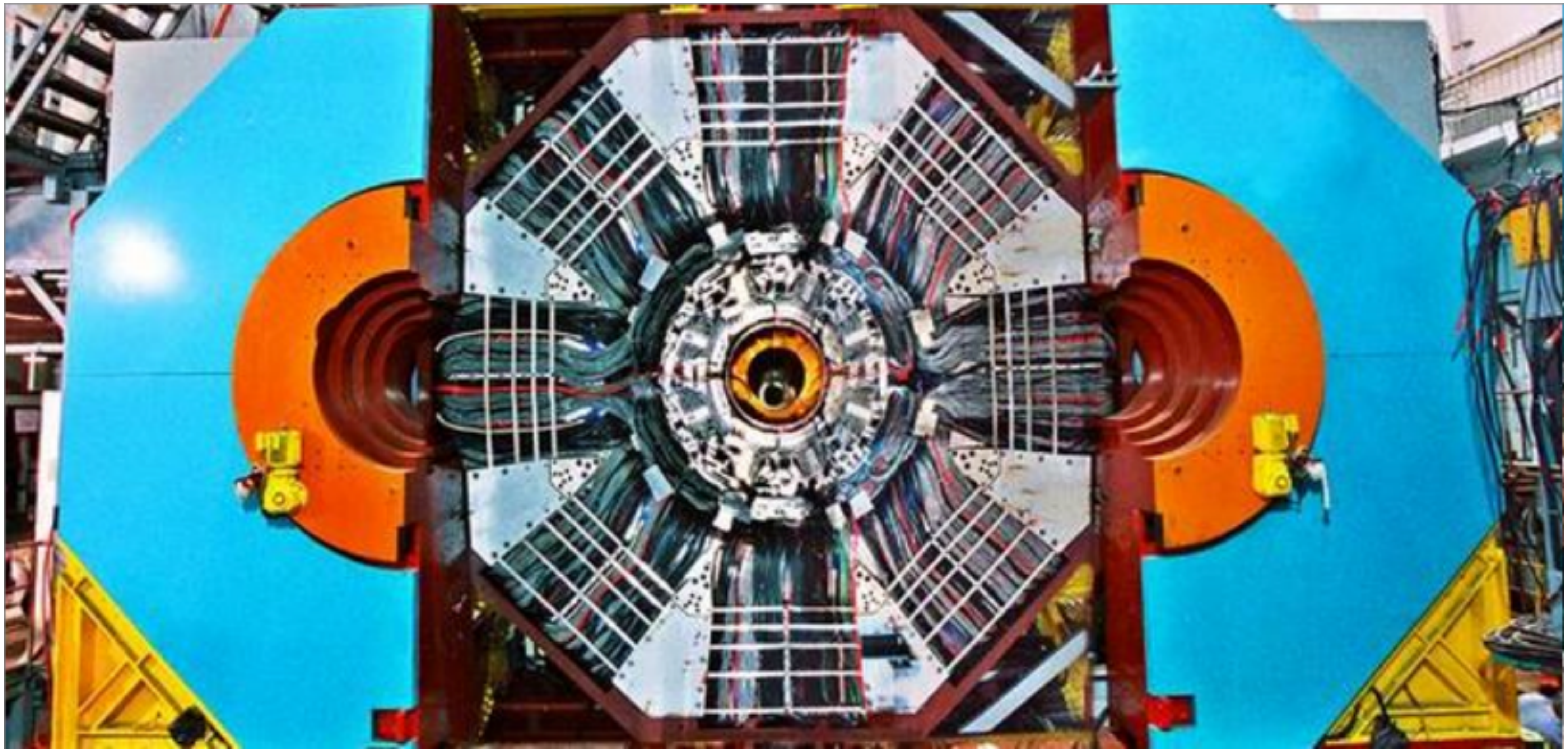

Recent results and prospects for charm mixing and CPV at Threshold

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The International Workshop on the CKM Unitarity Triangle (CKM2014)
8-12 September, 2014, Vienna University of Technology

Outline

- Introduction
- Recent results from charm threshold data
  - mixing parameter y_{CP}
  - strong phase $\delta_{K\pi}$
    (*see Roy Briere's talk for* $\delta_{Ks\pi+\pi-}$ *measurement at BESIII*)
  - CP asymmetries
- Prospects on future (dedicated) charm facility
- Summary

Neutral *D* meson oscillation

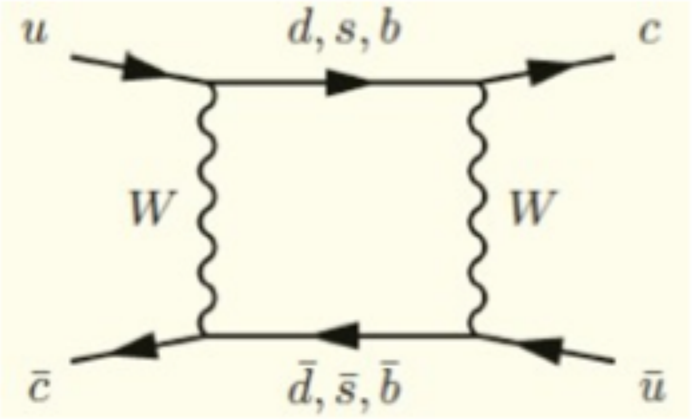
D^0 and $\overline{D}^0$ can transfer into each other, like K, B and Bs mesons

- The mass eigenstates are

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

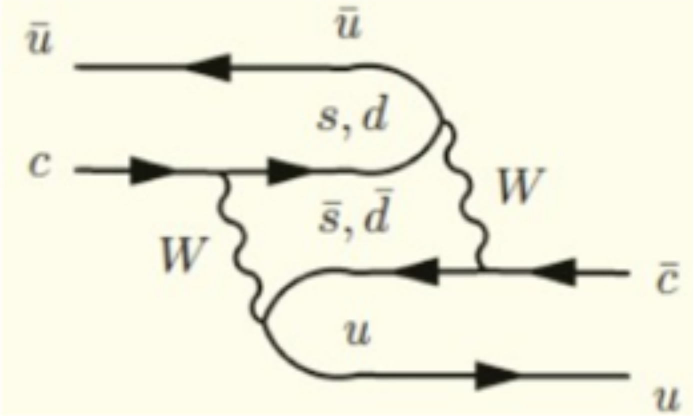
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

Short-distance:



CKM suppression: *b*
GIM suppression: *d, s*

Long-distance:



- With eigenvalues

$$\mu_1 = m_1 - \frac{i}{2}\Gamma_1$$

$$\mu_2 = m_2 - \frac{i}{2}\Gamma_2$$

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Delta m \equiv m_2 - m_1$$

$$\Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}, \qquad \Delta\Gamma \equiv \Gamma_2 - \Gamma_1$$

$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

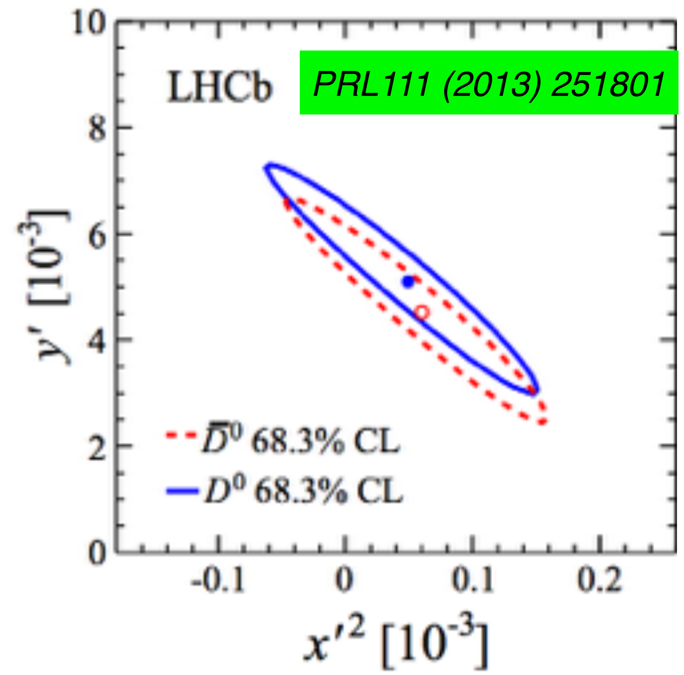
x mixing: Channel for New Physics.

y (long-distance) mixing: SM background.

D meson oscillation

- ✓ short distance is highly suppressed by the GIM mechanism and by the CKM matrix elements within the SM: x~O(10^{-5}); y~O(10^{-7})
  - new physics might manifest in the loop, such as FCNC processes with up-type quark, complementary to those with down quarks (K or B mesons, already studied with observed CPV)
- ✓ long distance is dominant: (x, y)~O(10^{-3})
  - but theoretical uncertainty is large
- ✓ Observation of $D\bar{D}$ oscillation by CDF and LHCb

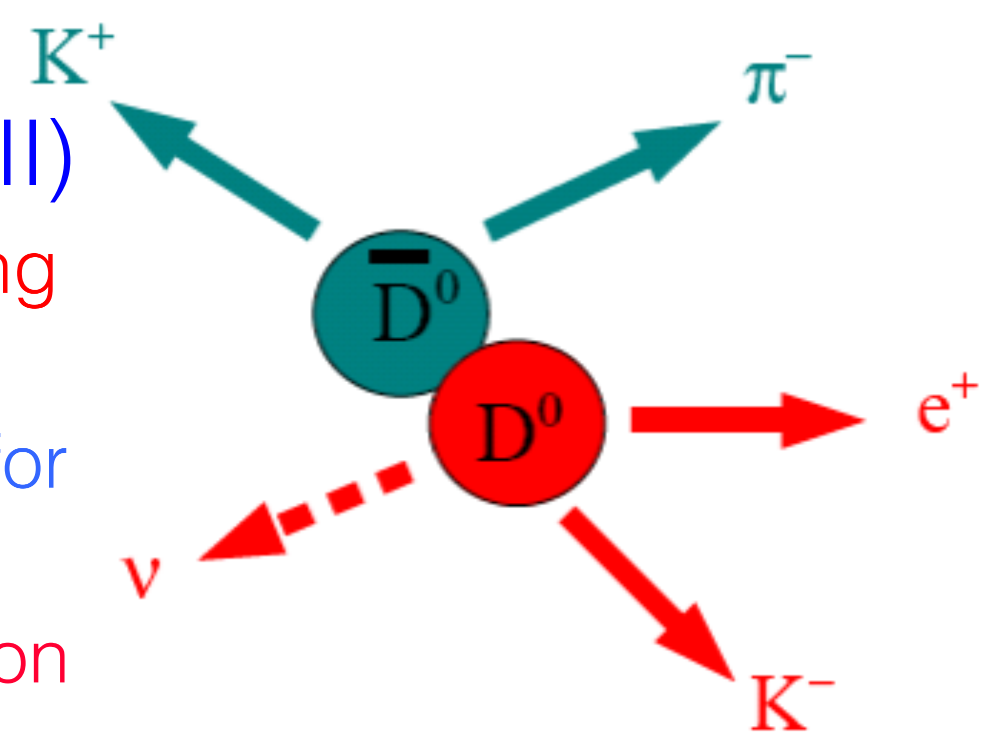
$$y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$
$$x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$



- ✓ Improving the constraints on the charm mixing parameters is important for testing the SM, such as long-distance effect
- ✓ At charm threshold, strong phase is a unique contribution:
  - to extract the mixing parameter (x,y) from (x′, y′)
  - to (over-)constrain the CKM unitarity triangle, which is crucial for searching for new physics

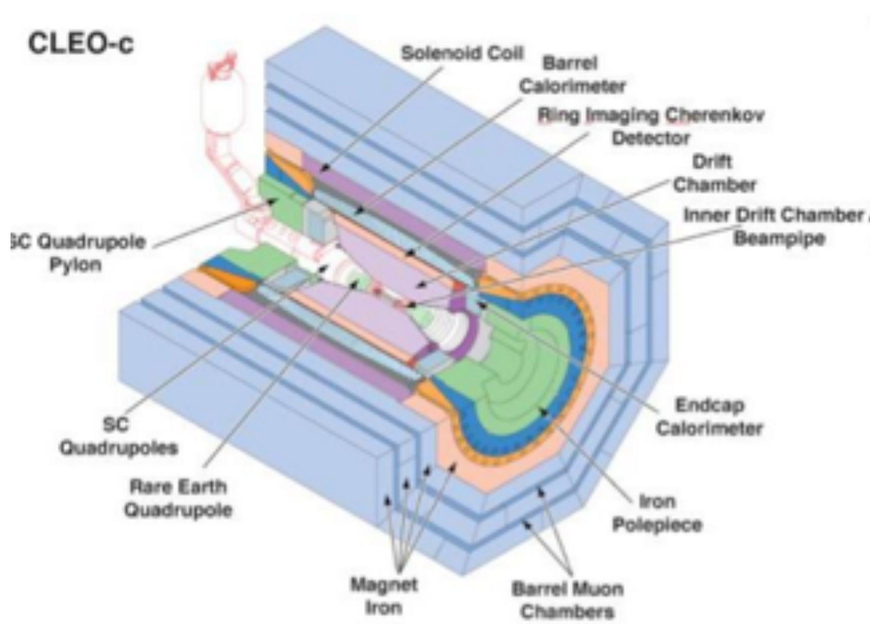
Charm facilities

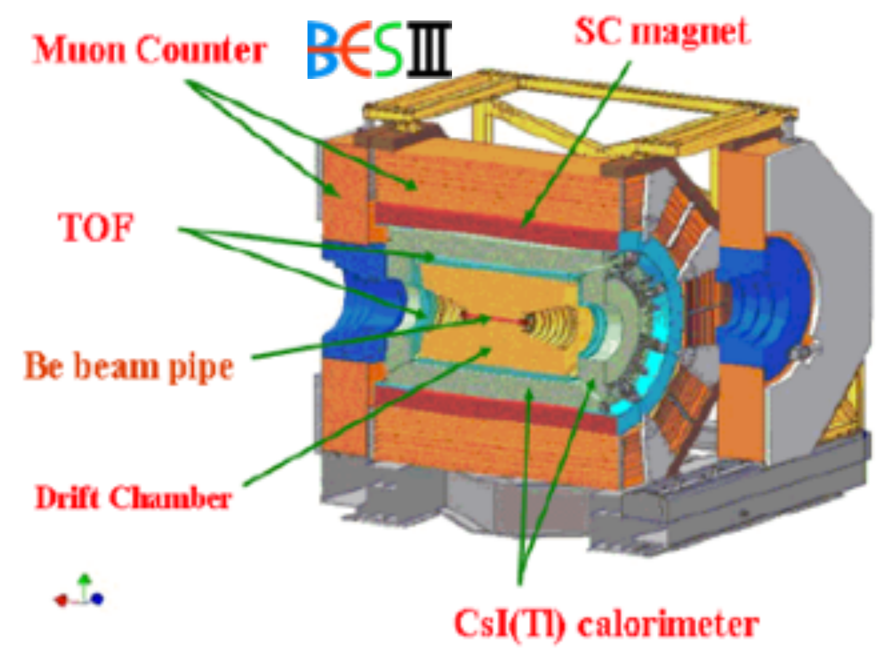
- Hadron colliders (huge cross-section, energy boost)
  - Tevetron (CDF, D0)
  - LHC (LHCb, CMS, ATLAS)
- e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - B-factories (Belle, BaBar)
  - Threshold production (CLEOc, BESIII)
    - ★ Quantum Correlations (QC)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

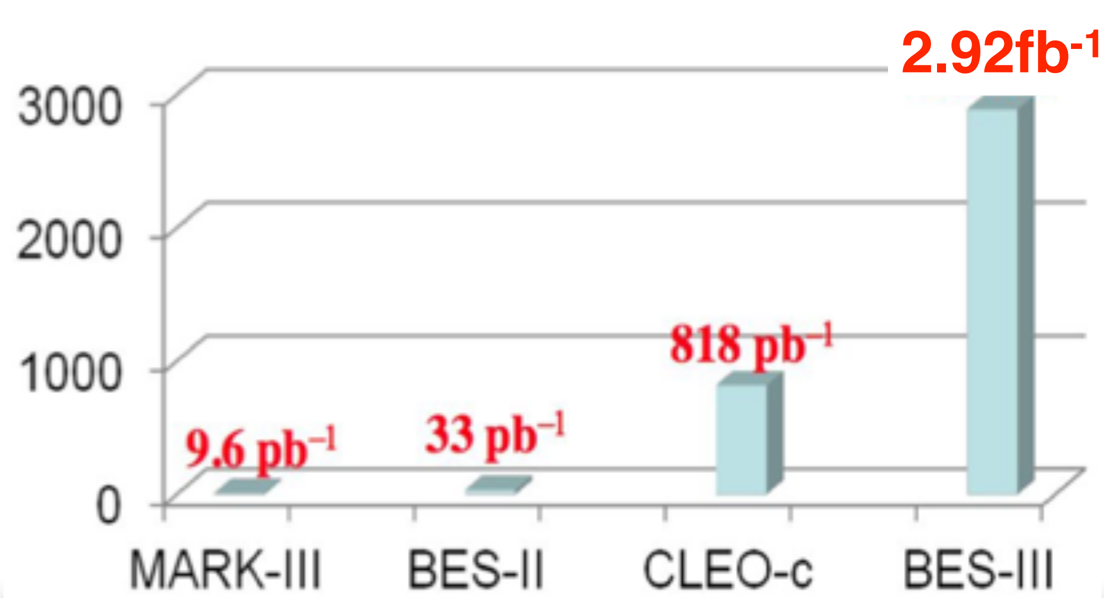


Data samples at charm threshold

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





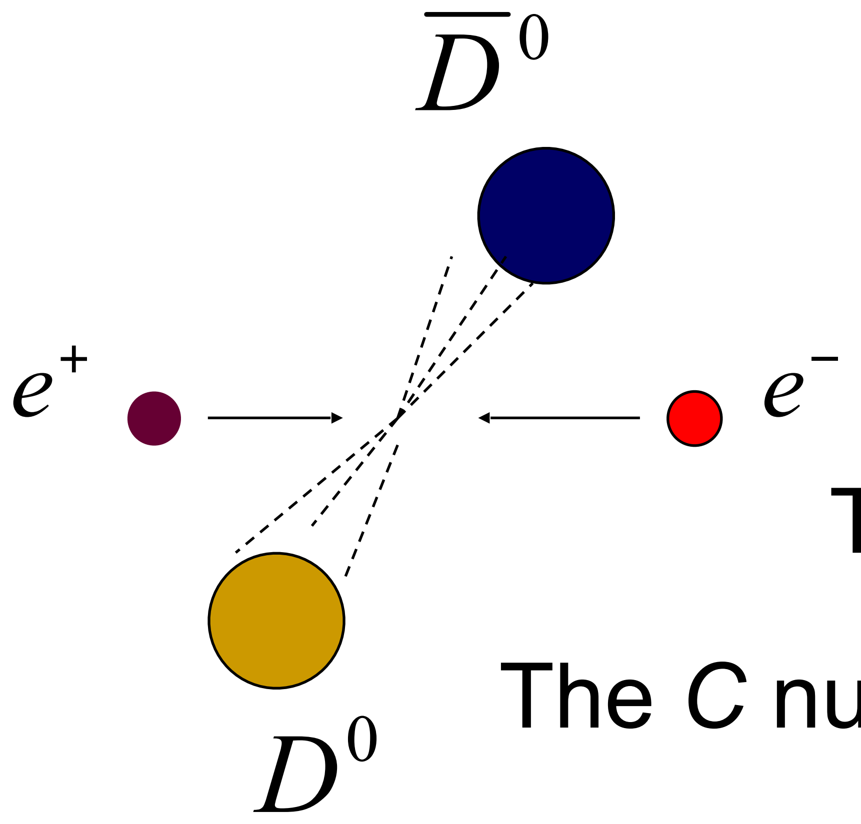


In the future, in total BESIII will accumulate ~10/fb data @ψ(3770)

The decay rate of a correlated state

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

$$e^+e^- \to \psi'' \to D^0\overline{D}^0$$



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

The quantum number of ψ'' is $J^{PC} = 1^{--}$

The *C* number of $D^0 \bar{D}^0$ pair in this process is $C = -$

Taking advantage the quantum coherence of $D\bar{D}$ pairs, we can study the D mixing and CPV in a unique way

- *strong phase in D decays*
- *D mixing parameters*
- *direct CP violation*
- *...*

Time-integrated decay rates

- No time dependent information at Charm threshold
- Anti-symmetric wavefuction:
  $\Gamma^2{}_{ij} = |\langle i|D^0\rangle\langle j|\bar{D}^0\rangle - \langle j|D^0\rangle\langle i|\bar{D}^0\rangle|^2$
- 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; $l^\pm$ 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	$R_M[1 + r_f^2(2 - z_f^2) + r_f^4]$					
$\bar{f}$	$1 + r_f^2(2 - z_f^2) + r_f^4$	$R_M[1 + r_f^2(2 - z_f^2) + r_f^4]$				
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	$1 + r_f^2 + r_f z_f y$		1		$2(1 \mp y)$	

Analysis techniques

Quantum Correlated topics

- **Mixing** (x^2+y^2)**:**$D\bar{D} \rightarrow (K^-l^+\nu)^2, (K^-\pi^+)^2$
- **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**

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

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

Global fit method

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

Global Analysis at CLEO-c (818 pb^{-1})

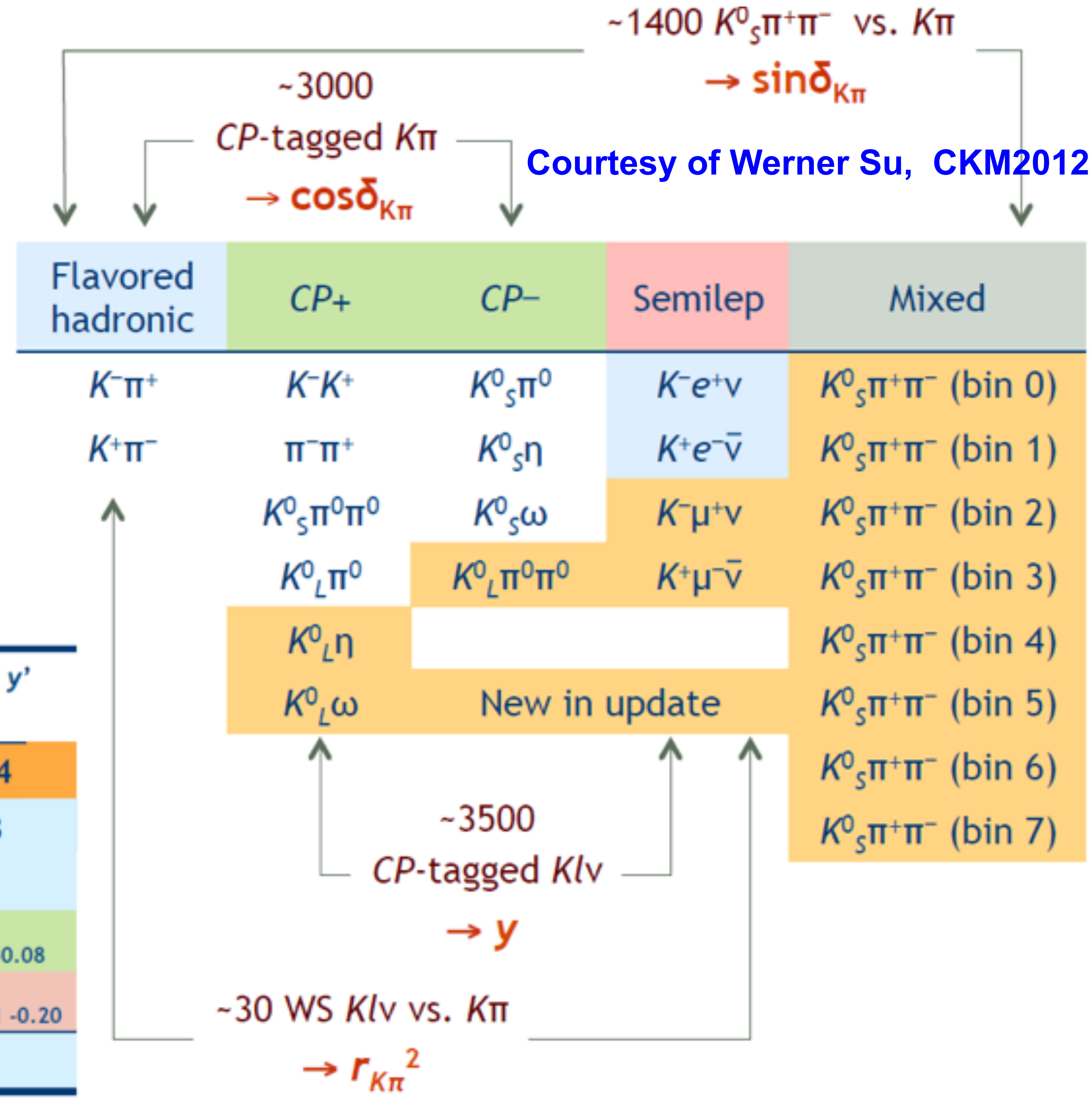
PRD86, 112001(2012)

- Updated analysis from the one in 2008:

$$\cos\delta = 1.03^{+0.31}_{-0.17} \pm 0.06$$

  [*PRL100, 221801 (2008)*; *PRD78, 012001 (2008)*]
- Included more modes
  - more ST and DT modes
  - $K_S\pi^+\pi^-$ strong phase bins [*PRD80, 032002 (2008)*]
- 251 yield measurements!

Courtesy of Werner Su, CKM2012

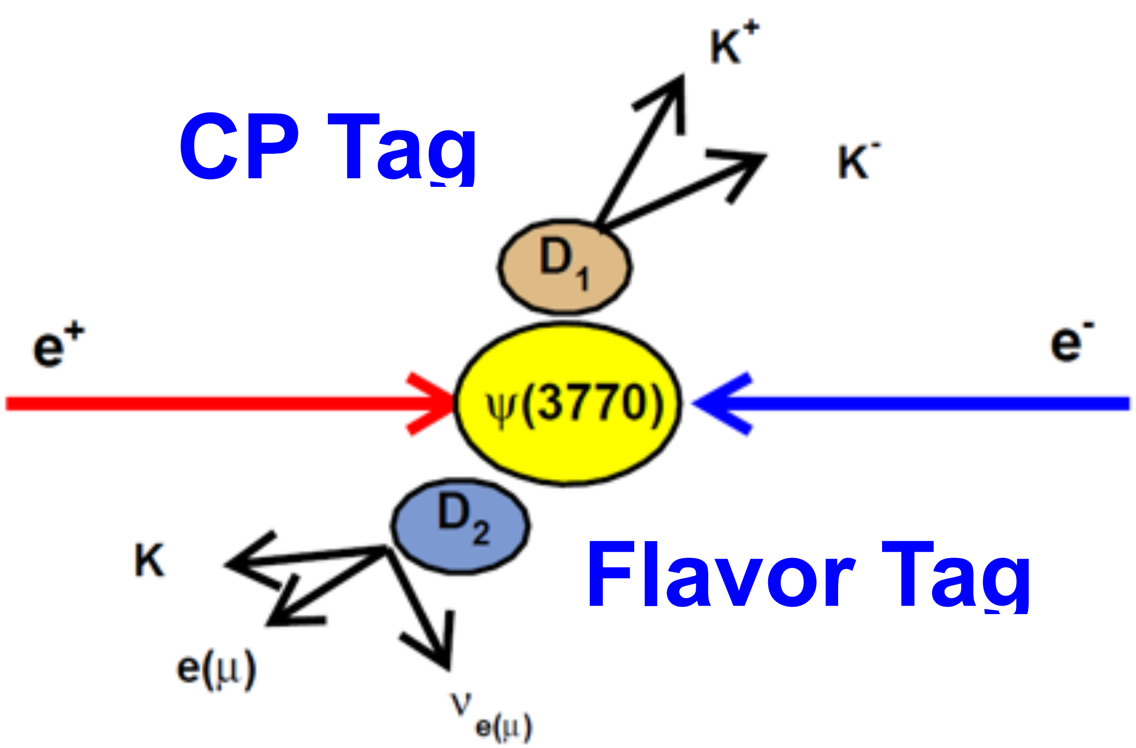


Parameter	Fit: no ext. meas. (standard)	Fit: w/ ext. y, x, y' (extended)
y (10^{-2})	$4.2 \pm 2.0 \pm 1.0$	0.636 ± 0.114
x^2 (10^{-3})	$0.6 \pm 2.3 \pm 1.1$	0.022 ± 0.023
$r_{K\pi}^2$ (10^{-3})	$5.33 \pm 1.07 \pm 0.45$	3.33 ± 0.08
$\cos\delta_{K\pi}$	$0.81\ ^{+0.22}_{-0.18}\ ^{+0.07}_{-0.05}$	$1.15\ ^{+0.19}_{-0.17}\ ^{+0}_{-0.08}$
$\sin\delta_{K\pi}$	$-0.01 \pm 0.41 \pm 0.04$	$0.56\ ^{+0.32}_{-0.31}\ ^{+0.21}_{-0.20}$
$\delta_{K\pi}$ (°) [derived]	$10\ ^{+28}_{-53}\ ^{+13}_{-0}$	$18\ ^{+11}_{-17}$

y_{CP} measurement

(BESIII: 2.92 fb^{-1})

We measure the y_{CP} using *CP*-tagged semi-leptonic *D* decays, which allows to access *CP* asymmetry in mixing and decays.



★ Single tag decay rate (CP tags)

$$\mathcal{B}_{CP\pm} \propto 2|A_{CP\pm}|^2(1 \mp y)$$

★ Double tag decay rates (flavor tags + CP tags)

$$\mathcal{B}_{l;CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$$

★ Neglect term y2 or high order

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

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

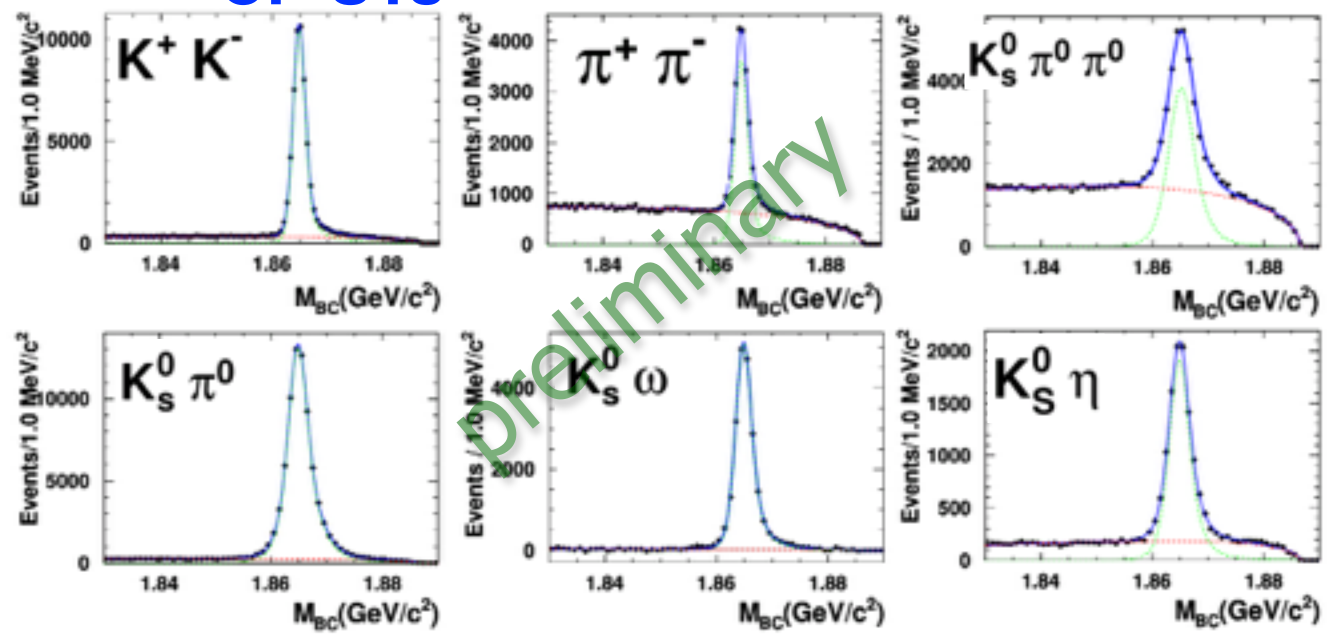
signals to determine y_{CP}

(BESIII: 2.92 fb^{-1})

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

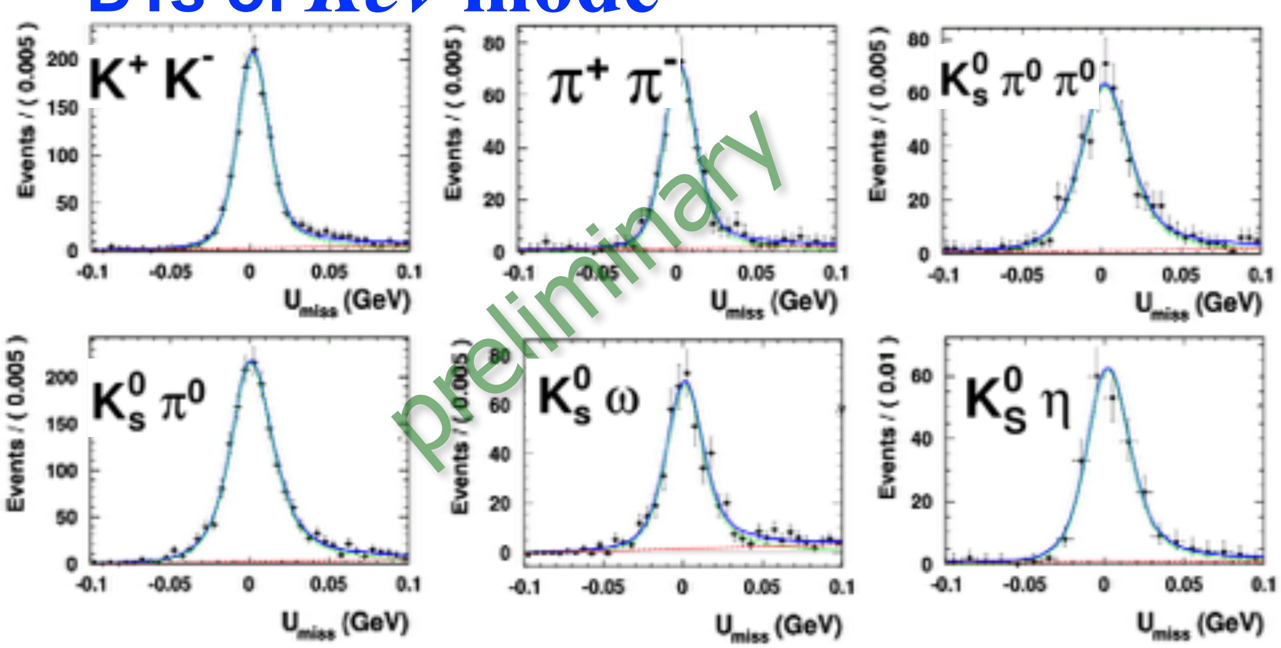
    $U_{miss} = E_{miss} - |\vec{P}_{miss}|$ (≈0 for signals)

CP STs

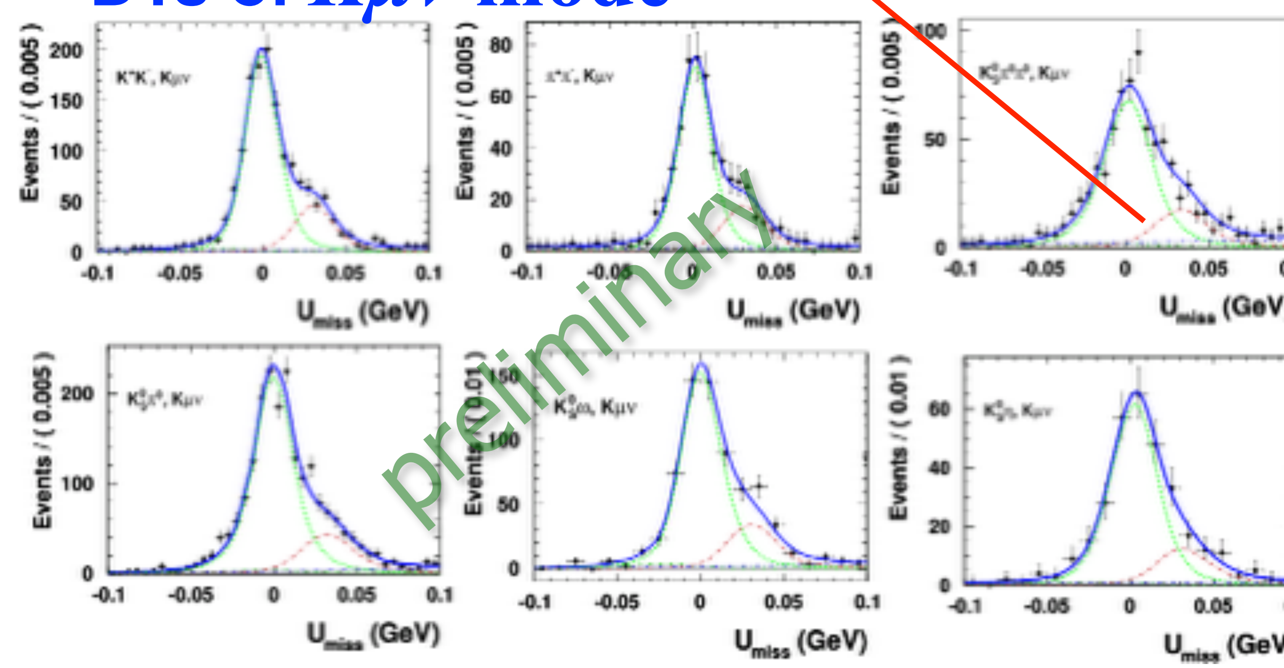


peaking bkg. from $K\pi\pi^0$

DTs of *Keν* mode



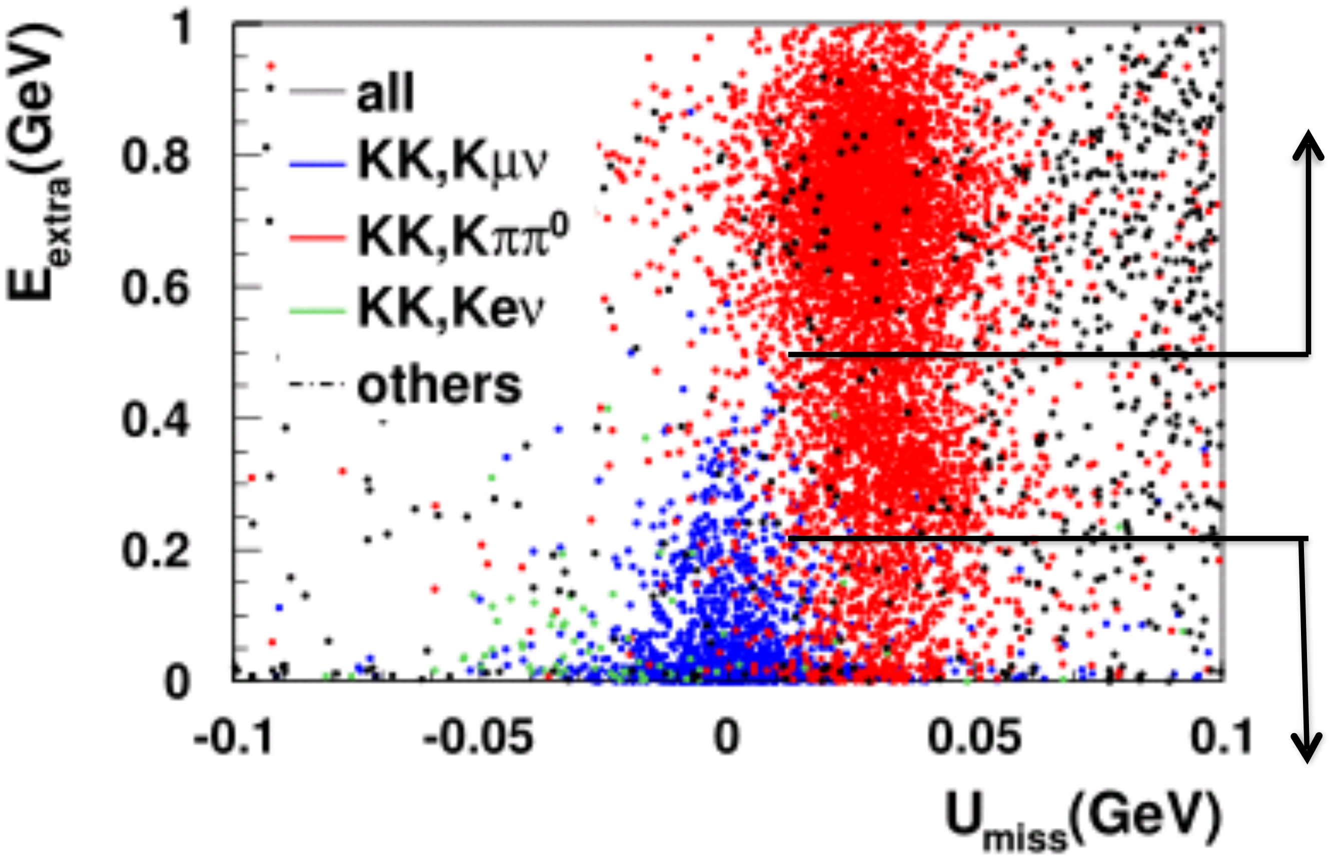
DTs of *Kμν* mode

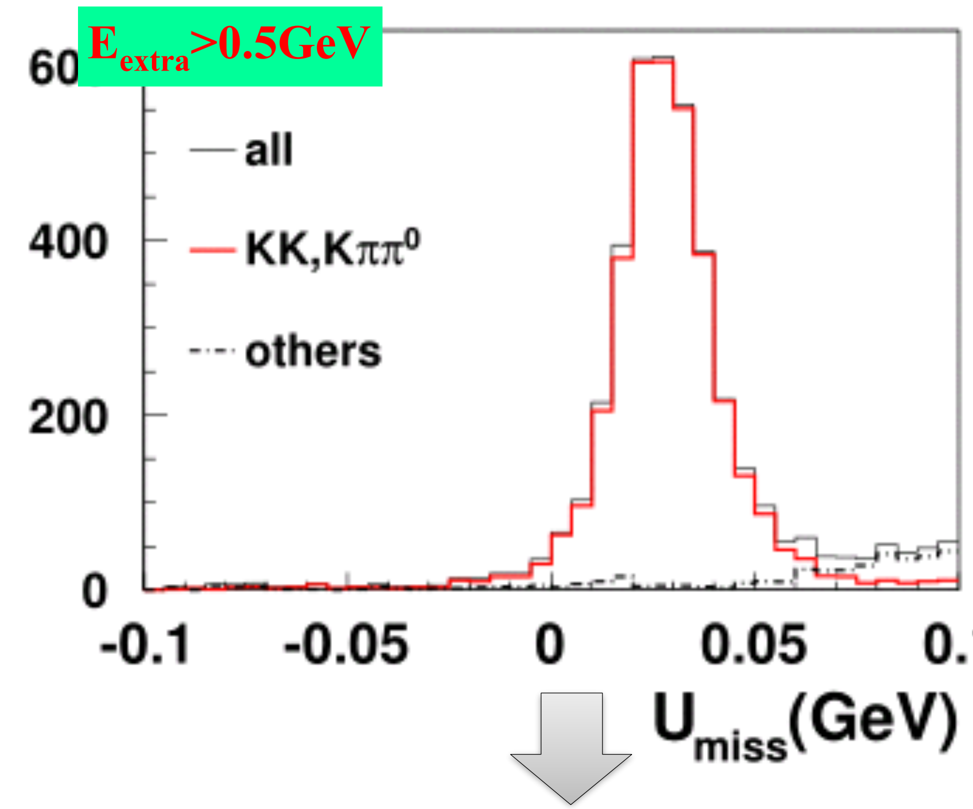


$K\pi\pi^0$ backgrounds in $K\mu\nu$ modes

define $\boldsymbol{E_{extra}}$ as total energy of the remaining showers other than those being used

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



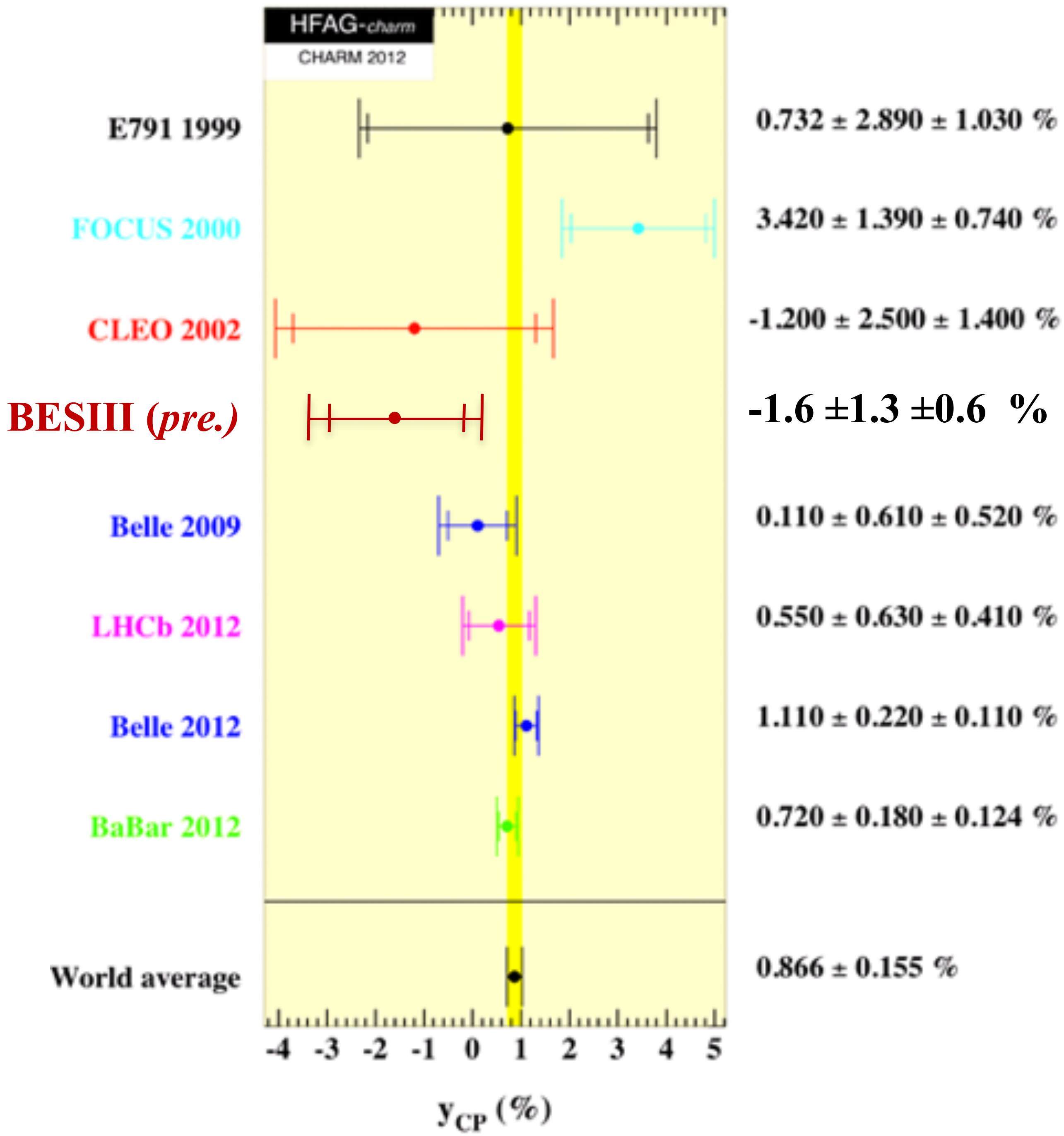


shape : MC shape smeared by a Gaussian, whose parameters are obtained from fit to the control sample

size: scale the MC-determined 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

y_{CP} preliminary result

(BESIII: 2.92 fb^{-1})



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

BESIII 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
- most precise measurement with QC D mesons
- in the limit of no CPV, y_{CP}=y

Paper is close to be submitted to journal.

Strong Phase $\delta_{K\pi}$

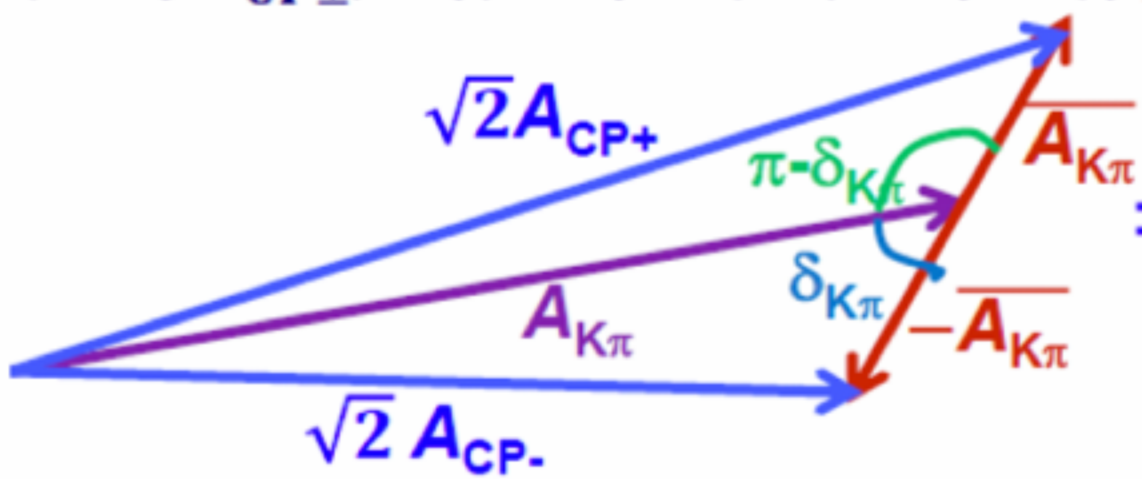
PLB734, 227 (2014)

(BESIII: 2.92 fb^{-1})

Strong phase: $\frac{\langle K^-\pi^+|\overline{D}^0\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$

Quantum correlation → Interference → access strong phase!

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



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

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

- 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^+, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$
  - CP- tags (3 modes): $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$

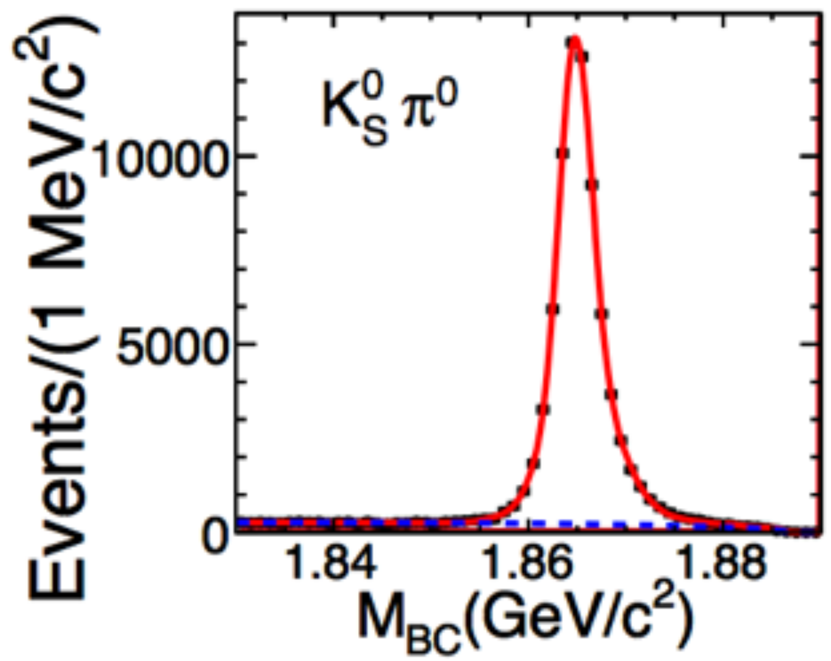
Strong Phase $\delta_{K\pi}$

PLB734, 227 (2014)

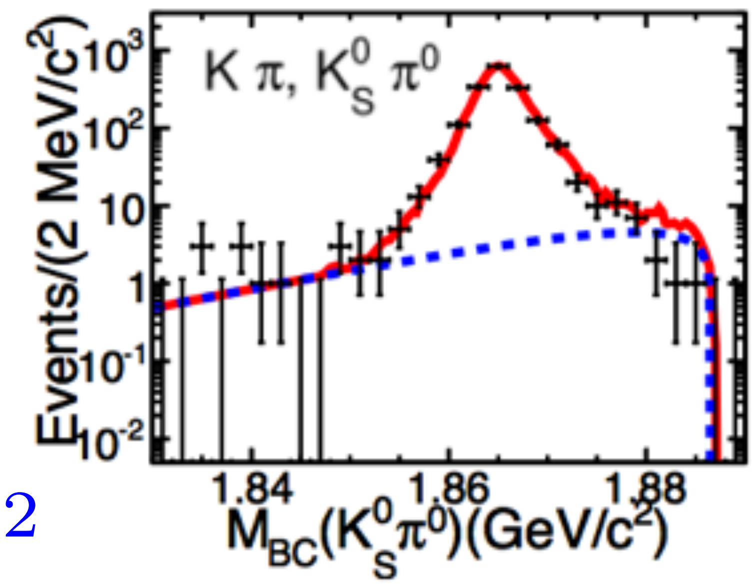
(BESIII: 2.92 fb^{-1})

- **Signal reconstruction:**
  - Single Tag (ST): CP tags
  - Double Tag (DT) : $K\pi$ + CP Tag
  - Kinematic variable: Beam Constrained Mass (M_{BC})
  - Singal shape: $\sigma\otimes$MC-truth
  - Background shape: ARGUS function
- $$Br(D_{CP\pm} \to K\pi) = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}$$
  - $n_{K\pi,CP\pm}$ 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 $\varepsilon_{CP\pm}/\ \varepsilon_{K\pi,CP\pm}$

Single Tags



Double Tags



BESIII direct product of results:

$$\mathcal{A}_{CP\to K\pi} = (12.7 \pm 1.3 \pm 0.7) \times 10^{-2}$$

Improvement from previous results and inputs for world average fit!

$\delta_{K\pi}$ in $D \to K\pi$

PLB734, 227 (2014)
(BESIII: 2.92 fb^{-1})

- If we don't ignore the mixing effect
- $2r_{K\pi}\cos\delta_{K\pi} + y = (1 + R_{WS}) \cdot A_{CP\to K\pi}$
  - $R_{WS} \equiv \frac{\Gamma(D^0\to K^+\pi^-)}{\Gamma(D^0\to K^-\pi^+)} = r^2_{K\pi} + r_{K\pi}y' + \frac{(x^2+y^2)}{2}$

with external inputs from HFAG2014 and PDG:

$r^2_{K\pi}=(3.50\pm0.04)\times10^{-3}$; $y_{CP}=(6.7\pm0.9)\times10^{-3}$; $R_{WS}=(3.80\pm0.05)\times10^{-3}$

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

- **The third error is due to the input parameters**
- **The statistical errors dominant the precision**
- **World best precision**

CLEO-c results *[Phys. Rev. D 86 (2012) 112001]*

$$\cos\delta_{K\pi} = 0.81^{+0.22+0.07}_{-0.18-0.05}$$

$$\cos\delta_{K\pi} = 1.15^{+0.19+0.00}_{-0.17-0.08} \quad \text{(globalfit)}$$

In the next 5 years, BESIII will in total accumulate about 10 /fb on-threshold *D* data:

➡ **precision of $\cos\delta_{K\pi}$ will reach ~0.06: level of syst. err.**

CLEO-c

CPV in charm factory

PRD89, 072002 (2014)

CP asymmetry: $A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}$

★ CPV in charm:

- ✤ SM: <= a few %
- ✤ NP: >~ 1%

★ World precision: ~ 0.1%

★ CLEO-c measured Acp based on single tag events

- ✤ at the order 1% for all modes
- ✤ no evidence of CPV
- ✤ systematics dominant

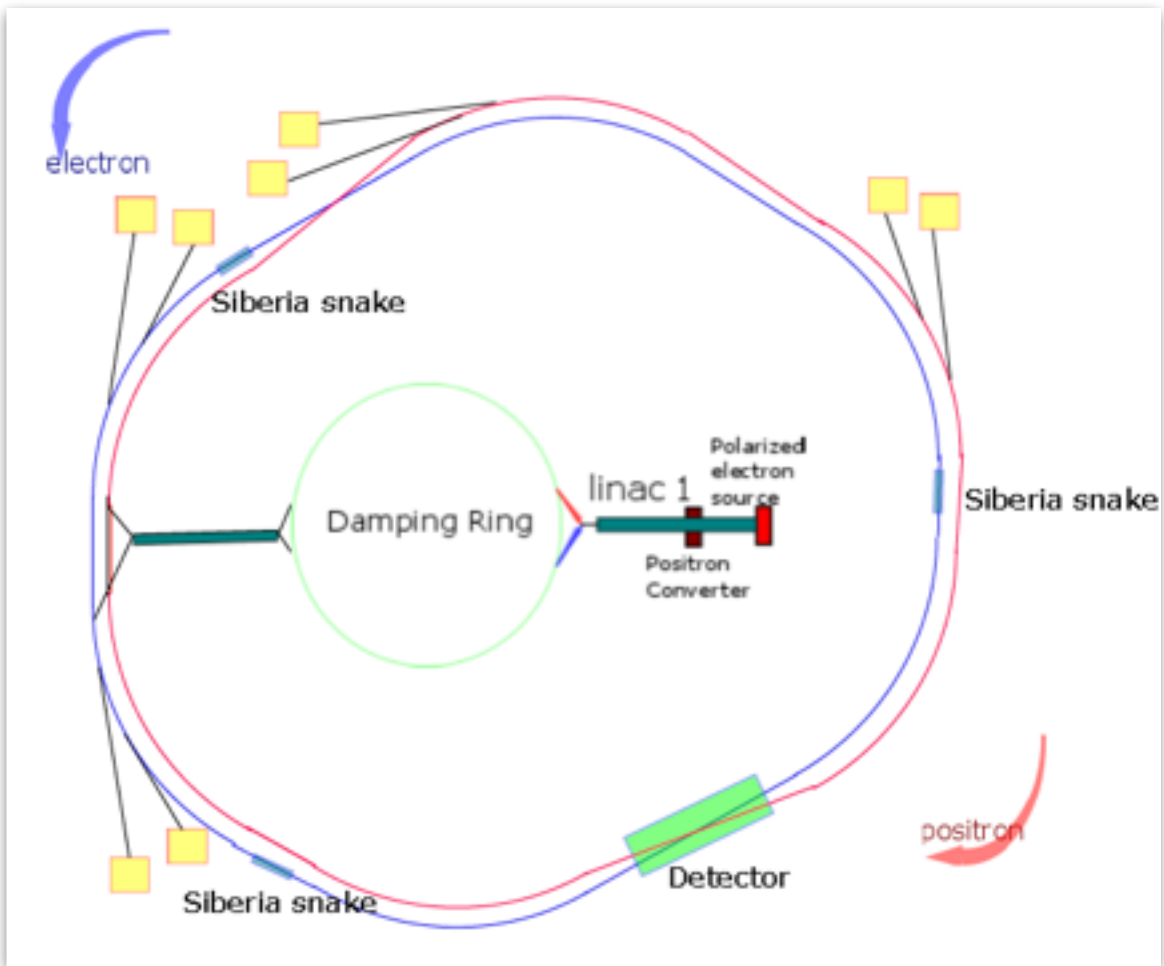
(CLEO-c: 818 pb^{-1})

Mode	CP Asymmetry (%)
$D^0 \to K^-\pi^+$	$0.3 \pm 0.3 \pm 0.6$
$D^0 \to K^-\pi^+\pi^0$	$0.1 \pm 0.3 \pm 0.4$
$D^0 \to K^-\pi^+\pi^+\pi^-$	$0.2 \pm 0.3 \pm 0.4$
$D^+ \to K^-\pi^+\pi^+$	$-0.3 \pm 0.2 \pm 0.4$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$-0.3 \pm 0.6 \pm 0.4$
$D^+ \to K^0_S\pi^+$	$-1.1 \pm 0.6 \pm 0.2$
$D^+ \to K^0_S\pi^+\pi^0$	$-0.1 \pm 0.7 \pm 0.2$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$0.0 \pm 1.2 \pm 0.3$
$D^+ \to K^+K^-\pi^+$	$-0.1 \pm 0.9 \pm 0.4$

- With the LHCb's updates (~0.1%), CPV test becomes not sensitive in charm factory
- In future charm factory, it is important to reduce the systematic uncertainty by using a large D threshold sample

High Intensity Electron Positron Accelerator (HIEPA)

- **China is proposing a future super-tau-charm factory: HIEPA**
- **Providing peak luminosity about 1x10^{35} $cm^{-2}s^{-1}$ at 4 GeV for physics at tau charm sector, covering E_{cm} = 2-7 GeV.**



by 2016: CDR & TDR

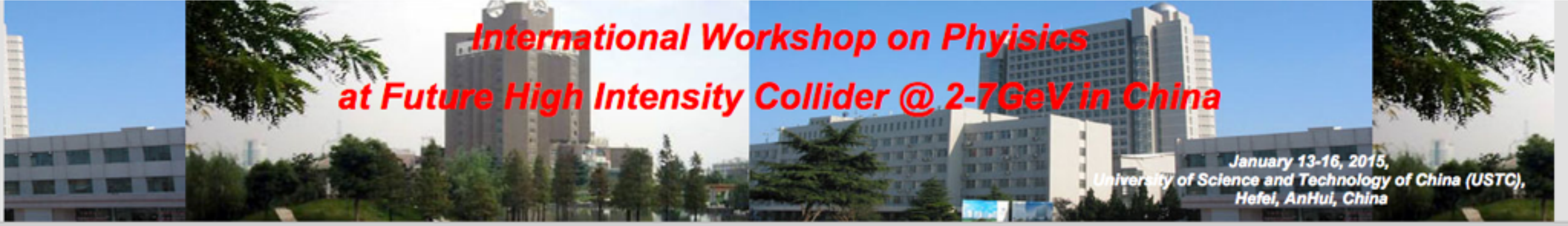
with $1ab^{-1}$ data @HIEPA

- ✓ Direct CP violation in $D^+ \to hh$ sensitivity: 10^{-3}~10^{-4}
- ✓ $\Delta(\cos\delta_{K\pi})$ ~0.007; $\Delta(\delta_{K\pi})$ ~2^o
- ✓ $R_M = (x^2+y^2)/2$ ~ 10^{-5} in $K\pi$ and $Ke\nu$ channels
- ✓ Probe y: $\Delta y_{CP} < 0.1\%$

clean background and better systematic control in threshold production would be complementary to the future *B* factory results

Summary

- ✦ Data at charm threshold provide unique ingredient on identifying D-$\underline{D}$ oscillations and CPV in charm sector
- ✦ CLEO-c have made great progress and paved a way for subsequent precision experiment
- ✦ BESIII has been involved in the world campaign
  - Many more QC analyses are undergoing.
  - The global fit package has been developed to measure strong phases and mixing parameters.
  - Precision required more stringent systematic control
- ✦ A super-tau-charm factory in China is being proposed:
  - ✦ Complementary to precision measurements at BELLEII and upgraded LHCb



AIM to explore possible future collider project post BEPCII/ BESIII. HIEPA is one of the options.

website: http://cicpi2011.lcg.ustc.edu.cn/hiepa2015/
online registration: Sep. 8 — Dec. 08, 2014

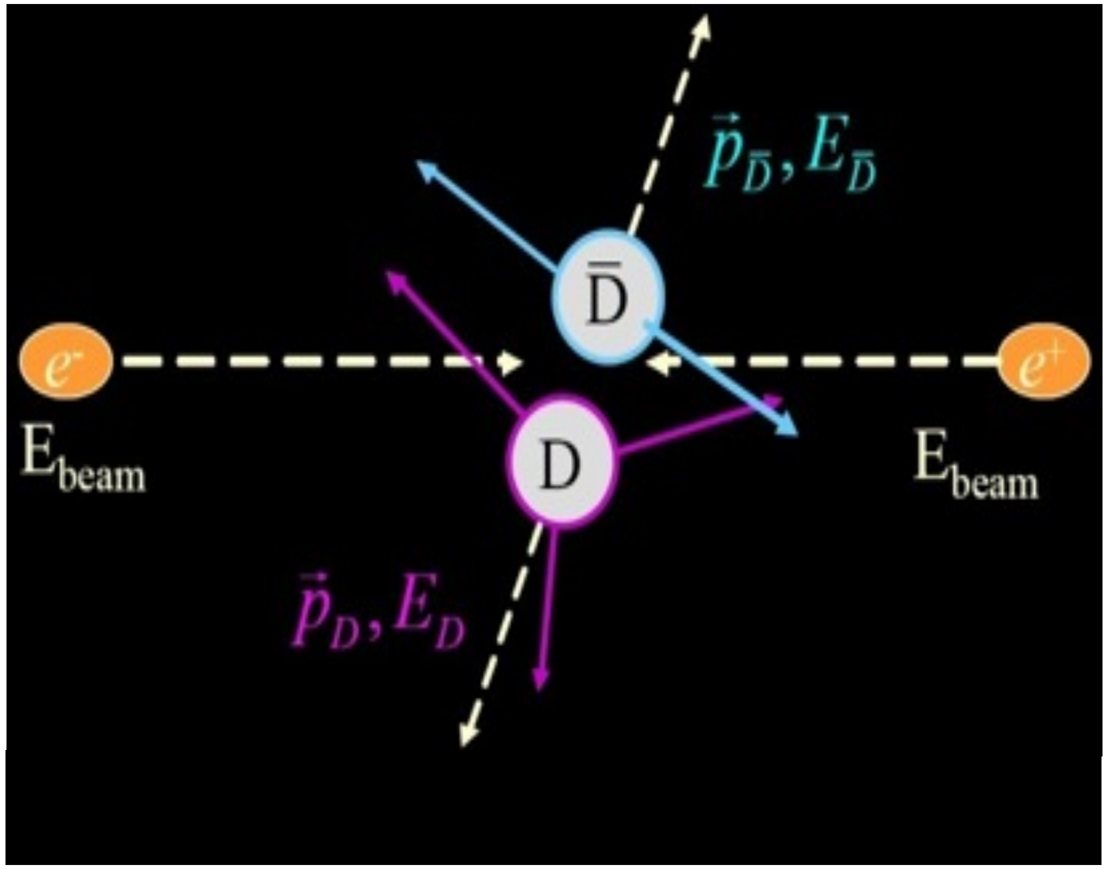
Thank you!

Danke!

谢谢！

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-}**

Toward global fit at BESIII

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

✤ MC study corresponding to 3.0 /fb data

✤ input parameters:

$$\delta_{K\pi} = 22.1^{+9.7}_{-11.1}(^o),$$

$$y_D = 0.75 \pm 0.12(\%)$$

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
$K^+K^-, Ke\nu_e$	$2(1+y_D)$
$K_S\pi^0, Ke\nu_e$	$2(1-y_D)$

✤ output after constrains :

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

- ~15% improvement on the parameters
- We expect larger improvements on the strong phase and mixing parameters based on 10 /fb data at BESIII