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Hadrons and Glue at a Tau–Charm Factory

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HADRONS AND GLUE AT A TAU-CHARM FACTORY

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Abstract

I discuss the special opportunities that a Tau-Charm Factory offers for identifying gluonic excitations, hybrid charmonium and other exotic hadronic states.

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1 Introduction

The QCD Lagrangian contains quarks and gluons and the successes of perturbative QCD confirm their existence. The behaviour of QCD in the strongly interacting regime, "non perturbative QCD", is less well understood theoretically. There is copious data in the form of hadron spectroscopy and decays which needs "only" to be interpreted in order to establish the properties of the full nonperturbative theory. It is clear that $J = 1/2$ quarks and antiquarks are excitable degrees of freedom in the strongly interacting regime and there are also manifestations of QCD in the spectrum (e.g. hyperfine splittings between $J^p = 0^-$ and 1^- mesons) but a great unsolved question is whether gluonic degrees of freedom can be excited in the non-perturbative limit and be manifested as a new spectroscopy. If this spectroscopy exists then its systematics may reveal insights into the nature of confinement and other aspects of strong interaction dynamics. There are two parts to the general question: is glue excited
i) on its own, forming "glueballs", G;
ii) in the presence of quarks, forming "hybrids", H.

Theoretical prejudice and models tends to suggest that the primitive G and H_q (hybrids involving u, d, s flavours) exist in the 1-2 GeV mass region [1,2,3] and so may be mixed with, and confused with, the $q\bar{q}$ spectrum. Heavy hybrids, H_Q, are expected to occur on a mass scale [4,5,6]

$$m(H_Q) \simeq m(Q\bar{Q}) + 0(1\ GeV).$$

Thus for the charmed hybrids one anticipates H_c at or around the DD^* threshold. Given that the conventional charmonium spectroscopy is rather well understood below 4 GeV, and that the region at and immediately above threshold is a high priority at a Tau-Charm Factory (TCF), there is a good prospect that gluonic charmonium may be isolated by a dedicated survey of the region from threshold up to 5 GeV of c.m. energy. Indeed, if at a TCF one is unable to determine whether hybrid or gluonium exist, then we may have to accept that this is a very difficult experimental question.

2 Light Hadrons

2.1 At all energies

A strategy for isolating glueballs or other exotics involves first identifying all of the expected $q\bar{q}$ states. Those with $C = +$ can be produced in $\gamma\gamma$ collisions. $\gamma\gamma$ is useful because the γ couples to the flavour and spin of the constituents in well-understood ways. There are detailed predictions for the relative couplings of states in a given supermultiplet and also selection rules [7] that can help to complete the $q\bar{q}$ spectroscopy. Study is needed to determine the extent to which $\gamma\gamma$ physics can parasite on dedicated studies at various energies.

2.2 At the ψ

$\psi \to \gamma X$ has been one of the most productive processes in modern strong interaction studies. It still offers us more. Questions include
i) $\psi \to \gamma(C=+)$ complements the $\gamma\gamma \to (C=+)$. This can help identify gluonic versus $q\bar{q}$ states by their "stickiness" (a preference for the former process). [8]
ii) $\psi \to \gamma\eta$ (1440): is this a single state and if so what is it (see $\psi \to \gamma\gamma V$ below).
iii) $\psi \to \gamma\theta$ (1700): is this state 0^+ or 2^+ - or both? If 2^+ is present, what are the relative strengths of its production in different helicity states? [9] Can this distinguish gluonic from $q\bar{q}$ or K^*K^*? [10]
iv) $\psi \to \gamma\eta\pi\pi$. When looking for the enigmatic scalars f_0 (975), a_0 (980) [11, 12] or other states in the $\eta\pi\pi$ system, this "clean" channel has advantages over $p\bar{p} \to \pi\pi$ as in the Crystal Barrel.
v) $\psi \to \gamma X, X \to \rho$ or γV where $V = \rho\omega$ or ϕ makes use of the ideal flavours of the vector mesons to enable a flavour tag to be made of the state X. An $X(s\bar{s})$ decays preferentially to $\gamma\phi$ rather than to $\gamma\rho$ or $\gamma\omega$; $X(u\bar{u}+d\bar{d}) \to \gamma\rho, \gamma\omega$ rather than $\gamma\phi$. A glueball or flavour singlet produces all in the ratio

$$\Gamma(G \to \gamma\rho : \gamma\omega : \gamma\phi) = 9 : 1 : 2$$

Such studies are at the limit b of present statistics for $X = \eta$ (1440) and beyond them for θ (1700); of the order of 1000 events per state could be extracted from 10^9 total ψ decays at TCF. In addition to isolating the flavour contents of the $C = +$ mesons, for $J_X \geq 2$ the relative helicity amplitudes for $X \to \gamma V$ may also be measured and give information on the internal structure of X.

2.3 At the ψ (3684)

In a single week of running at ψ (3684) one may obtain $2 \times 10^6 \chi$ in $\psi' \to \gamma\chi$. This is already a factor of 10 higher then the present world total. Thus, running at ψ (3684) makes the TCF a χ-**factory**.

i) $\chi_J \to$ hadrons: This will provide much new information as data on χ decays are very sparse. When looking for resonances in sequential decays, e.g. $\chi_J \to A + \pi \to (n\pi) + \pi$, the knowledge of J helps to constrain the analysis. This may make significant inroads into understanding the spectroscopy of light hadrons.

ii) J-filter: Particular values of J may be advantageous for studying specific J^{PC} of high interest. Examples include the S-waves,

$$\chi_0 \to (f_0(975)\ or\ a_0(980)) + 0^{++}\ ;$$

$$\chi_0 \to \pi + 1^{-+}\ ,$$

and so χ_0 provides a gateway to the 0^{++} system and χ_1 directly accesses the $I = 1$ exotic partial wave $J^{PC} = 1^{-+}$. Any resonance in this wave simply cannot be $q\bar{q}$. Light hybrids, H_q, may occur in the 1.5-2 GeV region [2,3,6] and appear in

$$\chi_1 \to \pi H_1 \to \pi(\pi f_1).$$

iii) Flavour filter: These complement the $\psi \to VX, TX$ decays but with different quantum numbers accessible in the final state. In particular the flavours of the f_0 (975) may be probed in the relative strengths of [12]

$$\chi_{\to} f_0 f_2(1270) : a_0 a_2(1320) : f_0 f(1525)$$

which emphasise respectively the $f_0(n\bar{n}) : a_0(n\bar{n})$ and $f_0(n\bar{n})$.

3 Charmonium $c\bar{c}$

The theory is "clean" for the narrow states below $D\bar{D}$ threshold. The strategy must be to complete the spectroscopy of narrow states and to clarify the situation above DD and DD^{**} thresholds.

We have heard about the possibility to isolate narrow states in $p\bar{p} \to \chi$. The advantage in $p\bar{p}$ is in the resolution by which widths can be measured; a disadvantage is that it can be like hunting for a needle in a haystack. The missing (or recently discovered ${}^1P_1$) states [13] can be accessed at TCF as follows

$$\begin{array}{rcl}
\eta_c'(2^1S_0) & : & \psi' \to \gamma\eta_c' \\
1^{+-}({}^1P_1) & : & \psi^* \to \eta^1 P_1\ at\ \sqrt{s} >\ 4\ GeV \\
2^{--}({}^3D_2) & : & \psi^* \to \eta(2^{--})\ at\ \sqrt{s} >\ 4.5\ GeV \\
2^{-+}({}^1D_2) & : & \psi^* \to \gamma(2^{-+})\ at\ \sqrt{s} =\ 4.03\ GeV\ peak
\end{array}$$

In the last example, if the B.R. = $0(10^{-3})$ then we anticipate 10^3 events in a single day; which illustrates the promise of TCF.

It is important to run on the structures already identified at 4.04, 4.16 and 4.42 GeV to identify the branching fractions to hadronic final states (essentially **nothing** is known here). It will be interesting to measure the relative abundance of $DD : DD^* : D^*D^*(D = 0^-, D^* = 1^-)$ as well as the $D^{**}(0^+, 1^+, 2^+)$ in the higher mass bumps.

According to heavy quark effective theory, in the limit in which fine and hyperfine mass splittings between the D_J states vanish, one expects various characteristic production ratios to occur in the continuum [14,15,16]. These may be measured to test HQET, probe non-trivial configurations within the D_J states, help to isolate missing D_J states (e.g. $0^+, 1^+_{1/2}$) and to identify the internal structure of ψ^* states above 4 GeV.

Thus, as one example, one expects either in the continuum or on a $\psi^*({}^3S_1)$ state to find the ratios

$$D\bar{D} : \bar{D}D^* + \bar{D}^*D : D^*\bar{D}^* = 1 : 4 : 7$$

(up to $0(\alpha_s)$ corrections) [14], whereas for $\psi^*({}^3D_1)$ one expects [15]

$$\psi({}^3D_1) \rightarrow DD : DD^* + D^*D : D^*D^* = 1 : 1 : 4$$

Interesting deviations from these ratios may be anticipated near to threshold for

$$\frac{\Delta m(D^* - D)}{\sqrt{s - 4M^2}} \simeq 0(1)$$

At the ψ (4.04) for example there is the possibility that, if this state is 3^3S_1 say, the nodes in the 3^3S_1 wavefunction may lead to a significant distortion of the above ratios. As D, D^*, F, F^* are produced with different values of momentum it may be possible to map out momentum space nodes for the ψ^*.

Ref (17) has argued that the apparent large ratio in favour of D^*D^* at the ψ (4.04) may be an example of this. Analogous arguments previously applied to the ψ (4.4) [18], when combined with the now known values of the $\Delta m(D^{**} - D)$, suggest that D_2^{**} may be copiously produced at the ψ (4.42). It is important to study the structures in the e^+e^- total cross-section above the charm threshold to see what the relative D_J content within each is, both to clarify which values of energy are optimal for producing particular states D_J and to distinguish true $\psi^* c\bar{c}$ resonances from threshold effects in $e^+e^- \rightarrow D_{J_1}D_{J_2}$.

4 Beyond $Q\bar{Q}$: $Q\bar{Q}g$ Hybrids

A summary of theoretical predictions for hybrid charmonium is:
i) **Mass** 4.4 ± 0.4 GeV (or 4.2 ± 0.2 GeV if less conservative). This range spans lattice QCD [5], MIT Bag model [2,4] and flux tube models [3,6].
ii) **Exotic quantum numbers**: All models include $J^{PC} = 1^{-+}$ in the lowest mass supermultiplet of hybrids. Flux tube models also expect the exotics 0^{+-} and 2^{+-} to be low lying.

iii) **Decay modes** : If $M > 4.3$ GeV the dominant decays will be to DD^{**} (i.e. $S+P$ states) in which case widths should be typically hadronic (perhaps 100 MeV if phase space allows). [3,6,19]

If $M < 4.3$ GeV widths will be reduced (*perhaps* ≤ 10 MeV) and the significant decays may include cascades into charmonium, $H_c \rightarrow \chi_c +$ hadrons, with some DD and DD^*. The relative importance of these modes is model dependent.

iv) **Production**. All models anticipate $J^{PC} = 1^{--} H_c$ in the lowest supermultiplet and so they will be accessible directly in $e^+e^- \rightarrow H_c$. In flux-tube models the flux has a transverse excitation around the $Q\bar{Q}$ axis and the $Q\bar{Q}$ are themselves in an orbitally excited state with a P-wave centrifugal barrier. Thus one may anticipate that

$$\Gamma^{ee}(\psi^3S_1) > \Gamma^{ee}(\psi_g) > \Gamma^{ee}(\psi^3D_1)$$

In the MIT bag approach, $0(\alpha_s)$ mixing between $^3S_1$ and $c\bar{c}g$ will drive the leptonic width and a similar pattern may be anticipated. For light quarks, where such suppression is not dramatic, one may anticipate a reasonable $\Gamma^{ee}(V_g)$ but this is confounded by the difficulty of unambiguously identifying the states among the detailed $\bar{q}$ spectroscopy. By contrast, for $b\bar{b}$ systems the spectroscopy is clean but $\Gamma^{ee}(\Upsilon_g)$ is more strongly suppressed (e.g. there is no evidence for any $\Upsilon(^3D_1)$ states in e^+e^- annihilation). The Catch-22 is that clean spectroscopy equates with minimal mixing (good news) but minimal mixing equates with a small Γ^{ee} for all but $^3S_1$ states. This argument suggests that $c\bar{c}$ may provide on balance a useful compromise: non-trivial mixing (e.g. $^3D_1$ states do appear in e^+e^- annihilation) but with a manageably clear spectroscopy.

For a vector hybrid below 4.4 GeV one may anticipate as order of magnitudes estimates $\Gamma_T = 0$ (10 MeV), Γ^{ee} 0(0.1 keV). This would give a local peak in $R \equiv \sigma(e^+e^- \rightarrow$ hadrons$)/\ \sigma(e^+e^- \rightarrow \mu^+\mu^-)$ of ΔR 0(1-2) and > 10 events per second at TCF. Allowing an order of magnitude for conservatism, a scan of R from threshold to the highest machine energy should be sensitive to

$$\Delta R = 0.1, \quad \Delta E = 5\ MeV.$$

This requires about 2000 events per energy setting. For $\ell = 10^{33} cm^{-2} sec^{-1}$, yielding 10 events/sec, one could scan this entire energy range in a week. A monochromator, enabling a very fine scan with high statistics, is desirable to reveal, and to clarify the nature of detailed structures in this region of resonances and open thresholds.

If above 4.4 GeV, $\psi_g, \psi(^3S_1)$ and $\psi(^3D_1)$ all have couplings to DD^{**} (S and P state charmed mesons). This will cause mixing and also coupling to e^+e^-. Thus one anticipates an excess of $J^{PC} = 1^{--}\psi$ states relative to that in the naive quark model. A strategy will include first determining the spectrum and then identifying the pattern of 0^{-+} or 1^{-+} states nearby.

Estimates of hyperfine mass shifts for hybrids suggest that 0^{-+} and 1^{-+} (exotic) are, respectively, of order 50 MeV and 25 MeV lower in mass than the 1^{--} hybrid. For $\psi(^3S_1)$ there should be an accompanying 0^{-+} state but no 1^{-+}. For $\psi(^3D_1)$ there is neither a 0^{-+} nor a 1^{-+} partner. These three distinct patterns are illustrated in fig 1.

The matrix element for the radiative transition $\psi_g \rightarrow \gamma\eta_{cg}$ is essentially the same as that for $\psi \rightarrow \gamma\eta_c$. The relative rates will depend on the mass splitting

$$\Gamma(\psi_g \rightarrow \gamma\eta_{cg}) \sim \Gamma(\psi \rightarrow \gamma\eta_c)\left(\frac{\Delta M(\psi_g - \eta_{cg})}{\Delta M(\psi - \eta_c)}\right)^3$$

If $M(\eta_{cg} < 4.3$ GeV) and its total width is thereby only a few MeV, it may be possible to detect the 20-50 MeV photons which accompany the transitions to 0^{-+} and 1^{-+}. However if $M(\eta_{cg} > 4.3$ GeV), the strong decays to DD^{**} will reduce the radiative branching ratio.

Instead of directly forming a ψ_H hybrid it may be possible to produce them [20] from e^+e^- at $\sqrt{s} \sim 5$ GeV. In the continuum process $e^+e^- \rightarrow c\bar{c}$, the separating quarks will be accompanied by a flux tube that in general will contain a superposition of modes including excitations or "hybrid" states. The dynamics of the flux tube may cause the cascade preferentially to contain S-wave mesons in a relative P-wave e.g. $\psi_H \rightarrow \eta\psi^*$ (where ψ^* could be ψ_H or normal ψ). The ψ^* state in turn may cascade into ψ via $\psi^* \rightarrow \eta\psi$ or $\psi^* \rightarrow \pi\pi\psi$. Thus running e^+e^- at high energy and triggering on ψ in the final state may reveal ψ^* in the $(\eta\psi)$ or $(\pi\pi\psi)$ invariant mass. These ψ^* will include states that have already shown up in the direct process $e^+e^- \rightarrow \psi^*$; it will be particularly interesting if ψ^* states which show up prominently in this "contimuum cascade" are suppressed in $e^+e^- \rightarrow \psi^*$. Thus in summary: seek hybrid states in

$$e^+e^- \rightarrow \eta\psi_H \rightarrow \eta(\eta\psi).$$

The qualitative pattern of such transitions is illustrated in fig 2.

Triggering on ψ may enable access to other exotic states that are not directly produced in e^+e^- annihilation. For example, there is considerable discussion about the possible existence of "meson-molecules"; the a_0 (980) and f_0 (975) being $K\bar{K}$ states and a possible KK^* state occurring in the 1^{++} partial wave around 1400 MeV. These suggest the question: is there molecular charmonium? Indeed, the apparent enhancement of $D^*\bar{D}^*$ around 4.04 GeV has been suggested as such. [21]

A clear example of such states would be if $I = 1$ states occur, thus

$$\begin{pmatrix} M_0 \\ M_1 \end{pmatrix} = \frac{1}{\sqrt{2}}(D^0D^0 \pm D^+D^-)$$

To the extent that $e^+e^- \rightarrow c\bar{c}$ initially, then only $I = 0$ direct channel bound states are formed:

$$e^+e^- \rightarrow \not\rightarrow (D\bar{D})_1$$

However, an $I = 1$ $D\bar{D}$ molecule state may be accessed by cascading, and in turn, would be revealed by its subsequent cascade into $\psi\pi$:

$$e^+e^- \to (c\bar{c}) \to \pi(D\bar{D})_1 \to \pi(\pi\psi)$$

This can be performed at any incident e^+e^- energy. An enhancement in the $\pi\psi$ state would signal either isospin violating decays of charmonium or the existence of isovector charmonium. Either result involves important information.

5 Which energies are optimal for hadron physics?

As an initial proposal for discussion I list some "interesting" energies, the "factory" physics immediately relevant, their associated relevance to the questions raised in this talk and guides as to the typical events in nominal running time.

The ψ and ψ' can provide increases in world statistics even if TCF operates at 10^{32} luminosity. Clearly early running of the machine will concentrate on these two peaks. A fine detail scanning of R, with ability to discriminate $\Delta R = 0.1$ on $\Delta E = 5$ MeV can be achieved in a week at 10^{33}, in 3 months at 10^{32}. There should be dedicated runs at 4.03 (see also CP violation review here), 4.16 (D_s factory), 4.42 (Λ_c factory) and at 4.8 - 5 GeV (Ξ_c and Ω_c). The first three bumps should be clarified as resonant, multiple resonances or as threshold effects; their branching ratios must be established. In addition higher spin D_J^{**} should be sought just above their production thresholds where the cross section peaks. At the top energy one should see if $e^+e^- \to Df_0\bar{D}$ or $Da_0\bar{D}$ is significant (as may occur in Gribov's theory of confinement [12]).

The ψ (3772) is a natural D factory. There is a tantalising glitch in three separate experiments which has $\Delta R \simeq 0.2$ at 3.9 GeV. This seems too sharp to be a threshold; it may be a clue to vector hybrid and is at least a place to start.

I am indebted to my collaborator Ted Barnes for discussions and comments in preparing this contribution.

References

[1] T. Burnett and S. Sharpe, Ann. Rev. Nucl. Part. Sci. **40**, 327 (1990).

[2] T. Barnes and F.E. Close, Phys. Lett. **116B**, 365 (1982);
M. Chanowitz and S. Sharpe, Nucl. Phys. **B222**, 211 (1983);
T. Barnes, F.E. Close and F. de Viron, Nucl. Phys. **B224**, 241 (1983).

[3] N. Isgur and J. Paton, Phys. Rev. **D31**, 2910 (1985).

[4] P. Hasenfratz, R. Horgan, J. Kuti and J. Richard, Phys. Lett. **95B**, 299 (1980).

[5] C. Michael and S. Perantonis, Nucl. Phys. **B347**, 854 (1990).

[6] T. Barnes, F.E. Close and E. Swanson, RAL-93- (in preparation)

[7] T. Barnes, F.E. Close and Z-P. Li, Phys. Rev. **D43**, 2161 (1991); E. Ackleh, T. Barnes and F.E. Close, Phys. Rev. **D46**, 2257 (1992).

[8] M. Chanowitz, Nucl. Phys. **A527**, 61 (1991).

[9] F.E. Close and Z-P. Li, Phys. Rev. Lett. **66**, 3109 (1991).

[10] F.E. Close and Z-P. Li, Z. Physik **C54**, 147 (1992);
K Dooley, E. Swanson and T. Barnes, Phys. Lett. **B275**, 478 (1992).

[11] R.L. Jaffe, Phys. Rev. **D15**, 267 (1977); **D17**, 1444 (1978);
N. Isgur and J. Weinstein, Phys. Rev. Lett. **48**, 569 (1982); Phys. Rev. **D27**, 588 (1983); Phys. Rev. **D41**, 2236 (1990);
F.E. Close, N. Isgur and S. Kumano, Nucl. Phys. **B389**, 513 (19913.

[12] F.E. Close, Y. Dokshitzer, V.N. Gribov, V. Khoze and M. Ryskin, RAL-93-049.

[13] K. Seth, these proceedings

[14] A. de Rujula, H. Georgi and S. Glashow, Phys. Rev. Lett. **37**, 398 (1976);
T. Mannel, W. Roberts and Z. Ryzak, Nucl. Phys. **B368**, 204 (1992).

[15] F.E. Close and G.J. Gounaris, Phys. Lett. (in press).

[16] P. Bialas, F.E. Close, J. Korner and K. Zalewski, RAL-93- (in prep).

[17] A Le Yaouanc, L Oliver, O. Pene and J. Raynal, Phys. Lett. **71B**, 57 (1977).

[18] A Le Yaouanc, L Oliver, O. Pene and J. Raynal, Phys. Lett. **71B**, 397 (1977).

[19] F.E. Close and H.J. Lipkin, Phys. Lett. **B196**, 245 (1987);
H.J. Lipkin, Phys. Lett. **B219**, 99 (1989);
F. Iddir et al, Phys. Lett. **B205**, 564 (1988).

[20] We thank D. Bugg for this suggestion.

[21] See also N. Tornqvist, Phys. Rev. Lett. **67**, 556 (1991); and P. Ball, H. Dosch and M. Shifman, Phys. Rev. **D47**, 4077 (1993).

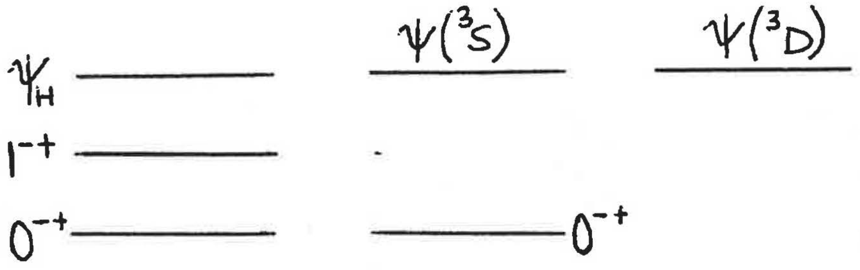
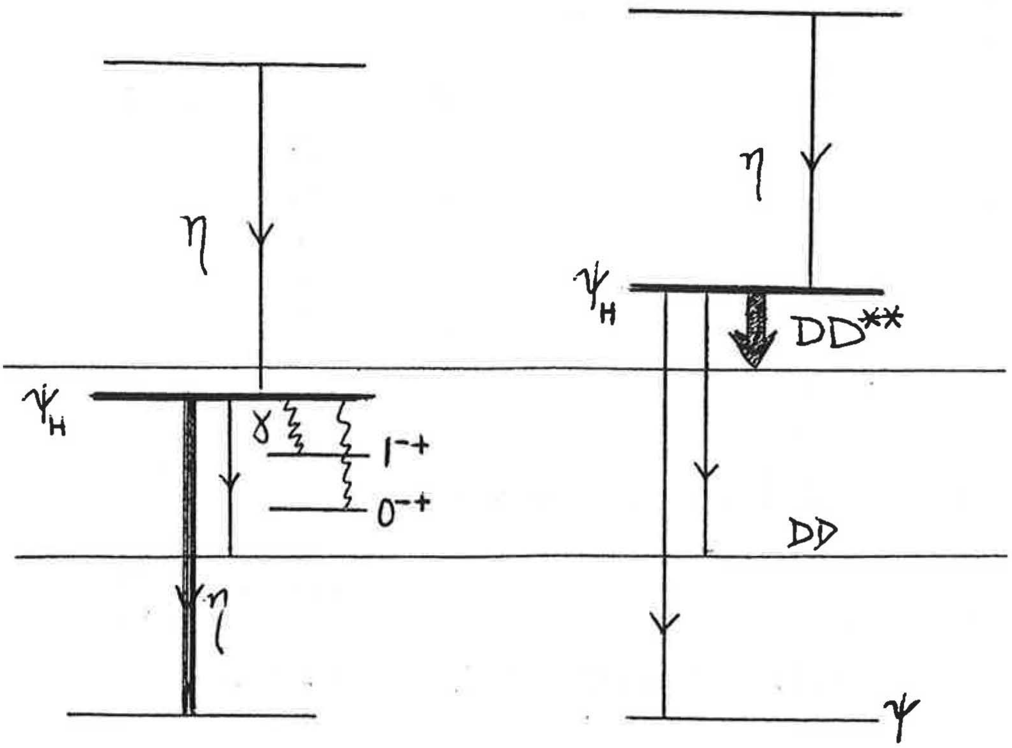


Figure 1. Qualitative picture of vector states and accompanying $C = +$ states for hybrid (ψ_H) and $^3S_1$ or $^3D_1$.

Figure 2. If ψ_H is above/below 4.3 GeV the dominant decays (solid lines) differ as do the anticipated order of magnitude of widths. The pattern of cascades from continuum "$c\bar{c}$ + string" to ψ_H and eventually to ψ are illustrated.



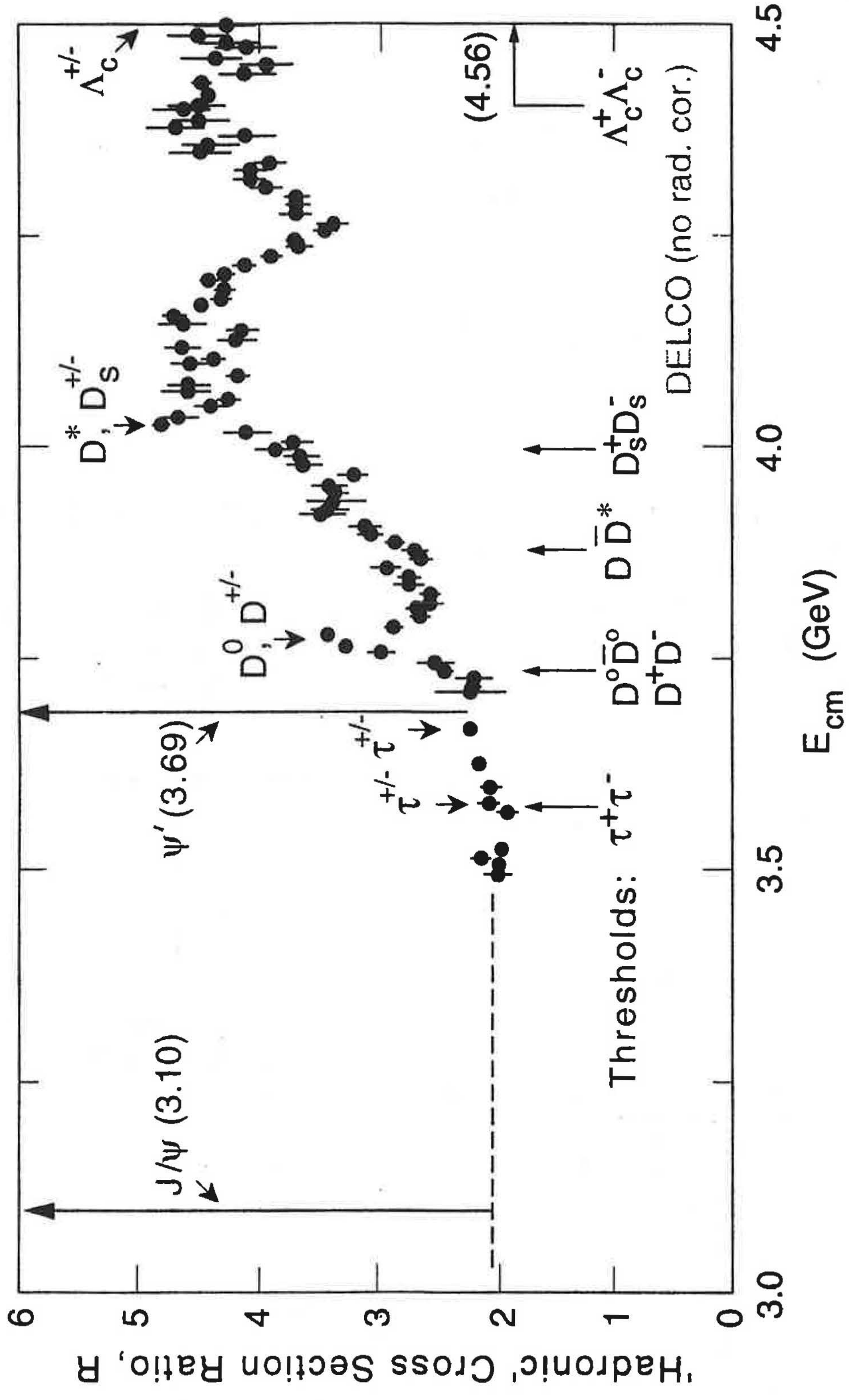


Figure 3. The hadronic cross section in the TCF region from DELCO.

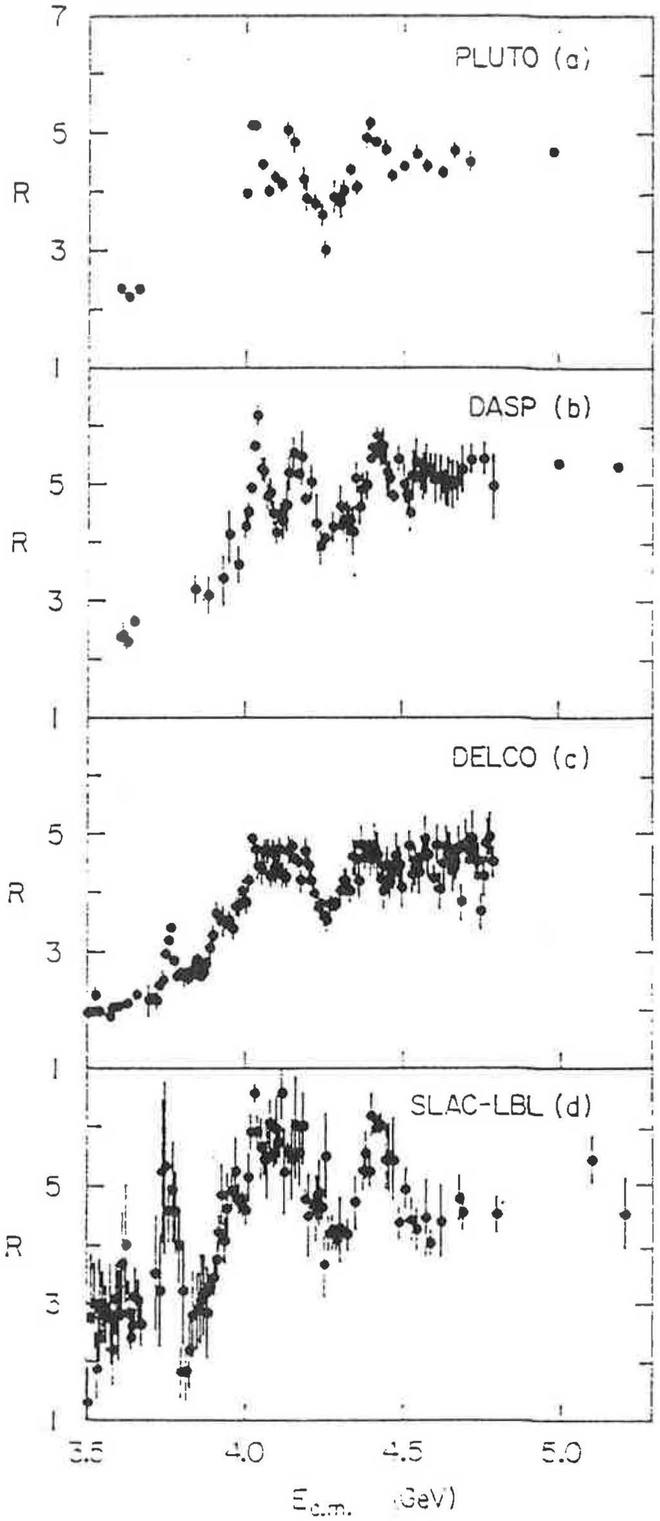


Figure 4. Comparison of DELCO with other experiments. DELCO is not radiatively corrected; other experiments are.