Charmed Baryons and Spectroscopy at CLEO II

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Charmed Baryons and Spectroscopy at CLEO-II

Given infinite preparation time on the part of the speaker, and infinite attention spans on the part of the audience, this talk would cover:

1. Charmed Baryon Studies at CESR

   (a) **Absolute decay rates**

      i. $\boxed{\Lambda_c \to pK\pi}$ (rel. to $\Lambda\ell\nu_\ell$, and from B-decay)

      ii. $\Xi_c^+ \to \Xi^0\ell\nu_\ell$ / $\boxed{\Xi_c^+ \to \Xi^-\pi^+\pi^+}$, $\Xi_c^+ \to \Xi^-\pi^+$, $\Xi_c^+ \to \Xi^-\pi^+\pi^0$

      iii. $\Xi_c^0 \to \Xi^-\ell\nu_\ell$, $\boxed{\Xi_c^0 \to \Xi^-\pi^+}$

      iv. Derived ratio of $\frac{\Gamma(\Xi_c^0)}{\Gamma(\Xi_c^+)} = \frac{\tau_{\Xi_c^+}}{\tau_{\Xi_c^0}}$

   (b) **Inclusive Rates: $\Lambda_c \to \Lambda + X$, e.g.**

      i. Charm-tagging: $\Lambda \leftarrow \to \ell$

      ii. In B-decay: $\Lambda\ell$ correlations, $\Lambda_c(\to pK\pi)\ell$ correlations

$B \to \Lambda_c \bar{p} W$
$\hookrightarrow \Lambda X$
$\hookrightarrow pK\pi$

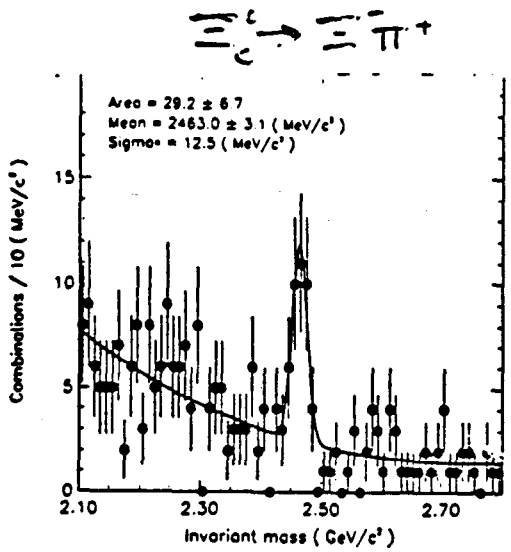


Figure 3. Invariant mass distribution of $\Xi^-\pi^+$ combinations for $x_p > 0.5$

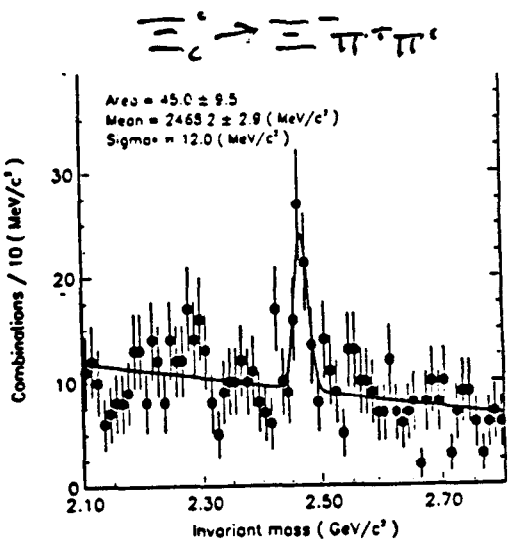


Figure 4. Invariant mass distribution of $\Xi^-\pi^+\pi^0$ combinations for $x_p > 0.5$.

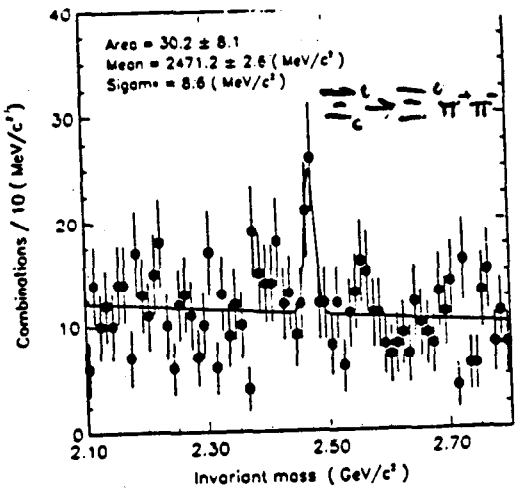


Figure 5. Invariant mass distribution of $\Xi^0\pi^+\pi^-$ combinations for $x_p > 0.5$

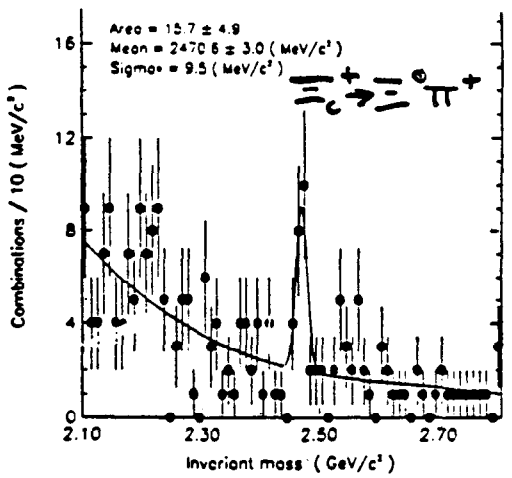


Figure 6. Invariant mass distribution of $\Xi^0\pi^+$ combinations for $x_p > 0.5$

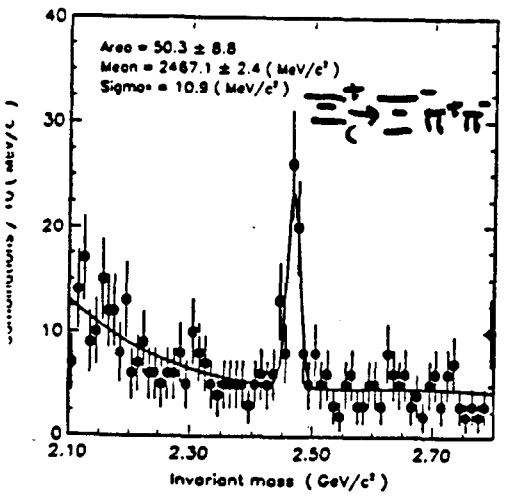


Figure 6. Invariant mass distribution of $\Xi^-\pi^+\pi^+$ combinations for $x_p > 0.5$

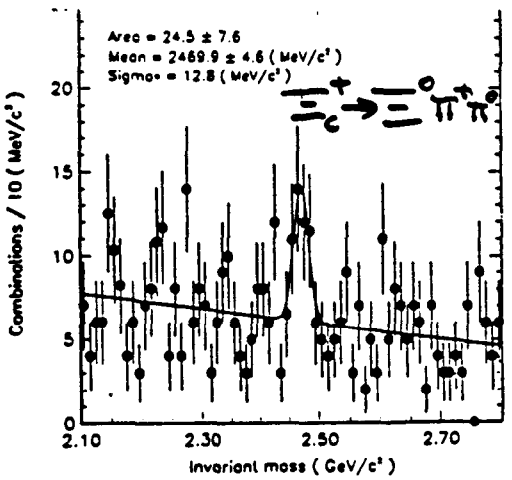


Figure 7. Invariant mass distribution of $\Xi^0\pi^+\pi^0$ combinations for $x_p > 0.5$.

(c) **Studies of exchange and W_{int} modes**

i. connection to $\tau_{\Lambda_c} \sim 0.5\tau_{D^0} \sim \tau_{D_s}$

ii. $\Lambda_c \underset{(CLEO93)}{\rightarrow} \Sigma^+\phi$, $\Lambda_c \underset{(CLEO94)}{\rightarrow} \eta + X$ $\left\{\begin{matrix}\Lambda\eta\pi \\ p\eta K \\ \Sigma\eta\end{matrix}\right\}$

iii. $\Xi_c^0 \rightarrow \Omega K^+$ (CLEO92)

(d) Study of the $c \rightarrow s$ transitions in baryons

i. Determination of the form factors in $\Lambda_c \rightarrow \Lambda\ell\nu_\ell$. (Multidimensional Maximum Likelihood fit a la' E691 $D^0 \rightarrow K^*\ell\nu_\ell$).

ii. Weak Decay asymmetries

A. $\Lambda_c \rightarrow \Lambda\pi^+$ (agrees w/ low Q^2 prediction)

B. $\Lambda_c \rightarrow \Sigma^+\pi^0$ (disagrees w/ theory)

(e) Production in e^+e-

i. Where is compensation of baryon number?

ii. Fragmentation dynamics (f.f., e.g.)

2. **Meson spectroscopy at CLEO-II**

(a) Precision (1−/0-+) splittings

i. $\underbrace{D^{*0} - D^0,\ D^{*+} - D^0,\ D^{*+} - D^+}_{\sim 100\ \text{keV precision}},\ \underbrace{D_s^{*+} - D_s}_{500\ \text{keV precision}}$

(b) Studies of orbitally excited mesons

i. Mass measurements and Mass splittings

A. $D_1^0 \to D^*\pi^+$

B. $D_1^+ \to D^*\pi^+$

C. $D_{s1}^+ \to D^*K$

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

E. $D_2^{*+} \to D\pi^+$, $D_2^{*+} \to D^*\pi^+$ ← 1st High Stat. Obs.

F. $D_{s2}^* \to DK$

ii. HQET tests:

A. D-wave nature of $D_2^{*+} \to D^*\pi^+$ decay

B. Ratios of BR's: $\frac{D_2^{*+} \to D\pi^+}{D_2^{*+} \to D^*\pi^+}$

3. Charmed baryon spectroscopy at CLEO-II

(a) **Masses and Widths of excitations**

i. $\Sigma_c^+ \rightarrow \Lambda_c \pi^0$, $\Sigma_c^{++} \rightarrow \Lambda_c \pi^+$, $\Sigma_c^0 \rightarrow \Lambda_c \pi^-$

ii. $\Lambda_c^*(2593) \rightarrow \Lambda_c \pi^+ \pi^-$

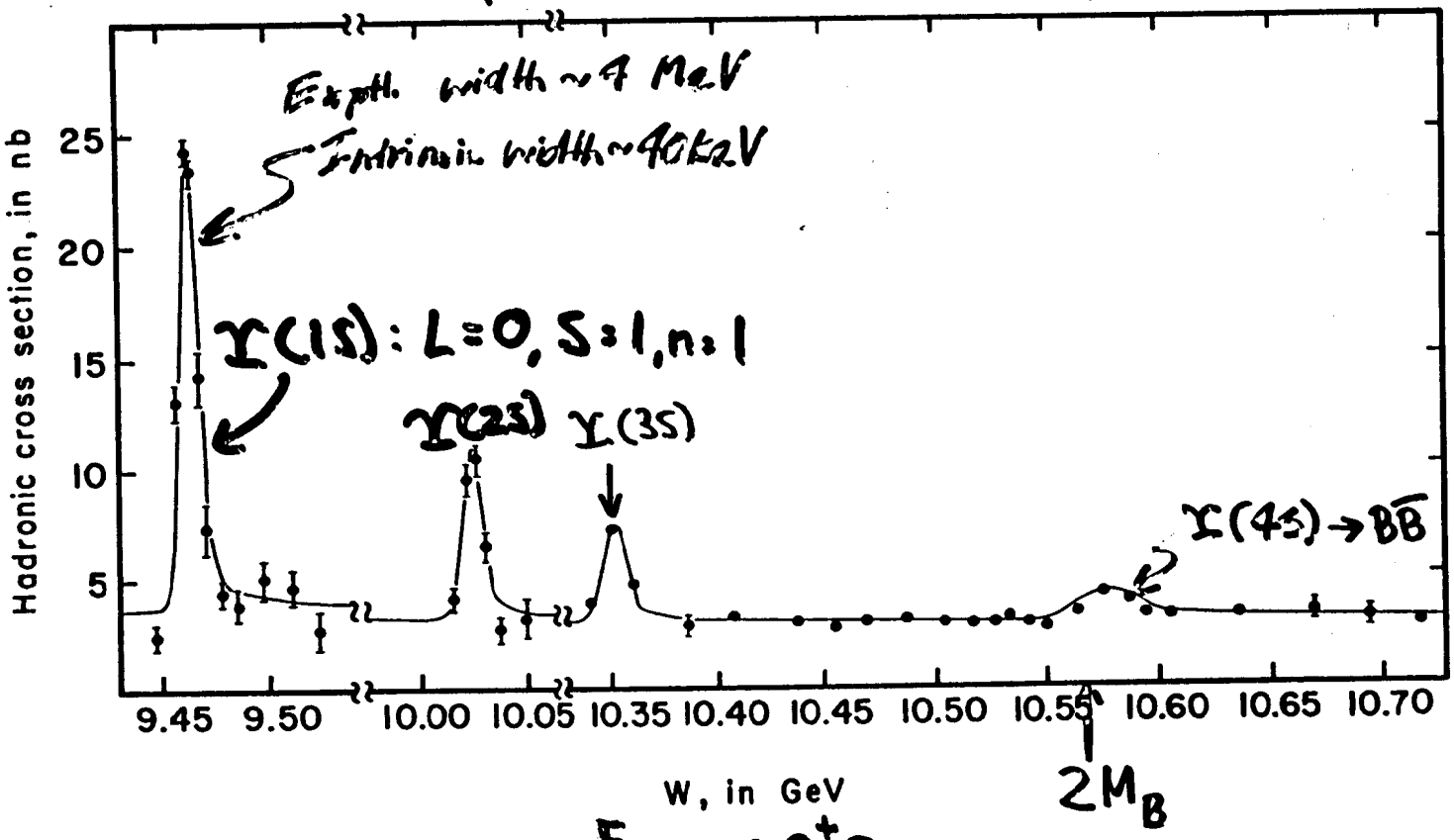
A. Σ_c content

iii. $\Lambda_c^*(2620) \rightarrow \Lambda_c \pi^+ \pi^-$

4. **Prospects for improvements**

(a) Outlook for 10 GeV e^+e^- studies of charmed baryons

Detect presence of resonances (bound $b\bar{b}$) as jumps in hadronic x-sect

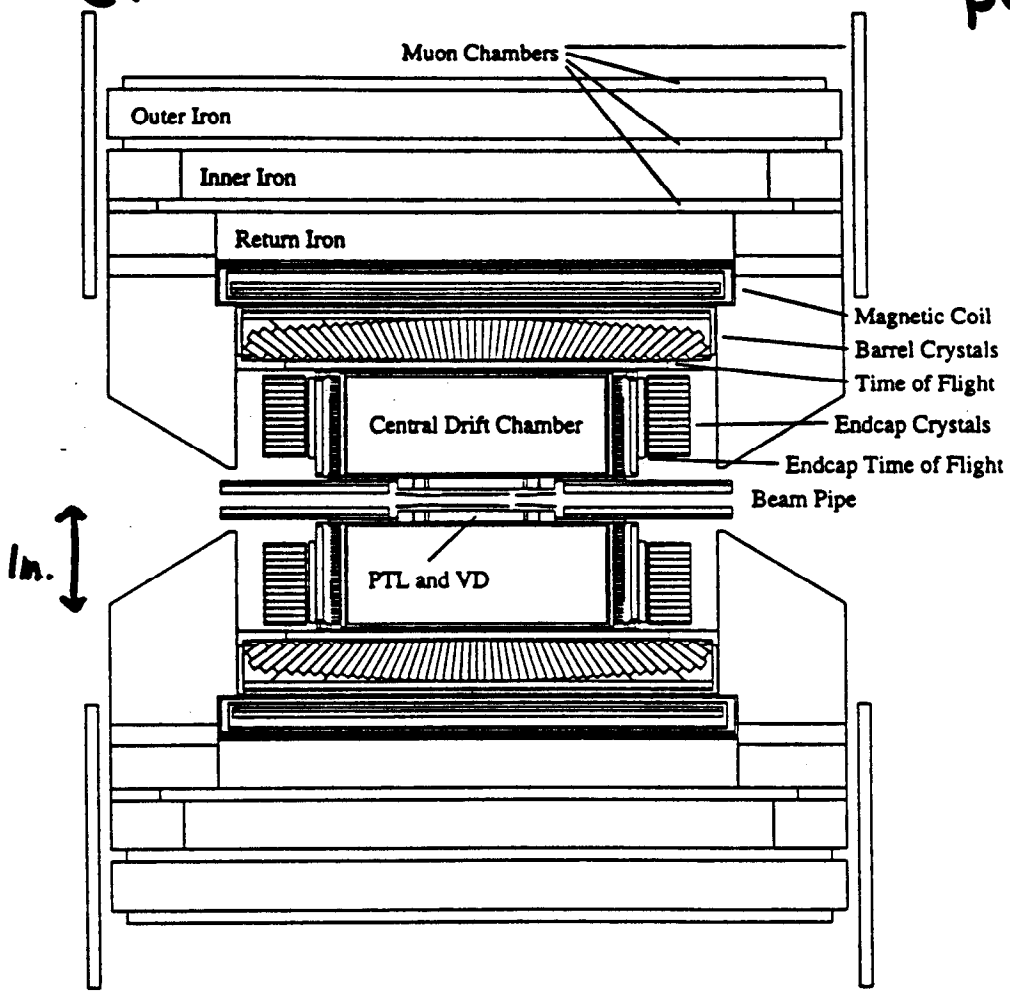


$E_{c.m.}$ = e^+ Energy + e^- Energy

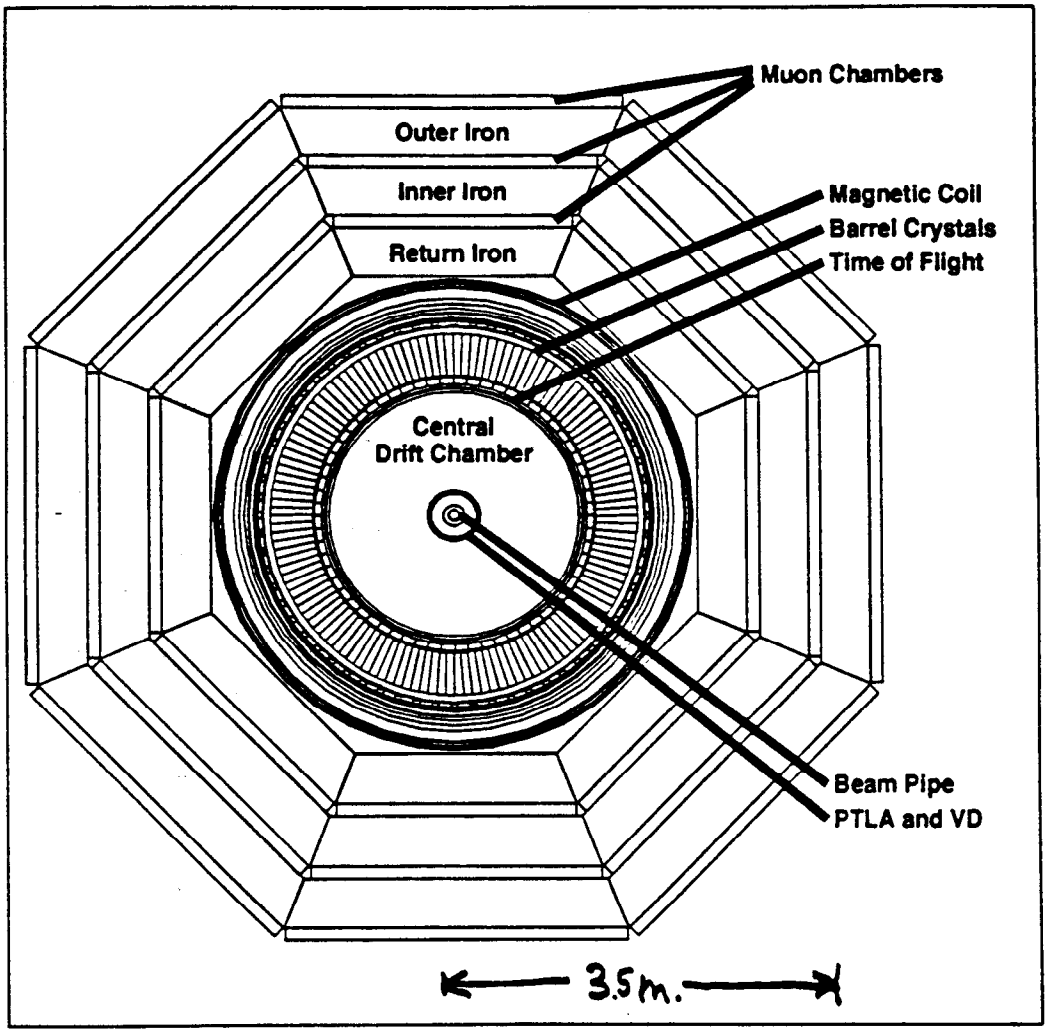
0050183-009

The CLEO detector

$\left(\frac{dp}{p}\right)^2 \sim (0.005)^2 + (0.0015p)^2$ for charged particles



- Present running very good
  250/pb collected in Dec (~250 K $B\bar{B}$ evts.)
  Total of 2.5M $B\bar{B}$ on tape, comparable # $c\bar{c}$, $\tau\bar{\tau}$
- Run on $\Upsilon(2S)/\Upsilon(3S)$ to precede **coming** shutdown for SVX installation/transition to 9x3 running


Muon Chambers
Outer Iron
Inner Iron
Return Iron
Magnetic Coil
Barrel Crystals
Time of Flight
Central
Drift Chamber
Beam Pipe
PTLA and VD
3.5m.

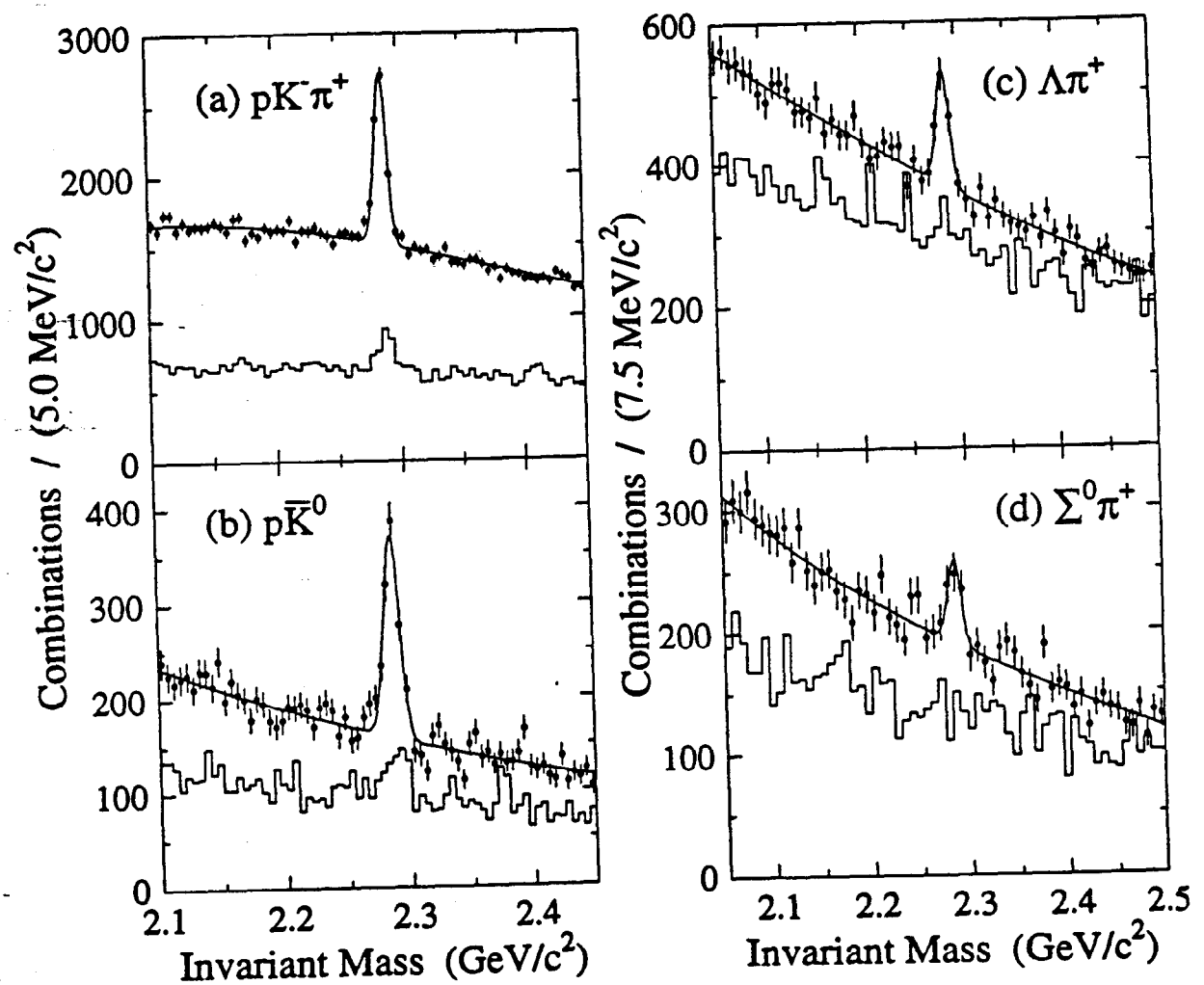
Systematics at 10 GeV

Particle	CO Inclusive σ	$B\bar{B}$ Inclusive σ
$c\bar{c}$	1.1 nb	1.20 nb
$D^0 + \bar{D}^0$	2×0.55 nb	2×0.60 nb
$D^+ + D^-$	2×0.25 nb	2×0.28 nb
$D^* + \bar{D}^*$	2×0.40 nb	2×0.45 nb
$D_s^+ + D_s^-$	2×0.15 nb	2×0.15 nb
$D_s^{*+} + D_s^{*-}$	2×0.07 nb	
$D^{**0} + \bar{D}^{**0}$ (all L=1)	2×0.15 nb	
$\Lambda_c + \bar{\Lambda}_c$	2×0.10 nb	2×0.08 nb
$\Lambda_c^*(2593) + \bar{\Lambda}_c^*(2593)$ 2620 2620	2×0.01 nb	()
$\Xi_c + \bar{\Xi}_c$	2×0.03 nb	2×0.015 nb
$\Omega_c + \bar{\Omega}_c$	2×0.01 nb	2×0.01 nb

B- as a source of charm has not been fully exploited. • $\boxed{B \to \Xi_c \to c\bar{c} \to \Xi_c}$ CLEO94

Present sample~3/fb, 30/fb by 1999 (with Silicon vertexing) - 10K $\Lambda_c \to pK\pi$ at present

$B \to \Lambda_c$, e.g. shows strong signals in many channels



Why the Λ_c is sooooo interesting

$\wedge_c$: c (S=1/2) + (ud) (S_{tot})=0

Simplest decay picture: External W-emission, inert diquark. Expect:

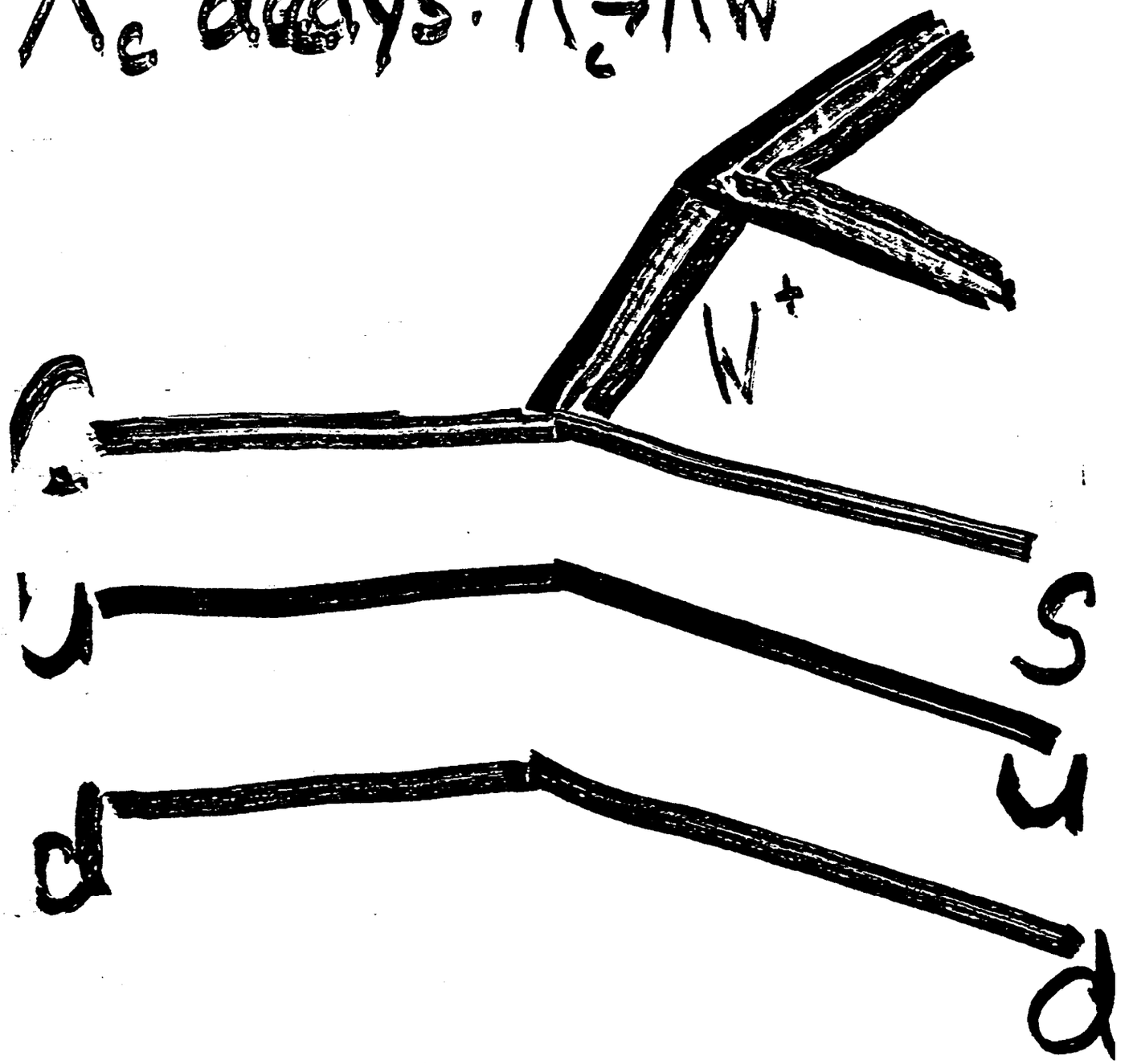
- $\Lambda_c \to \Lambda + X$ dominant

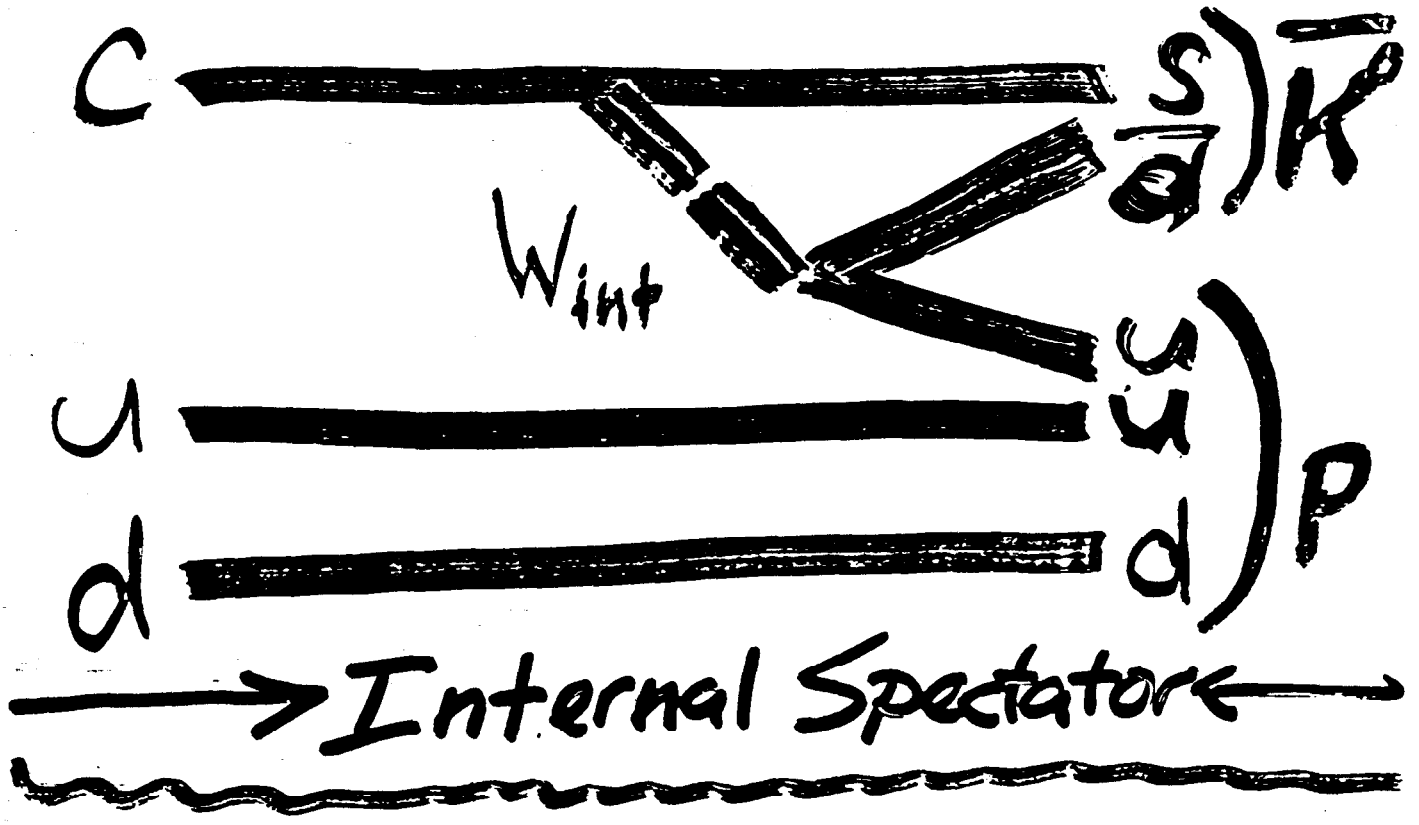
But:

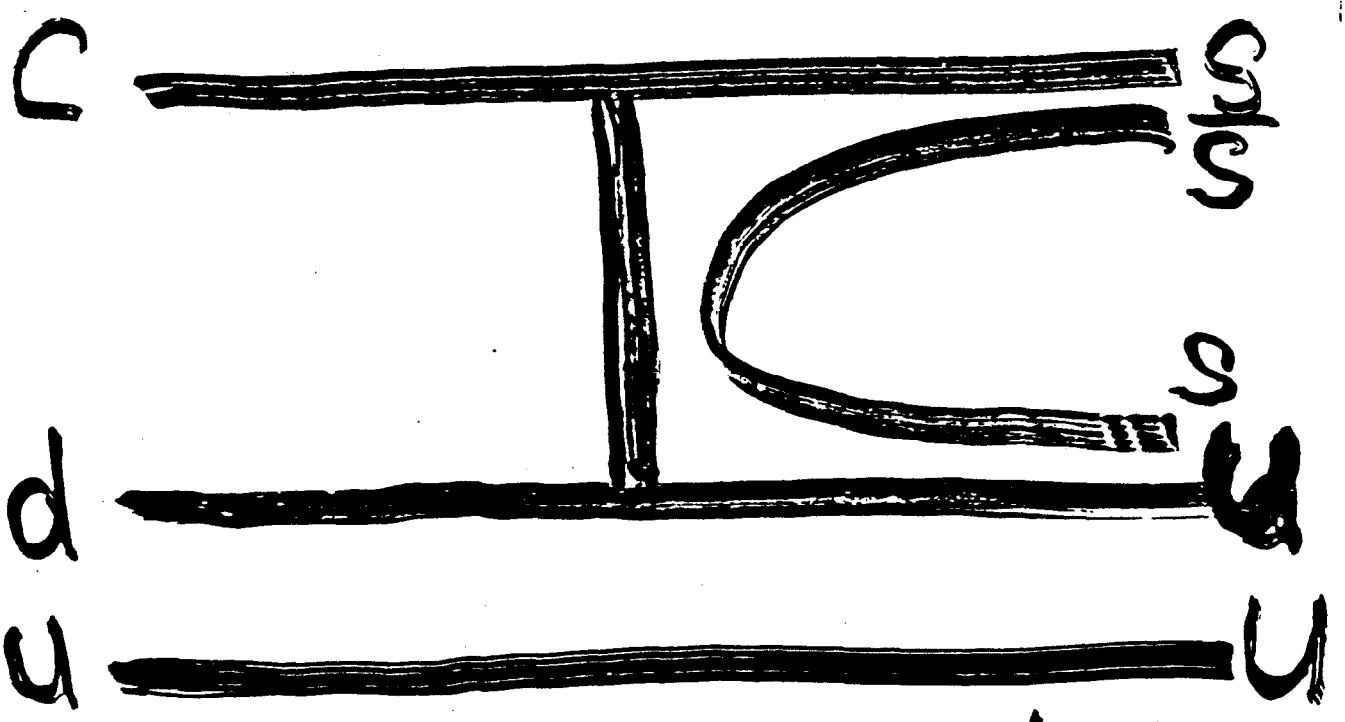
- $\Lambda_c \to \Lambda + X \sim 35 \pm 11\%$ (PDG '94) (27±9% - NO B-decay, 57±12% from B-decay, 15±10% JPW thesis from continuum) (1991)
- $\Lambda_c \to \Lambda\pi^+ \sim 0.5\%$ cf: $D^0 \to K^-\pi^+ \approx 4\%$
- $\Lambda_c \to \Lambda\pi^+\pi^0 \sim 1\%$ cf: $D^0 \to K^-\pi^+\pi^0 \approx 10\%$
- $\Lambda_c \to \Lambda\pi^+\pi^-\pi^+ \sim 2\%$ cf: $D^0 \to K^-\pi^+\pi^-\pi^+ \approx 10\%$
- $\tau_{\Lambda_c} \sim \tau_{D^0}/2$ $\Rightarrow$ large hadronic Λ_c decay width, many modes other than simple W_{ext}.

+

Simplest model of Λ_c decays: $\Lambda_c^+ \to \Lambda W^+$







Exchange: $\Lambda_c \to \Sigma^+ \phi$

MORE Λ_c INTRIGUE!

- $\Lambda_c \to \Lambda\pi \sim 0.5\%$ (cf. $D \to K\pi = 4\%$)
- $\Lambda_c \to \Lambda\pi\pi^0 \sim 1\%$
- $\Lambda_c \to \Lambda 3\pi \sim 2\%$

$\Longrightarrow$ Consistent w/ low $\Lambda_c \to \Lambda X$ (incl. $\Lambda_c \to \Sigma X$)

- $\tau_{\Lambda_c} \sim (\tau_{D^0} = \tau_{D_s})/2$

$\Longrightarrow$ More decay channels open to Λ_c

- $pK\pi$ 3-4% $\Rightarrow$ int. spect. large
- 3 quarks $\Rightarrow$ Exchange NOT hel. suppressed
- Understanding hadronic decays KEY:

Search for: $\Lambda_c \to p K^0_S \eta$

$\Lambda \eta \pi$

$\Lambda K^0_S K$

$\Sigma \eta$

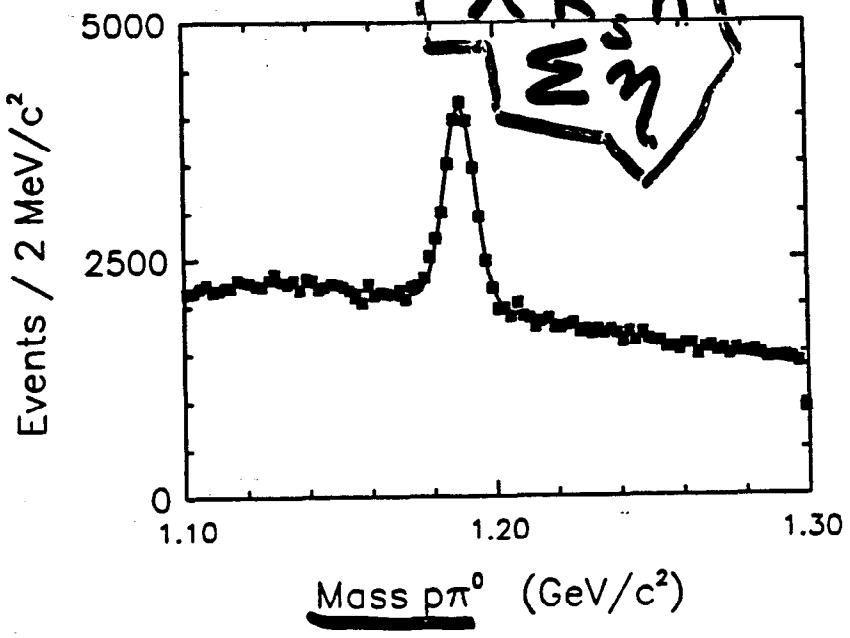


FIG. 4. Invariant mass distribution for $\Sigma^+ \to p\pi^0$ with $P_{\Sigma^+} > 1$ GeV/c.

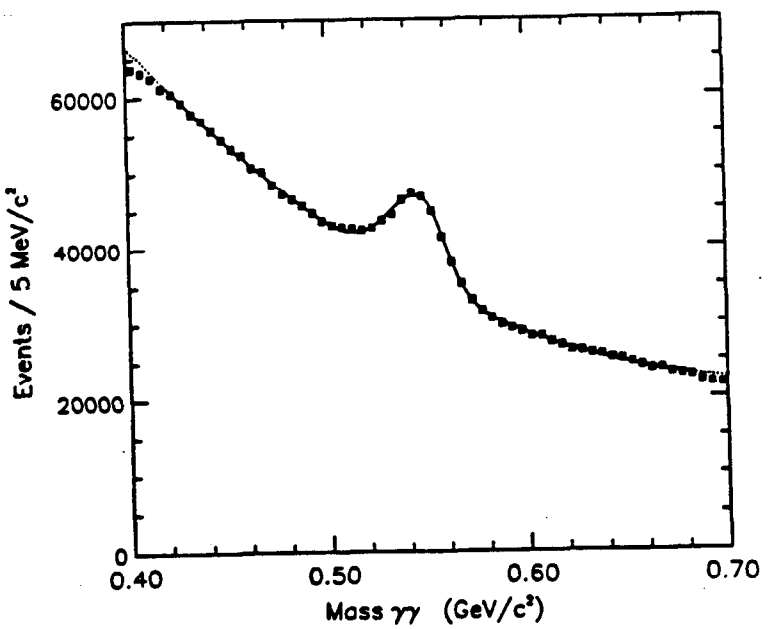
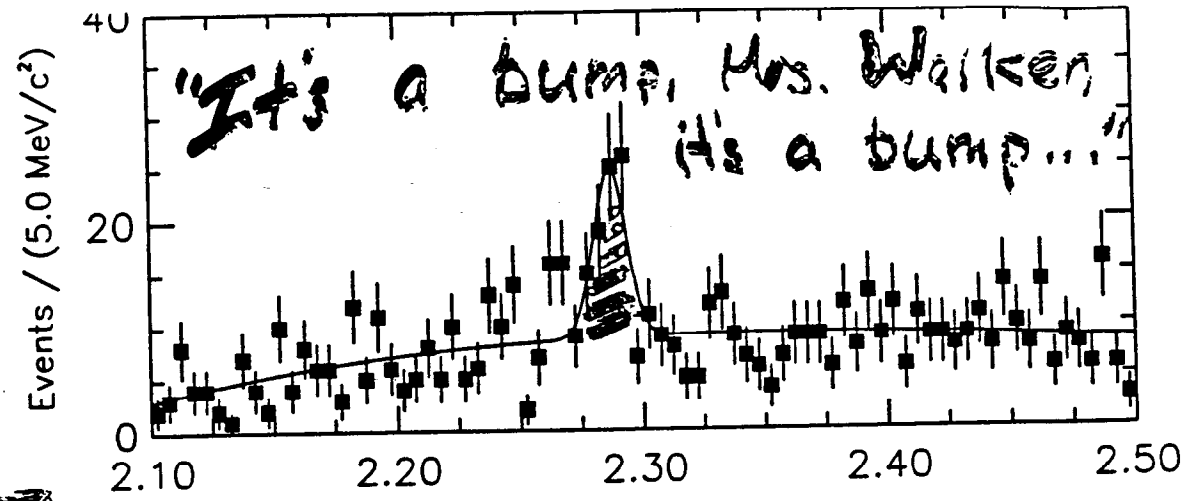
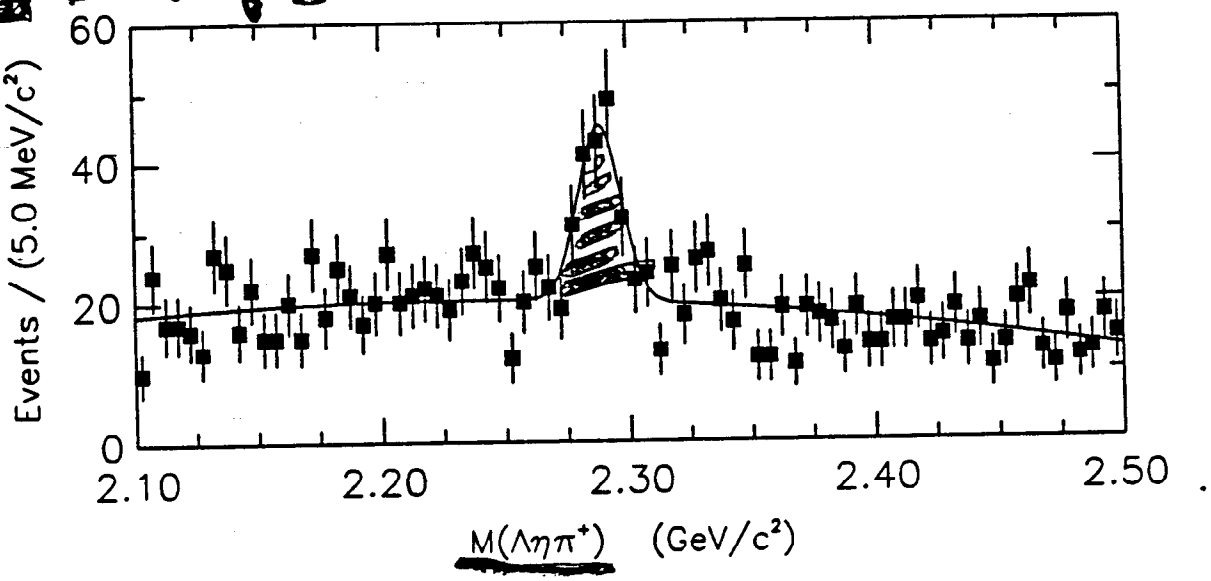


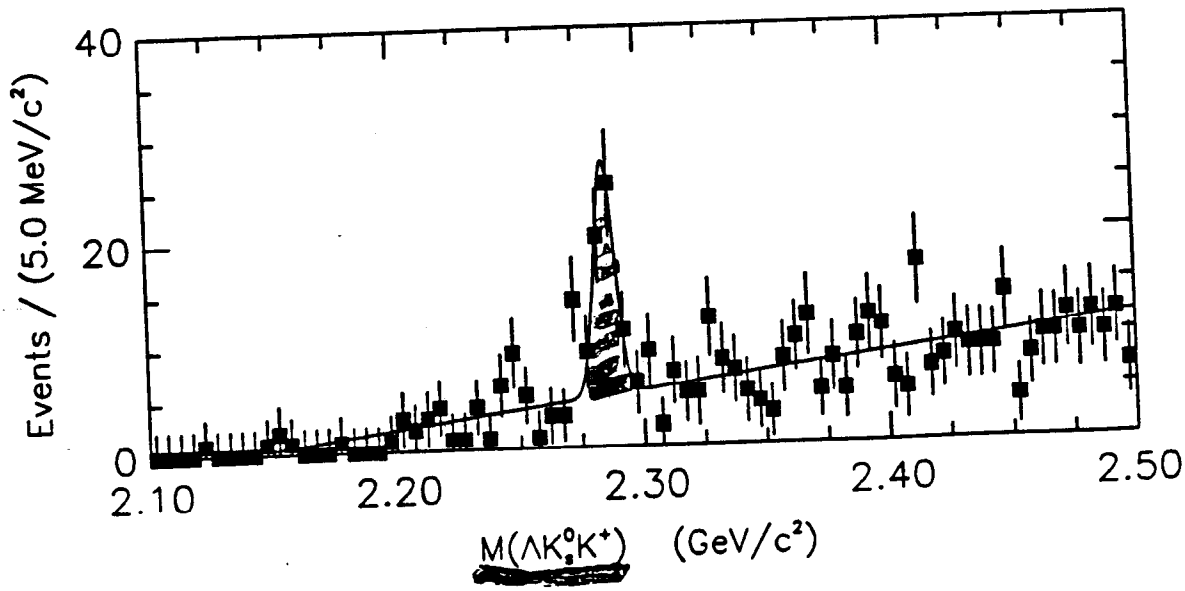
FIG. 2. Invariant mass distribution for $\eta \to \gamma\gamma$ with $P_\eta > 0.5$ GeV/c.

$\Lambda_c \to \eta X$ often non Weak.


"It's a bump, Mrs. Walken
it's a bump..."
Events / (5.0 MeV/c²)
40
20
0
2.10
2.20
2.30
2.40
2.50
M(pK⁰η) (GeV/c²)

bumps


Events / (5.0 MeV/c²)
60
40
20
0
2.10
2.20
2.30
2.40
2.50
M(Ληπ⁺) (GeV/c²)


Events / (5.0 MeV/c²)
40
20
0
2.10
2.20
2.30
2.40
2.50
M(ΛK⁰ₛK⁺) (GeV/c²)

Hmmm.... Is $\Lambda_c \to \Lambda\pi\eta$ actually $\Sigma^*(1385)\eta$ OR Λa_0?

"Is it 2 Body?"
(Alice Cooper (sic))

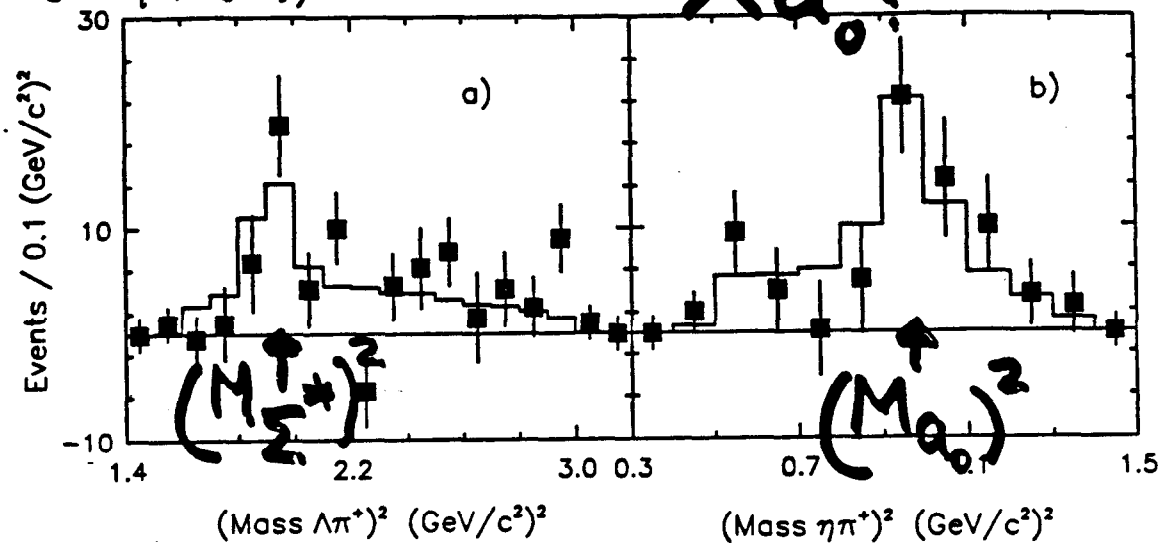


FIG. 8. Projection of Dalitz plot in the previous figure onto (a) the $M^2_{\Lambda\pi^+}$ axis and (b) the $M^2_{\eta\pi^+}$ axis

→ WEAK EVIDENCE FOR 2BODY ←

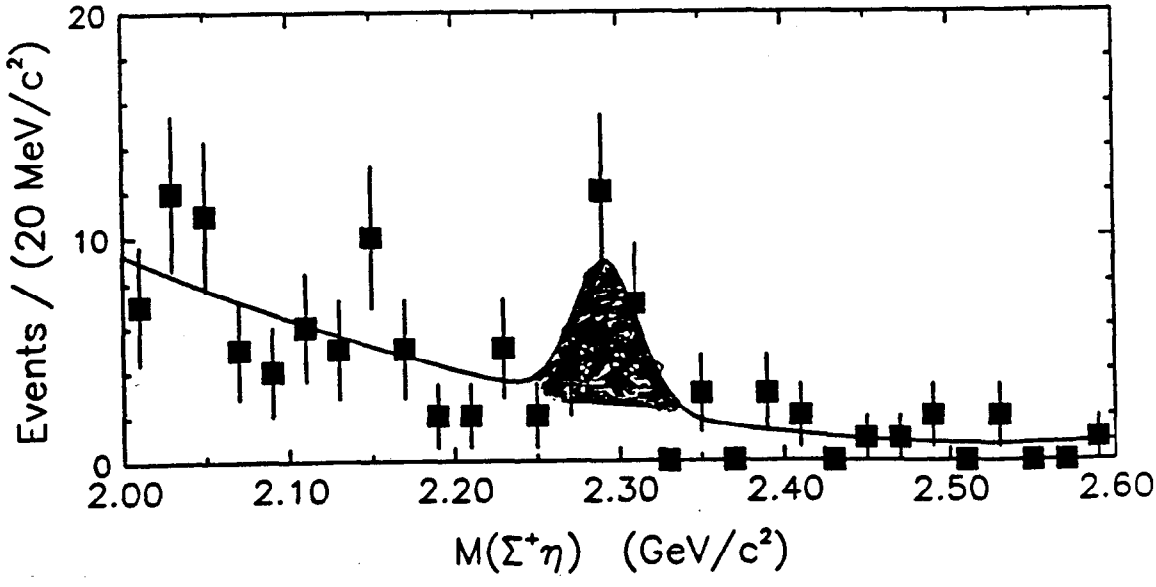


FIG. 9. Invariant mass distribution for $\Lambda_c^+ \to \Sigma^+\eta$

Λ_c^+ decay mode	Number of events	Efficiency (%)	$\mathcal{B}/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$
$p\bar{K}^0\eta$	53 ± 10	7.3	$0.25 \pm 0.05 \pm 0.04$
$\Lambda\eta\pi^+$	109 ± 16	8.5	$0.36 \pm 0.06 \pm 0.05$
$\Sigma^+\eta$	25 ± 7	5.2	$0.10 \pm 0.03 \pm 0.02$
$\Lambda\bar{K}^0K^+$	46 ± 8	7.9	$0.11 \pm 0.02 \pm 0.02$

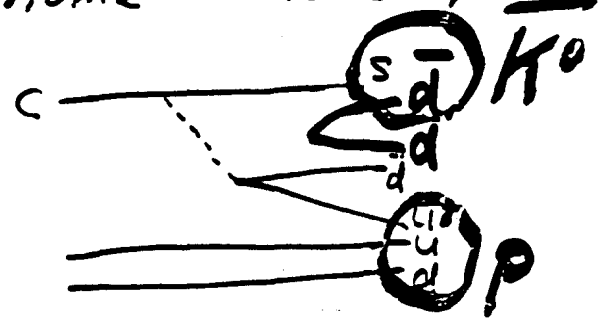
Source	Fractional Error (%)			
	$pK_S^0\eta$	$\Lambda\eta\pi^+$	$\Sigma^+\eta$	$\Lambda K_S^0K^+$
K_S^0, Λ, and Σ^+ finding	10	10	10	14
η and π^0 finding	5	5	7	—
Tracking efficiency	—	—	4	4
Proton and kaon identification	8	2	2	—
$pK^-\pi^+$ substructure	7	2	2	5
Λ_c^+ substructure	—	6	—	—
Uncertainties in $\sigma_{\Lambda_c^+}$	5	5	5	5
Monte Carlo statistics	3	3	3	3
TOTAL	16	14	14	16

	$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\pi^0)}{B(pK^-\pi^+)}$	$\frac{\mathcal{B}(\Lambda_c^+ \to \Sigma^+\eta)}{B(pK^-\pi^+)}$
CLEO	$0.20 \pm 0.03 \pm 0.03$	$0.10 \pm 0.03 \pm 0.02$
Körner and Krämer	0.10	0.05
Zenczykowski	0.13	0.08

Passing a few judgments

① $pK^0\eta / pK^0\pi^0 \sim 1/2$

Home audience predicted: $1/3$



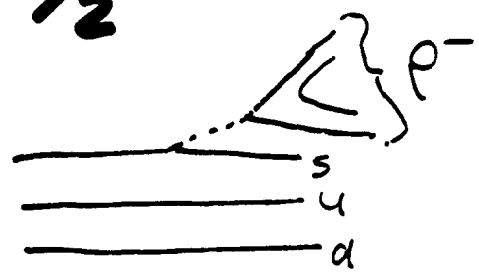
π^0: $\frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$

η: $\frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$

⇒ **Good Answer!!**

② $\Lambda\eta\pi^- / \Lambda\pi^0\pi^- \sim 1/2$

· Expected $\sim 1/3$ if no ρ^-:



CLEO look at $\pi^0\pi^-$ mass spectrum in $\Lambda\pi^0\pi^-$ ⇒ Consistent w/ P.S., no ρ^-

→ Possible $\Lambda a_0(980)$ enhancement of $\Lambda\eta\pi^-$

③ $\Lambda \bar{K}^0 K^+ / \Lambda \pi^0 \pi^+ \sim 1/6$

$\Rightarrow$ Consistent w/ $\dfrac{s\bar{s}}{(u\bar{u} + d\bar{d})} = 1/6$

$$\frac{s\bar{s} \text{ popping}}{u\bar{u} \text{ popping}} = \frac{s\bar{s} \text{ popping}}{d\bar{d} \text{ popping}} = 1/3$$

④ $\Sigma^+\pi^+\pi^- > \Sigma^+\omega > \Sigma^+\pi^0 \sim 2\Sigma^+\phi$
$\sim 2\Sigma^+\eta$

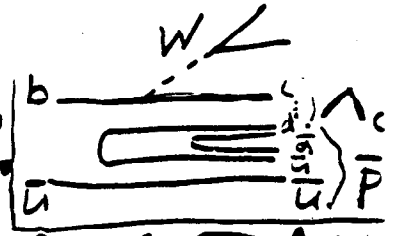
$\Sigma^+\eta \sim \Sigma^+\phi$

$\Rightarrow$ some combination of
W-int (a la $\Sigma^+\pi^0$)
+ exchange (a la $\Sigma^+\phi$)
contributing to $\Sigma^+\eta$

Point - Counterpoint

"Comment on $B(\Lambda_c \to pK\pi)$"

Previous extractions used $B \to p\bar{p}X$, e.g. to determine $B(B \to \text{baryons})$



→ Since $b \to c$, assume $B \to \text{baryons}$ via: $B \to \Lambda_c \bar{p} X$

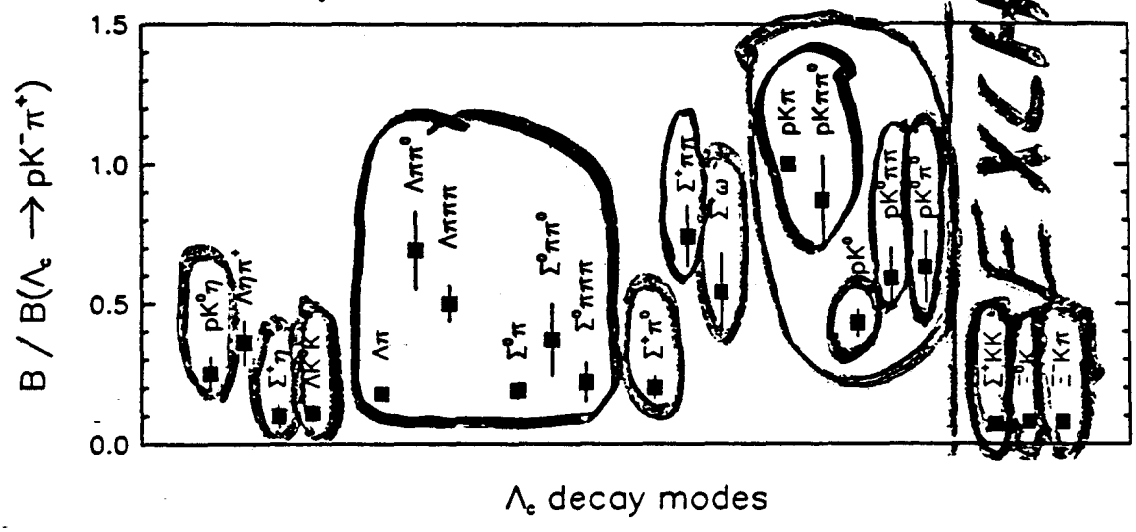
Knowing $B(B \to \text{baryons})$, and measuring $N_{pK\pi}$ ⇒ obtain $B_{pK\pi}$

→ Now know (PDB) $B \to \text{baryons}$ not only $B \to \Lambda_c \bar{p} X$, also: $B \to \Xi_c \bar{\Lambda}_c X$, $B \to \Xi_c \bar{\Lambda} X$

⇒ Readjust $B_{pK\pi} \sim 10.25\%$

Readjust $\Lambda_c \to \Lambda X$ down!!

• MANY Λ_c modes
<u>definitely</u> not W_{ext}
$\longrightarrow \Lambda_c \to \eta X$, e.g.



EXCHANGE

• Some most likely exchange
• Some " " $W_{internal}$
• Others accessible through ≥ 2 (interfering) diagrams
• BSW $(a_2/a_1) < 0$ mesons baryons?

Absolute BR's at 10 GeV

- $\Lambda_c \to pK\pi$
  - As w/ $D_s \to \phi\pi$, relate a semileptonic to an hadronic width: $\frac{\Lambda_c \to pK\pi}{\Lambda_c \to \Lambda\ell\nu}$
  - If π/electron separation is good enough, can use tags a la' $D^{*+} \to D^0\pi^+$ and measure $\frac{\Lambda_c(2630) \to \Lambda_c\pi^-}{\Lambda_c(2630) \to \Lambda}$
  - (Background from $D^{*0} \to D^0\gamma/\pi 0$ with photon conversion?)
  - Use $B \to baryons$: requires knowing the correct model for baryon production in B-decay.

- $\Xi_c \to \Xi\pi$ and $\Xi_c \to \Xi\pi\pi$ also possible with improved precision on rate wrt $\Xi\ell\nu$ and τ_{Ξ_c}
  - If model of Ξ_c production in B-decay is known, e.g. $B \to \Xi_c\bar{\Lambda}X$ can be used to tag the number of Ξ_c's produced. (need a correlation with a lepton from the opposite B). (In progress)

$$\Rightarrow \frac{\tau_{\Xi_c^+}}{\tau_{\Xi_c^0}} = 2.46 \pm 0.70 \pm^{0.33}_{0.23}$$

+ AND: $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = f(1.9 \pm 0.5^{+0.7}_{-0.6})\%$

$\mathcal{B}(\Xi_c^- \to \Xi^0\pi^-) = f(0.41 \pm 0.14^{+0.14}_{-0.13})\%$

3

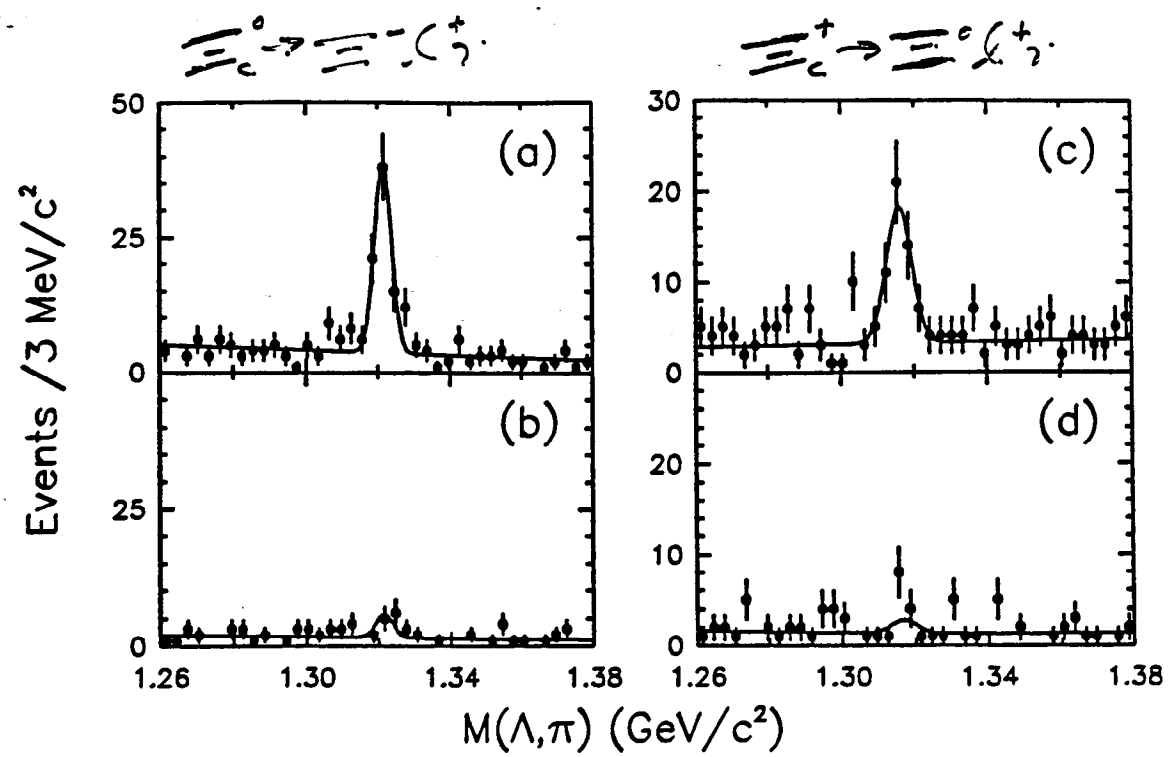


FIG. I. The $(p\pi)\pi$ invariant mass for right sign and wrong sign Ξe combinations satisfying the cuts described in the text; (a)$(p\pi)\pi^-$ right sign, (b)$(p\pi)\pi^-$ wrong sign; (c)$(p\pi)\pi^0$ right sign, (d)$(p\pi)\pi^0$ wrong sign.

TABLE I. Signals and backgrounds

mode	$\Xi_c^+ \to \Xi^0 e^+ \nu_e$	$\Xi_c^0 \to \Xi^- e^+ \nu_e$
$N_{\Xi e^+}$ (right sign)	47 ± 8	62 ± 9
$N_{\Xi e^-}$ (wrong sign)	6 ± 3	8 ± 4
corrected yield	41 ± 9	54 ± 10
efficiency (%)	1.17 ± 0.02	3.80 ± 0.05
$\sigma \cdot \mathcal{B}$ (pb)	$1.55 \pm 0.33 \pm 0.25$	$0.63 \pm 0.12 \pm 0.10$
fakes (right sign)	4 ± 2	7 ± 2
fakes (wrong sign)	4 ± 2	5 ± 2

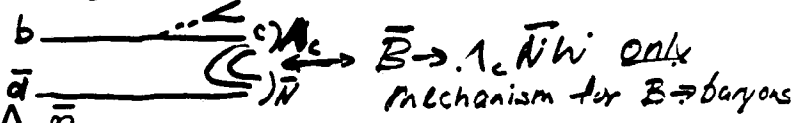
REFERENCES

[1] Particle Data Group, Phys. Rev. Lett. **45** 1 (1992).
[2] M. Bauer, B. Stech and M. Wirbel, Zeit. Phys. C **34**, 103 (1987) and references therein.
[3] B. Guberina, R. Rückl, and J. Trampetić, Zeit. Phys. C **33** 297 (1986).
[4] M.B. Voloshin and M.A. Shifman, Sov. Phys. JETP 64, 698 (1986).
[5] Y. Kubota *et al.*, Nucl. Instrum. Methods **A320** 66 (1992).
[6] Throughout this paper charge conjugate modes are implied.
[7] P. Avery *et al.*, Phys. Rev. Lett. **71** 2391 (1993).
[8] For example, see 'Note on Ξ resonances', Particle Data Group, Phys. Rev. Lett. **45**

Comment on $\Lambda_c \to pK\pi$ from B-decay

- Previously extracted by both ARGUS and CLEO

  ASSUMING:

  - $B \to \Lambda_c \bar{p} = B \to \Lambda_c \bar{n}$
  - $N_{\bar{p}} = 2 \times N_{\Lambda_c}$
  - Number of $pK\pi$, efficiency corrected, gives desired BR : $B_{pK\pi} = \dfrac{N_{\bar{p}+pK\pi}/\varepsilon_{pK\pi}}{N_{\bar{p}}}$

- BUT: How valid is the input model?

  CLEO94: $(20 \pm 13)\%$ of $\bar{p}$ from sources **NOT** associated w/ Λ_c $\Rightarrow$ revise $B \to pK\pi \uparrow$ ($\sim 20\%$)

Multidimensional fit to observables in $\Lambda_c \to \Lambda \ell \nu$ allows extraction of HQET f.f. ratio:

$R = f_2/f_1$

(~1000 evts.)

$$F_1^V(q^2) = -F_1^A(q^2) = f_1(q^2) + \frac{M_\Lambda}{M_{\Lambda_c}} f_2(q^2)$$

$$F_2^V(q^2) = -F_2^A(q^2) = \frac{1}{M_{\Lambda_c}} f_2(q^2)$$

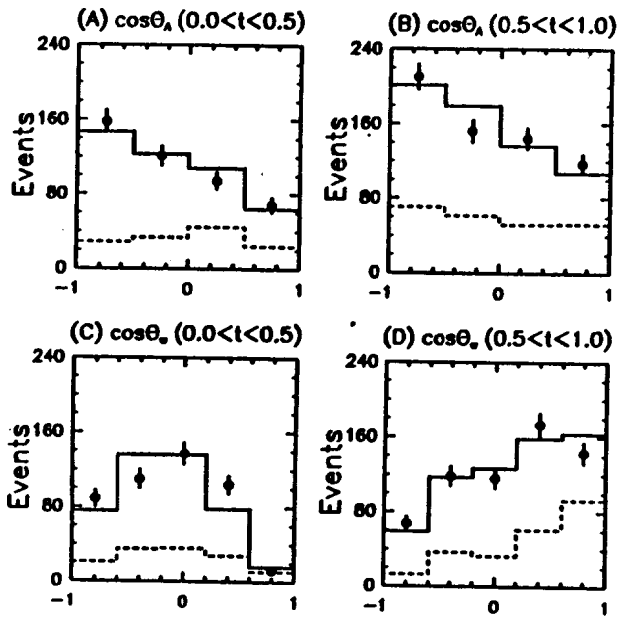


FIG. 3. Projections of the data (points with error bars) and the fit (solid histogram) onto $\cos\Theta_A$ and $\cos\Theta_W$ for different t regions. (A) and (C) are for $0.0 < t < 0.5$ and (B) and (D) are for $0.5 < t < 1.0$. The dashed lines show the background distributions.

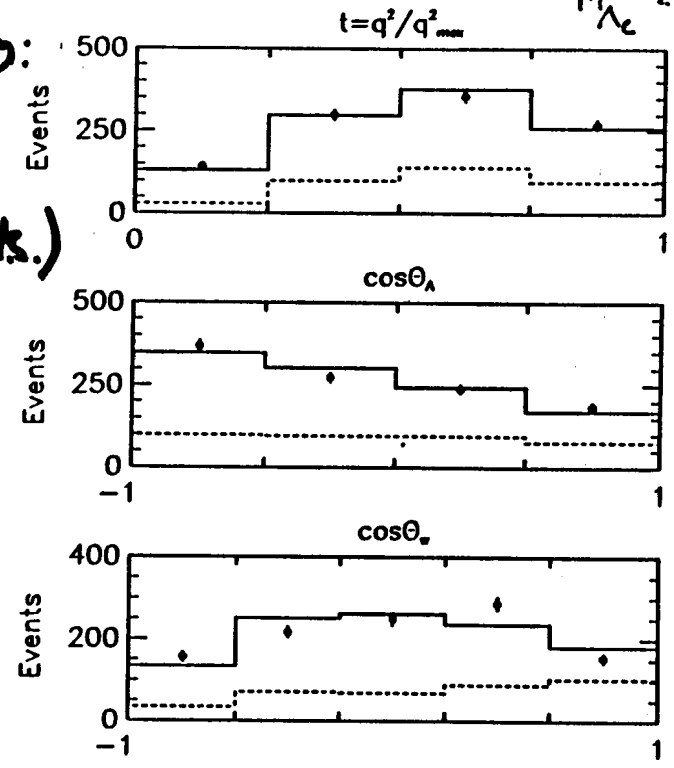


FIG. 2. Projections of the data (points with error bars) and the fit (solid histogram) for t, $\cos\Theta_A$ and $\cos\Theta_W$. The dashed lines show the background distributions.

Find: $R = -0.33 \pm 0.16 \pm 0.15$

Consistent w/ Körner + Krämer form for f.f. evolution as $f(q^2)$

(1989 ...)

Absolute BR's., cont.

Can also use continuum production

- For $D_s \to \phi\pi$, and $\Lambda_c \to pK\pi$, can also use constraint that c-quark emerges predominantly as D^+, D^0, D_s, Λ_c.
  - If three well known, then get 4th from $\sigma_{c\bar{c}}$.
  - Can get $\sigma_{c\bar{c}}$ from $\ell\bar{\ell}$ correlations on continuum.

the number of single tags N_X can be written as:

$$N_X = 2\sigma_{c\bar{c}} f_D \epsilon_X \mathcal{B}_X,$$

and the number of double tags $N_{X\bar{X}}$ as:

$$N_{X\bar{X}} = \sigma_{c\bar{c}} f_D^2 \epsilon_X^2 \mathcal{B}_X^2,$$

Now consider double-tags of $\Lambda_c|\bar{\Lambda}_c$, $D^0|\bar{\Lambda}_c$, and $D^0|\bar{D}^0$.

$\Rightarrow$ 5 eqns. in unknowns:

$\sigma_{c\bar{c}}$, f_D, f_{Λ_c}, $\mathcal{B}_D$, $\mathcal{B}_{\Lambda_c}$

Spectroscopy

- Heavy-heavy systems (ψ, Υ)
  - How do we construct mass level diagrams?
    - ⊙ "Why, it's child's play, Jim" (Bones)
  - mass levels and transitions

- Heavy-light systems (D, Λ_c) and connection to HQET
  - mass levels and transitions

Perturbative approach to mass levels:

(Godfrey and Isgur, e.g., PRD 32, p. 189-231 (1985))

- Requires at least one heavy-quark Q for a n.r. treatment H=p^2 + V(non-rel.) (H_0)

+V(spin-ind. relativistic corrections)

+V(spin-spin) $(\nabla^2 V_V \mathbf{S_1} \cdot \mathbf{S_2})/3m^2 r)$

-splits $^1P_1$ from $^3P_{J=0,1,2}$, Υ from η_b

+V(spin-orbit) $(3V_V' - V_S')/(3m^2 r)$

+V(tensor) $(V_V'/r - V_V'')(3(\mathbf{S_1} \cdot \mathbf{r})(\mathbf{S_2} \cdot \mathbf{r}) - \mathbf{S_1} \cdot \mathbf{S_2}))/2\mathbf{m}^2\mathbf{r})$

-splits states with $L > 0$ by J (χ_b :$^3 P_{J=0,1,2}$)

- where these corrections have been written as:

1. A piece which transforms as a vector (V_V) and
2. A piece which transforms as a scalar (V_S)

Theorists give different estimates for V_V, V_S; typical corrections approx. 10 MeV. for $b\bar{b}$.

Heavy-Heavy systems - masses

- Take a simple prescription for V:
  - $V_0(r) = \alpha r$ (confinement) $+ \beta/r$ (single-gluon exchange at high q^2)
  - Use exptl. data to determine α, β and pin
- GSE.

- J/ψ and Υ Quarkonia ($R^{2S+1}L_J$) well-described by such a simple model

Lattice calculations coming online like P.E. slam

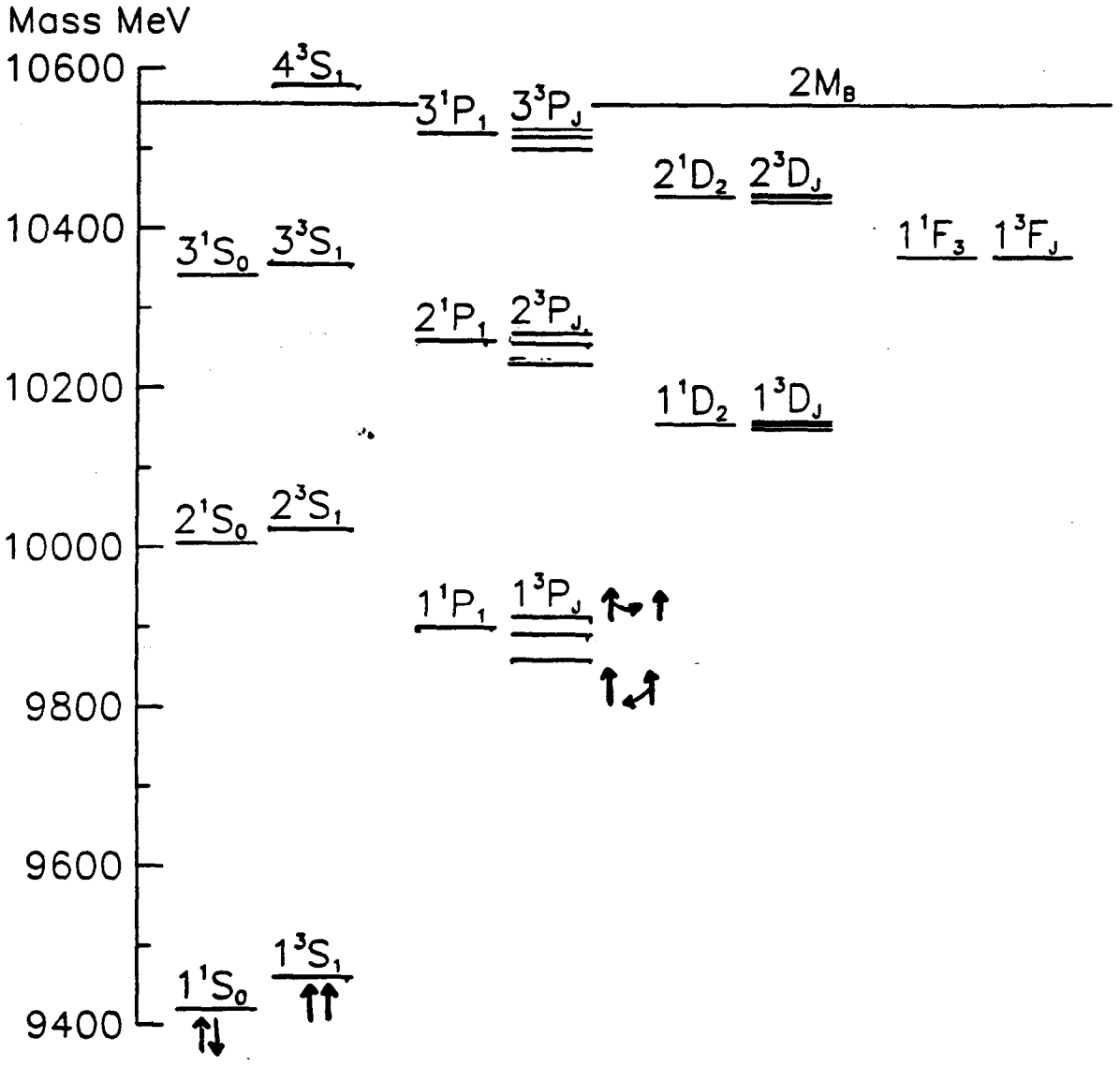
- CLEOII ($b\bar{b}$, e^+e^-) and E760 ($c\bar{c}$, internal target) study heavy quarkonia
  - M_{η_c} from E760 different from PDG by ~ 10 MeV
  - CLEO result for M_{η_c} ($K^0K^-\pi^+$): $\Gamma^{\gamma\gamma}_{\eta_c}$: 5.73±1.34±1.20±1.6 k
  - L3 contributing with $\gamma\gamma \to \bar{c}c$ modes: M_{η_c}: (3003±15) MeV
    $\Gamma^{\gamma\gamma}_{\eta_c}$ = 8.0±2.3±2.4 k

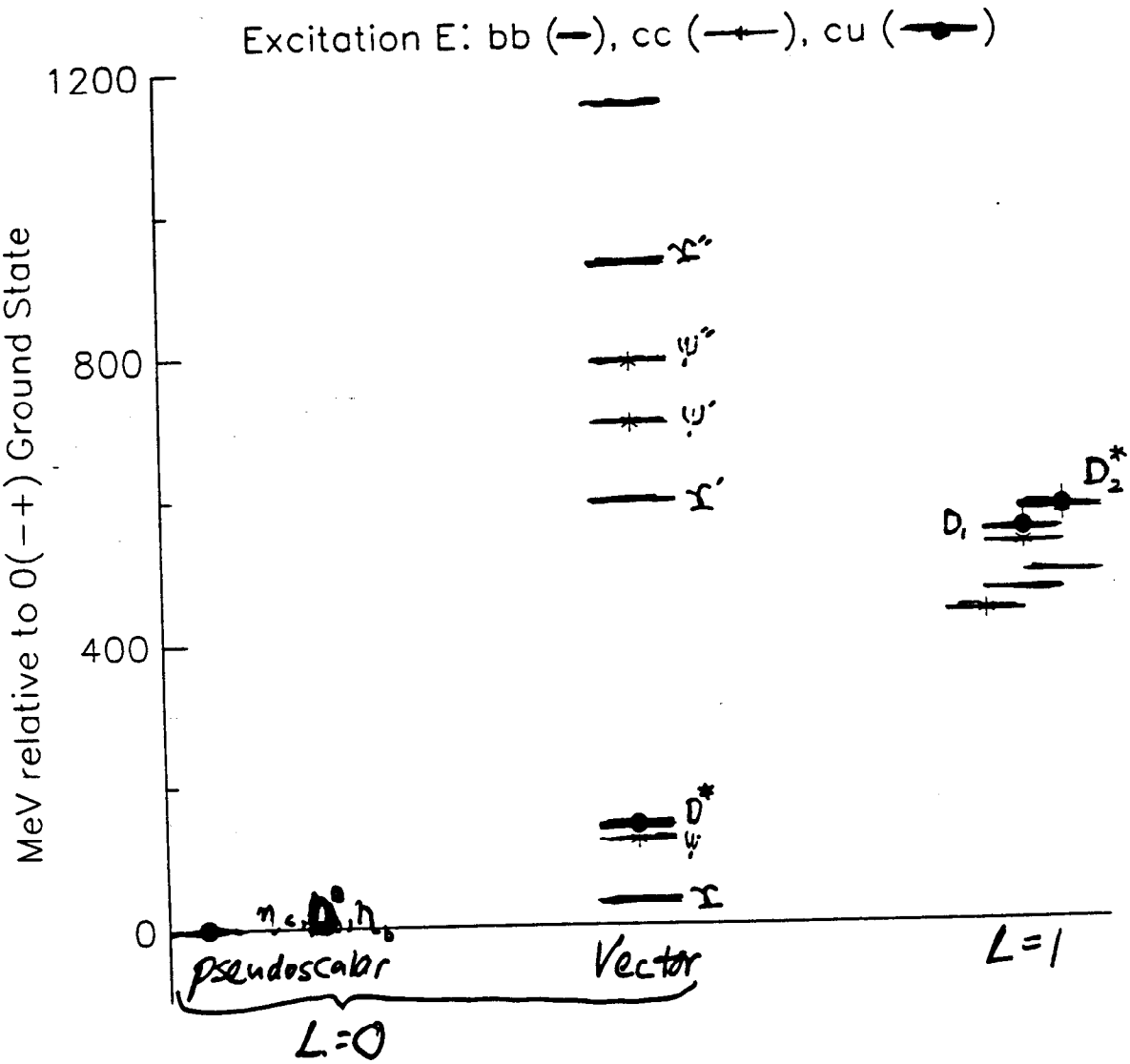
→ Can extract expected with using $\Gamma(\psi)$: ~ 8 keV

- Anomaly 1) $\Upsilon(4S)$ mass low relative to predictions (~ 40 MeV)

- Anomaly 2) Relative splitting of χ_b'/χ_b triplet also at variance with prediction. r(2P) < r(1P)

$b\bar{b}$ spectroscopy
– observed





$\Rightarrow$ (L=1, L=0) splittings comparable for $c\bar{c}/c\bar{u}$

Heavy-Light Spectroscopy in HQET

"Goo, goo, I want goo" (K. Gordon/T. Moore)

- HQET: Color sources and Brown goo.
  - static $Q_{heavy} + q_{light}$

- Just as electron determines atomic spectroscopy, light quark in HQET determines properties of heavy-light systems.
  - "Light degrees of freedom decouple".

- 'Usual' picture of spectroscopy:
  - For hadrons s.t. $L \neq 0$ (D^{**}, e.g.), define the quantum number J=L+S as the total angular momentum of:

    (spin of the heavy quark) +
    (spin of the light quark) +
    $L_{relative}$
  - For D^{**}, e.g., (L=1) get a triplet with L+S=J=2, $J_z = 2, 1, 0$ and a singlet with L+S=J=0. Total of four states.

Recast this picture alternately:

- Rewrite the four possible states, and incorporate L into definition of light quark spin: So, for the light quark: $j_{light} = L \pm s$=1/2 or 3/2.

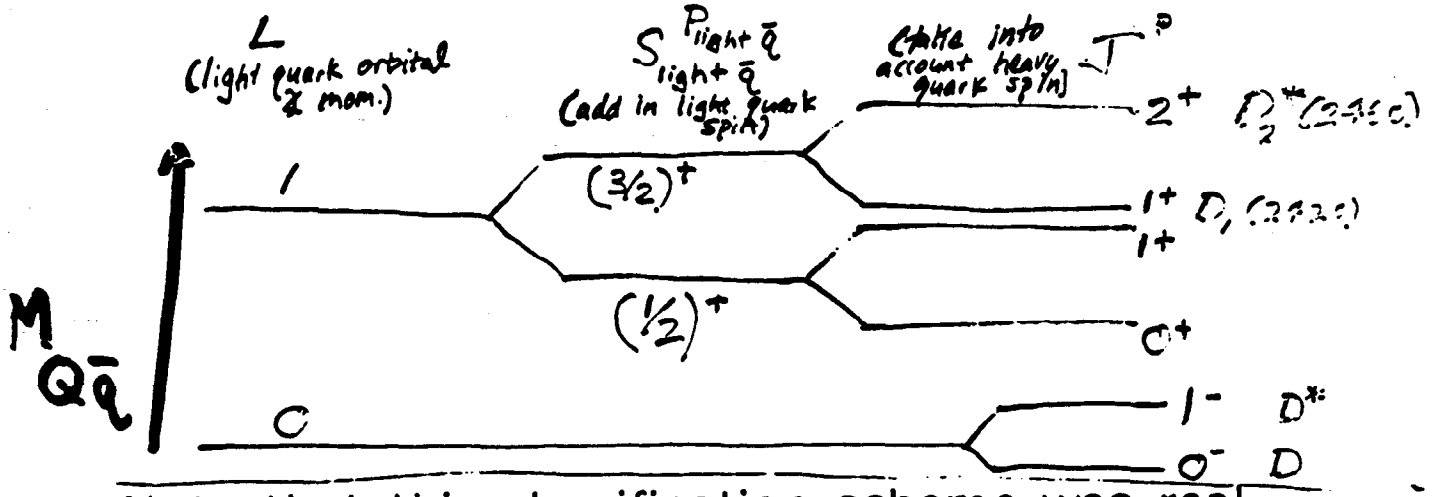
- So, now two doublets corresponding to ±1/2 spin projection of heavy quark: (j_{light}, s_{heavy}); mass ordered, get:

J(P)	j_{light}	s_{heavy}	Decays
0+	1/2	1/2	$D\pi$ (S-Wave) $D^*\pi$ (S-Wave
1+	1/2	1/2	$D^*\pi$ (S-Wave or D-Wave)
1+ (→1-0-)	3/2	1/2	$D^*\pi$ (S-Wave or D-Wave)
2+ (→0-0-/1-1-)	3/2	1/2	$D\pi$, $D^*\pi$ (D-Wave)

- D- and S- wave amplitudes of 1+ can MIX

- Two 1+ states can MIX!

- Small splitting between L=1, (1/2)+ in strange sector (~20 MeV) ⇒(1/2)+ doublet degenerate in charm sector



- Note that this classification scheme was realized 10 yrs ago (G. Garvey, *Comm. Nucl. Part. Phys. 3, 109 (1986)*)

- HQET: In limit $m_Q \to \infty$, S_Q and spin of light d.o.f. are separately conserved by S.I. (Isgur& Wise, PRL 66, 1130 (1991))

(J=1)3/2 states therefore decay D-wave! *(Both)*

- Exceptions: D_{sJ} close to threshold decays S-wave since D-wave is $p^{2\ell+1}$ suppressed.

Guidance from the strange sector

J(P)	j_{light}	s_{heavy}	
0+ ($K_0(1430)/\Gamma = 287 \pm 23$MeV)	1/2	1/2	$K\pi$ (S-Wave)
1+ ($K_1(1400)/\Gamma = 174 \pm 13$MeV)	1/2	1/2	$K^*\pi$ (S-Wav
1+ ($K_1(1270)/\Gamma = 90 \pm 20$MeV)	3/2	1/2	$K\rho$ (D-Wave
2+ ($K_2^*(1430)/\Gamma = 105 \pm 5$MeV)	3/2	1/2	$K\pi$ (50±1.2%)

Note that K_1 states are actually mixed versions of $^3P_1(1260)$ and $^1P_1(1235)$ with a mixing angle that can be derived from τ decay.

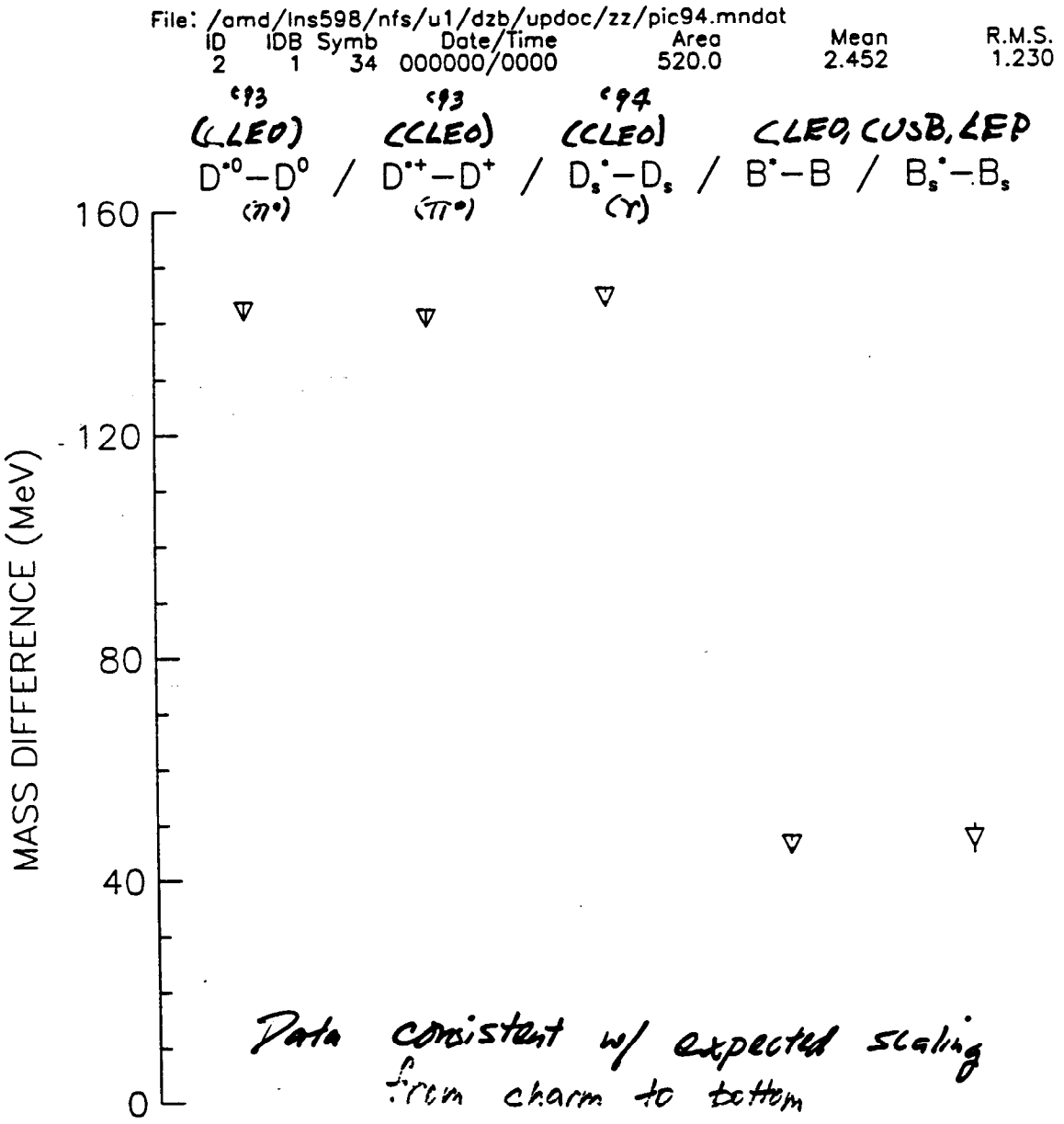
Splittings in Heavy-Light systems

Hyperfine splitting ($D^* - D$, e.g.): $\uparrow\uparrow - \uparrow\downarrow$

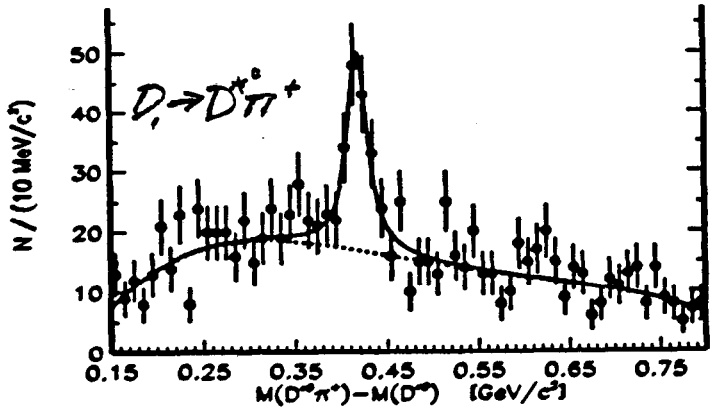
- (1−)/(0-+) splitting (V/P) is hyperfine:
  - $\Delta E_{ij}^{dipole,dipole} \sim \frac{q_i q_j}{m_i m_j} |\Psi(0)|^2 \sigma_{\mathbf{i}} \cdot \sigma_{\mathbf{J}}$ ($\uparrow\uparrow$ / $\uparrow\downarrow$)
  - Both electromagnetic as well as chromomagnetic terms $\Rightarrow \Delta_m \sim 1/m_Q$
  - (With enough theoretical/experimental precision can measure $\Psi(0)$, and therefore decay constants based on hfine splittings)

- So, expect: $\frac{m_{B^*} - m_B}{m_{D^*} - m_D} \sim \frac{m_c}{m_b}$ using simple $\frac{e\hbar}{2mc}$ model

HYPERFINE SPLITTINGS



Data consistent w/ expected scaling from charm to bottom



D^{**+} obsrution
CLEO-II

FIG. 2. The $M(D^{*0}\pi^+) - M(D^{*0})$ mass-difference distribution for $|\cos\alpha| \geq 0.8$, as described in the text.

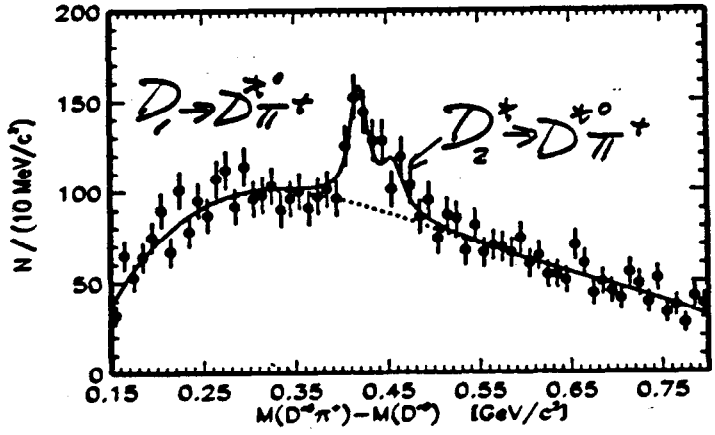
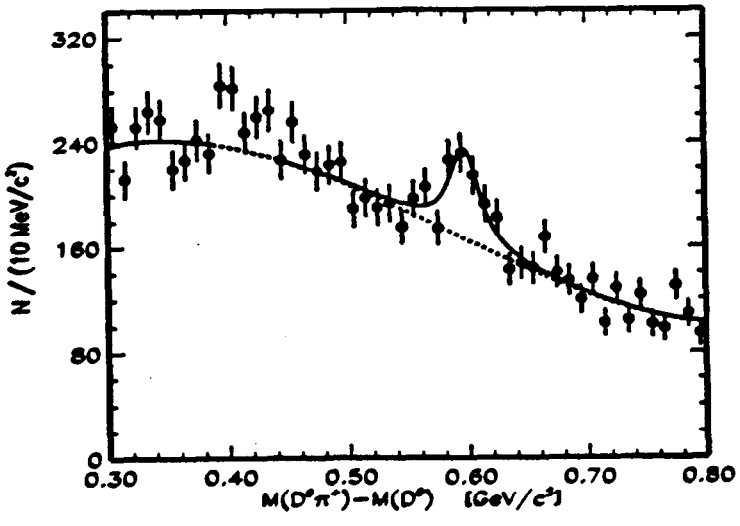


FIG. 3. The $M(D^{*0}\pi^+) - M(D^{*0})$ mass-difference distribution for $-1 \leq \cos\alpha \leq +1$, as described in the text.

FIGURES

10



$D_2^* \to D^0\pi^+$

FIG. 1. The $M(D^0\pi^+) - M(D^0)$ mass-difference distribution for $P_{tot} > 0.1$, as described in the text.

Spectroscopy summary

1. HQET picture of light-heavy systems correctly predicts widths and ratios of BR's (so far)

2. the known $c\bar{q}$ spectroscopy superimposes rather well on the $b\bar{b}$ spectroscopy

3. Simple model of heavy-light, heavy-heavy systems well described by potential models

4. Lattice Gauge calculations just coming on concur with potential calculations

Heavy-Light, L=1, new results
(charmed hadrons)

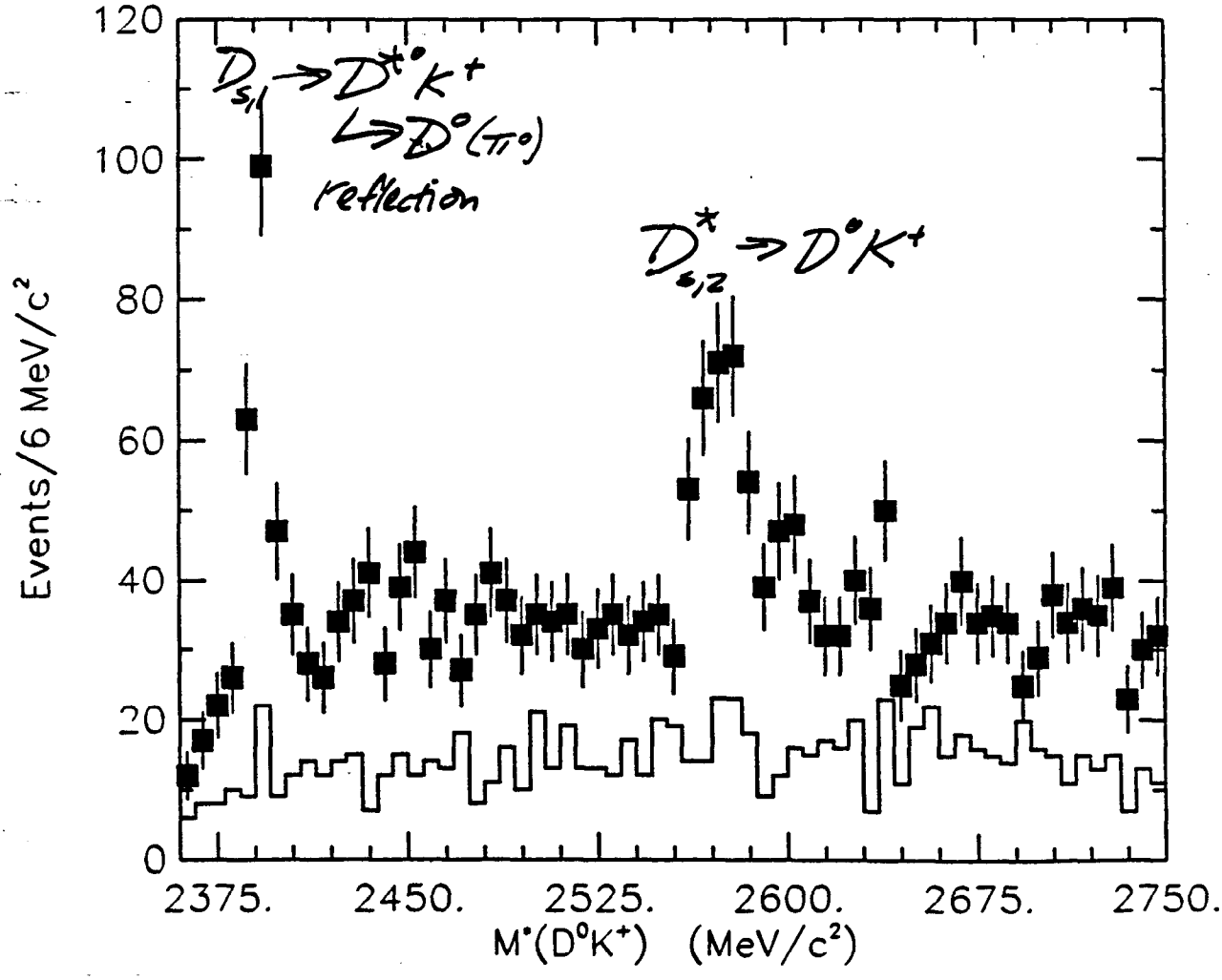
- D_1^0, D_2^{*0} well-studied since ARGUS discovery
- Good statistics observation of D^{**+} (CLEO-II)

- First observation of $D_s^{**}(2+)$ candidate, decaying to DK.

D_{sJ} production

· D_{s1} discovered by ARGUS, $D_{s1} \to D^{*+} K_S^0$

↳ LEO-II observe 2^+ state decaying to $D^0 K^+$

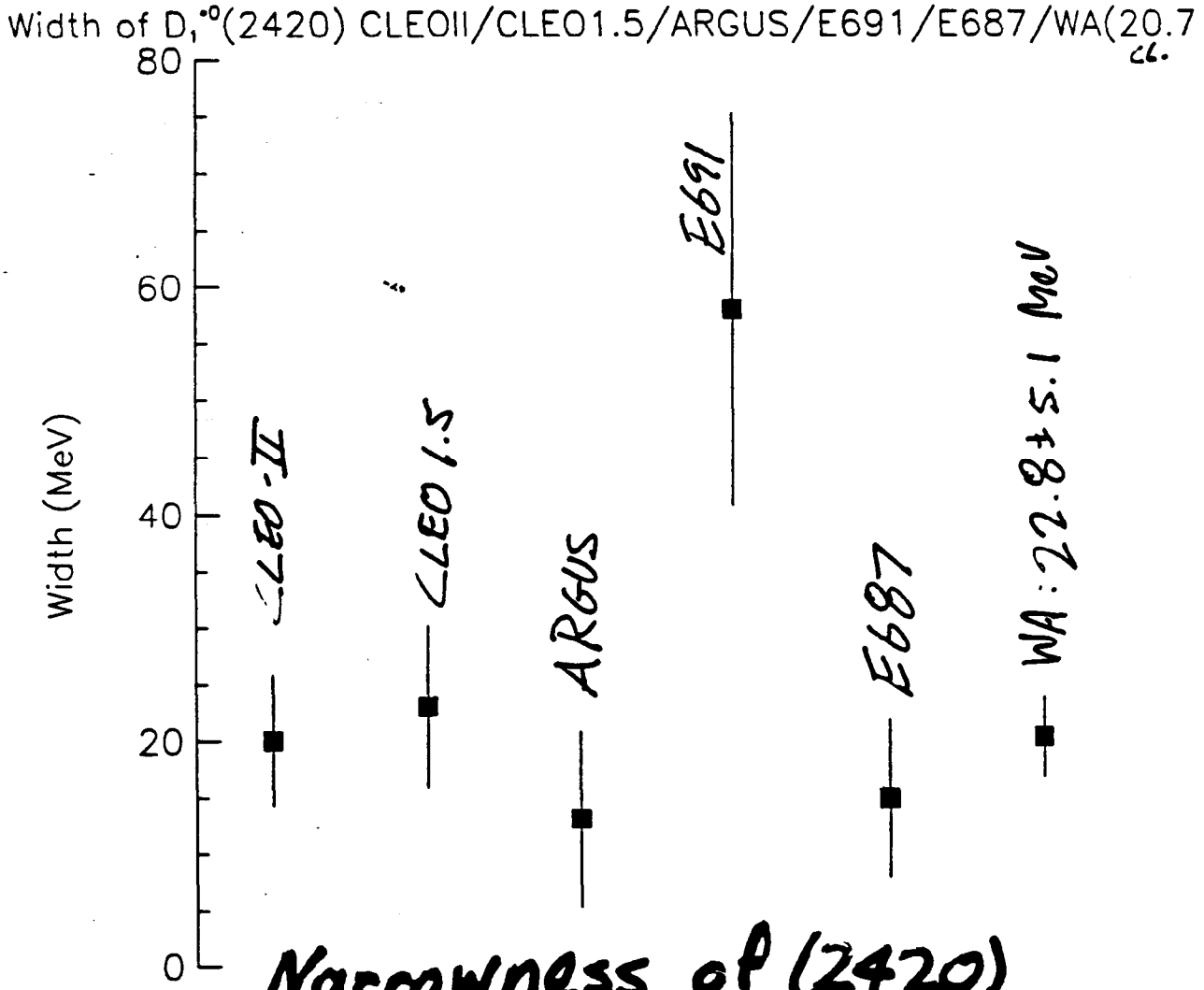


Check HQET prediction of narrow D_1, D_2^*

• $(3/2)$ decay D-wave $\Rightarrow p^{2l+1}$ barrier

File: /amd/lns598/nfs/u1/dzb/updoc/zz/pic94.mndat

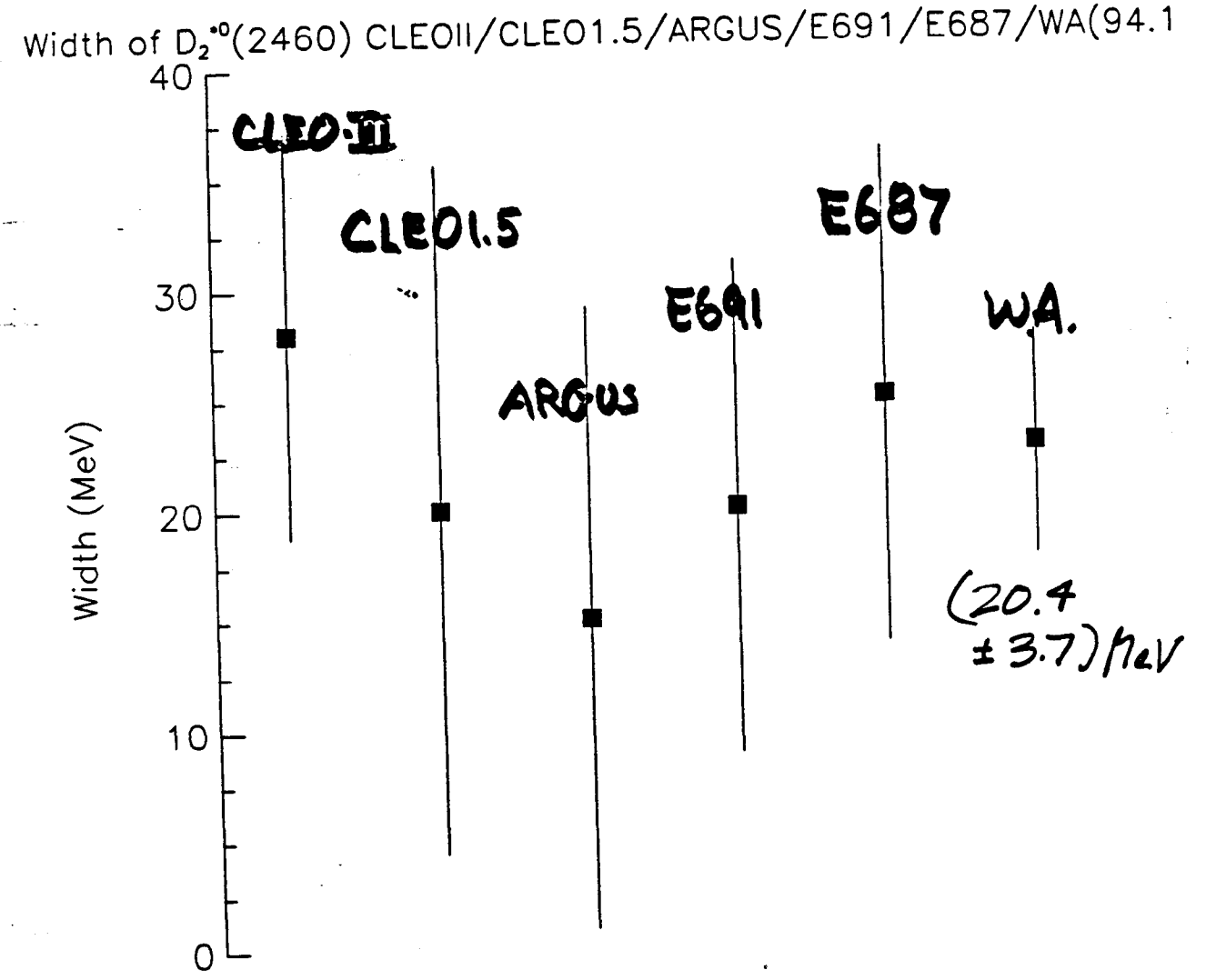
ID	IDB	Symb	Date/Time	Area	Mean	R.M.S.
6	1	−32	000000/0000	149.4	3.577	1.541



Narrowness of (2420) $\Rightarrow$ mixing w/ $(1/2)^+$ small.

File: /amd/lns598/nfs/u1/dzb/updoc/zz/pic94.mndat

ID	IDB	Symb	Date/Time	Area	Mean	R.M.S.
5	1	−32	000000/0000	130.8	3.476	1.808



L=1 baryons, charm

- For Λ_c, $S_{(ud)} = 0 \Rightarrow S_{light} = L$
- Observation of orbitally excited Λ_c states (L=1)
  - the baryonic analog of narrow D^{**} doublet in charmed baryon sector. (ARGUS, CLEO, E687). Expect $(1/2)^-, (3/2)^-$ doublet
  - Cho et al: $\Lambda_c(2593) \rightarrow \Sigma_c\pi^+$ (on-shell Σ_c) D-wave
  - $\Lambda_c(2630) \rightarrow \Sigma_c^*\pi^+$ (off-shell Σ_c^*) $\Rightarrow \Gamma_{\Lambda_c(2630)} < \Gamma_{\Lambda_c(2593)}$
  - Results in good agreement w/ expectation that J=2(j=3/2) - J=1(j=3/2) splitting same for D, D_s, Λ_c.
  - Decays very close to threshold: $\Gamma_{\Lambda_c^{**0}} \sim (0.1)\Gamma_{D^{**}}$
- $\Lambda_c^* \not\rightarrow \Lambda_c\pi \Rightarrow$ Ispin 0.

MINUIT χ^2 Fit to Plot 100&0

scms

File: Generated internally

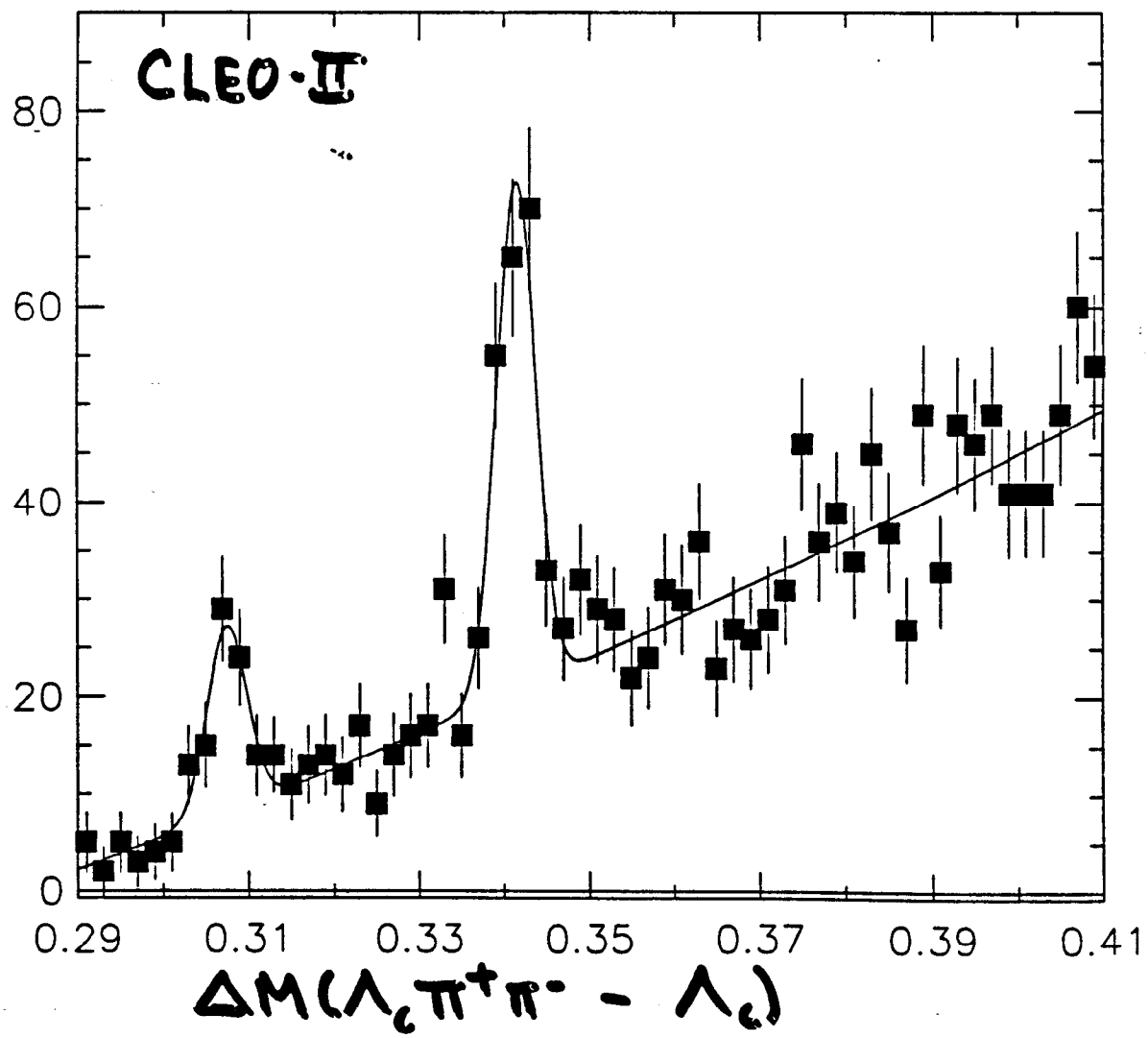
Plot Area Total/Fit 1721.0 / 1721.0 Fit Status 3

Func Area Total/Fit 1678.3 / 1678.3 E.D.M. 3.160E−06

Λ_c^{**} production

χ^2= 45.9 for 60 − 9 d.o.f., C.L.= 67.7%

Errors		Parabolic	Minos	
Function 1: Gaussian Distribution (sigma)				
AREA	149.86	±18.58	−0.0000E+00	+0.0000E+00
MEAN	0.34140	±2.9952E−04	−0.0000E+00	+0.0000E+00
SIGMA	2.28967E−03	±2.6658E−04	−0.0000E+00	+0.0000E+00
Function 2: Gaussian Distribution (sigma)				
AREA	55.622	±13.30	−0.0000E+00	+0.0000E+00
MEAN	0.30751	±5.5362E−04	−0.0000E+00	+0.0000E+00
SIGMA	2.32965E−03	±6.9150E−04	−0.0000E+00	+0.0000E+00
Function 3: Chebyshev Polynomial of Order 2				
NORM	24.874	±0.7948	−0.0000E+00	+0.0000E+00
CHEB01	23.644	±1.263	−0.0000E+00	+0.0000E+00
CHEB02	0.98001	±1.182	−0.0000E+00	+0.0000E+00



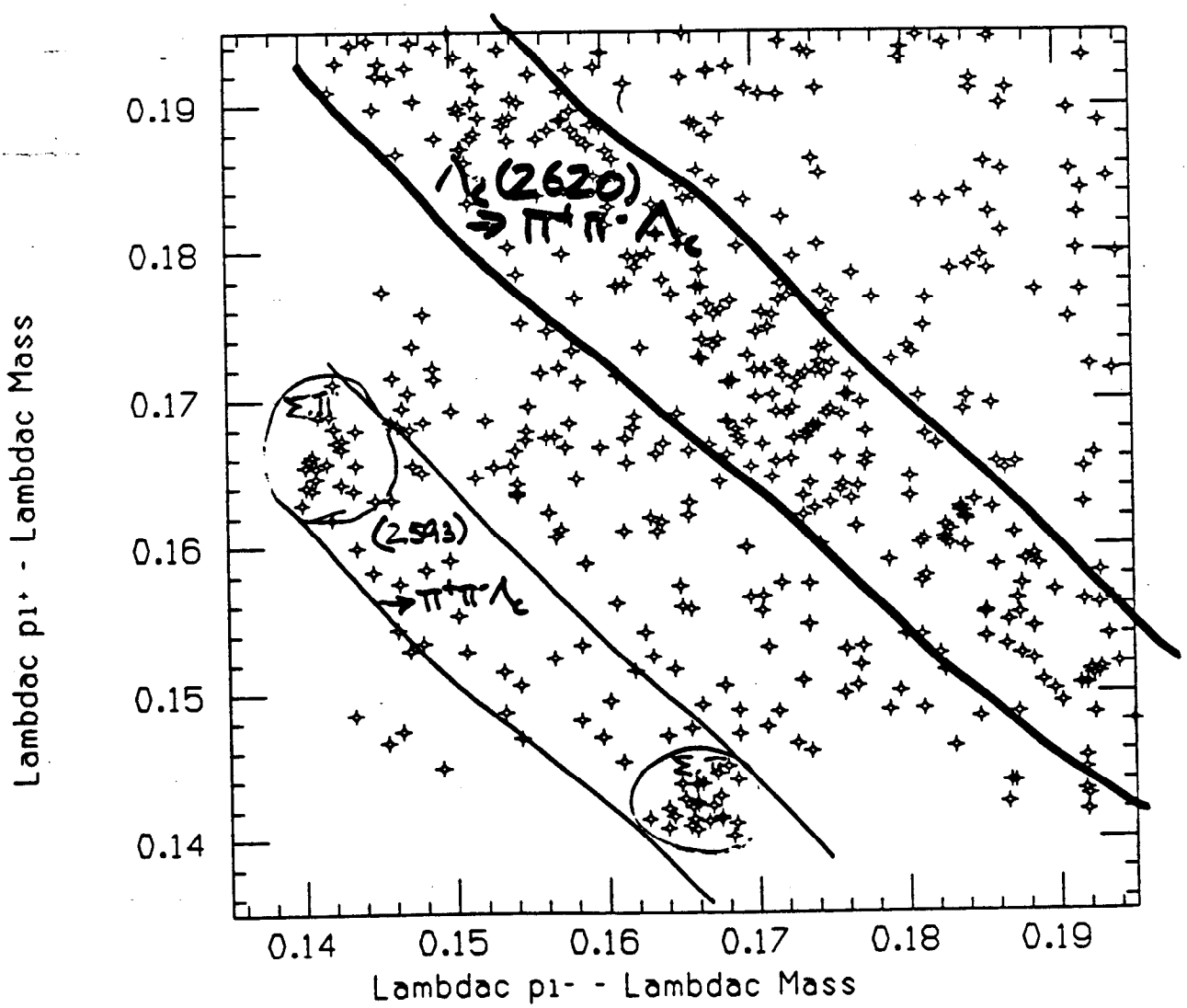
For evts. in previous plot, investigate Σ_c $\hookrightarrow \Lambda_c \pi$

Σ_c content (2630)

- ARGUS: $\Lambda_c^*(2630) \to \Sigma_c \pi \to \Lambda_c \pi\pi$: $(46 \pm 19)\%$
- E687: : $< 36\%$
- CLEO: "small"

Σ_c content (2593)

Figure 2 (CLEO)



- For orbitally excited states, splitting between J=2 and J=1 states scales similarly:
  - $\Delta M(D^{**}(2+) - M(D^{**}(1+)) =$
  - $\Delta M(D_s^{**}(2+)) - M(D_s^{**}(1+)) =$
  - $\Delta M(\Lambda_c^{**}(2630)) - M(\Lambda_c^{**}(2593)) =$
  - $(m_b/m_c)\Delta M(B^{**}(2+) - M(B^{**}(1+)) =$

- Note that magnitude of splitting smaller here since $|\Psi(0)|^2$ smaller (P-wave) than for, e.g. D^*-D splitting.

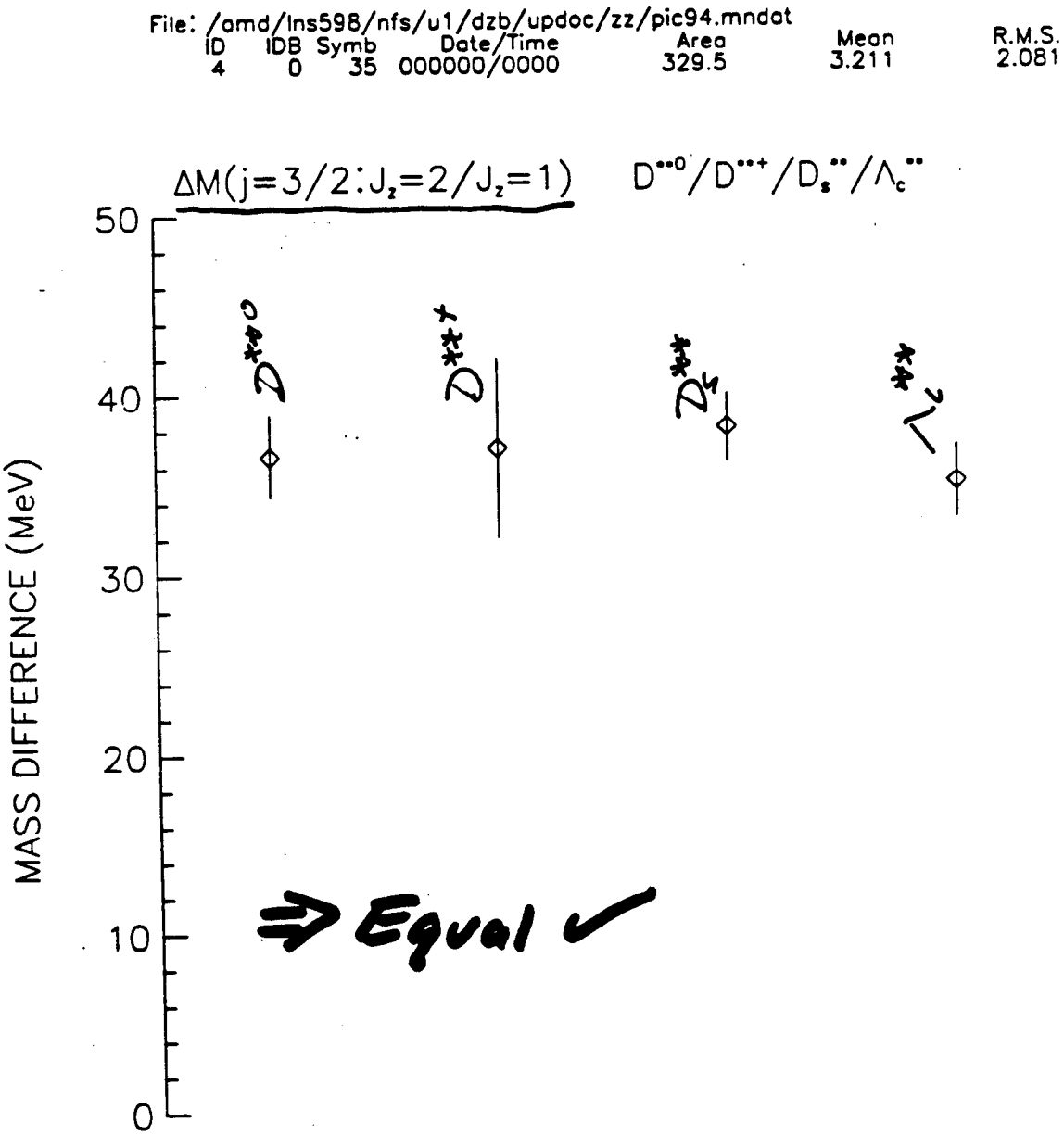
- "Excitation energies" for states with different Q.N. of light d.o.f. should be same for both c and b:
  - $m_{B_s} - m_B \sim m_{D_s} - m_D$
  - $m_{B_1} - m_B \sim m_{D_1} - m_D$

- Note that recent Lattice Gauge calculations (Duncan et al, FNAL) have done mass calculations from "first principles", find:
  - $m_{\bar{Q}s} - m_{\bar{Q}u} = 82 \pm 11 \pm 7$ MeV, for $m_Q \to \infty$

- GOOD agreement with $B_s - B_d$ mass splitting.

More tests of heavy quark symmetry:

- HFine splitting for L=1 states



Heavy-Light Transitions - Angular correlations

In addition to new measurements of masses and widths of $j = 3/2$ D^{**}

- Decay angle distributions for $D^* \to D\pi$ produced in $D^{**0}(1+) \to D^*\pi$ demonstrating non-S wave nature of decay.

For helicity angle α ($\measuredangle(\pi, D^{**})$ in D^* frame)

$$\frac{dN}{d(\cos\alpha)} = \begin{cases} \text{flat if } 1^+ \text{ decay pure S-wave} \\ 1+3\cos^2\alpha \quad \text{pure D-wave} \end{cases}$$

Extracting S/D p.w. and ϕ_{rel}

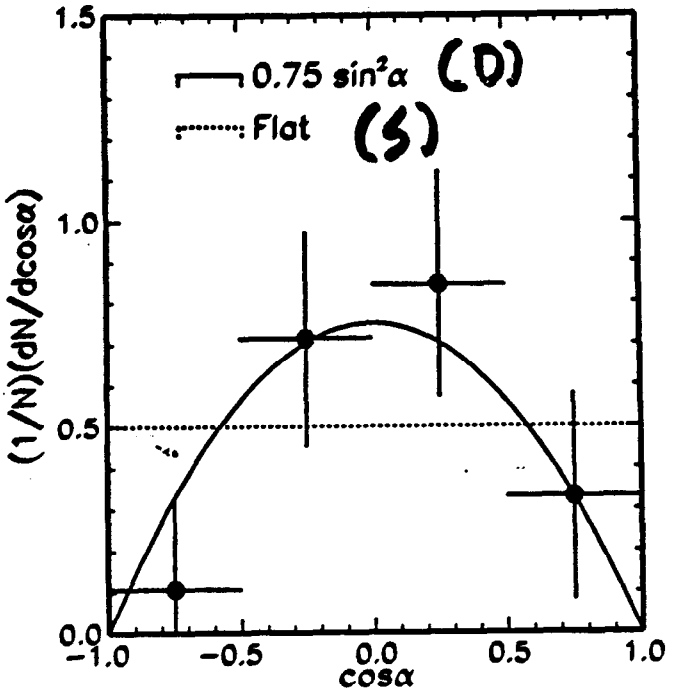
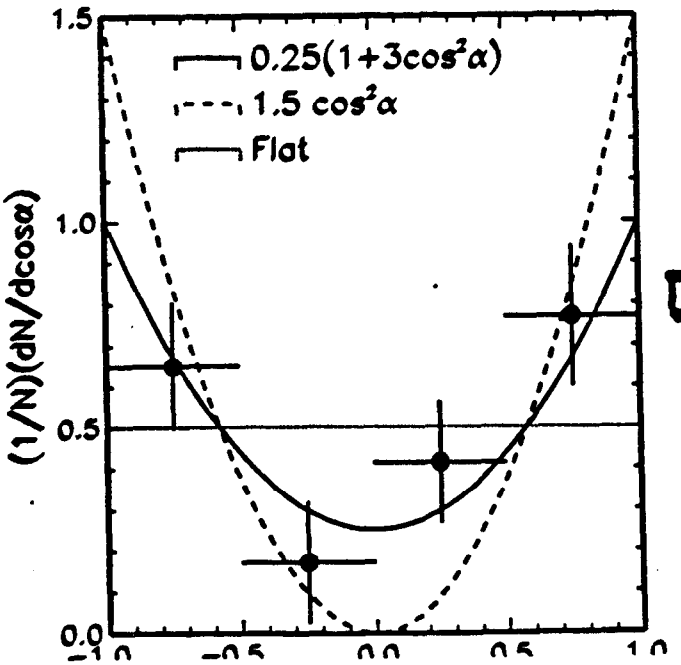


FIG. 4. The normalized helicity angle distribution for the $D_2^*(2470)^+$, as described in the text.



$D_1^+(2420) \to D^*\pi$

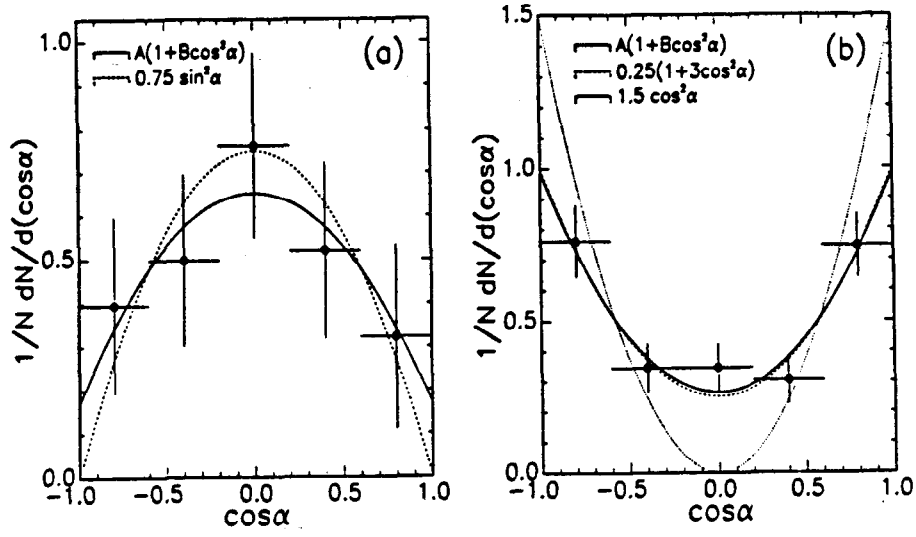


FIG. 4. The normalized helicity angular distributions for (a) $D_2^*(2460)^0$ decay and (b) $D_1(2420)^0$ decay.

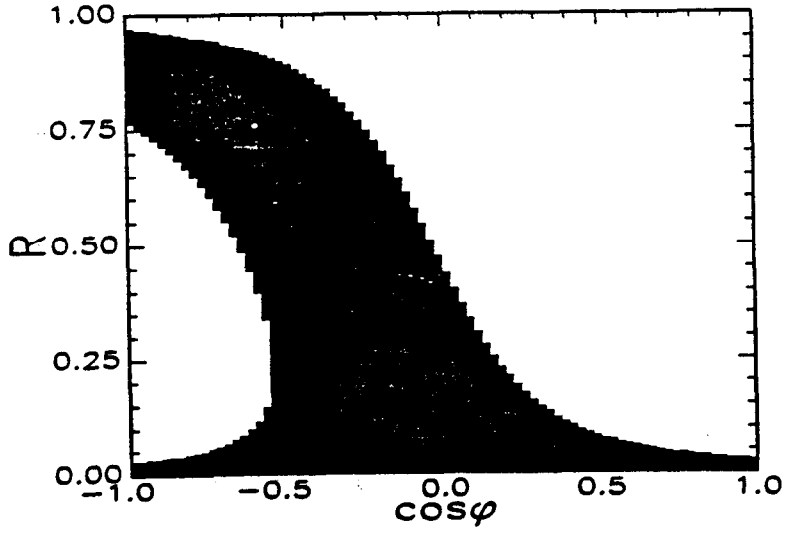


FIG. 5. Plot of $R = \Gamma_S/(\Gamma_S+\Gamma_D)$ versus cosine of the relative phase of S and D wave amplitudes in the $D_1(2420)^0$ decay. The shaded area represents the 90% confidence level allowed region.

$\Rightarrow$ Data consistent w/ $\Gamma_S = 0$

Partial Waves, cont.

Conclude that D_1 decay is, in fact, dominantly D-wave!

Also: can calculate $\frac{D_J \to D^* \pi}{D_J \to D \pi}$ under D-wave condition:

$$\Gamma \sim Clebsch - G \times p^{2\ell+1} \times f.f.$$

(f.f.↑ for D^* since momentum transfer smaller).

Obtain result for ratio agreement with present data.

Eichten, Hill, Quigg: $\frac{\Gamma(D_2^* \to D\pi)}{\Gamma(D_2^* \to D^*\pi)} = 1.8$ $\left\{ \begin{array}{l} \text{PDG92: } 2.4 \pm 0.7 \\ \text{CLEO93: } 2.1 \pm 0.84 \end{array} \right.$

Coming attractions from the Ithaca studios:

- Re-evaluate absolute exclusive and inclusive Λ_c BR's from B-decay data. ($\Lambda_c \to \Lambda + X \downarrow$, $\Lambda_c \to pK\pi \uparrow$)

- Measure widths of $\Lambda_c(2593)$ (Σ_c w/ SVX to get improved angle msrmnt.)

- Use $\Lambda_c(2620) \to \Lambda_c\pi^+\pi^-$ like $D^{*+} \to D^0\pi^+$ to measure *background-limited* BR's.

- Find the elusive Ω_c lurking somewhere in CLEO data?

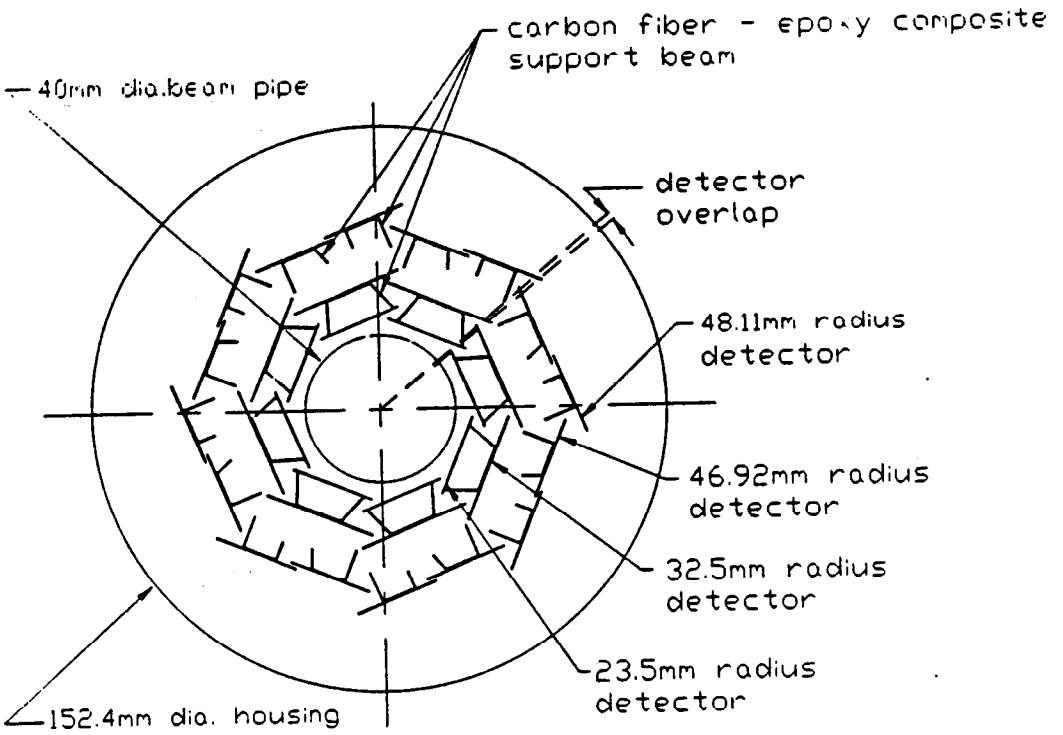
- Measure $\Lambda_c \to$ Cabibbo-suppressed
  $\Lambda_c \to \Lambda\pi$: Exchange + W_{EXT}
  $\Lambda_c \to \Lambda K$: W_{EXT} only
- Search for Σ_c^*, Ξ_c^*, $\Xi_c' \to \Xi_c\gamma$.

- Maybe, just maybe find the J=0 and J=1 $^3D_1$ states in exclusive B-decay if clean enough.

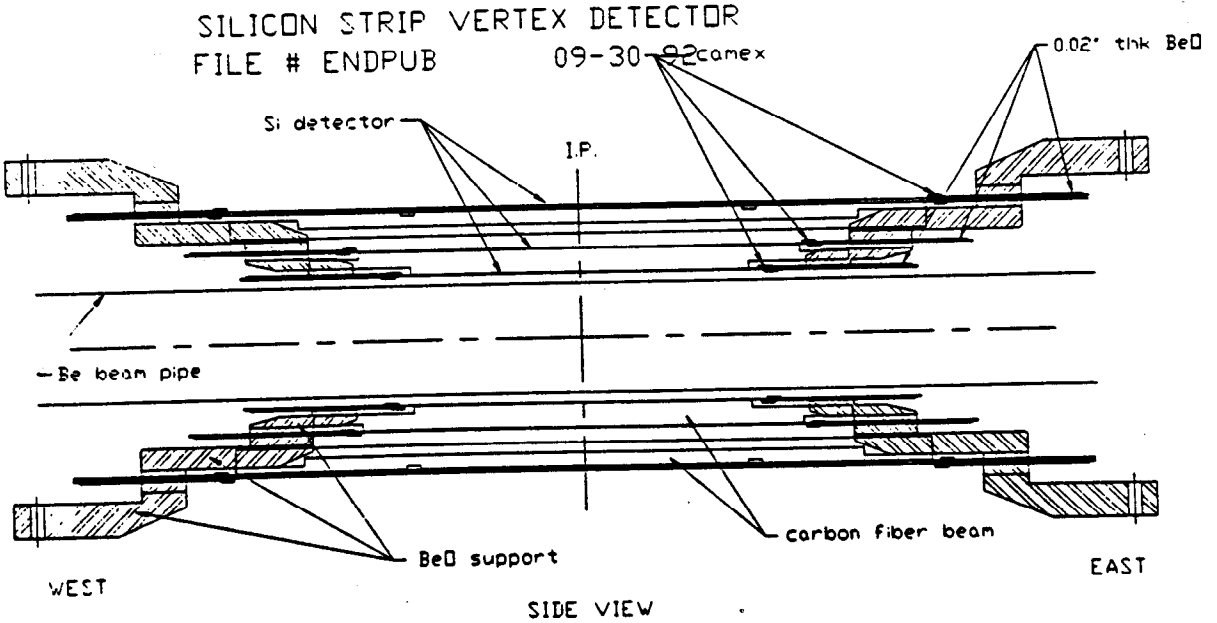
+ • cbary - anticbary correlation studies...

SVX spread sheet

	Layer 1	Layer 2	Layer 3
Radius to inner surface	23.5 mm	32.5 mm	46.9,48.1 mm
Total Length	65.580 mm	81.270 mm	2×65.580 mm
Total Width	22.568 mm	30.128 mm	2×22.568 mm
Active Length	59.535 mm	76.356 mm	2×59.535 mm
Active Width	21.168 mm	28.980 mm	2×21.168 mm
$\cos\theta$ coverage	0.92	0.92	0.92
Thickness	300 μm	300 μm	300 μm
Number of DSSD detectors	16	16	64
Number of CAMEX chips	96	128	192 (*JAMEX*)
Readout Bond Pad Pitch	97 μm	97 μm	97 μm
Number of Active Channels	6048	8064	12096
	Detector Outer Side (r–ϕ, σ=12 μm)		
Implant	p-type		
Implant Width	10 μm	10 μm	10 μm
Implant Pitch	28.00 μm	28.5 μm	28.00 μm
Number of Implants	753	1005	3012
Readout Pitch	112 μm	115 μm	112 μm
Readout Strips	189	252	378
	Detector Inner Side (r–z, σ=30 μm)		
Implant	n-type		
Implant Width	20 μm	20 μm	20 μm
Implant Pitch = Readout Pitch	105 μm	101 μm	105 μm
Approximate Barrier Width	69 μm	65 μm	69 μm
Number of Implants	567	756	1134
Readout Strips	189	252	378



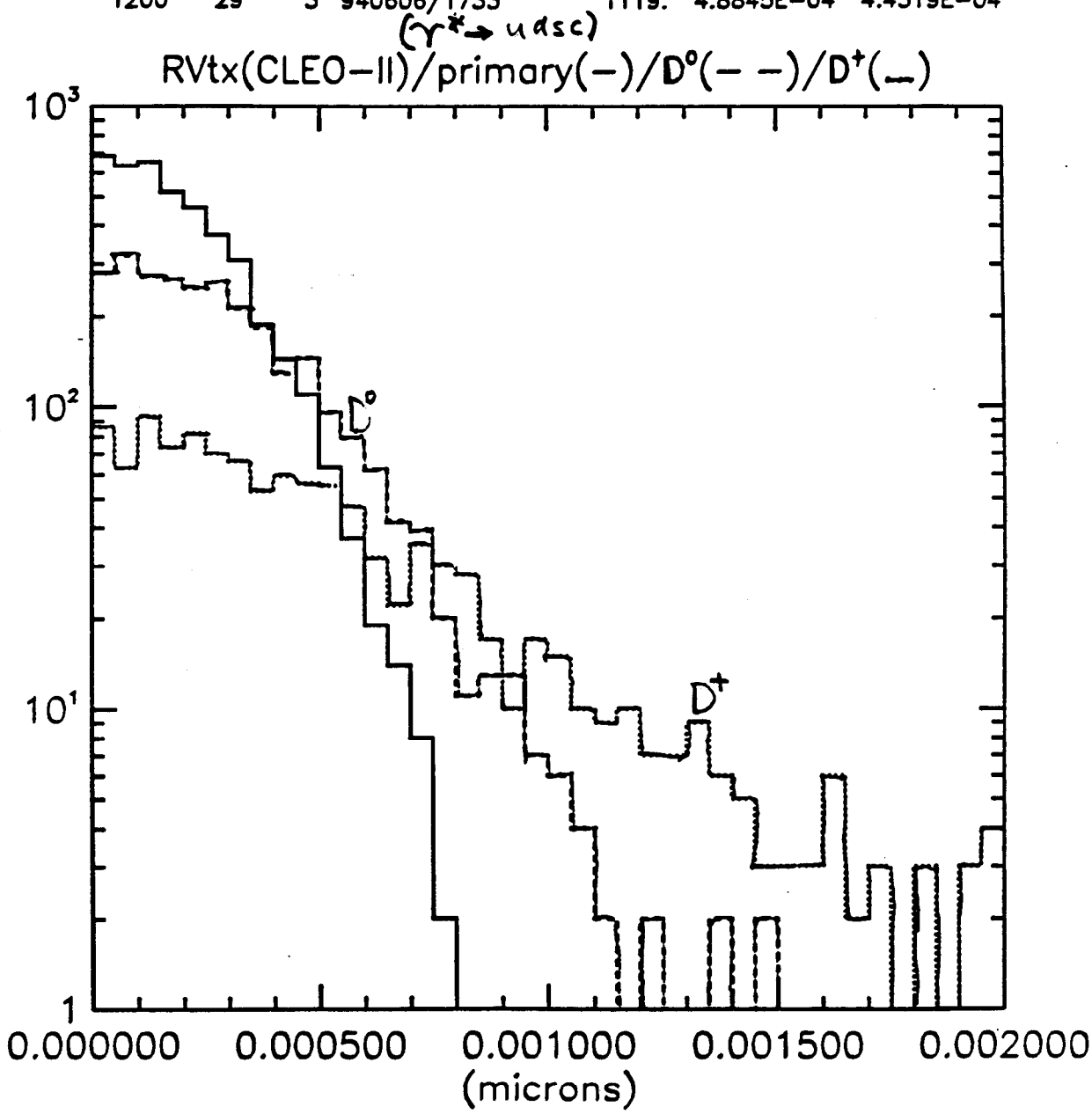
END VIEW FROM EAST
SILICON STRIP VERTEX DETECTOR
FILE # ENDPUB 09-30-92camex



SIDE VIEW
SILICON STRIP VERTEX DETECTOR
FILE # SIDEPUB 11-12-92

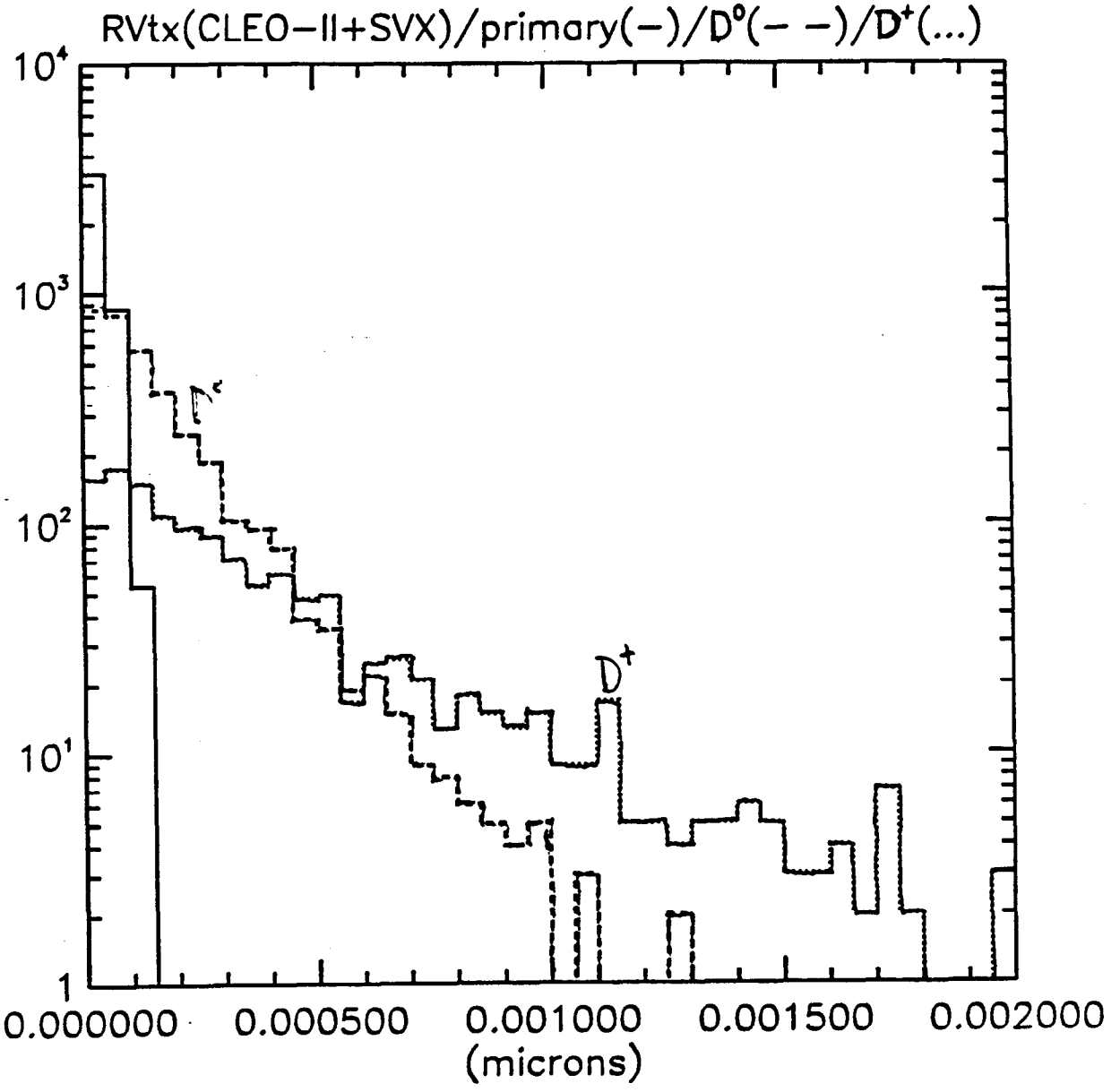
File: vrtxqq_5x5.hist

ID	IDB	Symb	Date/Time	Area	Mean	R.M.S.
1200	1	1	940606/1730	4220.	1.9225E−04	1.4185E−04
1200	27	2	940606/1732	2724.	2.8471E−04	2.1887E−04
1200	29	3	940606/1733	1119.	4.8845E−04	4.4319E−04



File: vrtxqq_5x5.hist

ID	IDB	Symb	Date/Time	Area	Mean	R.M.S.
1100	1	1	940606/1730	4240.	3.6415E−05	2.2453E−05
1100	27	2	940606/1732	3498.	1.5522E−04	1.5804E−04
1100	29	3	940606/1733	1329.	3.7425E−04	4.1082E−04



ξ correlations

CleoXD

Run: 55422 Event: 22909