

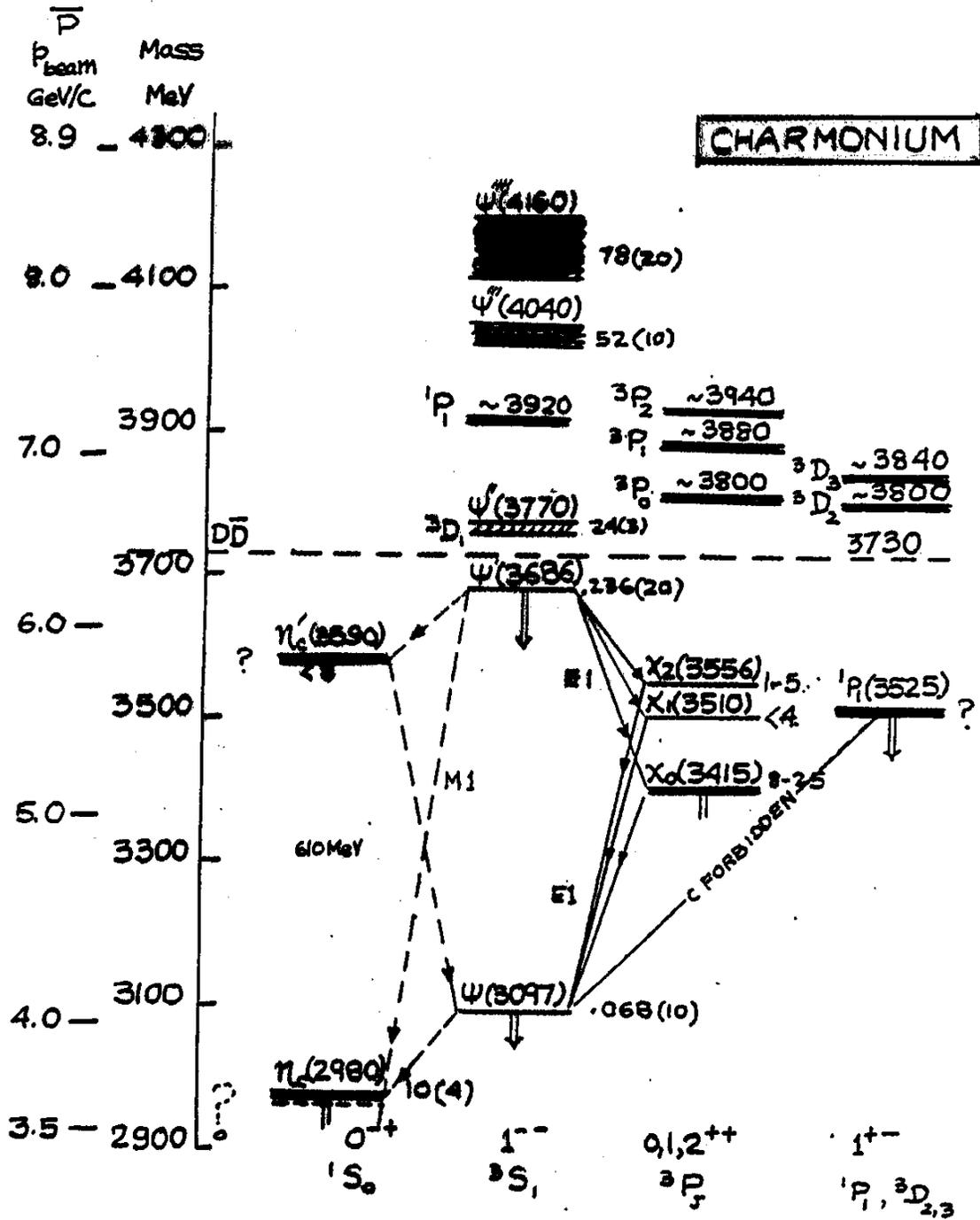
**CHALLENGES & OPPORTUNITIES
IN ANTIPROTON PHYSICS
IN THE CHARMONIUM REGION**

**Kamal K. Seth
Northwestern University
Evanston, IL 60208**

THE GREAT VARIETY OF ANTIPROTON PHYSICS

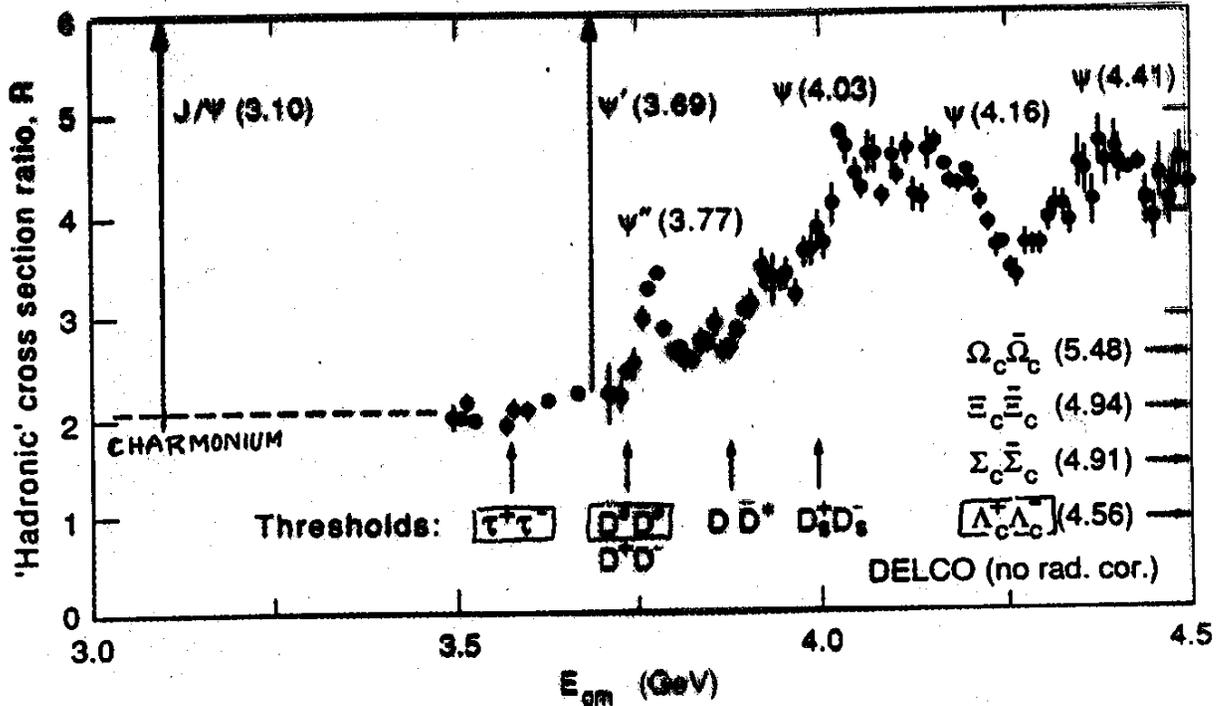
The wide range of physics which can be addressed with antiprotons has been discussed many times before in the context of KAON and SUPERLEAR. It extends from atomic, to nuclear, to particle physics. Some of the broad areas of interest are:

- Antihydrogen physics (at 10^{-8} GeV)
 - Symmetry tests (TCP) to parts in 10^{18} by $R_H - R_{\bar{H}}$.
 - Gravitational equivalence violation to parts in 10^8 .
 - Metastable \bar{p} He⁺ spectroscopy: precision determination of α , $\mu_{\bar{p}}$, Lamb shift, etc.
- Proton-antiproton physics (≤ 3 GeV)
 - Annihilation physics
 - $\bar{p}p$ interaction
- Light quark spectroscopy (≤ 3 GeV)
 - à la Crystal Barrell at LEAR: glueball searches, $\mathcal{O}P$
- Heavy quark spectroscopy (≥ 3 GeV)
 - Charmonium spectroscopy
 - Open charm spectroscopy
 - Charmed hybrids
 - $D\bar{D}$ mixing and CP invariance
- Charm in nuclei (≥ 3 GeV)
 - J/ψ interaction in nuclei
 - color transparency
 - subthreshold charm production



The first thing to notice is the incredible richness of this two-body spectrum. Just imagine how much you could learn if the deuteron had 8 bound states, instead of 1. (about NN)

The Charmonium Region



The physics reach of this energy region is clear from the various thresholds that open in this energy range:

Charmonium Physics: $E_{cm} \geq 2.9 \text{ GeV}$

Tau Physics: $E_{cm} \geq 3.6 \text{ GeV}$

Open Charm Physics: $E_{cm} \geq 3.8 \text{ GeV}$

- All of it is precision physics.
- All of it is as exciting as physics gets.

Within the allotted time, I will concentrate on Charmonium physics, and only titillate you about possibilities in tau and open charm physics!

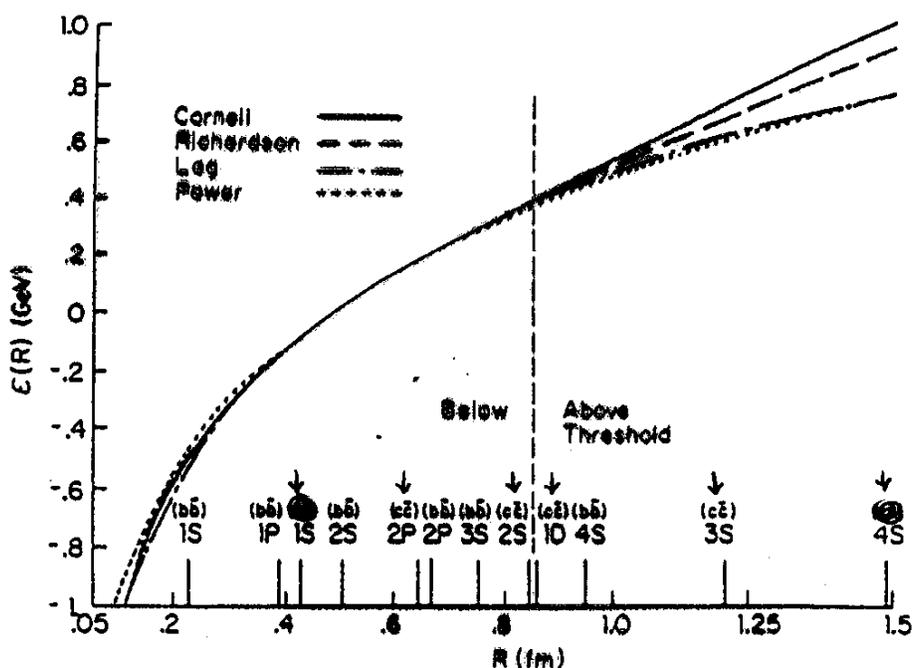


FIGURE 5
Comparison of four phenomenological central potentials.

- How well do we understand QCD ?

It never ceases to amaze me that many smart physicists, who should know better, think that QCD is a done deal.

As Bjorken has emphasized again and again, of the two pillars on which QCD stands:

Asymptotic freedom, &
Confinement

we have very little understanding of at least one,
Confinement

- The manifestations, the beauty, and the problems of confinement are themselves confined to low energies, i.e., in the spectroscopy of charmonium, open charm, & bottomonium.

WHY CHARMONIUM?

FORTUNATE FACT

- QCD interactions are flavor independent.
Study them between any flavor of quarks

u,d,s,c,b,t

WHAT MAKES THE CHOICE

- Capability to make precision measurements
Large cross sections. Hierarchy:

(u,d) - millibarns

(s,c) - microbarns → nanobarns

(b,t) - picobarns → femtobarns (?)

- Freedom from RELATIVISTIC TROUBLES

$\langle v^2/c^2 \rangle \cong 1$ for u, d mesons

$\cong 0.75$ for $s\bar{s}$

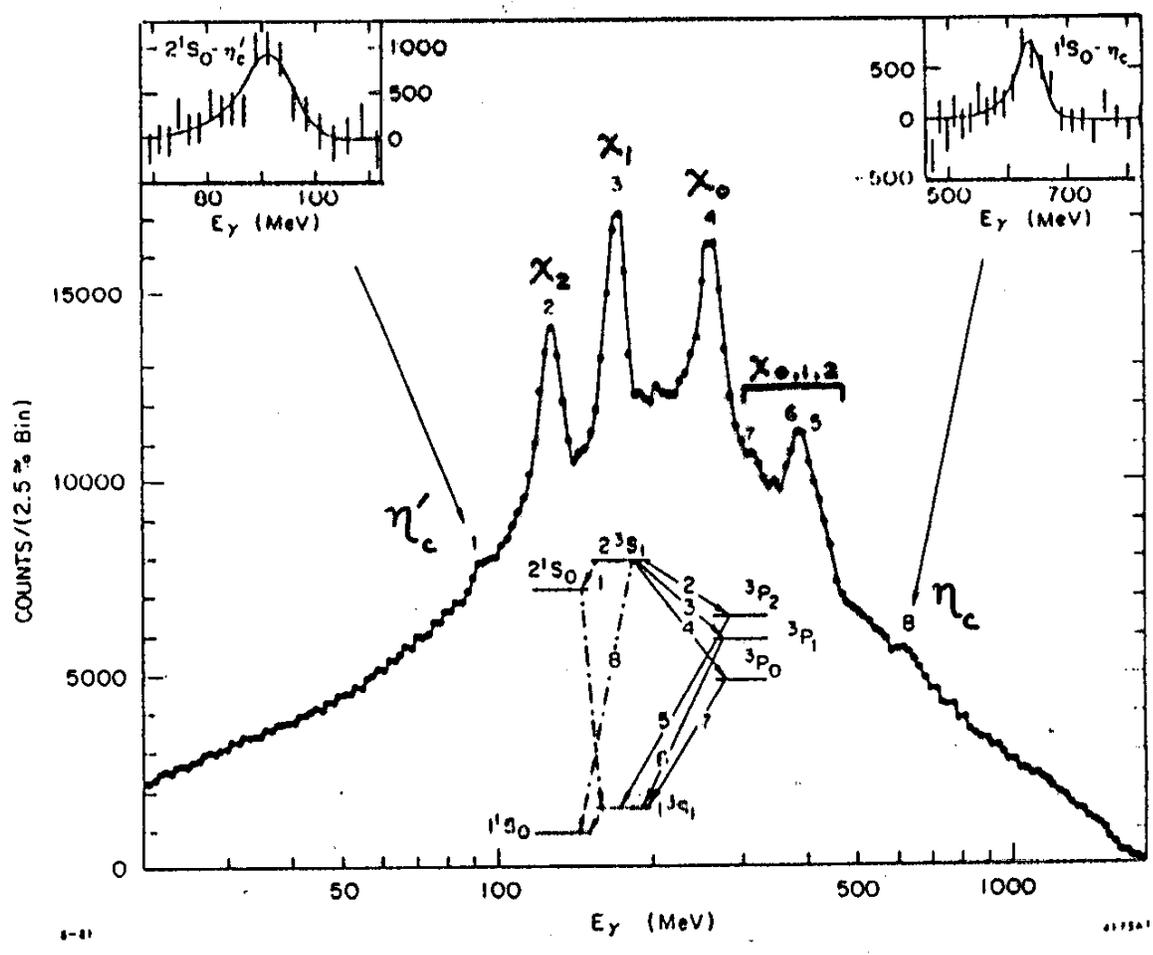
$\cong 0.24$ for $c\bar{c}$ charmonium

$\cong 0.08$ for $b\bar{b}$ beautionium

- Compromise best - **CHARMONIUM**

Charmonium by e^+e^- annihilation

- Prior to 1985 all $c\bar{c}$ spectroscopy by e^+e^- annihilation mediated by a 1^{--} virtual photon.
- Only Triplet 3S_1 states directly formed Masses and widths well (?) measured.
- Triplet 3P_J states only populated by E1 radiative transitions. Only upper limits of widths determined
 $\Gamma(\chi_0) = 8-21 \text{ MeV}$, $\Gamma(\chi_1) \leq 3.8 \text{ MeV}$, $\Gamma(\chi_2) = 0.8-4.9 \text{ MeV}$
- Singlet states "seen" as bare pimples in the photon spectra. Highly controversial results. 1P_1 , η'_c not found.
- Above $D\bar{D}$ threshold ($>3730 \text{ MeV}$) - A veritable chaos
 Claims for ψ'' , ψ''' , ψ^{IV} ... identification. Unreliable widths
 No $1D_J$ or $2P_J$ states observed.
- Hadronic decays: Except for J/ψ , very few measured
 Majority of decays have $\pm 35\%$ - $\pm 75\%$ errors in BR.
 Examples: The decay $\eta_c \rightarrow p\bar{p}$ is very important because it is forbidden by helicity conservation rule of QCD, and E760 depends on it for η_c formation.
 Its BR is based on 18 ± 6 (DM2) and 23 ± 11 (MK3) events!
- Less than 10% of the annihilation decays of ψ' have ever been identified



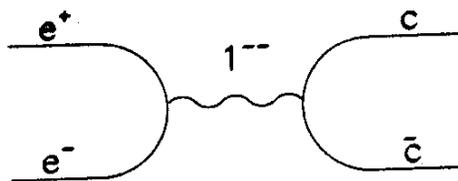
Notice the η_c, η_c' pimples!

THE THREE ERAS OF CHARMONIUM PHYSICS

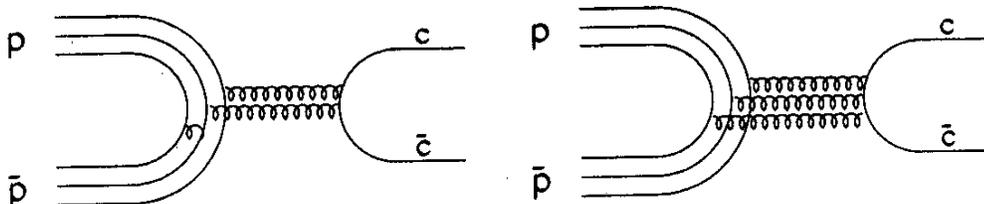
THE PAST (1974-85): e^+e^- annihilation, (SLAC, DESY, ORSAY)

Discovery physics. Limited by

- Only 1^{--} states could be directly populated.
- Poor mass resolution.
- Lack of precision



THE PRESENT (1985 -) $\bar{p}p$ annihilation, (FERMILAB)



Precision Spectroscopy

- Direct formation of states of any J^{PC} via 2 or 3 gluons.
- Superb mass resolution.
- But, small cross sections

REACHING THE LIMITS OF ITS CAPABILITY + LIFE EXPECTANCY

THE FUTURE (when? where?)

- Once, some of dreamt of a super tau-charm factory. But it is now clear that it is not to be.
- The only alternative, with comparable capabilities, is a super \bar{p} facility, with 10^{2-3} more intensity, even better mass resolution by improved cooling, and above all, a state-of-the-art detector. Where? FNAL, GSI, JHP, somewhere!

THE THEORETICAL SITUATION

- All theoretical predictions are based on pQCD.
- All analytic formulae are based on analogies with positronium, i.e., are true only for the 'Coulombic', or one gluon exchange, part of the interaction.
- Relativistic effects are generally not taken into account.
- Only first order radiative corrections are available, and they are often so large ($\sim 100\%$) as to be meaningless.
- Generally, no predictions for specific hadronic decays are available.

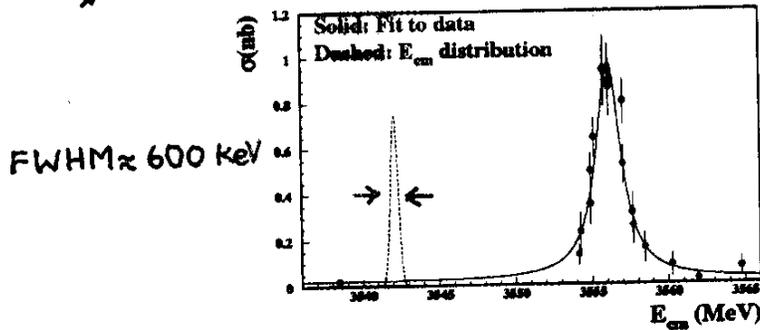
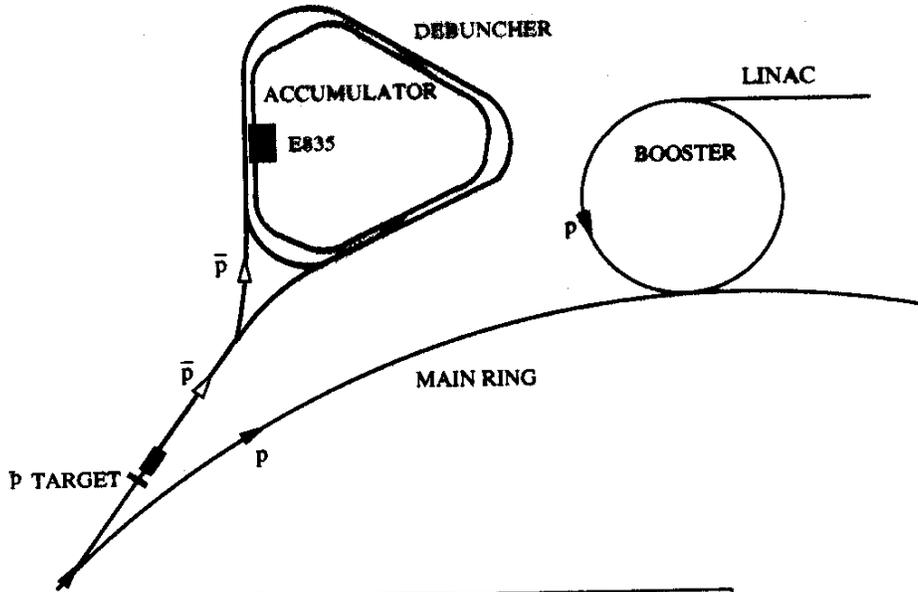
$(^1S_0, ^3P_0, ^3P_2) \rightarrow gg,$ yes,

$^3S_1 \rightarrow ggg, ^3S_1 \rightarrow \gamma gg$ yes,

$(gg, ggg) \rightarrow (h_1, h_2, \dots)$ no,

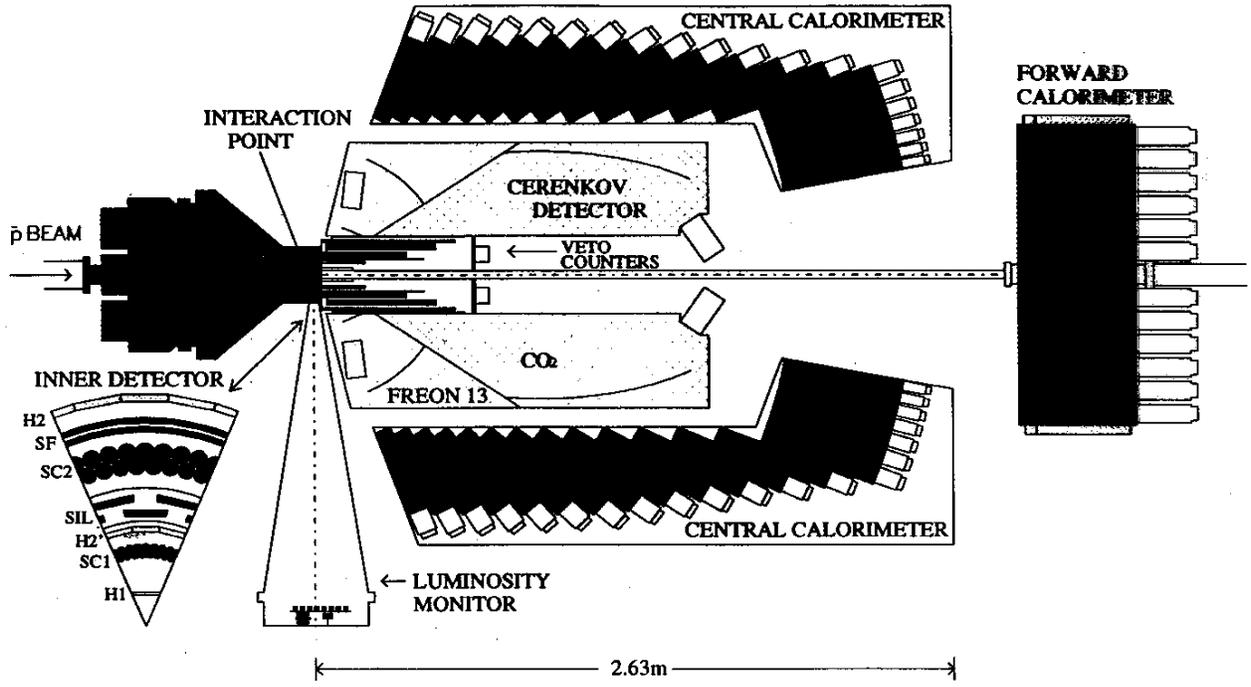
except in a few special cases for $m\bar{m}, b\bar{b}$ decays.

Fermilab Antiproton Source



- Energy Precision: \approx 1 part in 10^5 at J/ψ
- Mass Resolution: \sim 1 part in 10^4 , 300-600 keV
- Maximum Luminosity: $1 \times 10^{32} \text{ cm}^2\text{s}^{-1}$
- $\sigma(p\bar{p} \rightarrow e^+e^-)_{min}$: 1 picobarn out of $\sigma_T(p\bar{p}) = 70 \text{ mb}$
 \approx 1 part in 10^{11}
- Maximum \bar{p} momentum = 9 GeV/c, $\sqrt{s}_{max} = 4.3 \text{ GeV}$
 \bar{p} momentum for $(b\bar{b})_R$: 58 GeV/c, $\sqrt{s}_{max} = 10.5 \text{ GeV}!!$

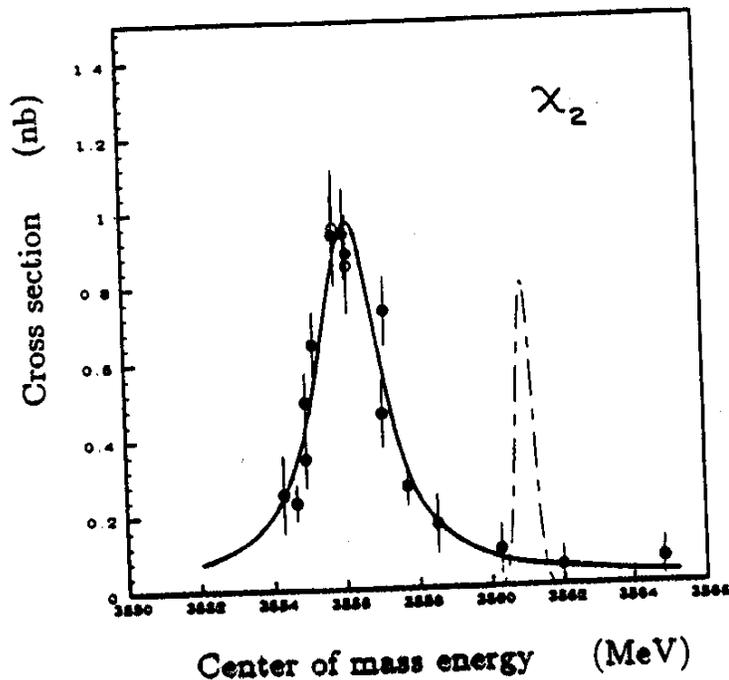
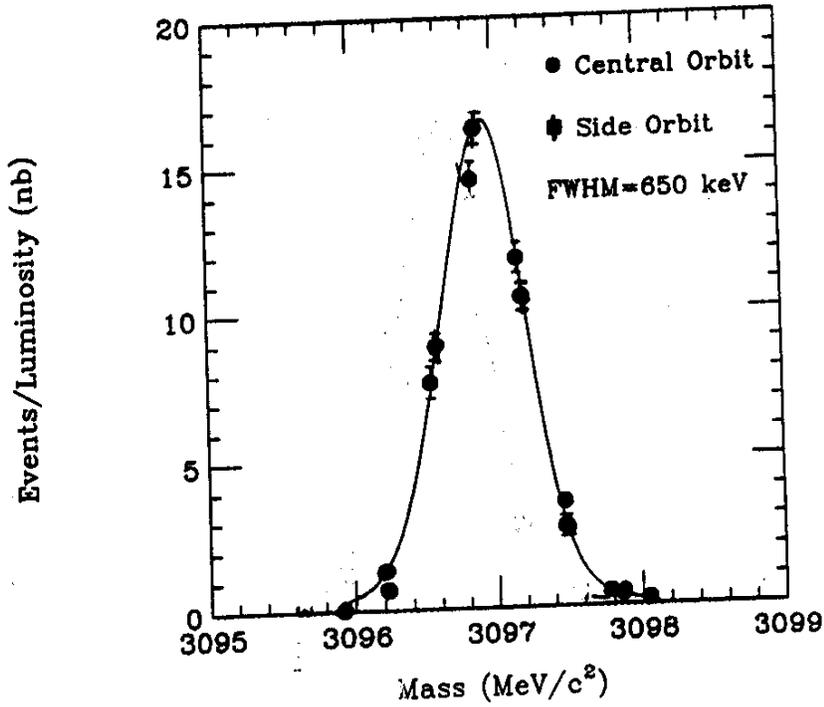
E835 EQUIPMENT LAYOUT



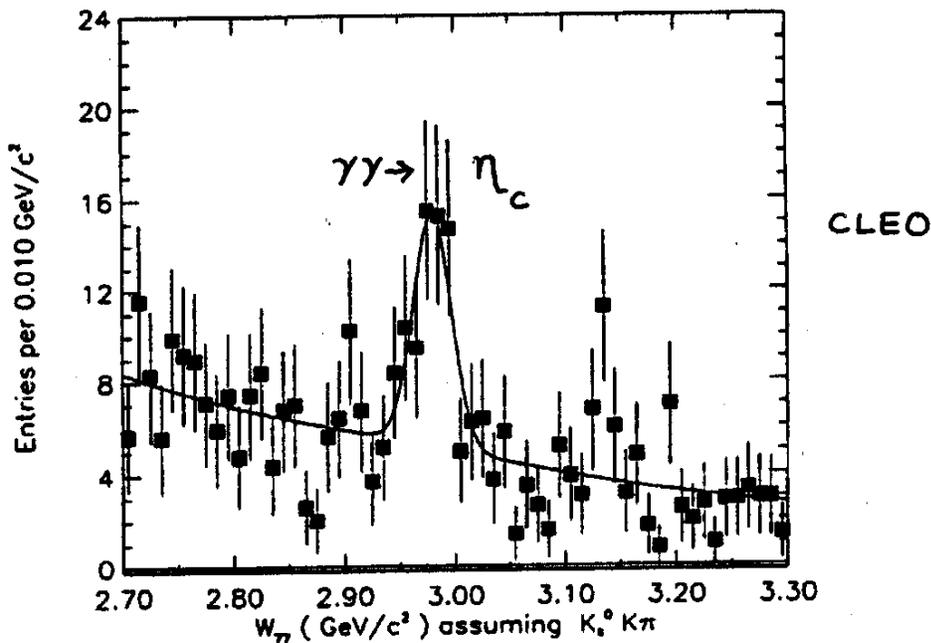
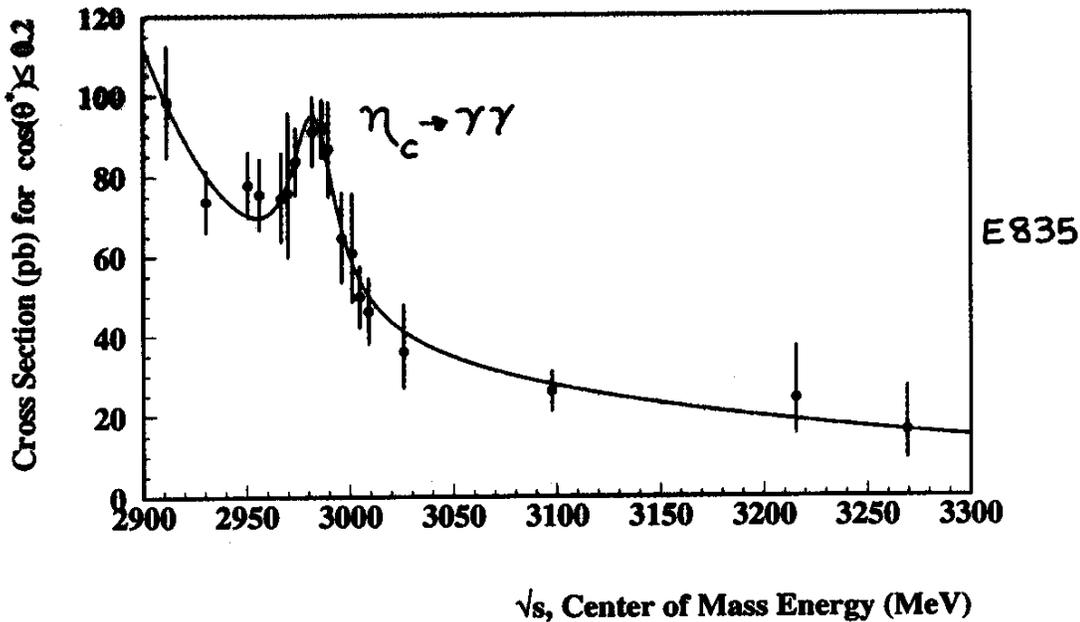
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- Orbit length calibration gives energy to 1 part in 10^5
- Stochastic cooling gives mass resolution of 1 part in 10^4

J/ψ Double Scan



Charmonium Spectroscopy: studies of $\bar{p}p \rightarrow c\bar{c} \rightarrow \gamma\gamma$ in Fermilab E835

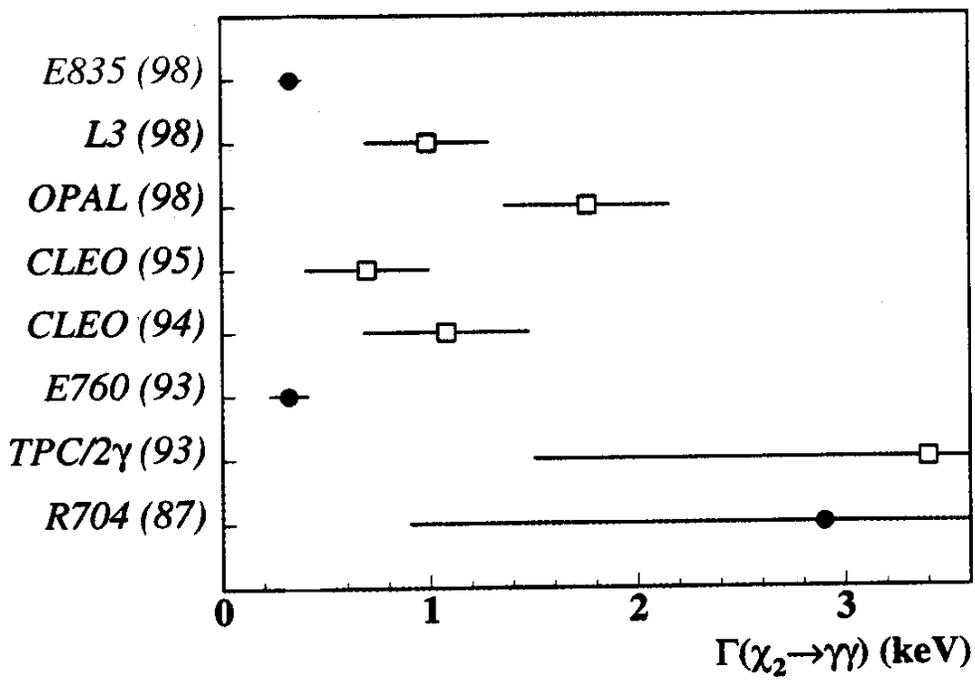


Kamal K. Seth

Northwestern University

TWO PHOTON WIDTH, $\Gamma(\chi_2 \rightarrow \gamma\gamma)$

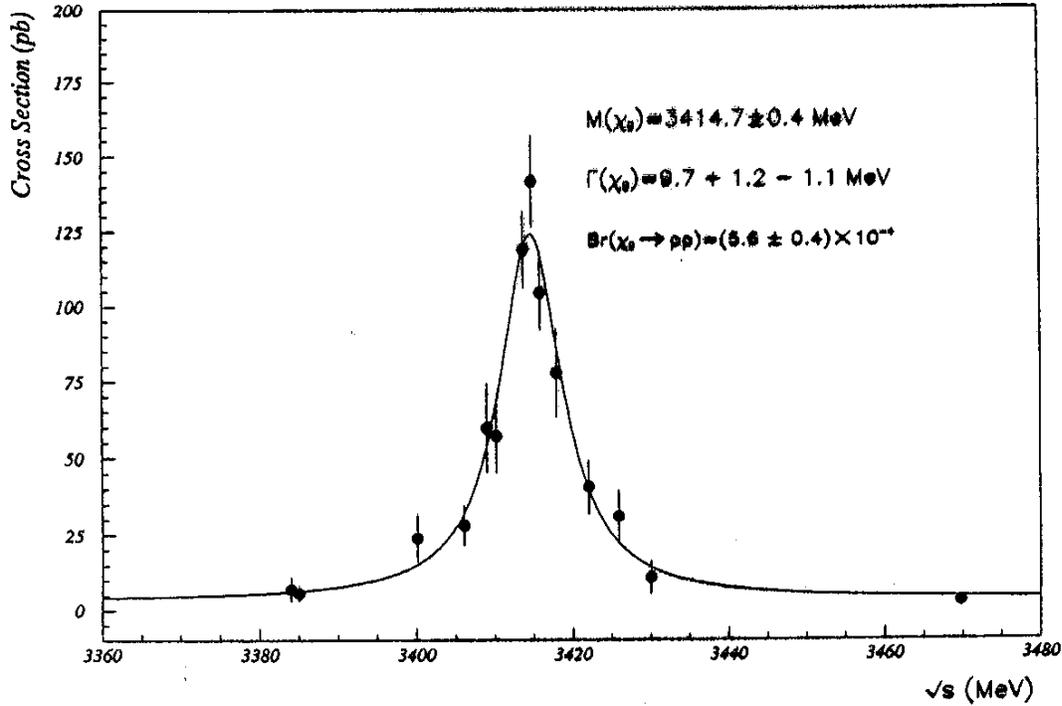
E835: $\Gamma(\chi_2 \rightarrow \gamma\gamma) = 0.343 \pm 0.052 \pm 0.041$ keV



New world average: $\Gamma(\chi_2 \rightarrow \gamma\gamma) = 0.38 \pm 0.08$ keV

This result also (as in case of η_c) can be used to determine $\alpha_S(m_c)$

E835 Year 2000 Run (FNAL)

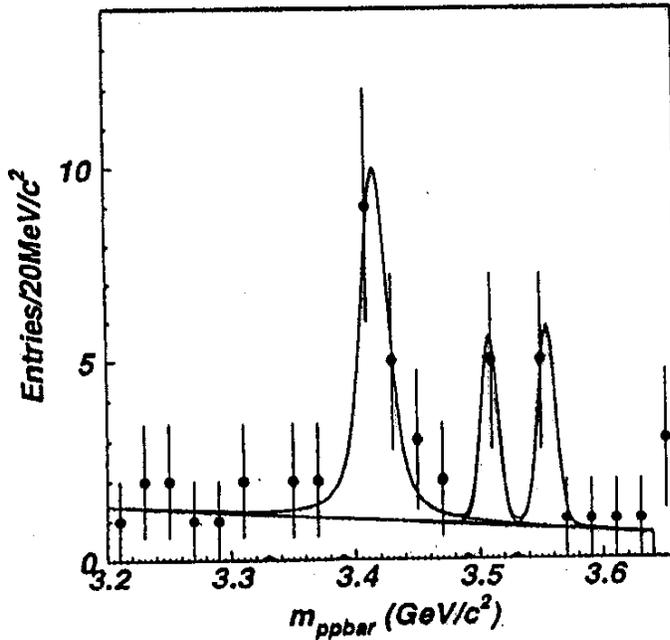


E835(2000)

$\Gamma(\chi_0) = 9.7 \pm 1.2 \text{ MeV}$

$\text{Br}(\chi_0 \rightarrow p\bar{p})$
 $= (5.6 \pm 0.4) \times 10^{-4}$

392 counts



BES (1998)

$\Gamma(\chi_0) = 14.3 \pm 3.6 \text{ MeV}$

$\text{Br}(\chi_0 \rightarrow p\bar{p}) = (1.6 \pm 0.7) \times 10^{-4}$

15 ± 4 counts.

FIG. 3. The $p\bar{p}$ mass distribution for selected $\psi(2S) \rightarrow \gamma p\bar{p}$ events.

SOME OUTSTANDING PROBLEMS BELOW DD THRESHOLD

- $\eta_c(1^1S_0)$ - charmonium ground state:
It is shocking how poorly measured just about everything is for the g.s. of charmonium.
- $\eta_c'(2^1S_0)$ - The radial:
No wonder, we do not even know where it is!
- $h_c(1^1P_1)$:
Bears crucially on the spin-dependence of the confinement potential. But do we even know where it is?
- $\chi_c(1^3P_J)$:
Less than 15% hadronic width accounted for, and flat too with Br errors $> 30\%$
- $Br(\chi_2 \rightarrow h)/Br(\chi_0 \rightarrow h)$ show peculiar behavior.
- $J/\psi(1^3S_1), \psi'(2^3S_1)$:
- $Br(\psi' \rightarrow h)/Br(J/\psi \rightarrow h)$ behave peculiarly, the $f-\pi$ problem
- α_s derived from $Br(J/\psi \rightarrow e^+e^-)/Br(J/\psi \rightarrow ggg)$ is anomalous (0.19 instead of ~ 0.35).

SOME OUTSTANDING PROBLEMS ABOVE $D\bar{D}$ THRESHOLD

- Very scant, old (pre 1980), and very problematic data.
 - The data for $R = \sigma(h)/\sigma(l^+l^-)$ from different detectors disagree.
 - Extremely unreliable identification of $\psi^{(n)}$, $n=4,5,6$.
 - Extremely unreliable $\text{Br}(\psi^{(n)} \rightarrow e^+e^-)$.
 - Extremely peculiar D, D^* production reported.
- Where are charmonium D-states?
Narrow $^3D_2, ^1D_2$ are of great interest.
- Where are P-state radials?
Narrow 2^1P_1 may be easier to find than bound 1^1P_1 .
- Do we have a D-factory at $\psi(4040)$?
That could open possibilities!!
- Is there interesting physics in $\sqrt{s} = 5-10$ GeV region?
I can think of some.

The spin 0 problem

$$\eta_c(1s_0), \eta_c(2s_0), \chi_0(3p_0)$$

The states which should not be populated by $\bar{p}p$

The ground state of charmonium, η_c (1^1S_0)

- Can $\bar{p}p$ annihilation populate 1S_0 states?

According to pQCD (for massless quarks) helicity conservation forbids the population of any spin-0 state ($\mathcal{J}_z=0$) by $\bar{p}p$ annihilation ($\mathcal{J}_z=1$).

- However, $\eta_c \rightarrow \bar{p}p$ was observed

Mark III (1986) 23 ± 11 events $BR = \underline{0.11(6)\%}$

DM2 (1990) 18 ± 6 events $BR = 0.10(5)\%$

Surprisingly enough, this helicity-forbidden branching ratio is only a factor two smaller than the helicity-allowed branching ratio for $J/\psi \rightarrow \bar{p}p$ ($BR = \underline{0.21(1)\%}$)

Numerous attempts have been made to try to explain this, with essentially no success. Even invoking instanton contributions does not appear to help (by factor 20).

- The measurements have poor statistics, but appear to be otherwise OK. Nevertheless, $BR(\eta_c \rightarrow \bar{p}p)$ must be remeasured. It is crucially important for all studies of η_c with $\bar{p}p$.
- Actually, not a single branching ratio for the decay of η_c is known to better than $\pm 30\%$. With η_c , the ground state of charmonium, playing such an important role in the understanding of QCD, all decay channels need to be measured with precision.
- With no capability of detecting decay channels with charged hadrons, E835 is helpless here.

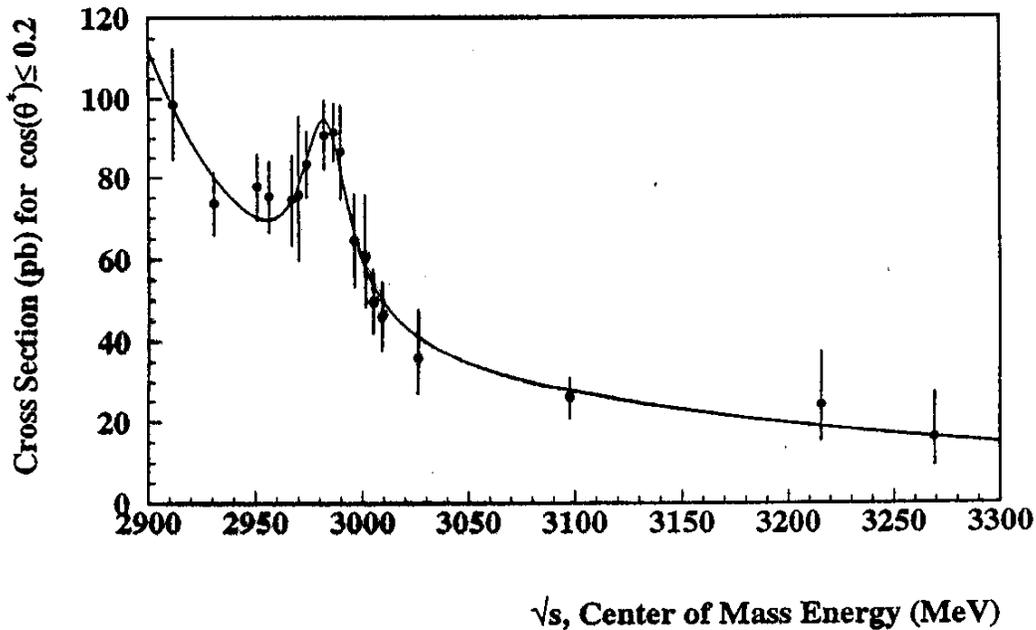
A new facility and detector is required.

η_c RESONANCE PARAMETERS

Crystal Ball *et.al.* observed η_c in radiative (M1) decays of J/ψ and ψ'.

E835 has studied it in direct formation via p \bar{p} and its decay into γγ. Remember that

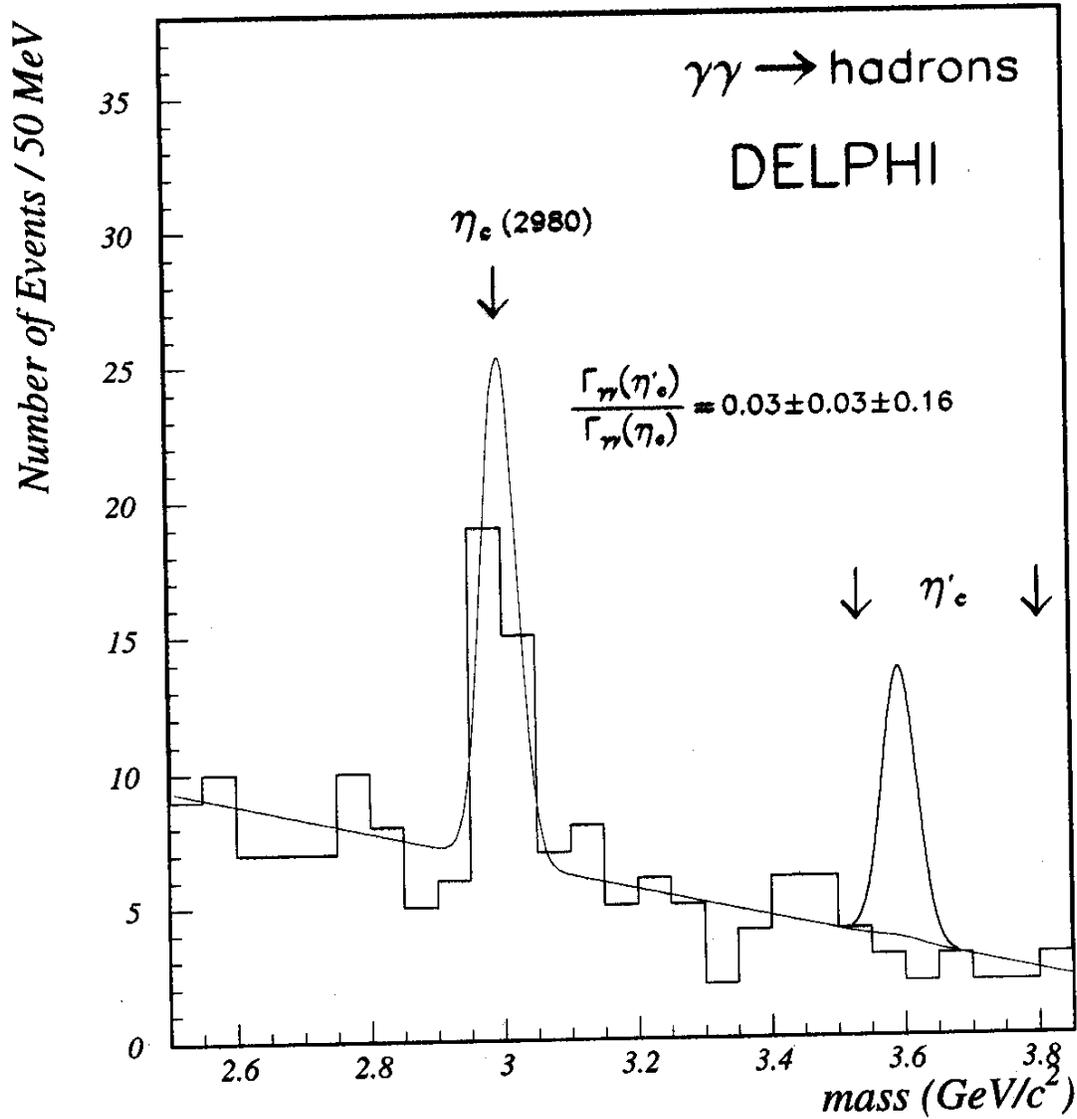
$$\begin{aligned}
 B(\bar{p}p \rightarrow \eta_c) &= 1.0 \pm 0.5 \quad (10 \pm 5 \text{ events}) && 1991 \text{ (DM2)} \\
 &= 1.1 \pm 0.6 \quad (23 \text{ events}) && 1986 \text{ (MkIII)}
 \end{aligned}$$



$$M(\eta_c) = 2982.4 \pm 2.3 \text{ MeV}$$

$$\Gamma(\eta_c) = 26.9 \pm 10.0 \text{ MeV}$$

$$\Gamma(\eta_c \rightarrow \gamma\gamma) = 5.7 \pm 2.6 \pm 2.2 \text{ keV}$$

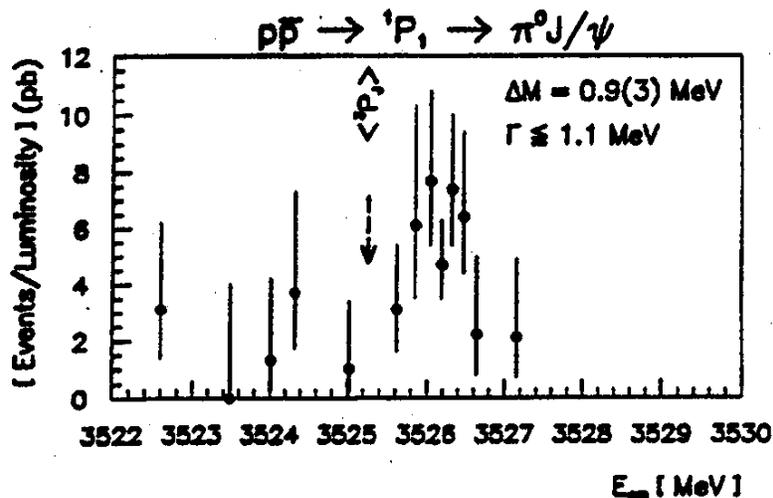


SINGLET STATES OF QUARKONIUM

These are notoriously difficult to populate.

- For e^+e^- colliders forming $1^{--} (^3S_1 : \psi, \Upsilon)$ states:
 - radiative transitions to $0^{-+} (^1S_0 : \eta_{c,b})$ are M1, and terribly weak.
 - radiative transitions to $1^{+-} (^1P_1 : h_{c,b})$ are C forbidden
- Therefore, no singlet states of $(b\bar{b})$ have ever been identified (no η_b, h_b, \dots).
- η_c was identified. η'_c was claimed, but never confirmed.
- For $p\bar{p}$ annihilation, all J^{PC} may be formed, except
 - $^1S_0(\eta_c, \eta'_c), ^1P_1(h_c)$ are forbidden by hadron helicity conservation rule of pQCD.

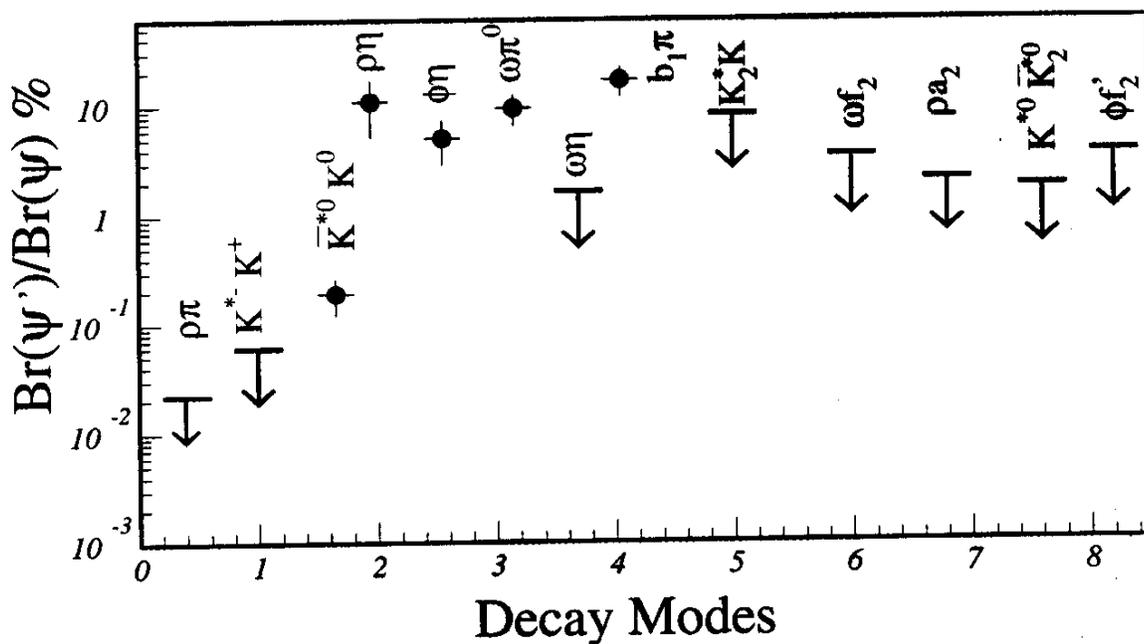
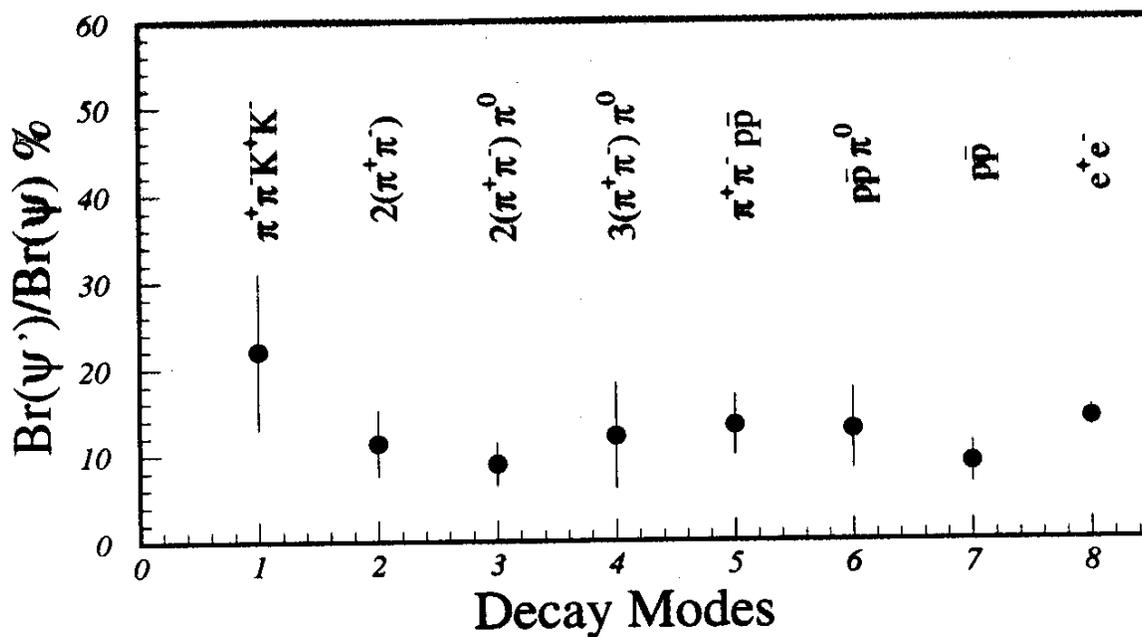
Nevertheless, E760 reported discovery of $h_c(^1P_1)$



$$M(^1P_1) = 3526.2 \pm 0.25 \text{ MeV} = M \langle ^3P_J \rangle + 0.9 \text{ MeV}$$

$$\Gamma(^1P_1) \leq 1.1 \text{ MeV, (90\%CL)}$$

Ratios of Hadronic Decays of ψ' and ψ



In PQCD, ${}^3S_1 \rightarrow e^+e^-$ and ${}^3S_1 \rightarrow ggg$ are both $\propto |\psi(0)|^2$

$$\therefore \frac{\text{B}(\psi' \rightarrow e^+e^-)}{\text{B}(\psi \rightarrow e^+e^-)} = 0.14 \pm 0.01 = \frac{\text{B}(\psi' \rightarrow \text{hadron}(i))}{\text{B}(\psi \rightarrow \text{hadron}(i))}$$

Direct Photon Production

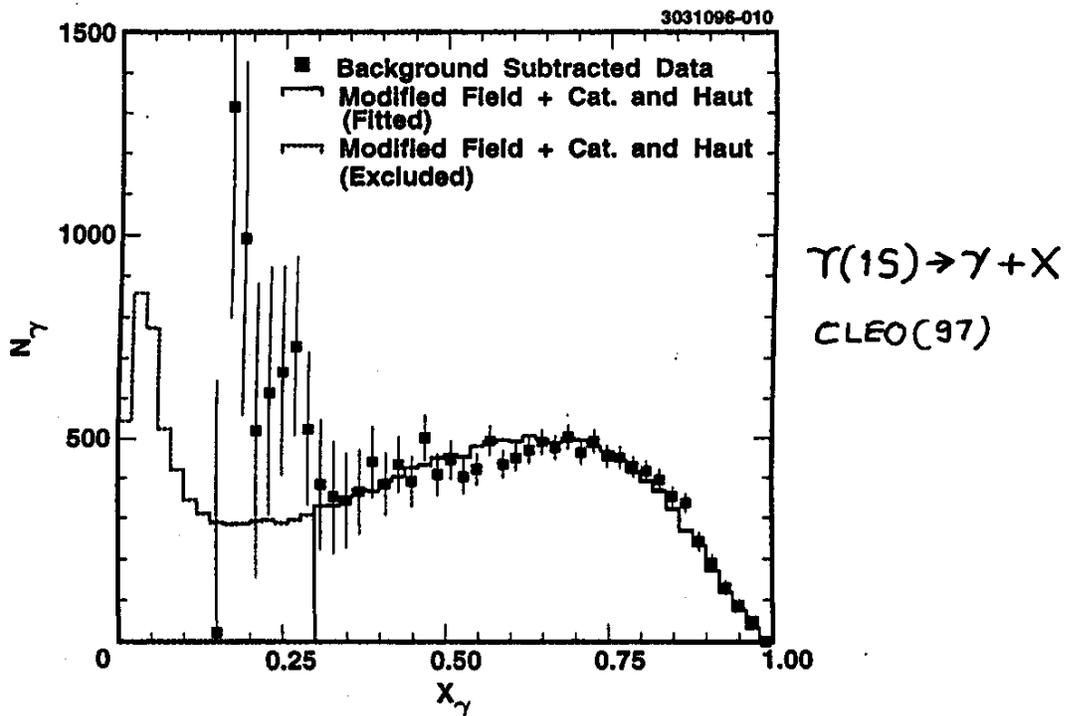
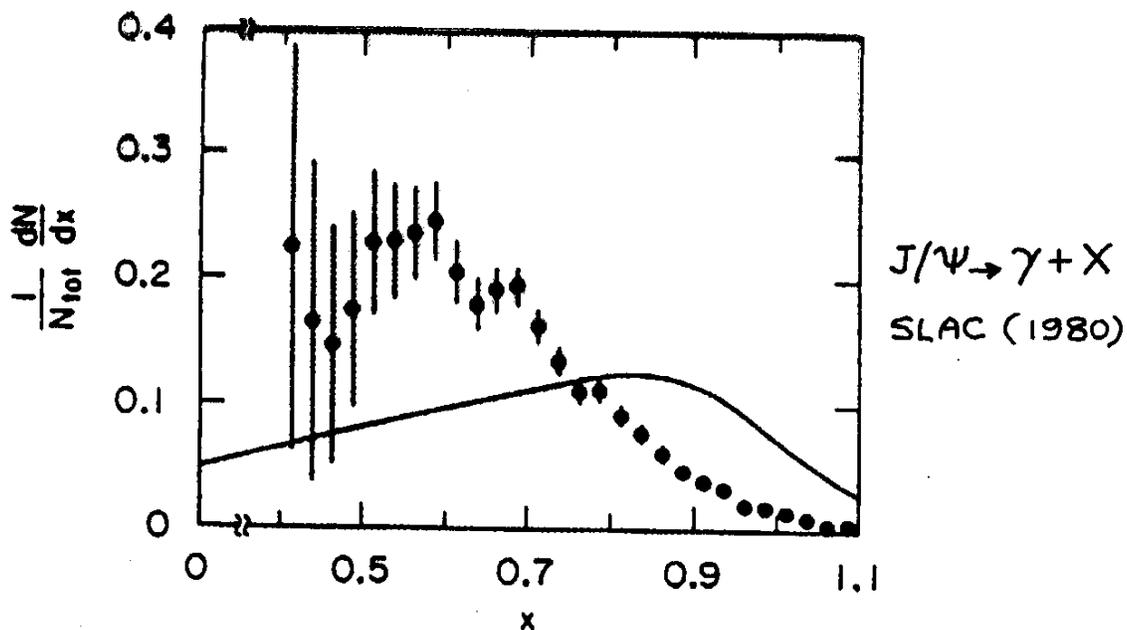
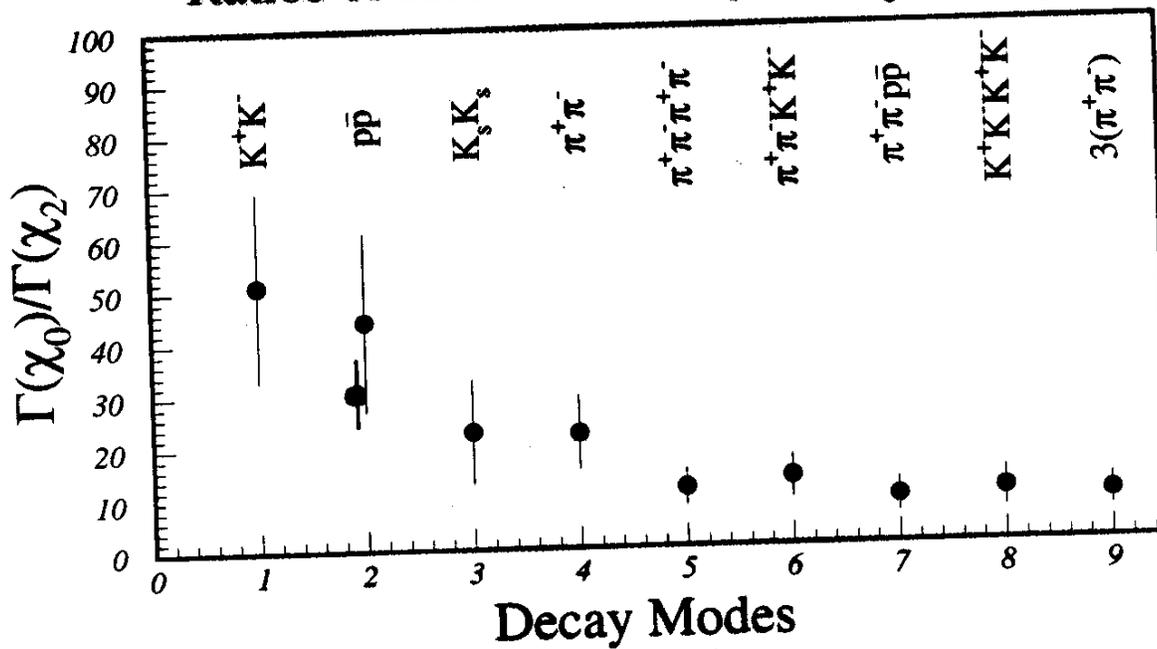


FIG. 7. The background subtracted photon spectrum (dark squares) fit to the Field distribution with the added fragmentation component predicted by Catani and Hautmann. Again, the errors shown on the data points are purely statistical.

$$x = p_\gamma / E(\text{beam})$$

Ratios of Hadronic Decays of χ_0 and χ_2



Theoretical predictions: $\frac{15}{4} \rightarrow 9.7$

0 for $\bar{p}p$.

α_s from charmonium decays

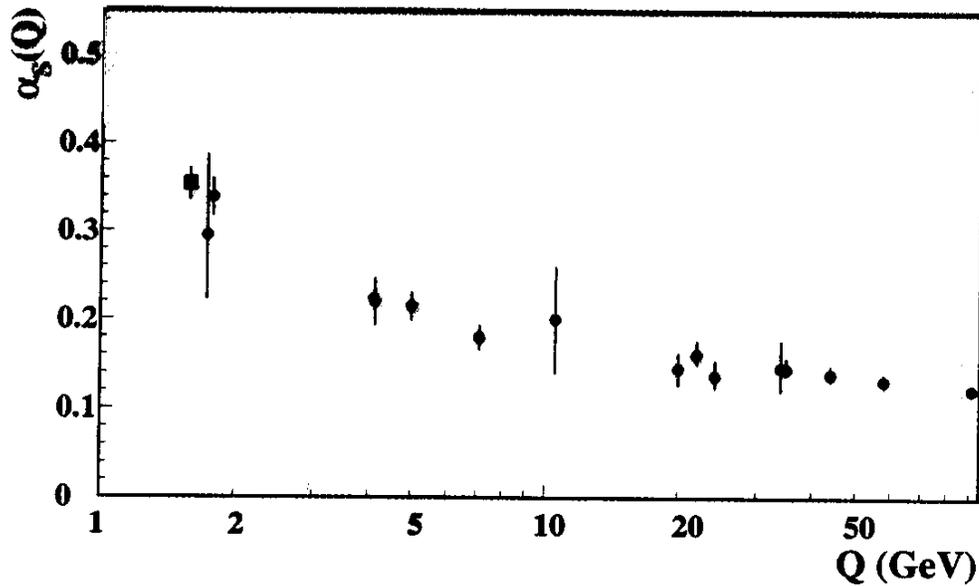
All decay widths contain two unknowns besides α_s. These are Ψ(0) (or its derivatives), and m_c, the quark mass.

α_s is best derived from ratios of gluonic widths / E.M. widths in order to cancel these unknowns out.

Ratio	pQCD (L.O)	× rad.corr.*	α _s (m _c)
$\frac{\Gamma(\eta_c \rightarrow gg)}{\Gamma(\eta_c \rightarrow \gamma\gamma)}$	$1.125\alpha_s^2/\alpha^2$	1.78	0.32 ± 0.05
$\frac{\Gamma(J/\psi \rightarrow ggg)}{\Gamma(J/\psi \rightarrow e^+e^-)}$	$0.077\alpha_s^3/\alpha^2$	1.15	0.186 ± 0.006
$\frac{\Gamma(J/\psi \rightarrow ggg)}{\Gamma(J/\psi \rightarrow \gamma gg)}$	$0.313\alpha_s/\alpha$	0.73	0.18 ± 0.08 <small>^{0.31}</small>
$\frac{\Gamma(\chi_2 \rightarrow gg)}{\Gamma(\chi_2 \rightarrow \gamma\gamma)}$	$1.125\alpha_s^2/\alpha^2$	1.3	0.36 ± 0.02

*(using α_s = 0.3)

- From τ decay, α_s (m_τ = 1.78 GeV) = 0.32 ± 0.04.
- Clearly there is a problem with J/ψ –based determinations. A similar problem exists with determinations of α_s at Υ(³S₁ (b \bar{b})).
- Several attempts have been made to explain these problems.



Our α_S (at $m_c = 1.5$ GeV) agrees well with α_S from τ decay (at $m_\tau = 1.78$ GeV)

$$\alpha_S(m_c) = 0.35 \pm 0.02$$

$$\alpha_S(m_\tau) = 0.34 \pm 0.02$$

Our result corresponds to

$$\alpha_S(M_Z) = 0.119 \pm 0.007 \pm 0.007$$

whereas the PDG98 average is:

$$\alpha_S(M_Z) = 0.119 \pm 0.002.$$

ABOVE $D\bar{D}$ THRESHOLD (3730 MeV)

This is essentially terra incognita. In this regime all that was ever done was to measure total hadronic cross sections, and no two measurements ever agreed.

- Mass resolutions were poor. Resonances were more or less "willed" into place by subjective radiative corrections
- $\Psi(4040), \Psi(4160), \Psi(4415)$ were all attributed branching ratios, $B(\Psi^{(n)} \rightarrow e^+e^-) \cong 1 \times 10^{-5}$, which is very unlikely.
- $D\bar{D}$ production was measured in one 1977 experiment at $\Psi(4040)$ with rather unbelievable results: $D^0\bar{D}^0 : D^*\bar{D}_0 : D^*\bar{D}^* = 1 : 20(12) : 640(240)$
This is exactly opposite to all expectations.
Bad measurement, or great physics. Must repeat !!
- Most important question: Is $\Psi(4040)$ a $D\bar{D}$ factory? (Beijing says - yes!)

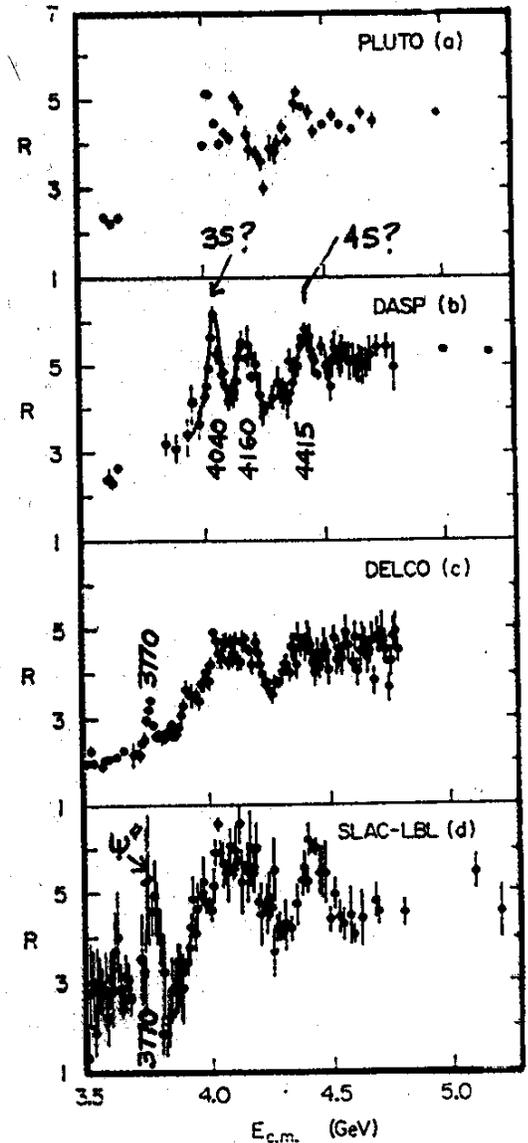


Fig. 5. R versus energy. The R values have been radiatively corrected in (a), (b), and (d), but not in (c). e^+e^- pair production is included in R.

GLUON CONDENSATE

The gluon condensate **essentially measures** the energy density of the QCD vacuum.

What could be more fundamental to QCD!

- Gluon condensate plays a central role in determining
 - properties of hadrons á la QCD sum rules
 - role of instantons in QCD
 - QCD in nuclear medium
 - Hot QCD (QGP, etc)
 (Cognoscenti: see Shuryak, *Rev. Mod. Phys* 70(1998)323-427)
- The empirical value of the gluon condensate was first determined (SVZ 1979) by fitting the data on charmonium 1^{--} states. ($\Psi^{(n)}$ states)

$$\langle (\alpha_s / \pi) G^2 \rangle = 0.012 (\text{GeV})^4$$

Since then, alternate determinations have indicated higher values. It is extremely important to settle this question.

- The 40% increase in $\Gamma_{e^+e^-}(J/\psi)$ and the 20% increase in $\Gamma_{e^+e^-}(\psi')$ found by the $\bar{p}p$ measurements of E760, already lead to $\sim 32\%$ increase in the condensate. But,

$$\langle (\alpha_s / \pi) G^2 \rangle \propto \sum_{i=0}^{\infty} f(\Gamma_{e^+e^-}^i, M_i),$$

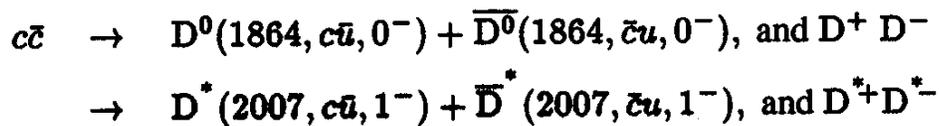
and we need accurate masses and widths of all 1^{--} (ψ^i) resonances of charmonium.

This requires a high resolution scan of $\bar{p}p \rightarrow e^+e^-$ in the entire region

$$3.5 \leq M(\text{GeV}) \leq 5$$

THE D⁰ PROBLEM

- At 3.73 GeV the charmonium system becomes unbound to open charm decays



and $\psi(4040)$ becomes a prolific source of $D\bar{D}$, so much so that it is called the $D\bar{D}$ factory. But...

- Only one 1977 measurement (Mark I) on these decays exists; and it gives very curious results.

$$\psi(4040) \rightarrow \Gamma(D^0\bar{D}^0) : \Gamma(\bar{D}^0D^*) : \Gamma(D^*\bar{D}^*) = 1 : 20(11) : 640(380),$$

after explicit removal of phase space factors.

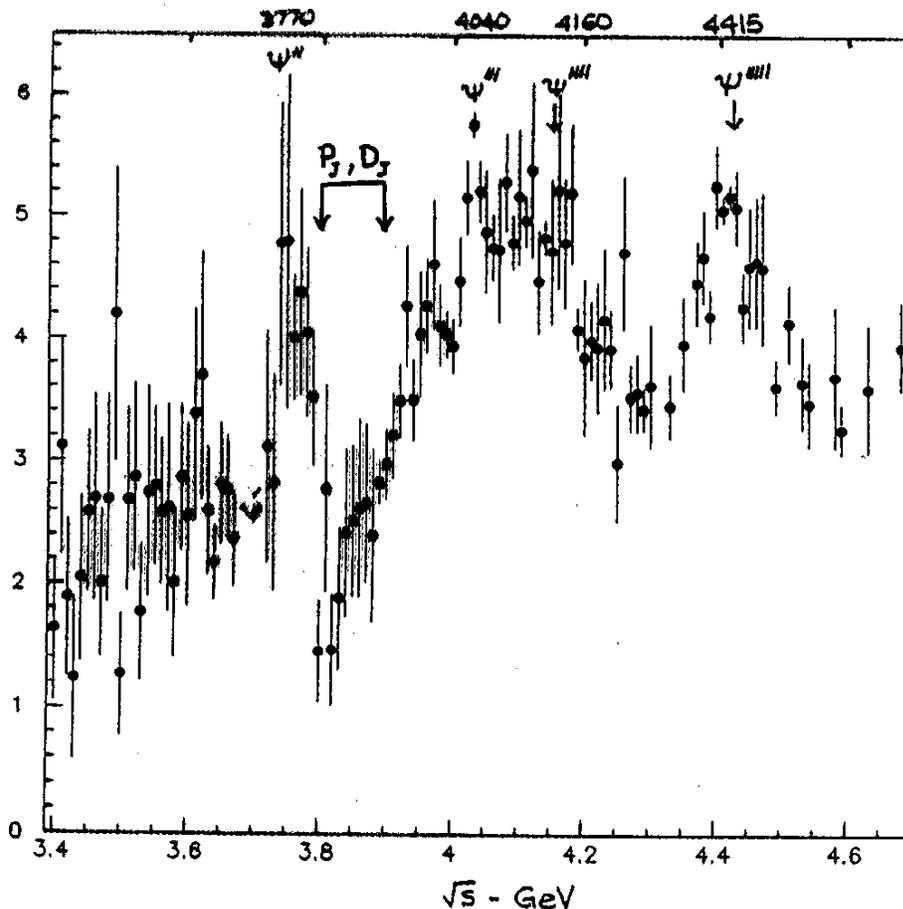
- Admittedly, the errors are large. Nevertheless, the result is clearly very peculiar. It is against all intuition that the 1^- system should prefer to decay into mesons with intrinsic spin sum of 1^+ and 2^+ rather than 0^+ . De Rujula, Georgi and Glashow estimated the ratios

$$\Gamma(D^0\bar{D}^0) : \Gamma(\bar{D}^0D^*) : \Gamma(D^*\bar{D}^*) = 1 : 4 : 7$$

- This measurement is of crucial importance in determining $D\bar{D}$ mixing and use of D mesons to test possible CP violation.

A modern high precision measurement of the open charm decay of $\psi(4040)$ (and other ψ states) is an absolute must.

THE HIDDEN RESONANCES OF $c\bar{c}$



- A consensus of potential model calculations predicts that 1^3D_J states lie near 3.80 GeV, and $2^{1,3}P_J$ states lie near 3.90 GeV. Most of them can decay into $D\bar{D}$, and are therefore likely to be broad. But 1^3D_2 and 2^1P_1 can not, and therefore they should be narrow. They should be searched - only a high resolution $\bar{p}p$ experiment can do that
- 2^1P_1 may actually turn out to be easier to find than the elusive 1^1P_1 , because $2^1P_1 \rightarrow J/\psi \eta$ is possible. That would be really great!!