New Results from Babar:

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

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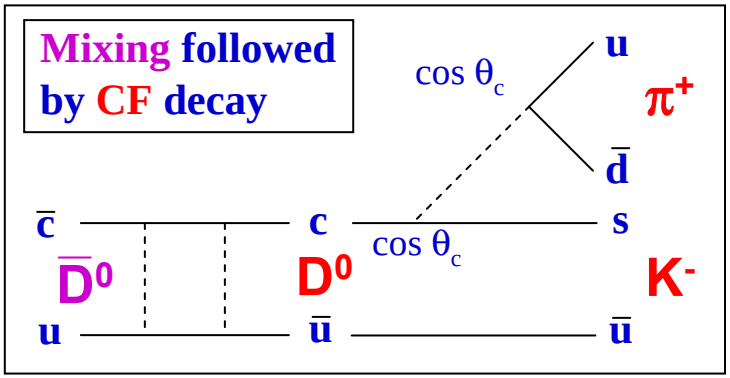
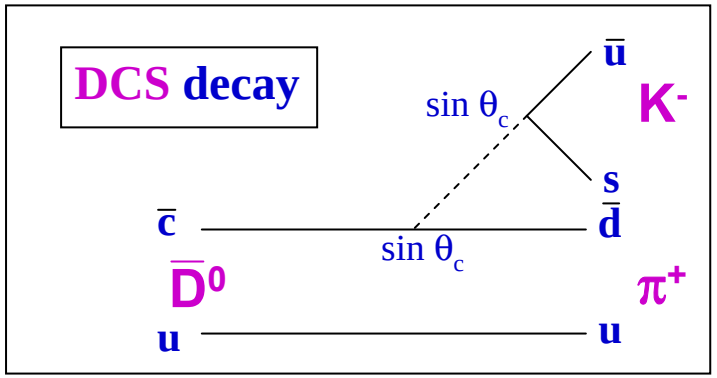
for

The Babar Collaboration

Moriond EW March 13, 2007

Mixing Formalism





- Right-sign (RS) CF decay
- Wrong-sign (WS) decays
  - mixing, DCS diagrams

- Mixing implies that the weak eigenstates are not pure flavor states

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle, \quad |p|^2 + |q|^2 = 1$$

- Charm mixing values typically quoted using scaled parameters *x*, *y*

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

$$\Gamma = \tfrac{1}{2}\left(\Gamma_2 + \Gamma_1\right)$$
$$\Delta M = M_2 - M_1$$
$$\Delta\Gamma = \Gamma_2 - \Gamma_1$$

Time Dependence of Mixed Final States

- For |x|, |y| << 1, time-dependence of a hadronic final state with mixing and DCS (R_D) amplitudes

$$\frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} = R_D + y'\sqrt{R_D}\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2$$

in the limit of no CP violation, and where

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \quad , \quad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

with $\delta_{K\pi}$ being the relative strong phase between DCS and CF amplitudes

- Time-integrated mixing rate

$$R_M = \frac{x^2 + y^2}{2} = \frac{x'^2 + y'^2}{2}$$

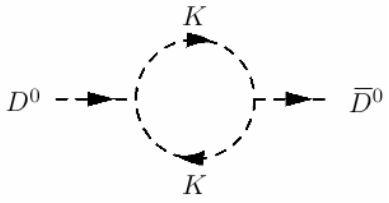
- If CP is not conserved, the time distribution for D^0 and $\bar{D}^0$ can differ

$$\frac{\Gamma^{\pm}_{WS}(t)}{e^{-\Gamma t}} = R^{\pm}_D + y'^{\pm}\sqrt{R^{\pm}_D}(\Gamma t) + \frac{x'^{\pm 2} + y'^{\pm 2}}{4}(\Gamma t)^2$$

Charm Mixing Predictions

Standard Model

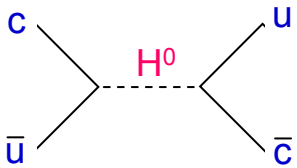
- Box diagram SM charm mixing rate naively expected to be very low ($R_M \sim 10^{-10}$) (Datta & Kumbhakar)
  - Z.Phys. C27, 515 (1985)
  - **CKM suppression → $|V_{ub}V^*_{cb}|^2$**
  - **GIM suppression → $(m^2_s - m^2_d)/m^2_W$**
  - Di-penguin mixing, $R_M \sim 10^{-10}$
    - **Phys. Rev. D 56, 1685 (1997)**
- Enhanced rate SM predictions generally due to long-distance ***y*** contributions:



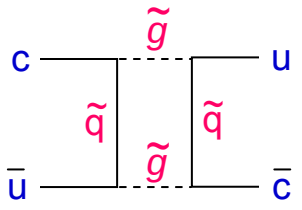
- Recent SM predictions can accommodate high mixing rate (Falk *et al.*)
  - ***x,y*** ≈ $\sin^2\theta_C$ x [SU(3) breaking]^2 ~1%
    - ***y***: Phys.Rev. D 65, 054034 (2002)
    - ***x***: Phys.Rev. D 69, 114021 (2004)

New Physics

- Possible enhancements to mixing due to new particles and interactions in new physics models
- Most new physics predictions for ***x***
  - Extended Higgs, tree-level FCNC
  - Fourth generation down-type quarks
  - Supersymmetry: gluinos, squarks
  - Lepto-quarks



FCNC



supersymmetry

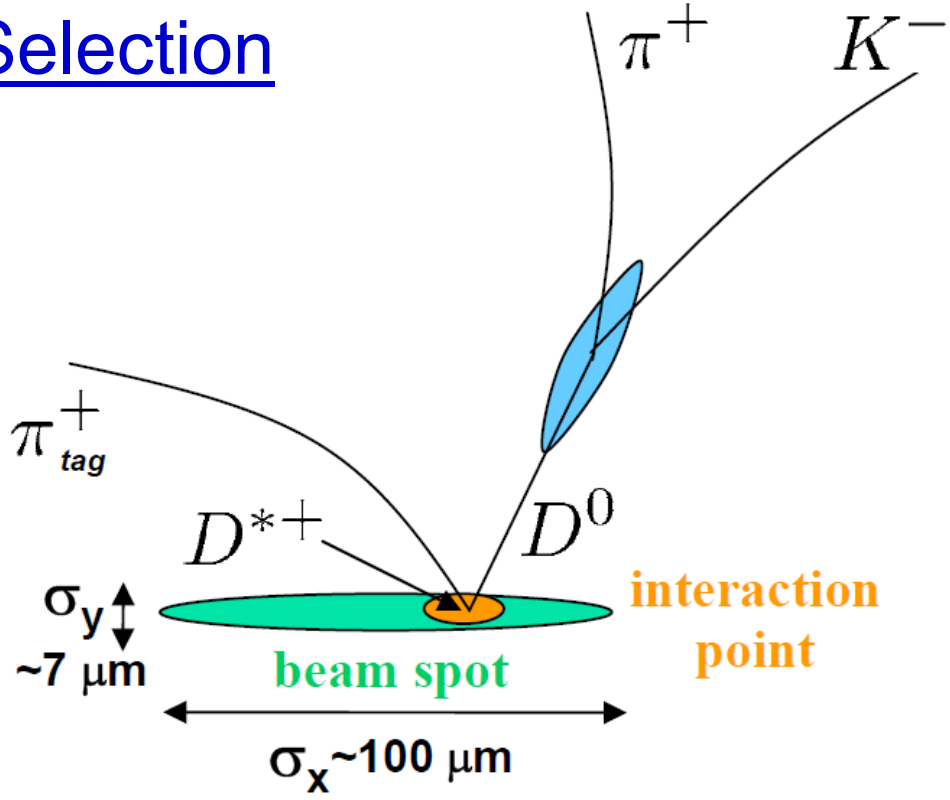
- Large possible SM contributions to mixing require observation of either a CP-violating signal or | ***x*** | >> | ***y*** | to establish presence of NP
  - Ann.Rev.Nucl.Part.Sci 53 431-499 (2003)

Mixing Analysis Strategy

- Blind analysis of $D^{*+} \rightarrow D^0(\rightarrow K^-\pi^+)\ \pi^+_{tag}$
  - **All event selection and fitting methodology determined before looking at the data**
- 384 fb^{-1} integrated luminosity, ~500 x 10^6 $c\bar{c}$ events
- Four-dimensional unbinned maximum likelihood fit
  - First, fit **M(Kπ)** vs **ΔM** [= $M(K\pi\pi_{tag}) - M(K\pi)$] distribution
  - Next, fix results of first fit and fit RS **decay time** and **per-event decay time error** using M(Kπ) and ΔM to separate backgrounds from signal
  - **High-statistics RS dataset determines WS signal PDFs**
    - **No MC dependence, all PDFs obtained from data**
  - Last, fit WS **decay time** and **per-event decay time error** to distinguish DCS and mixing contributions
- Several WS proper time fits
  - no mixing; mixing with/without CP violation allowed
  - extract x'^2, y', R_D from mixing fit

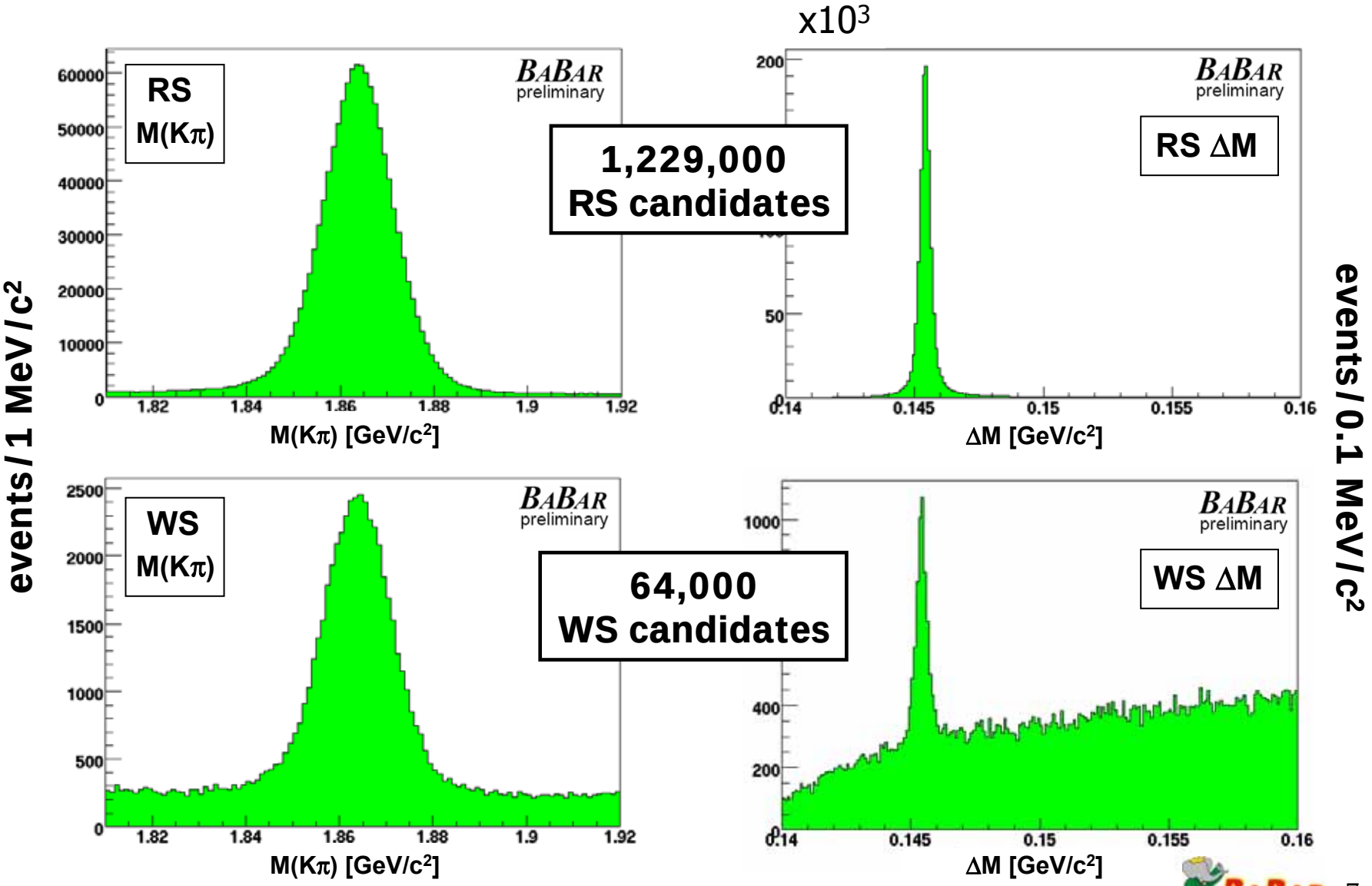
Event Selection

- Beam-constrained simultaneous fit of K, π, π_{tag} tracks
  - fit probability > 0.001
  - decay time error < 0.5 ps
  - -2 < decay time < 4 ps
- D^0 selection
  - CMS p* > 2.5 GeV/c
  - K, π particle identification
  - 1.81 < M(Kπ) < 1.92 GeV/c^2
- π_{tag} selection
  - CMS p* < 0.45 GeV/c
  - lab p > 0.1 GeV/c

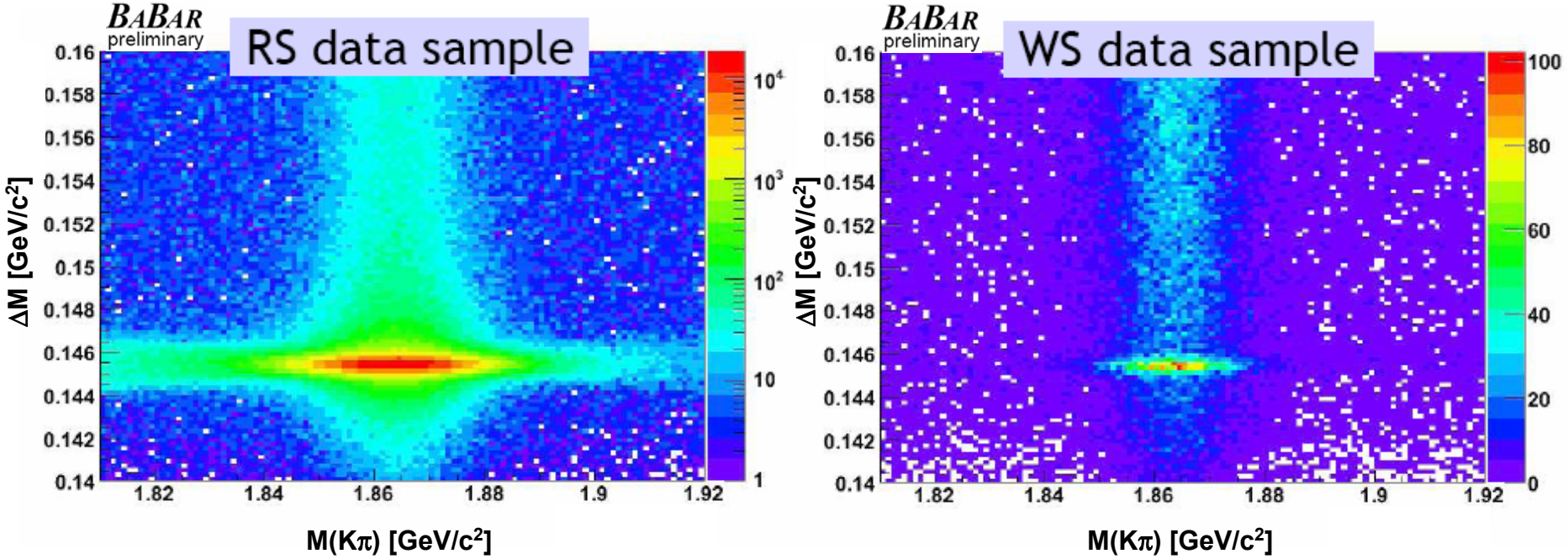


- 0.14 < ΔM < 0.16 GeV/c^2
- Select candidate with greatest fit probability for multiple D^{*+} candidates sharing tracks

RS and WS Datasets After Event Selection



RS and WS M(Kπ) vs ΔM Distributions



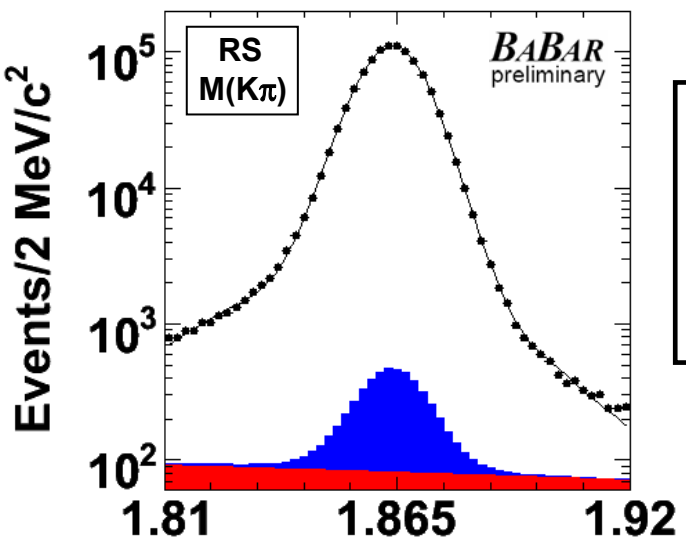
Correlation between M(Kπ) and ΔM in signal events taken into account in PDF

M(Kπ) vs ΔM Signal and Background Fit Categories

- RS categories
  - **Signal**: peaks in M(Kπ), ΔM
  - **Background true D^0 combined with random π_{tag}**: peaks in M(Kπ) only
  - **Misreconstructed D^0**: peaks in ΔM only
    - Semileptonic D^0 decays; singly misidentified $D^0 \to \pi^+\pi^-$, K^+K^-
  - **Purely combinatoric**: non-peaking

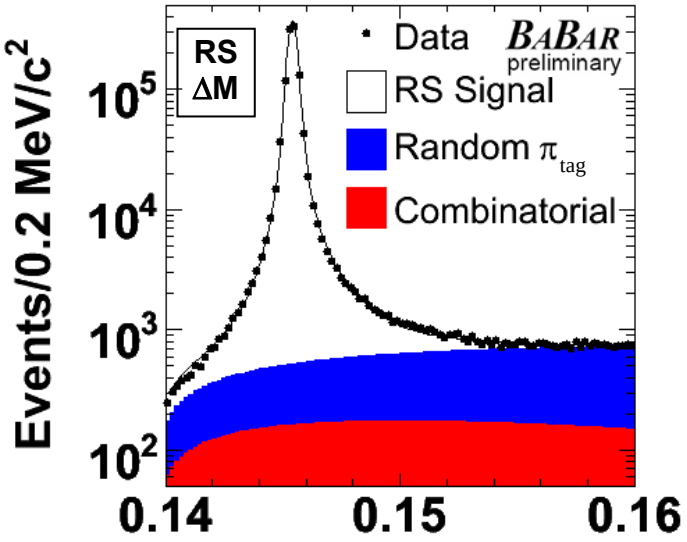
- WS categories
  - **Signal**: peaks in M(Kπ), ΔM
  - **Background true D^0 combined with random π_{tag}**: peaks in M(Kπ) only
  - **Misreconstructed D^0**: peaks in ΔM only
    - Doubly misidentified $D^0 \to K^-\pi^+$
    - Singly misidentified $D^0 \to \pi^+\pi^-$, K^+K^-
  - **Purely combinatoric**: non-peaking

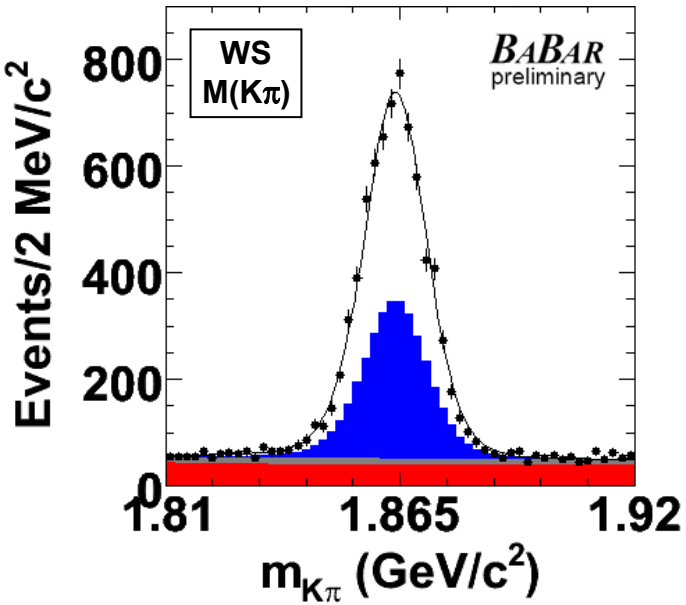
Simultaneous M(Kπ) vs ΔM Fit to RS and WS Data



RS signal

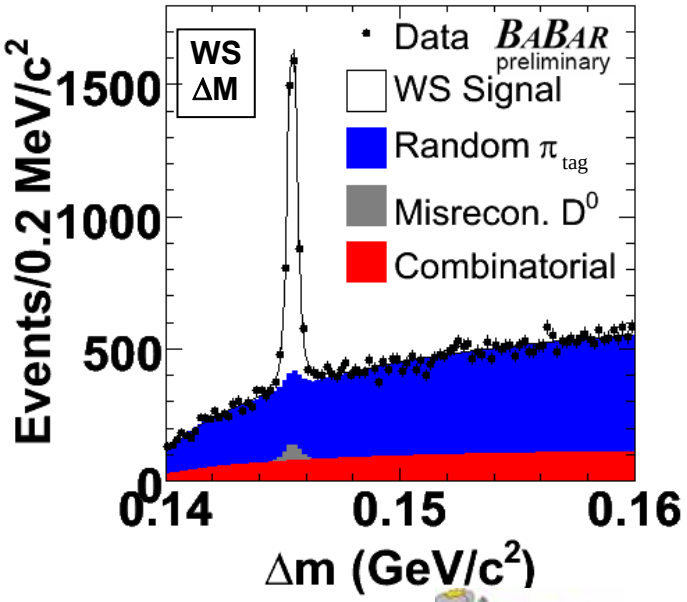
1,141,500 ± 1200 candidates





WS signal

4030 ± 90 candidates



Decay Time Analysis

- Fix M(Kπ) vs ΔM PDF shapes from results of first fit

- Fit RS decay time along with per-event errors to determine RS signal lifetime and resolution model
  - **Unmixed Signal, background true D^0 w/random π_{tag}**: Exponential PDF with sum of three Gaussians resolution model fit using per-event lifetime errors
  - **Random combinatoric**: Gaussian + Crystal Ball PDF

- Fix WS resolution to result of RS fit, then fit WS decay time and per-event error
  - **Mixed Signal**: theoretical mixed lifetime PDF convoluted with resolution model from RS fit
  - **DCS Kπ, misreconstructed D^0, background true D^0 w/random π_{tag}**: shares RS unmixed signal PDF
  - **Random combinatoric**: Gaussian + Crystal Ball PDF separate from RS fit

RS Decay Time Fit

- Fit to the full dataset with varied fit parameters:
  - Fit class normalizations
  - D^0 lifetime
  - Resolution model
  - Combinatoric shape

D^0 lifetime:

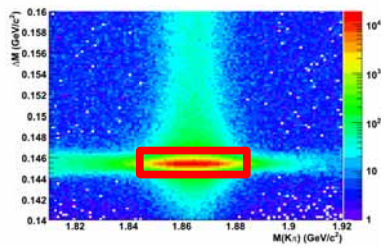
410.3 ± 0.6 (stat) fs

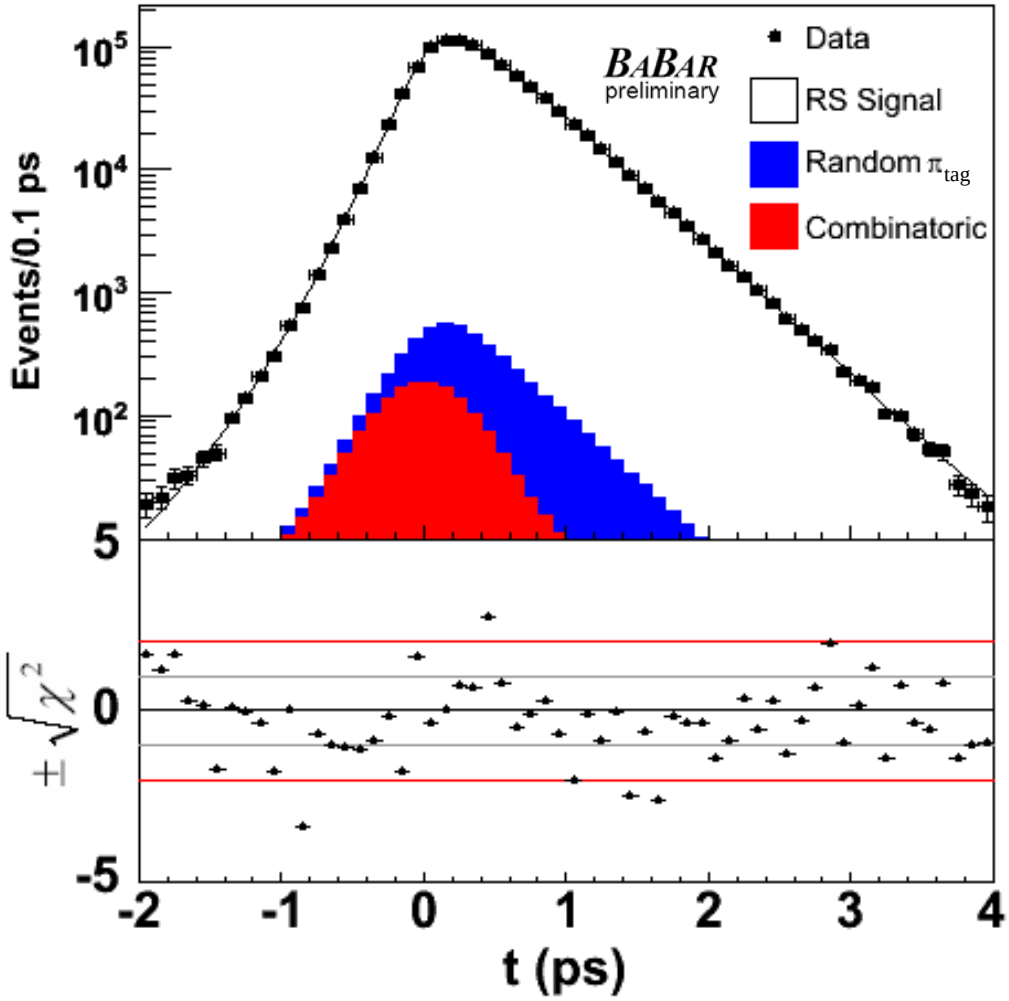
PDG 2006: 410.1 ± 1.5 fs

Decay time plot selection:

$1.843 < M(K\pi) < 1.883$ GeV/c^2

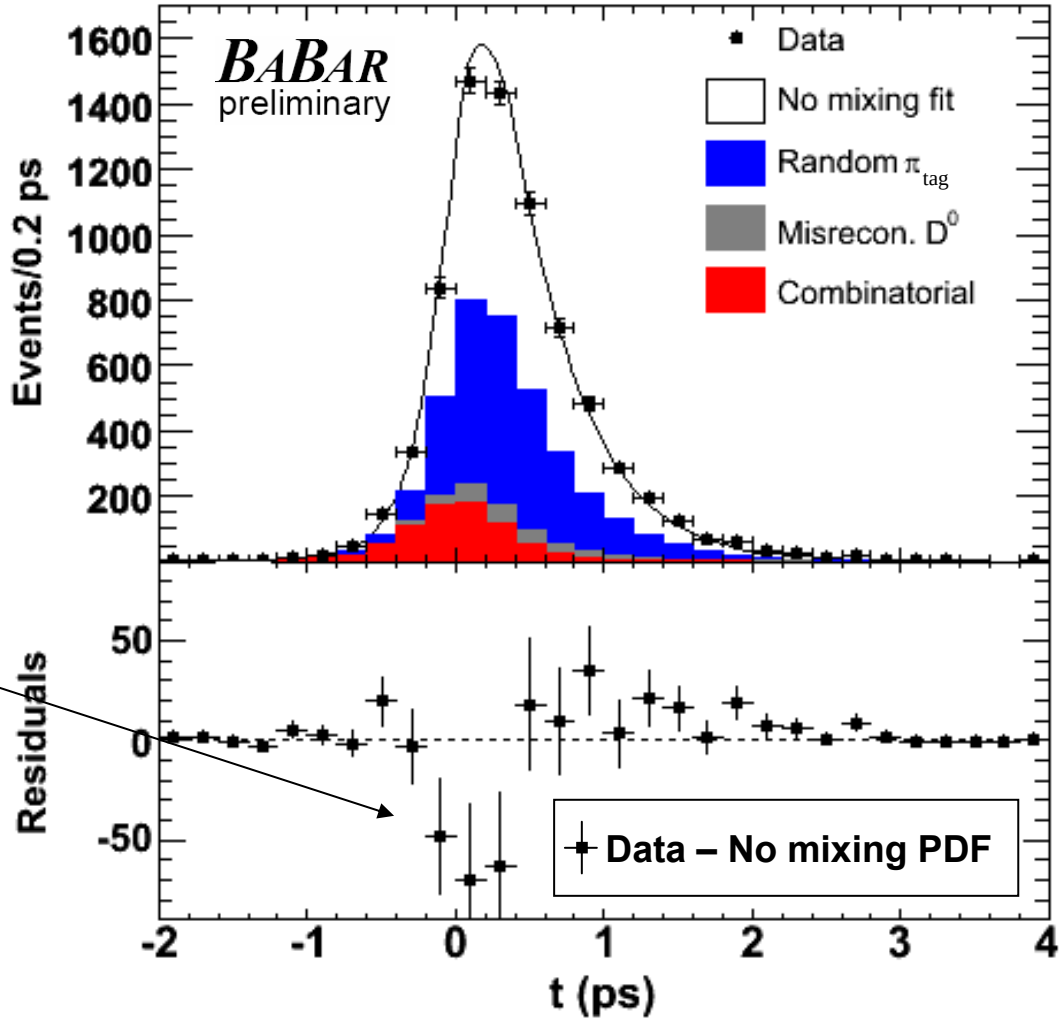
$0.1445 < \Delta M < 0.1465$ GeV/c^2





WS Decay Time Fit: Without Mixing PDF

- Fit to the full data-set with varied fit parameters:
  - Fit class normalizations
  - Combinatoric shape

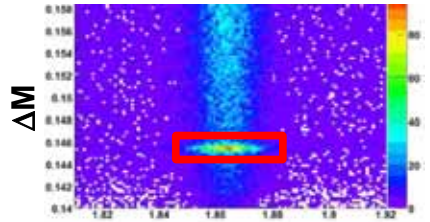


Poor residuals in signal region

Decay time plot selection:

$1.843 < M(K\pi) < 1.883$ GeV/c^2

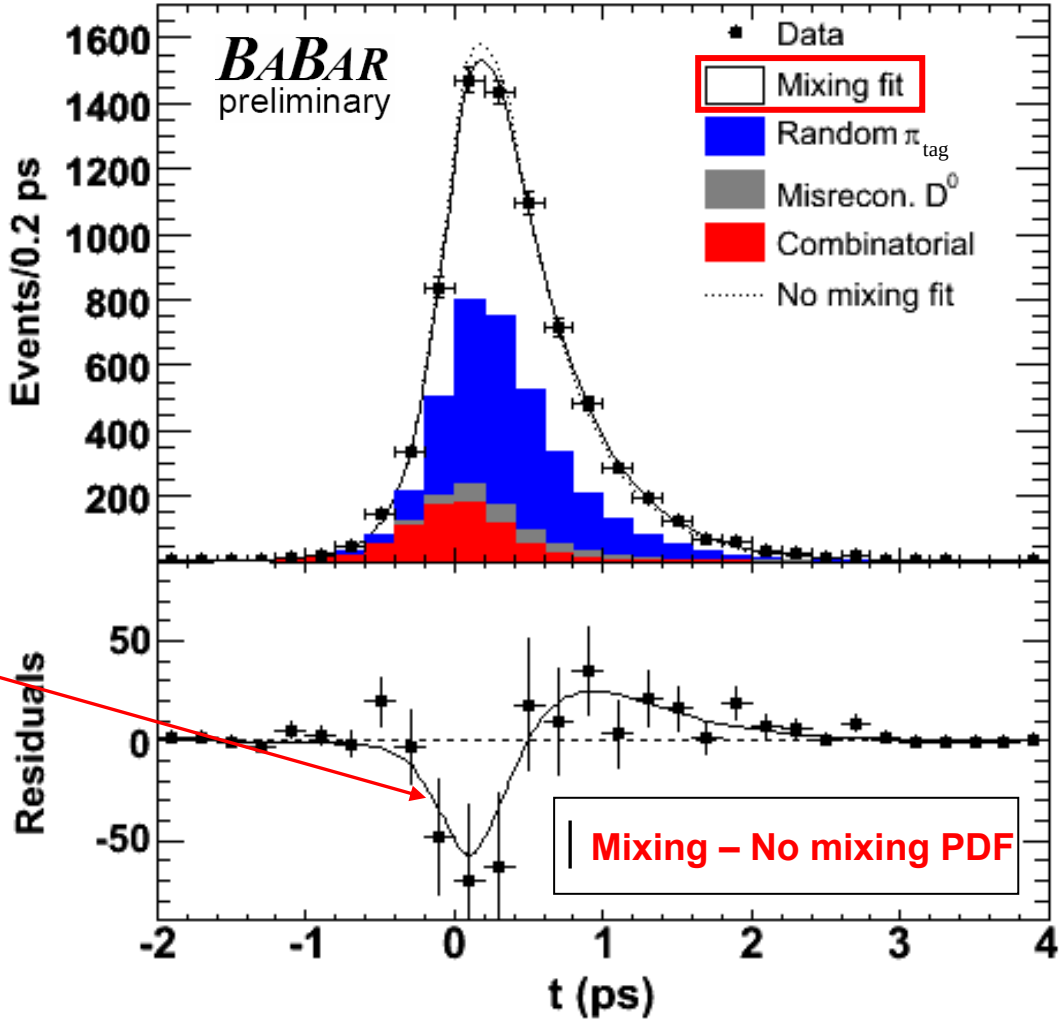
$0.1445 < \Delta M < 0.1465$ GeV/c^2



WS Decay Time Fit: With Mixing PDF

- Fit to the full data-set with varied fit parameters:
  - Fit class normalizations
  - Combinatoric shape
  - **Mixing parameters**

Mixing fit is better match to data



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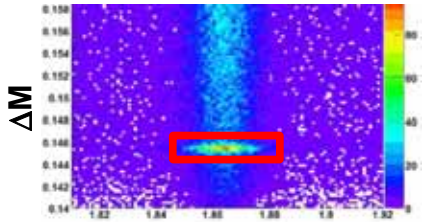
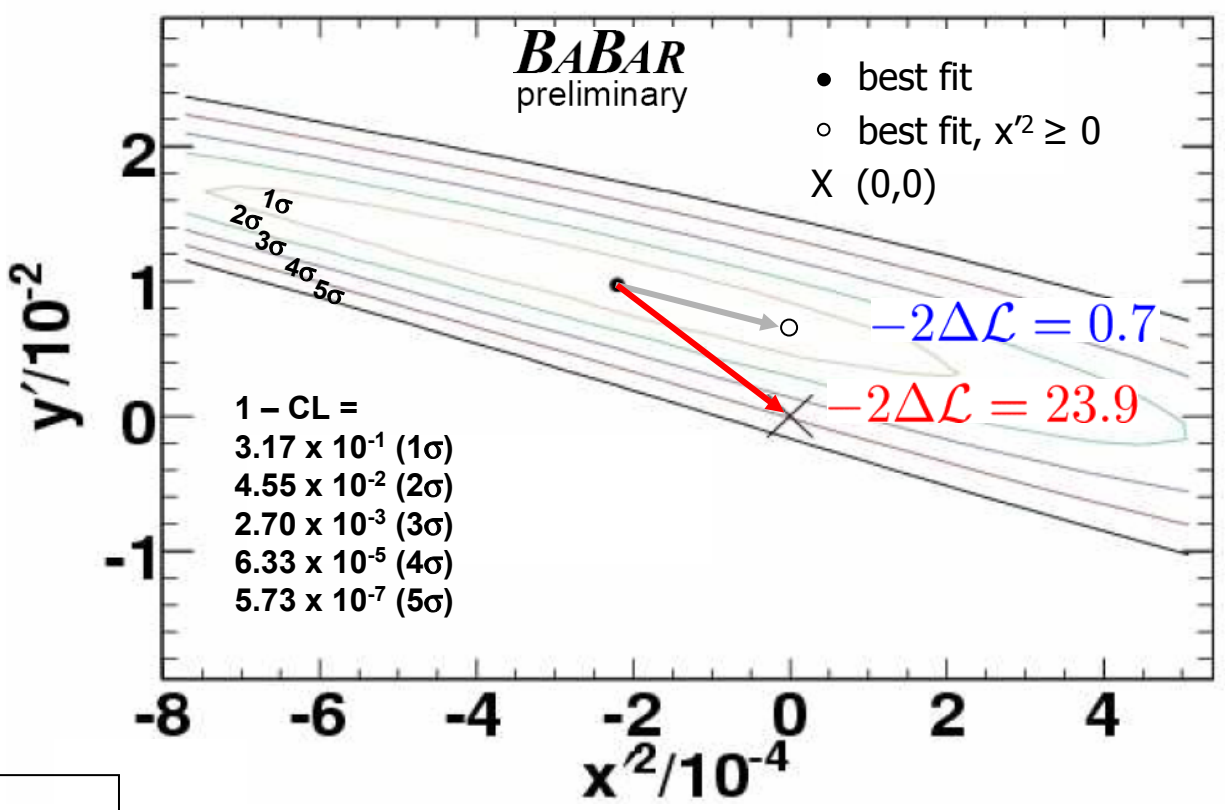


Mixing Contours

- y', x'^2 contours computed by change in log likelihood
  - Best-fit point is in non-physical region $x'^2 < 0$, but 1-sigma contour extends into physical region
  - correlation: -0.94
- Contours include systematic errors



- **Accounting for systematic errors, the no-mixing point is at ~4-sigma contour**

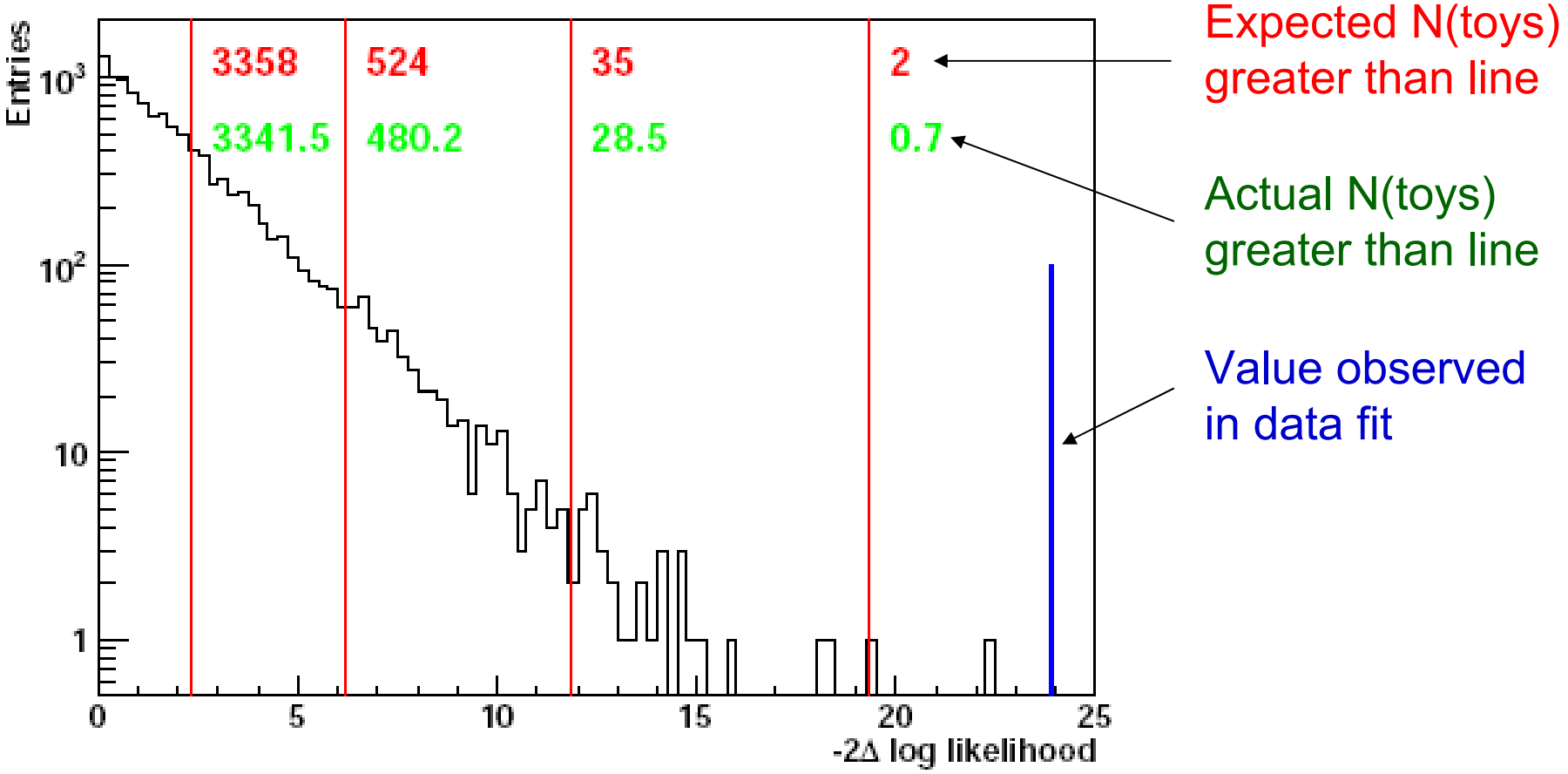
R_D: $(3.03 \pm 0.16 \pm 0.06) \times 10^{-3}$

x'^2: $(-0.22 \pm 0.30 \pm 0.20) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 2.9) \times 10^{-3}$

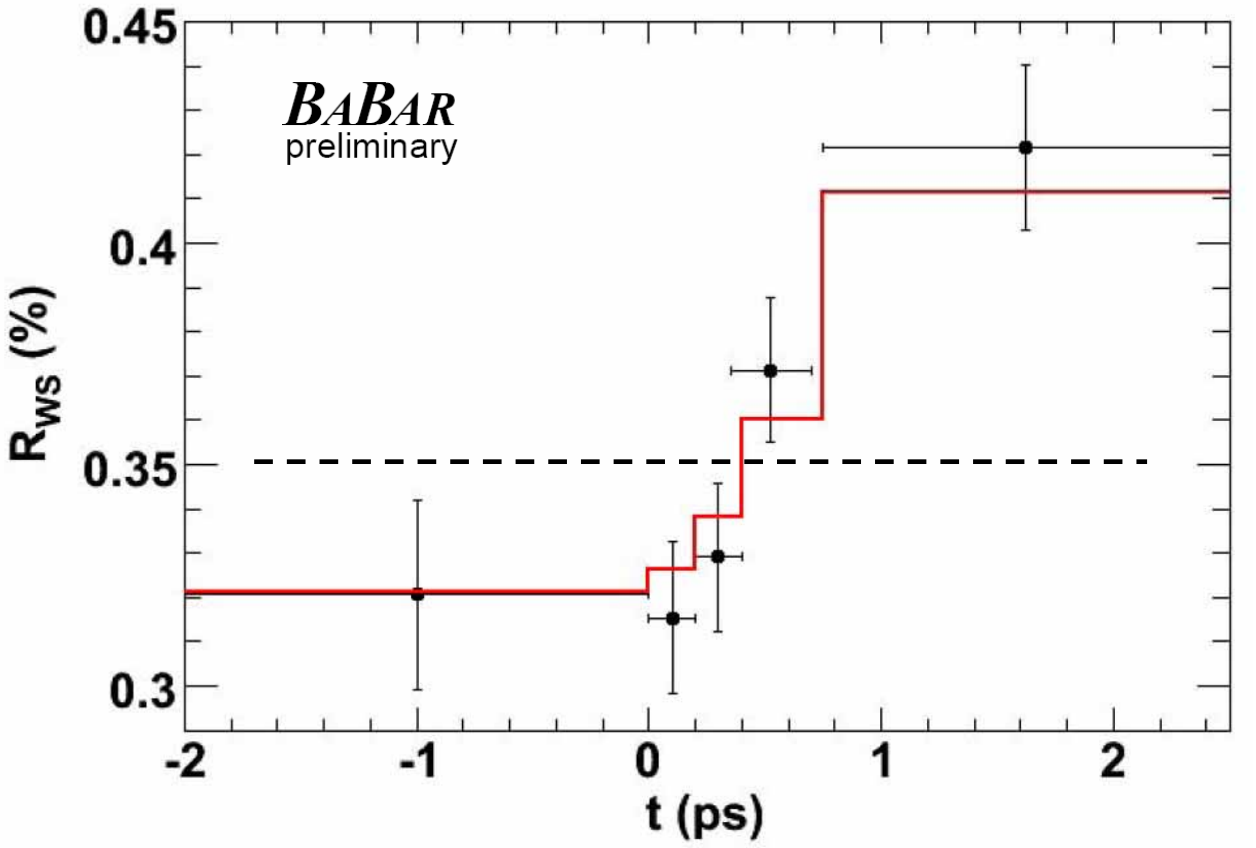
-2 Δ log L Frequentist Coverage

- Generated >10000 toys without mixing to test frequentist coverage



M(Kπ) vs ΔM Fits in Decay Time Bins

- Kinematic fit done independently in five decay time bins
  - Each bin has approximately the same number of RS candidates
- R_{WS} independent of any assumptions on resolution model



Prediction based on resolution and mixing parameters from full likelihood fit

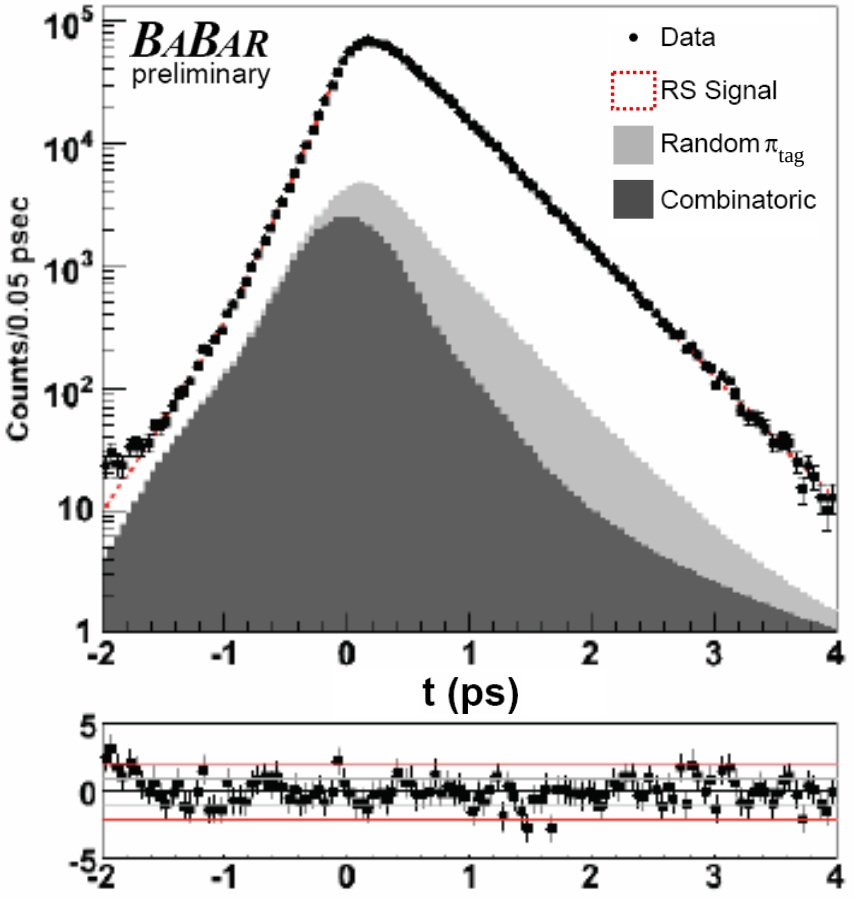
χ^2=1.5

Prediction from fit with no mixing

χ^2=24.0

Validation: Mixing Fit Using RS Data

- Perform mixing fit with RS data
  - No mixing signal expected
- $y' = (2.6 \pm 2.4) \times 10^{-4}$
- $x'^2 = (9.2 \pm 10.6) \times 10^{-6}$
- **$-2 (\log L_{mix} - \log L_{no\text{-}mix}) = 1.4$**
- **No mixing signal found**

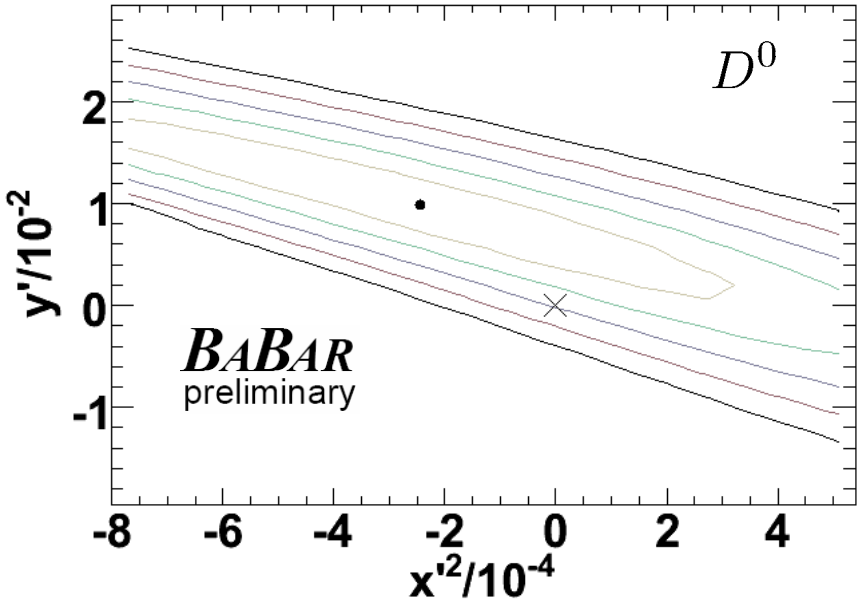


Mixing Contours: Mixing Fit Allowing CP Non-Conservation

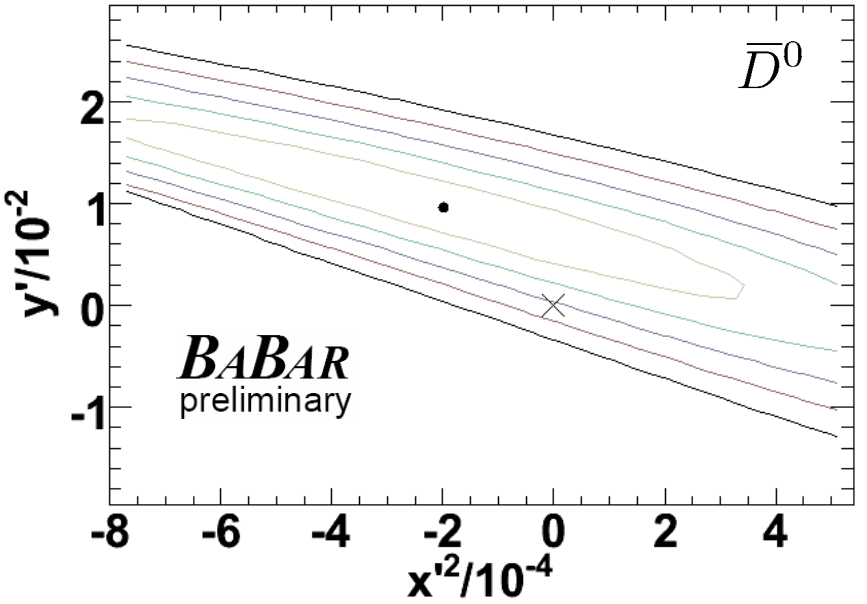
- Fit D^0 and $\bar{D}^0$ samples for mixing separately
  - Best fit in each case ~3 sigma from no-mixing hypothesis

No evidence for CP violation

$x'^{2+} = (-0.24 \pm 0.43 \pm 0.30) \times 10^{-3}$
$y'^{+} = (9.8 \pm 6.4 \pm 4.5) \times 10^{-3}$



$x'^{2+} = (-0.20 \pm 0.41 \pm 0.29) \times 10^{-3}$
$y'^{+} = (9.6 \pm 6.1 \pm 4.3) \times 10^{-3}$



Systematics

- Sources
  - Variations in functional form of signal and background PDFs
  - Variations in the fit parameters
  - Variations in the event selection
- Single parameter systematic estimates from difference between parameter value from fits with and without variation, expressed in units of statistical error

systematic source:	R_D	y'	x'^2
PDF:	0.59σ	0.45σ	0.40σ
selection criteria:	0.24σ	0.55σ	0.57σ
Quadrature total:	0.63σ	0.71σ	0.70σ

Summary

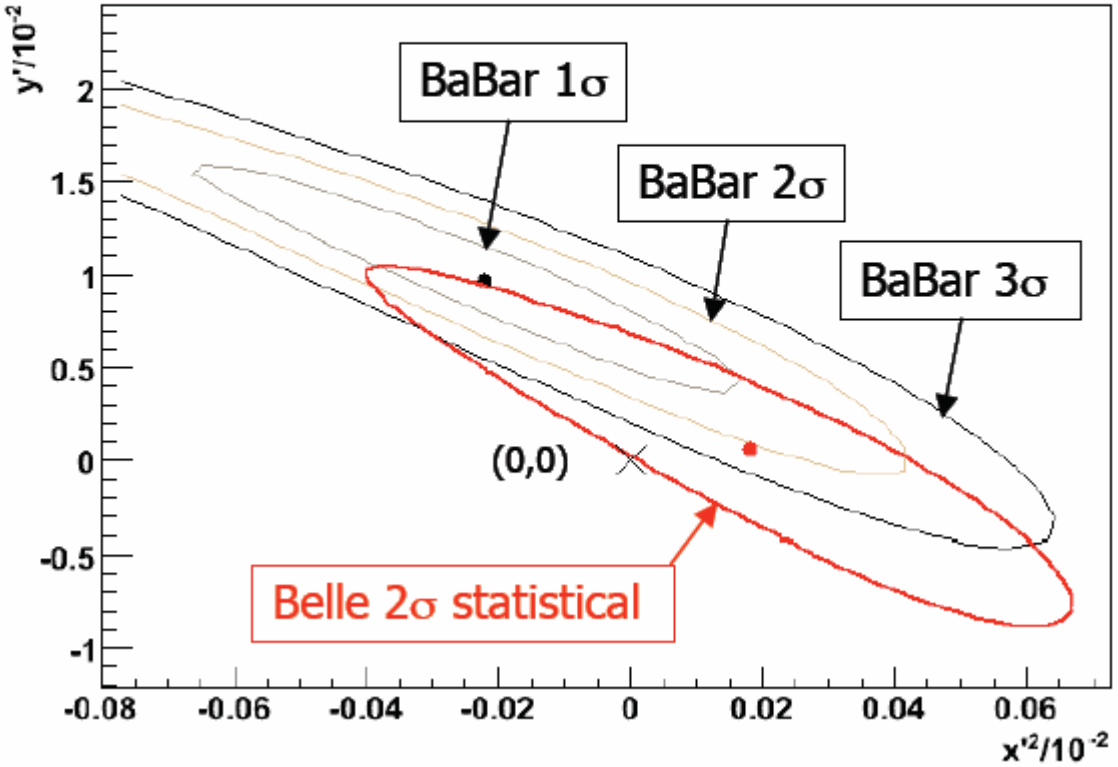
- Assuming CP conservation and including systematic effects, we find a charm mixing signal at ~4 sigma CL
  - **$y' = (9.7 \pm 4.4 \pm 2.7) \times 10^{-3}$**
  - **$x'^2 = (-0.22 \pm 0.30 \pm 0.20) \times 10^{-3}$**
- Submitted to PRL, hep-ex/0703020
- Strong phase ($\delta_{K\pi}$) introduces rotation of x,y into x',y'
  - If $\delta_{K\pi} \sim 0$, SM can likely accomodate the observed rate
  - If $\delta_{K\pi} \sim \pi/2$, then $|x| >> |y|$ and NP process may be more probable
- Results consistent with previous analyses
  - Babar Kπ, 2003: $(-56 < y' < 39) \times 10^{-3}$, $x' < 11 \times 10^{-3}$ (95% CL)
  - Belle Kπ, 2006: $(-28 < y' < 21) \times 10^{-3}$, $x' < 3.6 \times 10^{-3}$ (95% CL)
  - Assuming $\delta_{K\pi} \sim 0$, comparable with Babar and y_{CP} analyses
    - Belle, 2003: $y = (11.5 \pm 6.9 \pm 3.8) \times 10^{-3}$
    - Babar, 2003: $y = (9 \pm 4 \pm 5) \times 10^{-3}$
- No evidence for CP violation

Additional Slides

BaBar - Belle $K\pi$ mixing contour comparison

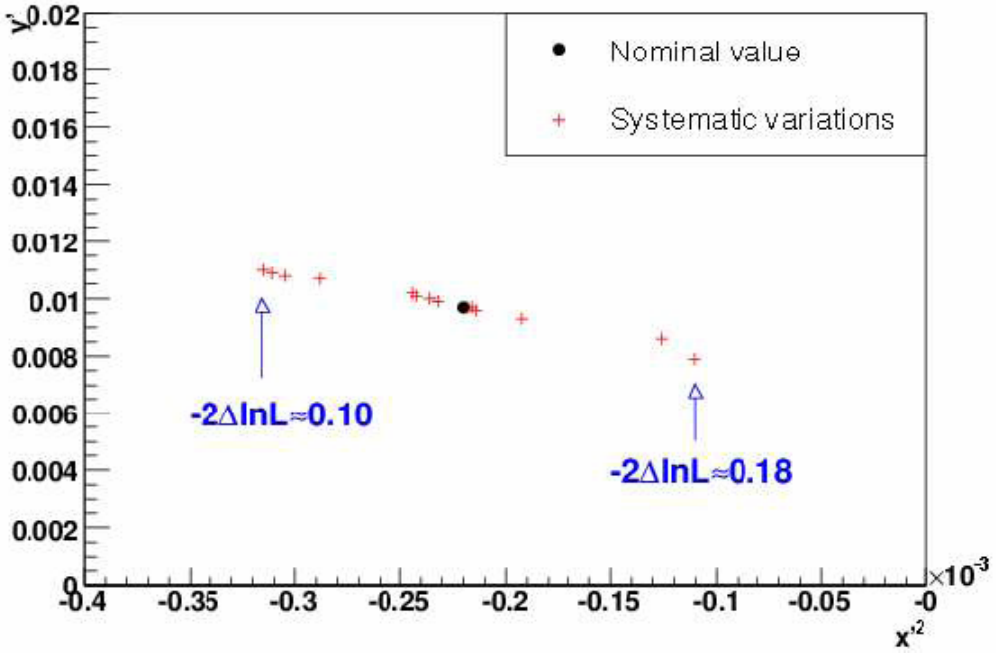
statistical contours from BaBar and Belle (400 fb^{-1})

best fit results are within 2σ (statistical)



Including Systematics in Contours

Systematic variations produce new mixing parameters sets
- tend to scatter along correlation axis:



Included in contours as follows:
- for each variation calculate change in likelihood between new and old point in old likelihood

$m_i^2=(-2\Delta\ln L)/2.3$ ← 1σ in 2D

- Scale likelihood with $\frac{1}{1+\sum m_i^2}$
- Should correspond to scaling the statistical uncertainty up

CPV systematics use same scale factor plus tiny correction for charge asymmetry in efficiency

Accounting for systematic errors in contours

- Sources
  - variations in functional form of signal and background terms
  - variations in the parameters
  - variations in proper time, proper time error and D* overlap removal criteria
- (x'2,y) contours:
  - for each variation, compute $s_i^2 = 2\left[\ln \mathcal{L}_0 - \ln \mathcal{L}_i\right]/2.3$ where $\mathcal{L}_0$ is the maximum likelihood from the standard fit and $\mathcal{L}_i$ is the likelihood from the standard fit with (x'^2_i, y'_i) fixed to the values obtained from the fit with the i^{th} variation
    - PDF variations: $\Sigma s_i^2 = .12$
    - selection criteria: $\Sigma s_i^2 = .18$
    - total: $\Sigma s_i^2 = .30$
  - divide change in $-2\log\mathcal{L}$ by the factor $f = 1 + \Sigma s_i^2 = 1.30$ to account for systematic errors

Final Systematics

fit:	y' ($\times 10^{-2}$)	$\delta_{y'}$	R_M ($\times 10^{-4}$)	δR_M^{corr}	m^2
default fit:	0.97 ± 0.44	-	-0.63 ± 1.07	-	-
No offset in core resolution:	1.10 ± 0.44	$+0.30\sigma$	-0.97 ± 1.06	-0.33σ	0.045
offset in all resolution Gaussians:	0.97 ± 0.44	-0.01σ	-0.61 ± 1.07	$+0.02\sigma$	0.000
Proper time error distributions from sidebands, not sPlot:	1.01 ± 0.44	$+0.09\sigma$	-0.70 ± 1.07	-0.07σ	0.003
widest core Gaussian without per-event errors:	0.96 ± 0.44	-0.02σ	-0.61 ± 1.07	$+0.02\sigma$	0.001
Fix scale factor $s_1 = 1$:	0.93 ± 0.44	-0.09σ	-0.53 ± 1.08	$+0.10\sigma$	0.004
Fix D^0 lifetime to PDG value:	0.97 ± 0.44	-0.00σ	-0.62 ± 1.07	$+0.01\sigma$	0.001
Change Category 3 Model:	0.96 ± 0.44	-0.05σ	-0.61 ± 1.07	$+0.02\sigma$	0.003
Cat.4 $t$from low sideband:	0.85 ± 0.43	-0.28σ	-0.46 ± 1.06	$+0.16\sigma$	0.060
Cat.4 $t$from high sideband:	1.01 ± 0.44	$+0.08\sigma$	-0.65 ± 1.07	-0.02σ	0.011
Vary $\{m_{K\pi}, \Delta m\}$ fit model:	1.00 ± 0.44	$+0.06\sigma$	-0.68 ± 1.07	-0.05σ	0.002
Vary $\{m_{K\pi}, \Delta m\}$ parameters:	1.02 ± 0.44	$+0.10\sigma$	-0.70 ± 1.06	-0.07σ	0.007
$(-1 < t < 3.5)$ ps:	0.86 ± 0.44	-0.26σ	-0.26 ± 1.10	$+0.34\sigma$	0.061
$(-5 < t < 10)$ ps:	1.08 ± 0.44	$+0.24\sigma$	-0.94 ± 1.05	-0.30σ	0.039
$(\delta_t < 0.4)$ ps	1.07 ± 0.45	$+0.23\sigma$	-0.87 ± 1.07	-0.22σ	0.023
$(\delta_t < 0.6)$ ps	0.79 ± 0.43	-0.41σ	-0.27 ± 1.07	$+0.34\sigma$	0.077
Keep all overlapping candidates	0.99 ± 0.44	$+0.05\sigma$	-0.67 ± 1.06	-0.04σ	0.002
Remove all overlapping candidates	1.09 ± 0.45	$+0.27\sigma$	-0.96 ± 1.07	-0.31σ	0.042
Total variation:		0.71σ		0.70σ	0.306

Systematics summary:

systematic source:	R_D	y'	x'^2
PDF:	0.59σ	0.45σ	0.40σ
selection criteria:	0.24σ	0.55σ	0.57σ
Quadrature total:	0.63σ	0.71σ	0.70σ

Validation: fit to generic Monte Carlo

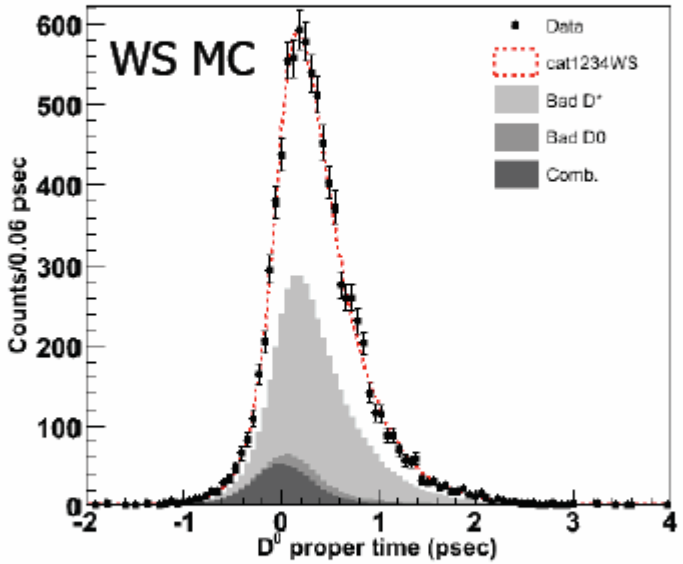
- repeat fitting procedure on R18b generic Monte Carlo sample (~400 fb^{-1})
  - WS mixing fit results:

$y' = (-0.22 \pm 0.30)\%$

$x'^2 = (2 \pm 18) \times 10^{-5}$

$R_D = (0.413 \pm 0.014)\%$

- MC generated without mixing
- No mixing is observed
- R_D consistent with dialed value



plot selection:
$1.845 < m < 1.885$ GeV/c^2
$0.1445 < \Delta m < 0.1465$ GeV/c^2

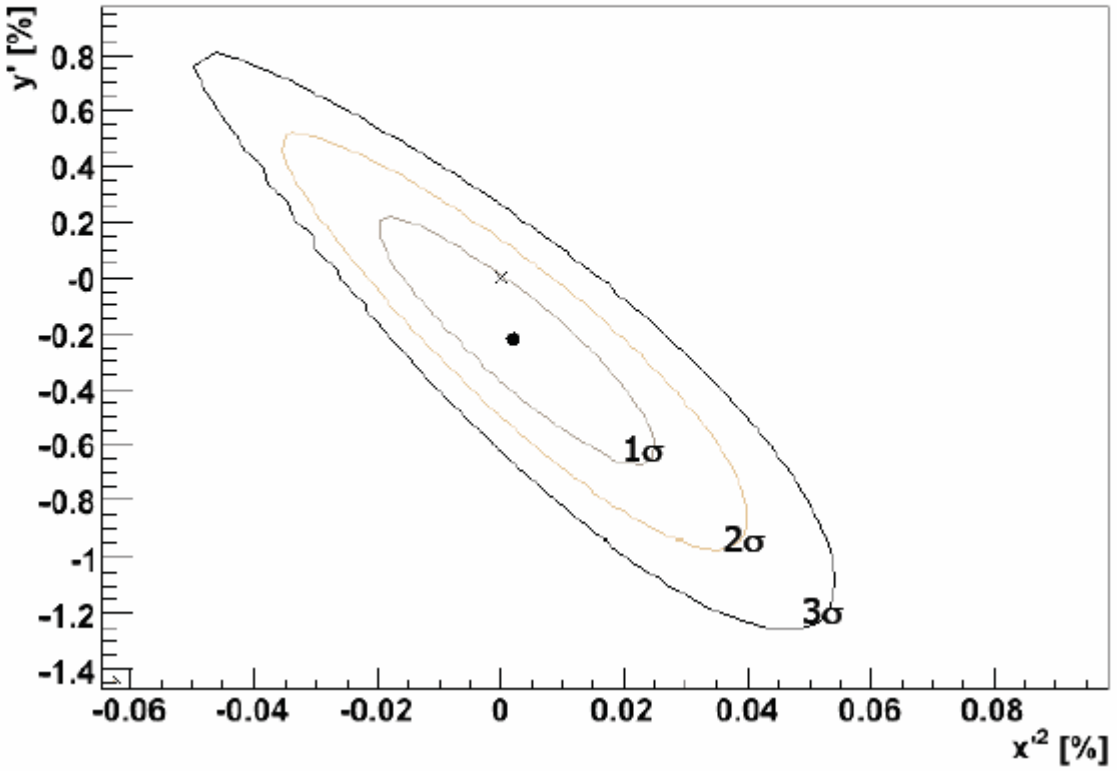
Validation: generic MC mixing contour

display of statistical contours from R18b generic Monte Carlo (~400 fb^{-1})

$x'^2 = (2.0 \pm 18)\times10^{-5}$
$y' = (-2.2 \pm 3.0)\times10^{-3}$

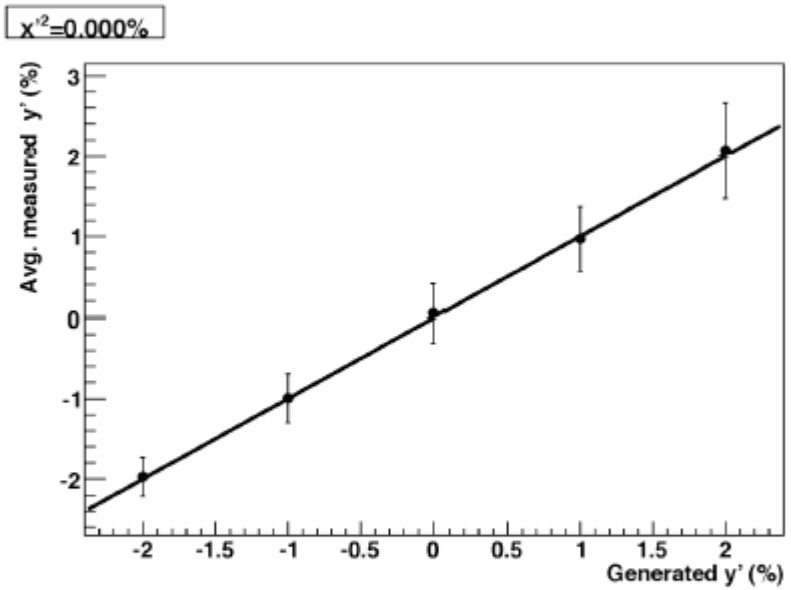
(0,0) point on the 1σ contour

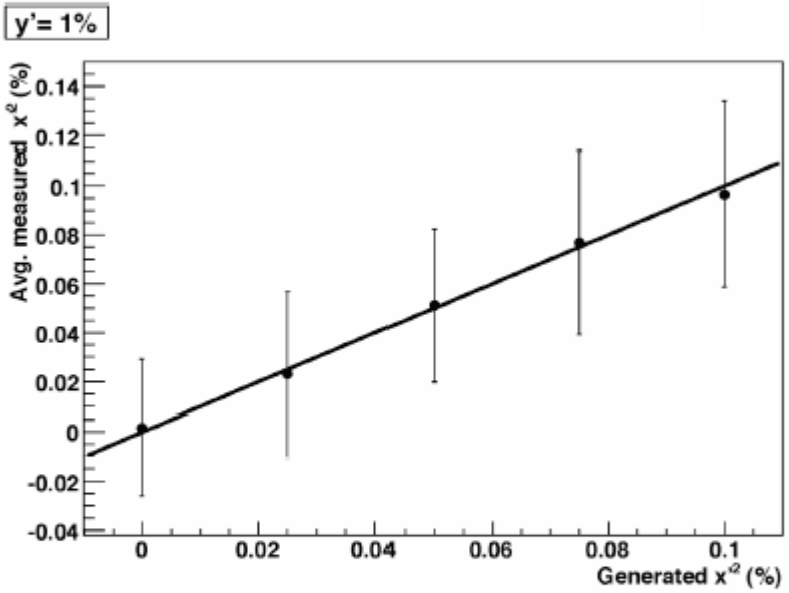
No evidence for a false mixing signal seen in MC (generated without mixing)



Validation: Toy studies

- test for unbiasedness:



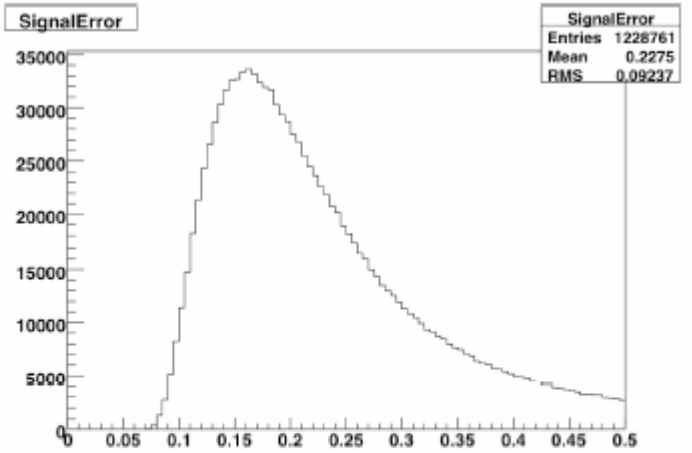


average fitted value of mixing parameter versus generated value.
Error bars: RMS of fitted values: expected parameter errors
Straight line has unit slope, 0 intercept.

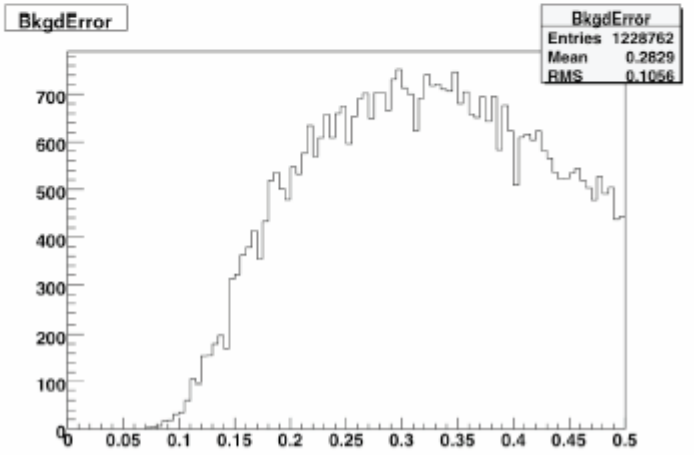
Results indicate no bias in estimating mixing parameters

R18b data decay time error distributions

category 1-3 DecayTimeError sPlot:



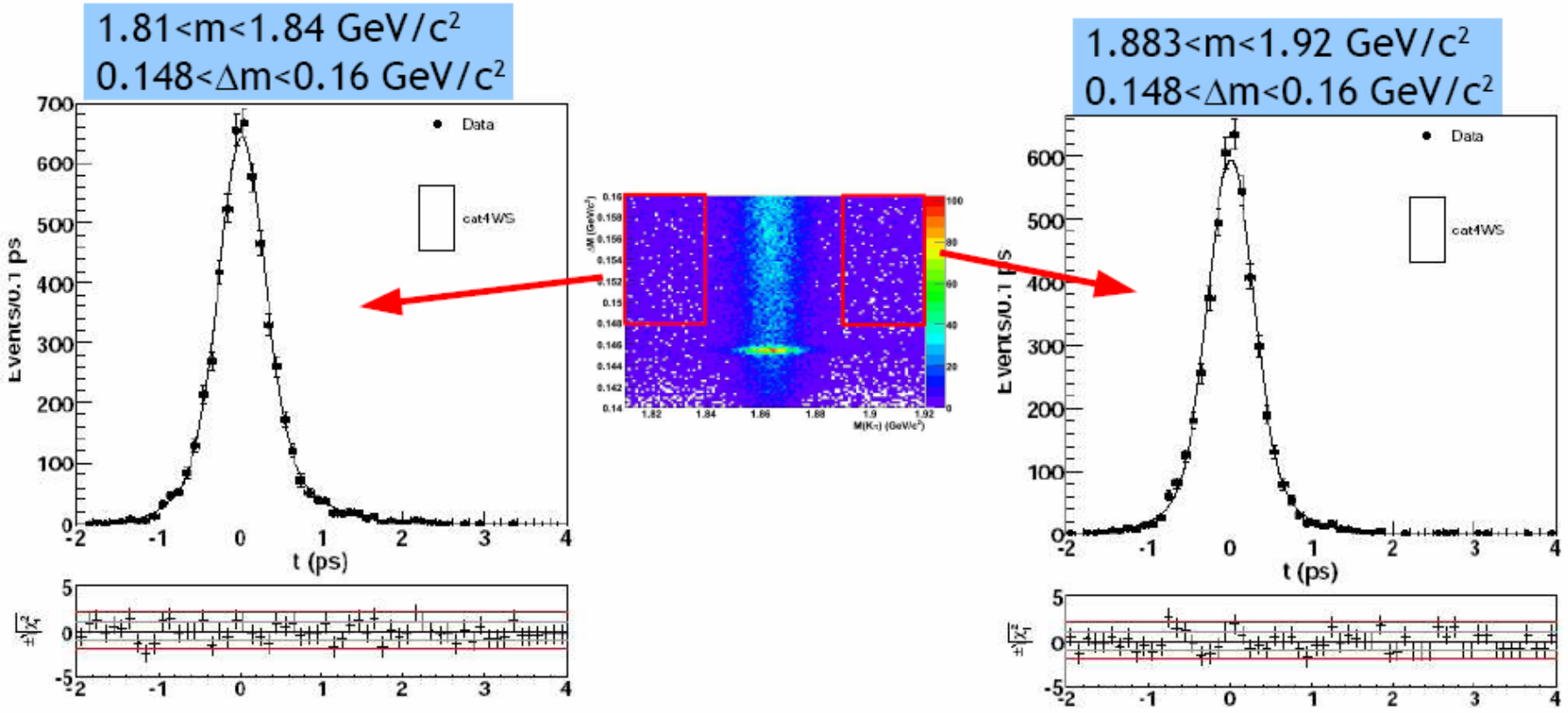
category 4 DecayTimeError sPlot:



Proper Time from Sidebands

Assigning systematic

Instead of fitting proper time for background in full fit, fix it to fits in pure background sidebands:



Time Dependence of Mixed Final States: CP Violation

- Define CP violating observables $\longrightarrow$ $A_{D,M} = \dfrac{R^+_{D,M} - R^-_{D,M}}{R^+_{D,M} + R^-_{D,M}}$
- Direct CP violation in DCS Decay $\longrightarrow$ $R^+_D \neq R^-_D$
- CP violation in mixing $\longrightarrow$ $\left|\dfrac{q}{p}\right| \neq 1 \quad \left[= 1 + A_M\right]$
- CP violation in interference between decay and mixing: $\longrightarrow$ $\cos\phi \neq 1$
- Rewrite time dependence to explicitly include asymmetries

$$\frac{\Gamma^{\pm}_{WS}(t)}{e^{-\Gamma t}} = \sqrt{\frac{1 \pm A_D}{1 \mp A_D}} R_D + \sqrt{R_D} \sqrt[4]{\frac{(1 \pm A_D)(1 \pm A_M)}{(1 \mp A_D)(1 \mp A_M)}} (y' \cos\phi \mp x' \sin\phi)(\Gamma t) + \sqrt{\frac{1 \pm A_M}{1 \mp A_M}} \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$