BEACH2004

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Charm Hadronic Decays

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(On behalf of FOCUS Collaborations)

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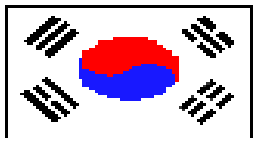
- Excited charm meson
- Conclusions

FOCUS Experiment

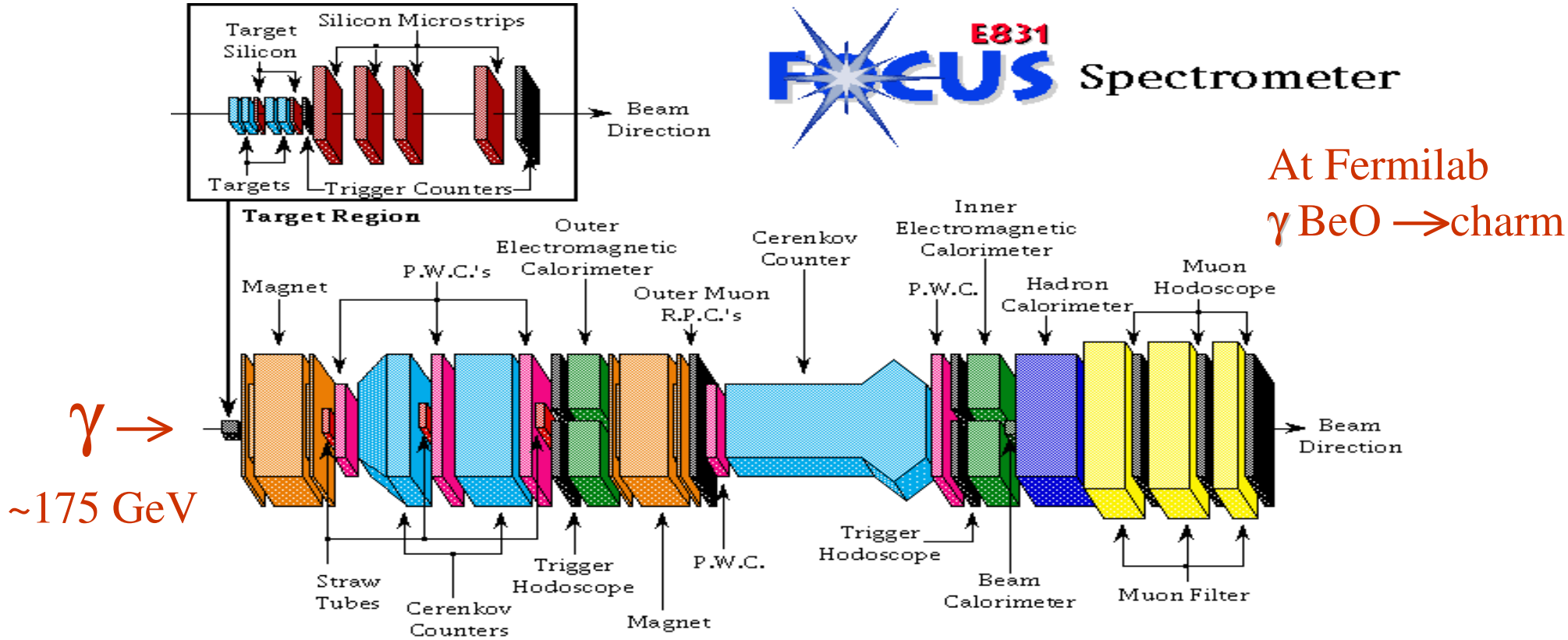
Photoproduction of Charm with an Upgraded Spectrometer

**Univ. of California-Davis, CBPF-Rio de Janeiro, CINVESTAV-Mexico City,
Univ. Colorado-Boulder, FERMILAB, Laboratori Nazionali di Frascati,
Univ. of Illinois-Urbana-Champaign, Indiana Univ.-Bloomington,
Korea Univ.-Seoul, Kyungpook National Univ.-Daegu, INFN and Univ.-Milano,
Univ. of North Carolina-Asheville, INFN and Univ.-Pavia, Univ. of Puerto Rico-Mayaguez,
Univ. of South Carolina-Columbia, Univ. of Tennessee-Knoxville,
Vanderbilt Univ.-Nashville, Univ. of Wisconsin-Madison**

~100 Physicists, 18 institutes from 5 countries

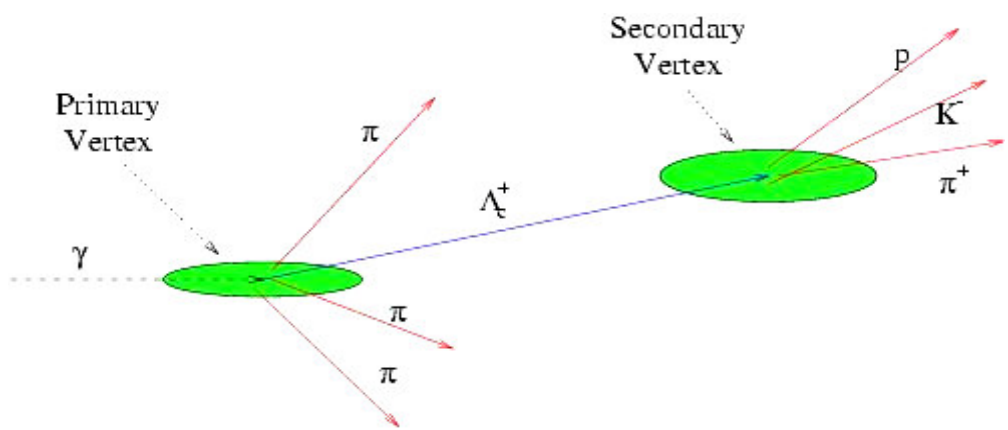


FOCUS Spectrometer



- Segmented target
- Silicon vertexing
- MWPC tracking
- Cenenkov ID
- EM/hadronic Calorimeter
- Muon detectors

Vertexing is the Key

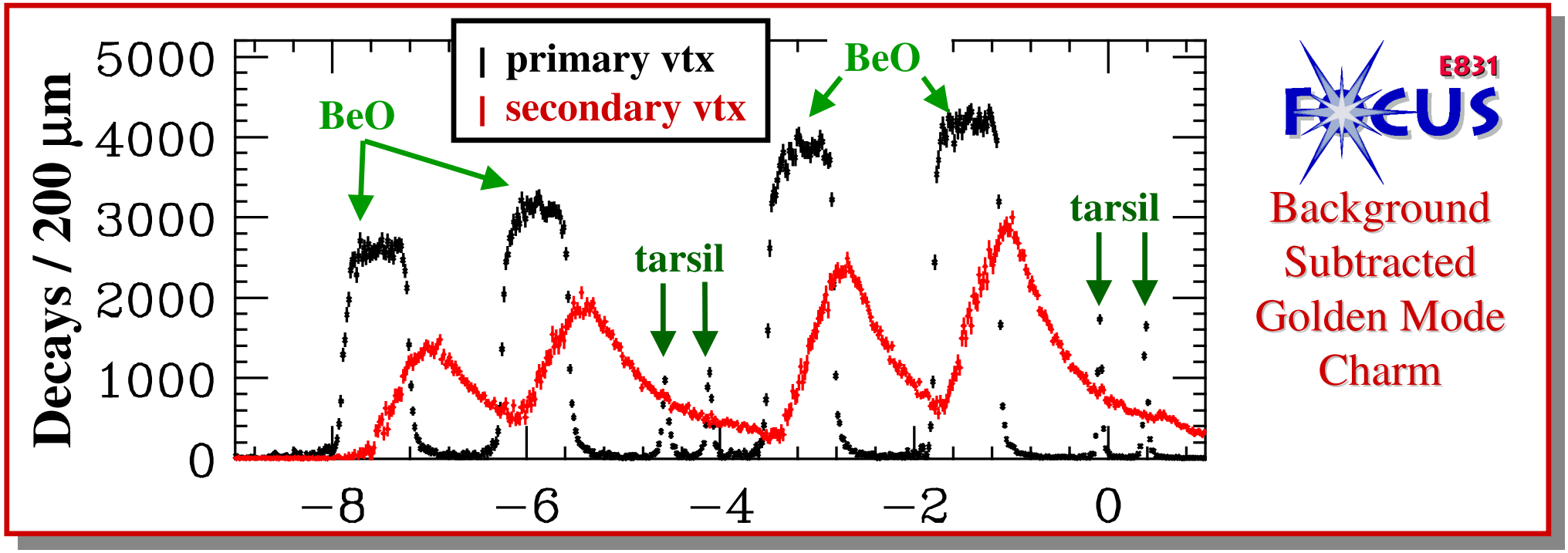


Golden Modes:

$D^+ \rightarrow K^- \pi^+ \pi^+$

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

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



$D^+, D_s \to \pi^+ \pi^- \pi^+$ K–Matrix

- Motivation
  - ❑ Charm Dalitz plot gives probes of charm decay mechanism and charm CP violation.
  - ❑ However, isobar model has problems when adding broad Breit-Wigner signals due to violation of unitarity.

  $\Rightarrow$ Unitarity can be achieved from K-matrix formalism.
- FOCUS analysis fits with K-matrix rather than isobar model.
  - ❑ Can deal with overlapping scalar states with large widths.
  - ❑ Anisovich & Sarantsev parameterize S-wave isoscalar scattering up to 1.9 GeV/c^2. Eur.Phys.J.A16 (2003) 229
    - Consider 5 virtual states: $\pi\pi$, $K\overline{K}$, 4π, $\eta\overline{\eta}$, $\eta\eta$,
    - Find 5 $IJ^{PC} = 00^{++}$ resonance: $f_0(980)$, $f_0(1300)$, $f_0(1500)$, $f_0(1750)$, $f_0(1200\text{-}1600)$
  - ❑ Using this parameterization and adding in vector and tensor particles, we can fit the $D^+, D_s \to \pi^+ \pi^- \pi^+$ Dalitz plot.

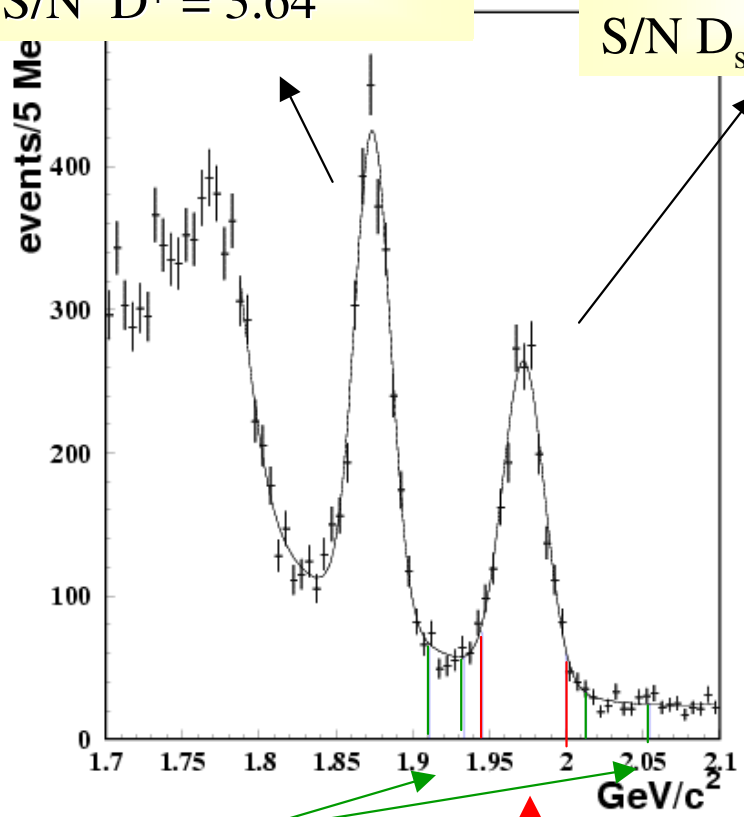
$D^+, D_s \rightarrow \pi^+ \pi^- \pi^+$ Analysis

Yield $D^+ = 1527 \pm 51$

S/N $D^+ = 3.64$

Yield $D_s^+ = 1475 \pm 50$

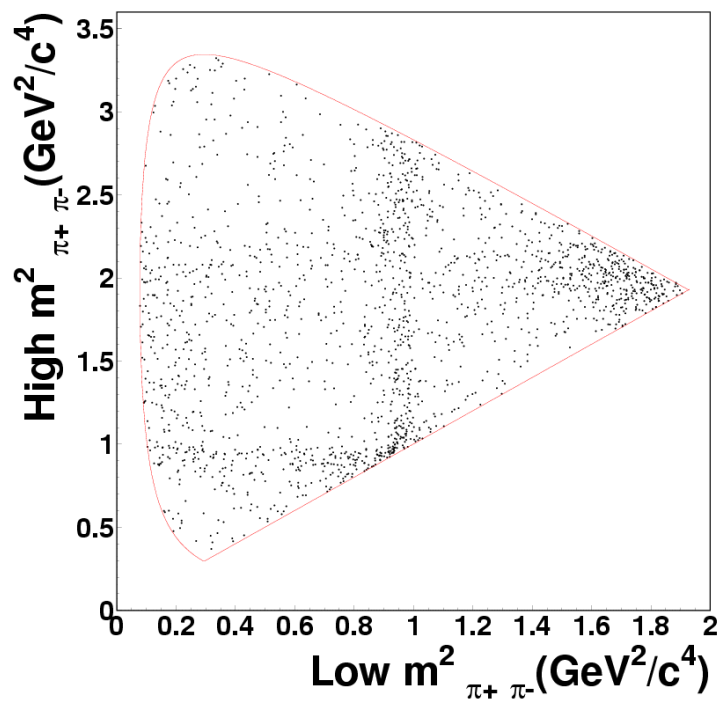
S/N $D_s^+ = 3.41$



Observe:

- $f_0(980)$
- $f_2(1270)$
- $f_0(1500)$

$D_s^+ \rightarrow \pi^+\pi^+\pi^-$

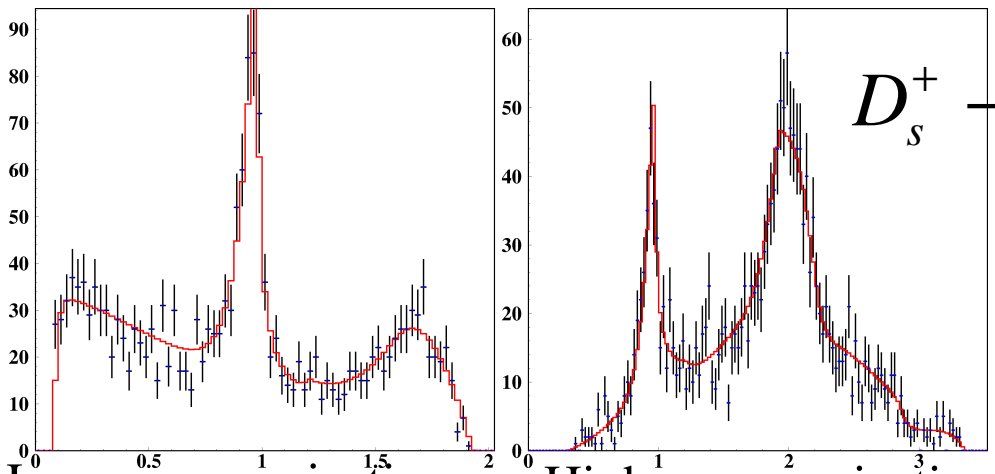


Sideband

Signal

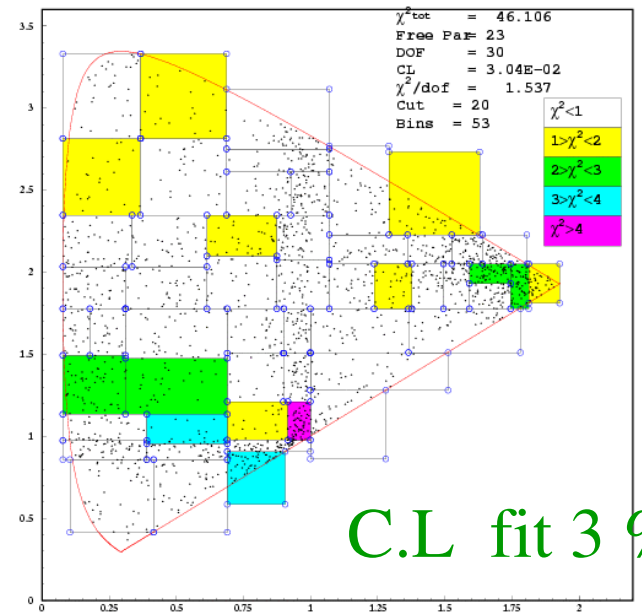
Several broad and overlapping resonance states

$D_s \to \pi^+ \pi^- \pi^+$ K–Matrix



Low mass projection High mass projection

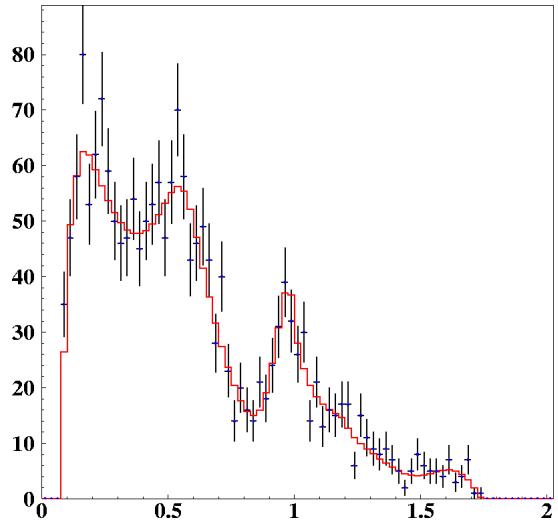
decay channel	fit fractions (%)	phase (deg)
(S - wave)π^+	$\boxed{87.04} \pm 5.60 \pm 4.17$	0(fixed)
$f_2(1275)\pi^+$	$9.74 \pm 4.49 \pm 2.63$	$168.0 \pm 18.7 \pm 2.5$
$\rho^0(1450)\pi^+$	$6.56 \pm 3.43 \pm 3.31$	$234.9 \pm 19.5 \pm 13.3$



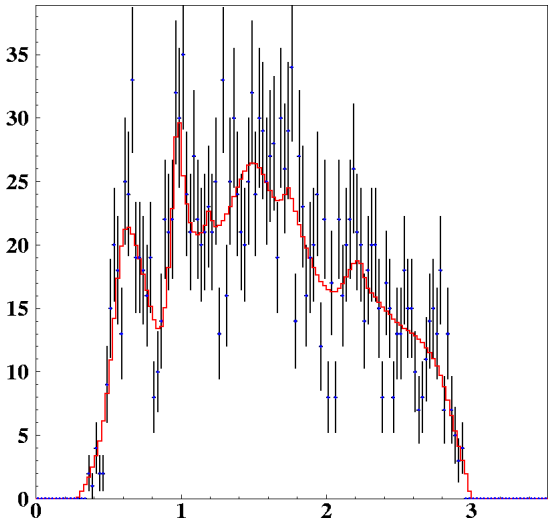
C.L fit 3 %

- We can fit it using K- matrix known from scattering data (A&S).
- The K-matrix approach has been applied to charm decays for the first time.

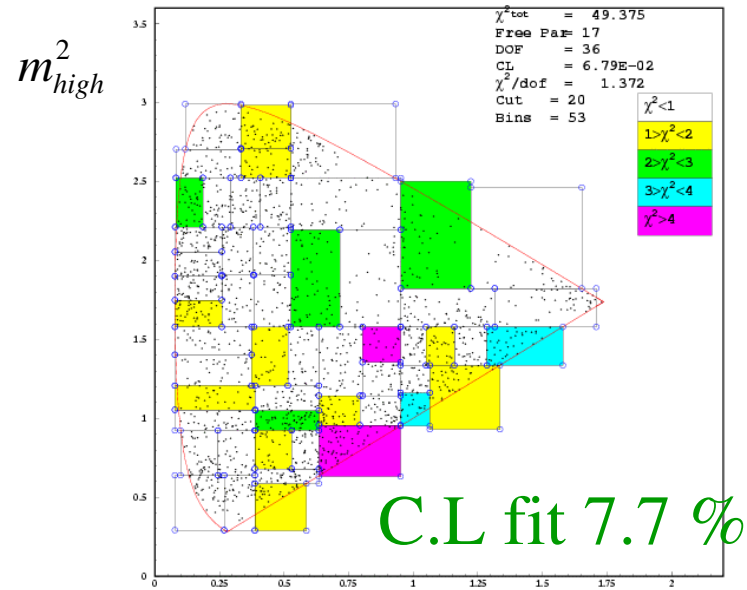
$D^+ \to \pi^+ \pi^- \pi^+$ K–Matrix



Low mass projection



High mass projection

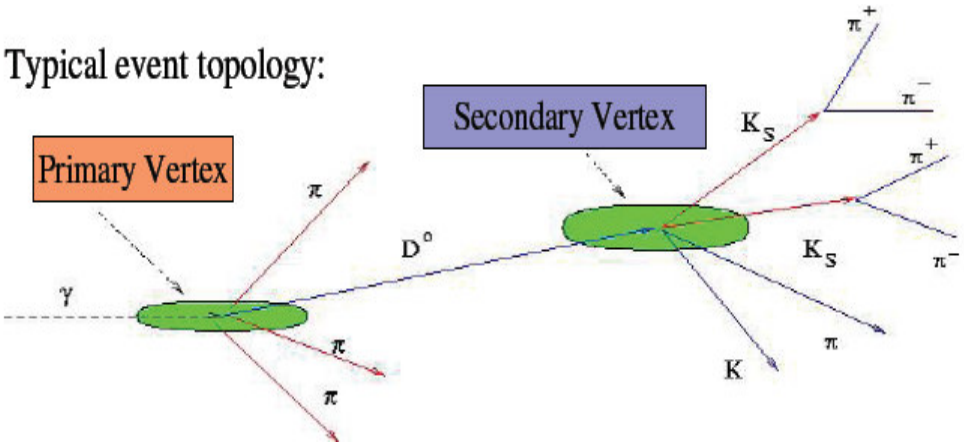


decay channel	fit fractions (%)	phase (deg)
(S - wave)π^+	$\boxed{56.00} \pm 3.24 \pm 2.08$	0(fixed)
$f_2(1275)\pi^+$	$11.74 \pm 1.90 \pm 0.23$	$-47.5 \pm 18.7 \pm 11.7$
$\rho^0(770)\pi^+$	$30.82 \pm 3.14 \pm 2.29$	$-139.4 \pm 16.5 \pm 9.9$

PLB585 (2004)200-212

- For D_s^+ and D^+, the S-wave decay amplitude is dominated by an intial production of $K\,K$, $\eta\eta$, $\eta\eta'$
- Dipion production is always much smaller.
- For D^+, the ssbar contribution competes with a ddbar contribution.
- This interpretation also bears on the role of the annihilation diagram in the $D_s^+ \to \pi^+\pi^-\pi^+$ decay.

$D^0 \to K^0\overline{K}^0$

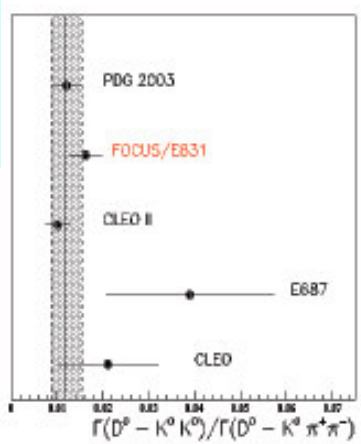


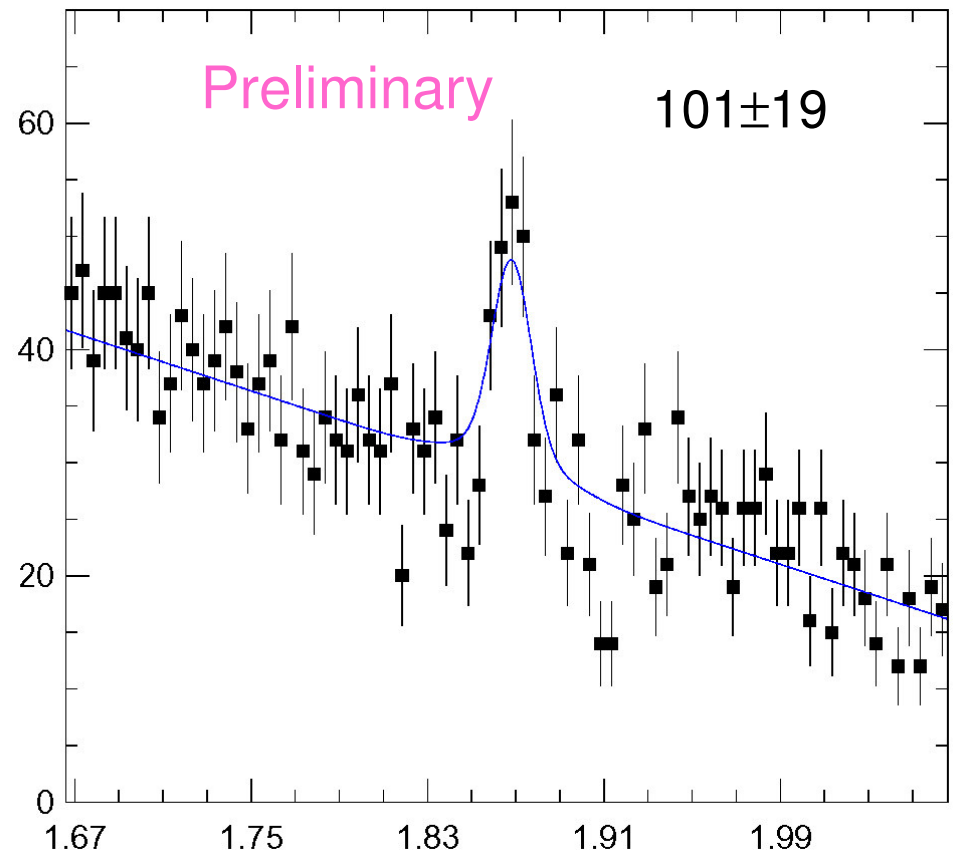
The errors reported are only Statistical.

Mass = 1.868±0.002 GeV/c²

σ =12.72 MeV/c²

$$\frac{\Gamma(D^0 \to K^0\overline{K^0})}{\Gamma(D^0 \to \overline{K^0}\pi^+\pi^-)} = 1.62 \pm 0.30\%$$





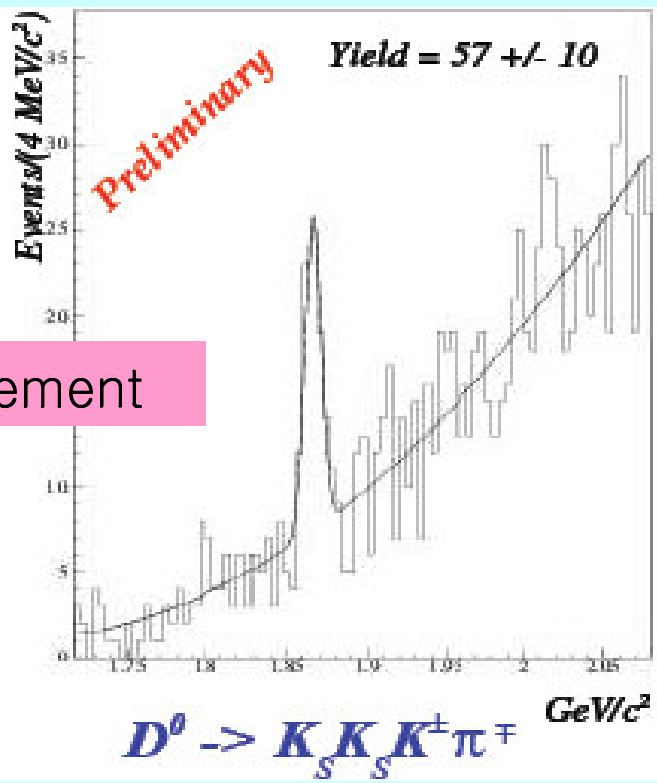
$D^0 \to KsKs$

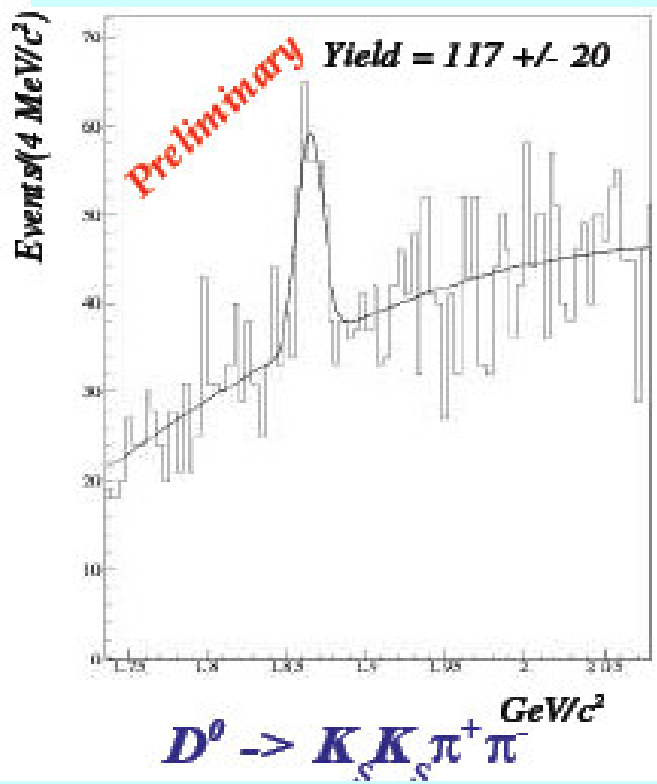
$D^0 \to K_sK_sK^{\pm}\pi^{\mp}$, $K_sK_s\pi^+\pi^-$

Mass = 1.8660±0.0011 GeV/ c^2
σ = 5.0 MeV/c^2

Mass = 1.8648±0.0011 GeV/ c^2
σ = 6.5 MeV/c^2

First Measurement



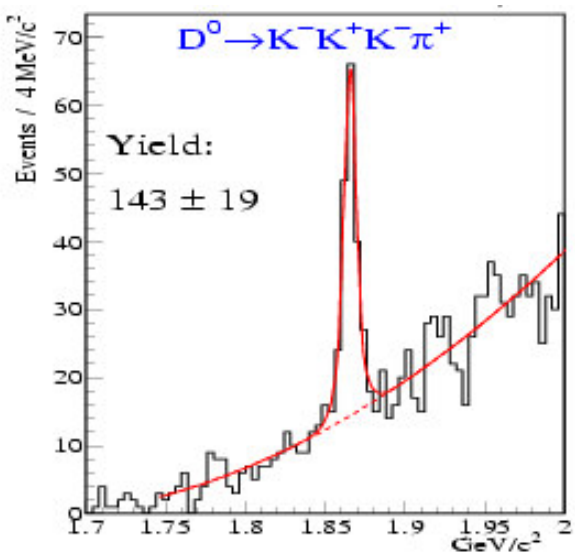


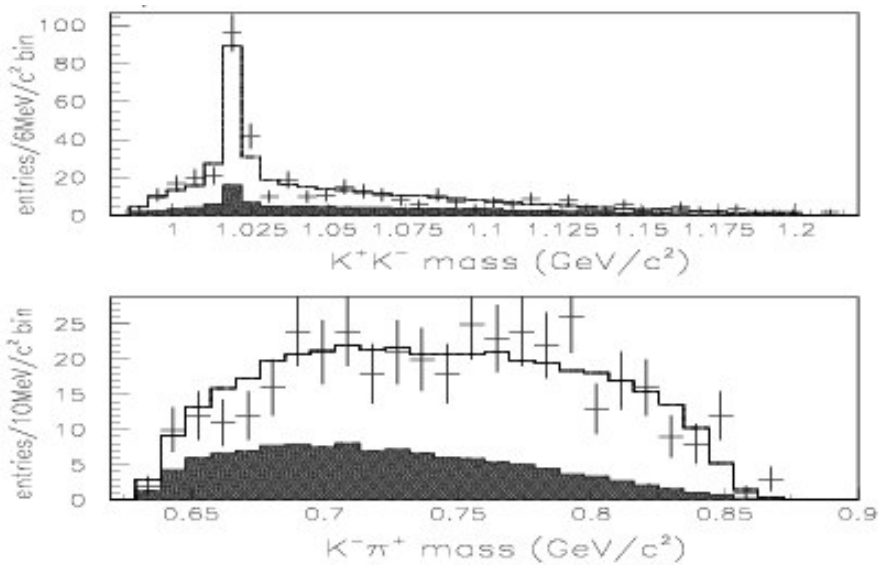
- Discovery of $D^0 \to K_sK_s K\pi$ mode
- $Br(D^0 \to K^0\overline{K^0}K^{\pm}\pi^{\mp}) \sim 2.5\times10^{-3}$ is large more like $D^0 \to K^+K^-\overline{K^0}\pi^0$.

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

$$\frac{\Gamma(D^0 \to K^-K^-K^+\pi^+)}{\Gamma(D^0 \to K^-\pi^-\pi^+\pi^+)} = 0.257 \pm 0.034 \pm 0.024\%$$

Compared to PDG2003: 0.32±0.09%

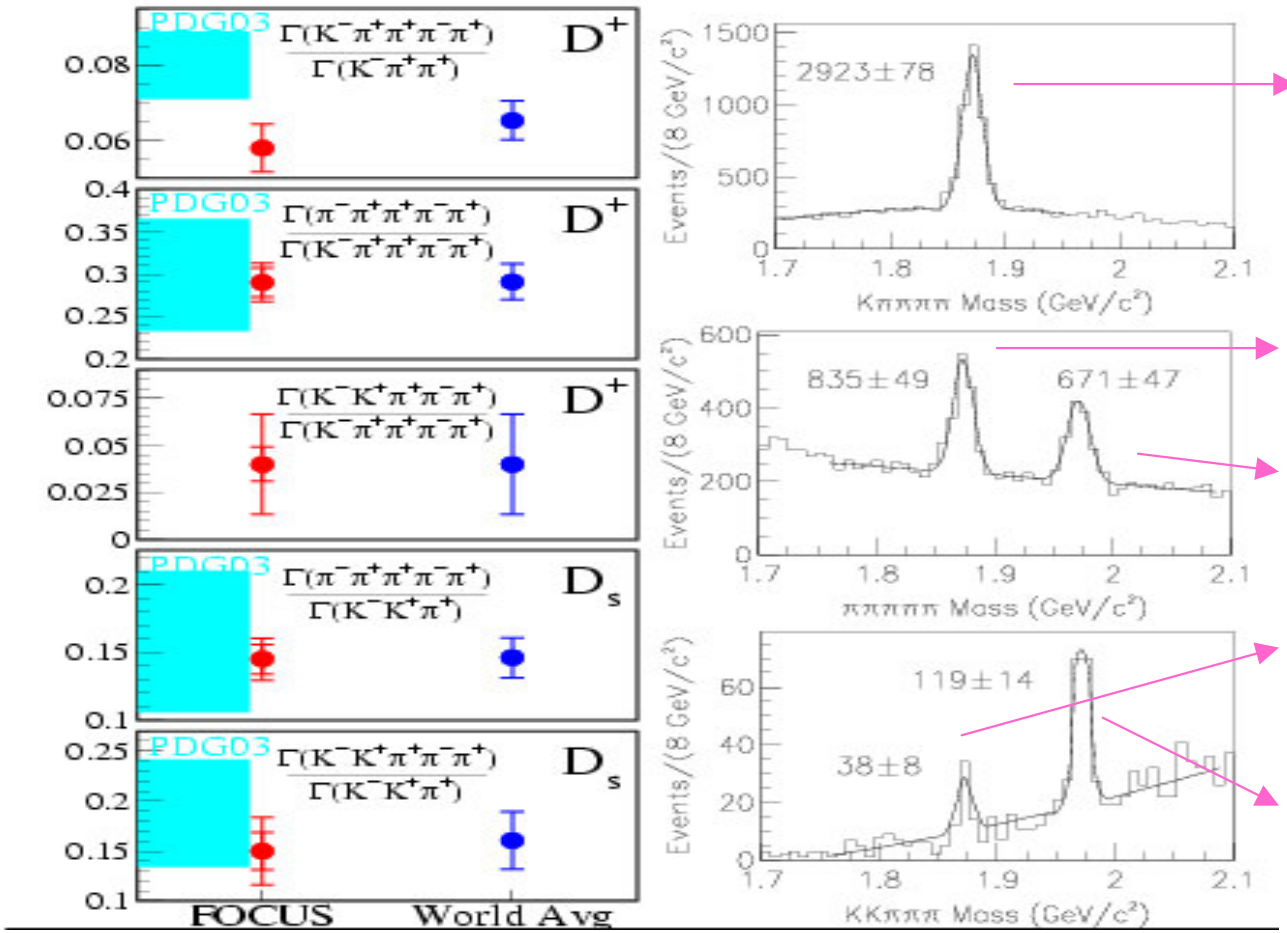




Mode	Magnitude	Phase (deg.)	Fraction (%)
$\phi\overline{K}^{*0}(892)$	1	0	$48 \pm 6 \pm 1$
$\phi K^-\pi^+$	0.60 ± 0.12	$194 \pm 24 \pm 8$	$18 \pm 6 \pm 4$
$\overline{K}^{*0}(892)K^+K^-$	0.65 ± 0.13	$255 \pm 15 \pm 4$	$20 \pm 7 \pm 2$
non-resonant	0.55 ± 0.14	$278 \pm 16 \pm 42$	$15 \pm 6 \pm 2$

PLB575 (2003)190-197

5 body decays with Charged Kaons (D^+, D_s)



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

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

$D^+_s \to \pi^-\pi^+\pi^+\pi^-\pi^+$

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

First Measurement

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

PLB561(2003)225-232

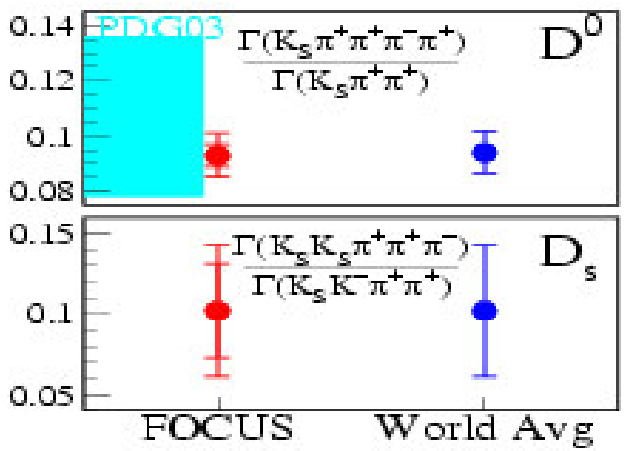
5 body decays (cont'd)

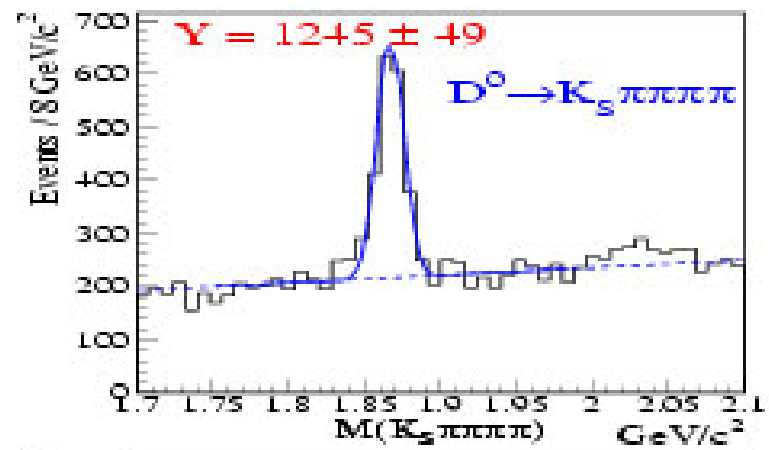
Table 1
Branching ratios for five-body modes and comparison to the previous measurements by E687. All branching ratios are inclusive of subresonant modes

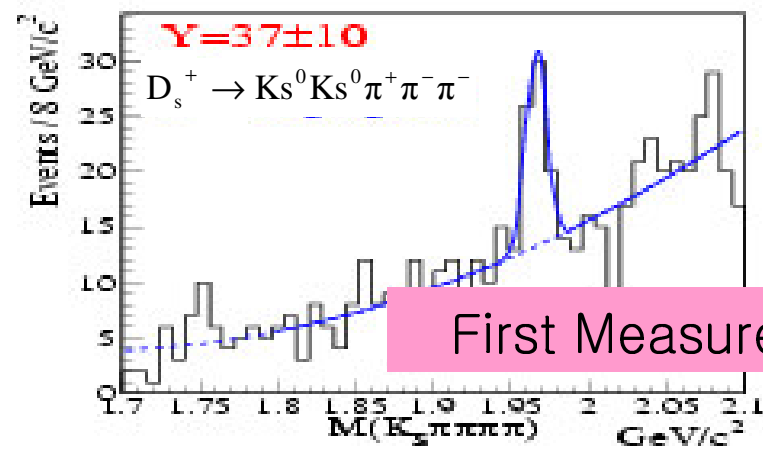
Decay mode	FOCUS	E687 [6]
$\frac{\Gamma(D^+\to K^-\pi^+\pi^+\pi^+\pi^-)}{\Gamma(D^+\to K^-\pi^+\pi^+)}$	$0.058\pm0.002\pm0.006$	$0.077\pm0.008\pm0.010$
$\frac{\Gamma(D^+\to\pi^+\pi^+\pi^+\pi^-\pi^-)}{\Gamma(D^+\to K^-\pi^+\pi^+\pi^+\pi^-)}$	$0.290\pm0.017\pm0.011$	$0.299\pm0.061\pm0.026$
$\frac{\Gamma(D_s^+\to\pi^+\pi^+\pi^+\pi^-\pi^-)}{\Gamma(D_s^+\to K^-K^+\pi^+)}$	$0.145\pm0.011\pm0.010$	$0.158\pm0.042\pm0.031$
$\frac{\Gamma(D_s^+\to K^+K^-\pi^+\pi^+\pi^-)}{\Gamma(D_s^+\to K^-K^+\pi^+)}$	$0.150\pm0.019\pm0.025$	$0.188\pm0.036\pm0.040$
$\frac{\Gamma(D_s^+\to\phi\pi^+\pi^+\pi^-)}{\Gamma(D_s^+\to\phi\pi^+)}$	$0.249\pm0.024\pm0.021$	$0.28\pm0.06\pm0.01$
$\frac{\Gamma(D^+\to K^+K^-\pi^+\pi^+\pi^-)}{\Gamma(D^+\to K^-\pi^+\pi^+\pi^+\pi^-)}$	$0.040\pm0.009\pm0.019$	

PLB561(2003)225-232

5 body decays with Ks







$$\frac{\Gamma(D^0 \to Ks^0\pi^+\pi^+\pi^-\pi^-)}{\Gamma(D^0 \to Ks^0\pi^+\pi^-)} = 9.3 \pm 0.4 \pm 0.7\%$$

$$\frac{\Gamma(D_s^+ \to Ks^0Ks^0\pi^+\pi^-\pi^-)}{\Gamma(D_s^+ \to Ks^0K^-\pi^+\pi^+)} = 10.2 \pm 2.9 \pm 2.9\%$$

First Measurement

PLB586 (2004)191-197

Resonant analyses of 5 body decays

- Incoherent fits are performed using projections.
- All 5 body decay mode shows strong vector ρ−π contributions.

❑ D^+ is consistent with ~60%

$$D^+ \to \overline{K}^{*0} a_1(1260)$$

❑ D_s^+ is consistent with ~100%

$$Ds^+ \to \phi\, a_1(1260)$$

❑ D^0 is also consistent 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

Subresonant mode	Fraction of $K4\pi$
$(K^-\pi^+\pi^+\pi^+\pi^-)_{NR}$	$0.07 \pm 0.05 \pm 0.01$
$\overline{K}^{*0}\pi^-\pi^+\pi^+$	$0.21 \pm 0.04 \pm 0.06$
$K^-\rho^0\pi^+\pi^+$	$0.30 \pm 0.04 \pm 0.01$
$\overline{K}^{*0}\rho^0\pi^+$	$0.40 \pm 0.03 \pm 0.06$

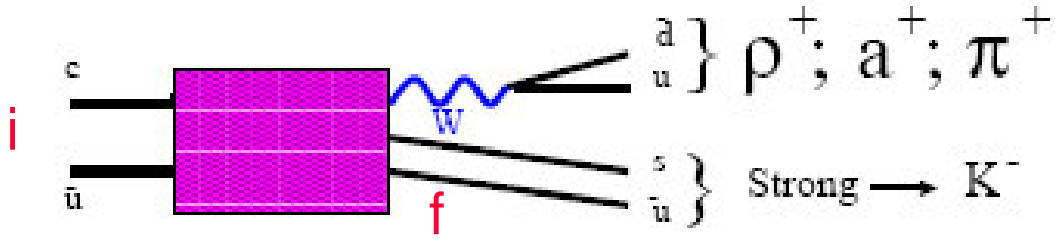
D_s^+ decay

Subresonant mode	Fraction of $2K3\pi$
$(K^+K^-\pi^+\pi^+\pi^-)_{NR}$	$0.10 \pm 0.06 \pm 0.05$
$\phi\pi^-\pi^+\pi^+$	$0.21 \pm 0.05 \pm 0.06$
$K^+K^-\rho^0\pi^+$	< 0.03 (90% C.L.)
$\phi\rho^0\pi^+$	$0.75 \pm 0.06 \pm 0.04$

D^0 decay

Subresonant mode	Fraction of $K^0_S\pi^+\pi^-\pi^+\pi^-$
$(K^0_S\pi^+\pi^+\pi^-\pi^-)_{NR}$	< 0.46 @90% CL
$K^{*-}\pi^+\pi^+\pi^-$	$0.17 \pm 0.28 \pm 0.02$
$K^0_S\rho^0\pi^+\pi^-$	$0.40 \pm 0.24 \pm 0.07$
$K^{*-}\rho^0\pi^+$	$0.60 \pm 0.21 \pm 0.09$

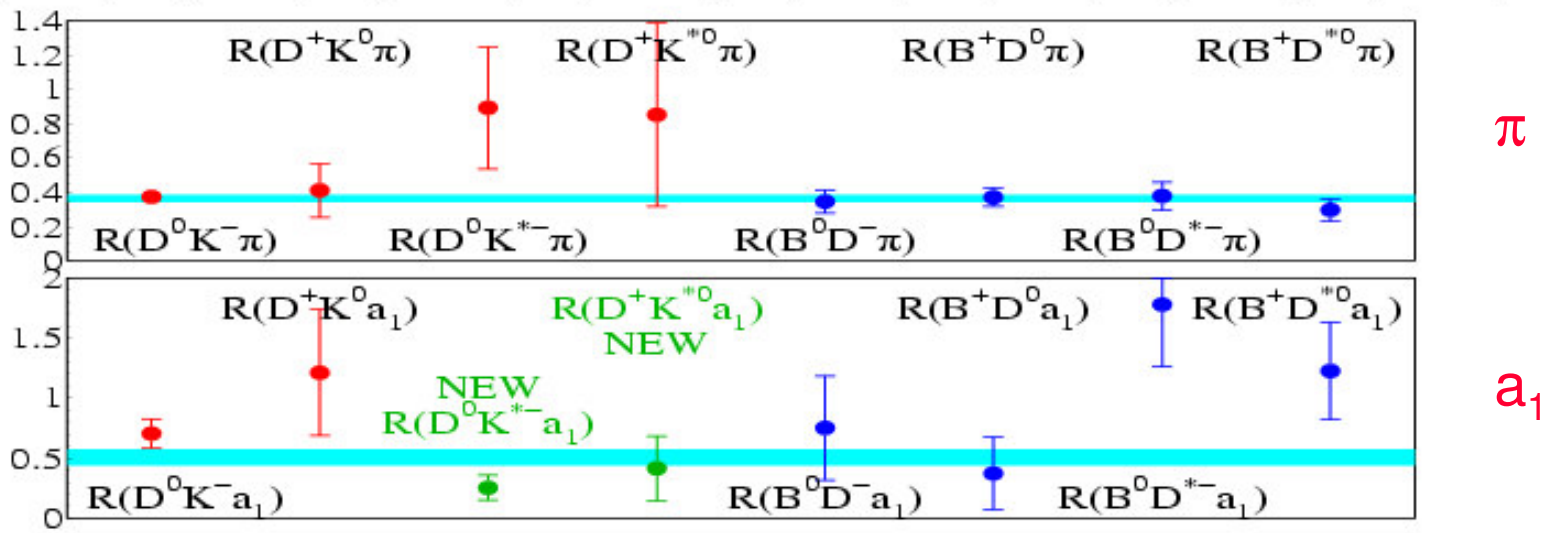
- Lipkin proposed that heavy flavor decays in which a radiated W hadronizes to one particle and the remaining quarks hadronize into another particle might exhibit some universality.
- Look at decays of the form i → f+W where W → ρ, a_1 or π



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

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

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

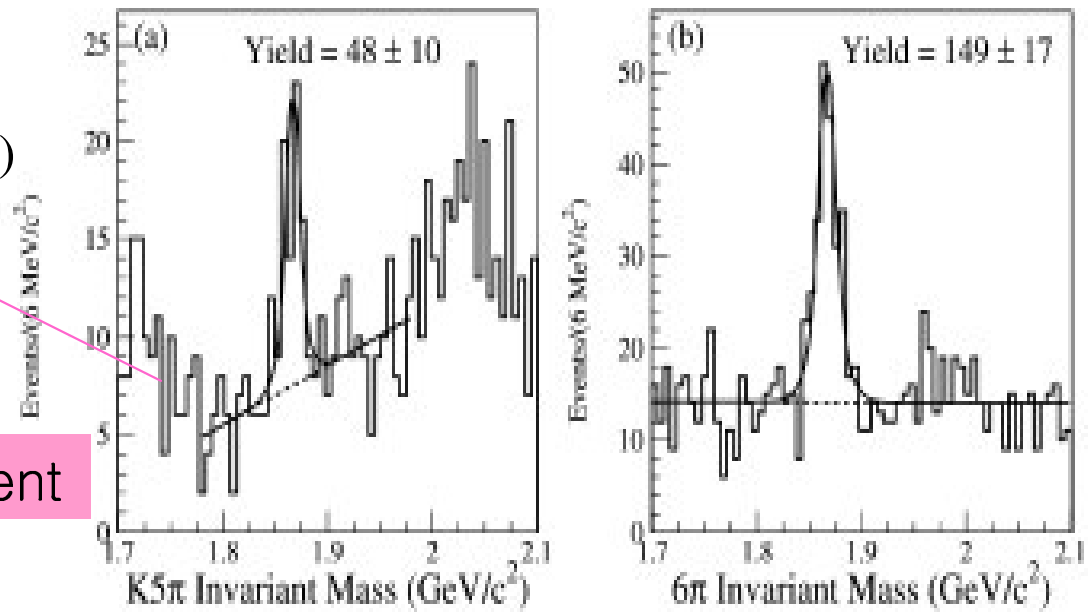


6 body decays

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

$D^0 \to K^-\pi^+\eta'(958)$

First Measurement



$$\frac{\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-)} = 0.270 \pm 0.058 \pm 0.038\%$$

$$\frac{\Gamma(D^0 \to \pi^+\pi^-\pi^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+\pi^+\pi^-\pi^+\pi^-)} = 1.93 \pm 0.47 \pm 0.48$$

- 6 body branching ratio is small compared to 4 body decays.
- Cabibbo suppressed branching ratio is larger than Cabibbo favored?

PLB586 (2004)21-26

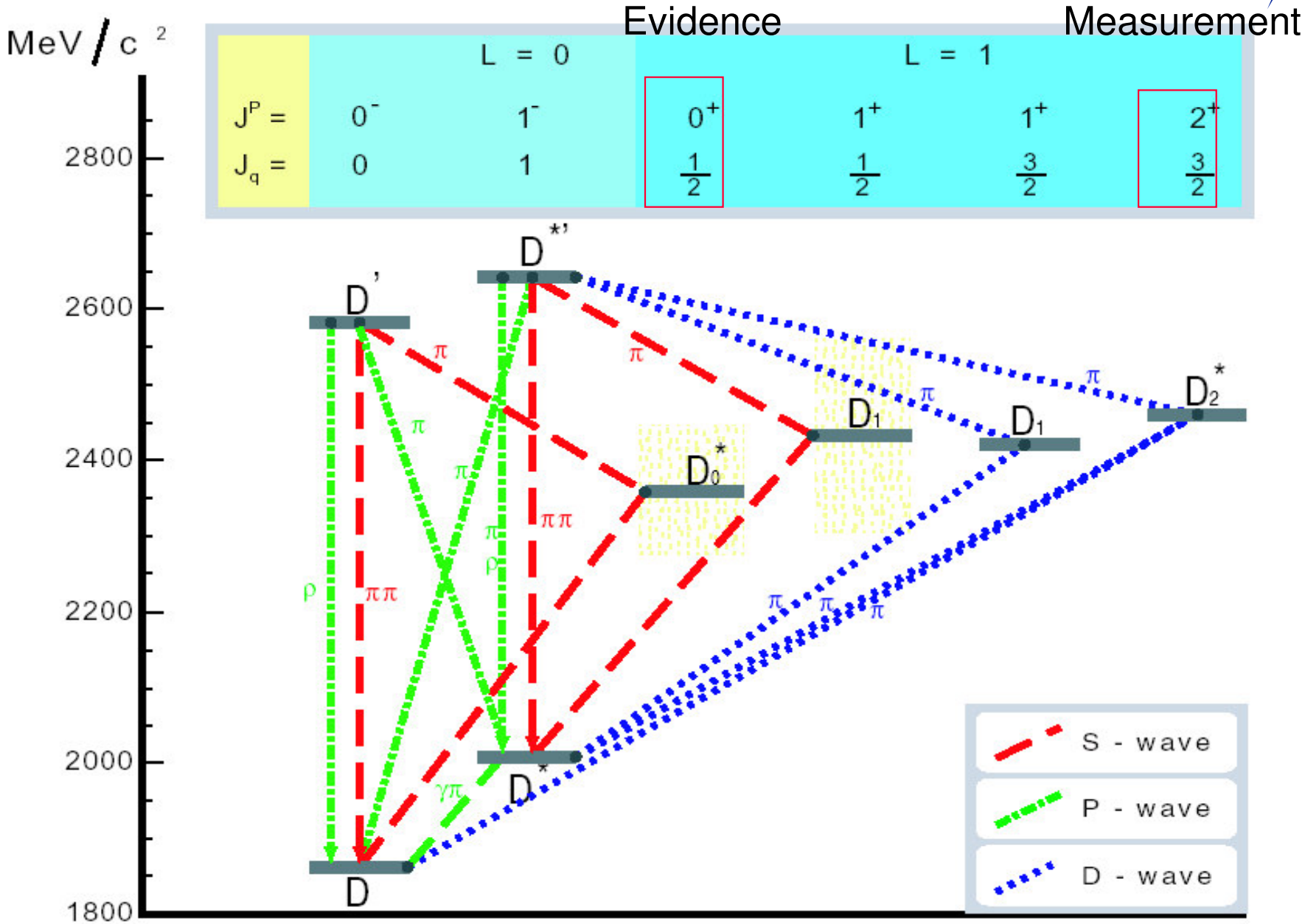
Excited charm meson

- L=1 between c and light quark (u,d)

$$J_q = s_q + L$$

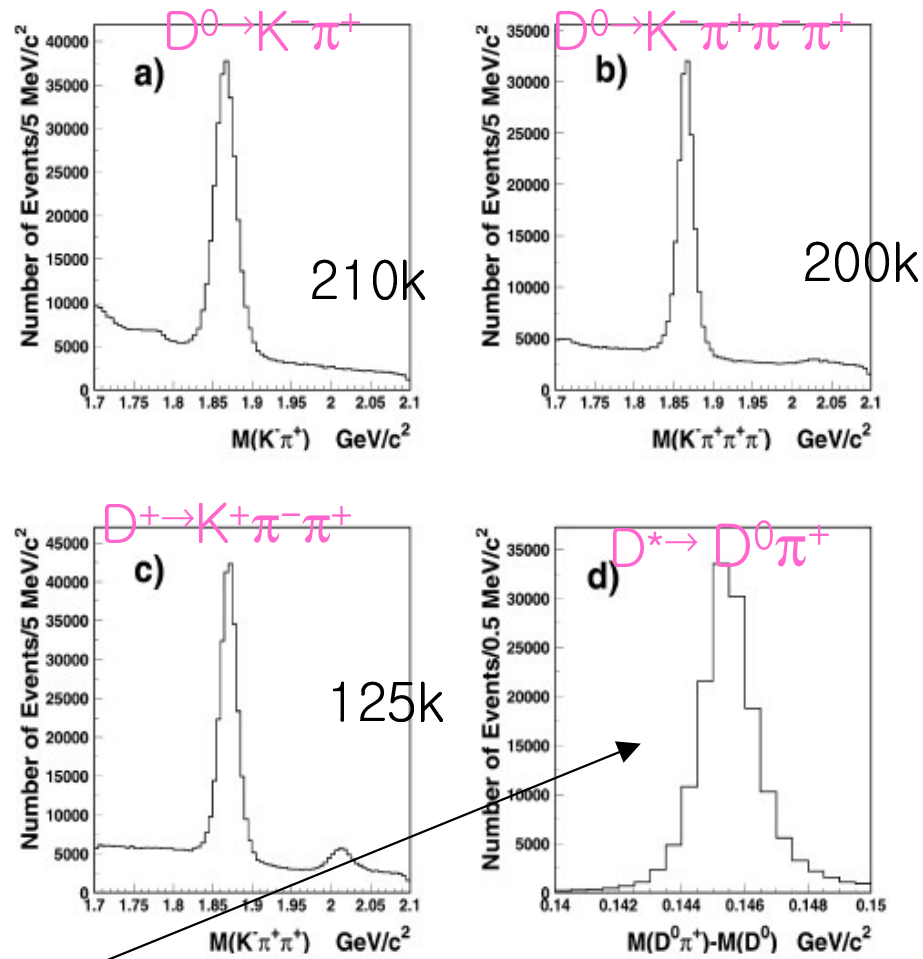
- HQET: approximately good
- Denote: D_0^*, $D_1(J_q=1/2)$, $D_1(J_q=3/2)$ and D_2^*

- L=1 charm meson were reconstructed via $D^+\pi^-$ & $D^0\pi^+$
  - ❑ $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^-\pi^+$
  - ❑ $D^+ \to K^+\pi^-\pi^+$
- D_2^{*+}, $D_2^{*0} \to D\pi^\pm$ measurements
- An evidence for D_0^* contributions


Evidence
Measurement
MeV / c 2
L = 0
L = 1
J^P = 0^- 1^- 0^+ 1^+ 1^+ 2^+
J_q = 0 1 1/2 1/2 3/2 3/2
2800
2600
2400
2200
2000
1800
D'
D*'
D
D*
D0*
D1
D1
D2*
π
ρ
ππ
γπ
S - wave
P - wave
D - wave

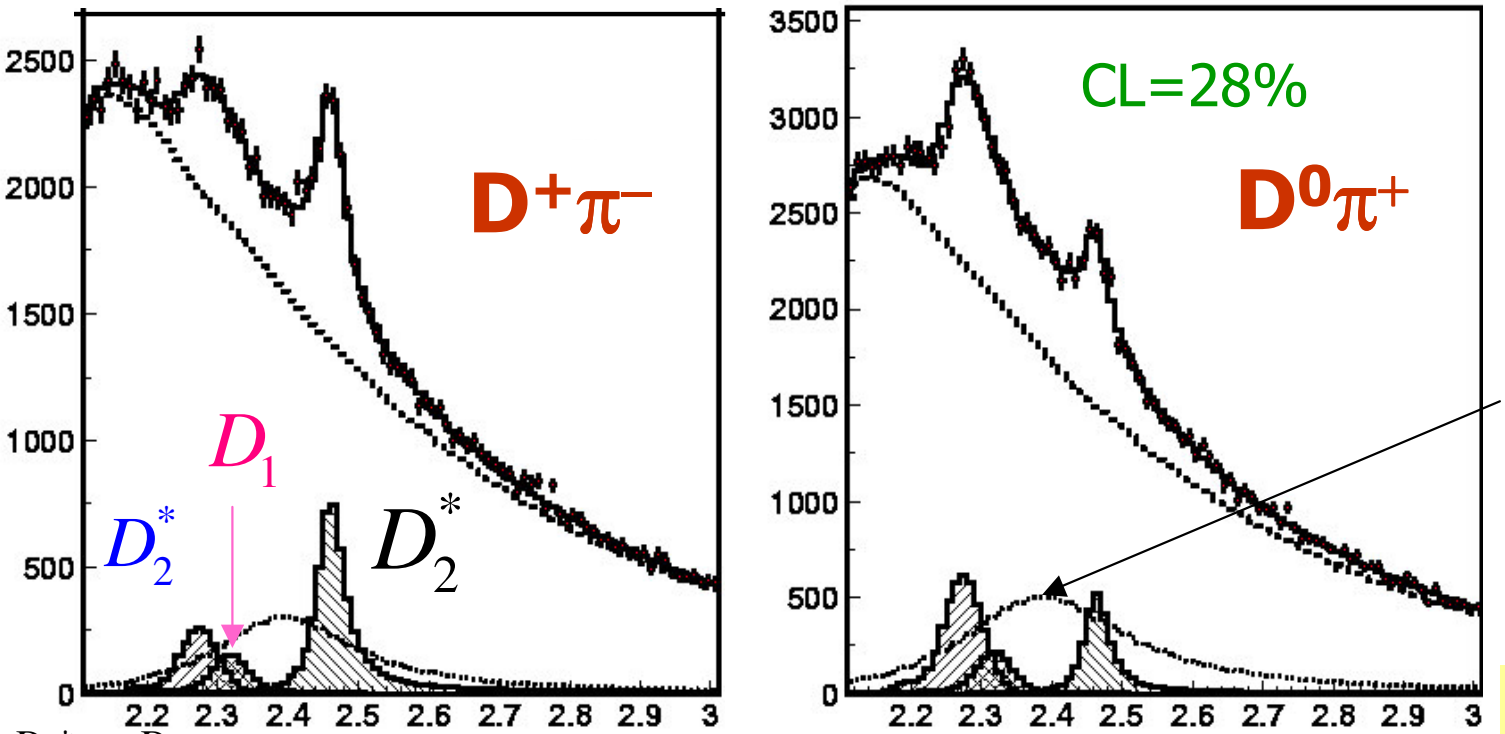
D samples for D_2 measurement

- Photo production gives significant number of events with low multiplicity.
- Process types are:
  - $\gamma N \rightarrow D^0\pi^+ + X$
    - $D^0 \rightarrow K^-\pi^+$
    - $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$
  - $\gamma N \rightarrow D^+\pi^- + X$
    - $D^+ \rightarrow K^+\pi^-\pi^+$



Remove any D^0 candidate with $D^* < 3\sigma$.
(Clean up $D^0\pi^+$)

$D^+\pi^-$ and $D^0\pi^+$ distributions



Fit improves dramatically with inclusion of a broad S-wave state.

Might be $D_0^* \to D\pi$ or $D_1' \to D^*\pi \to (D\pi)\gamma$ *or* both

PLB586 (2004)11-20

$D_2^* \to D\pi$

$D_2^* \to D^*\pi \to (D\pi)\gamma$

- $D^+\pi^-$ (ΔM_0) and $D^0\pi^+$ (ΔM_+) distributions
- $\Delta M_0 \equiv M((K^-\pi^+\pi^+)\pi^-) - M(K^-\pi^+\pi^+) + M_{PDG(D^+)}$
- $\Delta M_+ \equiv M(D^0\pi^+) - M(D^0) + M_{PDG(D^0)}$
- Consider feed downs from D_2^*, D_1 $\to D\pi^\pm\pi^0$ partially reconstructed
- Add S-wave contributions for D^*_0 state (j_l = ½)

$D^0\pi^+$ and $D^+\pi^-$ systematic checks

- Signals are fit with relativistic Breit-Wigner ⊕ experimental resolution.
- Background is exponential + roll-over: $e^{a+bx}(x-c)^d$
- Studied a large number of backgrounds
  - ❑ Wrong sign, D sidebands and simulations
  - ❑ All are consistent with single exponential background.
- S-wave contributions is needed for an acceptable fit. Many other systematic studies on fitting method shows significance of S-wave.

$D^0\pi^+$ and $D^+\pi^-$ results

	D_2^{*0}	D_2^{*+}	$D2^* \pm D_2^{*0}$
Yield	5776±869 ± 696	3434 ± 670 ± 656	
Mass PDG03 Belle03	2464.5 ± 1.1 ± 1.9 2458.9 ± 2.0 2461.6 ± 3.9	2467.6 ± 1.5 ± 0.8 2459 ± 4	3.1 ± 1.9 ± 0.9 0.0 ± 3.3
Width PDG03 Belle03	38.7 ± 5.3 ± 2.9 23 ± 5 45.6 ± 8.0	34.1 ± 6.5 ± 4.2 25^{+8}_{-7}	

	"D^{*0} (j_q=½)" or D_1^0 (j_q= ½)"	"D_0^{*+} (j_q=½)" or D_1^+ (j_q=½)"
Yield	9810 ± 2657	18754 ± 2189
Mass Belle03	2407 ± 21 ± 35 2308 ± 36	2403 ± 14 ± 35
Width Belle03	240 ± 55 ± 59 276 ± 66	283 ± 24 ± 34

- Errors on D_2^* masses and widths are smaller than or same as PDG03 and agree with recent Belle report (hep-ex/0307021).

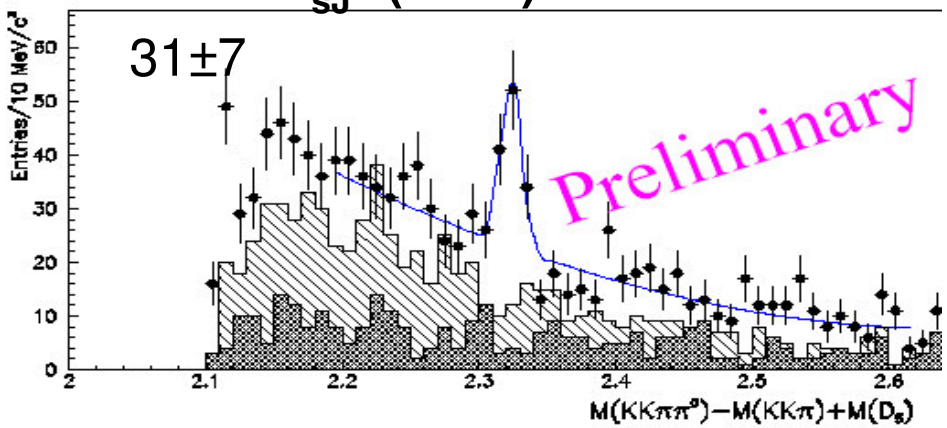
Conclusions

- Charm physics gives a rich source of new results.
- FOCUS is playing a major role in understanding the charm hadronic decays.
  - For the first time the K-matrix approach has been applied to charm decays.
  - Discovery of new multibody final states
  - New precise measurement of D_2^{*+} and D_2^{0}
  - Evidence for broad D_0^{*0} and D_0^{*+} (First evidence in $D^0\pi^+$)
- FOCUS is continuing studies of charm hadronic decays.

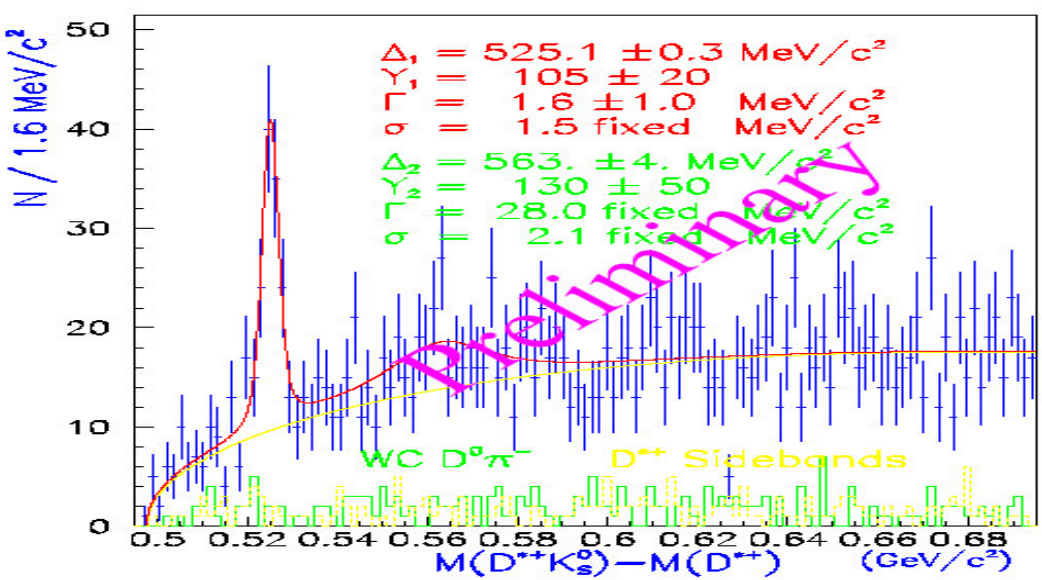
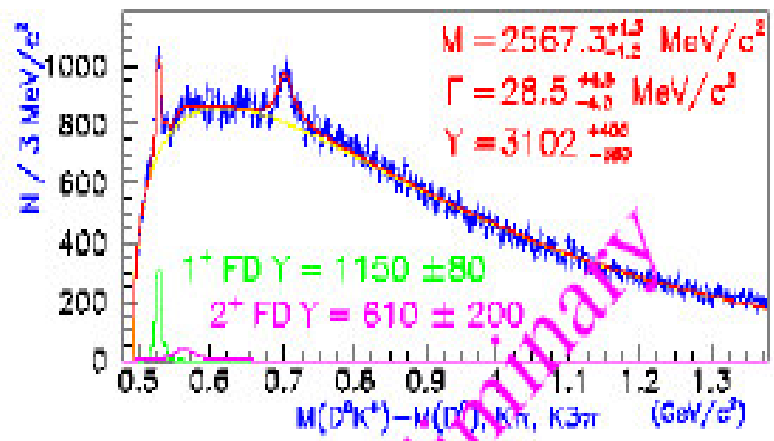
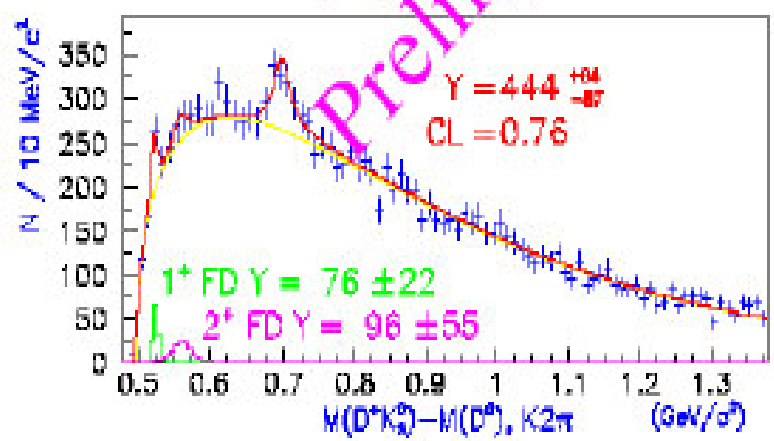
Some preliminary cs results

$D_s^+(\rightarrow K^-K^+\pi^+)\ \pi^0$

Another D_{sJ}^* (2317) confirmation!



$$D_{s1}^{*+} \rightarrow D^{*+} K_s$$



$D_{sJ}^+(2573) \rightarrow D^0 K^+$ and $D^+ K_s$