Charm Physics from FOCUS

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Outline

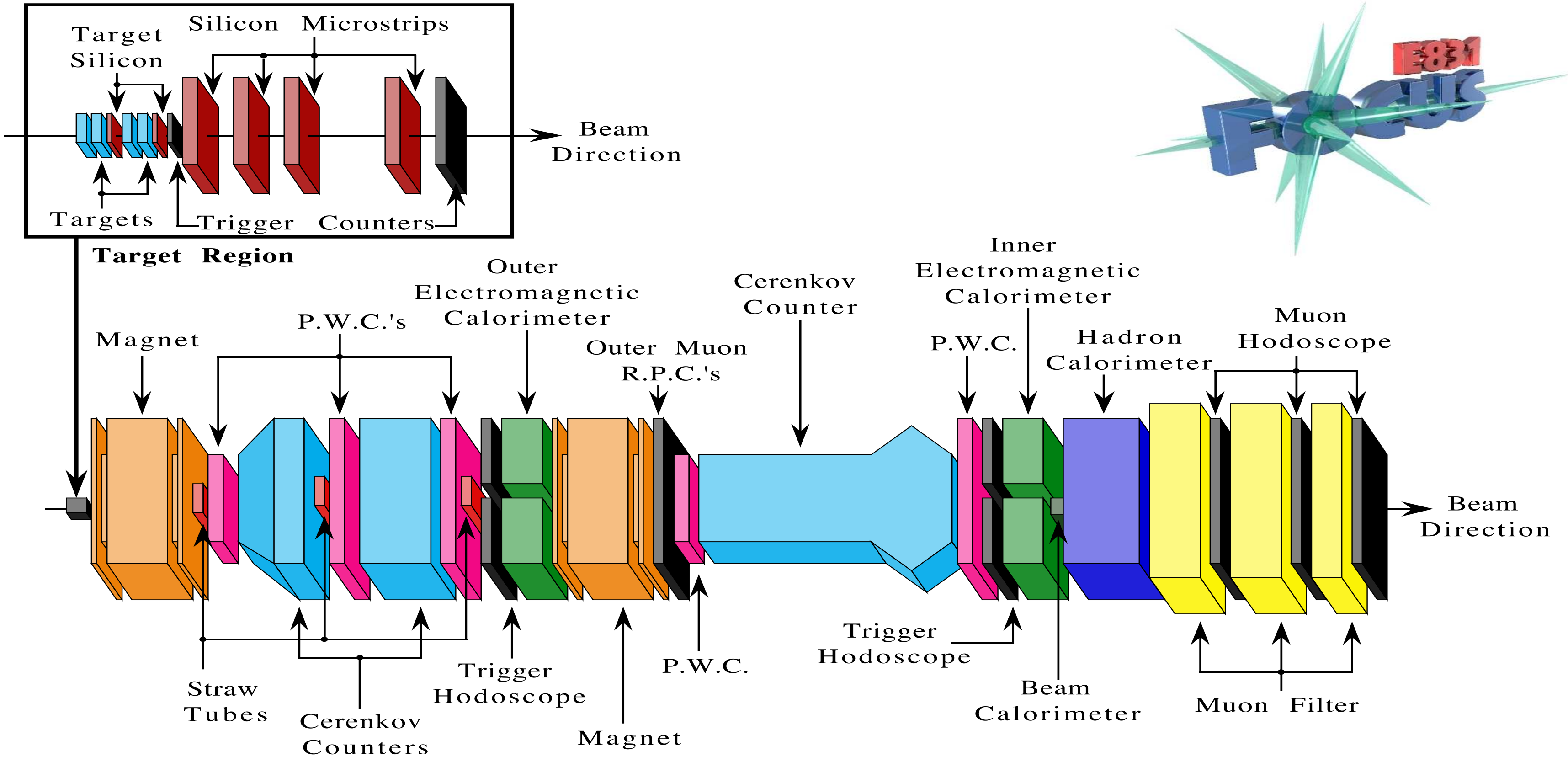
- Charm and FOCUS
- Lifetimes
- Hadronic Decays
- Rare Decays
- Mixing
- Summary

Why charm?

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

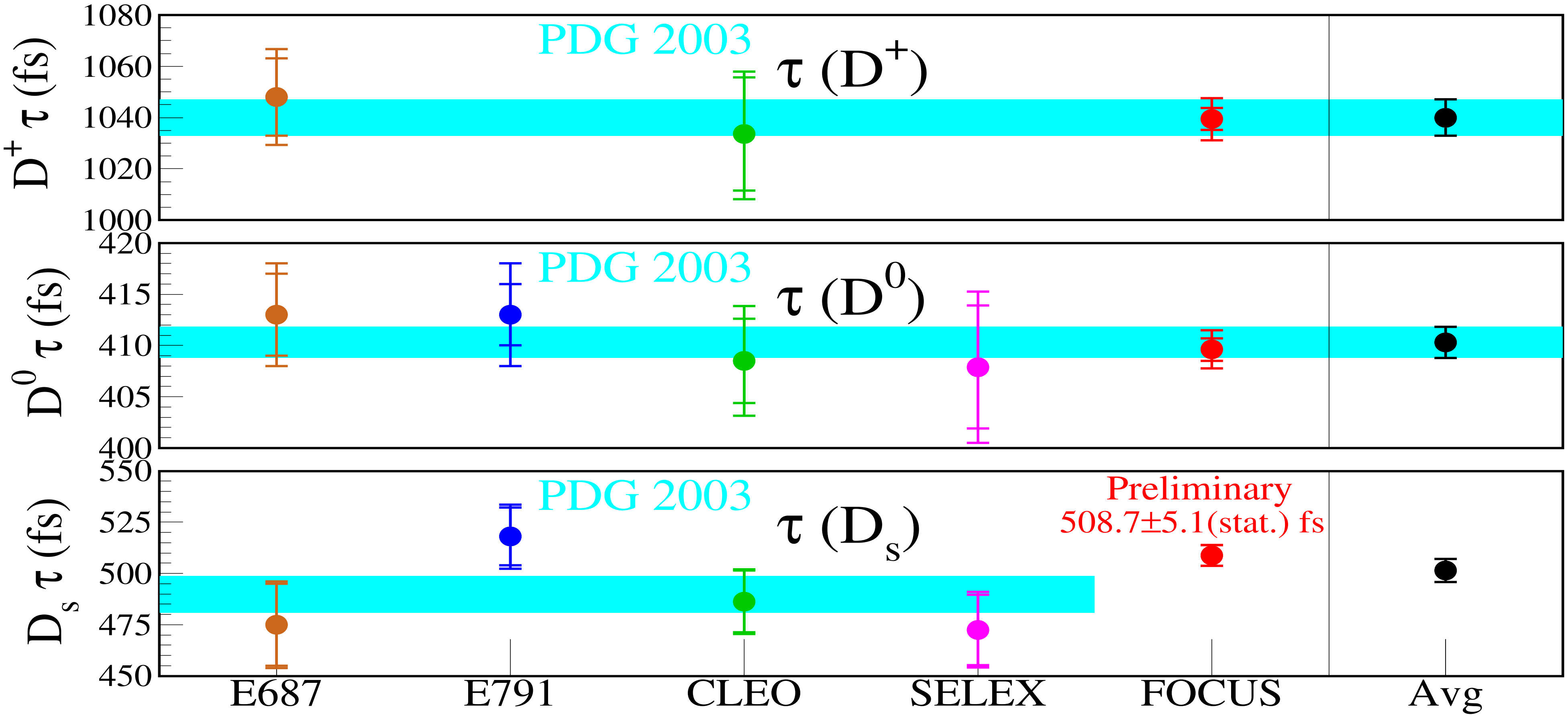
- Window to new physics
  - Standard model rates for rare decays, CP violation, mixing are very low
  - With current experiments, observation of CP violation, rare decays, or mixing $\Rightarrow$ new physics
- Provides information about QCD
  - Measurements of production characteristics, lifetimes, branching 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



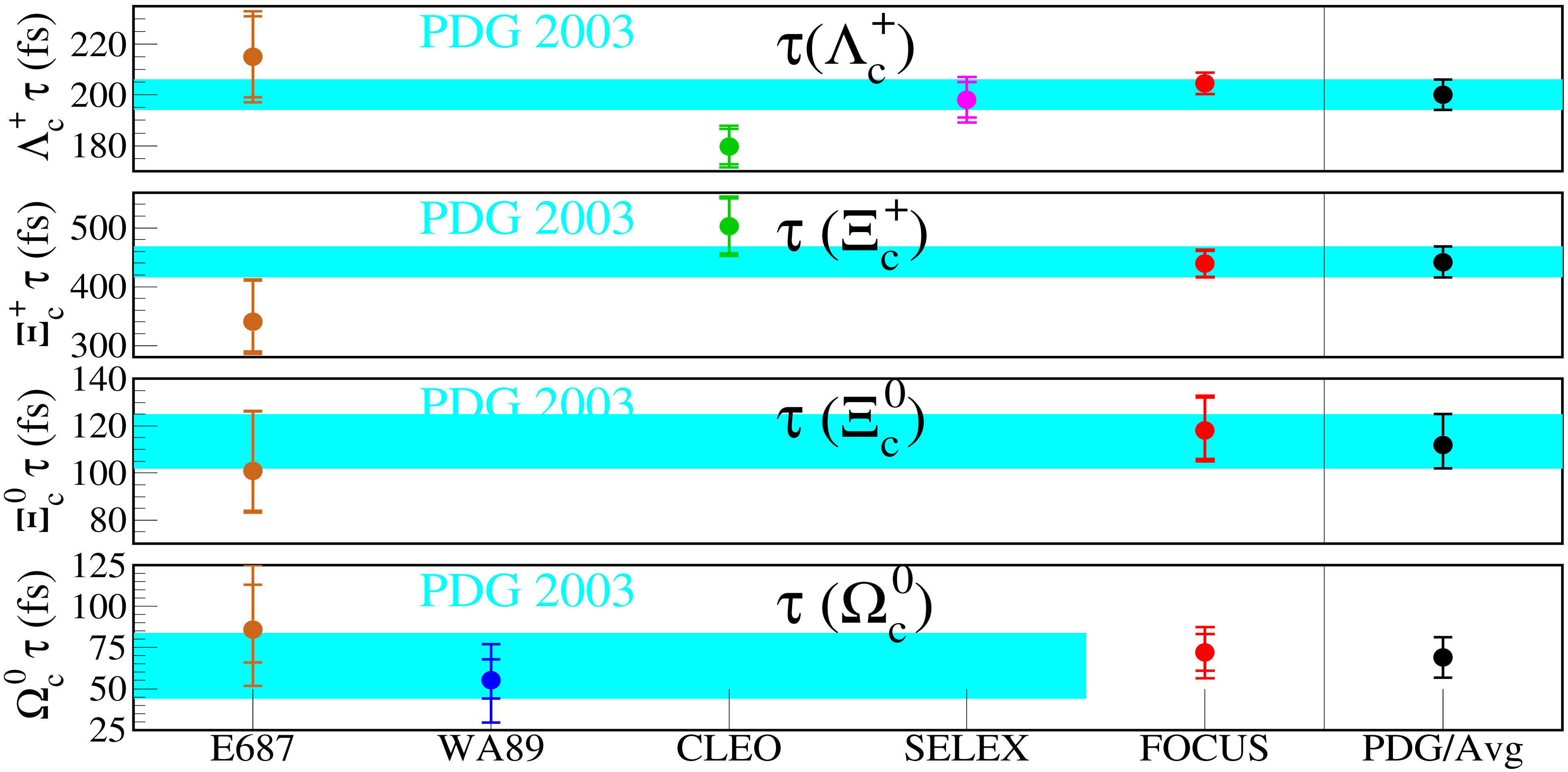
- FOCUS obtains charm from ~175 GeV γ on BeO interactions
- Open trigger requires hadronic energy and charged tracks
- Strengths are vertexing and particle ID
- Recorded 7 billion events in 1996–7 Fermilab fixed-target run
- Data analysis continues

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



- Λ_c^+ PDG error dominated by 2.7σ 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 σ 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

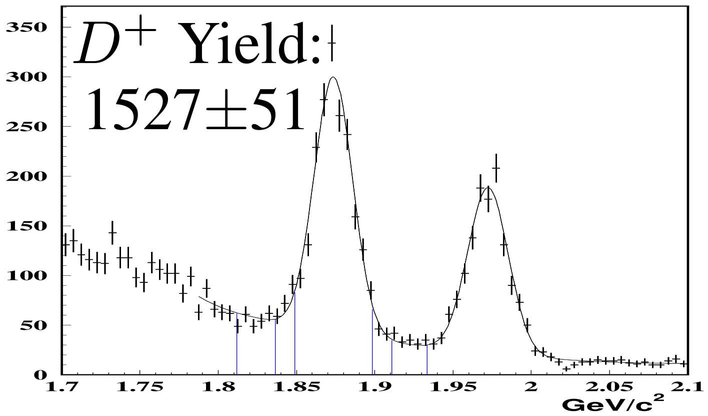
$D^+ \to \pi^+\pi^-\pi^+$ **Dalitz plot results**

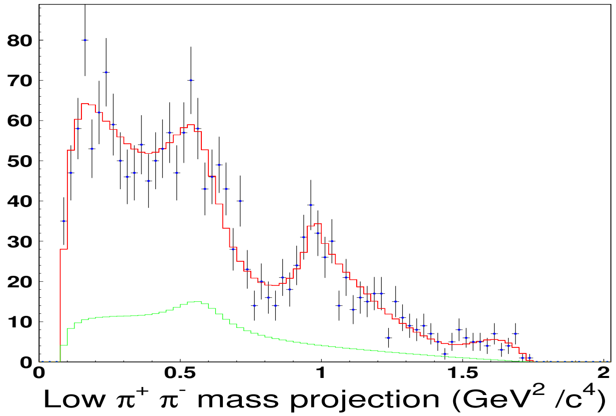
Dalitz plot fit (CL = 6.8%):

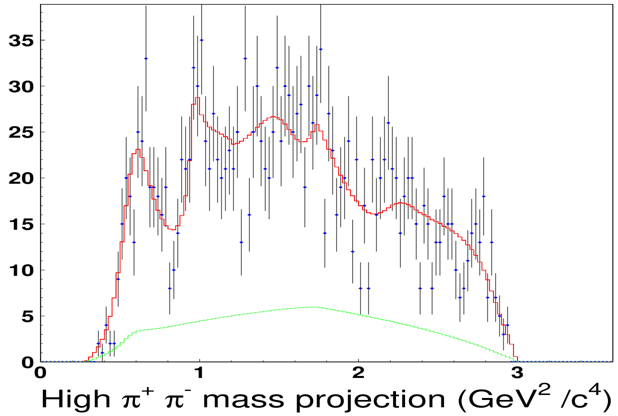
decay channel	fit fraction (%)	phase (deg)
$(S\text{-wave})\,\pi^+$	$56.46 \pm 3.78 \pm 1.02 \pm 1.10$	0 (fixed)
$f_2(1275)\,\pi^+$	$12.26 \pm 1.73 \pm 0.21 \pm 0.20$	$-38.6 \pm 20.9 \pm 4.2 \pm 5.2$
$\rho(770)\pi^+$	$26.89 \pm 3.78 \pm 1.08 \pm 1.54$	$-128.9 \pm 18.5 \pm 3.7 \pm 3.9$

Spin 0 components:

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







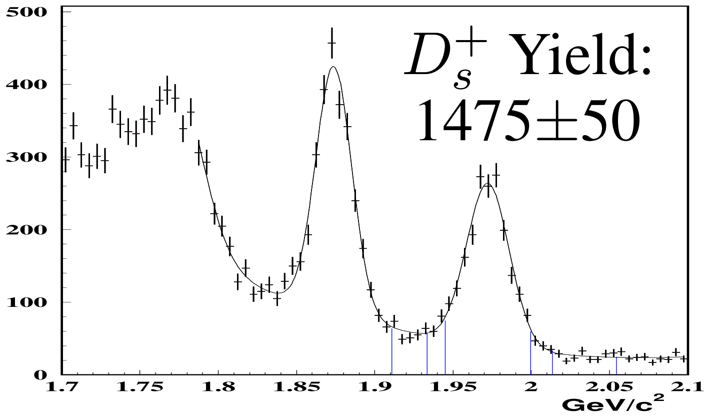
$D_s^+ \to \pi^+\pi^-\pi^+$ Dalitz plot results

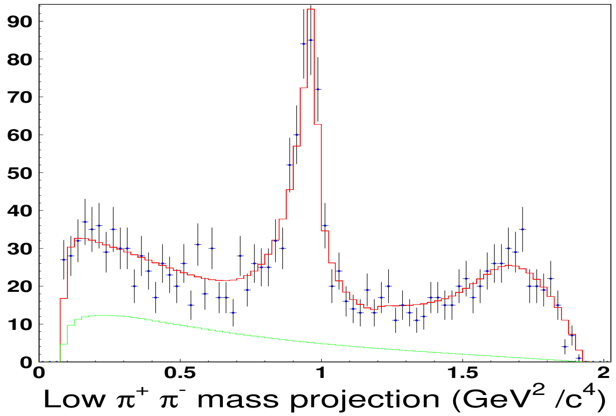
Dalitz plot fit (CL = 3.0%):

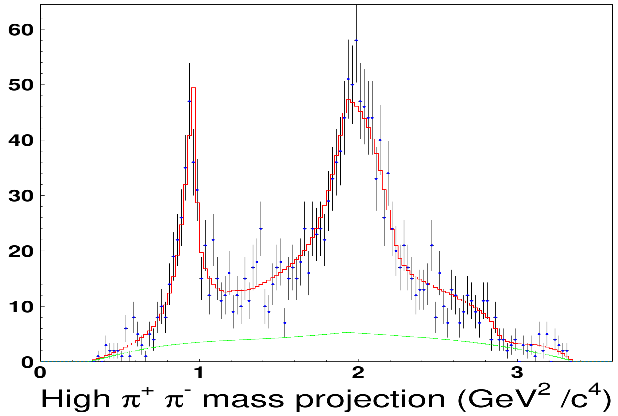
decay channel	fit fraction (%)	phase (deg)
$(S\text{-wave})\,\pi^+$	$87.04 \pm 5.60 \pm 4.17 \pm 1.34$	0 (fixed)
$f_2(1275)\,\pi^+$	$9.74 \pm 4.49 \pm 2.63 \pm 1.32$	$168.0 \pm 18.7 \pm 2.5 \pm 21.7$
$\rho(1450)\pi^+$	$6.56 \pm 3.43 \pm 3.31 \pm 2.90$	$234.9 \pm 19.5 \pm 13.3 \pm 24.9$

Spin 0 components:

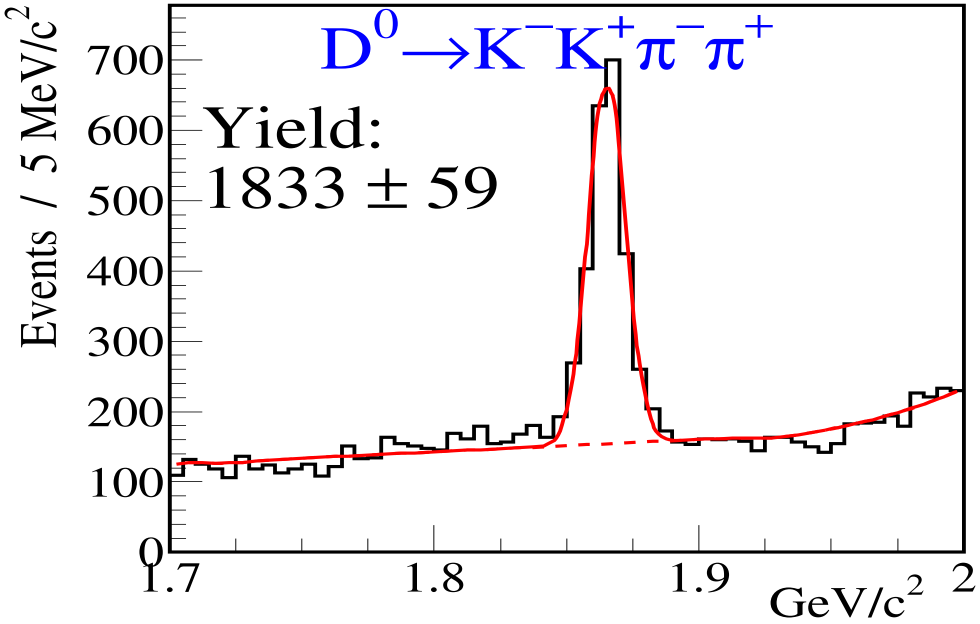
T-matrix pole	$(m, \Gamma/2)$ (GeV)	D_s^+ relative coupling (mag, phase)
$f_0(980)$	$(1.019,\ 0.038)$	$(1, 0)$
$f_0(1300)$	$(1.306,\ 0.170)$	$(0.43 \pm 0.04, -163.8 \pm 4.9)$
$f_0(1200-1600)$	$(1.470,\ 0.960)$	$(4.9 \pm 0.08, 80.9 \pm 1.06)$
$f_0(1500)$	$(1.489,\ 0.058)$	$(0.51 \pm 0.02, 83.1 \pm 3.03)$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

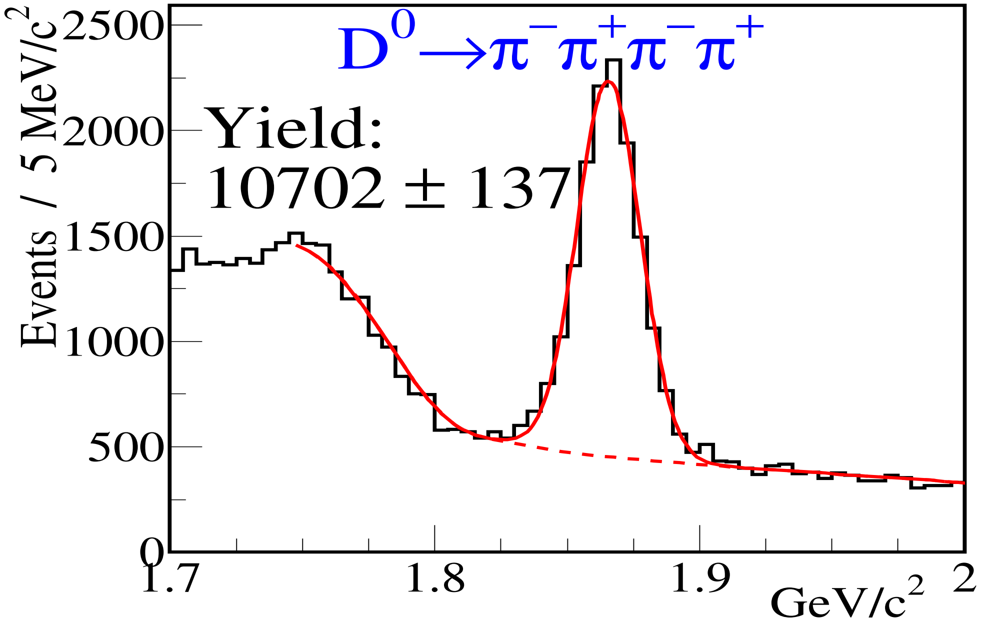






Preliminary $D^0 \to h^+h^-h^+h^-$ results





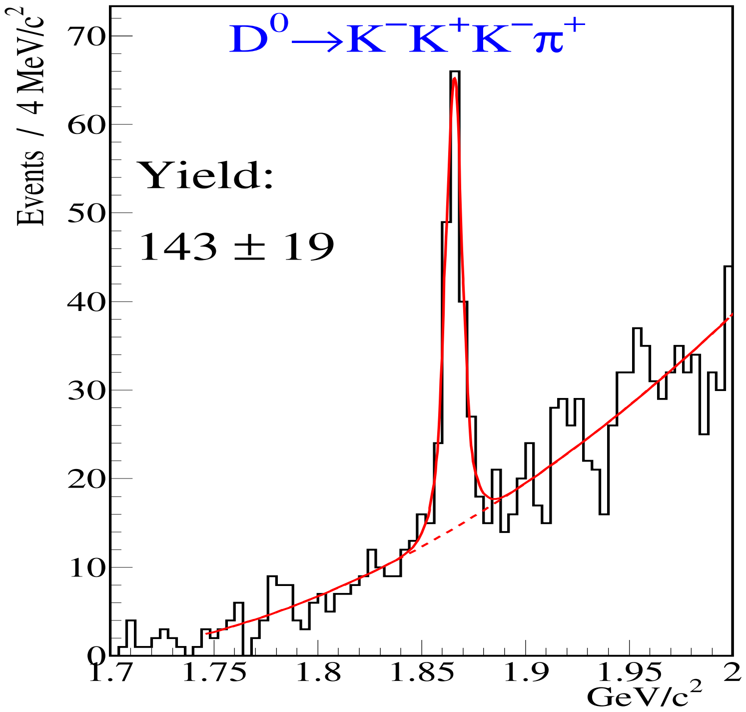
Branching ratio	FOCUS preliminary	PDG2003
$\frac{\Gamma(D^0 \to K^-K^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$(2.97 \pm 0.10(stat.))\,\%$	$(3.34 \pm 0.28)\,\%$
$\frac{\Gamma(D^0 \to \pi^-\pi^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$(8.66 \pm 0.12(stat.))\,\%$	$(9.8 \pm 0.6)\,\%$

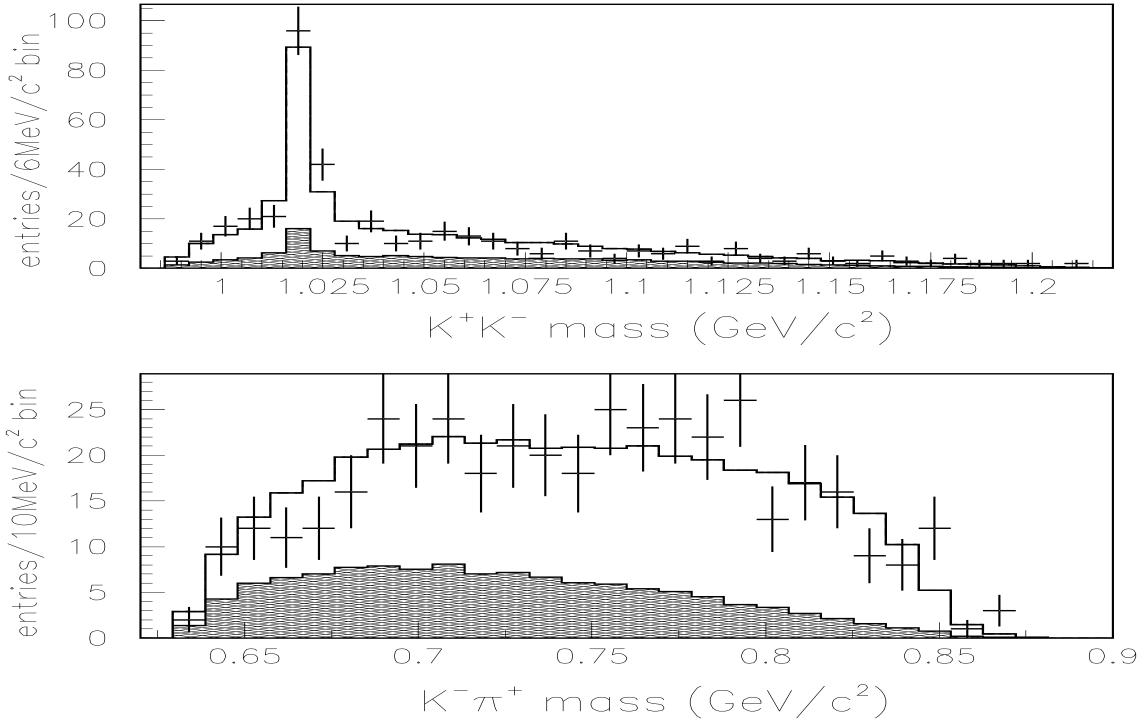
- Amplitude analysis is ongoing
- $D^0 \to K^-K^+\pi^-\pi^+$ dominated by $\phi\rho$ and $K^{*0}\overline{K}^{*0}$
- $D^0 \to \pi^-\pi^+\pi^-\pi^+$ decay complicated by many 2π & 3π resonances, σ possibilities, and $\rho\rho$ decays with various relative angular momenta

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

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

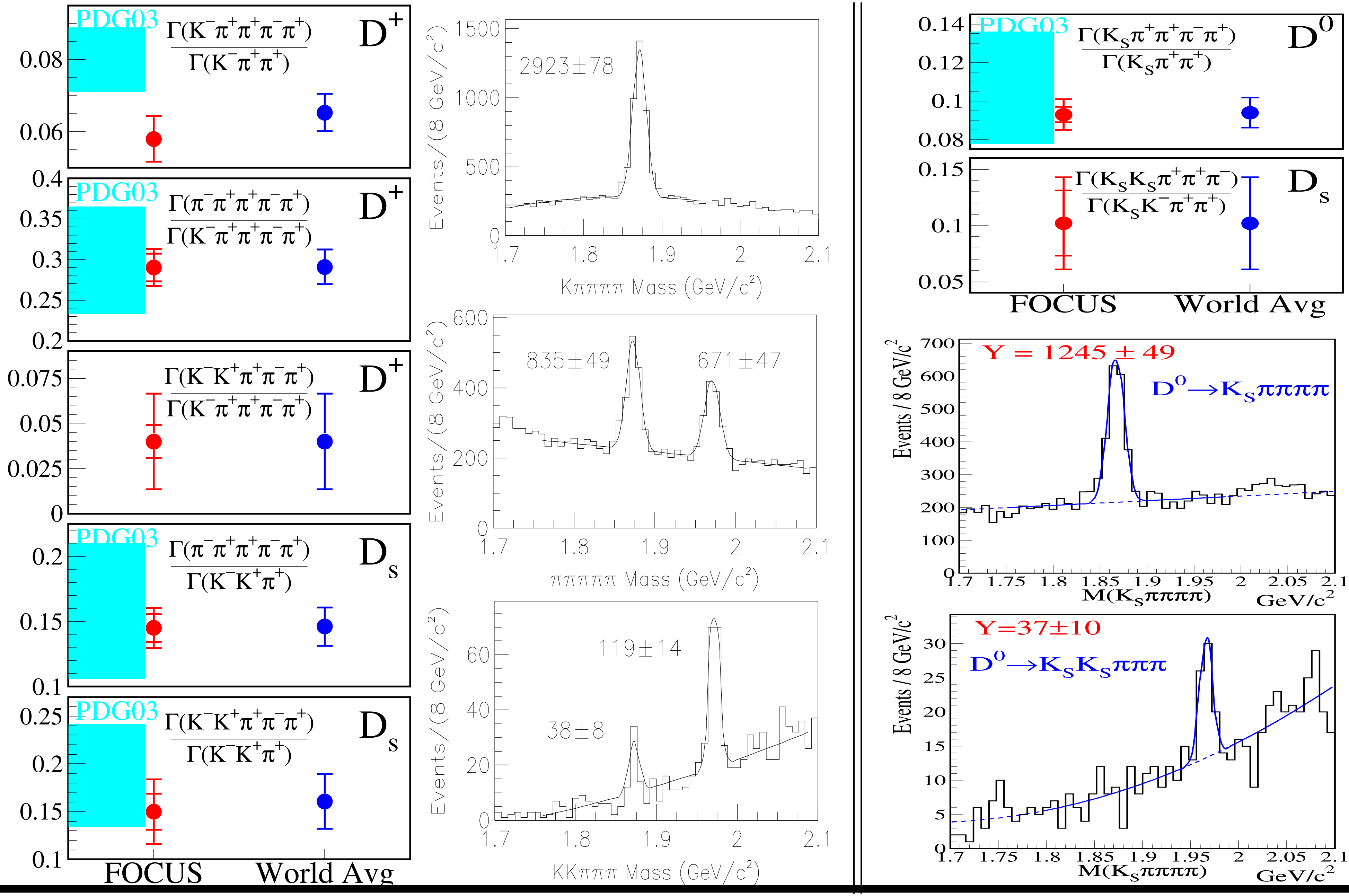
compared to PDG2003: $(0.32 \pm 0.09)\,\%$





Mode	Magnitude	Phase (deg.)	Fraction (%)
$\phi \overline{K}^{*0}(892)$	1	0	$48 \pm 6 \pm 1$
$\phi K^- \pi^+$	0.60 ± 0.12	$194 \pm 24 \pm 8$	$18 \pm 6 \pm 4$
$\overline{K}^{*0}(892) K^+ K^-$	0.65 ± 0.13	$255 \pm 15 \pm 4$	$20 \pm 7 \pm 2$
non-resonant	0.55 ± 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-ρ-π 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 (%)
$(K^-\pi^+\pi^+\pi^+\pi^-)_{\mathrm{NR}}$	$7 \pm 5 \pm 1$
$\overline{K}^{*0}\pi^-\pi^+\pi^+$	$21 \pm 4 \pm 6$
$K^-\rho^0\pi^+\pi^+$	$30 \pm 4 \pm 1$
$\overline{K}^{*0}\rho^0\pi^+$	$40 \pm 3 \pm 6$

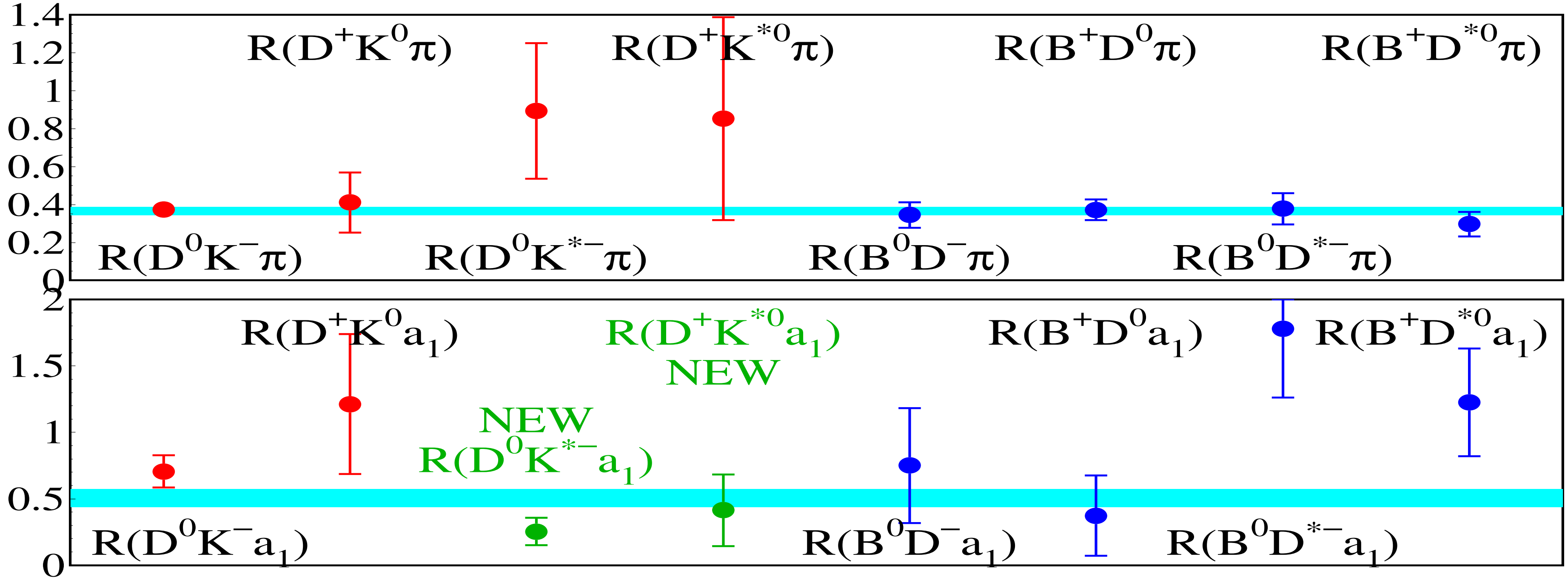
D_s^+ decay mode	Fraction (%)
$(K^+K^-\pi^+\pi^+\pi^-)_{\mathrm{NR}}$	$10 \pm 6 \pm 5$
$\phi\pi^-\pi^+\pi^+$	$21 \pm 5 \pm 6$
$K^+K^-\rho^0\pi^+$	<3@90% CL
$\phi\rho^0\pi^+$	$75 \pm 6 \pm 4$

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

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 π
- Define $R(ifX) \equiv \frac{BR[i \to fX]}{BR[i \to f\rho]} \approx \left| \frac{W \to X}{W \to \rho} \right|^2$

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

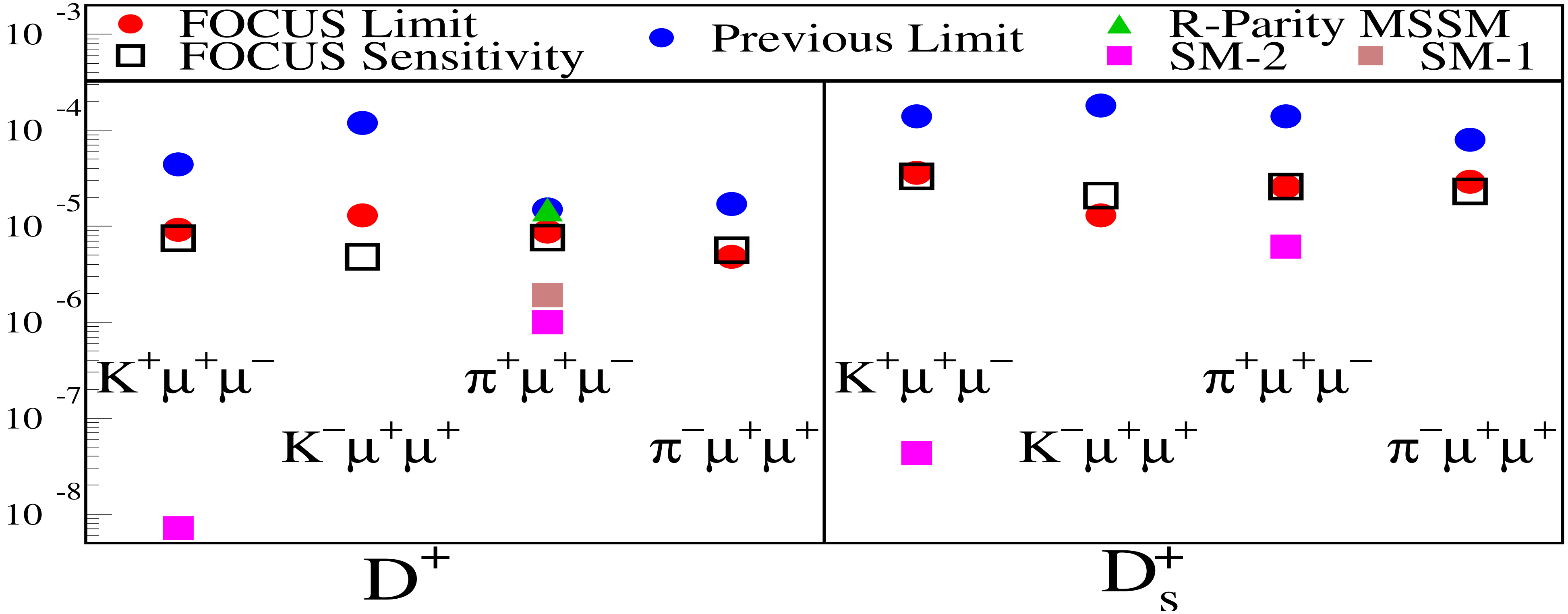


Rare decays

- 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

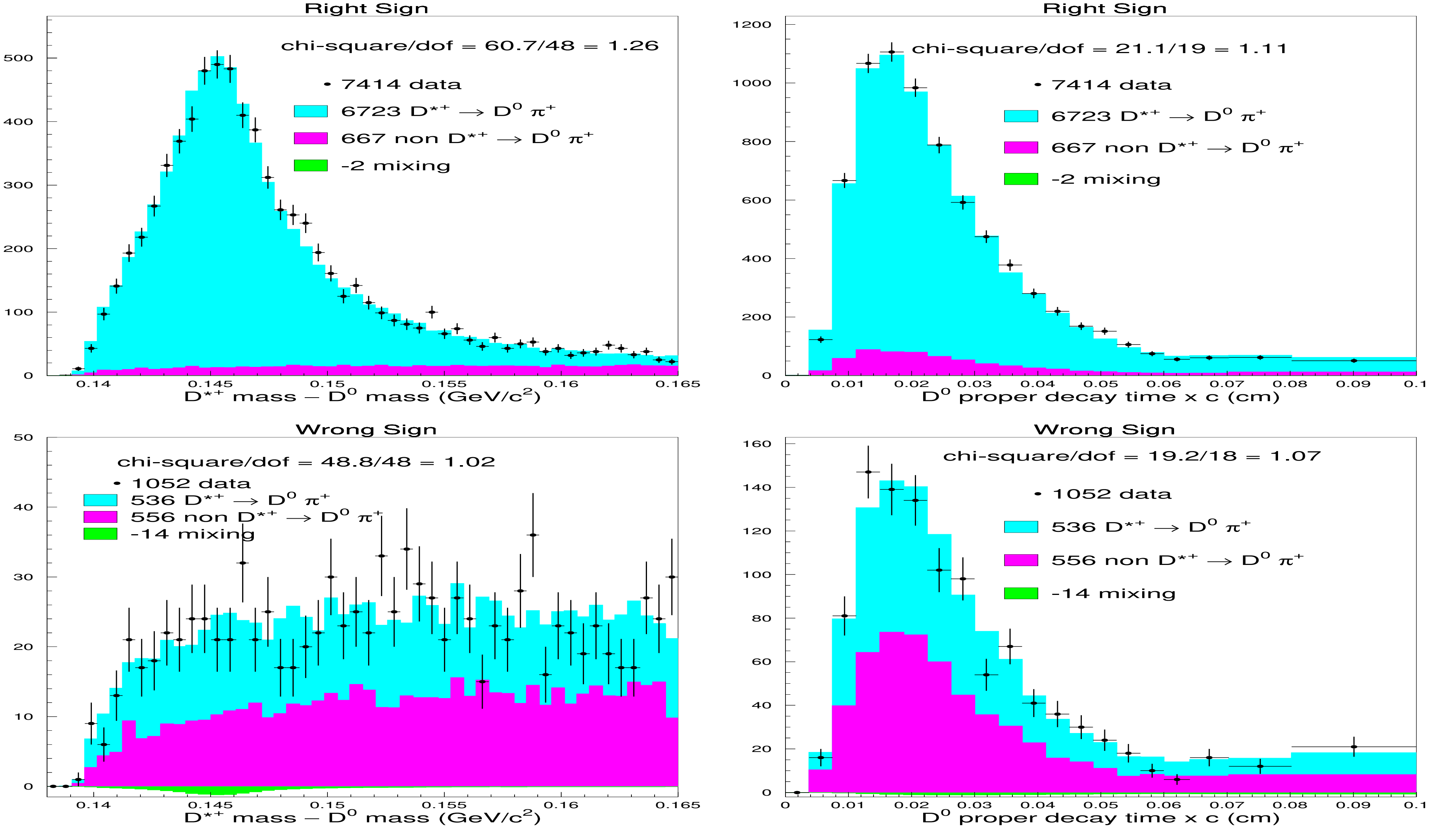
- Like K^0, B^0, & B_s^0 particles, D^0 particles can mix
- Mixing very suppressed in Standard Model $\Rightarrow$ room for new physics
- Look for mixing in wrong sign semileptonic or hadronic decays
- Doubly Cabibbo Suppressed decays complicate hadronic decays
- Definitions:
  - $x \equiv \frac{\Delta M}{\Gamma}$ — 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 δ
- 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.

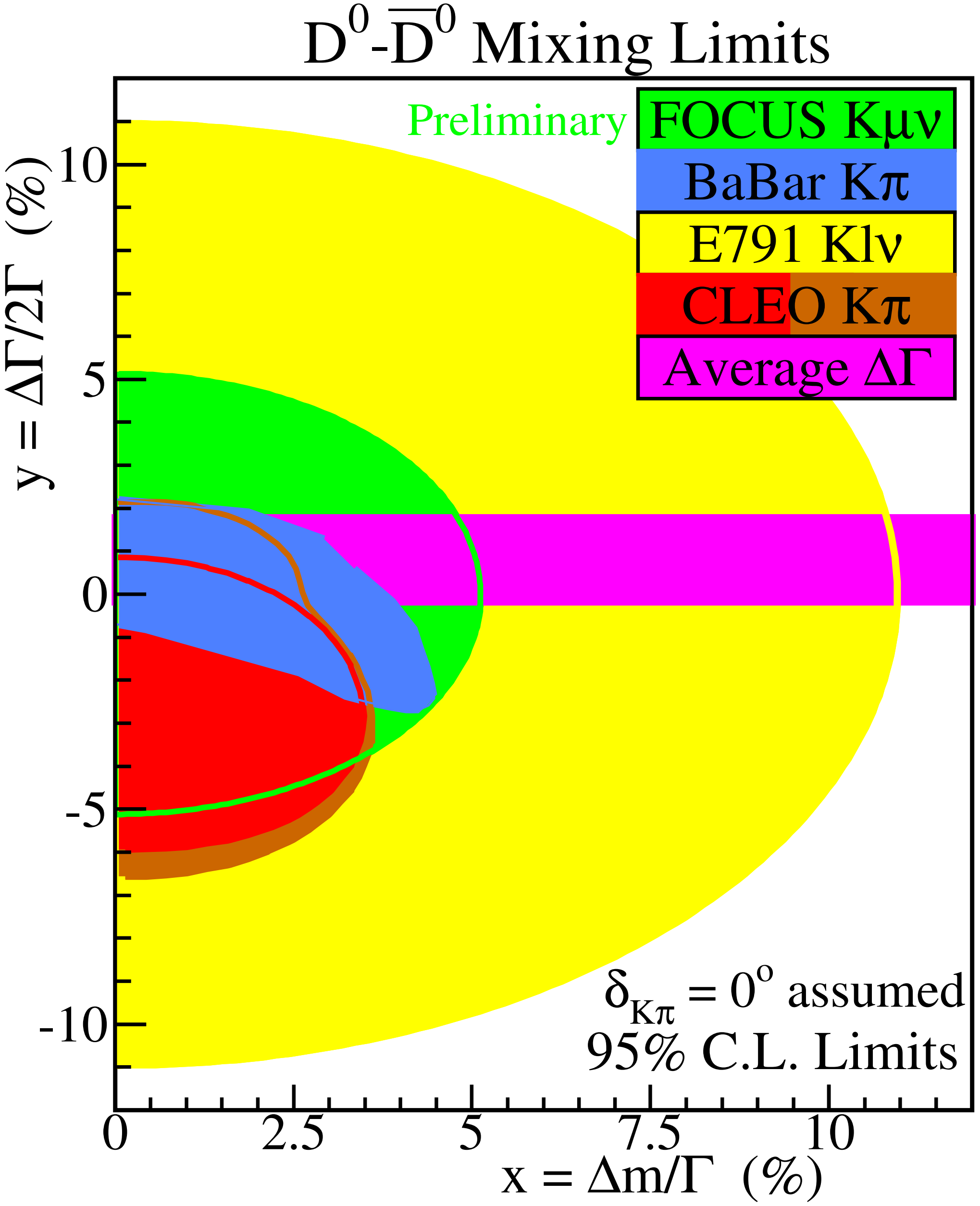
Preliminary FOCUS semimuonic mixing

- Reconstruct ν 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