

# $D^0-\bar{D}^0$ hadronic mixing and DCS decays

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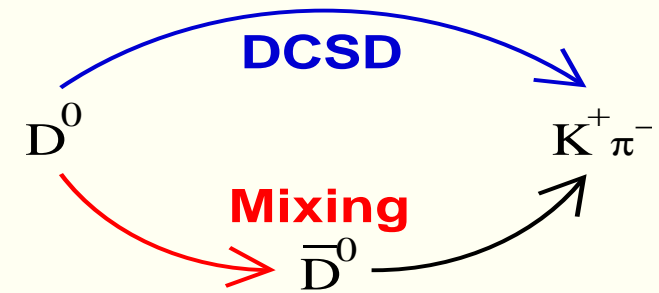
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*DPF 2004: Riverside, CA*

# Hadronic mixing 101

- Two paths to same final state (mixing + Cabibbo favored (CF) decay and DCS decay)  $\Rightarrow$  interference



- Assuming CP conservation, the  $D^0 \rightarrow K^- \pi^+$  wrong-sign to right-sign decay ratio can be written to first order as:

$$R_{WS}(t) = \left( R_{DCS} + \sqrt{R_{DCS}} y' \Gamma t + \frac{1}{4} (x'^2 + y'^2) \Gamma^2 t^2 \right) e^{-\Gamma t}$$

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

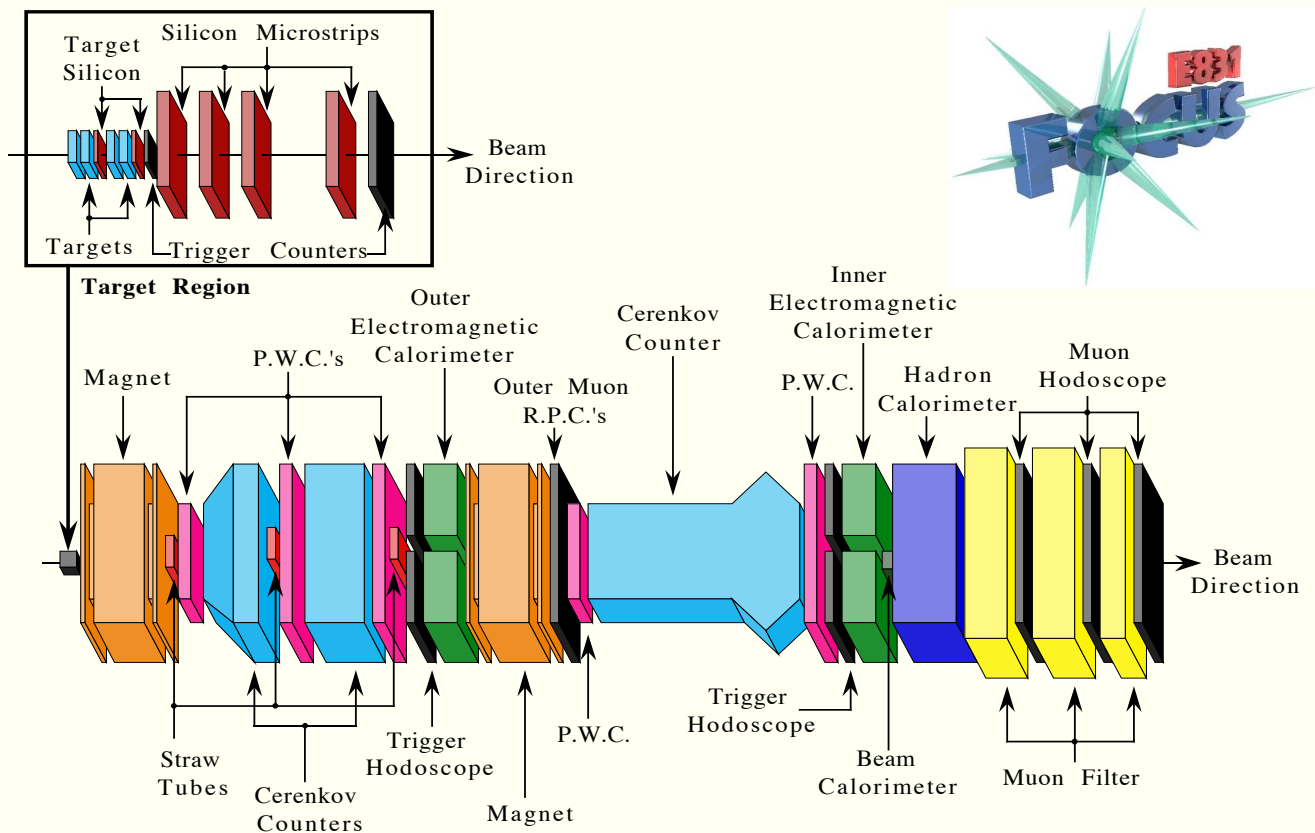
$$y' \equiv y \cos \delta - x \sin \delta$$

and  $x \equiv \Delta M / \Gamma$  and  $y \equiv \Delta \Gamma / 2\Gamma$  are the mixing parameters.

- The three terms are from DCS decays, interference, & mixing
- Initial  $D^0$  flavor is determined from  $\pi_s$  charge in  $D^{*+} \rightarrow D^0 \pi_s^+$  decays defining right-sign (RS) and wrong-sign (WS)
- Fit for  $R_{DCS}$ ,  $x'^2$ ,  $y'$

# The FOCUS experiment

- FOCUS took data in the Fermilab fixed-target run of 1996-7
- $e^\pm$  at  $\sim 300$  GeV bremsstrahlung on lead target to create photon beam
- Photons interact in BeO targets
- Charged particles tracked and momentum analyzed with silicon strips, wire chambers, and two magnets
- Three multicell threshold Čerenkov counters for particle ID
- Trigger required  $\sim 35$  GeV of energy in the hadron calorimeter
- 7 billion hadronic events on tape



# Mixing analysis

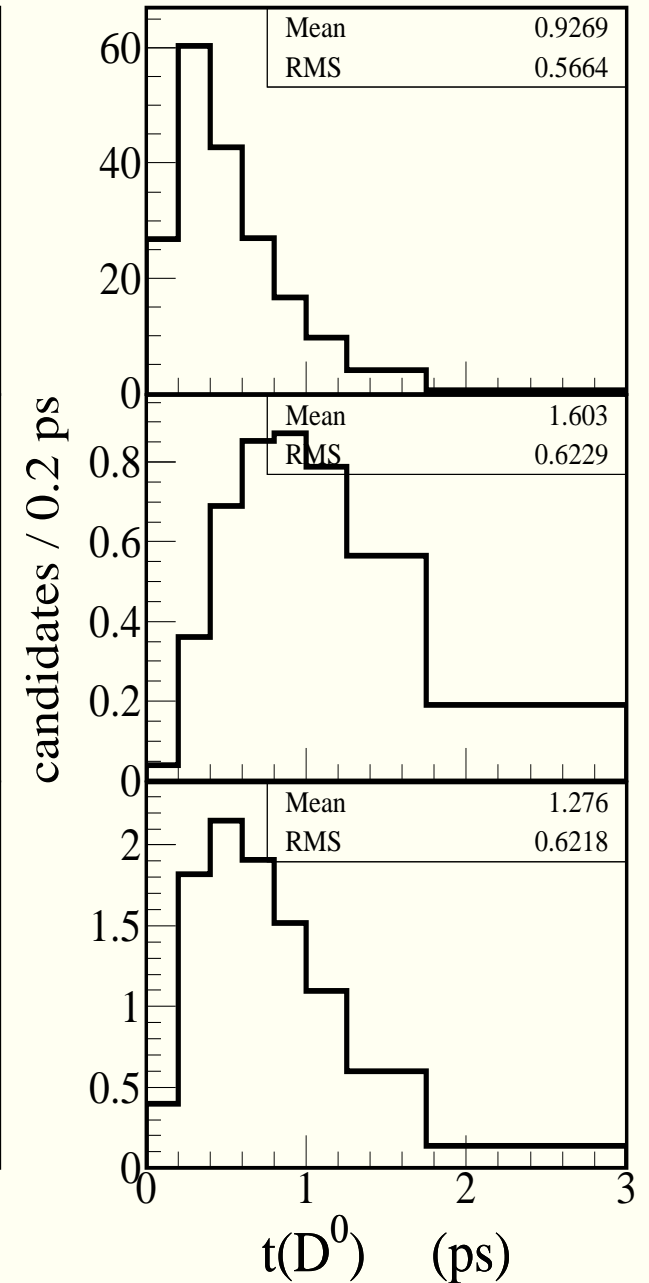
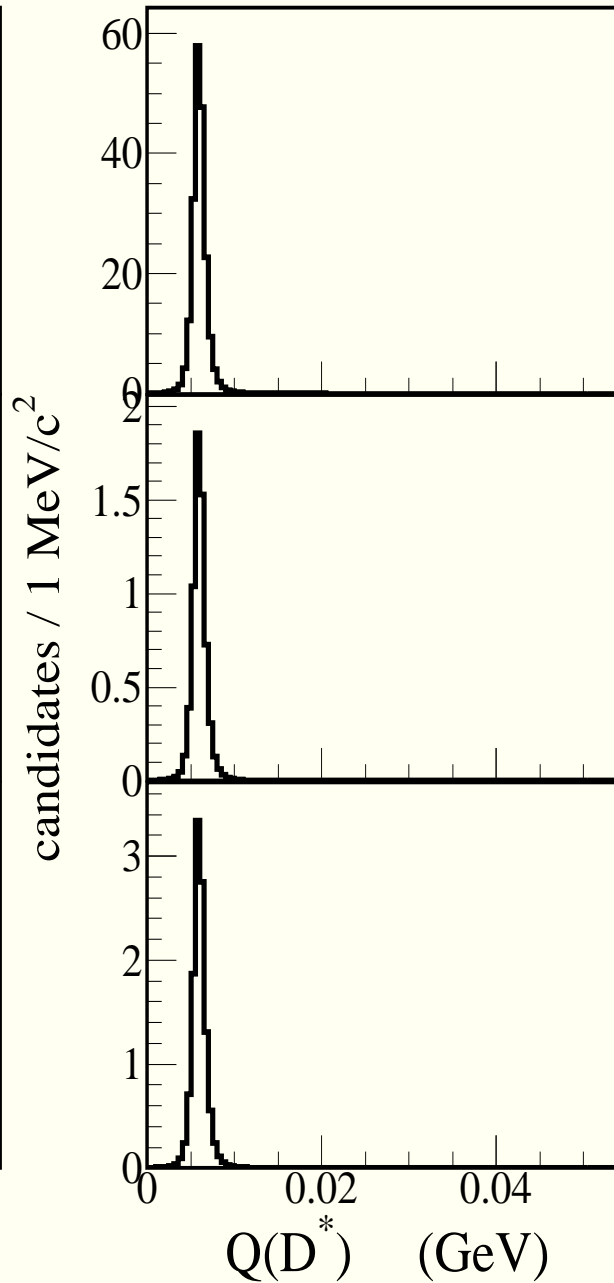
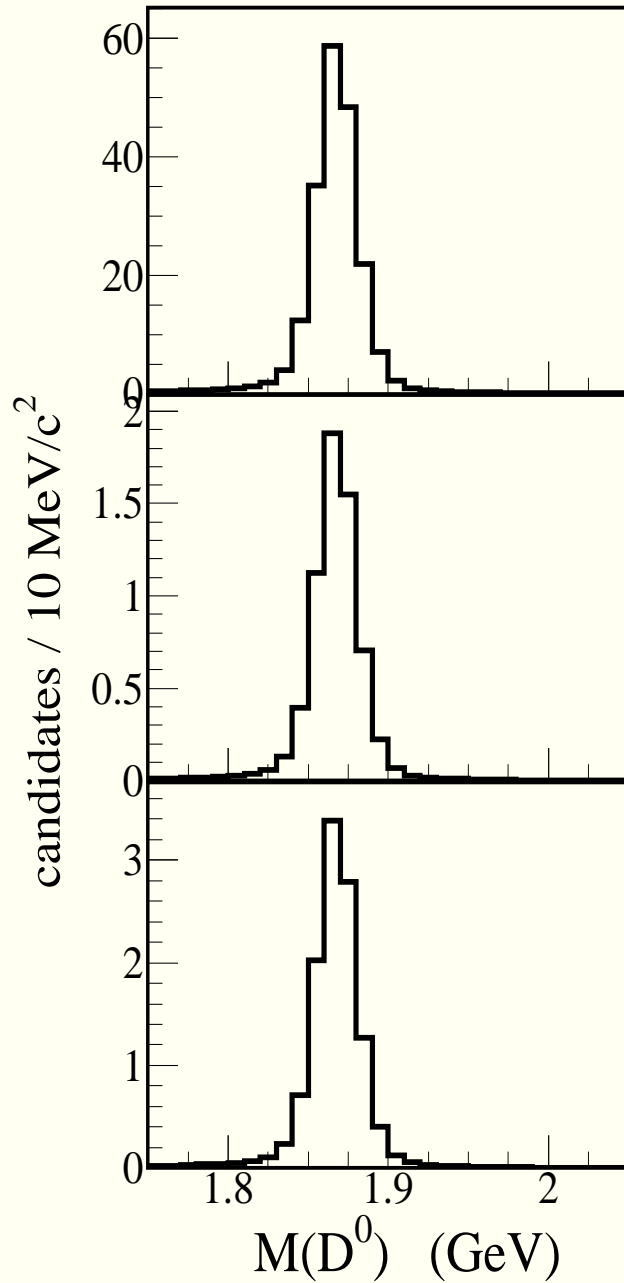
- Use  $M(D^0)$ ,  $Q(D^*)$  to separate signal from background
- Use  $\tau(D^0)$  to separate wrong-sign contributions
- 3D binned likelihood fit
- Build up fit model from many contributions: RS signal, WS DCSD, WS mixing, WS interference, real  $D^0$  with fake  $\pi_s$ ,  $D^0 \rightarrow K^- K^+$ ,  $\pi^+ \pi^-$ ,  $\pi^+ \pi^- \pi^0$ ,  $K^0 \pi^+ \pi^-$ ,  $K^- \pi + \pi^0$ ,  $K^- \ell \nu$ , double misid of  $D^0 \rightarrow K^- \pi^+$ , and random combination of tracks (broken charm or minimum bias)
- Obtain shapes from MC (checked with data) preserving correlations when necessary

# Fit shapes – Signal

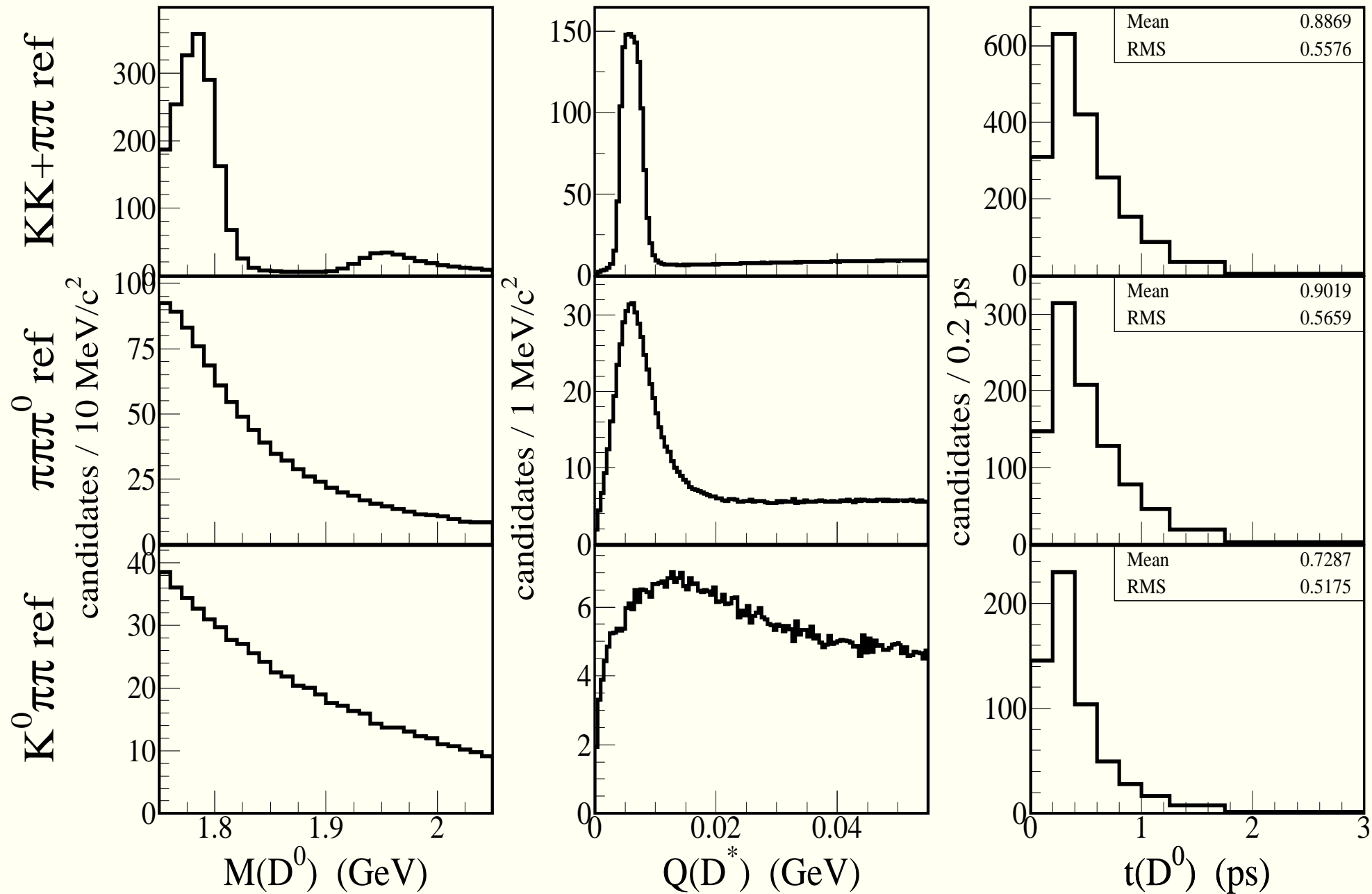
DCSD/RS

Mixing

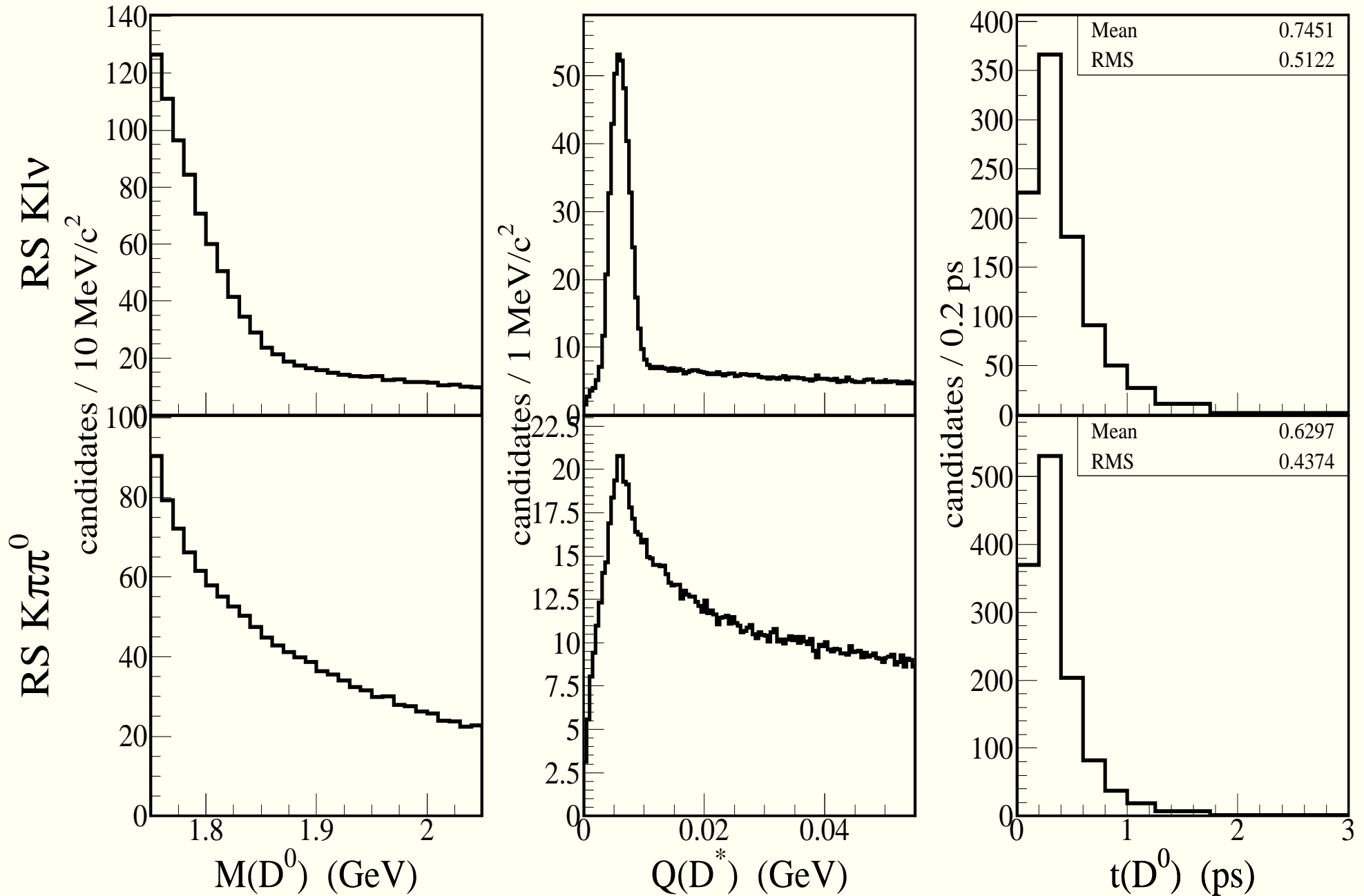
Interference



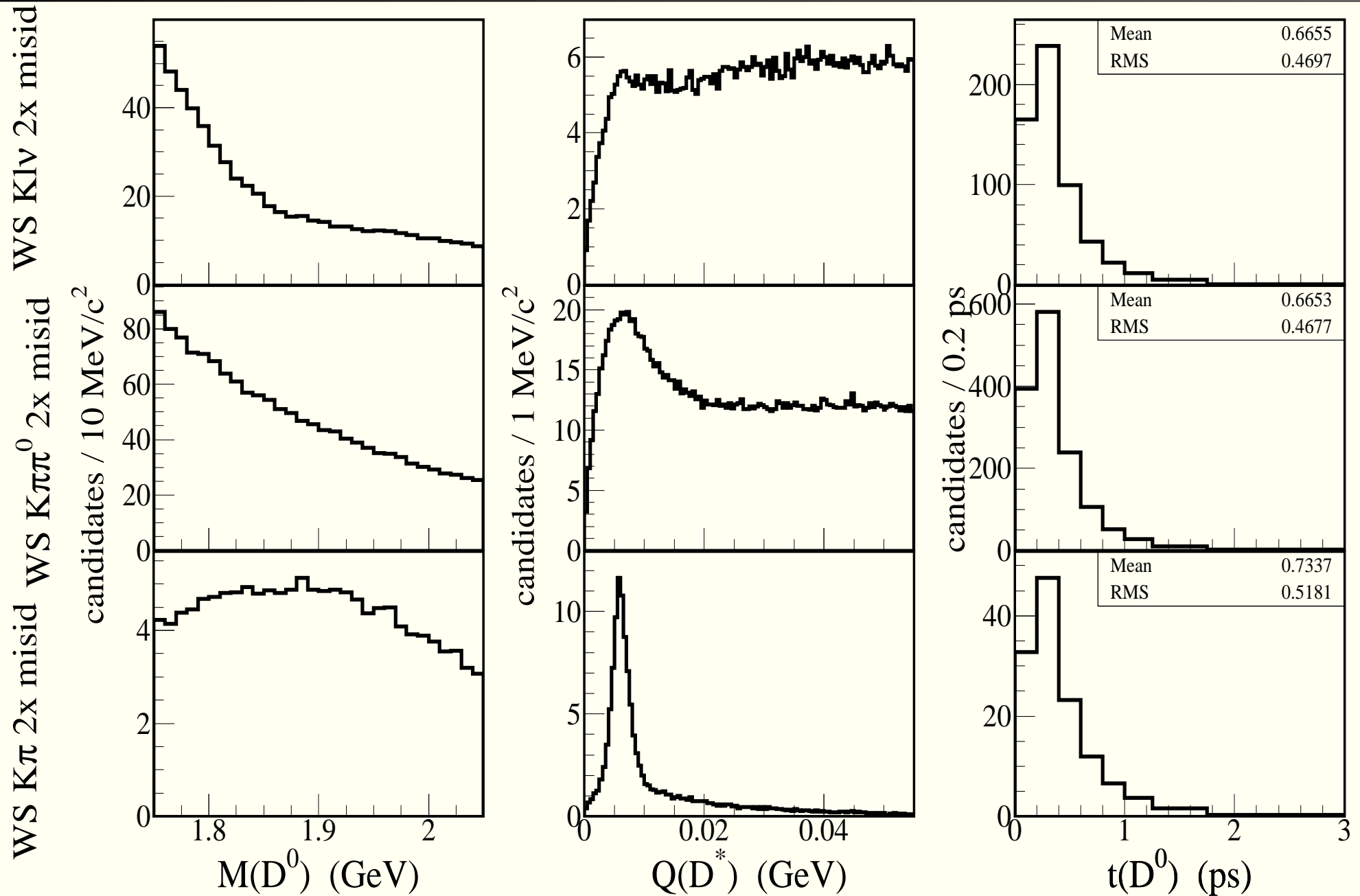
# Fit shapes – RS/WS reflections



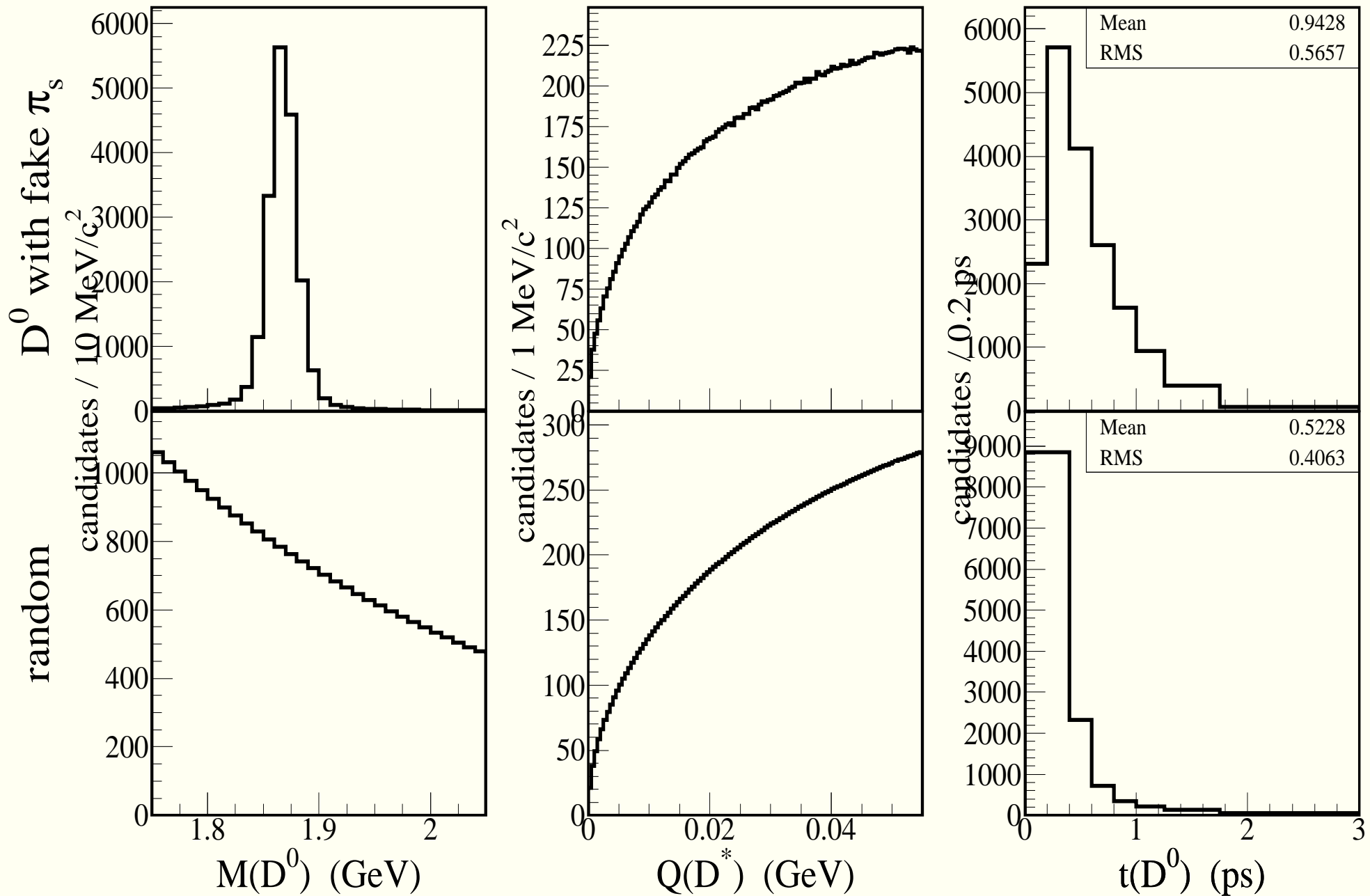
# Fit shapes – RS reflections



# Fit shapes – WS reflections

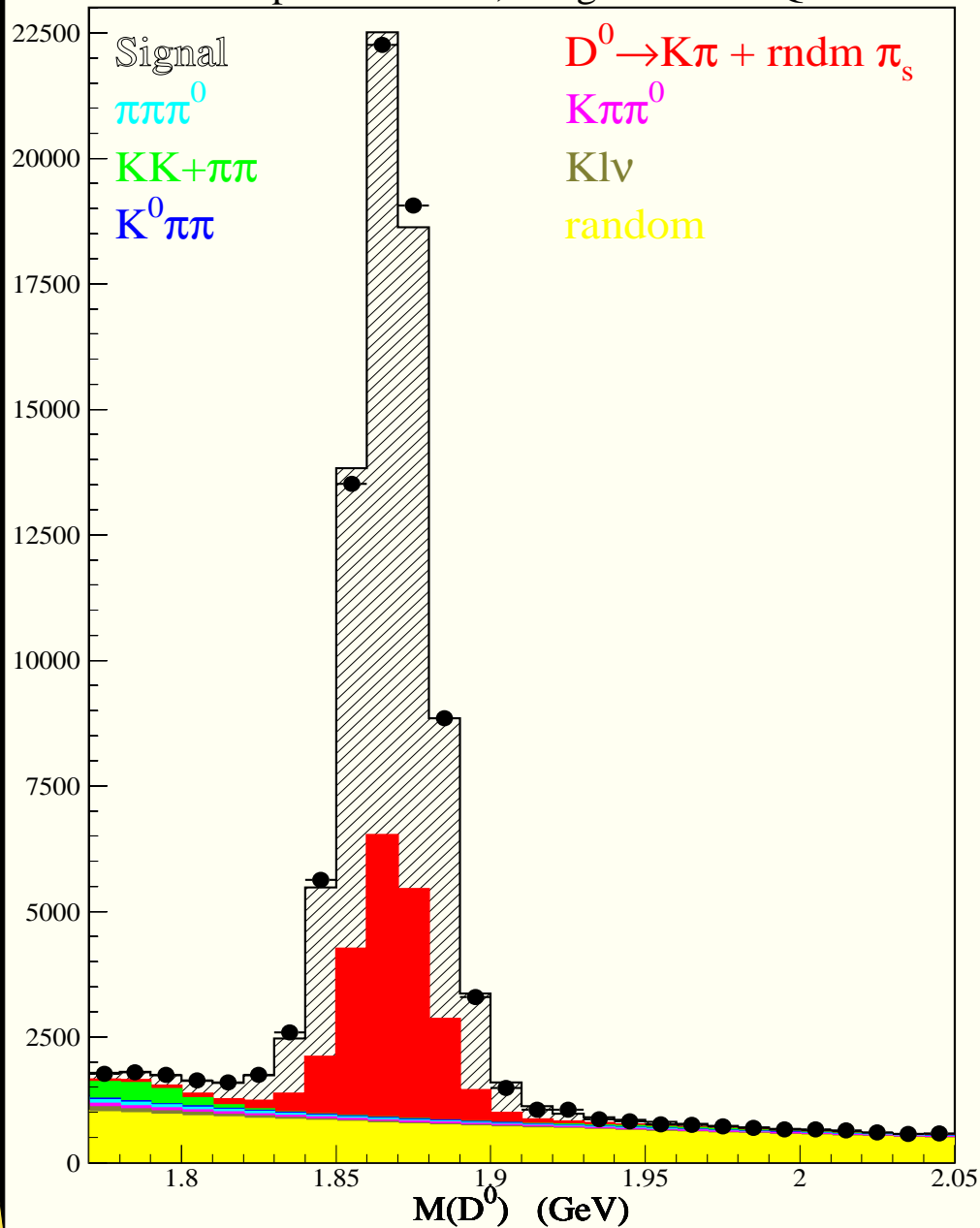


# Fit shapes – $D^0$ with fake $\pi_s$ & random

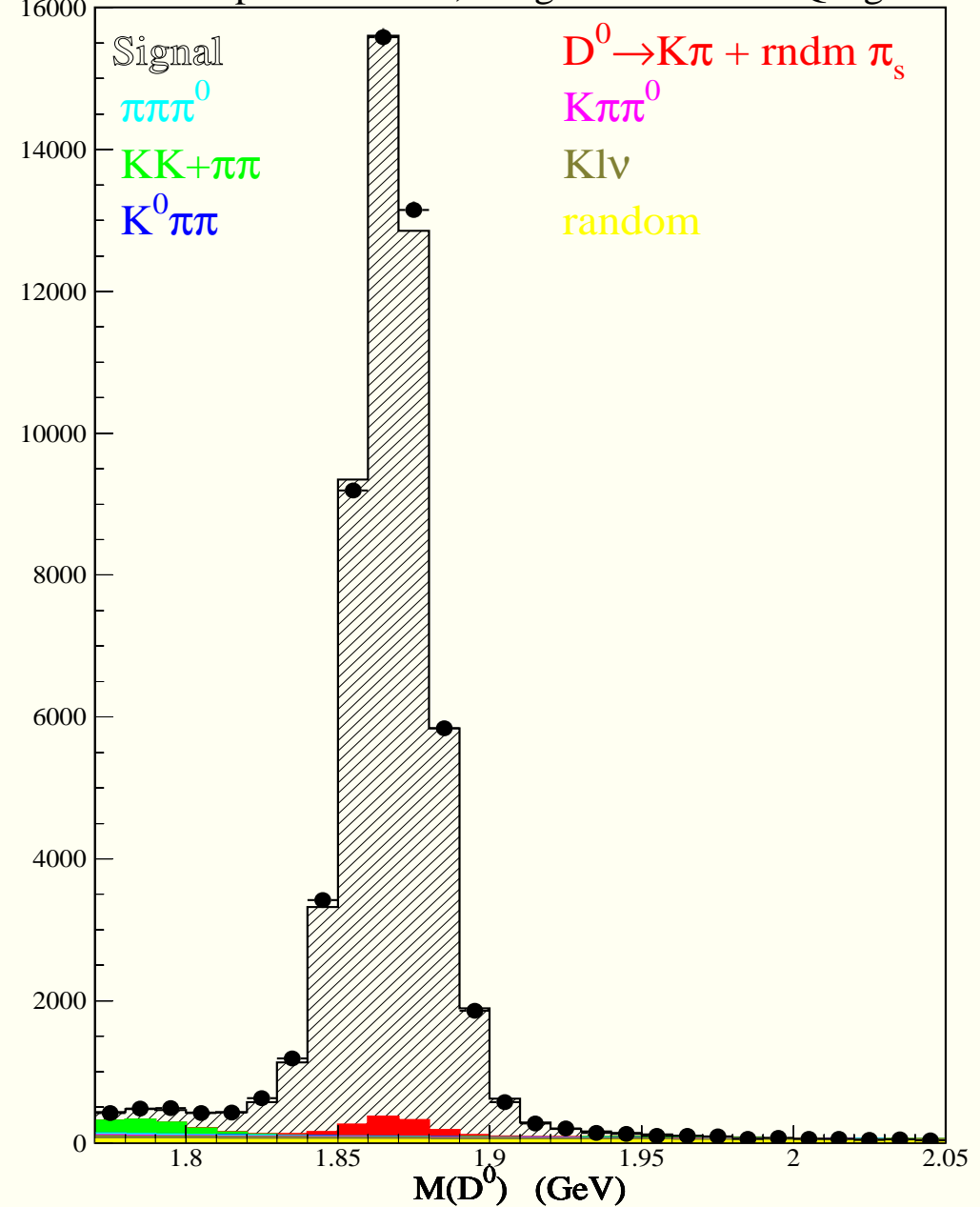


# RS $M(D^0)$ projection

$K\pi$  RS components vs  $M$ , integrated over  $Q$  and  $\tau$

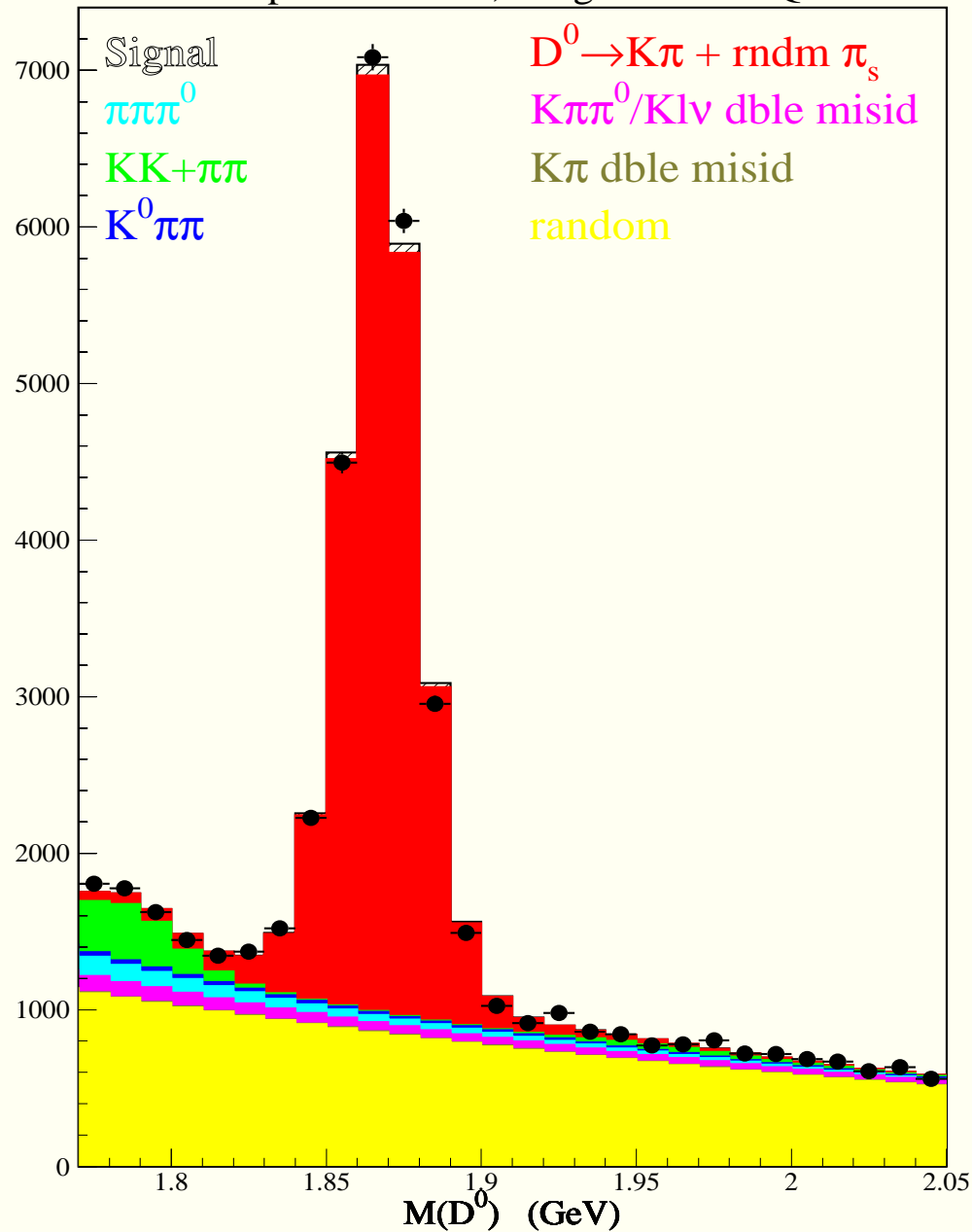


$K\pi$  RS components vs  $M$ , integrated over  $\tau$  in  $Q$  signal

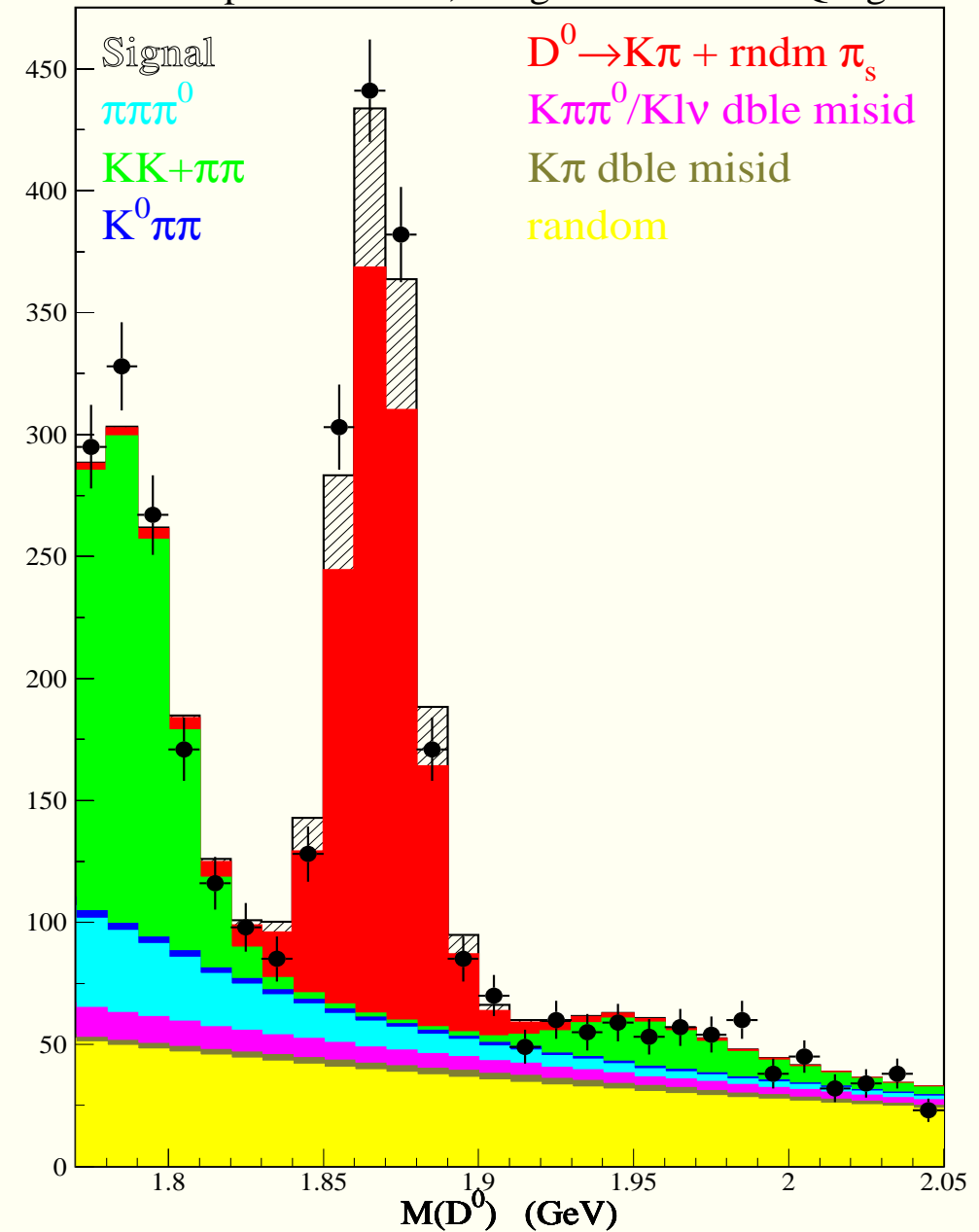


# WS $M(D^0)$ projection

$K\pi$  WS components vs  $M$ , integrated over  $Q$  and  $\tau$

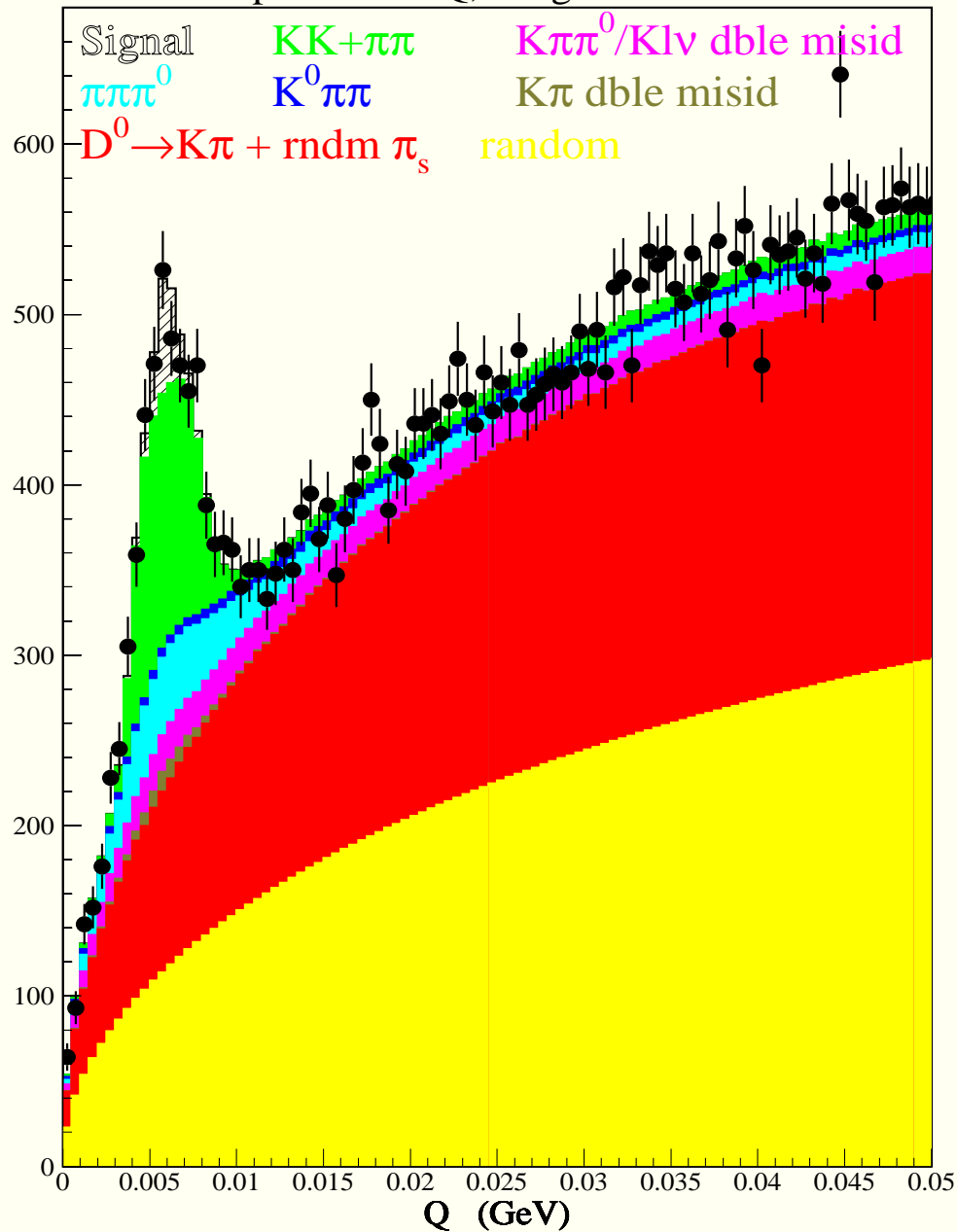


$K\pi$  WS components vs  $M$ , integrated over  $\tau$  in  $Q$  signal

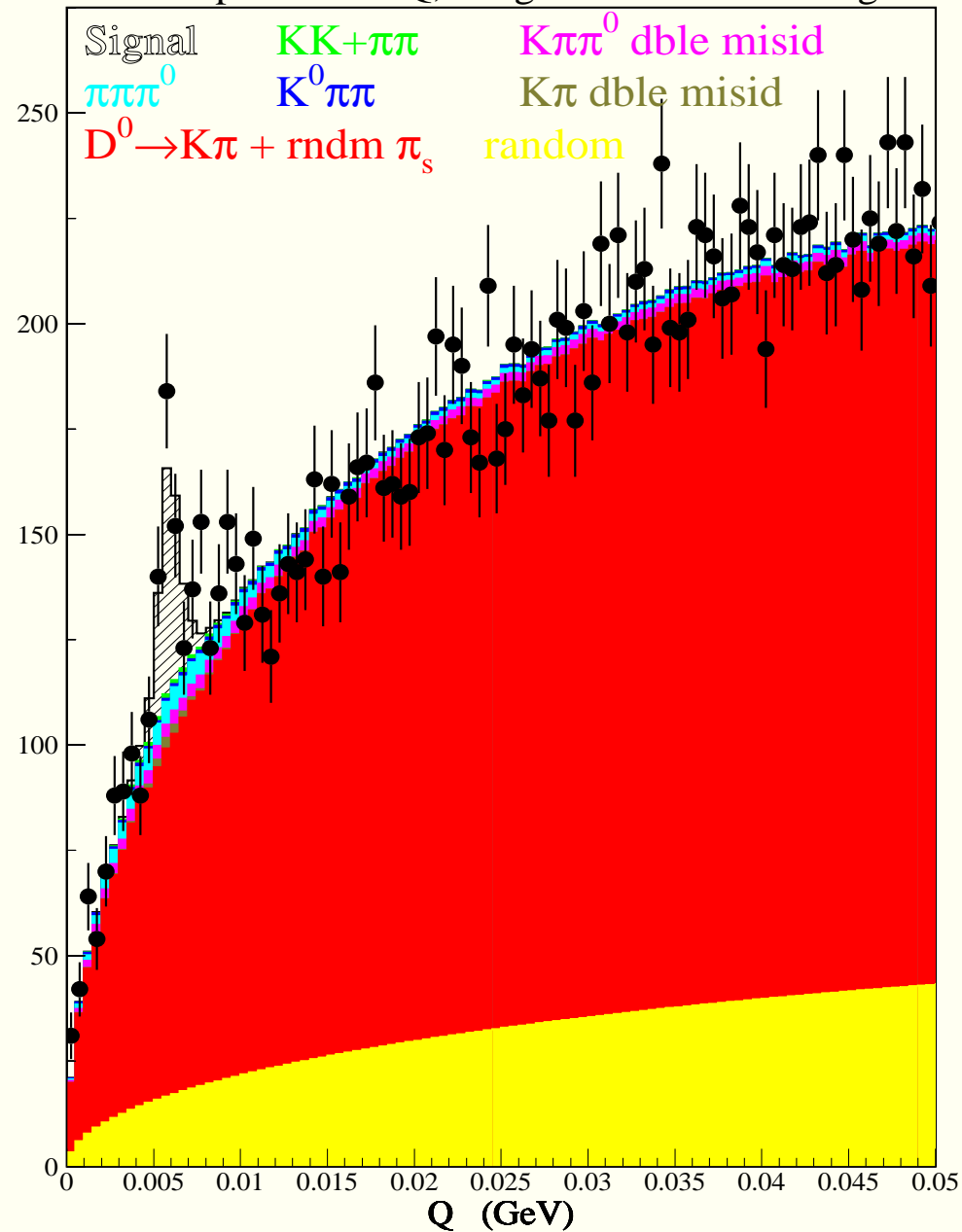


# WS $Q(D^*)$ projection

$K\pi$  WS components vs  $Q$ , integrated over  $M$  and  $\tau$

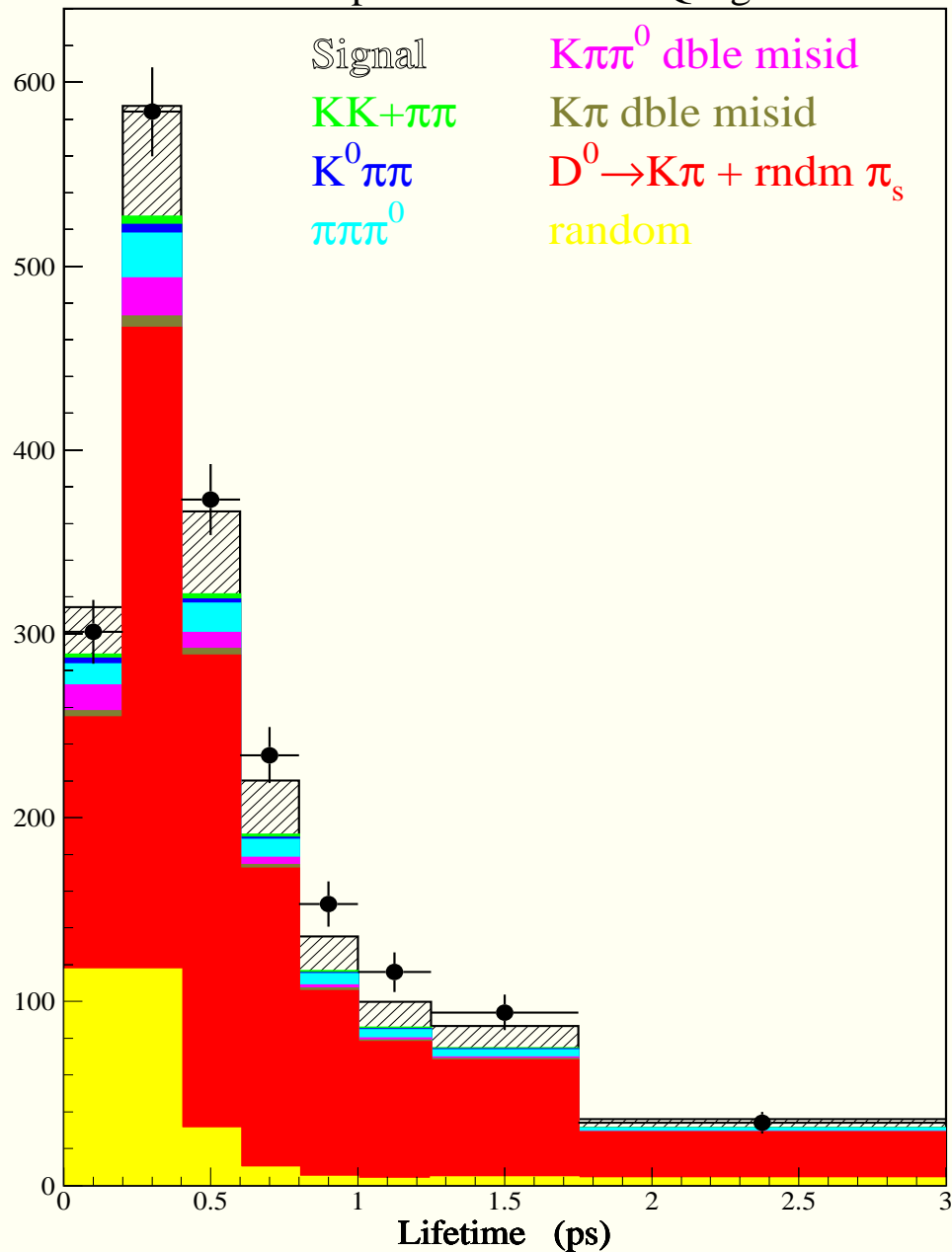


$K\pi$  WS components vs  $Q$ , integrated over  $\tau$  in  $M$  signal

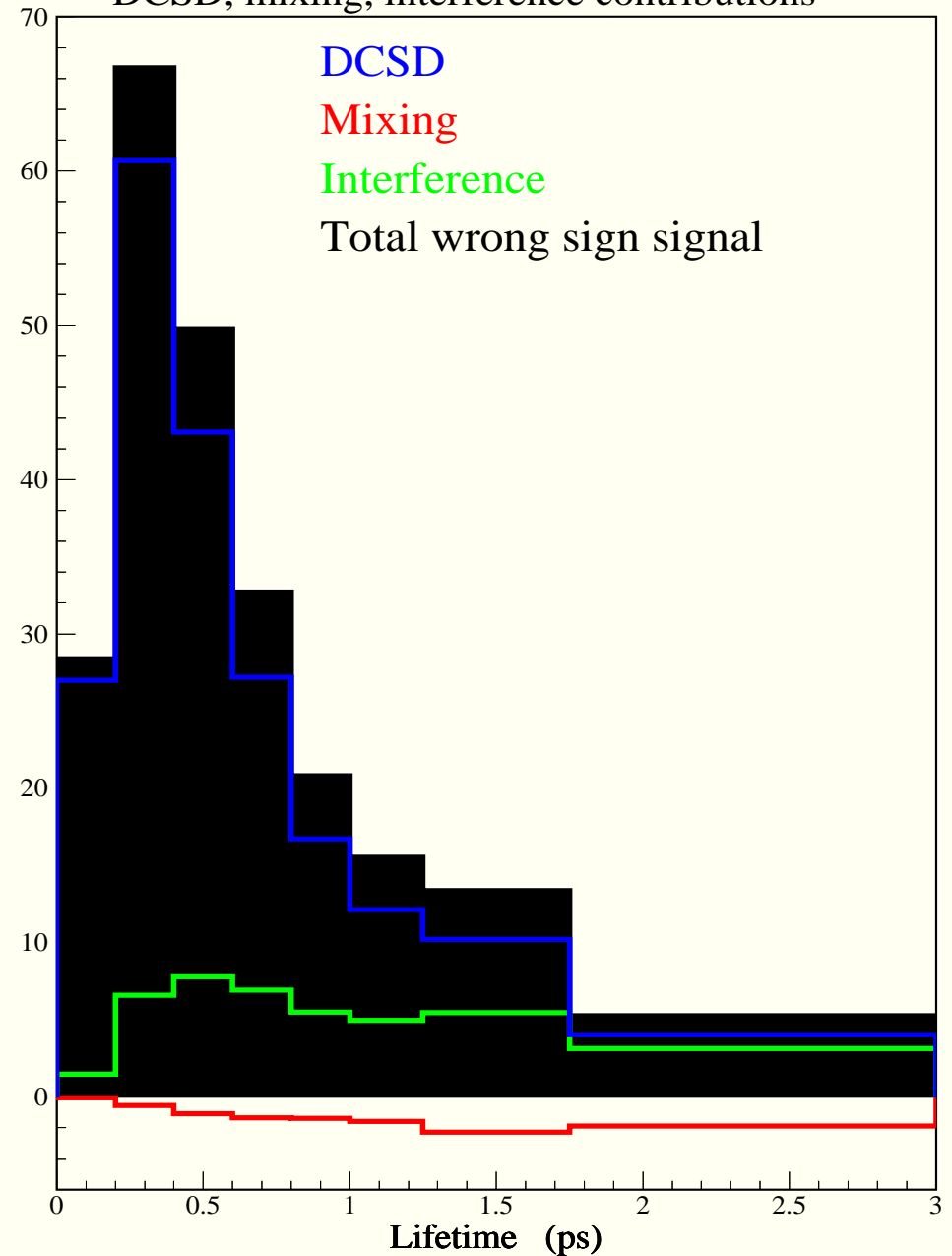


# WS $\tau(D^0)$ projection

$K\pi$  WS components vs  $\tau$  in M/Q signal



DCSD, mixing, interference contributions



# Branching ratio and mixing results

Expt	$R_{DCS}(\%) - \text{no mix}$	Events
E791	$0.68 \pm 0.34 \pm 0.07$	34
CLEO	$0.332 \pm 0.064 \pm 0.040$	$45 \pm 9$
FOCUS	$0.404 \pm 0.085 \pm 0.025$	$149 \pm 31$
BaBar	$0.357 \pm 0.022 \pm 0.027$	$\sim 440$
<b>FOCUS</b>	<b><math>0.430 \pm 0.062 \pm 0.031</math></b>	<b><math>234 \pm 34</math></b>

**FOCUS** systematic errors come from taking the standard deviation of the results obtained by varying selection criteria and fitting technique (120 variations).

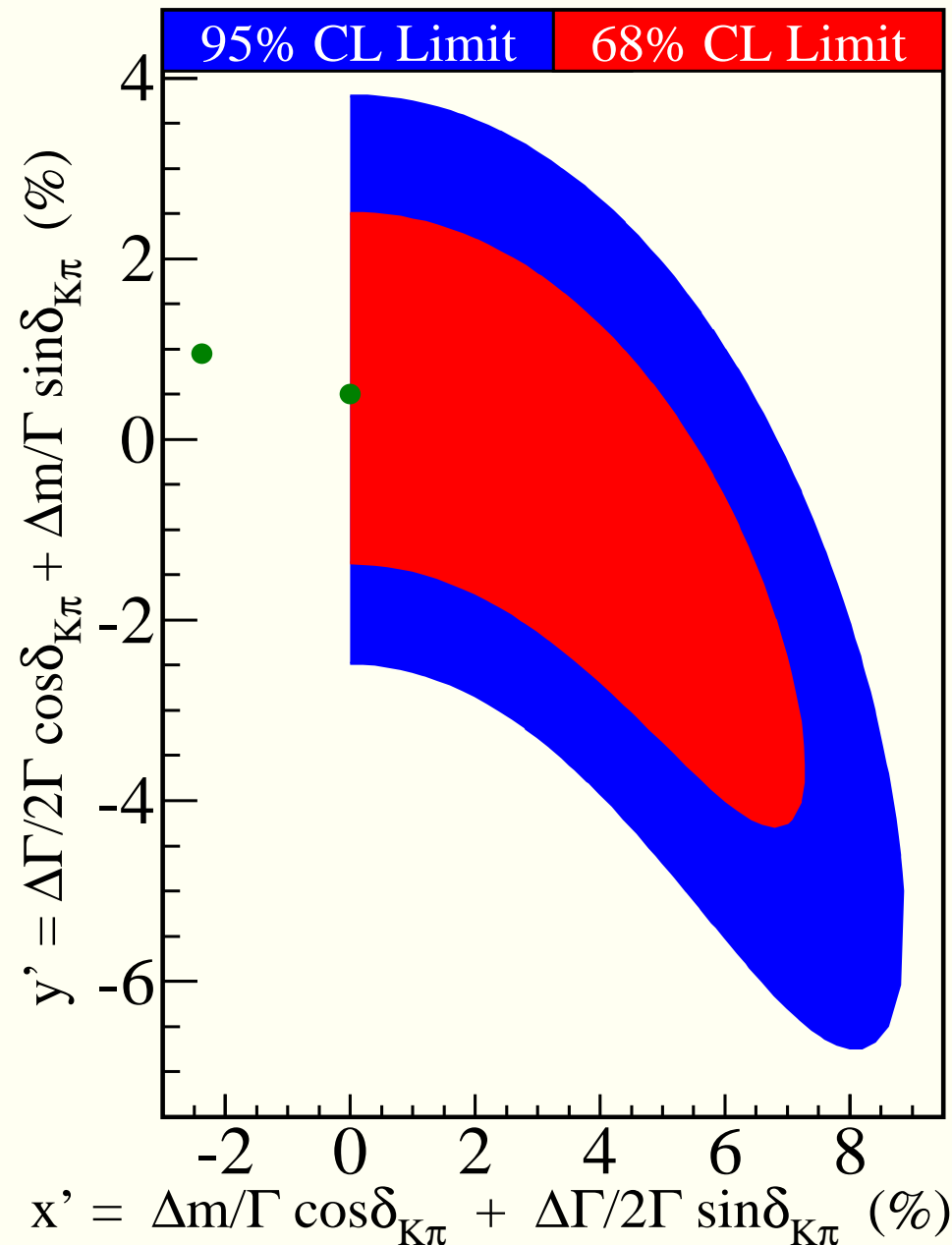
## FOCUS mixing results (no CP violation):

Component	Result
RS signal	$54452 \pm 242$
DCS BR	$(0.382^{+0.167}_{-0.163} \pm 0.087) \%$
$x'^2$	$(-0.06^{+0.42}_{-0.84} \pm 0.27) \%$
$y'$	$(1.0^{+5.5}_{-3.7} \pm 2.2) \%$

Due to the extreme correlations between DCS BR,  $x'^2$ , and  $y'$  the statistical and systematic errors are relatively useless. Thus, the  $x'-y'$  contour.

# $x'-y'$ contour

- Fit is to  $x'^2$  &  $y'$  but  $x'$  is plotted (retaining sign)
- Best fit at  $x'^2 = -0.0006$ ,  $y' = 0.095$
- Constraining  $x'^2 = 0$ :  
 $\Delta \log \mathcal{L} = 0.006$ ,  $y' = 0.050$   
(tiny change)
- 95% (68%) contour defines where  $\Delta \log \mathcal{L} = 2.995$  (1.150), allowing other parameters to float
- Feldman-Cousins frequentist approach gave identical results



# A toy model for systematic studies

- Construct RS & WS lifetime distributions using measured right-sign yield ( $Y_{RS}$ ),  $R_{DCS}$ ,  $x'^2$ ,  $y'$ ,  $D^0$  with fake soft pion background, and approximate lifetime efficiency function
- Fit these lifetime distributions to obtain  $Y_{RS}$ ,  $R_{DCS}$ ,  $x'^2$ , and  $y'$  (only 4 fit parameters). Background amount is fixed to the input value.
- Obtain contours just like for data
- Toy model contours mimic real data and  $100\times$  faster to construct
- Toy model reproduces data with very different fit techniques and cuts
- Contour shape is determined solely by  $x'^2$ ,  $y'$ ,  $R_{DCS}$ , and the statistics of signal & background
- Using toy model can remove effect of statistics (keep  $Y_{RS}$  and background the same)
- Thus, for given statistics, contours depend *only* on the *measured* value of  $x'^2$ ,  $y'$ , and  $R_{DCS}$ ; that is, the only source of systematic error is due to a different central value found by different variations

# Obtaining a contour including systematic errors

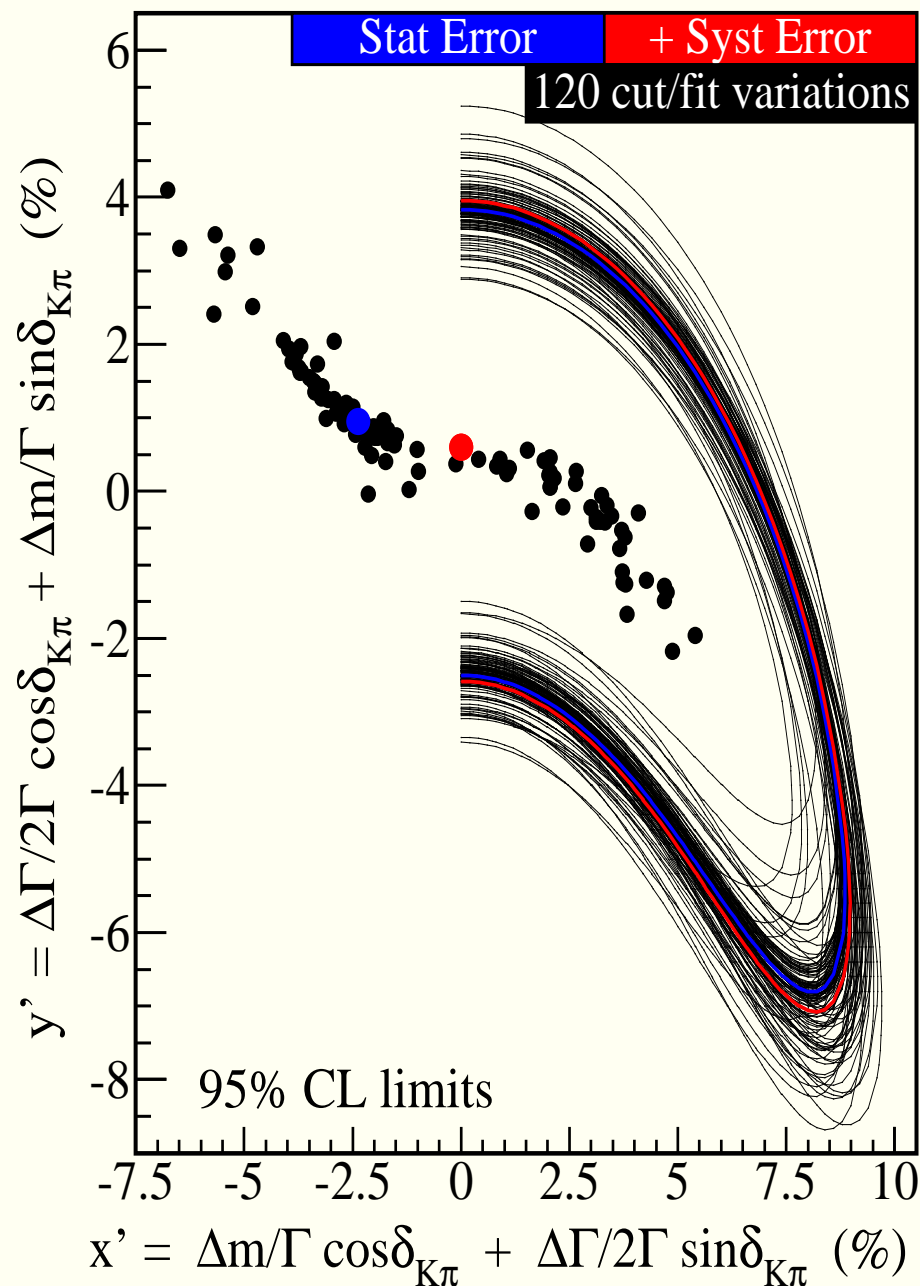
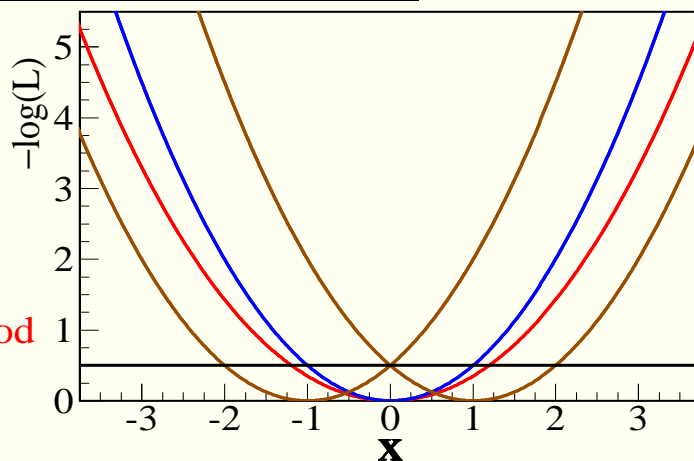
- Average  $\mathcal{L}$  of 120 variations to obtain grand likelihood
- $\log \mathcal{L}(\mathbf{x})_{grand} = \log \left( \sum_{i=1}^{120} \mathcal{L}_i(\mathbf{x}) - \mathcal{L}_i^{\min} \right)$
- 95% CL contour obtained from  $\Delta \log \mathcal{L}_{grand} = 2.995$
- Good: error is independent of number of variations
- Bad: no real justification

## Simple example

Statistical error  
default fit

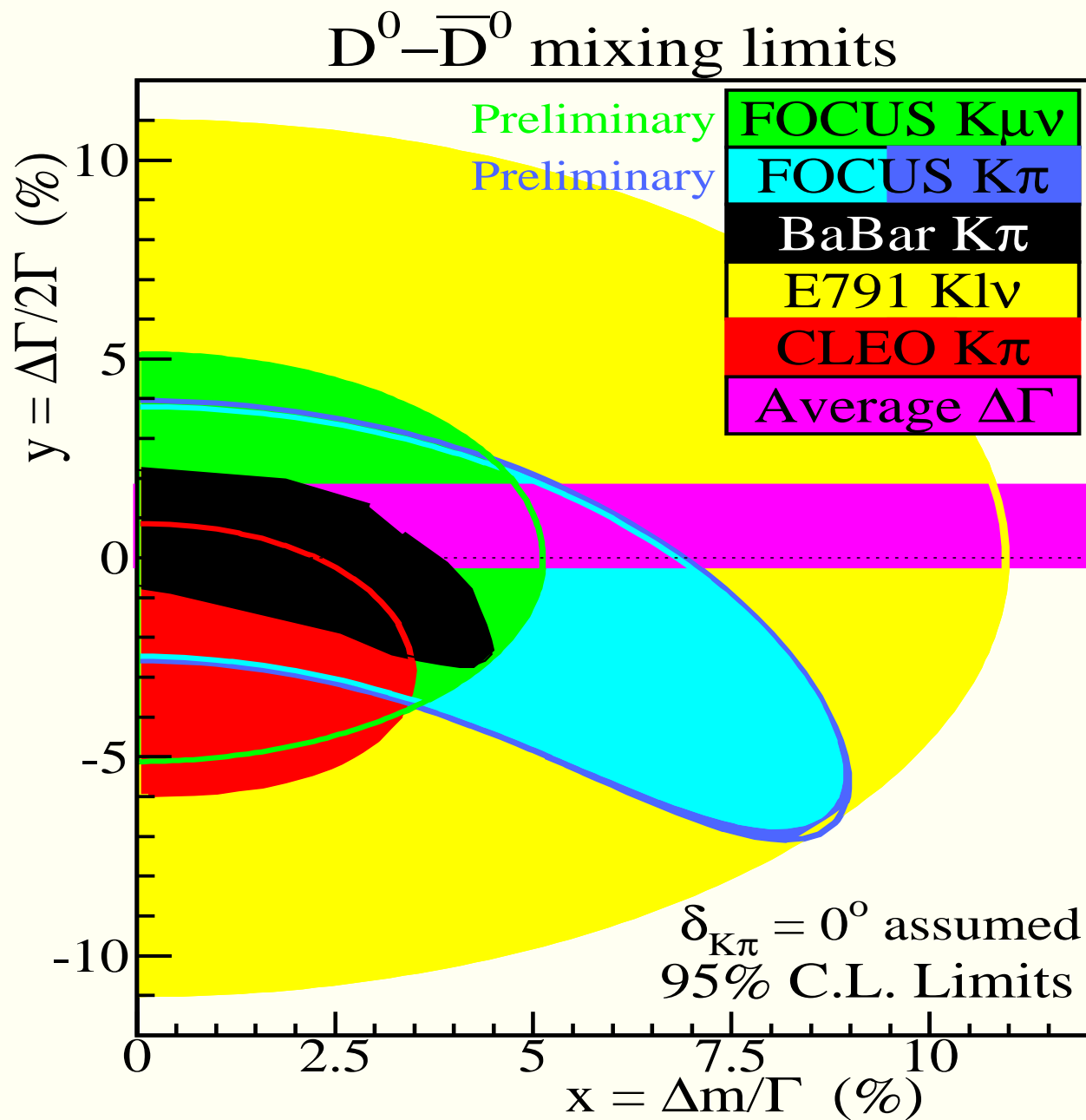
Statistical error  
two fit variants

Total error  
average likelihood



# Comparison with other mixing results

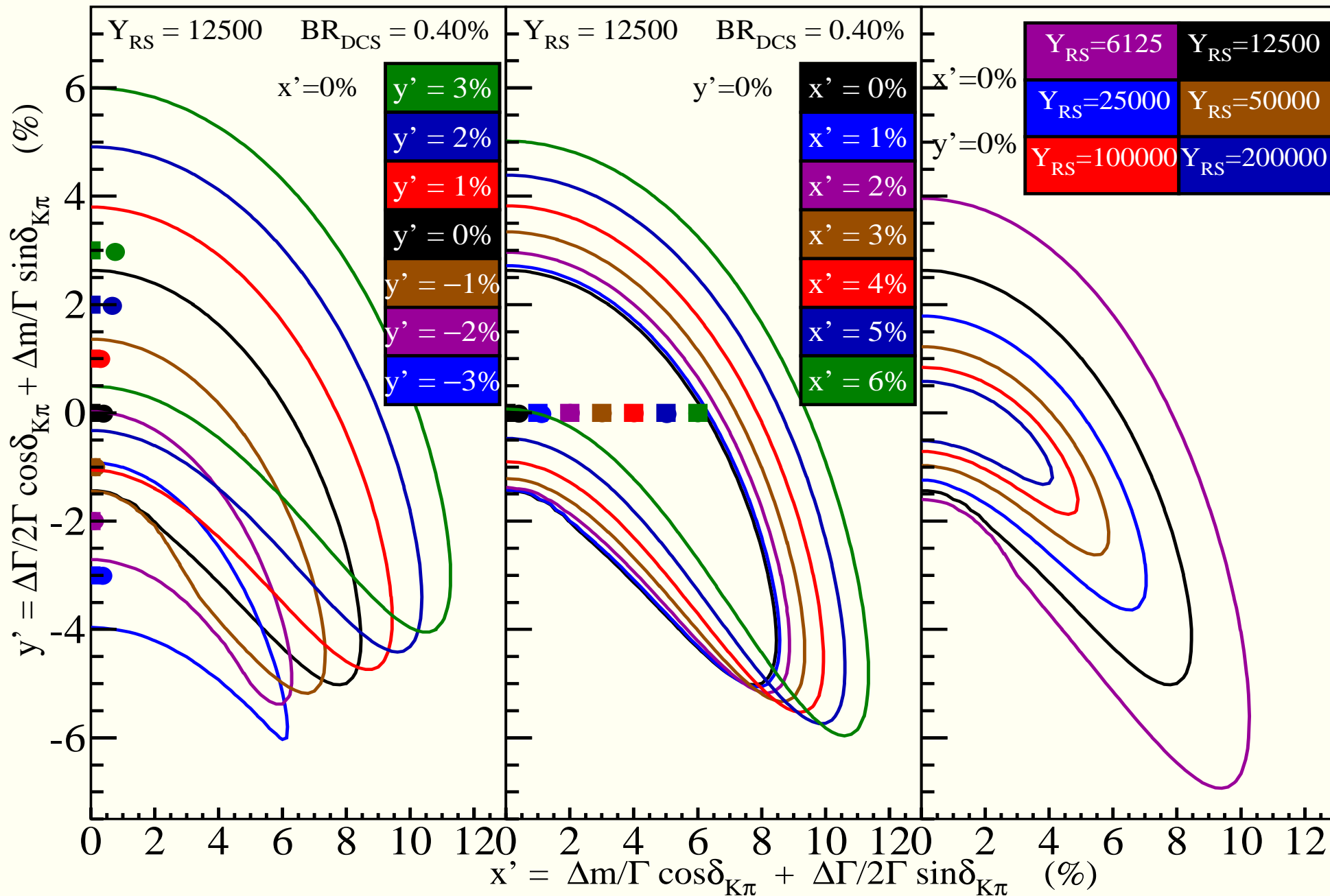
- All results shown assume CP conservation
- **FOCUS** results agree better with **BaBar** in location and shape than **CLEO**



# Understanding the contour shape

- Simplify toy model to perfect experiment
- Generate RS & WS lifetime signal distributions
- Input and fit four parameters:  $Y_{RS}$ ,  $R_{DCS}$ ,  $x'$  &  $y'$
- Map out  $x'-y'$  95% CL contour
- Assumes perfect resolution, perfect acceptance, and no background

# Study of $x'-y'$ contour



# Summary of new FOCUS results

- Preliminary measurement of wrong-sign branching ratio  
 $R_{WS} = 0.430 \pm 0.062 \pm 0.031$
- Preliminary hadronic mixing  $x' - y'$  contours; agrees better with BaBar than CLEO
- Found that *measured* value of  $y'$  dramatically affects size of  $x' - y'$  contour



# Backup slides



# Reconstruction and event selection

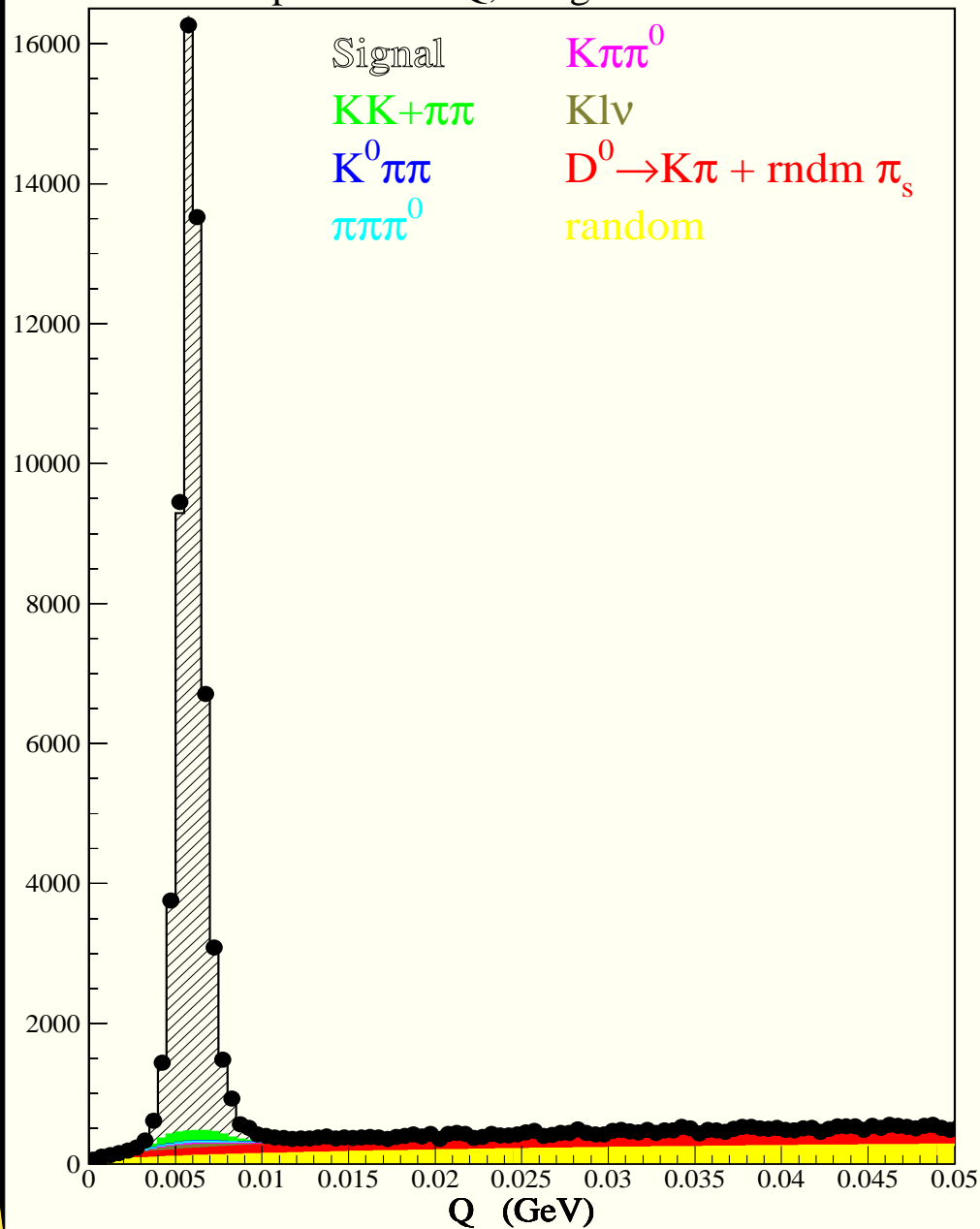
- Search for good  $K^- \pi^+$  vertices for a  $D^0$  candidate
- Use  $D^0$  vector to seed production vertex finding
- Require decay vertex be separated from production vertex and/or located outside of target material
- Čerenkov variable  $W_i(j)$  is the negative log-likelihood that track  $j$  is particle type  $i$
- $K^-$  candidate must have  $W_\pi(K) - W_K(K) > 0.5$
- $\pi^+$  candidate must have  $W_K(\pi) - W_\pi(\pi) > -3$
- Also,  $W_\pi(K) - W_K(K) + W_K(\pi) - W_\pi(\pi)$  must be  $> 3$  and  $> 8.5 - 0.5 |M_{ref}(D^0) - 1.865| / \sigma_M$  to remove double-misid
- Minor cleanup cuts also applied, mostly removing random combinatoric background

# Analysis summary

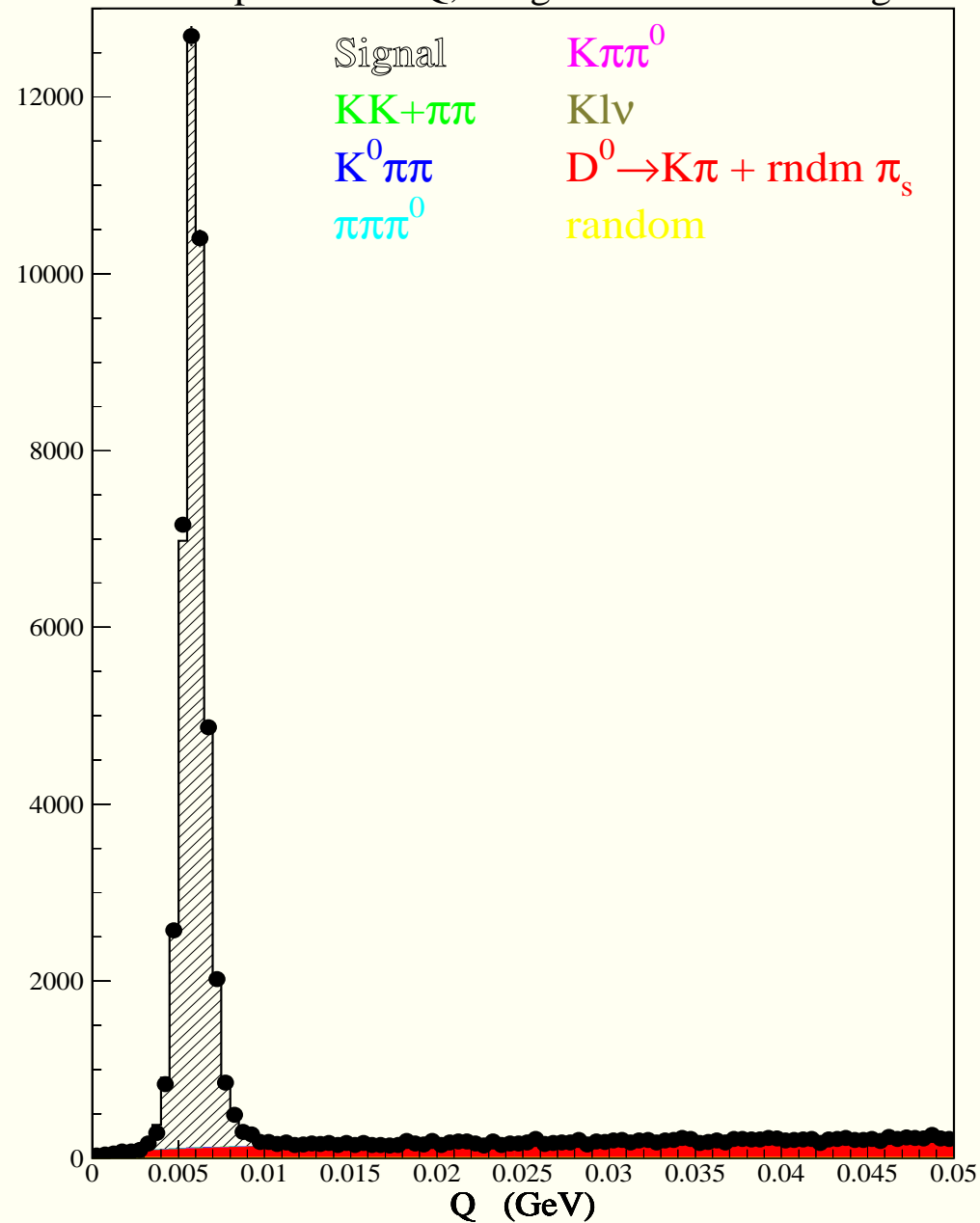
- 3D Binned likelihood fit to right- and wrong-sign using  $M(D^0)$ ,  $Q(D^*)$ , and  $\tau_{D^0}$  to extract DCSD & mixing information
- Build up fit model from many components
- Need accurate shapes for signal and backgrounds (PHOTOS needed for mass shapes)
- Shapes ( $D^0$  and  $D^*-D^0$  Q-value) obtained from MC for various reflections
- Signal shape from MC
- Lifetime efficiency  $\epsilon(t)$  from MC (check with data)
- $\tau$  of  $KK$ ,  $\pi\pi$ ,  $\pi\pi\pi^0$ ,  $K\ell\nu$ ,  $K\pi\pi^0$  dble misid from MC
- $\tau$  of  $D^0/D^*$  signal &  $D^0$ +rndm  $\pi$  from MC
- $\tau$  of mixing (interference) =  $\epsilon\tau_{D^0} \times t^2 (t)$

# RS $Q(D^*)$ projection

$K\pi$  RS components vs  $Q$ , integrated over  $M$  and  $\tau$

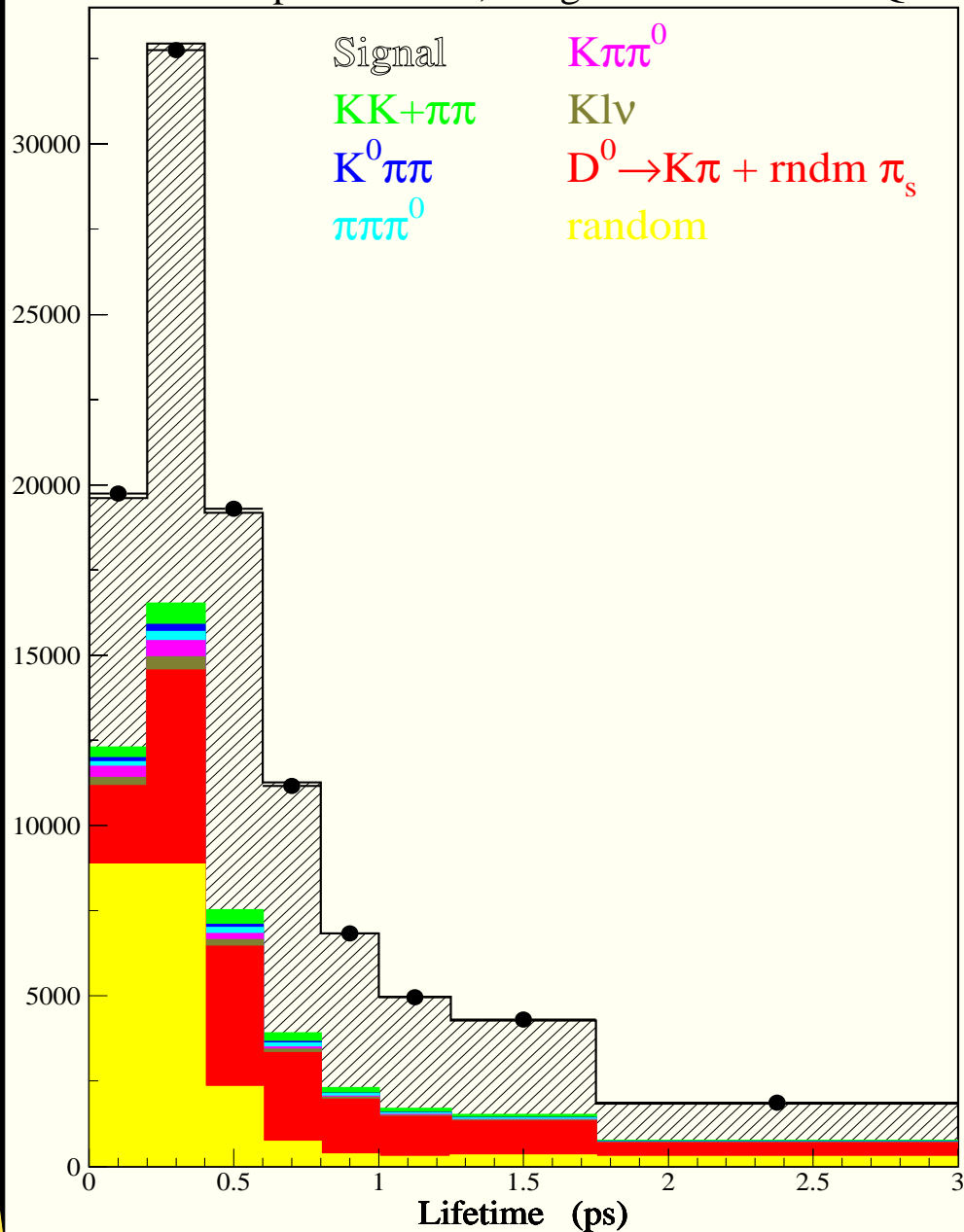


$K\pi$  RS components vs  $Q$ , integrated over  $\tau$  in  $M$  signal



# RS $\tau(D^0)$ projection

K $\pi$  RS components vs  $\tau$ , integrated over M and Q



K $\pi$  RS components vs  $\tau$  in M/Q signal

