D^0–$\overline{D}^0$ hadronic mixing and DCS decays

Kevin Stenson

stenson@fnal.gov

University of Colorado

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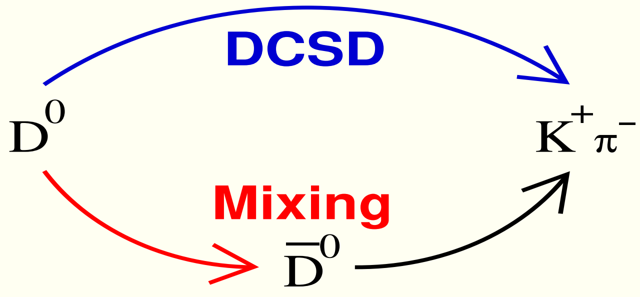
Hadronic mixing 101

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



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

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

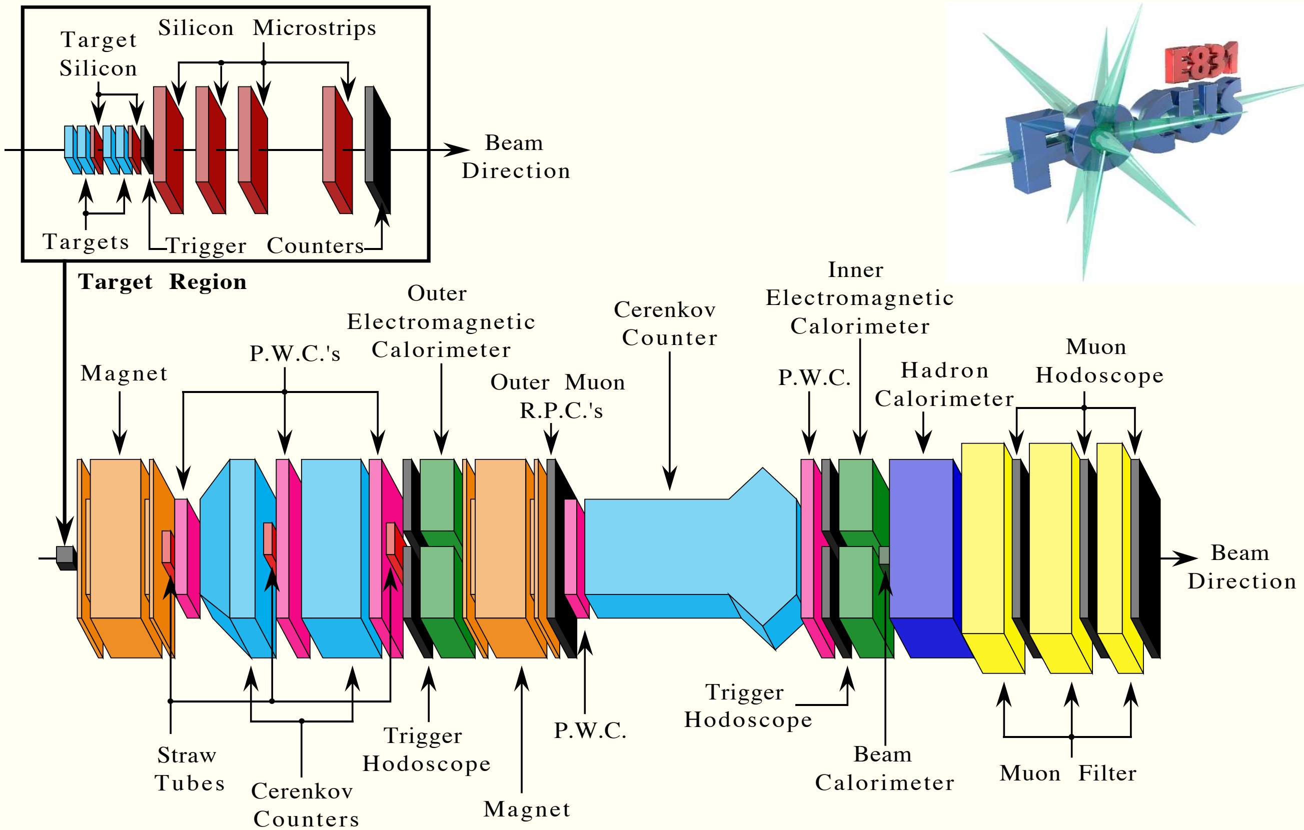
$$x' \equiv x \cos\delta + y \sin\delta \qquad\qquad y' \equiv y \cos\delta - x \sin\delta$$

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 π_s charge in $D^{*+} \to D^0\pi_s^+$ decays defining right-sign (RS) and wrong-sign (WS)
- Fit for R_{DCS}, x'^2, y'

The FOCUS experiment

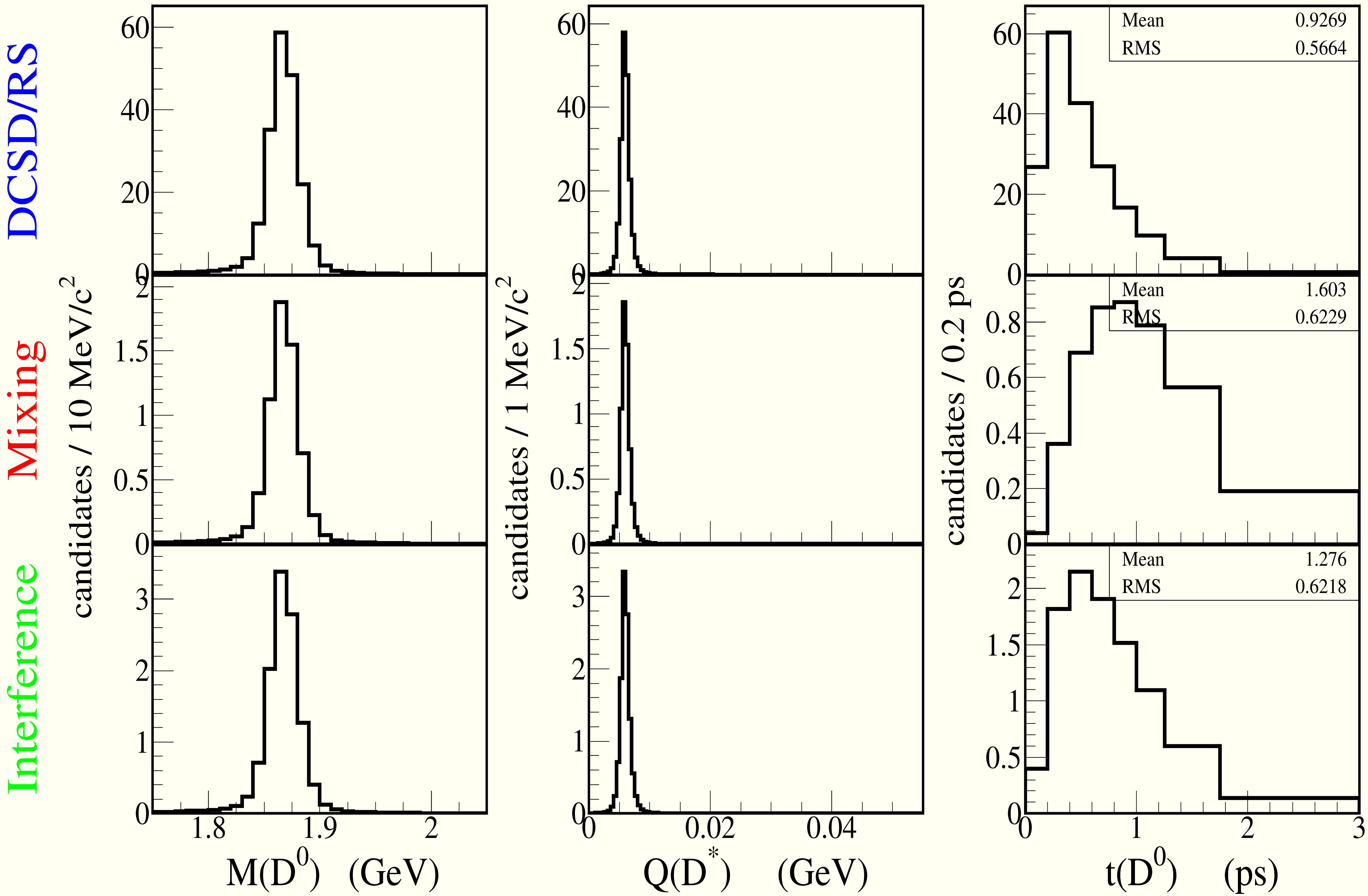
- FOCUS took data in the Fermilab fixed-target run of 1996-7
- $e^{\pm}$ at $\sim$300 GeV bremsstrahlung on lead target to create photon beam
- Photons interact in BeO targets
- Charged particles tracked and momentum analyzed with silicon strips, wire chambers, and two magnets
- Three multicell threshold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



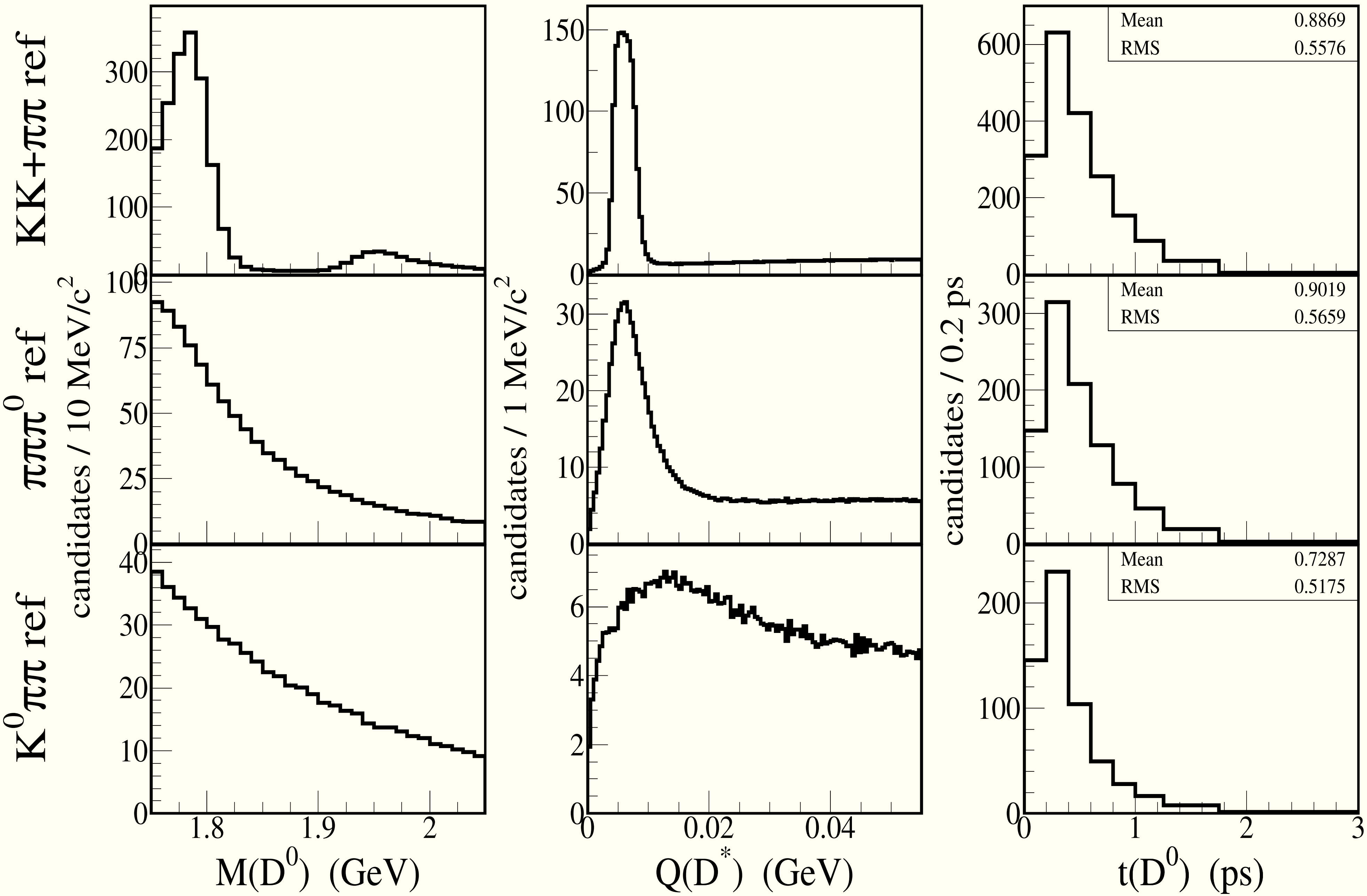
Mixing analysis

- 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 π_s, $D^0 \to K^-K^+, \pi^+\pi^-, \pi^+\pi^-\pi^0, K^0\pi^+\pi^-, K^-\pi^+\pi^0, K^-\ell\nu$, double misid of $D^0 \to K^-\pi^+$, and random combination of tracks (broken charm or minimum bias)
- Obtain shapes from MC (checked with data) preserving correlations when necessary

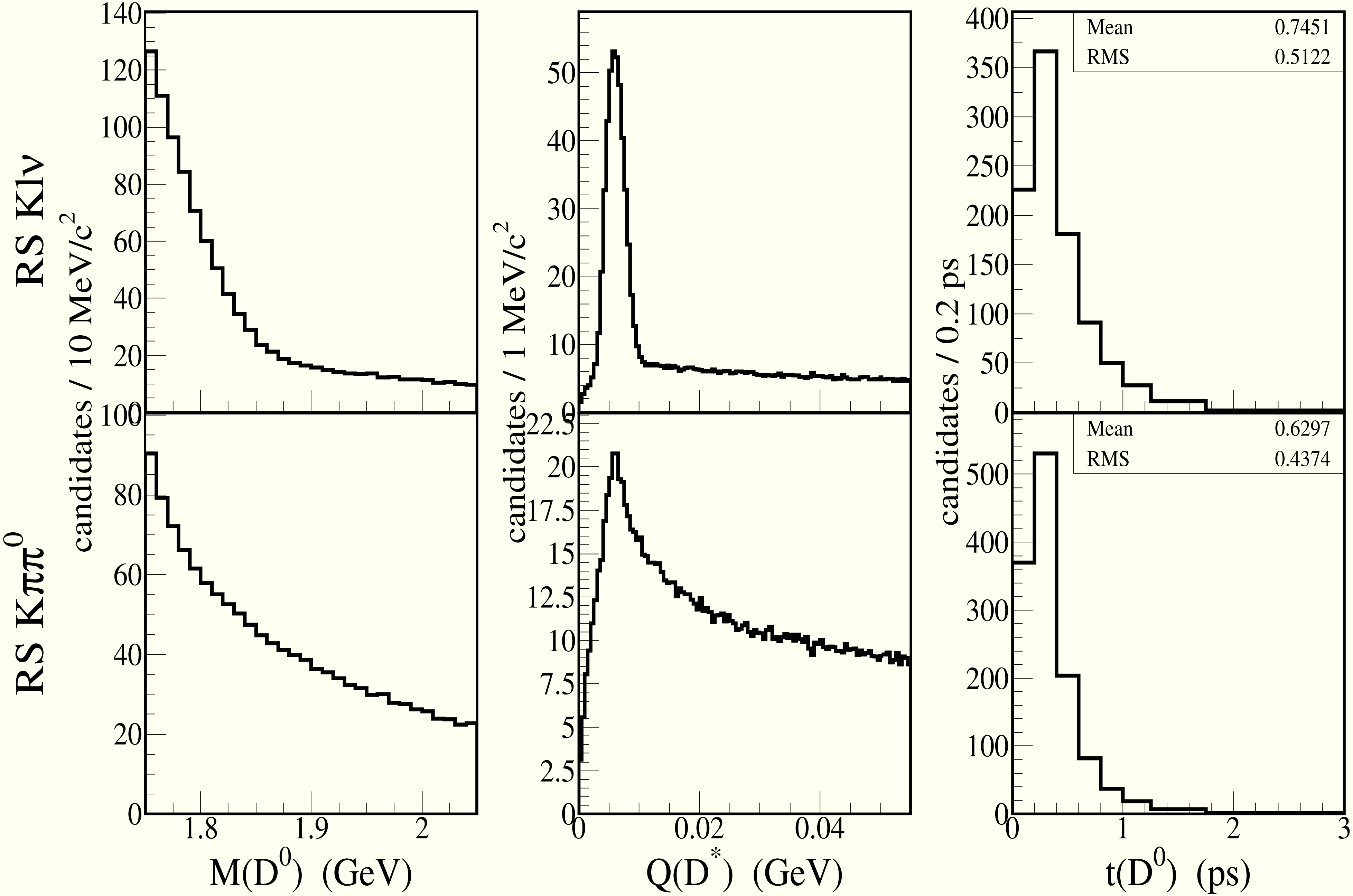
Fit shapes – Signal



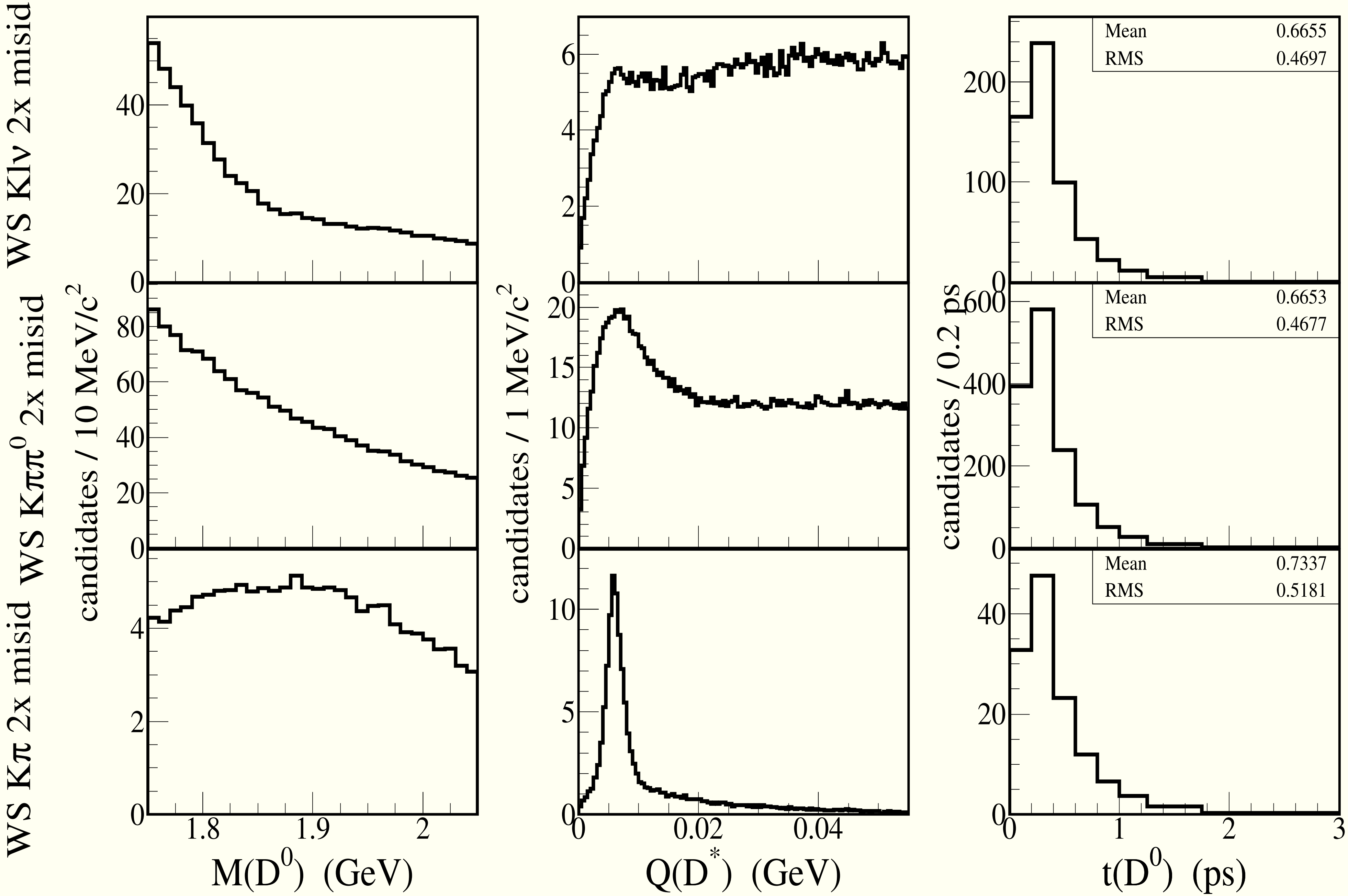
Fit shapes – RS/WS reflections



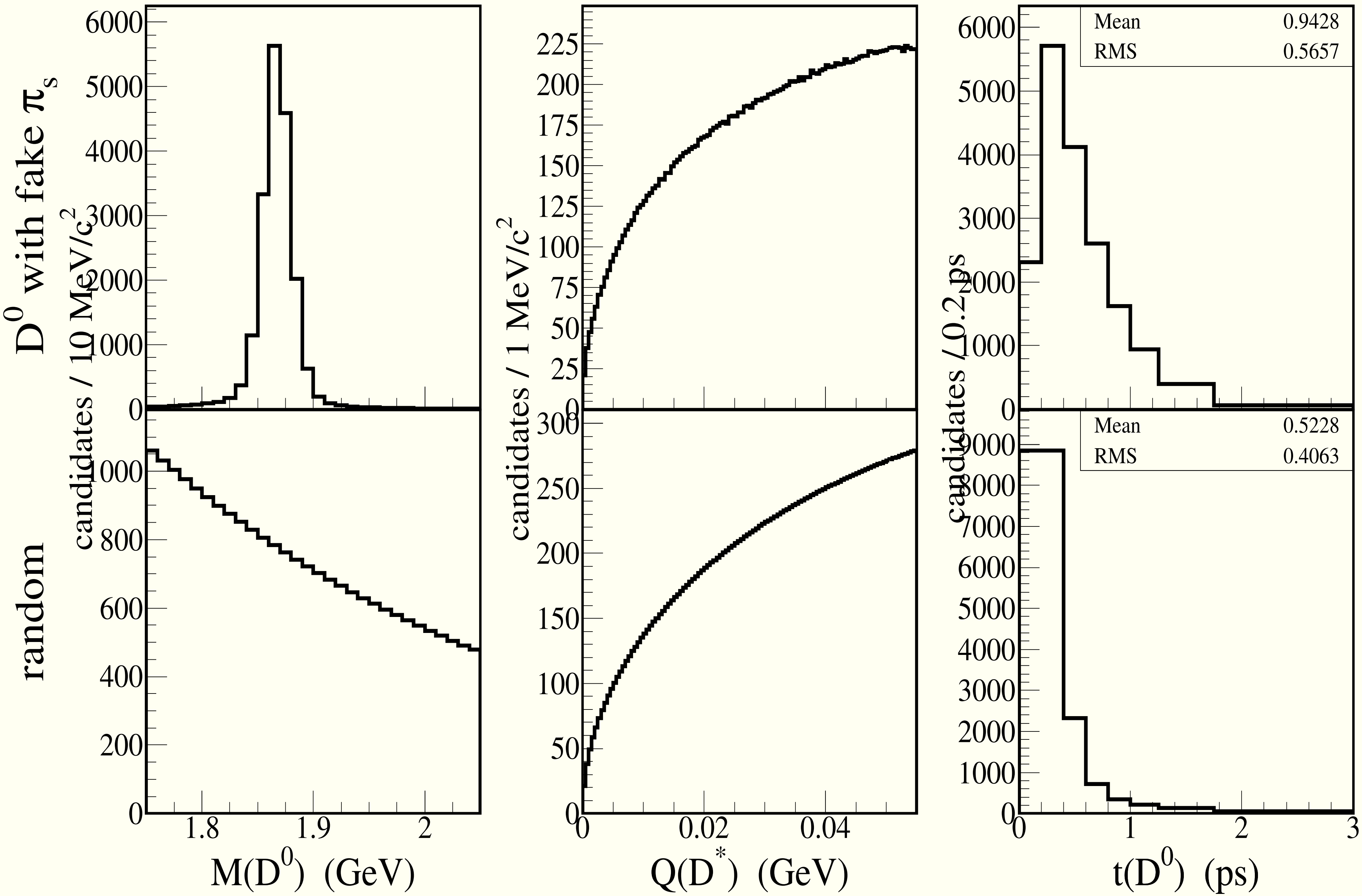
Fit shapes – RS reflections



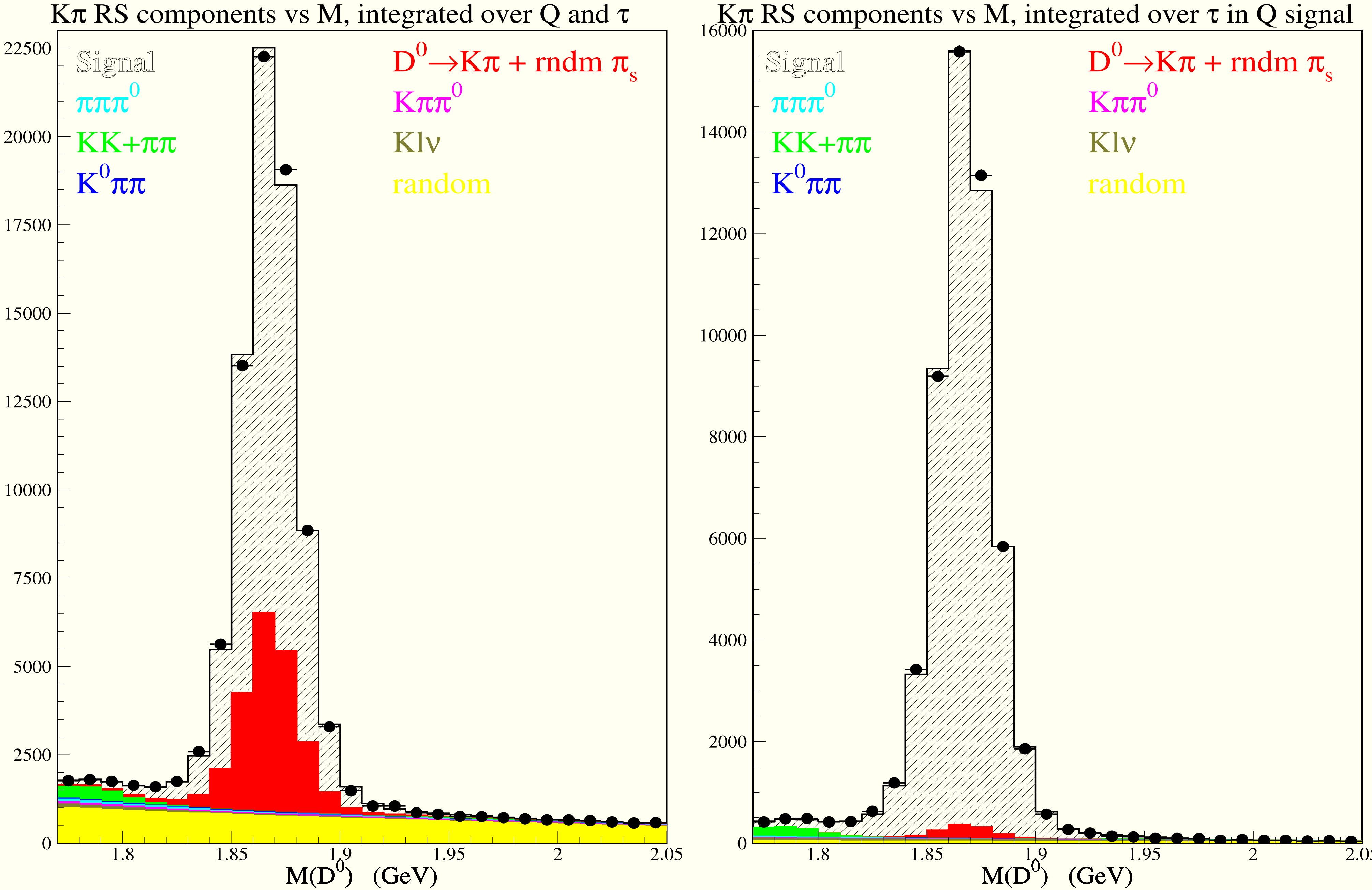
Fit shapes – WS reflections



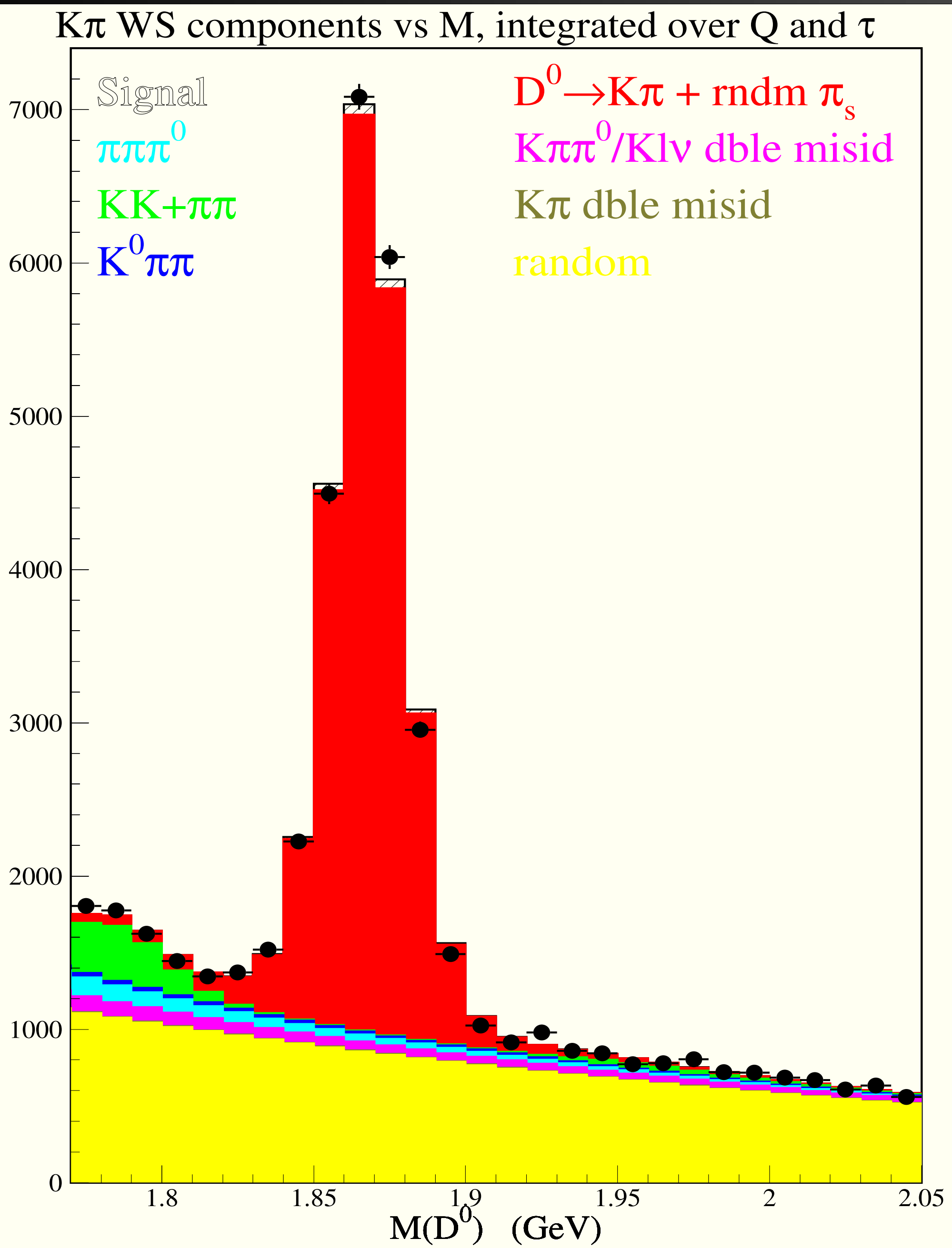
Fit shapes – D^0 with fake π_s & random

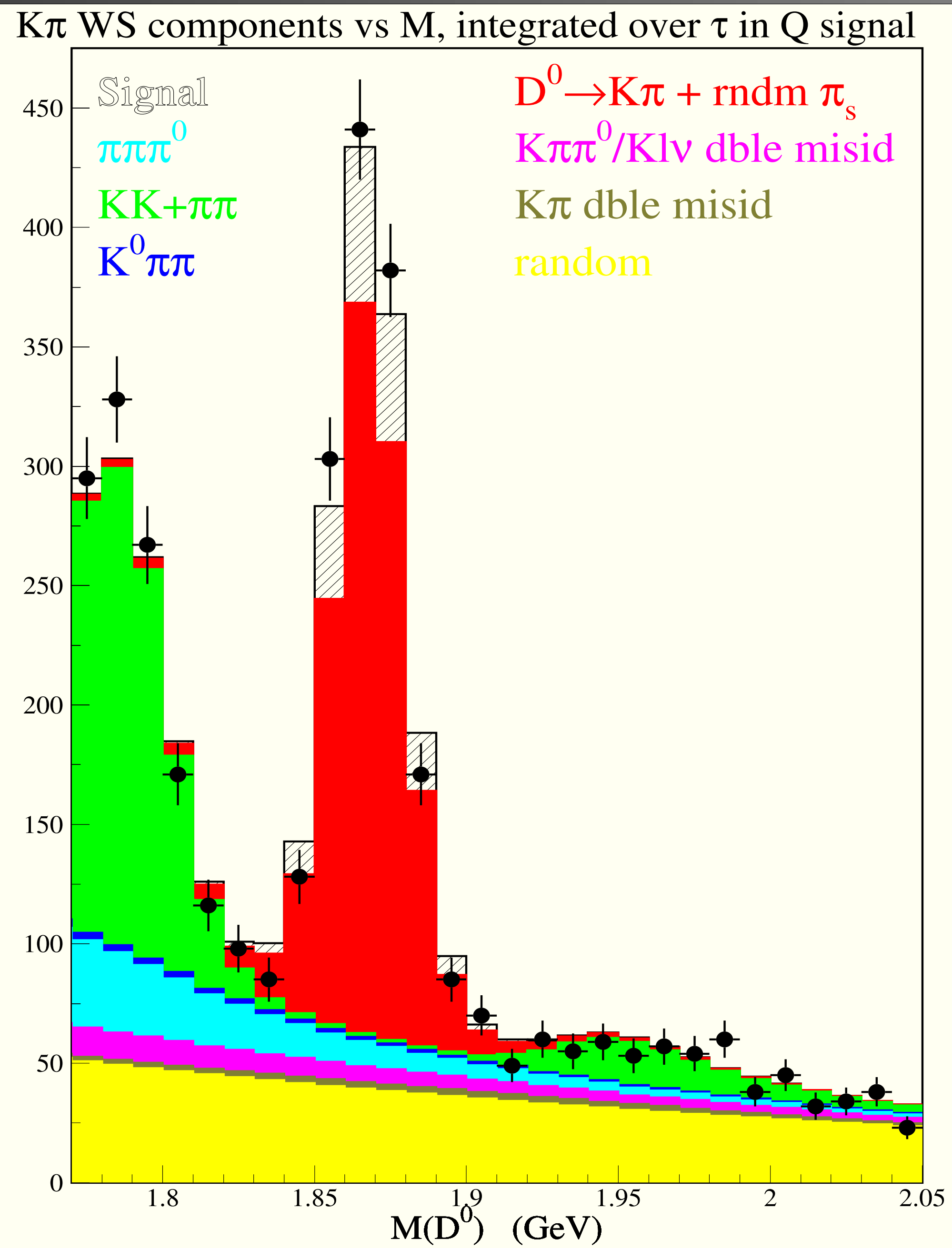


RS $M(D^0)$ projection

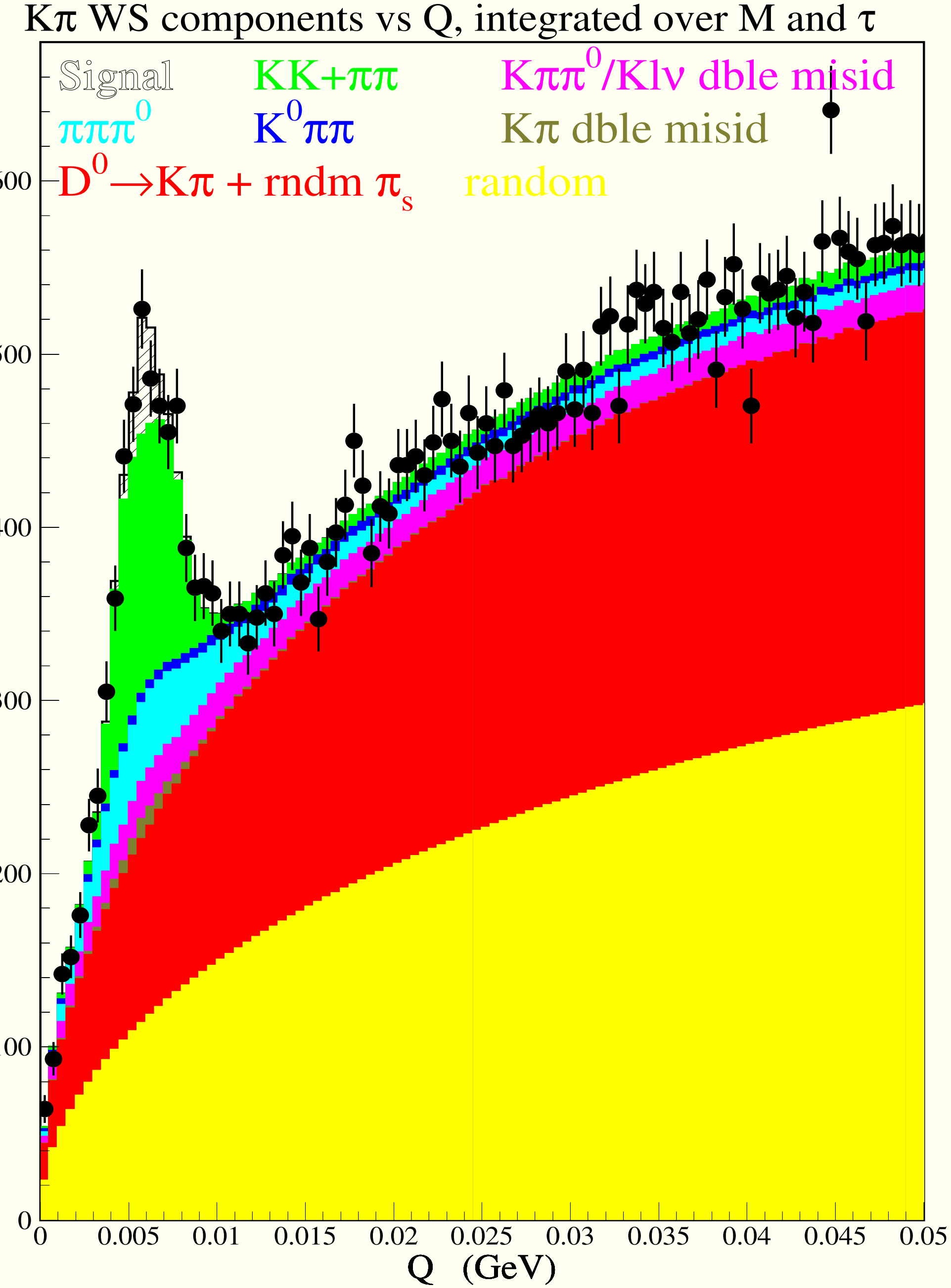


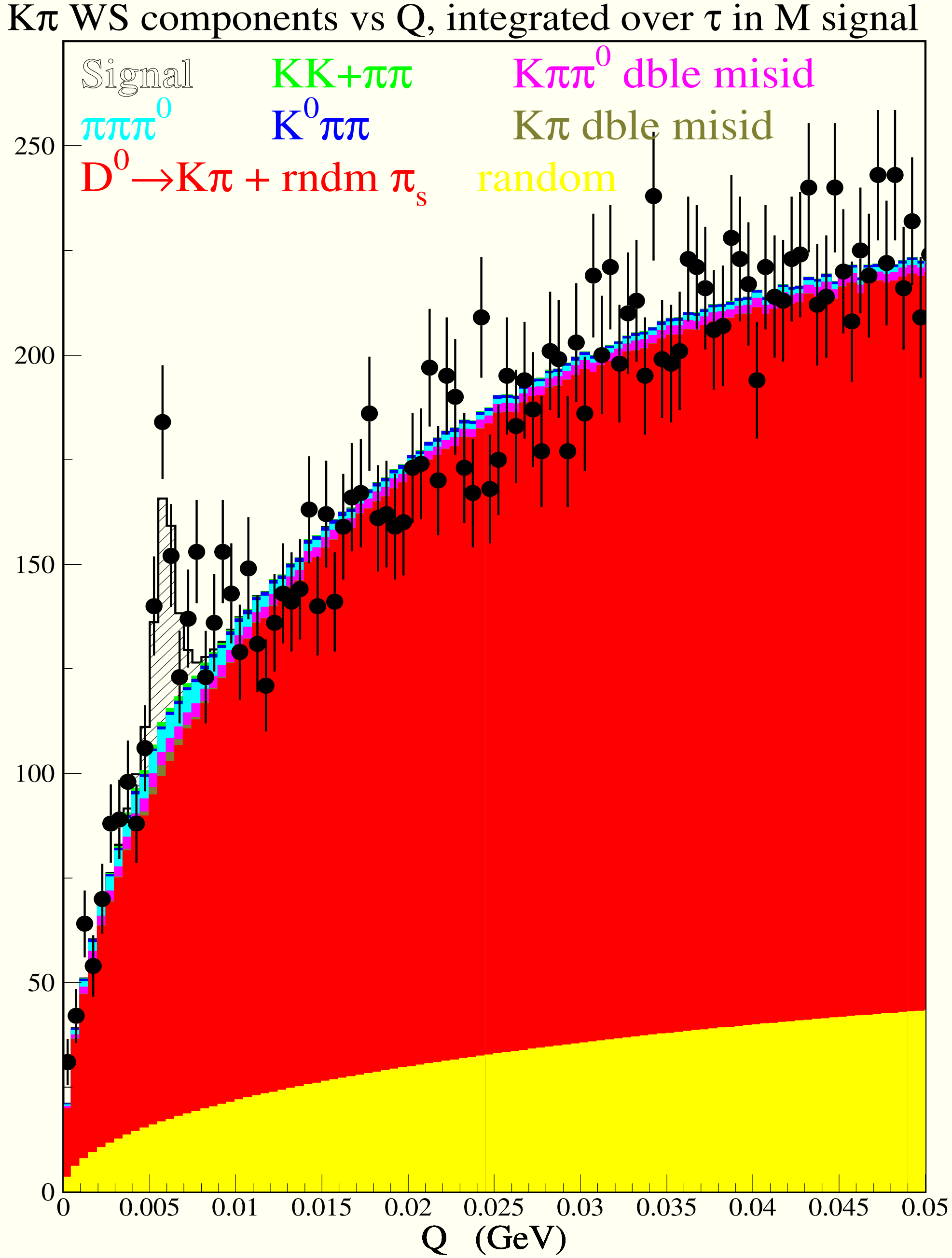
WS $M(D^0)$ projection



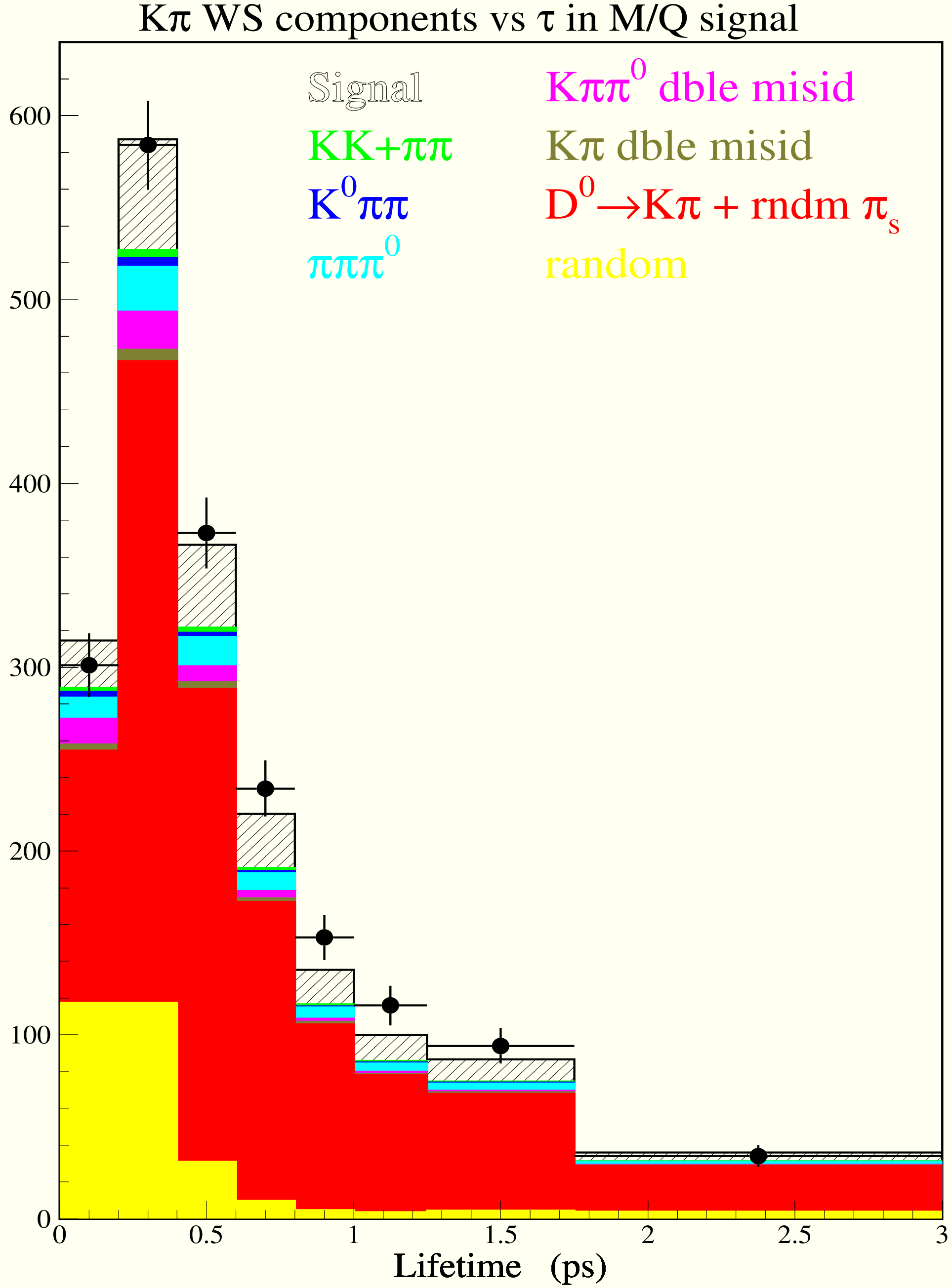


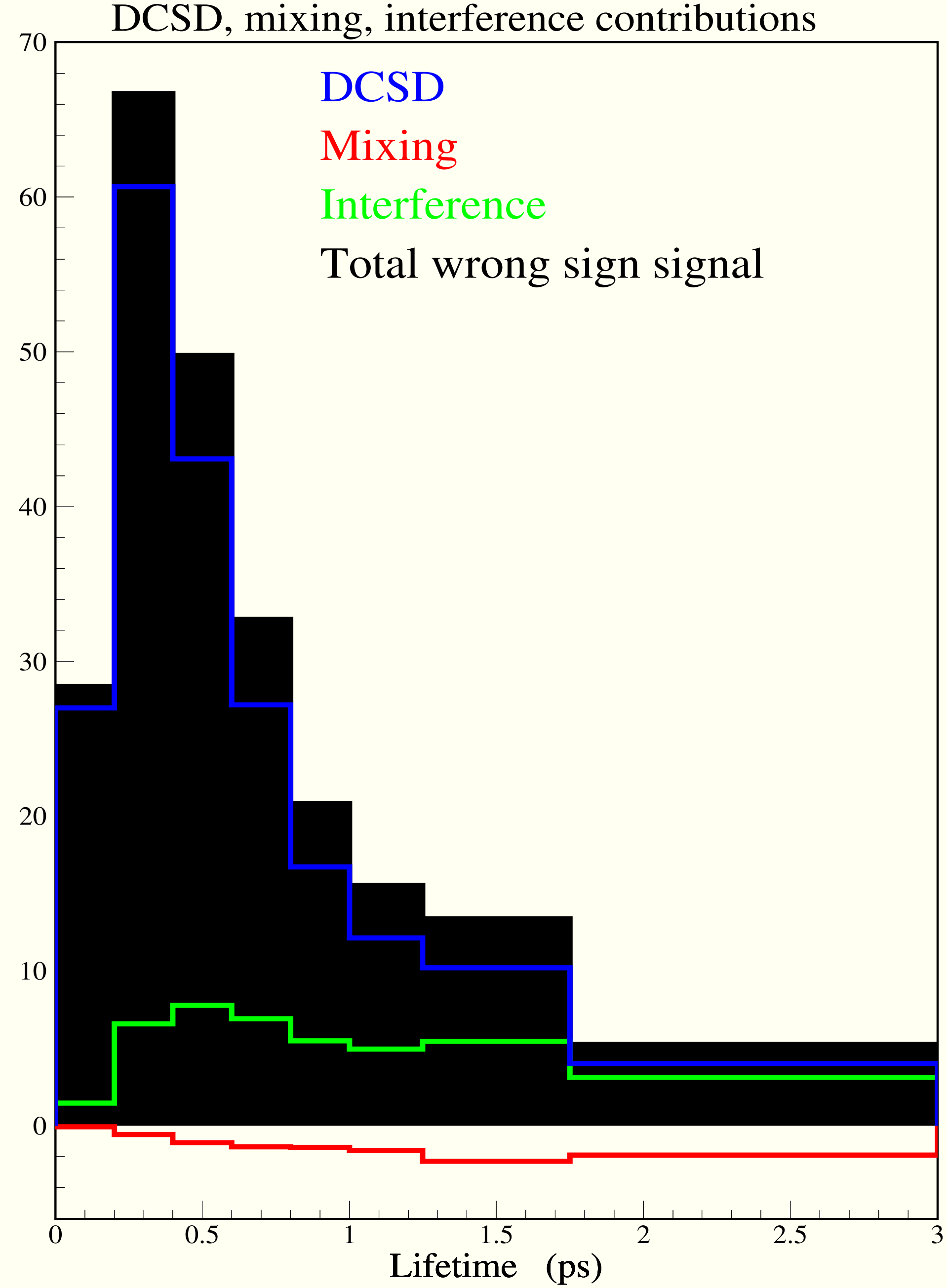
WS $Q(D^*)$ projection





WS $\tau(D^0)$ projection





Branching ratio and mixing results

Expt	R_{DCS}(%) – no mix	Events
E791	$0.68 \pm 0.34 \pm 0.07$	34
CLEO	$0.332 \pm 0.064 \pm 0.040$	45 ± 9
FOCUS	$0.404 \pm 0.085 \pm 0.025$	149 ± 31
BaBar	$0.357 \pm 0.022 \pm 0.027$	~ 440
FOCUS	$0.430 \pm 0.062 \pm 0.031$	234 ± 34

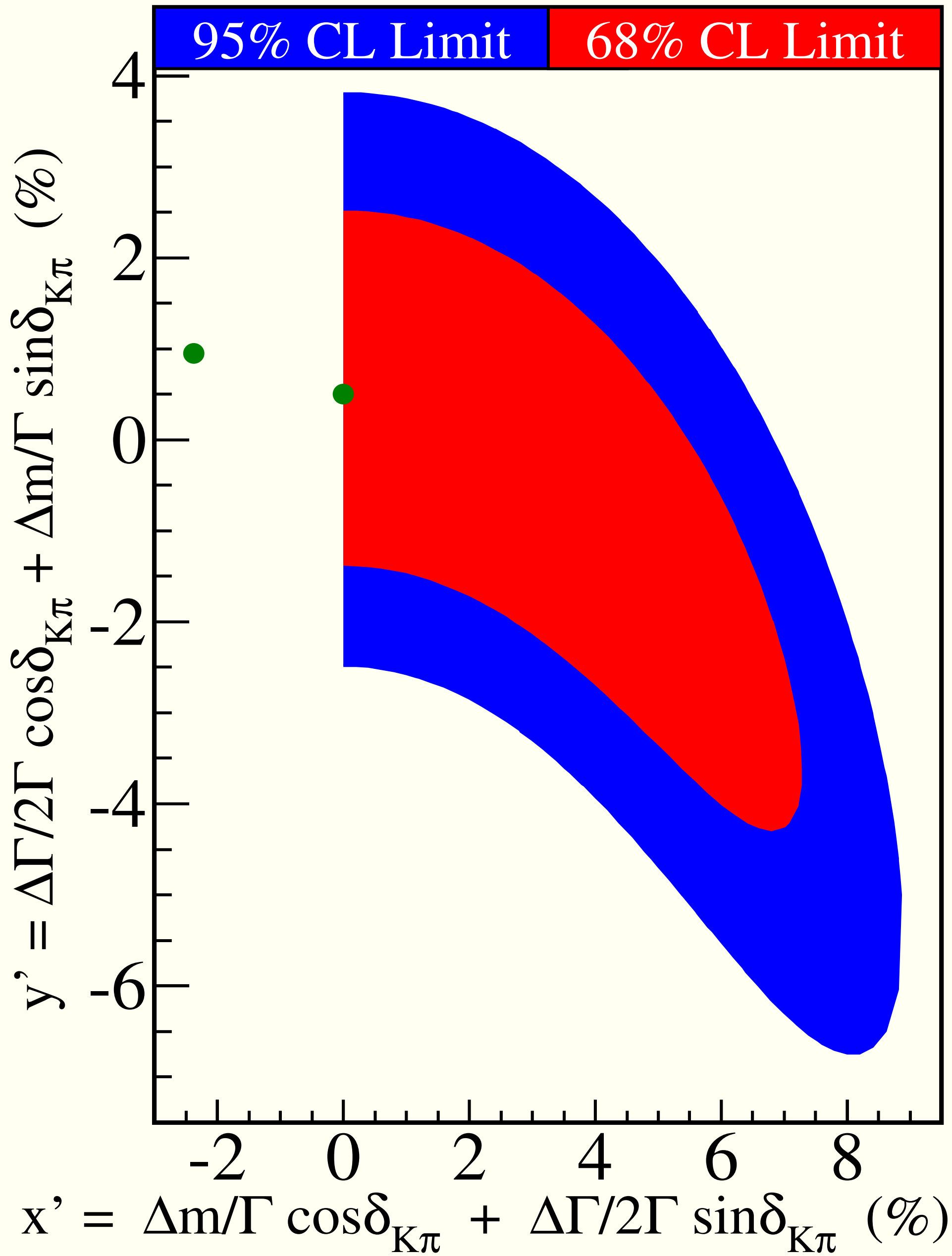
FOCUS systematic errors come from taking the standard deviation of the results obtained by varying selection criteria and fitting technique (120 variations).

FOCUS mixing results (no CP violation):

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

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.

- 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



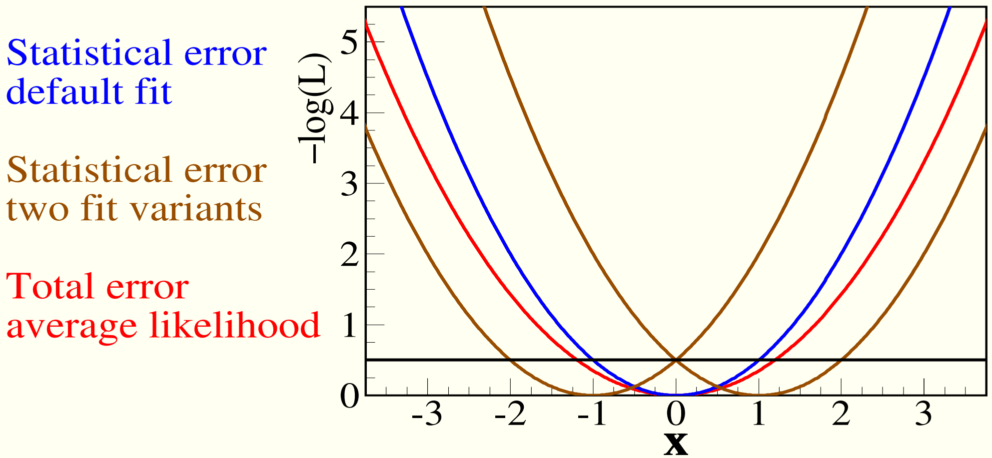
A toy model for systematic studies

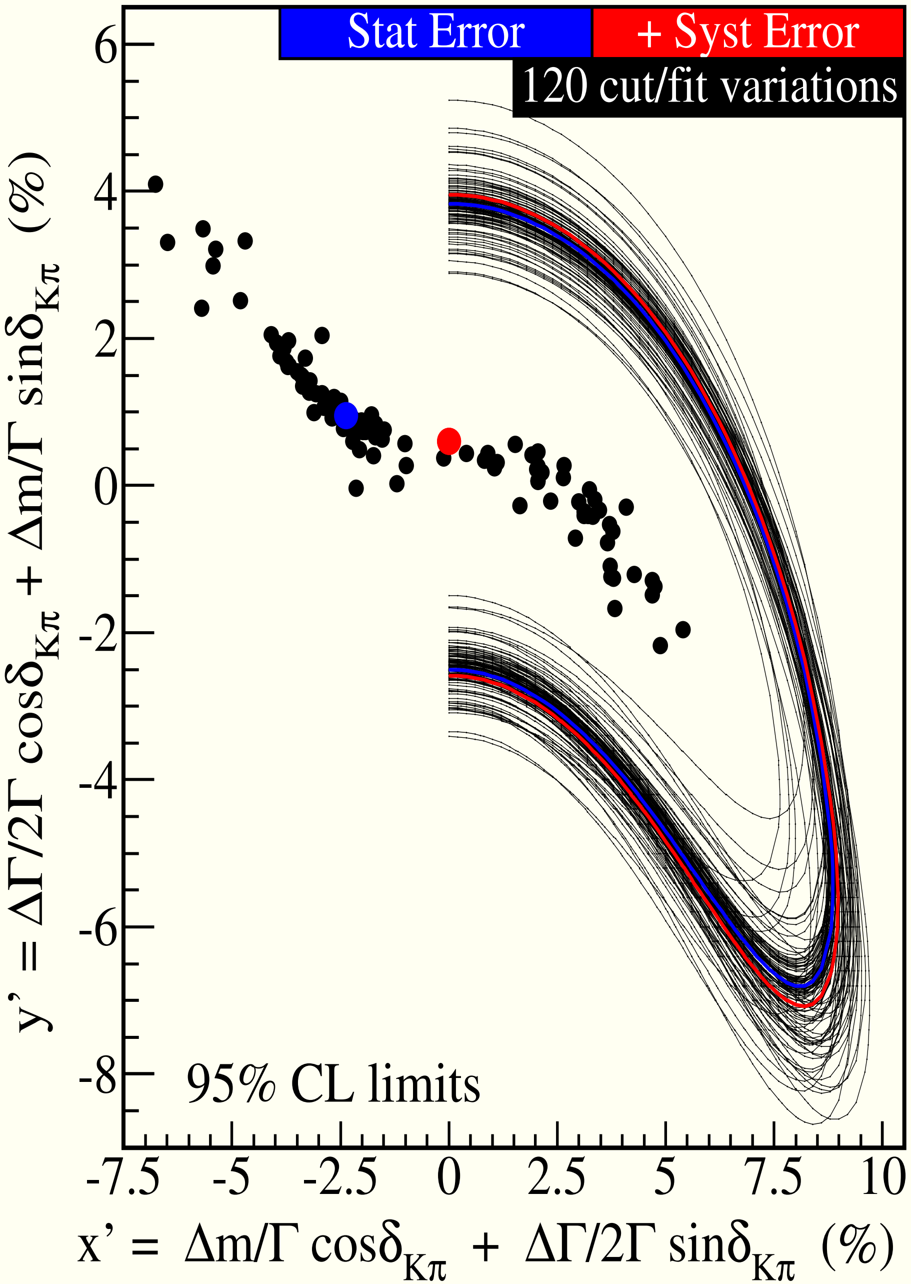
- Construct RS & WS lifetime distributions using measured right-sign yield (Y_{RS}), R_{DCS}, ${x'}^2$, y', D^0 with fake soft pion background, and approximate lifetime efficiency function
- Fit these lifetime distributions to obtain Y_{RS}, R_{DCS}, ${x'}^2$, and y' (only 4 fit parameters). Background 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

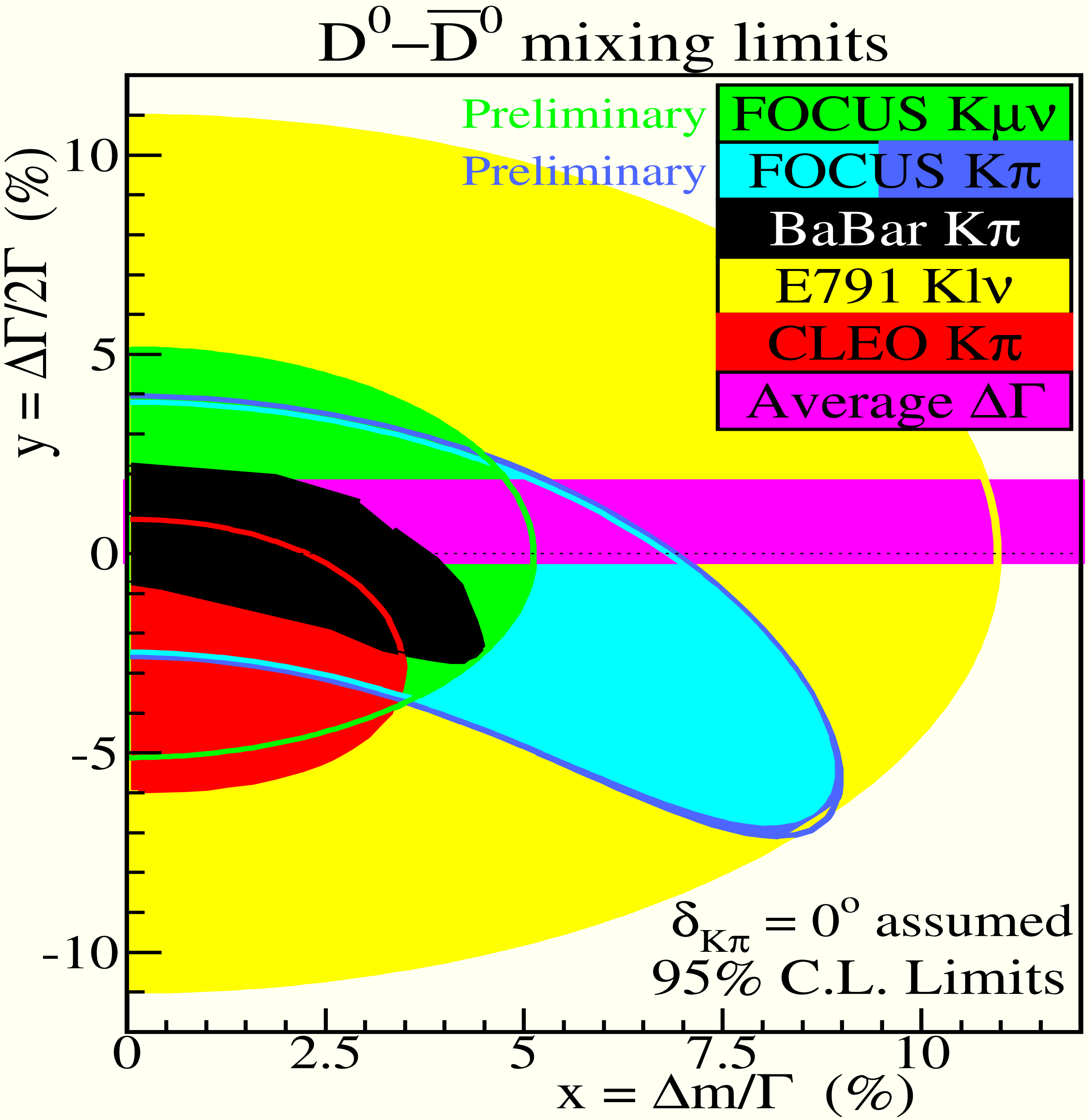
Simple example





Comparison with other mixing results

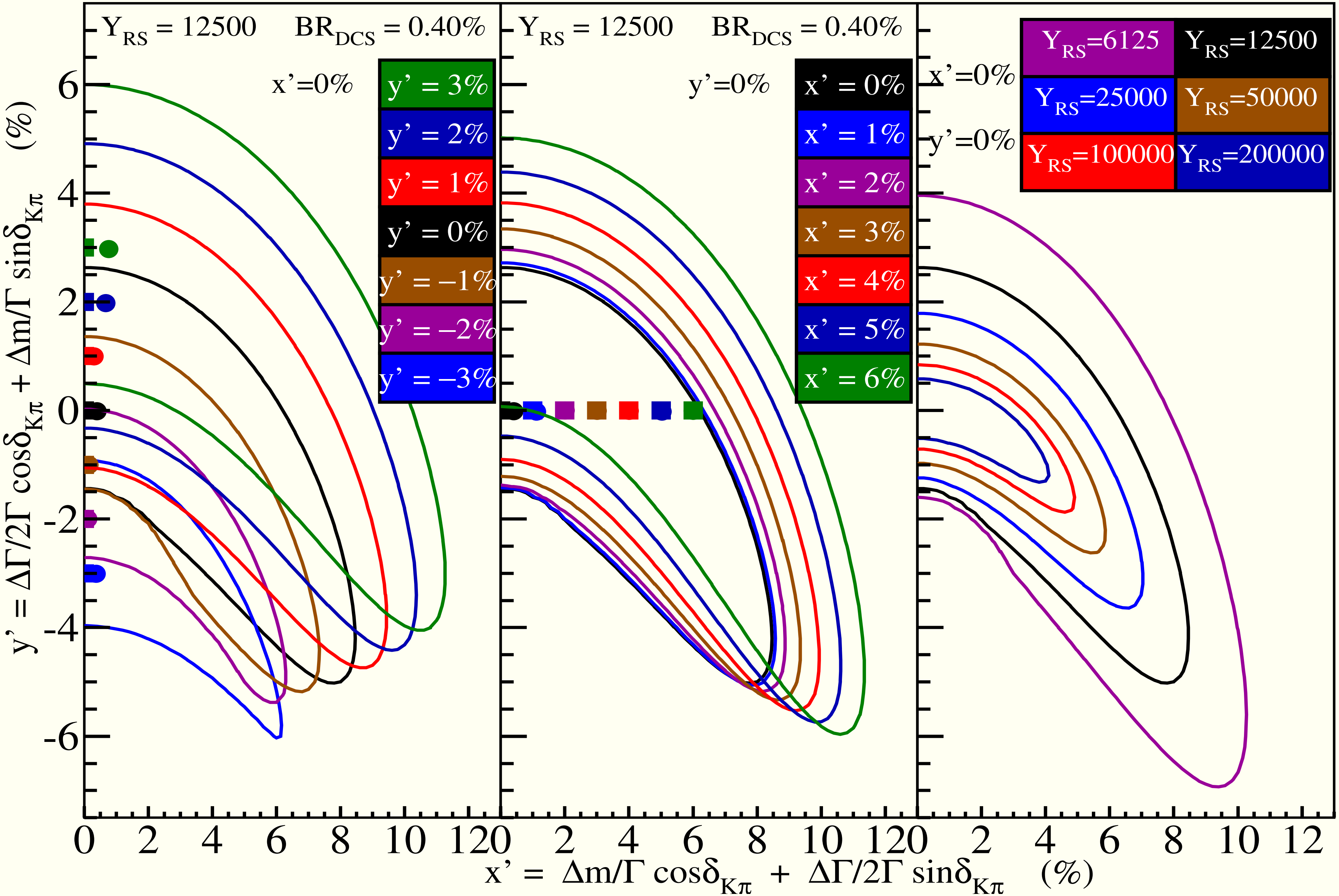
- All results shown assume CP conservation
- FOCUS results agree better with **BaBar** in location and shape than CLEO



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

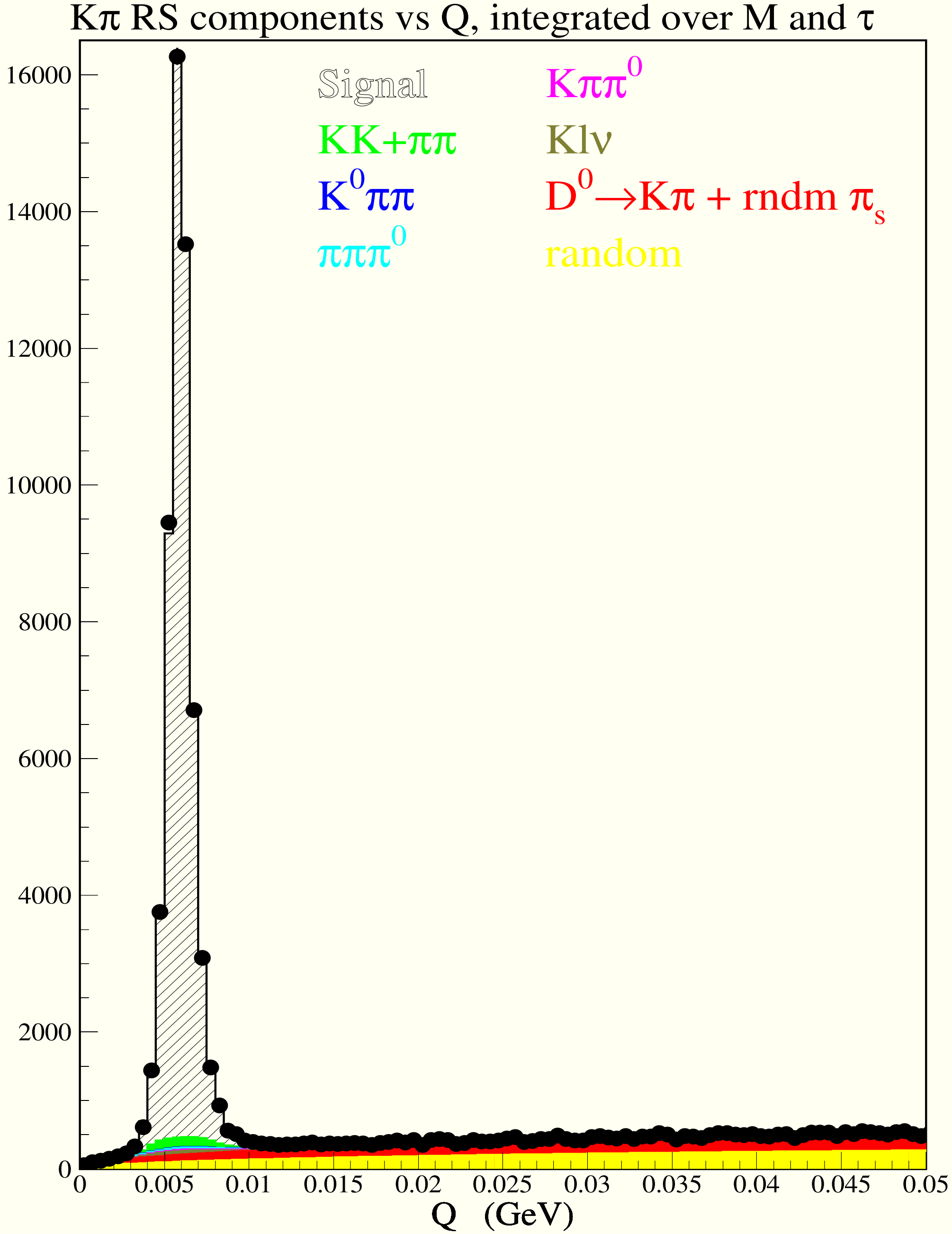
Reconstruction and event selection

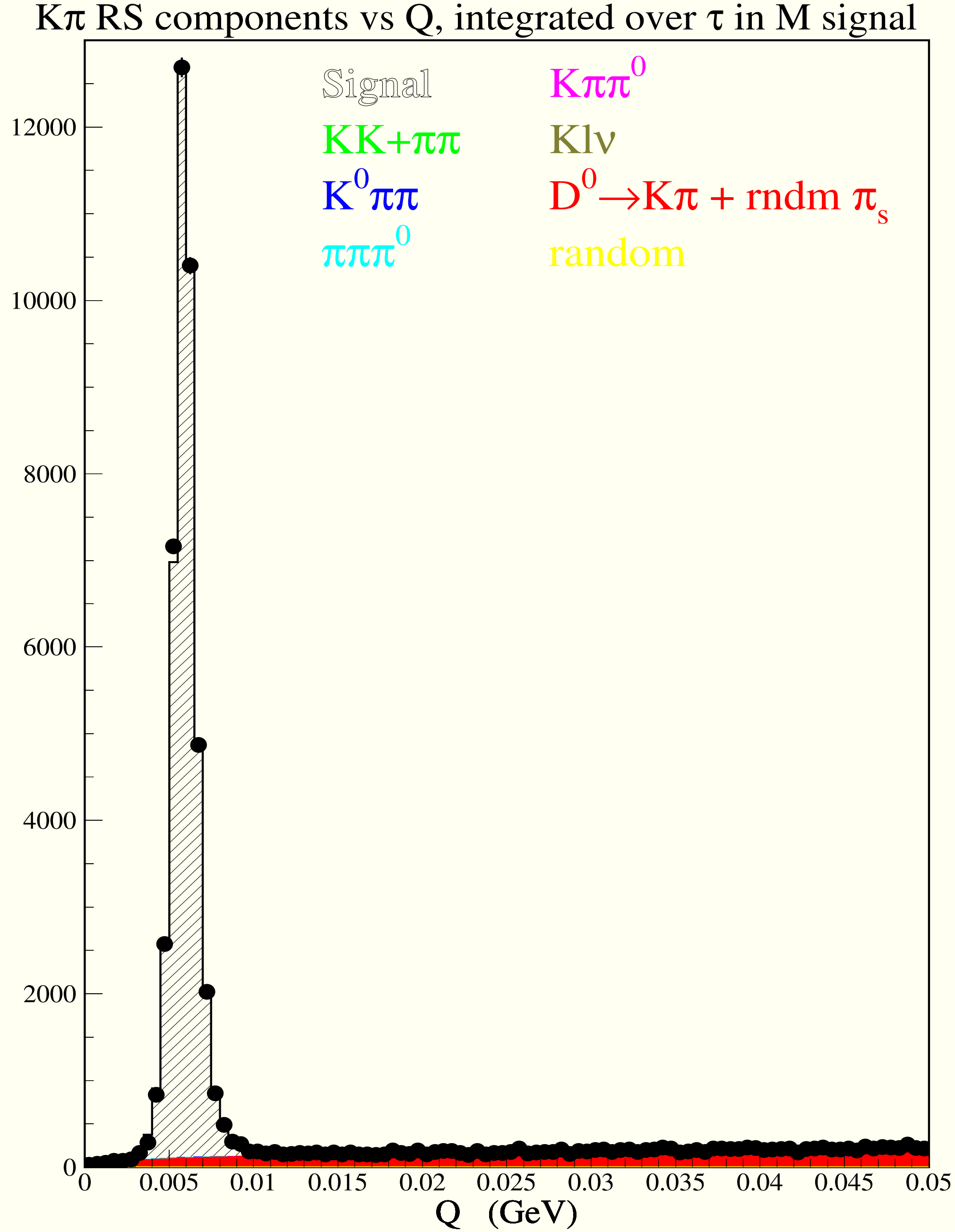
- Search for good $K^-\pi^+$ vertices for a D^0 candidate
- Use D^0 vector to seed production vertex finding
- Require decay vertex be separated from production vertex and/or located outside of target material
- Čerenkov variable $W_i(j)$ is the negative log-likelihood that track j is particle type i
- K^- candidate must have $W_\pi(K) - W_K(K) > 0.5$
- π^+ 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 $> 8.5 - 0.5\left|M_{ref}(D^0) - 1.865\right|/\sigma_M$ 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 τ_{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)
- τ of KK, $\pi\pi$, $\pi\pi\pi^0$, $K\ell\nu$, $K\pi\pi^0$ dble misid from MC
- τ of D^0/D^* signal & D^0+rndm π from MC
- τ of mixing (interference) = $\epsilon\tau_{D^0} \times t^2\ (t)$

RS $Q(D^*)$ projection





RS $\tau(D^0)$ projection