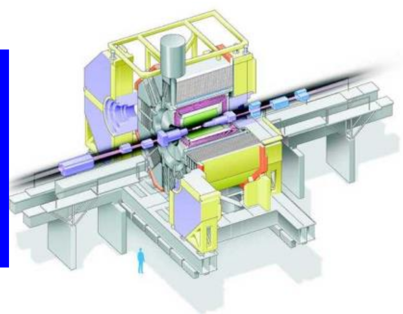
Latest results on mixing and CPV in the charm decays at the *B*-Factories



Vishal Bhardwaj (*on behalf of Belle*)

IISER Mohali

CKM 2016 28 Nov-2 Dec. 2016

Outline

- Study *D* at *B* factory

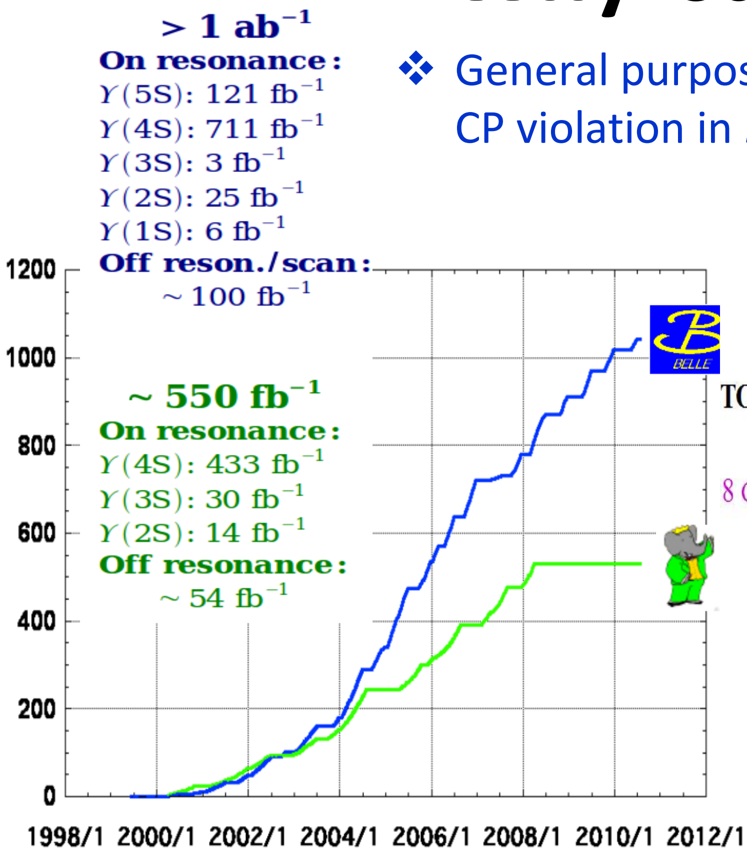
- *D* mixing
  - Wrong sign decay of $D^0 \rightarrow K\pi$
  - $D \rightarrow K_S^0 hh$ decay
  - $D \rightarrow \pi^+\pi^-\pi^0$ decay

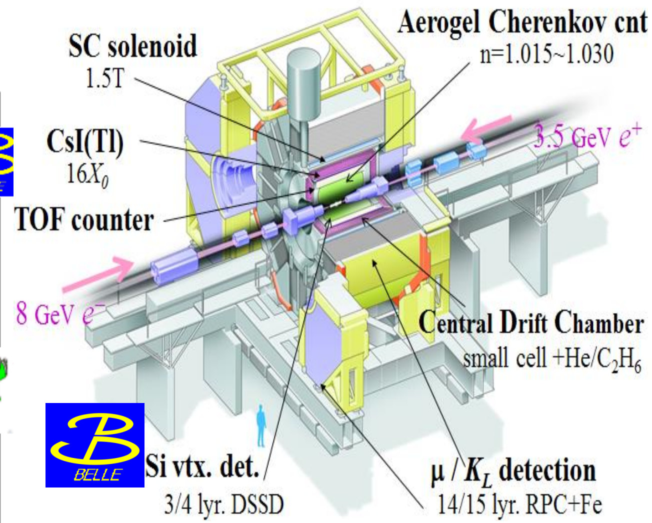
- Direct *CPV* in *D* decays
  - Radiative *D* decays
  - $D^0 \rightarrow K_S K_S$ decays

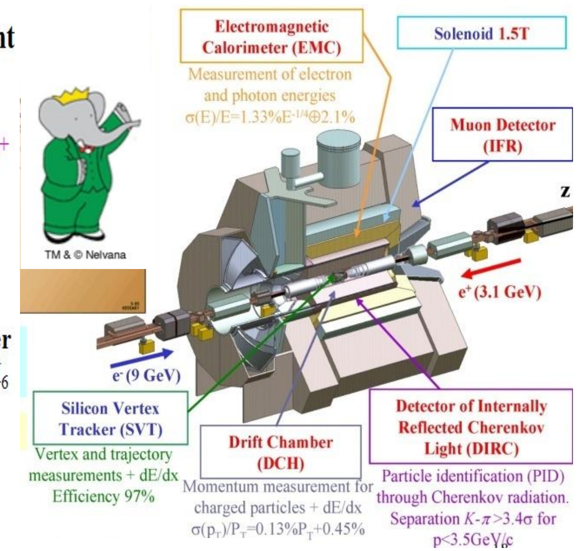
- Summary of mixing and *CPV* at *B* factories

Why study *D* at *B* factory ?

❖ General purpose detectors, built to test Standard Model mechanism for CP violation in *B* decays.







8 GeV e$^-$ on 3.5 GeV e$^+$

9 GeV e$^-$ on 3.1 GeV e$^+$

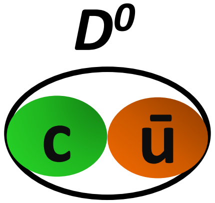
Strength:

- Excellent particle identification.
- γ, π^0 and K_S reconstruction can be done easily.
- Good background reduction and high signal efficiency (5-10%)

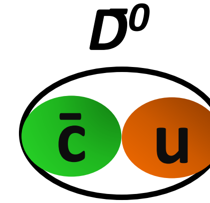
	No of (in x 10^9)*	
	$b\bar{b}$	$c\bar{c}$
Belle	0.77	1.3
BaBar	0.46	0.65

Based on which one can also call *B* factory to be a charm factory !

*$\sigma(b\bar{b})$ ~ 1.05 nb and $\sigma(c\bar{c})$ ~ 1.3 nb



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



Mass : (1864.83±0.05) MeV τ_{D0} = (410.1±1.5) x10^{-15} s

Phenomenon of mixing can be described as a decaying two-component quantum state.

Mass eigenstates (D_1, D_2) $\neq$ Flavor eigenstates (D^0, $\bar{D}^0$).

Time evolution : $|D_{1,2}(t)\rangle = e^{-im_{1,2}t} e^{-\frac{\Gamma_{1,2}t}{2}} |D_{1,2}(t=0)\rangle$

$m_1(m_2)$ and Γ_1 (Γ_2) are the mass and decay width of $D_1(D_2)$

Flavor states

$$|D^0(t)\rangle = \frac{1}{2p}[|D_1(t)\rangle + |D_2(t)\rangle] \text{ and } |\bar{D}^0(t)\rangle = \frac{1}{2q}[|D_1(t)\rangle - |D_2(t)\rangle]$$

At t=0, states are produced as pure D^0 or $\bar{D}^0$

$$|D_0(t)\rangle = \left[|D_0\rangle \cosh\left(\frac{ix+y}{2}\bar{\Gamma}t\right) - \frac{q}{p}|\bar{D}_0\rangle \sinh\left(\frac{ix+y}{2}\bar{\Gamma}t\right)\right] e^{-i\bar{m}t-\frac{\bar{\Gamma}}{2}t} \quad |\bar{D}_0(t)\rangle = \left[|\bar{D}_0\rangle \cosh\left(\frac{ix+y}{2}\bar{\Gamma}t\right) - \frac{q}{p}|D_0\rangle \sinh\left(\frac{ix+y}{2}\bar{\Gamma}t\right)\right] e^{-i\bar{m}t-\frac{\bar{\Gamma}}{2}t}$$

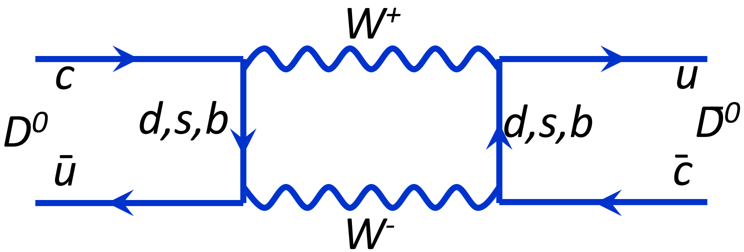
At later time can be $\bar{D}_0$ or D_0, depending on the value of mixing parameter *x, y*:

$$x \equiv \frac{m_1 - m_2}{\bar{\Gamma}};\ y \equiv \frac{\Gamma_1 - \Gamma_2}{2\bar{\Gamma}};\ \bar{\Gamma} \equiv \frac{\Gamma_1 + \Gamma_2}{2};\ \bar{m} \equiv \frac{m_1 + m_2}{2}$$

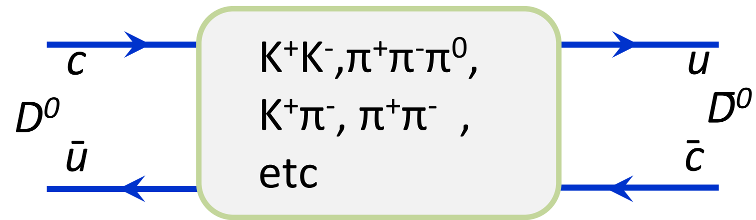
* under CPT conservation assumption: $|p|^2+|q|^2 = 1$

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

In SM, D^0 meson can change to $\bar{D}^0$ via



Double weak boson exchange
(Short distance effects)



Intermediate state common to both
(Long distance effects)

SM predictions for x and y suffers from larger uncertainties.
Generally, Mixing in charm system strongly suppressed : $|x|, |y| \sim 1\%$

Sensitive to New Physics effects : $|x| \gg |y|$

Observables at B factories :

$$\frac{dN(D^0 \to f)}{dt} \propto e^{-\bar{\Gamma} t} \left| A_f + \frac{q}{p} \frac{ix+y}{2} \bar{A}_f \bar{\Gamma} t \right|^2 \quad \frac{dN(\bar{D}^0 \to f)}{dt} \propto e^{-\bar{\Gamma} t} \left| \bar{A}_f + \frac{p}{q} \frac{ix+y}{2} A_f \bar{\Gamma} t \right|^2$$

$$A_f = \langle f | D^0 \rangle, \bar{A}_f = \langle f | \bar{D}^0 \rangle$$

Decay time distribution of accessible states D^0, $\bar{D}^0$ are sensitive to mixing parameters (x and y), depending on the final state.

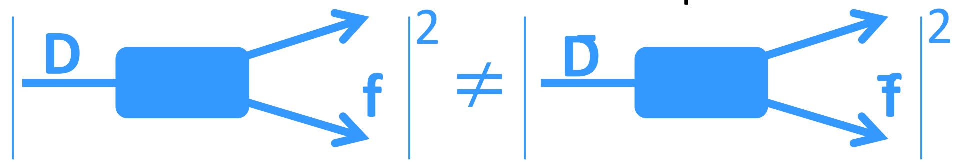
$dN(D^0 \to f)/dt$ is different function of x, y (and q, p) for different A_f, $\bar{A}_f$

CP violation in charmed mesons

Direct CPV (neutral and charged, mode dependent)

CP violation in decay appears on the amplitude level. Occurs if two different amplitude contribute to a single decay

$$\left|\frac{A(D\to f)}{A(\overline{D}\to \overline{f})}\right| \neq 1$$

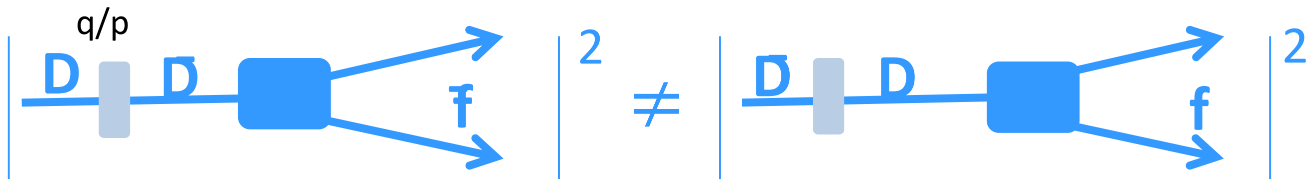


Indirect CPV (neutral, common for all decay modes)

In Mixing :

CP violation in mixing occurs if a particle D^0 can't decay into a final state f̄ buts CP-conjugate $\overline{D}^0$ can. $\boldsymbol{D^0 \longrightarrow \overline{D}^0 \longrightarrow Y^+X^- \nleftarrow D^0}$ $\boldsymbol{\overline{D}^0 \longrightarrow D^0 \longrightarrow Y^-X^+ \nleftarrow \overline{D}^0}$

$$\boldsymbol{r_m = |q/p| \neq 1}$$



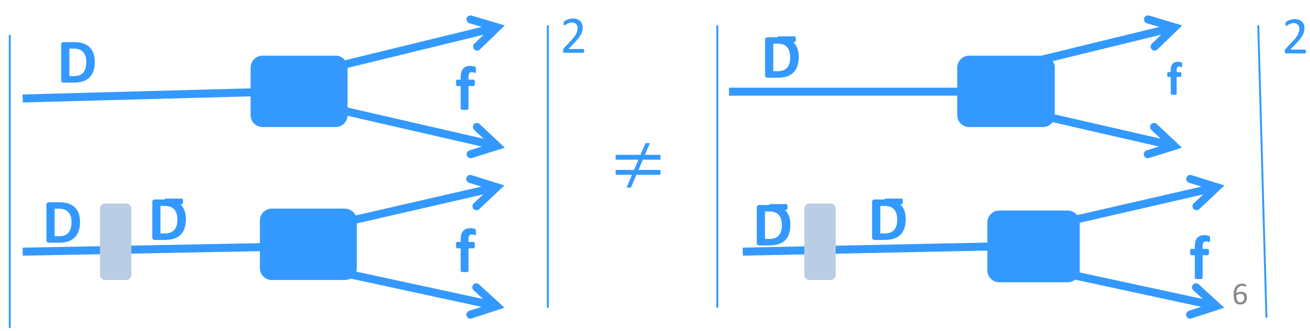
In interference of decays with and without mixing:

If mixing followed by decay and direct decay interfere. Final state must be common to D^0 and $\overline{D}^0$.

Two conditions :

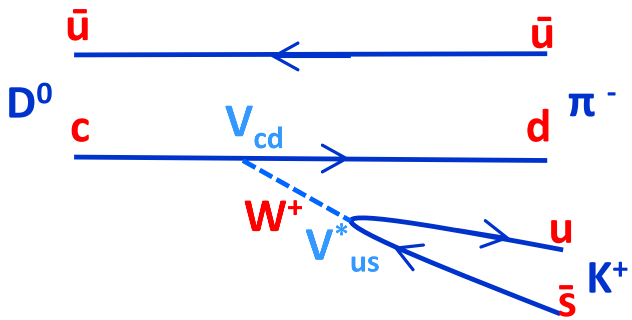
$$\boldsymbol{x = \frac{\Delta M}{\Gamma} \neq 0}$$

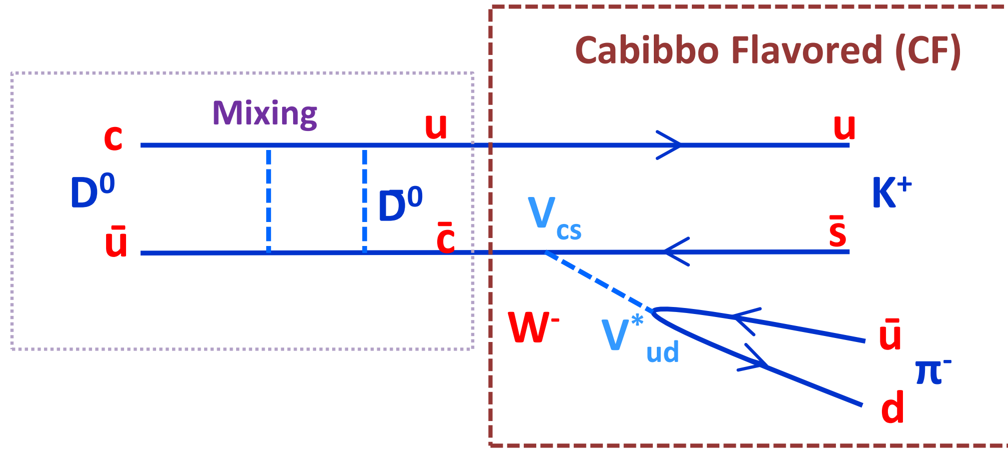
$$\boldsymbol{arg\left(\frac{q\overline{A}_f}{pA_f}\right) \neq 0}$$



$D^0 \rightarrow K^+\pi^-$ wrong sign analysis

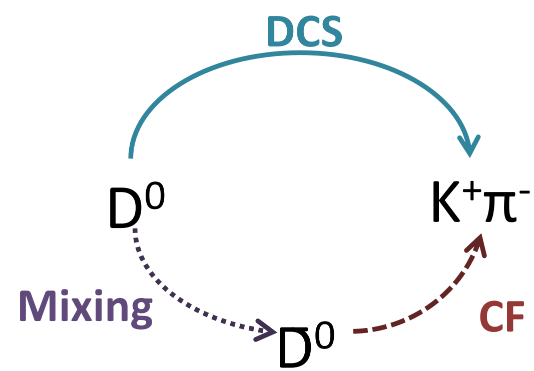
Doubly Cabibbo Suppressed (DCS)





Same initial-and final state

Interference between the two amplitude will occur



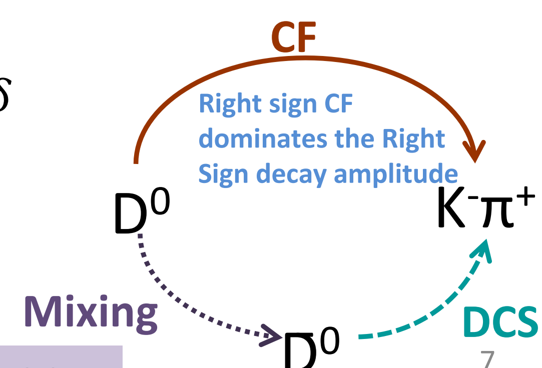
In the limit of CP conservation

Normalize wrong sign rate to the right sign to obtain

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = RD + \sqrt{R_D}\, y' \Gamma_{D^0}\, t + \frac{x'^2 + y'^2}{4} (\Gamma_{D^0}\, t) 2$$

$$R_D = \left| \frac{A_{DCS}}{A_{CF}} \right|^2 \qquad x' = x \cos\delta + y \sin\delta \,, y' = -x \sin\delta + y \cos\delta$$

$$\delta = arg\left(\frac{A_{DCS}}{A_{CF}}\right) \qquad x = \frac{\Delta m_{D^0}}{\Gamma_{D^0}} \qquad y = \frac{\Delta\Gamma_{D^0}}{2\Gamma_{D^0}}$$



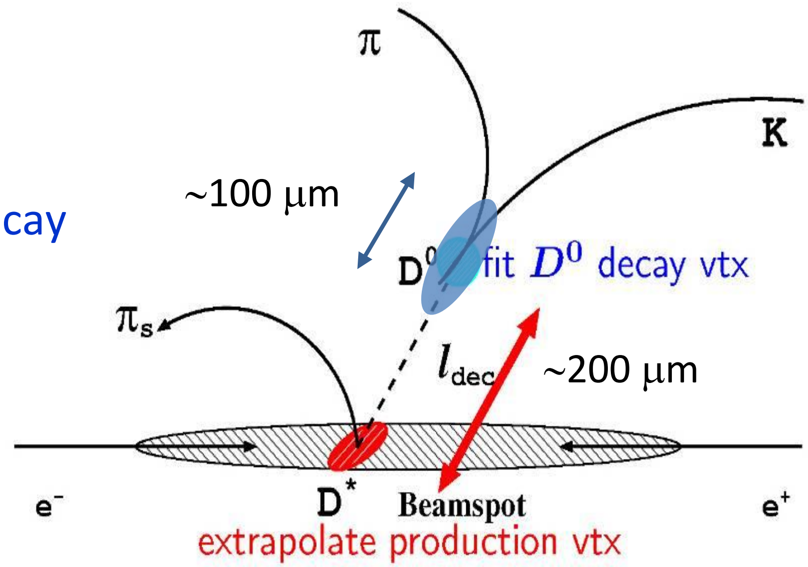
$\delta \rightarrow$ strong phase not directly measurable at B-factories

y' and x'^2 accessible

D^0-$\bar{D}^0$ mixing at B factories $D^0 \rightarrow K^+\pi^-$

Experimental method

Tag and suppress background
- $D^{*+} \rightarrow D^0\pi^+_{slow}$
- Flavor of D^0 → using charge of π_{slow}
- $p_{CMS}(D^*)$ > 2.5 GeV/c to eliminate D^0 from B decay



Measure D^0 proper time t, its error σ_t by reconstructing D^0 momentum and flight length l

$$t = \frac{l_{dec}}{c\beta\gamma} \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

σ_t calculated from vtx error matrices

Mixing parameters (x'^2,y') extracted by the fit to the time-dependent ratio of wrong sign to right sign decays

$$R\left(t/\tau_{D^0}\right) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS}\left(t'/\tau_{D^0}\right) \mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right) d(t'/\tau_{D^0})}{\int_{-\infty}^{+\infty} \Gamma_{RS}\left(t'/\tau_{D^0}\right) \mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right) d(t'/\tau_{D^0})}$$

$\mathcal{R}\left(t/\tau_{D^0} - t'/\tau_{D^0}\right)$ is resolution function of the real decay time t'.

Belle, PRL 112, 111801(2014)

976fb^{-1}

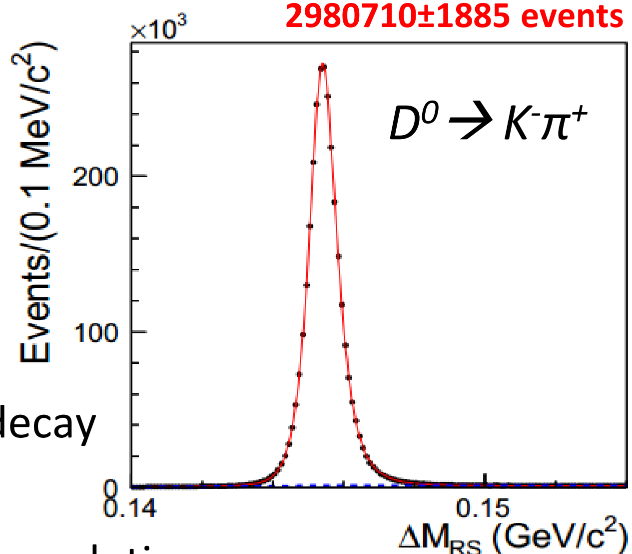
WS decay $D^0 \rightarrow K^+\pi^-$

$\Delta M = M(D^{*+} \rightarrow D^0(\rightarrow K\pi)\pi_s^+) - M(D^0 \rightarrow K\pi)$

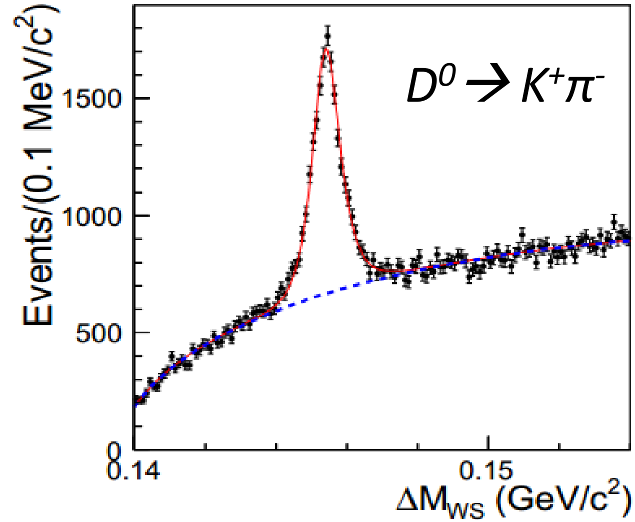
Gaussian + Johnson S_U

R_{WS}: (0.385±0.006) %

2980710±1885 events

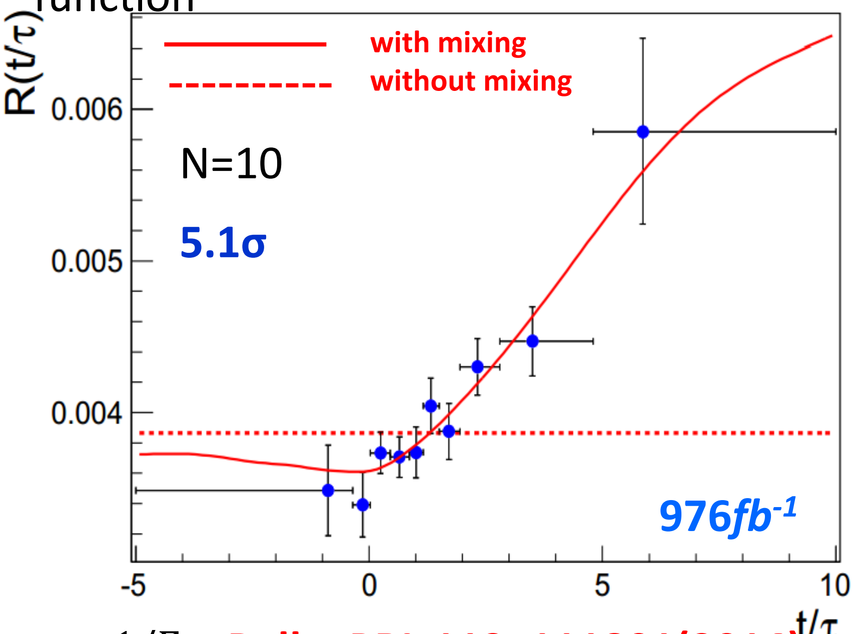


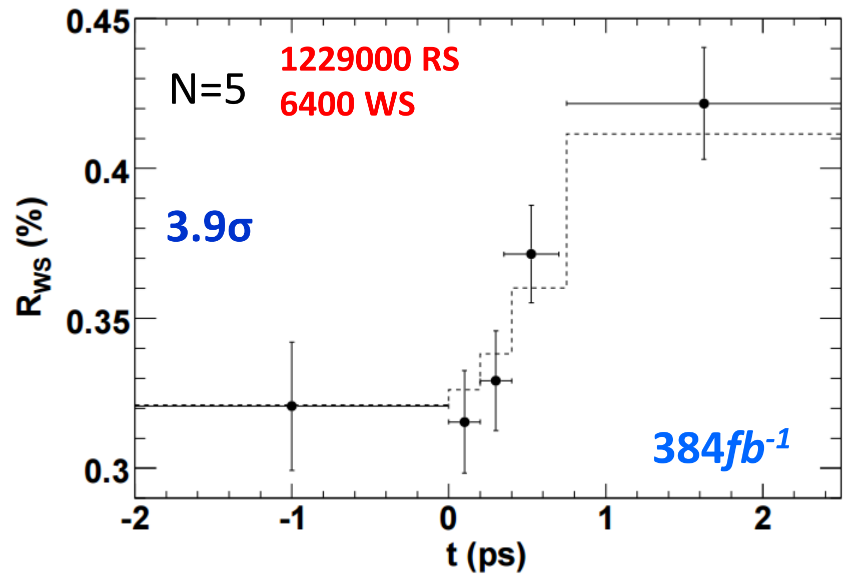
11478±177 events



Divide sample into **N** bins of decay time and fit ΔM

Fitting ratios less sensitive to resolution function





$\tau = 1/\Gamma_{D^0}$ **Belle, PRL 112, 111801(2014)**

BaBar, PRD 98, 211802(2007)

WS decay $D^0 \rightarrow K^+\pi^-$: Results

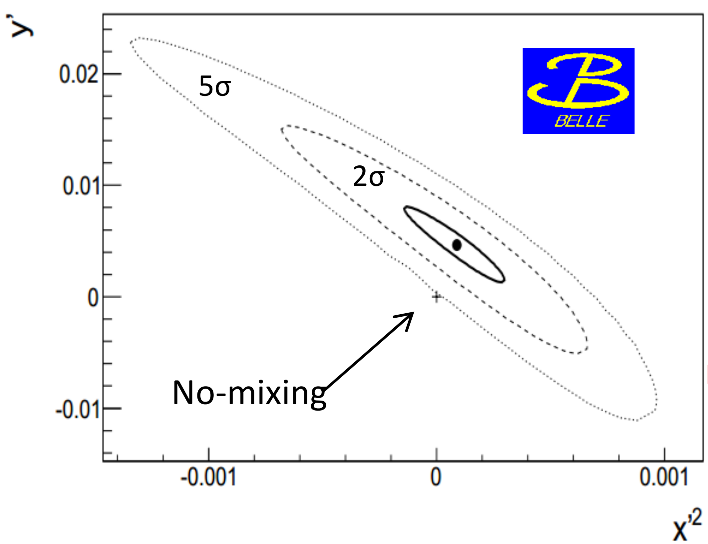
976fb^{-1}

Belle, PRL 112, 111801(2014)

Test hypothesis (χ^2/DOF)	Parameters	Fit results (10^{-3})
Mixing (4.2/7)	R_D y' x'^2	3.53±0.13 4.6±3.4 0.09±0.22
No mixing (33.5/9)	R_D	3.864±0.059

No CP Violation hypothesis

No-mixing hypothesis is excluded at 5.1σ



384fb^{-1}

BaBar, PRD 98, 211802(2007)

Test hypothesis	Parameters	Fit results (10^{-3})
Mixing with CPV	R_D y'^+ x'^{2+} y'^- x'^{2-}	3.03±0.19 9.9±7.8 -0.24±0.52 9.6±7.5 -0.20±0.50
Mixing No CPV	y' x'^2	9.7±5.4 -0.22±0.37
No mixing	R_D	3.53±0.1

No-mixing hypothesis is excluded at 3.9σ

Reference	Expt	R_D (x10^{-3})	y' (x10^{-3})	x'^2 (x10^{-3})
PRL112, 111801 (2014)	Belle	3.53±0.13	4.6±3.4	0.09±0.22
PRL 98, 211802 (2007)	BaBar	3.03±0.19	9.7±5.4	-0.22±0.37
PRL 111, 231802 (2013)	CDF	3.51±0.35	4.3±4.3	0.08±0.18
LHCb-PAPER-2016-033	LHCb	3.533±0.054	5.23±0.84	3.6±4.3

B factories results are competitive to that of Hadron colliders!

CP eigenstates decays $D^0 \rightarrow K^+K^- / \pi^+\pi^-$

Mixing in D^0 decays to CP eigenstates, give rise to an effective lifetime τ that differs from that in the decays to flavor eigenstates such as $D \rightarrow K^+\pi^-$.
Observables

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

PLB 486, 418 (2000)

y_{CP} is equal to the mixing parameter y if CP is conserved.
Otherwise, effective lifetimes of $\bar{D}^0$ and D^0 decaying to the same CP eigenstate differ and the asymmetry

$$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} \neq 0$$

In absence of direct CP violation, y_{CP} and A_Γ are related to x and y as

$$y_{CP} = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) ycos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) xsin\phi$$

$$A_\Gamma = \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) ycos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) xsin\phi$$

where $\phi = \arg(\frac{q}{p})$

PLB 486, 418 (2000)
JHEP 0705, 102 (2007)

We measure:

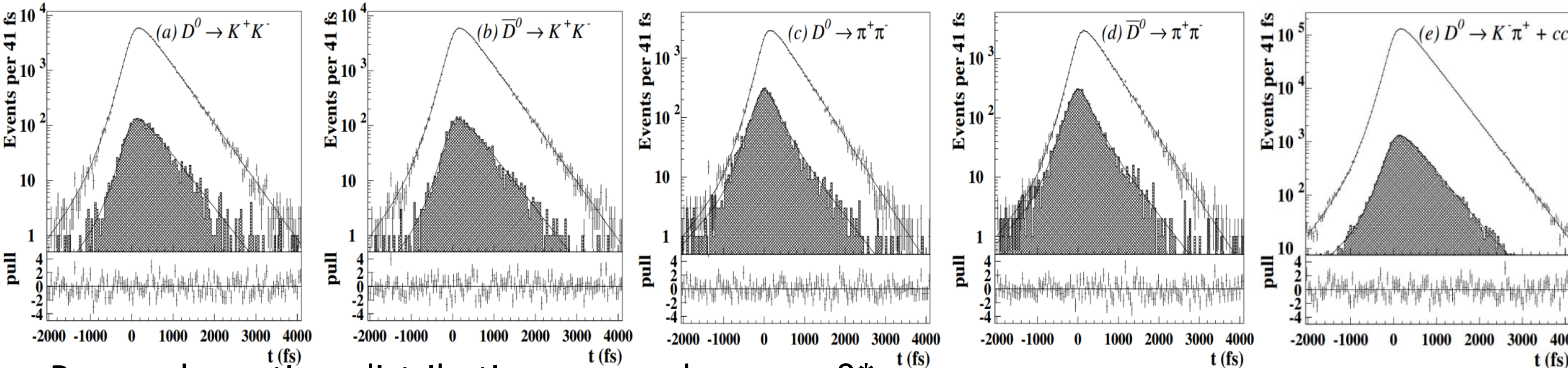
Difference in proper decay time distributions of $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$

CP eigenstates decays $D^0 \rightarrow K^+K^- / \pi^+\pi^-$

976fb^{-1}

Belle, PLB 753, 412 (2015)

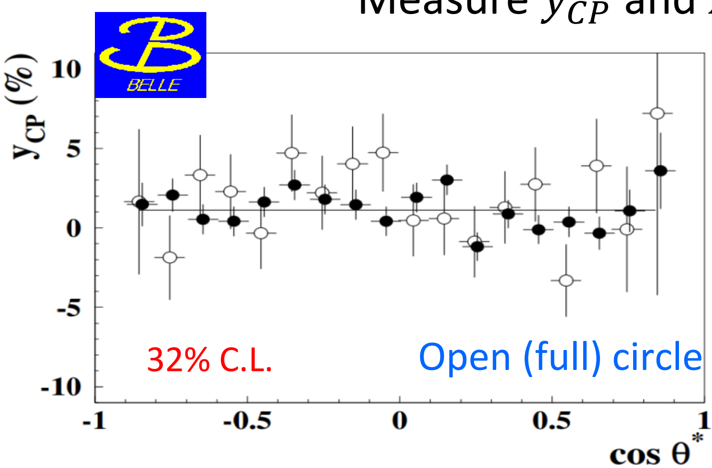
Tag D^0 flavor by charge of π_s from D*

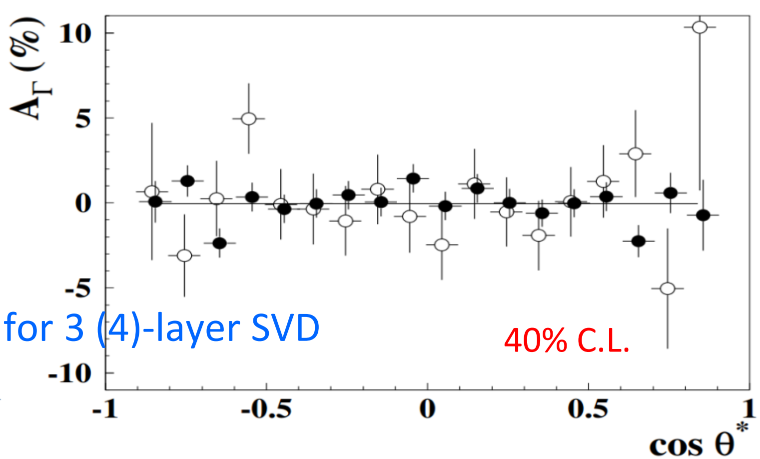


Proper decay time distribution summed over cosθ*

where θ* polar angle of D^0 in CMS with respect to the direction of e^+

Measure y_{CP} and A_Γ in bins of cosθ*





Open (full) circle for 3 (4)-layer SVD

Least Square fit

Fitted D^0 Lifetime: (408.46±0.54)fs (stat only)

World Average: (410.1±1.5) fs

$$y_{CP} = [+1.11 \pm 0.22(stat) \pm 0.09(syst)]\%$$ **(4.7σ)**

$$A_\Gamma = [-0.03 \pm 0.20(stat) \pm 0.07(syst)]\%$$

CP eigenstates decays $D^0 \to K^+K^- / \pi^+\pi^-$ *468fb^{-1}*

BaBar, PRD 87, 012004 (2013)

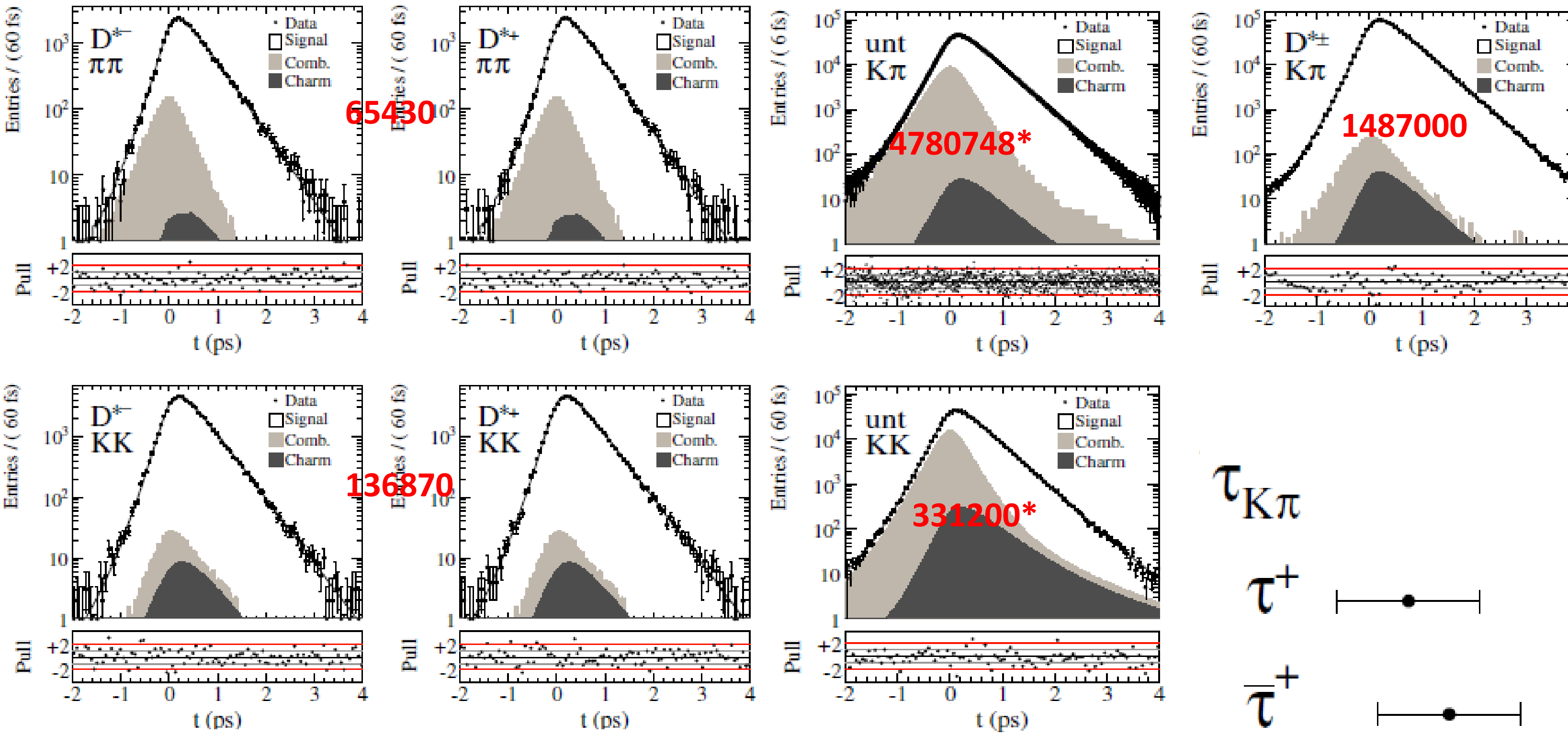
Measure the lifetimes

$\tau^+ : D^0 \to K^- K^+, \pi^- \pi^+$

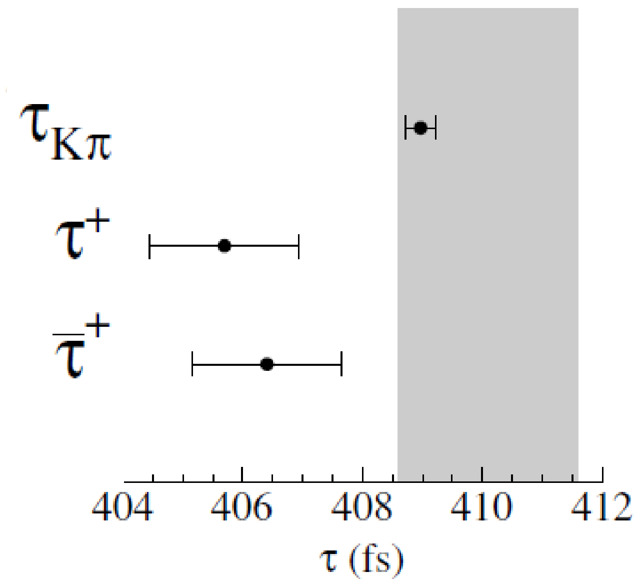
$\bar{\tau}^+ : \bar{D}^0 \to K^- K^+, \pi^- \pi^+$

$\tau_{K\pi} : D^0(\bar{D}^0) \to K^\mp \pi^\pm$

Use their inverse to compute $y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$ and $\Delta Y = -\frac{A_\Gamma}{2} = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$ $p_{CMS}(D^0) > 2.5$ GeV/c



Only tagged for $D^0 \to \pi\pi$ due to poor S/N in untagged



$$y_{CP} = [0.72 \pm 0.18 \pm 0.12]\% \ (3.3\sigma)$$

$$\Delta Y = -\frac{A_\Gamma}{2} = [0.09 \pm 0.26 \pm 0.06]\%$$

***I roughly subtract combinatorial background**

Mixing in three body $D^0 \rightarrow K_S^0\pi^+\pi^-$

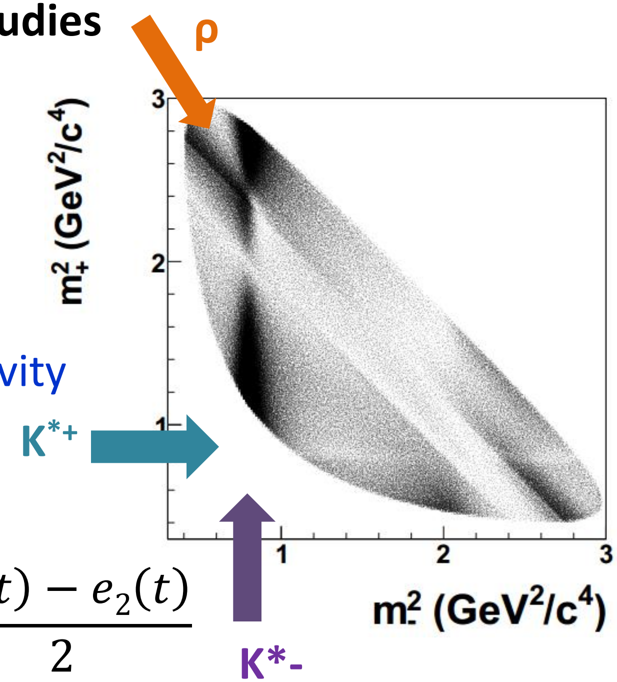
Powerful decay mode for flavor-tagged time-dependent D^0-$\bar{D}^0$ studies

Quasi two body intermediate state

CF : $D^0 \rightarrow K^{*-}\pi^+$

DCS : $D^0 \rightarrow K^{*+}\pi^-$

CP : $D^0 \rightarrow \rho K_S^0$



- Interference between intermediate resonance provide sensitivity to both magnitude and sign of the mixing parameters.
- Allows for probes for indirect CP violation

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2)\frac{e_1(t)+e_2(t)}{2} + \frac{q}{p}\bar{\mathcal{A}}(m_-^2, m_+^2)\frac{e_1(t)-e_2(t)}{2}$$

$$\bar{\mathcal{M}}(m_-^2, m_+^2, t) = \bar{\mathcal{A}}(m_-^2, m_+^2)\frac{e_1(t)+e_2(t)}{2} + \frac{p}{q}\mathcal{A}(m_-^2, m_+^2)\frac{e_1(t)-e_2(t)}{2}$$

CPV

$\mathcal{A}$ amplitude for $|D^0\rangle$ $\bar{\mathcal{A}}$ amplitude for $|\bar{D}^0\rangle$ $m_\pm^2 \equiv m^2(KS^0\pi^\pm)$

Sum of intermediates states

$$\mathcal{A}(m_-^2, m_+^2) = \sum a_r\, e i^{\varphi_r}\mathcal{A}_r(m_-^2, m_+^2) + aNRe i^{\varphi_r} \qquad \bar{\mathcal{A}}(m_-^2, m_+^2) = \sum a\bar{a}_r\, e i^{\overline{\varphi_r}}\bar{\mathcal{A}}_r(m_-^2, m_+^2) + aNRe i^{\overline{\varphi_r}}$$

Time dependence contained in terms $e_{1,2}(t) = \exp[-i\,(m_{1,2} - i\Gamma_{1,2}/2)t]$

Simultaneous determination of ***x*** and **y** via t-dependent amplitude analysis

Belle PRD89, 091103 (R)(2014)

$D^0 \rightarrow K_S^0\pi^+\pi^-$ decay

921fb^{-1}

Signal selected :

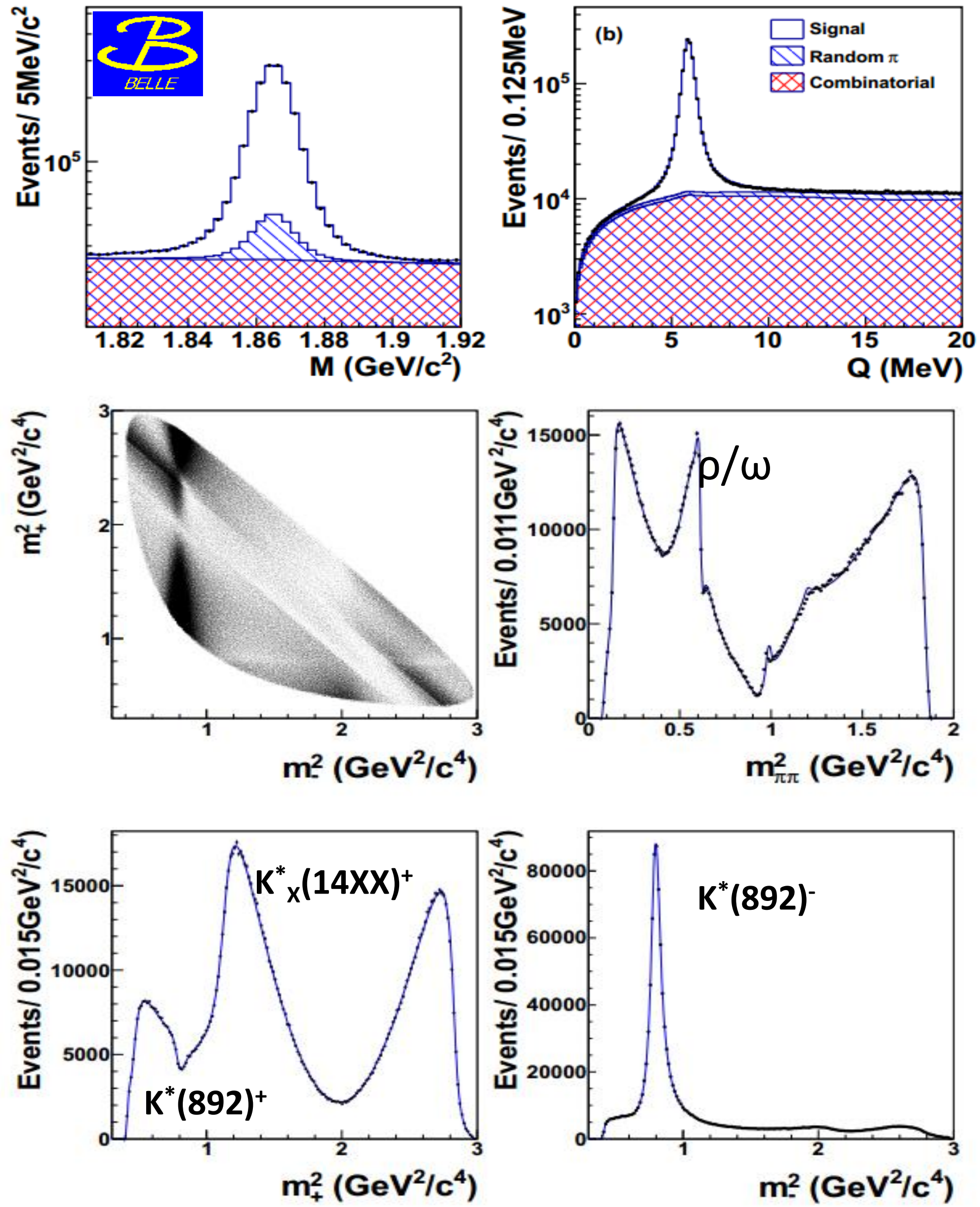
$M(K_S^0\pi^+\pi^-)$ and

$Q=M(K_S^0\pi^+\pi^-\pi_s)-M(K_S^0\pi^+\pi^-)-m(\pi_s)$

$|M-m_{D0}| < 15$ MeV

5.75 MeV < Q < 5.95 MeV

1231731±1633 signal events with purity of 95.5%



Dalitz model

- For P- and D-wave decays, include 12 relativistic BW
- Blatt-Weisskopf penetration factors as form factors
- Zemach tensors for the angular dependence.
- $\pi\pi$ S-wave dynamics : K-matrix formalism with P-vector approximation
- $K_S^0\pi$ S-wave : LASS parameterization

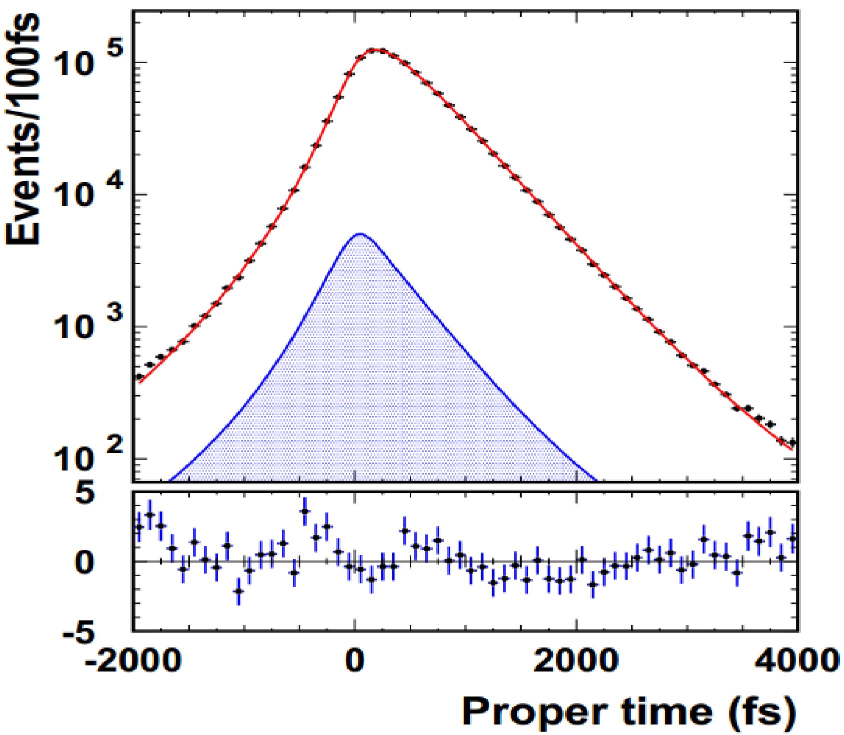
χ^2/ndf=1.207 for 14264-42 degrees of freedom

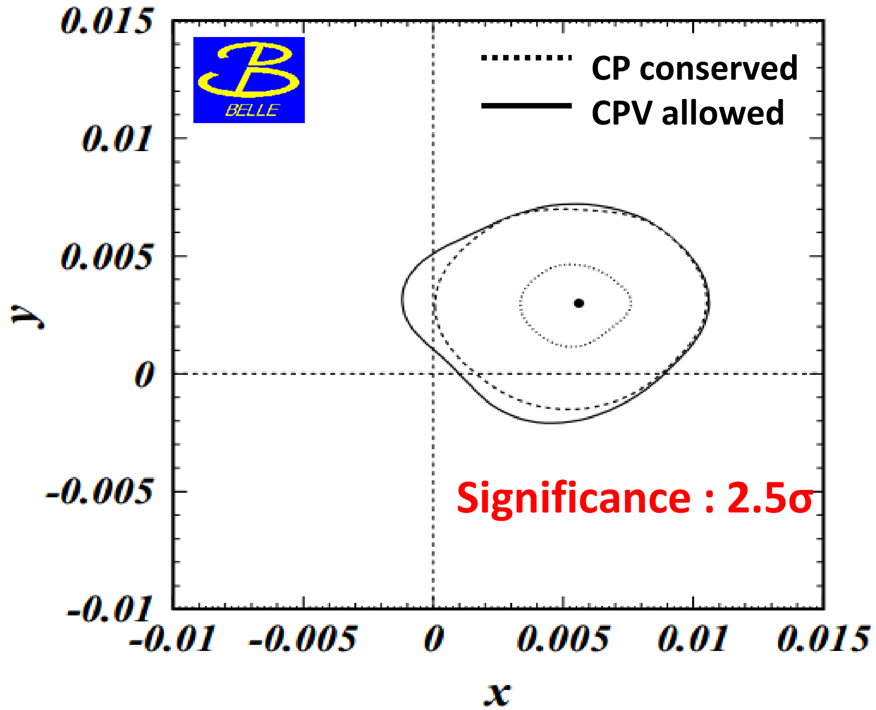
Belle PRD89, 091103 (R)(2014)

Measurement of x, y and q/p

921fb[-1]

Fit projection for CP conserved fit





D^0 mean lifetime = (410.3±0.6)fs

Consistent with PDG: (410.1±1.5)fs

$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$$

$$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$$

Also search for CPV in $D^0/\bar{D}^0 \to K_S^0\pi^+\pi^-$

Value of *x* and *y* consistent with CP conserved fit

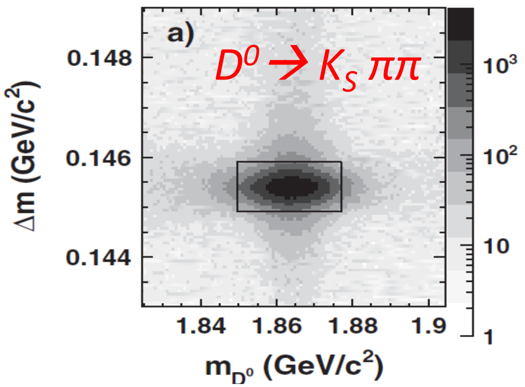
$$|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05} \qquad arg(q/p) = (-6 \pm 11^{+3+3}_{-3-4})^\circ$$

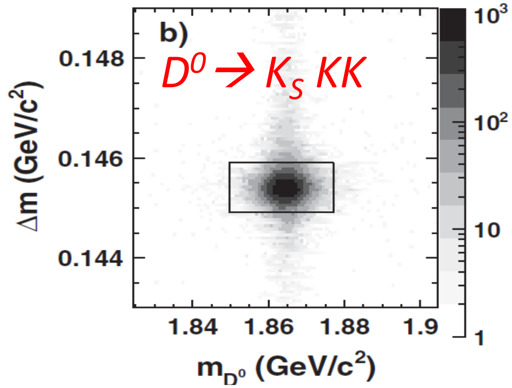
No hint for indirect CP violation

Using $D^0 \to K_S \pi\pi$ and $D^0 \to K_S K K$ decays

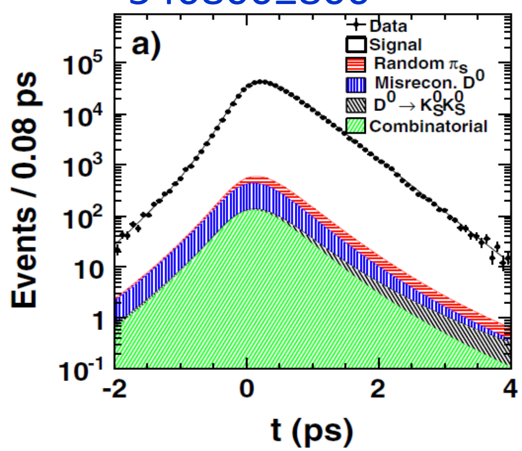
469fb^{-1}

BaBar, PRL 105 081803 (2010)

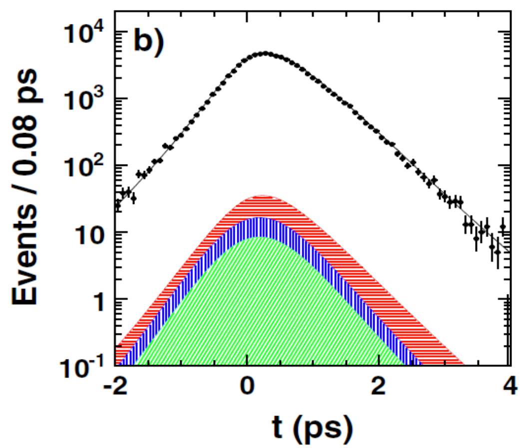


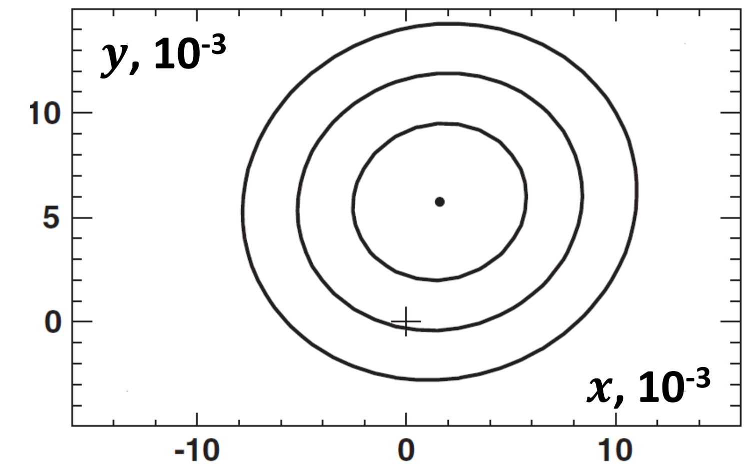


540800±800



79900±300





+ *Non Mixing*

Fit type	$x/10^{-3}$	$y/10^{-3}$
Nominal	$1.6 \pm 2.3 \pm 1.2 \pm 0.8$	$5.7 \pm 2.0 \pm 1.3 \pm 0.7$
$K^0_S\pi^+\pi^-$	2.6 ± 2.4	6.0 ± 2.1
$K^0_S K^+ K^-$	-13.6 ± 9.2	4.4 ± 5.7
D^0	0.0 ± 3.3	5.5 ± 2.8
$\bar{D}^0$	3.3 ± 3.3	5.9 ± 2.8

Disfavor non-mixing hypothesis with C.L. equivalent to 1.9σ

468fb^{-1}

Using $D^0 \rightarrow \pi^+\pi^-\pi^0$ decay

BaBar, PRD 93, 112014 (2016)

First measurement of mixing parameter of time dependent amplitude analysis.

Signal identified as :

$\Delta m \equiv m(\pi^+\pi^-\pi^0\pi_s^+) - m(\pi^+\pi^-\pi^0)$

$p_{\pi^0} > 350$ MeV

$p^*(D^0) > 2.8$ GeV

~138000 events

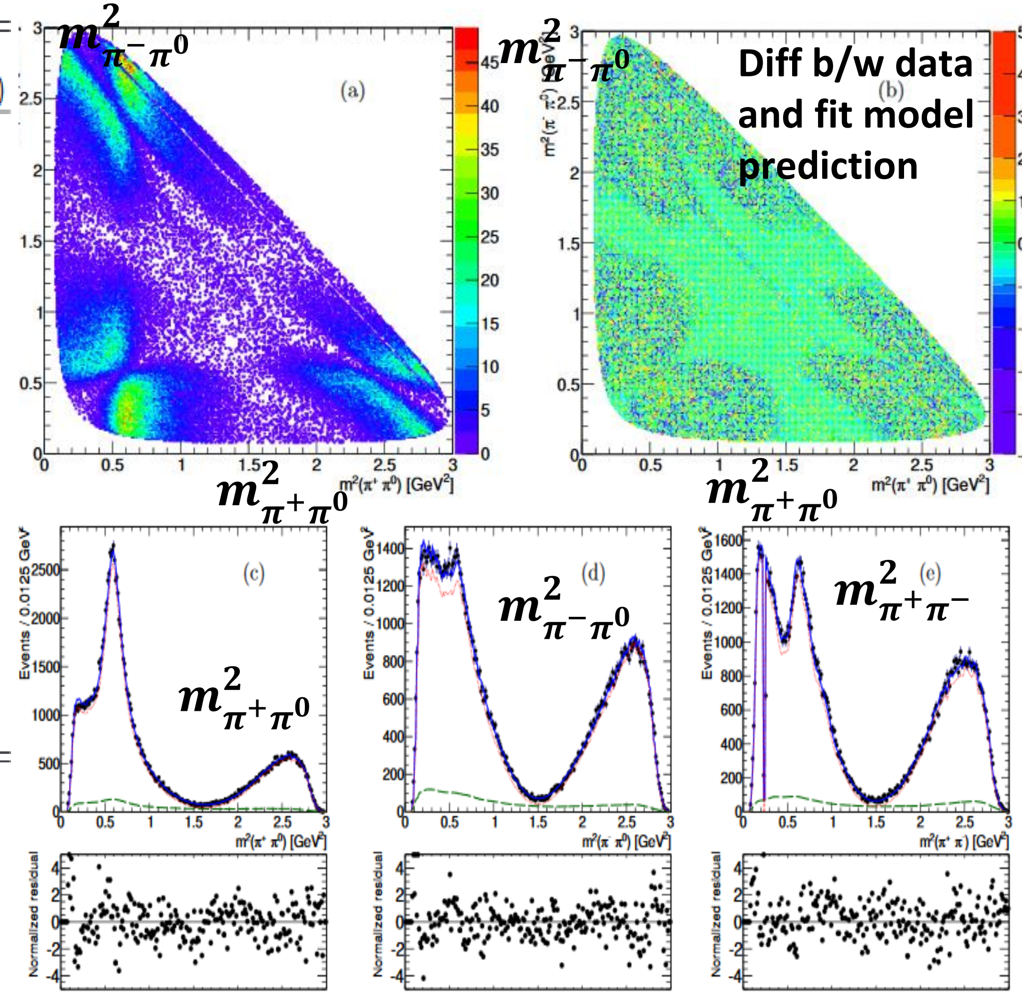
Background from:

$D \rightarrow K^-\pi^+, D \rightarrow K^-\pi^+\pi^0,$

$D \rightarrow K_s\pi^+\pi^-$ and $D \rightarrow K_s(\rightarrow \pi^+\pi^-)\pi^0$

Fit with isobar model of relativistic BW line shape

State	Resonance parameters			Fit to data results		
	J^{PC}	Mass (MeV)	Width (MeV)	Magnitude	Phase (°)	Fraction f_r (%)
$\rho(770)^+$	1^{--}	775.8	150.3	1	0	66.4±0.5
$\rho(770)^0$	1^{--}	775.8	150.3	0.55±0.01	16.1±0.4	23.9±0.3
$\rho(770)^-$	1^{--}	775.8	150.3	0.73±0.01	−1.6±0.5	35.6±0.4
$\rho(1450)^+$	1^{--}	1465	400	0.55±0.07	−7.7±8.2	1.1±0.3
$\rho(1450)^0$	1^{--}	1465	400	0.19±0.07	−70.4±15.9	0.1±0.1
$\rho(1450)^-$	1^{--}	1465	400	0.53±0.06	8.2±6.7	1.0±0.2
$\rho(1700)^+$	1^{--}	1720	250	0.91±0.15	−23.3±10.3	1.5±0.5
$\rho(1700)^0$	1^{--}	1720	250	0.60±0.13	−56.3±16.0	0.7±0.3
$\rho(1700)^-$	1^{--}	1720	250	0.98±0.17	78.9±8.5	1.7±0.6
$f_0(980)$	0^{++}	980	44	0.06±0.01	−58.8±2.9	0.3±0.1
$f_0(1370)$	0^{++}	1434	173	0.20±0.03	−19.6±9.5	0.3±0.1
$f_0(1500)$	0^{++}	1507	109	0.18±0.02	7.4±7.4	0.3±0.1
$f_0(1710)$	0^{++}	1714	140	0.40±0.08	42.9±8.8	0.3±0.1
$f_2(1270)$	2^{++}	1275.4	185.1	0.25±0.01	8.8±2.6	0.9±0.1
$f_0(500)$	0^{++}	500	400	0.26±0.01	−4.1±3.7	0.9±0.1
NR				0.43±0.07	−22.1±11.7	0.4±0.1



D^0 mean lifetime = (410.2±3.8)fs

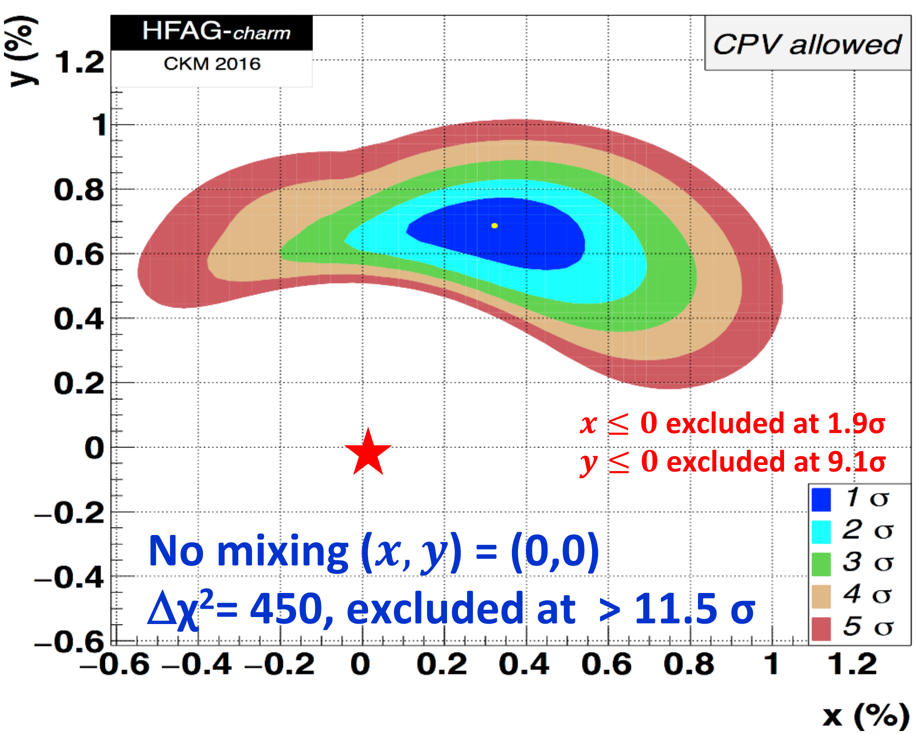
Consistent with PDG: (410.1±1.5)fs

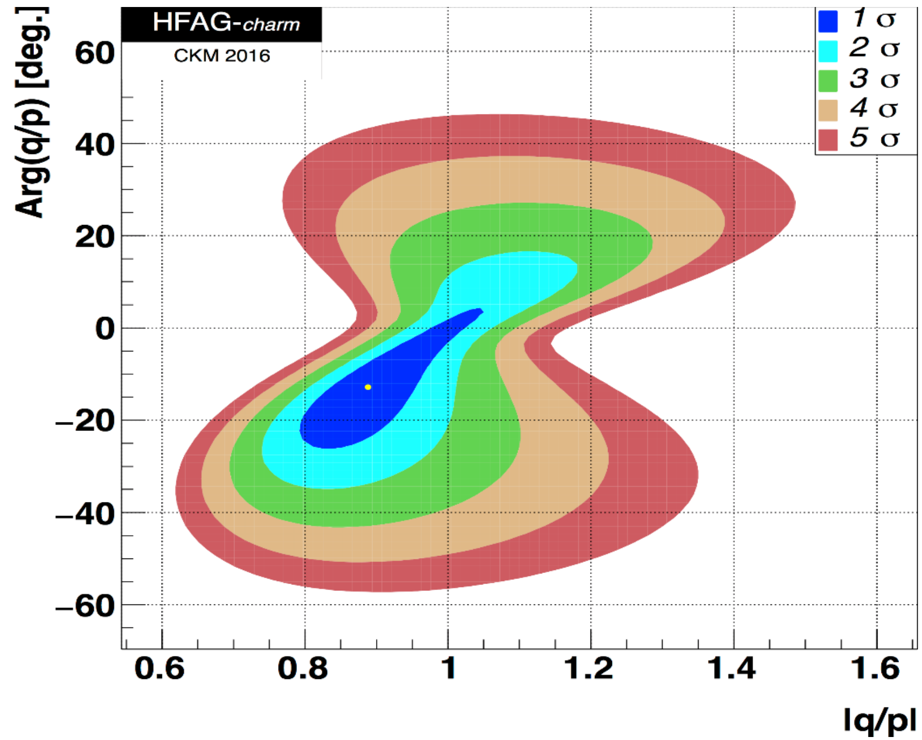
No CPV

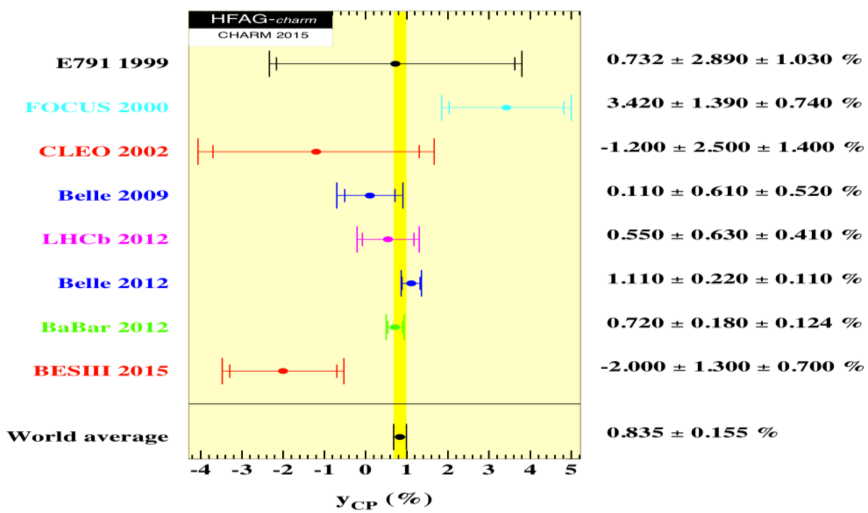
$\boldsymbol{x = (1.5 \pm 1.2 \pm 0.6)\%}$

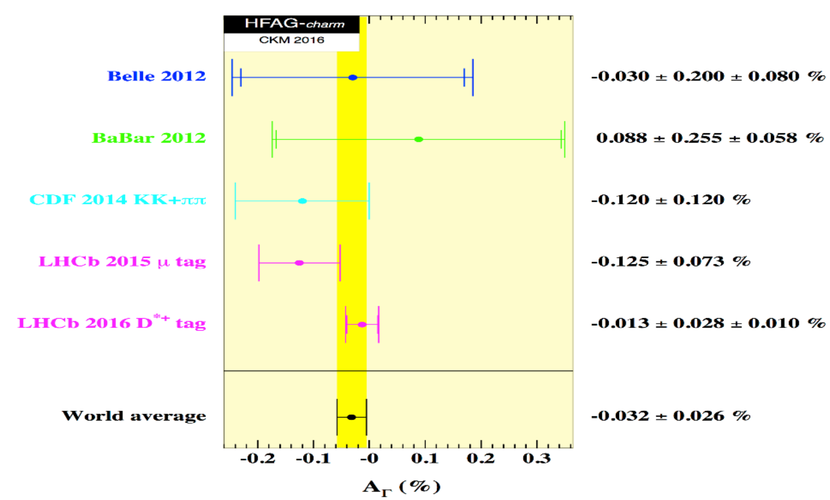
$\boldsymbol{y = (0.2 \pm 0.9 \pm 0.5)\%}$

D^0-$\bar{D}^0$ Mixing : Summary









***B* factories results quite competent with hadron machines**

Time integrated CPV measurements

Asymmetry of time-integrated decay rates:

$$A_{CP} = \frac{\Gamma(D\to f)-\Gamma(\bar{D}\to\bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to\bar{f})} \simeq a_{dir} + \frac{<t>}{\tau_D} a_{ind}$$

Charged D meson: $A_{CP} = a_{dir}$

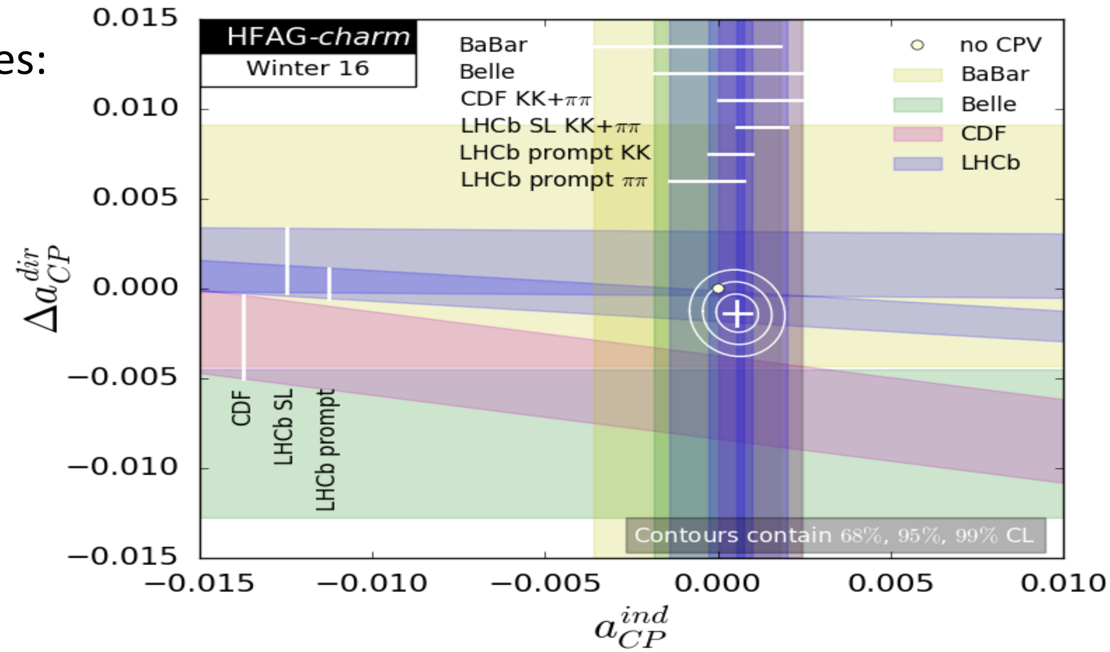
Neutral D meson: $A_{CP} = a_{dir} + a_{ind}$

Indirect *CPV* is universal

$$\boldsymbol{a_{ind} = (0.056 \pm 0.040)\%}$$

$$\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$$

$$\simeq A^d_{KK} - A^d_{\pi\pi} + \frac{\Delta < t >}{\tau_D} a_{ind}$$



This way, one can cancel the indirect component and experimental systematics to large extent.

SM estimate

$$\Delta A^{SM}_{CP} \sim \frac{\alpha_s}{\pi}\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} \sim 10^{-4}$$

But can also be as large as

$$\Delta A^{SM}_{CP} \sim \text{few} - \text{several} \times 10^{-3}$$

Latest HFAG average $\boldsymbol{\Delta A^{EXP}_{CP} \sim (-0.137 \pm 0.070)\ \%}$ **Agreement with no CP violation CL = 6.5 x 10^{-2}**

Belle and Babar provide competitive results.

Further, neutral modes not easy for LHCb.

Only limited results from CLEO.

B factories play important role here

$$\boldsymbol{A_{CP}(D^0 \to \pi^0\pi^0) = [-0.03 \pm 0.64 \pm 0.10]\%}$$

$$\boldsymbol{A_{CP}(D^0 \to K_S{}^0\pi^0) = [-0.21 \pm 0.16 \pm 0.07]\%}$$

Belle,PRL 112, 211601 (2014)

Search for *CP* violation in FCNC $D^0 \to V\gamma$, $V=\varphi, \bar{K}^{*0}, \rho^0$

Radiative charm decays are dominated by long-range non-perturbative processes

- enhance B.F. up to 10^{-4}, PRD 52, 6383 (1995)
- whereas short-range interactions are predicted to yield rates at the level 10^{-8}.

arXiv:1509.01997

Expt.	Lumi., fb^{-1}	Decay	B.F., X 10^{-5}
Belle	78	$D^0 \to \varphi\gamma$	$2.67^{+0.70+0.15}_{-0.61-0.17}$
BaBar	387	$D^0 \to \varphi\gamma$	$2.73 \pm 0.30 \pm 0.26$
BaBar	387	$D^0 \to \bar{K}^{*0}\gamma$	$32.2 \pm 2.0 \pm 2.7$

Belle, PRD 92, 101803 (2004)

BaBar, PRD 78,071101(2008)

- Decay $D^0 \to \rho\gamma$ has not been observed
- No A_{CP} measurement in $D^0 \to V\gamma$

❖ In some SM extensions sizeable CP asymmetry expected in radiative charm decays:

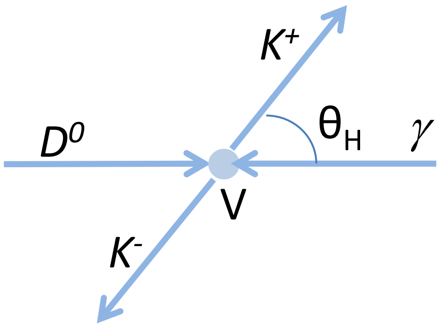
- $A^{V\gamma}_{CP} > 3\ \%$ signal of New Physics PRL 109, 171801 (2012), arXiv:1210.6546

Decay chain

$$D^0 \to \varphi\gamma \to K^+K^-\gamma$$
$$D^0 \to K^{*0}\gamma \to K^-\pi^+\gamma$$
$$D^0 \to \rho^0\gamma \to \pi^+\pi^-\gamma$$

Normalization mode

$$D^0 \to K^+K^-$$
$$D^0 \to K^-\pi^+$$
$$D^0 \to \pi^+\pi^-$$



Signal extraction : Simultaneous 2D fit of M_{D0} and $cos(\theta_H)$

$$A_{raw} = \frac{N(D \to V\gamma) - N(\bar{D} \to V\gamma)}{N(D \to V\gamma) + N(\bar{D} \to V\gamma)} = A_{CP} + A_{FB} + A_{\epsilon}^{\pi_s}$$

A_{FB}, $A_{\epsilon}^{\pi_s}$ eliminated through relative measurement of A_{CP}.

$$A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + A_{CP}^{norm}$$

A_{CP} : independent of all kinematic variables

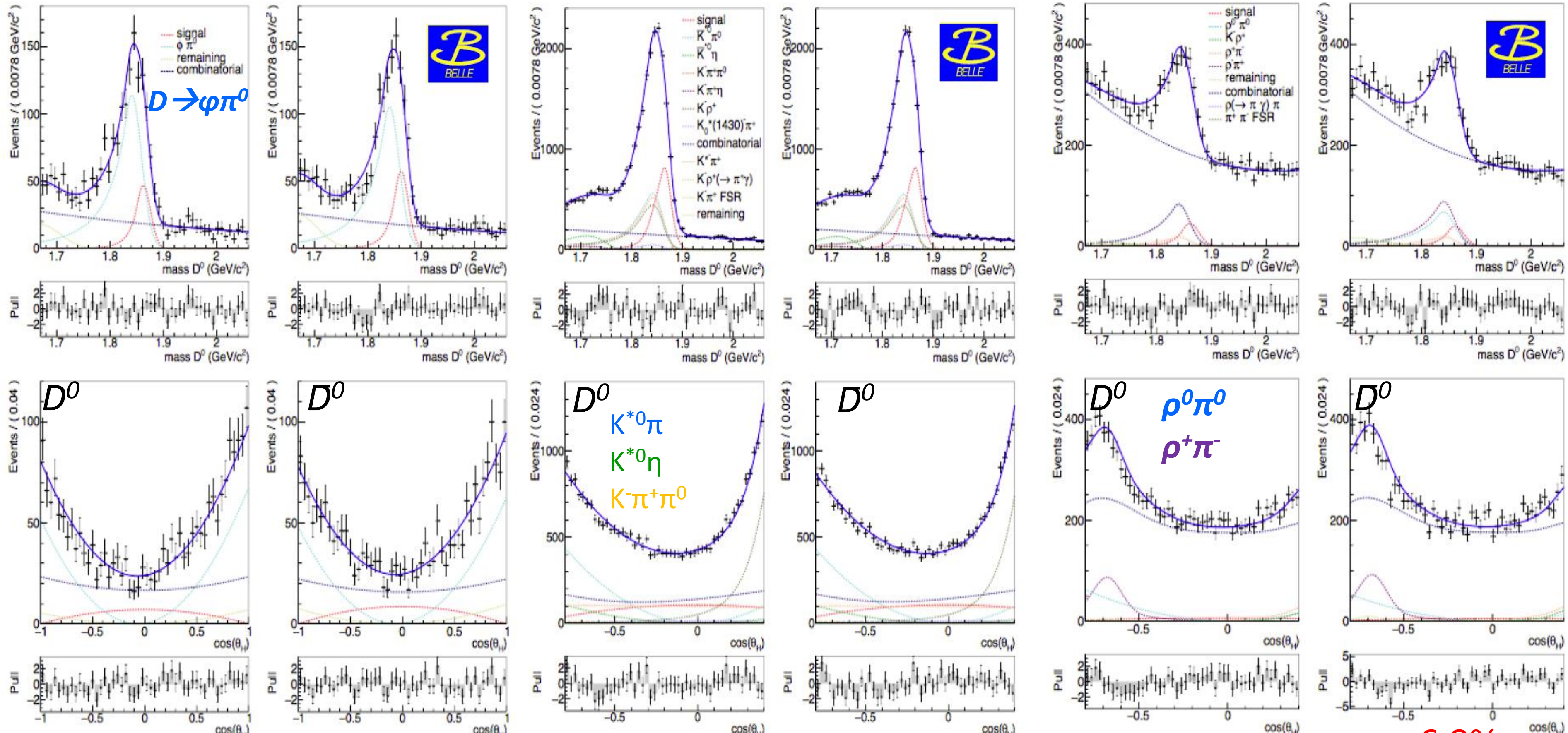
A_{FB} : due to γ-Z[0] interference; an odd function of cosθ* in CM frame

$A_{\epsilon}^{\pi_s}$: independent of final state,

arXiv:1603.03257
Submitted to PRL

Search for CP violation in FCNC $D^0 \to V\gamma$, $V=\phi, \bar{K}^{*0}, \rho^0$ $_{943fb^{-1}}$

First observation



Yield : 524±35 9.8%

Yield : 9104±396 7.8%

Yield : 500±85 6.8%

$\mathcal{A}_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$ $\quad \mathcal{A}_{CP}^{\bar{K}^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$ $\quad \mathcal{A}_{CP}^{\rho^0\gamma} = +0.056 \pm 0.151 \pm 0.006$

$\mathcal{B}$ $\quad (2.76\pm0.19\pm0.10)\times10^{-5}$ $\quad (4.66\pm0.21\pm0.21)\times10^{-4}$ $\quad (1.77\pm0.30\pm0.07)\times10^{-5}$

- First measurement of A_{CP}.
- Results consistent with no *CPV*

Search for CP violation in $D^0 \rightarrow K_S K_S$

Nierste, Schacht PRD92,054036 (2015)

- SM limit ≤1.1 %(95 C.L.) for direct CPV in $D^0 \rightarrow K_S^0 K_S^0$
- SCS decays (such as $D^0 \rightarrow K_S^0 K_S^0$) are special interest: possible interference with NP amplitude could lead to larger nonzero CPV

Previous measured A_{CP} ($D^0 \rightarrow K_S^0 K_S^0$) by:

CLEO	$(-23\pm19)\%$	$13.7\ fb^{-1}$
LHCb	$(-2.9\pm5.2\pm2.2)\%$	$3\ fb^{-1}$

CLEO, PRD 63, 071101 (2001)

LHCb, JHEP 10, 055 (2015)

Method:

$$A_{CP}(D^0 \to K_s K_s) = A_{raw}(D^0 \to K_S K_S) - A_{raw}(D^0 \to K_S \pi^0) + A_{CP}(D^0 \to K_S \pi^0) + A_{K^0/\bar{K}^0}$$

$A_{K^0/\bar{K}^0}$: Asymmetry originating from the different strong interaction of K^0 and $\bar{K}^0$ mesons with nucleons of the detector material = $(-0.11 \pm 0.01)\%$

Ko *et al* PRD 84, 111501 (2011)

A_{CP} ($D^0 \longrightarrow K_S^0 \pi^0$) = $(-0.20 \pm 0.17)\%$ [PDG]

Peaking background $D^0 \rightarrow K_S^0 \pi\pi$ ($D^0 \rightarrow \pi\pi\pi^0$) in $D^0 \rightarrow K_S K_S$ ($D^0 \rightarrow K_S \pi^0$) estimated in the K_S mass sideband.

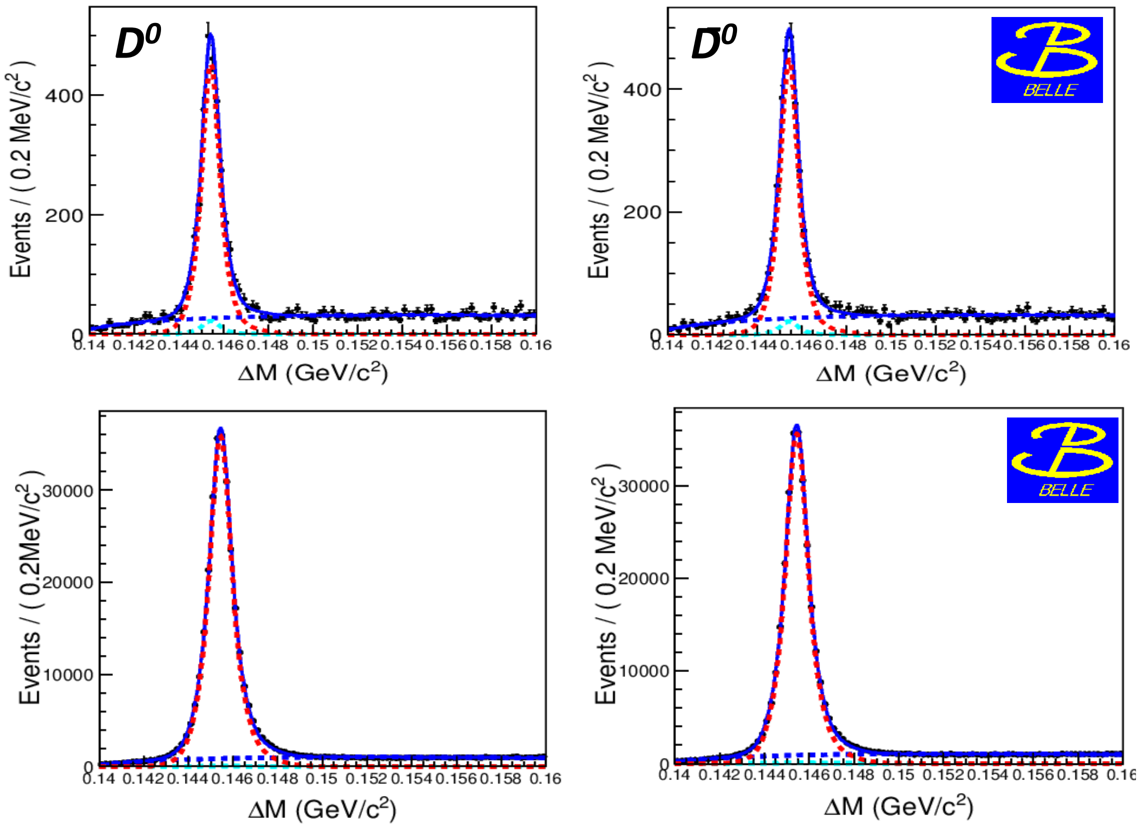
$0.470 < M_{\pi\pi} < 0.478$ GeV/c^2 and $0.516 < M_{\pi\pi} < 0.536$ GeV/c^2

A_{raw} extraction : Simultaneous fit of ΔM for D^0 and $\bar{D}^0$

Preliminary
arXiv:1609.06393

Search for CP violation in $D^0 \rightarrow K_S K_S$

921 fb^{-1}



$D^0 \rightarrow K_S^0 K_S^0$ decay mode

Efficiency = (11.04±0.02)%

Signal Yield = 5399±87

A_{raw} = (0.45±1.53)%

$D^0 \rightarrow K_S^0 \pi^0$ decay mode

Efficiency = (12.60±0.02)%

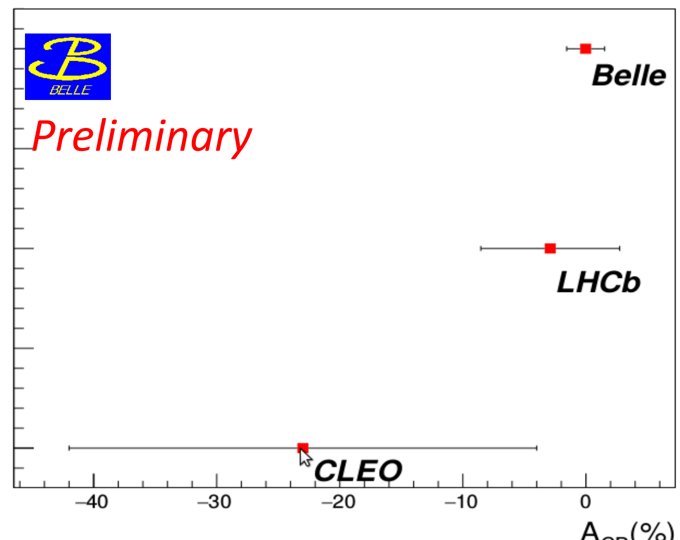
Signal Yield = 531807±796

A_{raw} = (0.16±0.14)%

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-0.02 \pm 1.53 \pm 0.17)\%$$

Preliminary

- Consistent with no CPV.
- Improve precision of previous best measurement (LHCb) by more than a factor 3 !



Mixing & *CPV* in *D* : Summary

Mixing in $D^0 - \bar{D}^0$ system is established with high confidence

Belle (BaBar) measured mixing parameters :

- x'^2 and y' in WS decay of $D^0 \to K^+\pi^-$ with 5.1σ (3.3σ)
- y_{CP} and A_Γ in $D^0 \to h^+ h^-$ with 4.7σ (3.3σ)
- x,y ($D \to \pi^+\pi^-\pi^0$), $|q/p|$, arg(q/p) using $D \to \pi\pi\pi$ and $D \to K_S hh$

B factory results comparable to the LHCb !

No significant *CP* violation been observed so far in the search carried out in variety of *D* mesons decays.

A_{CP} measurement in *B* factories →

✓ Strength lies in γ, π^0 reconstruction and clean environment.

CPV in *D* decays challenge for the LHCb and Belle II.

Mode	ACP (in %)	Expt.	References
$D^0 \to \pi^+\pi^-$	-0.20±0.19±0.10	LHCb	JHEP07,041 (2014)
	-0.22±0.24±0.11	CDF	PRD85,012009(2012)
	-0.24±0.52±0.22	Babar	PRL100,061803(2008)
	-0.43±0.52±0.12	Belle	PLB670,190(2008)
$D^0 \to \pi^0\pi^0$	-0.03±0.64±0.10	Belle	PRL112,211601(2014)
	+0.1±4.8	CLEO	PRD63,071101 (2001)
$D^0 \to K_S\pi^0$	-0.21±0.16±0.07	Belle	PRL112,211601(2014)
	+0.1±1.3	CLEO	PRD63,071101(2001)
$D^0 \to K_S K_S$	-0.02±1.53±0.17	Belle	arXiv:1609.06393 preliminary
	-2.9±5.2±2.2	LHCb	JHEP10,055 (2015)
	-23.0±19	CLEO	PRD63,071101(2001)
$D^0 \to \phi\gamma$	-9.4±6.6±0.1	Belle	arXiv:1603.03257
$D^0 \to \rho\gamma$	+5.6±15.2±0.6	Belle	arXiv:1603.03257
$D^0 \to \bar{K}^{*0}\gamma$	-3.0±2.0±0.0	Belle	arXiv:1603.03257

Both provide competitive and complementary results.

For more details regarding charm prospects in Belle II, please look at

- **Belle II Prospects for Time-Dependent CPV and Mixing by Alan Schwartz**
- **Belle II Prospects for Time-Integrated CPV by Seema Bahinipati**

Thank you

धन्यवाद

ਧੰਨਵਾਦ

ধন্যবাদ

આભાર

ಧನ್ಯವಾದಗಳು

നന്ദി

நன்றி

شکریہ

ଧନ୍ୟବାଦ୍