Recent Results in Charm Decays

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Outline

- Introduction to Charm
- Introduction to Charm Experiments
- Lifetimes
- Hadronic Decays
- Semileptonic Decays
- Rare Decays
- Mixing
- Summary

Why charm?

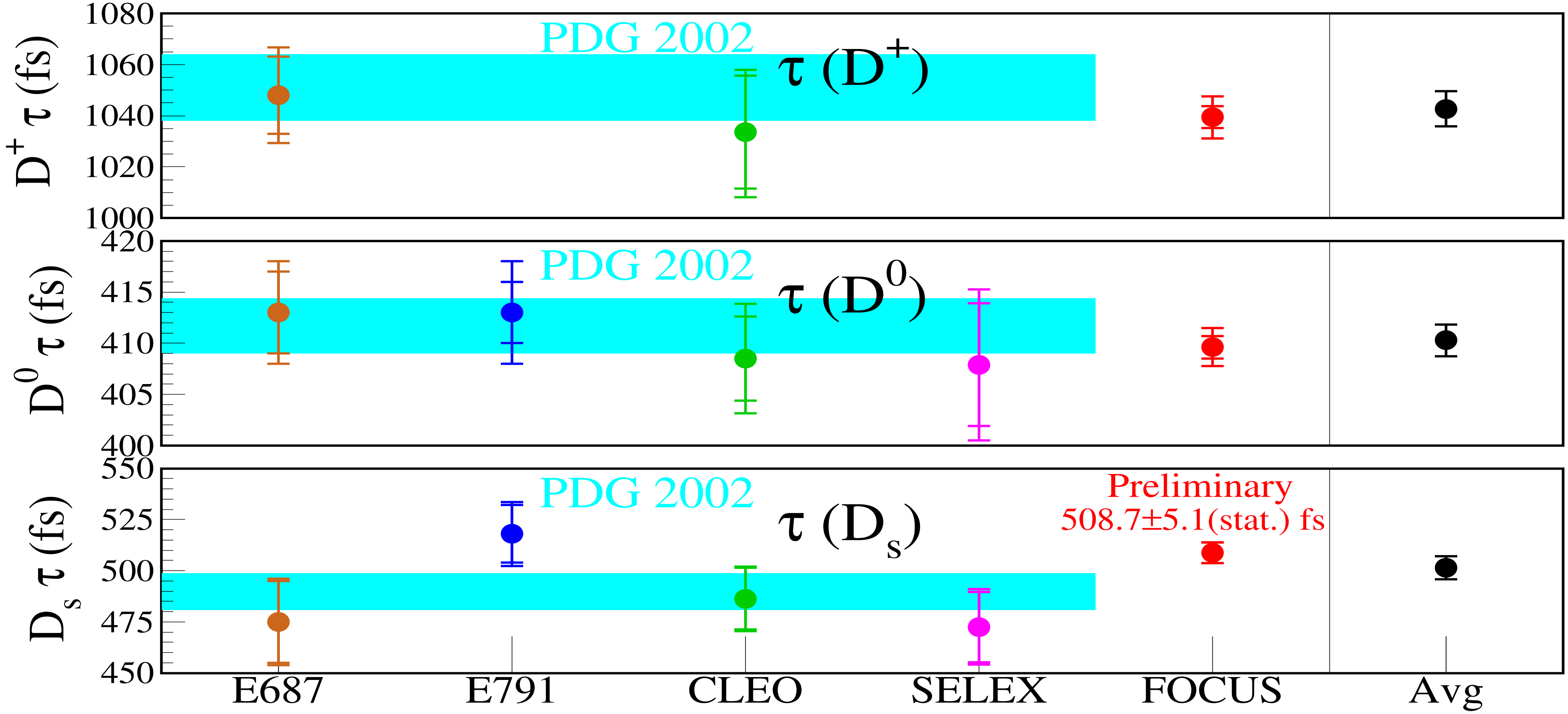
Charm has been around 30 years but, like strange physics, is still relevant

- 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 relevant experiments

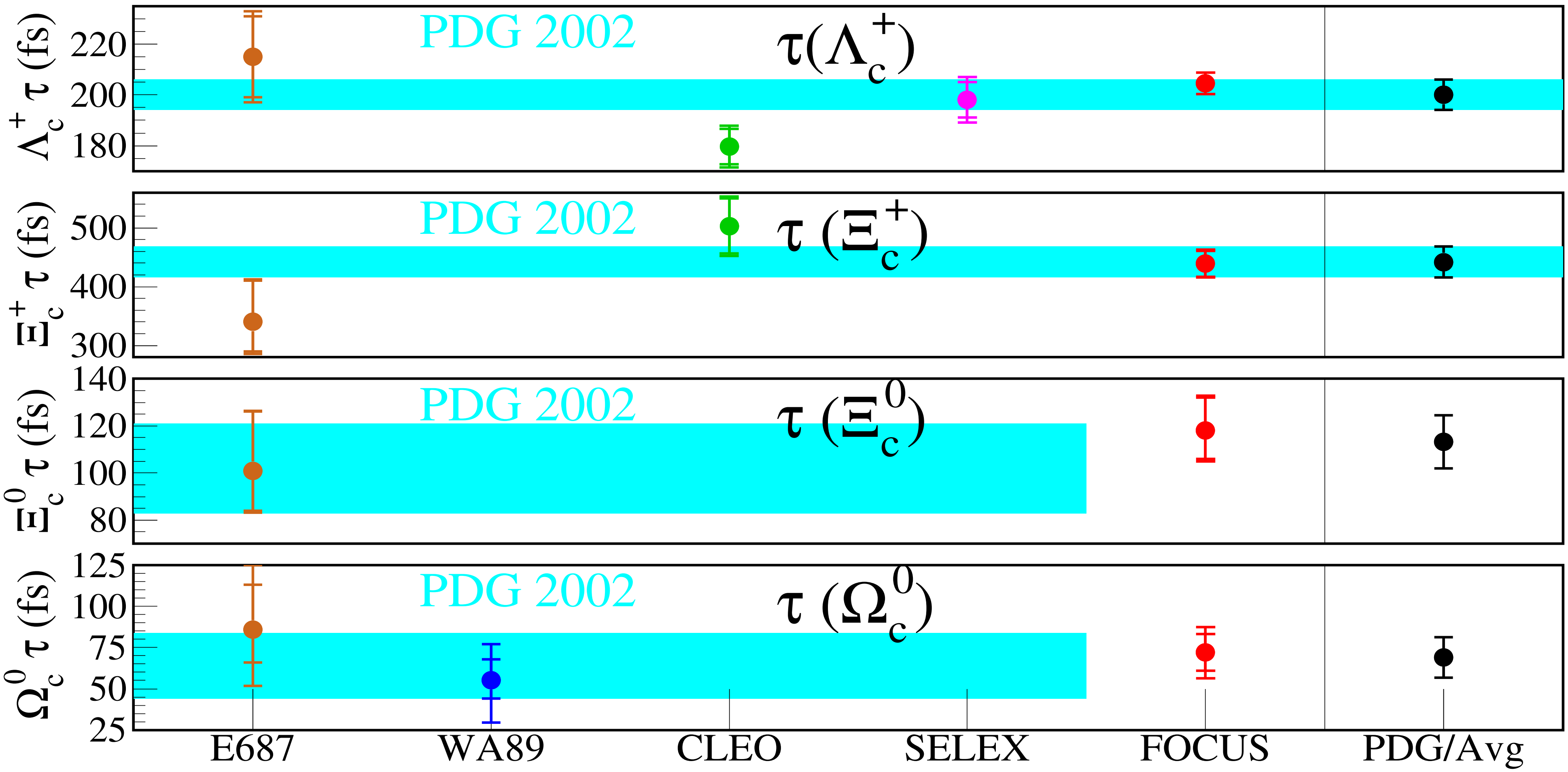
- E687, E791, FOCUS, and SELEX are Fermilab fixed-target experiments using γ, π^-, γ, and Σ^- beam particles. These experiments have excellent particle ID and vertexing.
- BaBar & Belle (CLEO) use asymmetric (symmetric) e^+e^- collisions at and below the $\Upsilon(4S)$ (10.58 GeV). Backgrounds are naturally low in these experiments.
- CDF is a Fermilab collider experiment using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The charm cross section is very high making up for not being tuned for charm work. Run II started about 1 year ago.
- BES utilizes a τ–charm factory (symmetric e^+e^- collider operating at $\sqrt{s} = 3 - 5$ GeV).

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

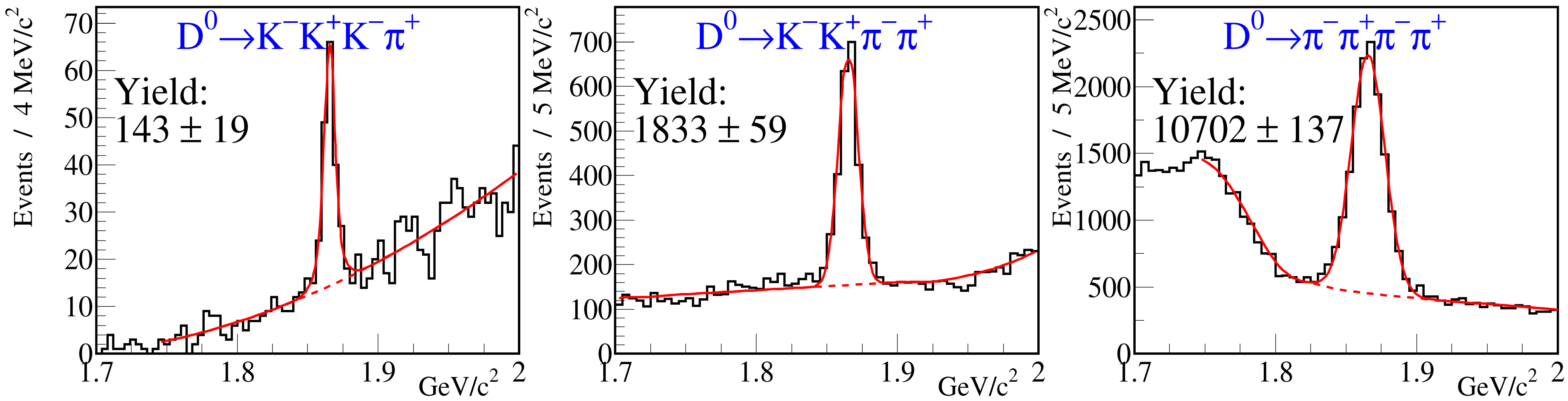
Hadronic decays are rich in information about QCD

- 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
- Hadronic decays can provide information on relative strengths of decay diagrams (spectator, W exchange, annihilation, etc.) and post-decay hadronization
- Analysis of charm decays can 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 complicates the analysis

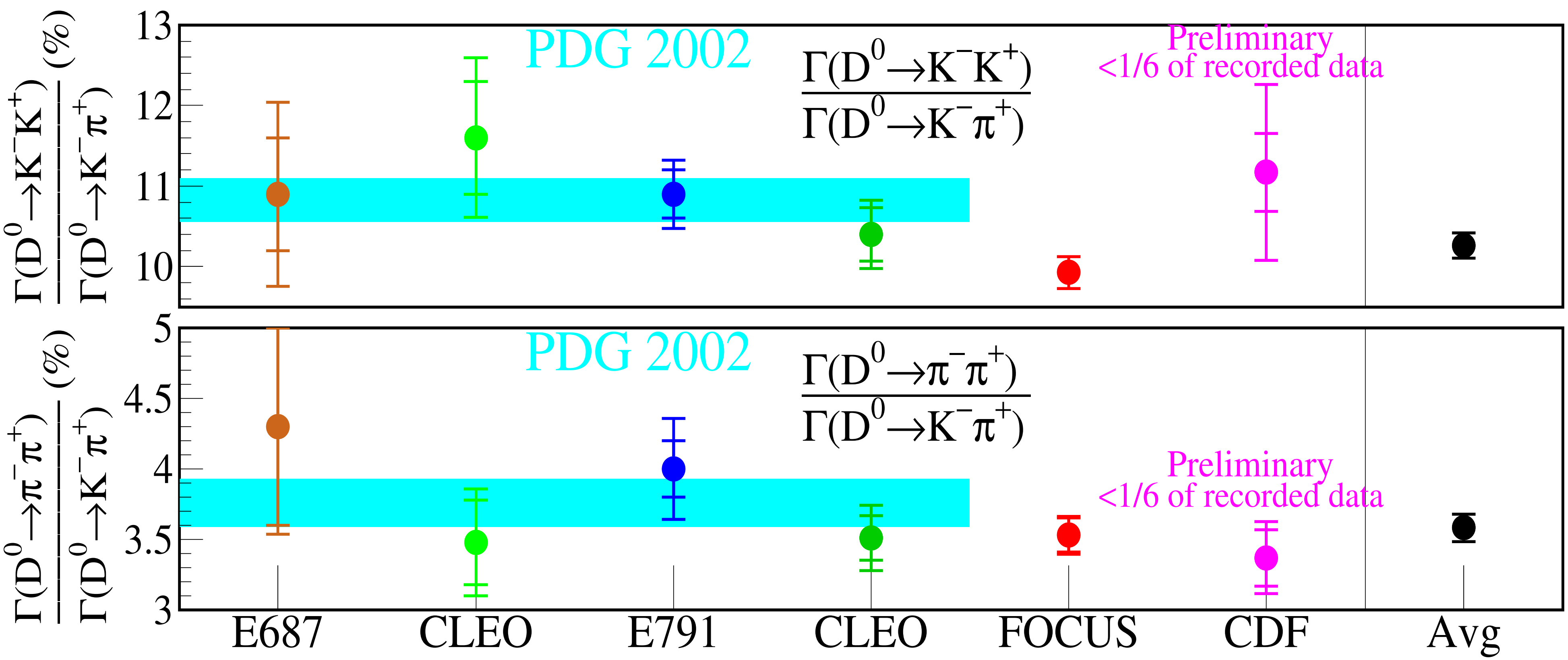
Prelim FOCUS $D^0 \to h^+h^-h^+h^-$ results



- $D^0 \to K^-K^+K^-\pi^+$ decays to ϕ 3/4 of the time, much of it is $\phi\overline{K}^{*0}$
- $D^0 \to K^-K^+\pi^-\pi^+$ 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
- Amplitude analysis is ongoing

Branching ratio	FOCUS (preliminary)	PDG2002
$\frac{\Gamma(D^0 \to K^-K^+K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$(0.257 \pm 0.034 \pm 0.023)\,\%$	$(0.32 \pm 0.09)\,\%$
$\frac{\Gamma(D^0 \to K^-K^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$(2.97 \pm 0.10(stat.))\,\%$	$(3.34 \pm 0.28)\,\%$
$\frac{\Gamma(D^0 \to \pi^-\pi^+\pi^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$	$(8.66 \pm 0.12(stat.))\,\%$	$(9.8 \pm 0.6)\,\%$

$D^0 \to h^+h^-$ decays



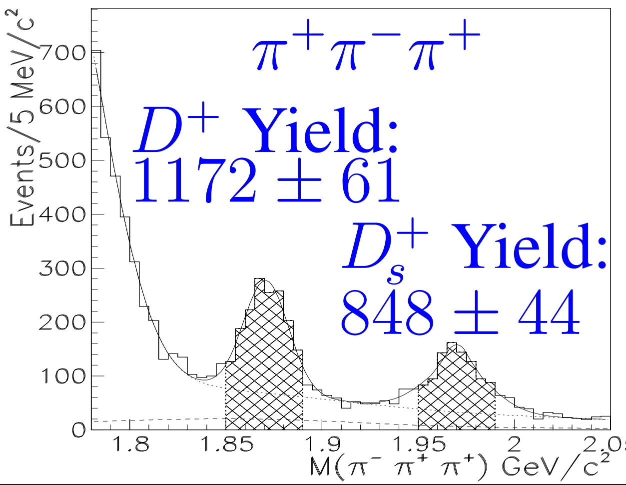
- CDF triggers on 2 displaced tracks (SVT) $\Rightarrow$ lots of charm (0.45 million $D^0 \to K^-\pi^+$ in 65 pb^{-1})
- From E791, CLEO, & FOCUS: $\left\langle \frac{\Gamma(D^0\to K^-K^+)}{\Gamma(D^0\to\pi^-\pi^+)} \right\rangle = 2.83 \pm 0.09$; Expect $\sim$1.3 $\Rightarrow$ strong example of final state interactions

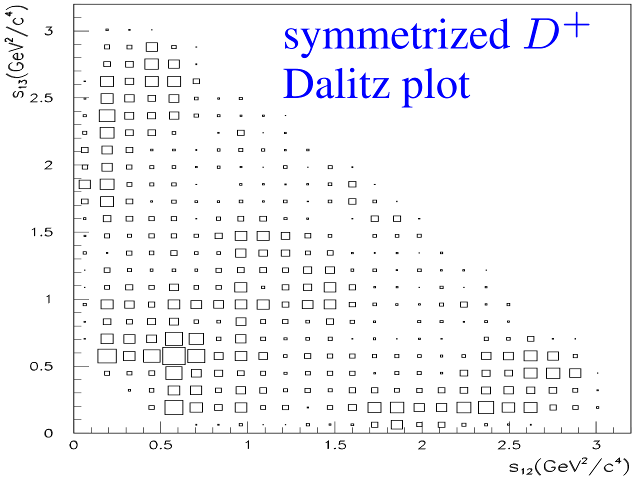
E791 $D^+, D_s^+ \to h^+h^-h^+$ Dalitz plot

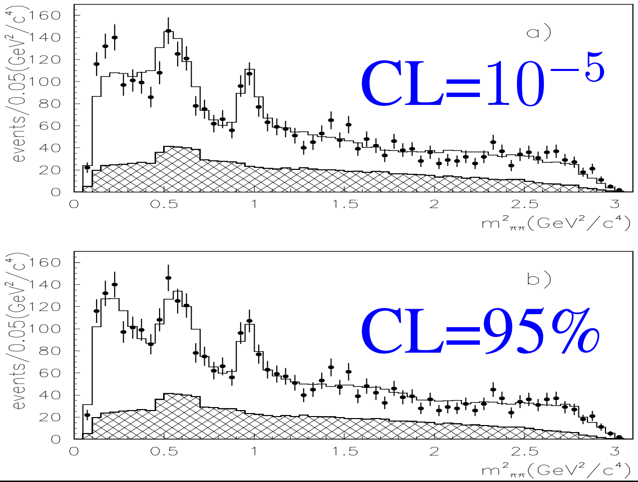
E791 uses high statistics samples to measure parameters of light mesons

Resonance	M (MeV/c^2)	Γ(MeV/c^2)	Decay Mode
σ	$478^{+24}_{-23}\pm17$	$324^{+42}_{-40}\pm21$	$D^+ \to \pi^+\pi^-\pi^+$
κ	$797\pm19\pm42$	$410\pm43\pm85$	$D^+ \to K^-\pi^+\pi^+$
$f_0(980)$	$975\pm3\pm2$	$44\pm2\pm2$	$D_s^+ \to \pi^+\pi^-\pi^+$
$f_0(1370)$	$1434\pm18\pm9$	$172\pm32\pm6$	$D_s^+ \to \pi^+\pi^-\pi^+$
$K_0^*(1430)$	$1459\pm7\pm6$	$175\pm12\pm12$	$D^+ \to K^-\pi^+\pi^+$

- σ required by $D^+ \to \pi^+\pi^-\pi^+$: fit CL 10^{-5} (no σ) $\Rightarrow$ 75% (with σ)
- κ required by $D^+ \to K^-\pi^+\pi^+$: fit CL 10^{-11} (no κ) $\Rightarrow$ 95% (with κ); also reduces mysterious nonresonant contribution from 90% to 13%
- All resonances fit as Breit–Wigner except $f_0(980)$







$D^+, D_s^+ \to h^+h^-h^+$ continued

FOCUS is a similar experiment to E791 with 2.5–10 times more data

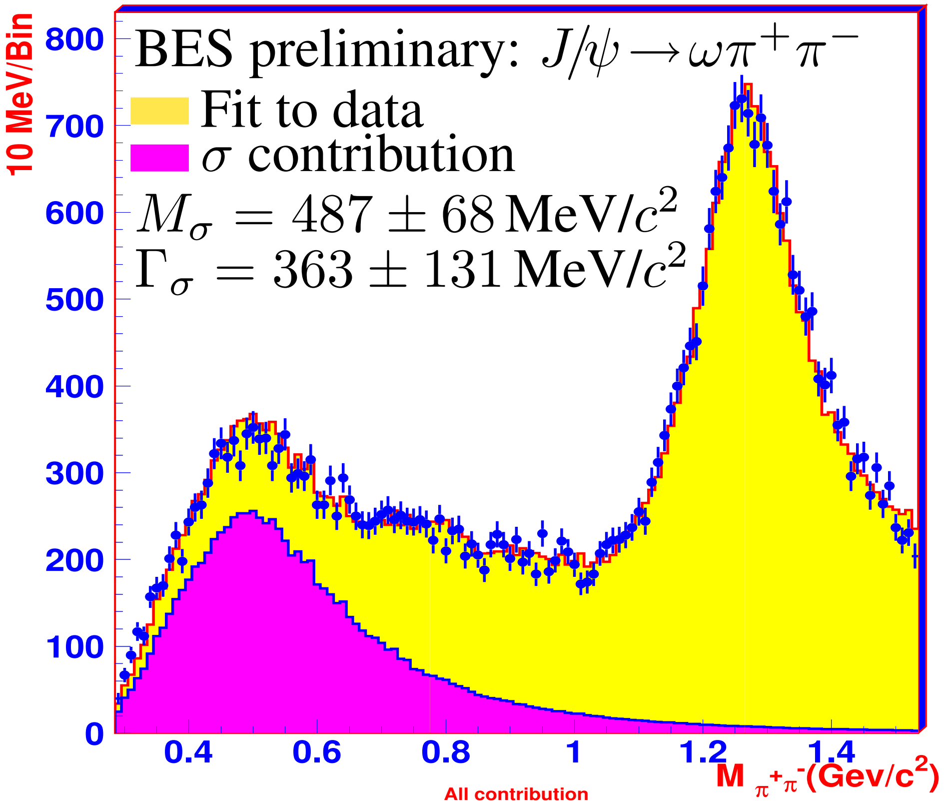
- Similar $\pi^+\pi^-\pi^+$ Dalitz plots observed
- Investigating fitting with K-matrix instead of isobar model
  - Allows coupled channel analysis
  - Allows determination of "true" pole parameters (not just observed Breit-Wigner parameters)
  - Can incorporate information from strong scattering experiments
- Anisovich & Sarantsev parameterize $IJ^{PC} = 00^{++}$ particles, $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$, $f_0(1200-1600)$. Using this parameterization, and adding in vector and tensor particles, one can fit the $D^+ \to \pi^+\pi^-\pi^+$ Dalitz plot.

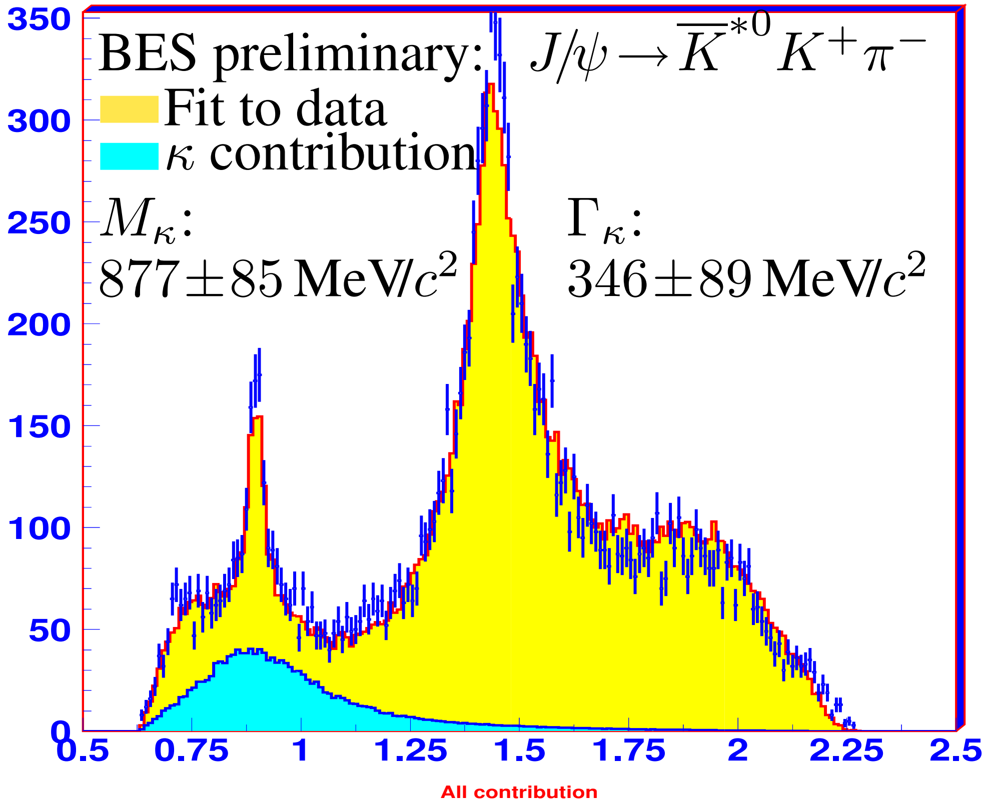
- CLEO did not see evidence for κ in $D^0 \to K^-\pi^+\pi^0$ decays
- Babar and Belle are starting to do Dalitz plot analyses

Preliminary BES σ & κ results

Preliminary BES results indicate significant contributions from σ and κ in $J/\psi \to \omega\pi^+\pi^-$ and $J/\psi \to \overline{K}^*(892)^0 K^+\pi^-$ decays

- Low mass enhancement not due to background or phase space
- Improves $J/\psi \to \omega\pi^+\pi^-$ fit by $>20\sigma$; other spins are $>20\sigma$ worse
- Improves $J/\psi \to \overline{K}^{*0} K^+\pi^-$ fit by $\sim 20\sigma$; other spins are $\gtrsim 9\sigma$ worse

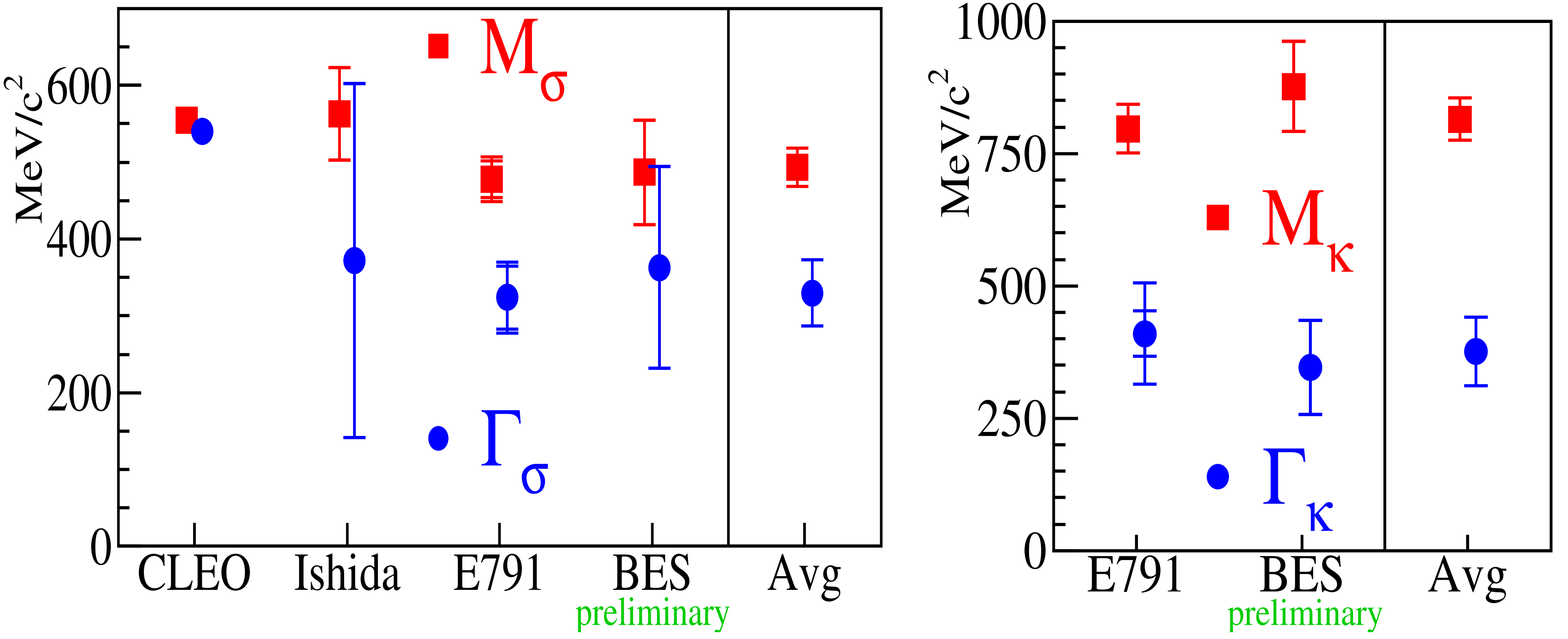




More on σ and κ

- CLEO finds $\tau^- \to \nu_\tau \pi^- \pi^0 \pi^0$ decays are dominated by a_1^- decays of which $\sim$15% are to σ: $M_\sigma = 555\,\mathrm{MeV}/c^2$, $\Gamma_\sigma = 540\,\mathrm{MeV}/c^2$
- Ishida *et al.* (via PDG) find $M_\sigma = 563 \pm 60\,\mathrm{MeV}/c^2$, $\Gamma_\sigma = 372 \pm 230\,\mathrm{MeV}/c^2$ from reanalyzed Υ' and $J/\psi^{(\prime)}$ decays.

Summary of recent results on mass & width of σ & κ



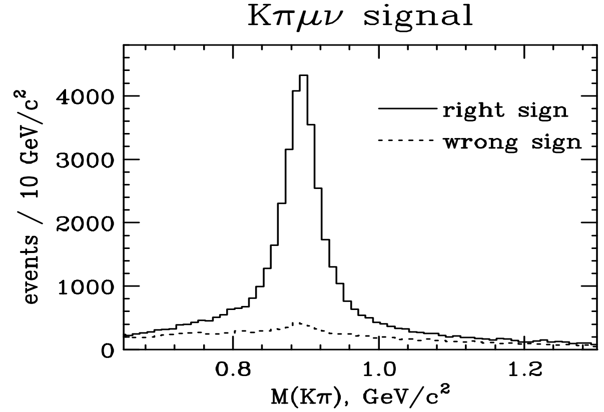
Effect of σ on $g_\mu - 2$

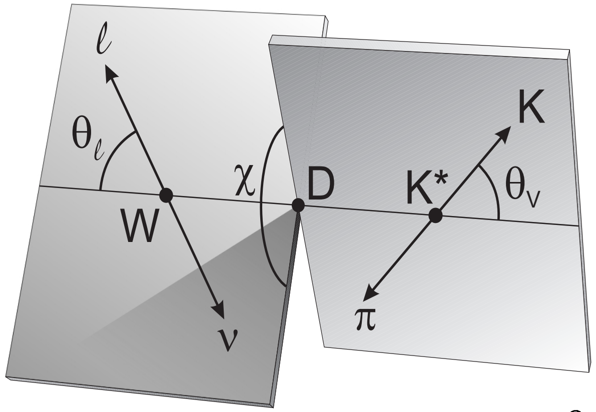
- Narison finds σ can significantly affect theoretical calculations for muon anomalous magnetic moment, $a_\mu \equiv (g_\mu - 2)/2$
- Recent comparisons of a_μ between theory and data indicate a 3.0σ or 0.9σ difference depending on whether e^+e^- annihilation or τ decay data is used in theory
- Narison finds including effects of the σ reduces the difference to 1.6σ or -0.2σ
- σ contribution introduces uncertainties larger than the old theoretical uncertainties due to lack of knowledge of M_σ and $\Gamma(\sigma \to \gamma\gamma, e^+e^-)$
- Need to learn more about the σ particle!

New scalar in $D^+ \to K^- \pi^+ \mu^+ \nu$ decays?

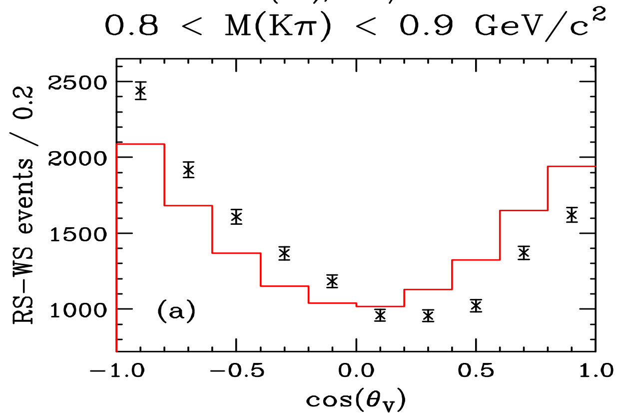
FOCUS analysis:

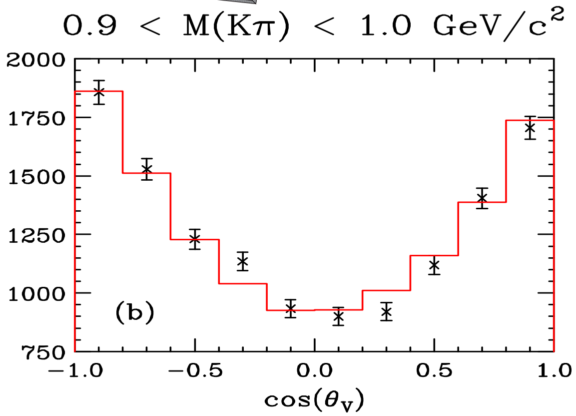
- FOCUS has large $D^+ \to K^- \pi^+ \mu^+ \nu$ sample



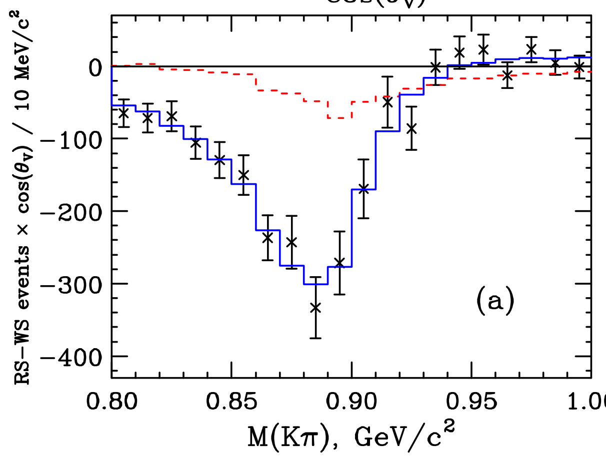


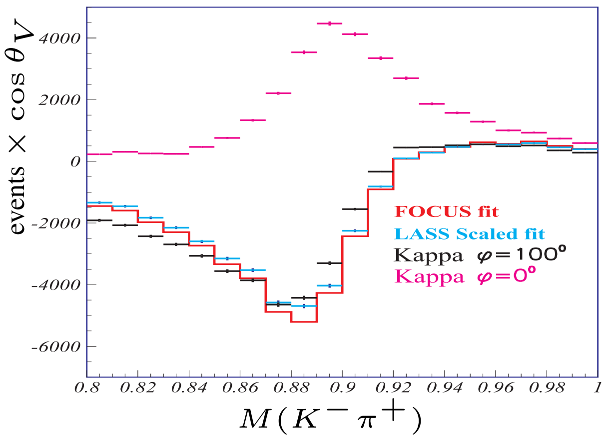
- Observe an asymmetry in $\cos\theta_V$ which depends on the $K^-\pi^+$ mass





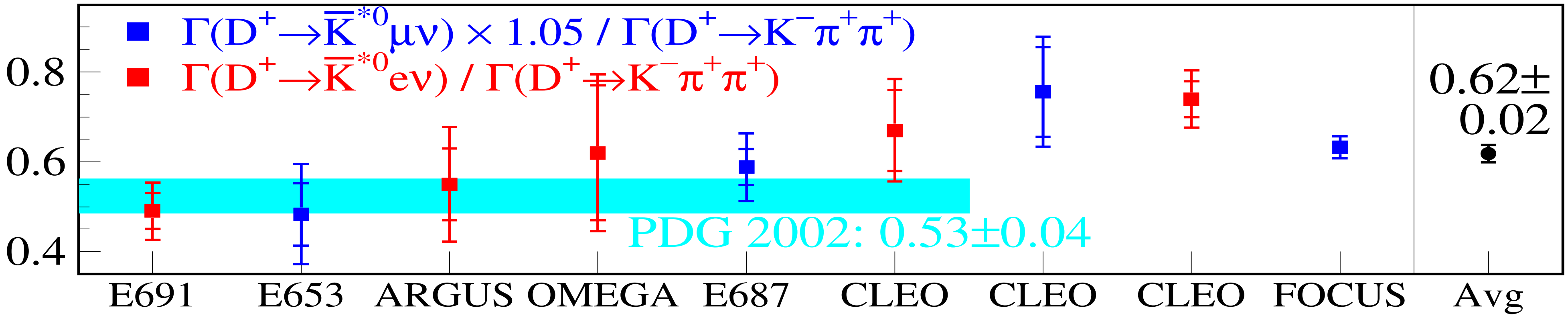
- Due to s-wave interference, $\delta = 45^\circ$
- Also in LASS $K\pi$ scattering
- κ unlikely; need extra phase shift



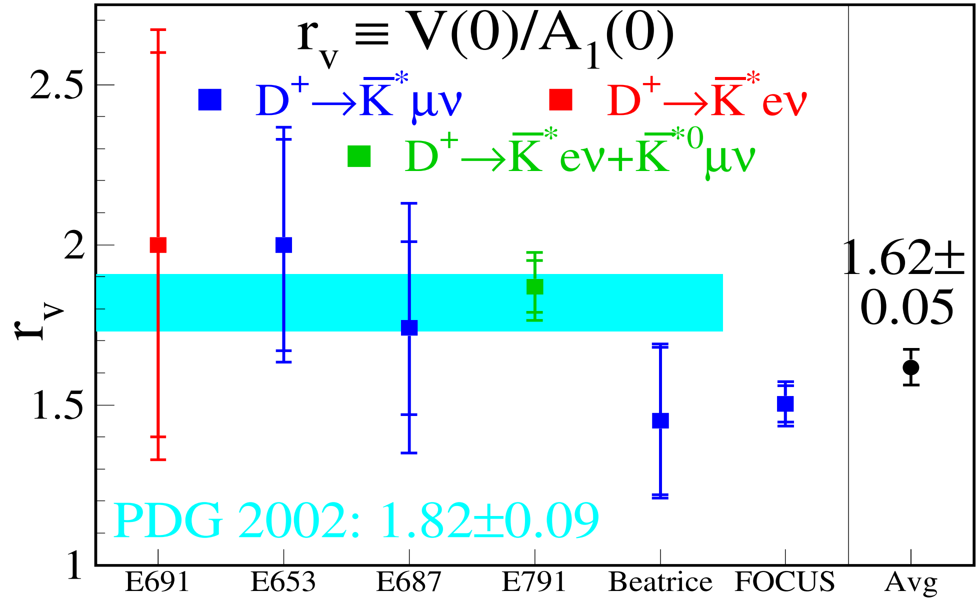


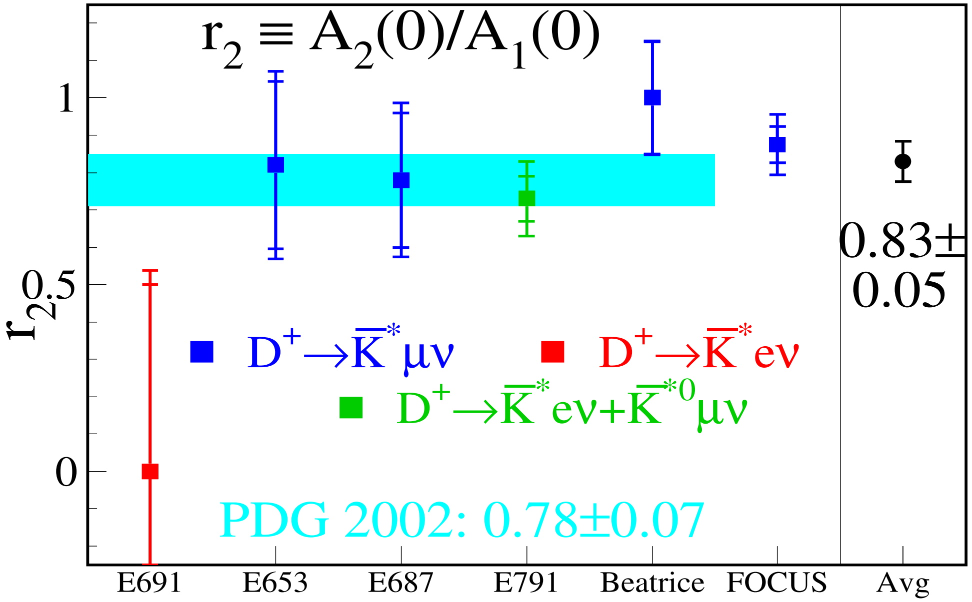
Recent $D^+ \to \overline{K}^{*0}\ell^+\nu$ results

Branching ratio: (FOCUS includes effect of scalar interference)



Form factors: (FOCUS includes effect of scalar interference)



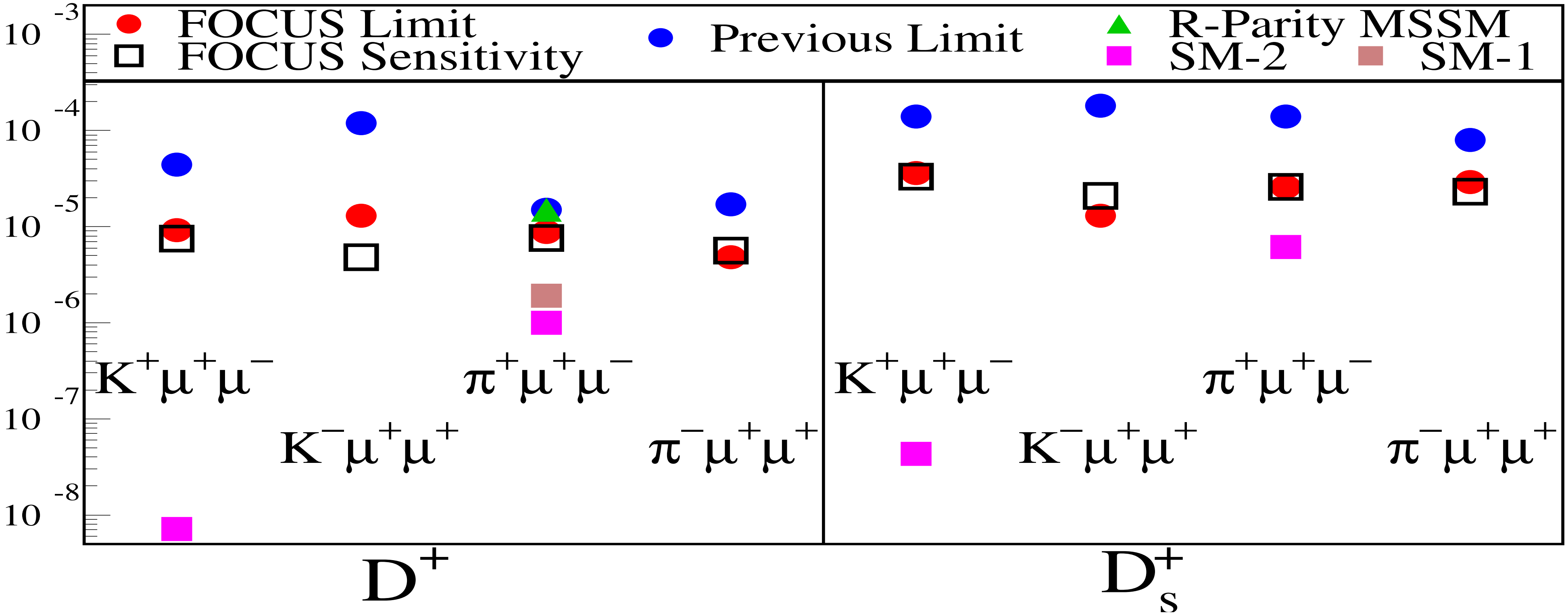


Rare decays

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

FOCUS preliminary 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



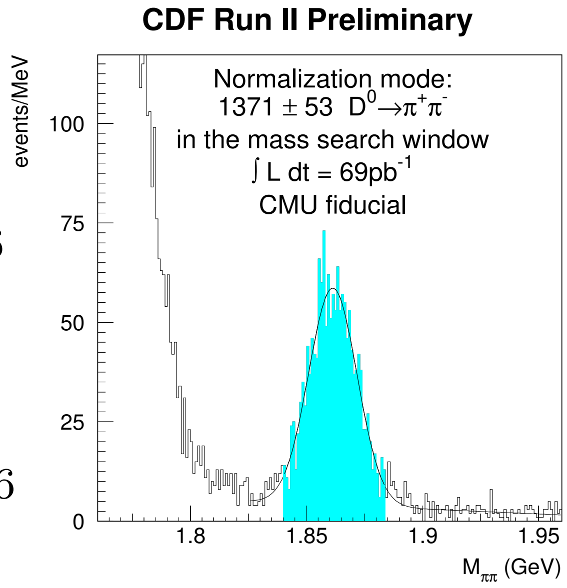
$D^0 \to \mu^+\mu^-, \gamma\gamma$ searches

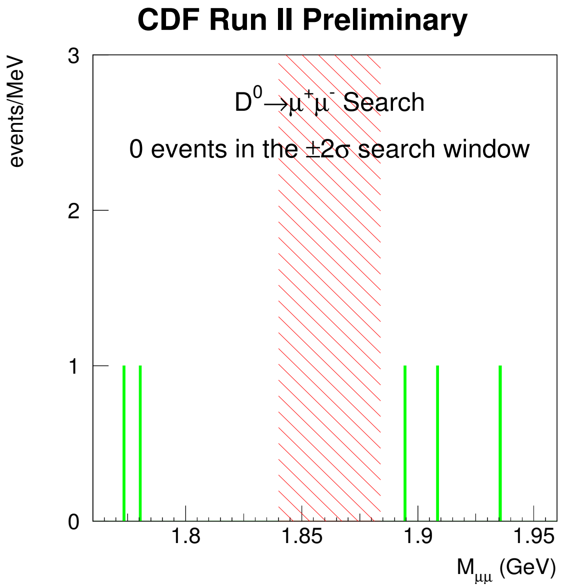
Preliminary CDF 90% CL upper limit on $D^0 \to \mu^+\mu^-$:

$\mathcal{B}(D^0 \to \mu^+\mu^-) < 2.4\times10^{-6}$

(sensitivity of 4.1×10^{-6})

current world best: 4.1×10^{-6}

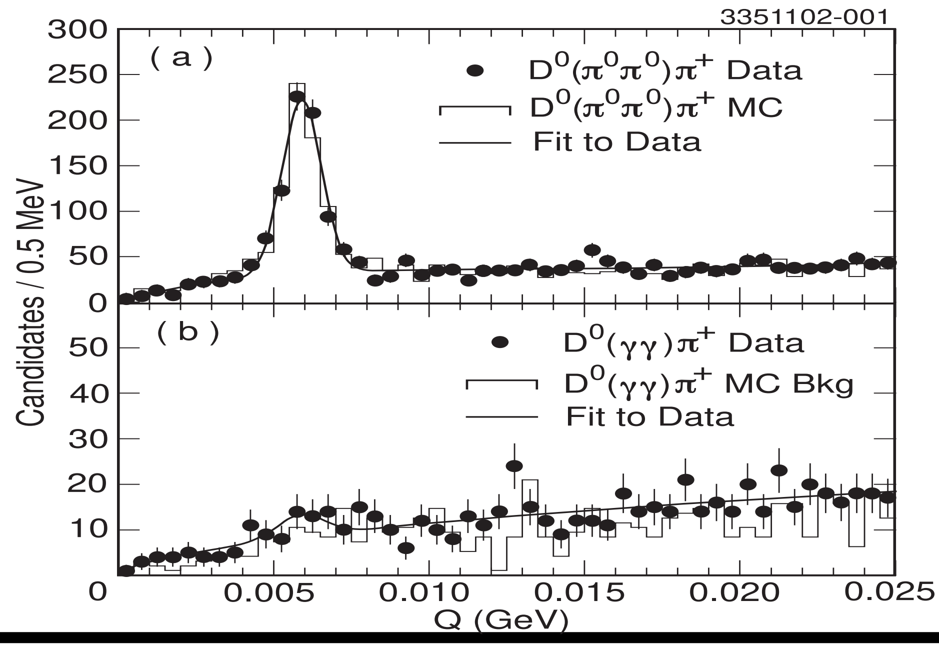




In 2003, CLEO published the first limit on $D^0 \to \gamma\gamma$:

$$\frac{\Gamma(D^0 \to \gamma\gamma)}{\Gamma(D^0 \to \pi^0\pi^0)} = (1.94 \pm 0.94)\%$$

$\mathcal{B}(D^0 \to \gamma\gamma) < 2.9\times10^{-5}$ @ 90% CL



Charm mixing

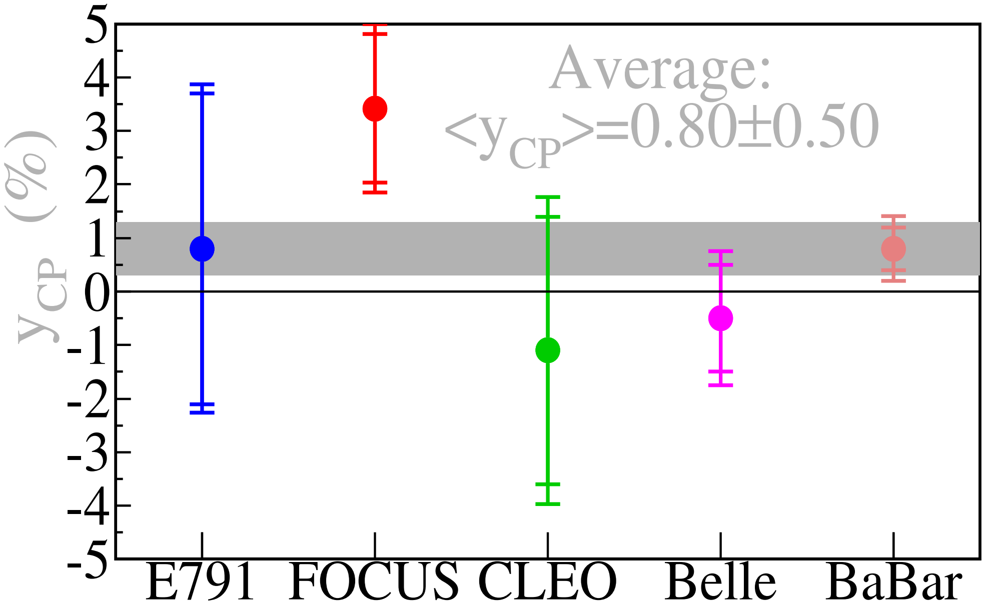
- Like K^0, B^0, & B_s^0 particles, D^0 particles can mix
- Mixing very suppressed in Standard Model $\Rightarrow$ room for new physics
- Look for mixing in wrong sign semileptonic or hadronic decays
- Doubly Cabibbo Suppressed decays complicate hadronic decays
- Definitions:
  - $x \equiv \frac{\Delta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

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

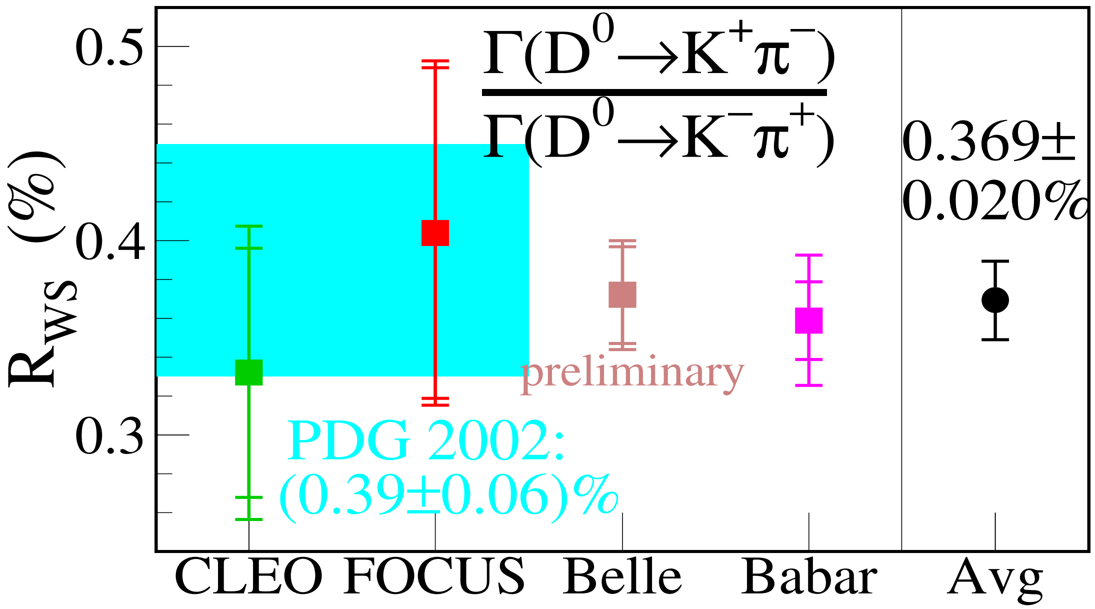
where the three terms come from DCS decays, interference, and mixing.
In semileptonic mixing only the mixing term appears.

Charm mixing results

- Assuming CP conservation: measure y by looking for lifetime difference between CP even, CP odd, and/or CP mixed states
- Compare $\tau\left(D^0 \to K^-\pi^+\right)$ to $\tau\left(D^0 \to K^-K^+, \pi^-\pi^+\right)$

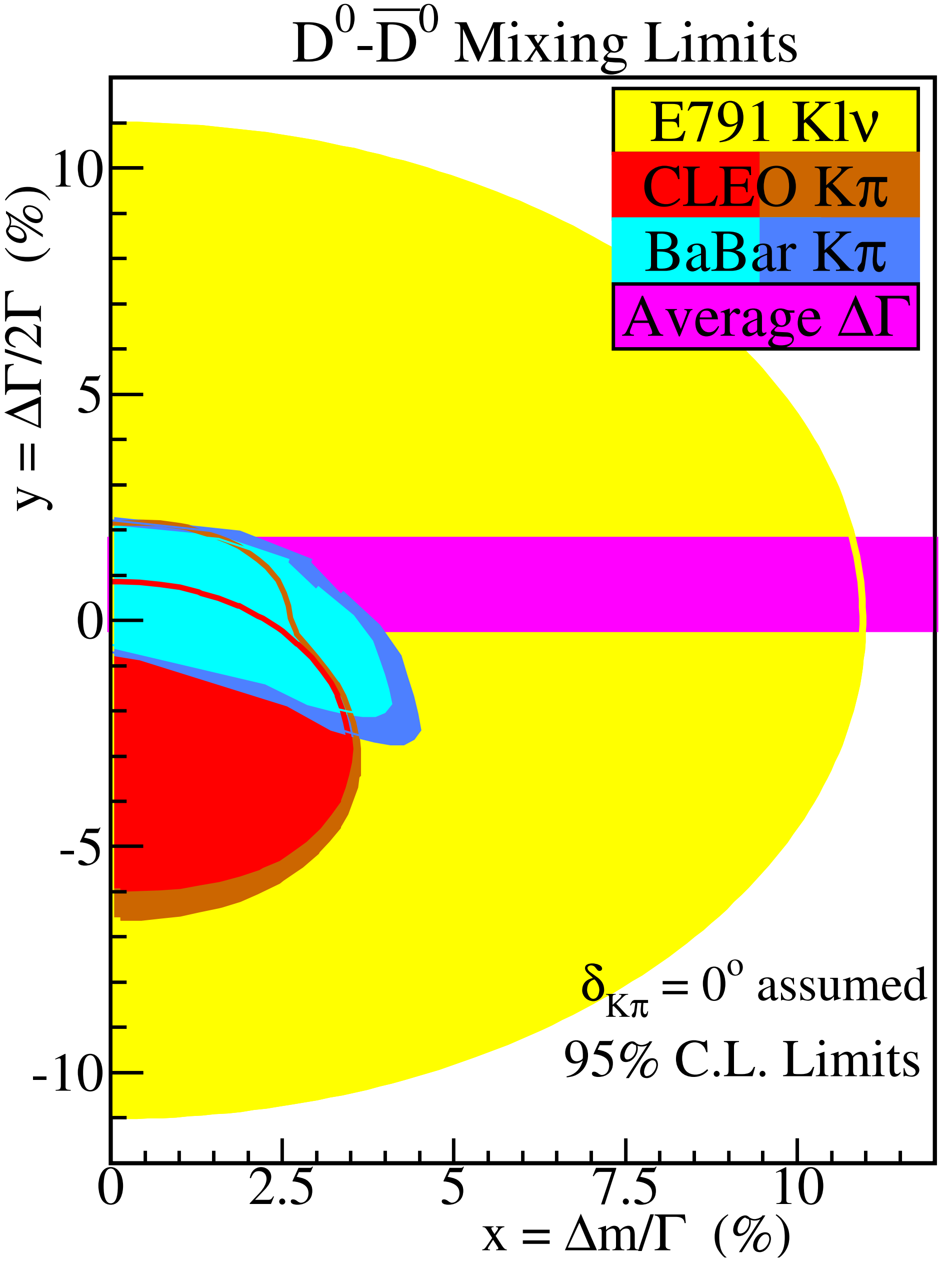


Measurements of the hadronic wrong sign decay rate (assumed DCS) have become quite precise with recent Babar and Belle measurements.



Charm mixing results continued

- E791 semileptonic mixing result measures $r_{mix} \equiv 1/2\,(x^2 + y^2)$.
- CLEO hadronic mixing results allowing or not allowing CP violation. Fit to x' and y'. Contour from scanning $\Delta\mathcal{L}$.
- BaBar CP conserving hadronic mixing results with statistical & statistical plus systematic errors. Fit to x'^2, y'. Contour from mini-MC frequentist approach.
- FOCUS, CLEO, BaBar, and Belle are all investigating mixing using semileptonics and various hadronic modes.



Some results which were missed

- See sessions **P12** and **C12** for a full list
- Babar results
  - Three-body D decays — **C12.004**
- Belle results
  - $J/\psi c\bar{c}$ excess and double charmonium cross sections — **P12.008**
  - Ω_c mass, semileptonic decay, production — **P12.001**
- CLEO results
  - $\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^+\pi^-\pi^0$ observation — **P12.015**
  - $D_s \rightarrow \mu\nu, \phi\pi$ branching ratios — **C12.006, C12.007**
  - Dalitz plot: $D^0 \rightarrow K_S^0\pi^0\pi^0, K^-K^+\pi^0$ — **C12.001, C12.009**
  - $D_s \rightarrow \eta\ell\nu, \Lambda_c^+ \rightarrow \Lambda e\nu$ form factors — **C12.005, P12.014**
  - $D^+ \rightarrow \pi^+\pi^0, K_S^0K^+, K^+\pi^0$ decays — **C12.008**
- CDF results
  - Charm production results — **C12.003**
- FOCUS results
  - $D^0 \rightarrow K^-\pi^+\pi^-\pi^+\pi^-\pi^+$ decays — **C12.010**

Future of charm

- FOCUS: Will continue to analyze semileptonics, baryon decays, resonant analyses of hadronic decays, etc.
- SELEX: Many interesting production studies to come.
- Babar & Belle: Continuing to take data. With large, clean data samples, they have the capability to provide very precise measurements of lifetimes, relative branching ratios, substructure of hadronic decays, etc.
- CDF: Should be competitive in rare decays and maybe in other areas as well.
- CLEO: Converting to CLEO-c which will operate at various charmonium resonances. Precise measurements of absolute branching fractions and f_D & f_{D_s} via $D^+ \to \ell^+ \nu$ & $D_s^+ \to \ell^+ \nu$ decays. Also interesting semileptonic and mixing studies.
- BTeV: Will obtain billions of reconstructed charm decays and will be strong in areas where fixed-target experiments like FOCUS and E791 are strong.