Measurement of D^0-$\overline{D}^0$ Mixing and *CP* Violation at *BaBar*

Giulia Casarosa
SLAC National Accelerator Laboratory
INFN & Università di Pisa

on behalf of the *BaBar* Collaboration

Charm 2012
The 5th International Workshop on Charm Physics

14-17 May 2012, Honolulu, Hawai'i

outline

- Mixing and *CP* Violation in the Charm Sector
- D^0 Lifetime Ratio Analysis at *BaBar*
  - Dataset & Backgrounds
  - Fit Strategy & PDFs
  - Fit Validation & Systematics
  - Results & Interpretation
- Conclusions

Flavour Mixing and CPV in the Charm Sector

➔ **Mixing** occurs when flavour eigenstates differ from mass eigenstates:

$|D_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle$ with $|p|^2 + |q|^2 = 1$ (CPT conserved), CP $|D^0\rangle = +|\bar{D}^0\rangle$

Mixing Parameters

$$x = \frac{m_1 - m_2}{\Gamma_D} \quad \& \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

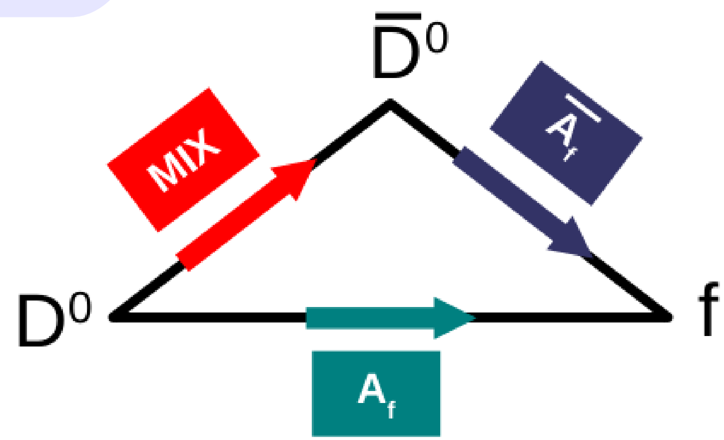
$m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $|D_{1,2}\rangle$ and $\Gamma_D = (\Gamma_1 + \Gamma_2)/2$

➔ ***CP* Violation** can occur in 3 ways:

- in decay: $|A_f| \neq |\bar{A}_{\bar{f}}|$
- in mixing: $r_m = |q/p| \neq 1$
- in the interference: $\varphi_f \neq 0$

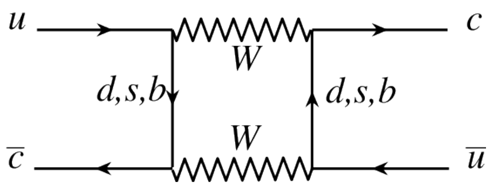
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| \exp[\, i(\Delta_f + \varphi_f)\,]$$

strong + weak phase

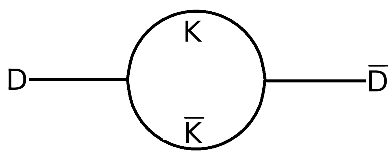


$\bar{A}_{\bar{f}} = \langle \bar{D}^0 | \mathcal{H} | \bar{f} \rangle$
$\bar{A}_f = \langle \bar{D}^0 | \mathcal{H} | f \rangle$
$A_f = \langle D^0 | \mathcal{H} | f \rangle$

Theoretical predictions ...



- virtual *down type* quarks involved in mixing loop (only in D system);
- *b* contribution CKM suppressed; *s* and *d* contributions GIM suppressed;
- possible New Physics (NP) contributions comparable to the SM ones;



- long-range contributions expected to be dominant;
- large theory uncertainties on their estimation;

→ The SM predictions for the mixing parameters vary in a range from 10^{-2} to 10^{-7};
[IJMP, A21:5686 (2006)]

→ (SM) CP Violation *was* expected to be below the experimental sensitivity.

... experimental situation

→ **First evidence** of **CPV** in the charm sector:

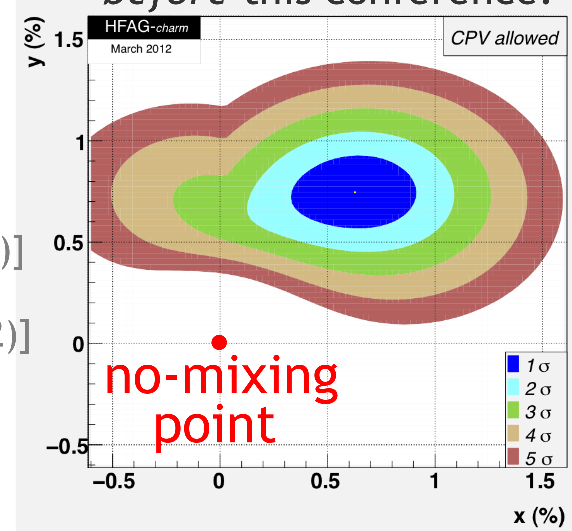
LHCb: $\Delta A_{CP}(D^0 \to KK - D^0 \to \pi\pi) = (-0.82 \pm 0.21^{stat} \pm 0.11^{syst})$
[PRL 108 111602 (2012)]

CDF: $\Delta A_{CP}(D^0 \to KK - D^0 \to \pi\pi) = (-0.62 \pm 0.21^{stat} \pm 0.10^{syst})$
[CDF note 10784 (2012)]

Interpretation is not straightforward, can't say if it's NP or SM.

→ The no-mixing hypothesis is excluded at 10σ but no single measurement exceeds 5σ.

before this conference:



[http://www.slac.stanford.edu/xorg/hfag/charm/index.html]

Mixing and CPV with Lifetime Ratio Analysis

➔ Other experimental observables sensitive to mixing and to *CP* Violation:

Mixing & CPV observables

$$y_{CP} = \frac{\Gamma(CP+)}{\Gamma_D} - 1 \quad \& \quad \Delta Y = \frac{\Gamma(CP+)}{\Gamma_D} A_\Gamma$$

$\Gamma(CP+) = [\, \Gamma(D^0 \to CP+) + \Gamma(\bar{D}^0 \to CP+) \,]/2$

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

$\Gamma(CP+)$ = effective D^0 width for decays to CP+ eigenstates

➔ In terms of the mixing & CPV parameters:

$$y_{CP}^{hh} = y\cos\phi_{\cancel{hh}} + \frac{1}{2}\left[A_M + A_D^{hh}\right] x\sin\phi_{\cancel{hh}} - \frac{1}{4}A_M A_D^{hh}\, y\cos\phi_{\cancel{hh}}$$

$$\Delta Y^{hh} = -x\sin\phi_{\cancel{hh}} + \frac{1}{2}\left[A_M + A_D^{hh}\right] y\cos\phi_{\cancel{hh}} + \frac{1}{4}A_M A_D^{hh}\, x\sin\phi_{\cancel{hh}}$$

direct CPV:

$$A_D^{hh} = \frac{|A_{hh}/\bar{A}_{hh}|^2 - |\bar{A}_{hh}/A_{hh}|^2}{|A_{hh}/\bar{A}_{hh}|^2 + |\bar{A}_{hh}/A_{hh}|^2}$$

CPV in mixing:

$$A_M = \frac{r_m^2 - r_m^{-2}}{r_m^2 + r_m^{-2}}$$

- in general, both observables depend on the final state
- sensitivity to direct CPV ~ 10^{-4}, below our current experimental precision [J.Phys.G G39. 045005 (2012)]
- in the SM, φ is the same for all the final states to a very good approximation [PRD 80. 076008 (2009)]
- in case of no *CP* violation: $y_{CP} = y$ and $\Delta Y = 0$.

outline

- Mixing and *CP* Violation in the Charm Sector
- D^0 Lifetime Ratio Analysis at *BaBar*
  - Dataset & Backgrounds
  - Fit Strategy & PDFs
  - Fit Validation & Systematics
  - Results & Interpretation
- Conclusions

D^0 Lifetime Ratio Analysis at *BaBar*

➔ Extract y_{CP} and ΔY from the full $\Upsilon(4S)$ *BaBar* data sample, L_{DATA} **= 468 fb^{-1}**

5 signal channels(*):

flavour tagged
- $D^{*+} \to D^0 \pi_s^+$; $D^0 \to K^+K^-$
- $D^{*+} \to D^0 \pi_s^+$; $D^0 \to \pi^+\pi^-$
- $D^{*+} \to D^0 \pi_s^+$; $D^0 \to K^-\pi^+, K^+\pi^-$

flavour untagged
- $D^0 \to K^+K^-$
- $D^0 \to K^-\pi^+, K^+\pi^-$

we perform a **simultaneous fit** to the tagged and the untagged modes and extract Γ_D from $K\pi$ final state, and $\Gamma(D^0 \to CP+)$ and $\Gamma(\overline{D}^0 \to CP+)$ from KK and $\pi\pi$ final states

➔ Experimental assumptions:

- small mixing ($|x|$, $|y| << 1$) → proper time distribution are exponential with effective lifetimes to a very good approximation;
- not sensitive to direct CPV + weak phase φ does not depend on final state → KK and $\pi\pi$ modes share common effective lifetimes,
  - ✔ crosscheck fit on data.

$$y_{CP} = y\cos\phi + \frac{A_M}{2} x\sin\phi$$
$$\Delta Y = -x\sin\phi + \frac{A_M}{2} y\cos\phi$$

(*) C-conjugation is implied

Reconstruction and Selection Criteria

- to benefit from the *simultaneous* fit to the 5 modes, we ensure that the resolutions of tagged and untagged modes are as similar as possible:
  - reconstruction of the *tagged* candidates is done without using the additional information coming from the slow pion;
- selection of the signal events:
  - remove D from B decays, $p_{CM}(D^0) > 2.5$ GeV/c
  - D^0 reconstructed mass: $1.80\ \mathrm{GeV}/c^2 \leq m \leq 1.93\ \mathrm{GeV}/c^2$
  - mass difference $\Delta m = m_{D^*} - m_D$: $0.14\ \mathrm{GeV}/c^2 \leq \Delta m \leq 0.16\ \mathrm{GeV}/c^2$ (tagged only)
  - vertex fit probability: $P(\chi^2) > 0.1\%$
  - apply quality cuts on the D^0 daughters and the slow pion tracks
  - D^0 proper time error: $\sigma_t < 0.5$ ps
  - D^0 proper time: $-2\ \mathrm{ps} < t < 4\ \mathrm{ps}$
- the tagged and untagged datasets are independent:
  - events containing a tagged candidate that satisfies $0.1447 \leq \Delta m\ (\mathrm{GeV}/c^2) \leq 0.1463$ are removed from the untagged dataset.

Background Categories

combinatorial background:

- random tracks,
- main background,
- ~ zero-lifetime component,
- extracted from the data sidebands.

charm background:

- common ancestor of the D^0 products is a long-living charm meson,
- very small component of the events in the signal region (<0.7%),
- has a signal-like long lifetime,
- studied on MC sample 10 x L_{DATA},
- extracted from MC.

in the signal region(*):

	Tagged			Untagged	
	$\pi^-\pi^+$	K^-K^+	$K^\pm\pi^\mp$	K^-K^+	$K^\pm\pi^\mp$
Signal	65429 $\pm$262	136867 $\pm$371	1487000 $\pm$1220	496200 $\pm$1150	5825300 $\pm$2600
Comb. Bkgd.	3760	653	2849	164970 $\pm$997	1044552
Charm Bkgd.	97	309	642	5477	4645

Mode	Fractional breakdown of Charm Bkgd. (%)				
$D^0 \to X\ell\nu$	15.4	10.3	29.9	7.2	≤ 2
$D^0 \to K^-\pi^+$	80.8	14.9	57.1	8.8	35.8
$D^0 \to \pi^0\pi^+K^-$	1.1	70.3	1.7	63.3	6.9
$D^+ \to \pi^+\pi^+K^-$	≤ 1	2.9	≤ 1	11.8	≤ 2
$D^0 \to K^+K^-$	≤ 1	≤ 1	1.3	≤ 1	3.5
$D^0 \to \pi^+\pi^-$	1.8	≤ 1	2.2	≤ 1	3.1
$D^0 \to \pi^+\pi^-\pi^0$	≤ 1	≤ 1	7.0	≤ 1	17.3
Λ decays	≤ 1	≤ 1	≤ 1	4.9	2.6

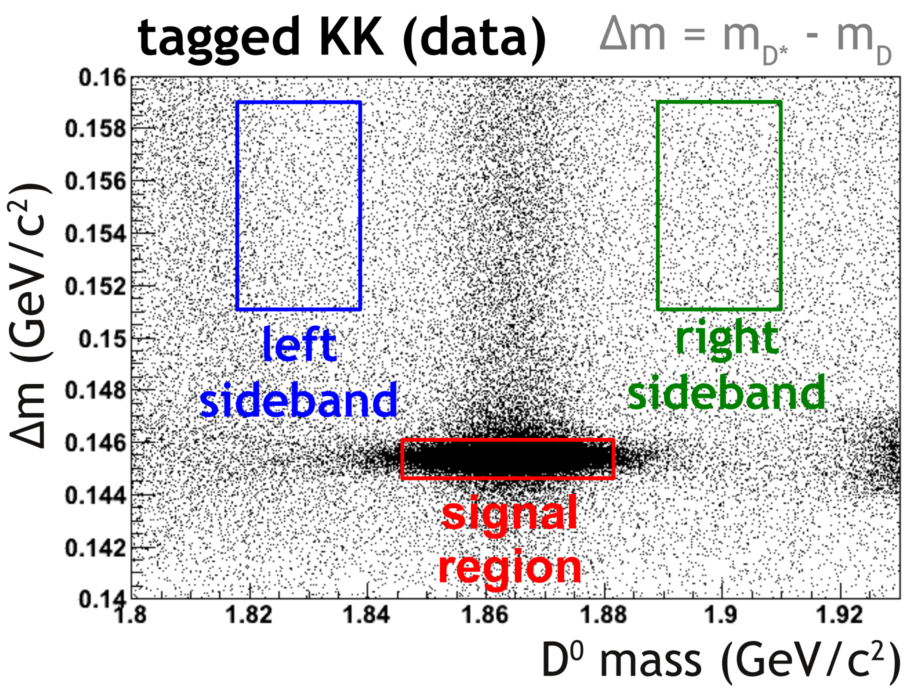
(*) charm yields evaluated on MC events

outline

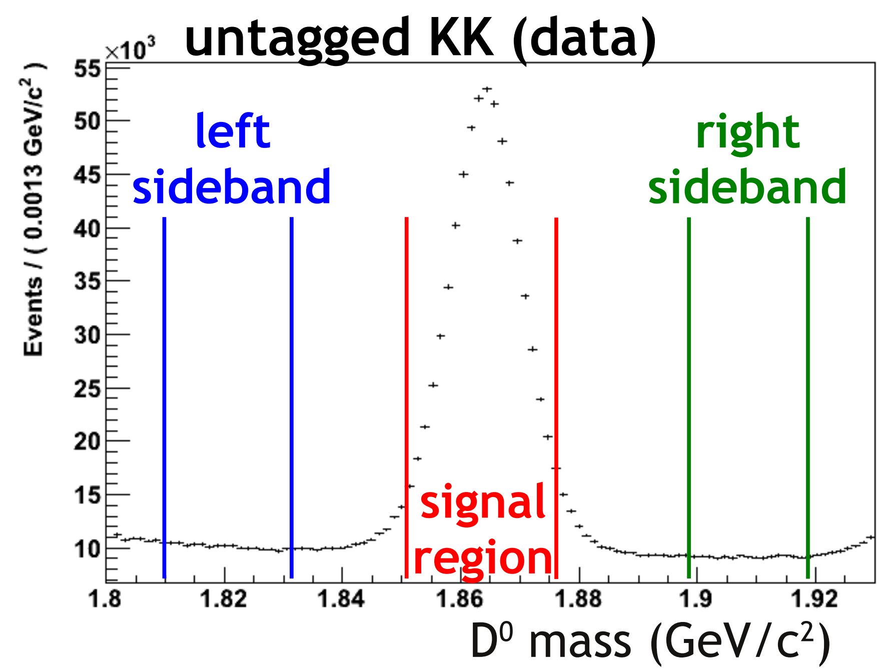
- Mixing and *CP* Violation in the Charm Sector
- D^0 Lifetime Ratio Analysis at *BaBar*
  - Dataset & Backgrounds
  - Fit Strategy & PDFs
  - Fit Validation & Systematics
  - Results & Interpretation
- Conclusions

Data Samples for the Lifetime Fit

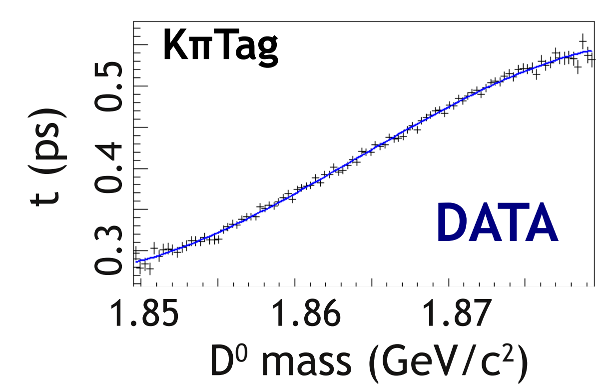
➔ we select events in a $(m_D, \Delta m)$ region for the tagged modes.



➔ we select events in a mass region for the untagged modes.



➔ An *optimization* of the signal region was performed for each of the 5 modes, directly on data, in order to reduce the effect of the proper time VS mass correlation.



Lifetime Fit Strategy

➔ **step1: extraction of the background yields**

- fit the mass distributions in data and extract the background yields;
- repeat the fit in MC and compute a correction factor for the bkg yields.

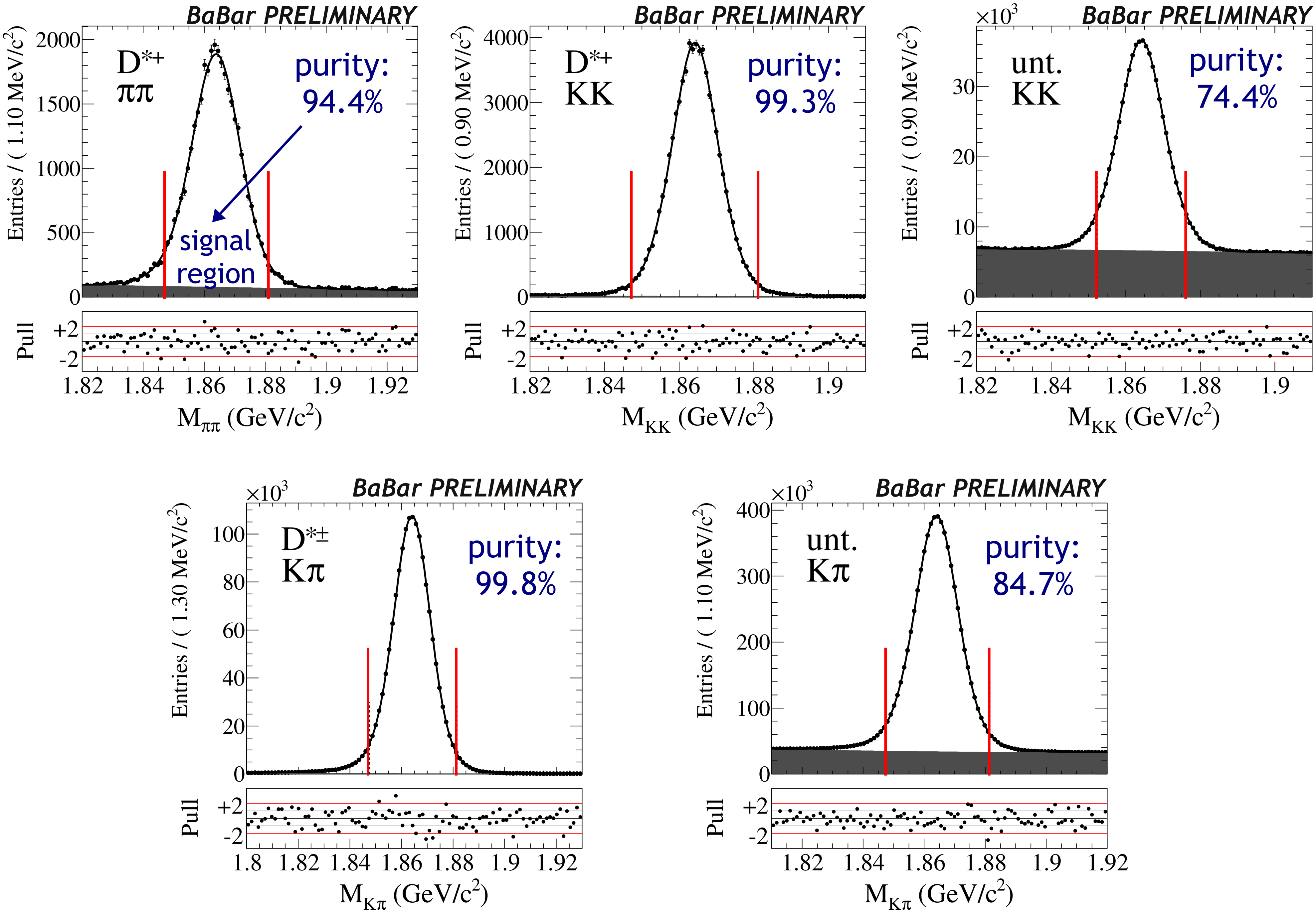
➔ **step2a: extraction of the background shapes**

- extract charm background PDF from MC;
- extract the combinatorial background PDF from the data sidebands;

➔ **step2b: simultaneous fit in the signal box**

- fix the background shapes in the signal box extracted in step2a;
- fix the background yields in the signal box extracted in mass fits in step1 *except for the combinatorial in the untagged KK mode*;
- extract the signal PDF by fitting the signal box (t, σ_t) distribution to a sum of signal, charm and combinatorial background PDFs.

Data Mass Fit



The Signal Lifetime Simultaneous PDF

conditional PDF = exponential convolved with a resolution function (sum of 3 Gaussians) $\mathcal{R}_X^Y(t,\sigma_t)$ *x proper time error PDF* $H_{\sigma_t}^{\mathrm{sig}}(\sigma_t)$

➔ the 3 Gaussians have a **common offset t_0** and independent scaling factors s_i:

$$
\begin{aligned}
\mathcal{R}_X^Y(t,\sigma_t) \;=\; & f_{t1}\mathcal{D}(t,\sigma_t;S'_Y S_X s_1, t_0, \tau) \\
& (1-f_{t1})\Big[f_{t2}\mathcal{D}(t,\sigma_t;S'_Y S_X s_2, t_0, \tau) \\
& (1-f_{t2})\mathcal{D}(t,\sigma_t;S'_Y S_X s_3, t_0, \tau)\Big]
\end{aligned}
$$

- τ^+ ⇨ $D^0 \to$ CP+
- $\bar{\tau}^+$ ⇨ $\bar{D}^0 \to$ CP+
- $\tau_{K\pi}$ ⇨ $D^0, \bar{D}^0 \to K\pi$

differences in D^0 momentum spectrum:
$Y = \mathrm{tag}, \mathrm{unt}$ & $S'_{\mathrm{unt}} \equiv 1$

differences in final state reconstruction:
$X = K\pi,\ KK,\ \pi\pi$ & $S_{K\pi} \equiv 1$

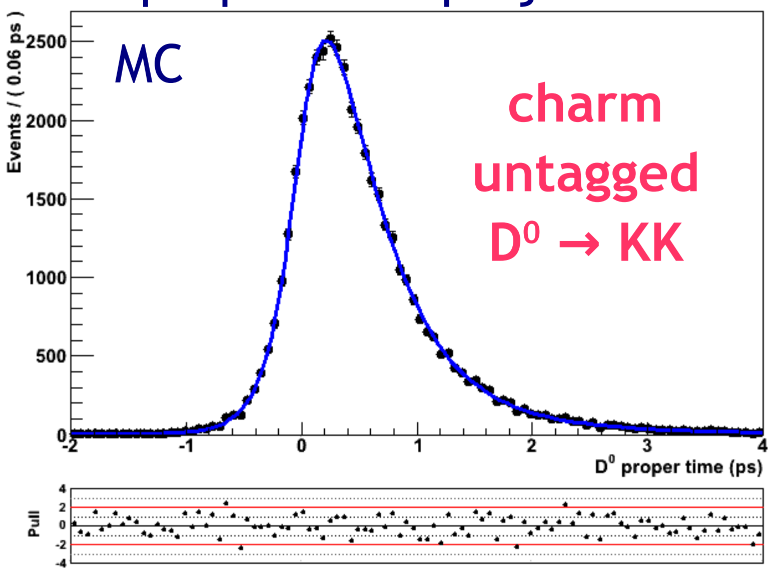
$$\mathcal{D}(t,\sigma_t;s,t_0,\tau) = C_{\sigma_t}\int \exp(-t_{\mathrm{true}}/\tau)\exp\left(-\frac{(t-t_{\mathrm{true}}+t_0)^2}{2(s\cdot\sigma_t)^2}\right)dt_{\mathrm{true}}$$

so that the product: $H_{\sigma_t}^{\mathrm{sig}}(\sigma_t)\cdot\mathcal{D}(t,\sigma_t;s,t_0,\tau)$ is a properly normalized 2D PDF.

- take into account the mistagged events in tagged KK and ππ modes
- assume untagged KK is 50% D^0 and 50% $\bar{D}^0$.

The Background Lifetime PDFs

proper time projection



charm background PDF:

- ➔ signal-like 2d PDF with per-event errors
- ➔ 2 long-lived components
- ➔ extracted from a 10 x L_{DATA} MC sample

combinatorial background PDF:

- ➔ prompt background
- ➔ weighted average of the PDFs extracted from the data sidebands
- ➔ mode-dependent PDF form:
  - tagged modes: fixed-width-bin 2d histogram in (t,σ_t)
  - untagged Kπ: adaptive binning 2d histogram in (t,σ_t)
  - untagged KK: signal-like analytic function with per-event error

outline

- Mixing and *CP* Violation in the Charm Sector
- D^0 Lifetime Ratio Analysis at *BaBar*
  - Dataset & Backgrounds
  - Fit Strategy & PDFs
  - Fit Validation & Systematics
  - Results & Interpretation
- Conclusions

Fit Validation

- Tests on *simulated* events:
  - fit 9 independent signal samples (L_{DATA})
  - fit 4 independent signal+bkg cocktails (L_{DATA})
  - studied large ensemble of pure toy datasets

no bias observed in y_{CP} nor on ΔY in MC studies

- Crosschecks on *data*:
  - fit tagged-only and untagged-only channels
  - checked compatibility of tagged and untagged KK (and Kπ) lifetimes in a 5-mode simultaneous fit
  - allowed tagged and untagged channels to have independent lifetimes in a 5-mode simultaneous fit

in all data crosschecks, the extracted lifetimes were compatible

  - released assumption of no *direct CPV* and of mode-*independent* weak phase φ (characterizing CPV in the interference)

KK and ππ results are statistically compatible

Summary of Systematic Uncertainties

BaBar PRELIMINARY

Category	Fit Variation	$\lvert\Delta[y_{CP}]\rvert$ (%)	$\lvert\Delta[\Delta Y]\rvert$ (%)
Fit Region	width of `sigBox`	0.057	0.022
	position of `sigBox`	0.005	0.001
Signal	`KKUnt` σ_t signal PDF	0.022	0.0
	Mistag Fraction	0.0	0.0
	D^0 Fraction in `KKUnt`	0.001	0.0
Charm	lifetimes	0.042	0.001
	yields	0.016	0.0
Combinatorial	yields	0.043	0.002
	weighting parameter	0.004	0.001
	PDF from sidebands	0.066	0.0
Selection	σ_t cut	0.052	0.053
	adjudication	0.028	0.011
	Total Systematic Error	0.124	0.058

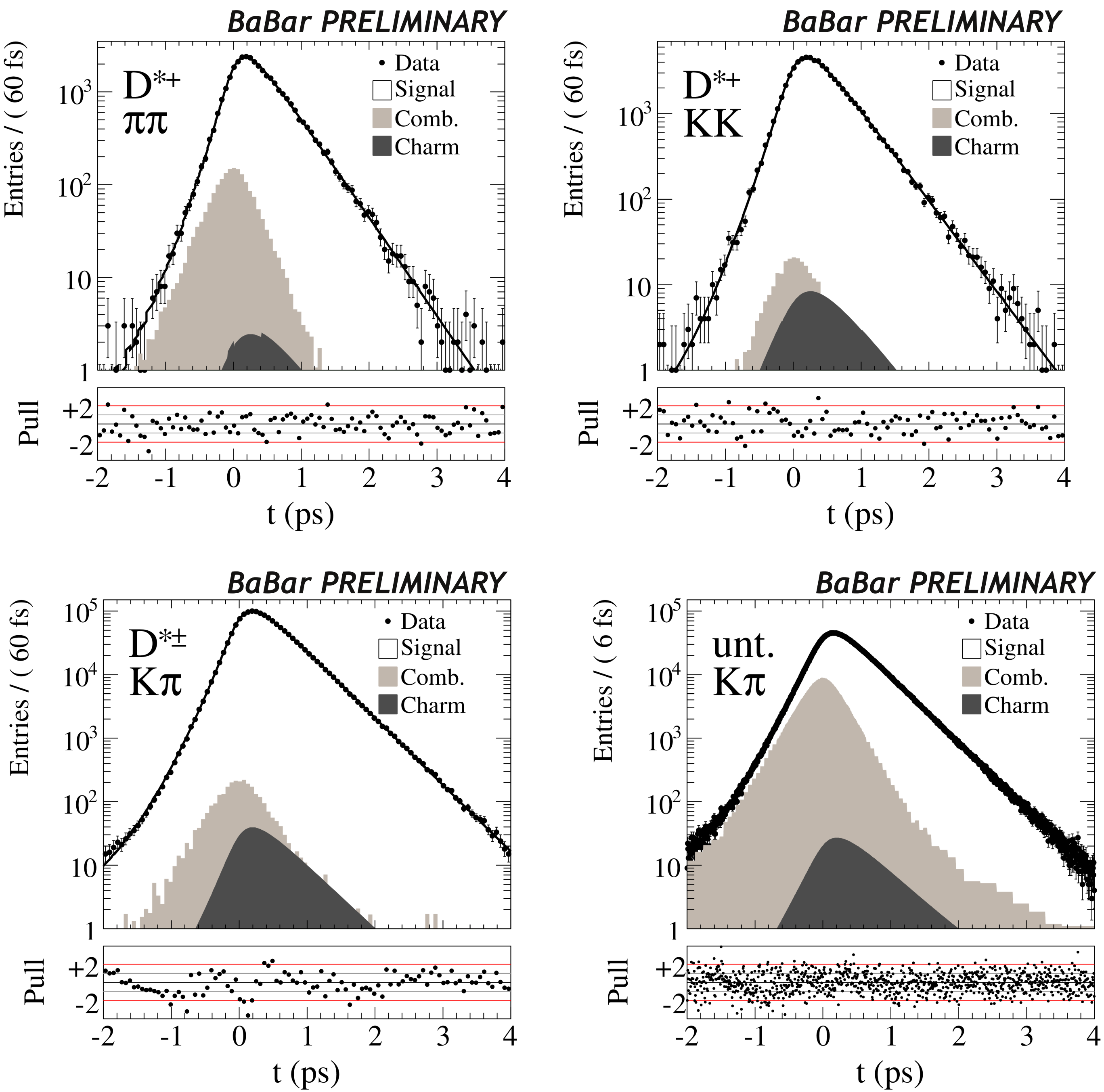
total systematics reduced w.r.t. previous *BaBar* analyses

- tagged-only analysis [PRD 78, 011105 (2008)]
- untagged-only analysis [PRD 80, 071103 (2009)]

outline

- Mixing and *CP* Violation in the Charm Sector
- D^0 Lifetime Ratio Analysis at *BaBar*
  - Dataset, Selection Criteria & Backgrounds
  - Fit Strategy & PDFs
  - Fit Validation & Systematics
  - Results & Interpretation
- Conclusions

Proper Time Fit Projections



CP+ lifetimes

$$\tau^{+} = (405.69 \pm 1.25)\ \text{fs}$$

$$\bar{\tau}^{+} = (406.40 \pm 1.25)\ \text{fs}$$

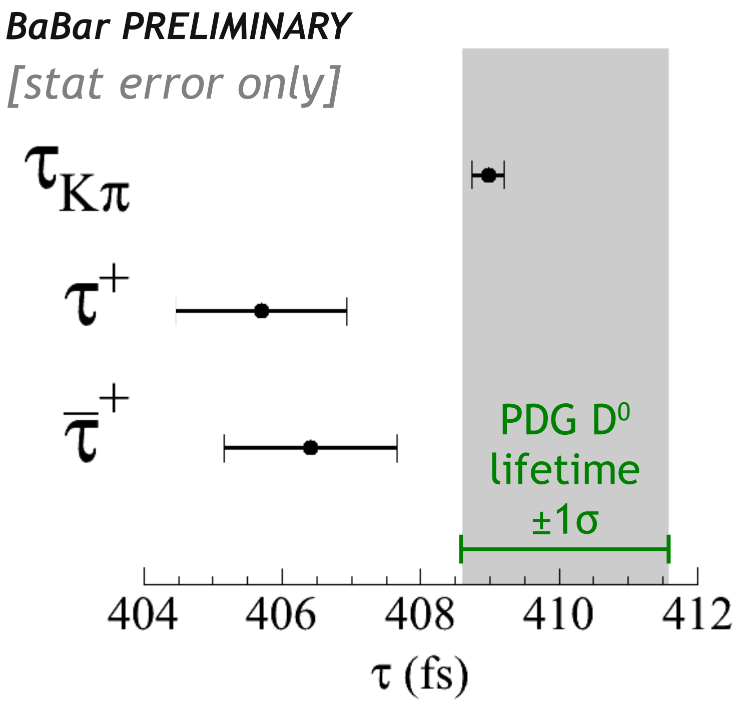
[stat error only]

D^0 lifetime

$$\tau_{K\pi} = (408.97 \pm 0.24)\ \text{fs}$$

[stat error only]

Lifetime Fit Results & Interpretation



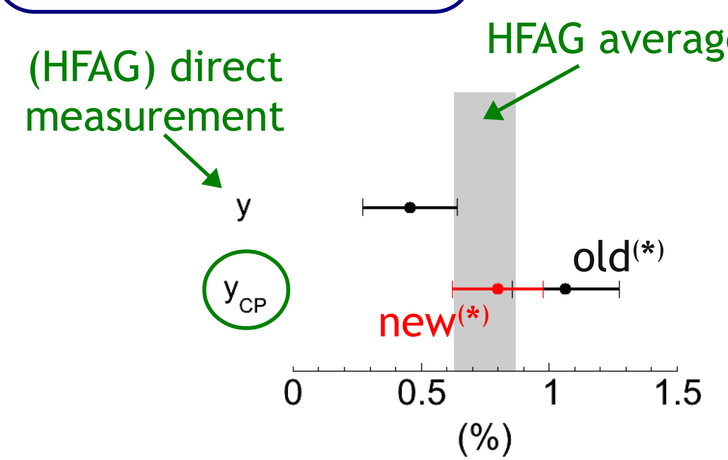
BaBar PRELIMINARY

$$y_{CP} = [0.720 \pm 0.180(\text{stat}) \pm 0.124(\text{syst})]\%$$

$$\Delta Y = [0.088 \pm 0.255(\text{stat}) \pm 0.058(\text{syst})]\%$$

- ➔ exclude no-mixing hypothesis @ 3.3σ
- ➔ no CPV observed

HFAG y averages



compatibility y vs y_{CP}: from 3% to 18%

- ➔ most precise single measurement of y_{CP};
- ➔ this result is compatible at least 2% (5%) with previous *BaBar* result [PRD 80, 071103 (2009)], considering:
  - systematic errors *fully* (63%) correlated,
  - 40% of the events in the current dataset are also present in the previous datasets (63% correlation);
- ➔ this result supersedes the previous *BaBar* results.

(*) "old" → (April 2012 HFAG average) excluding the measurement presented here
"new" → including this measurement and excluding the previous BaBar one

Conclusions

- We have measured the mixing observable y_{CP} and the CP-violating observable ΔY in a simultaneous fit to 5 signal channels;
- We observe no CP violation;
- We observe a shift of y_{CP} towards lower values, and exclude the no-mixing hypothesis at 3.3σ significance.

thank you!