Recent Results from FOCUS

E831

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SLAC Topical Conference

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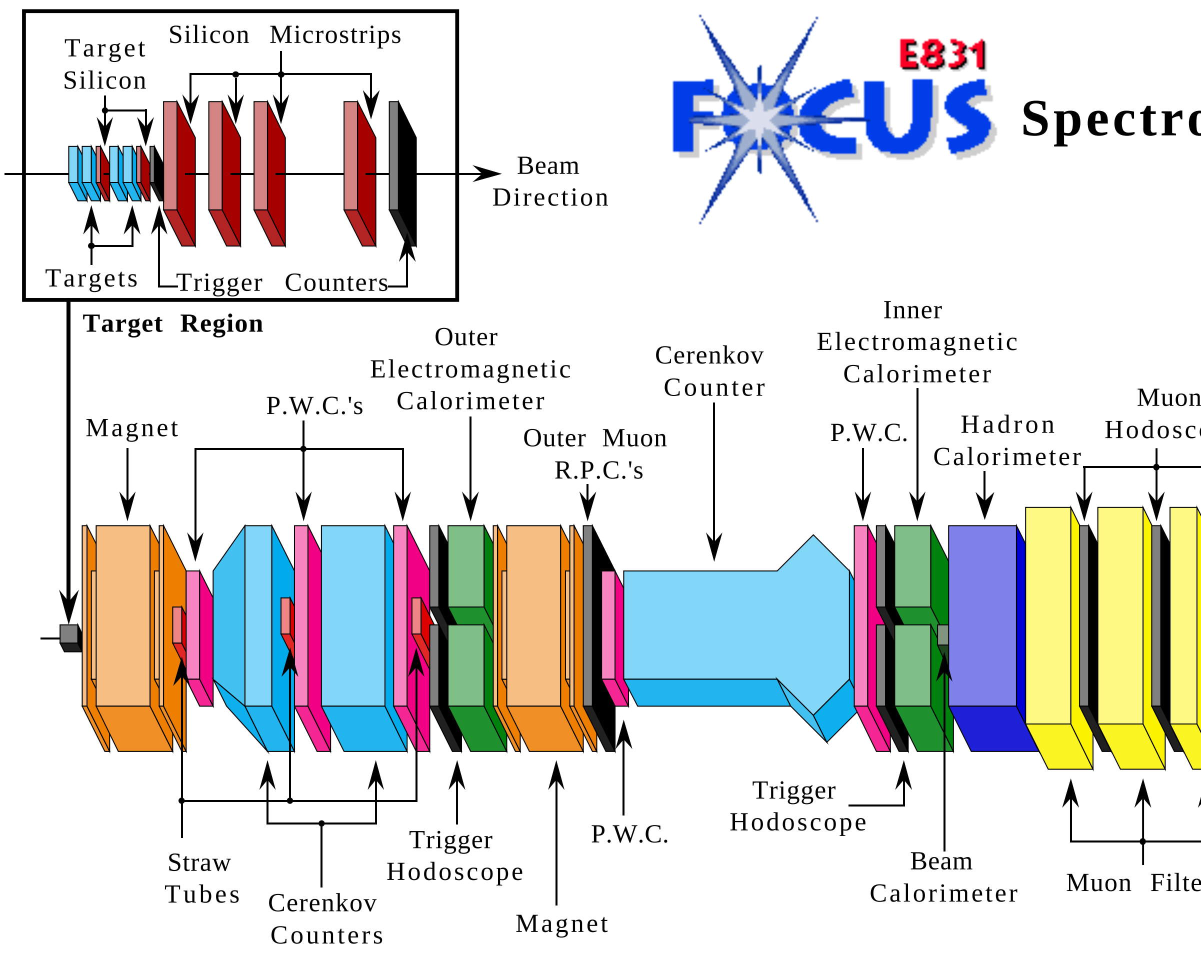
Outline

- An introduction to FOCUS.
- The decay $D^0 \to K^+\pi^-$ and it's implications for mixing.
- Charm lifetimes.
- Spectroscopy of excited charmed mesons.
- Branching Ratio measurements.
- FOCUS searches for Direct ~~CP~~ .
- Summary and prospects.

The E831 FOCUS Experiment

- Upgraded version of Fermilab-E687.
- Photoproduction of charm with $\langle E_\gamma \rangle \approx 180$ GeV.
- Excellent vertex reconstruction charged particle tracking, particle identification.
- Over 1 million reconstructed charm decays.



Target
Silicon
Silicon Microstrips
Beam
Direction
Targets
Trigger Counters
Target Region
E831
FOCUS
Spectro
Magnet
P.W.C.'s
Outer
Electromagnetic
Calorimeter
Outer Muon
R.P.C.'s
Cerenkov
Counter
P.W.C.
Inner
Electromagnetic
Calorimeter
Hadron
Calorimeter
Muon
Straw
Tubes
Cerenkov
Counters
Trigger
Hodoscope
Magnet
P.W.C.
Trigger
Hodoscope
Beam
Calorimeter
Muon

FOCUS Collaboration

University of California, Davis

CBPF, Rio de Janeiro, Brasil

CINVESTAV, México City, DF, México

University of Colorado, Boulder

Fermi National Accelerator Laboratory

INFN, Frascati Laboratory, Frascati, Italy

University of Illinois, Champaign

Korea University, Seoul, Korea

INFN and University of Milano, Milan, Italy

University of North Carolina, Asheville

INFN and University of Pavia, Pavia, Italy

University of Puerto Rico, Mayaguez

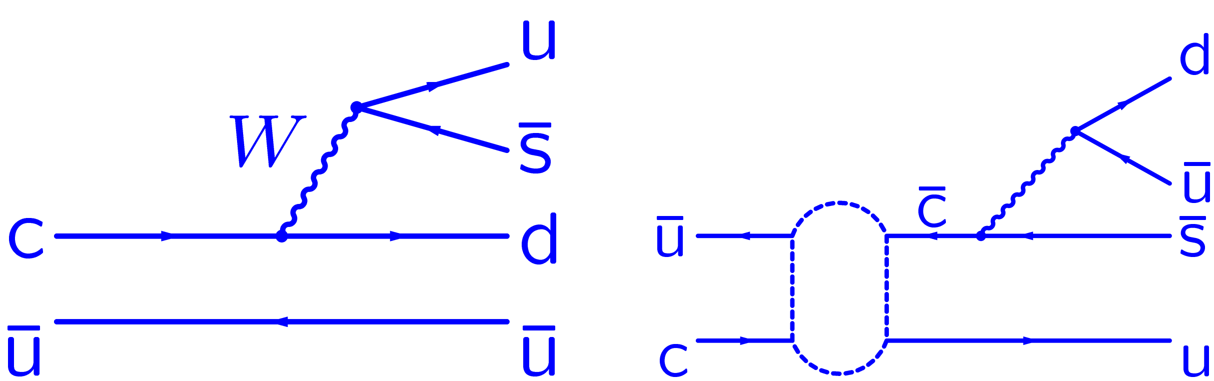
University of South Carolina, Columbia

University of Tennessee, Knoxville

Vanderbilt University, Nashville

University of Wisconsin, Madison

Study of the Decay $D^0 \to K^+\pi^-$



DCS decay OR Mixing CF decay

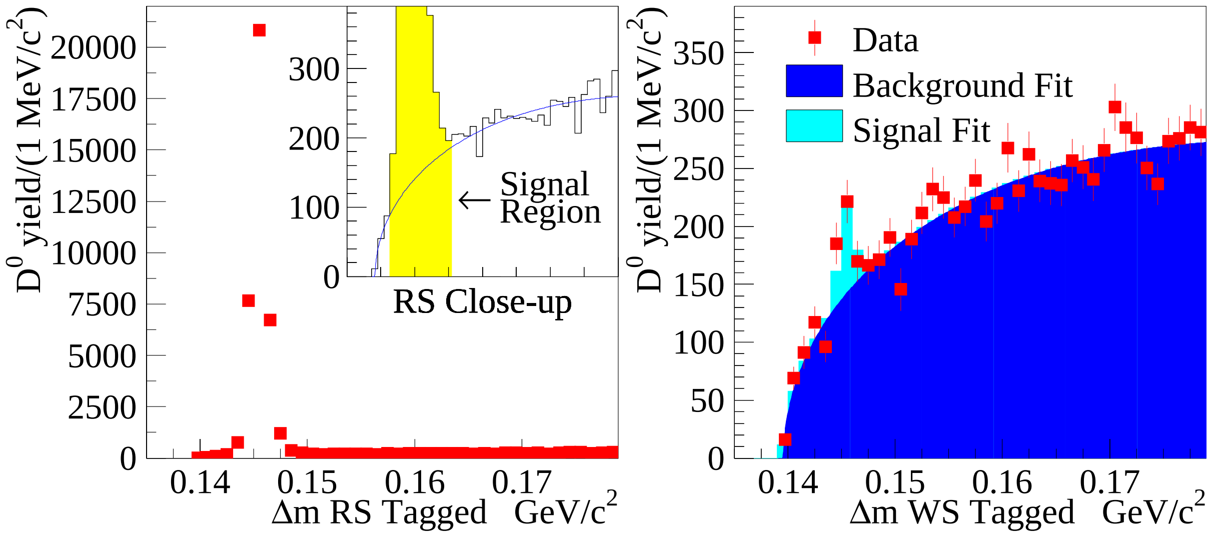
- Define $x = \frac{\Delta M}{\Gamma}$ and $y = \frac{\Delta\Gamma}{2\Gamma}$.Experimentally ΔM,$\Delta\Gamma \ll \Gamma$.

- R_{WS} the Wrong sign decay rate can have contributions from DCS and Mixing.

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

where x', y' are x and y rotated by an unknown strong phase δ.

Study of the Decay $D^0 \to K^+\pi^-$

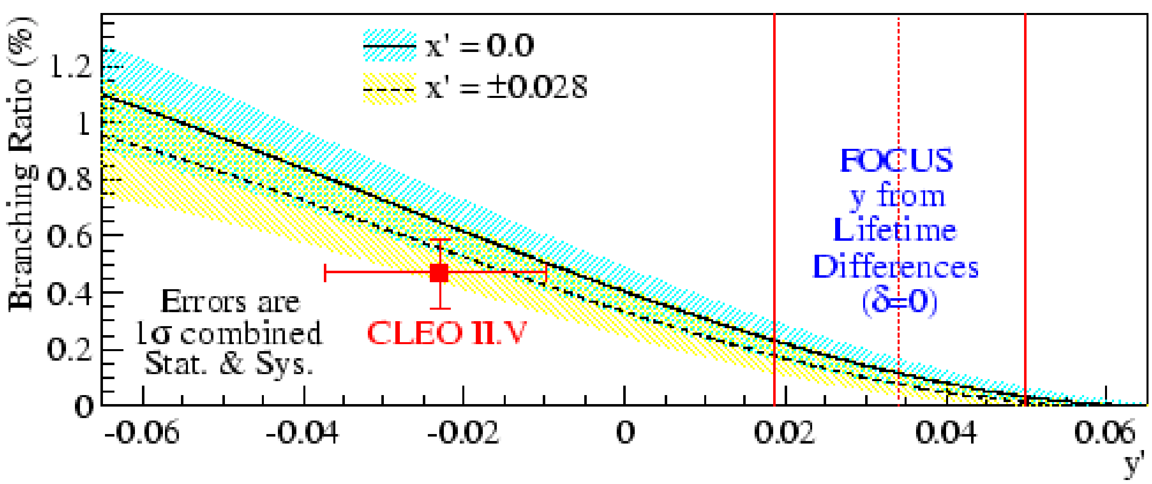


- Identify RS/WS decays by “tagging” the soft pion in the decay $D^{*+} \to D^0\pi^+$.
- Fit D^0 yield in bins of $D^{*+} - D^0$ mass difference.
- The WS fit is the sum of a background function and a scaled RS signal contribution i.e. R_{WS} .
- We obtain $R_{WS} = (0.404 \pm 0.085 \pm 0.025)\,\%$ and a WS yield of 149 ± 31 events.

Study of the Decay $D^0 \to K^+\pi^-$

- We can extract a relationship between R_{WS} , R_{DCS} , x' and y' :

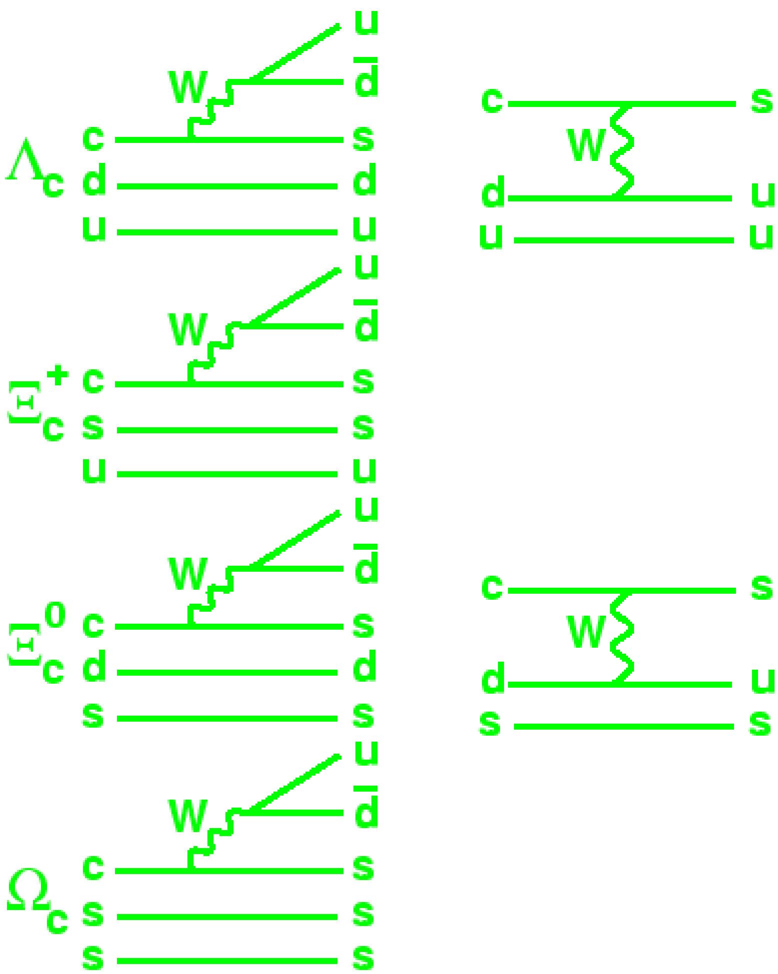
$$R_{WS} = R_{DCS} + \sqrt{R_{DCS}}y' \langle t \rangle + \frac{x'^2 + y'^2}{4} \langle t \rangle^2$$



Lifetimes

- Precise measurements of charmed lifetimes are needed to extract rates from branching ratios.
- Compare measured lifetimes to theoretical predictions.
- Contributions from various diagrams:
  - Spectator Decay
  - Internal Color Suppressed
  - W-exchange
  - W-annihilation
- FOCUS has excellent lifetime resolution and high statistics.
- Historically, we are the only collaboration to measure all of the stable charmed particle lifetimes.

Lifetimes



$\Gamma_{DEC} + \Gamma_{EXC} - \Gamma_{INT}^{-}$

$\Gamma_{DEC} + \Gamma_{INT}^{+} - \Gamma_{INT}^{-}$

$\Gamma_{DEC} + \Gamma_{EXC} + \Gamma_{INT}^{+}$

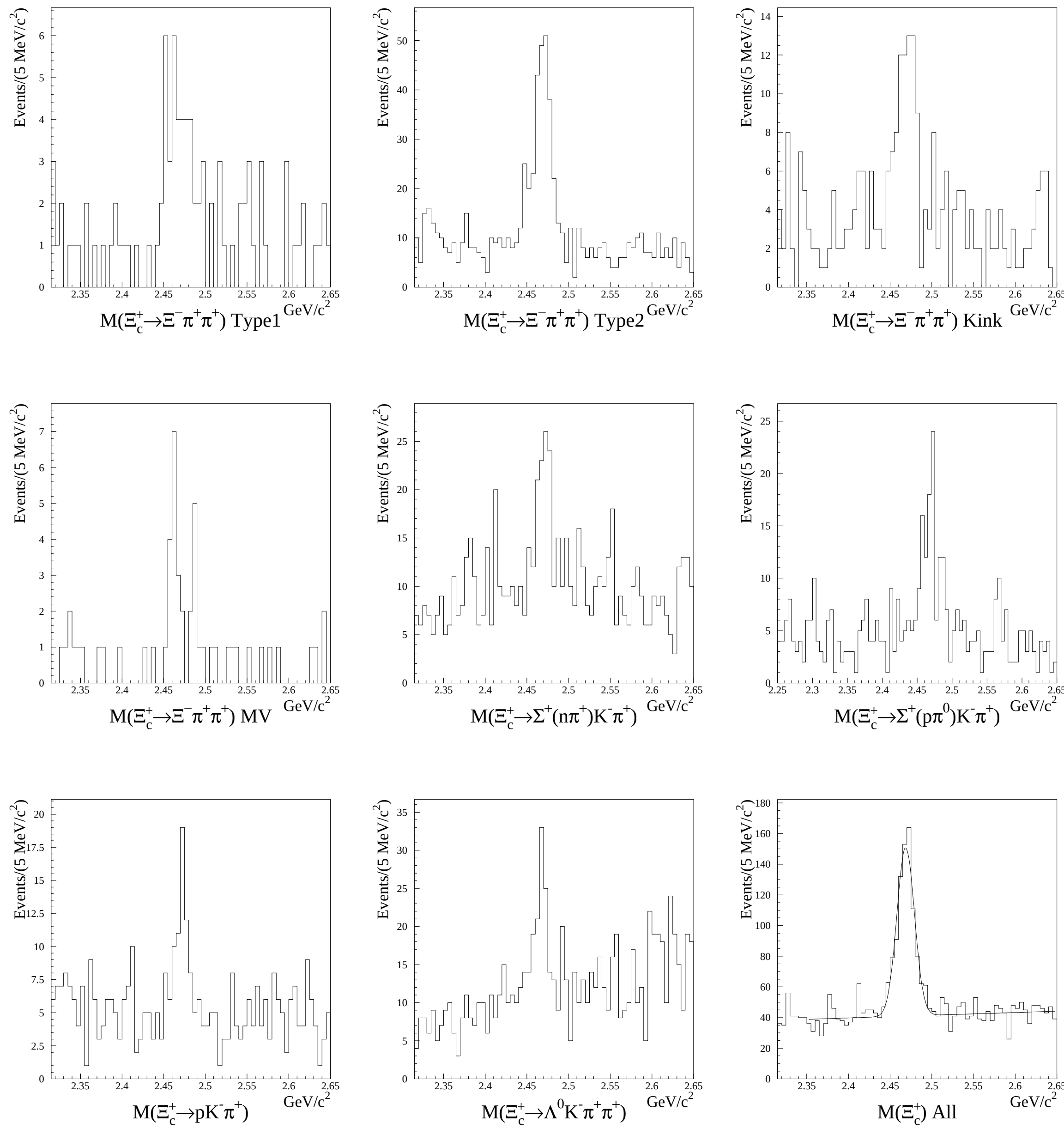
$\Gamma_{DEC} + (10/3)\, \Gamma_{INT}^{+}$

Expect $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} \approx \tau_{\Omega_c^0}$

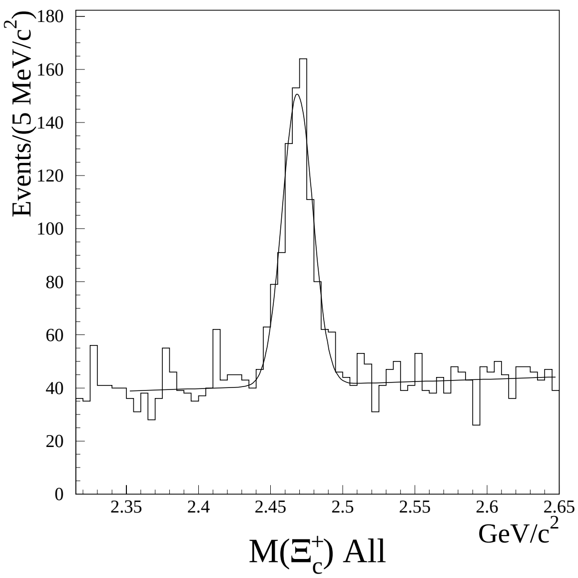
Lifetimes

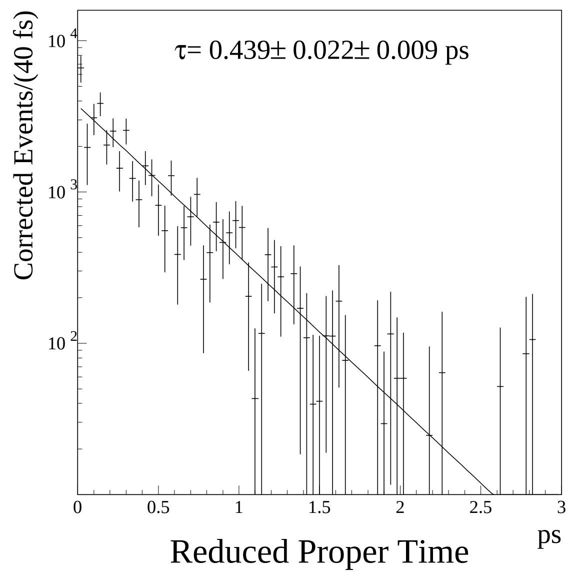
- Formalism: $1/m_Q$ expansion, but is the charm quark heavy enough?
- Duality: Inclusive transition rates between hadronic systems can be calculated in terms of quarks and gluons $\Longrightarrow$ lifetimes.
- Differences in meson lifetimes scale like $1/m_Q^3$ so $\approx$100% differences in charm meson lifetimes become a few percent differences between beauty mesons.
- For baryons there is also a significant scaling down but larger differences may survive for beauty.
- "the decays of charm hadrons act as nature's microscope onto the decays of beauty hadrons!" (Bellini, Bigi and Dornan)

Ξ_c^+ Lifetime



Ξ_c^+ Lifetime





- FOCUS has measured the Ξ_c^+ lifetime using 5 different decay modes and 8 different reconstruction algorithms.

- Our PRELIMINARY result is

$$439 \pm 22 \pm 9 \text{ fs}$$

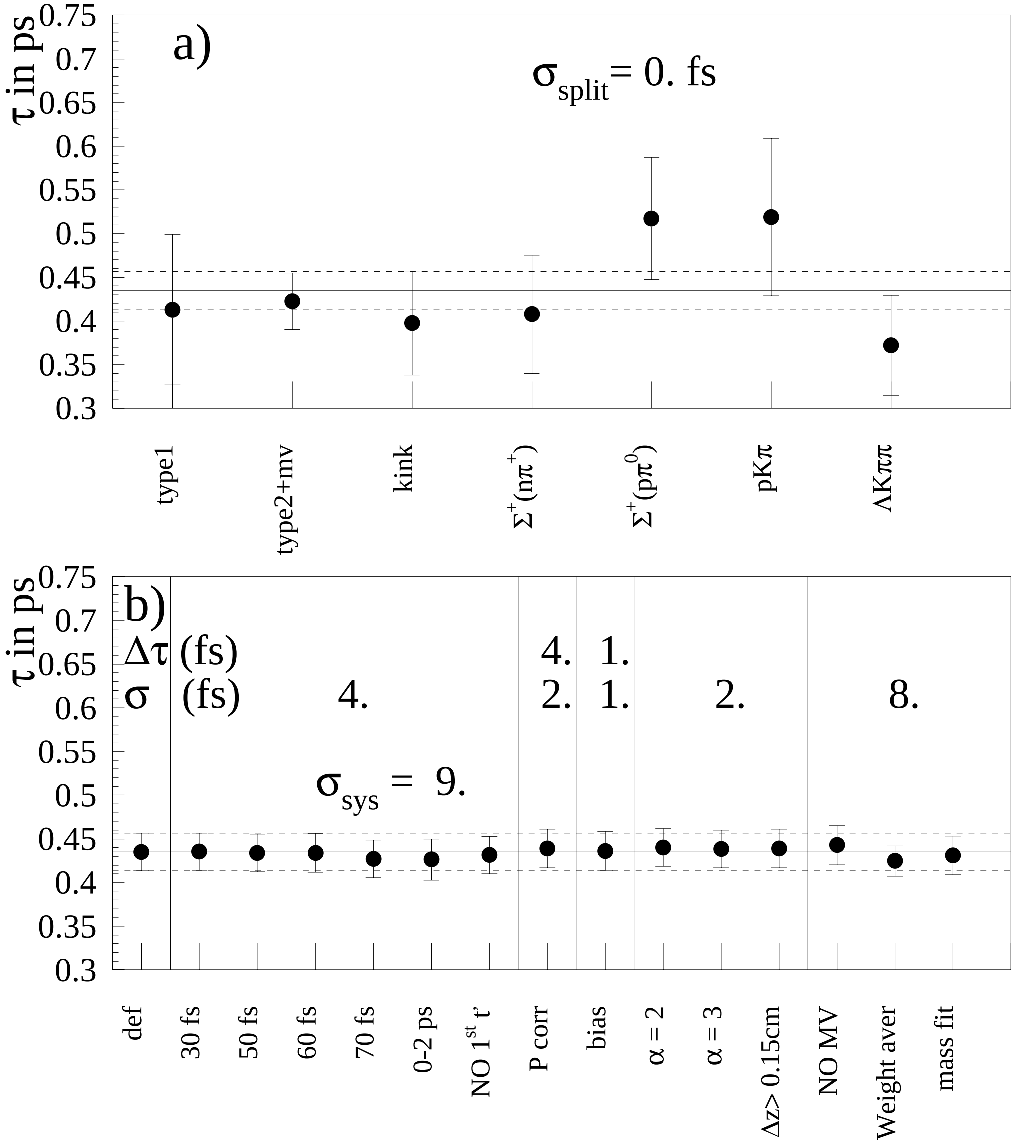
Ξ_c^+ Lifetime Systematics

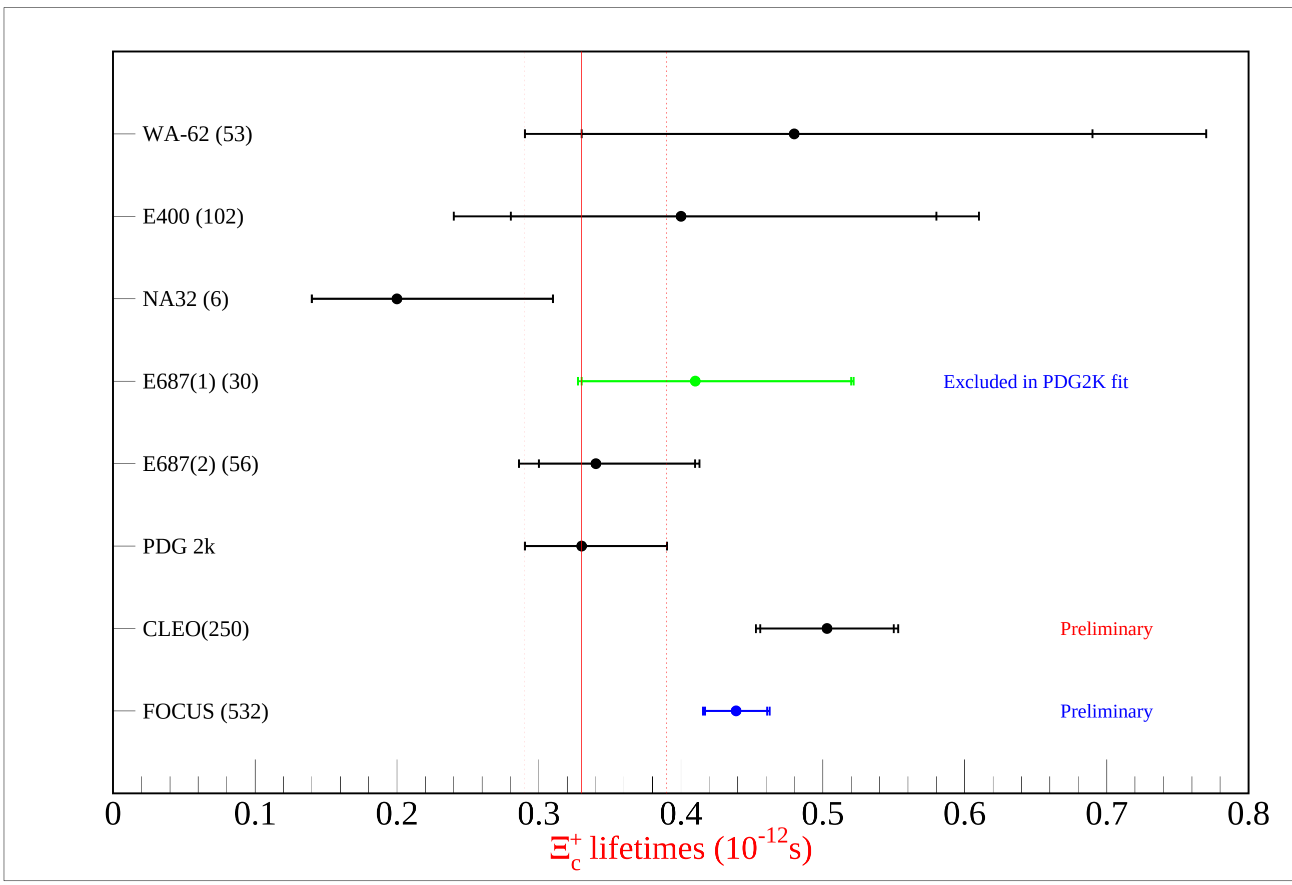
- In general the contributions to the systematic error are quite different from those in e^+e^- experiments.

Contribution	Uncertainty(fs)
Ξ_c^+ momentum	± 2
two solution bias	± 1
split sample	0
t' resolution	± 4
background	± 2
fit variant	± 8
Total	± 9

Table 1: Contributions to Ξ_c^+ systematic error.

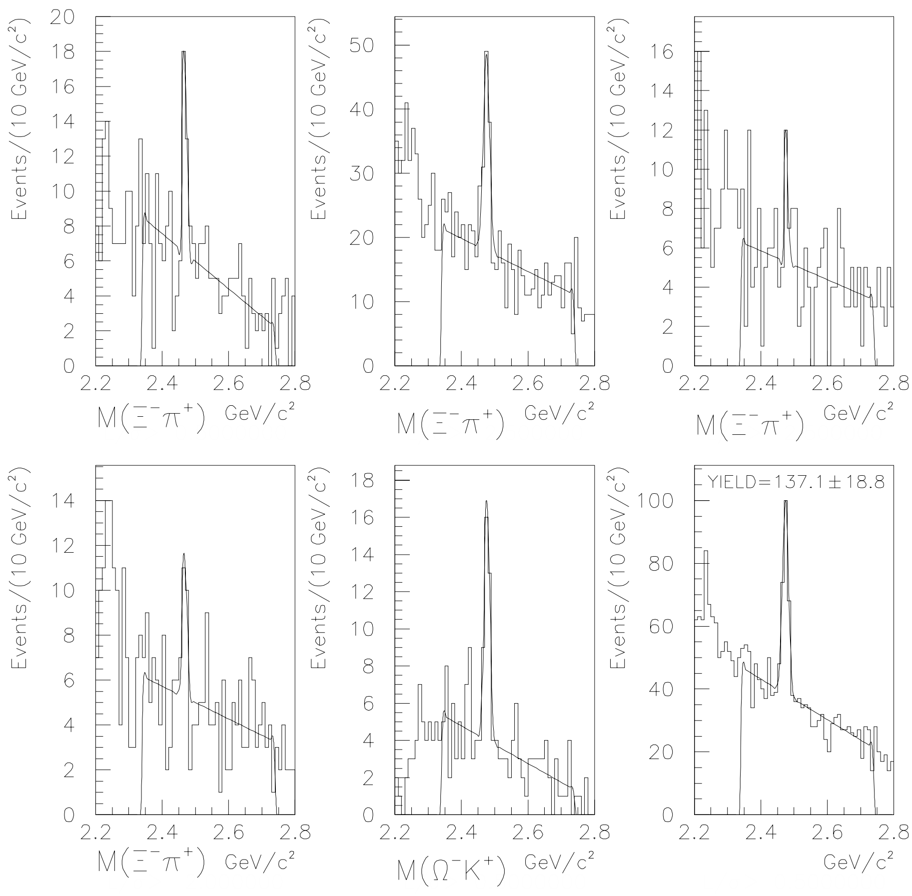
Ξ_c^+ Lifetime Systematics



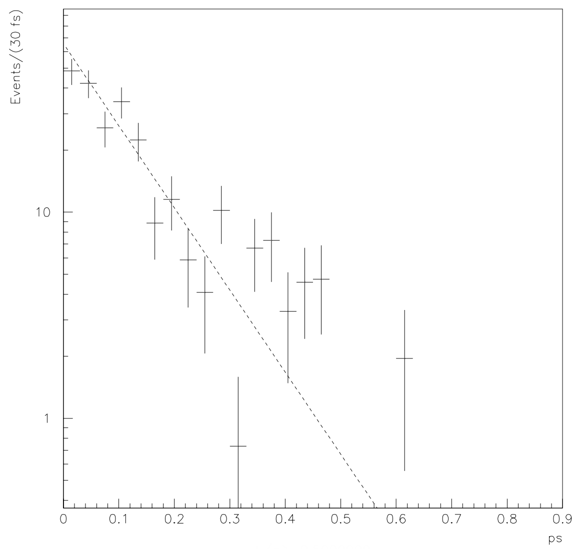

WA-62 (53)
E400 (102)
NA32 (6)
E687(1) (30)
Excluded in PDG2K fit
E687(2) (56)
PDG 2k
CLEO(250)
Preliminary
FOCUS (532)
Preliminary
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Ξ_c^+ lifetimes (10^{-12}s)

Ξ_c^0 Lifetime

- Currently studying 2 modes with 5 different topologies. More decay modes/topologies may be added.



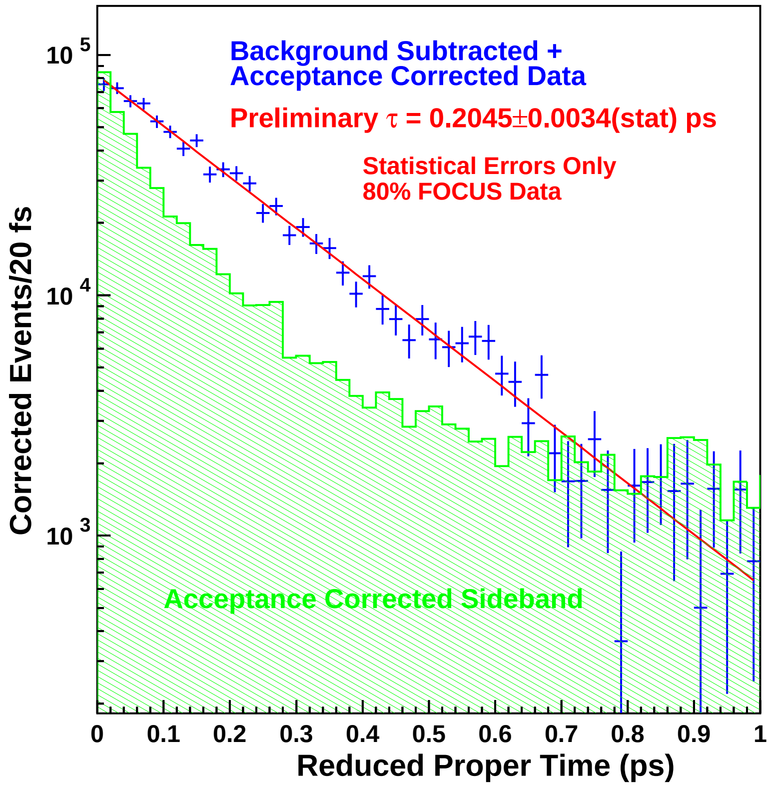
Ξ_c^0 Lifetime



- PRELIMINARY RESULT: 109^{+10}_{-9} fs (statistical errors only)

- Current PDG-2000 Average (mainly E687) is: 98^{+23}_{-15} fs

Λ_c^+ Lifetime



- Final result coming soon. Accuracy comparable to that shown here.

- PDG Average is 206 ± 12 fs. does not include SELEX: $198.1 \pm 7.0 \pm 5.6$ fs and CLEO: $179.6 \pm 6.9 \pm 4.4$ fs.

Lifetime Summary

- Analyses of meson lifetimes still in progress. We expect results in the next few months for D^+, D^0 , D_S^+ and Ξ_c^0 lifetimes.

- Ξ_c^+ and Λ_c^+ should be available in the very near future.

- We can already see that W-exchange seems to be very important for charmed baryon decays. If we measure all the weakly decaying charmed baryon lifetimes precisely we should be able to determine the importance of the different decay mechanisms.

- FOCUS lifetime results should be the most precise in the world for the next couple of years. Belle and BaBar may eventually supplant our results, at least in the longer lived states.

P-wave Charmed Mesons

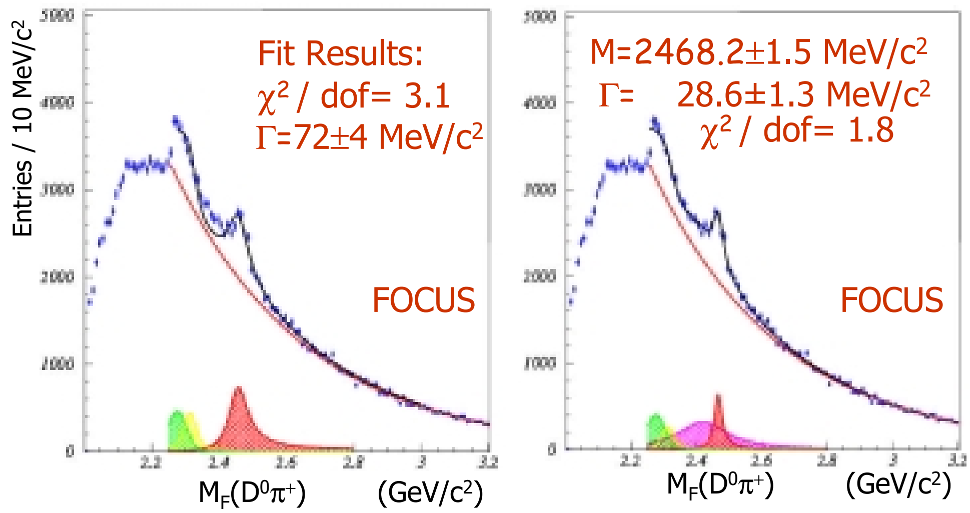
- L=1 between charmed and light quark (u,d,s).

- Rosner: 'The hydrogen atom of QCD', $j_{light} [= S_{light} + L]$ is an approximately good quantum number if $m_c \gg \Lambda_{QCD}$.
  - $j_{light} = \frac{1}{2}$ decays via an S-wave $\rightarrow$ broad
  - $j_{light} = \frac{3}{2}$ decays via a P-wave $\rightarrow$ narrow

- Decay strongly to $D^*\pi$ or D^*K .

- We observe the $j_{light} = \frac{3}{2}$ states narrow final states. For some of our fits a broad S-wave component improves the result. We are still investigating this effect.

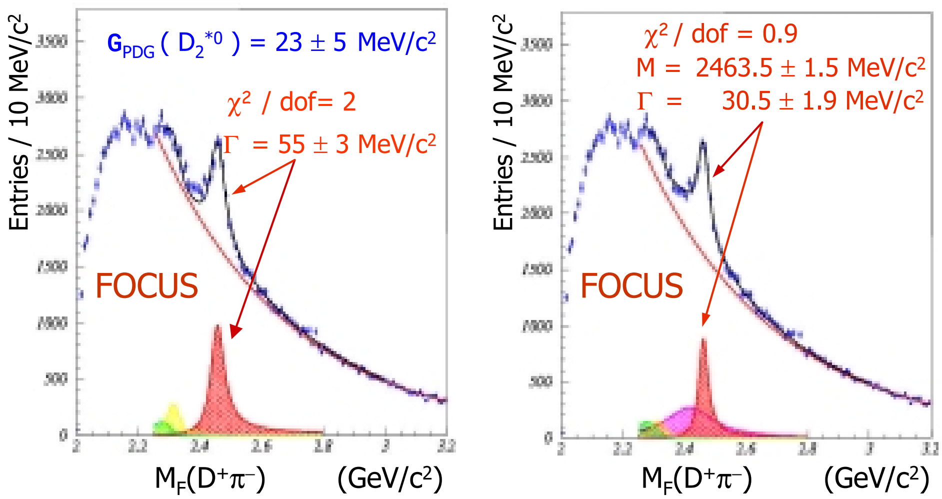
PRELIMINARY $D_2^{*+} \to D^0\pi^+$



$$j_{light} = \frac{3}{2},\ J^P = 2^+$$

- PDG:$M = 2459 \pm 4\,\mathrm{MeV/c^2},\ \Gamma = 25 \pm 8\,\mathrm{MeV/c^2}$
- The S-wave contribution improves the fit.

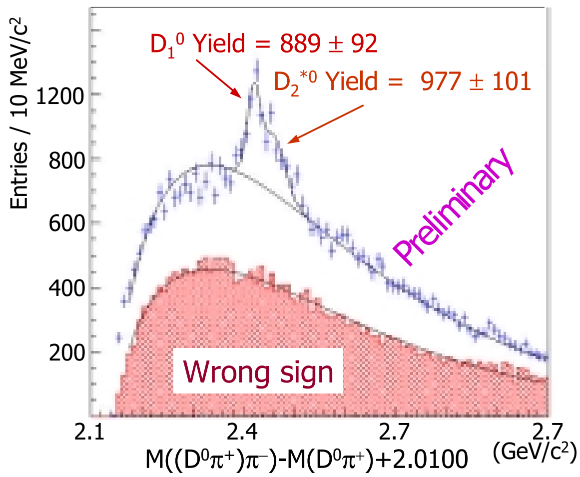
PRELIMINARY $D_2^{*0} \to D^+\pi^-$



$$j_{light} = \frac{3}{2},\ J^P = 2^+$$

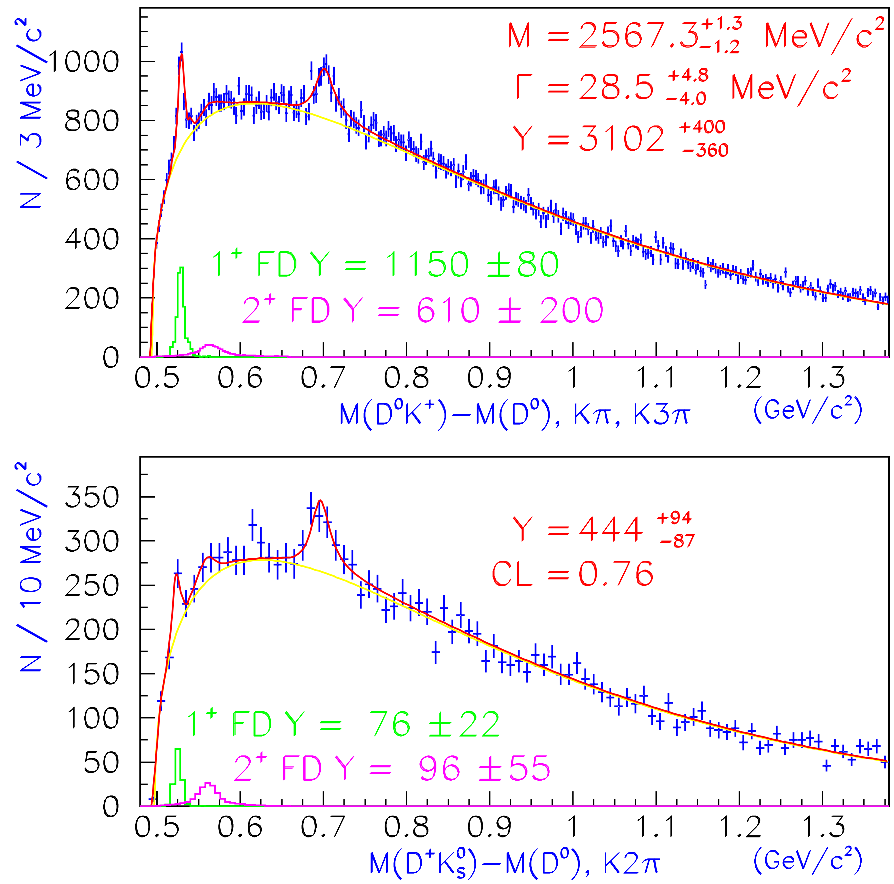
- PDG: 2458.9 ± 2.0 MeV/c^2, $\Gamma = 23 \pm 5$ MeV/c^2.
- Again the S-wave component improves the fit.

PRELIMINARY $D_2^{*0}, D_1^0 \to D^{*+}\pi^-$



$$j_{light} = \frac{3}{2},\ J^P = 1^+$$

PRELIMINARY $D_{s2} \to D^0 K^+, D_s K^0_S$

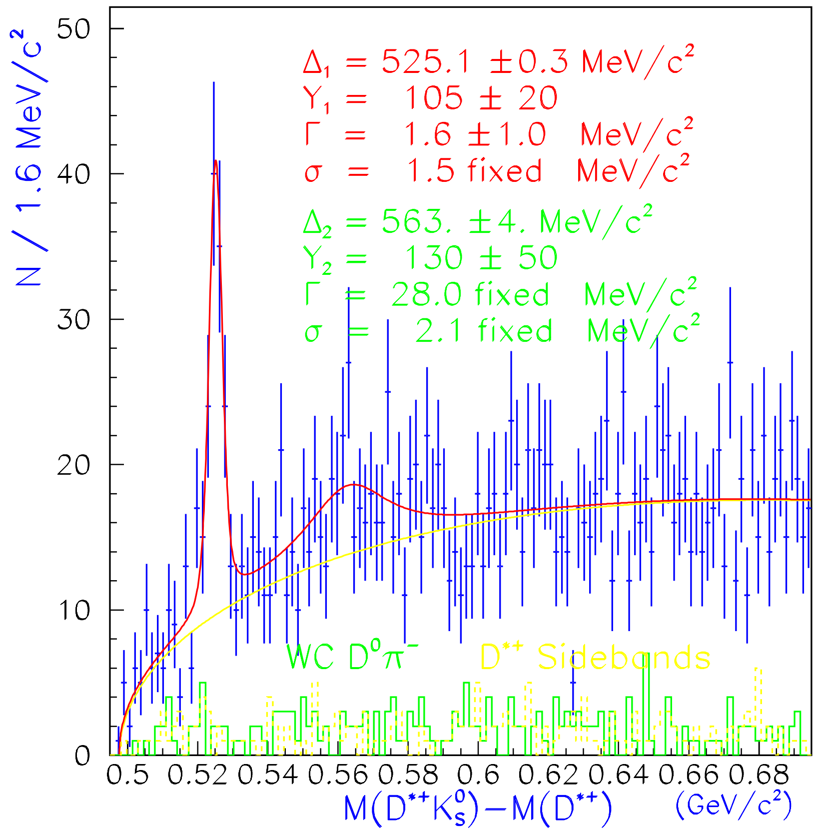


$j_{light} = \frac{3}{2}, J^P = 2^+$

$D_{s2} \to D^+ K^0_S \leftarrow$ First Observation

PDG: M=2573.5 ± 1.7 MeV/c^2 , $\Gamma = 15 \pm 5$ MeV/c^2

PRELIMINARY $D_{s1} \to D^{*+}K_S^0$



$$D_{s1} : j_{light} = \frac{3}{2}, J^P = 1^+$$

- PDG: $\Delta = 525.35 \pm 0.34$ MeV/c^2 , $\Gamma < 2.3$ MeV/c^2 @ 90% C.L.

- The D_{S2} signal is not significant.

Hadronic Decays

- Accurately measured branching ratios can help in our understanding of Final State Interactions(FSI).

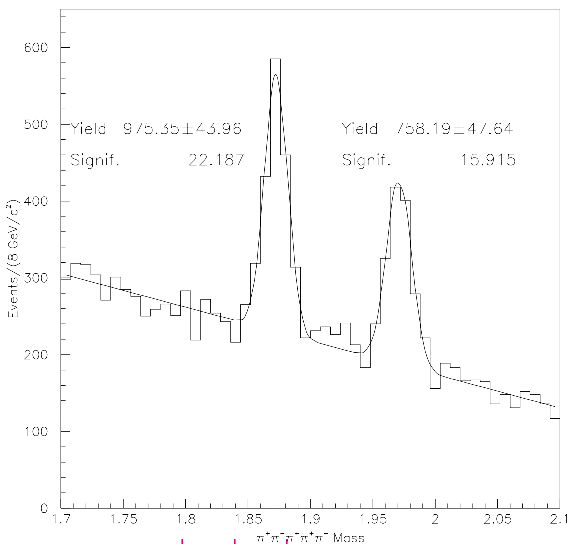
- For 3-body decays high statistics Dalitz analyses can be used to extract different contributions to the decay amplitude.

- For 4 and 5-body decay the situation is more complex. For now we only look at projections. For example $D^0 \to \pi^+\pi^+\pi^-\pi^-$ can occur as:

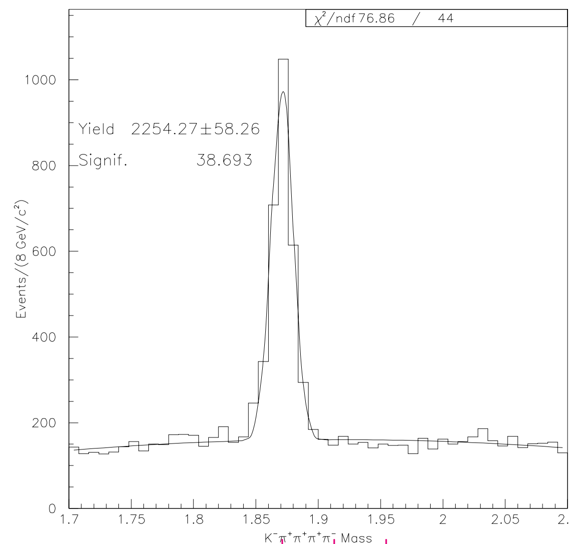
$$\begin{aligned} D^0 &\to R\pi \\ &\quad \hookrightarrow \quad \pi\pi\pi \\ &\quad \hookrightarrow \quad R'\pi \\ &\qquad\qquad \hookrightarrow \quad \pi\pi \\ &\quad \to \quad R_1 R_2 \end{aligned}$$

- We are working on an extension of the 3-body treatment in order to treat such decays in a coherent fashion.

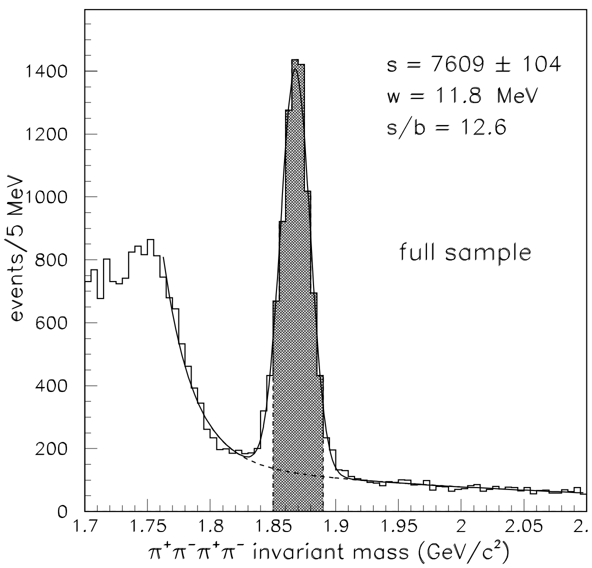
4,5-Body Signals



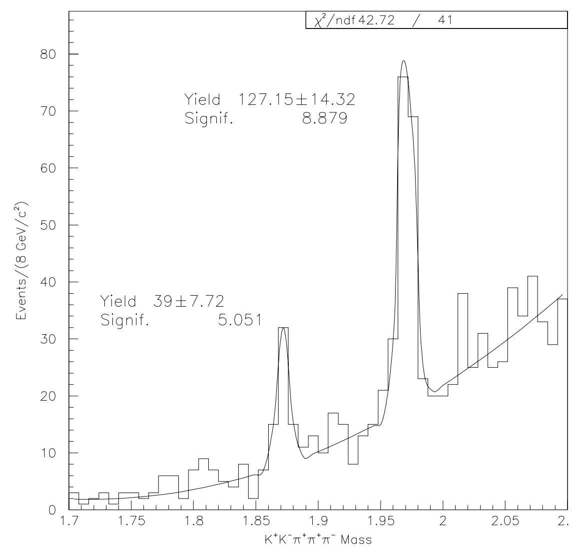
$\pi^+\pi^+\pi^+\pi^-\pi^-$ Mass



$K^-\pi^+\pi^+\pi^+\pi^-$ Mass



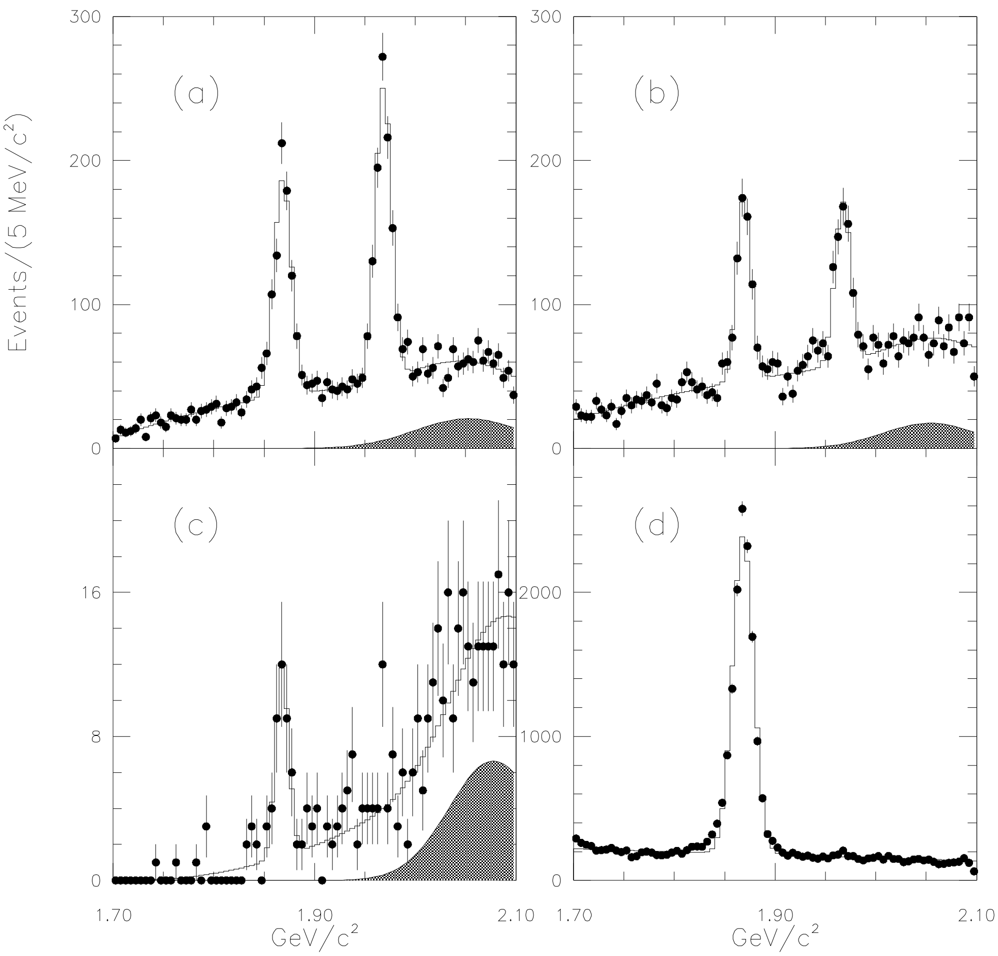
$\pi^+\pi^+\pi^-\pi^-$ Mass



$K^+K^-\pi^+\pi^+\pi^-$ Mass

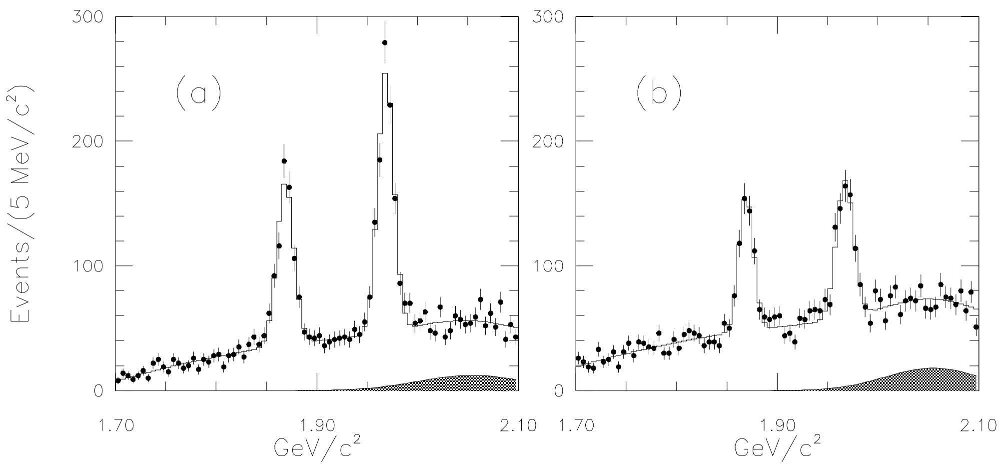
- At least 10 times yield of previous experiments. First evidence for $D^+ \to K^+K^-\pi^+\pi^+\pi^-$.

$D^+ \to K_S 3h$ decays



(a) $K_S K^- \pi^+ \pi^+$ (b) $K_S K^+ \pi^+ \pi^-$
(c) $K_S K^+ K^- \pi^+$ (d) $K_S \pi^+ \pi^+ \pi^-$

$D_s^+ \to K_S 3h$ decays



(a) $K_S K^- \pi^+ \pi^+$ (b) $K_S K^+ \pi^+ \pi^-$

- Three decay modes observed for the first time.

Branching Ratio	FOCUS	Others
$\Gamma\left(D^+ \to K^0 K^- \pi^+ \pi^+\right)$	$(0.54 \pm 0.08)\ \%$	$(1.0 \pm 0.6)\ \%$
$\Gamma\left(D^+ \to \overline{K^0} K^+ \pi^+ \pi^-\right)$	$(0.39 \pm 0.06)\ \%$	$< 2.0\%$
$\Gamma\left(D^+ \to \overline{K^0} K^+ K^- \pi^+\right)$	$(5.4 \pm 1.4) \times 10^{-4}$	-
$\Gamma\left(D_s^+ \to \overline{K^0} K^+ \pi^+ \pi^-\right)$	$(2.5 \pm 0.9)\ \%$	$< 2.8\%$

Direct CP Searches

- Usually direct CP violation is expected to occur in charm decays via the interference of a Cabibbo suppressed and a penguin amplitude. Final State Interactions (FSI) are needed to provide a strong phase shift.

- In the decay $D^+ \to K_S\pi^+$ there exists the possibility of CP violation due to the interference of the Cabibbo Favoured and Doubly Cabibbo suppressed amplitudes if new physics intervenes.

- In any case one expects to see a CP asymmetry at the level of 3×10^{-3} due to CP violation in the decays of the K^0 .

- New physics could enhance CP asymmetries to the level of 10^{-2}.

Direct CP Searches

- To correct for production asymmetries we take a ratio to a Cabibbo Favoured decay where no CP violation is expected to occur.

- We measure A_{CP}, an asymmetry parameter defined as:

$$A_{CP} = \frac{\eta\left(D^+ \to K_S\pi^+\right) - \eta\left(D^- \to K_S\pi^-\right)}{\eta\left(D^+ \to K_S\pi^+\right) + \eta\left(D^- \to K_S\pi^-\right)}$$

where $\eta()$ is defined as:

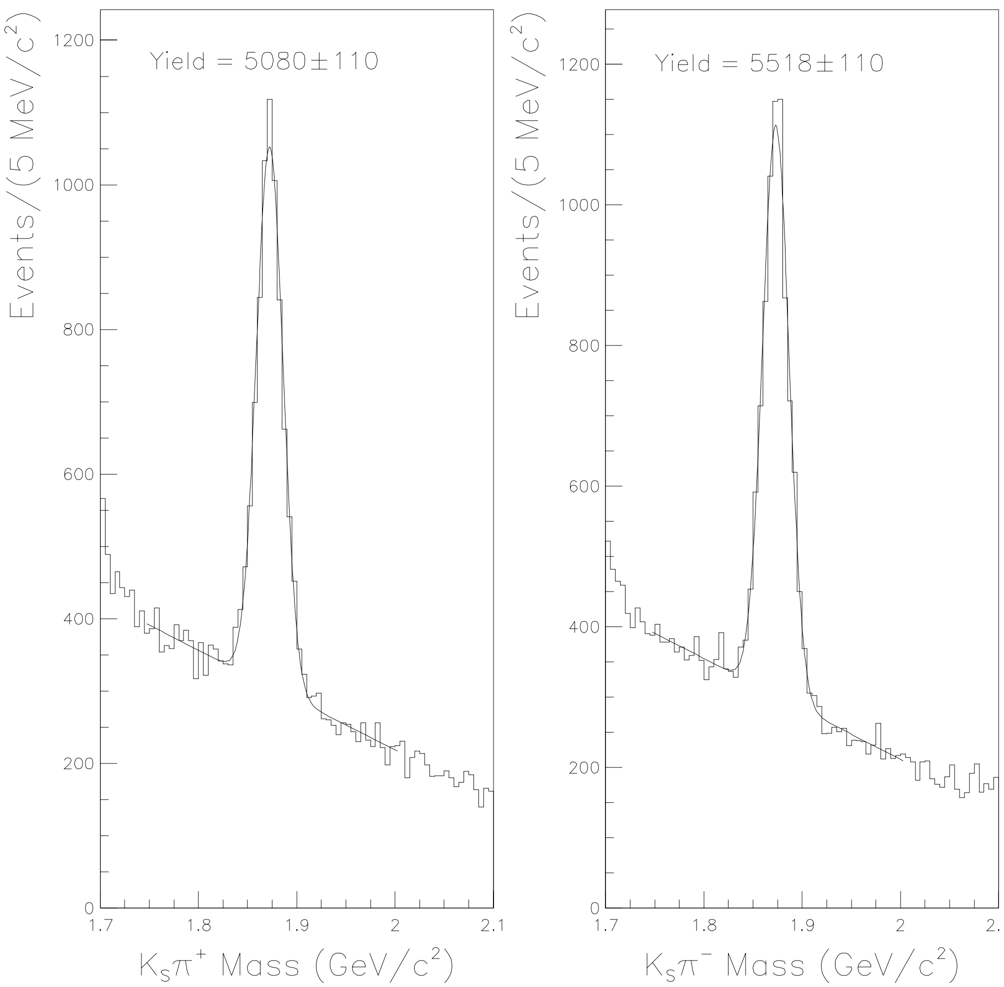
$$\eta\left(D^+ \to K_S\pi^+\right) = \frac{N\left(D^+ \to K_S\pi^+\right)}{N\left(D^+ \to K^-\pi^+\pi^+\right)}$$

with for example, N() being the yield corrected for efficiency and acceptance.

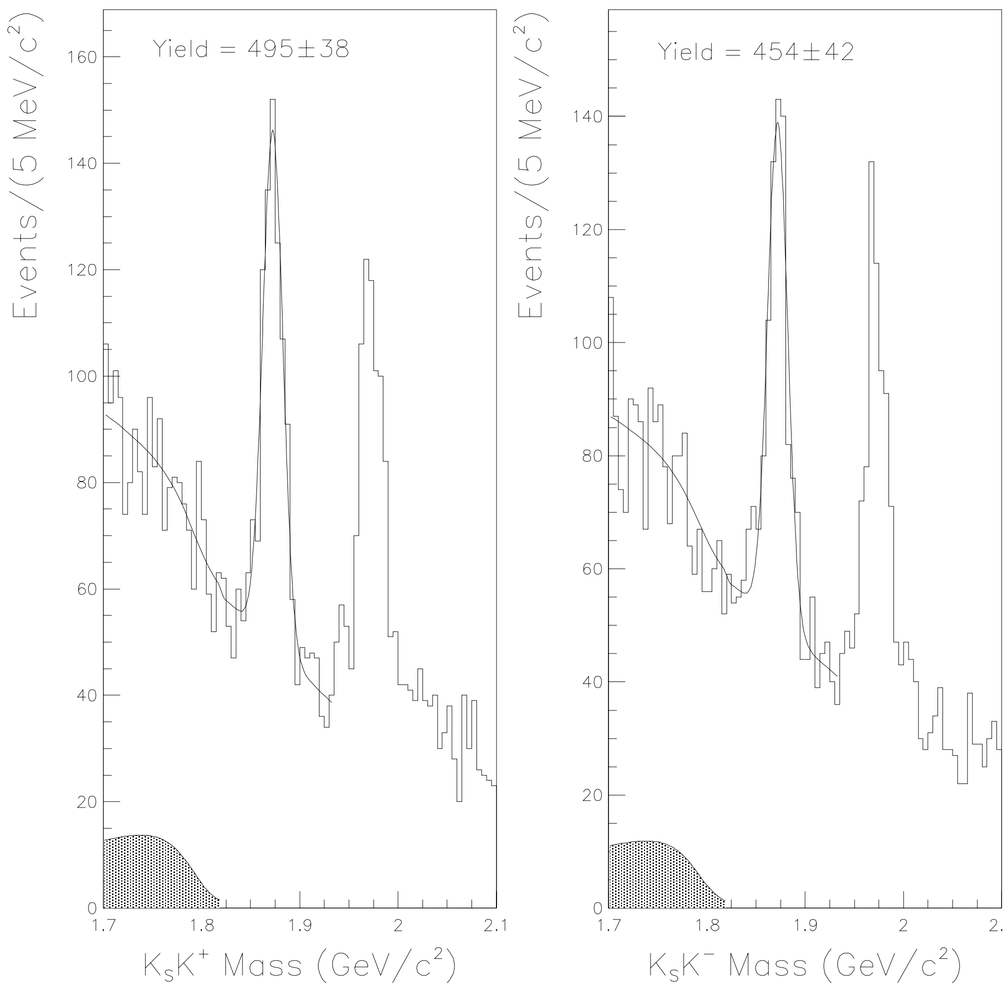
$D^+ \to K_S X^+$ Branching Ratios

- Measurement of the $D^+ \to K_S X^+$ branching ratios can also provide information on FSI.
- For example, the magnitude of the $I = 3/2$ decay amplitude can be obtained directly from the $D^+ \to K_S \pi^+$ partial width.
- Large phase differences in nonleptonic decays of charmed mesons are almost certainly due to FSI. The lower mass of the charmed particles (in comparison to B mesons) amplifies these effects.
- Nonleptonic decays of charmed mesons can serve as a laboratory for the examination of FSI (Rosner and others).

$D^+ \to K_S\pi^+$ Signals



$D^+ \to K_S K^+$ Signals



$D^+ \to K_S \pi^+$ PRELIMINARY Results

Measurement	Result	PDG Average
$\frac{\Gamma\left(D^+ \to \overline{K^0}\pi^+\right)}{\Gamma\left(D^+ \to K^-\pi^+\pi^+\right)}$	$(30.74 \pm 0.46 \pm 0.58)\,\%$	$(32.0 \pm 4.0)\,\%$
$\frac{\Gamma\left(D^+ \to \overline{K^0}K^+\right)}{\Gamma\left(D^+ \to K^-\pi^+\pi^+\right)}$	$(6.07 \pm 0.35 \pm 0.35)\,\%$	$(7.7 \pm 2.2)\,\%$
$\frac{\Gamma\left(D^+ \to \overline{K^0}K^+\right)}{\Gamma\left(D^+ \to \overline{K^0}\pi^+\right)}$	$(19.96 \pm 1.20 \pm 1.06)\,\%$	$(26.3 \pm 3.5)\,\%$

Measurement	Result
$A_{CP}\left(K_S\pi^+\right)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	$(-1.4 \pm 1.5 \pm 0.9)\,\%$
$A_{CP}\left(K_S K^+\right)$ w.r.t. $D^+ \to K^-\pi^+\pi^+$	$(7.2 \pm 6.0 \pm 1.8)\,\%$
$A_{CP}\left(K_S K^+\right)$ w.r.t. $D^+ \to K_S\pi^+$	$(7.1 \pm 6.1 \pm 1.4)\,\%$

Summary

- FOCUS has many physics analyses nearing completion.
- I have not mentioned (among other topics):
  - Dalitz Analyses.
  - Semileptonic Mixing analysis.
  - Semileptonic Branching ratios.
  - Form Factor measurements from Semileptonic decays.
  - Rare Decays.
  - Production studies.
- We have published six papers and have 13 analyses in the review process.
- We expect our measurements to set the standard in many areas for the next couple of years.