# Charm Physics from FOCUS

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*Weak Interactions and Neutrino Workshop, 2003*

# Outline

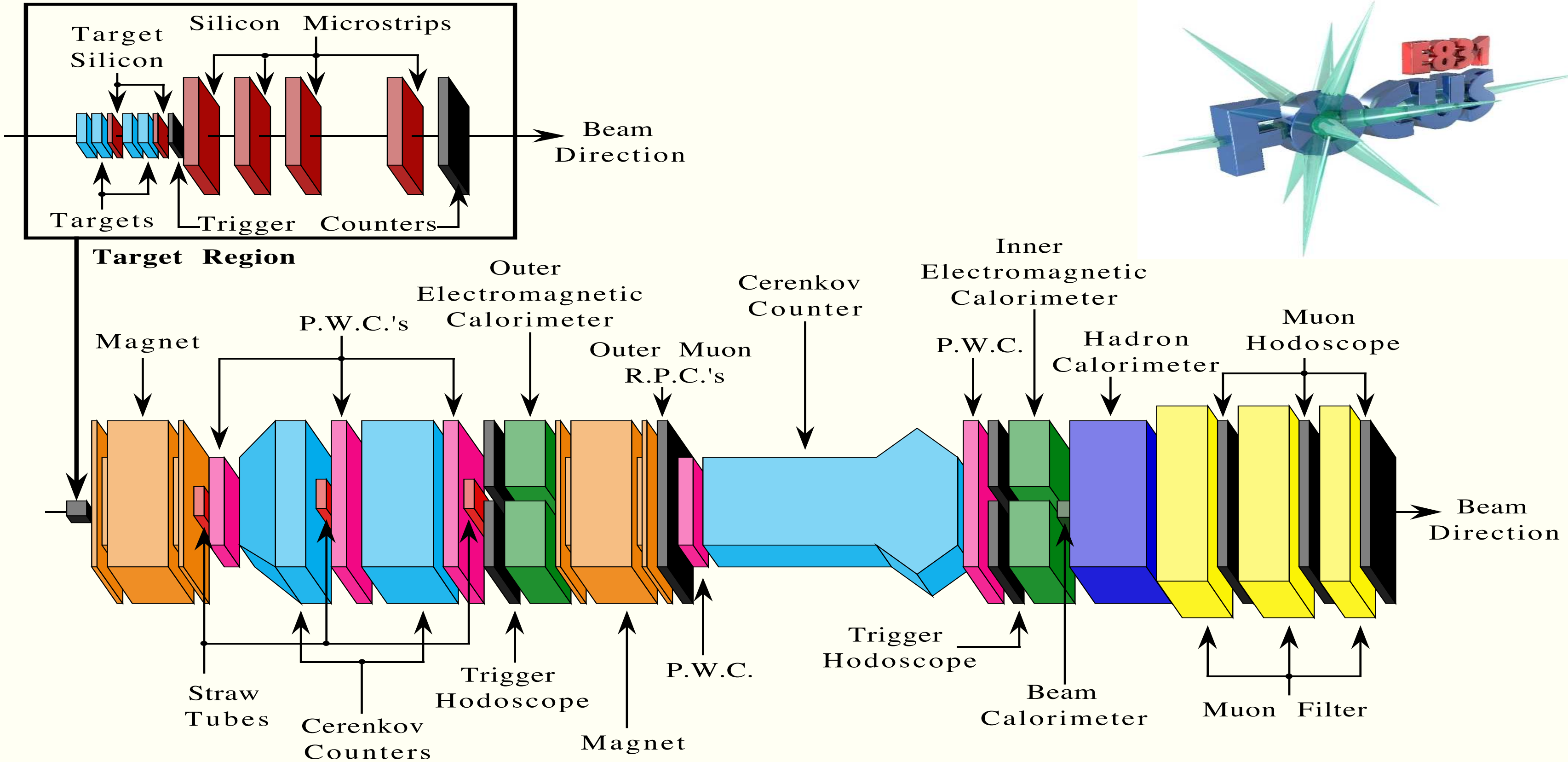
- Charm and FOCUS
- Lifetimes
- Hadronic Decays
- Rare Decays
- Mixing
- Summary

# Why charm?

Charm has been around 30 years but, like strange physics, is still relevant

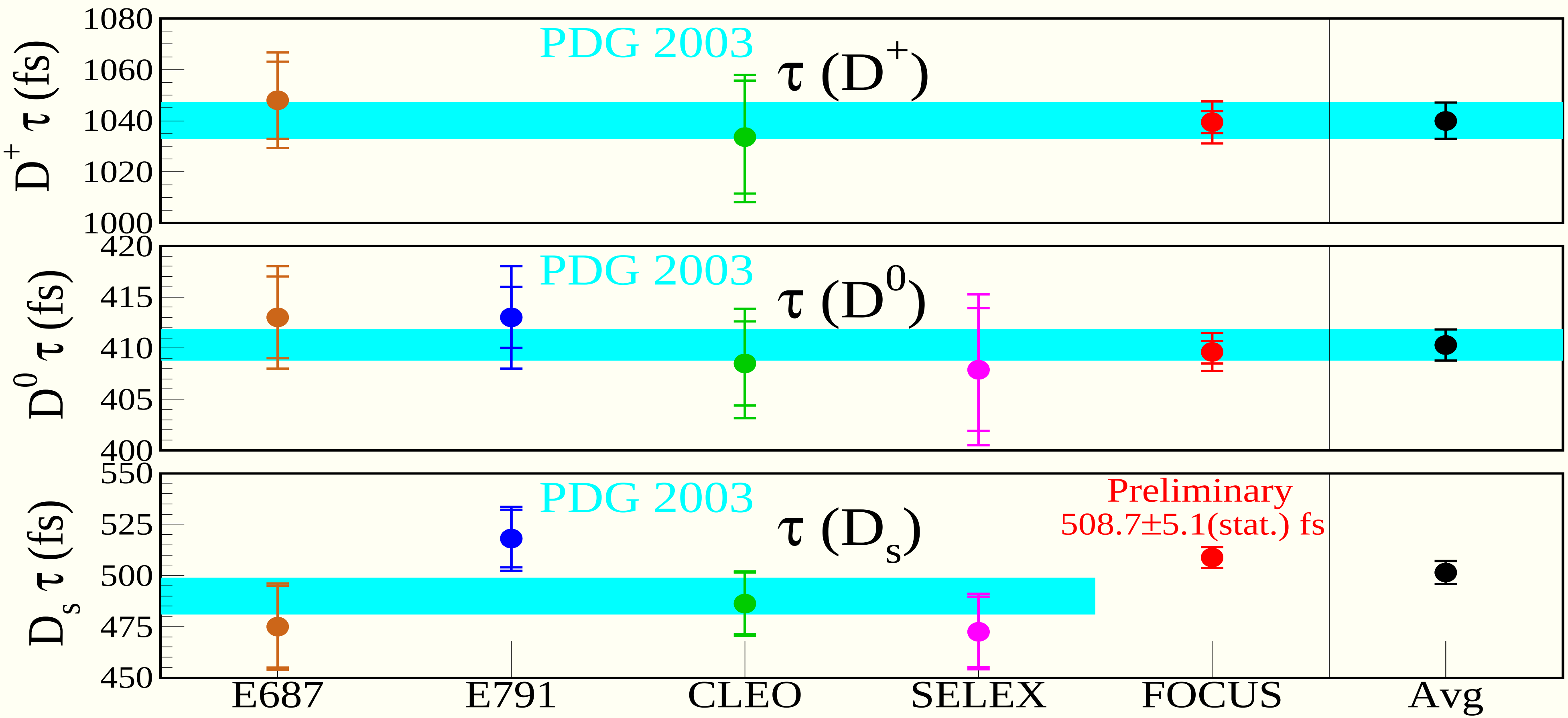
- Window to new physics
  - Standard model rates for rare decays, CP violation, mixing are very low
  - With current experiments, observation of CP violation, rare decays, or mixing $\Rightarrow$ new physics
- Provides information about QCD
  - Measurements of production characteristics, lifetimes, branching ratios, subresonant analyses, etc. provide insight into QCD
- Needed for $b$ physics
  - Many $b$ particles decay to charm so branching ratios, lifetimes, etc. needed for accurate $b$ results
  - Experimental techniques can be developed in charm (lifetime measurement, Dalitz plot analyses, etc.)
  - Heavy Quark Effective Theory often needs charm to bootstrap to $b$ physics

# Summary of FOCUS



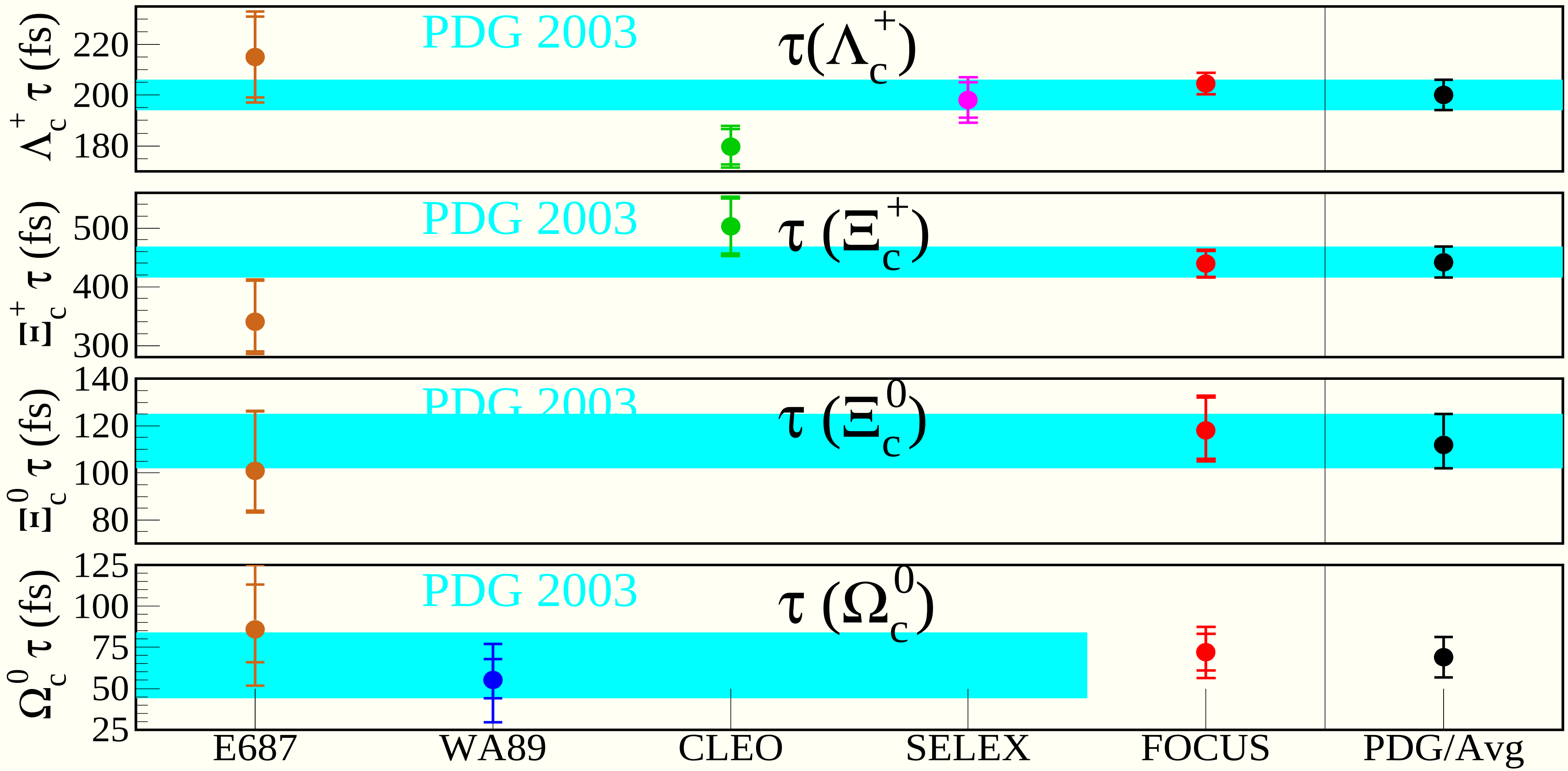

- FOCUS obtains charm from ∼175 GeV $\gamma$ on BeO interactions
- Open trigger requires hadronic energy and charged tracks
- Strengths are vertexing and particle ID
- Recorded 7 billion events in 1996–7 Fermilab fixed-target run
- Data analysis continues

# Charm meson lifetimes




- World avg (FOCUS+PDG) gives $\lesssim$1% measurements of all charm meson lifetimes
- $\tau_{D^+}/\tau_{D^0} = 2.54 \pm 0.02 \;\Rightarrow\;$ large destructive interference
- $\tau_{D_s}/\tau_{D^0} = 1.22 \pm 0.01 \;\Rightarrow\;$ evidence for weak annihilation?

# Charm baryon lifetimes




- $\Lambda_c^+$ PDG error dominated by 2.7$\sigma$ FOCUS/CLEO discrepancy. Systematic effect for short lived particles?
- $\tau_{\Omega_c^0} \approx 1/15 \times \tau_{D^+} \approx 1/3 \times \tau_{\Lambda_c^+}$; need boost & precise vertexing

# Hadronic decays

## Hadronic decays are rich in information about QCD

- Hadronic decays responsible for $D^+$ and $D^0$ lifetime difference
- Suppression of $D^0 \to \pi^-\pi^+$ to $D^0 \to K^-K^+$ proved importance of final state interactions in charm decays – FOCUS has best measurement: $\frac{\Gamma(KK)}{\Gamma(\pi\pi)} = 2.81 \pm 0.10 \pm 0.06$
- Hadronic decays can provide information on relative strengths of decay diagrams (spectator, W exchange, annihilation, etc.) and post-decay hadronization
- May provide information on light resonances
- The charm sector is rich in hadronic decay modes

## Accessing information from hadronic decays can be difficult

- Branching ratios are fairly simple to measure
- Resonant analyses of multi-body final states are not so easy
  - Resonance parameters often not well known
  - Quantum mechanical interferences complicate the analysis

# $D^+, D_s^+ \to \pi^+\pi^-\pi^+$

- E791 found evidence for $\sigma$ in $D^+ \to \pi^+\pi^-\pi^+$ decays and $D_s \to \pi^+\pi^-\pi^+$ decays dominated by $f_0(980)$
- FOCUS observes Dalitz plots with similar features
- FOCUS analysis fits with K-matrix rather than isobar model
  - Naturally include coupled-channel states like $f_0(980)$
  - Can deal with overlapping scalar states with large widths
  - Can incorporate information from strong scattering experiments
  - Anisovich & Sarantsev parameterize S-wave isoscalar scattering up to 1.9 GeV
    - Consider 5 channels: $\pi\pi$, $K\overline{K}$, $\eta\eta$, $\eta\eta'$, multimeson
    - Find 5 $IJ^{PC} = 00^{++}$ resonances: $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$, $f_0(1200-1600)$
  - Using this parameterization, and adding in vector and tensor particles, one can fit the $D^+$, $D_s \to \pi^+\pi^-\pi^+$ Dalitz plots.
  - Obtain good fits — will be published soon

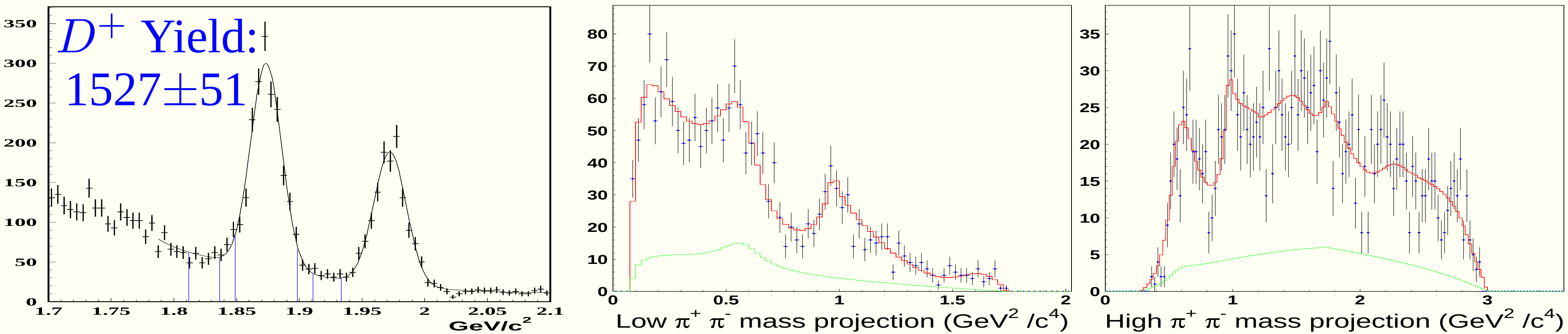
# $D^+ \to \pi^+\pi^-\pi^+$ Dalitz plot results

## Dalitz plot fit (CL = 6.8%):

| decay channel | fit fraction (%) | phase (deg) |
|---|---|---|
| $(S\text{-wave})\,\pi^+$ | $56.46 \pm 3.78 \pm 1.02 \pm 1.10$ | 0 (fixed) |
| $f_2(1275)\,\pi^+$ | $12.26 \pm 1.73 \pm 0.21 \pm 0.20$ | $-38.6 \pm 20.9 \pm 4.2 \pm 5.2$ |
| $\rho(770)\pi^+$ | $26.89 \pm 3.78 \pm 1.08 \pm 1.54$ | $-128.9 \pm 18.5 \pm 3.7 \pm 3.9$ |

## Spin 0 components:

| T-matrix pole | $(m, \Gamma/2)$ (GeV) | $D^+$ relative coupling (mag, phase) |
|---|---|---|
| $f_0(980)$ | $(1.019,\ 0.038)$ | $(1,\ 0)$ |
| $f_0(1300)$ | $(1.306,\ 0.170)$ | $(0.96 \pm 0.03,\ -164.3 \pm 2.3)$ |
| $f_0(1200-1600)$ | $(1.470,\ 0.960)$ | $(2.04 \pm 0.03,\ 2.9 \pm 1.9)$ |
| $f_0(1500)$ | $(1.489,\ 0.058)$ | $(0.71 \pm 0.03,\ -188.3 \pm 2.3)$ |
| $f_0(1750)$ | $(1.746,\ 0.160)$ | $(0.87 \pm 0.02,\ 62.5 \pm 1.4)$ |



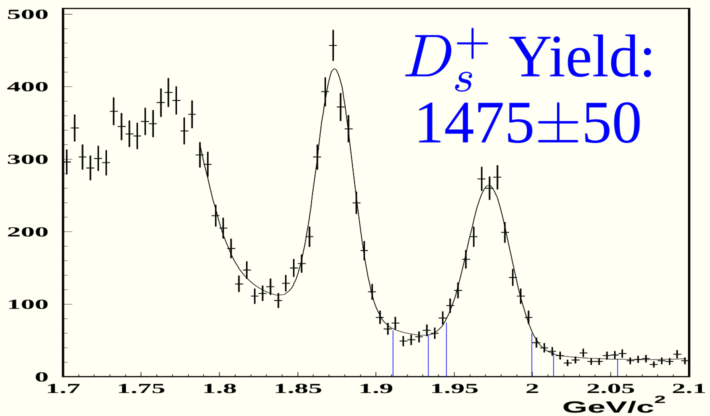
# $D_s^+ \to \pi^+\pi^-\pi^+$ Dalitz plot results

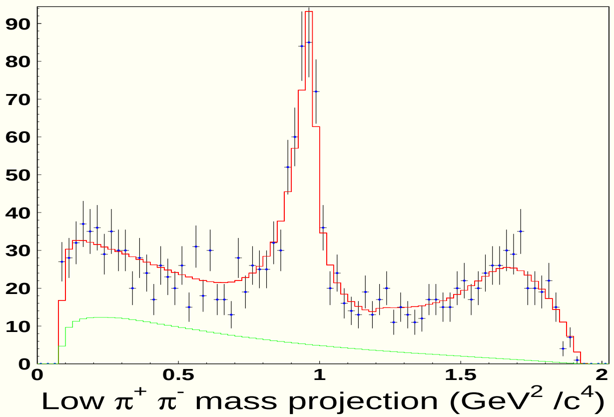
**Dalitz plot fit (CL = 3.0%):**

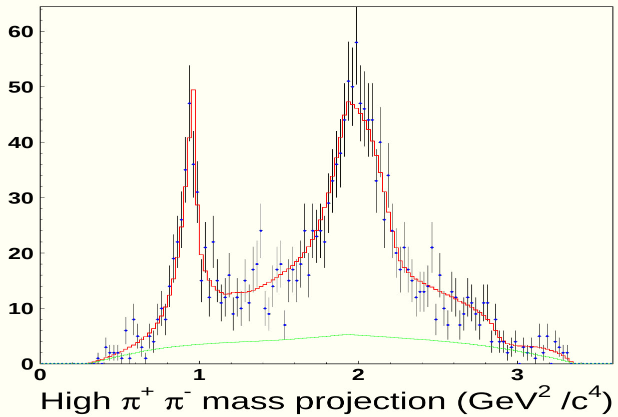
| decay channel | fit fraction (%) | phase (deg) |
|---|---|---|
| $(S\text{-wave})\,\pi^+$ | $87.04 \pm 5.60 \pm 4.17 \pm 1.34$ | 0 (fixed) |
| $f_2(1275)\,\pi^+$ | $9.74 \pm 4.49 \pm 2.63 \pm 1.32$ | $168.0 \pm 18.7 \pm 2.5 \pm 21.7$ |
| $\rho(1450)\pi^+$ | $6.56 \pm 3.43 \pm 3.31 \pm 2.90$ | $234.9 \pm 19.5 \pm 13.3 \pm 24.9$ |

**Spin 0 components:**

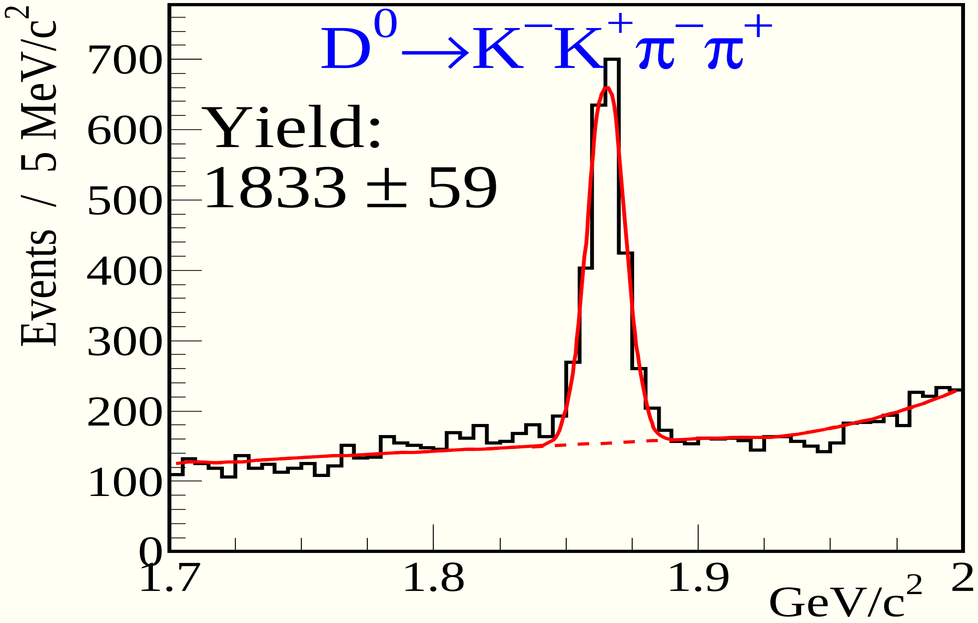
| T-matrix pole | $(m, \Gamma/2)$ (GeV) | $D_s^+$ relative coupling (mag, phase) |
|---|---|---|
| $f_0(980)$ | $(1.019,\ 0.038)$ | $(1, 0)$ |
| $f_0(1300)$ | $(1.306,\ 0.170)$ | $(0.43 \pm 0.04, -163.8 \pm 4.9)$ |
| $f_0(1200-1600)$ | $(1.470,\ 0.960)$ | $(4.9 \pm 0.08, 80.9 \pm 1.06)$ |
| $f_0(1500)$ | $(1.489,\ 0.058)$ | $(0.51 \pm 0.02, 83.1 \pm 3.03)$ |
| $f_0(1750)$ | $(1.746,\ 0.160)$ | $(0.82 \pm 0.02, -127.9 \pm 2.25)$ |

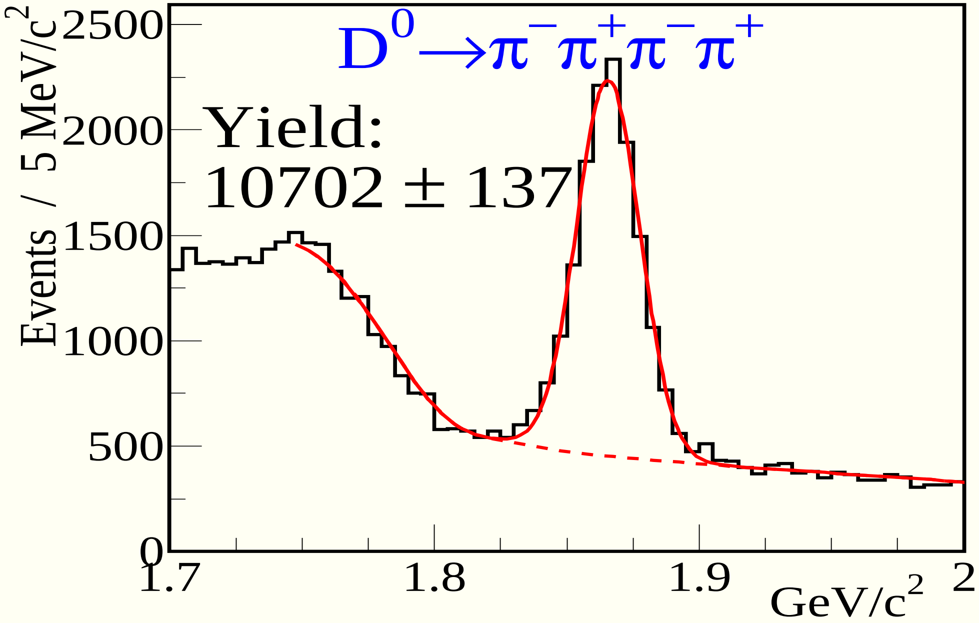


# Preliminary $D^0 \to h^+h^-h^+h^-$ results



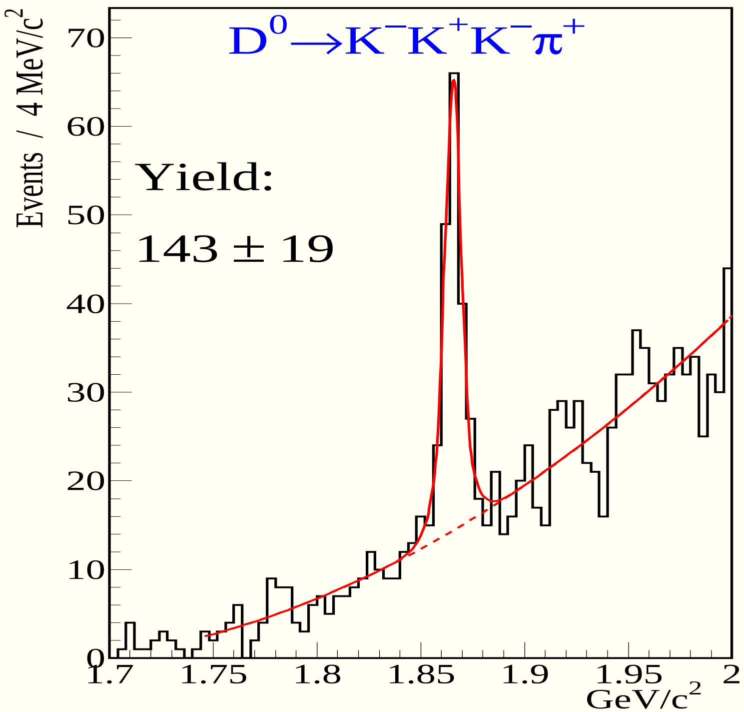

| Branching ratio | FOCUS preliminary | PDG2003 |
|---|---|---|
| $\frac{\Gamma(D^0 \to K^-K^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$ | $(2.97 \pm 0.10(stat.))\,\%$ | $(3.34 \pm 0.28)\,\%$ |
| $\frac{\Gamma(D^0 \to \pi^-\pi^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$ | $(8.66 \pm 0.12(stat.))\,\%$ | $(9.8 \pm 0.6)\,\%$ |

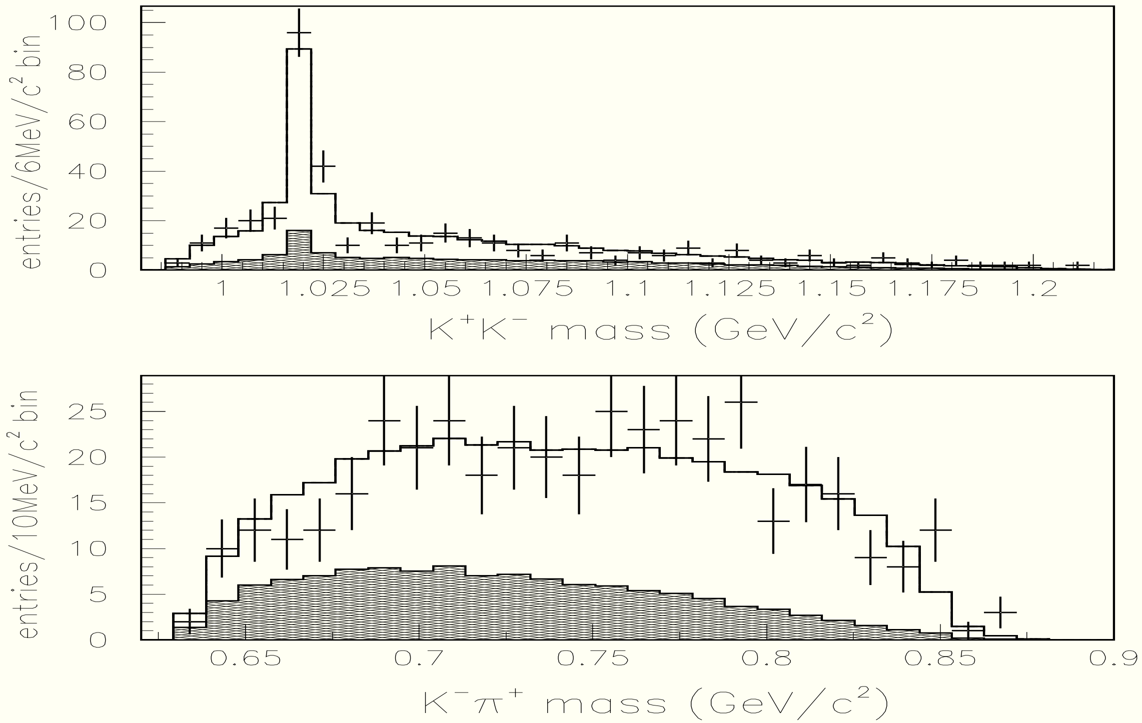
- Amplitude analysis is ongoing
- $D^0 \to K^-K^+\pi^-\pi^+$ dominated by $\phi\rho$ and $K^{*0}\overline{K}^{*0}$
- $D^0 \to \pi^-\pi^+\pi^-\pi^+$ decay complicated by many $2\pi$ & $3\pi$ resonances, $\sigma$ possibilities, and $\rho\rho$ decays with various relative angular momenta

# $D^0 \to K^- K^+ K^- \pi^+$

Measure $\frac{\Gamma(D^0 \to K^- K^+ K^- \pi^+)}{\Gamma(D^0 \to K^- \pi^+ \pi^- \pi^+)} = (0.257 \pm 0.034 \pm 0.023)\ \%$

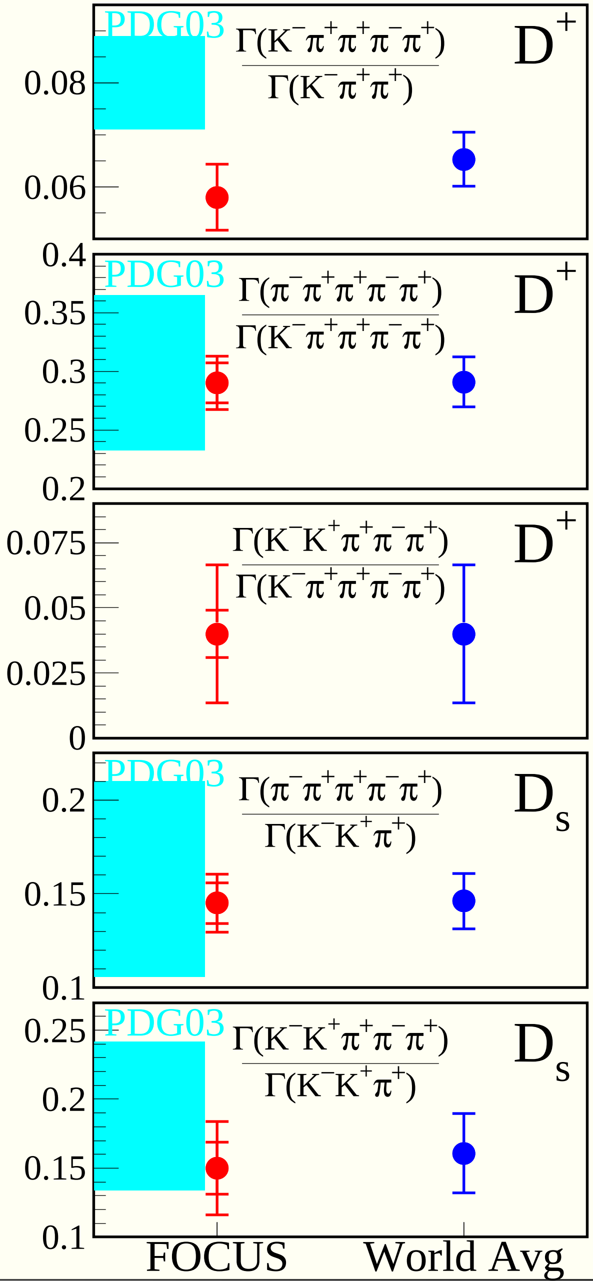
compared to PDG2003: $(0.32 \pm 0.09)\ \%$

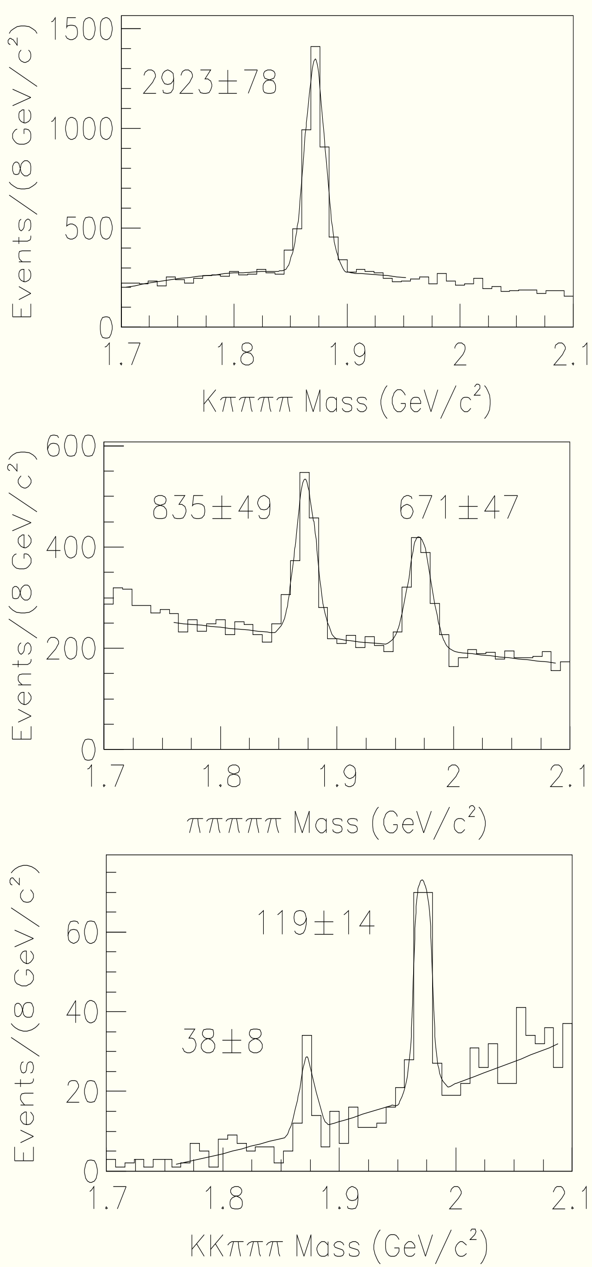


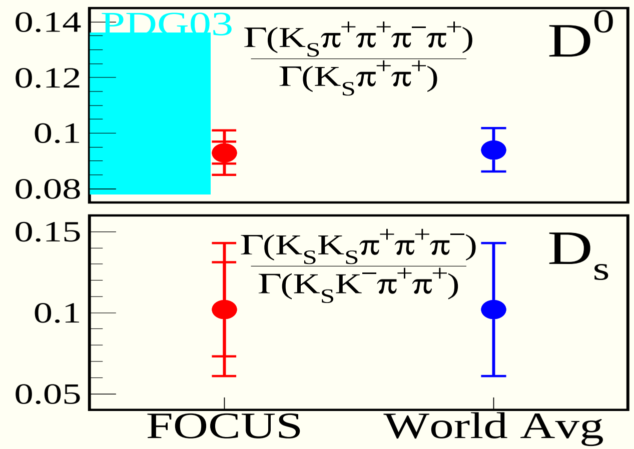



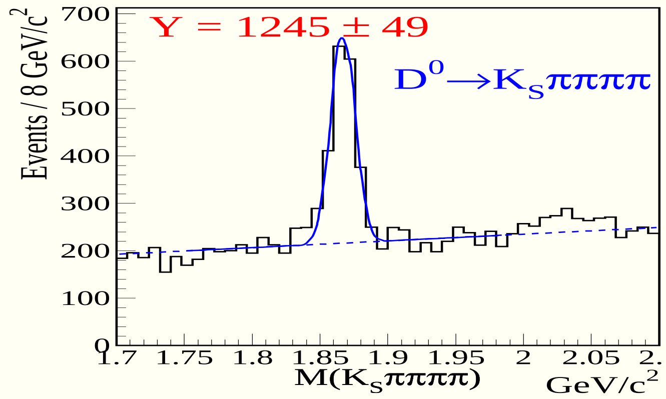

| Mode | Magnitude | Phase (deg.) | Fraction (%) |
|---|---|---|---|
| $\phi \overline{K}^{*0}(892)$ | 1 | 0 | $48 \pm 6 \pm 1$ |
| $\phi K^- \pi^+$ | $0.60 \pm 0.12$ | $194 \pm 24 \pm 8$ | $18 \pm 6 \pm 4$ |
| $\overline{K}^{*0}(892) K^+ K^-$ | $0.65 \pm 0.13$ | $255 \pm 15 \pm 4$ | $20 \pm 7 \pm 2$ |
| non-resonant | $0.55 \pm 0.14$ | $278 \pm 16 \pm 42$ | $15 \pm 6 \pm 2$ |

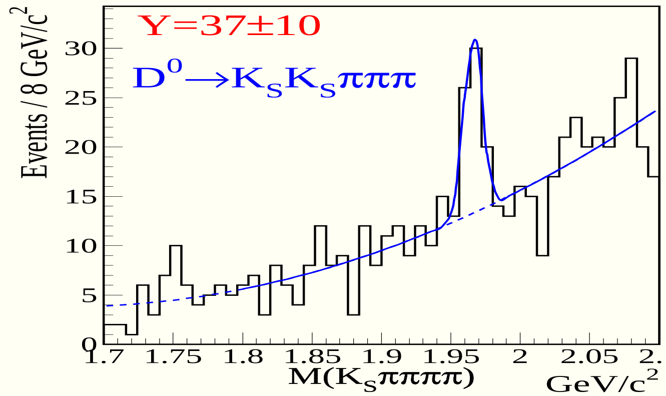
# 5-body charm meson decays



# Resonant analyses of 5-body decays

- Incoherent fit performed using projections
- All 5-body decay modes show strong vector-$\rho$-$\pi$ contributions
- $D^+$ consistent with $\sim$60% $D^+ \to \overline{K}^{*0} a_1(1260)$
- $D_s^+$ consistent with $\sim$100% $D_s^+ \to \phi a_1(1260)$
- $D^0$ consistent with being dominated by $D^0 \to K^{*-} a_1(1260)$
- All are consistent with being dominated by vector-$a_1(1260)^+$ with $a_1(1260)^+ \to \rho^0 \pi^+$

| $D^+$ decay mode | Fraction (%) |
|---|---|
| $(K^-\pi^+\pi^+\pi^+\pi^-)_{\rm NR}$ | $7 \pm 5 \pm 1$ |
| $\overline{K}^{*0}\pi^-\pi^+\pi^+$ | $21 \pm 4 \pm 6$ |
| $K^-\rho^0\pi^+\pi^+$ | $30 \pm 4 \pm 1$ |
| $\overline{K}^{*0}\rho^0\pi^+$ | $40 \pm 3 \pm 6$ |

| $D_s^+$ decay mode | Fraction (%) |
|---|---|
| $(K^+K^-\pi^+\pi^+\pi^-)_{\rm NR}$ | $10 \pm 6 \pm 5$ |
| $\phi\pi^-\pi^+\pi^+$ | $21 \pm 5 \pm 6$ |
| $K^+K^-\rho^0\pi^+$ | $< 3$@90% CL |
| $\phi\rho^0\pi^+$ | $75 \pm 6 \pm 4$ |

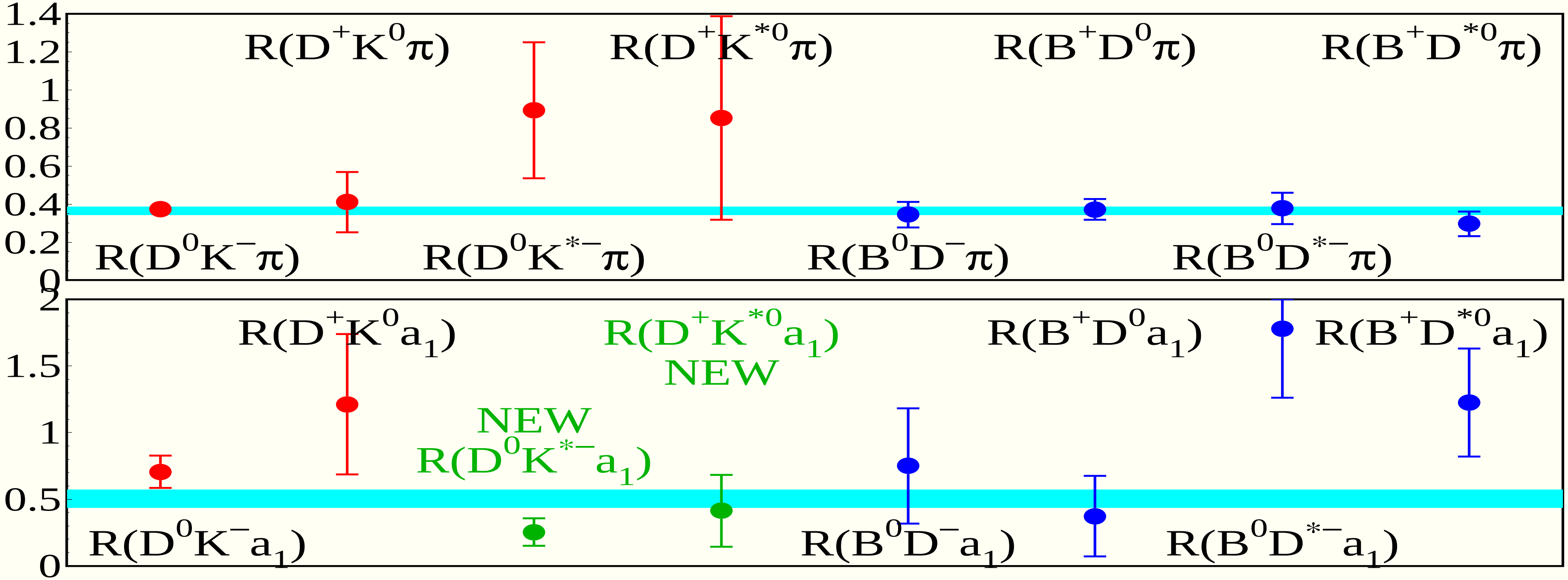
| $D^0$ decay mode | Fraction (%) |
|---|---|
| $(K_S\pi^+\pi^+\pi^-\pi^-)_{\rm NR}$ | $-17 \pm 34 \pm 2$ |
| $K^{*-}\pi^+\pi^+\pi^-$ | $17 \pm 28 \pm 2$ |
| $K_S\rho^0\pi^+\pi^-$ | $40 \pm 24 \pm 7$ |
| $K^{*-}\rho^0\pi^+$ | $60 \pm 21 \pm 9$ |

# Understanding hadronic decays?

- Lipkin proposed heavy flavor decays in which a radiated $W$ hadronizes to one particle and the remaining quarks hadronize into another particle might exhibit some universality
- Look at decays of the form $i \to f + W$ where $W \to a_1, \rho$, or $\pi$
- Define $R(ifX) \equiv \frac{BR[i\to fX]}{BR[i\to f\rho]} \approx \left|\frac{W\to X}{W\to\rho}\right|^2$

$$R(D^0K^-\pi)\approx R(D^+\overline{K}^0\pi)\approx R(D^0K^{*-}\pi)\approx R(D^+\overline{K}^{*0}\pi)\approx R(B^0D^-\pi)\approx R(B^+D^0\pi)\approx R(B^0D^{*-}\pi)\approx R(B^+D^{*0}\pi)$$

$$R(D^0K^-a)\approx R(D^+\overline{K}^0a)\approx R(D^0K^{*-}a)\approx R(D^+\overline{K}^{*0}a)\approx R(B^0D^-a)\approx R(B^+D^0a)\approx R(B^0D^{*-}a)\approx R(B^+D^{*0}a)$$

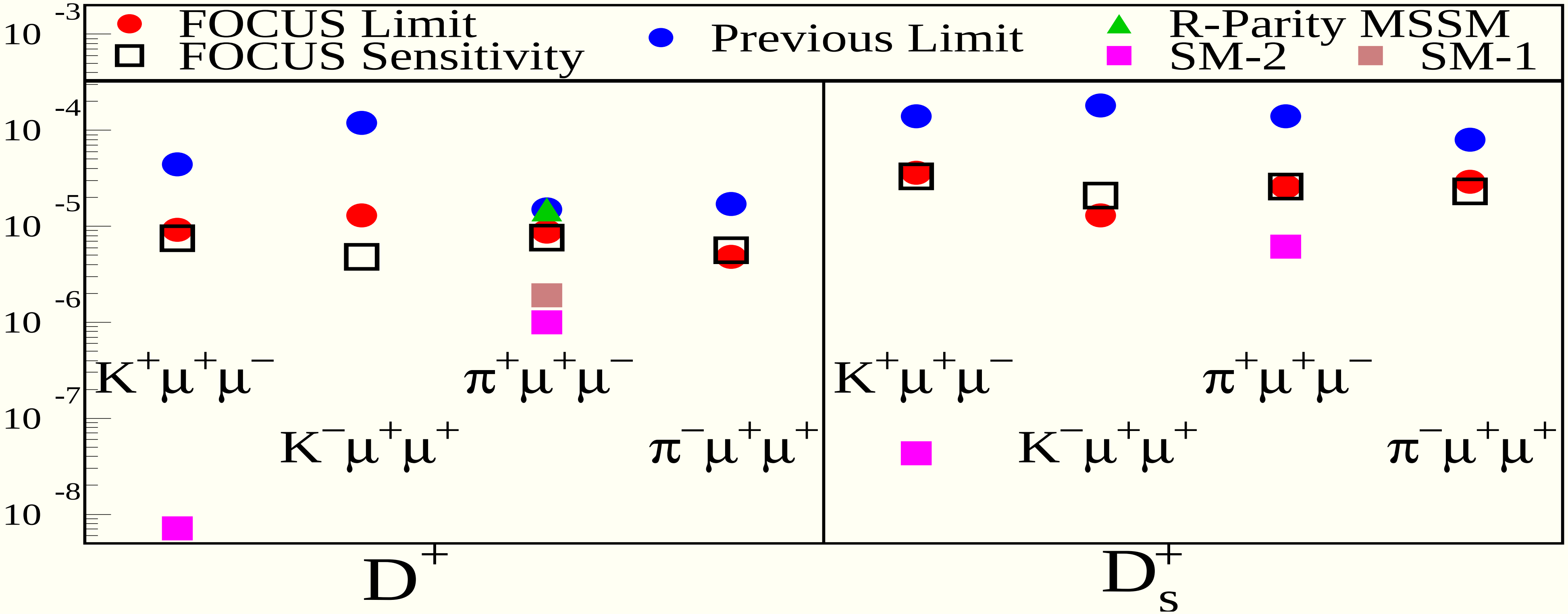


# Rare decays

- Rare decays are window to new physics
- Standard Model predictions much below current sensitivity
- Some new physics predictions are within range

FOCUS 90% CL limits on $\Gamma(D^+ \to h^\pm \mu\mu)$

- Use a new dual bootstrap technique to determine sensitivity/limits
- Use Wolfgang-Rolke tables to include error on background estimate



# Charm mixing

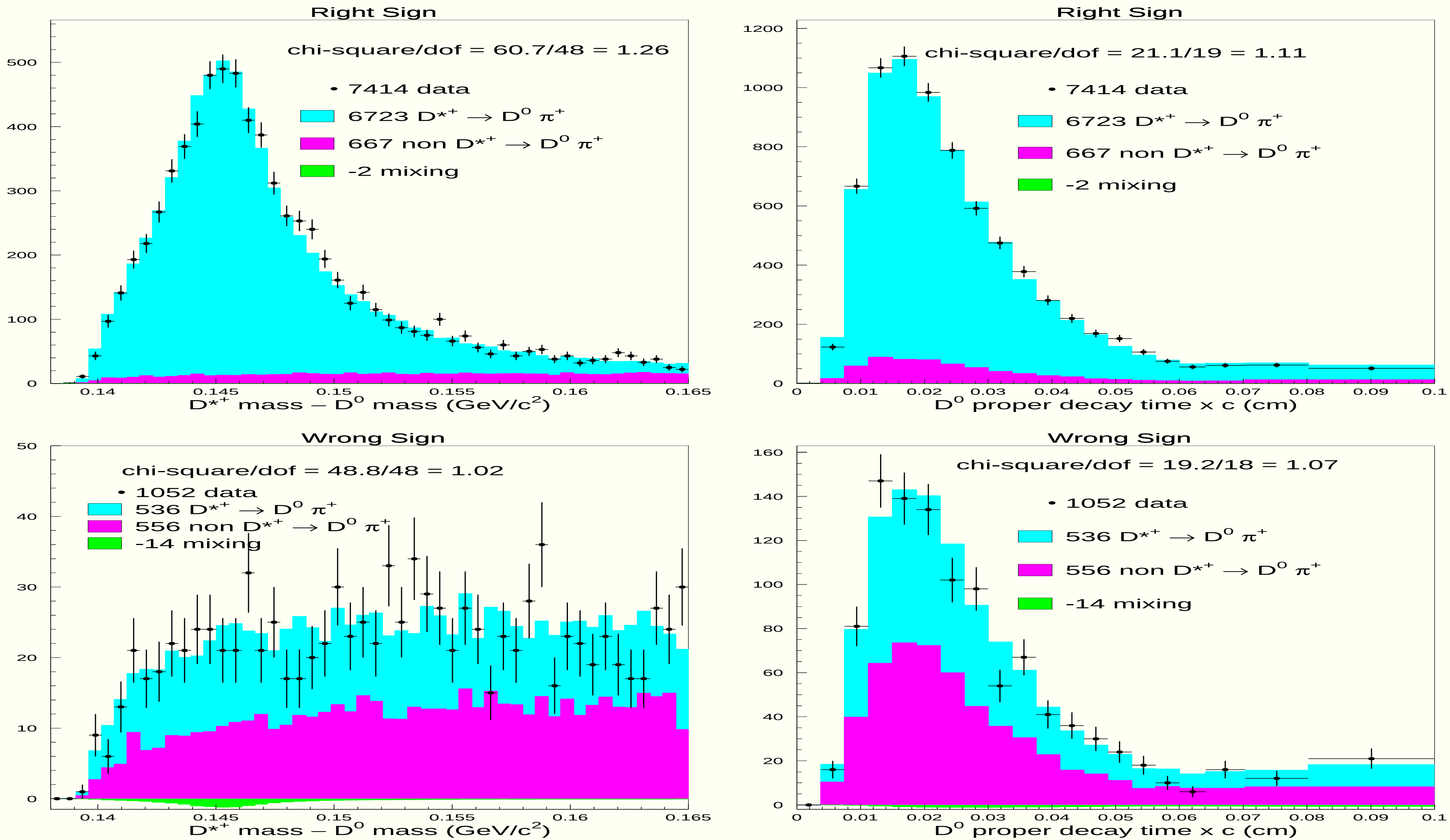
- Like $K^0$, $B^0$, & $B_s^0$ particles, $D^0$ particles can mix
- Mixing very suppressed in Standard Model $\Rightarrow$ room for new physics
- Look for mixing in wrong sign semileptonic or hadronic decays
- Doubly Cabibbo Suppressed decays complicate hadronic decays
- Definitions:
  - $x \equiv \frac{\Delta M}{\Gamma}$ — via virtual intermediate states
  - $y \equiv \frac{\Delta \Gamma}{2\Gamma}$ — via real intermediate states
  - $r_{mix} \equiv \frac{1}{2}\left(x^2 + y^2\right) = \frac{1}{2}\left(x'^2 + y'^2\right)$ — $x'$, $y'$ rotated by $\delta$
- With CP conservation, the wrong-sign to right-sign decay rate is:

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

where the three terms come from DCS decays, interference, and mixing. In semileptonic mixing, only the mixing term appears.

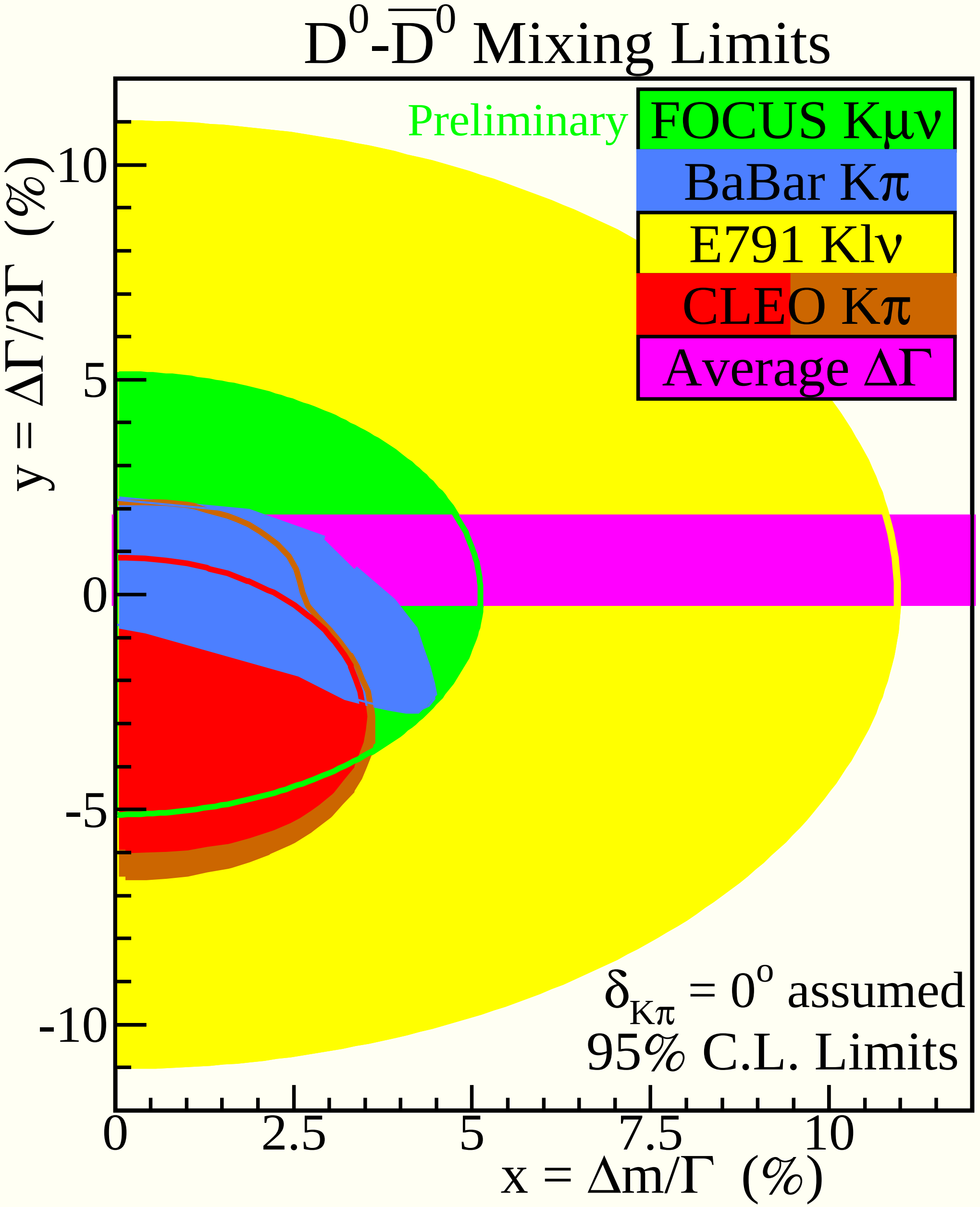
# Preliminary FOCUS semimuonic mixing

- Reconstruct $\nu$ using $D^0$ mass and vertex locations
- Fit to proper time and $D^{*+} - D^0$ mass difference



# Preliminary FOCUS semimuonic mixing

- Result is $r_{mix} = \left(-7.5\,{}^{+9.9}_{-9.3}\,{}^{+2.1}_{-2.6}\right) \times 10^{-4}$
- Obtain limit using Feldman–Cousins suggestion for confidence intervals near a boundary
- Limit is $r_{mix} < 0.131\%$ @ 95% CL
- Plan to add electronic mode soon
- Also working on hadronic mixing analysis



# Summary of FOCUS results

Shown here:

- FOCUS has nearly completed measuring every charm hadron lifetime (with by far the most precise measurement in every case)
- FOCUS continues to investigate high-multiplicity decays; historically not done at $e^+e^-$ machines
- FOCUS has significantly lowered limits on $D^+ \to h^\pm \mu^\pm \mu^\mp$ decays and will continue with other rare decay searches
- FOCUS will provide competitive limits on charm mixing

Not shown here:

- FOCUS has the most precise measurements of $D^+ \to \overline{K}^{*0} \mu^+ \nu$ branching ratio and form factors and the first observation of S-wave interference in this channel
- FOCUS has also published many other branching ratios
- FOCUS is continuing studies of spectroscopy and charm producion