Mixing and CP Violation in the Charm Sector

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outline

- ➔ Historical Overview on Mixing and CP Violation (CPV)
- ➔ Theory: Mixing and CPV in D vs K, B systems

- ➔ BaBar Detector and Charm Physics
- ➔ Lifetime Ratio Analysis at BaBar
- ➔ Other New Recent Measurements from BaBar and other Experiments

- ➔ Conclusions

Historical Overview on Mixing and CP Violation

References:

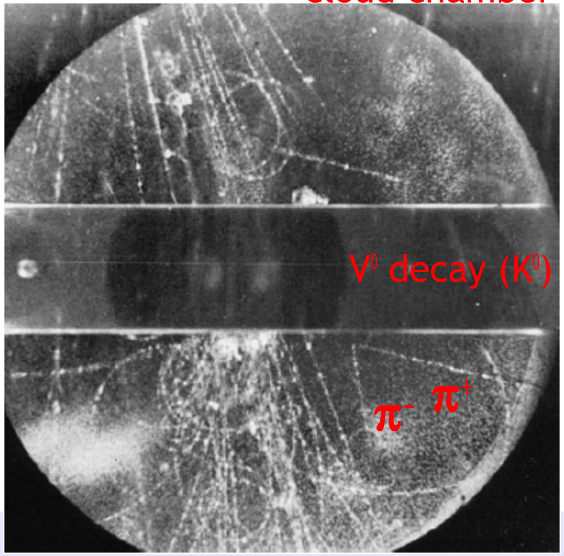
- "Inward Bound", Abraham Pais
- "The Harvest of a Century", Sigmund Brandt
- Ann. Rev. Nucl. Part. Sci. 2002.52:1-21
- K. Nakamura et al. (Particle Data Group), J. Phys G37 075021 (2010)

Strange Particles

- After World War II lots of groups studied cosmic rays content with cloud chambers and emulsion experiments → new unstable particles were discovered.

- 1953, Bagnères-de-Bigorre Conference:
  - scientists from all over the world had the opportunity to compare their results
  - the order emerged from chaos: first classification of these new states → two states correspond to different particles if they have different mass.

cloud chamber



Autumn 1946 – Manchester Group

- *Strange* Particles:
  - copiously produced in interactions of cosmic rays with nuclei
  - long lifetime (10^{-10}s vs 10^{-21}s)

- 1954 (and 1956) Padova and 1955 Pisa Conferences:
  - basic properties of the new states were known
  - accelerator started to take the leadership *“we are invaded, the accelerators are here”*

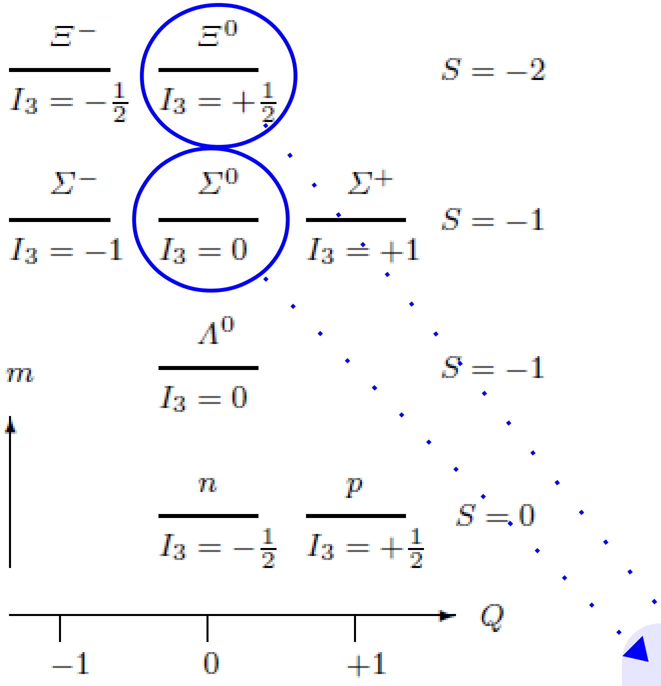
The Strangeness Scheme

- In 1952 Pais first proposed the idea of *associated production* for these strange states: strong production.
- 1953, Gell-Mann extended Heisenberg *isospin* idea to the new states
- 1955, Gell-Mann and Nishijima:

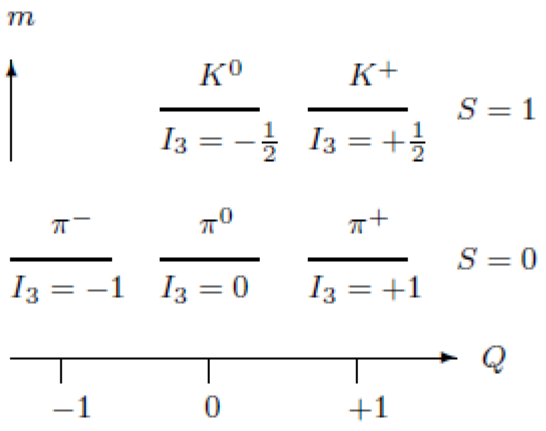
$$Q = I_3 + \frac{B}{2} + \frac{S}{2}$$

strangeness

- The *weak* interaction obeys the violation rule $|\Delta S| = 1$



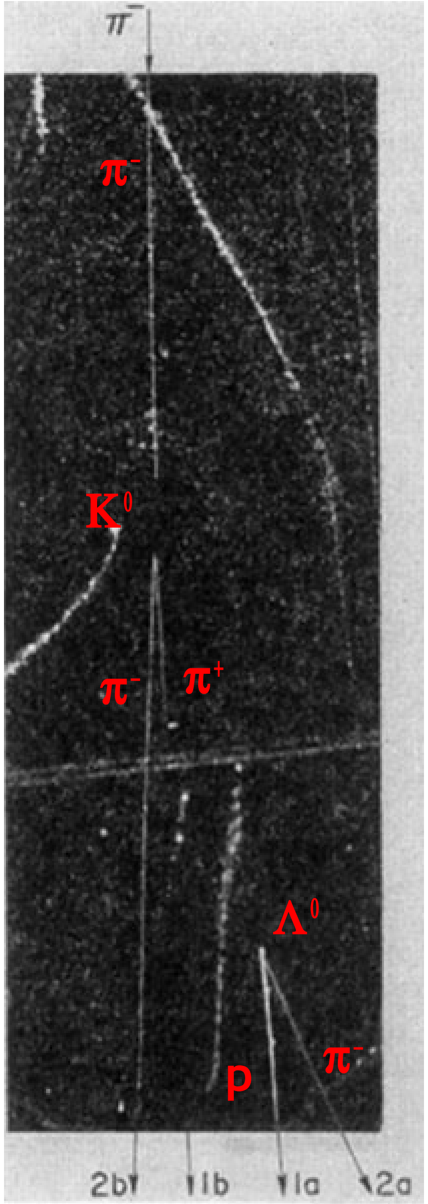
Long-lived baryons plotted in a diagram mass vs. charge; masses are not to scale.



Long-lived mesons plotted in a diagram mass vs. charge; masses are not to scale.

predicted and discovered:

Σ^0 in 1956 and Ξ^0 in 1959



π^- beam produced at the Cosmotron accelerator in Brookhaven entering a cloud chamber

The K^0 Mixing Predicted and Discovered

- 1955, *before* the observation of C Violation:

$K^0 \to \pi^+ \pi^-$, $S = +1$ $\xrightarrow{C}$ $\bar{K}^0 \to \pi^+ \pi^-$, $S = -1$

K^0 and $\bar{K}^0$ are non-identical particles, how does one see that in the laboratory?

- weak interaction acting twice: $K^0 \longleftrightarrow \pi^+\pi^- \longleftrightarrow \bar{K}^0$
  [Phys. Rev. 97, 5, 1955] (Gell-Mann and Pais)

MIXING predicted

- 1955, Gell-Mann and Pais: *real* particles are combinations of K^0 and $\bar{K}^0$:

$K_1 = (K^0 + \bar{K}^0)/\sqrt{2}$ $\quad$ $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$

can decay in C-even final states (2π) + can decay in C-odd final states (2π forbidden) ⇒ K_1 and K_2 have different lifetimes (and masses)

K_1 → already observed

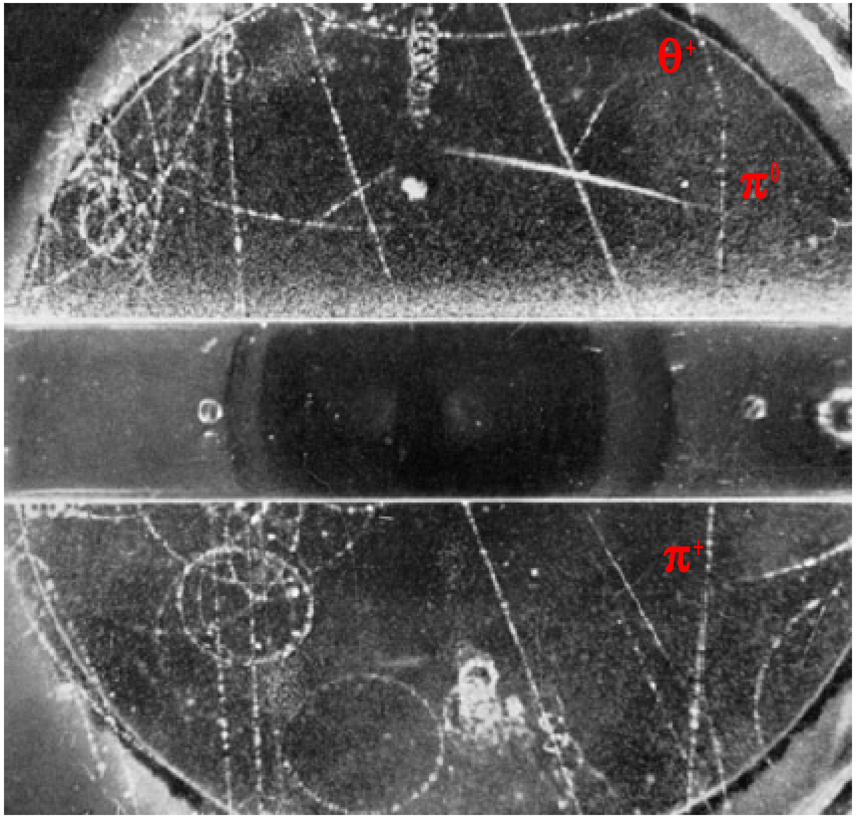
K_2 → *predicted* and *observed* very soon → long-living K observed: $\tau_2 = 5.2\text{x}10^{-8}\text{s} = 500\ \tau_1$

1956, Lederman

MIXING observed

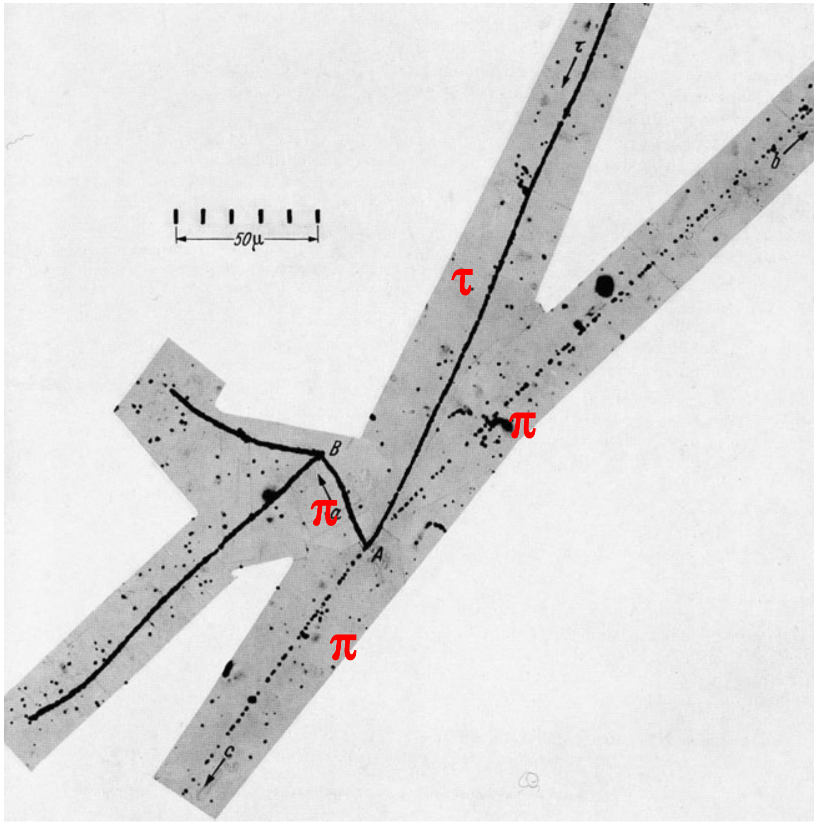
The theta-tau Puzzle

cloud chamber $\theta^+ \to \pi^+ \pi^0$



May 1947 – Manchester Group

photographic emulsion $\tau^+ \to \pi^+ \pi^+ \pi^-$



January 1949 – Bristol Group

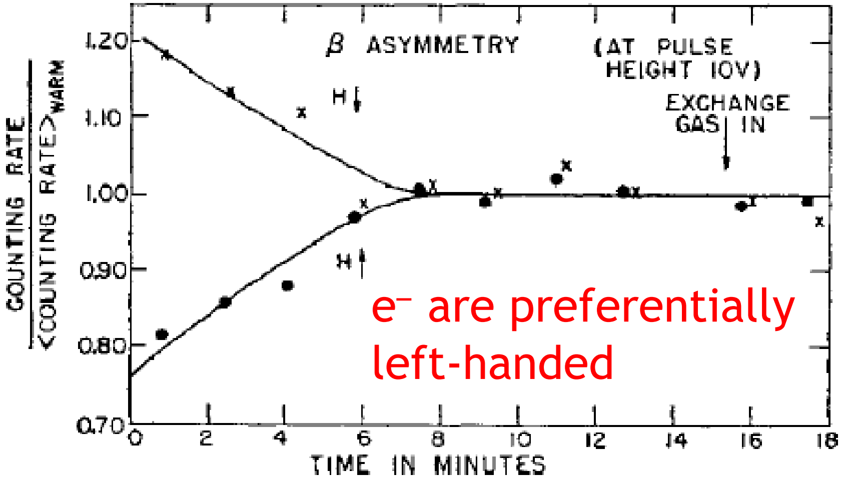
➔ Two states with same mass but different parity:

- the masses of the two mesons were compatible within experimental errors
- the first application of the Dalitz Plot (DP) was to the τ decay and it showed that the meson has spin 0 (DP uniformly populated)
- either τ and θ are different particles or parity is violated in weak interactions.

Parity *is* violated in weak interactions

- April 1956, Sixth Rochester Conference, the puzzle was intensely discussed:
  - In a introductory talk Yang (and Lee) proposed the existence of particle pairs with opposite parities but otherwise identical properties
  - Feynman brought up a question of Block's: "*could it be that θ and τ are different parity states of the same particle which has no definite parity, i.e., that parity is not conserved.*"

Madame Wu, $^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \bar{\nu}$



e^{-} are preferentially left-handed

- June 1956, Lee and Yang proposed a certain number of experiments to test the conservation of P in weak interactions, promptly realized (1957):

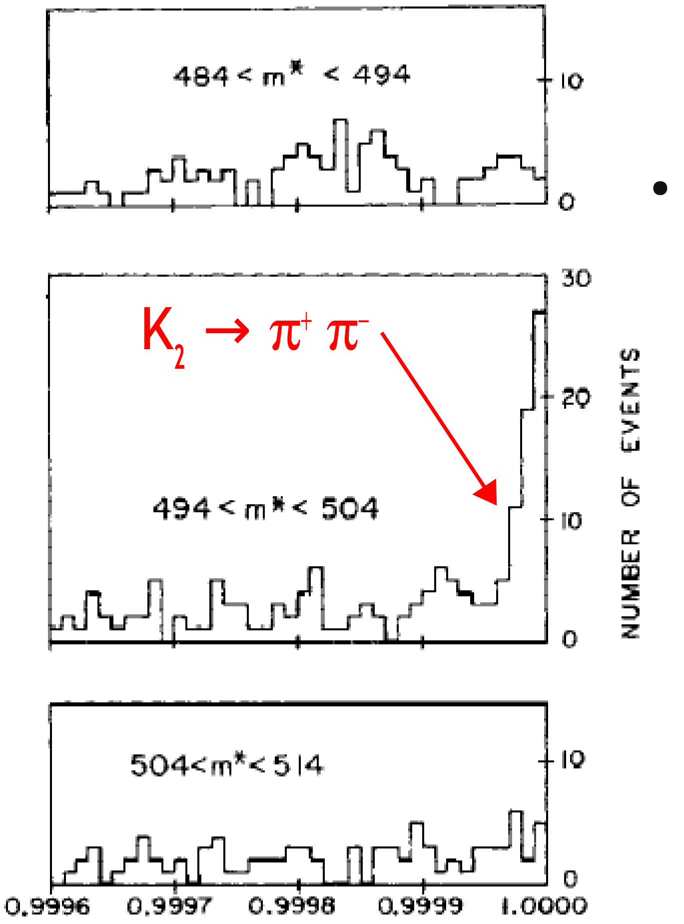
  Madame Wu, $^{60}Co \rightarrow {}^{60}Ni^{*} + e^{-} + \bar{\nu}$

  Garwin, $\pi \rightarrow \mu \, \nu$

- The discovery of P (and C) violation was a key ingredient for *Gell-Mann* and *Feynman* (independently) to write the **V - A theory** of weak interactions

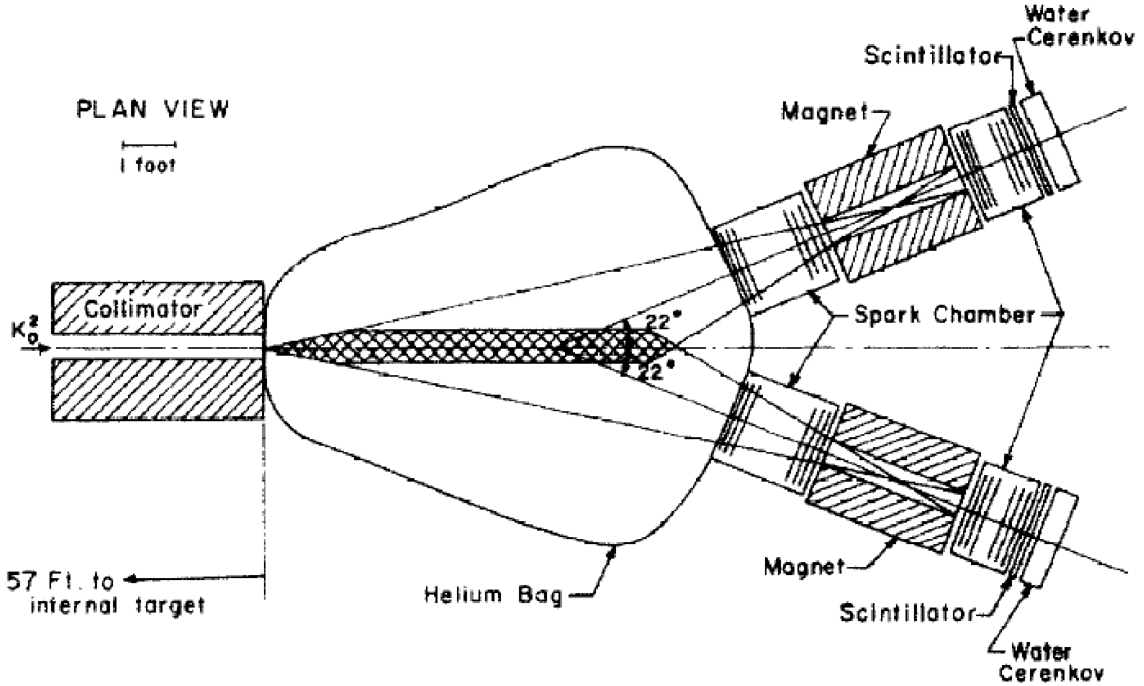
CP is violated as well

- 1964, Cronin and Fitch first observed of CP violation in K system:
  - the experiment aim was to study *regeneration* of K mesons and to obtain a much better limit on the partial rate $K_2 \rightarrow \pi\pi$. It ran June and July 1963.
  - K_2 mesons decay in 2π with 0.2% probability



$K_2 \rightarrow \pi^+ \pi^-$

$\cos\theta \rightarrow \dfrac{(\vec{p}_{\pi 1} + \vec{p}_{\pi 2}) \cdot \vec{p}_K}{|(\vec{p}_{\pi 1} + \vec{p}_{\pi 2}) \cdot \vec{p}_K|}$



Consequences of CP Violation

- 1967, *Sakharov* proposed a model which could explain that the universe consists essentially of matter with very little antimatter, although equal amounts of both are probably created at a very early stage.
  - Fitch: “Indeed, one might turn the question around and say that the first evidence of CP violation was the fact that we exist”

- Models to accommodate the observed CP violation were developed:
  - 1964, Wolfenstein: superweak model, CPV was due to very weak $\Delta S = 2$ 4-fermion interaction.

ruled out by the observation of direct CPV in $K_L \to \pi\pi$

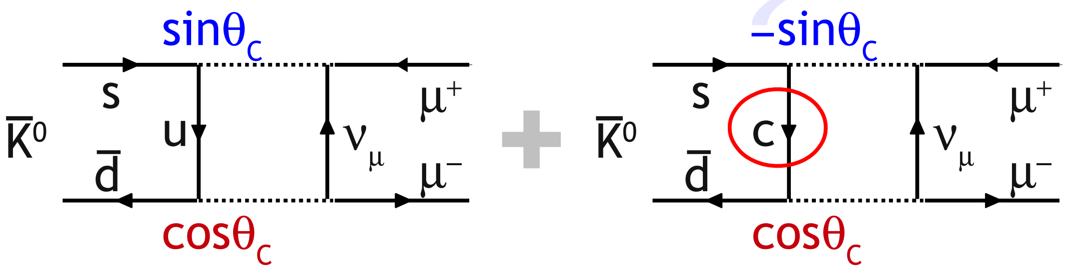
  - 1973, Kobayashi and Maskawa extended the 2x2 Cabibbo quark mixing matrix to a 3x3 CKM matrix within a six-quark model. CP Violation was naturally included.

confirmed by B-factories with mixing and CPV measurements in the B system

The Charm Quark Prediction

- 1964, Bjorken and Glashow proposed a four-quark model, but there was no evidence for that [Phys. Lett. 11 (3) 255-257 (1964)]

- 1970, Glashow-Iliopulos-Maiani (GIM) mechanism was proposed to justify suppression of FCNC and the ΔS = 2 processes. It required the existence of a 4th quark, the charm [Phys. Rev. D2, 1285-1292 (1970)]
  - e.g. suppression of the decay: $K^0 \to \mu^+ \mu^-$



$$BR(K_L \to \mu^+\mu^-) \propto g^4 \frac{\left(m_c^2 - m_u^2\right)}{m_w^2} \sim g^4 \frac{m_c^2}{m_w^2}$$

- 1974, Gaillard and Lee predicted the charm quark mass from K mixing:

$$\mathcal{A}(\underset{\text{mixing}}{\underline{K \to \overline{K}}}) \propto \sin^2\theta_C \, \cos^2\theta_C \cdot \frac{\boxed{m_c^2}}{M_W^2}$$

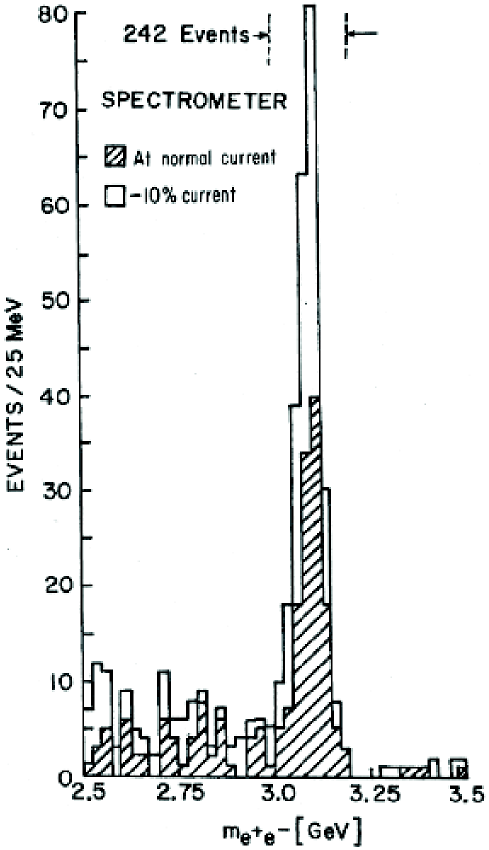
⇒ $m_c \sim 1.5$ GeV/c

The Charm Quark Discovery

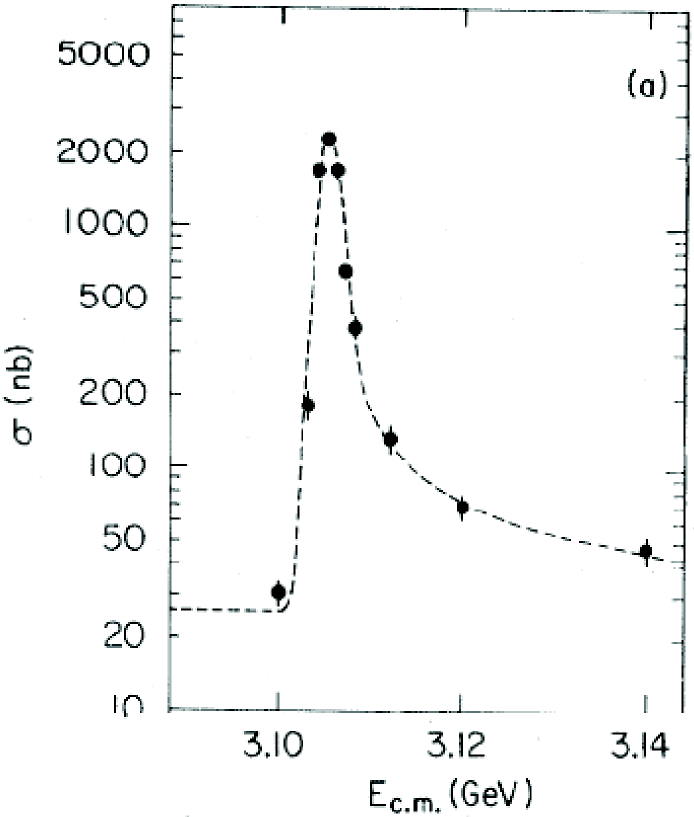
- 1974, charm discovery as $(c\bar{c})$ state, the J/Ψ:

J discovered at BNL in
$p + Be \rightarrow e^+ + e^- + X$

Ψ discovered at SLAC with Mark I
detector at $e^+ + e^-$ SPEAR storage rings



[PRL 33 1404-1406 (1974)]



[PRL 33 1406-1408 (1974)]

- 1975 discovery of open charm (Λ^0) and one year later discovery of the D^0

K system: Mixing and CPV, Short Story

- 1956, prediction and discovery of K^0-$\overline{K}^0$ mixing

first observation of mixing

- 1964, discovery of *indirect* CPV
  - in K → π π decays

first observation of CPV

- 1988, discovery of *direct* CPV by NA31 (confirmed by NA48 and KTeV in 1999)
  - in K → π π decays

ruled out the superweak model

NA31: [Phys. Lett. B206, 169 (1988)]
NA48: [Phys. Lett. B465, 355 (1999)]
KTeV: [PRL 83, 22, 355 (1999)]

- All 3 types of CPV have been observed in K → ππ decays
- CPV in K → 3π has not been observed yet

B systems: Mixing and CPV, Short Story

- 1987, observation of B^0-$\bar{B}^0$ mixing by ARGUS and UA1 Collaborations

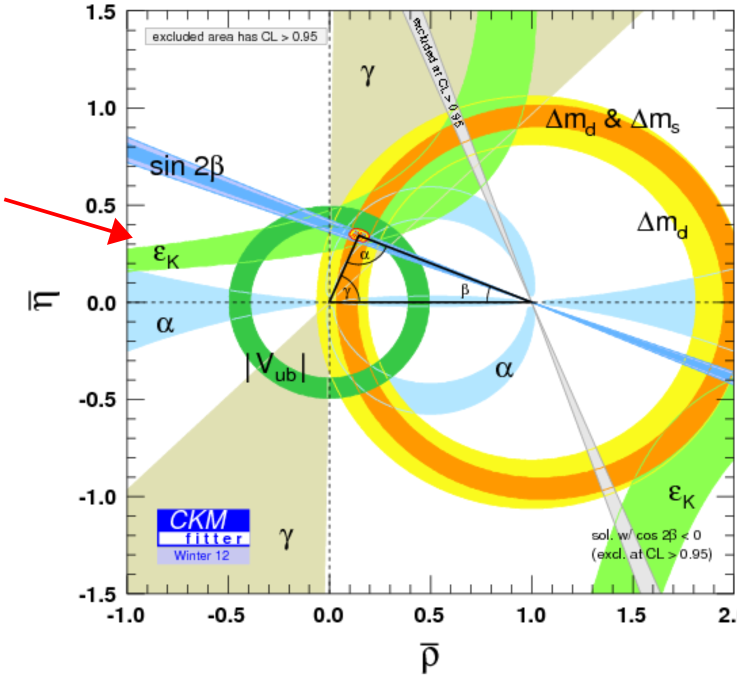
indication of **top** mass > 50 GeV/c^2

UA1: [Phys. Lett. B186, 247 (1987)]
ARGUS: [Phys. Lett. B192, 245 (1987)]

- 2006, observation of B_s - $\bar{B}_s$ mixing by CDF Collaboration

[PRL 97, 242003 (2006)]

- At present, *direct* CPV observed in B decays as well as CPV in the interference between decay with and without mixing. No CPV in mixing observed yet.



from K system

Unitarity Triange

All measurements of CPV in B and K systems are consistent with prediction of the CKM mechanism

Confirmation of the CKM mechanism

What about the D system?

- 1975, first theoretical paper on CP Violation in charmed particle decays

Pais and Treiman [PRD12, 9, 2744 (1975))]

- 2008, *evidence* of D^0-$\overline{D}^0$ mixing by BaBar and Belle Collaborations, then confirmed by CDF

BaBar: [PRL 98, 211802 (2007)]
Belle : [PRL 98, 211803 (2007)]
CDF : [PRL 100, 121802 (2008)]

- 2011, evidence of CPV reported by LHCb and CDF Collaborations:
  - in the difference of integrated asymmetries: $A_{CP}(D \to KK) - A_{CP}(D \to \pi\pi)$
  - Interpretation is not straightforward, maybe accommodated in the Standard Model but may also be a hint of New Physics!

is something going on in the charm sector?

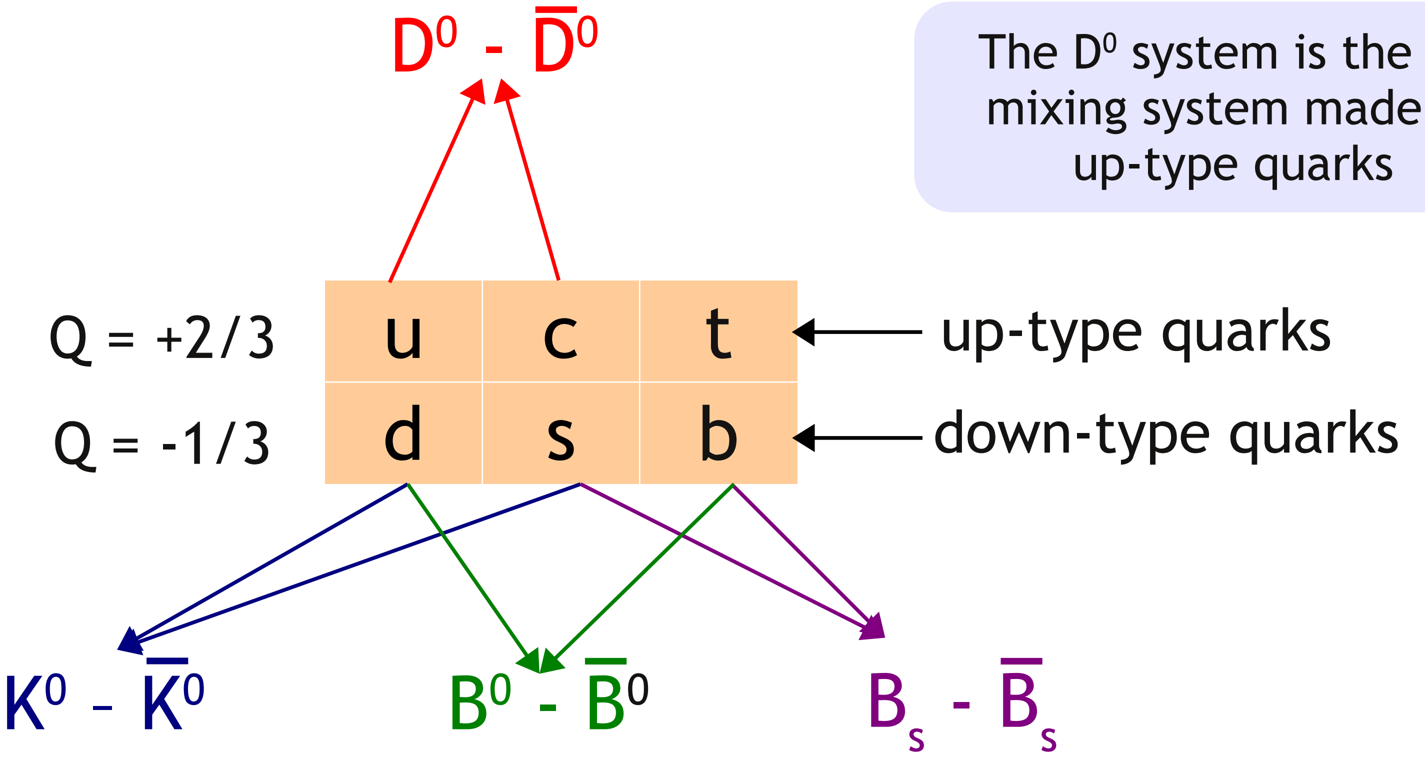
Theory, Mixing and CPV in D vs K and B

References:

- K. Nakamura et al. (Particle Data Group), J. Phys G37 075021 (2010)
- other reference are indicated on the slides

The Neutral Meson States

- In the Standard Model (SM) we have 4 systems of meson-antimeson that can mix:



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

The D^0 system is the only mixing system made of up-type quarks

Q = +2/3	u	c	t	← up-type quarks
Q = -1/3	d	s	b	← down-type quarks

K^0 – $\bar{K}^0$ $\quad$ B^0 - $\bar{B}^0$ $\quad$ B_s - $\bar{B}_s$

- Mixing has been experimentally established in all of them.

The Neutral Mesons Mixing Formalism

- Mixing occurs when the mass eigenstates differ from the flavor eigenstates

$$\boxed{|D_{1,2}\rangle} = p\boxed{|D^0\rangle} \pm q\boxed{|\overline{D}^0\rangle} \qquad \text{with} \quad |p|^2 + |q|^2 = 1$$

- The mass eigenstates and their time evolution are obtained solving the Schrödinger Equation:

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

$$\mathcal{H}_{\text{eff}} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma}$$

effective Hamiltonian

$\mathbf{\Gamma}$ and $\mathbf{M}$ are Hermitian Matrices

- The mass eigenstates propagate as free particles with *different* masses and lifetimes:

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

note:

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

The Time Evolution of the Flavor Eigenstates

- Mixing is described by:

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

- Time Evolution of a meson that was a D^0 at t = 0:

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

where $\Delta\gamma = \Gamma(y + ix)$ $\quad \bar{\gamma} = \Gamma - i(m_1 + m_2)$

- The probability that the flavour is changed at time t:

$$|\langle\overline{D}^0|D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

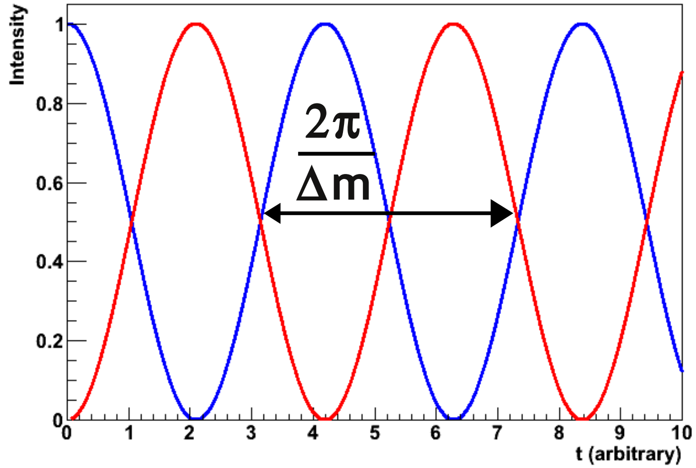
- The probability that the flavor is not changed after a time t:

$$|\langle D^0|D^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

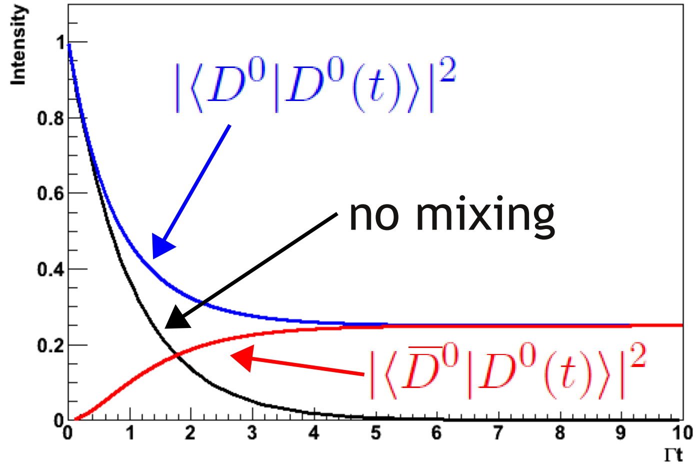
Visual Examples of Mixing

- Create a D^0 at $t = 0$. Compute the probability to find a D^0 or a $\overline{D}^0$ at time t, for different values of x and y.

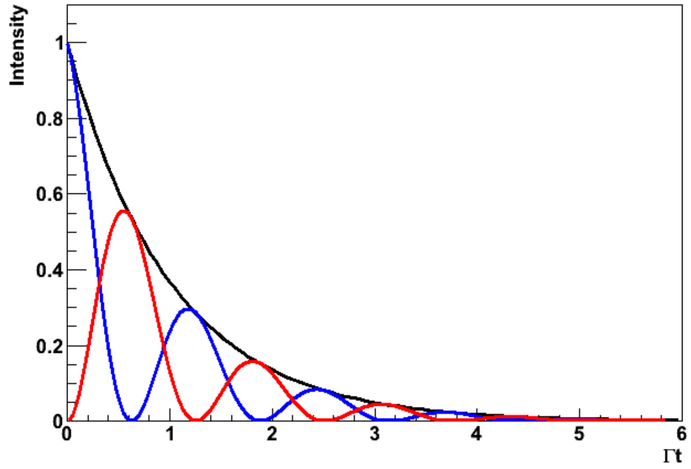
$\Gamma = 0$ and y = 0



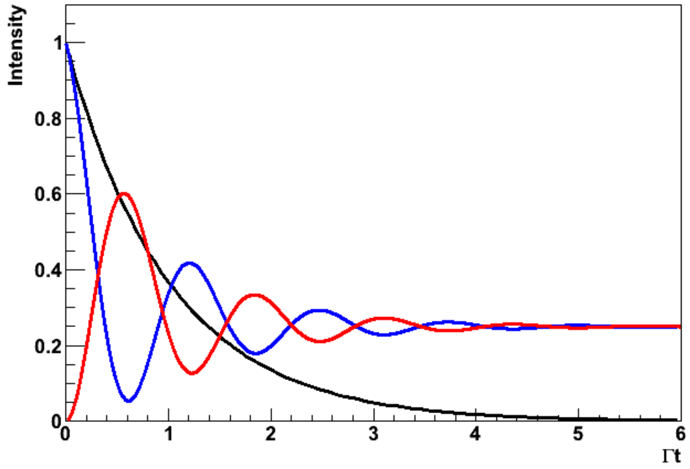
x = 0 and y = 1



x = 5 and y = 0

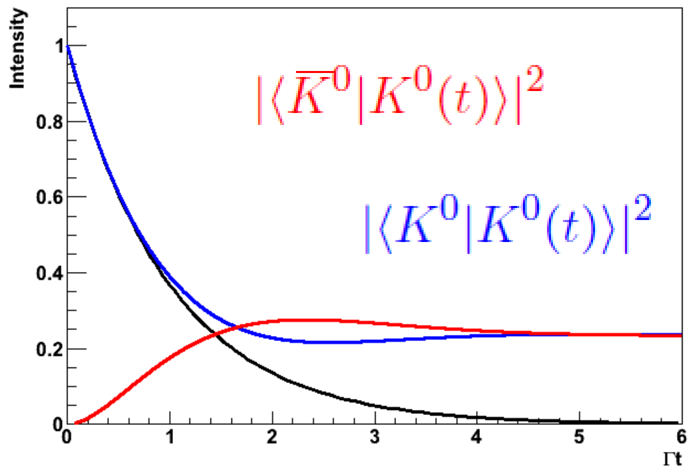


x = 5 and y = 1

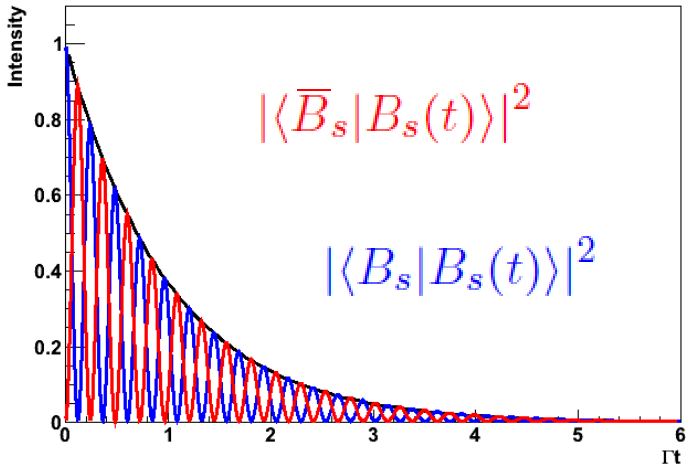


The Time Evolution: Physical Cases

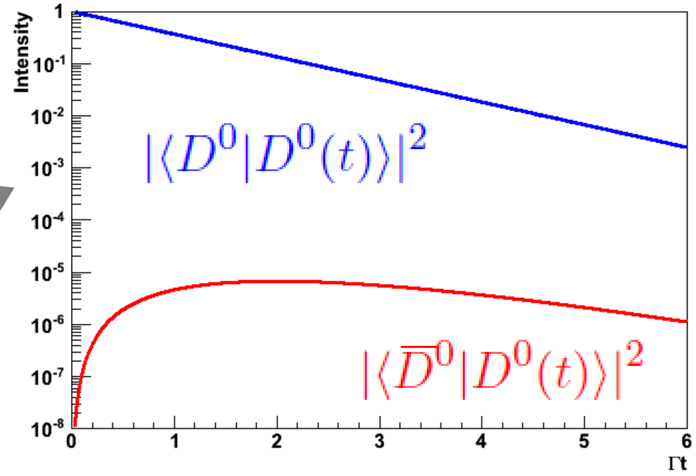
x = -0.95 and y = 0.99



x = 26 and y = 0.15

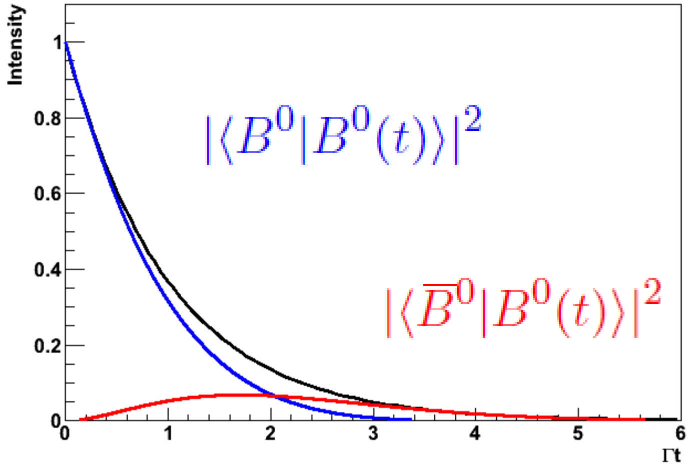


x = 0.5% and y = 0.5%



log scale!

x = 0.77 and y = 0.005



The D Mixing Diagrams

- Computation of the matrix elements:

$$\frac{\langle D_i|\mathcal{H}_{\text{eff}}|D_j\rangle}{2M_D} = M_D\delta_{ij} + \frac{1}{2M_D}\boxed{\langle\overline{D}^0|\mathcal{H}_{\text{w}}^{\Delta C=-2}|D^0\rangle} + \frac{1}{2M_D}\boxed{\sum_n \frac{\langle\overline{D}^0|\mathcal{H}_{\text{w}}^{\Delta C=-1}|n\rangle\langle n|\mathcal{H}_{\text{w}}^{\Delta C=-1}|D^0\rangle}{M_D - E_n + i\epsilon}}$$

short-distance
diagrams

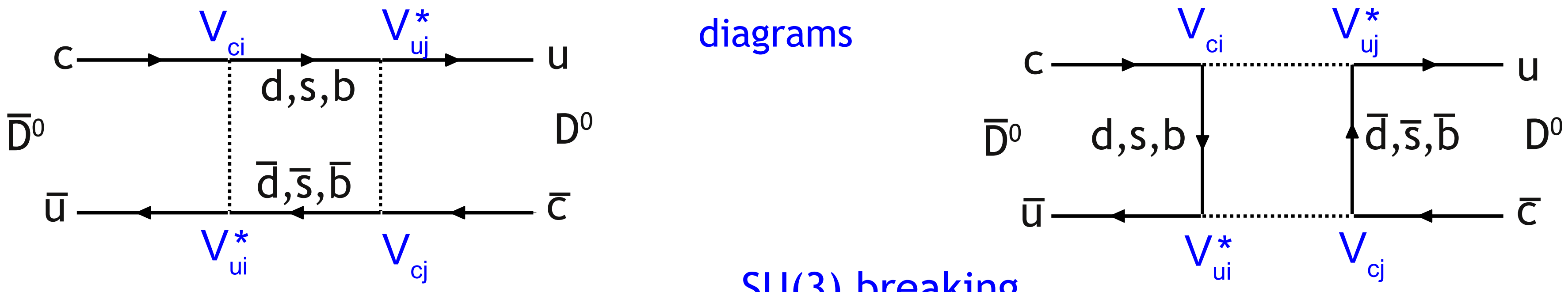
long-distance
diagrams

The D Mixing Diagrams: short-distance

➔ Computation of the matrix elements:

$$\frac{\langle D_i|\mathcal{H}_{\text{eff}}|D_j\rangle}{2M_D} = M_D\delta_{ij} + \frac{1}{2M_D}\boxed{\langle\overline{D}^0|\mathcal{H}_{\text{w}}^{\Delta C=-2}|D^0\rangle} + \frac{1}{2M_D}\sum_n \frac{\langle\overline{D}^0|\mathcal{H}_{\text{w}}^{\Delta C=-1}|n\rangle\langle n|\mathcal{H}_{\text{w}}^{\Delta C=-1}|D^0\rangle}{M_D-E_n+i\epsilon}$$

short-distance diagrams



$$\langle\overline{D}^0|\mathcal{H}_{\text{w}}^{\Delta C=-2}|D^0\rangle = \frac{G_F^2}{4\pi}\overset{\text{DCS}}{\boxed{V^*_{cs}V^*_{cd}V_{ud}V_{us}}}\overset{\text{SU(3) breaking}}{\boxed{\frac{(m_s^2-m_d^2)^2}{m_c^2}}}\langle\overline{D}^0|\bar{u}\gamma^\mu(1-\gamma_5)c\bar{u}\gamma_\mu(1-\gamma_5)c|D^0\rangle$$

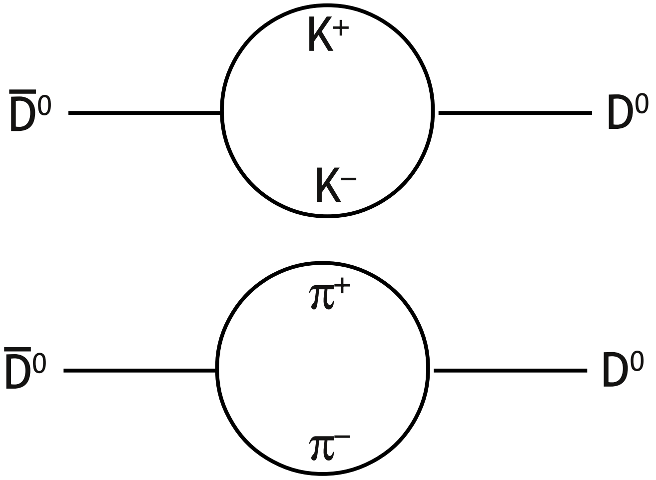
- GIM suppressed, b contribution is highly CKM suppressed
- mainly contribute to Δm: $|x| \sim O(10^{-5})$
- NP contributions in the loop → constraints on NP models

The D Mixing Diagrams: long-distance

- ➔ Computation of the matrix elements:

$$\frac{\langle D_i|\mathcal{H}_{\rm eff}|D_j\rangle}{2M_D} = M_D\delta_{ij} + \frac{1}{2M_D}\langle\overline{D}^0|\mathcal{H}_{\rm w}^{\Delta C=-2}|D^0\rangle + \boxed{\frac{1}{2M_D}\sum_n \frac{\langle\overline{D}^0|\mathcal{H}_{\rm w}^{\Delta C=-1}|n\rangle\langle n|\mathcal{H}_{\rm w}^{\Delta C=-1}|D^0\rangle}{M_D - E_n + i\epsilon}}$$

long-distance diagrams

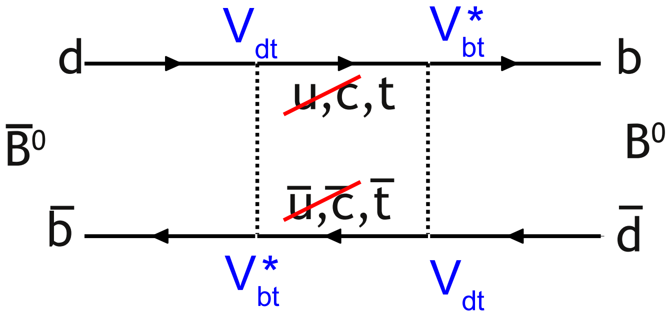


- the intermediate state is a *real* state, accessible by D^0 and $\overline{D}^0$
- computation of these contributions are affected by large theory uncertainties, 2 approaches:
  - OPE [Bigi, Uralsev [Nucl. Phys. B592, 92 (2001)]
  - exclusive approach Falk et al. [PRD69, 114021 (2004)]

- *dominant* contribution to mixing but affected by large theory uncertainties
- contribute to both Δm and $\Delta\Gamma$: $|x|,|y| < O(10^{-2})$
- no NP contributions expected

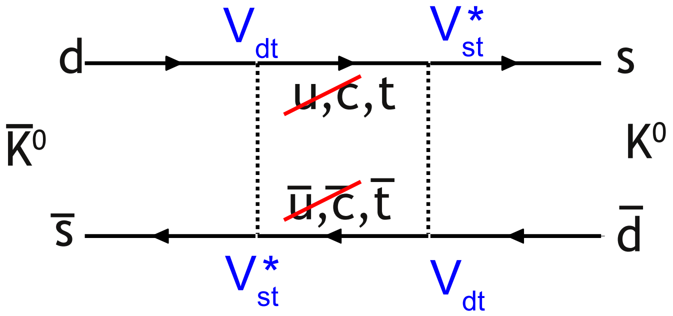
The Mixing Diagrams for the Other Systems

- ➔ In the B systems the dominant contribution comes from the short-distance

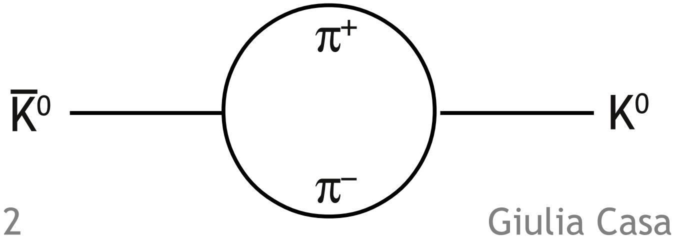


- no GIM suppression here!

- ➔ In the K system both contributions are important



- no GIM suppression here!
- different fraction of common final states w.r.t. B-system



CP Violation in the Standard Model

- In the Standard Model, CPV is naturally introduced by the unitary CKM matrix, that describes *quark* mixing:

interaction eigenstates

mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfeinstein parametrization up to λ^4

- The irreducible complex phase is responsible for CPV:
  - each term in the Lagrangian is transformed to its hermitian conjugate when CP is applied → any complex term will not be symmetric under CP

- Need 3 angles and 1 phase to completely parameterize it:
  - start with 18 parameters
  - unitary condition → 9 = 3 angles + 6 phases
  - redefinition of 5 over 6 quark phases → 4 = 3 angles + 1 phase.

CP Violation in the SM, Charm Sector

- In the Standard Model, CPV is naturally introduced by the unitary CKM matrix, that describes *quark* mixing:

interaction eigenstates

mass eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{array}{c} \begin{array}{ccc} u & c & t \end{array} \\ \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-\boxed{i\eta}) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-\boxed{i\eta}) & -A\lambda^2 & 1 \end{pmatrix} \end{array} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfeinstein parametrization up to λ^4

- Charm decays involve primarily the first 2 generations

naively, no CP Violation is expected in SM

- As for mixing, the *computation* of the SM prediction is affected by large theory uncertainties, preventing a straightforward interpretation of the recent experimental evidence of CPV

Three Types of CPV

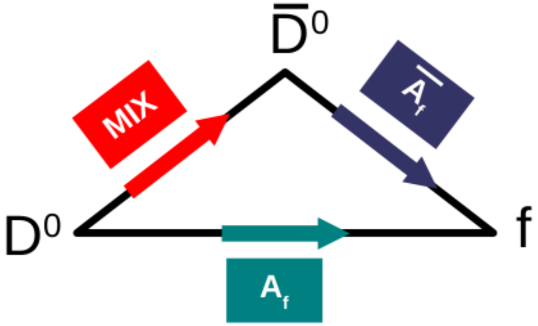
$$\begin{aligned} A_f &= \langle\, D^0 \mid \mathcal{H} \mid f \,\rangle \\ A_{\bar f} &= \langle\, D^0 \mid \mathcal{H} \mid \bar f \,\rangle \\ \bar A_f &= \langle\, \bar D^0 \mid \mathcal{H} \mid f \,\rangle \\ \bar A_{\bar f} &= \langle\, \bar D^0 \mid \mathcal{H} \mid \bar f \,\rangle \end{aligned}$$

- CP Violation in the decay if $|A_f| \neq |\bar A_{\bar f}|$
  - need at least 2 amplitudes with different strong and weak phases, the observables are in form of asymmetries:

$$A_{CP}(f) = \frac{|A_f|^2 - |\bar A_{\bar f}|^2}{|A_f|^2 + |\bar A_{\bar f}|^2} \quad \text{or} \quad A_D^f = \frac{|A_f/\bar A_f|^2 - |\bar A_{\bar f}/A_{\bar f}|^2}{|A_f/\bar A_f|^2 + |\bar A_{\bar f}/A_{\bar f}|^2}$$

- CP Violation in mixing if $R_M = \left|\frac{q}{p}\right| \neq 1$ or $A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}$
  - probability of $D^0 \to \bar D^0$ is different than the CP-conjugate $D^0 \to \bar D^0$

- CP Violation in the *interference* between decay with and without mixing:



if $\phi_f \neq 0$ where $\lambda_f = \frac{q}{p}\frac{\bar A_f}{A_f} = \left|\frac{q}{p}\frac{\bar A_f}{A_f}\right| \exp\left[i(\delta_f + \phi_f)\right]$

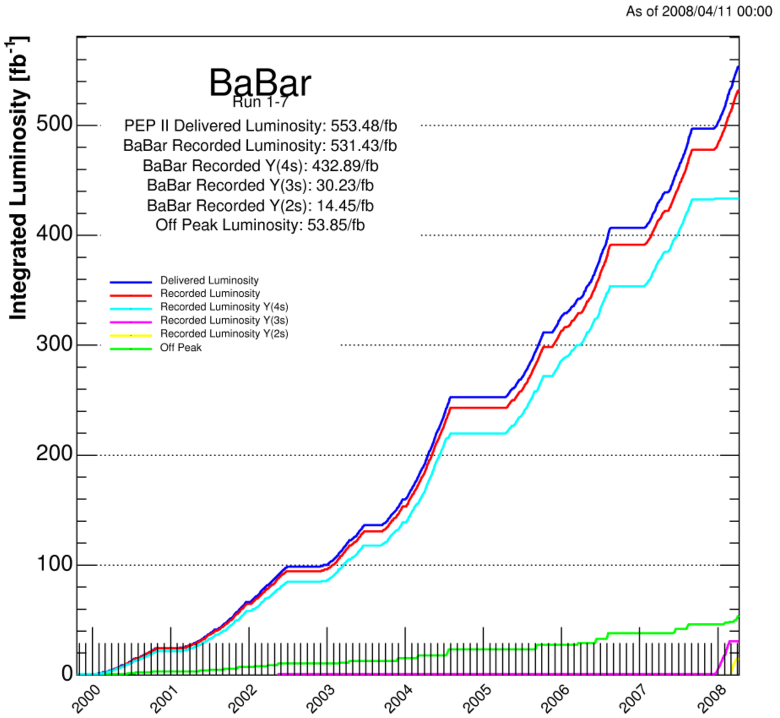
strong + *weak* phase

Why is Charm Special?

- ➔ It is *only* system made of up-type quark
  - provides a complimentary information on Mixing and CPV
  - constrains NP models
- ➔ Evidence of CPV has been reported by LHCb and CDF and has no straightforward interpretation, can be SM but also NP
  - theory uncertainties prevent the use of these results
- ➔ In order to understand the origin of the reported CPV evidence we need to study more channels and improve the precision on the existing measurements

BaBar Detector and Charm Physics

The BaBar Detector



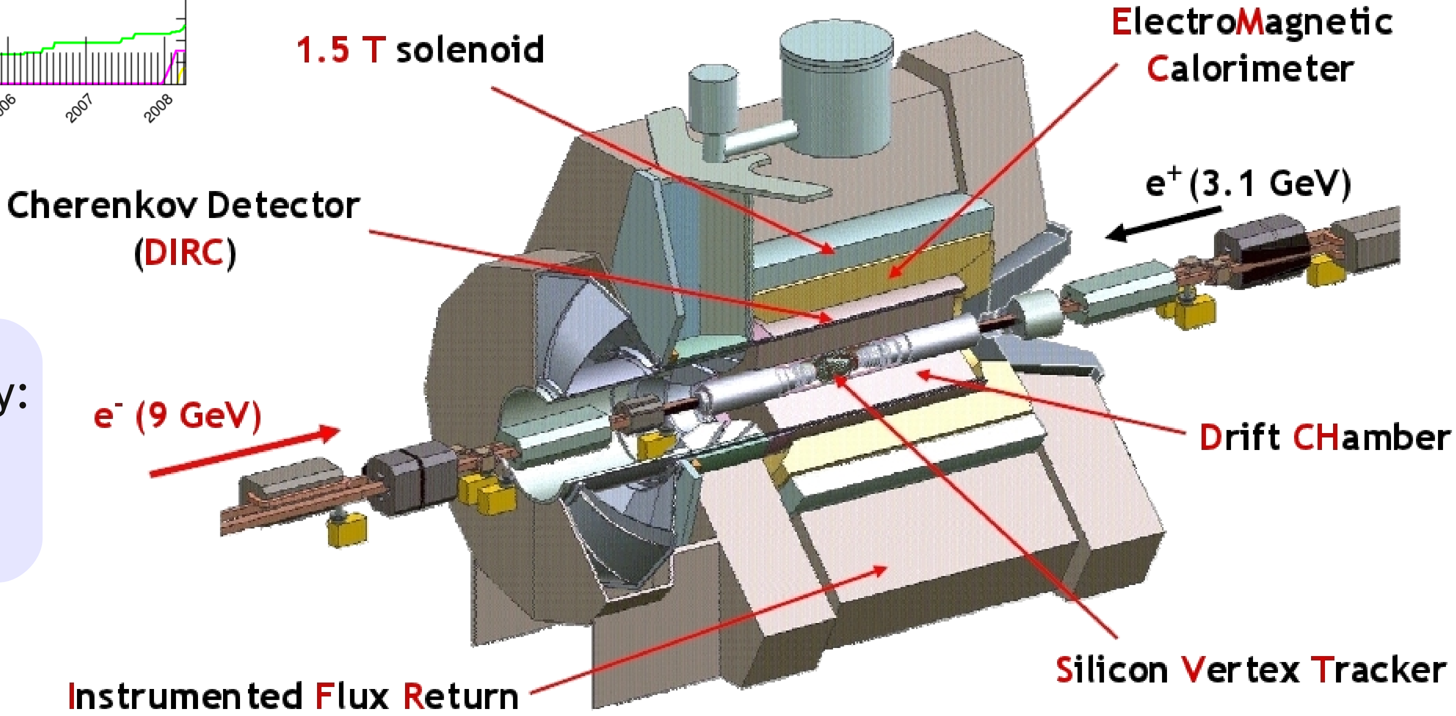
$e^+e^- \rightarrow \Upsilon(4S)$

Run1 to Run6: L(on + off peak) = 474 fb^{-1}

$e^+e^- \rightarrow \Upsilon(3S), \Upsilon(2S)$

Run7: L(on + off peak) = 47 fb^{-1}

PEPII is also a charm-Factory: it produced around 690M of $e^+e^- \rightarrow c\bar{c}$ events



Charm Physics at Babar

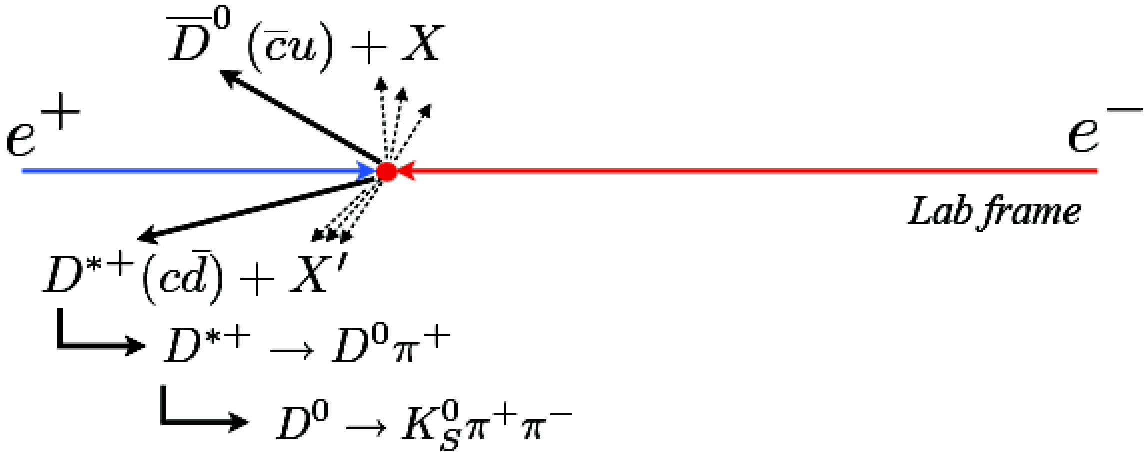
- ➔ BaBar principal aim was to study mixing and CPV in the B^0 mesons, secondary goals were the study of rare τ and charm processes

e^+**e**$^+$ → Y(4S) → B $\overline{\text{B}}$

- Y(4S) is boosted with βγ = 0.56
- B and $\overline{\text{B}}$ are produced in a *coherent* state

- ➔ A charm event is different:

no coherent production of D $\overline{\text{D}}$ state
- alternative ways to tag the D flavor ($D^{*+} \to D^0\,\pi^+$)
- information on D and D relative strong phases not available
  - x,y, → x',y' rotated by δ
  - alternative parameters, y_{CP}



Lifetime Ratio Analysis at BaBar

The Observables, y_{CP} and ΔY

Mixing

$$y_{CP} = \frac{\Gamma^+ + \overline{\Gamma}^+}{2\Gamma} - 1$$

CP Violation

$$\Delta Y = \frac{\Gamma^+ - \overline{\Gamma}^+}{2\Gamma}$$

Γ^+ is the width of the decay $D^0 \rightarrow$ CP+

$\overline{\Gamma}^+$ is the width of the decay $\overline{D}^0 \rightarrow$ CP+

➔ Expanding the effective width for $D^0 \rightarrow h^+h^-$ at 1st order in $x\Gamma t$ and $y\Gamma t$, and A_D^{hh} and A_M):

$$\begin{aligned}\Gamma^+_{hh} \quad \simeq \quad \Gamma \Big[& 1 + (y\cos\phi_{hh} - x\sin\phi_{hh}) + \frac{1}{2}(A_M - A_D^{hh})\ (y\cos\phi_{hh} - x\sin\phi_{hh}) + \\ & -\frac{1}{4}A_M A_D^{hh}\ (y\cos\phi_{hh} - x\sin\phi_{hh})\Big]\end{aligned}$$

depend on the final state:

- direct CPV term
- CPV in interference term

$$\begin{aligned} y_{CP}^{hh} \quad &= \quad y\cos\phi_{hh} - \frac{1}{2}\left[A_M + A_D^{hh}\right]\ x\sin\phi_{hh} - \frac{1}{4}A_M A_D^{hh}\ y\cos\phi_{hh} \\ \Delta Y^{hh} \quad &= \quad -x\sin\phi_{hh} + \frac{1}{2}\left[A_M + A_D^{hh}\right]\ y\cos\phi_{hh} + \frac{1}{4}A_M A_D^{hh}\ x\sin\phi_{hh} \end{aligned}$$

In case of *no CPV* then $y_{CP} = y$ and $\Delta Y = 0$

The Experimental Technique

➔ Perform a simultaneous fit to 5 signal channels and extract the *lifetimes*:

flavour tagged

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

flavour untagged

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

- τ_D = D^0 lifetime ($K^\pm\pi^\mp$)
- τ^+ ($\overline{\tau}^+$) = D^0 ($\overline{D}^0$) effective lifetime for decays to CP+ eigenstates (K^+K^- , $\pi^+\pi^-$)

$$y_{CP} = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} + \frac{1}{\overline{\tau}^+}\right) - 1$$

$$\Delta Y = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} - \frac{1}{\overline{\tau}^+}\right)$$

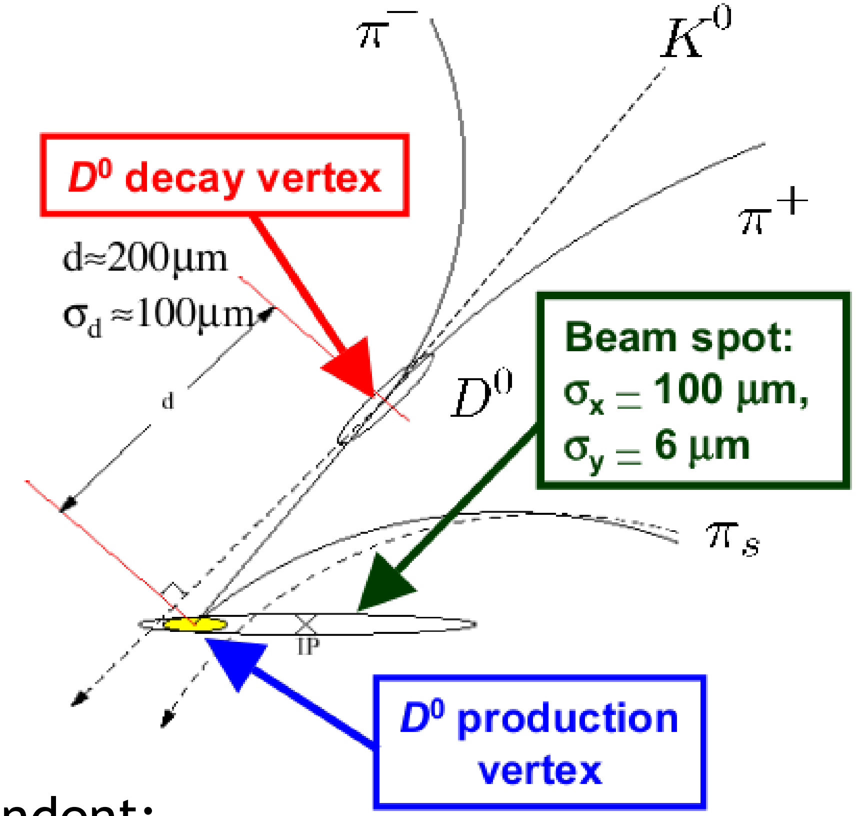
➔ Experimental assumptions:

- small mixing ($|x|$, $|y| \ll 1$) → proper time distributions are exponential with corresponding effective lifetimes to a very good approximation;
- not sensitive to direct CPV + weak phase φ does not depend on final state → KK and ππ modes share common effective lifetimes: [PRD 80. 076008 (2009)]

$$\begin{aligned} y_{CP} &= y\cos\phi - \frac{A_M}{2}\,x\sin\phi \\ \Delta Y &= -x\sin\phi + \frac{A_M}{2}\,y\cos\phi \end{aligned}$$

Reconstruction and Selection of the Events

- to benefit from the *simultaneous* fit to the 5 modes, we ensure that the resolutions of tagged and untagged modes are as similar as possible:
  - reconstruction of the *tagged* candidates is done without using the additional information coming from the slow pion;
- selection of the signal events:
  - remove D from B decays, $p_{CM}(D^0) > 2.5$ GeV/c
  - vertex fit probability: $P(\chi^2) > 0.1\%$
  - apply quality cuts on the D^0 daughters and the slow pion tracks



D^0 decay vertex

Beam spot:
$\sigma_x = 100\ \mu m$,
$\sigma_y = 6\ \mu m$

D^0 production vertex

- the tagged and untagged datasets are independent:
  - events containing a tagged candidate that satisfies $0.1447 \le \Delta m\ (\text{GeV}/c^2) \le 0.1463$ are removed from the untagged dataset.

Backgrounds

combinatorial background:

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

charm background:

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

in the signal region(*):

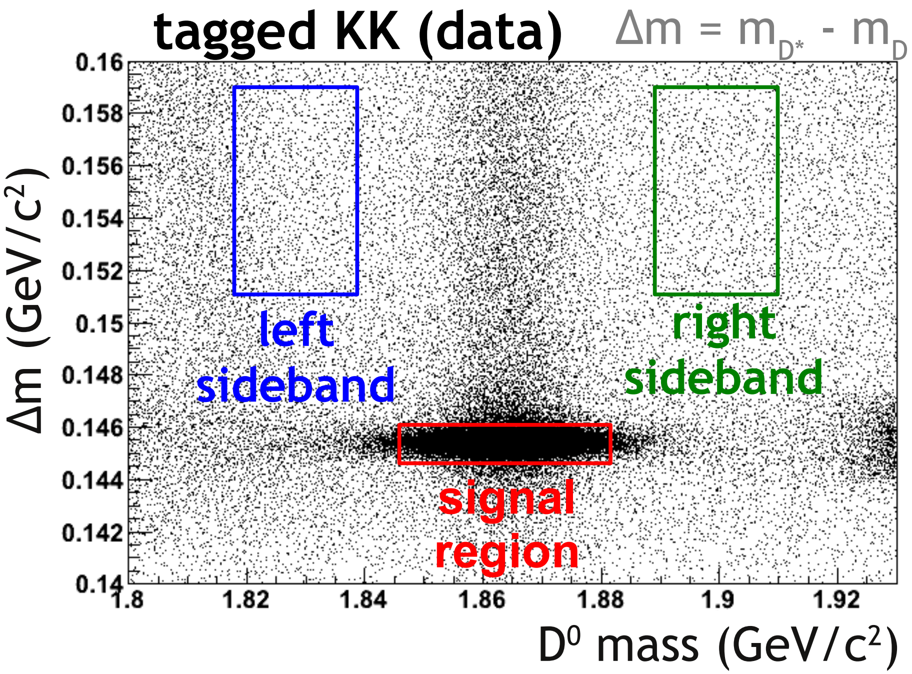
	Tagged			Untagged	
	$\pi^-\pi^+$	K^-K^+	$K^\pm\pi^\mp$	K^-K^+	$K^\pm\pi^\mp$
Signal	65429 ±262	136867 ±371	1487000 ±1220	496200 ±1150	5825300 ±2600
Comb. Bkgd.	3760	653	2849	164970 ±997	1044552
Charm Bkgd.	97	309	642	5477	4645

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

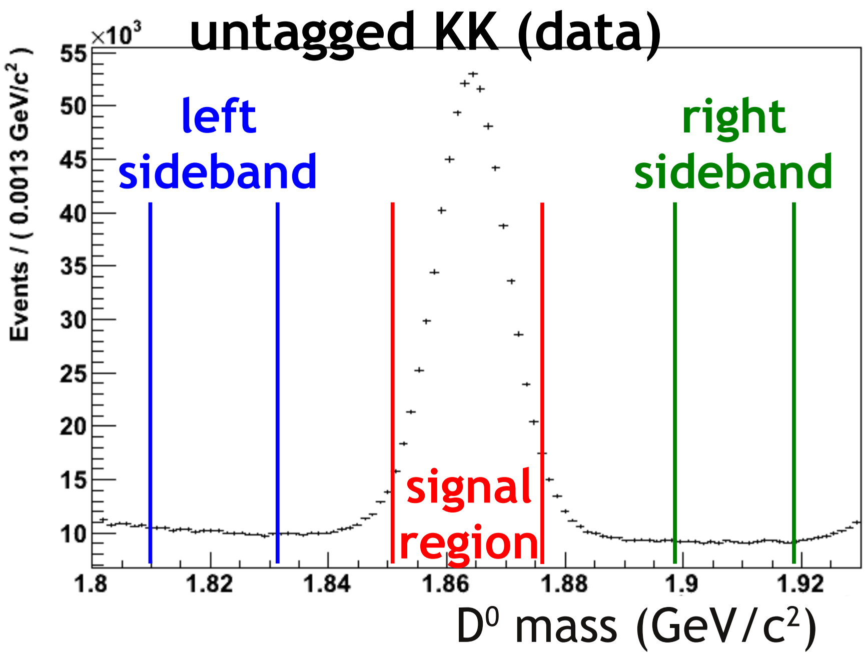
(*) charm yields evaluated on MC events

Data Samples for the Lifetime Fit

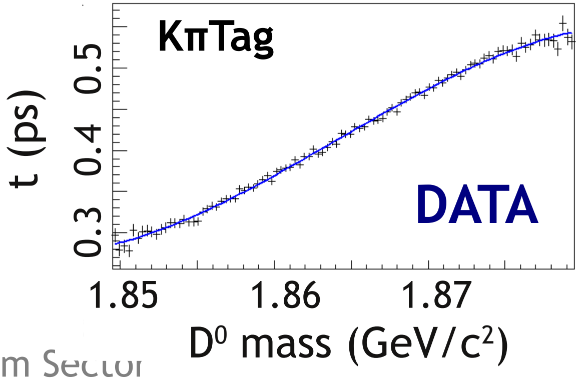
- we select events in a (m_D, Δm) region for the tagged modes.



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



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



Lifetime Fit Strategy

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

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

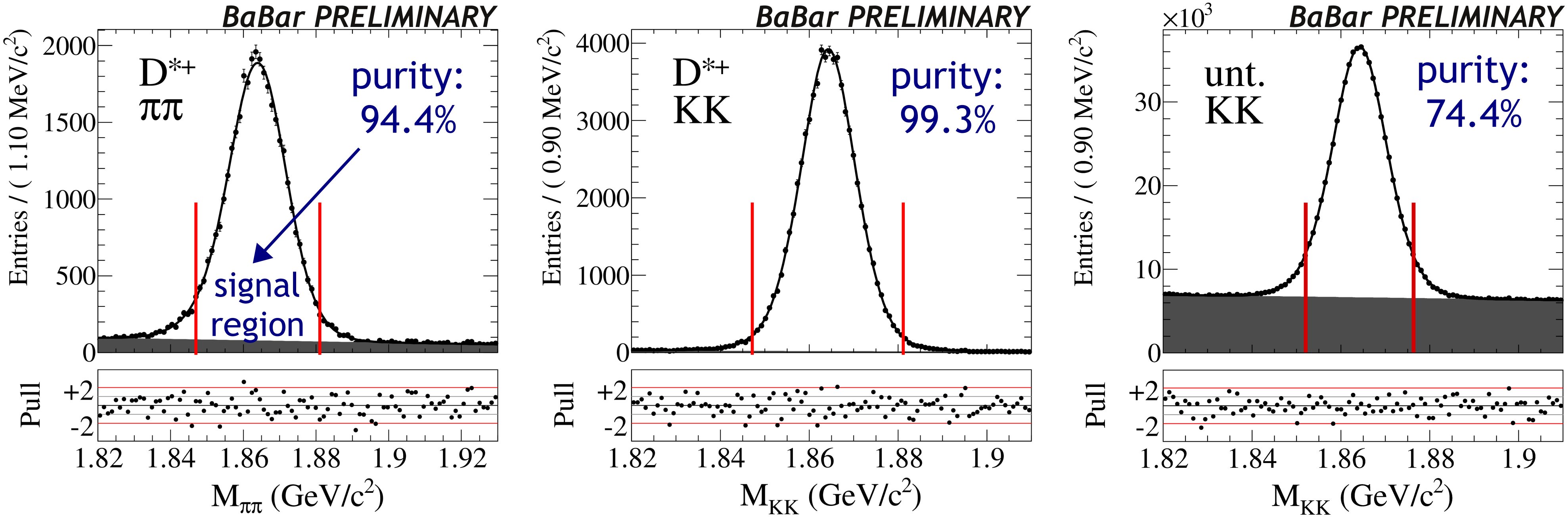
➔ **step2a: extraction of the background shapes**

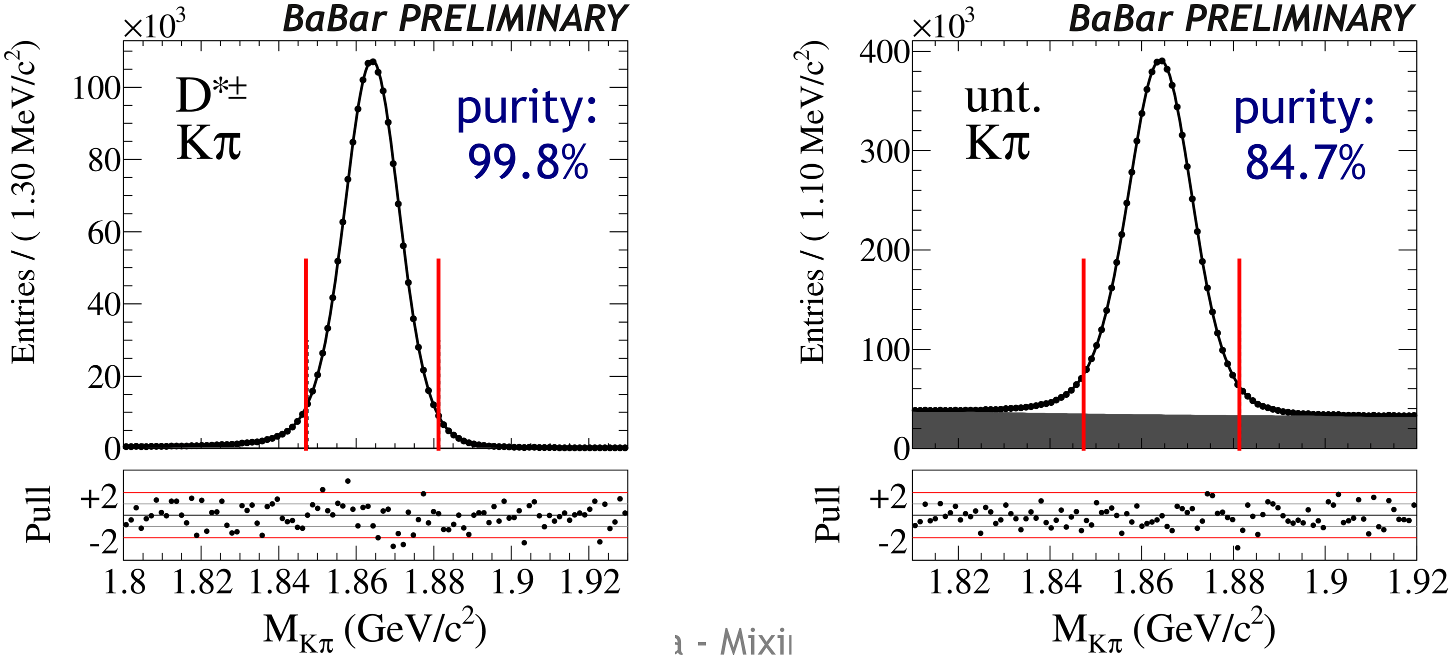
- extract charm background PDF from MC;
- extract the combinatorial background PDF from the data sidebands;

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

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

Data Mass Fits





The Signal Lifetime Simultaneous PDF

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

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

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

τ^+ ⇨ $D^0 \to CP+$

$\bar{\tau}^+$ ⇨ $\bar{D}^0 \to CP+$

$\tau_{K\pi}$ ⇨ $D^0,\bar{D}^0 \to K\pi$

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

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

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

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

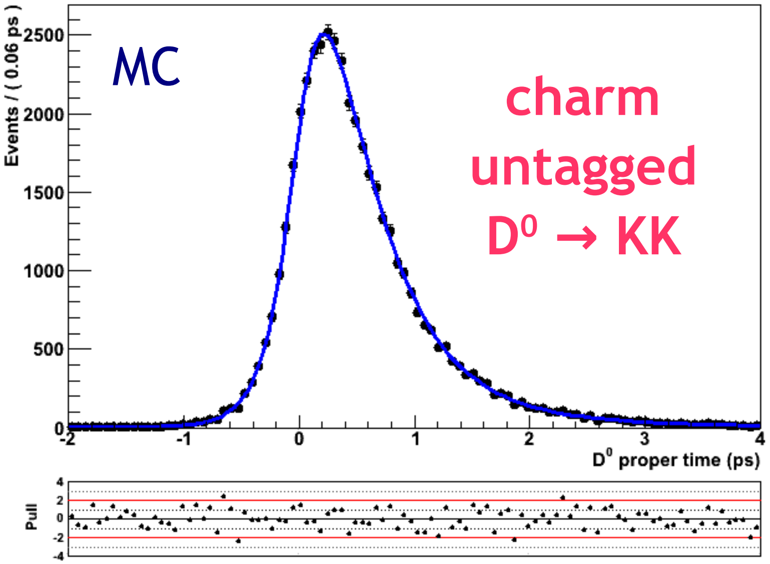
- take into account the mistagged events in tagged KK and ππ modes
- assume untagged KK is 50% D^0 and 50% $\bar{D}^0$.

The Background Lifetime PDFs

charm background PDF:

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

proper time projection



combinatorial background PDF:

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

Fit Validation

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

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

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

in all data crosschecks, the extracted lifetimes were compatible

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

KK and ππ results are statistically compatible

Systematics

BaBar PRELIMINARY

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

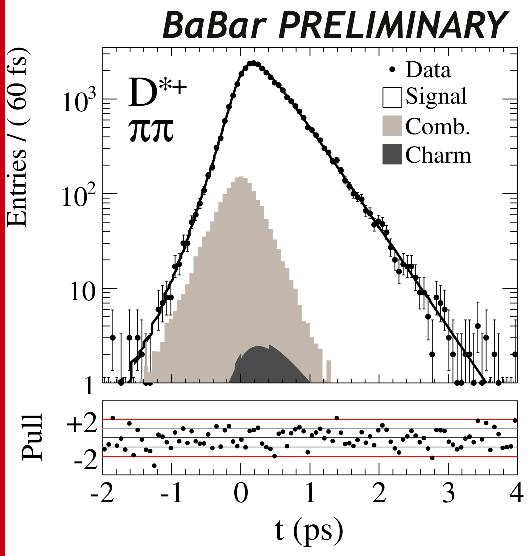
total systematics reduced w.r.t. previous *BaBar* analyses

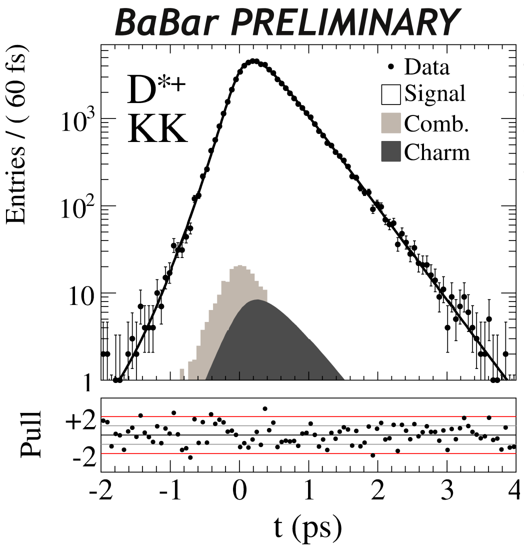
- tagged-only analysis [PRD 78, 011105 (2008)]
- untagged-only analysis [PRD 80, 071103 (2009)]

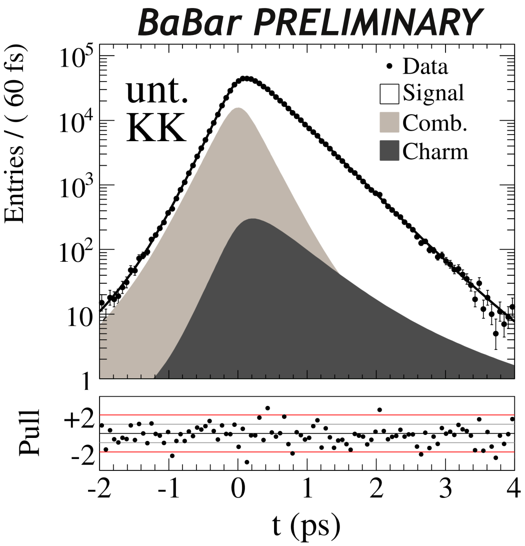
Proper Time Fit Projection

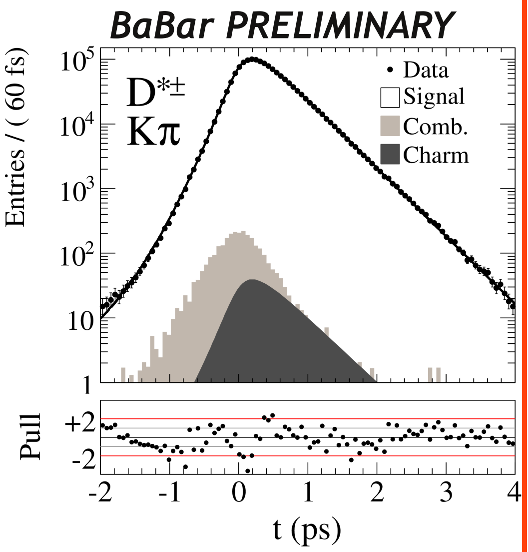
CP+ eigenstates

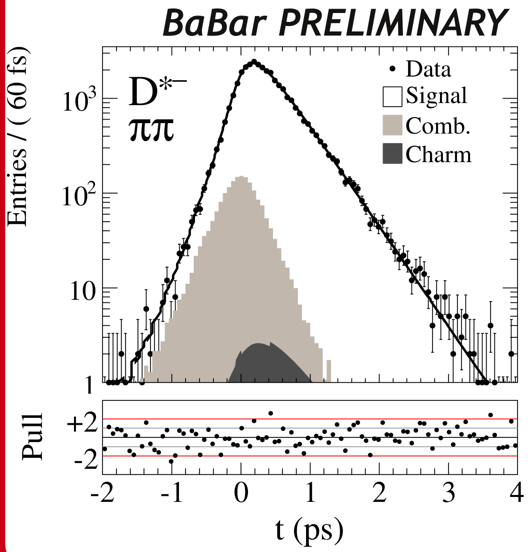
CP mixed states

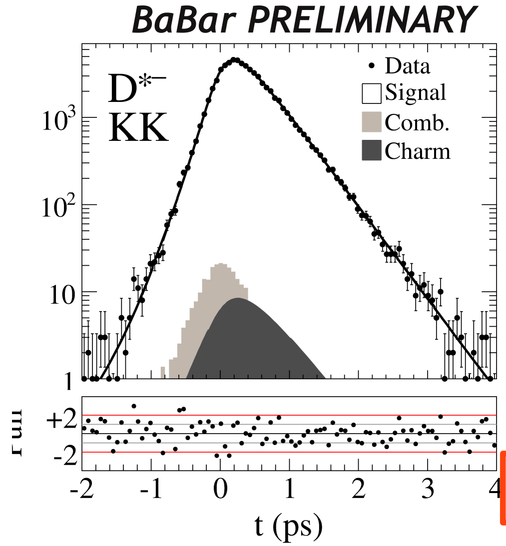












CP+ lifetimes

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

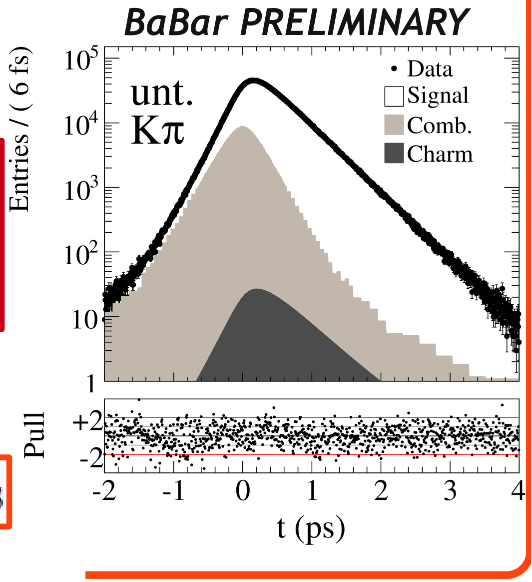
$$\bar{\tau}^+ = (406.40 \pm 1.25)\ \text{fs}$$

[stat error only]

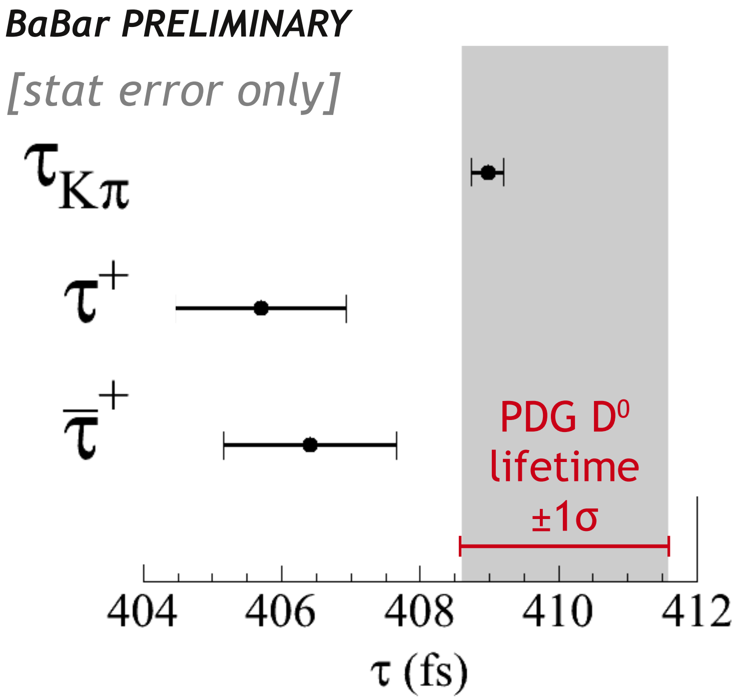
D^0 lifetime

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

[stat error only]



The Results



BaBar PRELIMINARY

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

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

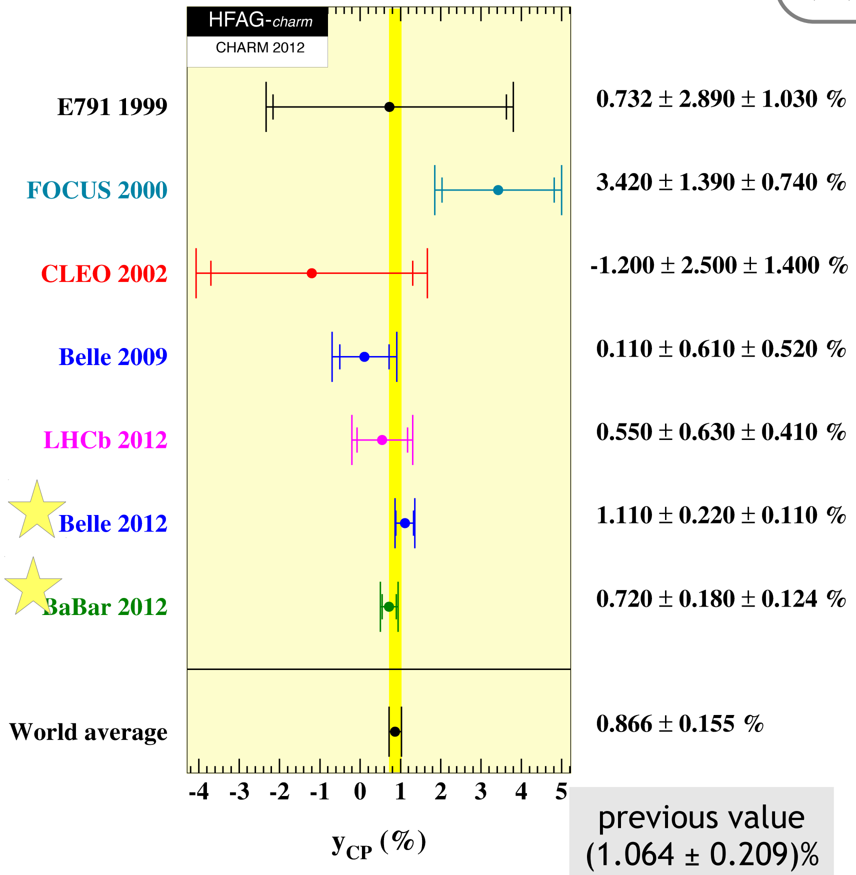
→ exclude no-mixing hypothesis @ 3.3σ

→ no CP Violation observed

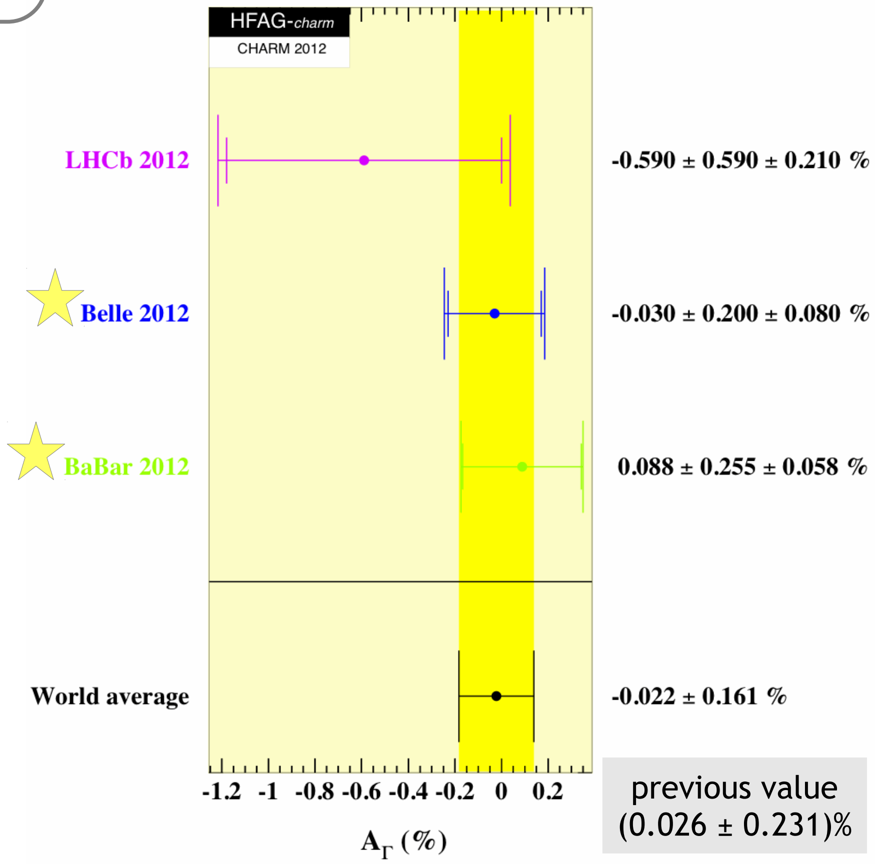
- most precise single measurement of y_{CP};
- this measurement favors a lower value for y_{CP}, in closer agreement with HFAG value for y:
  - HFAG y =(0.456 ± 0.186) % from direct measurements
- this result is compatible with previous BaBar results [PRD 80, 071103 (2009)], [PRD 78, 011105 (2008)] :
  - ΔY = (-0.26±0.36±0.08) % (sign difference in the def.)
  - y_{CP} = (1.16±0.22±0.18) %
- this result supersedes the previous BaBar results.

Comparison with other Experiments

★ = new



previous value
(1.064 ± 0.209)%



previous value
(0.026 ± 0.231)%

BaBar measurements are in agreement with the latest Belle results and contribute diminishing the statistical error on both observables of ~ 25-30%

Other New Recent Measurements from BaBar and other Experiments

References:

- reported on the slides
- all results presented without a reference are preliminary

Direct Measurement of x and y

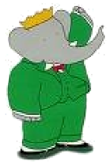
- Belle just presented a *direct* measurement of x and y with a time dependent Dalitz analysis of the decays $D^0 \rightarrow K_S\pi\pi$
  - assume a model for the distribution on the Dalitz Plot
  - assume no CP Violation

976 fb^{-1}

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

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

468 fb^{-1} with also $D^0 \rightarrow K_S KK$



2010

$$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$$

$$y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$$

[PRL105, 081803 (2010)]

- In case of no CP Violation we expect $y_{CP} = y$:

$$y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$$

$$y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%$$

BaBar y and y_{CP} values are compatible within 1 standard deviation.
Belle results show a tension between the two values of $\sim 2\sigma$

Searches for Direct CPV

- time-integrated CP asymmetries: $A_{CP} = \dfrac{\mathcal{B}(D \to f) - \mathcal{B}(\overline{D} \to \bar{f})}{\mathcal{B}(D \to f) + \mathcal{B}(\overline{D} \to \bar{f})}$
- if a K_S is present in the final state there is a contribution from CPV in K^0 mixing: $A_{CP} = A_{CP}^{\Delta C} + A_{CP}^{K^0}$ where $A_{CP}^{K^0} = (\pm 0.332 \pm 0.006)\%$ (+ if K^0 and – if $\overline{K}^0$)
- experimentally: $A_{\text{reco}} = \boxed{A_{CP}} + \boxed{A_{FB}(\cos\theta^*)} + \boxed{A_{\epsilon}^{h}(p, \cos\theta_h)}$

Forward-Backward asym. from $\gamma - Z^0$ interf. coupled to detector asym

detector-induced charge-reconstructed asymmetry

- the challenge is to keep systematic errors $O(10^{-3})$
- New measurements presented at CHARM (May) or ICHEP (July):

468 fb^{-1}

- $D^+ \to K^+K^-\pi^+$ $A_{CP} = (0.35 \pm 0.30 \pm 0.15)\%$
- (*)$D^+ \to K_S\,\pi^+$ $A_{CP} = (-0.44 \pm 0.13 \pm 0.10)\%$
- $D_S^+ \to K_S\,K^+$ $A_{CP}^{\Delta C} = (0.46 \pm 0.36 \pm 0.25)\%$
- $D^+ \to K_S\,K^+$ $A_{CP}^{\Delta C} = (0.28 \pm 0.23 \pm 0.24)\%$
- $D_S^+ \to K_S\,\pi^+$ $A_{CP}^{\Delta C} = (0.3 \pm 2.0 \pm 0.3)\%$

(*) [PRD-RC83, 071103 (2011)]

LHCb

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

no evidence of CPV

BELLE

976 fb^{-1}

$D^+ \to K_S\,\pi^+$

$A_{CP}^{\Delta C} = (-0.018 \pm 0.094 \pm 0.068)\%$

Difference of Integrated CP Asymmetries

➔ $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi)$ with $A_{CP}(KK) = -A_{CP}(\pi\pi)$ in SU(3)

- increased sensitivity to charm CPV: double central value while and statistical errors adds in quadrature
- cancellation in systematic errors:

$$A_{\text{reco}} = \boxed{A_{CP}} + \boxed{A_{FB}(\cos\theta^*)} + \boxed{A_\epsilon^h(p, \cos\theta_h)}$$

cancel in the difference !

experiment	$A_{CP}(KK)$ (%)	$A_{CP}(\pi\pi)$ (%)	ΔA_{CP} (%)
BaBar	0.00±0.34±0.13	-0.24±0.52±0.22	N.A.
LHCb	N.A.	N.A.	-0.82±0.21±0.11
CDF	-0.24±0.22±0.09	0.22±0.24±0.11	-0.62±0.21±0.10
Belle	-0.32±0.21±0.09	+0.55±0.36±0.09	-0.87±0.41±0.06

CDF (2012) PRD85,012009

BaBar (2008) PRL100,061803

LHCb (2012) PRL108,111602

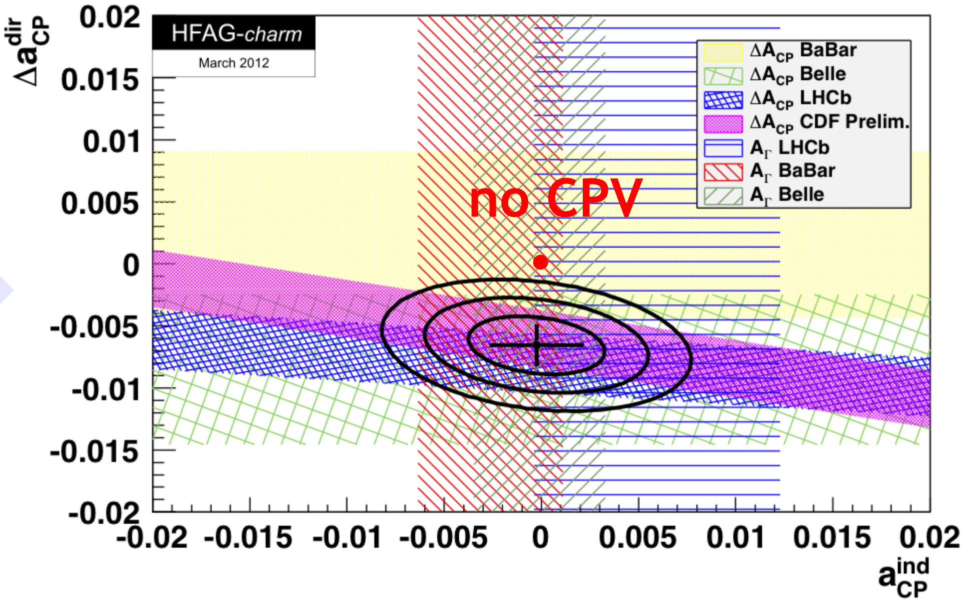
ΔA_{CP} Interpretation

- ΔA_{CP} has contributions from direct and indirect CPV:

$$\Delta A_{CP} = \left[a_{CP}^{\rm dir}(KK) - a_{CP}^{\rm dir}(\pi\pi)\right] + \frac{\Delta\langle t\rangle}{\tau_D} a_{CP}^{\rm ind}$$

After CHARM2012 (May)

data is consistent with no CP violation at 6.15 10^{-5} CL



- NOW: Including the new ΔY from BaBar and Belle and ΔA_{CP} from Belle:

data is consistent with no CP violation at 1.98 10^{-5} CL

Conclusions

Conclusions

- Historically mixing and CPV measurements have been of fundamental importance for the development of the Standard Model
- The D^0 system has unique features and provide complimentary information on mixing and CP violation w.r.t. the other mixing systems
- The evidence of CPV reported by LHCb and CDF has renewed the interest of the physics community into charm, as a place where to look for NP
- Increase in Precision and inclusion of more channels are needed to understand the origin of this CPV

stay tuned on charm physics!

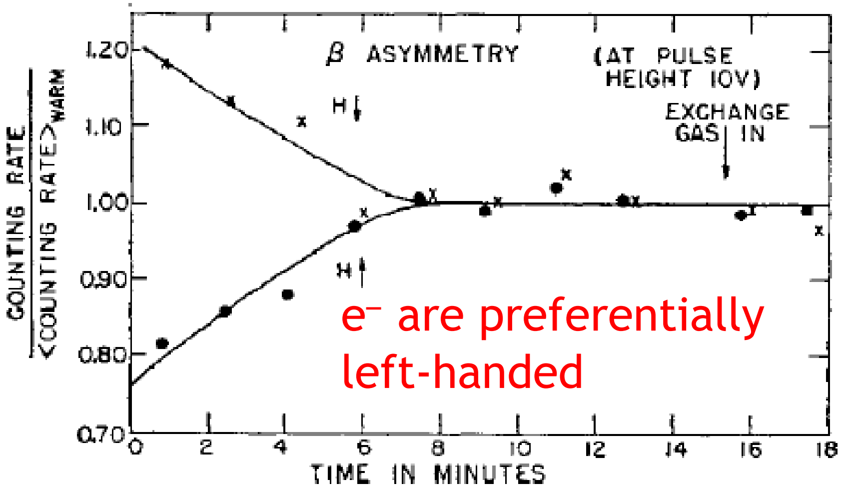
backup slides

Parity *is* violated in weak interactions

- April 1956, Sixth Rochester Conference, the puzzle was intensely discussed:
  - In a introductory talk Yang (and Lee) proposed the existence of particle pairs with opposite parities but otherwise identical properties
  - Feynman brought up a question of Block's: "*could it be that θ and τ are different parity states of the same particle which has no definite parity, i.e., that parity is not conserved.*"

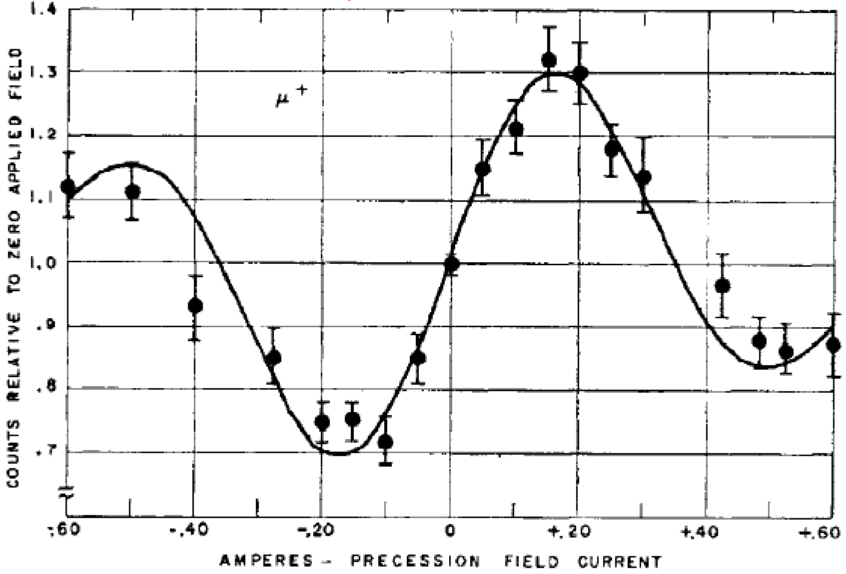
- June 1956, Lee and Yang proposed a certain number of experiments to test the conservation of P in weak interactions, promptly realized (1957):

Madame Wu, $^{60}Co \rightarrow {}^{60}Ni^* + e^- + \bar{\nu}$



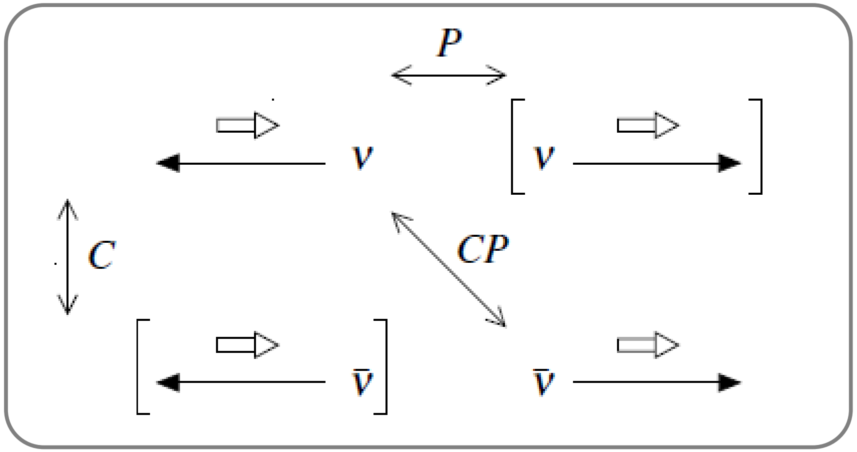
e⁻ are preferentially left-handed

Garwin, $\pi \rightarrow \mu\, \nu$



The V – A Theory

- The experimental proofs that P was maximally violated implied that also C was (maximally) violated
- The combination of C and P was still a symmetry



- The discovery of P and C violation was a key ingredient for *Gell-Mann* and *Feynman* (independently) to write the V – A theory of weak interactions starting from Fermi theory of β decays and extending the idea of Lee and Yang of left and right projectors applied to neutrino wave functions.

K system: Mixing and CPV, Short Story

- 1956, prediction and discovery of K^0-$\overline{K}^0$ mixing

first observation of mixing

- 1964, discovery of indirect CPV
  - in $K_L \rightarrow \pi\pi$ decays

first observation of CPV

- 1988, discovery of direct CPV by NA31 (confirmed by NA48 and KTeV in 1999)
  - in $K_L \rightarrow \pi\pi$ decays

ruled out the superweak model

NA31: [Phys. Lett. B206, 169 (1988)]
NA48: [Phys. Lett. B465, 355 (1999)]
KTeV: [PRL 83, 22, 355 (1999)]

- Parameters describing CPV in this system:
  - ε describes indirect CPV
  - ε' describes direct CPV

$|\varepsilon| = (2.228 \pm 0.011) \times 10^{-3}$
$\mathrm{Re}(\varepsilon'/\varepsilon) = (1.65 \pm 0.26) \times 10^{-3}$
phases of ε' and ε are both $\sim \pi/4$

D^0 mesons reconstruction at BaBar

Tag the flavour of the neutral D meson at production:

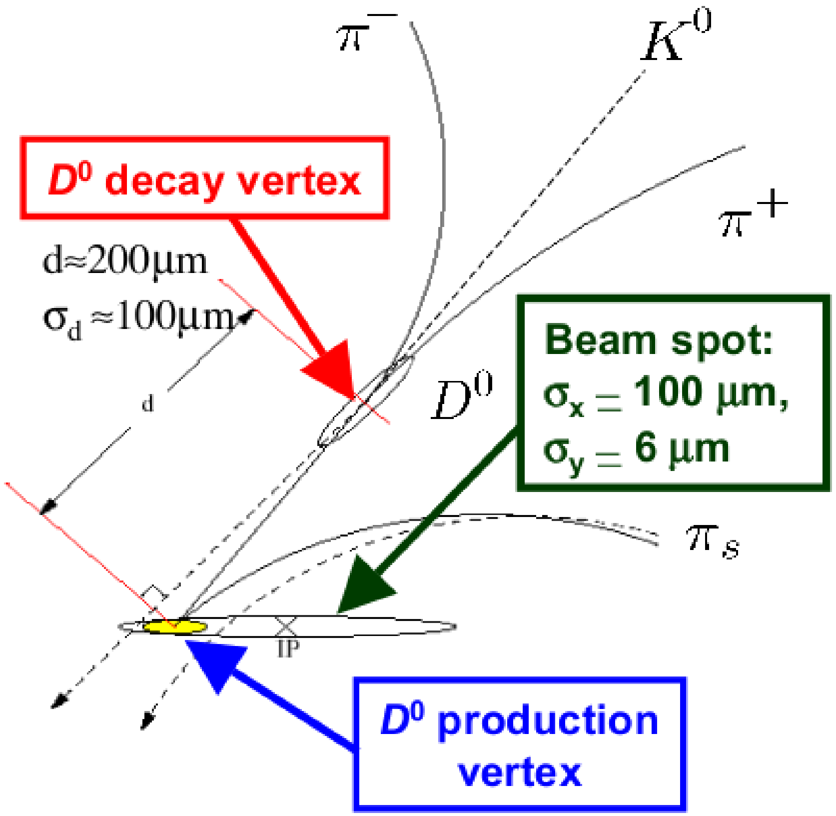
→ reconstruct the decay chain $D^{*+} \to D^0 \pi_s^+$, $D^{*-} \to D^0 \pi_s^-$

- identify the D^0 flavour at production using the charge of the π_s
- select events around the peak of $\Delta m = m_{D^*} - m_D$ ($\sigma \sim 350$ keV/c^2)
- $|p_{cm}(D^0)| > 2.5$ GeV/c to reject D from B decays and improve signal significance

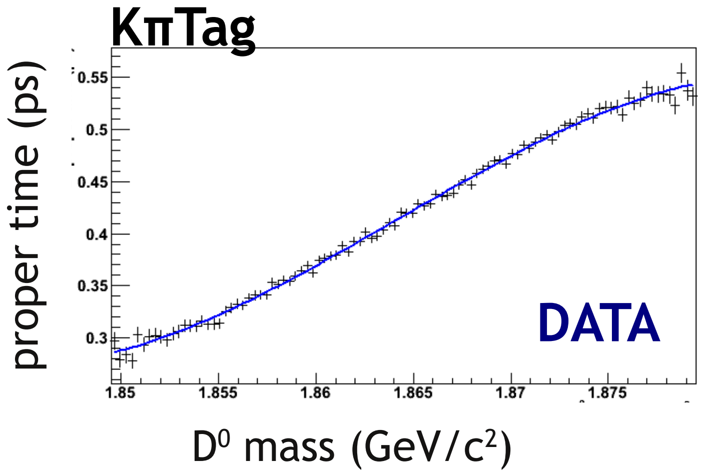
Measure the neutral D meson proper time:

→ require that the D^0 (and D*) production vertex fall inside the luminous region (beam spot)

- D* decays immediately after being created
- allows the determination of the D^0 flight time *t* and its error σ_t.



Mass Signal Region Optimization



WHY?

In order to obtain the cancellation of the effect of the correlation between mass and proper time;

secondary goal: reduction of the statistical error on the lifetimes;

the signal box should be centered in the mass peak and contain equal number of signal events in the left side and in the right side (in the approx. of linear correlation).

➔ The signal box position and width has been optimized separately for DATA and MC because the mass distributions show visible differences.

➔ In DATA the peaks position show differences among the different channels → taken into account in the definition.

➔ Adopted a smaller signal box for the KKUnt channel because of the lower purity of this sample.

Searches for Direct CPV

- ➔ need at least 2 amplitudes with different weak and strong phases:
  - Singly Cabibbo Suppressed: tree + penguin
  - Cabibbo Favoured + Doubly Cabibbo Suppressed

$D^+ \to K^+K^-\pi^+$	SCS tree+penguin	
$D_s^+ \to K_S K^+$	CF + DCS	
$D^+ \to K_S K^+$	SCS tree+penguin	
$D_s^+ \to K_S \pi^+$	SCS tree+penguin	

- ➔ time-integrated CP asymmetries:

$$A_{CP} = \frac{\mathcal{B}(D \to f) - \mathcal{B}(\overline{D} \to \bar{f})}{\mathcal{B}(D \to f) + \mathcal{B}(\overline{D} \to \bar{f})}$$

- ➔ if a K_S is present in the final state there is a contribution from CPV in K^0 mixing:

$A_{CP} = A_{CP}^{\Delta C} + A_{CP}^{K^0}$ where $A_{CP}^{K^0} = (\pm 0.332 \pm 0.006)\%$ (+ if K^0 and – if $\overline{K}^0$)

- ➔ experimentally: $A_{\text{reco}} = \boxed{A_{CP}} + \boxed{A_{FB}(\cos\theta^*)} + \boxed{A_\epsilon^h(p, \cos\theta_h)}$

Forward-Backward asym. from $\gamma - Z^0$ interf. coupled to detector asym.

- odd in cosθ* → decouple from A_{CP} (independent of cosθ*)

$$\boxed{A_{CP} = \frac{A(+|\cos\theta^*|) + A(-|\cos\theta^*|)}{2}}$$

(both analysis)

- use data-corrected MC ($D^+ \to K^+K^-\pi^+$)

detector-induced charge-reconstructed asymmetry;
to evaluate it and correct for it:

- data-driven method ($D_{(s)}^+ \to K_S h^+$)
- $e^+e^- \to \tau^+\tau^-$ data sample ($D^+ \to K^+K^-\pi^+$)

- ➔ In three-body decays CPV effects can be enhanced in certain Dalitz Plot (DP) regions
  - DP model-dependent and model-independent searches

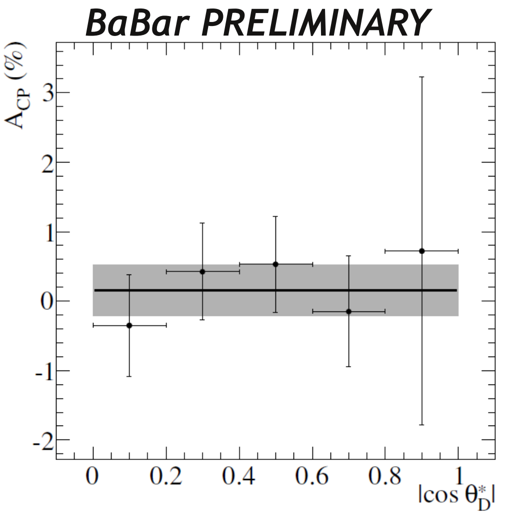
$D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ analysis

L = 469 fb^{-1}

- ➔ Precision goal is $o(10^{-3})$, need to keep systematic errors at that level
  - correct for the detector-induced charge-reconstruction asymmetry using a *data driven* method that makes use of physical-asymmetries-free charged track sample from B decays [PRD 83, 071103 (2011)]
- ➔ Perform simultaneous mass fit and extract the number of $D_{(s)}^+$ and $D_{(s)}^-$ in 10 bins of cosθ*
  - decouple CP from FB asymmetry and perform a χ^2 fit to a constant value, A_{CP}:

$D^+ \to K_S K^+$

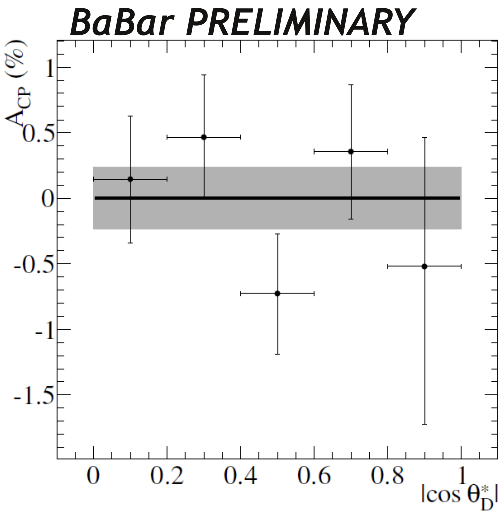
159k evts



$$A_{CP} = (0.16 \pm 0.36)\%$$

$D_s^+ \to K_S K^+$

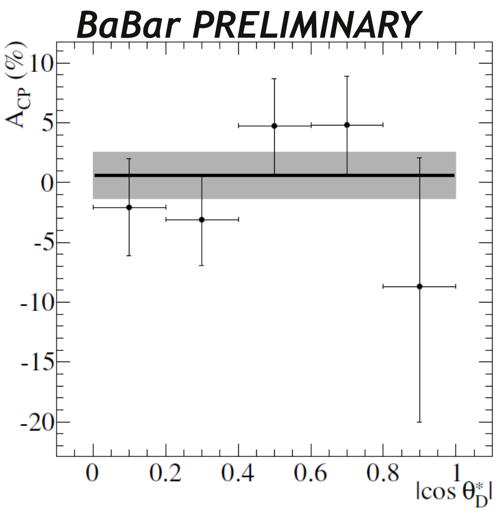
288k evts



$$A_{CP} = (0.00 \pm 0.23)\%$$

$D_s^+ \to K_S \pi^+$

14k evts

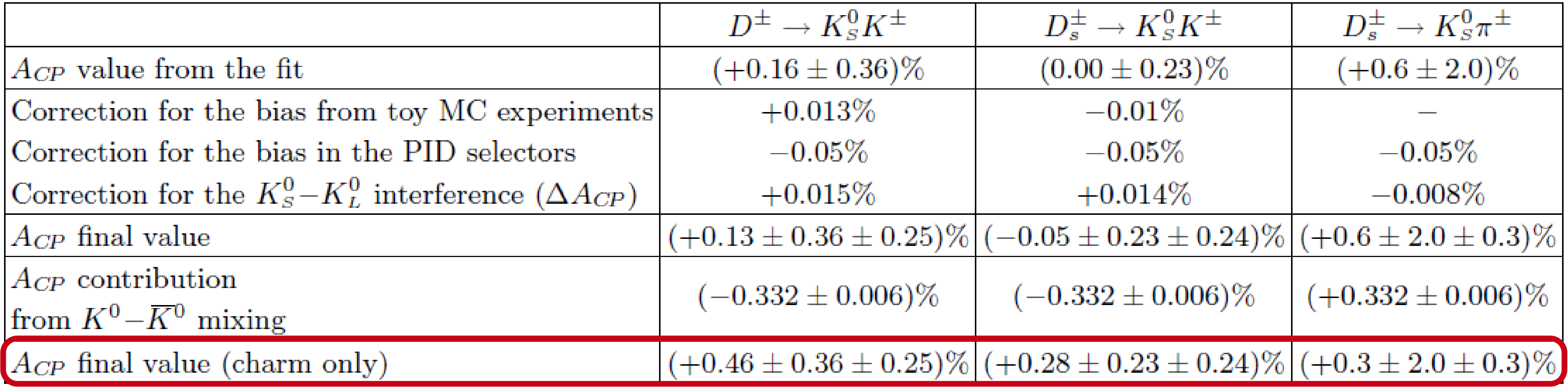


$$A_{CP} = (0.6 \pm 2.0)\%$$

$D^+ \to K_S K^+$, $D_s^+ \to K_S K^+$, $D_s^+ \to K_S \pi^+$ results

- **Dominant systematic uncertainties:**
  - statistics of the control sample used to correct for the charge asymmetry ($D^+_{(S)} \to K_S K^+$)
  - binning in cosθ* to decouple CP from FB asymmetry ($D^+_S \to K_S \pi^+$)

- Apply corrections and evaluate the contribution of CPV from charm:



	$D^\pm \to K^0_S K^\pm$	$D^\pm_s \to K^0_S K^\pm$	$D^\pm_s \to K^0_S \pi^\pm$
A_{CP} value from the fit	$(+0.16 \pm 0.36)\%$	$(0.00 \pm 0.23)\%$	$(+0.6 \pm 2.0)\%$
Correction for the bias from toy MC experiments	$+0.013\%$	-0.01%	$-$
Correction for the bias in the PID selectors	-0.05%	-0.05%	-0.05%
Correction for the $K^0_S - K^0_L$ interference (ΔA_{CP})	$+0.015\%$	$+0.014\%$	-0.008%
A_{CP} final value	$(+0.13 \pm 0.36 \pm 0.25)\%$	$(-0.05 \pm 0.23 \pm 0.24)\%$	$(+0.6 \pm 2.0 \pm 0.3)\%$
A_{CP} contribution from $K^0 - \overline{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(+0.332 \pm 0.006)\%$
A_{CP} final value (charm only)	$(+0.46 \pm 0.36 \pm 0.25)\%$	$(+0.28 \pm 0.23 \pm 0.24)\%$	$(+0.3 \pm 2.0 \pm 0.3)\%$

no CP Violation observed in charm

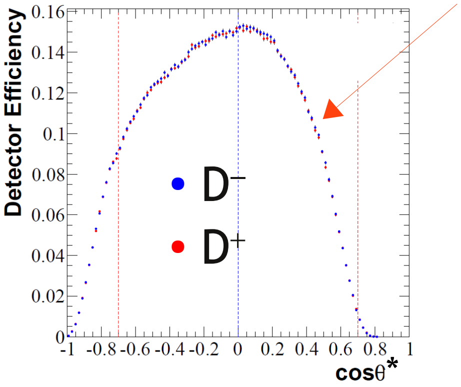
$D^+ \to K^+K^-\pi^+$, integrated asymmetry

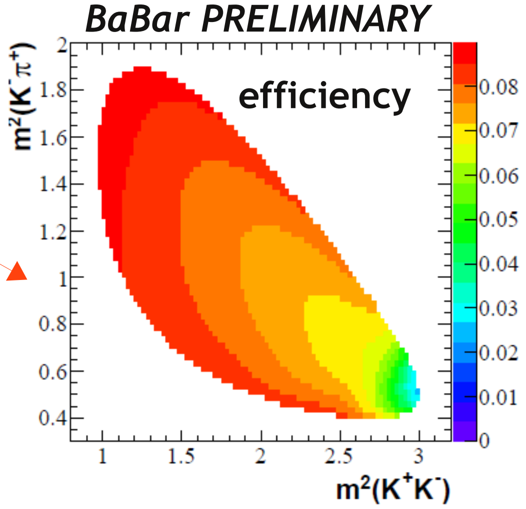
L = 476 fb^{-1}

228k evts
purity 92%

➔ The *reconstruction efficiency* is determined from MC (phase-space DP)

- the MC has been corrected for:
  - FB asymmetry using a PDF in (p*, cosθ*)
  - detector-induced charge-reconstruction asymmetry
- $\epsilon_i^{\pm} = \frac{N^{\pm}_{\rm i,reco}}{N^{\pm}_{\rm i,gen}}$ evaluated in bins of cosθ* and in DP bins



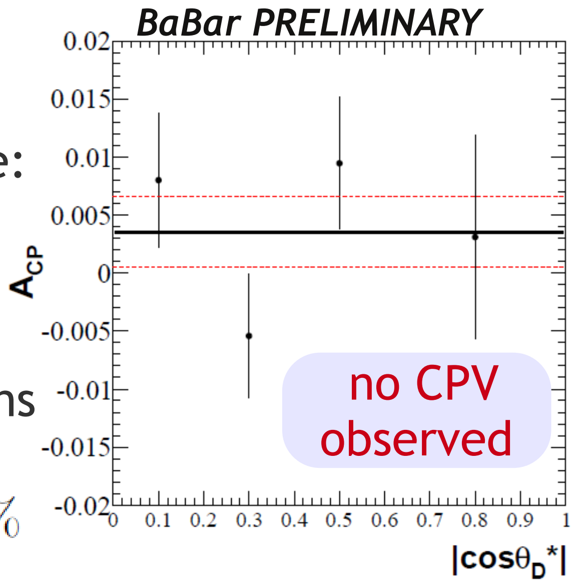


➔ Dalitz Plot integrated measurement:

- evaluate N(D$^{\pm}$) fitting the mass distributions in 8 bins of cosθ*
- in each bin, correct N(D$^{\pm}$) by the corresponding ϵ(D$^{\pm}$) and compute:

$$A_i = \frac{N_i(D^+)/\epsilon_i(D^+) - N_i(D^-)/\epsilon_i(D^-)}{N_i(D^+)/\epsilon_i(D^+) + N_i(D^-)/\epsilon_i(D^-)}$$

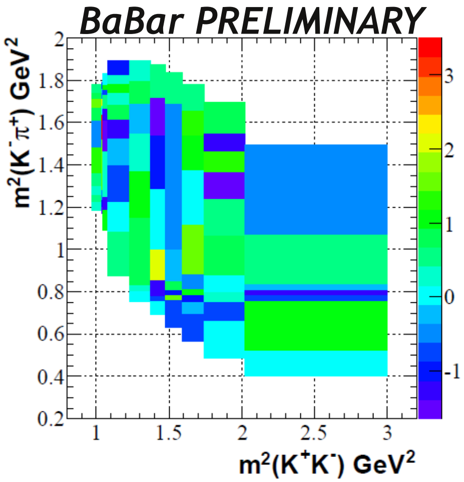
- decouple CP from residual FB asymmetry combining symmetric bins in cosθ*
- perform a χ^2 fit to a constant value: $A_{CP} = (0.35 \pm 0.30 \pm 0.15)\%$



no CPV observed

$D^+ \to K^+K^-\pi^+$, model independent analysis

➔ Normalized residuals of efficiency-corrected and background-subtracted DP for D^+ and D^-:

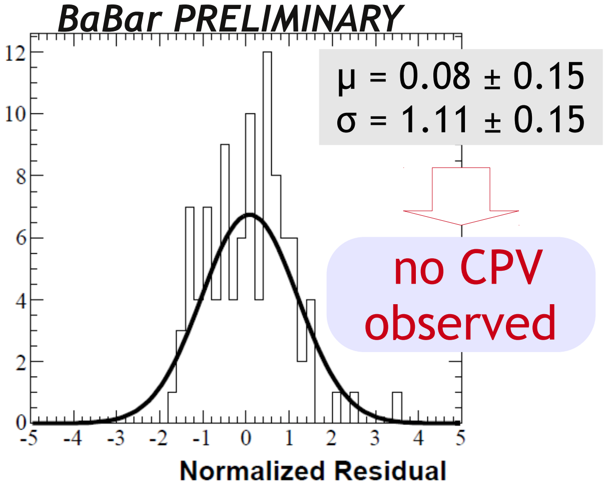


- in each DP adaptive bin:

$$\Delta_i = \frac{n_i^2(D^+) - R n_i^2(D^-)}{\sqrt{\sigma_i^2(D^+) + R^2\sigma_i^2(D^-)}}, \; n_i = N_i/\epsilon_i$$

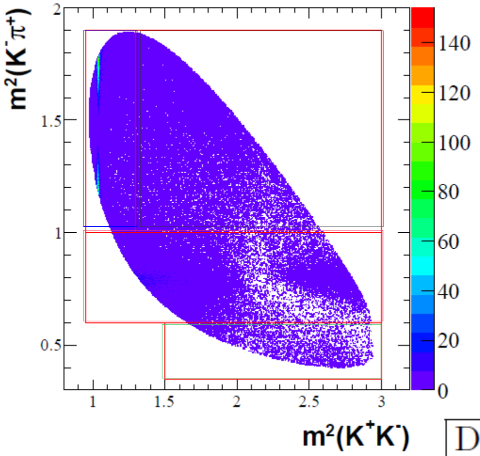
where R corrects for residual A_{FB}:

$$R = \frac{N(D^+)/\epsilon(D^+)}{N(D^-)/\epsilon(D^-)} = 1.020 \pm 0.006$$



no CPV observed

➔ Measurement of CP Violation in 4 regions of the DP:



- divide the DP into 4 regions
- evaluate $N(D^\pm)$ in each region by fitting the mass distribution
- correct $N(D^\pm)$ by the corresponding $\epsilon(D^\pm)$, and $N(D^-)$ by R (A_{FB}):

$$A_{CP} \equiv \frac{N(D^+)/\epsilon(D^+) - R\,N(D^-)/\epsilon(D^-)}{N(D^+)/\epsilon(D^+) + R\,N(D^-)/\epsilon(D^-)}$$

no CPV observed

BaBar PRELIMINARY

Dalitz plot region	$N(D^+)$	$\epsilon(D^+)[\%]$	$N(D^-)$	$\epsilon(D^-)[\%]$	$A_{CP}[\%]$
Below $\bar{K}^*(892)^0$	1882 ± 70	7.00	1859 ± 90	6.97	$-0.65 \pm 1.64 \pm 1.73$
$\bar{K}^*(892)^0$	36770 ± 251	7.53	36262 ± 257	7.53	$-0.28 \pm 0.37 \pm 0.21$
$\phi(1020)$	48856 ± 289	8.57	48009 ± 289	8.54	$-0.26 \pm 0.32 \pm 0.45$
Above $\bar{K}^*(892)^0$ and $\phi(1020)$	25616 ± 244	8.01	24560 ± 242	8.00	$1.05 \pm 0.45 \pm 0.31$

$D^+ \to K^+K^-\pi^+$, model dependent analysis

➔ Legendre polynomial moments analysis [PRD 78 051102] (model-independent method) shows no evidence of CPV.

➔ use a model to describe the DP distribution and allow each resonance to have a different amplitude and phase for D^+ and D^- .

- each resonance is parameterized with 4 parameters:

$\mathcal{M}_r,\ \phi_r$ → amplitude and phase of the D^+

CPV parameters

$$r = \frac{|\mathcal{M}_r|^2 - |\overline{\mathcal{M}}_r|^2}{|\mathcal{M}_r|^2 + |\overline{\mathcal{M}}_r|^2}$$

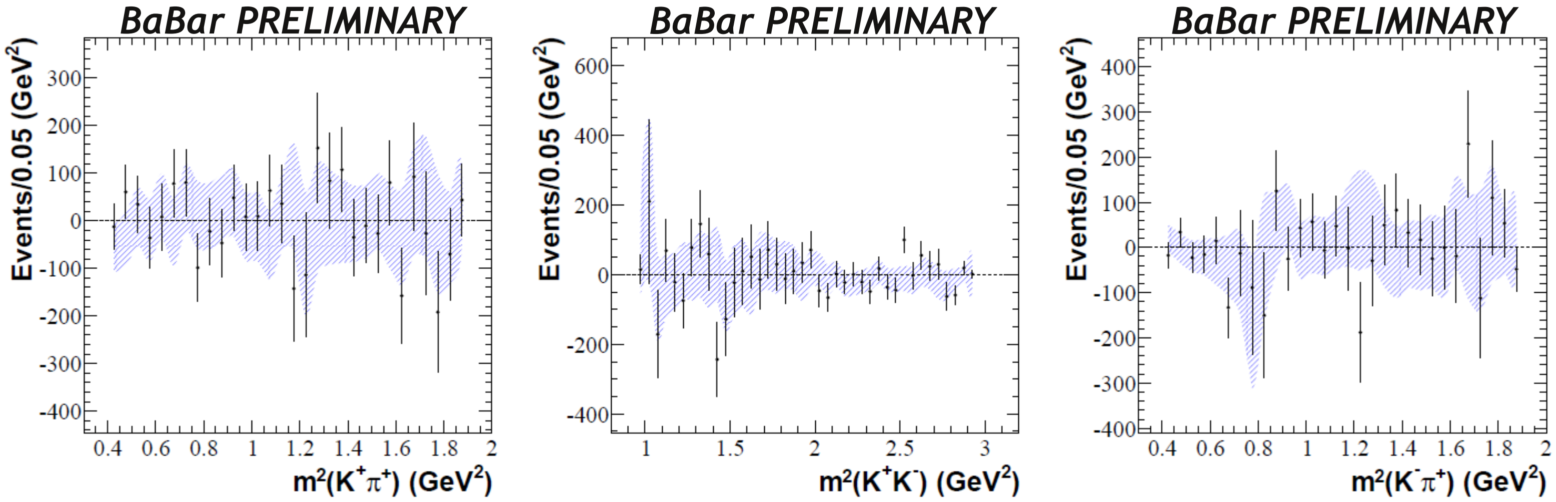
$$\Delta\phi = \phi_r - \overline{\phi}_r$$

- a simultaneous fit to the D^+ and D^- DPs is performed

BaBar PRELIMINARY

Resonance	r (%)	$\Delta\phi$ (°)
$\bar{K}^*(892)^0$	0. (FIXED)	0. (FIXED)
$\bar{K}_0^*(1430)^0$	$-9.40^{+5.65}_{-5.36} \pm 4.42$	$-6.11^{+3.29}_{-3.24} \pm 1.39$
$\phi(1020)$	$0.35^{+0.82}_{-0.82} \pm 0.60$	$7.43^{+3.55}_{-3.50} \pm 2.35$
NR	$-14.30^{+11.67}_{-12.57} \pm 5.98$	$-2.56^{+7.01}_{-6.17} \pm 8.91$
$\kappa(800)$	$2.00^{+5.09}_{-4.96} \pm 1.85$	$2.10^{+2.42}_{-2.45} \pm 1.01$
$a_0(1450)^0$	$5.07^{+6.86}_{-6.54} \pm 9.39$	$4.00^{+4.04}_{-3.96} \pm 3.83$
	Δx	Δy
$f_0(980)$	$-0.199^{+0.106}_{-0.110} \pm 0.084$	$-0.231^{+0.100}_{-0.105} \pm 0.079$
$f_0(1370)$	$0.019^{+0.049}_{-0.048} \pm 0.022$	$-0.0045^{+0.037}_{-0.039} \pm 0.016$

difference of the DP proj. of data (points) and fit (blue curve) ± 1σ:



no CPV observed