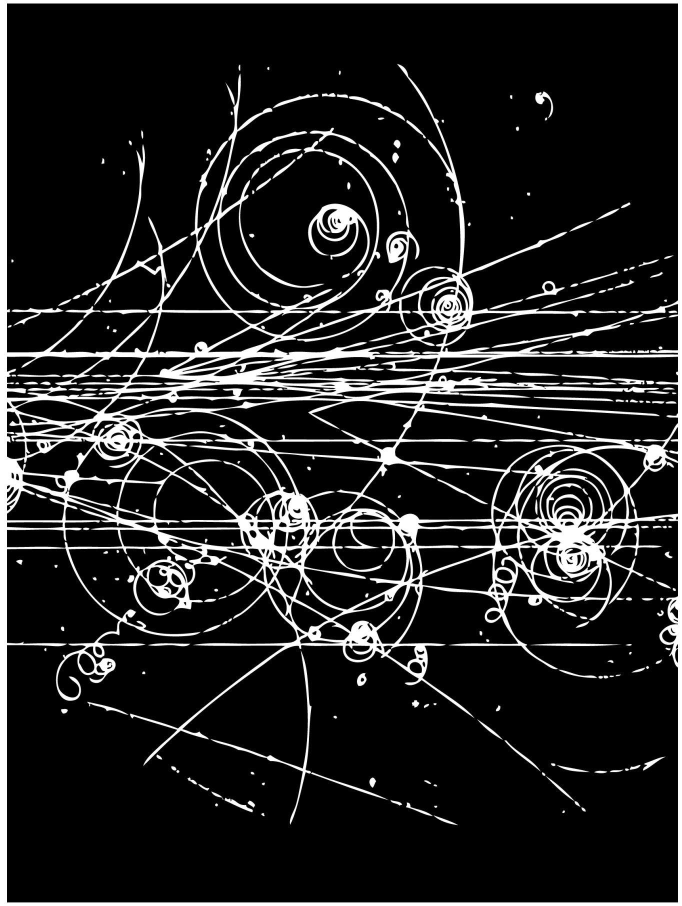
Hadron Spectroscopy



Stephen Lars Olsen

Institute for Basic Science (KOREA)

University of the Chinese Academy of Science

UCAS Physics-department, June 20 – July 6, 2014

Lect. 4: QCD & overview of Quarkonium
-- the simplest hadons --

◆A few remarks about QCD

◆Discovery of the J/ψ and charm

◆Properties of Charmonium
-- detailed (sorry, but important for BESIII)

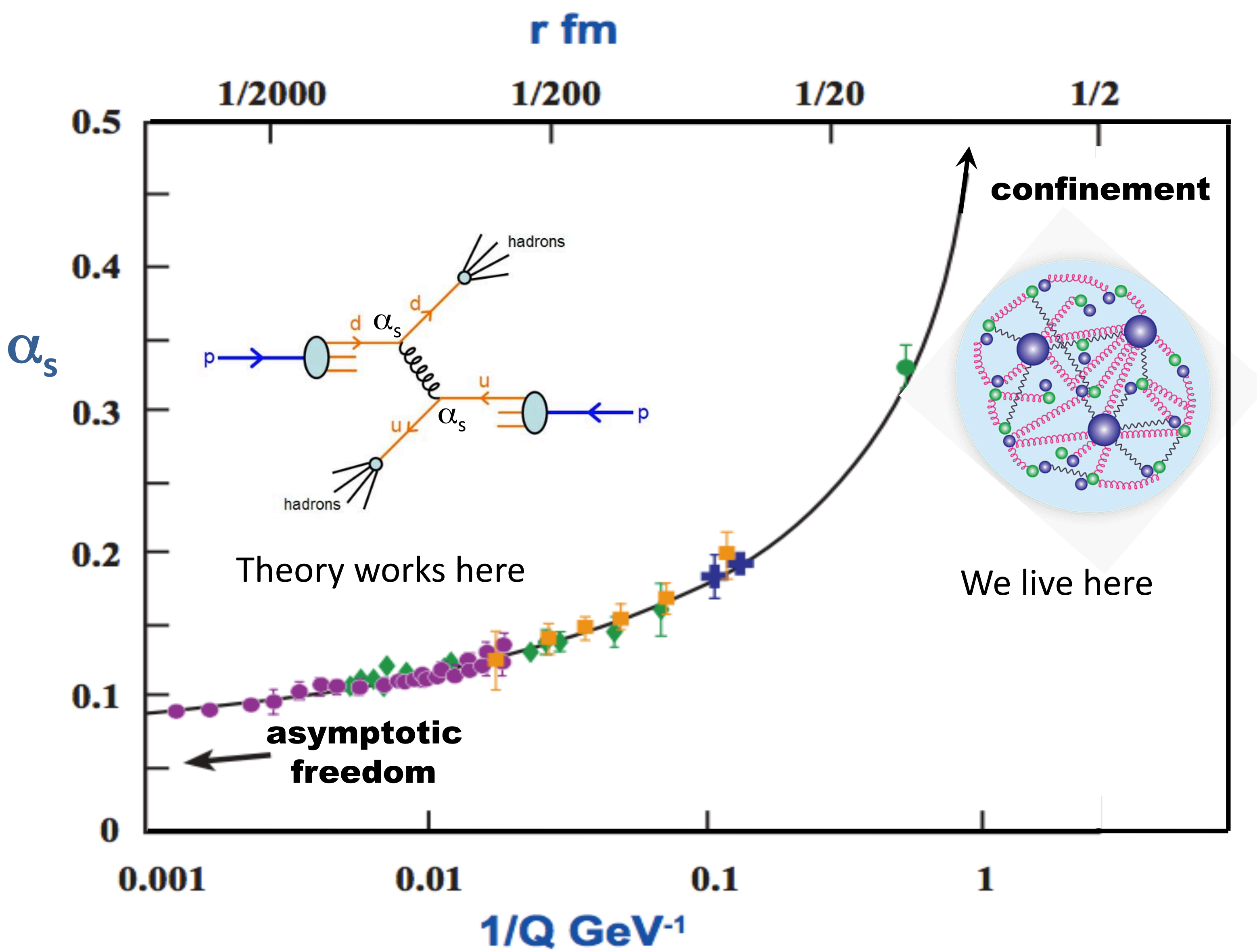
>> BESIII's "bread and butter" (主要的生計來源)

◆A little bit about Bottomonium

Summary (lecture 3)

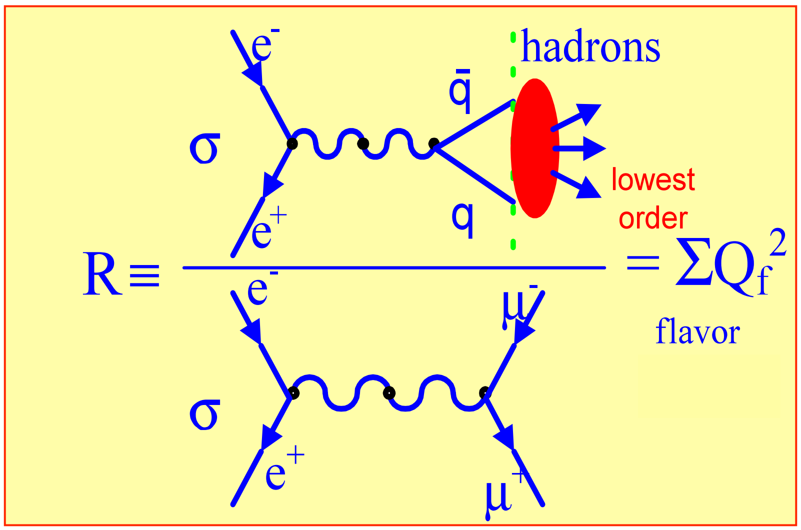
- The $q\bar{q}$=mesons and qqq=baryon prescriptions work well for the lowest-lying mesons & baryons, but fail otherwise
  - the mass hierarchy of the lowest-lying scalar mesons is opposite to expectations for $q\bar{q}$=mesons
  - The masses of the N*(1440), the 1st excited state of the nucleon, and the Λ(1405), the lowest excited sate of the Λ, defy simple QM predictions for qqq=baryons
- The quark model seriously violates the Pauli Principle
- Quarks come in 3 “colors” & are held by 8 colored gluons
- Do quarks really exist?

hadrons in QCD



A prediction of the quark model:

-- pre color --

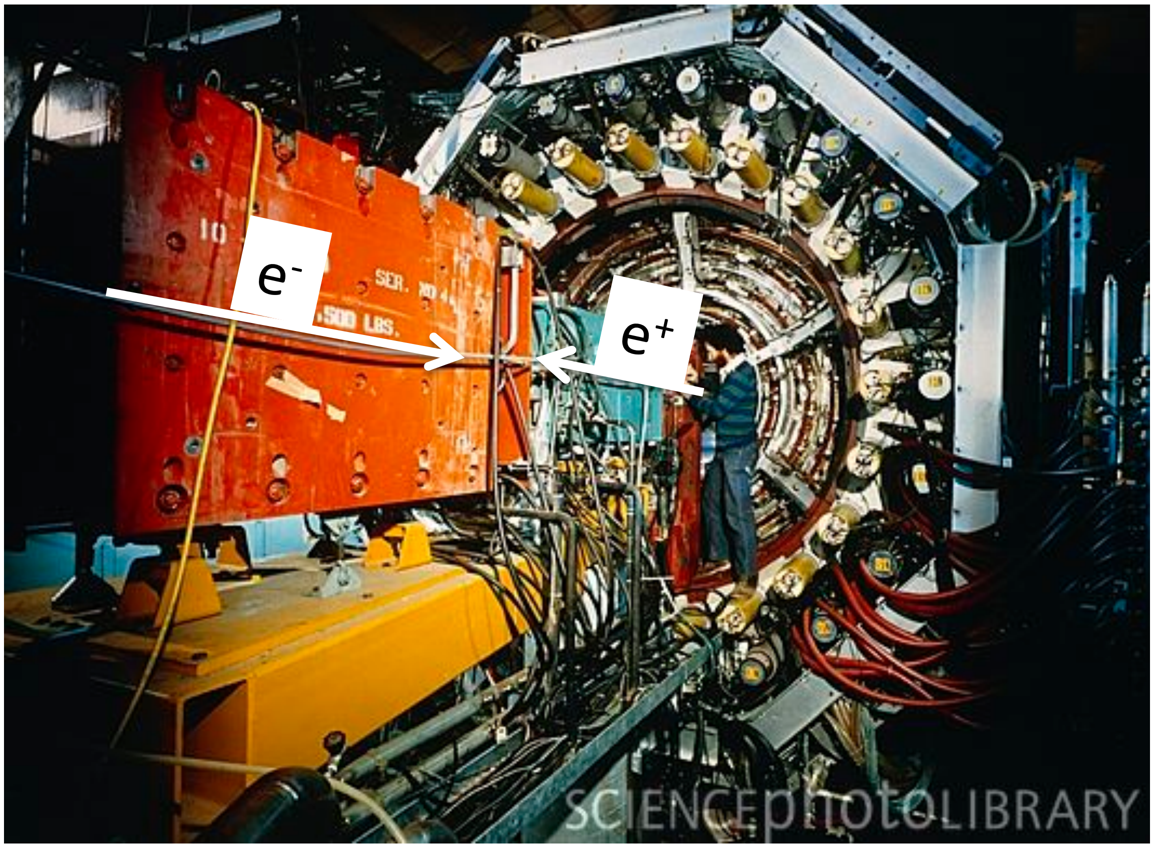


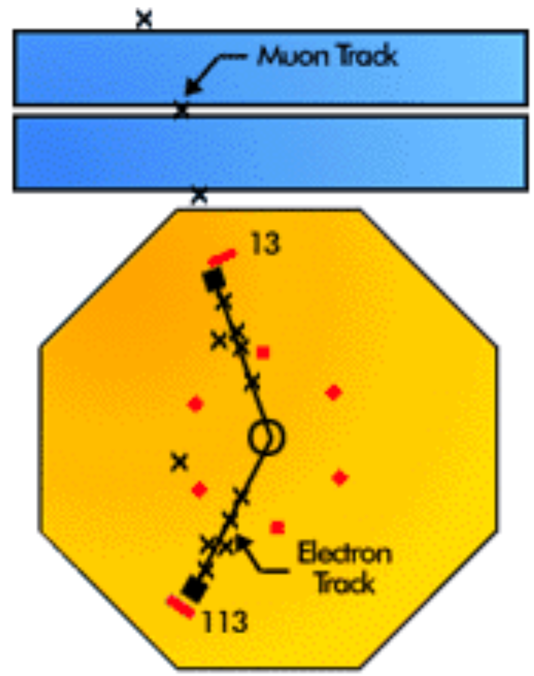
$$R \equiv \sum_{\text{flavor}} Q_f^2 = \left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 = 2/3$$

$$\text{prediction}: \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = const = 2/3$$

Mark I detector (1974)

At SLAC's "SPEAR" e^+e^- collider





R data in June 1974

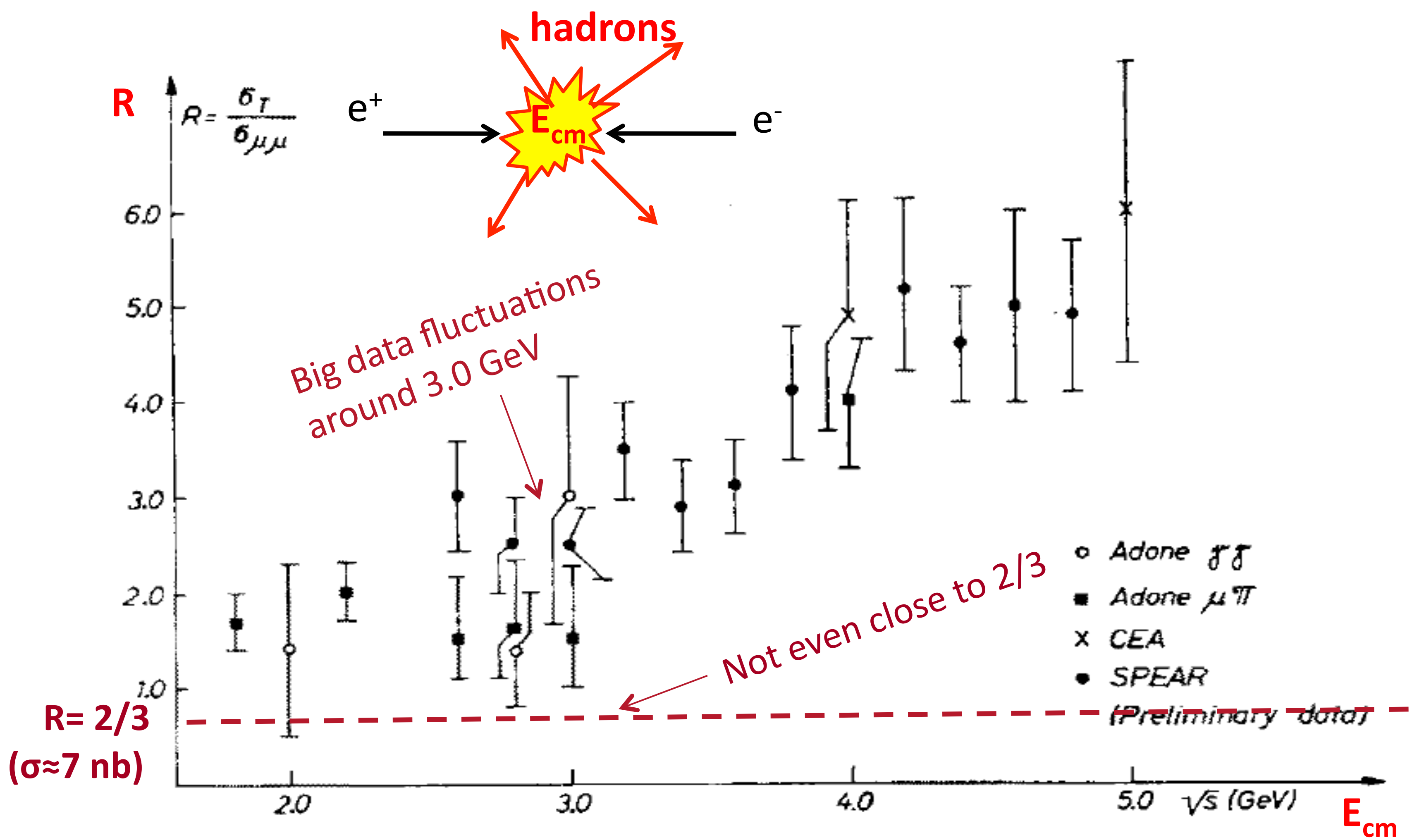
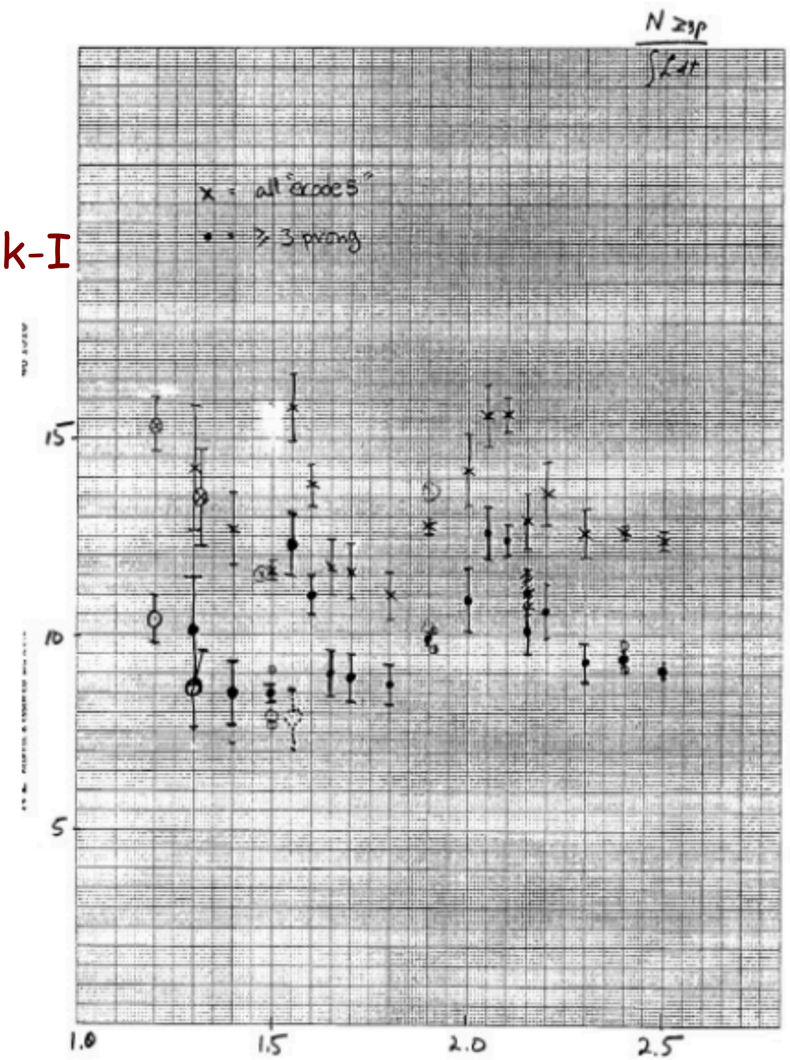


Fig. 35. $R = \sigma_{\text{hadrons, total}} / \sigma_{\mu\bar{\mu}}$ vs E

Compilation by: L. Paoluzi Acta Physica Polonica B5, 829 (1974)

Inconsistent data ?

From the Mark-I experiment's notebook



Let's do a careful energy scan

Roy Schwitters
-- post-doc --

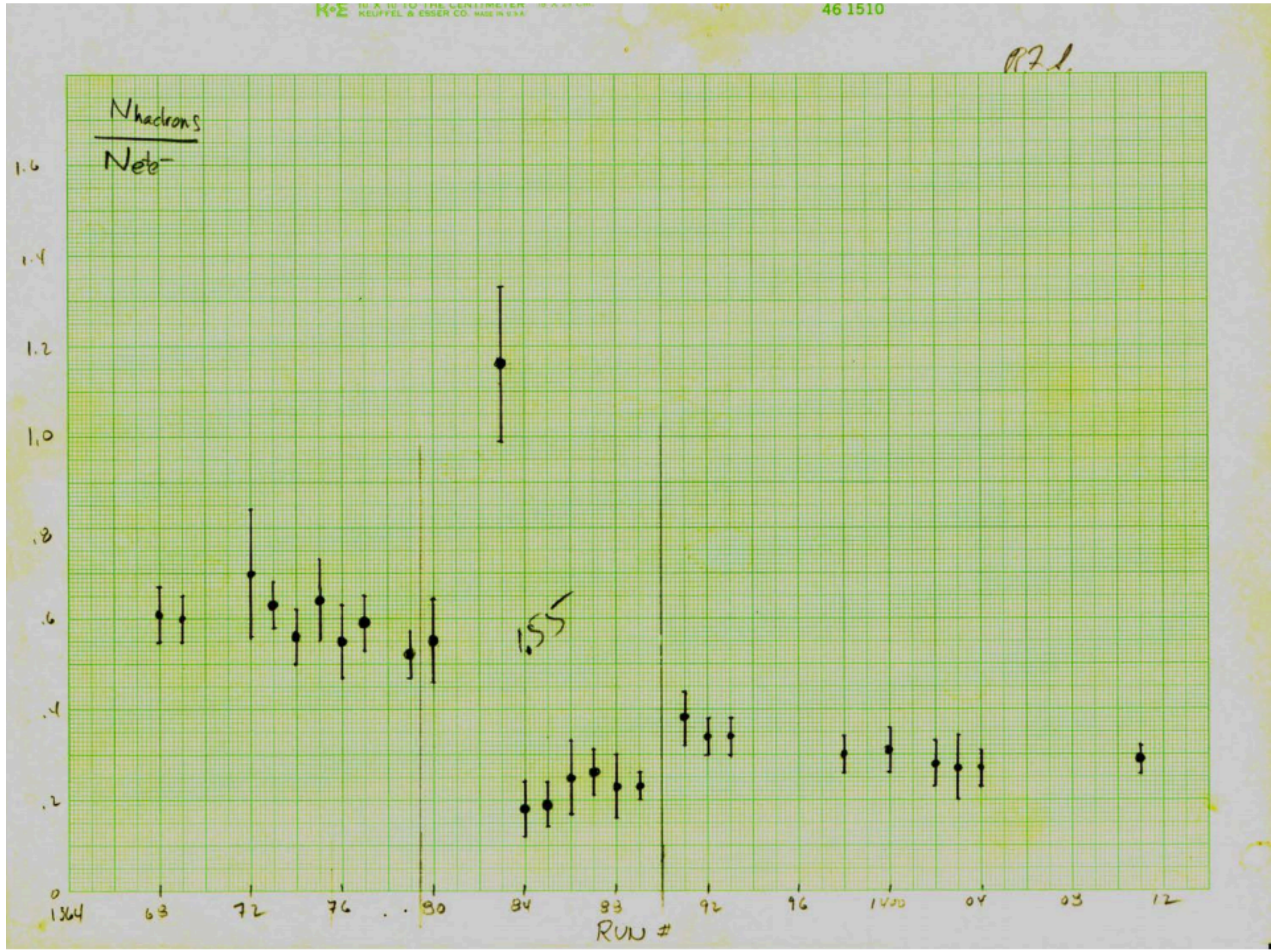
No. Let's go to higher energy.

Burton Richter
- group leader -

OK, do an energy scan, but only for one weekend

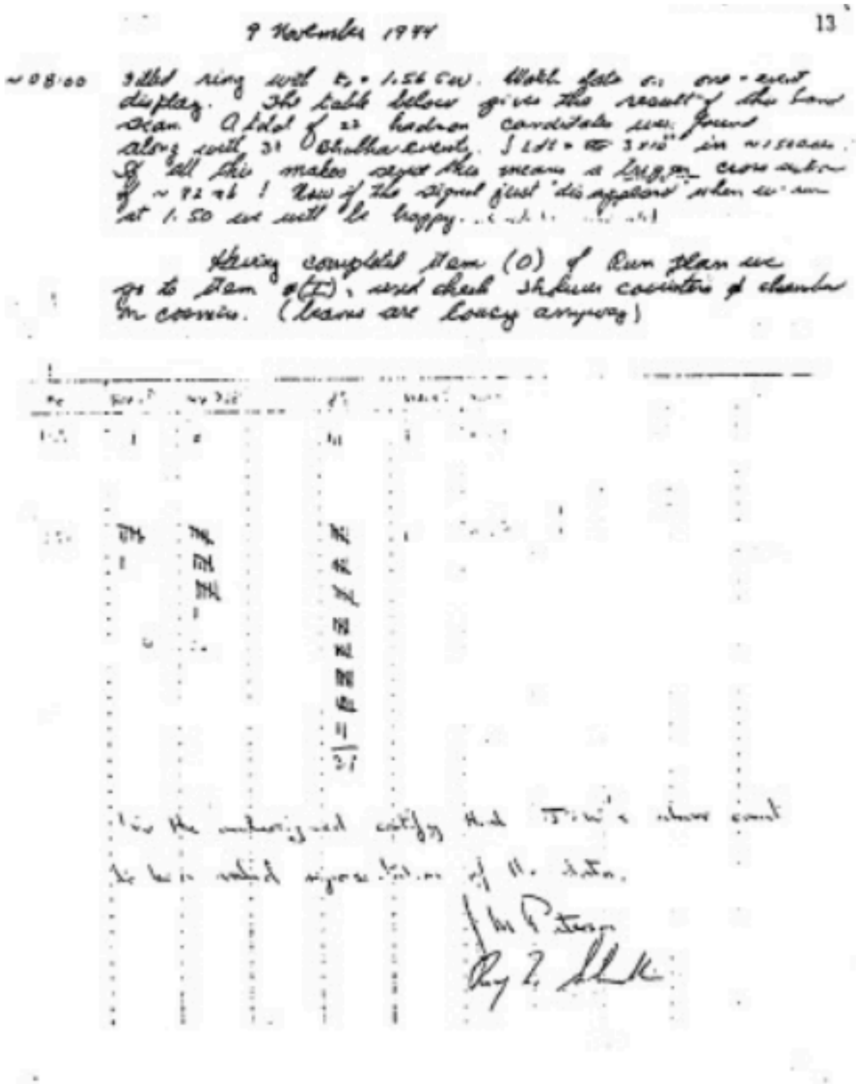
What?

From the Mark-I experiment's notebook



do a careful fine-step energy scan

From the Mark-I experiment's notebook


9 November 1974

13

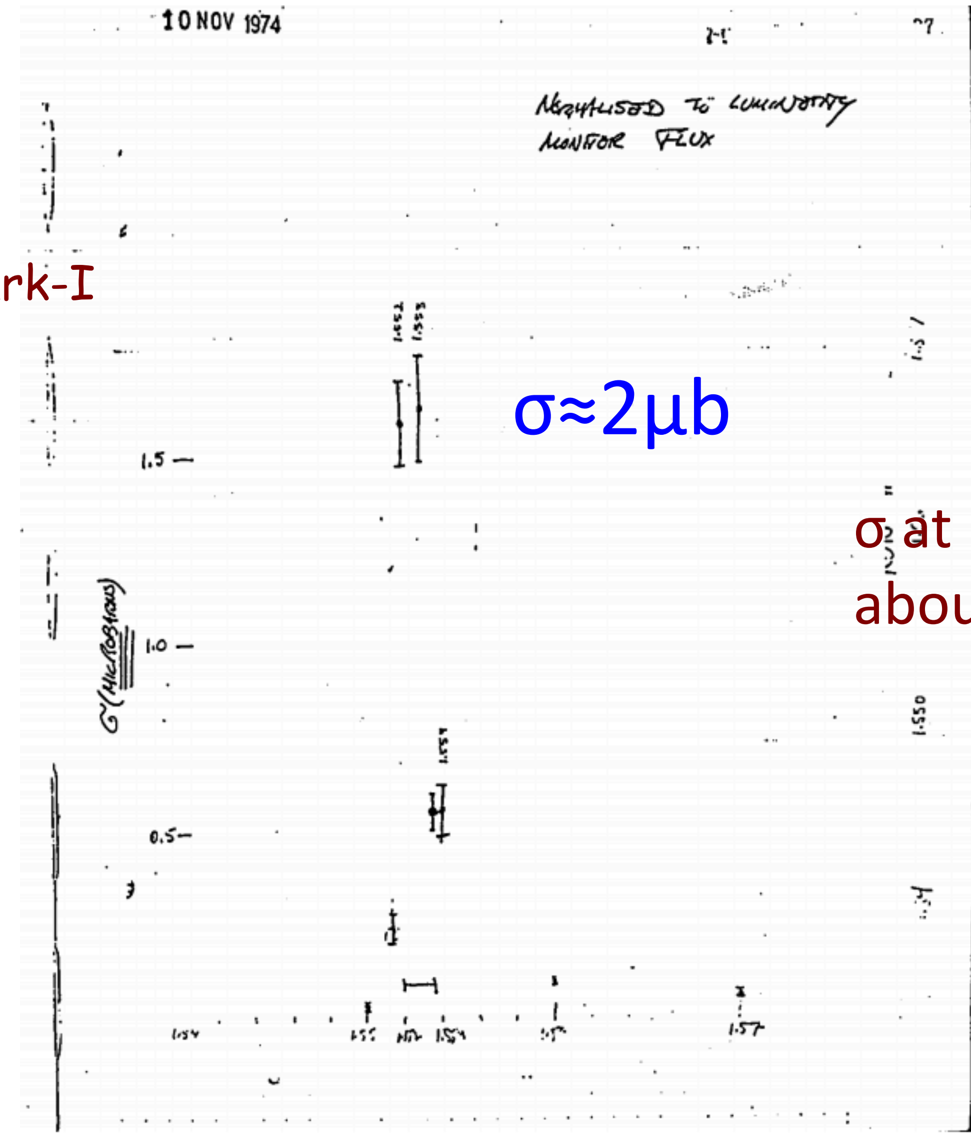
~08:00 Filled ring with E_b = 1.56 GeV. Watch data on one-event display. The table below gives the results of the low scan. A total of 22 hadron candidates was found along with 31 Bhabha events. If all this makes sense this means a large cross section of ~ 92 nb! Now if the signal just "disappears" when we are at 1.50 we will be happy...

Having completed Item (0) of Run plan we go to Item ... and check ... (beams are lousy anyway)

We the undersigned certify that ...'s above count to be a valid representation of the data.

Wow!!

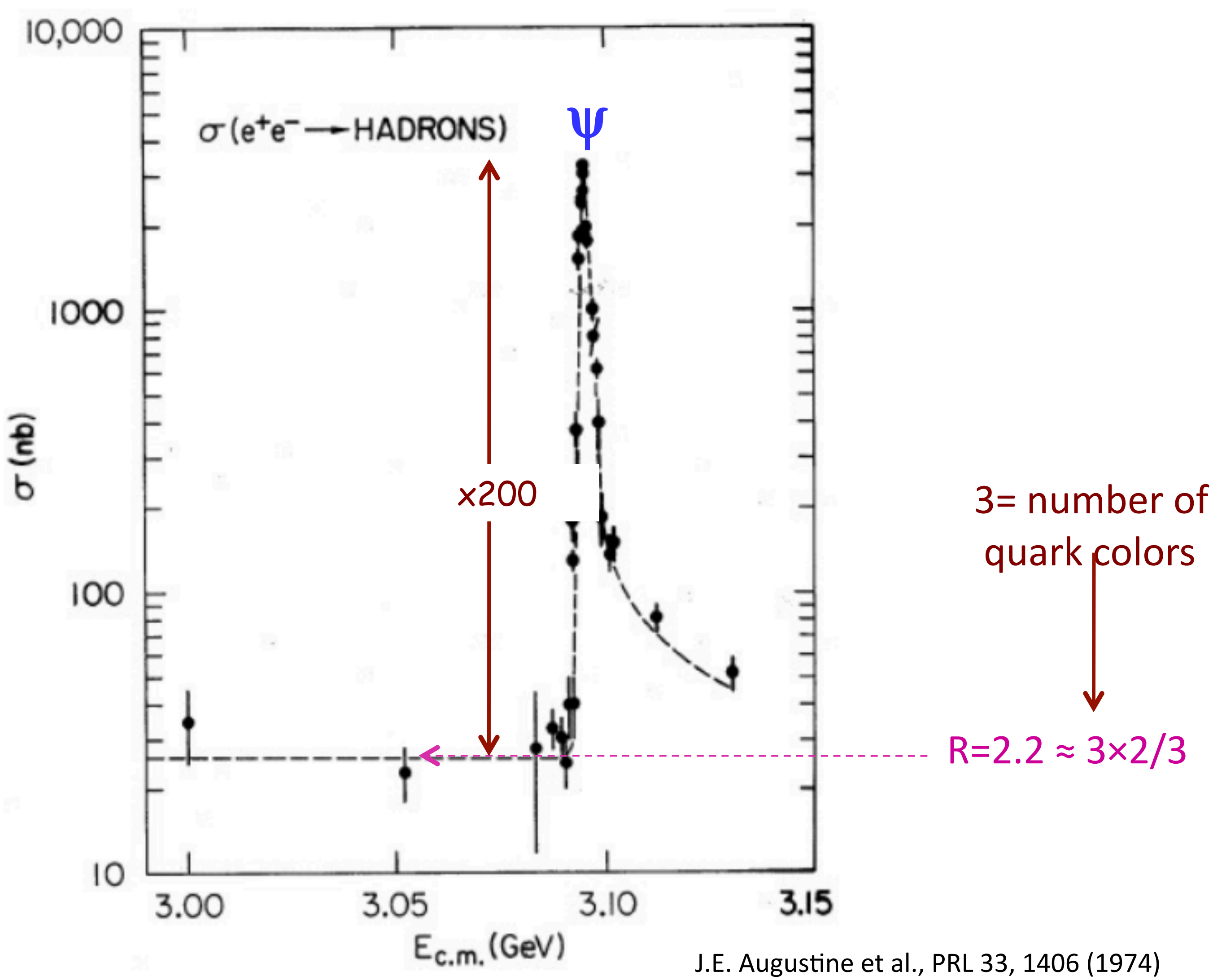
From the Mark-I experiment's notebook



σ≈2μb

σ at nearby energies are about 7 nb, 300x smaller!

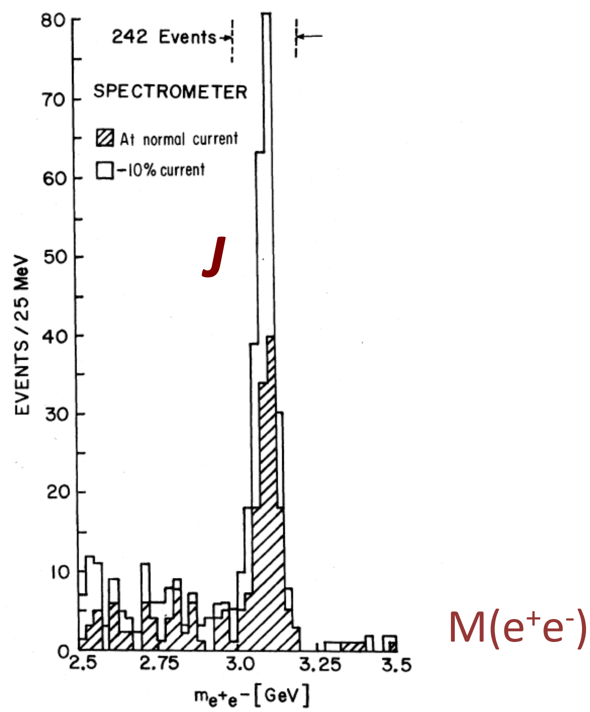
A needle in a haystack!!



J.E. Augustine et al., PRL 33, 1406 (1974)

Same time, at Brookhaven

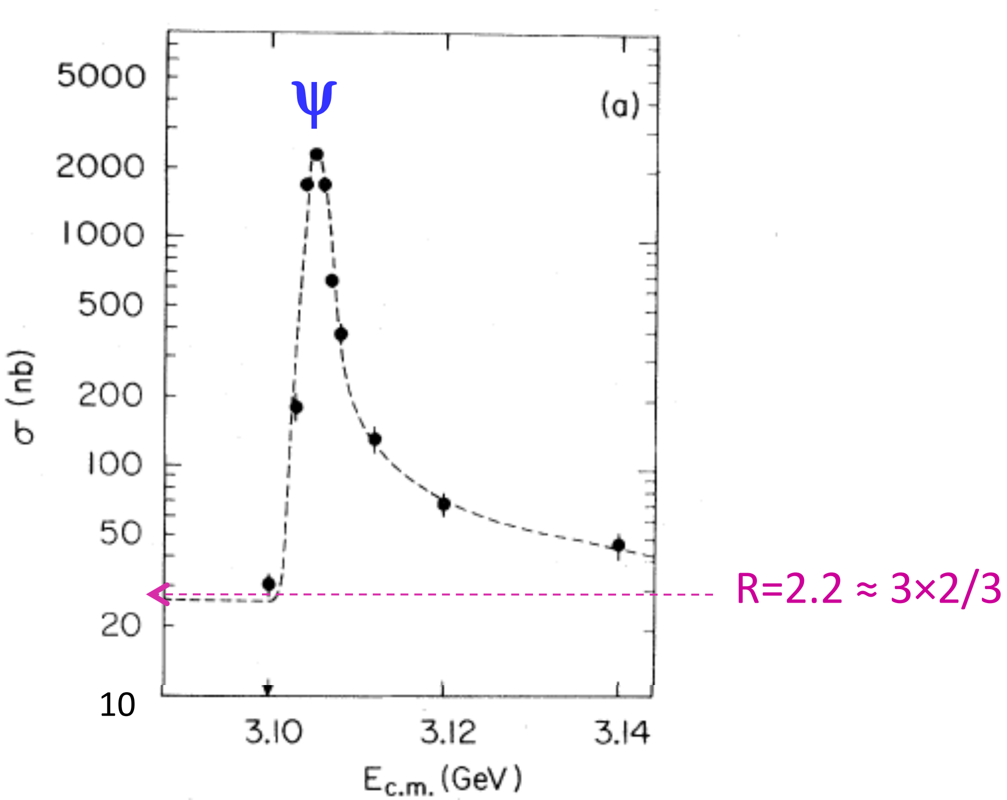
huge 3.1GeV $M(e^+e^-)$ peak in $pN \rightarrow e^+e^-X$



J.J. Aubert et al., PRL 33, 1404 (1974)

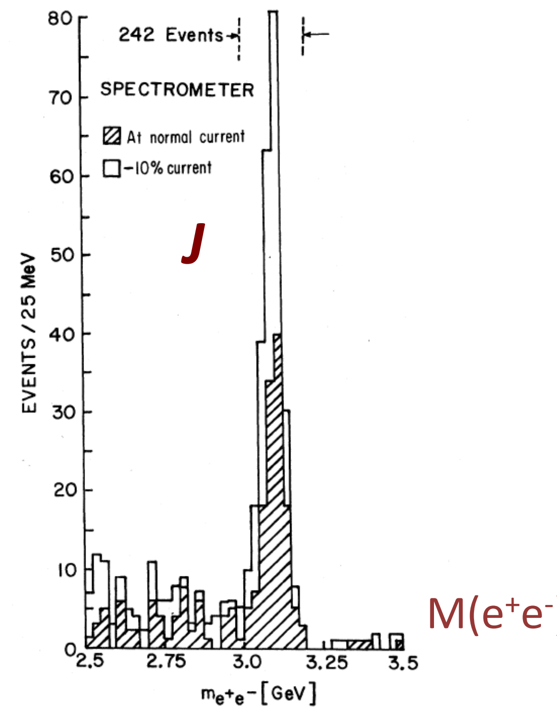
The "J/ψ" meson

SLAC:



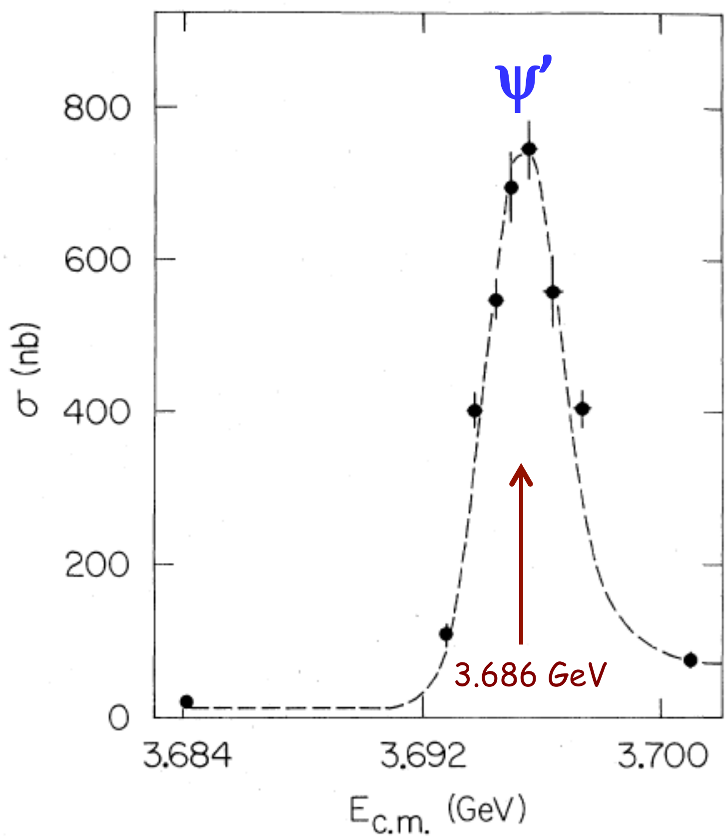
J.E. Augustine et al., PRL 33, 1406 (1974)

Brookhaven:



J.J. Aubert et al., PRL 33, 1404 (1974)

Mark-I: Another peak near 3.69 GeV



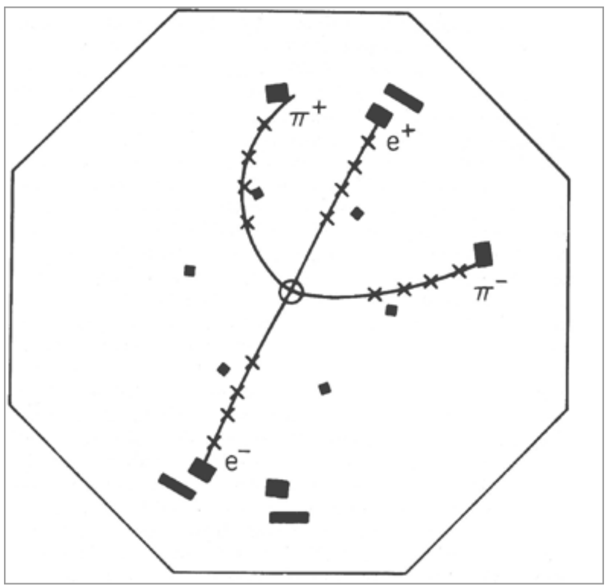
G.S. Abrams et al., PRL 33, 1453 (1974)

← About 2 weeks later

Why is the J/ψ called the J/ψ?

Event in Mark I

$\psi' \rightarrow \pi^+\pi^- J/\psi$
$\quad\quad\quad\quad\quad\quad \hookrightarrow e^+e^-$



Mark-I detector

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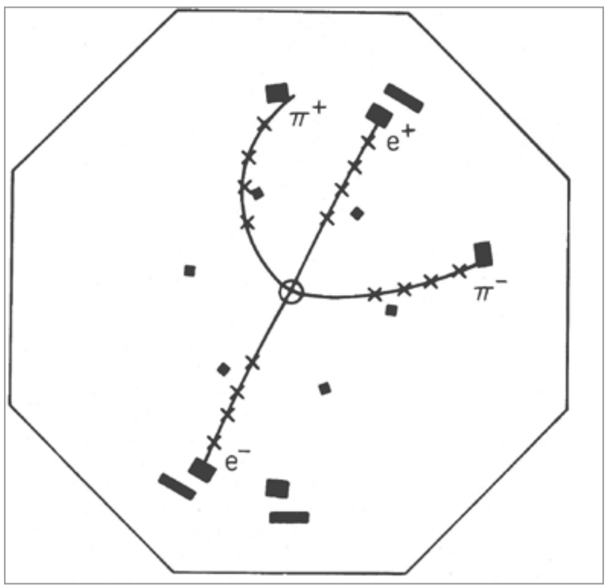

Mark-I detector

Group leader of the Brookhaven expt

Samuel C.C. Ting

Chinese character for Ting: 丁

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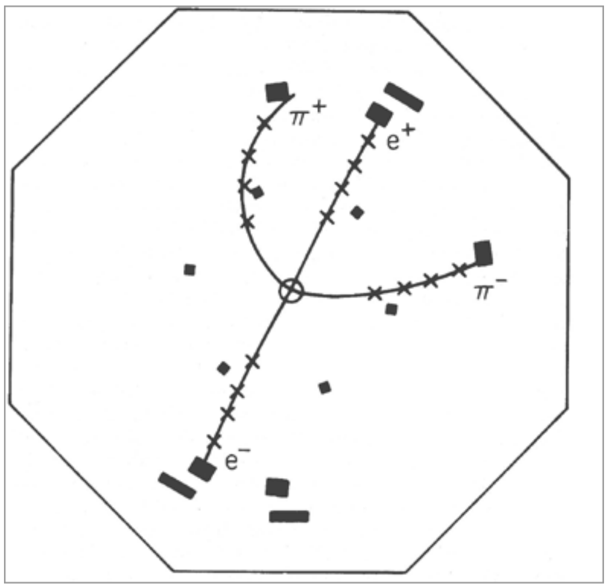

Mark-I detector

Group leader of the Brookhaven expt

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Chinese character for Ting: 丁

now, the Particle Data Group has claimed the right to name all particles.

1976 Nobel Prize

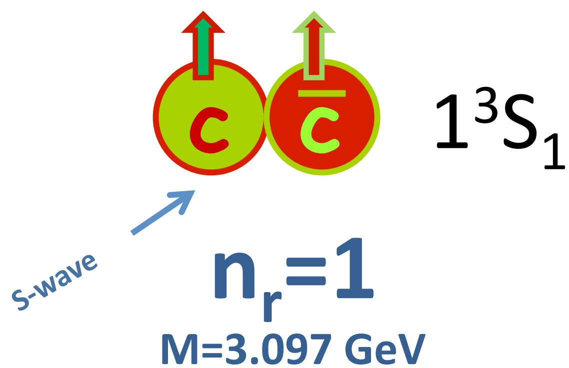
Burton Richter-

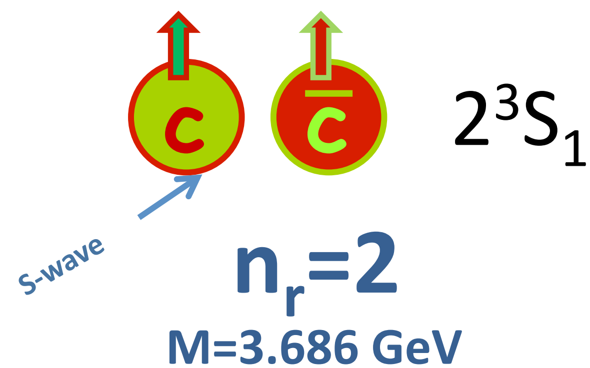
Samuel C.C. Ting

no prize for
Roy Schwitters

Interpretation of J/ψ and ψ’

charmed-quark anticharmed-quark mesons





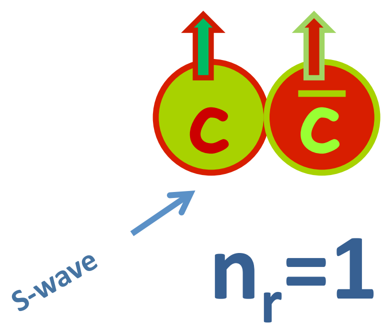
charmed quark ➔ q= +2/3 partner of the s-quark

before 1974

$$\begin{pmatrix} u^{+2/3} \\ d^{-1/3} \end{pmatrix} \begin{pmatrix} ? \\ s^{-1/3} \end{pmatrix}$$

Interpretation of J/ψ and ψ’

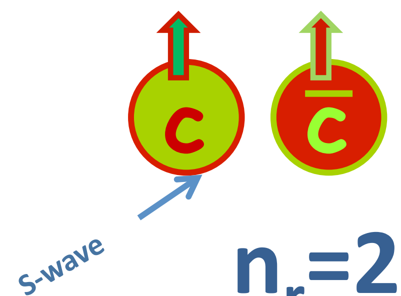
charmed-quark anticharmed-quark mesons



1^3S_1

n_r=1

M=3.097 GeV



2^3S_1

n_r=2

M=3.686 GeV

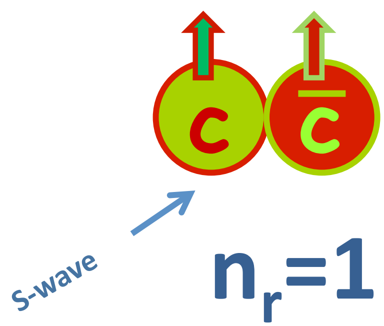
charmed quark ➔ q= +2/3 partner of the s-quark

after 1974

$$\begin{pmatrix} u^{+2/3} \\ d^{-1/3} \end{pmatrix} \begin{pmatrix} c^{+2/3} \\ s^{-1/3} \end{pmatrix}$$

Interpretation of J/ψ and ψ'

charmed-quark anticharmed-quark mesons



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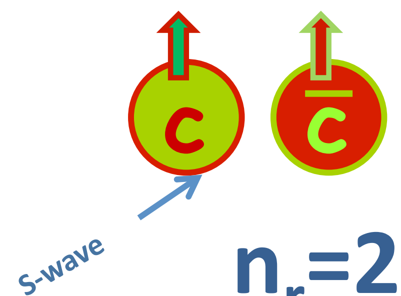

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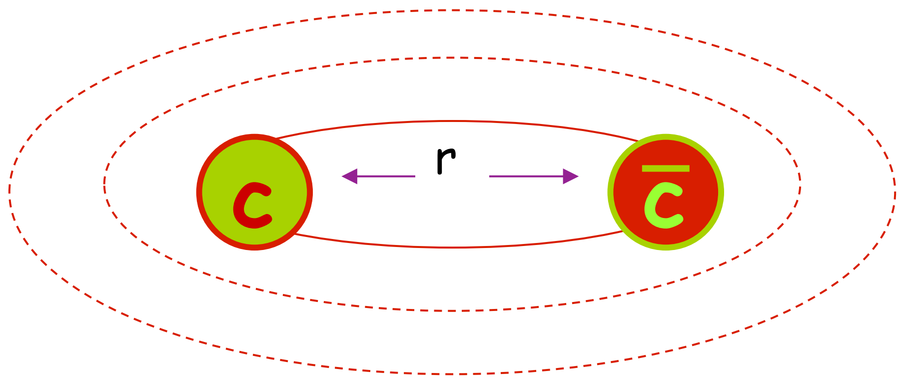
after 1974

$$\begin{pmatrix} u^{+2/3} \\ d^{-1/3} \end{pmatrix} \begin{pmatrix} c^{+2/3} \\ s^{-1/3} \end{pmatrix}$$

A q=+2/3rds partner of the s quark had been suggested by many theorists

Charmonium

mesons formed from c- and $\bar{c}$-quarks

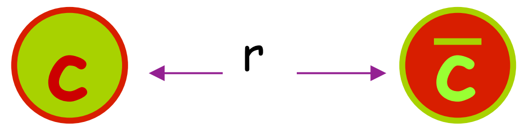


c-quarks are heavy: m_c ~ 1.5 GeV × $2m_p$

velocities small: v/c~1/4

non-relativistic, undergraduate-level QM applies

QM of $c\bar{c}$ mesons

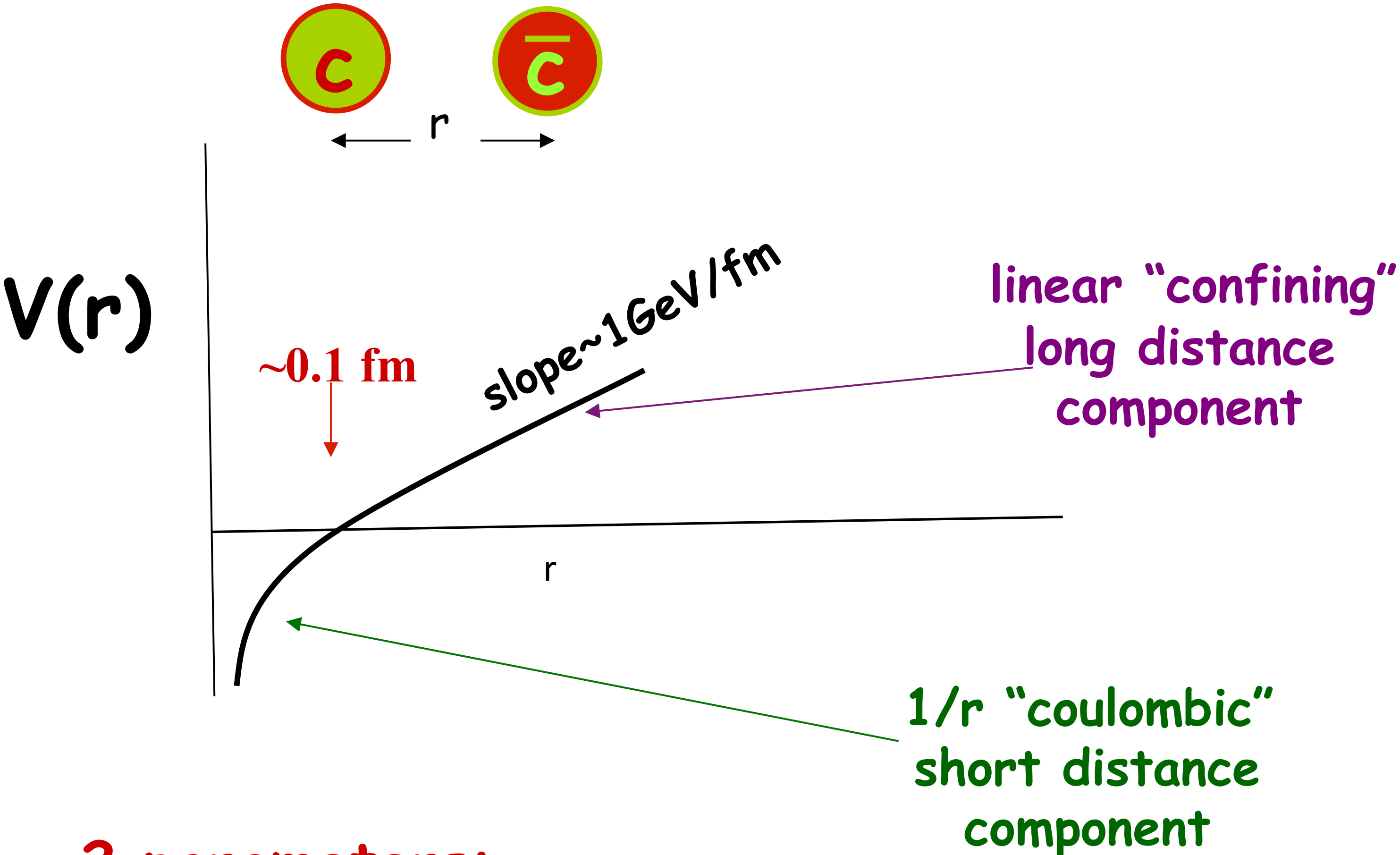


$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$

What is V(r) ??

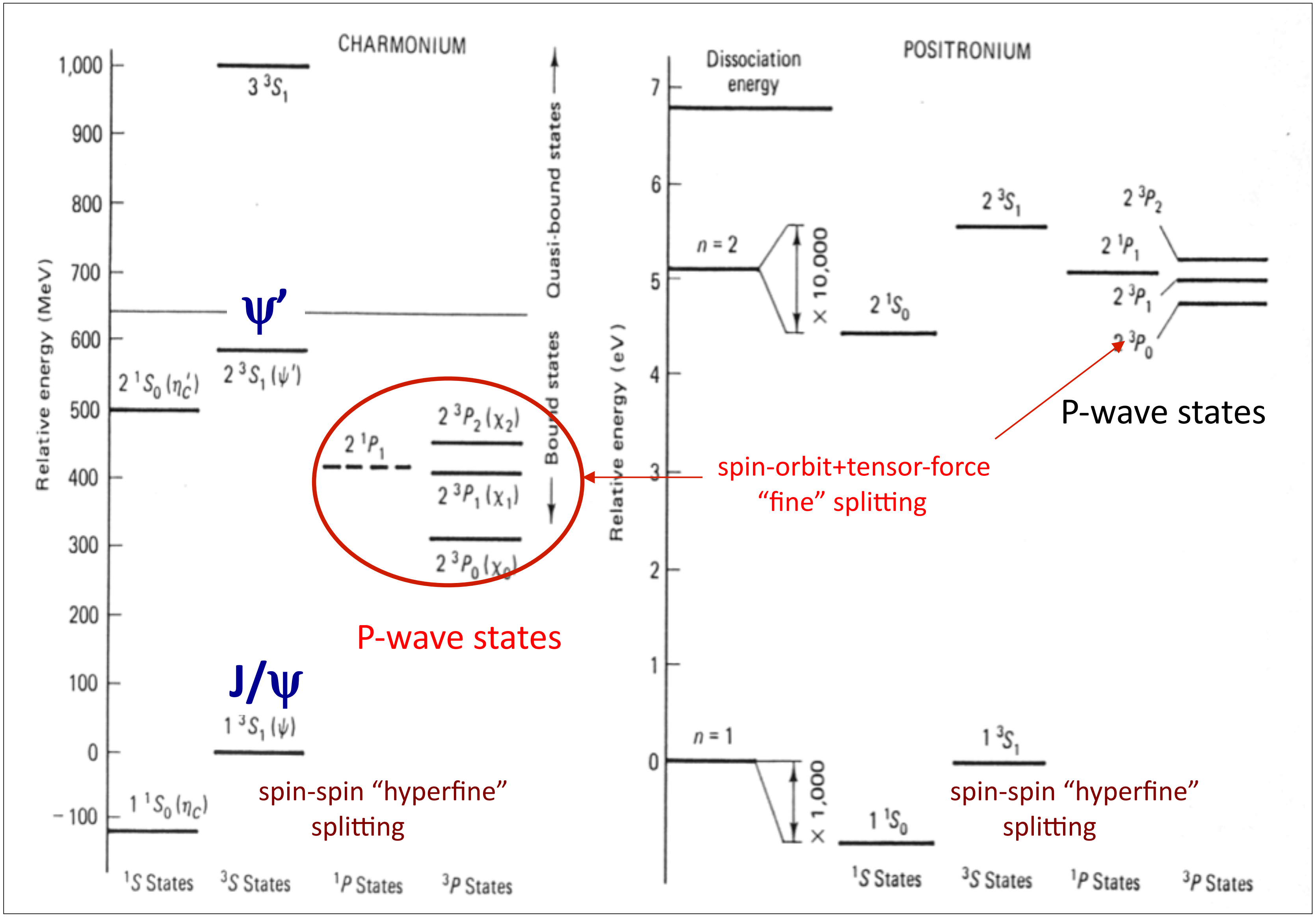
"derive" from QCD

"Cornell" potential



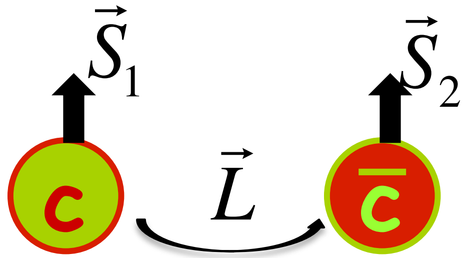
2 parameters:
slope & intercept

Charmonium ($c\bar{c}$) Positronium (e^+e^-)



ABC’s of Charmonium mesons

ABC part I: J^{PC} of charmonium mesons



J^{PC} quantum numbers

$$\vec{S} = \vec{S}_1 + \vec{S}_2$$

$$\vec{J} = \vec{L} + \vec{S}$$

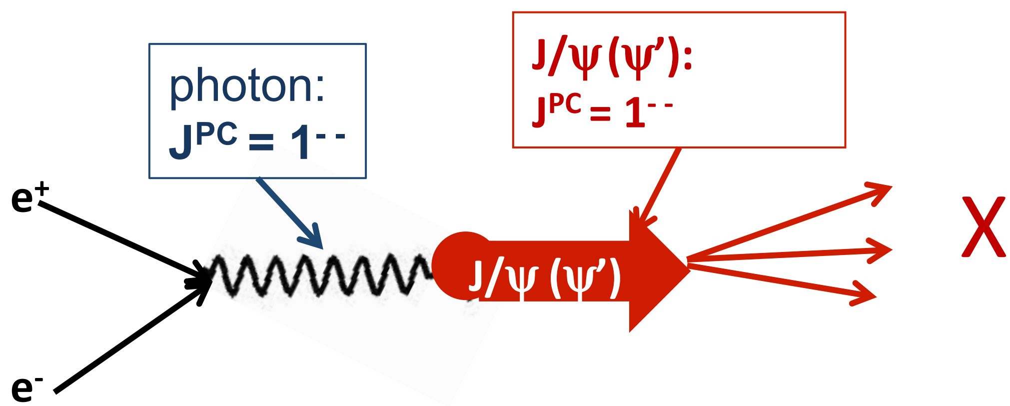
S=1 → triplet of state
S=0 → singlet

$$P = (-1)^{L+1}$$

Parity (x,y,z) ↔ (-x,-y,-z)

$$C = (-1)^{L+S}$$

C-Parity quark ↔ antiquark



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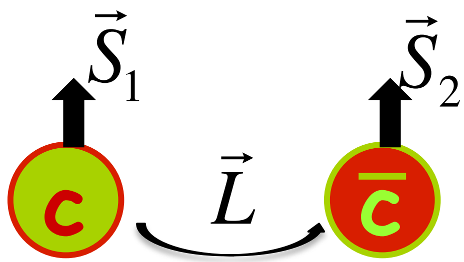

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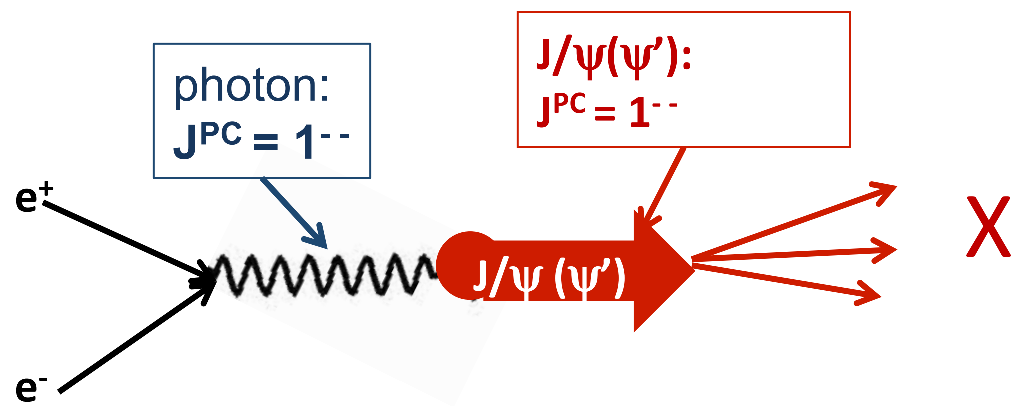
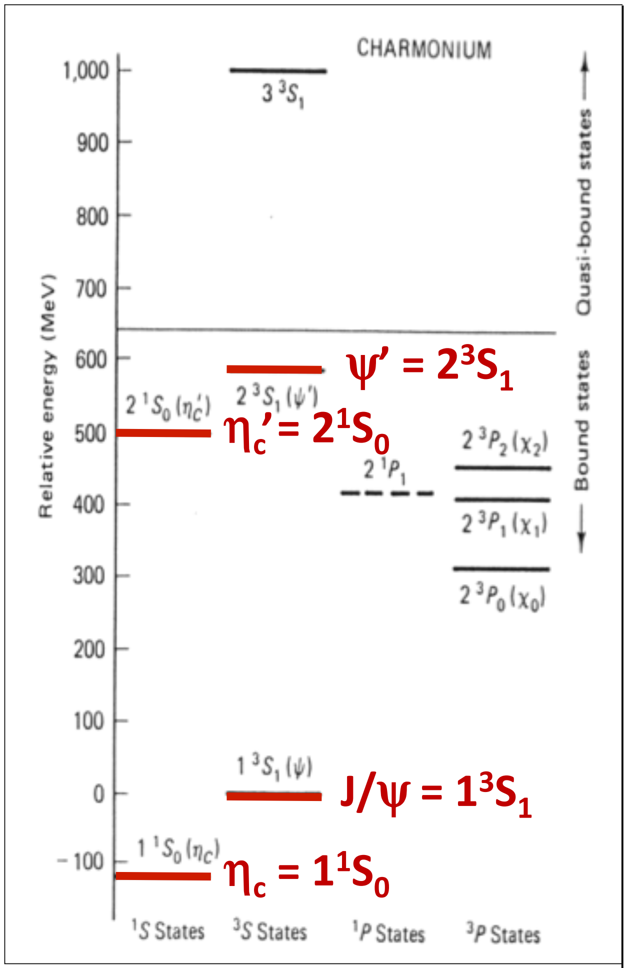
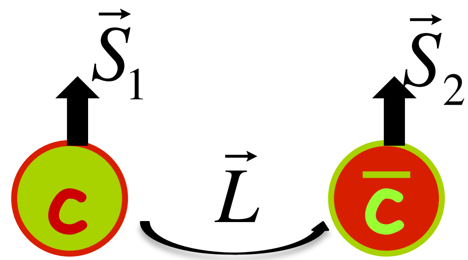


e^+e^- annihilation only produces $J^{PC}=1^{--}$ states

ABC's part II

spectroscopic notation





$$\vec{S} = \vec{S}_1 + \vec{S}_2$$

$$\vec{J} = \vec{L} + \vec{S}$$

S= spin (0 or 1)

J= total ang. mom.

$$n_r{}^{(2S+1)}L_J$$

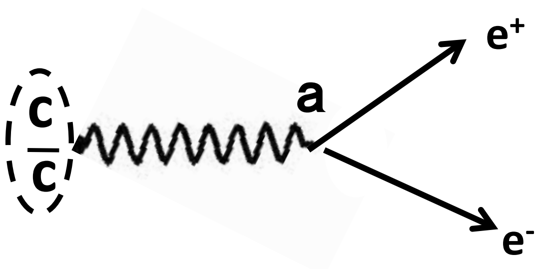
n_r=radial q.n.

L= S, P, D, …

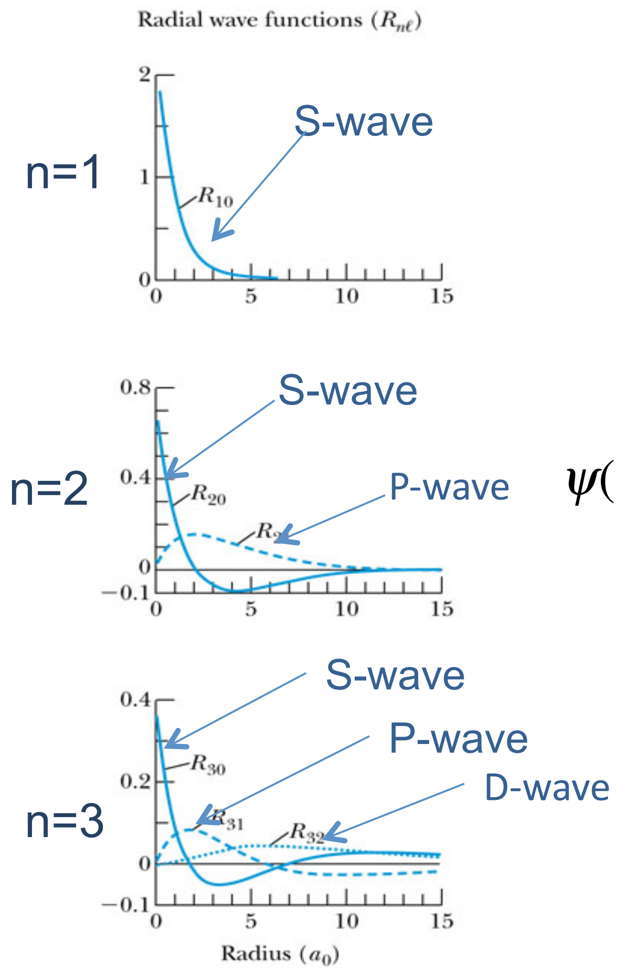
ABC's part III

"wave function at the origin"

In J/y decay, the c and $\bar{c}$ quarks have to annihilate each other



This only can happen when they are on top of each other:



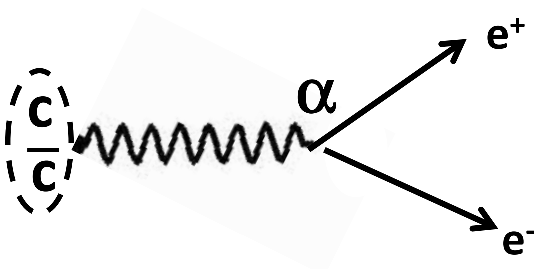
$\psi(r \to 0) \propto r$

$\psi(r \to 0) \propto r^2$

ABC's part III

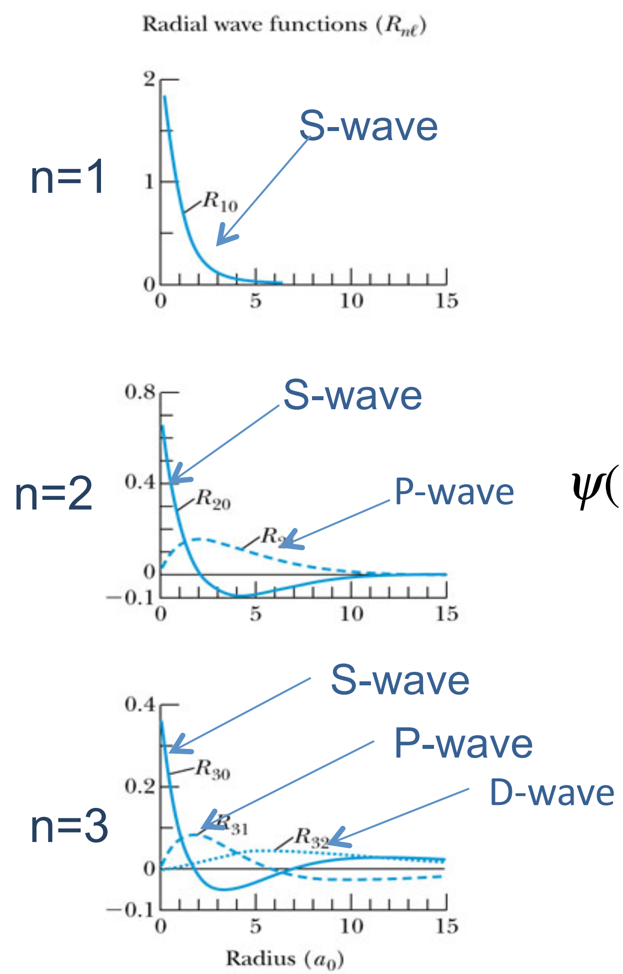
"wave function at the origin"

In J/ψ decay, the c and $\bar{c}$ quarks have to annihilate each other



This only can happen when they are on top of each other:

many J/ψ (& ψ') processes are ∝ |ψ(0)|², the "wave function at the origin," or, in the case of states with ψ(0)=0, derivatives of ψ(0), which are usually small.



$\psi(r \to 0) \propto r$

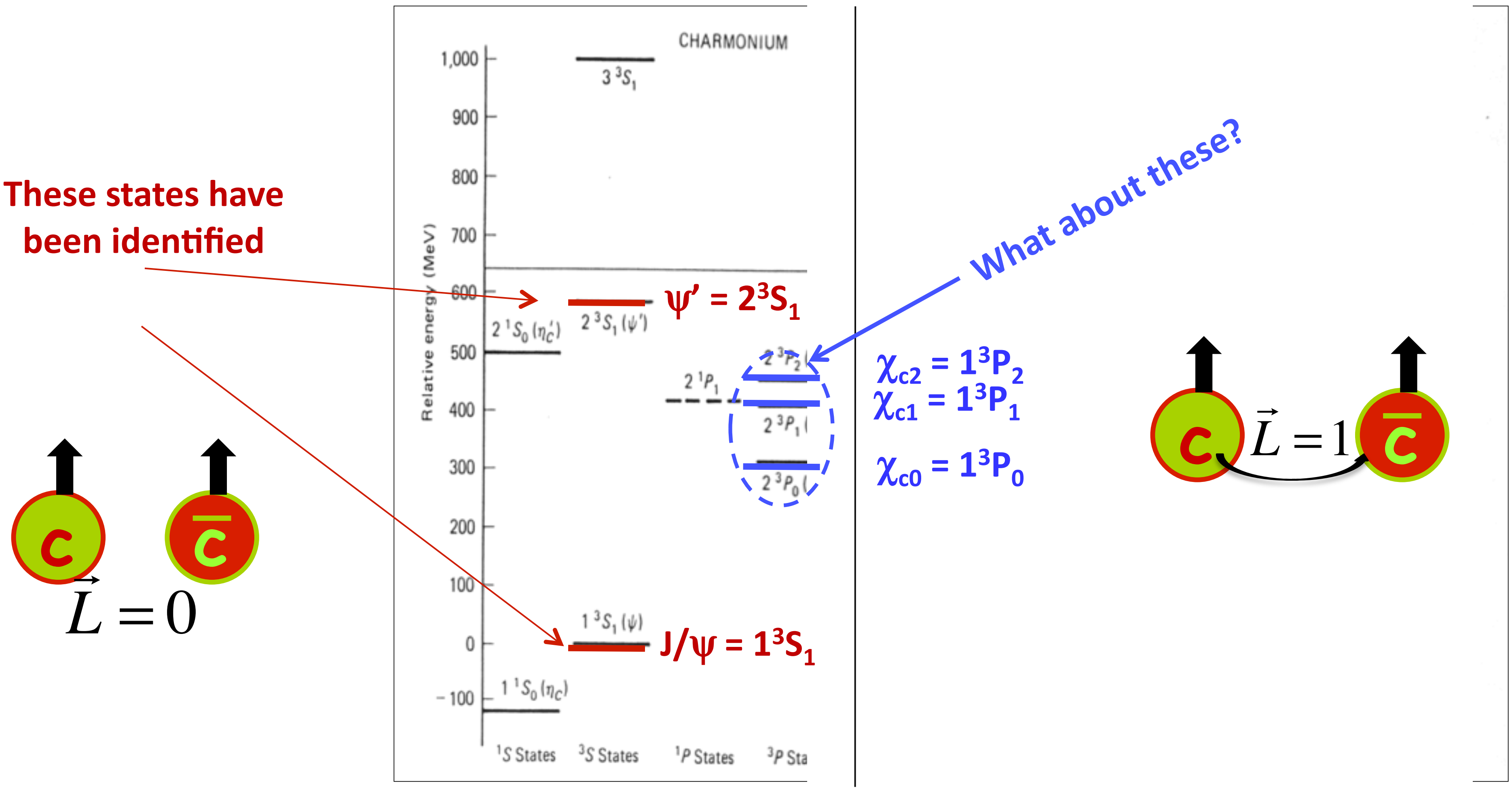
$\psi(r \to 0) \propto r^2$

Immediate questions:

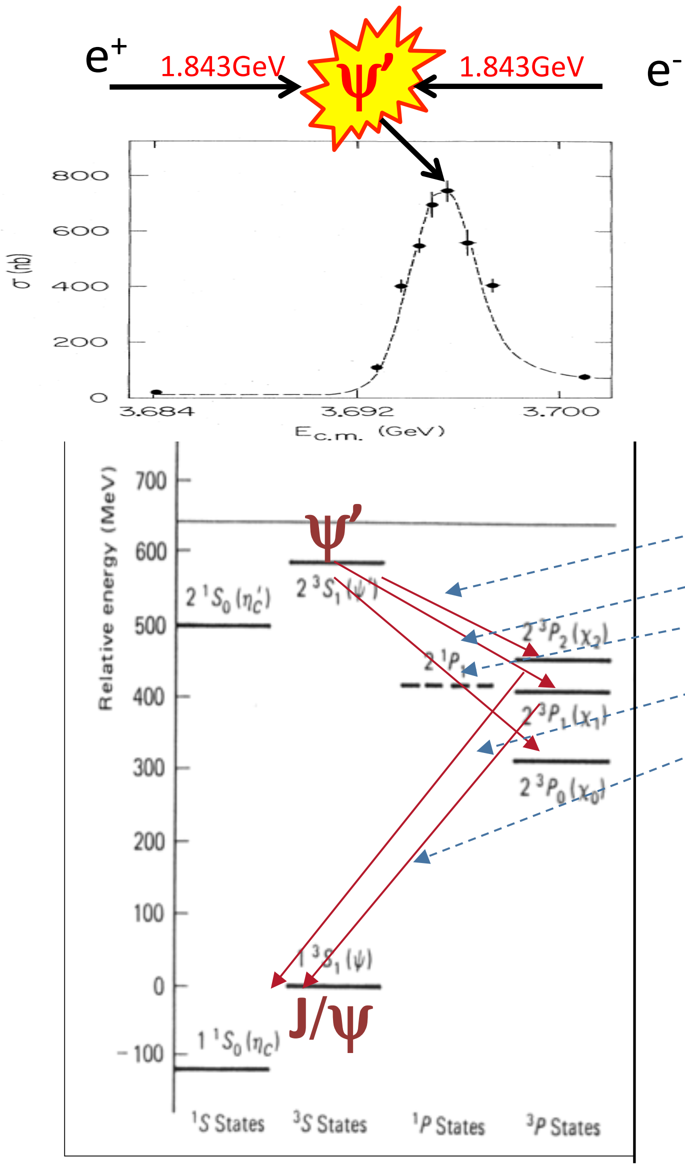
- Can the other meson states be found?

- Why are the J/ψ and ψ’ so narrow?

Finding other states



E-dipole γ transitions to $1^3P_{0,1,2}$



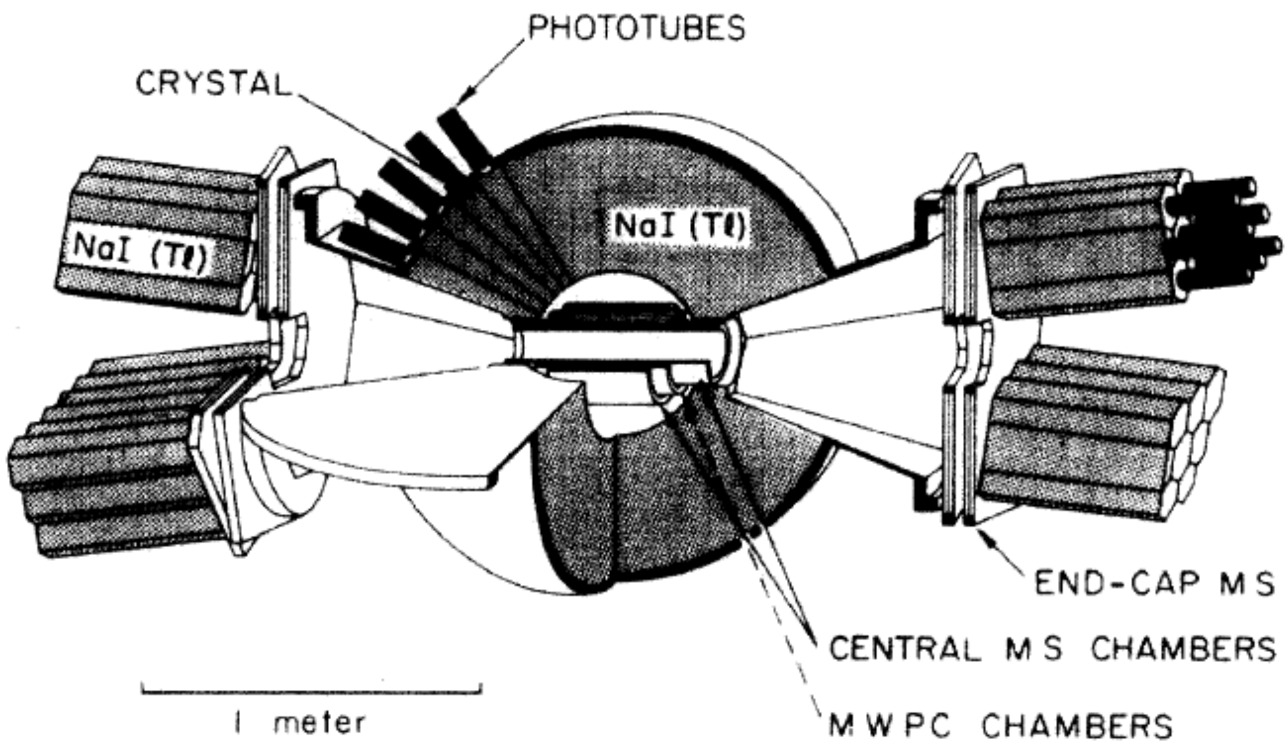
QM textbook formula:

$$\Gamma_{E1} = \frac{\alpha E_\gamma^3}{2\pi\hbar^3 c^2} \sum_\lambda \int d\Omega_\gamma \left| \langle \Psi_f | \hat{\varepsilon} \cdot \vec{r} | \Psi_i \rangle \right|^2$$

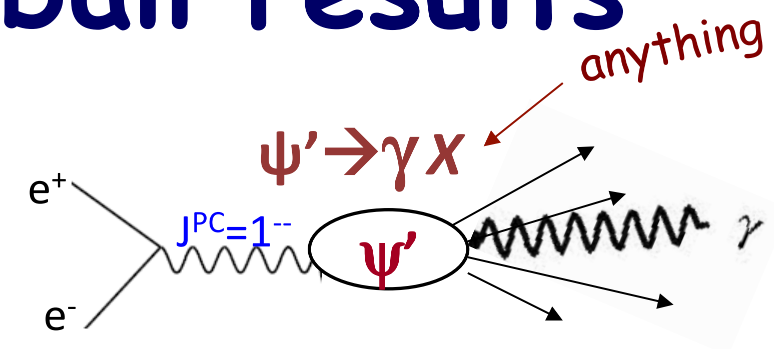
Transition	Γ_γ	Γ_γ (keV)
$2\,^3S \to {}^3P_2$	$5I_1\alpha k^3$	*24.*
$\to {}^3P_1$	$3I_1\alpha k^3$	*29.*
$\to {}^3P_0$	$1I_1\alpha k^3$	*26.*
${}^3P_2 \to 1\,^3S$	$I_2\alpha k^3$	*313.*
${}^3P_1 \to 1\,^3S$	$I_2\alpha k^3$	*239.*
${}^3P_0 \to 1\,^3S$	$I_2\alpha k^3$	*114.*

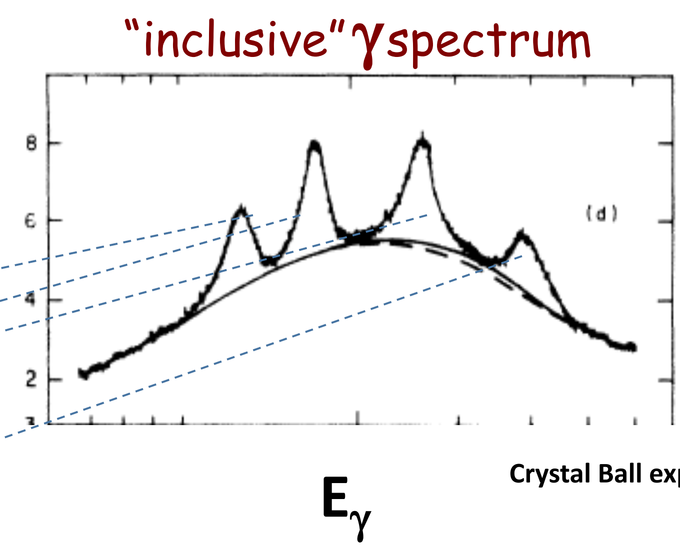
E. Eichten et al., PRL 34, 369(1975)

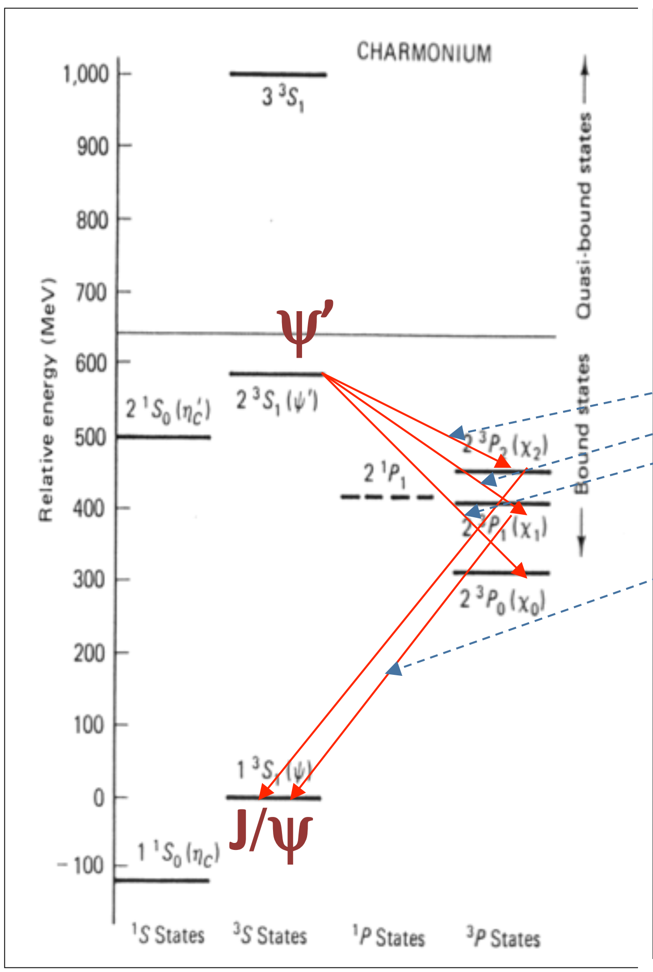
The Crystal Ball Detector



Crystal ball results



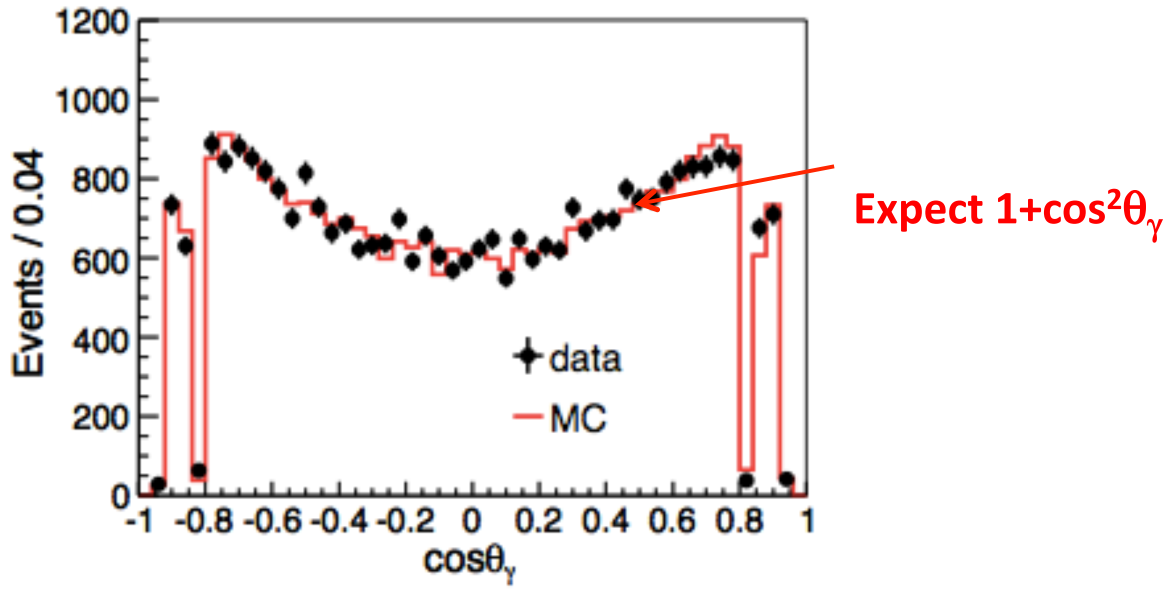




Crystal Ball expt: Phys.Rev.D34:711,1986.

"smoking gun" evidence that quarks are real spin=1/2 objects

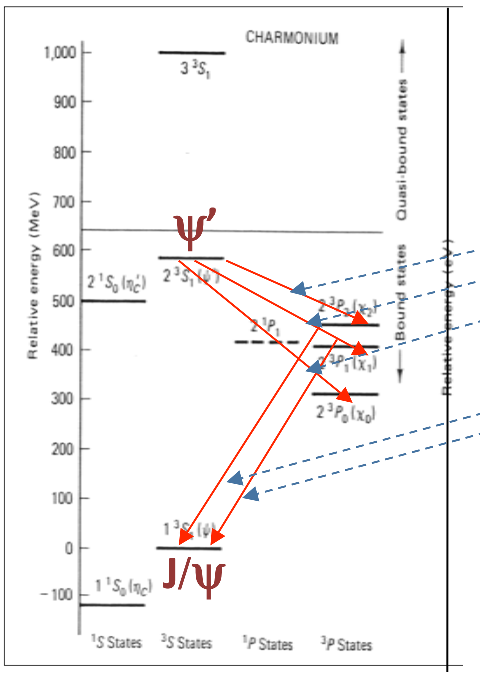
$\psi' \rightarrow \gamma\chi_{c0}$ radiative transition

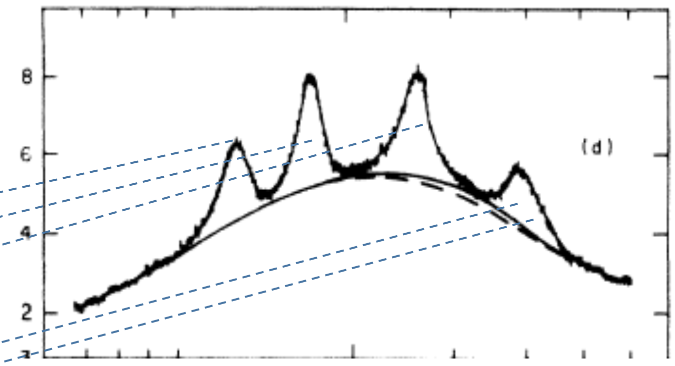


BESIII PRD 84, 092006 (2011)

Discovery of the P-wave triplet states ($\chi_{c0,1,2}$) convinced everyone quarks were real

e$^-$

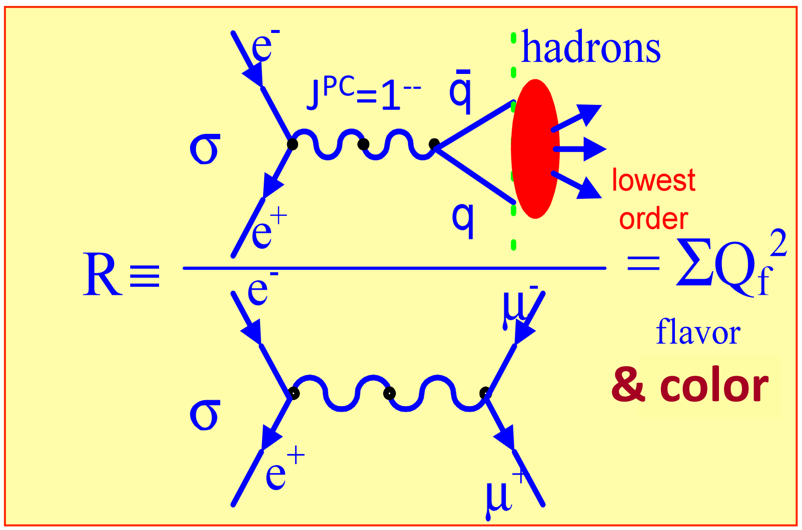




E_γ

Crystal Ball expt: Phys.Rev.D34:711,1986.

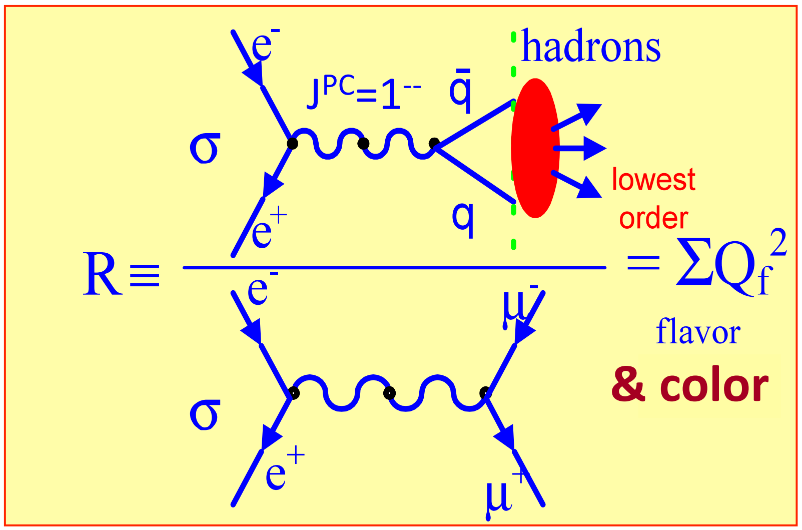
Color explains the discrepancy in R



$$= 3 \times [(\tfrac{2}{3})^2 + (\tfrac{1}{3})^2 + (\tfrac{1}{3})^2] = 2$$

Each favored quark comes with 3 different colors

Color explains the discrepancy in R

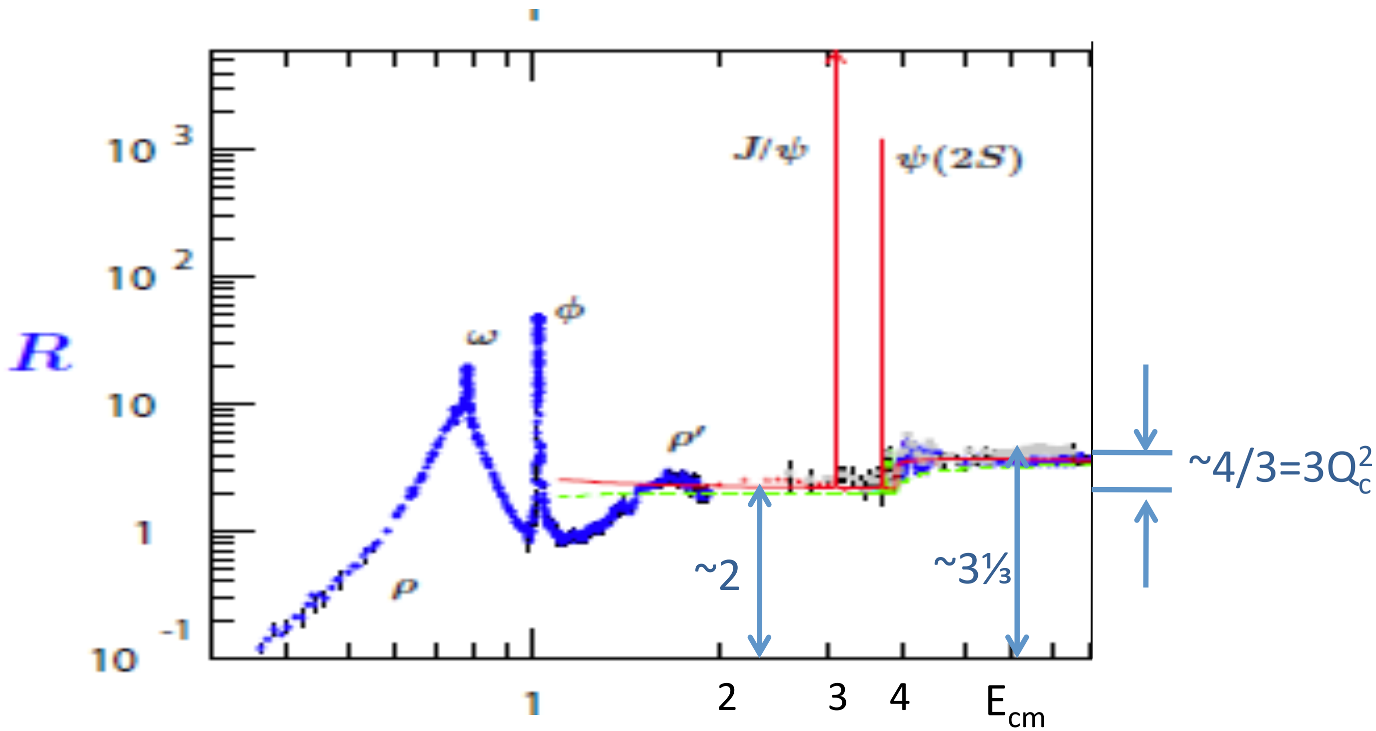


$$= 3 \times [(\tfrac{2}{3})^2 + (\tfrac{1}{3})^2 + (\tfrac{1}{3})^2] = 2$$

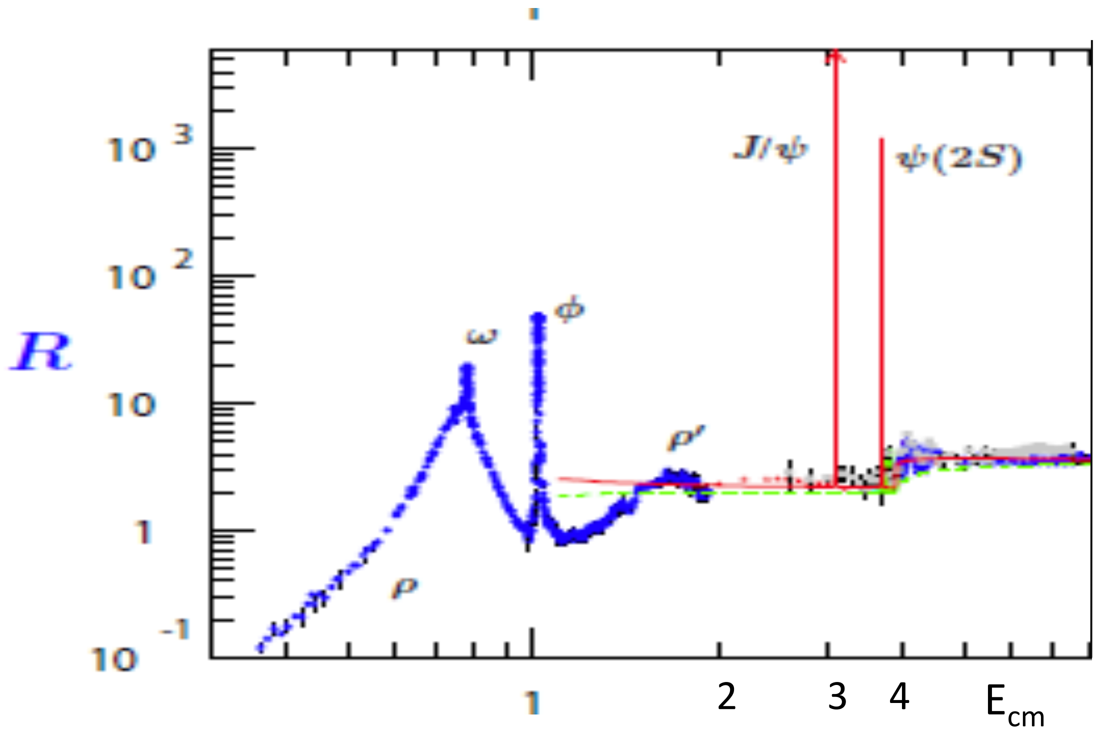
Each favored quark comes with 3 different colors

above the charmed particle threshold, add another $(2/3)^2$ to account for the c quark

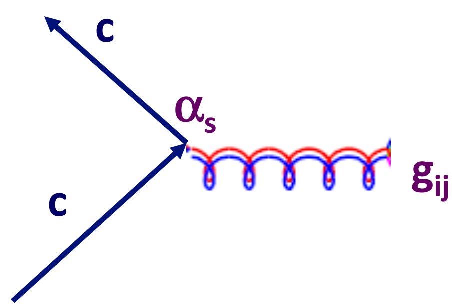
R measurements near charm threshold



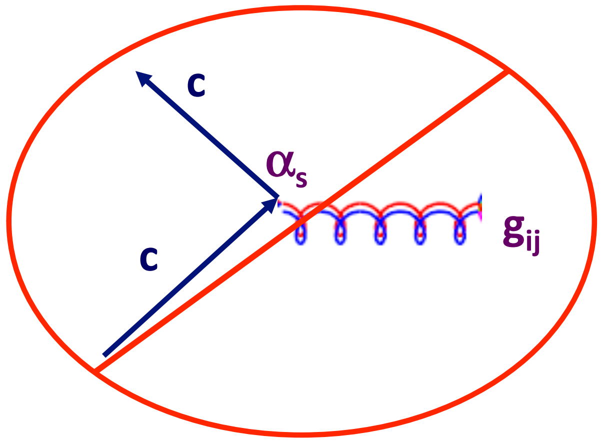
why are the J/ψ and ψ’ so narrow?



How does the J/ψ (ψ’) decay?

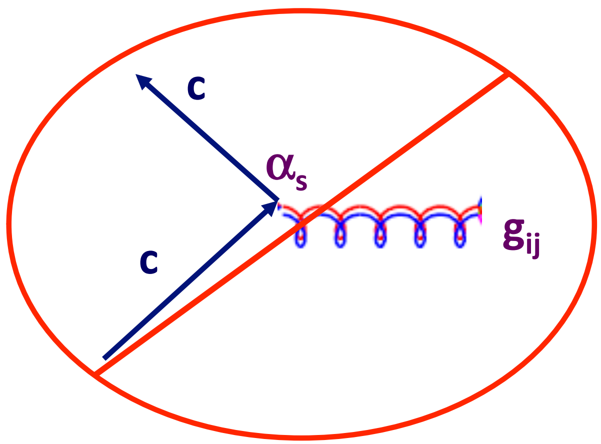


How does the J/ψ (ψ') decay?

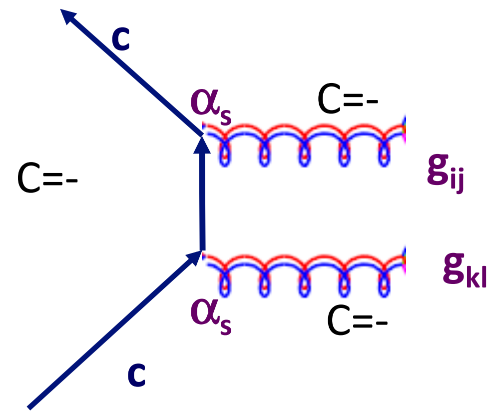


violates color symmetry

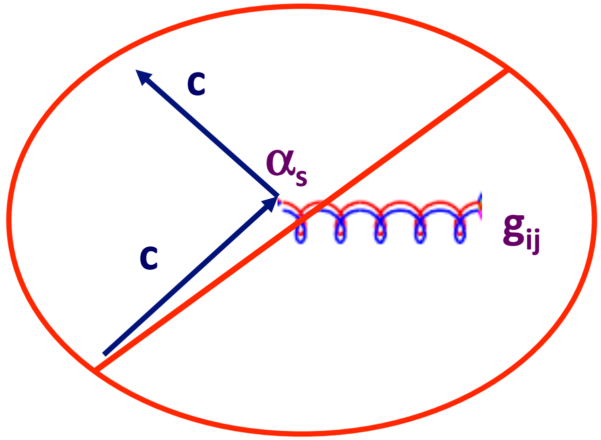
How does the J/ψ (ψ') decay?



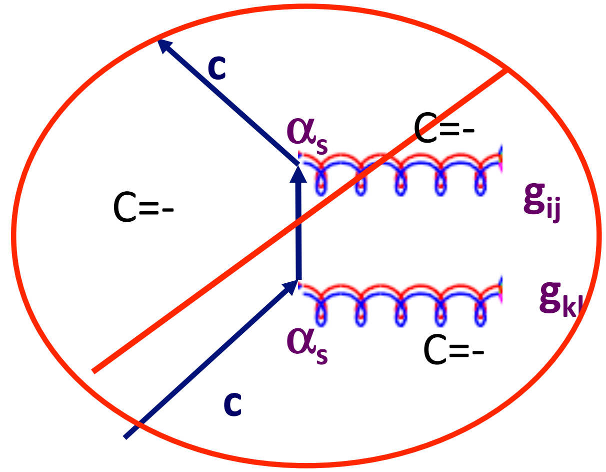
violates color symmetry



How does the J/ψ (ψ') decay?

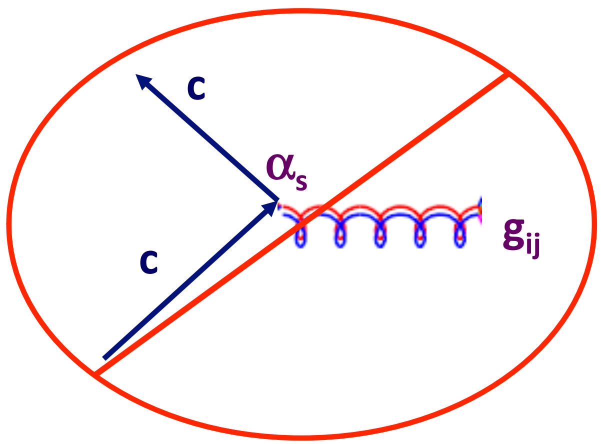


violates color symmetry

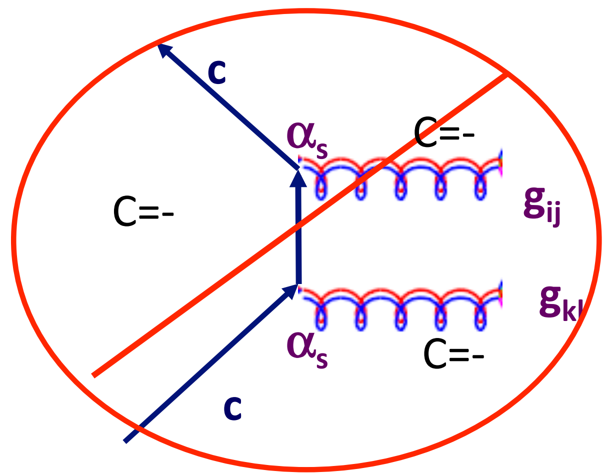


violates C parity

How does the J/ψ(ψ') decay?

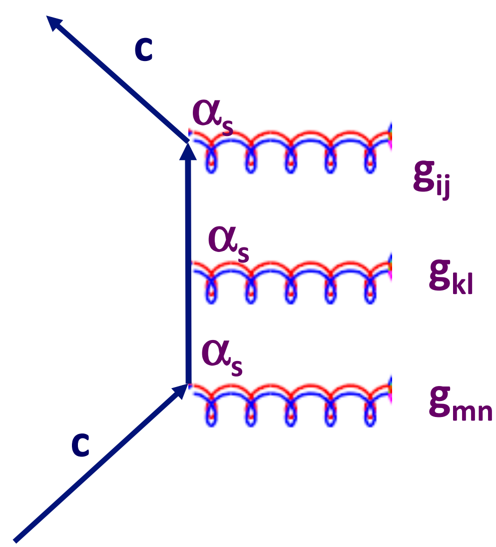


violates color symmetry

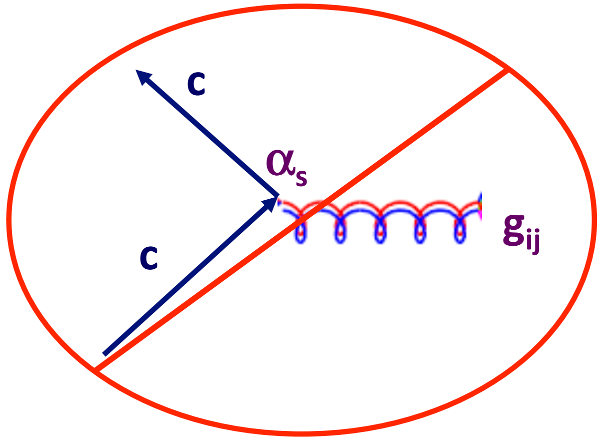


violates C parity

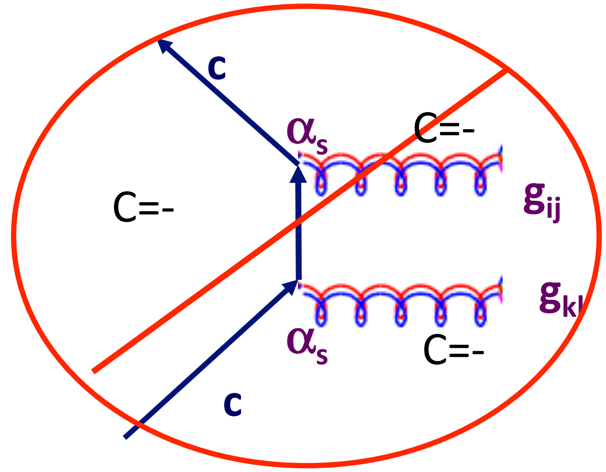
Lowest-order
allowed QCD process:



How does the J/ψ (ψ') decay?

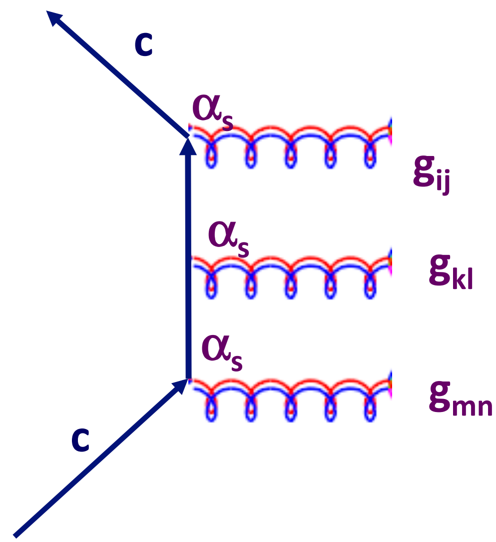


violates color symmetry



violates C parity

Lowest-order allowed QCD process:

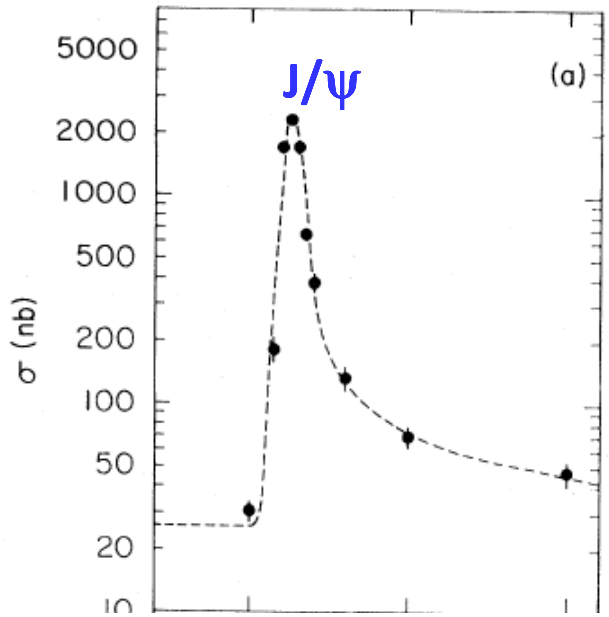


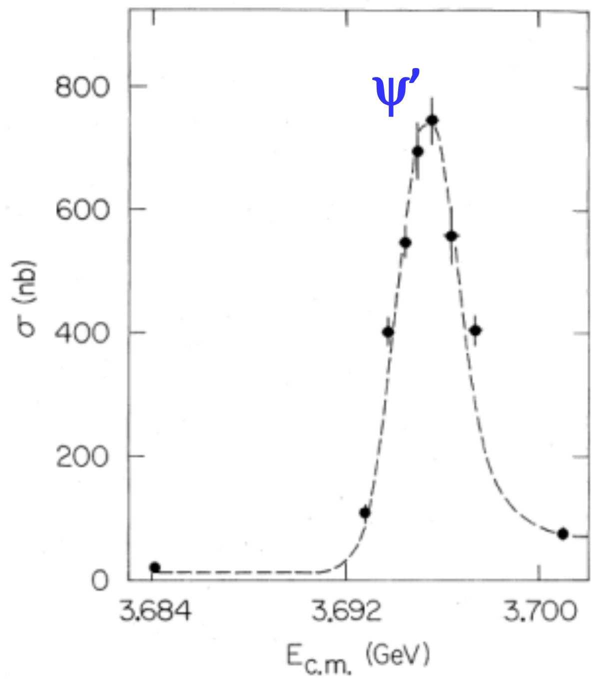
← suppressed by α_s^3

This is called "OZI"* suppression

***Okubo-Zweig-Iizuka**

How wide are the J/ψ & ψ'?

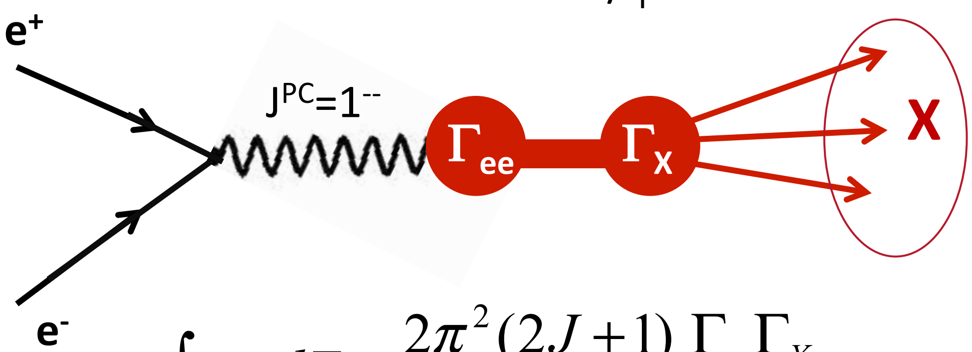




The observed widths of these peaks are due entirely to experimental resolution, which is typically a few MeV

Determining the J/ψ (& ψ') widths

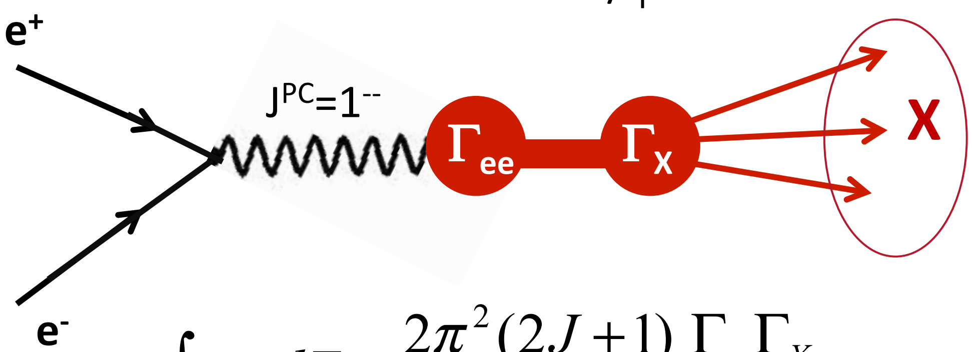
cross section for $e^+e^- \to J/\psi \to X$



$$\int \sigma_X dE = \frac{2\pi^2(2J+1)}{m^2}\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}}$$

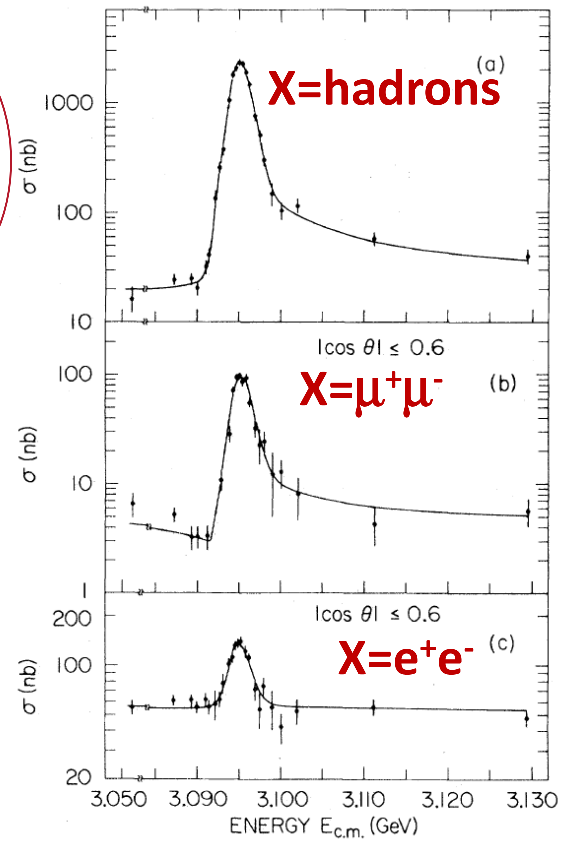
Determining the J/ψ (& ψ') widths

cross section for $e^+e^- \rightarrow J/\psi \rightarrow X$



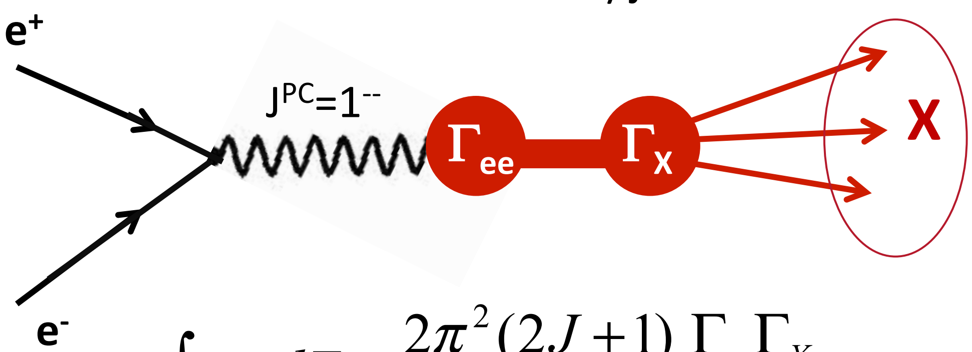
$$\int \sigma_X dE = \frac{2\pi^2(2J+1)}{m^2}\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}}$$

Mark-I PRL 34, 1357 (1975)



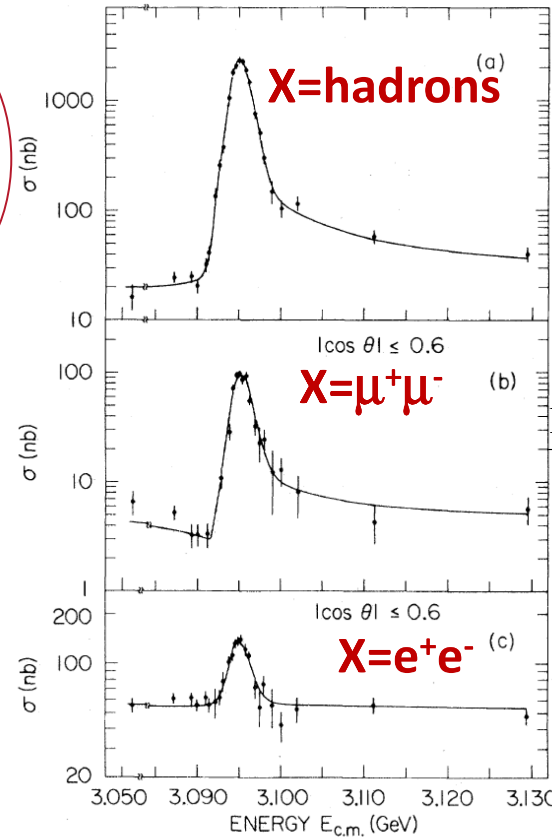
Determining the J/ψ (& ψ') widths

cross section for $e^+e^- \to J/y \to X$



$$\int \sigma_X dE = \frac{2\pi^2(2J+1)}{m^2}\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}}$$

Mark-I PRL 34, 1357 (1975)



$$\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}} = \frac{m^2\int \sigma_X dE}{2\pi^2(2J+1)}$$

$$\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_{tot}} = \frac{m^2\int \sigma_{\mu\mu} dE}{2\pi^2(2J+1)}$$

$$\frac{\Gamma_{ee}^2}{\Gamma_{tot}} = \frac{m^2\int \sigma_{ee} dE}{2\pi^2(2J+1)}$$

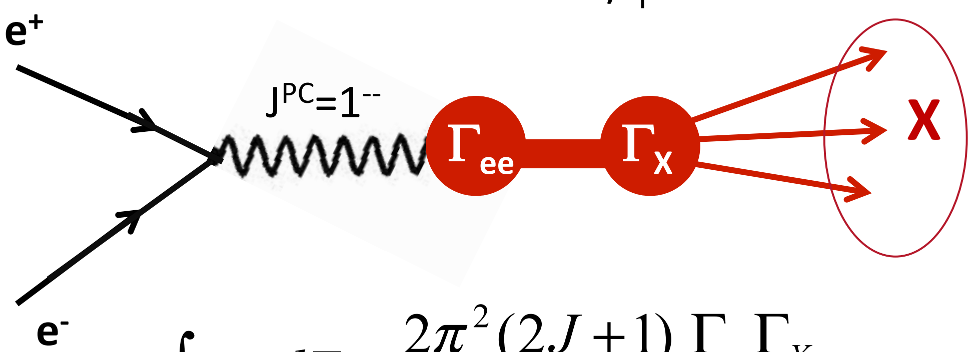
$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_X$$

$$\Gamma_{ee} = \Gamma_{\mu\mu}$$

5 eqns, 4 unknowns: determine Γ_{tot}

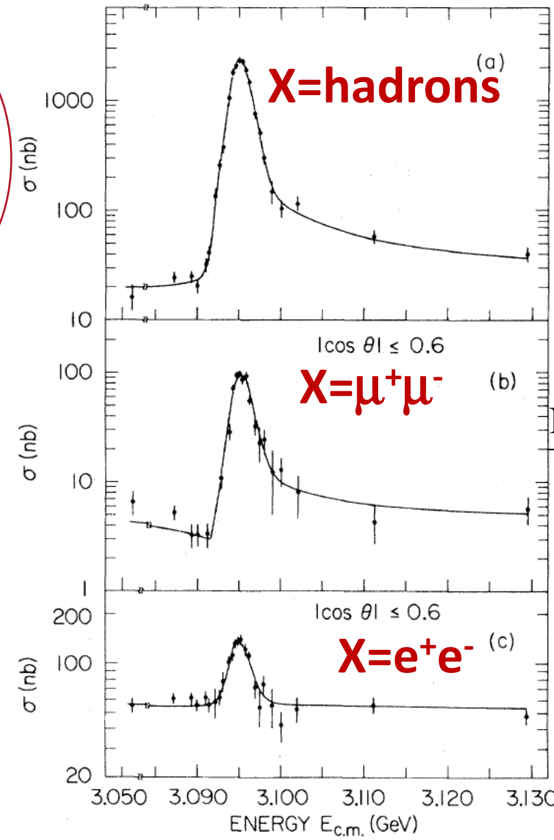
Determining the J/ψ (& ψ') widths

cross section for $e^+e^- \rightarrow J/\psi \rightarrow X$



$$\int \sigma_X dE = \frac{2\pi^2(2J+1)}{m^2}\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}}$$

Mark-I PRL 34, 1357 (1975)



$$\frac{\Gamma_{ee}\Gamma_X}{\Gamma_{tot}} = \frac{m^2\int\sigma_X dE}{2\pi^2(2J+1)}$$

$$\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_{tot}} = \frac{m^2\int\sigma_{\mu\mu} dE}{2\pi^2(2J+1)}$$

$$\frac{\Gamma_{ee}^2}{\Gamma_{tot}} = \frac{m^2\int\sigma_{ee} dE}{2\pi^2(2J+1)}$$

2009 values

	J/ψ	ψ'
Γ_{tot}	93±2 keV	309±9 keV
Γ_{ee}	5.55±0.14 keV	5.1±0.5 keV

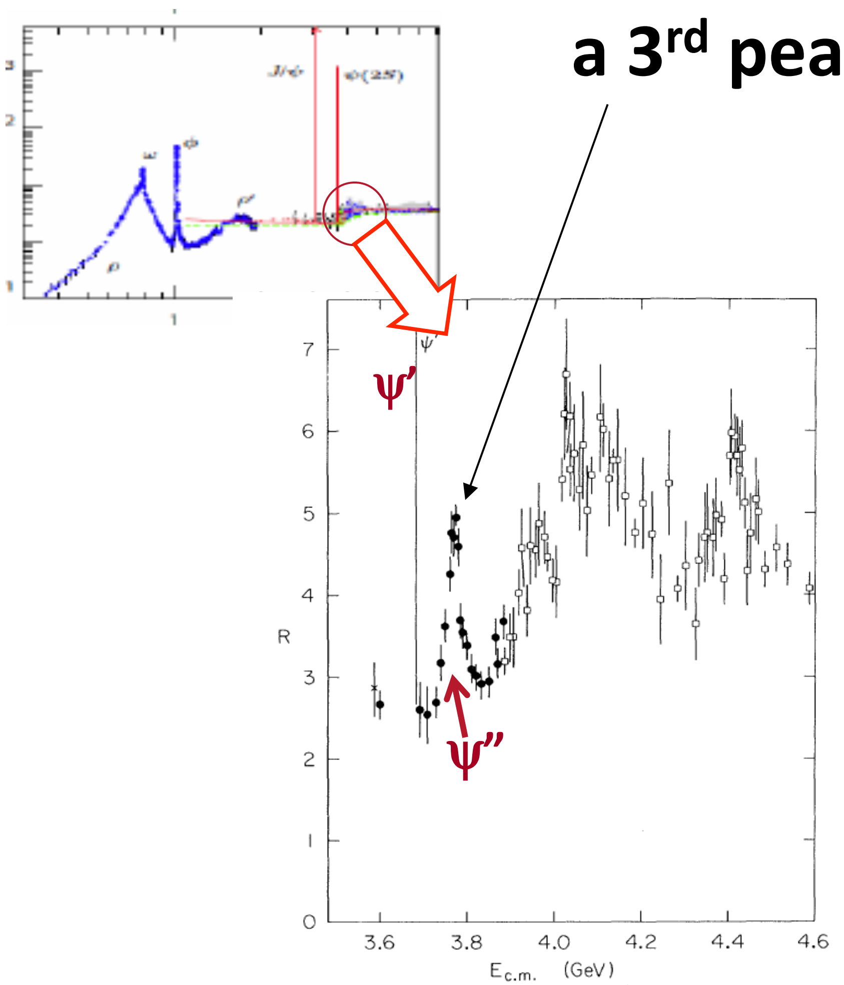
$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_X$$

$$\Gamma_{ee} = \Gamma_{\mu\mu}$$

5 eqns, 4 unknowns: determine Γ_{tot}

$e^+e^- \rightarrow$ hadrons at higher E_{cm}:

a 3rd peak: the ψ'' (ψ(3770))



LGW PRL 39, 526 (1977)

Γ_{tot} ~150x bigger

2009 values

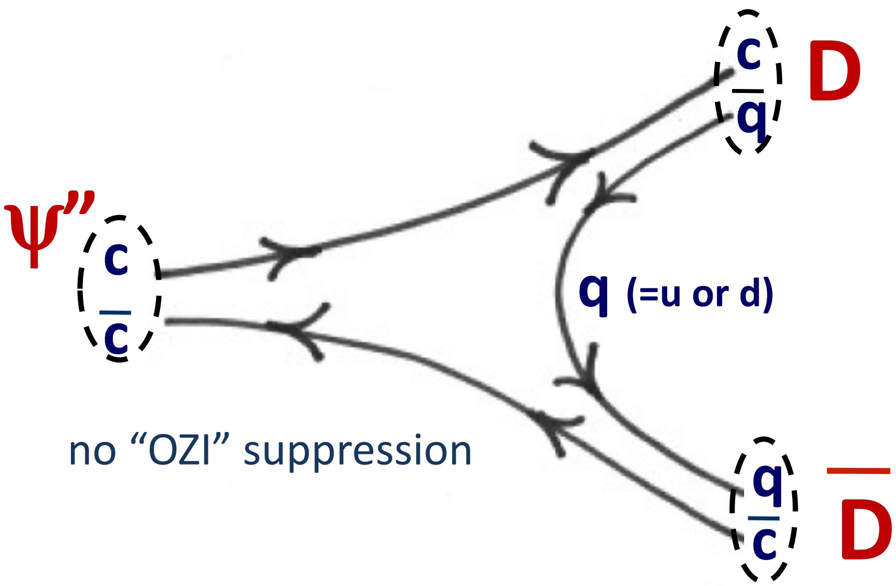
	J/ψ	ψ'	ψ''
Γ_{tot}	93 keV	209 keV	**27.3+1.0 MeV**
Γ_{ee}	5.55 keV	5.1 keV	**0.26+0.02 keV**

Γ_{ee} ~20x smaller

Why is $\Gamma_{tot}(\psi'')$ much bigger?

← "charmed" mesons

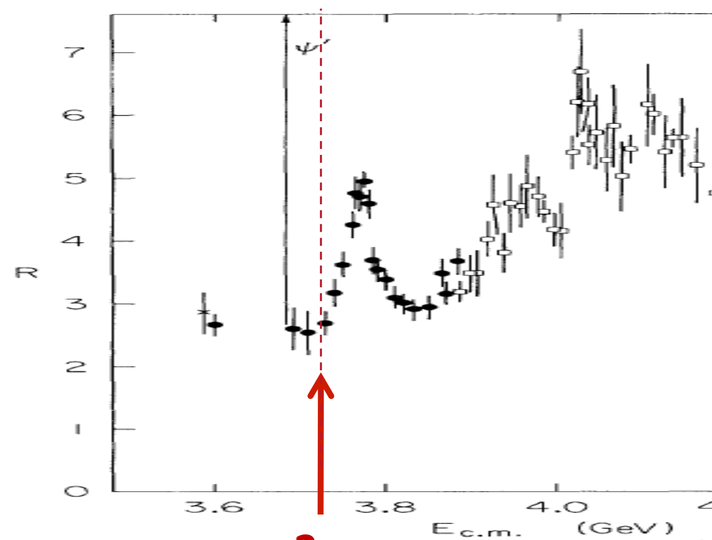
New decay channel is available $\psi'' \rightarrow D\bar{D}$



← D^0 or D^+

← $\bar{D}^0$ or D^-

no "OZI" suppression



$2m_D$
"open charm"
threshold

($M_{\psi''}$=3775 MeV)

$2m_{D+}$=3739 MeV

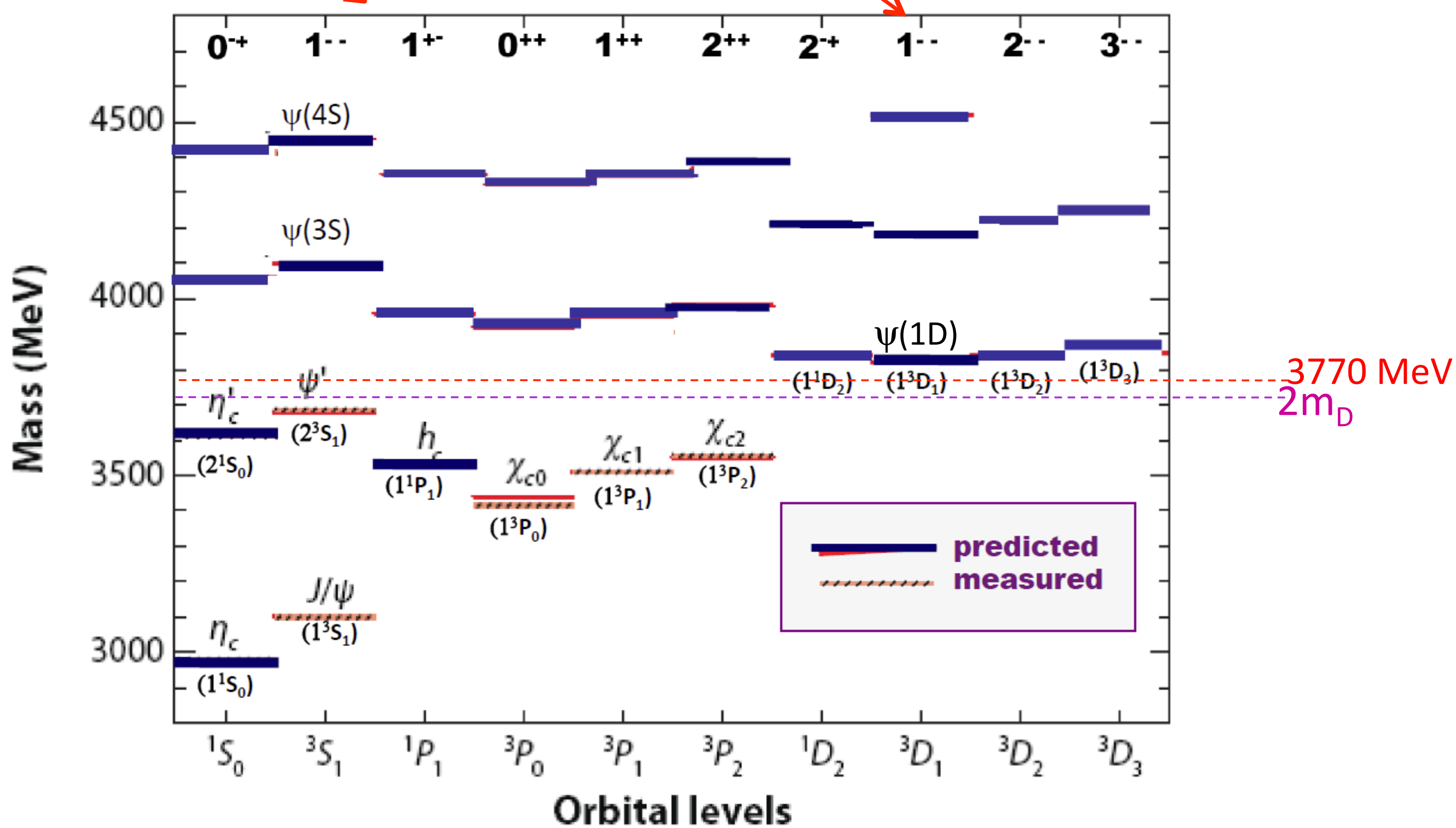
$2m_{D0}$ =3729 MeV

($M_{\psi'}$=3686 MeV)

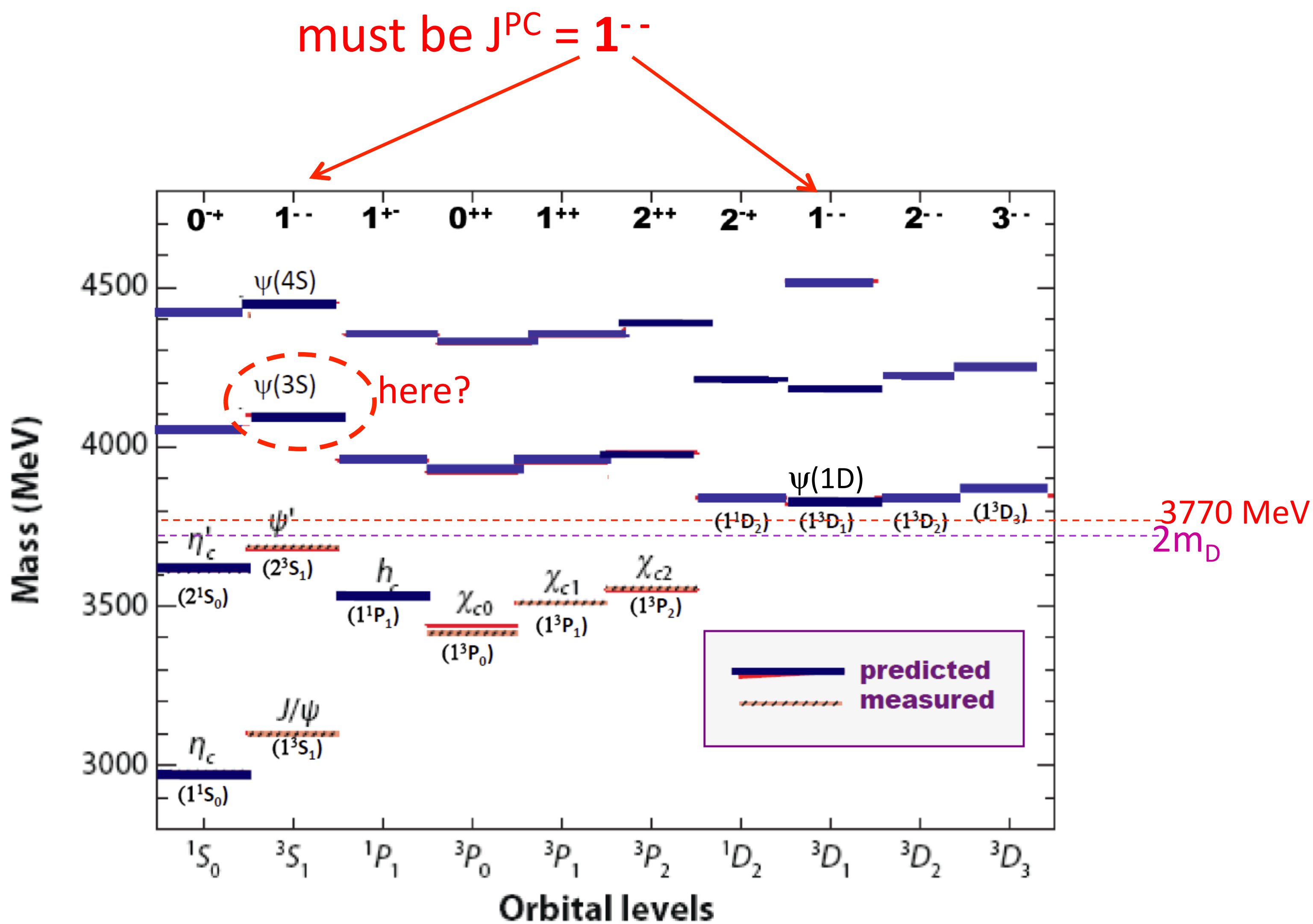
"fall apart" decay modes

does ψ" fit in the $c\bar{c}$ spectrum?

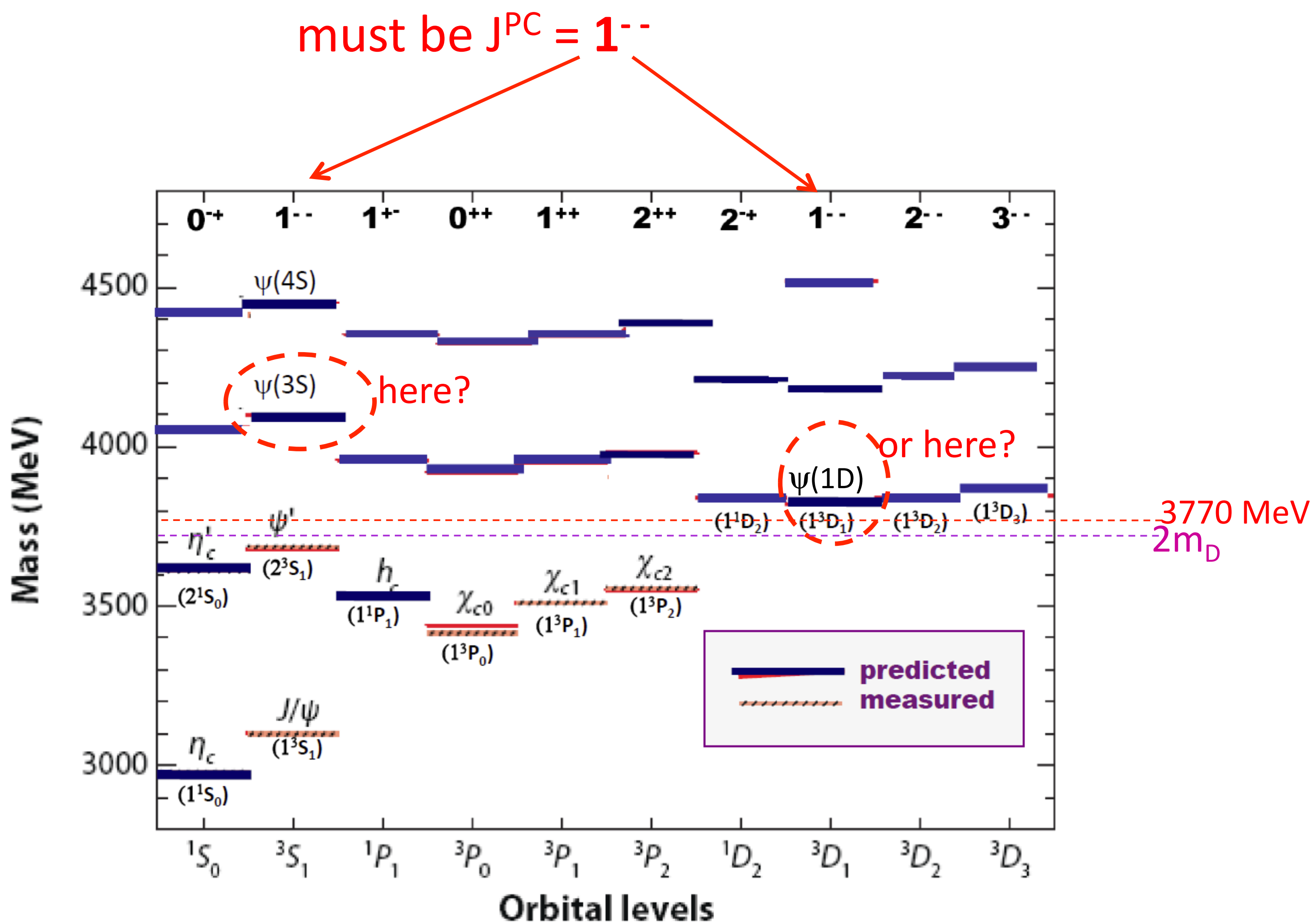
must be J^{PC} = **1**$^{--}$



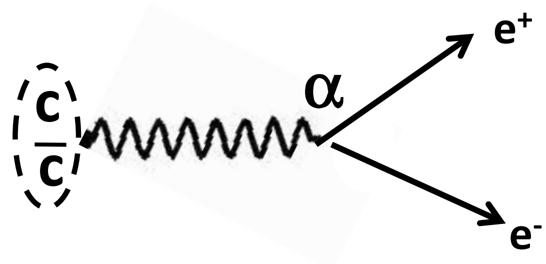
does ψ” fit in the $c\bar{c}$ spectrum?



does ψ” fit in the $c\bar{c}$ spectrum?



$\Gamma_{ee}(\psi'')$ considerations



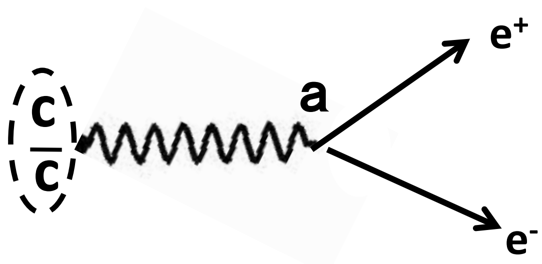
S-wave

$$\Gamma_{ee}(^3S_1) = \frac{16}{9}\alpha^2 \frac{|\Psi(0)|^2}{M_{c\bar{c}}^2}$$

D-wave

$$\Gamma_{ee}(^3D_1) = \frac{50}{9}\frac{\alpha^2}{M_{c\bar{c}}^2}\left|\frac{\partial^2\Psi(0)}{\partial r^2}\right|^2$$

$\Gamma_{ee}(\psi'')$ considerations



S-wave

$$\Gamma_{ee}(^3S_1) = \frac{16}{9}\alpha^2 \frac{|\Psi(0)|^2}{M_{c\bar{c}}^2}$$

D-wave

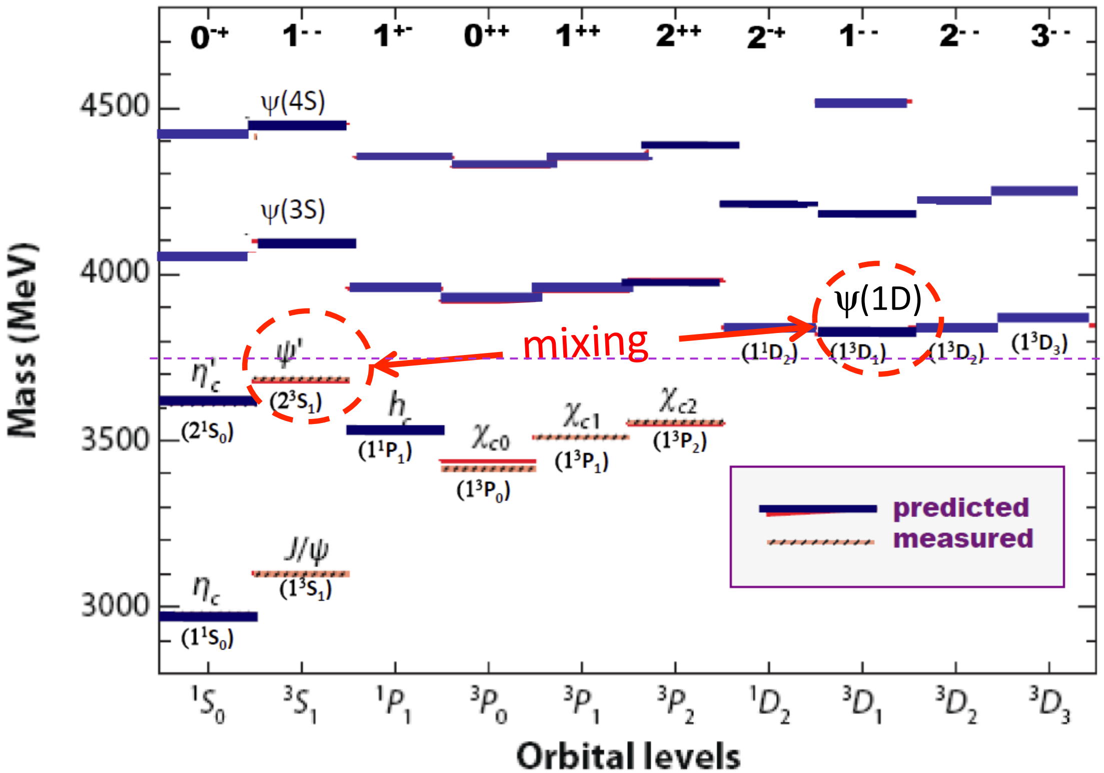
$$\Gamma_{ee}(^3D_1) = \frac{50}{9}\frac{\alpha^2}{M_{c\bar{c}}^2}\left|\frac{\partial^2\Psi(0)}{\partial r^2}\right|^2$$

Γ_{ee} = too small for the ψ" to be the ψ(3S) state & too big for it to be the ψ(1D)

all in keV

	J/ψ	ψ'	ψ"(S-wave)	ψ"(D-wave)
Γ_{ee}(Theory)	12.13	5.03	3.5	0.056
Γ_{ee}(expt)	5.55±0.14	5.1±0.5	0.26±0.02	0.26±0.02

ψ′ and ψ″ = $2^3S_1 - 1^3D_1$ mixtures



$$\psi' = \psi(2^3S_1)\cos\theta_{mix} - \psi(1^3D_1)\sin\theta_{mix}$$

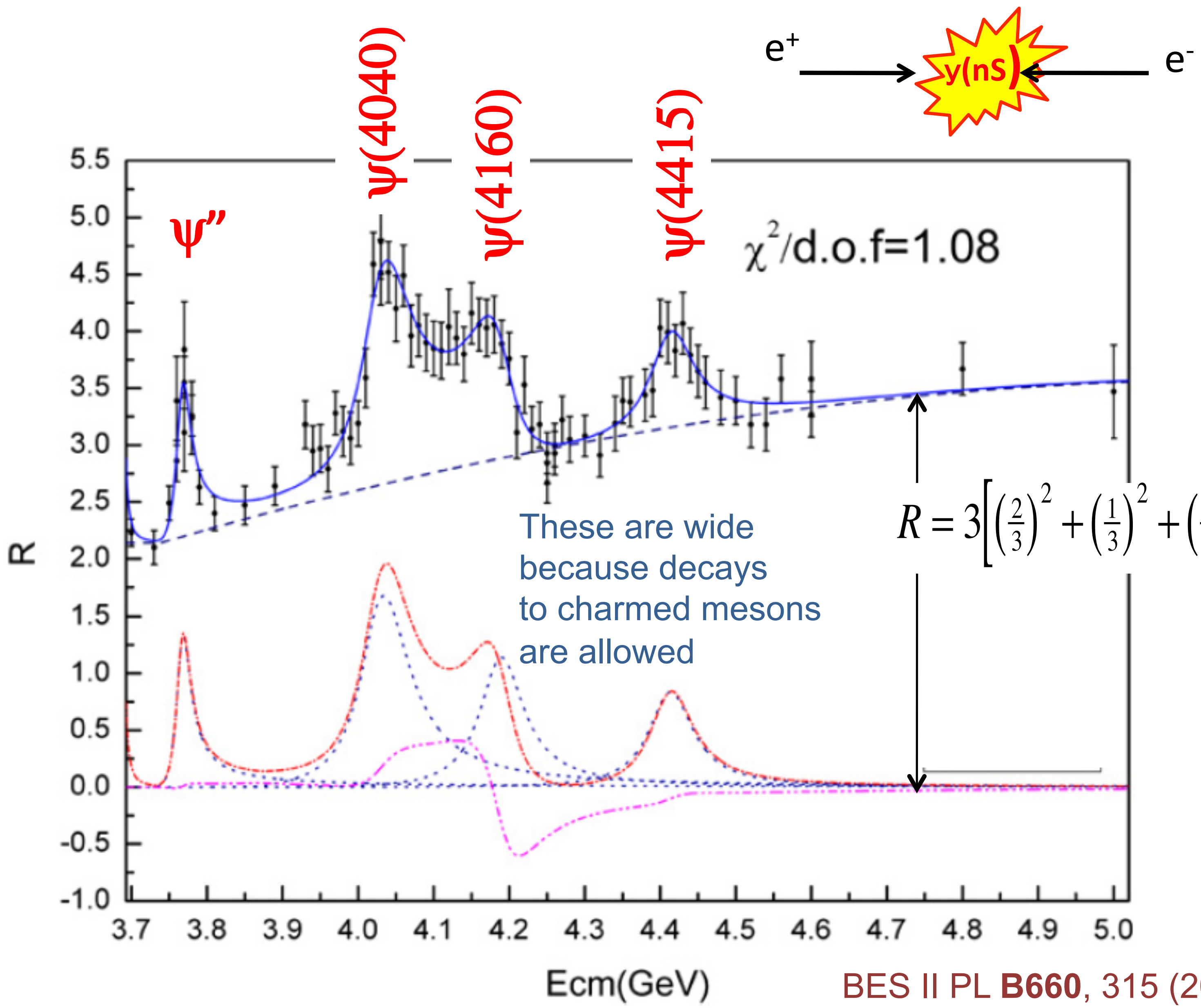
$$\psi'' = \psi(1^3D_1)\cos\theta_{mix} + \psi(2^3S_1)\sin\theta_{mix}$$

$$\theta_{mix} = 10.6^o \pm 1.3^o$$

"preferred" value

This mixing was predicted by Eichten et al, PRL 34, 369 (1975)
-- before the ψ″ was discovered --

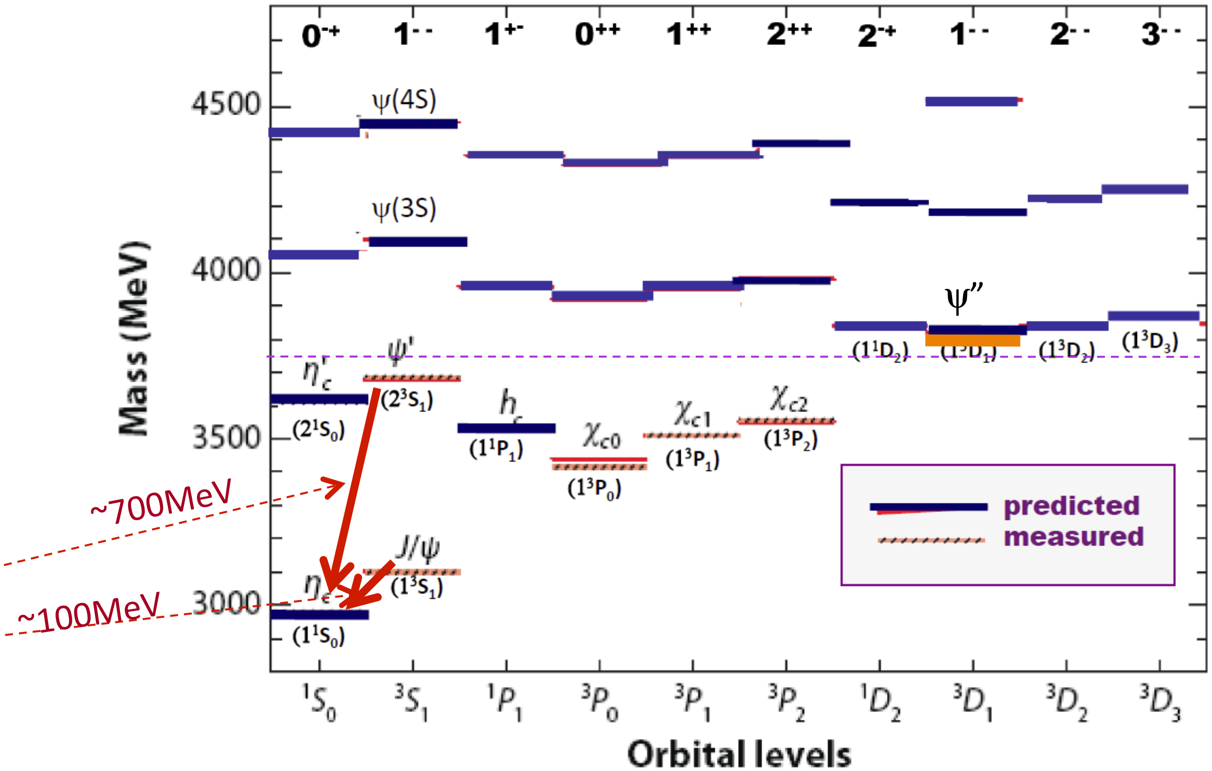
$J^{PC} = 1^{--}$ states produce peaks in R_{had}



$$R = 3\left[\left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{2}{3}\right)^2\right] = 3.3$$

BES II PL **B660**, 315 (2008)

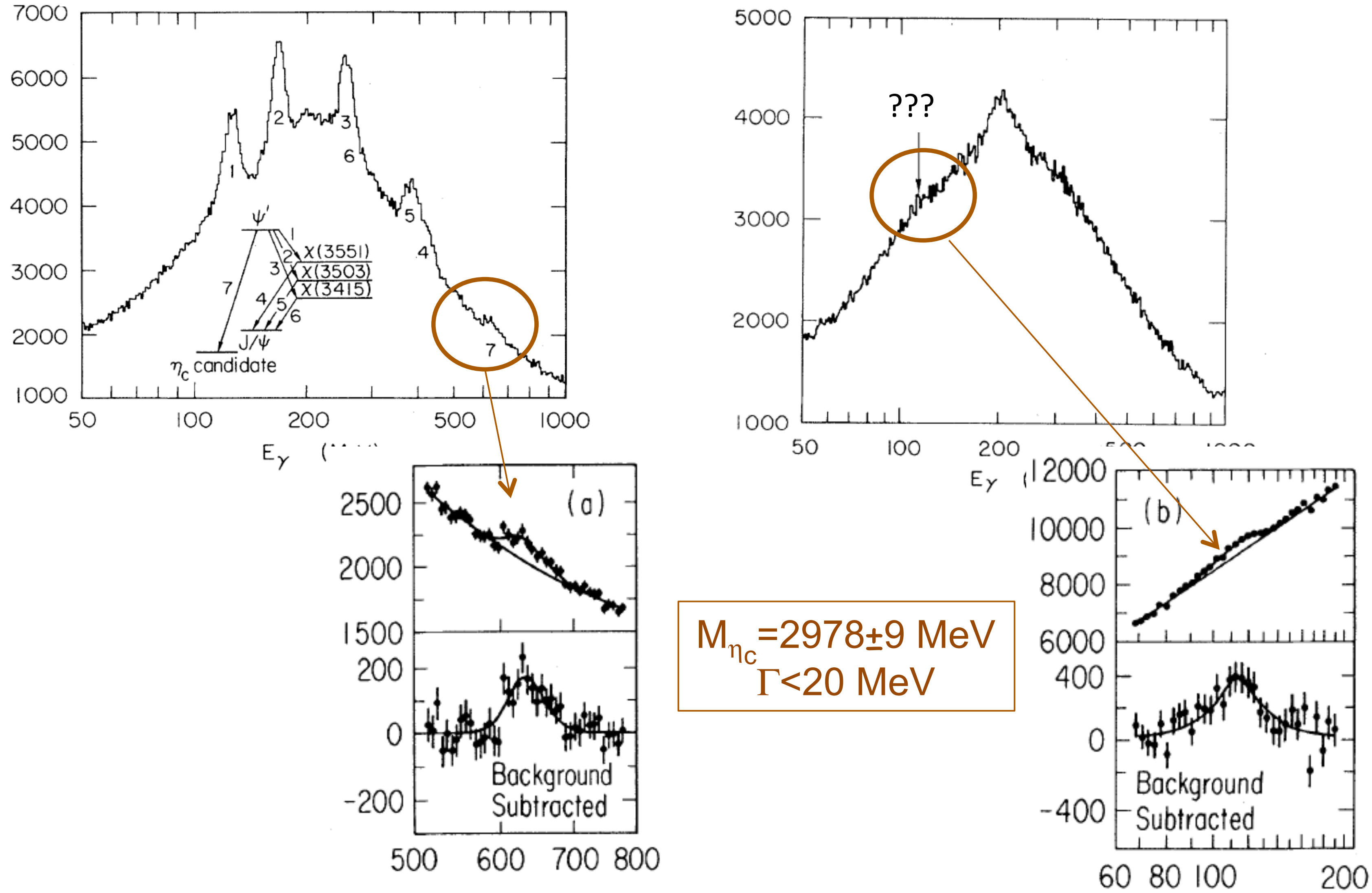
Finding other charmonium mesons



Look for the η_c
via $\psi' \rightarrow \gamma\eta_c$
or $J/\psi \rightarrow \gamma\eta_c$

Xtal-ball: $J/\psi(\psi') \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ inclusive

$\psi' \rightarrow \gamma$ + anything **$J/\psi \rightarrow \gamma$ + anything**



M_{η_c}=2978±9 MeV
Γ<20 MeV

Xtal-Ball PRL 45, 1150 (1980)

Mark II $\psi' \to \gamma\eta_c$: $\eta_c \to$ exclusive

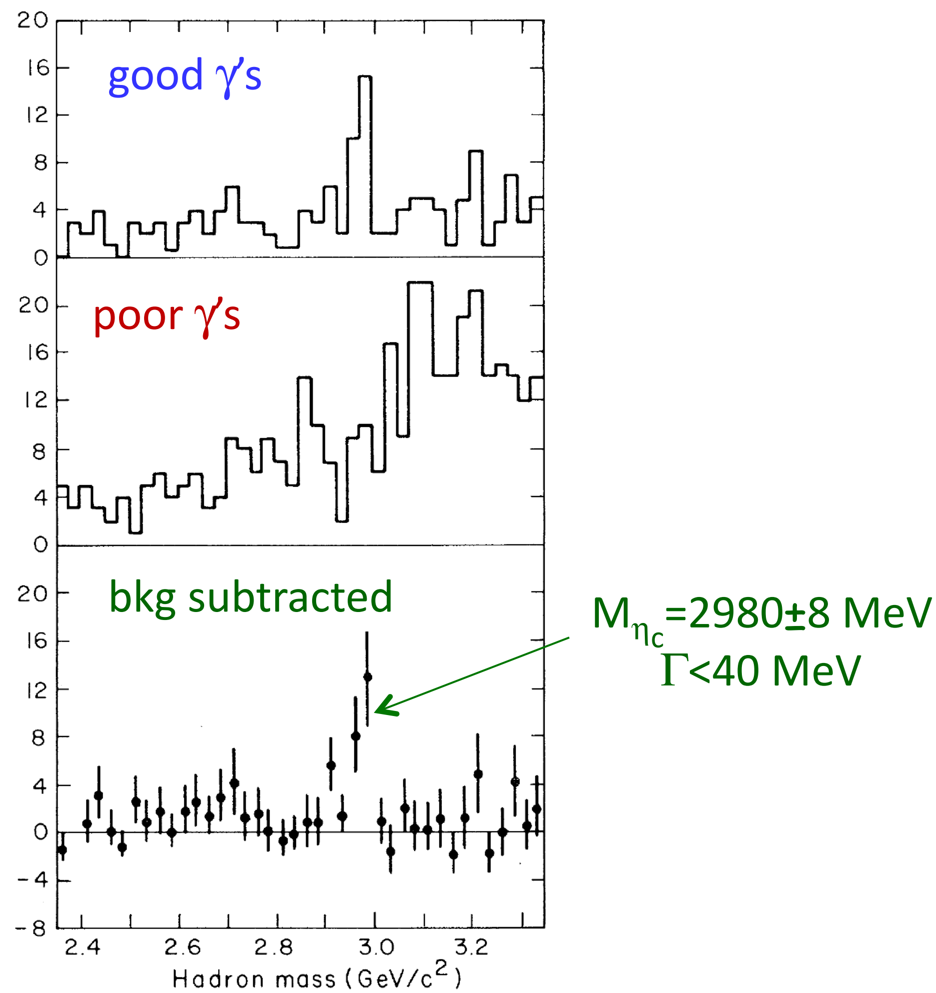
$$\psi' \to \gamma p\bar{p},$$

$$\psi' \to \gamma\pi^+\pi^-\pi^+\pi^-,$$

$$\psi' \to \gamma\pi^+\pi^-K^+K^-,$$

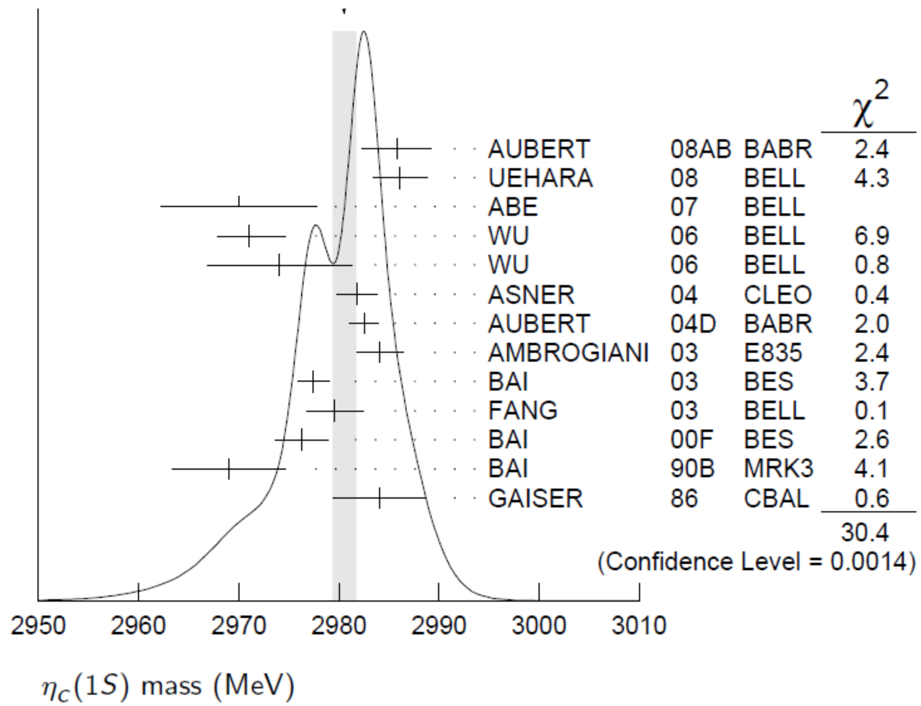
$$\psi' \to \gamma\pi^+\pi^-p\bar{p},$$

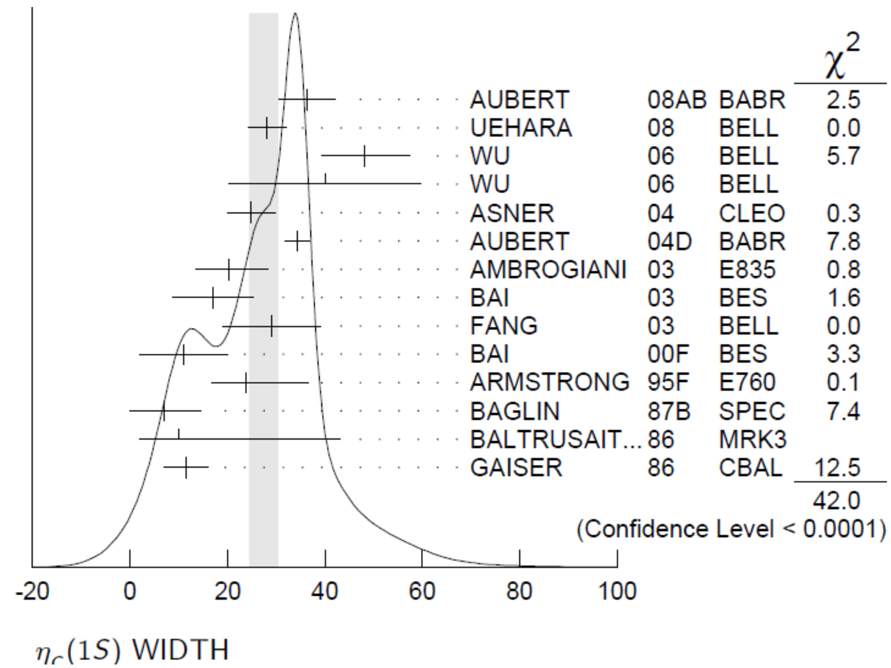
$$\psi' \to \gamma K^{\pm}\pi^{\mp}K_S, \quad K_S \to \pi^+\pi^-$$



Mark II PRL 45, 1146 (1980)

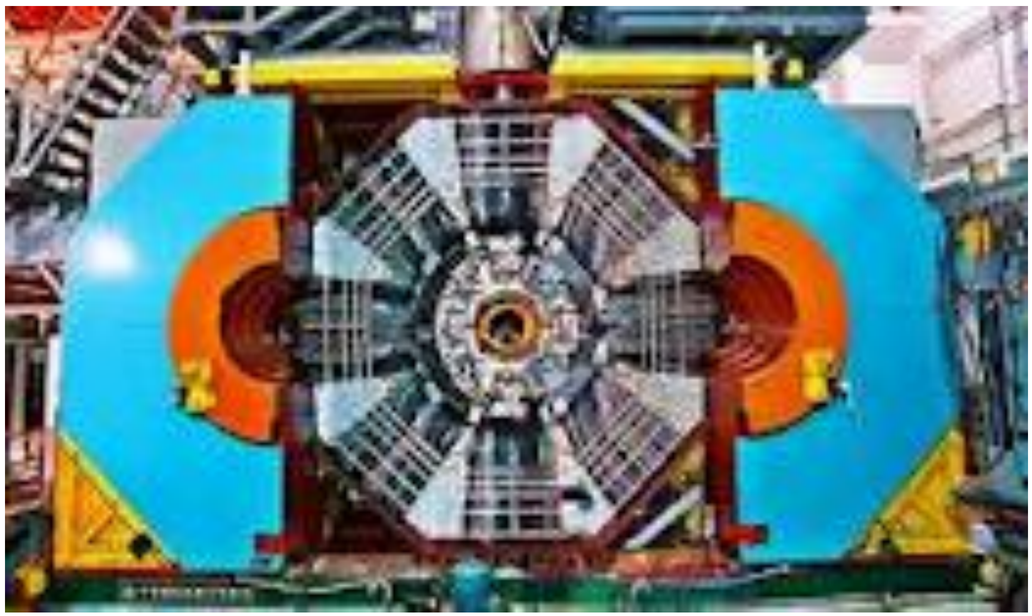
The η_c in 2010 (30 years later)



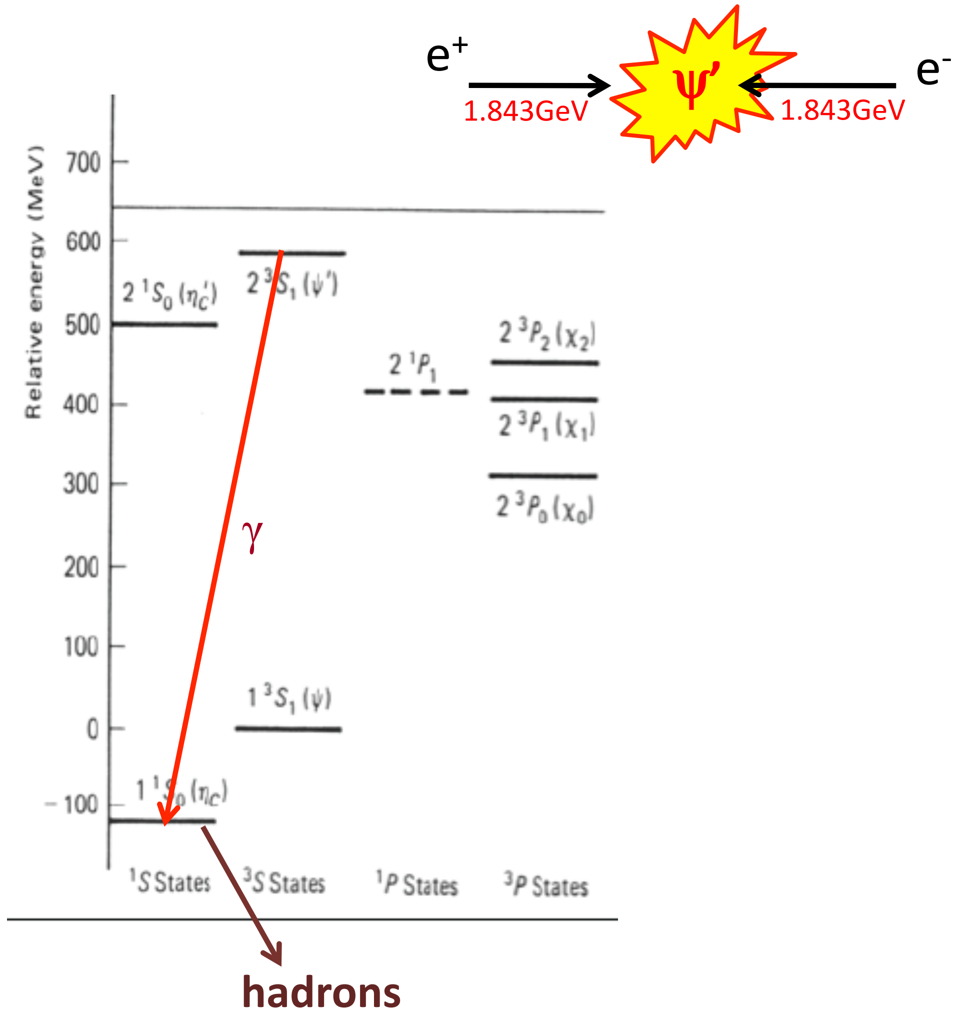


M & Γ not well measured!

BESIII experiment at IHEP(Beijing)

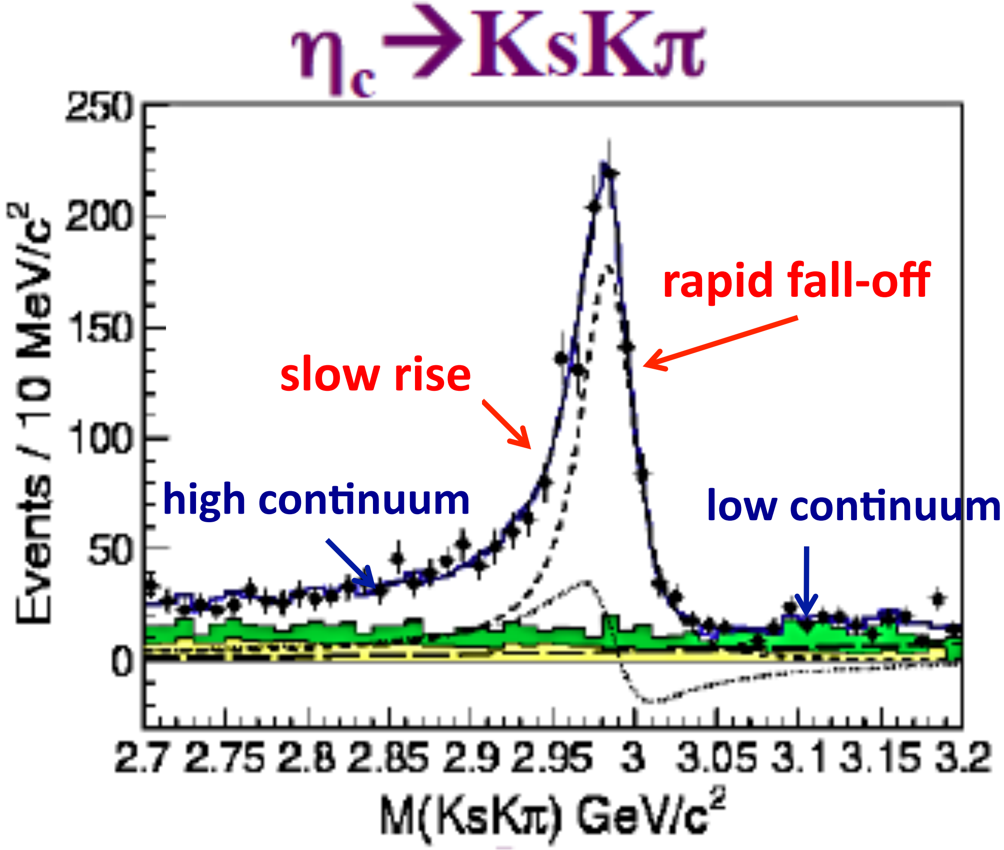


η_c resonant parameters from $\psi' \rightarrow \gamma\eta_c$

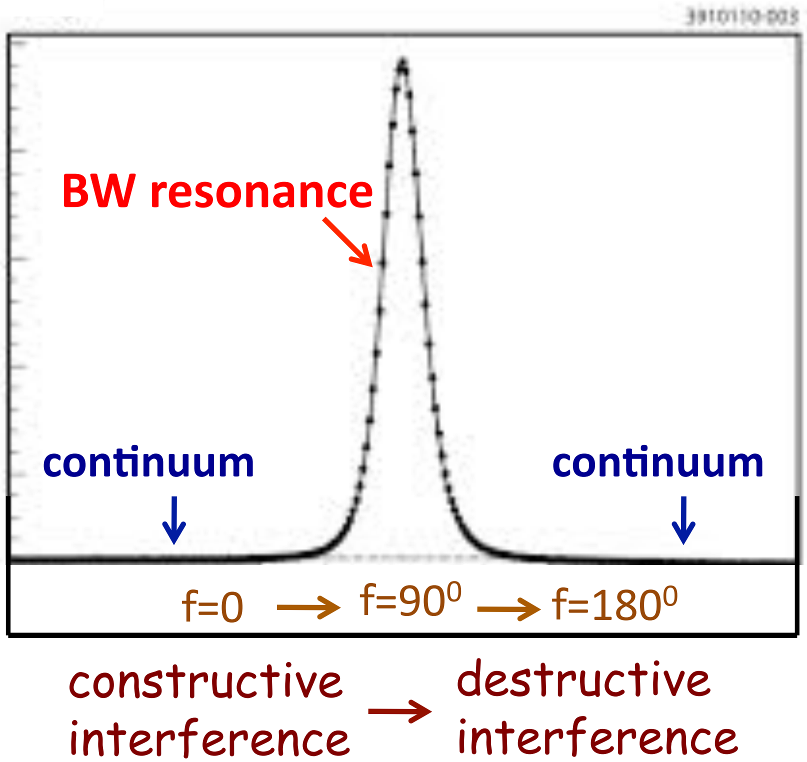


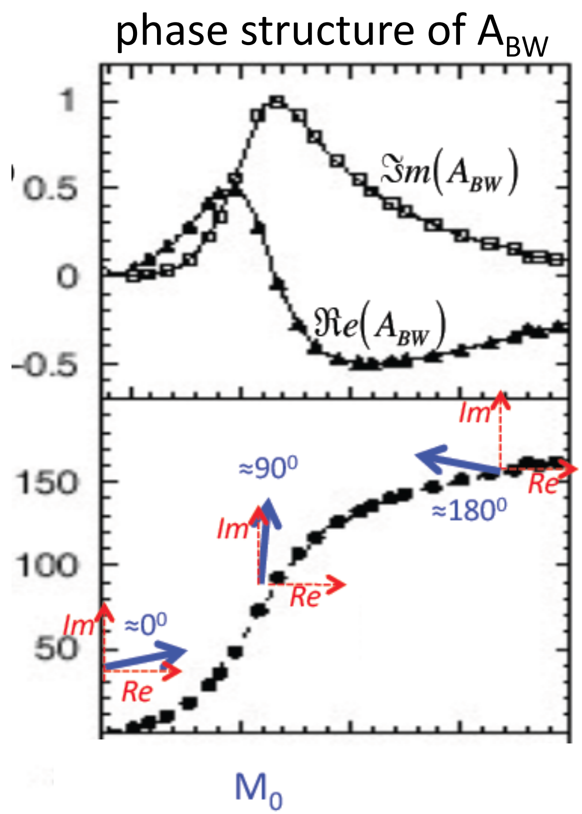
$\psi' \rightarrow \gamma\eta_c$: $\eta_c \rightarrow K_s K \pi$

BESIII experiment

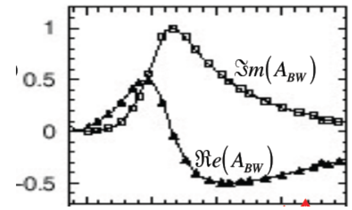


Breit Wigner resonance + constant background





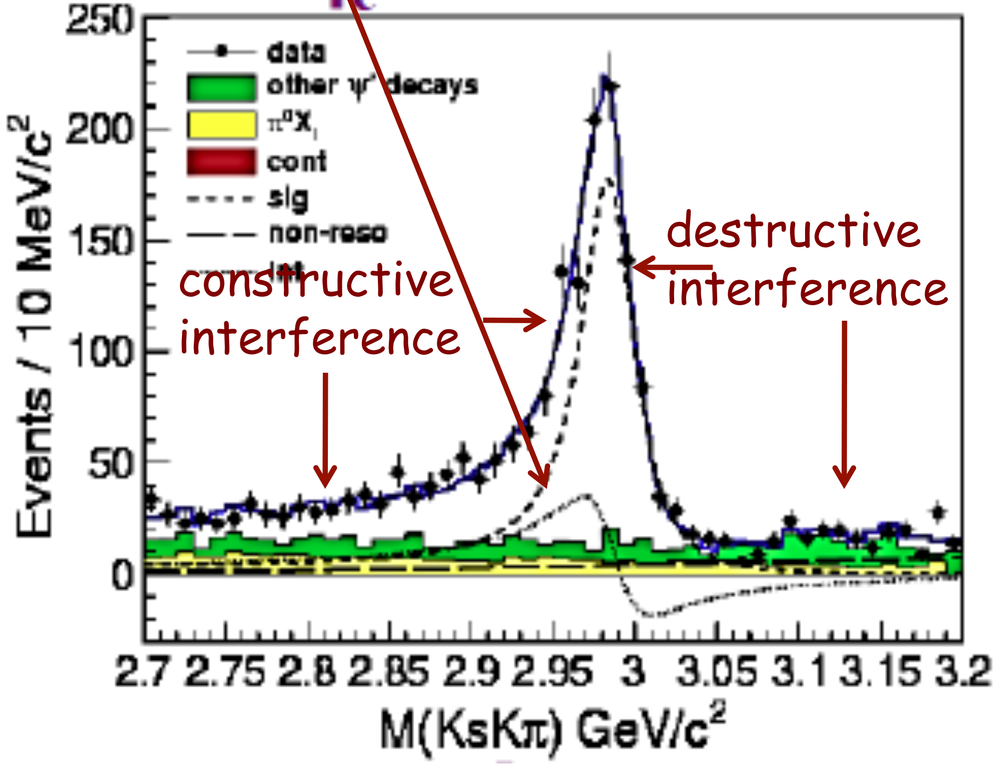
$$|BW + A|^2 = |BW|^2 + |A|^2 + 2A \cdot \mathcal{R}e(BW)$$



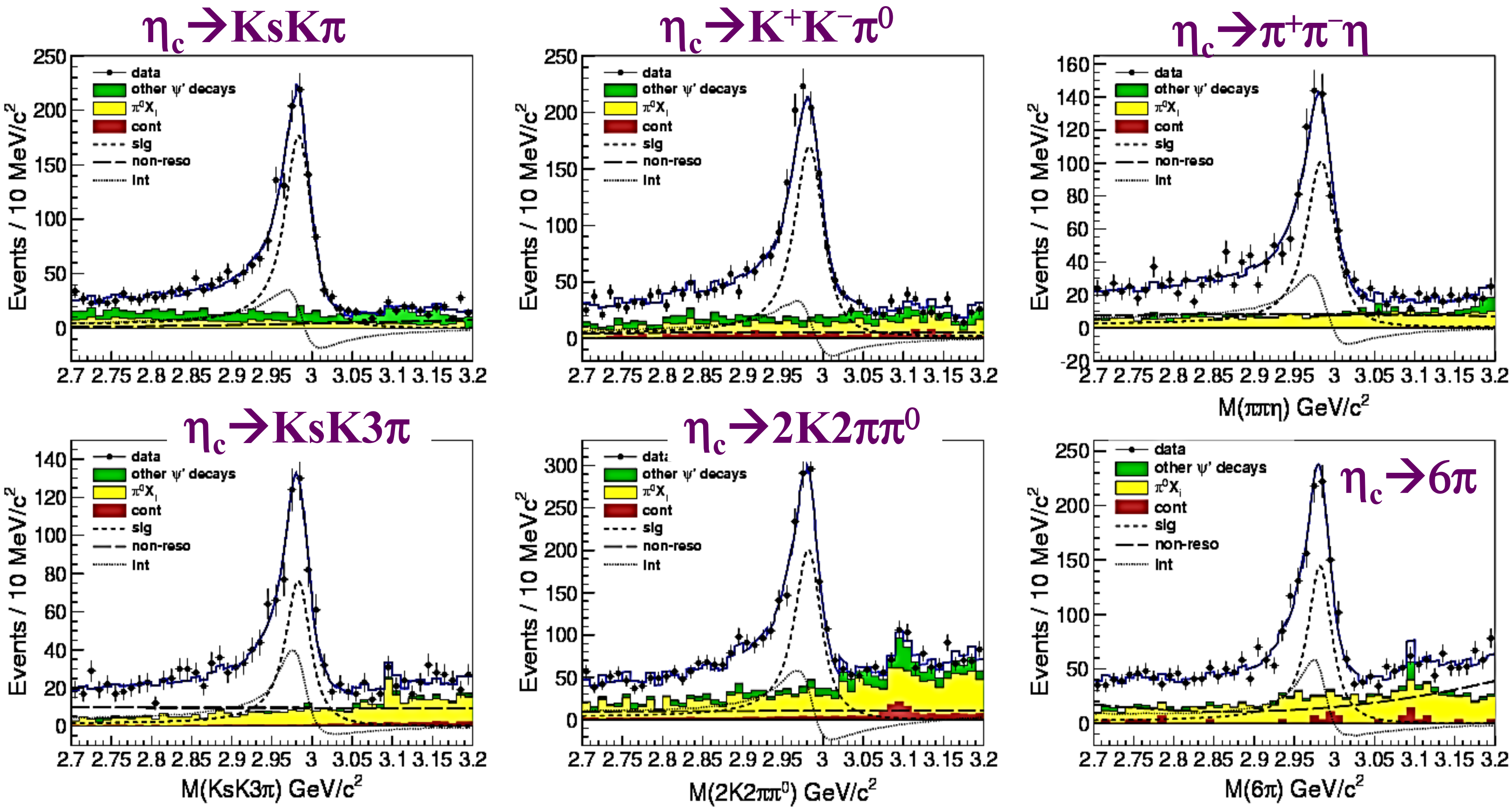
η_c

coherent bkg take as a real constant

$\eta_c \rightarrow K_s K \pi$

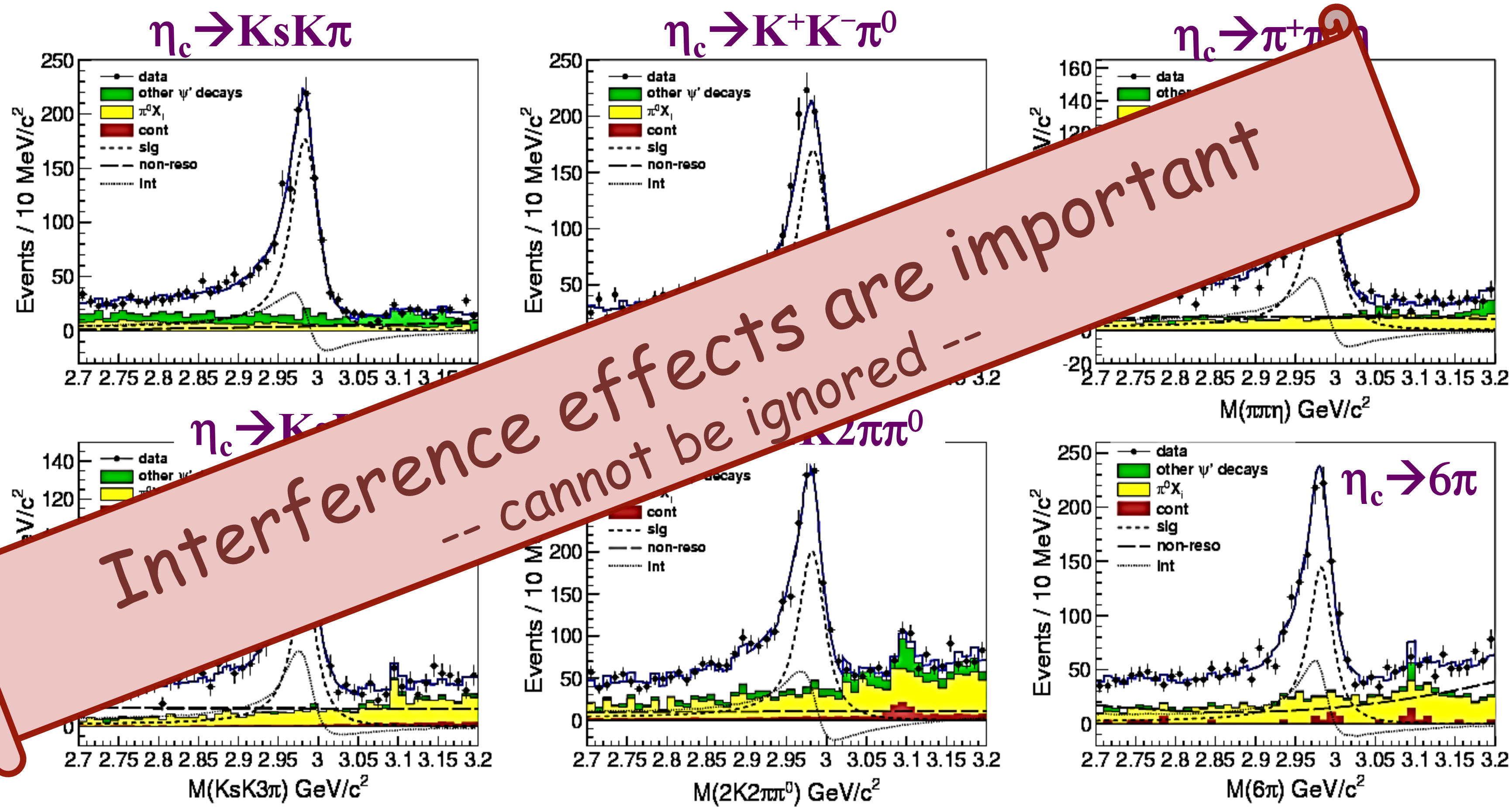


Interference in $\eta_c \rightarrow$ hadrons



similar pattern in all $\eta_c \rightarrow$ hadron decay modes

Interference in $\eta_c \rightarrow$ hadrons



Interference effects are important

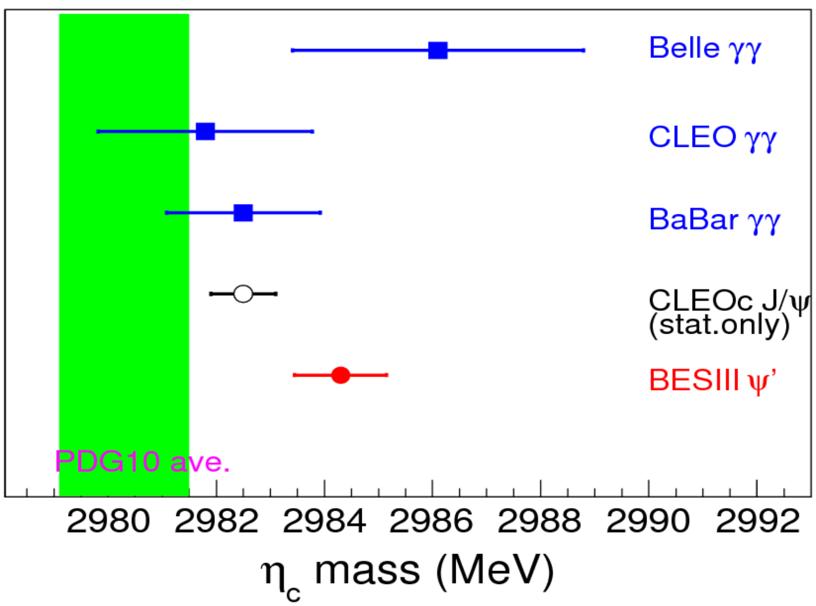
-- cannot be ignored --

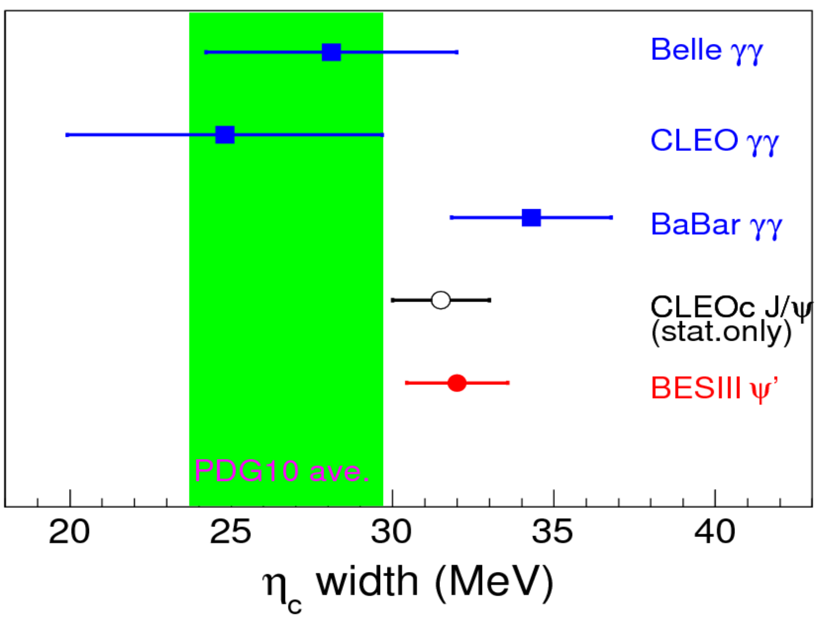
similar pattern in all $\eta_c \rightarrow$ hadron decay modes

Mass and width of η_c

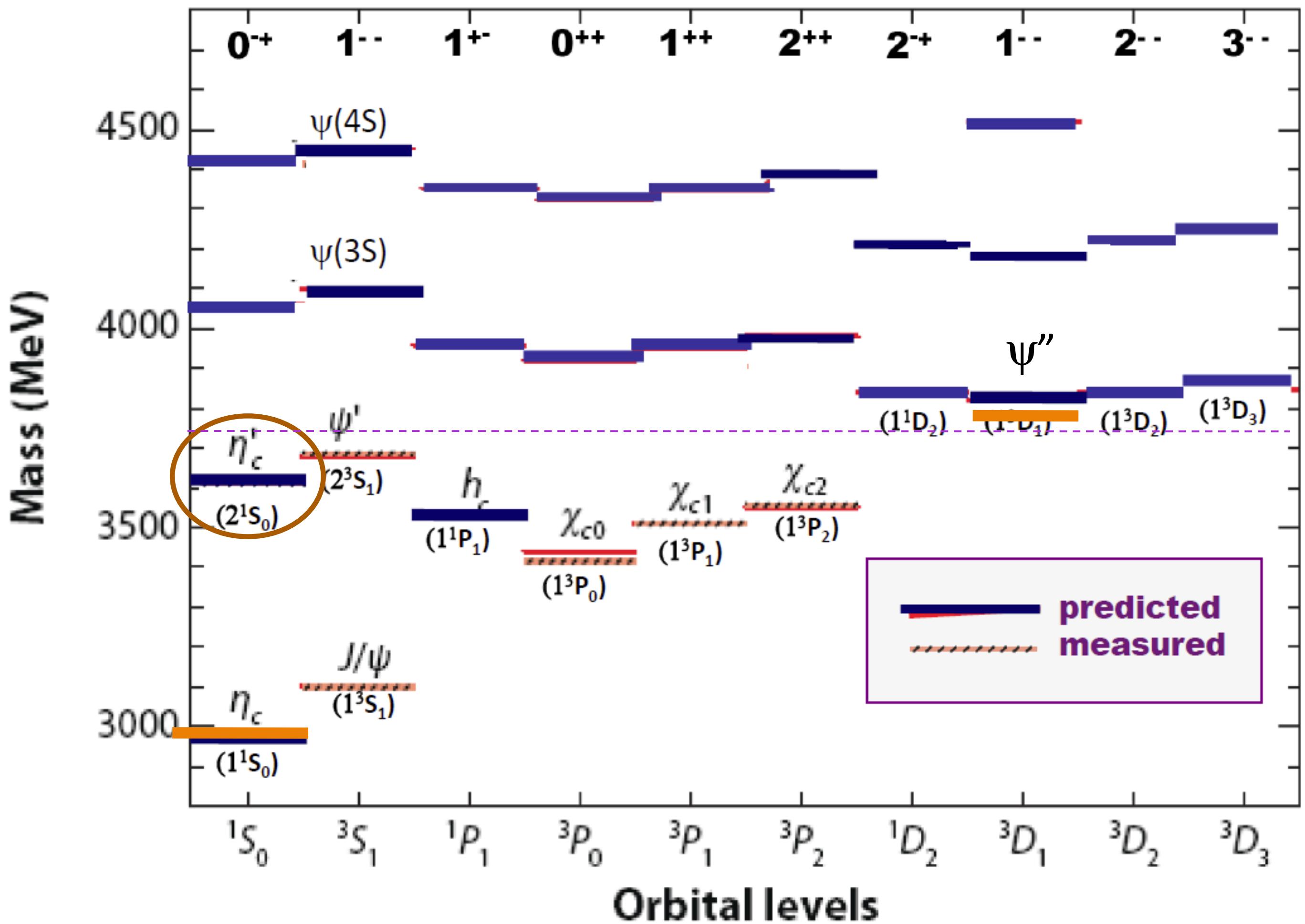
Mass = $2984.3 \pm 0.6 \pm 0.6$ MeV/c^2
Width = $32.0 \pm 1.2 \pm 1.0$ MeV

BESIII PRL108, 222002 (2012)

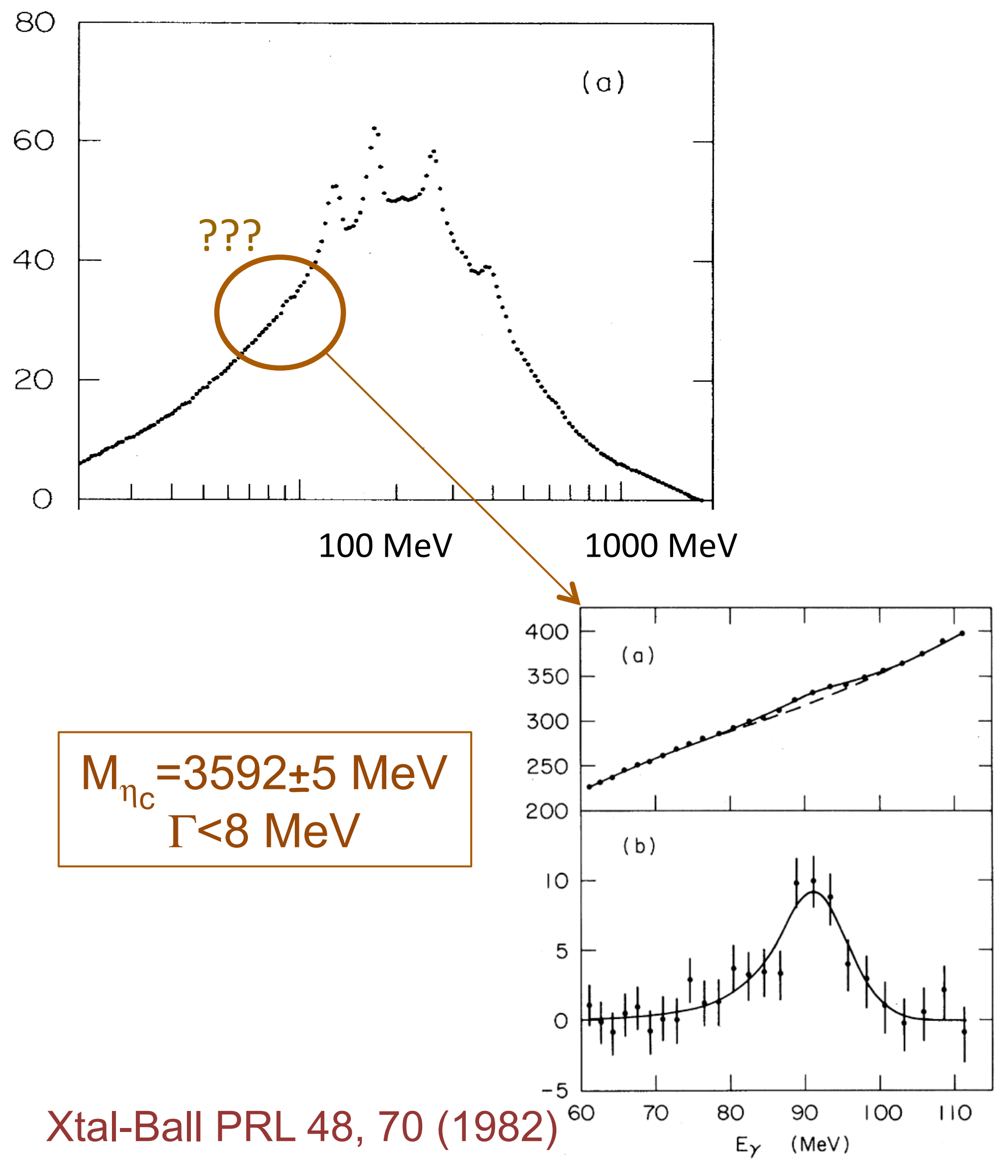




Search for the η_c'



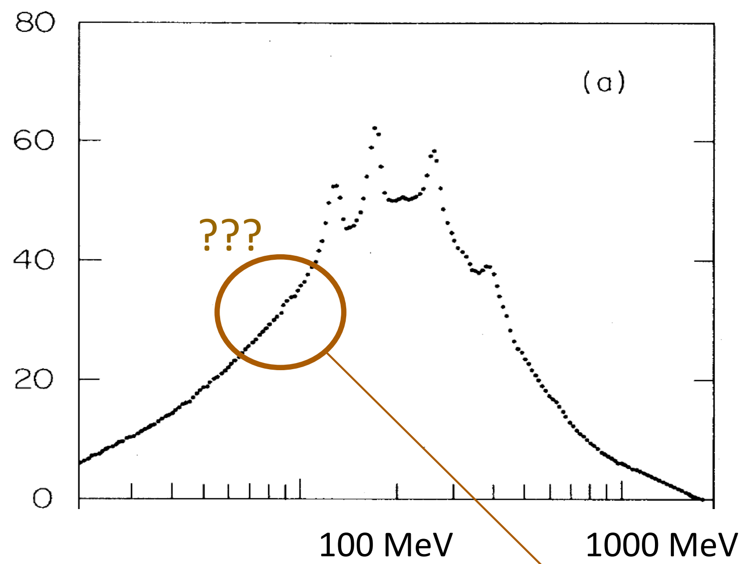
$\psi' \rightarrow \gamma\, \eta_c'$ in the Crystal Ball?



M_{η_c}=3592±5 MeV
Γ<8 MeV

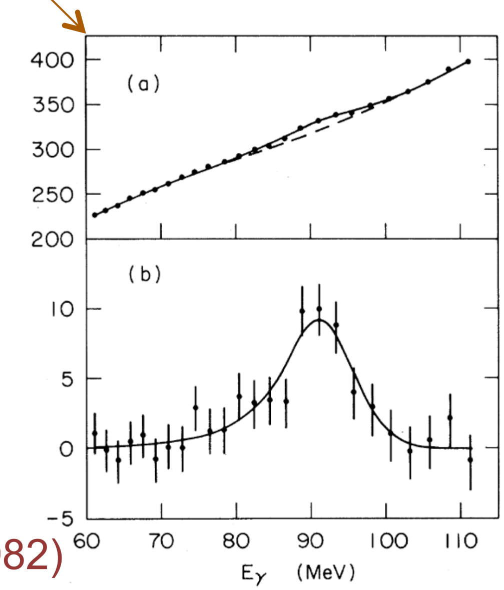
Xtal-Ball PRL 48, 70 (1982)

$\psi' \rightarrow \gamma\eta_c'$ in the Crystal Ball?



never confirmed

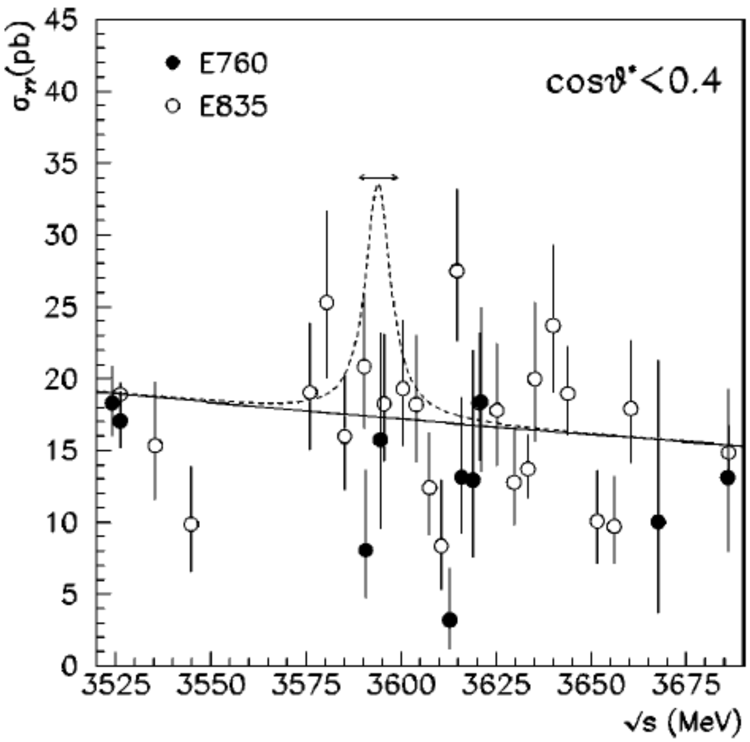
M_{η_c}=3592±5 MeV
Γ<8 MeV



Xtal-Ball PRL 48, 70 (1982)

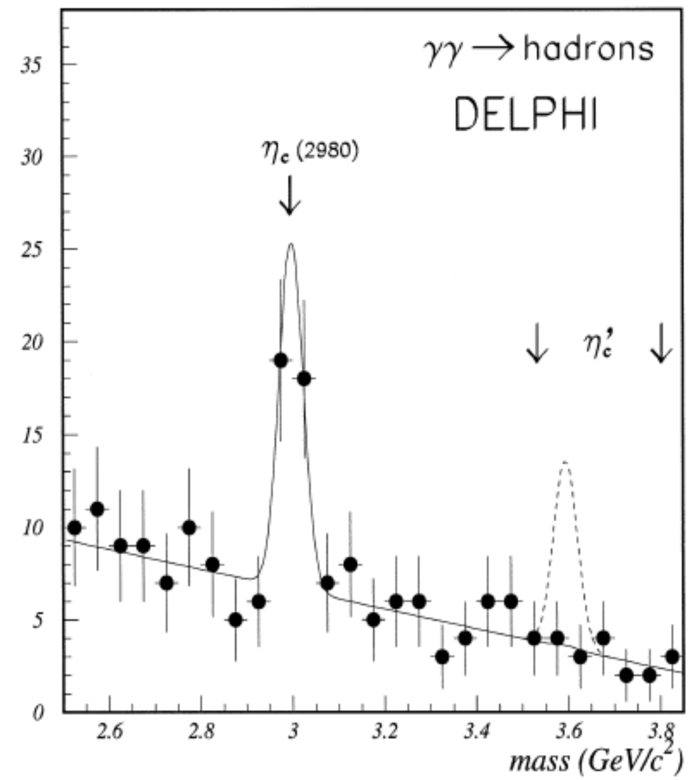
M=3592 MeV η_c' not seen elsewhere

$\bar{p}p \rightarrow \eta_c' \rightarrow \gamma\gamma$ (@ Fermilab)



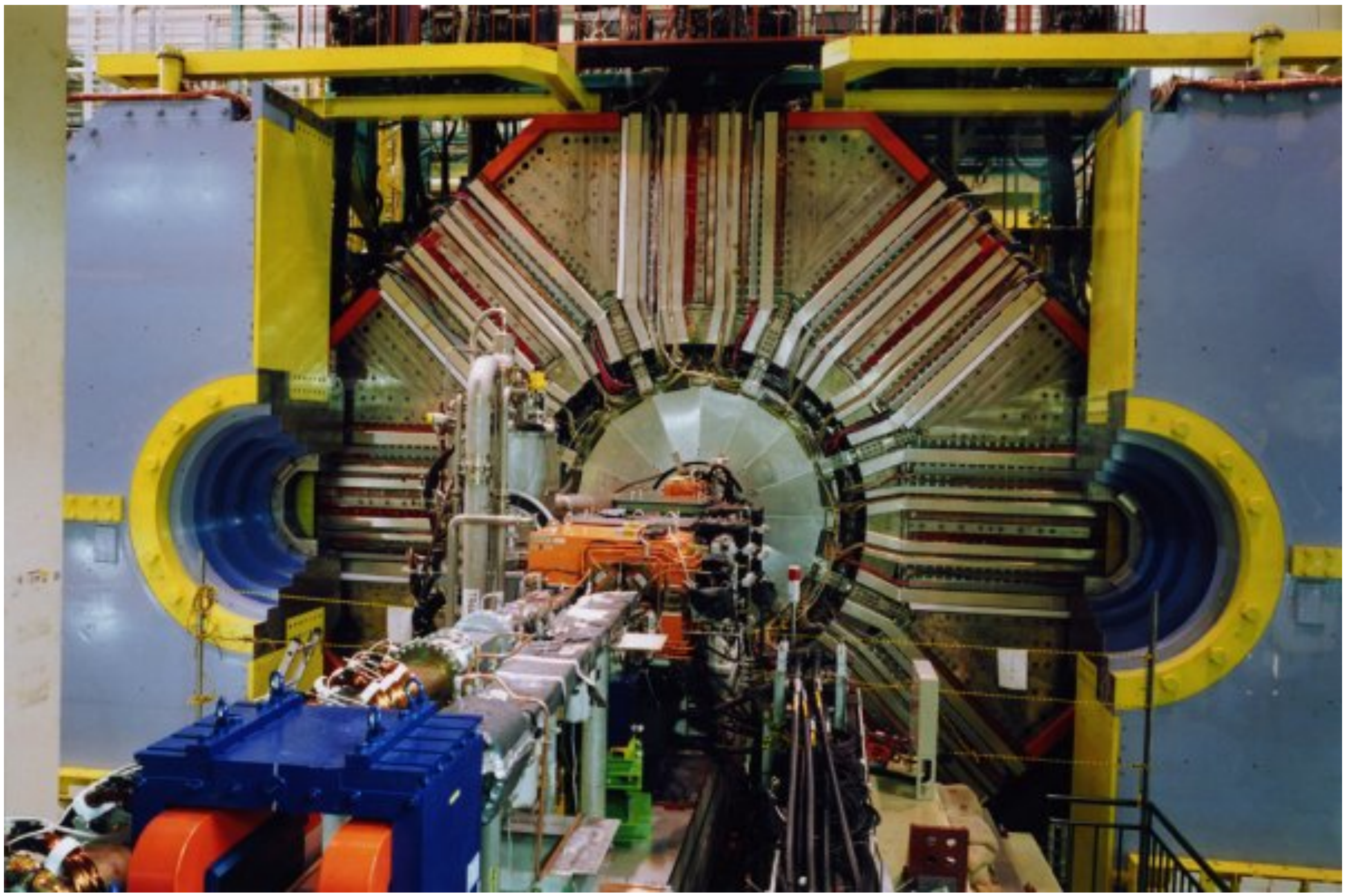
E835 PRD **64**, 052003 (2001)

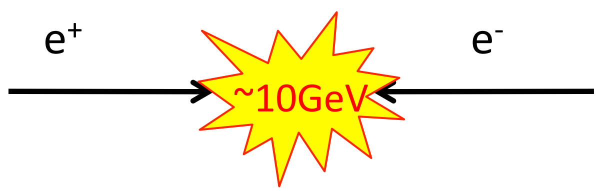
$\gamma\gamma \rightarrow \eta_c' \rightarrow$ hadron (@ LEP)



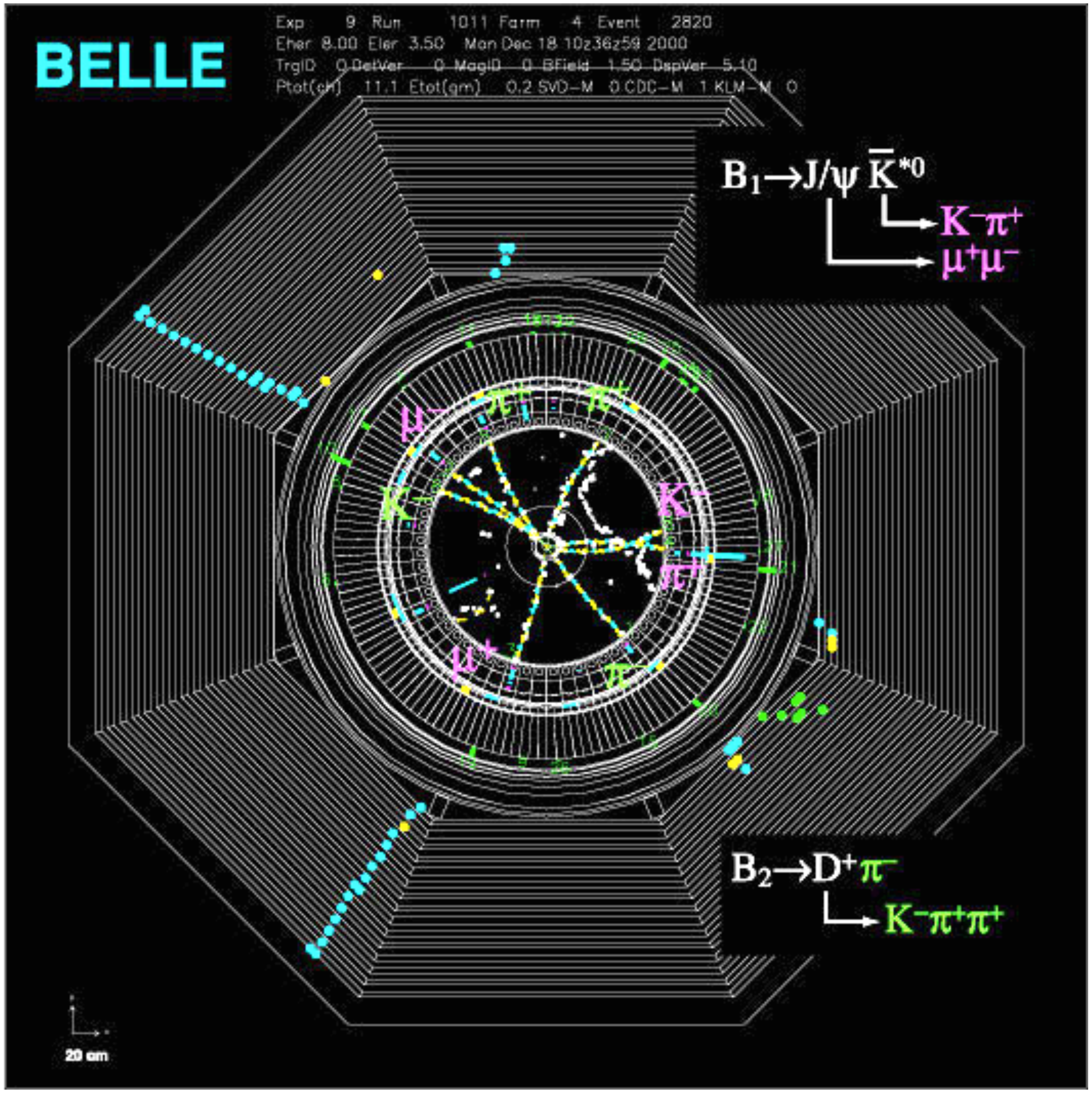
DELPHI PL **B441**, 479 (1998)

The Belle experiment at KEK

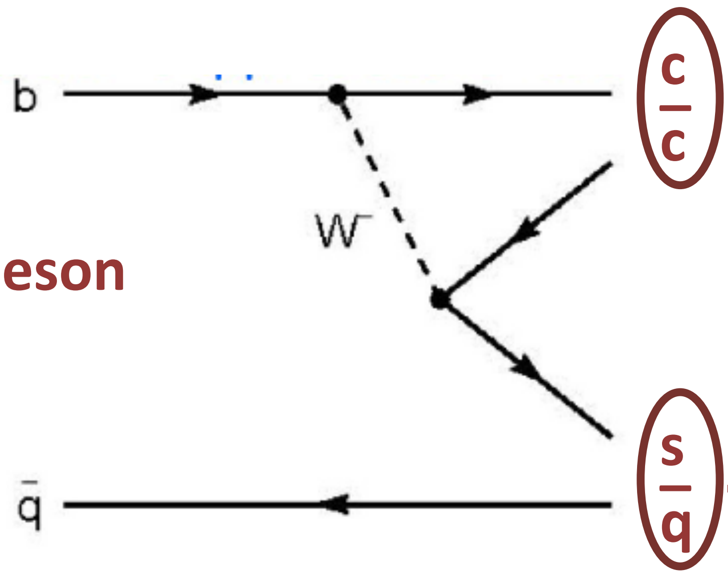




Event in the Belle Detector



Belle in 2002 (20 yrs later)

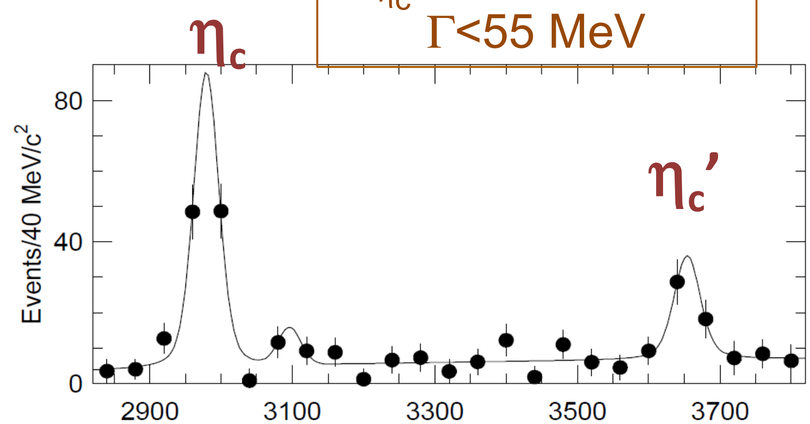


$\rightarrow \eta_c$ (η_c' ??) $\rightarrow K_S K^+ \pi^-$

B meson

$\rightarrow$K

$M_{\eta_c'}$=3654±10 MeV
Γ<55 MeV

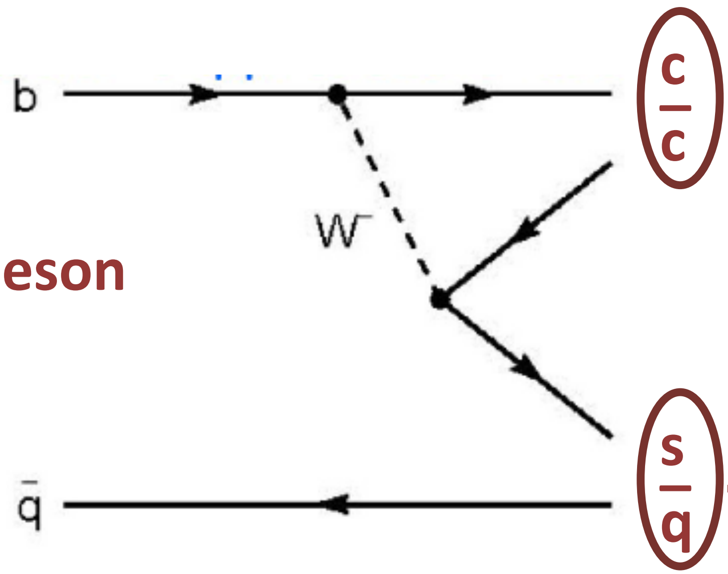


$M(K_S K^+ \pi^-)$

Belle PRL **89**, 102001 (2002)

Belle in 2002 (20 yrs later)

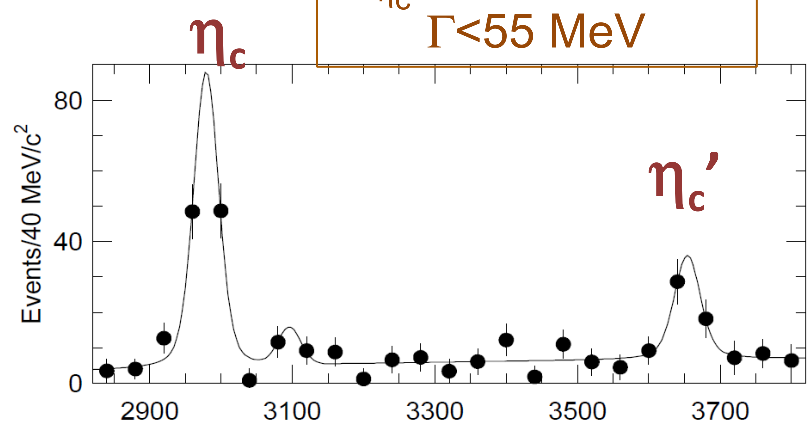
B meson



→η_c (η_c' ??) →$K_S K^+ \pi^-$

→K

$M_{\eta_c'}$=3654±10 MeV
Γ<55 MeV



$M(K_S K^+ \pi^-)$

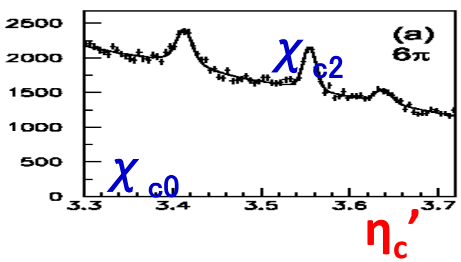
"invariant mass"

$$M(K_S K^+ \pi^-) = \sqrt{(E_{K_S} + E_{K^+} + E_{\pi^-})^2 - (\vec{p}_{K_S} + \vec{p}_{K^+} + \vec{p}_{\pi^=})^2}$$

Belle PRL **89**, 102001 (2002)

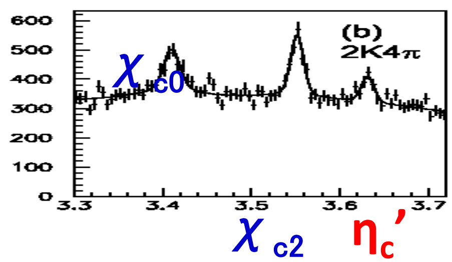
Confirmed by other measurements

Belle: γγ→ $3(\pi^+\pi^-)$



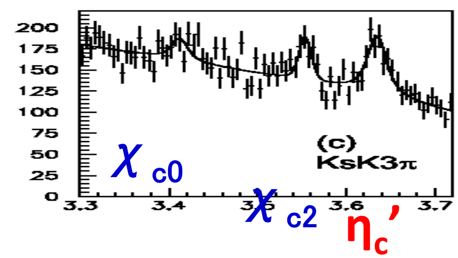
$M(3(\pi^+\pi^-))$

γγ→ $K^+K^-2(\pi^+\pi^-)$



$M(K^+K^-2(\pi^+\pi^-))$

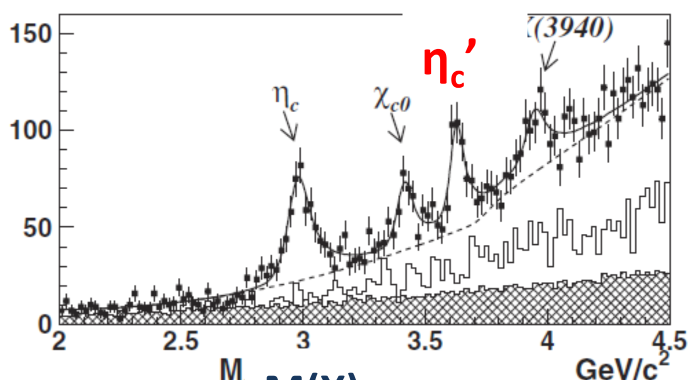
γγ→ $K_SK^+\pi^+\pi^-\pi^-$



$M(K_SK^+\pi^+\pi^-\pi^-)$

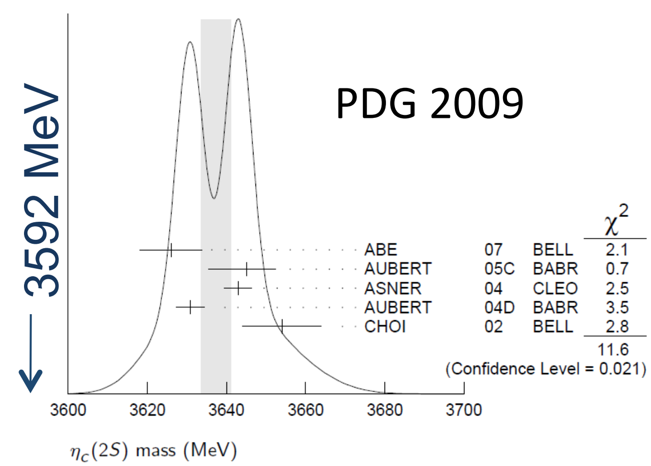
Belle: 2010

Belle: e^+e^-→ $J/\psi + X$

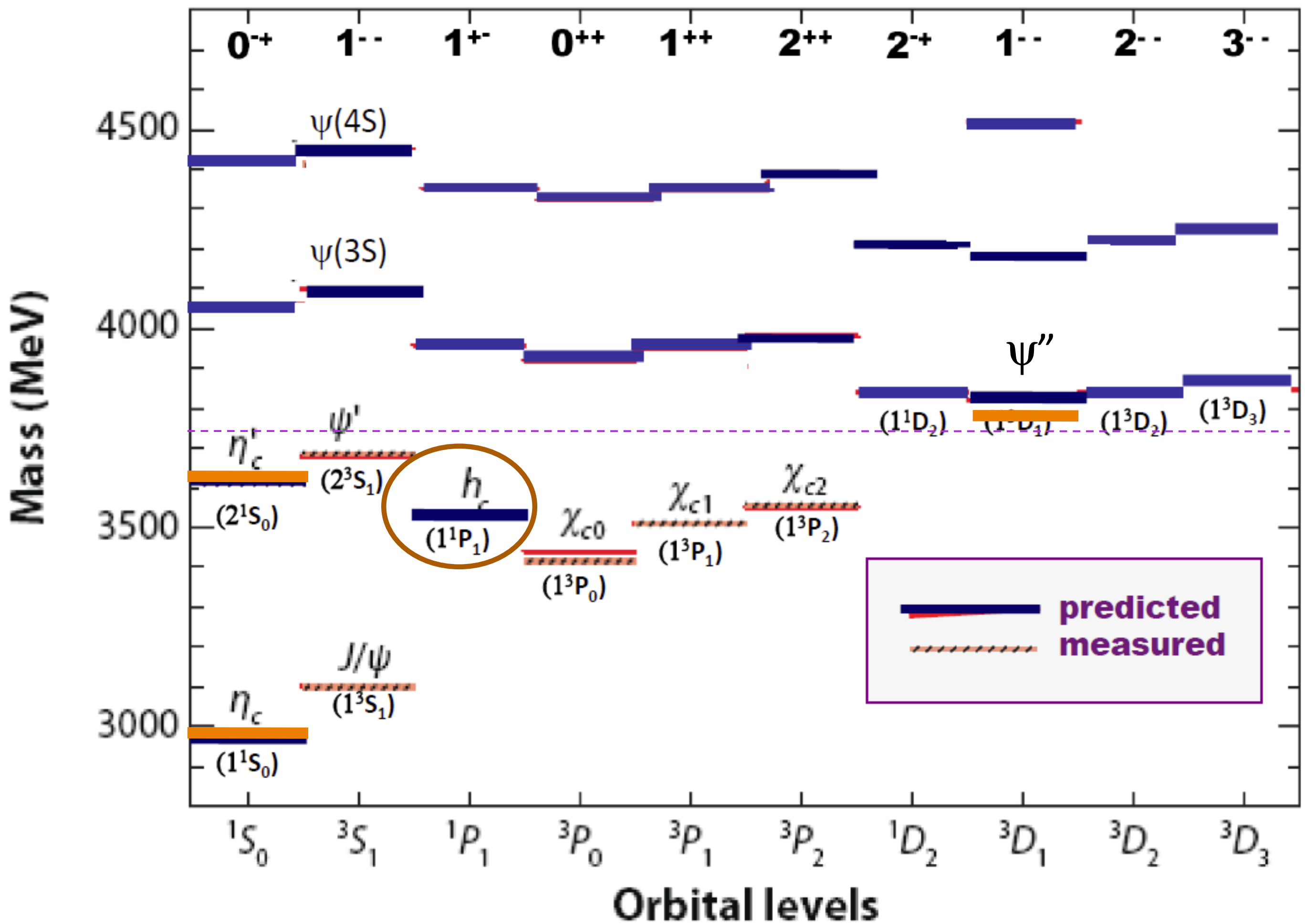


M(X)

Belle PRL **98**, 082001 (2007)



Search for the h_c

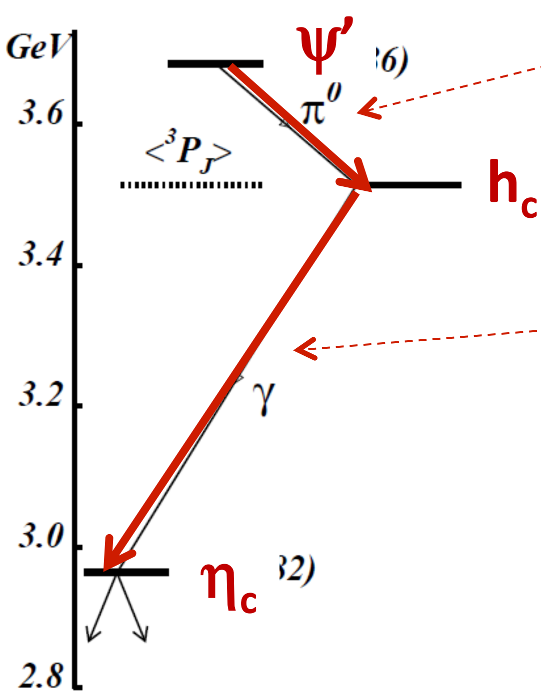


Strategy

$J^{PC}(\psi'):= 1^{--}$

$J^{PC}(h_c) = 1^{+-}$

} ➔ $\psi' \rightarrow \gamma h_c$ not allowed



$\psi' \rightarrow \pi^0 h_c$ allowed but Ispin-suppressed

expected branching fraction ≈ 10^{-3}

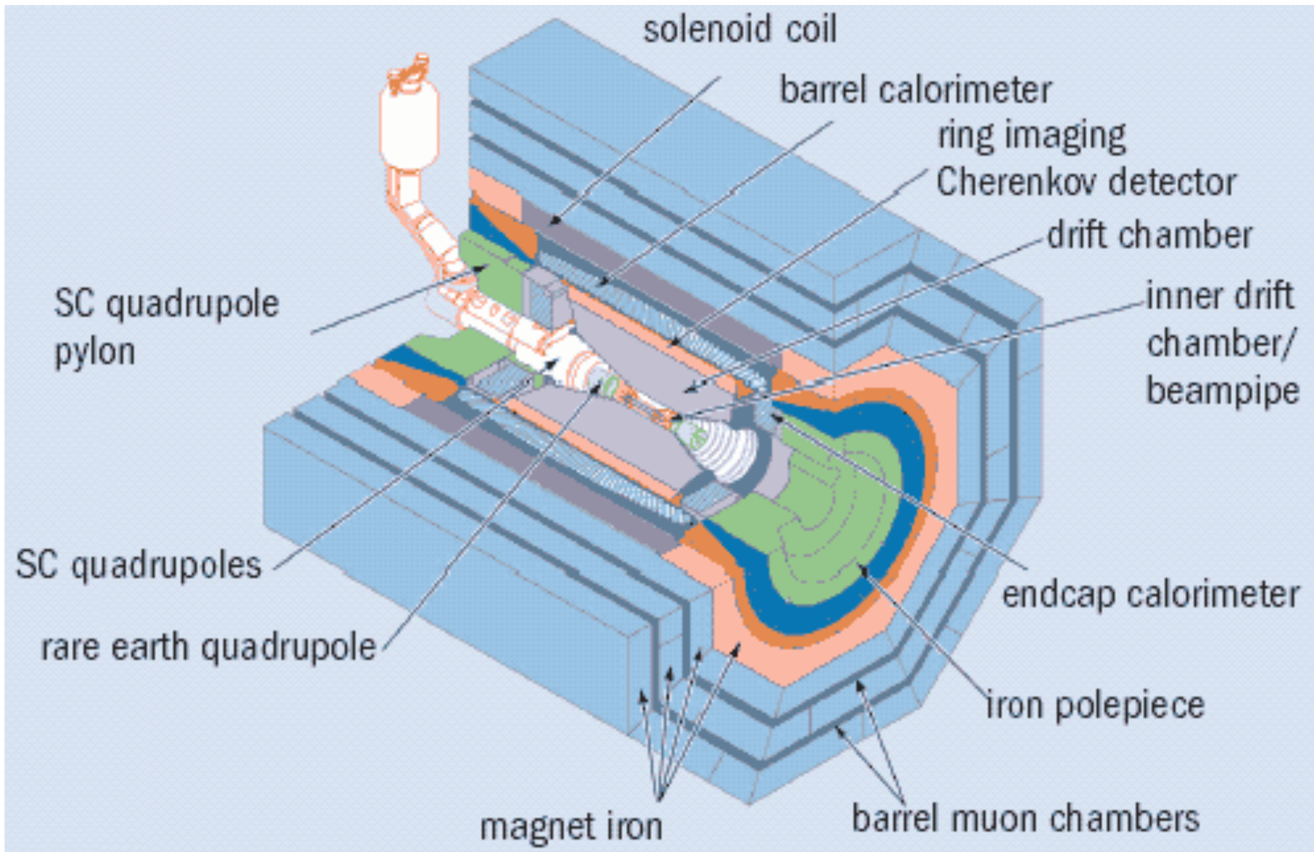
preferred h_c decay mode is $h_c \rightarrow \gamma\eta_c$

expected branching fraction ≈ 0.4

Expected mass = "center-of-gravity" of $M(\chi_{c0,1,2})$

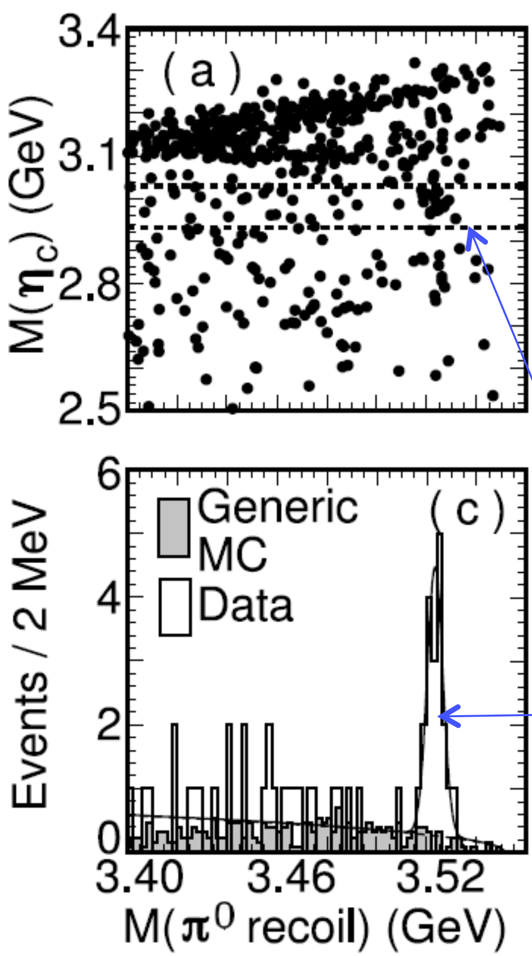
$=[M(\chi_{c0}) + 3\,M(\chi_{c1}) + 5\,M(\chi_{c2})]/9 = 3.525$ MeV

CLEO detector at Cornell Univ



h_c: CLEO 2005 (exclusive)

Exclusive analysis: $\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)\ ,\ \eta_c \to hadrons$



$\eta_c \to K_s K^\pm \pi^\mp$

$\eta_c \to K^+ K^- \pi^0$

$\eta_c \to K^+ K^- \pi^+ \pi^-$

$\eta_c \to 2\pi^+ 2\pi^-$

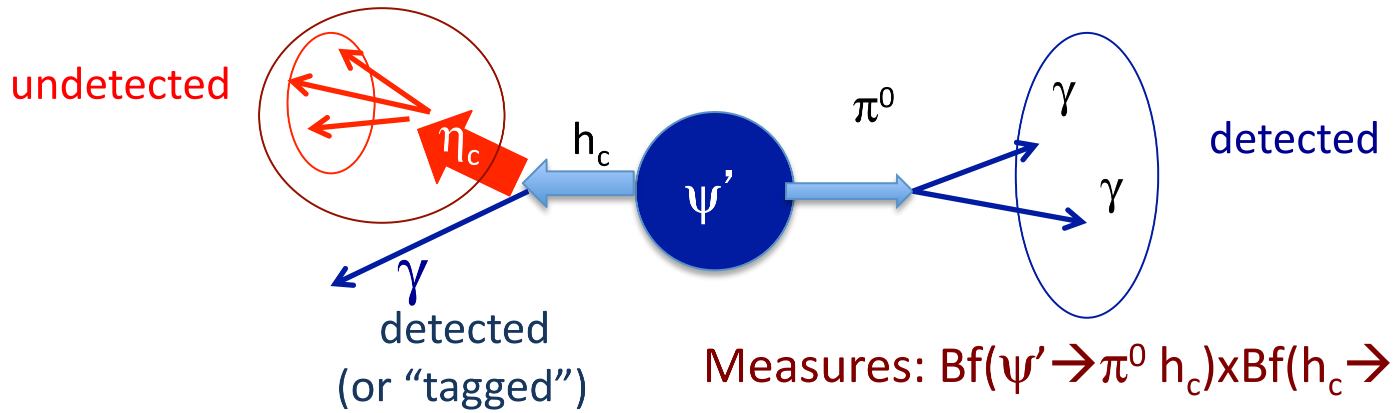
$\eta_c \to \pi^+ \pi^- \eta, \quad \eta \to \gamma\gamma$

$\eta_c \to \pi^+ \pi^- \eta, \quad \eta \to \pi^+ \pi^- \pi^0$

clean $h_c \to \gamma\eta_c$ signal   about 20 events

$$M(\pi^0 \text{ recoil}) = \sqrt{(E_{cm} - E_{\pi^0})^2 - \left|\vec{p}_{\pi^0}\right|^2}$$

semi-inclusive h_c reconstruction



Measures: $Bf(\psi' \rightarrow \pi^0 h_c) x Bf(h_c \rightarrow \gamma\eta_c)$

4-momentum conservation

$$E_{\psi'} = E_{\pi^0} + E_{\eta_c} + E_{tag-\gamma} \Rightarrow E_{\eta_c} = E_{\psi'} - E_{\pi^0} - E_{tag-\gamma}$$

$$\vec{p}_{\psi'} = \vec{p}_{\eta_c} + \vec{p}_{\pi^0} + \vec{p}_{tag-\gamma} \Rightarrow \vec{p}_{\eta_c} = \vec{p}_{\psi'} - \vec{p}_{\pi^0} - \vec{p}_{tag-\gamma}$$

In the cm: $\vec{p}_{\psi'} = 0$

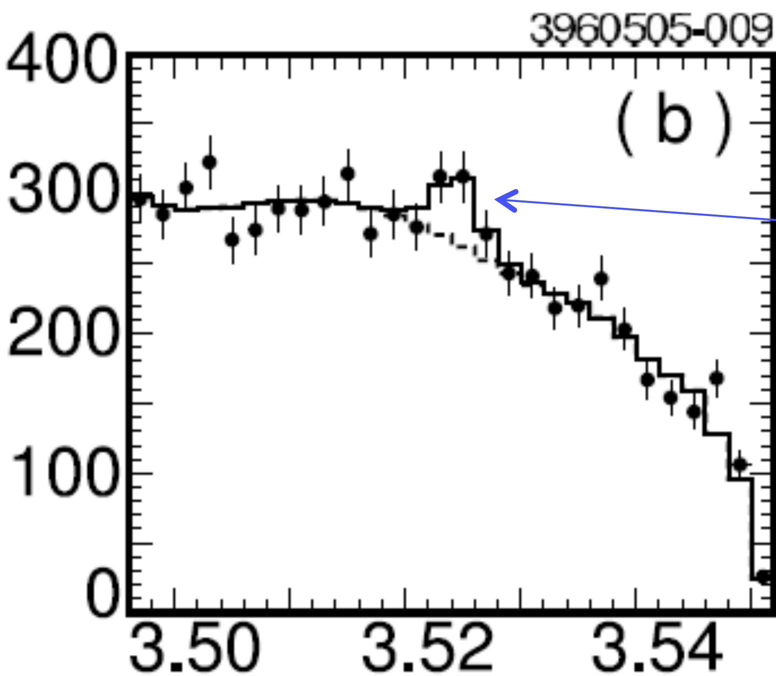
$$\Rightarrow M_{\eta_c} = "M(\pi^0 \gamma_{tag} \text{ recoil})" = \sqrt{(E_{cm} - E_{\pi^0} - E_{tag-\gamma})^2 - \left|\vec{p}_{\pi^0} + \vec{p}_{tag-\gamma}\right|^2}$$

h_c: CLEO 2005 (semi-inclusive)

undetected

Inclusive analysis: $\psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)\ ,\ \eta_c \to hadrons$

detect the $\pi^0 \to \gamma\gamma$ & the γ from $h_c \to \gamma\eta_c$



Mass recoiling from the p^0

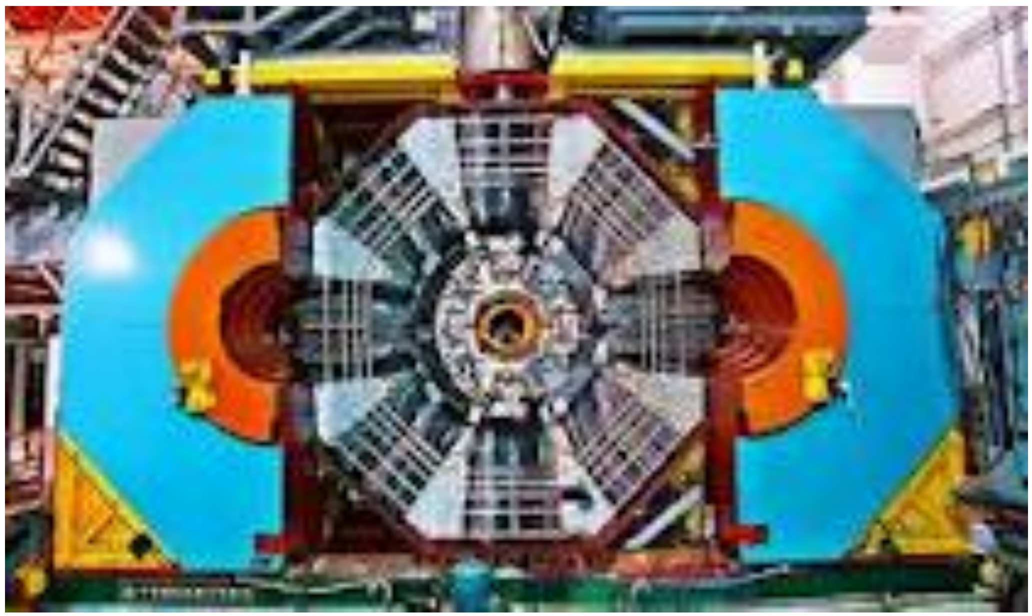
$h_c \to \gamma\eta_c$ signal

Measures: $Bf(\psi' \to \pi^0\ h_c) x Bf(h_c \to \gamma\eta_c)$

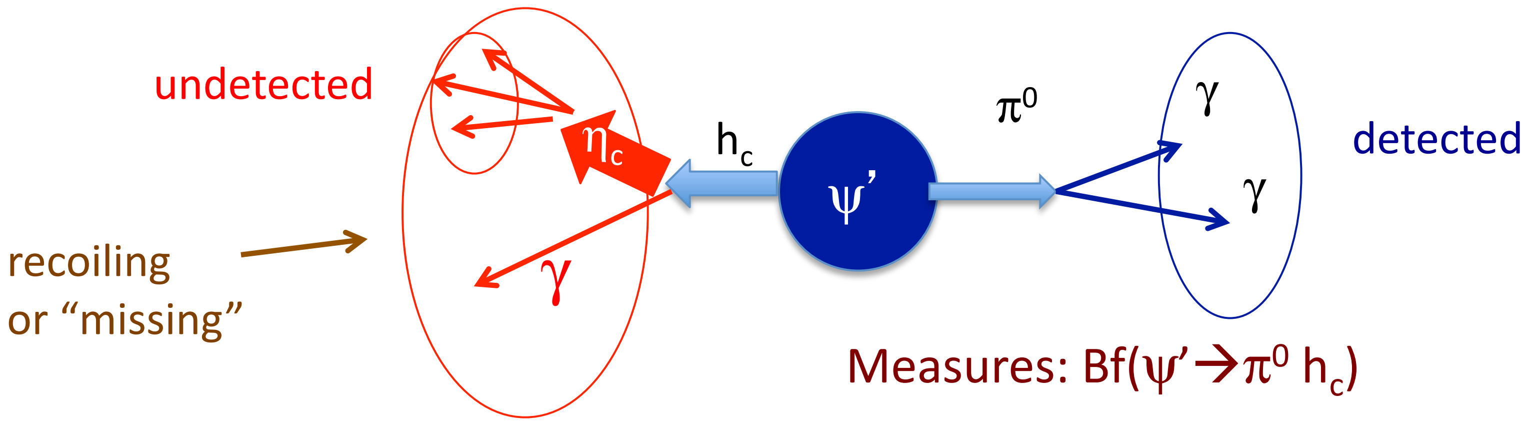
	Inclusive	Exclusive
Counts	150 ± 40	17.5 ± 4.5
Significance	$\sim 3.8\sigma$	6.1σ
$M(h_c)$ (MeV)	$3524.9 \pm 0.7 \pm 0.4$	$3523.6 \pm 0.9 \pm 0.5$
$\mathcal{B}_\psi \mathcal{B}_h$ (10^{-4})	$3.5 \pm 1.0 \pm 0.7$	$5.3 \pm 1.5 \pm 1.0$

CLEO PRL **95**,102003 (2005)

BESIII experiment at IHEP(Beijing)



fully inclusive h_c reconstruction



Measures: Bf($\psi' \rightarrow \pi^0 h_c$)

4-momentum conservation

$$E_{\psi'} = E_{\pi^0} + E_{h_c} \Rightarrow E_{h_c} = E_{\psi'} - E_{\pi^0}$$

$$\vec{p}_{\psi'} = \vec{p}_{h_c} + \vec{p}_{\pi^0} \Rightarrow \vec{p}_{h_c} = \vec{p}_{\psi'} - \vec{p}_{\pi^0}$$

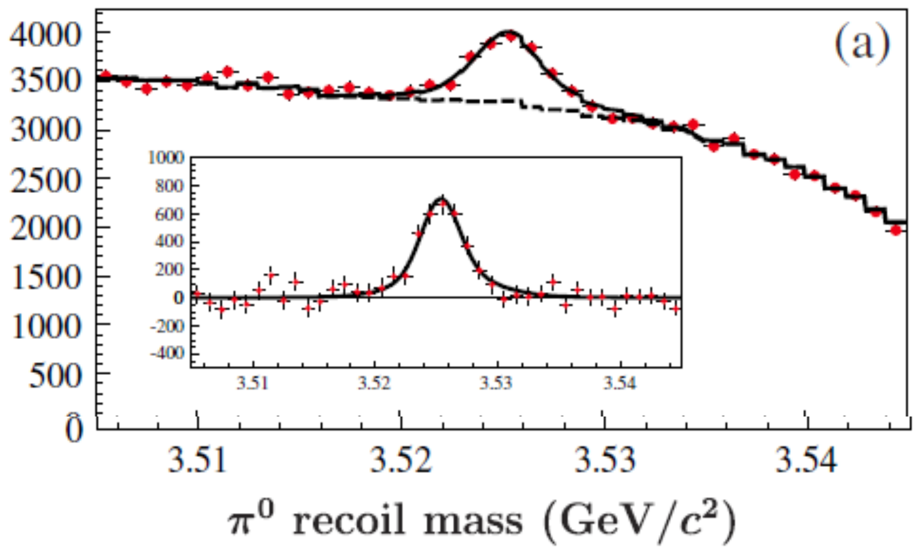
In the cm: $\vec{p}_{\psi'} = 0$

$$\Rightarrow M_{h_c} = \text{"}M(\pi^0 \text{ recoil})\text{"} = \sqrt{(E_{cm} - E_{\pi^0})^2 - \left|\vec{p}_{\pi^0}\right|^2}$$

h_c: BES III 2010 (fully inclusive)

Semi-inclusive: $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$

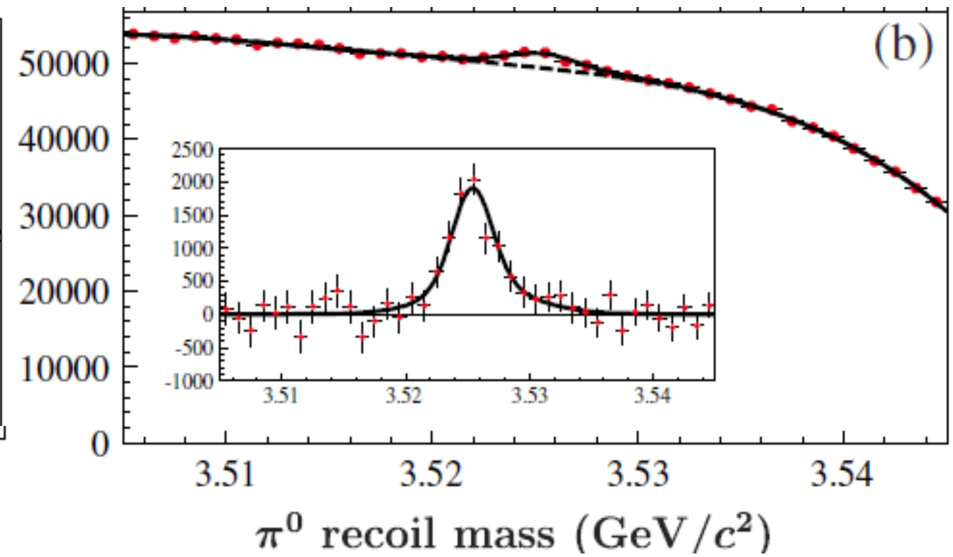
Detect: π^0 & γ



Measures: $Bf(\psi' \rightarrow \pi^0 h_c) x Bf(h_c \rightarrow \gamma \eta_c)$

Fully inclusive: $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta \eta_c$

Detect: π^0 only



Measures: $Bf(\psi' \rightarrow \pi^0 h_c)$

BES III PRL **104**,132002 (2010)

h_c: BES III results

results: $Bf(\psi' \rightarrow \pi^0 h_c) = (8.4 \pm 1.3) \times 10^{-4}$

$Bf(h_c \rightarrow \gamma \eta_c) = (54.3 \pm 6.7)\%$

$M(h_c) = 3525.4 \pm 0.22$ MeV

$\Gamma(h_c) = 0.73 \pm 0.53$ (< 1.44) MeV

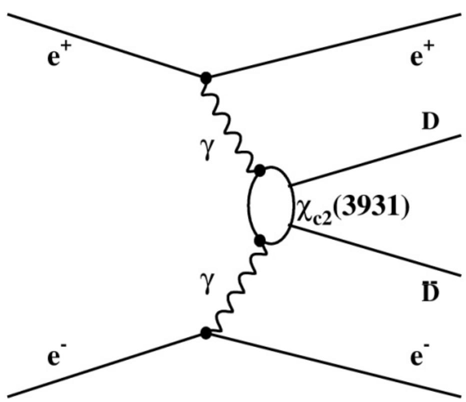
agree with theory
YP Kuang PRD 65 094024

$M_{cog}(\chi_{c0,1,2}) = 3525.3$ MeV

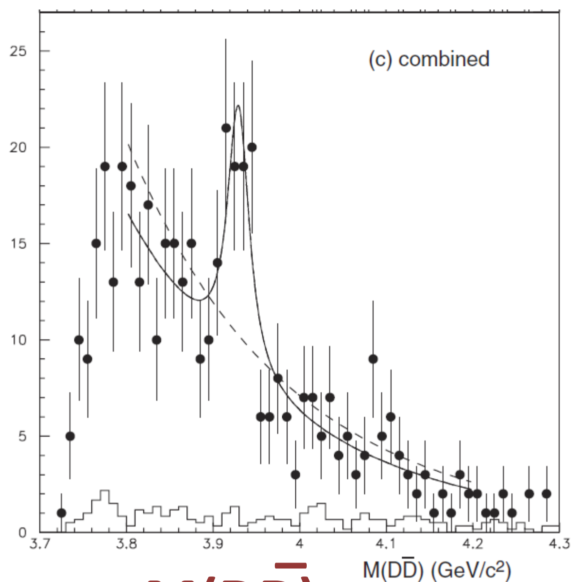
BES III PRL **104**,132002 (2010)

χ'_{c2} discovered by Belle

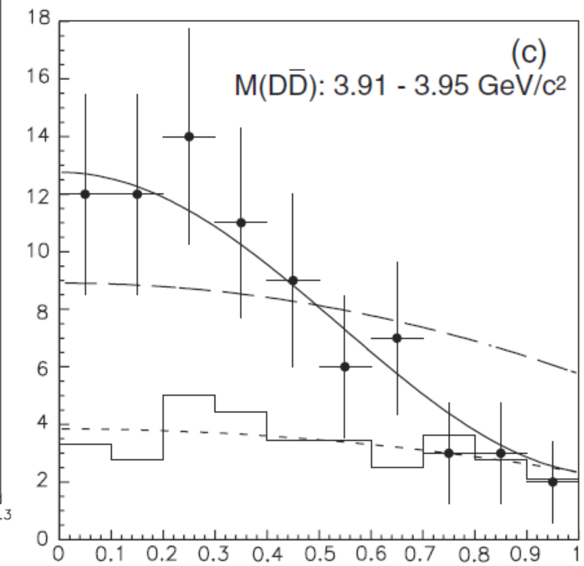
$\gamma\gamma \rightarrow \chi'_{c2} \rightarrow D\bar{D}$



“two-photon”
collisions



M(DD̄)



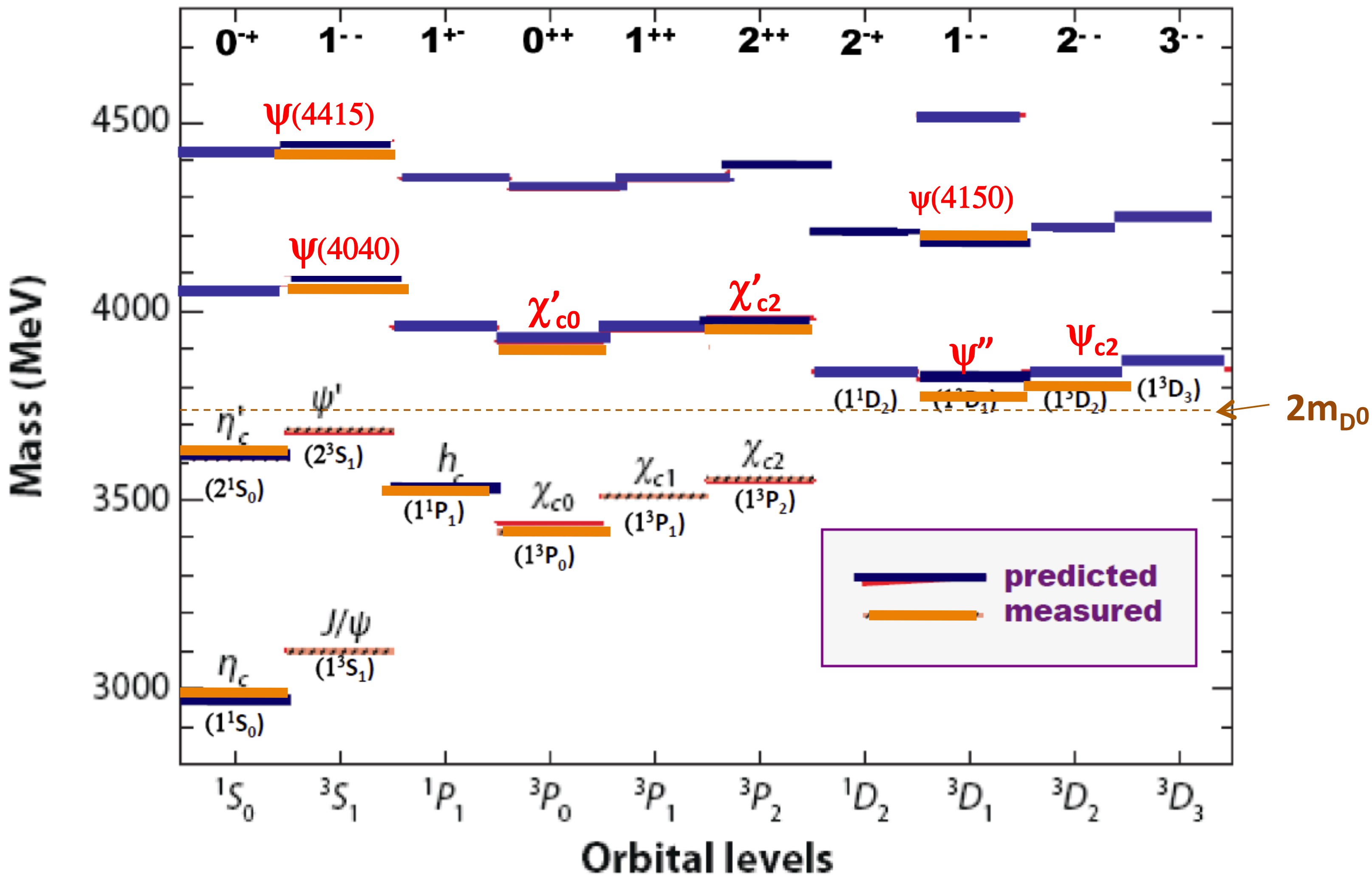
|cosθ|

results: $M(\chi'_{c2}) = 3929 \pm 5$ MeV

$\Gamma(\chi'_{c2}) = 29 \pm 10$ MeV

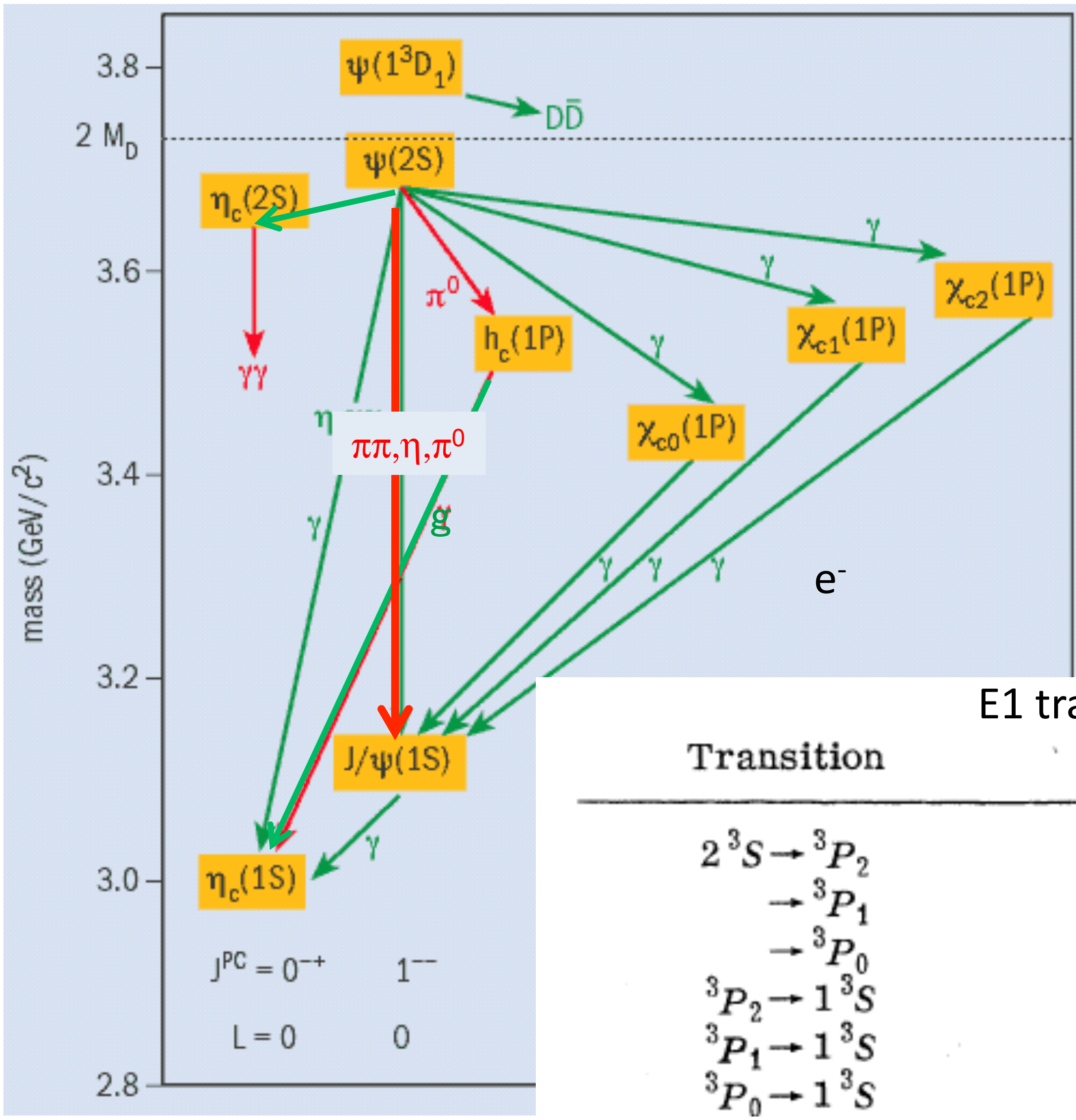
Charmonium spectrum today

Masses in pretty good agreement with theoretical expectations
-- biggest discrepancies ~ 50 MeV --



Inter-charmonium transitions

γ Transitions



$$\Gamma_{M1} = \frac{16\alpha E_\gamma^3}{27\pi\hbar^3 m_c^2 c^2}\sum_\lambda \int d\Omega_\gamma \left|\left\langle \Psi_f \left| \frac{\sin\frac{\omega_\gamma r}{2}}{\frac{\omega_\gamma r}{2}} \right| \Psi_i \right\rangle\right|^2$$

M1 transitions (Γ(keV))

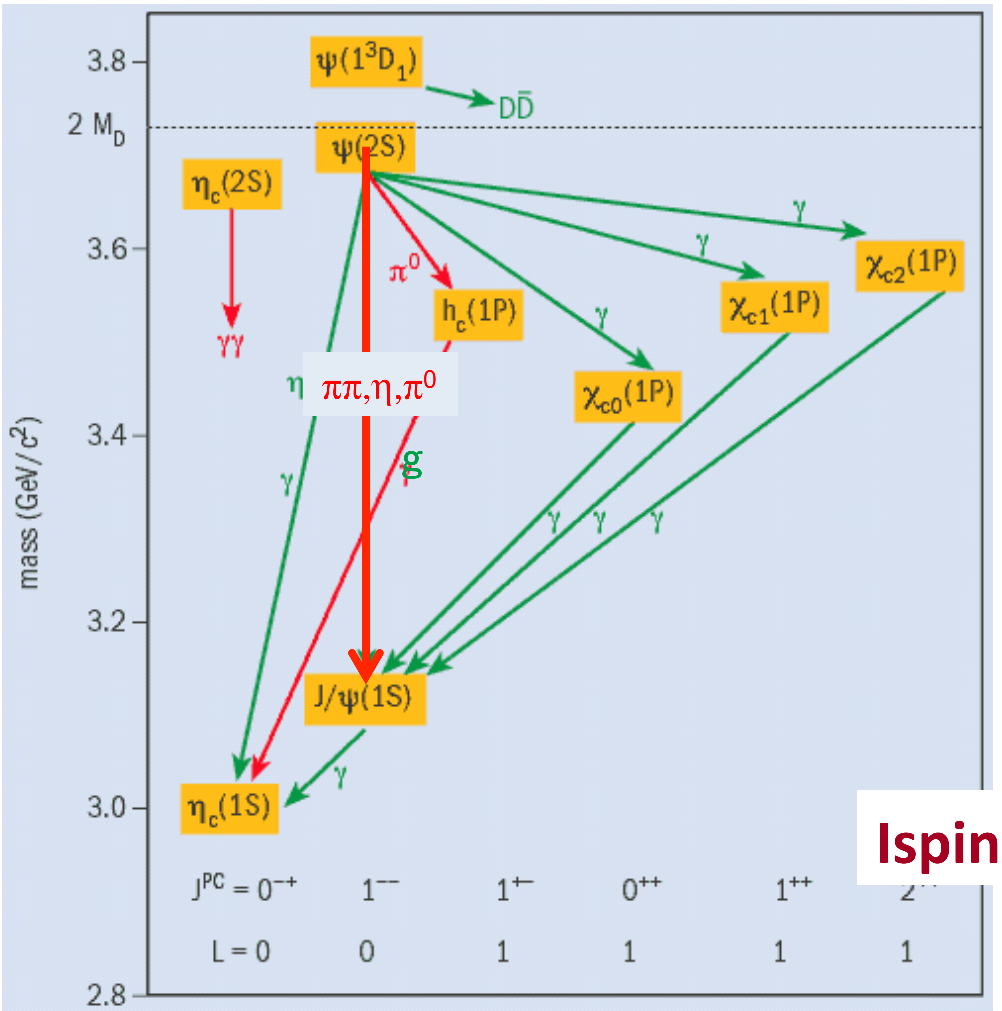
	Th.	*Expt*
$J/\psi \rightarrow \gamma\eta_c$	*2.4*	*1.6 ± 0.4*
$\psi' \rightarrow \gamma\eta_c$	*4.6*	*1.1 ± 0.2*

$$\Gamma_{E1} = \frac{\alpha E_\gamma^3}{2\pi\hbar^3 c^2}\sum_\lambda \int d\Omega_\gamma \left|\left\langle \Psi_f \left| \hat{\varepsilon}\cdot\vec{r} \right| \Psi_i \right\rangle\right|^2$$

E1 transitions

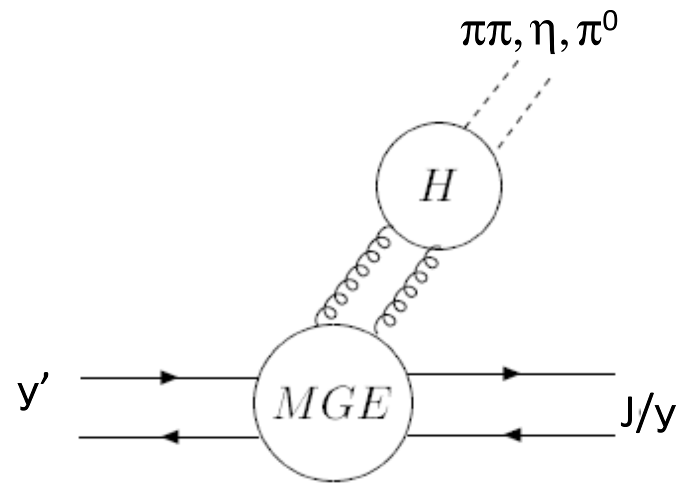
Transition	Γ_γ	Γ_γ (keV) *Th.*	*Expt*
$2\,^3S \rightarrow {}^3P_2$	$5I_1\alpha k^3$	24	27 ± 4
$\rightarrow {}^3P_1$	$3I_1\alpha k^3$	29	27 ± 3
$\rightarrow {}^3P_0$	$1I_1\alpha k^3$	26	27 ± 3
${}^3P_2 \rightarrow 1\,^3S$	$I_2\alpha k^3$	313	426 ± 51
${}^3P_1 \rightarrow 1\,^3S$	$I_2\alpha k^3$	239	291 ± 48
${}^3P_0 \rightarrow 1\,^3S$	$I_2\alpha k^3$	114	110 + 19

Hadronic transitions



$\psi' \rightarrow J/\psi$ +hadrons

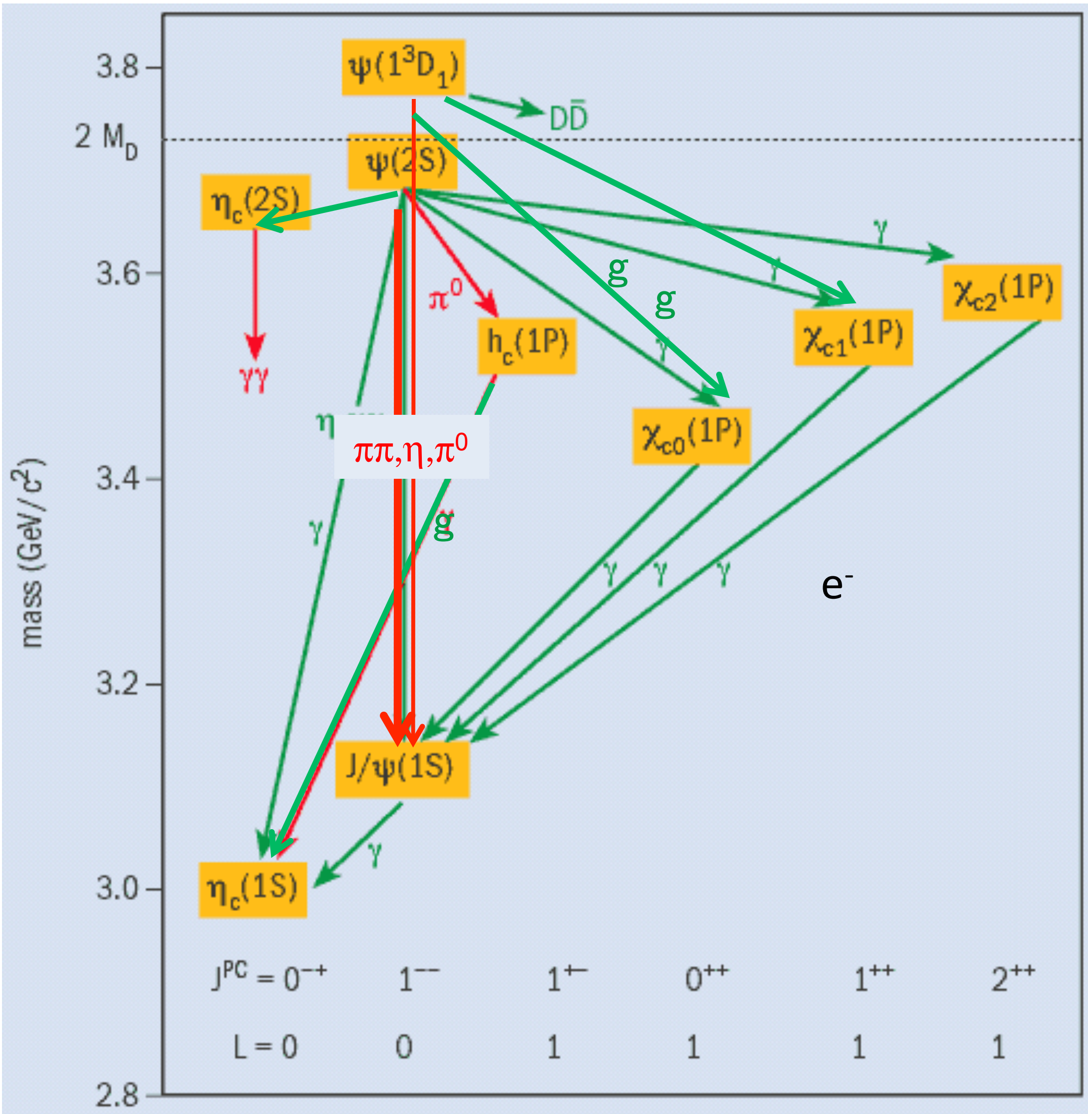
	Γ_{exp}(keV)
$\psi' \rightarrow \pi^+\pi^- J/\psi$	*88 ± 7*
$\psi' \rightarrow \eta J/\psi$	*9 ± 1*
$\psi' \rightarrow \pi^0 J/\psi$	*0.4±0.1*



Ispin violation:

$$\frac{\Gamma(\psi' \rightarrow \pi^0 J/\psi)}{\Gamma(\psi' \rightarrow \pi\pi J/\psi)} \sim 1/200$$

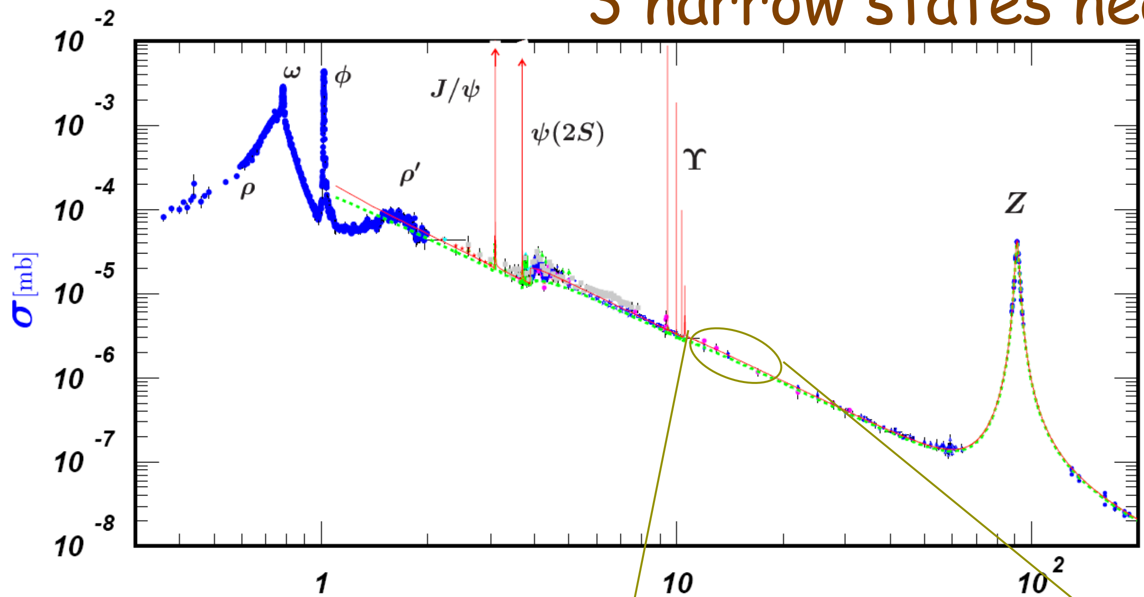
Predictions & measurements for the ψ”



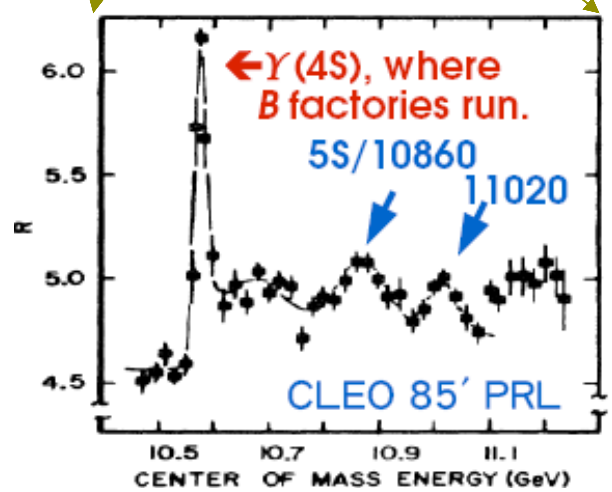
	Γ_{exp}(keV)	
	th.	*Expt*
$\psi'' \rightarrow \pi^+\pi^-\ J/\psi$	*~80*	*55 ± 15*
$\psi'' \rightarrow \gamma\chi_{c1}$	*77*	*70 ± 17*
$\psi'' \rightarrow \gamma\chi_{c0}$	*213*	*172 ±30*

Bottomonium: history repeats itself

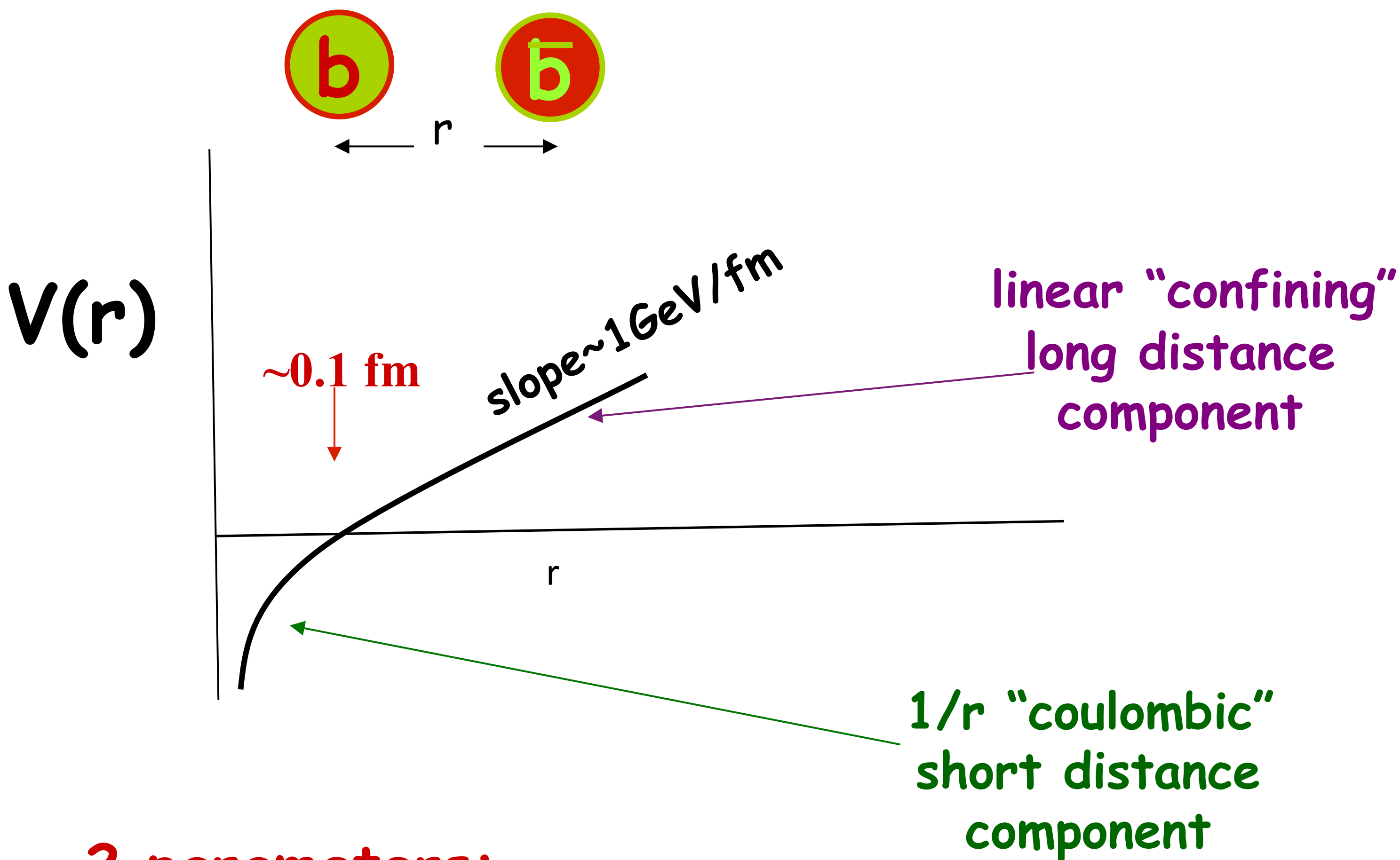
3 narrow states near 10 GeV



Plus broad states at higher masses



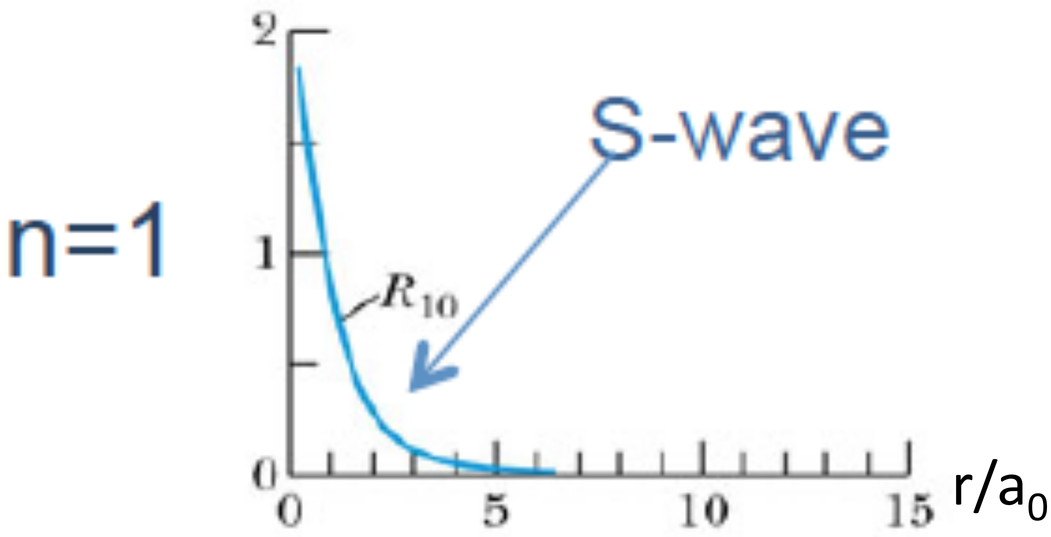
Same potential works



2 parameters:
slope & intercept

charmonium-bottomonium differences

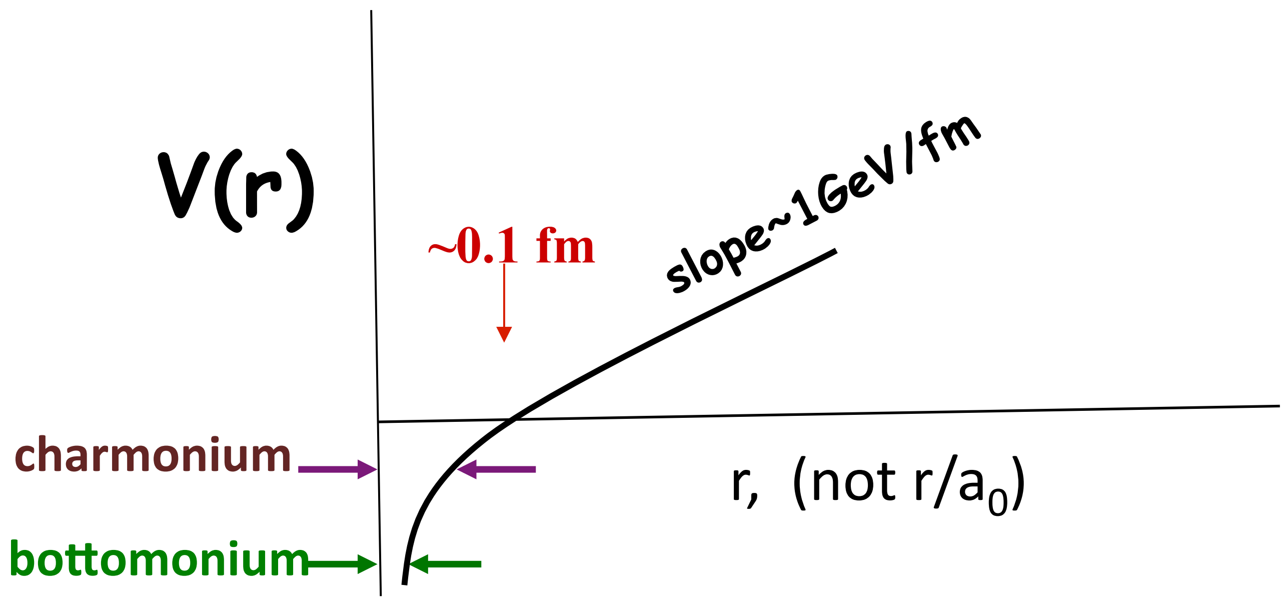
Ground-state Radial wave functions ($R_{n\ell}$)



$$a_0 = \text{"Bohr radius"} \propto 1/m_Q$$

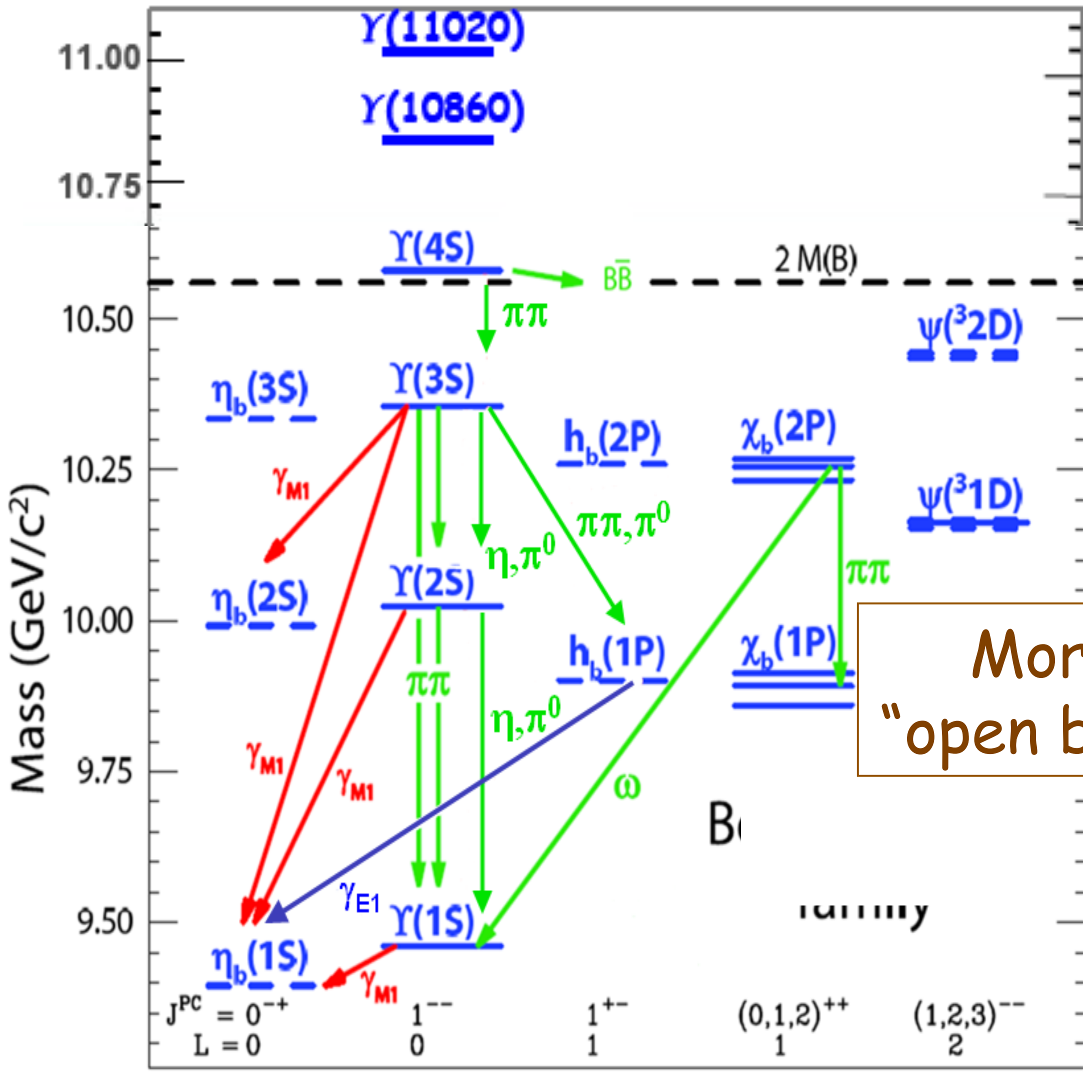
	$c\bar{c}$	$b\bar{b}$
m_Q	~1.5 GeV	~4.5 GeV
$\langle R_{rms} \rangle$	~0.15 fm	~0.05 fm

Bottomonium probes deeper (stronger) region of the potential



Bottomonium is more tightly bound than charmonium

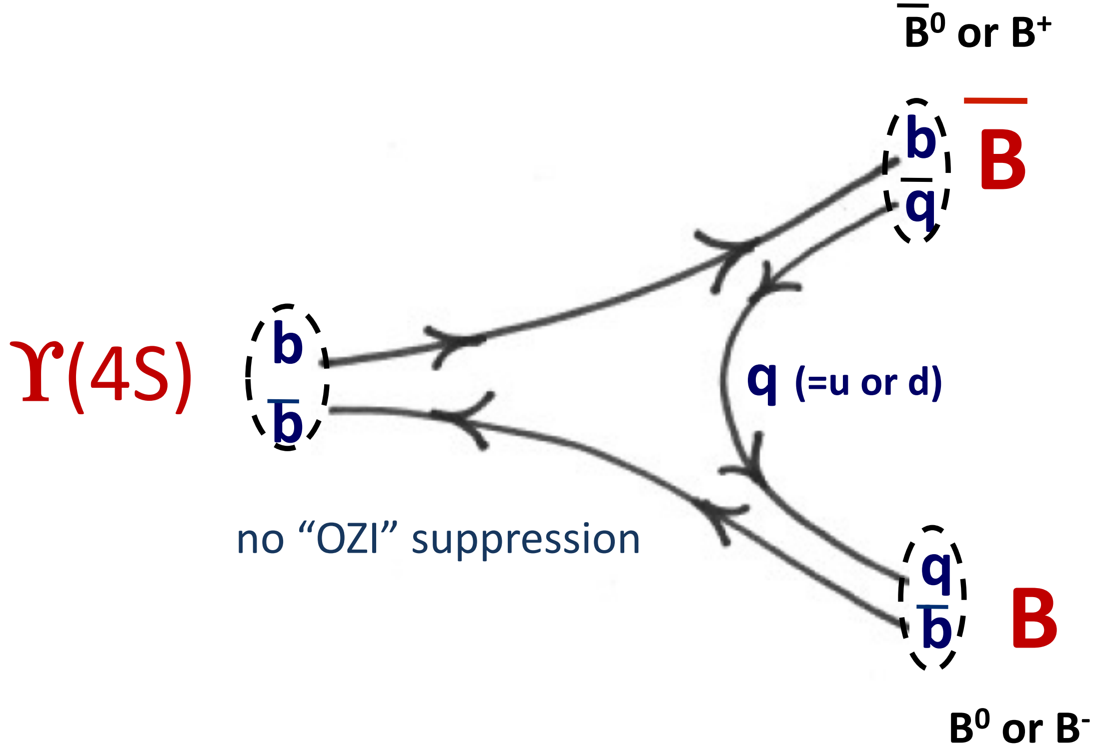
Bottomonium spectrum

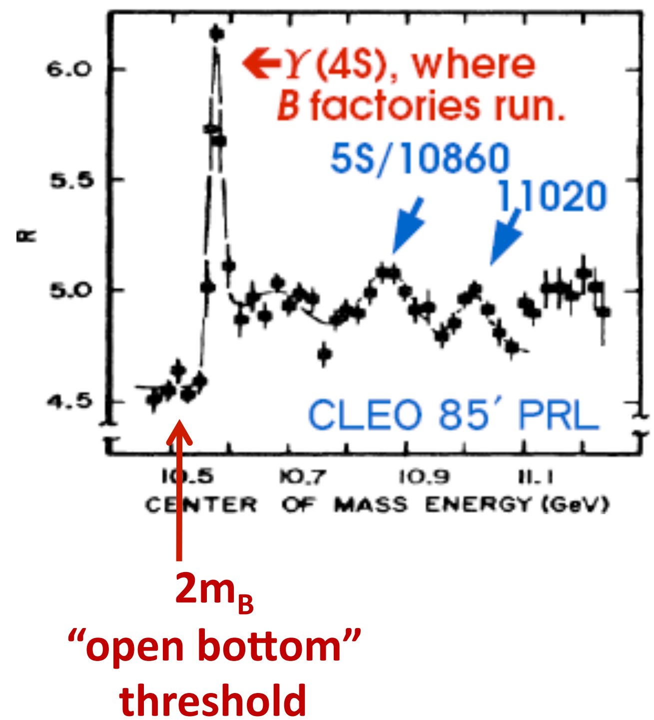


$2M_B = 10.56$ GeV

More states below "open bottom" threshold

"Fall apart" decays to "B" mesons



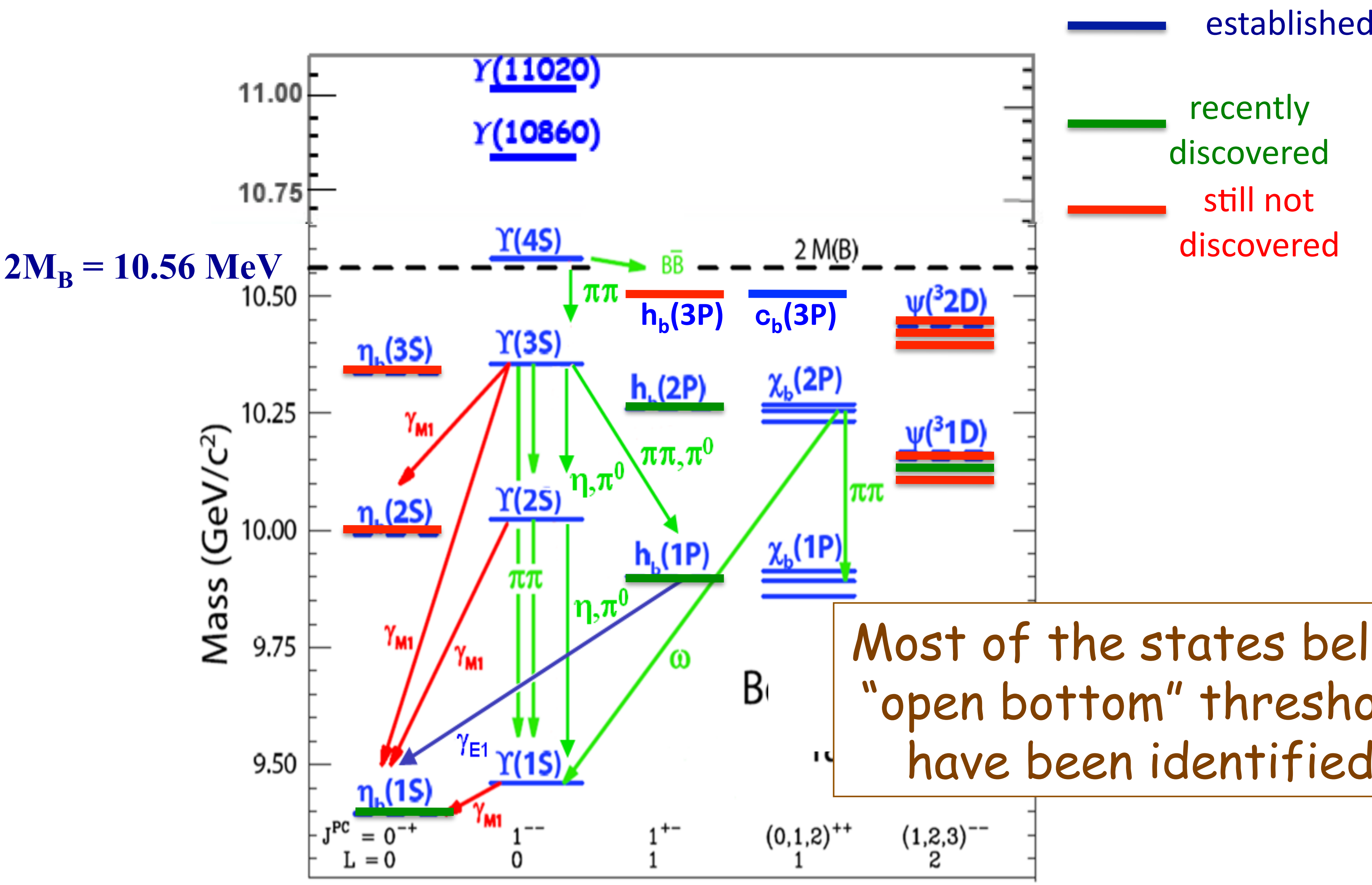


($M_{\Upsilon'(4S)}$=10.58 GeV) ——

- - - - ← $2m_B$=10.56 GeV

($M_{\Upsilon'(3S)}$=10.36 GeV) ——

Bottomonium spectrum 2011



Most of the states below "open bottom" threshold have been identified

Summary (lecture 4)

- The quarkonium spectra are the strongest evidence that hadrons are composed of spin=1/2 constituent particles

- All of the charmonium states below the $M=2m_D$ "open charm" threshold have been found
  - -most of the bottomonium states below $M=2m_B$ have been identified

- Above the $M=2m_D$ threshold, most of the 1^{--} states, but only three of the others (the χ_{c0}' , χ_{c2}' & ψ_{c2}) have been discovered.

- The masses of the assigned states match theory predictions
  - -variations are less than ~50 MeV

- Transitions between quarkonium states are in reasonably good agreement with theoretical expectations

General comments

- The charmed and bottom "quarkonium systems" are relatively simple and reasonably well understood.
  - The "hydrogen atoms" of QCD.

- Let's try to use them to search for new and unpredicted phenomena.
  - If we find a meson that contains a $c\bar{c}$ ($b\bar{b}$) pair but doesn't fit into one of the remaining unassigned states, we have a candidate for an *exotic* hadron, the subject of the next lecture