Evidence for D^0-$\bar{D}^0$ Mixing at BaBar

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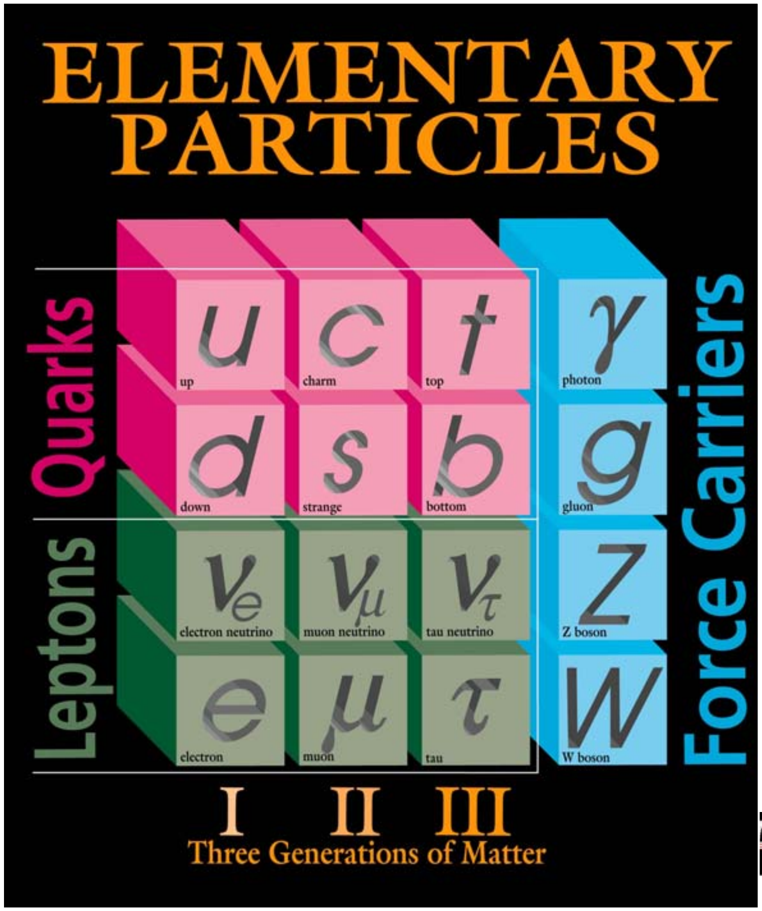
Outline

- *Introduction*
- D^0-$\bar{D}^0$ oscillations
- Search for Mixing / CP violation using $D^0 \to K^- \pi^+$ decays
- Other searches for mixing / CPV:
  - Lifetime Ratios: $\tau(D^0 \to K^+K^-, \pi^+\pi^-)$ vs $\tau(D^0 \to K^-\pi^+)$
  - CPV in time-integrated $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ rates.
  - Mixing study using $D^0 \to K^+\pi^-\pi^0$ decays
- Comparison with other results, theory

Introduction

Particle Physics

- In the last 100 years or so, starting with the discoveries of the electron, atoms, nuclei, and so on, we have discovered a lot about what the world is made of.
- After 50 years of intense effort, we now know that the physical world is
  - Composed of quarks and leptons
  - Interacting via force carriers called gauge bosons



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

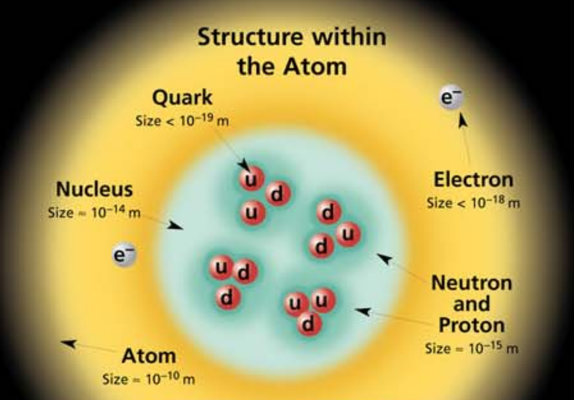
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

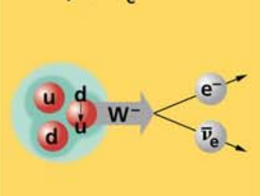
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

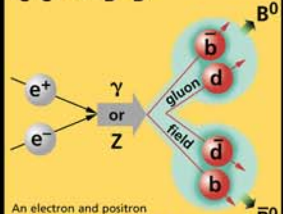
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



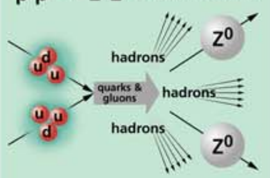
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

$p\, p \rightarrow Z^0 Z^0$ + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:
U.S. Department of Energy
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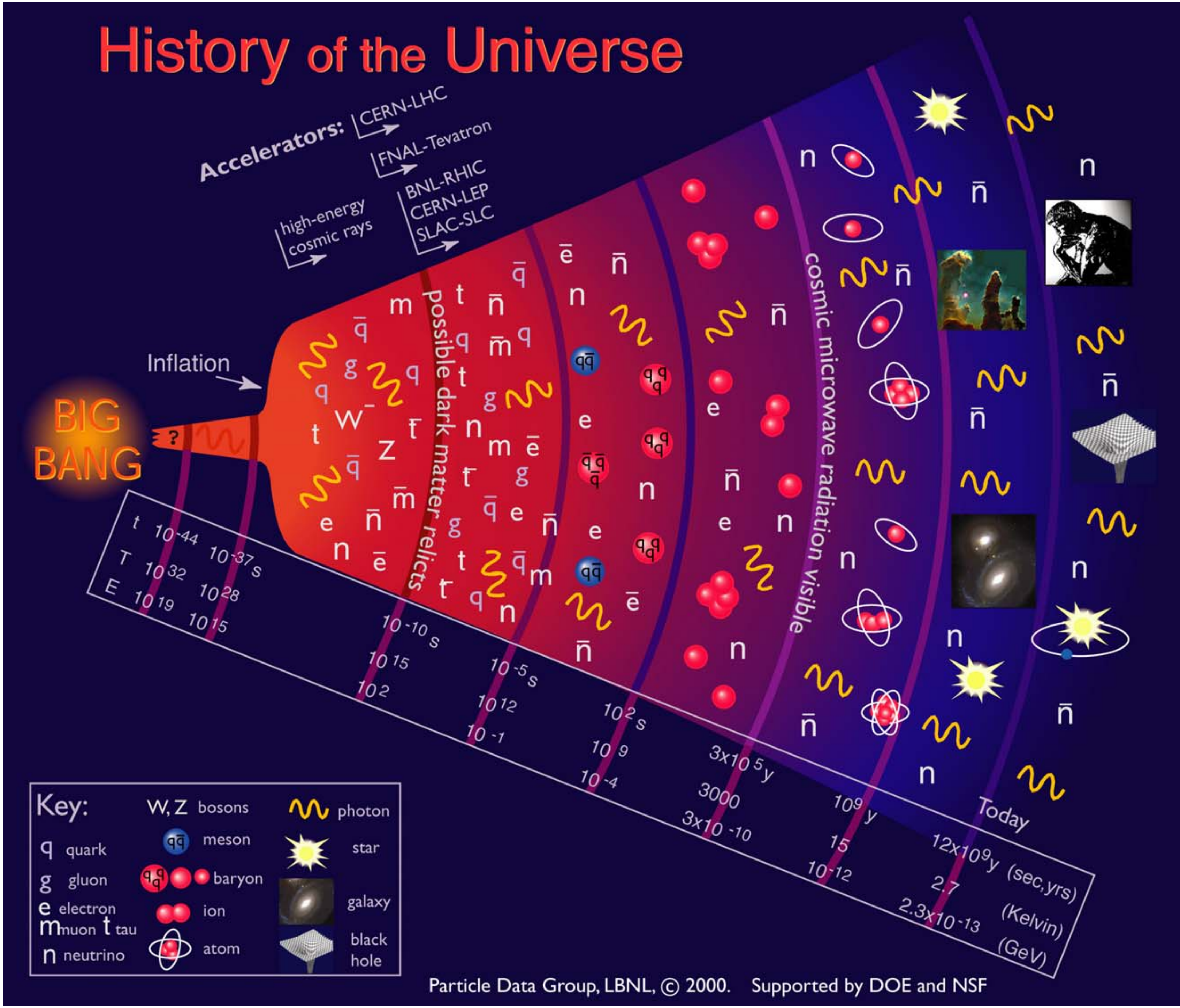
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

HEP

Beyond the Standard Model

Is the Standard Model the final picture of particle physics?

Answer: Most certainly not!

How do we go beyond it?

- Study existing problems with the model
- Look for new particles / effects directly
- Look for new particles / effects indirectly

Neutral Meson Oscillations

Neutral Meson Mixing

Mixing can occur in four neutral mesons:

K^0	Mass: ~0.5 GeV/c^2
D^0	Mass: ~1.9 GeV/c^2
B^0	Mass: ~5.3 GeV/c^2
B^0_s	Mass: ~5.4 GeV/c^2

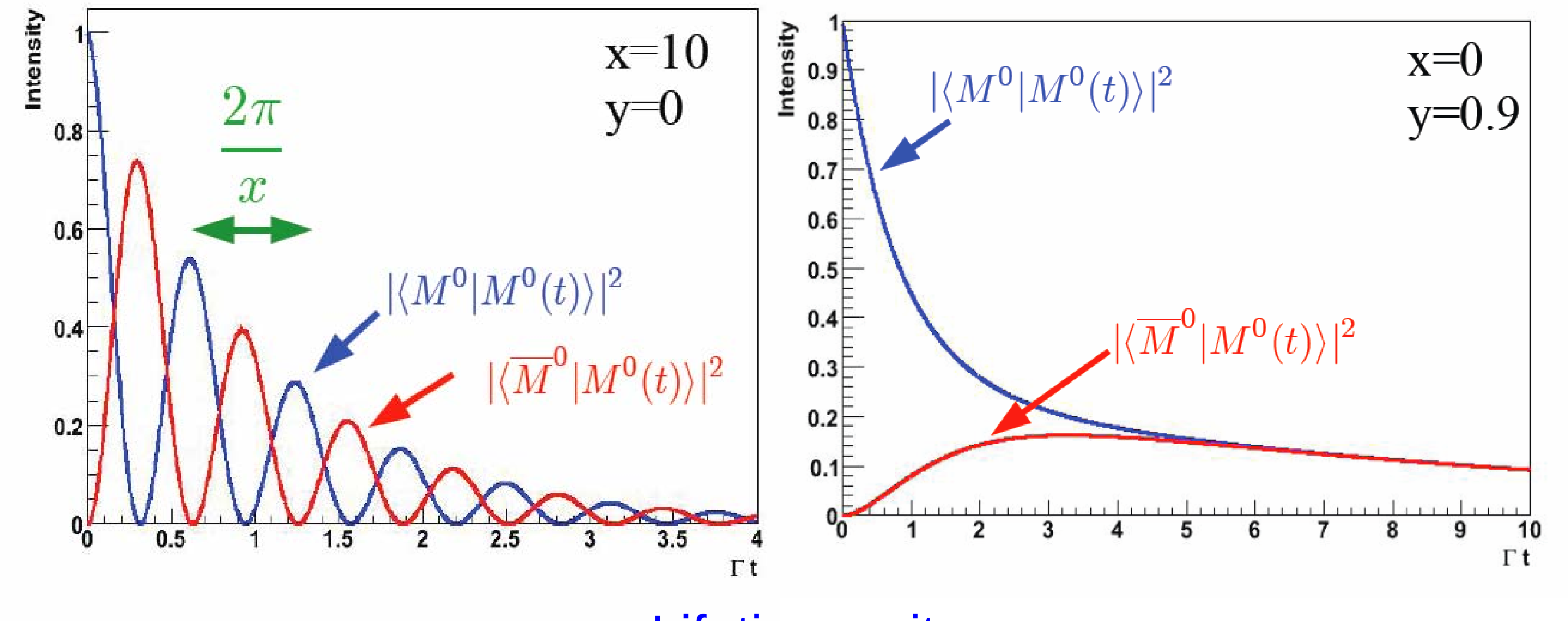
Will present mixing measurement for D^0 meson

Note: D^0 meson first discovered at SLAC

Mark-I, PRL 37, 255 (1976)

Some visual examples

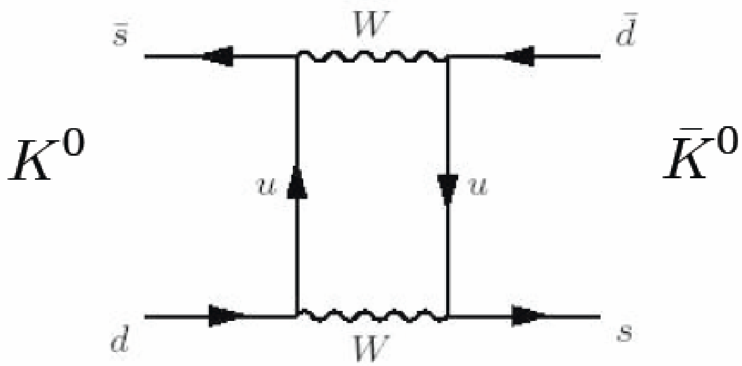
Probability to find a $M^0(\overline{M}^0)$ after a given time



Lifetime units

The prediction of charm

Mixing through box diagram:



No tree level Flavor Changing Neutral Currents (FCNC) in SM

Glashow, Iliopoulus and Maiani (1970):

FCNC calculated from single quark loop still too large

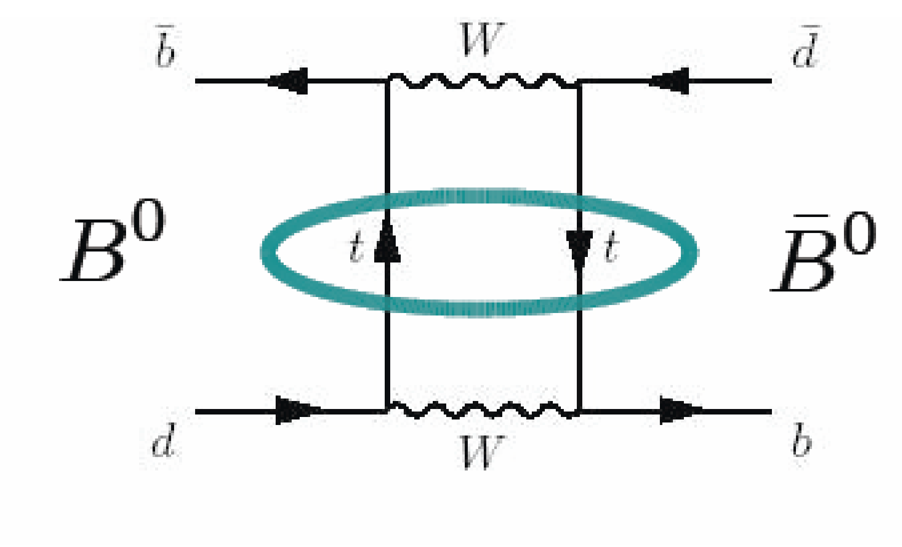
Introduce additional loop with new *c* quark

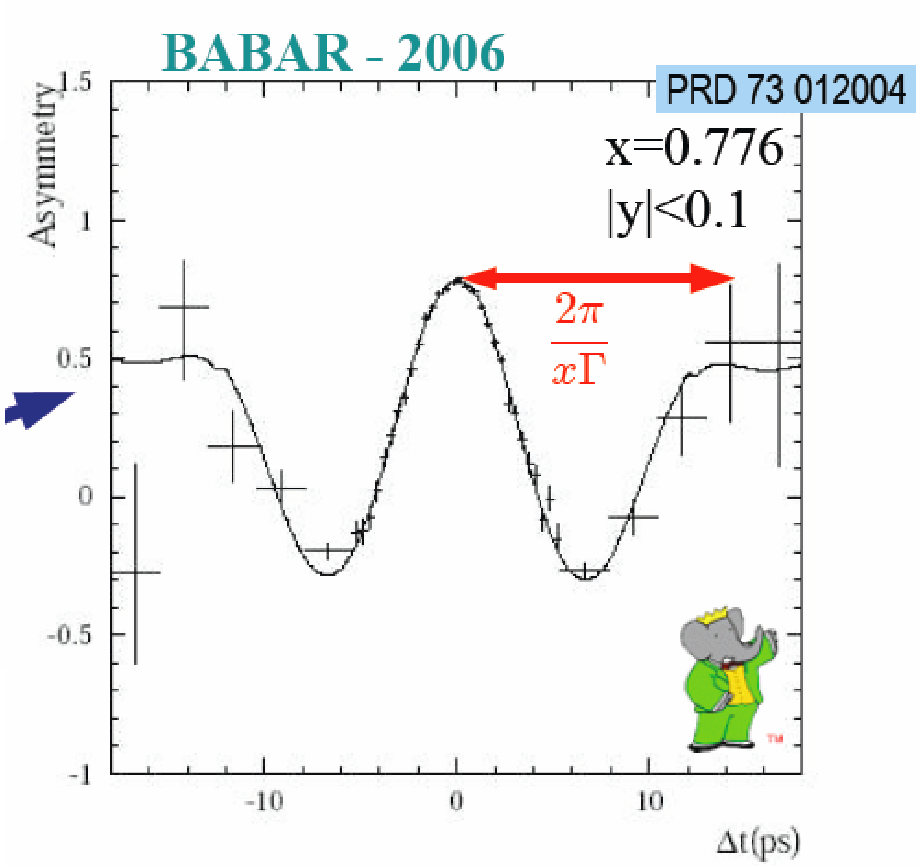
GIM predicted charm quark 4 years before observation

B^0 mixing and the discovery of the t

B^0 mixing was argued by UA1 and directly observed by ARGUS in 1987

Large mixing frequency implied *t* quark was heavy (m_t > 50 GeV/c^2)





And the top was discovered 8 years after!

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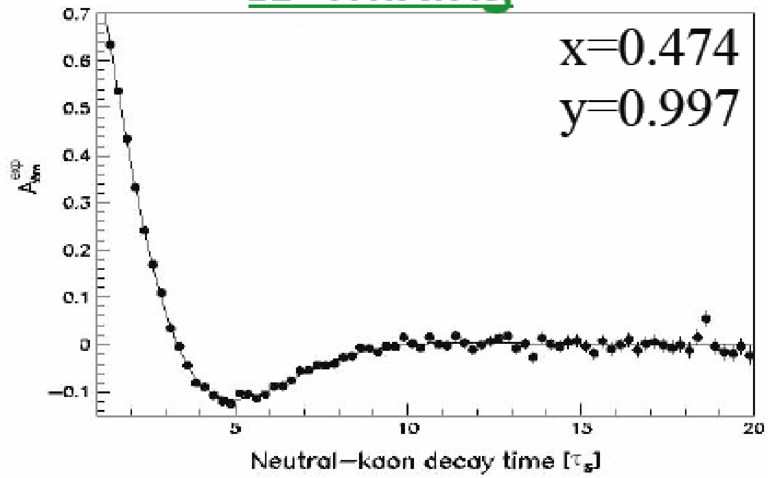
The missing tile

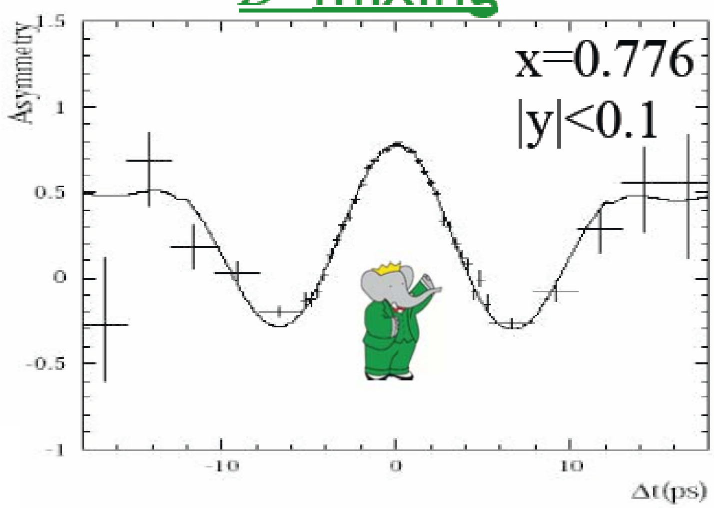
K^0 mixing



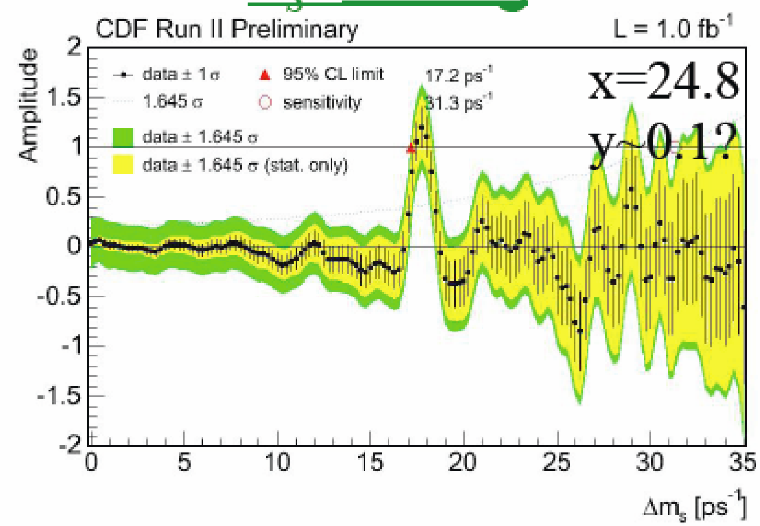
D^0 mixing

?

B^0 mixing



B_s^0 mixing



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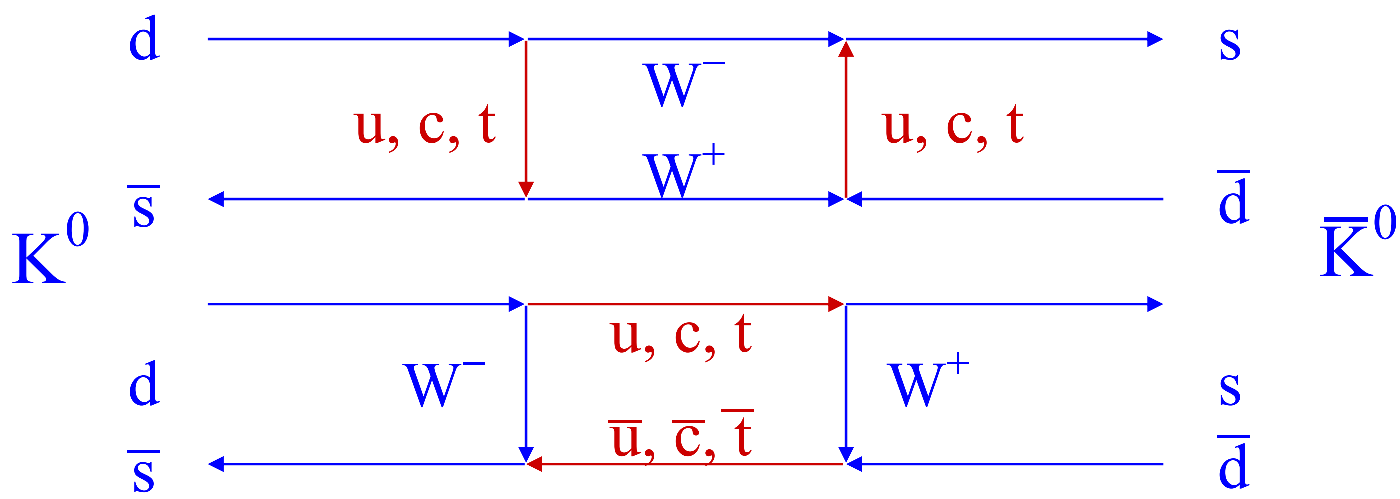
Kaon oscillations



- So say at t=0, pure K°,
  - later a superposition of states

Assume CP

K^0 Decay

$$|K_s\rangle \approx |K_1\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right)$$ CP=+1

$$|K_L\rangle \approx |K_2\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle - |\overline{K^0}\rangle\right)$$ CP=-1

mass eigenstates $\left\{ \begin{array}{l} K_S \\ K_L \end{array} \right.$

$$p = q = \frac{1}{\sqrt{2}}$$

- In that case

K_S branching fractions: $\pi^+\pi^- \approx 69\%$, $\pi^0\pi^0 \approx 31\%$

K_L branching fractions: $\pi^0\pi^0\pi^0 \approx 21\%$, $\pi^+\pi^-\pi^0 \approx 13\%$, $\ell^\mp\pi^\pm\nu \approx 66\%$

$$\tau_S = \frac{1}{\Gamma_S} = (0.8934 \pm 0.0008) \times 10^{-10}\,\mathrm{s}$$

$K_S \to \pi^0\pi^0$, $K_S \to \pi^+\pi^-$ } CP=+1

$K_L \to \pi^+\pi^-\pi^0$, $K_L \to \pi^0\pi^0\pi^0$ } CP=-1

$$\tau_L = \frac{1}{\Gamma_L} = (5.17 \pm 0.04) \times 10^{-8}\,\mathrm{s}$$

$$\Delta m = m_L - m_S = (0.5301 \pm 0.0014) \times 10^{10}\,\hbar\mathrm{s}^{-1}$$

$$\therefore x = \frac{\Delta M}{\overline{\Gamma}} \approx 0.95$$

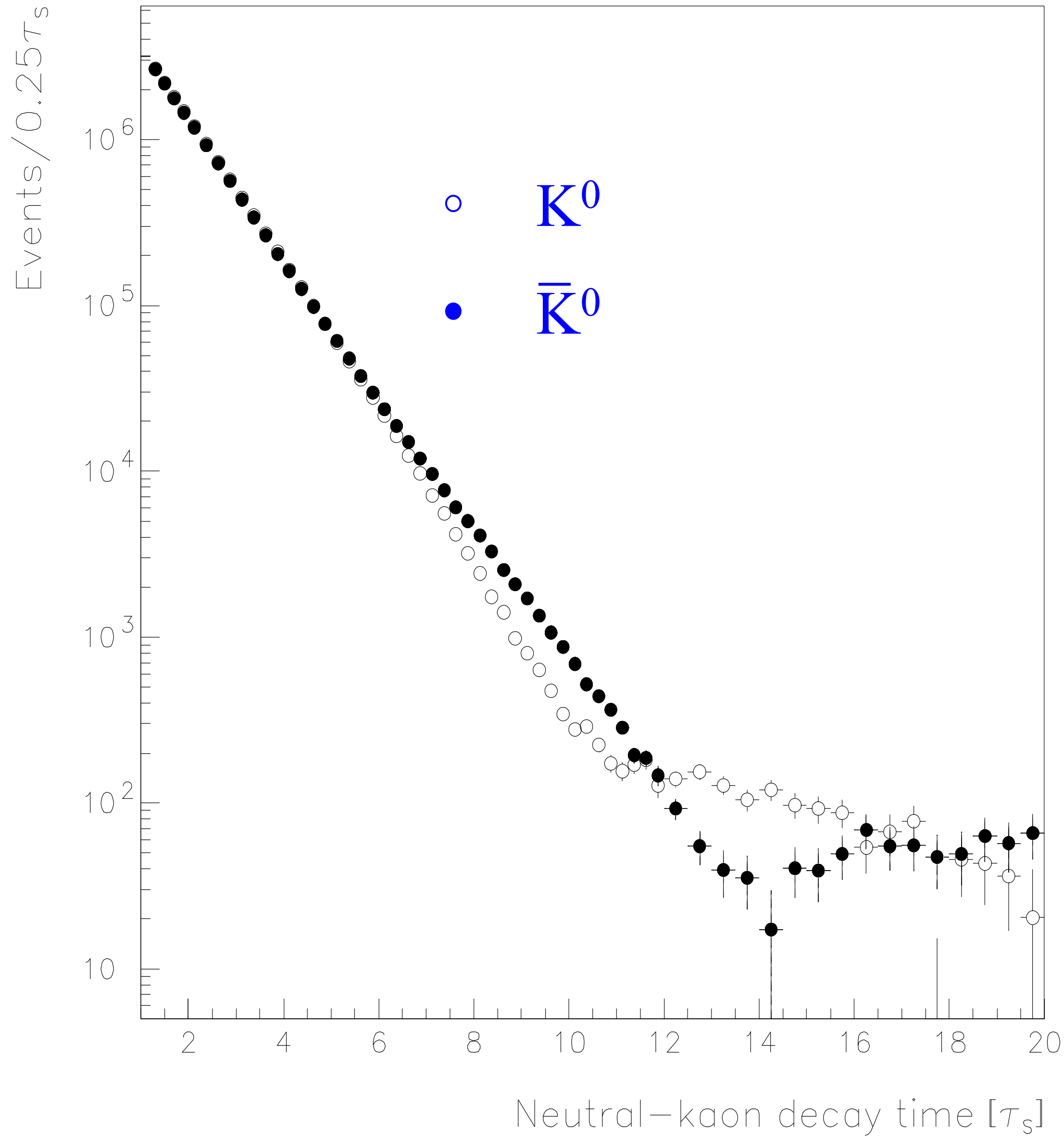
CPLEAR

$R_{+-}(t)$

and

$\overline{R}_{+-}(t)$

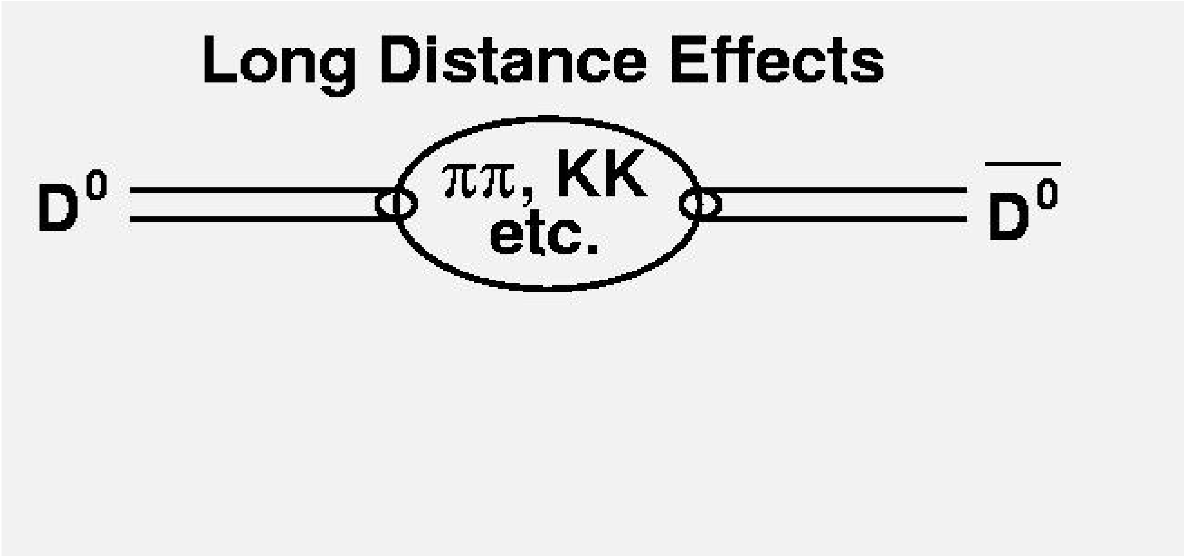
CP violation



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

Physics of $D^0\bar{D}^0$ – mixing

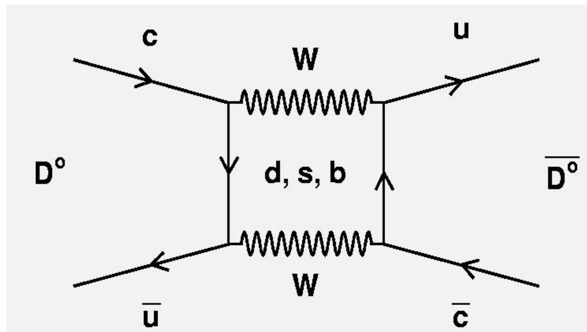
- Common final states lead to mixing:



- One can naively estimate the mixing rate:
  Since BR ~ few x 10^{-3}, one expects rate "r" ~ 10^{-5}.

Physics of $D^0\bar{D}^0$ – mixing, contd.

- Mixing at the quark level in the Standard Model:



- Predicted rate for mixing: $r_{mix} \sim 10^{-7}$

Possibility of CP violation in mixing:

- First noted by Pais and Treiman (Phys. Rev. D12, 2744 (1975)).
- It is possible that

$$r(D^0 \rightarrow D^0\,\mathrm{bar}) \neq r(D^0\,\mathrm{bar} \rightarrow D^0)$$

- This is most likely to happen in the interference between the mixing and DCS amplitudes, since CP violation requires two amplitudes.

Neutral Meson systems

– Two-level system $(M^0, \overline{M}^0)$
  - Weak interactions remove degeneracy, make them unstable

Time evolution by Schrödinger eq.:

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

2x2 hermitian matrices   Mesons decay!

Mass eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Propagate with separate mass $m_{1,2}$ and width $\Gamma_{1,2}$:

$$|M_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}|M_{1,2}(t=0)\rangle$$

Neutral meson oscillations

Time evolution for meson of ***known flavor at t=0***

$$x = \frac{m_2 - m_1}{\Gamma} \qquad \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

$$|M^0(t)\rangle = e^{-\bar{\gamma}t/2}\left(\cosh(\Delta\gamma t/2)|M^0\rangle - \frac{q}{p}\sinh(\Delta\gamma t/2)|\overline{M}^0\rangle\right)$$

Where $\Delta\gamma = (y + ix)\Gamma \qquad \bar{\gamma} = (\Gamma_1 + \Gamma_2)/2 - i(m_1 + m_2)$

M^0 "oscillates" into $\overline{M}^0$!

(also dubbed "mixing")

An opposite flavor component appears after a while!

Short and Long distance

- Predictions for x and y:

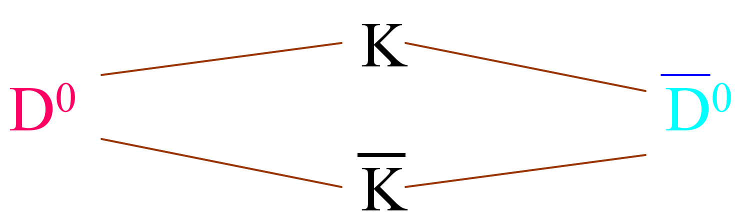
$$\left(M - \frac{i}{2}\Gamma\right)_{ij} = \frac{\langle D_i|H_{\text{eff}}|D_j\rangle}{2m_D} = m_D^{(0)}\delta_{ij} + \frac{\langle D_i|H_w|D_j\rangle}{2m_D} + \frac{1}{2m_D}\sum_n \frac{\langle D_i|H_w|n\rangle\langle n|H_w|D_j\rangle}{m_D^{(0)} - E_n + i\epsilon}.$$

x *VIRTUAL* states

y

$$\Gamma_{ij} = \frac{1}{2m_D}\sum_n \langle D_i|H_w|n\rangle\langle n|H_w|D_j\rangle\,\delta(E_n - m_D).$$

Sum of intermediate
REAL states



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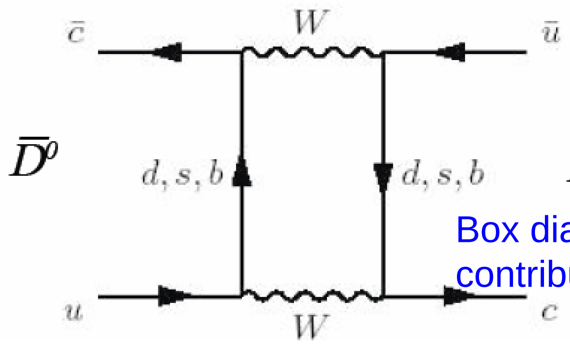
SM prediction for charm mixing

SM charm mixing box has down-type quarks in loop



Box diagram contribution

Effective GIM suppression:

$$x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2}$$

(bottom quark ruled out by V_{CKM})

→ $x \sim 10^{-5}$ Tiny!

$$x,\ y \sim \sin\theta_c^2 \times [\mathrm{SU(3)\ breaking}].$$ →

Naively

$$x,\ y \sim \sin\theta_c^2 \times \left(\frac{m_s}{\Lambda_{\mathrm{hadr.}}}\right)^2 \lesssim O(10^{-3})$$

Always hard to evaluate SU(3) breaking !!!

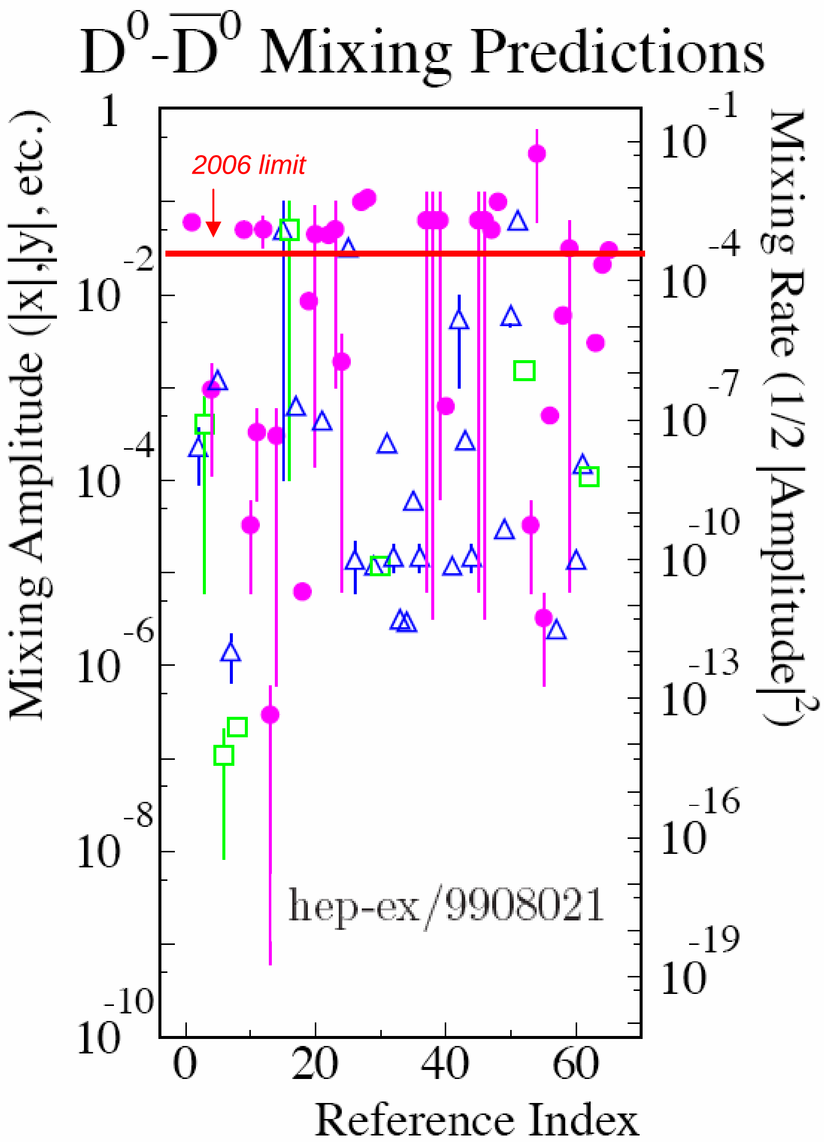
(HQET, propagation of common hadronic states,…)

G. Burdman and I. Shipsey, Ann. Rev. Nucl. and Part. Sci. **53**, 431 (2003).

SU(3) breaking effect more important for y

$$x \lesssim 10^{-3}, \qquad y \lesssim 10^{-2}.$$

New Physics in Charm ?



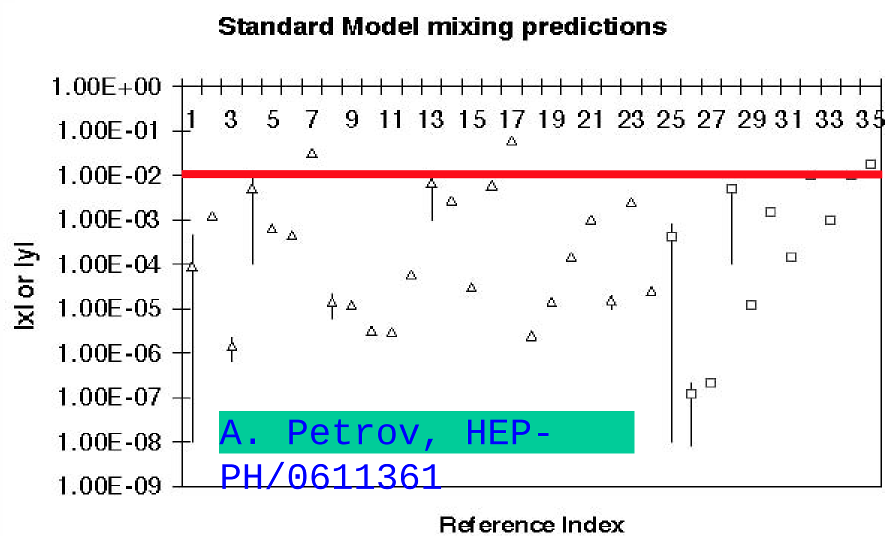
Δ: Standard model predictions for x

□: Standard model predictions for y

●: New physics predictions for x

– Hard to see a clear prediction
– *Pushing the limit down excludes models*

Try to separate x and y!



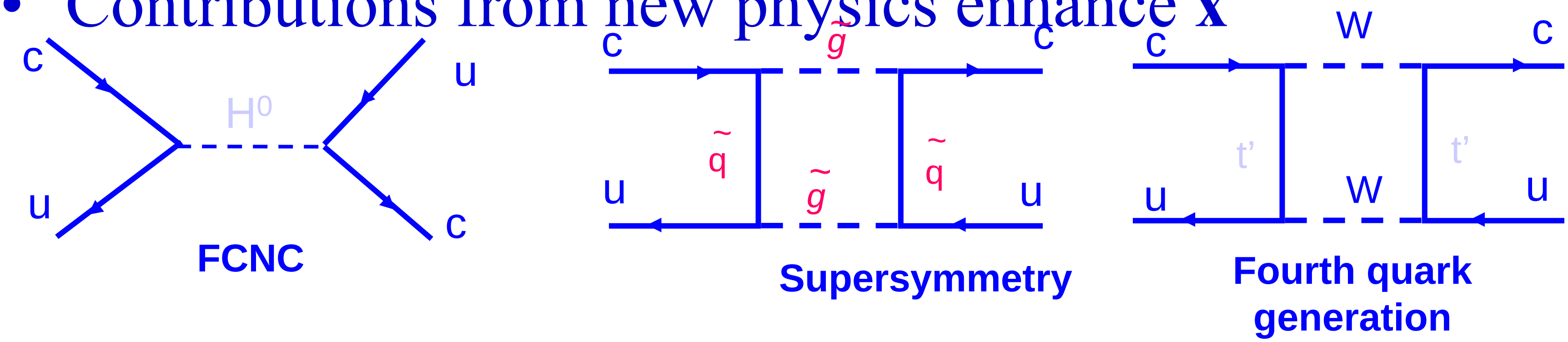
New Physics

- Small Standard Model mixing ⇒ Large window for discovery of new physics
- However, in 1995 Wolfenstein reminded us that long distance contributions can be large
- SM calculations of box diagram redone: r_{mix} in the SM could be as large as 10^{-3} according to Georgi (1992). Confirmed by Ohl, Ricciardi and Simmons (1993). More recently Falk *et al*. (2002) show that phase space effects alone can yield y ~ 1% via SU(3) breaking in the SM.

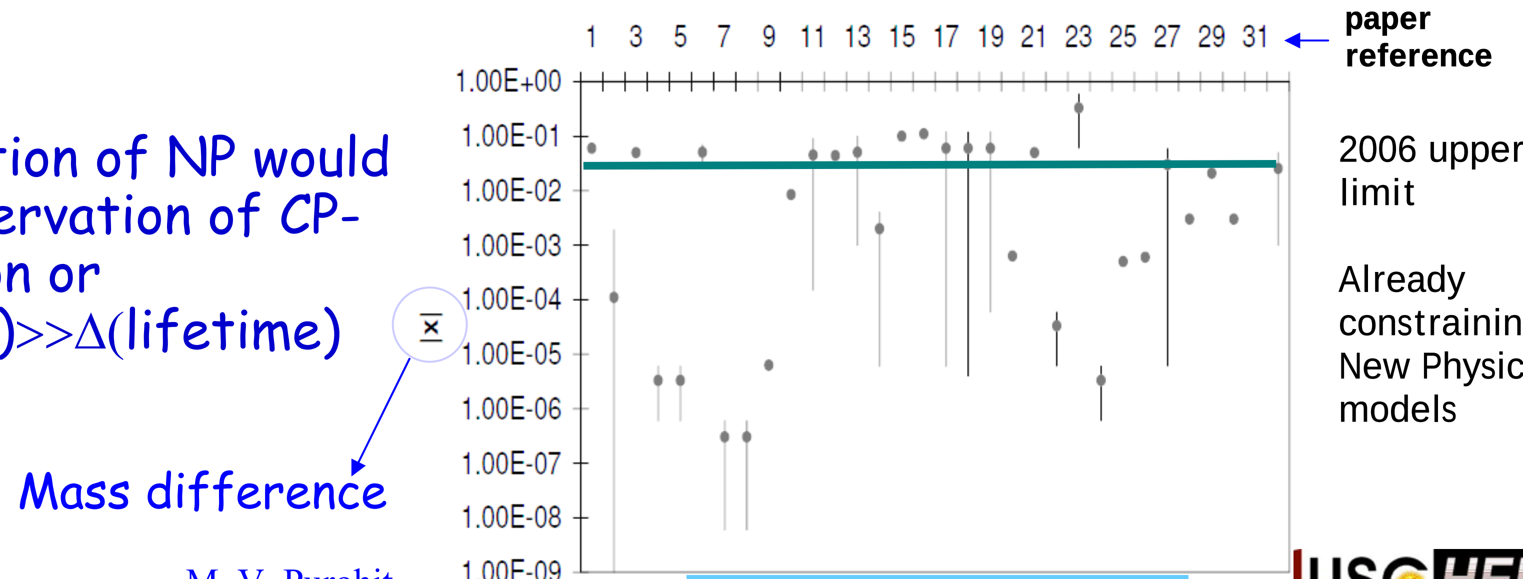
New Physics Contribution to Charm Mixing

G.Burdman, I.Shipsey, Ann.Rev.Nucl.Part.Sci. 53 (2003) 431-499

- Possible enhancements to mixing due to new physics
- Contributions from new physics enhance **x**



- Indication of NP would be observation of CP-violation or Δ(mass)>>Δ(lifetime)



BABAR

Charm Mixing in $D^0 \to K\pi$ Decay at BaBar

(Phys. Rev. Lett. 98:211802, 2007)

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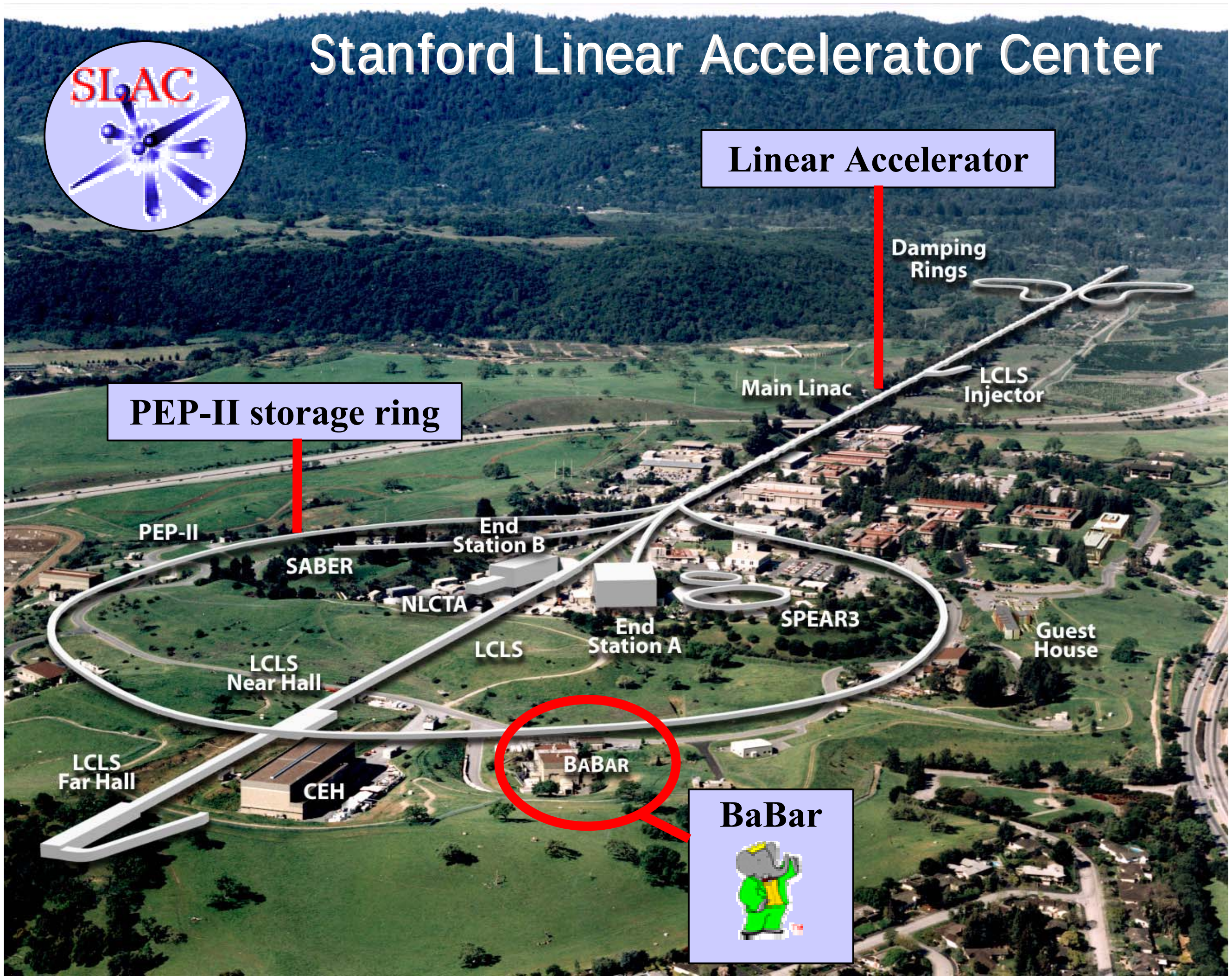
PEP-II, a B-Factory (and Charm)



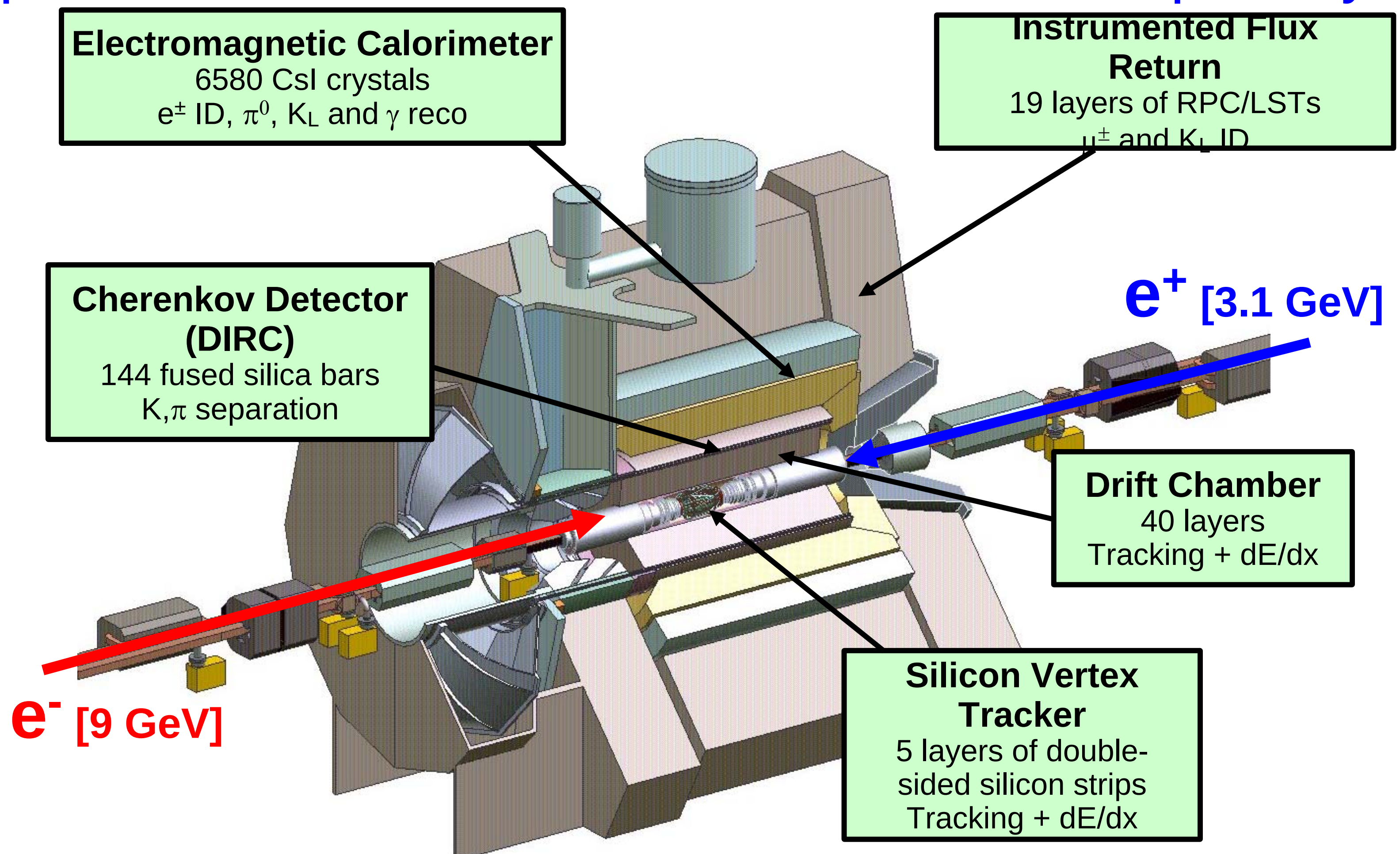
High-luminosity asymmetric energy e^+e^- collider at $\Upsilon(4S)$ resonance

B-Factory built for study of CP-violation and other CKM-physics in B meson decays

~10 Hz of $B\overline{B}$

The BaBar Experiment

BaBar is a large acceptance experiment with excellent particle reconstruction and identification capability



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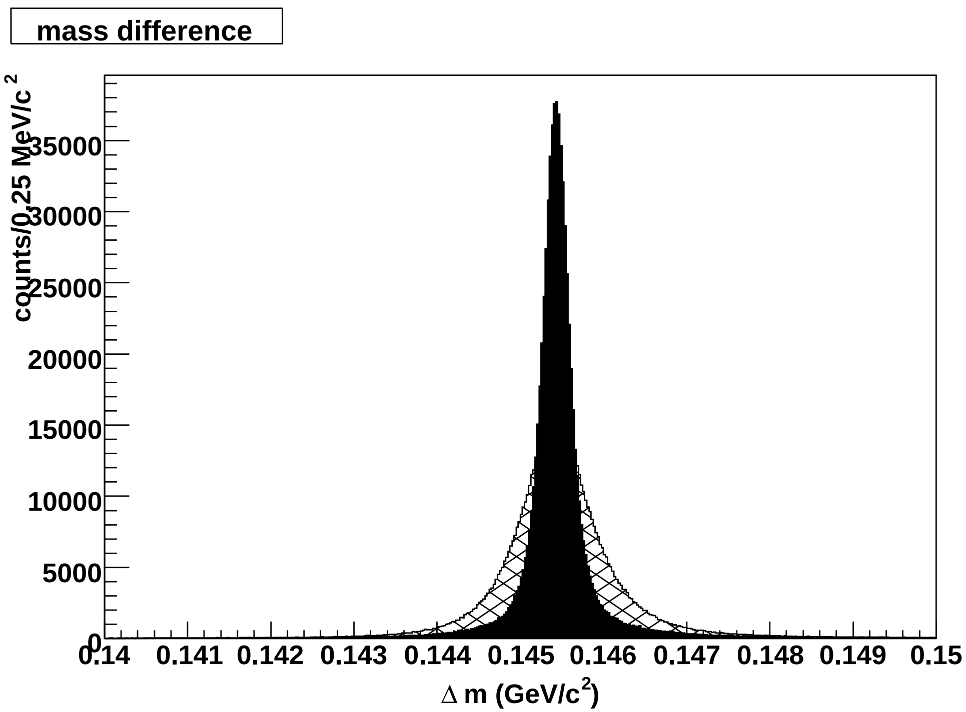
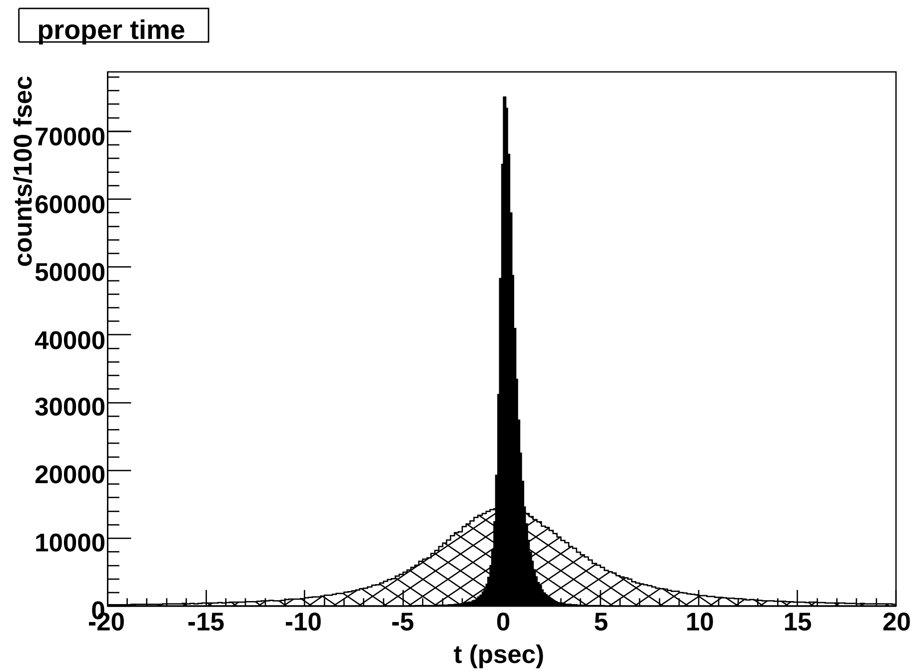
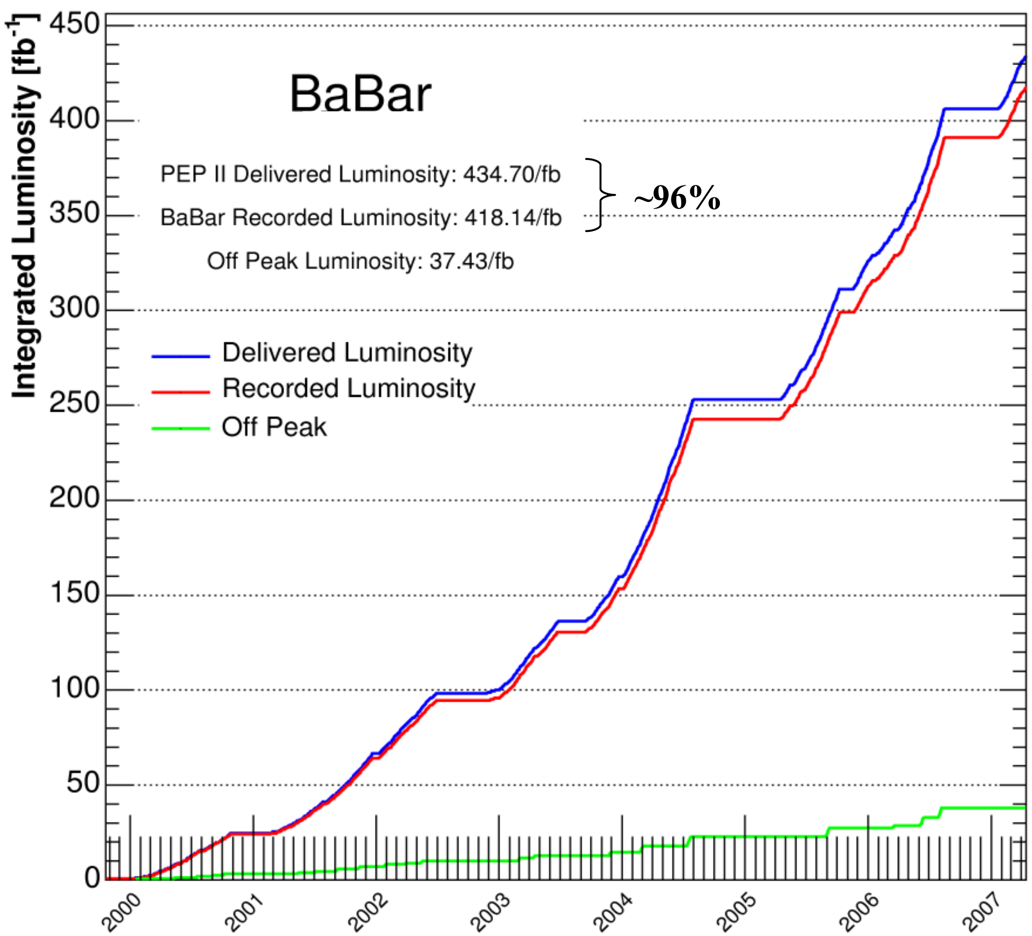
Effect of Beam Spot Constraint on ΔM and t





B-Factory: High Luminosity

High luminosity recorded efficiently



$\sigma_{eff}(b\bar{b})$=1.1 nb
$\sigma(c\bar{c})$=1.3 nb

Recorded >400M $B\bar{B}$ events, and >500M $c\bar{c}$ events

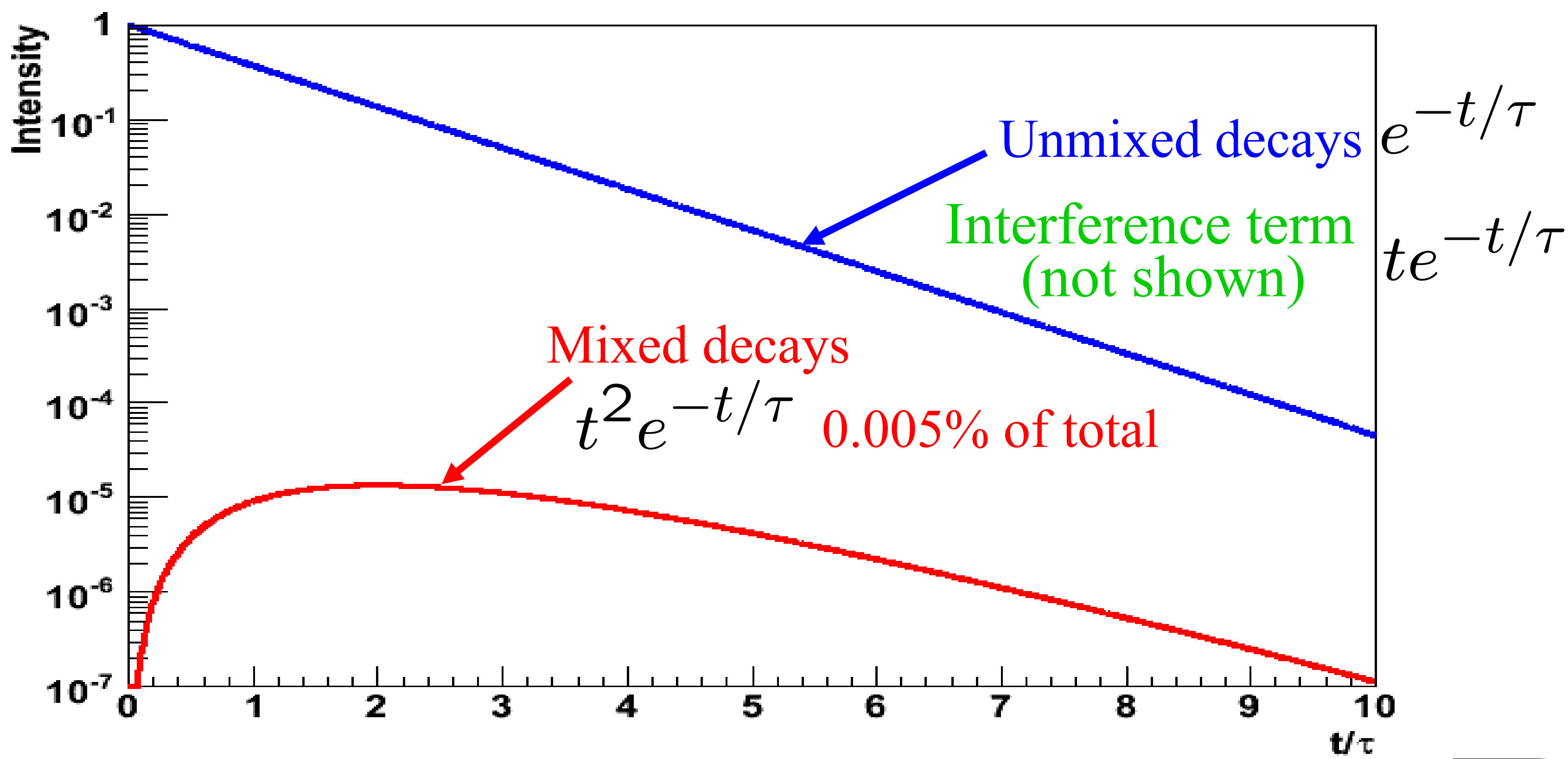
Add ~1M $c\bar{c}$ each day

Excellent sample to search for charm mixing

Principle of Mixing Measurement

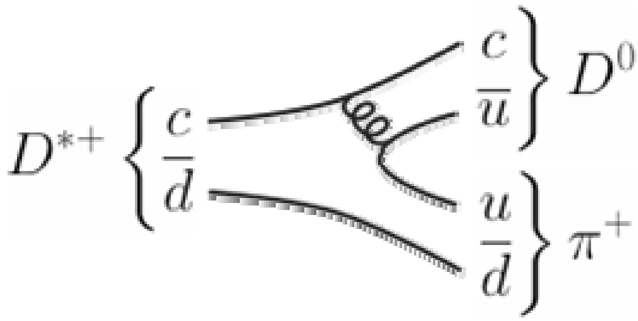
- Produce clean sample of D^0 and $\bar{D}^0$
- Identify flavor (D^0 or $\bar{D}^0$?) at decay time
- Measure rate of mixed decays as function of time

(Distributions shown without time smearing)



Production Flavor

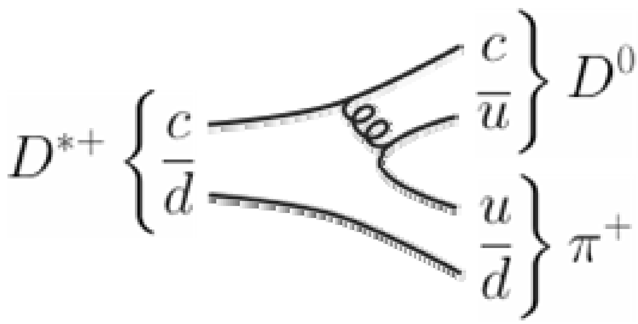
Use D^0 from $D^{*+} \to D^0 \pi^+$ decays:



Charge of pion "tags" initial flavor as D^0 or $\overline{D^0}$

Production Flavor

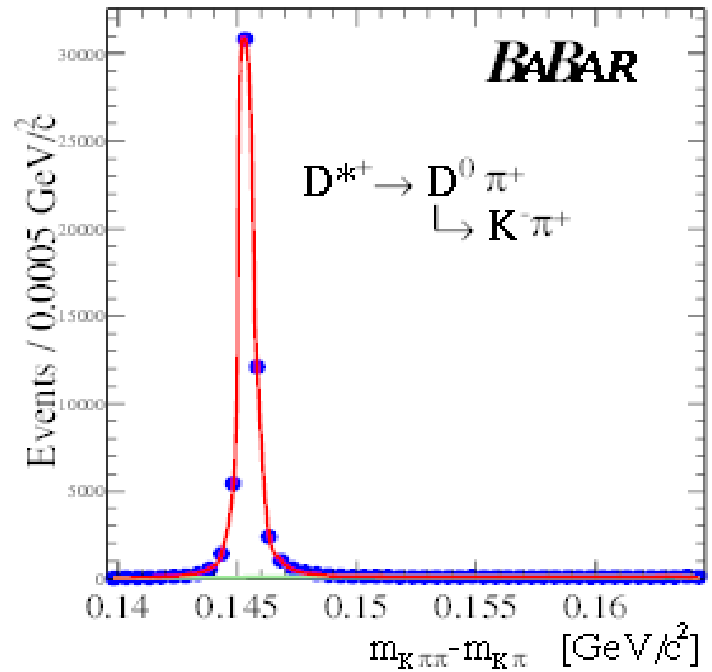
Use D^0 from $D^{*+} \to D^0 \pi^+$ decays:



Charge of pion "tags" initial flavor as D^0 or $\overline{D^0}$

Additional benefit: small Q

Gives narrow mass peak



Excellent background suppression

$\Delta m = m(D^0 \pi^+) - m(D^0)$

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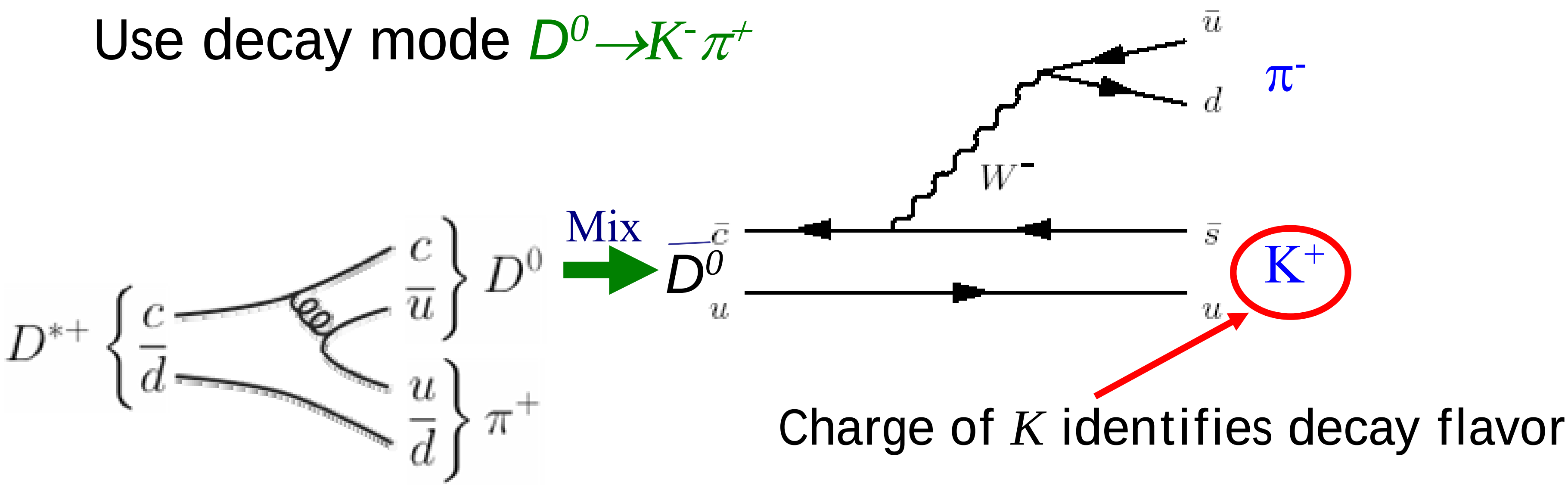
Flavor at Decay

Use decay mode $D^0 \to K^- \pi^+$



If opposite flavor: Wrong-sign (WS) event – mixing occurred
If same flavor: Right-sign (RS) events – unmixed decay

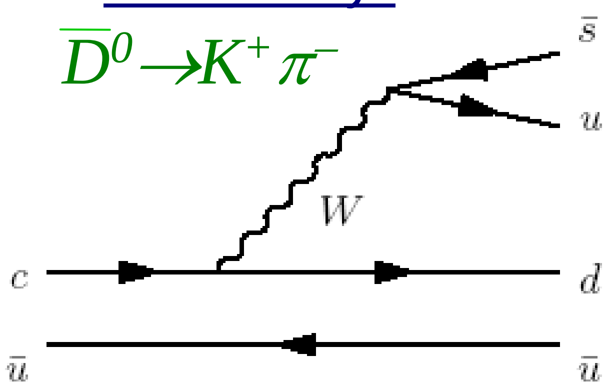
Doubly-Cabibbo Suppressed Decays

Hadronic decays do not uniquely identify decay flavor

Get unmixed wrong-sign decays from DCS decays

<u>DCS decay:</u>

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



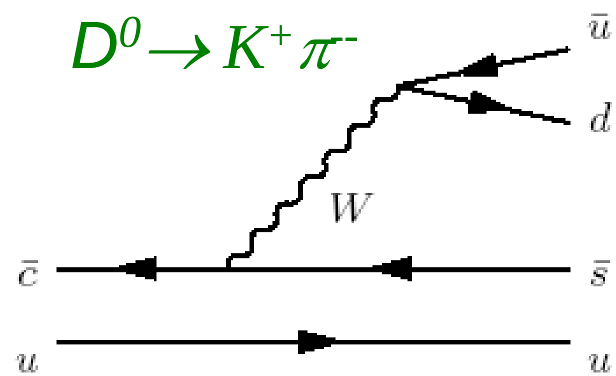
Relative rate ~0.3%

Mix

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

<u>Mixed decay:</u>

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

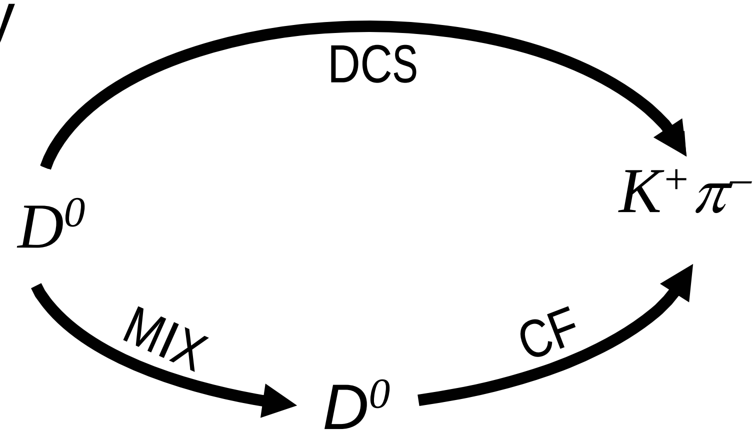


Relative rate: 0.005% (for x=0.01)

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

Discriminate DCS and mixing by their different time evolution

Also have interference effect:



Time evolution:

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

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

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

Event Selection

D^0 selection:

❖Identified K and π

❖p*(D^0)> 2.5 GeV/c

❖1.81<m($K\pi$)<1.92 GeV/c^2

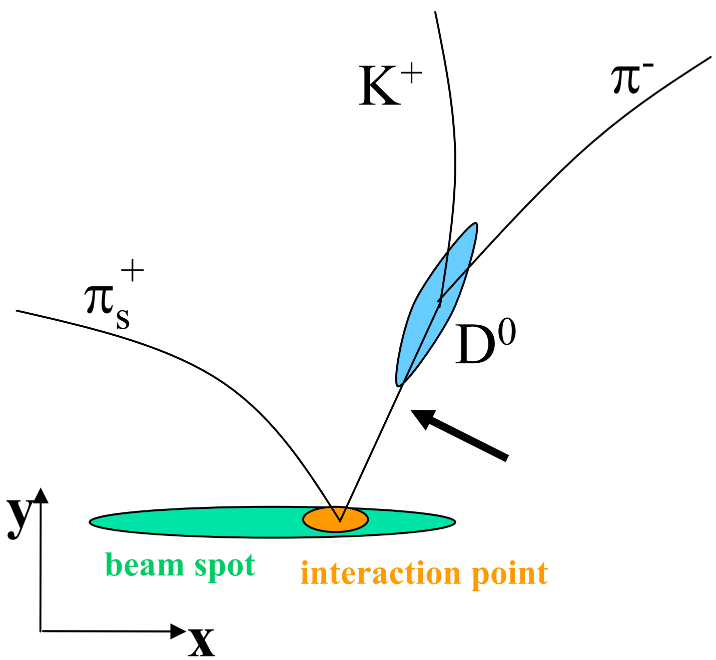
Slow π selection:

❖p*(π_s)< 0.45 GeV/c

❖p_{lab}(π_s)> 0.1 GeV/c

❖0.14<Δm<0.16 GeV/c^2

$\Delta m = m(K\pi\pi_s) - m(K\pi)$



Vertexing: (Also greatly improves t resolution)

❖D^0 and π_s constrained to luminous region

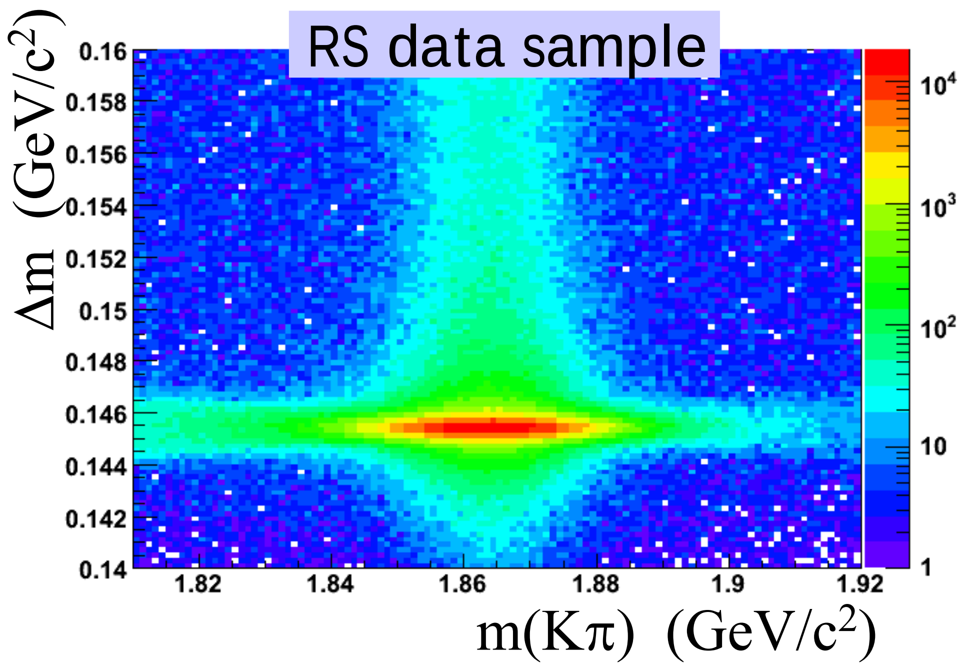
❖Fit probability > 0.1%

❖Reconstructed decay time, t: -2<t<4 ps

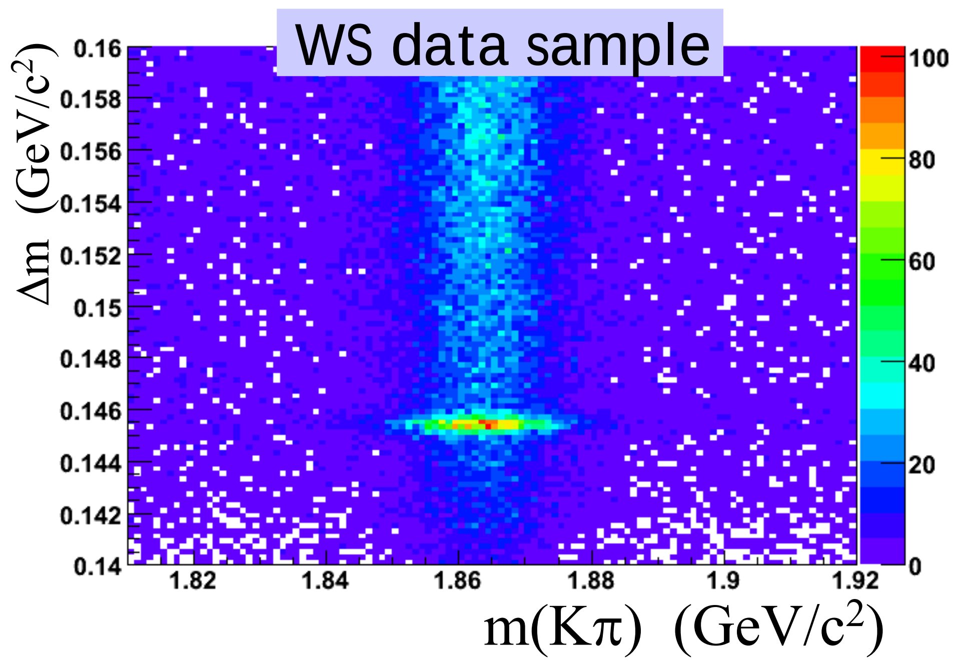
❖Estimated decay time error, δt<0.5 ps

Selected Events

1,229,000 RS events



64,000 WS events



Separate signal from background using m(Kπ) and Δm

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)

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- Compare fit with and without mixing (and CP violation)

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Signal and Background Components

$\Delta m \equiv m(K\pi\pi) - m(K\pi)$

$Q \equiv m(K\pi\pi) - m(K\pi) - m(\pi)$

Signal: (MC)

- Correct $D^{*+} \to D^0 \pi^+$
- Peaks in $m(K\pi)$ and Δm

Random π_s: (MC)

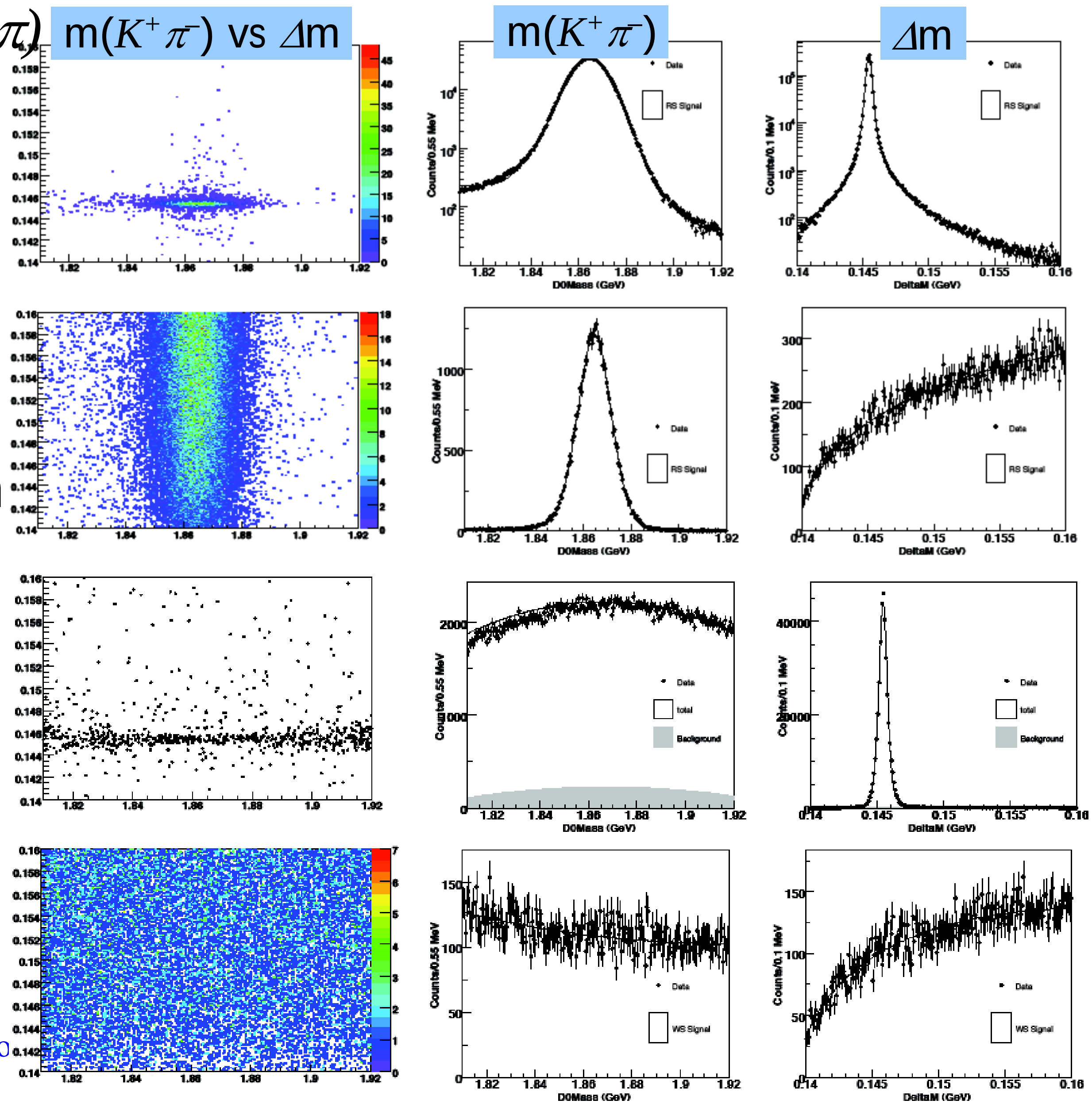
- Correct $\bar{D}^0$, wrong π_s
- Peaks in $m(K\pi)$, not Δm

Mis-reco D^0: (Data)

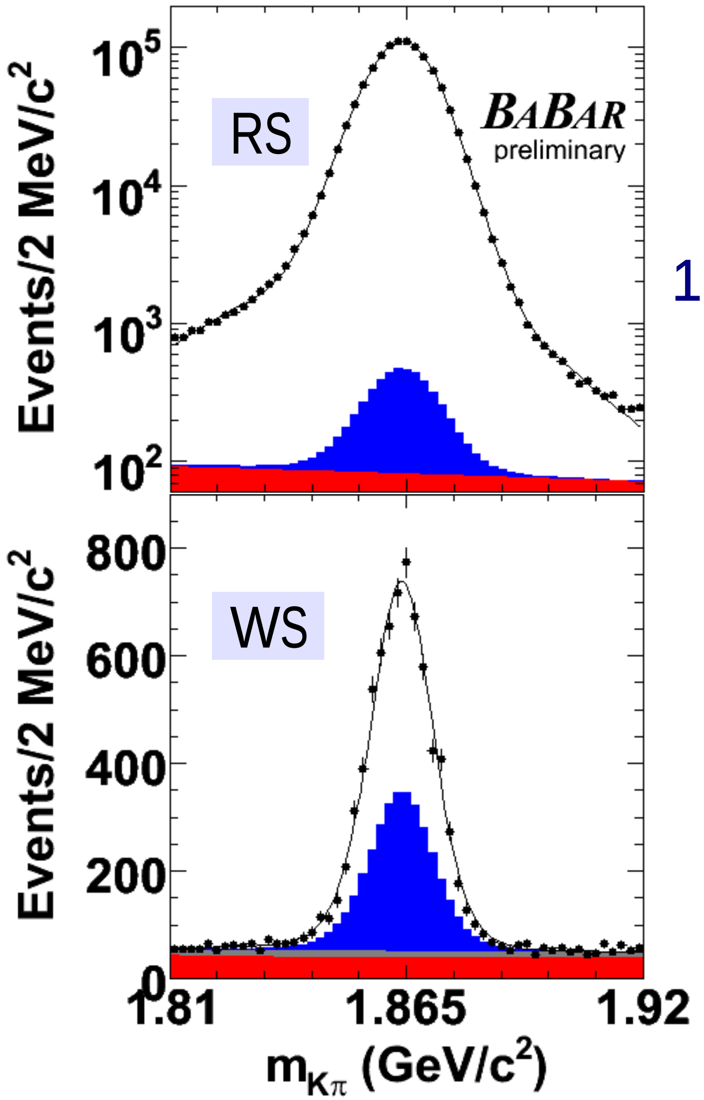
- Real $D^{*+} \to D^0 \pi^+$
- $D^0 \to K^- \mu^+ \nu$
- Double misid $D^0 \to K^- \pi^+$ (WS events only)

Combinatoric: (MC)

- Random tracks

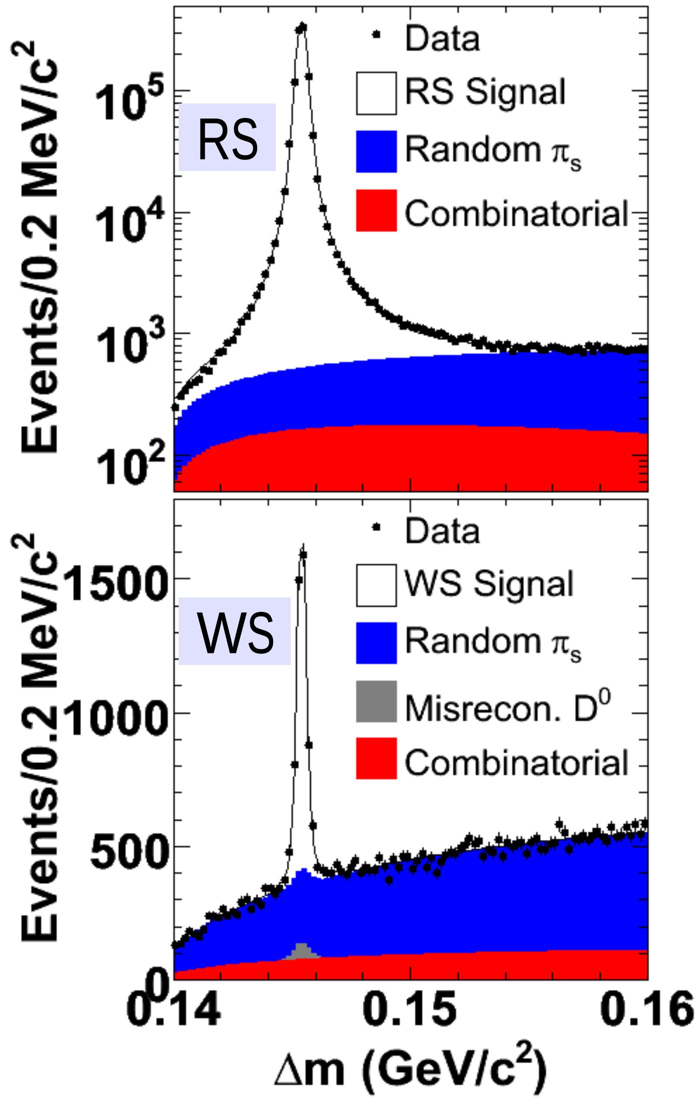


m(Kπ)-Δm Fit Results



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



RS Decay Time Fit

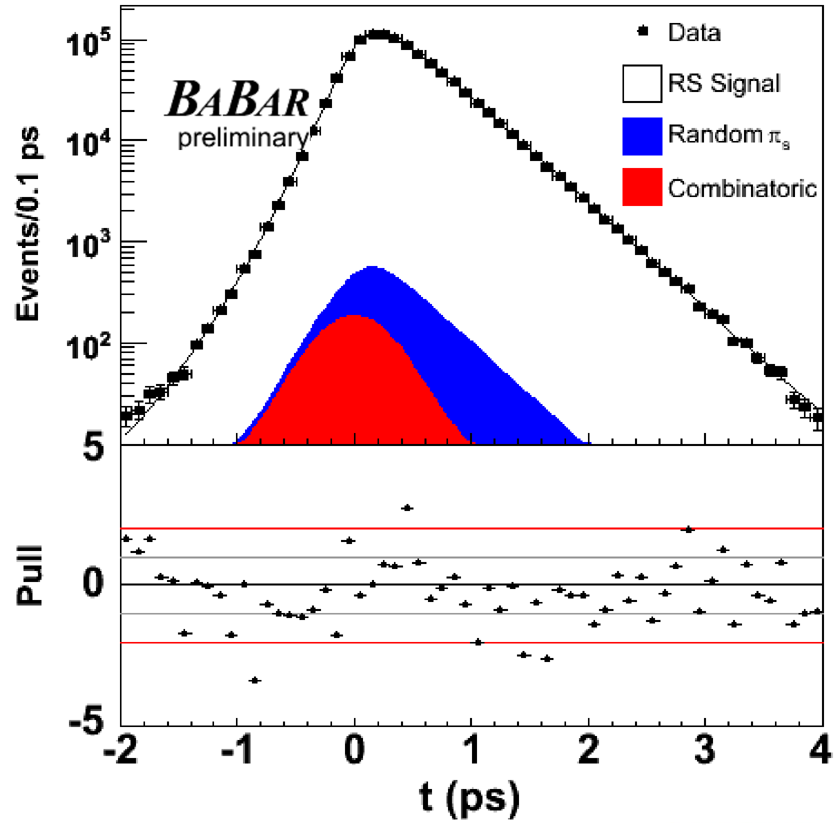
RS decay time, signal region

D^0 lifetime and resolution function fitted in RS sample

$\tau = (410.3 \pm 0.6(\text{stat.}))$ fs

Consistent with PDG (410.1±1.5 fs)

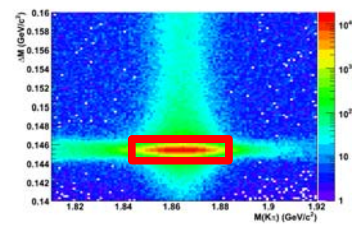
Systematics dominated by resolution function



plot selection:

$1.843 < m < 1.883$ GeV/c^2

$0.1445 < \Delta m < 0.1465$ GeV/c^2



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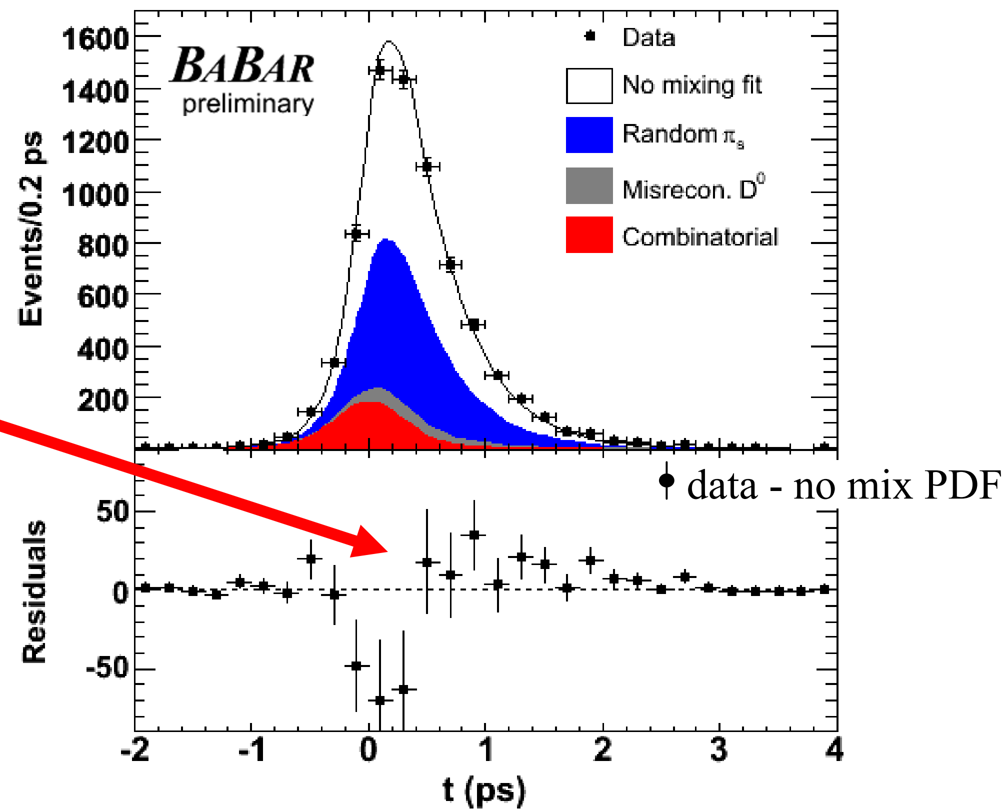
WS Fit with no Mixing

Fit results assuming no mixing:

R_D: $(3.53\pm0.08\pm0.04)\times10^{-3}$

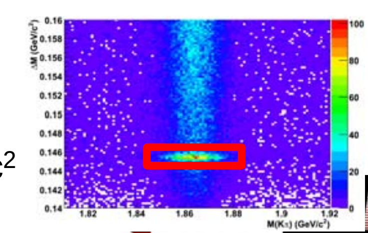
WS decay time, signal region



However, residuals in signal region are not good

Data and pdf projection are for signal region shown here:

plot signal region:
$1.843 < m < 1.883$ GeV/c^2
$0.1445 < \Delta m < 0.1465$ GeV/c^2



WS Fit with Mixing

Fit results allowing mixing:

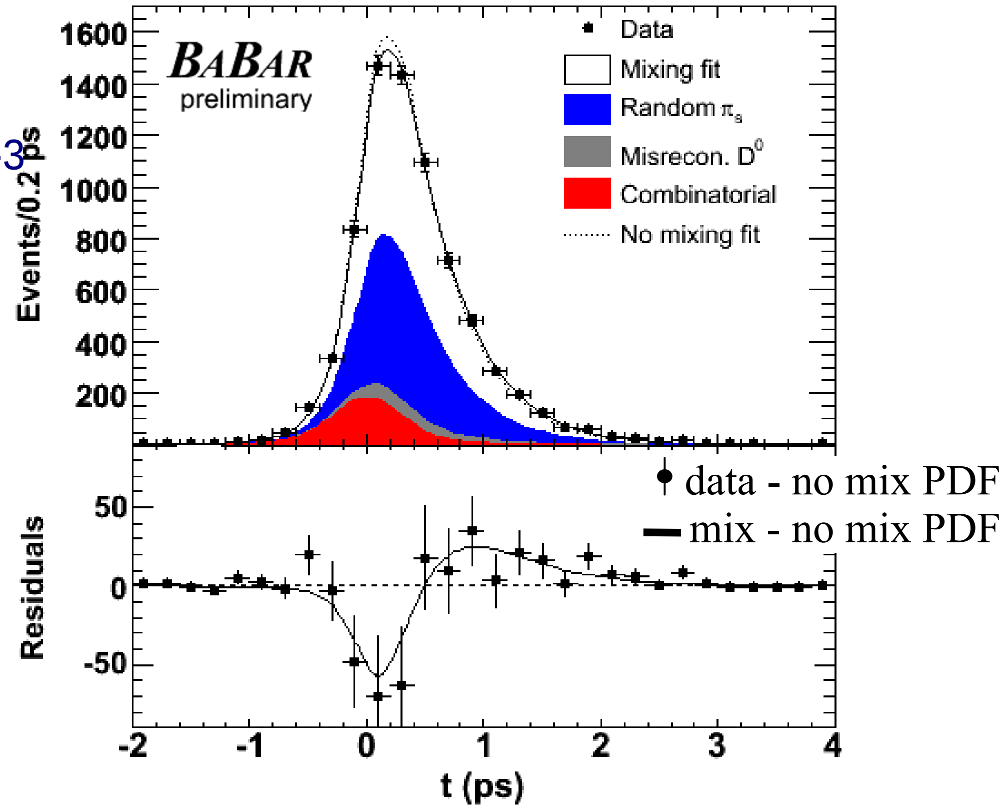
R_D: $(3.03\pm0.16\pm0.10)\times10^{-3}$

x'^2: $(-0.22\pm0.30\pm0.21)\times10^{-3}$

y': $(9.7\pm4.4\pm3.1)\times10^{-3}$

x'^2, y' correlation: -0.94

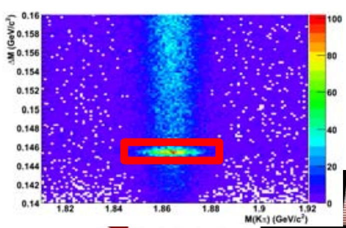
WS decay time, signal region



Fit with gives better description of data

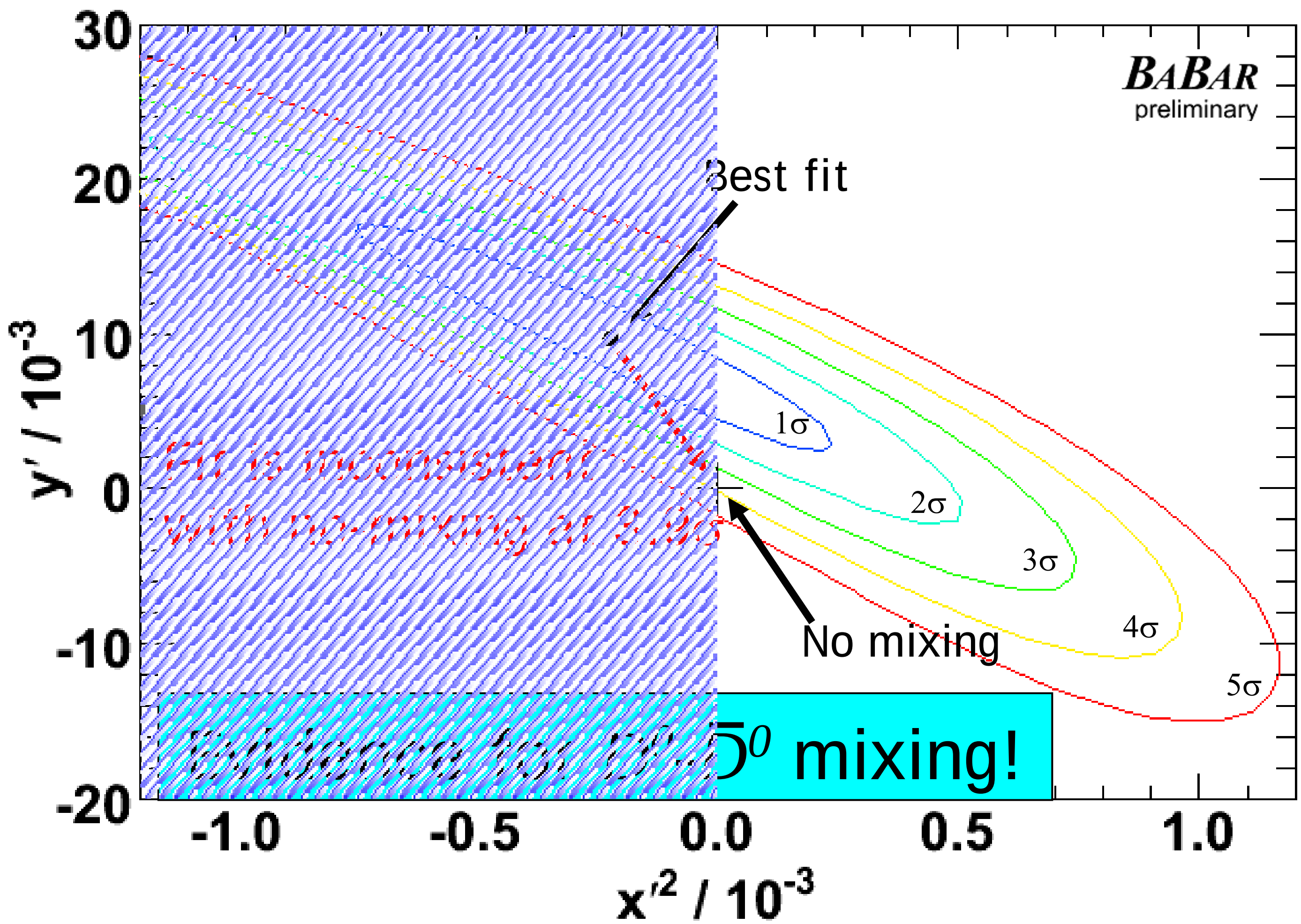
How significant?

plot signal region:
$1.843 < m < 1.883$ GeV/c^2
$0.1445 < \Delta m < 0.1465$ GeV/c^2



Signal Significance with Systematics

Including systematics decreases signal significance



Validation Studies

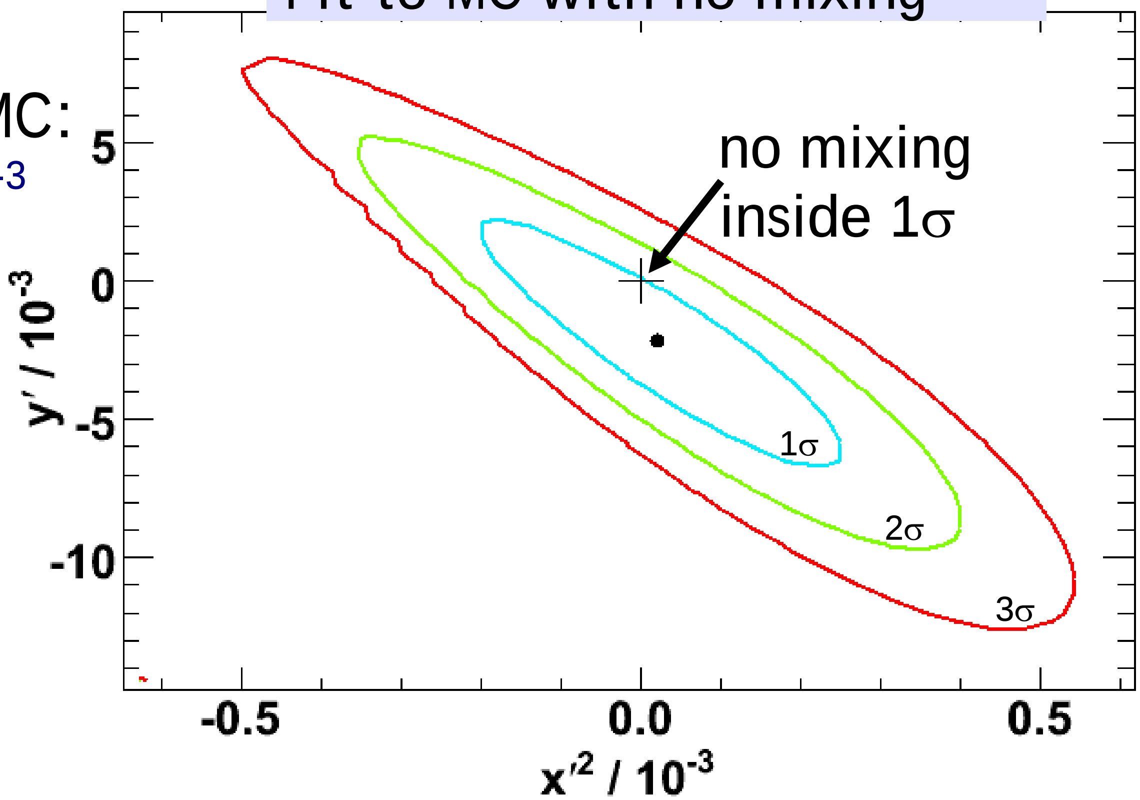
Performed extensive checks of mixing signal:

- Could something fake signal?
- Is significance estimated correctly?
- Are mixing parameters unbiased?

No signal found in MC:
x'^2: $(-0.02\pm0.18)\times10^{-3}$
y': $(-2.2\pm3.0)\times10^{-3}$

In MC with signal,
fit reproduces signal
- no intrinsic bias

Fit to MC with no mixing



Validation: Alternative Fit Strategy

<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

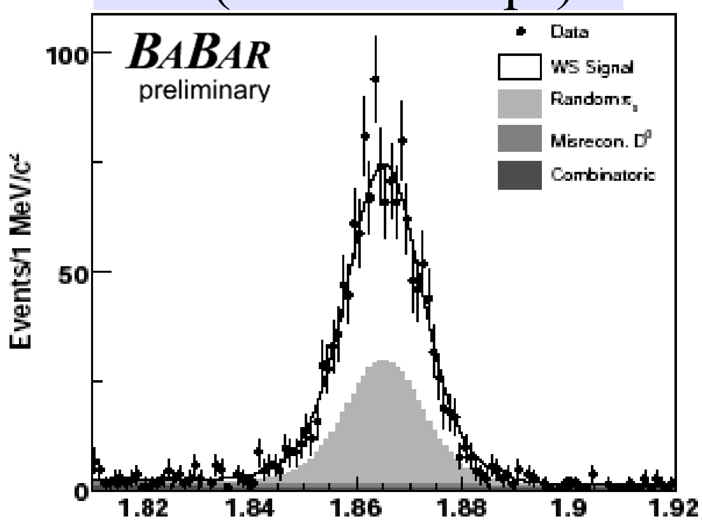
$0 < t < 0.2$ psec

$0.2 < t < 0.4$ psec

$0.4 < t < 0.75$ psec

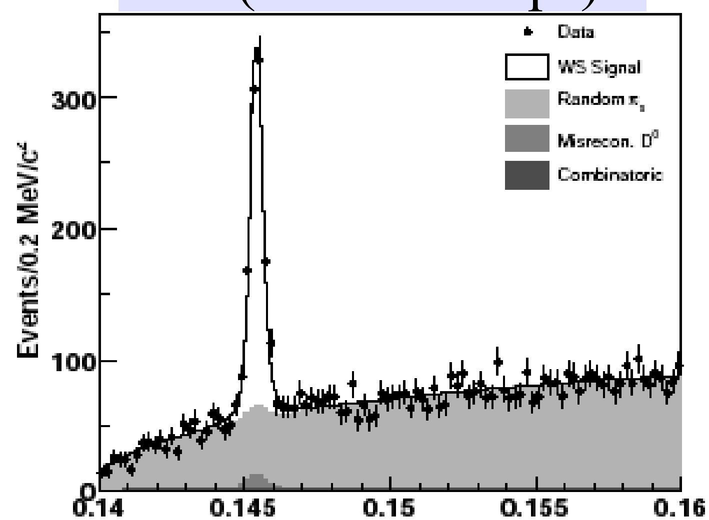
$0.75 < t < 2.5$ psec

WS (0.75<t<2.5 ps)



$m(K^+\pi^-)$

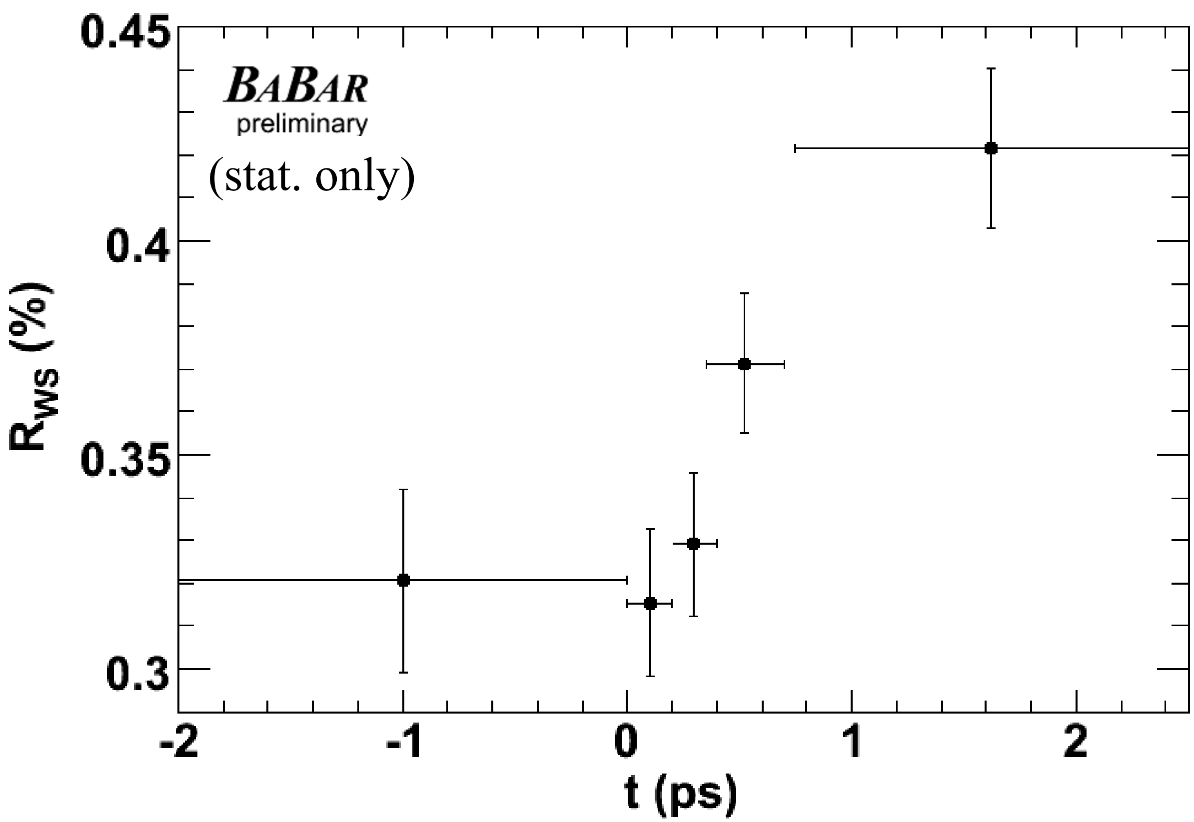
WS (0.75<t<2.5 ps)



Δm

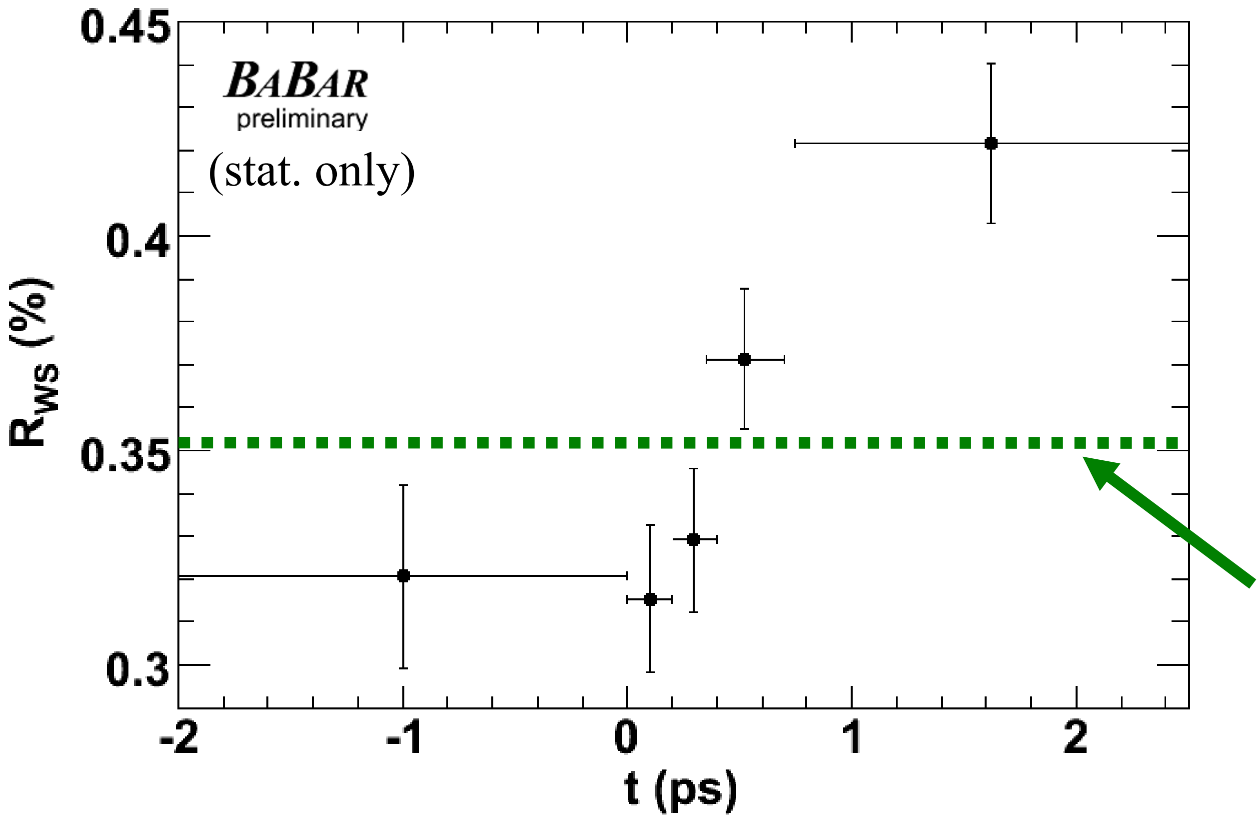
Validation: Alternative Fit Strategy

Rate of WS events clearly increase with time:



Validation: Alternative Fit Strategy

Rate of WS events clearly increase with time:

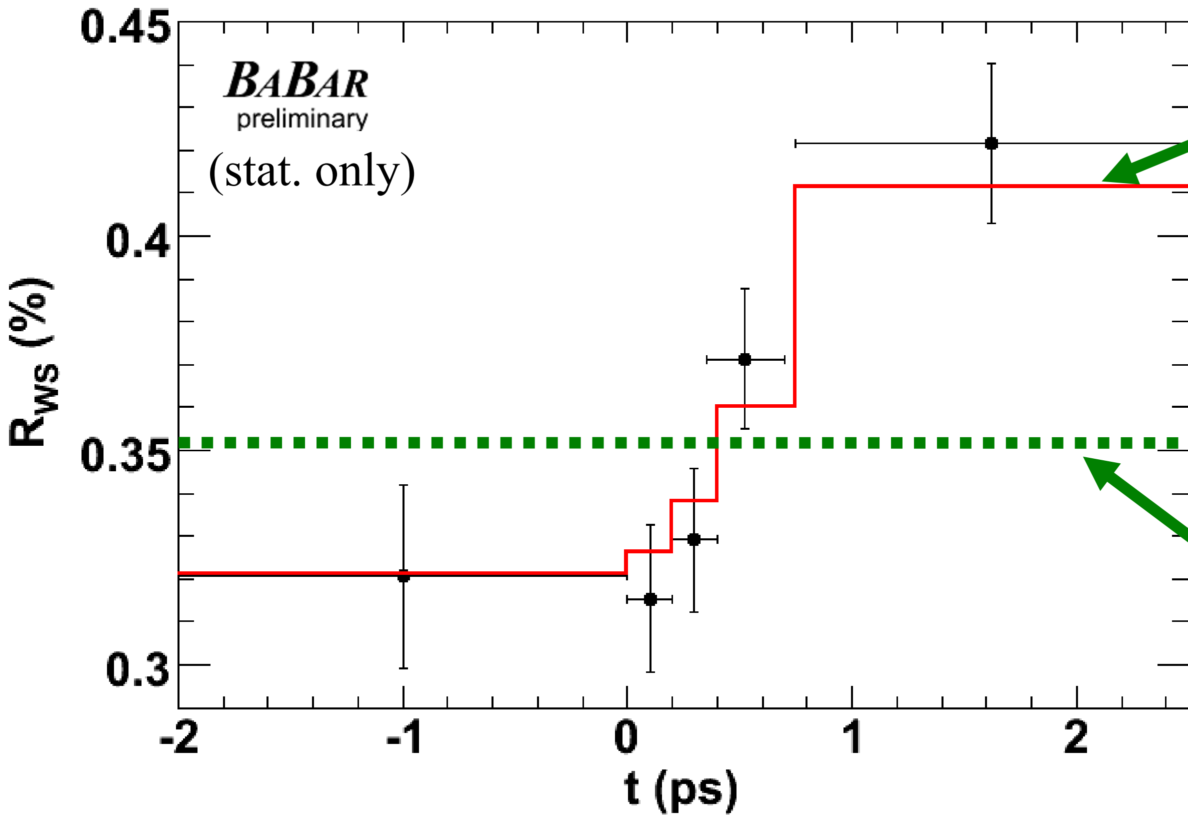


Inconsistent with no-mixing hypothesis

χ^2=24

Validation: Alternative Fit Strategy

Rate of WS events clearly increase with time:



Consistent with prediction from full likelihood fit
$\chi^2=1.5$

Inconsistent with no-mixing hypothesis
$\chi^2=24$

Validation: Fit RS Data for Mixing

Fit RS data with PDF allowing mixing

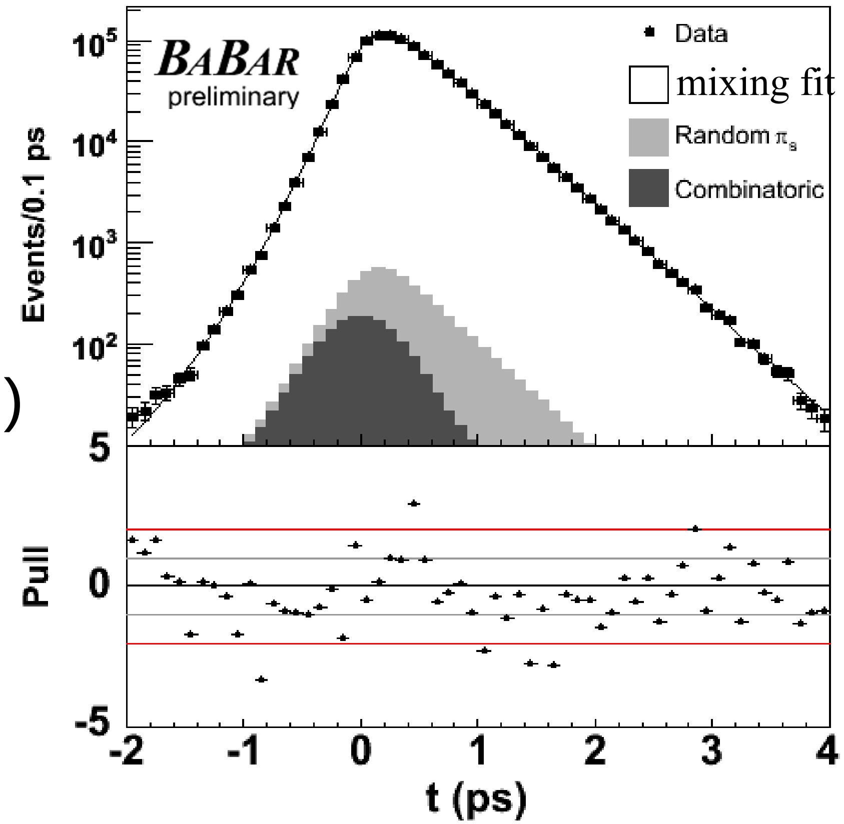
x'^2: $(-0.01\pm0.01)\times10^{-3}$

y': $(0.26\pm0.24)\times10^{-3}$

(w.r.t. no mixing)

D^0 decay time distribution is described properly

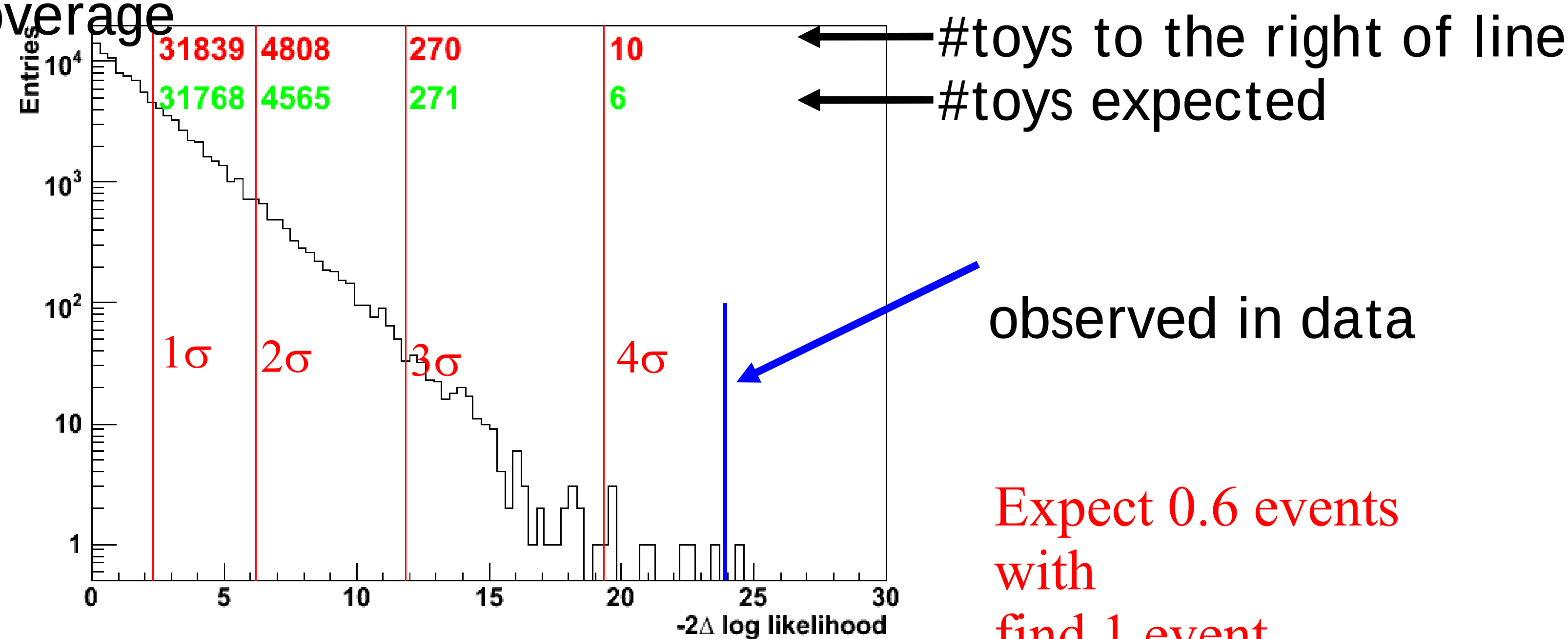
RS decay time, signal region



Validation: Coverage of -2ΔLog$\mathscr{L}$

Significance of signal is calculated as change in log likelihood with respect to no-mixing hypothesis

Generated >100000 toys without mixing to test gives correct frequentist coverage



Expect 0.6 events with
find 1 event

Systematic Uncertainties

Two types of systematic uncertainties considered:

Fit model variations:

❖Change signal and background models used in fit, to test assumptions made

Selection criteria:

❖Mainly decay time (error) ranges used in fit

Systematic:	R_D	x'^2	y'
Fit Model	0.59σ	0.40σ	0.45σ
Selection Criteria	0.24σ	0.57σ	0.55σ
Total	0.63σ	0.70σ	0.71σ

Fraction of statistical uncertainty

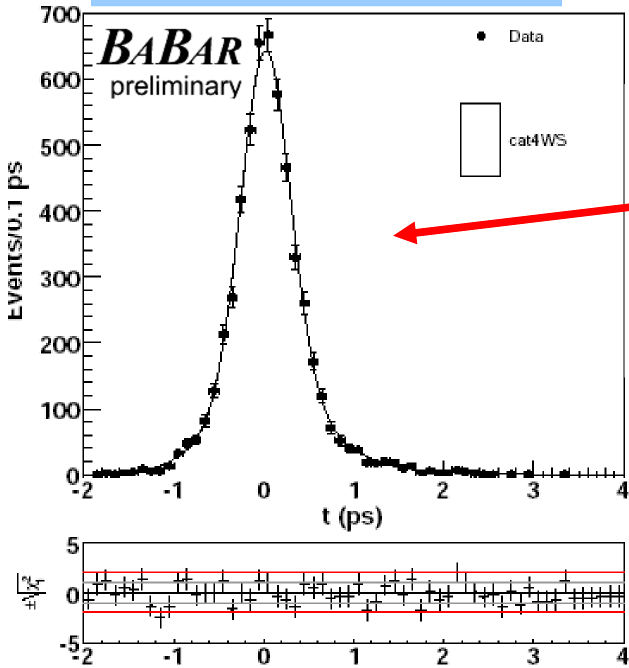
x'^2-y' correlation also present in systematics

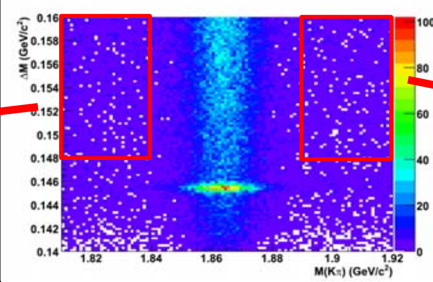
Effectively the (x'^2, y') contours increase by ~15%

Systematic: Combinatorial Decay Time

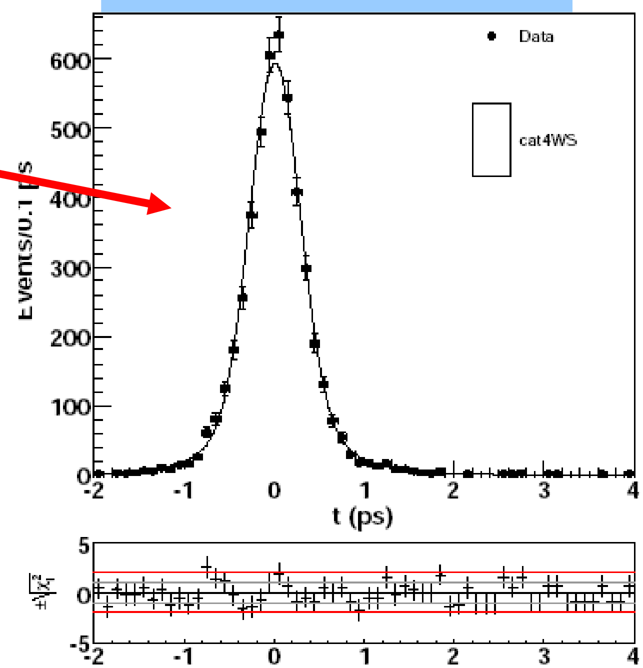
Decay time in combinatorial bkgd not independent of m(Kπ)
Fix PDF parameters to fits in different background sidebands:

$1.81 < m < 1.84$ GeV/c^2
$0.148 < \Delta m < 0.16$ GeV/c^2





$1.883 < m < 1.92$ GeV/c^2
$0.148 < \Delta m < 0.16$ GeV/c^2



Systematic variation:

y' -0.3σ
x'^2 $+0.2\sigma$

Systematic: Decay Time Resolution

Decay time resolution function in data has non-zero mean

Core Gaussian shifted 3.6±0.6fs

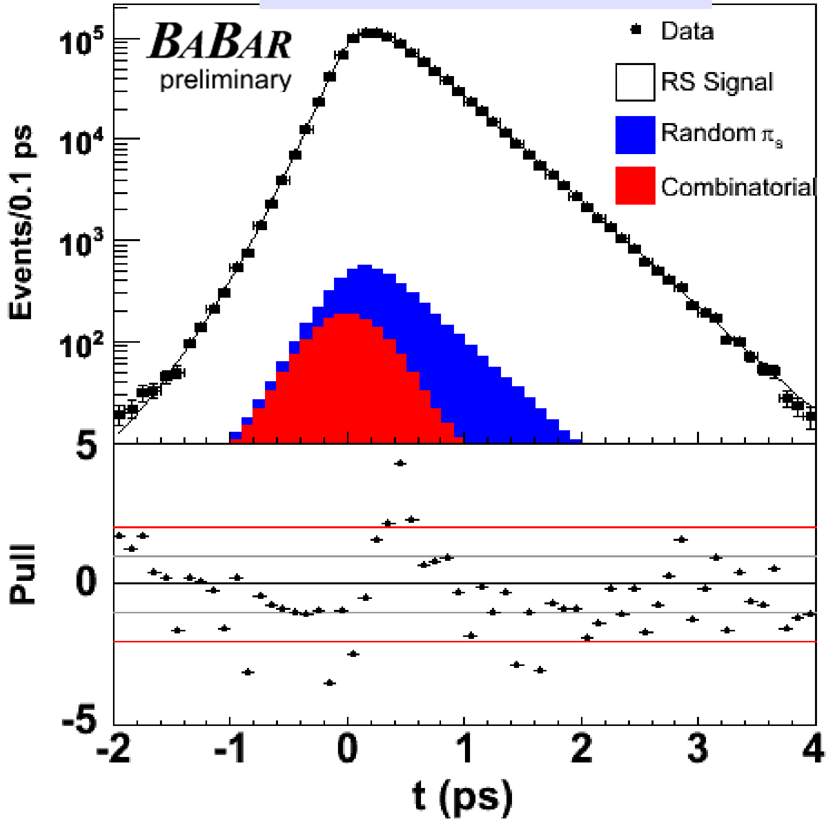
Effect is not seen in MC
- probably due to misalignment

For systematics set mean to 0:

Variation: y' 0.3σ
x'^2 -0.3σ

No reason why resolution should be different for RS and WS decays

RS decay time, resolution mean fixed to zero



Allowing for CP Violation

CP violation could introduce different time dependence for *D⁰* (+) and *D⁰* (-):

$$\frac{T^{\pm}_{\mathrm{WS}}(t)}{e^{-\Gamma t}} = \sqrt{\frac{1 \pm A_{\mathrm{D}}}{1 \mp A_{\mathrm{D}}}} R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}} \sqrt[4]{\frac{(1 \pm A_{\mathrm{D}})(1 \pm A_{\mathrm{M}})}{(1 \mp A_{\mathrm{D}})(1 \mp A_{\mathrm{M}})}} (y' \cos\varphi \mp x' \sin\varphi)\Gamma t + \sqrt{\frac{1 \pm A_{\mathrm{M}}}{1 \mp A_{\mathrm{M}}}} \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

Three possible types of CP violation:

- ❖Direct CP violation in DCS decay
- ❖CP violation in mixing
- ❖CP violation in interference between mixing and decay

Simpler to fit *D⁰* (+) and *D⁰* (-) separately:

$$\frac{\Gamma^{\pm}_{WS}(t)}{e^{-t/\tau}} \propto R^{\pm}_{D} + \sqrt{R^{\pm}_{D}} y'^{\pm} \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right) \left(\frac{t}{\tau}\right)^2$$

CP violation if one or more "±" parameters are different

CPV Allowed Contours

Results of fitting D^0 and $\bar{D}^0$ separately:

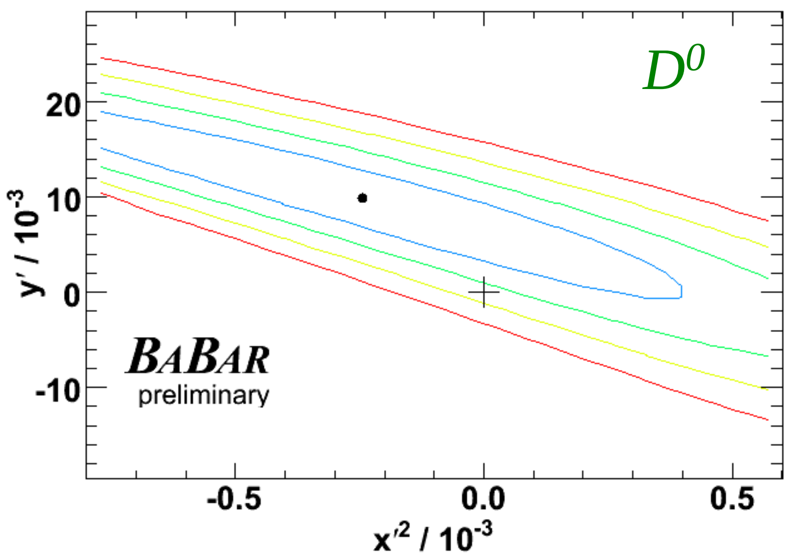
x'^{+2}: $(-0.24 \pm 0.43 \pm 0.30) \times 10^{-3}$

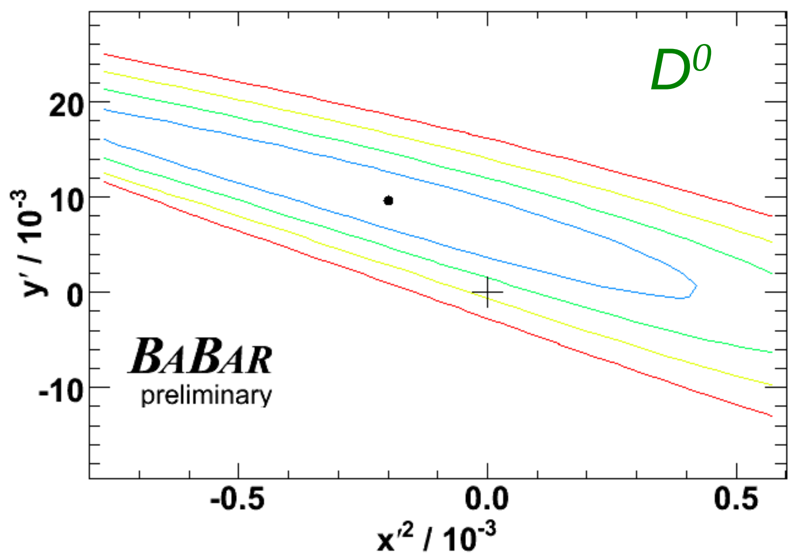
y'^{+}: $(9.8 \pm 6.4 \pm 4.5) \times 10^{-3}$

x'^{-2}: $(-0.20 \pm 0.41 \pm 0.29) \times 10^{-3}$

y'^{-}: $(9.6 \pm 6.1 \pm 4.3) \times 10^{-3}$

$A_D = (-2.1 \pm 5.2 \pm 1.5)\%$





No evidence for CP violation found

Other searches for D^0 mixing and for CP violation in D^0 decays

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D^0-$\overline{D}^0$ Mixing in Lifetime Ratio of $D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $D^0 \to K^-\pi^+$

$D^0 \to K^-\pi^+$: CP-mixed $D^0(t) \to K^+K^-$, $\pi^+\pi^-$: CP–even

Determine the quantities

$$h = K \text{ or } \pi$$

$$\begin{aligned} \langle\tau_{hh}\rangle &= (\tau_{hh}^+ + \tau_{hh}^-)/2 \\ A_\tau &= (\tau_{hh}^+ - \tau_{hh}^-)/(\tau_{hh}^+ + \tau_{hh}^-) \end{aligned}$$

$$\boldsymbol{y_{CP} = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} - 1, \qquad \Delta Y = \frac{\tau_{K\pi}}{\langle\tau_{hh}\rangle} A_\tau}$$

$$x \equiv 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2} \qquad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

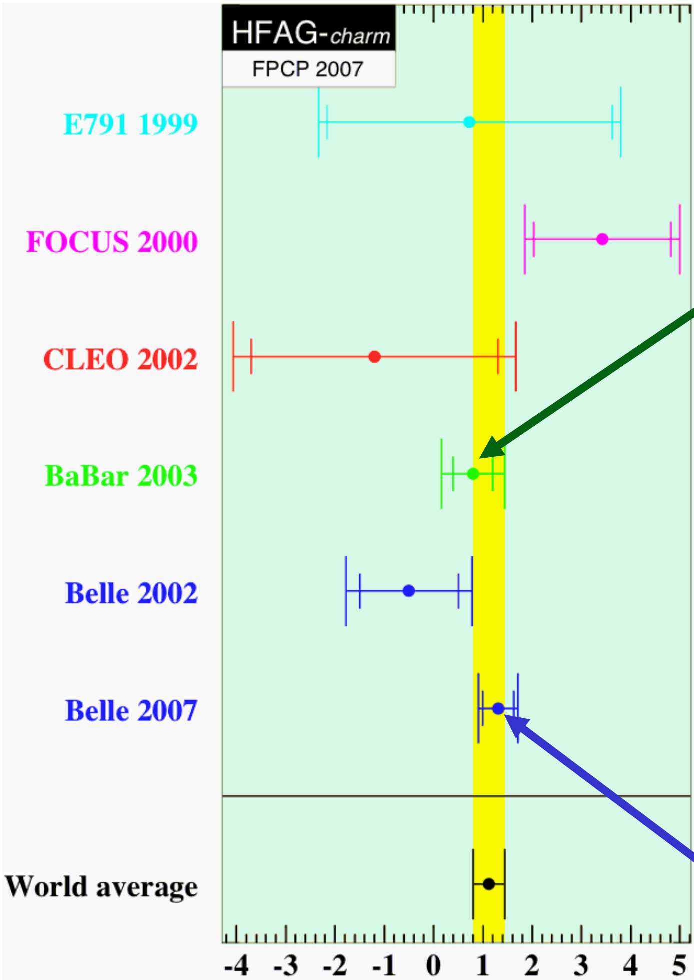
CPV in interference of mixing and decay:

$$\varphi_f \equiv \arg\left(\frac{q}{p}\frac{\langle f|\mathcal{H}_D|\overline{D}^0\rangle}{\langle f|\mathcal{H}_D|D^0\rangle}\right) \neq 0$$

If CP is conserved $y_{CP} = y$, $\Delta Y = 0$

$$\begin{aligned} \boldsymbol{y_{CP}} &= \boldsymbol{y\cos\varphi_f} \\ \boldsymbol{\Delta Y} &= \boldsymbol{x\sin\varphi_f} \end{aligned}$$

Previous lifetime ratio results



$\langle y_{CP} \rangle = (1.122 \pm 0.321)\%$

BaBar, PRL 91, 162001(2002) 91 fb^{-1}

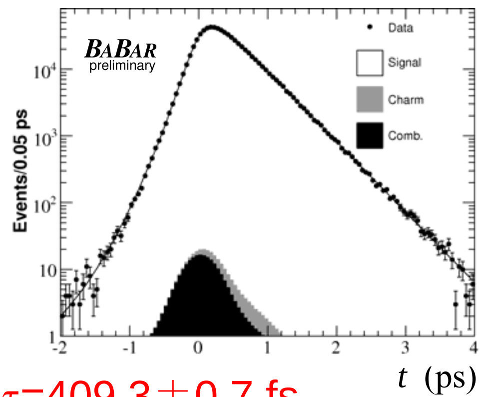
Sample	Y (%)	ΔY (%)
K^-K^+	$1.5 \pm 0.8 \pm 0.5$	$-1.3 \pm 0.8 \pm 0.2$
$\pi^-\pi^+$	$1.7 \pm 1.2\ ^{+1.2}_{-0.6}$	$0.3 \pm 1.1 \pm 0.2$
Untagged K^-K^+	$0.2 \pm 0.5\ ^{+0.5}_{-0.4}$	—
Combined	$0.8 \pm 0.4\ ^{+0.5}_{-0.4}$	$-0.8 \pm 0.6 \pm 0.2$

BELLE, PRL 98, 211803 (2007) 540 fb^{-1}

Sample	Y (%)	$A_\Gamma \approx -\Delta Y (\%)$
K^-K^+	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^-\pi^+$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

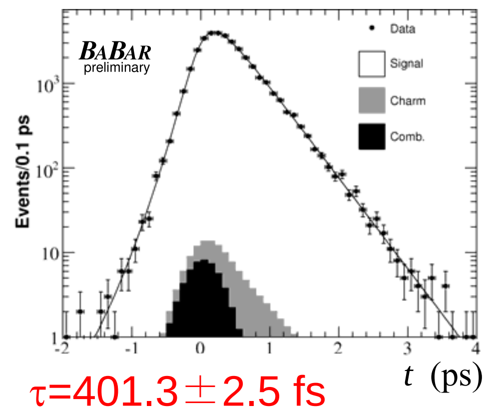
Decay time fits to determine (y_{CP}, ΔY)

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



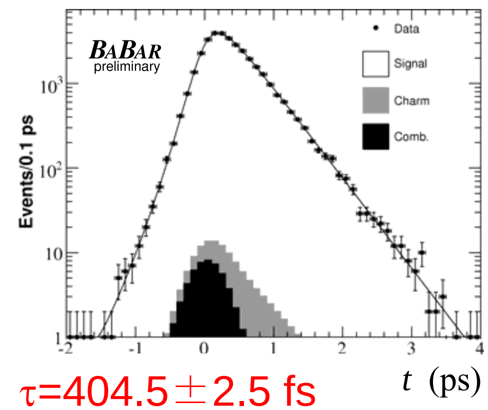
τ=409.3±0.7 fs

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

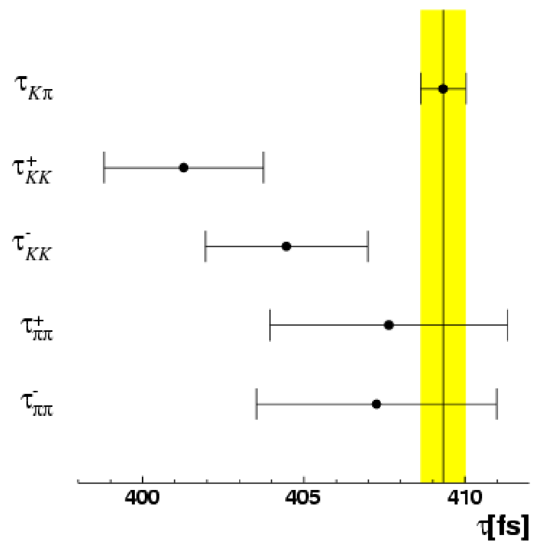


τ=401.3±2.5 fs

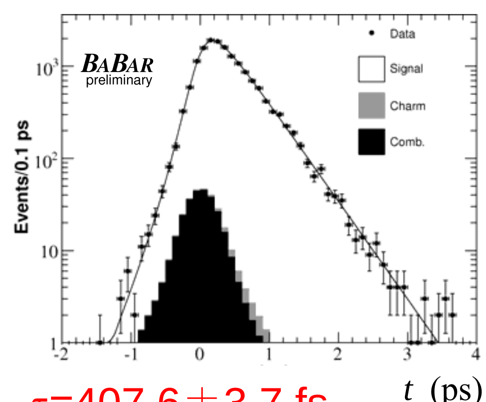
$\overline{D}^0 \to K^+K^-$



τ=404.5±2.5 fs

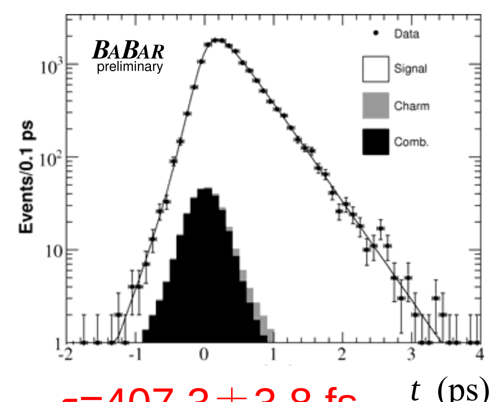


$D^0 \to \pi^+\pi^-$



τ=407.6±3.7 fs

$\overline{D}^0 \to \pi^+\pi^-$



τ=407.3±3.8 fs

***Kπ* and *KK* lifetimes differ!**

BaBar (y_{CP}, ΔY) results

Tagged results from 384 fb^{-1}:

	y_{CP}	ΔY
K^+K^-	$(1.60 \pm 0.46(\text{stat}) \pm 0.17(\text{syst}))\%$	$(-0.40 \pm 0.44(\text{stat}) \pm 0.12(\text{syst}))\%$
$\pi^+\pi^-$	$(0.46 \pm 0.65(\text{stat}) \pm 0.25(\text{syst}))\%$	$(0.05 \pm 0.64(\text{stat}) \pm 0.32(\text{syst}))\%$
Combined	$(1.24 \pm 0.39(\text{stat}) \pm 0.13(\text{syst}))\%$	$(-0.26 \pm 0.36(\text{stat}) \pm 0.08(\text{syst}))\%$

3.0σ

0

Good agreement with Belle 540 fb^{-1} measurement:

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

$A_\Gamma = (0.01 \pm 0.30 \pm 0.15\ )\%$

M. Staric et al. (Belle Collab.), Phys. Rev. Lett. 98, 211803 (2007).

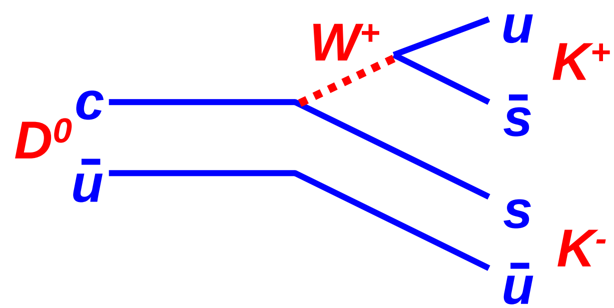
Search for direct CPV in time-integrated $D^0 \to K^+K^-, \pi^+\pi^-$ rates

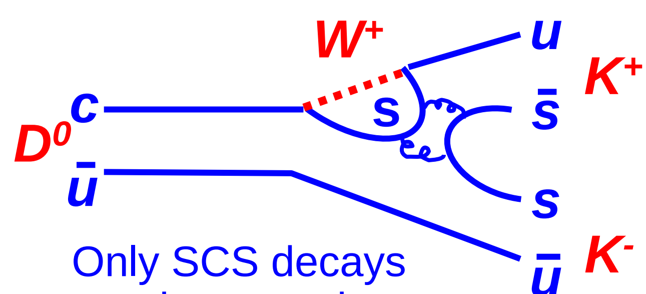
$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2\,\mathrm{Im}(A_1 A_2^*)\,sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\mathrm{Re}\,A_1 A_2^* cos(\delta_1 - \delta_2)}$$

2 weak amplitudes with phase difference

strong phase difference

e.g., $D^0 \to K^+K^-$:





Only SCS decays probe penguins

Two amplitudes with different strong & weak phases needed to observe CPV (in SM from tree and penguins)

Standard model predictions for direct CPV asymmetries in these modes: O(0.001% - 0.01%)

F. Bucella et al., Phys. Rev. **D51**, 3478 (1995).
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003).

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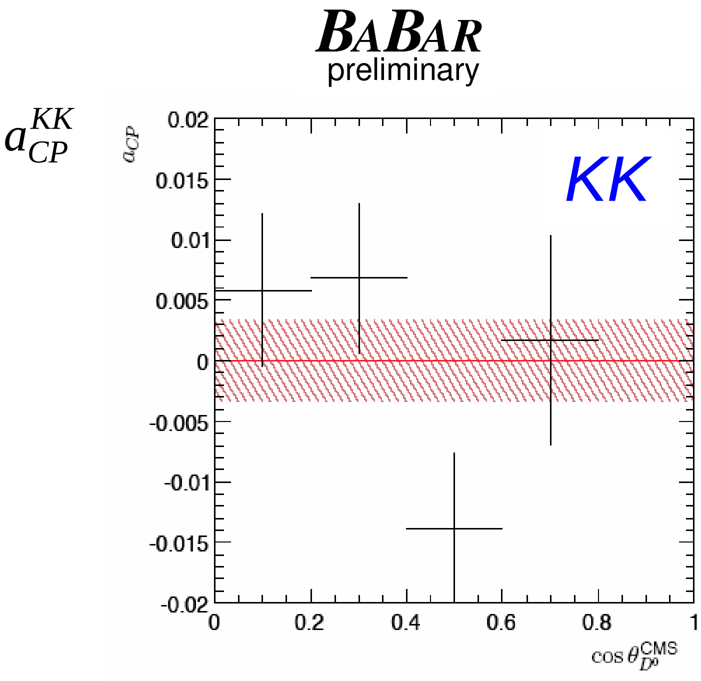
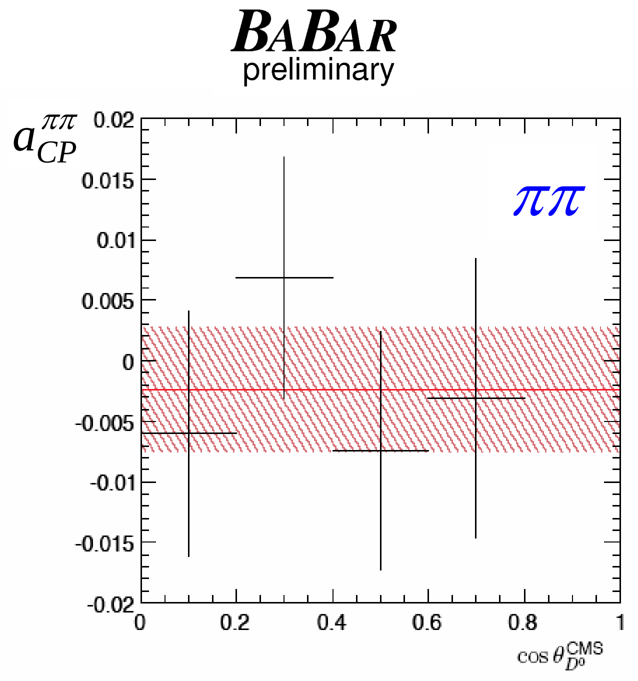
Search for CPV in $D^0 \to K^+K^-$, $\pi^+\pi^-$





$$a_{CP}^{KK} = (\ \ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

No evidence for CPV in either mode

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

Two types of WS Decays:

- Doubly Cabbibo-supressed (DCS) $D^0 \to K^+\pi^-\pi^0$
- Mixing followed by Cabibbo-Favored (CF) decay $D^0 \underset{\text{mix}}{\to} \overline{D}^0 \to K^+\pi^-\pi^0$

Two ways to reach same final state $\Rightarrow$ interference!

Time dependent WS rate :

$$\Gamma_{\bar{f}}(s_{12}, s_{13}, t) = e^{-\Gamma t}\{|A_{\bar{f}}|^2 \quad \leftarrow \text{DCS}$$

$$\text{Interference} \rightarrow + |A_{\bar{f}}||\bar{A}_{\bar{f}}| \left[y'' \cos\delta_{\bar{f}} - x'' \sin\delta_{\bar{f}}\right] (\Gamma t)$$

$$\text{Mixing} \rightarrow + \frac{x''^2 + y''^2}{4} |\bar{A}_{\bar{f}}|^2 (\Gamma t)^2\}$$

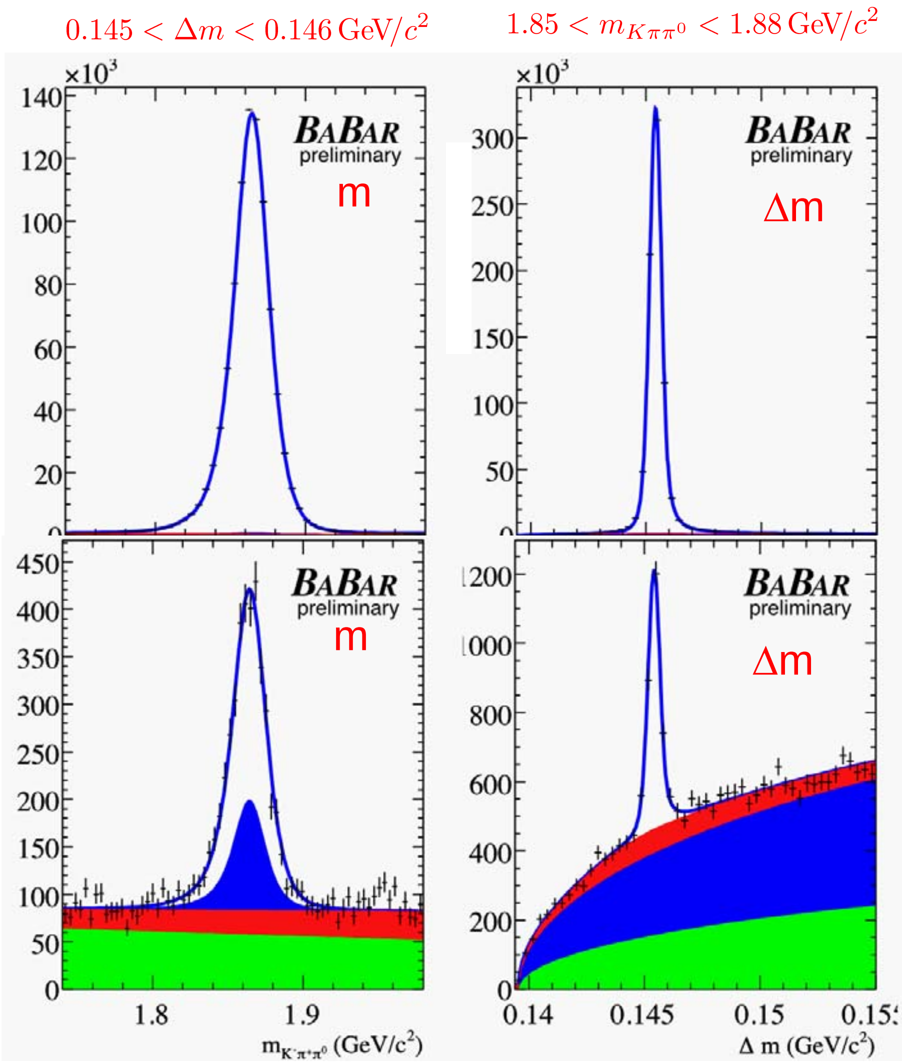
$\bar{f} = K^+\pi^-\pi^0$ $\qquad A_{\bar{f}} = \langle \bar{f}|\mathcal{H}|D^0\rangle,\ \bar{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}|\overline{D}^0\rangle$

$$y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}$$
$$x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$

$\delta_{K\pi\pi^0}$: strong phase difference between CF and DCS decay amplitudes

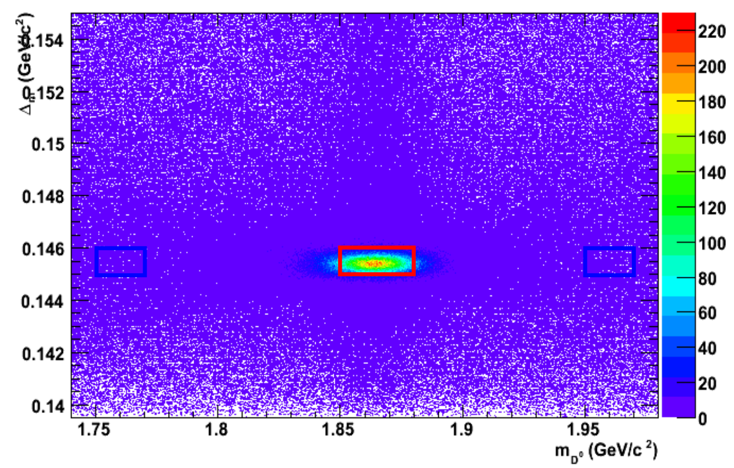
RS and WS ($m_{K\pi\pi}$, Δm) fits

Determine signal and background yields in subsequent Dalitz analyses.



- signal
- mis-tagged D^0
- mis-reconstructed D^0
- combinatoric

signal and sideband regions

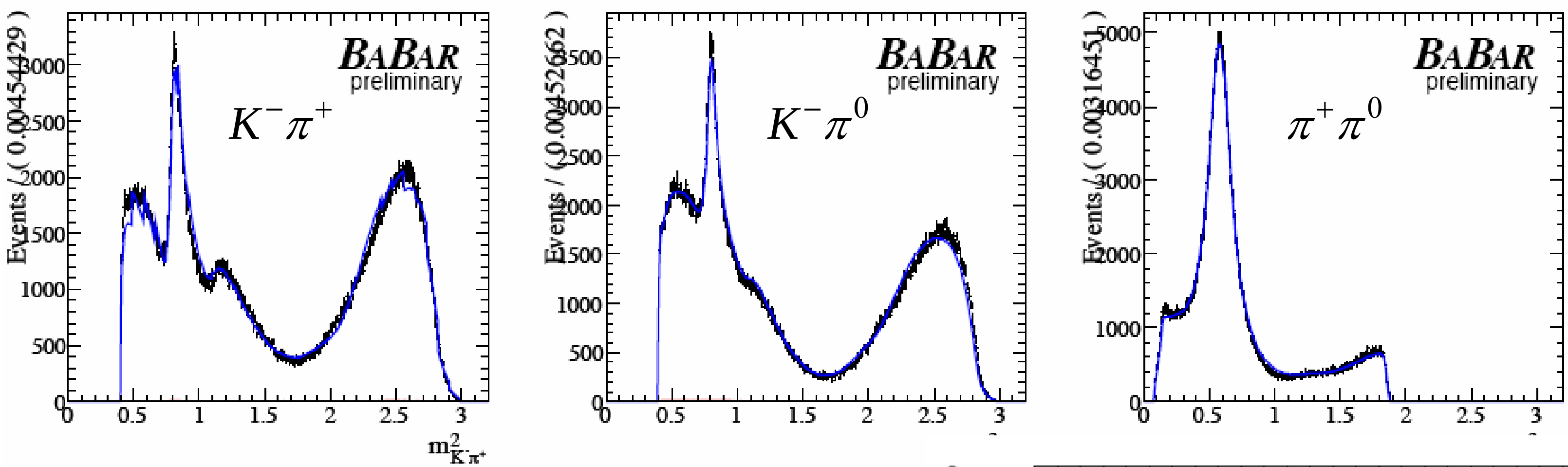


signal box yields:

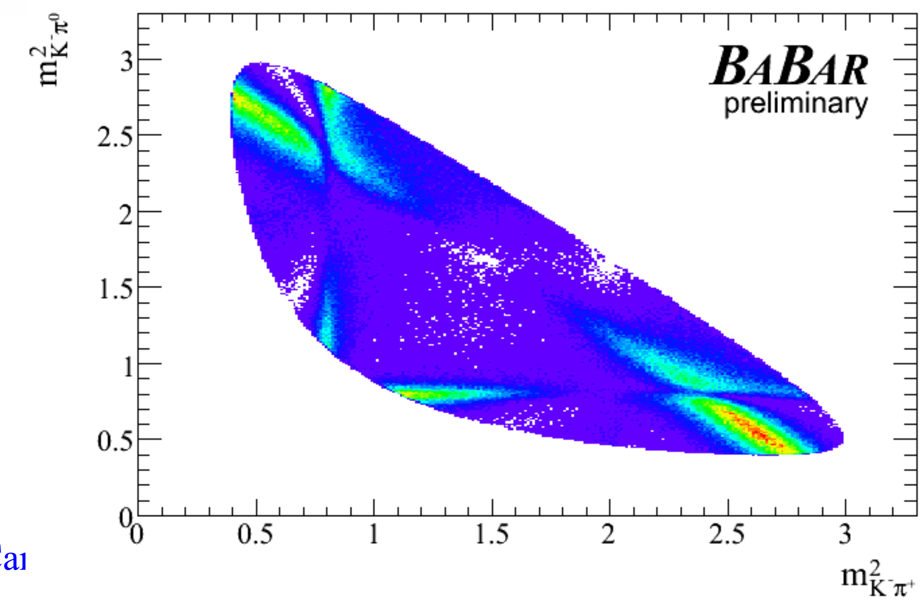
Category	N events (RS)	N events (WS)
Signal	639802 ± 1538	1483 ± 56
Combinatoric	1537 ± 57	499 ± 57
Mistag	2384 ± 57	765 ± 29
Misreconstructed D^0	3117 ± 93	227 ± 75

$D^0 \to K^-\pi^+\pi^0$ RS Dalitz fit

Time-integrated analysis to determine CF amplitudes, $\bar{A}_{\bar{f}}$

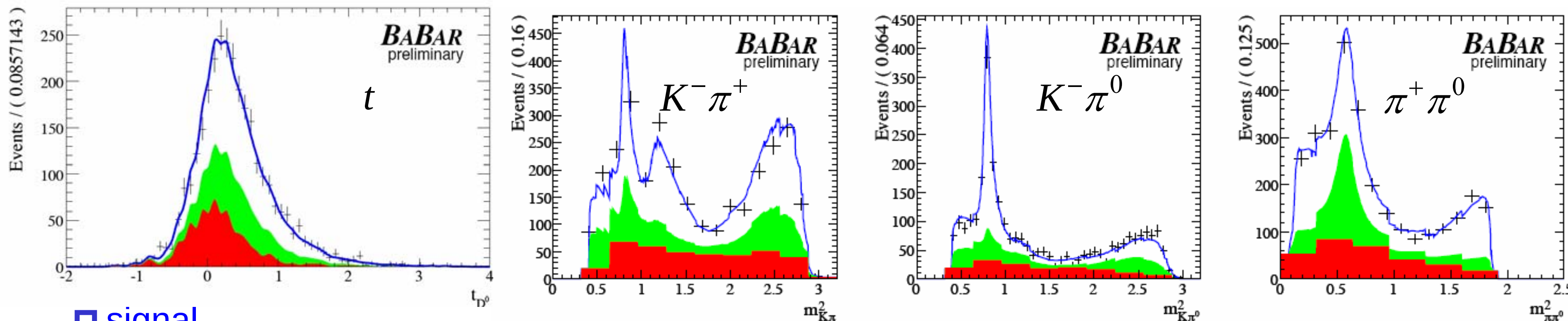


Resonance	Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	65.2 ± 4.5
$K^{*-}(1680)$	1.52 ± 0.06	144.3 ± 3.2	0.39 ± 0.04
$K_2^{*-}(1430)$	0.030 ± 0.001	-167.5 ± 2.5	0.31 ± 0.03
$K_2^{*0}(1430)$	0.0431 ± 0.0007	13.4 ± 0.9	0.73 ± 0.06
$K^{*-}(1410)$	0.24 ± 0.01	39.1 ± 4.1	0.17 ± 0.02
$K_0^{*-}(1430)$	2.95 ± 0.05	183.7 ± 0.9	3.6 ± 0.3
$K^{*-}(892)$	0.382 ± 0.001	163.3 ± 0.2	10.3 ± 0.7
$K^{*0}(1410)$	0.17 ± 0.01	-221.0 ± 3.5	0.009 ± 0.0001
$K_0^{*0}(1430)$	2.53 ± 0.01	91.6 ± 0.3	8.3 ± 0.6
$K^{*0}(1680)$	2.74 ± 0.07	-17.0 ± 1.5	1.4 ± 0.1
$K^{*0}(892)$	0.400 ± 0.001	3.4 ± 0.3	11.1 ± 0.7
$\rho(1700)$	6.06 ± 0.09	136.3 ± 0.7	4.1 ± 0.3
Total fit fraction = 106%			



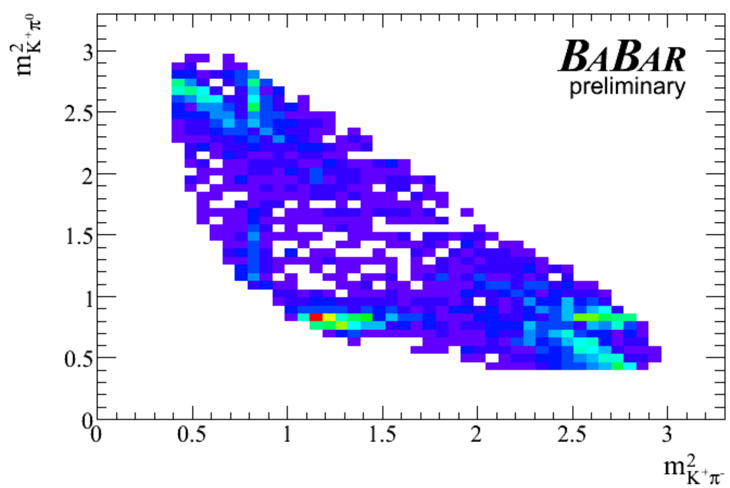
$D^0(t) \to K^+\pi^-\pi^0$ WS Dalitz fit results

Through t-dependence, distinguish DCS amplitudes from the CF amplitudes arising from mixing.



- signal
- mis-tagged D^0
- mis-reconstructed D^0 +combinatoric

Resonance	Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	39.8 ± 6.5
$K_2^{*0}(1430)$	0.088 ± 0.017	-17.2 ± 12.9	2.0 ± 0.7
$K_0^{*+}(1430)$	6.78 ± 1.00	69.1 ± 10.9	13.1 ± 3.3
$K^{*+}(892)$	0.899 ± 0.005	-171.0 ± 5.9	35.6 ± 5.5
$K_0^{*0}(1430)$	1.65 ± 0.59	-44.4 ± 18.5	2.8 ± 1.5
$K^{*0}(892)$	0.398 ± 0.038	24.1 ± 9.8	6.5 ± 1.4
$\rho(1700)$	5.4 ± 1.6	157.4 ± 20.3	2.0 ± 1.1
$\chi^2/ndof = 188/215 = 0.876$			
Total fit fraction = 102%			



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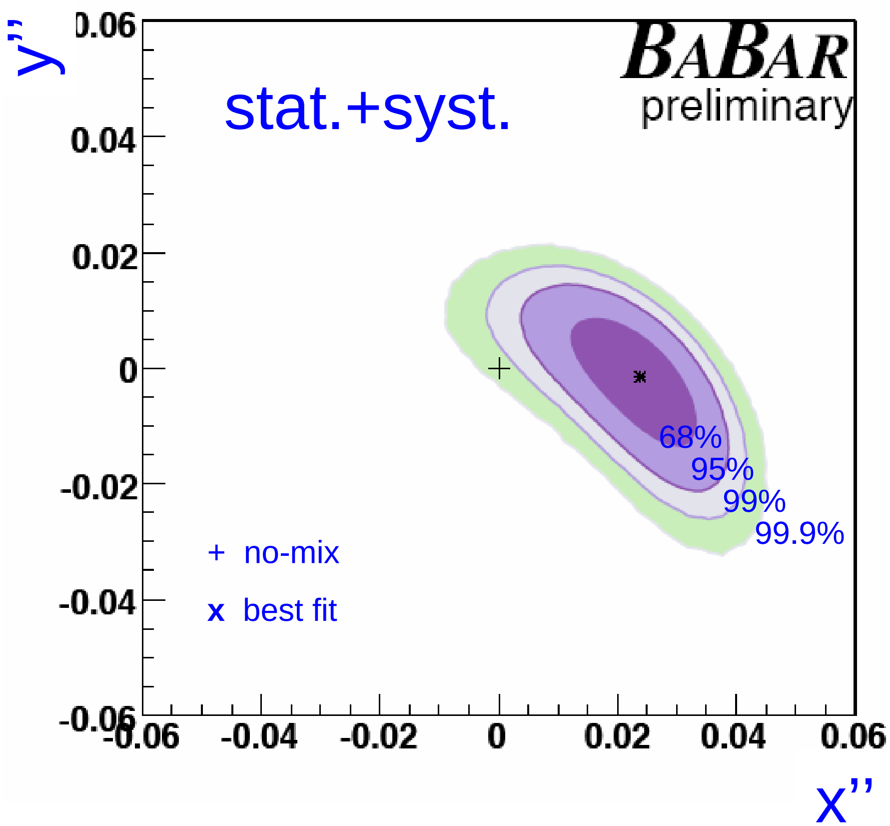
Mixing parameter contours and results



$$x'' = (\ \ 2.39 \pm 0.61\ (\text{stat.})\ \pm 0.32\ (\text{syst.}))\%$$
$$y'' = (-0.14 \pm 0.60\ (\text{stat.})\ \pm 0.40\ (\text{syst.}))\%$$

$$R_{\text{mix}} \equiv \frac{x''^2 + y''^2}{2} = (2.9 \pm 1.6) \times 10^{-4}$$
$$\text{world average} = (2.1 \pm 1.1) \times 10^{-4}$$

Results are consistent with no mixing at 0.8%, including systematics

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

From $K^{\pm}\pi^{\mp}$ decays:

x'^2: $(-0.22\pm0.30\pm0.21) \times 10^{-3}$, y': $(9.7\pm4.4\pm3.1) \times 10^{-3}$

Further evidence for D^0-$\bar{D}^0$ mixing from the *BaBar* experiment:

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

$$y_{CP} = (\ 1.24 \pm 0.39\ (\text{stat.})\ \pm 0.13\ (\text{syst.}))\%$$

– $D^0 \to K^+\pi^-\pi^0$ time-dependent Dalitz analysis:

$$x'' = (\ 2.39 \pm 0.61\ (\text{stat.})\ \pm 0.32\ (\text{syst.}))\%$$
$$y'' = (-0.14 \pm 0.60\ (\text{stat.})\ \pm 0.40\ (\text{syst.}))\%$$

In $D^0 \to K^+K^-$, $\pi^+\pi^-$ decays,

– no evidence for direct CP violation

$$a_{CP}^{KK} = (\ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

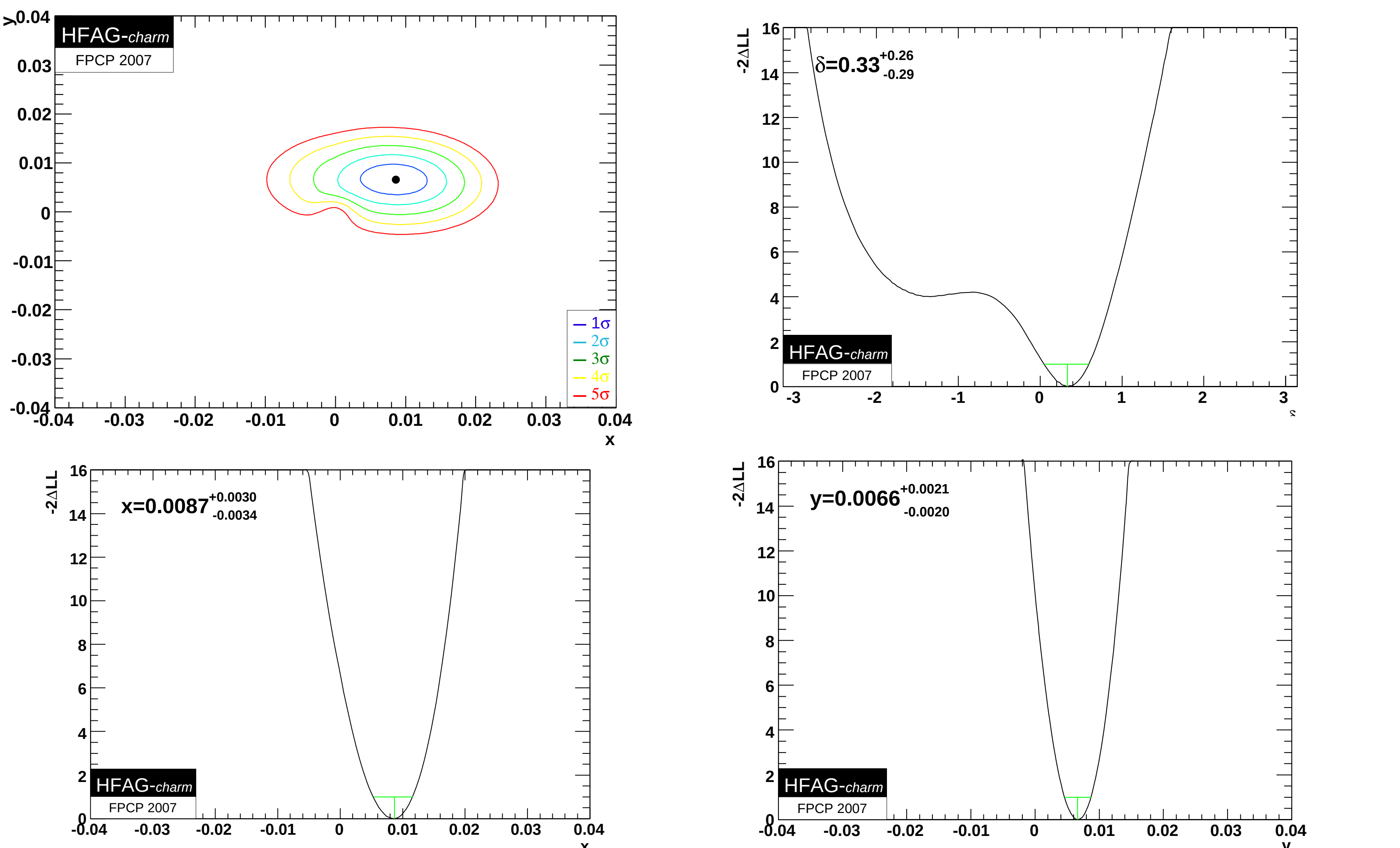
– no evidence for CP violation in mixing:

$$\Delta Y = (-0.26 \pm 0.36\ (\text{stat.})\ \pm 0.08\ (\text{syst.}))\%$$

Combining with other results, a comparison with Theory, and Conclusions

HFAG Results assuming no CPV

(Visit http://www.slac.stanford.edu/xorg/hfag/charm/index.html)



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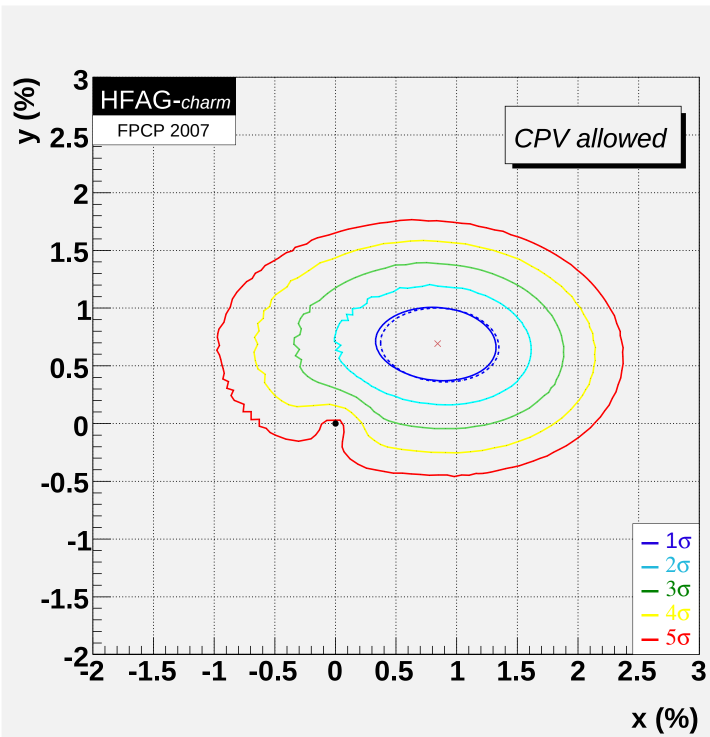
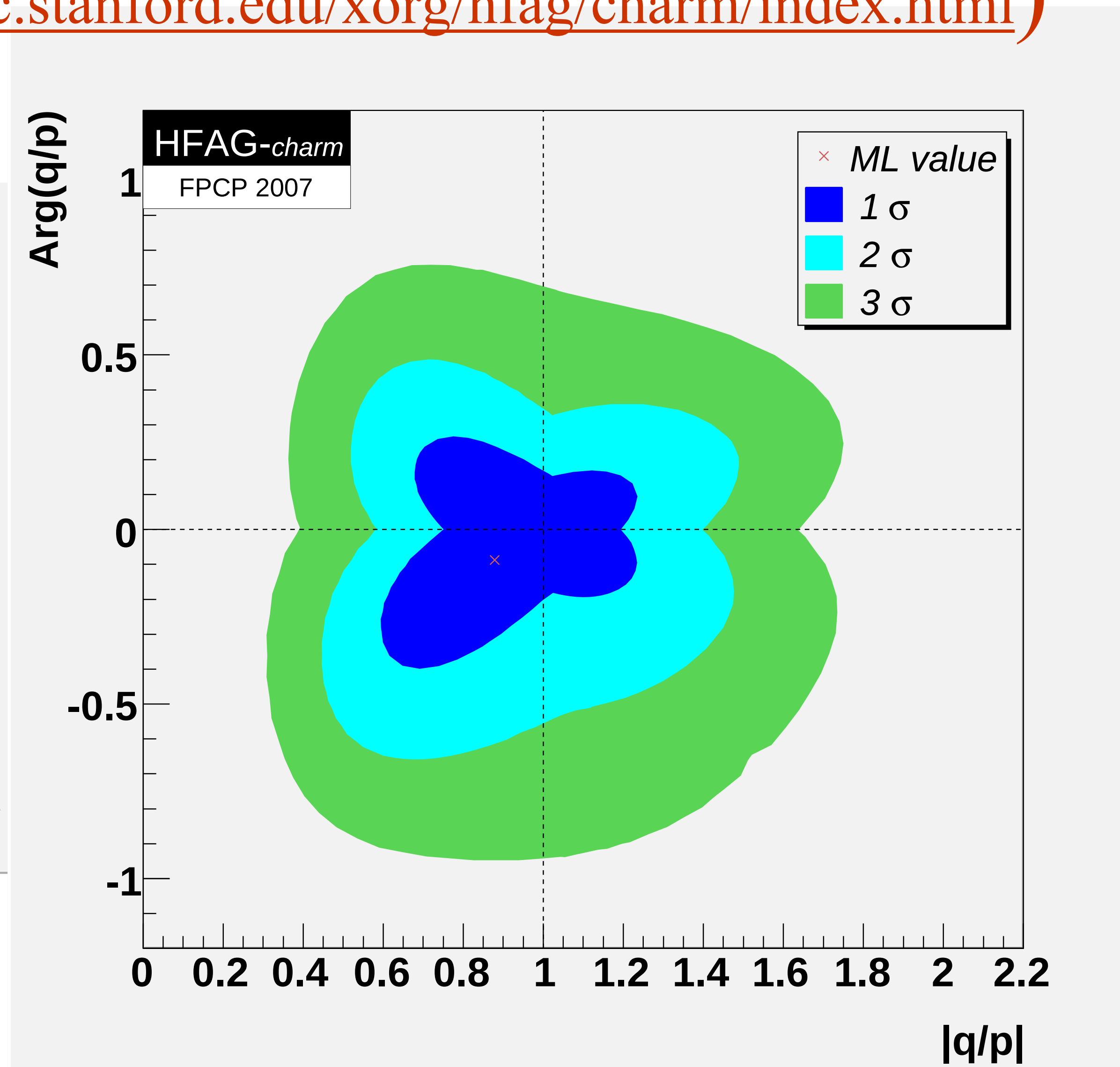
HFAG results allowing for CPV

(Visit http://www.slac.stanford.edu/xorg/hfag/charm/index.html)





Implications of Charm Mixing

BaBar and Belle mixing results first presented at Moriond electroweak conference on March 17

Several new hep-ph preprints on charm mixing since then, e.g.,

Five use D^0 mixing results to evaluate limits on:

- ❖Certain SUSY models (flavor suppresion by "alignment") hep-ph/0703204 hep-ph/0703235
- ❖Several little Higgs models hep-ph/0703254, arXiv:0704.0601
- ❖Non-universal Z' model hep-ph/0703270

"Models are further constrained, but constraints are limited by lack of precise SM value" → "Light non-degenerate squarks unlikely to be observed at LHC"

Currently, only an observation of CP violation in mixing would be a clear sign of New Physics

Interpreting the results

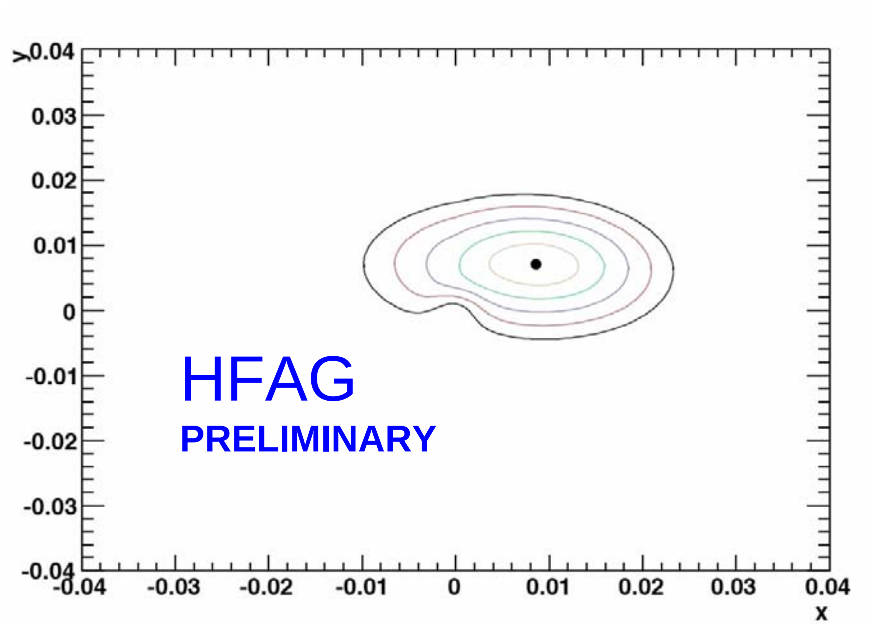
D^0 and $\bar{D}^0$

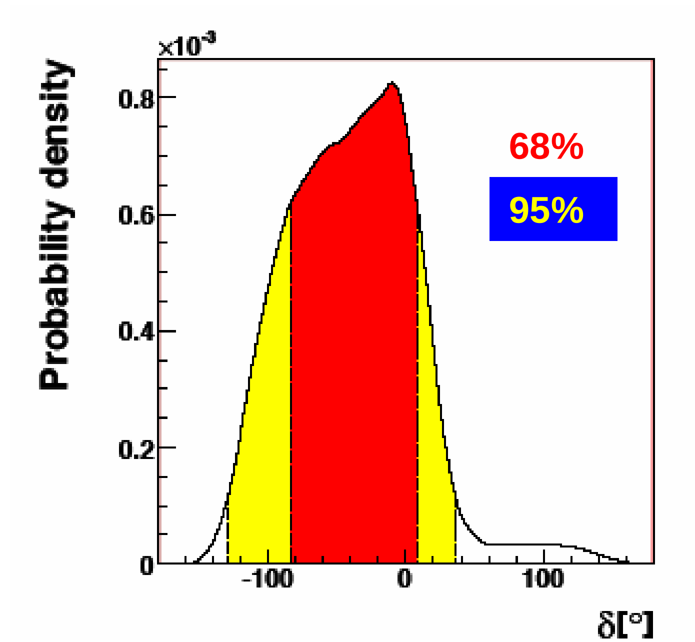
weak phase $2\phi_D$ of the mixing amplitude

$$y'_{\pm} = (1 \pm A_m)(y' \cos 2\phi_D \mp x' \sin 2\phi_D)\,,$$
$$x'^2_{\pm} = (1 \pm 2A_m)(x' \cos 2\phi_D \pm y' \sin 2\phi_D)^2\,,$$
$$y_{CP} = y \cos 2\phi_D - A_m x \sin 2\phi_D\,,$$
$$A_\Gamma = A_m y \cos 2\phi_D - x \sin 2\phi_D\,,$$

$$A_m = 1 - |q/p|$$

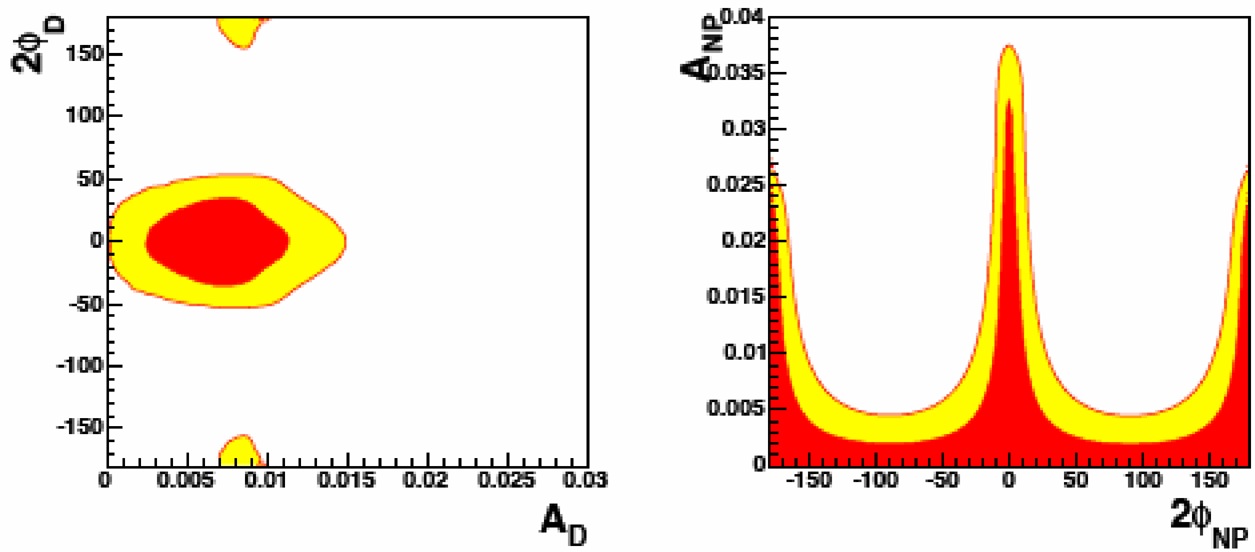
Ciuchini et al.
hep-ph/0703294





And CP violation?

In the standard model, $\phi \sim 2\,A^2\lambda^4\eta \lesssim 10^{-3}$



Ciuchini et al. hep-ph/0703294

In general NP weakly constrained if SM not known

Nevertheless SUSY coupling can be constrained hints on **squark and gluino masses**!

Neutral meson mixing always a window into unknown (virtual) states!

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Model	Approximate Constraint
Fourth Generation (Fig. 2)	$\lvert V_{ub'}V_{cb'}\rvert \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$\lvert\lambda_{uc}\rvert < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed x_D
Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV
	(with $m_1/m_2 = 0.5$)
Left-Right Symmetric (Fig. 9)	No constraint
Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/\lvert\Delta_{uc}\rvert > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/\lvert\Delta y\rvert > (6 \cdot 10^2$ GeV)
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$\lvert(\delta^u_{12})_{\rm LR,RL}\rvert < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\lvert(\delta^u_{12})_{\rm LL,RR}\rvert < .25$ for $\tilde{m} \sim 1$ TeV
Supersymmetric Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

75

Table from

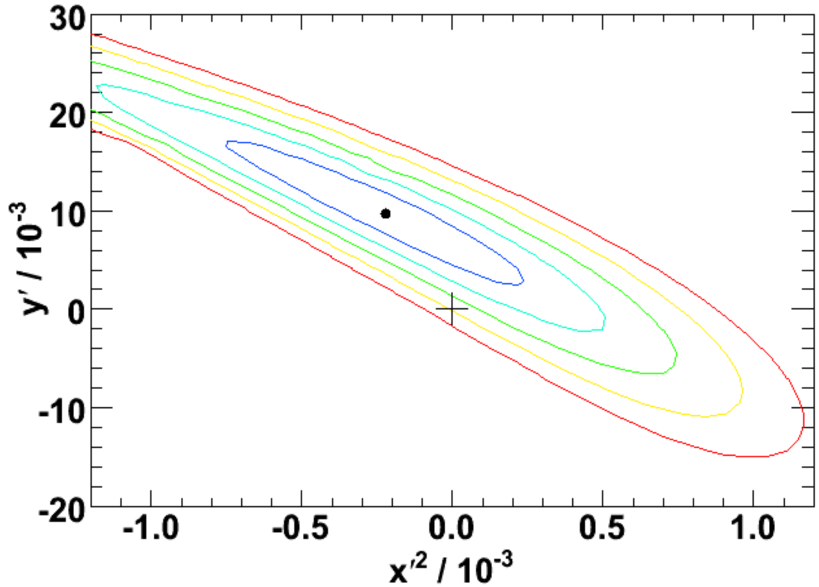
Golowich, Hewett, Pakvasa and Petrov:

arXiv:0705.3650 [hep-ph]

"… for some models (Split Fermions, Flavor Changing Neutral Higgs) the constraints can be strong."

"Such a list is by nature approximate, and we refer the reader to the body of the paper for a more precise presentation of our results."

Summary and Outlook



BaBar
preliminary

PRL 98:211802, 2007

BaBar studied $D^0 \rightarrow K\pi$ and other D^0 decays for mixing, CPV

- ❖Evidence for mixing in $K\pi$ decays (3.9σ)
- ❖Evidence for mixing in lifetime differences (3.0σ)
- ❖No sign of CP violation at the ~½% level
- ❖Consistent with other measurements and SM
- ❖More BaBar data and analyses coming up

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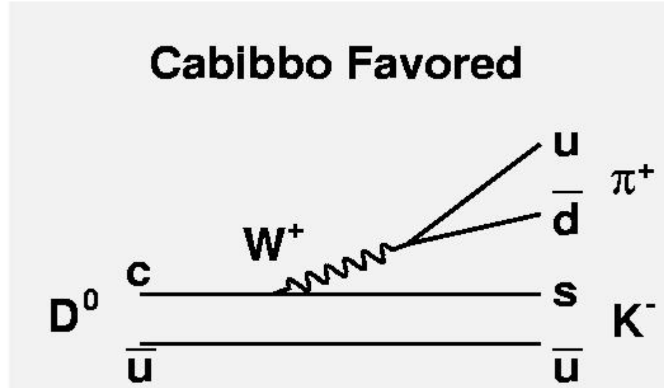
Backup Slides

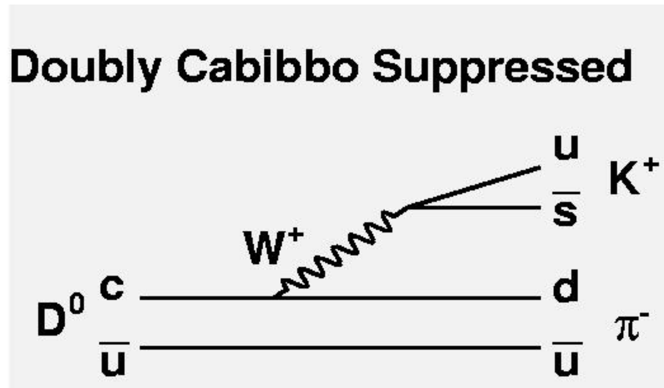
“Right-sign” and “Wrong-sign” decays

- Most decays of the D^0 are “Cabibbo-favored”, e.g., $D^0 \rightarrow K^-\pi^+$.
- Hadronic “wrong-sign” decays ($D^0 \rightarrow K^+\pi^-$ in this case) can occur either via double Cabibbo-suppression (DCS) or due to mixing.
- Semileptonic “wrong-sign” decays only occur due to mixing.

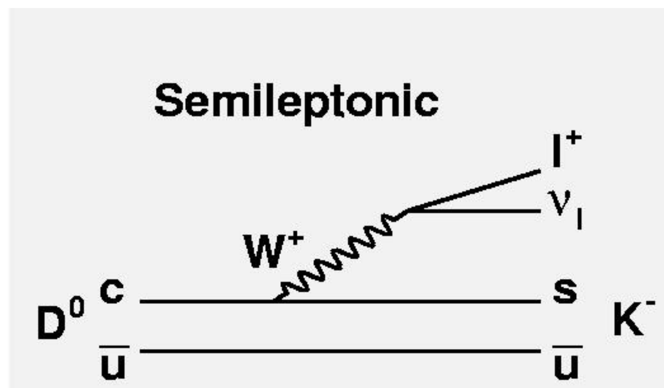
Right Sign Decays:



Wrong Sign Decays:



Semileptonic Decays:



Definitions of x, y, etc.

- The off-diagonal elements of the DDbar mass and decay matrices give rise to mass

  and lifetime differences:
- $\Delta m \equiv m_1 - m_2$, $\Delta\Gamma \equiv \Gamma_1 - \Gamma_2$

  Γ_1 corresponds to CP even final states as in the decay $D^0 \rightarrow K^- K^+$.
- It is convenient to define

  $x \equiv \Delta m / \Gamma$ and $y \equiv \Delta\Gamma / 2\Gamma$
- When there is a possible strong phase δ between the RS and WS amplitudes, we use instead

  $x' = x \cos\delta + y \sin\delta$ and

  $y' = y \cos\delta - x \sin\delta$

Time dependence of mixing:

- Ordinarily, decays proceed according to the exponential law:

  $r_{CF}(t) \sim e^{-\Gamma t}$

- However, mixed decays have a modified time dependence:

  $r_{WS}(t) \sim [R_{DCS} + \sqrt{R_{DCS}}\, y't + (x^2 + y^2)t^2]\, e^{-\Gamma t}$

- This different time dependence is crucial in separating mixed and DCS contributions to the wrong-sign (WS) rate.

Semileptonic Modes

- In semileptonic modes such as $D^0 \rightarrow K^- e^+ \nu_e$ we need not worry about DCS backgrounds and simply observe a "wrong-sign" signal, correct for any time-dependent acceptance effects and thereby measure $(x^2 + y^2)$.

Hadronic modes

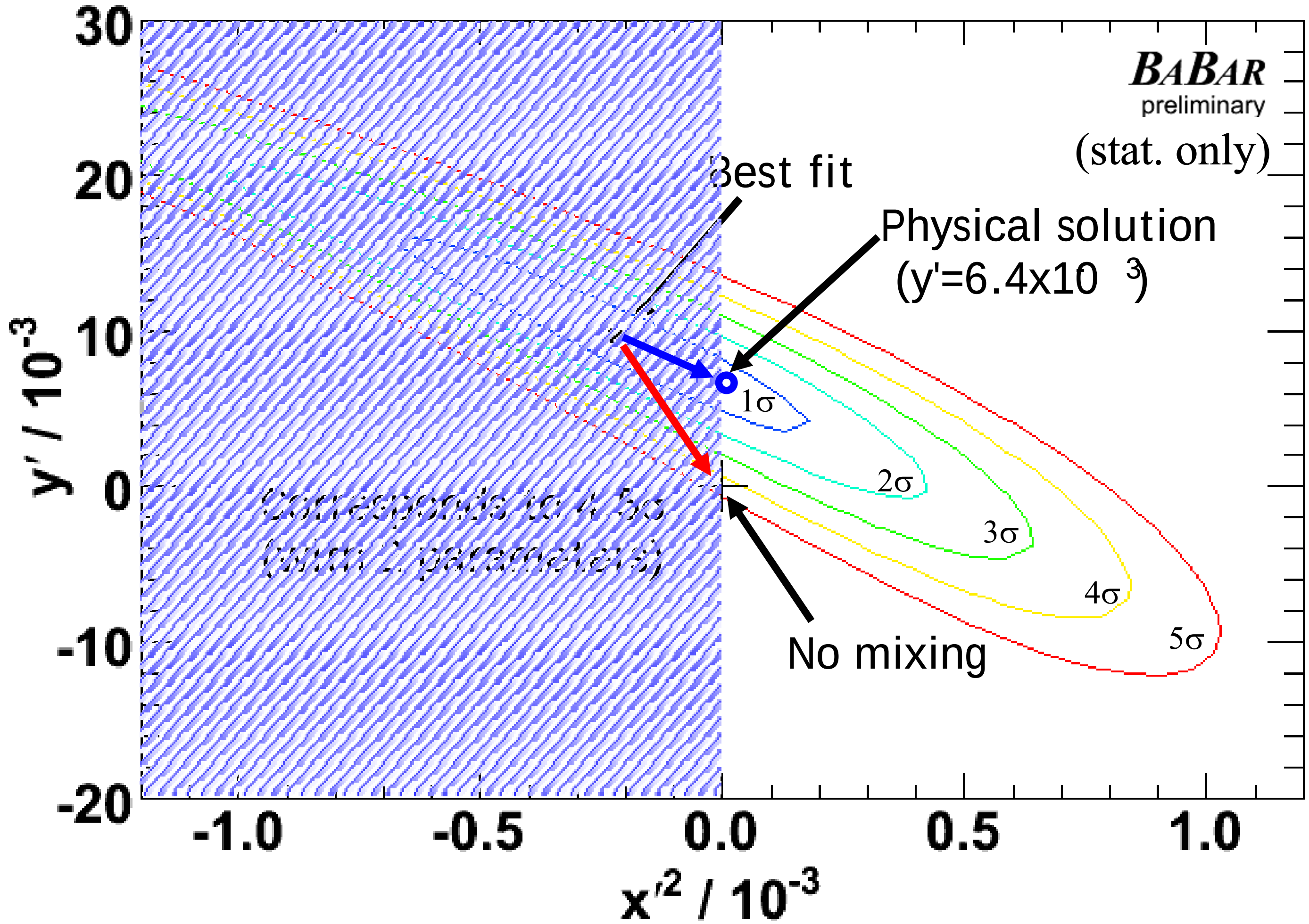
- If a D^0 - D^0bar pair is produced at the ψ'' then the pair must remain coherent until the first decay. Thus, one decay can be used for tagging, while the other (WS) decay is used to measure the rate. This technique was used by Mark III and will be used by CLEO-c.
- In a technique first suggested by Val Fitch, one can use the decay chain $D^{*+} \rightarrow D^0\pi^+$ followed by $D^0 \rightarrow K^-\pi^+$. The Q in the D^{*+} decay is so small that combinatoric backgrounds are kinematically suppressed. The "slow pion" from the D^{*+} tags the flavor of the D^0 at birth.

The lifetime difference technique

- First suggested by Ted Liu, in this technique one simply measures the lifetime of the D^0 in modes such as K^-K^+, which are CP eigenstates and measure Γ_1, and in copious modes such as $K^-\pi^+$ which yield an average of Γ_1 and Γ_2.
- Then $y \equiv \Delta\,\Gamma / 2\Gamma \cong (\tau_{K\pi} / \tau_{KK}) - 1$

Signal Significance

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



Systematic Uncertainties

Two types of systematic uncertainties considered:

Fit model variations:

❖Change signal and background models used in fit, to test assumptions made

Selection criteria:

❖Mainly decay time (error) ranges used in fit

Systematic:	R_D	x'^2	y'
Fit Model	0.59σ	0.40σ	0.45σ
Selection Criteria	0.24σ	0.57σ	0.55σ
Total	0.63σ	0.70σ	0.71σ

Fraction of statistical uncertainty

x'^2-y' correlation also present in systematics

Effectively the (x'^2,y') contours increase by ~15%

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Double tag at ψ(3770) [CLEO-c]

$D_{CP\pm}$

neutral D CP eigenstate

ψ(3770) decay conserves CP

- Reconstruct Double Tags: CP vs Kπ
- Asymmetry in CP+ vs CP- related to cosδ

$$A \equiv \frac{B(D_{CP+} \to K^-\pi^+) - B(D_{CP-} \to K^-\pi^+)}{B(D_{CP+} \to K^-\pi^+) + B(D_{CP-} \to K^-\pi^+)}$$

- R_D is ratio of DCS to Cabibbo favored rates

$$\cos\delta = \frac{A}{2\sqrt{R_D}}$$

- Input R_D =(3.60±0.08)‰ from PDG2006+CDF ~±2%,

Need to run

On threshold

- Updated results with 281 pb^{-1} at Winter Conferences
  - Expect σ(y)~ ±1.5% and σ(cos $\delta_{K\pi}$) ~ ±0.3
  - Including systematic uncertainties
- Full CLEO-c dataset ~750 pb^{-1}
  - Expect σ(y)~ ±1.0% and σ(cos $\delta_{K\pi}$) ~ ±0.1-0.2

BaBar (y_{CP}, ΔY) systematics

Systematic uncertainties (%):

Systematic	Δy_{CP}^{KK}	$\Delta y_{CP}^{\pi\pi}$	Δy_{CP}	$\Delta(\Delta Y^{KK})$	$\Delta(\Delta Y^{\pi\pi})$	$\Delta(\Delta Y)$
Signal Model	0.130	0.059	0.085	0.072	0.265	0.062
Charm Bkgd	0.062	0.037	0.043	0.001	0.002	0.001
Combinatorial Bkgd	0.019	0.142	0.045	0.001	0.005	0.002
Selection	0.068	0.178	0.046	0.083	0.172	0.011
Detector Model	0.064	0.080	0.064	0.054	0.040	0.054
Quadrature sum	0.172	0.251	0.132	0.122	0.318	0.083

Variations:

- Signal: PDF shape, polar angle dependent resolution offset, signal interval
- Charm backgrounds: yields and charm lifetime
- Combinatorial backgrounds: yields, shape and sideband region
- Selection: σ_t criterion, treatment of multiple candidates
- Detector: Alignment and energy loss

Search for CPV in $D^0 \to K^+K^-, \pi^+\pi^-$

Measure the time integrated CP asymmetries

$$a_{CP}^{KK} = \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\overline{D}^0 \to K^+K^-)}$$

$$a_{CP}^{\pi\pi} = \frac{\Gamma(D^0 \to \pi^-\pi^+) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^-\pi^+) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}.$$

Experimental procedure:

- fit $m, \Delta m$ distributions to determine raw signal weights
- Determine relative $D^0/\overline{D}^0$ soft pion tagging efficiency using $\overline{D}^0 \to K\pi$ data

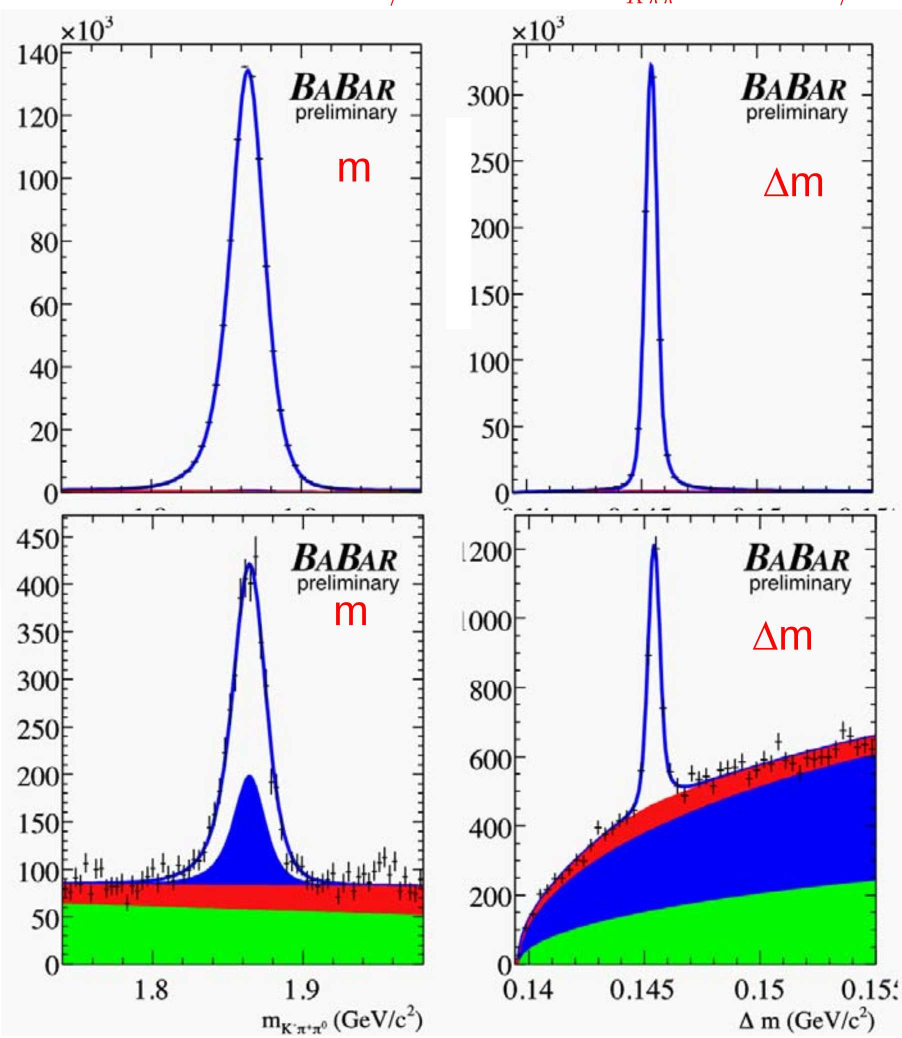
  ⇒greatly reduces systematic uncertainties

Category	Δa_{CP}^{KK}	$\Delta a_{CP}^{\pi\pi}$
2-Dim. PDF shapes	±0.04%	±0.05%
π_s correction	±0.08%	±0.08%
a_{CP} extraction	±0.09%	±0.20%
Quadrature sum	±0.13%	±0.22%

RS and WS ($m_{K\pi\pi}$, Δm) fits

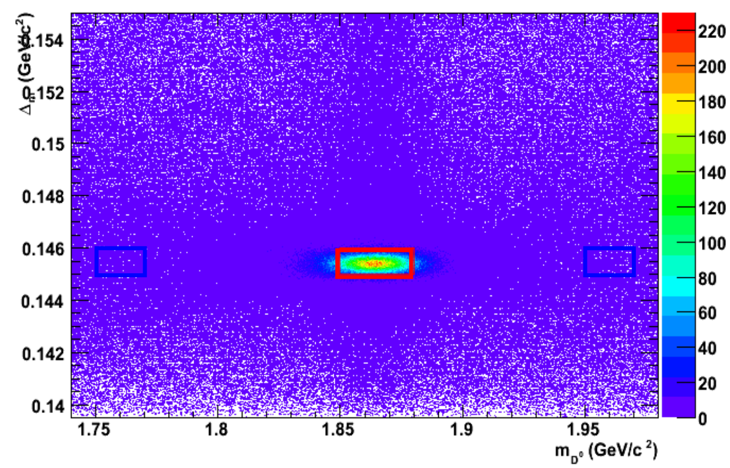
Determine signal and background yields in subsequent Dalitz analyses.

$0.145 < \Delta m < 0.146\,\mathrm{GeV}/c^2$ $1.85 < m_{K\pi\pi^0} < 1.88\,\mathrm{GeV}/c^2$



- signal
- mis-tagged D^0
- mis-reconstructed D^0
- combinatoric

signal and sideband regions



signal box yields:

Category	N events (RS)	N events (WS)
Signal	639802 ± 1538	1483 ± 56
Combinatoric	1537 ± 57	499 ± 57
Mistag	2384 ± 57	765 ± 29
Misreconstructed D^0	3117 ± 93	227 ± 75

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