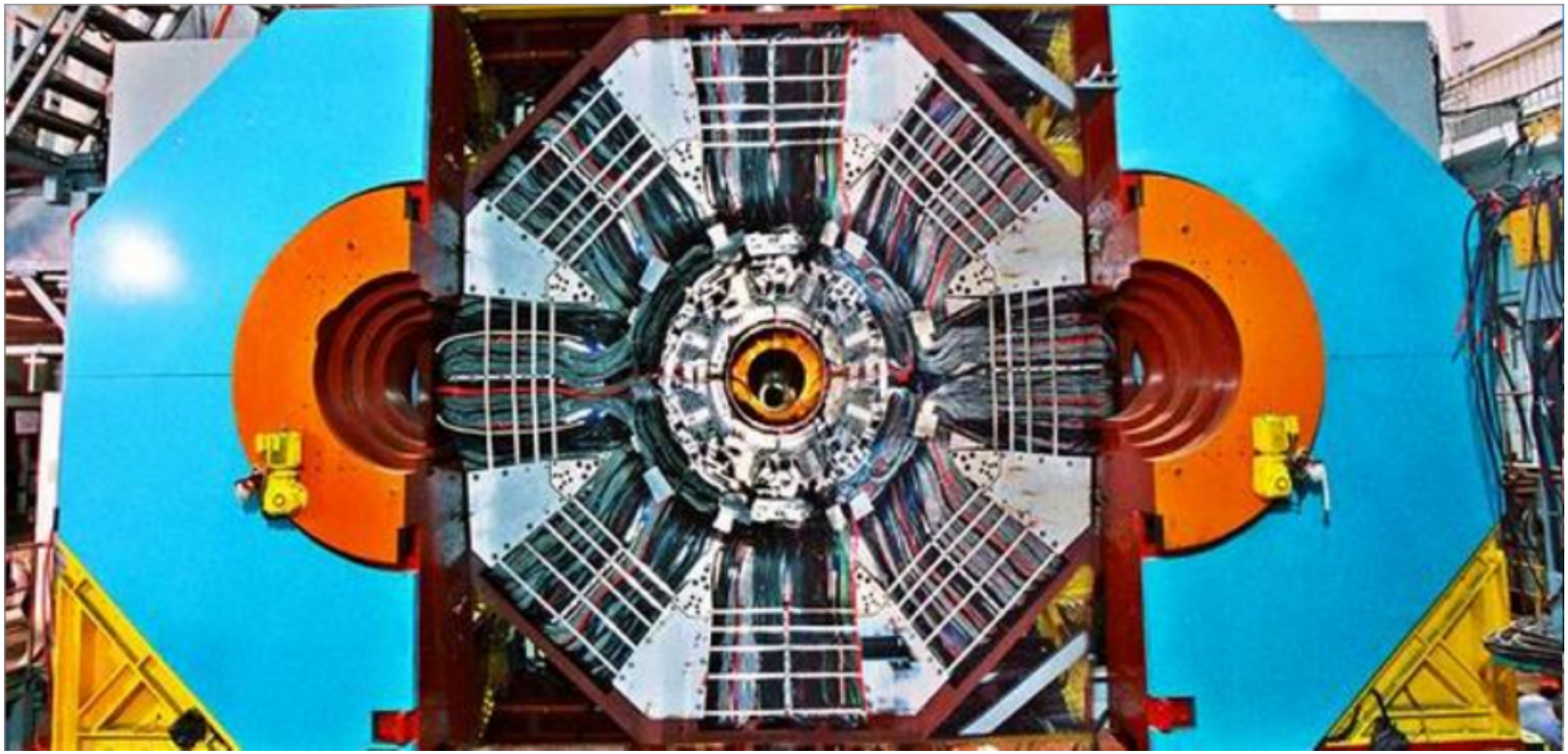

Physics with entangled neutral *D* mesons at BESIII and future perspectives

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Outline

- Introduction
- The BESIII experiment
- Physics with entangled neutral D mesons
- Recent BESIII charm results
- Summary & prospectives

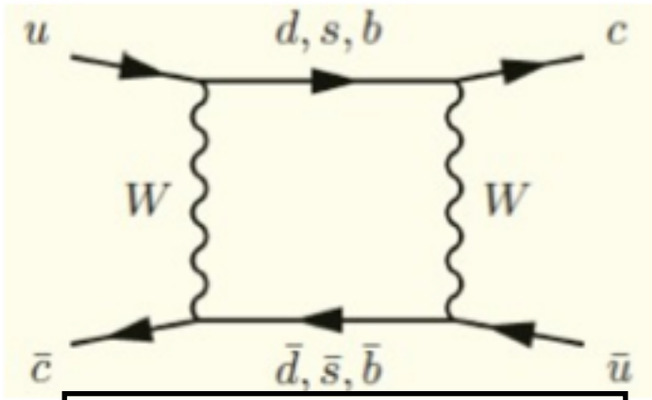
Neutral *D* meson oscillation

- D_0 and $\overline{D}_0$ can transform into each other (like Kaons an Bs)
- The mass eigenstates are

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

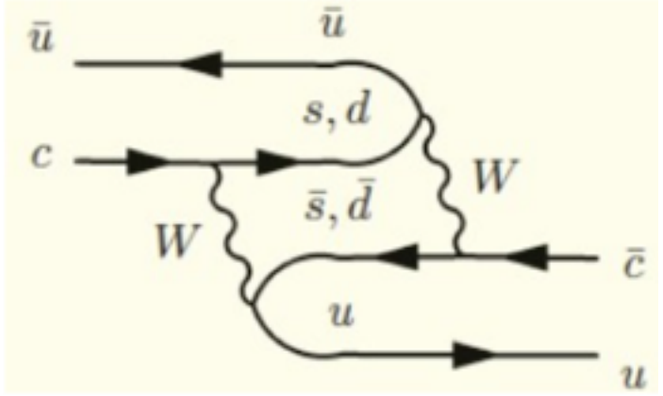
$$\left|D_2\right\rangle = p\left|D^0\right\rangle - q\left|\overline{D}^0\right\rangle$$

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 mixing: Channel for New Physics.

y (long-distance) mixing: SM background.

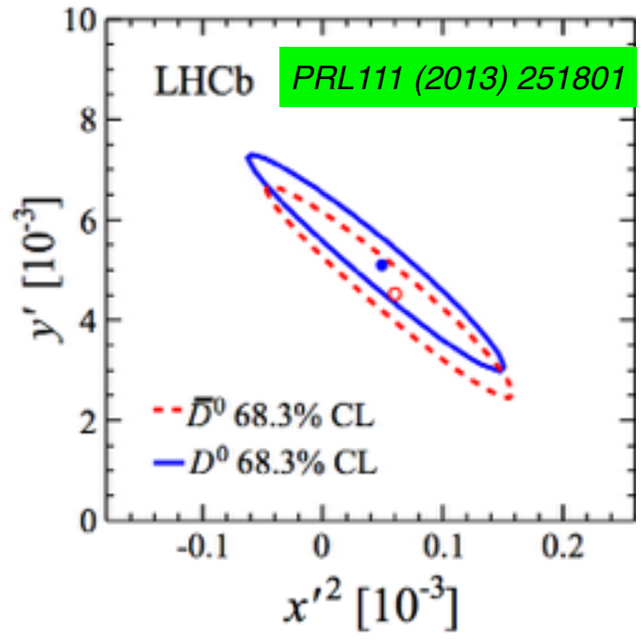
$$x \equiv \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

D oscillation and strong phase

- ✓ short distance is highly suppressed by the GIM mechanism and by the CKM matrix elements within the SM $x \sim \mathcal{O}(10^{-5}),\ y \sim \mathcal{O}(10^{-7})$
  - NP 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: $x\,,\ y \sim \mathcal{O}(10^{-3})$
  - but theoretical uncertainty is large
- ✓ Observation of D$\underline{\text{D}}$ oscillation by CDF and LHCb

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

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

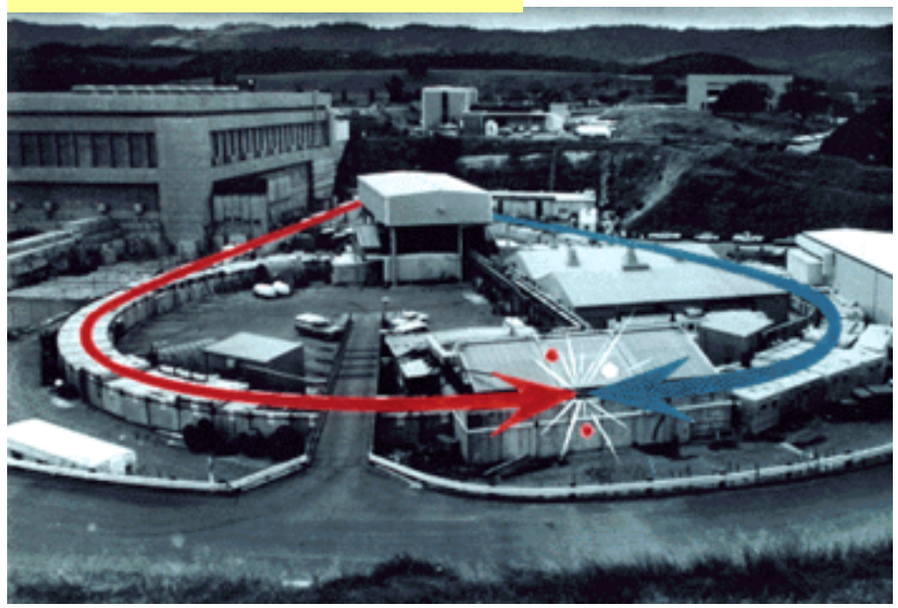


- ✓ Improving the constraints on the charm mixing parameters is important for testing the SM, such as long-distance effect
- ✓ In addition, strong phase is an important ingredient for
  - (over-)constraining the CKM unitarity triangle, which is crucial for searching for new physics
  - extract the mixing parameter (x,y) from (x′, y′)

D mesons from dedicated colliders

ADONE, FRASCATI ’69-’93

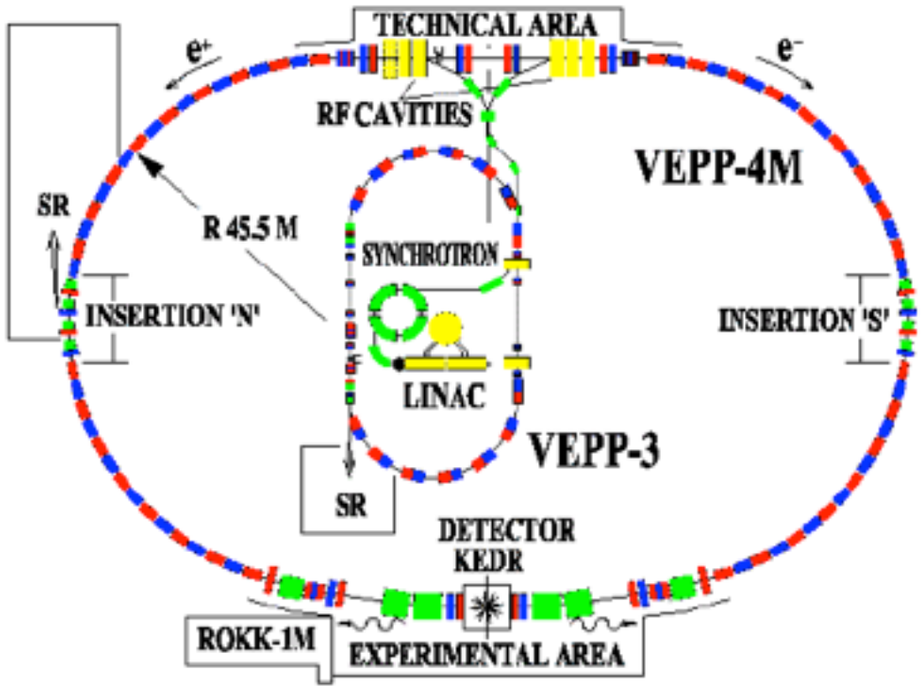
SPEAR, SLAC, ’72-’90
6×10^{29} cm^{-2}.s^{-1}



BEPC, IHEP, ’90-’04
5×10^{30} cm^{-2}.s^{-1}

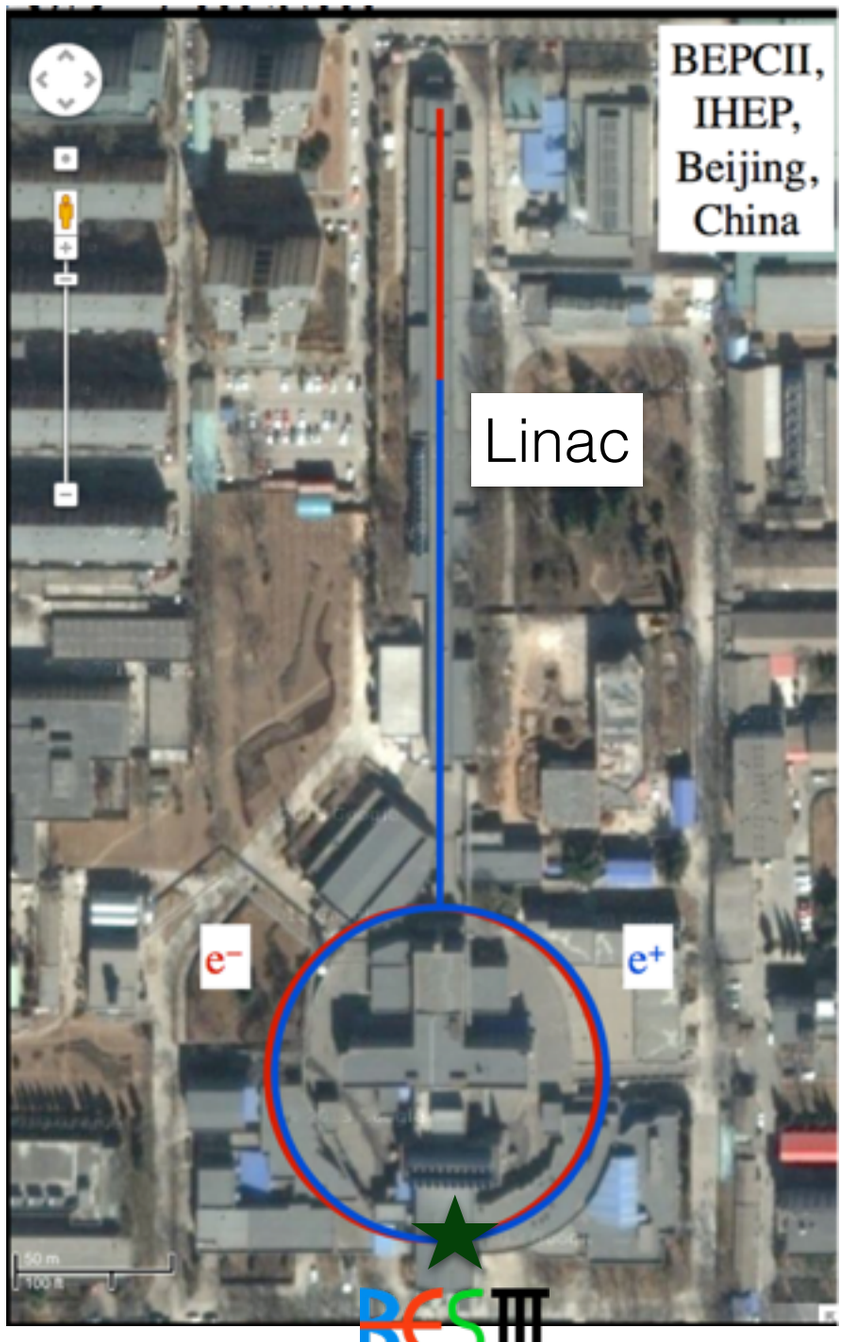
CESRc, Cornell, ’04-’08
7×10^{31} cm^{-2}.s^{-1}

VEPP-4M, Novosibisk, ’02-’12
1×10^{30} cm^{-2}.s^{-1}



BEPCII, IHEP, ’08-’18(?)
1×10^{33} cm^{-2}.s^{-1}

Beijing Electron Positron Collider-II (BEPCII)



- **2004: started BEPCII/BESIII construction**
- **2008: test run**
- **2009 - now: BESIII physics run**
  - ~60% Physics run
  - ~30% Synchrotron radiation run

The BEPCII Collider

Beam energy: 1.0 – 2.3 GeV

Peak Luminosity:

Design: **1×10^{33} $cm^{-2}s^{-1}$**

Achieved: **$0.7\times10^{33}cm^{-2}s^{-1}$@3770MeV**

Optimum energy: 1.89 GeV

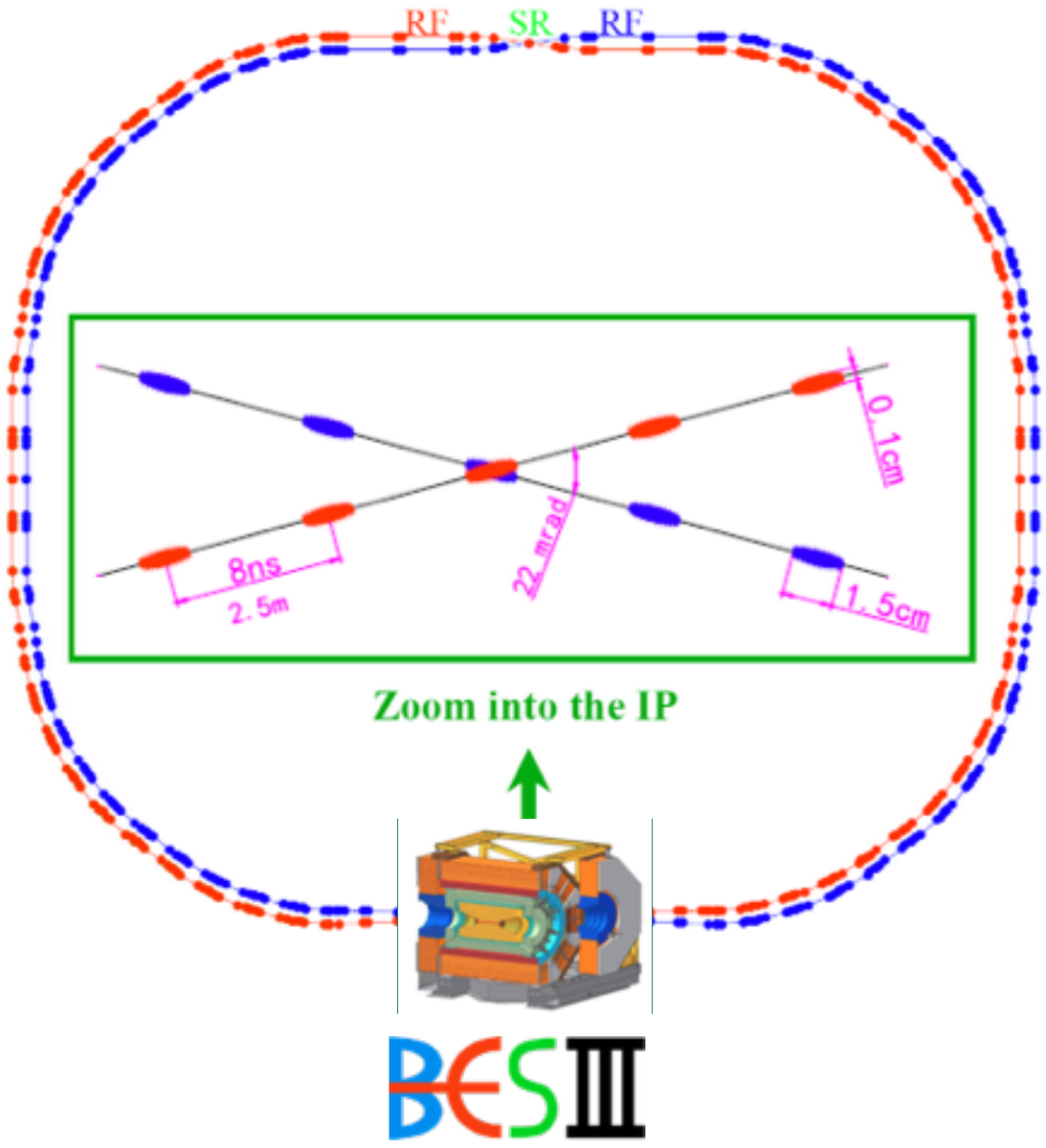
Energy spread: 5.16×10^{-4}

No. of bunches: 93

Bunch length: 1.5 cm

Total current: 0.91 A

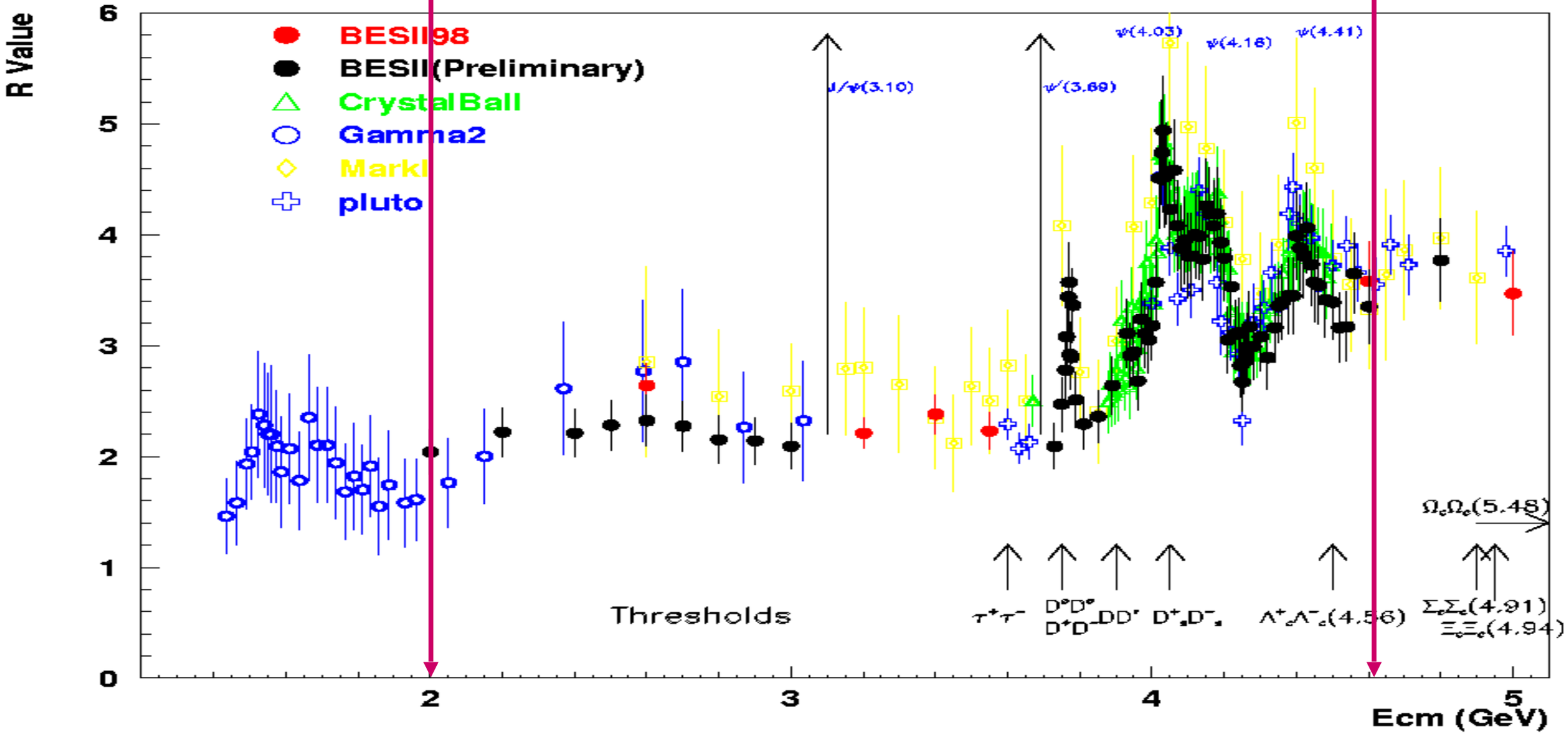
Circumference: 237m



Beam energy measurement: **Using Compton backscattering technique. accuracy up to 5×10^{-5}**

Energies of the BEPCII Collider

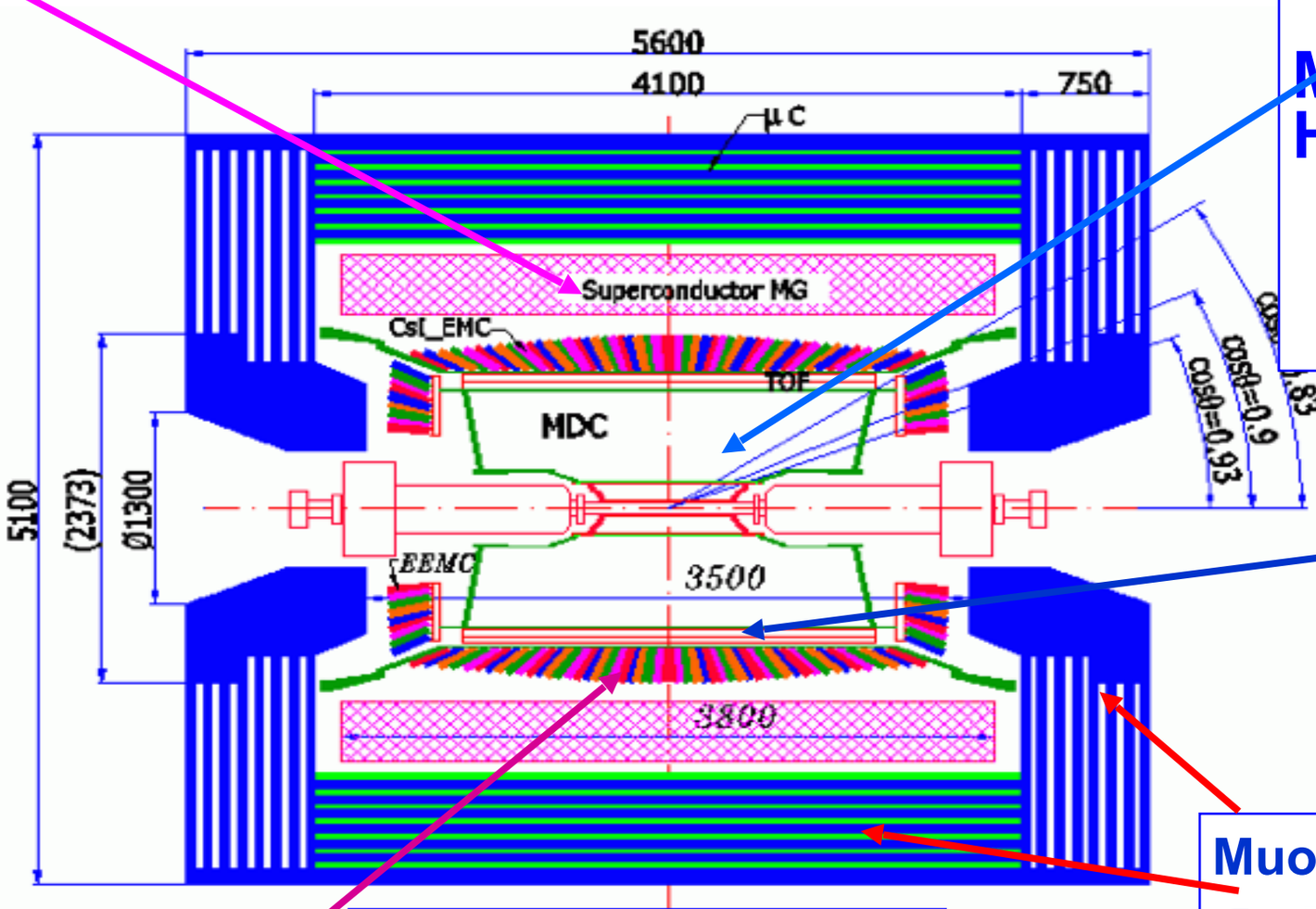
2 ~ 4.6 GeV



NIM A614, 345 (2010)

The BESIII detector

Solenoid Magnet: 1 T Super conducting



MDC: small cell & He gas

σ_{xy}=130 μm

$\delta p/p$ = 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.

The BESIII collaboration

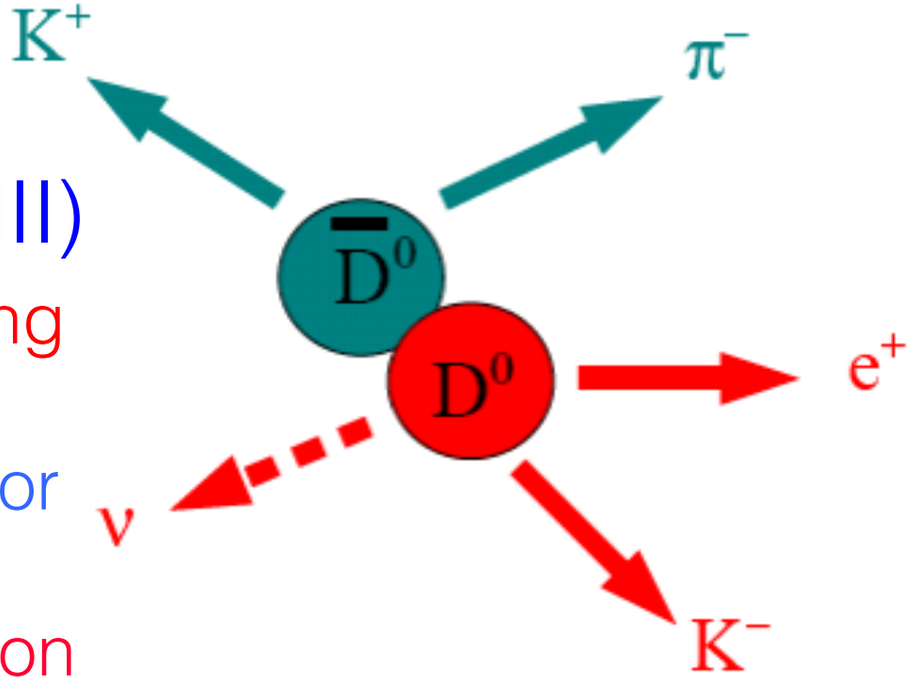
Data samples at BESIII

	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 2014: 0.6 /fb @ 4.6 GeV 1.0 /fb @ 4.42 GeV and data for line shape	5-10 /fb
R Scan	*BESII*	2012: R @2.23,2.4,2.8,3.4GeV 25/pb tau threshold 2014: 0.8 /fb @ 3.85—4.59 GeV	

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

Charm facilities

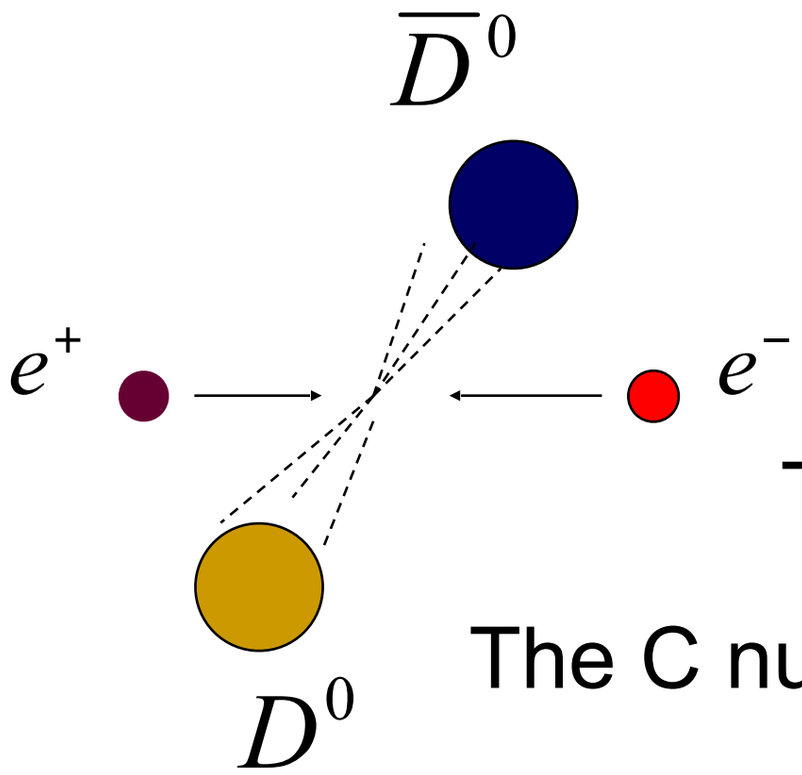
- Hadron colliders (huge cross-section, energy boost)
  - Tevetron (CDF, D0)
  - LHC (LHCb, CMS, ATLAS)
- e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - B-factories (Belle, BaBar)
  - Threshold production (CLEOc, BESIII)
    - Quantum Correlations (QC) and 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



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 $C = -$

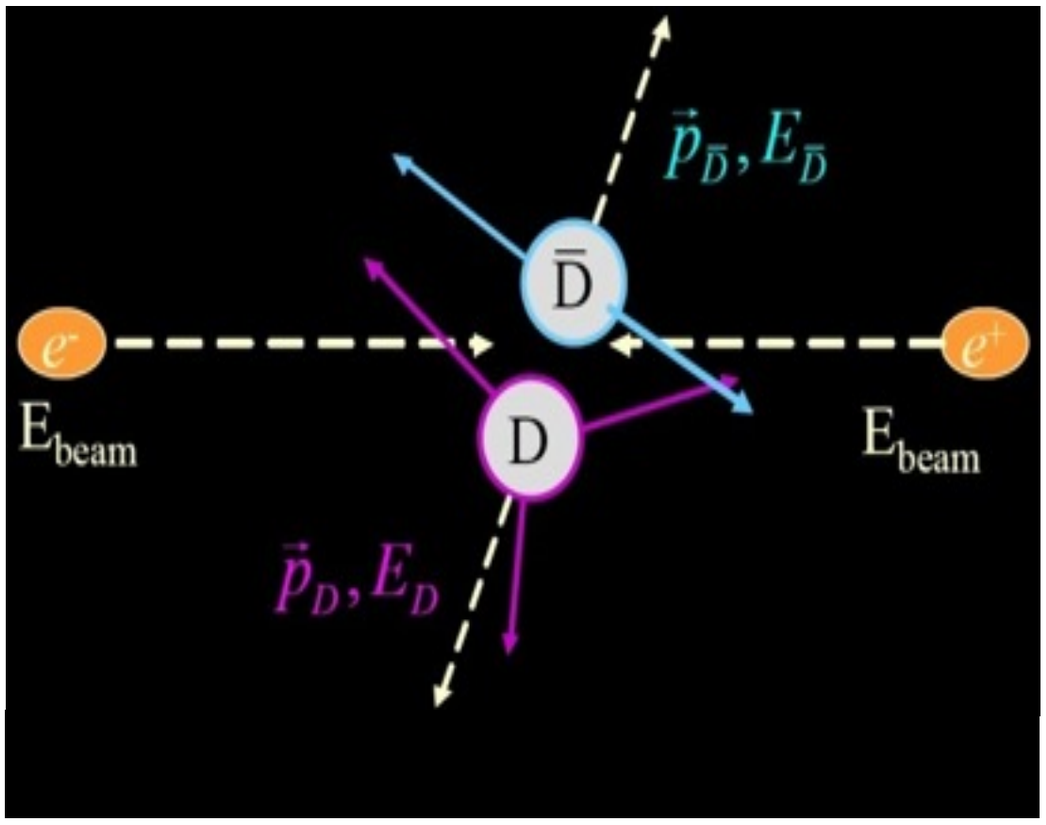
Taking advantage the quantum coherence of D<u>D</u> pairs, BESIII can study the charm physics in an unique way

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

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:**

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

  - **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	$R_M[1 + r_f{}^2(2 - z_f{}^2) + r_f{}^4]$					
$\bar{f}$	$1 + r_f{}^2(2 - z_f{}^2) + r_f{}^4$	$R_M[1 + r_f{}^2(2 - z_f{}^2) + r_f{}^4]$				
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	$1 + r_f{}^2 - r_f z_f(A - y)$		1		$2[1 \pm (A - y)]$	

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**

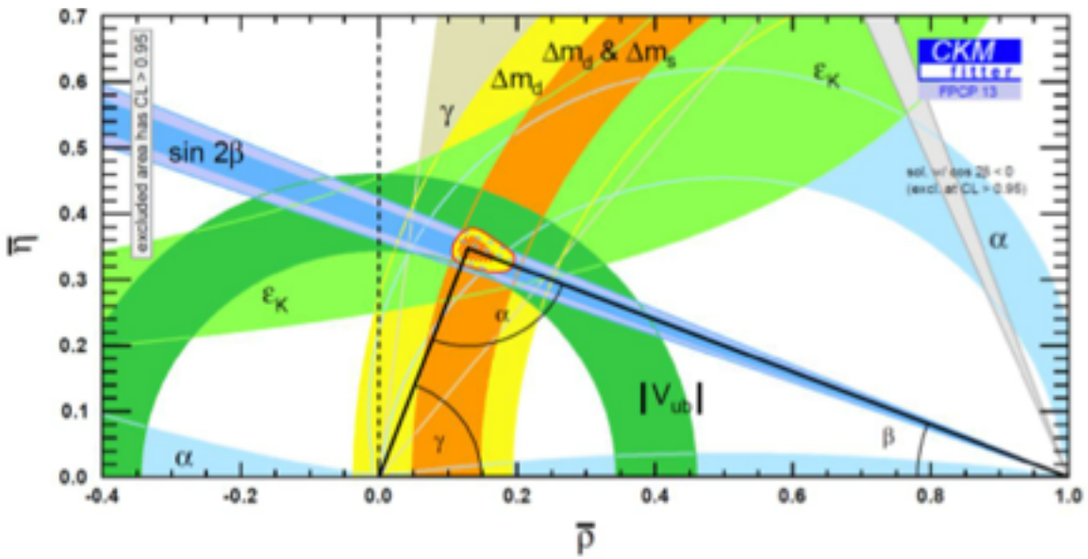
$$\Delta E = E_D - E_{\mathrm{Beam}}$$

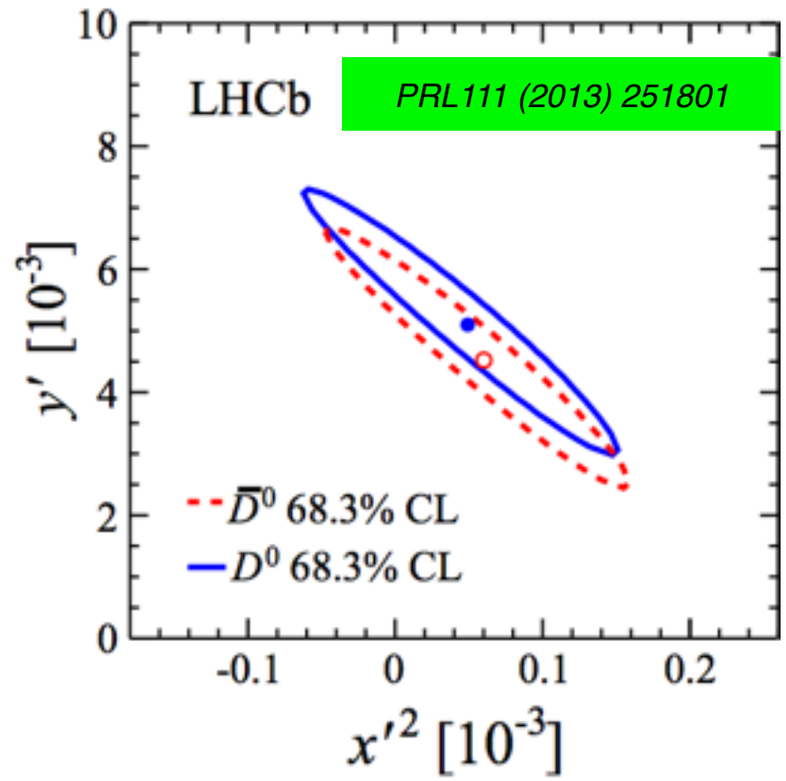
$$M_{\mathrm{BC}} = \sqrt{E^2_{\mathrm{Beam}} - \vec{p}^{\,2}_{D}}$$

Global fit method

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

QC inputs for Charm Physics





Precision CKM test **Charm Mixing & CP violation**

- 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

Strong phase δ and γ/ϕ_3 in the CKM unitarity triangle

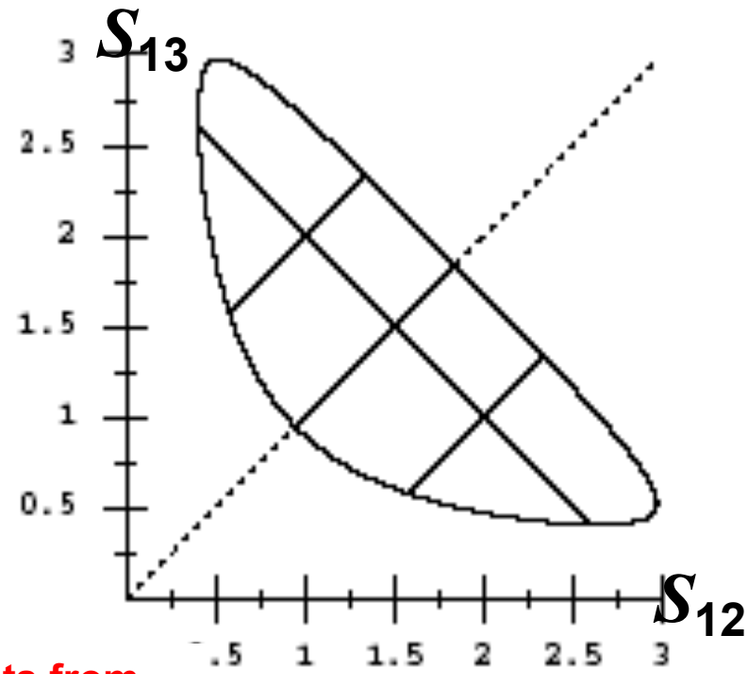
- **D hadronic parameters for a final state f:** $\frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)} \equiv -r_D e^{-i\delta_D}$
- **Charm mixing parameters:** $x = \frac{\Delta M}{\Gamma}$, $y = \frac{\Delta\Gamma}{2\Gamma}$
  - **Time-dependent WS $D^0 \to K^+\pi^-$ rate $\Rightarrow$**
    $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} = (4.8 \pm 1.0) \times 10^{-3}$ (LHCb2013)
  - **$\delta_{K\pi}$: 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:**

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

  - **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



extracted from fit to the $B^{\pm}$ yields — QC measurements from Charm factories

$B^{\pm} \to DK^{\pm}$ yields — from flav.-tagged D→Ksππ

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

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

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

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

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

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

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

c_i, s_i : weighted average of $\cos(\Delta\delta_D)$ and $\sin(\Delta\delta_D)$ respectively where $\Delta\delta_D$ is the difference between phase of D^0 and $\overline{D}^0$

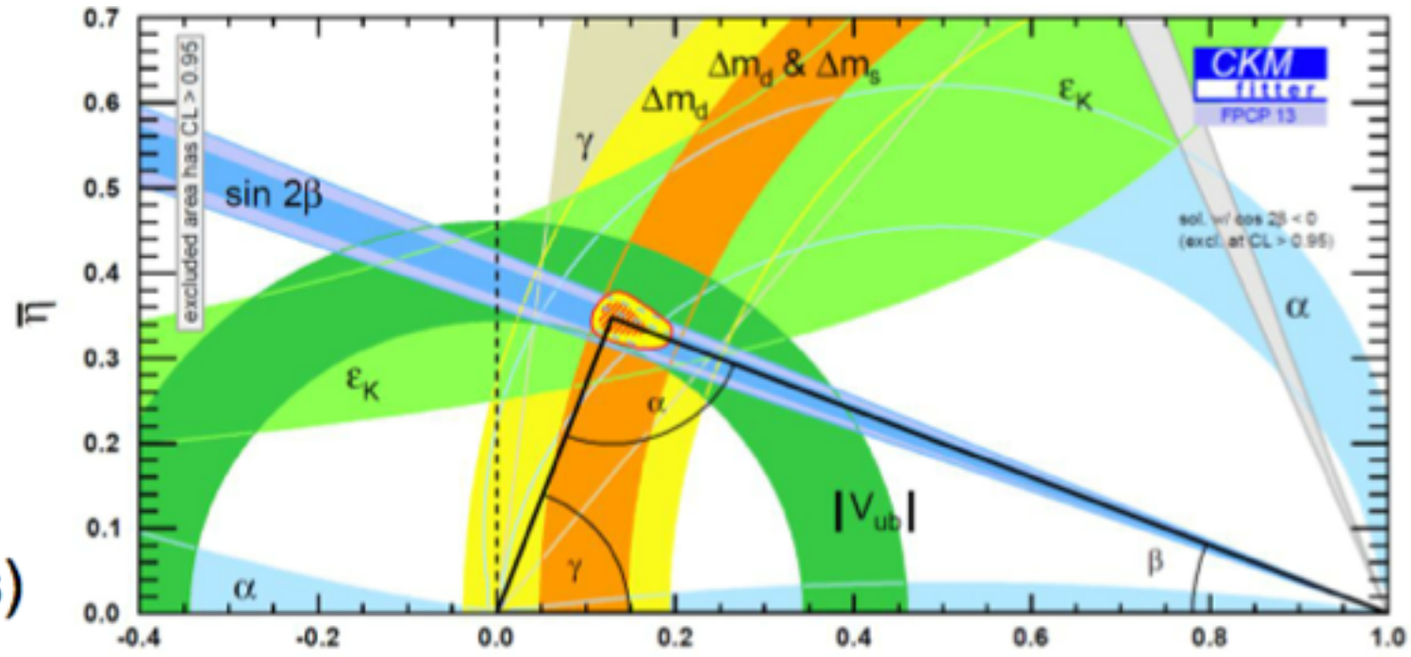
CKM measurements: current status

$$\alpha/\phi_2 = \left(85.4^{+4.0}_{-3.9}\right)^{\circ}$$

$$\beta/\phi_1 = \left(21.38^{+0.79}_{-0.77}\right)^{\circ}$$

$$\gamma/\phi_3 = \left(68^{+8.0}_{-8.5}\right)^{\circ}$$

2013 CKMfitter (direct measurements)



- γ is the least precisely measured angle.
- Precision can still be improved by BESIII with cooperation from BaBar, Belle, LHCb.
- Precise measurement of γ is needed to test the consistency of the CKM UT.
- Any difference between Tree measurements to Loop measurements might be a sign of New Physics in the flavor sector.

Example of γ measurements from Dalitz

Belle Model-Dependent Dalitz [Phys. Rev. D 81, 112002 (2010)]

$$78.4^{+10.8}_{-11.6}(stat) \pm 3.6(syst) \pm 8.9(Model)$$

Belle Model-Independent Dalitz [Phys. Rev. D 85, 112014 (2012)]

$$77.3^{+15.1}_{-14.9}(stat) \pm 4.2(syst) \pm 4.3(c_i/s_i)$$

Currently statistically limited,
but soon systematically limited

Strong Phase $\delta_{K\pi}$

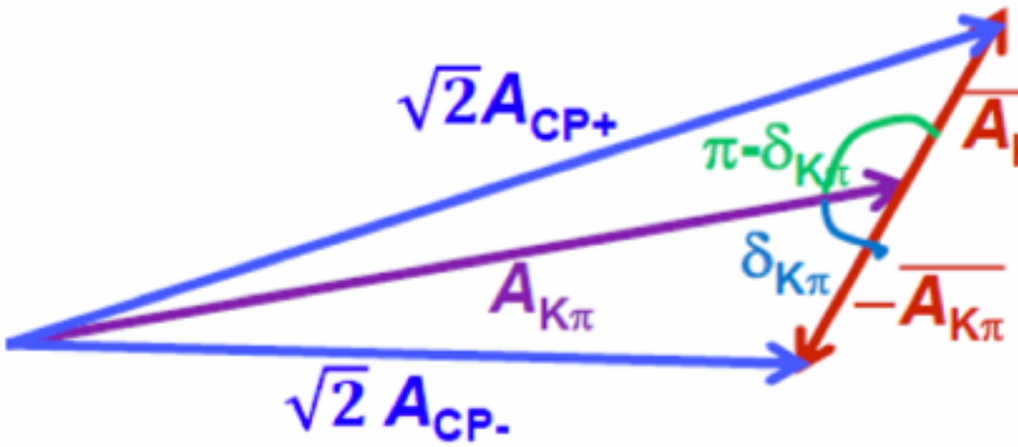
arXiv:1404.4691 (BESIII: 2.9 fb^{-1})

Strong phase:

$$\frac{\left\langle K^-\pi^+\middle|\overline{D}^0\right\rangle^{DCS}}{\left\langle K^-\pi^+\middle|D^0\right\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

Quantum correlation → Interference → access strong phase!

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



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

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

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

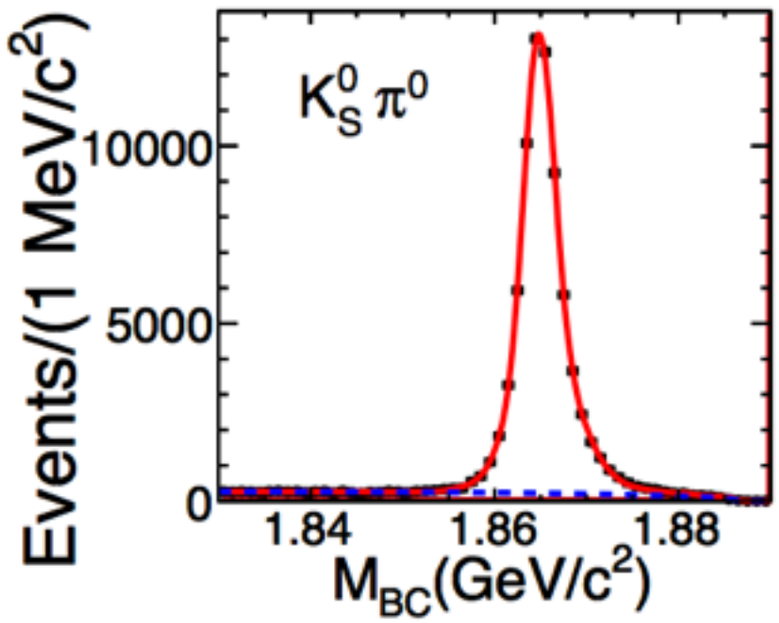
Strong Phase $\delta_{K\pi}$

arXiv:1404.4691

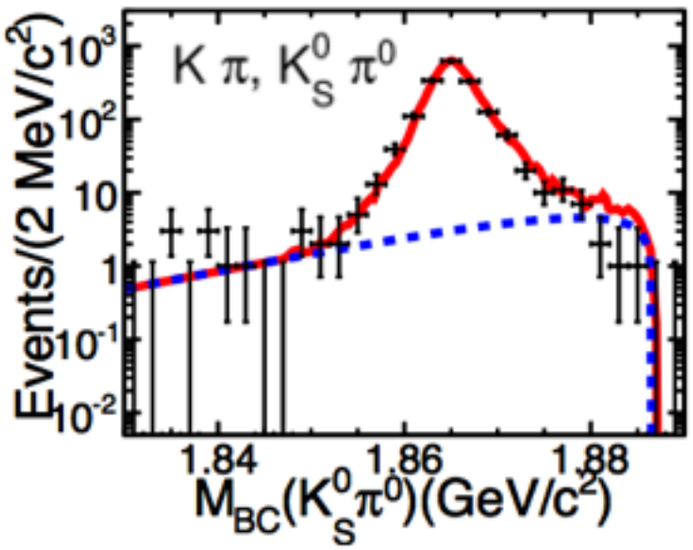
(BESIII: 2.9 fb^{-1})

- **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**
- $Br(D_{CP\pm} \to K\pi) = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}$
  - $n_{K\pi,CP\pm}$ 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 results:

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

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

arXiv:1404.4691

(BESIII: 2.9 fb^{-1})

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

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

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

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

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**
- **In 20 /fb BESIII data, precision of $\cos\delta_{K\pi}$ will reach ~0.05**
  → updated LHCb: stat. $\sigma(\phi_3)$ will be ~1.3° ***EPJC73, 2373(2013)***
  We need super-charm factory for a 1 /ab data, which can improve $\sigma(\phi_3)$ due to strong phase to ~1°!

c_i, s_i in $D^0 \to K_{S,L}\pi^+\pi^-$ Dalitz analysis

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

from flav.-tagged D→Ksππ

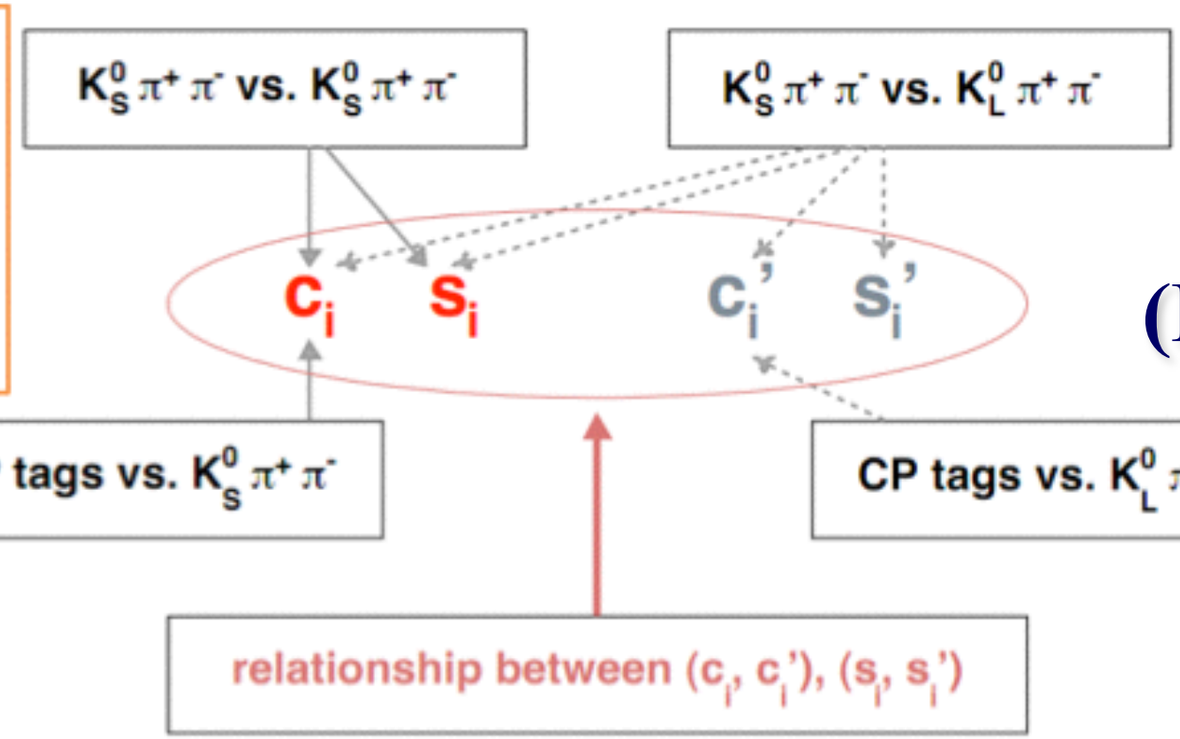
extracted from fit to the $B^\pm$ yields

measured by CLEO [PRD82, 112006 (2010)]

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

We can calculate c_i and s_i from double tags of
$D^0 \to K_S\pi^+\pi^-$ vs $D^0 \to (K_{S,L}\pi^+\pi^-$ or CP eigenstates)

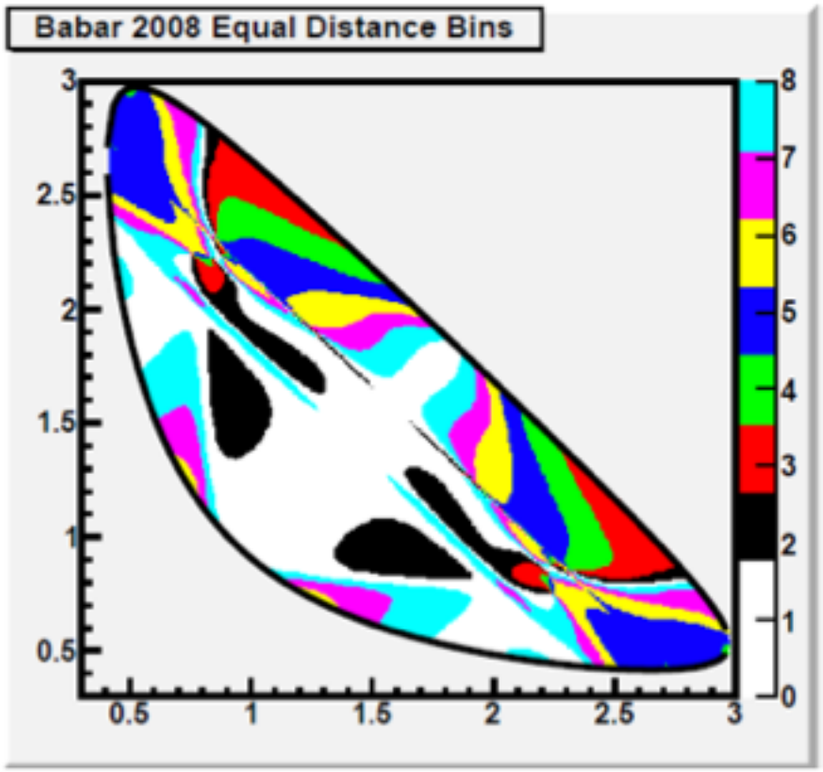
A relationship can be shown between Dalitz bin yields and c_i and s_i (in backup slides)



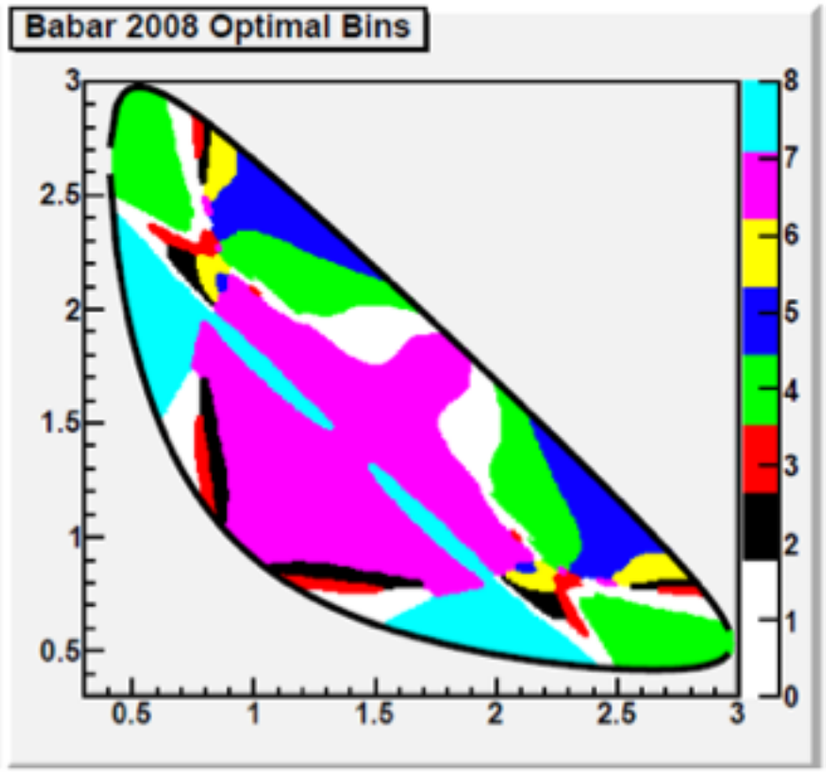
(BESIII: 2.9 fb^{-1})

Only c_i, s_i from $K_S\pi^+\pi^-$ is used to calculate γ.
However adding in $D^0 \to K_L\pi^+\pi^-$ we can calculate c'_i, s'_i and use how they relate to c_i, s_i to further constrain our results in a Global fit.

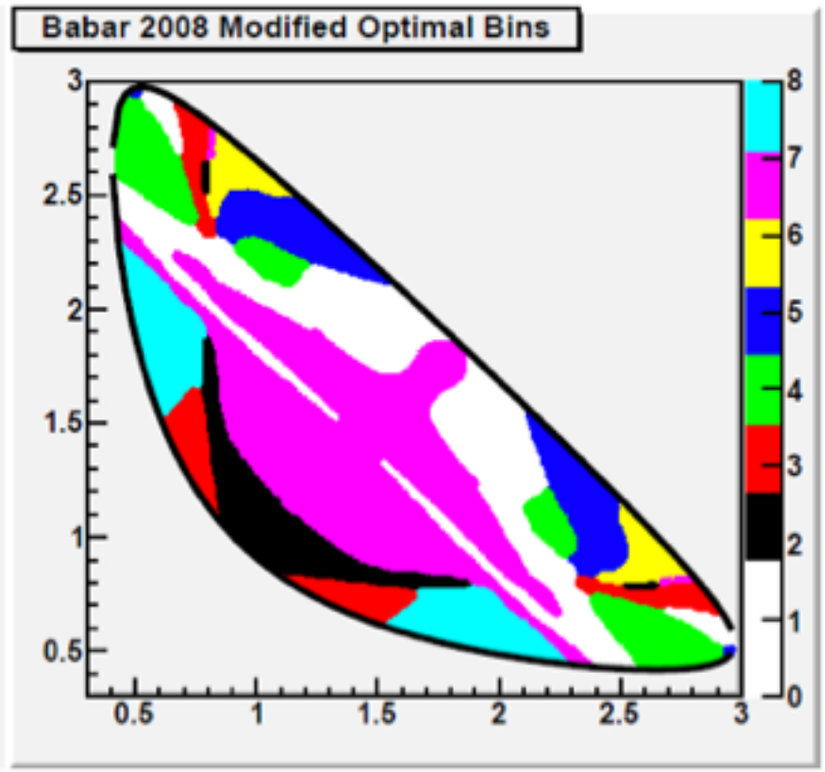
Binning in Dalitz plots



Result of splitting the Dalitz phase space into 8 equally spaced phase bins based on the BaBar 2008 Model.

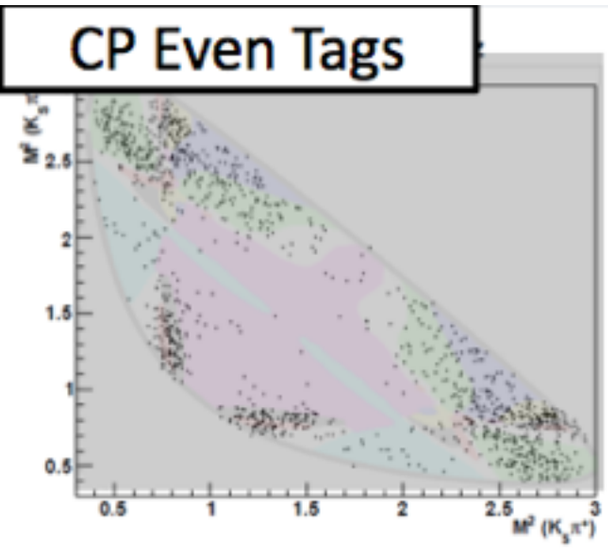


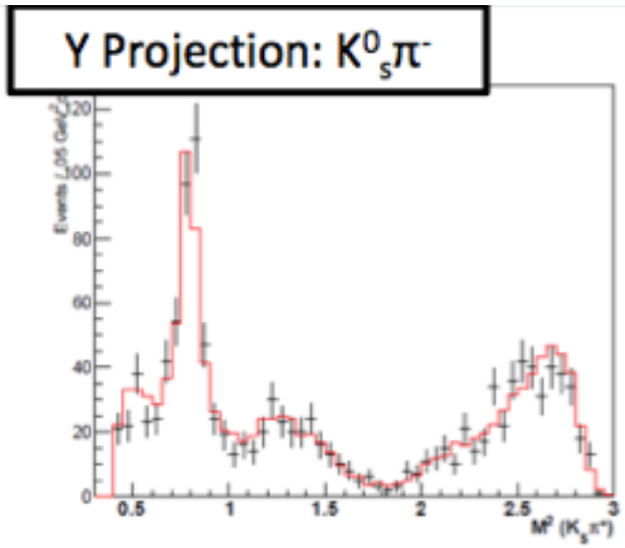
Starting with the equally spaced bins, bins are adjusted to optimize the sensitivity to γ. A secondary adjustment smooths binned areas smaller than detector resolution.

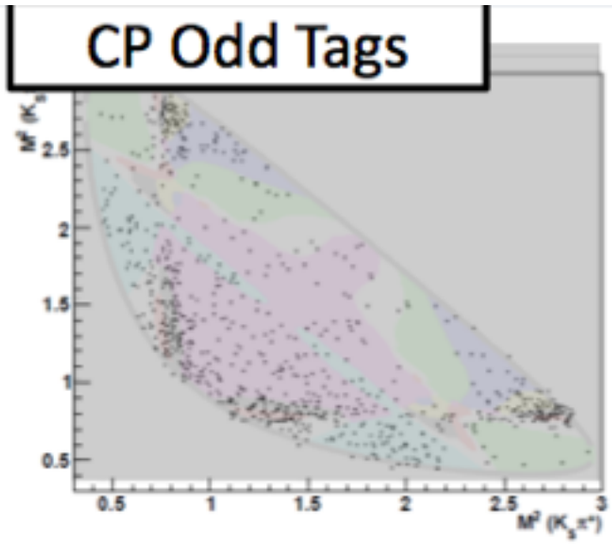


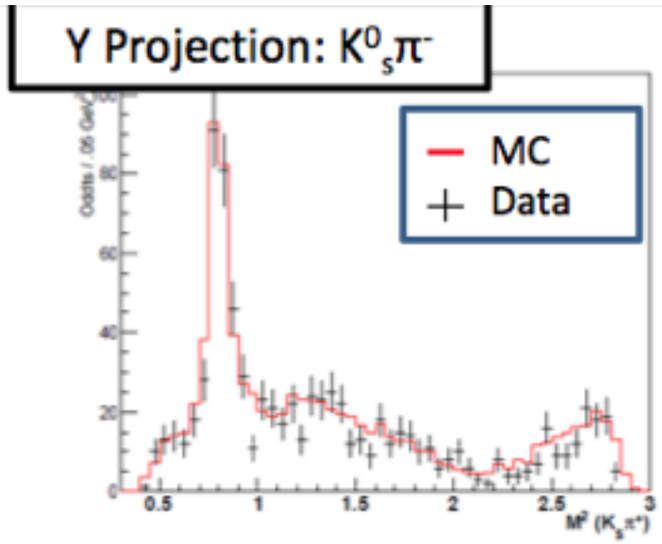
Similar to the “optimal binning” except the expected background is taken into account before optimizing for γ sensitivity.

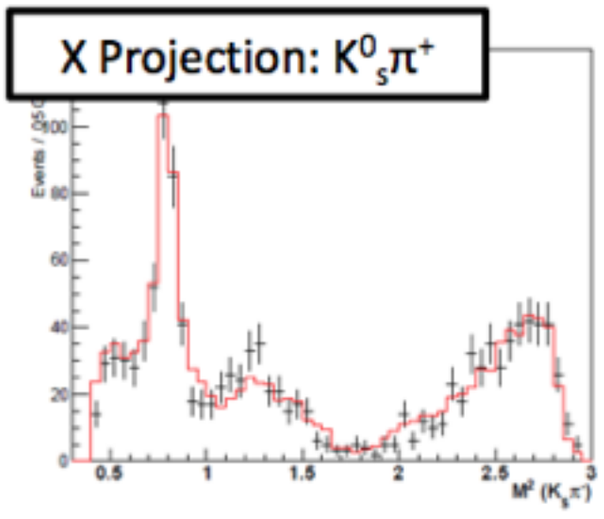
$K^0_S\pi^+\pi^-$ Dalitz plots vs *CP* Modes

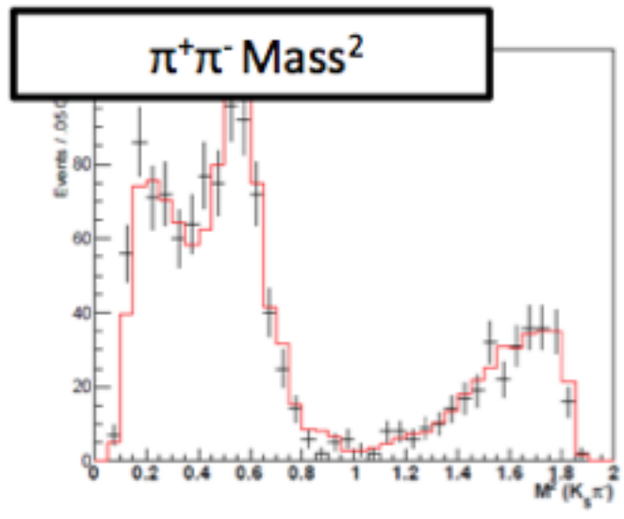


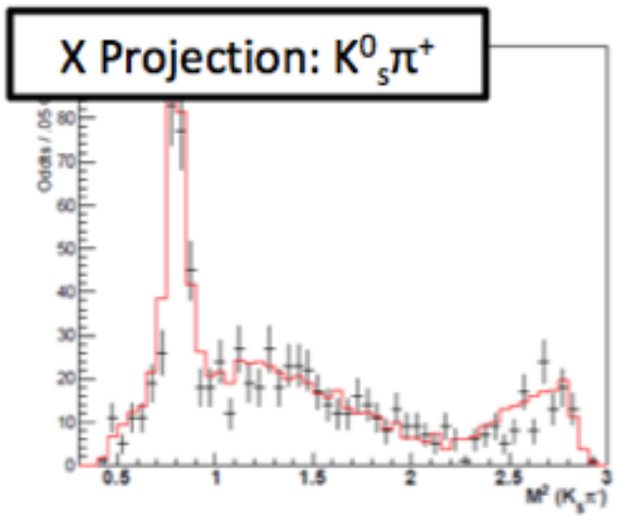


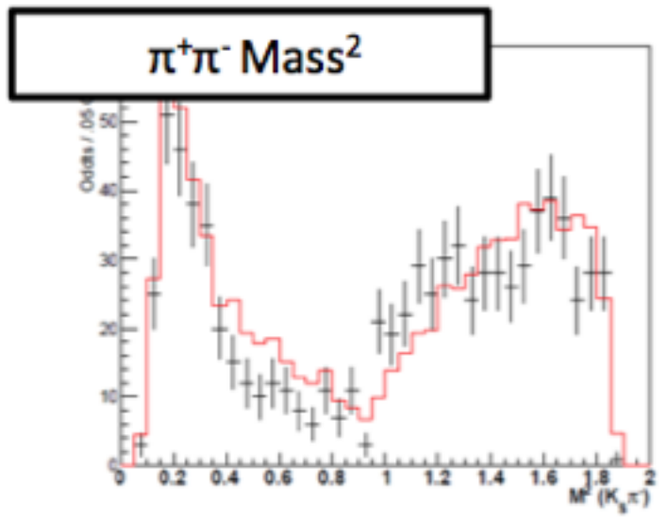










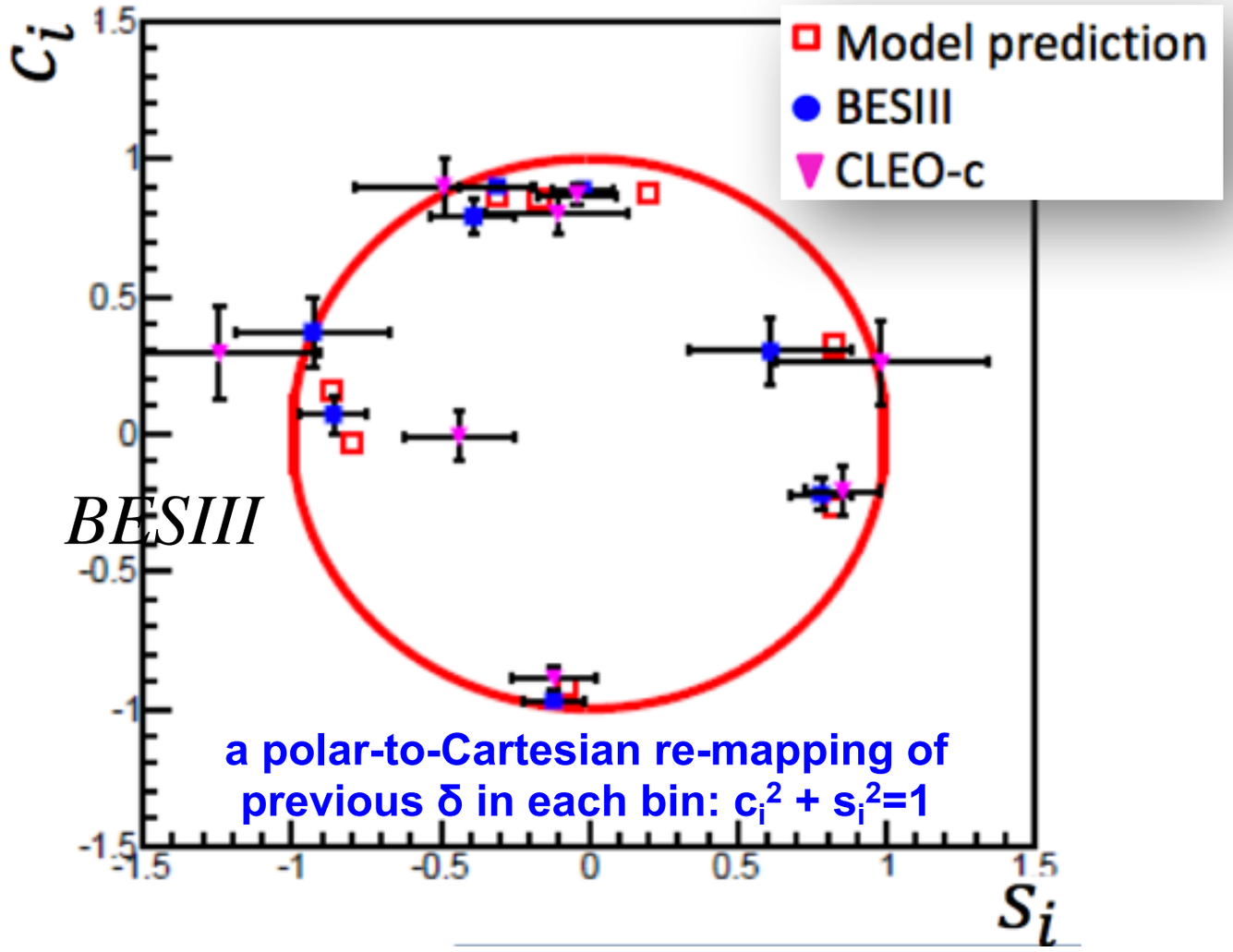


- Data is using the full 2.9 fb^{-1} $\psi(3770)$ dataset
- Results presented here will be using Optimal Binning scheme.

Type	Tag List
Dalitz	$K_S\pi^+\pi^-$, $K_L\pi^+\pi^-$
Flavored	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$
S^+	K^+K^-, $\pi^+\pi^-$, $K_S\pi^0\pi^0$, $K_L\pi^0$
S^-	$K_S\pi^0$, $K_S\eta(\to\gamma\gamma)$, $K_S\eta(\to\pi^+\pi^-\pi^0)$, $K_S\omega$, $K_S\eta'$

BESIII preliminary

Preliminary Data Results



- Still statistical limited.
- Only statistical errors are listed.
- Consistent agreement with CLEO-c measurements, but superior in statistical errors

- Based on the BESIII results, we expect a reduction in the (c_i, s_i) contribution to the uncertainty in γ/ϕ_3 of ~40% (**~80% in 20 /fb data**).

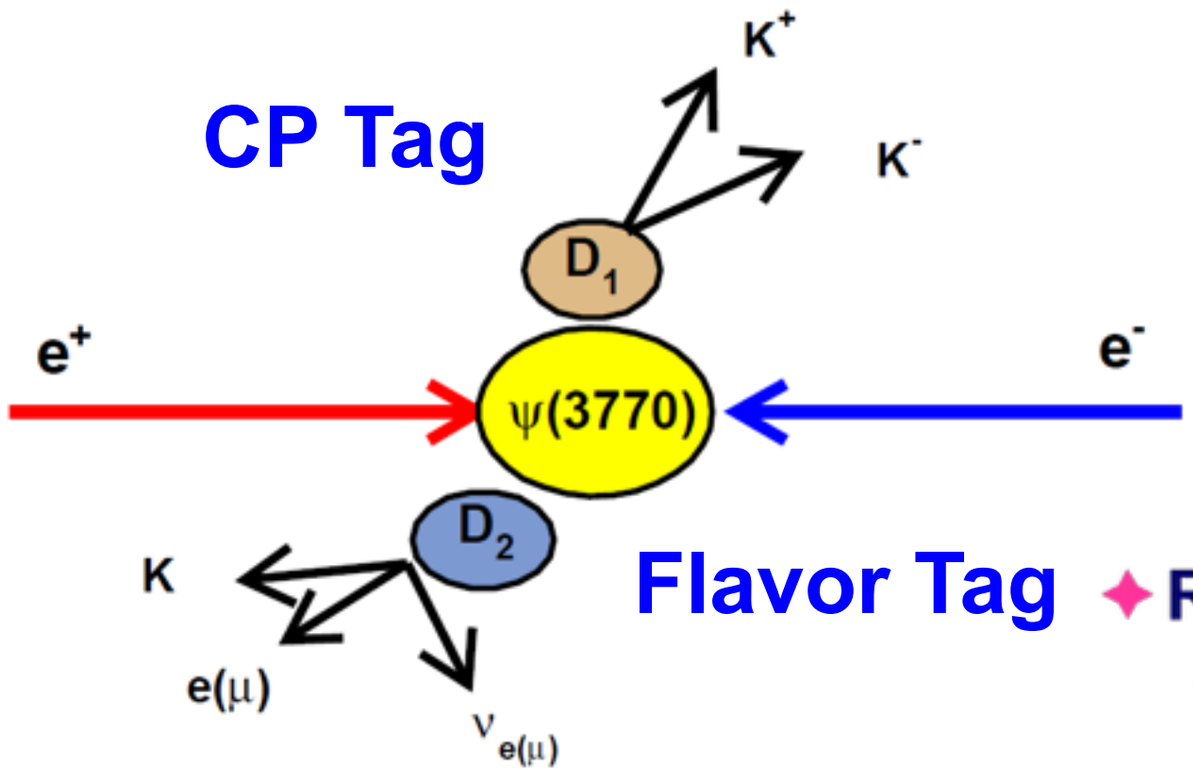
$$77.3^{+15.1}_{-14.9}(stat) \pm 4.2(syst) \pm \boxed{4.3(c_i/s_i)} \rightarrow \boxed{\pm 2.5\ (\mathbf{0.9})\ (c_i/s_i)}$$

- Crucial inputs for the future analysis carried out in the LHCb and super-B experiment (stat. sensitivity reaches 1~2°).

y_{CP} measurement

(BESIII: 2.9 fb^{-1})

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

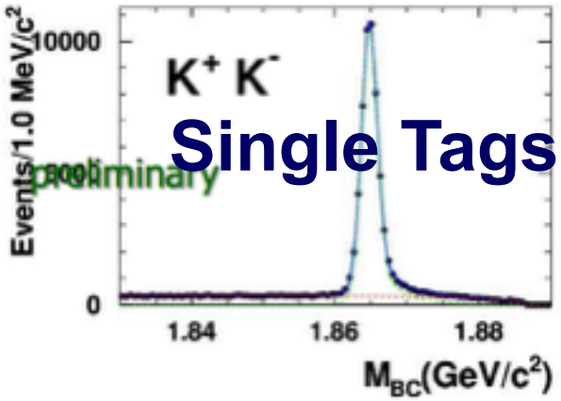


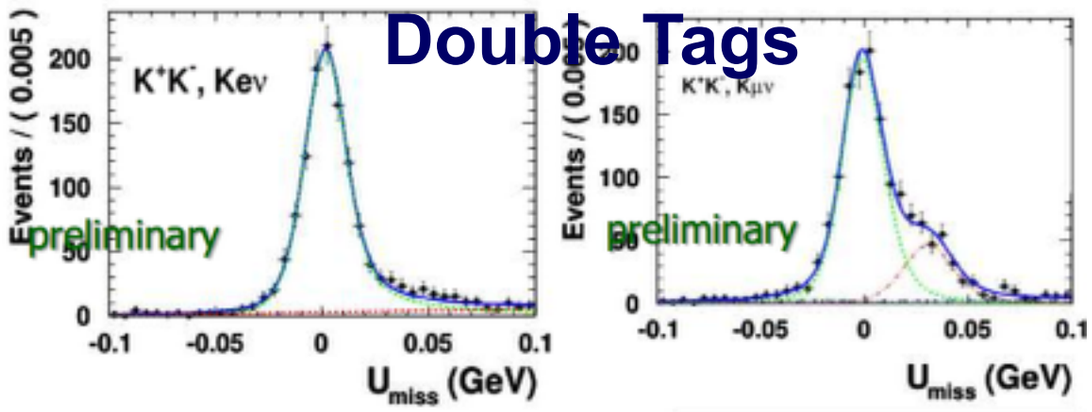
- **Single Tag decay rate (CP tags)**
  - $\Gamma_{CP\pm} \propto 2|A_{CP\pm}|^2(1 \mp y)$
- **Double Tag decay rate (Flavor tags + CP tags)**
  - $\Gamma_{l;CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$
- **Neglect term y^2 or higher order**
  - $y_{CP} \approx \frac{1}{4}\left(\frac{\Gamma_{l;CP+}\Gamma_{CP-}}{\Gamma_{l;CP-}\Gamma_{CP+}}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

- **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})

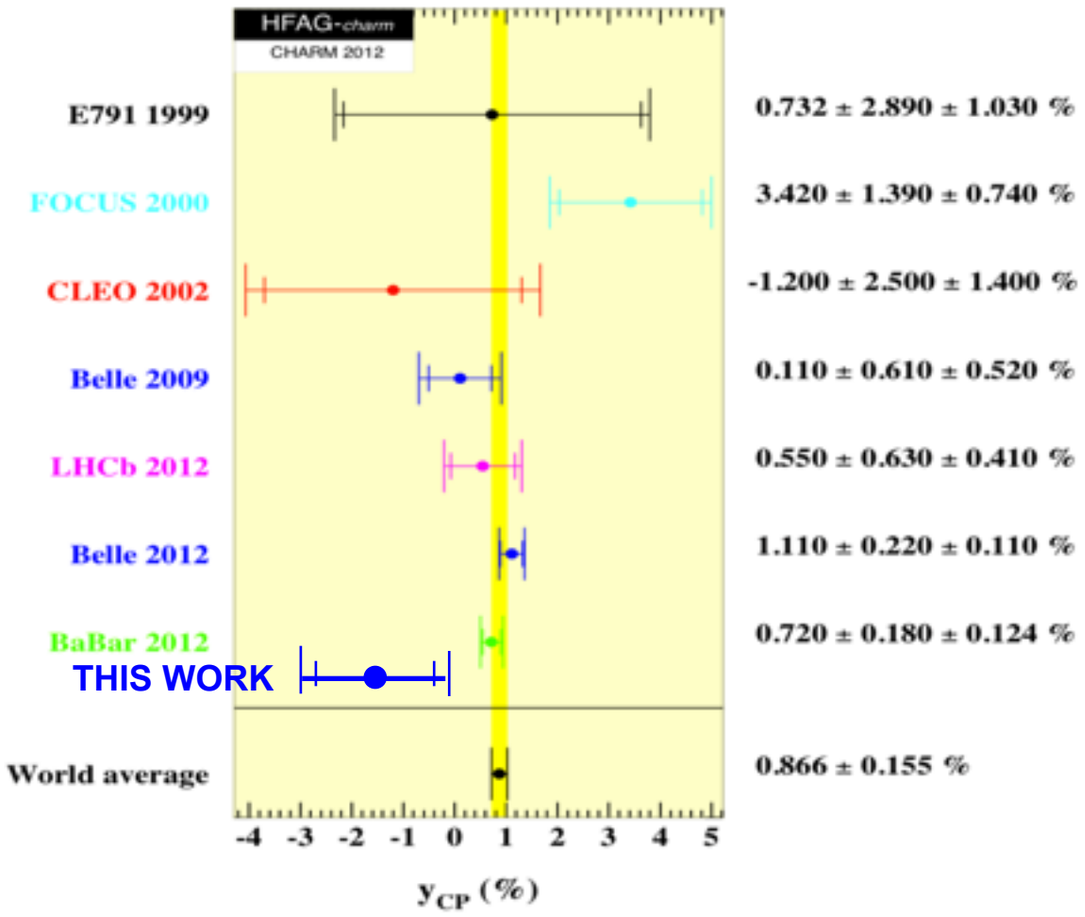




- **Signal reconstruction:**
  - **Single tag yields extraction:**
    - Singal shape: σ⊗MC-truth
    - Background: ARGUS function
    - Kinematic variable: M_{BC}
  - **Double tag yields extraction:**
    - Singal shape: σ⊗MC-truth
    - Background: Polynomial
    - $K\pi\pi^0$ background shape from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

      $U_{miss} = E_{miss} - |\vec{P}_{miss}|$ (≈0 for signals)
- **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: $y_{CP} = y$**



Other Quantum Correlation work

Coherence factors: feed into CKM γ/ϕ_3 with B's

$K^-\pi^+\pi^0$
$\pi^+\pi^-\pi^0$
} likely to pursue both model-independent analyses, and also detailed Dalitz analyses

+ other modes e.g., $K^-\pi^+\pi^+\pi^-$ & $K_SK^+\pi^-$ have been done by CLEO-c

BESIII will publish these works in the future with best precisions.

BESIII runs in the future

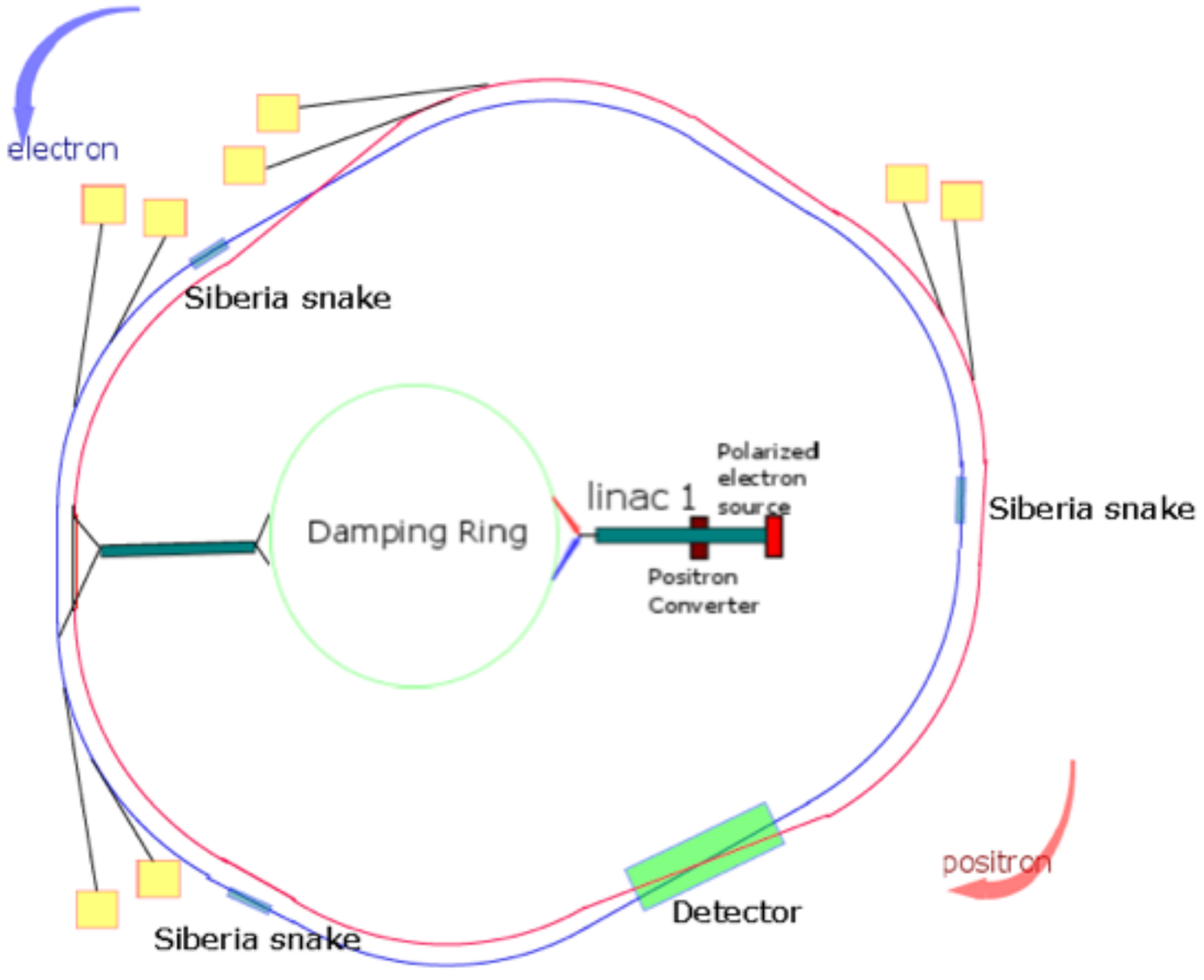
Future Runs: (no particular order)

- lower-energy R scan
- $D_s^* D_s$ data @ 4170 MeV
- More ψ(3770), J/ψ, ψ'
- More "XYZ"

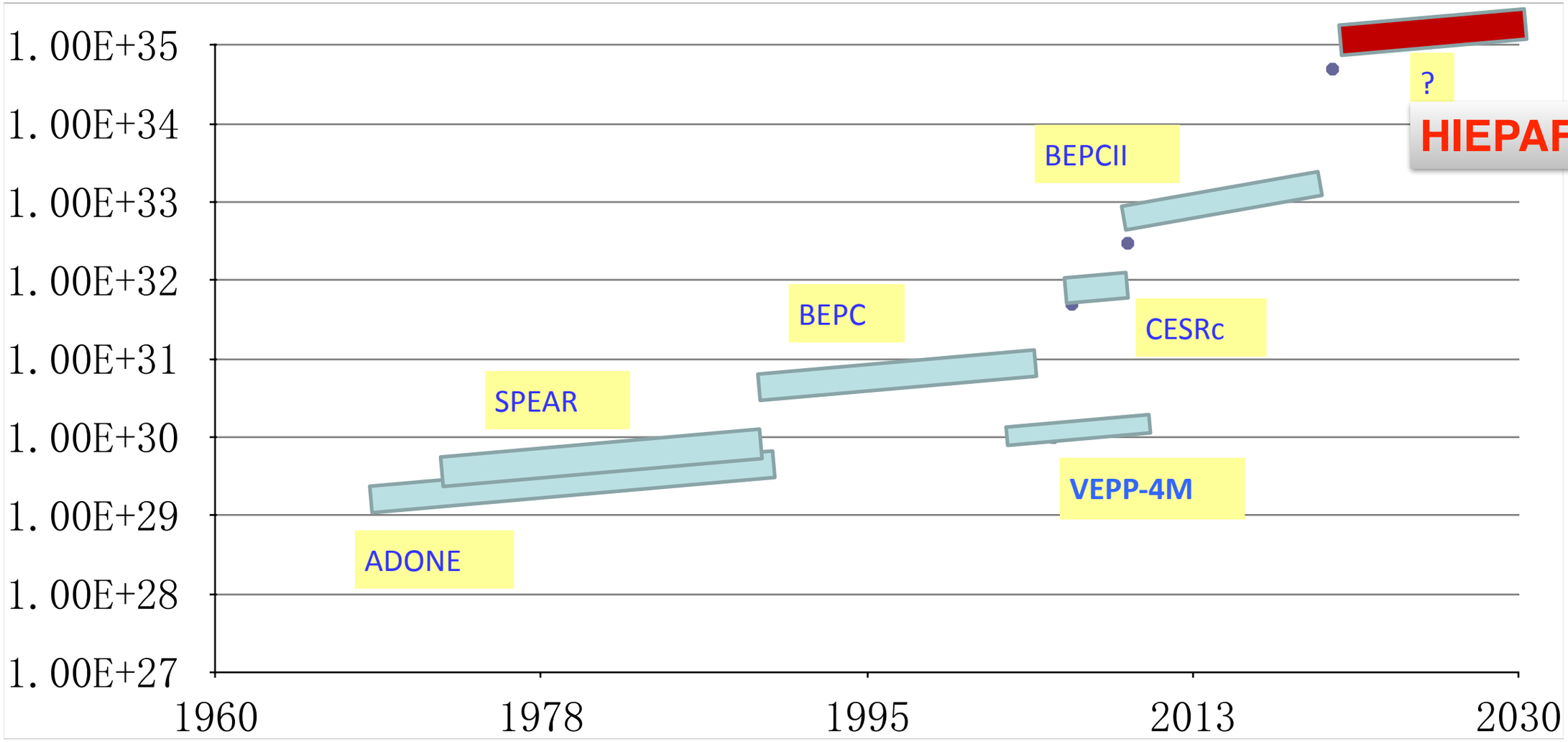
Easy to feed the BESIII spectrometer in many years!

High Intensity Electron Positron Accelerator Facility (HIEPAF)

- **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.**



HIEPAF


Luminosity(cm-2s-1)
1.00E+35
1.00E+34
1.00E+33
1.00E+32
1.00E+31
1.00E+30
1.00E+29
1.00E+28
1.00E+27
1960
1978
1995
2013
2030
?
HIEPAF
BEPCII
BEPC
CESRc
SPEAR
VEPP-4M
ADONE

HIEPAF Study Time Line

2013				2014				2015				2016				2017			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

Kick-off
collaboration forming

Workshops
Feasibility study
Review

CDR, R&D → TDR?

Direct CP violation in D->hh

- World measurements of $\Delta A_{CP} = A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)$

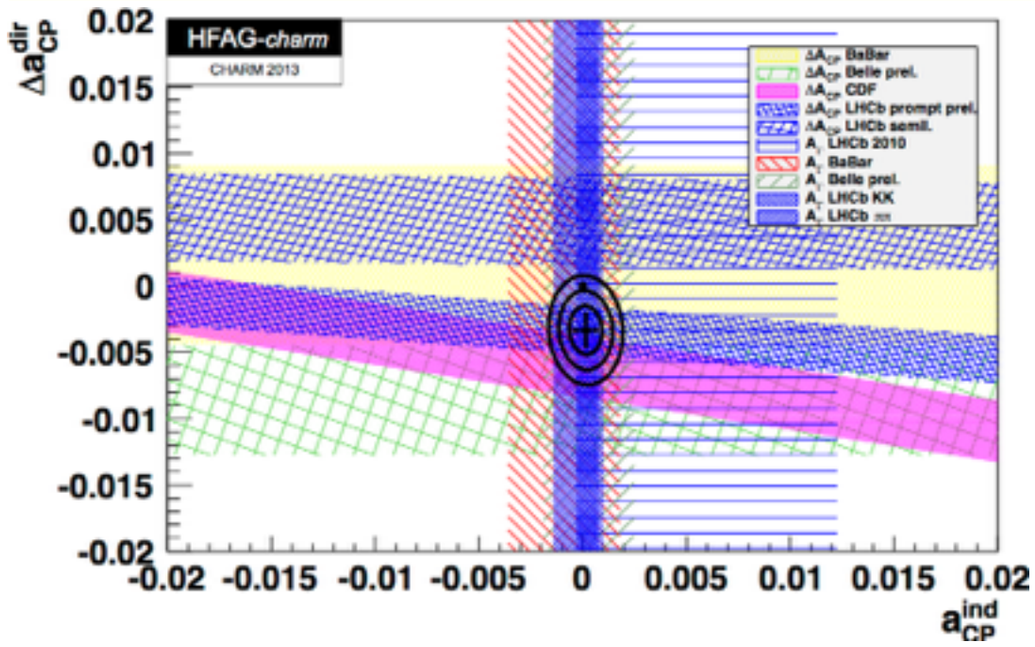
HFAG world-average:

- $\Delta A_{CP} = (-0.33 \pm 0.12)\%$

the individual asymmetries:

- $A_{KK} = -0.16 \pm 0.20$
- $A_{\pi\pi} = +0.16 \pm 0.21$

No CPV observed yet in charm sector.



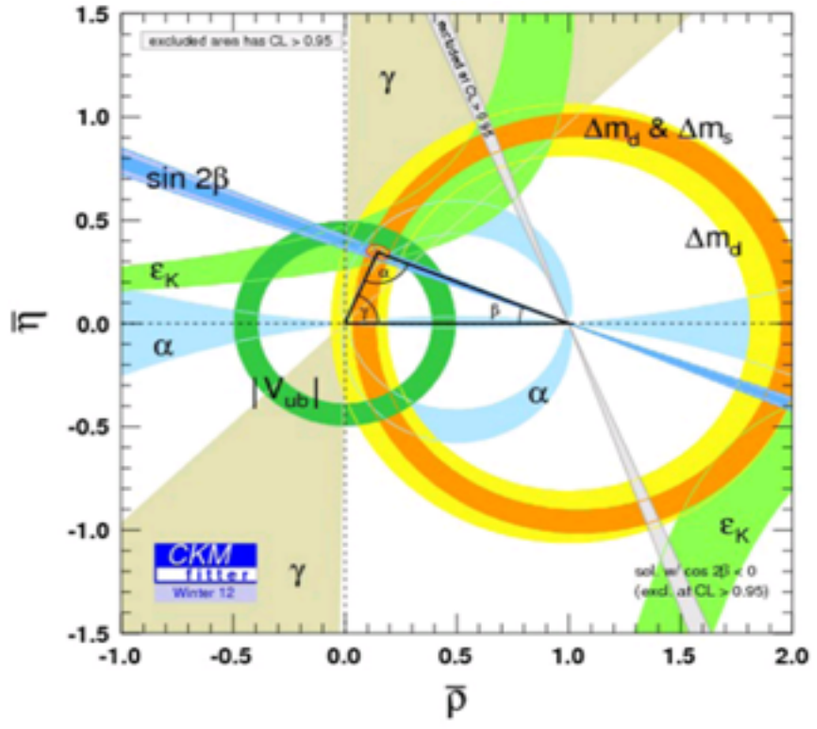
- In New Physics: *CPV* up to ~1%;
- If *CPV* ~1% were observed, is it NP or hadronic enhancement of SM?
- **Strategy**: analyze many channels to elucidate source of CPV.
- 50ab^{-1} BELLE-II data can reach to sensitivity of 10^{-3}~10^{-4} for different channels
- Measurement of direct *CPV* at threshold at HIEPAF with 1ab^{-1} data, sensitivity: **10^{-3}~10^{-4}**
- clean background and better systematic control in threshold production would be complementary to the future *B* factory results

Determination of the γ angle in the CKM matrix

The cleanest way to extract γ is from *B*→*DK* decays:

- current uncertainty σ(γ) ~8°
- however, theoretical error: 10^{-6} (!)
- over-constrain the Unitarity Triangle

Information of ***D* decay strong phase** is needed, which can only be accessed through quantum coherence of *DD* production at threshold:



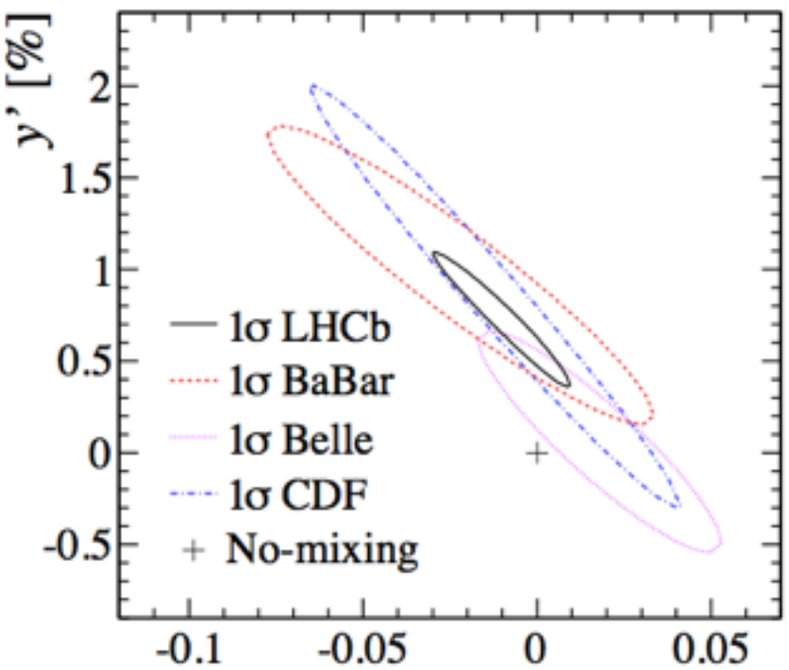
- ADS method: use D doubly Cabibbo-suppressed decays, e.g. $D^0 \to K^+\pi^-$
  - ✓ With 1 ab^{-1} at HIEPAF: $\sigma(\cos\delta_{K\pi}) \sim 0.007$; $\sigma(\delta_{K\pi}) \sim 2^o$
  - ✓ With this data, upgraded LHCb: $\sigma(\gamma) \sim 1.3^o$
- GGSZ method: use Dalitz plot analysis of 3-body D^0 decays, e.g. $K_s\pi^+\pi^-$; high statistics; need precise Dalitz model
  - ✓ Belle results from GSSZ method in 2012: $\gamma=(77\pm15\pm4\pm4)^o$ → **from *D* decay model**
  - ✓ HIEPAF would reduce the contribution of *D* Dalitz model to a comfort level of ~0.1°, since expected precision from future B projects would be ~2°.

D–$\underline{D}$ mixing at HIEPAF

- **D^0 – $\underline{D^0}$ mixing rate at threshold**

charm mixing is established!

$$R_M = \frac{x^2 + y^2}{2} = \frac{N[(K^{\pm}\pi^{\mp})(K^{\pm}\pi^{\mp})]}{N[(K^{\pm}\pi^{\mp})(K^{\mp}\pi^{\pm})]}$$



with 1ab^{-1} data:

- $R_M = (x^2+y^2)/2 \sim 10^{-5}$ in Kπ and Keν channels
- Probe y: $\Delta y_{CP} < 0.1\%$

While at LHCb by 2015 assuming 5 fb^{-1} @ 14 TeV:

- $(x'^2, y') \pm (0.004, 0.08)\%$ with WS $D^0 \to K\pi$
- D^0-D^0 WS rate asymmetry (like $|q/p|$) ±1%
- y_{CP}, A_Γ ± 0.02% in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays
- $(x,y) \pm (0.045, 0.030)\%$ using $D^0 \to K_S\pi\pi$

- **Implication of strong phase**
  - phase to relate (x', y') with (x, y)
  - upgraded LHCb/BELLE-II expect statistical error

$$\sigma(x,y) \sim 0.2 \times 10^{-3},\ \sigma(r_{CP}) \sim 1\%, \sigma(\alpha_{CP}) \sim 0.7^\circ$$

arXiv:1209.0172

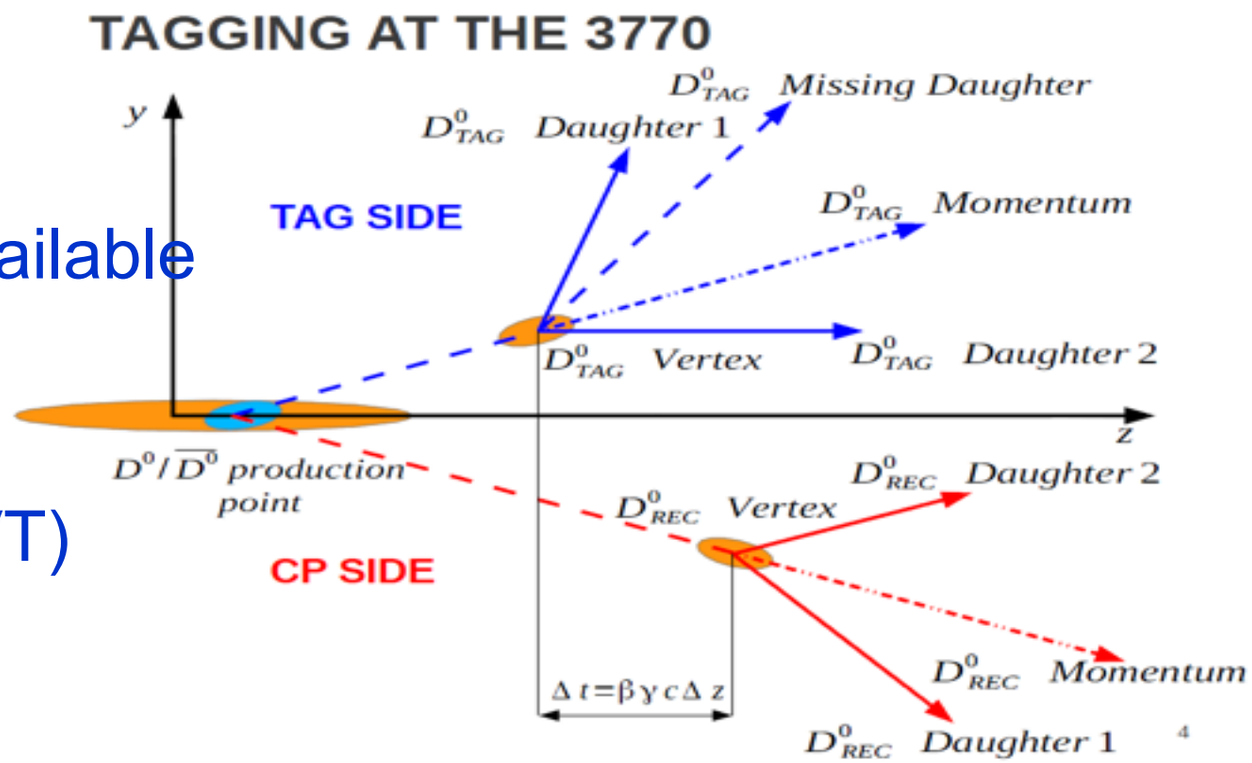
  - 1 ab^{-1} D data at HIEPAF would reach to the sub-level of the above stat. errors

Asymmetric beam? charm mixing at Ψ(4040)?

- Flavor tagging($D^0 \to K^- l^+ \nu$)
- Time-dependent measurement available

$$\mathcal{A}(\Delta t) = \frac{\bar{\Gamma}(\Delta t) - \Gamma(\Delta t)}{\bar{\Gamma}(\Delta t) + \Gamma(\Delta t)}$$

- Require good $\Delta z/\Delta t$ resolution (SVT)



Considering $\Psi(4040) \to DD^* \to DD\gamma$, DD pairs are in C-even states and charm mixing contribution is doubled compared with time-dependent (un-correlated) case.

CPV and D mixing reach

courtesy by Neri&Rama

3 ab^{-1} data @Ψ(3770):
asymmetric γβ=0.2~0.6
3 ab^{-1} data @Ψ(4040)
50 fb^{-1} data at upgrade LHCb
50 ab^{-1} at BELLE-II

Parameter	Ψ(3770)	Ψ(4040)	LHCb	Belle-II
$x(\%)$	0.02-0.05	0.03	0.015	0.08
$y(\%)$	0.02-0.03	0.03	0.010	0.04
$\lvert q/p \rvert(\%)$	2-5	0.9	1	5
$\arg(q/p)(^\circ)$	2-3	0.8	3	2.6

Summary

- ✦ BESIII has started to be involved in the world campaign on identifying the $D\underline{D}$ oscillation, searching for the *CPV* in charm and over-constraining the CKM unitarity triangles.
  - ‣ We provide unique data on strong phases.
  - ‣ Many more QC analyses are undergoing.
  - ‣ The simultaneous fitting package has been developed at BESIII. The package will be applied on measuring strong phases and mixing parameters.
- ✦ Possible extensions: C-even (C=+1) Quantum Correlated Analysis $\boldsymbol{D^0\underline{D}^0\gamma}$, $\boldsymbol{D^0\underline{D}^0\pi^0}$ from higher-energy data?
- ✦ Project of a super-tau-charm factory in China is being proposed

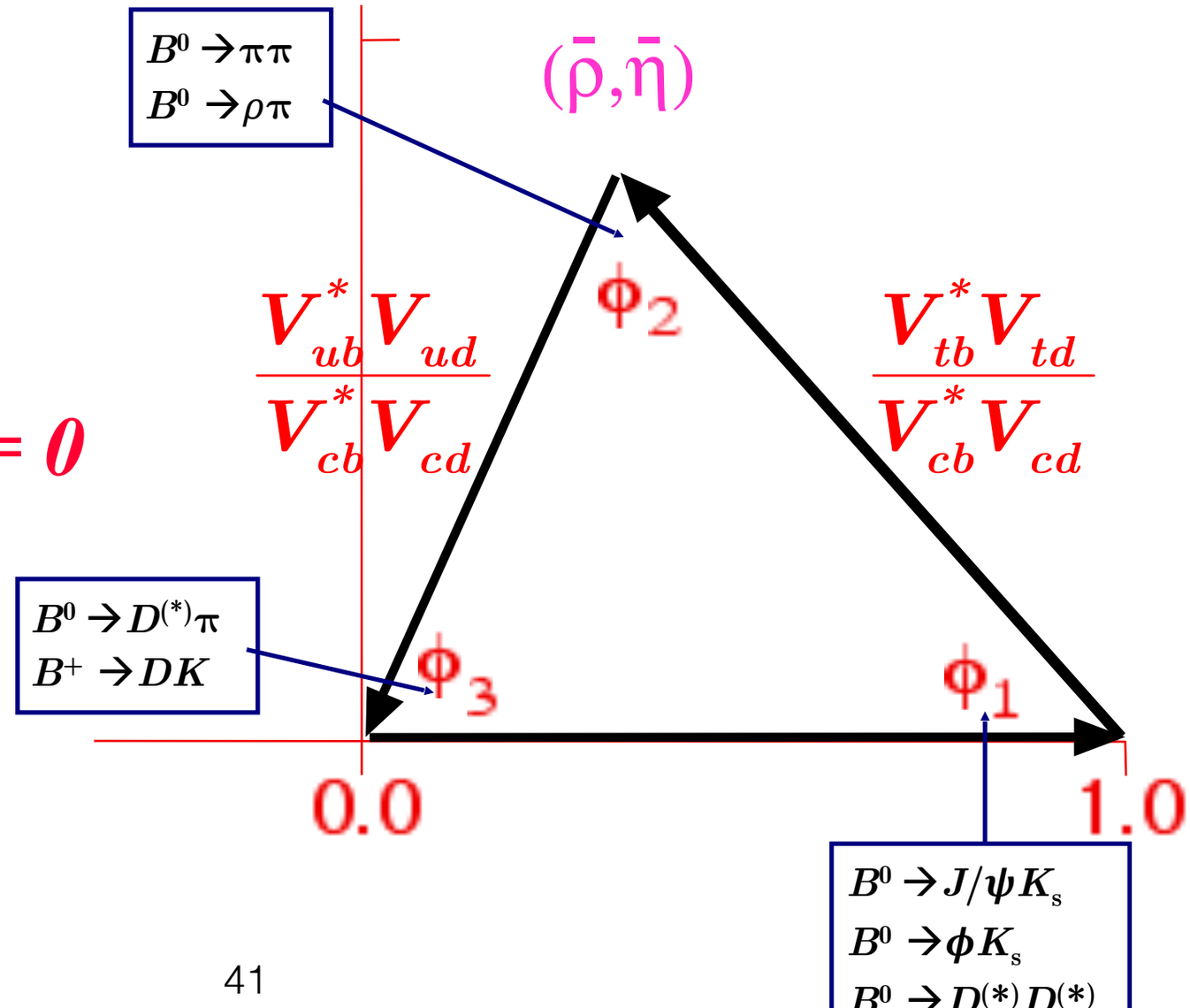
Backup

Unitarity Triangle

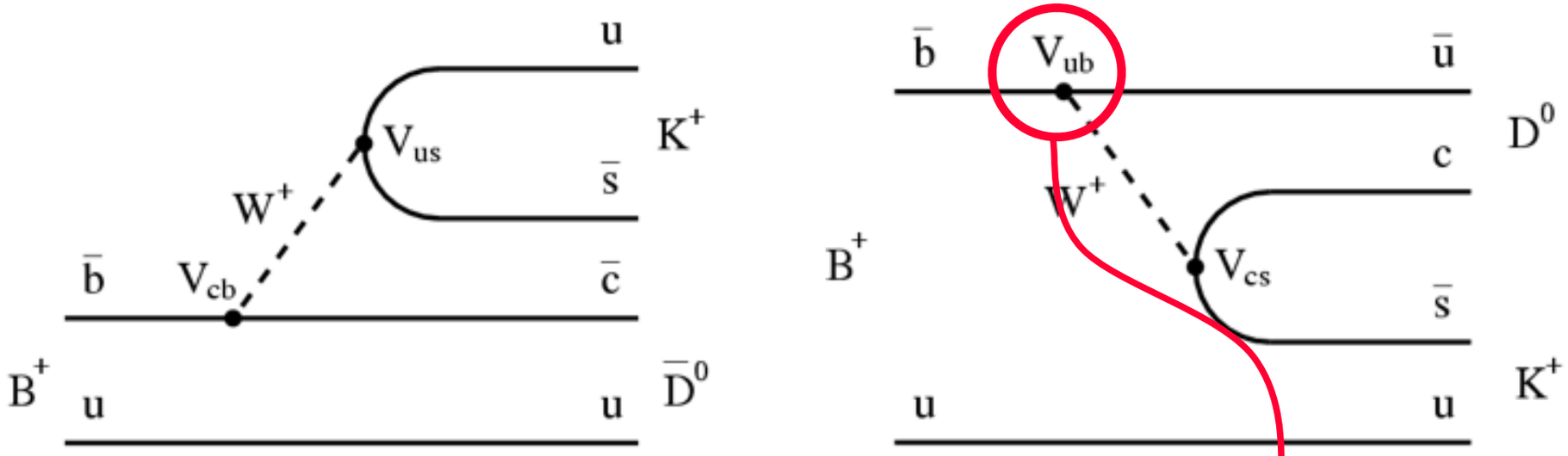
$$V^{+}V = I \Rightarrow \begin{pmatrix} V_{ud}^{*} & V_{cd}^{*} & V_{td}^{*} \\ V_{us}^{*} & V_{cs}^{*} & V_{ts}^{*} \\ V_{ub}^{*} & V_{cb}^{*} & V_{tb}^{*} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix}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

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

(B system)



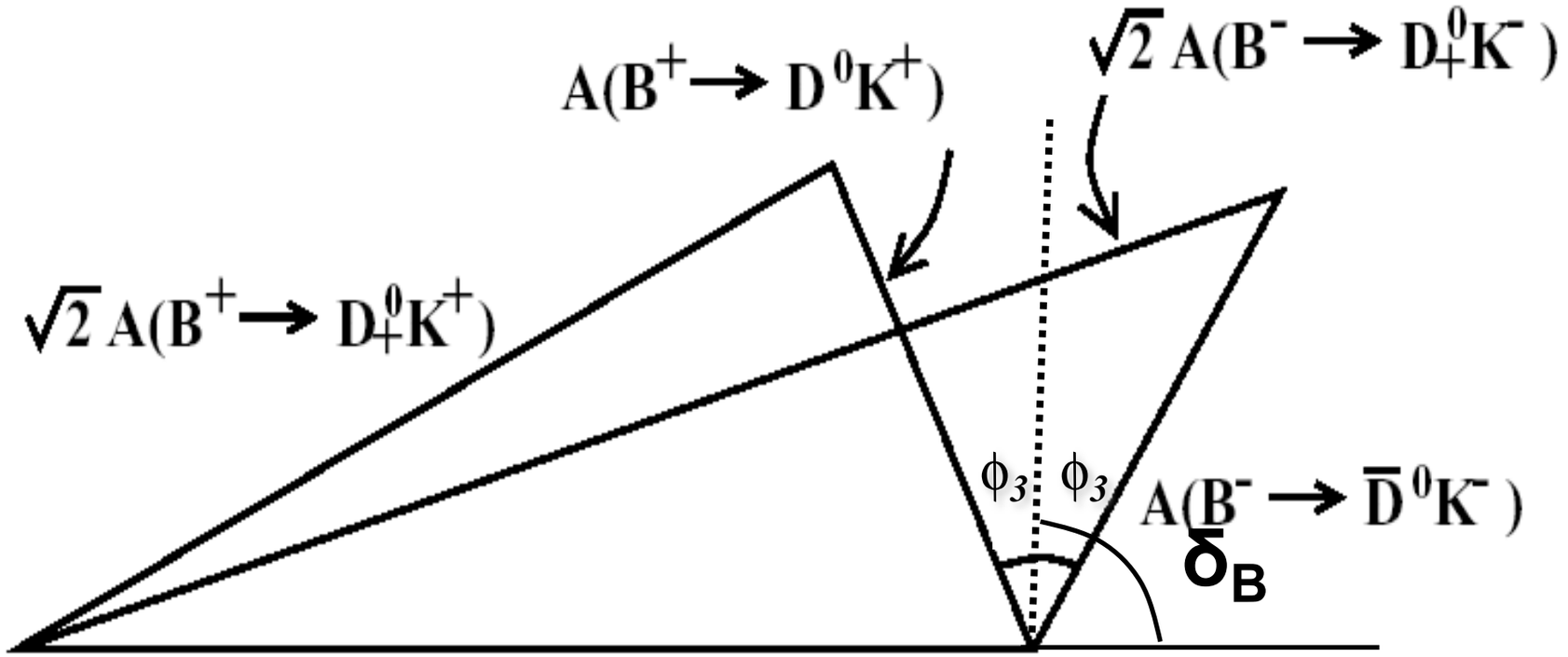
ϕ_3 from $B^- \to D^0 K^-$



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

- ★ No hadronic uncertainty
- ★ Three methods for exploiting interference (choice of D^0 decay modes):
  - ✤ Gronau, London, Wyler (GLW): Use CP eigenstates of $D^{(*)0}$ decay, e.g. $D^0 \to K_s\pi^0$, $D^0 \to \pi^+\pi^-$
  - ✤ Atwood, Dunietz, Soni (ADS): Use doubly Cabibbo-suppressed decays, e.g. $D^0 \to K^+\pi^-$
  - ✤ Giri, Grossman, Soffer, Zupan (GGSZ): Use Dalitz plot analysis of 3-body D^0 decays, e.g. $K_s\pi^+\pi^-$; high statistics; need precise Dalitz model
- ★ Problem: statistics

Gronau-Wyler original method



$$A(B^+ \to \bar{D}^0 K^+) = A(B^- \to D^0 K^-)$$

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**
  - $B^+ \to DK^+$ **and** $B^+ \to \overline{D}K^+$ **follows by** $D\ (\overline{D}) \to f$
- **To get a common final state** f**, we need**
  - **Double Cabibbo Suppression (DCS):** $f = K^+\pi^-$, K^+K^-
  - K **-** $\overline{K}$ **mixing:** $f = K_S\pi^0$, $K_S\pi^+\pi^-$
- 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:**

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

- r_D, δ_D **:measured from Charm factory (see next slides)**
- (r_B, δ_B, ϕ_3) **3 unknowns, 4 measurements** $\Rightarrow \phi_3$

Calculation of c_i, c'_i, s_i, s'_i

From the CP tag modes, we are able to find c_i and c'_i

' indicates numbers from $K_L\pi^+\pi^-$ decays

$M_i = \frac{S_\pm}{2S_f}(K_i \pm 2c_i\sqrt{K_iK_{\bar{i}}} + K_{\bar{i}})$	$(CP, K^0_S\pi^+\pi^-)$
$M'_i = \frac{S_\pm}{2S_f}(K'_i \mp 2c'_i\sqrt{K'_iK'_{\bar{i}}} + K'_{\bar{i}})$	$(CP, K^0_L\pi^+\pi^-)$

M_i yields in each bin of Dalitz plot for CP even(odd) modes.
$S_+(S_-)$, number of single tags for CP even(odd) modes.
$K_i(K_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

From the Double Dalitz modes, we are able to find c_i, c'_i, s_i, s'_i

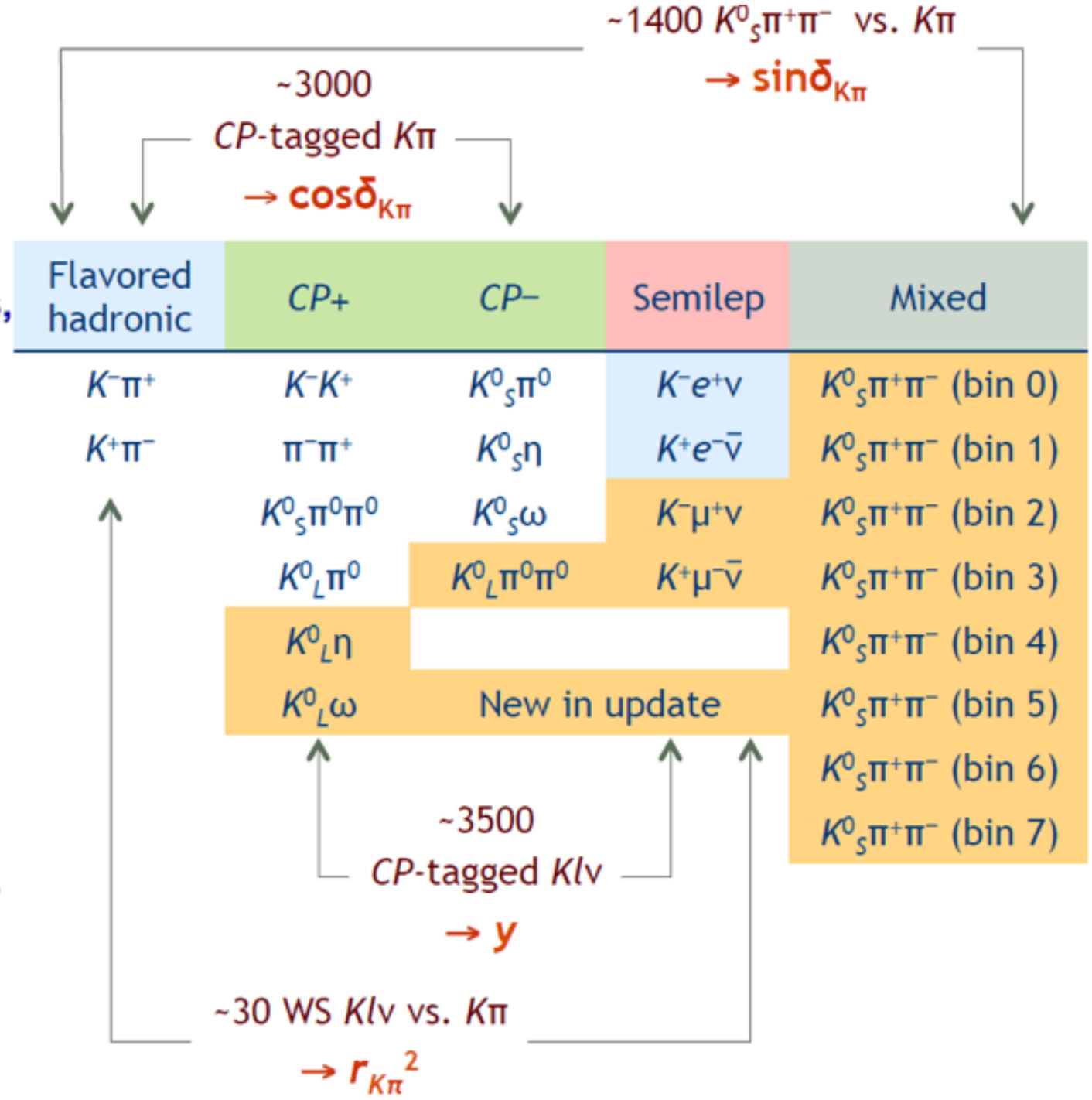
$M_{i,j} = \frac{N_{D,\overline{D}}}{2S_f^2}(K_iK_{\bar{j}} + K_{\bar{i}}K_j - 2\sqrt{K_iK_{\bar{j}}K_{\bar{i}}K_j}(c_ic_j + s_is_j))$	$(K^0_S\pi^+\pi^-, K^0_S\pi^+\pi^-)$
$M'_{i,j} = \frac{N_{D,\overline{D}}}{2S_f}(K_iK'_{\bar{j}} + K_{\bar{i}}K'_j + 2\sqrt{K_iK'_{\bar{j}}K_{\bar{i}}K'_j}(c_ic'_j + s_is'_j))$	$(K^0_S\pi^+\pi^-, K^0_L\pi^+\pi^-)$

$M_{i,j}$ yields in each ith bin of the first Dalitz plot and the jth bin for the second Dalitz plot.
S_f, number of single tags for flavor modes.
$K_i(K_{\bar{i}})$, yields in each bin of Dalitz plot in flavor modes.

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 Su, 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**
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	**$0.81\ ^{+0.22\ +0.07}_{-0.18\ -0.05}$**	**$1.15\ ^{+0.19\ +0}_{-0.17\ -0.08}$**
$\sin\delta_{K\pi}$	---	**$-0.01 \pm 0.41 \pm 0.04$**	**$0.56\ ^{+0.32\ +0.21}_{-0.31\ -0.20}$**
$\delta_{K\pi}$ ($^\circ$) [derived]	$22\ ^{+11}_{-12}\ ^{+9}_{-11}$	$10\ ^{+28\ +13}_{-53\ -0}$	$18\ ^{+11}_{-17}$

Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$

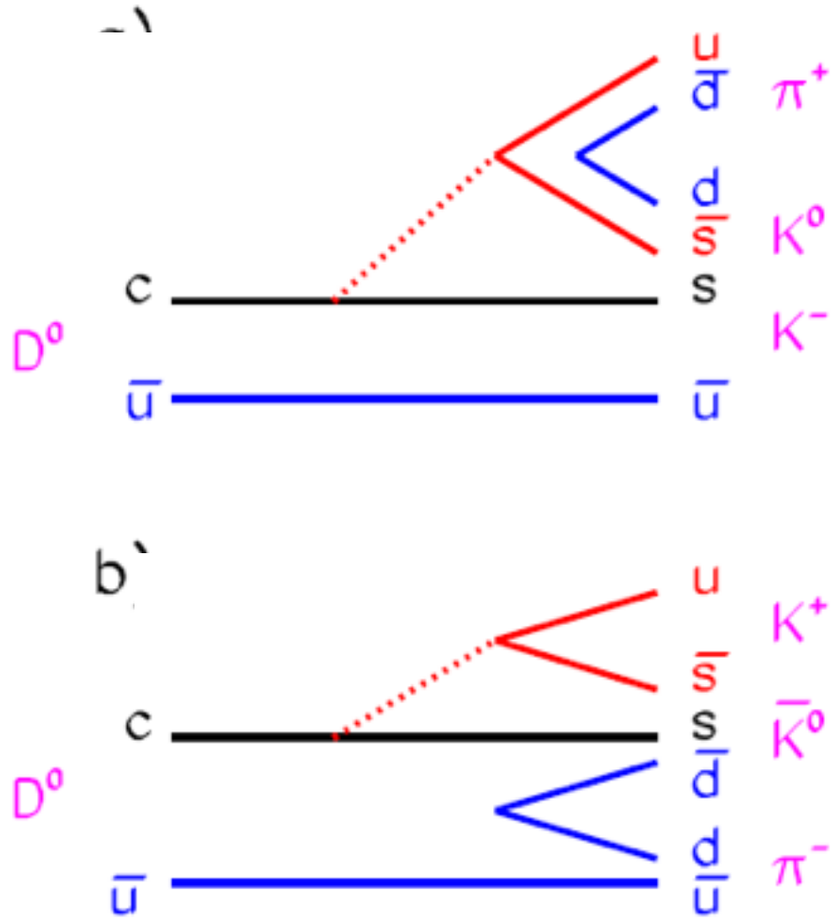
2.5σ diff. due to fluctuations in r^2 and y, correlated with $\cos\delta_{K\pi}$

Courtesy of Werner Sun, CKM2012

$D^0 \to K_S K^+ \pi^-$ 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)**

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

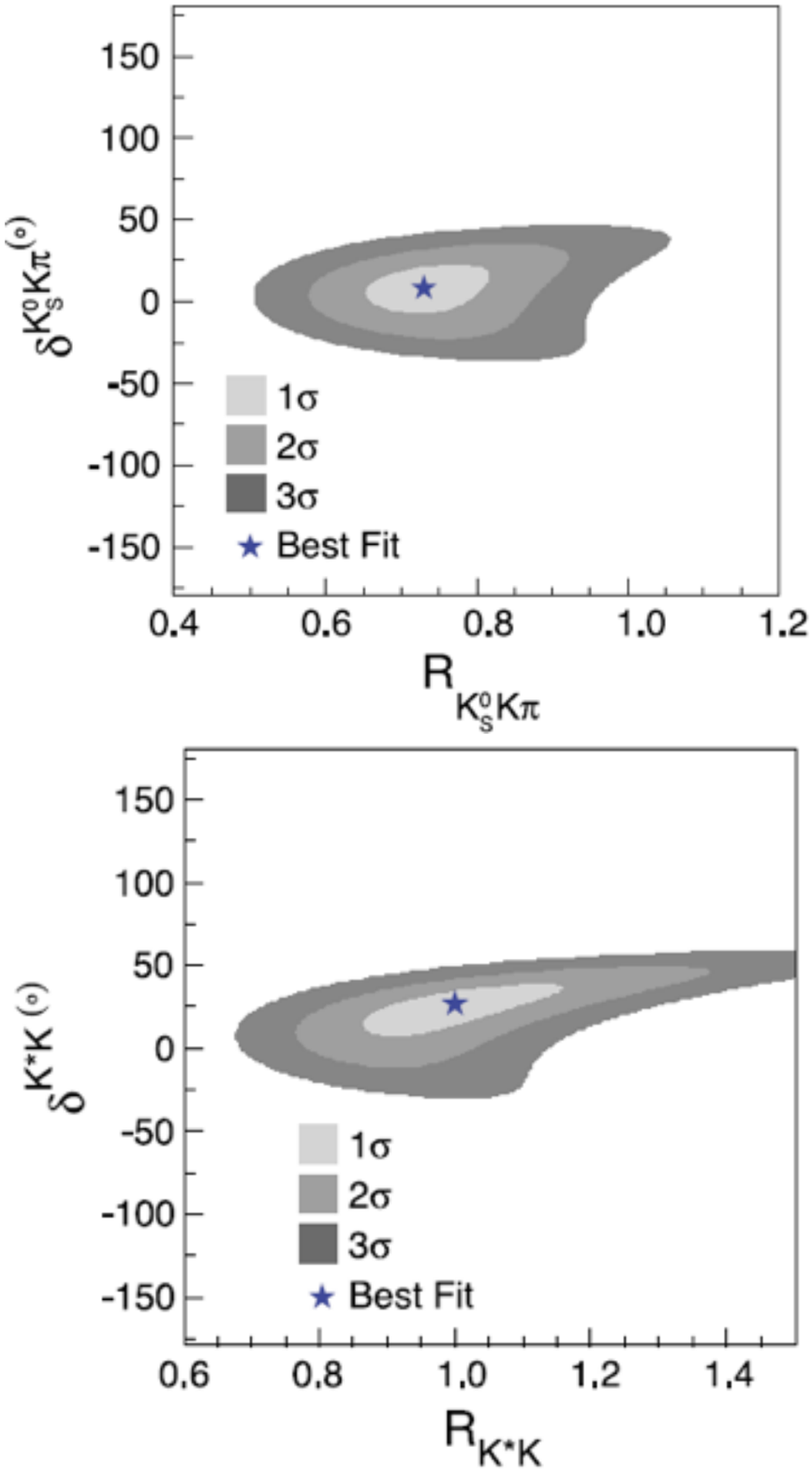
$$\Gamma(B^{\mp} \to D(K_S^0 K^{\pm}\pi^{\mp})K^{\mp}) \propto (r_B)^2 + (r_D^{K_S^0 K\pi})^2 + 2r_B r_D^{K_S^0 K\pi} R_{K_S^0 K\pi} \cos(\delta_B + \delta_D^{K_S^0 K\pi} \mp \gamma),$$

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

- **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^+, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\eta$, $K^0_L\omega$, $K^0_L\eta'$**
  - **CP- tags: $K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, $K^0_L\pi^0\pi^0$**
  - **Mixed CP tags: $K^0_S\pi^+\pi^-$, $K^0_L\pi^+\pi^-$**
- **Results in full Dalitz plot region:**
  - **R = 0.73 ± 0.08**
  - **δ = (8.3 ± 15.2)°**
- **Results for a restricted region (±100 MeV around K*(892)$^+$):**
  - **R = 1.00 ± 0.16**
  - **δ = (26.5 ± 15.8)°**



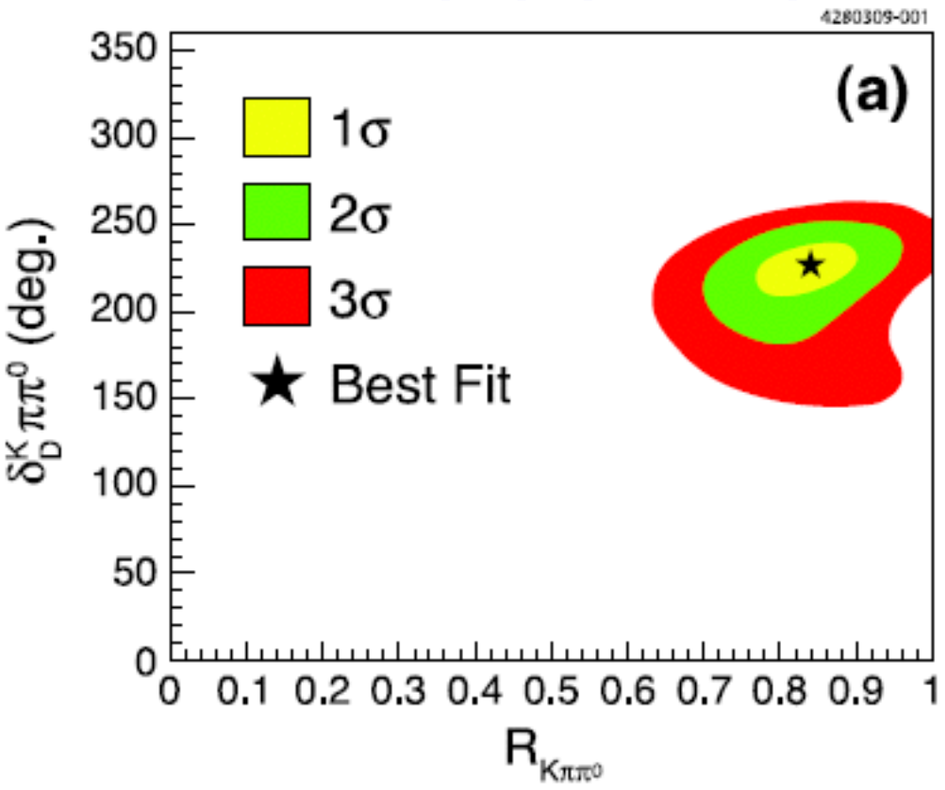
$D\to K\pi\pi^0$ and $D\to K3\pi$ (CLEO-c: 818 pb^{-1})

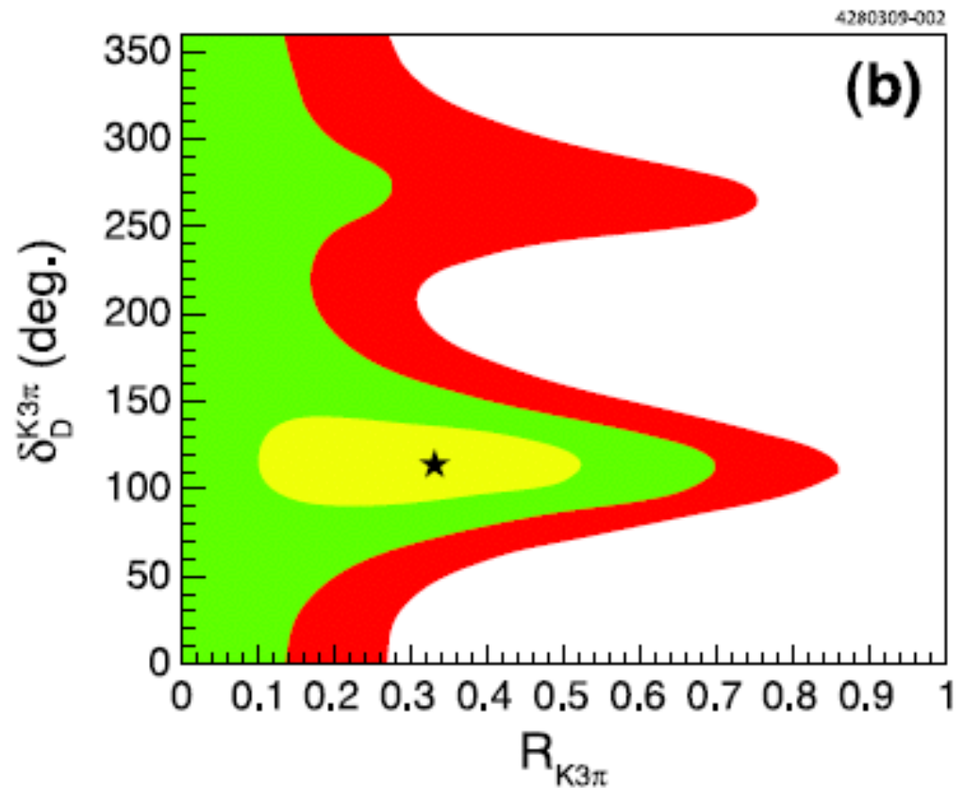
PRD80, 031105(R) (2009)

- **Motivation**
  - **Coherence factors & Strong phases ⇒ 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 ⇒ Significant coherence**
- **$D\to K3\pi$: R ~ 0.3, No significant coherence**
  - **LHCb time dependent analysis ⇒ Constrain R and δ**





Toward global fit at BESIII

Chinese Phys. C 37 (2013) 106201

- **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**

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

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

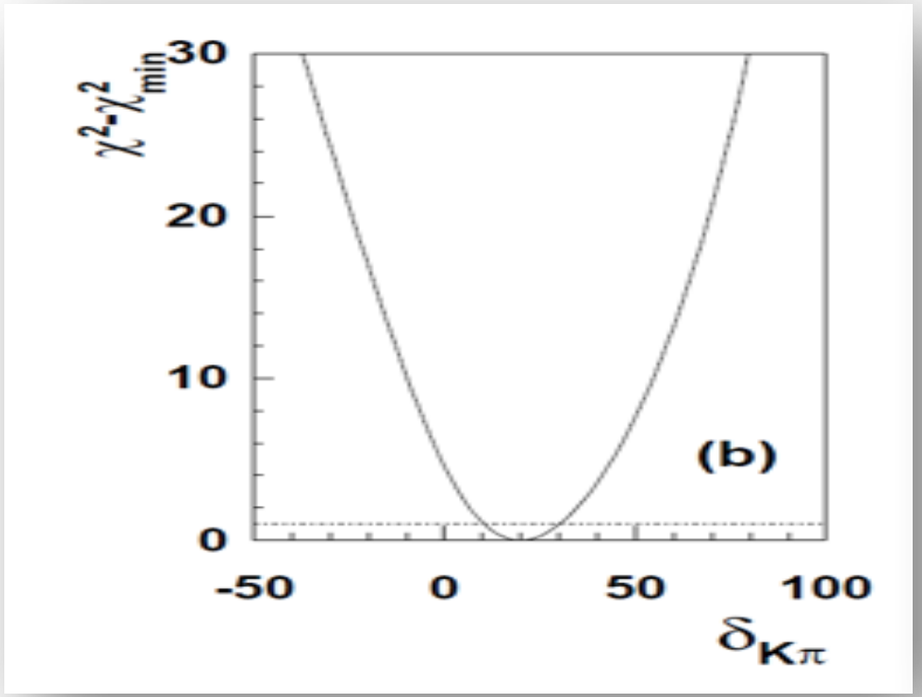
Sensitivity of the global fit at BESIII

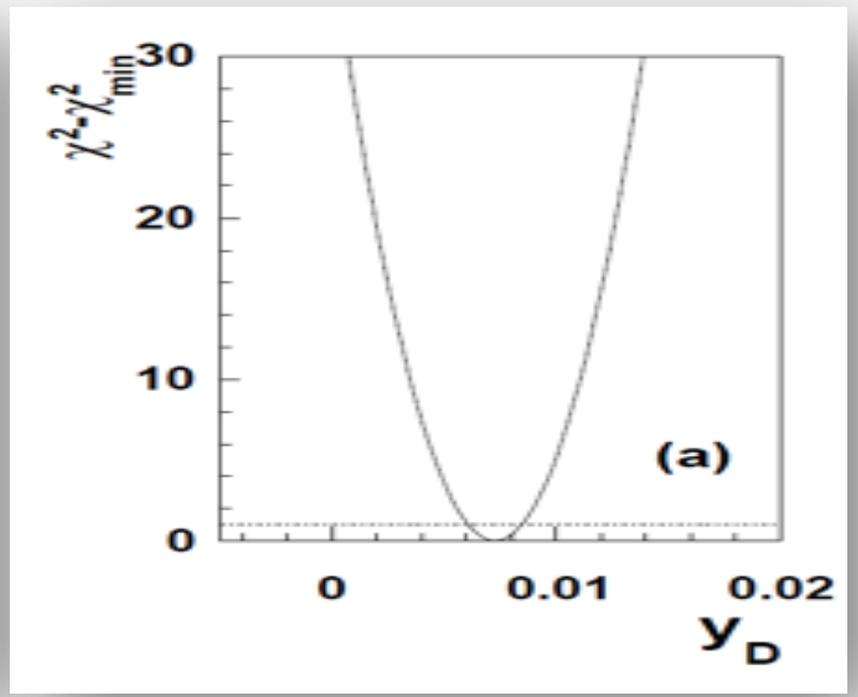
Chinese Phys. C 37 (2013) 106201

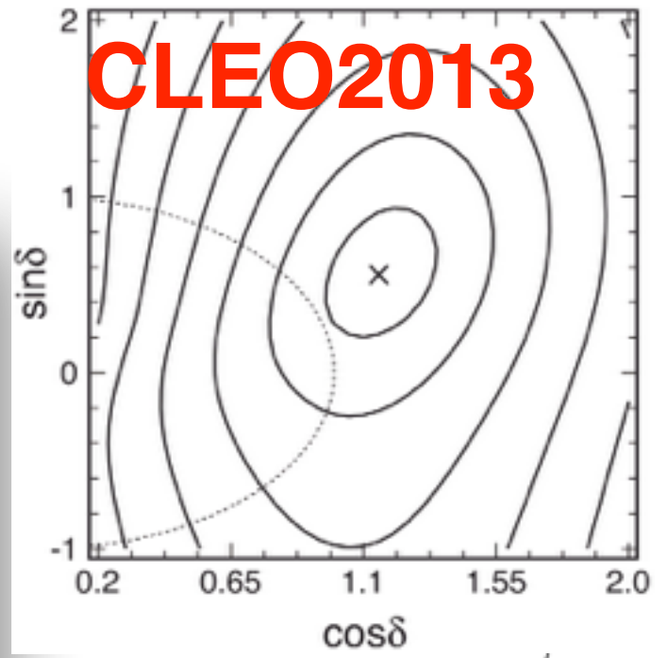
- MC study corresponds to 3.0 / fb data
- input of the central values of the world average in 2012:
- with the external constrains of :

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

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







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

- ~15% improvement on the parameters
- We expect large improvements on the strong phase and mixing parameters based on 20 /fb data.