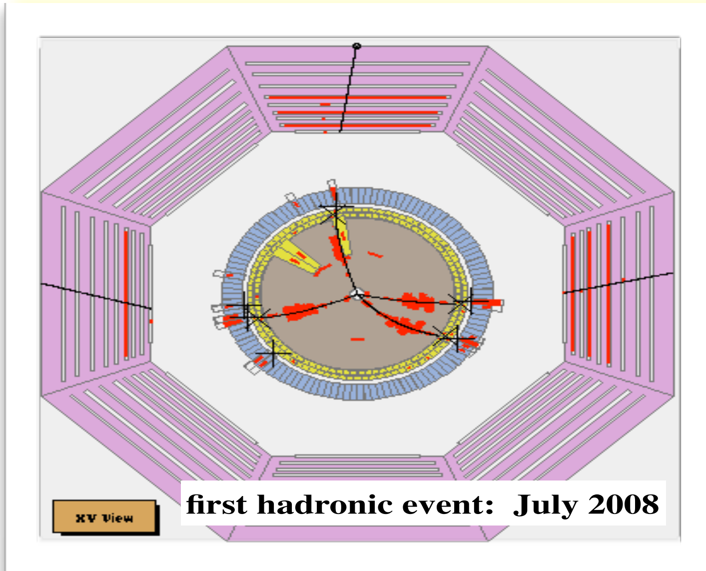
Hadronic Decay Studies in Charmonium with BESIII

Johan Messchendorp, KVI/University of Groningen
Workshop on Charmonium Decays,
Orsay, 7th of March 2013

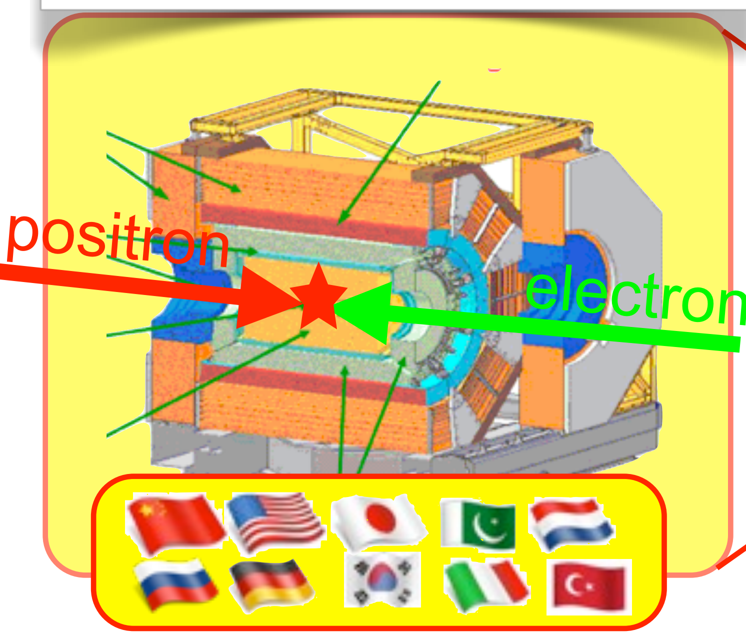
Discovery and precision with Charmonium

- B (looks like DD for D or charm physics)
- E (looks like cc for charmonium physics)
- S (for light hadron Spectroscopy)
- T (for tau physics, looks like a Roman number “III”)

From 1974 till today: charmonium factories...

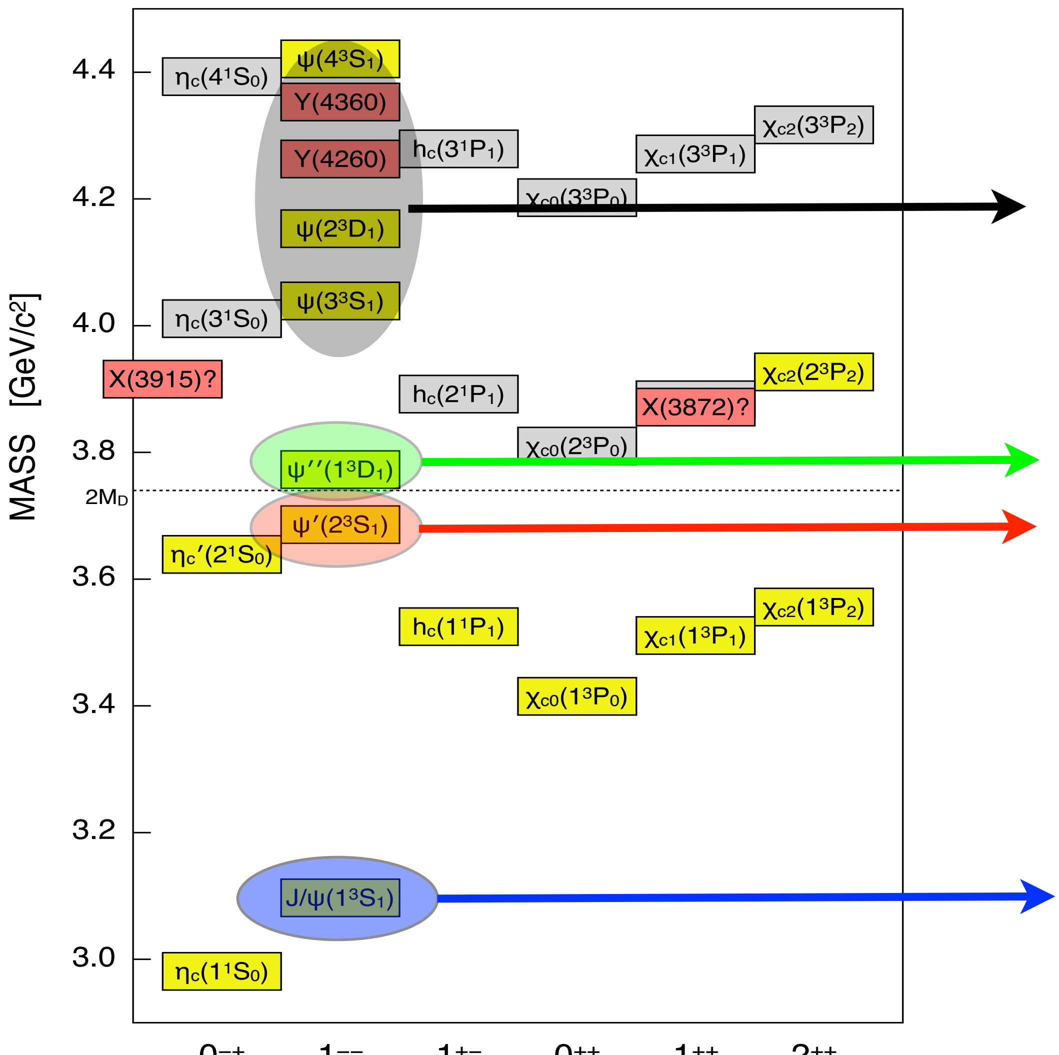


July 2008: first hadronic event
March 2009: physics data taking



BEijing **S**pectrometer - **III**

BESIII@BEPCII - breaking all records



NEW

~0.5 fb^{-1} @4360 MeV

~0.5 fb^{-1} @4260 MeV

~0.5 fb^{-1} @4010 MeV

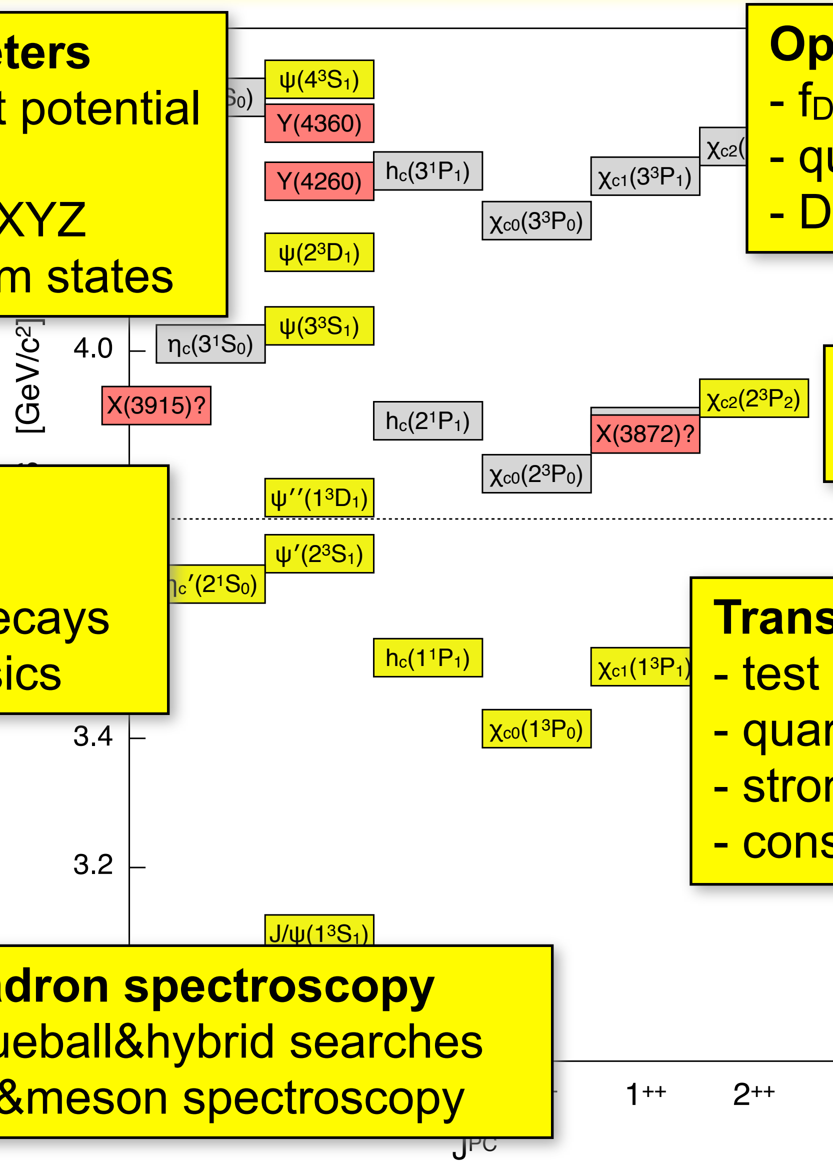
~2.9 fb^{-1}

~106 million (+more)

~225 million (+more)

~10-20x previous generation charmonium factories

Charmonium physics potentials



Resonance parameters
- details confinement potential
- line shape studies
- exotic resonances/XYZ
- missing charmonium states

Open charm ($D_{(s)}$)
- f_D decay constant
- quark mixing matrix
- D_s spectroscopy

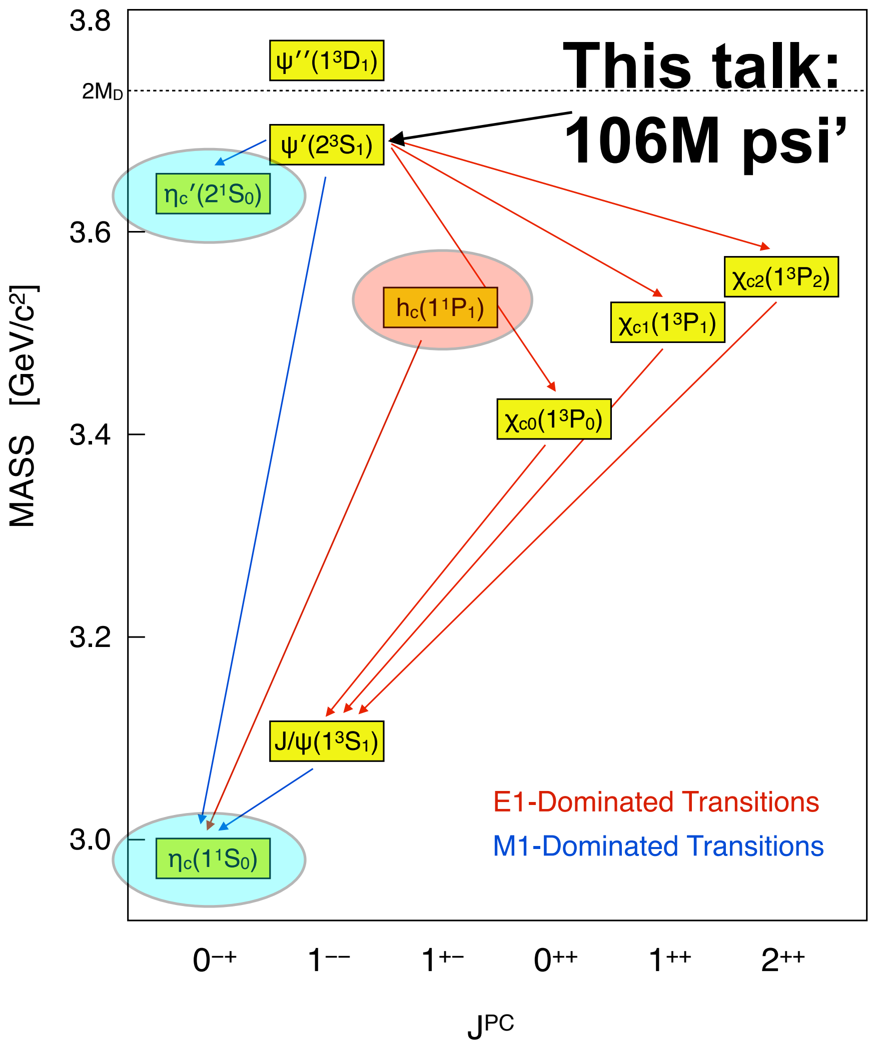
Tau physics
- decays & mass

Miscellaneous
- e.m. formfactors
- rare/forbidden decays
- beyond SM physics

Transitions & decays
- test validity pQCD
- quark masses
- strong coupling constant
- constrain EFTs

Light hadron spectroscopy
- light glueball&hybrid searches
- baryon&meson spectroscopy

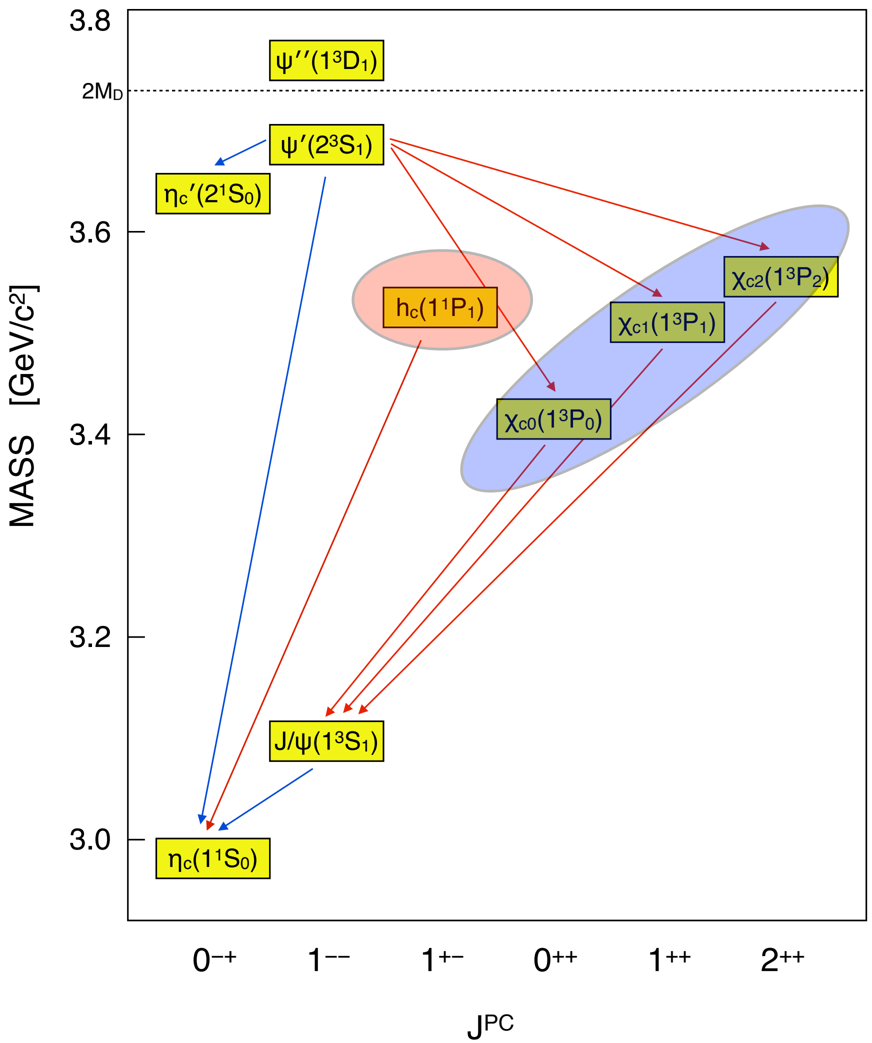
Hadronic Decay Studies with Charmonium



Physics aspects:

- Resonance parameters
- Rho-pi puzzle (12% rule)
- Perturbative QCD tests
- Hadronic loop effects
- Color Octet Mechanism
- Helicity Selection Rule
- Search for new states

“P-wave hyperfine splitting”



Barnes, Godfrey, Swanson
PRD72, 054026 (2005)

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr + \frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c\vec{S}_{\bar{c}} + \frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S} + \frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)$$

P-wave hyperfine splitting:

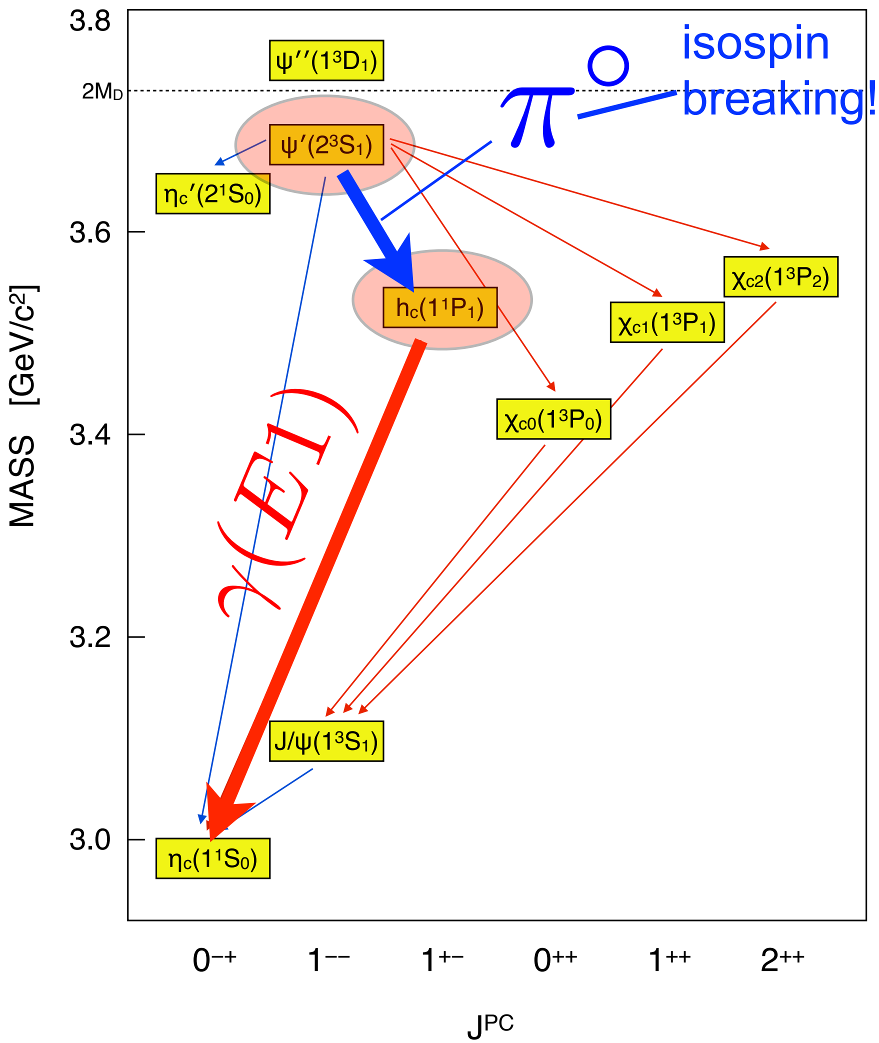
$$\propto |\psi(0)|^2$$

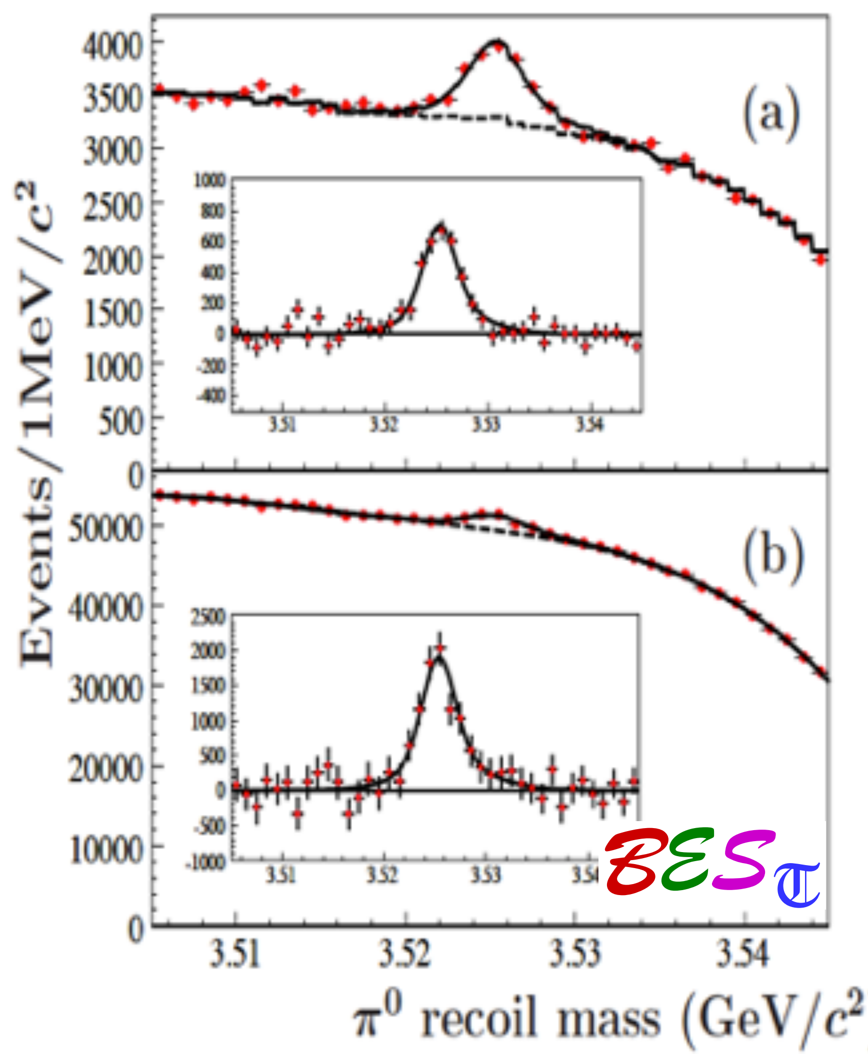
$$m(h_c) \overset{?}{=} \frac{m(\chi_{c0}) + 3\cdot m(\chi_{c1}) + 5\cdot m(\chi_{c2})}{9}$$

$\Delta M_{\rm hf} = m_{h_c} - \bar{m}_{\chi_c}$ deviation from zero?

singlet P-wave h_c

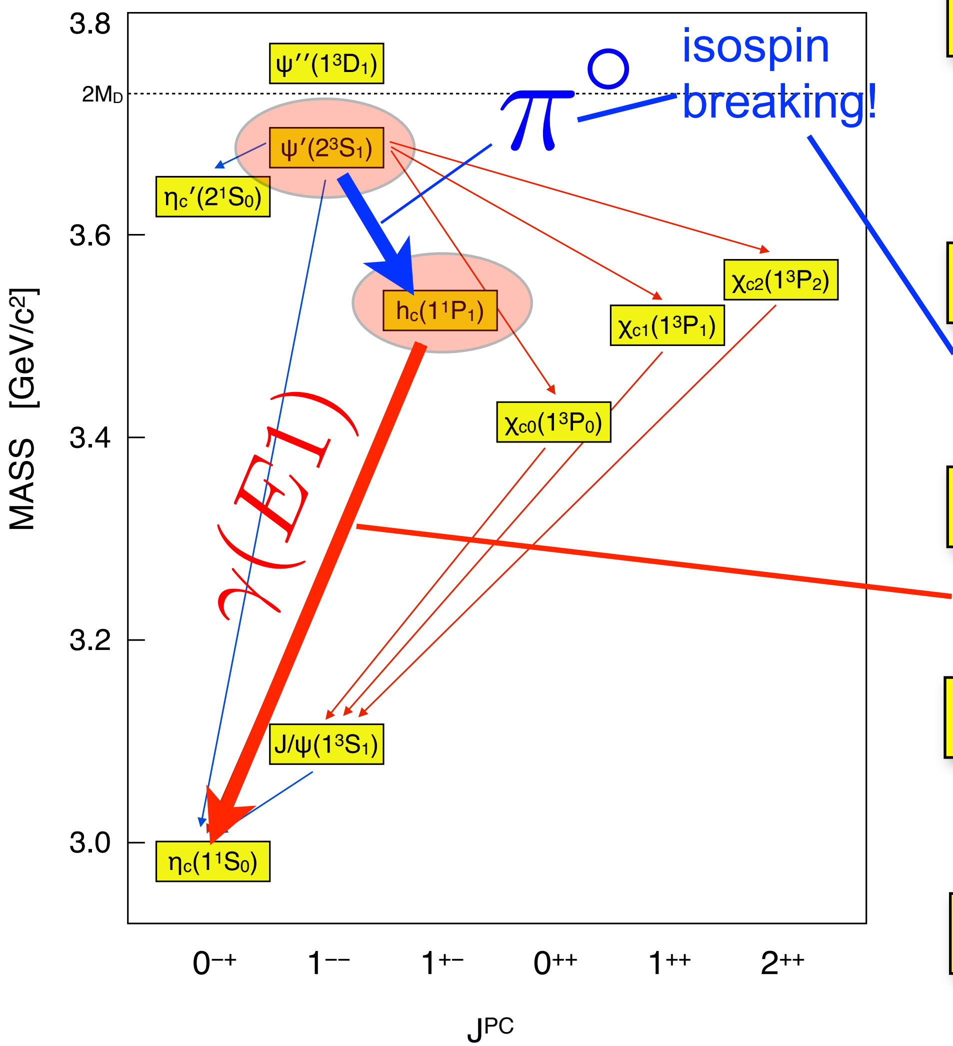
PRL 104, 132002 (2010)





singlet P-wave h_c

PRL 104, 132002 (2010)



Tag the E1 photon, yields:

$B(\psi(2S) \to \pi^0 h_c) \times B(h_c \to \gamma\eta_c)$
$= (4.58 \pm 0.40 \pm 0.50) \times 10^{-4}$
(consistent with CLEO-c)

Inclusive analysis provides:

$B(\psi(2S) \to \pi^0 h_c)$ (first measurement)
$= (8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$

Combining the two results:

$B(h_c \to \gamma\eta_c) = (54.3 \pm 6.7 \pm 5.2)\%$
(first measurement)

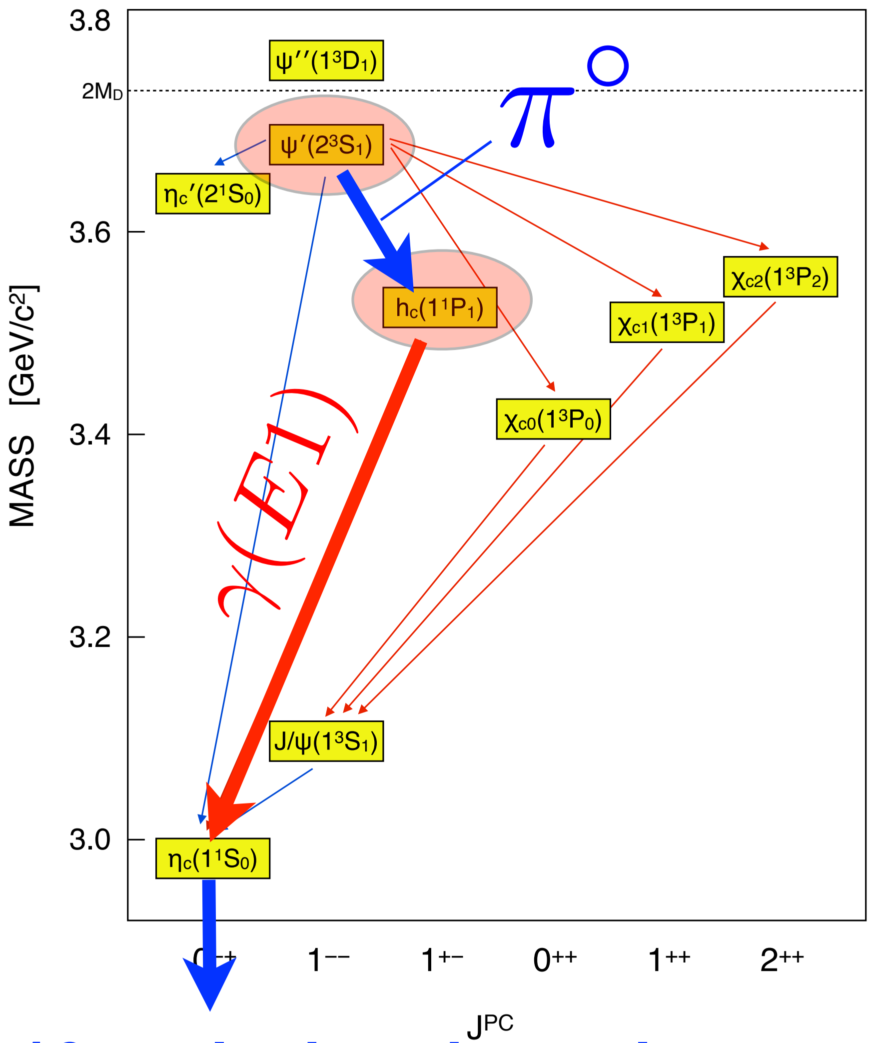
Natural width of h_c:

$$\Gamma(h_c) = 0.73 \pm 0.45 \pm 0.28\,\mathrm{MeV}/c^2$$
(first measurement)

Hyperfine splitting:

$$\Delta M_{hf} = -0.10 \pm 0.13 \pm 0.18\,\mathrm{MeV}/c^2$$
(consistent with zero)

singlet P-wave h_c

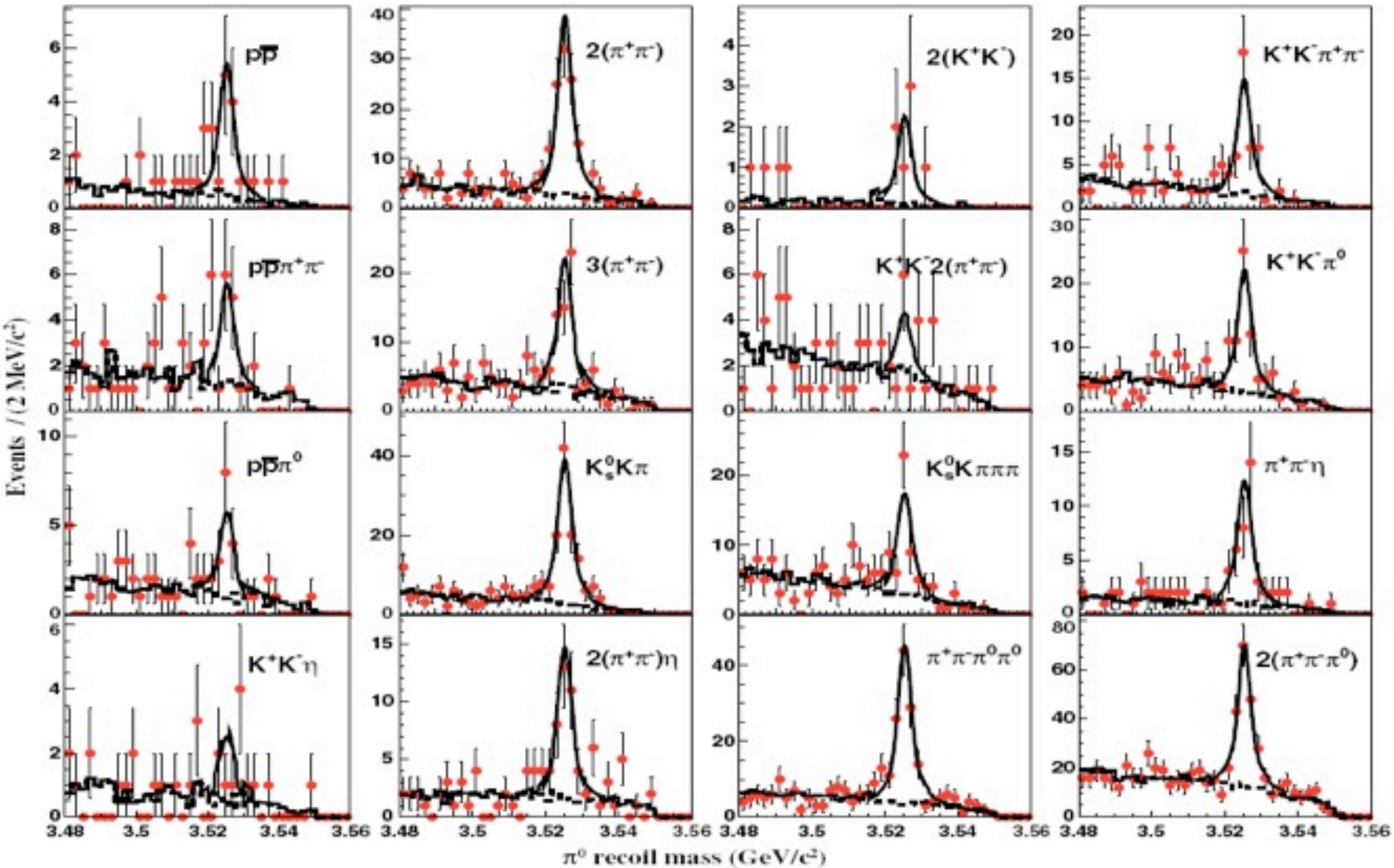


16 exclusive channels

two years later...

singlet P-wave h_c ; exclusive decays of etac

PRD 86, 092009 (2012)



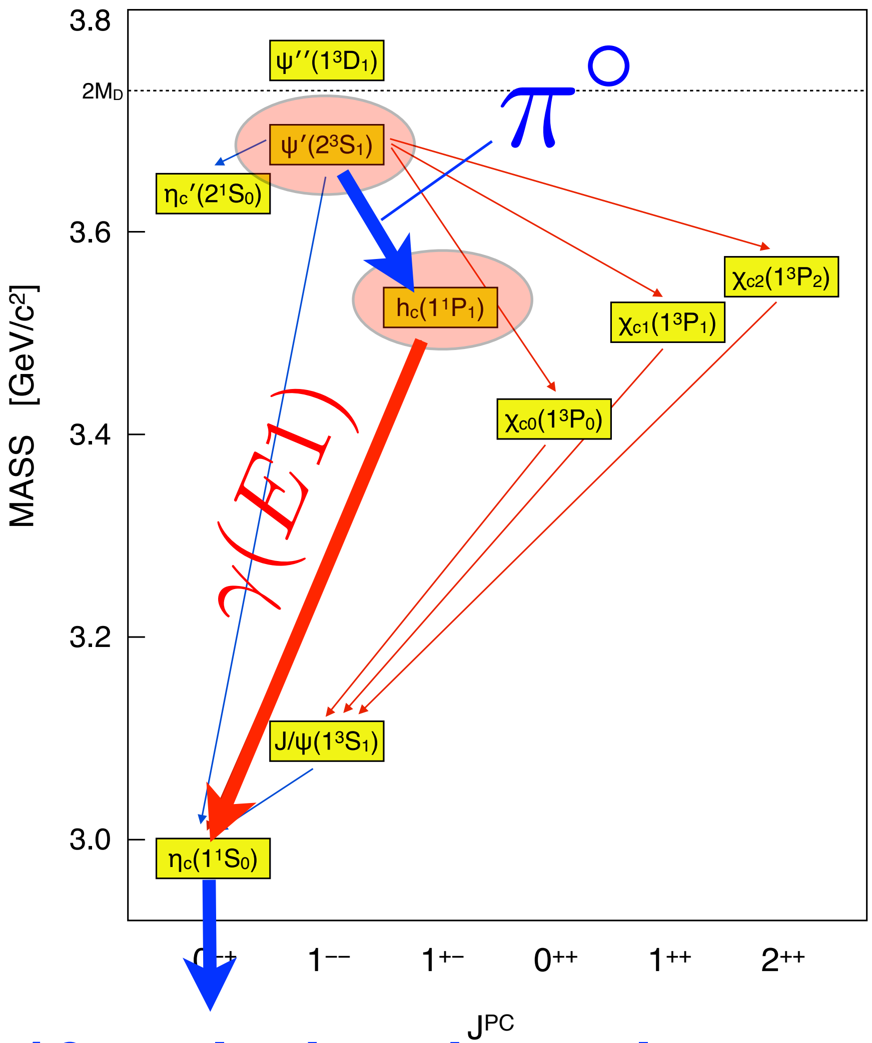
singlet P-wave h_c ; exclusive decays of etac

PRD 86, 092009 (2012)

X_i	$\mathcal{B}_1 \times \mathcal{B}_2 \times \mathcal{B}_3$ ($\times 10^{-6}$)	$\mathcal{B}_3$ (%)	$\mathcal{B}_3$ in PDG (%)
$p\bar{p}$	$0.65 \pm 0.19 \pm 0.10$	$0.15\pm0.04\pm0.02\pm0.01$	0.141 ± 0.017
$\pi^+\pi^-\pi^+\pi^-$	$7.51 \pm 0.85 \pm 1.11$	$1.72\pm0.19\pm0.25\pm0.17$	0.86 ± 0.13
$K^+K^-K^+K^-$	$0.94 \pm 0.37 \pm 0.14$	$0.22\pm0.08\pm0.03\pm0.02$	0.134 ± 0.032
$K^+K^-\pi^+\pi^-$	$4.16 \pm 0.76 \pm 0.59$	$0.95\pm0.17\pm0.13\pm0.09$	0.61 ± 0.12
$p\bar{p}\pi^+\pi^-$	$2.30 \pm 0.65 \pm 0.36$	$0.53\pm0.15\pm0.08\pm0.05$	<1.2 (at 90% C.L.)
$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-$	$8.82 \pm 1.57 \pm 1.59$	$2.02\pm0.36\pm0.36\pm0.19$	1.5 ± 0.50
$K^+K^-\pi^+\pi^-\pi^-\pi^-$	$3.60 \pm 1.71 \pm 0.64$	$0.83\pm0.39\pm0.15\pm0.08$	0.71 ± 0.29
$K^+K^-\pi^0$	$4.54 \pm 0.76 \pm 0.48$	$1.04\pm0.17\pm0.11\pm0.10$	1.2 ± 0.1
$p\bar{p}\pi^0$	$1.53 \pm 0.49 \pm 0.23$	$0.35\pm0.11\pm0.05\pm0.03$	–
$K^0_S K^\pm\pi^\mp$	$11.35 \pm 1.25 \pm 1.50$	$2.60\pm0.29\pm0.34\pm0.25$	2.4 ± 0.2
$K^0_S K^\pm\pi^\mp\pi^\pm\pi^\mp$	$12.01 \pm 2.22 \pm 2.04$	$2.75\pm0.51\pm0.47\pm0.27$	–
$\pi^+\pi^-\eta$	$7.22 \pm 1.47 \pm 1.11$	$1.66\pm0.34\pm0.26\pm0.16$	4.9 ± 1.8
$K^+K^-\eta$	$2.11 \pm 1.01 \pm 0.32$	$0.48\pm0.23\pm0.07\pm0.05$	<1.5 (at 90% C.L.)
$\pi^+\pi^-\pi^+\pi^-\eta$	$19.17 \pm 3.77 \pm 3.72$	$4.40\pm0.86\pm0.85\pm0.42$	–
$\pi^+\pi^-\pi^0\pi^0$	$20.31 \pm 2.20 \pm 3.33$	$4.66\pm0.50\pm0.76\pm0.45$	–
$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0$	$75.13 \pm 7.42 \pm 9.99$	$17.23\pm1.70\pm2.29\pm1.66$	–

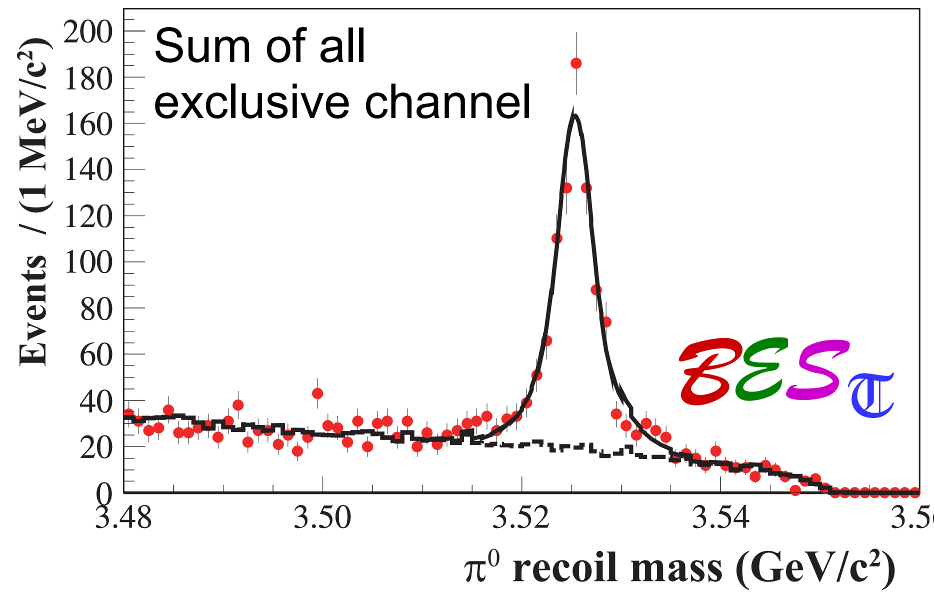
$$\mathcal{B}_1(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}_2(h_c \to \gamma\eta_c) \times \mathcal{B}_3(\eta_c \to X_i)$$

singlet P-wave h_c ; exclusive decays of etac



16 exclusive channels

PRD 86, 092009 (2012)

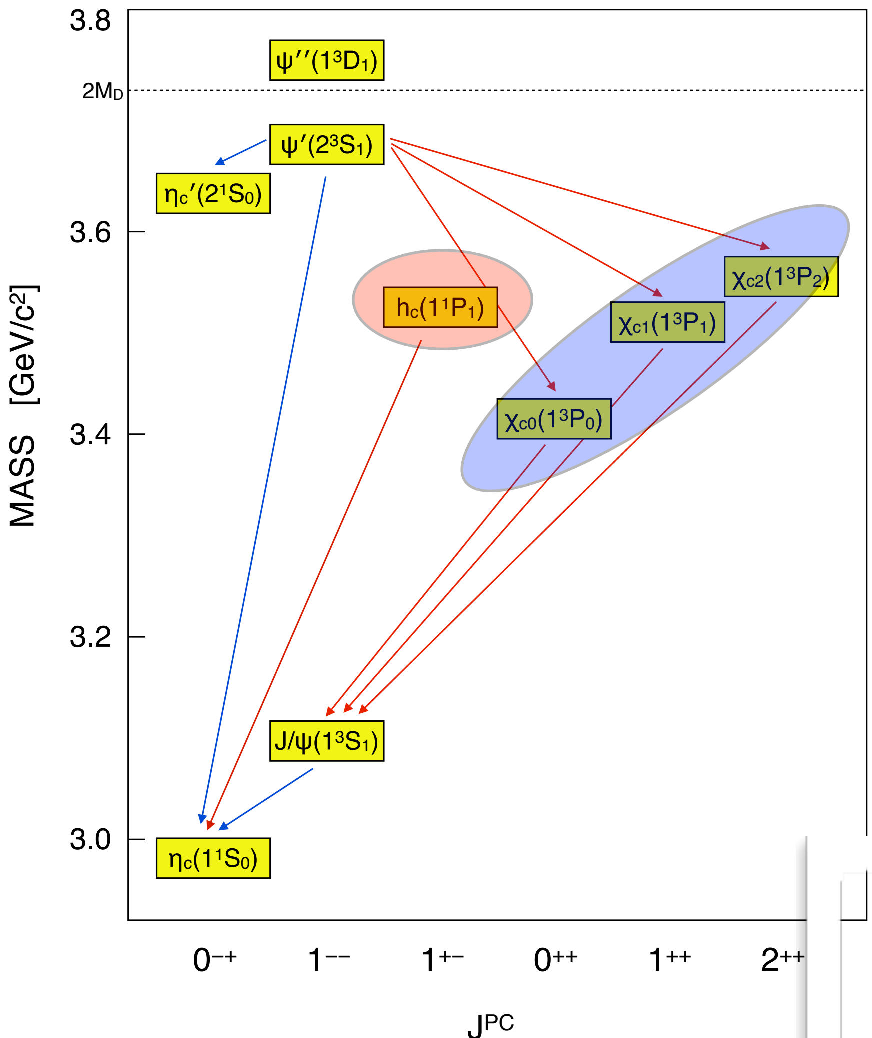


Precision!

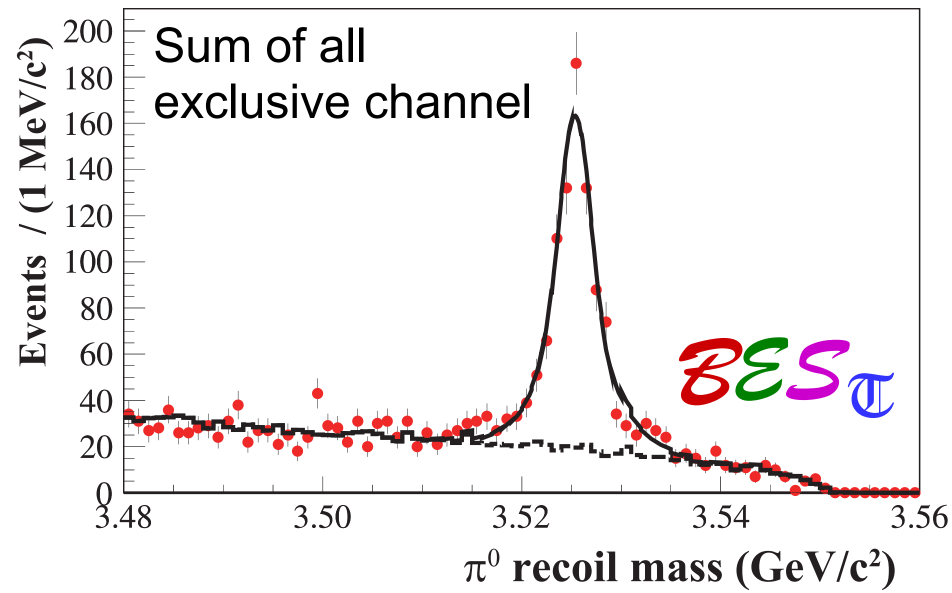
$$M = 3525.31 \pm 0.11 \pm 0.14 \text{ MeV}$$

$$\Gamma = 0.70 \pm 0.28 \pm 0.22 \text{ MeV}$$

“P-wave hyperfine splitting”



PRD 86, 092009 (2012)



$$\Delta M_{hf} \equiv \langle M(1^3P)\rangle - M(1^1P_1)$$
$$= -0.01 \pm 0.11(\text{stat}) \pm 0.15(\text{syst})\ \text{MeV}/c^2$$

“exploiting isospin breaking”

breaking of
isospin symmetry: u <-> d

probe the ratio m_u/m_d

$$\frac{m_u}{m_d} \Leftrightarrow R = \frac{B\left(\Psi' \to \pi^0 J/\psi\right)}{B\left(\Psi' \to \eta J/\psi\right)}$$

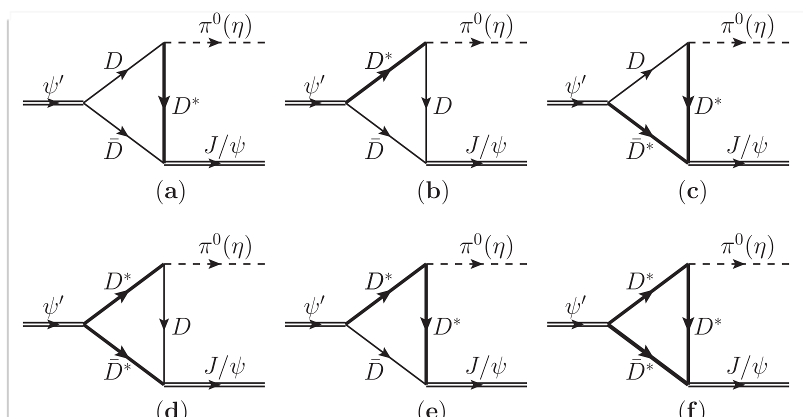
“exploiting isospin breaking”

breaking of
isospin symmetry: u <-> d

probe the ratio m_u/m_d

size of hadronic loops in charmonium

$$\frac{m_u}{m_d} \Leftrightarrow R = \frac{B\left(\Psi' \to \pi^0 J/\psi\right)}{B\left(\Psi' \to \eta J/\psi\right)} + loops\,!$$



Guo, Hanhart, Meissner PRL **103,** 082003 (2009)

“exploiting isospin breaking”

breaking of
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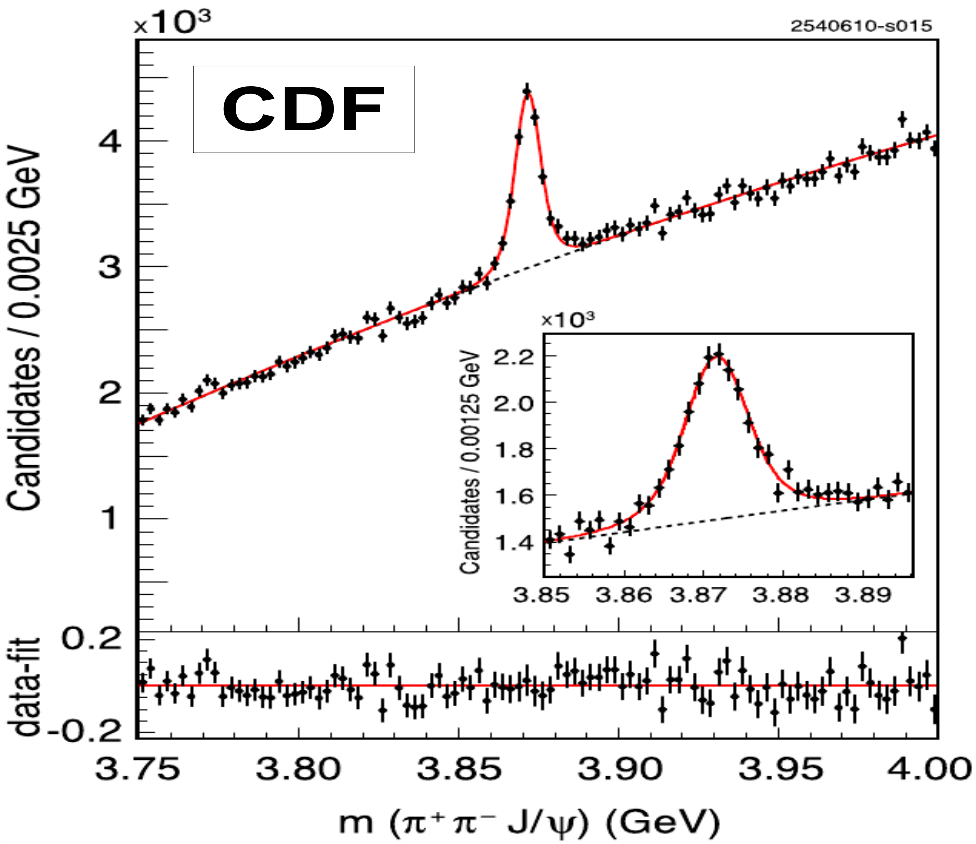
probe the ratio m_u/m_d

size of hadronic loops in charmonium

understand nature of the X(3872) state



“exploiting isospin breaking”

breaking of
isospin symmetry: u <-> d

probe the ratio m_u/m_d

size of hadronic loops in charmonium

understand nature of the X(3872) state

$$X(3872) \to J/\Psi\pi^+\pi^-$$

Experiment	
CDF 2	3871.61 ± 0.16 ± 0.19 MeV
BaBar (B^+)	3871.4 ± 0.6 ± 0.1 MeV
BaBar (B^0)	3868.7 ± 1.5 ± 0.4 MeV
D0	3871.8 ± 3.1 ± 3.0 MeV
Belle	3871.84 ± 0.27 ± 0.19 MeV
LHCb	3871.96 ± 0.46 ± 0.10 MeV
World Average	**3871.67 ± 0.17 MeV**
$M(D^0)+M(D^{*0})$ PDG2010	3871.79 ± 0.30 MeV

$\Gamma < 1.2$ MeV

$\Delta m = -0.12 \pm 0.35$ MeV

"exploiting isospin breaking"

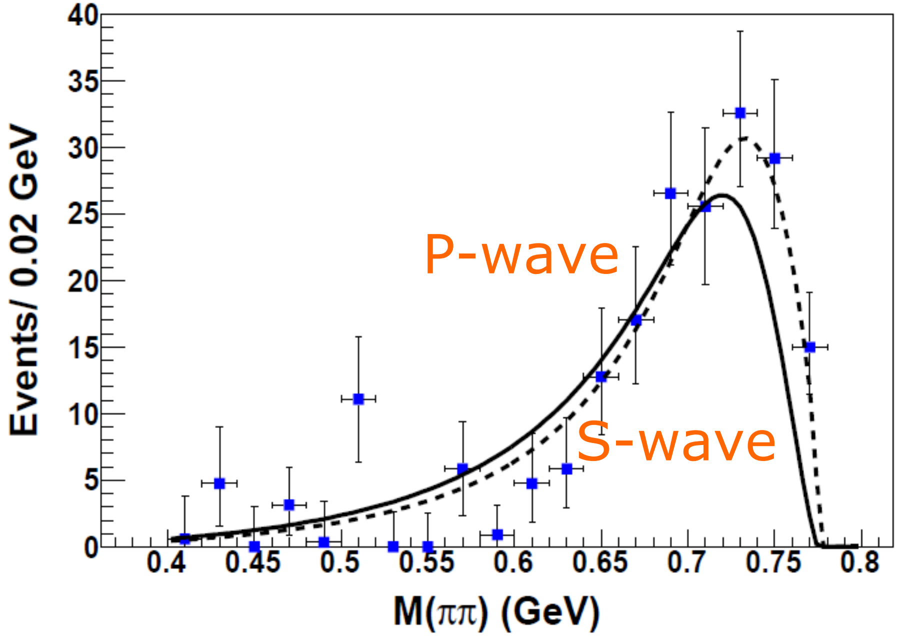
breaking of
isospin symmetry: u <-> d

probe the ratio m_u/m_d

size of hadronic loops in charmonium

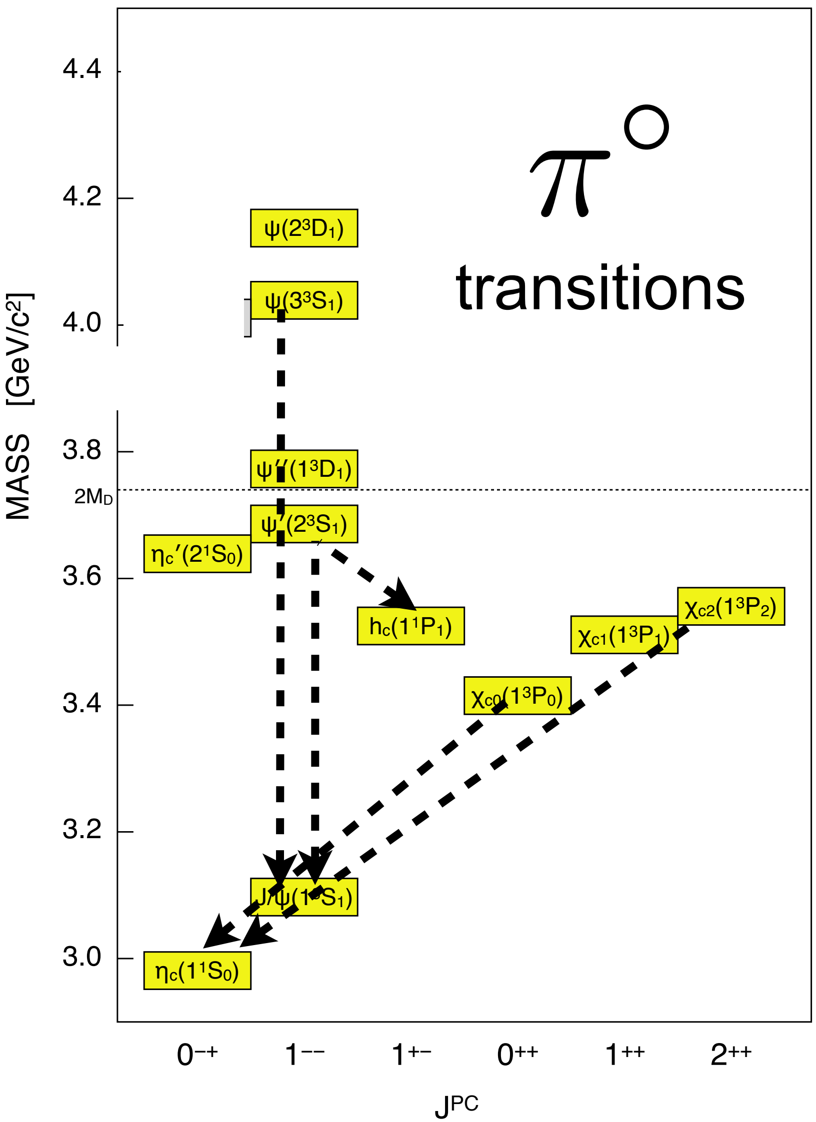
understand nature of the X(3872) state

$$X(3872) \to J/\Psi\rho$$



Isospin breaking enhanced for X(3872)

“exploiting isospin breaking”



BESIII

$B(\psi(4010)\to \pi^0 J/\psi) < 2.8 \cdot 10^{-4}$

Phys. Rev. D 86, 071101(R) (2012)

$B(\psi' \to \pi^0 h_c) = (8.4 \pm 1.3 \pm 1.0) \cdot 10^{-4}$

PRL 104, 132002 (2010)

$B(\psi'\to\pi^0 J/\psi)/B(\psi'\to\eta J/\psi) = (3.74 \pm 0.06 \pm 0.04) \cdot 10^{-2}$

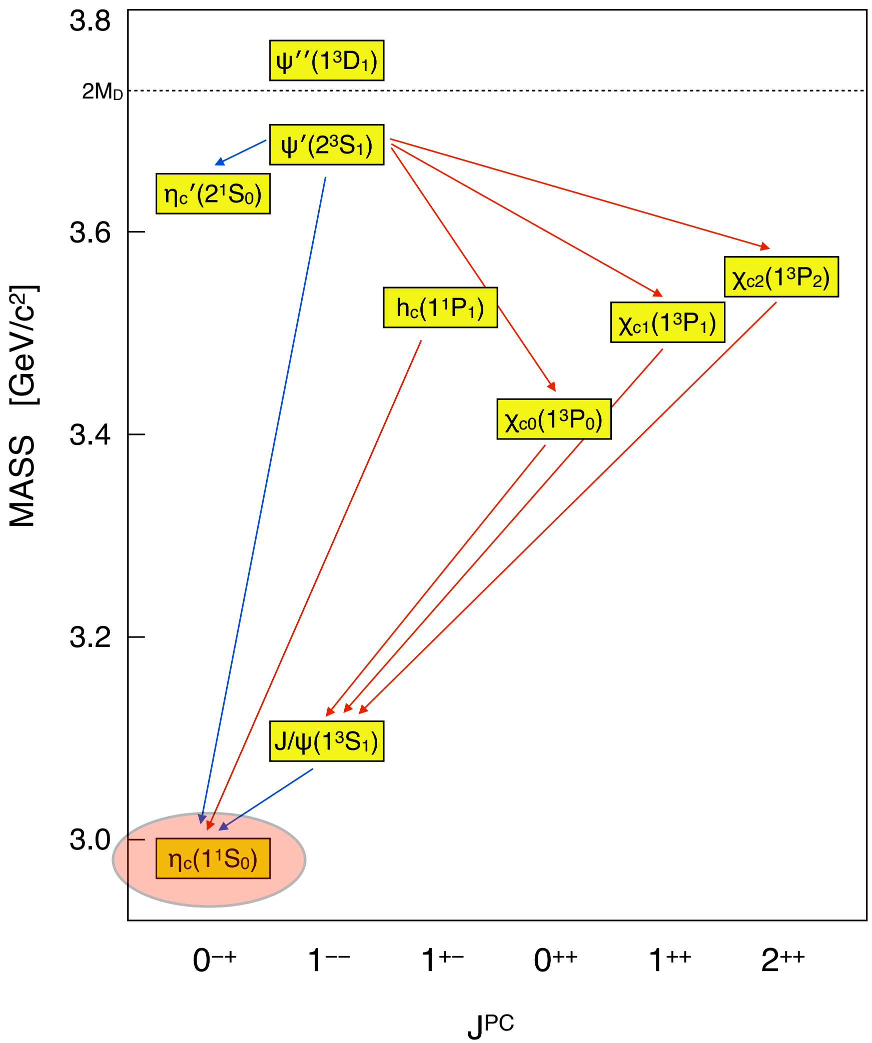
PRD 86, 092008 (2012)

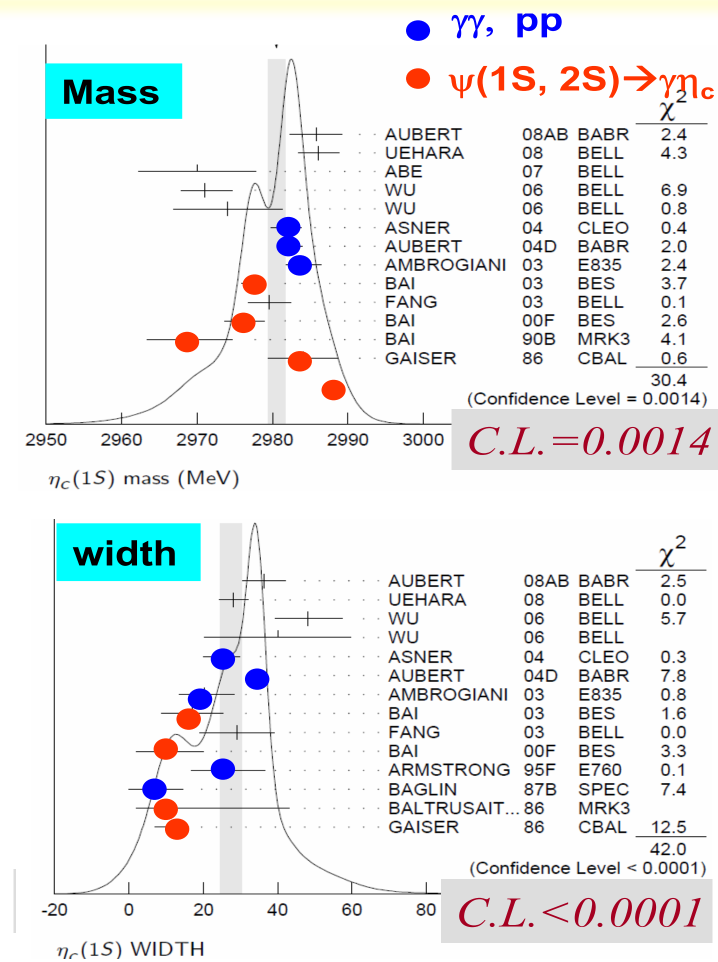
$B(\chi_{c0,2}\to \pi^0\eta_c) < ?$

In Progress

valuable input to EFT approaches

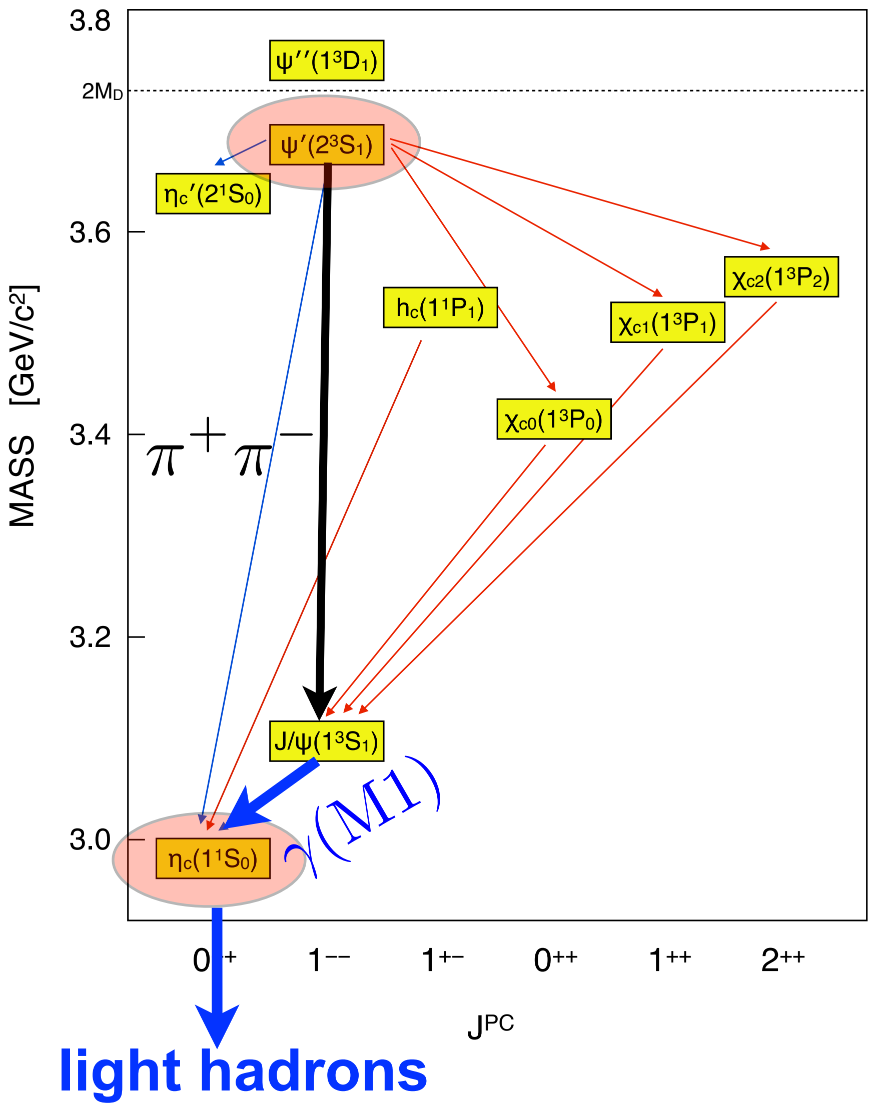
“charmonium ground state”



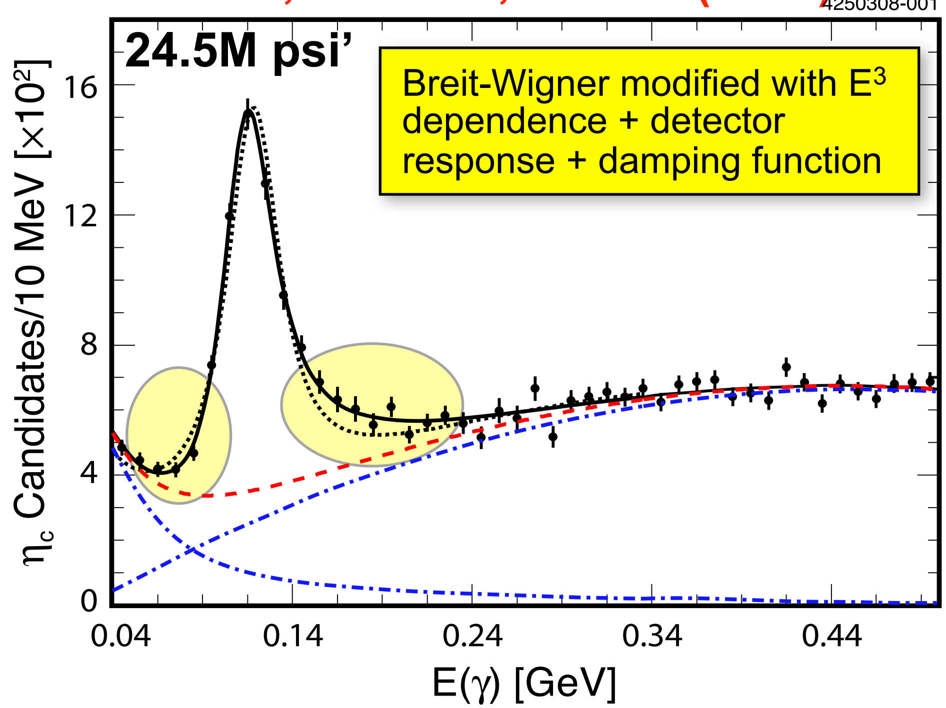


Even on simplest parameters of the ground state there are consistency problems!

“charmonium ground state”

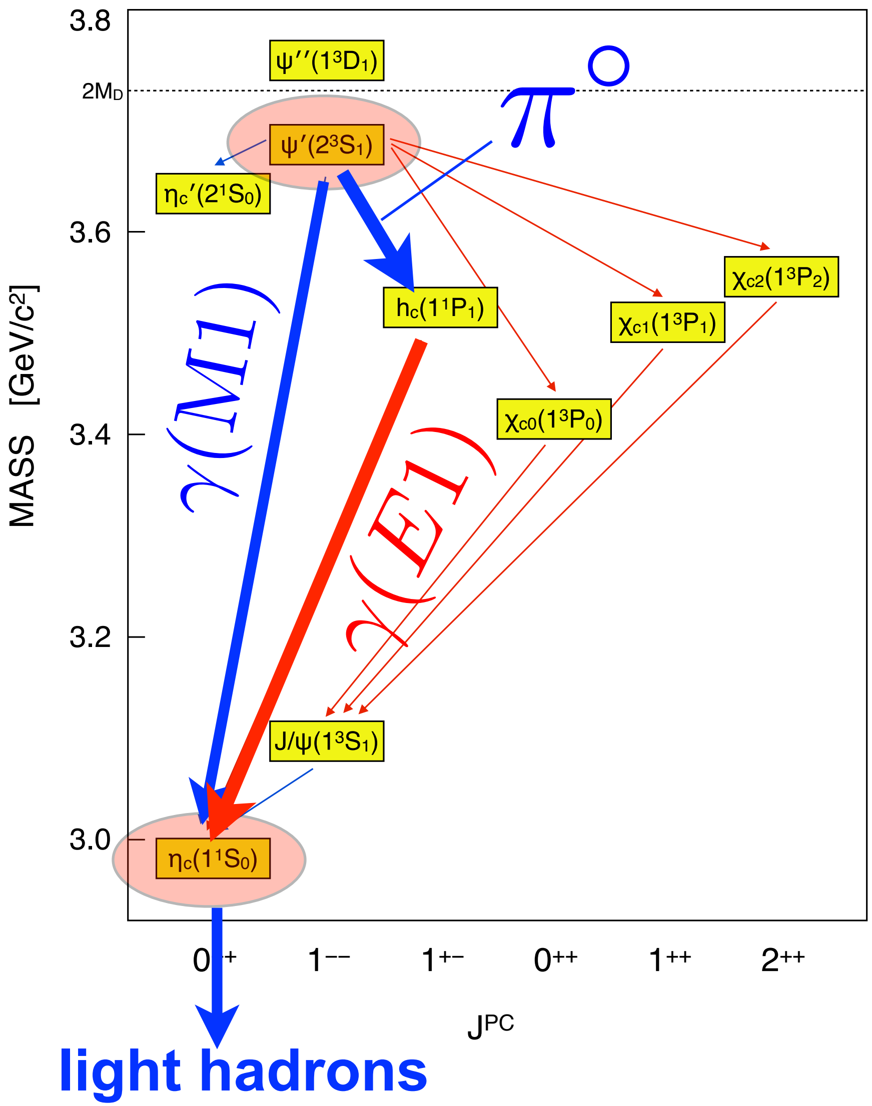


CLEO-c, PRL 102, 011801 (2009)

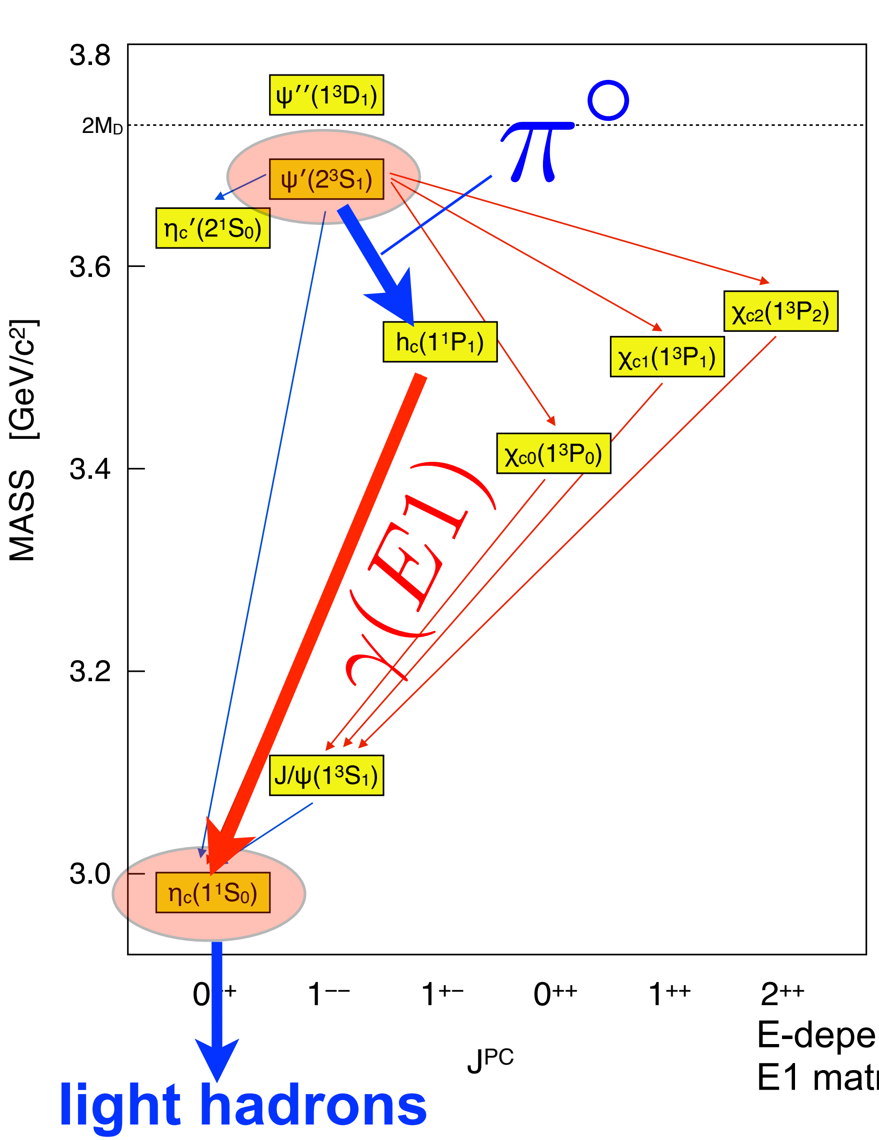


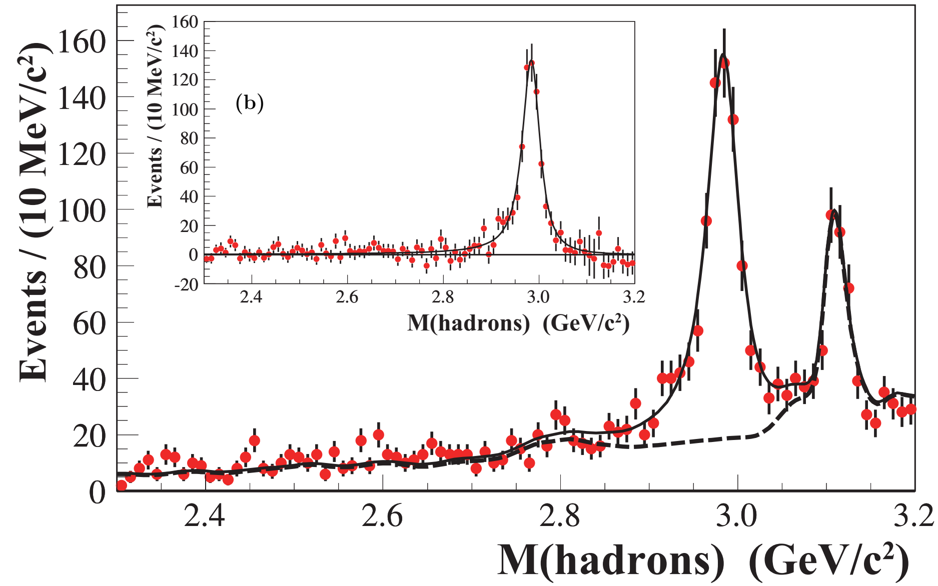
Precise resonance parameters require a thorough theoretical understanding of line shape!

"charmonium ground state"



“charmonium ground state”





Lineshape parameterization:

$$\left(E_\gamma^3 \times BW(m) \times f_d(E_\gamma)\right) \otimes R_i(m)$$

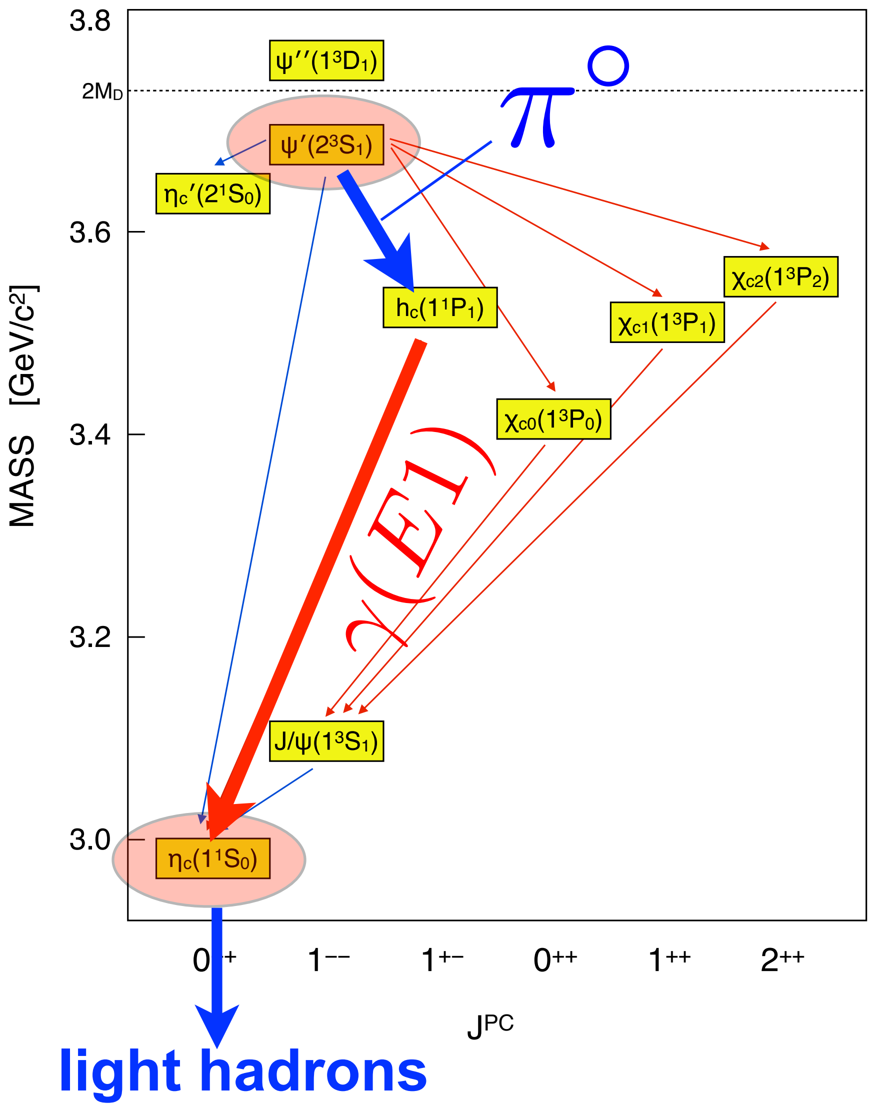
E-dependence of E1 matrix element

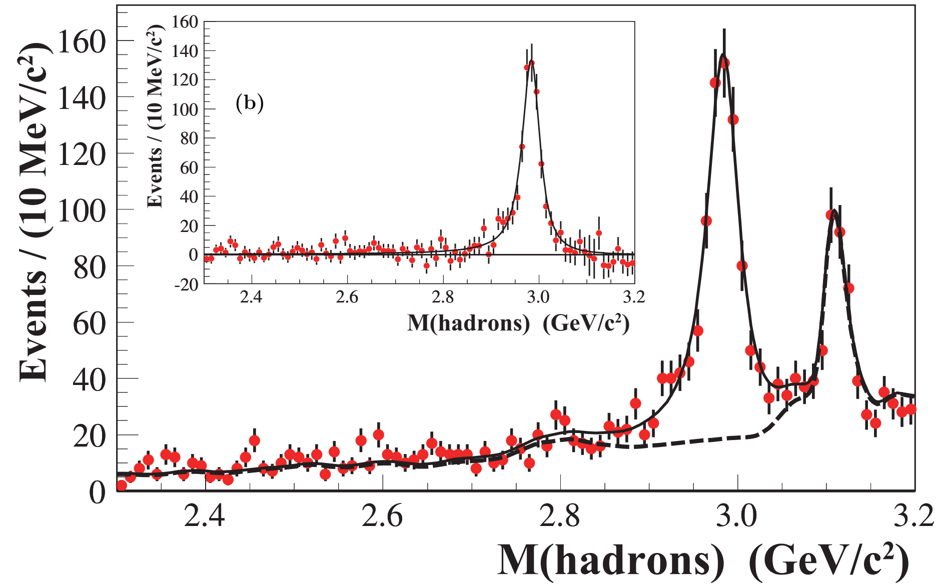
Breit-Wigner resonance

Damping factor (KEDR coll.)

Detector response

“charmonium ground state”



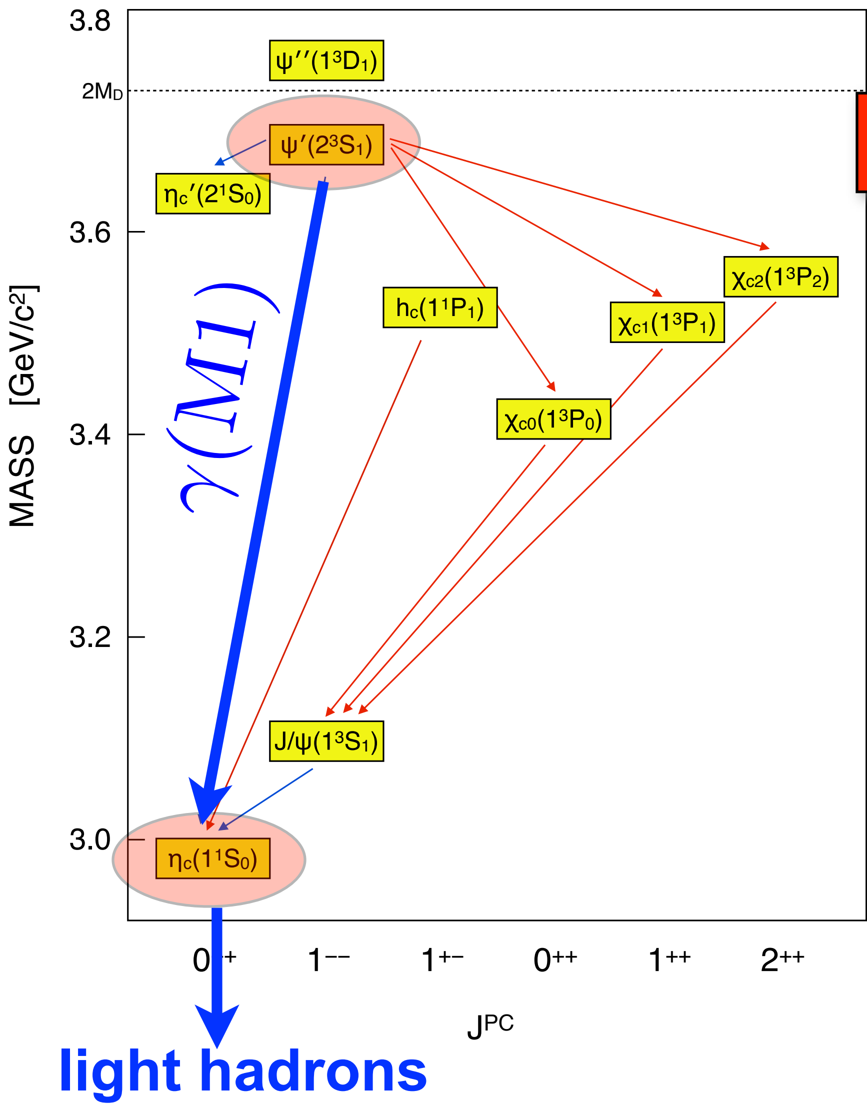


$$M(\eta_c) = 2984.49 \pm 1.16 \pm 0.52\,\mathrm{MeV}/c^2$$

$$\Gamma(\eta_c) = 36.4 \pm 3.2 \pm 1.7\,\mathrm{MeV}/c^2$$

Interference with non-resonant background small....

“charmonium ground state”



M1 transition to ground state:

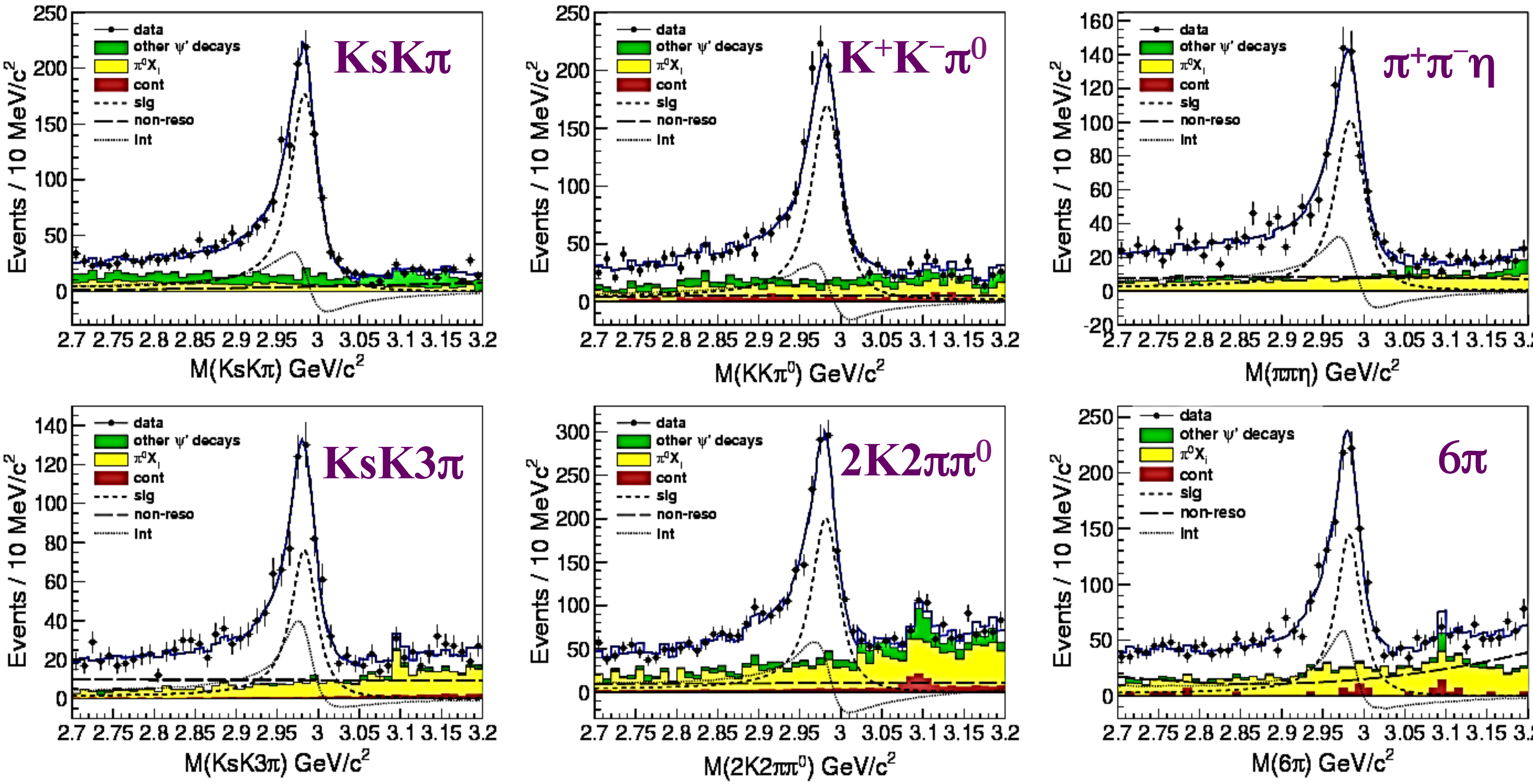
Significant larger statistics
(no pi0 isospin-forbidden transition involved)

hindered M1 transition small
(large contribution of non-resonant background)

“charmonium ground state”

PDF: $F(m) = \sigma \otimes \left[\epsilon(m)\left|e^{i\phi}E_\gamma^{7/2}\mathcal{S}(m) + \alpha\mathcal{N}(m)\right|^2\right] + \mathcal{B}(m)$

PRL108, 222002 (2012)



“charmonium ground state”

Statistical significance of interference: 15σ

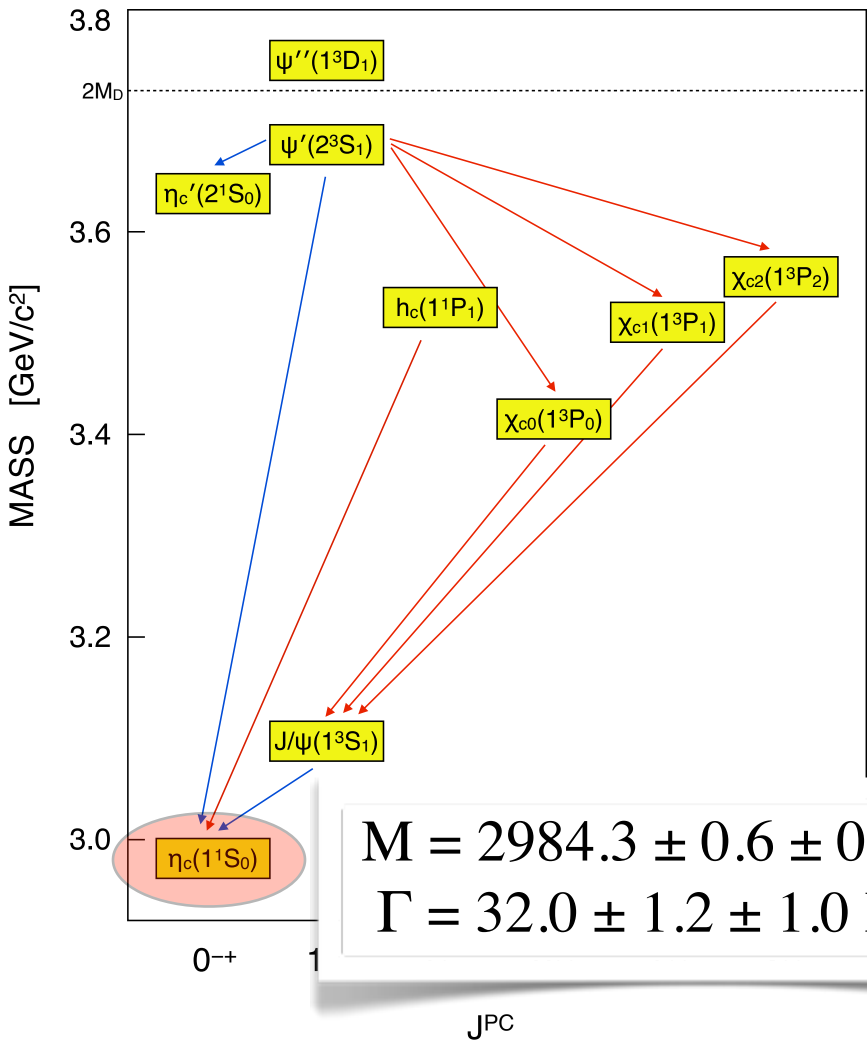
mode	constructive	destructive
$K_S K^+ \pi^-$	2.94 ± 0.27	3.75 ± 0.26
$K^+ K^- \pi^0$	2.63 ± 0.21	3.96 ± 0.19
$\eta \pi^+ \pi^-$	2.41 ± 0.13	4.28 ± 0.09
$K_S K^+ \pi^+ \pi^- \pi^-$	2.16 ± 0.11	4.46 ± 0.07
$K^+ K^- \pi^+ \pi^- \pi^0$	2.73 ± 0.19	4.00 ± 0.16
$3(\pi^+ \pi^-)$	2.28 ± 0.10	4.43 ± 0.06

$\phi\,[\mathrm{rad}]$

Bottom line: must take into account distorted line-shape and interferences with “non-resonant” decays

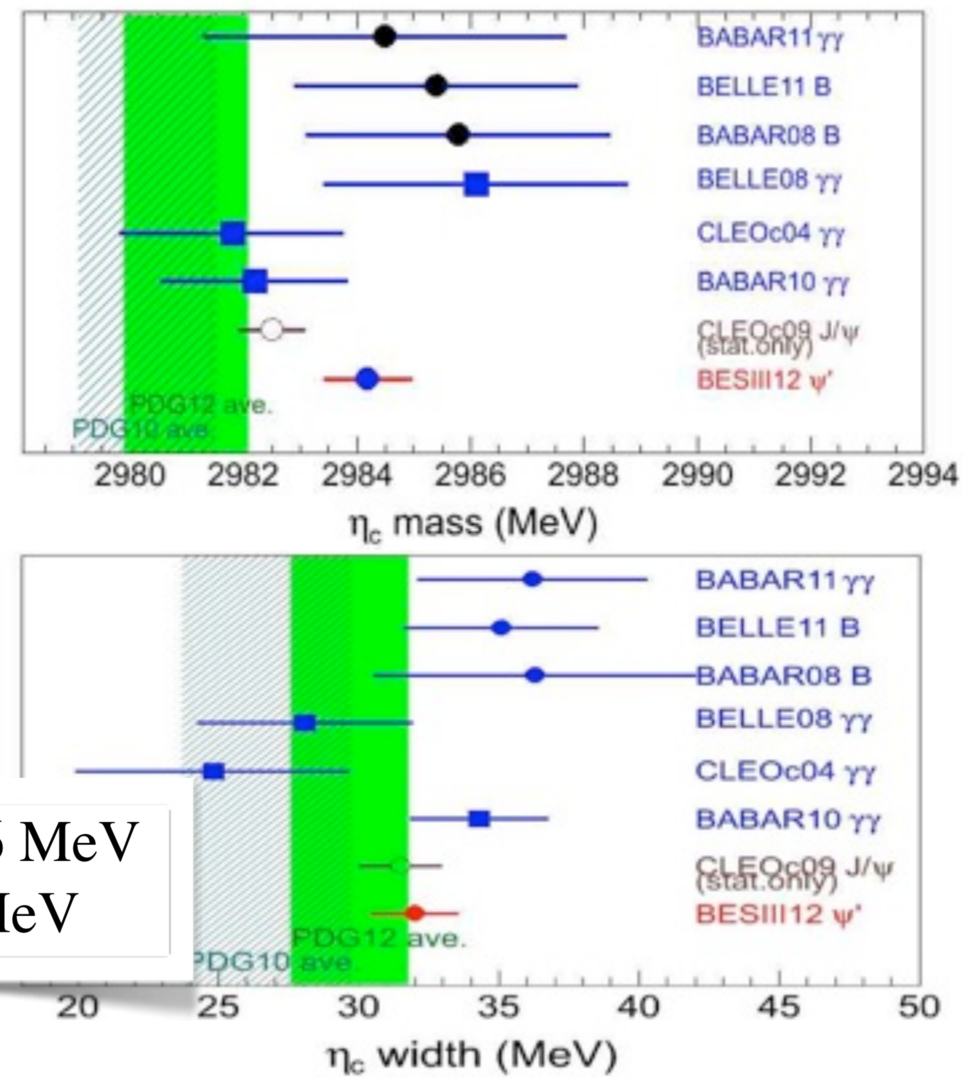
"charmonium ground state"

PRL108, 222002 (2012)



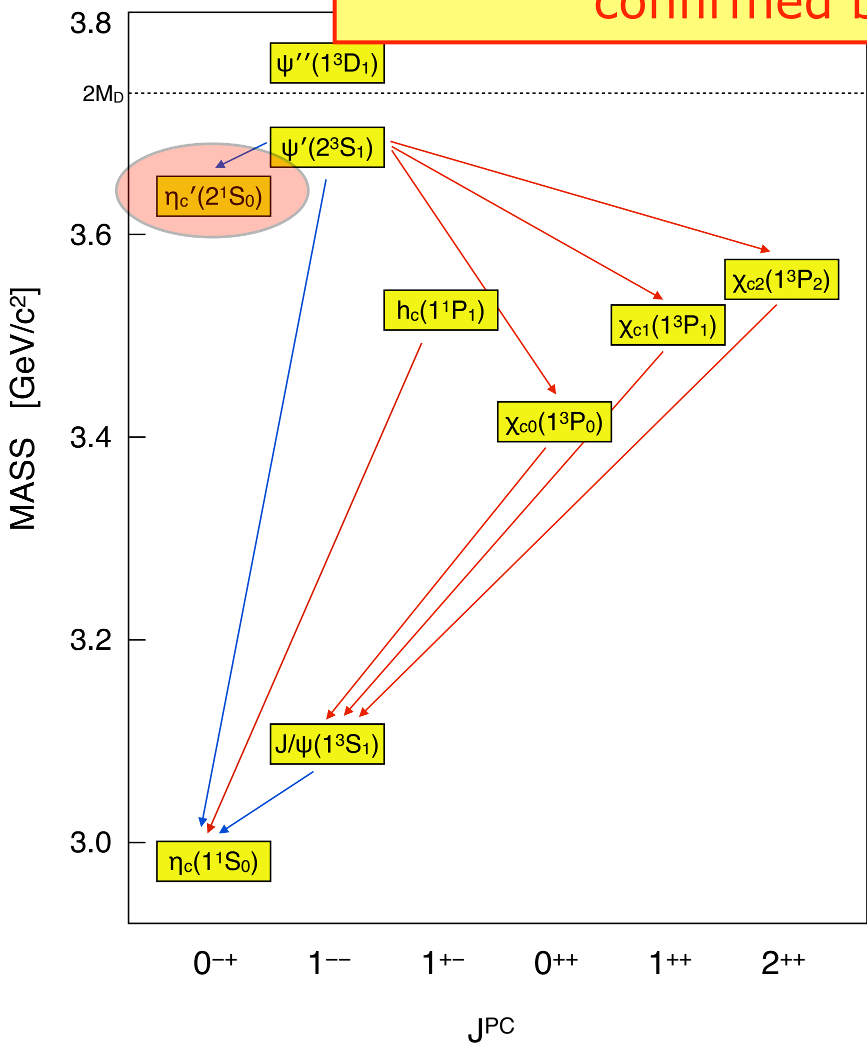
$$M = 2984.3 \pm 0.6 \pm 0.6\ \mathrm{MeV}$$

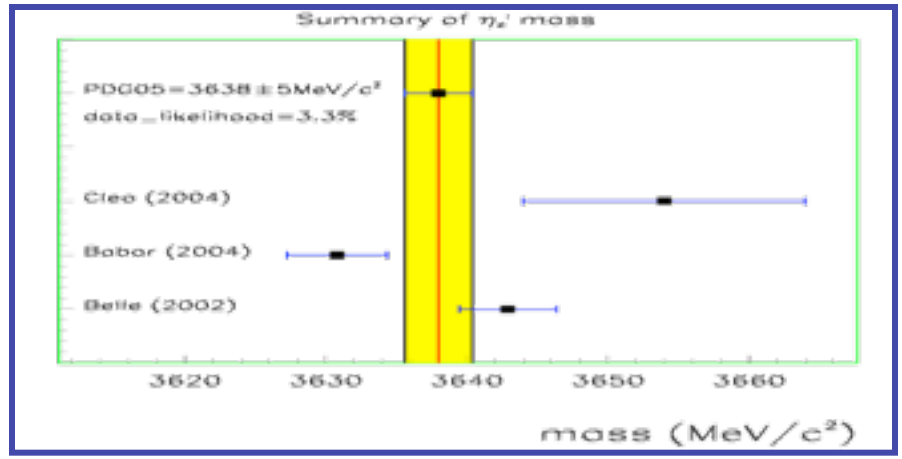
$$\Gamma = 32.0 \pm 1.2 \pm 1.0\ \mathrm{MeV}$$

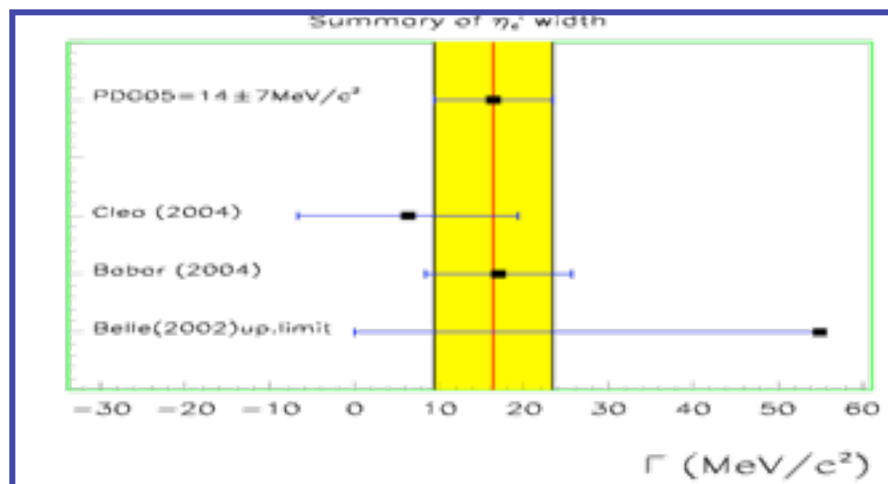


radial excitation of the g.s.

Discovery of η'_c by Belle in $B \to K \eta_c'(\to KK\pi)$
confirmed by BaBar, Cleo







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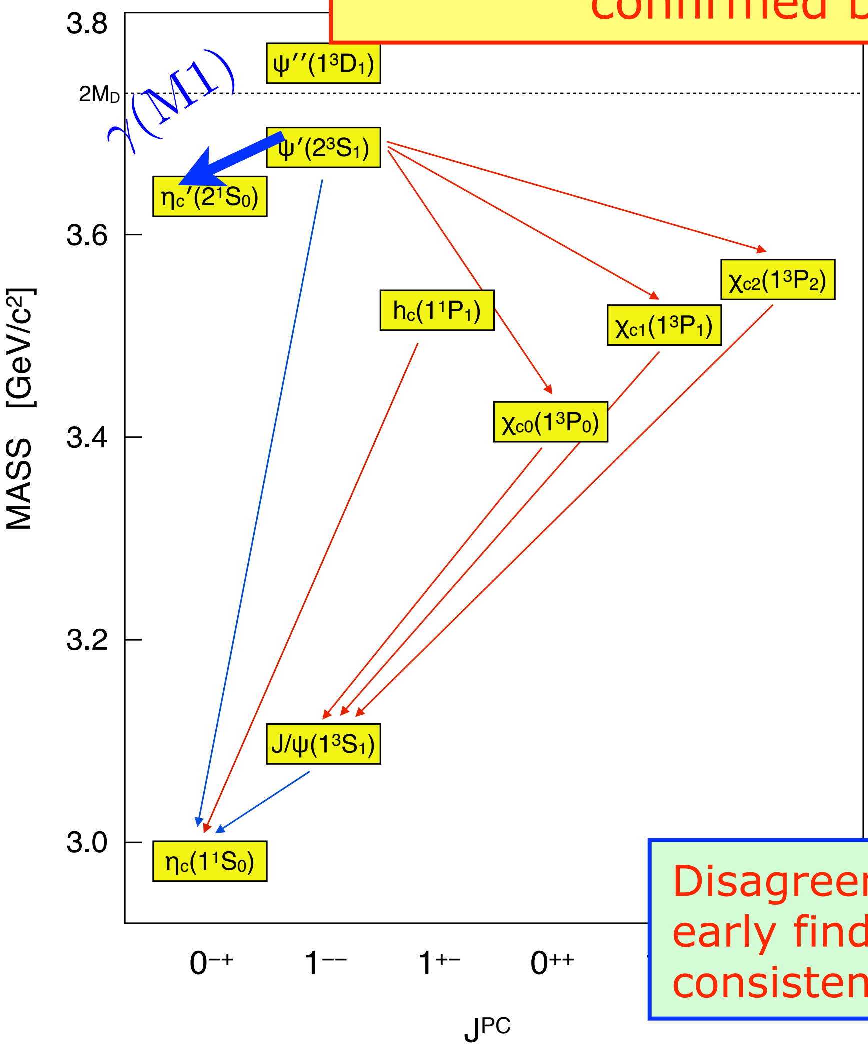
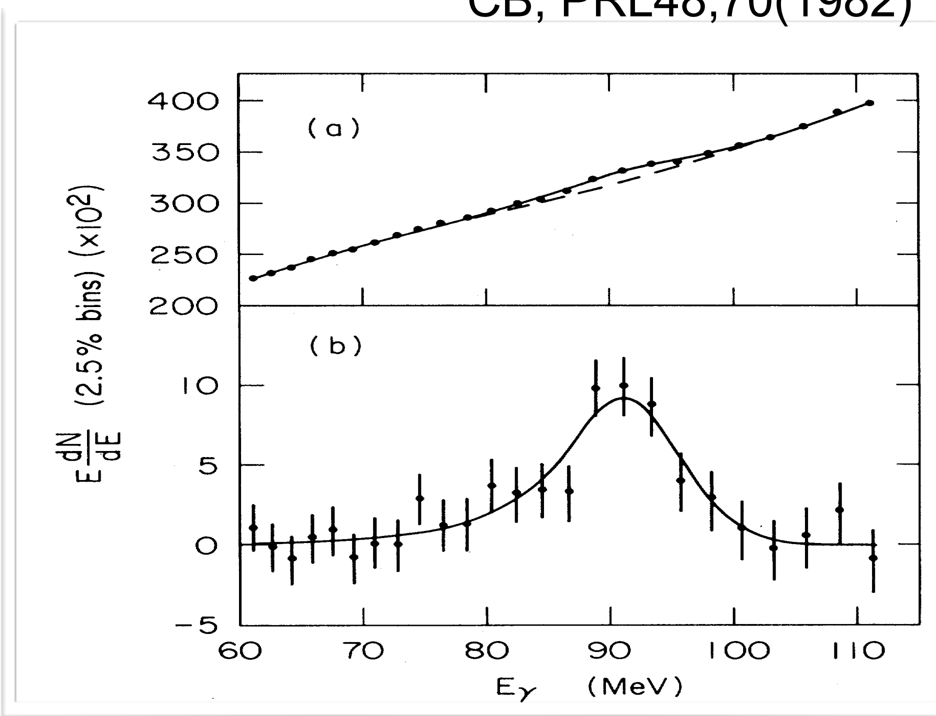


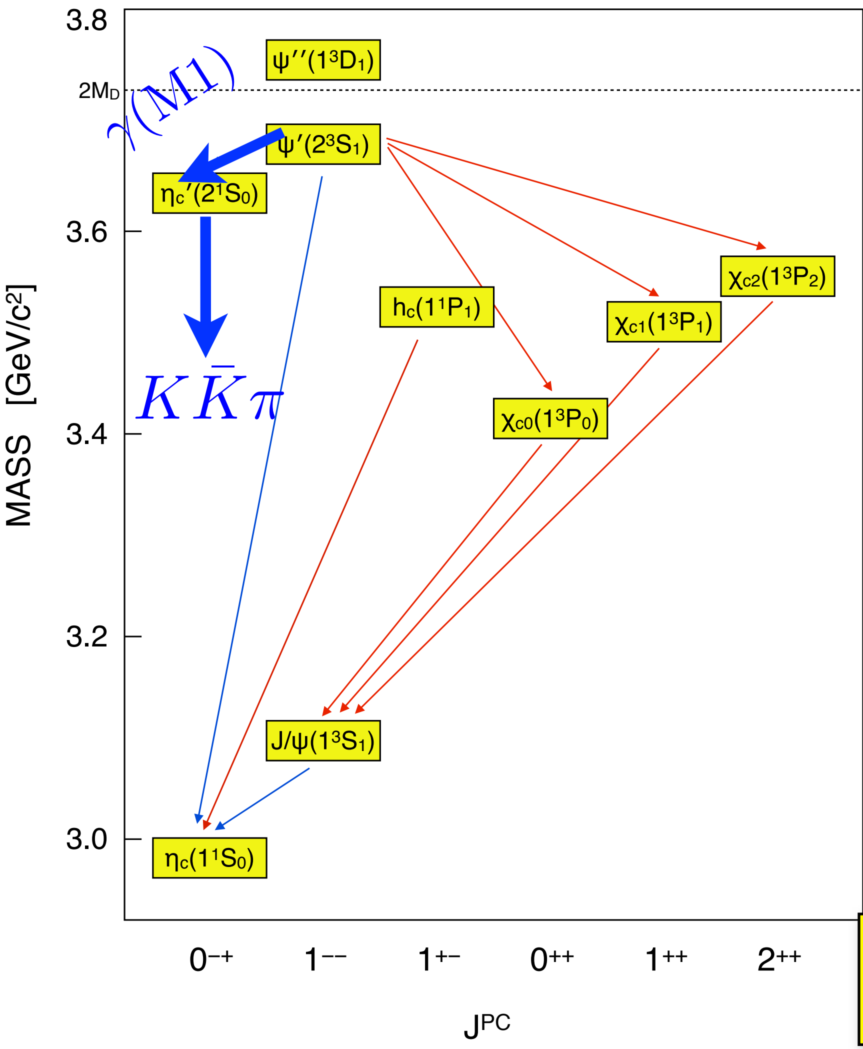
CB, PRL48,70(1982)

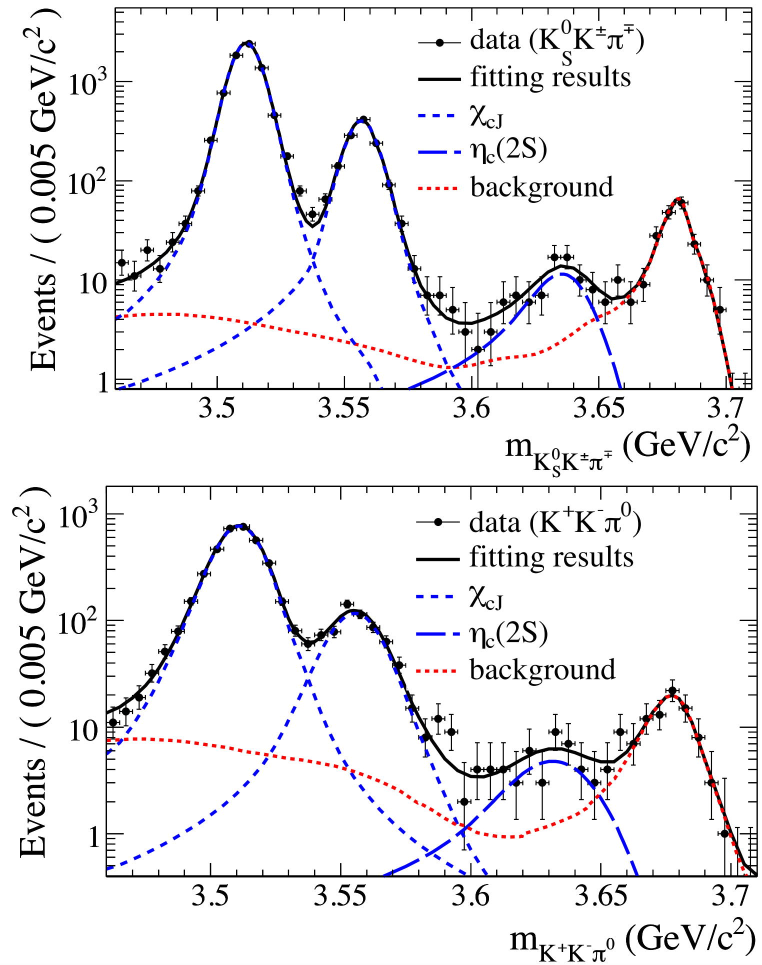


Disagreement of experiments on the mass and with early findings by Crystal Ball (3594). Only marginal consistency with most theoretical predictions.

radial excitation of the g.s.

PRL 109, 042003 (2012)

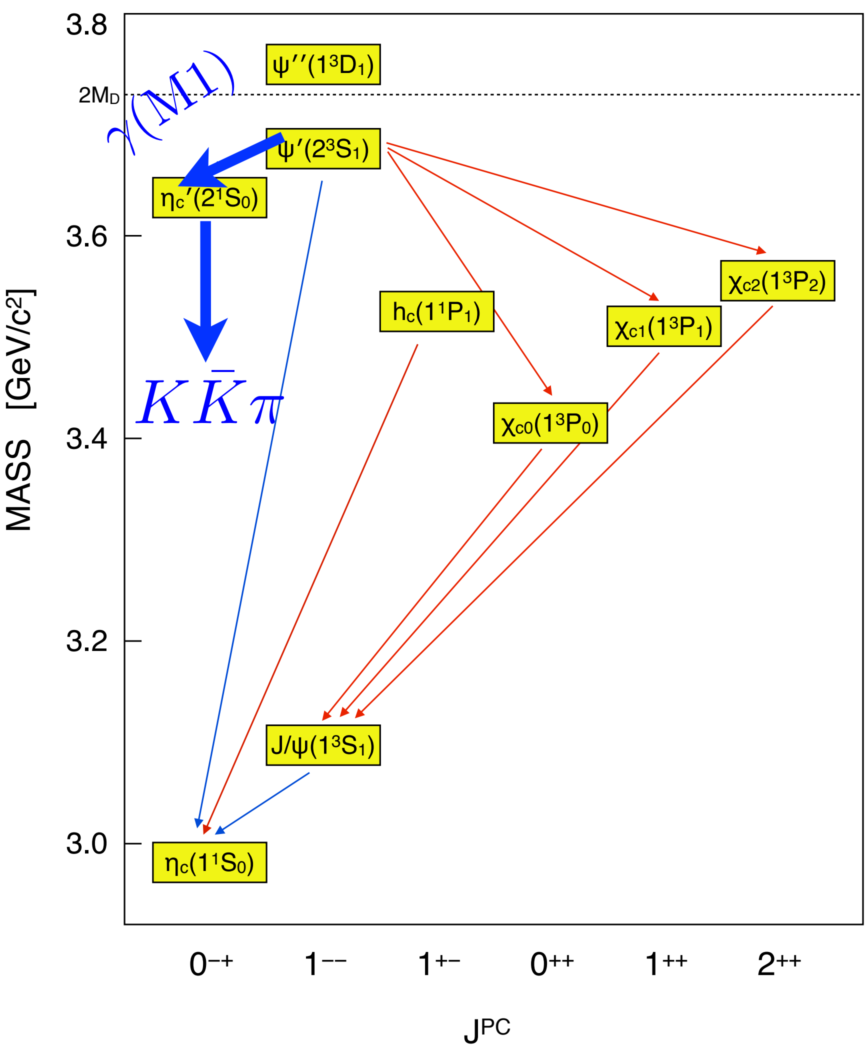




First observation of M1 transition to etac(2S): significance ~10 sigma

radial excitation of the g.s.

PRL 109, 042003 (2012)



$$M = 3637.6 \pm 2.9 \pm 1.6 \text{ MeV}$$

$$\Gamma = 16.9 \pm 6.4 \pm 4.8 \text{ MeV}$$

$$\mathbf{B(\psi(2S) \to \gamma\eta_c(2S)) = (6.8 \pm 1.1 \pm 4.5) \times 10^{-4}}$$

Notes:

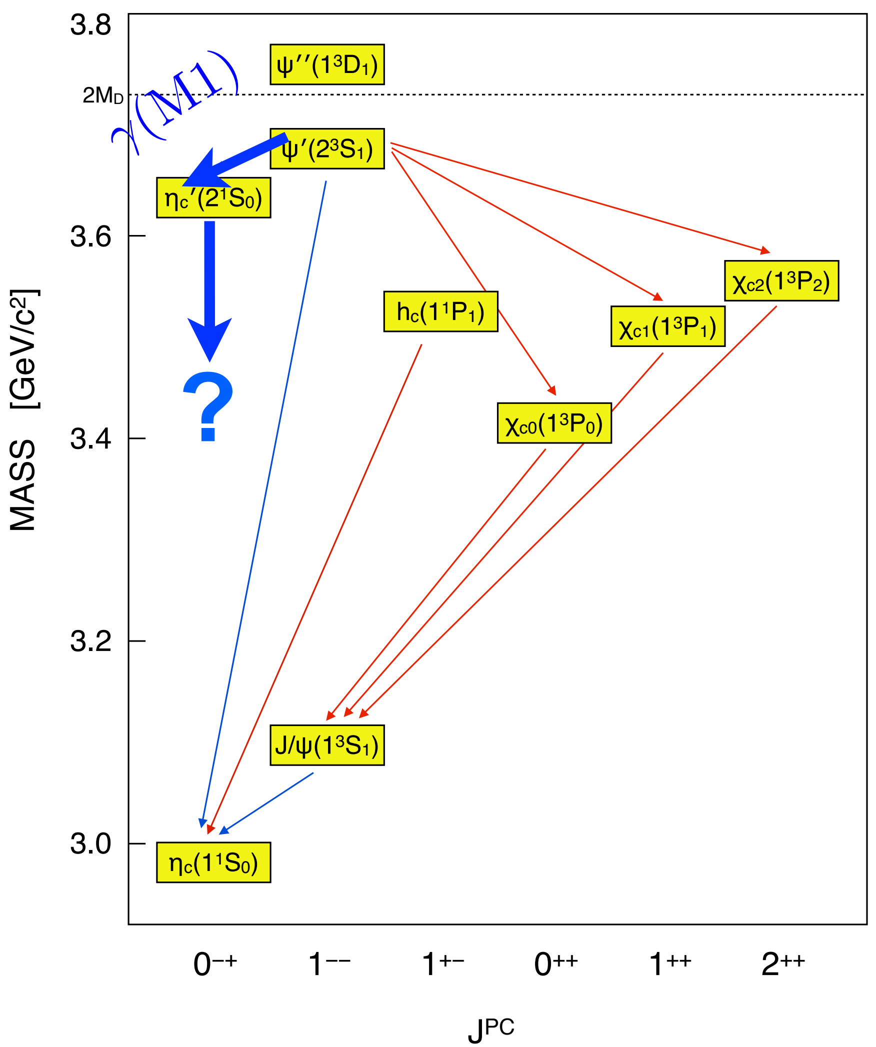
1) using Babar result:

$B(\eta_c(2S) \to K K\pi) = (1.9 \pm 0.4 \pm 1.1)\%$

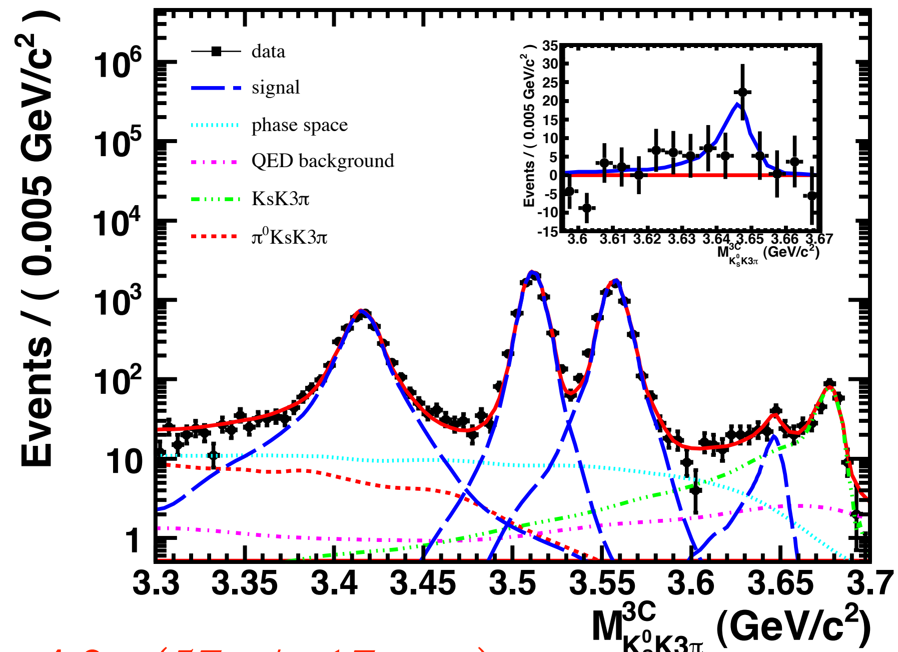
2) consistent with

CLEO-c: < 7.6×10^{-4} [PRD 81, 052002 (2010)]

radial excitation of the g.s.



PRD87, 052005 (2013)

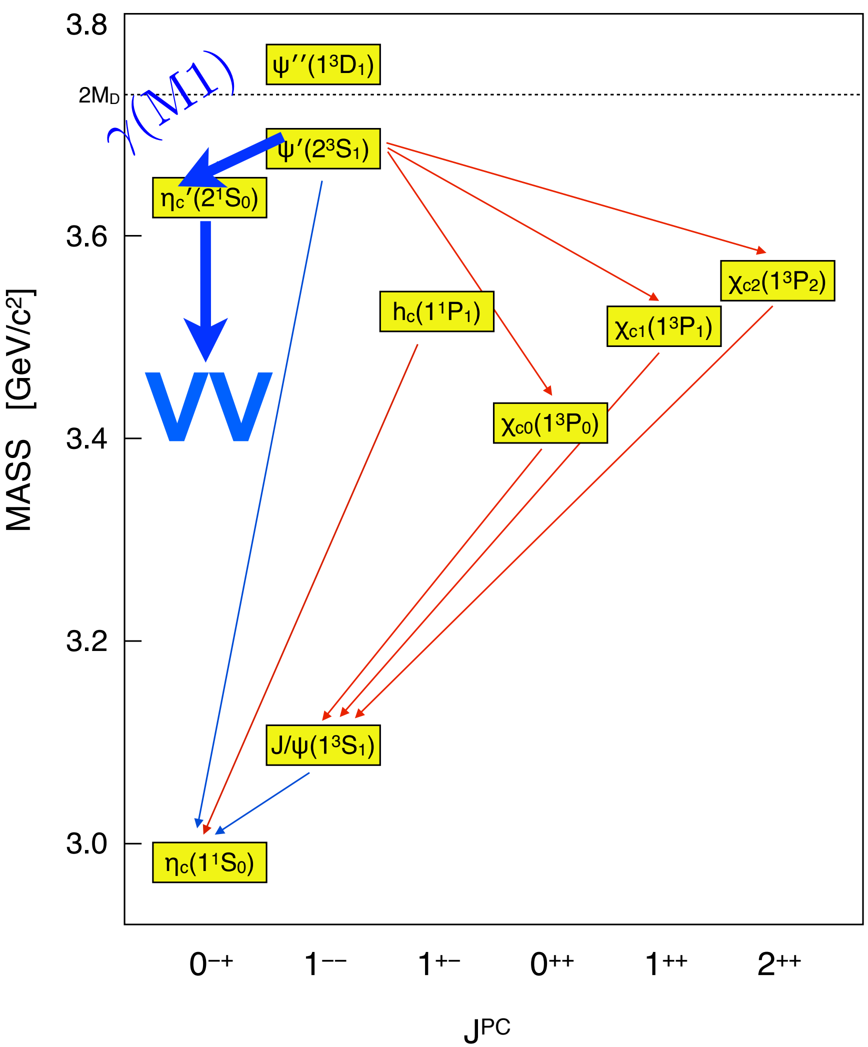


4.2σ (57 +/– 17 cnts)

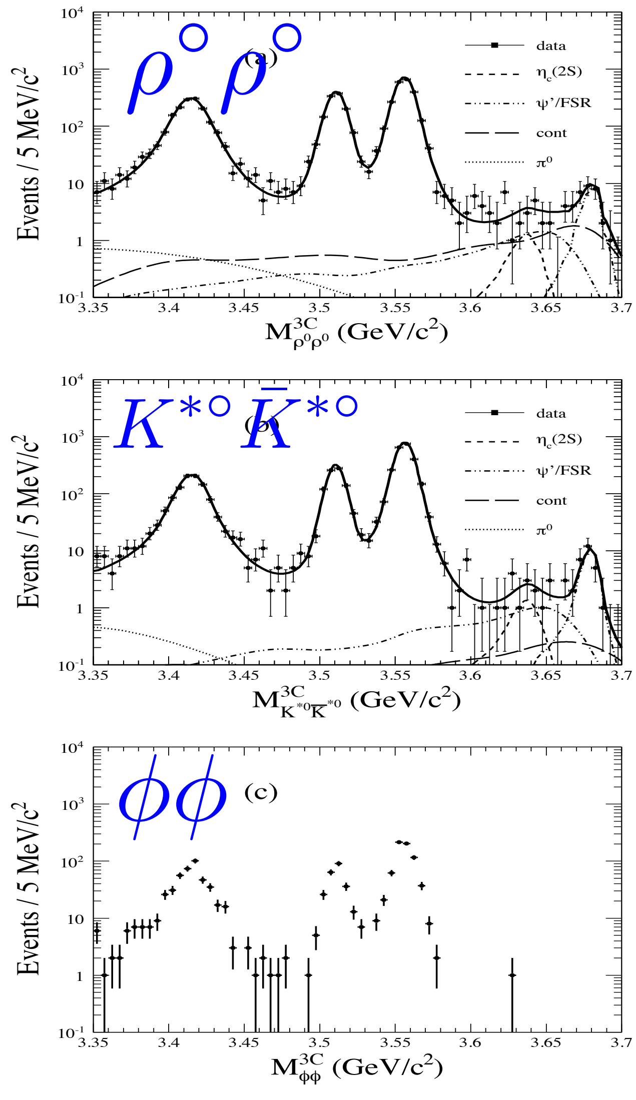
- $M(\eta_c') = 3646.9 \pm 1.6 \pm 3.6$ MeV/c^2
- $\Gamma(\eta_c') = 9.9 \pm 4.8 \pm 2.9$ MeV
- $Br(\psi' \to \gamma \eta_c' \to \gamma K_S K \pi\pi\pi) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$

radial excitation of the g.s.

Suppressed by helicity selection rule
--> charmed meson loops (Liu, Zhao)?



PRD84, 091102(R) (2011)



Upper limits (90% C.L.)

$< 3.1 \times 10^{-3}$

$(6-29) \times 10^{-3}$

$< 5.4 \times 10^{-3}$

$(8-36) \times 10^{-3}$

$< 2.0 \times 10^{-3}$

$(2-10) \times 10^{-3}$

arXiv:1004.0496

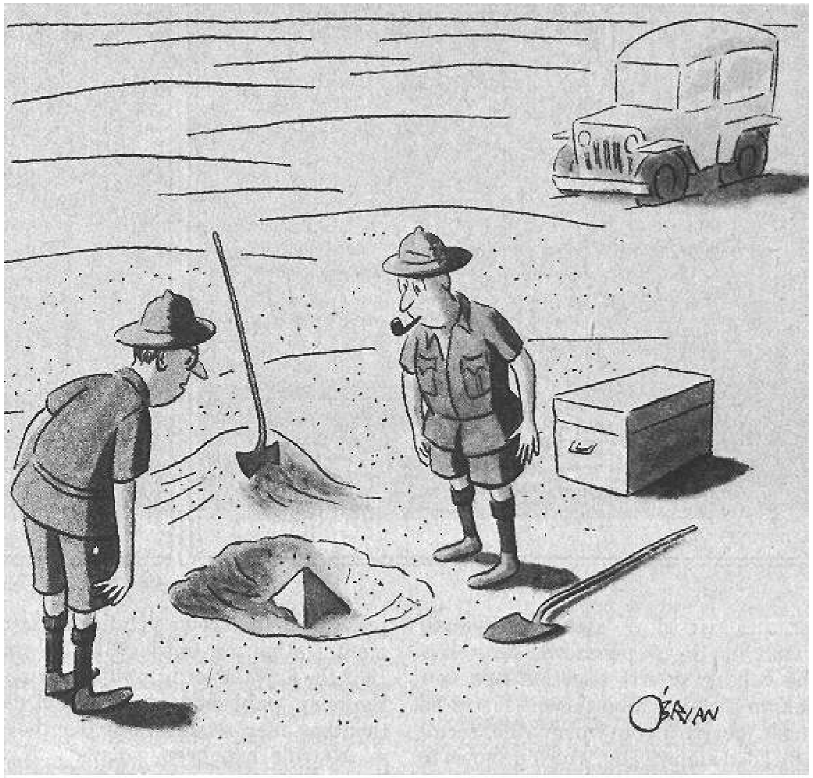
Charmonium Hadron Decay Studies with BESIII

Quality data to study charmonium decays with world's best precision

charmonium g.s. + radial excitation:
new insights and discoveries! But thorough theory input required!

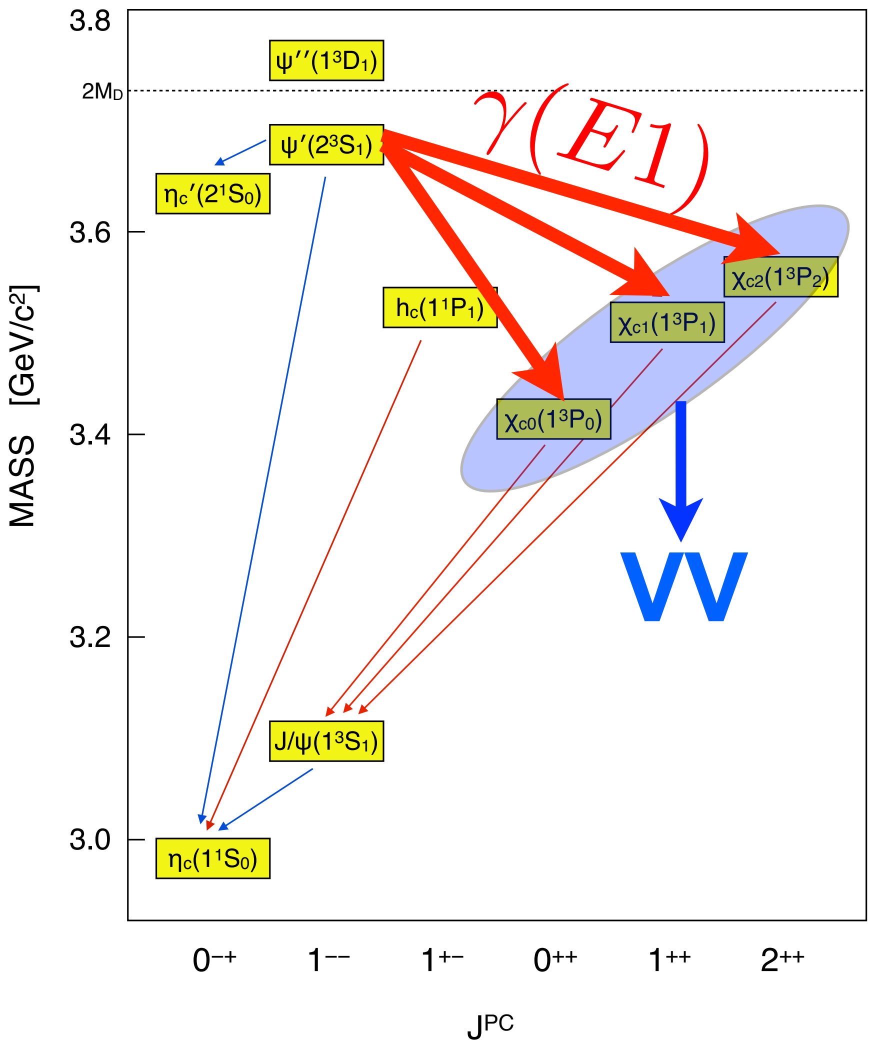
P-wave singlet state (h_c):
mass and width measured, hadronic decay properties in progress ....

BESIII and the near future:
more results at psi(2S) mass to be expected
new data at >4 GeV: discovery potential!



"This could be the discovery of the century. Depending, of course, on how far down it goes."

VV decays in P-wave charmonium



Huge statistics due to large E1 transition rate

Ideal testing ground for (perturbative) QCD calculations:

$$\chi_{c1} \to (\phi\phi, \omega\omega, \omega\phi)$$

HSR: highly suppressed?

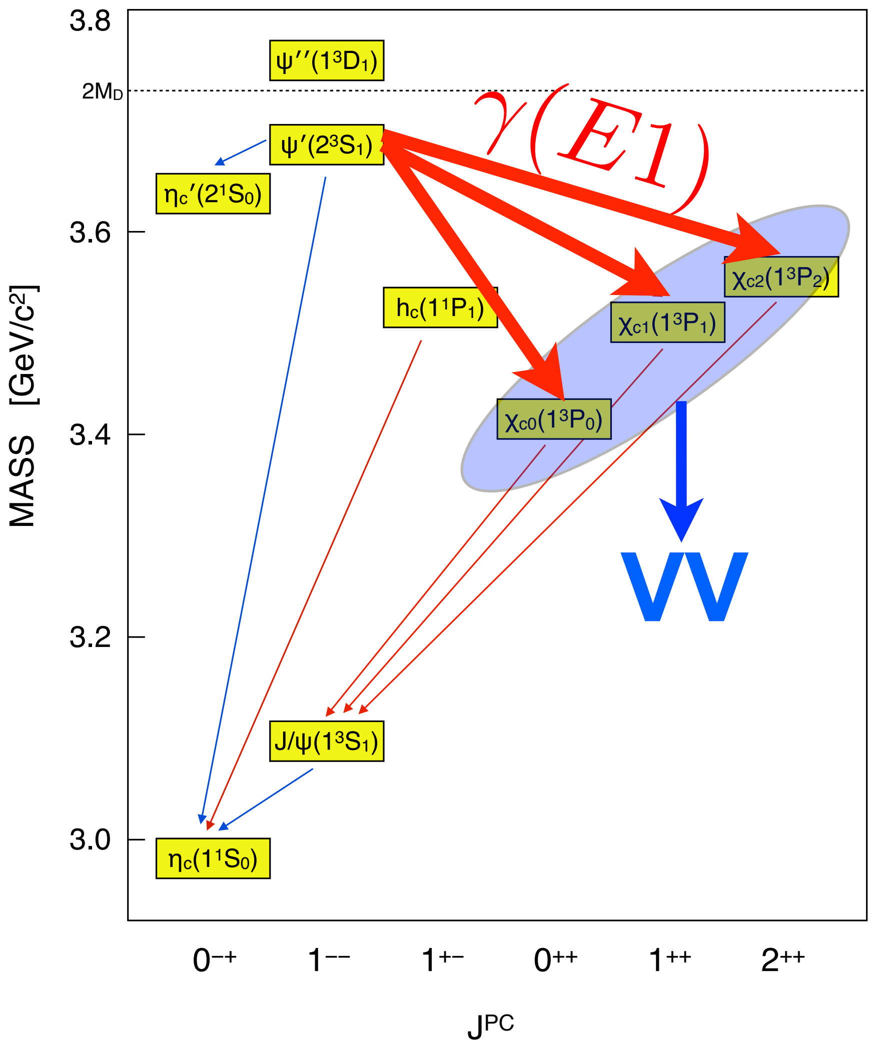
long-distance effects?

$$\chi_{cJ} \to \omega\phi$$

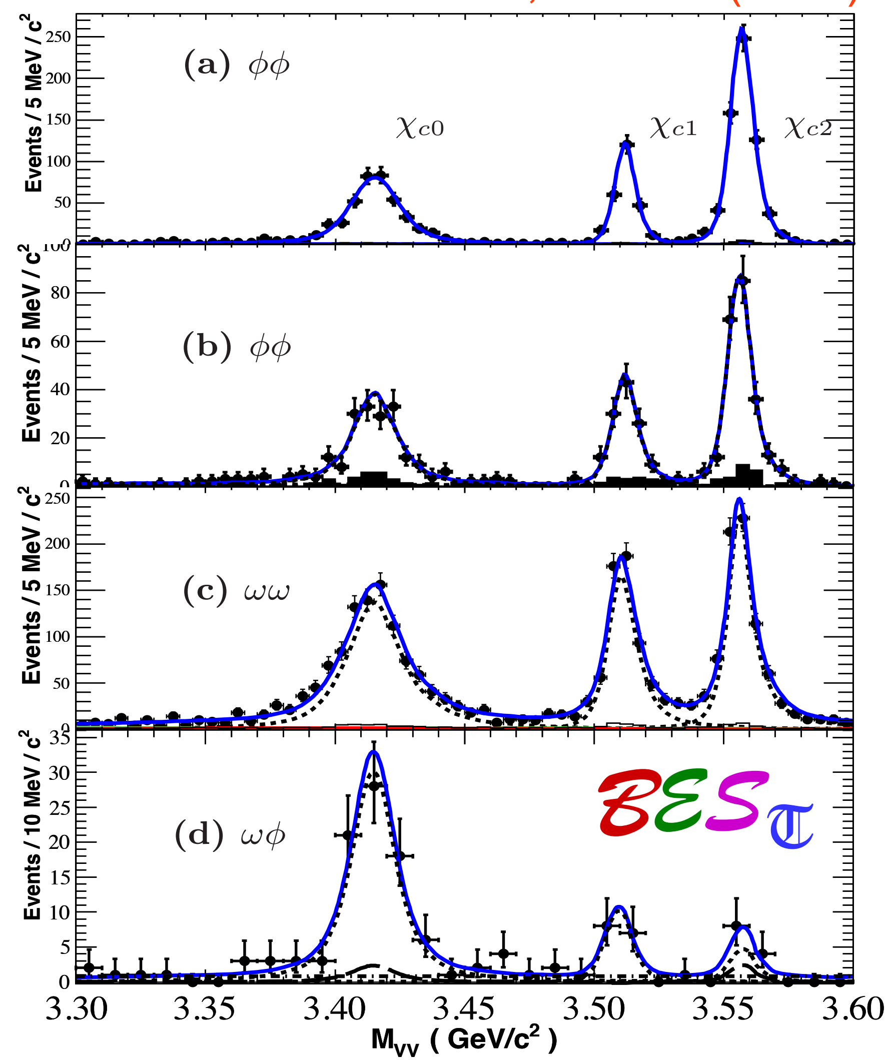
Doubly OZI suppressed

To be observed?

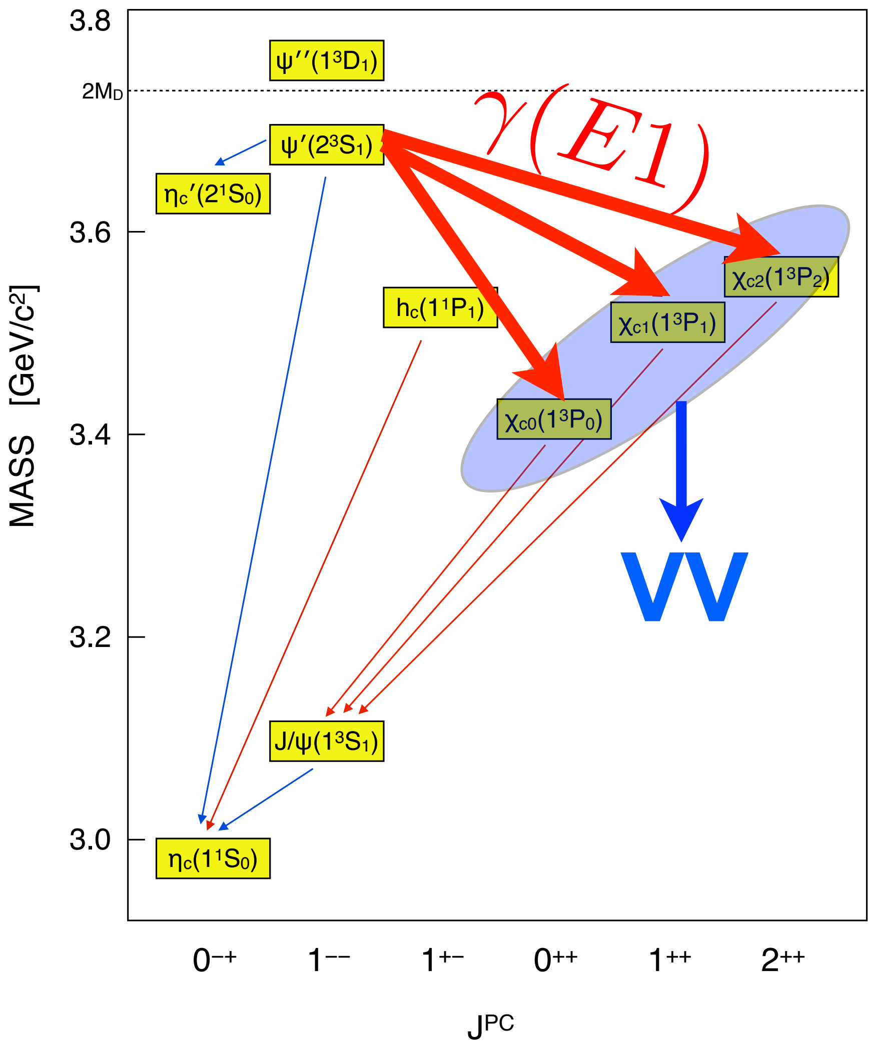
VV decays in P-wave charmonium



PRL107, 092001 (2011)



VV decays in P-wave charmonium



Mode	$N_{\rm net}$	ϵ (%)	$\mathcal{B}(\times 10^{-4})$
$\chi_{c0} \to \phi\phi$	433 ± 23	22.4	$7.8 \pm 0.4 \pm 0.8$
$\chi_{c1} \to \phi\phi$	254 ± 17	26.4	$4.1 \pm 0.3 \pm 0.4$
$\chi_{c2} \to \phi\phi$	630 ± 26	26.1	$10.7 \pm 0.4 \pm 1.1$
$\to 2(K^+K^-)$			
$\chi_{c0} \to \phi\phi$	179 ± 16	12.8	$9.2 \pm 0.7 \pm 1.0$
$\chi_{c1} \to \phi\phi$	112 ± 12	15.3	$5.0 \pm 0.5 \pm 0.6$
$\chi_{c2} \to \phi\phi$	219 ± 16	14.9	$10.7 \pm 0.7 \pm 1.2$
$\to K^+K^-\pi^+\pi^-\pi^0$			
Combined:			
$\chi_{c0} \to \phi\phi$	—	—	$8.0 \pm 0.3 \pm 0.8$
$\chi_{c1} \to \phi\phi$	—	—	$4.4 \pm 0.3 \pm 0.5$
$\chi_{c2} \to \phi\phi$	—	—	$10.7 \pm 0.3 \pm 1.2$
$\chi_{c0} \to \omega\omega$	991 ± 38	13.1	$9.5 \pm 0.3 \pm 1.1$
$\chi_{c1} \to \omega\omega$	597 ± 29	13.2	$6.0 \pm 0.3 \pm 0.7$
$\chi_{c2} \to \omega\omega$	762 ± 31	11.9	$8.9 \pm 0.3 \pm 1.1$
$\to 2(\pi^+\pi^-\pi^0)$			
$\chi_{c0} \to \omega\phi$	76 ± 11	14.7	$1.2 \pm 0.1 \pm 0.2$
$\chi_{c1} \to \omega\phi$	15 ± 4	16.2	$0.22 \pm 0.06 \pm 0.02$
$\chi_{c2} \to \omega\phi$	< 13	15.7	< 0.2
$\to K^+K^-\pi^+\pi^-\pi^0$			

Observation

Evidence

Unique constraints for calculations!