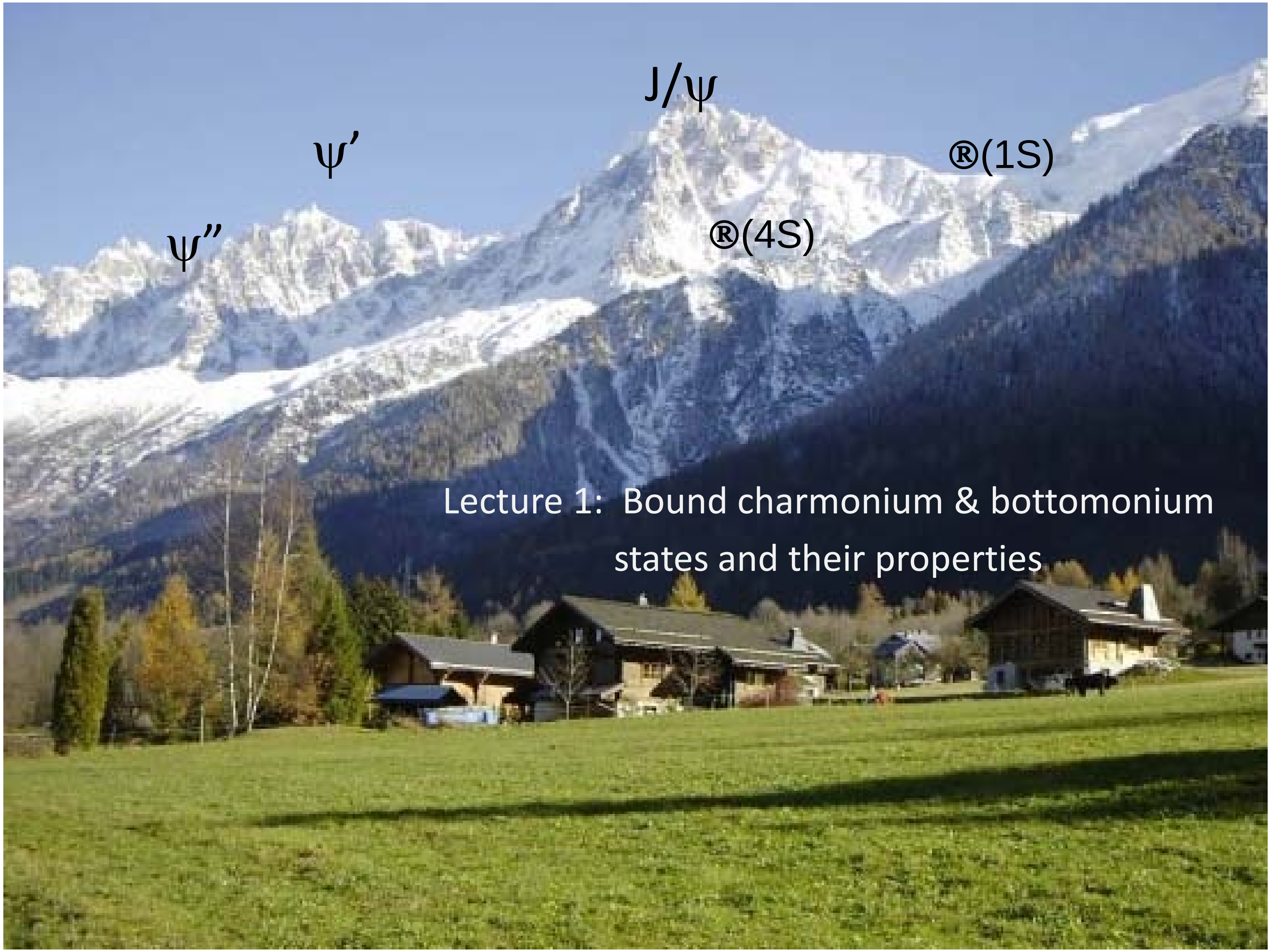
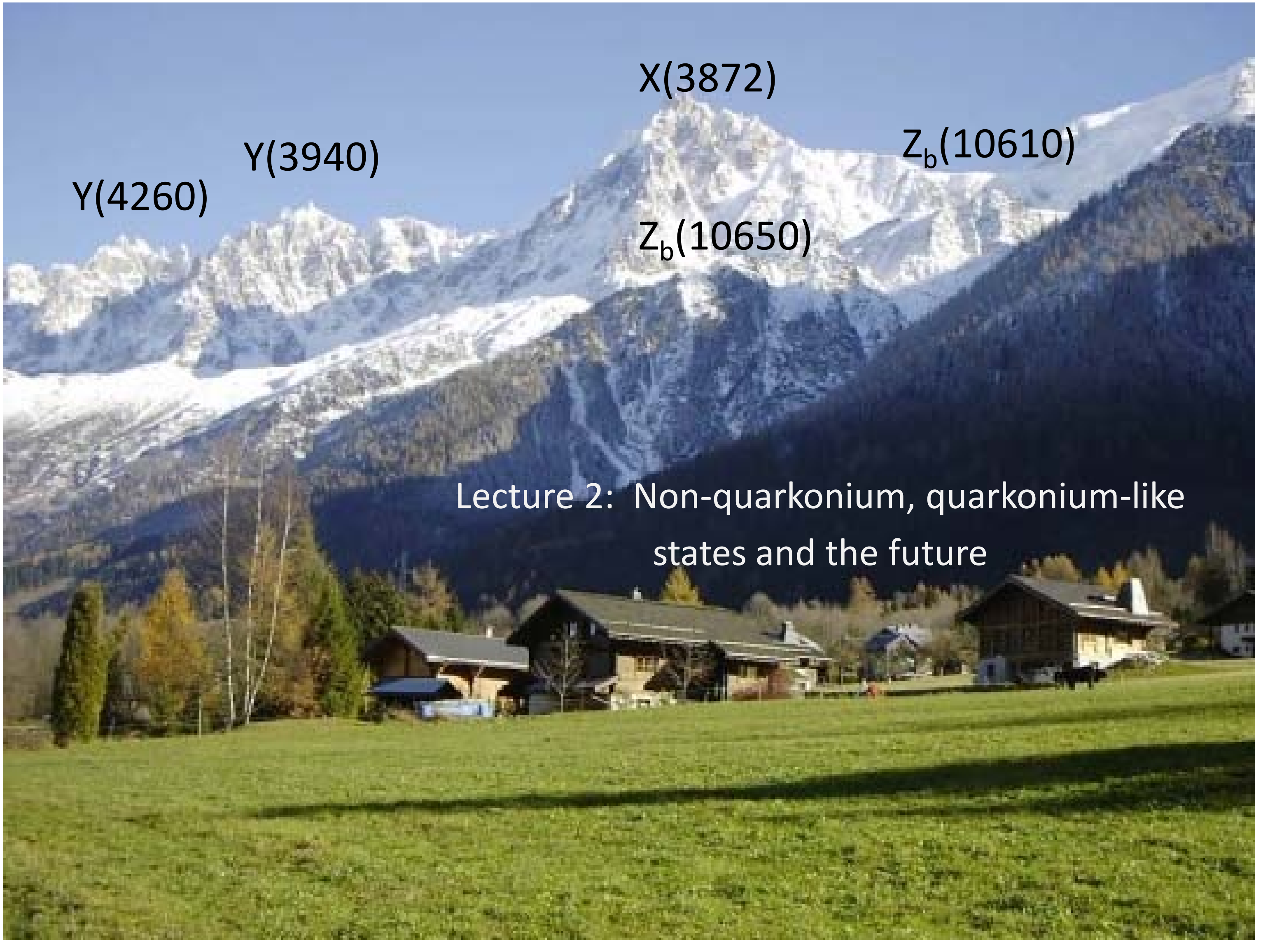
Quarkonium
experimental overview I

France-Asia Particle Physics School, Les Houches, FRANCE
October 11-12, 2011

Outline


J/ψ
ψ'
®(1S)
ψ''
®(4S)
Lecture 1: Bound charmonium & bottomonium states and their properties

Outline


X(3872)
Y(3940)
Y(4260)
Z_b(10610)
Z_b(10650)
Lecture 2: Non-quarkonium, quarkonium-like
states and the future

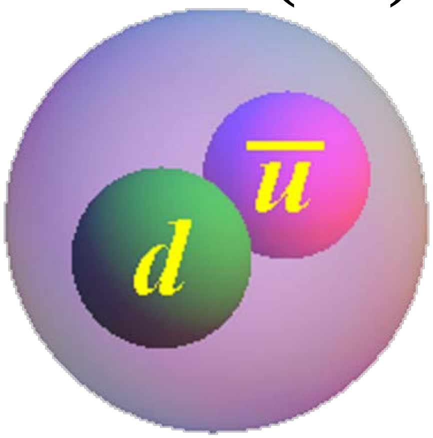
Lecture 1

Bound charmonium & bottomonium states and their properties

Constituent Quark Model

1964 The model was proposed independently by Gell-Mann and Zweig
Three fundamental building blocks 1960's $(p,n,\lambda) \Rightarrow$ 1970's (u,d,s)

$$\pi^- = (d\bar{u})$$



mesons are bound states of a of quark and anti-quark:
Can make up "wave functions" by combining quarks:

$$\pi^+ = u\bar{d}, \quad \pi^- = d\bar{u}, \quad \pi^o = \frac{1}{\sqrt{2}}(u\bar{u} - d\,\bar{d}), \quad k^+ = d\bar{s}, \quad k^o = d\bar{s}$$

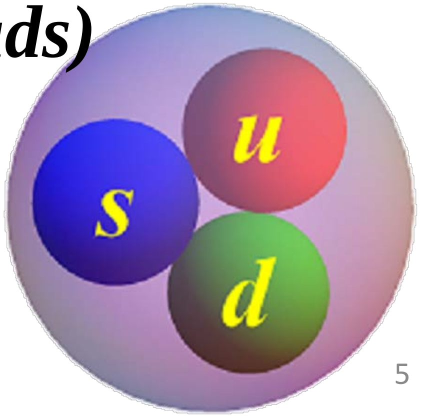
baryons are bound state of 3 quarks:

proton = (uud), neutron = (udd), Λ= (uds)

anti-baryons are bound states of 3 anti-quarks:

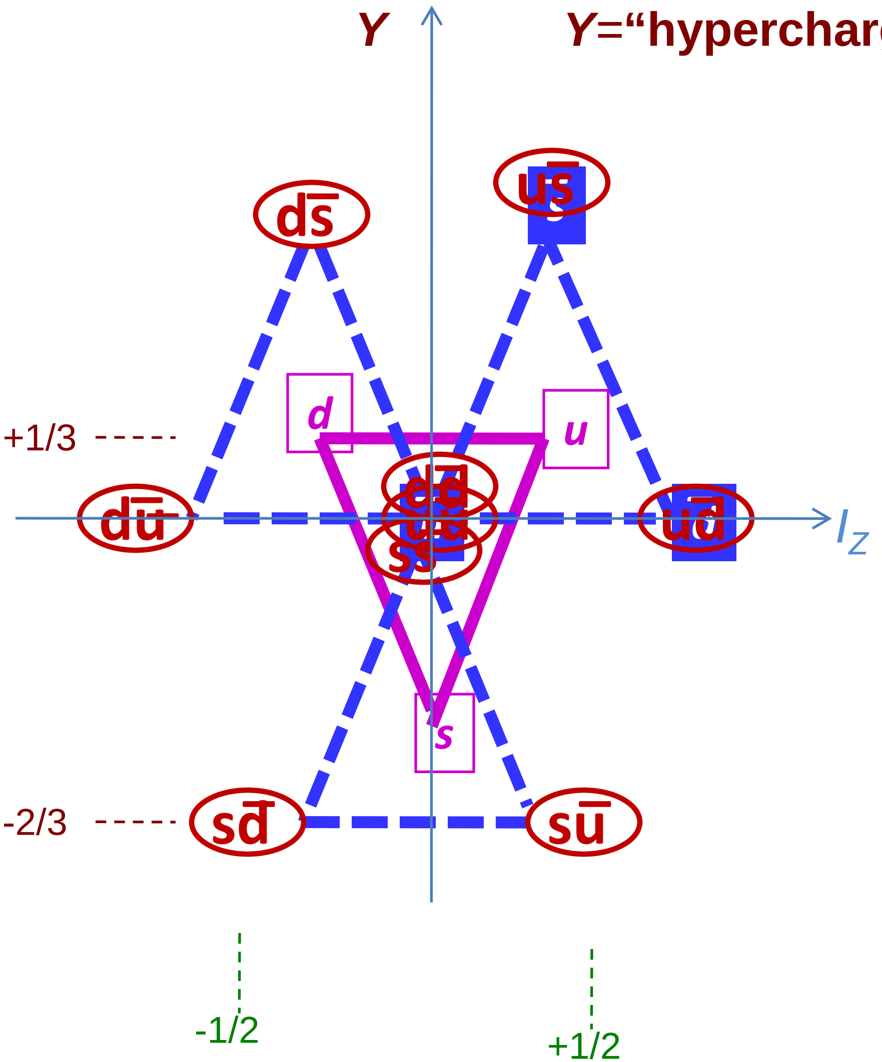
$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

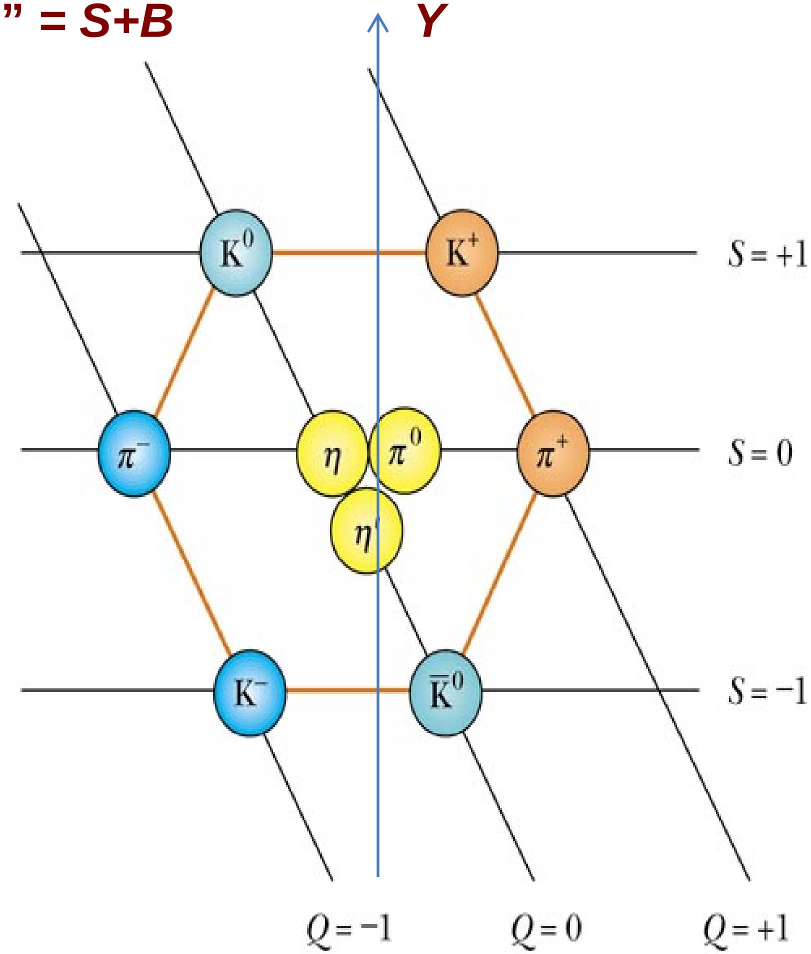
***Λ* = (uds)**



Make mesons from quark-antiquark

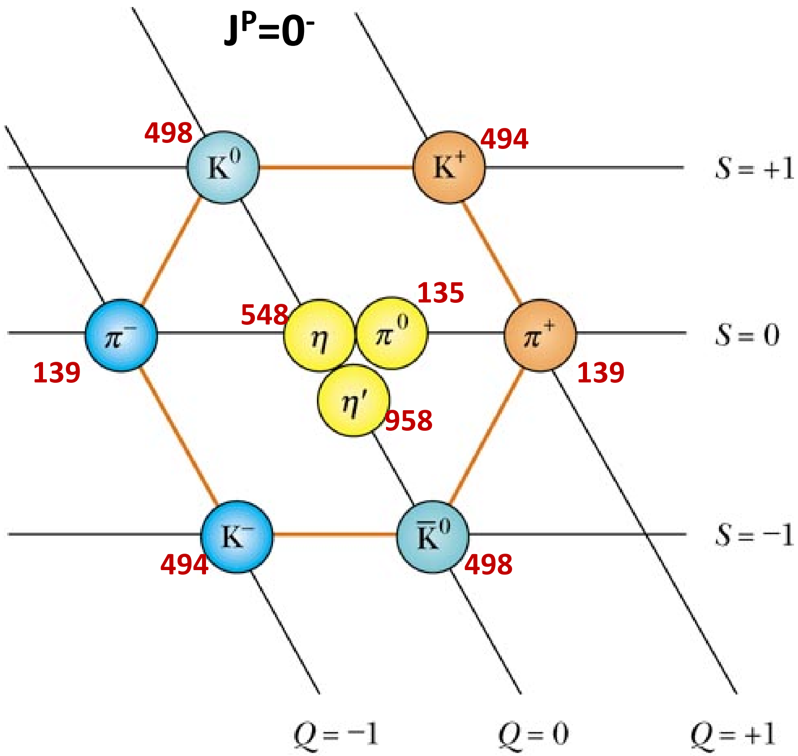
Y="hypercharge" = $S+B$

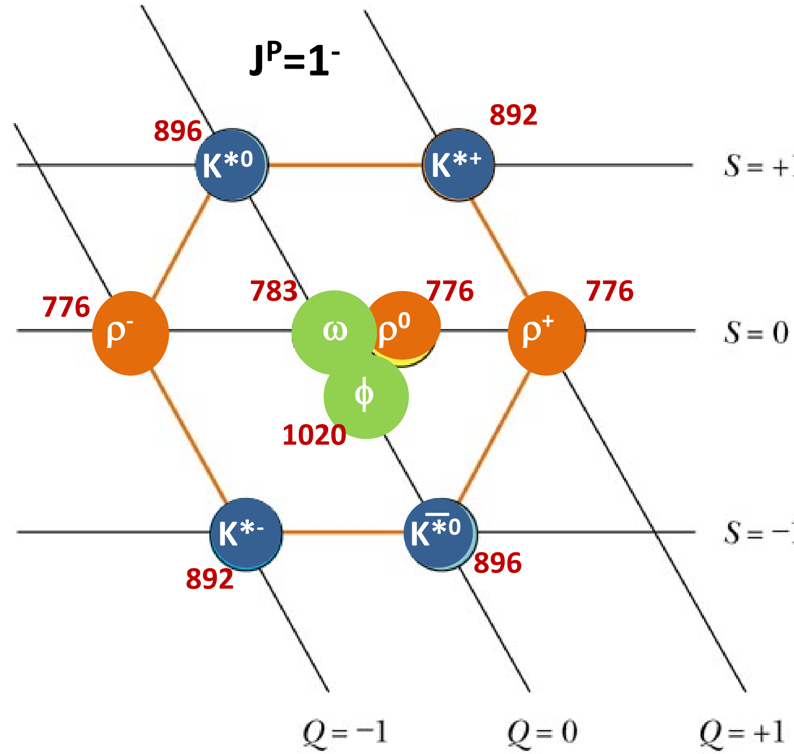




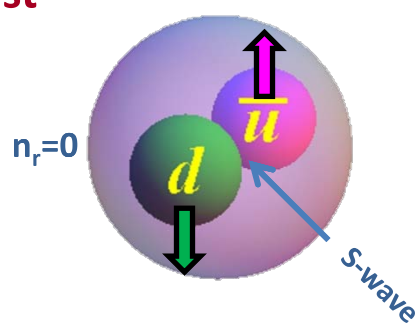
$$3 \otimes \overline{3} = 1 \oplus 8$$

Ground state mesons (today)

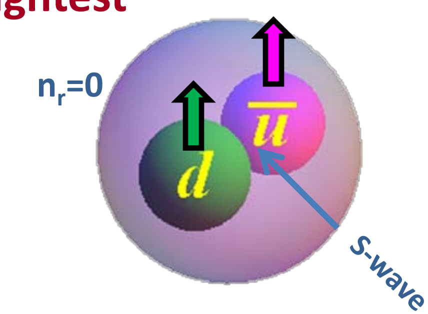




(π^+,π^0,π^-)=lightest

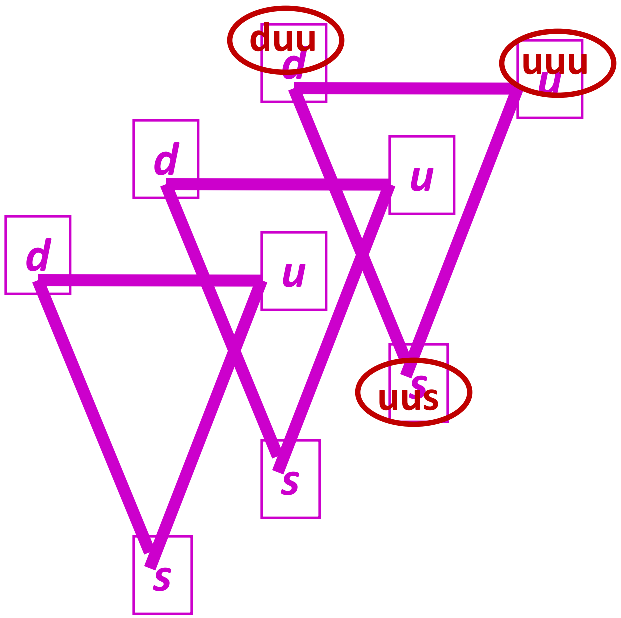


(ρ^+,ρ^0,ρ^-)=lightest



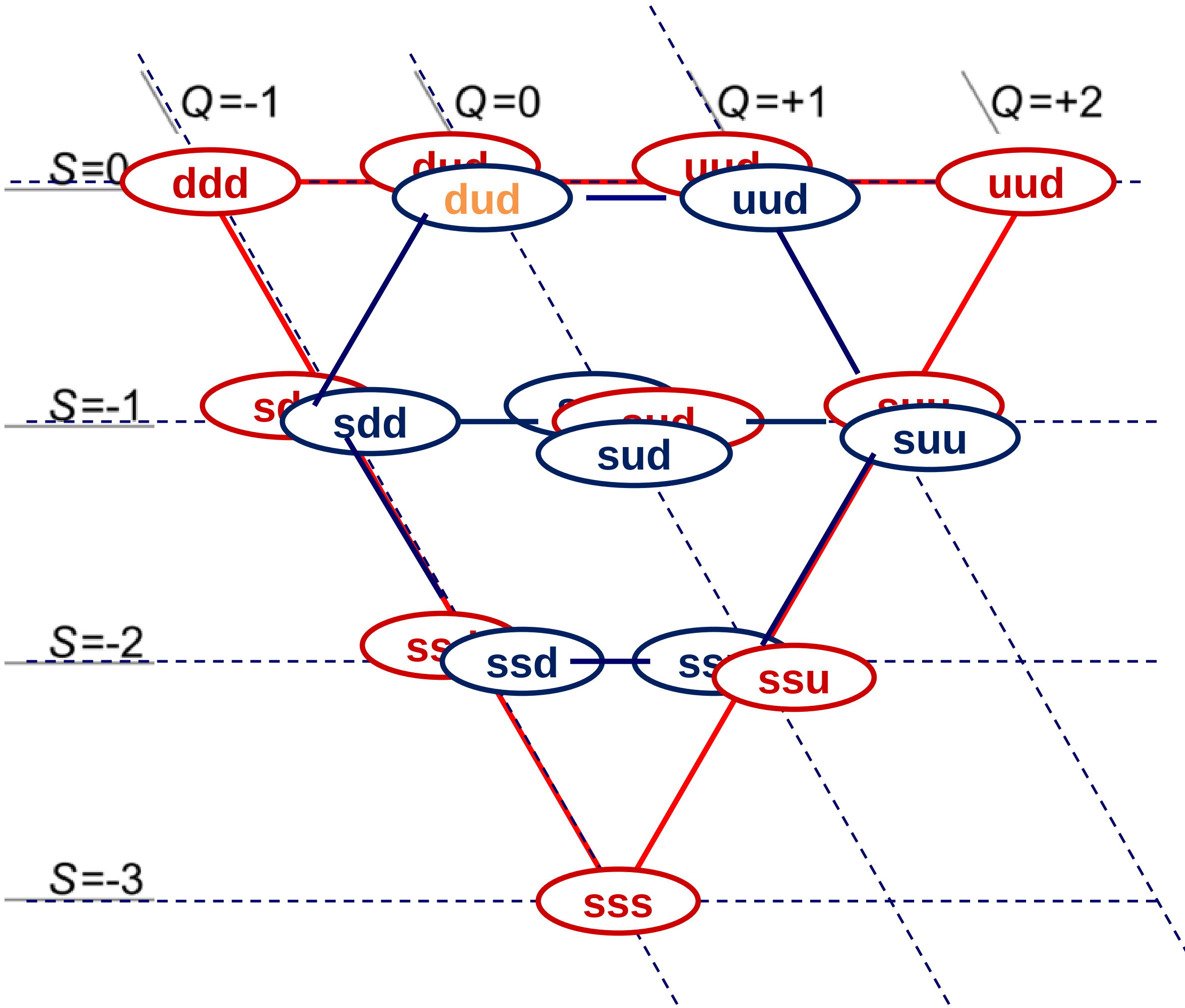
HW:

Construct baryon octet and decuplet combinations of three uds triplets



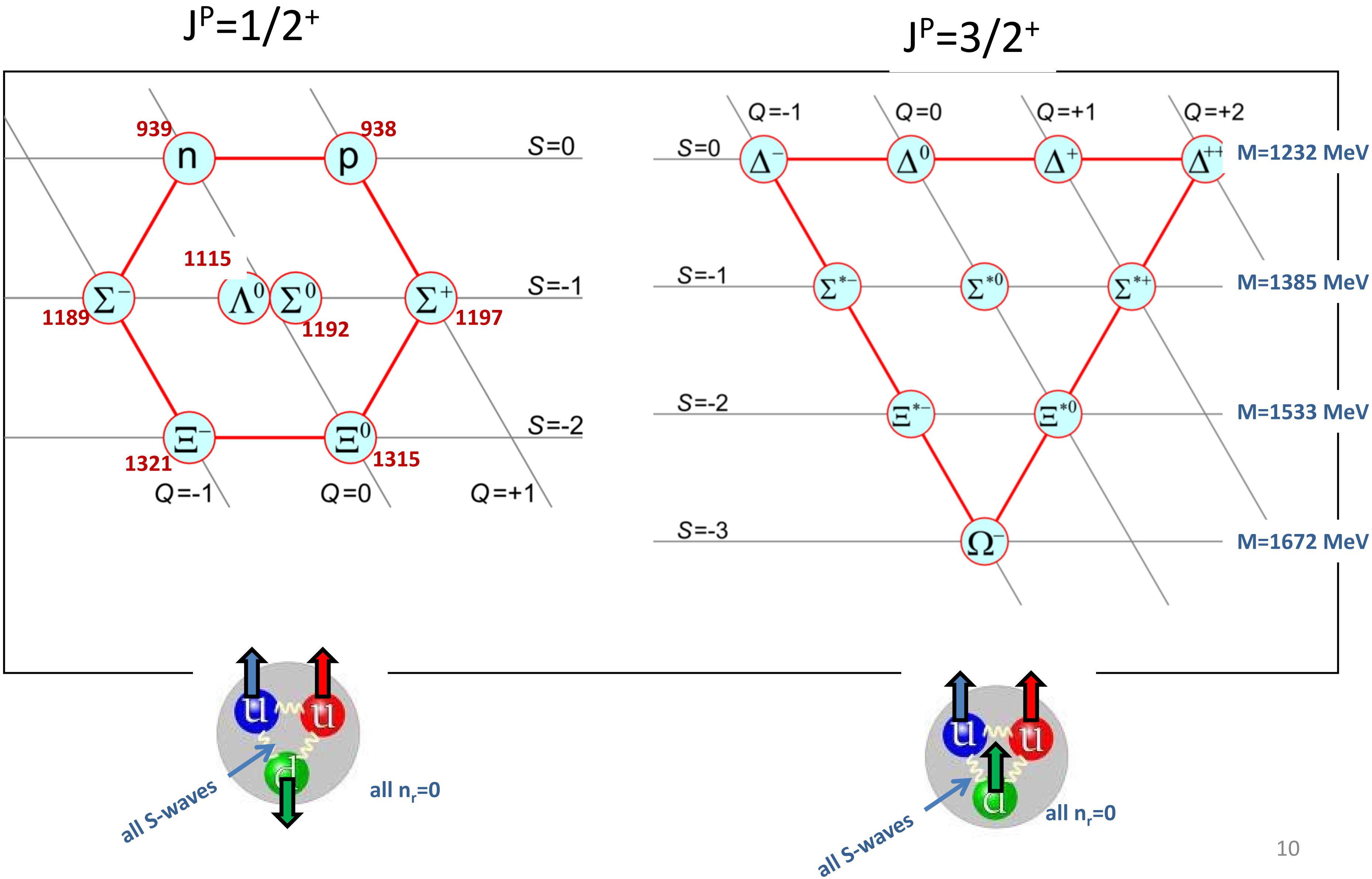
Finish the procedure

Answer ➔ 2(8-tet)s + 10-plet ⊕ singlet



$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

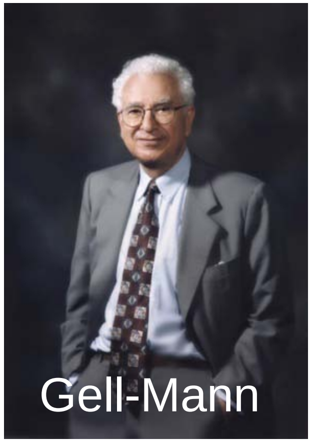
Ground state Baryons



Are quarks real objects? or just mathematical mnemonics?

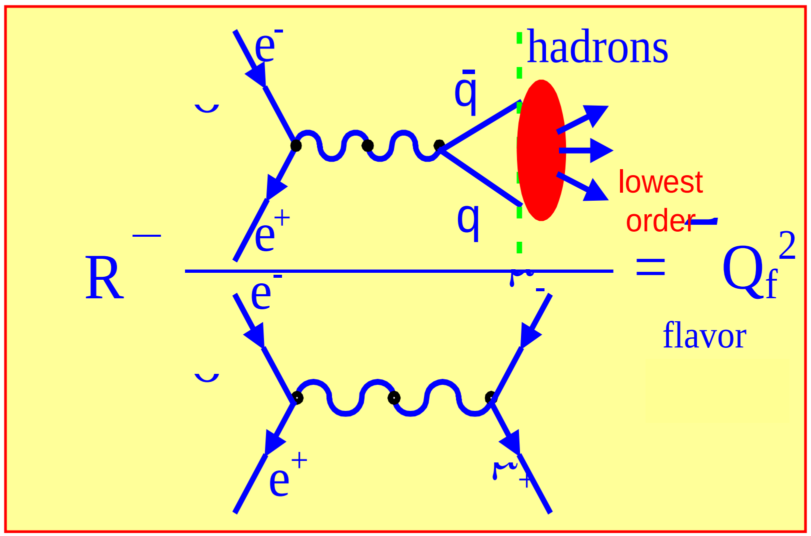
助记符 기억하는

Are quarks actually real objects?" Gell-Mann asked. "My experimental friends are making a search for them in all sorts of places -- in high-energy cosmic ray reactions and elsewhere. A quark, being fractionally charged, cannot decay into anything but a fractionally charged object because of the conservation law of electric charge. Finally, you get to the lowest state that is fractionally charged, and it can't decay. So if real quarks exist, there is an absolutely stable quark. Therefore, if any were ever made, some are lying around the earth."
But since no one has yet found a quark, Gell-Mann concluded that we must face the likelihood that quarks are not real.



Nobel Prize 1969

A prediction of the quark model:

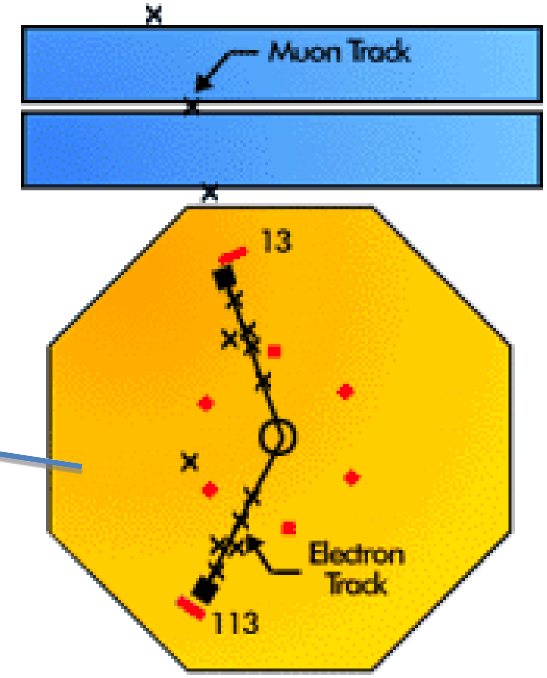


$$= \left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 = 2/3$$

Mark I detector

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

muon identifier



tracking chamber

R data in June 1974

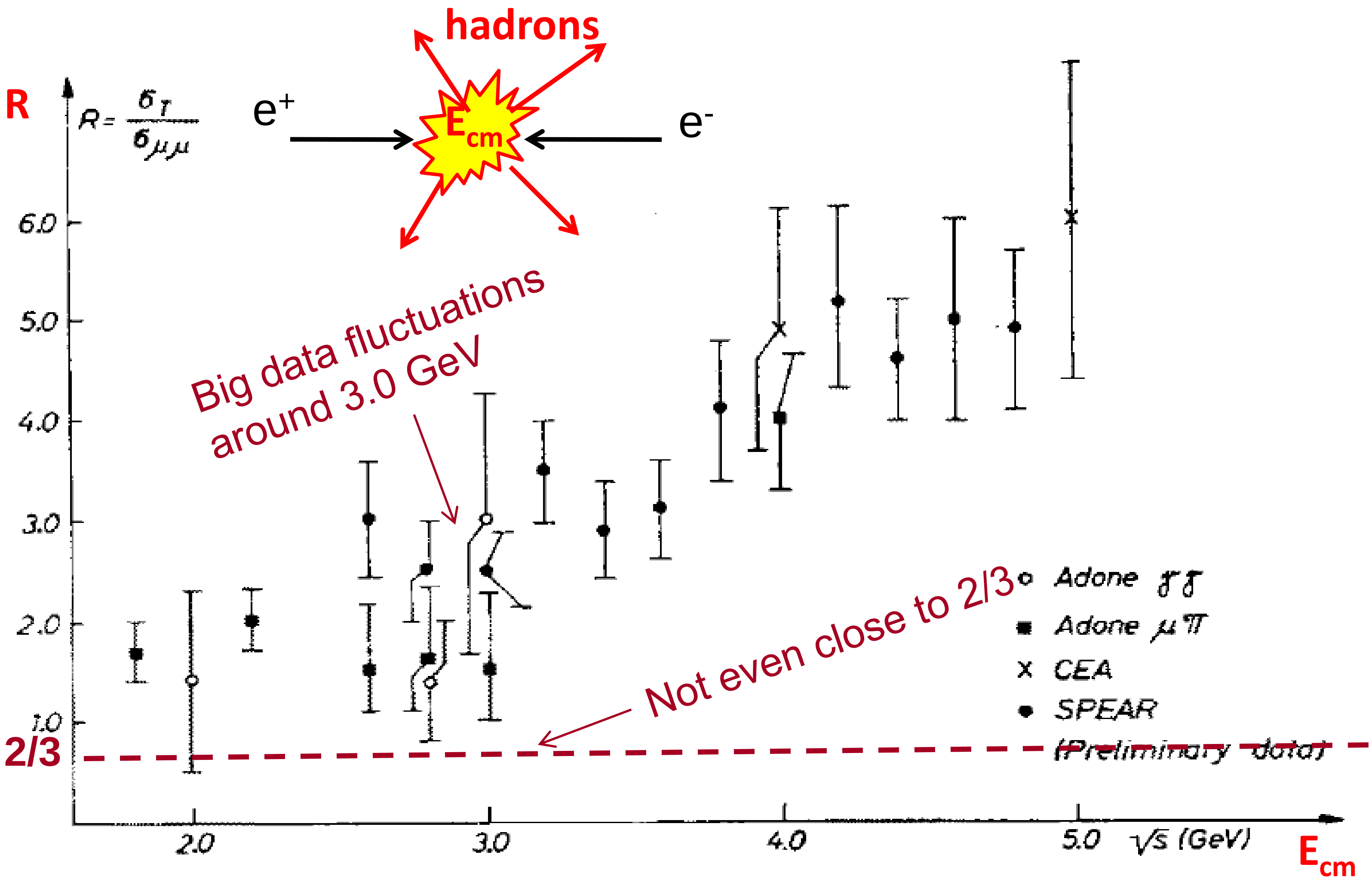
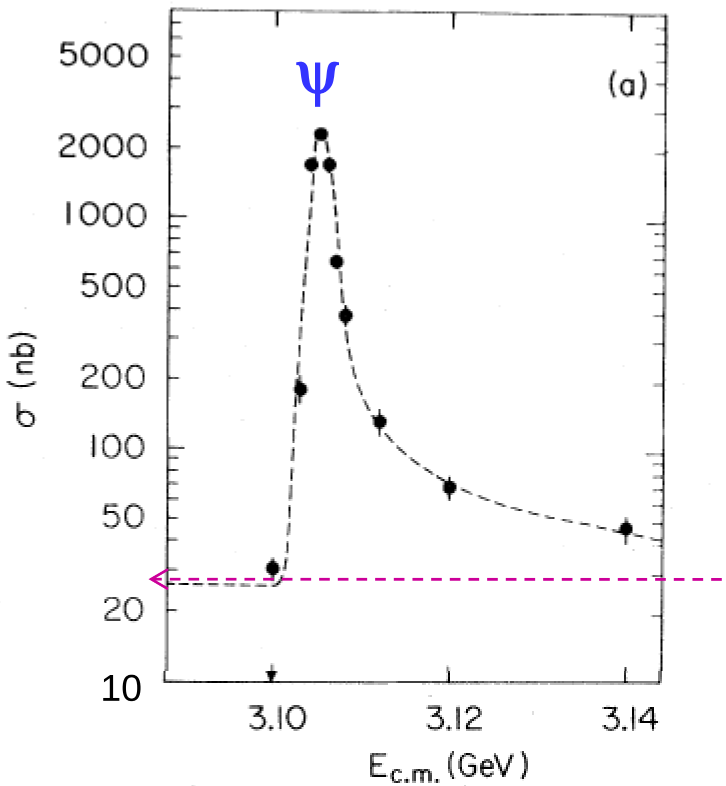


Fig. 35. $R = \sigma_{\text{hadrons, total}} / \sigma_{\mu\bar{\mu}}$ vs E

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

after a fine energy scan near 3 GeV:

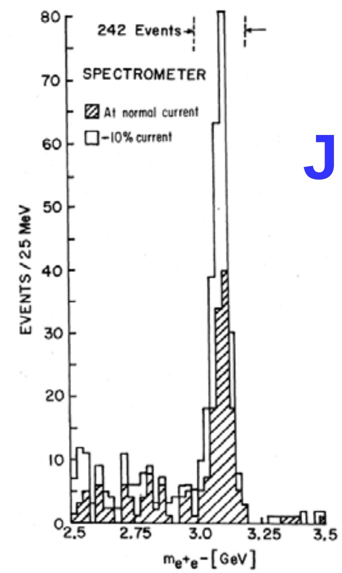
A huge, narrow peak near 3.1 GeV



R=2.2
>>2/3

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

Also seen in pN→e^+e^-X
at Brookhaven

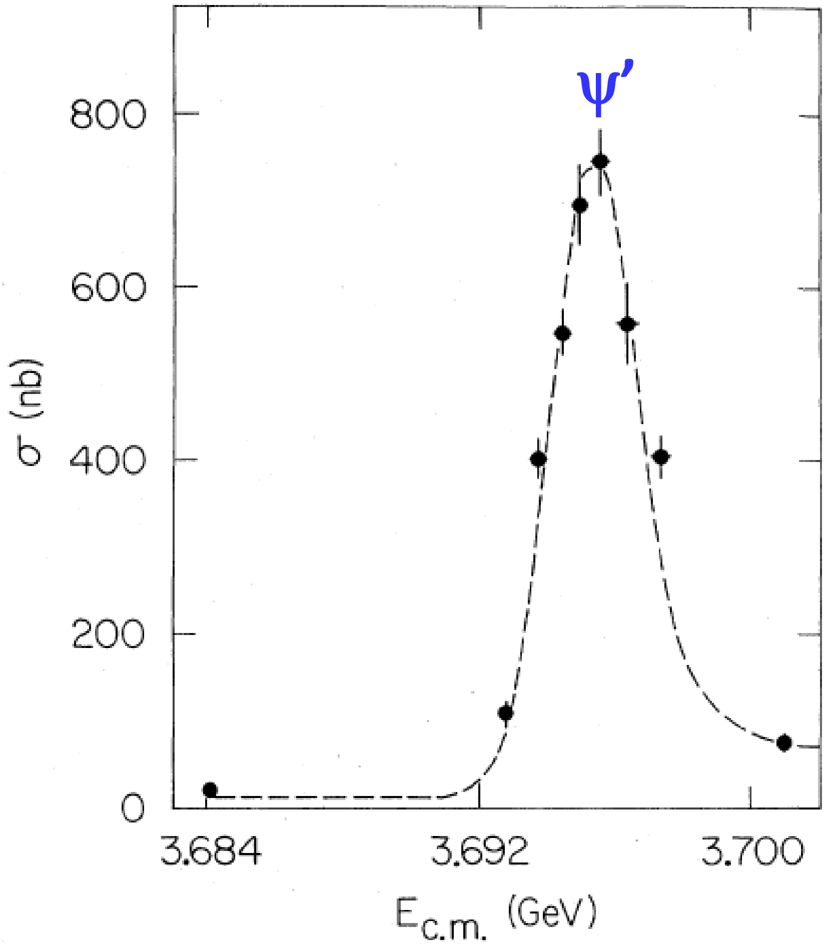


M(e^+e^-)

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

The "J/ψ" meson

Another peak near 3.69 GeV



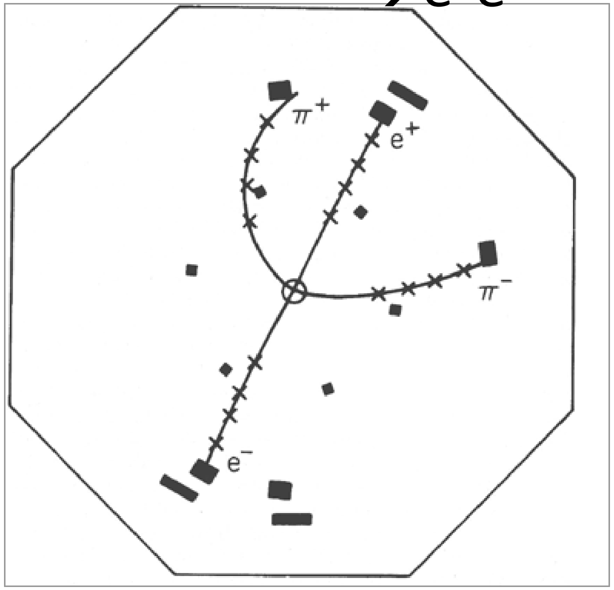
G.S. Abrams et al., PRL 33, 1453 (1974)

← About 2 weeks later

Why J/ψ?

Event in Mark I

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



Mark-I detector

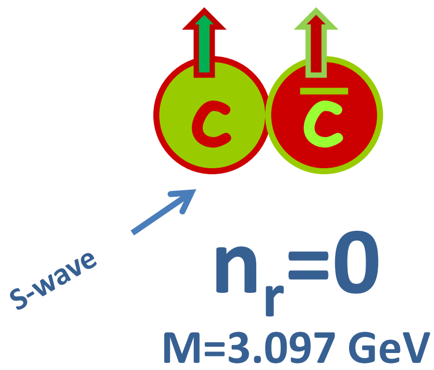
Group leader of the Brookhaven expt

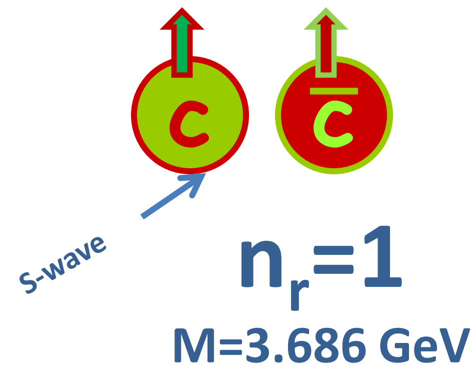
Samuel C.C. Ting

Chinese character for Ting: 丁

Interpretation of J/ψ and ψ’

charmed-quark anticharmed-quark mesons





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

before 1974

after 1974

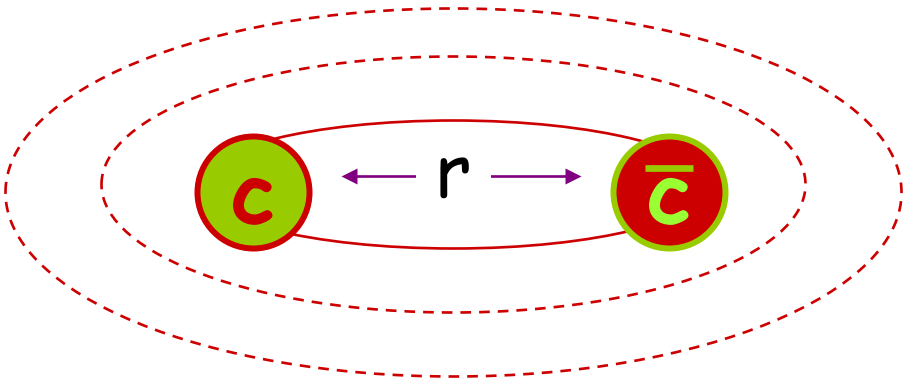
$$\begin{pmatrix} u^{+2/3} \\ d^{-1/3} \end{pmatrix} \begin{pmatrix} ?^{+2/3} \\ s^{-1/3} \end{pmatrix}$$

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

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

Charmonium

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

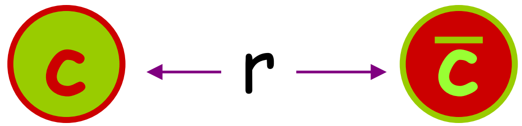


c-quarks are heavy: $m_c \sim 1.5$ GeV $\approx 2m_p$

velocities small: $v/c \sim 1/4$

non-relativistic, undergraduate-level QM applies

QM of $c\bar{c}$ mesons

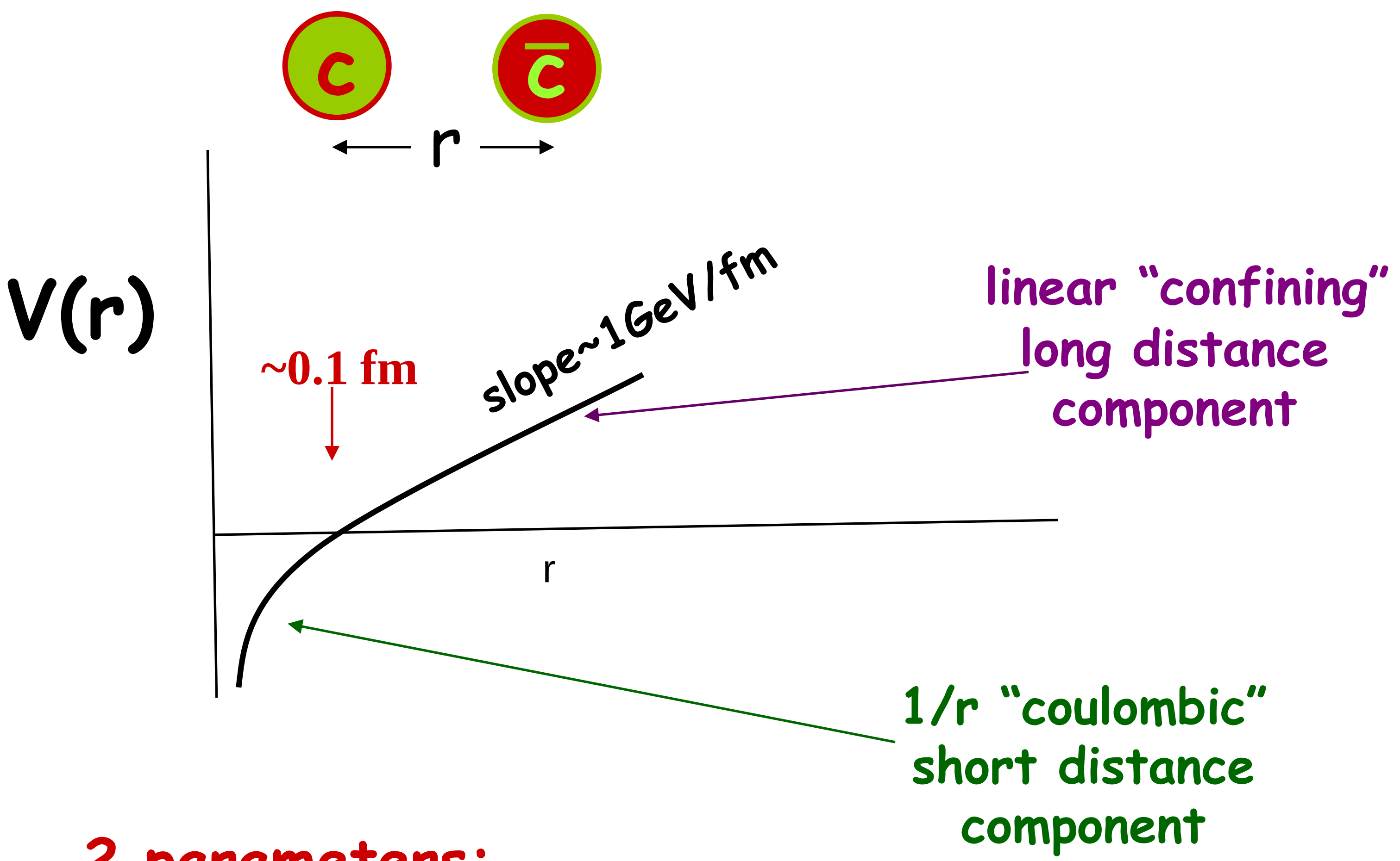


$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$

What is V(r) ??

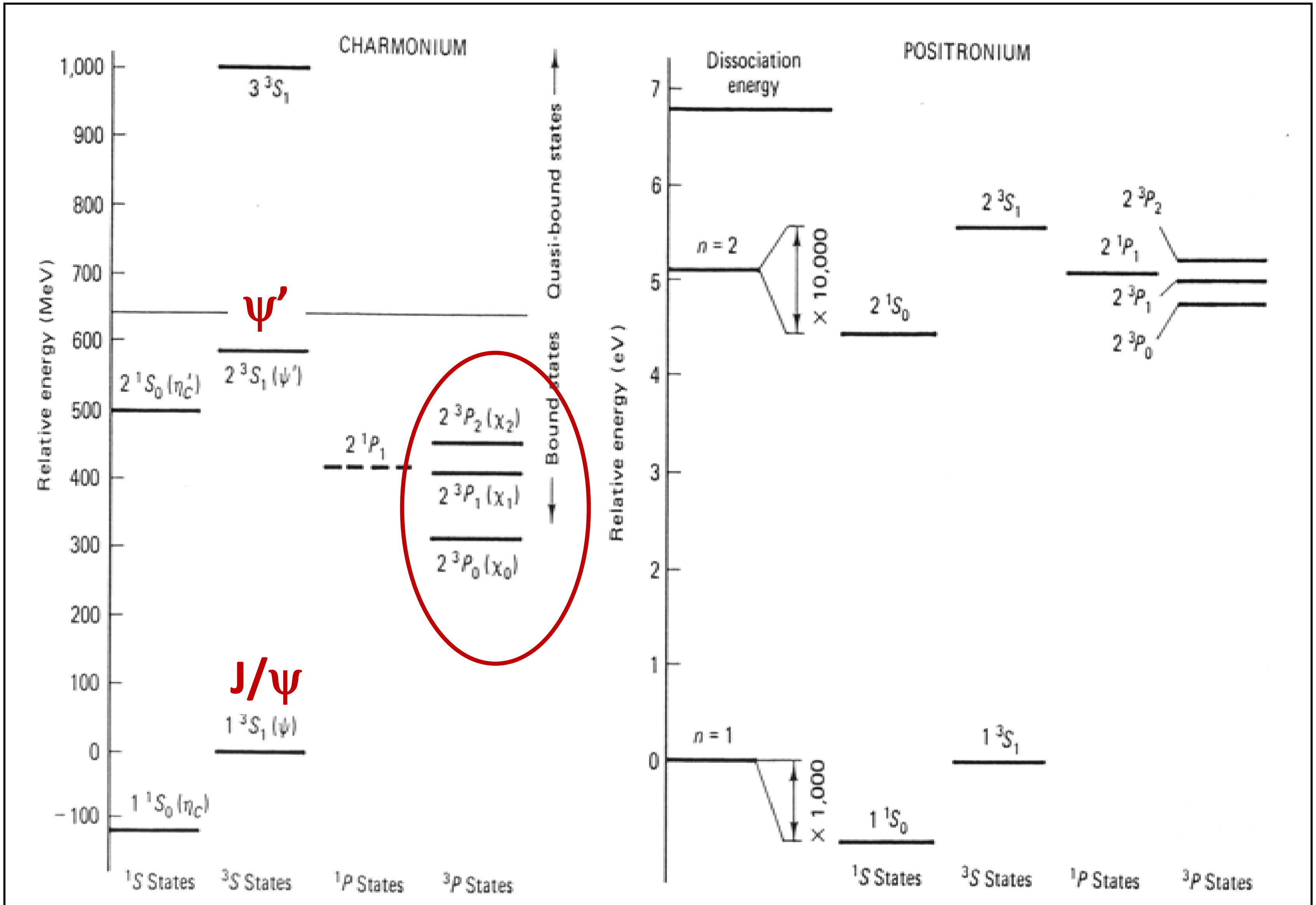
"derive" from QCD

"Cornell" potential

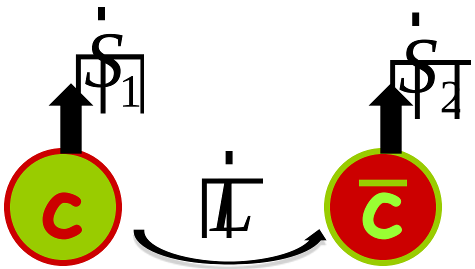


2 parameters:
slope & intercept

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



The “ABC’s” of charmonium mesons



J^{PC} quantum numbers

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

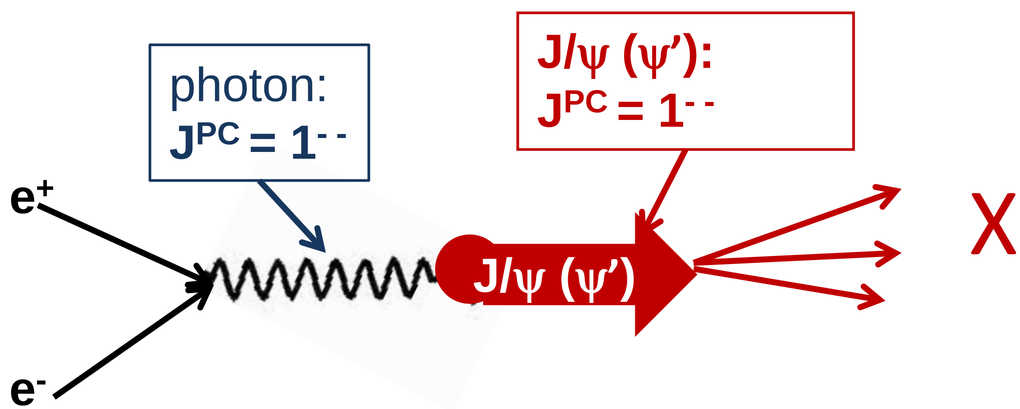
S=1 ➔ triplet of state
S=0 ➔ singlet

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

Parity (x,y,z) ↔ (-x,-y,-z)

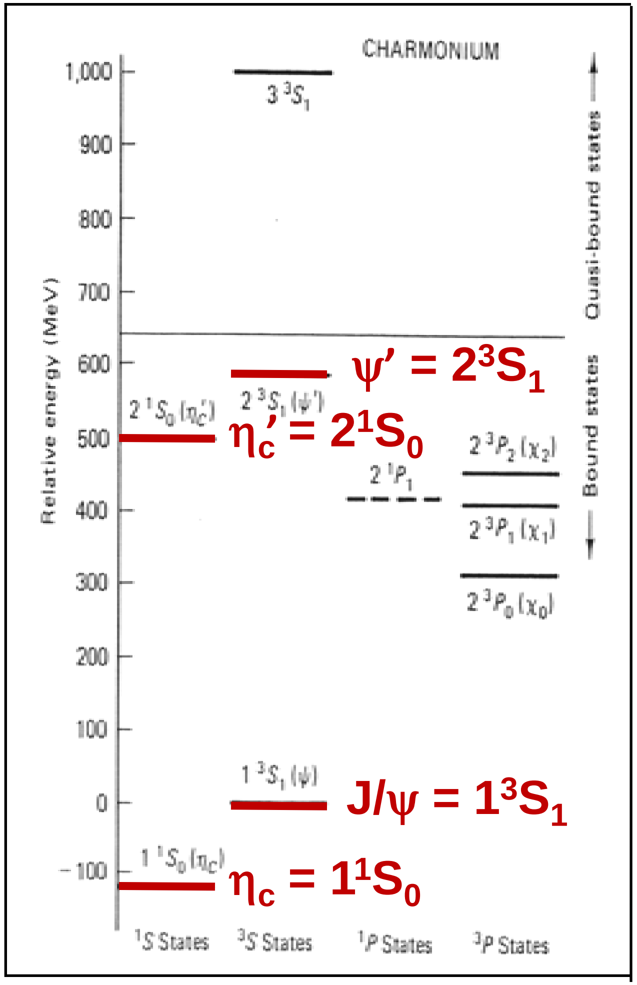
$$C = (-1)^{L+S}$$

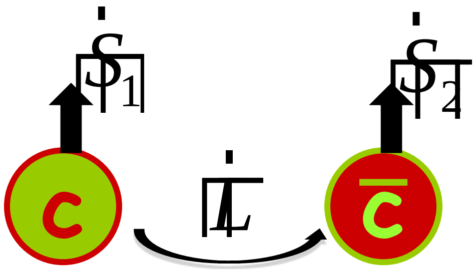
C-Parity quark ↔ antiquark



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.

$$n\,^{(2S+1)}L_J$$

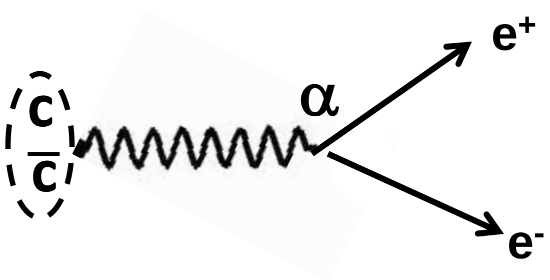
n=radial quant. nmbr

L= S, P, D, F, …
0, 1, 2, 3, …

ABC's part III

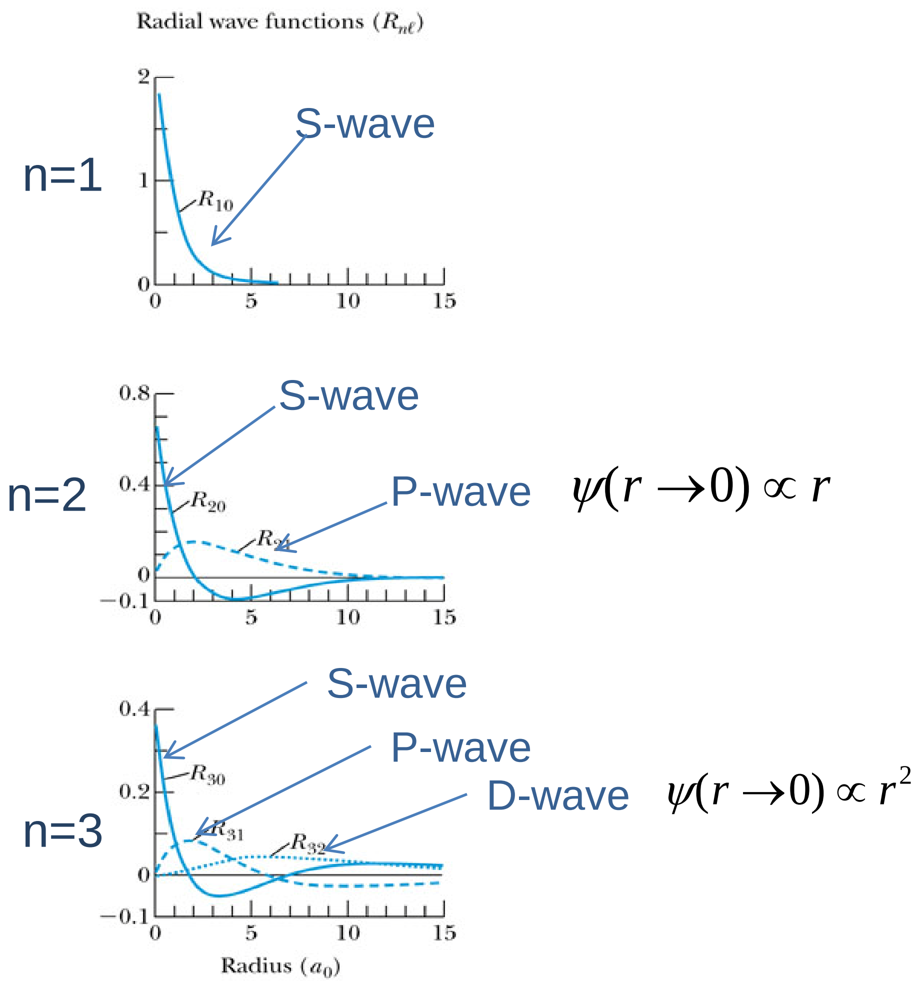
"wave function at the origin"

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



This only can happen when they are very near each other:

Many J/ψ processes are ∝ $|\Psi(0)|^2$, the "wave function at the origin," or, in the case of states with $\Psi(0)=0$, derivatives of $\Psi(0)$, which are usually small.



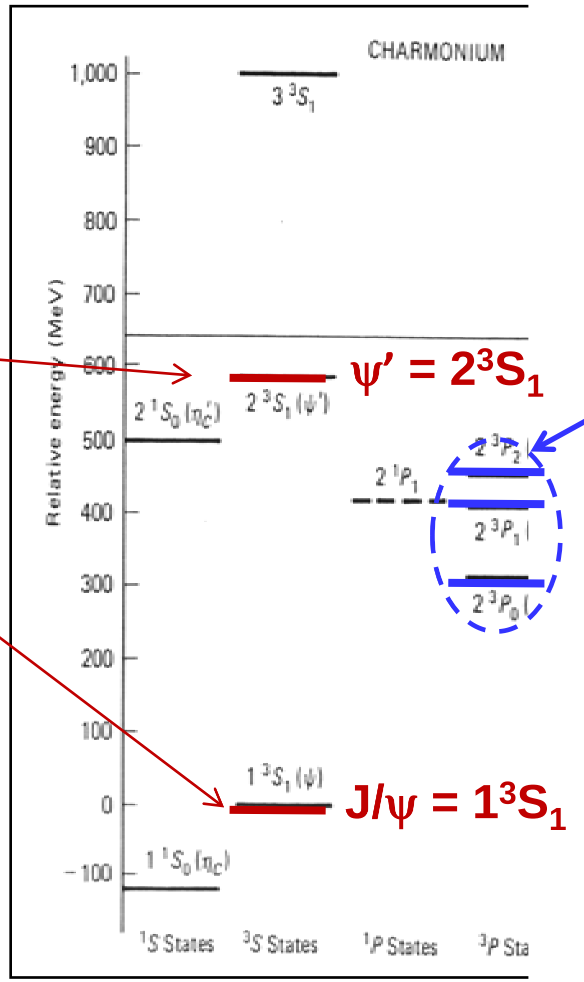
Immediate questions:

- Can the other meson states be found?

- Why are the J/ψ and ψ' so narrow?

Finding other states

These states have been identified



$\psi' = 2^3S_1$

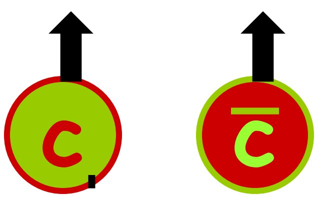
$J/\psi = 1^3S_1$

What about these?

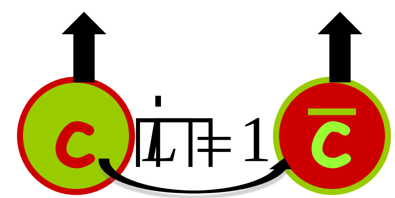
$\chi_{c2} = 1^3P_2$

$\chi_{c1} = 1^3P_1$

$\chi_{c0} = 1^3P_0$

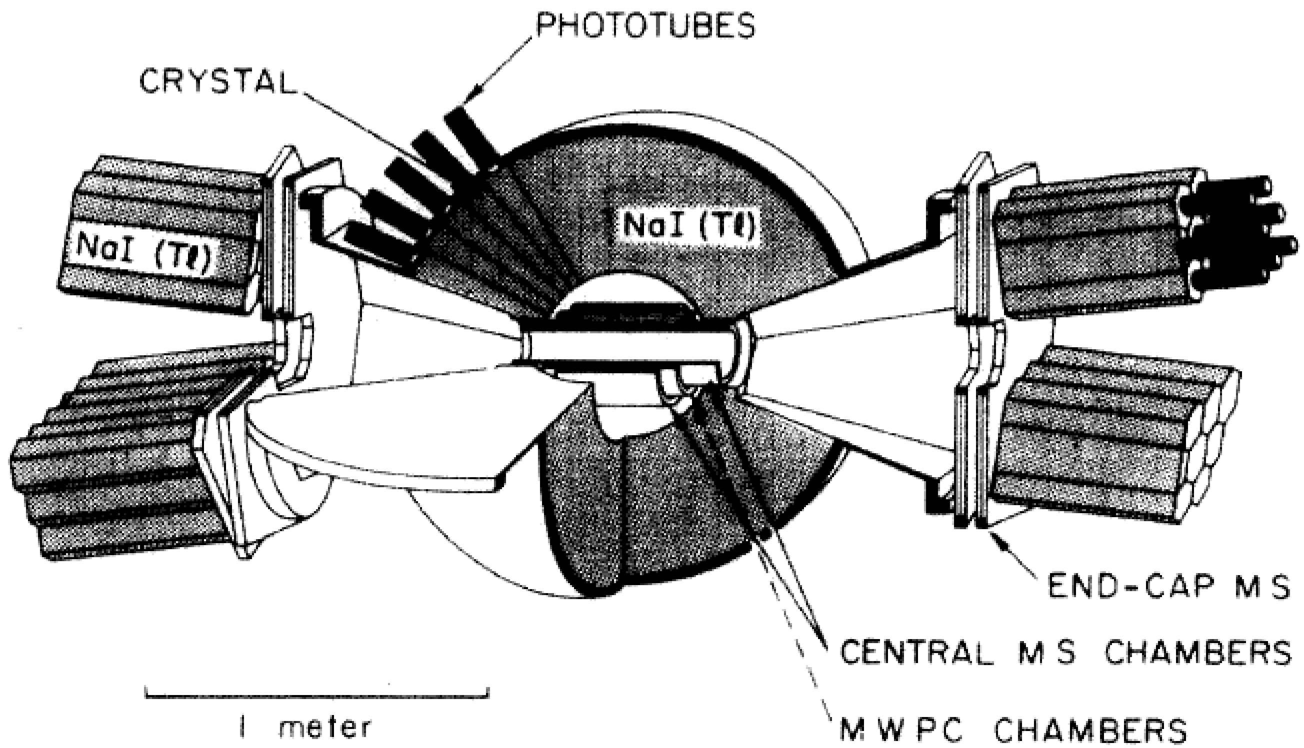


$|L| = 0$

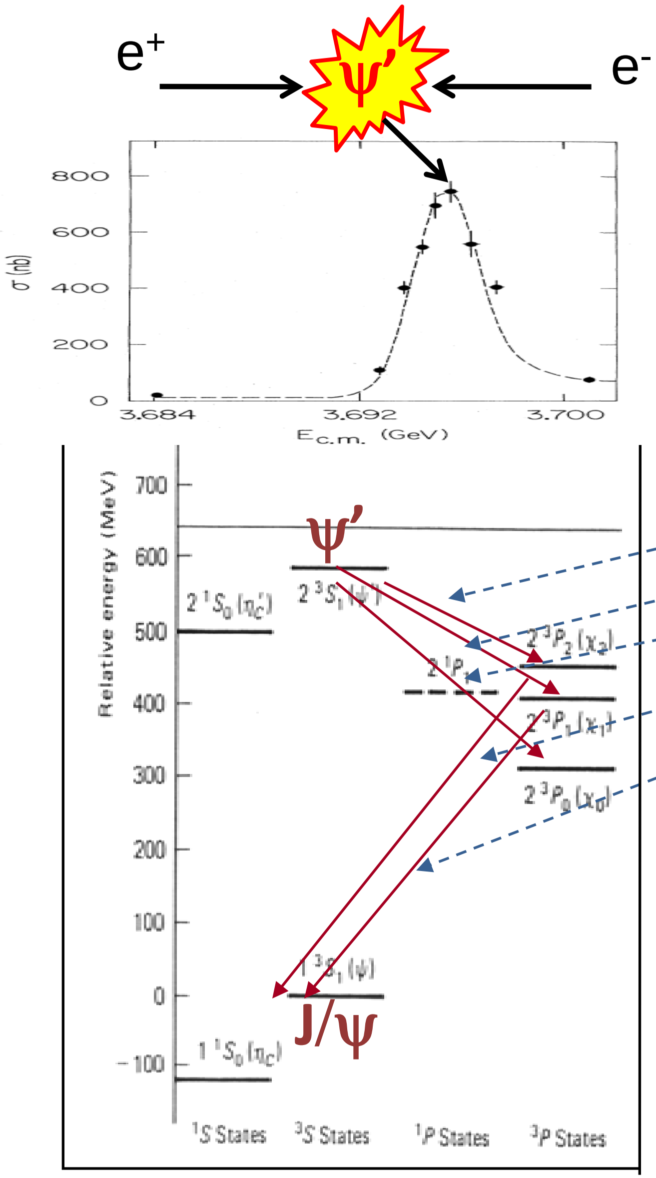


$|L| = 1$

The Crystal Ball Detector



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



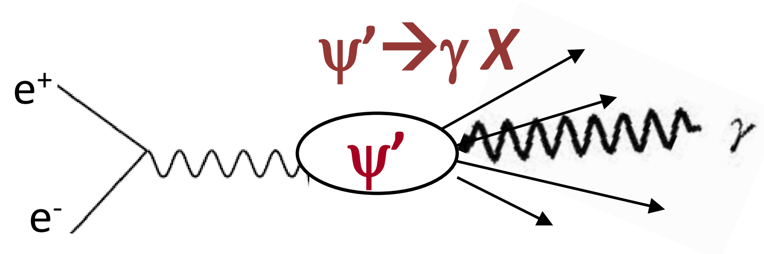
QM textbook formula:

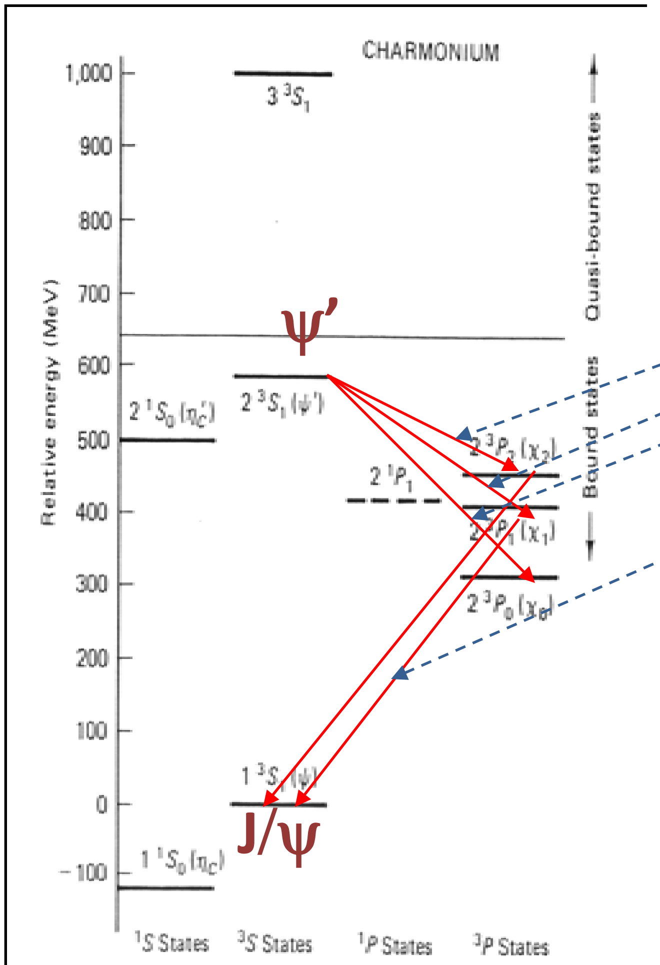
$$\Gamma_{E1} = \frac{\alpha E_\gamma^3}{2\pi\hbar^3 c^2} \sum_\lambda \int d\Omega_\gamma \left| \left\langle \Psi_f \middle| \hat{\varepsilon} \cdot \vec{r} \middle| \Psi_i \right\rangle \right|^2$$

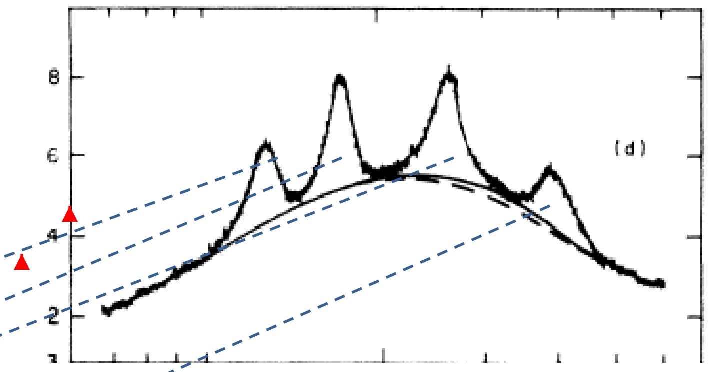
Transition	Γ_γ	Γ_γ (keV)
$2\,^3S \rightarrow {}^3P_2$	$5I_1\alpha k^3$	*24.*
$\rightarrow {}^3P_1$	$3I_1\alpha k^3$	*29.*
$\rightarrow {}^3P_0$	$1I_1\alpha k^3$	*26.*
${}^3P_2 \rightarrow 1\,^3S$	$I_2\alpha k^3$	*313.*
${}^3P_1 \rightarrow 1\,^3S$	$I_2\alpha k^3$	*239.*
${}^3P_0 \rightarrow 1\,^3S$	$I_2\alpha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

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

Crystal ball results





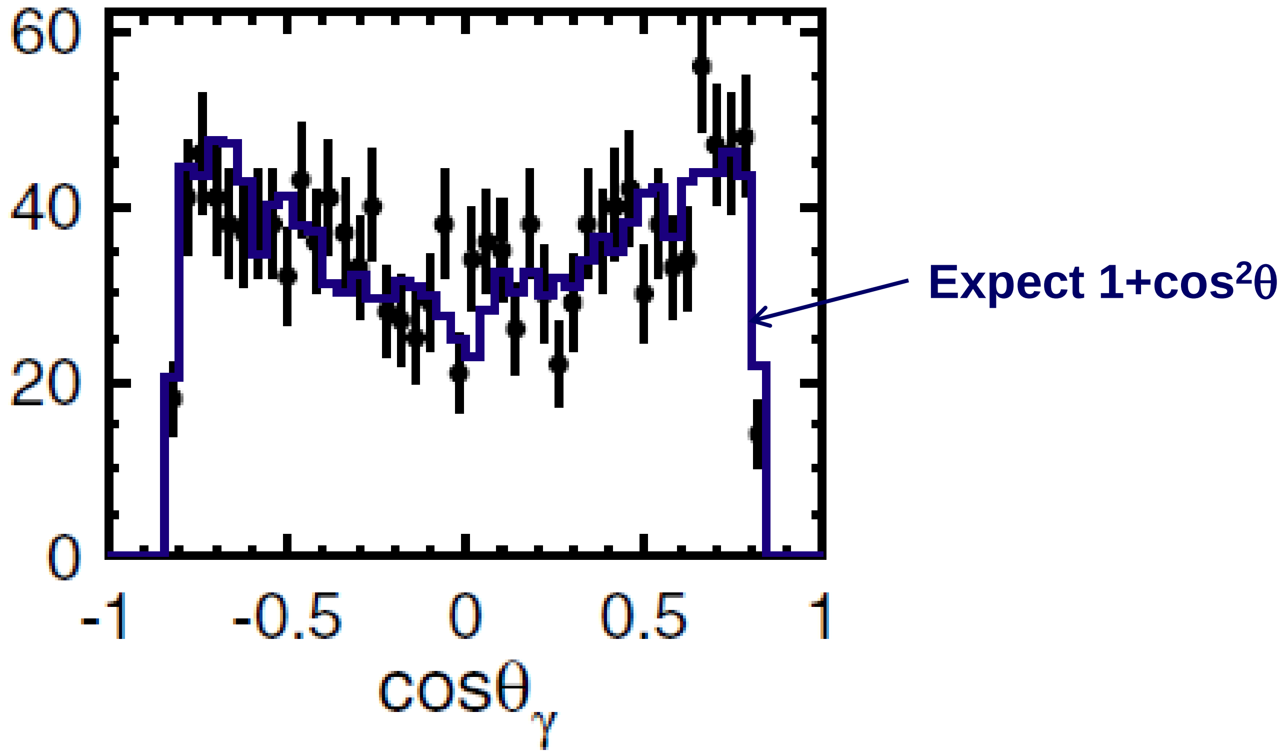


E_γ

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

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

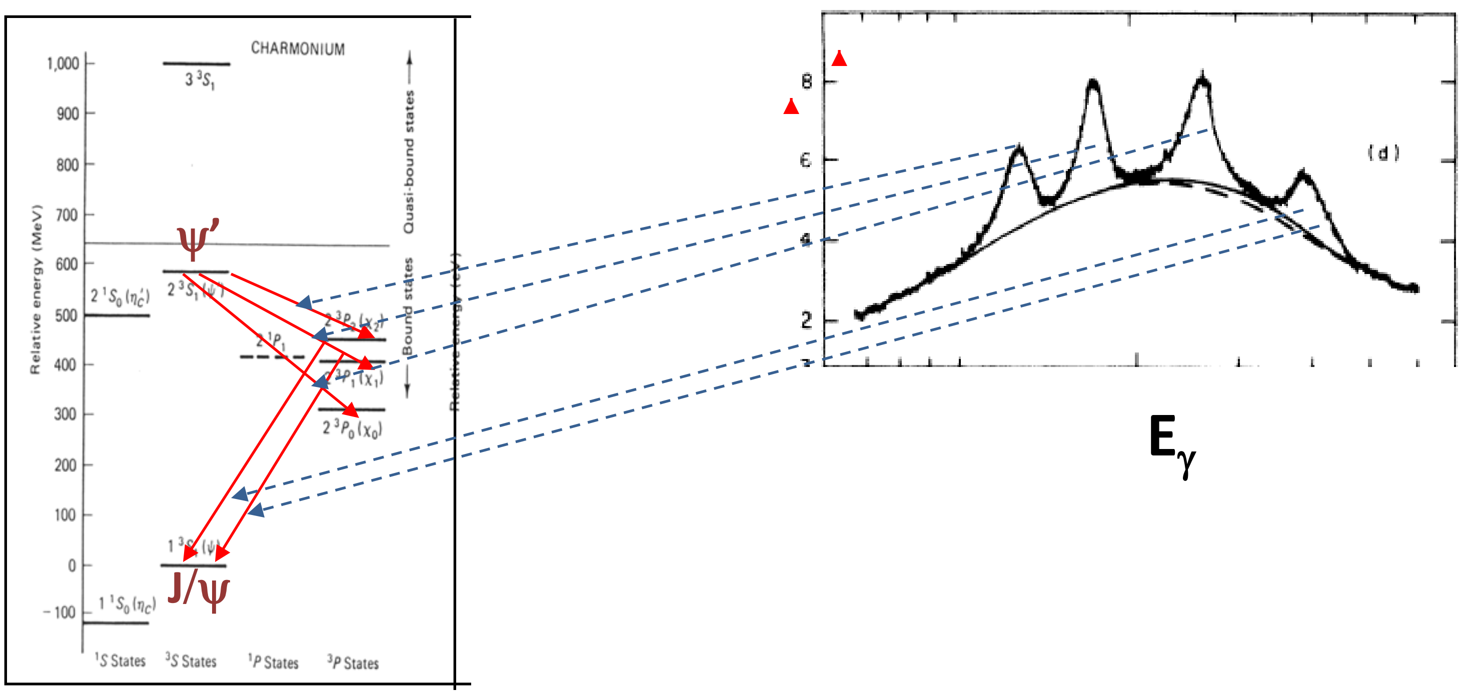
$\psi' \rightarrow \gamma\chi_{c0}$ radiative transition



BESII PRD 70, 092004 (2004)

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

e^-



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

Immediate questions:

- Can the other meson states be found?

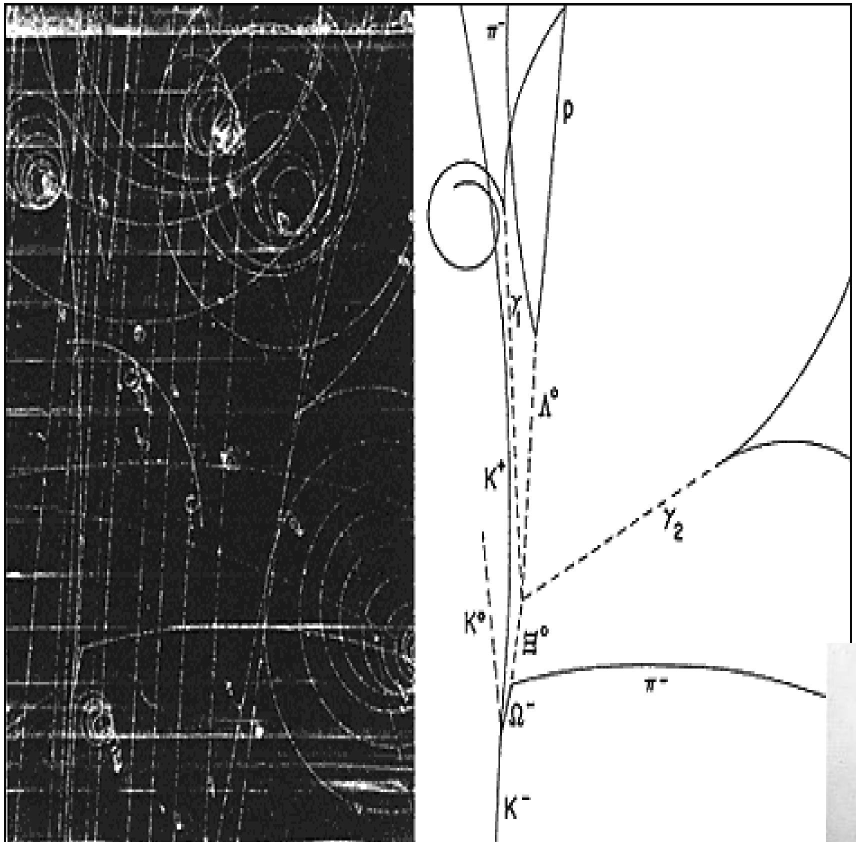
Done!

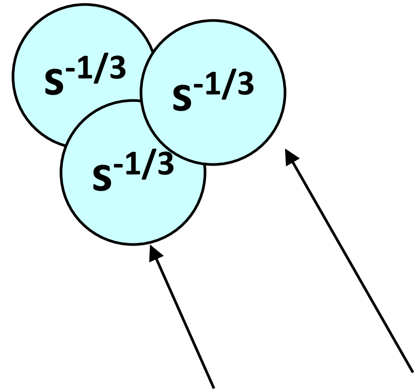
- Why are the J/ψ and ψ′ so narrow?

Problems with the quark model:

- Individual quarks are not seen
- why only qqq and $q\bar{q}$ combinations?
- violation of spin-statistics theorem?

Ω^-



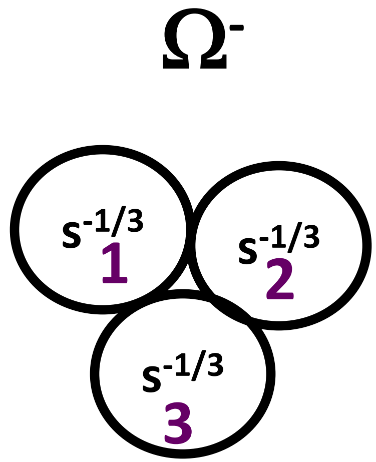


three s-quarks
in the same
quantum state

The strong interaction "charge" of each quark comes in 3 different varieties

Y. Nambu

M.-Y. Han



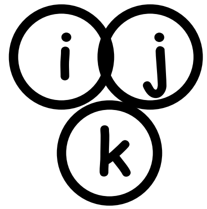
the 3 $s^{-1/3}$ quarks in the Ω^- have different strong charges & evade Pauli

Attractive configurations

Baryons:

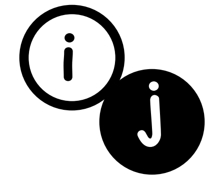
$\varepsilon_{ijk}\, e_i e_j e_k$

$i \neq j \neq k$



Mesons:

$\delta_{ij}\, e_i\, \bar{e}_j$



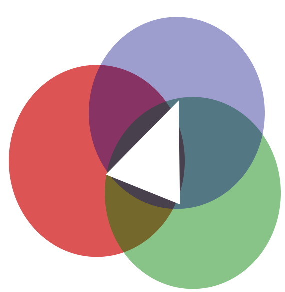
same as the rules for combining colors to get white:

add 3 primary colors -or- add color+complementary color

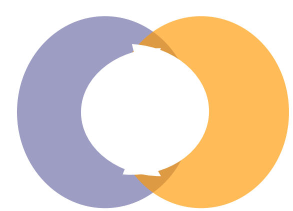
quarks: $e_i e_j e_k$ → color charges

antiquarks: $\bar{e}_i\ \bar{e}_j\ \bar{e}_k$ → anticolor charges

$\varepsilon_{ijk}\, e_i e_j e_k$

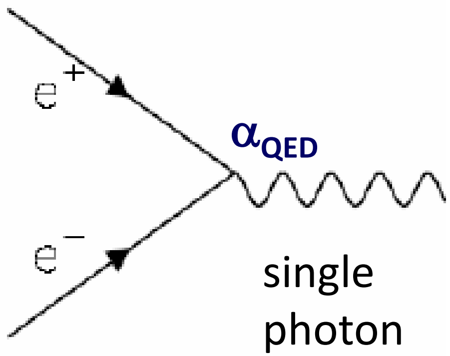


$\delta_{ij}\, e_i\, \bar{e}_j$



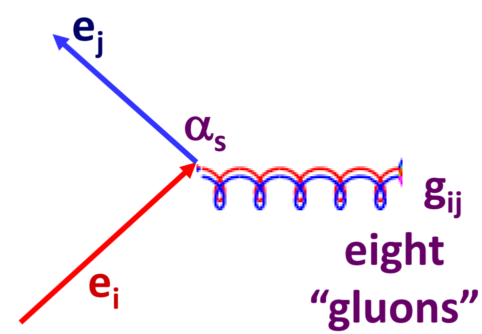
Quantum Chromodynamics

QED: scalar charge e



Non-Abelian extension of QED

QCD triplet charge: $\begin{pmatrix} e_r \\ e_b \\ e_g \end{pmatrix}$



QED gauge transform

$$\vec{\nabla} \rightarrow \vec{\nabla} + i\, e\, \vec{A}$$

1 vector field (photon)

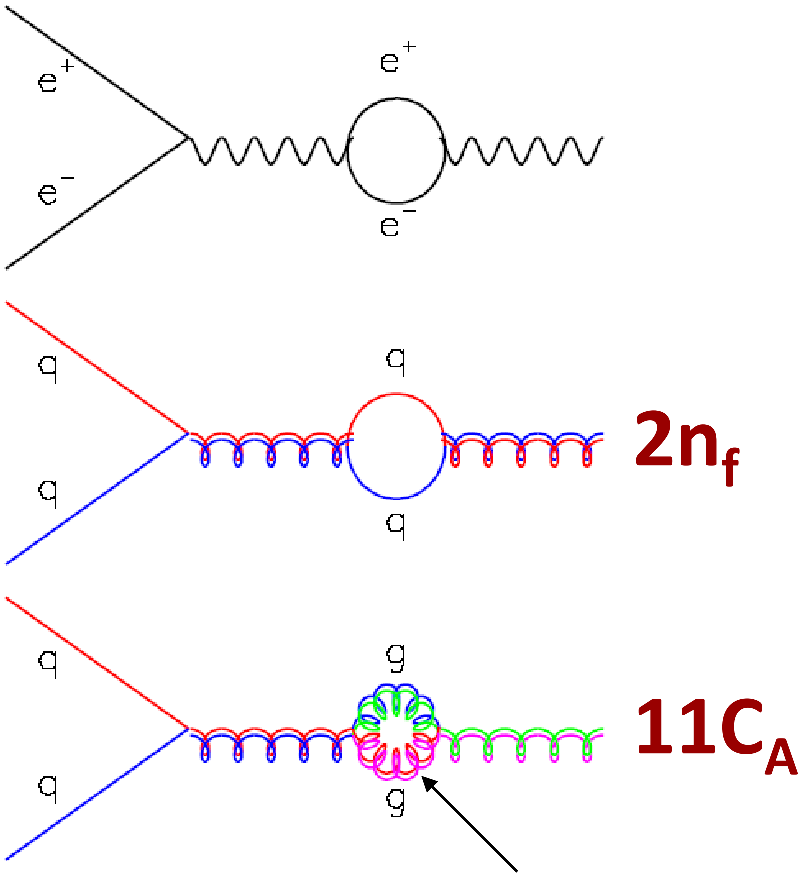
QCD gauge transform

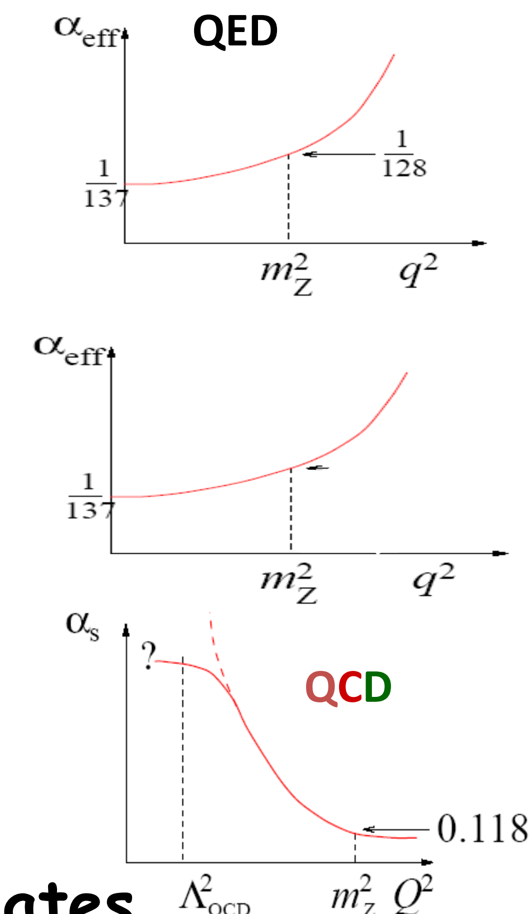
$$\vec{\nabla} \rightarrow \vec{\nabla} + i\, \alpha\, \lambda_i\, \vec{G_i}$$

eight 3x3 SU(3) matrices

8 vector fields (gluons)

Vacuum polarization QED *vs* QCD





in QCD: C_A=3, & this dominates
α_s increases with distance

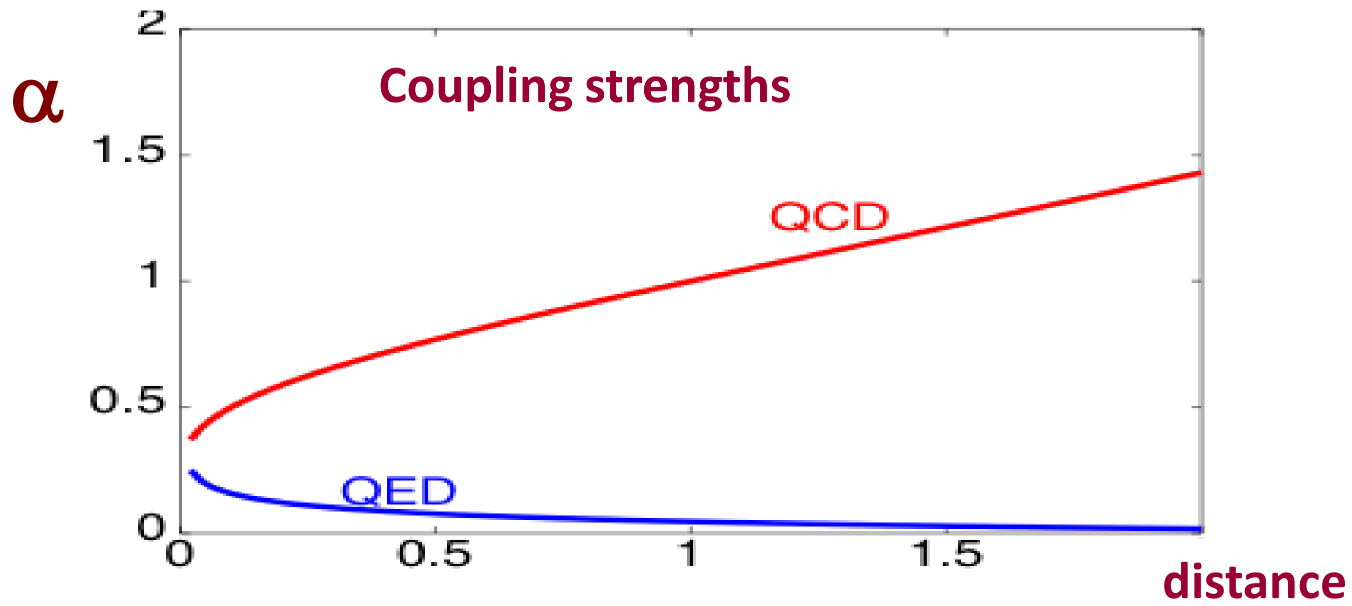
QED: photons have no charge

coupling decreases at large distances

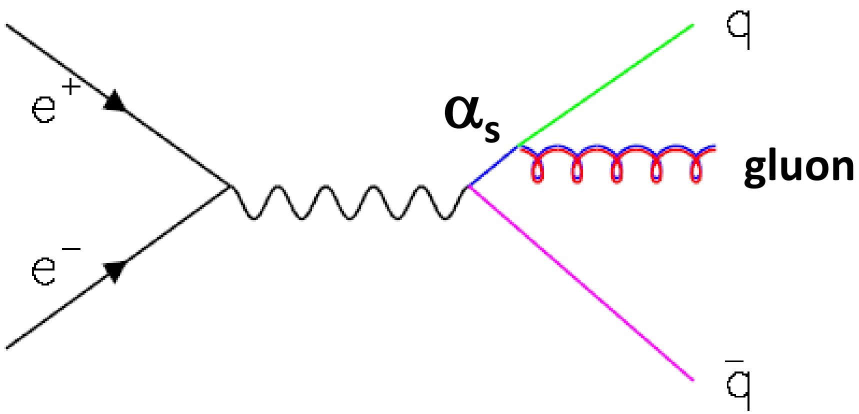
QCD: gluons carry color charges

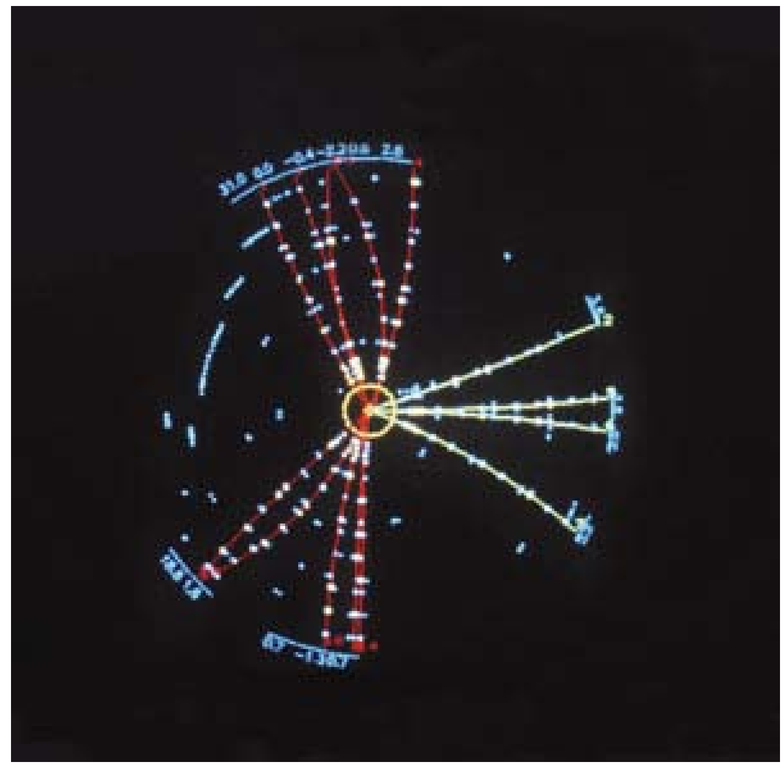
gluons interact with each other

coupling increases at large distances



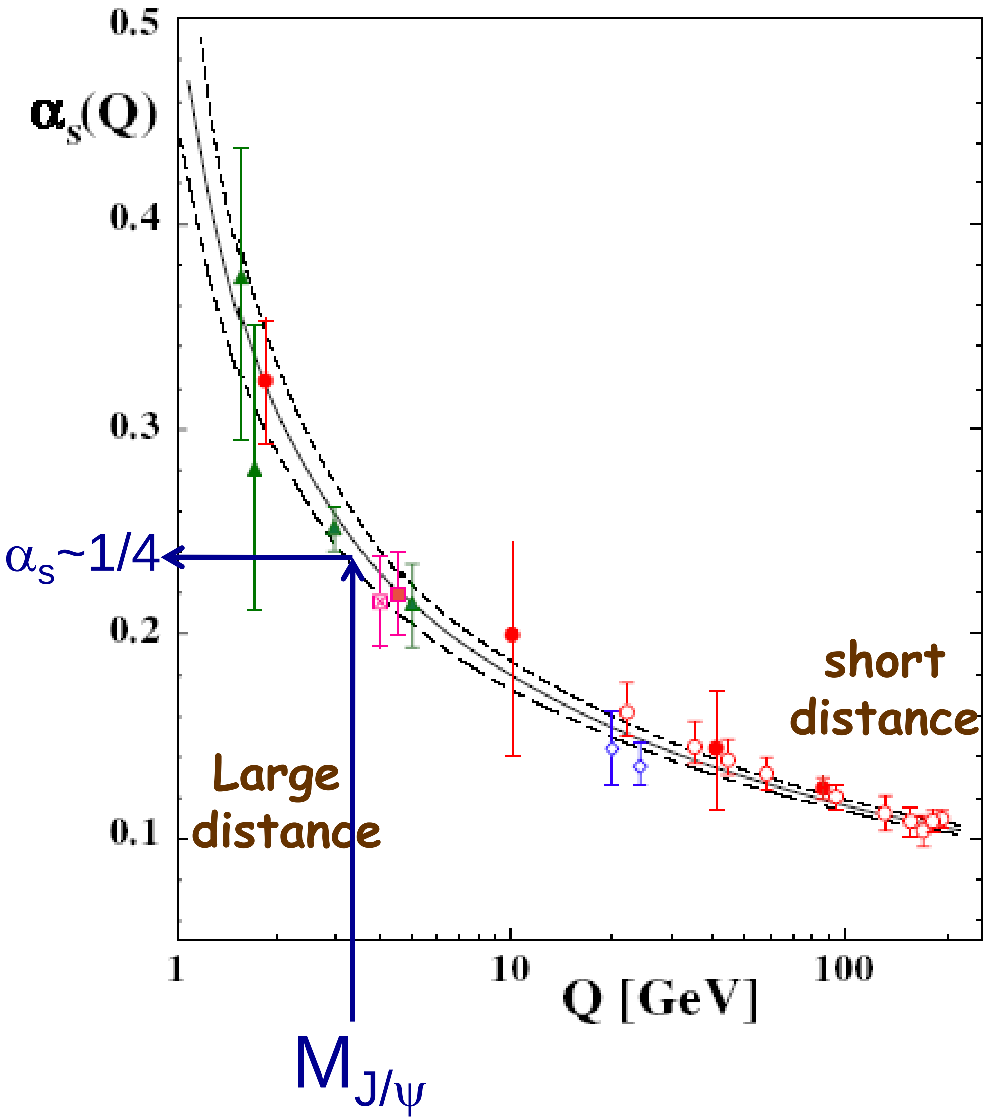
Test QCD with 3-jet events
(& deep inelastic scattering)



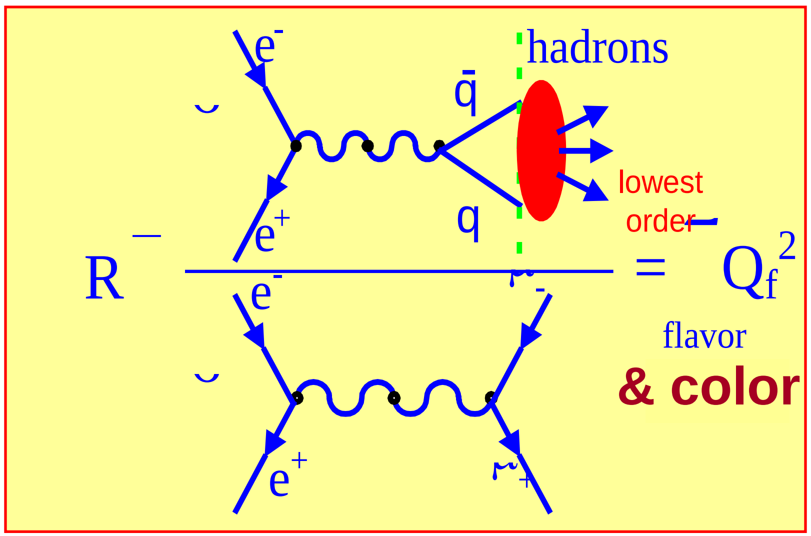


rate for 3-jet events should decrease with E_{cm}

“running” α_s

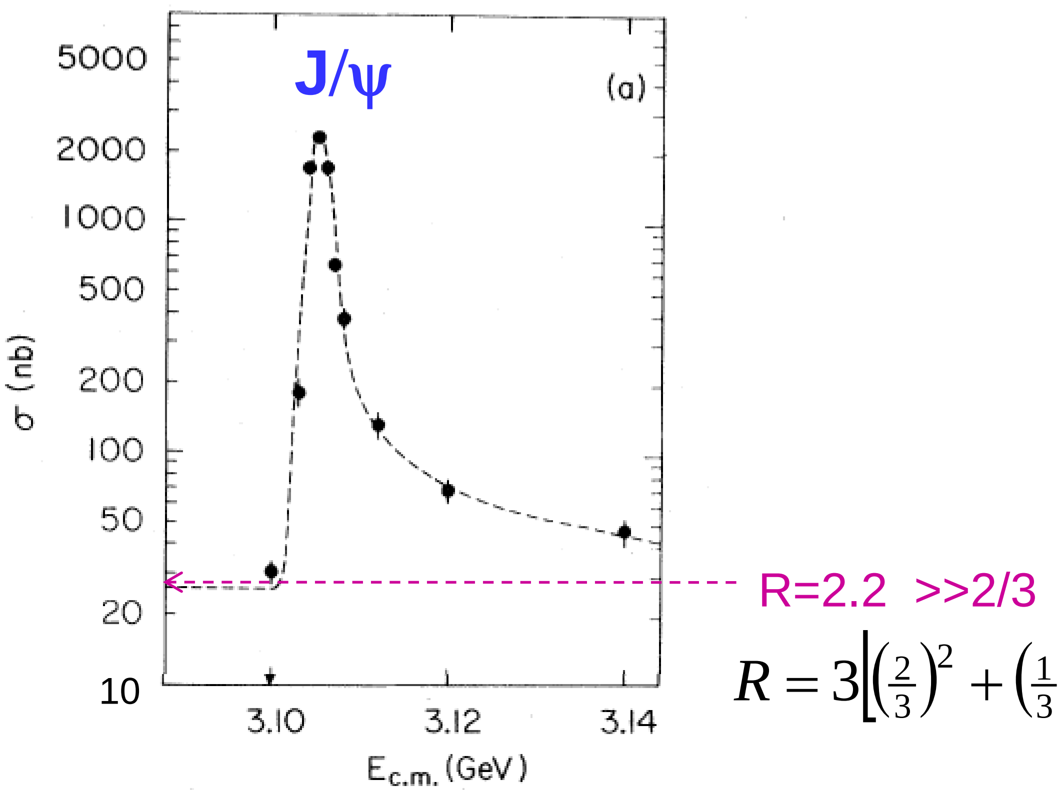


Color explains the discrepancy in R



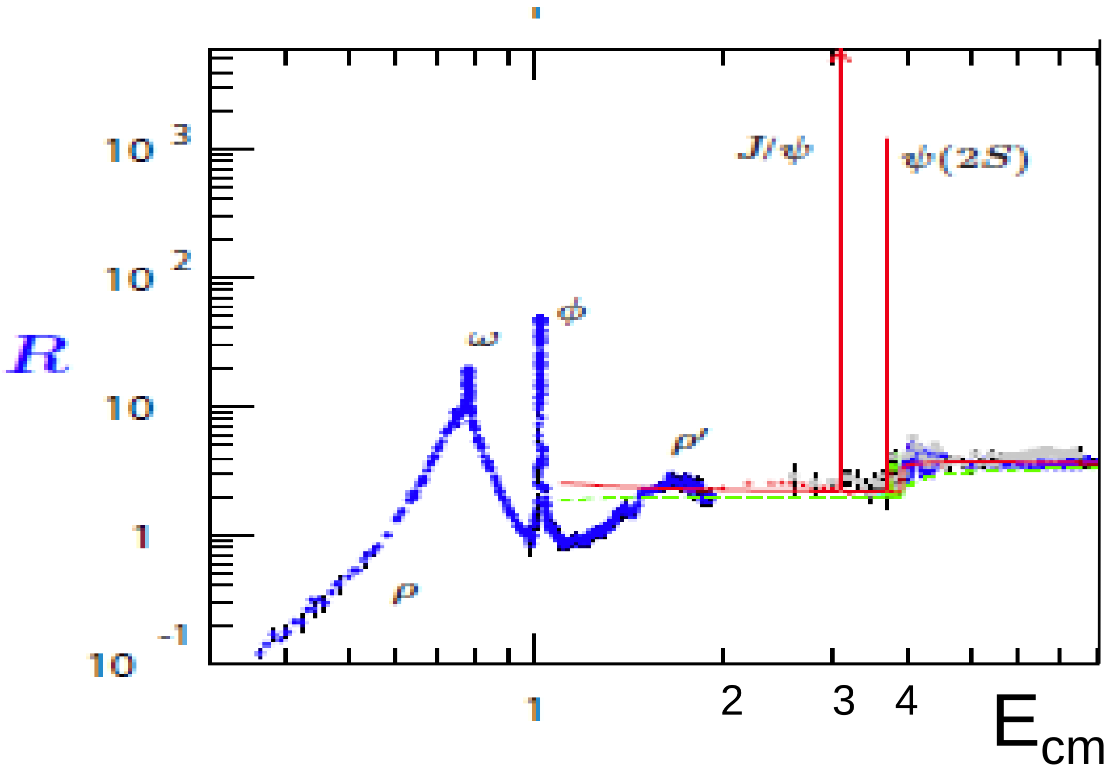
$$= 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2$$

Each quark has 3 colors

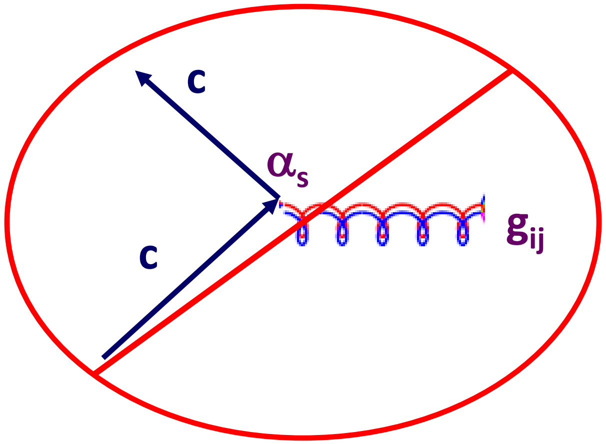


$$R = 3\left[\left(\tfrac{2}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2 + \left(\tfrac{1}{3}\right)^2\right] \approx 2.2$$

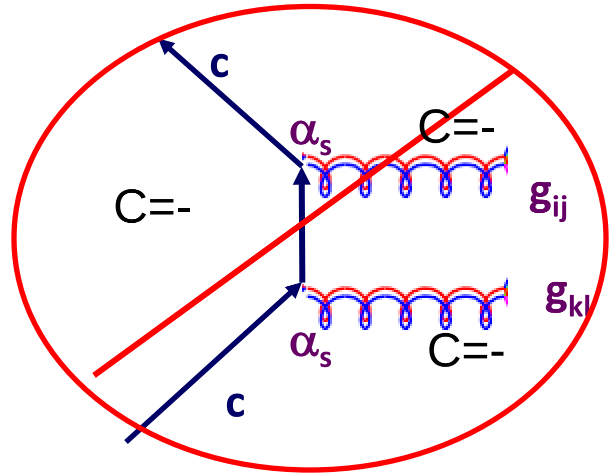
why are the J/ψ and ψ' so narrow?



How does the J/ψ (ψ') decay?

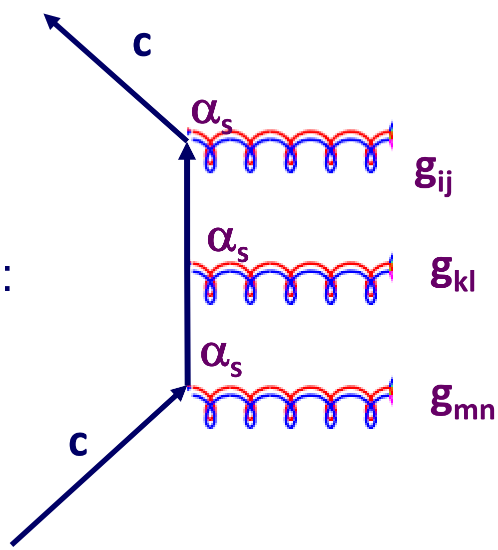


violates color symmetry



violates C parity

Lowest-order
allowed QCD process:

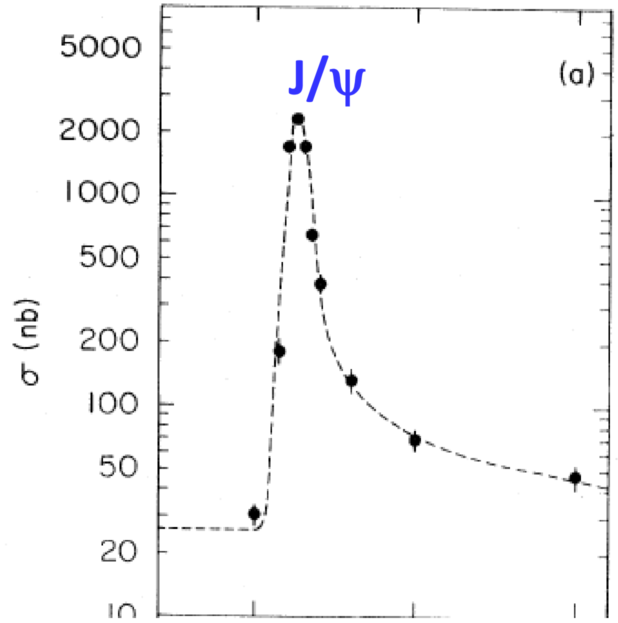


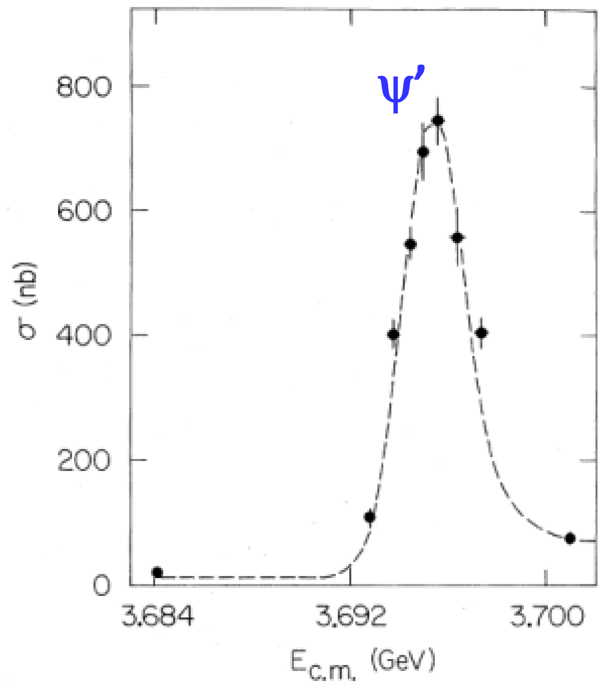
← suppressed by α_s^3

This is called "OZI"* suppression

***Okubo-Zweig-Iizuka**

How wide is the J/ψ (& ψ')?

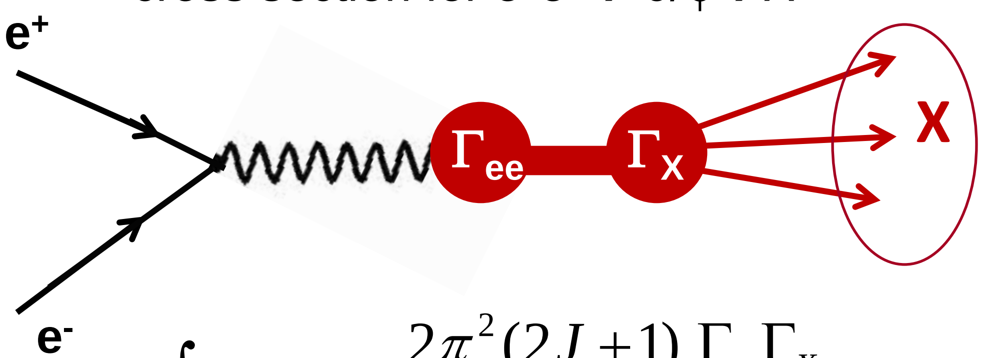




The observed widths of these peaks are due entirely to experimental resolution, which is typically a few MeV

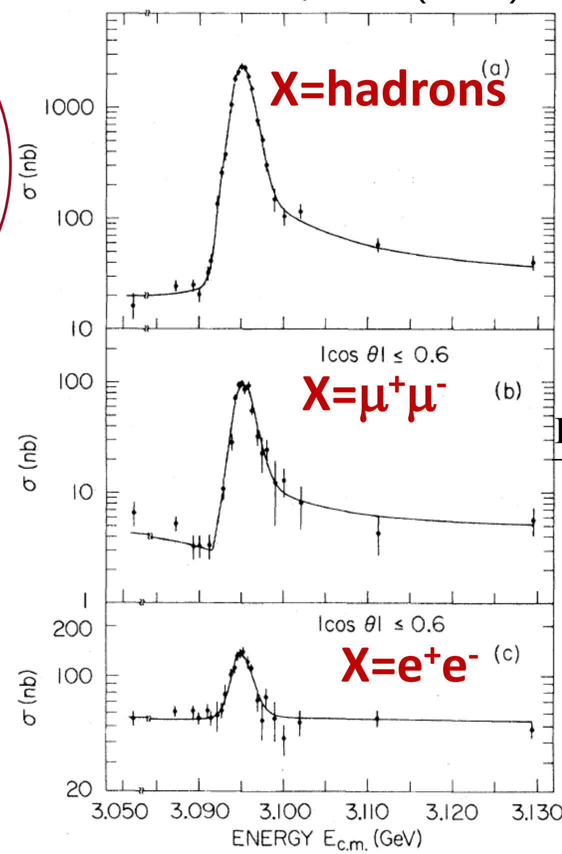
Determining the J/ψ (& ψ′) widths

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



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

Mark-I PRL 34, 1357 (1975)



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

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

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

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

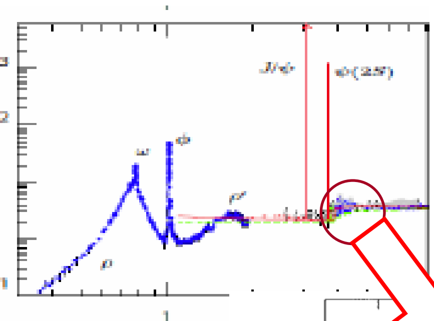
4 eqns, 4 unknowns

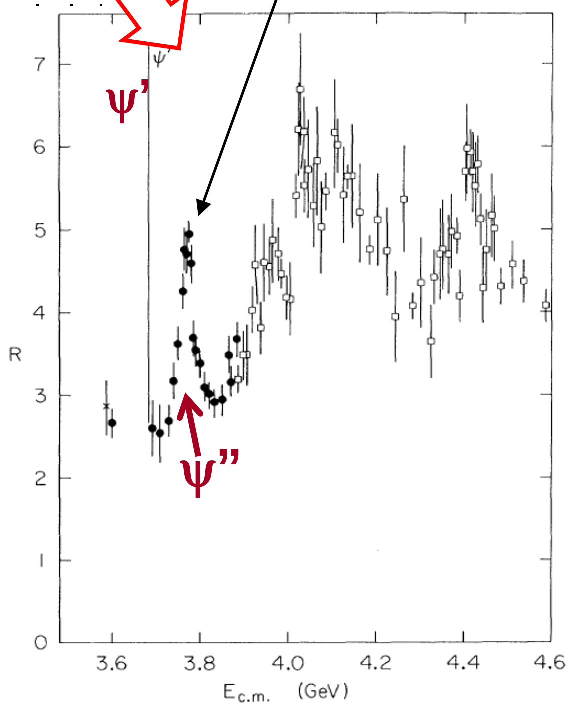
2009 values

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

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

a 3rd peak: the ψ” (ψ(3770))





LGW PRL 39, 526 (1977)

Γ_{tot} ~150x bigger

2009 values

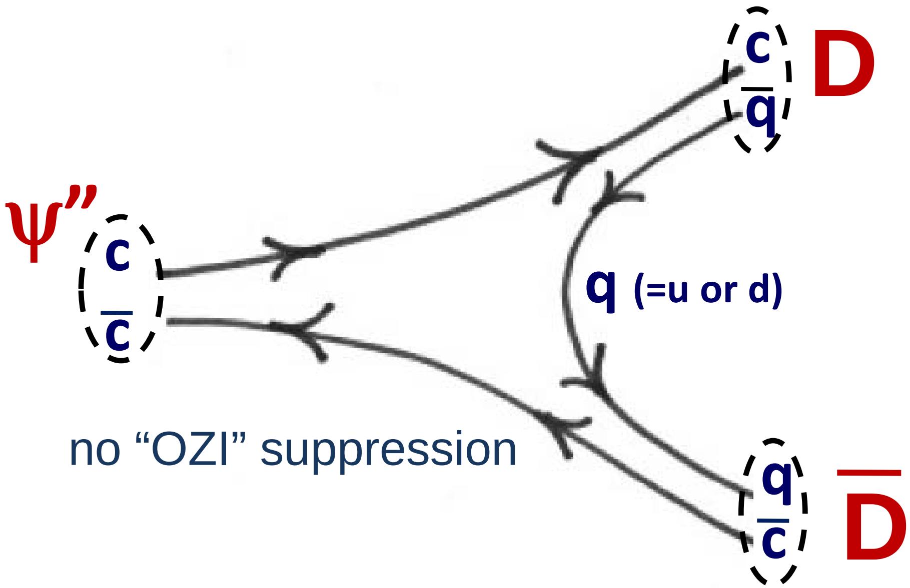
	J/ψ	ψ’	ψ”
Γ_{tot}	93 keV	209 keV	**27.3+1.0 MeV**
Γ_{ee}	5.55 keV	5.1 keV	**0.26+0.02 keV**

Γ_{ee} ~20x smaller

Why is Γ_{tot} (ψ'') much bigger?

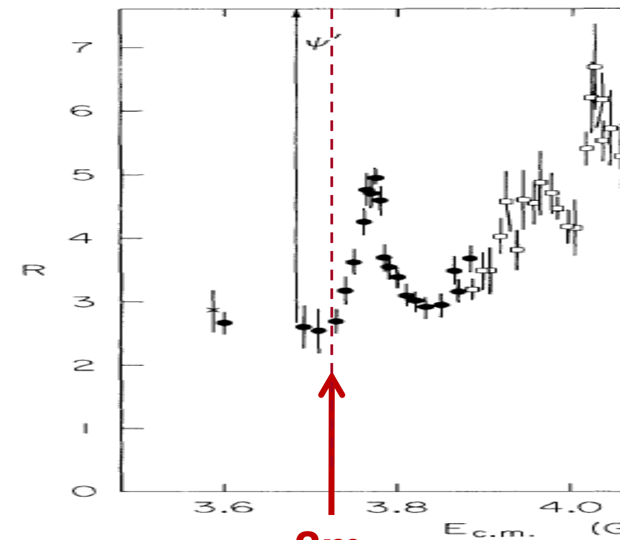
"charmed" mesons

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



←D^0 or D^+

←$\bar{D}^0$ or D^-



$2m_D$
"open charm" threshold

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

$2m_{D+}$=3739 MeV

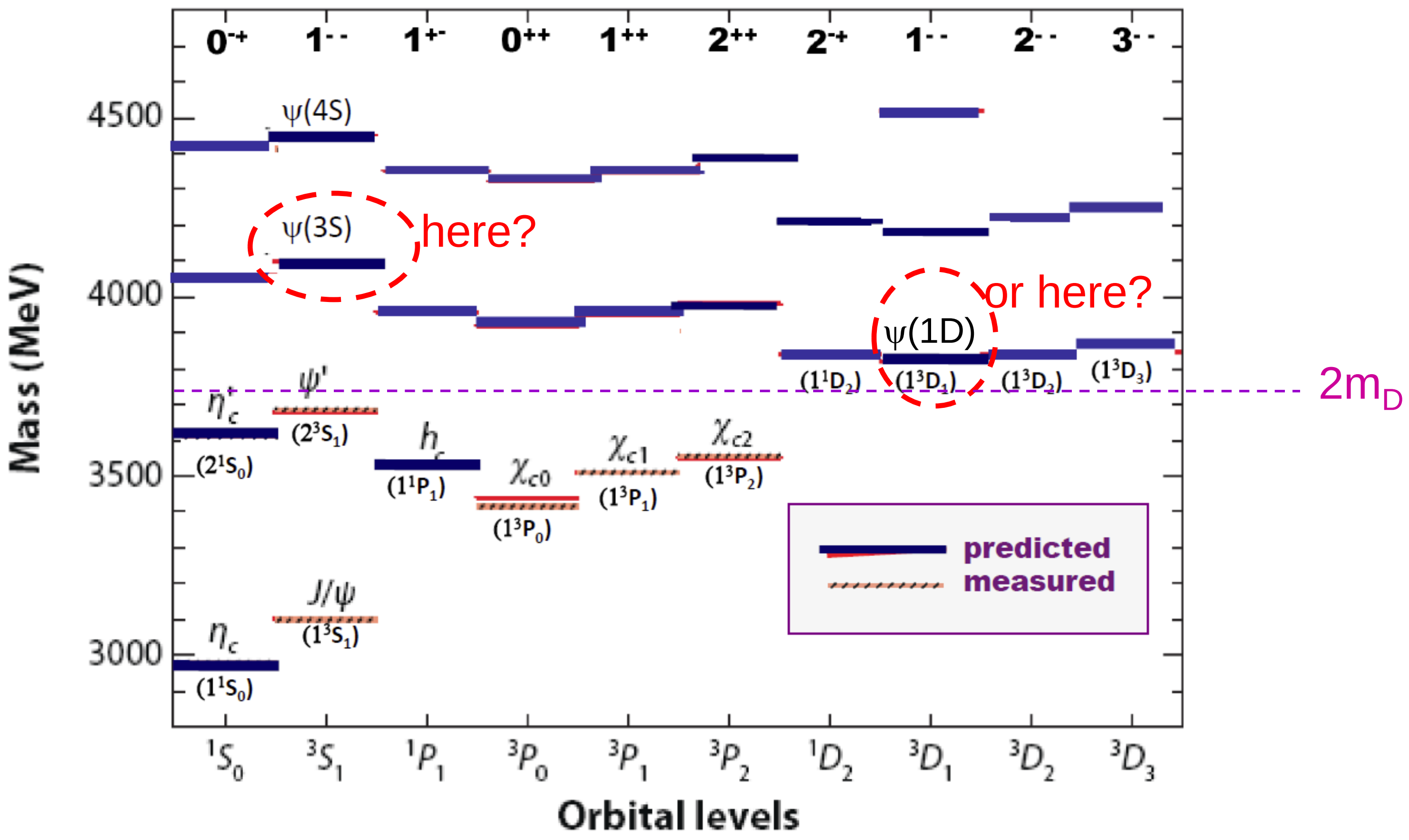
$2m_{D0}$ =3729 MeV

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

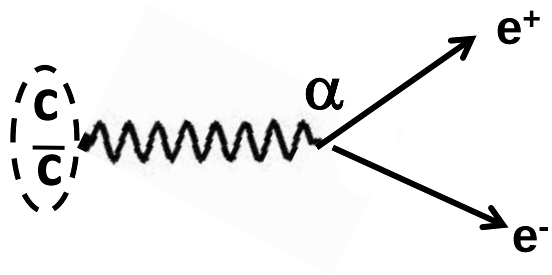
"Fall apart" Decay modes

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

must be J^{PC} = **1⁻⁻**



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



S-wave

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

D-wave

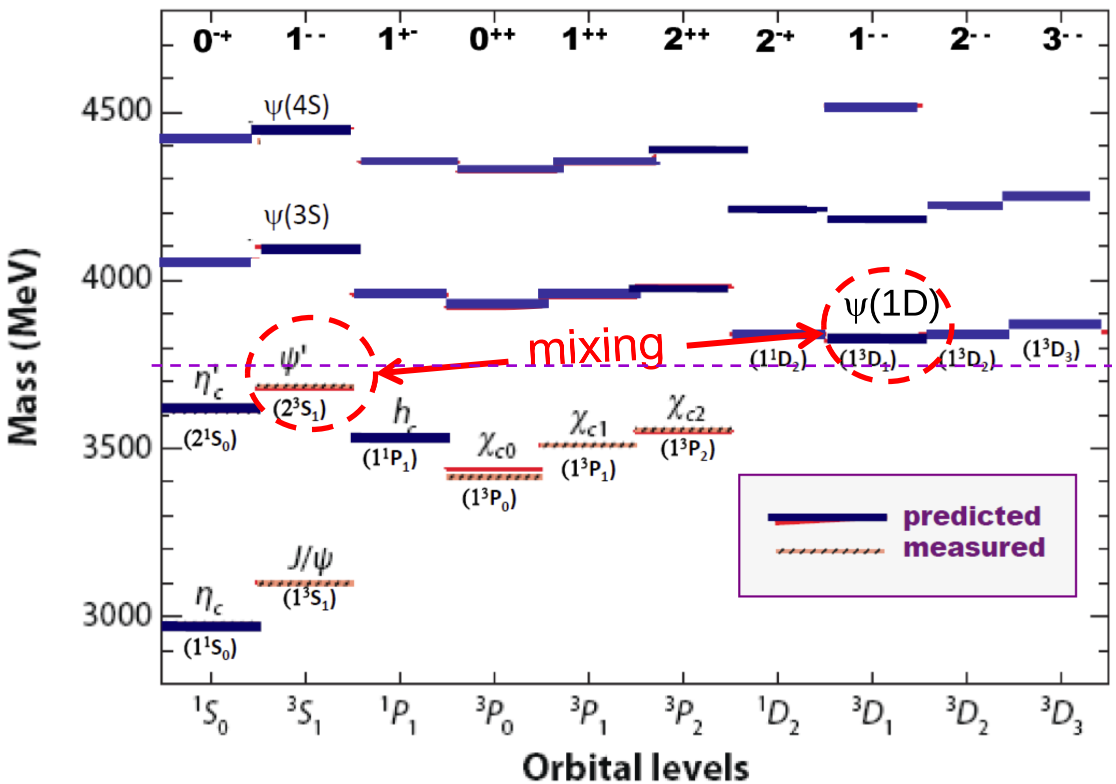
$$\Gamma_{ee}(^3D_1) = \frac{50}{9}\frac{\alpha^2}{M_{c\bar{c}}^2}\left|\frac{\partial^2\Psi(0)}{\partial r^2}\right|^2$$

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



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

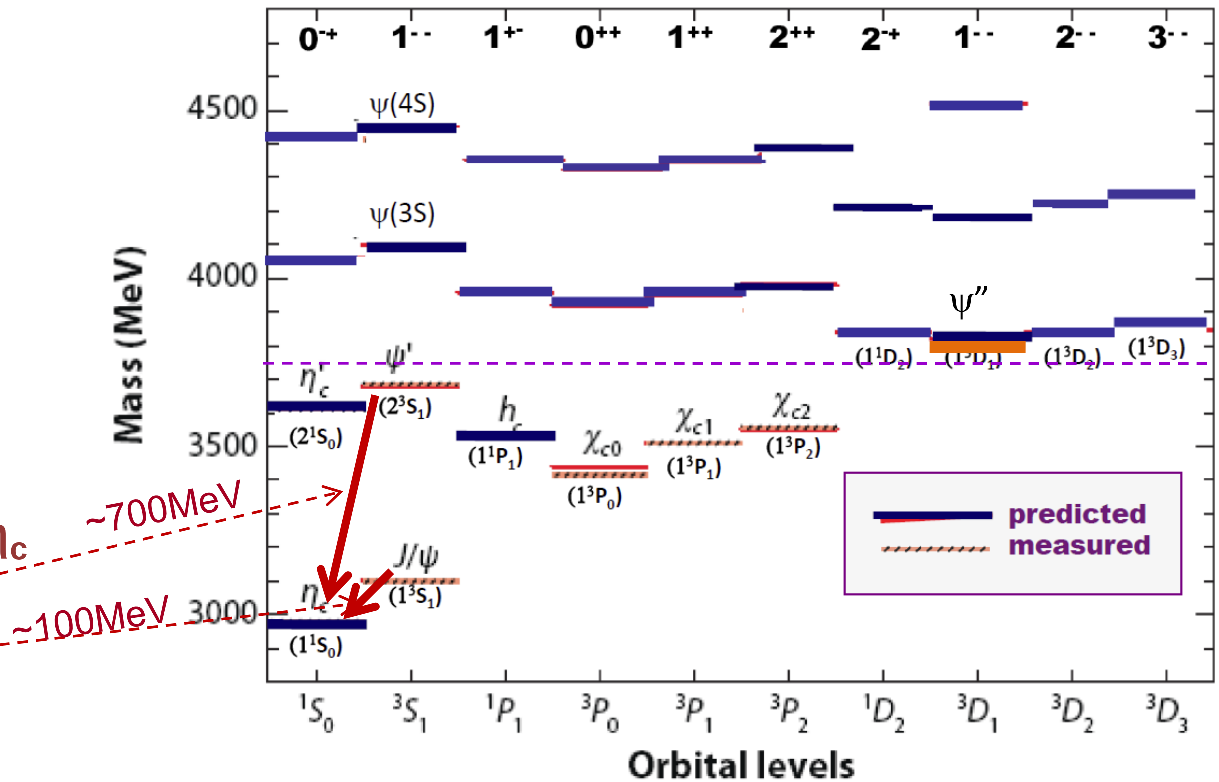
$$\psi'' = \psi(1^3D_1)\cos\theta_{mix} + \psi(2^3S_1)\sin\theta_{mix}$$

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

"preferred" value

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

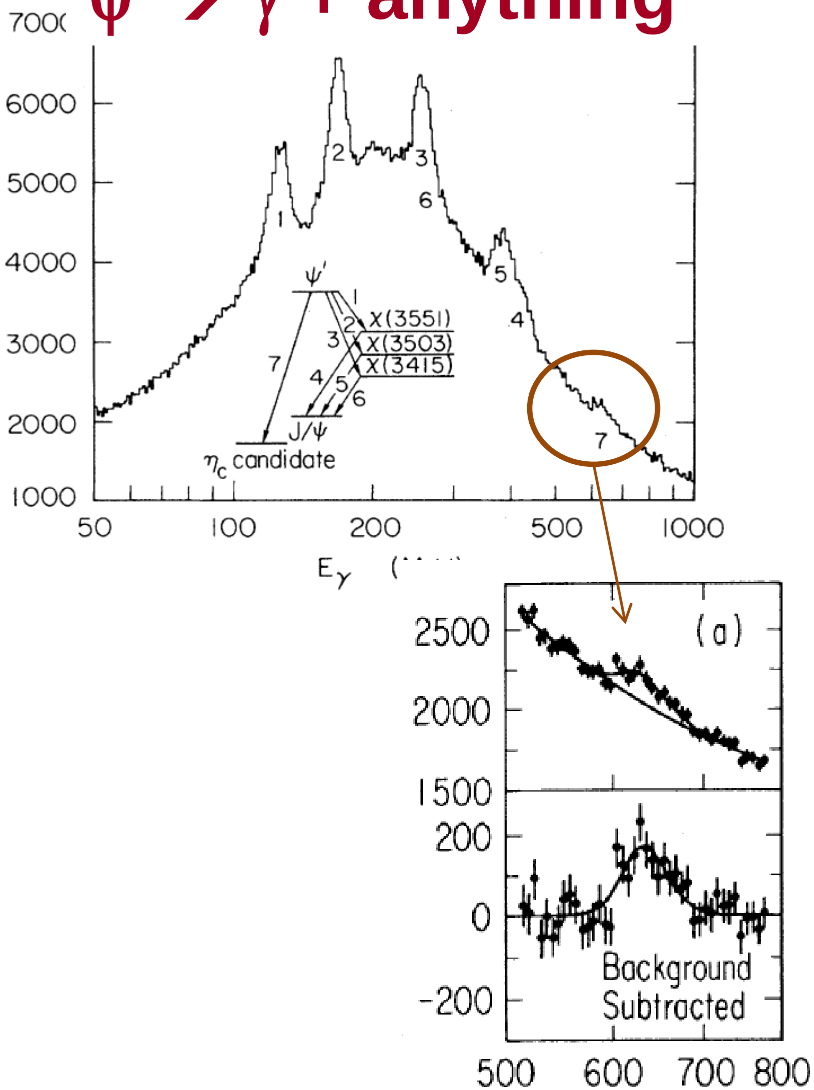
Finding other charmonium mesons



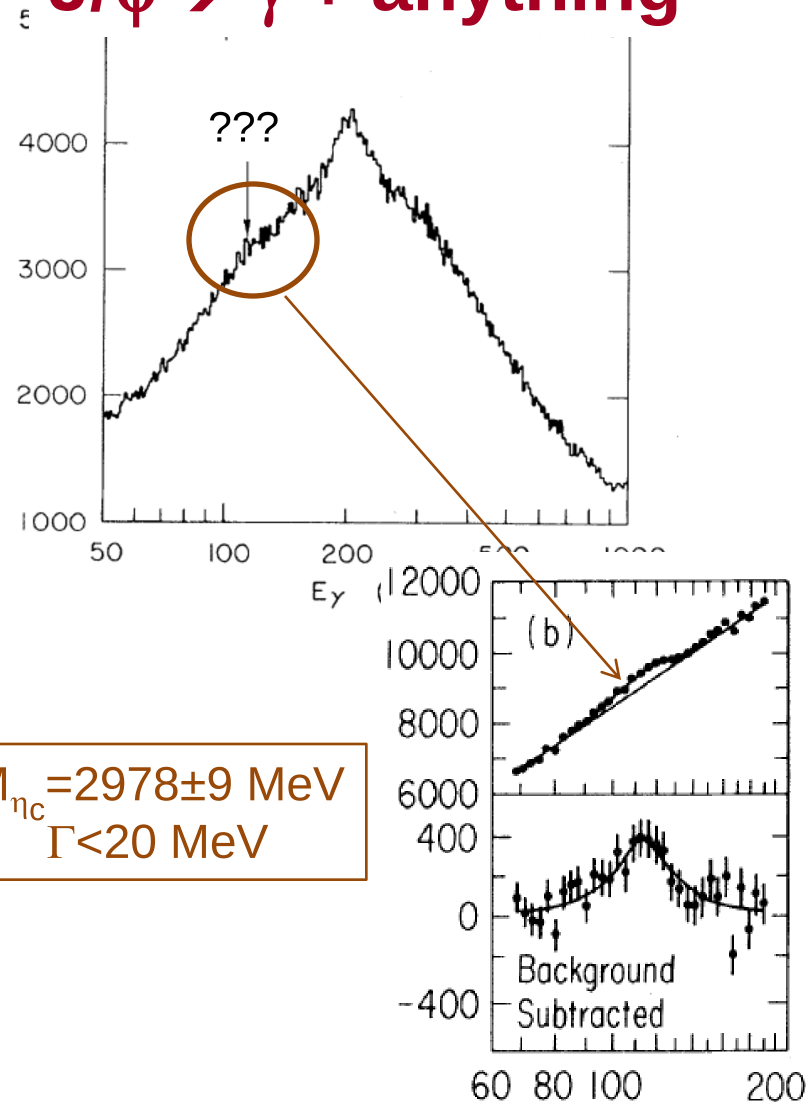
Look for the η_c
via $\psi' \rightarrow \gamma\ \eta_c$
or $J/\psi \rightarrow \gamma\ \eta_c$

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

$\psi'\to\gamma$ + anything



$J/\psi\to\gamma$ + anything



M_{η_c}=2978±9 MeV
Γ<20 MeV

Xtal-Ball PRL 45, 1150 (1980)

Mark II $\psi' \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$ exclusive

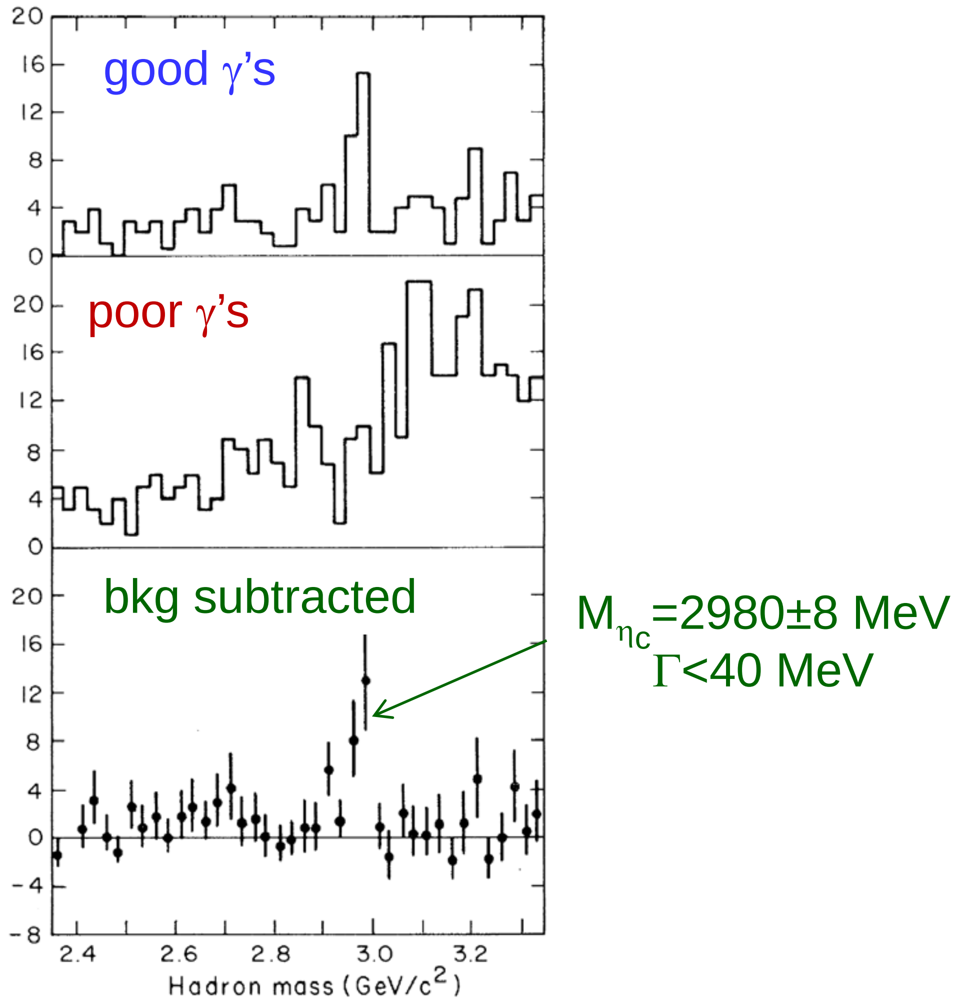
$\psi' \rightarrow \gamma p\bar{p}$,

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

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

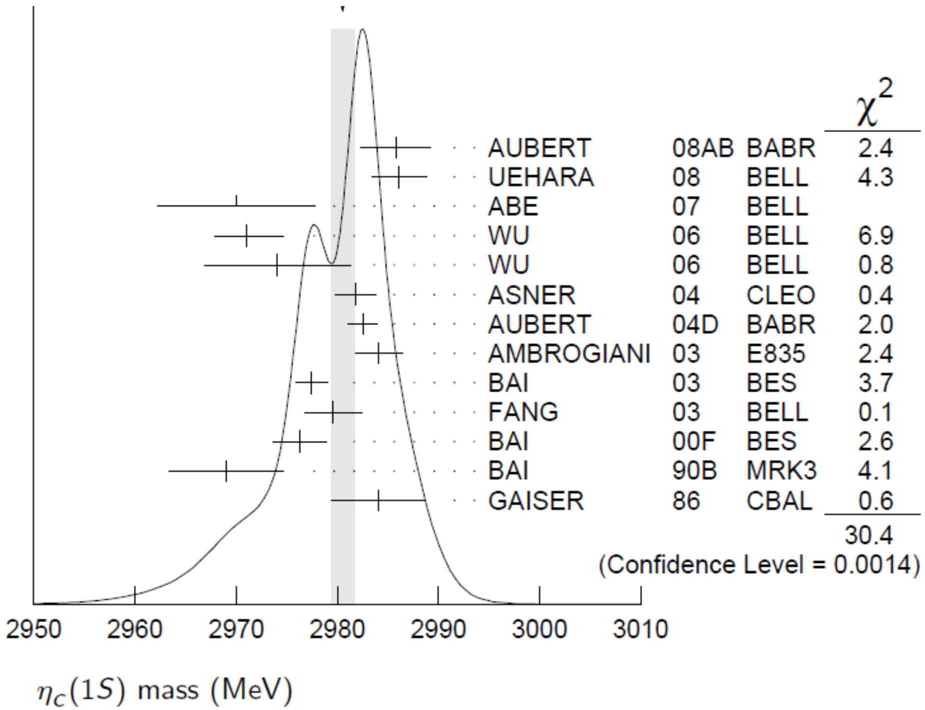
$\psi' \rightarrow \gamma\pi^+\pi^-p\bar{p}$,

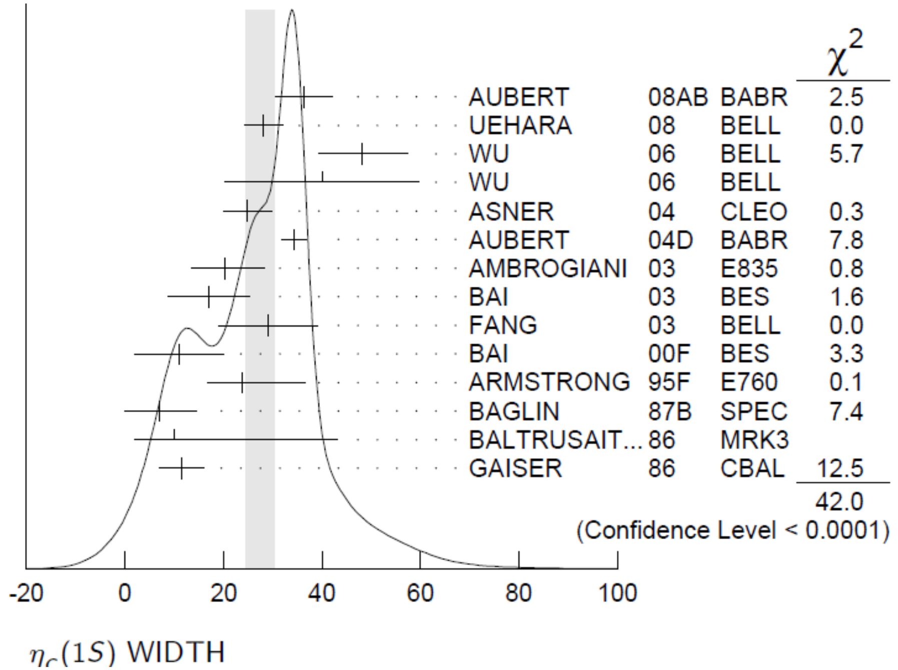
$\psi' \rightarrow \gamma K^\pm\pi^\mp K_S$, $K_S \rightarrow \pi^+\pi^-$



Mark II PRL 45, 1146 (1980)

The η_c in 2010 (30 years later)

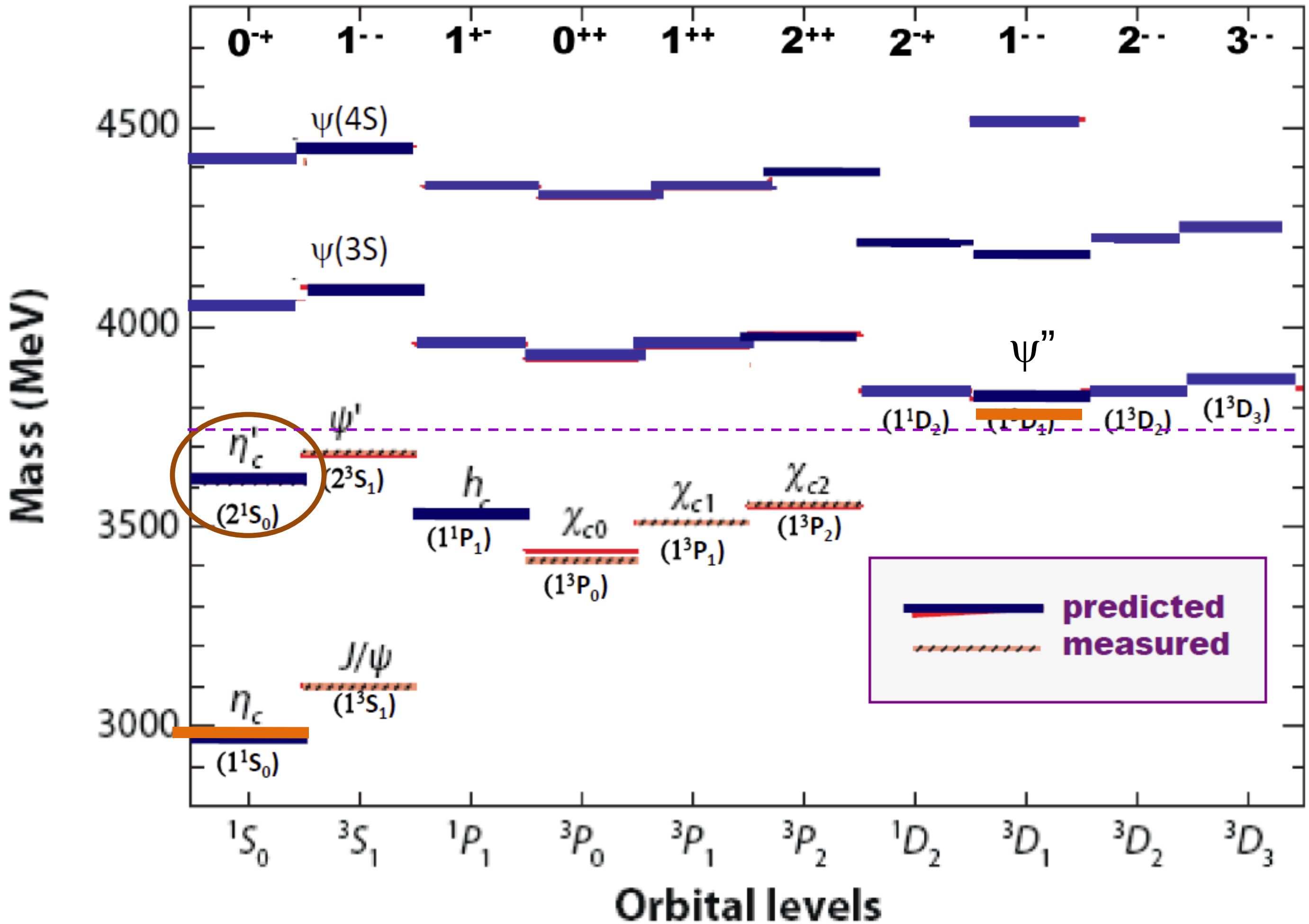




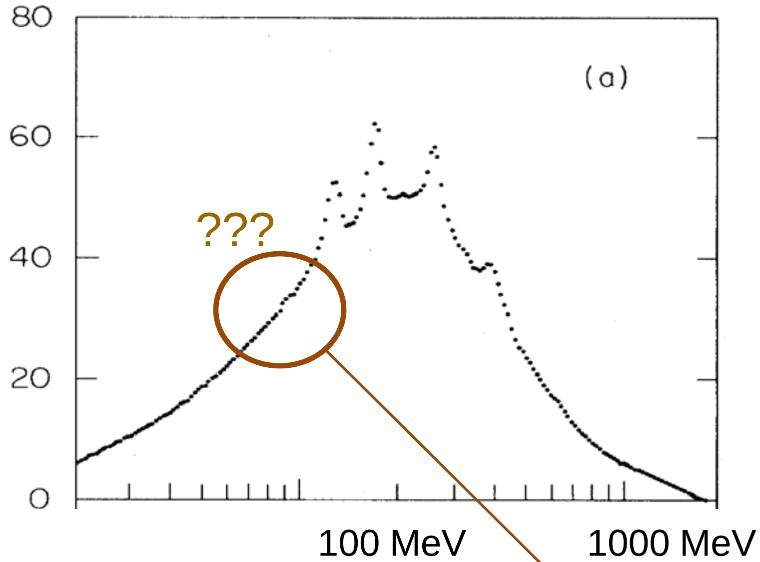
M & Γ still not well measured!

However, see recent papers by BES III, Belle & BaBar

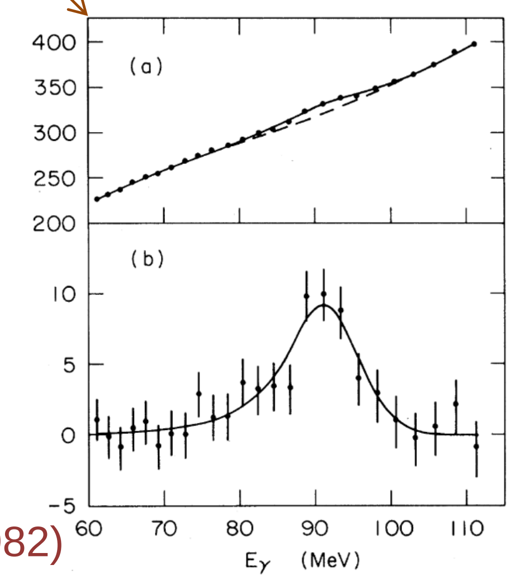
Search for the η_c'



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



Never Confirmed

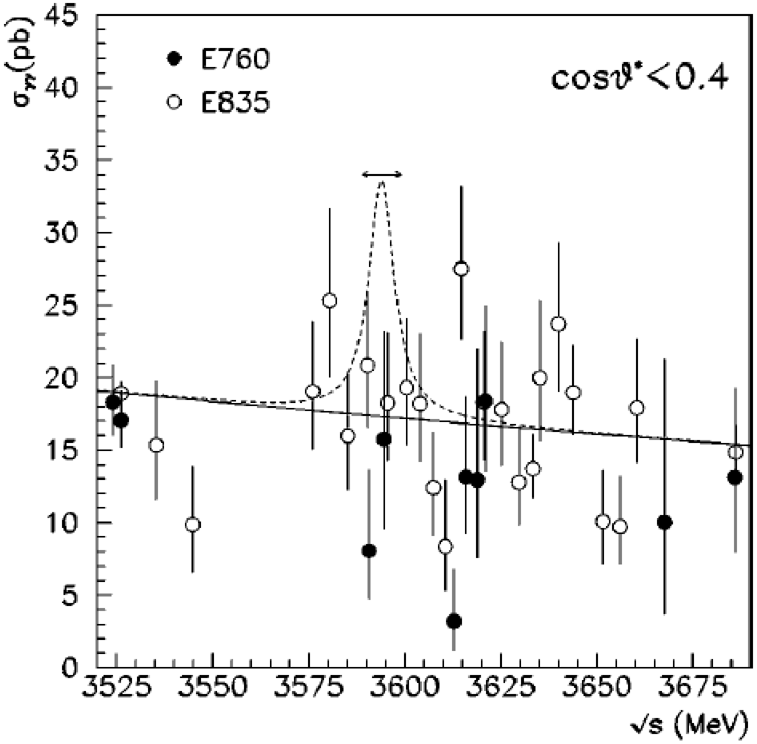


M_{η_c}=3592±5 MeV
Γ<8 MeV

Xtal-Ball PRL 48, 70 (1982)

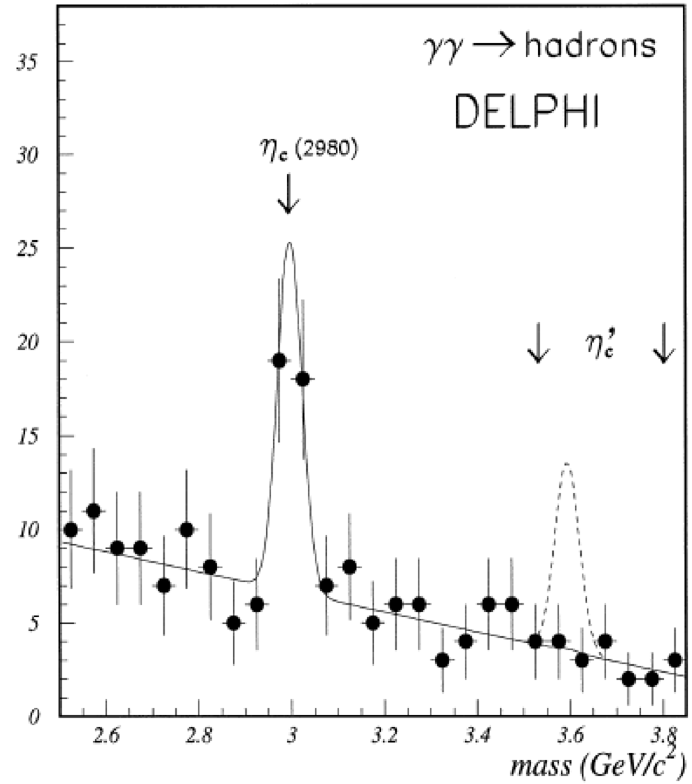
M=3592 MeV η_c' not seen elsewhere

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



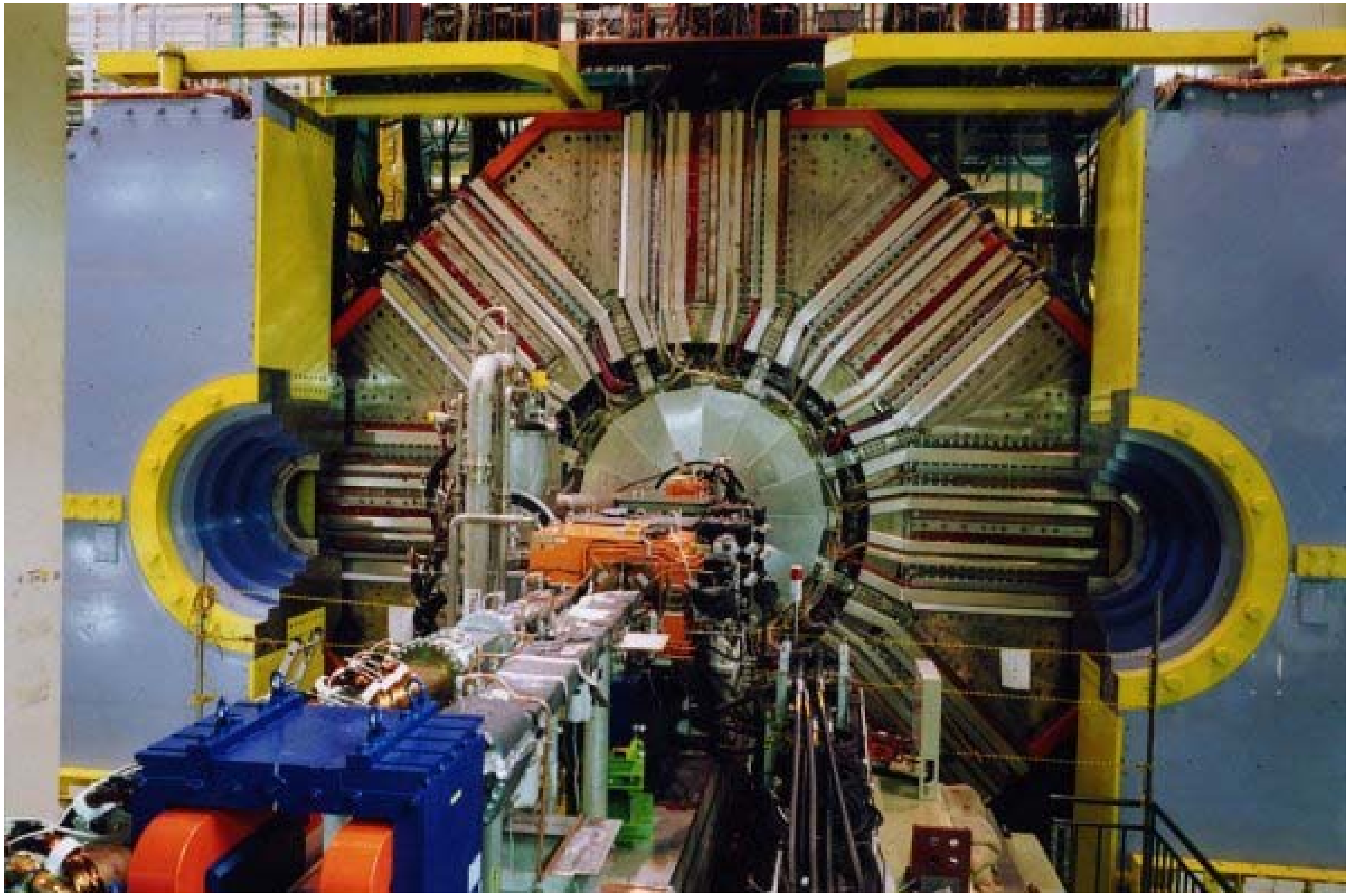
E835 PRD **64**, 052003 (2001)

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



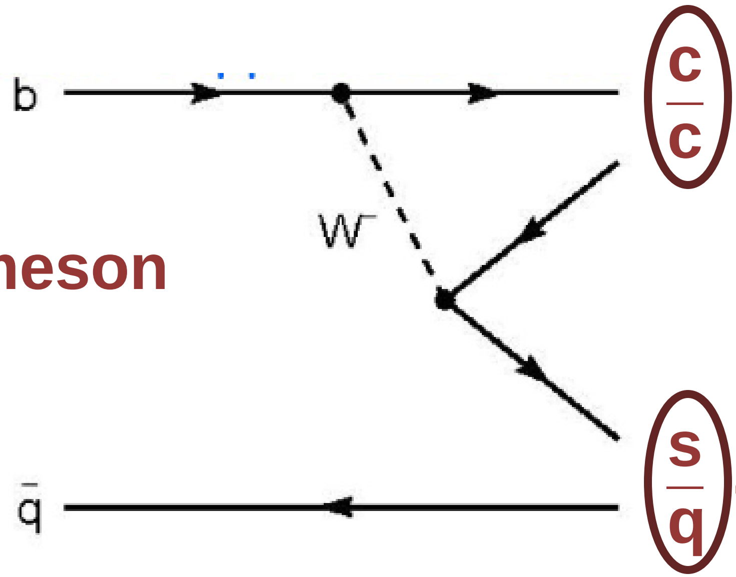
DELPHI PL **B441**, 479 (1998)

The Belle experiment at KEK



Belle in 2002 (20 yrs later)

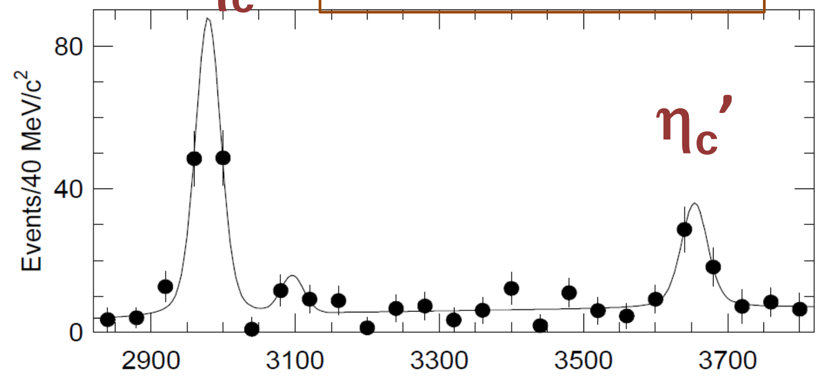
B meson



→η_c (η_c' ??) →$K_S K^+ \pi^-$

→K

M_{η_c}=3654±10 MeV
Γ<55 MeV



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

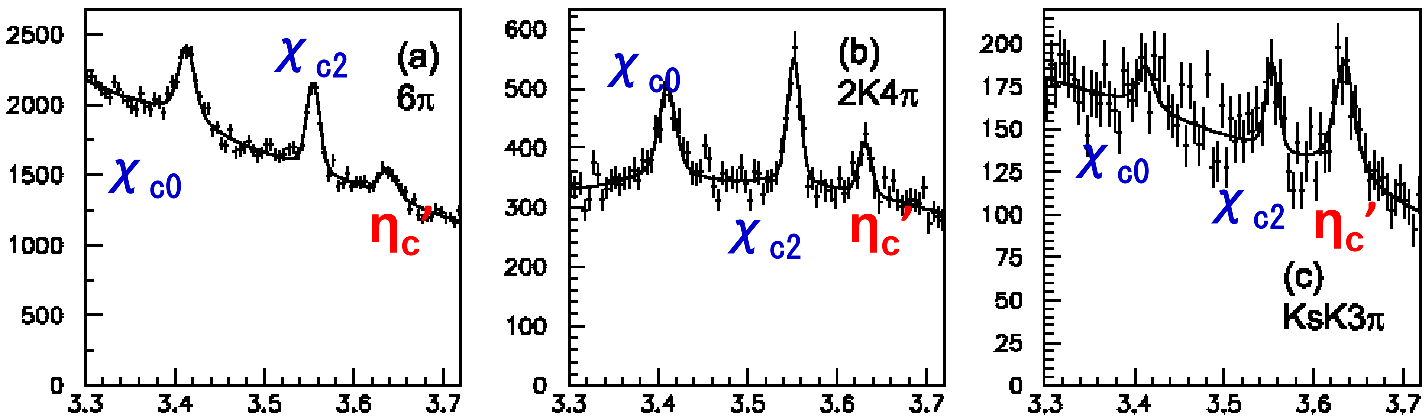
"invariant mass" →

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

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

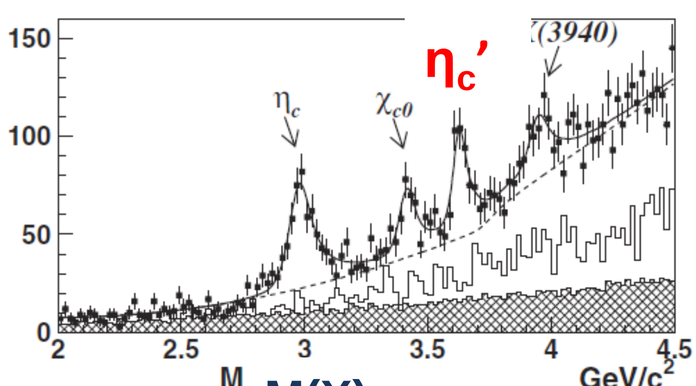
Confirmed by other measurements

Belle: $\gamma\gamma \rightarrow 3(\pi^+\pi^-)$ $\gamma\gamma \rightarrow K^+K^- 2(\pi^+\pi^-)$ $\gamma\gamma \rightarrow K_S K^+\pi^+\pi^-\pi^-$

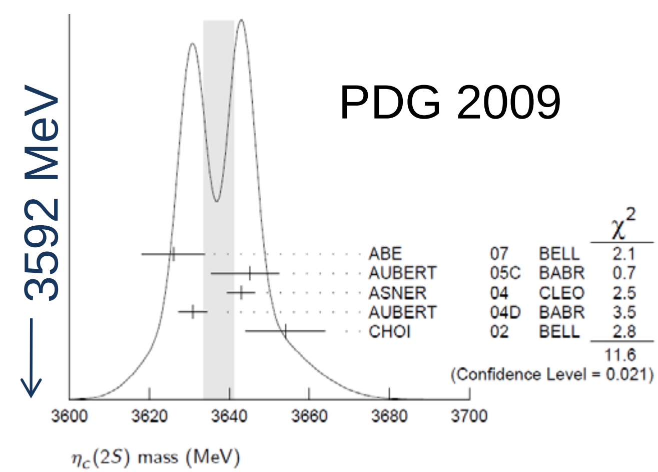


Belle: 2010 (preliminary)

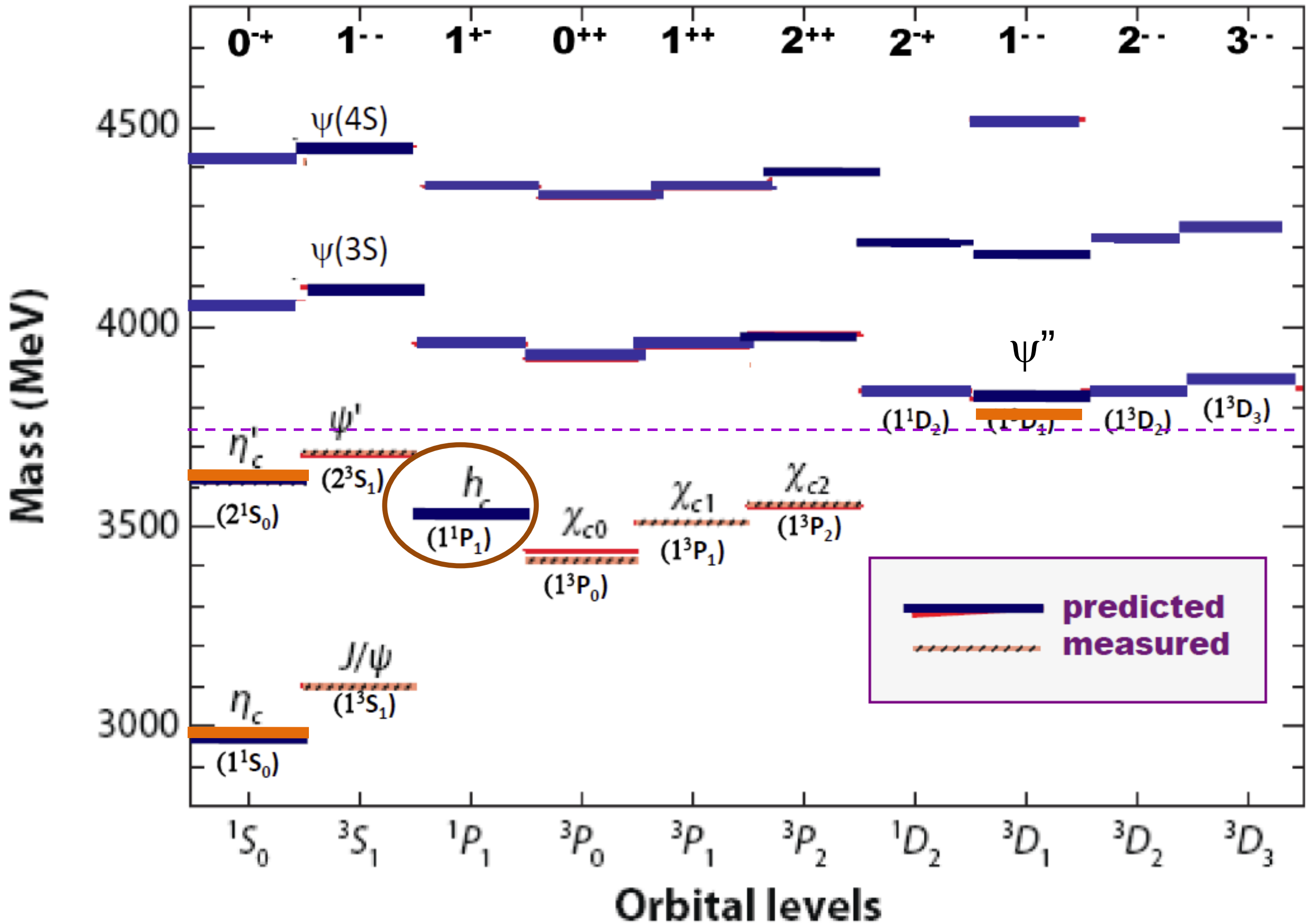
Belle: $e^+e^- \rightarrow J/\psi + X$



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

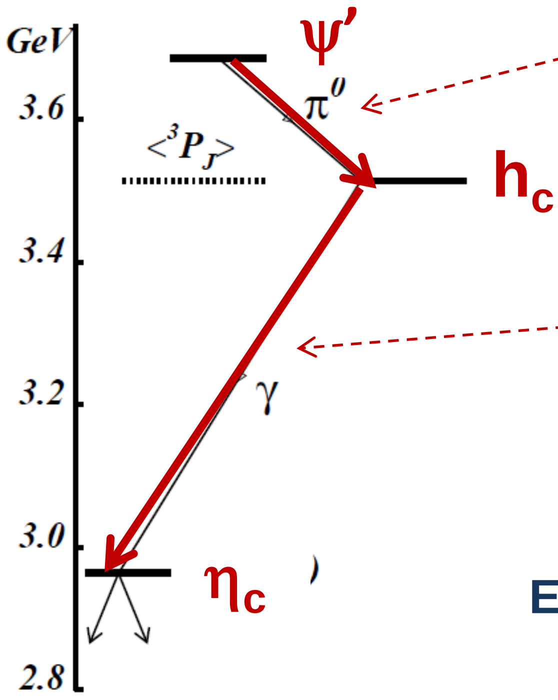


Search for the h_c



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 suppressed

expected branching fraction ≈ 10^{-3}

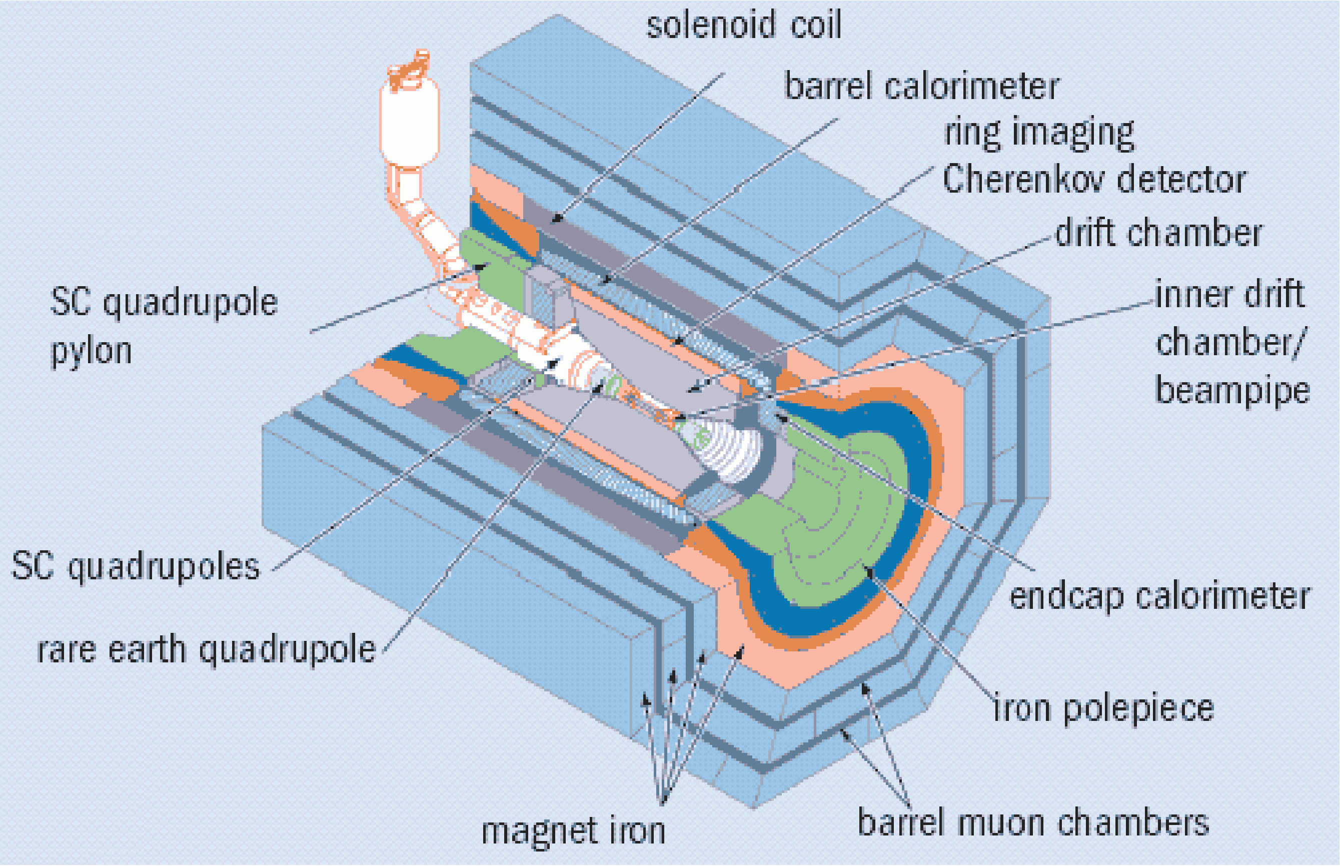
preferred h_c decay mode is $h_c \rightarrow \gamma\eta_c$

expected branching fraction ≈ 0.4

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

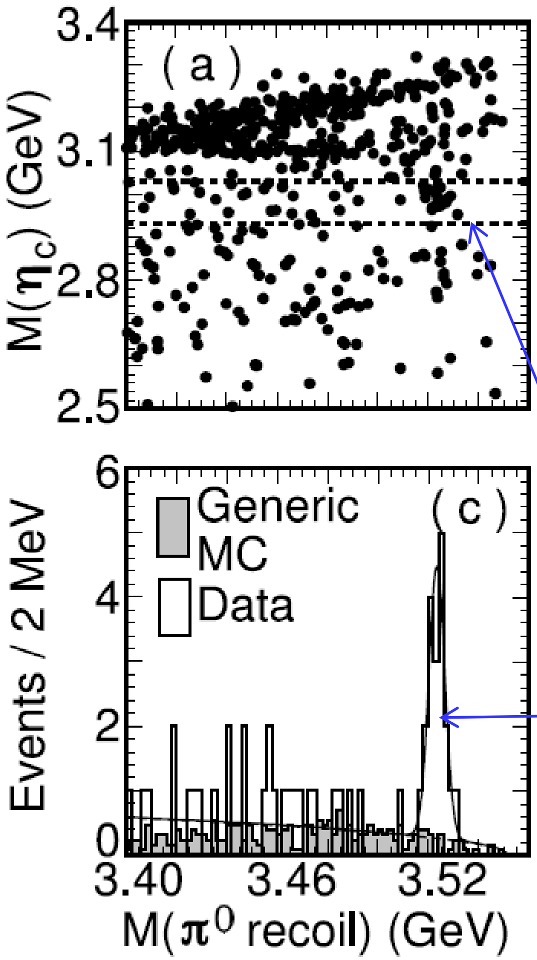
$=[M(\chi_{c0}) + 3\,M(\chi_{c1}) + 5\,M(\chi_{c2})]/9 = 3.525$ MeV

CLEO detector at Cornell Univ



h_c: CLEO 2005 (exclusive)

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



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

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

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

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

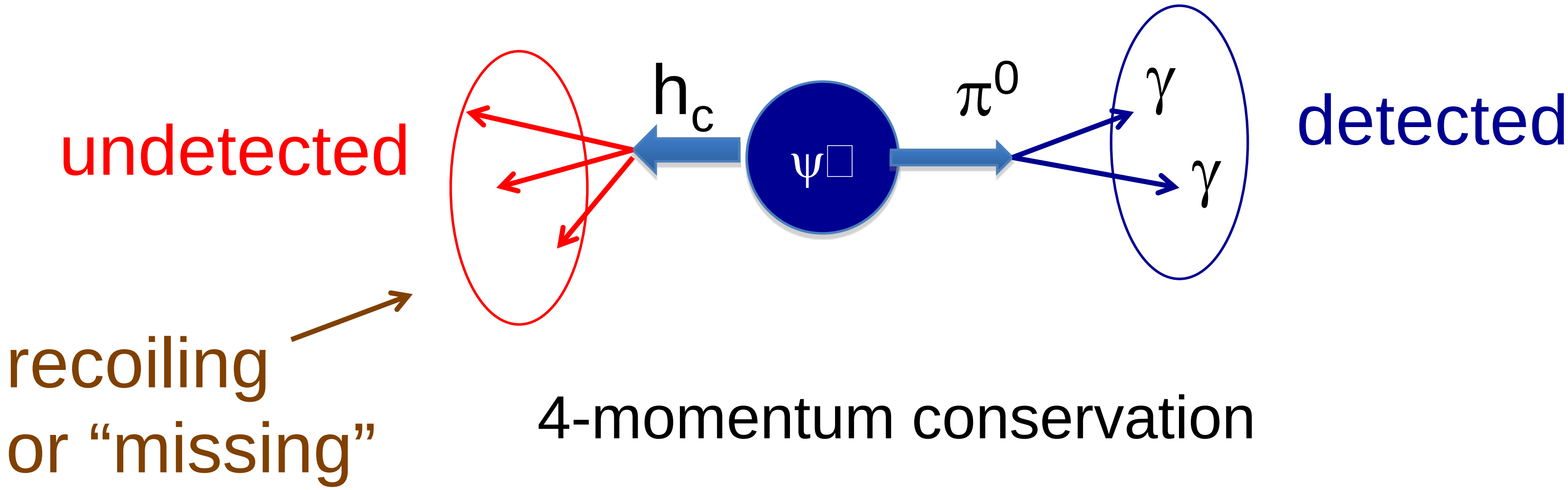
$\eta_c \to \pi^+ \pi^- \eta, \quad \eta \to \gamma\gamma$

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

clean $h_c \to \gamma\, \eta_c$ signal

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

Recoil mass (or “Missing mass”}



4-momentum conservation

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

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

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

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

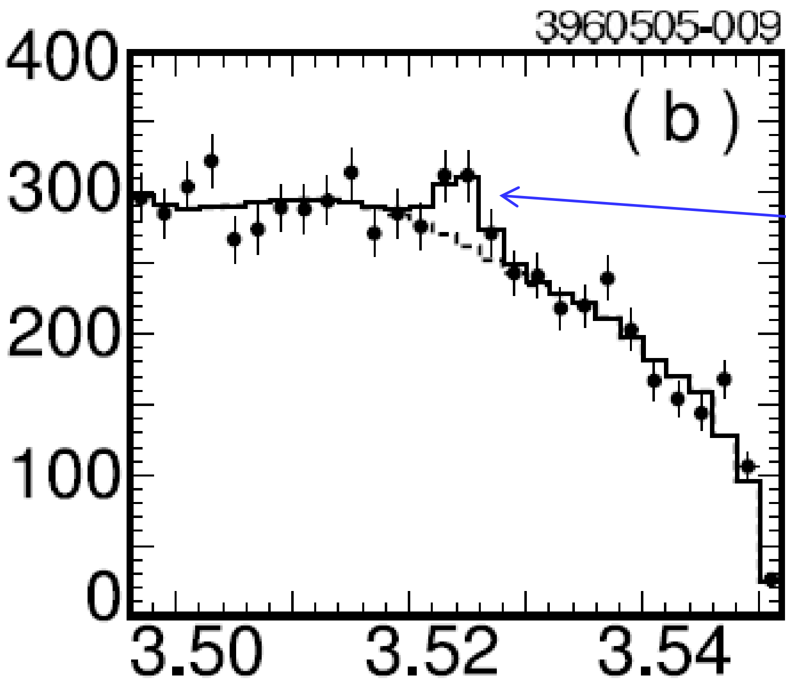
Recoil mass (or “missing mass”

h_c: CLEO 2005 (semi-inclusive)

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

undetected

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



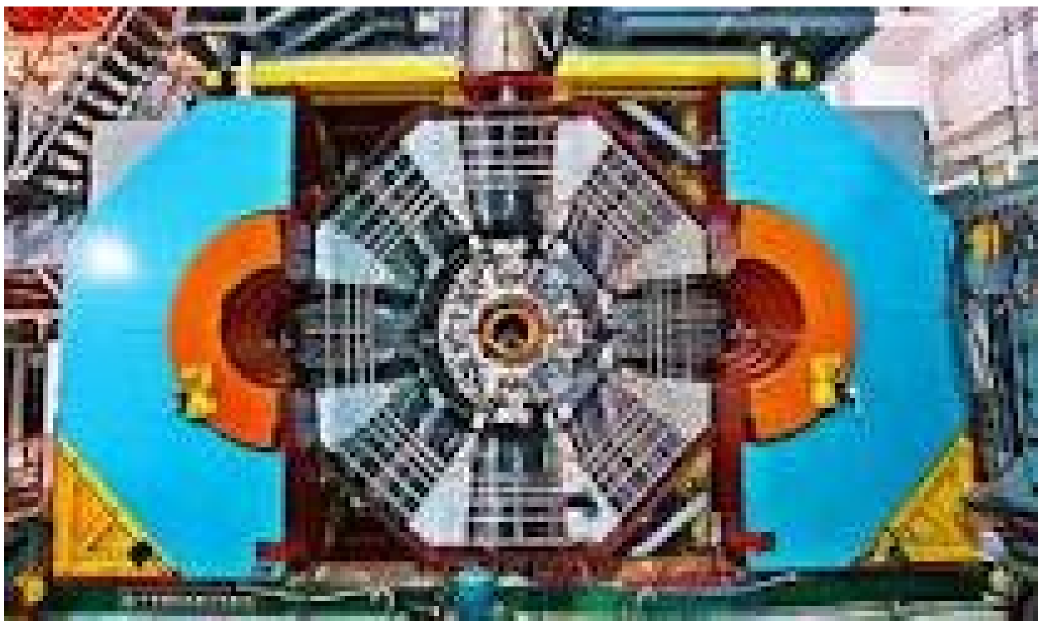
Mass recoiling from the π^0

$h_c \to \gamma\ \eta_c$ signal

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

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

BESIII experiment at IHEP(Beijing)



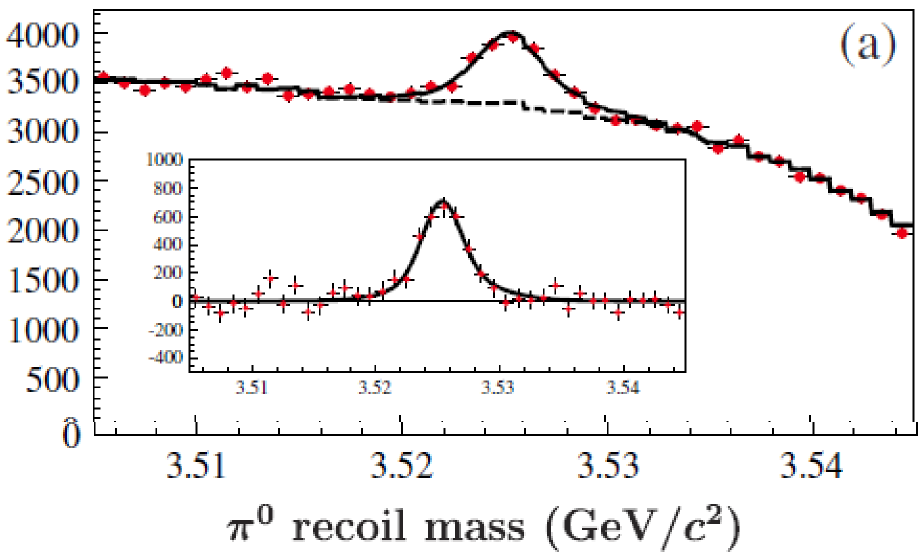
h_c: BES III 2010 (fully inclusive)

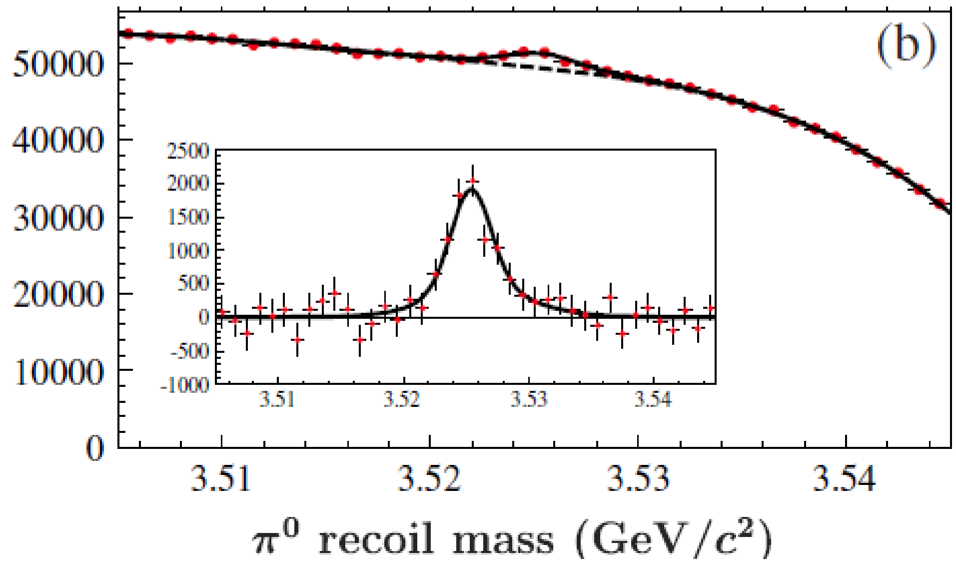
Semi-inclusive: $\psi' \rightarrow \pi^0 h_c$, $h_c \rightarrow \gamma \eta_c$

Detect: π^0 & γ

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

Detect: π^0 only





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

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

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

h_c: BES III results

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

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

agree with theory
YP Kuang PRD 65 094024

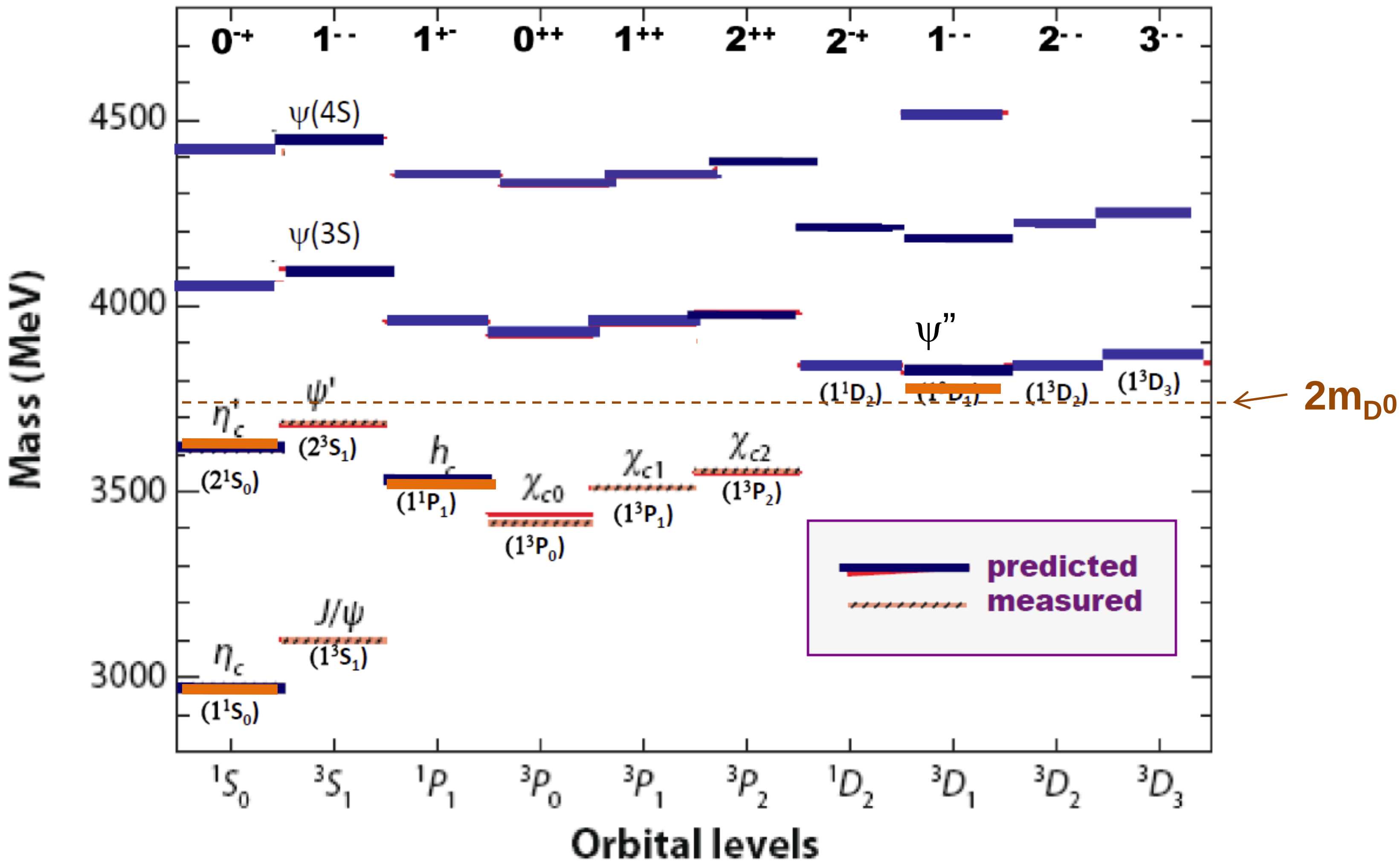
$M(h_c) = 3525.4 \pm 0.22$ MeV

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

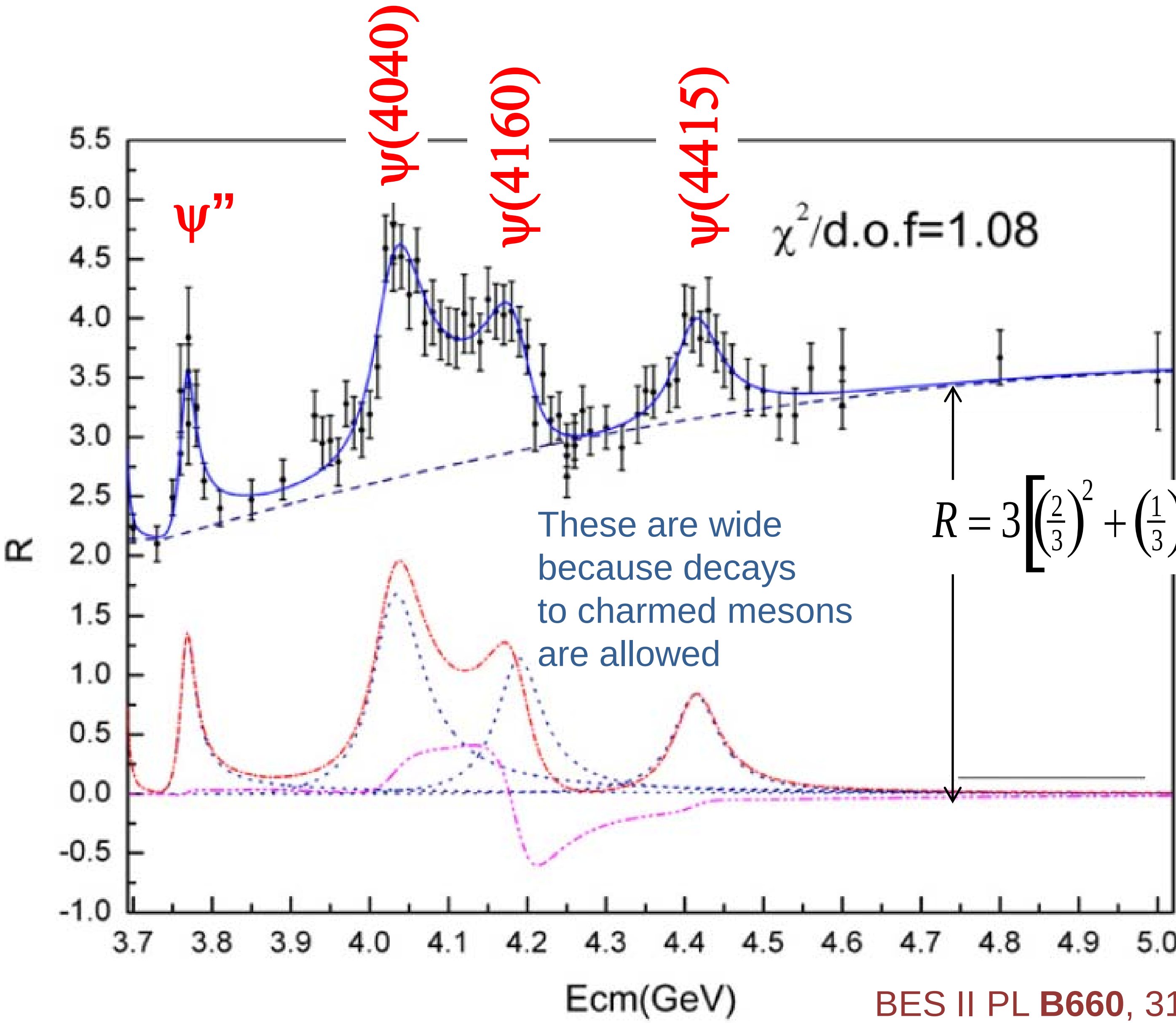
$M_{cog}(\chi_{c0,1,2}) = 3525.3$ MeV

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

All states below "open charm" threshold are identified



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

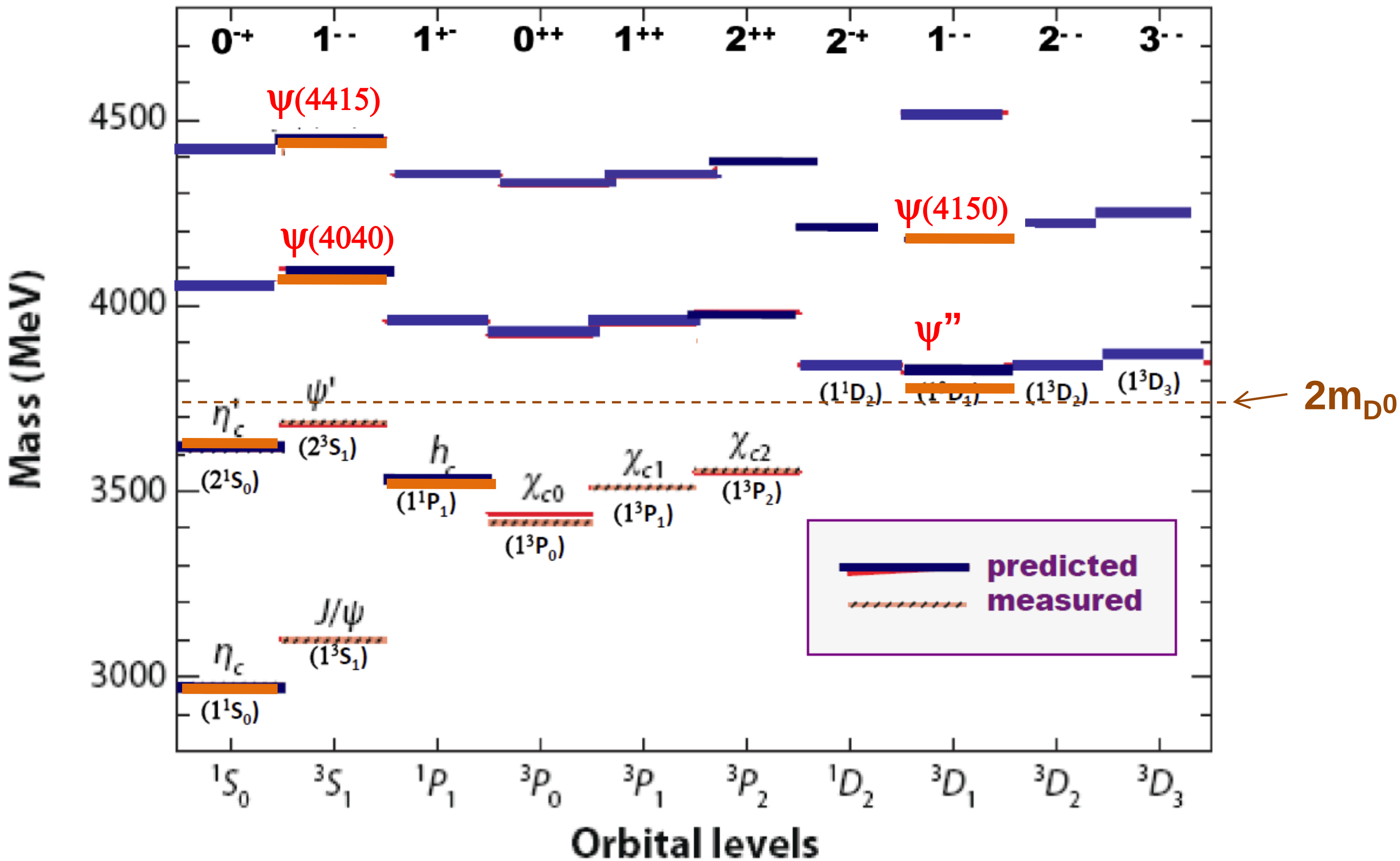


These are wide because decays to charmed mesons are allowed

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

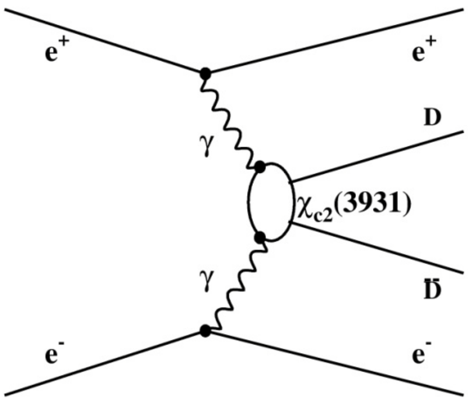
BES II PL **B660**, 315 (2008)

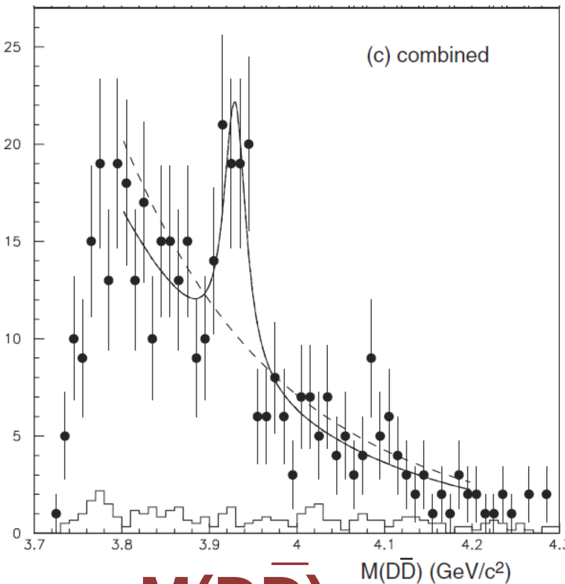
All 1^{--} states below 4500 MeV are identified



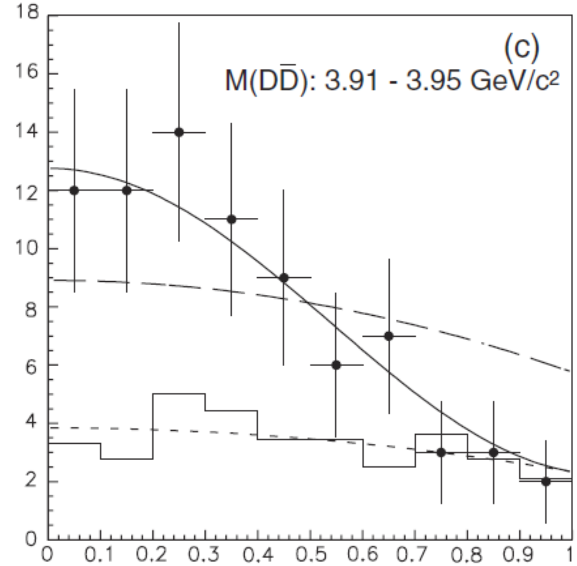
χ'_{c2} discovered by Belle

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





M(DD̄)



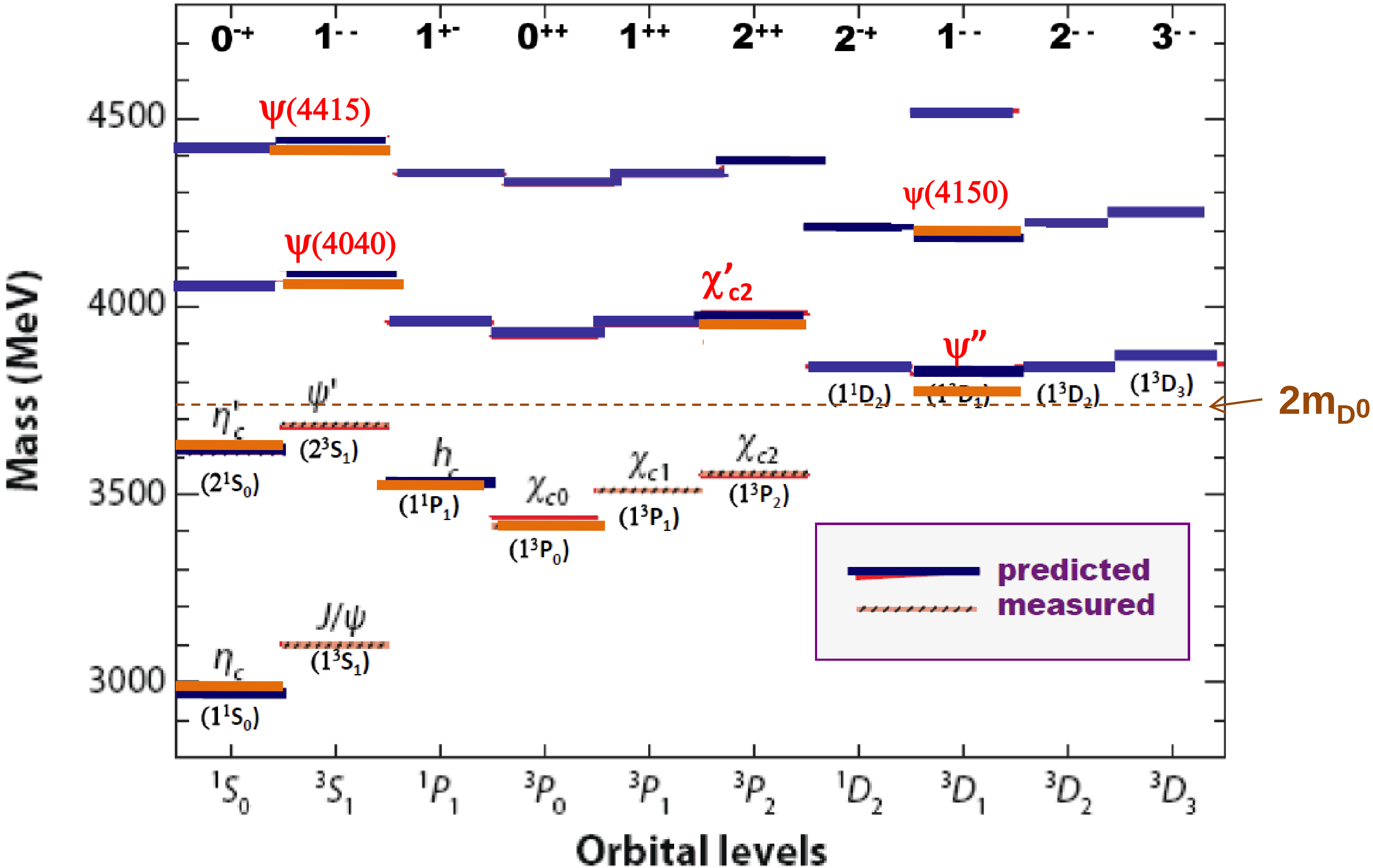
|cosθ|

"two-photon" collisions

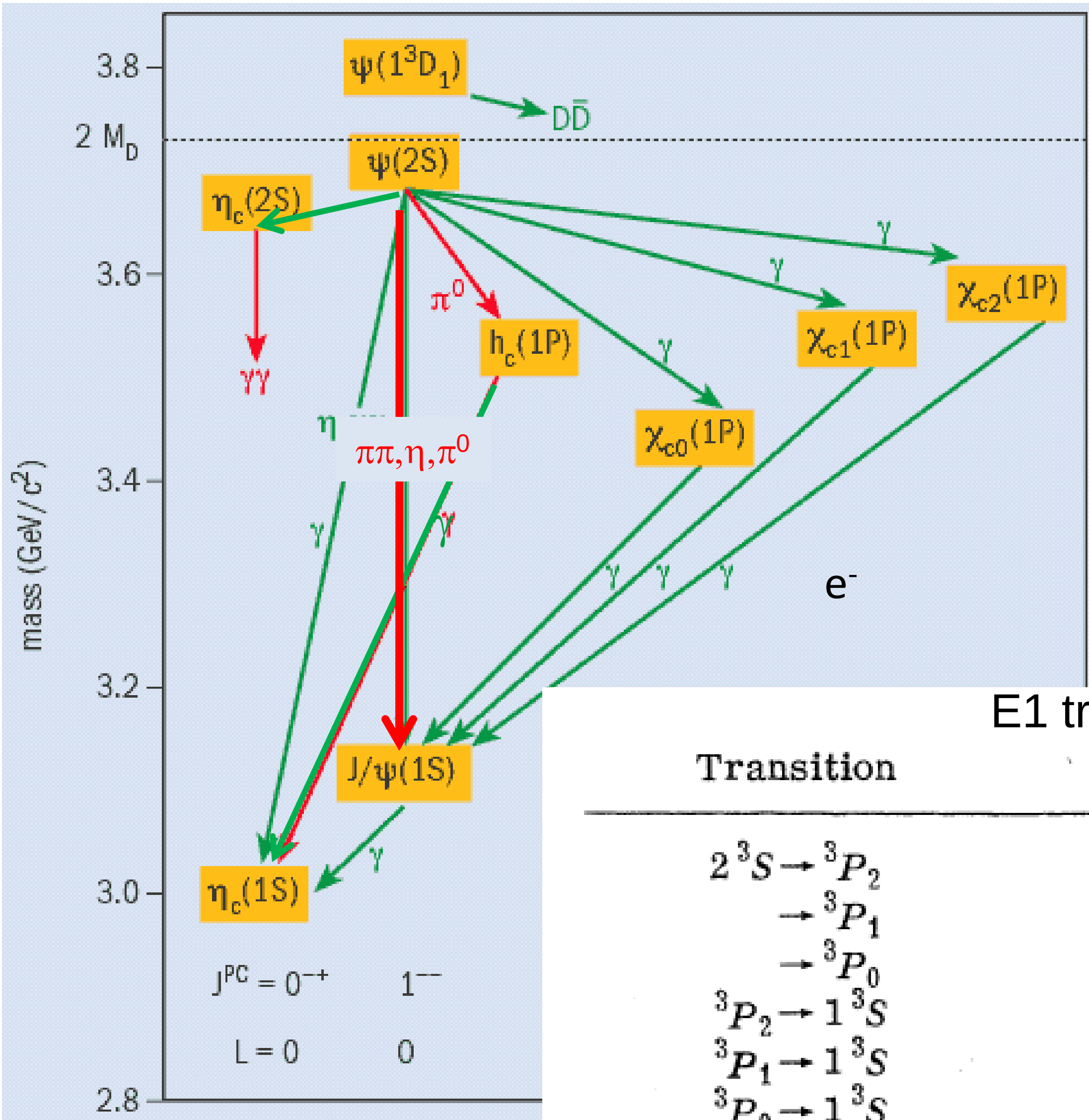
results: $M(\chi_{c2}) = 3929 \pm 5$ MeV
$\Gamma(\chi_{c2}) = 29 \pm 10$ MeV

Charmonium spectrum today

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



γ Transitions



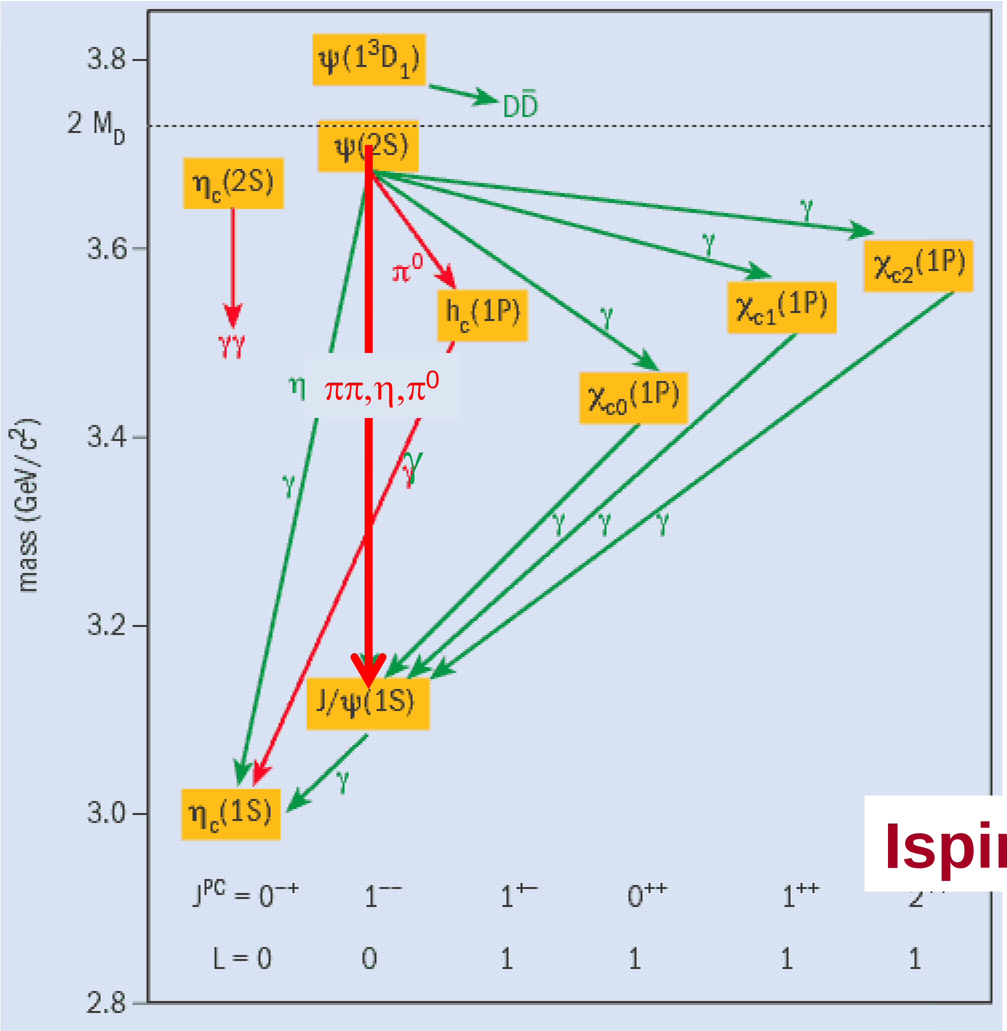
M1 transitions (Γ(keV))

	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*

E1 transitions

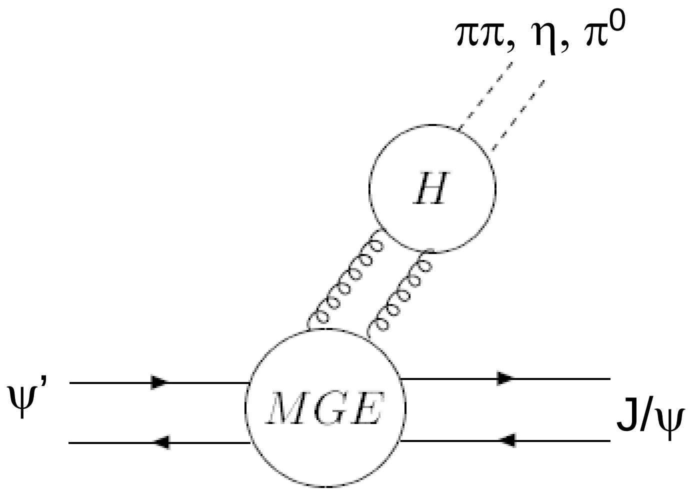
Transition	Γ_γ	*Th.*	Γ_γ (keV) *Expt*
$2\,^3S \rightarrow {}^3P_2$	$5 I_1 \alpha k^3$	*24*	*27 ± 4*
$\rightarrow {}^3P_1$	$3 I_1 \alpha k^3$	*29*	*27 ± 3*
$\rightarrow {}^3P_0$	$1 I_1 \alpha k^3$	*26*	*27 ± 3*
${}^3P_2 \rightarrow 1\,^3S$	$I_2 \alpha k^3$	*313*	*426 ± 51*
${}^3P_1 \rightarrow 1\,^3S$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

Hadronic transitions



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

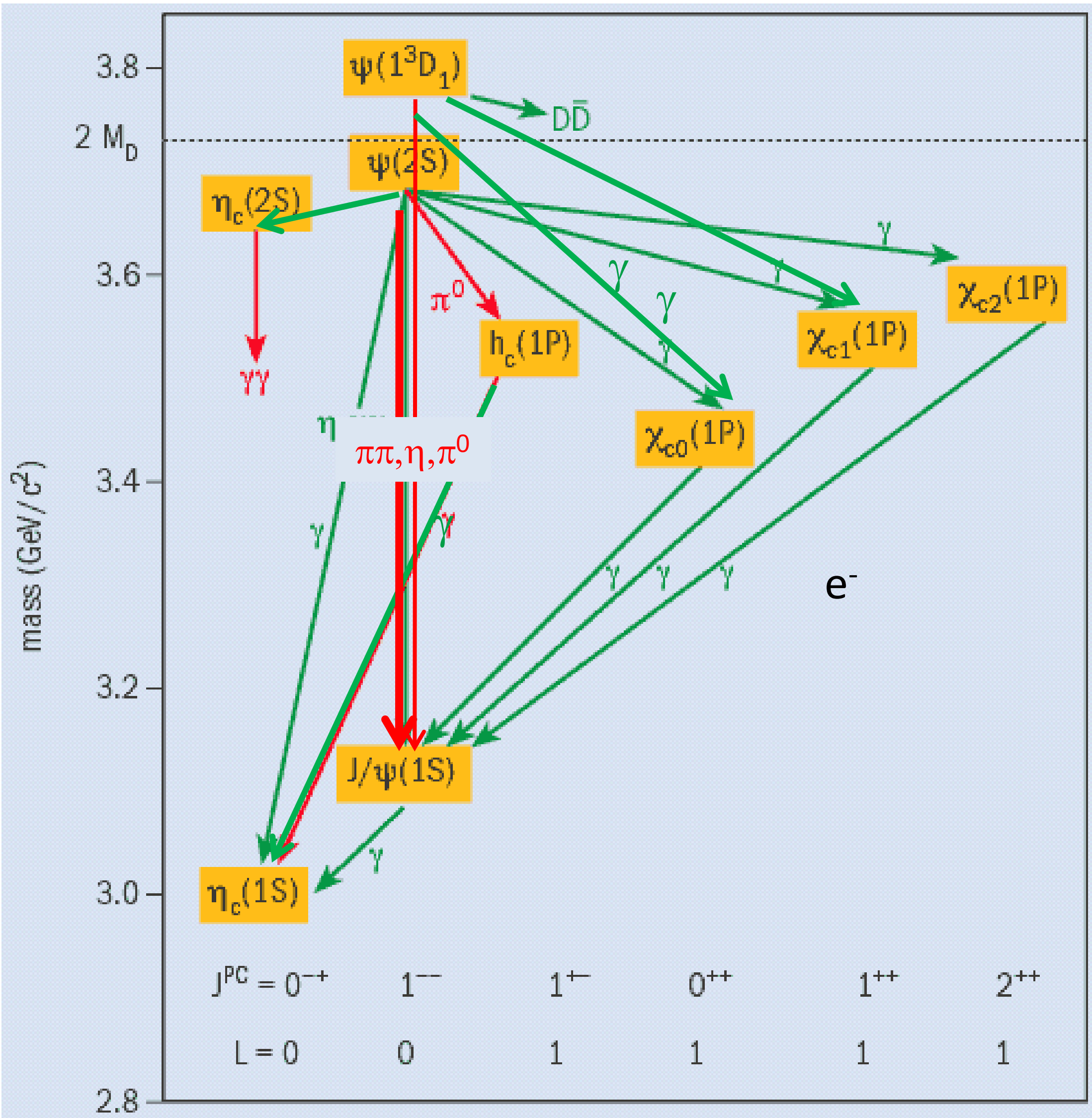
	Γ_{exp}(keV)
$\psi' \rightarrow \pi^+\pi^- J/\psi$	*88 ± 7*
$\psi' \rightarrow \eta J/\psi$	*9 ± 1*
$\psi' \rightarrow \pi^0 J/\psi$	*0.4±0.1*



Ispin violation:

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

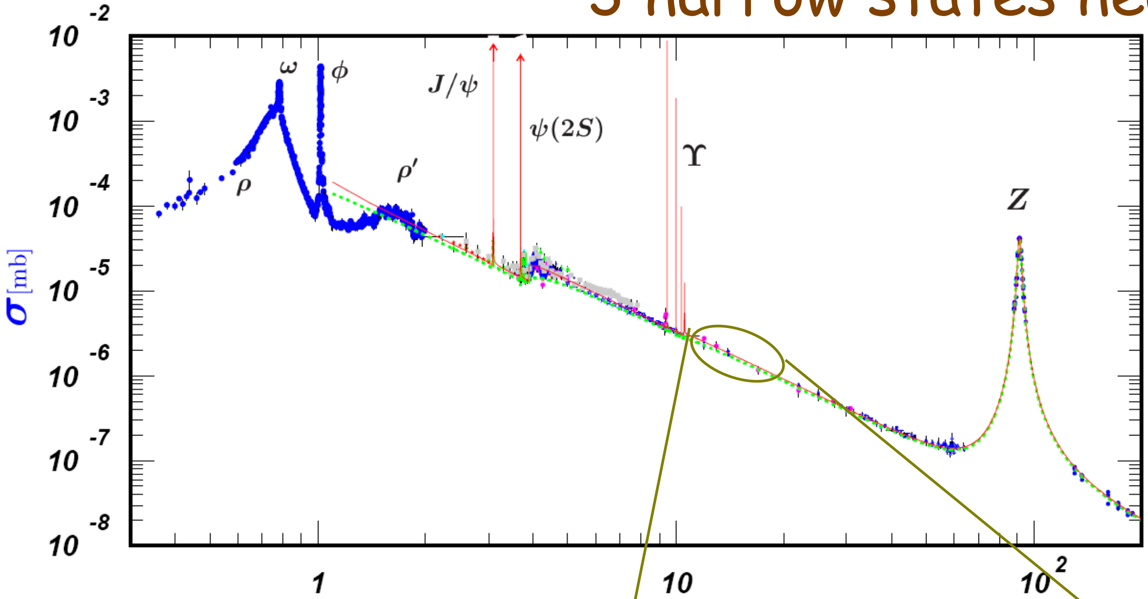
Predictions & measurements for the ψ”



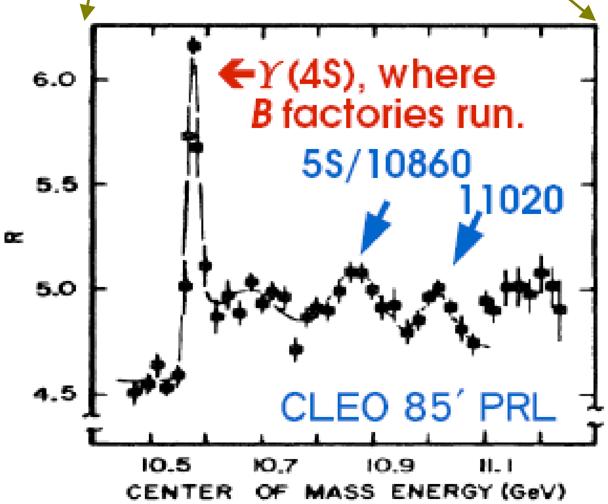
	Γ_{exp}(keV) *th.*	*Expt*
$\psi'' \rightarrow \pi^+\pi^- J/\psi$	*~80*	*55 ± 15*
$\psi'' \rightarrow \gamma\, \chi_{c1}$	*77*	*70 ± 17*
$\psi'' \rightarrow \gamma\chi_{c0}$	*213*	*172 ±30*

Bottomonium: history repeats itself

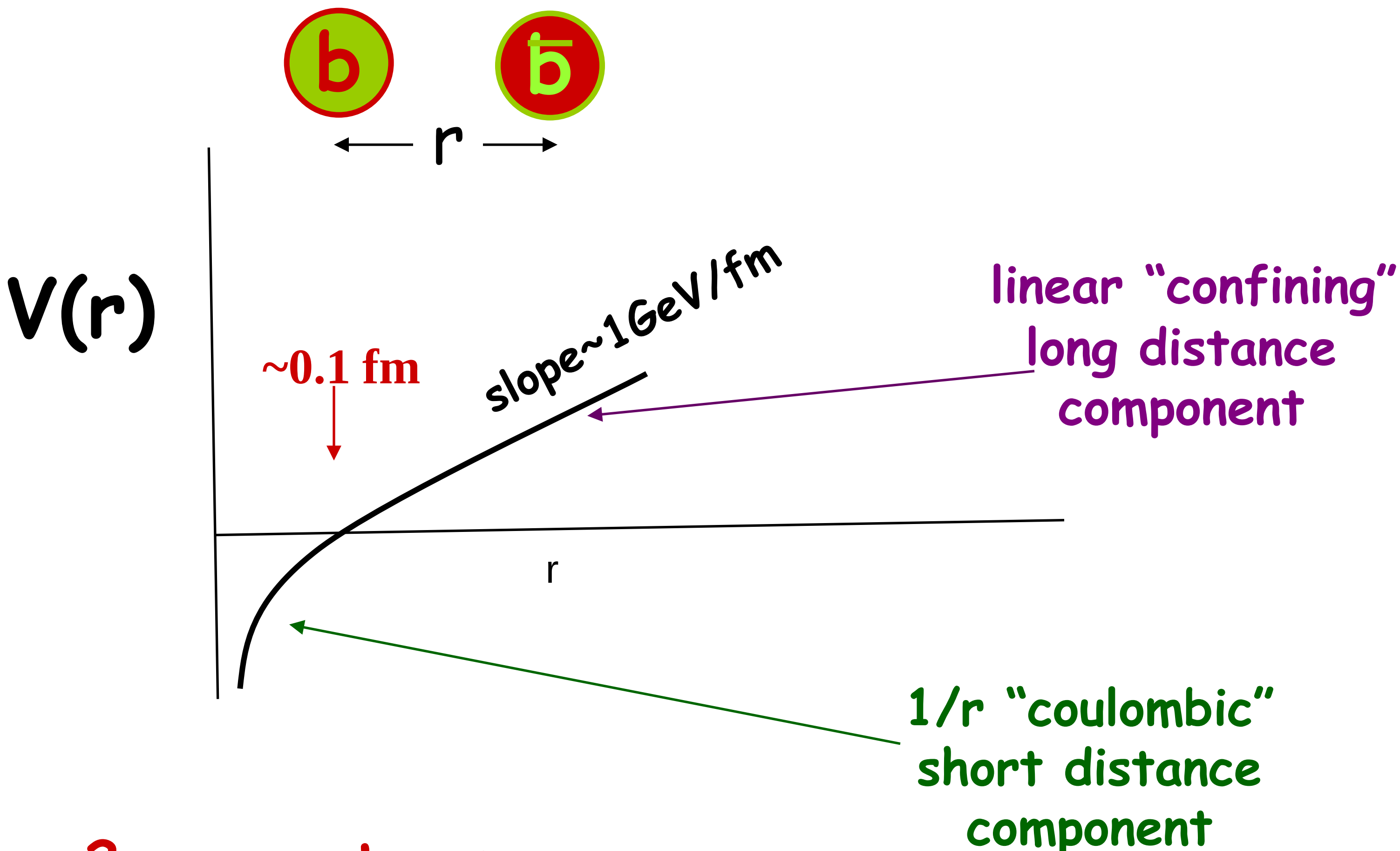
3 narrow states near 10 GeV



Plus broad states at higher masses

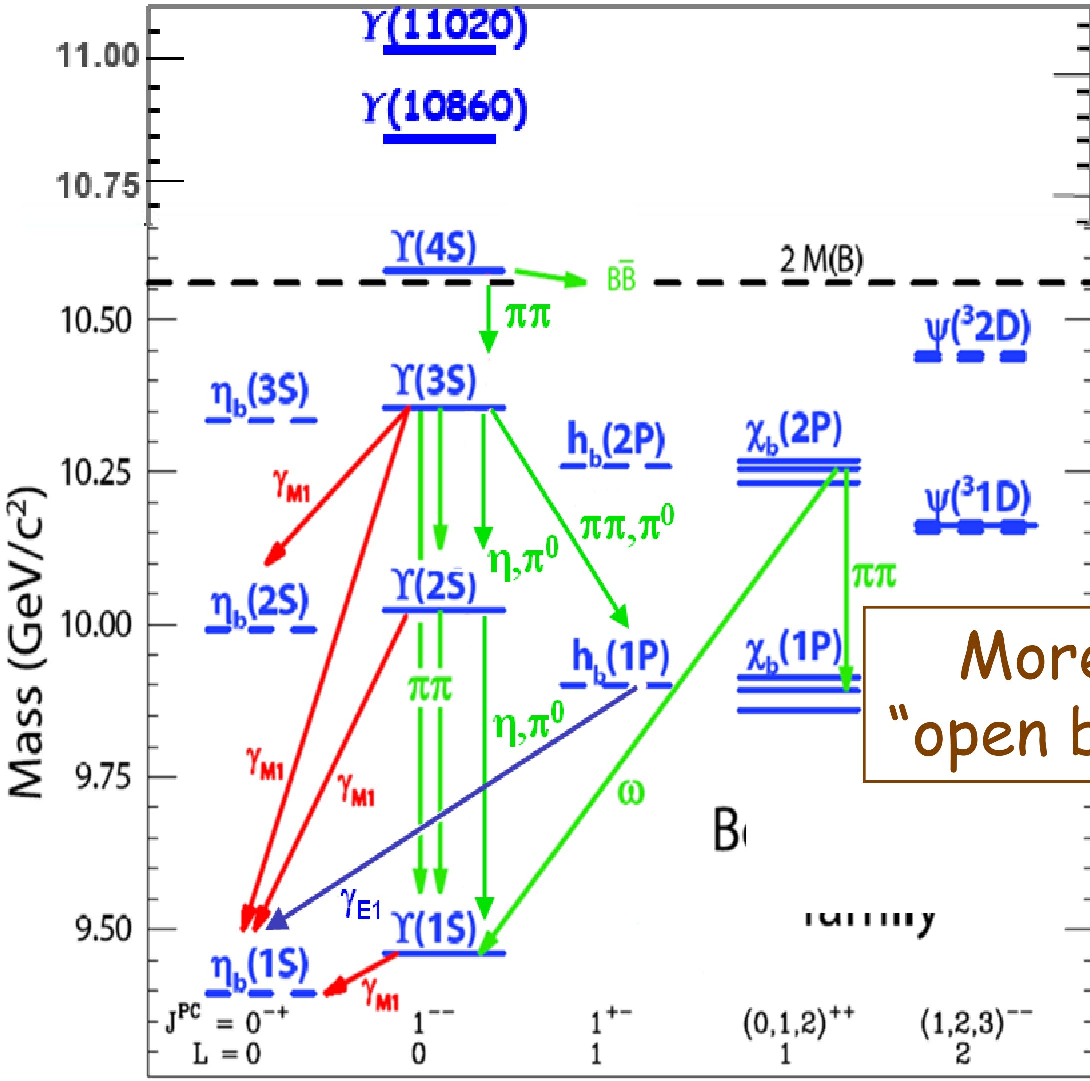


Same potential works



2 parameters:
slope & intercept

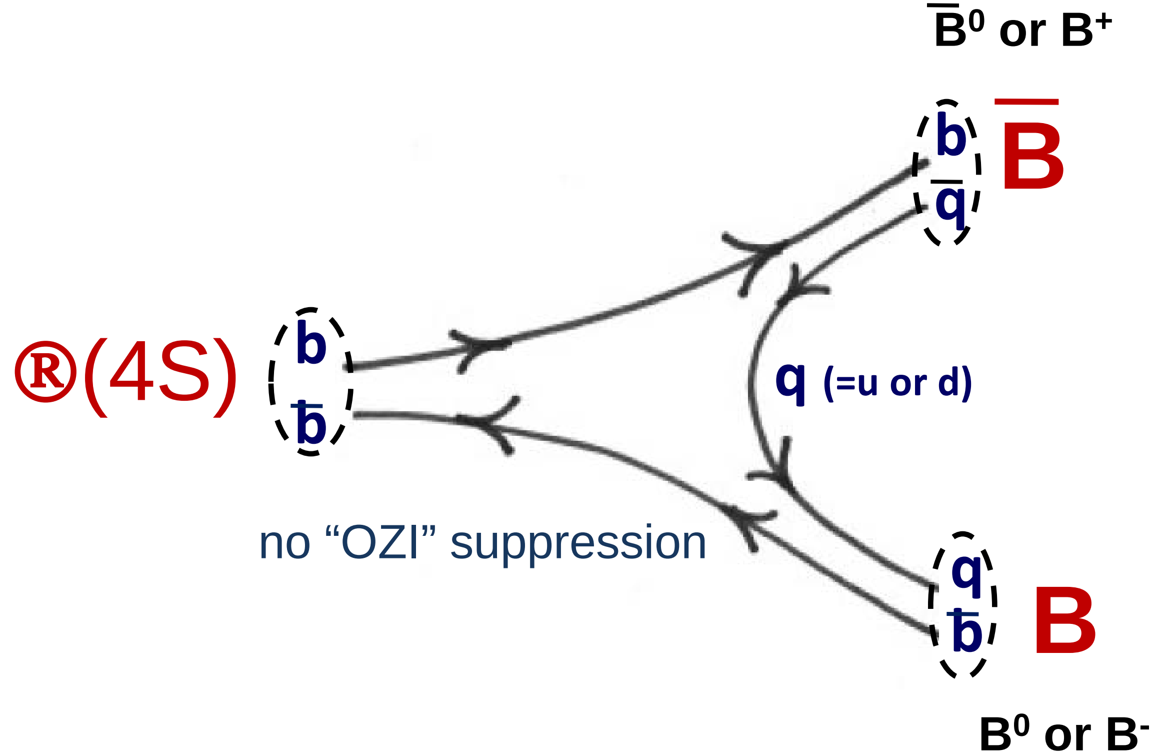
Bottomonium spectrum

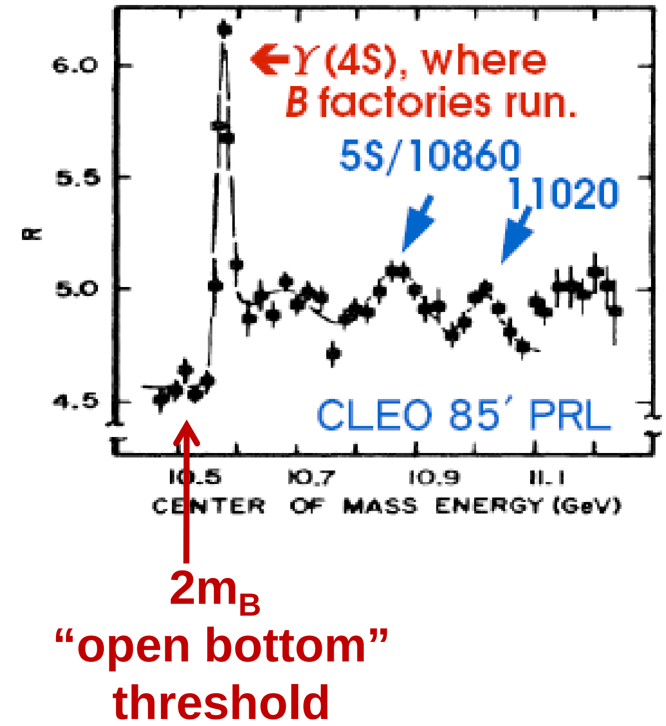


$2M_B$ = 10.56 GeV

More states below "open bottom" threshold

“Fall apart” decays to “B” mesons



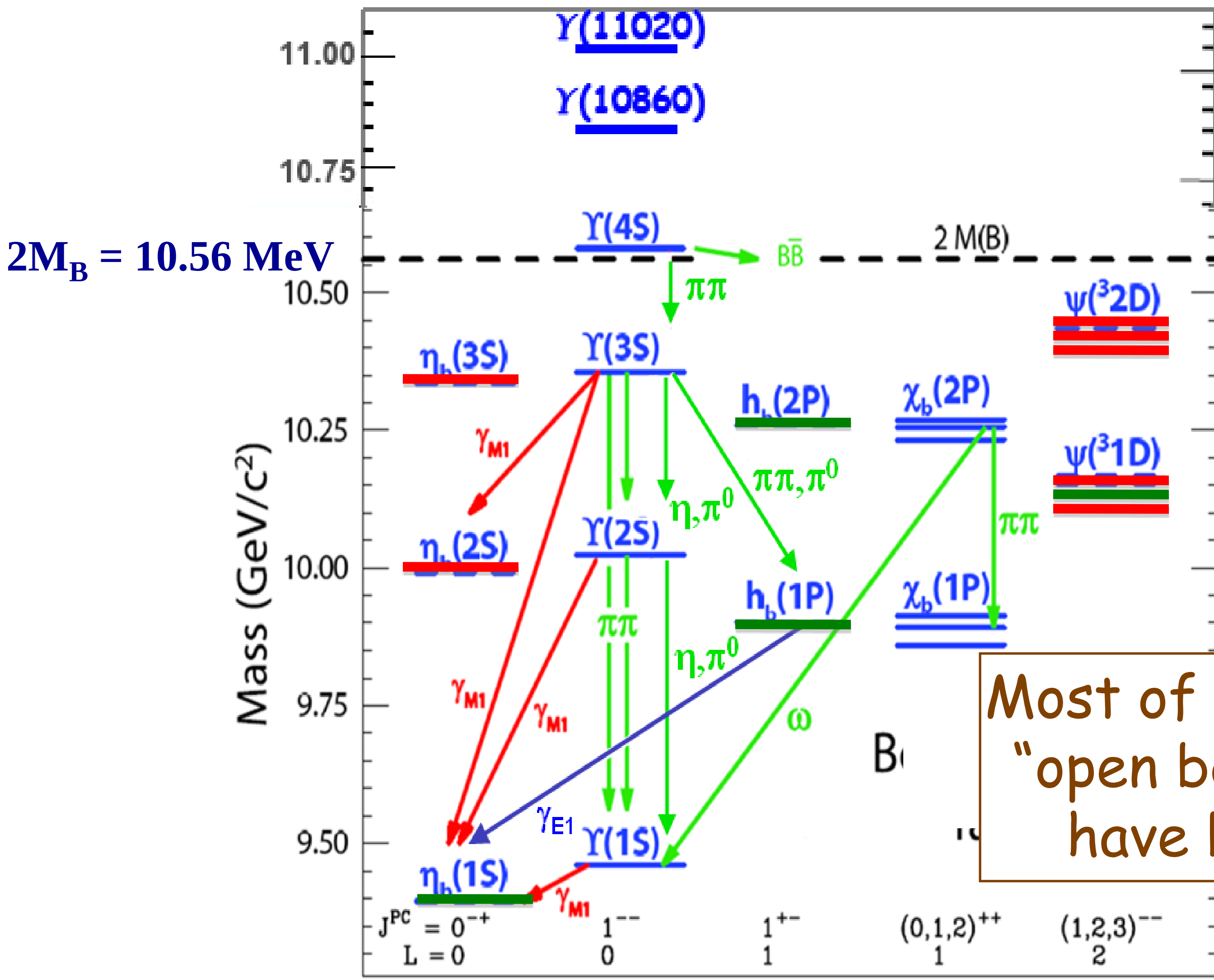


$(M_{\text{®’(4S)}}=10.58$ GeV)

$2m_B=10.56$ GeV

$(M_{\text{®’(3S)}}=10.36$ GeV)

Bottomonium spectrum 2011



- established
- recently discovered
- still not discovered

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

Summary (lecture 1)

- The quarkonium spectra are strong 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 threshold, most of the 1^{--} states, but only one of the others (the χ_{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.
    - The subject of lecture 2

Thank You

Merci

どもぅ　ありがとぅ

감사합니다

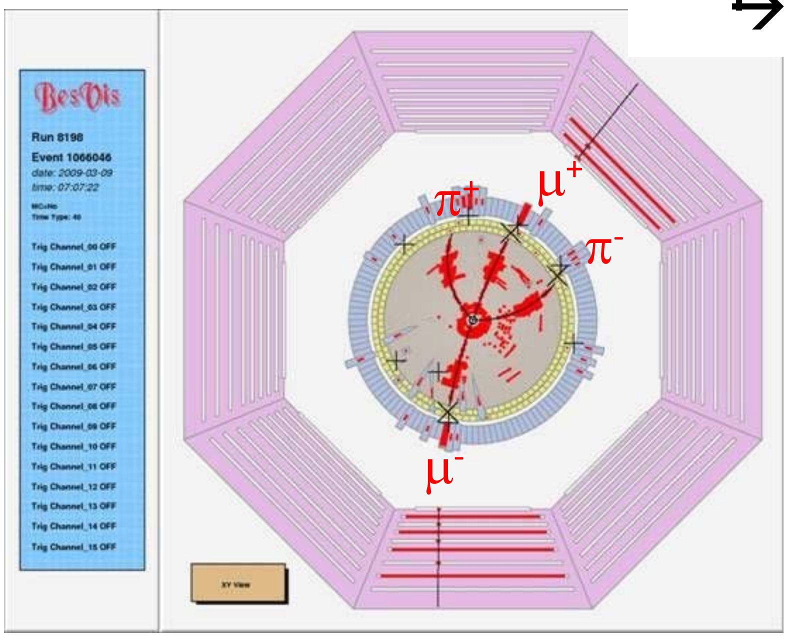
謝謝

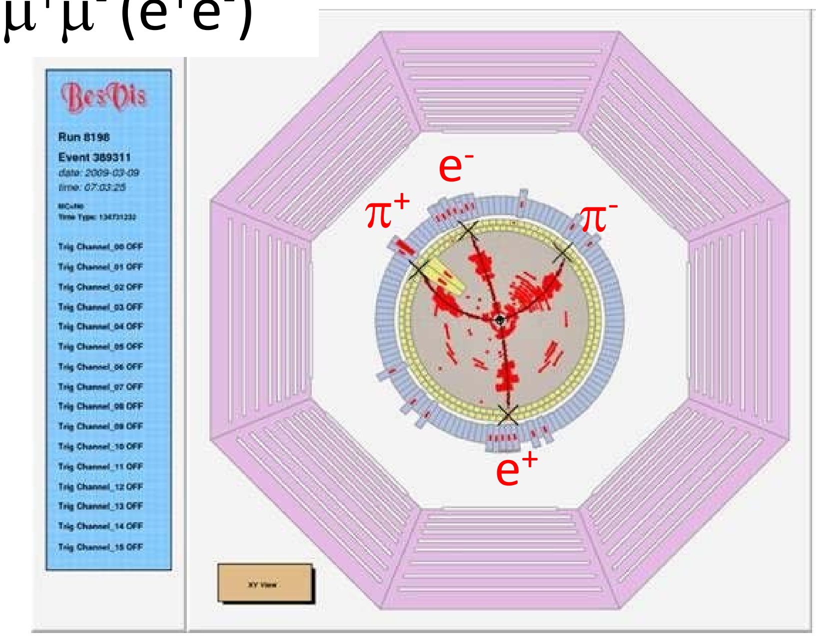
Quarkonium

experimental overview I

$\psi' \to \pi^+\pi^- J/\psi$ in the BESIII detector

↳ $\mu^+\mu^-$ (e^+e^-)





Stephen Lars Olsen

Seoul National University

France-Asia Particle Physics School, Les Houches, FRANCE

October 11-12, 2011

outline

Lecture1: The bound charmonium & bottomonium states and their properties

Lecture 2: The non-quarkonium, quarkonium-like states & the future