coherence of DDbar pairs, BESIII can study the charm physics in an unique way

- *strong phase*
- *mixing parameters*
- *direct CP violation*
- *...*

Beijing Electron Positron Collider (BEPC)



Beam energy: 1.0 – 2.3 GeV

Energy spread: 5.16×10^{-4}

L_{peak}: $0.7 \times 10^{33}/cm^2s$

2004: started BEPCII upgrade,
BESIII construction

2008: test run

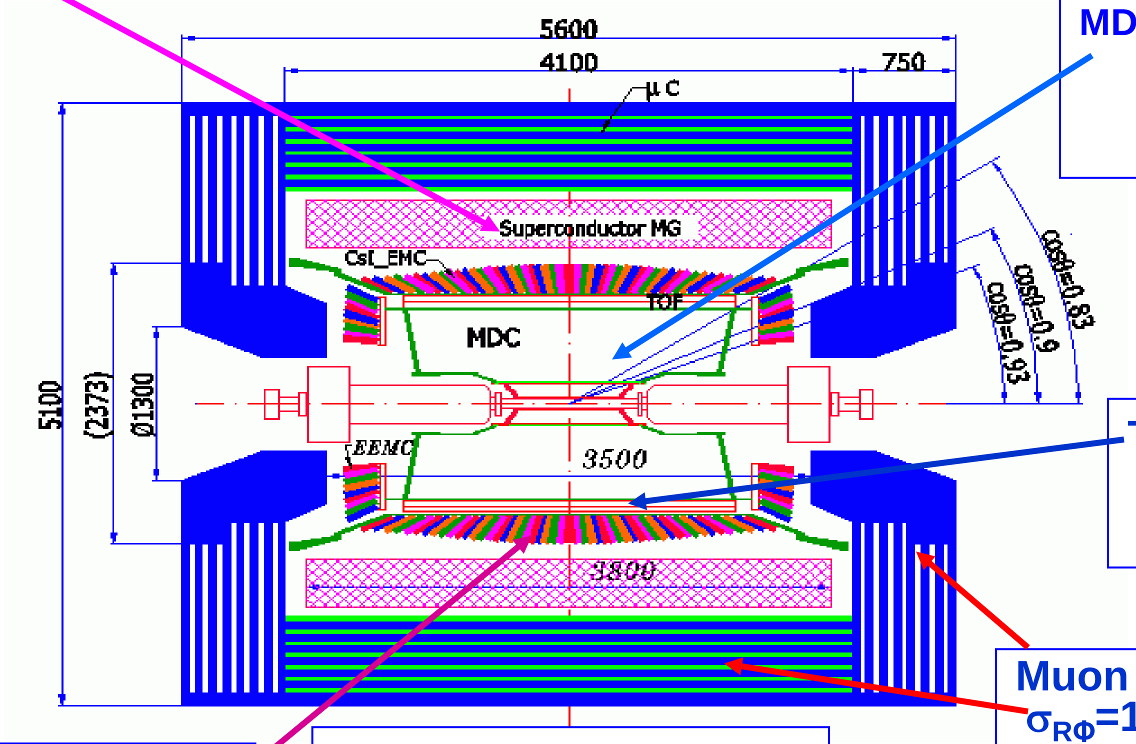
2009 - now: BESIII physics run

IHEP, Beijing

NIM A614, 345 (2010)

The BESIII detector

Magnet: 1 T Super conducting



MDC: small cell & He gas
σ_{xy}=130 μm
s_p/p = 0.5% @1GeV
dE/dx=6%

TOF:
σ_T = 90 ps Barrel
110 ps Endcap

Muon ID: 8~9 layer RPC
$\sigma_{R\Phi}$=1.4 cm~1.7 cm

EMCAL: CsI crystal
$\Delta E/E$ = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/$\sqrt{E}$

Data Acquisition:
Event rate = 3 kHz
Throughput ~ 50 MB/s

Trigger: Tracks & Showers
Pipelined; Latency = 6.4 μs

The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.

Collected data samples at BESIII

	Previous data	BESIII now	Goal
J/ψ	BESII: 58 M	1.2 B 20*BESII	10 B
ψ(3686)	CLEO: 28 M	0.5 B 20*CLEO	3 B
ψ(3770)	CLEO: 0.8 /fb	2.9 /fb 3.5*CLEO	20 /fb
Above open charm threshold	CLEO: 0.6/fb @4160MeV	2011: 0.5 /fb @ 4.009 GeV 2013: 1.9 /fb @ 4.26 GeV, 0.5 /fb @ 4.36 GeV and data for lineshape	5-10 /fb
R scan	BESII	2012: R @2.23,2.4,2.8,3.4 GeV 25 /pb tau mass	

- world’s largest samples of on-threshold *ψ(3770)* data and keep increasing in the future
- the aim is to have 20 /fb data

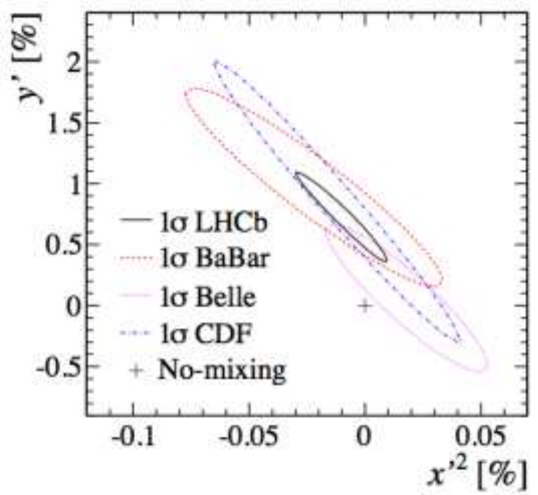
Implications of strong phase difference

- Time-dependent $D^0 \to K\pi$ analysis:
  phase difference δ to relate (x', y') with (x, y).

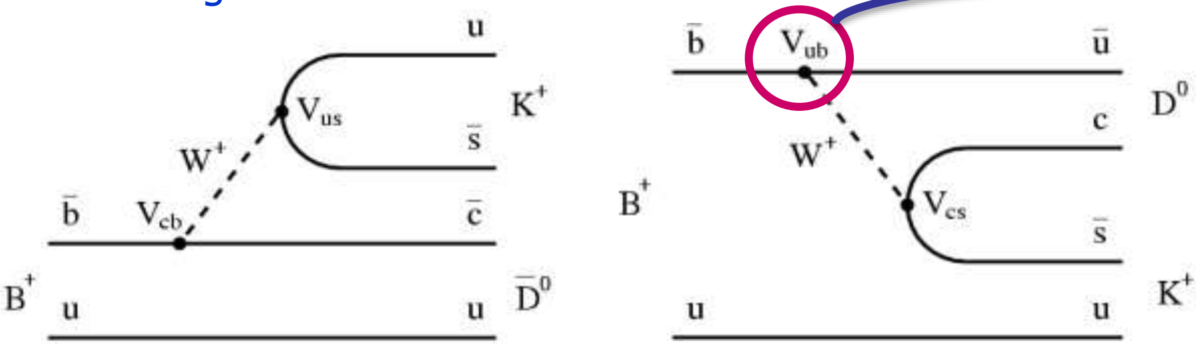
$$x' = x_D \cos\delta_{K\pi} + y_D \sin\delta_{K\pi},$$
$$y' = y_D \cos\delta_{K\pi} - x_D \sin\delta_{K\pi}.$$

PRL 110, 101802 (2013)

Parameter	Fit result (10^{-3})
R_D	3.52 ± 0.15
y'	7.2 ± 2.4
x'^2	-0.09 ± 0.13



- *CKM unitarity triangle γ/ϕ_3 extraction* from $B^- \to D^0 K^-$
  - Atwood, Dunietz, Soni (ADS): Use doubly Cabibbo-suppressed decays, e.g. $D^0 \to K^+\pi^-$



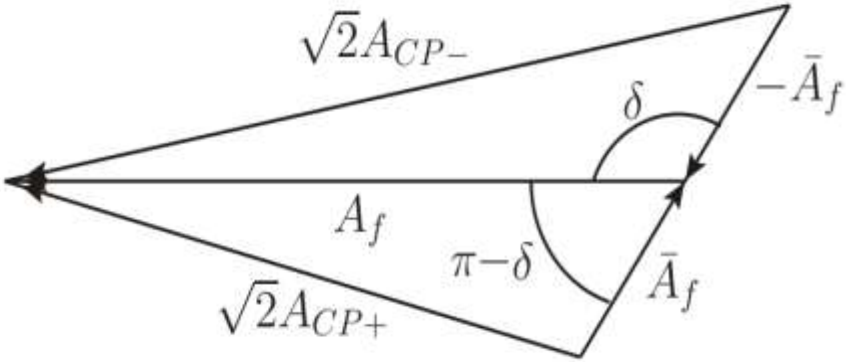
$$\frac{A(B^+ \to D^0 K^+)}{A(B^+ \to \overline{D^0} K^+)} \equiv r_B e^{i(\delta_B + \phi_3)}$$

Strong phase in $D^0 \to K\pi$ decay: formalism

The strong phase difference $\delta_{K\pi}$ between the doubly Cabibbo-suppressed (DCS) decay $\underline{D}^0 \to K^-\pi^+$ and the corresponding Cabibbo-favored (CF) $D^0 \to K^-\pi^+$ is denoted as

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

Omitting the higher orders of the mixing parameters, and assuming *CP* conservation, we have



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

$$\mathcal{A}_{CP\to K\pi} = \frac{\mathcal{B}_{D_2\to K^-\pi^+} - \mathcal{B}_{D_1\to K^-\pi^+}}{\mathcal{B}_{D_2\to K^-\pi^+} + \mathcal{B}_{D_1\to K^-\pi^+}}.$$

$$|D_1\rangle \equiv \frac{|D^0\rangle + |\overline{D}^0\rangle}{\sqrt{2}} \quad |D_2\rangle \equiv \frac{|D^0\rangle - |\overline{D}^0\rangle}{\sqrt{2}}.$$

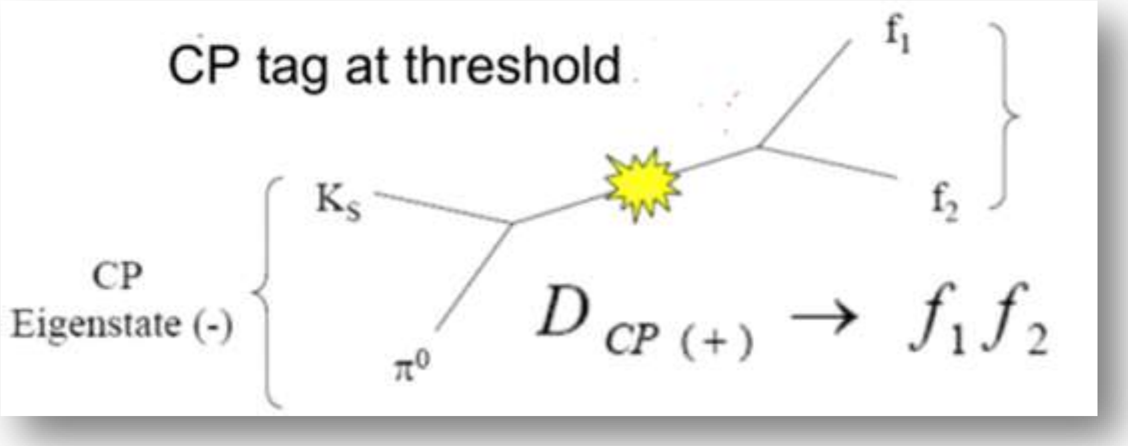
$$A_f \equiv \langle f|D^0\rangle,\ \overline{A}_f \equiv \langle f|\overline{D}^0\rangle$$

$$A_{CP+} \equiv \langle f\,|D_1\rangle$$

$$A_{CP-} \equiv \langle f\,|D_2\rangle$$

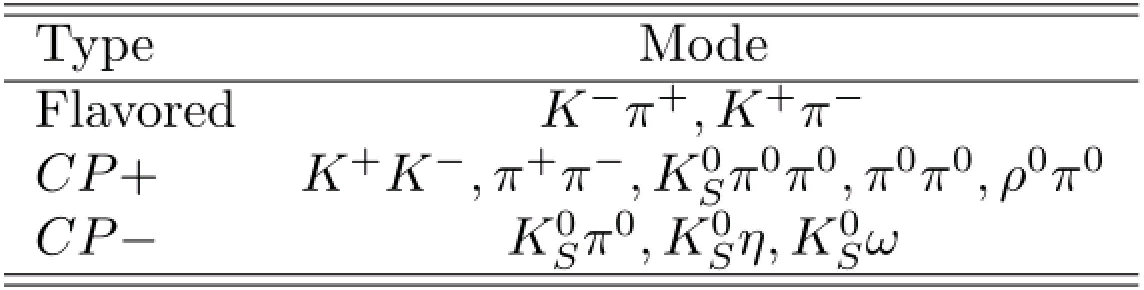
Accessing strong phase $\delta_{K\pi}$ at threshold

We measure the strong phase difference using quantum correlated production of D-Dbar at the production threshold



based on 2.9 fb^{-1} $\psi(3770)$ data

When we neglect *CPV*, *CP* of the two *D* mesons are anti-symmetric.



Type	Mode
Flavored	$K^-\pi^+, K^+\pi^-$
$CP+$	$K^+K^-, \pi^+\pi^-, K^0_S\pi^0\pi^0, \pi^0\pi^0, \rho^0\pi^0$
$CP-$	$K^0_S\pi^0, K^0_S\eta, K^0_S\omega$

To determine $\delta_{K\pi}$ in experiment

For the CP-eigenstates, yields of D → CP ST events will be

$$n_{CP\pm} = 2N_{D\overline{D}} \cdot \mathcal{B}_{CP\pm} \cdot \varepsilon_{CP\pm}.$$

The DT yields with $D \to CP$ and $D \to K\pi$ will be

$$n_{K\pi,CP\pm} = 2N_{D\overline{D}} \cdot \mathcal{B}_{CP\pm} \times \mathcal{B}_{D^{CP\mp}\to K\pi} \cdot \varepsilon_{K\pi,CP\pm}$$

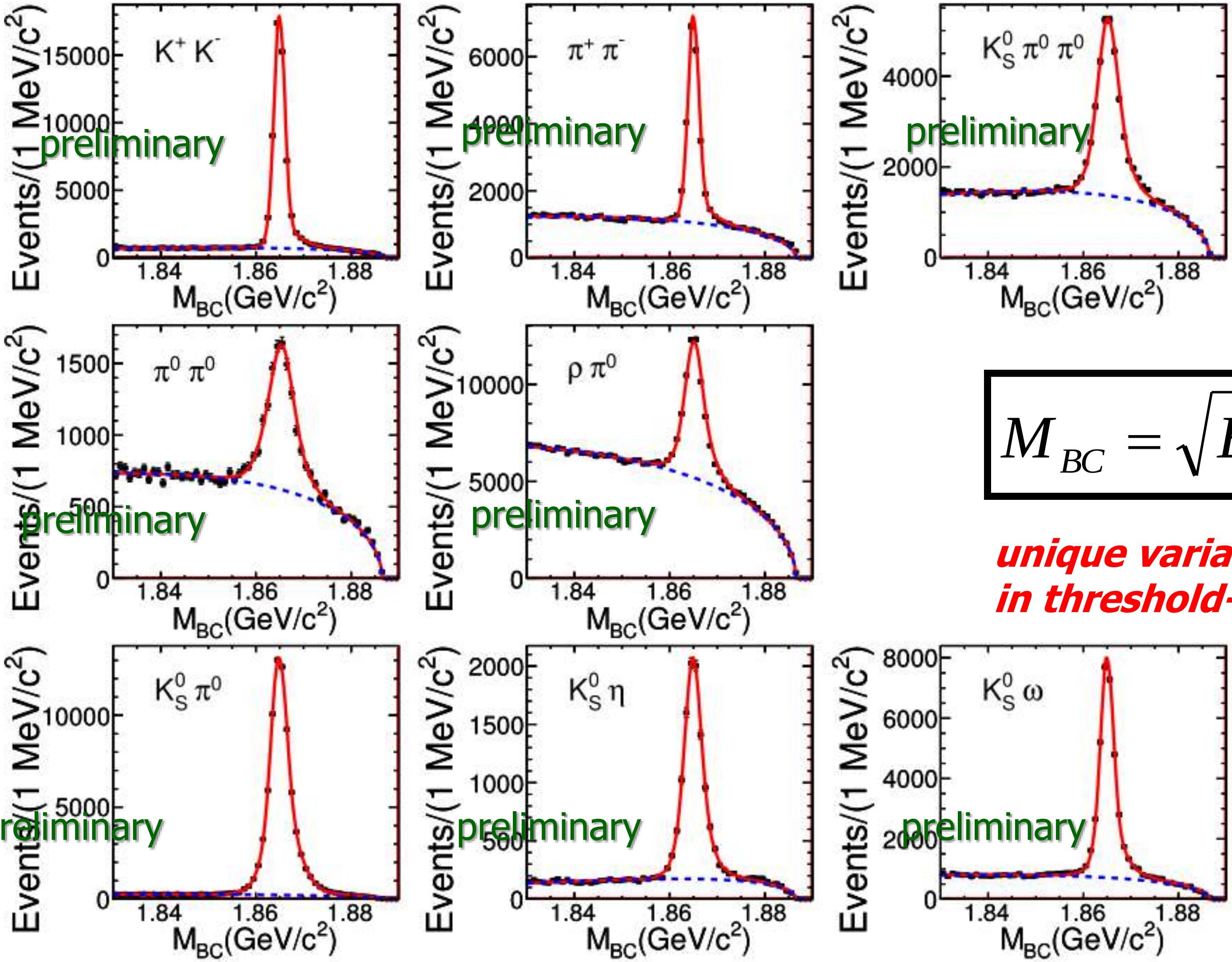
Therefore, the branching fraction is

$$\mathcal{B}_{D^{CP\pm}\to K\pi} = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}.$$

Here, $\varepsilon_{CP\pm}/\varepsilon_{K\pi,CP\pm}$ cancels most systematic effects within the $D \to CP\pm$ decay mode.

Therefore, $A_{CP\to K\pi}$ can be obtained. With external inputs of the other parameters, we can obtain $\delta_{K\pi}$.

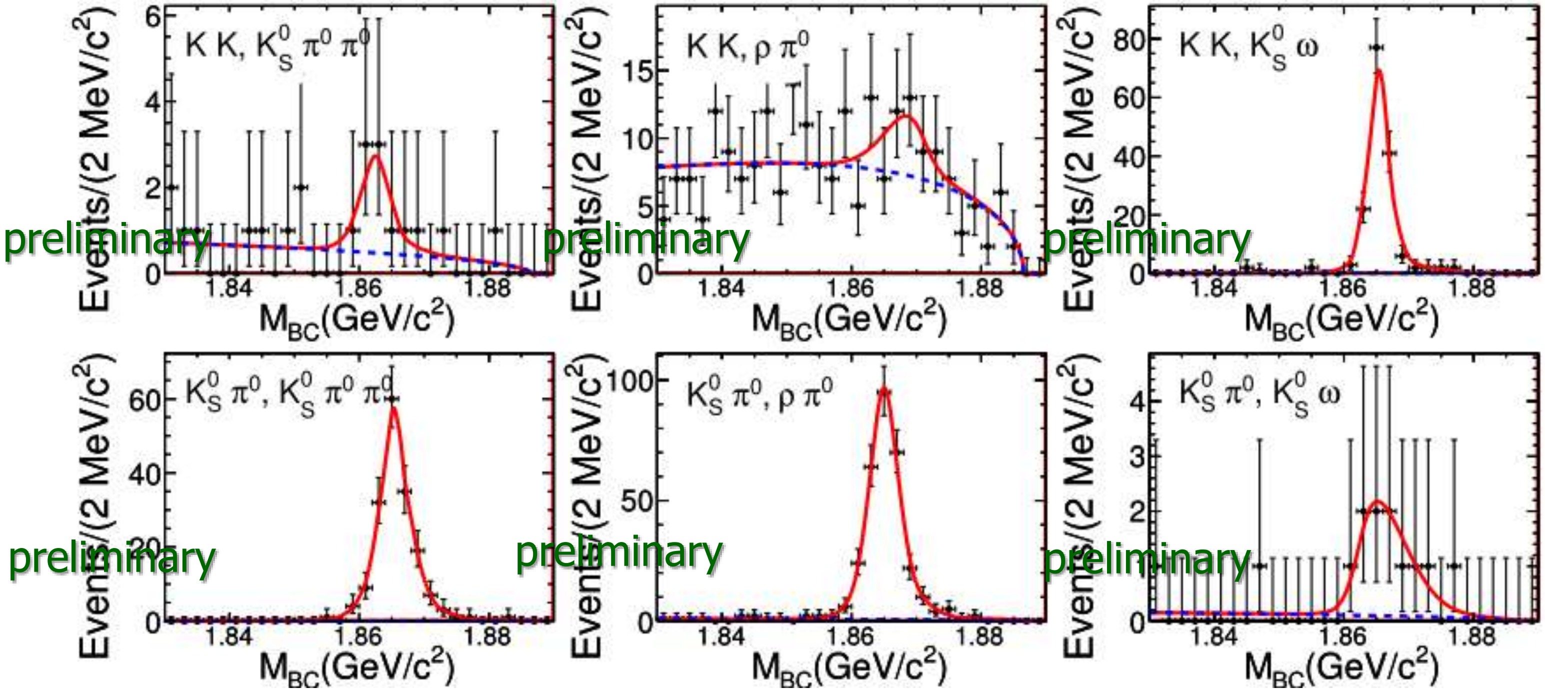
Single tags of CP modes

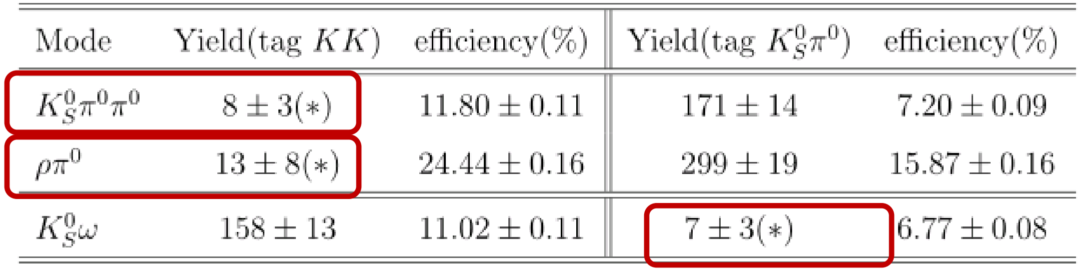


$$M_{BC} = \sqrt{E_{beam}^2 - \vec{p}_D^{\,2}}$$

unique variable
in threshold-production

CP purity check of *CP*-tag modes



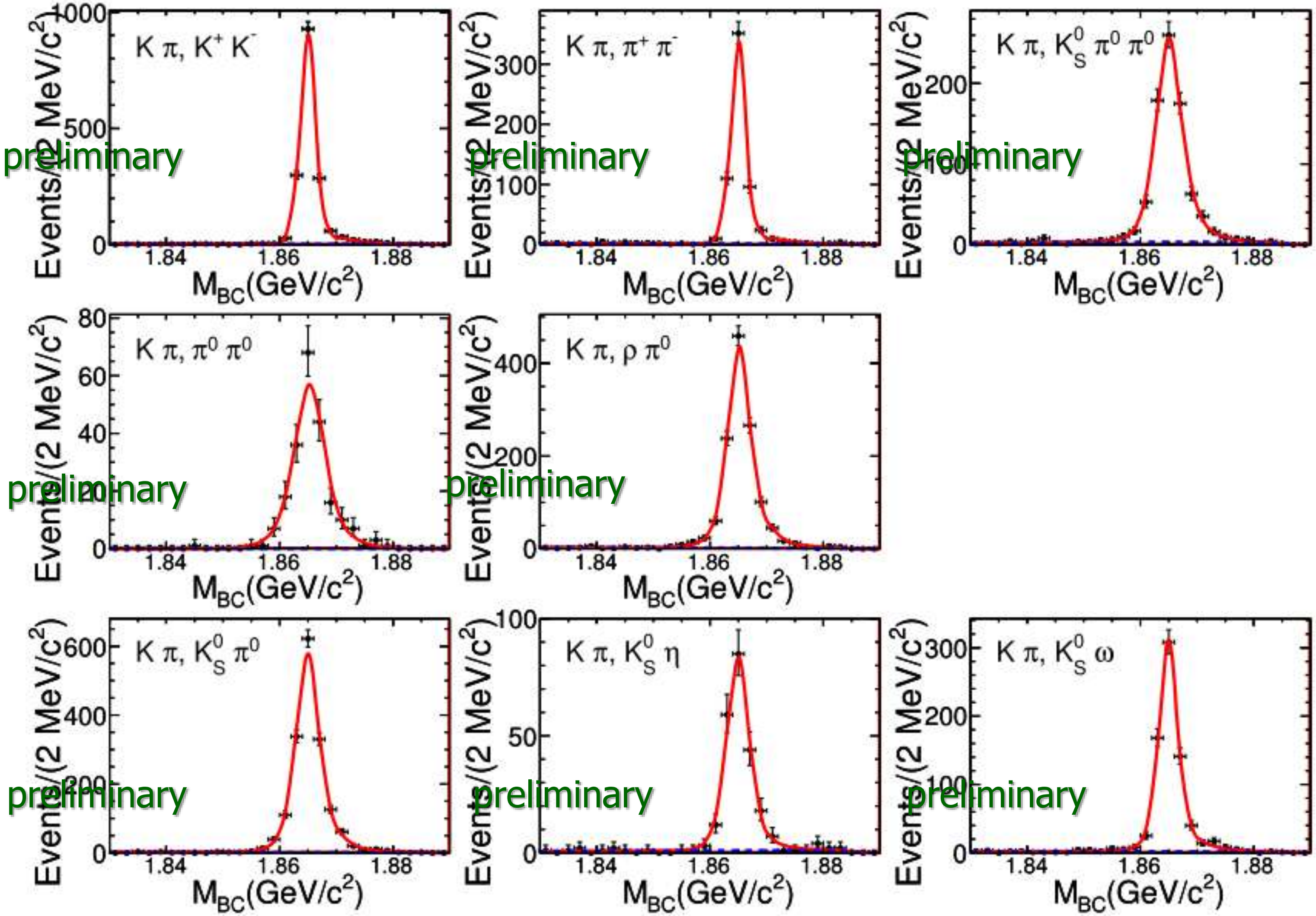


Mode	Yield(tag KK)	efficiency(%)	Yield(tag $K_S^0\pi^0$)	efficiency(%)
$K_S^0\pi^0\pi^0$	$8 \pm 3(*)$	11.80 ± 0.11	171 ± 14	7.20 ± 0.09
$\rho\pi^0$	$13 \pm 8(*)$	24.44 ± 0.16	299 ± 19	15.87 ± 0.16
$K_S^0\omega$	158 ± 13	11.02 ± 0.11	$7 \pm 3(*)$	6.77 ± 0.08

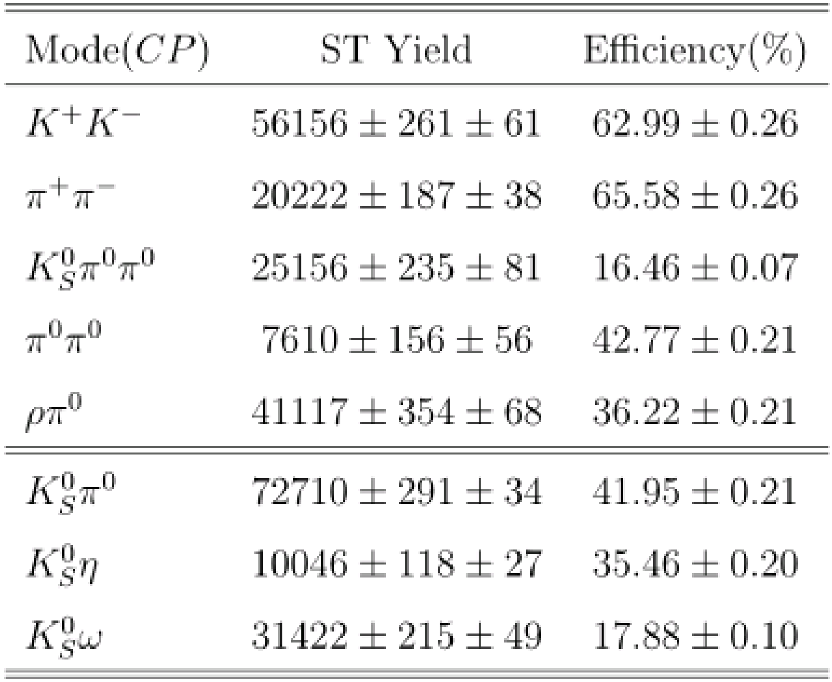
events with same-*CP* decays are consistent with 0

consider as systematic uncertainty

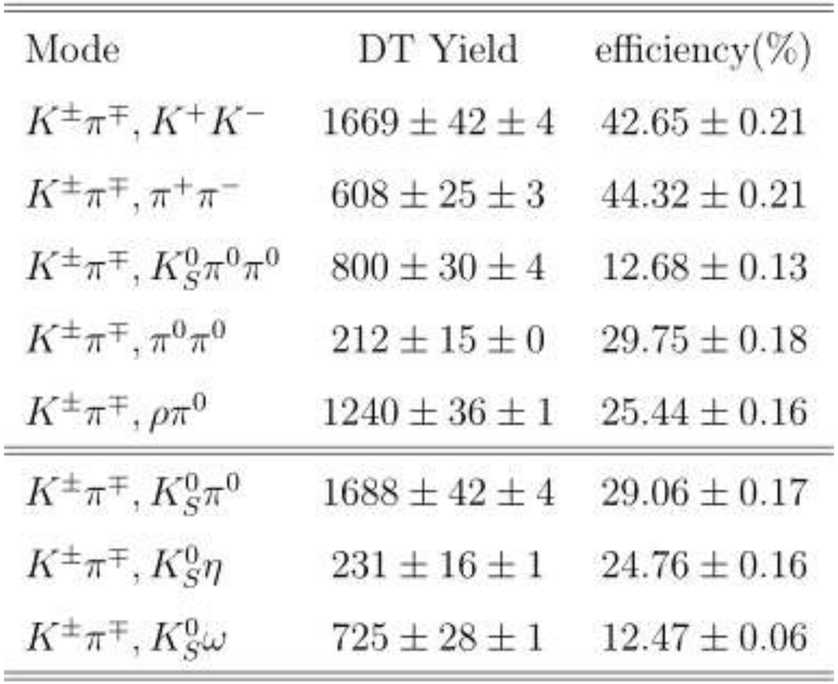
Double tags of (*CP*, $K\pi$) modes



Preliminary numerical results



Mode(CP)	ST Yield	Efficiency(%)
K^+K^-	$56156 \pm 261 \pm 61$	62.99 ± 0.26
$\pi^+\pi^-$	$20222 \pm 187 \pm 38$	65.58 ± 0.26
$K^0_S\pi^0\pi^0$	$25156 \pm 235 \pm 81$	16.46 ± 0.07
$\pi^0\pi^0$	$7610 \pm 156 \pm 56$	42.77 ± 0.21
$\rho\pi^0$	$41117 \pm 354 \pm 68$	36.22 ± 0.21
$K^0_S\pi^0$	$72710 \pm 291 \pm 34$	41.95 ± 0.21
$K^0_S\eta$	$10046 \pm 118 \pm 27$	35.46 ± 0.20
$K^0_S\omega$	$31422 \pm 215 \pm 49$	17.88 ± 0.10



Mode	DT Yield	efficiency(%)
$K^\pm\pi^\mp, K^+K^-$	$1669 \pm 42 \pm 4$	42.65 ± 0.21
$K^\pm\pi^\mp, \pi^+\pi^-$	$608 \pm 25 \pm 3$	44.32 ± 0.21
$K^\pm\pi^\mp, K^0_S\pi^0\pi^0$	$800 \pm 30 \pm 4$	12.68 ± 0.13
$K^\pm\pi^\mp, \pi^0\pi^0$	$212 \pm 15 \pm 0$	29.75 ± 0.18
$K^\pm\pi^\mp, \rho\pi^0$	$1240 \pm 36 \pm 1$	25.44 ± 0.16
$K^\pm\pi^\mp, K^0_S\pi^0$	$1688 \pm 42 \pm 4$	29.06 ± 0.17
$K^\pm\pi^\mp, K^0_S\eta$	$231 \pm 16 \pm 1$	24.76 ± 0.16
$K^\pm\pi^\mp, K^0_S\omega$	$725 \pm 28 \pm 1$	12.47 ± 0.06

$$\mathcal{A}_{\mathcal{CP}\to\mathcal{K}\pi} = (12.77 \pm 1.31(stat.)^{+0.33}_{-0.31}(sys.))\%$$

Preliminary results of $\delta_{K\pi}$

We measure $\mathcal{A}_{CP\to K\pi} = (12.77 \pm 1.31(stat.)^{+0.33}_{-0.31}(sys.))\%$

We have $2r\cos\delta_{K\pi} + y = (1 + R_{\mathrm{WS}}) \cdot \mathcal{A}_{CP\to K\pi},$

With external inputs of the parameters in HFAG2013 and PDG,

$$R_{\mathrm{D}} = 3.47 \pm 0.06‰, \; y = 6.6 \pm 0.9‰ \quad R_{\mathrm{WS}} = 3.80 \pm 0.05‰$$

we obtain

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

CLEO measurements of strong phase differences and coherence factors done with 0.8 fb^{-1} at ψ(3770). ***[CLEO, PRD 86 (2012) 112001]***

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

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

BESIII result: the most precise measurement of $\delta_{K\pi}$ and compatible with the world average

Determination of the mixing parameter y_{CP}

For any final states of CP eigenstates, the decay rate is:

$$R_{CP\pm} \propto |A_{CP\pm}|^2(1 \mp y_{CP})$$

where

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

Considering the process in which one *D* decays into CP eigenstates and the other D decays semileptonically, the decay rate is:

$$R_{l,CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$$

Neglecting terms to order y^2 or higher, we can derive

$$y_{CP} \approx \frac{1}{4}(\frac{R_{l;CP+}R_{CP-}}{R_{l;CP-}R_{CP+}} - \frac{R_{l;CP-}R_{CP+}}{R_{l;CP+}R_{CP-}})$$

In the limit of no CPV, $y_{CP} = y$

Measurement of y_{CP}: formalism

On experiments. we have

$$y_{CP} \approx \frac{1}{4}\left[\frac{\sum_{k,j} C^{k,j}_{CP+;l} \sum_i C^i_{CP-}}{\sum_{i,j} C^{i,j}_{CP-;l} \sum_k C^k_{CP+}} - \frac{\sum_{i,j} C^{i,j}_{CP-;l} \sum_k C^k_{CP+}}{\sum_{k,j} C^{k,j}_{CP+;l} \sum_i C^i_{CP-}}\right]$$

where the efficiency-corrected yields are denoted to be

$$C^i_{CP\pm} = \frac{N^i_{CP\pm}}{\epsilon^i_{CP\pm}}, \qquad C^{i,j}_{CP\pm;l} = \frac{N^{i,j}_{CP\pm;l}}{\epsilon^{ij}_{CP\pm;l}}$$

We define the ratio $B_+ \equiv \frac{C_{CP+;l}}{C_{CP+}}$ and $B_- \equiv \frac{C_{CP-;l}}{C_{CP-}}$

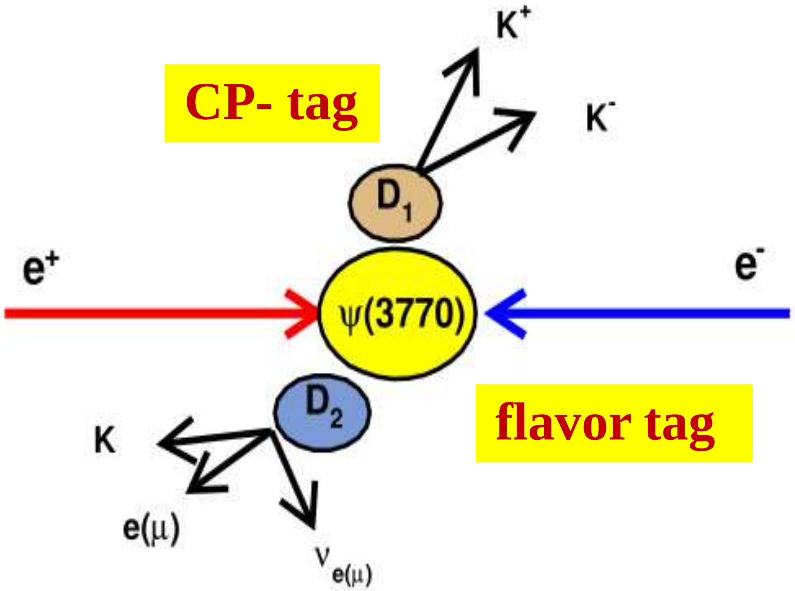
then $$y_{CP} = \frac{1}{4}\left[\frac{\tilde{B}_+}{\tilde{B}_-} - \frac{\tilde{B}_-}{\tilde{B}_+}\right]$$

$\tilde{B}_\pm$ is the average ratio over different *CP* modes by minimizing

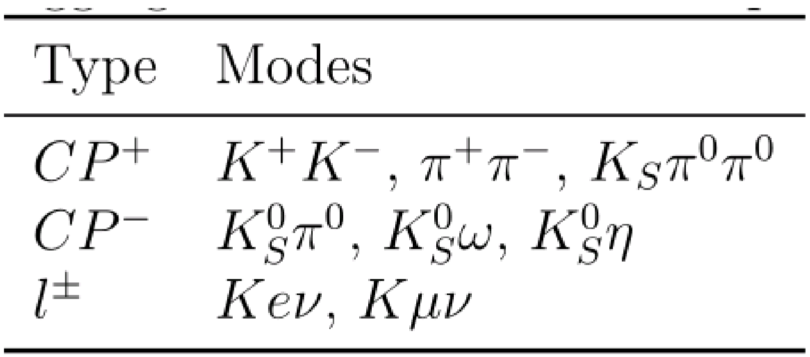
$$\chi^2 = \sum \frac{(\tilde{B}_\pm - B^\alpha_\pm)^2}{(\sigma^\alpha_\pm)^2}$$

Measurement of y_{CP}: CP tag and flavor tag

We measure the y_{CP} using *CP*-tagged semi-leptonic *D* decays



based on 2.9 fb^{-1} ψ(3770) data



Type	Modes
CP^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$
CP^-	$K^0_S\pi^0$, $K^0_S\omega$, $K^0_S\eta$
$l^\pm$	$Ke\nu$, $K\mu\nu$

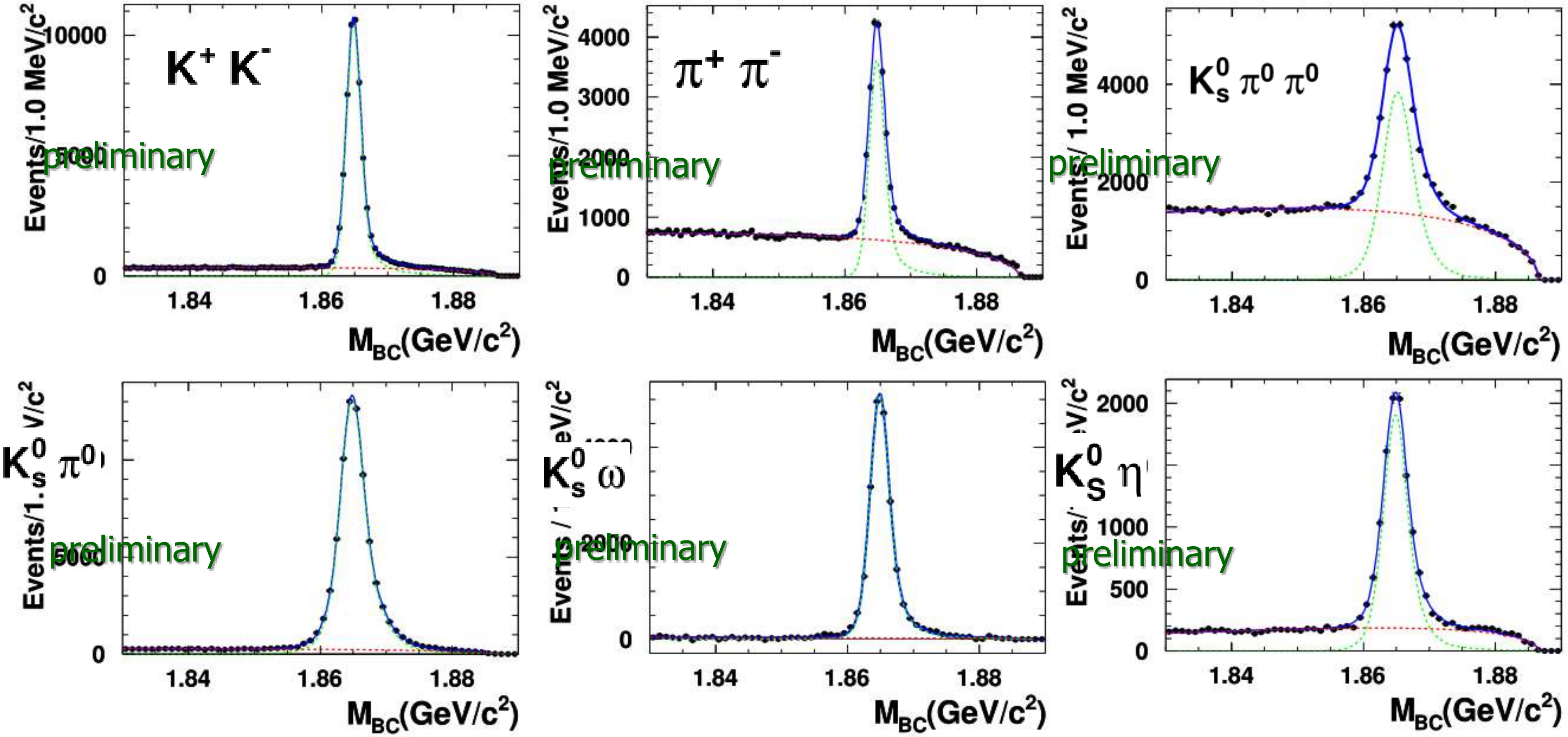
The observable can be :

$$\boxed{U_{miss} = E_{miss} - c\left|\vec{p}_{miss}\right|}$$

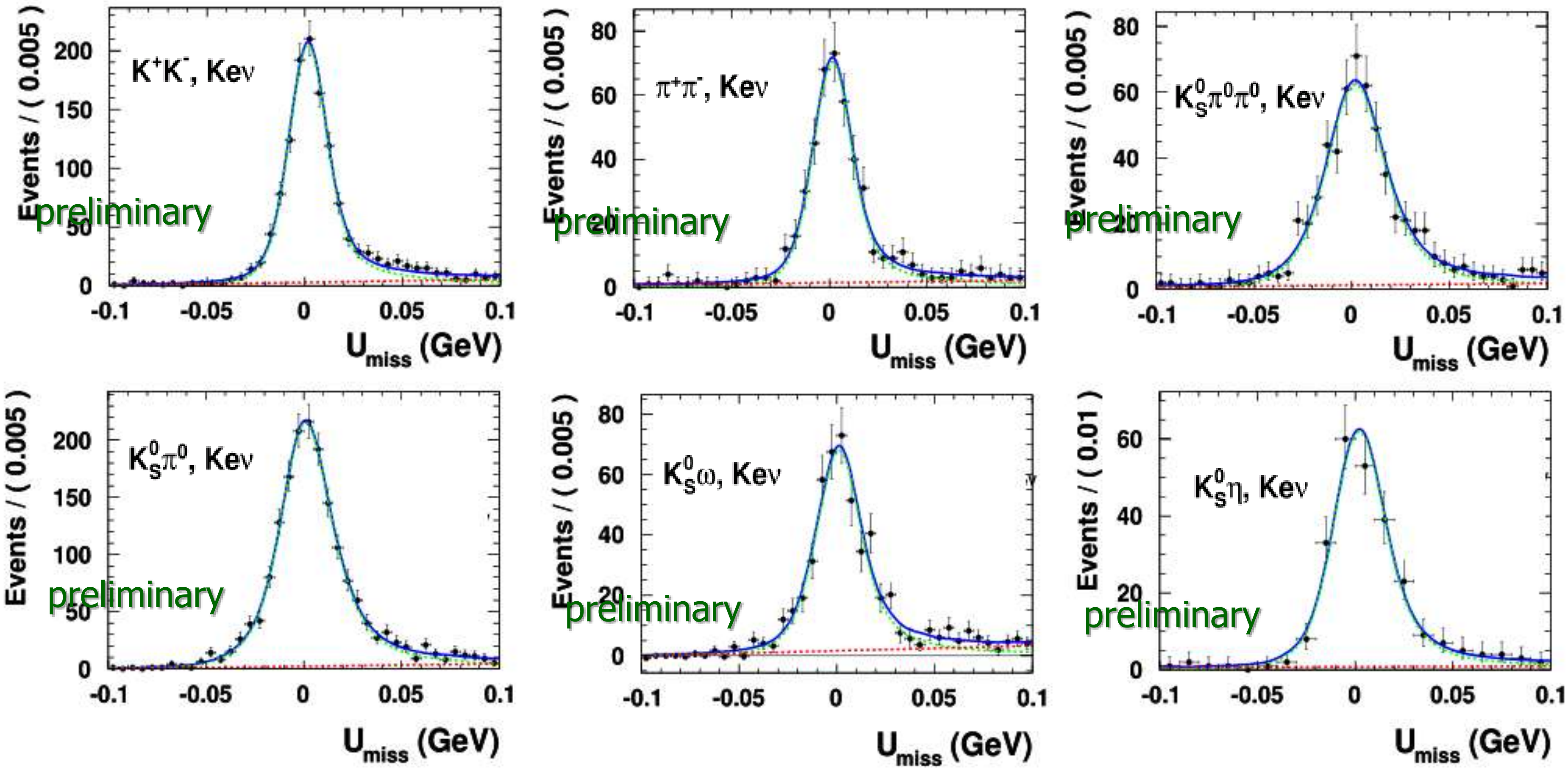
$$\vec{p}_{miss} = -\sqrt{E_{beam}^2 - m_D^2}\,\hat{p}_{D_{CP}} - \vec{p}_K - \vec{p}_l \qquad E_{miss} = E_{beam} - E_K - E_l$$

Semi-leptonic signal peaks at zero!

Single tags of CP modes

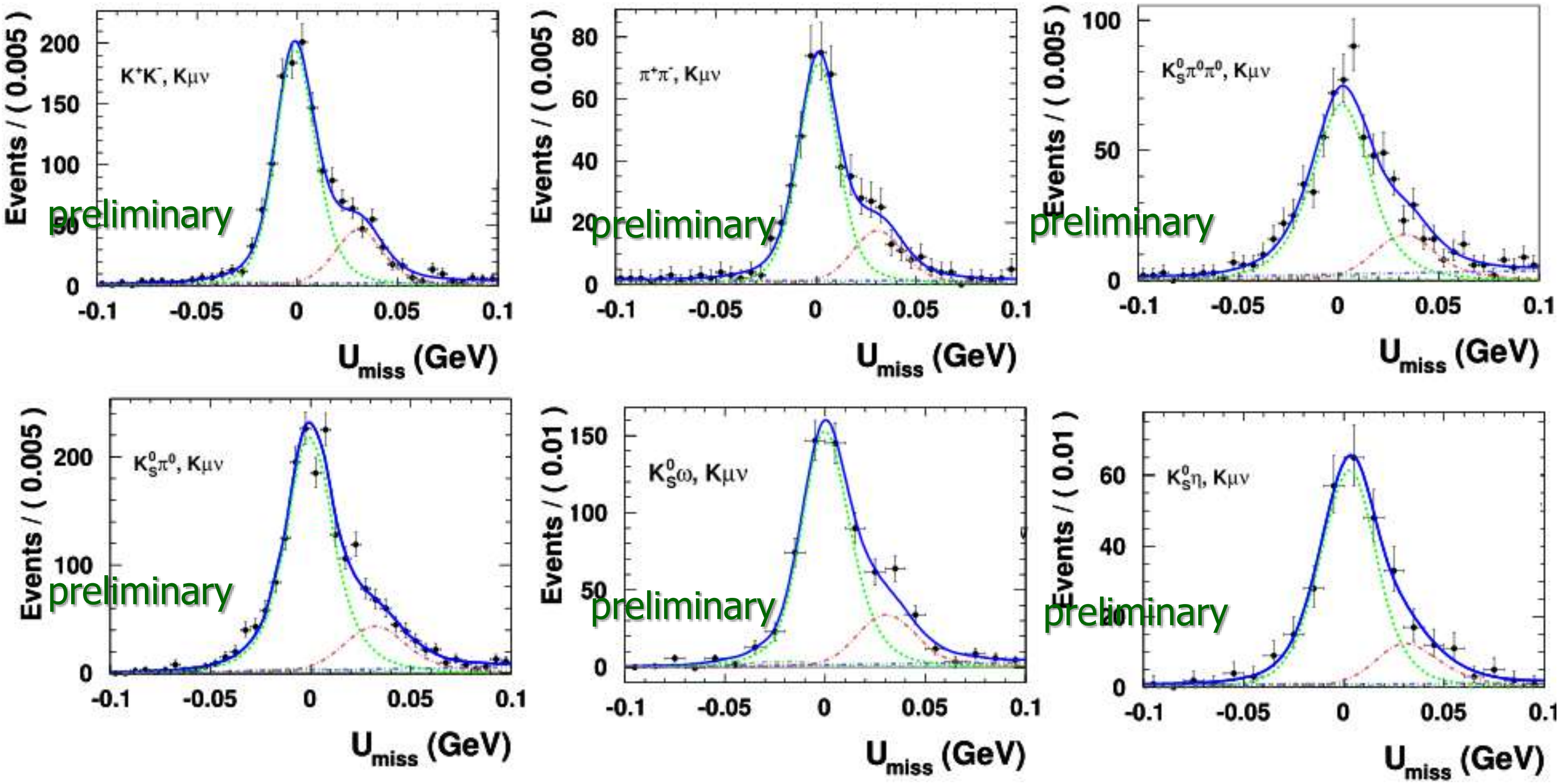


Double tags of *Kev* modes



- signal: MC shape convoluted with an asymmetric Gaussian
- background: a 1st-order polynomial function

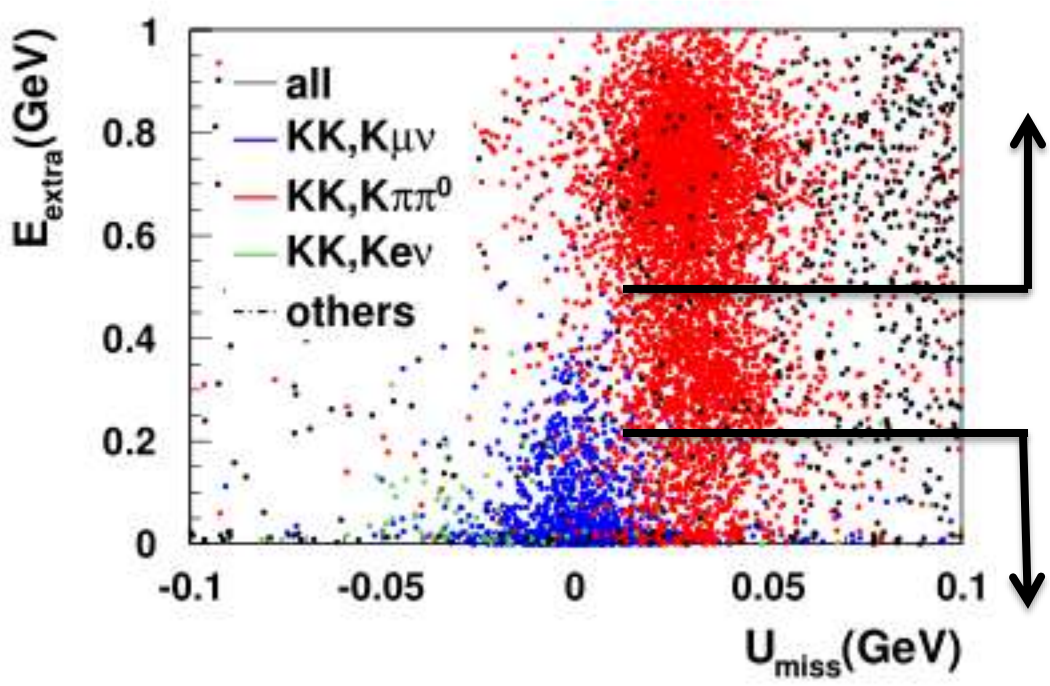
Double tags of *Kμν* modes

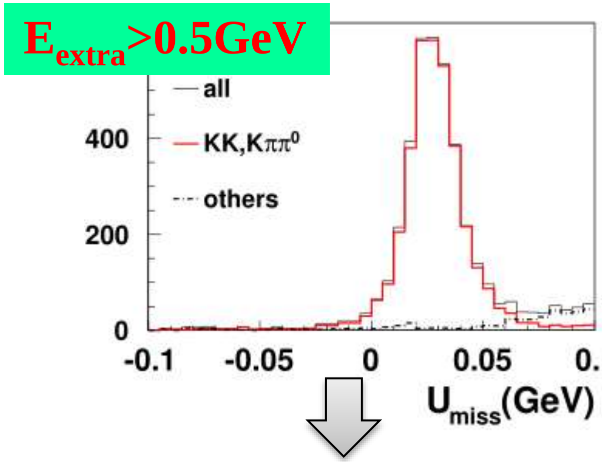


- signal: MC shape convoluted with an asymmetric Gaussian
- backgrounds:
  - ✓ *Kππ⁰*: use control sample of *D→Kππ⁰* in data
  - ✓ *Kev*: fixed to MC shape and size
  - ✓ others: a 1st-order polynomial function

To evaluate $K\pi\pi^0$ backgrounds in $K\mu\nu$ modes

take E_{extra}>0.5GeV as control sample to estimate the shape and size of $K\pi\pi^0$ backgrounds





shape : the smearing Gaussian is fixed to the parameters obtained from fit in the control sample

size: scale the MC size in the signal region with the ratio of the number of $K\pi\pi^0$ events in data to that in MC in the control sample

Preliminary numerical results

Signal yields of the full data set

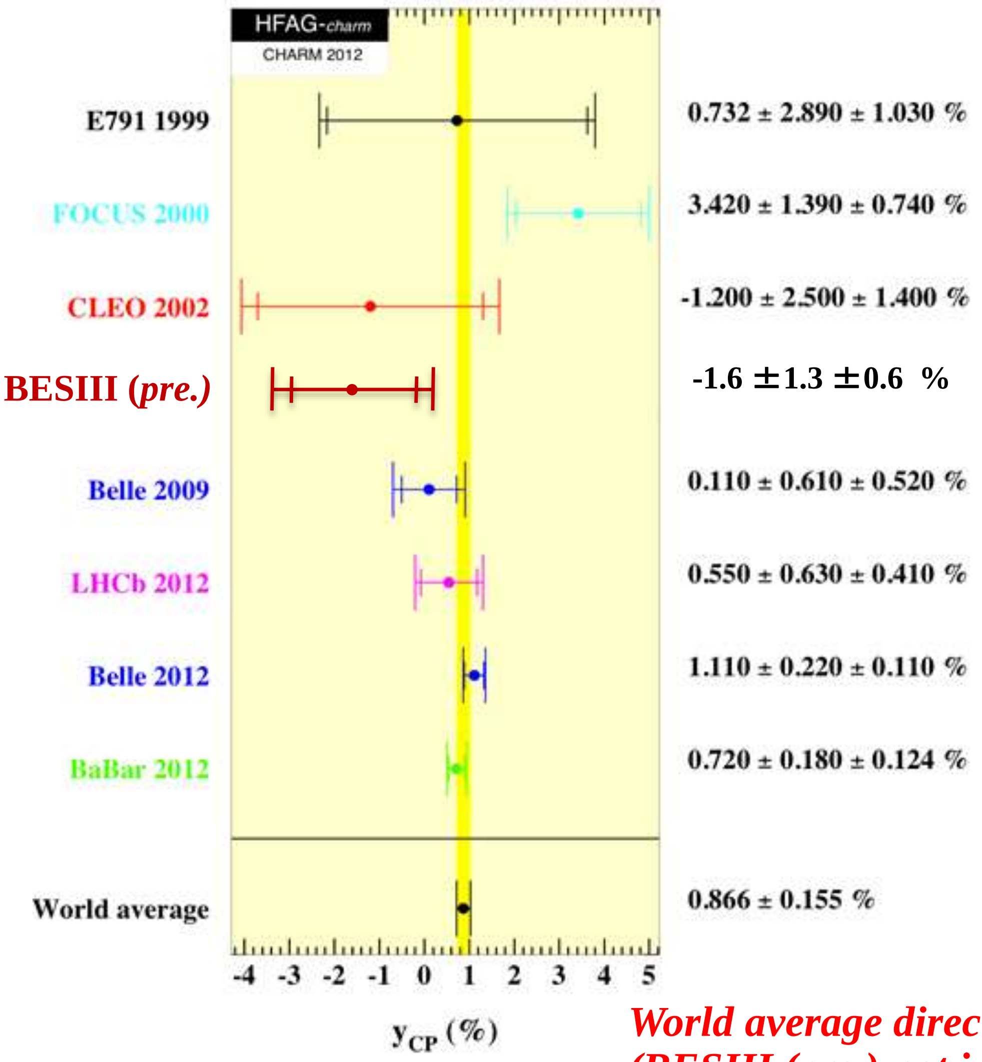
Modes	N_{tag}	$N_{tag,Ke\nu}$	$N_{tag,K\mu\nu}$
K^+K^-	54307 ± 252	1216 ± 40	1093 ± 37
$\pi^+\pi^-$	19996 ± 177	427 ± 23	400 ± 23
$K_S^0\pi^0\pi^0$	24369 ± 231	560 ± 28	558 ± 28
$K_S^0\pi^0$	71419 ± 286	1699 ± 47	1475 ± 43
$K_S^0\omega$	21249 ± 157	473 ± 25	501 ± 26
$K_S^0\eta$	9843 ± 117	242 ± 17	237 ± 18

preliminary result:

$$y_{CP} = -1.6\% \pm 1.3\%(\text{stat.}) \pm 0.6\%(\text{syst.})$$

- result is statistically limited
- systematic uncertainty is relatively small

Comparison with world measurement



compatible with
world average results

CLEOc 2012:
[PRD 86 (2012) 112001]
y_{CP}=(4.2±2.0 ±1.0)%

best precision in Charm factory

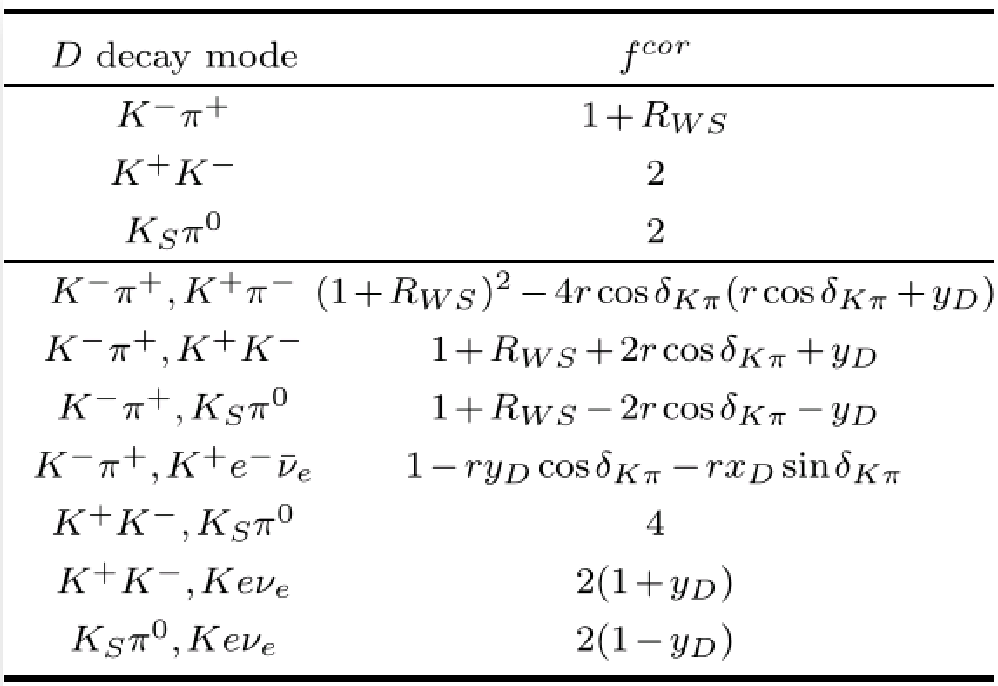
World average directly from HFAG2013
(BESIII (pre.) not included)

arXiv:1304.6170

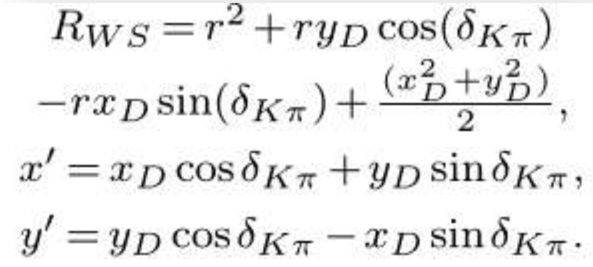
Toward global fit at BESIII

- **least squares fitter: used for extracting expected physics parameters from the correlated experimental data**
- **Monte Carlo validation of the fitter**

- **seven external inputs in the test: R_{WS}, r^2, $\delta_{K\pi}$, x_D, y_D, x'^2 and y'**
- **their uncertainties are assumed to be uncorrelated**



D decay mode	f^{cor}
$K^-\pi^+$	$1+R_{WS}$
K^+K^-	2
$K_S\pi^0$	2
$K^-\pi^+, K^+\pi^-$	$(1+R_{WS})^2-4r\cos\delta_{K\pi}(r\cos\delta_{K\pi}+y_D)$
$K^-\pi^+, K^+K^-$	$1+R_{WS}+2r\cos\delta_{K\pi}+y_D$
$K^-\pi^+, K_S\pi^0$	$1+R_{WS}-2r\cos\delta_{K\pi}-y_D$
$K^-\pi^+, K^+e^-\bar{\nu}_e$	$1-ry_D\cos\delta_{K\pi}-rx_D\sin\delta_{K\pi}$
$K^+K^-, K_S\pi^0$	4
$K^+K^-, Ke\nu_e$	$2(1+y_D)$
$K_S\pi^0, Ke\nu_e$	$2(1-y_D)$



$$R_{WS}=r^2+ry_D\cos(\delta_{K\pi})$$
$$-rx_D\sin(\delta_{K\pi})+\frac{(x_D^2+y_D^2)}{2},$$
$$x'=x_D\cos\delta_{K\pi}+y_D\sin\delta_{K\pi},$$
$$y'=y_D\cos\delta_{K\pi}-x_D\sin\delta_{K\pi}.$$

arXiv:1304.6170

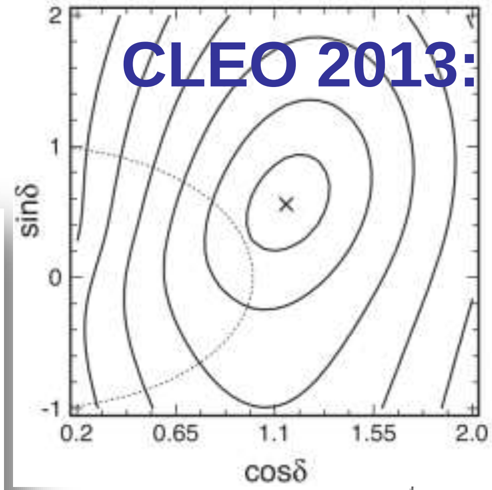
Sensitivity of the global fit at BESIII

- MC study corresponds to 3.0 / fb data
- input of the central values of the world average in 2012:
- with the external constrains of :

$$\delta_{K\pi} = 22.1^{+9.7}_{-11.1}(^{o}),\ y_D = 0.75 \pm 0.12(\%)$$

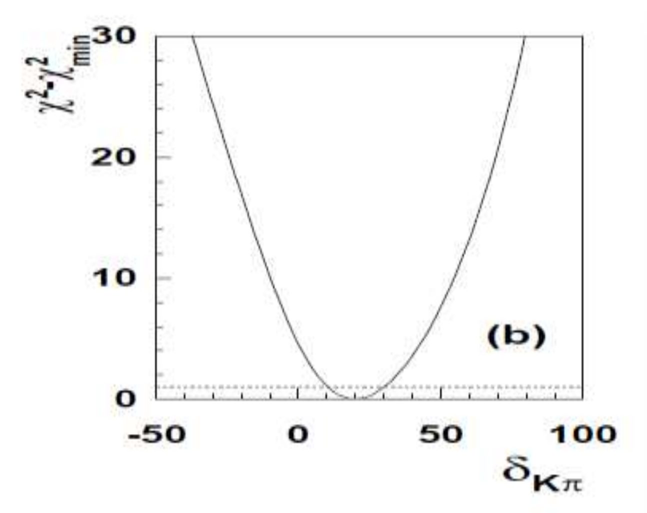
- output:

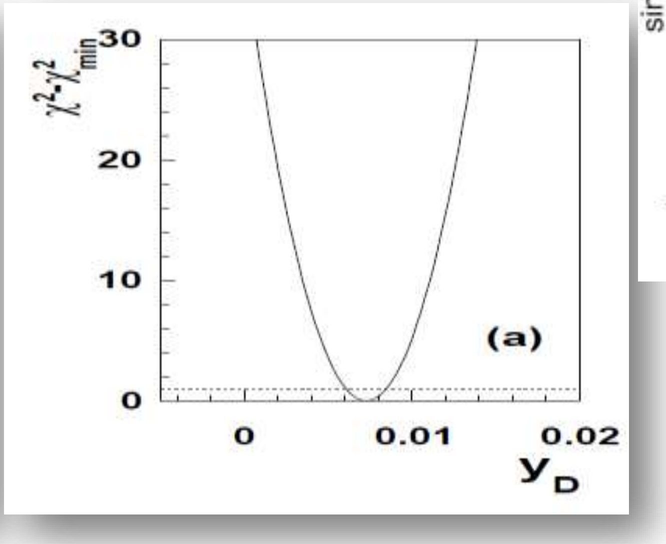
$$\delta_{K\pi}:\ \pm 8.3(^{o}),\ y_D:\ \pm 0.10(\%)$$



CLEO 2013:

$$\delta = (18^{+11}_{-17})^{\circ}$$





Summary

- Quantum-correlated D^0-$\underline{D}^0$ production on threshold provide an unique way to measure the charm mixing parameters
- BESIII collected 2.9 /fb e^+e^- collision data at 3.773 GeV
  the world-largest on-threshold data in charm factory
- Strong phase difference in $D^0 \rightarrow K\pi$ decays is measured with the best accuracy
  help to improve the world measurement of the mixing parameters x and y
- The mixing parameter y_{CP} is determined, which is compatible with the world average
  still statistically limited
- More charm data will be collected at BESIII; work on global fit is ongoing

Thank you!

谢谢大家！