D^0 MIXING AND CP VIOLATION IN D DECAYS

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With results from LHCb, BaBar, Belle and CDF

XXXII Physics in Collision 2012

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INTRODUCTION

- Mixing in the kaon and B_d,B_s is well established and provide precision tests of the SM CKM parameters
- Why looking into charm ?
  - Mixing occurs very slowly
  - Probe for NP via FCNC in the down- type quark sector

MIXING AND CPV PARAMETERS

Mass states are: $|D_1\rangle : m_1, \Gamma_1$ **and** $|D_2\rangle : m_2, \Gamma_2$

$$|D_1\rangle = p|D^0\rangle + q\bar{D}^0\rangle \qquad \sqrt{p^2 + q^2} = 1$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$$x \equiv \frac{m_1 - m_2}{\Gamma},$$

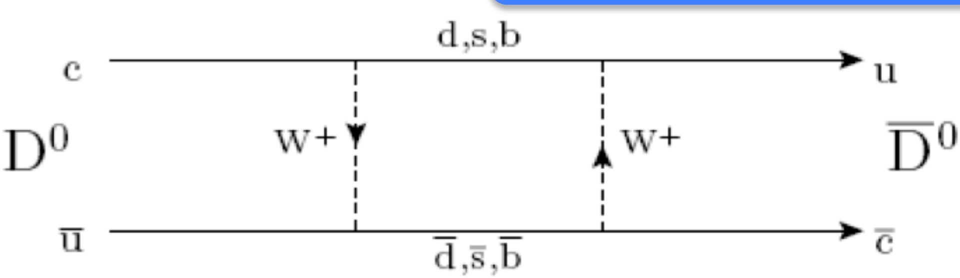
Oscillation frequency — Virtual intermediate states

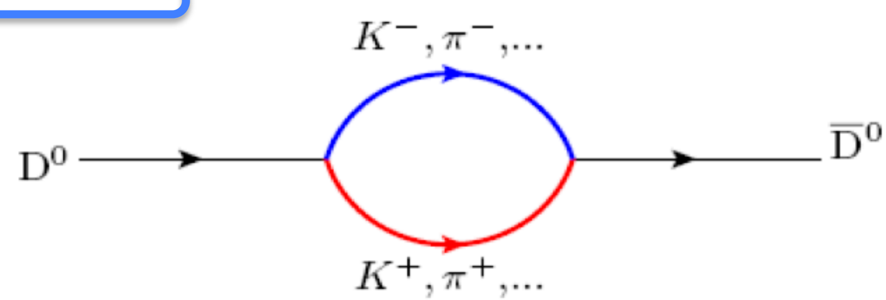
$$y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma},$$

Decay width difference — On-shell transitions

SM predictions: $x,y \lesssim 10^{-2}$ (large uncertainties due to long distance contributions)

Unambiguous evidence for NP : x>>y





Experimentally: first evidences of mixing in 2007, now firmly established at the % level

❖ CP can be violated

✧In the mixing : $P(D^0 \to \bar{D}^0, t) \neq P(\bar{D}^0 \to D^0, t)$ $|q| \neq |p|$

✧In the interference between mixing and decay $\phi \neq 0$

➔ SM: indirect CPV $\mathcal{O}(10^{-4})$ and universal

✧In the decay: $P(D^0 \to f) \neq P(\bar{D}^0 \to \bar{f})$ $|\mathcal{A}_f| \neq |\bar{\mathcal{A}}_{\bar{f}}|$

➔SM: direct CPV could reach 10^{-3} depending on final state

only for SCS modes which have penguin contribution (second weak phase)

NP contributions can enhance both indirect and direct CPV up to $\mathcal{O}(10^{-2})$

Interest in charm is to look for NP effects in a SM suppressed environment

CHARM MIXING AND CPV: OBSERVABLES*

- Time Integrated rate of semileptonic (Wrong Sign) relative to CF (Right Sign) decays

$\Gamma(D^{*+}\rightarrow\pi_s D^0\rightarrow\pi_s \bar{D}^0(\ell^- \nu_\ell X^-)/ \Gamma(D^{*+}\rightarrow\pi_s D^0(\ell^+ \nu_\ell X^-)/)$

$$R_m = \frac{x^2+y^2}{2}$$

- Time dependent or integrated rates of tagged DCS (WS) decays compared to CF (RS)*

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

$$x', y', \phi, \left|\frac{q}{p}\right|, \left|\frac{\mathcal{A}_f}{\bar{\mathcal{A}}_{\bar{f}}}\right|$$

- Ratios of lifetimes of tagged CP even final states wrt mixed CP states

$$D^0 \rightarrow K^-K^+, \pi^-\pi^+ \text{ wrt } D^0 \rightarrow K^-\pi^+$$

$$x, y, \phi, \left|\frac{q}{p}\right|$$

- Time dependent amplitude analyses of tagged 3 body CP states

$$D^0 \rightarrow K_s^0\pi^+\pi^- \text{ and } D^0 \rightarrow K_s^0 K^+K^-$$

$$x, y, \phi, \left|\frac{q}{p}\right|$$

- Time integrated CP asymmetries

  Several neutral and charged modes

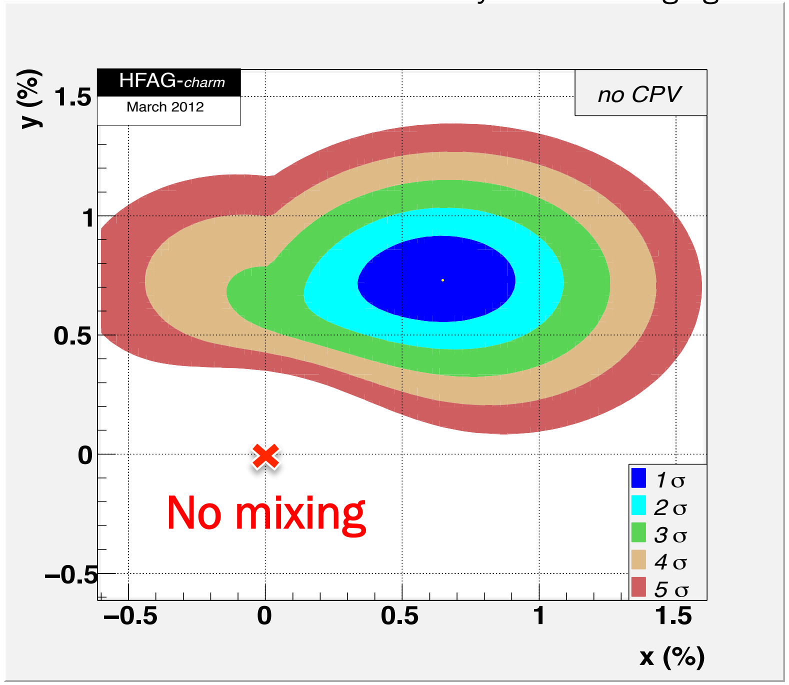
$$\left|\frac{\mathcal{A}_f}{\bar{\mathcal{A}}_{\bar{f}}}\right| \quad x, y, \phi, \left|\frac{q}{p}\right|$$

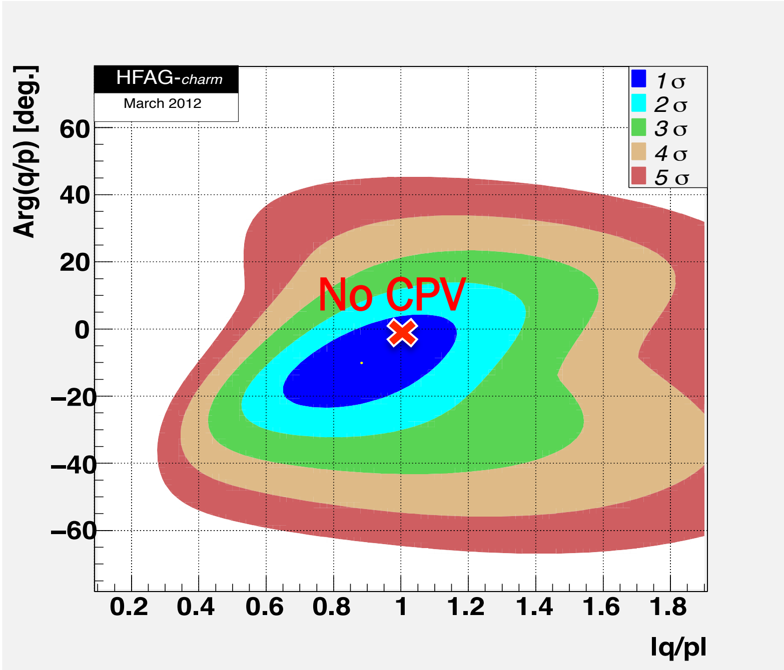
* Different sensitivities are obtained for different modes and observables

D^0 MIXING AND CPV STATUS

HFAG: Heavy Flavor Averaging Group: http://www.slac.stanford.edu/xorg/hfag

N. Neri, arXiv:1208.5877





$$x = 0.65^{+0.18}_{-0.19}\%$$

$$y = 0.73 \pm 0.12\%$$

No mixing excluded with > 10 σ significance

$$\left|\frac{q}{p}\right| = 0.88^{+0.18}_{-0.16}$$

$$\phi = -10.1^{+9.5}_{-8.9}$$

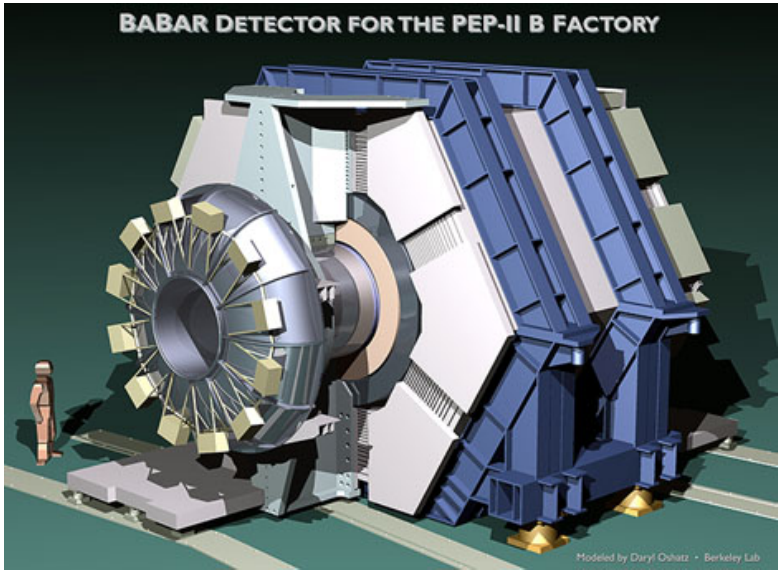
Consistent with no CPV at 1σ

Mixing measurements are at the upper values of the SM

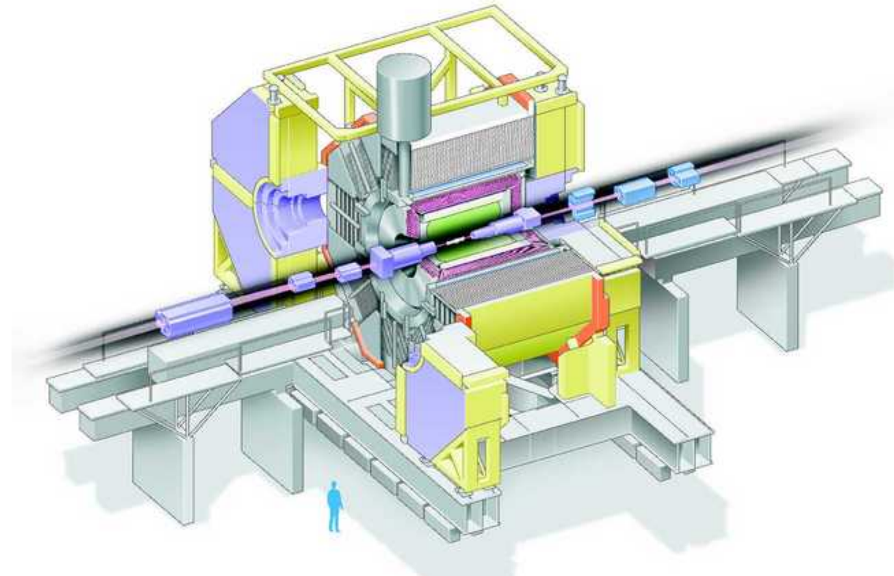
Can impose constraints to NP models

- Experimental facilities

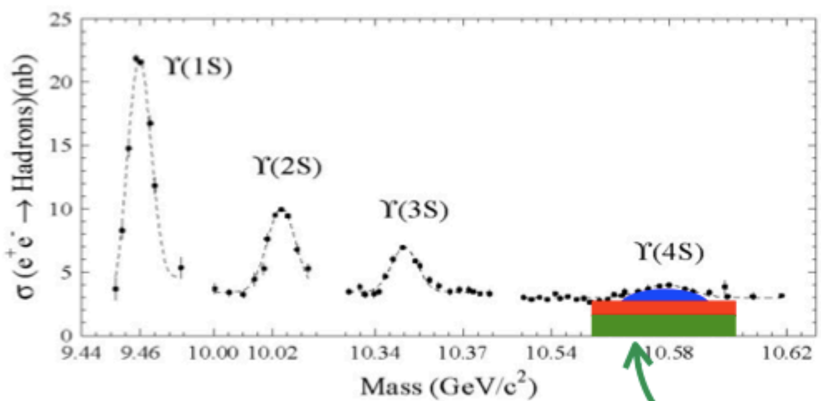
EXPERIMENTAL FACILITIES



Belle @ KEK



BaBar @ SLAC



On resonance production of B meson pairs

$$e^+e^- \to \Upsilon(4S) \to B^0\overline{B}^0, B^+B^-$$

$$\sigma(B\overline{B}) \approx 1.1 \text{ nb } (\sim 10^9 \; B\overline{B} \text{ pairs})$$

Continuum production of Charm pairs

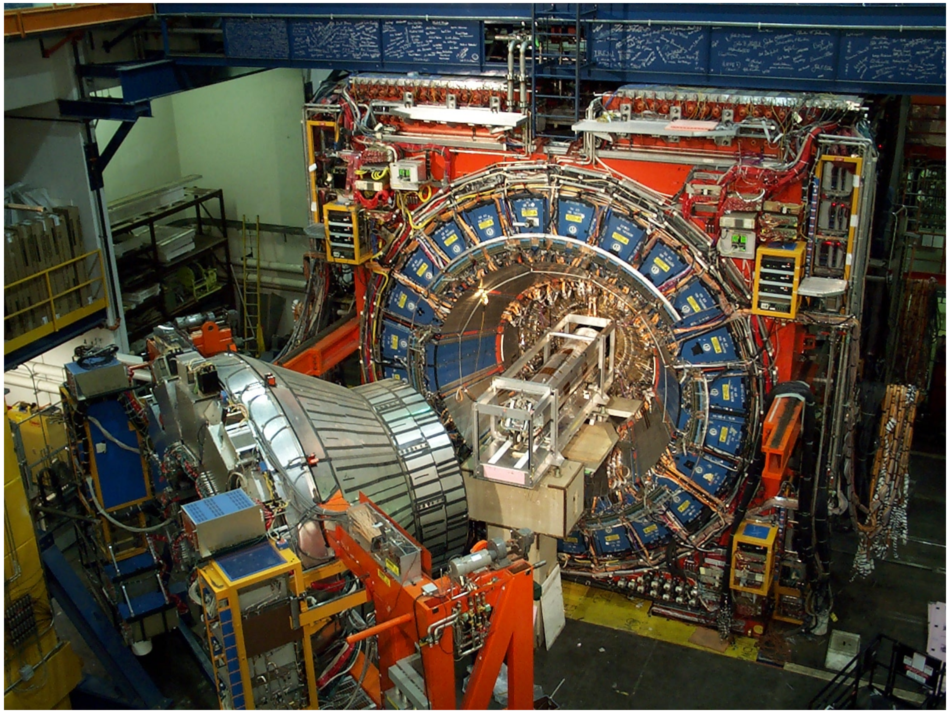
$$e^+e^- \to X_c Y_{\overline{c}}$$

$$\sigma(c\overline{c}) \approx 1.3 \text{ nb } (\sim 1.3 \times 10^9 \; X_c Y_{\overline{c}} \text{ pairs})$$

From E.Won, PIC2011

So a B-factory = a charm factory

EXPERIMENTAL FACILITIES



CDF@FNAL

$p\bar{p}$ collisions

Designed for high p_T physics

σ(pp→ccX)~13μb in the CDF acceptance

CP symmetric

LHCb@LHC

pp collisions

Heavy flavor dedicated experiment

σ(pp->ccX) ~1500 μb within acceptance

High boost, excellent vertex and p resolution

CP asymmetric

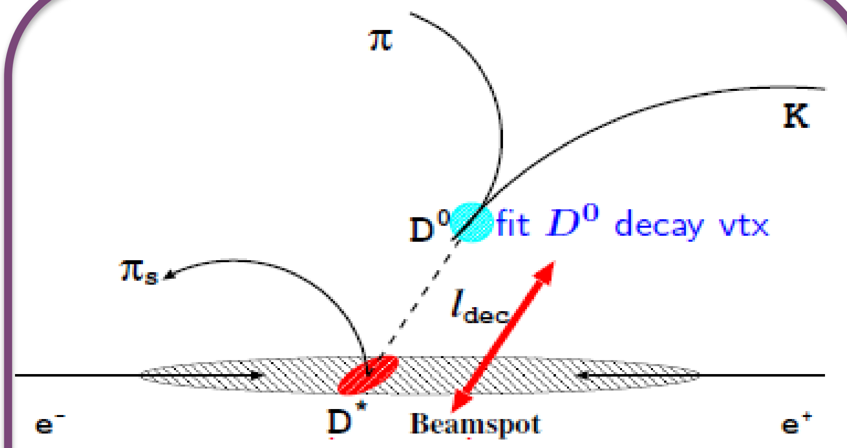
EXPERIMENTAL DETAILS

- Determination of D^0 flavour at production and decay, RS and WS

$$D^{*+} \to \pi_s^+ D^0(K^- X^+) : RS(\text{CF})$$

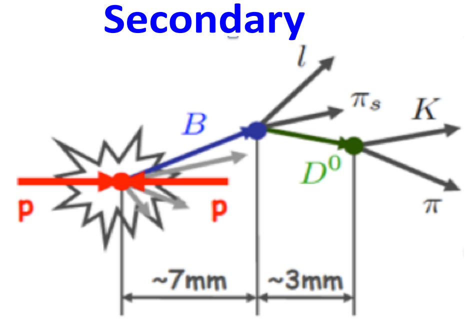
$$D^{*+} \to \pi_s^+ D^0(K^+ X^-) : WS(\text{DCS or mixing})$$

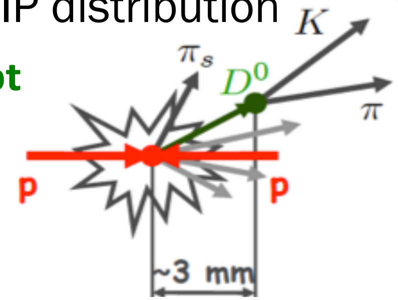
- Measurement of proper time



B factories

secondary D contamination by IP distribution





IP resolution, $p_t > 2$ GeV	
CDF II	35 μm
LHCb	22 μm

Hadron colliders

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

- Experimental status: mixing and CPV
  - Many results available from different experiments
  - Here only most recent measurements

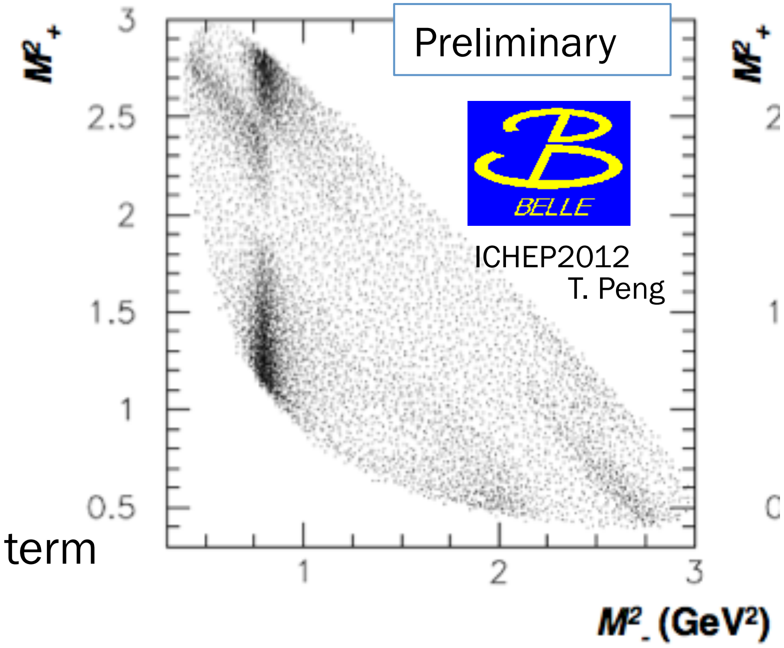
    (due to lack of time)

- Time dependent amplitude analysis of $D^0 \to K_s^0 K^- K^+, K_s^0 \pi^- \pi^+$

$$\mathcal{R}(t) \propto |A_1|^2 e^{-yt} + |A_2|^2 e^{-yt}$$

$$+2Re[A_1 A_2^*] \cos(xt) + 2Im[A_1 A_2^*] \sin(xt)$$

$$A_{1,2} = \frac{\mathcal{A} \pm \bar{\mathcal{A}}}{2}$$



$\mathcal{A}, \bar{\mathcal{A}}$: Sum of quasi-two-body amplitudes + non-resonant term

Direct extraction of x and y !

(along with many resonance parameters)

Variation of average decay time across the m^2_+, m^2_- plane is sensitive to mixing

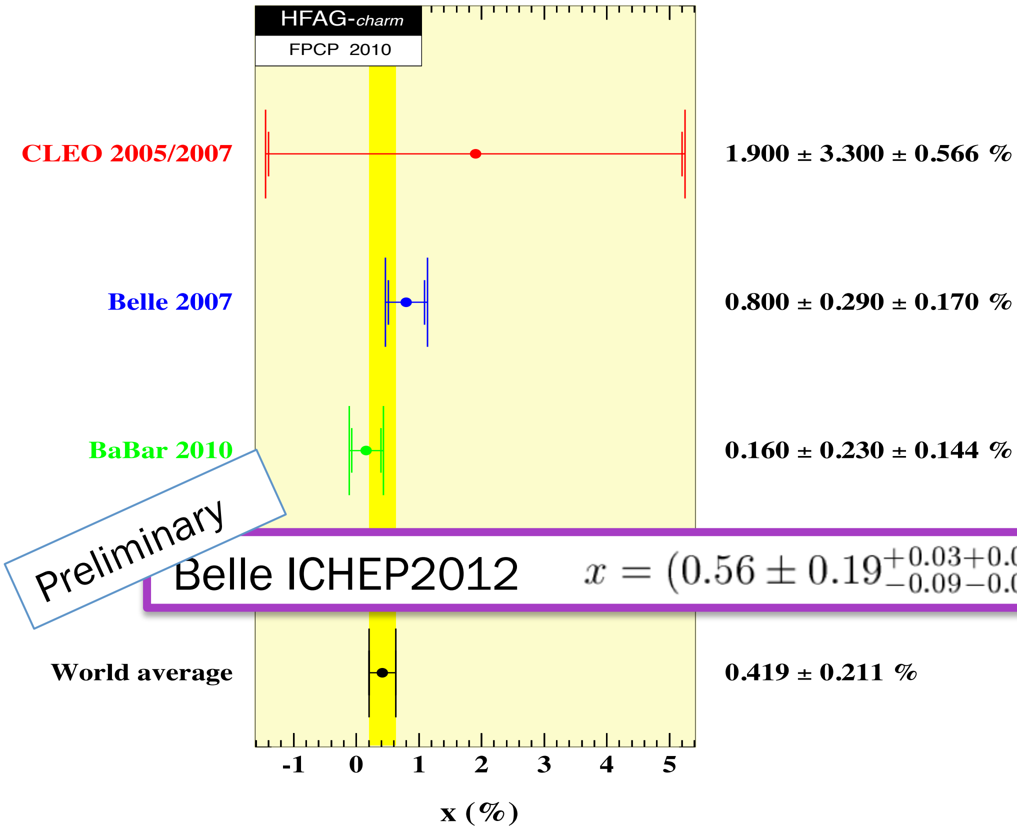
$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%, \; y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$$

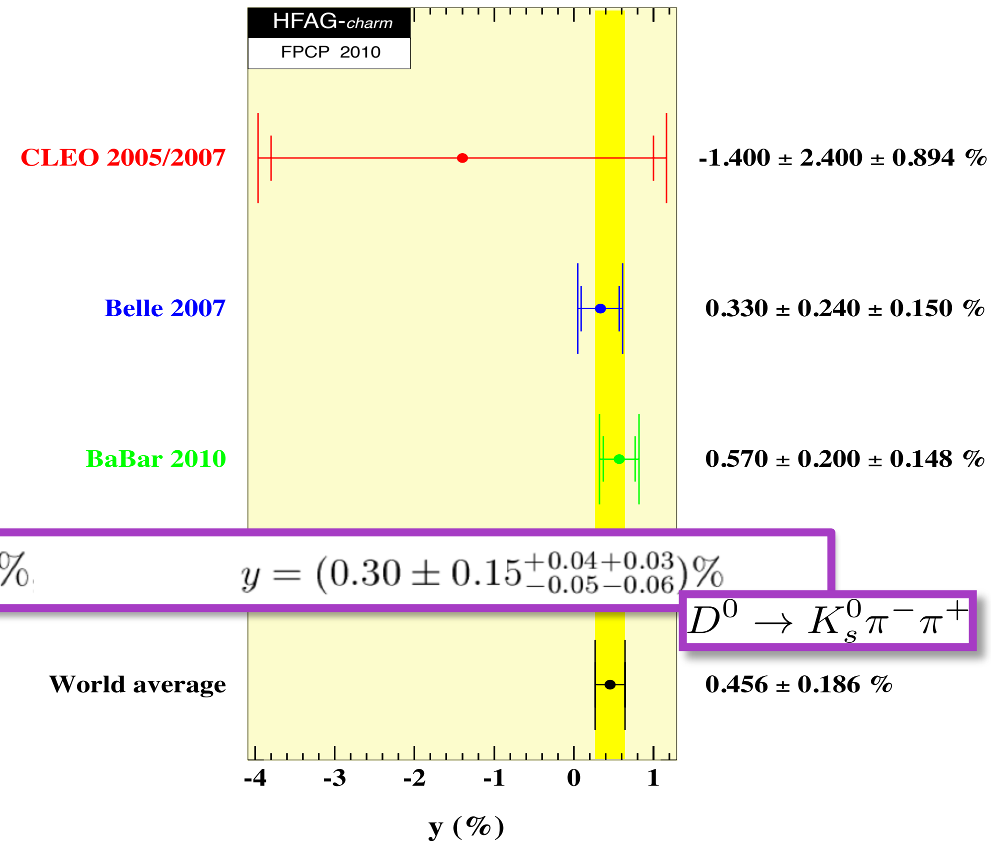
Complex analysis with many resonance parameters extracted along with x,y

MEASUREMENTS OF MIXING PARAMETERS

❖ Time dependent Dalitz Plot Analyses of $D^0 \to K_s^0 K^- K^+, K_s^0 \pi^- \pi^+$

BaBar/Belle measurements also fit D^0 and $\bar{D}^0$ separately to test for CPV with null results





Preliminary

Belle ICHEP2012 $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$ $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$

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

Most precise determination up to date

❖ Comparison of effective lifetimes of CP eigenstates to CP mixed

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

mixing

$$\mathbf{y_{CP}} = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\mathbf{y}\cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\mathbf{x}\sin\phi\right]$$

$$\phi = 0, \left|\frac{q}{p}\right| = 1 \rightarrow y_{CP} = y$$

$$y_{CP} \neq 0 \quad \text{➔mixing}$$

systematics dominated by secondary-like bkg

225×10^3 $K^-\pi^+$, 30×10^3 K^-K^+

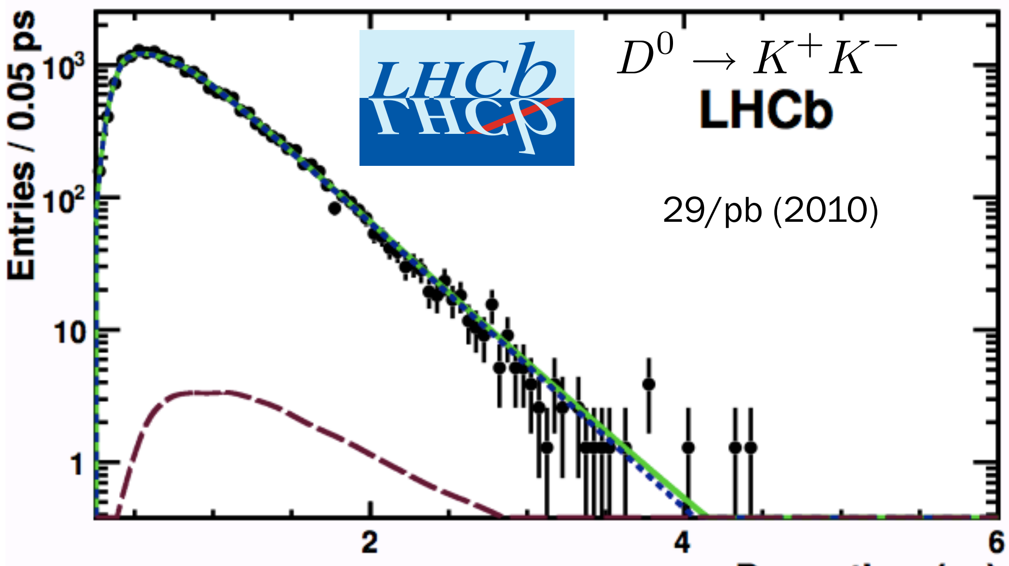
$$y_{CP} = (5.5 \pm 6.3_{\text{stat}} \pm 4.1_{\text{syst}}) \times 10^{-3}$$
$$A_\Gamma = (-5.9 \pm 5.9_{\text{stat}} \pm 2.1_{\text{syst}}) \times 10^{-3}$$

$$A_\Gamma = \frac{\bar{\tau}_{KK} - \tau_{KK}}{\tau_{KK} + \bar{\tau}_{KK}}$$

CPV

$$\mathbf{A_\Gamma} = \frac{1}{2}\left[\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\mathbf{y}\cos\phi - \left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\mathbf{x}\sin\phi\right]$$

$$\phi = 0, \left|\frac{q}{p}\right| = 1 \rightarrow A_\Gamma = 0$$



JHEP04(2012)129

NEW MEASUREMENTS BABAR AND BELLE

arXiv:1208.6436 [hep-ex]

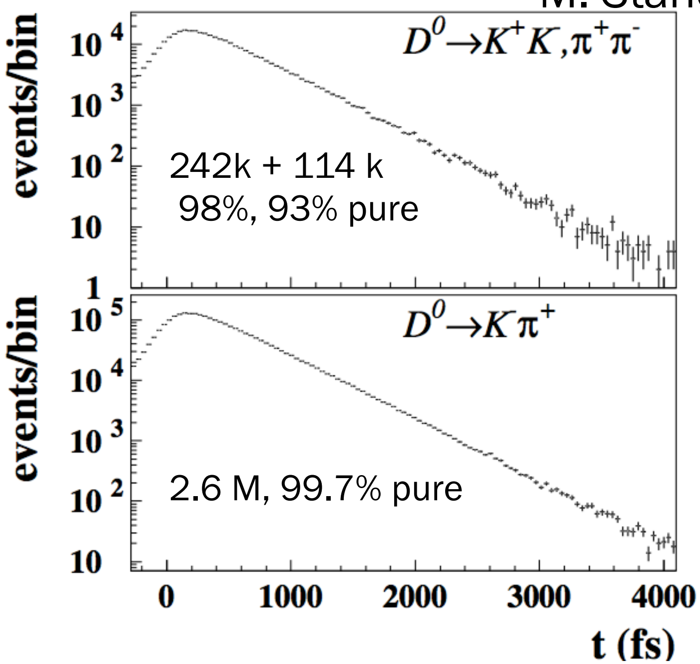
$$A_\Gamma = \frac{\bar{\tau}_{CP} - \tau_{CP}}{\bar{\tau}_{CP} + \tau_{CP}}$$

$$\Delta Y = (1 + y_{CP}) A_\Gamma$$

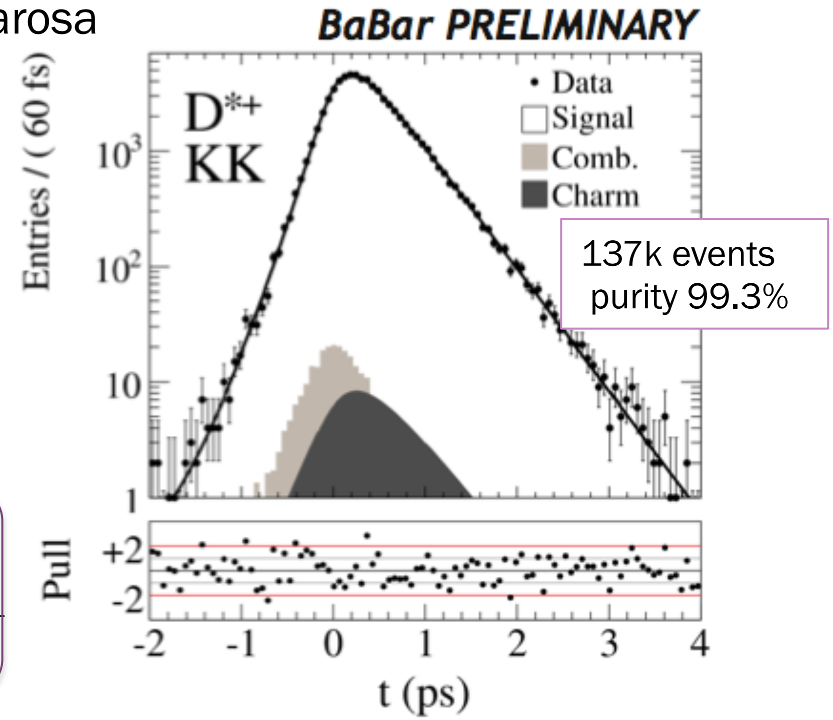
Belle Preliminary

CHARM 2012
M. Staric

CHARM 2012
G. Casarosa



Averaged over $K^-K^+, \pi^-\pi^+$

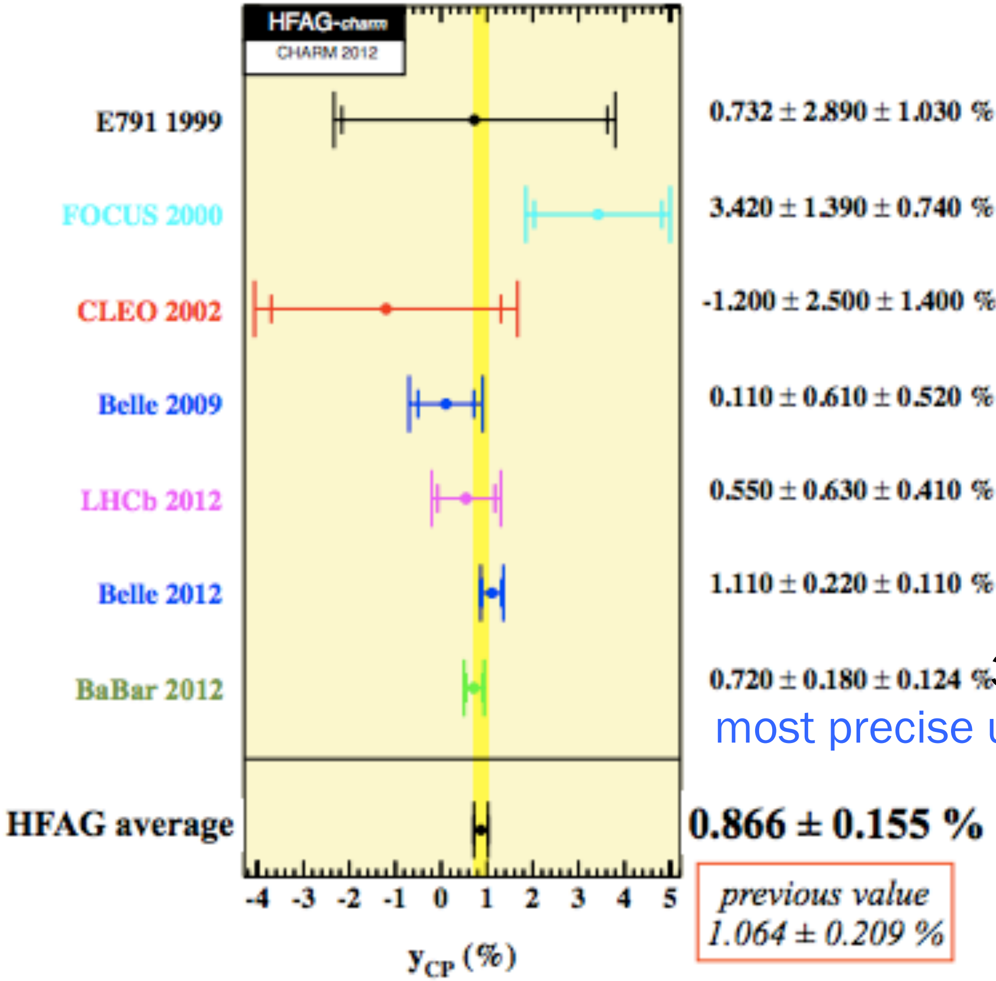


$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$$

$$y_{CP} = (0.720 \pm 0.180 \pm 0.124)\%$$
$$\Delta Y = (0.088 \pm 0.255 \pm 0.058)\%$$

All consistent with $A_\Gamma = 0$

NEW HFAG AVERAGES



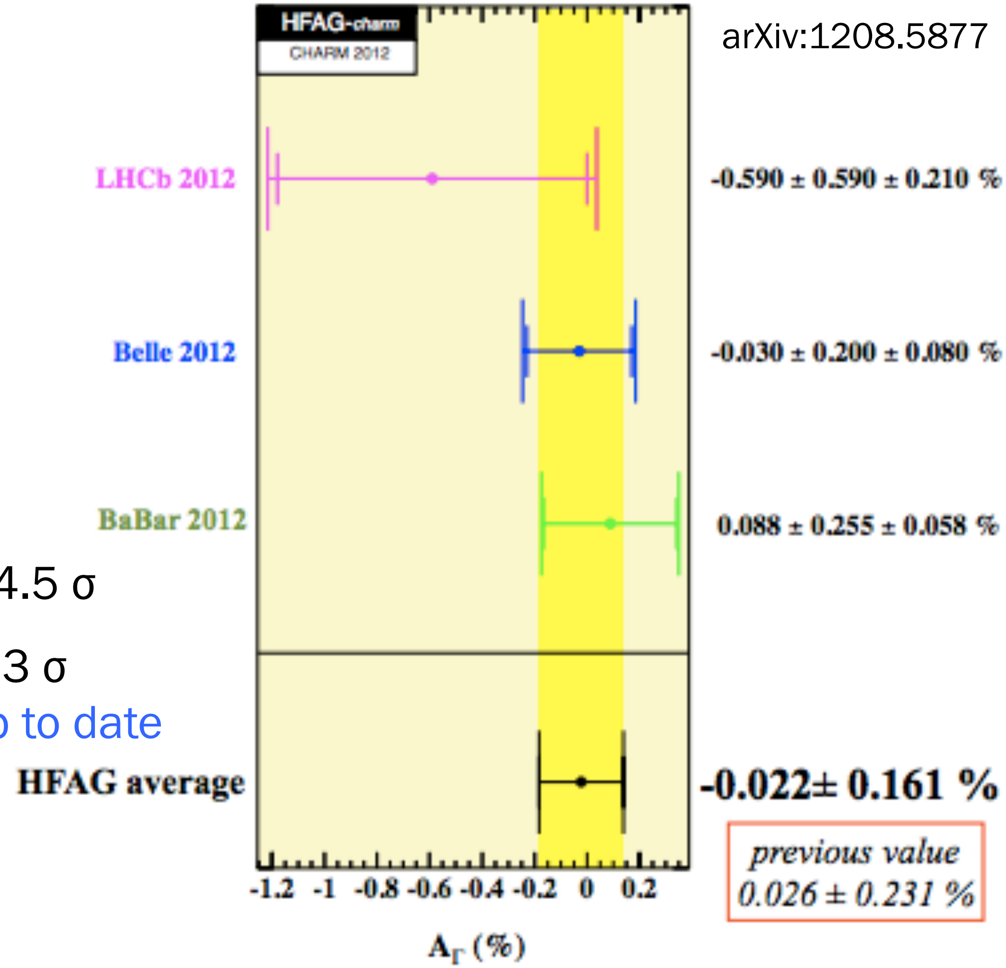
4.5 σ

3.3 σ

most precise up to date

previous value
1.064 ± 0.209 %

arXiv:1208.5877



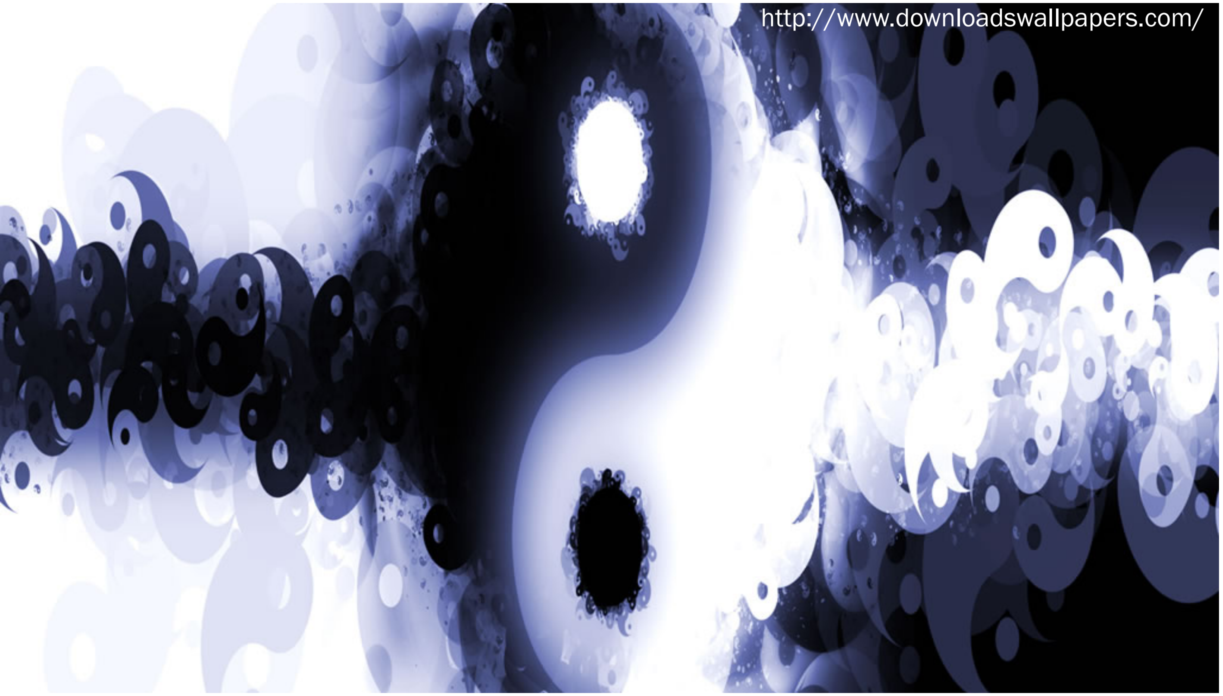
previous value
0.026 ± 0.231 %

Including new BaBar and Belle results: significant improvement in the uncertainty and lower value for y_{CP}.

(y_{CP} results compatible with y)

37 Nicola Neri - Charm mixing/CP violation results and HFAG averages 16 May 2012

SUMMARY: MIXING



No single measurement of mixing at 5 σ

Recent results from B factories show improved sensitivity

Combination of measurements establishes mixing at > 10 σ level

Time dependent measurements consistent with no CPV in mixing and in the interference between mixing and decay

- **Experimental status:**
  time integrated CPV asymmetries

TIME INTEGRATED ASYMMETRIES

$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$$

For a CP eigenstate f (K^-K^+ or $\pi^+\pi^-$):

$$A_{\mathrm{raw}}(f) = A_{CP}(f) + \xcancel{A_{\mathrm{D}}(f)} + A_{\mathrm{D}}(\pi_{\mathrm{s}}) + A_{\mathrm{P}}(D^{*+}) \quad *$$

Physics CP asymmetry

Detection asymmetry of D0

Detection asymmetry of "slow" pions

Production asymmetry

*To first order

A more robust measurement is given by

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

ΔA_{CP} MEASUREMENT

❖ In terms of the direct and indirect components

$$A_{CP}(f) = a_{CP}^{dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

$$\Delta A_{CP} = \Delta a_{CP}^{dir} + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind}$$

a^{ind} : asymmetry due to mixing or interference between mixing and decay
a^{dir} : asymmetry in the decay amplitude

τ : D^0 lifetime $\langle t \rangle$: average signal decay time

$\Delta \langle t \rangle \neq 0$: due to different decay time acceptances

$\Delta \langle t \rangle \approx 0$ → ΔA_{CP} mostly a measurement of direct CPV

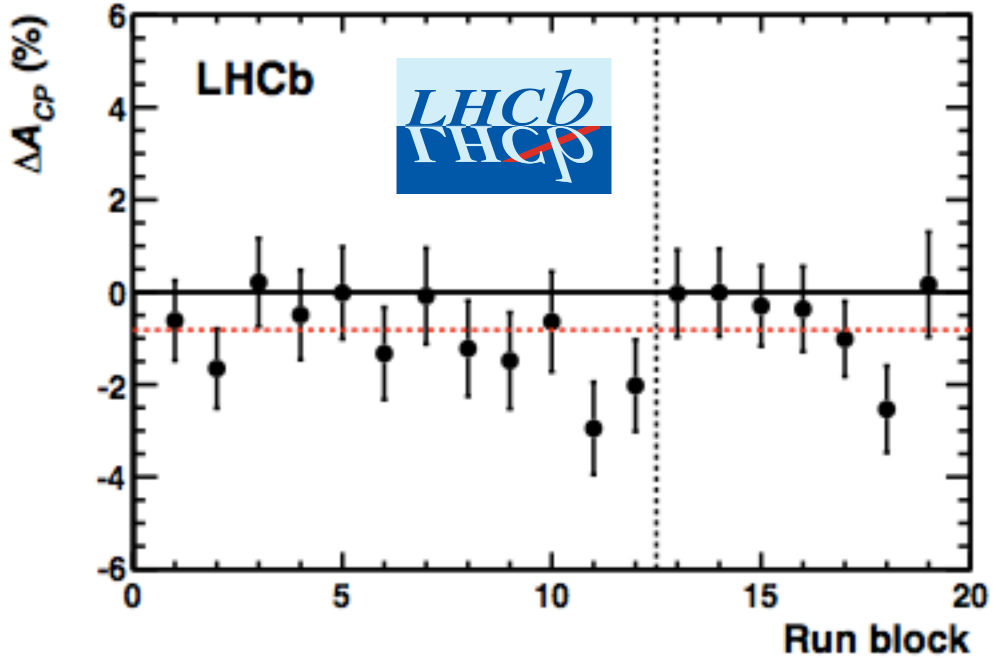
ΔA_{CP} MEASUREMENT

Until last year

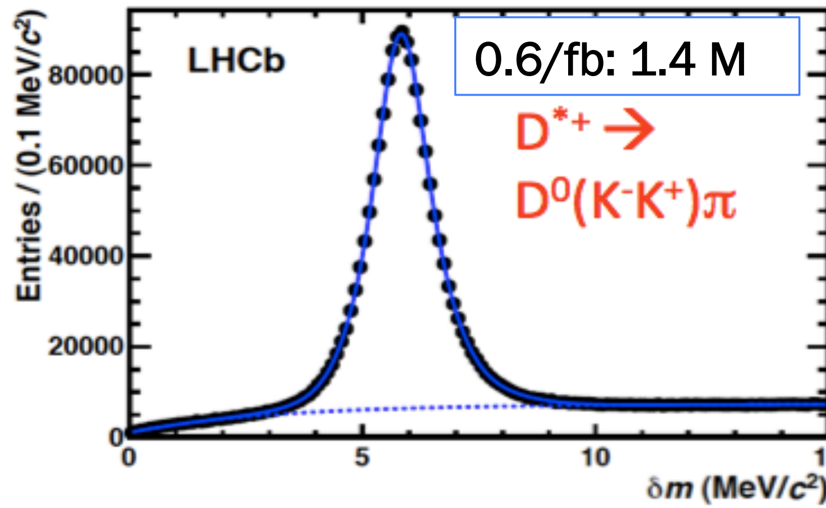
Year	Experiment	Results	$\Delta\langle t\rangle/\tau$	Comment
2007	Belle	$A_\Gamma = (0.01 \pm 0.30\ (stat.) \pm 0.15\ (syst.))\%$	-	540 fb^{-1} near Y(4S) resonance
2008	BaBar	$A_\Gamma = (0.26 \pm 0.36\ (stat.) \pm 0.08\ (syst.))\%$	-	384 fb^{-1} near Y(4S) resonance
2011	LHCb	$A_\Gamma = (-0.59 \pm 0.59\ (stat.) \pm 0.21\ (syst.))\%$	-	28 pb^{-1} $\sqrt{s} = 7$ TeV pp collisions
2008	BaBar	$A_{CP}(KK) = (0.00 \pm 0.34\ (stat.) \pm 0.13\ (syst.))\%$ $A_{CP}(\pi\pi) = (-0.24 \pm 0.52\ (stat.) \pm 0.22\ (syst.))\%$	0.00	385.8 fb^{-1} near Y(4S) resonance
2008	Belle	$\Delta A_{CP} = (-0.86 \pm 0.60\ (stat.) \pm 0.07\ (syst.))\%$	0.00	540 fb^{-1} near Y(4S) resonance
2011	CDF	$\Delta A_{CP} = (-0.46 \pm 0.31\ (stat.) \pm 0.12\ (syst.))\%$	0.26	5.9 fb^{-1} $\sqrt{s} = 1.96$ TeV $p\bar{p}$ collisions

http://www.slac.stanford.edu/xorg/hfag/charm/

Results compatible with no CPV



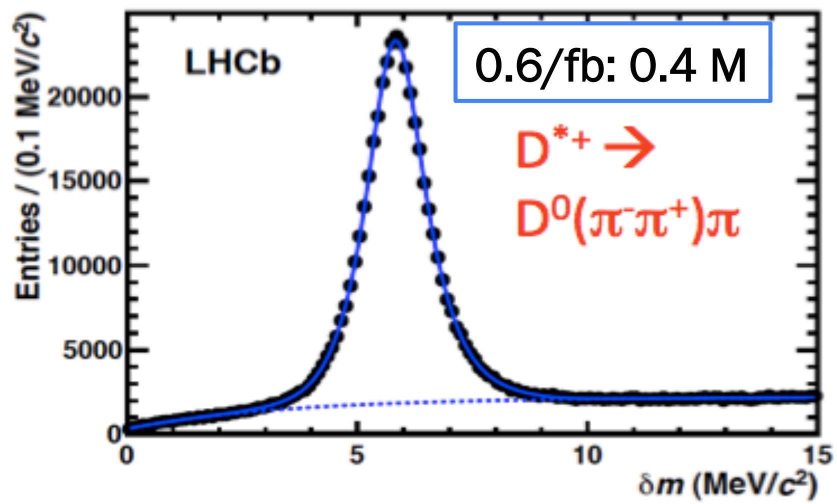
PRL **108**, 111602 (2012)



$$\Delta\langle t\rangle = (9.83 \pm 0.22 \pm 0.19)10^{-2}\tau$$

$\delta m = m(hh\pi) - m(hh) - m(\pi)$

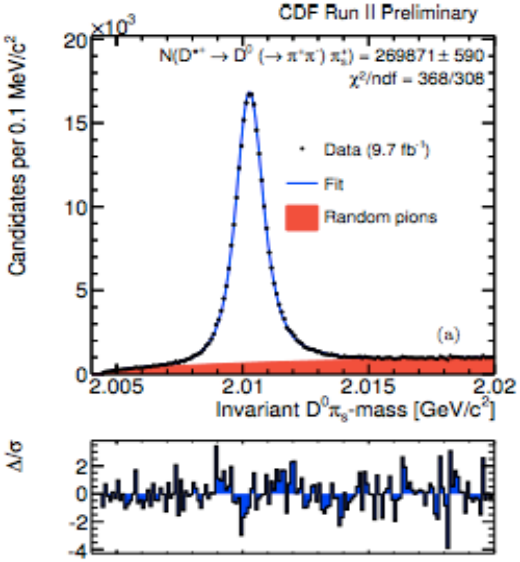
$$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$$



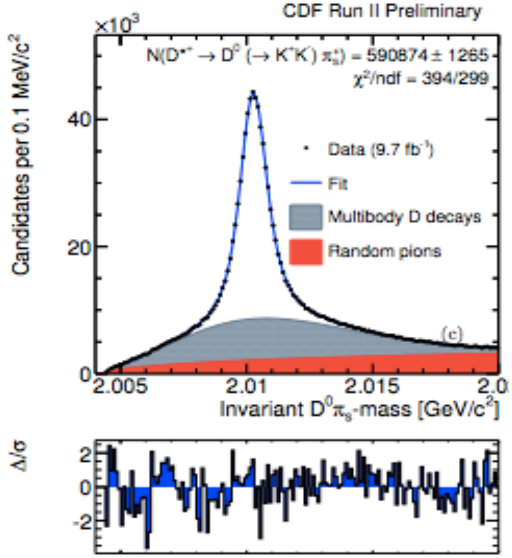
3.5 σ away from zero
First evidence of CPV in the charm sector

ΔA_{CP} MEASUREMENT

CDF Note 10784 (full RUNII data sample)



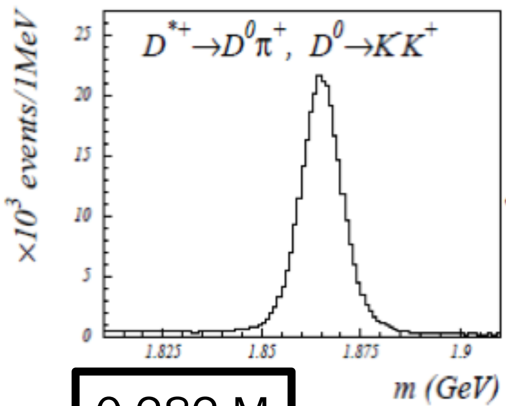
0.55 M



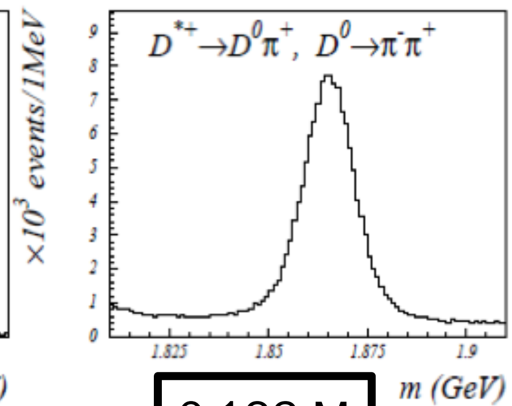
1.2 M

$$\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$
$$\Delta \langle t \rangle = (0.26 \pm 0.01)\tau$$

Byeong Rok Ko ICHEP 2012



0.282 M

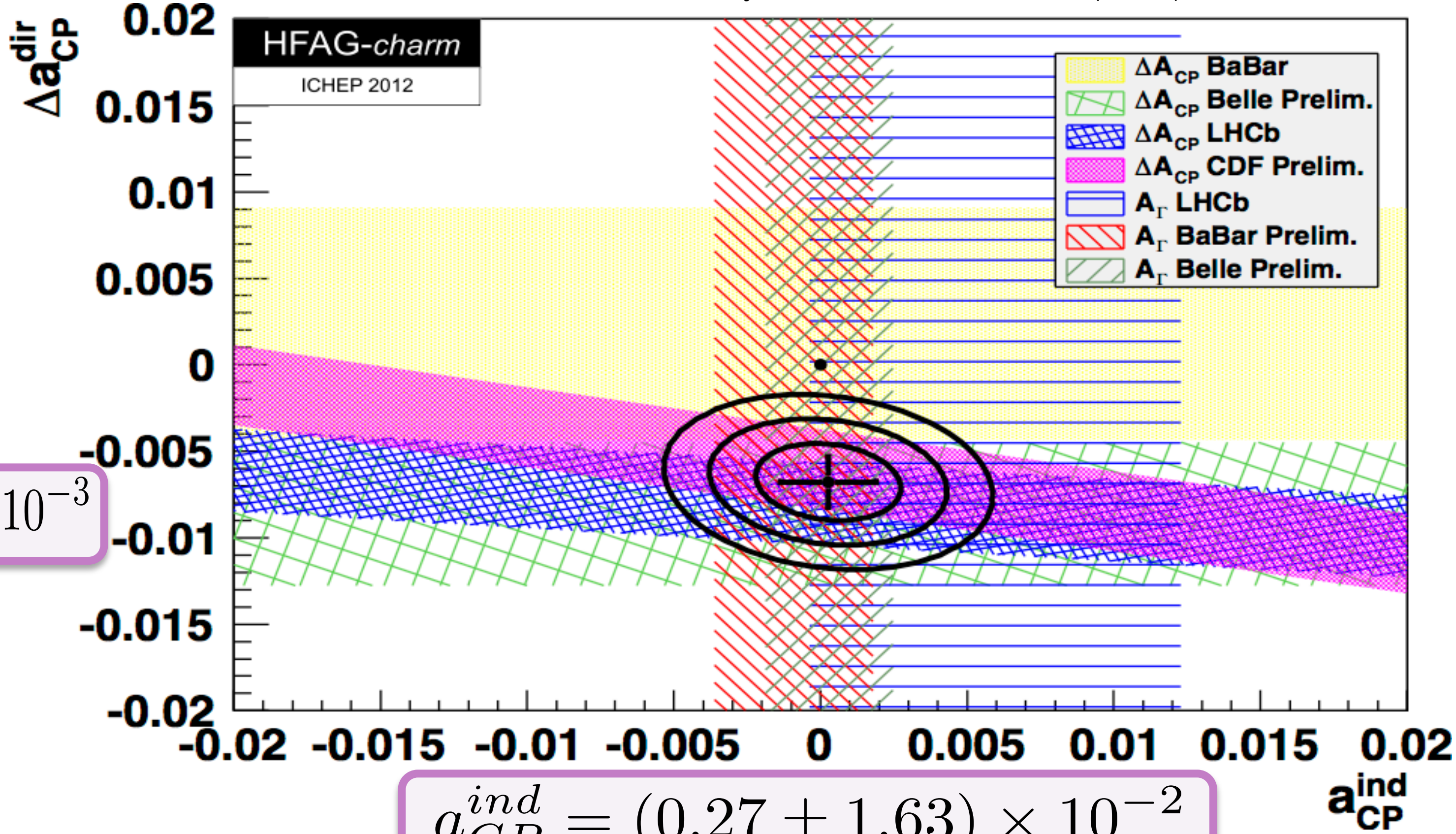


0.123 M

BELLE	$976\ fb^{-1}$ $540\ fb^{-1}$
$A_{CP}^{D^0\to K^+K^-}$	(-0.32±0.21±0.09)% (-0.43±0.30±0.11)%
$A_{CP}^{D^0\to \pi^+\pi^-}$	(+0.55±0.36±0.09)% (+0.43±0.52±0.12)%
ΔA_{CP}	(-0.87±0.41±0.06)% (-0.86±0.60±0.07)%

Belle preliminary

Kindly provided by M. Gersabeck/HFAG,
Mod. Phys. Lett. A, Vol. 27, No. 26 (2012) 1230026



$$\Delta a_{CP}^{dir} = (-6.78 \pm 1.47) \times 10^{-3}$$

CL for no CPV : 2×10^{-5}

$$a_{CP}^{ind} = (0.27 \pm 1.63) \times 10^{-2}$$

- Plenty of theoretical papers since the evidence for $\Delta A_{CP} \neq 0$ (see backup slides)
- Values of the order of 10^{-2} seem possible due to enhanced penguin amplitudes
- Still , no clear picture on whether SM or NP➔ more measurements needed

- New time integrated asymmetries

- New results from B factories using full data samples

$D^+ \to K_s^0 K^+$: SCS tree+penguin
$D_s^+ \to K_s^0 \pi^+$: SCS tree+penguin
$D^+ \to K_s^0 \pi^+$: CF+DCS
$D_s^+ \to K_s^0 K^+$: CF+DCS

No CPV in the SM

Channel	A_{CP} (Preliminary)	Experiment
$D^+ \to K_s^0 K^+$	(0.46±0.36±0.25)%	BaBar: arXiv:1209.0138v1[hep-ex]
$D_s^+ \to K_s^0 \pi^+$	(0.3±2.0±0.3)%	BaBar: arXiv:1209.0138v1[hep-ex]
$D^+ \to K_s^0 \pi^+$	(-0.018±0.094±0.068) %	Belle: PhysRevLett.109.021601
$D_s^+ \to K_s^0 K^+$	(0.28±0.23±0.24)%	BaBar: arXiv:1209.0138v1[hep-ex]

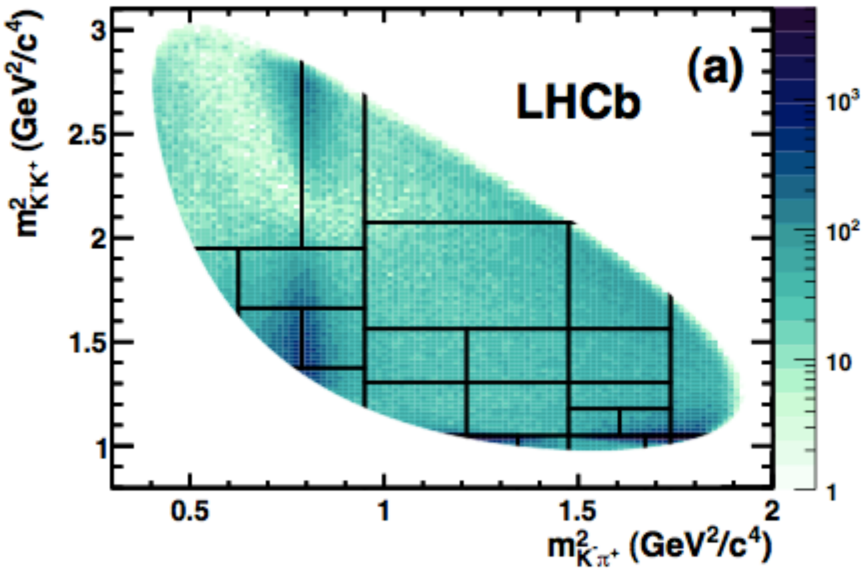
* after subtraction of indirect CPV contribution from K_s

→ All channels compatible with no DCPV in the charm transition

MULTI-BODY DECAYS

- Full amplitude analyses can provide magnitudes and phases for intermediate states and their CP conjugates in a model dependent way
- Model independent methods able to detect local asymmetries are important to avoid systematic uncertainties introduced by models
- Recent results using the distribution of the asymmetry significance
- If CP is conserved, S^{i}_{CP} is distributed as a normal (μ=0, σ=1).

$$\mathcal{S}^{\,i}_{CP} = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}, \qquad \alpha = \frac{N_{\rm tot}(D^+)}{N_{\rm tot}(D^-)},$$



Phys. Rev. D 78, 051102 (2008) , Phys. Rev. D 80, 096006 (2009)

CPV ASYMMETRY $D^+K^-K^+\pi^+$ IN LHCb

Phys. Rev. D 84, 112008 (2011

Sensitivities studies with toy MC

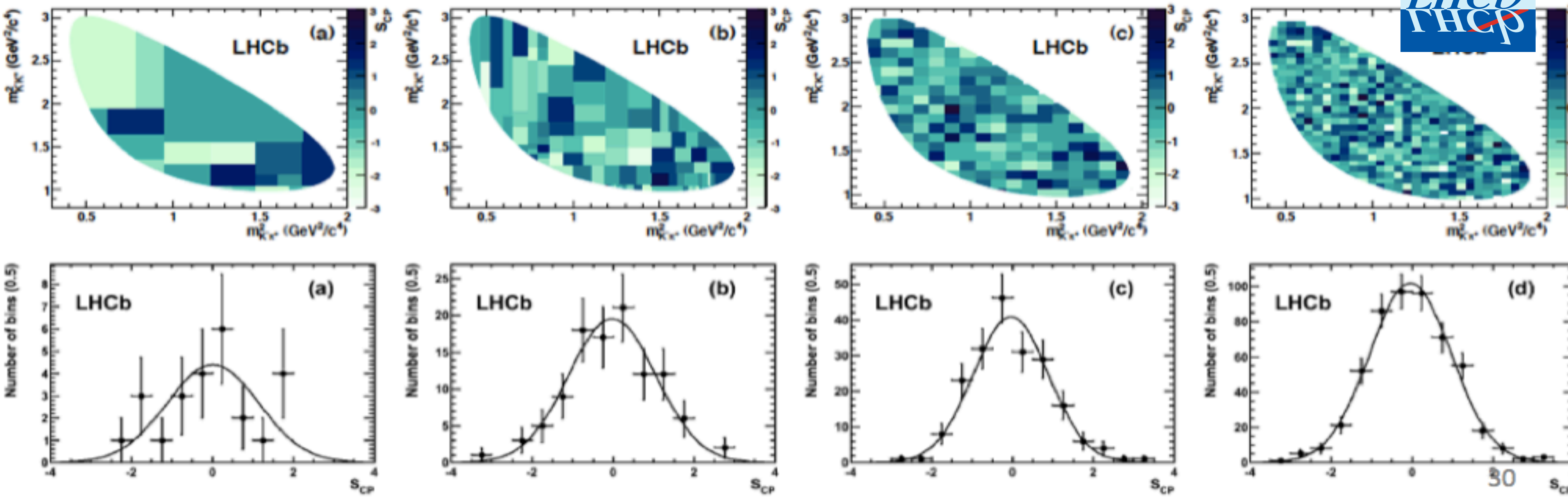
No evidence of CPV in this decay with different binning strategies

With 35 pb^{-1}: 370 k signal events
purity ~90%

P-value for consistency with no CPV

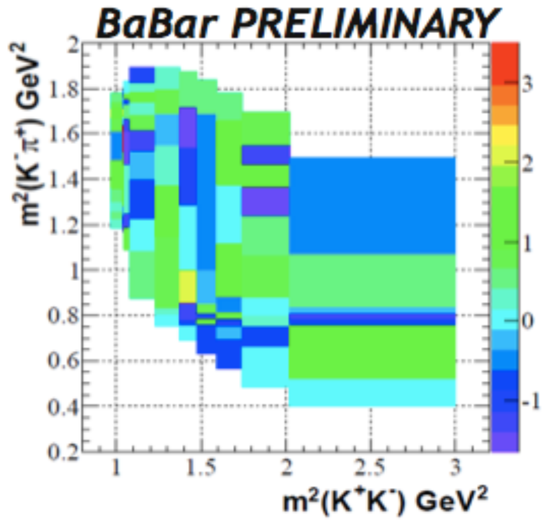
Binning	χ^2/ndf	p-value (%)
(a) Adaptive I	32.0/24	12.7
(b) Adaptive II	123.4/105	10.6
(c) Uniform I	191.3/198	82.1
(d) Uniform II	519.5/529	60.5

Expect $\mathcal{O}(10^7)$ events reconstructed with ~2fb^{-1} !

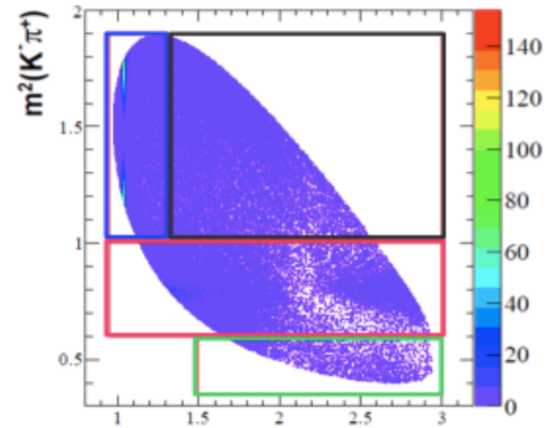


DCPV IN SCS $D^+ \longrightarrow K^-K^+\pi^+$ IN BaBar

- Model independent efficiency corrected anisotropy-like measurement

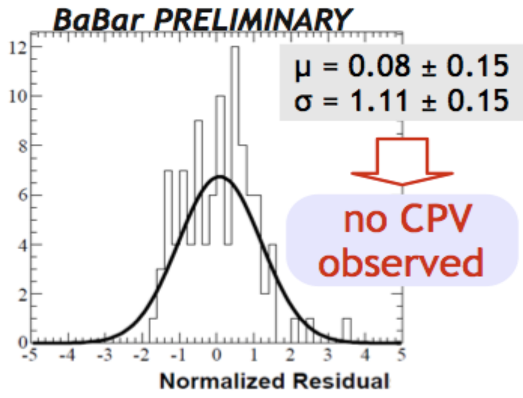


Asymmetries across resonant regions



no CPV observed

A_{CP}[%]
-0.65 ± 1.64 ± 1.73
-0.28± 0.37 ± 0.21
-0.26 ± 0.32 ± 0.45
1.05 ± 0.45 ± 0.31



- Full amplitude analysis with allowed CPV phase differences and fractions also provide null CPV
- Corrected DP integrated asymmetry also consistent with 0

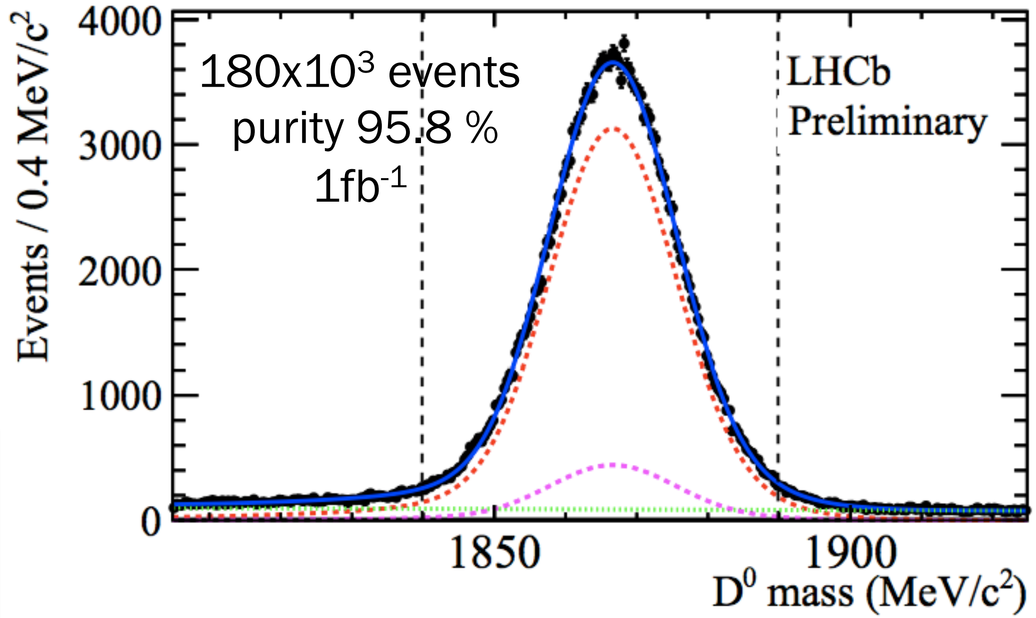
CHARM2012
http://indico.phys.hawaii.edu/getFile.py/access?contribId=48&resId=0&materialId=slides&confId=338

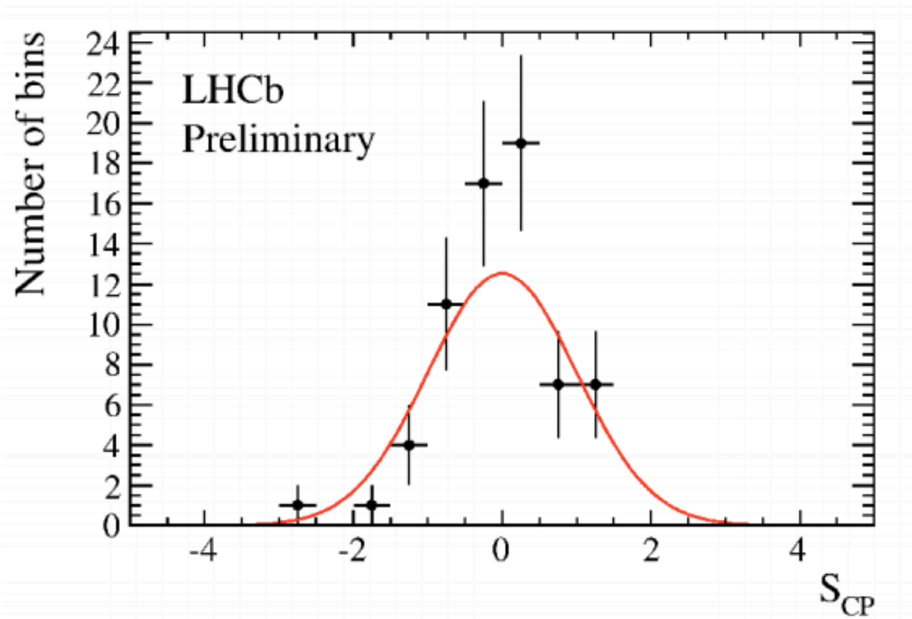
CPV IN $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$ from LHCb

Phase space is 5-D

Extension of 3-body method: 5-D binning

Control channel is $K^- \pi^+ \pi^+ \pi^-$





N_{bins}	p-valucs (%)
15	97.1
29	95.6
66	99.8

All consistent with no CPV

LHCb-CONF-2012-019

$D^0 \to K_s^0\pi^-\pi^+$ FROM CDF

SM prediction for CPV : $\mathcal{O}(10^{-6})$

Bin by bin asymmetry significances show no evidence for CPV

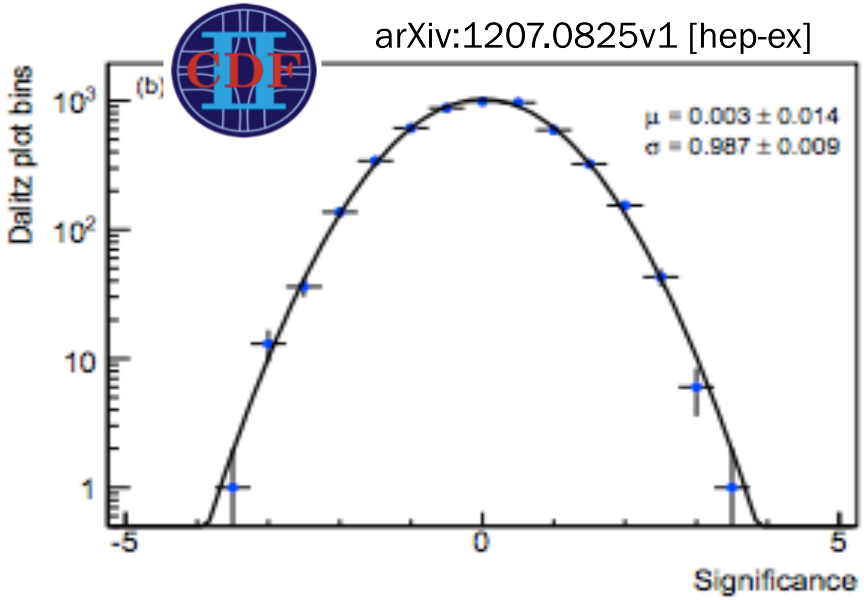
Full amplitude analysis with allowed CPV phase differences and fractions also provide null CPV

Dalitz Plot distribution reweighted according to instrumental asymmetries

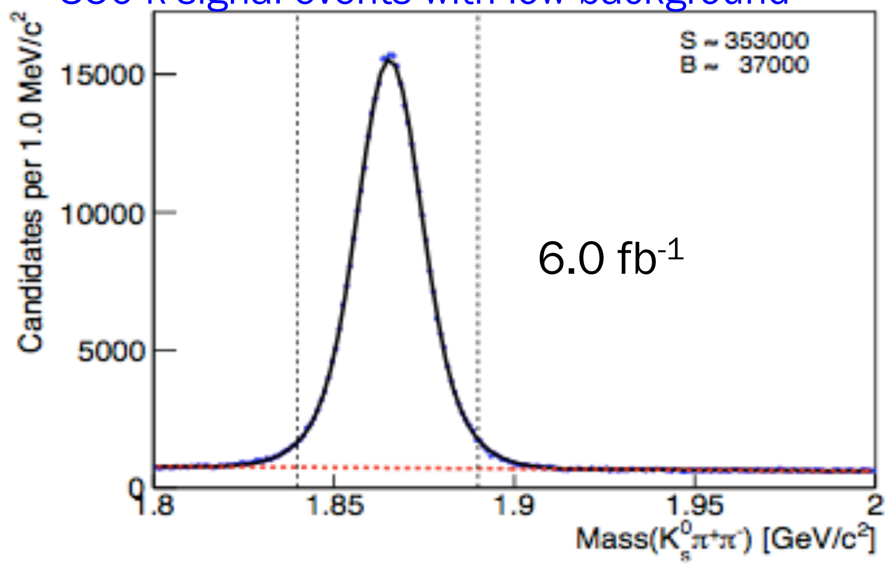
Corrected global asymmetry consistent with null CPV

Results consistent and with comparable precision as Babar/Belle

arXiv:1207.0825v1 [hep-ex]



~350 k signal events with low background



SUMMARY OF CPV

- Several new or updated results from B factories and CDF during 2011/2012
- LHCb presented the first evidence of CPV in charm decays, supported by updated CDF and Belle results.
- If confirmed, most likely a direct CPV effect
- Still not clear whether SM or NP

- High precision measurements in different decay modes are needed in order to clarify
- CLEO-c, Babar, Belle and CDF are analysing their final datasets
- LHCb has already in disk the world biggest charm samples in many decay modes
  - Similar purities as the B factories
  - Careful analysis of systematic effects using data driven (often CF control samples) methods
- BESII can give important contributions (strong phases for time dependent WS measurements)

SUMMARY

Charm mixing and CPV in charm decays are considered a promising laboratory to probe for NP effects due to the predicted SM suppressions

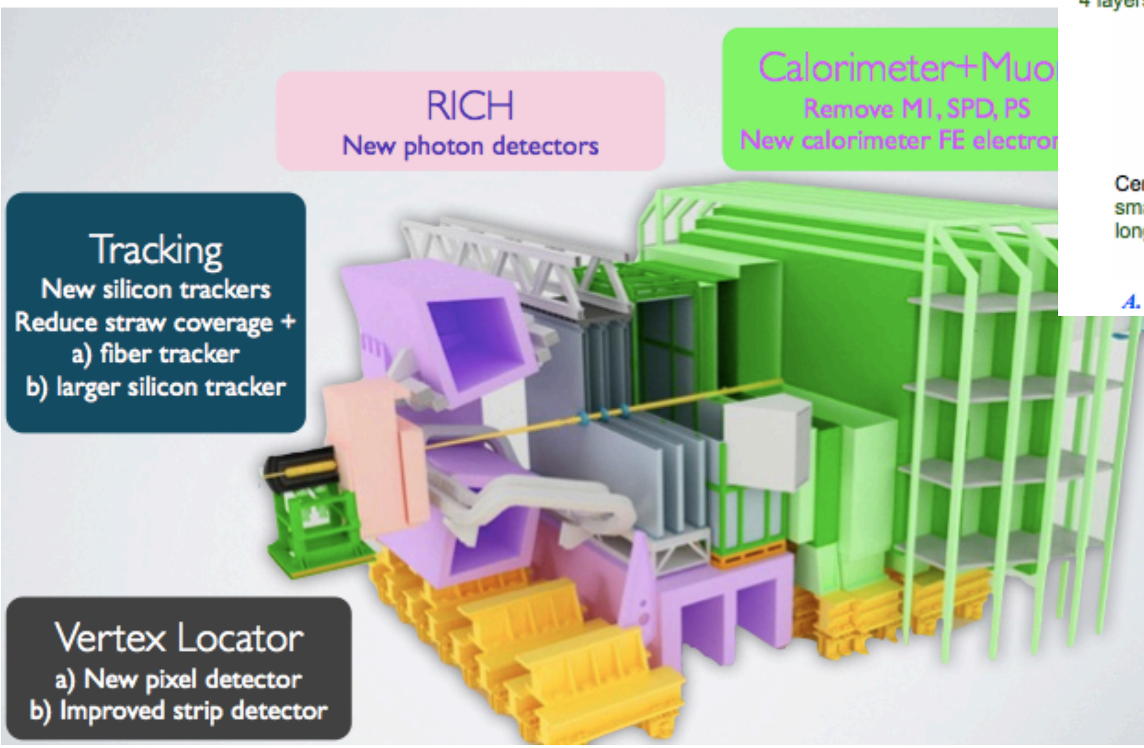
- Pioneering work of hadron and e^+e^- charm factories and excellent work by BaBar, Belle and CDF established mixing
- High luminosity and charm cross-section at the LHC, excellent performance of LHCb are producing large samples of many charm decays
- ΔA_{CP} measurement from LHCb may be the first hint of NP from the LHC
- No any other evidence of CPV in the charm sector
- CDF and the B factories are analysing final datasets
- LHCb will be able to see large effects, if they exist
- Measurements provide constraints to NP parameters
- To go below SM expectations we need a big step forward

arXiv:1208.3355v1 [hep-ex]

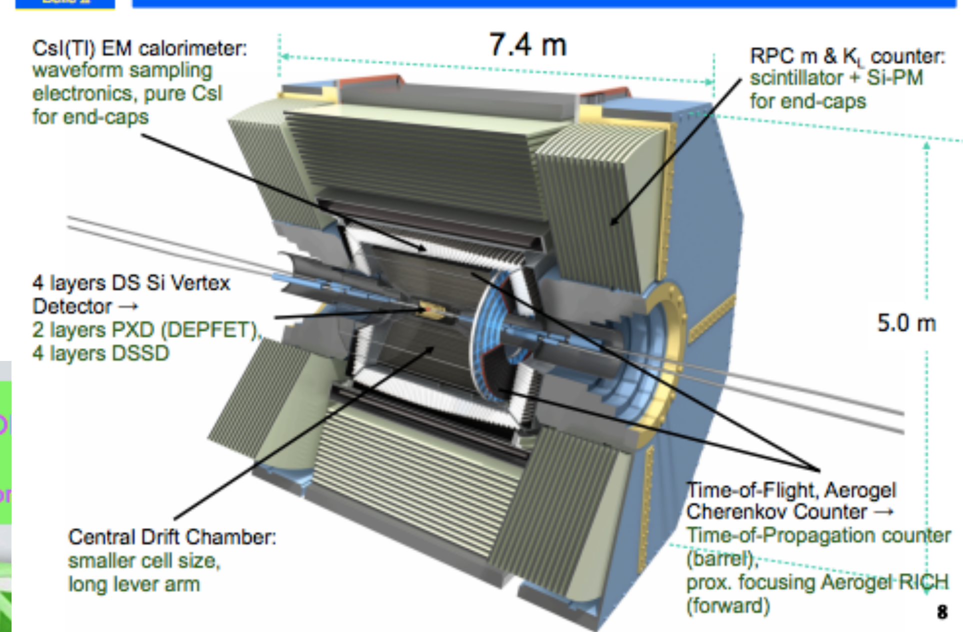
OUTLOOK: FUTURE FACILITIES

2019

CERN-LHCC-2012-007



The Belle II Detector: arXiv:1011.0352v1 [physics.ins-det]



A. J. Schwartz *CHARM 2012, Hawaii: Belle II Charm Prospects* 8

2017

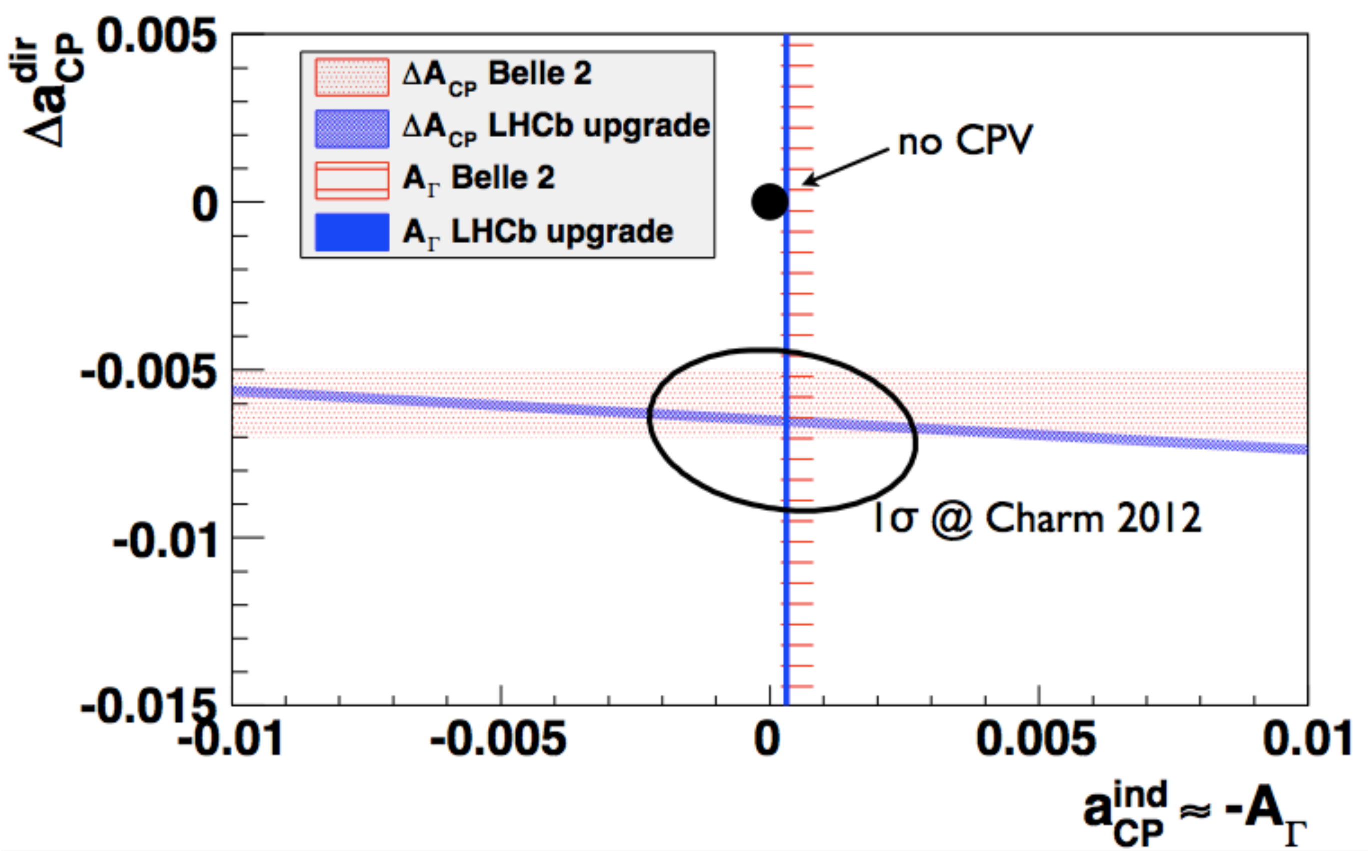
arXiv:1008.1541v1 [hep-ex]

Extra slides


From Zazzle.com.br

THANK YOU !

Projected Precisions



MORE DETAILS ON THE FORMALISM

A. Zupanc, arXiv:1109.1362v1 [hep-ex]

$$i\frac{d}{dt}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left[\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right]\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}, \quad (1)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are 2×2 Hermitian matrices. Diagonal elements of the effective Hamiltonian $\mathbf{H}_{\text{eff}} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$ describe flavor-conserving transitions $D^0 \to D^0$ and $\overline{D}^0 \to \overline{D}^0$, while off-diagonal elements describe the flavor-changing transitions $D^0 \leftrightarrow \overline{D}^0$. The hermiticity of $\mathbf{M}$ and $\mathbf{\Gamma}$ requires $M_{12} = M_{21}^*$, $M_{ii} = M_{ii}^*$, $\Gamma_{12} = \Gamma_{21}^*$ and $\Gamma_{ii} = \Gamma_{ii}^*$, and the CPT invariance requires $M_{11} = M_{22} \equiv M$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$.

The eigenstates of the effective Hamiltonian $\mathbf{H}_{\text{eff}}$ are

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \quad (2)$$

while the corresponding eigenvalues are

$$\lambda_{1,2} = \left(M - \frac{i}{2}\Gamma\right) \pm \frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right) \equiv m_{1,2} - \frac{i}{2}\Gamma_{1,2}. \quad (3)$$

The coefficients p and q are complex coefficients, satisfying $|p|^2 + |q|^2 = 1$, and

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} = \left|\frac{q}{p}\right| e^{i\phi}. \quad (4)$$

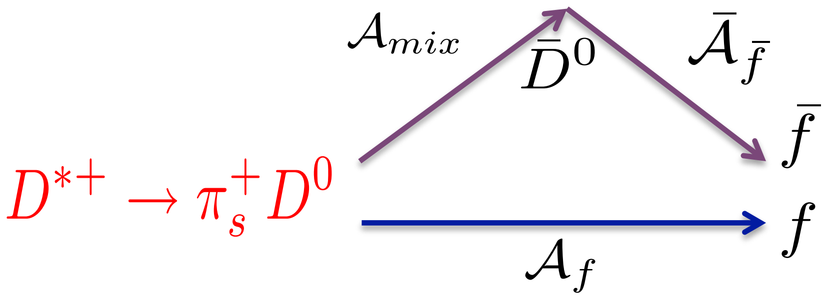
The real parts of the eigenvalues $\lambda_{1,2}$ represent masses, $m_{1,2}$, and their imaginary parts represent the widths $\Gamma_{1,2}$ of the two eigenstates $|D_{1,2}\rangle$, respectively. The time evolution of the eigenstates is given by

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}\rangle, \qquad e_{1,2}(t) = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}. \quad (5)$$

- Ratios of time integrated rates of WS to RS semileptonic decays

Theoretically clean, however experimentally difficult (very high rates required)

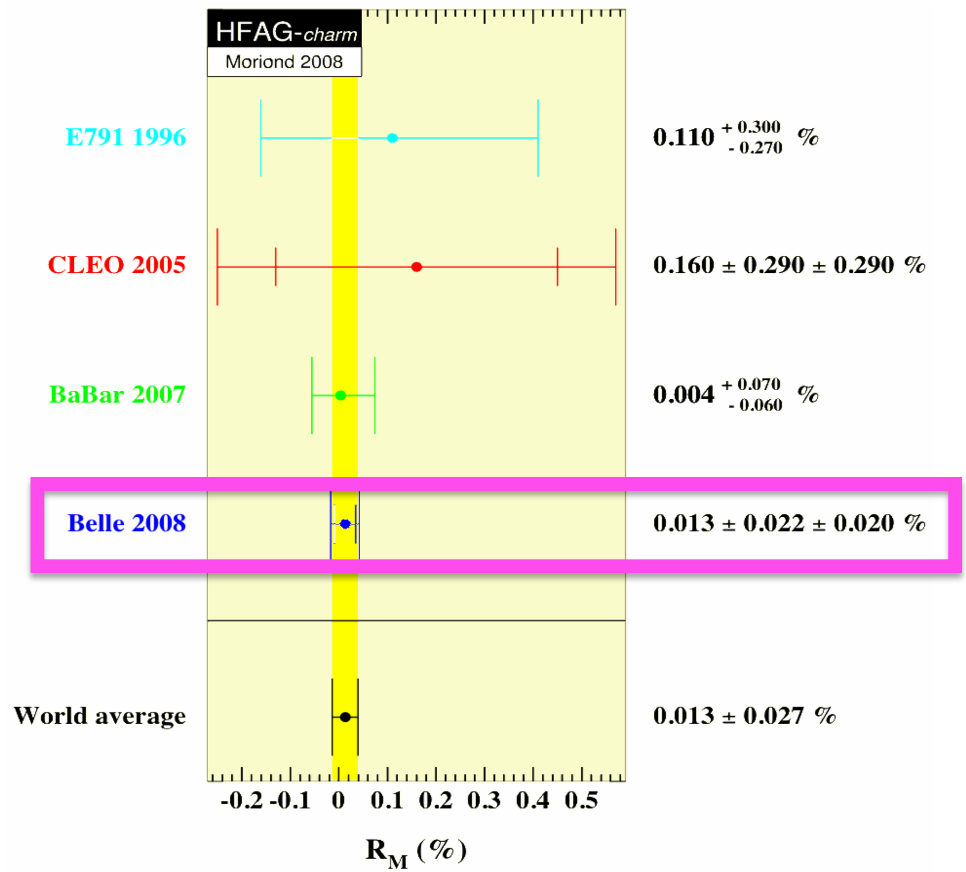
$$\mathrm{SM}: \mathcal{A}_{\bar{f}} = \bar{\mathcal{A}}_f = 0$$



$$R_m \equiv \frac{\Gamma(D^0 \to K^+ \mu^- \bar{\nu}_\mu)}{\Gamma(D^0 \to K^- \mu^+ \nu_\mu)}$$

$$R_m \approx \frac{x^2 + y^2}{2}^*$$

* $x^2, y^2 << 1$, $|q|^2 \simeq |p|^2$

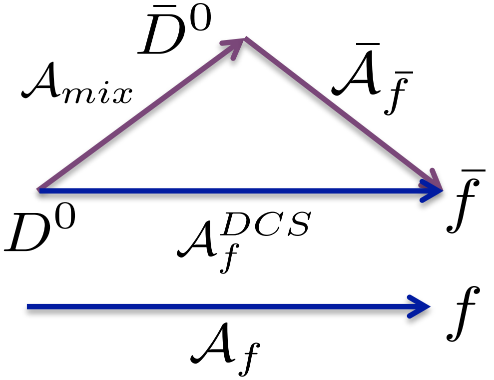


Still not sensitive to reveal mixing

EVIDENCES OF MIXING

- Ratio of WS $D^{*+}\to\pi^+D^0(K^+\pi^-)$ to RS $D^{*+}\to\pi^+D^0(K^-\pi^+)$

(cc included)



$$R(t/\tau) = R_D + \sqrt{R_D}y'(t/\tau) + \frac{x'^2+y'^2}{4}(t/\tau)^2$$

DCSD Interference Mixing

$$\mathcal{A}_f \approx \bar{\mathcal{A}}_{\bar{f}} \qquad R_D = \frac{|\mathcal{A}_{\bar{f}}^{DCS}|^2}{|\mathcal{A}_f^{CF}|^2}$$

$$x' = y\sin\delta_f + x\cos\delta_f$$
$$y' = y\cos\delta_f - x\sin\delta_f$$

$$\delta_f = \text{strong phase (can be obtained by CLEO/BESIII)}^*$$

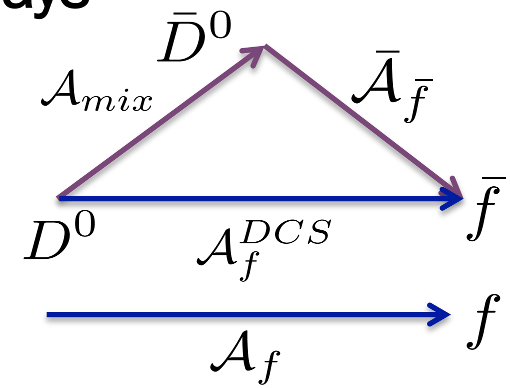
Fit to decay time distributions of RS and WS provides : $y',\ x'^2$ and R_D

Ratio of integrated rate of RS and WS provides : $\mathbf{R_B \equiv R_D + \sqrt{R_D}y' + \frac{x'^2+y'^2}{2}}$

*Measurements are available from CLEO and are used in HFAG fits

EVIDENCES OF MIXING

❖ Interference between DCS (WS) and Mixing+CF decays



$$\frac{D^0 \to K^+\pi^-}{D^0 \to K^-\pi^+}$$

Year	Experiment	Result	Comment
1998	FNAL E791	$R_B = (0.68\ ^{+0.34}_{-0.33} \pm 0.07)\%$	500 GeV π^-N interactions (2×10^{10} events)
2000	CLEO II.V	$R_B = (0.332\ ^{+0.063}_{-0.065} \pm 0.040)\%$ $R_D = (0.47\ ^{+0.11}_{-0.12} \pm 0.04)\%$ $x' = (0.0 \pm 1.5 \pm 0.2)\%$ $y' = (-2.3\ ^{+1.3}_{-1.4} \pm 0.3)\%$	9.0 fb^{-1} near Υ(4S) resonance
2005	FOCUS	$R_B = (0.429\ ^{+0.063}_{-0.061} \pm 0.027)\%$ $R_D = (0.381\ ^{+0.167}_{-0.163} \pm 0.092)\%$ $x'^2 = -0.059\%$ $y' = 1.0\%$	γN interactions (1×10^6 reconstr. $D \to K\, n(\pi)$ decays)
2006	Belle	$R_B = (0.377 \pm 0.008 \pm 0.005)\%$ $R_D = (0.364 \pm 0.017)\%$ $x'^2 = (0.018\ ^{+0.021}_{-0.023})\%$ $y' = (0.06\ ^{+0.40}_{-0.39})\%$	400 fb^{-1} near Υ(4S) resonance
2007	BaBar	$R_D = (0.303 \pm 0.016 \pm 0.010)\%$ $x'^2 = (-0.022 \pm 0.030 \pm 0.021)\%$ $y' = (0.97 \pm 0.44 \pm 0.31)\%$	384 fb^{-1} near Υ(4S) resonance
2007	CDF (Run II)	$R_B = (0.415 \pm 0.010)\%$ $R_D = (0.304 \pm 0.055)\%$ $x'^2 = (-0.012 \pm 0.035)\%$ $y' = (0.85 \pm 0.76)\%$	1.5 fb^{-1} at $\sqrt{s} = 1.96$ TeV (Tevatron)

First Evidences of Mixing

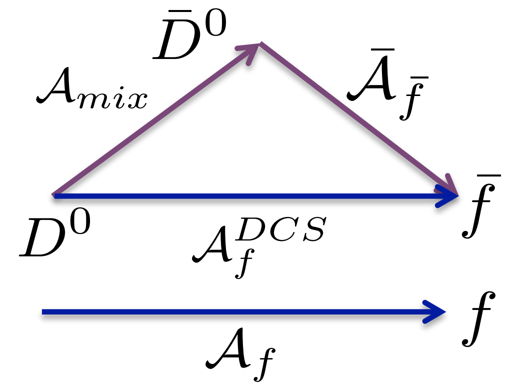
no mixing excluded at 3.9 σ

no mixing excluded at 3.8 σ

EVIDENCES OF MIXING

$D^0 \to K^+\pi^-\pi^0$ (WS) wrt $D^0 \to K^-\pi^+\pi^0$ (RS)

Year	Experiment	Result	Comment
2005	Belle	$R_B(K^+\pi^-\pi^0) = (0.229 \pm 0.015\ ^{+0.013}_{-0.009})\%$ $R_B(K^+\pi^-\pi^+\pi^-) = (0.320 \pm 0.018\ ^{+0.018}_{-0.013})\%$	281 fb^{-1} near Y(4S) resonance
2006	BaBar	$R_B(K^+\pi^-\pi^0) = (0.214 \pm 0.008 \pm 0.008)\%$ $R_M = (0.023\ ^{+0.018}_{-0.014} \pm 0.004)\%$ $\langle R_D(K^+\pi^-\pi^0)\rangle = (0.164\ ^{+0.026}_{-0.022} \pm 0.012)\%$ $\alpha\langle y'(K^+\pi^-\pi^0)\rangle = (-0.012\ ^{+0.006}_{-0.008} \pm 0.002)\%$	230.4 fb^{-1} near Y(4S) resonance
2006	BaBar	$R_M = (0.019\ ^{+0.016}_{-0.015} \pm 0.002)\%$ $\alpha\langle y'(K^+\pi^-\pi^+\pi^-)\rangle = (-0.6 \pm 0.5 \pm 0.1)\%$	230.4 fb^{-1} near Y(4S) resonance
2008	BaBar	$x''(K^+\pi^-\pi^0) = (2.61\ ^{+0.57}_{-0.68} \pm 0.39)\%$ $y''(K^+\pi^-\pi^0) = (-0.06\ ^{+0.55}_{-0.64} \pm 0.34)\%$	384 fb^{-1} near Y(4S) resonance



BaBar 2008 (PRL 103,211801 (2009)

no mixing excluded at 3.2 σ

$$\frac{dN_{\bar{f}}(s_{12}, s_{13}, t)}{ds_{12}ds_{13}dt} = e^{-\Gamma t}\Big\{|A_{\bar{f}}|^2 + |A_{\bar{f}}||\bar{A}_{\bar{f}}|[y\cos\delta_{\bar{f}} - x\sin\delta_{\bar{f}}](\Gamma t) + \frac{x^2+y^2}{4}|\bar{A}_{\bar{f}}|^2(\Gamma t)^2\Big\}.$$

DCSD — Interference — Interference — Mixing

$s_{12} = s_{K^-\pi^+}$
$s_{13} = s_{K^-\pi^0}$

Time dependent amplitude analysis:

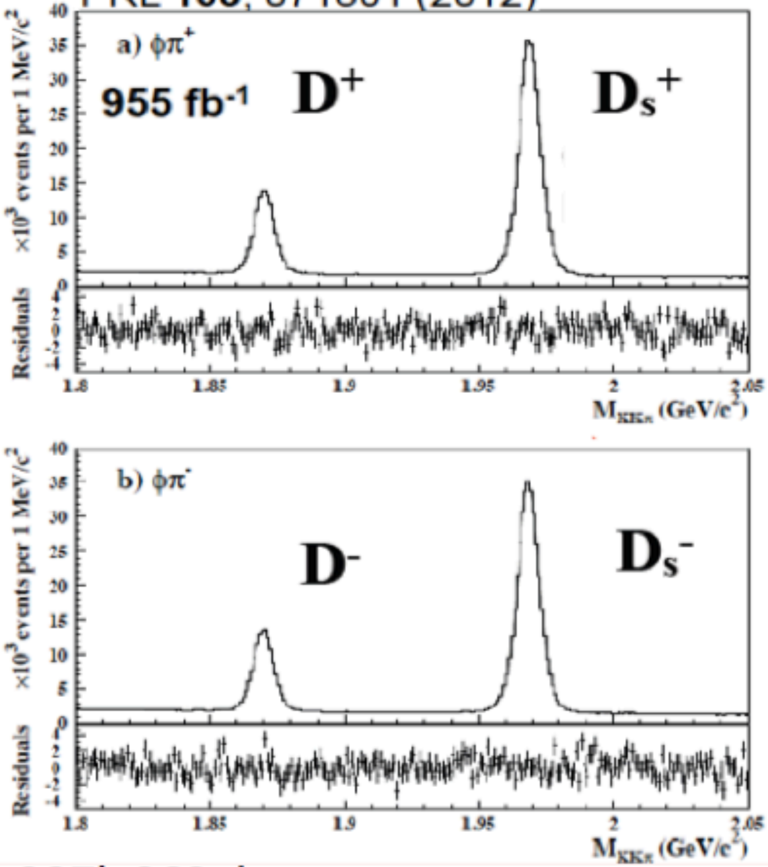
-Resonances magnitudes and phases

-x'' and y$''$

Determination of x'' and y'' for D^0 and $\bar{D}^0$ tagged sample $\to$ noCPV

CPV FROM BELLE

PRL **108**, 071801 (2012)

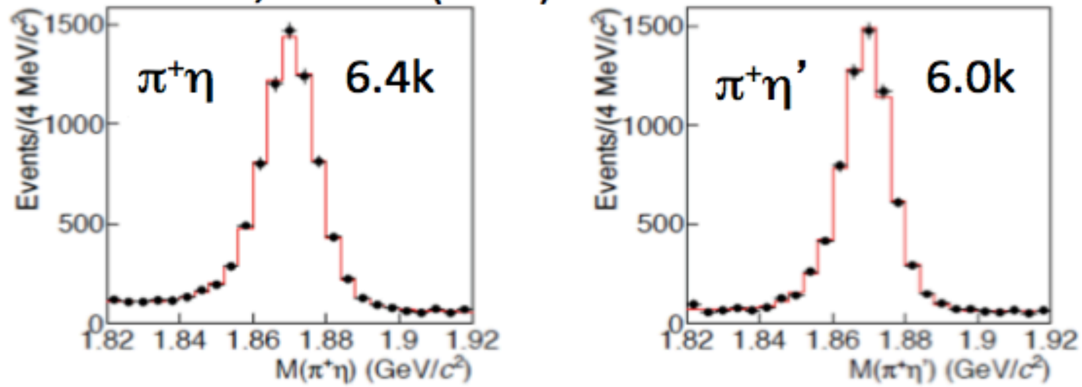


237k SCS decays 723k CF decays

$\Delta A_{CP} = (+0.51 \pm 0.28 \pm 0.05)\%$

Assuming no CPV in CF decay, measures CPV in SCS decay

PRL **107**, 221801 (2011) 791 fb^{-1}



Red histogram: fit to the data points

decay	A_{CP} (%)
$D^+ \to \pi^+\eta$	$+1.74 \pm 1.13 \pm 0.20$
$D^+ \to \pi^+\eta'$	$-0.12 \pm 1.12 \pm 0.20$

No evidence for CPV

Great improvements wrt previous results

25

From V. Vagnoni FPCP 2012

Already presented at PIC2011

From V. Vagnoni FPCP 2012

- With 4-body decays the phase space becomes 5-dim.
  - difficulty grows dramatically
- A possibility is to use T-odd moments, e.g. BaBar in $D^+ \rightarrow K_S K\pi\pi$ decays PRD 84 031103(R) (2011)
  - Define a triple product $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$
  - Define the quantity A_T for D^+ and its analogue for D^-

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

  - Then the difference $\mathcal{A}_T \equiv \frac{1}{2}(A_T - \bar{A}_T)$ measures T violation
  - BaBar gets

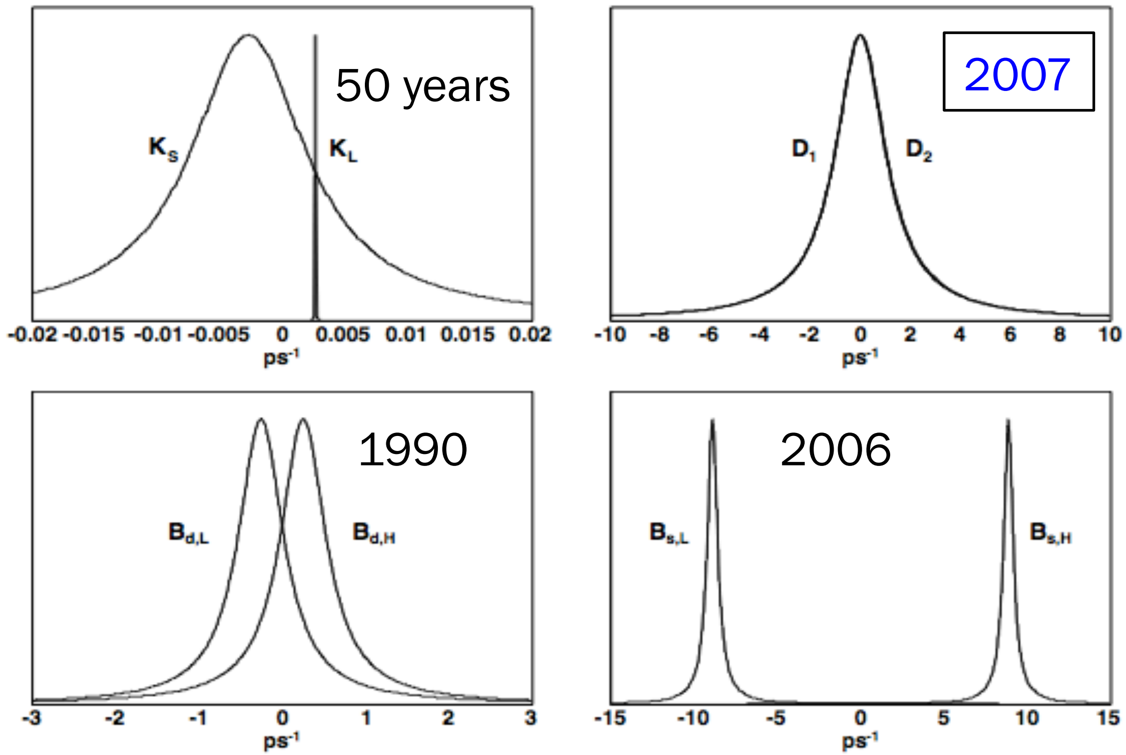
$\mathcal{A}_T(D^+)$ = [-1.20 ± 1.00 (stat.) ± 0.46 (syst.)] %

$\mathcal{A}_T(D_s^+)$ = [-1.36 ± 0.77 (stat.) ± 0.34 (syst.)] %

INTRODUCTION

Mass and widths of physical neutral meson states

From M.Gersabeck, Mod. Phys. Lett. A27 (2012) 1230026.



Charm: both x and y very small ($\sim 10^{-2}$)

First evidences only in 2007

Now firmly established

Already presented at PIC2011

- Modes include $D^0 \rightarrow K_S\pi^0$, $D^0 \rightarrow K_S\eta$, and $D^0 \rightarrow K_S\eta'$
  - Events tagged via D* decay

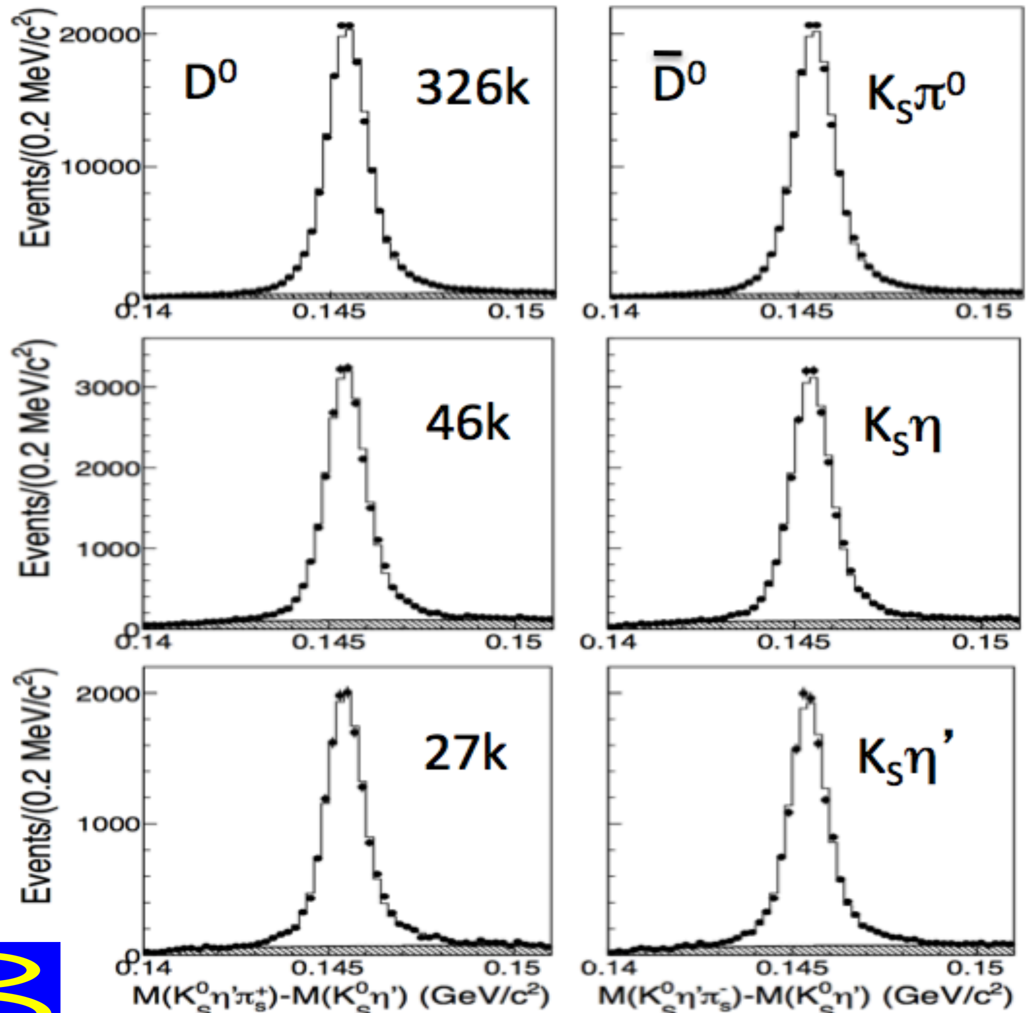
PRL **106**, 211801 (2011)

$A_{CP}^{D^0\to K^0_S\pi^0}$	$-0.28\pm0.19\pm0.10$
$A_{CP}^{D^0\to K^0_S\eta}$	$+0.54\pm0.51\pm0.16$
$A_{CP}^{D^0\to K^0_S\eta'}$	$+0.98\pm0.67\pm0.14$

- No evidence for CPV

From V. Vagnoni FPCP 2012

791 fb^{-1}



Black histogram: fit to the data points