Measurements of strong phase in $D^0 \rightarrow K\pi$ decay and y_{CP} via quantum-correlations at BESIII

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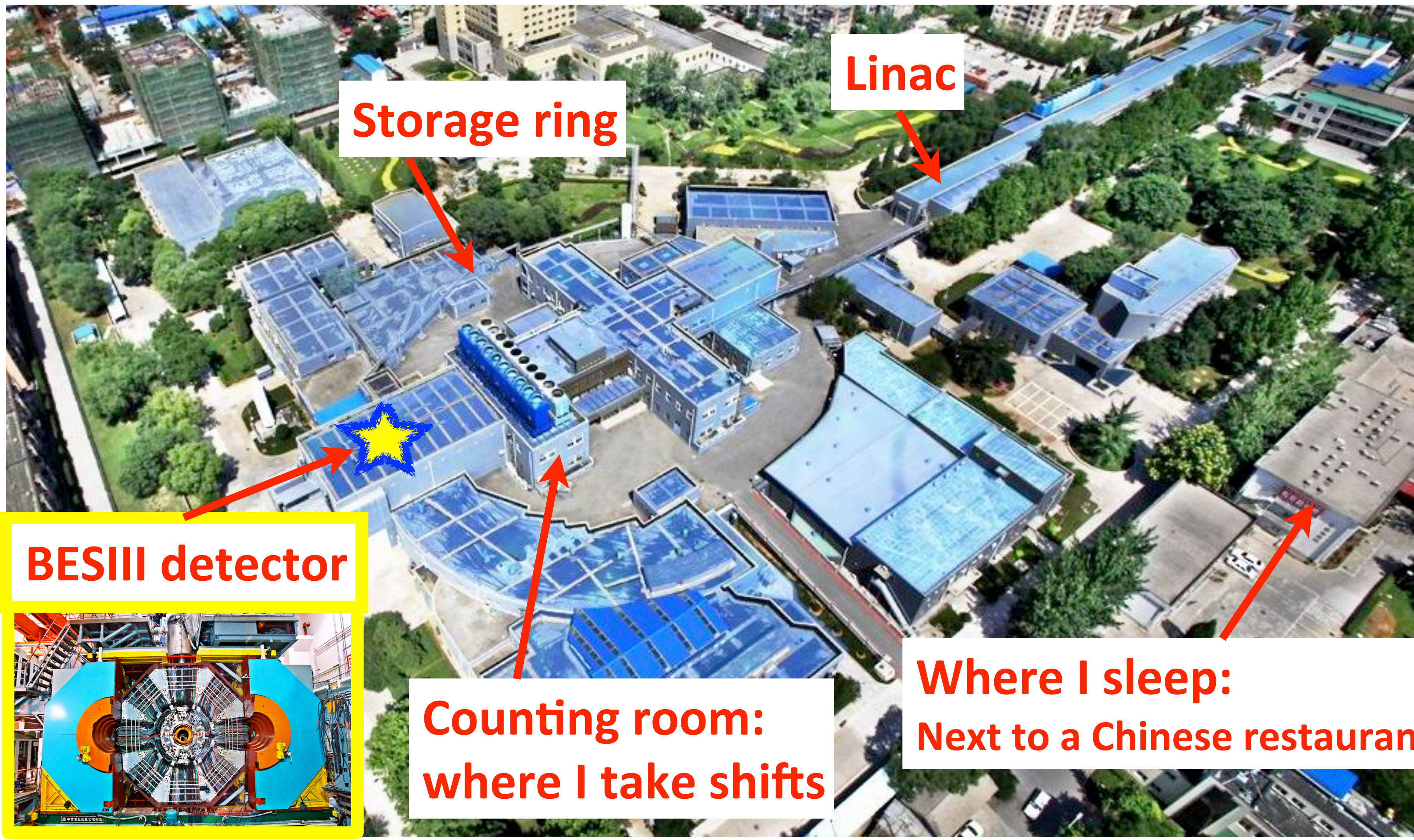
(for the BESIII collaboration)

- Strong phase in $D^0 \rightarrow K\pi$ decay
- y_{CP} measurement

Beijing Electron Positron Collider (BEPC-II)

- A symmetric e^+e^- collider, operating at Ecm ~ 2.0 ~4.6 GeV (Charm factory!).
- It's in Beijing: Easy access to the downtown area of Beijing with a nearby subway station!

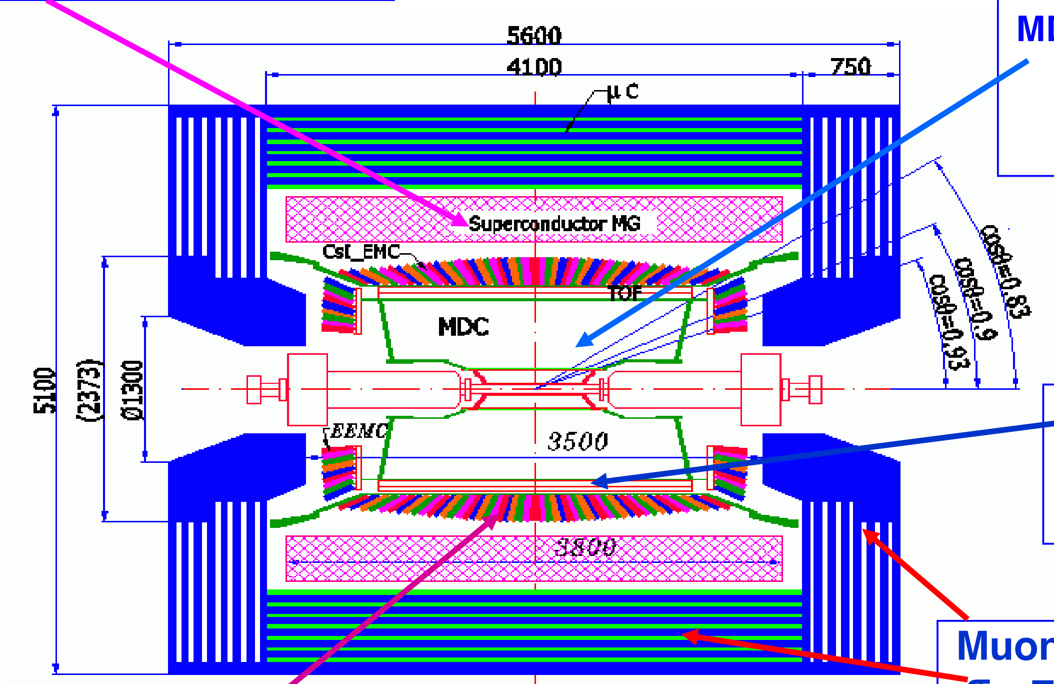


BESIII detector

- A powerful general purpose detector.
- Excellent neutral and charged particle detection and identification with a large coverage.

Magnet: 1 T Super conducting

MDC: small cell & He gas
σ_{xy}=130 μm
σ_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

Data samples we have

- @ J/ψ peak : 1.2 B J/ψ decays
  and some scan in the vicinity of the peak.
- @ $\psi(3686)$ peak : 0.5 B $\psi(3686)$ decays
  and some scan in the vicinity of the peak.
- Above $D\bar{D}$ threshold: 0.5/fb @ Ecm = 4.009 GeV,
  1.9/fb @ Ecm = 4.26 GeV,
  0.5/fb @ Ecm = 4.36 GeV,
  plus some scan samples as well.

  The above samples have been producing very rich Physics results such as hadron spectroscopy of Charmonia (e.g., h_c/η_c) and of Charmonium-like states (X/Y/Z).
- Today, I report recent results from BESIII based on a sample that was taken near $D\bar{D}$ threshold:

  2.92/fb @Ecm = 3.773 GeV

Sample at E_{cm} = 3.773 GeV

- The total integrated luminosity of 2.92 fb^{-1} at this energy point is the largest in the world to date.

- In the selected hadronic events (multiple reconstructed charged/ neutral hadrons or tracks), they are dominated by;

  $e^+e^- \to \gamma^* \to \psi(3770)$ and $e^+e^- \to \gamma^* \to (q\bar{q})$ light hadrons

  in which

  $\sigma(e^+e^- \to \psi(3770) \to \text{hadrons})/\sigma(e^+e^- \to \text{NR} \to \text{hadrons}) \sim 1/2$.

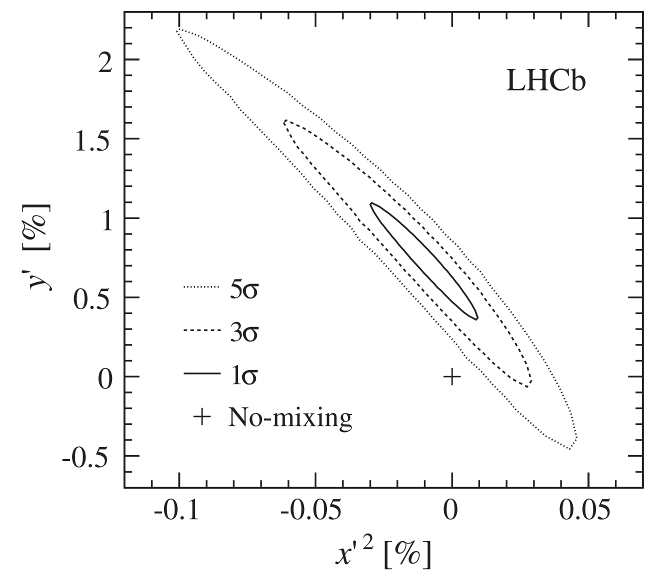
- Once $\psi(3770)$ is produced, it predominantly decays into a $D\bar{D}$ pair. For instance, we have ~21 M D^0 (or $\bar{D}^0$) decays in this sample.
  - Relatively clean event environment.
  - When the two D mesons are reconstructed, the sample becomes almost background free.

Things can be done with the sample taken at or around E_{cm} = 3.773 GeV

- There are many interesting possible topics to study in D (weak) decays based on our sample, such as;
  - pure leptonic decays
    (e.g., extraction of $|V_{cd}|$ and/or its decay constant, f_D).
  - Semi-leptonic decays
    (e.g., extraction of their form factors, and then compare them vs B meson case).
  - With the largest sample of D mesons taken at the near threshold, one should look for rare/forbidden decays (e.g., FCNC, LNV, LFV).
  - or even ψ(3770) itself such as $\psi(3770) \rightarrow$ non-$D\bar{D}$ final states.
- But today, I report our attempt to measure some of the parameters of $D\bar{D}$ mixing using the unique characteristics of our ψ(3770) data set taken at E_{cm} = 3.773 GeV.

Introduction

- $D\bar{D}$ mixing is highly suppressed by the GIM mechanism and by the CKM matrix elements within the Standard Model.
- Observation of $D\bar{D}$ mixing, first seen by the B factories (HFAG: arXiv 1207.1158) and now observed by LHCb: PRL110, 101802 (2013).



- Improving the constraints on the charm mixing parameter is important for testing the SM, such as long distance effects.
- $D\bar{D}$ mixing is conventionally described by two parameters:

$$x = 2(M_1-M_2)/(\Gamma_1+\Gamma_2),\ y = (\Gamma_1-\Gamma_2)/(\Gamma_1+\Gamma_2),$$

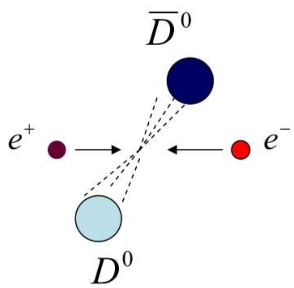
where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the neutral D meson mass eigenstates. (Flavor eigenstates, $D^0/\bar{D}^0$, are not the same as mass eigenstates, D_1/D_2)

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

- $\delta_{K\pi}$ is the strong phase difference between the doubly Cabibbo suppressed (DCS) decay, $\bar{D}^0 \to K^-\pi^+$ and the Cabibbo favored (CF) decay, $D^0 \to K^-\pi^+$ or $\langle K^-\pi^+|\bar{D}^0\rangle/\langle K^-\pi^+|D^0\rangle = -r\cdot e^{-i\delta}$. So one can connect (x,y) with (x',y') via $\delta_{K\pi}$.
- In this talk, I present preliminary results on $\delta_{K\pi}$ and y using the quantum correlation between the produced D^0 and $\bar{D}^0$ pair in data taken at BESIII.

The decay rate of a correlated state

- For physical process producing $D^0\bar{D}^0$ such as



$e^+e^- \to \gamma^* \to \psi(3770) \to D^0\bar{D}^0$,
the $D^0\bar{D}^0$ pair are in a quantum-correlated state.
The quantum number of $\psi(3770)$ is $J^{PC} = 1^{--}$.
Thus, the $D^0\bar{D}^0$ pair in this process has C = -.
For a correlated state with C = -, the two D mesons are anti-symmetric in the limit of CP invariance:

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

- The two produced neutral mesons must have opposite CP (i.e., see Goldhaber and Rosner, PRD15, 1254 (1977). That is;
  - Final states of (CP+, CP+) or (CP-, CP-) are forbidden.
  - Final states of (CP+, CP-) are maximally enhanced (doubled).
  - Final states of CP± against inclusive states (Single tag or ST) are not affected.
  - Final states of ($K^-\pi^+$, CP±) are affected due to the interference between CF and DCS ($\delta_{K\pi}$).

Extracting $\delta_{K\pi}$

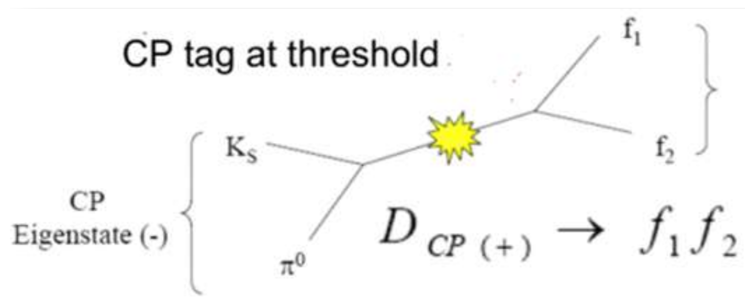
- Neglecting higher orders in the mixing parameters (e.g., y^2), one can arrive at the following relation:

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

where $R_{WS} \equiv \Gamma(\bar{D}^0\to K^-\pi^+)/\Gamma(D^0\to K^-\pi^+)$ and

$$A_{CP\to K\pi} \equiv [B(D_2\to K^-\pi^+) - B(D_1\to K^-\pi^+)]/B(D_2\to K^-\pi^+) + B(D_1\to K^-\pi^+)].$$

- We can extract $A_{CP\to K\pi}$ by tagging one D (tag side) with exclusive CP-eigenstates which then defines the eigenvalue of the other D ($A_{CP\pm} \equiv \langle K^-\pi^+|D^{1,2}\rangle$).



- Then, with the knowledge of r, y, and R_{WS} from the 3rd parties (HFAG2013 and PDG), we could derive $\cos\delta_{K\pi}$ in the end.
- The rest of the analysis becomes measurements of $B(D_{CP\pm}\to K^-\pi^+)$ while simultaneously reconstructing the $D_{CP\mp}$ on the tag side.

Measuring $B(D_{CP\pm} \to K^-\pi^+)$

- Double-Tag technique:
  $B(D_{CP\pm} \to K\pi) = [B(D_{CP\mp} \to CP^\mp \text{ states}) \times B(D_{CP\pm} \to K\pi)] / B(D_{CP\mp} \to CP^\mp \text{ states})$
  $= (n_{K\pi,CP\mp}/n_{CP\mp}) \cdot (\varepsilon_{CP\mp}/\varepsilon_{K\pi,CP\mp})$,
  where $n_{K\pi,CP\mp}$ are yields of "Kπ" when CP states are simultaneously reconstructed on the tag side
  $n_{CP\mp}$ are yields of CP states (independent of how the other D decays)
  $\varepsilon_{CP\mp}$ and $\varepsilon_{K\pi,CP\mp}$ are the corresponding reconstruction efficiencies.
- "Yields" are extracted from M_{bc} distributions : $M_{BC} = \sqrt{E^2_{beam} - \vec{p}^{\,2}_D}$
- CP states on Tag side (8 modes):

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

  where we reconstruct $K_S \to \pi^+\pi^-$, $\pi^0/\eta \to \gamma\gamma$, $\omega \to \pi^+\pi^-\pi^0$, $\rho \to \pi^+\pi^-$.
- Notice that most of systematics on the tag side get canceled in $B(D_{CP\pm} \to K\pi)$. The remaining systematics (reconstruction/simulation) of Kπ are also canceled in the determination of $A_{CP\to K\pi}$.

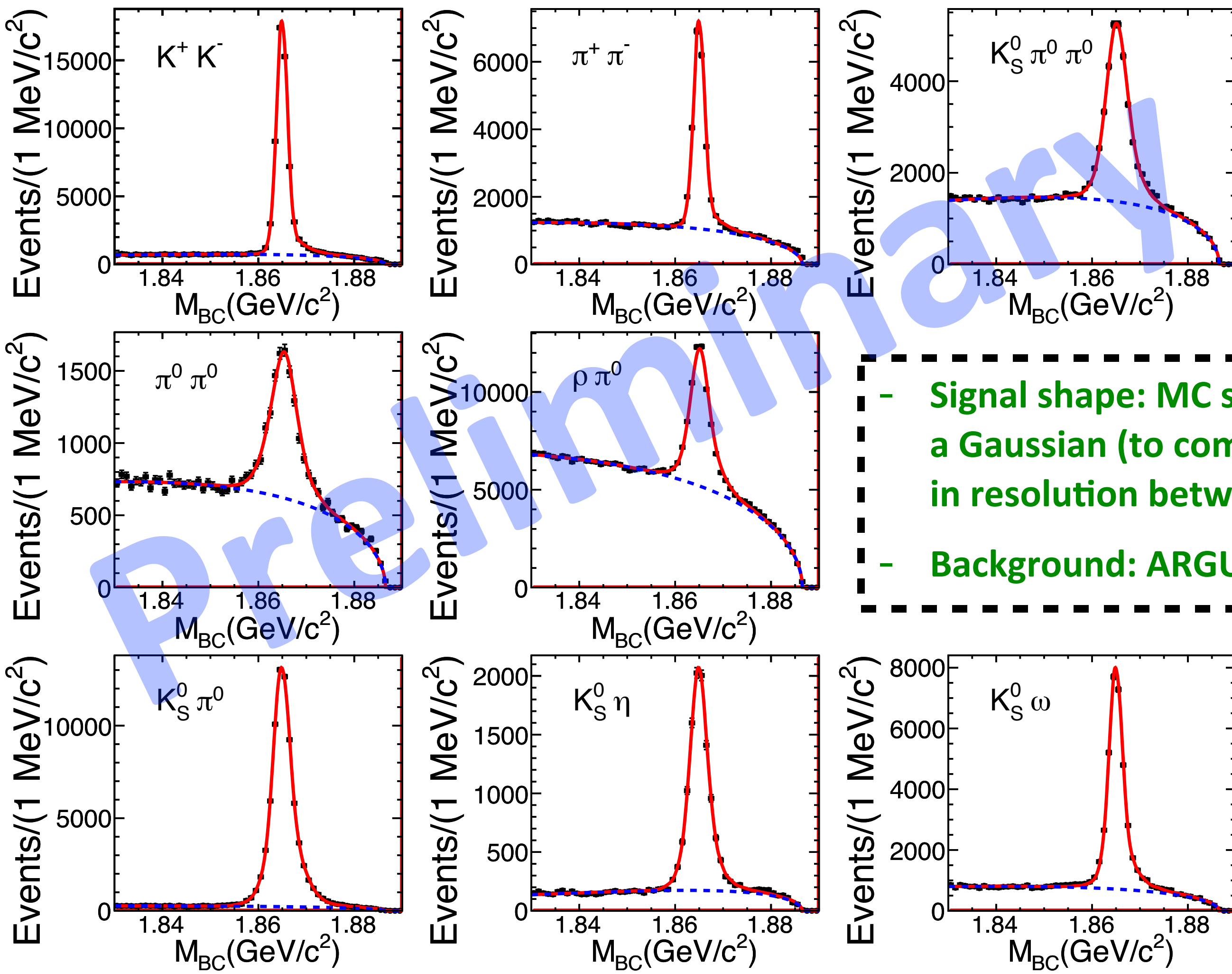
Yields of CP states ($n_{CP\mp}$)

(reconstruct only one of the two neutral D)

CP+

CP+

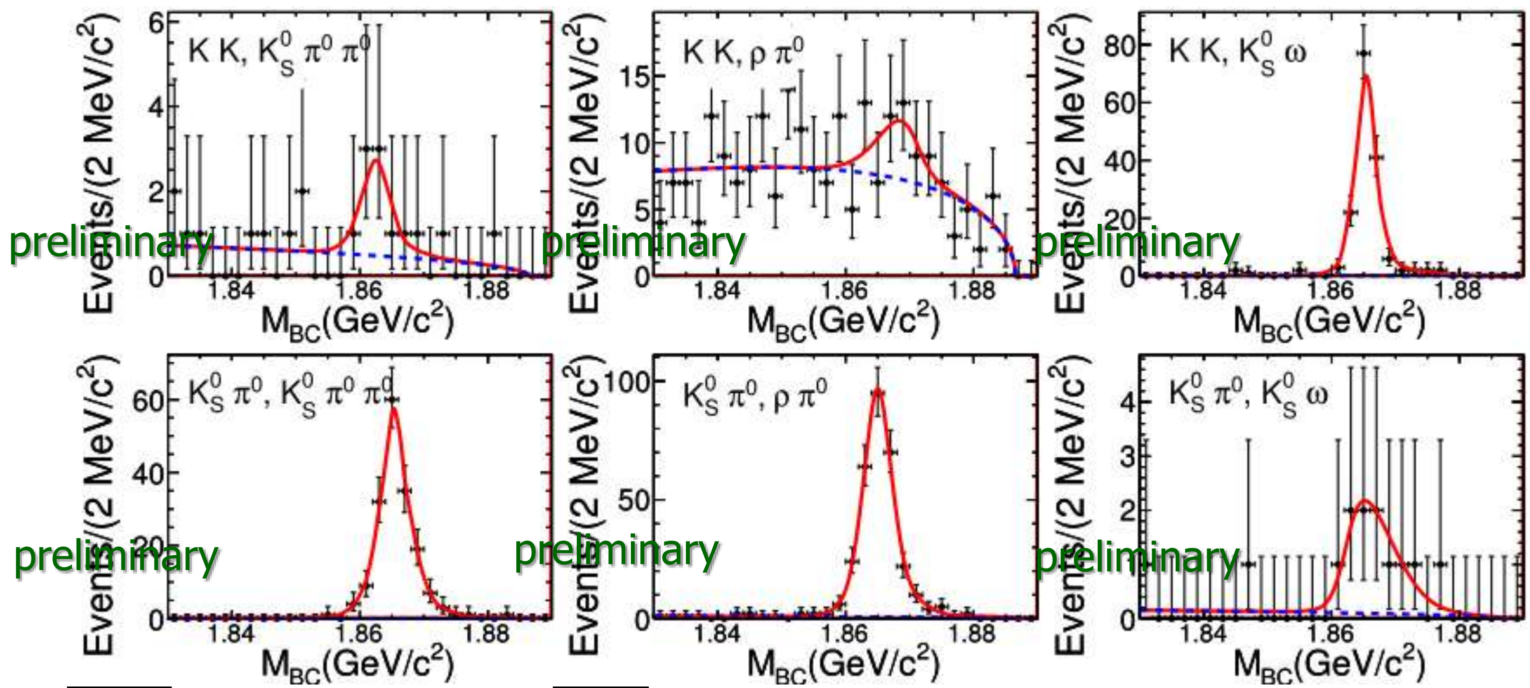
CP-



- Signal shape: MC shape, convoluted with a Gaussian (to compensate the difference in resolution between data and MC).
- Background: ARGUS background function.

Can also check “CP purity”

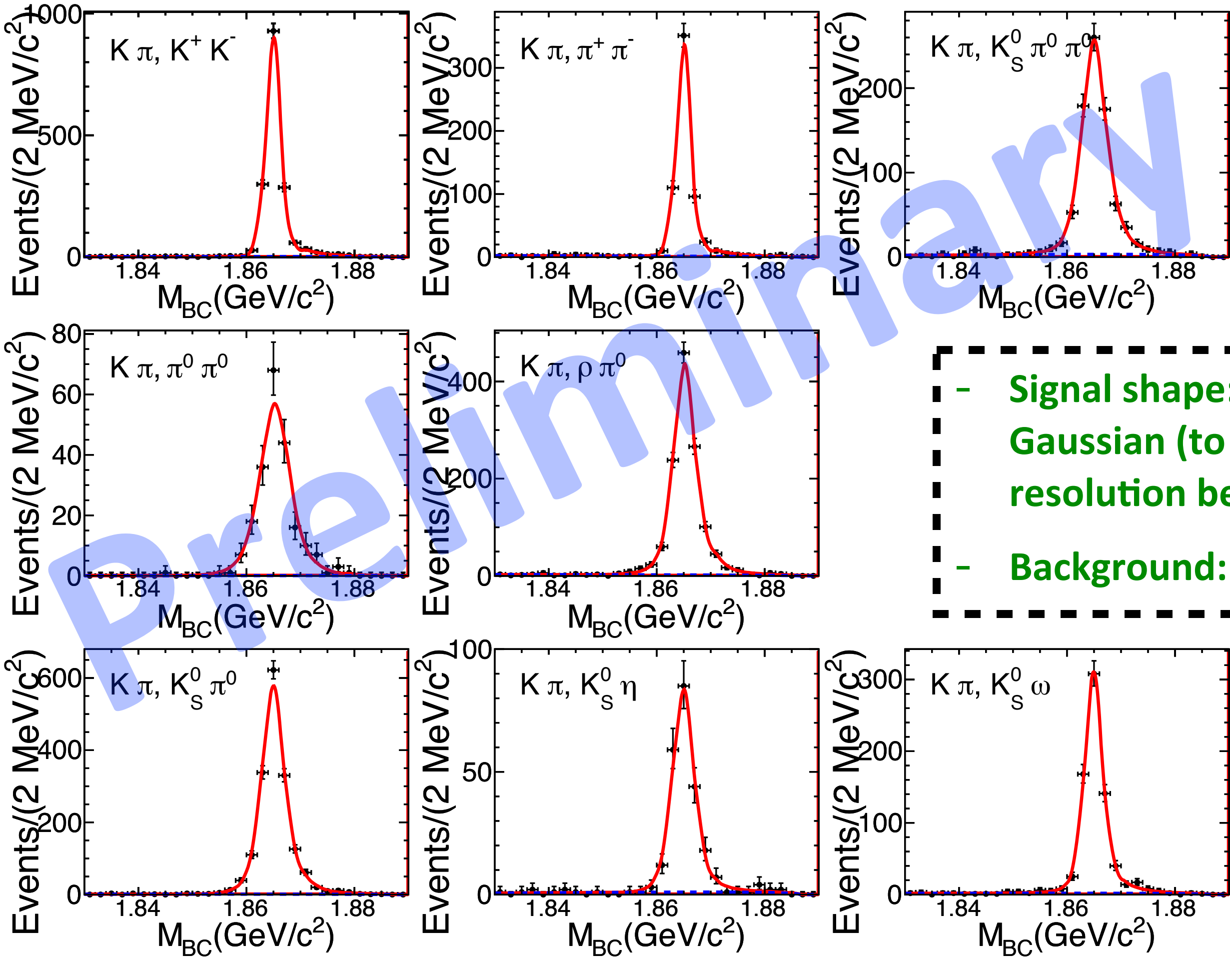
- When D^0 and $\bar{D}^0$ are reconstructed, final states with the same CP should yield zero events.



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

- ✳ Consistent with zero.
- ✳ Consider as one of the systematics.

Yields of Kπ in double tags ($n_{K\pi,CP\mp}$)
(reconstruct CP-final state from one D decay, with "Kπ" from the other D)



- Signal shape: MC shape, convoluted with a Gaussian (to compensate for the difference in resolution between data and MC).
- Background: ARGUS background function.

Preliminary fit 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
$K_S^0\pi^0\pi^0$	$25156 \pm 235 \pm 81$	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
$K_S^0\pi^0$	$72710 \pm 291 \pm 34$	41.95 ± 0.21
$K_S^0\eta$	$10046 \pm 118 \pm 27$	35.46 ± 0.20
$K_S^0\omega$	$31422 \pm 215 \pm 49$	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
$K^\pm\pi^\mp, K_S^0\pi^0\pi^0$	$800 \pm 30 \pm 4$	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
$K^\pm\pi^\mp, K_S^0\pi^0$	$1688 \pm 42 \pm 4$	29.06 ± 0.17
$K^\pm\pi^\mp, K_S^0\eta$	$231 \pm 16 \pm 1$	24.76 ± 0.16
$K^\pm\pi^\mp, K_S^0\omega$	$725 \pm 28 \pm 1$	12.47 ± 0.06

Preliminary

- These yields allow us to obtain $B(D_{CP\pm}\to K^-\pi^+)$ which then provides $A_{CP\to K\pi}$.
- $A_{CP\to K\pi} = (12.77 \pm 1.31(\text{stat.})^{+0.33}_{-0.31}(\text{syst.}))\%$.

Preliminary result on $\delta_{K\pi}$

- We have measured $A_{CP\to K\pi}$ = $(12.77\pm1.31(\mathrm{stat.})^{+0.33}_{-0.31}(\mathrm{syst.}))\%$.
- Using the relation, $2\cdot r\cdot\cos\delta_{K\pi}+y = (1+R_{WS})\cdot A_{CP\to K\pi}$, and with external inputs from HFAG2013 and PDG ($R_D = 3.47\pm0.06\%$, $y=6.6\pm0.9\%$, $R_{WS} = 3.80\pm0.05\%$), we obtain

$$\cos\delta_{K\pi} = 1.03\pm0.12(\mathrm{stat.})\pm0.04(\mathrm{syst.})\pm0.01(\mathrm{external}).$$

- Our result is consistent with and more precise than the recent CLEO result (PRD86, 112001 (2012)):

$$\cos\delta_{K\pi} = 1.15^{+0.19}_{-0.17}(\mathrm{stat.})^{+0.00}_{-0.08}(\mathrm{syst.}).$$

Determination of the mixing parameter, y_{CP}

- y_{CP} is defined as;

  $2 \cdot y_{CP} = (|q/p|+|p/q|) \cdot y \cdot \cos\phi - (|q/p|-|p/q|) \cdot x \cdot \sin\phi$,

  where p and q are mixing parameters,
  and $\phi = \arg(q/p)$ is the weak phase difference of the mixing amplitudes.
  Notice: for no CPV case, $p = q = 1/\sqrt{2}$ and $y_{CP} \equiv y$.

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

- For D decays into any CP-eigenstate, its decay rate can be described as;

  $R(D^0/\overline{D}^0 \to CP^{\pm}) \propto |A_{CP\pm}|^2 \cdot (1 \mp y_{CP})$.

- When one D decays into a CP-eigenstate, while the other D decays semi-leptonically, the decay rate can be given by;

  $R(D^0/\overline{D}^0 \to CP^{\pm}$, and $\overline{D}^0/D^0 \to$ semi-lep $) \propto |A_l|^2 \cdot |A_{CP\pm}|^2$.

  - Semileptonic decay width does not depend on the CP of its parent D.
  - Yet, the total width of its parent D depends on CP.
  - Result: semileptonic BF of $D_{1,2}$ gets modified by a factor of $1 \pm y_{CP}$.

- Combining the above two, and neglecting terms with y^2 (or higher), one can arrive at

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

Extracting y_{CP} in our experiment

- The expression for y_{CP} can be written as;

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

  where $\tilde{B}_\pm$ is the branching fraction, averaged over different CP tag modes, α, that is obtained by minimizing

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

- All branching fractions are obtained in a similar way, the double-tag method.
- When the semileptonic decays are reconstructed, however, we use U_{miss} distributions to obtain their yields, instead of M_{bc},

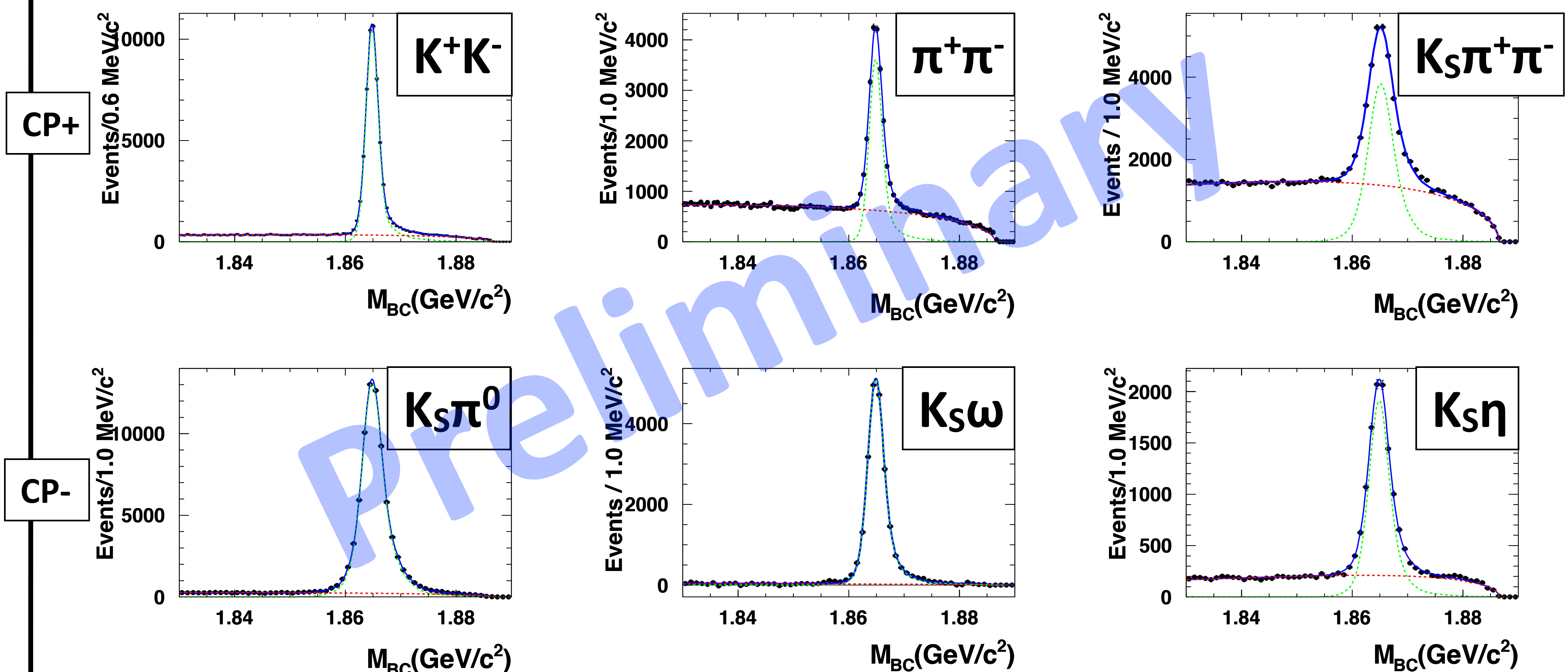
$$U_{\text{miss}} \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|,$$

  which peaks ~ 0 if only missing particle is neutrino.
- Tag modes:

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

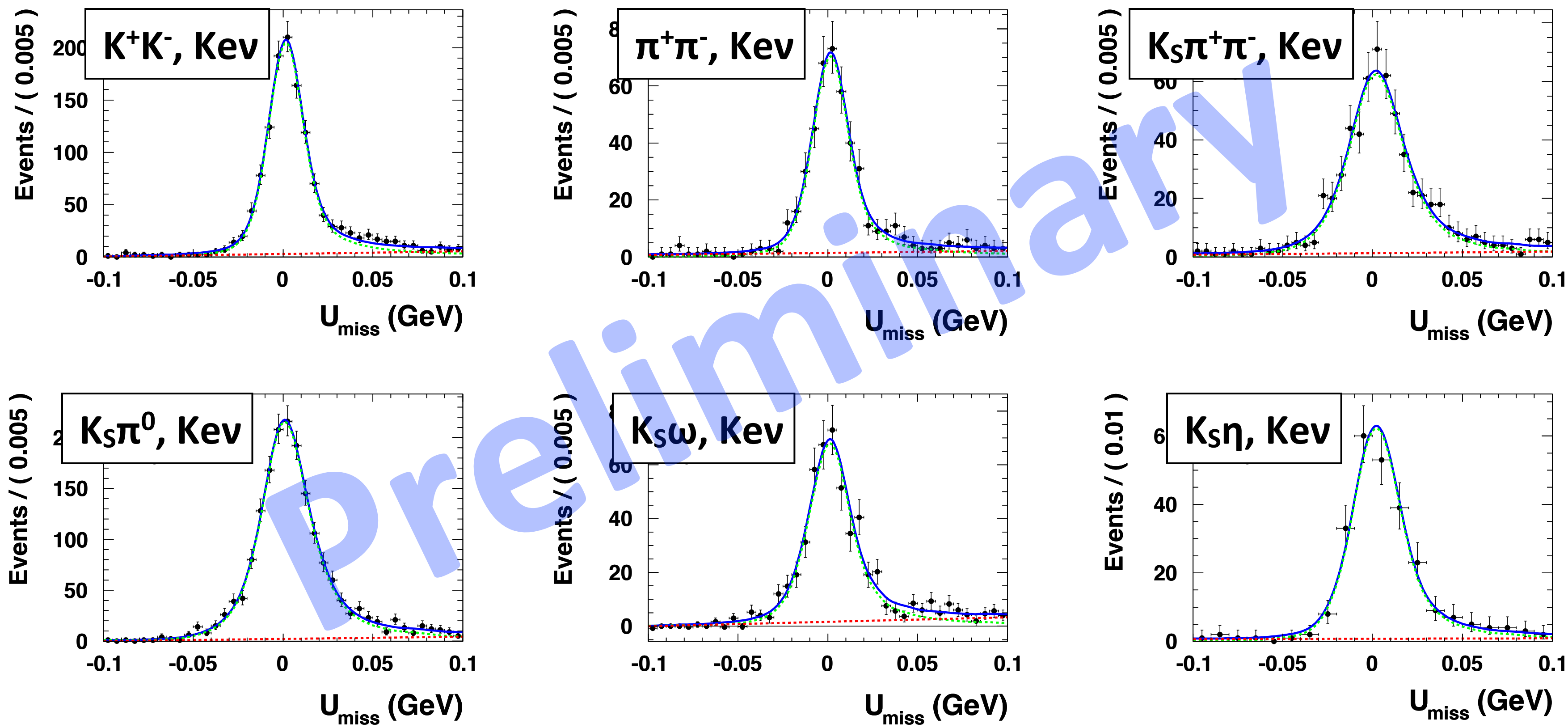
Yields of CP states ($n_{CP\mp}$)

(reconstruct only one of the two neutral D)



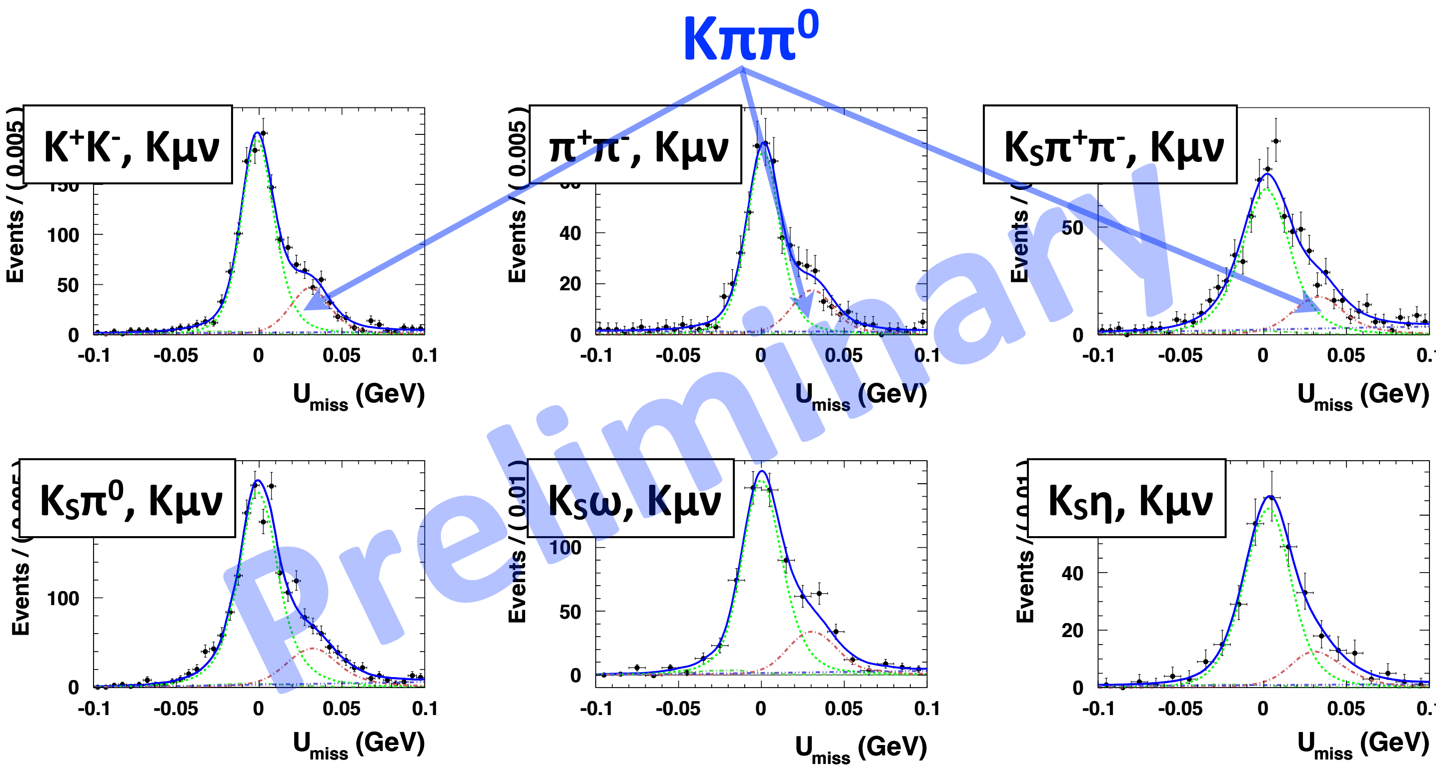
Yields of Kev in double tags ($n_{Kev,CP\mp}$)

(reconstruct CP-final states from one D decay, with "Kev" from the other D)



- Signal shape: MC shape, convoluted with an asymmetric Gaussian.
- Background: A 1st order polynomial.

Yields of Kμν in double tags ($n_{K\mu\nu,CP\mp}$)
(reconstruct CP-final states from one D decay, with "Kμν" from the other D)



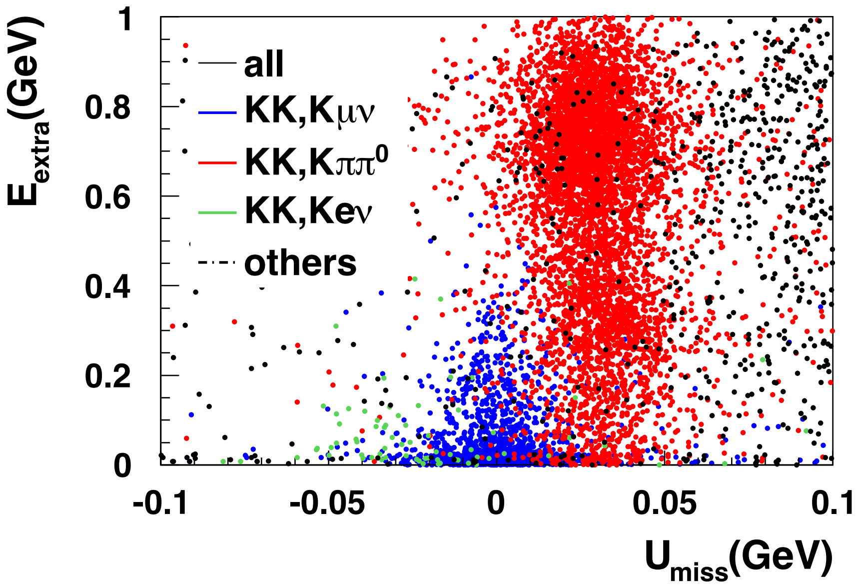
- $K\pi\pi^0$ shapes and sizes are fixed based on control samples of actual data.
- The control samples are obtained by the same CP states and $K\pi\pi^0$, while ignoring the two photons from π^0 decays to calculate U_{miss}.

See the next slide for detail.

- Signal shape: MC shape, convoluted with an asymmetric Gaussian.
- Background: A 1st order polynomial. $K\pi\pi^0$ (dominant).

Fixing the $K\pi\pi^0$ shape

- Obtain E_{extra} ≡ Sum of the all un-used energies deposited in EM calorimeter.
- E_{extra} tends to be larger if it is $K\pi\pi^0$ due to the ignored extra photons from π^0 decay and is small if it is $K\mu\nu$.
- We actually do require $E_{extra}<0.2$ GeV to select $K\mu\nu$ signal candidates.



Fix shape

- Fit to U_{miss} in $E_{extra}>0.5$ GeV where $K\mu\nu$ peak is suppressed.
- The fitted shape ≡ MC shape, convoluted with a Gaussian.

Fix size

($K\pi\pi^0$ yields in data in $E_{extra}<0.2$ GeV) = R×($K\pi\pi^0$ yields in data in $E_{extra}>0.5$ GeV), where R = ($K\pi\pi^0$ yields in MC in $E_{extra}<0.2$ GeV)/($K\pi\pi^0$ yields in MC in $E_{extra}>0.5$ GeV).

Preliminary results

- **Fitted yields for each mode:**

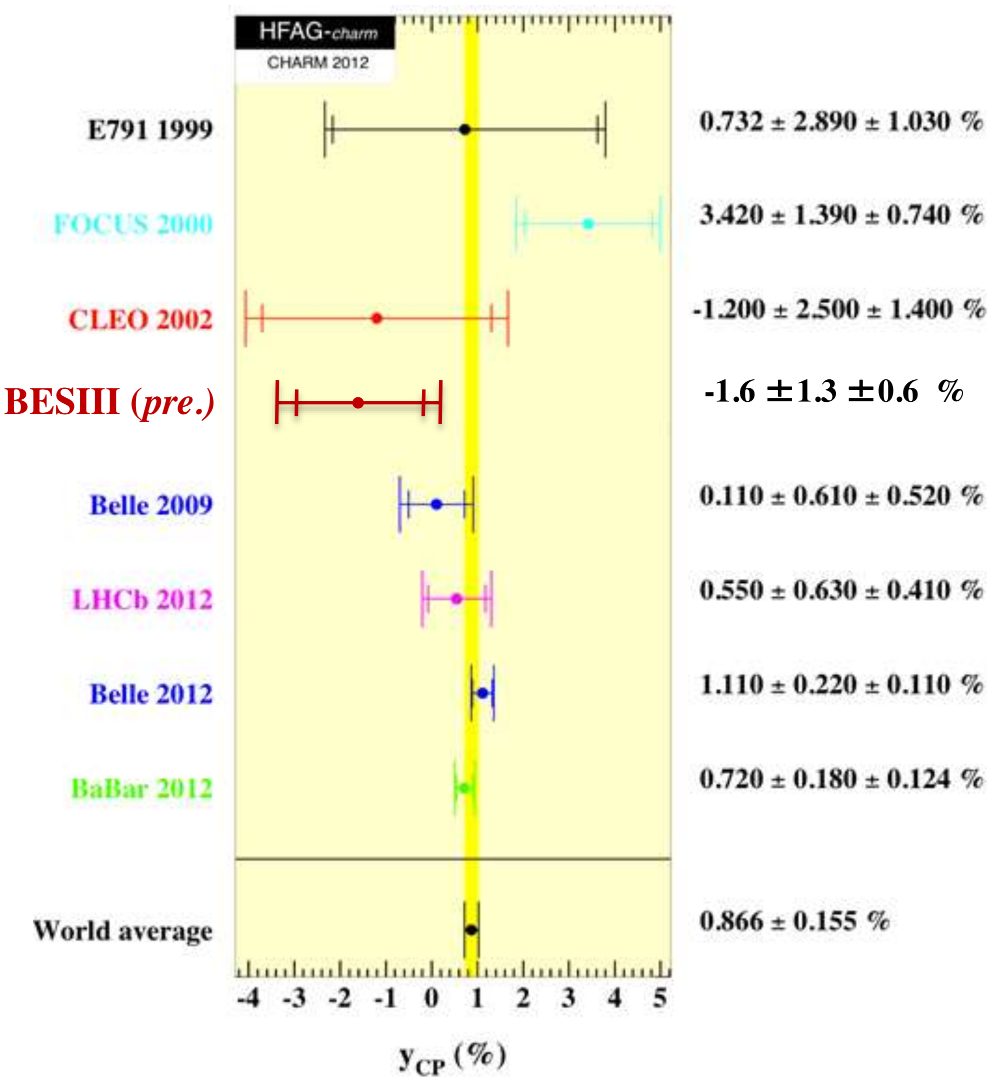
Modes	N_{tag}	$N_{tag,Ke\nu}$	$N_{tag,K\mu\nu}$
K^+K^-	54307 ± 252	1216 ± 40	1093 ± 37
$\pi^+\pi^-$	19996 ± 177	427 ± 23	400 ± 23
$K_S^0\pi^0\pi^0$	24369 ± 231	560 ± 28	558 ± 28
$K_S^0\pi^0$	71419 ± 286	1699 ± 47	1475 ± 43
$K_S^0\omega$	21249 ± 157	473 ± 25	501 ± 26
$K_S^0\eta$	9843 ± 117	242 ± 17	237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

- **After correcting for efficiencies (branching fractions), we arrive at**

$$y_{CP} = [-1.6\pm1.3(\text{stat.})\pm0.6(\text{syst.})]\%.$$

  - **The result is statistically limited.**
  - **The systematic uncertainty mainly comes from fitting procedures.**

Comparison with other measurements



- Our result is consistent with the world average (HFAG2013; this preliminary result is not included in the average).
- Also consistent with the latest result from CLEO-c (PRD86, 112001 (2012)); y_{CP} = (4.2±2.0±1.0)%. (not listed in the figure).

Summary

- Quantum-correlated $D^0\bar{D}^0$ in e^+e^- annihilations near threshold: Unique way to measure the Charm mixing parameters.

- Most precise measurement of strong phase difference in $D^0 \to K\pi$. Will improve the determination of mixing parameters, x and y.

- Measurement of y_{CP}: Statistically limited, consistent with the world average.

- Will collect larger "open-charm" data samples in years to come: Expect many interesting results.