

Search for Charm Mixing Using Semileptonic Decays at Babar

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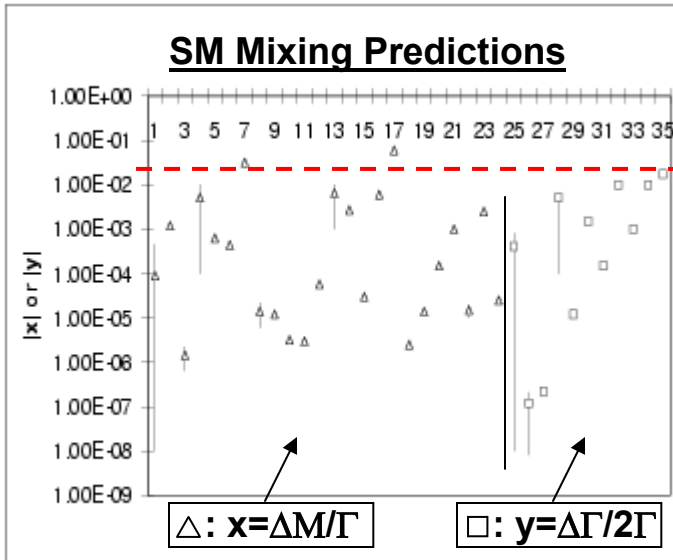
Outline

- Charm mixing rate predictions and mixed event time-dependence
- Analysis methodology
- Event selection and reconstruction
- Unmixed/mixed fits
- Summary

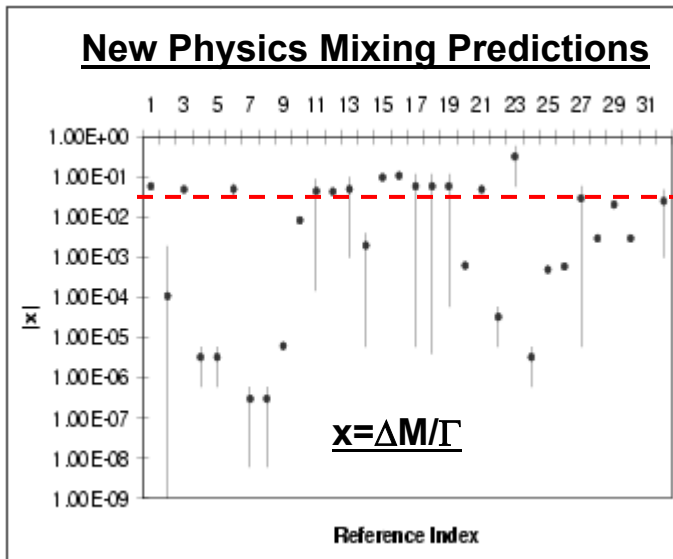


Charm Mixing Rate Predictions

mixing rate = $|\text{amplitude}|^2$



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current experimental sensitivity

- Box diagram SM charm mixing rate naively expected to be very low ($R_{\text{mix}} \sim 10^{-10}$)
- Enhanced mixing rates possible in many SM scenarios
- More possible enhancements due to new physics:
 - gluinos, squarks
 - fourth generation quarks
 - lepto-quarks, etc.
- No CP-violating effects expected in SM – CP violation observation would be unambiguous signal of new physics



(Plots courtesy of A. Petrov, [hep-ph 0311271](https://arxiv.org/abs/hep-ph/0311271))



Semileptonic Mixed Event Time-Dependence

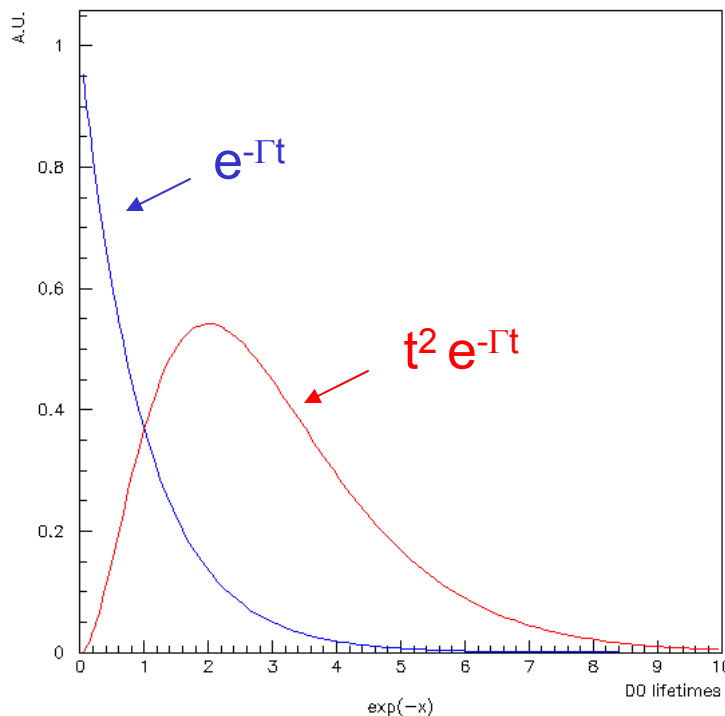
- In the limit of small mixing and no CP violation, mixed D^0 states decaying semileptonically have a simple time-dependence
- Analogous to the second-order term of the Taylor expansion of $1-\cos(\Delta Mt)$ in B-mixing

- time-integrated semileptonic mixing rate

$$R_{mix} \approx \frac{x^2 + y^2}{2}$$

$$\Gamma_{WS}(t) \approx \left[\exp\left(-\frac{t}{\tau_{D^0}}\right) \right] \left(\frac{t}{\tau_{D^0}} \right)^2 \left(\frac{x^2 + y^2}{4} \right)$$

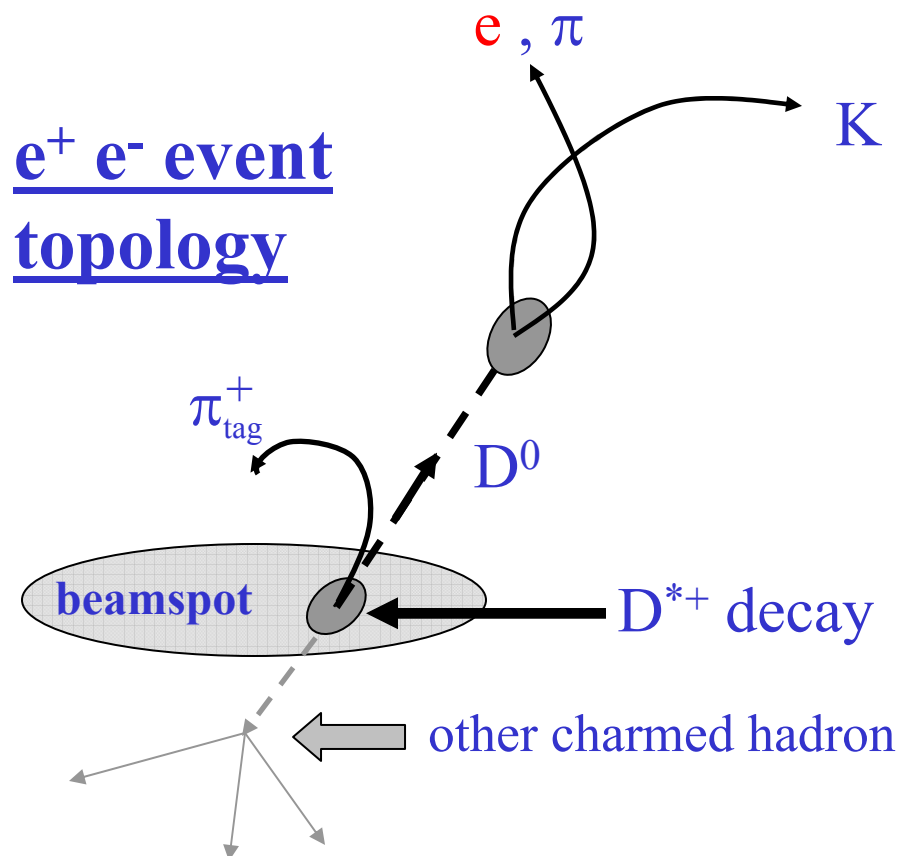
↑ exponential envelope
 ↑ quadratic time dependence
 ↑ mixing rate



Outline of Analysis Methodology

- Signal modes: $D^{*+} \rightarrow D^0 \pi_{\text{tag}}^+ (+ \text{c.c.})$
 $\hookrightarrow (K/K^*) e \nu$ (e^+ : RS unmixed D^0)
(e^- : WS mixed D^0)

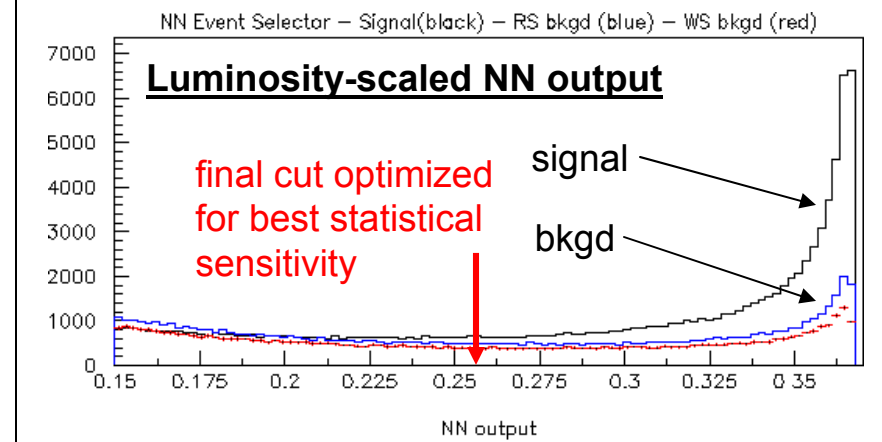
- Blind analysis on 87-fb^{-1} Babar dataset (Runs 1-2)
- Neural network event selection
- Neural network $p^*(D^0)$ reconstruction
- 2-d unbinned extended maximum likelihood fit:
 - $\Delta M = M(D^{*+}) - M(D^0)$
 - transverse lifetime
- Initial fit to high-statistics RS sample to obtain signal pdf
- Subsequent fit to WS sample for $N(\text{mix})$
- $R(\text{mix}) \approx N(\text{mix}) / N(\text{unmix})$



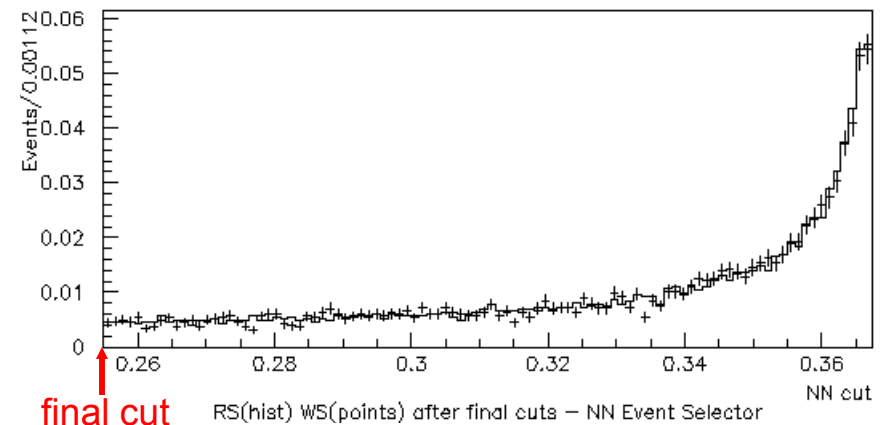
Neural Network Event Selection

- Events are selected using a **neural network** with the following inputs taken from signal and generic MC:
 - $p^*(K/e \text{ vertex})$
 - $p^*(\pi)$
 - thrust magnitude (w/o K, e)
 - Opening angle between $p^*(K/e)$ and thrust (w/o K, e)
 - opening angle between $p^*(K)$ and $p^*(e)$

• RS/WS signal/bkgd NN event selector output



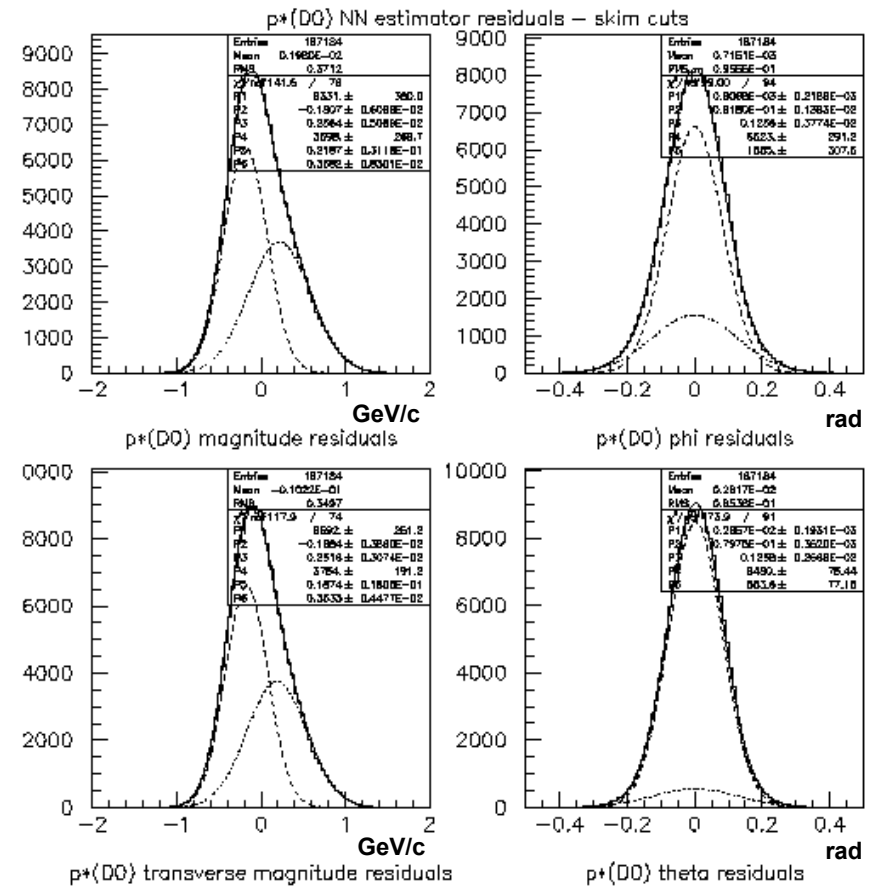
• Identical RS/WS signal selection efficiencies



Neural Network D^0 Reconstruction

- Two hidden-layer neural network
- ΔM distribution ~ 3 MeV FWHM
- Momentum **resolution** fit to double gssn
 - **phi** core sigma/fraction: **82 mrad** / 0.81
 - **theta** core sigma/fraction: **80 mrad** / 0.94
 - **transverse magnitude** RMS: **350 MeV/c**
 - **total magnitude** RMS: **370 MeV/c**
- Trained with inputs from signal MC:
 - $\vec{p}^*(K/e \text{ vertex})$
 - $\vec{p}^*(\pi)$
 - thrust vector (w/o K, e)
 - opening angle between $\vec{p}^*(K/e)$ and thrust (w/o K,e)
 - opening angle between $\vec{p}^*(\pi)$ and thrust (w/o K,e)
 - opening angle between $\vec{p}^*(K)$ and $\vec{p}^*(e)$
 - opening angle between $\vec{p}^*(K/e)$ and $\vec{p}^*(\pi)$

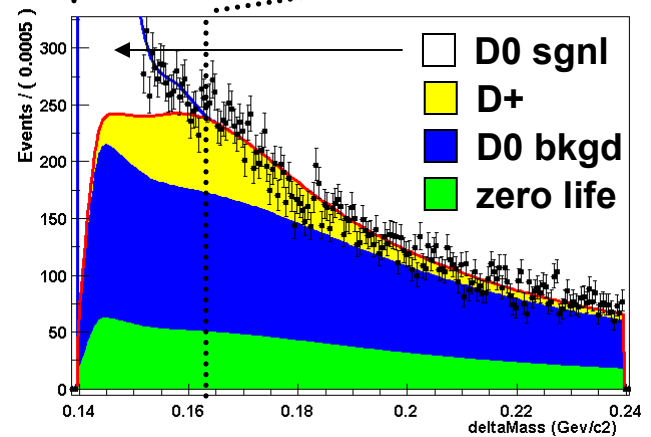
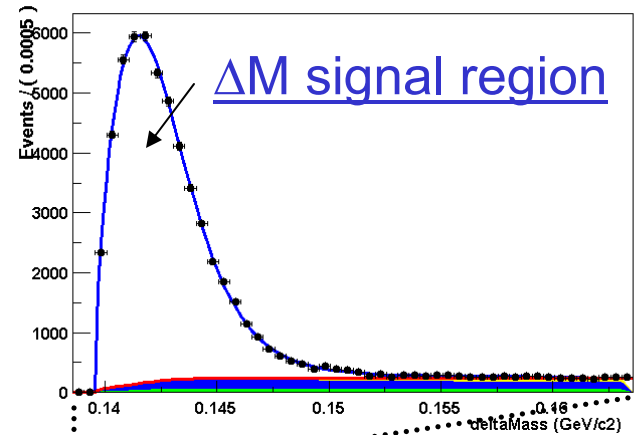
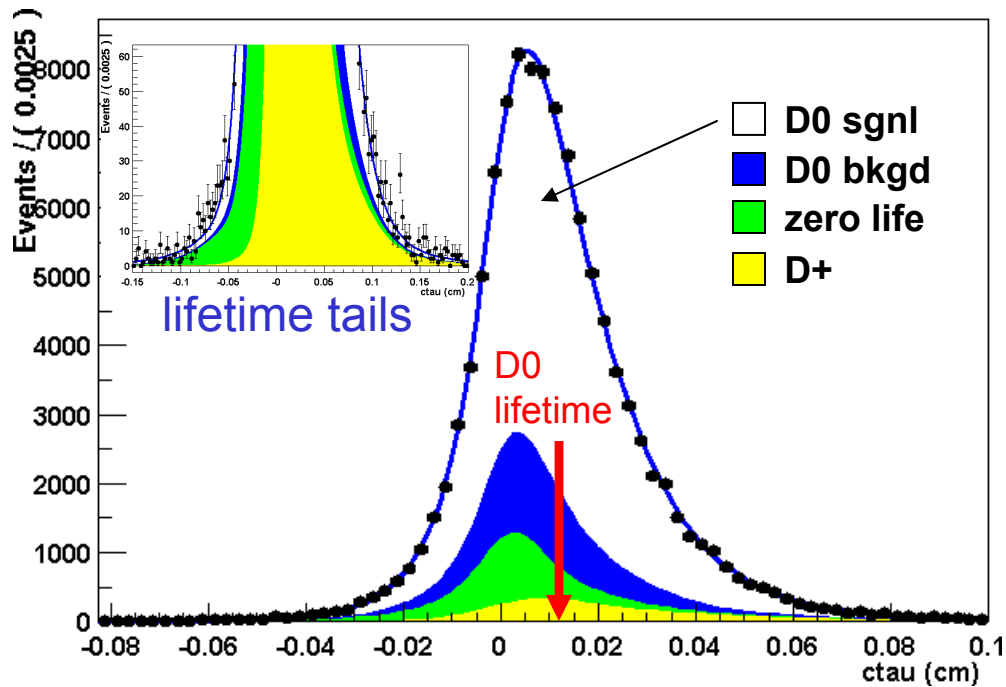
$p^*(D^0)$ Neural Network Residuals



BABAR

RS Unmixed Fit to Run 1,2 Data

- Unbinned extended maximum likelihood fit to transverse **lifetime** and $\Delta M = M(D^*) - M(D^0)$ with 15 floated parameters
- Unmixed D^0 yield: **49620 ± 324 evts** (stat)
- Unmixed lifetime: consistent with PDG
 - **± 2.5 fs** statistical error

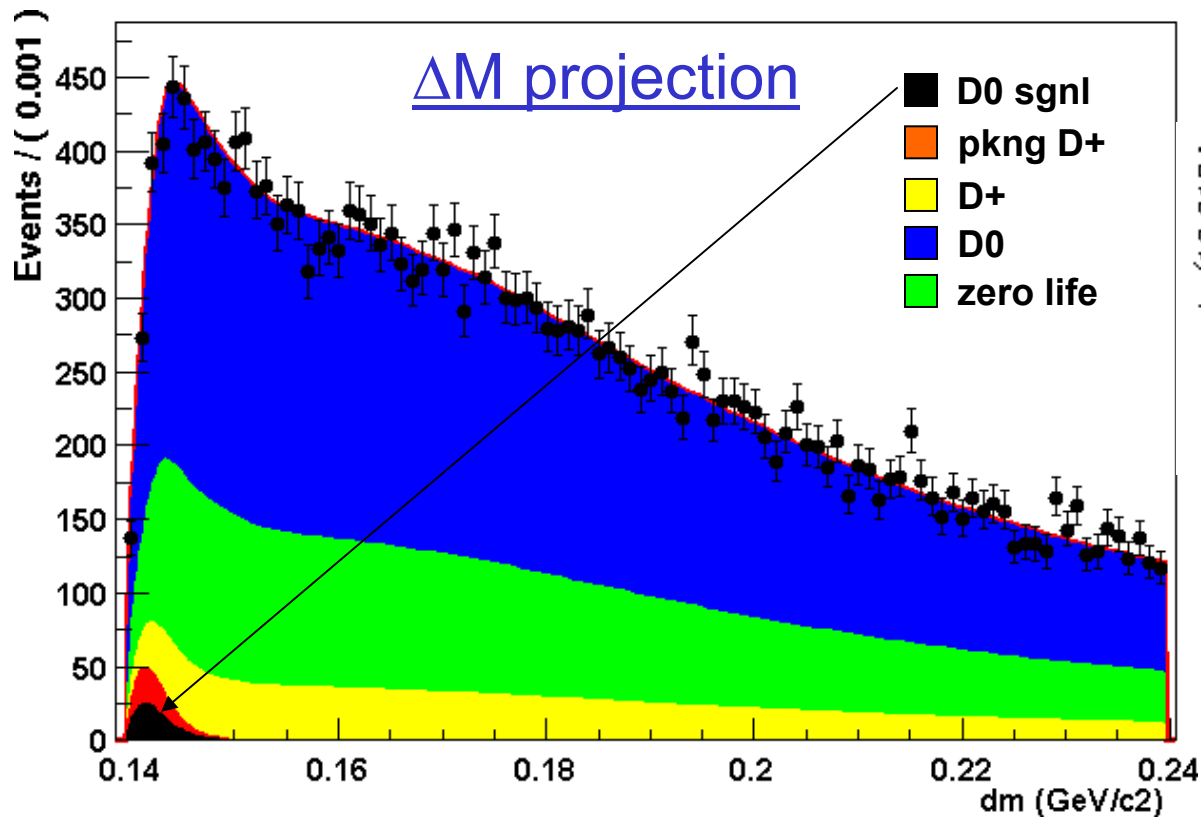


ΔM sideband

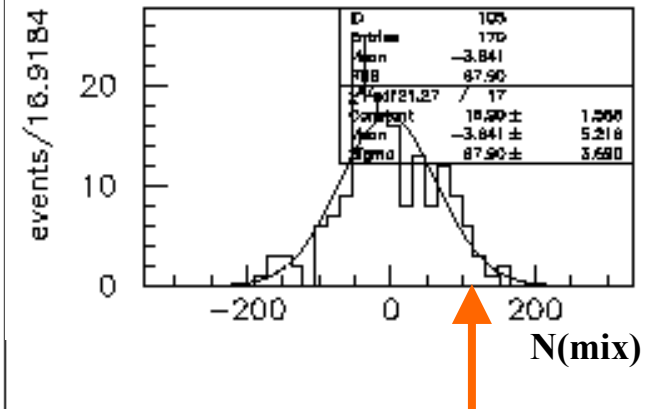


WS Mixed D⁰ Fit to Run 1,2 Data

- Mixed signal pdf parameters taken from high-statistics unmixed data fit
 - unbinned extended maximum likelihood fit with 11 parameters



- Distribution of N(mix) from fits to an ensemble of 170 WS generic MC datasets with zero embedded mixed signal events

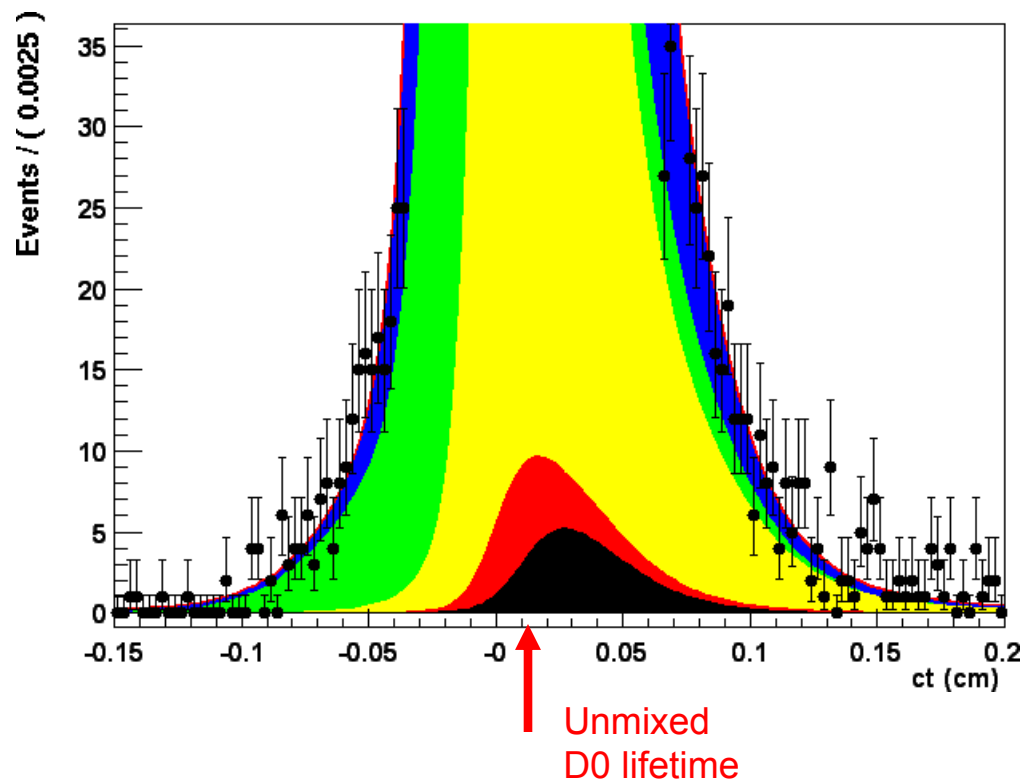


- **Unblinded N(mix):**
114 ± 61 evts
 (~5% probability of getting a larger result for $R_{\text{mix}}=0$)

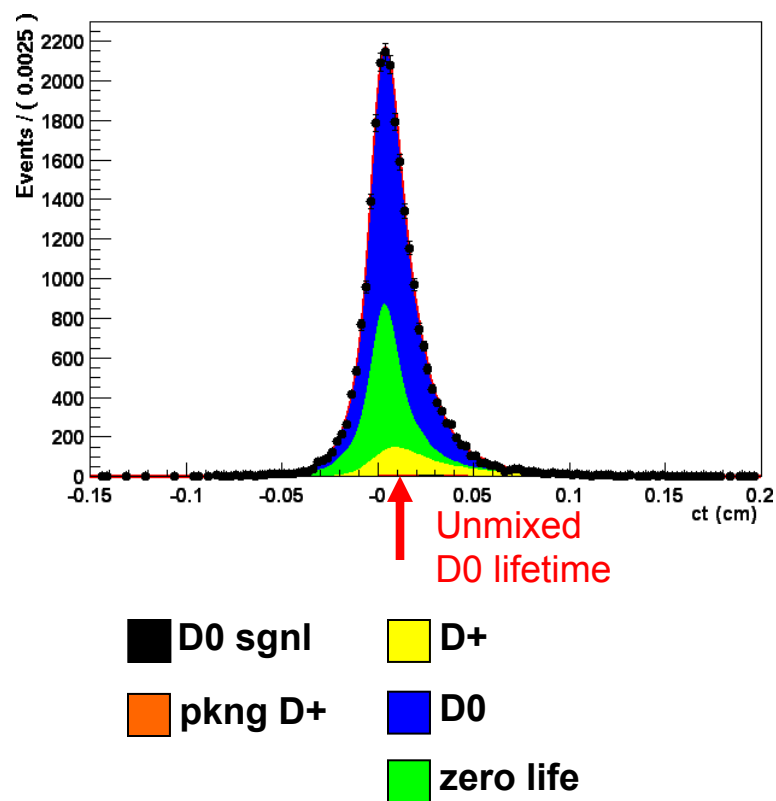


WS Mixed D^0 Fit to Run 1,2 Data

Lifetime projection showing mixed signal



Full lifetime projection



Systematic Error & Upper Limit Calculation

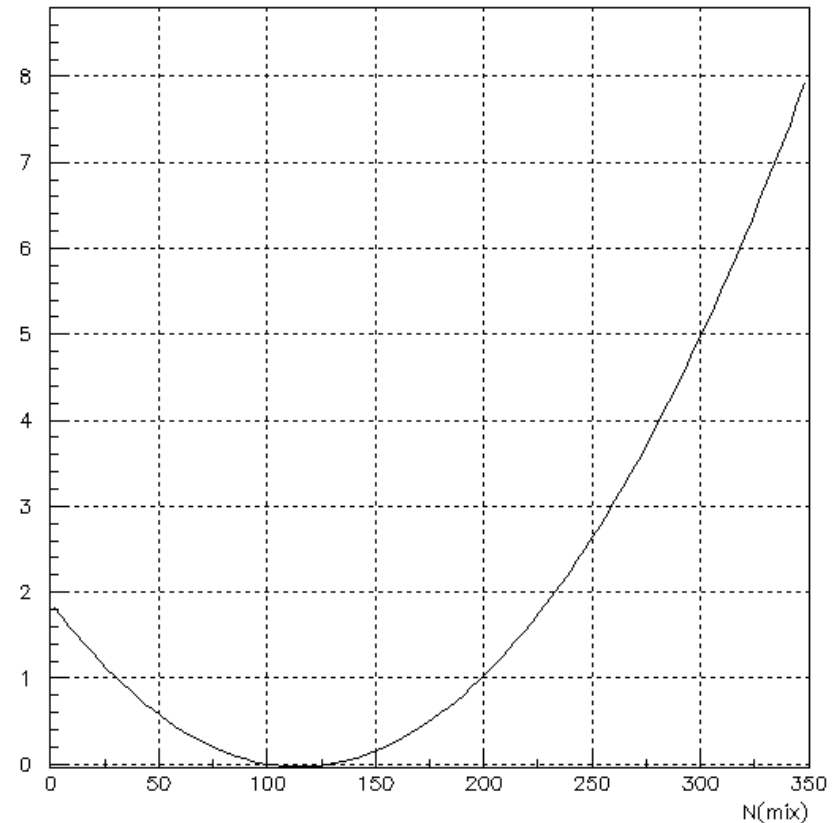
- Predominant contribution from statistical errors on **unmixed fit RS signal ΔM shape**
- Minor contributions from
 - background lifetime models
 - random combinatoric shape

Variation	delta R(mix)
deltaM shape	0.00032
unmixed D0 lifetime	0.00008
random comb. shape	0.00015
lifetime resolution model	0.00000
Bkgd D0 lifetime model	0.00016
Bkgd D+ lifetime model	0.00012

- Total systematic error

$$\sigma^{\text{sys}} = 0.00042 = 0.340 \sigma^{\text{stat}}$$

N(mix) NLL Scan



Summary

- Final value of R_{mix} consistent with no mixing

$$R_{\text{mix}} = 0.0023 \pm 0.0012 \pm 0.0004$$

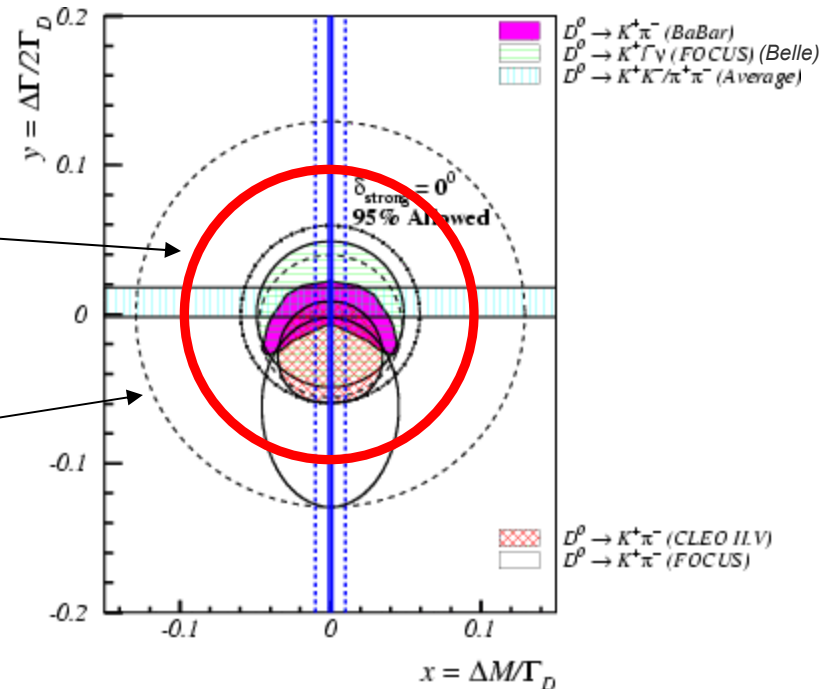
- CP fit was performed and no CP-violating effects were found

- $R_{\text{mix}} < 0.0046$ (95% C.L.)

- PRD-RC submitted (hep-ex/0408066)

- Current best published limit (E791)

- Next analysis iteration will hadronically reconstruct opposite charmed hadron to get an independent initial flavor tag
 - complementary to existing analysis
 - combination of old and new methodology on $\sim 250 \text{ fb}^{-1}$ dataset increases sensitivity by factor of ~ 3



(Plot courtesy of G. Burdman & I. Shipsey, hep-ph/0310076)



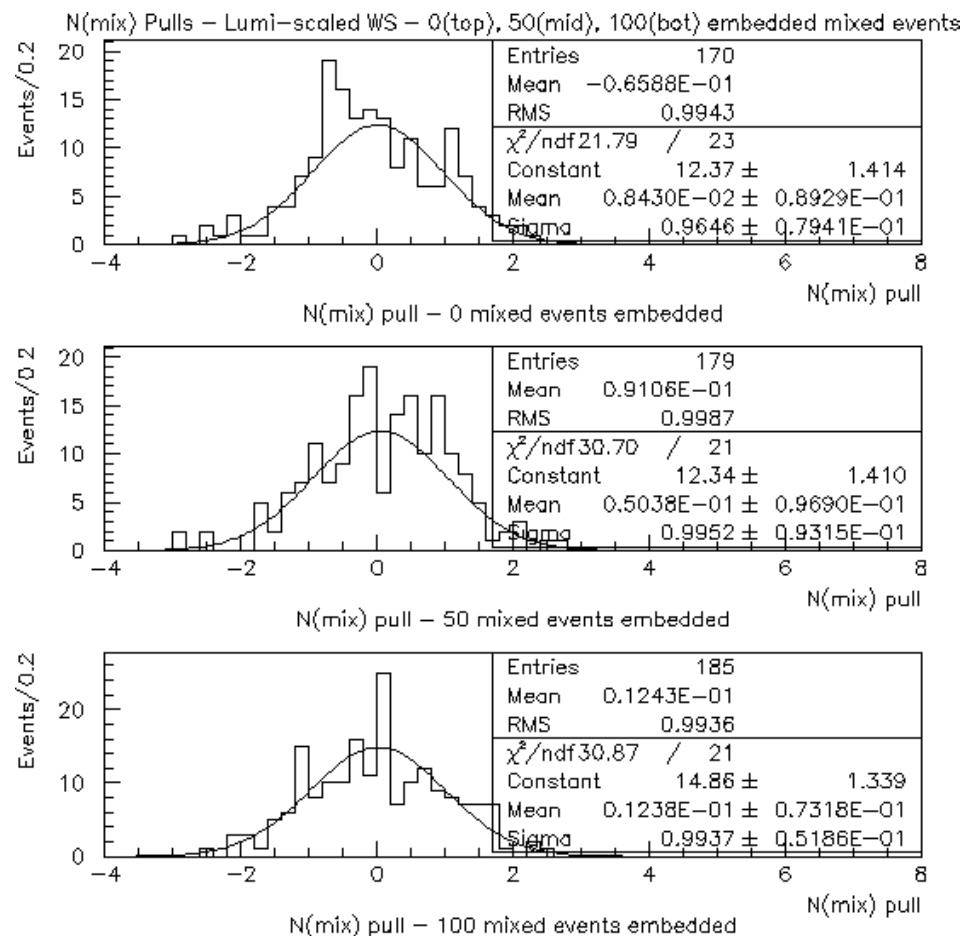
Backup slides

Testing the Mixed Fit with Generic MC and Embedded Mixed Events

- WS mixed fit tested with full fit on ~540 lumi-scaled generic MC datasets with different levels of embedded mixed events
- N(mix) pull plots (right) show no evidence of bias or improperly scaled errors in the fit number of N(mix) with or w/o the presence of mixed events

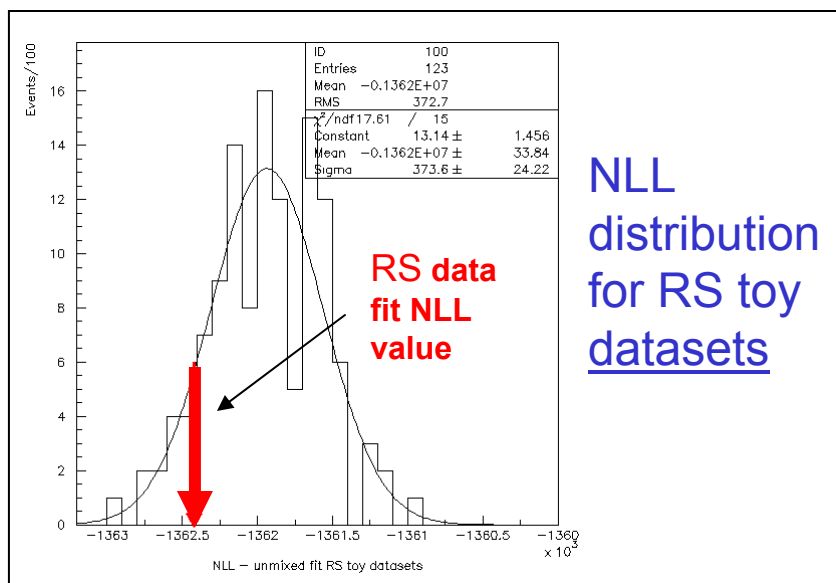
N(mix)	R(mix)	fit mean	err	stat mean
0	0	0.008	0.089	-0.066
50	0.001	0.05	0.097	0.091
100	0.002	0.012	0.07	0.012

N(mix)	R(mix)	fit sigma	err	stat rms
0	0	0.965	0.079	0.994
50	0.001	0.995	0.093	0.999
100	0.002	0.994	0.052	0.994

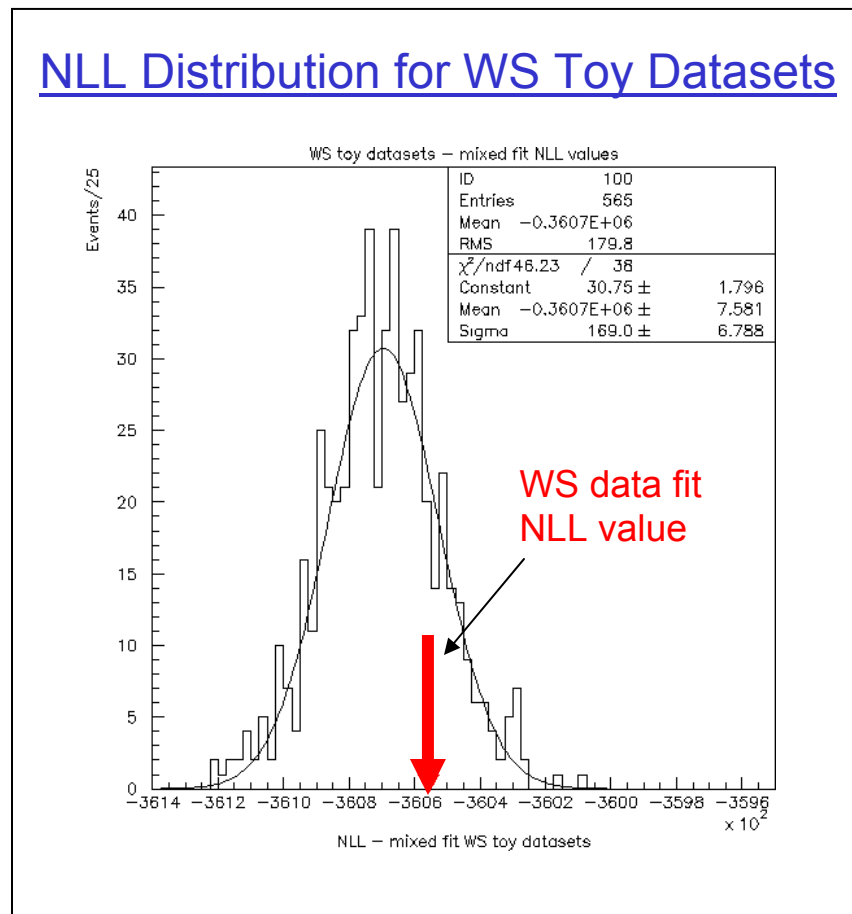


Goodness-of-Fit to Run 1,2 Data

- Toy MC datasets generated from RS/WS data fit pdfs and fit with unmixed/mixed fit models to determine goodness-of-fit
- Both RS/WS NLL values from data fits lie well within range predicted by the fits to toy MC



NLL Distribution for WS Toy Datasets



Event Selection I

- Identified Kaon candidates

- ~99% purity
- ~80% reconstruction efficiency
 - charge asymmetry ~1-2%

- Identified electron candidates

- ~99.8% purity
- ~90% reconstruction efficiency
 - charge asymmetry ~1-2%
- γ conversion veto

- K/e vertex

- vertex prob. > 0.01
- $M(KeVtx) < 1.82 \text{ GeV}/c^2$
- Lifetime error $< 2 D^0$ lifetimes
 - mean lifetime error $\sim 0.6 D^0$ lifetime

- Pion candidates

- beamspot refit prob. > 0.01
- ≥ 2 SVT r-phi (z) hits with at least 1 hit on inner 3 r-phi (z) layers
- ≥ 6 total SVT hits

- Multiple D^0 candidates

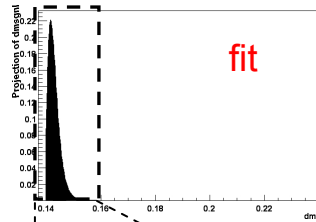
- Veto events with more than one RS or WS D^0 candidate passing all selection criteria
 - ~11% of RS signal lost after all other cuts



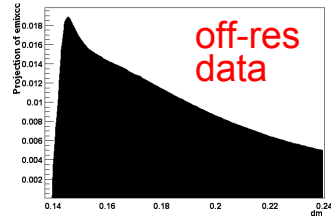
ΔM , Lifetime PDFs

1-d ΔM pdfs

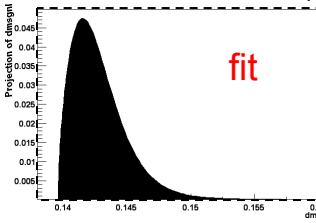
$$\Delta M = M(D^*) - M(D^0)$$



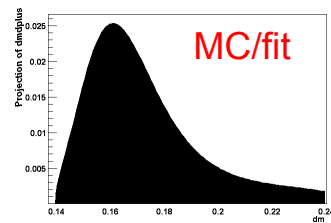
signal



random comb.

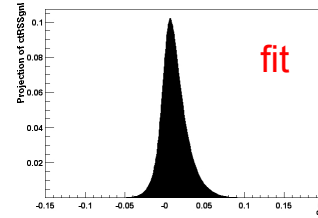


signal (zoom)

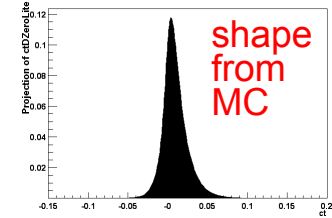


D^+ (RS only)

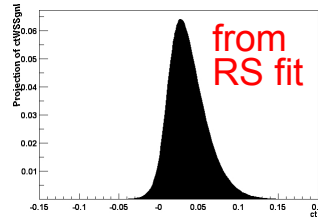
1-d lifetime pdfs



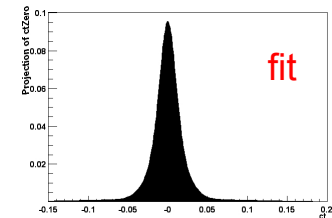
RS unmixed D^0



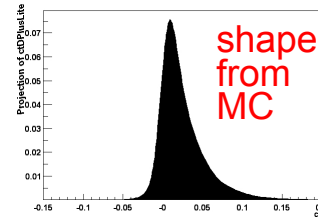
mis-reco'd D^0



WS mixed D^0



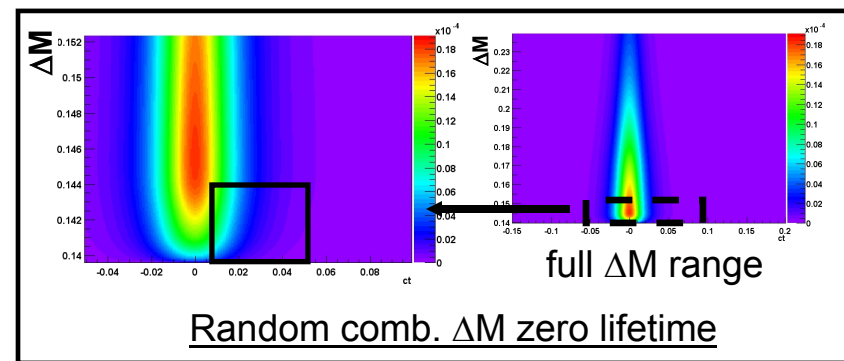
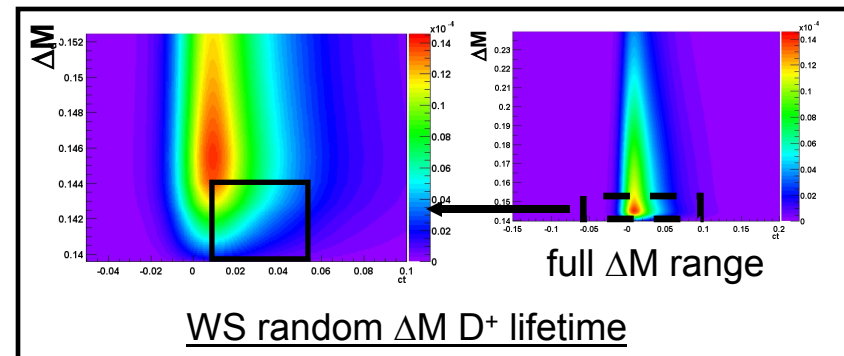
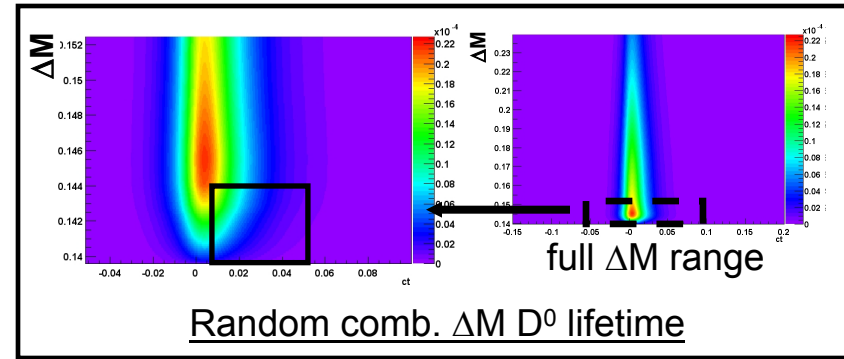
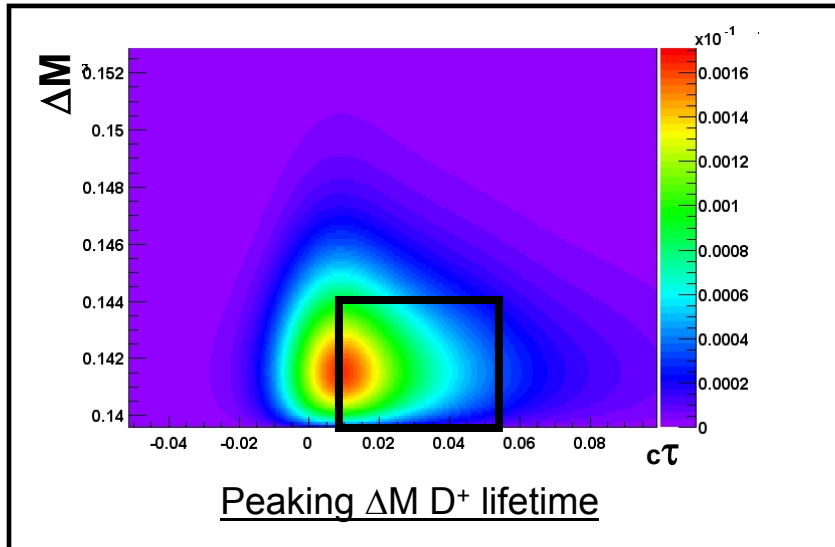
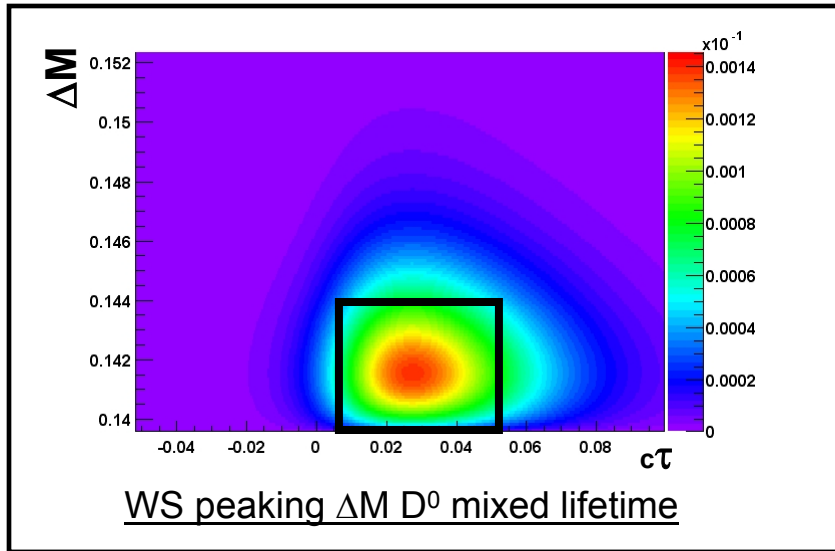
zero lifetime



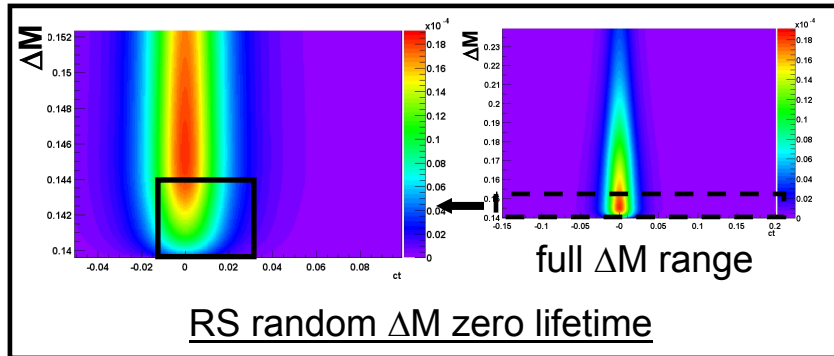
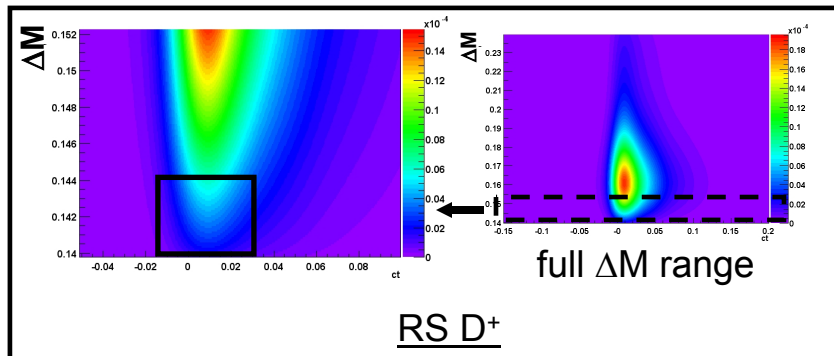
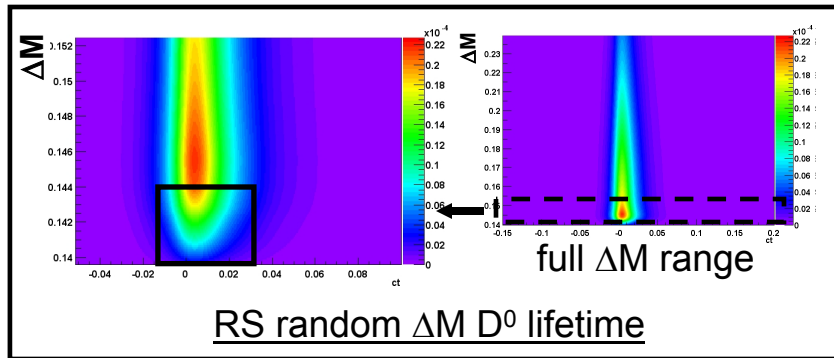
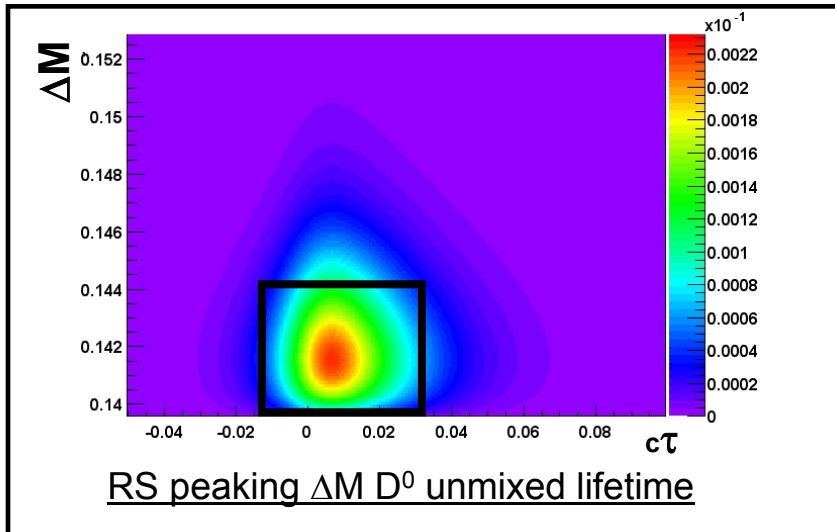
D^+



WS Mixed ΔM , Lifetime PDF Fit Classes



RS Unmixed ΔM , Lifetime PDF Fit Classes



Time Dependence of DCS/Mixed Hadronic & Semileptonic Final States

- **Hadronic** WS time-dependence:
 - $R_{DCS} \equiv 1, y' = -0.3, |x'| = 0.3$
 - mixed time-dependence close to a pure exponential

- **Semileptonic** WS time-dependence well-distinguished from exponential

