CP Violation and Mixing in Charm Sector

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Outline

- CP Violation in D sector
- D-$\bar{D}$ Mixing Parameters
- Asymmetric beam?
- C-even correlated production
- Summary

Current/Future Facilities for Charm study

Current:

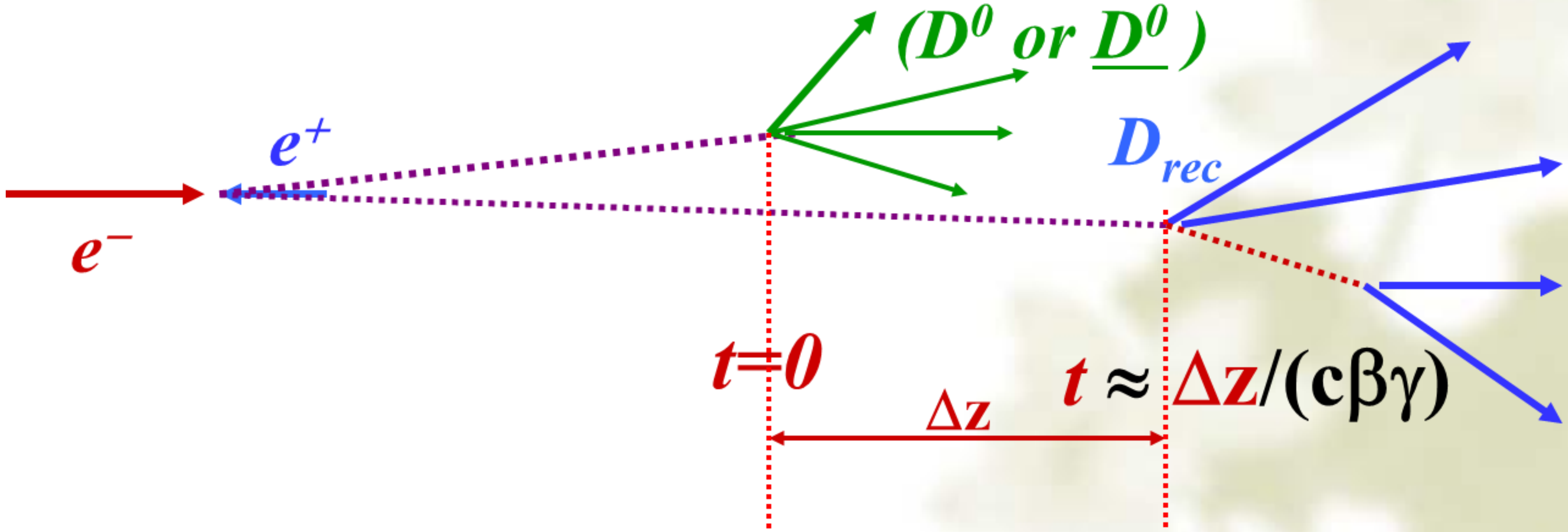
- Hadron colliders (huge cross-section, energy boost)
  - LHCb: 3fb^{-1} until now; world's largest sample of c-hadron decays in charged modes (x10 current B factories)
  - B-factories (Belle, BaBar): ~e^+e^- Colliders (more kinematic constrains, clean environment, ~100% trigger efficiency)
  - Threshold production (CLEOc, BESIII)
    - Quantum correlations and CP-tagging are unique

Future:

- BELLE II:
  - 10ab^{-1} per year. 10 ab^{-1} until 2019; 50ab^{-1} until 2023;
- Upgrade LHCb: **beyond 2018**
  - @14TeV 5fb^{-1} per year; in total 50fb^{-1} data *[EPJC (2013) 73:2373]*

Super τ-charm factory

- Luminosity: 10^{35} or higher? 1 ab^{-1}/year
- symmetric or asymmetric?
  - Time dependent measurement: βγ=0.425 for Belle (cτ: D^0 122.9μm, D^+ 311.8μm, B^0 455.4 μm), Vertex detector: resolution ~few 10 μm



CP Violation in D meson

CP Violation

1. Direct CP Violation (in decay)

$$A = \frac{\Gamma(D_q^+ \to f^+) - \Gamma(D_q^- \to f^-)}{\Gamma(D_q^+ \to f^+) + \Gamma(D_q^- \to f^-)}$$

$$D^0 \to f \;\Leftrightarrow\; \overline{D}^0 \to \bar{f}$$

2. Indirect CP Violation (in mixing)

$$A = \frac{\Gamma(D^0_{phys}(t) \to Xl^+\nu) - \Gamma(\overline{D^0_{phys}}(t) \to Xl^-\nu)}{\Gamma(D^0_{phys}(t) \to Xl^+\nu) + \Gamma(\overline{D^0_{phys}}(t) \to Xl^-\nu)}$$

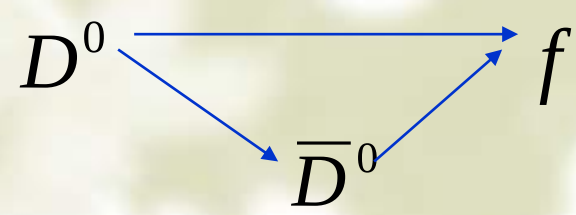
$$D^0 \to \overline{D}^0 \to f$$

$$\Updownarrow$$

$$\overline{D}^0 \to D^0 \to \bar{f}$$

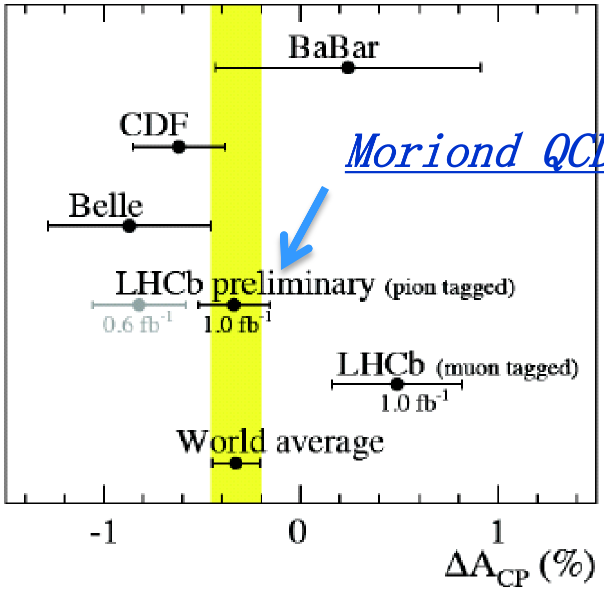
3. CP violation in the interference between decays with/without mixing

$$A = \frac{\Gamma(D^0_{phys}(t) \to f_{CP}) - \Gamma(\overline{D^0_{phys}}(t) \to f_{CP})}{\Gamma(D^0_{phys}(t) \to f_{CP}) + \Gamma(\overline{D^0_{phys}}(t) \to f_{CP})}$$



Direct CP violation results in D→hh

- LHCb, CDF and Belle measurements of $\Delta A_{CP} = A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)$ suggested CP violation of the order 0.7%.
- More recent measurements by LHCb do not support evidence of CPV. Still, SM expects CPV of the order 10^{-3},



[Moriond QCD2013]

HFAG world-average:

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

Measurements of the individual asymmetries:

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

- New Physics up to ~1%;
- If CPV~1% observed, is it NP or hadronic enhancement of SM?
- **Strategy**: analyze many channels to elucidate source of CPV.

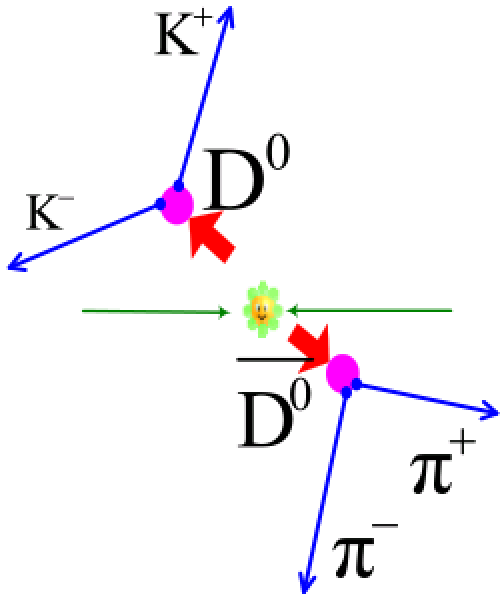
Direct CP violation: prospect at BELLE II

BELLE II can reach $\delta(A_{CP})<0.1\%$ for many modes

Mode	$\mathcal{L}$ [fb^{-1}]	A_{CP} [%]	Belle II with 50 ab^{-1} [%]
$D^0 \to K_S^0\pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	±0.05
$D^0 \to K_S^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	±0.10
$D^0 \to K_S^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	±0.10
$D^0 \to \pi^+\pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	±0.07
$D^0 \to K^+K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	±0.05
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	
$D^0 \to K^+\pi^-\pi^0$	281	-0.6 ± 5.3	
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.8 ± 4.4	
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	±0.05
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	±0.20
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	±0.20
$D^+ \to K_S^0\pi^+$	673	$-0.71 \pm 0.19 \pm 0.20$	±0.05
$D^+ \to K_S^0K^+$	673	$-0.16 \pm 0.58 \pm 0.25$	±0.10
$D_s^+ \to K_S^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	±0.30
$D_s^+ \to K_S^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	±0.10

*Systematics related to control sample statistics are assumed to scale with luminosity.

CPV at threshold



CP violating asymmetries can be measured by searching for events with two CP odd or two CP even final states:

$\pi^+\pi^-$, K^+K^-, $\pi^0\pi^0$, $K_S\pi^0$,

for the decay of $\psi'' \to f_1 f_2$

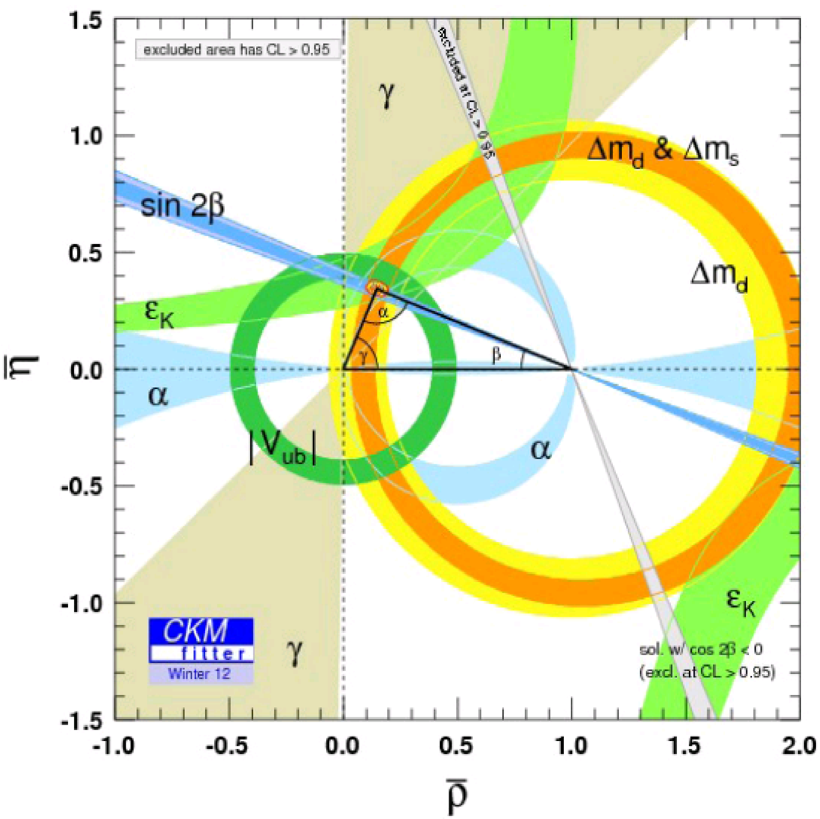
$$CP(f_1 f_2) = CP(f_1)\cdot CP(f_2)\cdot(-1)^L = -$$

$$CP(\psi'') = +$$

- At BESIII 20 fb^{-1} , A_{CP} sensitivity : 10^{-2}~10^{-3}
- 1ab^{-1} at super tau-charm, A_{CP} sensitivity : 10^{-3}~10^{-4}
- clean background and better systematic control in threshold production would facilitate our competition with future B projects

CKM measurements: current status

Various experimental inputs (sides and angles of the Unitarity Triangle) are combined by averaging groups (CKMfitter and UTfit) to get the general picture. Reasonable consistency so far, although some slight tensions exist.



γ is an important input:

- Indirect constraint: $(68 \pm 4)^\circ$ from decays with loops.
- Direct measurement: Current precision: $10 - 15^\circ$. Tree-level decays.

  Theoretical uncertainty: $10^{-6}(!)$.

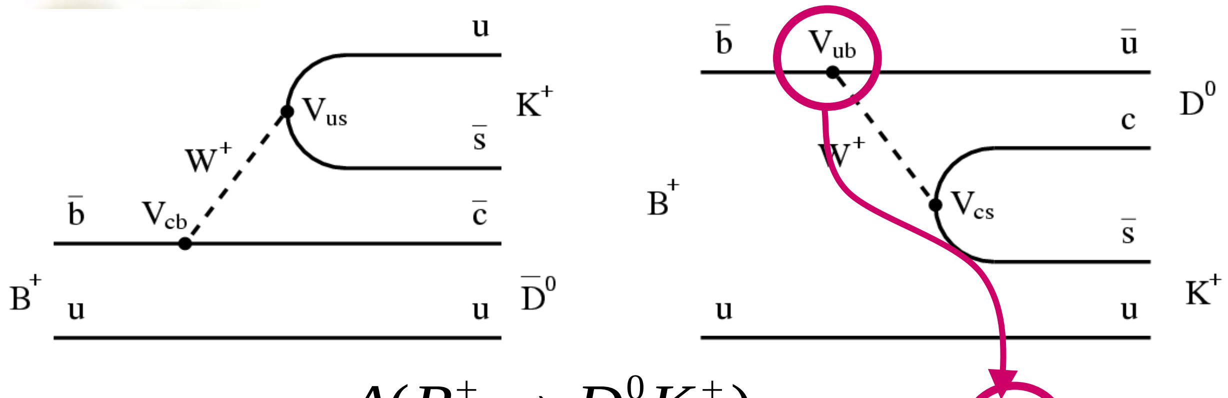
γ is a high-precision SM reference for other CKM measurements.

The cleanest way to extract γ is from $B \to DK$ decays...

How tau-charm factory can help?

γ/ϕ_3 from $B^- \to D^0 K^-$

Interference between tree-level decays; theoretically clean



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

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

GLW/ADS method

Observables for $D \to hh$ (GLW) and $D \to K\pi$ (ADS) modes:

$$\mathcal{R}_{GLW} = \frac{\Gamma(B \to D_{CP}K)}{\Gamma(B \to D_{fav}K)} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\gamma$$

$$\mathcal{A}_{GLW} = \frac{\Gamma(B^+ \to D_{CP}K) - \Gamma(B^- \to D_{CP}K)}{\Gamma(B^+ \to D_{CP}K) + \Gamma(B^- \to D_{CP}K)} = 2r_B \sin\delta_B \sin\gamma / R_{GLW}$$

$$\mathcal{R}_{ADS} = \frac{\Gamma(B \to D_{sup}K)}{\Gamma(B \to D_{fav}K)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D) \cos\gamma$$

$$\mathcal{A}_{ADS} = \frac{\Gamma(B^+ \to D_{sup}K) - \Gamma(B^- \to D_{sup}K)}{\Gamma(B^+ \to D_{sup}K) + \Gamma(B^- \to D_{sup}K)} = 2r_B r_D \sin(\delta_B + \delta_D) \sin\gamma / R_{ADS}$$

γ is what we are mainly interested in.

r_B and δ_B are strong parameters (ampl. ratio and strong phase) related to B decay. Free parameters.

δ_D is the strong phase between $D^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^+\pi^-$.
Can be measured at threshold.

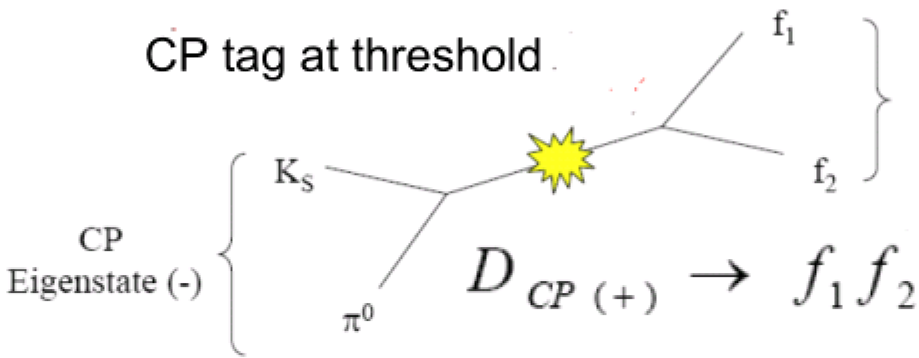
Accessing strong phase at threshold

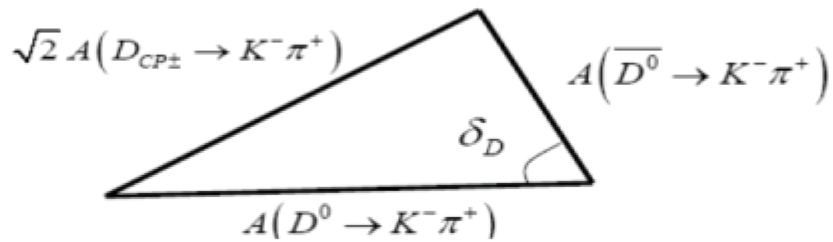
If CP violation in charm is neglected: mass eigenstates = CP eigenstates

$$|D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle \pm |\overline{D^0}\rangle\right]$$

$$\sqrt{2}\,A(D_{CP\pm} \to K^-\pi^+) = A(D^0 \to K^-\pi^+) \pm A(\overline{D^0} \to K^-\pi^+)$$

CP tag at threshold





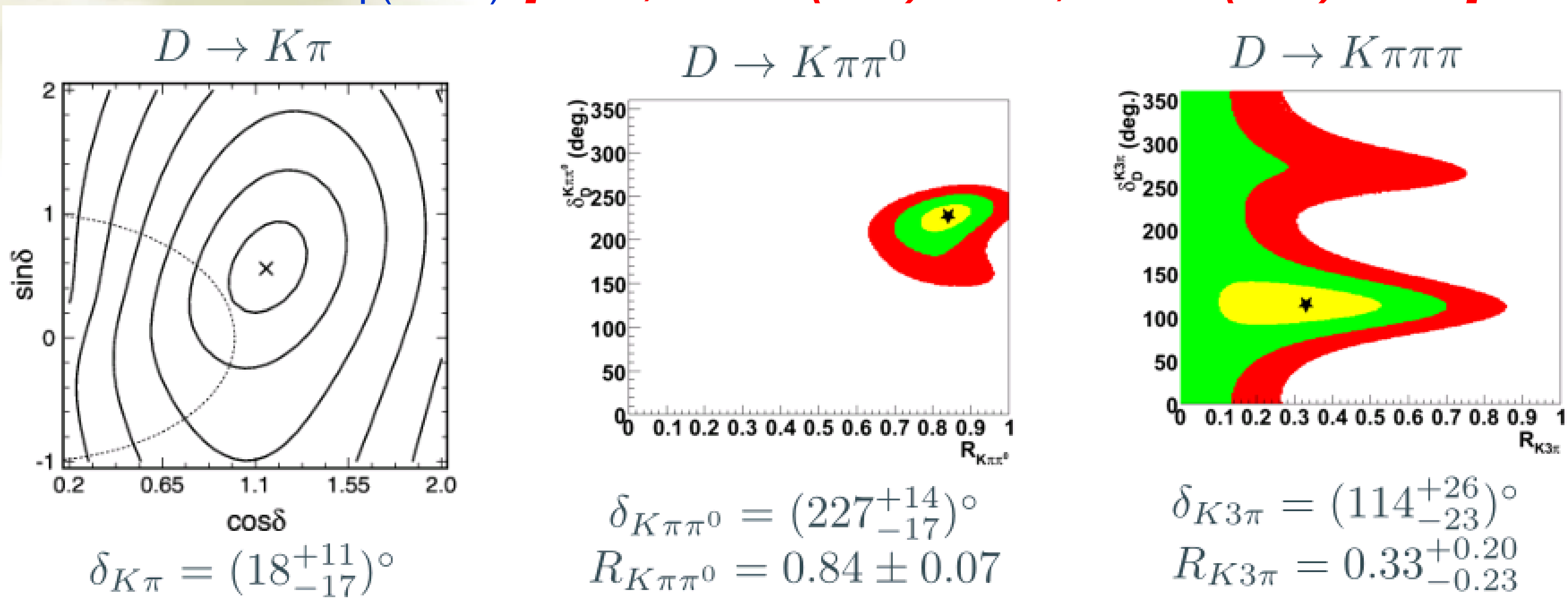
$$\frac{\langle K^-\pi^+|\overline{D}^0\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

ψ(3770)L=1 C=-1
CP anti-correlated

$$\cos\delta_D = \frac{Br(D_{CP+} \to K^-\pi^+) - Br(D_{CP-} \to K^-\pi^+)}{2\sqrt{r_D}\,Br(D^0 \to K^-\pi^+)}$$

CLEO-c measurements in ADS modes

CLEO measurements of strong phase differences and coherence factors done with 0.8 fb^{-1} at ψ(3770). ***[CLEO, PRD 86 (2012) 112001; PRD 80 (2009) 031105]***

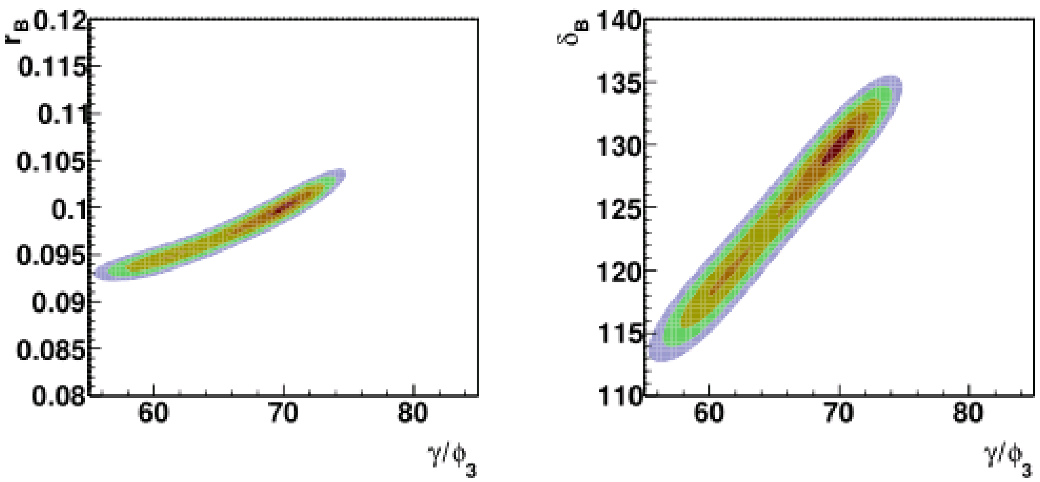


2.9 fb^{-1} BES III sample: $\sigma(\cos\delta_{K\pi}) \sim 0.12$

1 ab^{-1} super **τ**-charm factory: $\sigma(\cos\delta_{K\pi}) \sim 0.007$; $\sigma(\delta_{K\pi}) \sim 2^o$

Prospects for future measurements with ADS

- Expected sensitivity using ADS/GLW modes ($D \to hh$) alone is:
  - Belle II: $\sigma(\gamma) = 5^\circ$ [CKM2010]
  - Upgraded LHCb: $\sigma(\gamma) = 1.3^\circ$ [EPJ C (2013) 73:2373]
- This precision critically depends on the precision of δ_D. Strong correlation btw. γ and strong phase, precision required for δ_D is of the order $\sigma(\gamma)$.



No δ_D constraint.

- Precision can be improved by adding other D modes (e.g. $D \to K\pi\pi^0$) with different strong phases.

Prospects for future measurements with ADS

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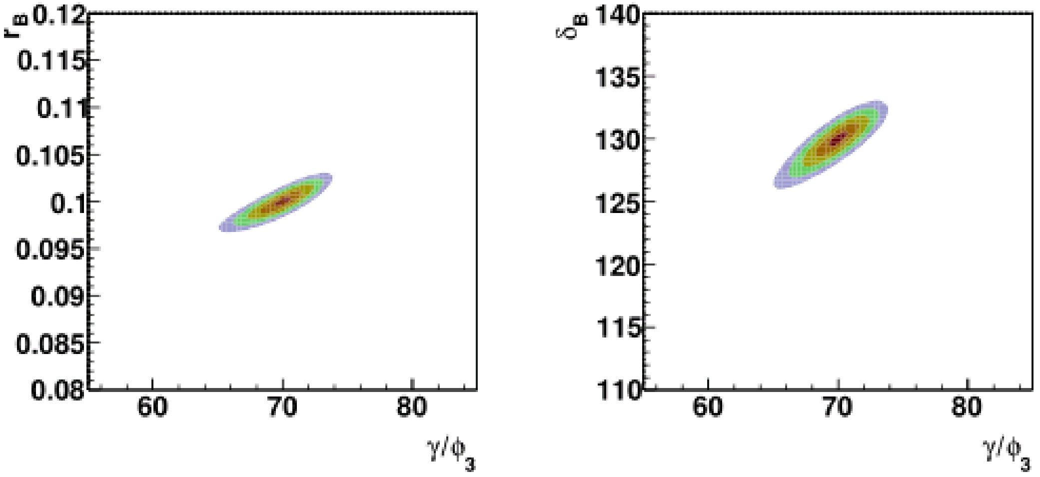


$\sigma(\delta_D) = 1^\circ$.

- Precision can be improved by adding other D modes (e.g. $D \to K\pi\pi^0$) with different strong phases.

GSSZ method

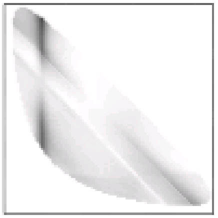
- Three body *D* decays: $K_S\pi^+\pi^-$, $\pi^+\pi^-\pi^0$, $K_SK^+K^-$…
- Effect of *D–Dbar interference*

$B^+ \to DK^+$, $D \to K_S\pi^+\pi^-$ Dalitz plot analysis

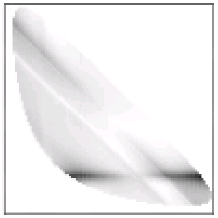
$D \to K_S^0\pi^+\pi^-$ Dalitz distribution:
$d\sigma(m_+^2, m_-^2) \sim |A|^2 dm_+^2 dm_-^2$
where $m_\pm^2 = m_{K_S\pi^\pm}^2$

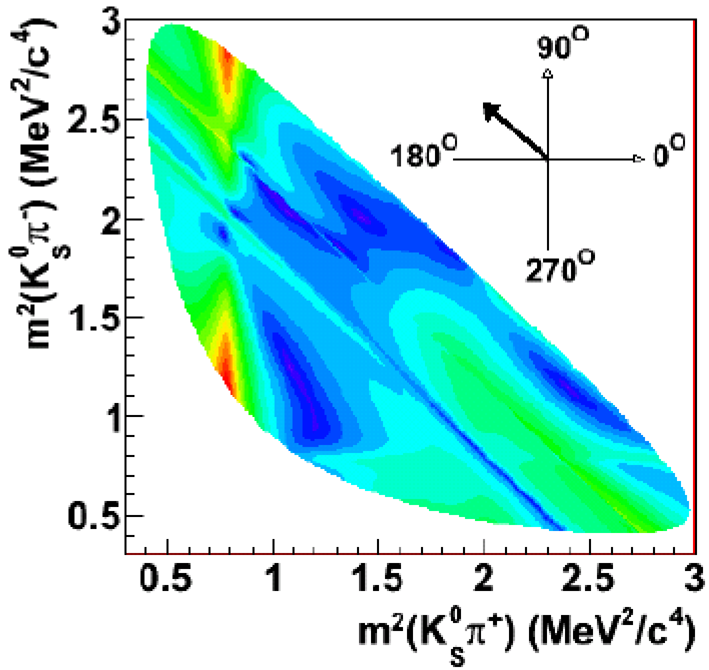
$\mathcal{CP}$ conservation in D decays:
$\overline{A}_D(m_+^2, m_-^2) = A_D(m_-^2, m_+^2)$

D decay amplitude from $B^+ \to DK^+$:
$A_B(m_+^2, m_-^2) =$



$+ r_B e^{i\delta_B \pm i\gamma}$





Rotation of phase $\delta_B + \gamma$
$r_B = 0.1$

GSSZ Formalism

- $B^{\pm} \to (K_S\pi^+\pi^-)_D K^{\pm}$ (hep-ph/0303187)
- *D* hadronic parameters

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

$$s_{12} \equiv m^2_{K_s\pi^-}, s_{13} \equiv m^2_{K_s\pi^+} \qquad = A(\overline{D^0} \to K_s^0(p_1)\pi^+(p_2)\pi^-(p_3))$$

- Partition the Dalitz plot to *2k* bins
- Label bins below symmetry axis *i*, above axis *i*

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

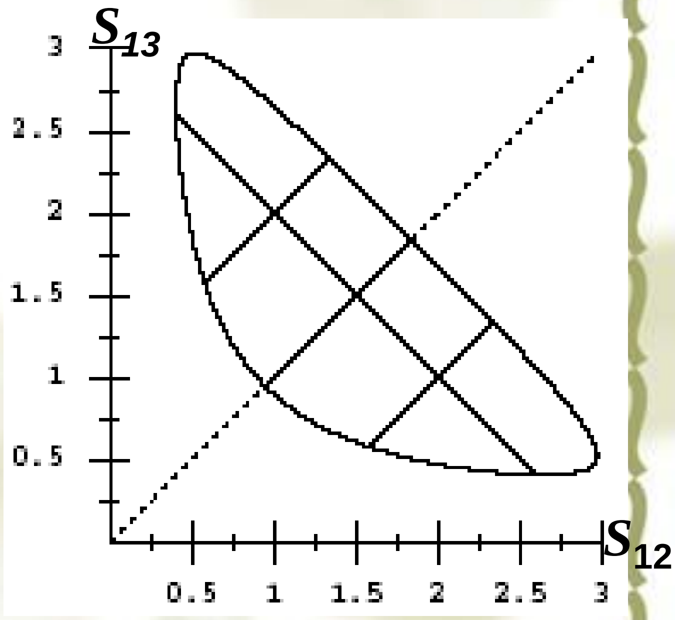
unknown

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

Measurable from tagged *D*

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

$$C_{\bar{i}} = C_i, S_{\bar{i}} = -S_i$$



γ/ϕ_3 extraction with GSSZ method

- $2k$ bins × $2(B$ modes$)$ = $4k$ equations
- For the i^{th} bin:

$$\hat{\Gamma}_i^- \equiv \int_i d\hat{\Gamma}(B^- \to (K_s^0\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{\bar{i}} + 2r_B\left[\cos(\delta_B - \varphi_3)c_i + \sin(\delta_B - \varphi_3)s_i\right]$$

$$\hat{\Gamma}_{\bar{i}}^- \equiv \int_{\bar{i}} d\hat{\Gamma}(B^- \to (K_s^0\pi^-\pi^+)_D K^-) = T_{\bar{i}} + r_B^2 T_i + 2r_B\left[\cos(\delta_B - \varphi_3)c_i - \sin(\delta_B - \varphi_3)s_i\right]$$

$$\hat{\Gamma}_i^+ \equiv \int_i d\hat{\Gamma}(B^+ \to (K_s^0\pi^-\pi^+)_D K^-) = T_{\bar{i}} + r_B^2 T_i + 2r_B\left[\cos(\delta_B + \varphi_3)c_i - \sin(\delta_B + \varphi_3)s_i\right]$$

$$\hat{\Gamma}_{\bar{i}}^+ \equiv \int_{\bar{i}} d\hat{\Gamma}(B^+ \to (K_s^0\pi^-\pi^+)_D K^-) = T_i + r_B^2 T_{\bar{i}} + 2r_B\left[\cos(\delta_B + \varphi_3)c_i + \sin(\delta_B + \varphi_3)s_i\right]$$

- $2k+3$ unknowns: c_i, s_i, r_B, δ_B, $\phi_3 \Leftarrow$ Solvable for $k \geq 2$
- Belle results from GSSZ method in 2010:

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

→ ***D Decay model***

(c_i ,s_i) *from charm-factory*

- D double tag: ($K_S\pi^+\pi^-$ vs General state: g)

$$\Gamma_{i,j} \propto T_i T^g_{\bar{j}} + T_{\bar{i}} T^g_j - 2(c_i c^g_j + s_i s^g_j)$$

- If g= $K_S\pi^+\pi^-$ and j=i $\Rightarrow$ $c^2_i + s^2_i$

$$\Gamma_{i,i} \propto 2T_i T_{\bar{i}} - 2(c_i^2 + s_i^2)$$

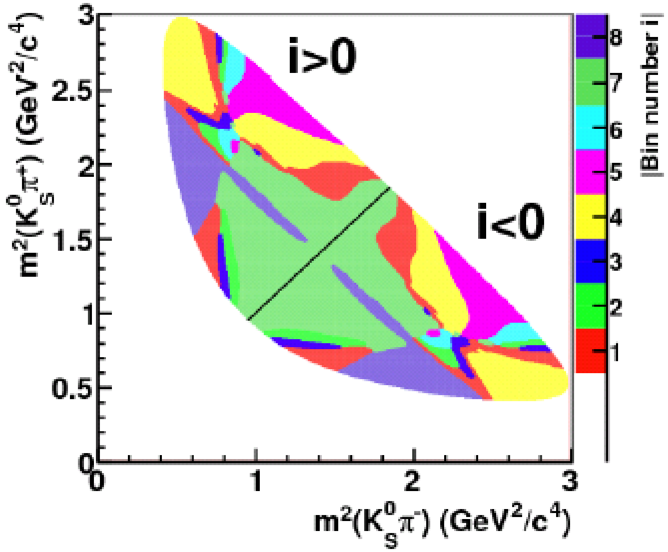
- If g=$CP\pm$ $\Rightarrow$ $s^g_j=0$, $T^g_j = T^g_{\bar{j}} = \pm c^g_j \Rightarrow$ c_i

$$\Gamma_i \propto T_i + T_{\bar{i}} \pm 2c_i$$

- (c_i , s_i) measurement has been done by CLEO-c and can be done in future at BES-III (and hopefully at super tau-charm factory!).

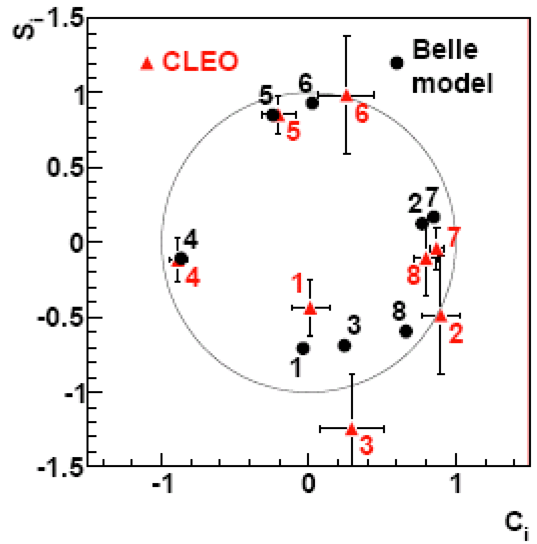
(c_i , s_i) measurement at CLEO-c

Optimal binning



Optimised $D \to K_S^0\pi^+\pi^-$ binning using BaBar 2008 measurement.

[CLEO , PRD 82, 112006 (2010)]



Measured c_i, s_i values and predictions by Belle model

- ✓ impact to measurement of γ/ϕ_3 using CLEO-c's model-independent Dalitz
  BELLEL: $\gamma = (77 \pm 15 \pm 4 \pm 4)^\circ$ *[Belle, PRD 85, 112014 (2012)]*
  LHCb: $\gamma = (57 \pm 16)^\circ$ *[LHCb-CONF-2013-004]*
- ✓ third syst. err. is from CLEO-c's measurement

strong phase measurement at super tau-Charm

- Precision on γ expected at Belle II (~ 50 ab^{-1}) and upgraded LHCb (~ 50 fb^{-1}) is of order 2° (for $B \to DK$, $D \to K_S^0\pi^+\pi^-$ only).
- Other channels can use $D \to K_S^0\pi^+\pi^-$ (such as $B^0 \to DK^*$, $B \to DK\pi\pi$ etc.) and provide more constraints on γ.
- If recalculated to γ, the current uncertainty due to CLEO measurement of c_i, s_i is $\sim 4^\circ$ (Belle).
- Uncertainty of BES III sample (10 fb^{-1}) would be $\sim 1^\circ$. so similar or somewhat less than stat. error due to B sample.

BES III measurement is expected ...

- τ-charm factory sample (1 ab^{-1}) would reduce the contribution of c_i, s_i precision to a comfortable level of $\sim 0.1^\circ$.

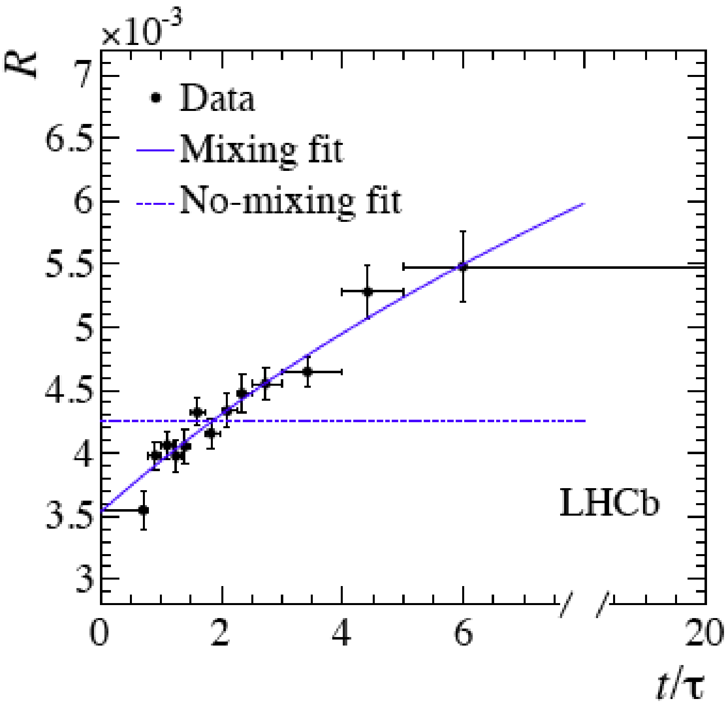
This sub-degree precision need more careful handling of some subtle effects

$D^0 - \bar{D}^0$ *mixing*

$D^0 - \bar{D}^0$ mixing from LHCb

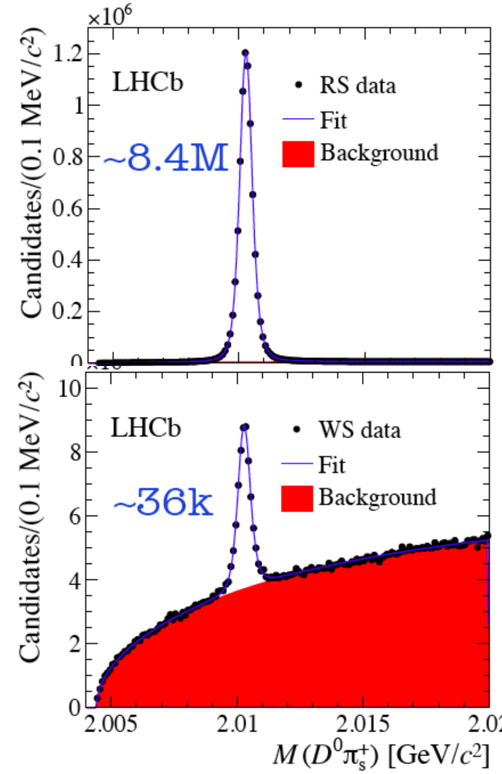
First observation of charm mixing in time dependent $D^0 \to K\pi$ RS & WS decays by a single measurement (9σ)

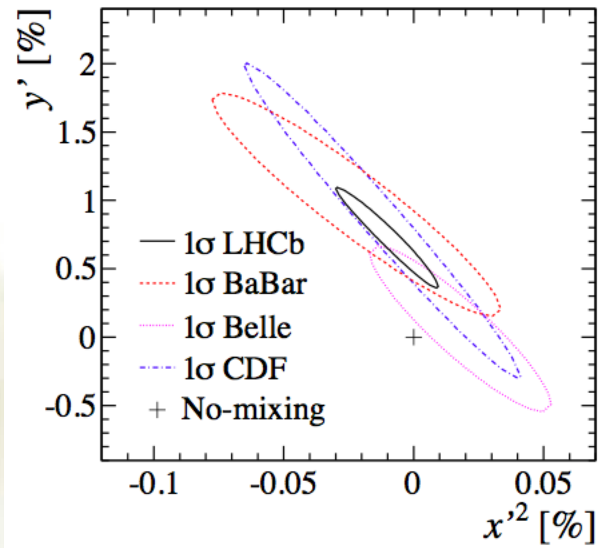
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y't + \frac{x'^2 + y'^2}{4}t^2$$



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

PRL 110, 101802 (2013)





Unofficial LHCb Statistical Sensitivities Circa 2015

Mike Sokoloff

- Assume 5 fb^{-1} @ 13 TeV; charm cross sections grow linearly with $\sqrt{s}$. Mostly scale from 2011/2012 analyses.
- 10^6 WS $D^0 \rightarrow K\pi$
  - $(x'^2, y') \pm (0.004, 0.08)\%$
  - D^0-$\overline{D}^0$ WS rate asymmetry (like |q/p|) ±1%
- 3.7×10^6 $D^0 \rightarrow K^-K^+$, 1.7×10^6 $D^0 \rightarrow \pi^-\pi^+$
  - y_{CP}, A_Γ ± 0.02%
- 20×10^6 $D^0 \rightarrow K_S\pi\pi$
  - $(x,y) \pm (0.045, 0.030)\%$
- Many systematic uncertainties cancel in CPV measurements, e.g., A_Γ from $D^0 \rightarrow K^-K^+$.

Quantum correlation at threshold

$D\overline{D}$ pair with L =1 must be in anti-asymmetric state

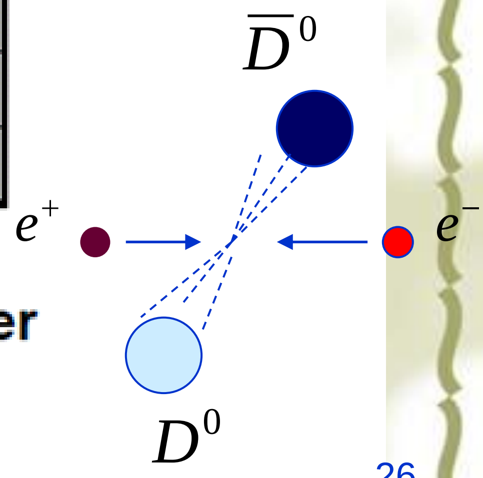
$$|D^0\overline{D}^0\rangle^{C=-1} = \frac{1}{\sqrt{2}}\left[|D^0\rangle|\overline{D}^0\rangle - |\overline{D}^0\rangle|D^0\rangle\right]$$

the interference comes for free:

$$M_{ij}^2 = \left|\langle i|D^0\rangle\langle j|\overline{D}^0\rangle - \langle j|D^0\rangle\langle i|\overline{D}^0\rangle\right|^2$$

PRD 73, 034024 (2006)
Asner and Sun
I.I.Bigi SLAC report-33, 1989 page 169

(C=–1) $e^+e^- \to \psi(3770) \to$	D	$\overline{D}$
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Forbidden if no mixing	$K^-l^+\nu$	$K^-l^+\nu$
Forbidden by CP conservation	CP+	CP+
Forbidden by CP Conservation	CP–	CP–
Interference of CF with DCS	$K^-\pi^+$	CP±



The mixing rate R_M can be measured at the first order
Strong phase $\delta_{K\pi}$ is from CP tagged $D \to K\pi$
CP violation is measured in a production rate.

$D^0 - \bar{D}^0$ mixing rate at threshold

$\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K^-\pi^+)(K^-\pi^+)$

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

There's a very nice well-known D^0 mixing signature at $\Psi(3770)$

✓ No DCSD: cancels with these correlated D pairs

✓ Like-sign $(K^-\pi^+)(K^-\pi^+)$ (+ c.c.) are pure mixing !

But it's HARD in practice :

✓ The only number we have control over is the efficiency, $\varepsilon_{K\pi}$

✓ But PID needs to be tight, to avoid background from Kπ swaps …

BESIII with 20 fb^{-1} data:

- $R_M = (x^2+y^2)/2 < 10^{-4}$ in $K\pi$ and $Ke\nu$ channels
- Probe y: $\Delta y_{CP} < 0.7\%$

SCT with $1ab^{-1}$ data:

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

Implication of strong phase to mixing parameters

- Time-dependent measurements of charm mixing can be performed with boosted D mesons (Belle II, LHCb), but need the same strong phases as γ/ϕ_3 measurement.
  - Time-dependent $D^0 \rightarrow K\pi$ analysis: phase difference δ_D to relate y' with (x, y).
  - Time-dependent $D^0 \rightarrow K_s\pi^+\pi^-$ analysis

$$|A_D(t)|^2 \simeq |A_D + (x+iy)t\overline{A}_D|^2$$

Measures both x and y independently. Can be done in the similar model-independent binned fashion as γ. [Bondar et al., PRD 82 (2010) 034033]

upgraded LHCb, Belle II: expect ∼100M decays. Stat. precision:

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

[G. Wilkinson, C. Thomas, arXiv:1209.0172]

Current precision of c_i, s_i would dominate the precision of x, y and CP violation parameters already for ∼10M $D \to K^0_S\pi^+\pi^-$ samples $\Rightarrow$

need 100 fb^{-1} at $D\overline{D}$ threshold to reduce it to the level of stat. error.

Quantum Correlation Analysis

(PRD.86(2012) 112001; PRL100(2008) 221801)

Forbidden by CP conservation	CP+	CP+
	CP−	CP−
Maximal enhancement	CP+	CP−
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS (gives $\cos\delta$)	$K^-\pi^+$	CP±
	CP±	$K^-\pi^+$
Single Tags Unaffected	CP± $K^-\pi^+$ SL	X

Useful reference

PRL100(2008) 221801

- Single tags for all fully-reconstructed modes except $K^0_S\pi^+\pi^-$.
- Double tags for almost all combinations of modes.
  - Like-sign and opposite-sign.
  - At most one missing particle (K^0_L or ν).
    - Except for *Kev* vs. $K^0_L\pi^0$ (2 missing particles).
- 261 yield measurements
  - $K^0_S\pi^+\pi^-$ from PRD 80, 032002 (2009)

~1400 $K^0_S\pi^+\pi^-$ vs. $K\pi$ → $\sin\delta_{K\pi}$

~3000 *CP*-tagged $K\pi$ → $\cos\delta_{K\pi}$

Flavored hadronic	CP+	CP−	Semilep	Mixed
$K^-\pi^+$	K^-K^+	$K^0_S\pi^0$	$K^-e^+\nu$	$K^0_S\pi^+\pi^-$ (bin 0)
$K^+\pi^-$	$\pi^-\pi^+$	$K^0_S\eta$	$K^+e^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 1)
	$K^0_S\pi^0\pi^0$	$K^0_S\omega$	$K^-\mu^+\nu$	$K^0_S\pi^+\pi^-$ (bin 2)
	$K^0_L\pi^0$	$K^0_L\pi^0\pi^0$	$K^+\mu^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 3)
	$K^0_L\eta$			$K^0_S\pi^+\pi^-$ (bin 4)
	$K^0_L\omega$	New in update		$K^0_S\pi^+\pi^-$ (bin 5)
				$K^0_S\pi^+\pi^-$ (bin 6)
				$K^0_S\pi^+\pi^-$ (bin 7)

~3500 *CP*-tagged *Klν* → *y*

~30 WS *Klν* vs. $K\pi$ → $r_{K\pi}^2$

Key variables:

x,y : familiar D0 mixing variables

$r_{K\pi}$: Wrong-to-right sign amplitude ratio $|A(D^0 \to K^+\pi^-) / A(\bar{D}^0 \to K^+\pi^-)|$

$\delta_{K\pi}$: strong $K\pi$ FSI phase (which rotates x,y to x',y')

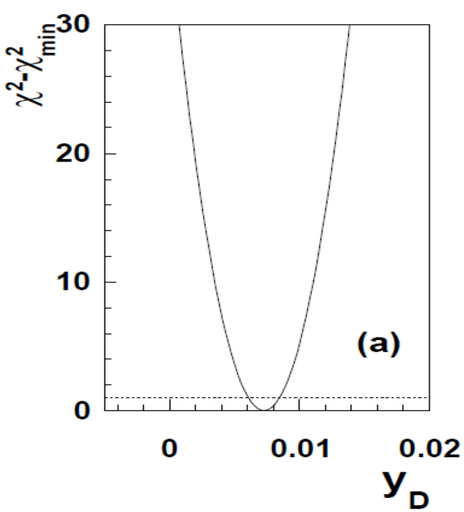
This is the -phase of the previous amplitude ration

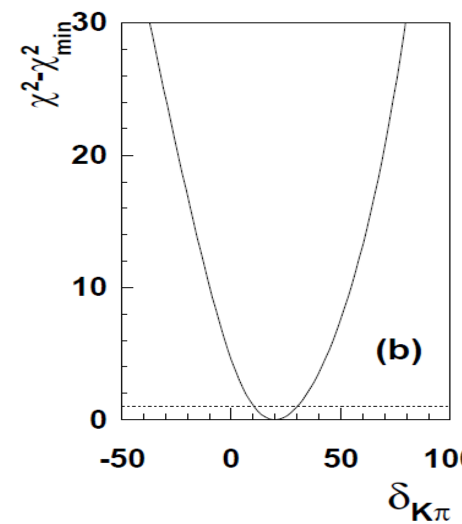
Global fit with quantum correlation analysis always helps to provide the improved world average!

Global fit at BESIII

arXiv:1304.6170

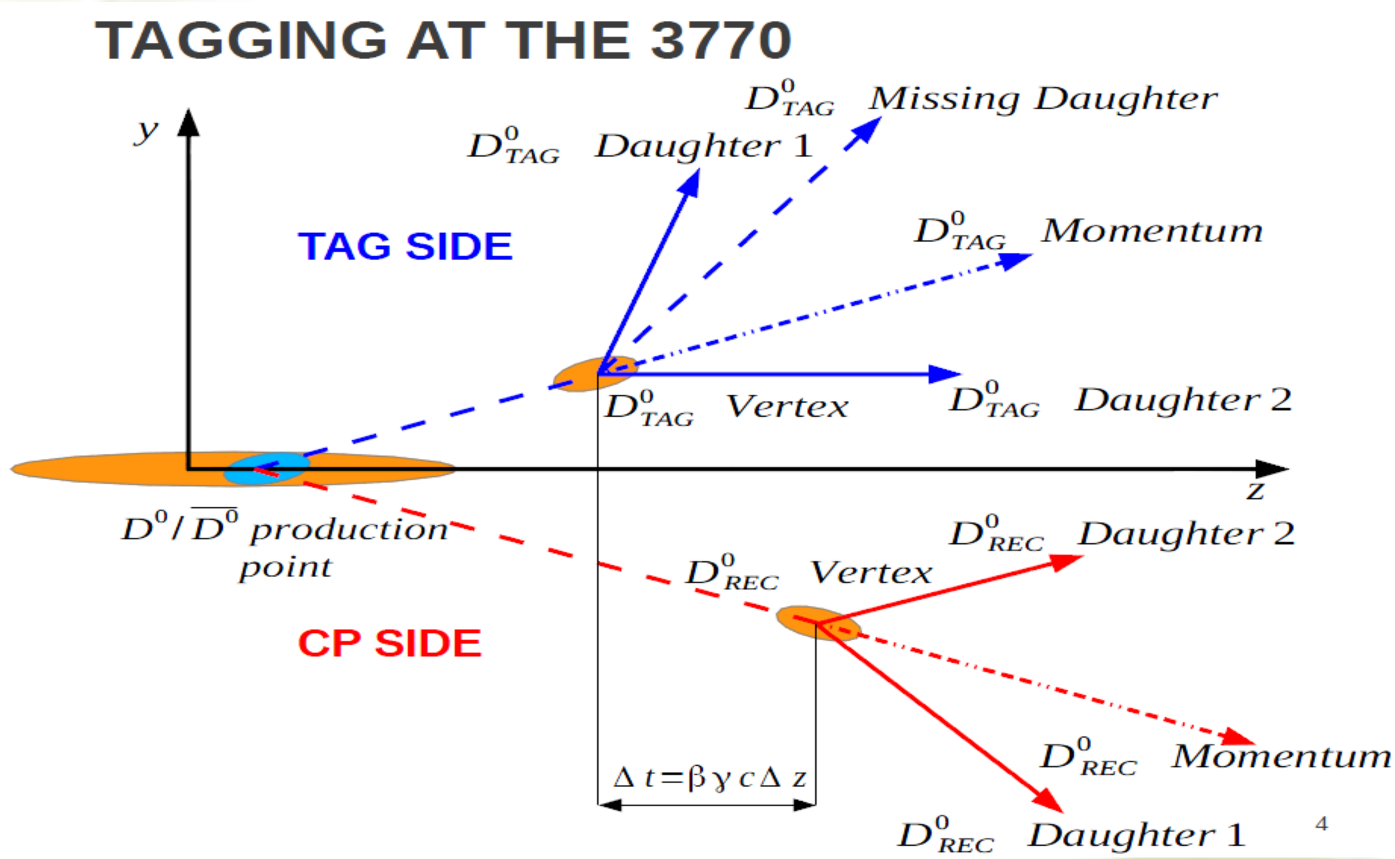
- MC估计混合参数*y*和$\delta_{K\pi}$的测量精度
  - 以目前BESIII的统计量 (2.9fb^{-1})
    - 输入世界平均：$\delta_{K\pi} = 22.1^{+9.7}_{-11.1}(^o),\ y_D = 0.75 \pm 0.12(\%)$
    - 拟合得误差： $\delta_{K\pi}:\ \pm 8.3(^o),\ y_D:\ \pm 0.10(\%)$
    - 两者的误差均改善约~15%
    - 好于CLEO-c的联合拟合





Asymmetric beam?

Semi-leptonic flavor tag at charm Threshold



- Flavor tagging($D^0 \rightarrow K^- l^+ \nu$)
- Time-dependent measurement available
- Require good Δz/Δt resolution(SVT)

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

Time resolution for asymmetric beams

$$e^+e^- \rightarrow \Psi(3770) \rightarrow (\overline{D^0})(D^0) \rightarrow (K^+e^-\nu_e)(\pi^+\pi^-)$$

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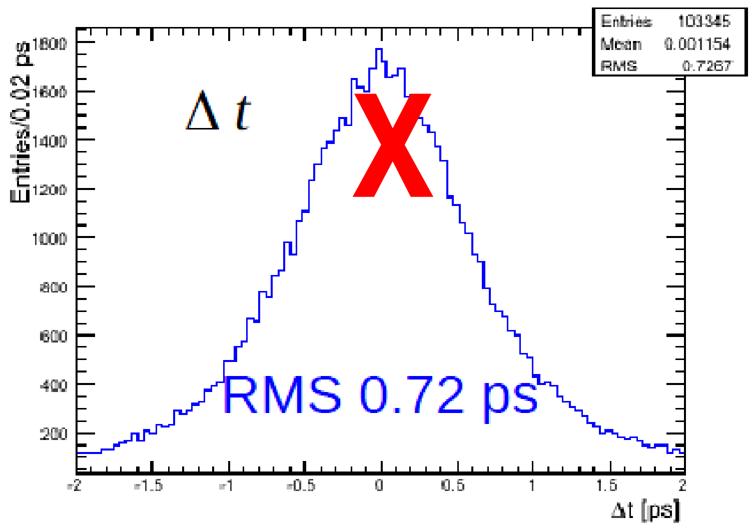
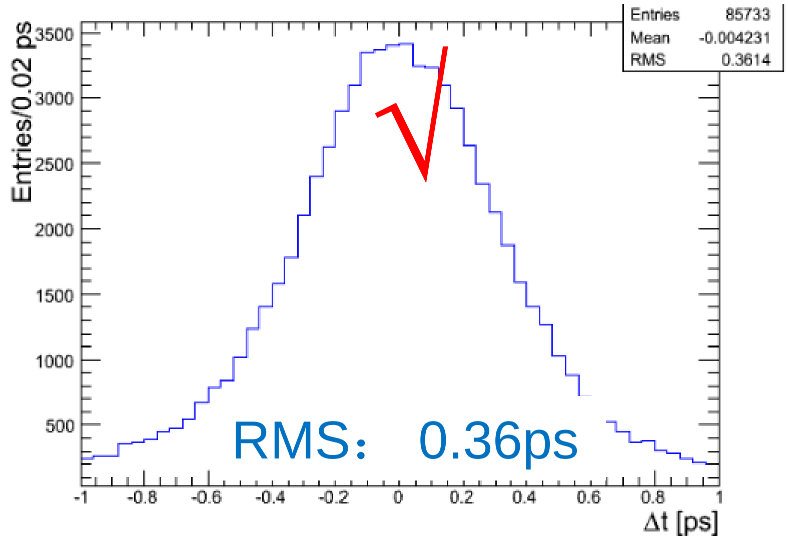
$$A_{CP}^{S_\eta}(t) \equiv \frac{R(l^+, S_\eta) - R(l^-, S_\eta)}{R(l^+, S_\eta) + R(l^-, S_\eta)}.$$

$$A_{CP}^{S_\eta}(t) = \eta x \sin\phi \times \Gamma t$$

$[\beta\gamma = 0.28]$

$[\beta\gamma = 0.56]$





- With βγ=0.56, time-dependent analysis can be performed (D^0 lifetime 0.41ps)！ ***(need to be confirmed!)***

Measurement of charm mixing at Ψ(4040)

Time-integrated decays of quantum-correlated DDbar pairs, with Dbar decaying in a flavor-specific final state:

$$1 - r_f \cos(\delta_f+\phi)(1+\eta_c)\, y + r_f \sin(\delta_f+\phi)(1+\eta_c)\, x + O(x^2, y^2),$$

with $r_f = \overline{A}_f / A_f$, δ_f strong phase

Time-integrated $\psi(3770) \to D\overline{D}$ decays are insensitive to mixing in the first order. $D\overline{D}^*$ is a different case. Consider $e^+e^- \to \psi(4040) \to D^0\overline{D}^{*0}$ production.

- $D^0\overline{D}^0\pi^0$: $\mathcal{C} = -1$, nothing changes wrt. $D\overline{D}$.
- $D^0\overline{D}^0\gamma$: $\mathcal{C} = +1$, now the wave function is symmetric:

$$|A(D_1 D_2)|^2 = |A(D_1)\overline{A}(D_2) + \overline{A}(D_1)A(D_2)|^2$$

Charm mixing contribution is *doubled* compared to time-dependent (uncorrelated) case.

Analysis should involve reconstruction of both $D^0\overline{D}^0\gamma$ (mixing-sensitive) and $D^0\overline{D}^0\pi^0$ (w/o mixing contribution) [Bondar et al., PRD 82, 034033 (2010)].

CPV and D mixing reach

courtesy by Neri&Rama

The sensitivies to mixing and CP violation observables reported in Table II are based on studies considering statistical error only but Belle-II that includes also systematic uncertainties:

- $\Psi(3770)$: time-dependent analyses with a CM boost in the range of $\beta\gamma = 0.3 - 0.6$ and a SuperB-like vertex detector (radius of Layer0 at about 1.5 cm);
- $\Psi(4040)$: based on sensitivity studies of Bondar et al. [2] using time-integrated measurements of $D^0 \to K_s^0\pi^+\pi^-$ and $D^0 \to K^+\pi^-\pi^0$;
- LHCb: based on sensitivity studies reported in [3]. Errors on x, y and $\arg(q/p)$ are based on $D^0 \to K_s^0\pi^+\pi^-$ and errors on $|q/p|$ are based on Wrong-sign/Right-sign $D^0 \to K\mu\nu$.
- Belle-II: based on sensitivity studies reported in [4]. Systematic uncertainties are included. Do not include $D^0 \to K^+\pi^-\pi^0$, $D^0 \to K_s^0K^+K^-$ and $\Psi(3770)$ results from BES-III.

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	$\Psi(3770)$	$\Psi(4040)$	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
$\|q/p\|(\%)$	2-5	0.9	1	5
$\arg(q/p)(^\circ)$	2-3	0.8	3	2.6

Summary

- Threshold measurements employing quantum correlations is still important to study CPV and mixing in charm sector in the next two decades.
- Sensitivity of direct CP Violation measurement at threshold will be competitive in the future, especially the systematic is under control: $\sigma(A_{CP})=10^{-3}\sim10^{-4}$
- Input from charm threshold measurements is important for all methods of γ measurement: $\sigma(\gamma)=(1.3^o\sim2^o)$
- Global fit using quantum correlation is complementary to improve the world average of CPV and mixing parameters
- Asymmetric beams give more potential for super tau-charm factory in the future charm landscape
- Ability to run the machine at E = 4040 MeV (DD^* production) is essential. Precision in x, y and CPV parameters is comparable to pre-upgrade LHCb/Belle II.