Mixing in the D^0-System at BaBar

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DESY seminar
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- What is mixing and why is it interesting ?
- What does PEPII/BaBar offer for studying it?
- Results so far obtained by BaBar

Mixing formalism

Mesons are produced in strong interactions as flavor eigenstates with well defined quark content. They are observed as mass and lifetime eigenstates that decay in weak interactions.

Production: $\mathcal{H}_0 = \mathcal{H}_{strong} + \mathcal{H}_{em}$ with flavor/interaction ES D^0 and $\overline{D^0}$

Decay : $\mathcal{H} = \mathcal{H}_{strong} + \mathcal{H}_{em} + \mathcal{H}_{weak}$ with mass/decay ES D_1 and D_2

Time evolution of a $D^0(t) \rightarrow \overline{D^0}(t)$ follows Schroedinger's equation:

$$\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} = -i\,\mathcal{H}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} = -i\,[\mathcal{M} - i\gamma/2]\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix} = \begin{bmatrix} -iM - \gamma/2 & -iM_{12} - \gamma_{12}/2 \\ -iM^*_{12} - \gamma^*_{12}/2 & -iM - \gamma/2 \end{bmatrix}\begin{pmatrix} D^0 \\ \overline{D^0} \end{pmatrix}$$

- Off-diagonal elements mix flavor eigenstates
- Solutions have mass and width eigenvalues $m_{1,2}$, $\Gamma_{1,2}$
- Eigenstates $|D_1\rangle = p\,|D^0\rangle + q\,|\overline{D^0}\rangle$, $|D_2\rangle = p\,|D^0\rangle - q\,|\overline{D^0}\rangle$

In the absence of CP violation, i.e. if $|q/p|=1$: D_1 and D_2 are CP eigenstates.
Assume in following for D^0-system, experimentally proven not to be true in K^0 system.

Mixing formalism (II)

D^0 CP-eigenstates in absence of CP-violation :

CP-even D_1 with m_1, Γ_1 CP-odd D_2 with m_2, Γ_2

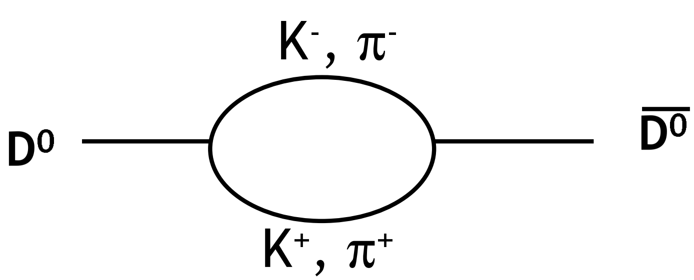
Definition of mixing parameters:

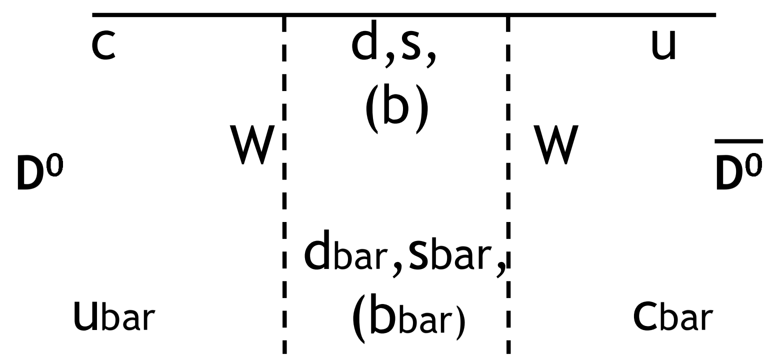
$y = (\Gamma_1 - \Gamma_2) / (\Gamma_1 + \Gamma_2) = \Delta\Gamma / 2\Gamma$ $x = (m_1 - m_2) / \Gamma = \Delta m / \Gamma$

Mixing rate of D^0 to final state f: $R_{mix} = (x^2+y^2)/2 = Br(D^0 \to \overline{D^0} \to \overline{f}) / Br(D^0 \to f)$.

Mixing, i.e. evolution of a neutral meson into its anti-particle, through:

- on-shell intermediate states amplitude $-iy$
- off-shell intermediate states amplitude x (in units of $\Gamma/2$ and absence of CPV)





New physics enters in x !

Motivation - Some history

"Studies of the evolution of K^0 and B^0 into their respective anti-particles have guided the form and content of the Standard Model" (H. Nelson, CLEO)

K^0 system: $|x|$ and y are both of order 1
Non-zero y: Solution of τ-θ puzzle given by Gell-Mann and Pais
Value of x: Prediction of charm mass before its discovery

B^0 system: $|x| \sim 0.75$, firm theoretical prediction that y is negligible
Large value of x: Evidence for large top mass in mid-80s

D^0 system: According to conventional wisdom both $|x|$ and y are expected to be $<10^{-3}$ in the SM.
A large number of extensions to the SM (e.g. via new particles in loop) predict $|x|$ up to 0.01 and $|y| << |x|$.

Mixing rate R_{mix}: $K^0 : \sim 1$, $B^0 : \sim 0.3$, $D^0 : <10^{-6}$

Motivation (II)

So, for finding new physics, is x alone of interest ?

Beware: D^0 too heavy for typical treatment of light quark systems
D^0 too light for perturbative treatment
Huge theoretical uncertainties in description of mixing in D-system

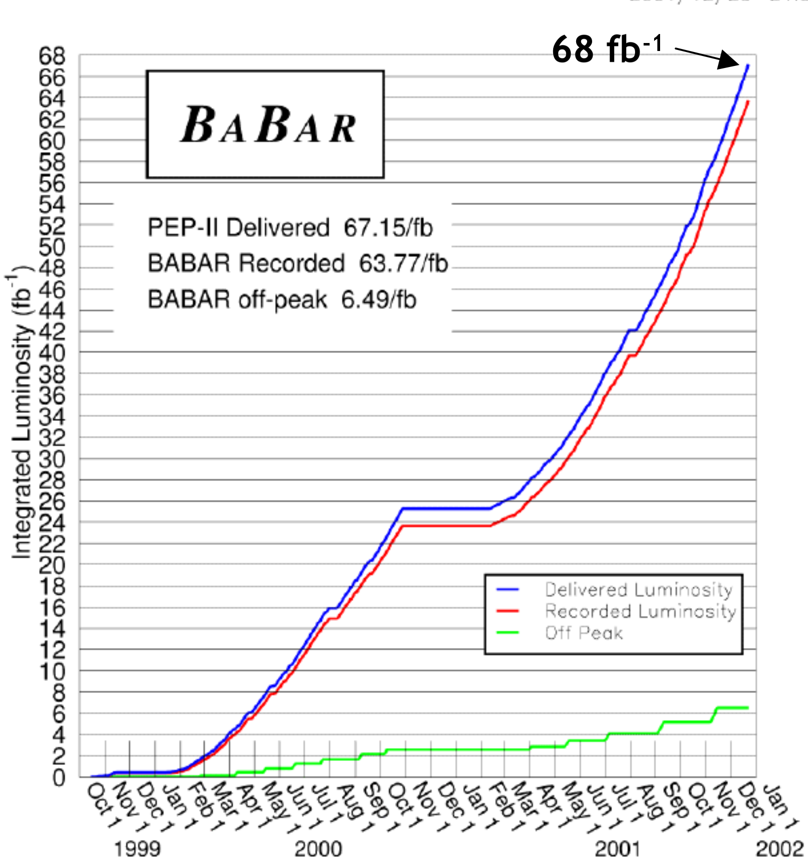
- Conventional wisdom: x and y are very small in SM
- Recent theoretical work shows possibility that large SU(3) flavor breaking can enhance y so that a large value $y \sim 0.01$ might be natural in the SM.
  (Bergmann, Grossman, Ligeti, Nir, Petrov, Phys. Lett. B486(2000) 418)
- A large value of y reduces the sensitivity of mixing ($R_{mix}=(x^2+y^2)/2$) to new physics in x.
  - $|y| \gtrsim |x|$ probably large SU(3) flavor breaking
  - $|y| << |x|$ probably new physics

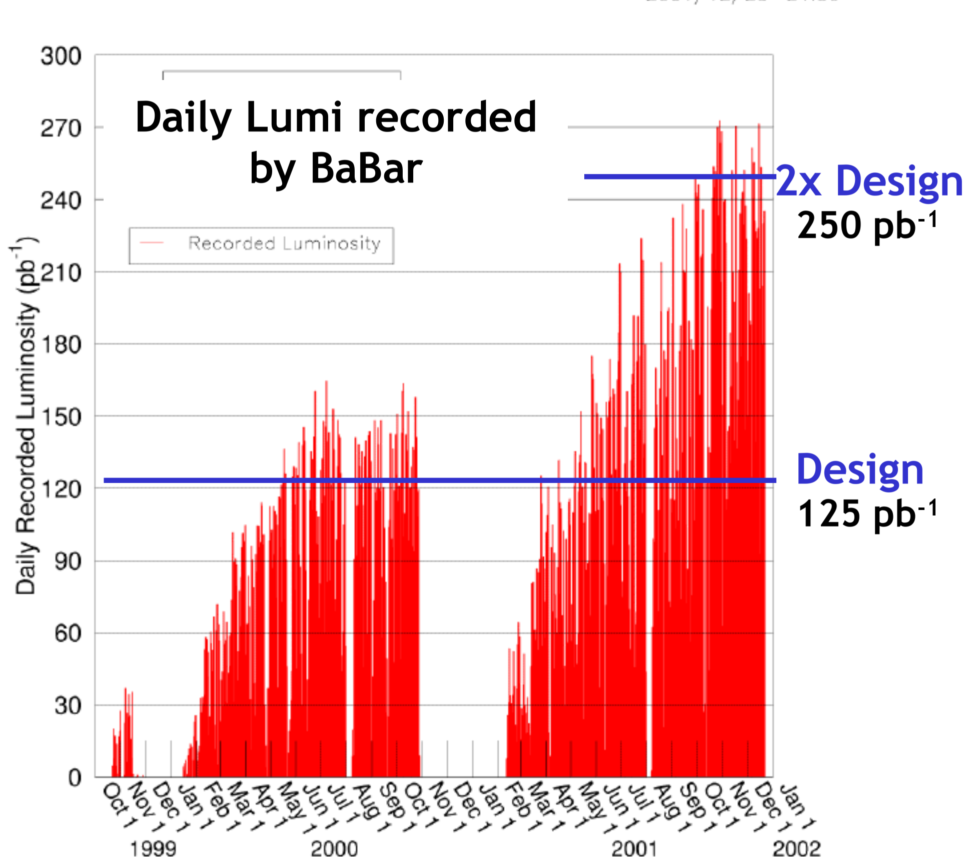
⇨ Important to measure x & y !

An e+e- storage ring running at the $\Upsilon(4S)$ resonance is an excellent laboratory for studying charm physics → the B-factory PepII as charm factory:
$e^+e^- \rightarrow$ qqbar: 4.45 nb of which 1.05 nb bbbar, 1.30 nb ccbar

Per fb^{-1} of collected data: 1.3 million ccbar events from continuum production

BaBar recorded: 24 fb^{-1} in 2000, 40 fb^{-1} in 2001

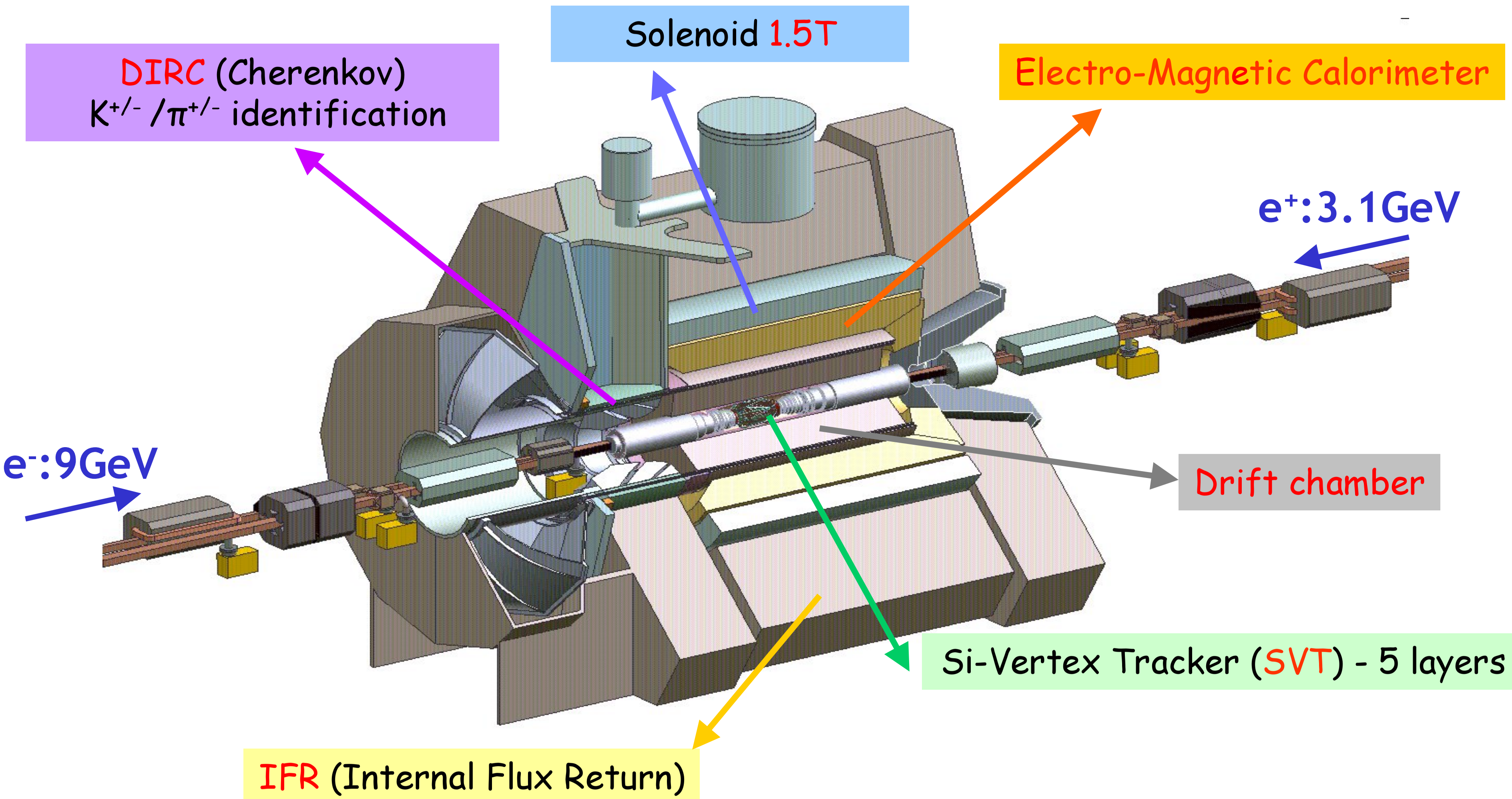




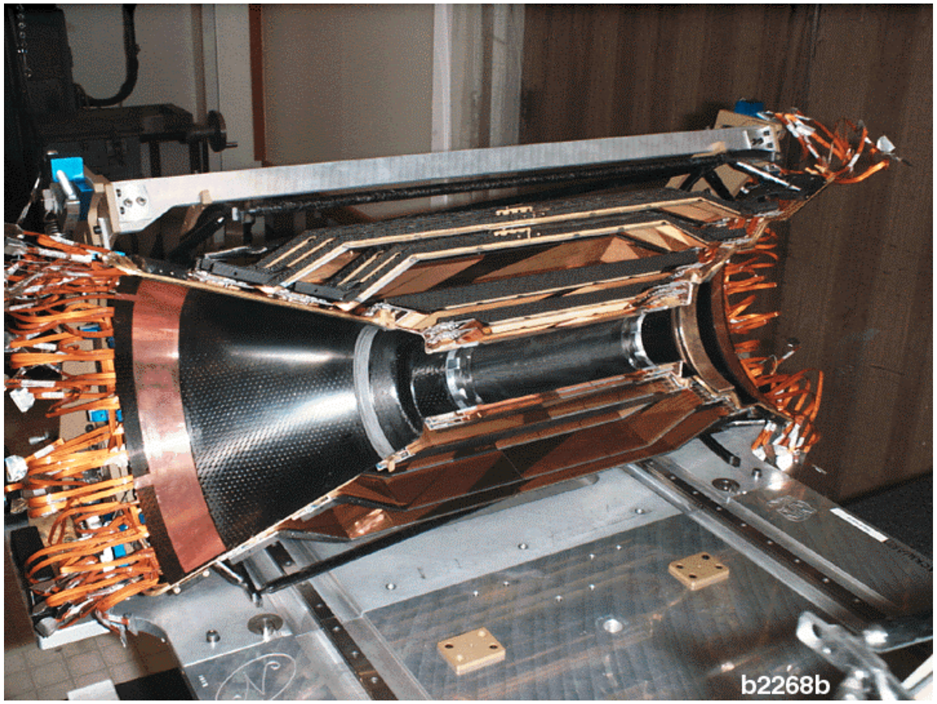
BABAR

PepII CM energy: 10.58 GeV $\Upsilon(4S)$
Asymmetric: Lorentz boost $\beta\gamma = 0.56$

Vertex reconstruction: SVT
Particle ID: SVT+DCH (dE/dx) ,
DIRC (Cherenkov light)



The Silicon Vertex Tracker (SVT)



- 5 layers of double-sided Si-strip detectors with readout strip pitch
  $r\phi$: 50-100 μm, z: 100-200 μm
- Layers 1-3: measure impact parameters
  Layer 4,5: stand-alone tracking
- Single-hit resolution for perpendicular tracks with p_t>1GeV:
  Layer 1-3: 10-15 μm
  Layer 4,5: 30-40 μm
- Vertex resolution for fully reconstructed decay of a B^0 typically $\sigma_z \sim 70\ \mu$m

Alignment crucial, done in 2 steps:

1) **Local alignment: Align 340 silicon sensors in SVT w.r.t. each other**
   → needed every few months, typically after access to BaBar
   → utilizes di-muons, cosmics, overlap tracks, optical survey of SVT
2) **Global alignment: Align SVT as whole w.r.t. global coord. system defined by DCH**
   → needed on run-by-run basis because of diurnal variations (caused by local temperature changes) of e.g. typically $\pm$ 50 μm in x,y
   → utilizes stiff high-quality Bhabha and di-muon tracks

Kaon/pion separation in BaBar

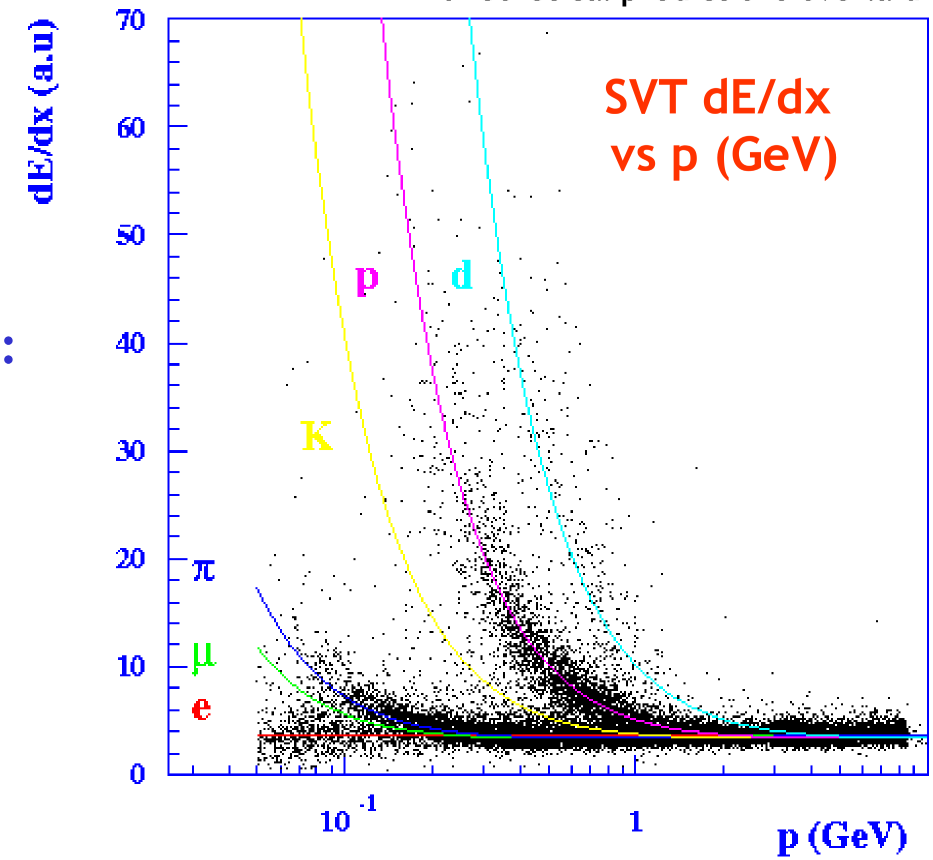
Better than 2σ K/π separation:
- by SVT dE/dx for $p_{particle} \lesssim 0.6$ GeV
- by DCH dE/dx for $p_{particle} \lesssim 0.7$ GeV
- by DIRC for $0.5 \lesssim p_{particle} \lesssim 4$ GeV

PID relies primarily on dE/dx below 0.7 GeV

Selection based on ratios of likelihoods for different particle hypotheses

SVT is only source of PID for particles from primary vertex with $p_t \lesssim 120$ MeV:
- SVT read-out chip measures Time-over-threshold (ToT)
- ToT depends approx. logarithm. on pulse-height
- dE/dx calculated from 60% truncation
- Resolution for MIPs: ~14% (factor of 2 worse than DCH)

Theoretical predictions overlaid

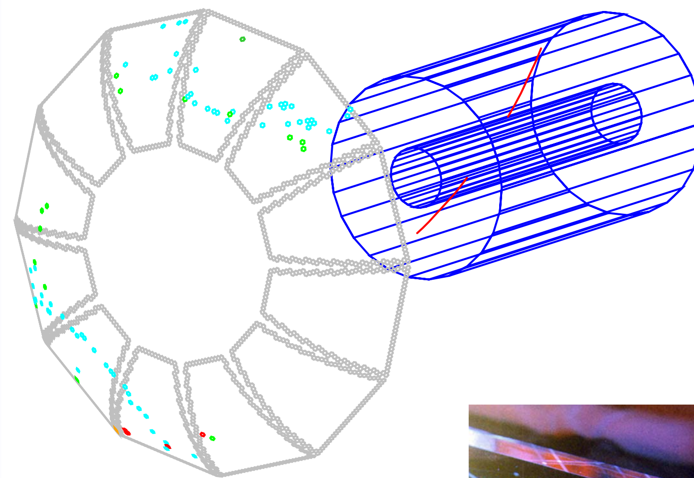


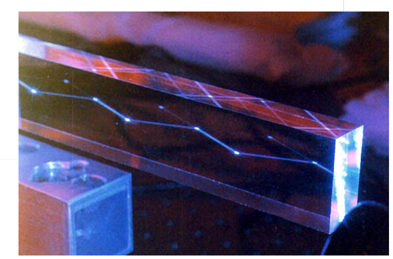
Kaon/pion separation in BaBar (II)

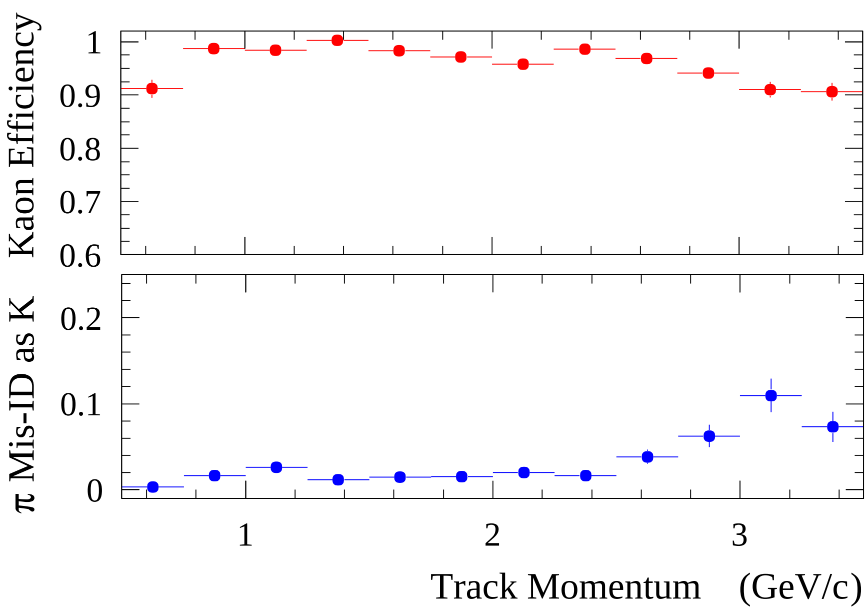
Detector of internally reflected Cherenkov light - DIRC

- Cherenkov light produced in 4.9m long quartz bars of (1.7 x 3.5) cm^2 Xsection
- light transported by total internal reflection to array of PM tubes at bckwrd wall of toroidal water tank at bckwrd end of BaBar
- angle of emission is preserved
- Cherenkov rings reco'd from position & time of arrival of signals in PMTs

$\sigma(\Delta t)$=1.7 nsec $\sigma(\Delta\theta_c)$=10.2 mrad







From $D^0 \rightarrow K^- p^+$ decays, selected kinematically from inclusive D* production:

$K^{\pm}$ Efficiency

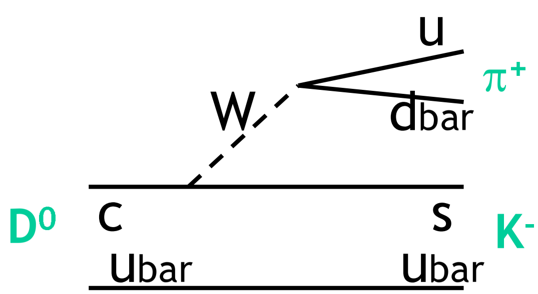
π mis-ID as $K^{\pm}$

as function of particle momentum (GeV)

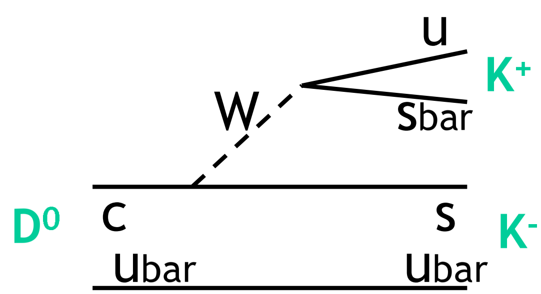
Outline of my presentation of BaBar results:

- Search for a lifetime difference in $D^0 \to K^- \pi^+$, K^-K^+ (y)
- Time evolution of the $D^0 \to K^+ \pi^-$ (wrong-sign) decay (x'^2, y')
- Measurement of the wrong-sign decay rate

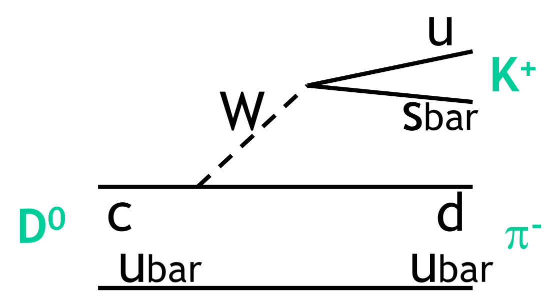
Cast of characters: Two-prong decays of the D^0



$D^0 \to K^- \pi^+$
Cabibbo favored
right-sign (RS) decay
BR ~ 4%
Relativ rate 1



$D^0 \to K^- K^+$
singly Cabibbo suppressed
CP-even decay
1/9



$D^0 \to K^+ \pi^-$
doubly Cabibbo suppressed
wrong-sign (WS) decay
1/300

Two datasets, taken by BaBar on & off $\Upsilon(4S)$:

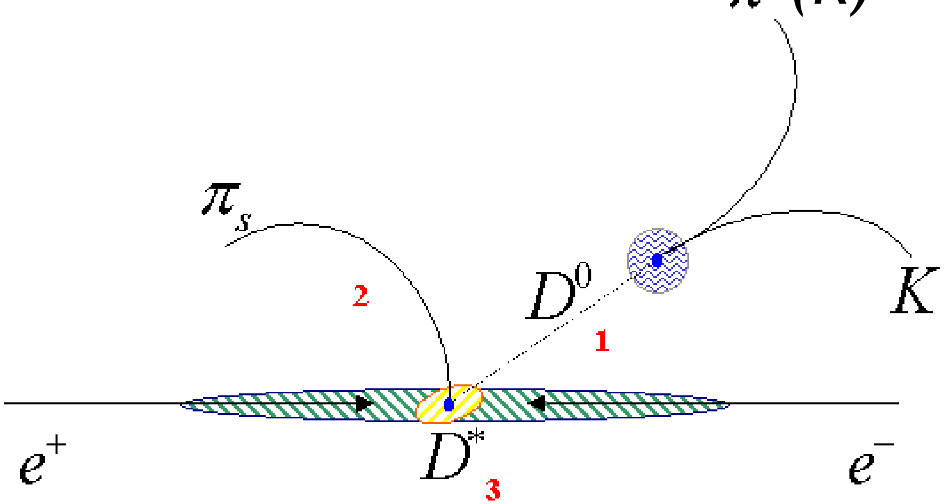
- y measurement: 12.4 fb^{-1} of Run2 BaBar data, taken in 2001, reconstructed with most advanced internal alignment of SVT
- Wrong-sign measurements: 23.2 fb^{-1} of Run1 BaBar data, taken in 1999/2000

Method of measurements

D^0 candidates reconstructed through decay $D^{*\pm} \rightarrow D^0 \pi^\pm$

Slow pion π_s

$ct = m_{D0}(PDG)\, [\overrightarrow{v(D^*\text{-}D^0)} \cdot \vec{p}_{D0} / |\vec{p}_{D0}|^2]$



Global vertex fit in 3 dim to all tracks in candidate decay chain to take correlations properly into account

Main constraints:

- Beamspot and D* vertex have to coincide
- D^0 momentum vector points back to D* decay point

→ refitting π_s to coincide with D* vertex greatly improves $\delta m(D^* - D^0)$ resolution

Beamspot: 1 σ envelope in plane transverse to beam:
6 μm vertically (yIP), 120 μm horizontally (xIP)
compare to 8 mm along beam direction

Transverse flight length of $D^0 \approx$ 200 μm

Measurement of y

Method: In absence of CP violation

$D^0 \to K^- K^+$: CP even

$D^0 \to K^- \pi^+$: equal mix of CP-even, CP-odd

$$y = \frac{\tau_{D0}(K^- \pi^+)}{\tau_{D0}(K^- K^+)} - 1$$

Data set: 12.4 fb^{-1} of Run2 BaBar data, taken in 2001 on and off $\Upsilon(4S)$ reconstructed with most advanced internal alignment of SVT

Selection of events:

- D* momentum p* > 2.6 GeV (continuum ccbar)
- Track quality and vertex probability cuts
- δm window $\pm$ 3 σ (value depends on whether or not π_s track has drift chamber hits)
- Particle ID requirement for kaon D^0 daughter candidates

After all cuts:

$D^0 \to K^- \pi^+$ candidates ~45 k with purity in MC 98%

$D^0 \to K^- K^+$ candidates ~ 4 k with purity in MC 95%

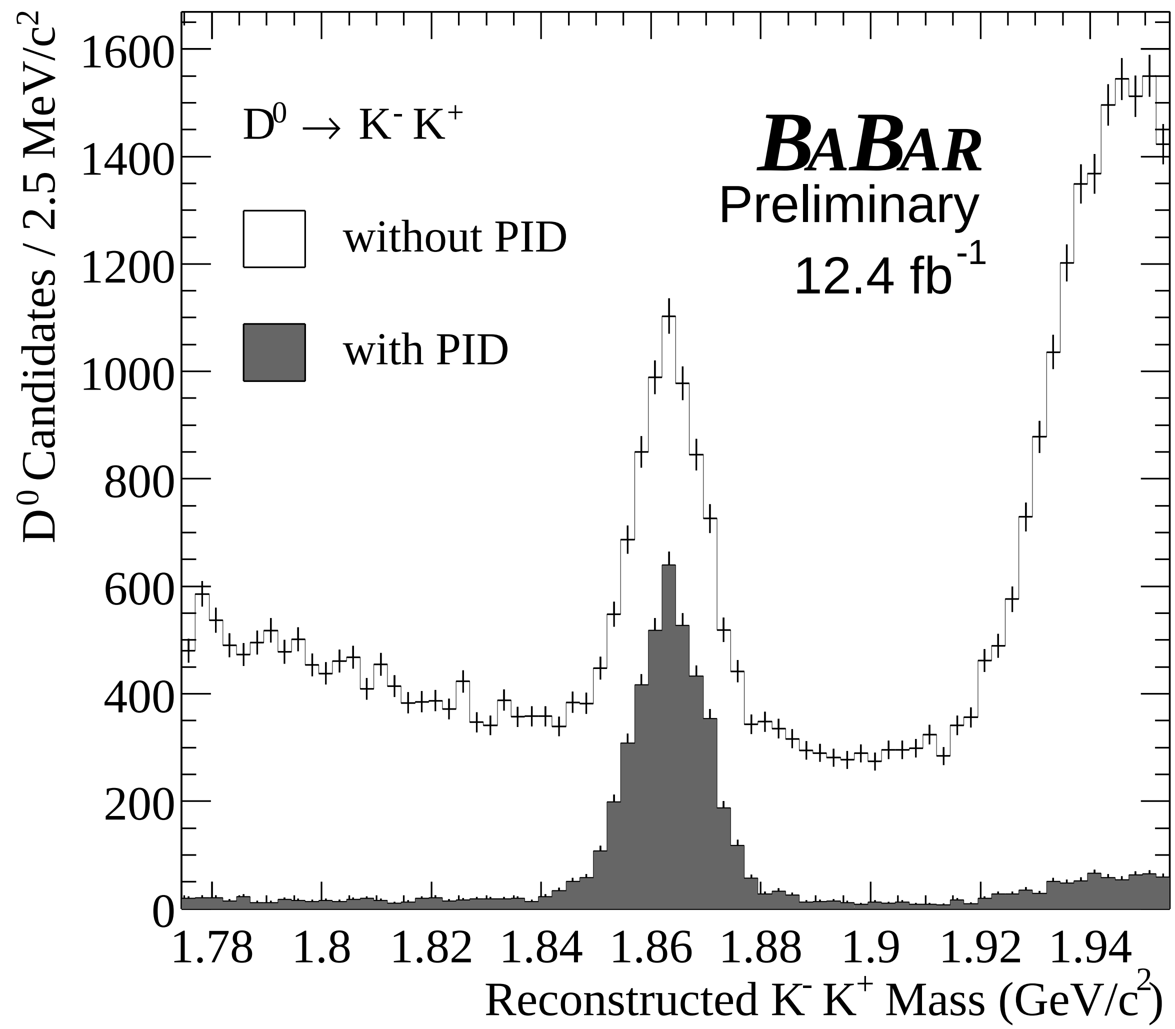
In ± 20 MeV window around D^0 mass peak

Importance of particle ID

$p \gtrsim 0.7$ GeV
mainly DIRC

$p \lesssim 0.7$ GeV
mainly dE/dx
from SVT
and drift chamber

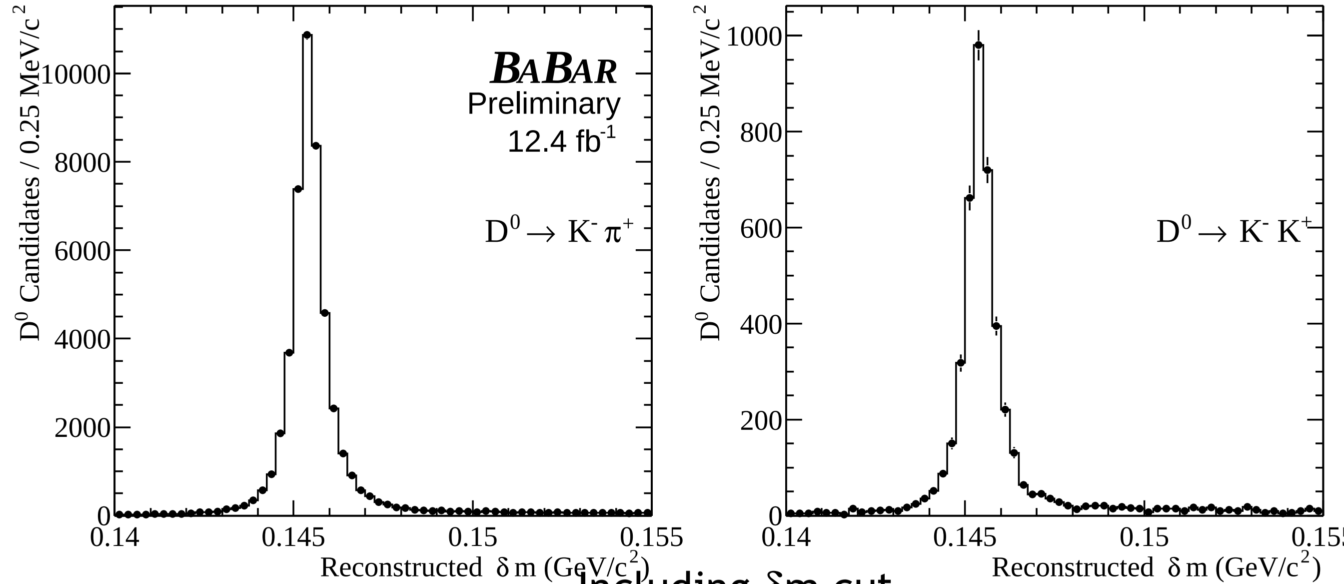
Kaon PID required for both kaon candidates



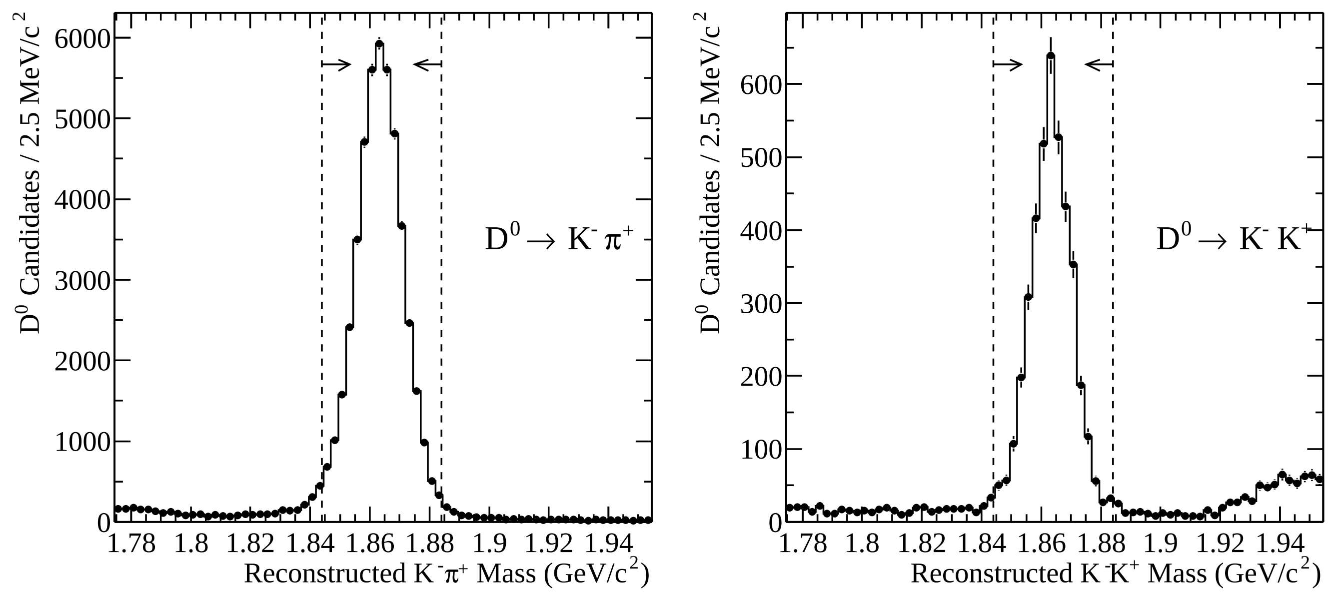
D^0 signals after event selection

δm:
mass difference between D* and D^0

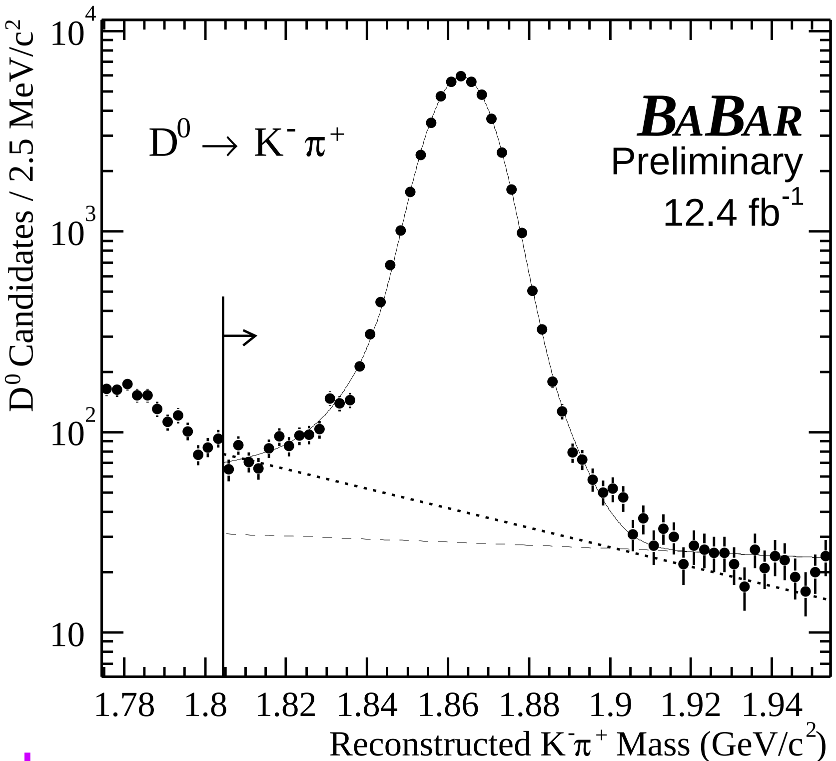
Excluding δm cut

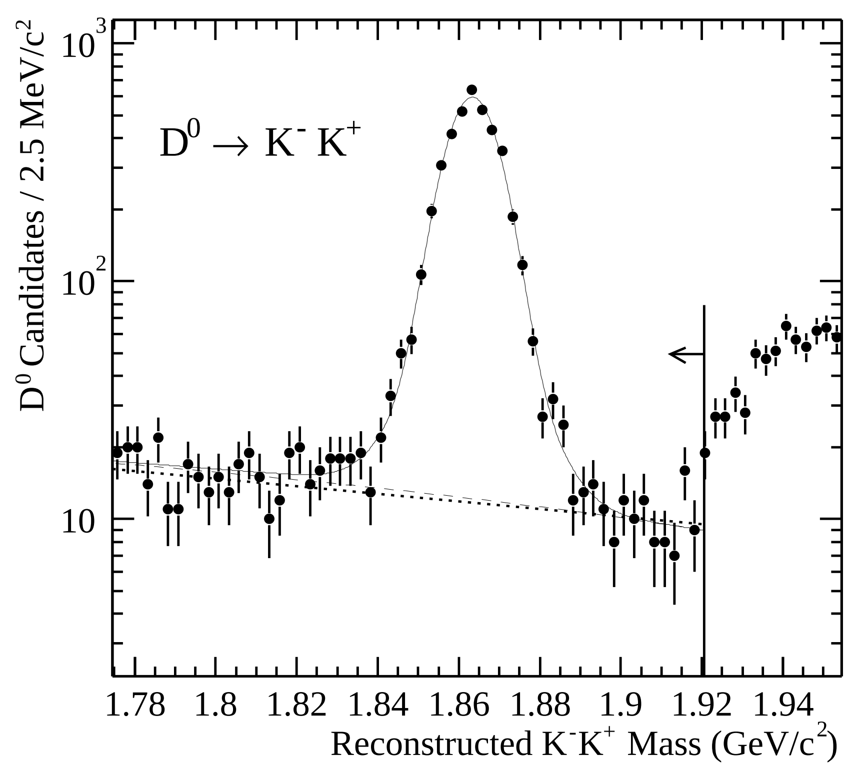


Including δm cut



Elements of fit to the D^0 decay time distribution
Signal probability

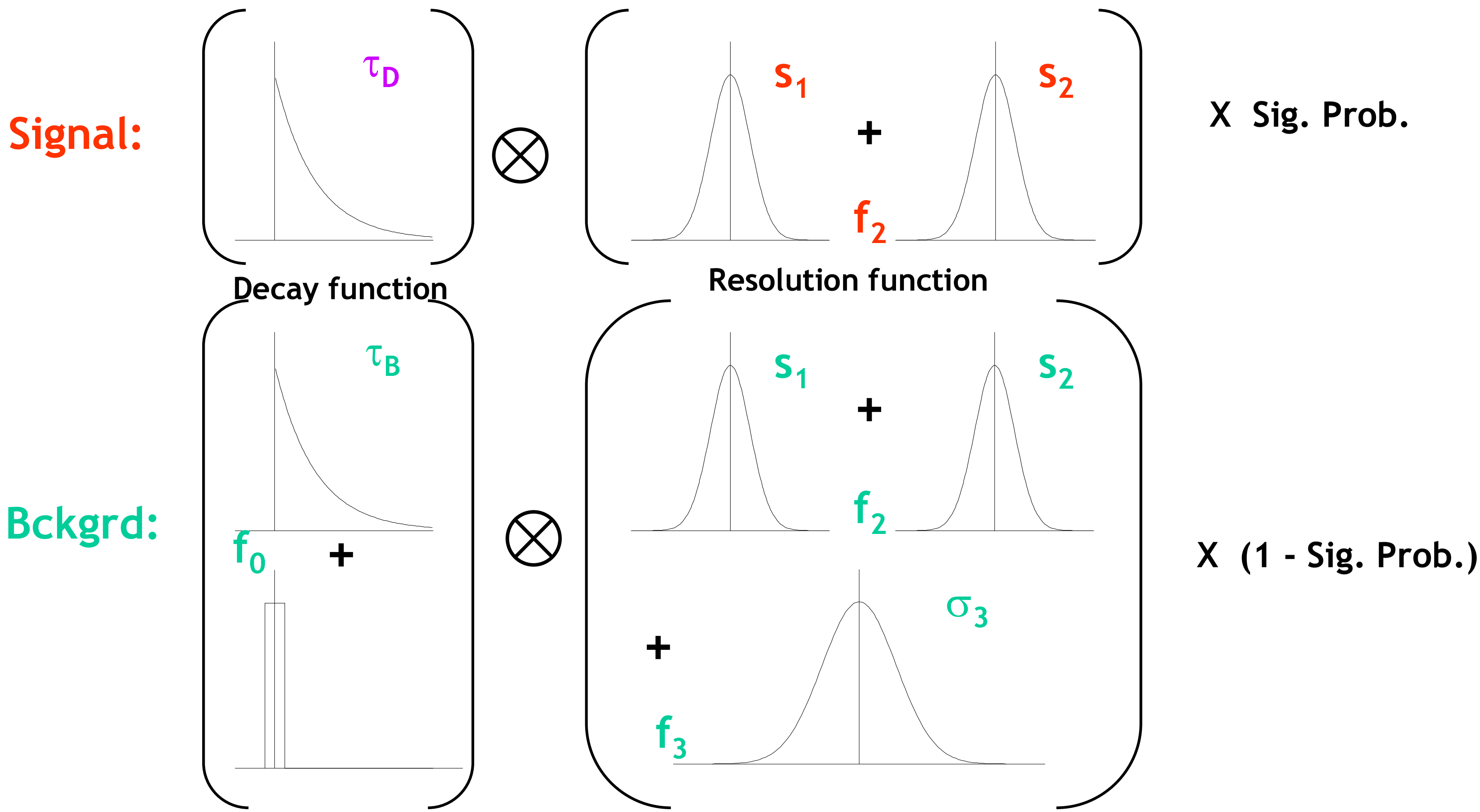




Log
Scale !

Per-evt probability to be signal evt from reco'd mass of D^0 candidate
Assume linear distribution for background, double Gaussian for signal

Elements of fit to the D^0 decay time distribution
Lifetime fit function

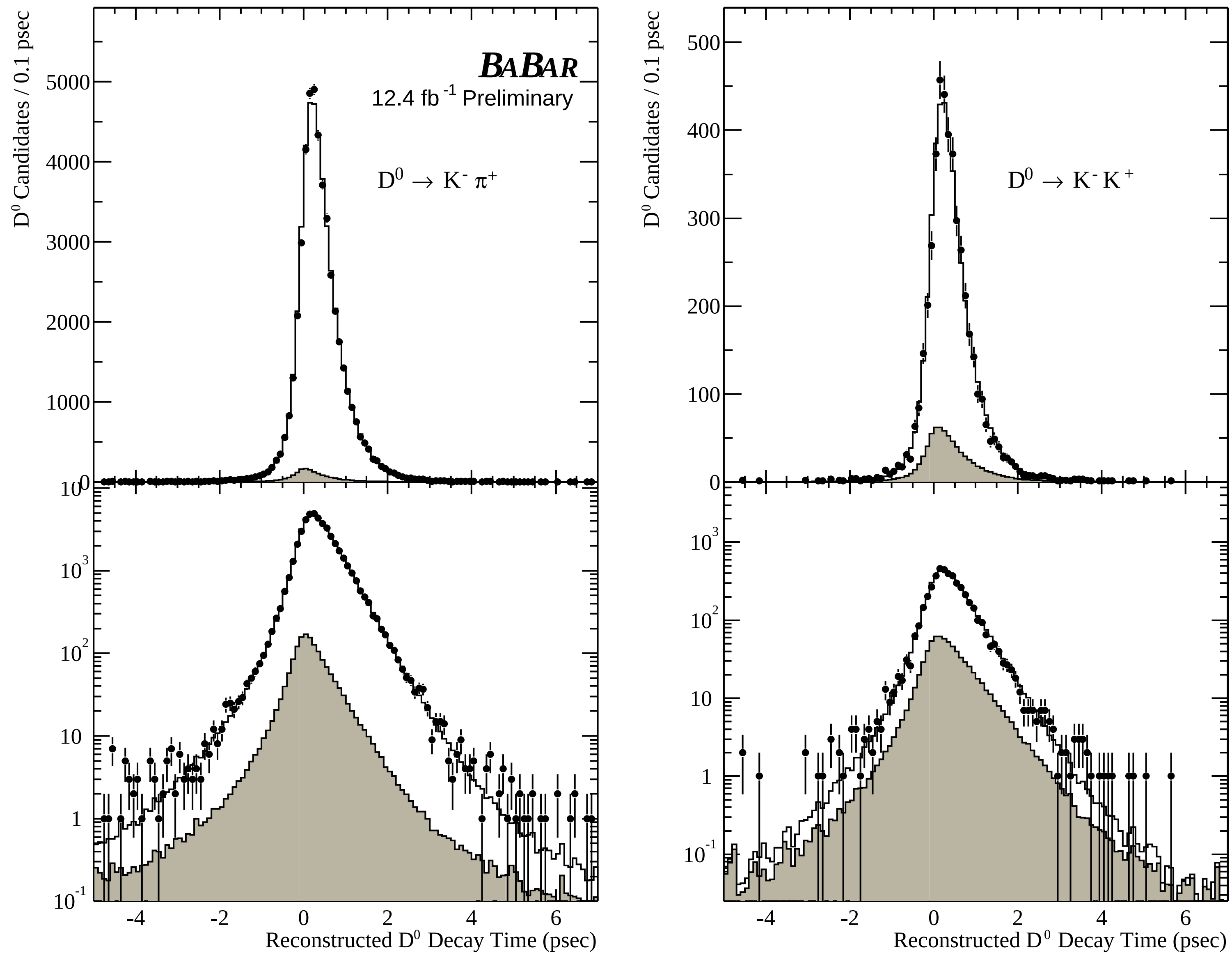


Typical value σ(decay time) ~ 180 fs; τ_D was blinded throughout analysis

Overlay data - Fit result

Unbinned maximum likelihood fit

Points:
Data with stat. error
White:
Sig + Bckgrd
Grey:
Bckgrd only



Note: Fit does not rely on any MC input.

Systematic checks for y

Many sys. errors of lifetimes cancel in ratio $y = \frac{\tau_{D0}(K^- \pi^+)}{\tau_{D0}(K^- K^+)} - 1$

A: Event selection and background	**± 1.7 %**
B: Reconstruction and vertexing	**± 0.4 %**
C: Alignment	**± 0.3 %**
TOTAL:	**± 1.7 %**

A: Vary event sel. cuts within their uncertainties and re-measure y

- χ^2 criterion to differentiate between purely statistical and systematic fluctuation
- Checks vary size of background contribution and composition of background events
- Biggest contributors are varying δm window and varying kaon-PID criterion

B: Use alternative reconstruction methods

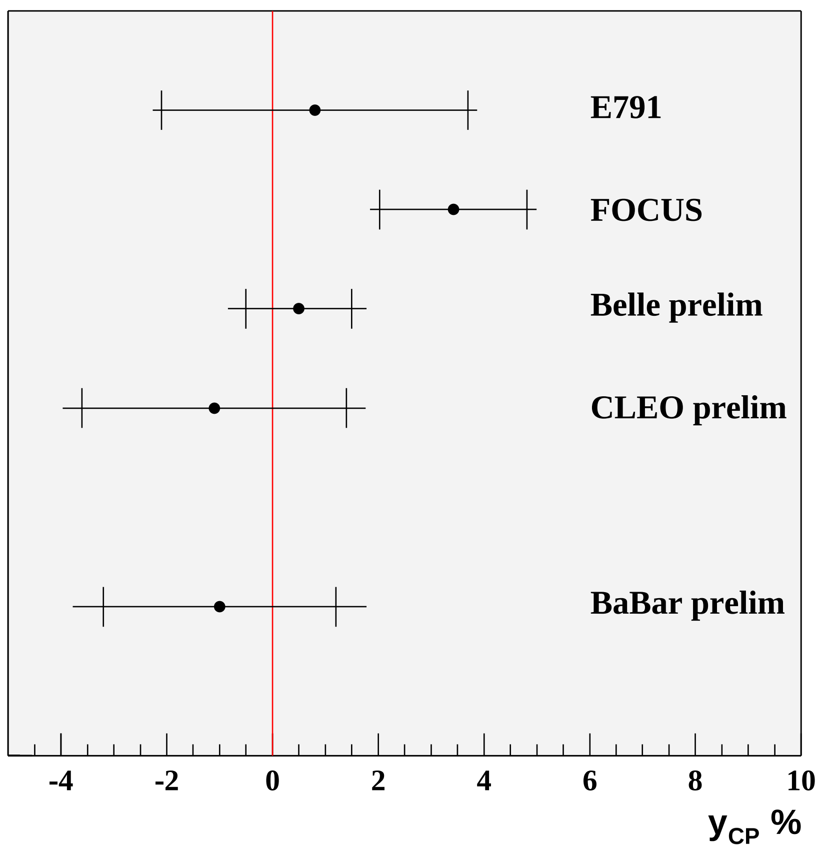
- Biggest contributors are using an alternative vertexing method and changing the $\vec{p}(\pi_s)$ resolution so that MC matches data

C: Si-vertex tracker (SVT) internal alignment

- Biggest contributors are shifting yIP position and yIP correction from e+e- -> $\gamma\gamma$ -> 4π

Result for y (preliminary)

$y = (-1.0 \pm 2.2 \pm 1.7)$ %
stat. sys.

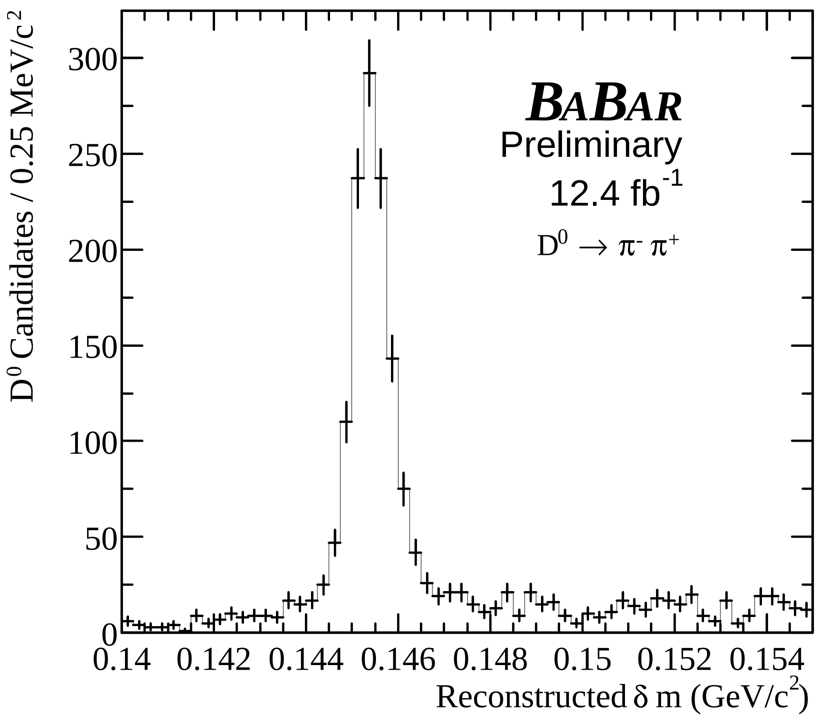


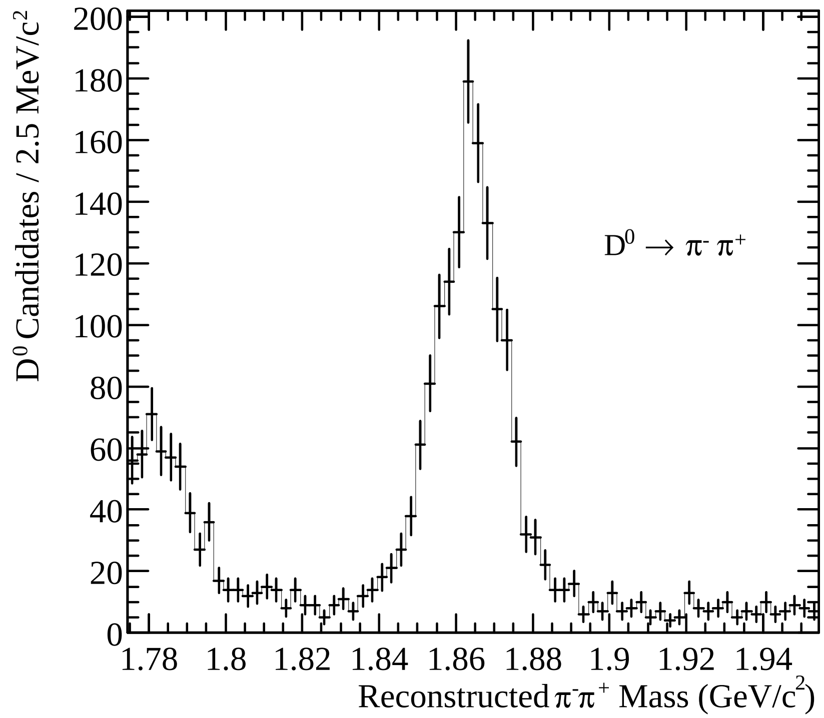
y and the two lifetimes were kept blind throughout analysis

Lifetime of $D^0 \to K^-\pi^+$:

- used as cross check, provided criterion whether or not to unblind y
- $\tau_{D(K\pi)} = (412 \pm 2)$ fs
  compare to $\tau_D(PDG) = (412.6 \pm 2.8)$ fs
- sys. error of order 6 fs, dominated by SVT alignment
- correction of $(+5 \pm 5$ fs), applied to fit result, derived from
  $e^+e^- \to \gamma\gamma \to 4\pi$ events

Near-term prospects for measurement of y





Add CP-even $D^0 \to \pi^+\pi^-$ channel: ~1.2 k events in 12.4 fb^{-1} of 2001 data

➡ reduces stat. error in y to ~1.9 %

Add 23 fb^{-1} of 2000 data reprocessed with most advanced SVT alignment

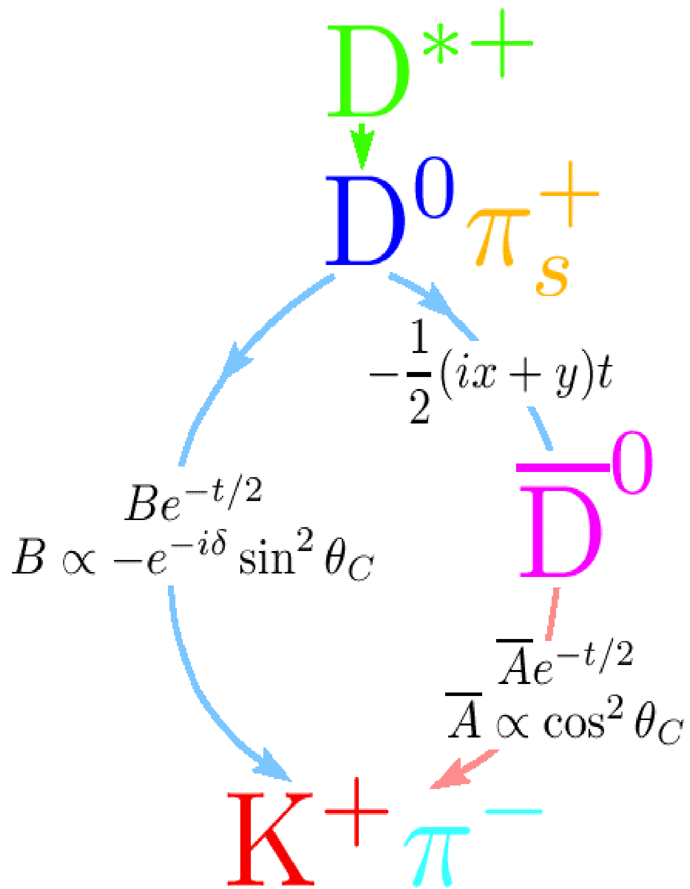
➡ reduces stat. error in y to ~ 1.1 %

Use full 2000+2001 data set: reduces stat. error in y to well below 1%

Measurements with $D^0 \to K^+\pi^-$ (WS) decays

For D^0 two paths to arrive at $K^+\pi^-$ final state:

1) Doubly Cabibbo suppressed decay
2) Mixing followed by Cabibbo favored $\overline{D}^0$ decay



Time evolution of $D^0 \to K^+\pi^-$

$\Gamma(t) \propto \exp(-t)$

[R	DCSD
$+ \sqrt{R}\, y'\, t$	interference
$+ \frac{1}{4} (x'^2 + y'^2)\, t^2$	mixing
]	t in units of τ_D

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

$y' = y \cos\delta - x \sin\delta$; δ strong phase

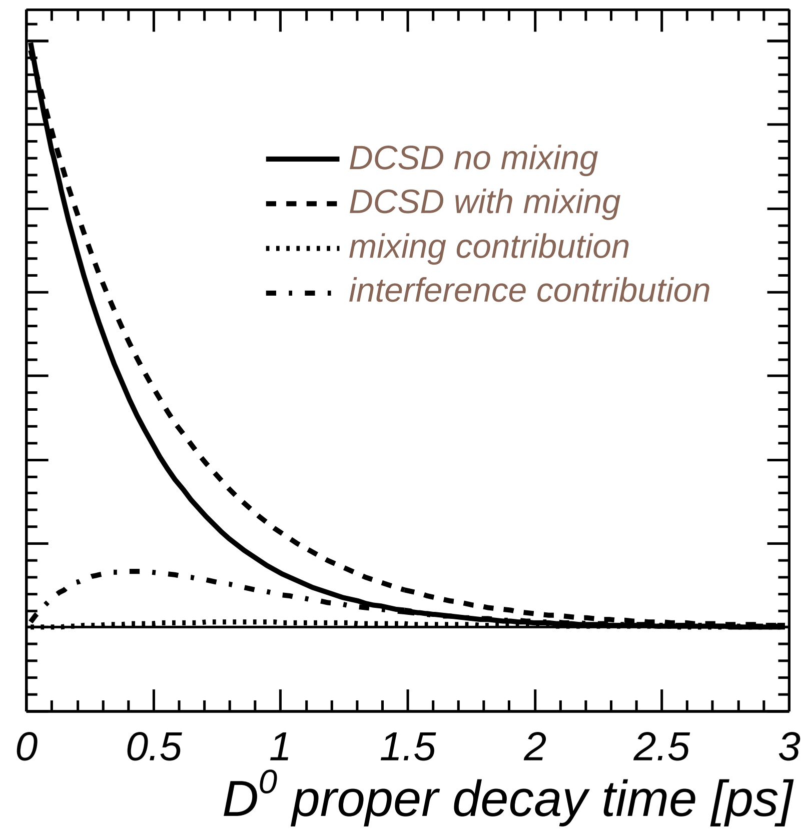
SM: $R = R_{DCS} \sim \tan^4\theta_c \sim 0.25\%$

Goal: Measure deviation from exponential decay law ⇨ mixing !

Data set: 23.2 fb^{-1} of Run1 BaBar data, taken in 2000 on & off $\Upsilon(4S)$

Reconstr. and selection of events similar to that in y measurement

Tag for WS events:
π_s and kaon have same charge



After all cuts:

$D^0 \rightarrow K^+ \pi^-$ candidates ~200 with purity in MC 40%

In ± 20 MeV window around D^0 mass peak

Background much more serious problem than for y measurement

Background sources

1) True D^0 with fake π_s
2) Combinatorial background
3) Partially reco'd D^0 with correct π_s
4) Correctly reco'd D^0 with K and π hypothesis swapped

Backgrounds differ from signal events and from each other

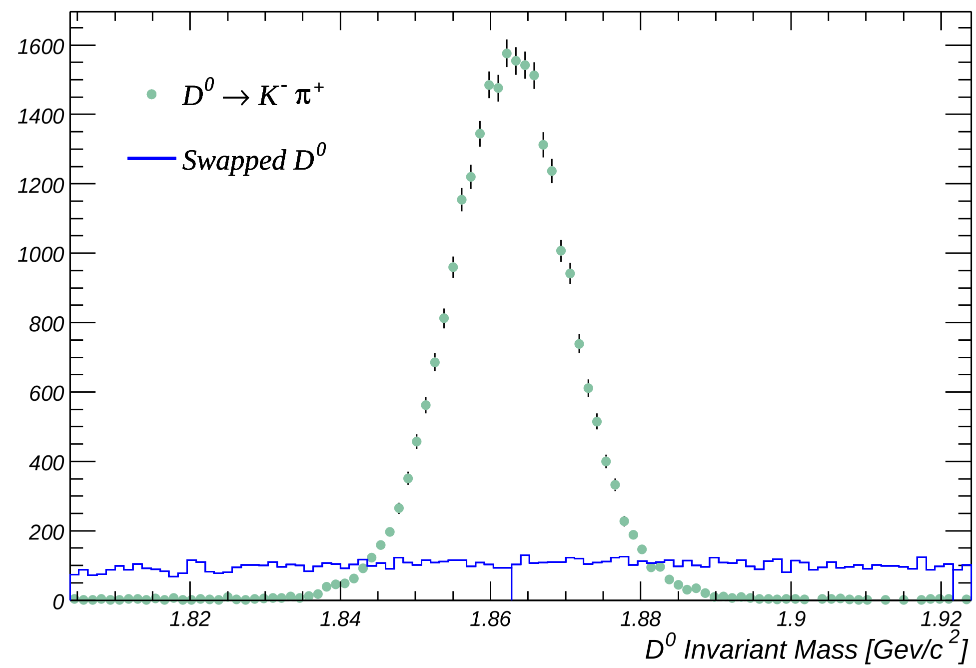
- in their lifetime evolution
- in their $m(K\pi)$ spectrum
- in their δm spectrum

Input to fit: t, $\sigma(t)$, $m(K\pi)$, δm
Output: 33 parameter

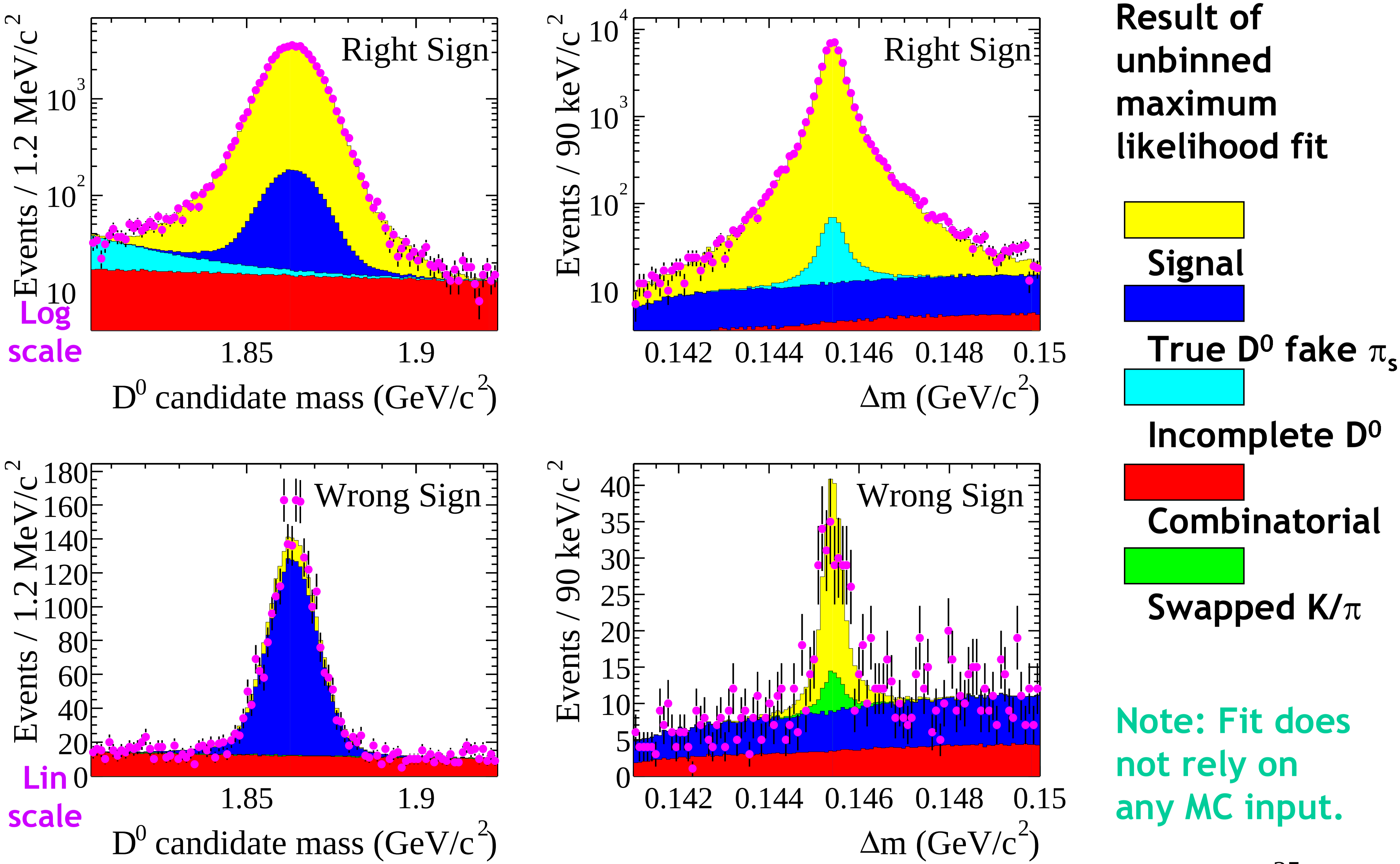
Fit simultaneously decay time distr. in WS and RS decays:

- Resolution and background description in $m(K\pi)$ & δm from RS events
- Decay function
  - → for WS: 3 components DCSD, mixing, interference
  - → for RS: only pure exponential

MC study of swapped K/π shape



Fit result in m(Kπ) and δm (preliminary)

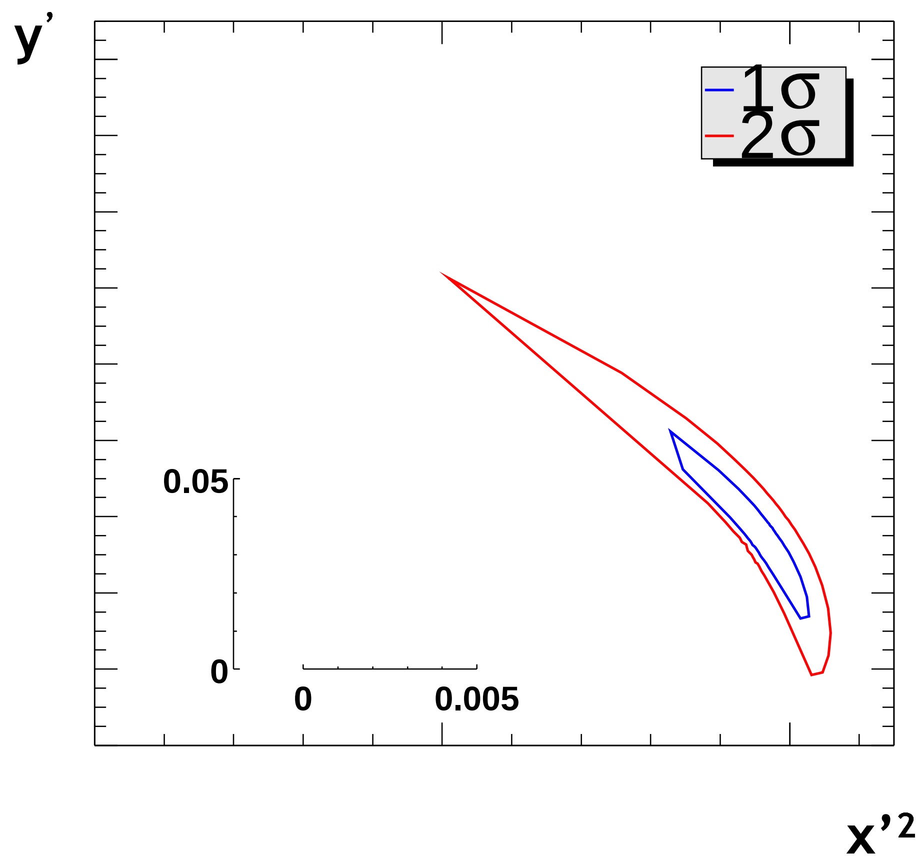


Note: Fit does not rely on any MC input.

Statistical uncertainty in (x'^2, y') plane - preliminary

- Strong correlation x'^2, y'
- Important to fit with unphysical ($x'^2<0$) region
- Study of systematic effects: SVT internal alignment in 2000 data dominating
- Extraction of central values with combined 2000+2001 data set on-going

Axis labels omitted, only scale given !

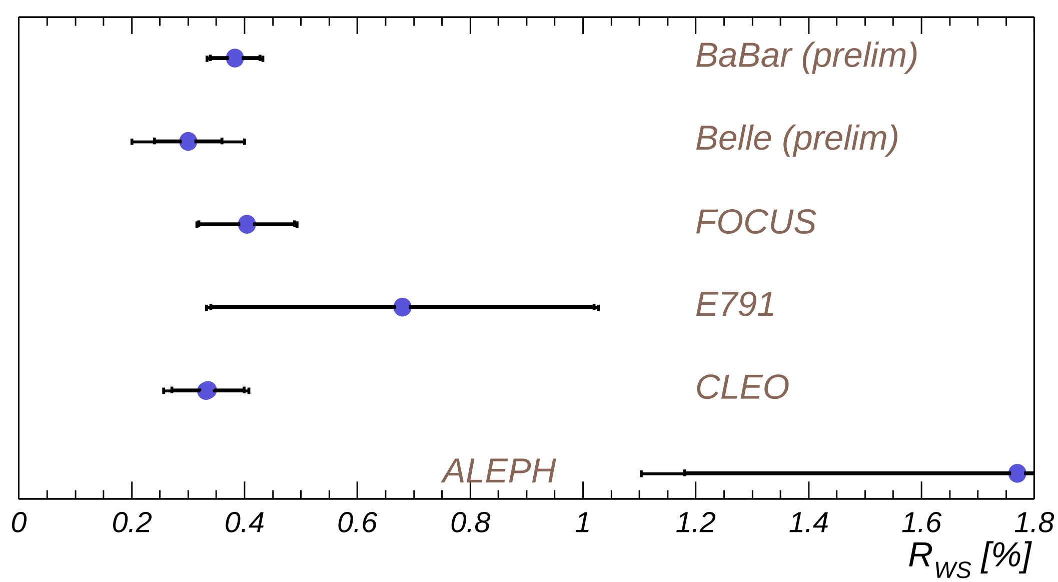


$D^0 \to K^+\pi^-$ (wrong sign) decay rate (preliminary)

$$R_{WS} = \frac{\text{number wrong sign decays}}{\text{number right sign decays}}$$

$$= (\,0.38 \pm 0.04\ (\text{stat.}) \pm 0.02\ (\text{sys.})\,)\ \%$$

Extracted from fit to D^0 decay time distribution (n_{WS} ~ 0.2 k)



SM expectation if there is no mixing, i.e. $R_{WS} = R_{DCS}$:
$R_{WS} \sim \tan^4\theta_c \sim 0.25\%$

Summary and outlook

- Result from 12.4 fb^{-1} of 2001 BaBar data:

  $y = (-1.0 \pm 2.2\ (stat.) \pm 1.7\ (sys.)\ )\ \%$ preliminary

  ($y<0$ corresponds to a shorter than average lifetime for CP-even eigenstates.)

- Prospect of cutting statistical error by more than half in the near future

- Extraction of mixing parameters x^2,y from combined 2000+2001 BaBar data sample of ~60 fb^{-1} on-going

- Already with 23 fb^{-1} of 2000 BaBar data alone achieved most precise existing measurement of wrong-sign decay rate:

  $R_{WS} = (\ 0.38 \pm 0.04\ (stat.) \pm 0.02\ (sys.)\ )\ \%$ preliminary

With current errors no indication for something unexpected,
but given theoretical situation:
Every experimental bit helps.

Compilation of D0 mixing predictions

H.Nelson, hep-ex9908021

X-axis: Ref. no. of publication
Y-axis left: prediction for x,y
Y-axis right: equivalent R_{mix}

SM predictions for x: △

SM predictions for y: □

Non-SM predictions for x: ○

Every little (experimental) bit helps !