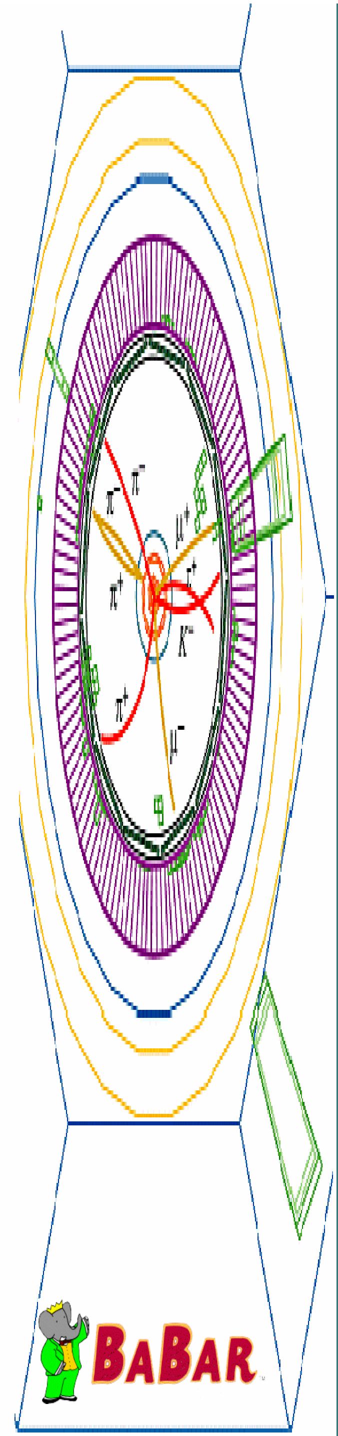


CHARM PHYSICS

in BABAR

Alexis POMPILI

(University & I.N.F.N. of Bari)

[representing the BABAR Collaboration]

Les Rencontres de Physique de la Vallee d'Aoste

La Thuile – March 3, 2004

Charm Physics @ BaBar - Outline

Analyses results reviewed here:

- **D^0 mixing with 2-body hadronic decays (wrong sign & CP final states)**
- $c\overline{s}$ **states spectroscopy** $[D^*_{sJ}(2317), D_{sJ}(2458)]$

Other Studies in progress:

- **D^0 mixing with semi-leptonic decays**
- **3-body decays of D^0, D^+, D_s^+ (B. R., Light Meson Spectroscopy, ~~CP~~, mixing)**
- **charmed baryons**
- **ISR processes**

Charm Physics @ PEP-II B-factory

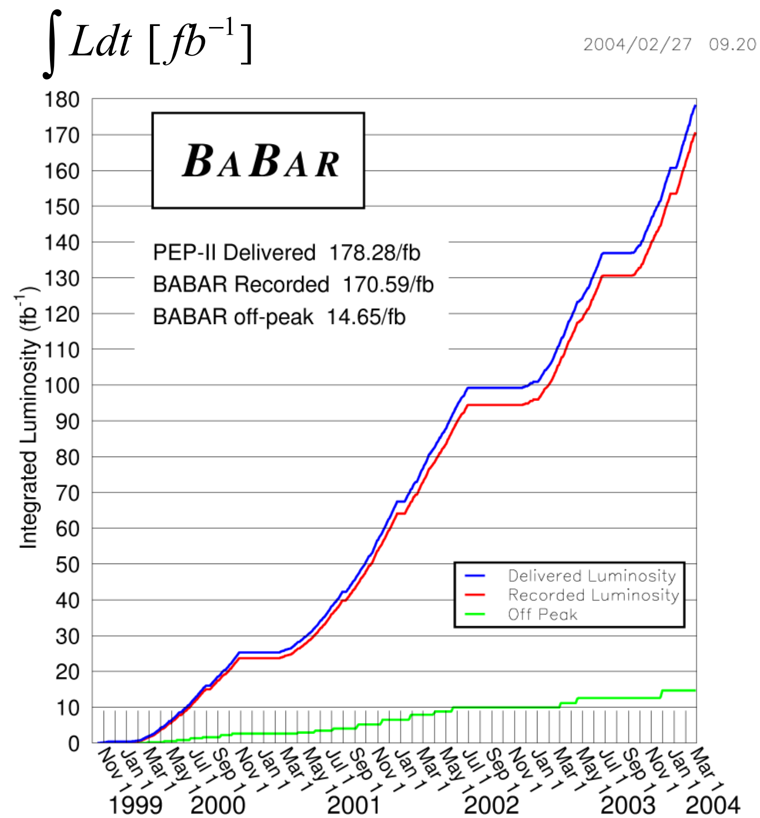
PEP-II (SLAC) : **asymmetric e^+e^- collider @ Υ(4S)**

Integrated luminosity delivered : ~178fb^{-1}

Effective $q\bar{q}$ cross sections at the energy of the Υ(4S)

$e^+e^- \rightarrow$	σ (nb)
bb	1.05
cc	1.30
ss	0.35
uu	1.39
dd	0.35
$\tau^+\tau^-$	0.94
$\mu^+\mu^-$	1.16
e^+e^-	≈ 40

Powerful tool for charm physics



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

BABAR (90fb^{-1}):		**~220K**
Focus	**:**	**120K**
E791	**:**	**~36K**

The BABAR detector

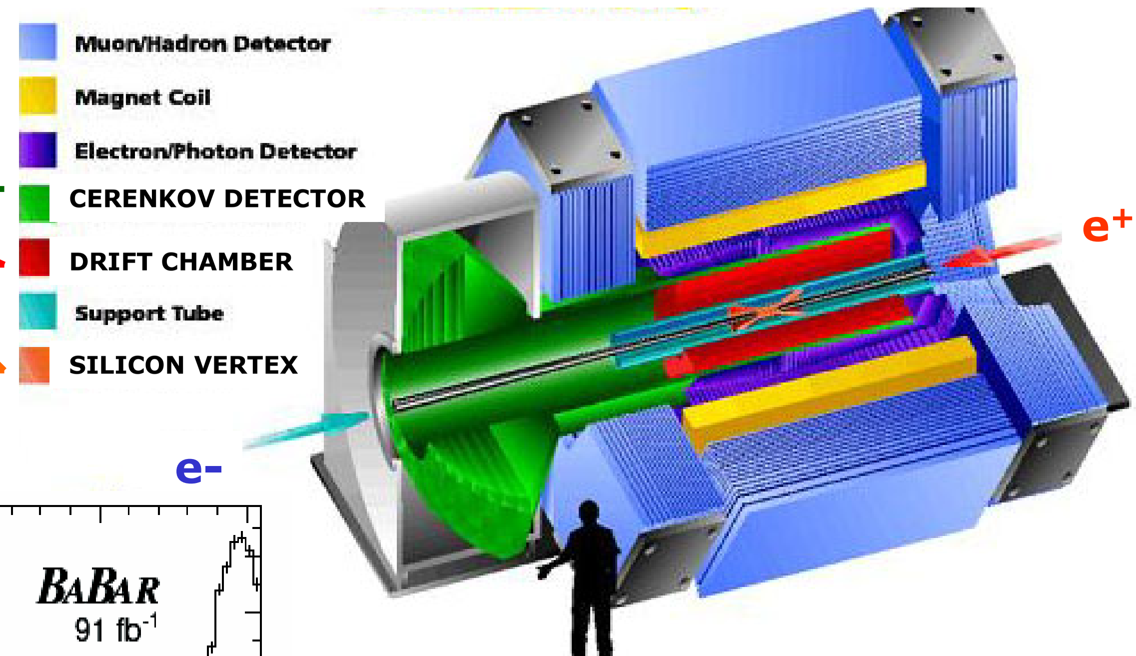
Crucial for charm physics

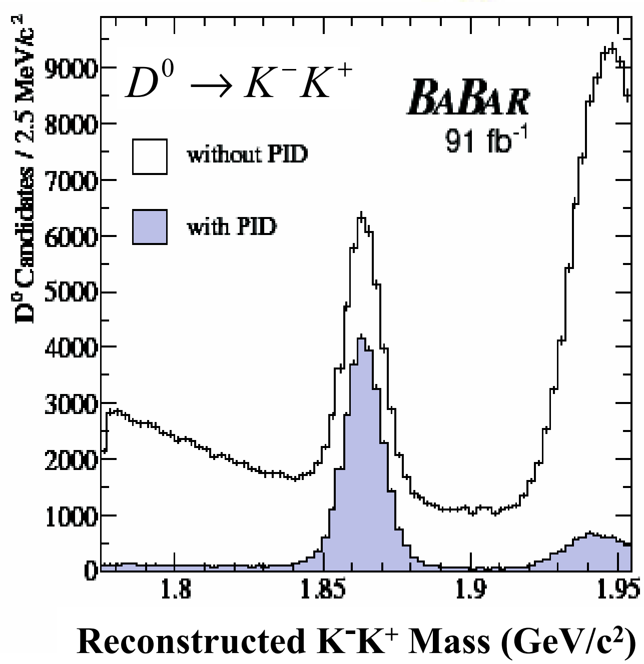
PID

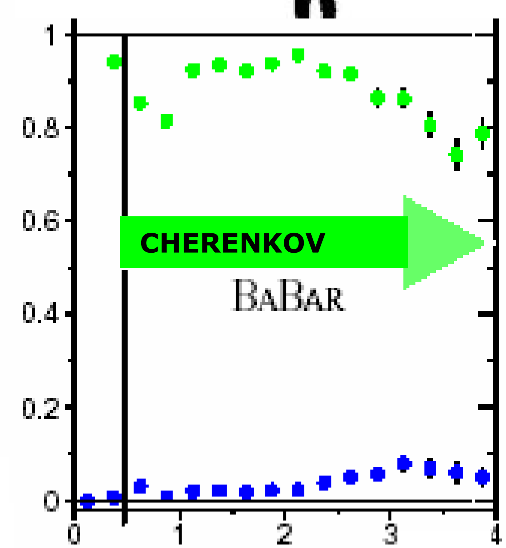
TRACKING

VERTEXING

***K*-Id**



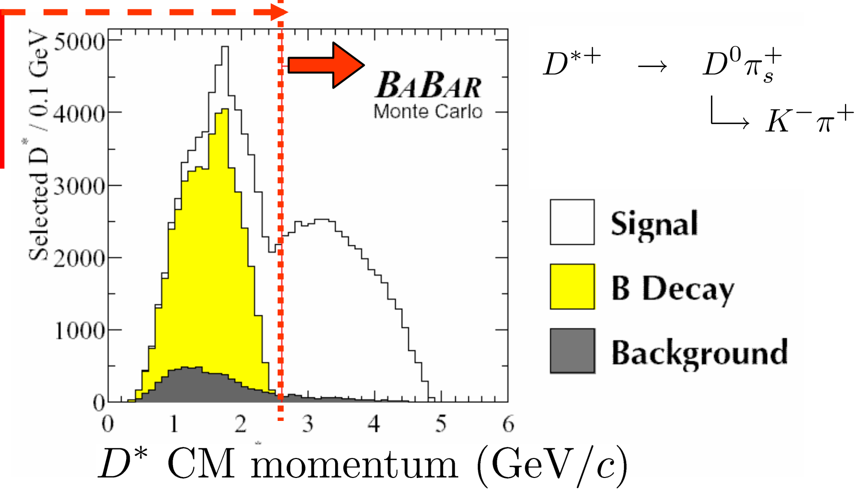




Selecting charm decays from continuum

Kinematical selection: require cut on CMS momentum of charmed meson : $p^*_{D^{(*)}} > 2.5\,GeV/c$

- combinatorial background strongly reduced
- $D^{(*)}$ from B-decays rejected



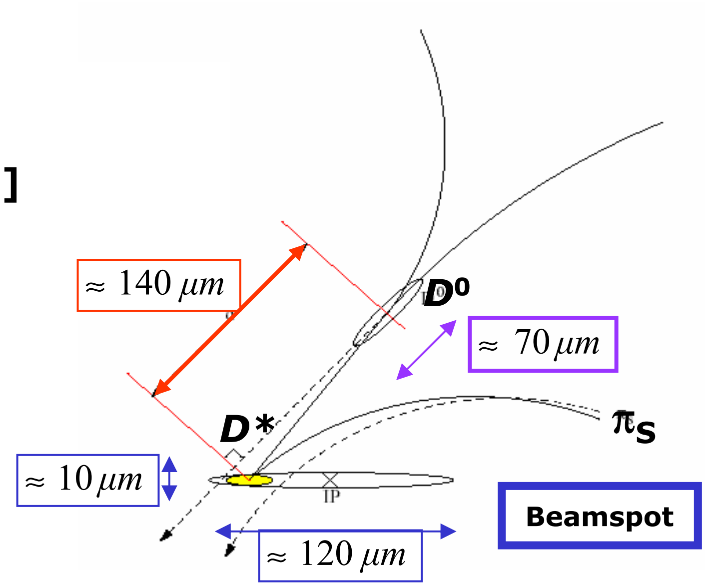
D^*-TAG with π_S

$e^+e^- \to c\bar{c} \to D^{*\pm}X \;;\; D^{*+} \to D^0\pi_s^+ \;;\; D^0 \to K^-\pi^+$

- allows flavor-tagging
- reduces BKGD through $\delta m = [m(K^-\pi^+\pi_s) - m(K^-\pi^+)]$

Refitting technique with beamspot - constraint

- improves δm resolution



D-mixing: parameters & search methods

- **Mass eigenstates:** $|D^0_{1,2}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle\ ,\ |p|^2+|q|^2=1$ ($|D^0\rangle, |\overline{D}^0\rangle$ **flavour eigenstates**)

masses: M_1, M_2
widths: Γ_1, Γ_2

$\Delta\Gamma = \Gamma_1 - \Gamma_2$
$\Gamma = (\Gamma_1 + \Gamma_2)/2$
$\Delta M = M_1 - M_2$

MIXING PARAMETERS: $x \equiv \frac{\Delta M}{\Gamma}\ ,\ y \equiv \frac{\Delta\Gamma}{2\Gamma}$

SM : $|x|, |y| \lesssim 10^{-3}$ **beyond the reach of current experimental sensitivity**

…but
- **NEW PHYSICS may enhance x**
- **FSI & SU(3)-breaking can enhance y**

- **Experimental goal : to put limits on the transition D^0-$\overline{D}^0$**

1) LIFETIME DIFFERENCE searches → **y [if *CP* conserved]**

2) WRONG-SIGN searches in hadronic decays → x^2 , **y** ; δ: **unknown strong phase difference**

- **NP may not conserve CP** → **consider ~~CP~~ when measuring mixing**

$r_m \equiv |q/p| > 0$

$\overline{A}_f \equiv \langle f\,|\,H_D\,|\,\overline{D}^0\rangle$

$\varphi \equiv \arg[(q/p)\cdot(\overline{A}_f/A_f)] \in [-\pi/2, +\pi/2]$

$r_m \neq 1$ → **~~CP~~ in mixing (sure sign of NP)**

$\varphi \neq 0$ → **~~CP~~ in interference mixing–decay**

Lifetime difference searches

- Mixing would alter the decay-time distributions of D^0 and $\overline{D}^0$ that decay into *CP* eigenstates. They can be considered to a good approx. as pure exponential with effective lifetimes:

$$\tau^{\pm} = \tau^0 \cdot \left[1 + r_m^{\pm 1}(y\cos\varphi \mp x\sin\varphi)\right]^{-1}$$

for CSD of D^0 ($\overline{D}^0$) into *CP-even* final states (such as K^+K^-, $\pi^+\pi^-$)

for CFD $D^0 \to K^-\pi^+$ ($\overline{D}^0 \to K^+\pi^-$)

- These effective lifetimes can be combined into:

LIFETIME RATIO

$$Y = \frac{\tau^0}{<\tau>} - 1 \ , \ \Delta Y = \frac{\tau^0}{<\tau>} \cdot A_\tau \quad \text{where} \quad \begin{cases} <\tau> = \frac{1}{2}(\tau^+ + \tau^-) \\ A_\tau = \frac{\tau^+ - \tau^-}{\tau^+ + \tau^-} \end{cases}$$

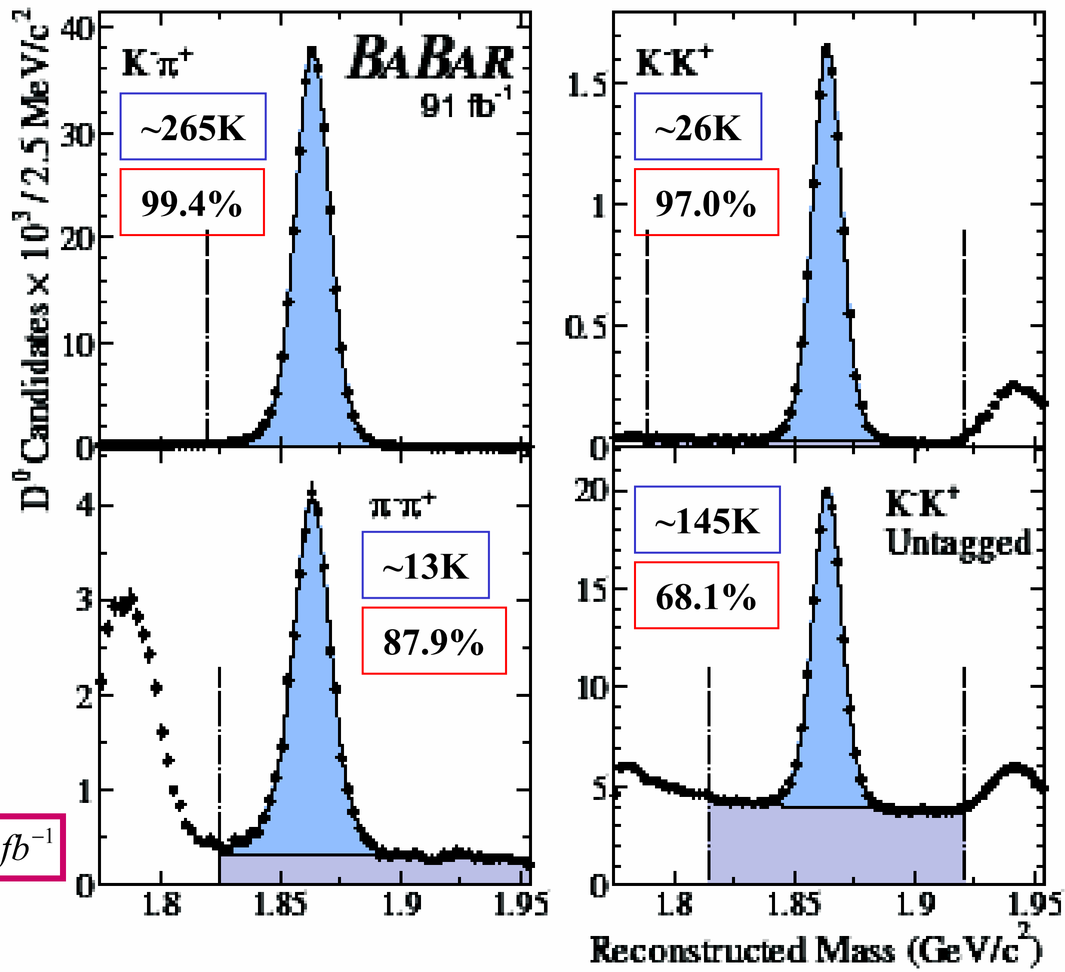
- IF NO MIXING : $x = y = 0 \Rightarrow \tau^{\pm} = \tau^0 \Rightarrow Y, \Delta Y = 0$

- IF CP-CONSERVATION IN MIXING : $r_m = 1 \Rightarrow \begin{cases} Y = y\cos\varphi \\ \Delta Y = x\sin\varphi \end{cases}$

- IF ALSO … CP-CONSERVATION IN INTERFERENCE MIXING -DECAY : $\sin\varphi = 0 \Rightarrow \begin{cases} Y = y \\ \Delta Y = 0 \end{cases}$

- Systematics effects on lifetime tend to cancel in the lifetime RATIO

Mass fits



$91\, fb^{-1}$

DATA — FIT RESULT

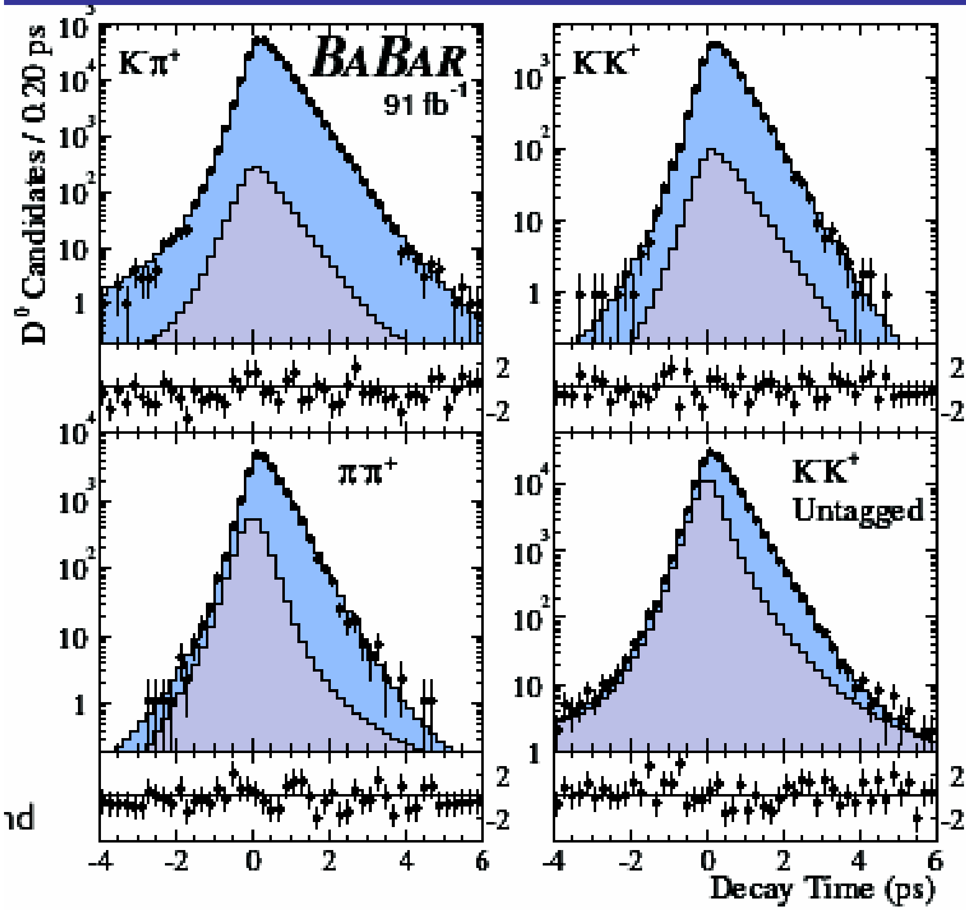
FROM THE FITS :

- SIGNAL (S)
- yield
- BKGD (B)
- S/S+B — $\pm 15\, MeV/c^2$ mass window

Mass fits determine event-by-event signal probability

"sidebands" candidates included as part of proper time fit → **BKGD constrained in data**

Decay-time distributions fit



within mass signal window: $\pm 15\, MeV/c^2$

FROM THE FITS : SIGNAL / BKGD

DATA | UNBINNED MAXIMUM LIKELIHOOD **FIT** RESULT

$\tau^0, \tau^{\pm}$

D^0 SAMPLES	MEASURED QUANTITY	MEASURED PARAMETER
K^-K^+, $\pi^-\pi^+$ [CSD – *CP-even*]	$<\tau>, A_\tau$	$\to Y, \Delta Y$
$K^-\pi^+$ [CF – *CP-mixed*]	τ^0	-
D*-untagged K^-K^+	$<\tau>$	$\to Y$

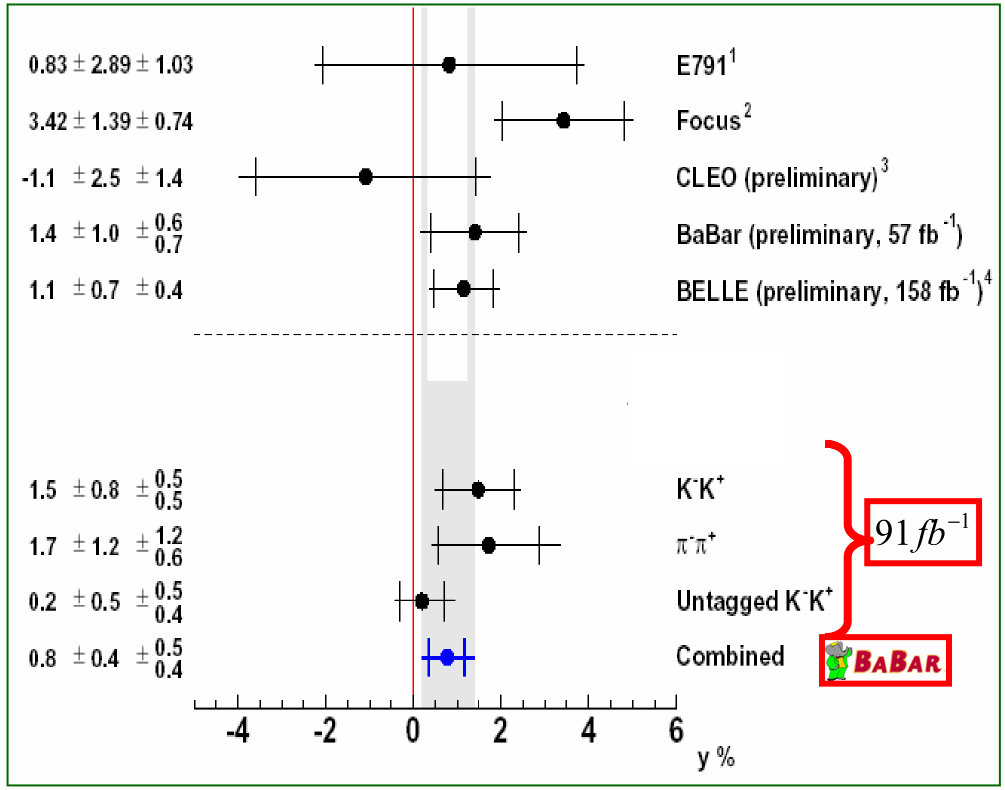
Summary of lifetime ratio results [Phys.Rev.Lett.91,12(2003)]

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

BaBar has the most stringent limits on y

BaBar has the first measurement of a ~~CP~~ parameter with the method of lifetime ratio

1. E791 Collaboration, Phys.Rev.Lett.83 (1999)
2. Focus Collaboration, Phys.Lett. B485 (2000)
3. CLEO CONF-01.
4. BELLE Collaboration, hep-ex/0308034



Wrong-sign searches in hadronic decays

- Study time-evolution of $D^0 \to K^+\pi^-$ looking for a signal $D^0 \to \overline{D}^0 \to K^+\pi^-$

DCSD & CFD may have different FSI → $\delta_{K\pi}$: **unknown relative strong phase (not measurable in a mixing analysis): rotation of $\delta_{K\pi}$ in the x-y plane :**

$$\begin{cases} x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \\ y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi} \end{cases}$$

- Assuming $x', y' \ll 1$ and **CP conservation** $(r_m = 1, \varphi = 0)$:

$$\Gamma_{WS}(t) \equiv \Gamma\left(D^0 \to K^+\pi^-\right)(t) \propto e^{-\Gamma t}\left[R_D + y'\sqrt{R_D}\,\Gamma t + \frac{1}{4}\left(x'^2 + y'^2\right)\Gamma^2 t^2\right]$$

where $\Gamma = 1/\tau_{D^0}$

DCSD | INTERFERENCE | MIXING

deviation from pure exponential

enhances mixing signal

$$R_D = \frac{\Gamma(D^0 \xrightarrow{DCS} K^+\pi^-)}{\Gamma(\overline{D}^0 \xrightarrow{CF} K^+\pi^-)}$$

Integrating : $R_{WS} = R_D + y'\sqrt{R_D} + \left(x'^2 + y'^2/2\right)$

mixing rate : R_M

- **Additional ~~CP~~ effects are included by measuring this distribution for D^0 and $\overline{D}^0$ separately:**

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-};\ A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-},\ \varphi(\to \text{rotation of } x', y')$$

~~CP~~ in DCSD | ~~CP~~ in MIXING | ~~CP~~ in their INTERFERENCE

Mass-mass difference Fit

- Assign each candidate to one of 4 categories: D^0(RS,WS),$\overline{D^0}$(RS,WS)

- **Unbinned extended max-likelihood fit to RS and WS samples simultaneously in 4D variable space $[m(K\pi),\ \delta m = [m(K\pi\pi_S) - m(K\pi)],\ t\ ,\ \sigma_t]$ performed in steps :**

proper time error (σ_t)

1st step fit

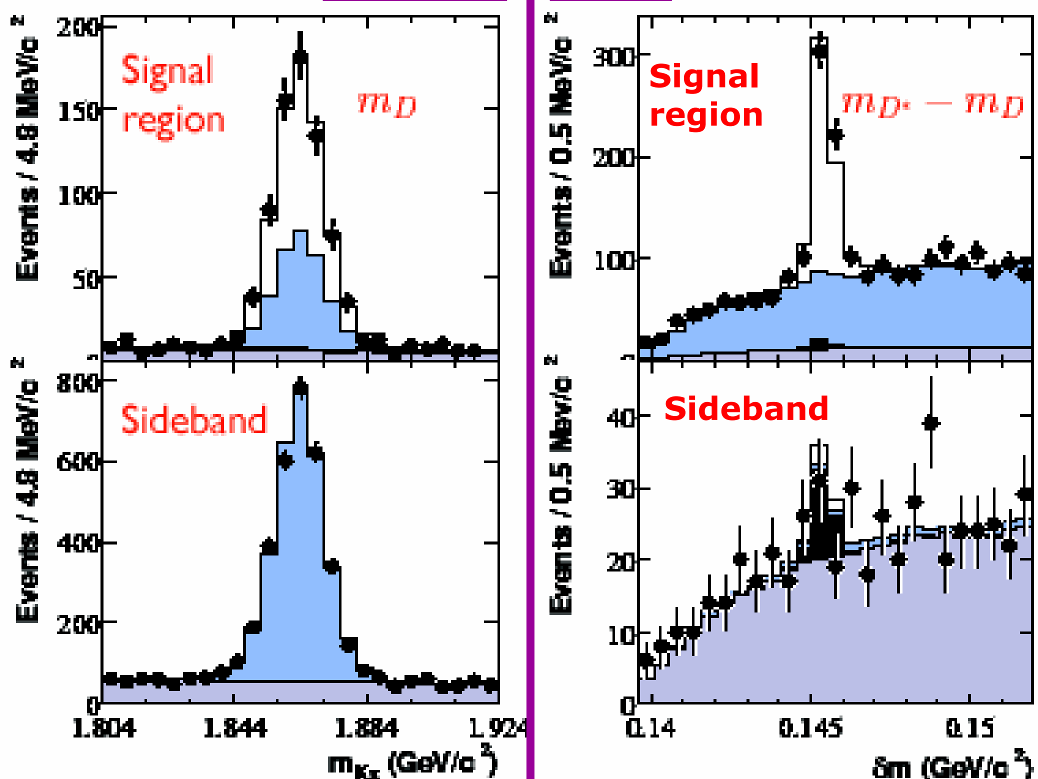
Number of SIGNAL and BKGD candidates from a fit to m-δm plane (both RS and WS) by modelling BKGD categories

- Signal
- Wrong slow pion
- Combinatorial
- Double mis-id

WS

With 57fb^{-1}: ~120,000 RS
~ 440 WS

m(Kπ) | **δm**

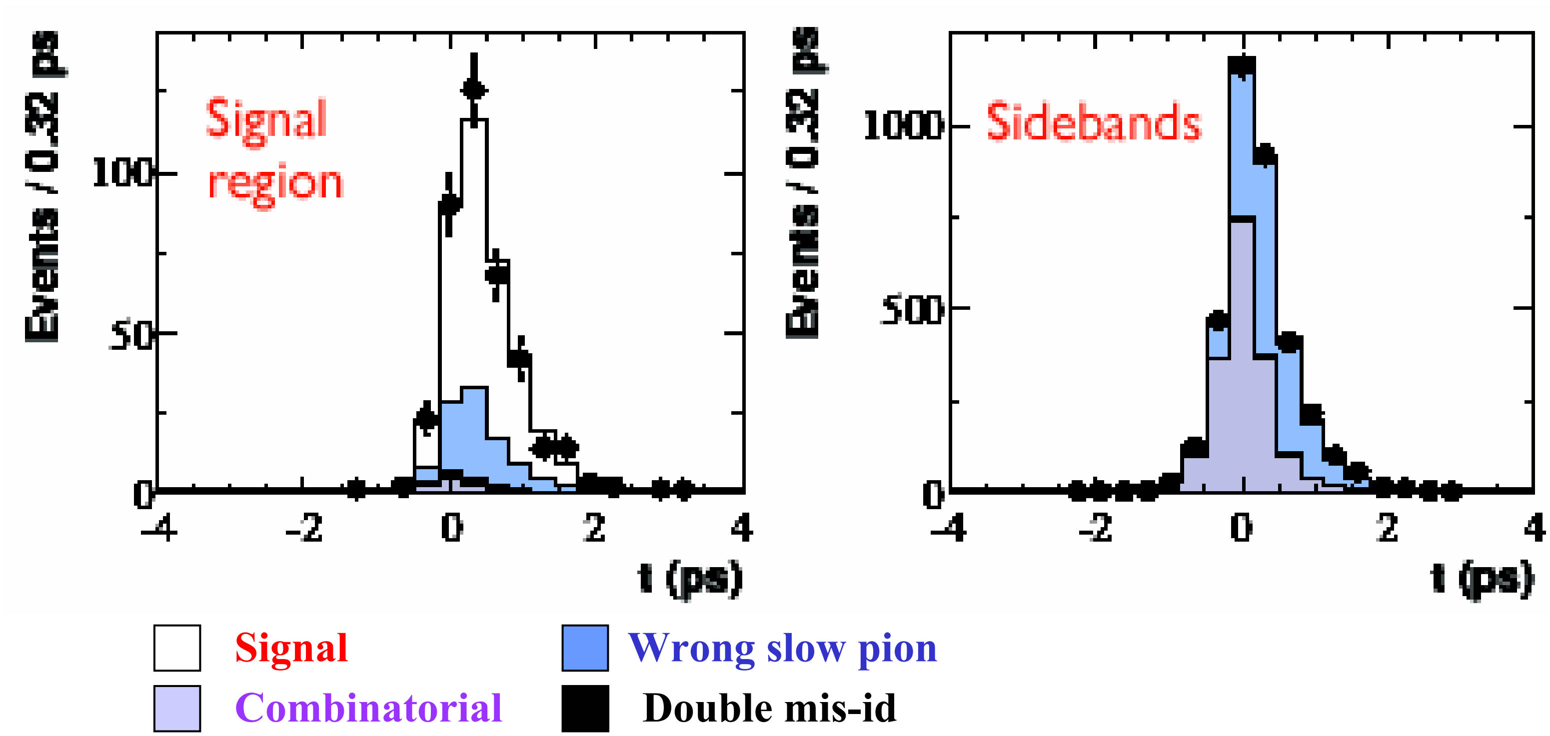


Decay time Fit

2nd step fit

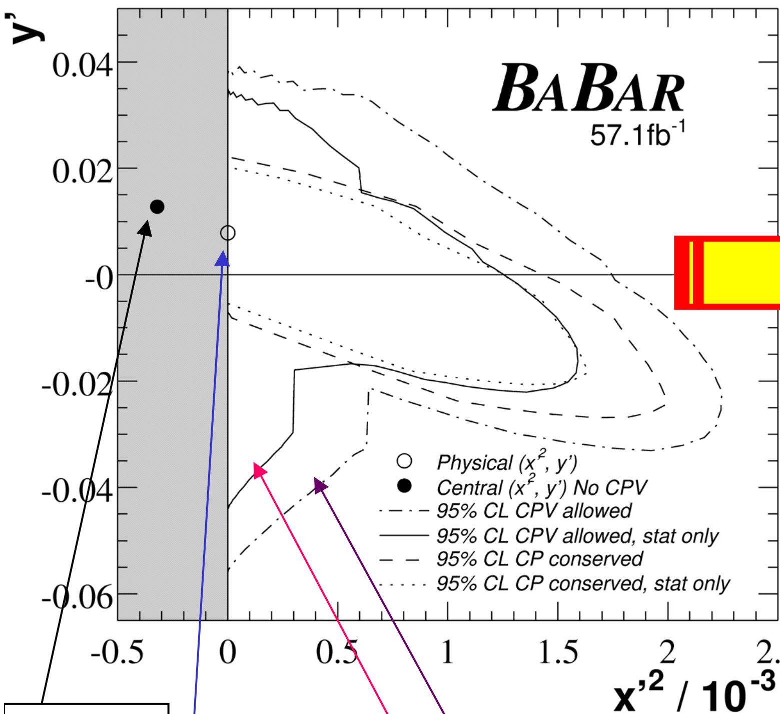
Simultaneous fit time-distribution to RS and WS (include mixing parameters).
The larger/clean RS sample fixes D^0 lifetime and resolution model parameters for unmixed decays.
BKGD time distributions determined from m,δm sidebands in data.

WS



Summary of wrong-sign results [Phys.Rev.Lett.91,17(2003)]

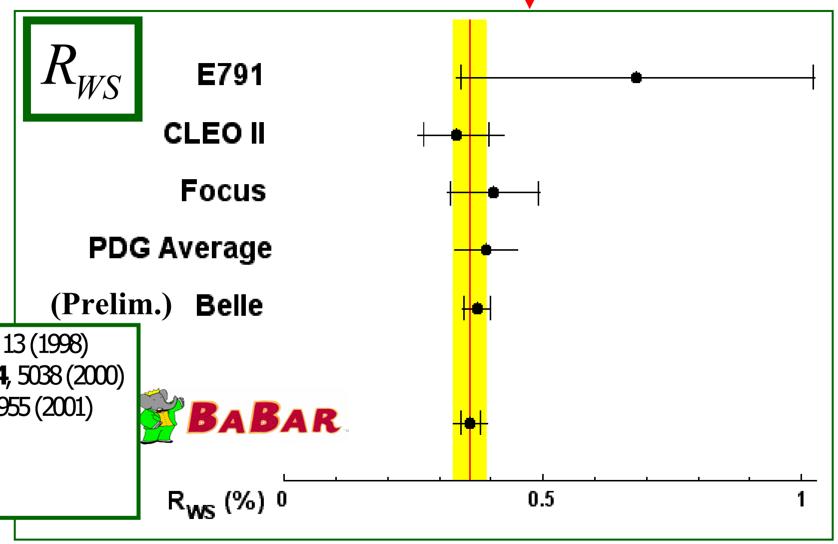
95% C.L. contours by a frequentistic approach (based on toy Monte Carlo experiments) :



Results presented in 4 cases :

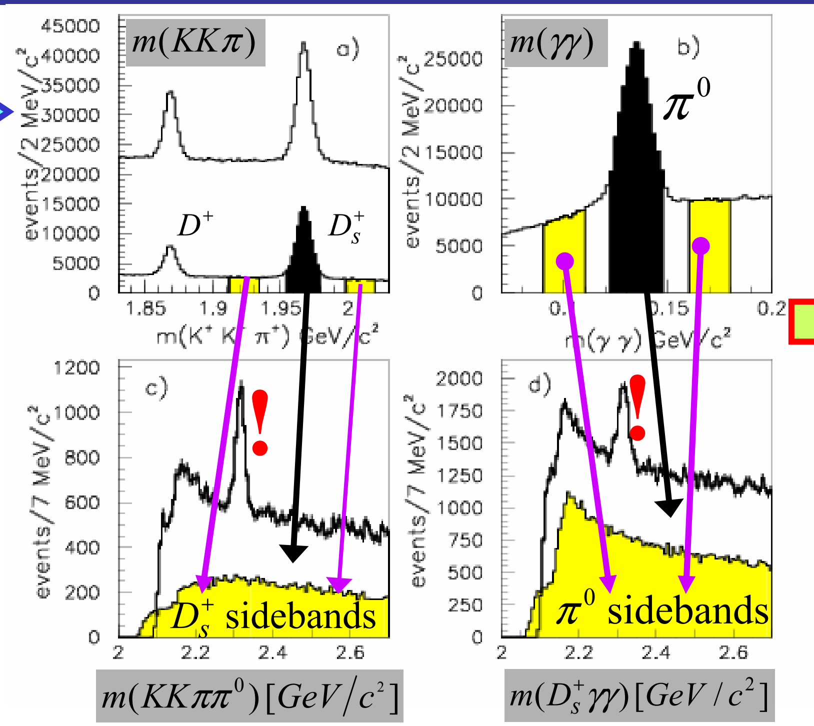
Parameter	95% CL range or value (all $\times 10^{-3}$)			
	CPV allowed	No CPV	No mixing	No CPV nor mixing
R_D	2.3 to 5.2	2.4 to 4.9	$3.57 \pm .22 \pm .27$	$3.59 \pm .20 \pm .27$
A_D	-2.8 to 4.9	-	$95 \pm 61 \pm 83$	-
x'^2	< 2.2	< 2.0	-	-
y'	-56 to 39	-27 to 22	-	-
R_M	< 1.6	< 1.3	-	-

$R_D \equiv R_{WS}$



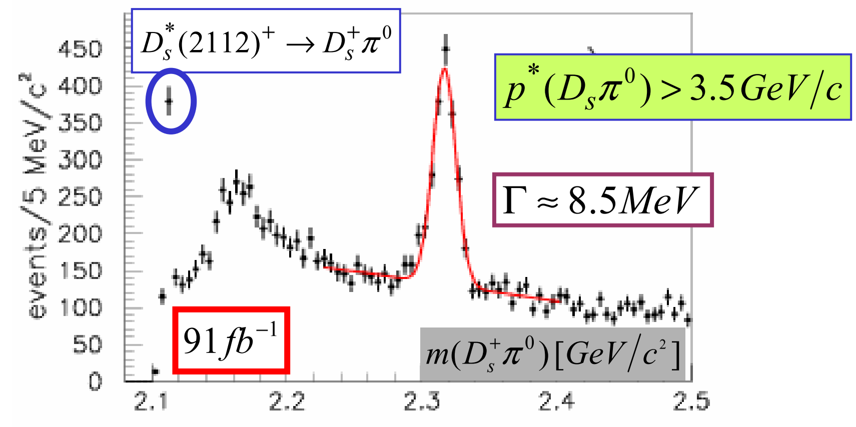
E791: Aitala et al., PRD **57**, 13 (1998)
CLEO II: Godang et al., PRL **84**, 5038 (2000)
FOCUS: Link et al., PRL **86**, 2955 (2001)
PDG: 2002
Belle: hep-ex/0208051

Two surprising new Charmed Mesons : $D^*_{sJ}(2317)^+$ & $D_{sJ}(2458)^+$



[Phys.Rev.Lett. 90,24(2003)]

BaBar discovered a new narrow state in the $D_s^+\pi^0$ invariant mass distribution near 2.32GeV/c²

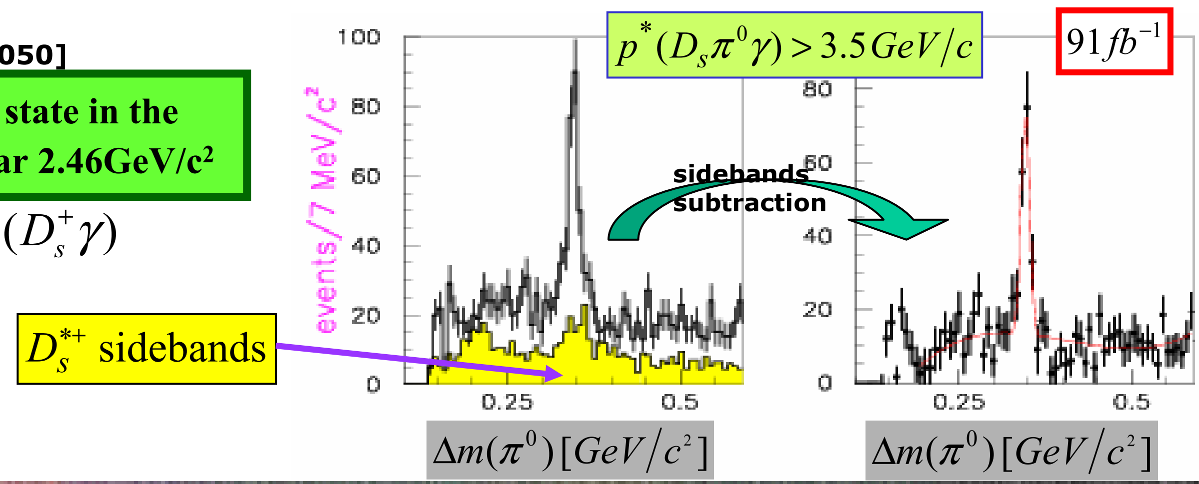


[Accepted by P.R.L. ; hep/ex-0310050]

BaBar observed a second new narrow state in the $D_s^{*+}\pi^0$ invariant mass distribution near 2.46GeV/c²

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

This state may decay to $D_s^+\pi^0\gamma$ through $D_s^{*+}\pi^0$ or $D_{sJ}^{*+}(2317)\gamma$



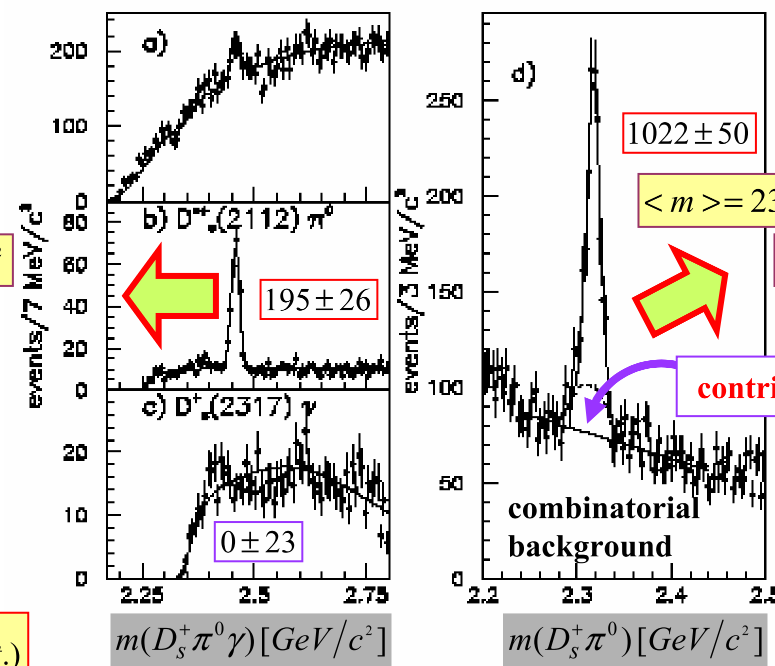
Channel Likelihood Fit

To disentangle these 2 possible $D_{sJ}(2458)$ decay modes & extract signal parameters: unbinned maximum likelihood fit using the channel likelihood method

$D_{sJ}(2458)^+$

$<m> = 2458.0 \pm 1.0(stat.) \pm 1.0(syst.)\ MeV/c^2$

$\Gamma = 8.5 \pm 1.0(stat.) MeV$

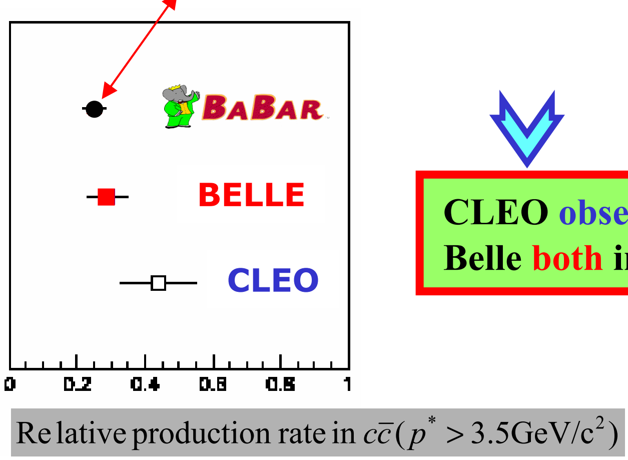


$D^*_{sJ}(2317)^+$

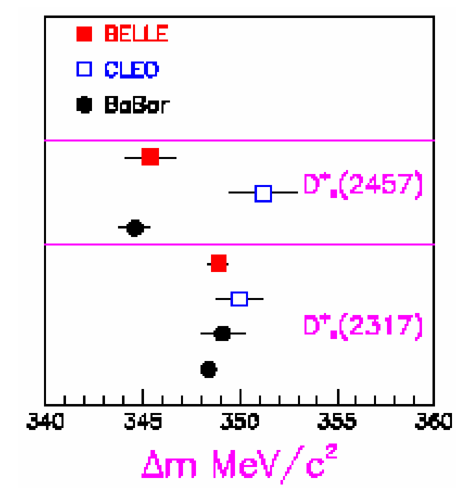
$<m> = 2317.3 \pm 0.4(stat.) \pm 0.8(syst.)\ MeV/c^2$

$\Gamma = 7.3 \pm 0.2(stat.) MeV$

$$\frac{R[D_{sJ}(2458)]}{R[D^*_{sJ}(2317)]} = 0.25 \pm 0.03(stat.) \pm 0.03(syst.)$$



CLEO observed them in continuum and…
Belle both in continuum and in B decays $[B \to \overline{D} D^*_{sJ}]$



SPIN-PARITY

$D^*_{sJ}(2317)^+$

- Decay to $J^P=0^-$ mesons → only natural spin-parity allowed $[0^+,1^-,2^+,\ldots]$
- $J^P=0^+$ suggested by: 1) low mass compared to $D_{s1}(2535)$ & $D_{sJ}^*(2573)$
  2) absence of decay to $D_s^+\gamma$ (not allowed if $J^P=0^+$)
  3) absence of decay to $D_s^+\pi^+\pi^-$ (not allowed if $J^P=0^+$)

$D_{sJ}(2458)^+$

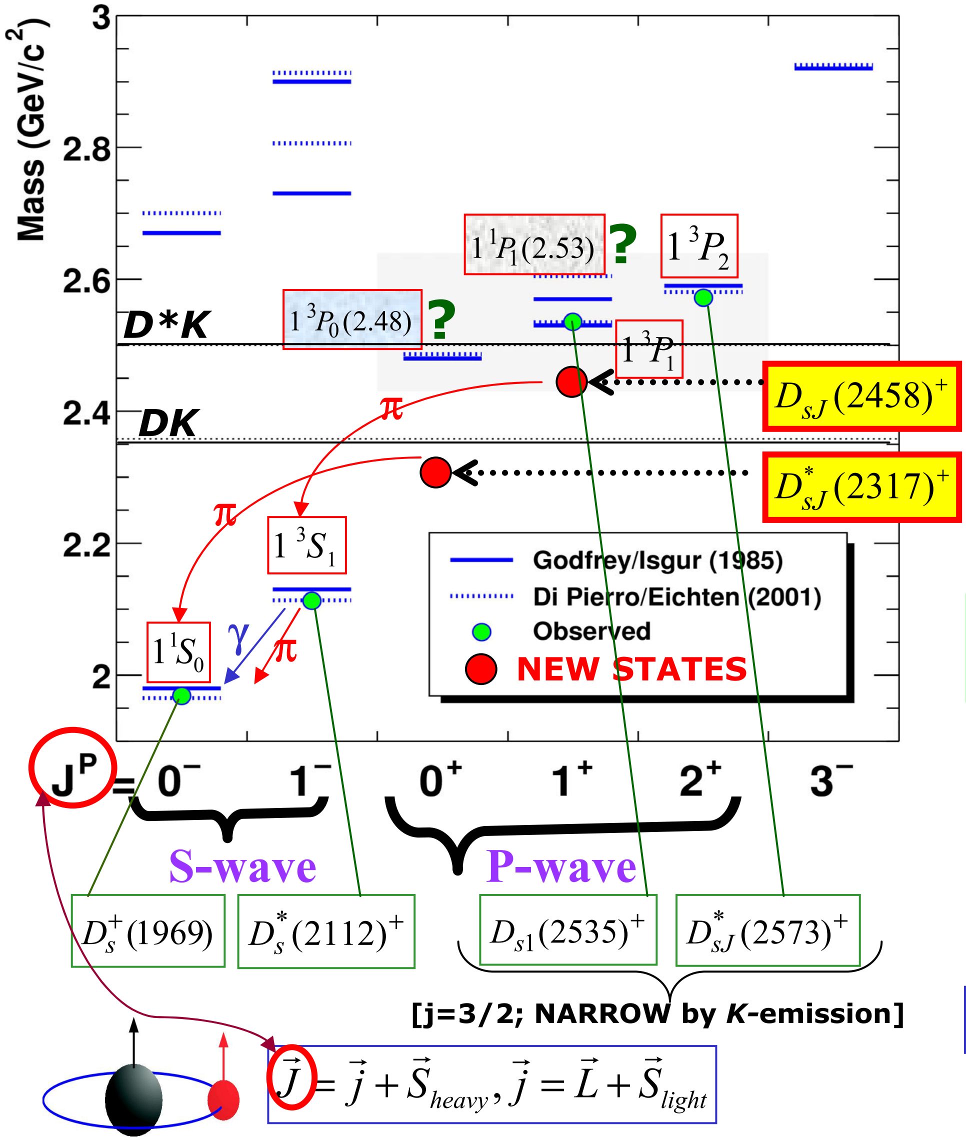
- Un-natural spin-parity more likely (lack of decays to DK)
- $D_{sJ}(2458)^+ \to D_s^+\gamma$[by Belle] $\Rightarrow J \neq 0$
- Belle helicity analysis from *B*-decays favours J=1
- Decay to $D_s\pi^+\pi^-$ (by Belle) allowed by $J^P=1^+$

EXPERIMENTAL SUMMARY

Two narrow states observed, in the inclusive $D_s\pi^0$ & $D_s^*\pi^0$ invariant mass distributions, near $2.317GeV/c^2$ & $2.458GeV/c^2$.
The widths $[\Gamma<10MeV]$ are consistent with experimental resolution.
The most likely assignment for their spin-parity is 0^+ & 1^+.

Spectroscopy of $c\bar{s}$ states (before & after)

Potential models of [heavy-quark | light-quark] mesons: so far reasonable success for spectroscopy of D, D_s, B, B_s systems



New states do not fit well :
masses below the $DK[D^*K]$ threshold.

IF interpreted as ordinary $c\bar{s}$ states, they decay mainly by isospin-violating π-emission thus having widths quite narrow.

A possible decay mechanism is through a virtual η followed by η-π^0 mixing [Cho-Wise,PRD49].

$$m[D^*_{sJ}(2317)] - m[D_s(1969)] \cong$$
$$\cong m[D_{sJ}(2458)] - m[D^*_s(2112)]$$

…as predicted by models based on HQET & chiral symmetry [*Bardeen et al.*,…] if new states are 0^+ & 1^+

40(!) papers by theorists:
Exotic (4-quark, molecule, …)
VS
Ordinary explanations (HQET+chiral symmetry, …)

Crucial to measure radiative decays & di-pion emission

SUMMARY

- **Competitive D^0 mixing results obtained with 2 different experimental methods are consistent with no mixing and no ~~CP~~.**
  - **wrong-sign D^0 mixing limits** (95% CL,57fb^{-1};~~CP~~-allowed): $x'^2 < 0.0022, -0.056 < y' < 0.039, R_M < 0.0016$
  - **D^0 lifetime ratio** (91fb^{-1}):
    $$\begin{cases} Y = [0.8 \pm 0.4(stat.)^{\pm 0.5}_{-0.4}(syst.)]\% \equiv y \text{ (if CP conserved)} \\ \Delta Y = [-0.8 \pm 0.6(stat.) \pm 0.2(syst.)]\% \text{ (~~CP~~ parameter)} \end{cases}$$
  - Wrong-sign D^0 mixing limits from semileptonic decays coming soon

- **Charmed mesons are a rich laboratory for Heavy Quark studies.**

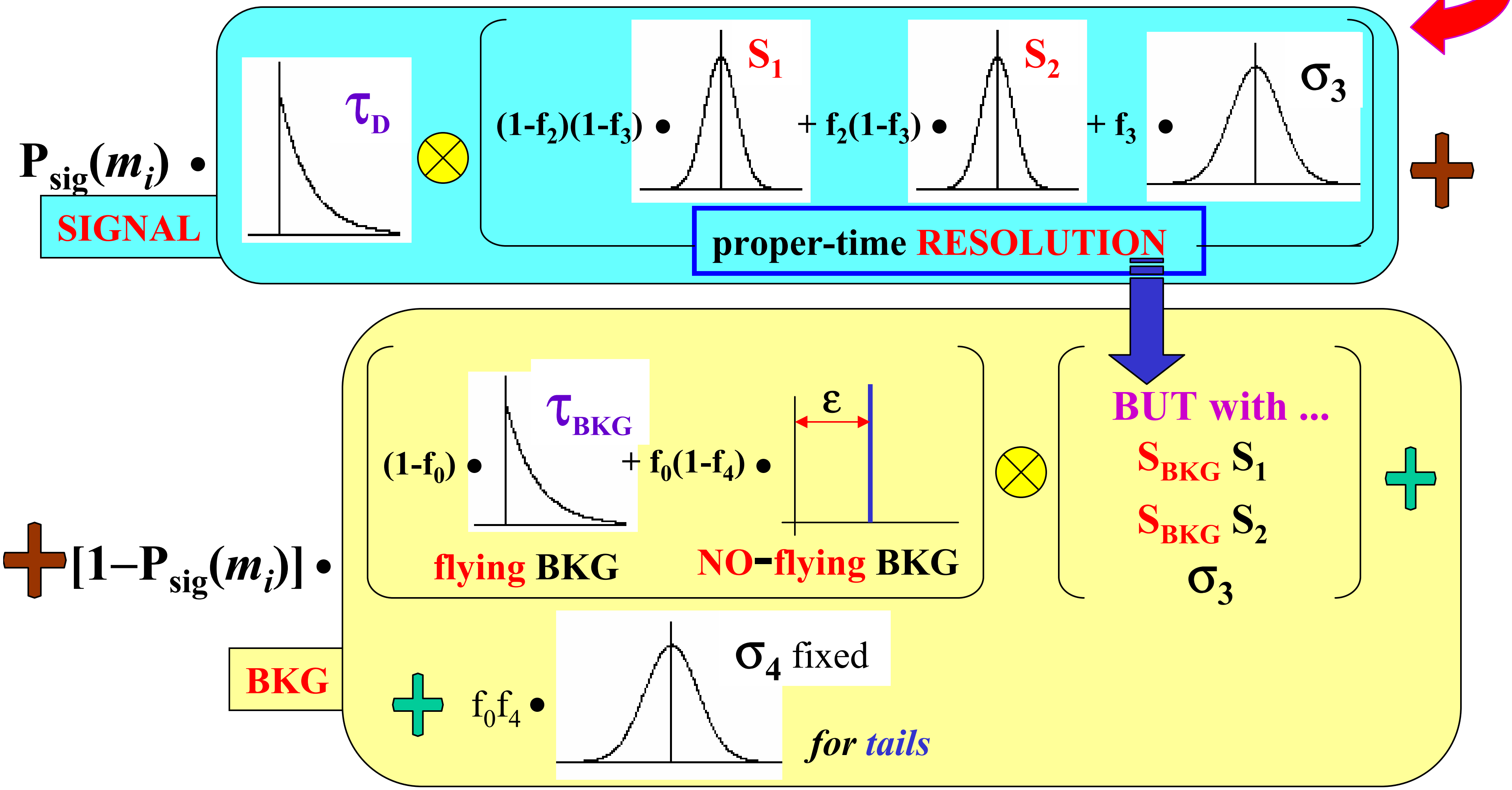
  After the discovery of $D^*_{sJ}(2317)$ and the observation of $D_{sJ}(2458)$… … further D_s mesons (spectroscopic) studies are ongoing.

- **BaBar is a promising place to study charm physics … studies have just began !**

Backup Slides

Unbinned maximum likelihood fit

$$L = \Pi_i P_i \text{ where } P_i(m_i, t, \delta t; \text{ 11 parameters}) =$$



Statistical error on lifetime extracted from the fit

Sample	σ_τ (fs)
$K^-\pi^+$	0.9
K^-K^+	3.1
$\pi^-\pi^+$	4.5
K^-K^+ Untagged	1.8

Compare to PDG:

$$\tau = 411.7 \pm 2.7 \text{ (fs)}$$

	Change in Y(%)			ΔY(%)	
	Tagged		Un-tagged	Tagged	
Category	K^-K^+	$\pi^-\pi^+$	K^-K^+	K^-K^+	$\pi^-\pi^+$
Tracking	± 0.1	± 0.3	± 0.2	± 0.1	± 0.1
Background	$^{+0.3}_{-0.5}$	± 0.5	± 0.3	± 0.2	± 0.2
Alignment	± 0.1	± 0.1	± 0.1	± 0.1	$^{+0.0}_{-0.1}$
MC Statistics	$^{+0.4}_{-0.1}$	$^{+1.0}_{-0.1}$	$^{+0.4}_{-0.1}$	< 0.1	< 0.1
Quadrature Sum	± 0.5	$^{+1.2}_{-0.6}$	$^{+0.5}_{-0.4}$	± 0.2	± 0.2

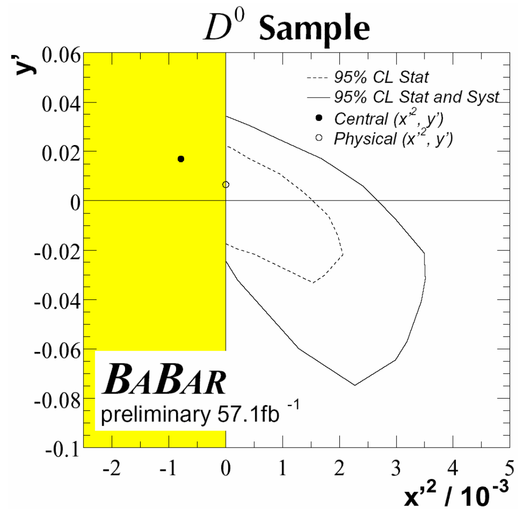
- Fit allowed $x'^2<0$.
  Central values for fits of both separate samples gave $x'^2<0$.

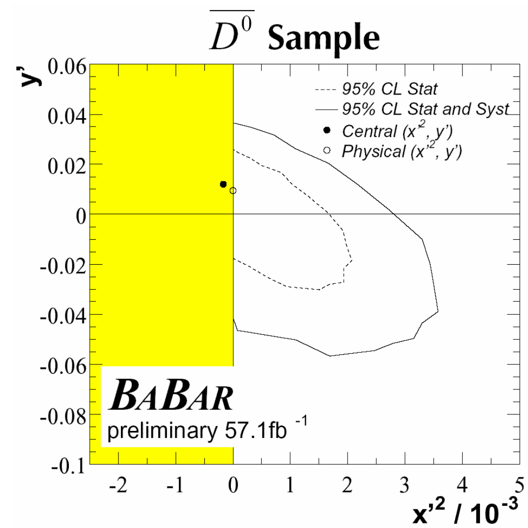
- Due to allowing $x'^2<0$ in the fits it is not clear how to apply a Bayesian ansatz to derive an error estimate from the 2D likelihood distributions. Moreover these ones depend strongly on the most likely fitted values of x'^2 and y.

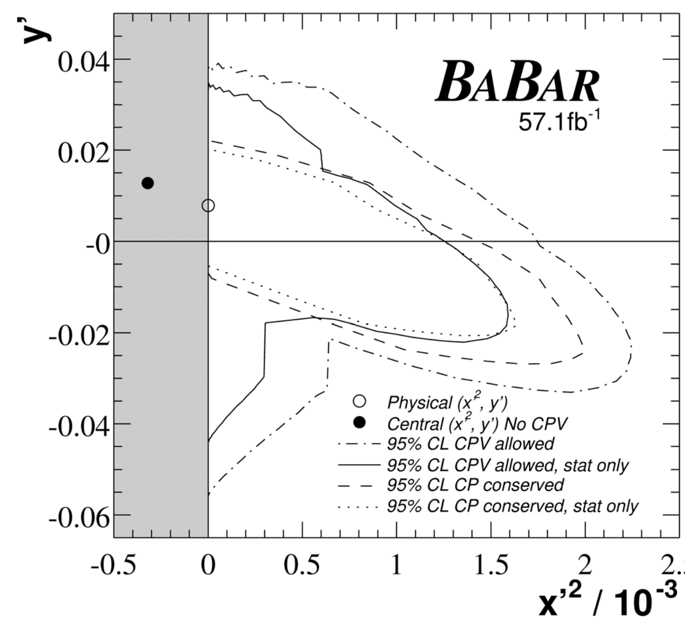
95% C.L. limits are determined using toy Monte Carlo samples at each point on the contour (frequentistic approach).

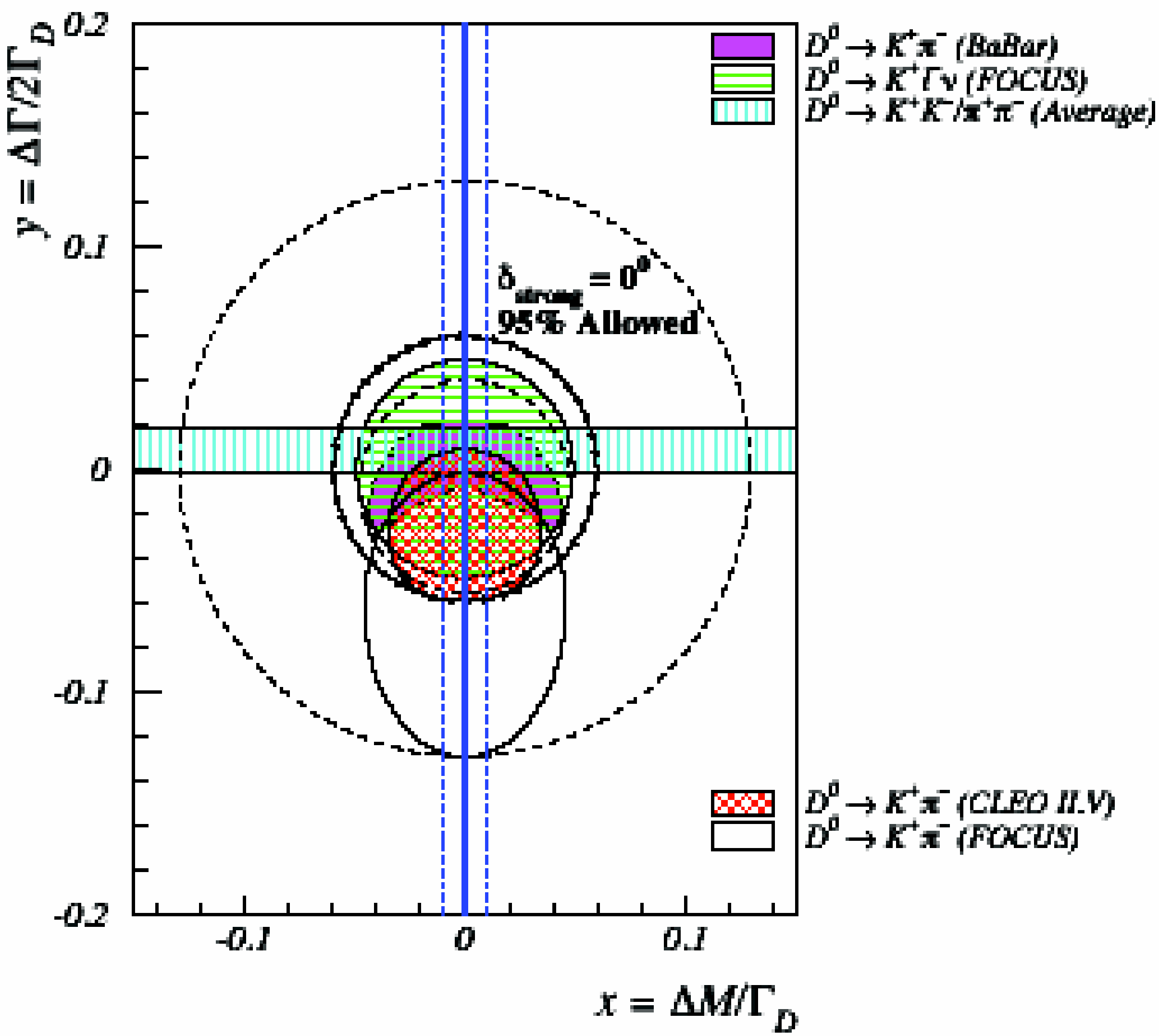
- (x'^2,y) points on separate contours are combined in pairs to determine (x'^2,y) on 95% ~~CP~~ contours.

- Systematic uncertainties included by calculating equivalent statistical deviation for each systematic check and expanding the 95% C.L. contour appropriately.









G. Burdman and I. Shipsey, *Ann. Rev. Nucl. Part. Sci.* **53**, 431 (2003)
[arXiv:hep-ph/0310076]

BACKUP-4

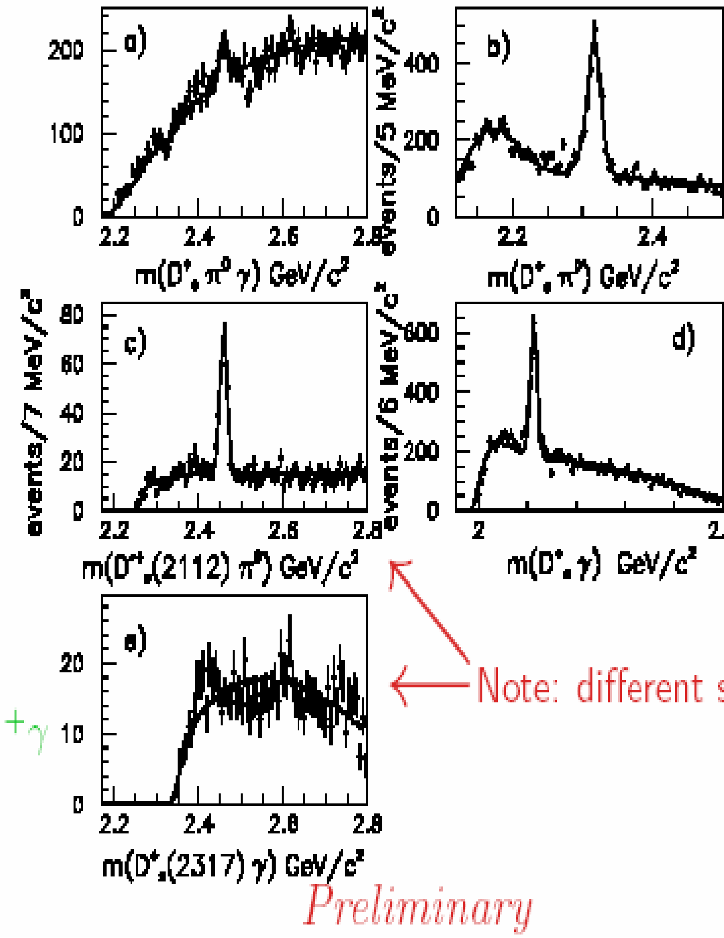
Unbinned maximum likelihood fit

Assign likelihood to each event for:

- $D_{sJ}(2458)^+ \rightarrow D_s^*(2112)^+ \pi^0$
- $D_{sJ}(2458)^+ \rightarrow D_{sJ}^*(2317)^+ \gamma$
- Combinatorial $D_s^+ \pi^0 \gamma$ bkgd
- $D_s^*(2112)^+$ + random π^0
- $D_{sJ}^*(2317)^+$ + random γ
- $D_{sJ}(2458)^+ \rightarrow D_s^*(2112)^+ \pi^0$

  … using wrong γ

Channel Likelihood Fit Results



The $D_{sJ}(2458)$ signal for a particular decay mode can be isolated by calculating a weight for each $D_s\pi^0\gamma$ combination proportional to the relative likelihood contributed by the decay mode of interest