Particle-Antiparticle Oscillation and CP Violation in the Neutral Charm Meson System

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Particle-antiparticle oscillation (also called mixing) and CP violation (CPV) are sensitive to Beyond the Standard Model (BSM) amplitudes as well as Standard Model amplitudes. Studies of mixing and CPV in the neutral K, $B_{(s)}$, and D meson systems probe mass scales much higher than the Higgs mass and complement direct searches for BSM physics at the LHC. This talk will provide a general introduction to the phenomenology of particle-antiparticle mixing and CPV, followed by discussions of specific measurements. The primary focus will be the study of $D^0 \to \overline{D}^0$ and $\overline{D}^0 \to D^0$ oscillations using $\sim 2.3 \times 10^5$ "wrong-sign" (WS) $K\pi$ decays and approximately 230 times more "right sign" (RS) decays. The differences of the D^0 and $\overline{D}^0$ WS/RS ratios as functions of decay time are sensitive to both direct indirect CPV. I will discuss the results themselves and bounds on CP violation when they are combined with other measurements.

Gell-Mann and Pais, Phys. Rev 97, 138 (1955)

"It is generally accepted that the microscopic laws of physics are invariant to the operation of charge conjugation (CC); we shall take the rigorous validity of this postulate for granted."

At that time, the discovery that weak interactions violate CC symmetry almost maximally was two years in the future.

Nonetheless, the essential insights from their seminal paper hold true:

- **neutral kaons are produced in strong interactions in two "opposite" flavors, as particle and antiparticle;**
- **the eigenstates of the strong interaction in which flavor is produced and the eigenstates of the weak interaction by which neutral kaons decay differ;**
- **the weak eigenstates are (approximately) equal admixtures of flavor eigenstates;**
- **the lifetimes of the weak neutral eigenstates could differ substantially, and that the "mass difference is surely tiny."**

Mixing Phenomenology

Neutral *D* mesons are produced as *flavor eigenstates* D^0 and $\bar{D}^0$ and decay via

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

as *mass, lifetime eigenstates* D_1, D_2

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

where $|q|^2 + |p|^2 = 1$ and

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

D_1, D_2 have masses M_1, M_2 and widths Γ_1, Γ_2

Mixing occurs when there is a *non-zero* mass

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

For convenience define, ***x*** and ***y***

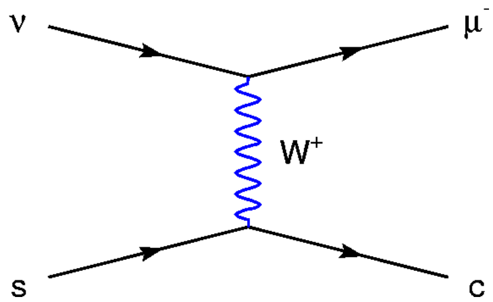
where
$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

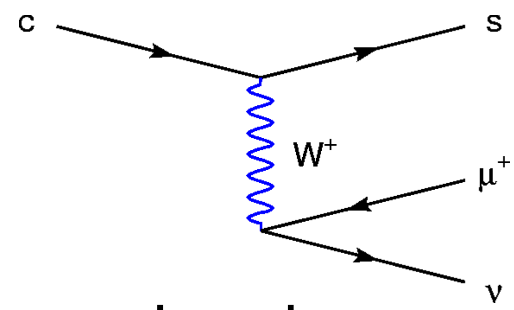
and define the mixing rate

$$R_M = \frac{x^2 + y^2}{2} \; (< 5 \times 10^{-4})$$

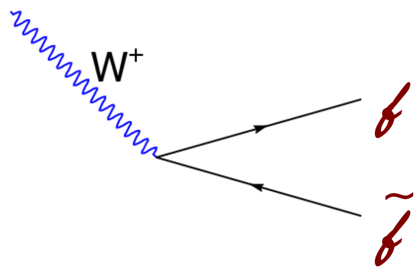
Weak Charged Current Interactions



neutrino scattering



charm decay



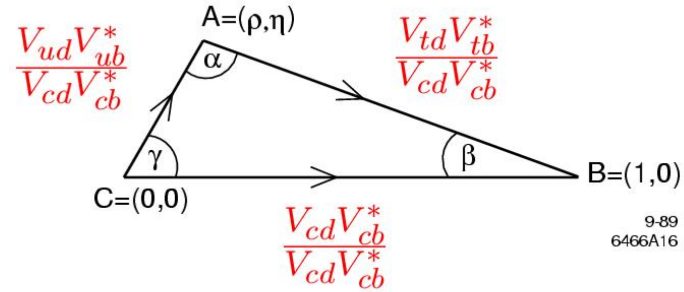
$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

As a first approximation, the weak charged current interaction couples fermions of the same generation. The Standard Model explains couplings between quark generations in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matirx.

Weak Phases in the Standard Model

The Cabibbo-Kobayashi-Maskawa (*CKM*) matrix transforms flavor eigenstates to weak eigenstates at the quark level:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$\beta = \phi_1;\ \alpha = \phi_2;\ \gamma = \phi_3$

The *CKM* matrix should be unitary:

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

$$e.g., \quad V_{ub}V^*_{ud} + V_{cb}V^*_{cd} + V_{tb}V^*_{td} = 0$$

In the Wolfenstein parameterization:

$$V_W = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Charm Meson Mixing

Why is observing charm mixing interesting?

- It *completes the picture* of quark mixing already seen in the K, B_d, and B_s systems.
  - K — PR 103, 1901 (1956); PR 103, 1904 (1956).
  - B_d — PL B186, 247 (1987); PL B192, 245 (1987).
  - B_s — PRL 97, 021802 (2006); PRL 97, 242003 (2006).
- In the Standard Model, it relates to processes with *down-type quarks* in the mixing loop diagram.

- Mixing, *itself*, could indicate *new physics*.
- It is a significant step toward observation of *CP violation* in the charm sector, a clear indication of *new physics*

Standard Model Mixing Predictions
(mostly 20th century)

Box diagram SM charm mixing rate naively expected to be very low (R_M~10^{-10}) (Datta & Kumbhakar)

Z.Phys. **C27**, 515 (1985)

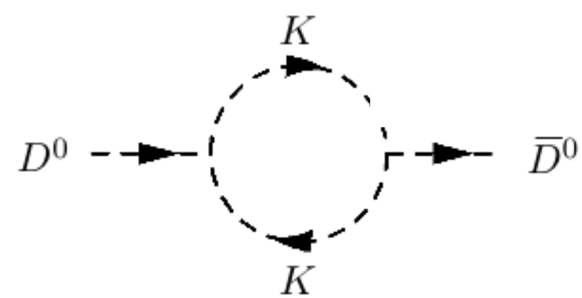
- CKM suppression → $|V_{ub}V^*_{cb}|^2$
- GIM suppression → $(m^2_s-m^2_d)/m^2_W$
- Di-penguin mixing, R_M~10^{-10}

Phys. Rev. D **56**, 1685 (1997)

Enhanced rate SM calculations generally due to long-distance contributions:

- first discussion, L. Wolfenstein

Phys. Lett. B **164**, 170 (1985)



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Partial History of Long-Distance Calculations

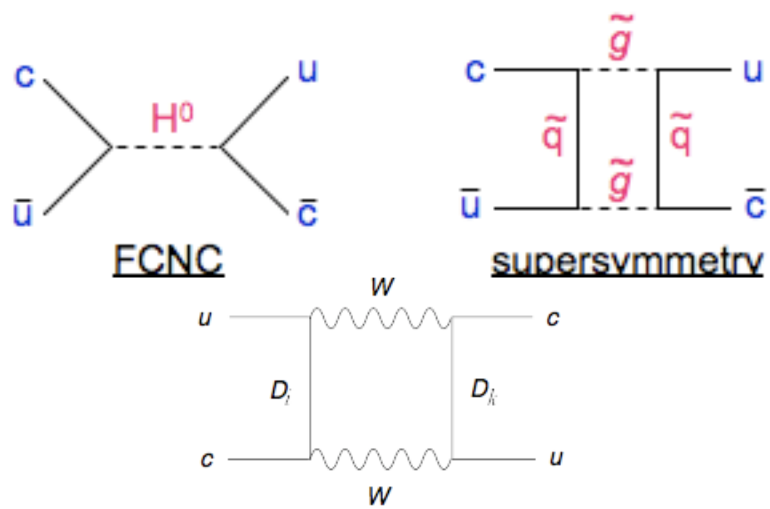
- Early SM calculations indicated long distance contributions produce $x \ll 10^{-2}$:
  - $x \sim 10^{-3}$ (dispersive sector)
    - PRD **33**, 179 (1986)
  - $x \sim 10^{-5}$ (HQET)
    - Phys. Lett. B **297**, 353 (1992)
    - Nucl. Phys. **B403**, 605 (1993)
- More recent SM predictions can accommodate x, y ~1% [of opposite sign] (Falk *et al.*)
  - $x,y \approx \sin^2\theta_C \times [SU(3)\text{ breaking}]^2$
    - Phys.Rev. D **65**, 054034 (**2002**)
    - Phys.Rev. D **69**, 114021 (**2004**)

New Physics Mixing Predictions
(possible 21st century physics)

Possible enhancements to mixing due to new particles and interactions in new physics models

Most new physics predictions for x

- Extended Higgs, tree-level FCNC
- Fourth generation down-type quarks
- Supersymmetry: gluinos, squarks
- Lepto-quarks



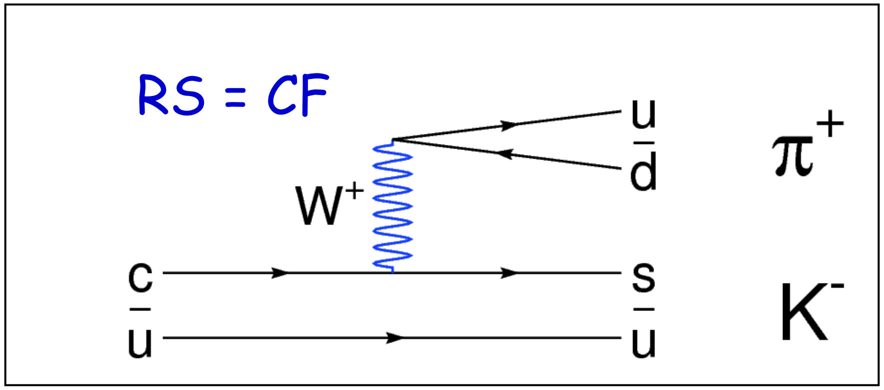
Heavy weak iso-singlet quarks

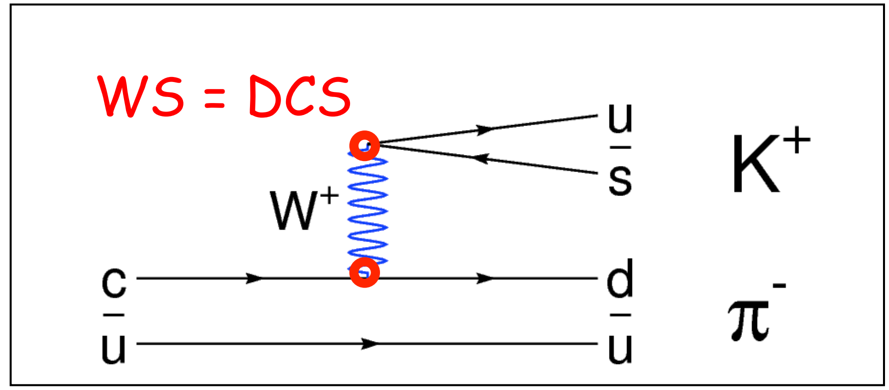
- Large possible SM contributions to mixing require observation of either a CP-violating signal or | x | >> | y | to establish presence of NP
- A relatively recent survey (Phys. Rev. D76, 095009 (2007), [et al. & Petrov]) summarizes models and constraints:

Fourth generation	Vector leptoquarks
Q = -1/3 singlet quark	Flavor-conserving Two-Higgs
Q = +2/3 singlet quark	Flavor-changing neutral Higgs
Little Higgs	Scalar leptoquarks
Generic Z’	MSSM
Left-right symmetric	Supersymmetric alignment

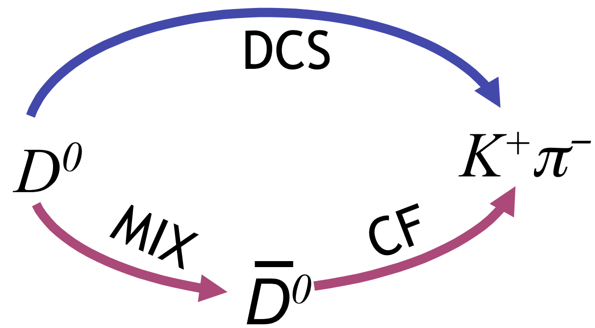
and more

Time-Evolution of $D^0 \to K\pi$ Decays





DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}\,y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$

where $x' = x\cos\delta + y\sin\delta$ $\quad y' = y\cos\delta - x\sin\delta$

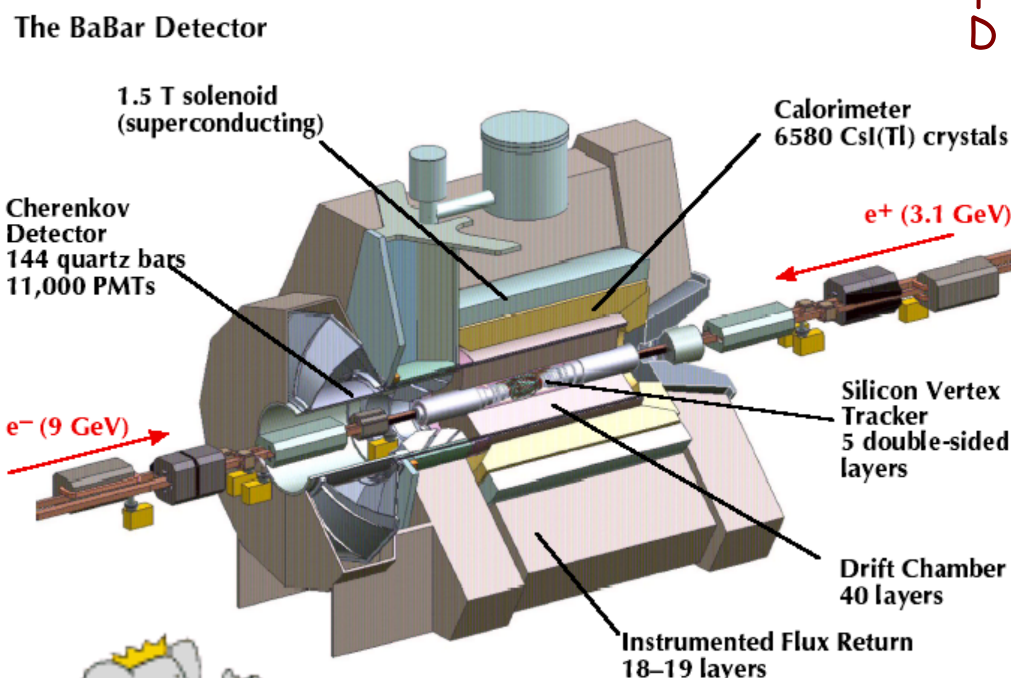
and δ is the phase difference between DCS and CF decays.

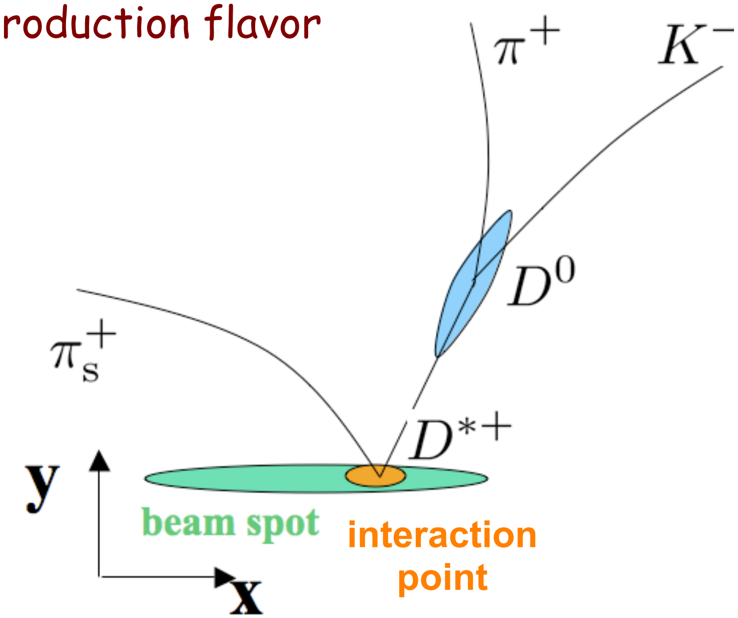
$D^0 \rightarrow K\pi$ Reconstruction

384 fb^{-1} $e^+e^- \rightarrow c,\bar{c}$

$$D^{*\pm} \rightarrow \pi_s^{\pm} D^0,\ D^0 \rightarrow K^{\mp}\pi^{\pm}$$

Slow pion charge tags neutral
D production flavor





Typical D^0 flight length $d \sim 240\ \mu m$
Average resolution $\sigma_d \sim 95\ \mu m$

Beam spot:
$\sigma_x \approx$ 100 μm
$\sigma_y \approx$ 7 μm

Full Fit Procedure

Unbinned maximum likelihood fit in several steps
(fitting 1+ million events takes a long time)

Fit to m(Kπ) and Δm distribution:

- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

Fit RS decay time distribution:

- Determines D^0 lifetime and resolution function
- Include event-by-event decay time error δt in resolution
- Use m(Kπ) and Δm to separate signal/bkgd (fixed shapes)

Fit WS decay time distribution:

- Use D^0 lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)

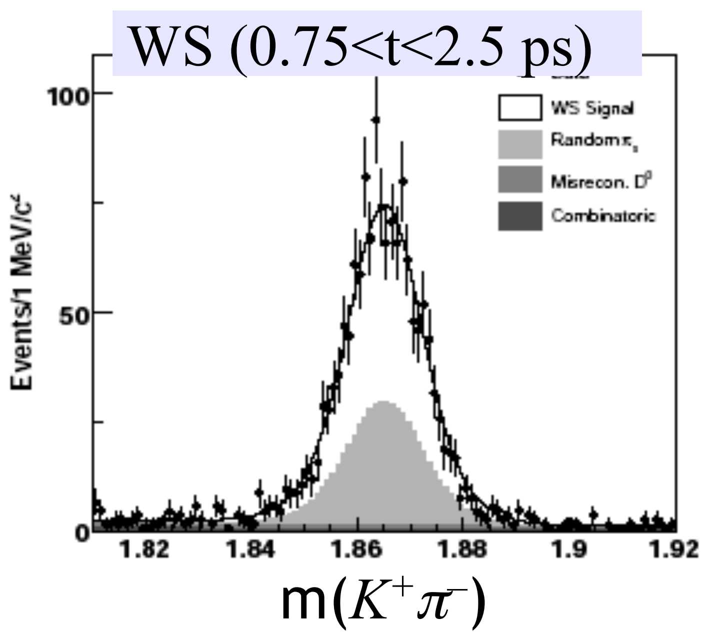
Simplified Fit Strategy & Validation

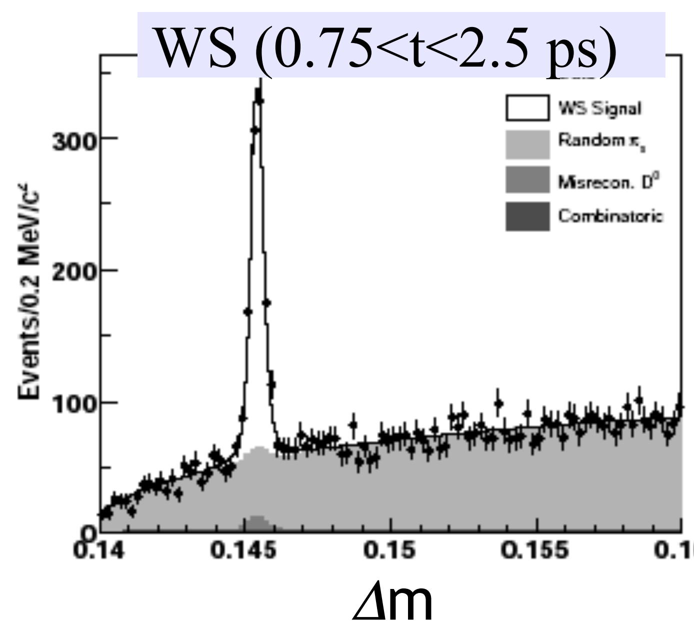
<u>Fit m(Kπ) and Δm in bins of time:</u>

- If no mixing, ratio of WS to RS signal should be constant
- No assumptions made on time evolution of background
- Each time bin is fit independently

Time bins:

$-2 < t < 0$ psec
$0 < t < 0.2$ psec
$0.2 < t < 0.4$ psec
$0.4 < t < 0.75$ psec
$0.75 < t < 2.5$ psec

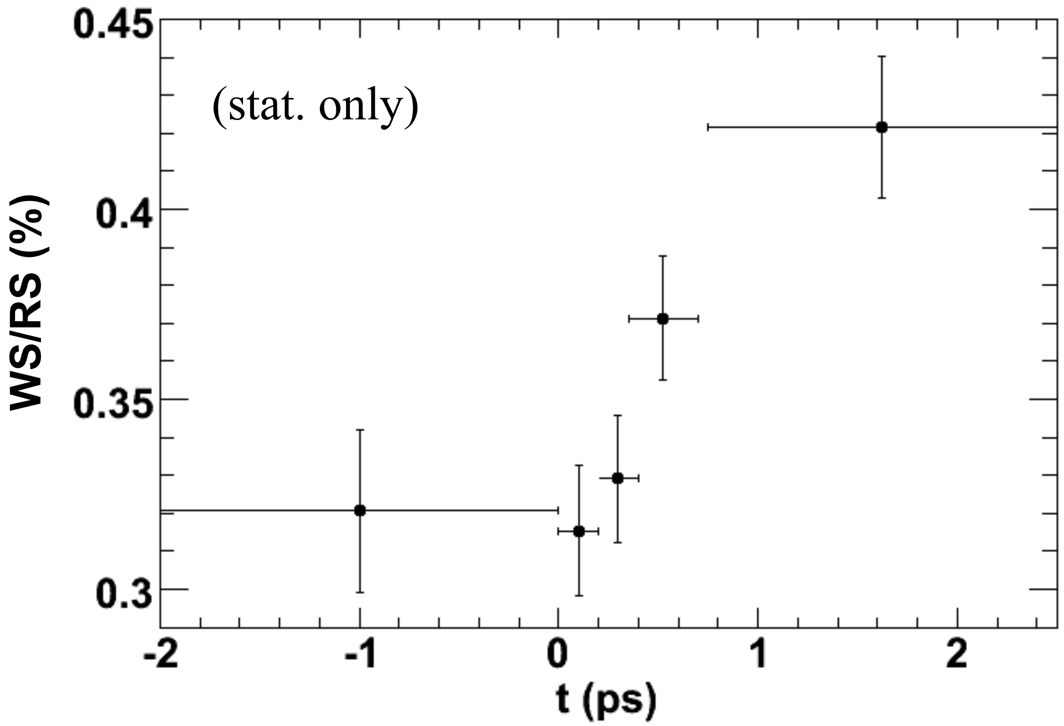




Simplified Fit Strategy & Validation

Rate of WS events clearly increases with time:

$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$



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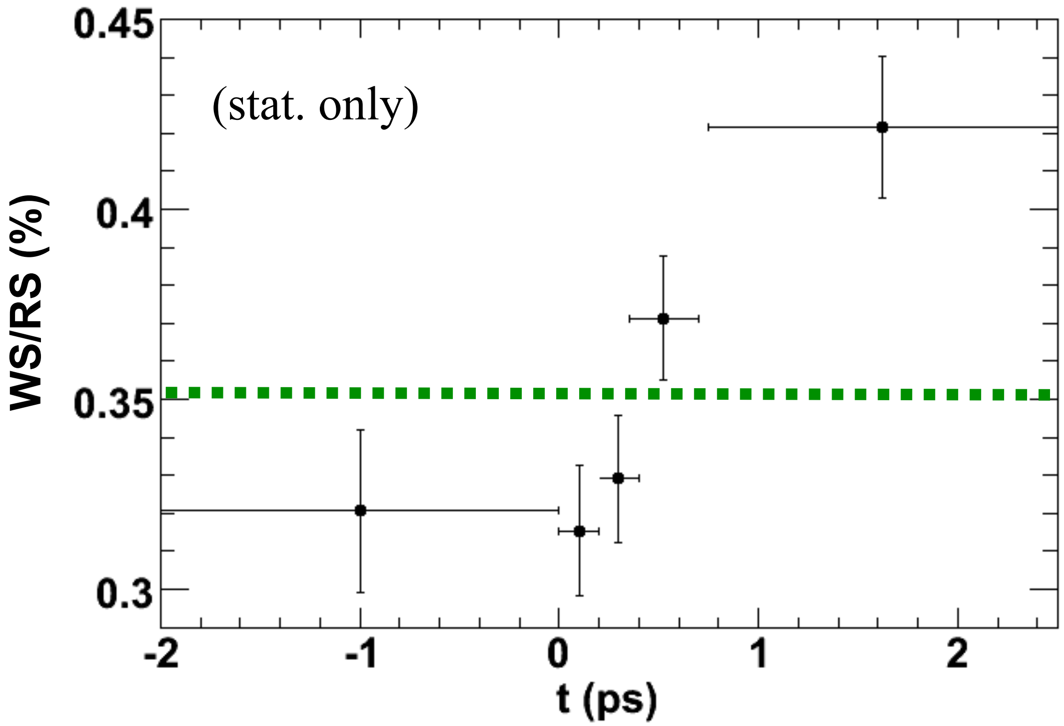

Inconsistent with no-mixing hypothesis: χ^2=24

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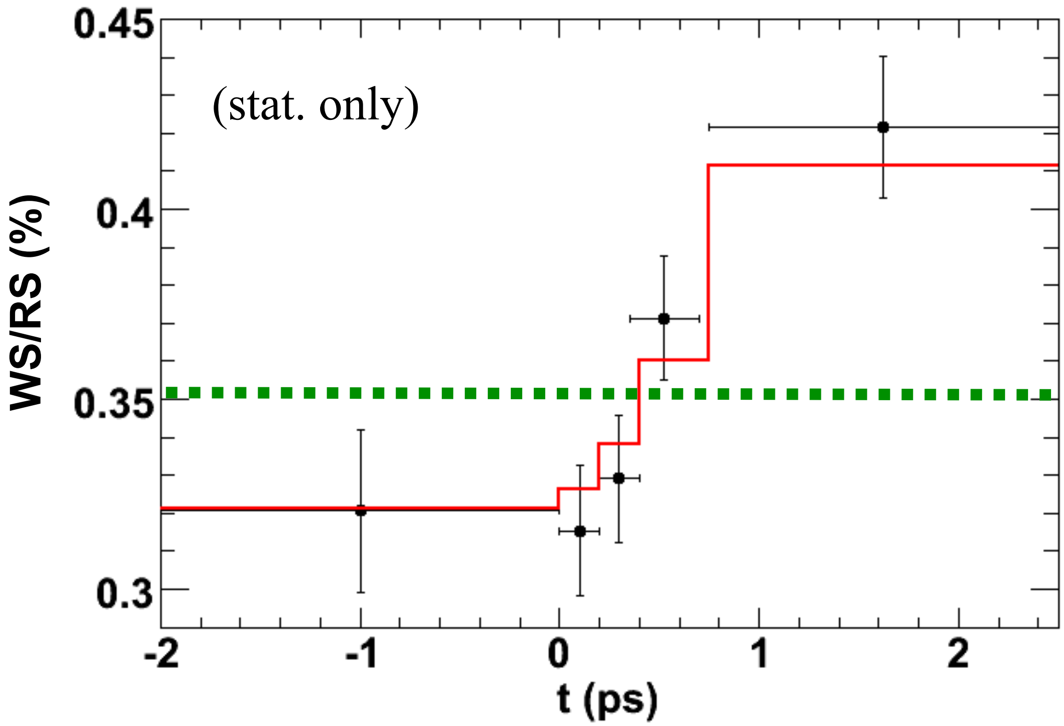
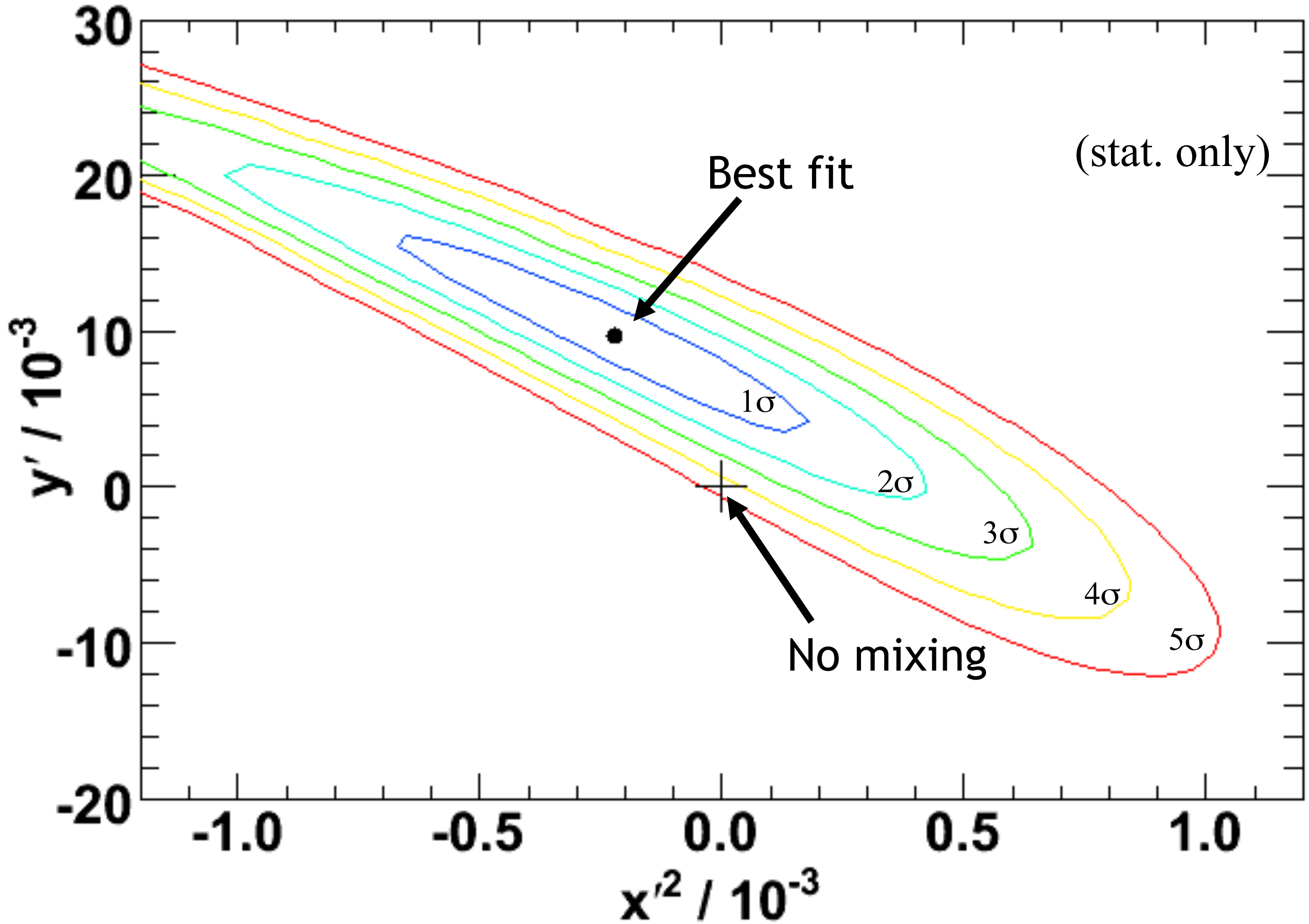


Consistent with prediction from full likelihood fit
χ^2=1.5

Inconsistent with no-mixing hypothesis:
χ^2=24

Signal Significance

Significance calculated from change in log likelihood:



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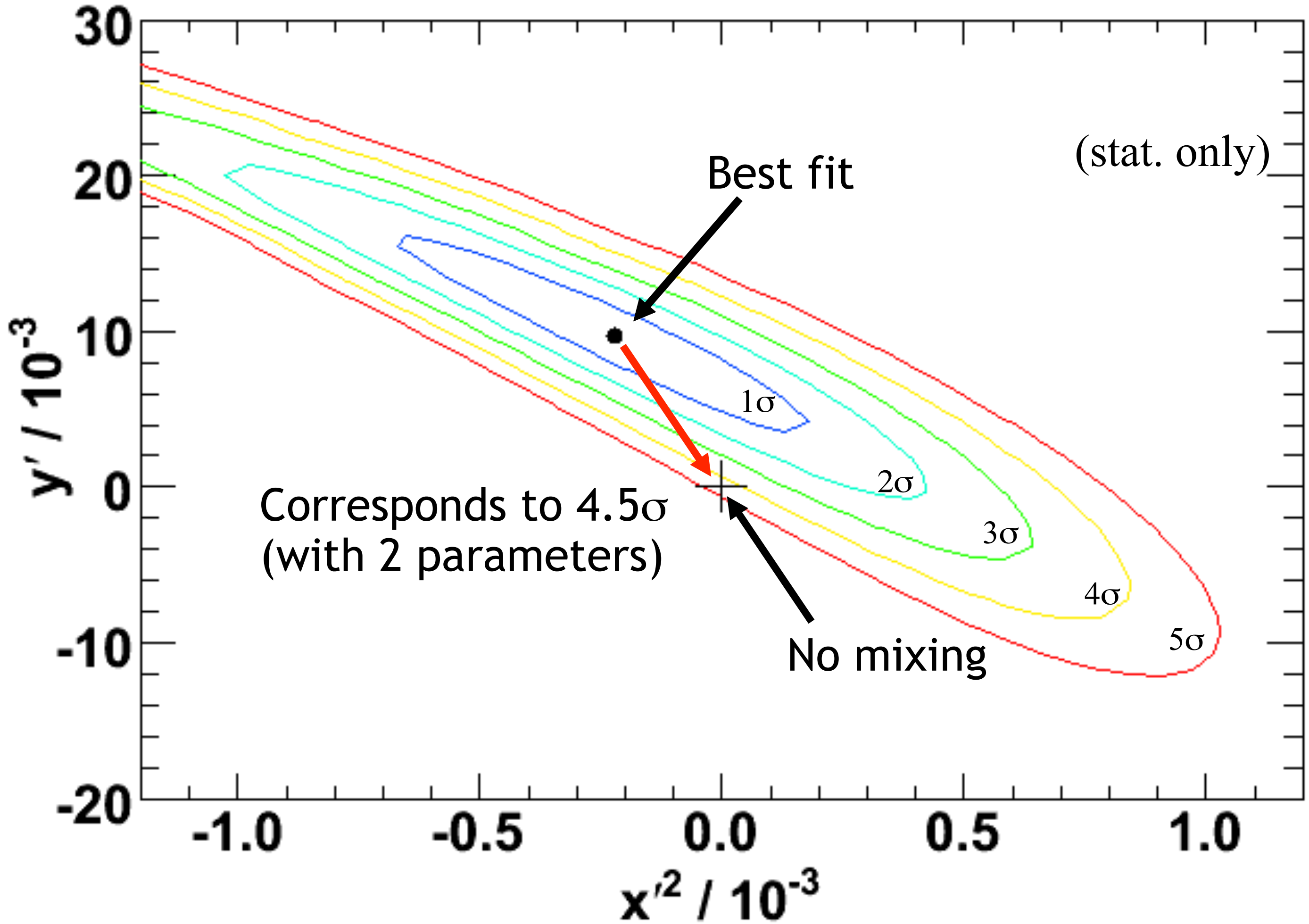
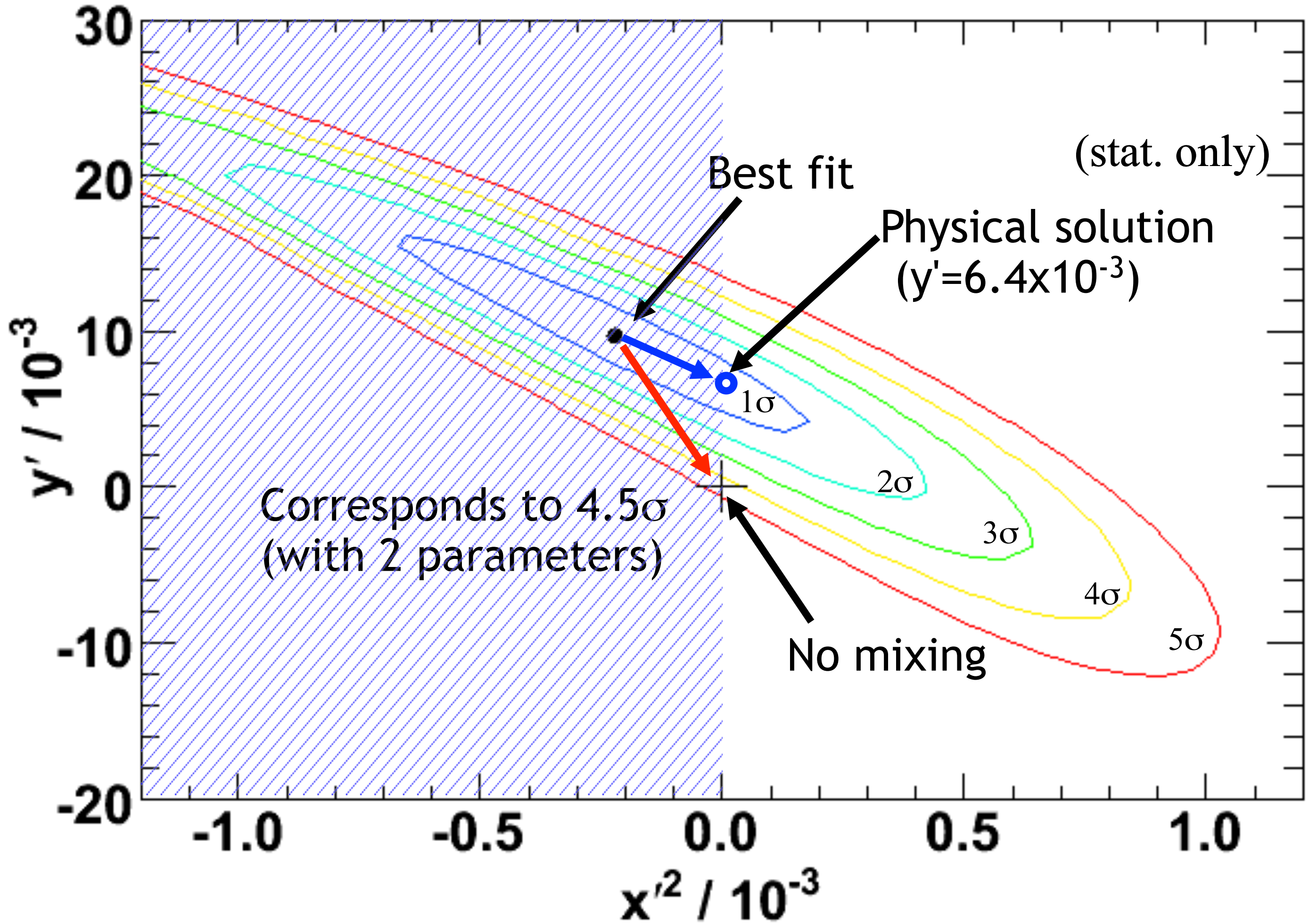


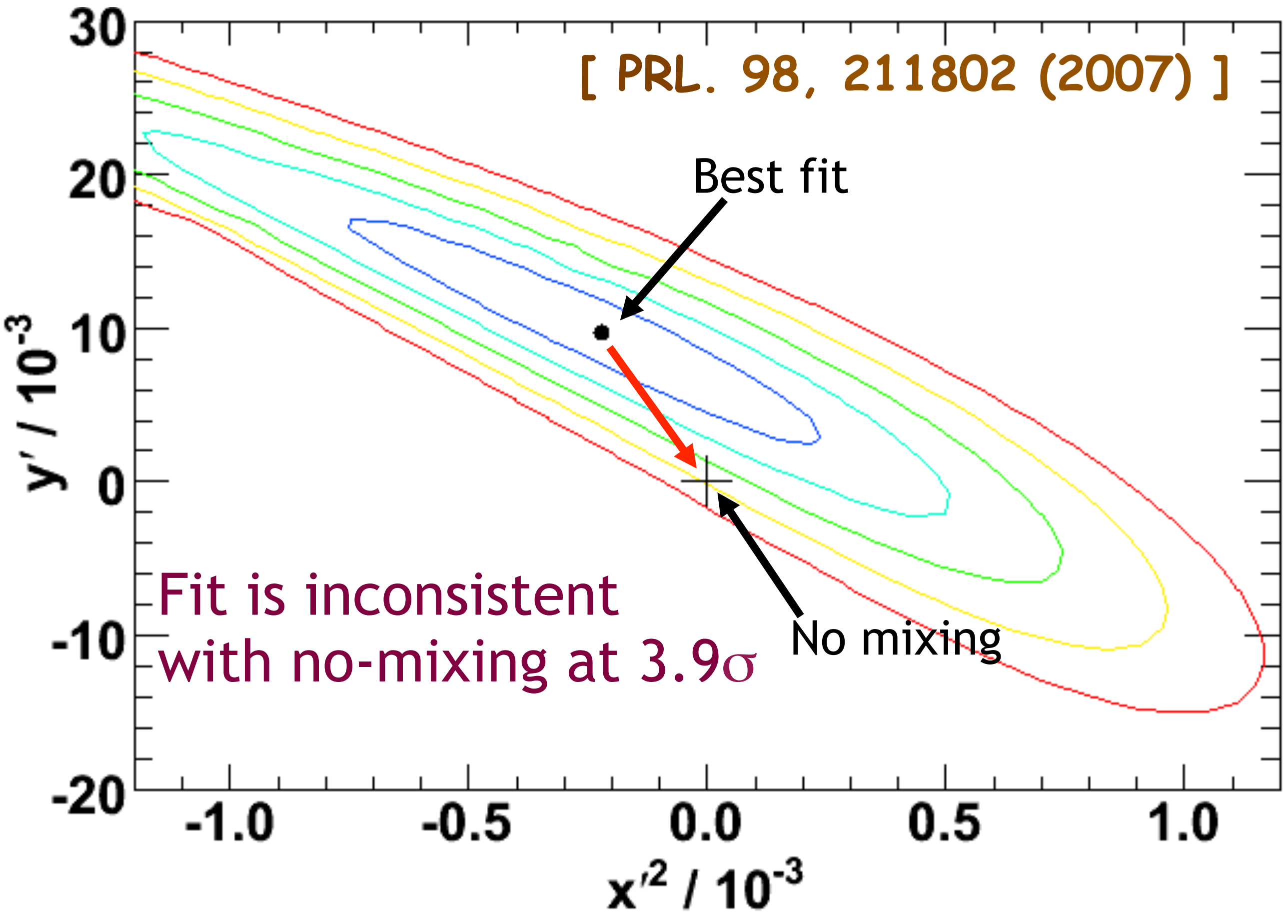
Signal Significance

Best fit is in unphysical region ($x'^2<0$)

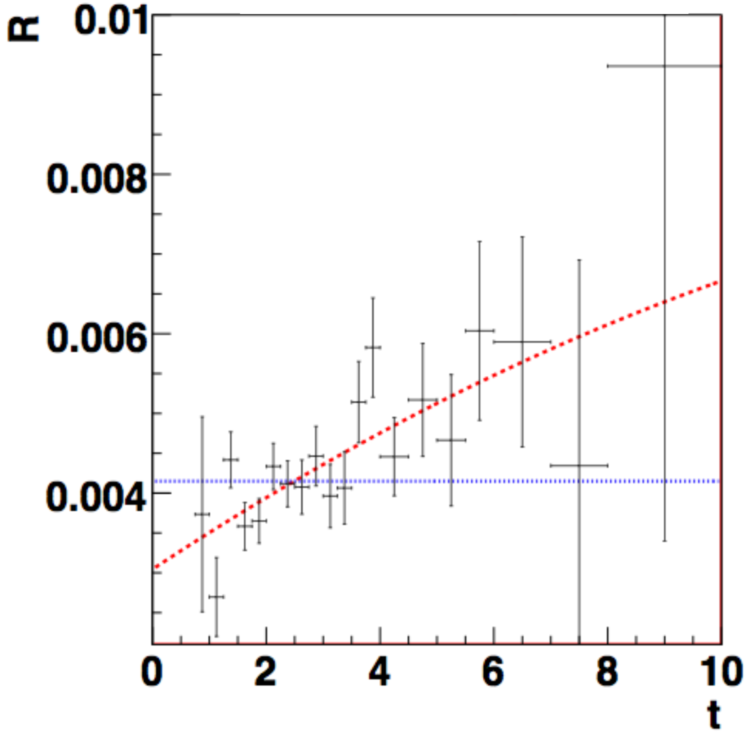


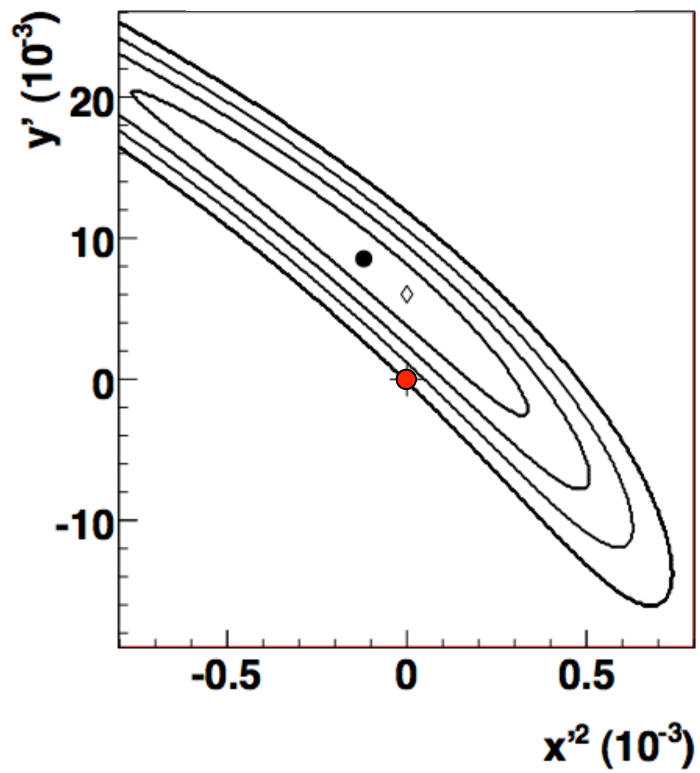
Signal Significance with Systematics

Including systematics (~ 0.7 x stat)
decreases signal significance



1.5 fb^{-1} $K\pi$ Mixing Results from CDF
[arXiv:0712.1567 (fall 2007) & PRL 100, 121802 (2008)]





Best fit for mixing parameters (uncertainties are combined stat. and systematic)

- Fit χ^2 = 19.2 for 17 dof
- 3.8 σ from Null Hypothesis

R_D: $(3.04 \pm 0.55) \times 10^{-3}$

x'^2: $(-0.12 \pm 0.35) \times 10^{-3}$

y' : $(8.5 \pm 7.6) \times 10^{-3}$

First Evidence for $\Delta\Gamma \neq 0$ in $D^0 \to h^+h^-$

[Belle: PRL. 98, 211803 (2007)]

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle \ ,$$
$$|p|^2 + |q|^2 = 1$$

$$r_m \equiv \left|\frac{q}{p}\right| \quad \text{and} \quad \varphi_f \equiv \arg\left(\frac{q\,\overline{A}_f}{p\,A_f}\right) \ ,$$

- $r_m \neq 1 \Rightarrow CP$ violation in mixing.
- non-zero $\varphi_f \Rightarrow CP$ violation in the interference of mixing and decay amplitudes.

To a good approximation, D^0 and $\overline{D}^0$ mesons decay into specific CP eigenstates (even for K^-K^+ and $\pi^-\pi^+$) with effective lifetimes

$$\tau^+_{hh} = \tau_{K\pi}\left[1 + r_m\left(y\cos\varphi_f - x\sin\varphi_f\right)\right]^{-1}$$
$$\tau^-_{hh} = \tau_{K\pi}\left[1 + r_m^{-1}\left(y\cos\varphi_f + x\sin\varphi_f\right)\right]^{-1} \ .$$

These effective lifetimes can be combined into

$$y_{CP} = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} - 1 \ , \quad \to y \text{ for } r_m = 1,\ \varphi_f = 0$$

$$\Delta Y = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} A_\tau \ , \quad A_\tau \equiv \frac{(\tau^+_{hh} - \tau^-_{hh})}{(\tau^+_{hh} + \tau^-_{hh})}$$

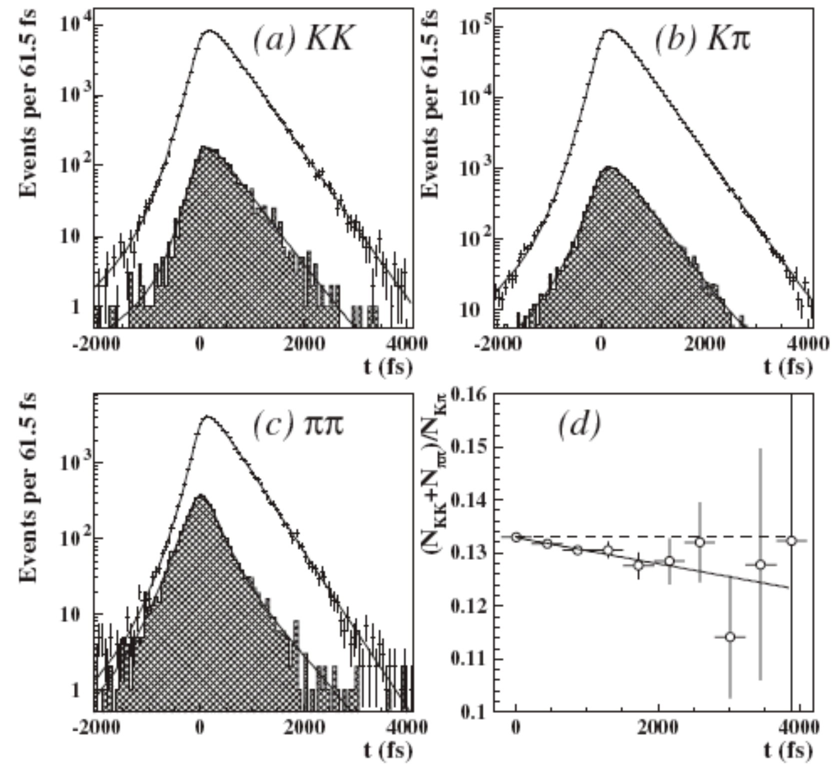


FIG. 2. Results of the simultaneous fit to decay-time distributions of (a) $D^0 \to K^+K^-$, (b) $D^0 \to K^-\pi^+$, and (c) $D^0 \to \pi^+\pi^-$ decays. The cross-hatched area represents background contributions, the shape of which was fitted using M sideband events. (d) Ratio of decay-time distributions between $D^0 \to K^+K^-$, $\pi^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The solid line is a fit to the data points.

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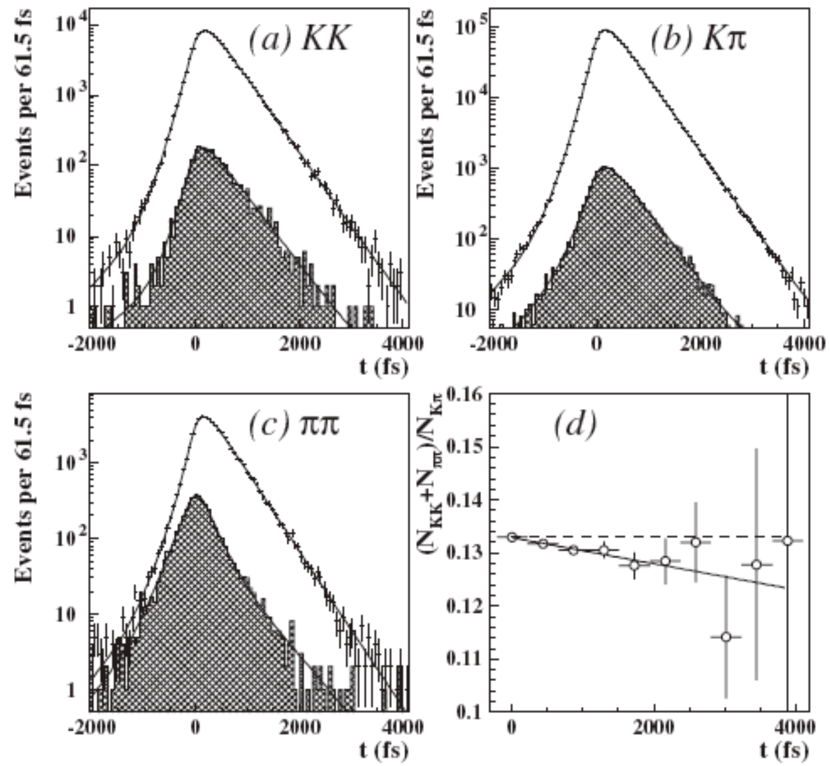
[Belle: PRL. 98, 211803 (2007)]



$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$

540 fb^{-1}

Adding Babar's $D^0 \rightarrow h^+h^-$ Results

[arXiv:0712.2249 (Dec 2007) & PRD 78, 011105(R) (2008)]

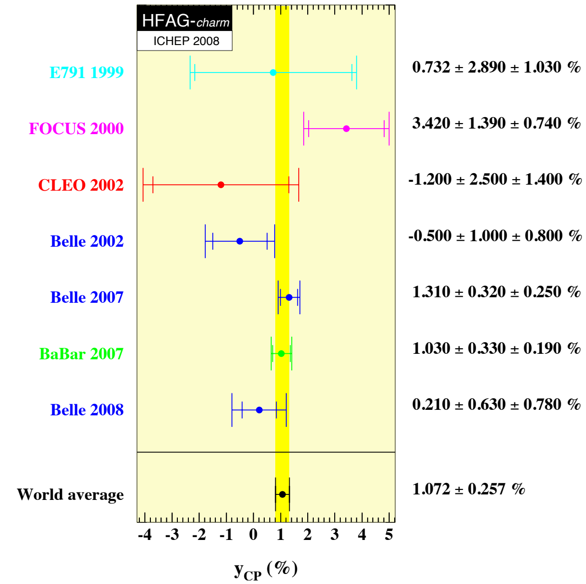
Babar's results from 384 fb^{-1}

	y_{CP} [%]	ΔY [%]
K^+K^-	$1.60 \pm 0.46 \pm 0.17$	$-0.40 \pm 0.44 \pm 0.12$
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$

Combining KK and $\pi\pi$ results gives

$y_{CP} = (1.24 \pm 0.39 \pm 0.13)\%$

CP violation consistent with zero.



my private fall 2007 y_{CP} average

BaBar	Tagged (384 fb^{-1})	$(1.24 \pm 0.39 \pm 0.13)\%$
BaBar	Untagged (91 fb^{-1})	$(0.2 \pm 0.4 \pm 0.5)\%$
BaBar	Combined	$(0.94 \pm 0.35)\%$
Belle	Tagged	$(1.31 \pm 0.32 \pm 0.25)\%$
BaBar + Belle	Combined	$(1.10 \pm 0.27)\%$

Mixing in $D^0 \to K_S\pi^+\pi^-$
[Phys.Rev.Lett.99:131803,2007]

The decay amplitude at time t of an initially produced $|D^0\rangle$ or $|\overline{D}^0\rangle$ can be expressed as

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

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

The time dependence is contained in the terms

$$e_{1,2}(t) = \exp[-i(m_{1,2} - i\Gamma_{1,2}/2)t].$$

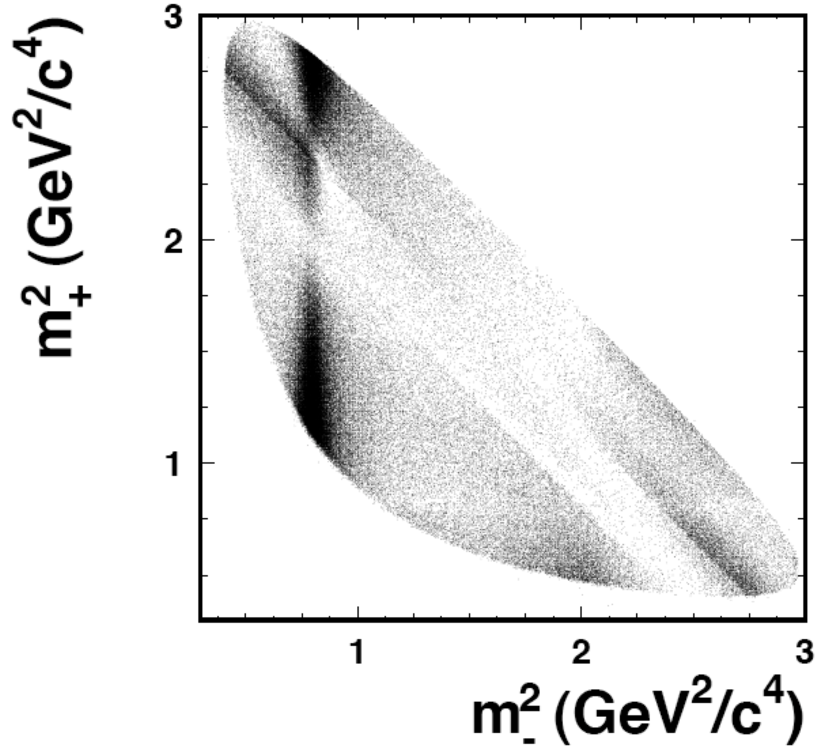
Upon squaring $\mathcal{M}$ and $\overline{\mathcal{M}}$, one obtains decay rates containing terms $\exp(-\Gamma t)\cos(x\Gamma t)$, $\exp(-\Gamma t)\sin(x\Gamma t)$, and $\exp[-(1 \pm y)\Gamma t]$.

Each amplitude is a function of m_+^2 and m_-^2, expressed as a sum of quasi-two-body amplitudes (subscript r) and a constant non-resonant term (subscript NR):

$$\mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_-^2, m_+^2) + a_{\rm NR}e^{i\phi_{\rm NR}}$$

$$\overline{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \overline{a}_r e^{i\overline{\phi}_r}\mathcal{A}_r(m_+^2, m_-^2) + \overline{a}_{\rm NR}e^{i\overline{\phi}_{\rm NR}}$$

The $\mathcal{A}_r$ are products of Blatt-Weisskopf form factors and relativistic Breit-Wigner functions.

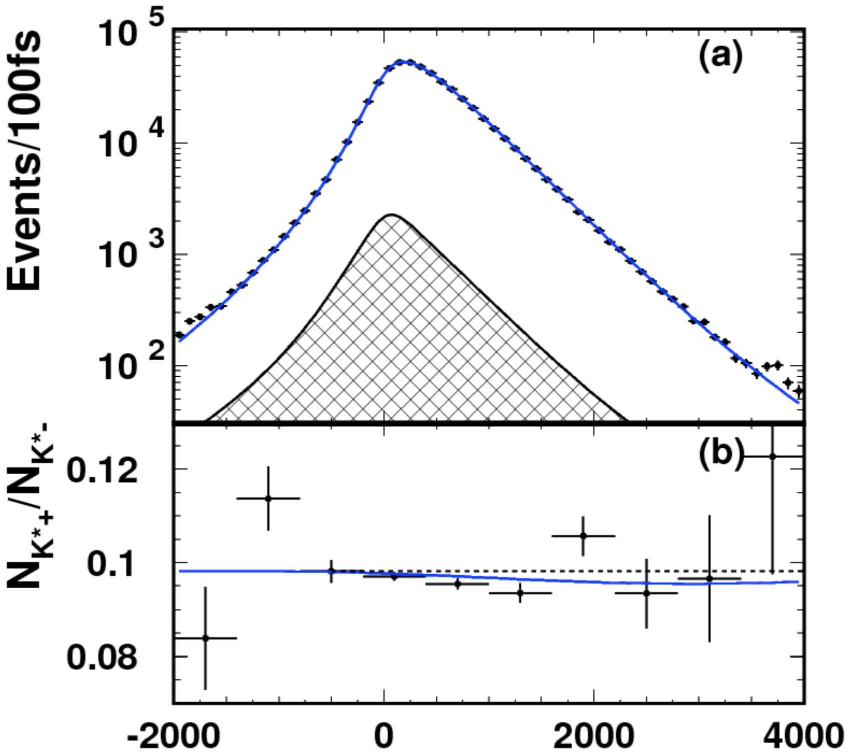


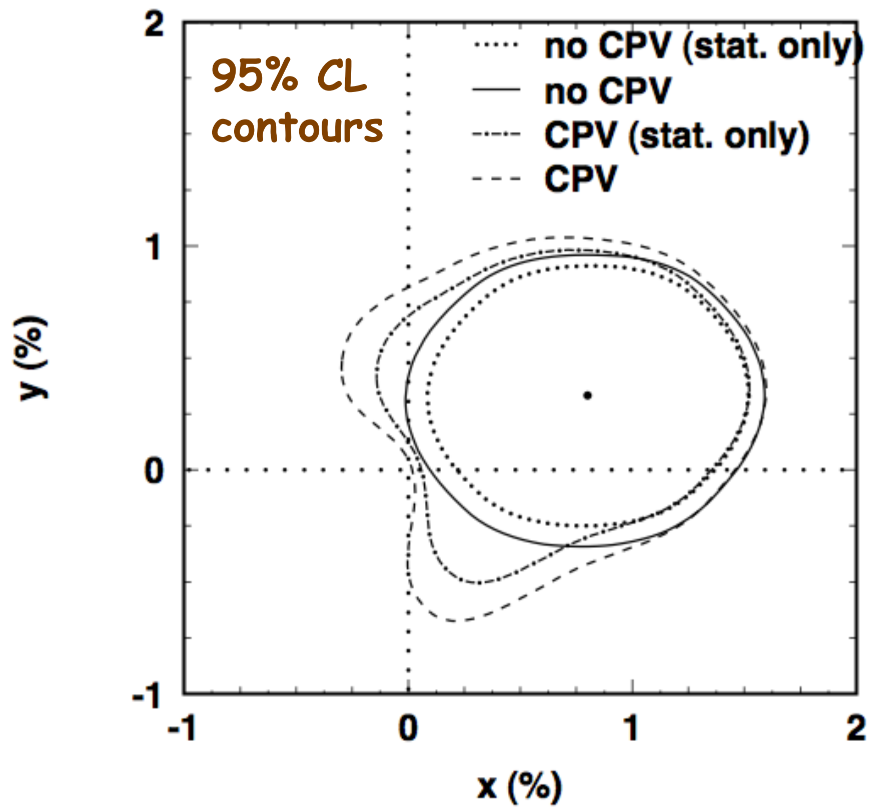
Mixing in $D^0 \rightarrow K_S\pi^+\pi^-$

x : $(0.80 \pm 0.35 \pm 0.15)\%$

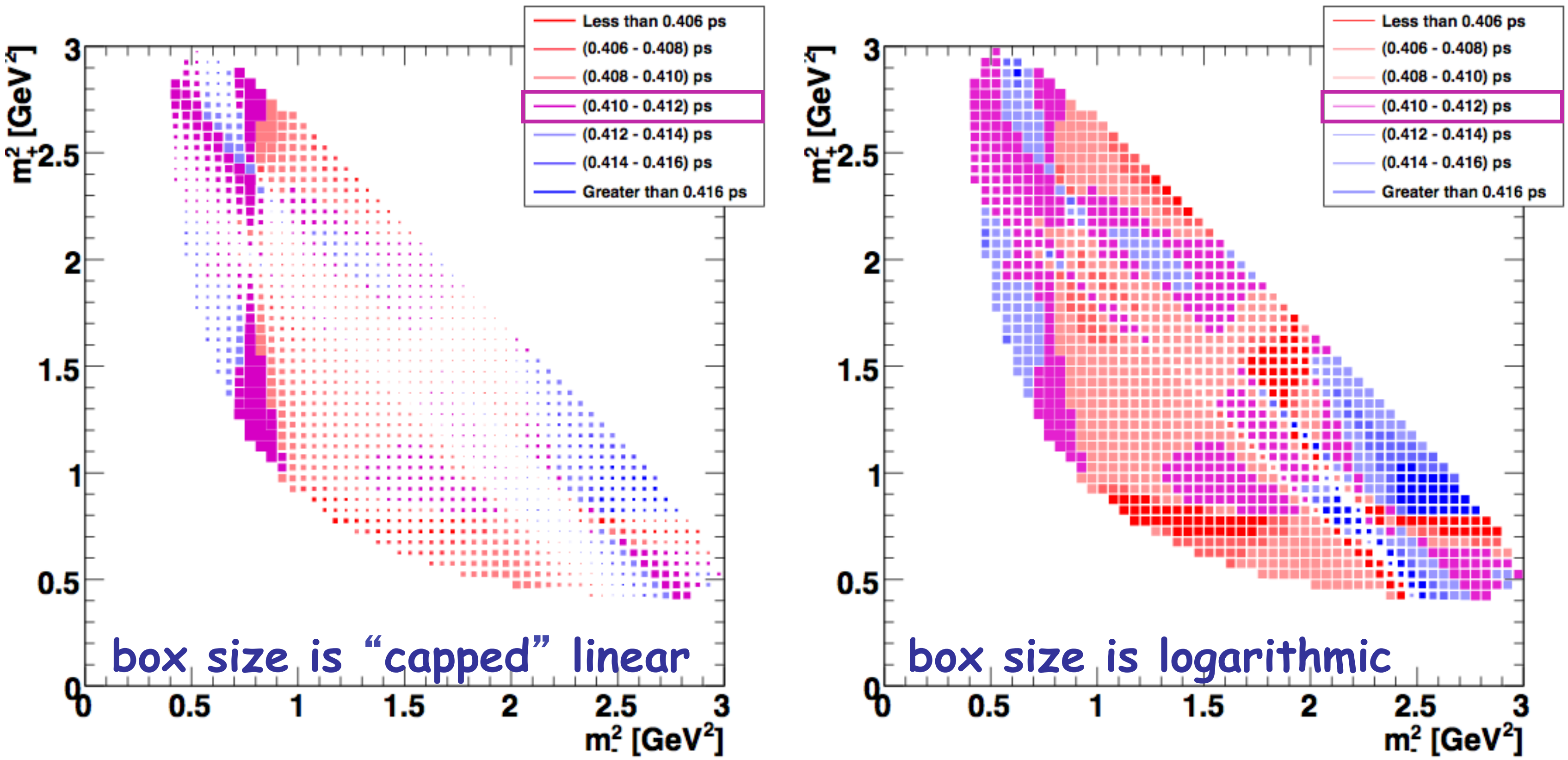
y : $(0.33 \pm 0.24 \pm 0.14)\%$

(assuming no CP violation)



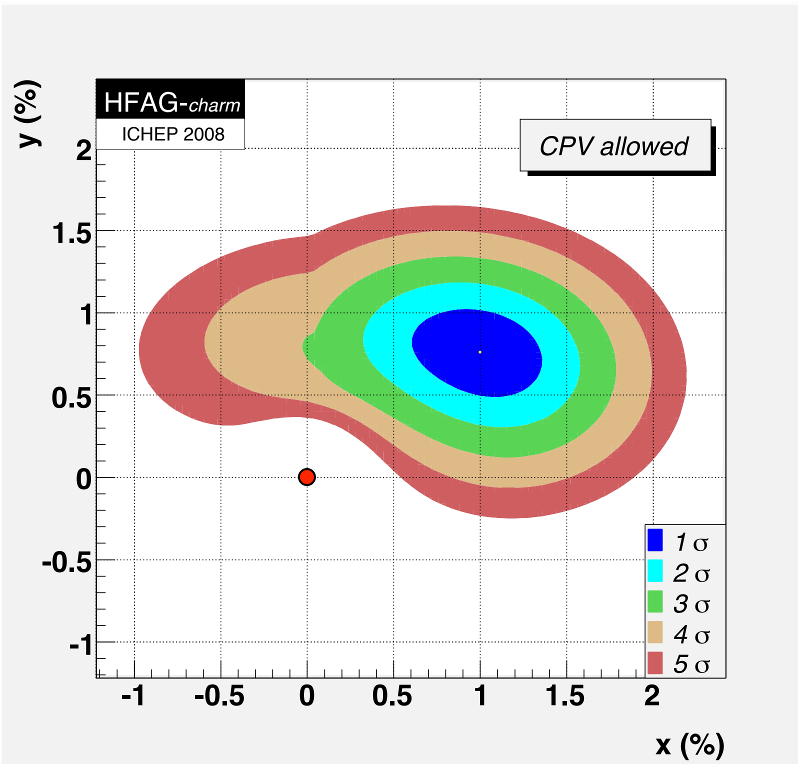


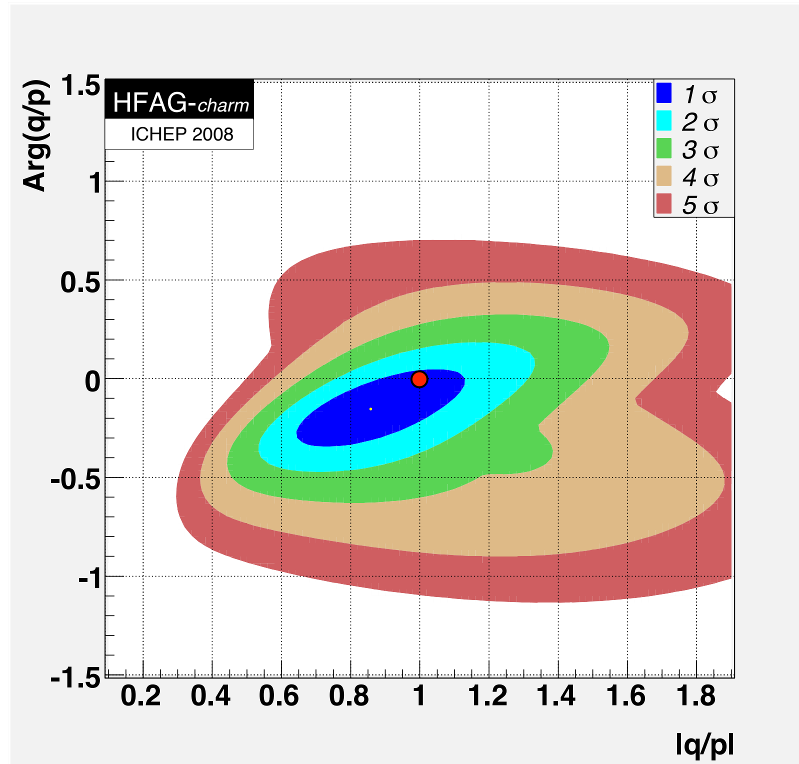
Time-Dependence in $D^0 \to K_S\pi^+\pi^-$



Τηεσε plots illustrate the average decay time as a function of position in the Dalitz plot for (x,y) = (0.8%, 0.3%). The sizes of the boxes reflect the number of entries, and the colors reflect the average decay time.

Mixing Well Established by Summer 2008





CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 = 102.6$, CL = 5.3×10^{-23}, no mixing excluded at 9.8σ

No CPV (|q/p|, φ) = (1,0) point: $\Delta\chi^2 = 1.33$, CL = 0.486 , consistent with CP conservation

$SU(3)$ Breaking and D^0-$\overline{D}^0$ mixing

Falk, Grossman, Ligeti, and Petrov; Phys. Rev D65, 054034 (2002)

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | \mathcal{H}_w | n \rangle \langle n | \mathcal{H}_w | \overline{D}^0 \rangle + \langle \overline{D}^0 | \mathcal{H}_w | n \rangle \langle n | \mathcal{H}_w | D^0 \rangle \right]$$

$$y = \sum_n \eta_{\rm CKM}(n)\, \eta_{CP}(n)\ \cos\delta_n \sqrt{(\mathcal{B}(D^0 \to n)\, \mathcal{B}(\overline{D}^0 \to n)}$$

- δ_n is the strong phase difference between the $D^0 \to n$ and $\overline{D}^0 \to n$ amplitudes
- $\eta_{\rm CKM} = (-1)^{n_s}$, where n_s is the number of s and $\overline{s}$ quarks in the final state.
- $CP|f\rangle = \eta_{CP}|\overline{f}\rangle$, well-defined as $|f\rangle$, $|\overline{f}\rangle$ in the same $SU(3)$ multiplet

$$y = \sum_a y_a\,, \qquad y_a = \eta_{CP}(a) \sum_{n \in a} \eta_{\rm CKM}(n) \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\, \mathcal{B}(\overline{D}^0 \to n)}$$

$$y_{\pi K} = \mathcal{B}(D^0 \to \pi^+\pi^-) + \mathcal{B}(D^0 \to K^+K^-)$$
$$- 2\cos\delta_{K\pi} \sqrt{\mathcal{B}(D^0 \to K^-\pi^+)\, \mathcal{B}(D^0 \to K^+\pi^-)}$$

$$y_{\pi K} \approx (5.76 - 5.29\cos\delta_{K\pi}) \times 10^{-3}$$

$SU(3)$ Breaking and D^0-$\overline{D}^0$ mixing

Falk, Grossman, Ligeti, and Petrov; Phys. Rev D65, 054034 (2002)

Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
PP	8	-0.0038	-0.018
	27	-0.00071	-0.0034
PV	8_S	0.031	0.15
	8_A	0.032	0.15
	10	0.020	0.10
	$\overline{10}$	0.016	0.08
	27	0.040	0.19
$(VV)_{s\text{-wave}}$	8	-0.081	-0.39
	27	-0.061	-0.30
$(VV)_{p\text{-wave}}$	8	-0.10	-0.48
	27	-0.14	-0.70
$(VV)_{d\text{-wave}}$	8	0.51	2.5
	27	0.57	2.8

Values of $y_{F,R}$ for two-body final states. This represents the value which y would take if elements of F_R were the only channel open for D^0 decay.

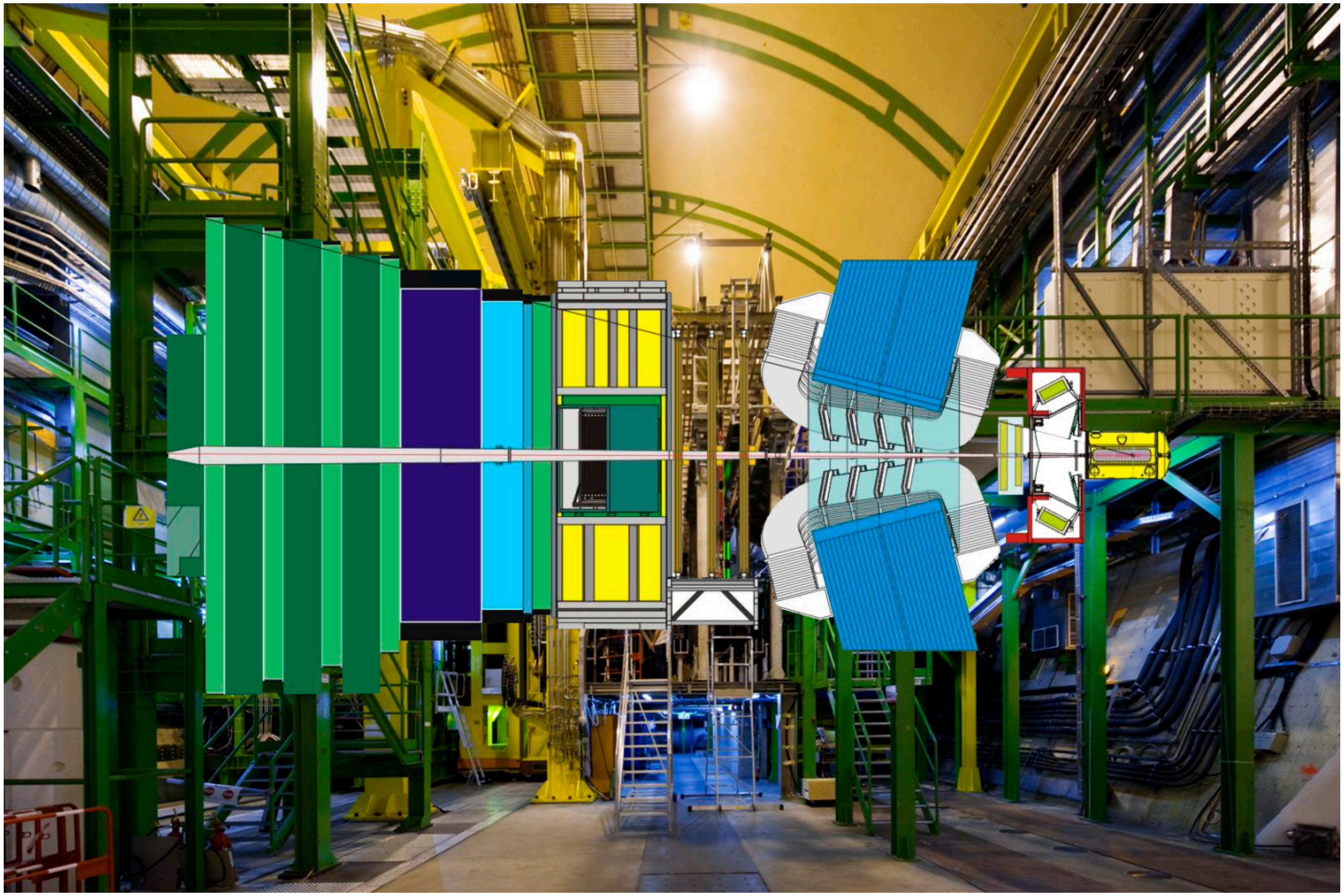
Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
$(3P)_{s\text{-wave}}$	8	-0.48	-2.3
	27	-0.11	-0.54
$(3P)_{p\text{-wave}}$	8	-1.13	-5.5
	27	-0.07	-0.36
$(3P)_{\text{form-factor}}$	8	-0.44	-2.1
	27	-0.13	-0.64
$4P$	8	3.3	16
	27	2.2	9.2
	27′	1.9	11

Values of $y_{F,R}$ for three- and four-body final states.

"On the basis of this analysis, in particular as applied to the $4P$ final state, we would conclude that y on the order of a percent would be completely natural. Anything an order of magnitude smaller would require significant cancellations which do not appear naturally in this framework. Cancellations would be expected only if they were enforced by the OPE, that is, if the charm quark were heavy enough that the "inclusive" approach were applicable. The hypothesis underlying the present analysis is that this is not the case."

Fast Forward to Charm at LHCb

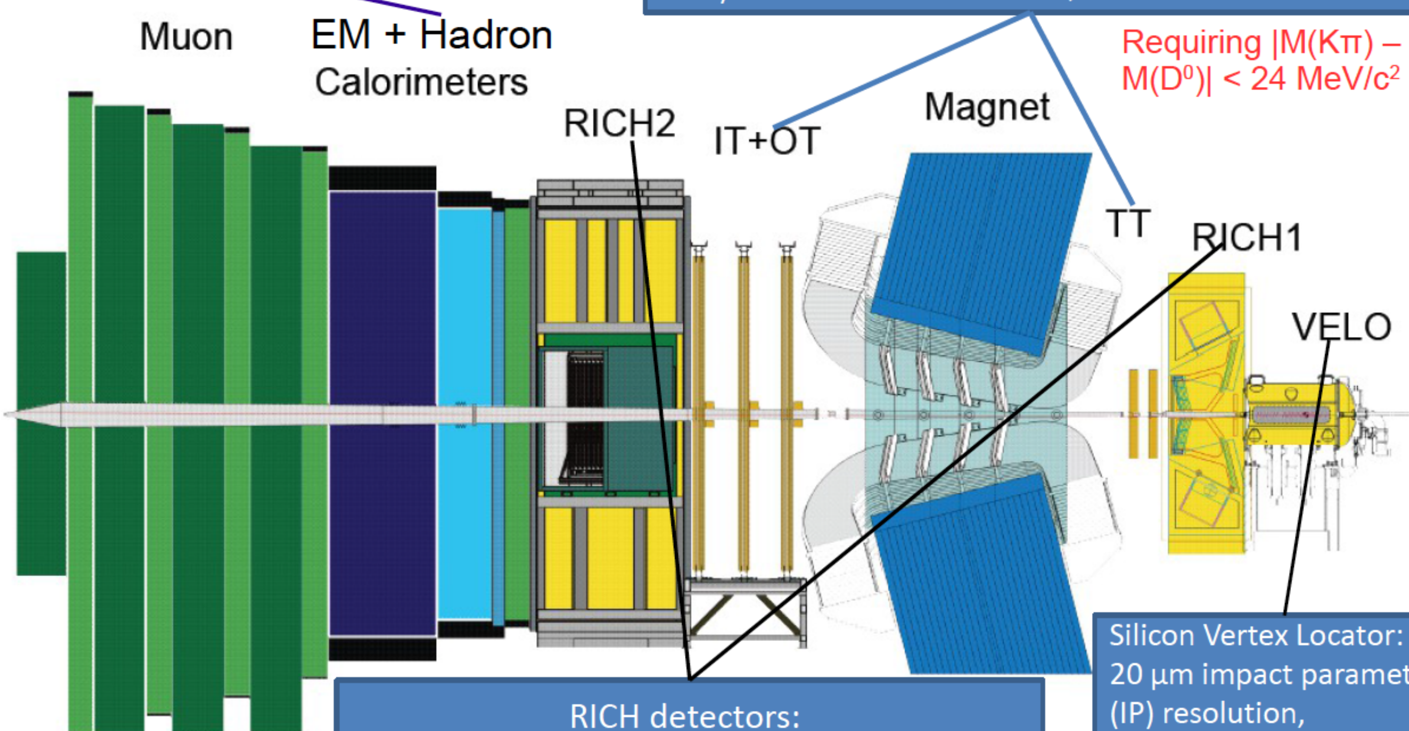
Fast Forward to Charm at LHCb



The LHCb Detector

Hardware trigger system for hadrons: based on large E_T depositions in the hadron Cal.

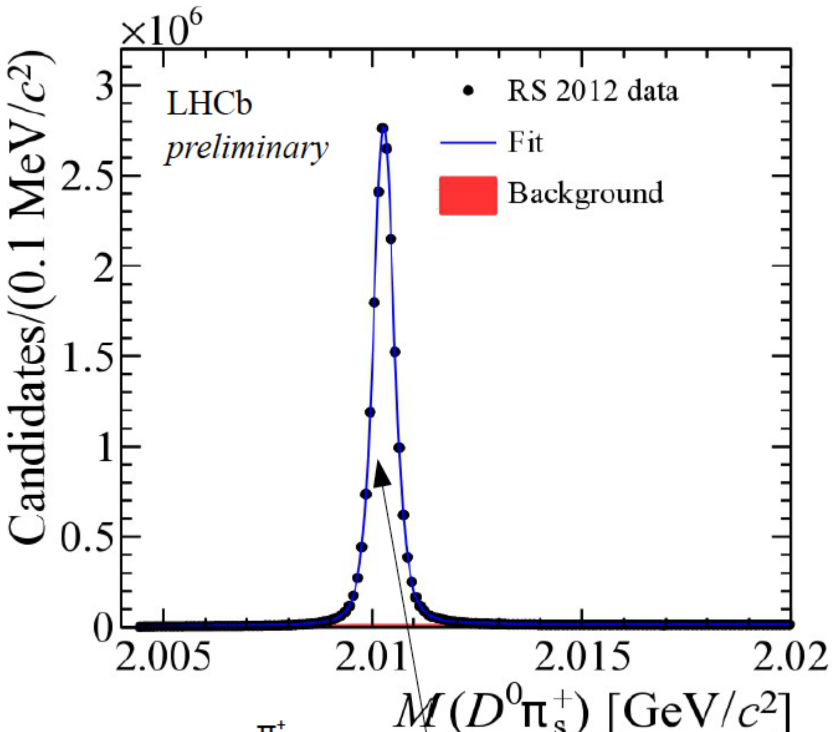
Tracking system:
$\Delta p/p$ = 0.4-0.6% @ 5-100 GeV/c, corresponding to ~8 MeV/c^2 mass resolution for $D \to K\pi$

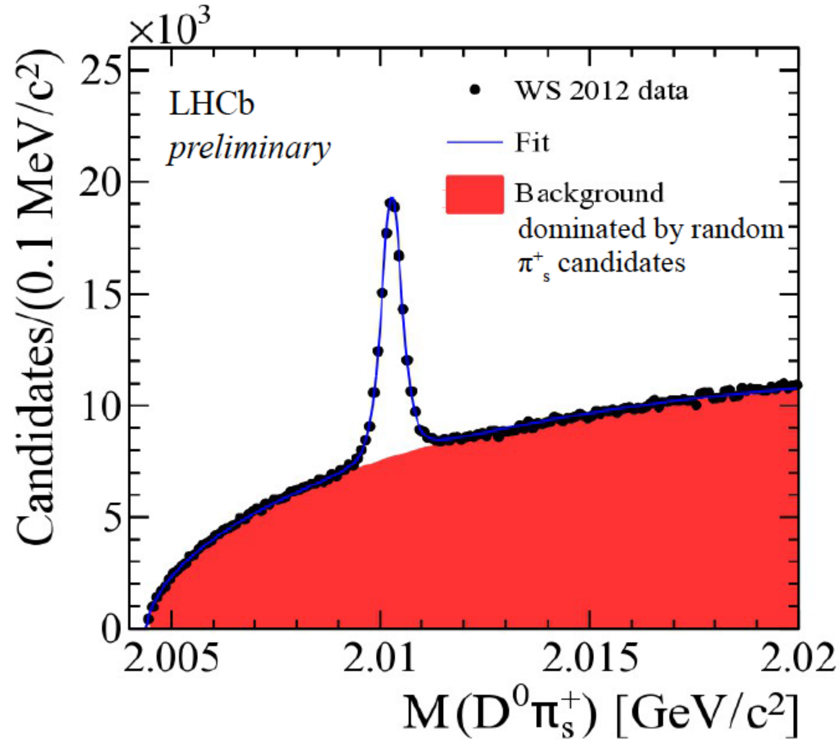


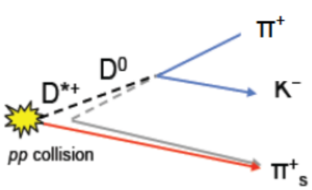
RICH detectors:
Good K/π separation for p < 100 GeV/c with mis-ID rate at a few percent

Silicon Vertex Locator:
20 μm impact parameter (IP) resolution, corresponding to ~0.1τ decay-time resolution for $D \to K\pi$

$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb







Mass resolution at ~ 0.3 MeV/c^2 due to D^* vertex being well constrained to measured PV position

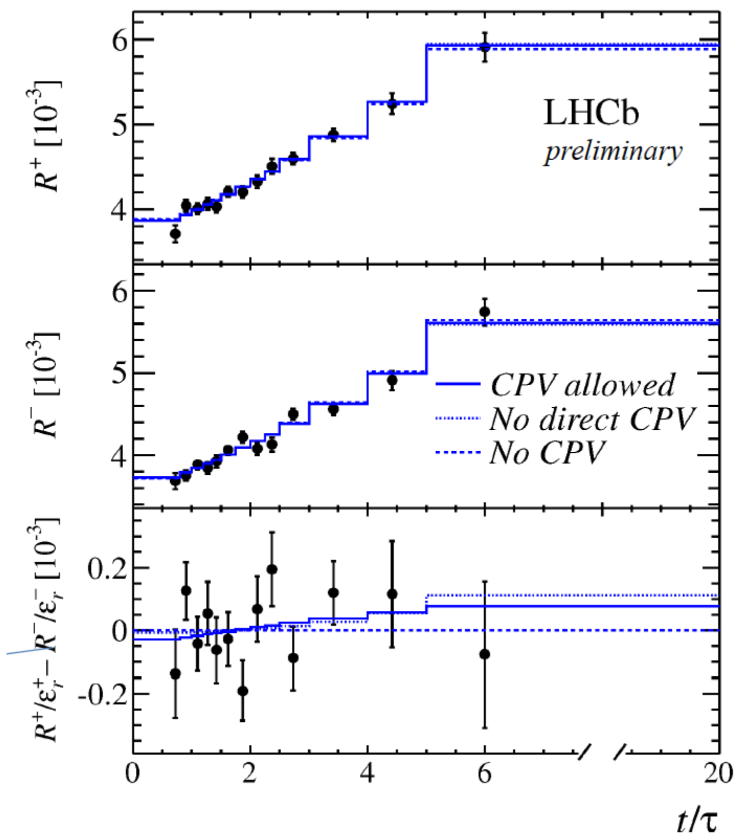
Example fits with part of full data. In total ~54 M RS candidates and ~0.23 M WS candidates are collected.

$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb

$$R^{\pm}(t) \equiv \frac{WS(t)}{RS(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

- Measure the WS/RS ratio in each of 13 decay time bins, separately for D^0 and $\overline{D}^0$.
- Fit the WS/RS ratio as a function of decay time under three hypotheses:
  - No CPV
  - No direct CPV $(R_D^+ = R_D^-)$
  - Full CPV allowed
- Account for feed-through from secondary charm production.
- Account for relative reco efficiency $\varepsilon_R = \varepsilon(K^-\pi^+)/\varepsilon(K^+\pi^-)$

arXiv:1309.6534



$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb

$$R^{\pm}(t) \equiv \frac{WS(t)}{RS(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

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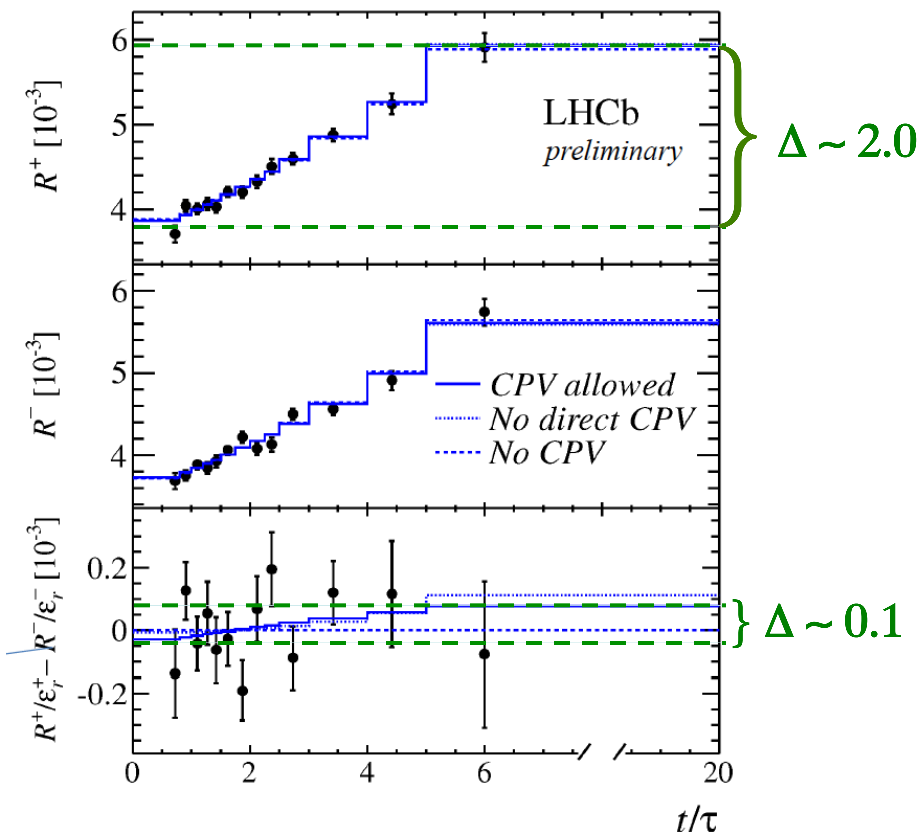
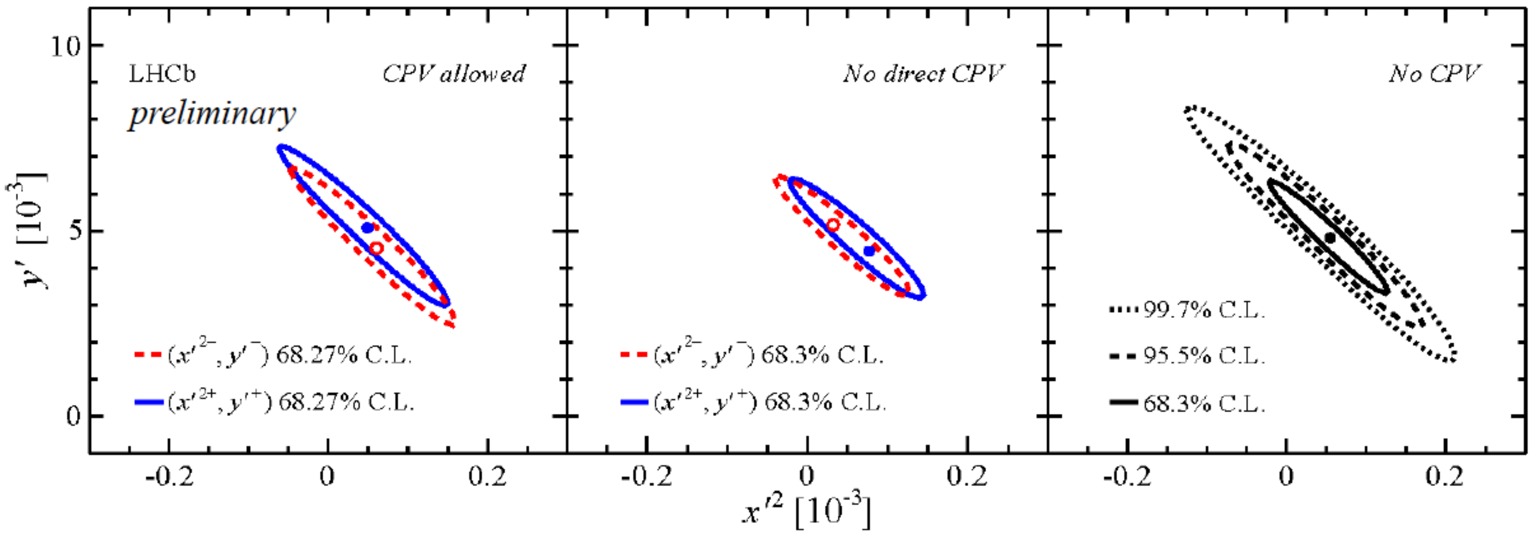
arXiv:1309.6534



$D^0 \rightarrow K\pi$ Mixing and CPV Results



LHCb *preliminary* *Uncertainties are statistical and systematic combined*

Direct and indirect CP violation			no direct CP violation			no CP violation		
R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066	R_D	$[10^{-3}]$	3.568 ± 0.066
A_D	$[10^{-2}]$	-0.7 ± 1.9	y'^{+}	$[10^{-3}]$	4.78 ± 1.07	y'	$[10^{-3}]$	4.81 ± 1.00
y'^{+}	$[10^{-3}]$	5.1 ± 1.4	x'^{2+}	$[10^{-5}]$	6.4 ± 5.5	x'^{2}	$[10^{-5}]$	5.5 ± 4.9
x'^{2+}	$[10^{-5}]$	4.9 ± 7.0	y'^{-}	$[10^{-3}]$	4.83 ± 1.07	χ^2/ndf		$86.41/101$
y'^{-}	$[10^{-3}]$	4.5 ± 1.4	x'^{2-}	$[10^{-5}]$	4.6 ± 5.5			
x'^{2-}	$[10^{-5}]$	6.0 ± 6.8	χ^2/ndf		$85.99/99$			
χ^2/ndf		$85.87/98$						

Results are consistent with *CP* conservation

Formalism for $D^0 \to K\pi$ Mixing and CPV

Using standard notation, and in the limit $x, y \ll 1$, the rates for $\overline{D}^0$ and D^0 decay to the wrong-sign (WS) $K\pi$ final states are

$$\left|\langle f|H\left|\overline{D}^0(t)\right\rangle\right|^2 \approx \frac{e^{-\Gamma t}}{2}|\mathcal{A}_f|^2\Big\{R_D + \left|\frac{p}{q}\right|\sqrt{R_D}\left[y\cos(\delta+\varphi) - x\sin(\delta+\varphi)\right](\Gamma t) + \left|\frac{p}{q}\right|^2\frac{x^2+y^2}{4}(\Gamma t)^2\Big\} \quad (1)$$

and

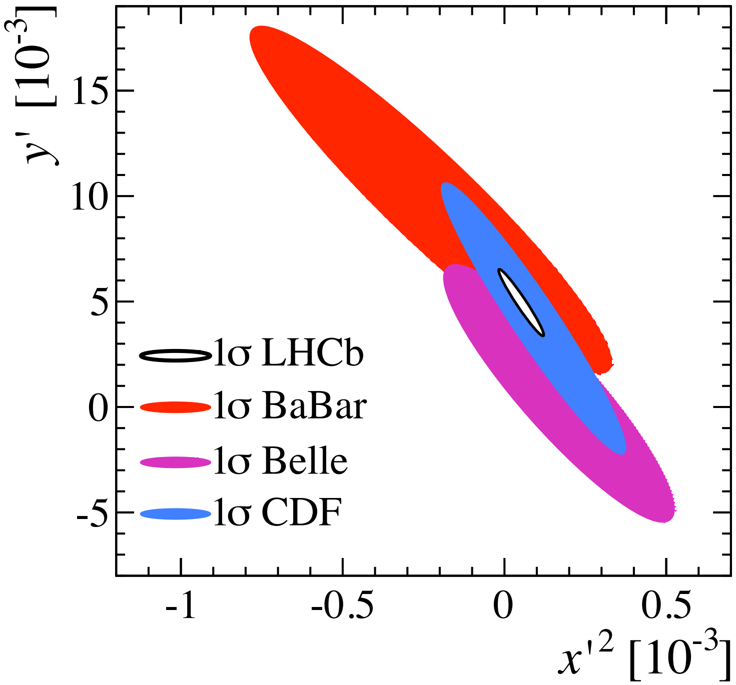
$$\left|\langle \overline{f}|H\left|D^0(t)\right\rangle\right|^2 \approx \frac{e^{-\Gamma t}}{2}|\overline{\mathcal{A}}_{\overline{f}}|^2\Big\{\overline{R}_D + \left|\frac{q}{p}\right|\sqrt{\overline{R}_D}\left[y\cos(\delta-\varphi) - x\sin(\delta-\varphi)\right](\Gamma t) + \left|\frac{q}{p}\right|^2\frac{x^2+y^2}{4}(\Gamma t)^2\Big\}\,. \quad (2)$$

In the Standard Model and in most New Physics scenarios, the CF and DCS $K\pi$ amplitudes are CP symmetric. In the limit that all direct CPV is negligible, to a very good degree of precision

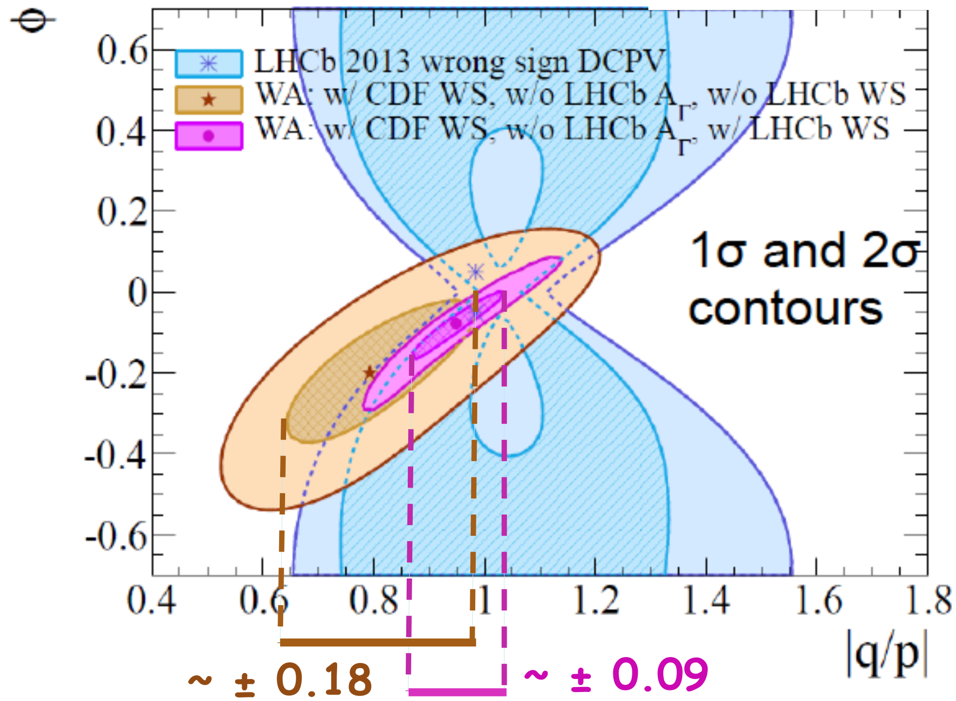
$$\tan\varphi = \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y}$$

analogous to Wolfenstein's superweak relationship

$D^0 \to K\pi$ Mixing and CPV Results



M. Karbach



BaBar: PRL 98, 211802 (2007)

Belle: PRL 96, 151801 (2006)

CDF: Public Note 109990 (2013)

LHCb: PRL 111, 251801 (2013)

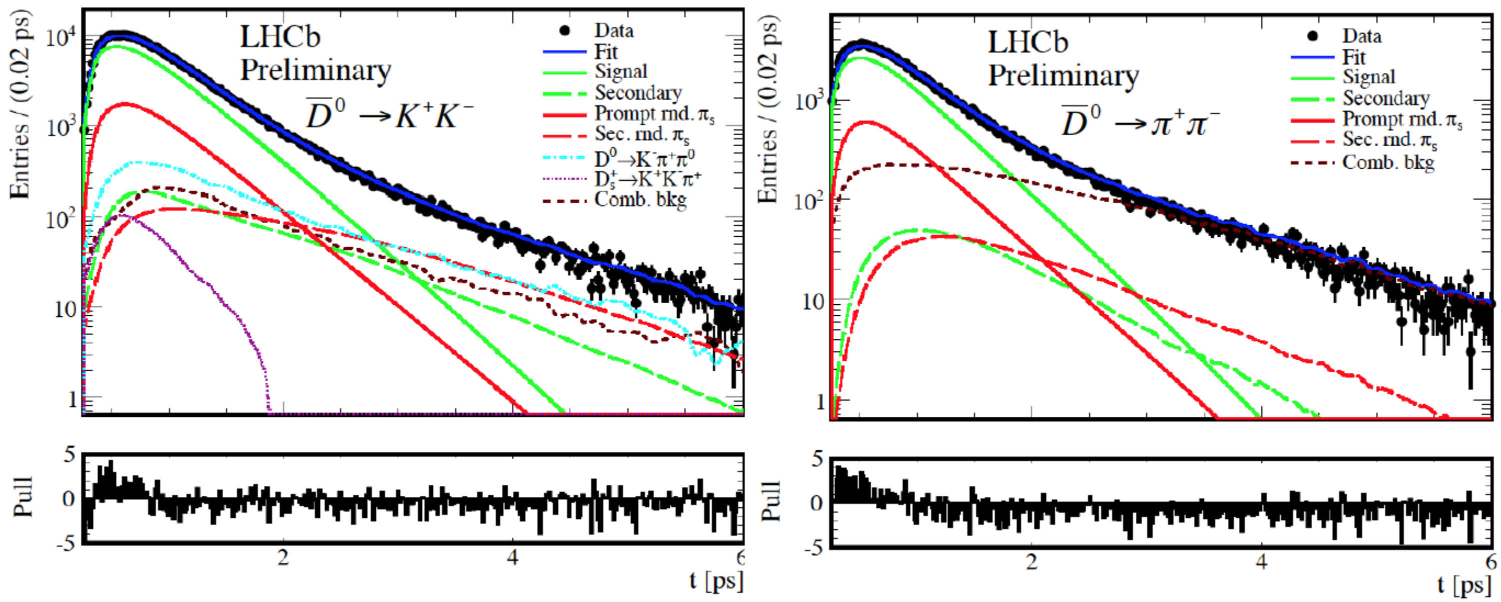
|q/p|	(100.9 ± 1.6)%	no other CPV
φ	(-0.5 ± 0.8)°	params used
|q/p|	(99.3 ± 1.3)%	use prior CPV
φ	(+0.4 ± 0.7)°	measurements
|q/p|	(100.4 ± 6.5)%	HFAG 4/2013
φ	(-1.6 ± 2.5)°	

with superweak constraint
(Rolf Andreassen, Adam Davis, MDS)

New A_Γ Measurement from LHCb

$$\mathbf{A}_\Gamma \equiv \frac{(\tau^+_{\mathbf{hh}} - \tau^-_{\mathbf{hh}})}{(\tau^+_{\mathbf{hh}} - \tau^-_{\mathbf{hh}})} = (|\mathbf{q}/\mathbf{p}| - |\mathbf{p}/\mathbf{q}|)\,\mathbf{y}\cos\phi - (|\mathbf{q}/\mathbf{p}| + |\mathbf{p}/\mathbf{q}|)\,\mathbf{x}\sin\phi$$

- Measurement of the lifetime for each final state and each D^0 flavour



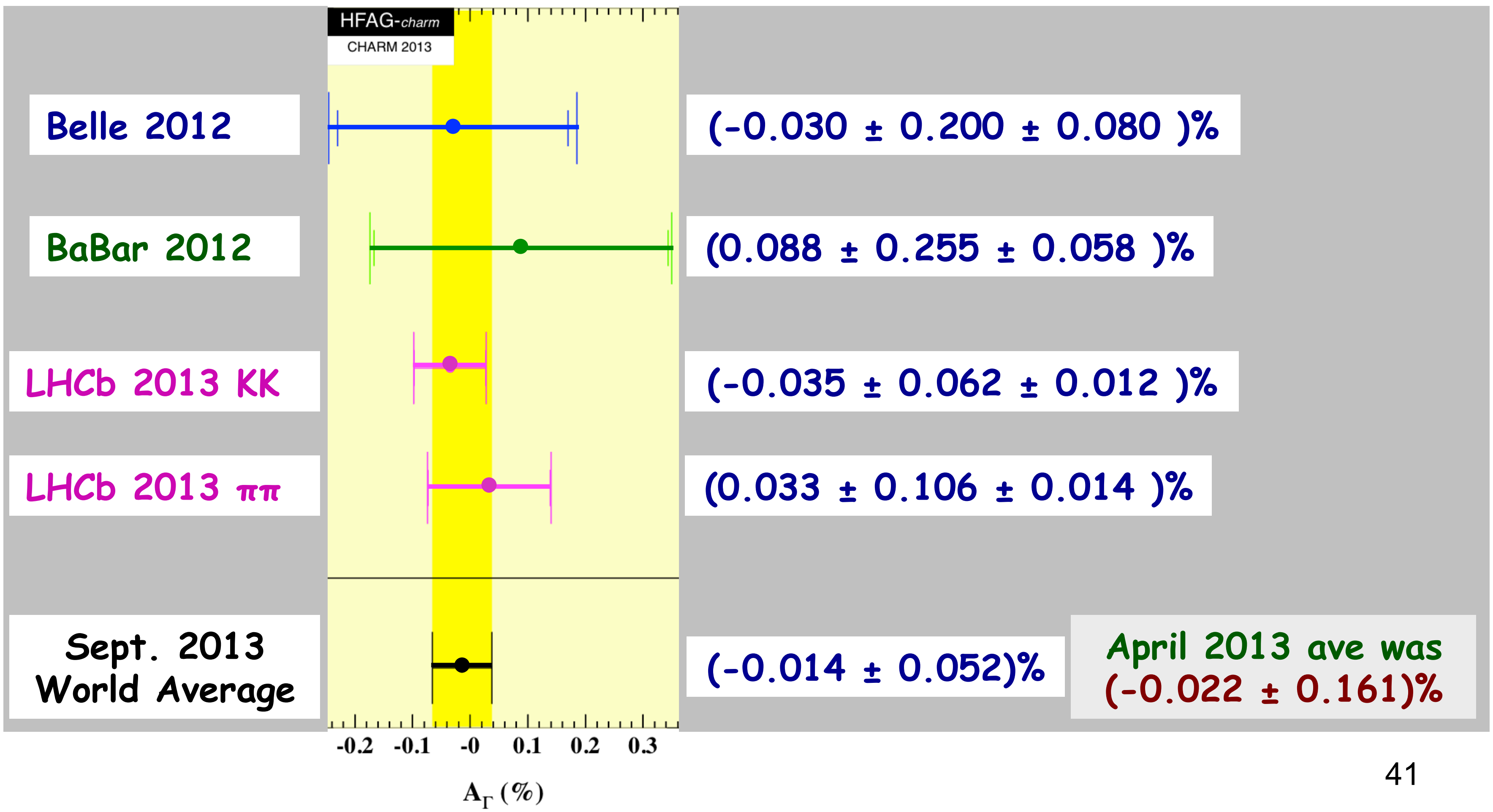
$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat})\ 10^{-3}$

$A_\Gamma(\pi\pi) = (\ 0.33 \pm 1.06_{stat})\ 10^{-3}$

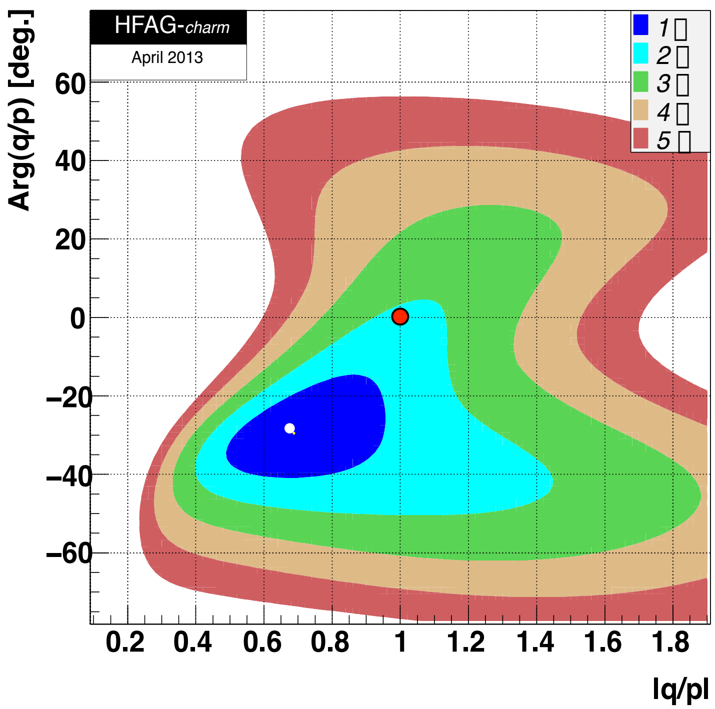
LHCb preliminary

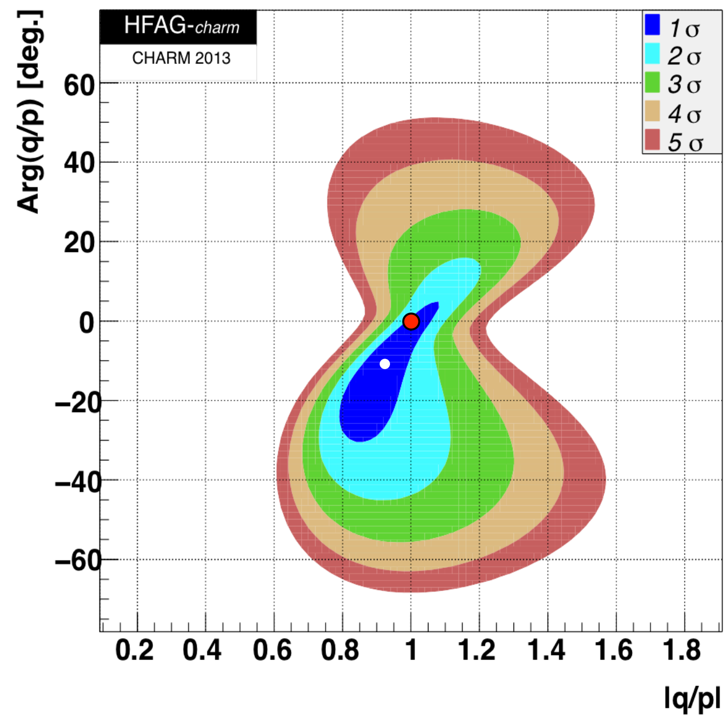
New HFAG Average for A_Γ

$$A_\Gamma \equiv \frac{(\tau^+_{hh} - \tau^-_{hh})}{(\tau^+_{hh} - \tau^-_{hh})} = (|q/p| - |p/q|)\, y \cos\phi \; - \; (|q/p| + |p/q|)\, x \sin\phi$$



April → September, 2013





$$\tan\varphi = \left(1 - \left|\frac{q}{p}\right|\right)\frac{x}{y} \Rightarrow$$

|q/p|	(100.9 ± 1.6)%	no other CPV
φ	(-0.5 ± 0.8)°	params used
|q/p|	(99.3 ± 1.3)%	use prior CPV
φ	(+0.4 ± 0.7)°	measurements
|q/p|	(100.4 ± 6.5)%	HFAG 4/2013
φ	(-1.6 ± 2.5)°	

26 Years Ago

VOLUME 60, NUMBER 13 PHYSICAL REVIEW LETTERS 28 MARCH 1988

Study of D^0-$\bar{D}^0$ Mixing

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(Received 18 December 1987)

We present a study of D^0 mixing using events of the type $D^{*+} \to \pi^+ D^0$, with $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$. The decay time is used to separate mixing from doubly Cabibbo-suppressed decays. We observe no evidence for mixing in either mode. Combining the results from the two decay modes, we find $r_M = 0.0005 \pm 0.0020$ or $r_M < 0.0037$ at the 90% confidence level, where r_M is the ratio of wrong-sign decays from mixing to right-sign decays. We also present limits on doubly Cabibbo-suppressed decays and consider the effect of possible interference.

PHYSICAL REVIEW D VOLUME 57, NUMBER 1 1 JANUARY 1998

Search for D^0-D^0 mixing and doubly-Cabibbo-suppressed decays of the D^0 in hadronic final states

E. M. Aitala,[9] S. Amato,[1] J. C. Anjos,[1] J. A. Appel,[5] D. Ashery,[15] S. Banerjee,[5] I. Bediaga,[1] G. Blaylock,[8] S. B. Bracker,[16] P. R. Burchat,[14] R. A. Burnstein,[6] T. Carter,[5] H. S. Carvalho,[1] N. K. Copty,[13] L. M. Cremaldi,[9] C. Darling,[19] A. Fernandez,[12] P. Gagnon,[2] C. Gobel,[1] K. Gounder,[9] A. M. Halling,[5] G. Herrera,[4] G. Hurvits,[15] C. James,[5] P. A. Kasper,[6] S. Kwan,[5] D. C. Langs,[11] J. Leslie,[2] B. Lundberg,[5] S. MayTal-Beck,[15] B. Meadows,[3] J. R. T. de Mello Neto,[1] R. H. Milburn,[17] J. M. de Miranda,[1] A. Napier,[17] A. Nguyen,[7] A. B. d'Oliveira,[3,12] K. O'Shaughnessy,[2] K. C. Peng,[6] L. P. Perera,[3] M. V. Purohit,[13] B. Quinn,[9] S. Radeztsky,[18] A. Rafatian,[9] N. W. Reay,[7] J. J. Reidy,[9] A. C. dos Reis,[1] H. A. Rubin,[6] A. K. S. Santha,[3] A. F. S. Santoro,[1] A. J. Schwartz,[11] M. Sheaff,[18] R. A. Sidwell,[7] A. J. Slaughter,[19] M. D. Sokoloff,[3] N. R. Stanton,[7] K. Stenson,[18] D. J. Summers,[9] S. Takach,[19] K. Thorne,[5] A. K. Tripathi,[10] S. Watanabe,[18] R. Weiss-Babai,[15] J. Wiener,[11] N. Witchey,[7] E. Wolin,[19] D. Yi,[9] S. Yoshida,[7] R. Zaliznyak,[14] and C. Zhang[7]

(Fermilab E791 Collaboration)

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(Received 29 August 1996; revised manuscript received 27 August 1997; published 8 December 1997)

We present results of a search for D^0-D^0 mixing and doubly-Cabibbo-suppressed decays of the D^0 in Fermilab experiment E791, a fixed-target charm hadroproduction experiment. We look for evidence of mixing in the decay chain $D^* \to \pi D \to \pi(K\pi$ or $K\pi\pi\pi)$. If the charge of the pion from the D^* decay is the same as the charge of the kaon from the D decay (a ''wrong-sign'' event), mixing may have occurred. Mixing can be distinguished from other sources of wrong-sign events (such as doubly-Cabibbo-suppressed decays) by analyzing the distribution of decay times. We see no evidence of mixing. Allowing for CP violation in the interference between DCS and mixing amplitudes our fitted ratio for mixed to unmixed decay rates is $r_{mix} = (0.39^{+0.36}_{-0.32} \pm 0.16)\%$. This corresponds to a 90% C.L. upper limit of $r_{mix} < 0.85\%$. The sensitivity of this result is comparable to that of previous measurements, but the assumptions made in fitting the data are notably more general. We present results from many fits to our data under various assumptions. If we assume $r_{mix} = 0$, we find a two-sigma wrong-sign enhancement in the $K\pi$ mode which we ascribe to doubly Cabibbo-suppressed decays. The ratios of doubly Cabibbo-suppressed decays to Cabibbo-favored decays are $r_{dcs}(K\pi) = (0.68^{+0.34}_{-0.33} \pm 0.07)\%$ and $r_{dcs}(K\pi\pi\pi) = (0.25^{+0.36}_{-0.34} \pm 0.03)\%$. [S0556-2821(98)01103-5]

Charm Mixing: Thoughts and Projections

- D^0 - $\overline{D}^0$ mixing is firmly established
  - level is consistent with Standard Model or New Physics amplitudes, or both.

- CPV in mixing is being probed at the n% level
  - Observation at this level would indicate New Physics.

- Data already on tape will help us probe CPV in mixing with somewhat greater precision ($D^0 \to K^0_S \pi^- \pi^+$ from Belle and LHCb, in particular).

- Forthcoming experiments (LHCb, Belle-II) will enable measurements of CPV in mixing at the 0.n% level.

- Relax superweak constraint:
  - use $\tan(\phi_{\lambda_f} + \phi^{\Gamma}_{12,f}) = -A_M\, x/y$; $\lambda_f \equiv \frac{q}{p} \frac{\overline{A}_f}{A_f}$

Summary and Conclusions

- Flavor physics provides **complementary sensitivity** to **Beyond the Standard Model** physics with respect to the general purpose LHC detectors ATLAS and CMS.
- Our $D^0 \rightarrow K\pi$ mixing measurement **constrains CPV in mixing (|q/p|) to ± (10% - 1%)** depending on what assumptions are made with respect to direct CPV in CF and DCS amplitudes.
- More results from the **3 fb^{-1} Run 1 (2011/2012)** data set are on the way. We expect to record ~ **3 times as many B's and > 5 times as many D's in the LHC's Run 2.**
- The **upgrade** should provide **another order of magnitude** increase in statistics.