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INTERNAL REPORT
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International Atomic Energy Agency

and

United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

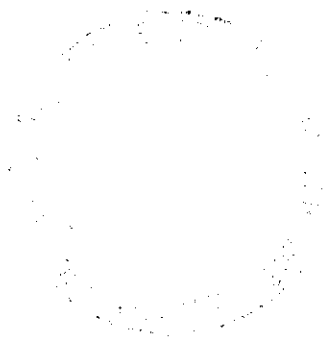
T O P I C A L M E E T I N G

ON LEPTON INTERACTIONS AND NEW PARTICLES

6 - 9 July 1976

P A R T II

(Contributions)



MIRAMARE - TRIESTE

July 1976

THEORY OF e^+e^- ANNIHILATION

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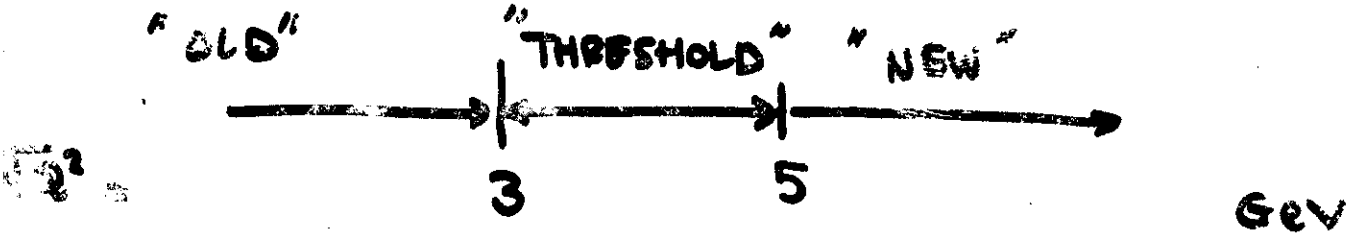
Switzerland.

e^+e^- ANNIHILATION

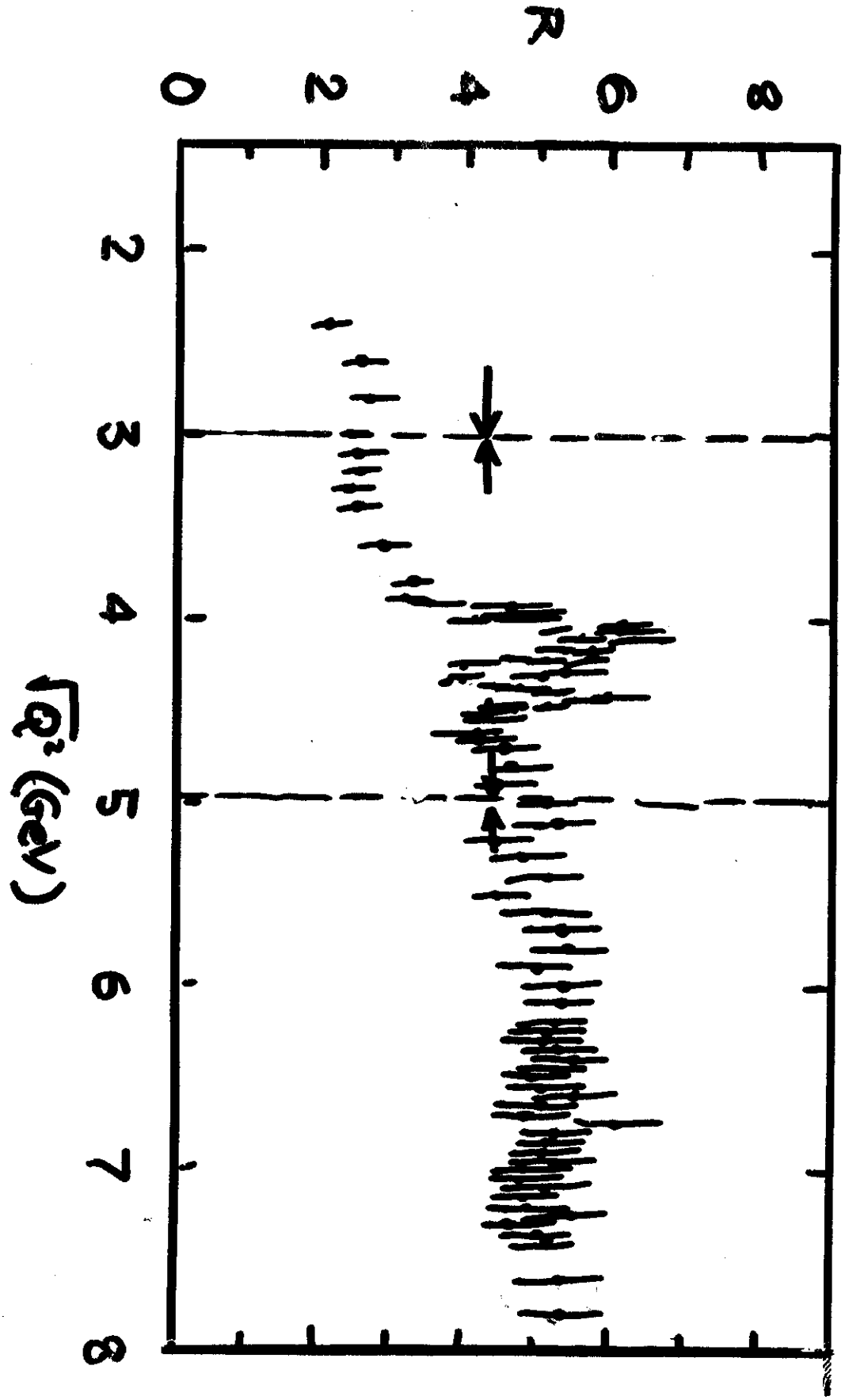
AND THE NEW PARTICLES

IT IS CUSTOMARY TO SEPARATE THE PHYSICS OF e^+e^- ANNIHILATION INTO THREE REGIONS



THIS IS SUGGESTED BY THE BEHAVIOR OF

$$R(q^2) = \frac{\sigma(e^+e^- \to \text{HADRONS})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$


R
0
2
4
6
8
2
3
4
5
6
7
8
$\sqrt{Q^2}$ (GeV)

AND BY THE THEORETICAL PREJUDICE THAT AROUND $3 \div 4$ GeV A NEW QUARK DEGREE OF FREEDOM (TO BE CALLED CHARMED QUARK c) IS BEING EXCITED.

I SHALL FOLLOW THIS PREJUDICE, BUT MY THEORETICAL ANALYSIS SHALL NOT BE BASED ON ANOTHER (LESS MOTIVATED) PREJUDICE LIKE THE PARTON MODEL (OR ITS SOPHISTICATED VERSION CALLED ASYMPTOTIC FREEDOM) BUT ON A NON-CONVENTIONAL APPROACH TO THE QUARK DEGREE OF FREEDOM : THE HQM (G.P, '72 ; G.P. & N. CRAIGIE '75).

THE QUARK DEGREE OF FREEDOM IS NOTHING BUT A MEANS TO INTRODUCE THE HADRONIC COORDINATES

NECESSARY TO TAKE INTO ACCOUNT TWO FUNDAMENTAL ASPECTS OF HADRODYNAMICS

- THE SPACE-TIME EXTENSION OF HADRONS
- THEIR INTERNAL STRUCTURE (SPIN, UNITARY SPIN, SU_4? ...)

I. HADRONIC PRODUCTION BELOW 3 GEV.

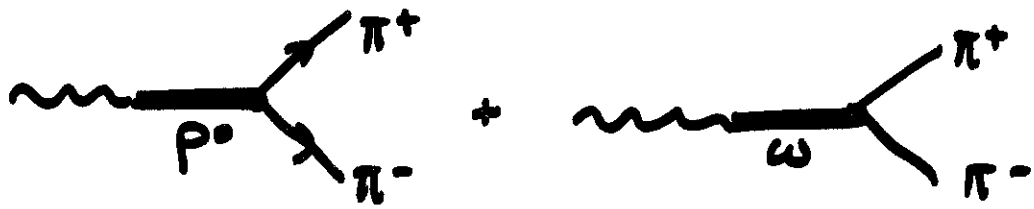
THE PROCESS IS

FOR ENERGIES UP TO $Q^2 \lesssim 1$ GeV^2 (ACO, ORSAY, VEPP NOVOSIBIRSK) ONE MAINLY PRODUCES THE WELL KNOWN VECTOR MESONS

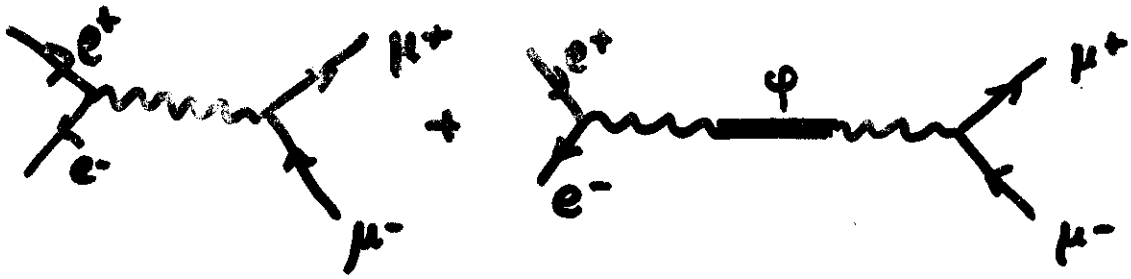
$$\rho, \omega, \varphi$$

AND ONE CAN STUDY THEIR BASIC PROPERTIES (WIDTHS, BRANCHING RATIOS, ...) AS WELL AS SEVERAL INTERESTING FINE STRUCTURE EFFECTS:

ρ-ω INTERFERENCE



AND φ-VACUUM POLARIZATION



(THIS INTERFERENCE WITH $\varphi \to \psi(3094)$ HAS BEEN OBSERVED AND USED TO DETERMINE THE SPIN-PARITY OF THE ψ)

— GOING UP IN ENERGY (ADONE, FRASCATI) ONE BEGINS TO SEE A VERY ABOUNDANT HADRON PRODUCTION. MODULO SOME UNRE-

SOLVED STRUCTURES, THE MULTIHADRON X-SCT EXHIBITS

$$R(Q^2) \nearrow \text{CONST} \simeq 2.5$$

Q: CAN ONE DESCRIBE THIS HADRONIC PRODUCTION BY ASSUMING THE EXISTENCE OF AN INFINITE FAMILY OF HIGHER VECTOR MESONS :

$$\rho'(1600), \rho''(\cdots), \ldots \; ?$$

A: YES. (EXTENDED VECTOR DOMINANCE : SAKURAI, SCHILDKNECHT, GRECO, GOUNARIS ....) ACCORDING TO THE PICTURE :

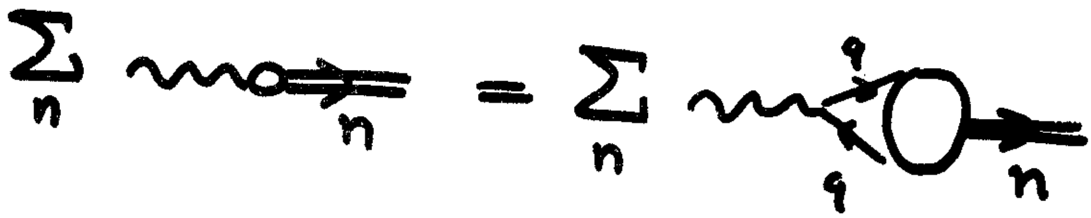
$$\sigma = \left| \sum_n \rho_n \right|^2$$

AND ONE CAN, QUITE NATURALLY, ARRANGE THE COUPLINGS AND THE WIDTHS IN SUCH A WAY THAT $R(Q^2)$ BE CONSTANT.

SO IT IS QUITE CONCEIVABLE THAT HADRONIC PRODUCTION PROCEEDS IN TWO

STEPS AS CONJECTURED BY EVD.

MY VIEW IS QUITE CLOSE TO EVD BUT WITH THE QUARK NOTION ALSO VERY CLOSE TO THE PARTON MODEL:



WHERE THE VM STATE  IS A QUASI STATIONARY STATE DESCRIBING THE MOTION OF A $q\bar{q}$ PAIR INSIDE A REGION OF SPACE-TIME DETERMINED IN A UNIQUE WAY BY THEIR ENERGY-MOMENTUM. THIS PICTURE IS QUITE PRECISE AND ALLOWS US TO DERIVE:

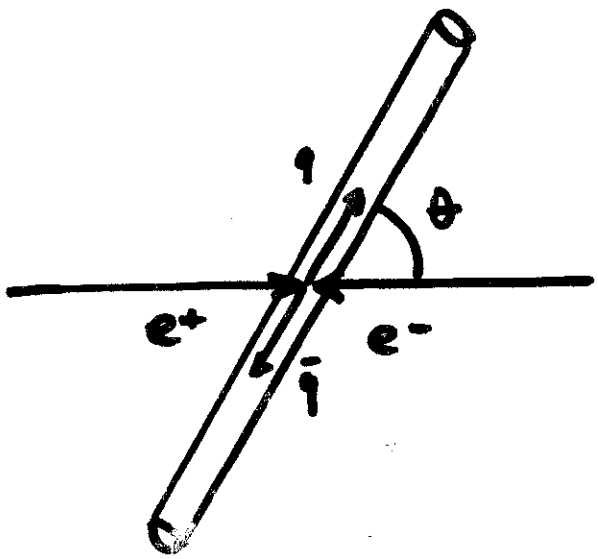
— $$R(Q^2) \underset{Q^2 \to \infty}{\longrightarrow} \lambda \sum_i Q_i^2$$

Q_i = CHARGE OF THE i-TH QUARK

λ IS A NUMBER WHICH DEPENDS ON THE VARIOUS STRUCTURAL PARAMETERS OF THE HADRONS (RADIUS, COUPLING ETC) WHICH IS IN GENERAL DIFFERENT FROM 1.
A CALCULATION OF λ IN THE COMPLETELY

REALISTIC CASE OF SPINNING QUARK HAS YET TO BE PERFORMED. (8)

— AS FOR THE STRUCTURE OF FINAL STATES, QUALITATIVELY (ASYMPTOTICALLY)



$P(\theta) \sim (1+\cos^2\theta)$

A FIRESAUSAGE (COHERENT SUPERPOSITION OF $\frac{l_0}{2} = \frac{M R_L}{4}$ STATES DEGENERATE AT MASS M) IS CREATED WHICH SUBSEQUENTLY DECAYS INTO A MULTIHADRON STATES GIVING A PECULIAR JET STRUCTURE.

ASYMPTOTICALLY THE ONE-PARTICLE DISTRIBUTION IS GIVEN BY THE BJ-SCALING FORM

$$Q^2 \frac{d^2\sigma}{dx\, d\cos\theta} = F(x)\,(1+\cos^2\theta) \qquad x \geq \frac{E_{had}}{\sqrt{Q^2}_L}$$

FURTHERMORE

$$F(x) \underset{x\to 0}{\longrightarrow} \frac{c}{x}$$

THUS $\langle n \rangle_p = c_p \log Q^2 + \text{const}$

EVENT BY EVENT THE STRUCTURE OF FINAL STATES IS IDENTICAL WITH THE ONE OBSERVED IN HADRON-HADRON COLLISIONS.

THE VOCABULARY IS

HADRON-HADRON		e^+e^-
FEYNMAN SCALING	$\longleftrightarrow$	BJORKEN SCALING
CENTRAL PLATEAU	$\longleftrightarrow$	$\frac{1}{x}$ BEHAVIOR FOR $F(x)$
LOG INCREASING PARTICLE MULTIPLICITY	$\longleftrightarrow$	SAME
CUT-OFF IN TRANSV. MOM	$\longleftrightarrow$	JETS

ANOTHER CONFIRMATION OF THIS FACT IS FROM THE RATIOS

$$c_\pi : c_k : c_{\bar{p}} \simeq 1 : \frac{1}{10} : \frac{1}{100}$$

IN PP COLLISIONS, WHICH ARE ALSO OBSERVED IN e^+e^- COLLISIONS.

— THE REGION $\sqrt{Q^2} = 3 \div 5$ GeV.

- $J/\psi(3095)$
- $\psi'(3684)$
- P or χ-STATES
- HIGHER $c\bar{c}$ VECTOR STATES
- RISE IN R
- ~~POSSIBLE~~ CHARMED PARTICLE SIGNAL

i) $\psi(3095)$

EXTRAORDINARY SIGNAL!

$$\Gamma_{TOT} = 69 \pm 15 \text{ Kev}$$

$$\Gamma_e = 4.8 \pm .6 \text{ kev}$$

$J^{PC} = 1^{--}$ $I = 0$ DEFINITELY ESTABLISHED

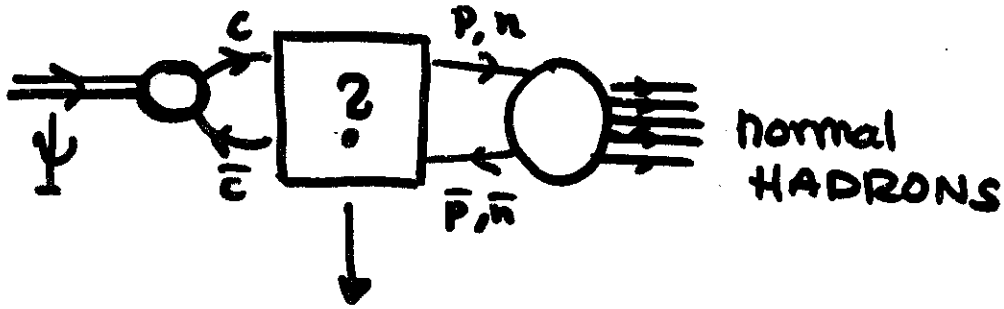
Q: CAN WE UNDERSTAND IT?

A: THE MOST POPULAR EXPLANATION

IS IN TERMS OF $c\bar{c}$ STATE (CHARMONIUM). C IS A NEW QUARK FOR WHOSE "MASS" IS MUCH HIGHER THAN USUAL QUARKS $m_c \simeq 1.5$ GeV. (11)

WALL THIS IS VERY APPEALING, BUT WE FACE A BIG PROBLEM: ITS RIDICOLOUSLY SMALL WIDTH.

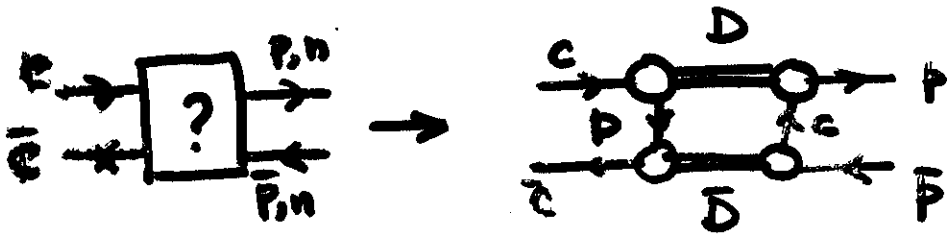
THE ZWEIG RULE IS USUALLY INVOKED TO SUPPRESS THE ψ DECAY:



SUPPRESSES THE DECAY AMPLITUDE BY $\sim 10^{-2}$ FACTOR

BUT, CAN WE REALLY UNDERSTAND THIS SUPPRESSION?

FOR INSTANCE A CONTRIBUTION IS



AND IF SU_4 IS A GOOD SYMMETRY THIS SUPPRESSION CANNOT BE BETTER THAN A FACTOR 10 (COMPARE WITH THE ANALOGOUS SITUATION WITH THE $\varphi \to \rho\pi$ DECAY, WHERE $\lambda \leftrightarrow c$). HOW CAN WE ACCOUNT FOR THE EXTRA FACTOR OF 10.

IN THE QUARK THEORY I MENTIONED WE CAN EXPLICITLY CALCULATE AN EXTRA SUPPRESSION WITH RESPECT TO $\varphi \to \rho\pi$ GIVEN BY

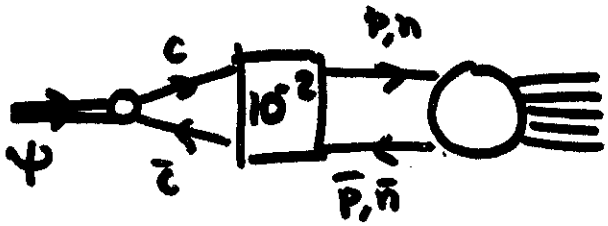
$$\sim e^{-\frac{R^2}{\pi}(m_c^2 - m_\lambda^2)} \propto \frac{1}{10}$$

FOR $R^2 \simeq \pi$ GeV^{-2} AND $m_c \simeq 1.5$ GeV, $m_\lambda \simeq .3$ GeV.

$R^2 \simeq \pi$ GeV^{-2} → RELATED TO SLOPE OF REGGE TRAJECTORIES.

THUS WE CAN UNDERSTAND THE ZWEIG RULE !!!

ALL THE DECAY PROPERTIES OF $\psi(3095)$ CAN BE OBTAINED BY THE PICTURE (13)



HADRONS (I=0)

WHERE THE FINAL STATE IS A I=0 FIRESAUSAGE WITH MASS M = 3.1 GEV. THUS MULTIPLICITIES, K/π RATIO, INCLUSIVE DISTRIBUTION SHOULD BY NO MEANS DIFFER FROM WHAT HAPPENS OFF-RESONANCE. THIS IS BORNE OUT BY THE DATA!

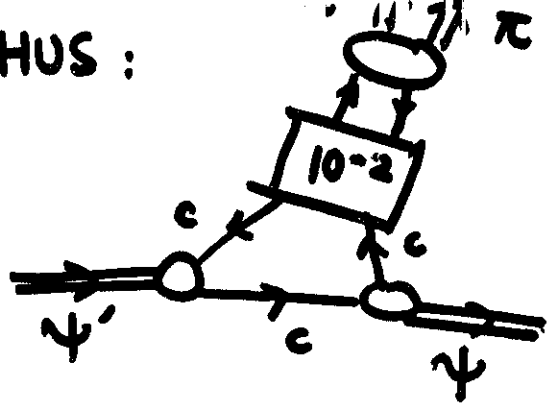
ii) $\psi'(3684)$.

IF THE CHARMED MESONS ARE ABOVE 1.8 GEV IN MASS ALSO THIS MESON IS EXPECTED TO HAVE A NARROW WIDTH. ZWEIG SUPPRESSION OPERATES AS USUAL. IN FACT

$$\Gamma_{TOT} = 228 \pm 56 \text{ keV}$$

$$\Gamma_e = 2.1 \pm .3 \text{ keV}$$

THUS :



$$\therefore \quad \frac{\Gamma(\psi' \to \psi + \pi\pi)}{\Gamma(\rho' \to \rho + \pi\pi)} \simeq 10^{-4} \quad \text{EXP} \quad \frac{130 \text{ keV}}{250 \text{ MeV}}$$

IT CHECKS QUITE WELL !

iii) <u>P-STATES</u>

THESE STATES POPULATE THE REGION 3400 – 3550 MeV REGION.

THEY HAVE BEEN EXCITED AND OBSERVED THROUGH THE SCHEME

$$e^+e^- \longrightarrow \psi' \longrightarrow \gamma + P \to (\pi\pi, K\bar{K}, 4\pi, 6\pi)$$

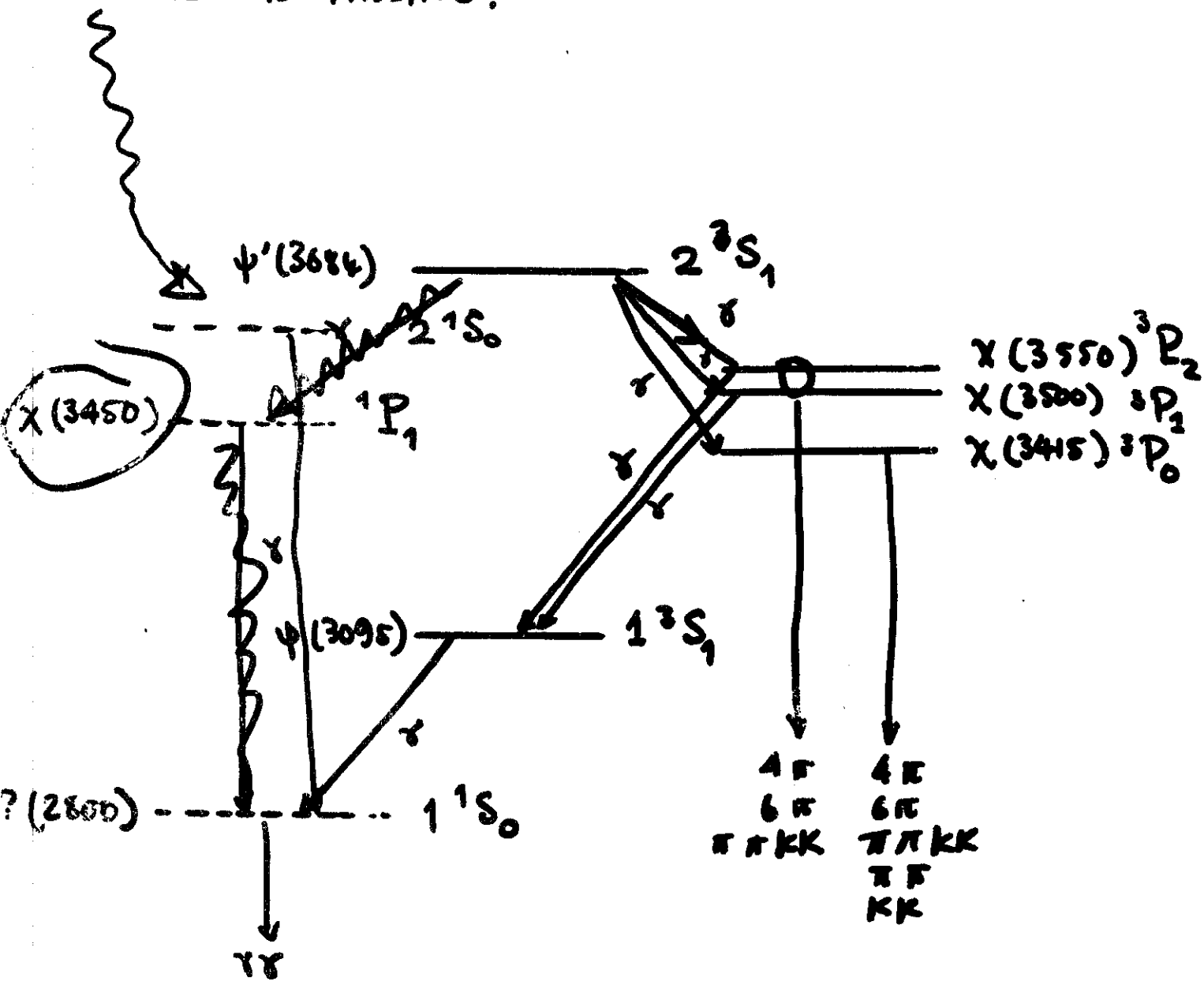
$$\downarrow$$

$$\gamma + \psi(3095) \to \text{HADRONS}$$

$$\downarrow$$

$$(\mu^+\mu^-, e^+e^-)$$

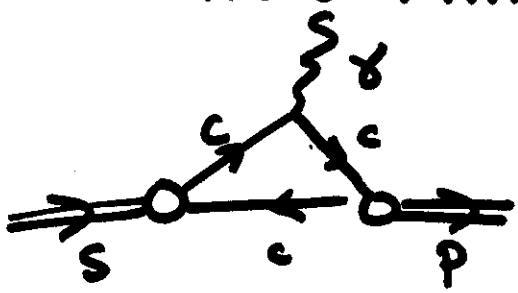
IN A QUARK PICTURE THE SPECTRUM EXPECTED IS QUITE CLOSE TO THE ONE OBSERVED. SO FAR ONLY A PSEUDOSCALAR STATE AROUND 3600 MEV IS MISSING.



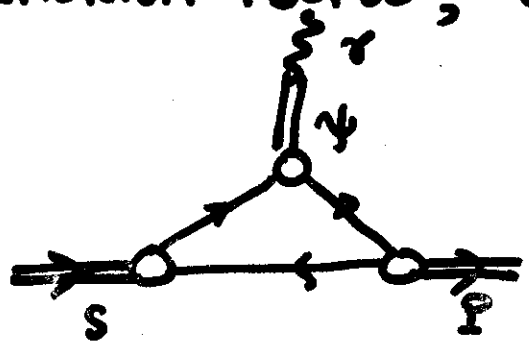
THE CHARMONIUM SPECTROSCOPY IS GOING TO GIVE US IMPORTANT INSIGHTS INTO A QUARK DYNAMICS UNOBSCURED BY THE TYPICAL UNITARITY EFFECTS (LARGE WIDTHS, MIXINGS WITH CONTINUUM, ETC.)

HOW ABOUT γ-RATES?

SHOULD WE COMPUTE WITH



LIKE CHARMONIUM PEOPLE, OR WITH



LIKE VECTOR DOMINANCE PEOPLE?

I BELIEVE THAT BOTH PIECES SHOULD BE TAKEN INTO ACCOUNT.

TO DESCRIBE (ROUGHLY) THE $c\bar{c}$-SPECTRUM WE HAVE THE SIMPLE FORMULA

$$m^2(n^3L_{L-1}^{L+1}) \simeq 9.6 + 2\left[2(n-1)+L\right] \text{ GeV}^2$$

WHICH CORRECTLY LOCATES THE P-STATES AROUND 3.4 GeV, THE D-STATES CLOSE TO $\psi'(3.7)$ AND THE NEXT ψ-STATE

ψ'' AROUND 4.2 GeV.

THE WHOLE PICTURE SEEMS QUITE HEALTHY. ABOVE THRESHOLD FOR STATES OF $(c\bar{p}, c\bar{n}, c\bar{\lambda})$ CHARACTER ZWEIG SUPPRESSION DOES NOT OPERATE ANY MORE.

THUS THE LARGER WIDTHS FOR THE STRUCTURES AROUND 4 GeV SUGGEST THAT SOMETHING LIKE CHARMED PARTICLES ARE PRODUCED AND THAT THEIR MASS SHOULD LIE BELOW 2 GeV.

IN FACT:

— POSSIBLE EVIDENCE FOR CHARM.
(G. Goldhaber et al. SPEAR June '76)

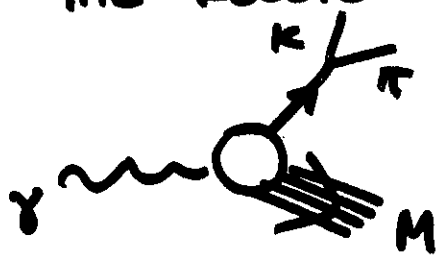
$\gtrsim 7$ s.d	peak	$K^{\pm}\pi^{\mp}$	1.865 ± 15 MeV
5 s.d		$K^{\pm}\pi^{\pm}\pi^{+}\pi^{-}$	

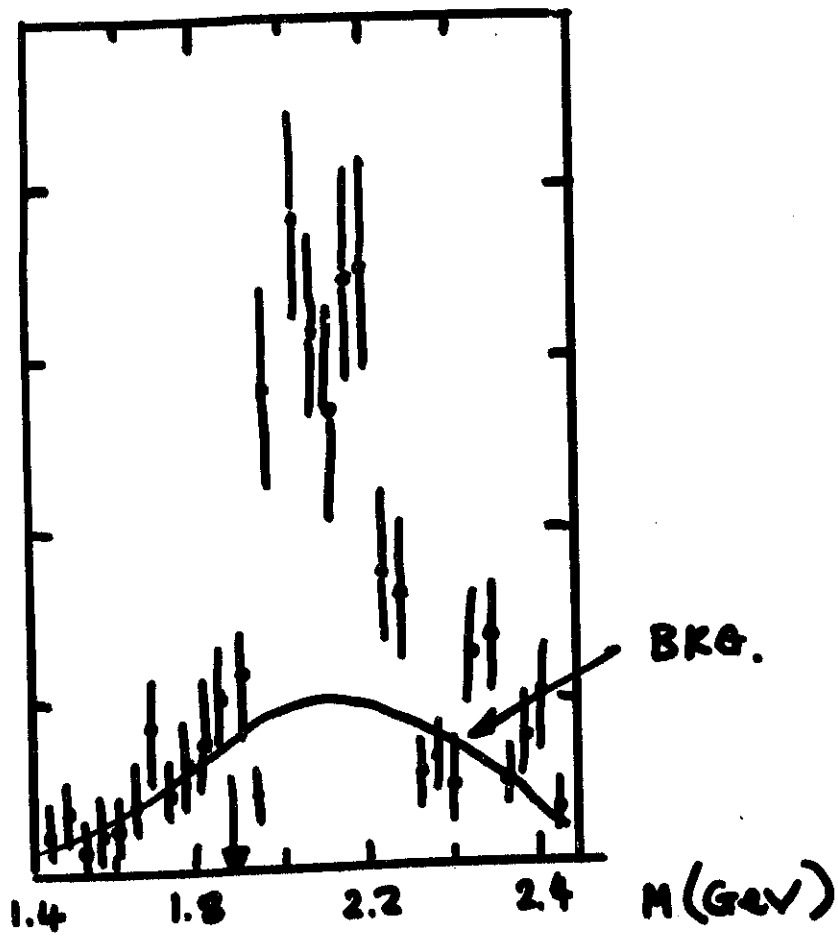
$K^{*}\pi^{+}\pi^{+}$ FOUND. ALSO,
THE WIDTH $\leq$ 30 MEV (EXP. RES.)

CAN IT BE A K^{*} BELONGING TO THE $g(1700)$ FAMILY? [RECENT REPORT OF $K^{*}(1650)$ $\Gamma \gtrsim 40$ MeV]

NO!

LOOK AT THE RECOIL MASS.

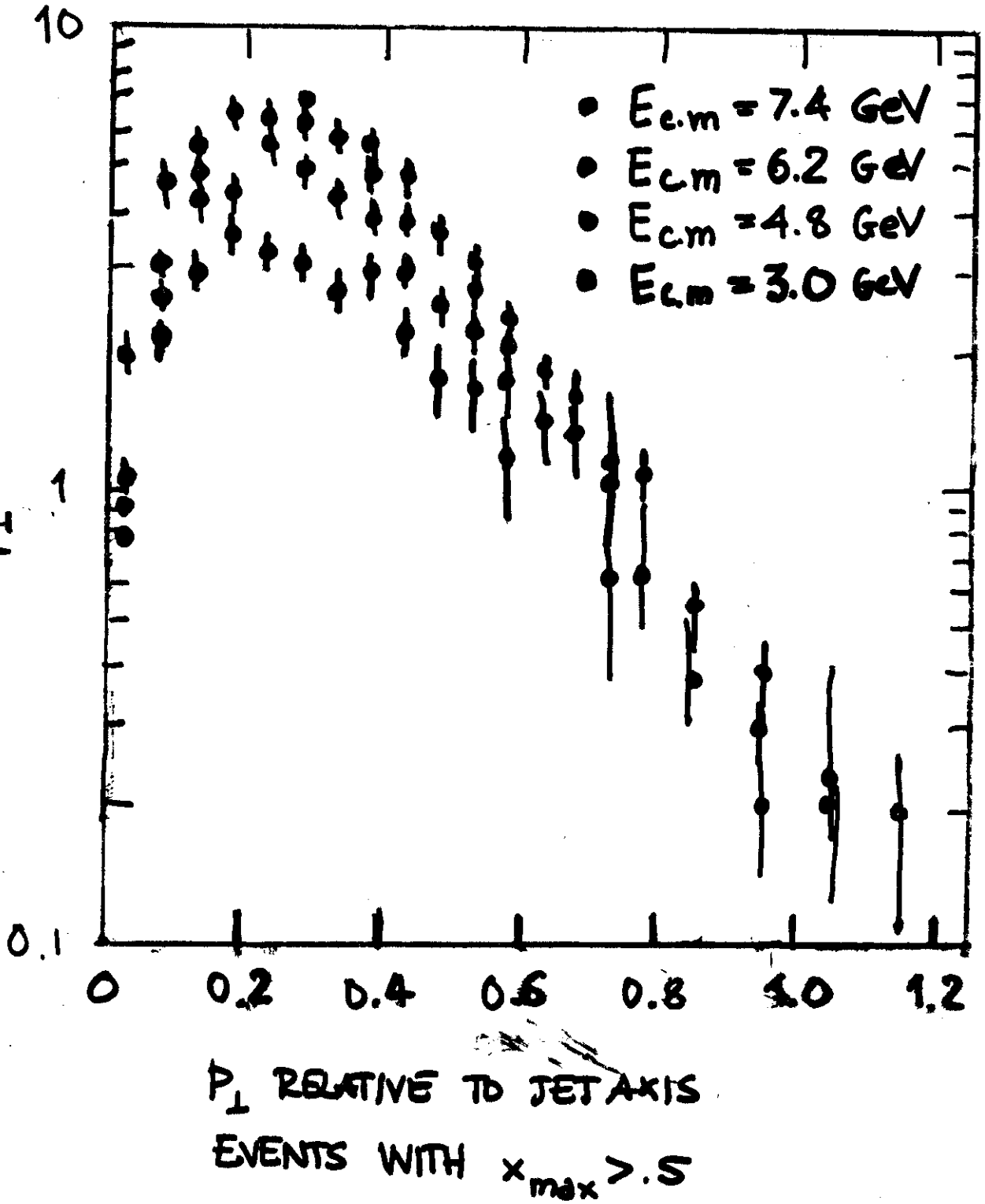


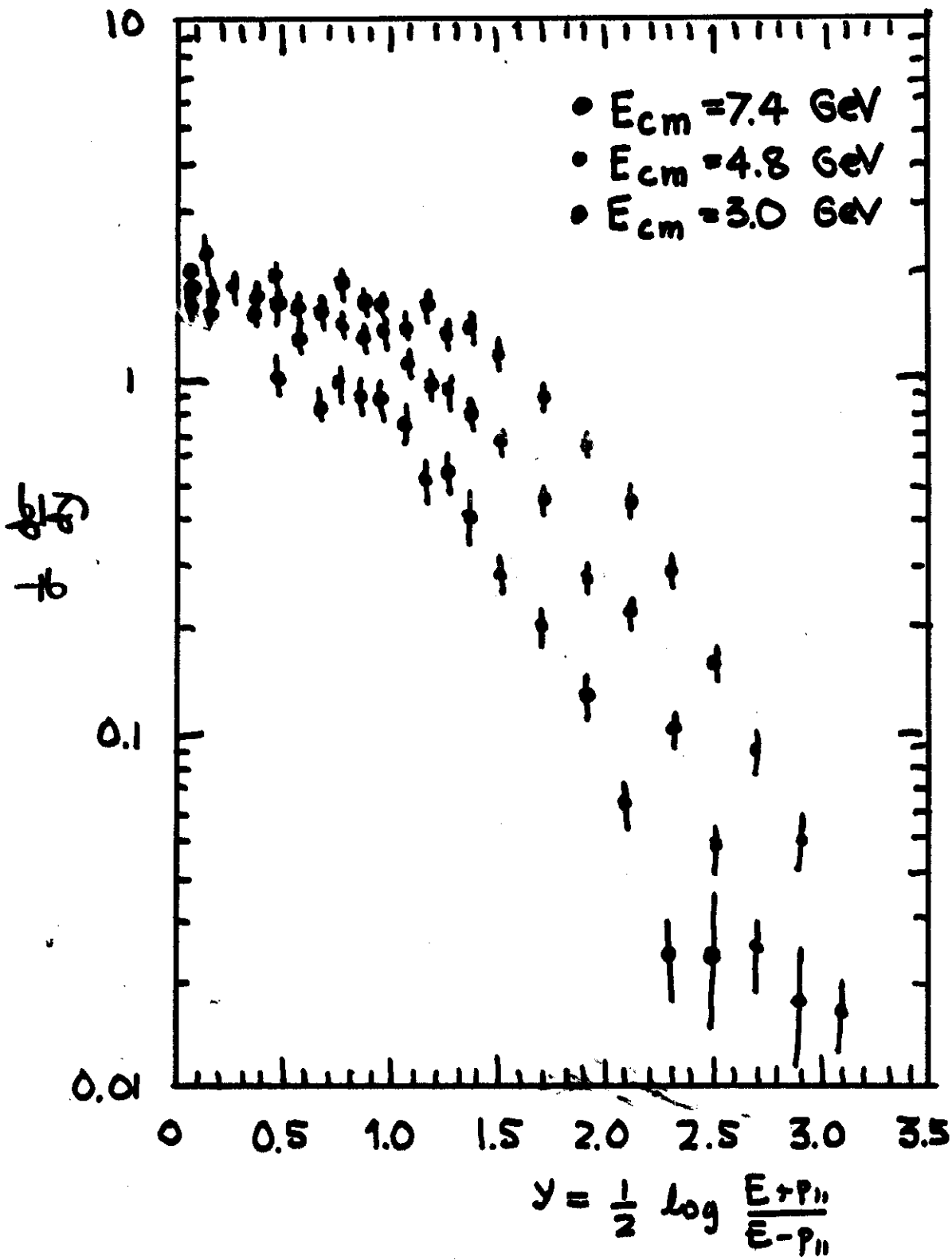


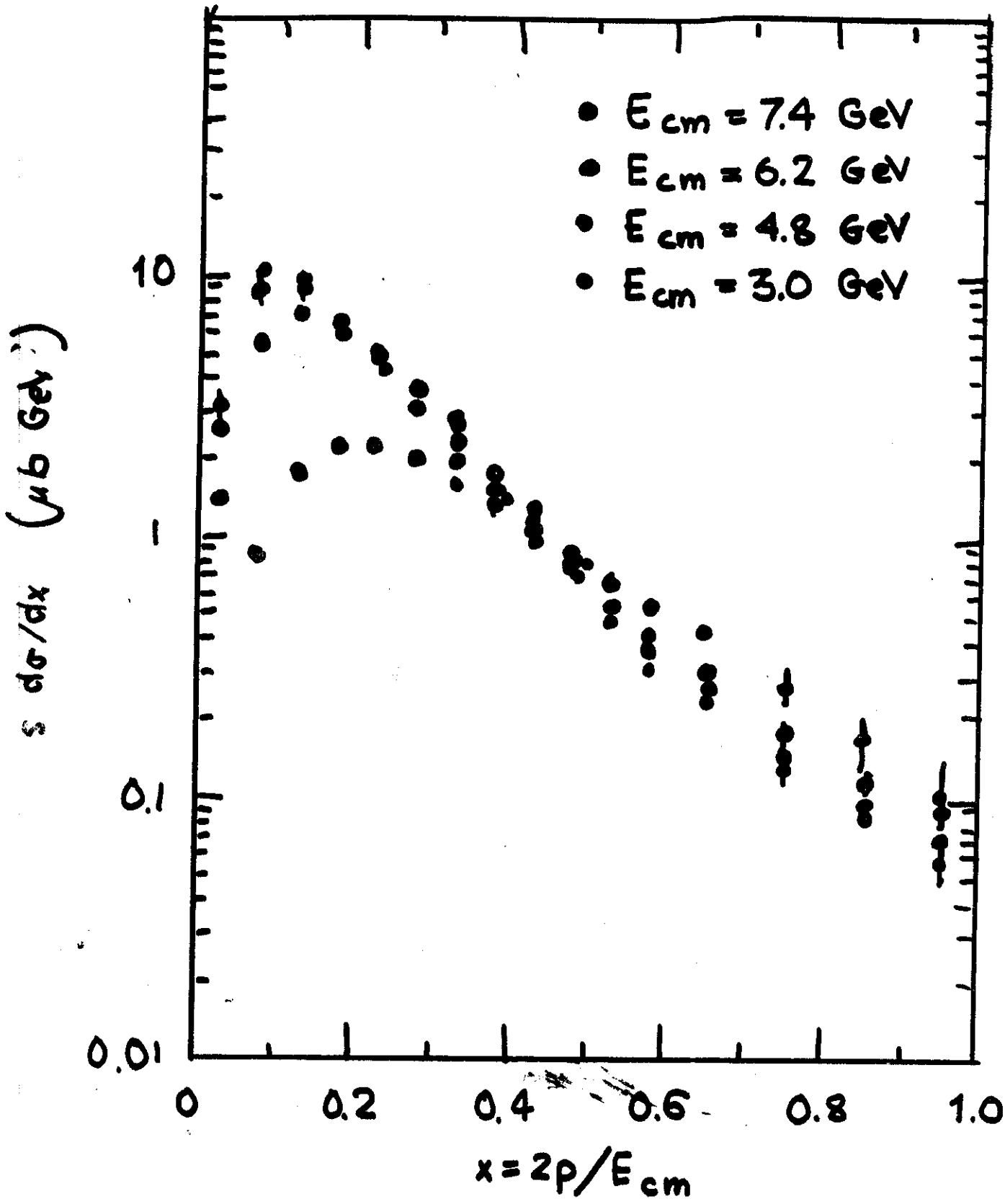
IT SUGGESTS VERY STRONGLY ASSOCIATED PRODUCTION WITH A MASS ≳ 2 GeV.

ALSO THERE IS A THRESHOLD AROUND $\sqrt{Q^2} = 4$ GeV

THIS IS THE BEST EVIDENCE SO FAR FOR PRODUCTION OF PARTICLES ASSOCIATED WITH A NEW QUANTUM NUMBER.


10
1
0.1
0
0.2
0.4
0.6
0.8
1.0
1.2
• $E_{c.m} = 7.4$ GeV
• $E_{c.m} = 6.2$ GeV
• $E_{c.m} = 4.8$ GeV
• $E_{c.m} = 3.0$ GeV
$\frac{1}{\sigma}\frac{d\sigma}{dP_\perp}$ (GeV^{-1})
$P_\perp$ RELATIVE TO JET AXIS
EVENTS WITH $x_{max} > .5$


10
1
0.1
0.01
• E_{cm} = 7.4 GeV
• E_{cm} = 4.8 GeV
• E_{cm} = 3.0 GeV
$\frac{d\sigma}{dy}$
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$y = \frac{1}{2} \log \frac{E+p_{\parallel}}{E-p_{\parallel}}$
RAPIDITY RELATIVE TO JET AXIS
($x_{max} > .5$).

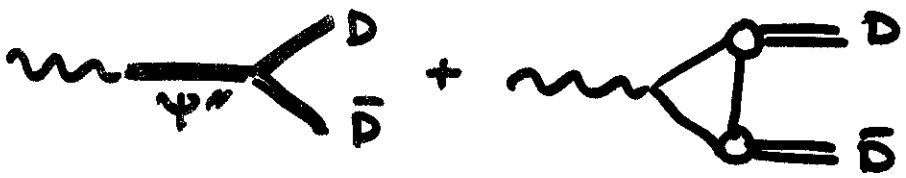

• E_{cm} = 7.4 GeV
• E_{cm} = 6.2 GeV
• E_{cm} = 4.8 GeV
• E_{cm} = 3.0 GeV
10
1
0.1
0.01
$s\, d\sigma/dx$ (μb GeV^2)
0
0.2
0.4
0.6
0.8
1.0
$x = 2p/E_{cm}$

- RISE IN R.

AT LEAST THREE CAUSES :

a) NON ASYMPTOTIC EFFECTS, THRESHOLDS ETC. (GATTO, PREPARATA '74)

b) CHARM - THRESHOLD



c) PRODUCTION OF HEAVY LEPTON (See PERL'S ANALYSIS) $\Delta R = 1$

ALL THESE EFFECTS, SURPRISINGLY, ARE LOCATED IN THE SAME REGION.

— ABOVE 5 GeV.

LITTLE OR NO STRUCTURE IS SHOWING UP IN THIS REGION;

$R \simeq 5.5$

JETS AND THE SPIN ½ NATURE OF QUARKS SEEMS TO BE EMERGING VERY CLEARLY.

THIS IS IN PERFECT AGREEMENT WITH THE PREVIOUS PICTURE; WHERE NON ASYMPTOTIC EFFECT ARE GRADUALLY DISAPPEARING, AND THE NEW DEGREES OF FREEDOM ARE ATTAINING REGIME CONDITIONS.

— CONCLUSIONS

THROUGH OUR UNCONVENTIONAL APPROACH TO THE DESCRIPTION OF THE QUARK DEGREE OF FREEDOM, WE BEGIN TO UNDERSTAND THE COMPLEX STRUCTURES OF e^+e^- PHYSICS.

THE NEW HEAVY QUARK (c), STRONGLY SUGGESTED BY THE "NEW" PHYSICS, APPEARS AS A WONDERFUL TOOL TO CLARIFY SOME INVOLVED ASPECT OF QUARK HADRODYNAMICS.

LOOKING IN THE FUTURE, BY 1980 PETRA AND PEP WILL PEEP INTO THIS PHYSICS WITH

$$Q^2 \simeq 1600 \text{ GeV}^2 \quad [Q^2 \leq 60 \text{ GeV}^2 \text{ TODAY}]$$

AND WILL PROBABLY BEGIN TO SHOW THE EFFECTS OF WEAK INTERACTION.

BY 1985 ORSO, A NEW MACHINE MAY POSSIBLY LEAD US TO Q^2 AS HIGH AS 4.10^4 GeV^2, RIGHT IN THE DOMAIN OF W-BOSONS.

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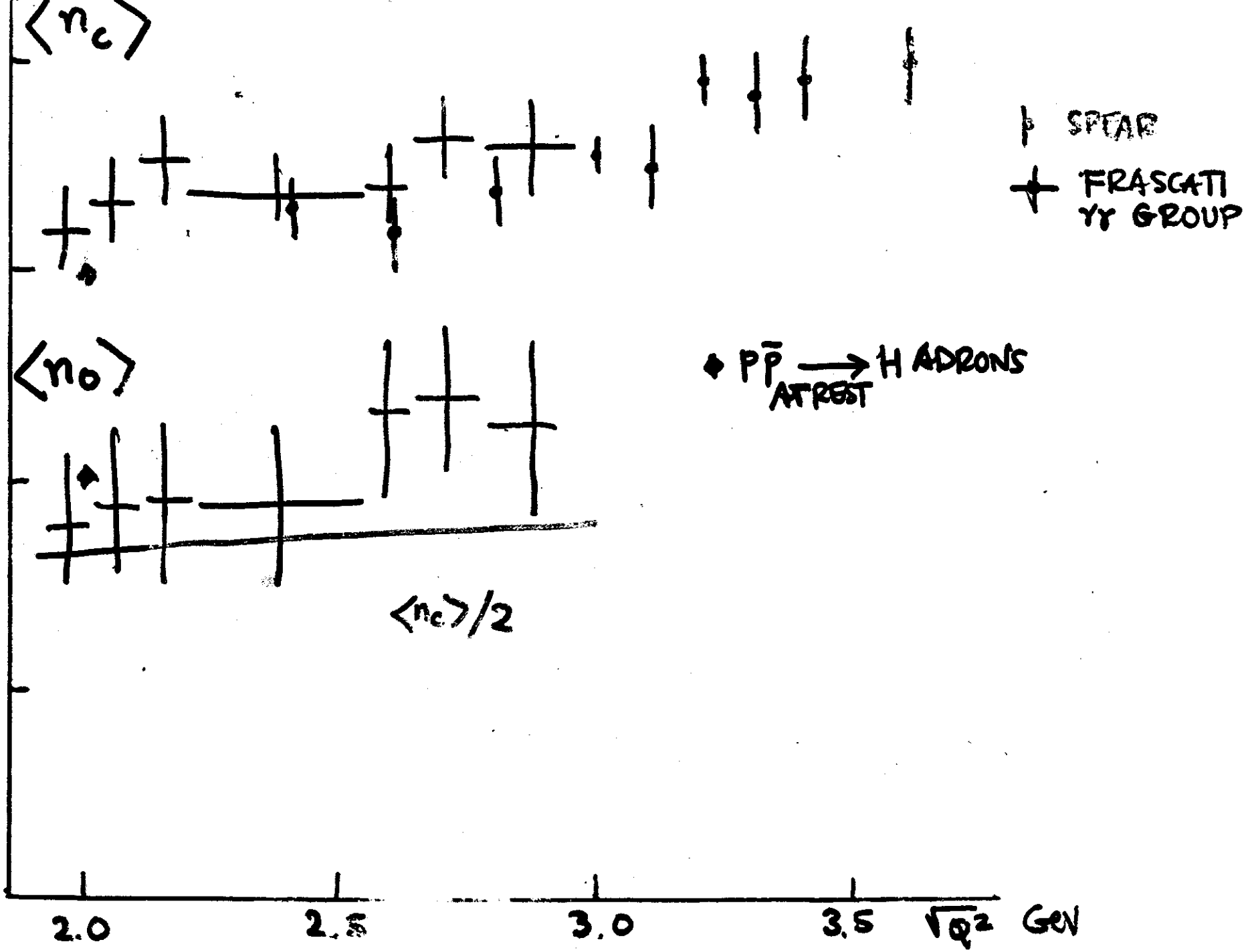
e^+e^- PHYSICS PROMISES TO BE THE MOST EFFICIENT WAY TO UNRAVEL NATURE'S MOST JEALOUS SECRETS!


4
3
2
1
⟨nc⟩
⟨no⟩
⟨nc⟩/2
SPEAR
FRASCATI
γγ GROUP
$P\bar{P}$ AT REST → HADRONS
2.0
2.5
3.0
3.5
$\sqrt{Q^2}$ GeV

$R = \frac{\sigma_t}{\sigma_{\mu\mu}}$

+ ADONE 88-GROUP
† SPEAR