Some Important Questions in Charmonium Physics

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- I am a late arrival in CHARMONIUM PHYSICS, having been involved with it only since 1986 with the FERMILAB E760 experiment, in which we study charmonium by its formation in $p\bar{p}$ ANNIHILATION.

- On the otherhand, I have all the enthusiasm of a NEW CONVERT.

- Of course, the enthusiasm wouldn't, and shouldn't, matter if all the important questions have already been answered, and the field has been MINED OUT long ago. BUT, HAS IT?

- This talk is devoted to three propositions:

  1. Some of the most basic questions in heavy-quark physics remain unanswered.
  2. Charmonium physics is the best place to address those questions at the required level of precision.
  3. A tau-charm factory, with a commensurate state-of-the-art detector, are mandatory for doing the job.

- Finally, let me add that while open-charm and tau physics will certainly be also done at beauty factories, charmonium physics will not. It must, therefore, form an important part of the physics program at a τCF.

QCD at small Q^2

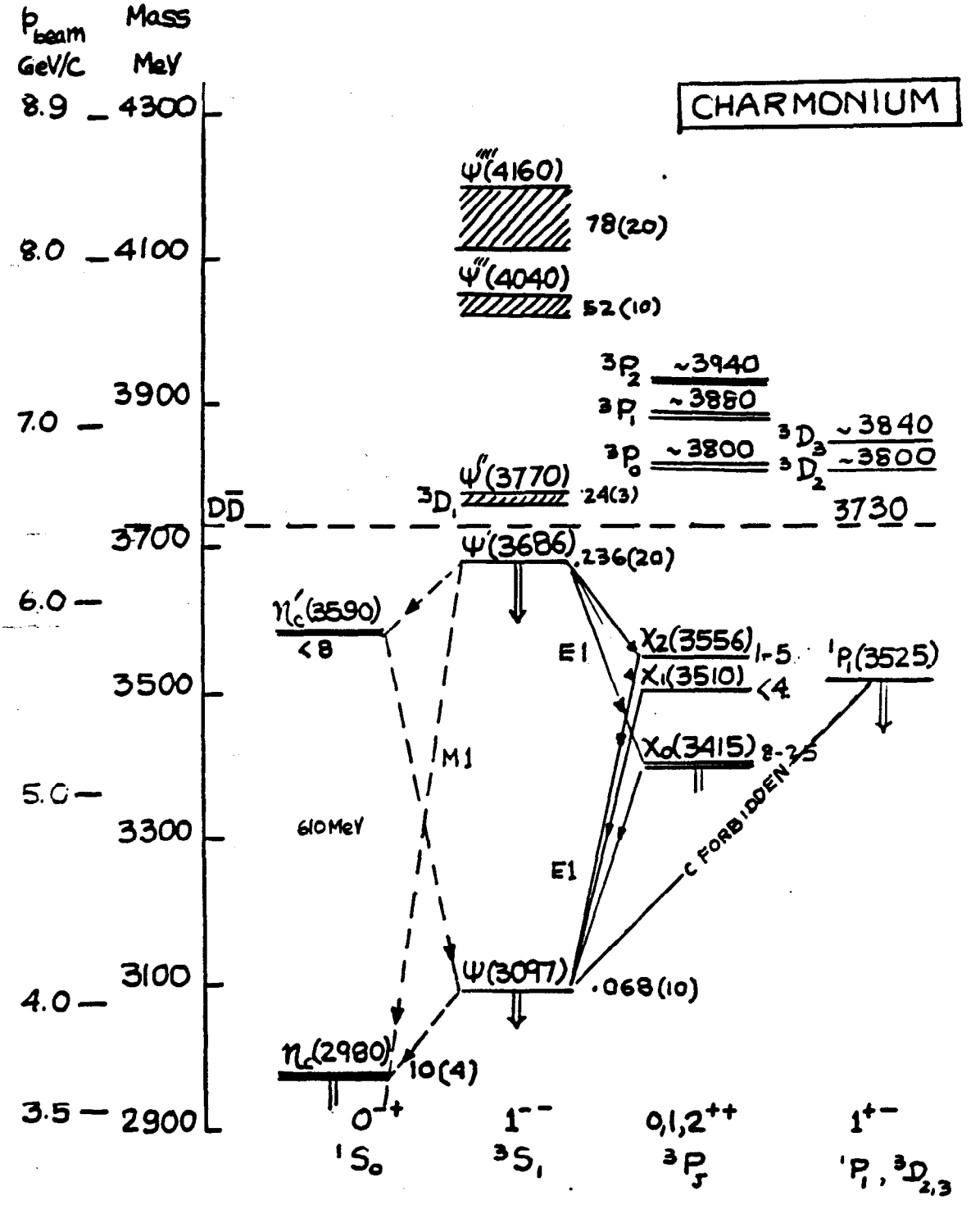
- The QCD sector of the standard model has received impressive experimental support in the perturbative domain of very large Q^2. However, the universal truth of QCD, which must include its validity in the small Q^2 domain, remains an open question.

  Wilczek, for example, has emphasized that -

  > "if you are interested in quantitative results for α_s, (which provide) a quantitative measure of how good PQCD is, there is a large premium for working at small Q^2."

- The small Q^2, or small mass scale that Wilczek has in mind, is not the scale of u- and d- quarks, because they present very difficult (e.g., relativistic) problems. It is the scale of c-quarks, which are heavy enough, but where α_{strong} is already run to 3 times its value at $m(Z^0)$.

- So, I will be presumptuous enough to assume that
  - electroweak physics is not the end-all,
  - strong interaction physics is exciting and challenging.
  - charm quark scale is an excellent scale to study QCD.



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)

CHARMONIUM PHYSICS Á LA e^+e^-

$\psi, \psi' \ldots$

	SLAC+DM2	BEPC	τCF/month *	E760
J/ψ	18 million	9 million	1000 million	<5000
ψ'	3 million	~~0.4~~ 1.5 million	200 million	<5000

* $\mathcal{L} = 10^{33}\ cm^{-2}s^{-1}$, usable luminosity = 1000 pb^{-1}/10 day month
FWHM(ψ) = 2 MeV , FWHM(ψ') = 3 MeV

- Where do we stand at the end of 20 yrs of e^+e^- ?

	Mass	Width	# of decays		Mass	Width	# of decays
J/ψ	✓	?	120(18)	ψ'	✓	✓	39(10)
η_c	?	?	19(8)	η_c'	?	?	(1) → NO D-STATES NO P-STATE RADIALS
χ_0	✓	UL	13(1)	$\psi''(3770)$	✓	?	2
χ_1	✓	UL	10(2)	$\psi^3(4040)$	✓	?	4
χ_2	✓	UL	14(2)	$\psi^4(4160)$	✓	?	1
$^1P_1$	?	?	—	$\psi^5(4410)$	✓	?	2

For hadronic decays (65% to 99% of total) the branching ratios are generally very poorly measured, with 25%-75% errors and many upper limits. Often the data come from one measurement only, e.g., χ_J-decays (Tannenbaum, 1978)

- An important example:

$BR(\eta_c \to p\bar{p}) = (10 \pm 5) \times 10^{-4}$, Bisello (DM2), 18 ± 6 events
$= (11 \pm 6) \times 10^{-4}$, Baltrusitis (Mk3), 23 ± 11 events
$J/\psi = 22(1)$

Important for QCD, because it is helicity forbidden.
Important for E760 $p\bar{p}$ measurements.

MODELING QCD INTERACTIONS

- Naive approximation to non-linear field theory: Potential models
  — Do not expect too much!

SPIN - INDEPENDENT POTENTIAL

— Physically motivated Cornell potential to fit masses.

$$V(r) = -(4/3)\frac{\alpha_{strong}}{r} + kr$$

one-gluon exch. multigluon flux-tube

— Many other potentials do just as well.

log potential : $V(r) = C \ln (r/r_0)$
Power-law pot.: $V(r) = C\,(r)^{\beta}$
Richardson pot.: $V(q) = C\,\{ q^2 \ln [\, 1 + (q^2/\Lambda^2)\,]\,\}^{-1}$

— No unique determination.

SPIN - DEPENDENT POTENTIAL

— The OGE vector potential gives spin - dependent splitting:

$$\Delta M = a < \vec{L}.\vec{S} > + b < \vec{T} > + c < 2\vec{S}_1.\vec{S}_2 - 3 >$$

— Scalar potential (confinement part ?) only effects $< \vec{L}.\vec{S} >$ part and reduces it.

— No unique determination for confinement potential, scalar. vector or even other Lorentz invariants (PS. AV. T)

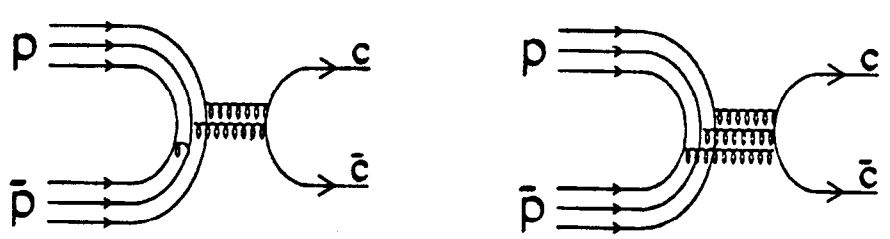
OPEN QUESTIONS

- How valid is the potential model?
- How singular is the 'Coulombic' potential? Is it really 1/r ?
- What is the nature of the confinement potential? What Lorentz transformation properties does it have?
- Are scalar and vector exchanges the only ones involved?
- What are the relativistic and channel coupling effects on the $q\bar{q}$ spectrum?
- How valid is our borrowing the 'positronium physics' in view of the confinement problem?
- How meaningful and trustworthy are the one-loop radiative corrections?
- How does the strong coupling constant α_s run?

CHARMONIUM BY $p\bar{p}$ ANNIHILATION

Two great advantages:

- In contrast to e^+e^- which can only populate vector (1^{--}) states, $\bar{p}p$ can directly populate states of all J^{PC} via annihilations mediated by two or three gluons.



- Stochastically cooled $\bar{p}$ beam and a hydrogen gas-jet target can lead to unprecedented mass resolution.

FERMILAB E-760, E-835

COLLABORATION

Fermilab, Universities of Ferrara, Genoa, Torino, University of California (Irvine), Northwestern University, Pennsylvania State University.

PRINCIPLE

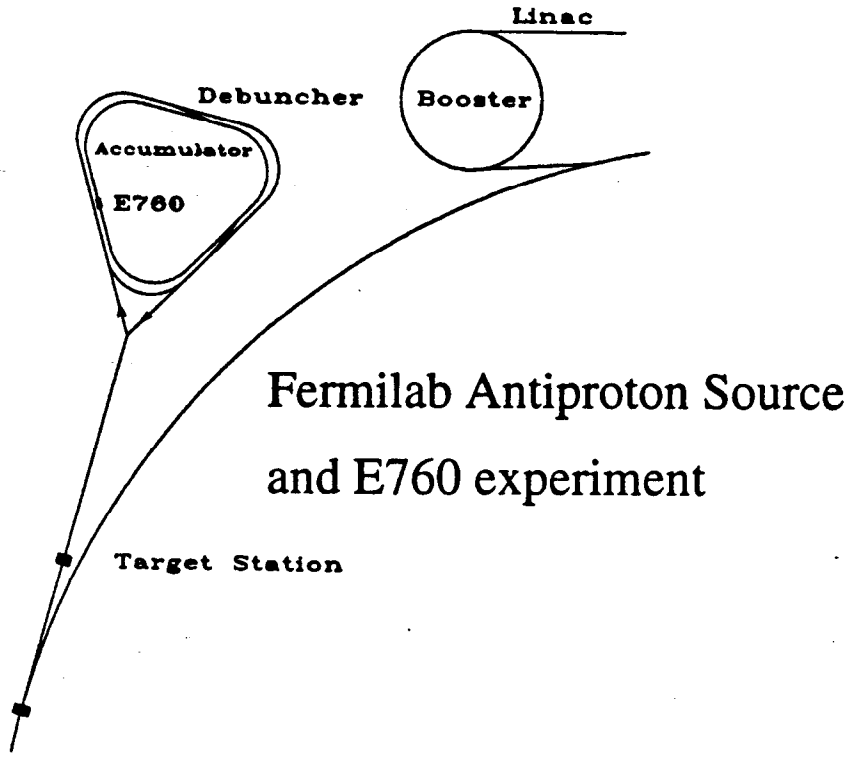
A variable energy circulating beam of ~ 4 x 10^{11} antiprotons in the Fermilab accumulator traverses an internal hydrogen gas jet target of density ~ 0.5 x 10^{14} atoms/cm^2 to yield a luminosity of

$$\mathcal{L} \cong 10^{31}\ cm^{-2}s^{-1}.$$

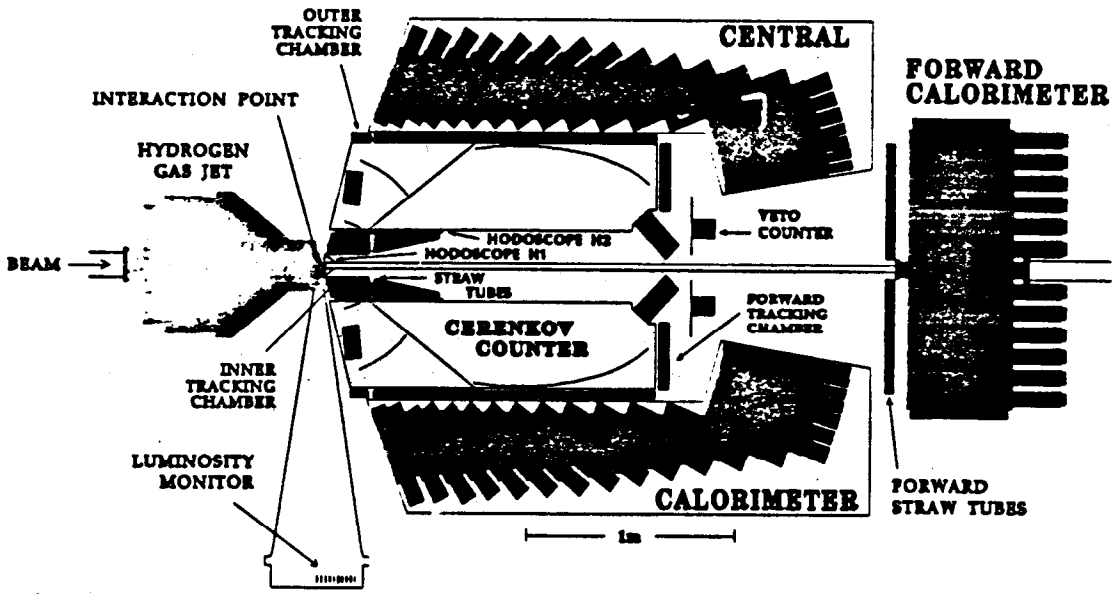
$p\bar{p}$ annihilations resonantly produce $c\bar{c}$ charmonium states which are identified by their electromagnetic decays (e^+e^-, γ's, ...)

E760 Approved - 1985, DATA RUN: 1990, 1991

E835 Approved - 1993, DATA RUNS: 1995



E760 EQUIPMENT LAYOUT



E760-Detector optimized for e^+e^-, $\gamma\gamma$, etc

THE INGREDIENTS OF PRECISION

BEAM ENERGY

$\beta = \frac{1}{c} L_{orb} f_{orb}$, $\gamma = E_{beam} / m$

$$\Delta E_{beam} = mc^2\beta^2\gamma^3 \left[(\Delta f / f)^2 + (\Delta L_{orb} / L_{orb})^2 \right]^{1/2}$$

- Revolution frequency, f, is measured from Schottky noise spectrum to 2×10^{-7}.
- Orbit length normalization at ψ' ($M(\psi') = \pm 100$ keV) gives

$$L_{orbit} = 474.0457 \text{ m} \pm 0.7 \text{ mm}$$

- 48 beam position monitors determine deviations from reference orbit to $\pm$ 1 mm ($\equiv \pm$ 30 keV at J/ψ).

BEAM MOMENTUM RESOLUTION

$$dp / p = (1 / \eta) \, df / f$$

- The lattice parameter η can be determined in many ways. The double scan method gives it at a resonance enitrely in terms of frequencies.

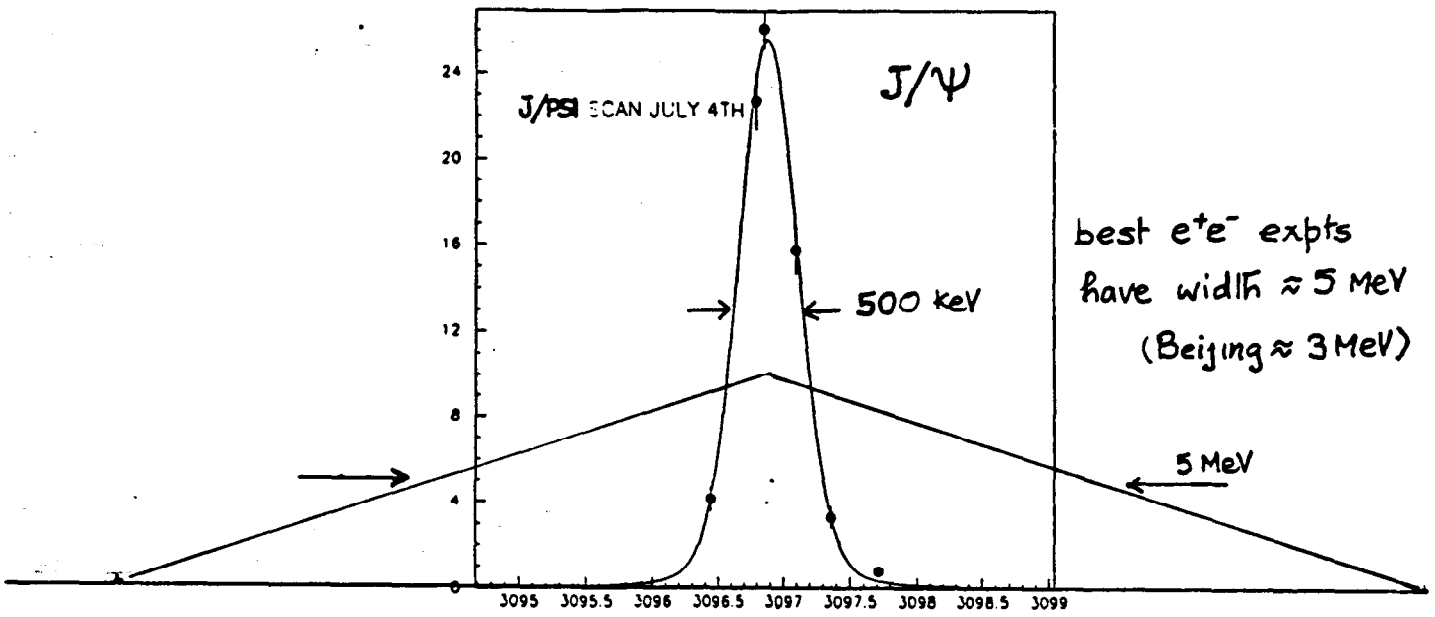
$$\eta = (1 / \gamma^2) (f_2 - f_3) / (f_1 - f_3)$$

EVENT SELECTION

- The electromagnetic calorimeter allows us to pull out electromagnetic final states, for example e^+e^-, at the level of

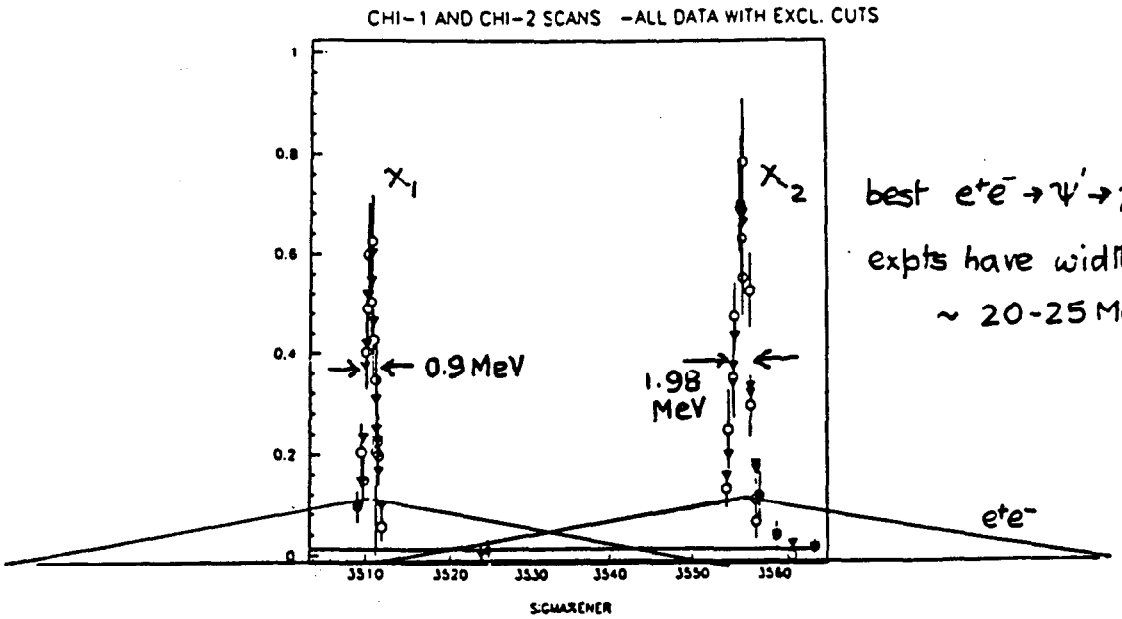
$$1 \text{ pb } (=10^{-12} \text{ b}) \text{ out of } \sigma_T (pp) = 70 \text{ mb } (\sim 10^{-1} \text{ b})$$

Part of C.G's dissertation.



best e^+e^- expts have width ≈ 5 MeV (Beijing ≈ 3 MeV)

Fig. 4 An excitation function scan for the J/ψ (3097) resonance from E760. Notce that the c.m. energy resolution is FWHM = 0.4 MeV. Phys. Rev. D47 (1993) 772



best $e^+e^- \to \psi' \to \gamma\chi$ expts have widths ~ 20-25 MeV

Fig. 5 A composite of E760 scans of χ_1(3510), and χ_2(3556), and the background level in between. Phys. Rev. Lett. 68 (1992) 1468, Nucl. Phys B373 (1992) 35.

What has E760 done so far?

1. Precision measurement of J/ψ, ψ' widths
   Phys. Rev. D47 (1993) 772
2. First measurements of χ_1, χ_2 widths
   PRL 68 (1992) 1468, Nucl. Phys B373 (1992) 35
3. Angular distribution of $\chi_2 \to \gamma J/\psi$
   Phys. Rev. D48 (1993) 3037
4. Discovery of $^1P_1$ state of charmonium
   PRL 69 (1992) 2337
5. Measurement of $\Gamma(\chi_2 \to \gamma\gamma)$
   PRL 70 (1993) 2988
6. Measurement of $\Gamma(\eta_c \to \gamma\gamma)$; Search for η_c'.
   under preparation
7. Timelike form-factors of proton, $p\bar{p} \to e^+e^-$
   PRL 70 (1993) 1212
8. New resonances in $\pi\pi$, $\pi\eta$, and $\eta\eta$ final states
   Phys. Lett. B307 (1993) 394, 397
9. $p\bar{p}$ forward scattering parameters
   under preparation

What we can not do —

- almost no hadronic decay channels
- searching for $c\bar{c}$ states whose energies are not, at least approximately, known

THE NEW RESULTS FROM E760

TRIPLET STATES: J/ψ

- J/ψ is the cornerstone of all "-onium physics.
- For J/ψ there are significant changes.

	e^+e^- (since 1975)	E760
Mass (J/ψ) - MeV	3096.93 ± 0.09	3096.87 ± 0.04
Γ(tot) - keV	69 ± 10	99 ± 14
BR (e^+e^-) (1990)	6.9 ± 0.9 %	
(1992)	5.91 ± 0.23 %	

  - Γ(tot) from (e^+e^-) depends on knowledge of efficiencies and acceptances for the separate detection of electrons, muons and hadrons. Also upto 40% correction for bremsstrahlung.
  - Γ(tot) for E760 is obtained from analysis of the shape of the excitation function and has none of the above problems.

- The 45 % change in Γ(tot) and the 25 % change in $\Gamma(e^+e^-)$ has serious consequences. For example, in the QCD sum rule models the gluon condensate will need to be substantially enhanced.

This large a change in such a basic quantity must be checked in an independent measurement. Nobody but a τCF in the monochromator mode can do it. And it should take it just a few hours

The $\rho\pi$ Problem

Is it a pseudoscalar-vector problem?
Premature conclusion. Real character will not be revealed unless we have lots better data.
The expectation:

$$\frac{\Gamma(\psi' \to f)}{\Gamma(\psi \to f)} = \frac{\Gamma(\psi' \to ggg)}{\Gamma(\psi \to ggg)} \doteq \frac{R^2(0)_{\psi'}}{R^2(0)_{\psi}} = \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(\psi \to e^+e^-)}$$

$$\text{or,} \quad \frac{BR(\psi' \to f)}{BR(\psi \to f)} = \frac{BR(\psi' \to e^+e^-)}{BR(\psi \to e^+e^-)} = 0.14(2)$$

The data:

$f = K^+K^- =$	0.4(3)
$\pi^+\pi^-K^+K^-$	0.23(8)
$p\bar{p}\pi^0$	0.13(4)
$3(\pi^+\pi^-)\pi^0$	0.12(6)
$p\bar{p}$	0.09(3)
$2(\pi^+\pi^-)\pi^0$	0.09(3)
$\boxed{\rho\pi \quad 0.005(3)}$	
$K^\pm K^{*\mp}$	<0.003
$\gamma\pi^0$	<1.4
$\gamma\eta$	<0.25
$\gamma\eta'$	<0.25

ψ' decays are all upper limits

Too many serious explanations.
Too little serious data. τCF can certainly fix that.

THE NEW RESULTS FROM E760

TRIPLET STATES - ^3P_J

- Accurate determination of widths.

	(e^+e^-)	$(p\bar{p})$	$(p\bar{p})$
$\Gamma(\chi_2)$ MeV	1 - 5	1.98 (19)	$\Gamma_{\gamma\gamma} = 0.4(1)$ keV
$\Gamma(\chi_1)$ MeV	< 4	0.88 (14)	

- For the first time we can get α_s for P-states.
  — More on this later.
- By doing multipole analysis of $\chi_2 \rightarrow \gamma + J/\psi$ angular distribution, we get the magnetic quadrupole coefficient,

$$a_2(\chi_2) = -0.14\ (6)$$

— But,

$$a_2(\chi_2) = (9/5)^{1/2}\,(E_\gamma / 4m_c)\,(1 + \kappa_c)$$

— Here κ_c is the anomolous part of the magnetic moment, which bears on the compositeness of quarks.

— Present result is consistent with 0.

$$\kappa_c = 0.46 \pm 0.62 \pm (0.4)$$

— We intend for E835 to make better measurements of a_2 for χ_2 and χ_0.

— The above result is with 600 events.
Imagine what we can do with 16 million/month χ_2 produced at a $\bar{p}$CF via $\psi' \rightarrow \gamma \chi_2$!!

THE NEW PHYSICS: Singlet states $^1S(\eta)$, $^1P(h)$, ^1D

— None known in bottomonium ($b\bar{b}$)

— Only η_c well established in charmonium ($c\bar{c}$)

— η'_c, $^1P_1$, $^1D_2$ not known

- Difficult to form or identify because of opposite parity and charge conjugation: $P = (-1)^{L+1}$, while $C = (-1)^L$.

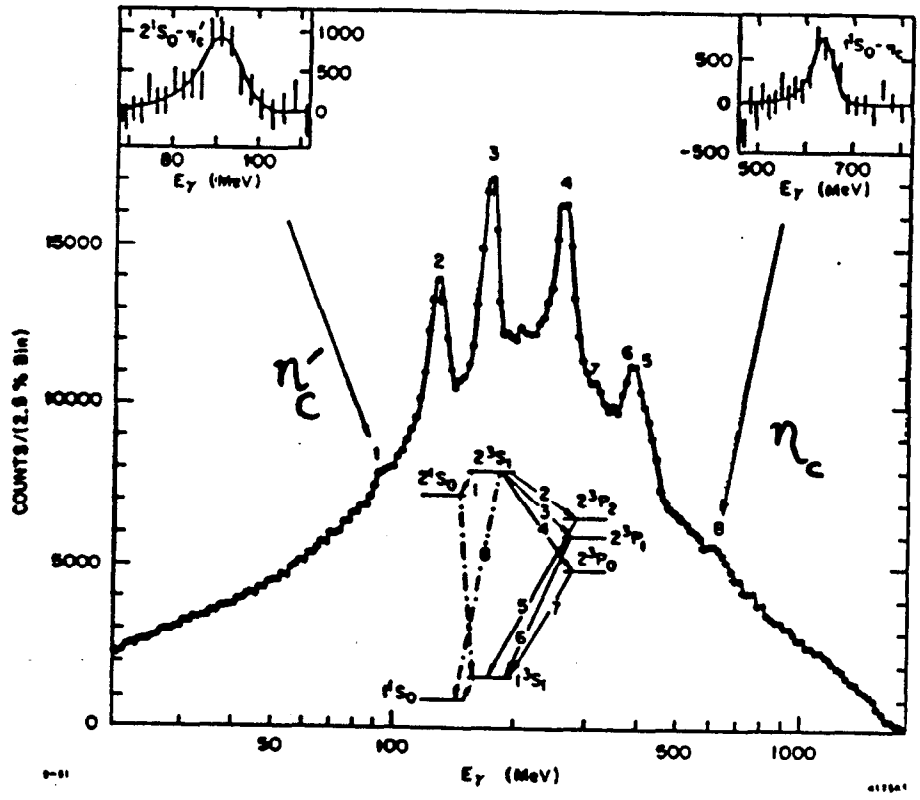
  ∴ Cannot be formed by e^+e^- (1^{--}) virtual photon

- Decays from ^3S states either forbidden $^3S_1(1^{--}) \underset{C}{\not\rightarrow} {}^1P_1(1^{+-})$, or greatly inhibited $^3S_1(1^{--}) \underset{M1}{\rightarrow} {}^1S_0\,(0^{-+})$

- Crystal Ball has reported observation of both η_c and η'_c in M1 radiative decays of J/ψ and ψ'.

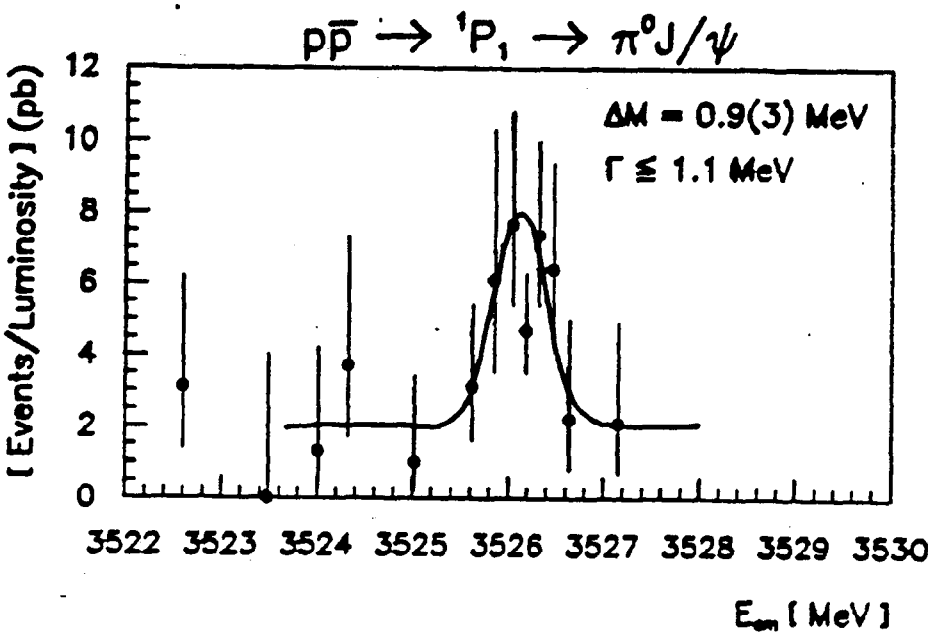
$M(\eta_c) = 2979\ (2)$ MeV, $\Gamma = 10.3\ (36)$ MeV (many)

$M(\eta'_c) = 3592\ (5)$ MeV, $\Gamma < 8$ MeV (only CB)



Crystal Ball.

THE SINGLET P - STATE



It is obvious that E835 has to do a much higher statistics experiment to determine accurate resonance parameters of ${}^1P_1$. Approximately 30% of the E835 run-time is assigned to this work.

This may very well be one of those cases where the 10^{33} $cm^{-2}s^{-1}$ ICF is not enough. Populating ${}^1P_1$ through $\psi' \rightarrow \pi^0 + {}^1P_1$ has almost no phase space (3686-3526-140=20) and the overlap between 2S and 1P is likely to be bad.
∴ ${}^1P_1$ production rate ≪ 100/month.

THE ONE AND ONLY η_c ($^1S_0$)

MASS

- After a chequered history of false identifications, η_c was firmly identified in e^+e^- experiments in many J/ψ decay channels:

$J/\psi \to \eta_c\gamma$	:	CB (86)	$M(\eta_c) = 2984 \pm 2.3 \pm 4.0$ MeV
	:	DM2 (91)	$M(\eta_c) = 2974.4 \pm 1.9$ MeV
$\eta_c \to$ many	:	MRK3 (86)	$M(\eta_c) = 2980.2 \pm 1.6$ MeV
		PDB92	$M(\eta_c) = 2978.8 \pm 1.9$ MeV

- E760 has identified η_c by its direct formation and its $\gamma\gamma$ decay.

$p\bar{p} \to \eta_c \to \gamma\gamma$	:	E760	$M(\eta_c) = 2988 \pm 3$ MeV

The 9 MeV higher mass is quite significant, because

— $M(J/\psi) - M(\eta_c)$ is often used to 'tune' potential model calculations.

— $M(J/\psi) - M(\eta_c)$ is used to estimate the mass difference $M(\psi) - M(\eta_c')$, and hence $M(\eta_c')$.

WIDTH

- From e^+e^- experiments, there are two estimates

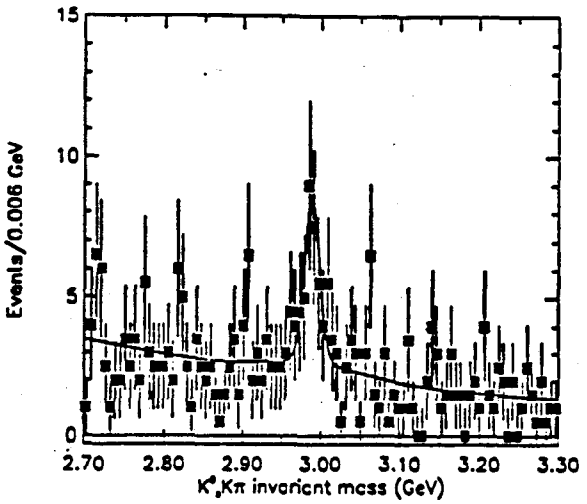
$J/\psi, \psi' \to \gamma\eta_c$	:	CB (86)	$\Gamma(\eta_c) = 11.5 \pm 4.5$ MeV
$J/\psi \to \gamma p\bar{p}$	:	MRK (3)	$\Gamma(\eta_c) = 10^{+33}_{-8}$

- E760 width measurement is not very precise yet, but indications are that $\Gamma(\eta_c) > 15$ MeV.

$\Gamma(\gamma\gamma)$ .....

η_c

CLEO

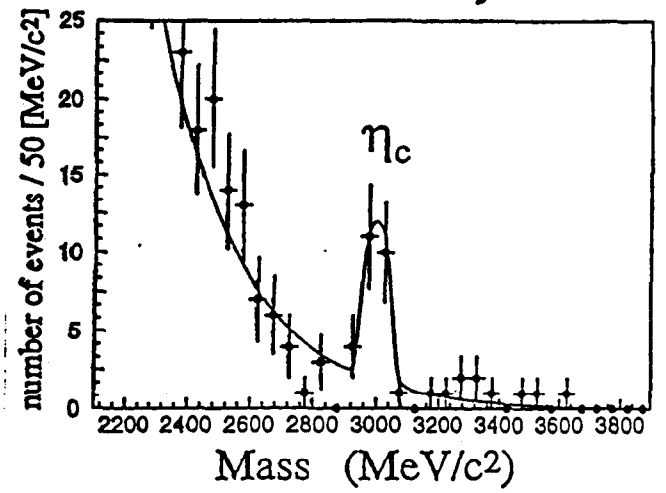


$\gamma\gamma \to \eta_c \to K^0_S K\pi$

42 cts in 1630 pb^{-1}

$\Gamma_{\gamma\gamma} = 5.7 \pm 2.4$ keV

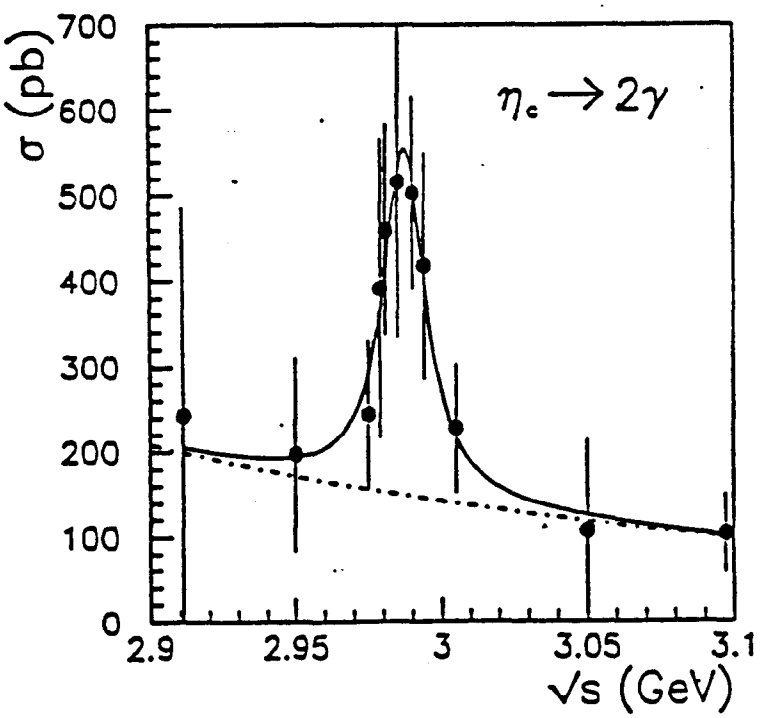
L3 (LEP)



$\gamma\gamma \to \eta_c \to$ 12 decay ch.

28 cts. in 30 pb^{-1}

$\Gamma_{\gamma\gamma} = 7.8 \pm 3.4$ keV



E760

$p\bar{p} \to \eta_c \to \gamma\gamma$

~100 cts in 4 pb^{-1}

$\Gamma_{\gamma\gamma} = 7 \pm 3$ keV

$\Gamma_{tot} > 15$ MeV

$M(\eta_c) = 2988(3)$ MeV

TCF is expected to produce

$10^7\ \eta_c$/month, via $\psi \to \gamma \eta_c$

- Any of the hadronic decays should then lead to excellent determination of η_c mass and width. For example, for $\eta_c \to p\bar{p}$ the present world events 41 ± 17 would change to <u>16,000 events/month</u>

and channels like

$\eta_c \to \phi\phi$, $\eta_c \to \omega\omega$, $\eta_c \to K^* \bar{K}^*$

can be studied with precision.

$\eta_c \to \gamma\gamma$ should yield ~ <u>500 events/month</u>

Remember that

CLEO has all of 42 events

LEP has 28 events.

THE ELUSIVE η_c'

- Crystal Ball (1982) claimed observation in $\psi' \to \gamma\,(M1) + X$

$$M(\eta_c') = 3686 - 94 = 3592 \pm 5 \text{ MeV}$$

$$\Gamma(\eta_c') < 6 \text{ MeV}$$

- Never again observed.
- PQCD predicts

$$\frac{\Delta M(\psi' - \eta_c')}{\Delta M(\psi - \eta_c)} = \frac{\alpha_s(\psi')}{\alpha_s(\psi)} \; \frac{M(\psi)^2}{M(\psi)^2} \; \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(\psi \to e^+e^-)}$$

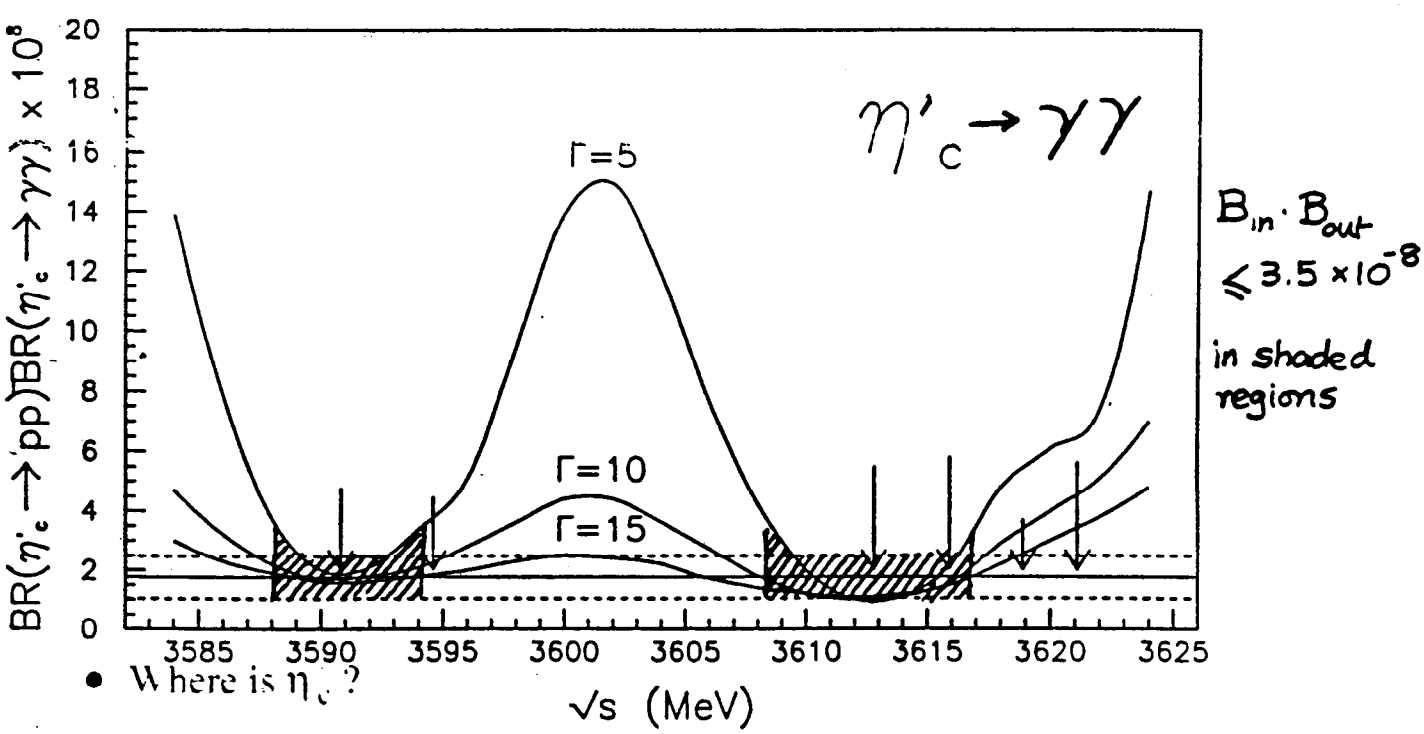
$$= 0.92 \times 1.42 \times 0.46 = 0.60\,(14)$$

PDB $M(\eta_c) = 2979$ MeV, gives $M(\eta_c') = 3615(16)$ MeV

E760 $M(\eta_c) = 2988$ MeV, gives $M(\eta_c') = 3621(15)$ MeV

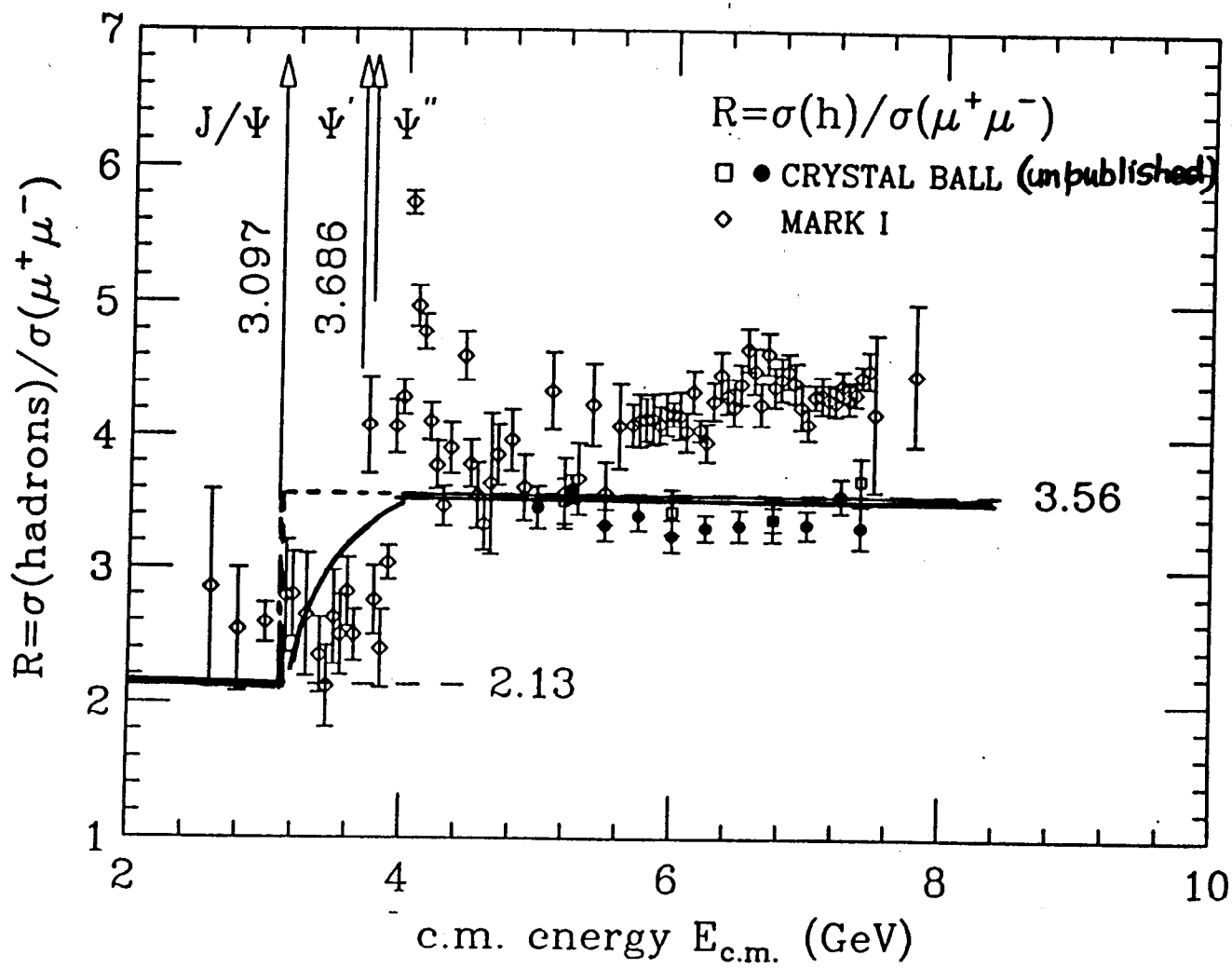
- E760 made a preliminary search. For $\Gamma < 10(5)$ MeV

$M(\eta_c') = 3588 - 3595$
$M(\eta_c') = 3608 - 3617$
} with $B_{in}\, B_{out} < 3.5 \times 10^{-8}$ = 1/10 of η_c observed

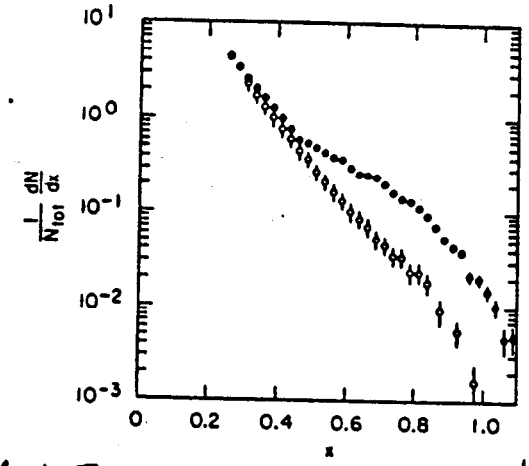


- Where is η_c'?

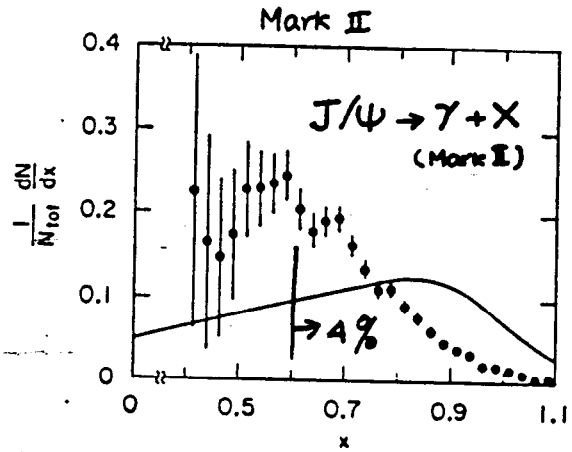
CCF will produce 100 $\eta_c' \to \gamma\gamma$ events/m

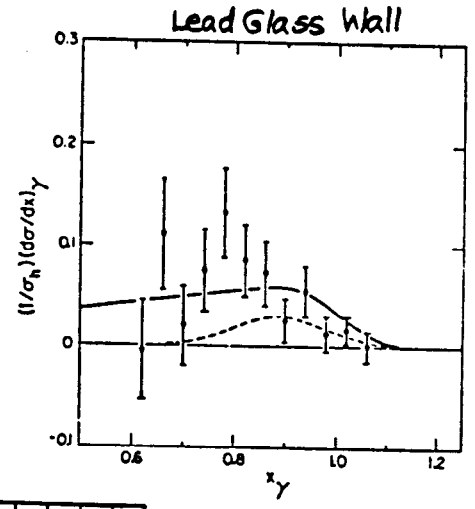

R=σ(h)/σ(μ⁺μ⁻)
CRYSTAL BALL (unpublished)
MARK I
J/Ψ
Ψ'
Ψ''
3.097
3.686
3.56
2.13
R=σ(hadrons)/σ(μ⁺μ⁻)
c.m. energy E_c.m. (GeV)
1
2
3
4
5
6
7
2
4
6
8
10

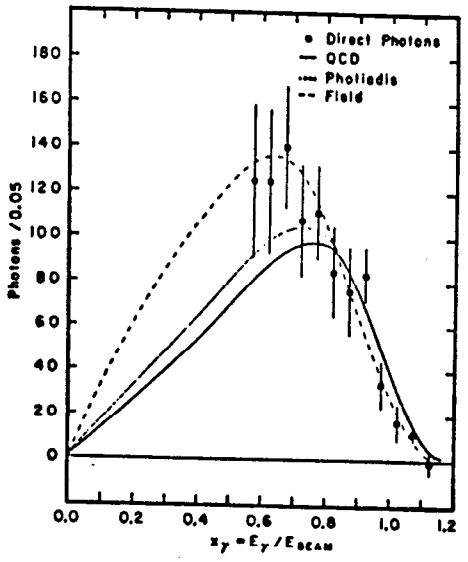
$J/\Psi \to \gamma + X$



Mark II







$\Upsilon(1S) \to \gamma + X$ (CLEO)

1^{--} TRIPLET STATES ABOVE $D\bar{D}$ THRESHOLD (3.73 GeV)

The entirity of our knowledge about these is reproduced here, and it is not much.

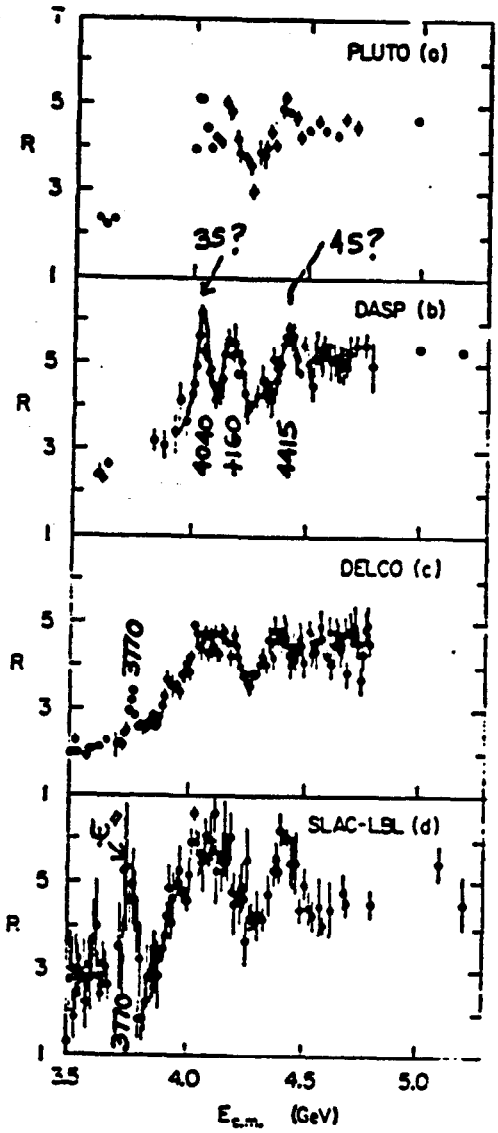


Fig. 5. R versus energy. The R values have been radiatively corrected in (a), (b), and (d), but not in (c). τ pair production is included in R.

	?	Γ(MeV)	Γ_{ee}(KeV)
$\psi''(3770)$	1^3D_1 ?	24(3)	0.26(4)
$\psi(4040)$	3^3S_1	52(10)	0.75(15)
$\psi(4160)$	2^3D_1	78(20)	0.77(23)
$\psi(4415)$	4^3S_1	43(15)	0.47(10)

$\psi(4040) \to$	$D^*\bar{D}^*$	$\propto 600$
	$D^*\bar{D}$	20
	$D\bar{D}$	1

We have here potential candidates for $D, \bar{D}, D^*, \bar{D}^*$ factory. (e.g.) $\psi(4040)$

- But, what a mess!
- Even the experiments don't agree

For these states $p\bar{p}$ is not likely to be of much help.
They have to be studied seriously and by e^+e^- (τCF again)

THE STRONG COUPLING CONSTANT α_s

- F. Wilczek :

  — "A quantitative measure (of how good PQCD is) is how tightly is α_s constrained."

  — "Large Q^2 measurements are limited in their power to resolve possible values of α_s, qualitatively."

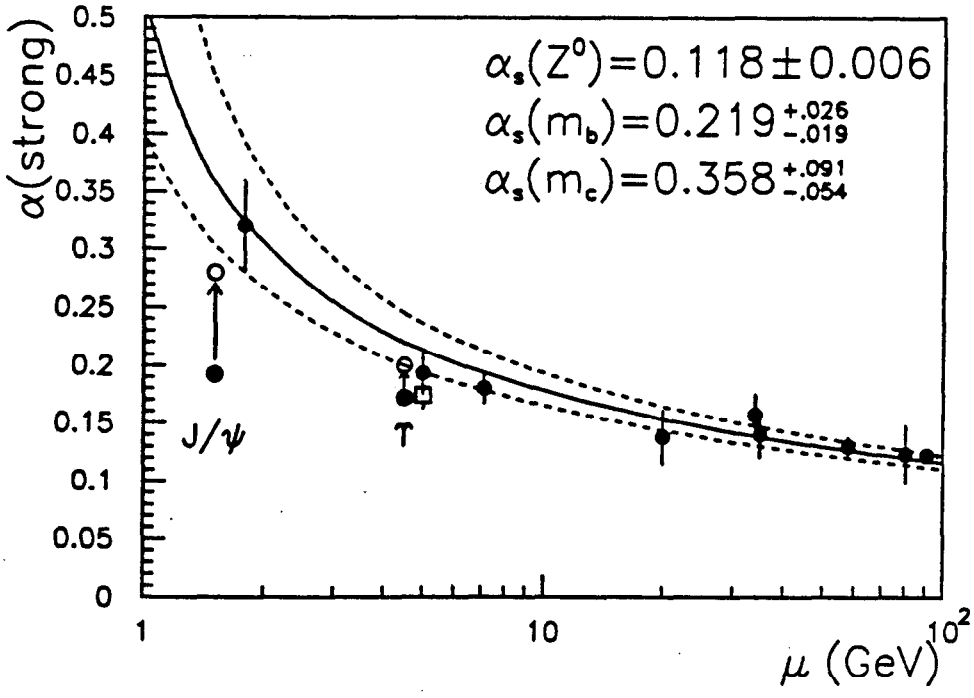
  — "If you are interested in quantitative results for α_s, there is a large premium for working at small Q^2."

  — So, how well do we know α_s at small Q^2 ?

$$\alpha_s(\mu) = \frac{12\pi}{(33 - 2n_f)\ln k}\left[1 - \frac{6(153-19n_f)\ln(\ln k)}{(33 - 2n_f)^2 \ln k}\right]$$

where, $k = \mu^2 / \Lambda^2$.

  — α_s rises rapidly at small μ.



α_s FROM CHARMONIUM DECAYS

J/ψ DECAY

- Use ratios of decay widths to cancel dependence on the radial wave function, its derivitives, and quark masses in PQCD predictions.
- Use one loop radiative corrections, but beware of them. They are often too large to be reliable.

$$\text{e.g., } \Gamma(\chi_0 \to \gamma\gamma) = [6\alpha_s^2 / m_c^4]\, |R'_p(0)|^2 (1-3.0\alpha_s)$$

Observable	Proportionality	α_s (LO)	α_s (NLO)	α_s from Z^0
Tau Decay	at 1.78 GeV		0.32 (4)	0.33(6)
ΔM ($J/\psi - \eta_c$)	at 1.5 GeV		0.37(6)	0.37(6)
$\Gamma(J/\psi \to ggg) / \Gamma(J/\psi \to e^+e^-)$	α_s^3 / α^2 at 1.5 GeV	0.198 (6)	0.192 (6)	0.36(7)
$\Gamma(\Upsilon \to ggg) / \Gamma(\Upsilon \to e^+e^-)$	α_s^3 / α^2 at 4.5 GeV	0.173(3)	0.172 (3)	0.22(2)

- What is wrong with the very precise α_s from J/ψ and Y widths?
- A relativistic "fix" (Mackenzie and Lapage) is to add a term: $[\,1-C(v^2/c^2)\,]$ to the ratios. Arbitrarily chosen

  C=3.5 moves $\alpha_s(J/\psi) \to 0.36$
  C=6.5 moves $\alpha_s(\Upsilon) \to 0.22$

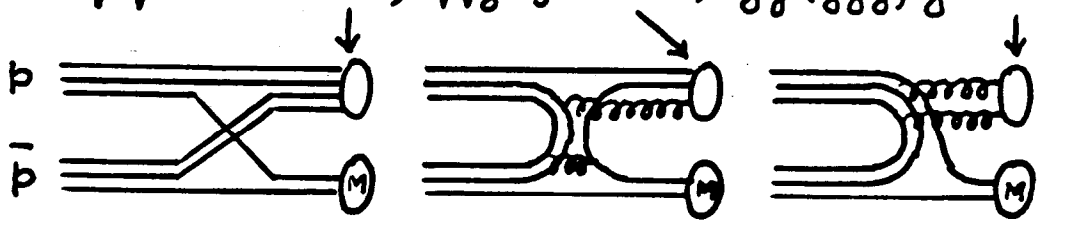
- Finite size annihilation vertex corrections (Chiang et al, 1994)

$$\alpha_s(J/\psi) = 0.29(1)$$
$$\alpha_s(\Upsilon) = 0.20(1)$$

— Gradually, better understanding is emerging.

LIGHT-QUARK STRUCTURES

- $p\bar{p}$ annihilation is rich in glue.
  - one of the best ways to make $q^2\bar{q}^2$ molecules, $q\bar{q}g$ hybrids, gg (ggg) glueballs



- E760 has identified several new structures.
  - What are they?

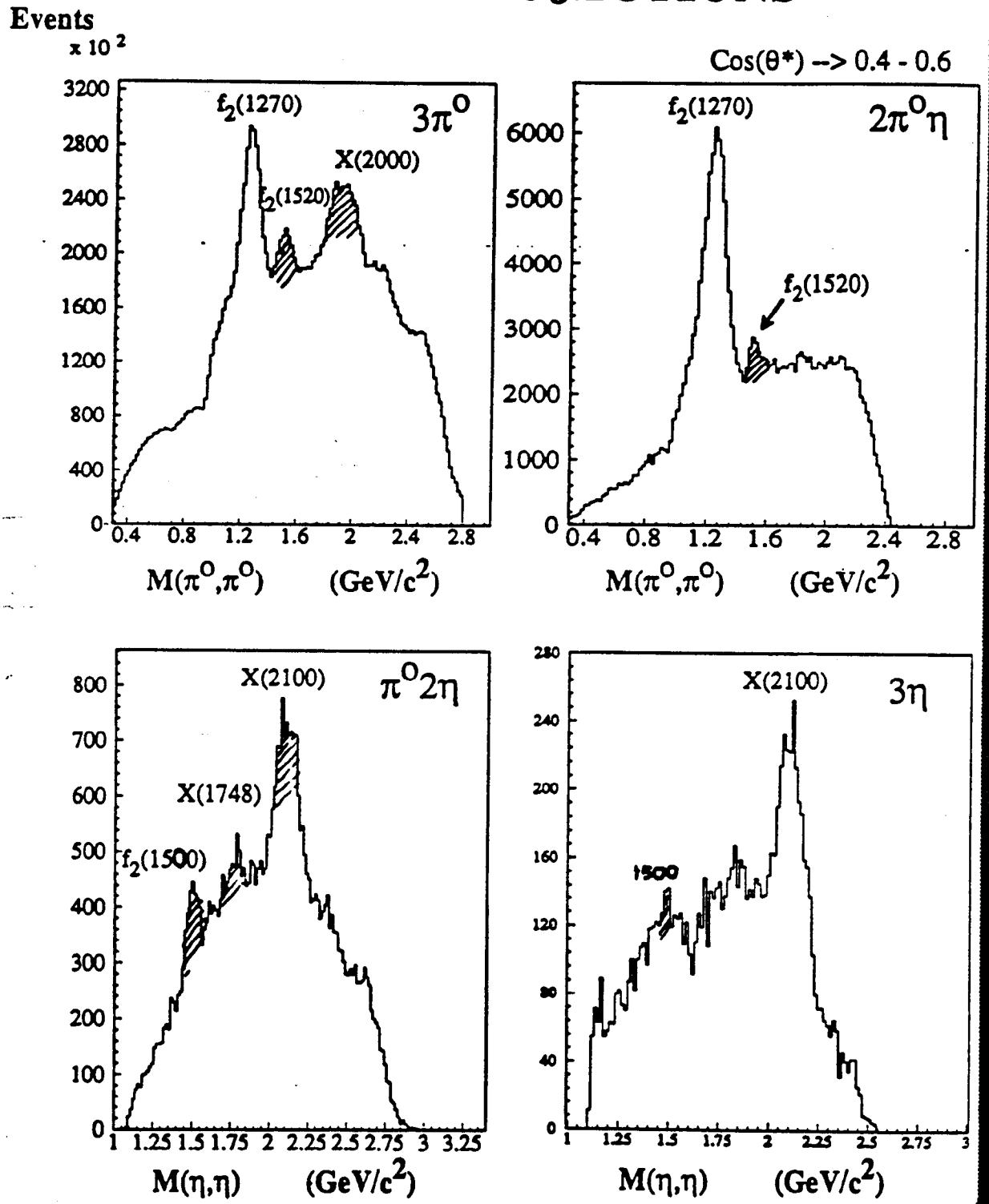
e.g., the story of $A_x(1520)$ —

Channel	Resonance	Decay	Mass (MeV/c^2)	Width (MeV/c^2)
$3\pi^0$	$f_2(1520)$	$\pi^0\pi^0$	1508±10	103±15
	X(2000)	$\pi^0\pi^0$	1964±35	225±50
$2\pi^0\eta$	$f_2(1520)$	$\pi^0\pi^0$	1525±10	111±10
$\pi^0 2\eta$	$a_2(1320)$	$\pi^0\eta$	1324±5	118±10
	X(1500)	$\eta\eta$	1488±10	148±17
	X(1748)	$\eta\eta$	1748±10	264±25
	X(2100)	$\eta\eta$	2104±20	203±10
3η	X(2100)	$\eta\eta$	2008±20	131±10

Ref: Phys. Lett., B 307 (1993) 394-398 and Phys. Lett., 307 (1993) 399-402.

Glueball ??

MASS PROJECTIONS



IEC-HEP'93

THE SINGLET P - STATE

For a pure vector interaction, the hyperfine splitting due to spin-spin interactions is

$$\Delta M_{ss} = M\,(S=1) - M\,(S=0) = \frac{32\pi}{9m^2}\,\alpha_s\,|R(0)|^2$$

- $\Delta M_{ss} = 0$ only for $l=0$.

  For charmonium $M\,(^3S_1) - M\,(^1S_0) = 117.3$ MeV

- For $l=1$, $|R\,(0)| = 0$, and ΔM_{ss} should be 0.

  A non-zero value of

$$\Delta M = \langle M\,(^3P_J)\rangle - M\,(^1P_1)$$

signals a long-range vector contribution.

∴, It is very important to find the $^1P_1$ state of charmonium.

- Of the three electromagnetic-decay channels investigated,

$$^1P_1 \rightarrow \eta_c + \gamma \rightarrow (\gamma\gamma) + \gamma$$
$$^1P_1 \rightarrow J/\psi + 2\pi \rightarrow (e^+e^-) + 2\pi$$
$$^1P_1 \rightarrow J/\psi + \pi^0 \rightarrow (e^+e^-) + (\gamma\gamma)$$

we found the $^1P_1$ in the isospin-forbidden π^0- decay channel, with the following results:

$M\,(^1P_1) = 3526.2 \pm 0.15 \pm 0.20$ MeV

$\Delta M = -0.9 \pm 0.2 \pm 0.2$ MeV $\longrightarrow$ $\alpha_s(m_c)=0.31(3)$

$\Gamma < 1.1$ MeV (Halzen, 1993)

$$BR\,(^1P_1 \rightarrow pp)\,.\,BR\,(^1P_1 \rightarrow J/\psi + \pi^0) \cong 2.1\,(8) \times 10^{-7}$$

- Isospin-allowed 2π decay is a factor 5 smaller than the isospin forbidden π^0 decay. This is counterintuitive, but predicted by Voloshin.

Tau-Charm Factory

—what it can do for charmonium physics—

TABLE VII. Event Rate per/year (10^7 sec) for charmonium decays at the τCF

Particles and Decays	World Detected Events	Branching Ratios	τCF Produced Events/year
ψ	2.7×10^7	Direct formation	1.0×10^{10}
$\psi \to \gamma\eta_c$	3×10^4	1.27%	1.3×10^8
$\psi \to \gamma\gamma\gamma$	0	(7×10^{-6})	7×10^4 ✓
$\eta_c \to \gamma\gamma$	150	0.5 ~~3~~$\times10^{-4}$	~~4×10^4~~ 6×10^3
$\eta_c \to p\bar{p}$	<50	1.2×10^{-3}	1.6×10^5 ✓
$\eta_c \to \phi\phi$	35	7.1×10^{-3}	9×10^5
$\eta_c \to \omega\omega$	0	$<3\times10^{-3}$	$\leq4\times10^5$
$\eta_c \to K^*\bar{K}^*$	9	8.5×10^{-3}	1.1×10^6
$\eta_c \to \rho\rho$	113	2.6%	3×10^6
ψ'	3.1×10^6	Direct formation	2×10^9
$\psi' \to \gamma\eta_c$	5×10^3	2.8×10^{-3}	6×10^6
$\psi' \to \gamma\eta_c'$	?	0.5 %	10^7 ✓
$\psi' \to \gamma\chi_0$	2.3×10^5	9.3%	1.9×10^8
$\psi' \to \gamma\chi_1$	1.9×10^5	8.7%	1.7×10^8
$\psi' \to \gamma\chi_2$	1.7×10^5	7.8%	1.6×10^8
$\psi' \to \pi^0 h_c$	0	~~(2×10^{-5})~~ $<6\times10^{-7}$	~~(4×10^3)~~ $<10^3$
$\psi' \to \pi^0 J/\psi$	30	9.7×10^{-4}	1.9×10^6
χ_2, χ_0		Direct formation	$(\sim10^4)$
$\eta_c' \to \gamma\gamma$	0	1 ~~(3×10^{-4})~~	~~(6×10^4)~~ 10^3
$\chi_2 \to \gamma\gamma$	35	1.6×10^{-4}	2.5×10^4
$\chi_0 \to \gamma\gamma$	0	(1×10^{-4})	(1.6×10^4) ✓

DOC#KKS003.93