IC/76/79
INTERNAL REPORT
(Limited distribution)

International Atomic Energy Agency

and

United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

TOPICAL MEETING

ON LEPTON INTERACTIONS AND NEW PARTICLES

6 - 9 July 1976

PART II

(Contributions)

MIRAMARE - TRIESTE

July 1976

NEW PARTICLE SPECTROSCOPY

P.T. Matthews

Blackett Laboratory, Imperial College of Science and Technology,
Prince Consort Road, London SW7, England.

P.T. Matthews

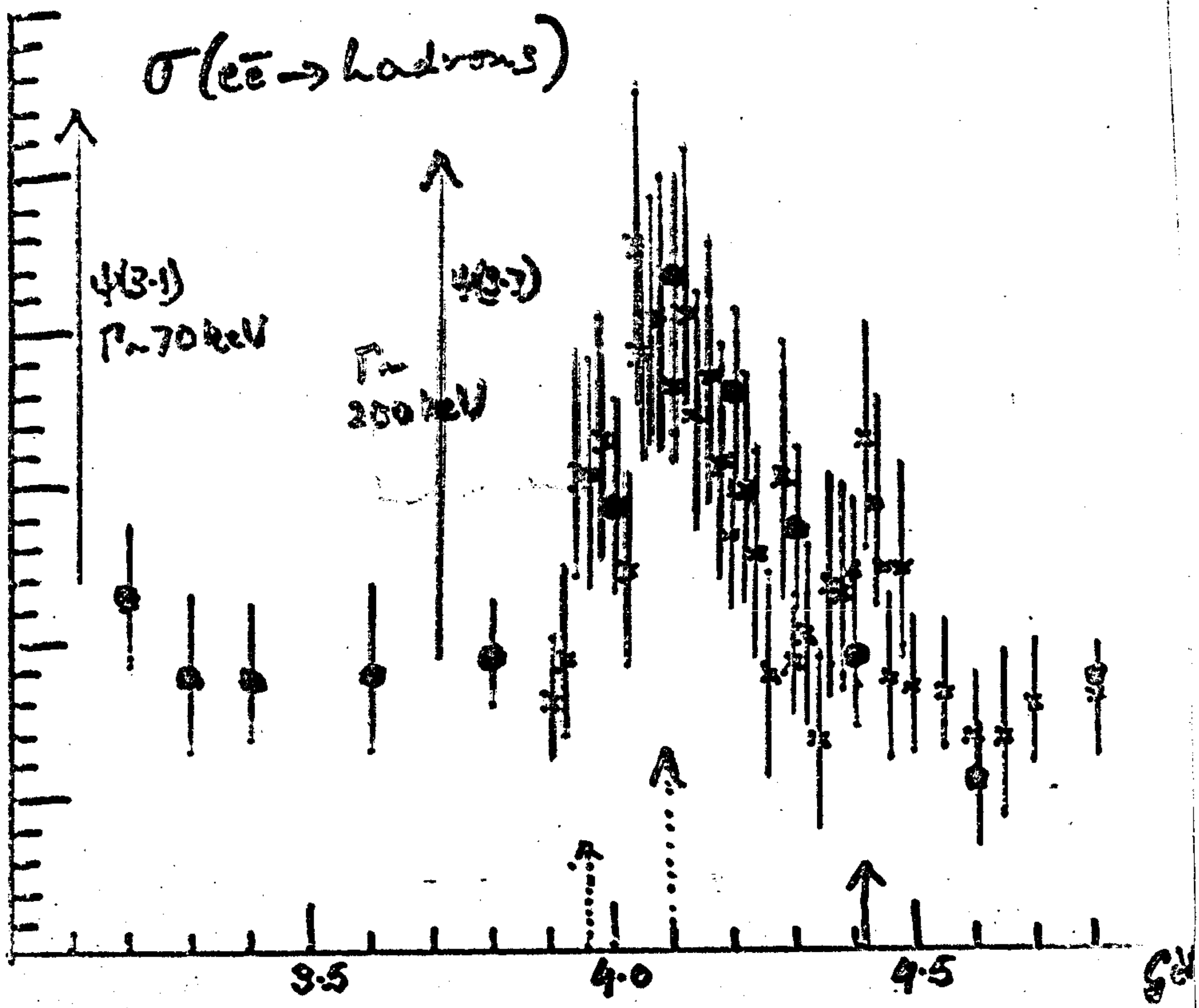
THE NEW SPECTROSCOPY

Trieste "Lepton + New Particle Conf"
July 1976.

Apparent confirmation of Charm may be self fulfilling prophecy.

Experiments strongly charm motivated. When results as expected Charm "confirmed"
When results unexpected:
either
(i) theory modified to fit
e.g. Zweig rule
or (ii) largely ignored e.g
ψ resonances in 3.9 — 4.6

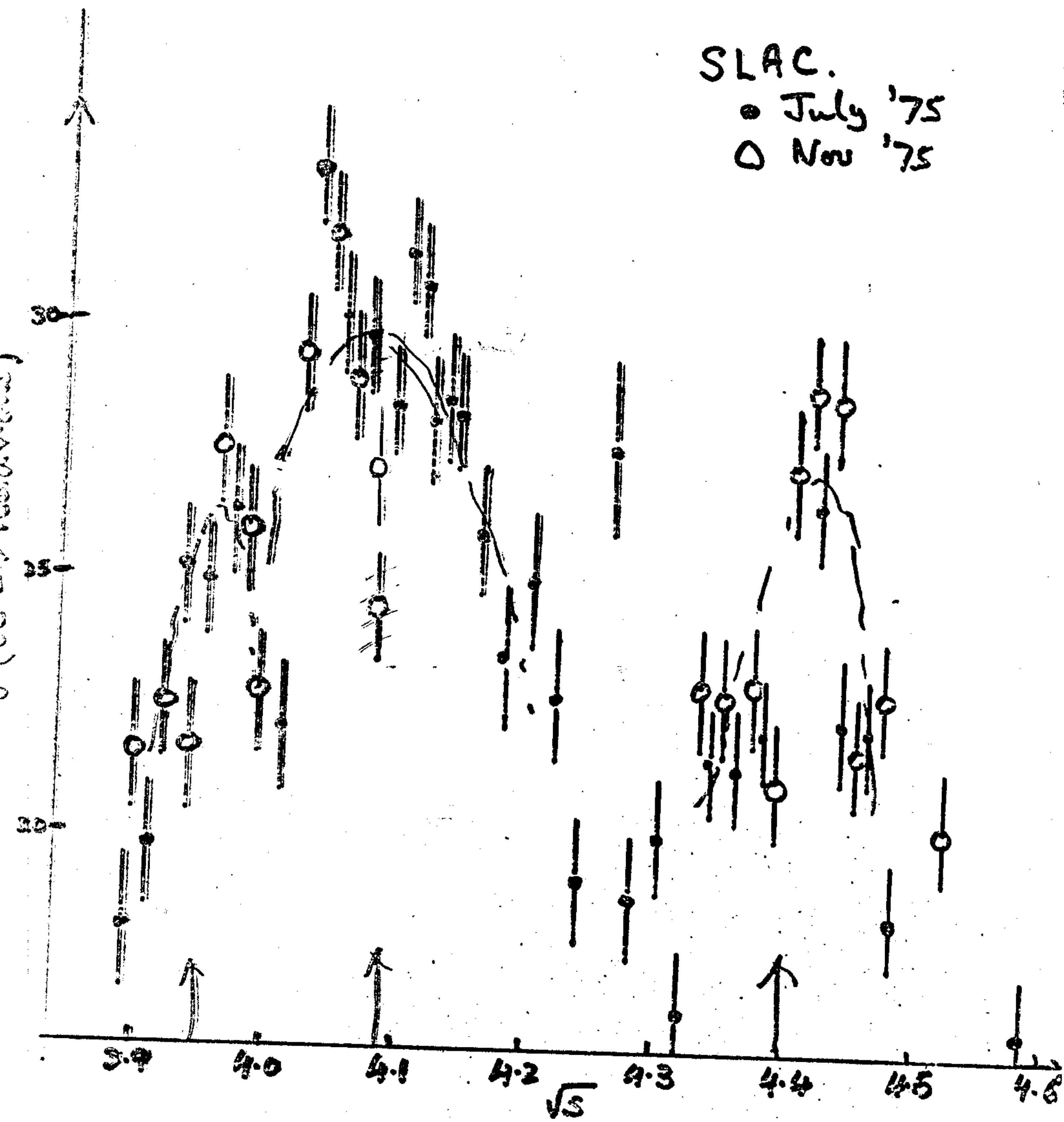
Critical review to consider possible alternatives.

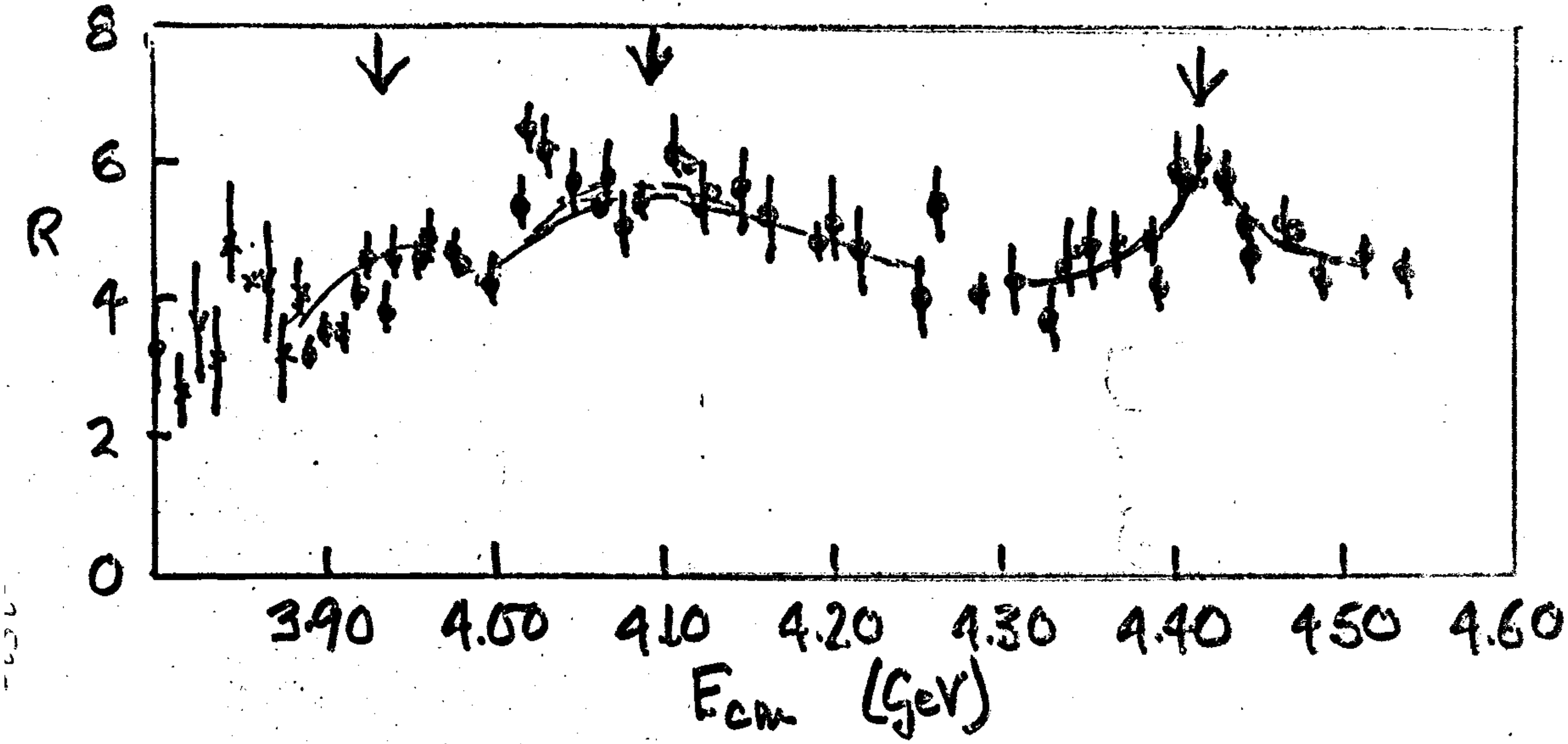


SLAC. Aug 1975.

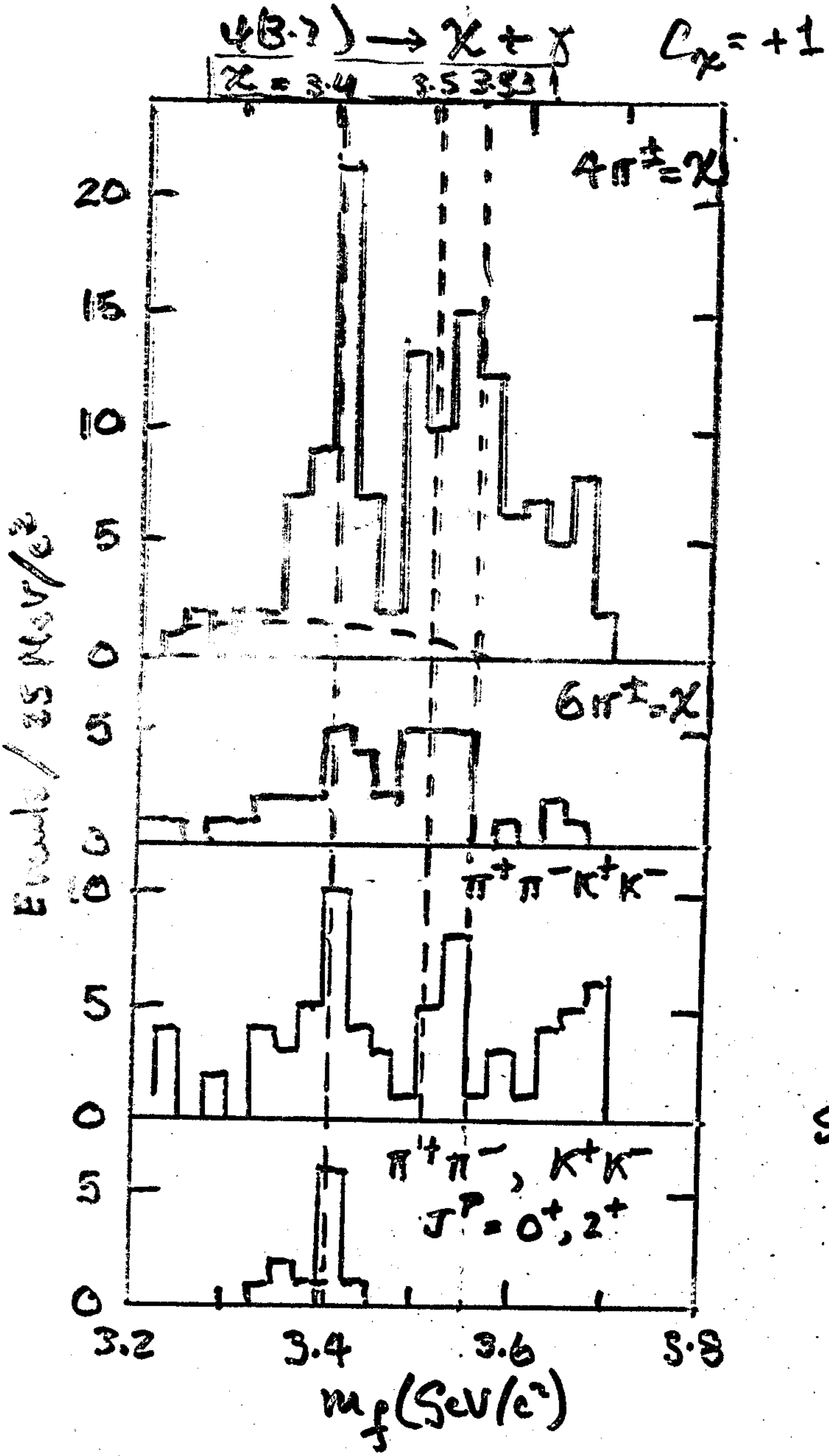
See. Siegrist et. al. P.R.L <u>36</u> 700 (1976)
Feb 1976

ψ(4.4) Γ ~ 33 ± 10 MeV


SLAC.
• July '75
O Nov '75
30
25
20
3.9
4.0
4.1
4.2
4.3
4.4
4.5
4.6
√s

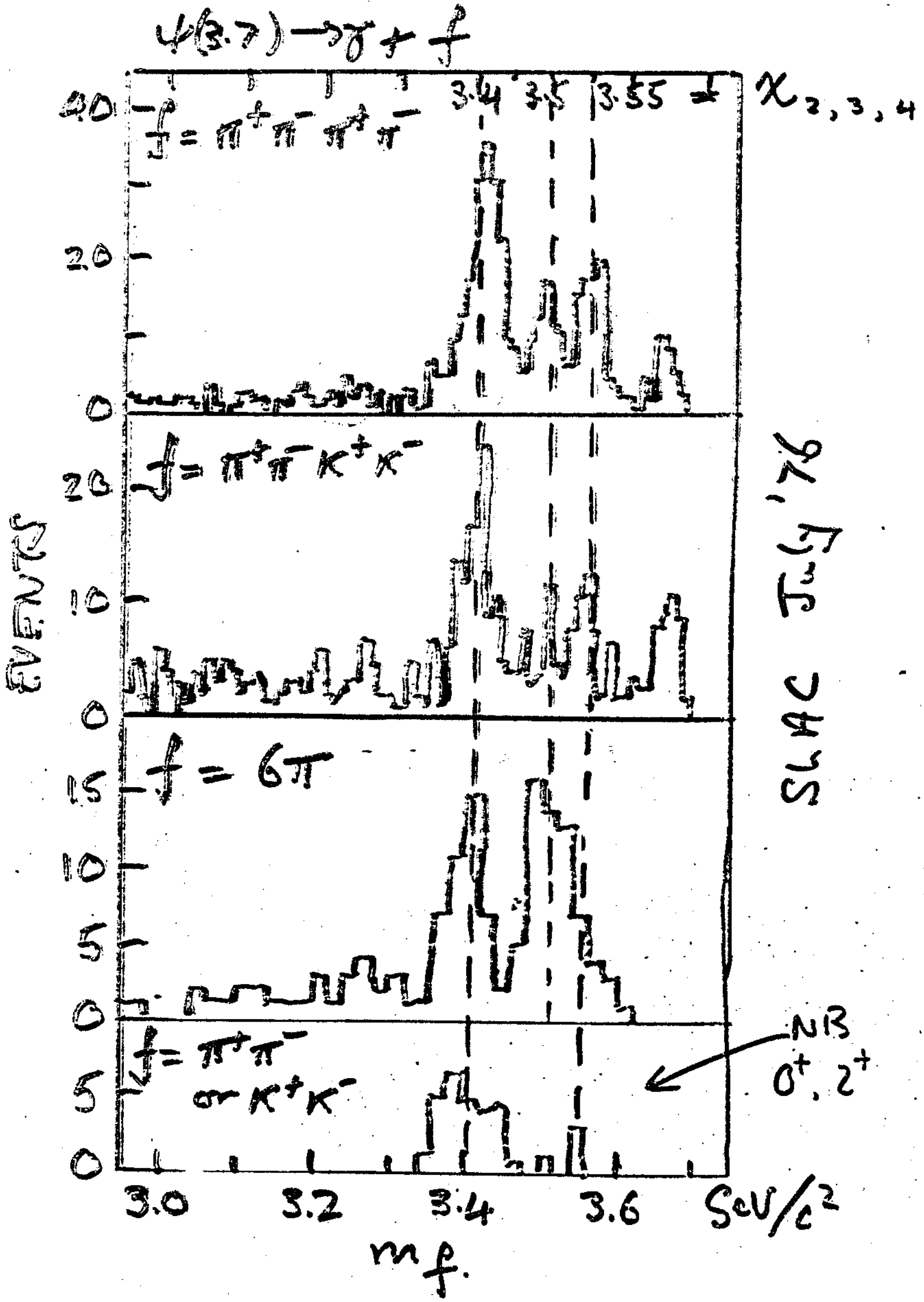


SLAC. July '76

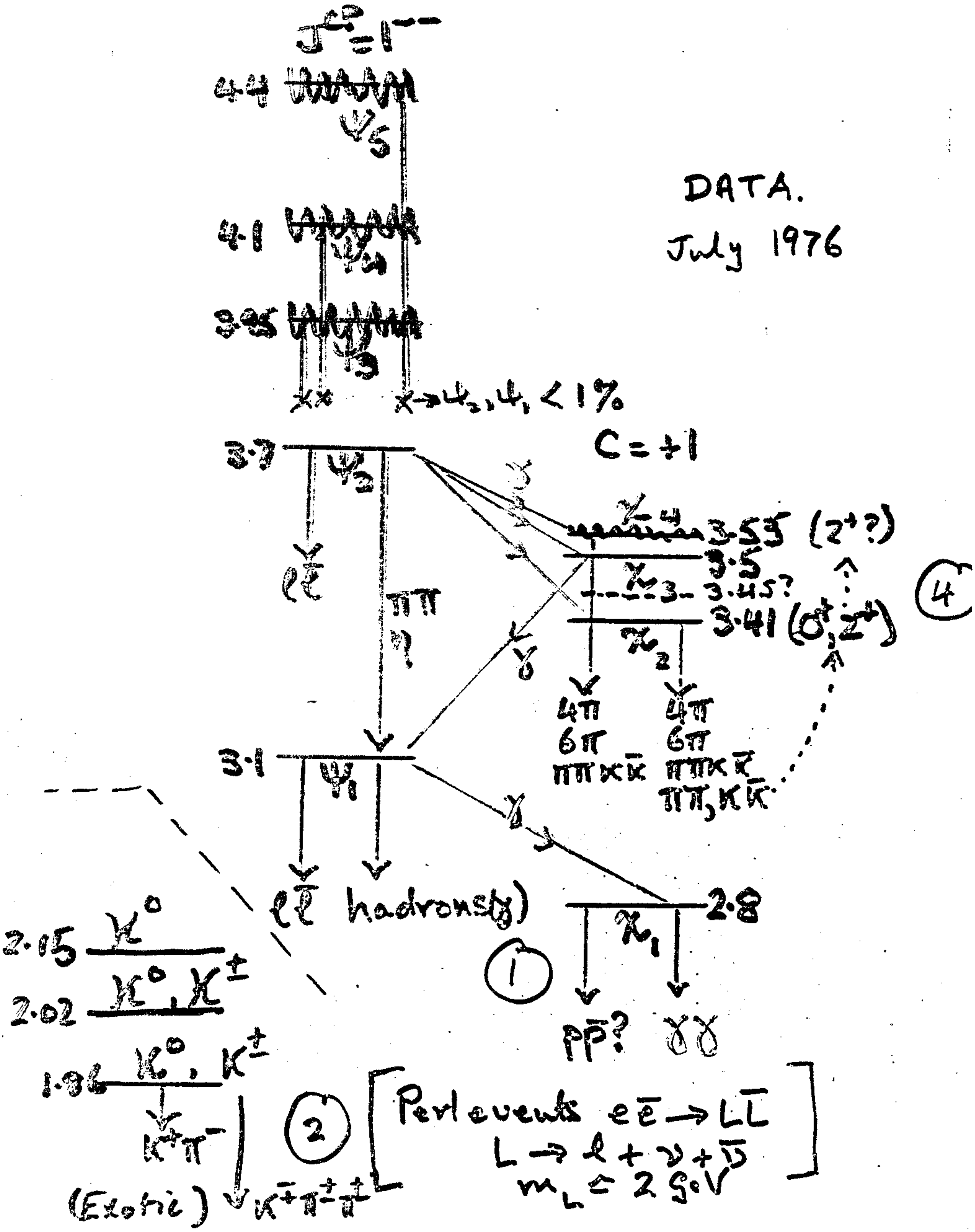


ψ(3.7) → χ + γ
$C_\chi = +1$
χ = 3.4
3.5
3.53
4π± = χ
6π± = χ
π+π−K+K−
π+π−, K+K−
$J^P = 0^+, 2^+$
Events / 25 MeV/c²
20
15
10
5
0
3.2
3.4
3.6
3.8
m_f (GeV/c²)

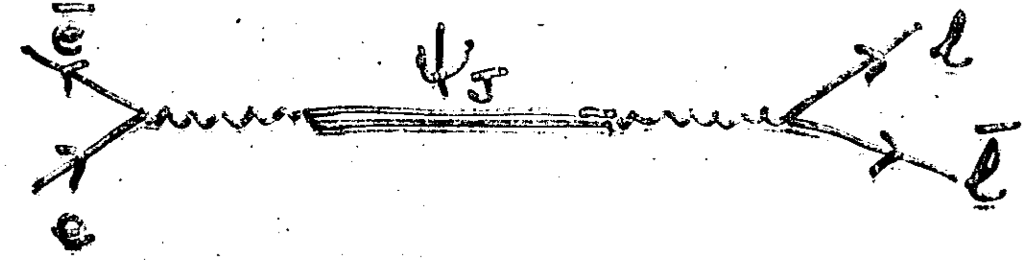
SLAC
Aug. '75


ψ(3.7) → γ + f
3.4
3.5
3.55
χ 2, 3, 4
f = π+π−π+π−
f = π+π−K+K−
f = 6π
f = π+π− or K+K−
NB 0+, 2+
EVENTS
SLAC July '76
3.0
3.2
3.4
3.6
GeV/c²
mf.

DATA.
July 1976



COMMON THEORETICAL GROUND



(i) ψ produced via photon, $\Gamma(\psi \to e\bar{e}) \cong 4.8$ keV
$J^{PC} = 1^{--}$

(ii) ψ, χ, K strongly interacting particles

(a) $\psi_{3,4,5}$ normal hadronic widths.

(b) rich spectroscopy (hadronic c.f $W^{\pm 0}$)

(c) photoproduction

$\sigma^{tot}_{\psi p} \sim$ mb.

(iii) Narrow widths imply new Q-number

$\begin{bmatrix} \text{Weak-E+M} \\ \Delta Q = 0, \Delta Y = 0 \end{bmatrix}$ $\not\Rightarrow$ extension of $SU(3)_F$

$\Rightarrow$ more quarks $q \sim (p, n, \lambda \ldots)$

(iv) $\psi, \chi, K \sim q\bar{q}$ states.

i.e. simple representations of extended Strong group.

POSSIBLE THEORIES

(a) Covert Theories (Charm-like)

New quark c

$\psi, \chi \sim c\bar{c}$

— do not carry new Q number

$\Gamma_{\psi,\chi} \sim$ narrow $\Rightarrow$ Zweig rule

$\phi(1^{-}) \to K\bar{K}$

$\not\to 3\pi$

(b) Overt Theories (Colour-like)

New vector Q-number I_c^2

ψ, χ (and γ) carry $I_c \neq 0$

$\Gamma_{\psi,\chi} \sim$ narrow $\Delta I_c = 0$

$\psi(3.1)$ strong stable

E.M decays. $\Gamma_\psi \sim \alpha$

Group theory $\Rightarrow$ $\begin{cases} \text{selection rules} \\ \text{multiplets} \end{cases}$ "natural"

CHARM (12 quark)

Strong Group $SU(4)_{F} \times SU(3)_{c}$
$(p.n\lambda.c)^{F}$ $1,2,3$

$$q \sim \begin{pmatrix} p_1 & p_2 & p_3 \\ n_1 & n_2 & n_3 \\ \lambda_1 & \lambda_2 & \lambda_3 \\ c_1 & c_2 & c_3 \end{pmatrix}$$

$$q\hat{q} \sim (1,1), \quad (15,1) \quad = (n_F, n_c)$$

"ψ", $\phi, \omega, \rho, \underline{K}, \underline{D}; F^{\pm}$.

<u>All hadrons Colour singlets</u> $\Rightarrow$ the BAG

$$Q = (I_3 + Y/2 + Ch)_F$$

$$\gamma \sim (15,1)$$

$I_F = 0, 1$, Colour sing

$SU(3)_c \times$
$SU(4)_F \Rightarrow SU(2)_F \times U(1)_{Y_F} \times U(1)_{Ch_F} \times 1_c$

$\underline{I}_F, Y_F, Ch_F$ good

HAN-NAMBU COLOUR. (9 quark)

Strong Group $\underset{(p,n,\lambda)}{SU(3)_F} \times \underset{1,2,3}{SU(3)_c}$

$$(3,\bar{3}_c) \sim q \sim \begin{pmatrix} p_1 & p_2 & p_3 \\ n_1 & n_2 & n_3 \\ \lambda_1 & \lambda_2 & \lambda_3 \end{pmatrix} \sim \begin{pmatrix} \Sigma^0 & \Sigma^+ & p^+ \\ \Sigma^- & \Lambda^0 & n^0 \\ \Xi^- & \Xi^0 & \Lambda^{0\prime} \end{pmatrix}$$

$$q\bar{q} \sim \underset{\substack{\omega,\phi,\rho,K^* \\ \text{"white"}}}{(1,1),(8,1)}, \underset{\text{coloured.}}{(1,8),(8,8)} \pm (\eta_c$$

$$Q = (I_3 + Y/2)_F + (I_3 + Y/2)_c$$

$$\gamma \sim \underset{I_F = 0,1}{(8,1)} + \underset{I_c = 0,1}{(1,8)}$$

$$\Rightarrow SU(2)_F \times U(1)_F \times SU(2)_c \times U(1)_c$$

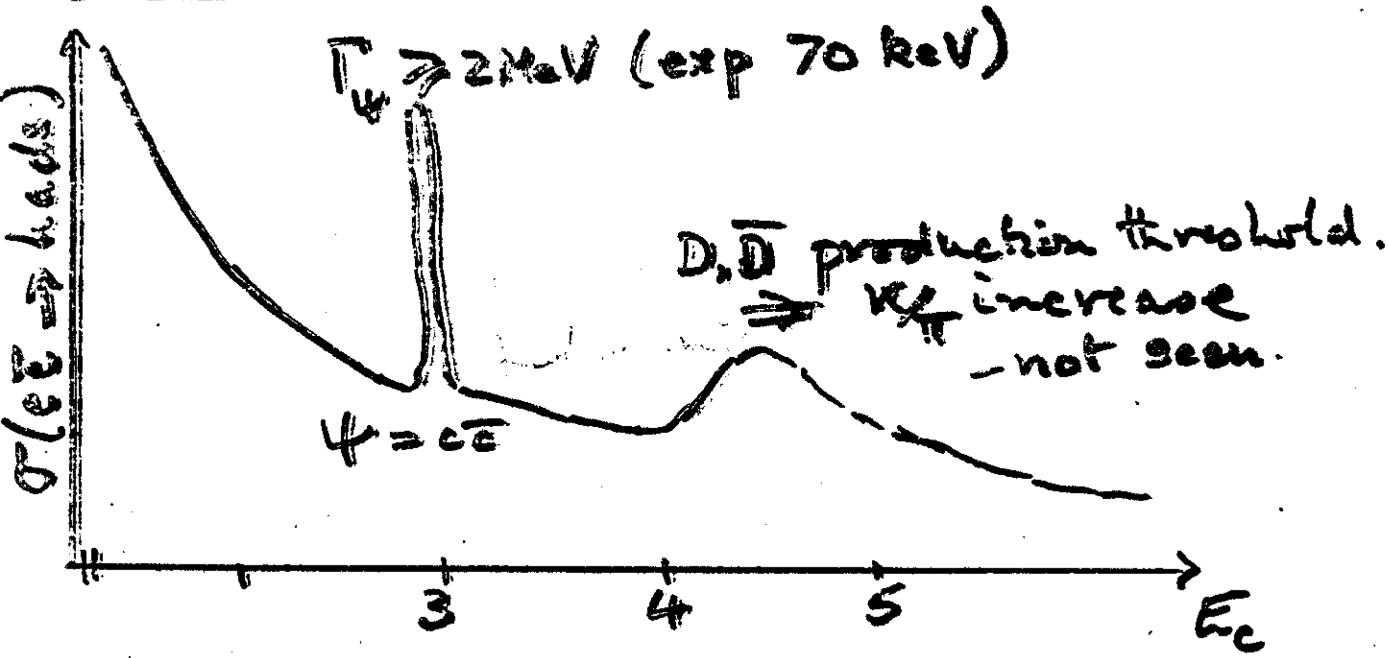
$\underline{I_F}$, Y_F, $\underline{I_c}$, Y_c good.

N. B. $\boxed{\text{photon carries } \underline{I_c = 1}}$

[Pati - Salam Hybrid theory]

HARM SPECTRUM.

Predictions (Lee, Gaillard, Rosner. RMP 1975)



N.B. one $\psi(c\bar{c})$ state c.f ρ, ω, ϕ.

$\psi_{2,3,4,5}$ radial excitations $\rho', \rho'', \rho''', \rho''''$

g 10^{-4}; "English prose" dynamics $\phi', \phi'', \phi''', \phi''''$

χ states; q spin $\frac{1}{2}\hbar$. $SU(n) \Rightarrow SU(2n)$

$\underline{S} + \underline{L} = \underline{J}$ Common to all theories. $\Rightarrow J^P$

	S	L	J^P	Charm $c\bar{c}$
$= +1)$	0	0	0^-	$\chi_1(2.8)$ --- π
$= -1)$	1	0	1^-	$\psi_{1,2,4}$ --- ρ, ρ' ρ
$= +1)$	1	1	$0^+, 1^+, 2^+$	χ_2, χ_3, χ_4 --- δ, A_1, A_2
$= +1)$	0	1	1^+	
$= -1)$	1	2	1^- $2^-, 3^-$	$\psi_{3,5}$ --- ρ'', ρ''''

$J^P = 1^-$

2^3D_1 — ψ_5

3^3S_1 — ψ_4

1^3D_1 — ψ_3

2^3S_1 — ψ_2

1^3S_1 — ψ_1

CHARM
SPECTRUM

$c\bar{c}$ states

χ_5 — $2^1S_0(0^-)$

χ_4 — $^3P_2\ (2^+)$

χ_3 — $^3P_1\ (1^+)$

χ_2 — $^3P_0\ (0^+)$

χ_1 — $1^1S_0(0^-)$

2.15

2.03

$c\bar{\lambda}$

1.86 D

<u>Decays of higher ψ-states</u>

(2) $\psi_{3.4.5} \not\rightarrow \psi_{1.2}$? cf $\psi_2 \rightarrow \psi_1$

$\psi_{3.4.5} \rightarrow D\bar{D}$. c.f. Ting ?

v. K/π

COLOUR SPECTRUM.

$$(q\bar{q}) \sim (1_F, 1_c) \quad (8_F, 1_c) \quad (1_F, 8_c) \quad (8_F, 8_c)$$

$$\begin{array}{cccc} & \rho & \rho_c & \\ \phi_0 & \omega_8 & \omega_c & \begin{pmatrix} \rho \\ \omega_8 \\ K \end{pmatrix} \times \begin{pmatrix} \rho_c \\ \omega_c \\ K_c \end{pmatrix} \\ & K & K_c & \end{array}$$

<u>Coupling to photon</u>, $\psi \quad J^P = 1^-$,

(i) $SU(3) \Rightarrow SU(2)_I \times \underbrace{U(1)_Y}$ U-singlet

$$\begin{array}{cc} \rho & \rho_c \\ \omega & \omega_c \end{array}$$

COLOUR SPECTRUM.

$$(q\bar{q}) \sim (1_F, 1_c) \quad (8_F, 1_c) \quad (1_F, 8_c) \quad (8_F, 8_c)$$

$$\phi_0 \qquad \begin{matrix} \rho \\ \omega_8 \\ K \end{matrix} \qquad \begin{matrix} \rho_c \\ \omega_c \\ K_c \end{matrix} \qquad \begin{pmatrix} \rho \\ \omega_8 \\ K \end{pmatrix} \times \begin{pmatrix} \rho_c \\ \omega_c \\ K_c \end{pmatrix}$$

Coupling to photon. ψ $J^P = 1^-$, U-singlet

(i) $SU(3) \Rightarrow SU(2)_I \times U(1)_Y$

(ii) 1, 8 mixing.

$$\rho \dashrightarrow (\rho, \omega_c) = \rho_B$$

$$\rho_c \dashrightarrow (\omega, \rho_c) = \rho_D$$

$$\phi \dashleftarrow \omega \qquad \omega_c \dashrightarrow (\omega, \omega_c) = \omega_D$$

i.e. 5 new states!

ρ_c, ρ_D narrow $\Delta I_c = 0$

$\omega_c, \omega_D, \rho_B$ broad. $I_c, Y_c, I_F, Y_F = 0$

Direct extension of ρ, ω, ϕ.

[... Salam broken — mixed. $11 = 3 + 8$ states]

Identification

$\psi(3.1) \sim \rho_c$ stable $\Delta I_c = 0$

$\psi(3.7) \sim \rho_D \rightarrow \rho_c + 2\pi(I_F=0)$ $\frac{g^2}{4\pi} \sim 10$ narrow

$$\left.\begin{matrix}\psi_3\\ \psi_4\\ \psi_5\end{matrix}\right\} \sim \left\{\begin{matrix}\omega_c \not\Rightarrow \text{hadrons} & I_F=0\ I_c=0\\ \omega_D \not\Rightarrow \quad " & I_F=0\ I_c=0\\ \rho_B \not\Rightarrow \quad " & I_F=1\ I_c=0\end{matrix}\right.$$ broad.

also $e\bar{e} \rightarrow K_n K_{n'}$

Selection Rules

$\Delta I_c = 0$

(i) $\underset{\omega_c,\,\omega_D,\,\rho_B}{\psi_{3,4,5}} \not\Rightarrow \underset{\rho_c,\,\rho_D}{\psi,\ \psi'}$ exp. $< 1\%$.

(ii) $\rho_D(\psi') \not\Rightarrow \rho_c(\psi) + \pi^0$ $\Delta I_F = 0$

$\Rightarrow \rho_c(\psi) + \eta$, seen

$\Rightarrow \rho_c(\psi) + 2\pi(I_F=0)$ seen.

"stringent upper limit" charm $(\psi_1 \to \pi^0\gamma) = 3(\psi_1 \to \eta\gamma)$

(iii) $\rho_c(\psi) \rightarrow \gamma\eta$, seen.

$\not\Rightarrow \gamma\pi^0$, not seen.

(iv) K/π unchanged 4 – 4.5 region

Sum Rule. (arbitrary mixing angles)

$$\Gamma(\alpha \to e\bar{e}) \sim |\langle 0|J^Q|\alpha\rangle|^2 \cdot M_\alpha .$$

$$\left[\frac{\Gamma_\rho}{M_\rho} + \frac{\Gamma_\rho^B}{M_\rho^B} + \frac{\Gamma_\rho^C}{M_\rho^C} + \frac{\Gamma_\rho^D}{M_\rho^D}\right]$$

$$= 3\left[\frac{\Gamma_\phi}{M_\phi} + \frac{\Gamma_\omega}{M_\omega} + \frac{\Gamma_\omega^C}{M_\omega^C} + \frac{\Gamma_\omega^D}{M_\omega^D}\right]$$

$$(9 = 3(2+1))$$

χ states

$$\psi_{1,2} \equiv \rho_{Col}\,(I_F=0, I_c=1, C=-1, J^P=1^-)$$

$\rho_{Col} \to \chi + \gamma$. $\therefore C_\chi = +1$.

χ narrow $\Rightarrow I_c = 1$

If $I_c = 0$ G parity opposite to ρ_{Col}

$$\therefore \chi \equiv \pi_{Col}\,(I_F=0, I_c=1, C=+1)$$

$$\rho_{Col} \not\to \pi_{Col} + \pi, \quad \Delta I_F = 0$$

$$\rho_{Col} \not\to \pi_{Col} + 2\pi, \quad \Delta G = 0$$

$$\rho_{Col} \longrightarrow \pi_{Col} + 3\pi\,(I_F=0)$$

To avoid strong decay (by $\Delta E = 0$)

$\psi(3.7) \not\to \pi_c + 3\pi$ if $\pi_c > 3.26$ GeV/c^2

$\pi_c \not\to \psi(3.1) + 3\pi$ " " < 3.52

$\psi(3.1) \not\to \pi_c + 3\pi$ " " > 2.68

All observed χ states lie in allowed region

$\psi(3.7) \to \chi(2.8) + \underset{C=-1}{3\pi\,(\omega)}$ missing modes?

(As for Charm)

Expected $J^P = 0^-, 0^+, 1^+, 2^+$

i.e. $\pi_c(2.8)$, $\delta_c(3.41)$, $A_{1c}(3.5)$, $A_{2c}(3.52)$.

Then $K_c^0(1.86) \equiv K_c^0(J^P = 0^-, I_c = 1/2, Y_c = 1)$

companion to $\pi_c^0(2.8)$.

$K(2.02) \sim \chi_{2.34}$

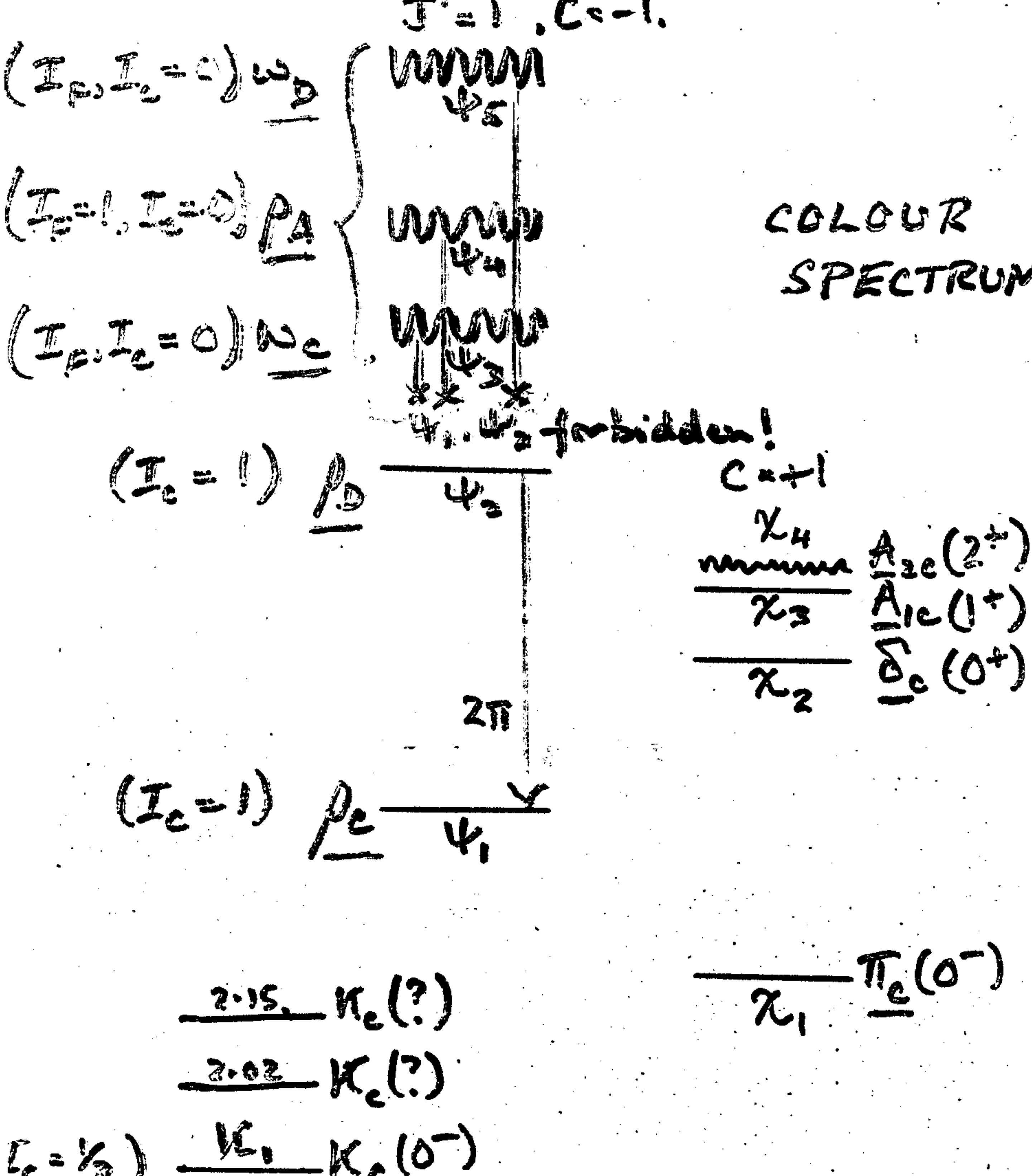
$K(2.15) \sim$ or ψ

$K_c' \not\to K_c + \pi \quad \Delta I_F = 0$

$\not\to K_c + 2\pi \quad \Delta I = 0$

$\therefore$ <u>narrow</u>

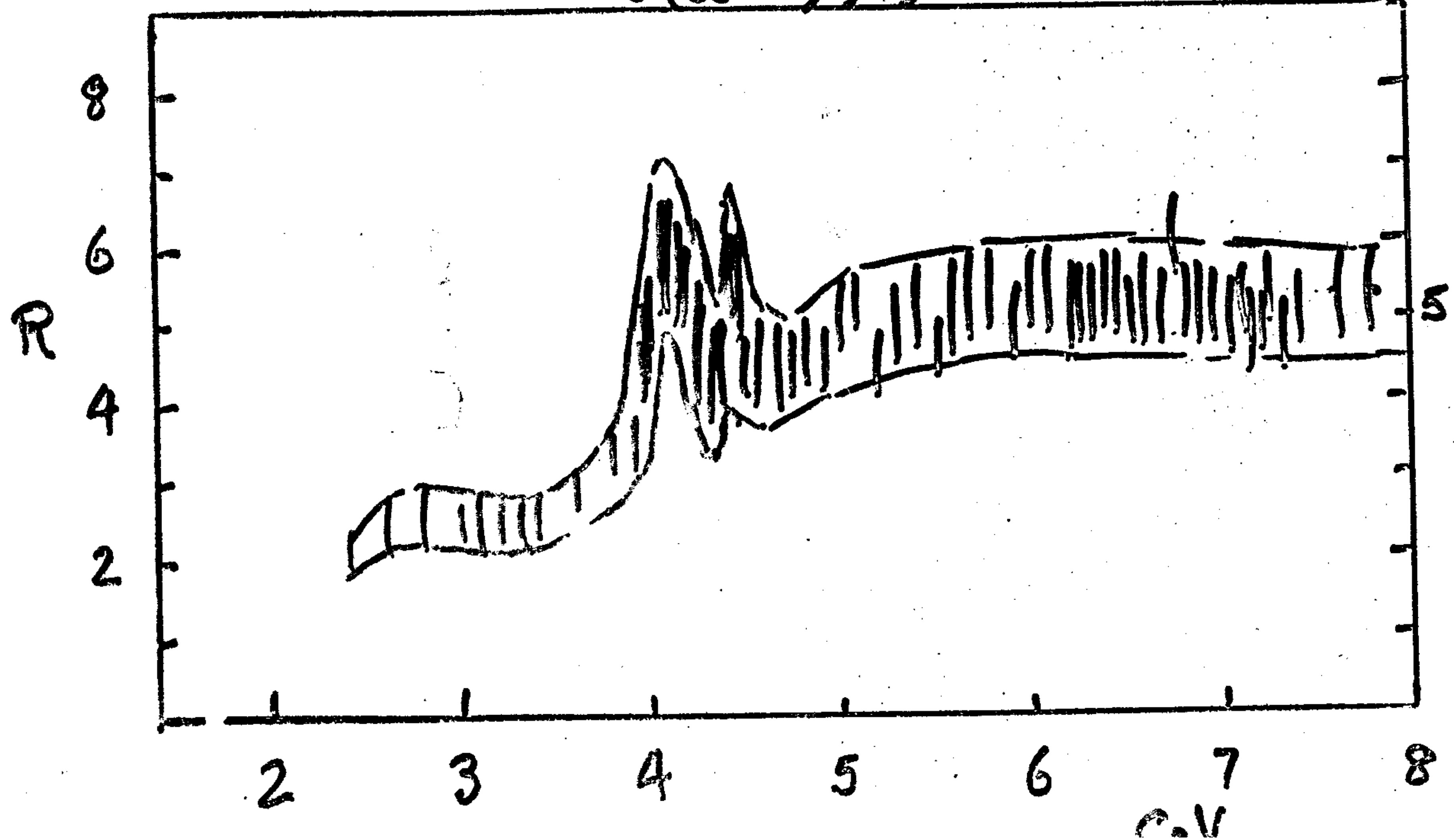
COLOUR SPECTRUM



NB. $K_c'(2.15) \not\to K_c(1.86) + 2\pi \quad (\Delta E = 0)$.

$$R = \frac{\sigma(e\bar{e} \to \text{hads})}{\sigma(e\bar{e} \to \mu\bar{\mu})}$$

SLAC. Aug 1975



$$R \equiv \frac{\sigma(e\bar{e} \to \text{hadrons})}{\sigma(e\bar{e} \to \mu\bar{\mu})}$$

$=$ Im 

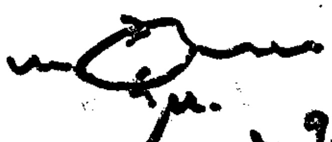
over

Im 

If quarks q_i, charge e_i: e.g. $\left(\frac{2}{3}, -\frac{1}{3}, -\frac{1}{3}\right)$

$= \sum_i e_i^2$ 

over

Im 

$\overset{???}{=}$ $\sum_i e_i^2$ 

over

$= \sum e_i^2$

Perl events. $e\bar{e} \to e^{\pm}\mu^{\mp}$ + neutrals

if $\to L\bar{L}$

$$R = R_{\text{strong}} + R_L = \underset{\text{colour}}{4} + 1 = 5 \checkmark$$

$$= \underset{\text{charm}}{3\tfrac{1}{3} + 1} = 4\tfrac{1}{3}$$

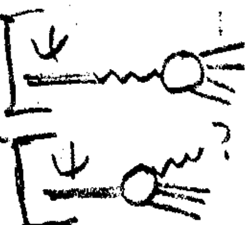
3.1) Decays

identified.

$\Gamma_{lep} \sim 10\ \text{keV} \sim 14\%$

$\Gamma_{(\gamma)had} \sim 12\ \text{keV} \sim 18\%$ ← 2~3 %.

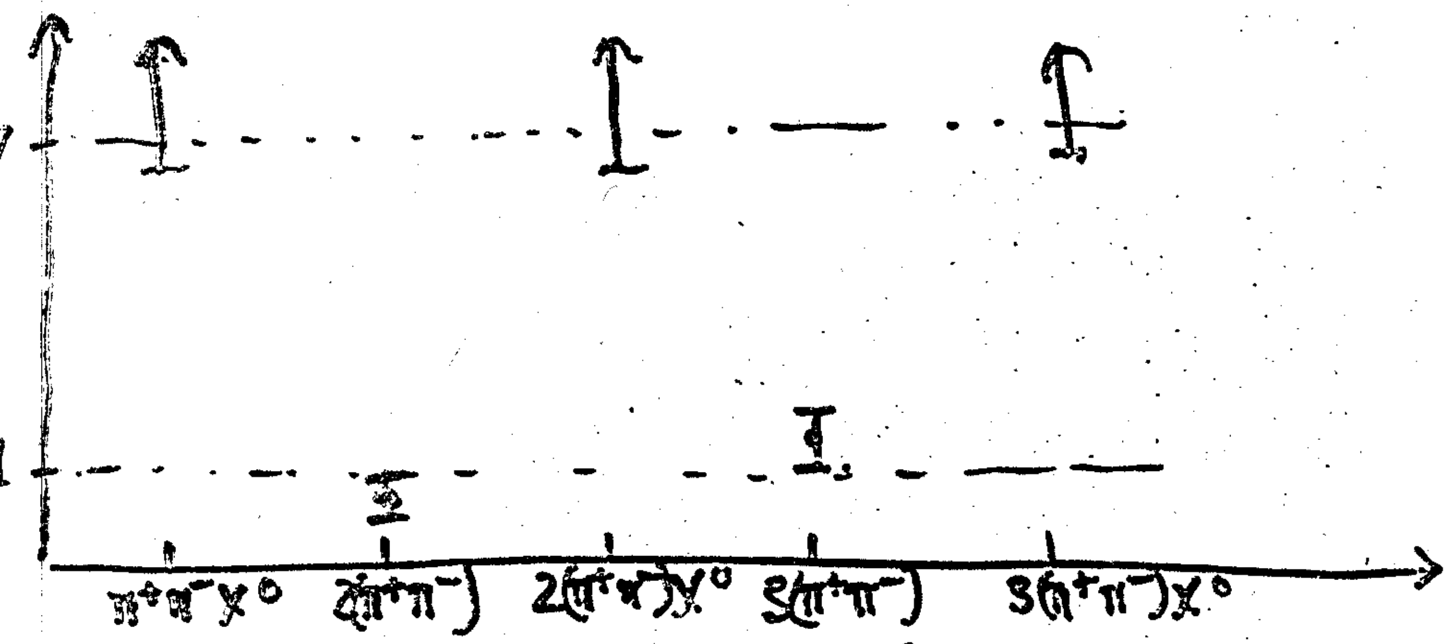
$\Gamma_{direct} \sim 50\ \text{keV} \sim 68\%$ ← 10~11 % non-radiative.



$\therefore\ \underline{\Gamma_{radiative} \sim 0 - 50\%}$

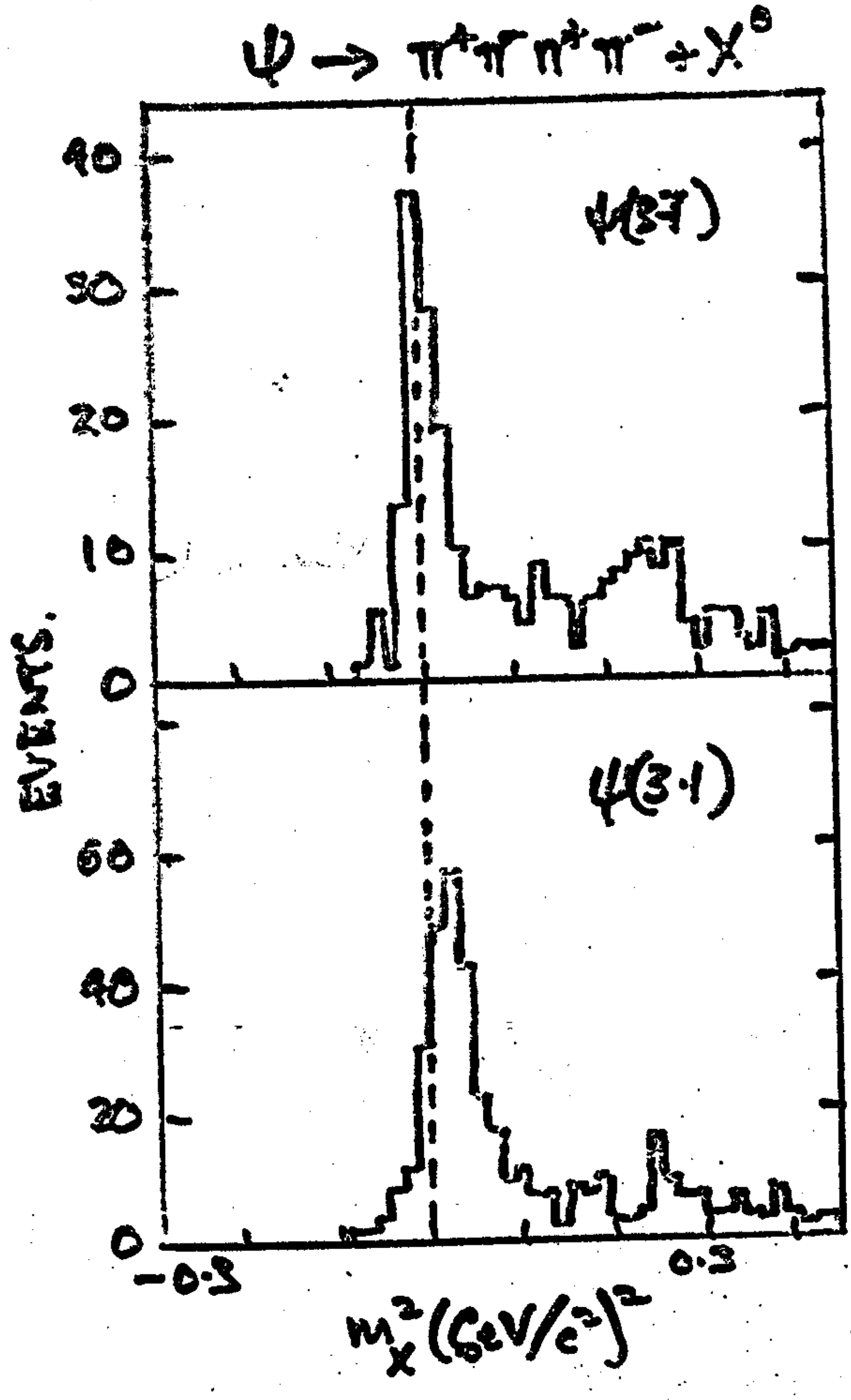
$\psi \longrightarrow$ specific final state f.

$$r_f \equiv \frac{R_f^{\psi}}{R_f^{J^0}} \quad \left(\simeq 1 \text{ if } \psi \to f \simeq 0\right)$$



(see below) (a) $X^0 = \pi^0 > 75\%$, $X_0 = \gamma < 25\%$?

(b) $n(\pi^+\pi^-)\pi^0$ $I = 0$. $\pi^+\pi^-\pi^0 = \rho\pi > 70\%$



SLAC. Aug 1975

Monte Carlo $X^0_{3.1} \simeq \pi^0$ $>75\%$

$X^0_{3.7} \simeq \gamma$ "

DESY. Similar analysis — no conclusion.

charm theory. $\Rightarrow X^0 \to \pi^0$ 100%

$$\Gamma_{strong} \equiv M/10 \hat{=} 300 \text{ MeV}$$

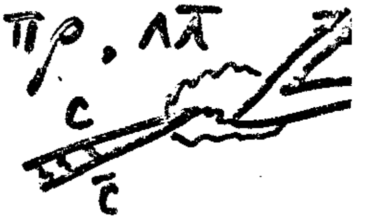
$$\Gamma^{exp}_{direct} = \Gamma_{strong} \times \underline{(10^{-3}-10^{-4})}$$ nor

f $\phi \to 3\pi$ $\Gamma(G.L.R) \hat{=} 3\text{ MeV} = \frac{\Gamma_{strong}}{100}$ Zw

Gaillard, Lee, Rosner

$$\Gamma^{exp}_{direct} \hat{=} \Gamma(G.L.R) \times \frac{1}{50}$$ abno

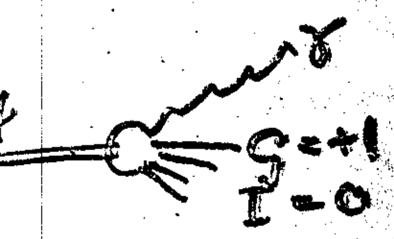
CE $I_c = 0$. $G = -1$. $\pi\rho$, $\Lambda\bar{\Lambda}$



s non tollit usum" $\underline{\Gamma \sim \alpha_\psi \quad \alpha_\psi} \sim 1/3$.

Colour theory.

$$G = C e^{iI\pi} e^{iI_c\pi} \quad ; \quad G_\psi = +1$$



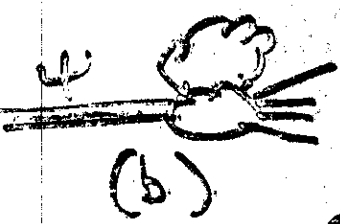
$$\Gamma^{th}_{rad} \hat{=} \Gamma_{strong}\alpha$$
$$\hat{=} 3 \text{ MeV}$$ nor

$$\Gamma^{exp}_{rad} \hat{=} \Gamma_{strong}\alpha \times \frac{1}{100}$$ "Zw

e. $n(\pi^+\pi^-)\gamma$

as observed!

$$\Gamma_\gamma \hat{=} \Gamma_{strong} \times \alpha^2$$



$$\Delta I_c^G = 1^- \times 10$$ enhan

cf. Coleman + Glashow 1964
$\Delta I^G = 1^-$

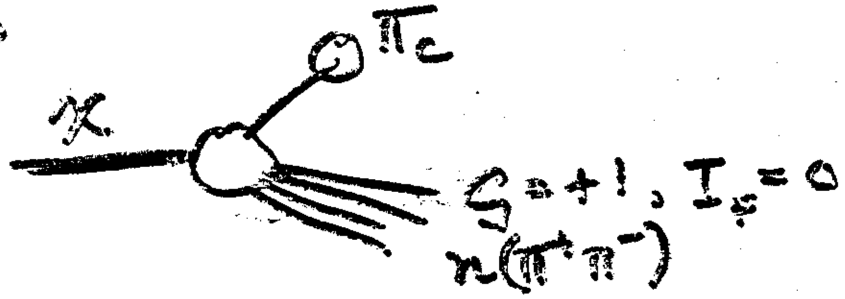
$G=-1$, $I_c=0$
$n(\pi^+\pi^-)\pi^0$
$\Rightarrow r_f$ as observed.

Similarly $\chi \to$ hadrons

$$G_{\chi} = -1$$

$$\Delta I_c^{G} = 1^{-} \quad \text{enhancement}$$

implies



as observed.

$$\frac{\psi(3.1) \to \gamma + \text{hadrons}}{\psi(3.1) \to \text{all}} = ???$$

important!

Maryland-Pavia-Princeton $\Rightarrow$ no result?

San Diego-Stanford-SLAC

Han-Nambu WEAK INTERACTION

i) renormalizable ('t Hooft)

ii) unified with Electromagem (Salam-Weinberg)

iii) for white hadrons (Cabibbo)

$\Delta Q = 1$, $\Delta Y = 0$, $\Delta I = 1$

or $\Delta Y = 1$, $\Delta I = 1/2$

with Cabibbo angle,

$\Delta Q = 0$, $\Delta Y = 0$. (motivation for charm)

iv) universal. (CVC) Feynman Gell-Mann

(ii) $\Rightarrow$ weak I-spin.

(i) $\Rightarrow$ .. U-spin

(Feldman & Mathews. ICTP/74/8)

(J^+, J^0, J^-) I_W spin triplet

also U_W spin singlets

e.g. charm.

$$q^{(i)} = \begin{pmatrix} p \\ n_\theta \end{pmatrix}, \begin{pmatrix} c \\ \lambda_\theta \end{pmatrix} \quad I_W \text{ spin doublets.}$$

$$\begin{pmatrix} p \\ c \end{pmatrix} \quad \begin{pmatrix} n(\theta) \\ \lambda(\theta) \end{pmatrix} \quad U_W \text{ spin doublets}$$

$$\underline{J}_\mu = \bar{q}^{(i)} \underline{\tau}_\mu q^{(i)}$$

$$J_0 = p\bar{p} - \underline{n\bar{n}} + c\bar{c} - \underline{\lambda\bar{\lambda}}$$

U spin singlet.

Cabibbo rotation

$$\bar{n}(\theta)\, n(\theta) - \bar{\lambda}(\theta)\, \lambda(\theta)$$

does not generate $\underline{\underline{\bar{n}\lambda}}$ terms.

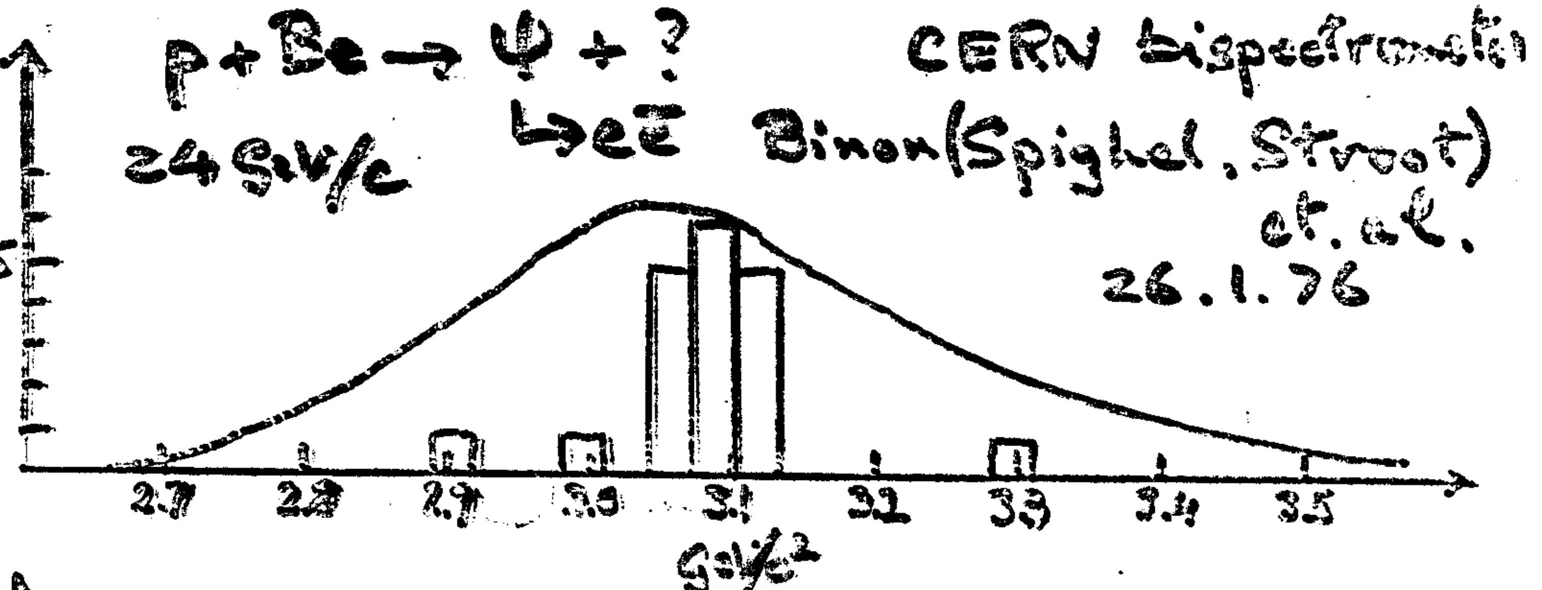
i.e. $\Delta Q = 0.$ $\Delta Y \neq 0.$

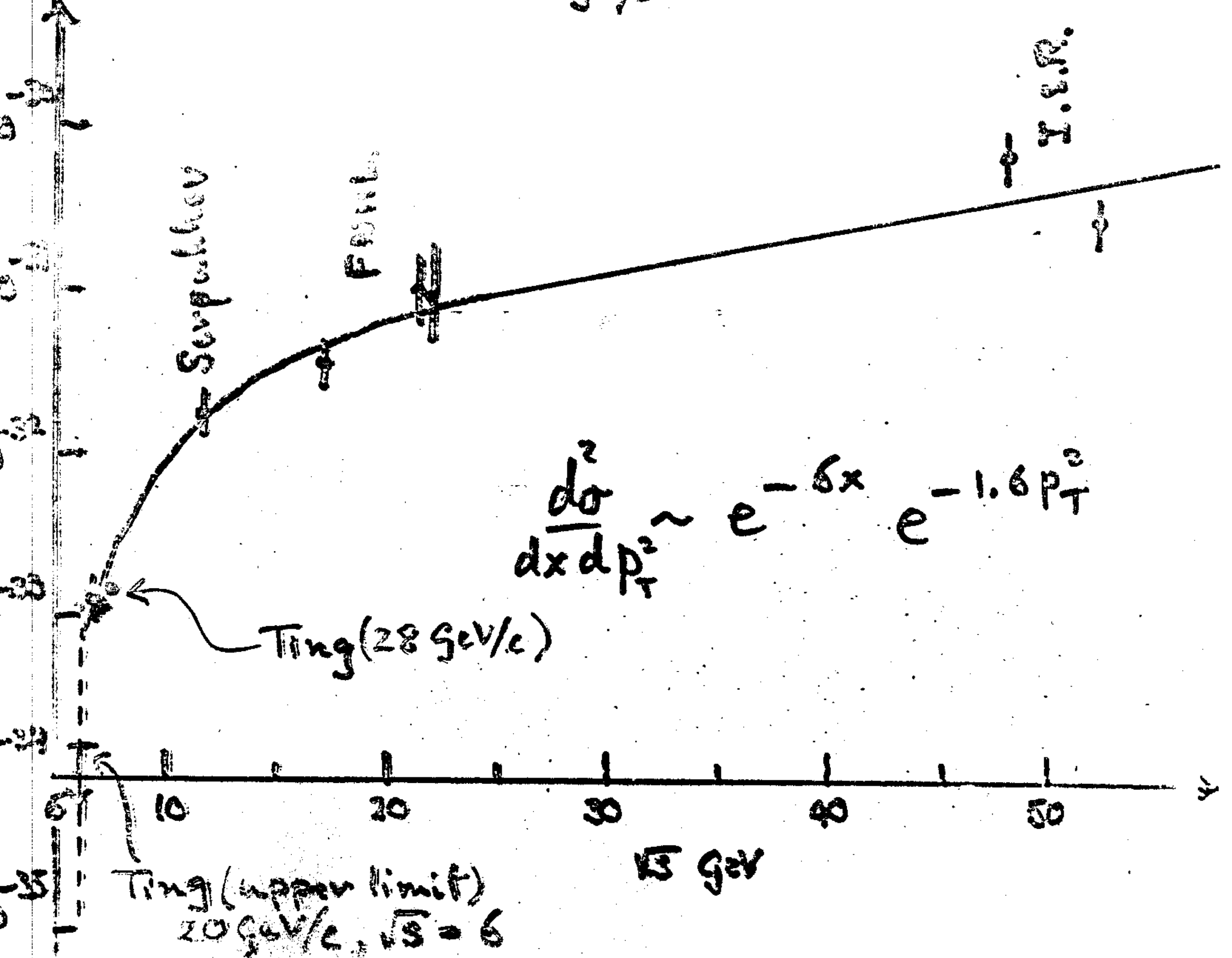
[...]loan. e.g.

$$I_W \sim \begin{pmatrix} p_1 \\ n_1 \end{pmatrix} \begin{pmatrix} n_2 \\ \lambda_1 \end{pmatrix}_\theta ; \begin{pmatrix} p_1 \\ n_2 \end{pmatrix} \begin{pmatrix} n_1 \\ \lambda_1 \end{pmatrix} U_W$$

$\nu \to \mu^- \mu^+$ cf. $K \to$ exotics.

Strong Production.





SLAC $\Delta E = 2$ MeV. $\frac{\text{signal}((\psi \to \mu\bar{\mu})}{\text{Bgd } \mu\bar{\mu}} \sim 6/1$

Binon et al.

$\Delta E \approx 75$ MeV $\frac{\text{signal}}{\text{Bgd}} \sim 16/1$

$\therefore$ $\Delta E \sim 2$ MeV " $\sim 500/1$

$\therefore$ ψ not produced via photons (reverse SLAC)

Allowing for fermi motion. $\bar{p}\bar{p} \to \psi + ?$

$$6 \leq E_{lt} \leq 7.5$$

If $\bar{p}\bar{p} \to pp\,\psi X^0$, $1 \leq M_x \leq 2.5$

$$\therefore X^0 \neq \bar{\psi}$$

If $\bar{p}\bar{p} \to p\,\psi\,\bar{B}_c^+$ $\quad 2 \leq M_B \leq 3.5$

(Ting) $T_{lab} = 30.6$ $\quad \sqrt{s}_{fermi} \doteq 8.1$

$$\sigma(\psi') < \frac{7}{100}\,\sigma(\psi)$$

$$\doteq 0$$

If below threshold $M_B \to 3.5$. $\therefore M_B \to 3.5$

$\bar{B}_c^+ = (p^+, \rho_c^0)$ consistent with

$\longrightarrow p + \gamma$ Col/FNAL $(\mu\bar{\mu}) + \mu$

Binon et al. (preliminary)

24 GeV/c Hydrogen target

$$p + p \rightarrow \psi + ?$$
$$\quad\quad\quad\; \hookrightarrow e\bar{e}$$

23 events

80 "

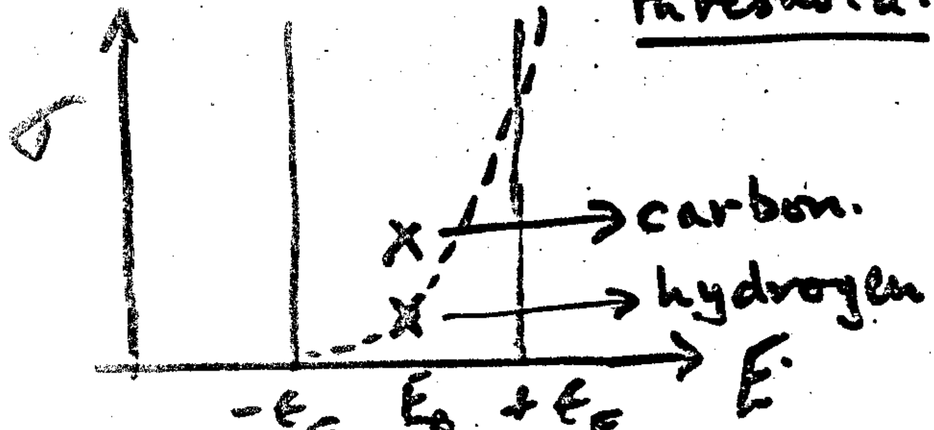
$$\frac{\sigma(\psi)_{\text{hydrogen}}}{\left[\sigma(\psi)\text{ per nucleon}\right]_{\text{carbon}}} = 2.1^{+0.9}_{-0.7}$$

90%

Fermi motion important.

i.e. threshold.

ψ charm
→ pp ψ
threshold 11 GeV



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