Charmonium Spectroscopy and the Role of BESIII

Ryan Mitchell

Indiana University

MIAMI 2012

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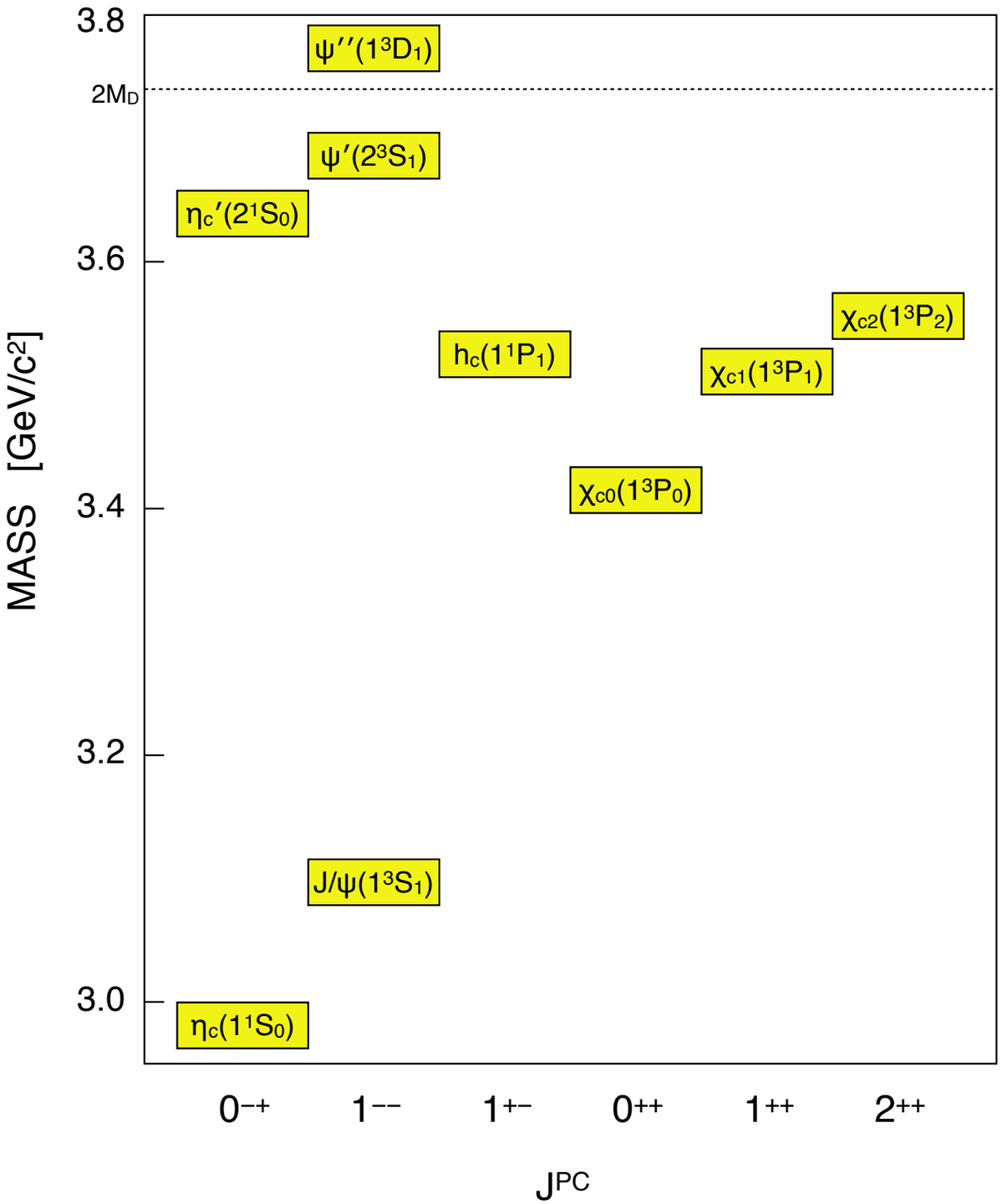

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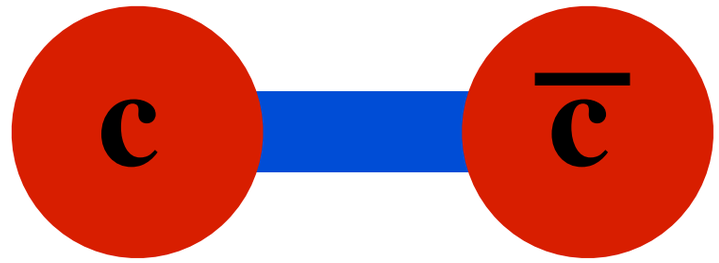
II. The Original Era of Discovery:
establishing the quark model states

III. From Discovery to Precision:
the quark model states at BESIII

IV. A New Era of Discovery:
beyond the quark model and the role of BESIII



CHARMONIUM

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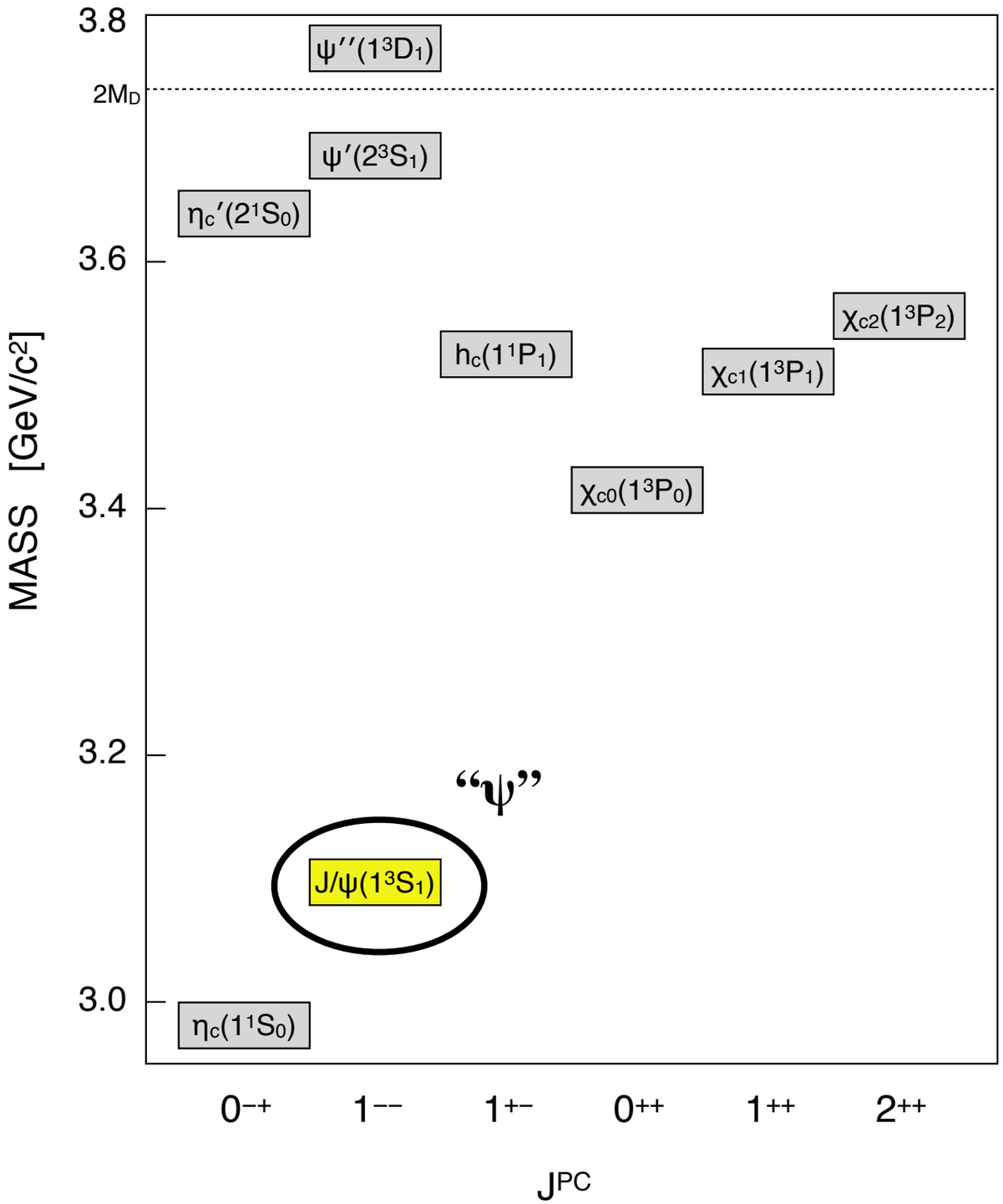

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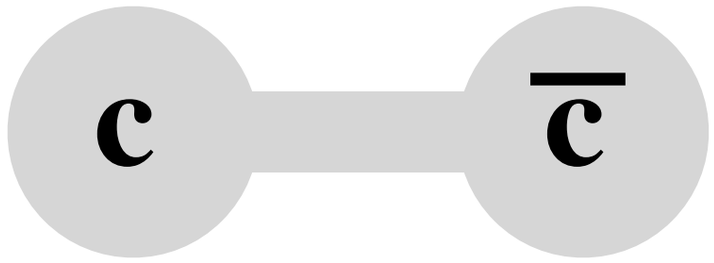

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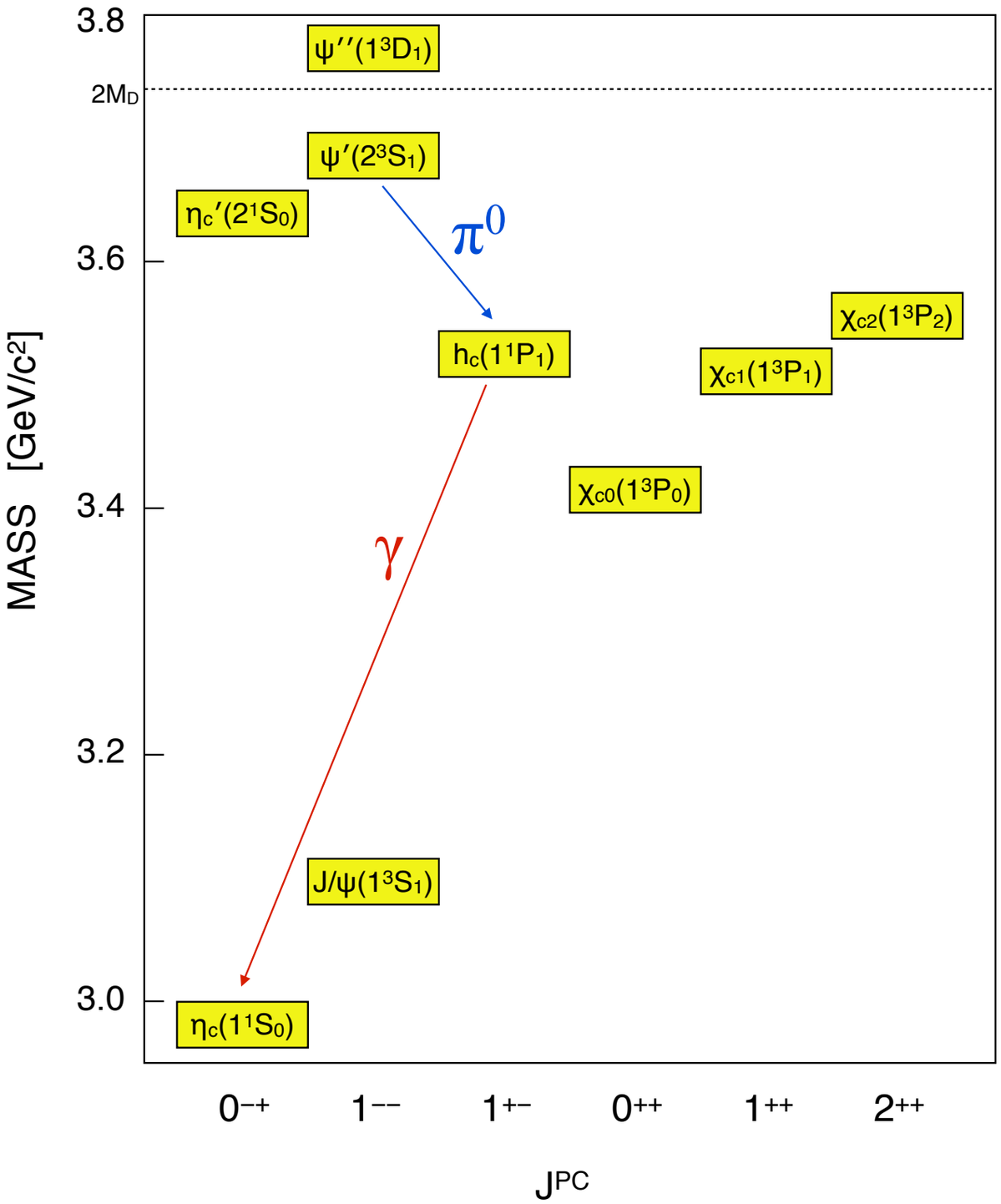

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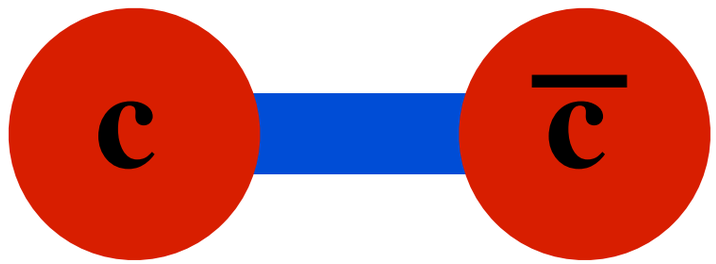

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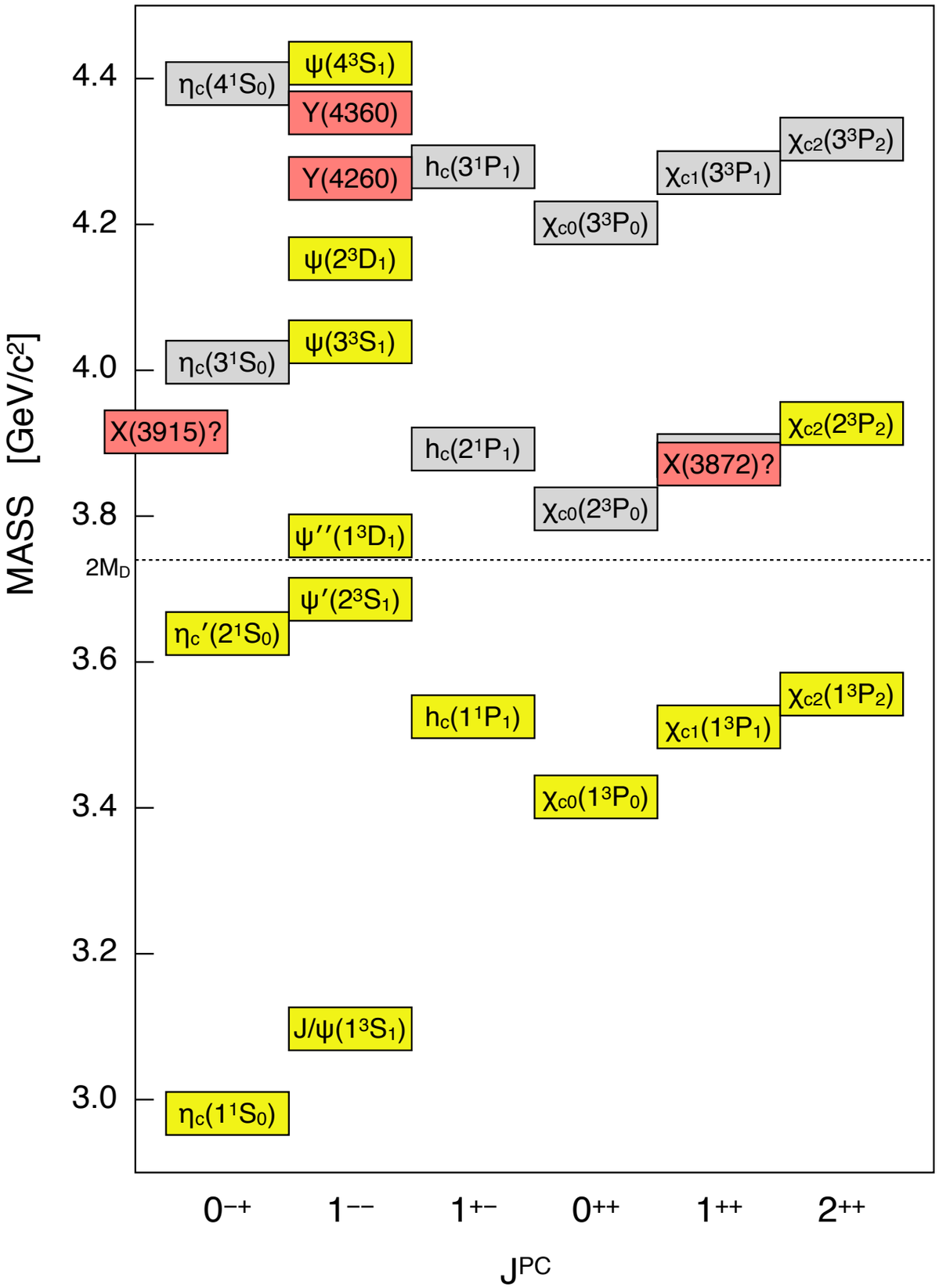

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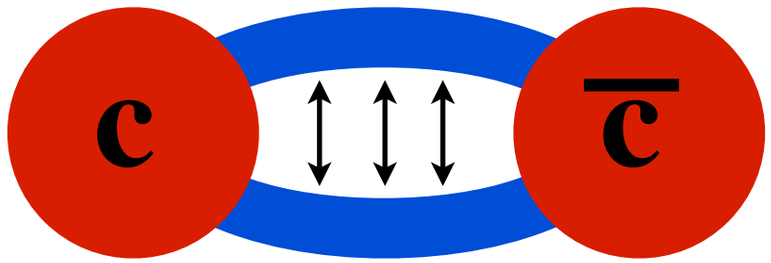
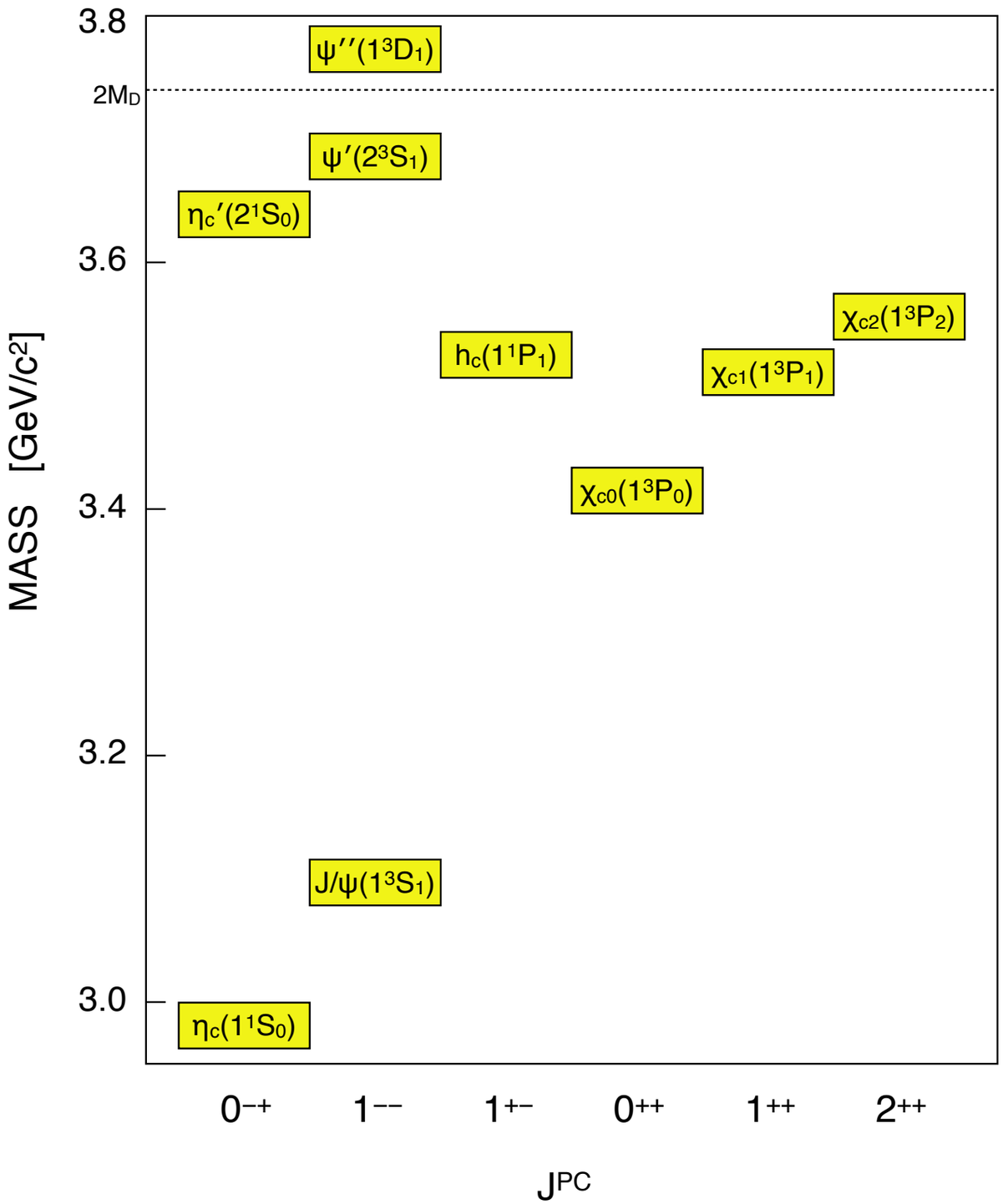
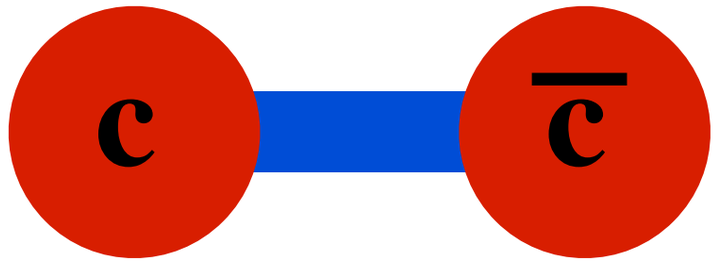


HYBRID CHARMONIUM?





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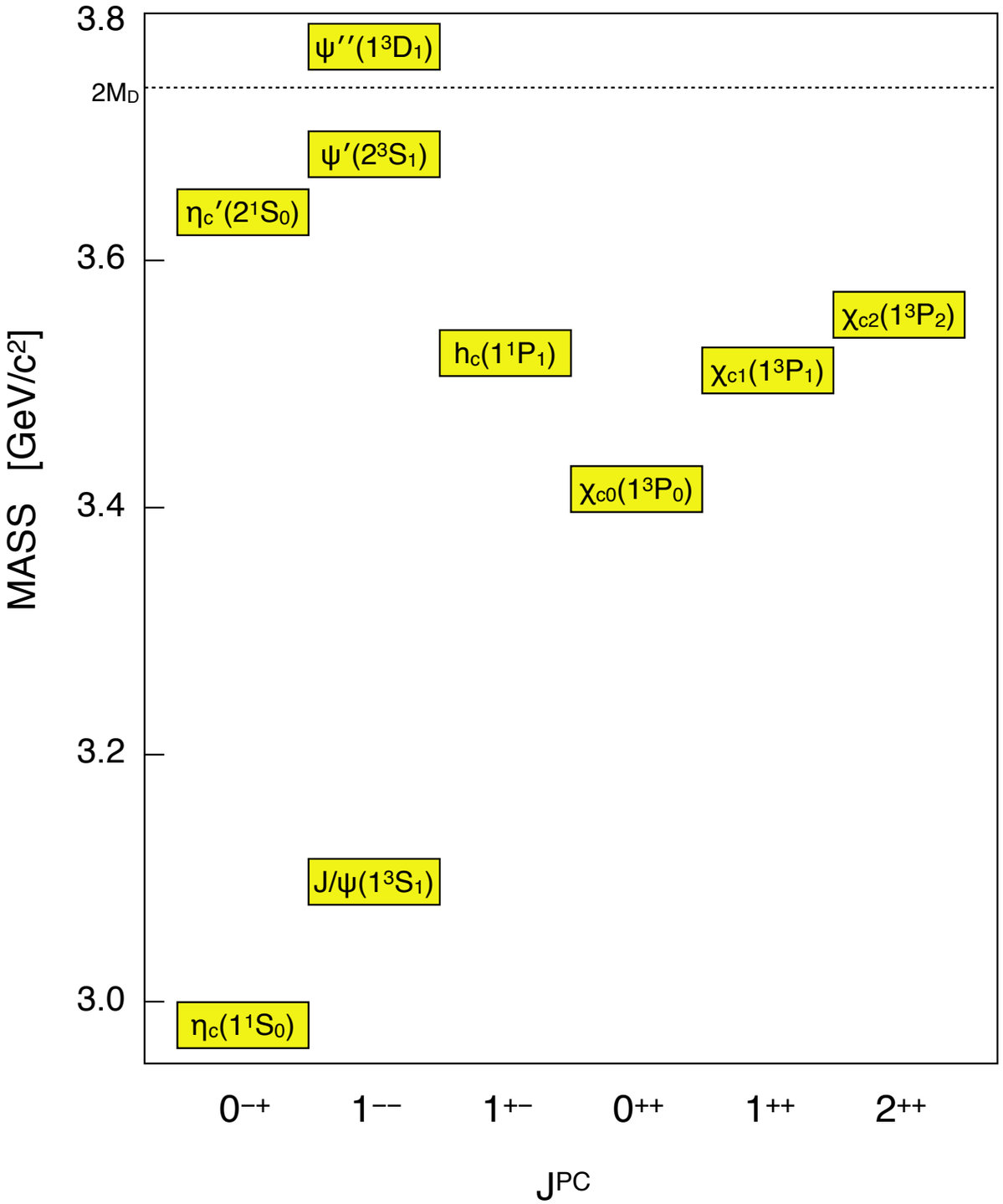
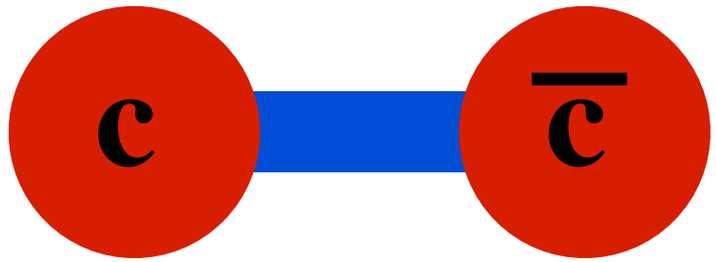


Why charmonium?

It is one of the simplest bound states of QCD.

(like positronium or Hydrogen in QED)



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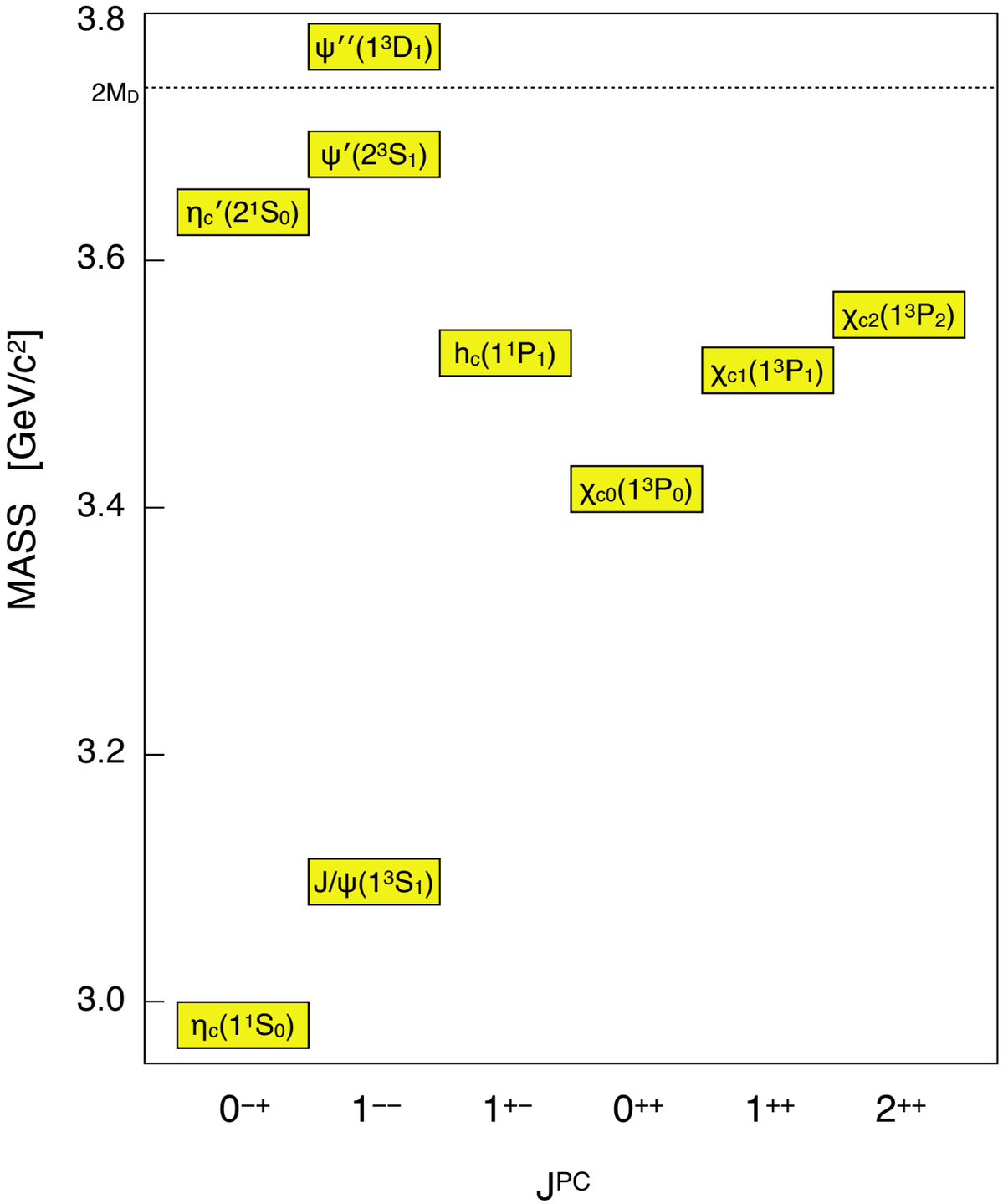
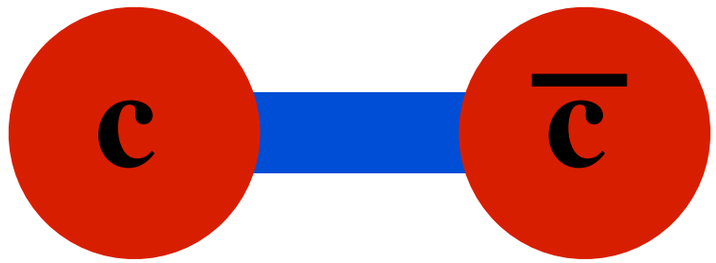


Classify using $\mathbf{J^{PC}}$

(experimentally determined)



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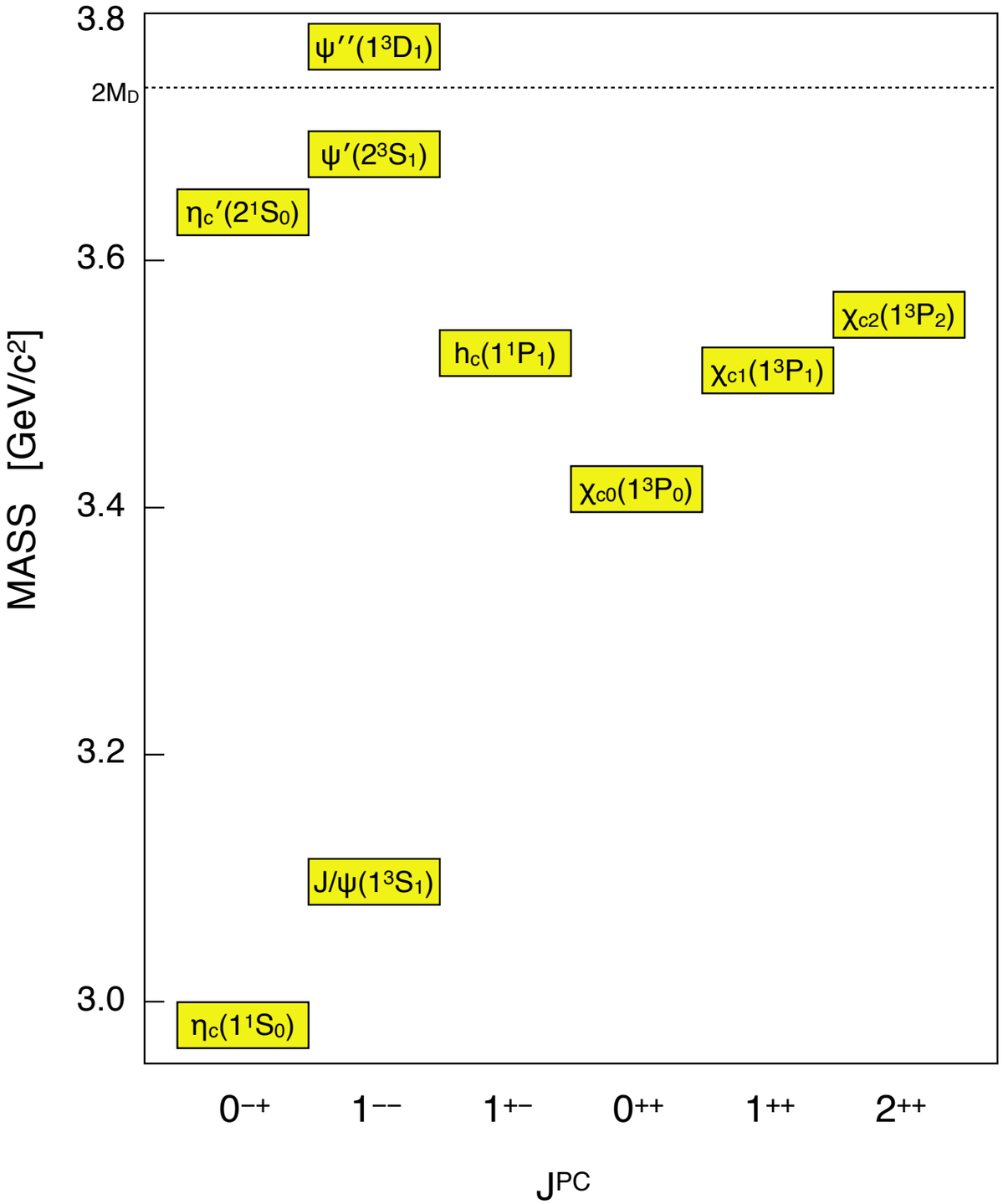
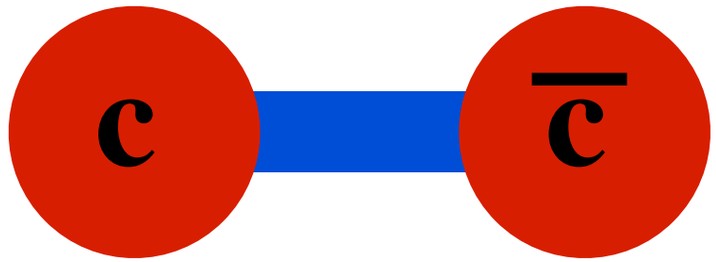


Match to $\mathbf{n^{2S+1}L_J}$
quark model states

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

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

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



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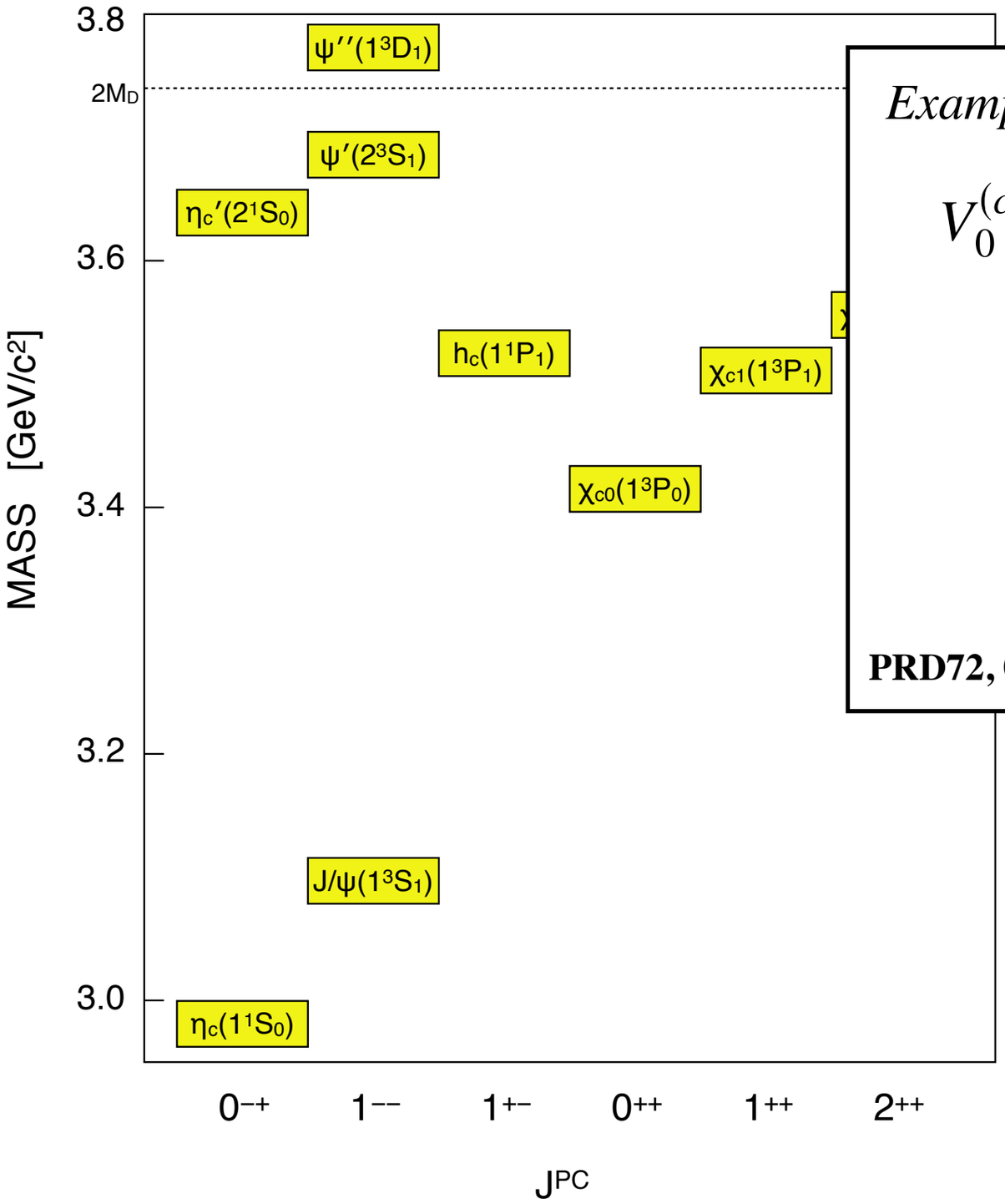


Potential models:

Example from Barnes, Godfrey, Swanson:

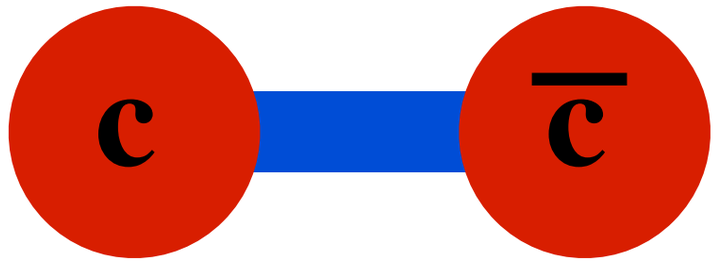
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)



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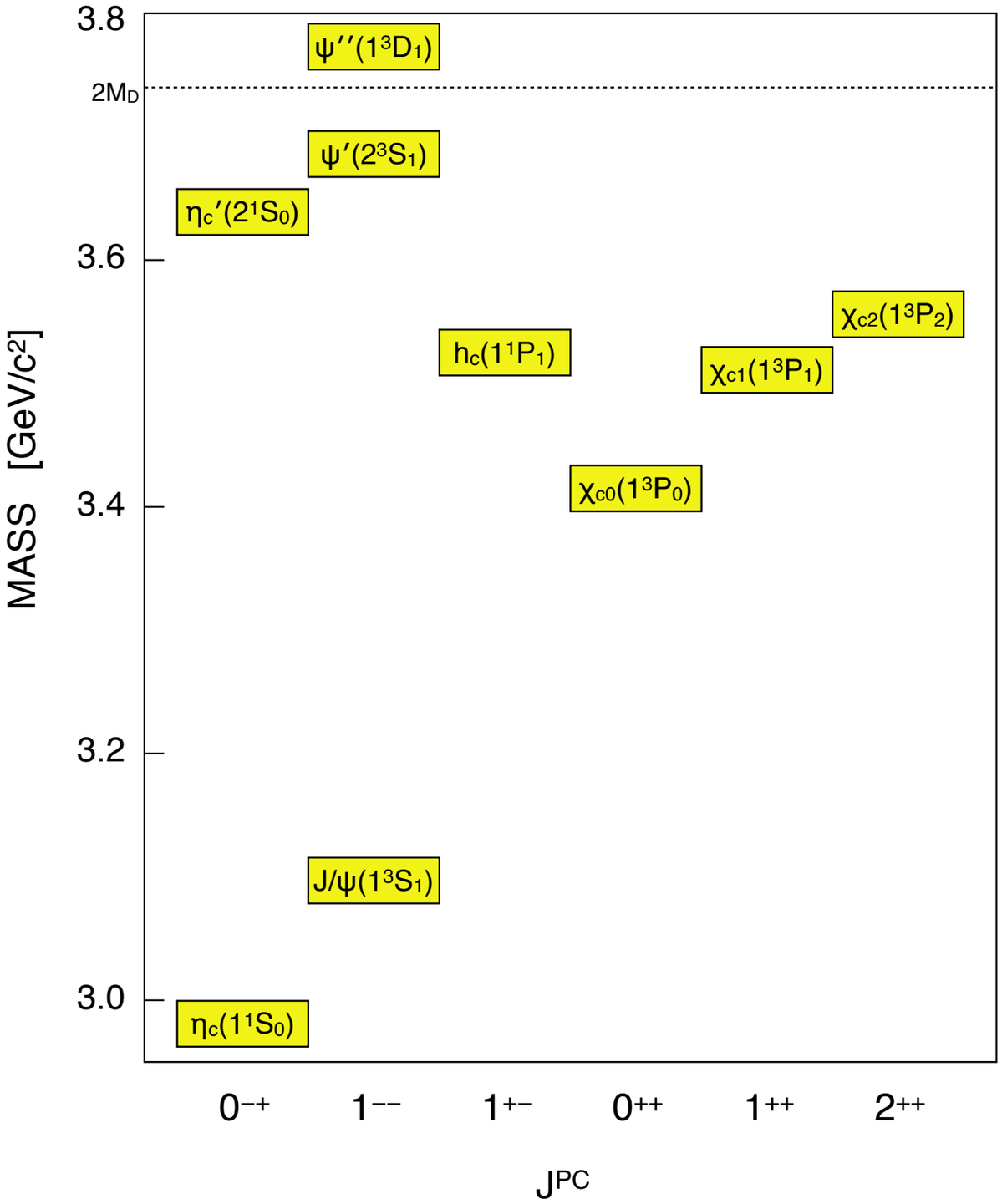

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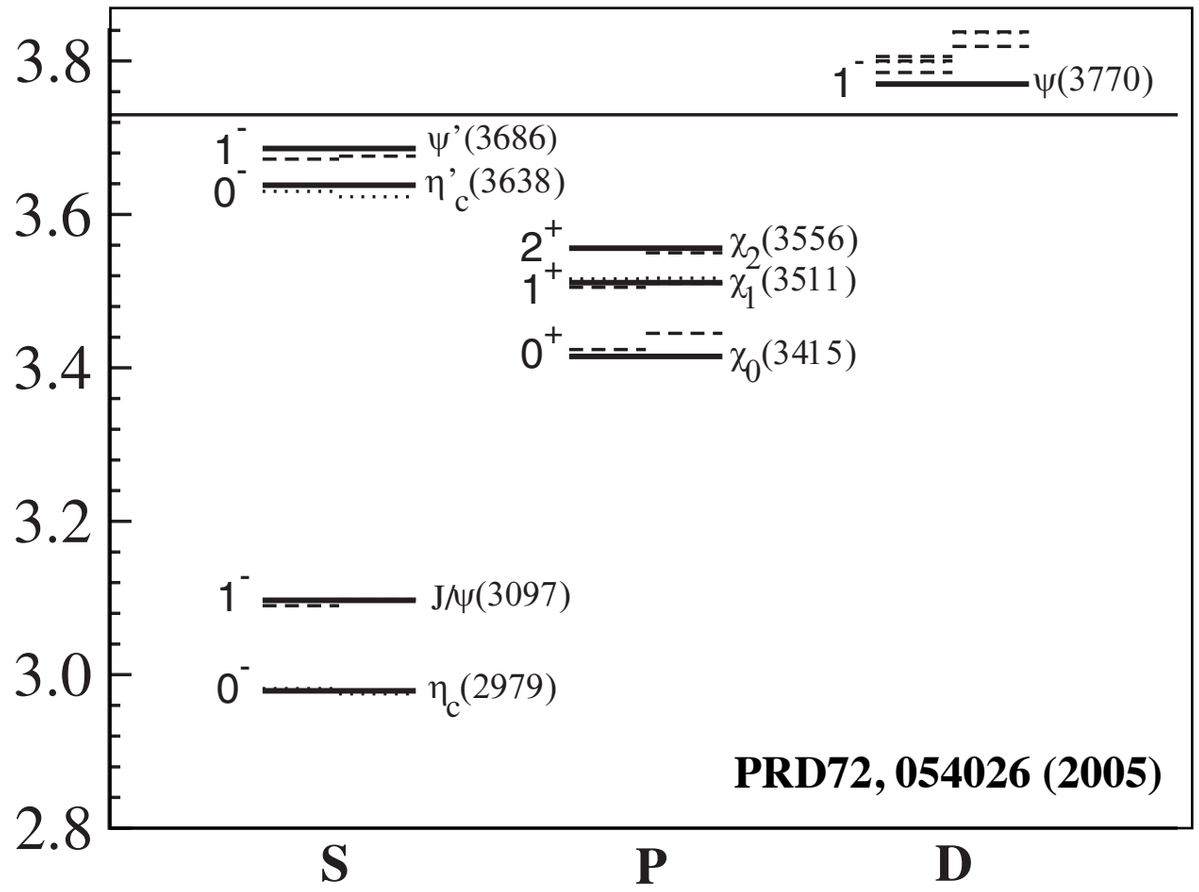

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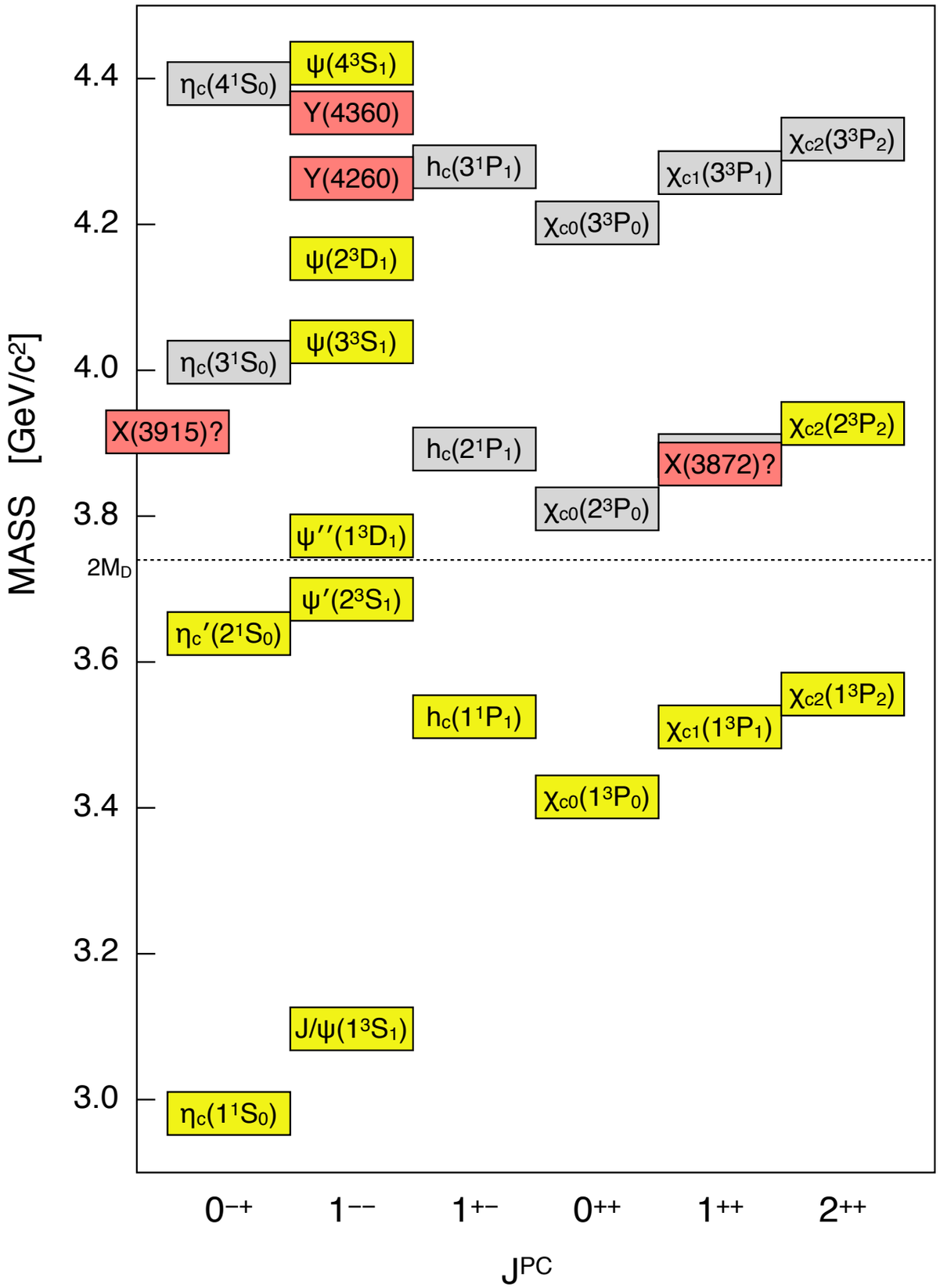

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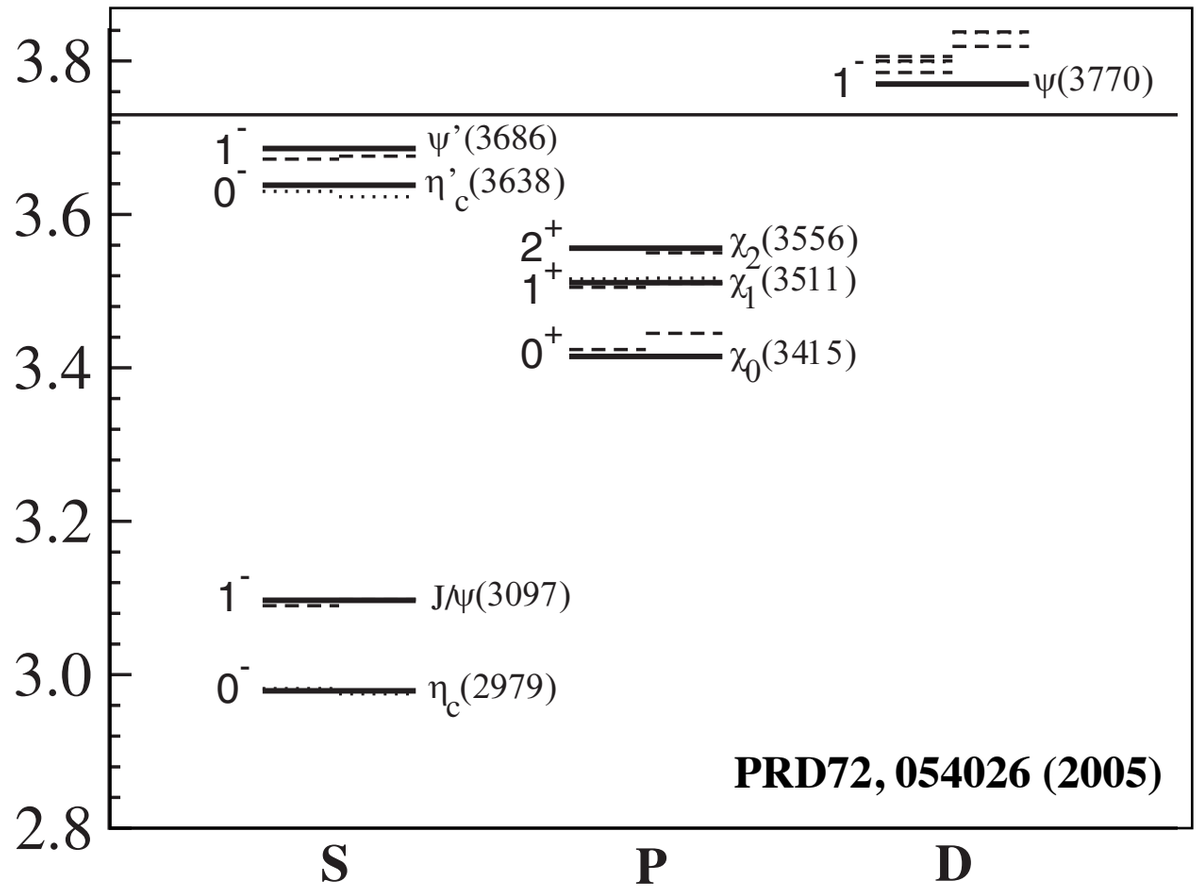

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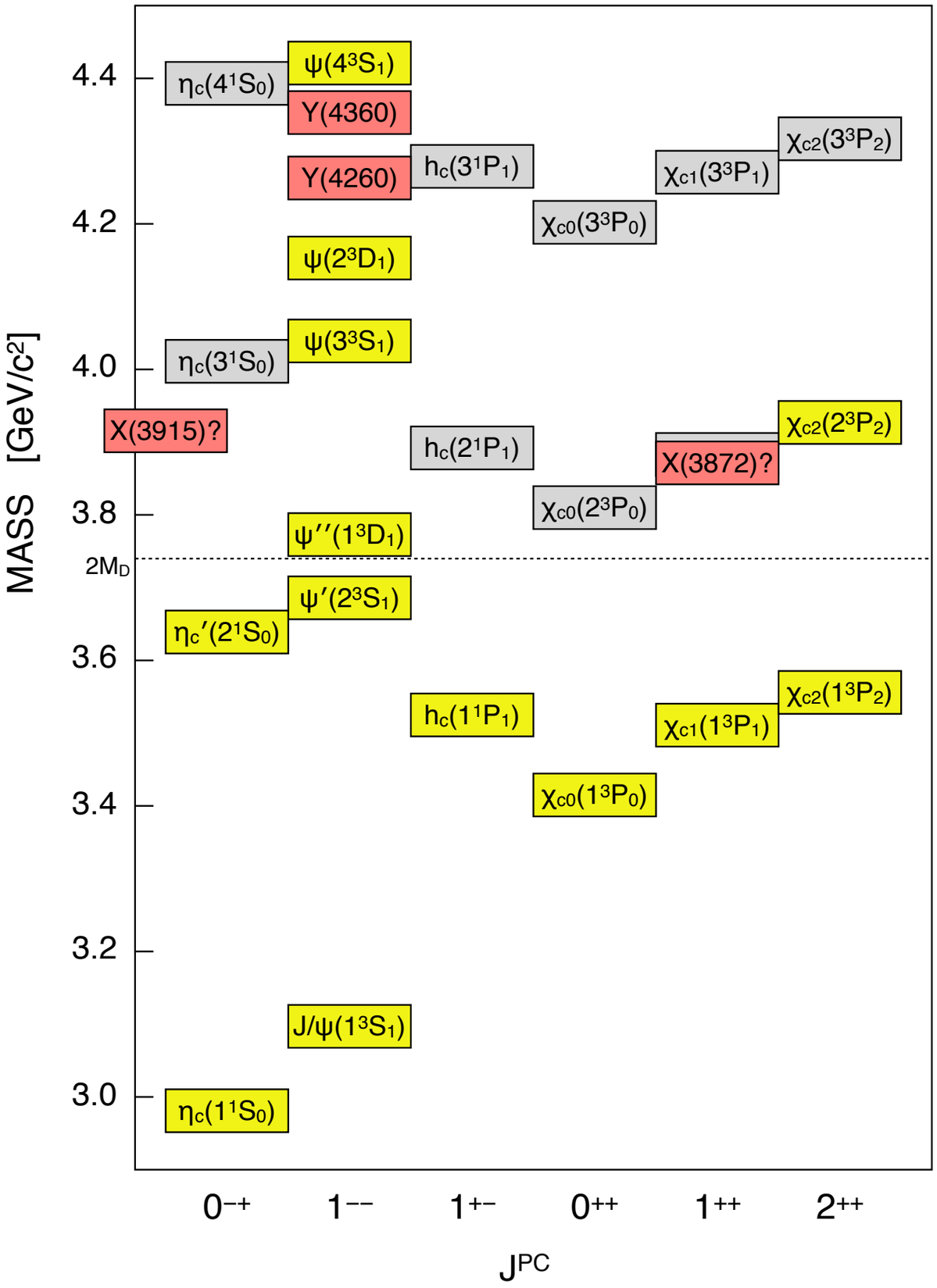
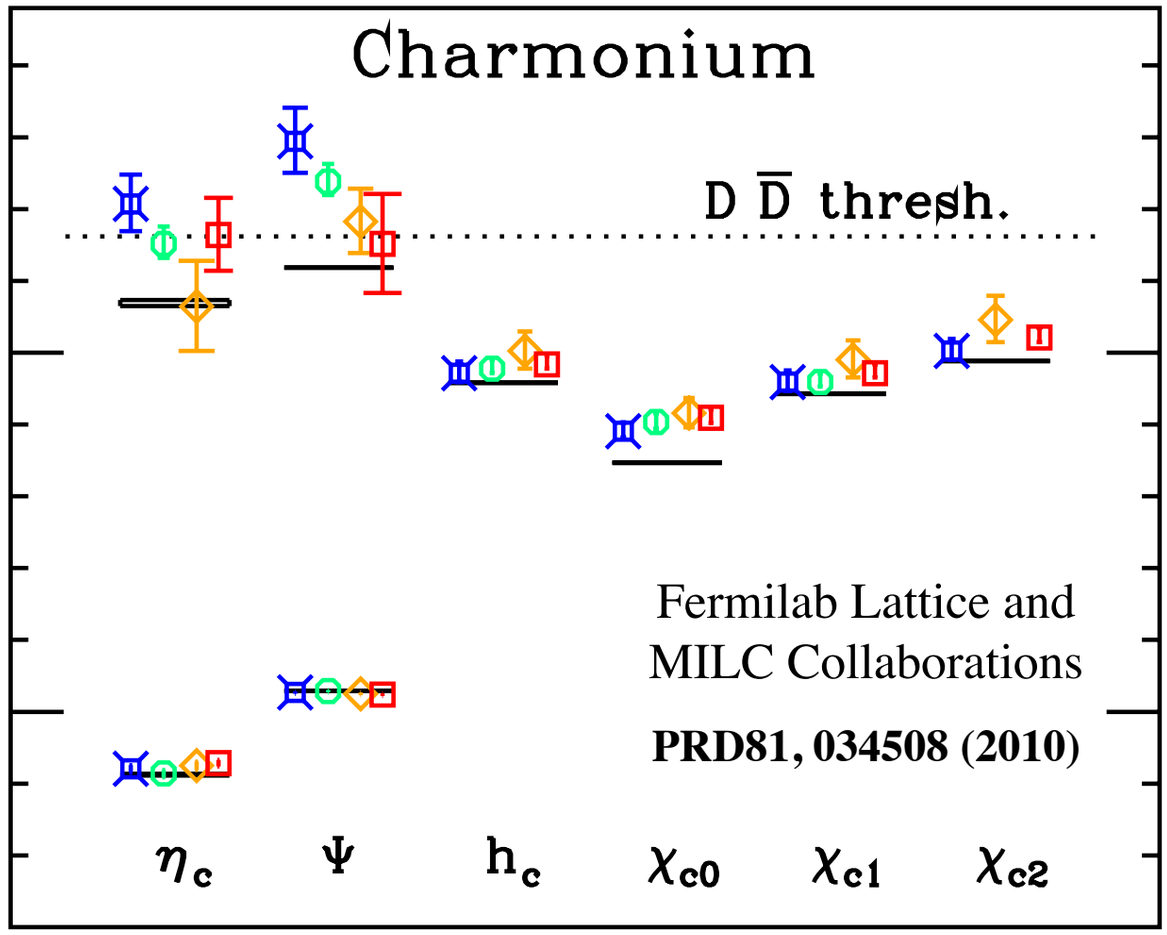


A more fundamental approach,
Lattice QCD:



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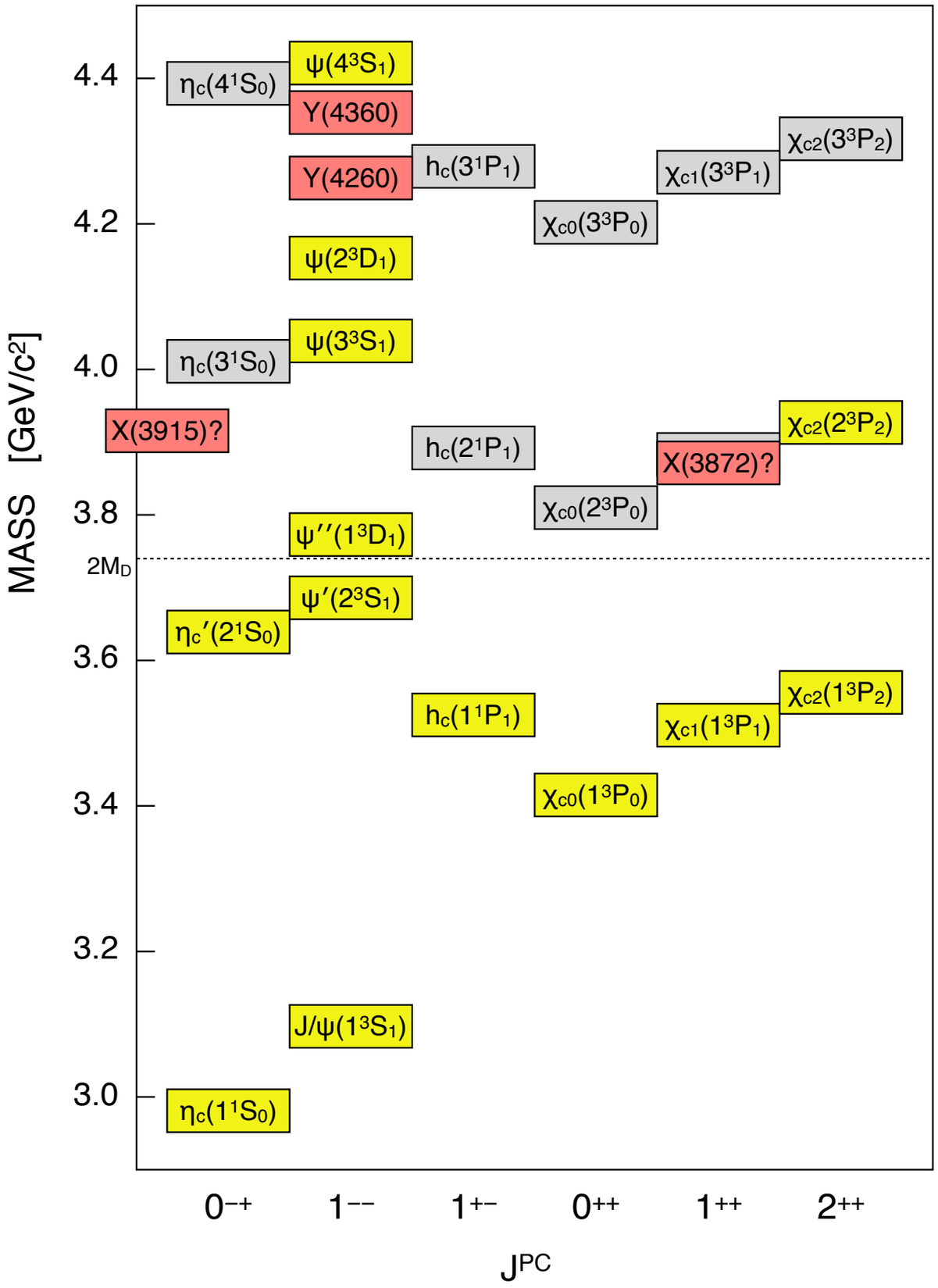

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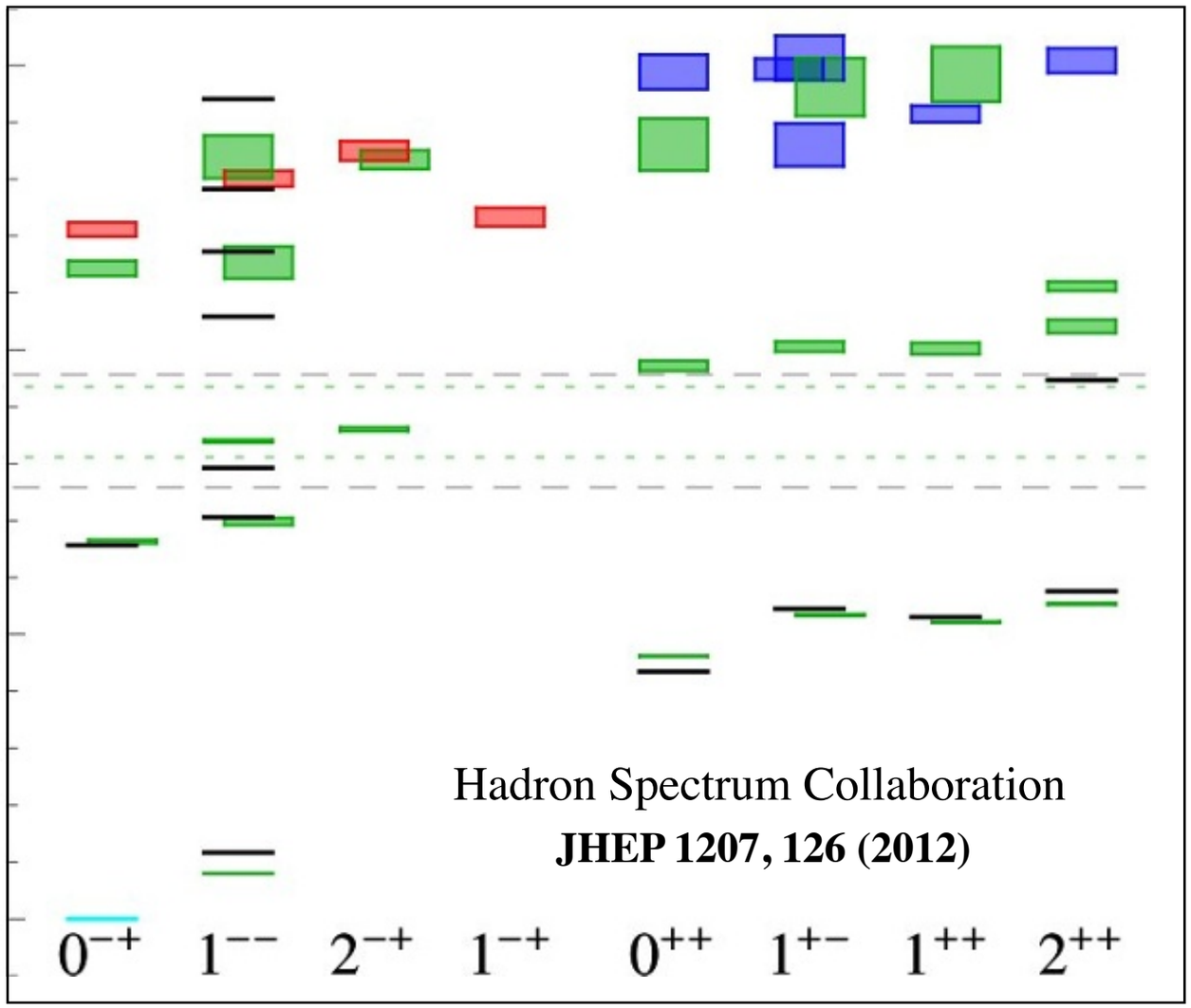
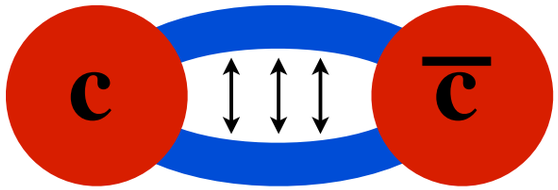


Hadron Spectrum Collaboration

JHEP 1207, 126 (2012)



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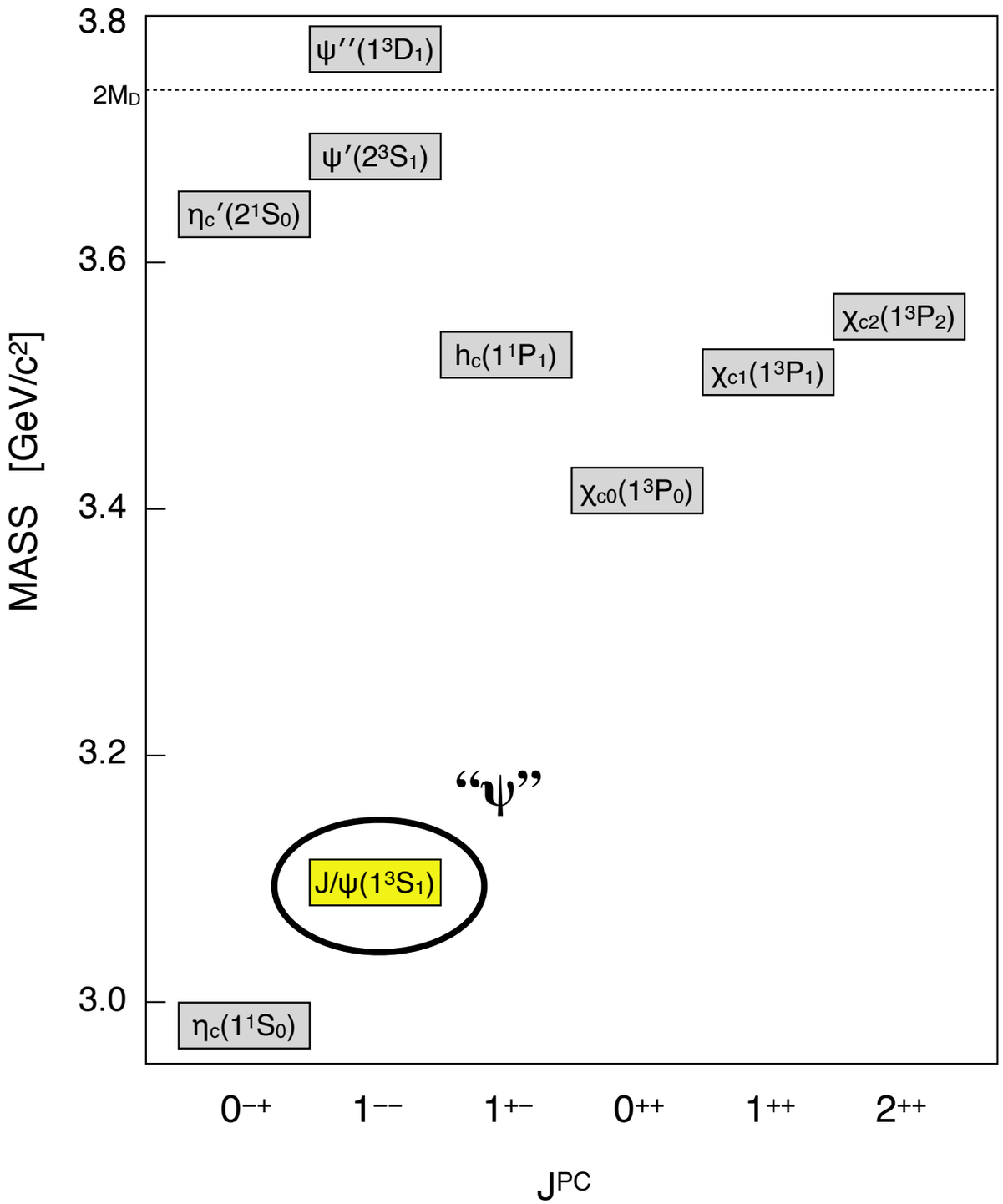

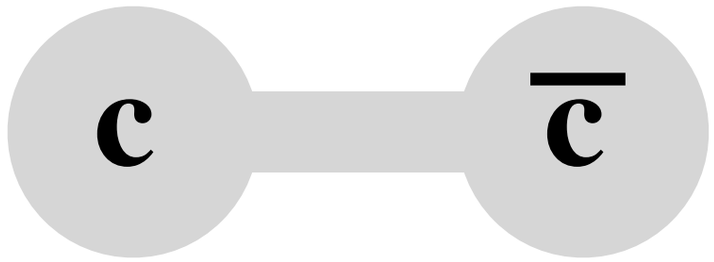

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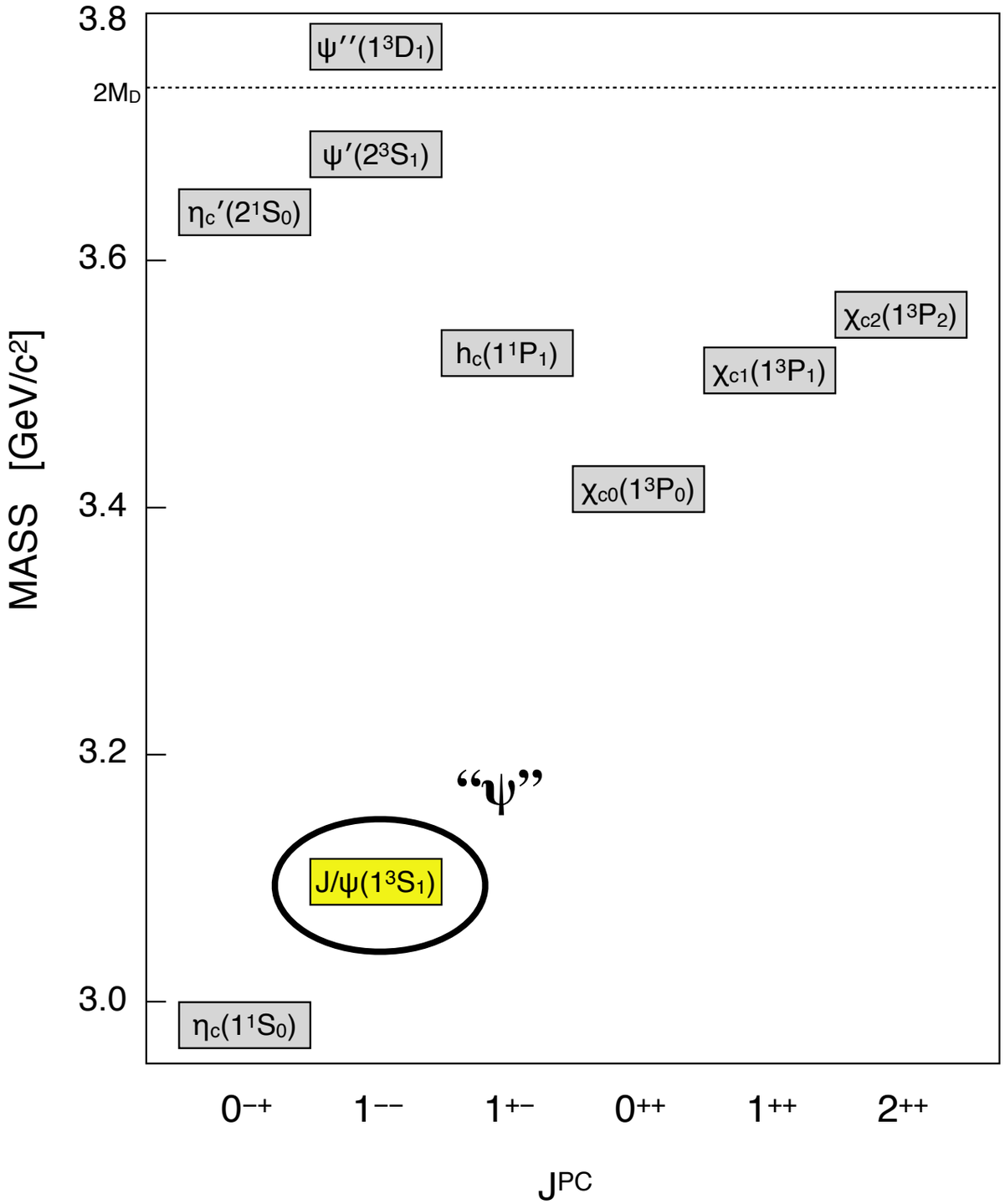
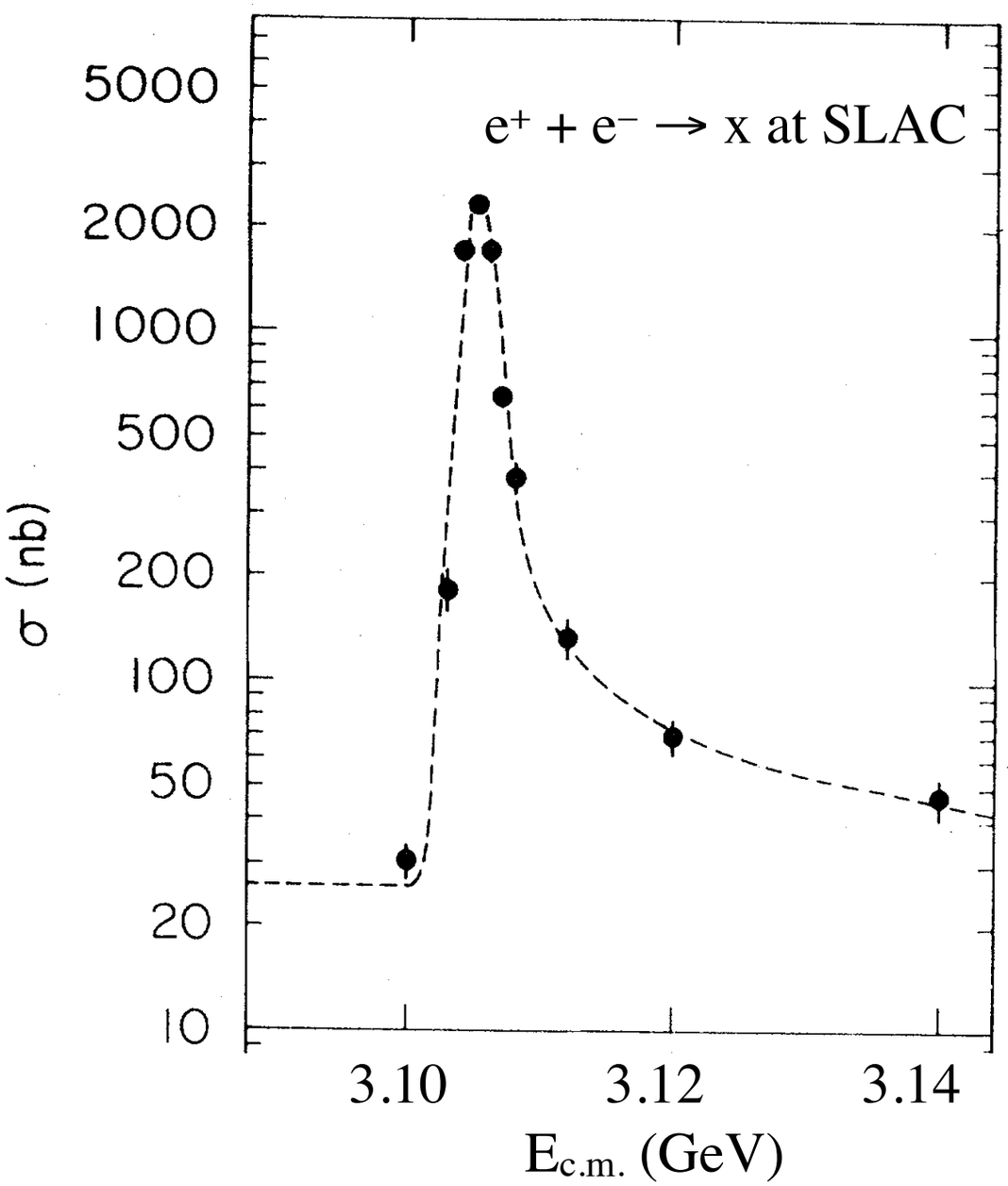


November (1974) Revolution



PRL33, 1406 (1974)

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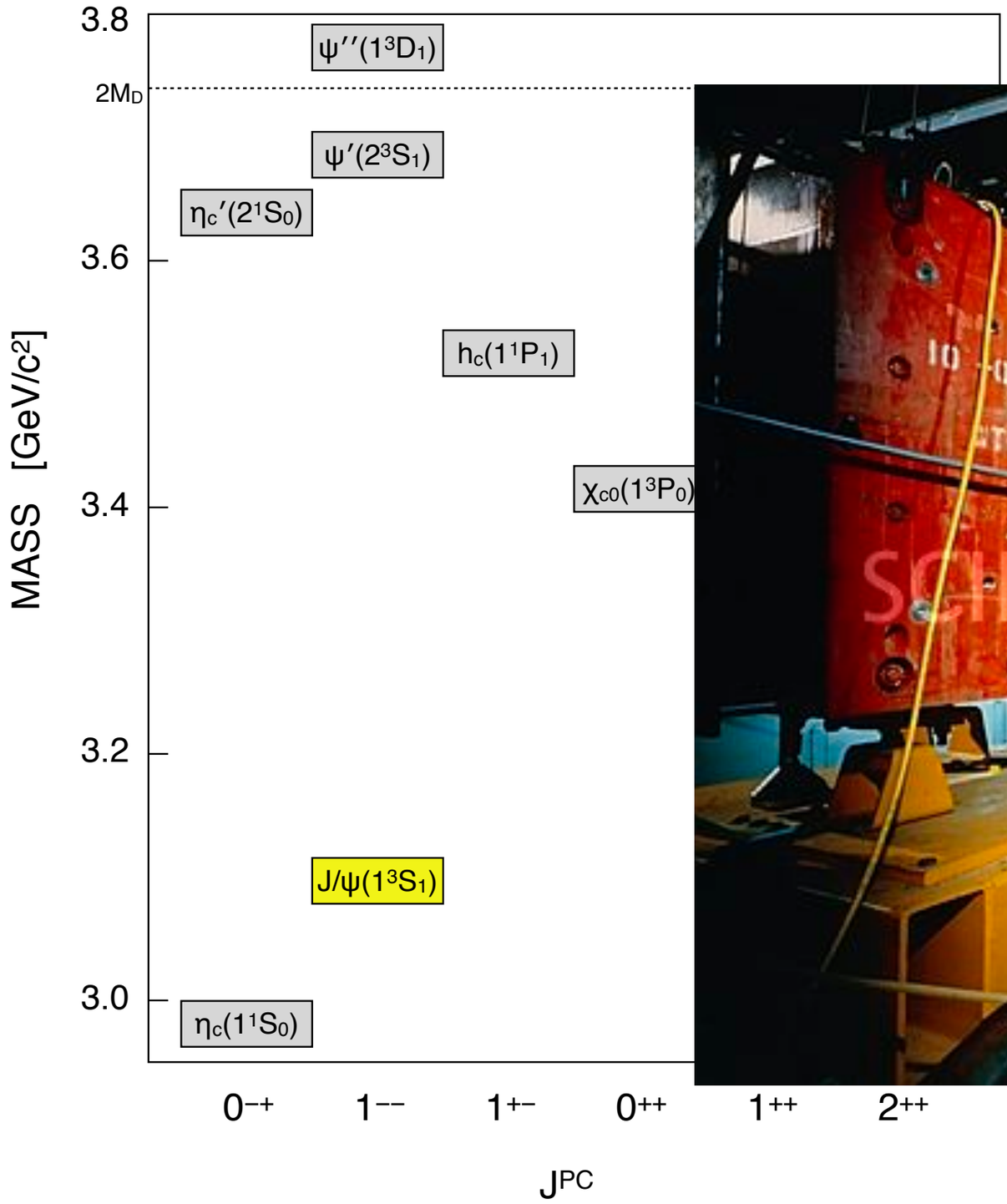
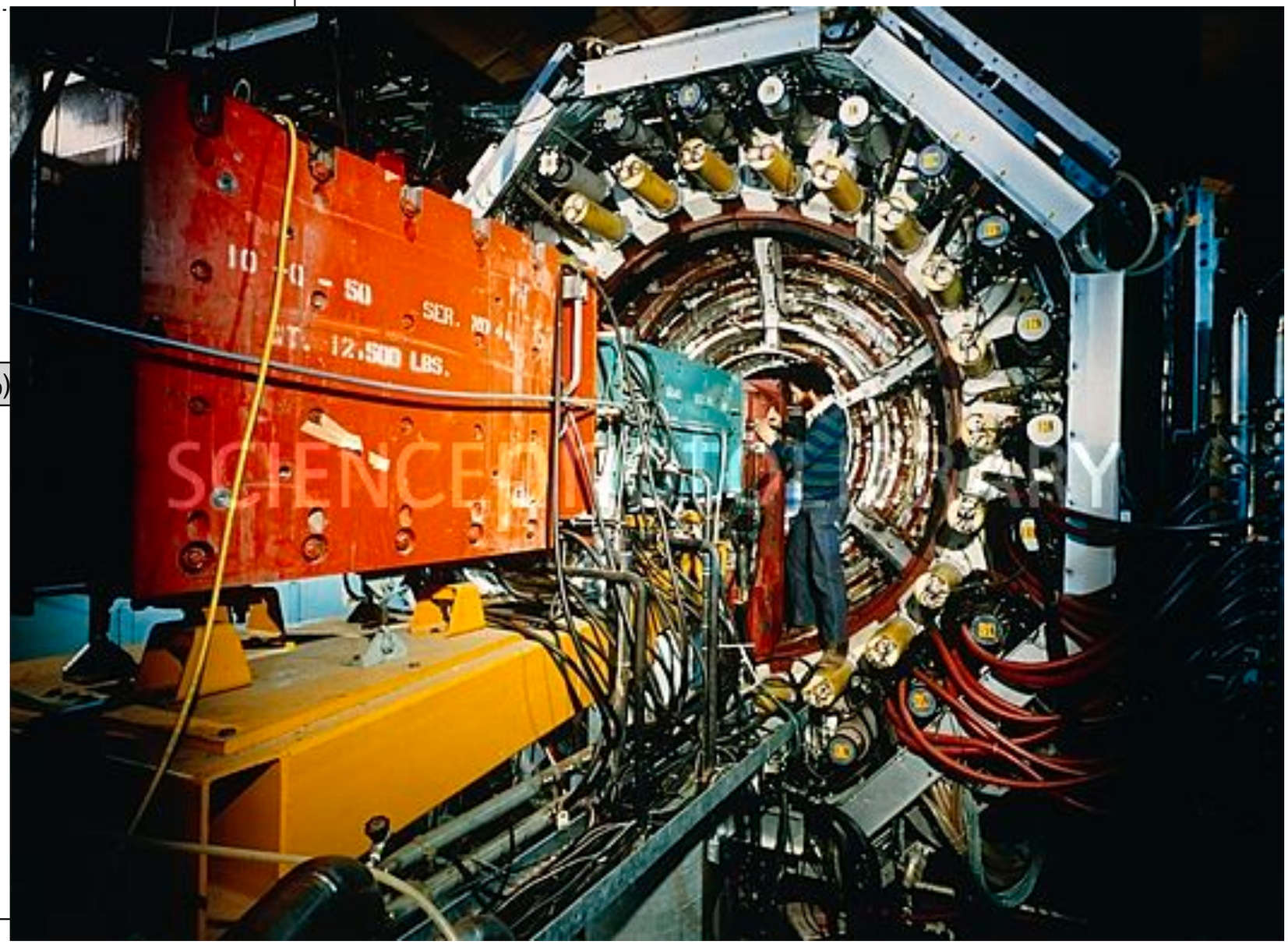


Mark I Detector at SLAC



http://www.sciencephoto.com/media/1065/

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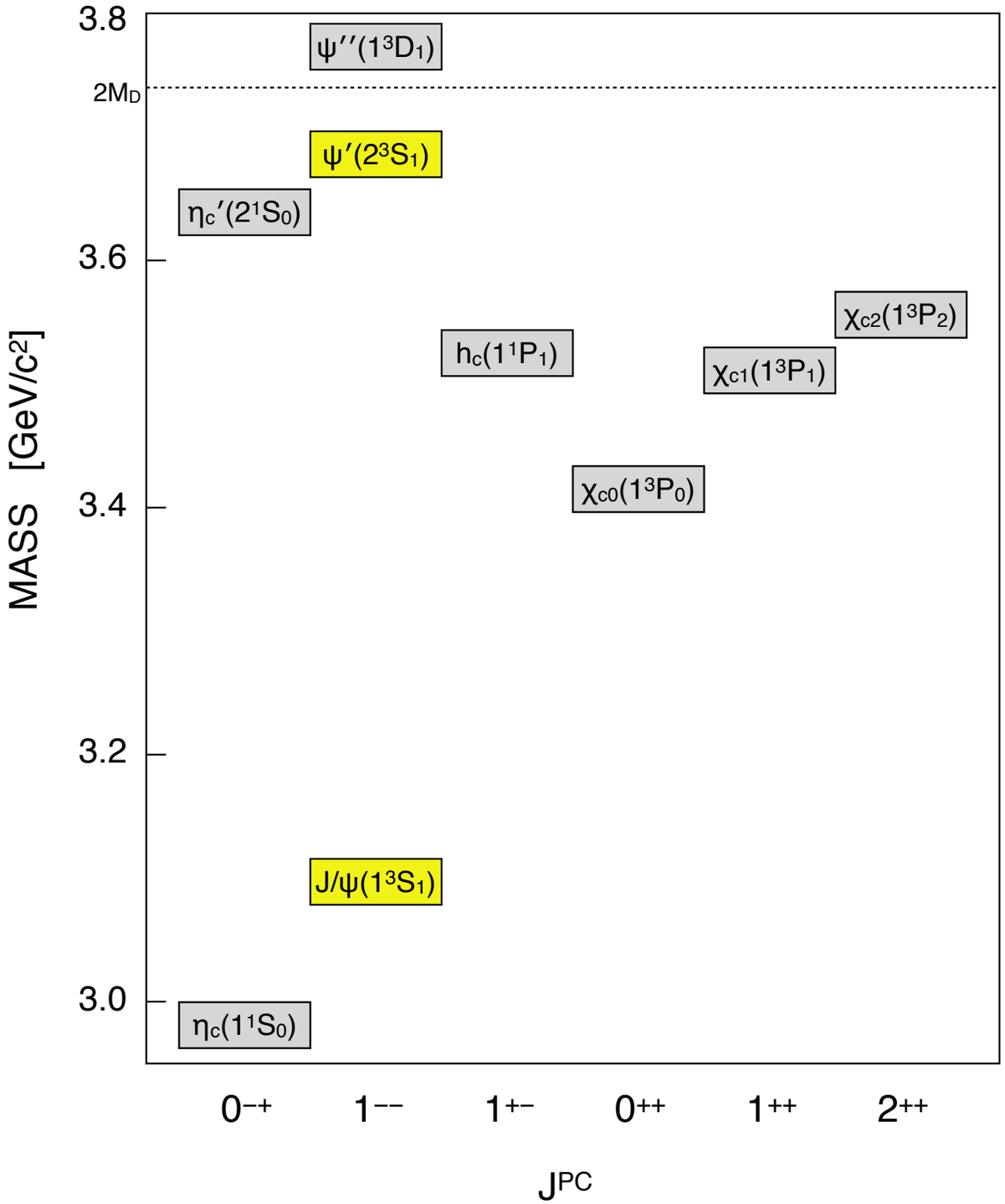

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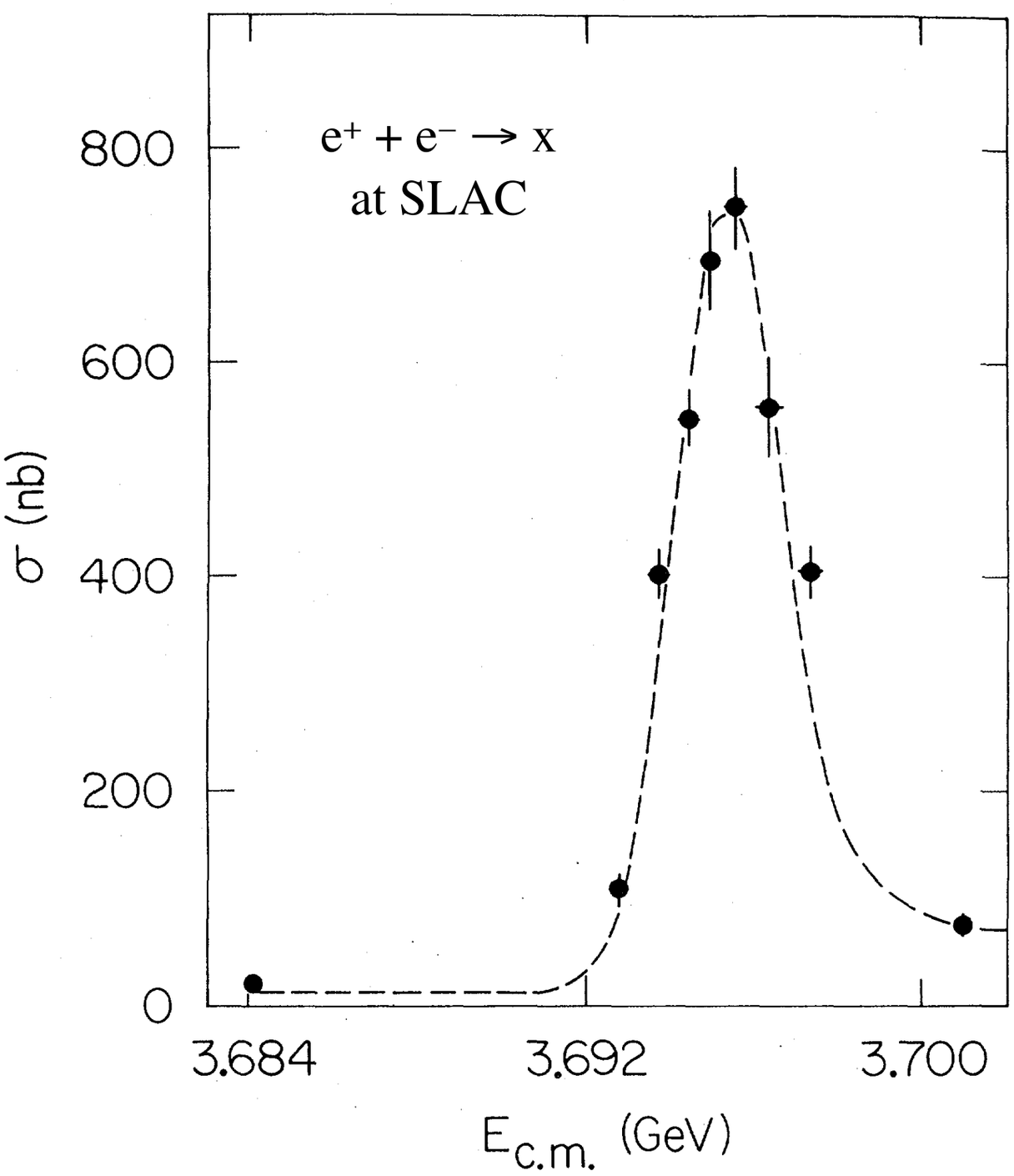

PRL33, 1453 (1974)

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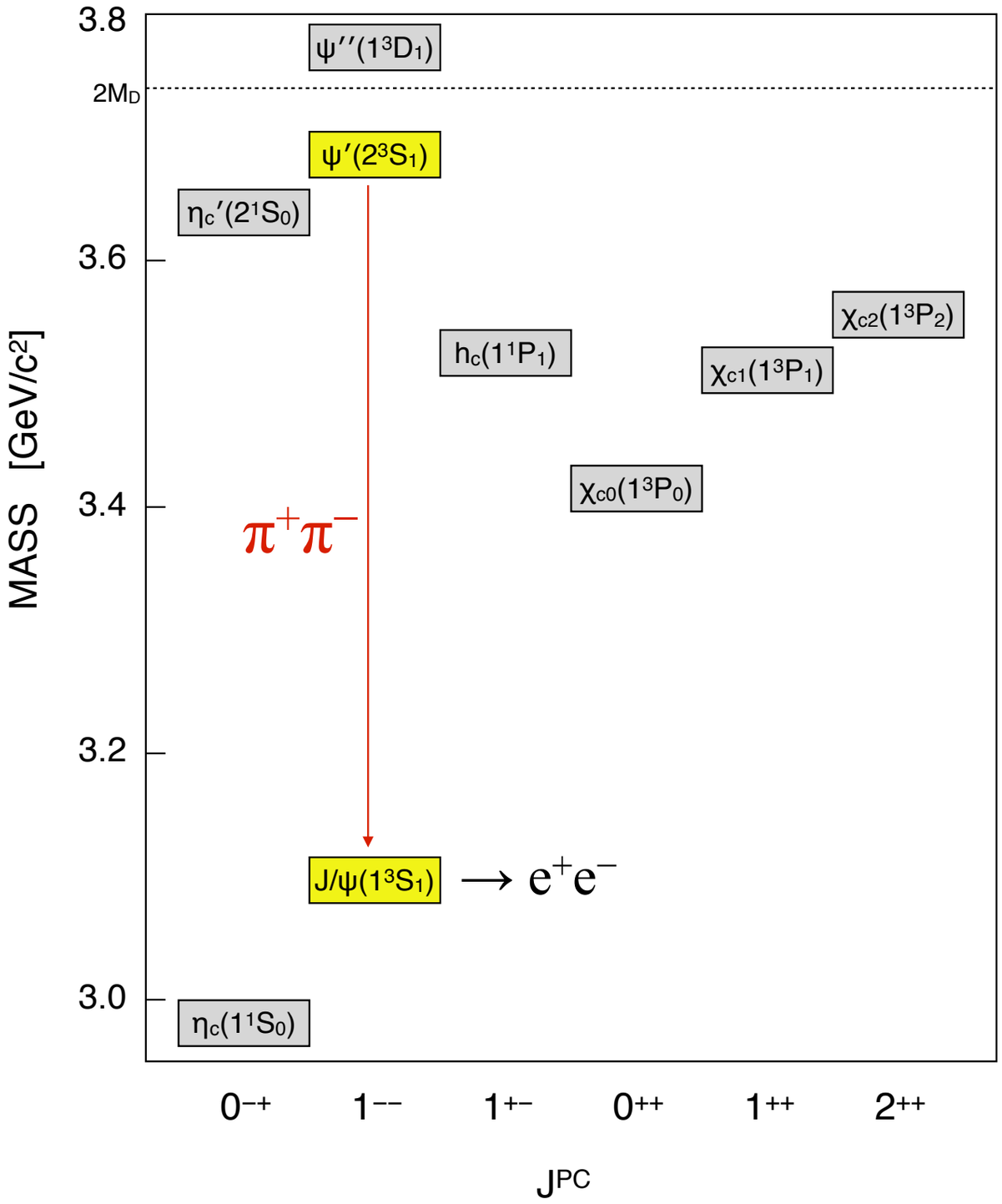

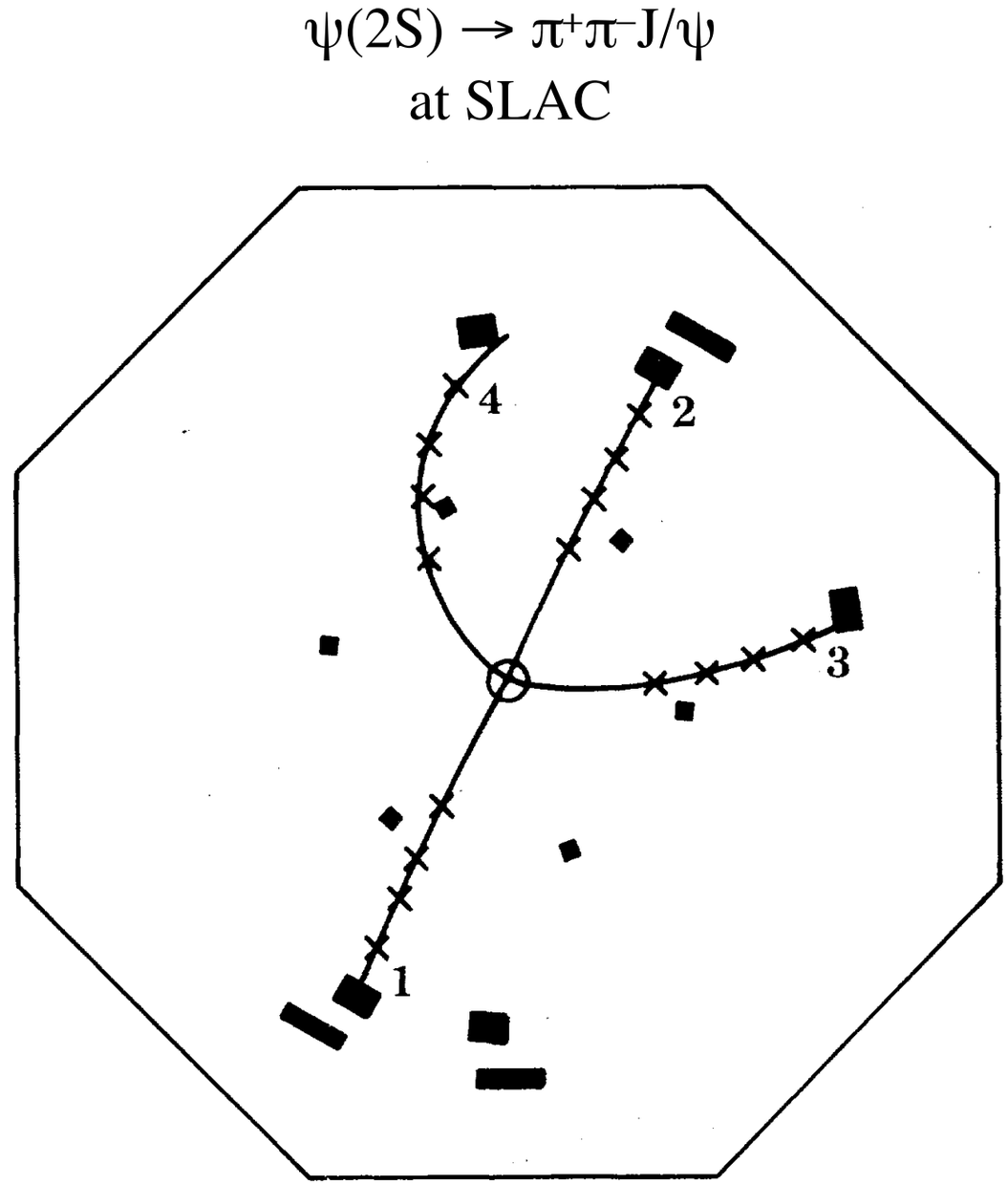

PRL34, 1181 (1975)

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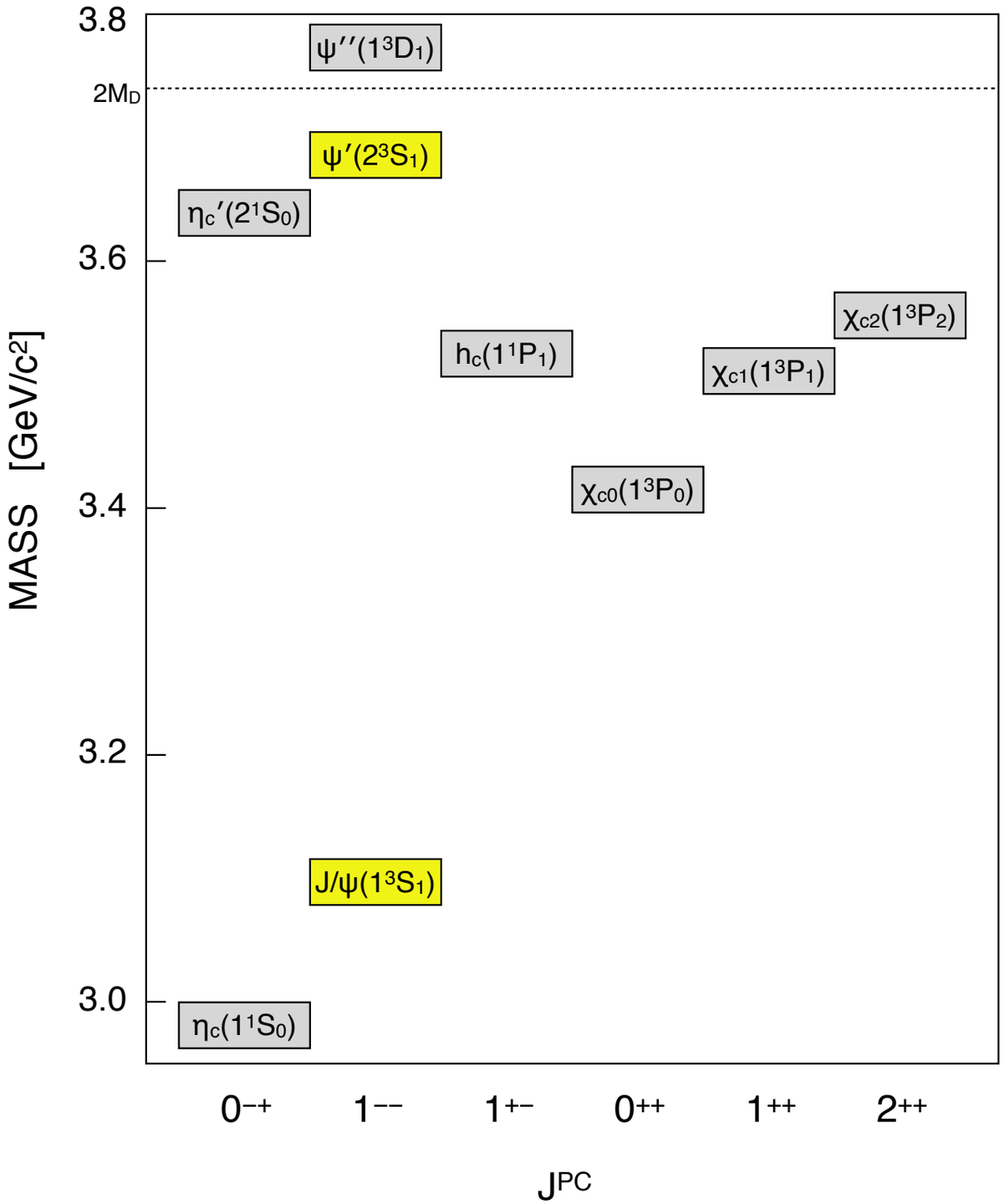

<u>Theoretical Ideas on J/ψ and ψ′:</u>

Baryon-AntiBaryon bound states
(PRL34, 36 (1975))

Spin-1 meson alternative to GIM
(PRL34, 37 (1975))

Three charm quarks (partners to u, d, s)
(PRL34, 41 (1975))

Lighter Z_0
(PRL34, 56 (1975))

Charmonium
(PRL34, 43 (1975), PRL34, 46 (1975))

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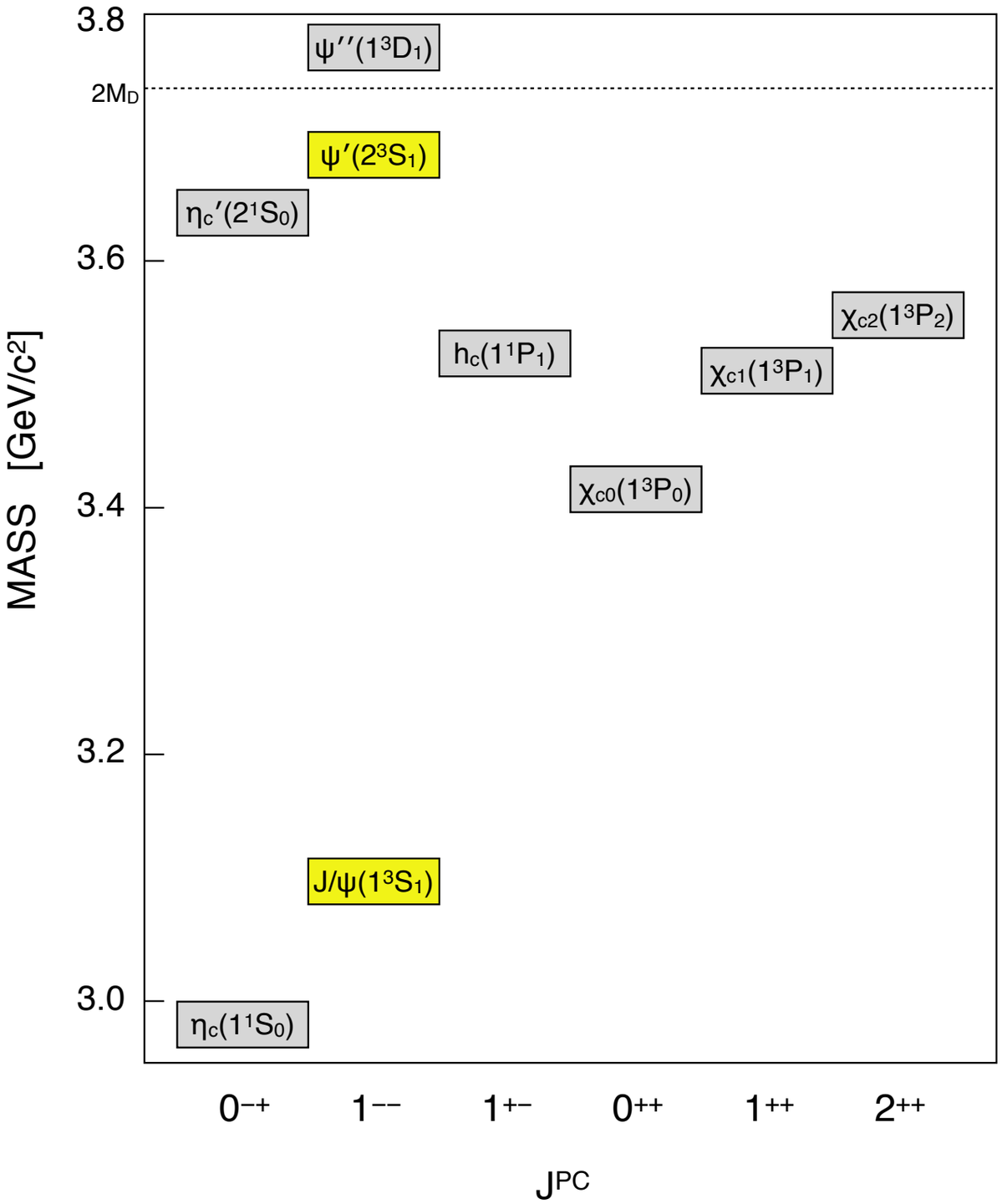

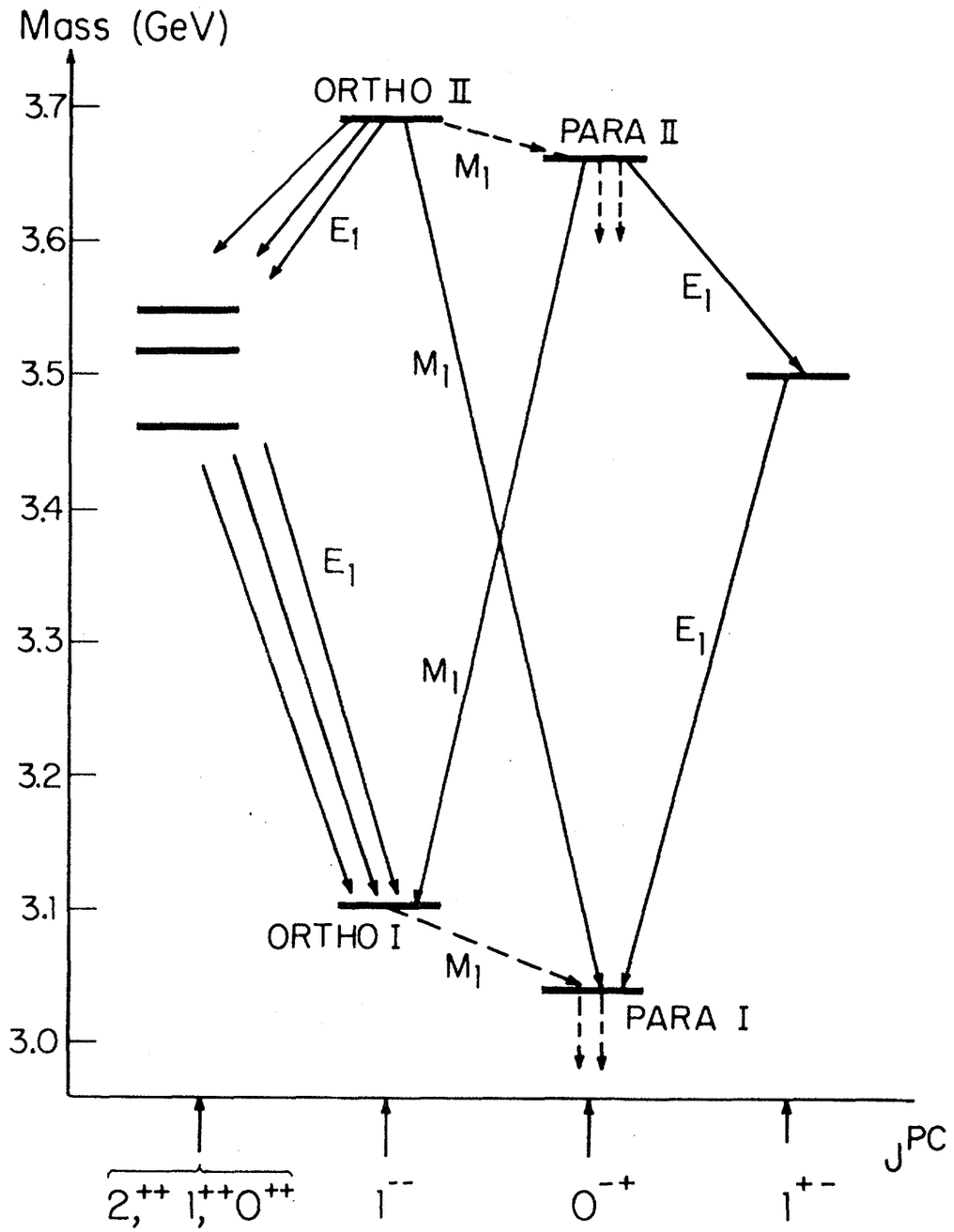

PRL34, 365 (1975)

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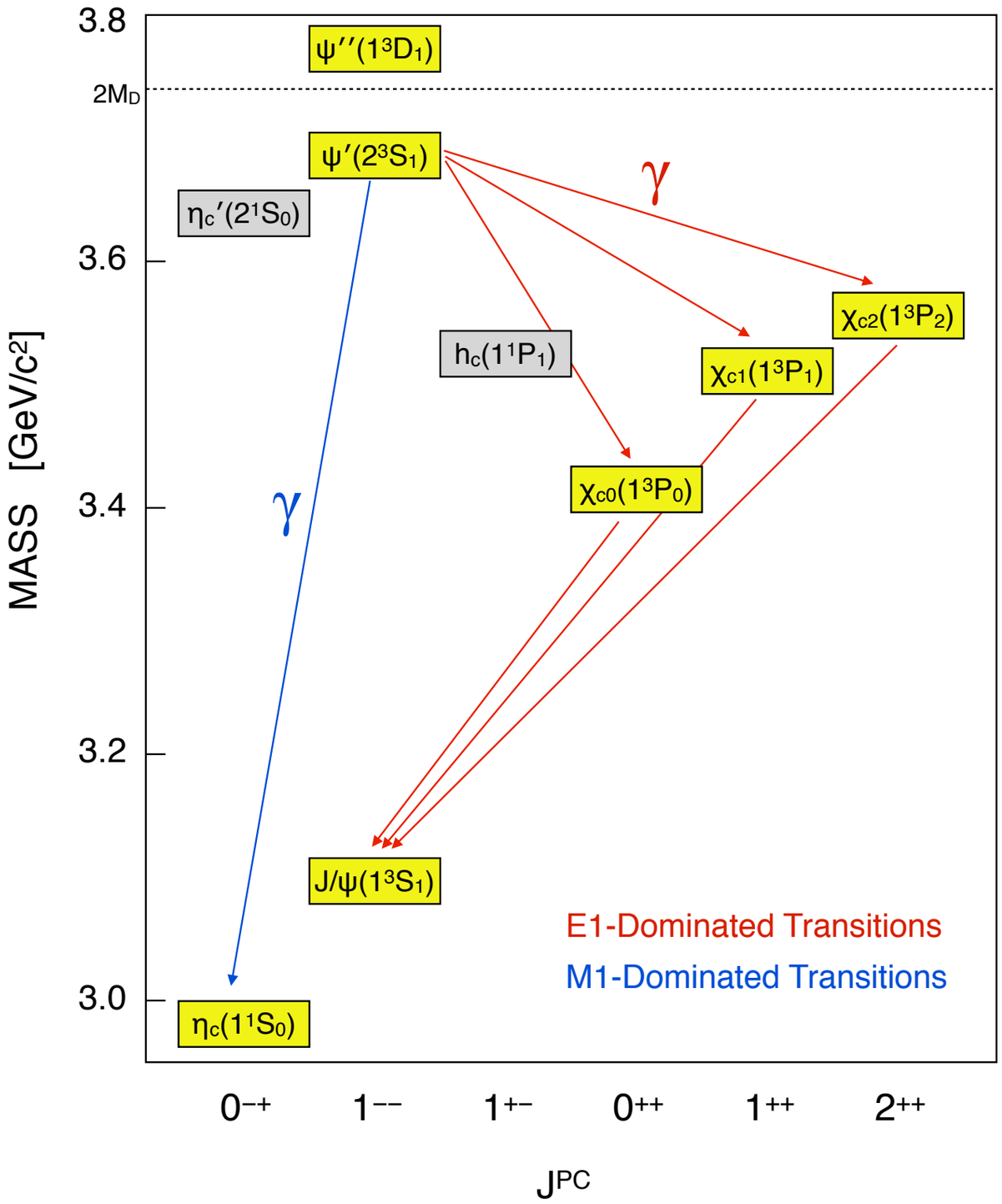
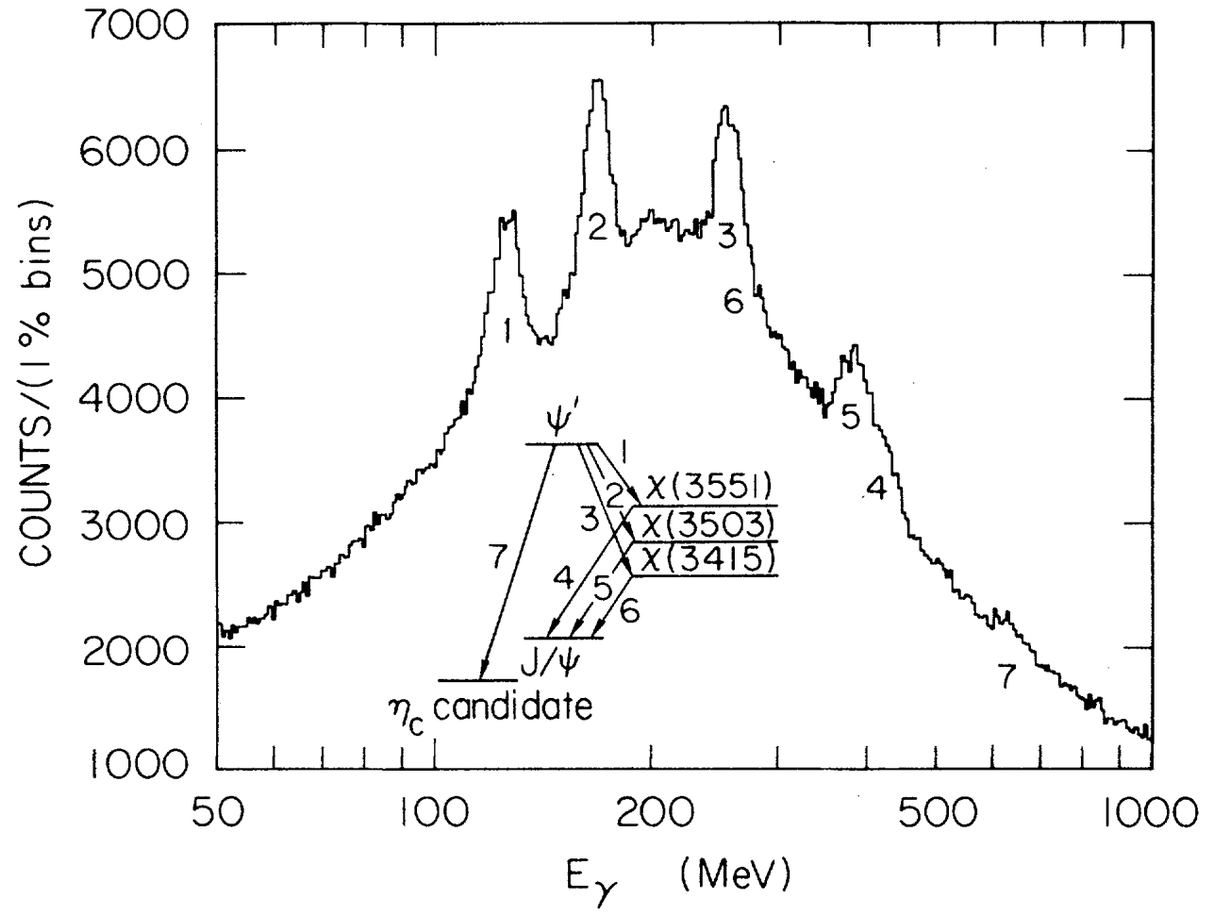


Crystal Ball at SLAC
(discovery of η_c)



PRL45, 1150 (1980)

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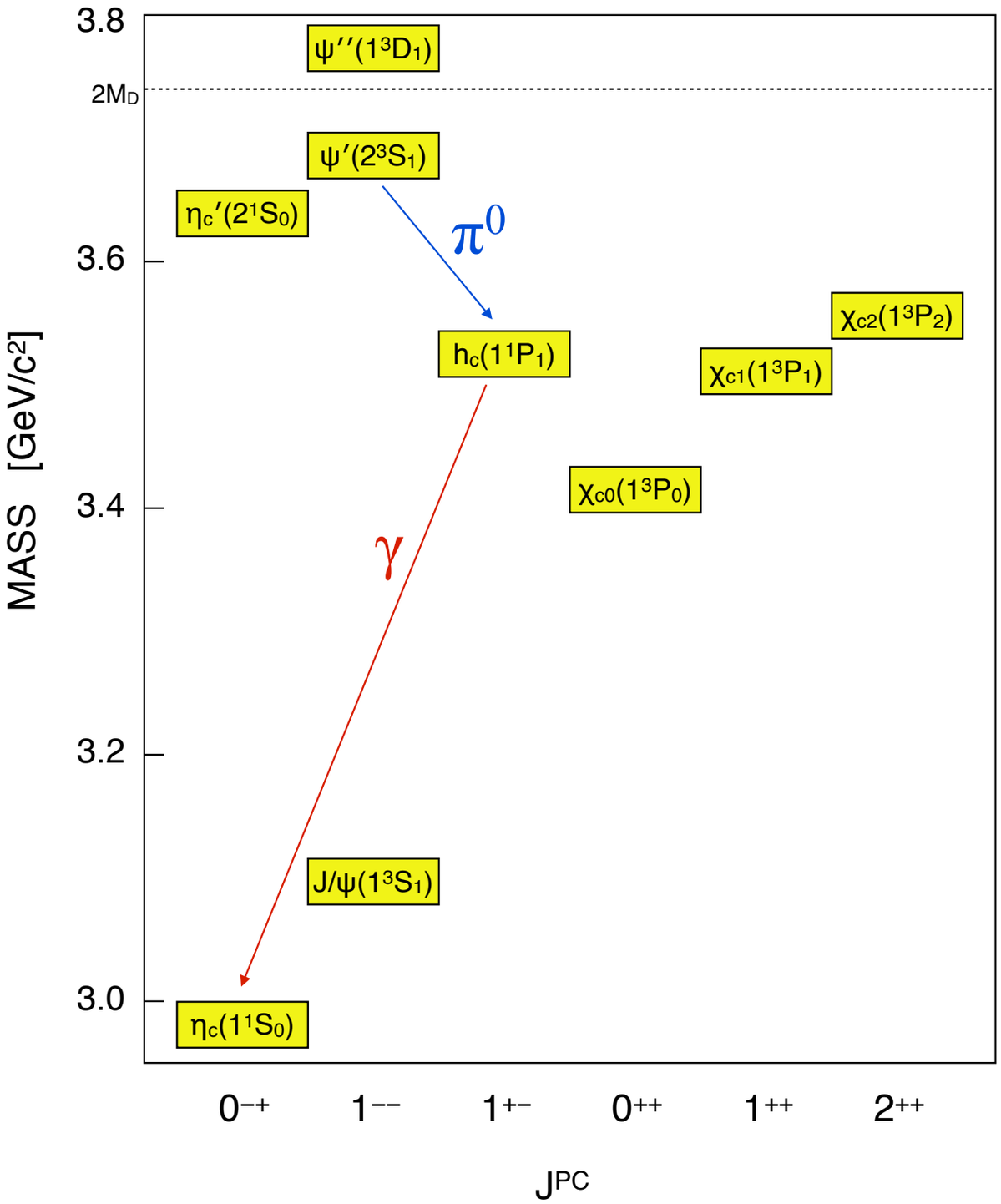

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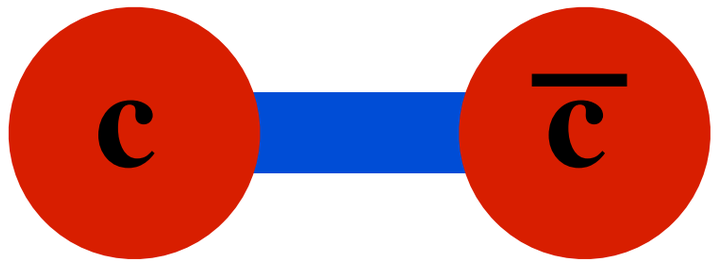

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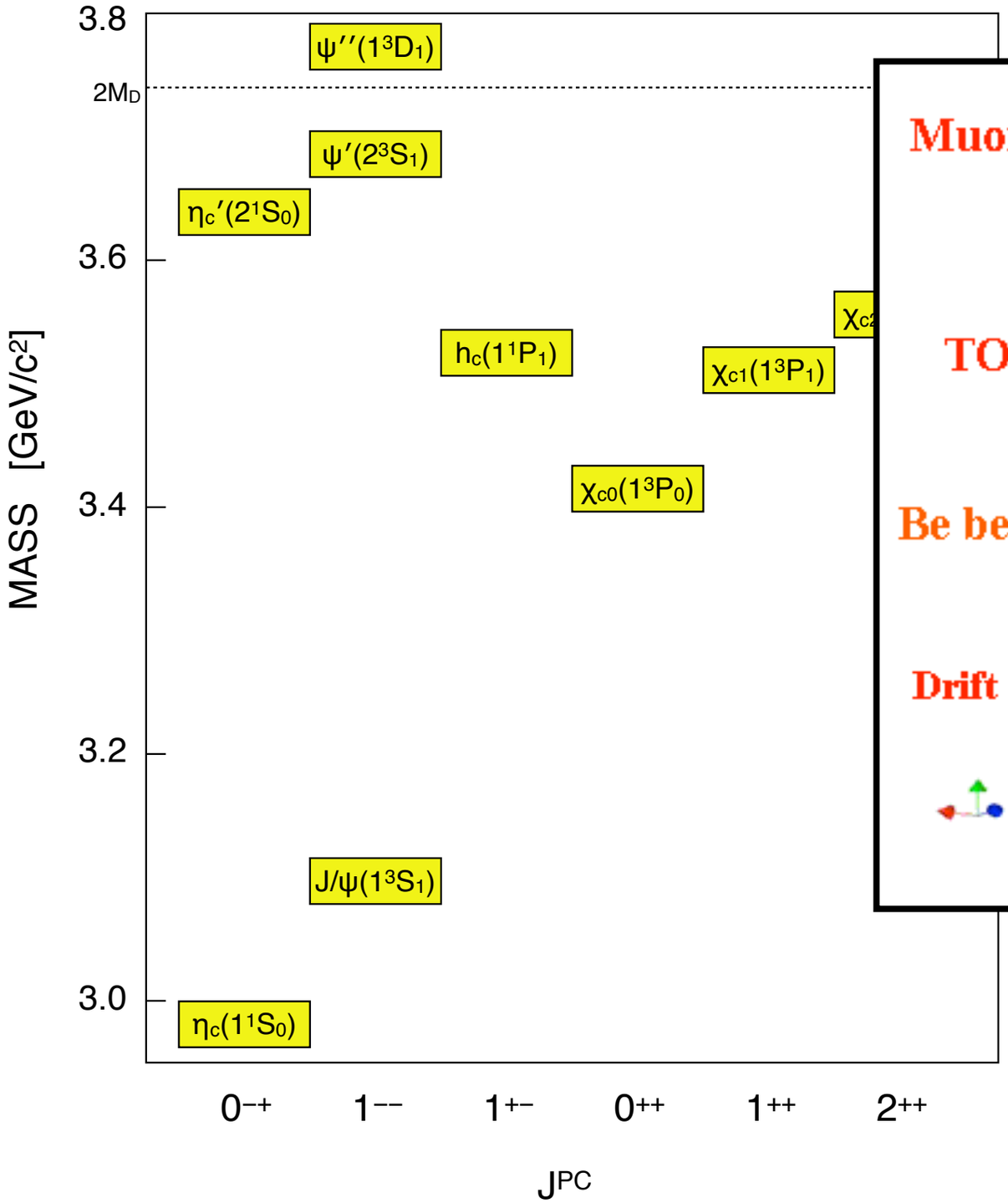
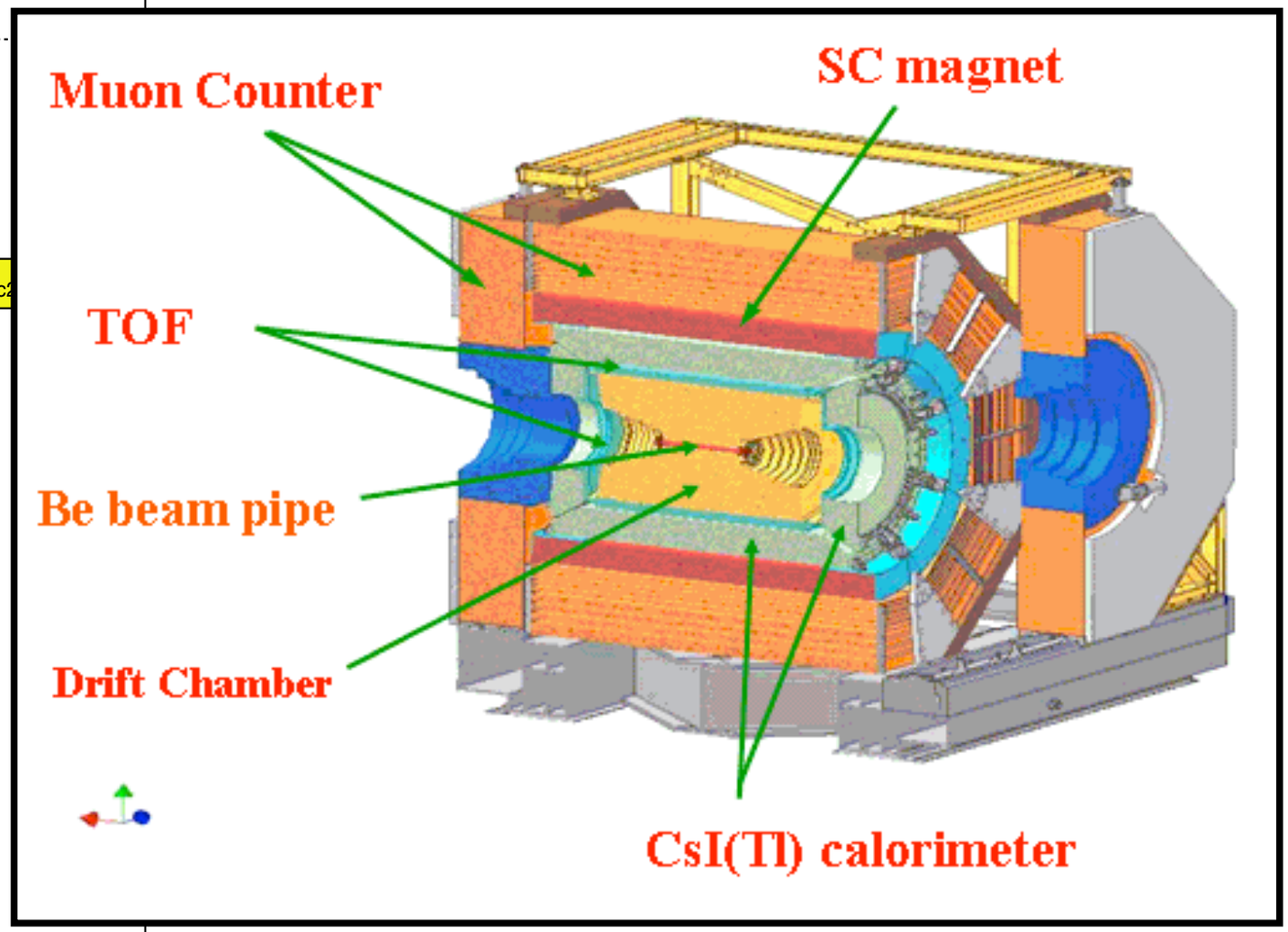


BES III Detector in Beijing, China
(BEPC2 e^+e^- collider)



Select data samples (2008-present):

~500 pb^{-1} at 4.009 GeV

~2.9 fb^{-1} at ψ''

225 million J/ψ decays (+ more)

106 million ψ(2S) decays (+ more)

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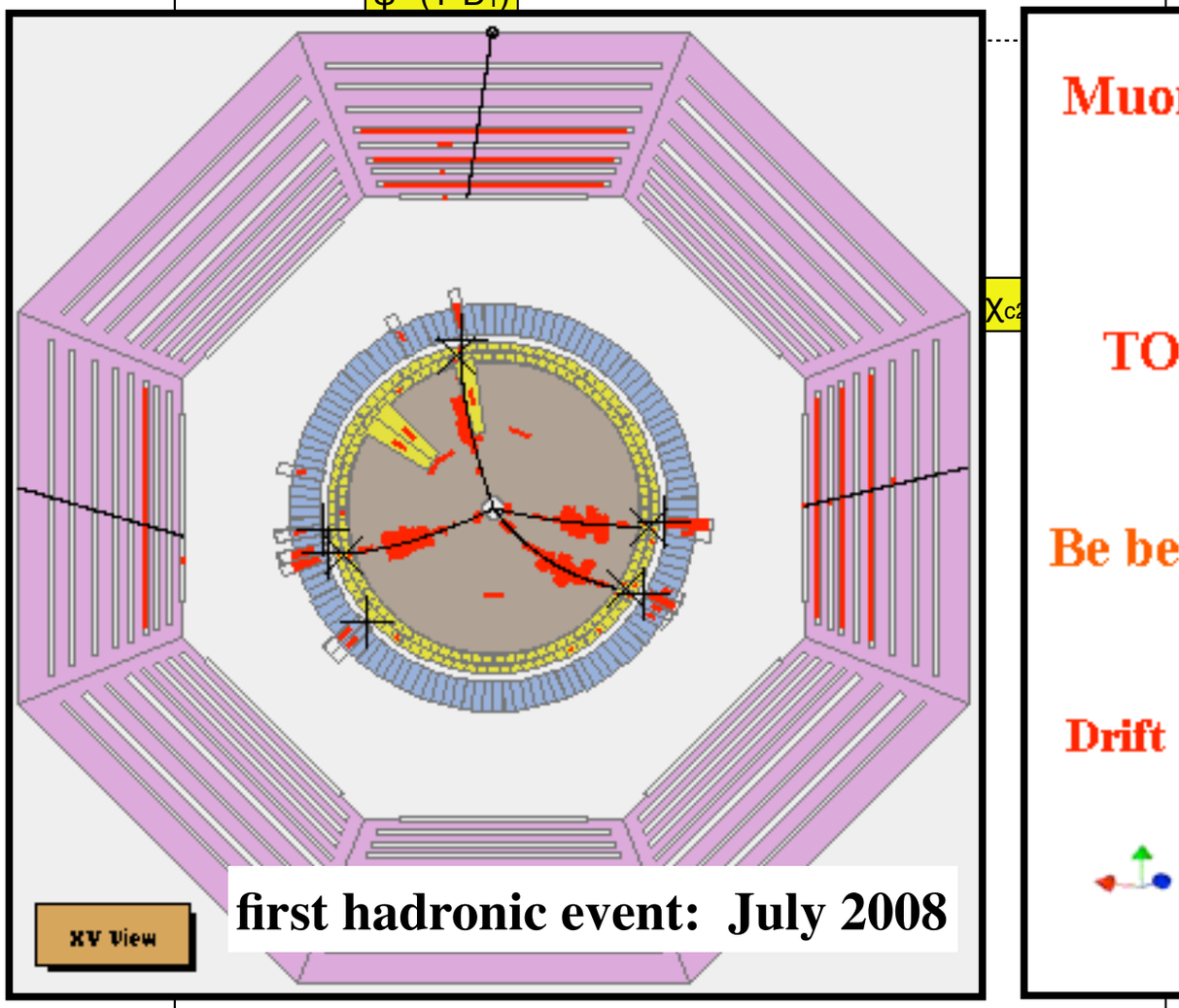

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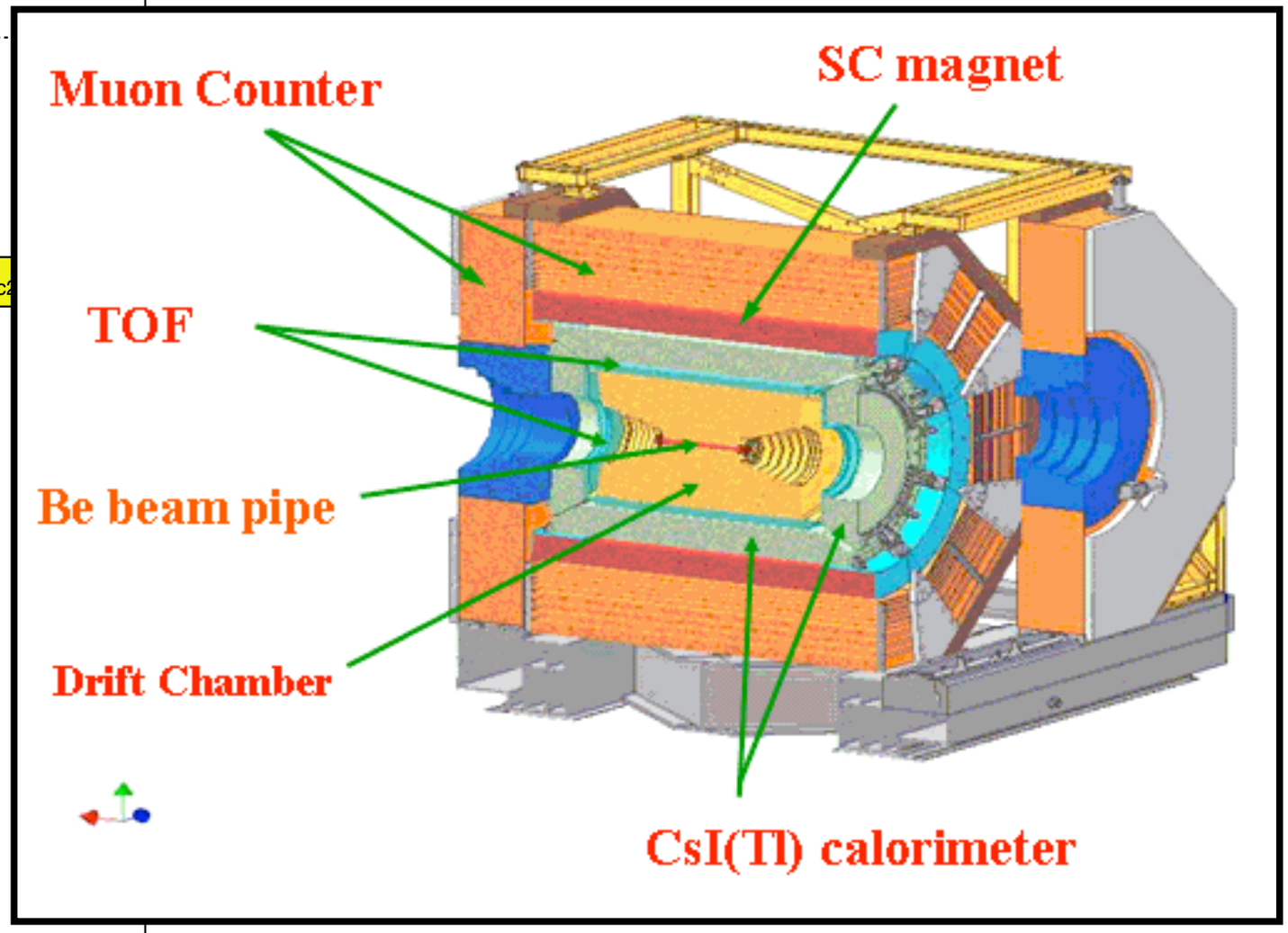

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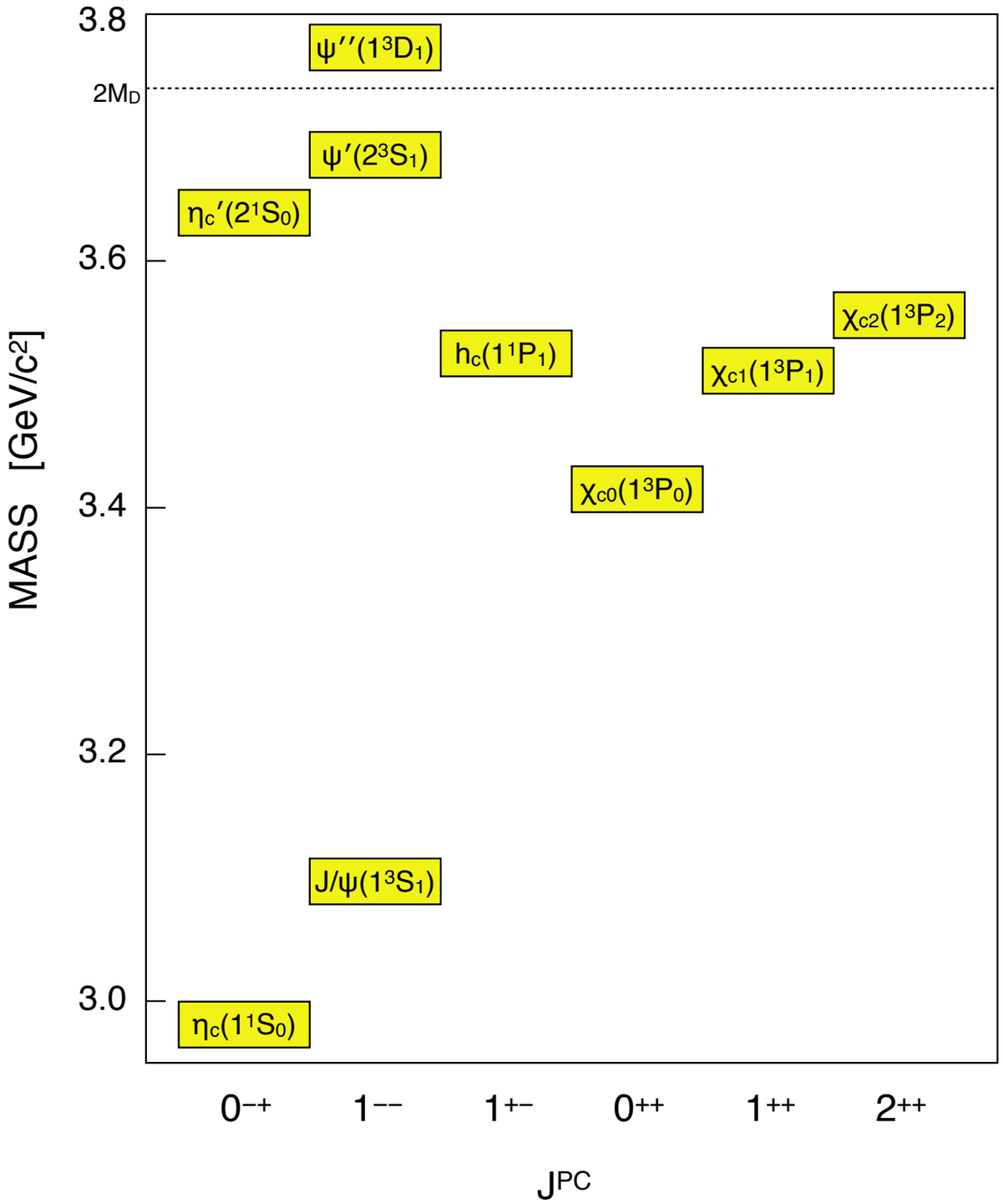


A few BESIII charmonium results from 2012:

1. Measurements of the mass and width of the $\eta_c(1S)$ using the decay $\psi(2S) \rightarrow \gamma\eta_c(1S)$

PRL 108, 222002 (2012)

2. First observation of the M1 transition $\psi(2S) \rightarrow \gamma\eta_c(2S)$

PRL 109, 042003 (2012)

3. Study of $\psi(2S) \rightarrow \pi^0 h_c(1P)$, $h_c(1P) \rightarrow \gamma\eta_c(1S)$ via $\eta_c(1S)$ exclusive decays

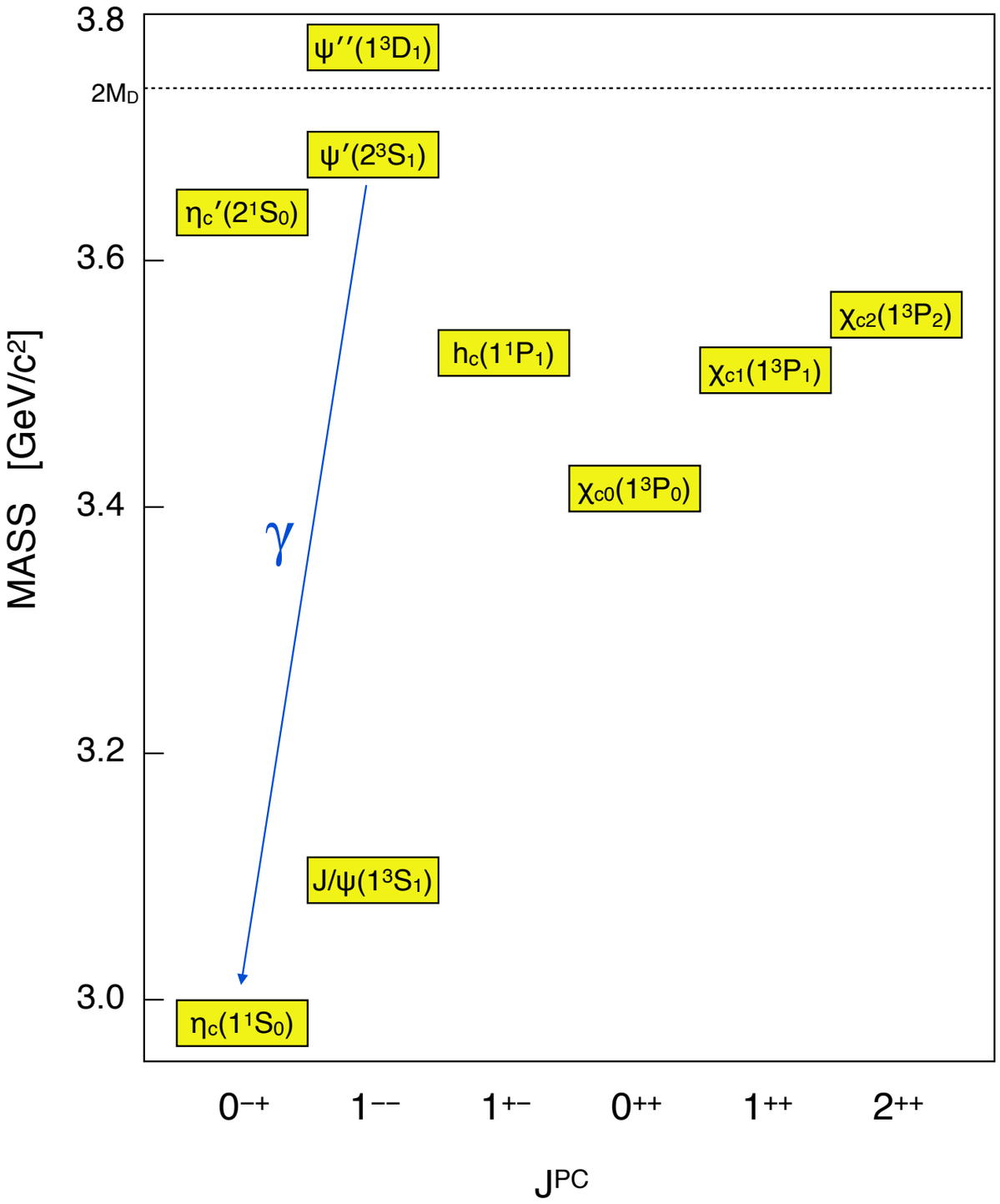
PRD 86, 092009 (2012)

4. Two-photon widths of the $\chi_{c0,2}(1P)$ states and helicity analysis for $\chi_{c2}(1P) \rightarrow \gamma\gamma$

PRD 85, 112008 (2012)

5. Search for the hadronic transition $\chi_{cJ}(1P) \rightarrow \eta_c(1S)\pi^+\pi^-$

arXiv:1208.4805



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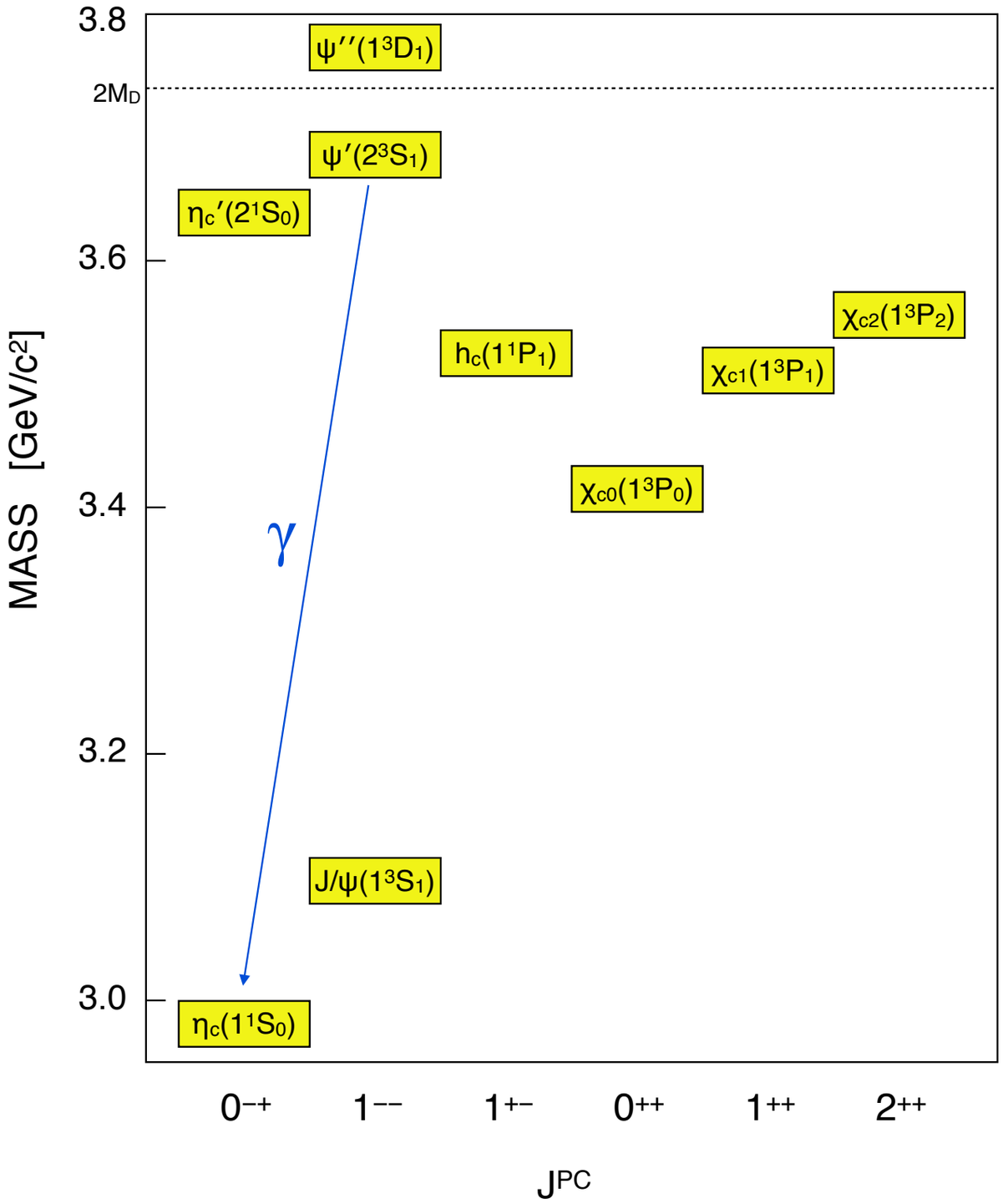
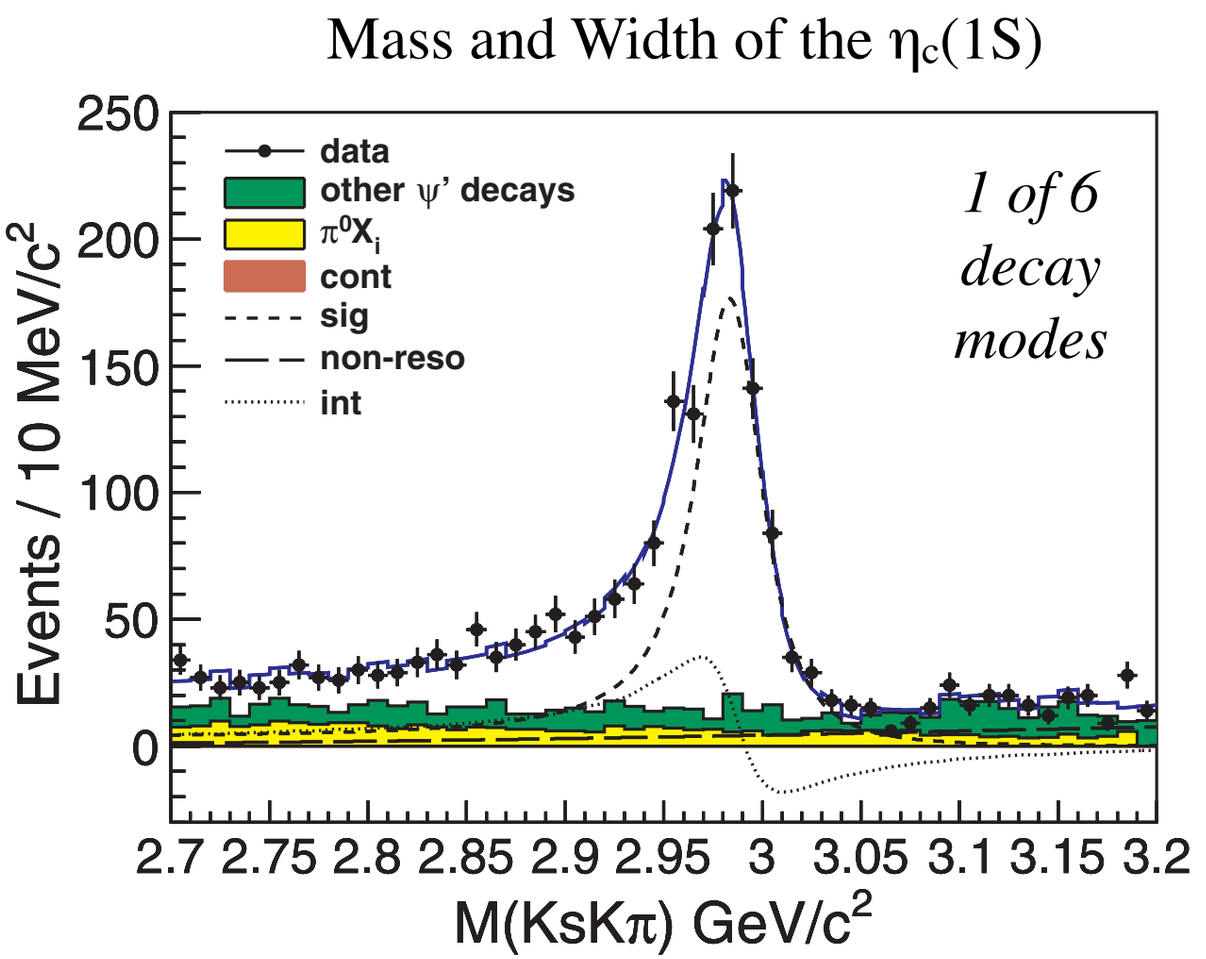
III. From Discovery to Precision





⇒ must take into account the distorted line-shape (E^7) and interference with "non-resonant" decays

$M = 2984.3 \pm 0.6 \pm 0.6$ MeV

$\Gamma = 32.0 \pm 1.2 \pm 1.0$ MeV

⇒ significant discrepancies with older results (e.g. **PRD 62, 072001 (2000)**)

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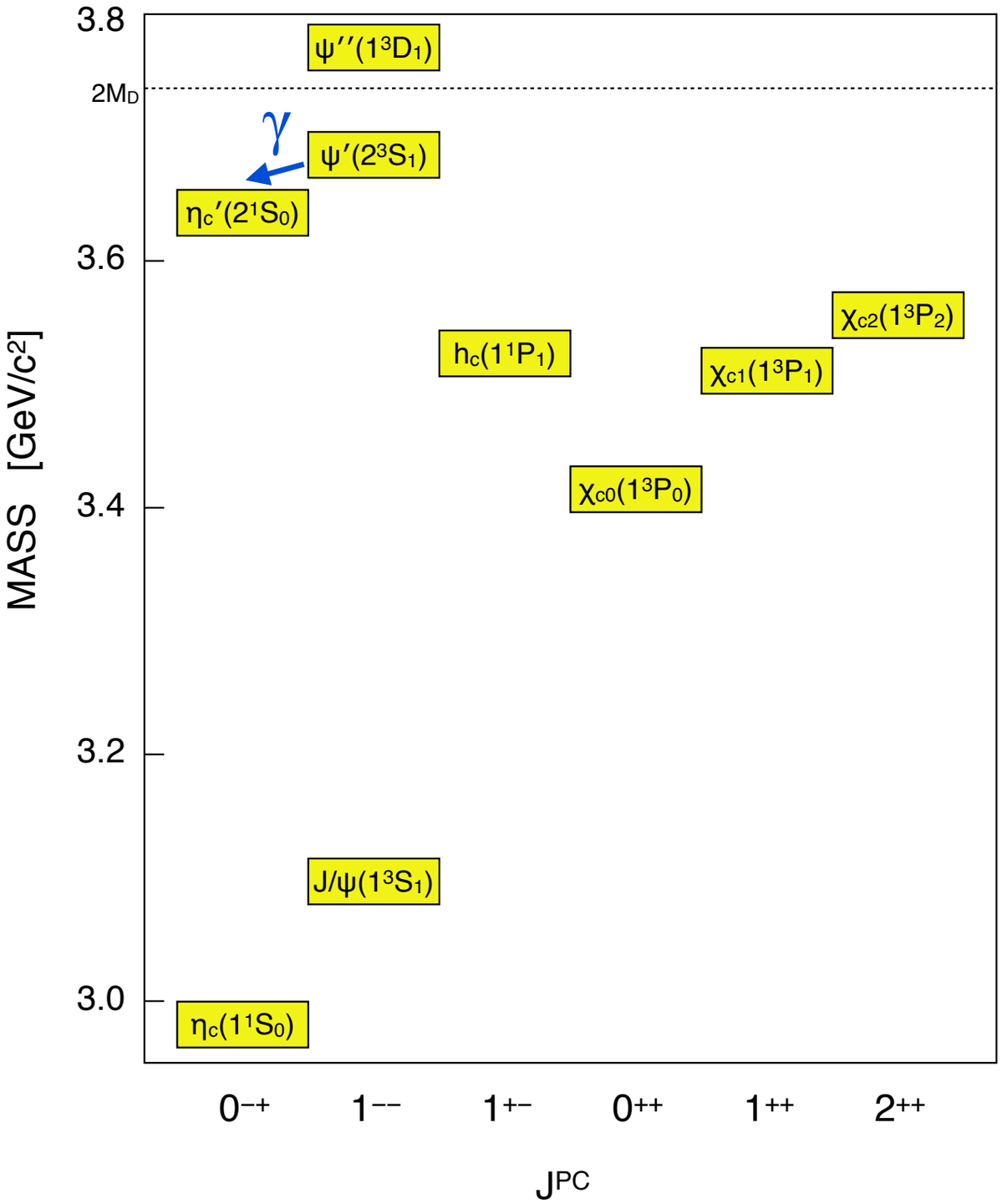

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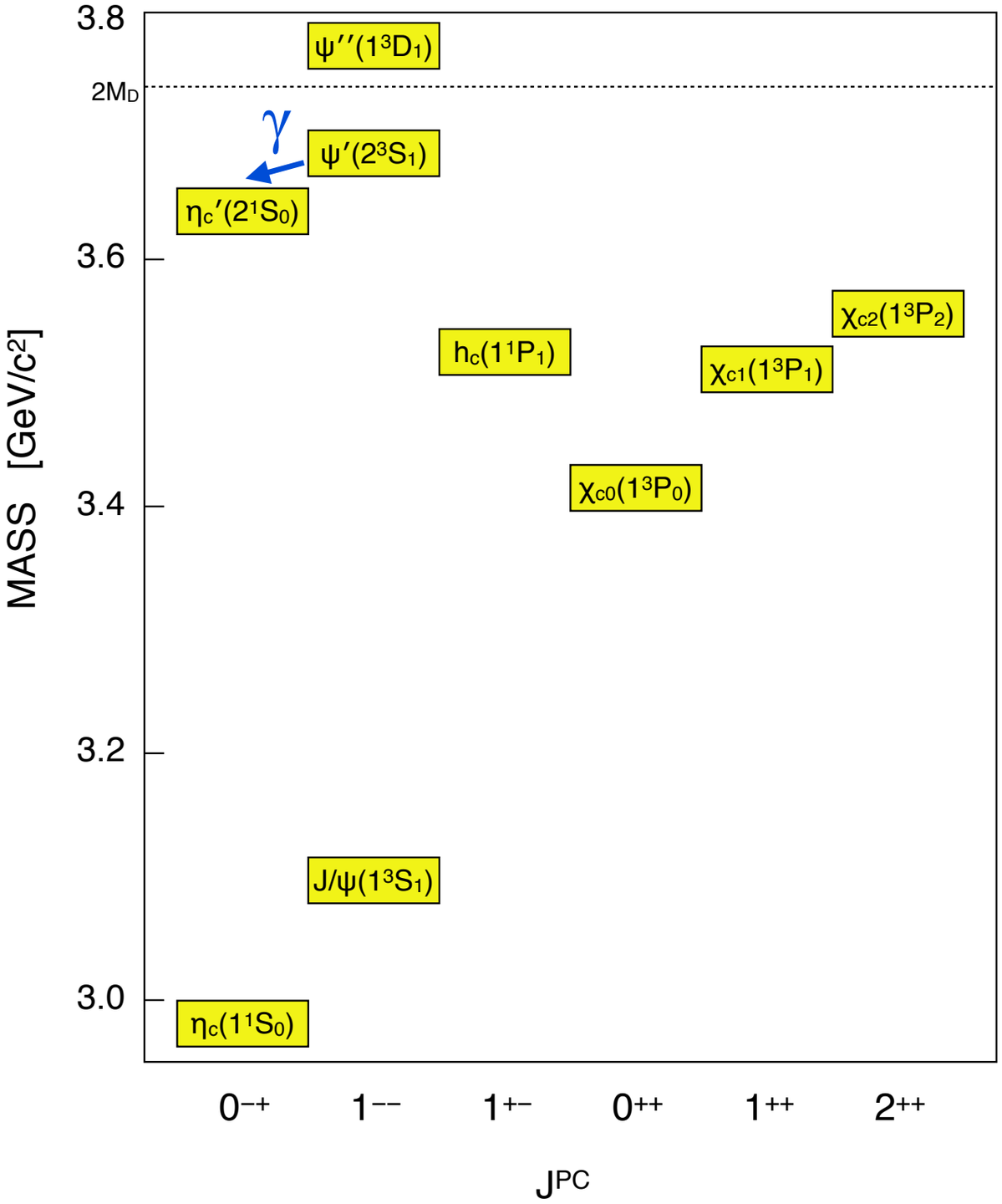
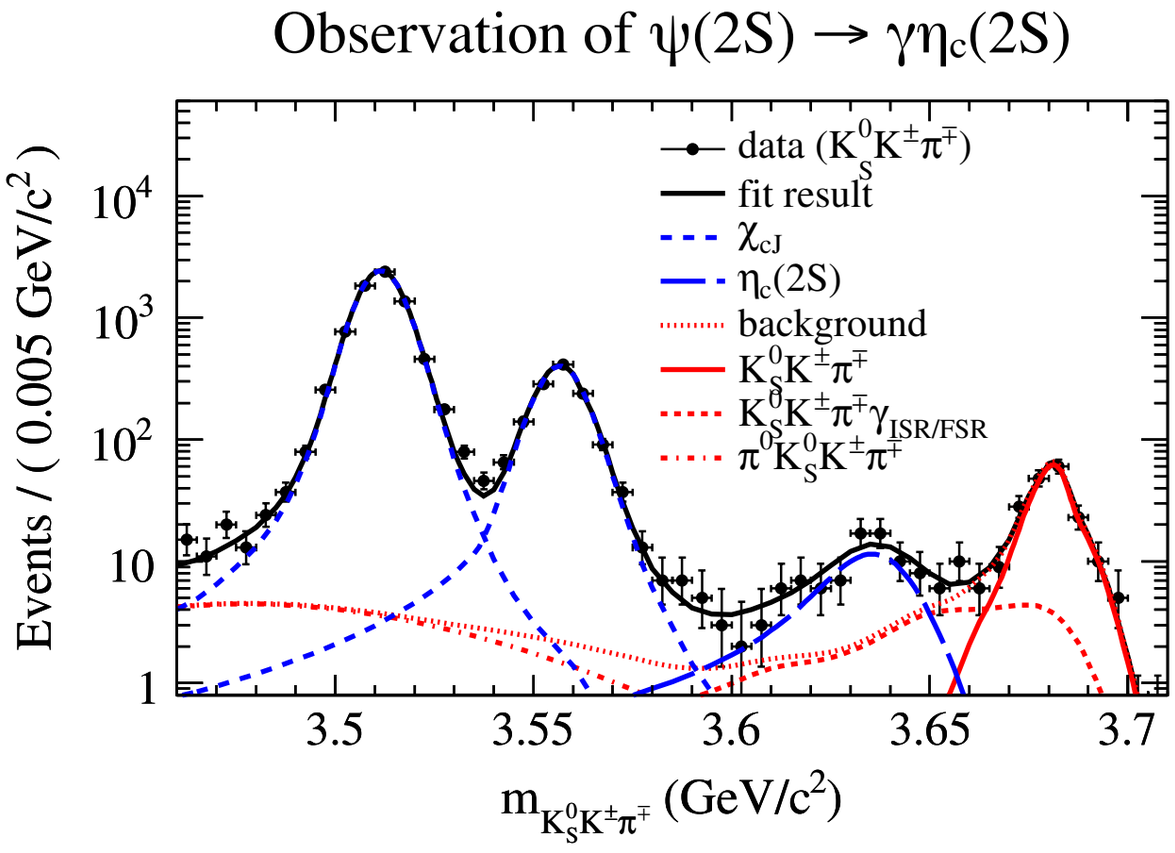


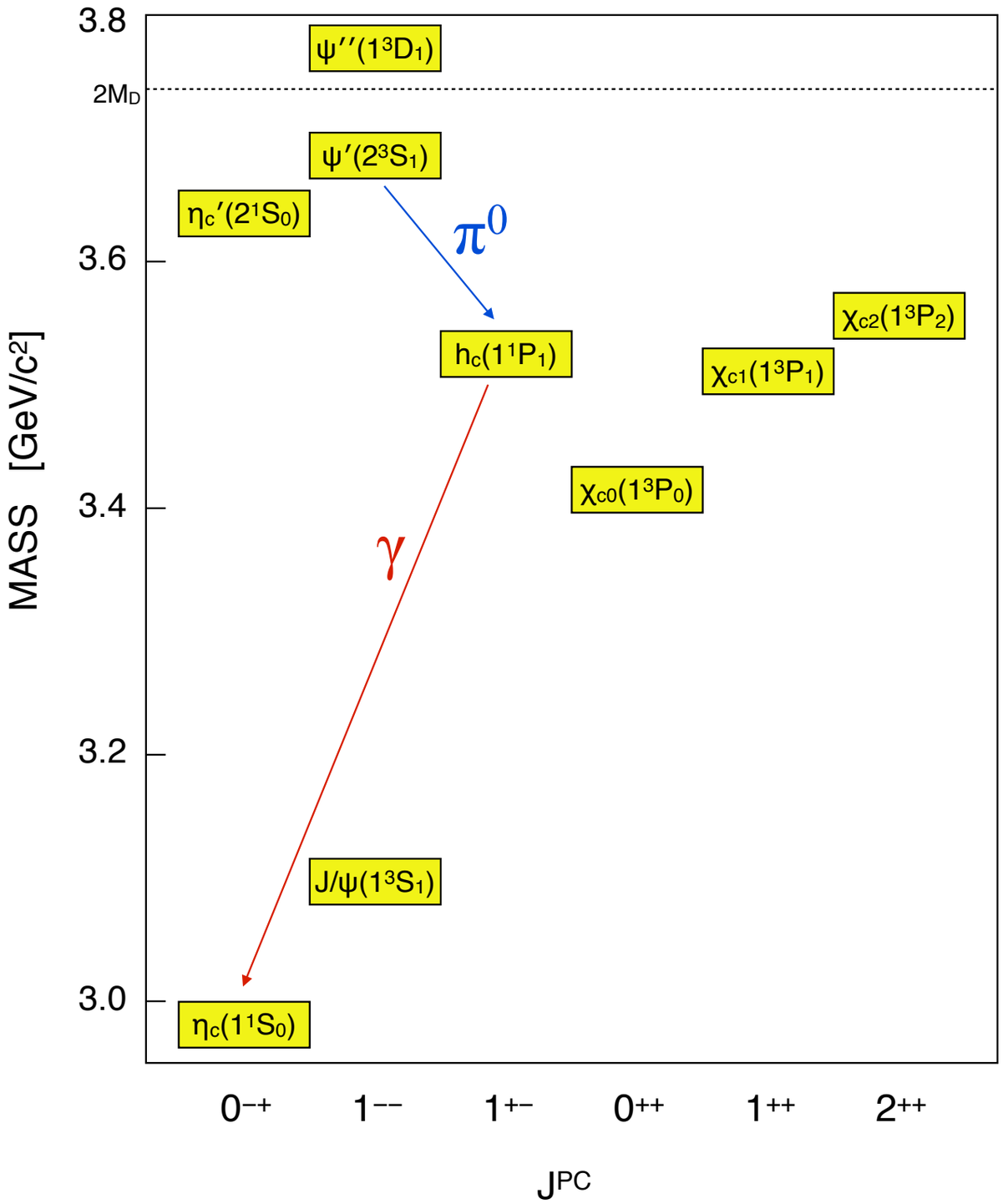


$M = 3637.6 \pm 2.9 \pm 1.6$ MeV

$\Gamma = 16.9 \pm 6.4 \pm 4.8$ MeV

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

III. From Discovery to Precision



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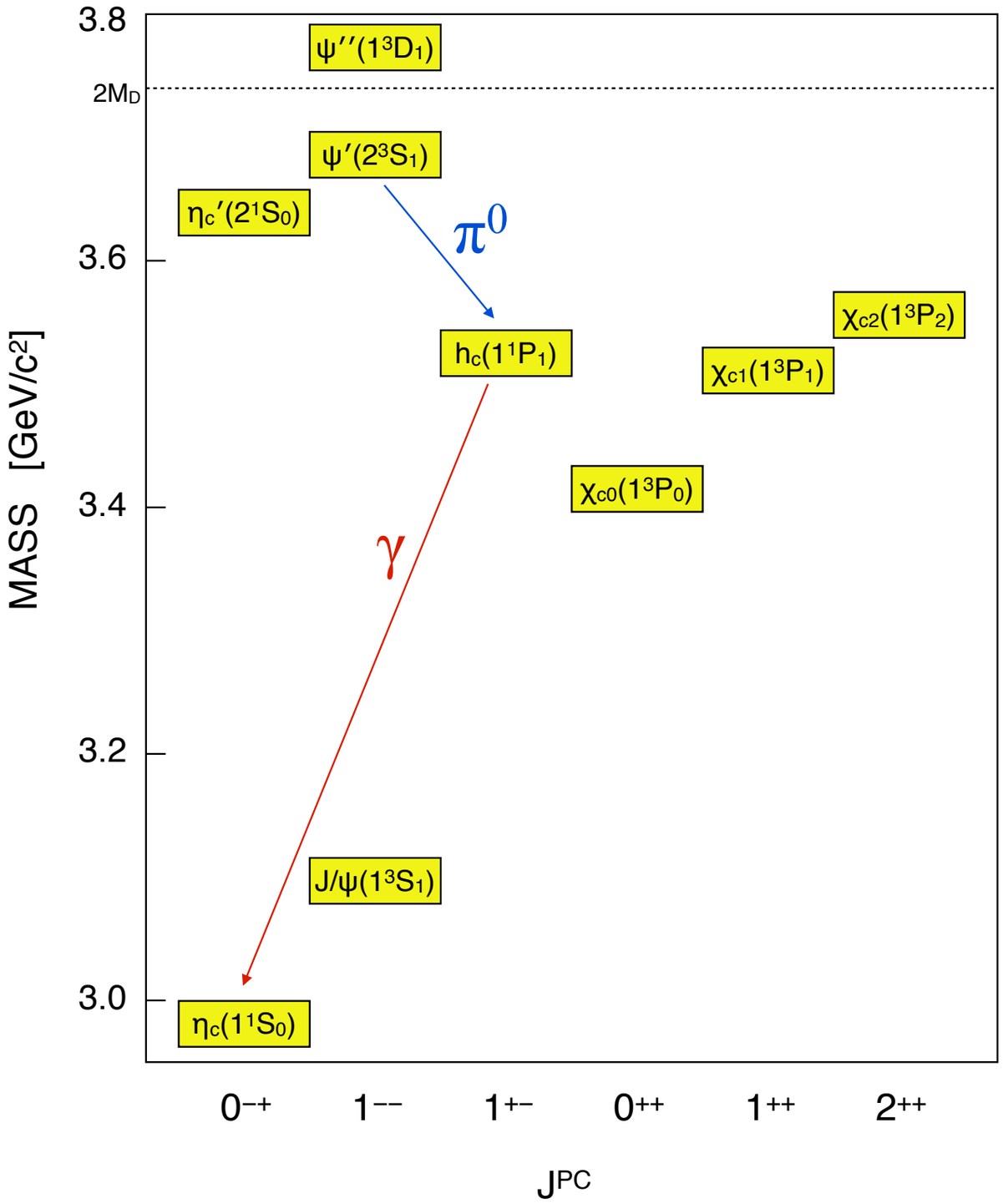
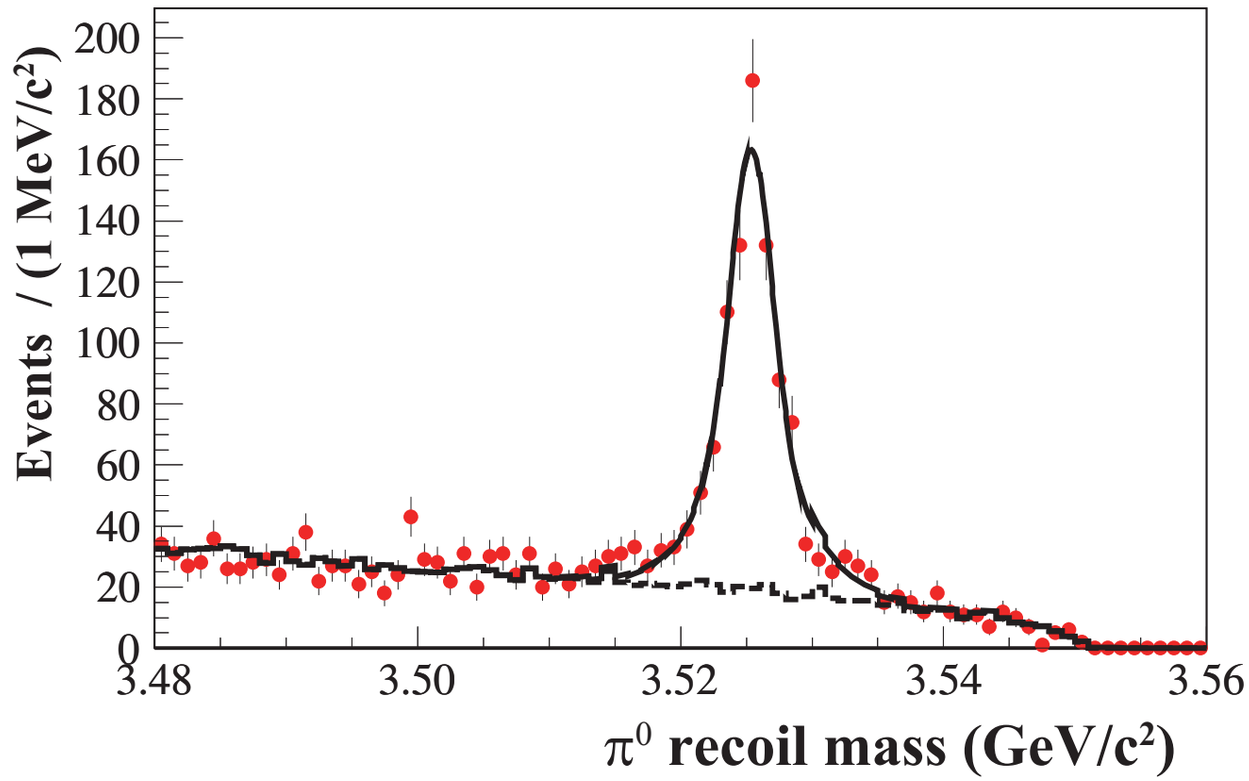


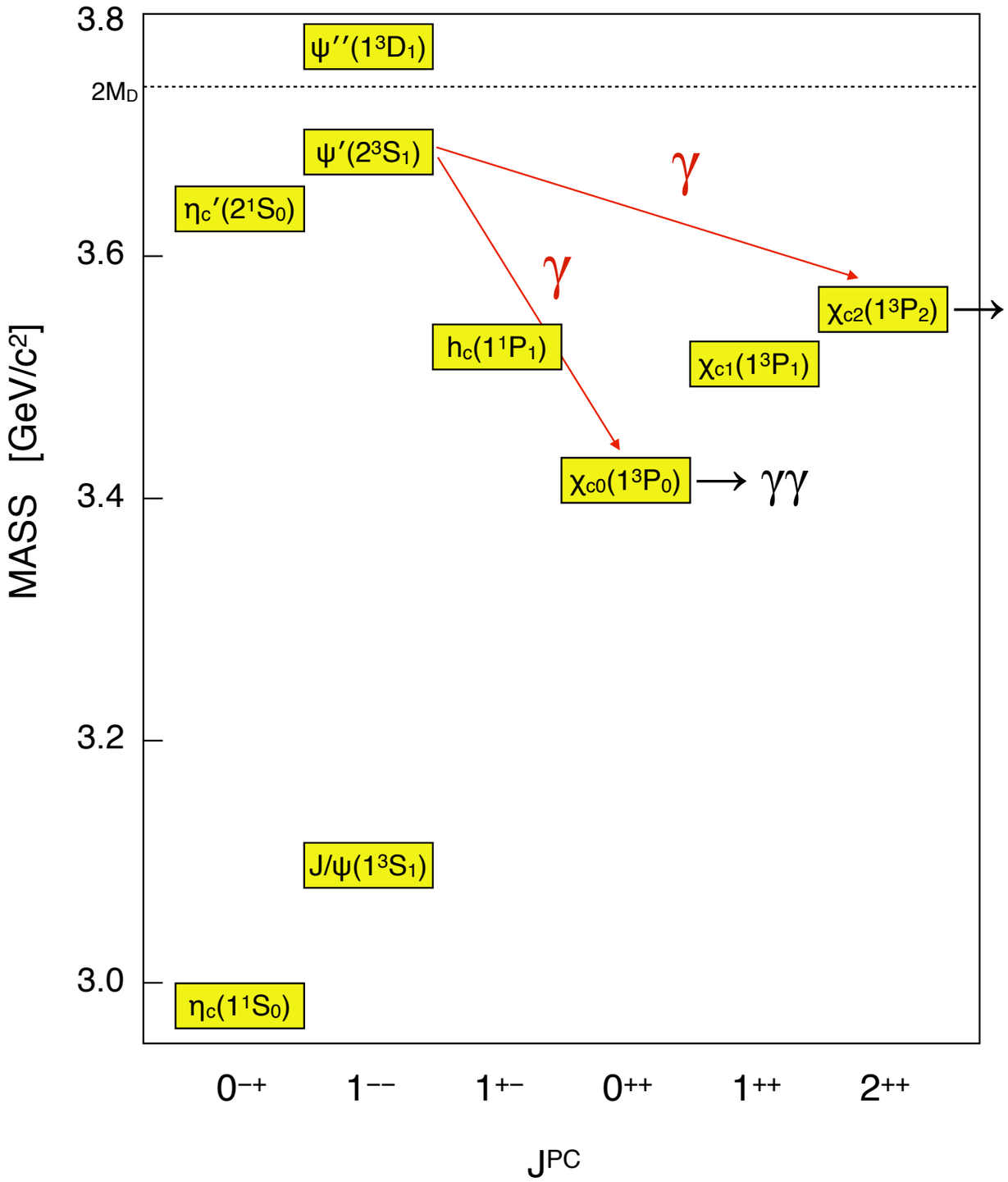
Precision Measurements of the Mass and Width of the $h_c(1P)$



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

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

III. From Discovery to Precision



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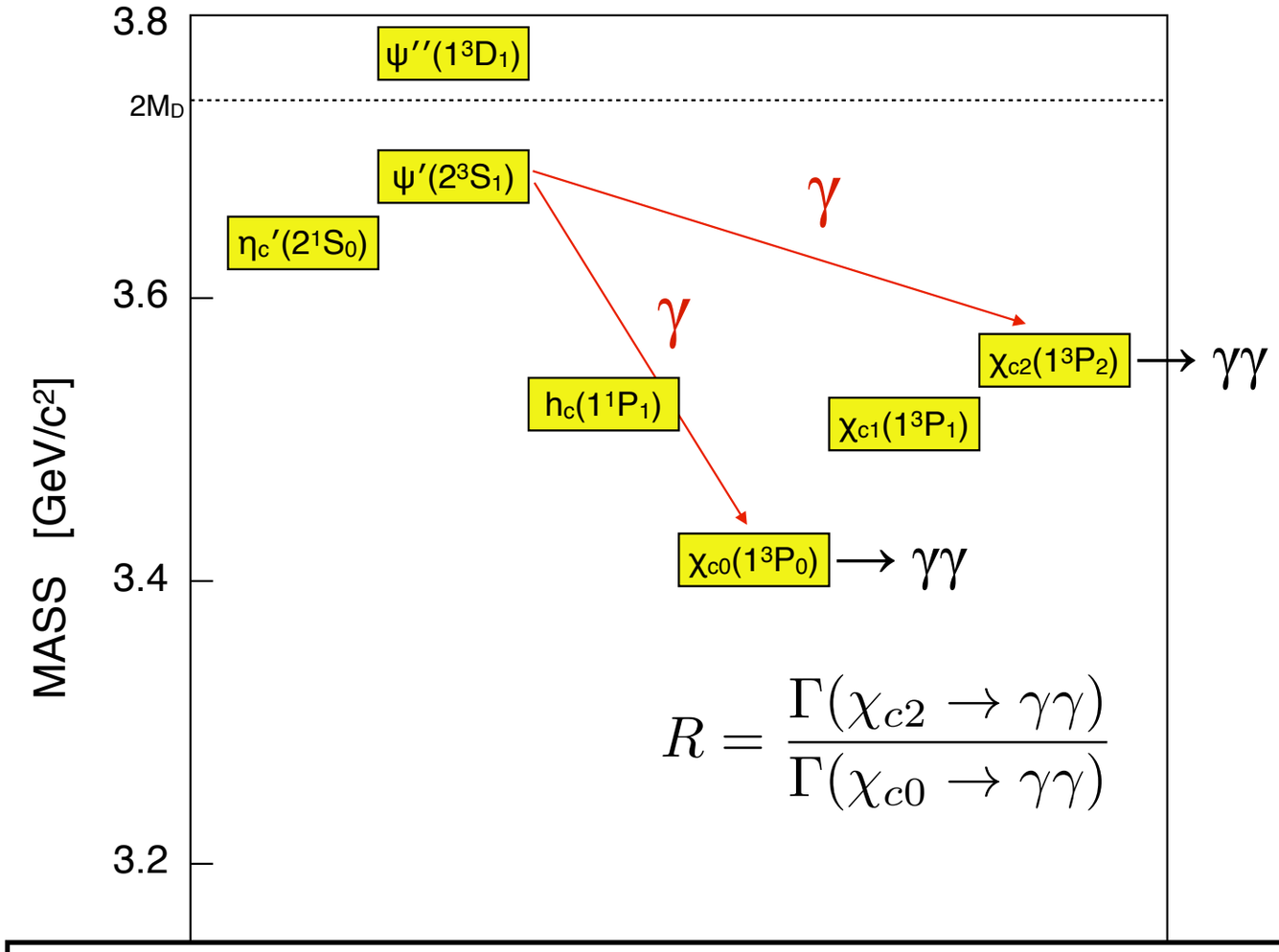
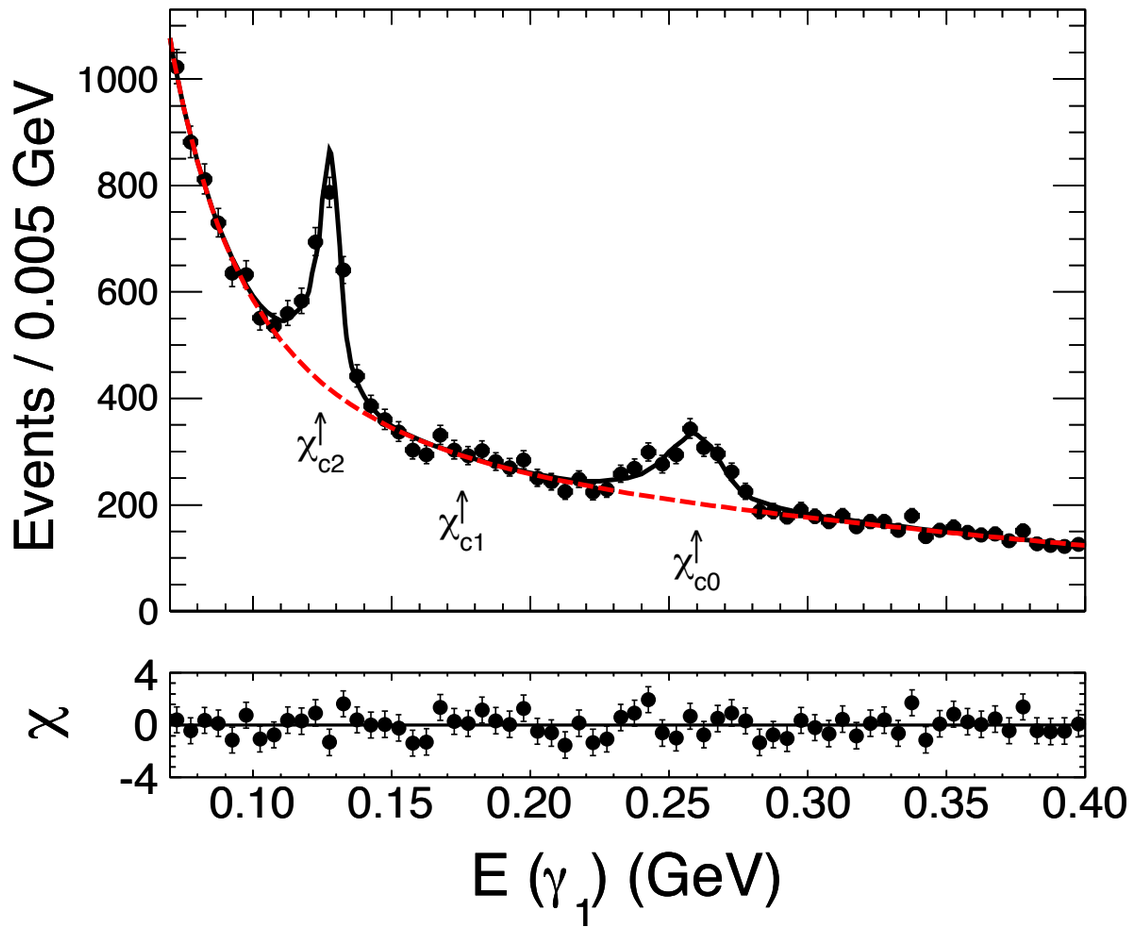


$$R = \frac{\Gamma(\chi_{c2} \to \gamma\gamma)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$$

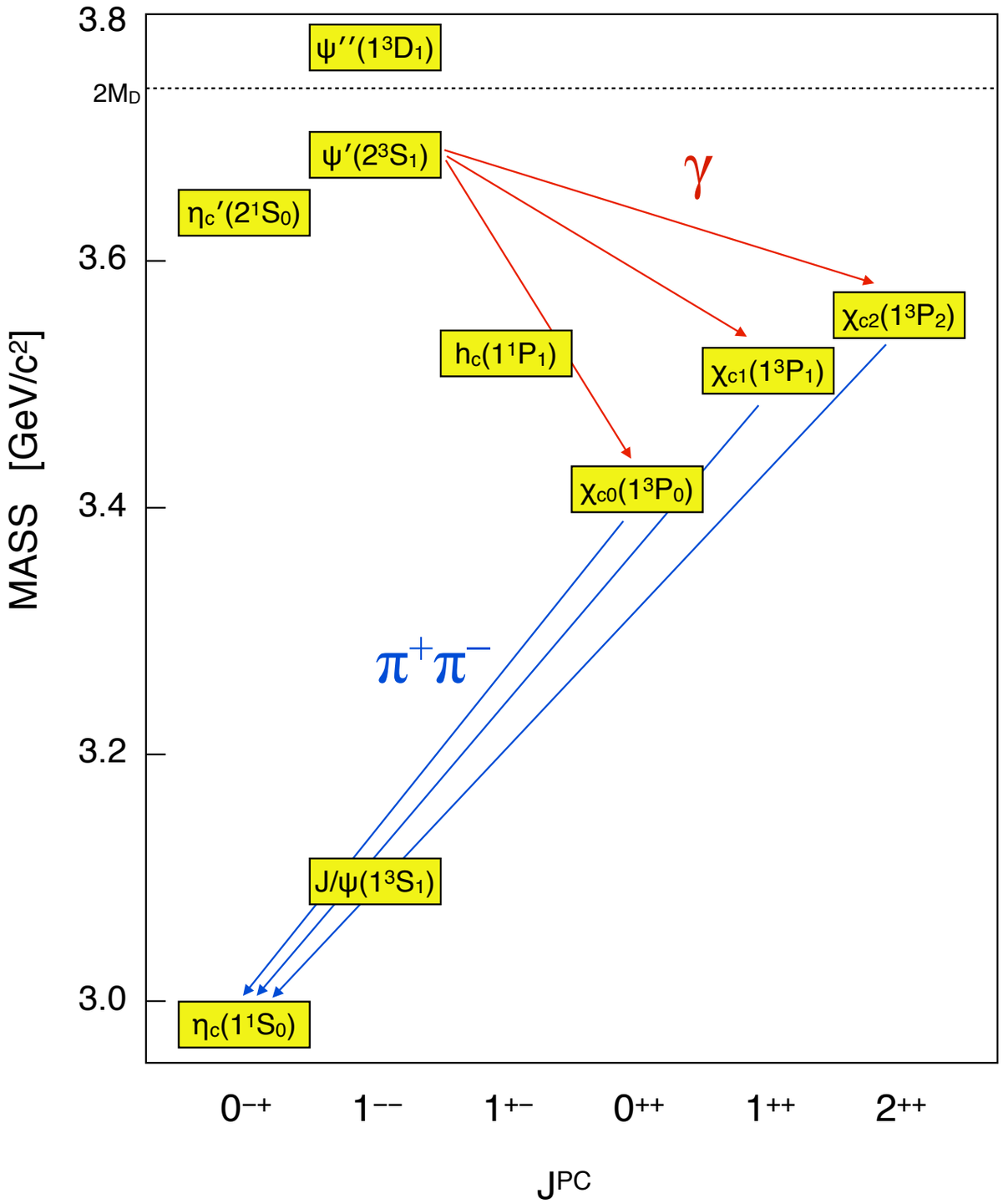


Quantity	χ_{c0}	χ_{c2}
$\mathcal{B}_1 \times \mathcal{B}_2 \times 10^5$	$2.17 \pm 0.17 \pm 0.12$	$2.81 \pm 0.17 \pm 0.15$
$\mathcal{B}_2 \times 10^4$	$2.24 \pm 0.19 \pm 0.12 \pm 0.08$	$3.21 \pm 0.18 \pm 0.17 \pm 0.13$
$\Gamma_{\gamma\gamma}$ (keV)	$2.33 \pm 0.20 \pm 0.13 \pm 0.17$	$0.63 \pm 0.04 \pm 0.04 \pm 0.04$
$\mathcal{R}$	$0.271 \pm 0.029 \pm 0.013 \pm 0.027$	

Results for R are consistent with the lowest order (QED) prediction!

(but many calculations of higher order corrections (QCD) deviate from this value…??…)

III. From Discovery to Precision



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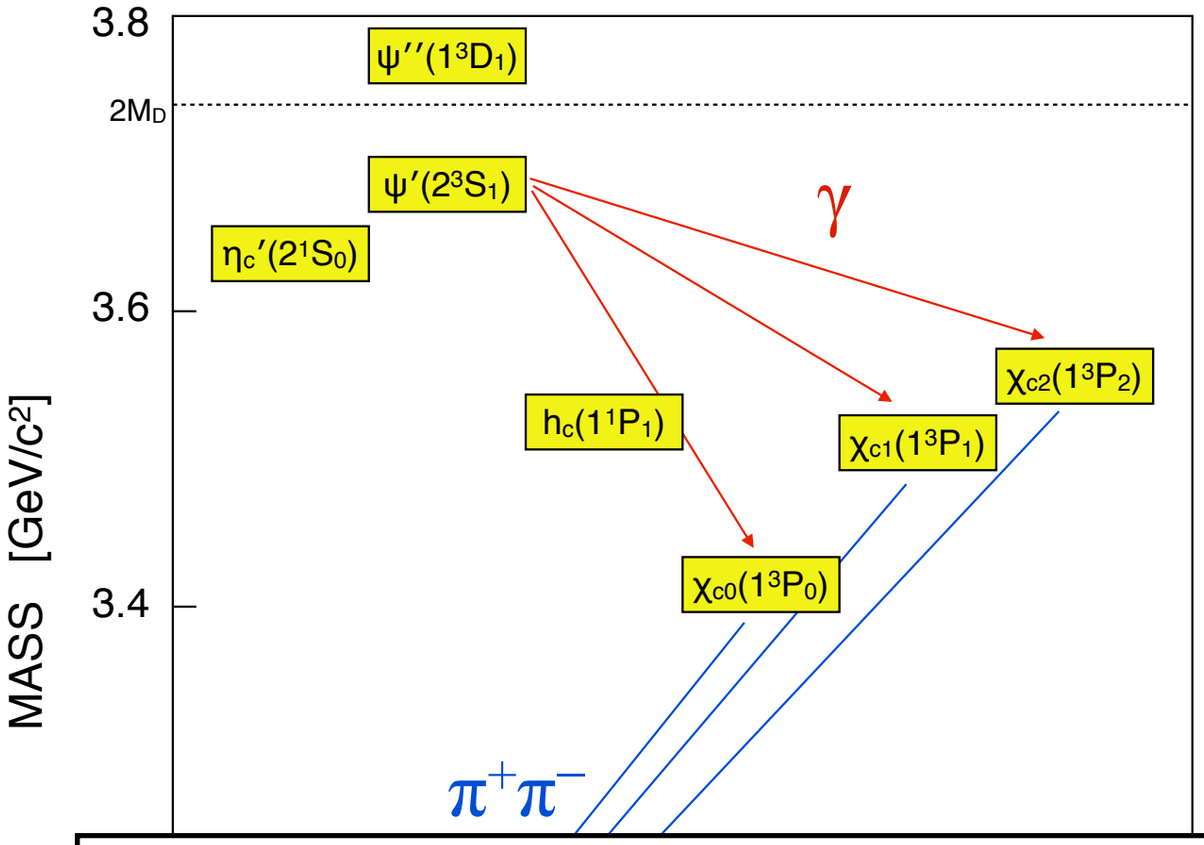
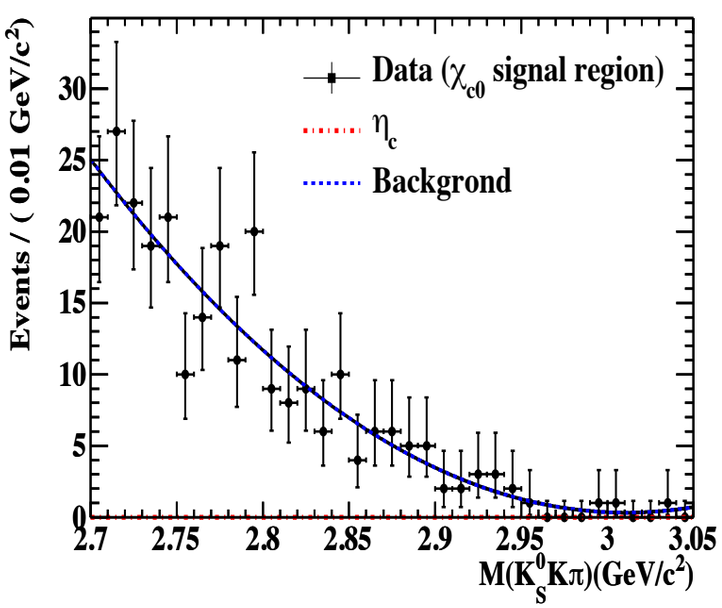


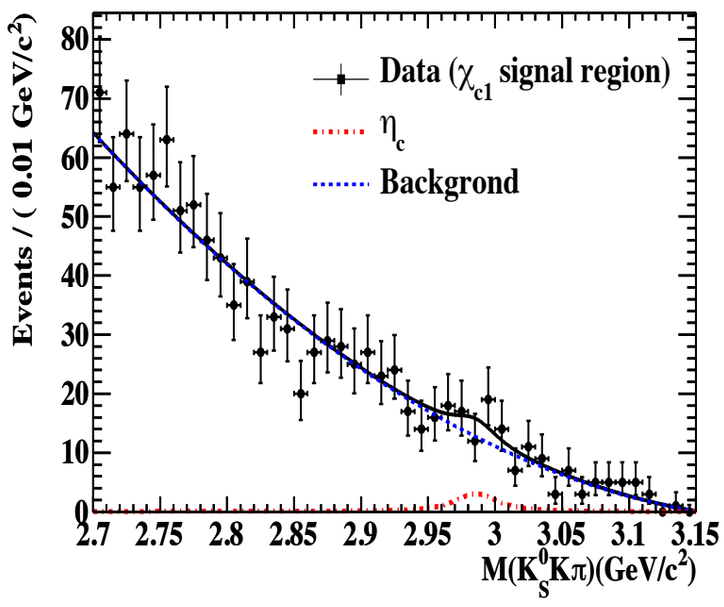
$$B(\chi_{c0}(1P) \to \pi^+\pi^-\eta_c(1S)) < 0.07\%$$

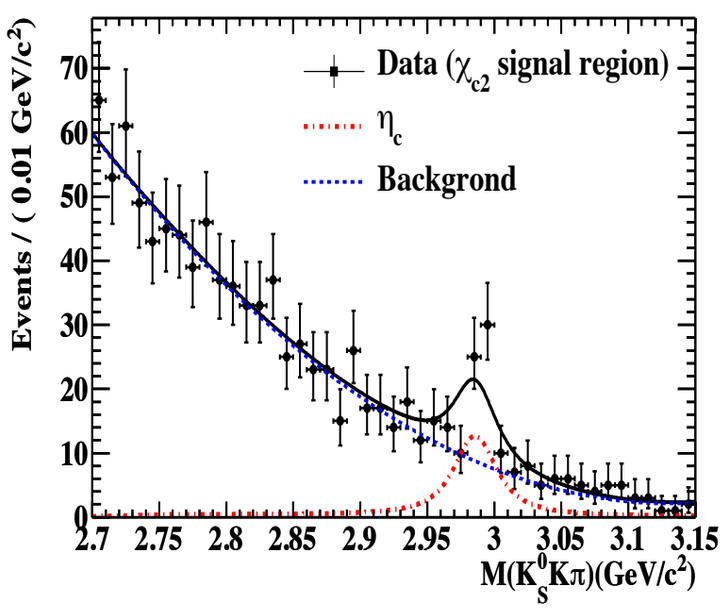
$$B(\chi_{c1}(1P) \to \pi^+\pi^-\eta_c(1S)) < 0.32\%$$

(compared to a prediction of 1.81 ± 0.26% using a E1-M1 soft gluon emission model)

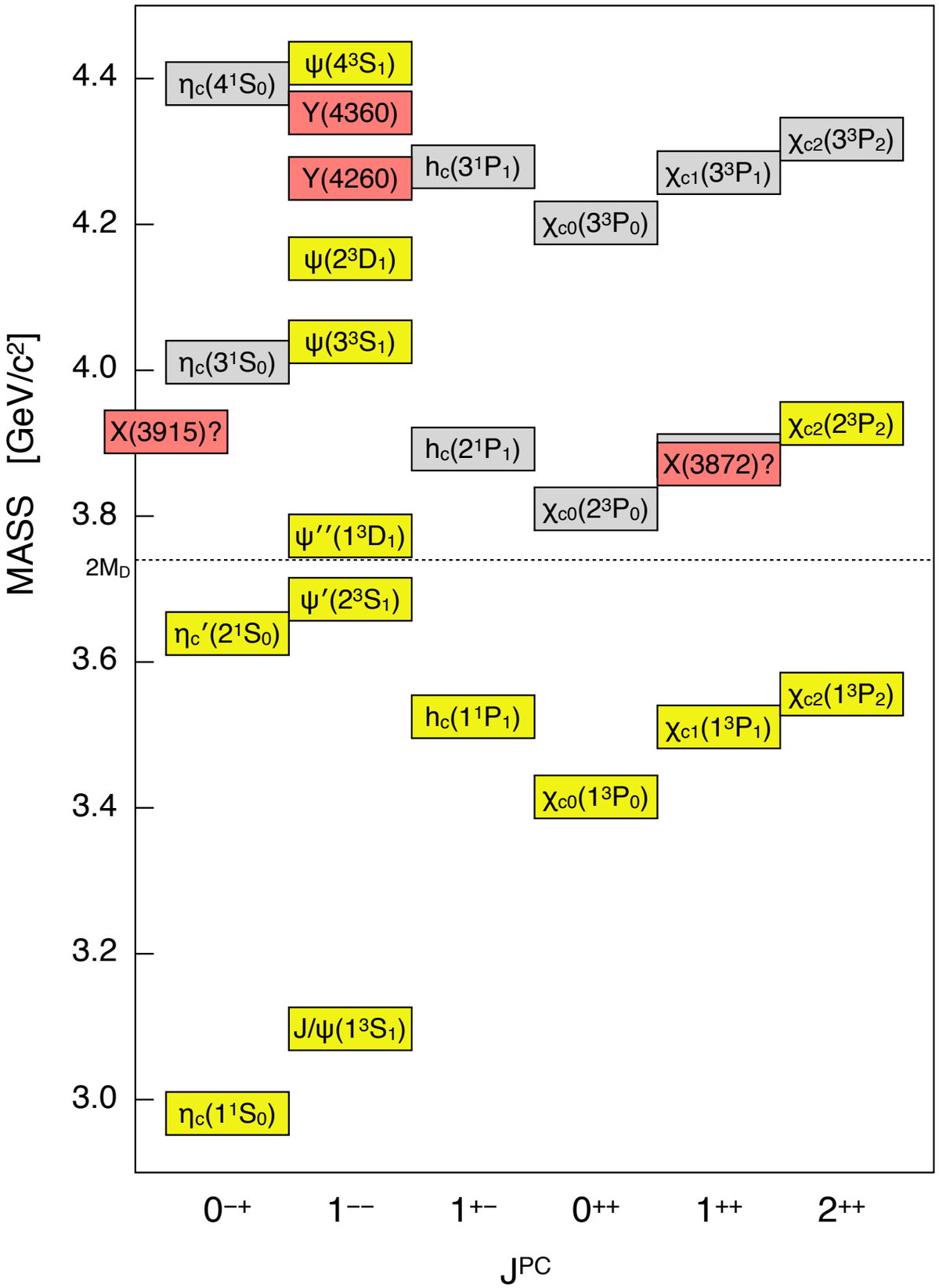
$$B(\chi_{c2}(1P) \to \pi^+\pi^-\eta_c(1S)) < 0.54\%$$







IV. A New Era of Discovery

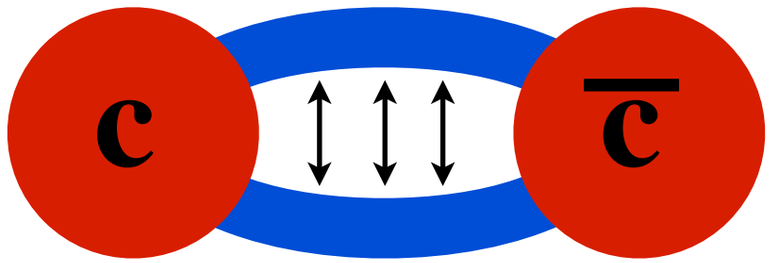


I. An Introduction to Charmonium

II. The Original Era of Discovery:
establishing the quark model states

III. From Discovery to Precision:
the quark model states at BESIII

IV. A New Era of Discovery:
beyond the quark model and the role of BESIII



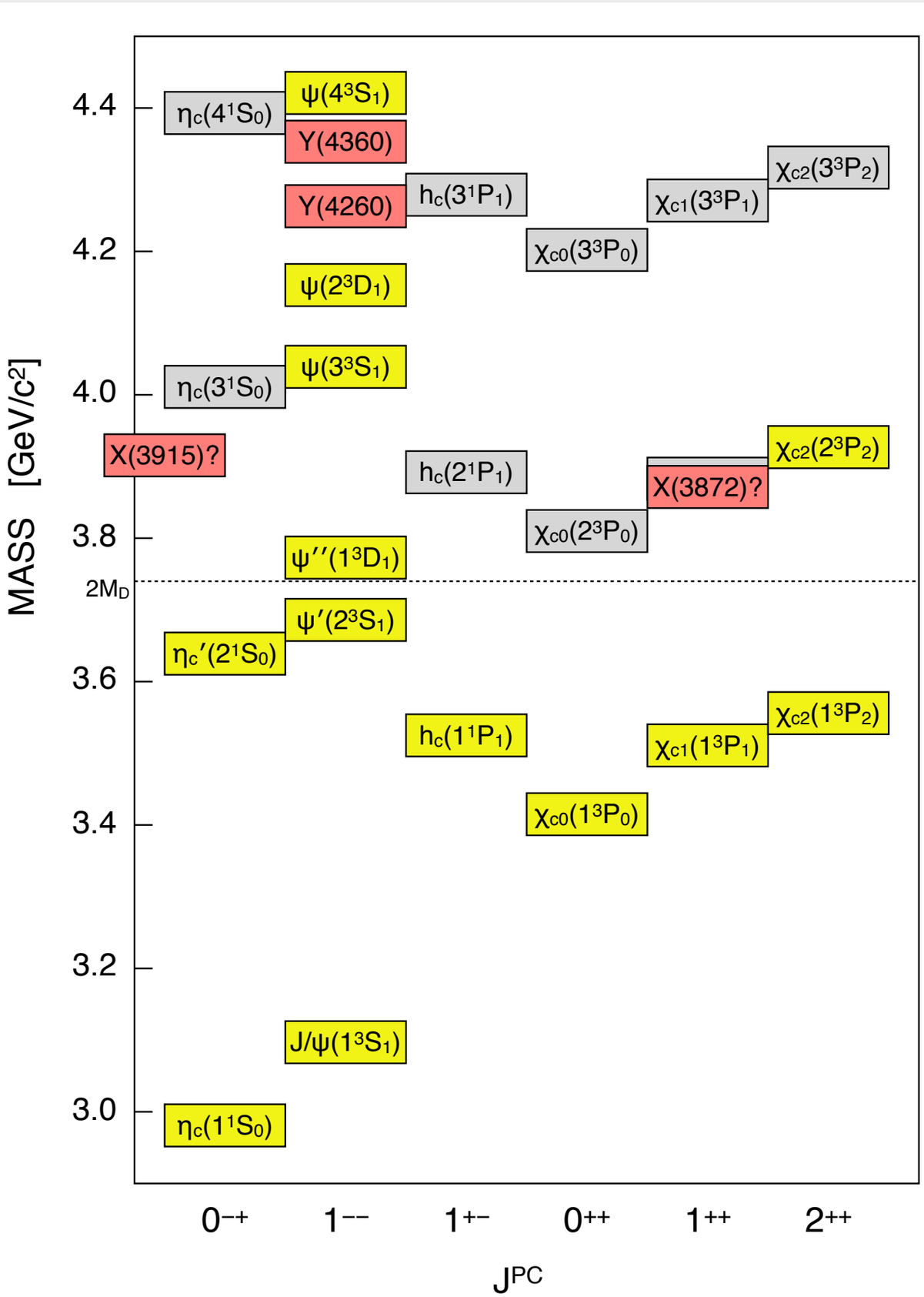
HYBRID CHARMONIUM?

IV. A New Era of Discovery

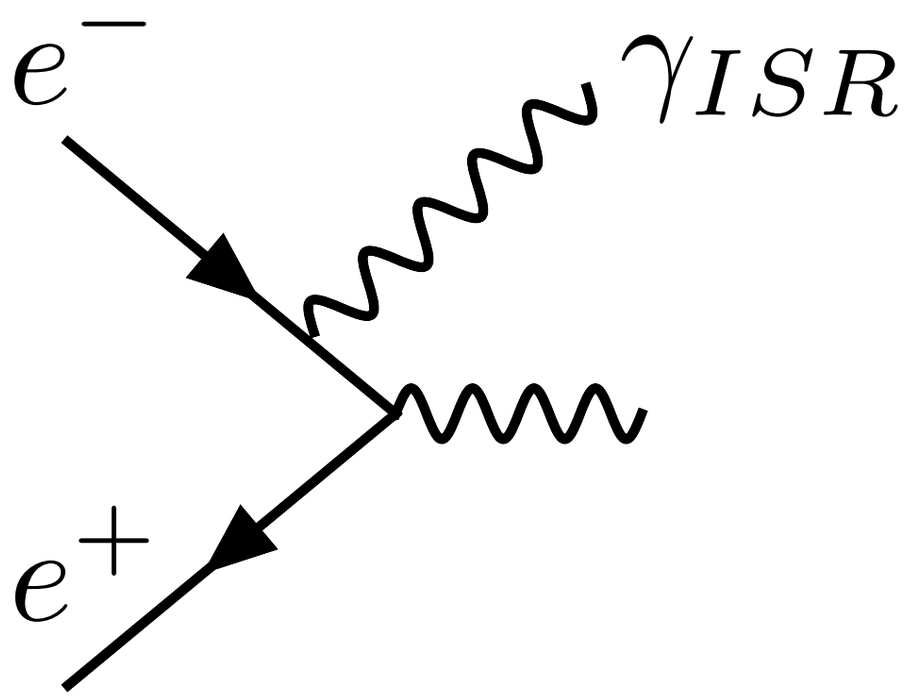
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		($<$2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \cdots$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

EPJ C71, 1534 (2011)

IV. A New Era of Discovery



Initial State Radiation (ISR)
at Belle and BaBar



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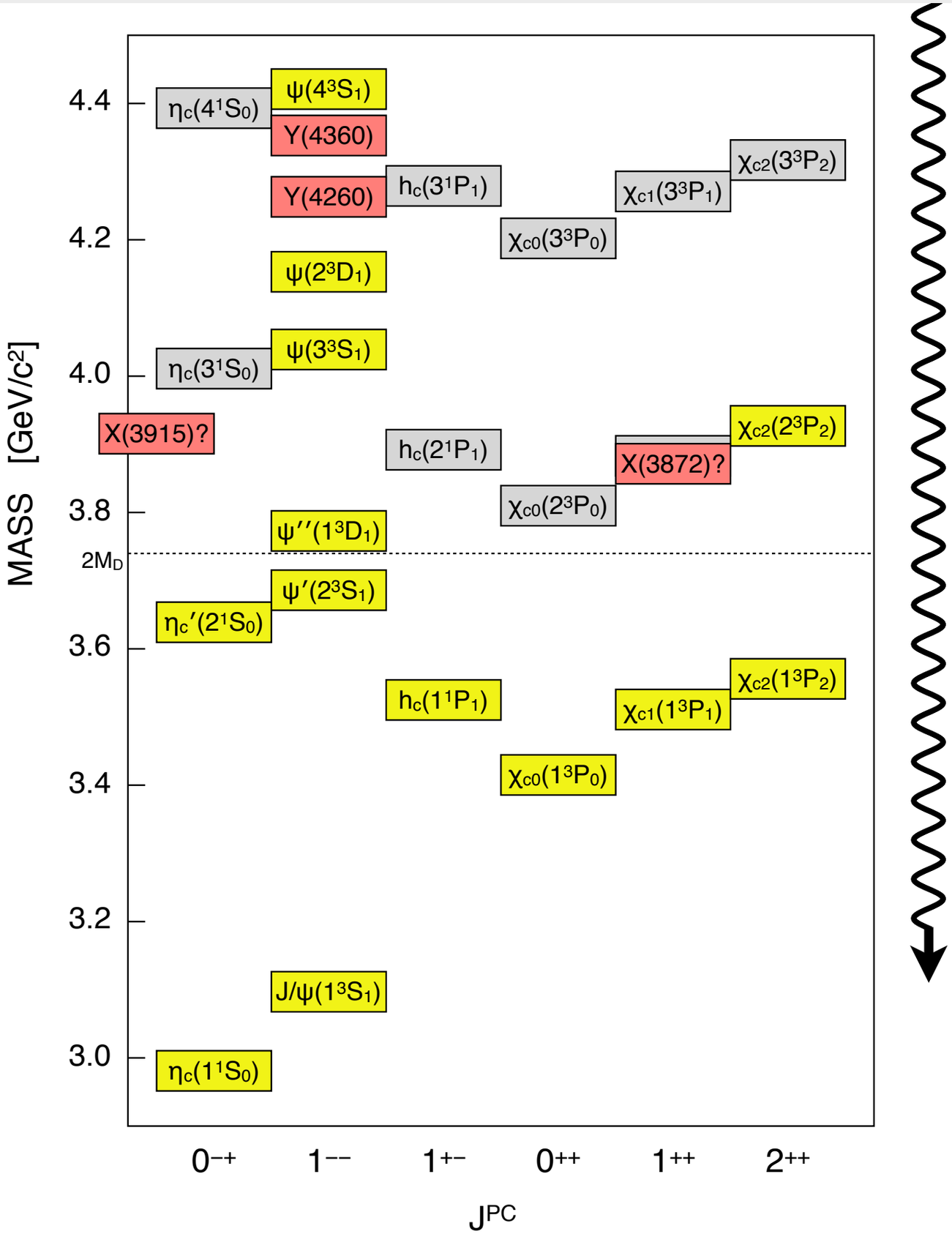
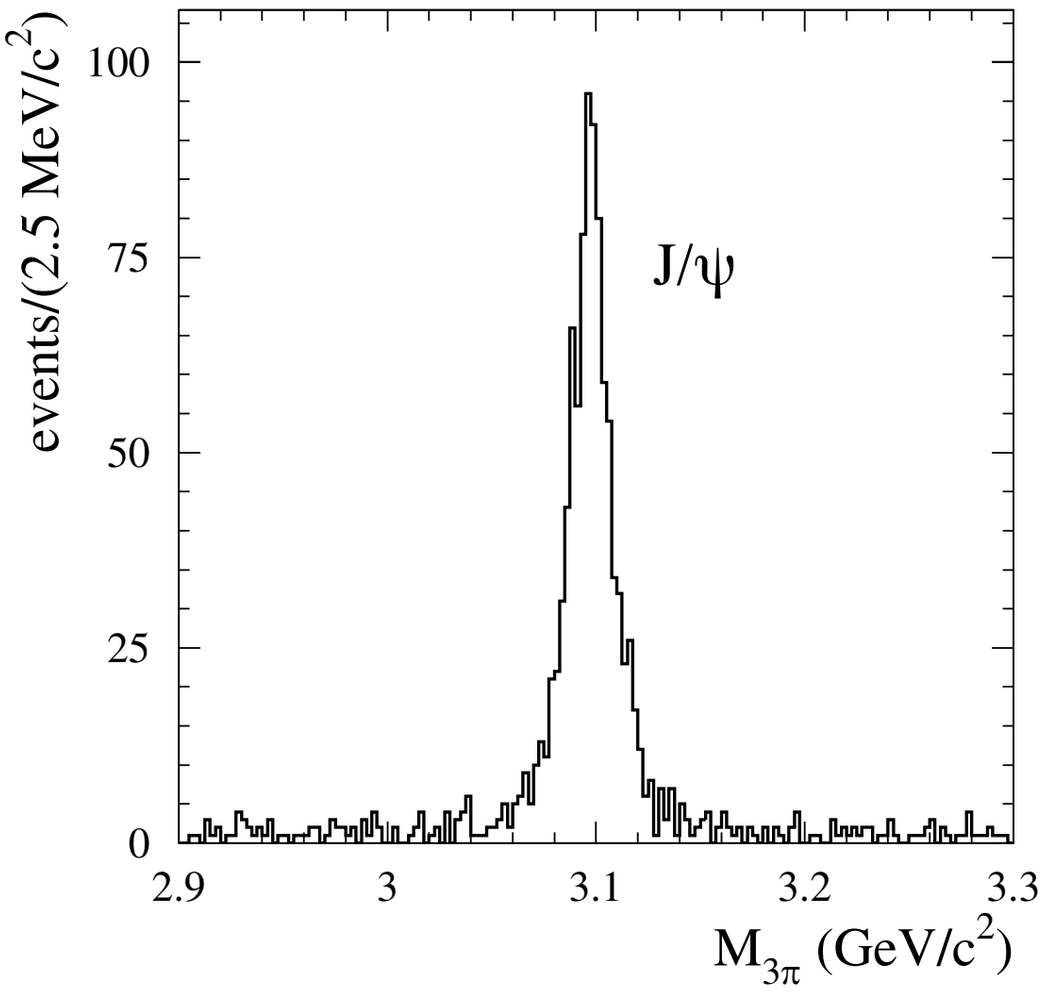


$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^-\pi^0$ at BaBar



PRD 70, 072004 (2004)

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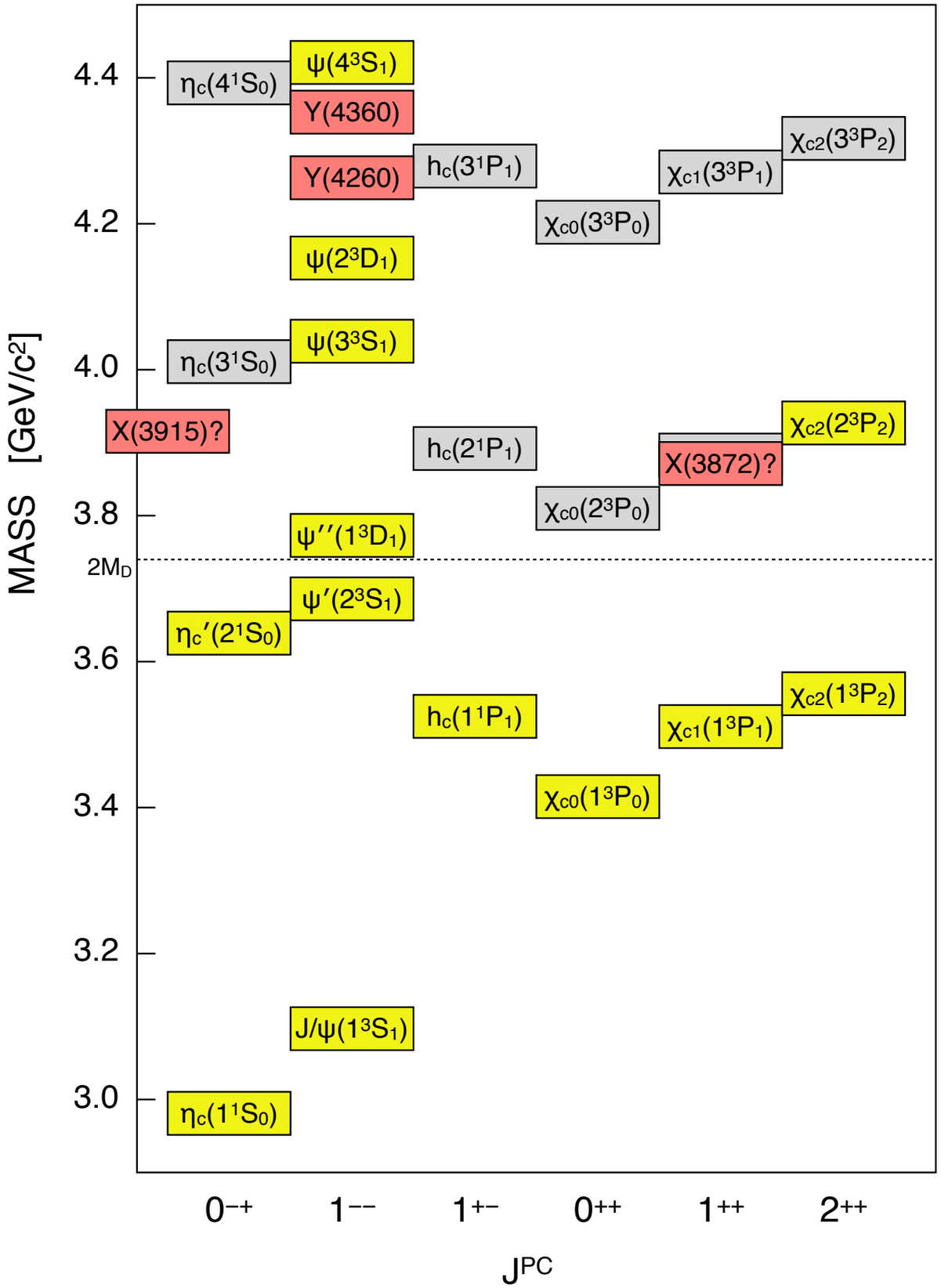

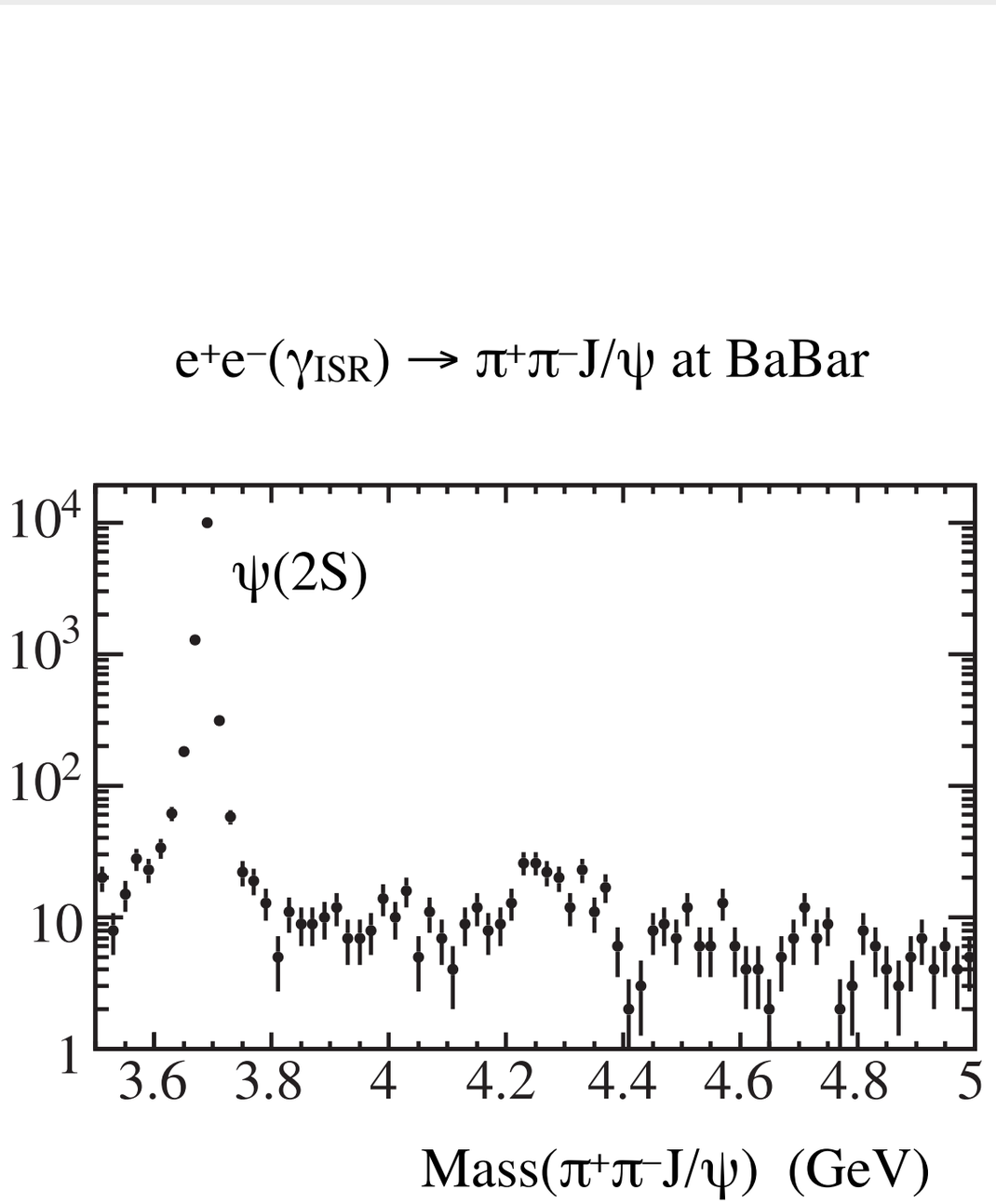

PRL 95, 142001 (2005)

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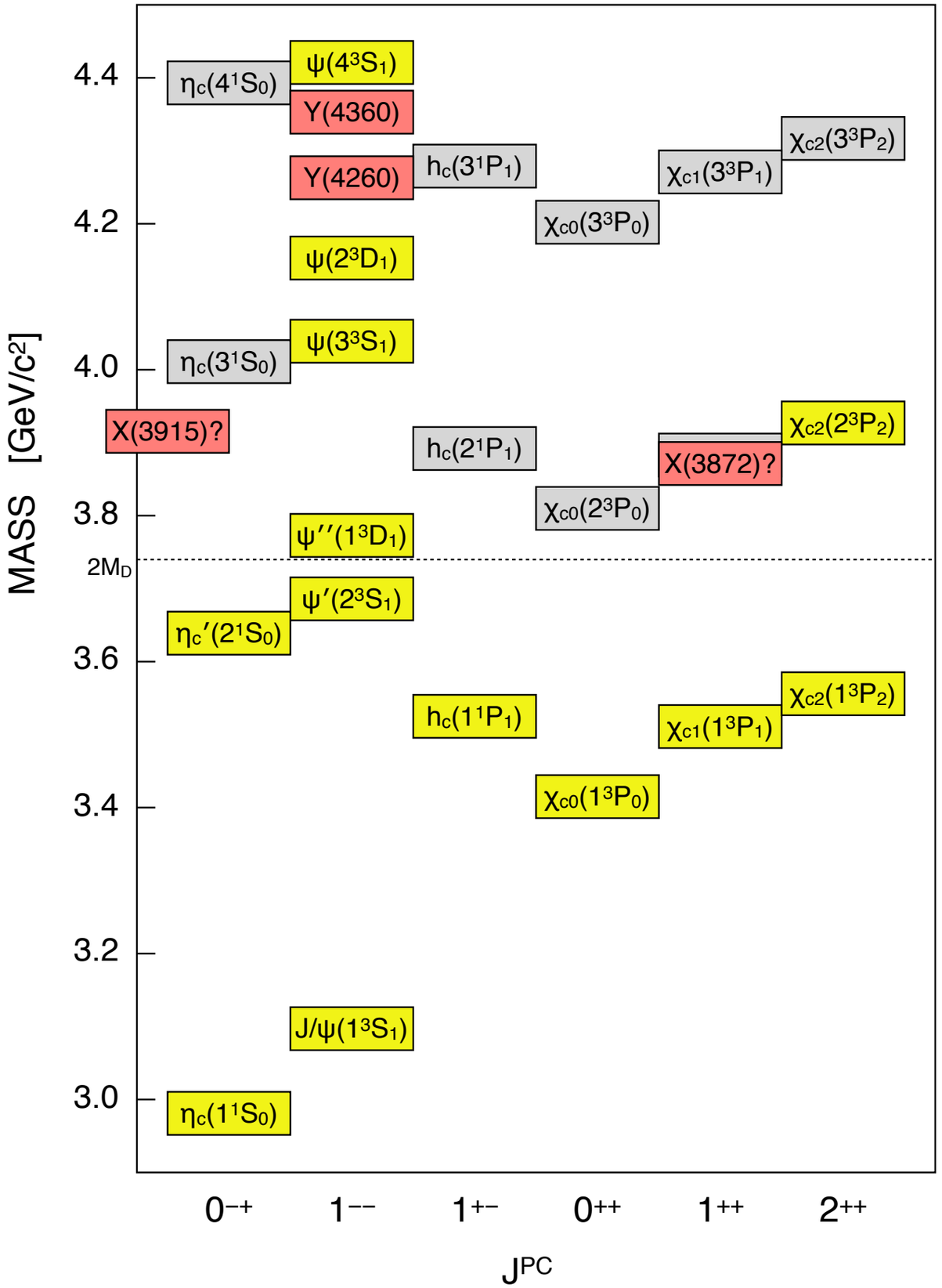
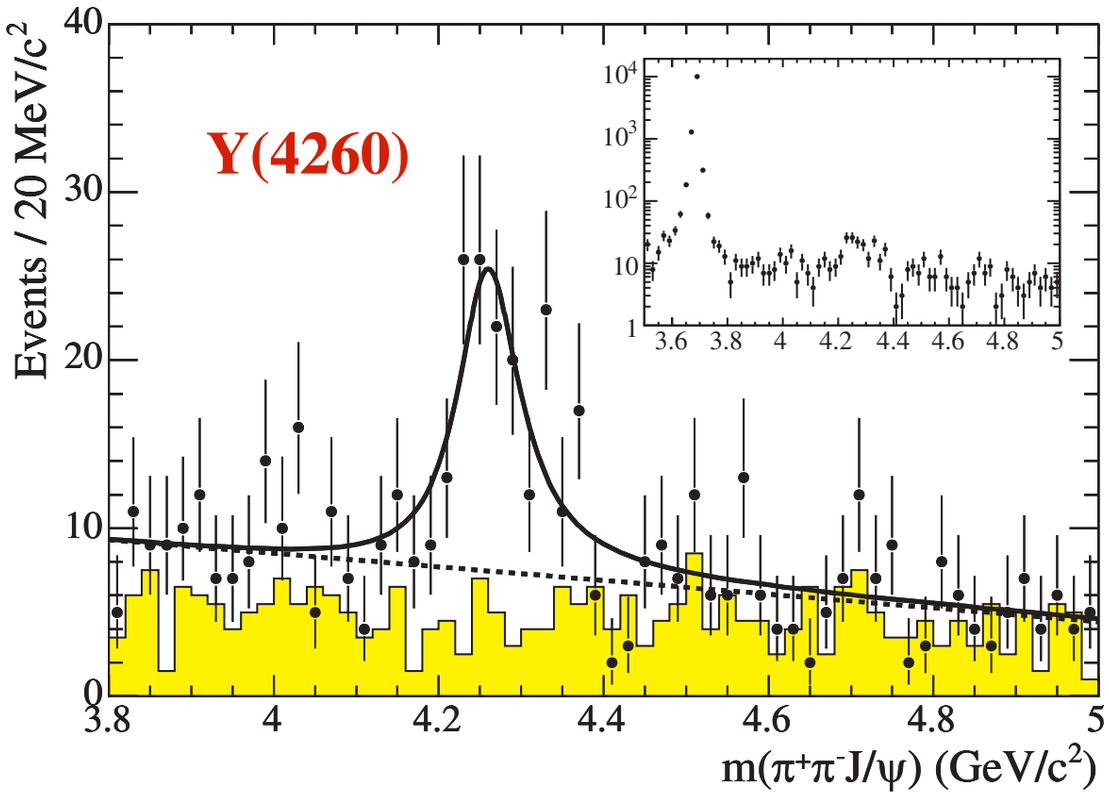


$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^- J/\psi$ at BaBar



PRL 95, 142001 (2005)

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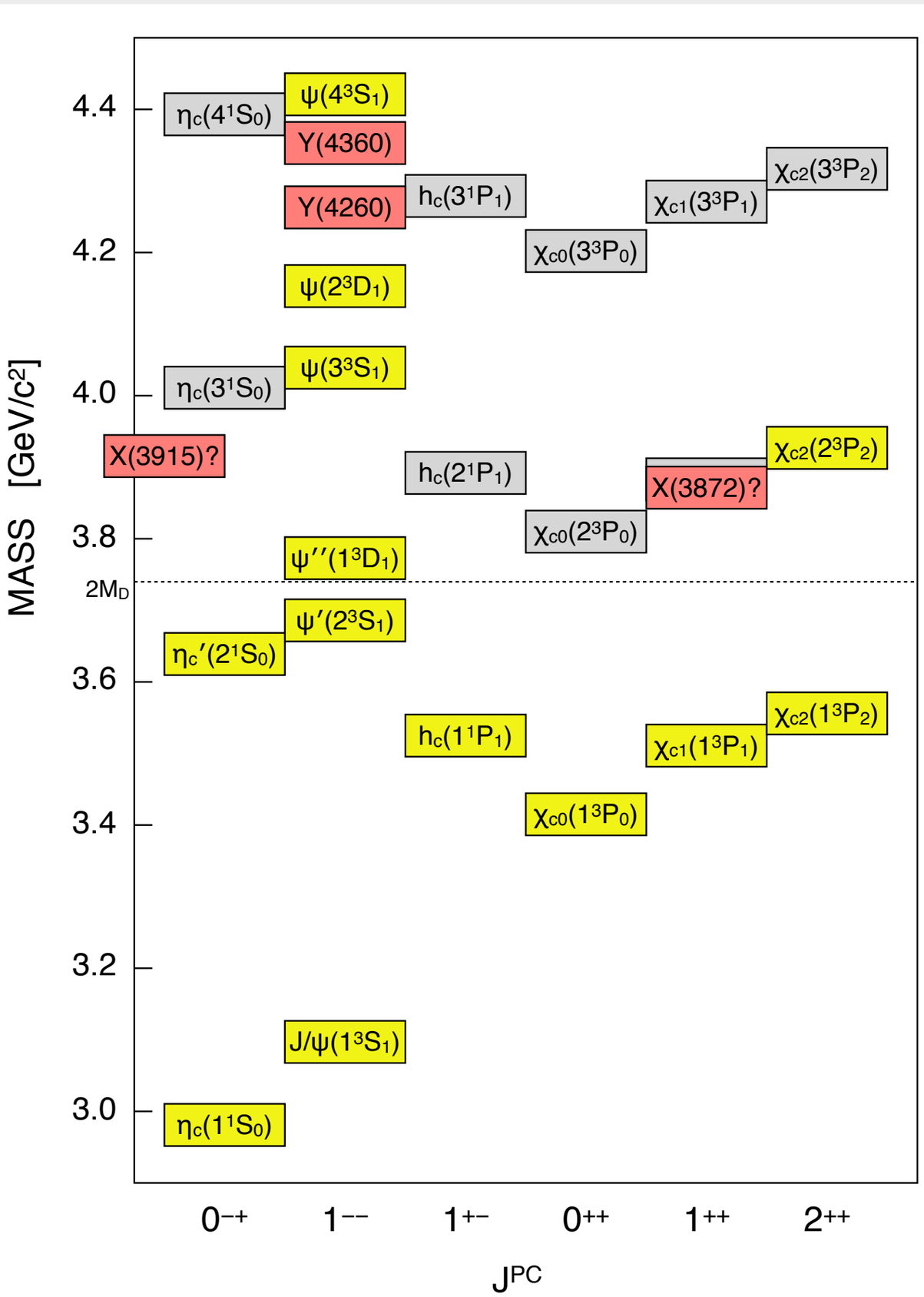

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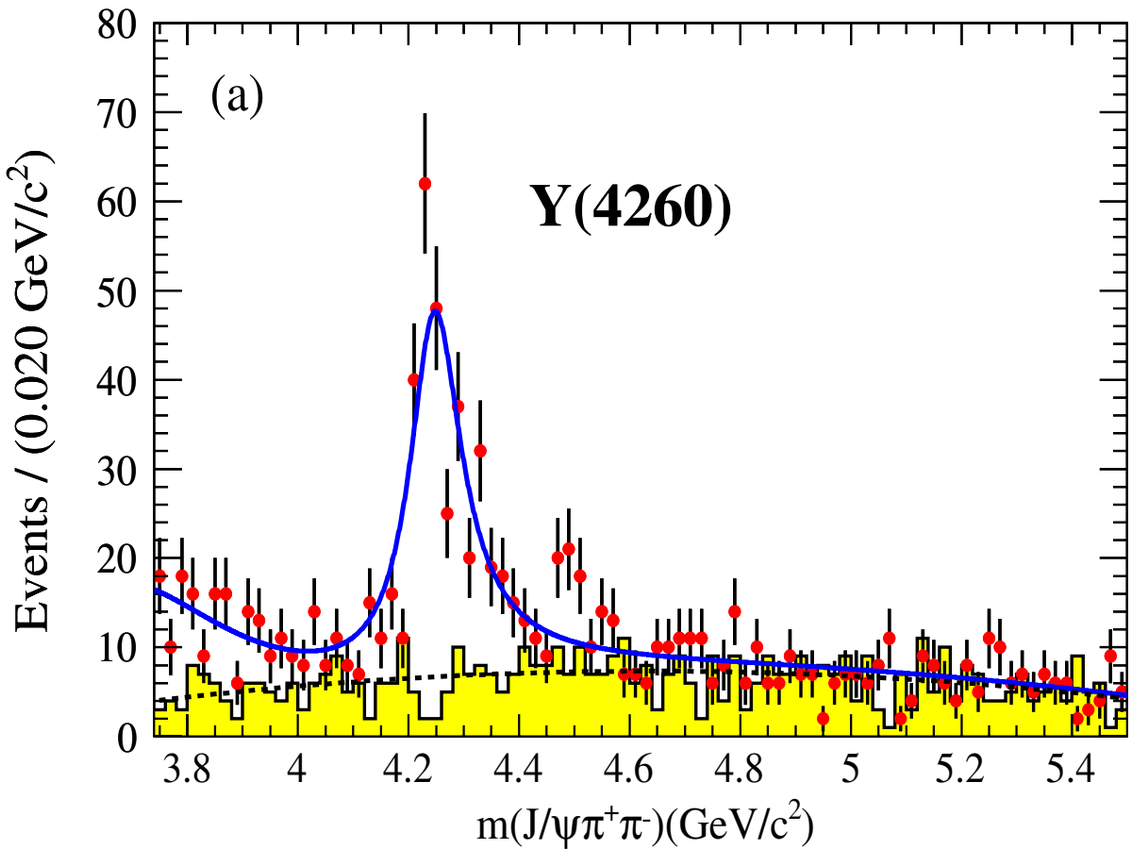

PRD 86, 051102(R) (2012)

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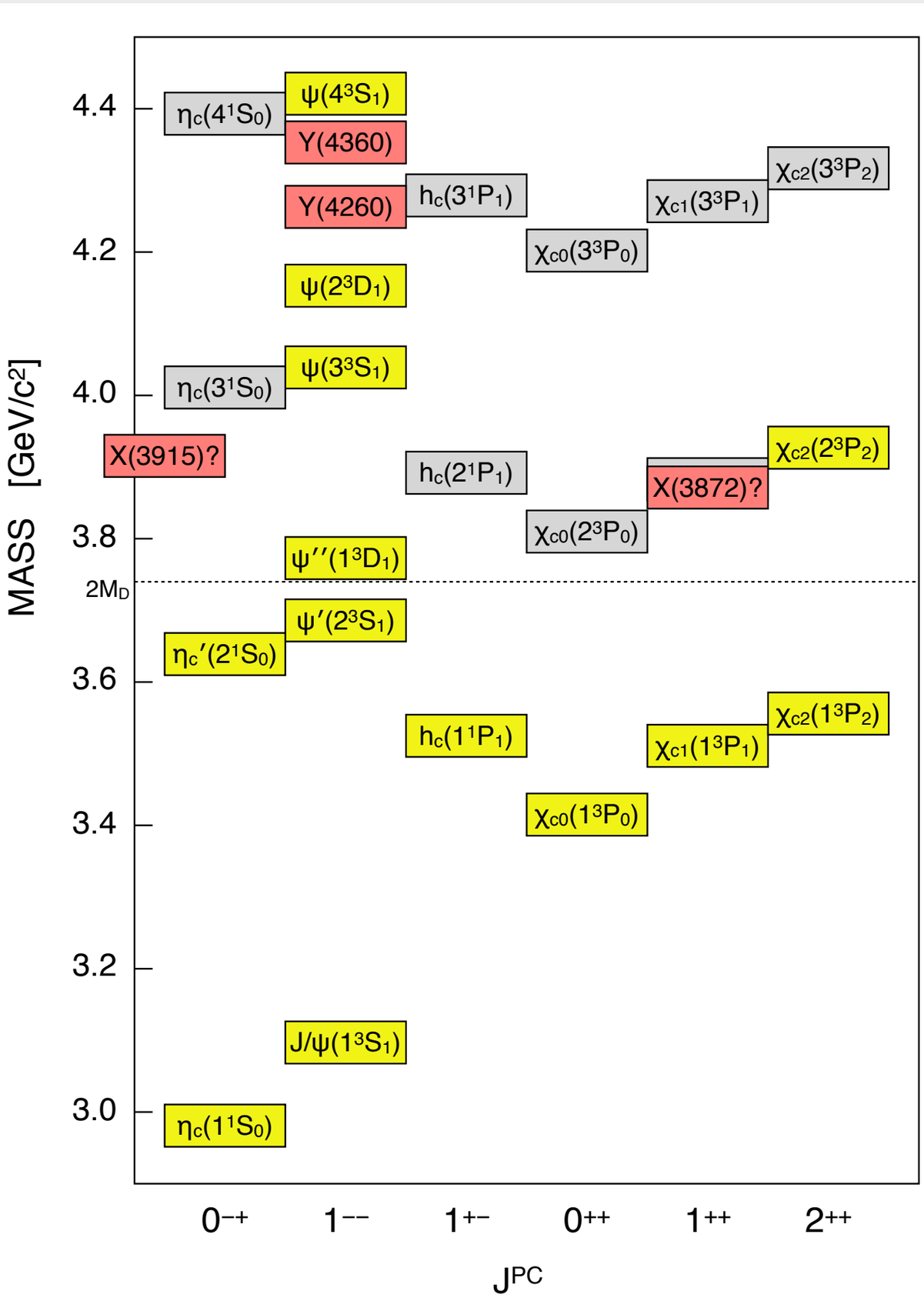
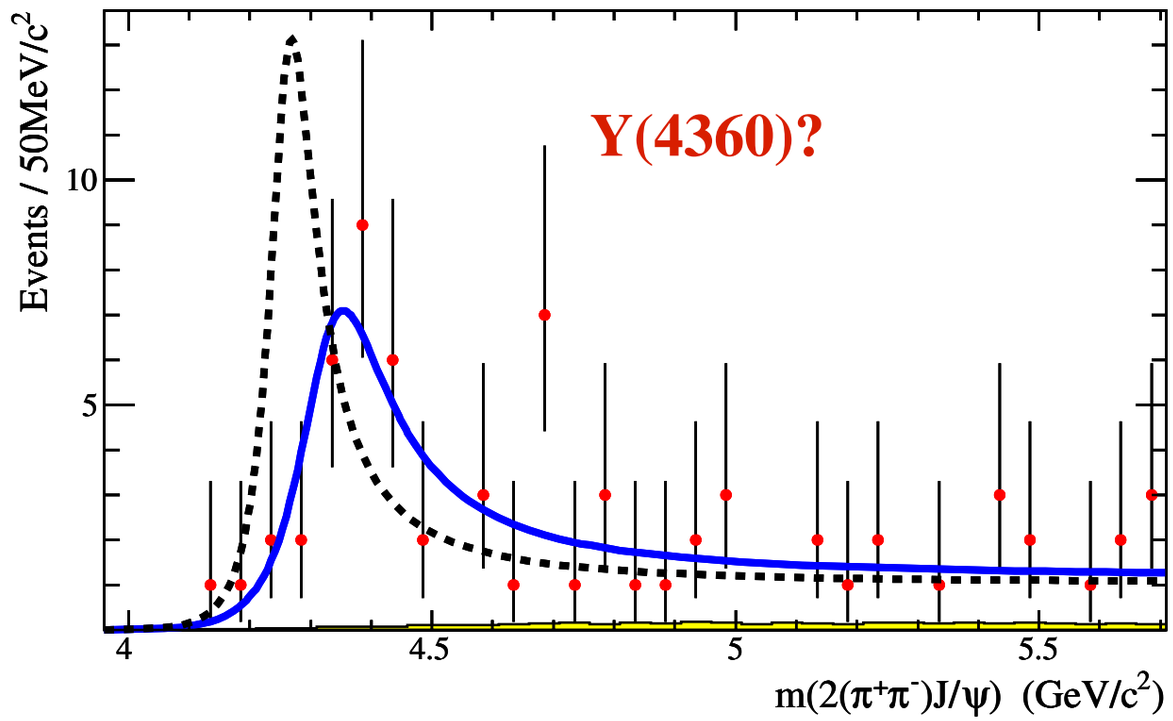
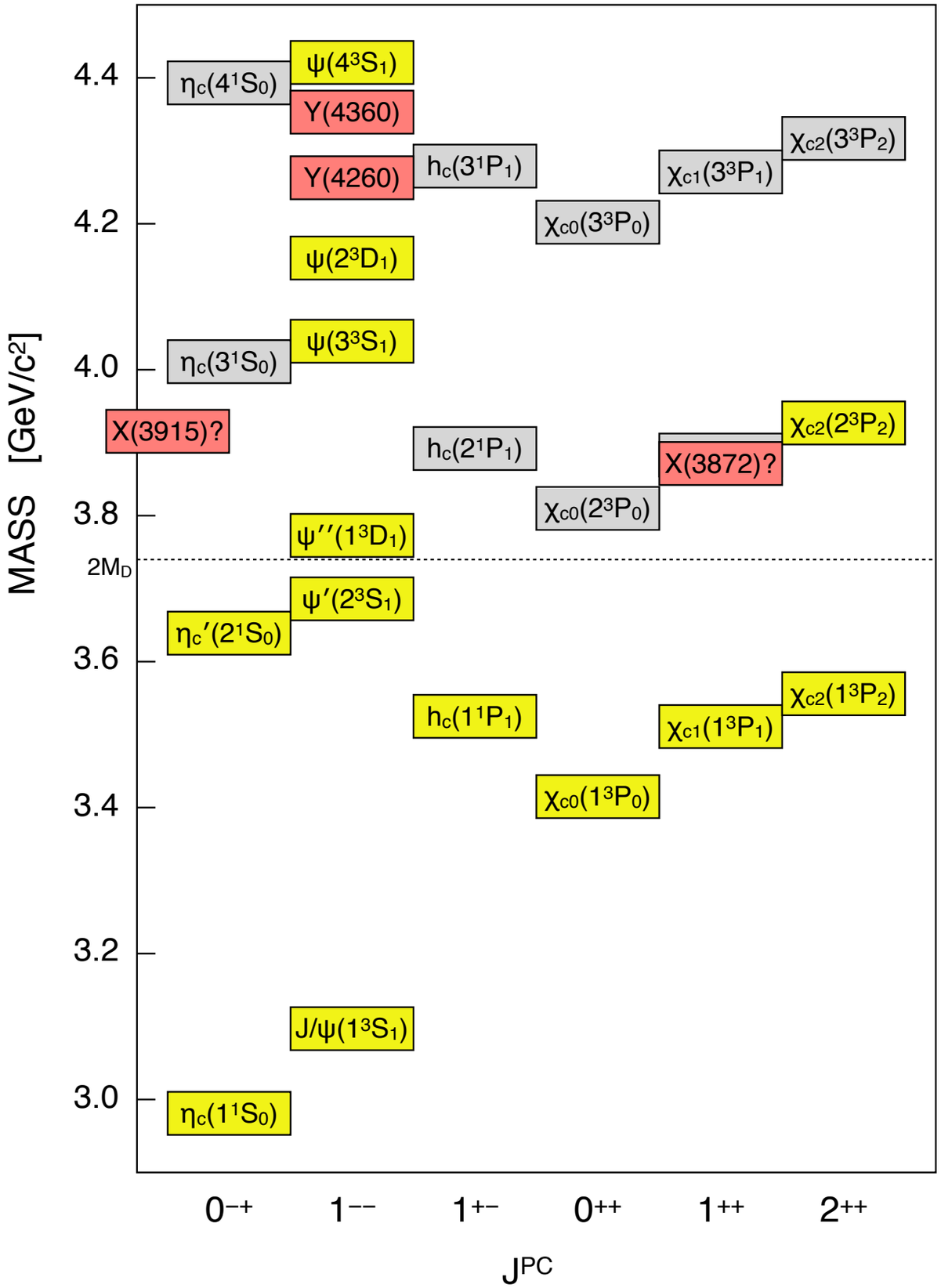


$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^-\psi(2S)$ at BaBar

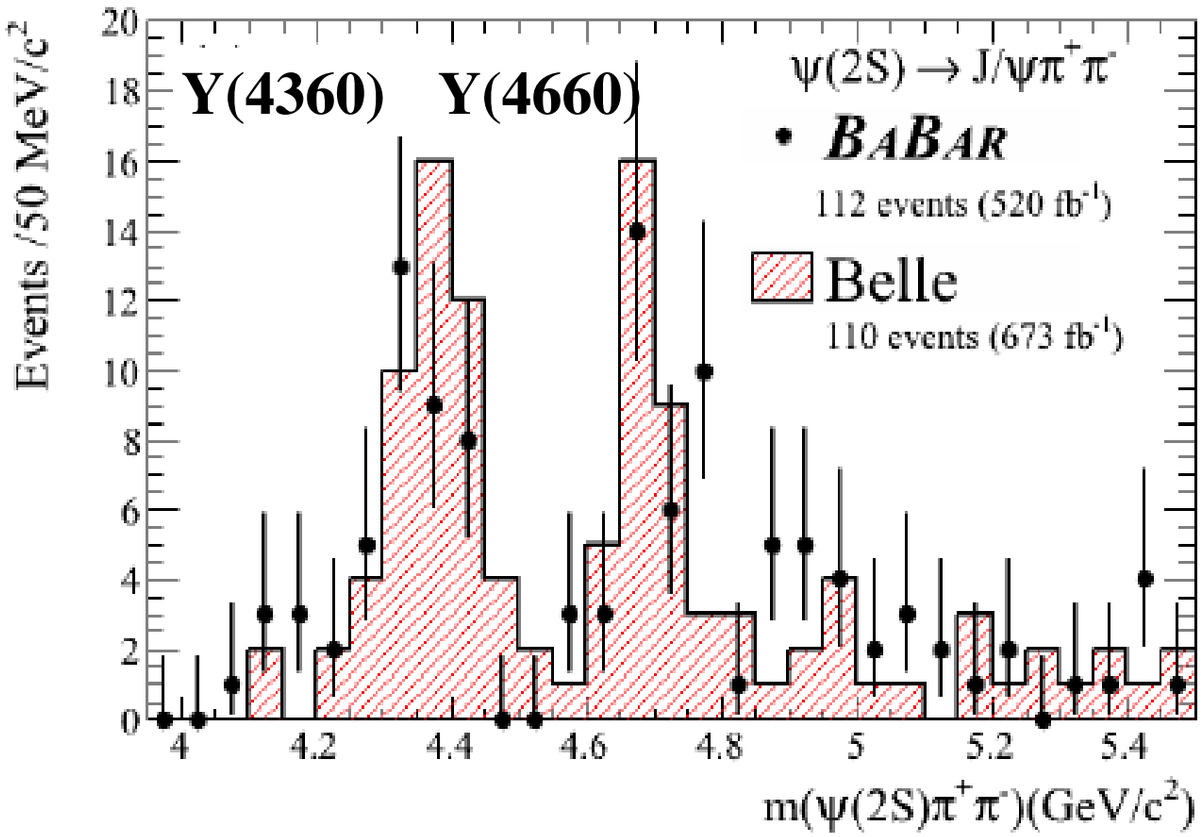


PRL 98, 212001 (2007)

IV. A New Era of Discovery

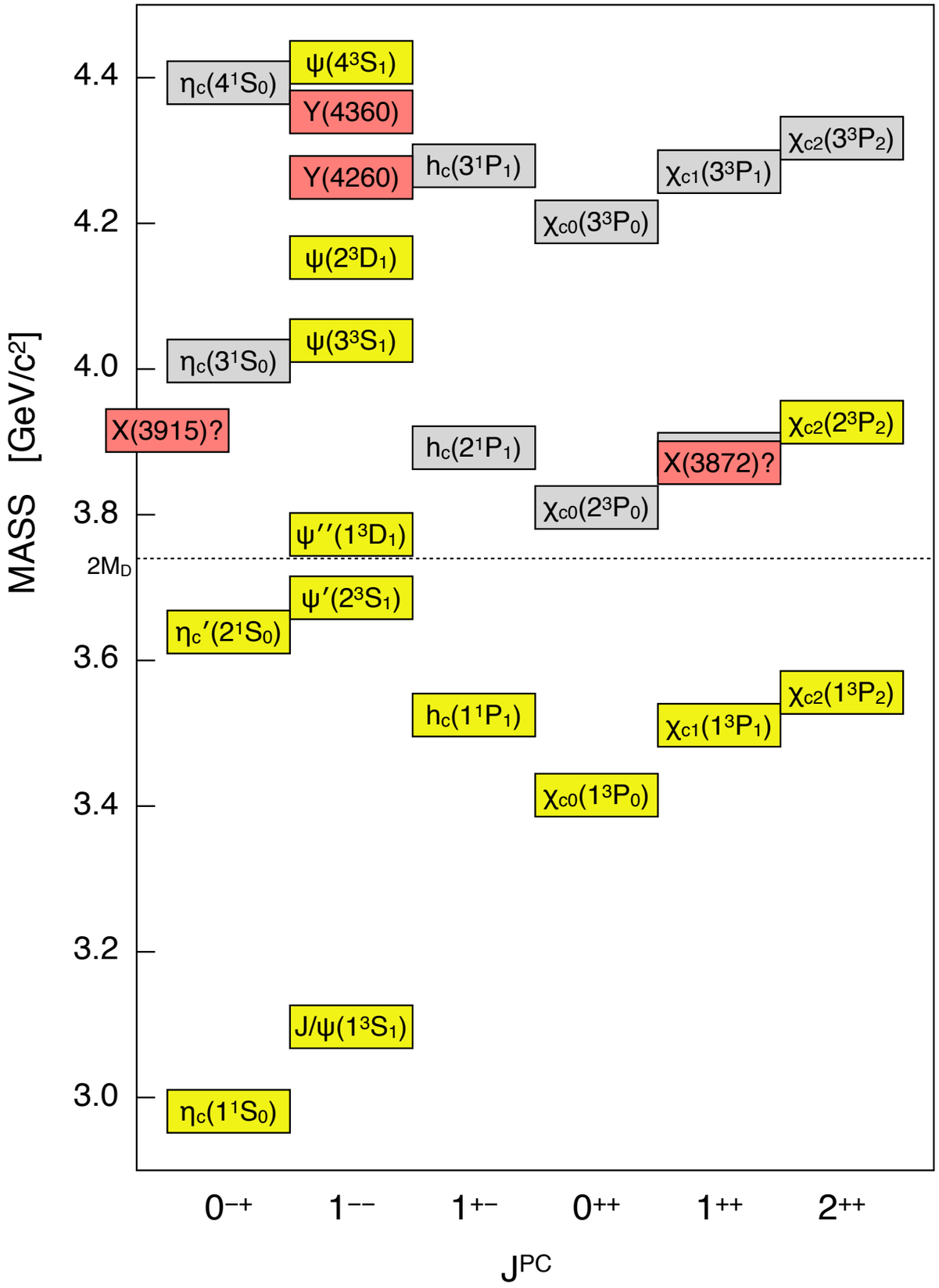


$e^+e^-(\gamma_{ISR}) \rightarrow \pi^+\pi^-\psi(2S)$ at BaBar and Belle



arXiv:1211.6271 and CHARM 2012

IV. A New Era of Discovery



Upper Limits on B(Y → DD) / B(Y → ππψ)

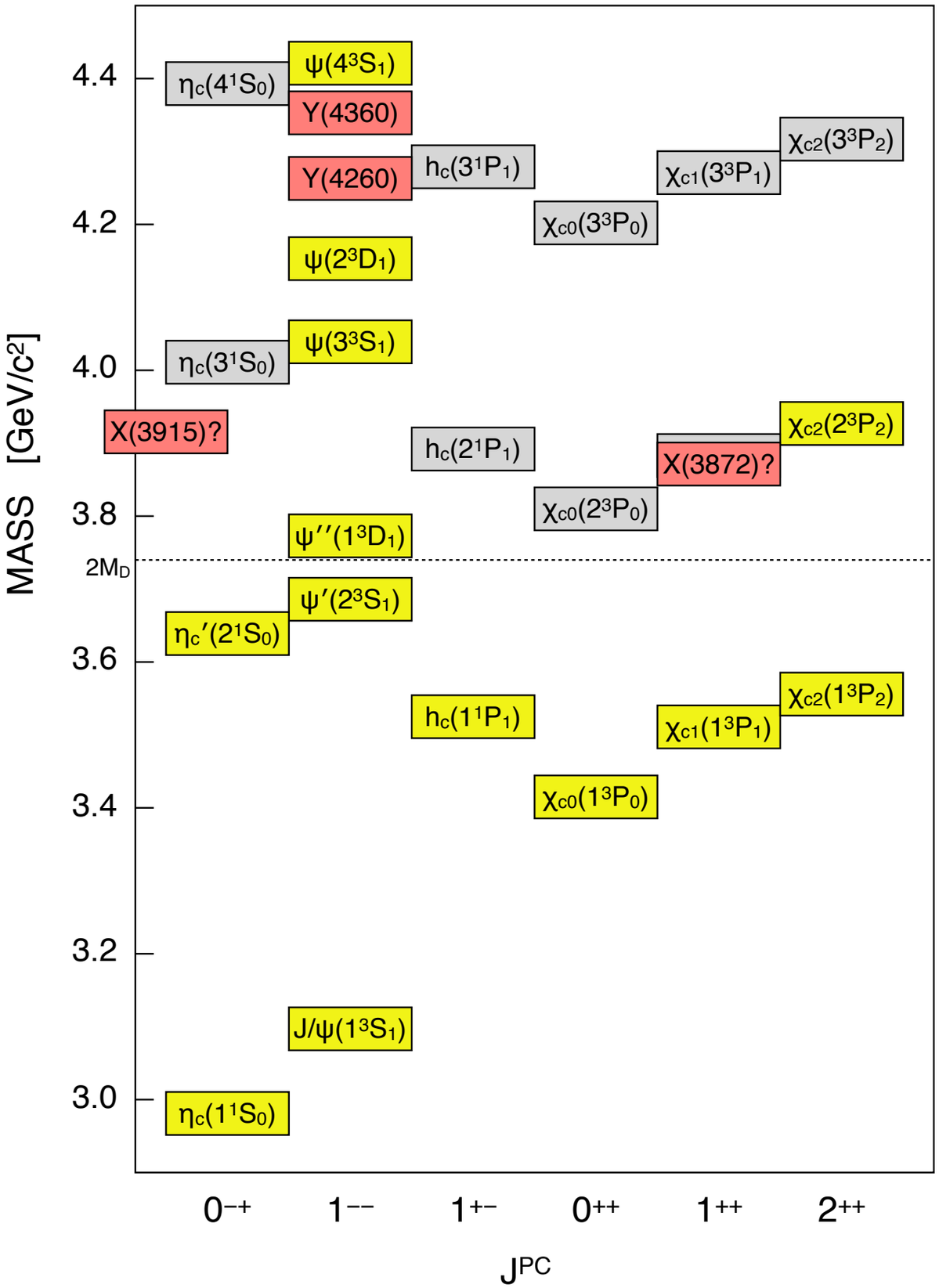
(from CLEO, BaBar, and Belle)

T	$Y(4260)$	$Y(4360)$
$D\bar{D}$	4.0 [16], 7.6 [27]	
$D\bar{D}^*$	45 [16], 34 [28]	
$D^*\bar{D}^*$	11 [16], 40 [28]	
$D\bar{D}^*\pi$	15 [16], 9 [22]	8 [22]
$D^*\bar{D}^*\pi$	8.2 [16]	
$D_s^+ D_s^-$	1.3 [16], 0.7 [29]	
$D_s^+ D_s^{*-}$	0.8 [16], 44 [29]	
$D_s^{*+} D_s^{*-}$	9.5 [16]	

EPJ C71, 1534 (2011)

$$B(\psi'' \to DD)/B(\psi'' \to \pi\pi\psi) \approx 500$$

IV. A New Era of Discovery



Theoretical Ideas on Y(4260), Y(4360):

DD* bound states (Y(4360) = $D_sD_s^*$)

(NPA815, 53 (2009))

J/ψf_0 bound state (with KK → ππ)

(PRD80, 094012 (2009))

Tetraquarks (or two diquarks)

(PRD72, 031502(R) (2005))

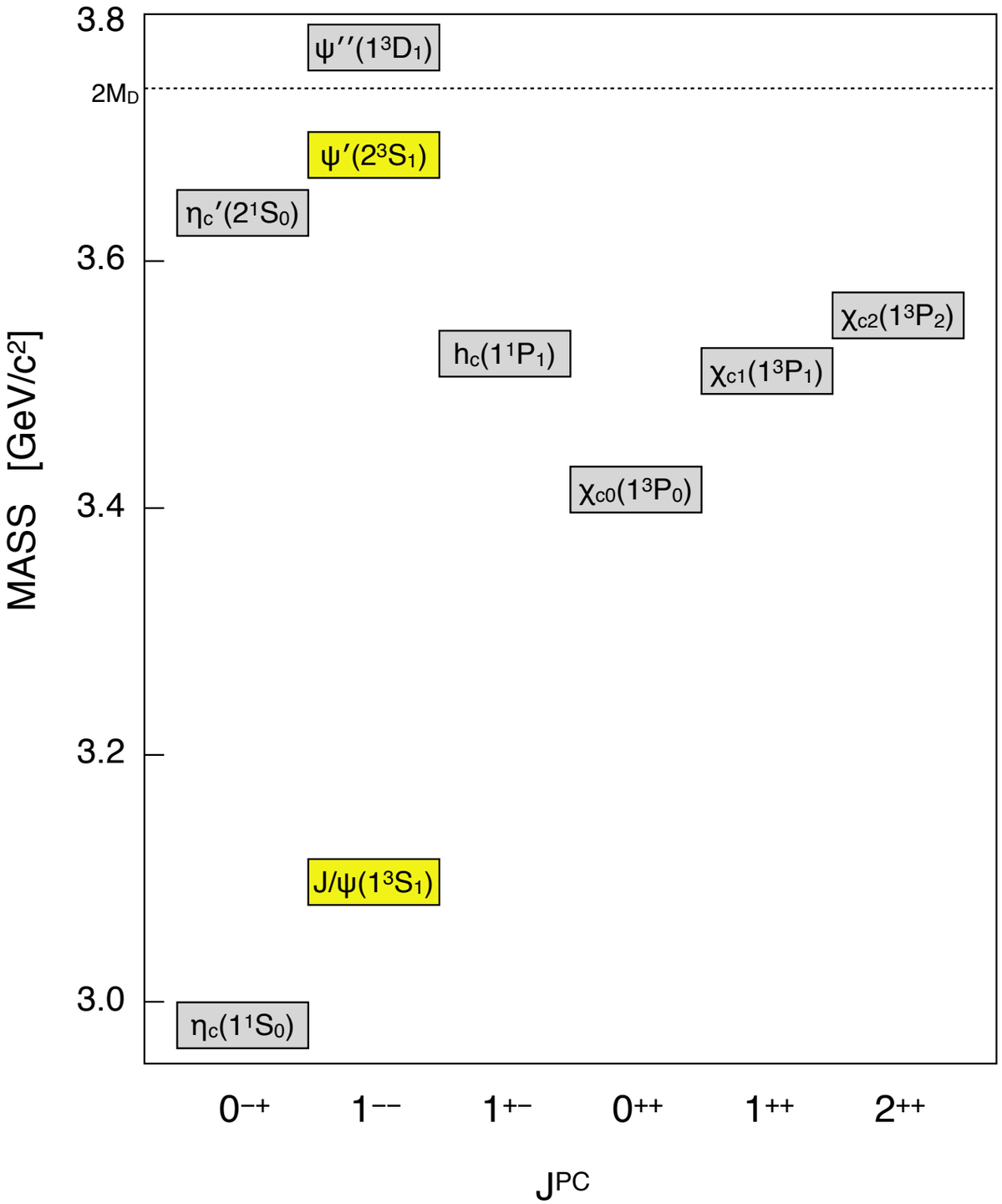
Hadrocharmonium

(PLB666, 344 (2008))

Hybrid Charmonium

(PLB628, 215 (2005), PRD78, 094504 (2008))

II. The Original Era of Discovery



<u>Theoretical Ideas on J/ψ and ψ′:</u>

Baryon-AntiBaryon bound states
(PRL34, 36 (1975))

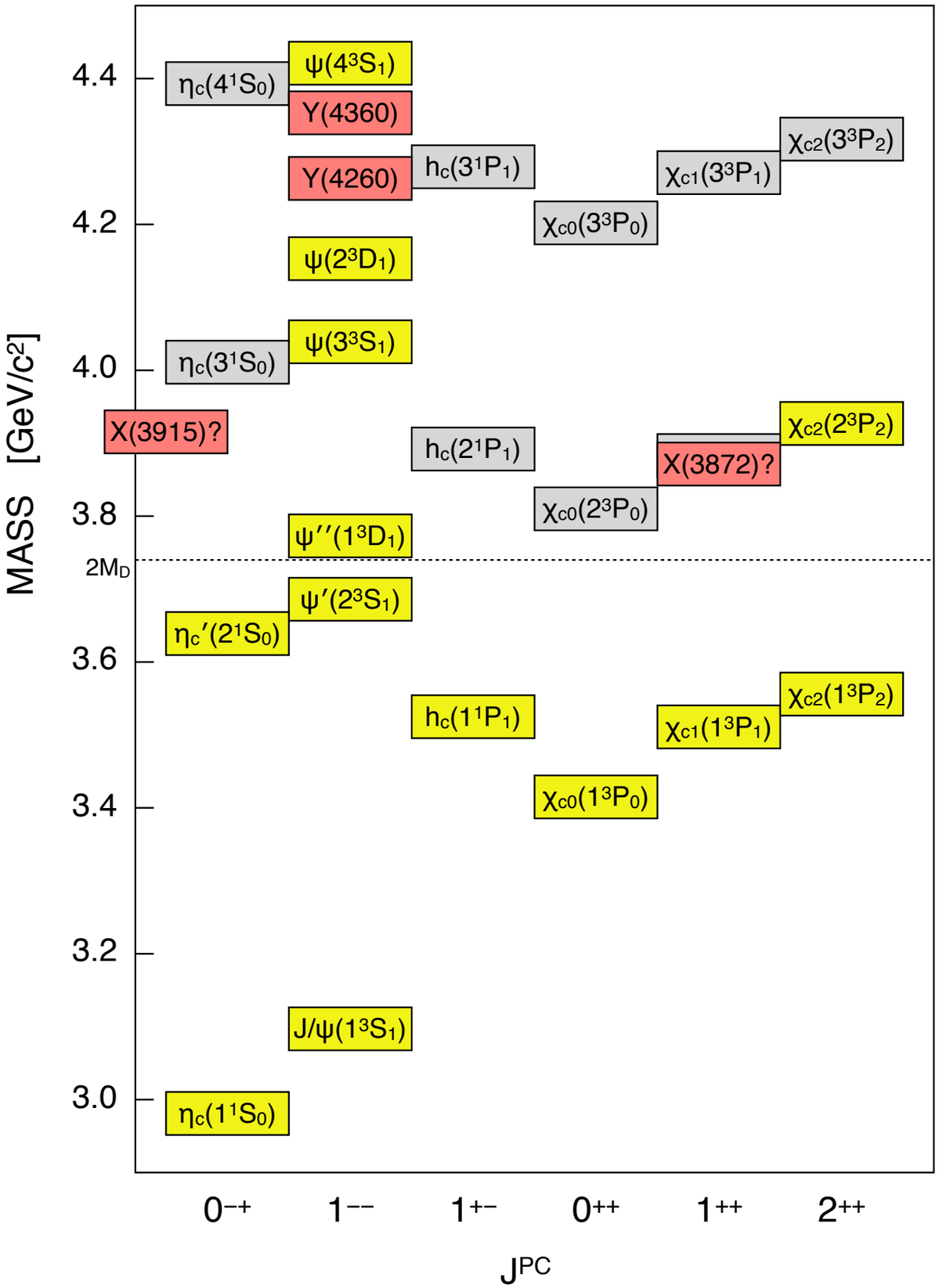
Spin-1 meson alternative to GIM
(PRL34, 37 (1975))

Three charm quarks (partners to u, d, s)
(PRL34, 41 (1975))

Lighter Z_0
(PRL34, 56 (1975))

Charmonium
(PRL34, 43 (1975), PRL34, 46 (1975))

IV. A New Era of Discovery



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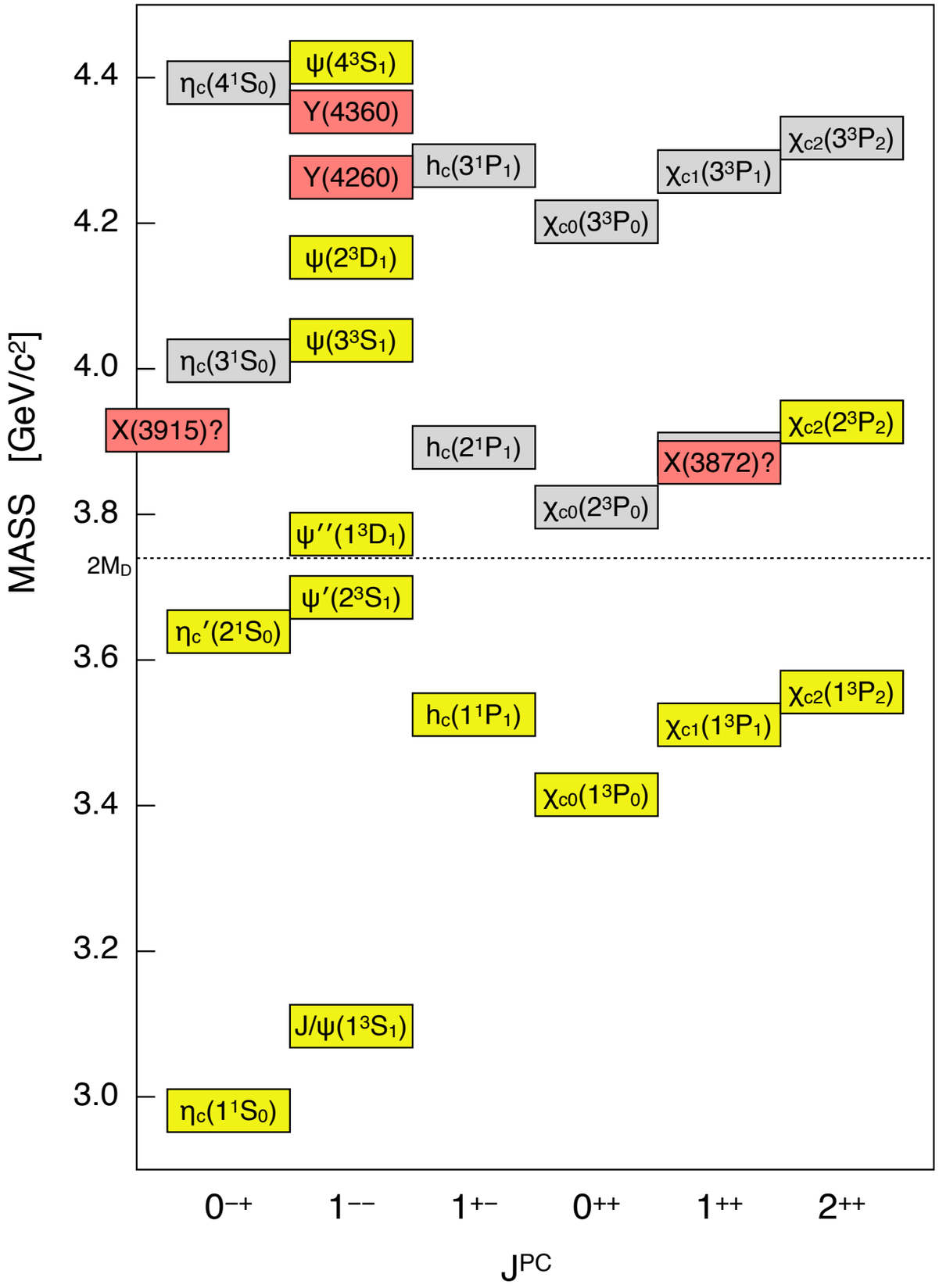
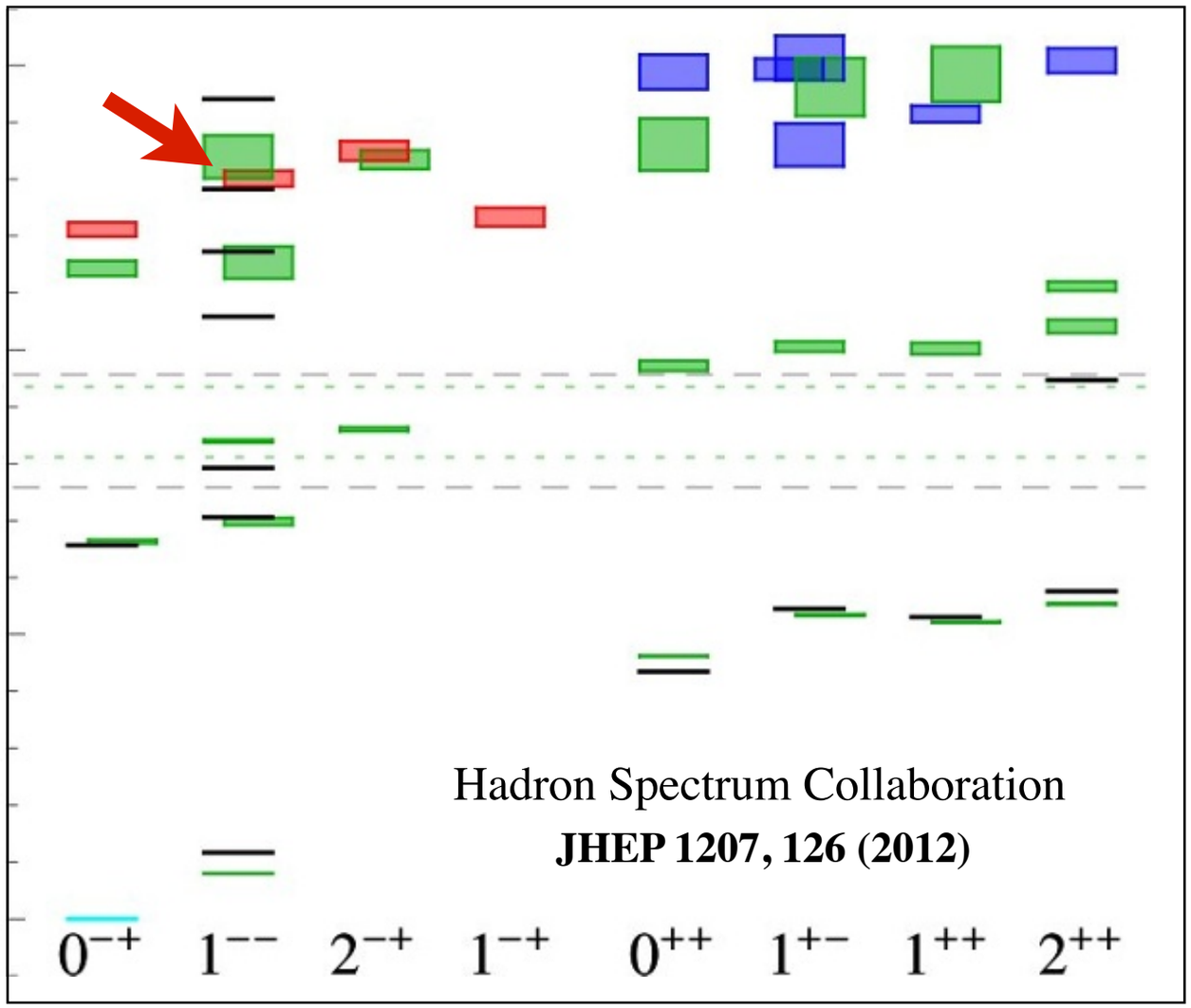
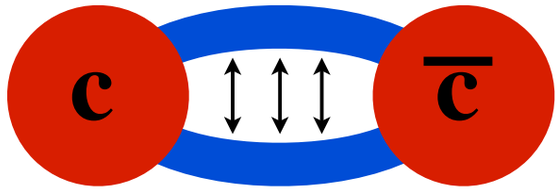


A more fundamental approach,

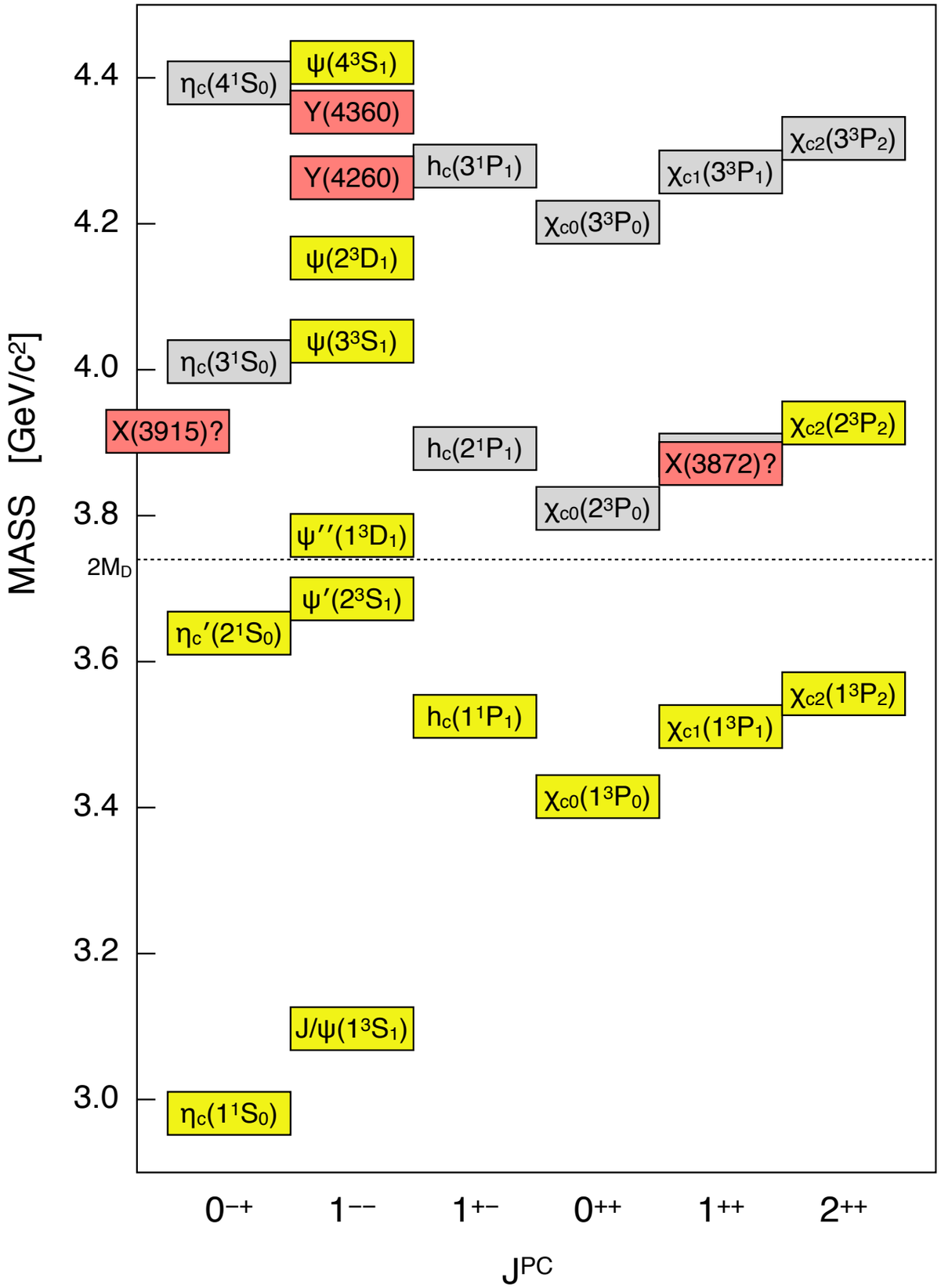
Lattice QCD:





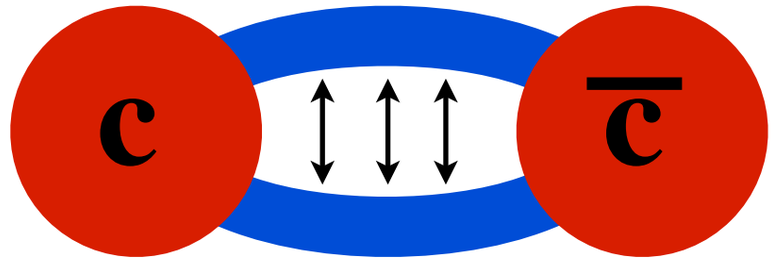
HYBRID CHARMONIUM**?**

IV. A New Era of Discovery



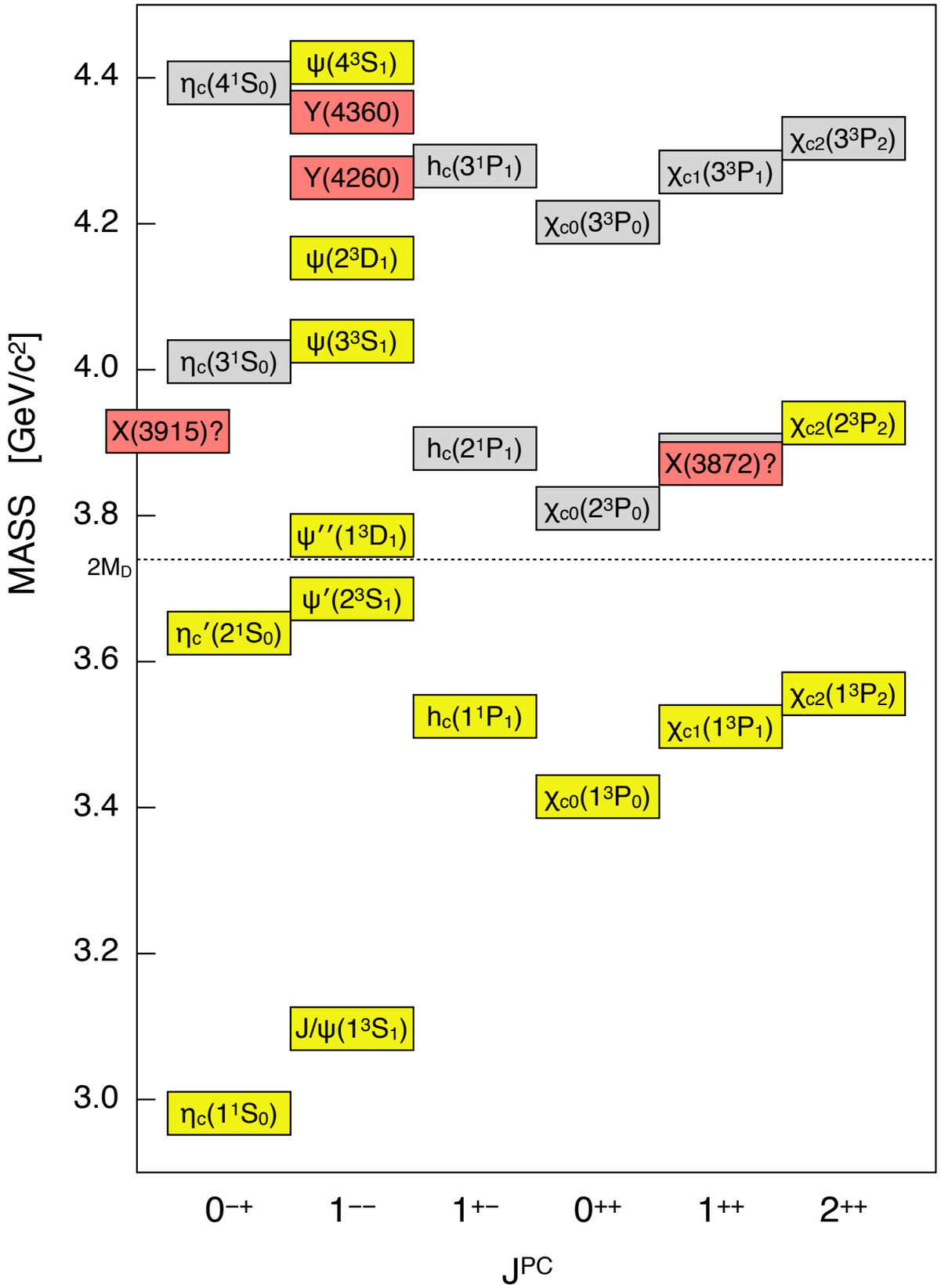
Find more decays of the Y(4260) and Y(4360).

Can we show S = 0?



HYBRID CHARMONIUM

IV. A New Era of Discovery



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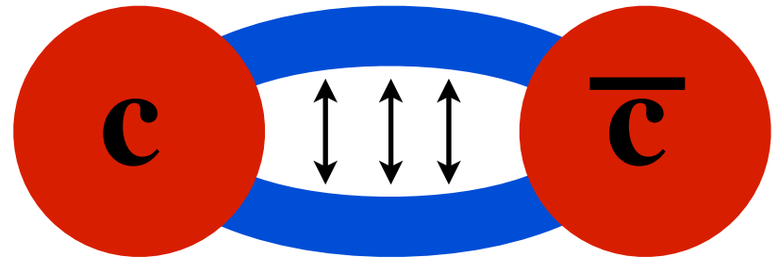
even L (since $P = (-1)^{L+1}$) and

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

So $\mathbf{J^{PC} = 1^{--}}$ and **S = 0**

⇒ a non-quark model state



HYBRID CHARMONIUM

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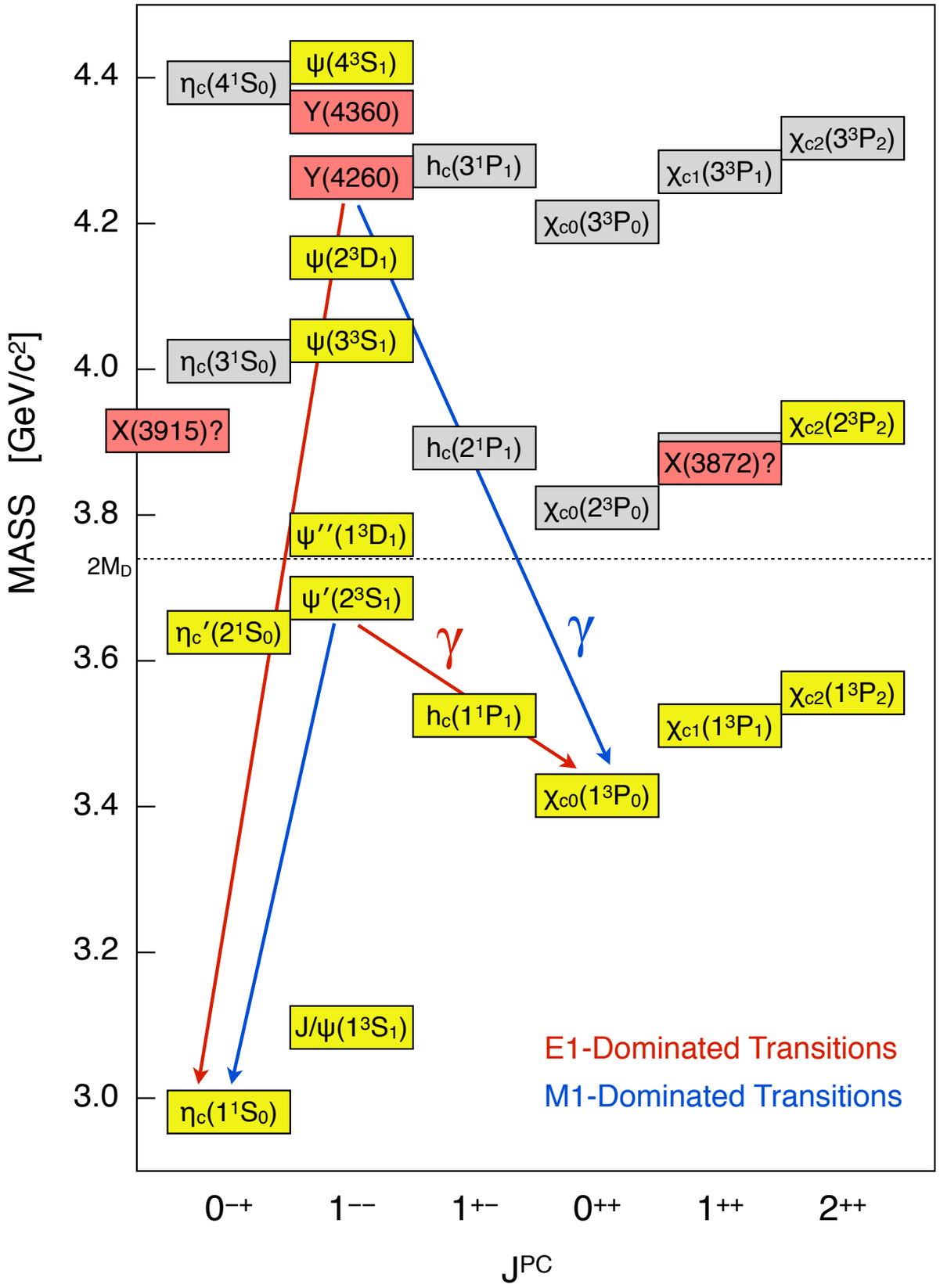

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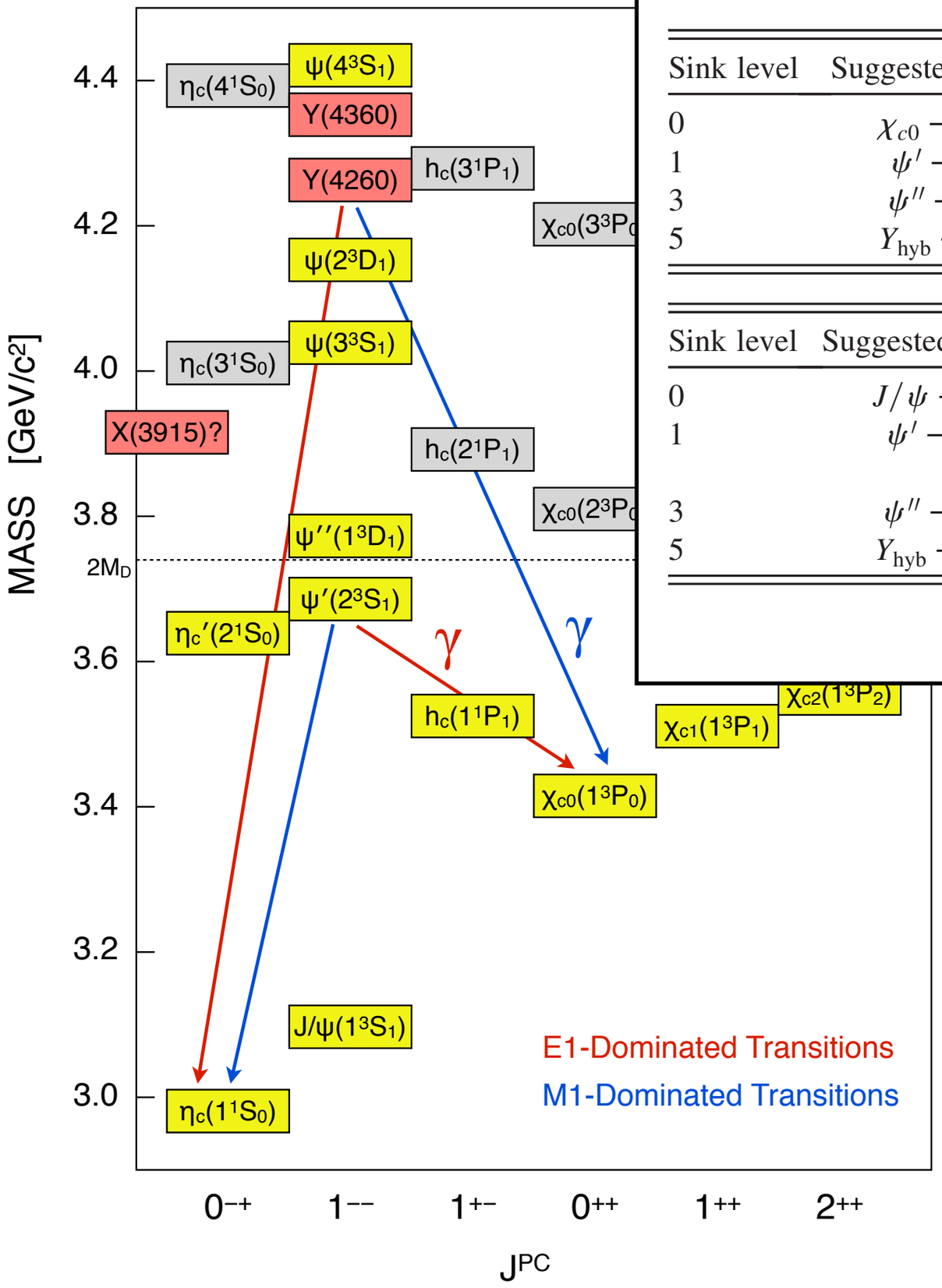
If S = 0,

$$\mathbf{B(Y \to \gamma\eta_c) > B(Y \to \gamma\chi_{c0})}$$

IV. A New Era of Discovery



Lattice QCD Calculations

Sink level	Suggested transition	$a_t\hat{E}_1(0)$	β/MeV	λ/GeV^{-2}	Γ_{lat}/keV	Γ_{expt}/keV
0	$\chi_{c0} \to J/\psi\gamma$	0.127(2)	409(12)	1.14(5)	199(6)	131(14)
1	$\psi' \to \chi_{c0}\gamma$	0.092(19)	164(55)	0 (fixed)	26(11)	30(2)
3	$\psi'' \to \chi_{c0}\gamma$	0.265(33)	324(77)	0.58(56)	265(66)	199(26)
5	$Y_{\text{hyb}} \to \chi_{c0}\gamma$	0.00(3)	Linear	Fit	$\lesssim 20$	···

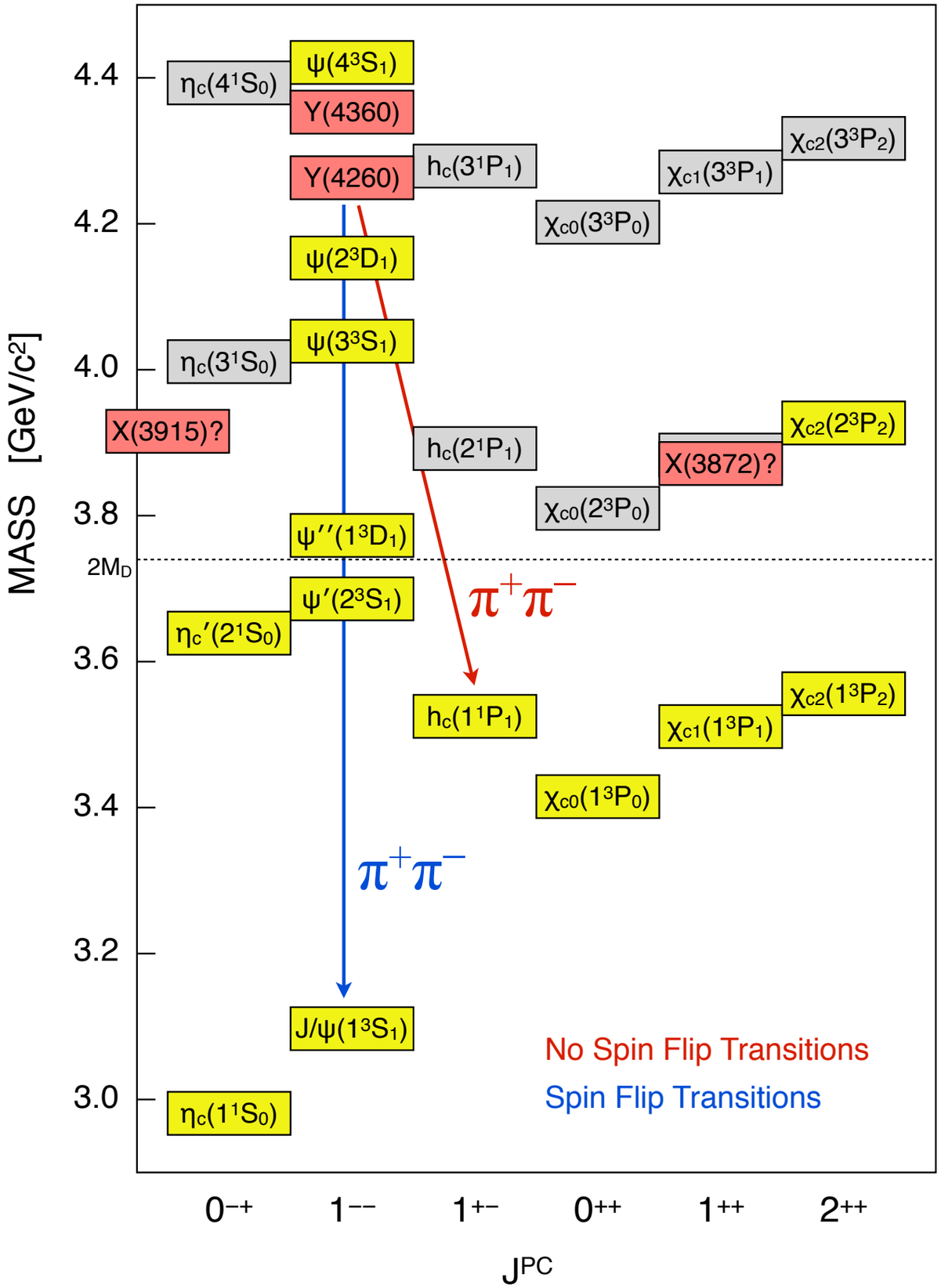
Sink level	Suggested transition	$\hat{V}(0)$	β/MeV	λ/GeV^{-2}	Γ_{lat}/keV	Γ_{expt}/keV
0	$J/\psi \to \eta_c\gamma$	1.89(3)	513(7)	0 (fixed)	2.51(8)	1.85(29)
1	$\psi' \to \eta_c\gamma$	0.062(64)	530(110)	4(6)	0.4(8)	0.95(16)
						1.37(20)
3	$\psi'' \to \eta_c\gamma$	0.27(15)	367(55)	−1.25(30)	10(11)	···
5	$Y_{\text{hyb}} \to \eta_c\gamma$	0.28(6)	250(200)	0 (fixed)	42(18)	···

PRD 79, 094504 (2009)

If S = 0,

$B(Y \to \gamma\eta_c) > B(Y \to \gamma\chi_{c0})$

IV. A New Era of Discovery



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⇒ a non-quark model state

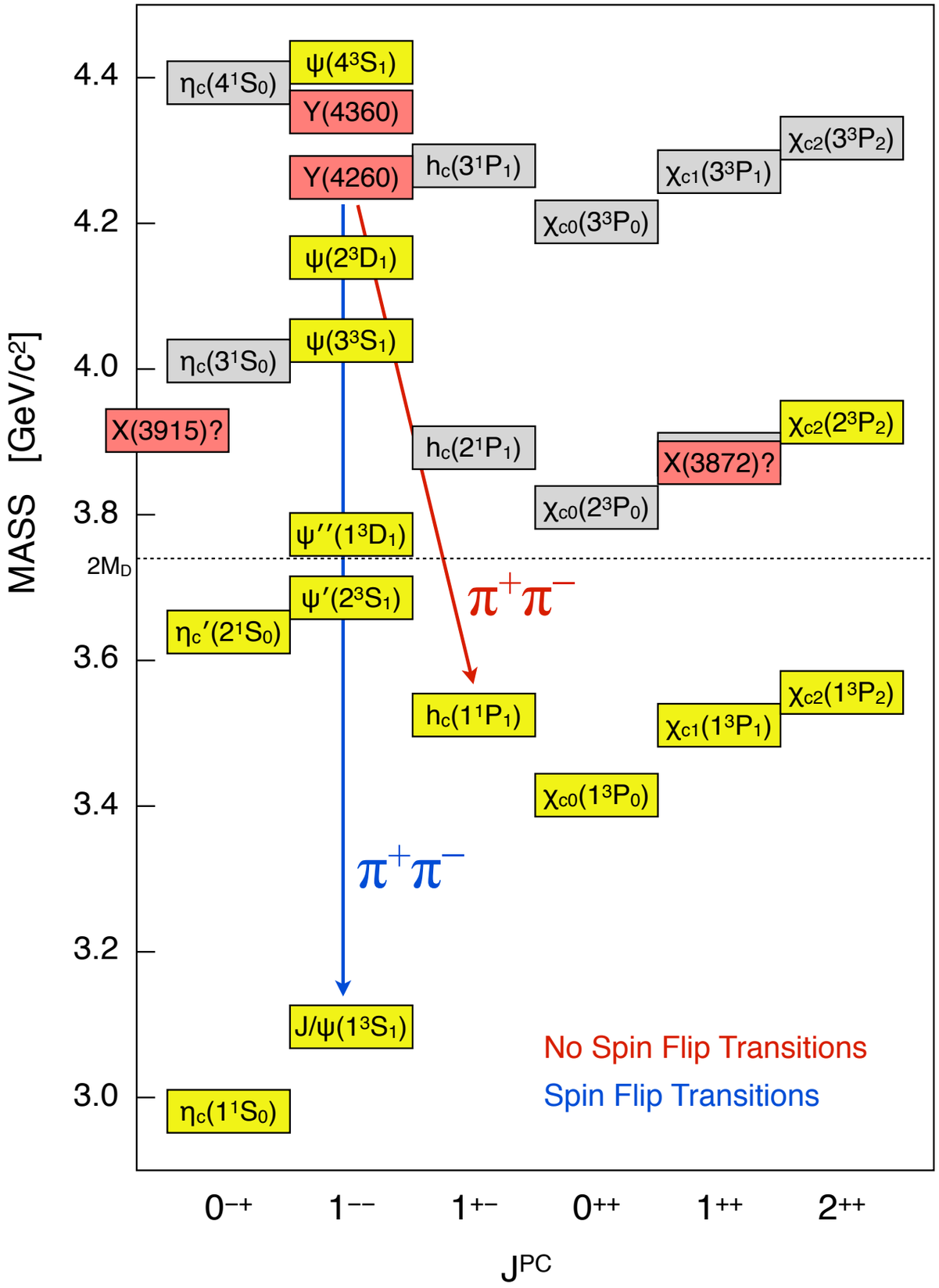
If S = 0,

$B(Y \to \gamma\eta_c) > B(Y \to \gamma\chi_{c0})$

If S = 0,

$\mathbf{B(Y \to \pi^+\pi^- h_c) \approx B(Y \to \pi^+\pi^- J/\psi)?}$

IV. A New Era of Discovery



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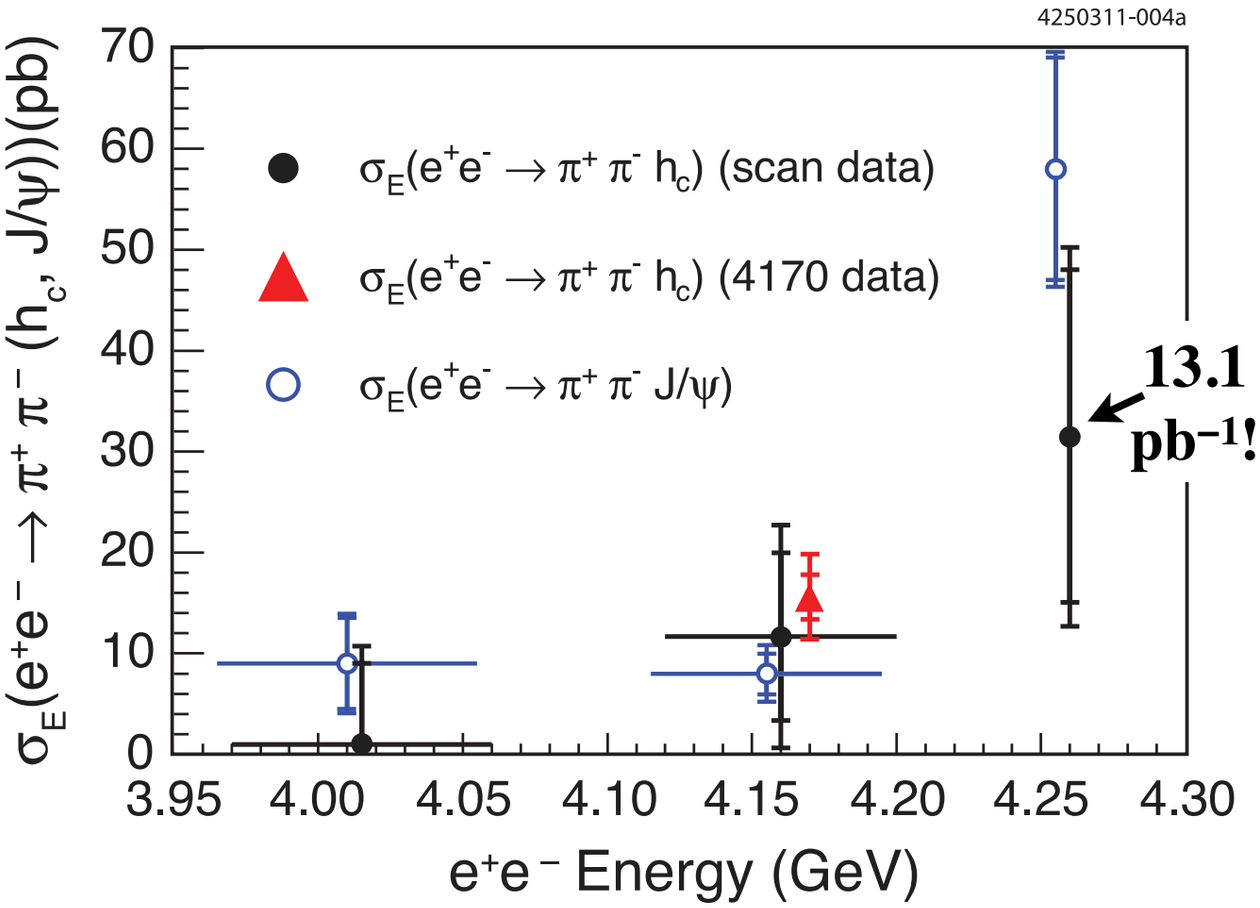
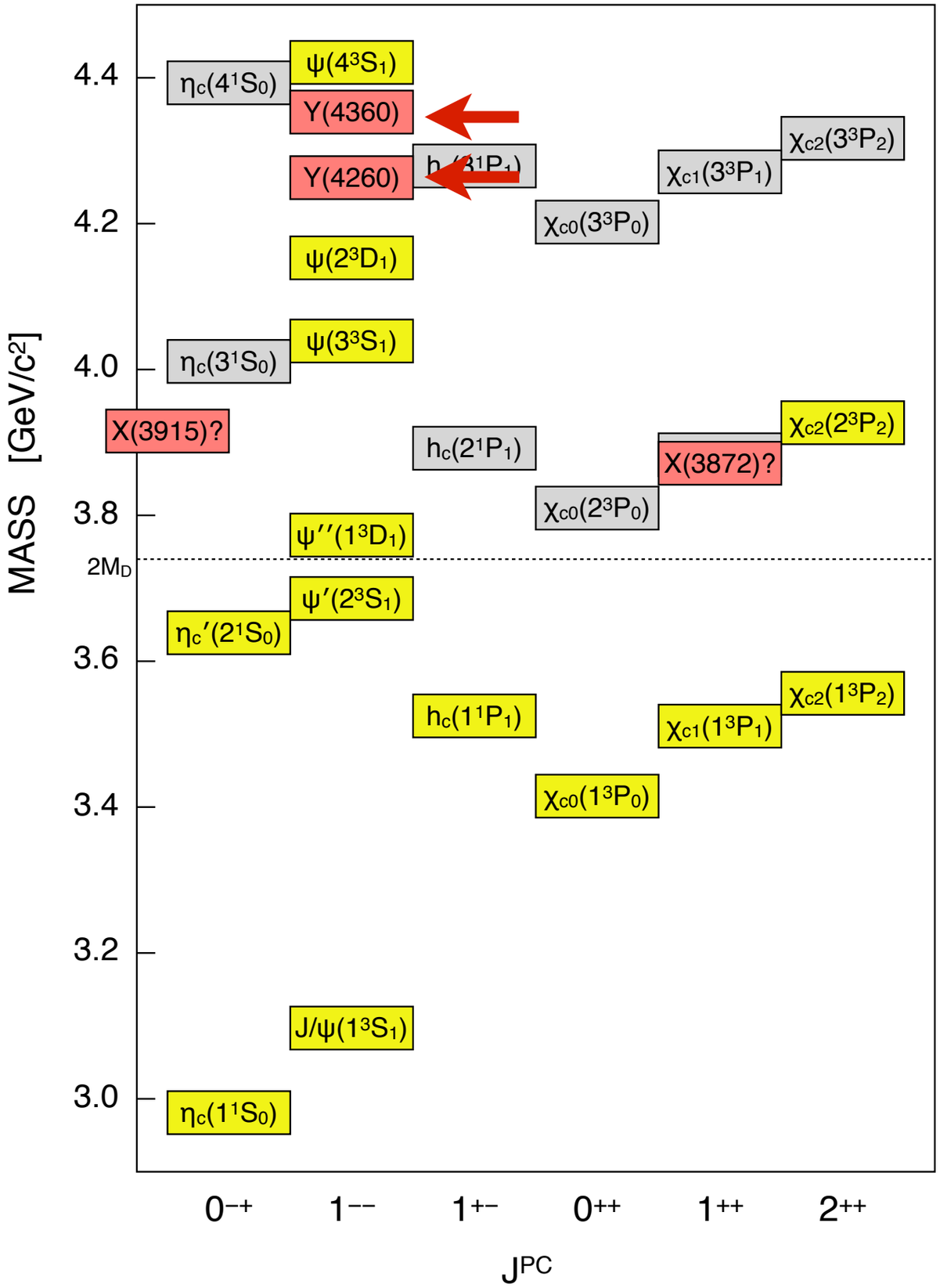
$e^+e^- \to \pi^+\pi^-(h_c, J/\psi)$ at CLEO-c



PRL 107, 041803 (2011)

IV. A New Era of Discovery



Data-taking plan at BESIII:

collect ≥ 500 pb^{-1} at 4260 MeV

collect ≥ 500 pb^{-1} at 4360 MeV

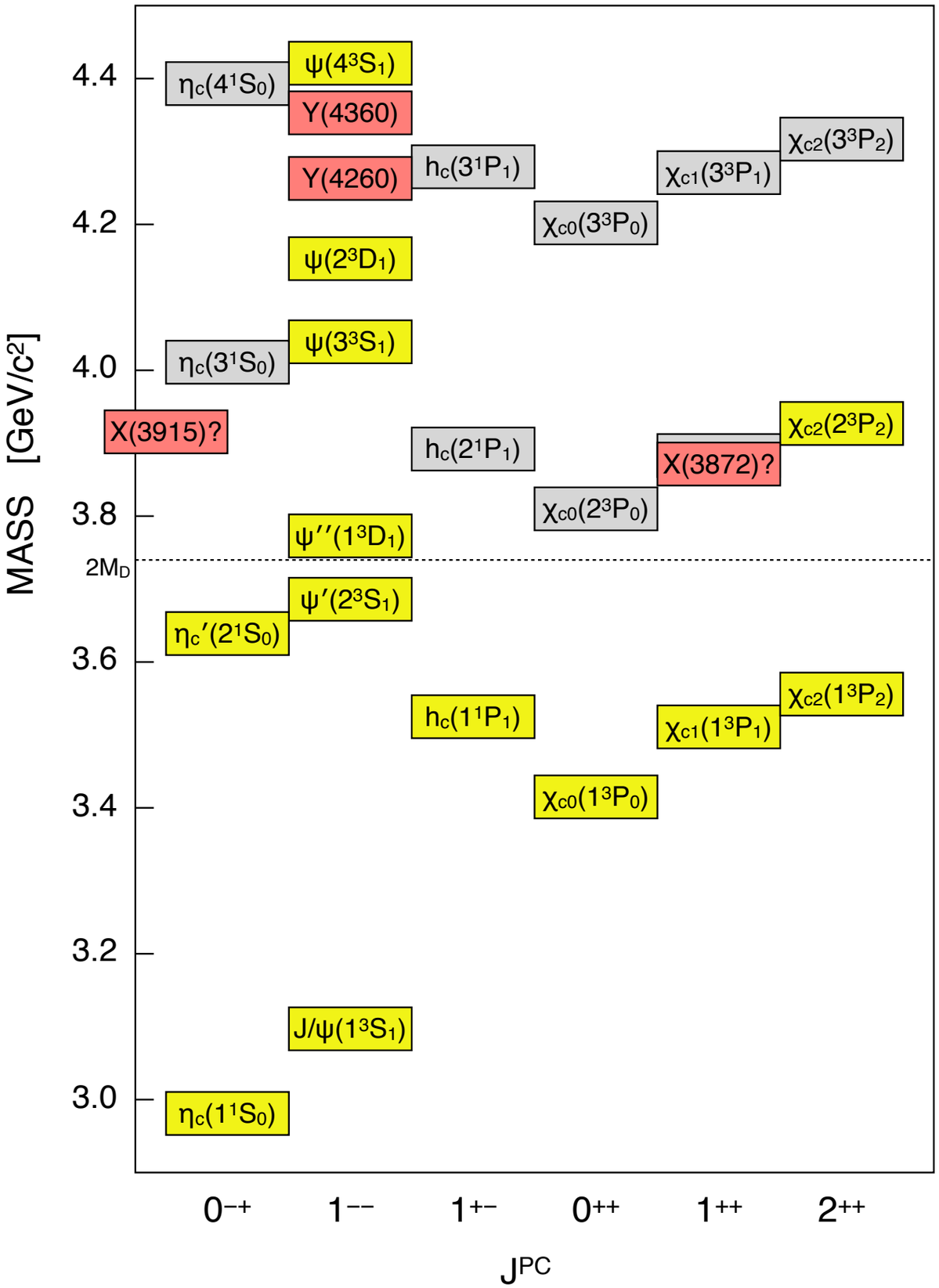
to study Y(4260) and Y(4360) decays.

Run "on-resonance" to maximize statistics.

Use two points to study energy-dependence.

Data-taking is beginning NOW!

IV. A New Era of Discovery



A few key analyses:

1. Measurement of
   $B(Y(4260) \to \gamma\chi_{c0})/B(Y(4260) \to \gamma\eta_c)$
   to test lattice QCD
   to test $S = 0$ vs. $S = 1$

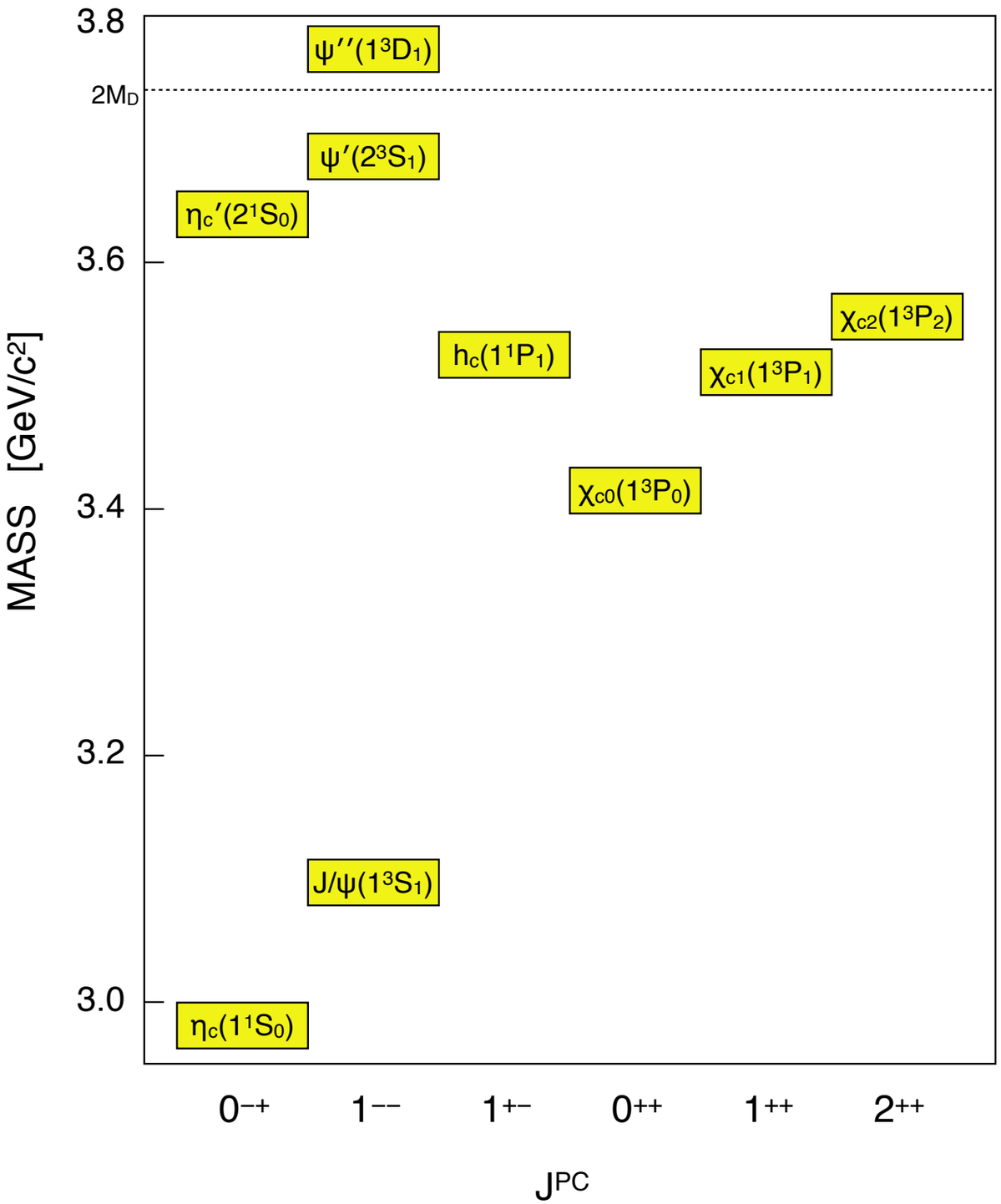
2. Measurement of
   $B(Y(4260) \to \pi^+\pi^- h_c(1P))/B(Y(4260) \to \pi^+\pi^- J/\psi)$
   to help determine the quark spin-alignment of the Y(4260)

3. Dalitz analyses of $Y(4260) \to \pi^+\pi^- J/\psi$ and $Y(4360) \to \pi^+\pi^- \psi(2S)$
   to look for charged Z_c states

4. Measurement of
   $B(Y(4360) \to \pi^+\pi^- h_c(2P))/B(Y(4360) \to \pi^+\pi^- \psi(2S))$?
   to discover the $h_c(2P)$?
   to test $S = 0$ vs. $S = 1$

(and searches for any other decay modes)

Summary

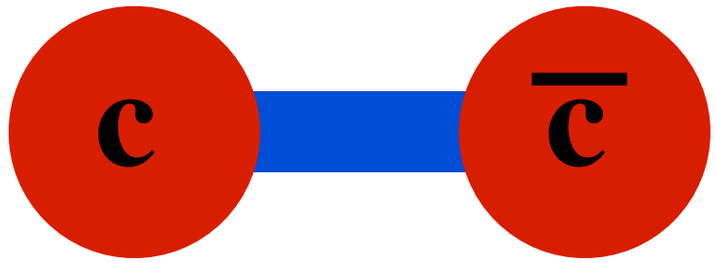


I. An Introduction to Charmonium

II. The Original Era of Discovery:
establishing the quark model states

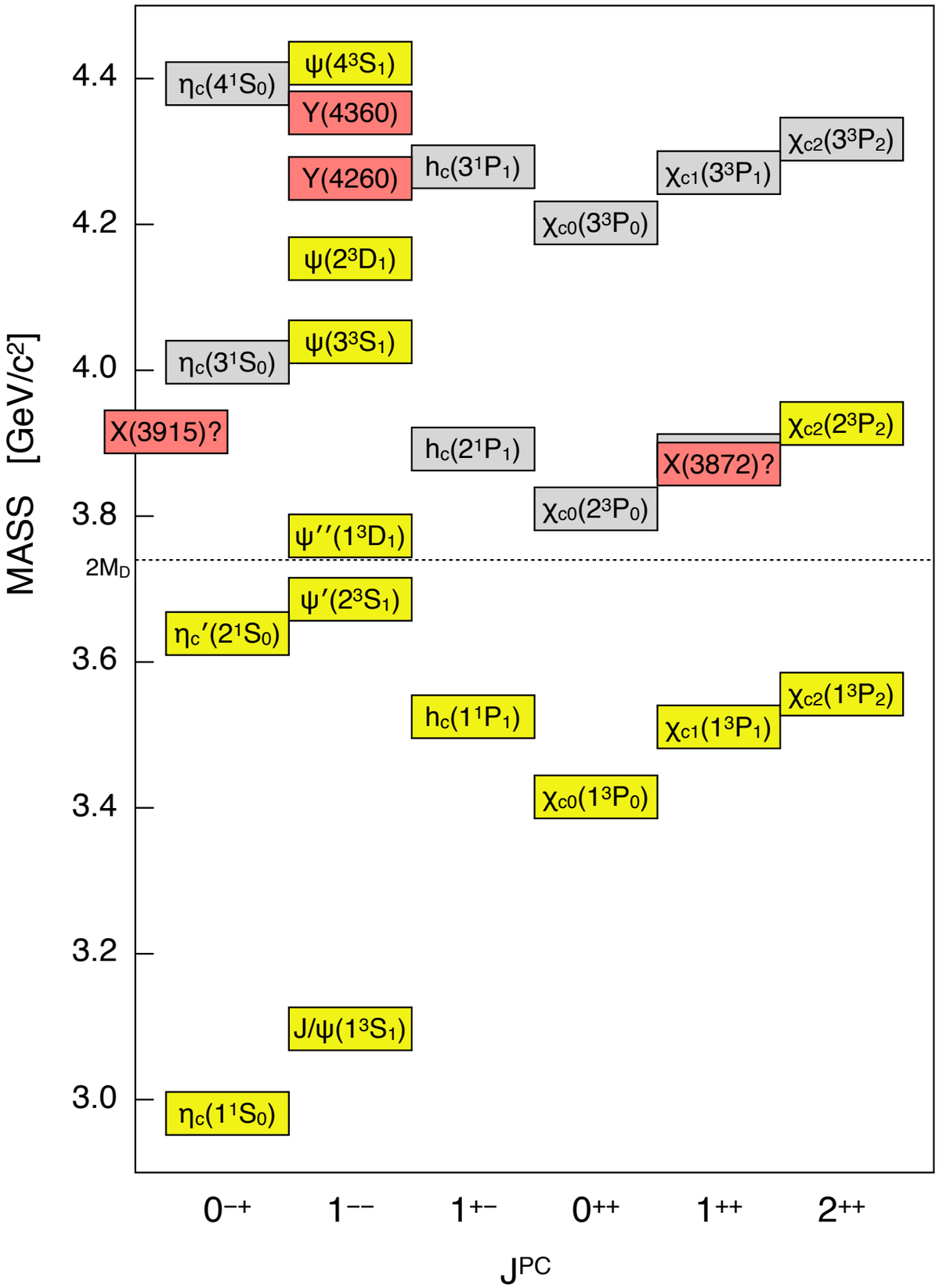
III. From Discovery to Precision:
the quark model states at BESIII

IV. A New Era of Discovery:
beyond the quark model and the role of BESIII



CHARMONIUM

Summary



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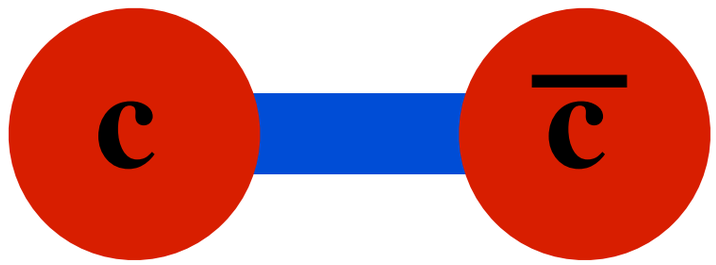

CHARMONIUM