

# Exploring Charmonium with the BESIII Experiment

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Beijing, China

**BESIII** (Beijing Spectrometer)  
at **BEPCII** (Beijing Electron-Positron Collider)  
at **IHEP** (Institute for High Energy Physics)



# the BESIII Experiment



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# The BESIII Experiment



**BESIII** (Beijing Spectrometer)  
at **BEPCII** (Beijing Electron-Positron Collider)

1984



# The BESIII Experiment



2017



(Collider)  
(Physics)

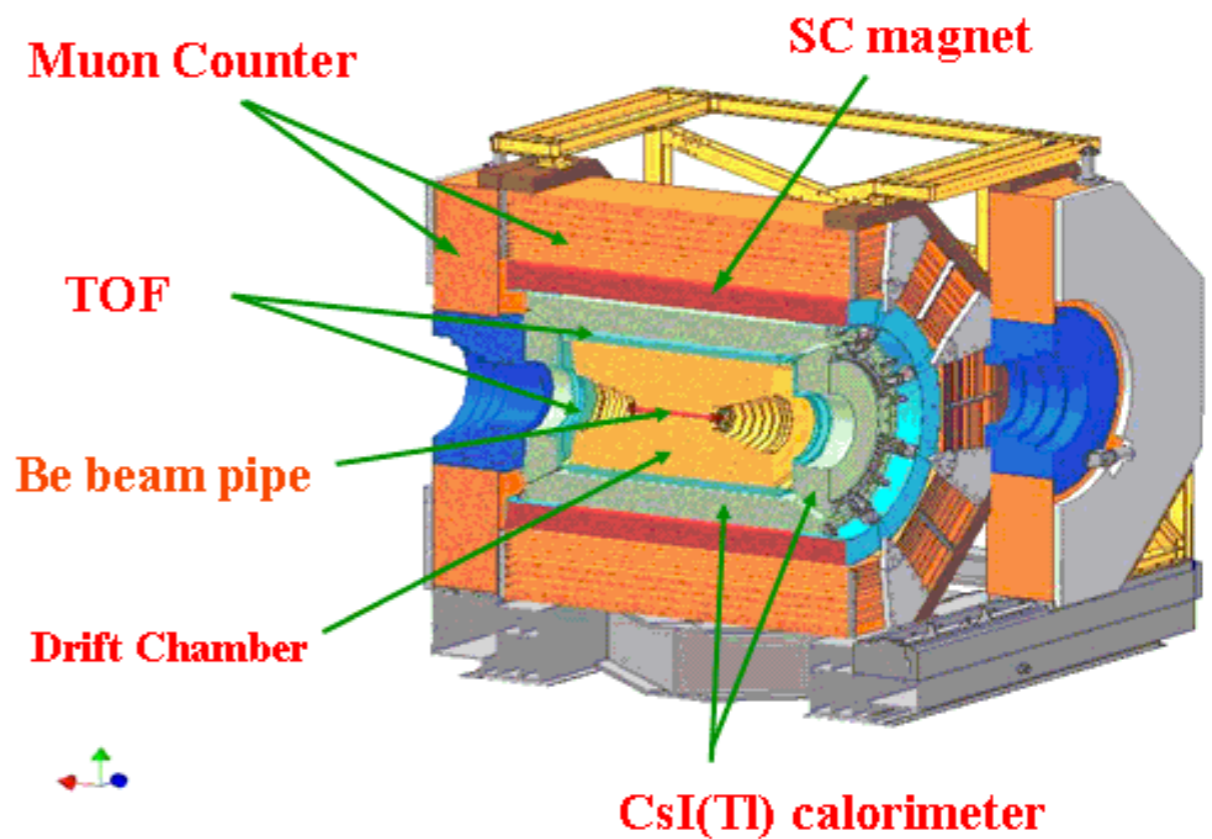


# the BESIII Experiment



## BESIII Detector (a standard high-energy physics experiment)

- (1) Calorimeter: photon energy and direction
- (2) Drift Chamber and Magnet: charged particle momentum
- (3) Time-of-Flight (TOF): charged particle mass

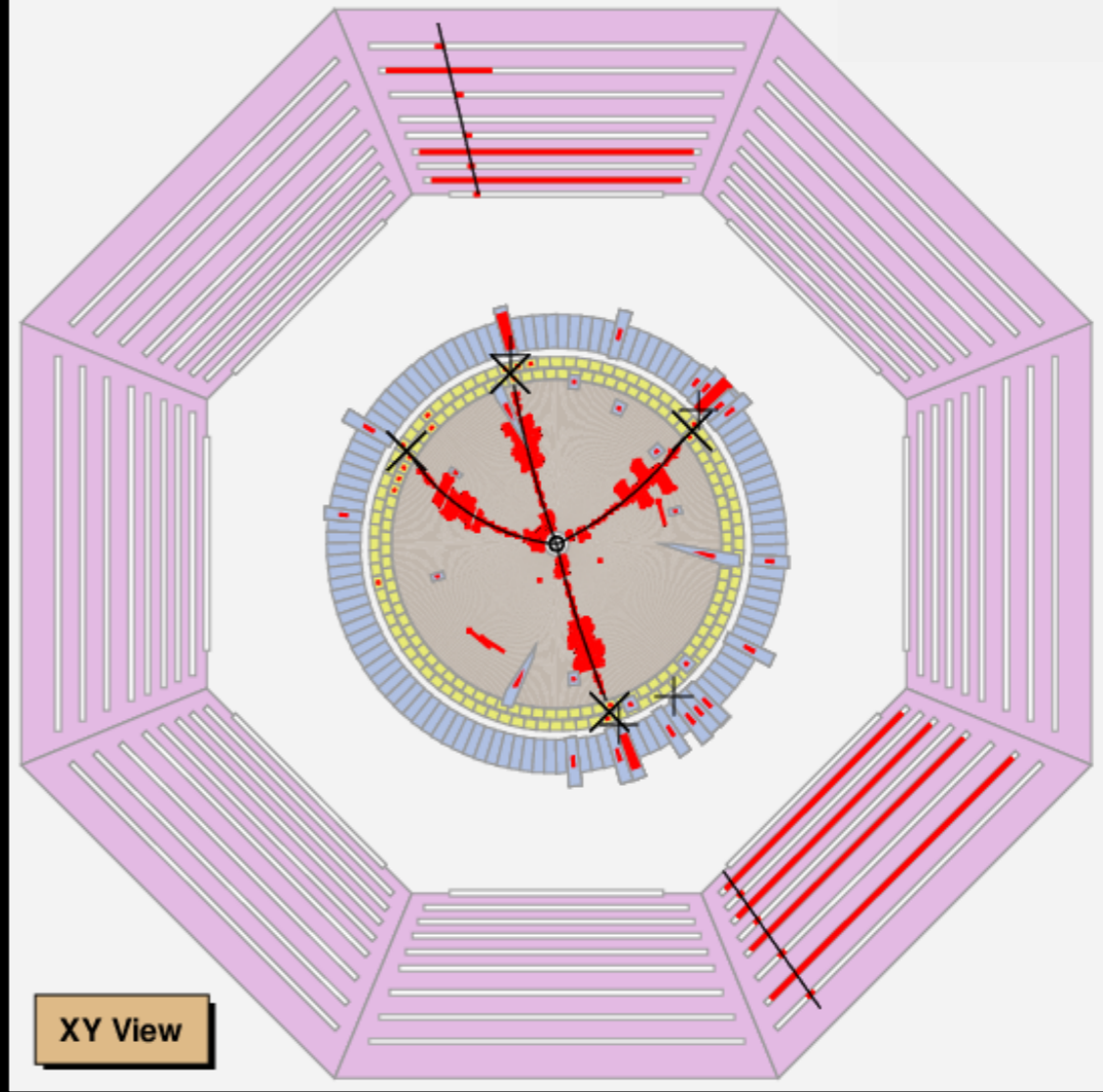


Collider)  
ysics)

# The BESIII Experiment



$$e^+e^- \rightarrow \pi^+\pi^- J/\psi; \quad J/\psi \rightarrow \mu^+\mu^-$$



(eter)  
(on Collider)  
(y Physics)



### Precise Measurement of the $e^+e^- \rightarrow \pi^+\pi^-J/\psi$ Cross Section at Center-of-Mass Energies from 3.77 to 4.60 GeV

M. Ablikim,<sup>1</sup> M. N. Achasov,<sup>9,e</sup> S. Ahmed,<sup>14</sup> X. C. Ai,<sup>1</sup> O. Albayrak,<sup>5</sup> M. Albrecht,<sup>4</sup> D. J. Ambrose,<sup>44</sup>  
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 J. V. Bennett,<sup>5</sup> N. Berger,<sup>22</sup> M. Bertani,<sup>20</sup> D. Bettoni,<sup>21</sup> J. M. Bian,<sup>43</sup> F. Bianchi,<sup>49a,49c</sup> E. Boger,<sup>23,c</sup> I. Bozko,<sup>23</sup>  
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 G. Chelkov,<sup>23,c,d</sup> G. Chen,<sup>1</sup> H. S. Chen,<sup>1</sup> J. C. Chen,<sup>1</sup> M. L. Chen,<sup>1,a</sup> S. Chen,<sup>41</sup> S. J. Chen,<sup>29</sup> X. Chen,<sup>1,a</sup>  
 X. R. Chen,<sup>26</sup> Y. B. Chen,<sup>1,a</sup> X. K. Chu,<sup>31</sup> G. Cibinetto,<sup>21</sup> H. L. Dai,<sup>1,a</sup> J. P. Dai,<sup>34</sup> A. Dbeyssi,<sup>14</sup> D. Dedovich,<sup>23</sup>  
 Z. Y. Deng,<sup>1</sup> A. Denig,<sup>22</sup> I. Denysenko,<sup>23</sup> M. Destefanis,<sup>49a,49c</sup> F. De Mori,<sup>49a,49c</sup> Y. Ding,<sup>27</sup> C. Dong,<sup>30</sup> J. Dong,<sup>1,a</sup>  
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 Y. Fang,<sup>1</sup> R. Farinelli,<sup>21a,21b</sup> L. Fava,<sup>49b,49c</sup> F. Feldbauer,<sup>22</sup> G. Felici,<sup>20</sup> C. Q. Feng,<sup>46,a</sup> E. Fioravanti,<sup>21</sup> M. Fritsch,<sup>14,22</sup>  
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 W. Gradl,<sup>22</sup> M. Greco,<sup>49a,49c</sup> M. H. Gu,<sup>1,a</sup> Y. T. Gu,<sup>12</sup> Y. H. Guan,<sup>1</sup> A. Q. Guo,<sup>1</sup> L. B. Guo,<sup>28</sup> R. P. Guo,<sup>1</sup> Y. Guo,<sup>1</sup>  
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 J. S. Huang,<sup>15</sup> X. T. Huang,<sup>33</sup> X. Z. Huang,<sup>29</sup> Z. L. Huang,<sup>27</sup> T. Hussain,<sup>48</sup> W. Ikegami Andersson,<sup>50</sup> Q. Ji,<sup>1</sup> Q. P. Ji,<sup>15</sup>  
 X. B. Ji,<sup>1</sup> X. L. Ji,<sup>1,a</sup> L. W. Jiang,<sup>51</sup> X. S. Jiang,<sup>1,a</sup> X. Y. Jiang,<sup>30</sup> J. B. Jiao,<sup>33</sup> Z. Jiao,<sup>17</sup> D. P. Jin,<sup>1,a</sup> S. Jin,<sup>1</sup>  
 T. Johansson,<sup>50</sup> A. Julin,<sup>43</sup> N. Kalantar-Nayestanaki,<sup>25</sup> X. L. Kang,<sup>1</sup> X. S. Kang,<sup>30</sup> M. Kavatsyuk,<sup>25</sup> B. C. Ke,<sup>5</sup>  
 P. Kiese,<sup>10</sup> R. Kliemt,<sup>10</sup> B. Kloss,<sup>22</sup> O. B. Kolcu,<sup>40b,h</sup> B. Kopf,<sup>4</sup> M. Kornicer,<sup>42</sup> A. Kupsc,<sup>50</sup> W. Kühn,<sup>24</sup> J. S. Lange,<sup>24</sup>  
 M. Lara,<sup>19</sup> P. Larin,<sup>14</sup> L. Lavezzi,<sup>49c,1</sup> H. Leithoff,<sup>22</sup> C. Leng,<sup>49</sup> C. Li,<sup>50</sup> Cheng Li,<sup>46,a</sup> D. M. Li,<sup>53</sup> F. Li,<sup>1,a</sup> F. Y. Li,<sup>31</sup>  
 G. Li,<sup>1</sup> H. B. Li,<sup>1</sup> H. J. Li,<sup>1</sup> J. C. Li,<sup>1</sup> Jin Li,<sup>32</sup> K. Li,<sup>13</sup> K. Li,<sup>33</sup> Lei Li,<sup>3</sup> P. R. Li,<sup>7,41</sup> Q. Y. Li,<sup>33</sup> T. Li,<sup>33</sup> W. D. Li,<sup>1</sup>  
 W. G. Li,<sup>1</sup> X. L. Li,<sup>33</sup> X. N. Li,<sup>1,a</sup> X. Q. Li,<sup>30</sup> Y. B. Li,<sup>2</sup> Z. B. Li,<sup>38</sup> H. Liang,<sup>46,a</sup> Y. F. Liang,<sup>36</sup> Y. T. Liang,<sup>24</sup>  
 G. R. Liao,<sup>11</sup> D. X. Lin,<sup>14</sup> B. Liu,<sup>34</sup> B. J. Liu,<sup>1</sup> C. X. Liu,<sup>1</sup> D. Liu,<sup>46,a</sup> F. H. Liu,<sup>35</sup> Fang Liu,<sup>1</sup> Feng Liu,<sup>6</sup> H. B. Liu,<sup>12</sup>  
 H. H. Liu,<sup>1</sup> H. H. Liu,<sup>16</sup> H. M. Liu,<sup>1</sup> J. Liu,<sup>1</sup> J. B. Liu,<sup>46,a</sup> J. P. Liu,<sup>51</sup> J. Y. Liu,<sup>1</sup> K. Liu,<sup>39</sup> K. Y. Liu,<sup>27</sup> L. D. Liu,<sup>31</sup>  
 P. L. Liu,<sup>1,a</sup> Q. Liu,<sup>41</sup> S. B. Liu,<sup>46,a</sup> X. Liu,<sup>26</sup> Y. B. Liu,<sup>30</sup> Y. Y. Liu,<sup>30</sup> Z. A. Liu,<sup>1,a</sup> Zhiqing Liu,<sup>22,\*</sup> H. Loehner,<sup>25</sup>  
 X. C. Lou,<sup>1,a,g</sup> H. J. Lu,<sup>17</sup> J. G. Lu,<sup>1,a</sup> Y. Lu,<sup>1</sup> Y. P. Lu,<sup>1,a</sup> C. L. Luo,<sup>28</sup> M. X. Luo,<sup>52</sup> T. Luo,<sup>42</sup> X. L. Luo,<sup>1,a</sup>  
 X. R. Lyu,<sup>41</sup> F. C. Ma,<sup>27</sup> H. L. Ma,<sup>1</sup> L. L. Ma,<sup>33</sup> M. M. Ma,<sup>1</sup> Q. M. Ma,<sup>1</sup> T. Ma,<sup>1</sup> X. N. Ma,<sup>30</sup> X. Y. Ma,<sup>1,a</sup>  
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 J. G. Messchendorp,<sup>25</sup> G. Mezzadri,<sup>21</sup> J. Min,<sup>1,a</sup> T. J. Min,<sup>1</sup> R. E. Mitchell,<sup>19</sup> X. H. Mo,<sup>1,a</sup> Y. J. Mo,<sup>6</sup>  
 C. Morales Morales,<sup>14</sup> N. Yu. Muchnoi,<sup>9,e</sup> H. Muramatsu,<sup>43</sup> P. Musich,<sup>4</sup> Y. Nefedov,<sup>23</sup> F. Nerling,<sup>10</sup> I. B. Nikolaev,<sup>9,c</sup>  
 Z. Ning,<sup>1,a</sup> S. Nisar,<sup>8</sup> S. L. Niu,<sup>1,a</sup> X. Y. Niu,<sup>1</sup> S. L. Olsen,<sup>32</sup> Q. Ouyang,<sup>1,a</sup> S. Pacetti,<sup>20</sup> Y. Pan,<sup>46,a</sup> P. Patteri,<sup>20</sup>  
 M. Pelizaeus,<sup>4</sup> H. P. Peng,<sup>46,a</sup> K. Peters,<sup>10,i</sup> J. Pettersson,<sup>50</sup> J. L. Ping,<sup>28</sup> R. G. Ping,<sup>1</sup> R. Poling,<sup>43</sup> V. Prasad,<sup>1</sup>  
 H. R. Qi,<sup>2</sup> M. Qi,<sup>29</sup> S. Qian,<sup>1,a</sup> C. F. Qiao,<sup>41</sup> L. Q. Qin,<sup>33</sup> N. Qin,<sup>51</sup> X. S. Qin,<sup>1</sup> Z. H. Qin,<sup>1,a</sup> J. F. Qiu,<sup>1</sup>  
 K. H. Rashid,<sup>48</sup> C. F. Redmer,<sup>22</sup> M. Ripka,<sup>22</sup> G. Rong,<sup>1</sup> Ch. Rosner,<sup>14</sup> X. D. Ruan,<sup>12</sup> A. Sarantsev,<sup>23,f</sup> M. Savrié,<sup>21</sup>  
 C. Schnier,<sup>4</sup> K. Schoenning,<sup>50</sup> W. Shan,<sup>31</sup> M. Shao,<sup>46,a</sup> C. P. Shen,<sup>2</sup> P. X. Shen,<sup>30</sup> X. Y. Shen,<sup>1</sup> H. Y. Sheng,<sup>1</sup>  
 W. M. Song,<sup>1</sup> X. Y. Song,<sup>1</sup> S. Sosio,<sup>49a,49c</sup> S. Spataro,<sup>49a,49c</sup> G. X. Sun,<sup>1</sup> J. F. Sun,<sup>15</sup> S. S. Sun,<sup>1</sup> X. H. Sun,<sup>1</sup>  
 Y. J. Sun,<sup>46,a</sup> Y. Z. Sun,<sup>1</sup> Z. J. Sun,<sup>1,a</sup> Z. T. Sun,<sup>19</sup> C. J. Tang,<sup>36</sup> X. Tang,<sup>1</sup> I. Tapan,<sup>40</sup> E. H. Thorndike,<sup>44</sup>  
 M. Tiemens,<sup>25</sup> I. Uman,<sup>40</sup> G. S. Varner,<sup>42</sup> P. Wang,<sup>40</sup> B. L. Wang,<sup>41</sup> D. Wang,<sup>31</sup> D. Y. Wang,<sup>31</sup> K. Wang,<sup>1,a</sup>  
 L. L. Wang,<sup>1</sup> L. S. Wang,<sup>1</sup> M. Wang,<sup>33</sup> P. Wang,<sup>1</sup> P. L. Wang,<sup>1</sup> W. Wang,<sup>1,a</sup> W. P. Wang,<sup>46,a</sup> X. F. Wang,<sup>39</sup> Y. Wang,<sup>37</sup>  
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 T. Weber,<sup>22</sup> D. H. Wei,<sup>11</sup> P. Weidenkaff,<sup>22</sup> S. P. Wen,<sup>1</sup> U. Wiedner,<sup>4</sup> M. Wolke,<sup>50</sup> L. H. Wu,<sup>1</sup> L. J. Wu,<sup>1</sup> Z. Wu,<sup>1,a</sup>  
 L. Xia,<sup>46,a</sup> L. G. Xia,<sup>39</sup> Y. Xia,<sup>18</sup> D. Xiao,<sup>1</sup> H. Xiao,<sup>47</sup> Z. J. Xiao,<sup>28</sup> Y. G. Xie,<sup>1,a</sup> Yuehong Xie,<sup>6</sup> Q. L. Xiu,<sup>1,a</sup>  
 G. F. Xu,<sup>1</sup> J. J. Xu,<sup>1</sup> L. Xu,<sup>1</sup> Q. J. Xu,<sup>13</sup> Q. N. Xu,<sup>41</sup> X. P. Xu,<sup>37</sup> L. Yan,<sup>49a,49c</sup> W. B. Yan,<sup>46,a</sup> W. C. Yan,<sup>46,a</sup>  
 Y. H. Yan,<sup>18</sup> H. J. Yang,<sup>34,j</sup> H. X. Yang,<sup>1</sup> L. Yang,<sup>51</sup> Y. X. Yang,<sup>11</sup> M. Ye,<sup>1,a</sup> M. H. Ye,<sup>7</sup> J. H. Yin,<sup>1</sup> Z. Y. You,<sup>38</sup>  
 B. X. Yu,<sup>1,a</sup> C. X. Yu,<sup>30</sup> J. S. Yu,<sup>26</sup> C. Z. Yuan,<sup>1</sup> Y. Yuan,<sup>1</sup> A. Yuncu,<sup>40b,b</sup> A. A. Zafar,<sup>48</sup> Y. Zeng,<sup>18</sup> Z. Zeng,<sup>46,a</sup>  
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 Z. P. Zhang,<sup>46</sup> Z. Y. Zhang,<sup>51</sup> G. Zhao,<sup>1</sup> J. W. Zhao,<sup>1,a</sup> J. Y. Zhao,<sup>1</sup> J. Z. Zhao,<sup>1,a</sup> Lei Zhao,<sup>46,a</sup> Ling Zhao,<sup>1</sup>

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Beijing Spectrometer)  
(Beijing Electron-Positron Collider)  
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Explori

Experiment

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Beijing Spectrometer)  
ing Electron-Positron Collider)  
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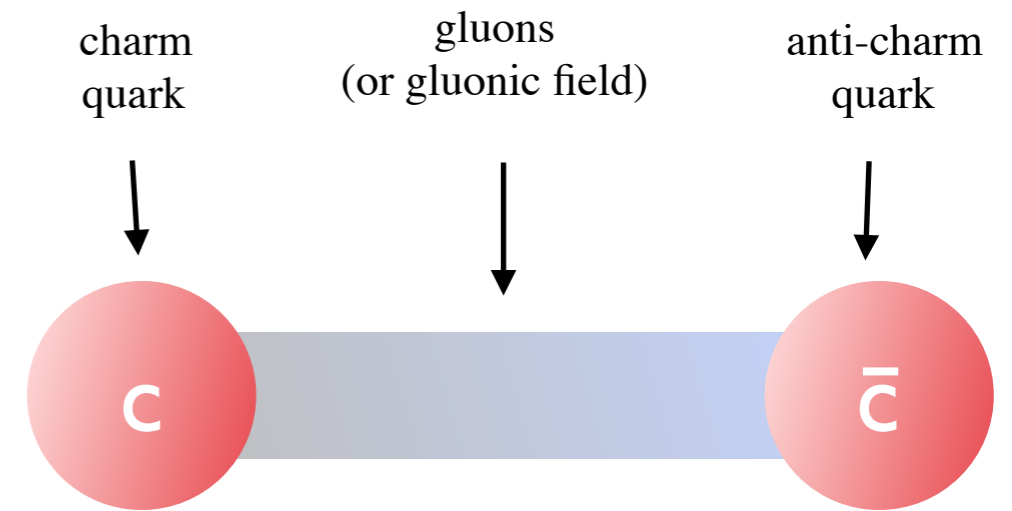


I. Charmonium

II. “Charmonium”

III. “Charmonium” at BESIII

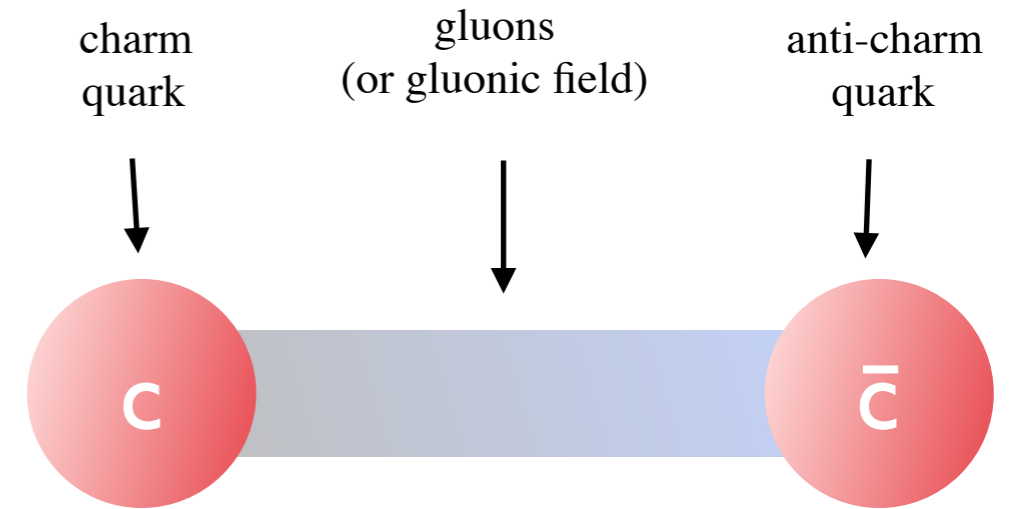
# I. Charmonium



# II. “Charmonium”

# III. “Charmonium” at BESIII

# I. Charmonium

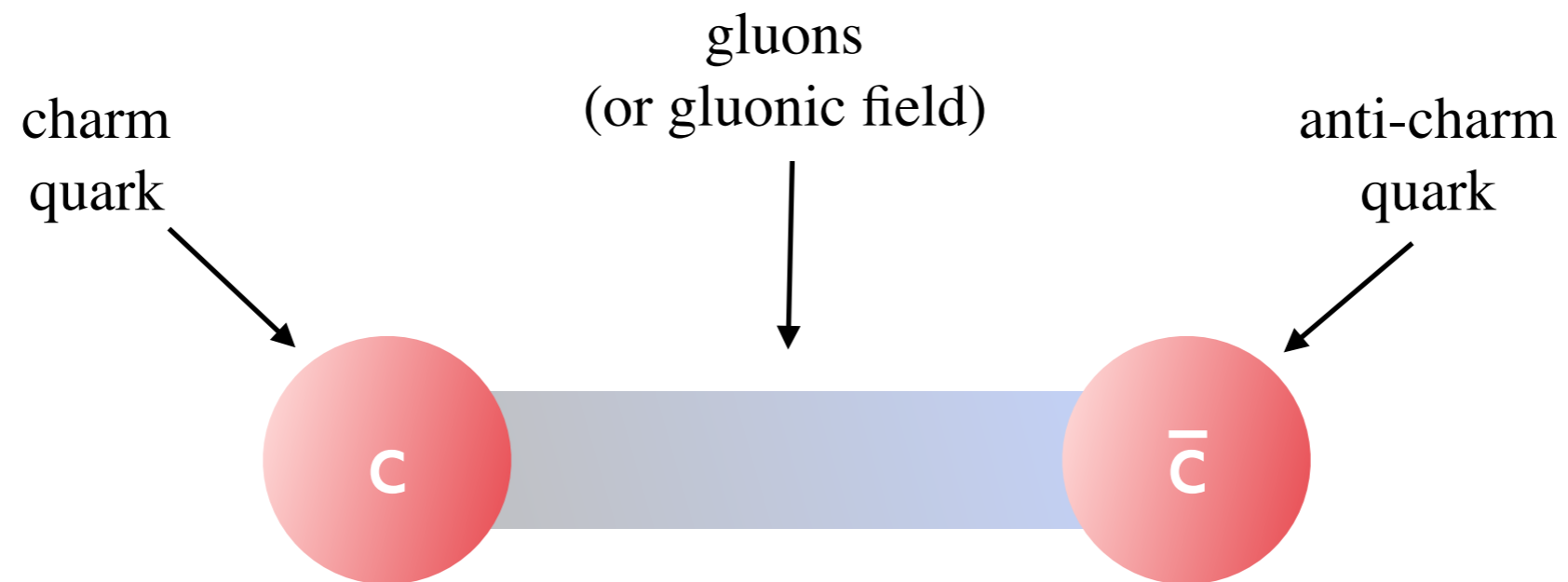


# II. “Charmonium”

# III. “Charmonium” at BESIII



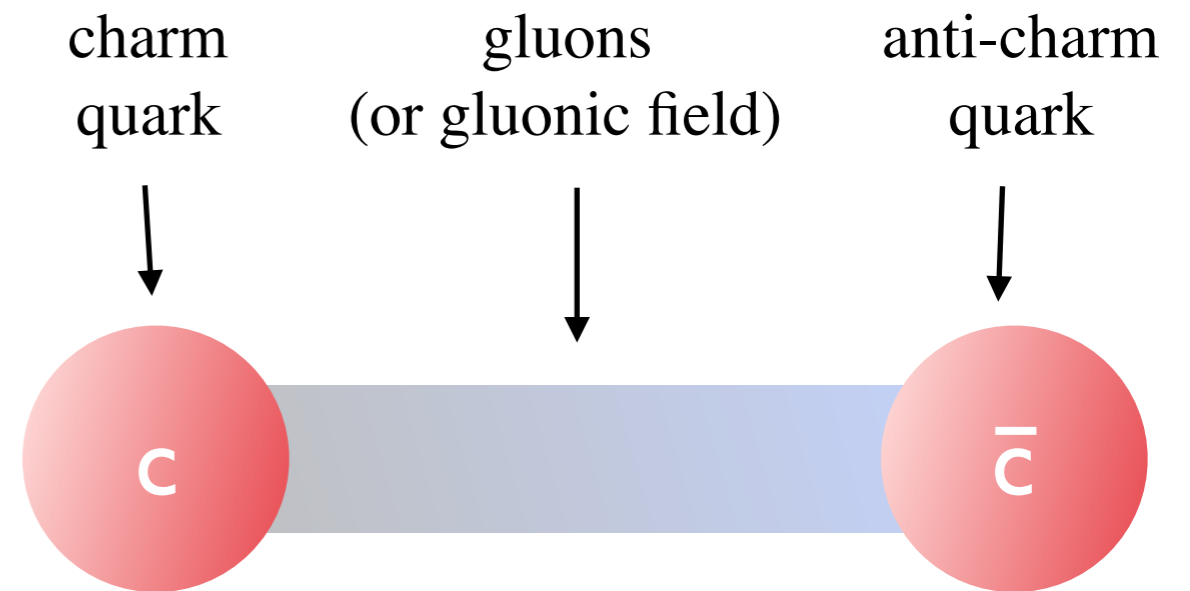
# I. Charmonium: the Hydrogen atom of the strong force



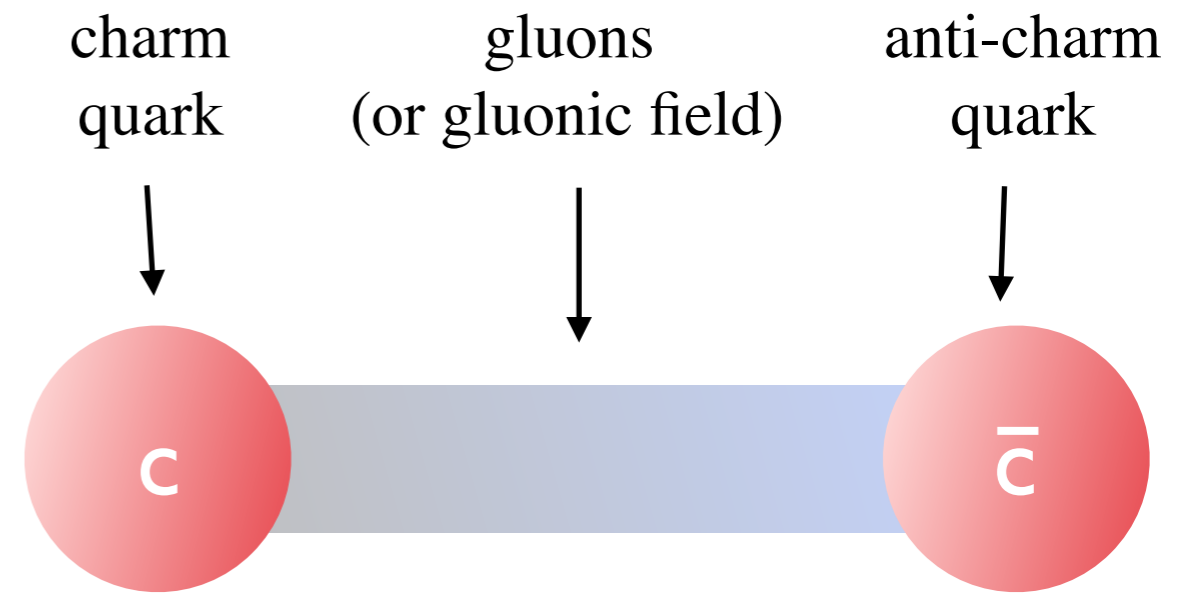
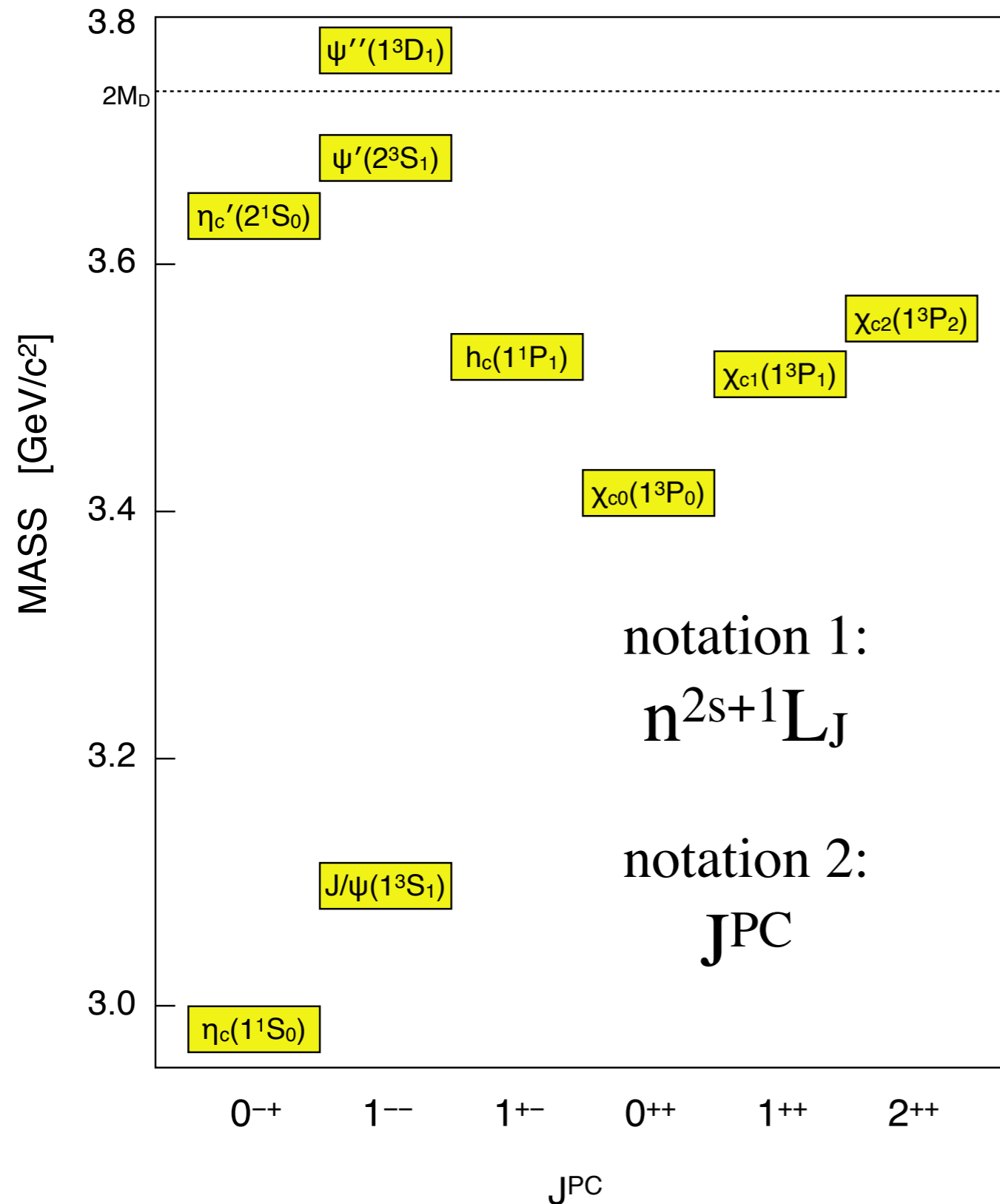
# I. Charmonium: the Hydrogen atom of the strong force

## Properties of the strong force:

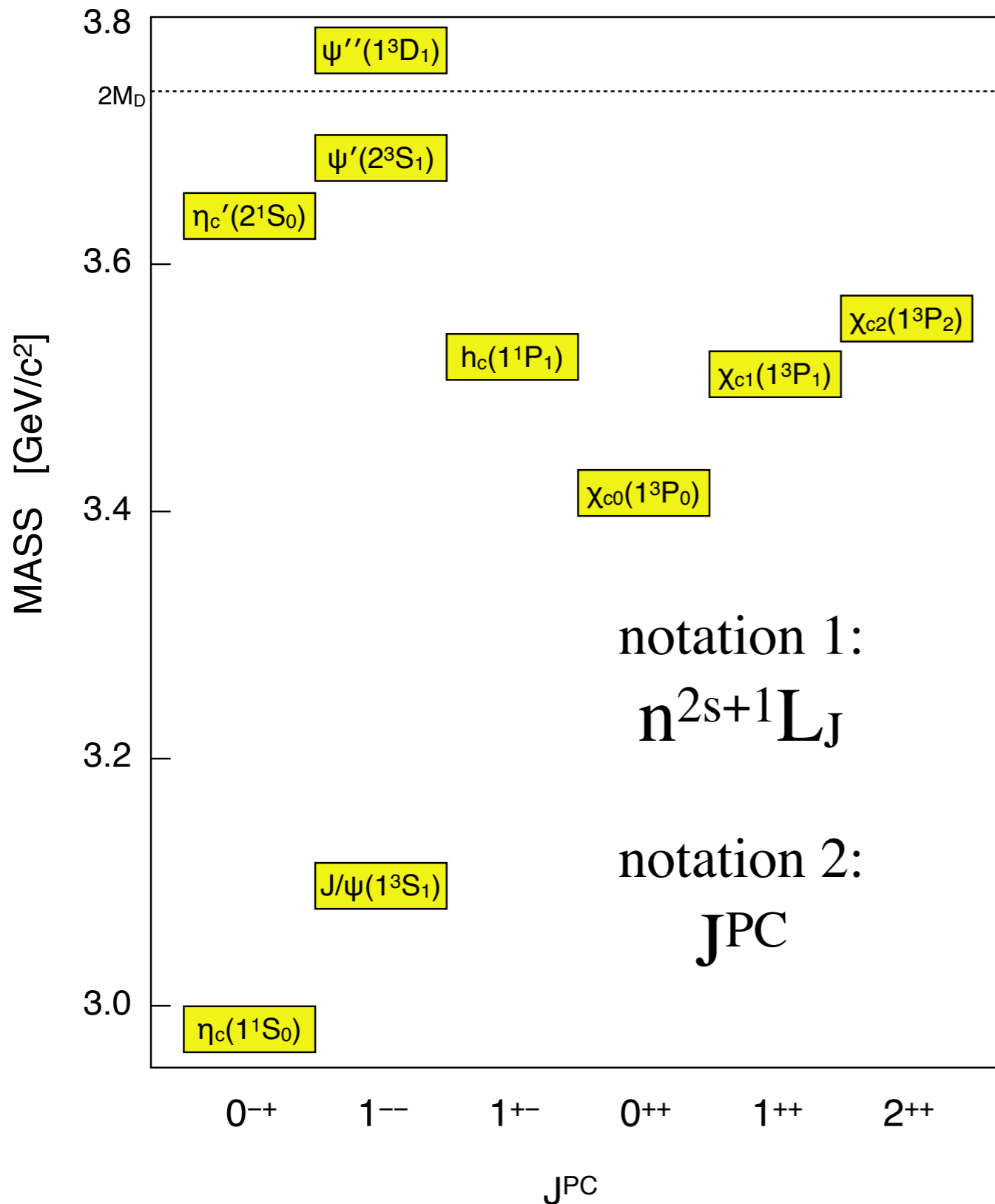
- color charges
- gluons
- quark confinement
- QCD
- models



# I. Charmonium: the Hydrogen atom of the strong force



# I. Charmonium: the Hydrogen atom of the strong force



Potential models:

Example from Barnes, Godfrey, Swanson:

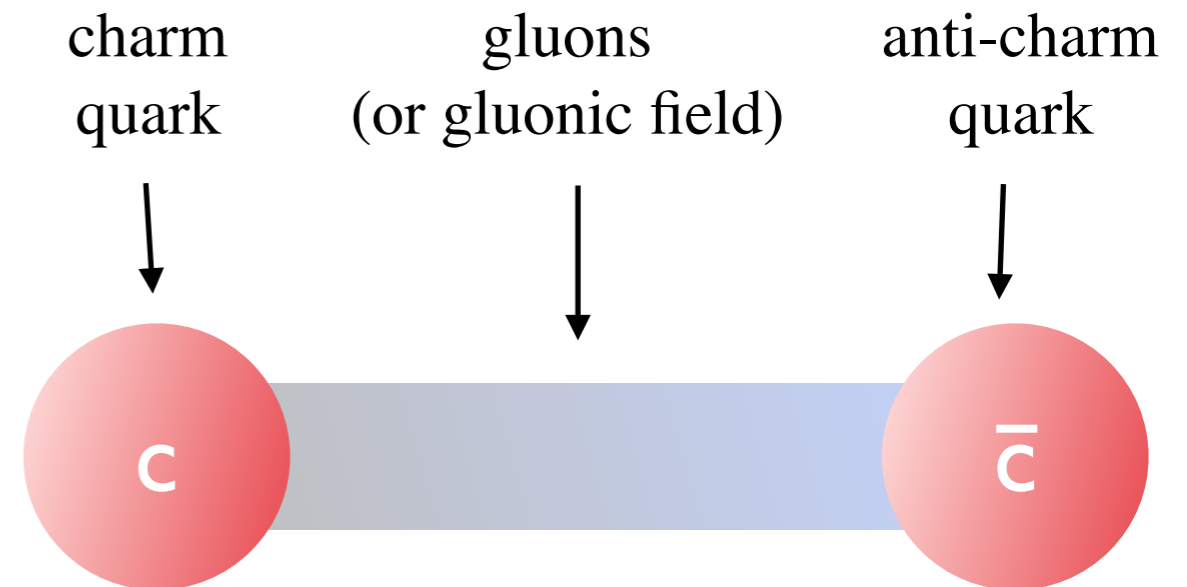
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2} \tilde{\delta}_\sigma(r) \vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

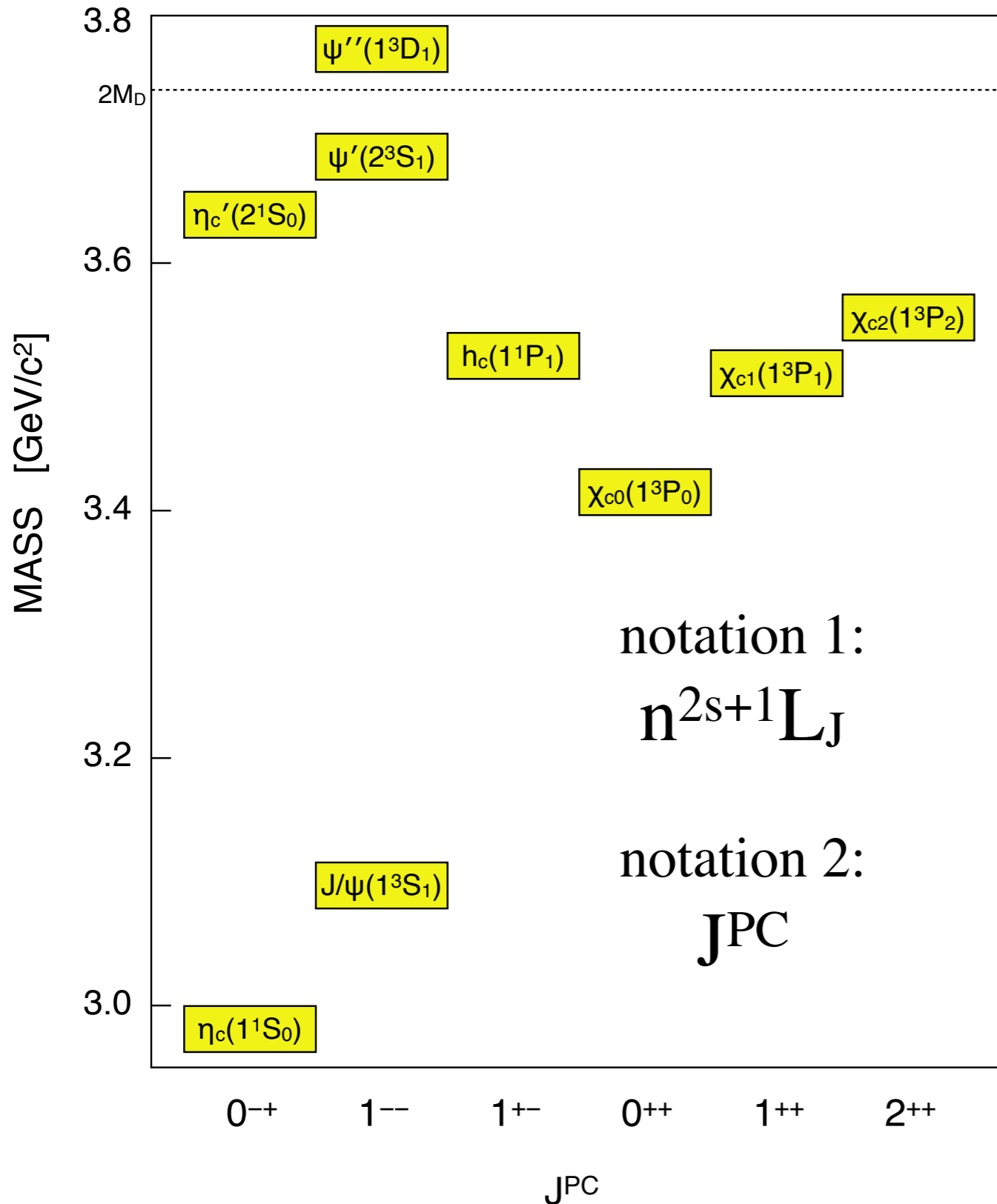
$$V_{\text{spin-dep}} = \frac{1}{m_c^2} \left[ \left( \frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} \mathbf{T} \right]$$

(Spin-Orbit + Tensor)

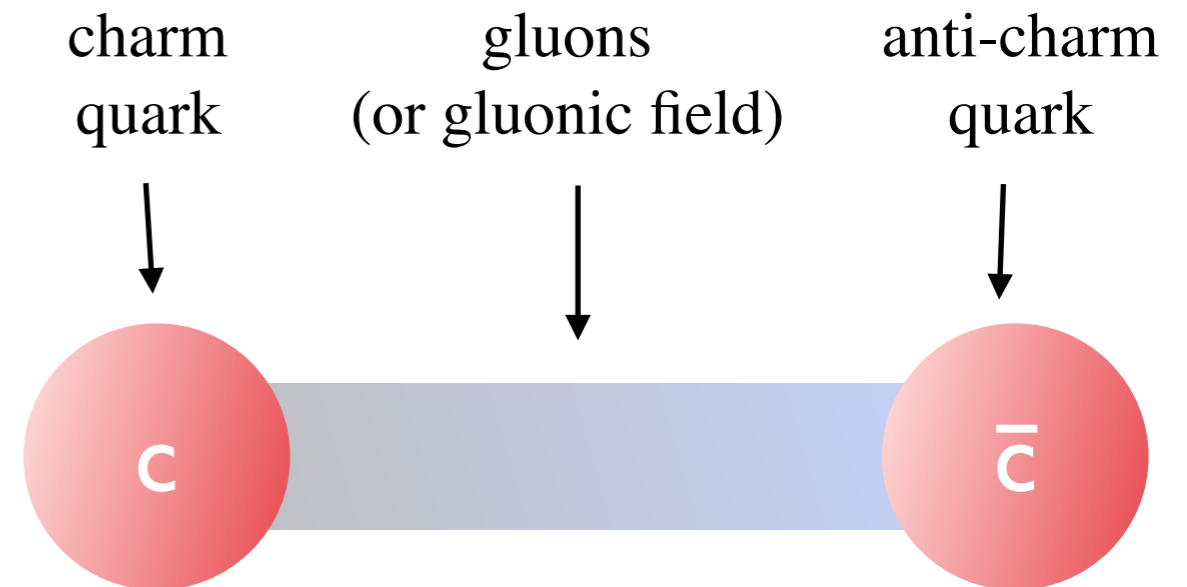
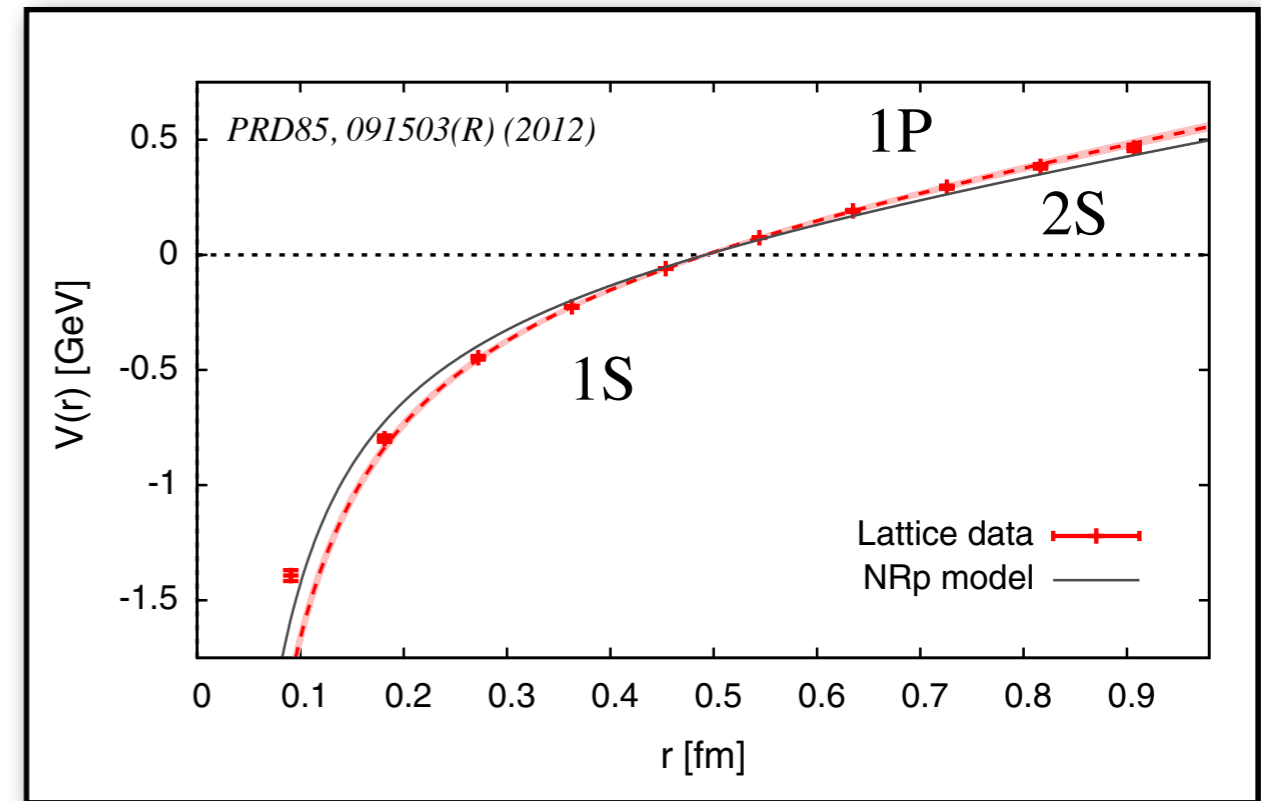
PRD72, 054026 (2005)



# I. Charmonium: the Hydrogen atom of the strong force

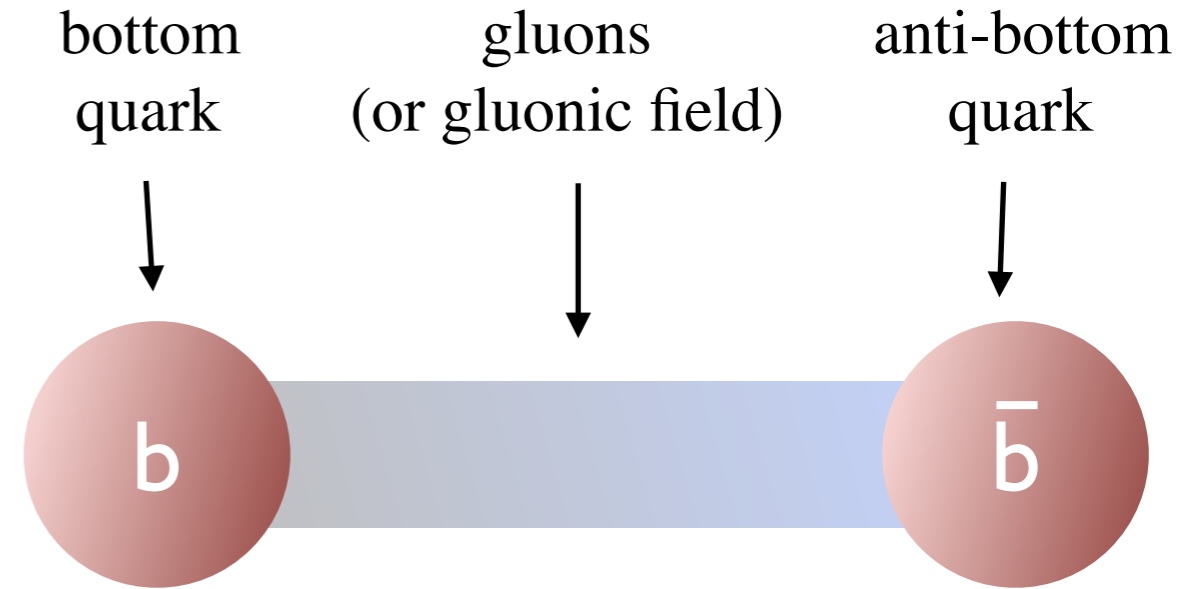
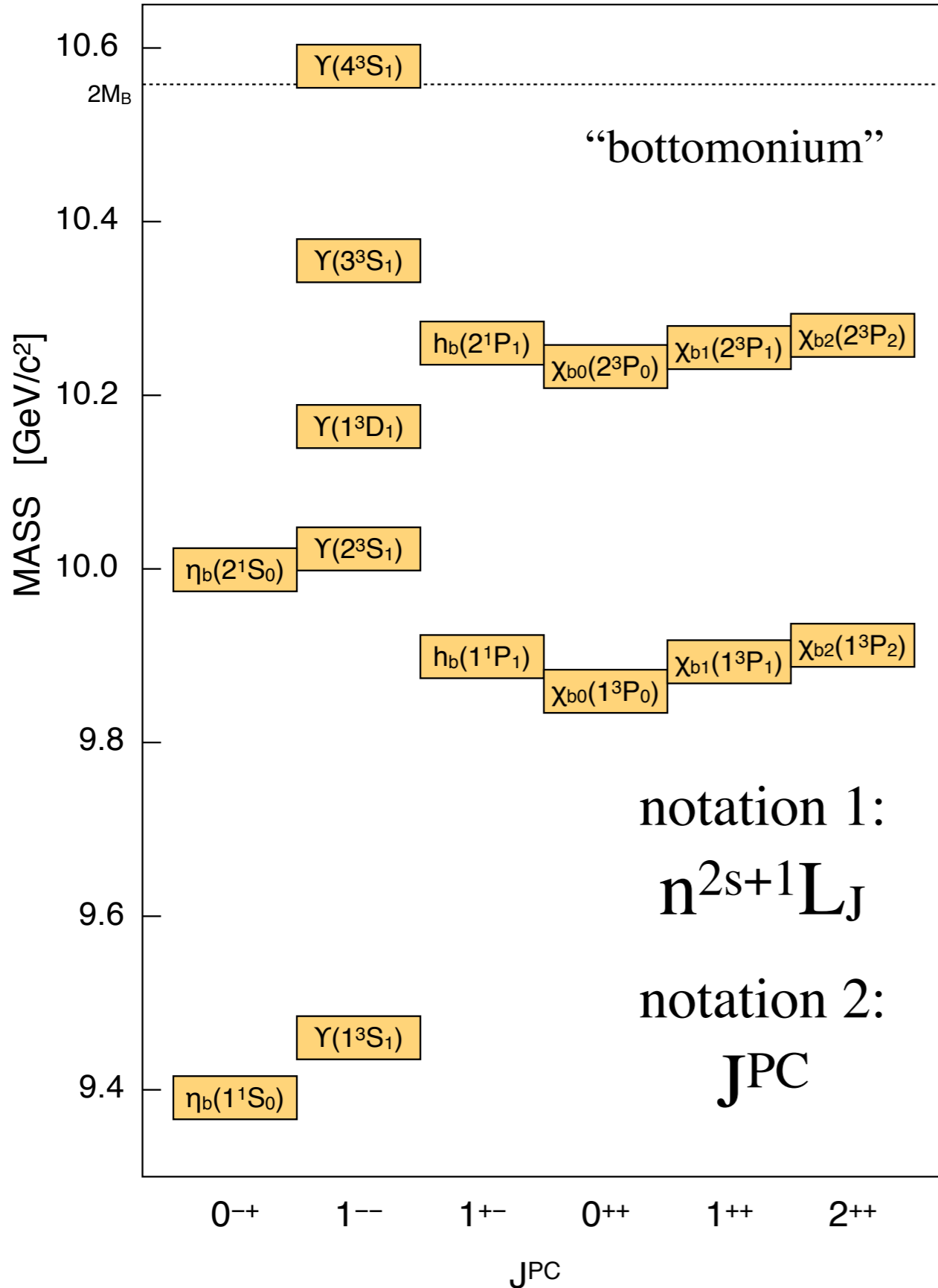


Potential models and Lattice QCD:

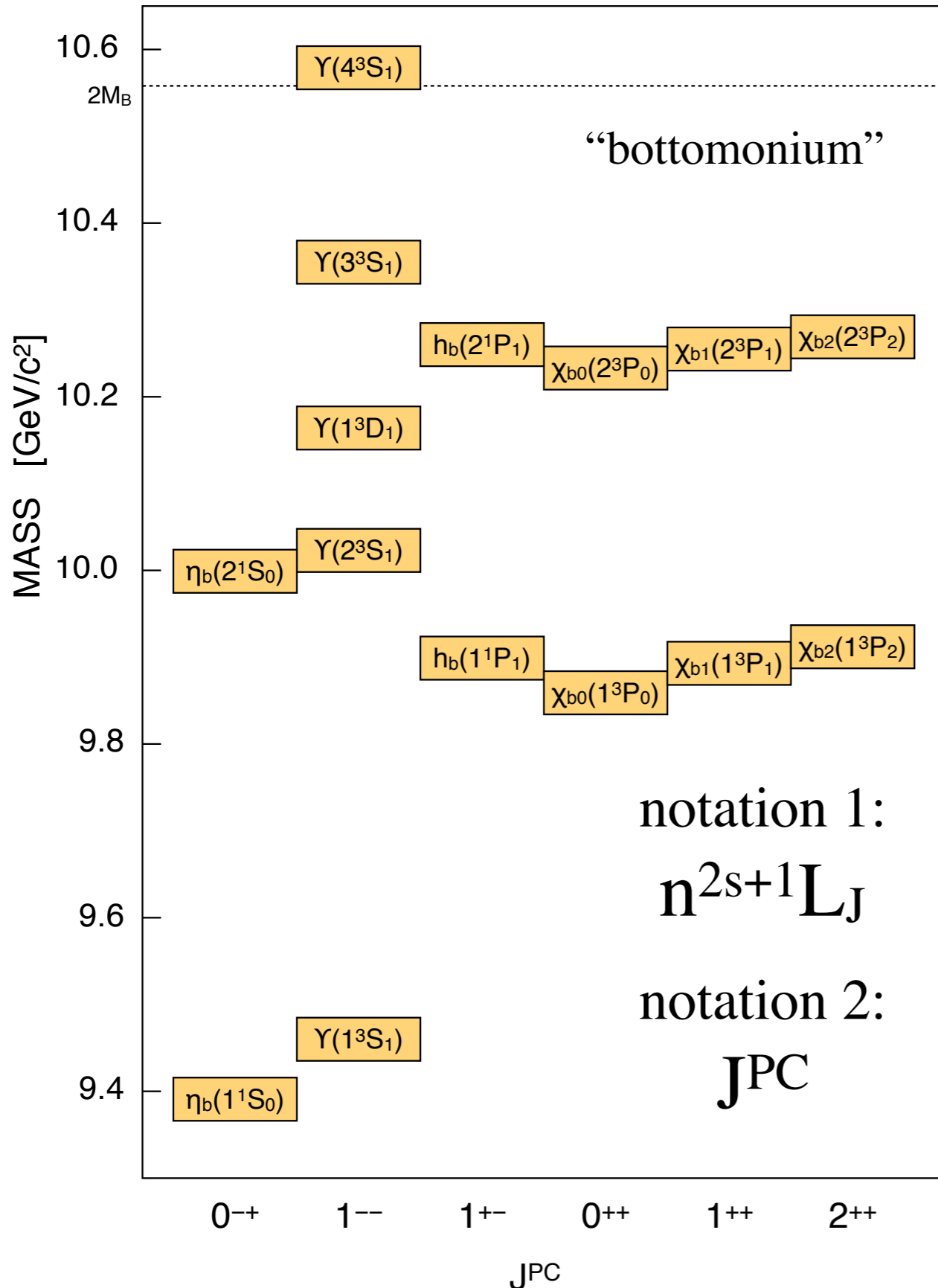




# Side Note: bottomonium and other hadrons



# Side Note: bottomonium and other hadrons



Other quark anti-quark combinations (**mesons**):

$u\bar{u}, d\bar{d}$  (1) :

$\pi, \rho, b_1, a_0, a_1, a_2$

$u\bar{u}, d\bar{d}$  (2) :

$\eta, \omega, h_1, f_0, f_1, f_2$

$s\bar{s}$  :

$\eta', \phi, h'_1, f'_0, f'_1, f'_2$

$u\bar{s}$  :

$K^+, K^{*+}, K_1^+, K_0^{*+}, K_1^{*+}, K_2^{*+}$

$c\bar{d}$  :

$D^+, D^{*+}, D_1^+, D_0^{*+}, D_1^{*+}, D_2^{*+}$

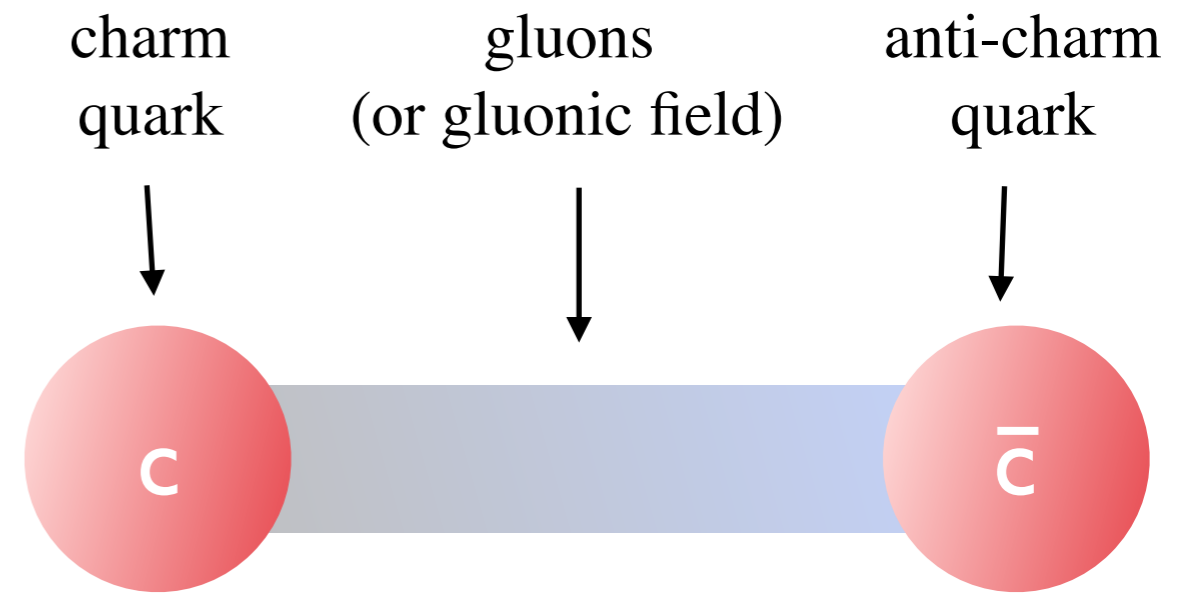
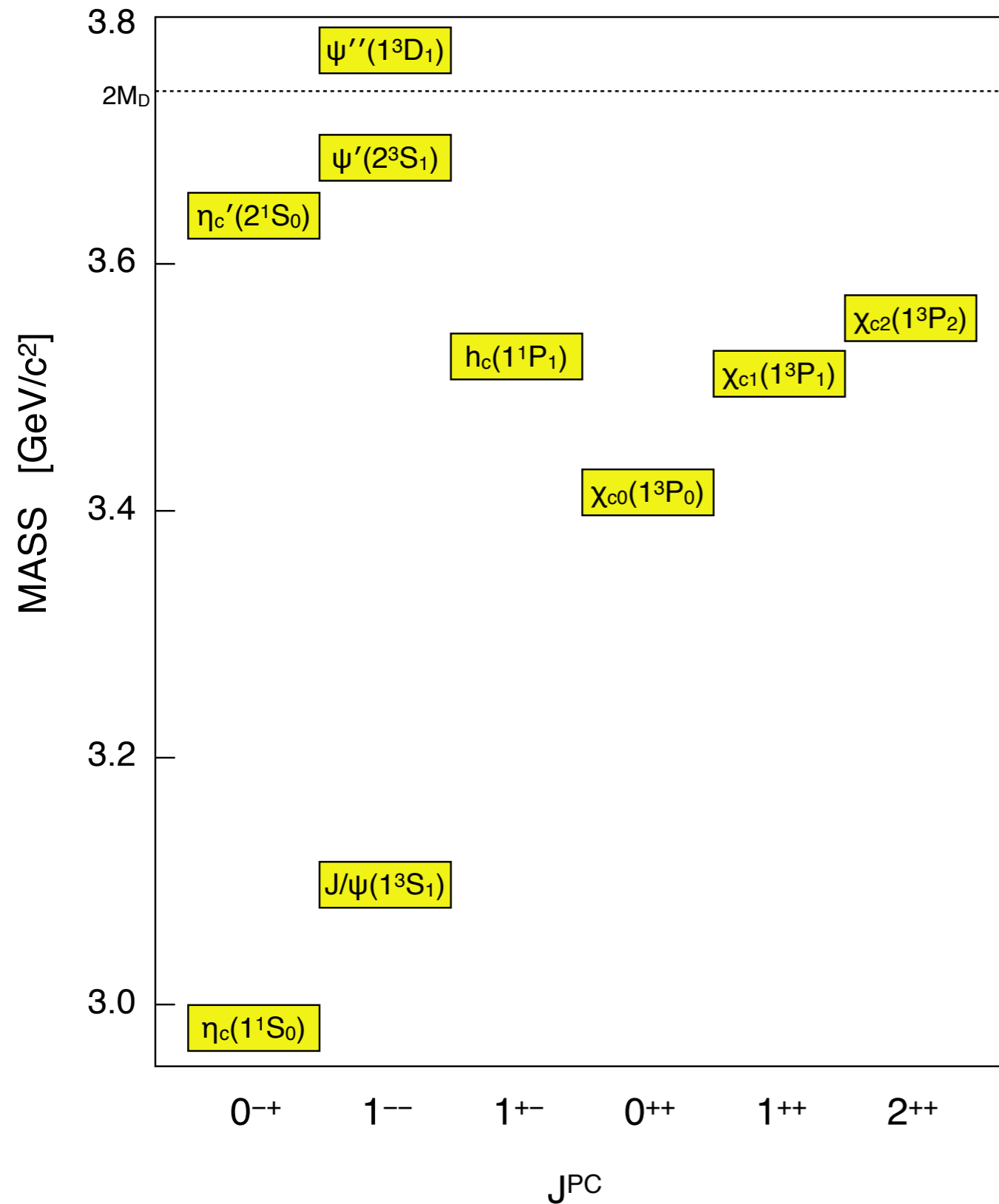
$u\bar{b}$  :

$B^+, B^{*+}, B_1^+, B_0^{*+}, B_1^{*+}, B_2^{*+}$

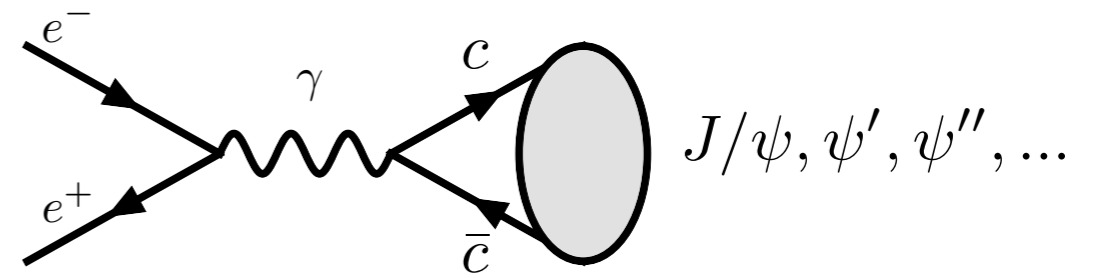
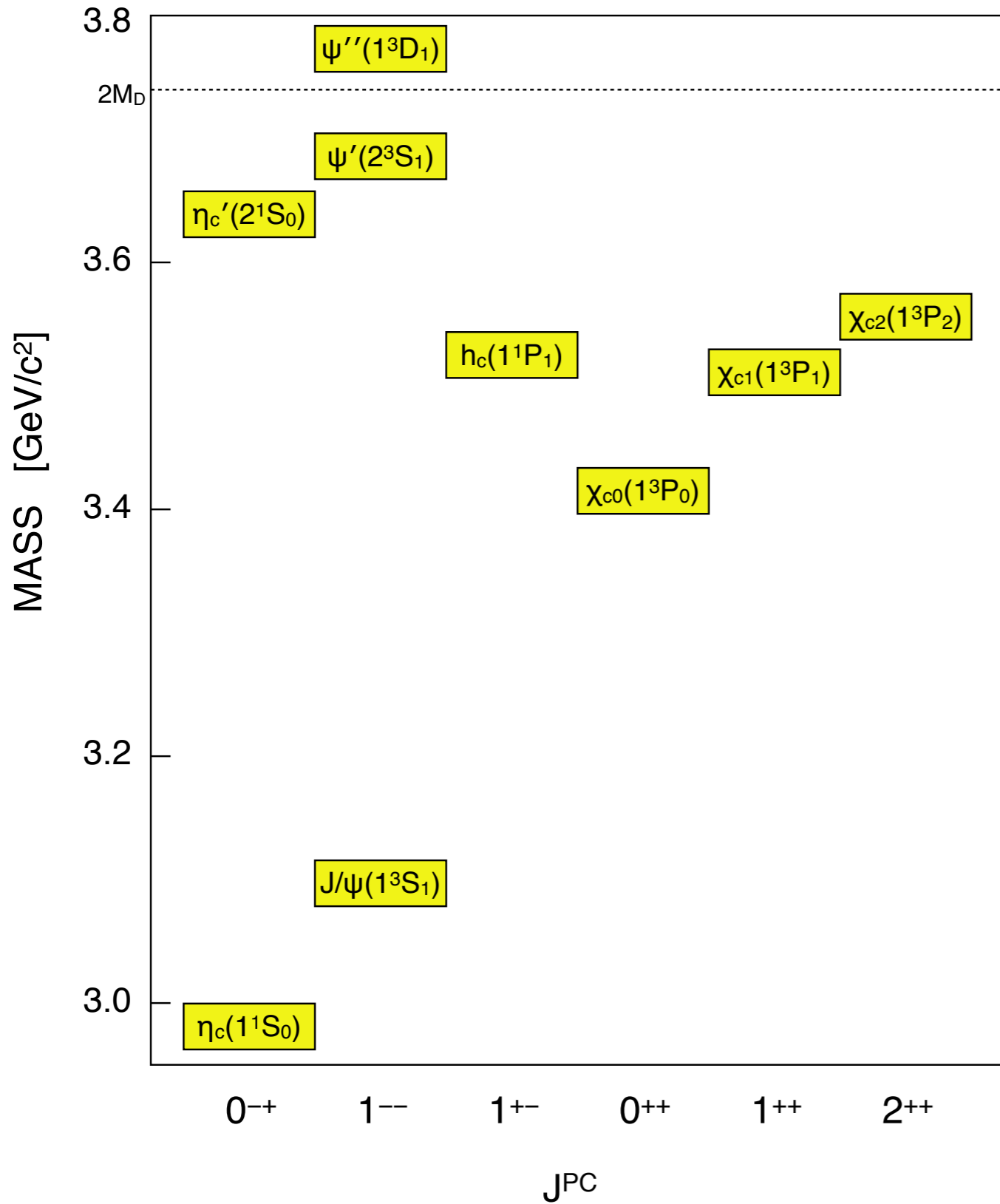
Plus three-quark combinations (**baryons**):

$p, n, \Delta, \Sigma, \Xi, \Omega, \text{etc.}$

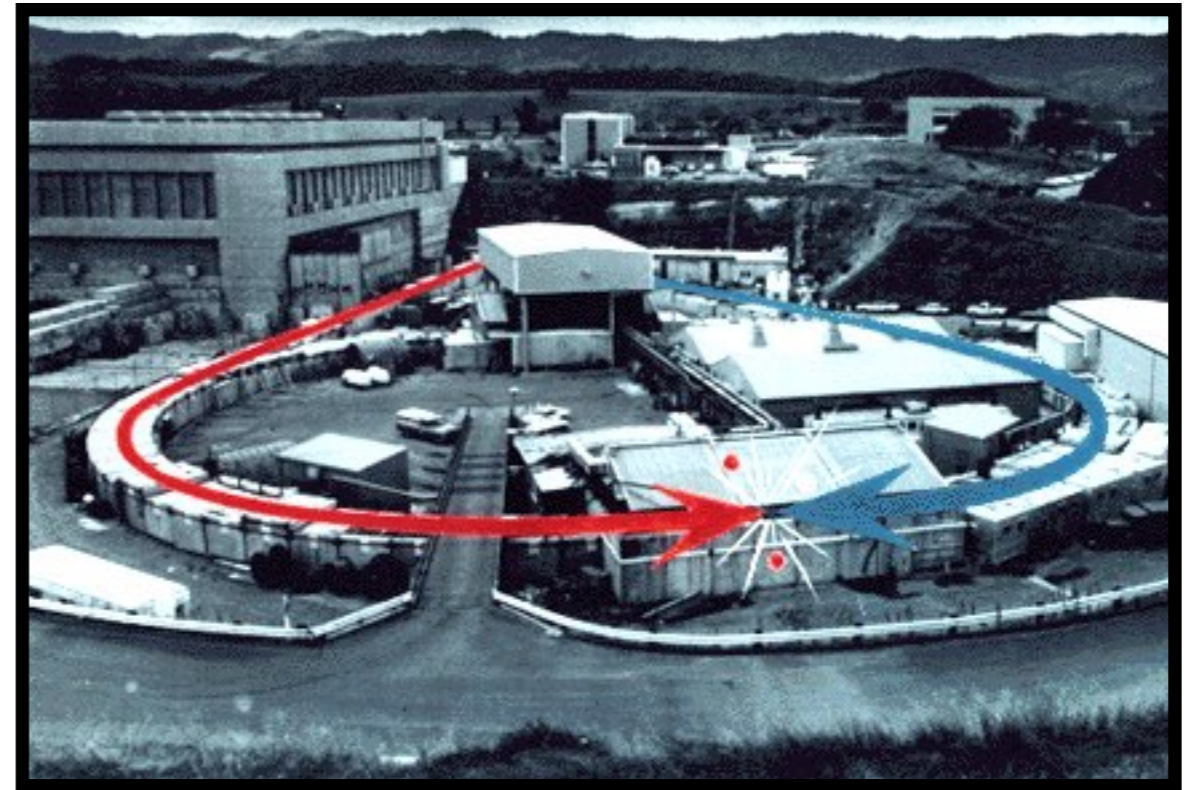
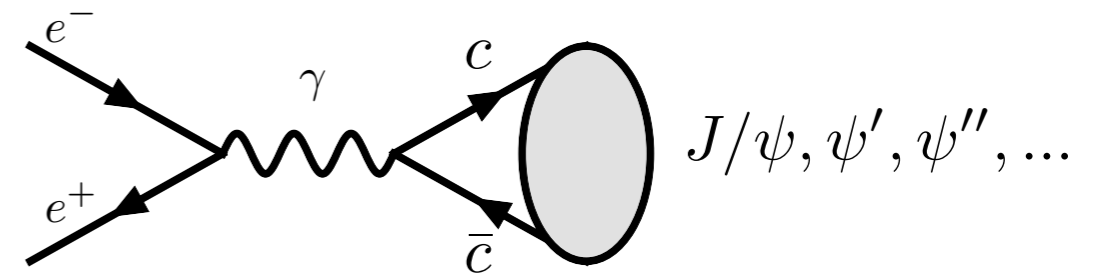
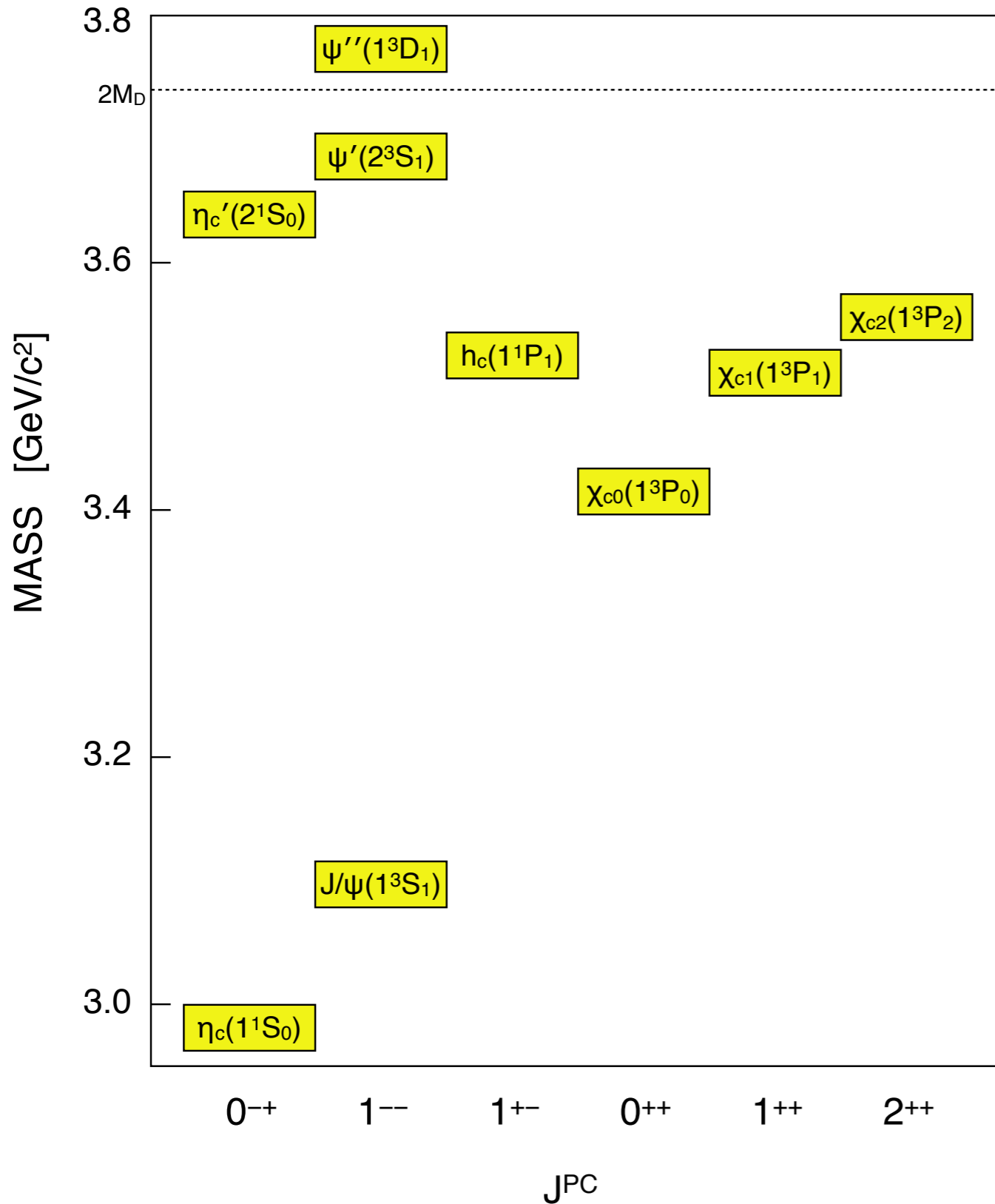
# I. Charmonium: the Hydrogen atom of the strong force



# I. Charmonium: the Hydrogen atom of the strong force

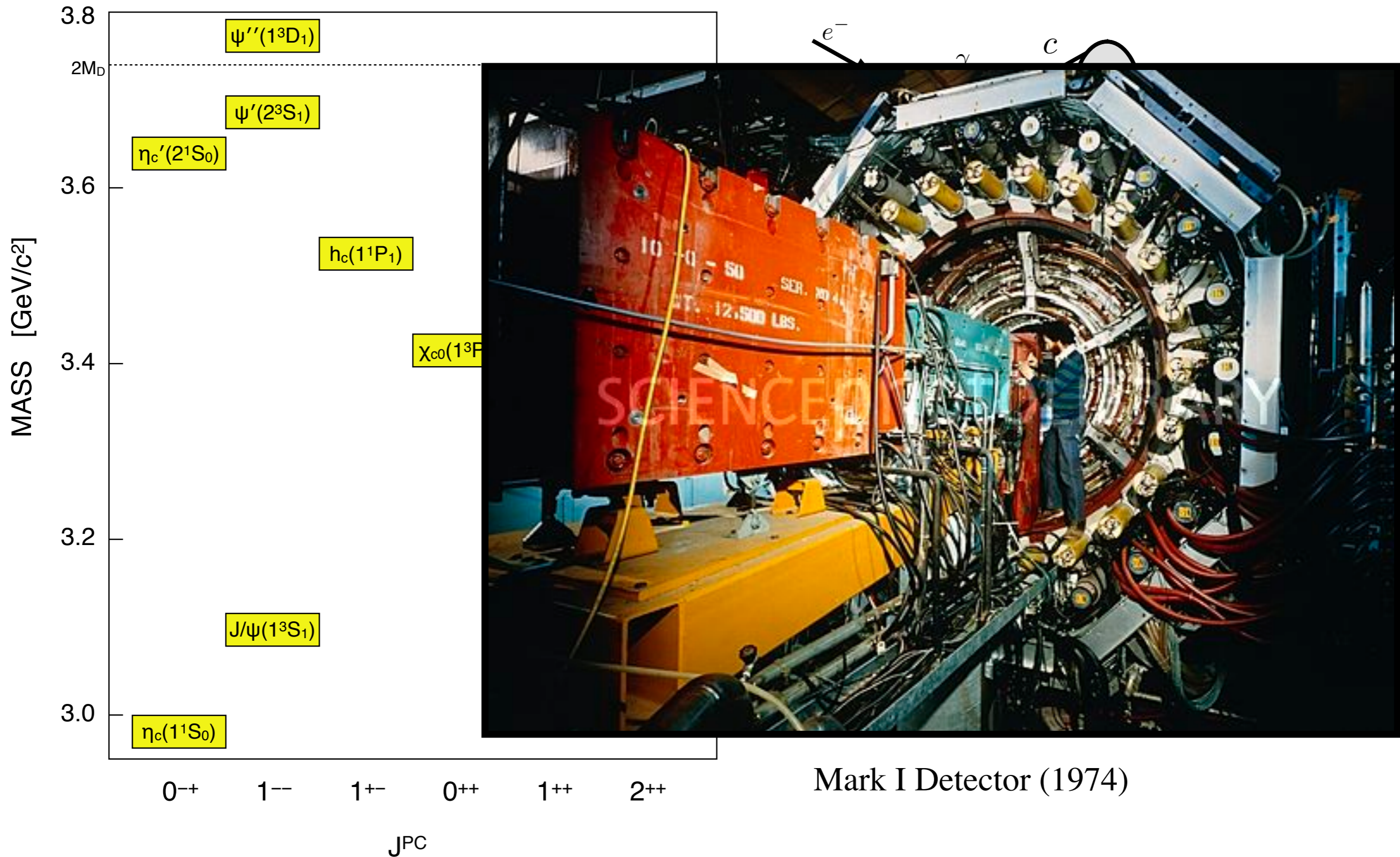


# I. Charmonium: the Hydrogen atom of the strong force

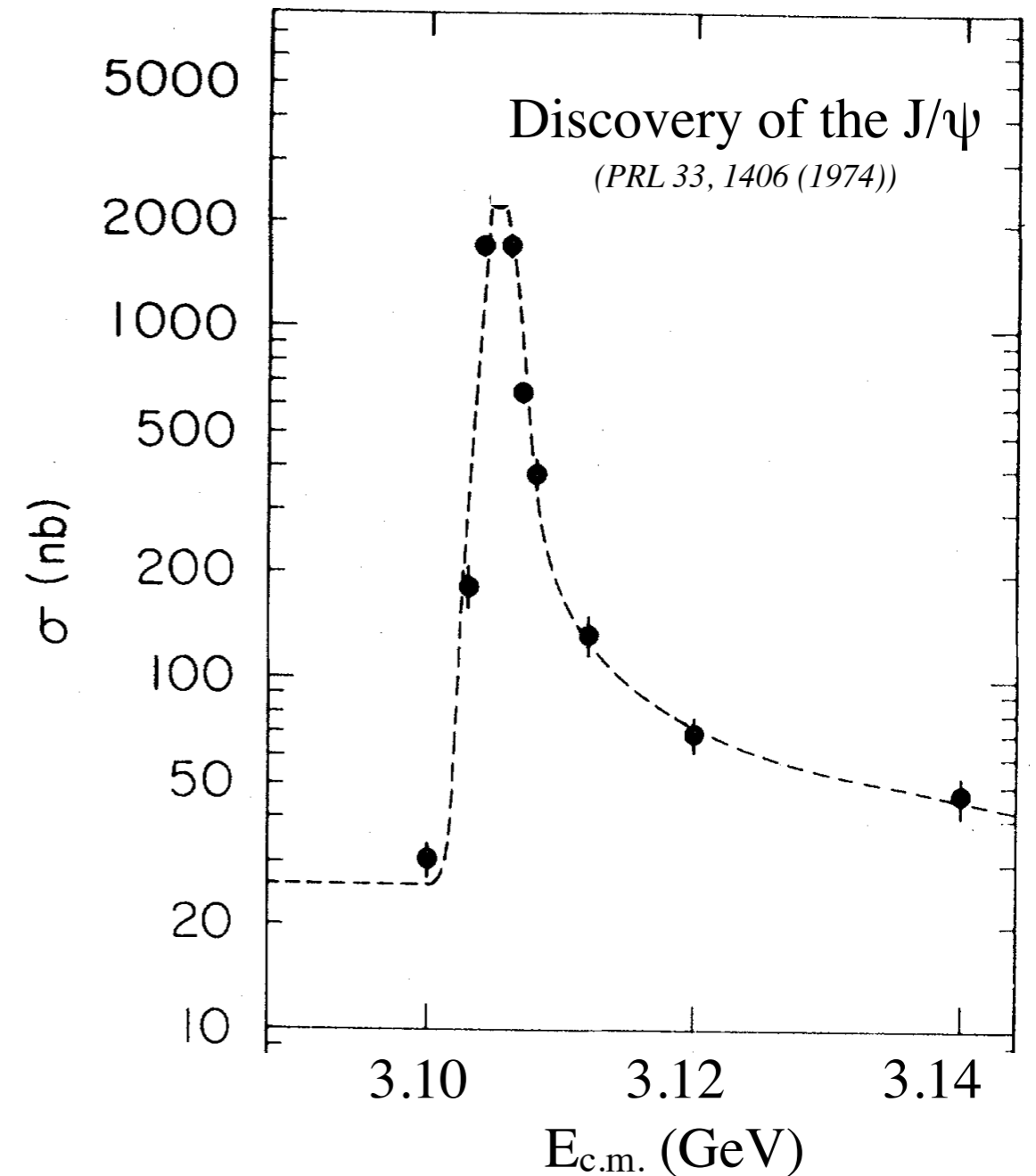
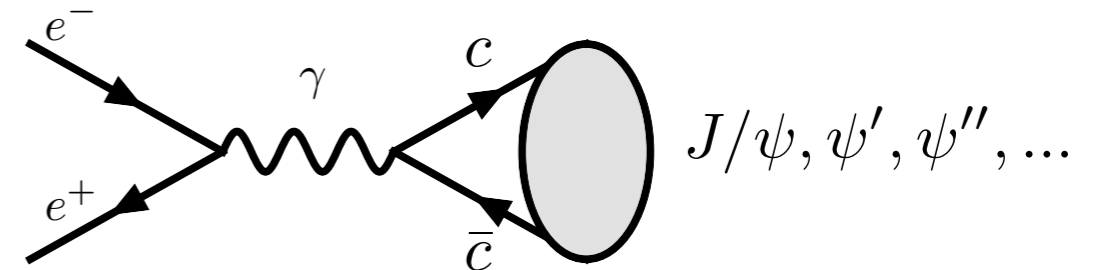
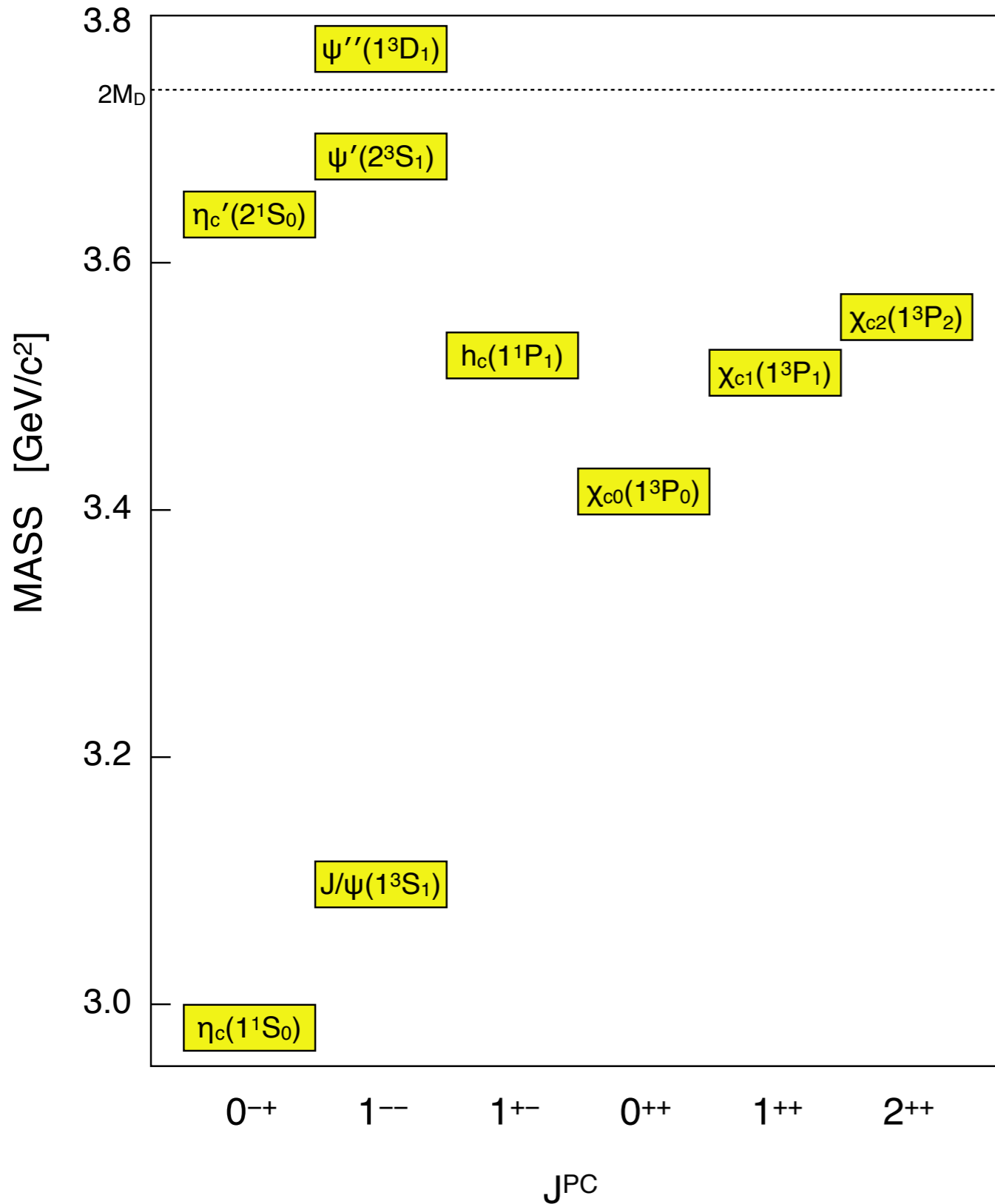


SPEAR (1972)

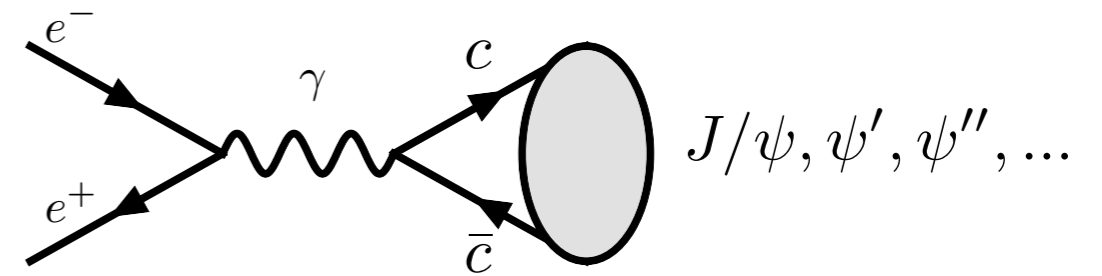
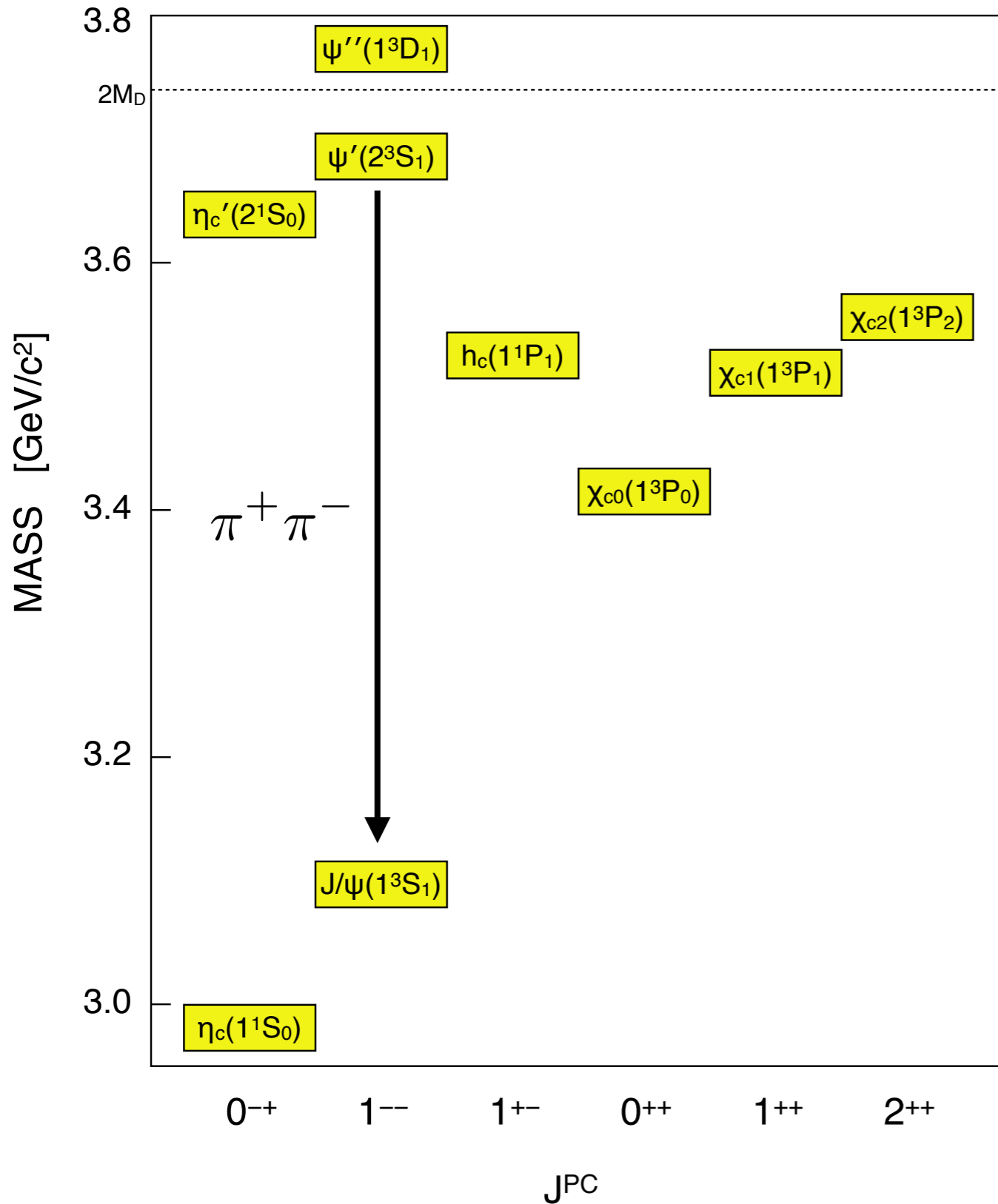
# I. Charmonium: the Hydrogen atom of the strong force



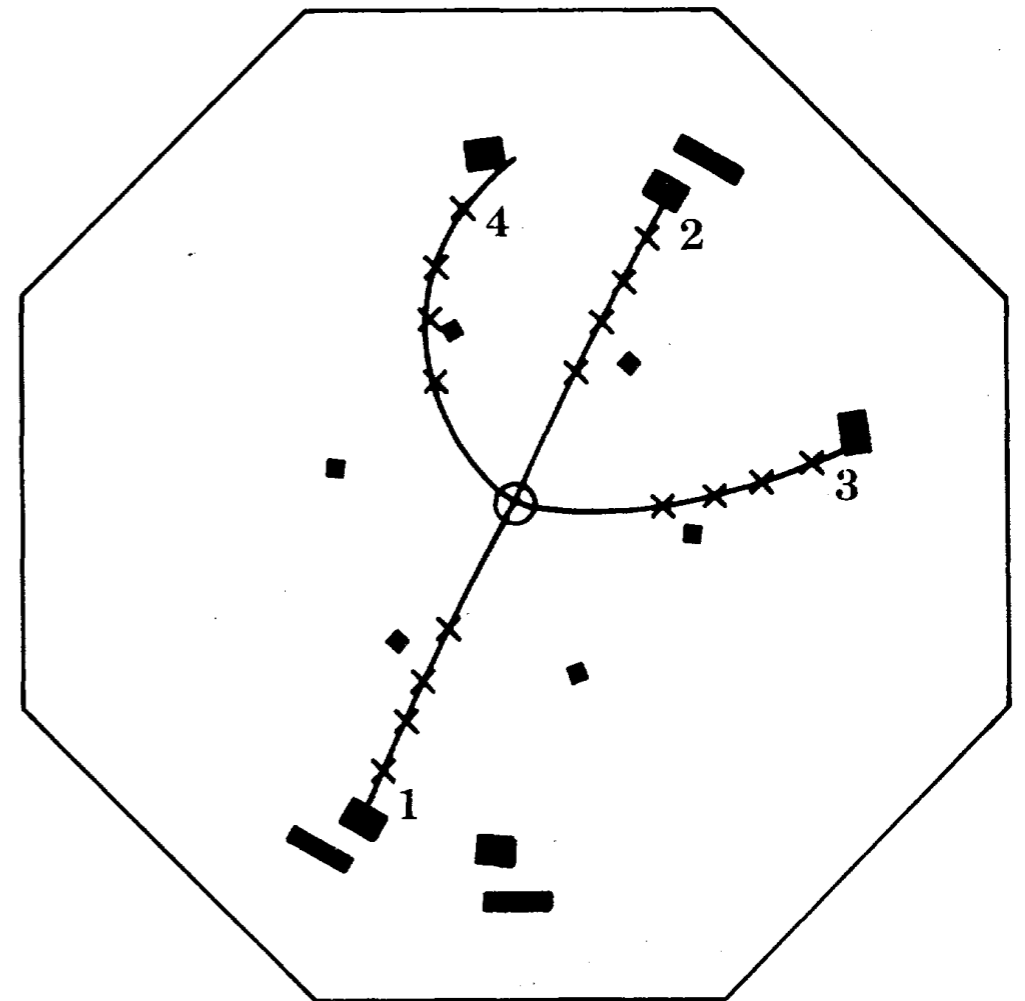
# I. Charmonium: the Hydrogen atom of the strong force



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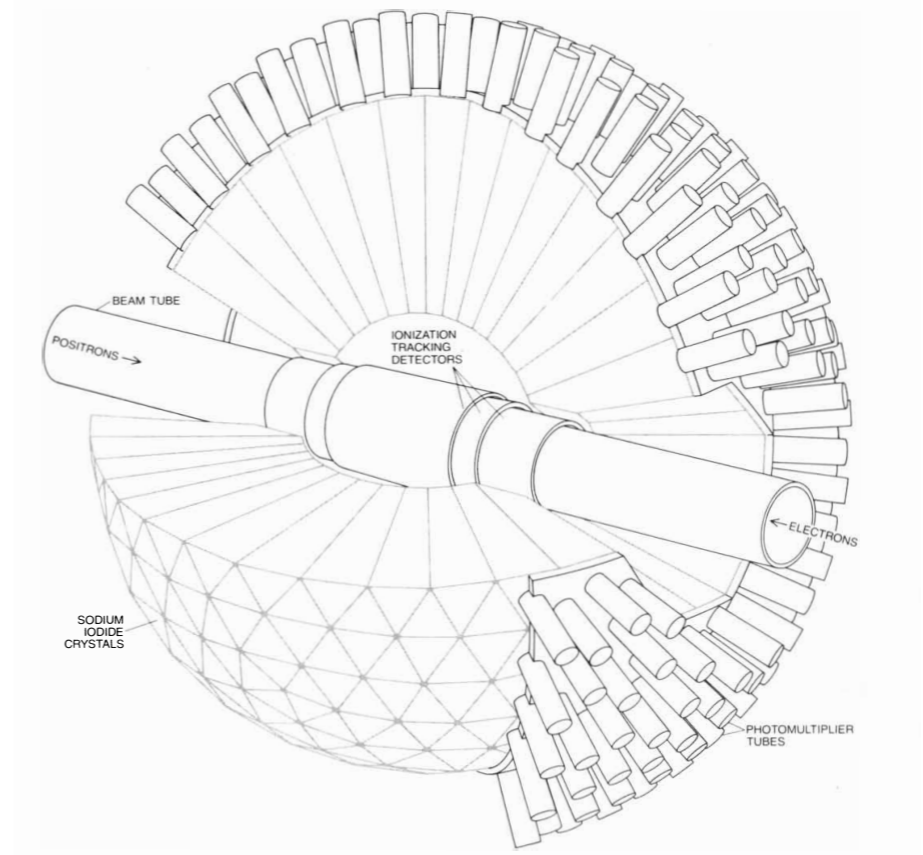
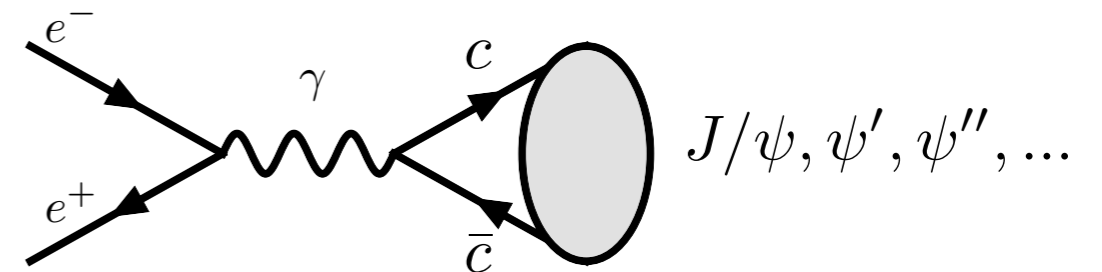
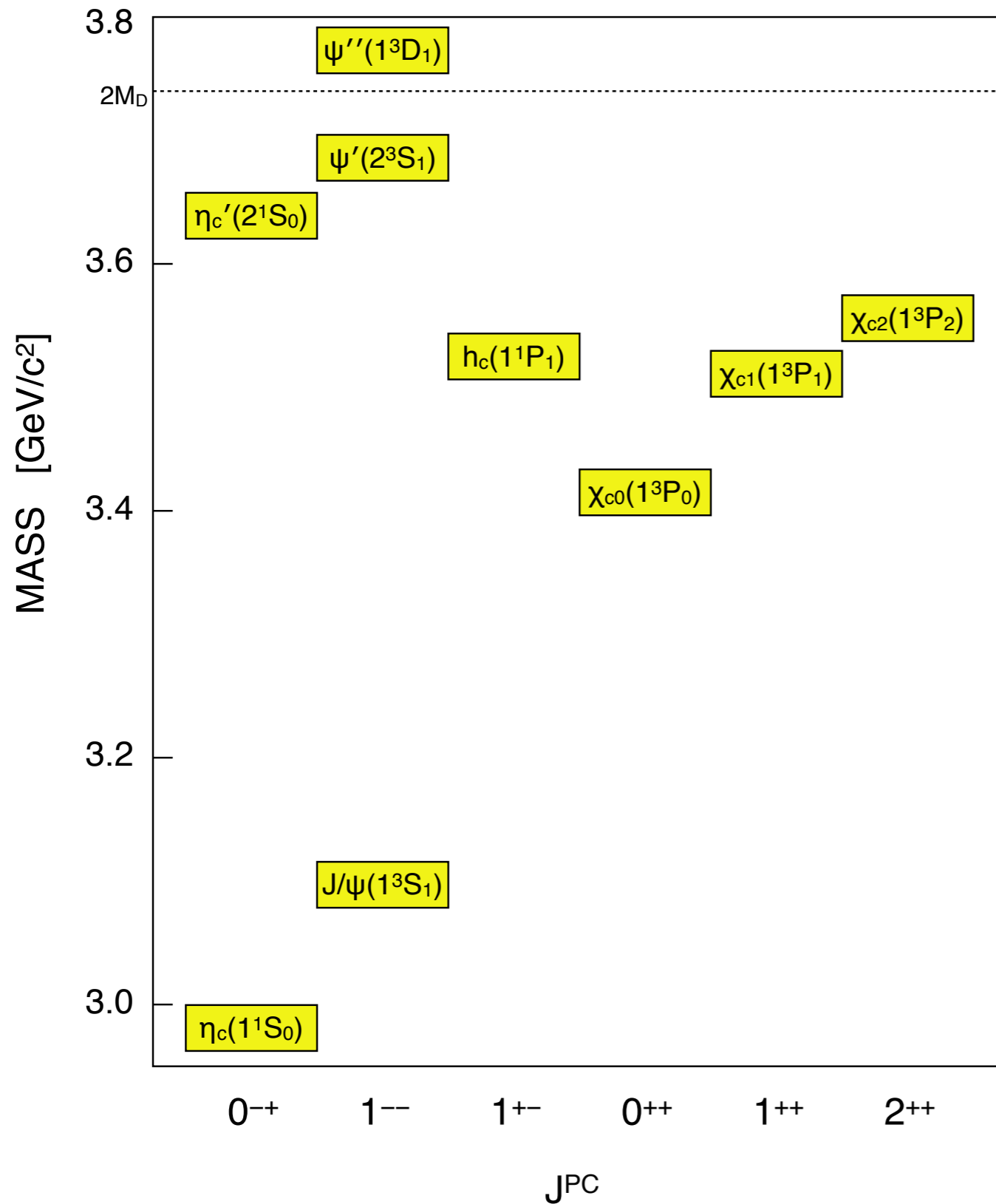


Observation of  $\psi' \rightarrow \pi^+\pi^-J/\psi$   
(PRL 34, 1181 (1975))



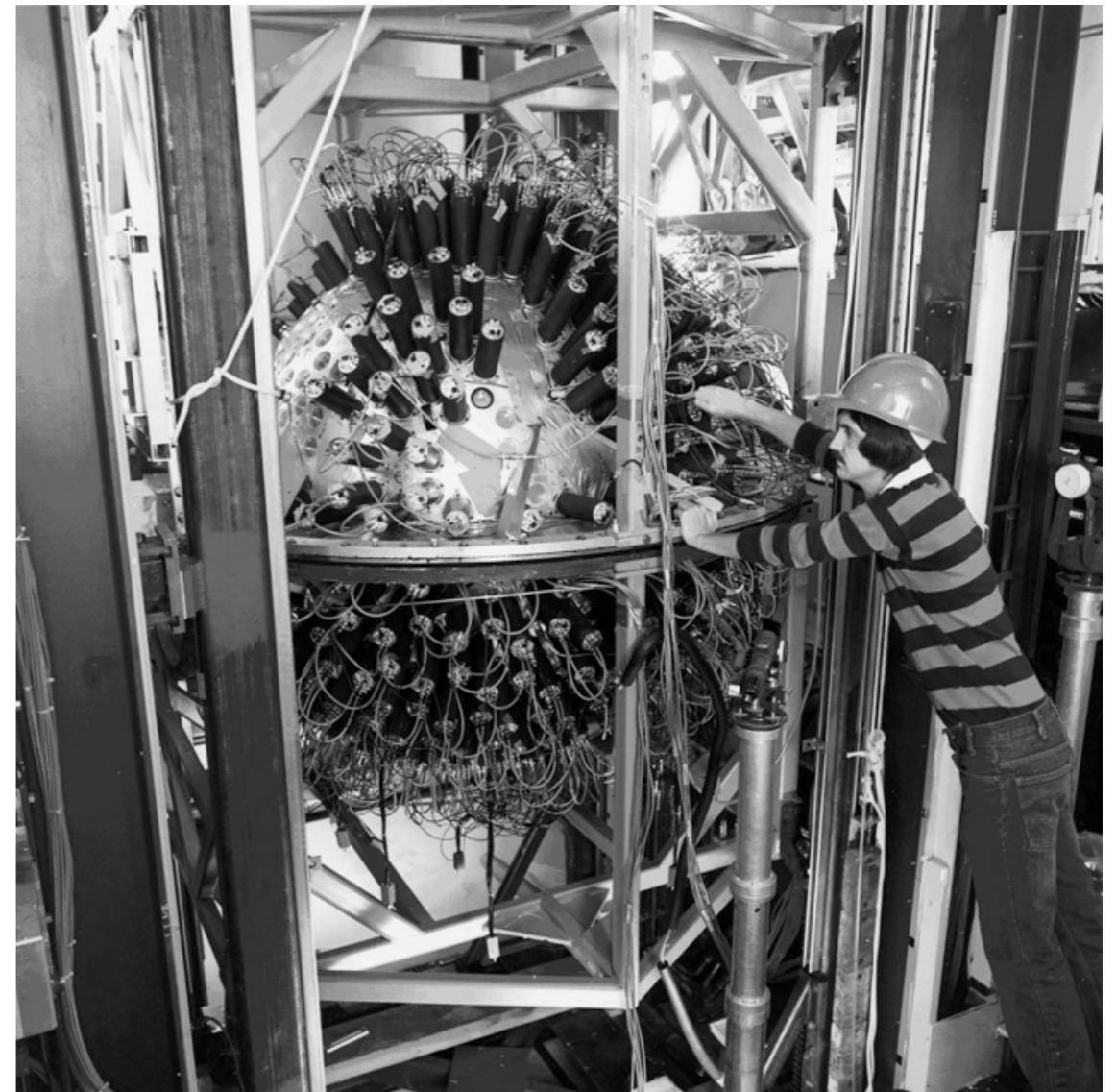
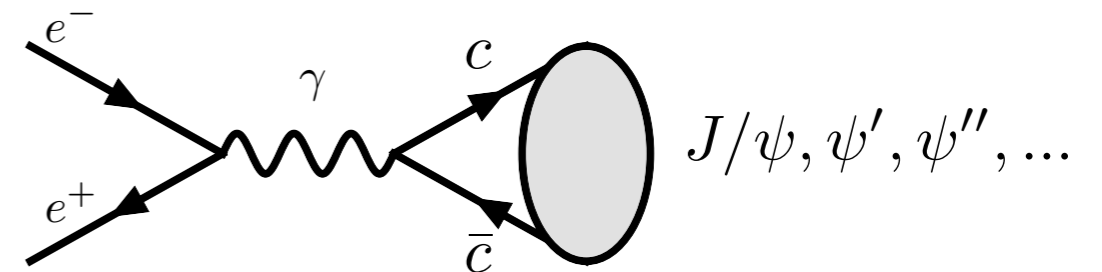
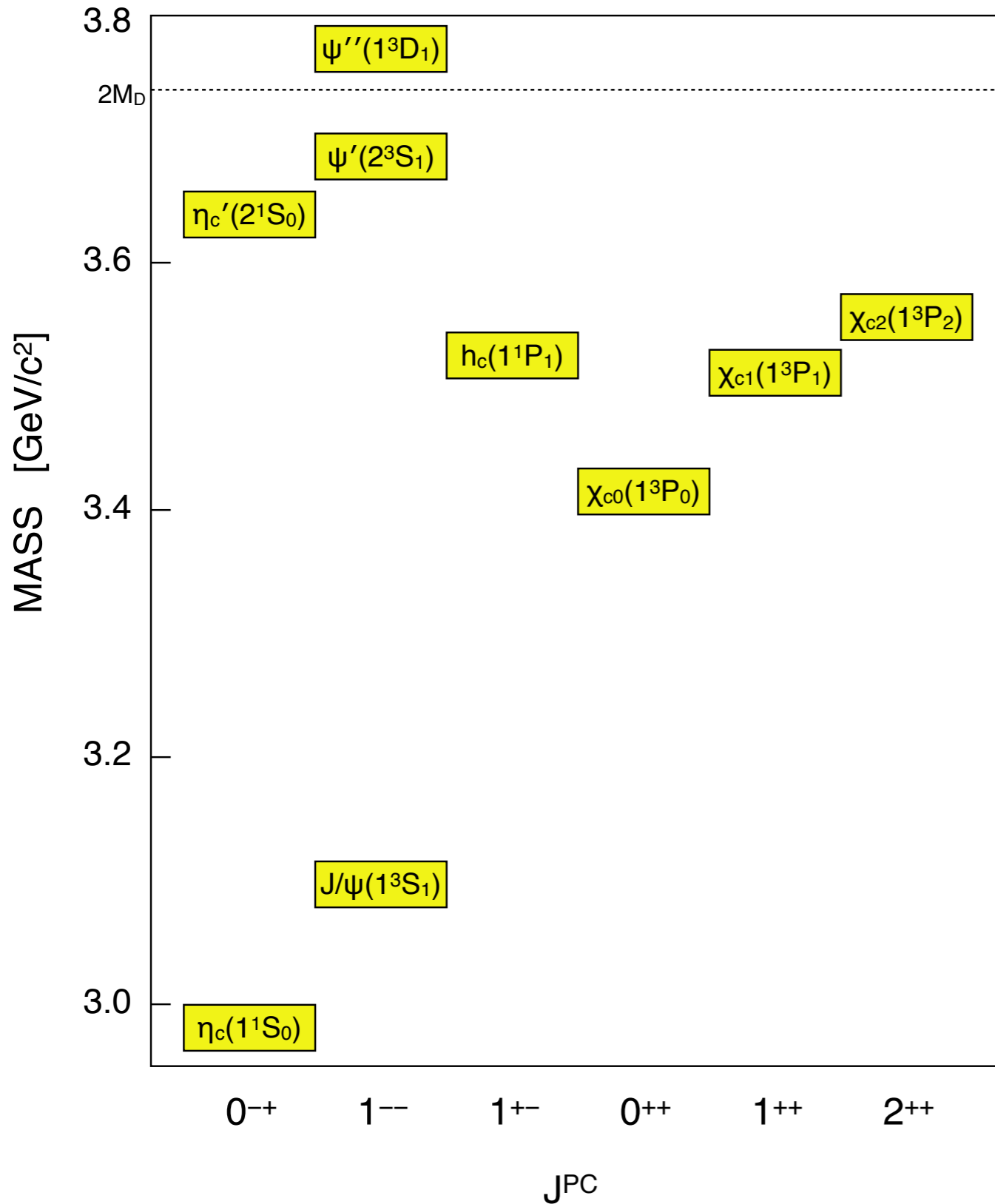


# I. Charmonium: the Hydrogen atom of the strong force



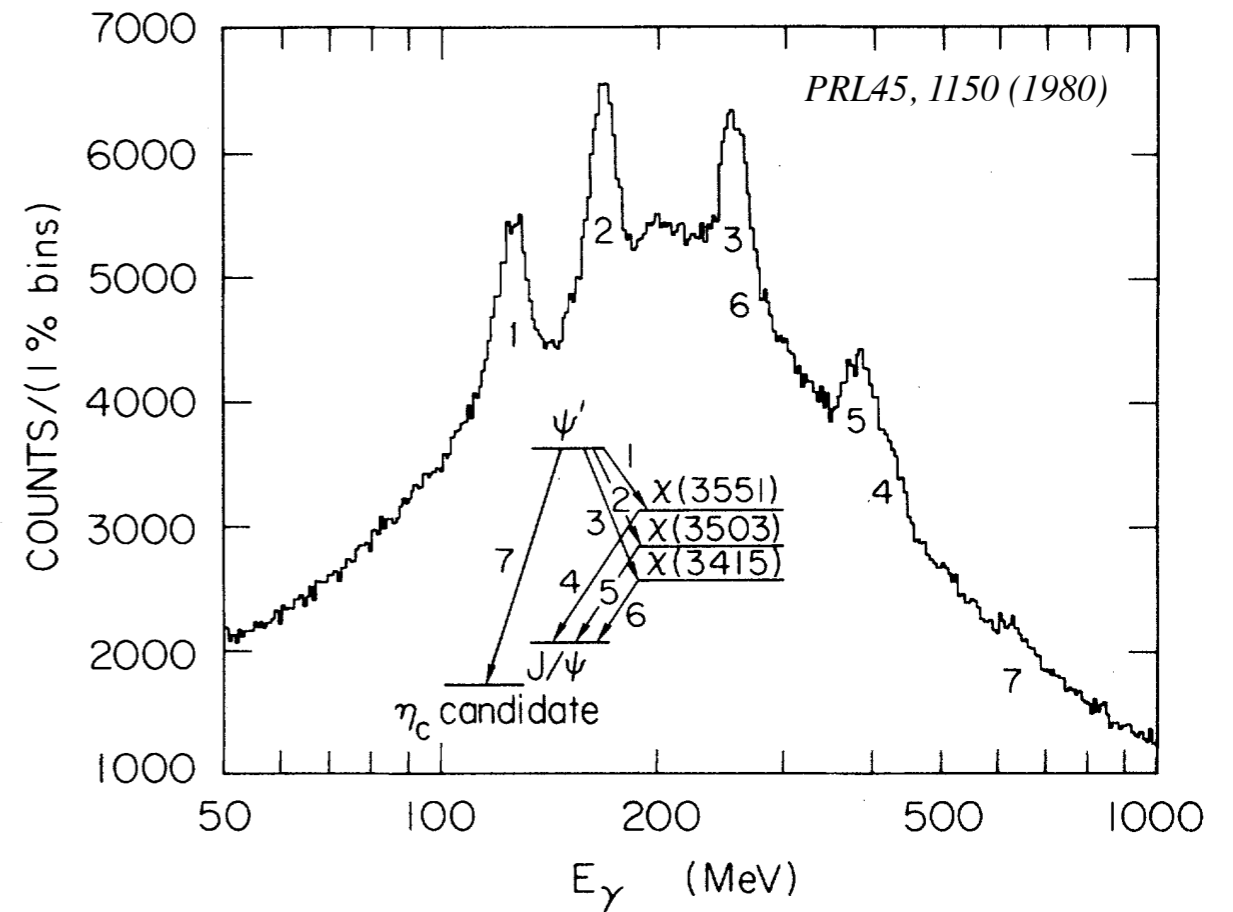
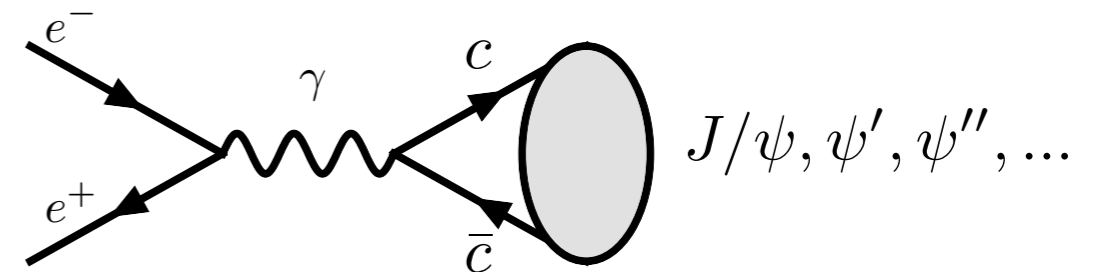
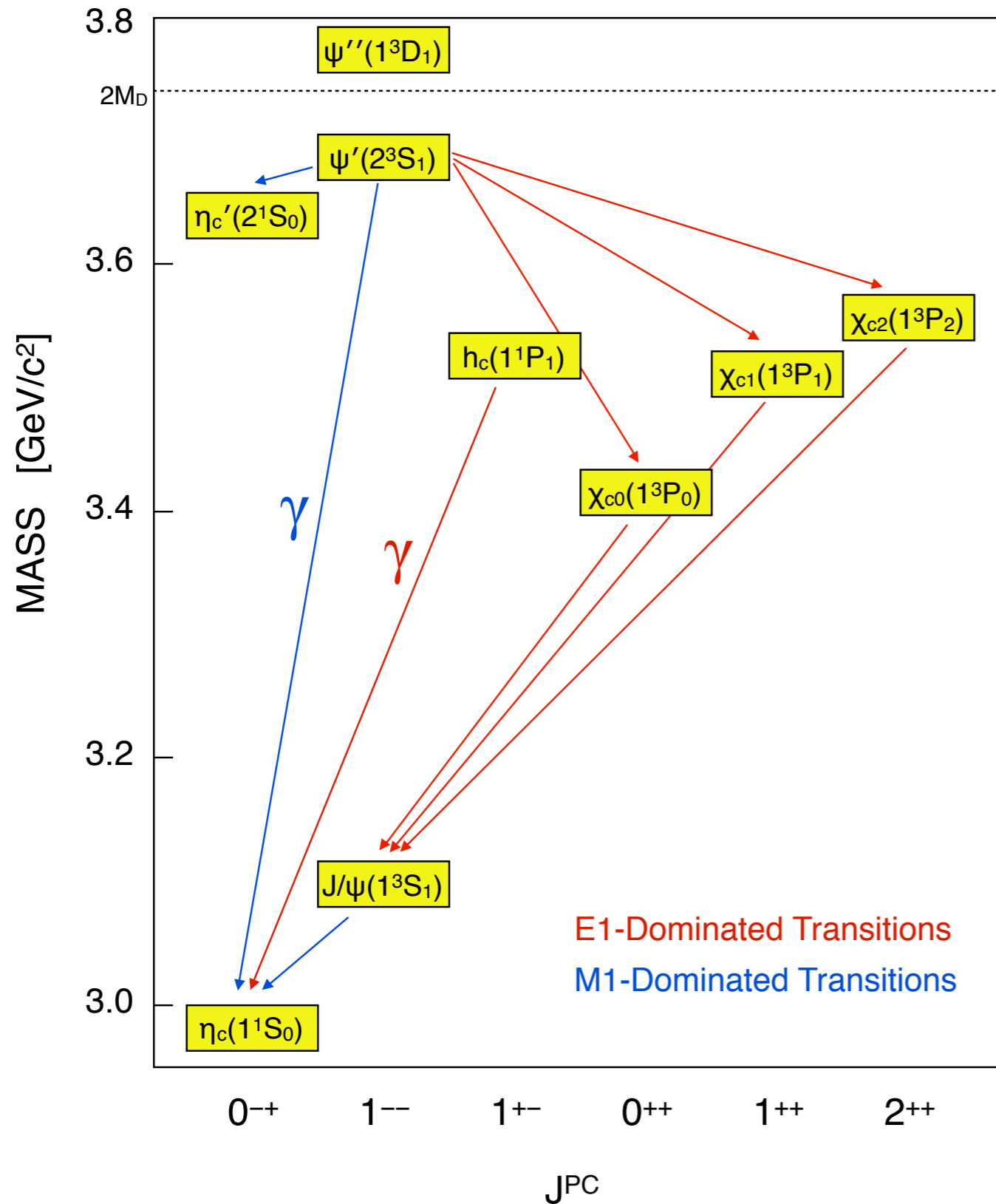
Crystal Ball (1976)

# I. Charmonium: the Hydrogen atom of the strong force

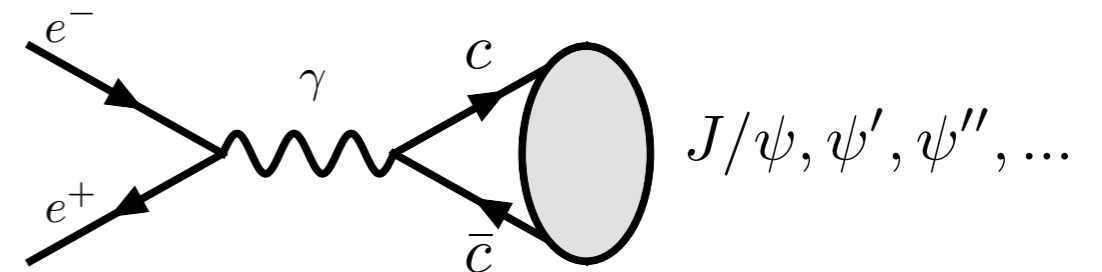
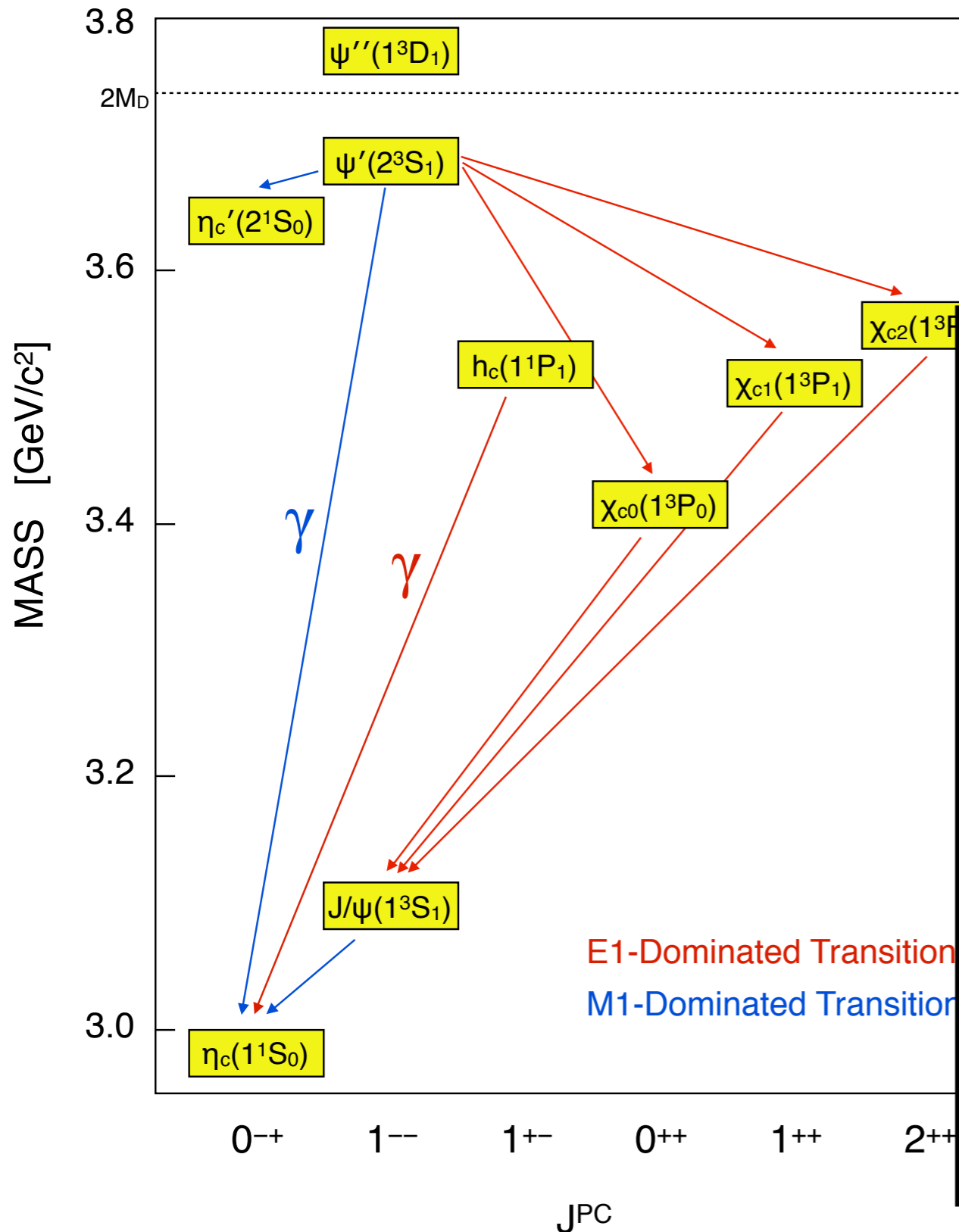


Crystal Ball (1976)

# I. Charmonium: the Hydrogen atom of the strong force

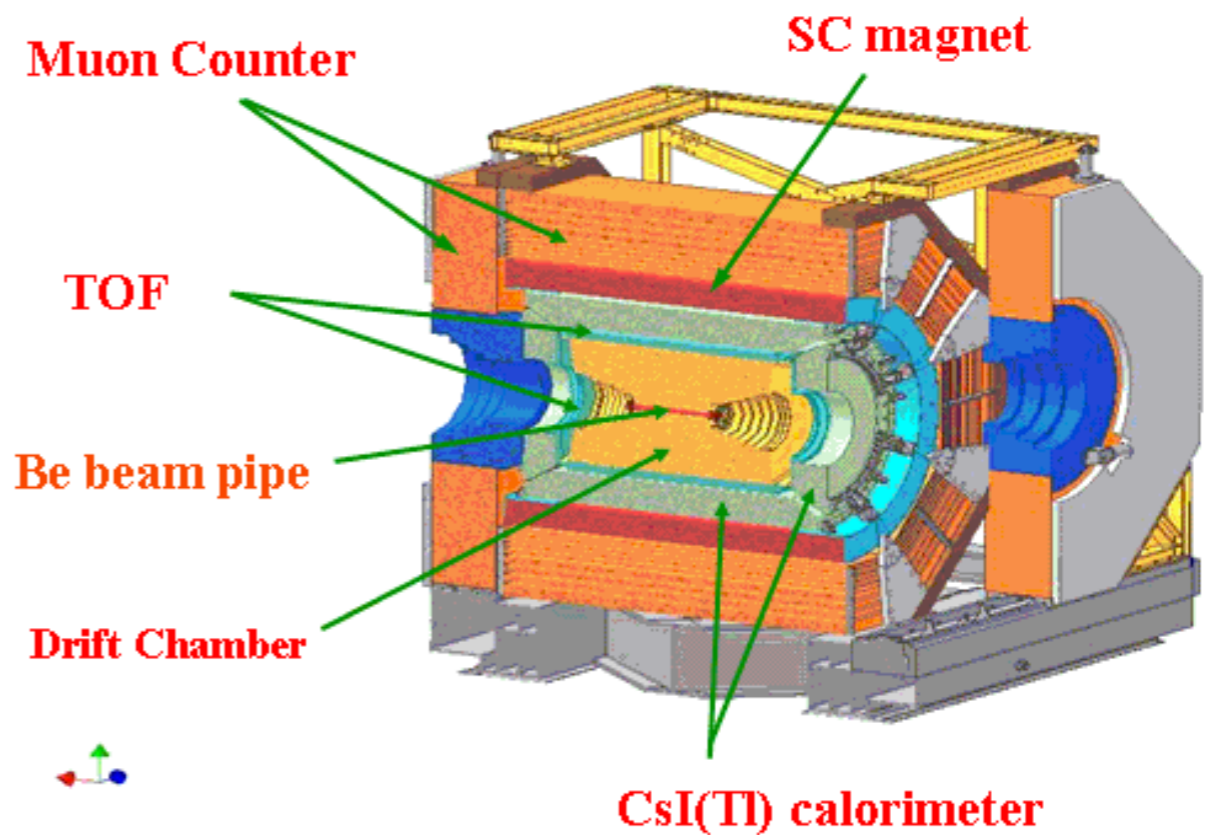


# I. Charmonium: the Hydrogen atom of the strong force

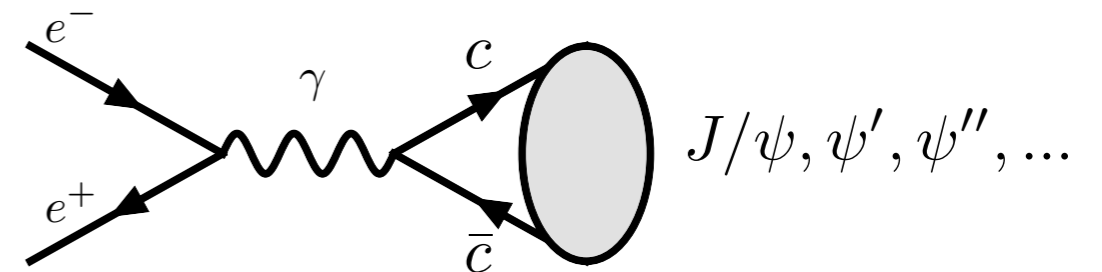
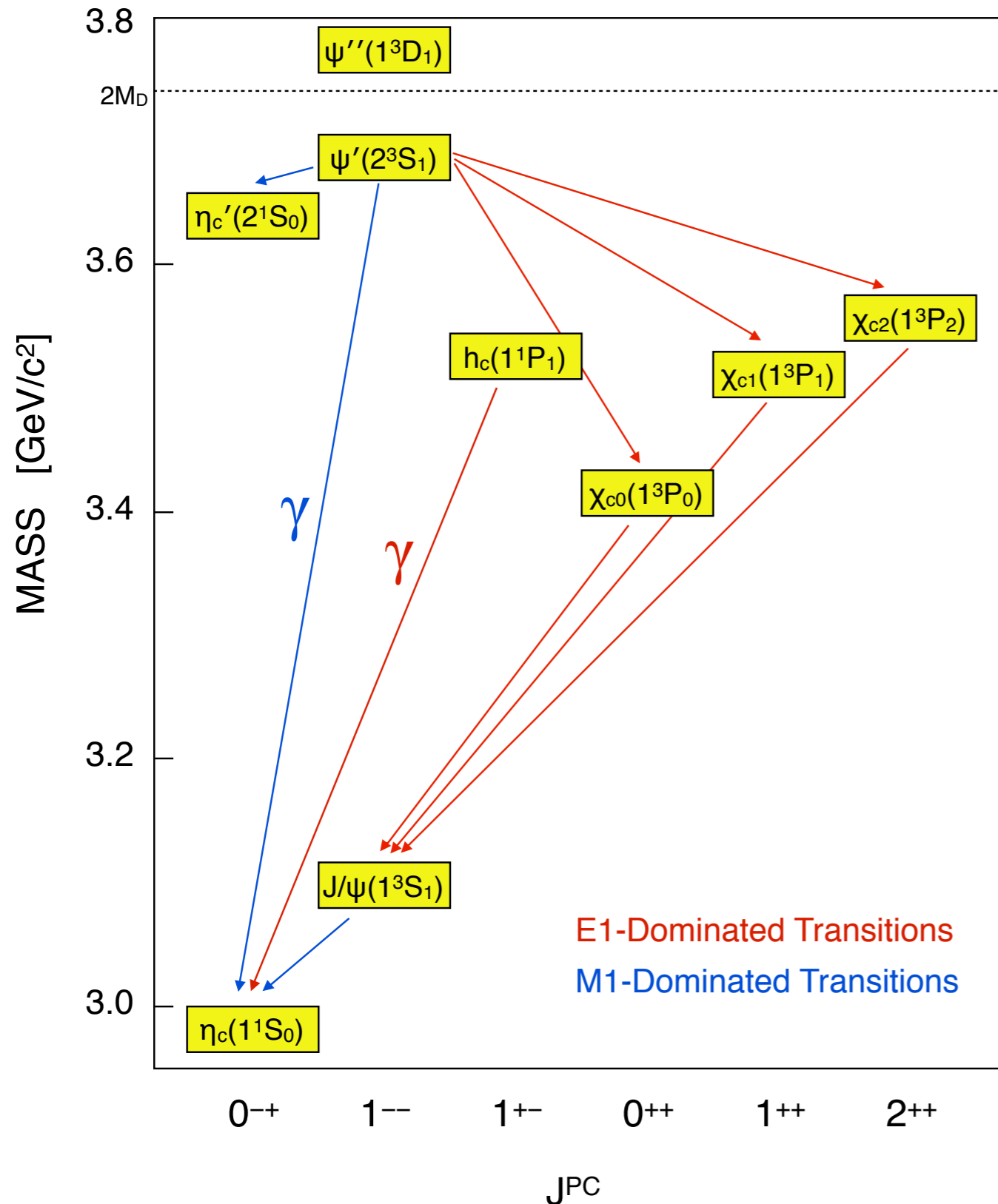


## BESIII Detector (a standard high-energy physics experiment)

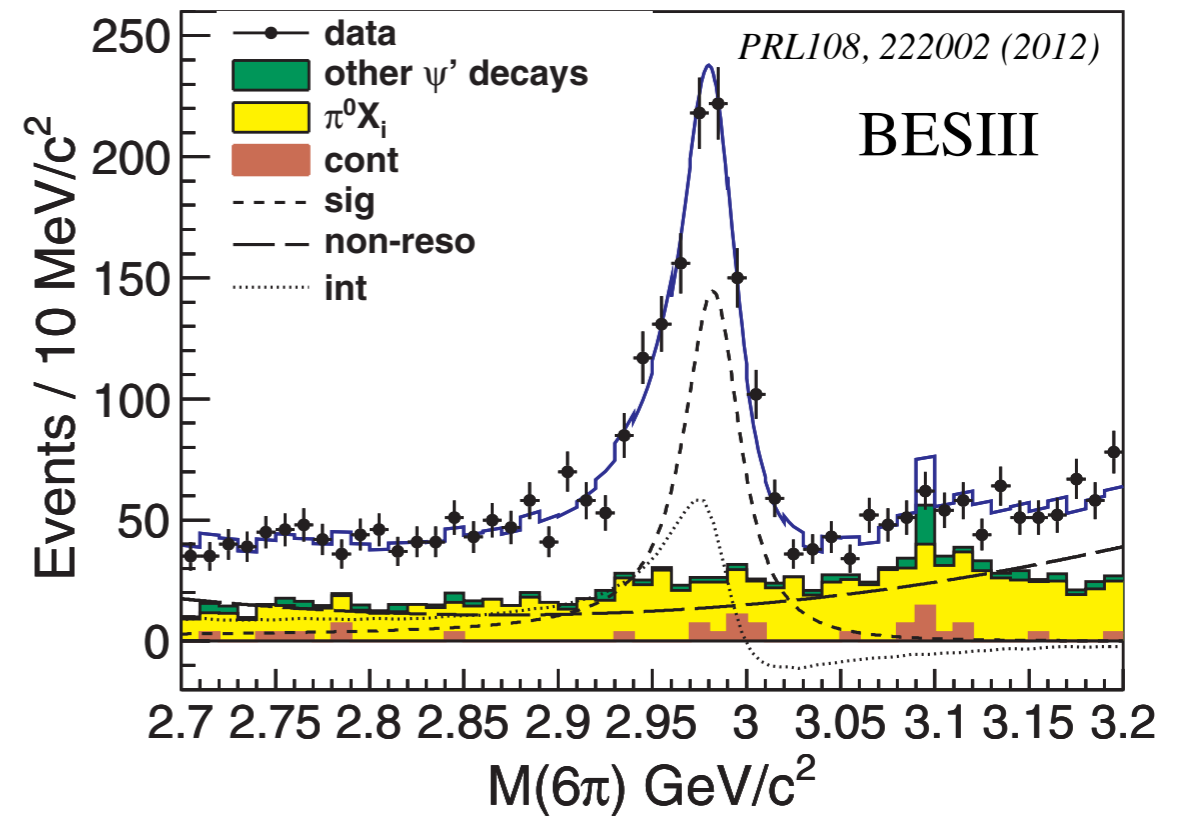
- (1) Calorimeter: photon energy and direction
- (2) Drift Chamber and Magnet: charged particle momentum
- (3) Time-of-Flight (TOF): charged particle mass



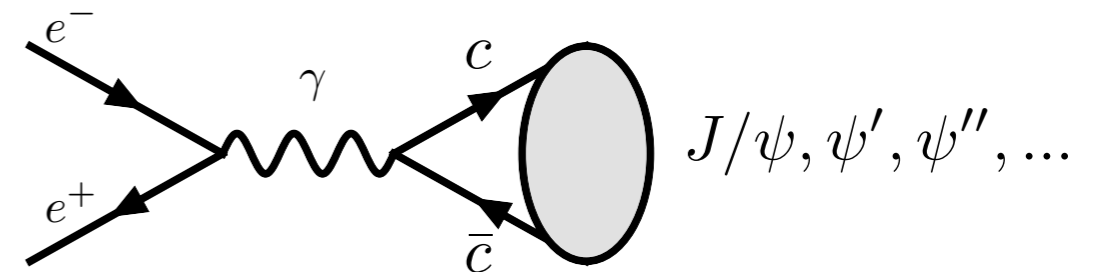
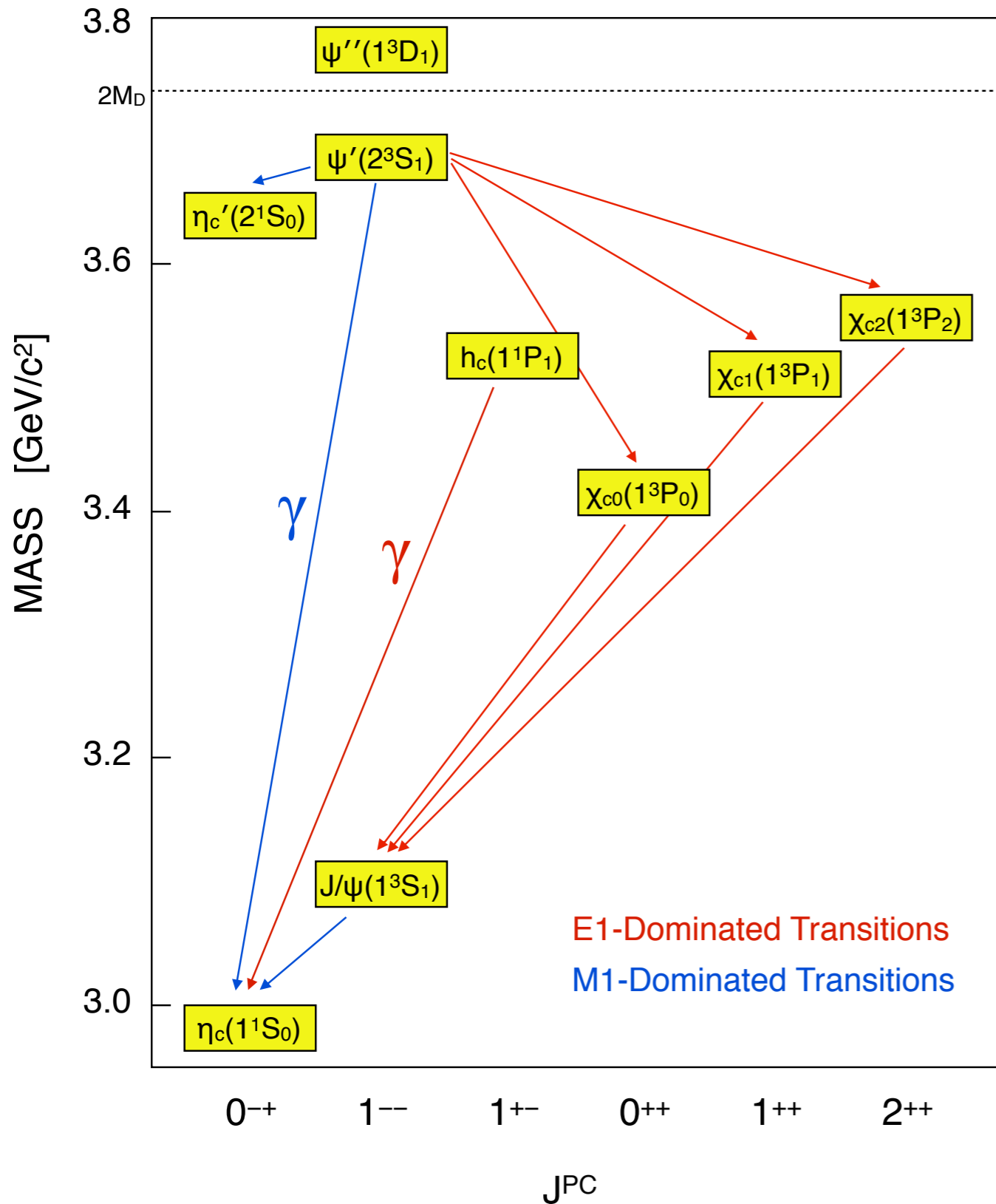
# I. Charmonium: the Hydrogen atom of the strong force



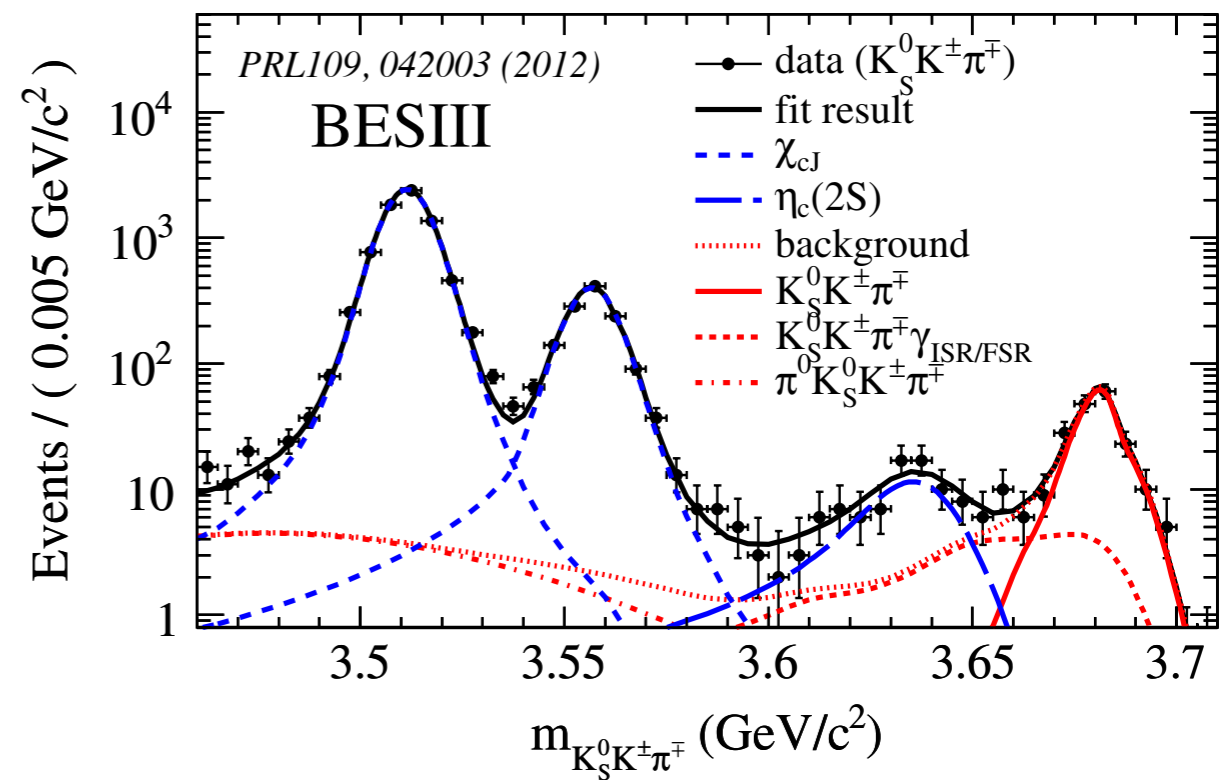
$$\psi' \rightarrow \gamma \eta_c; \eta_c \rightarrow 6\pi$$



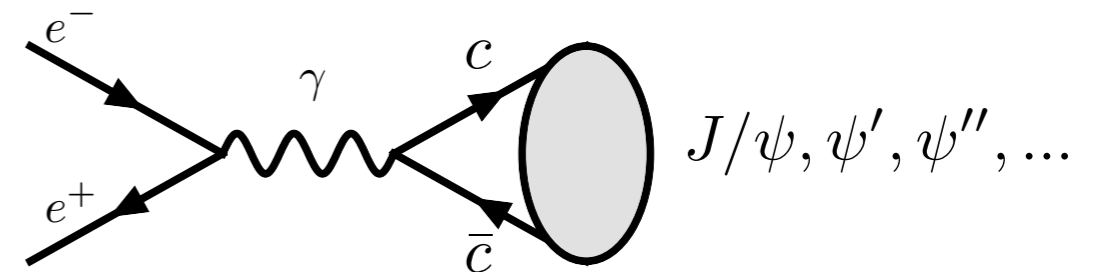
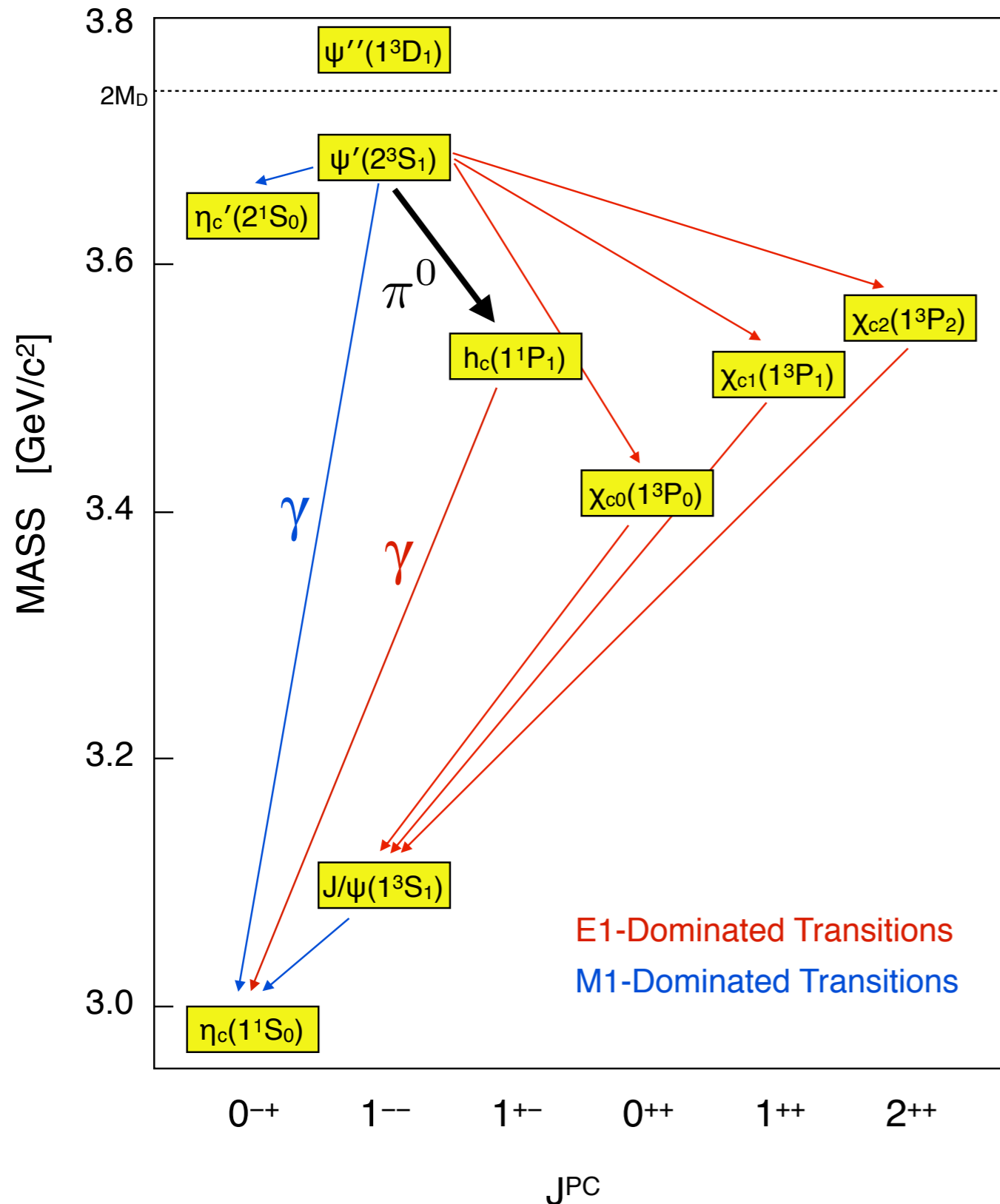
# I. Charmonium: the Hydrogen atom of the strong force



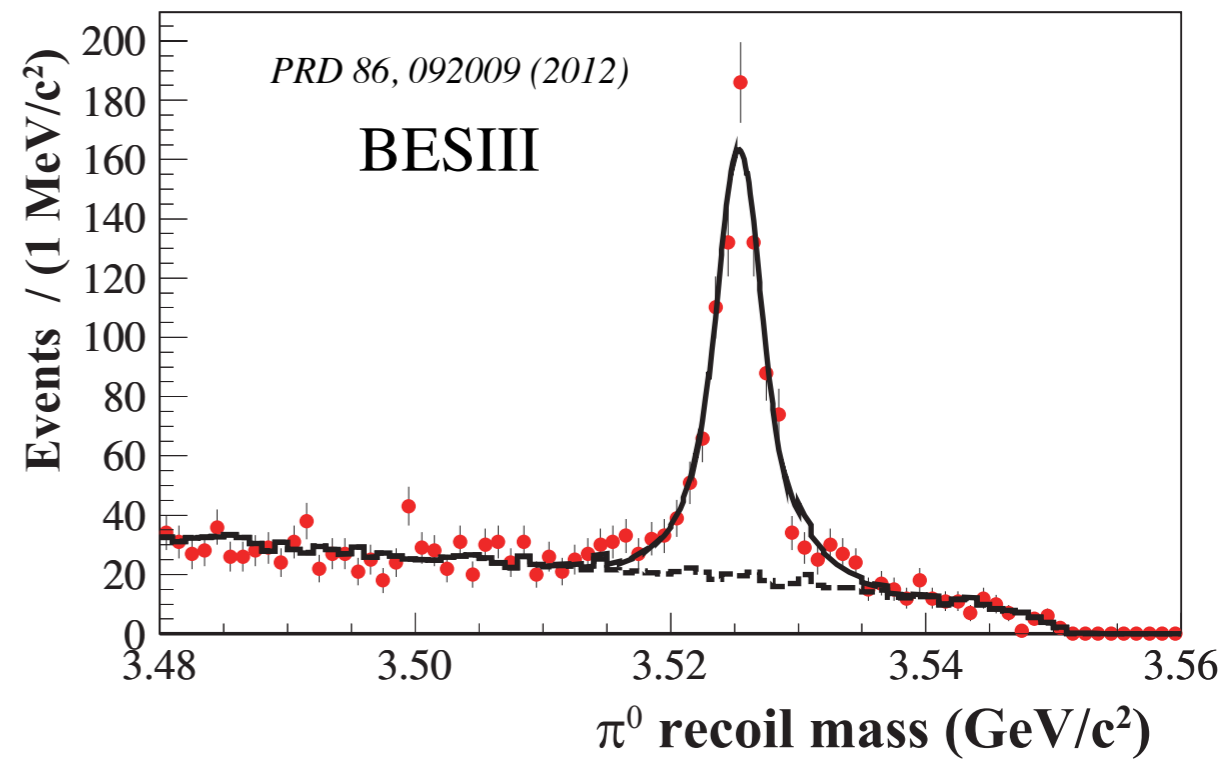
$$\psi' \rightarrow \gamma \eta'_c; \eta'_c \rightarrow K_S^0 K^\pm \pi^\pm$$



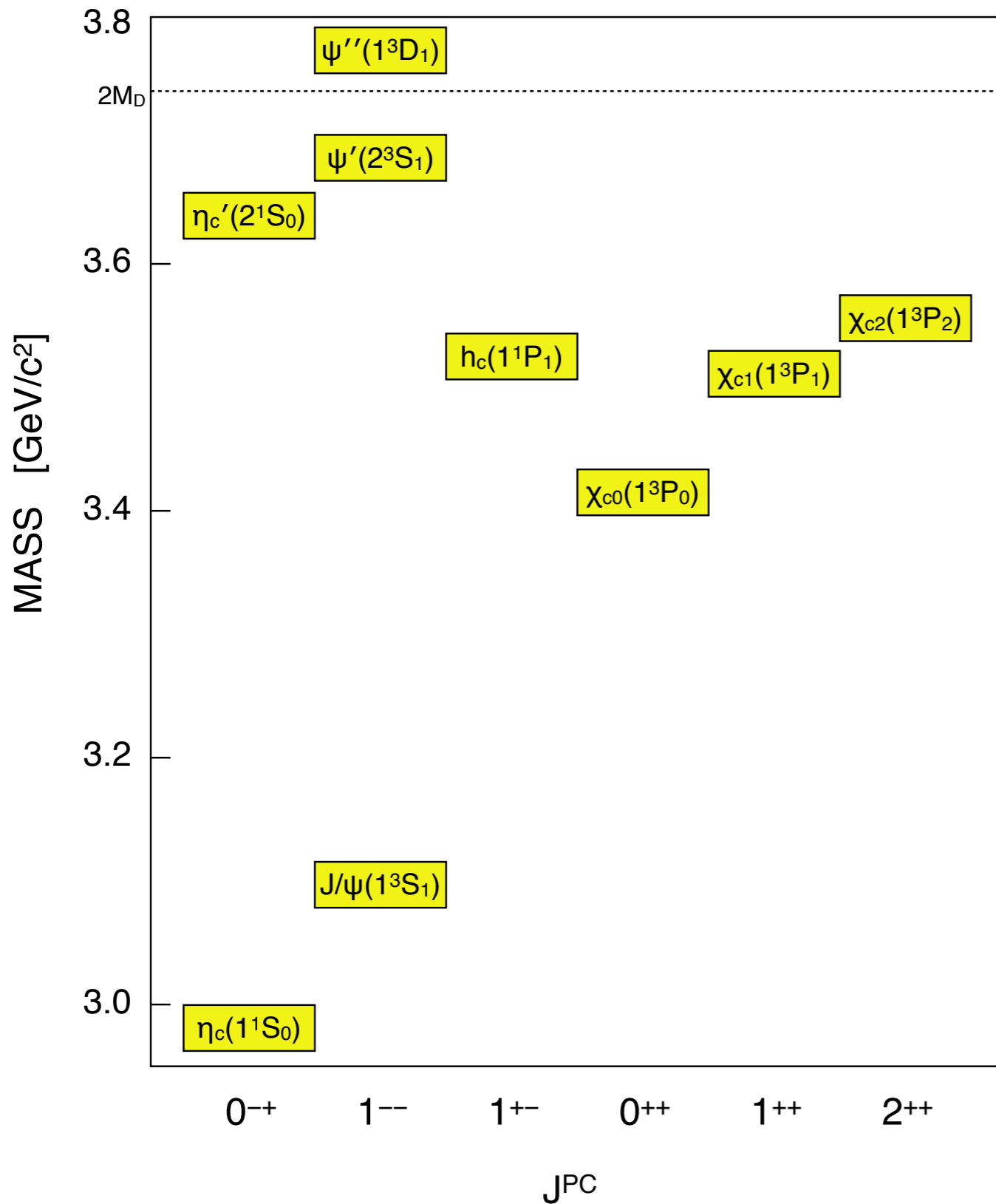
# I. Charmonium: the Hydrogen atom of the strong force



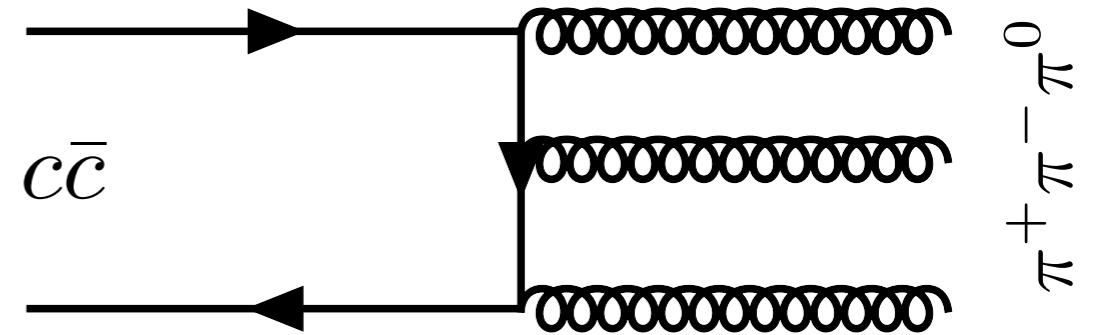
$$\psi' \rightarrow \pi^0 h_c; \quad h_c \rightarrow \gamma \eta_c$$



# I. Charmonium: the Hydrogen atom of the strong force

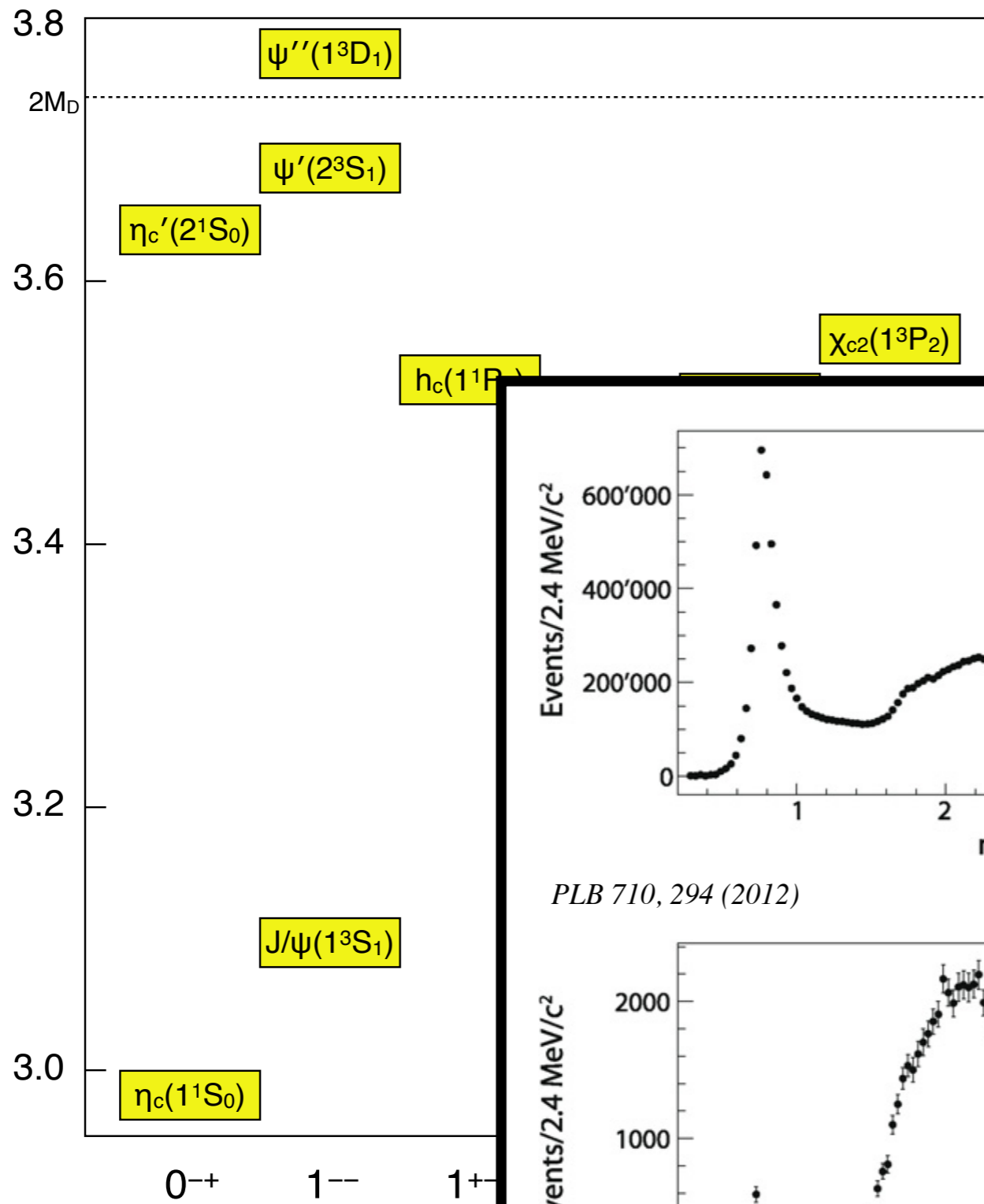


Hadronic decays of the  $J/\psi$  and  $\psi(2S)$ :

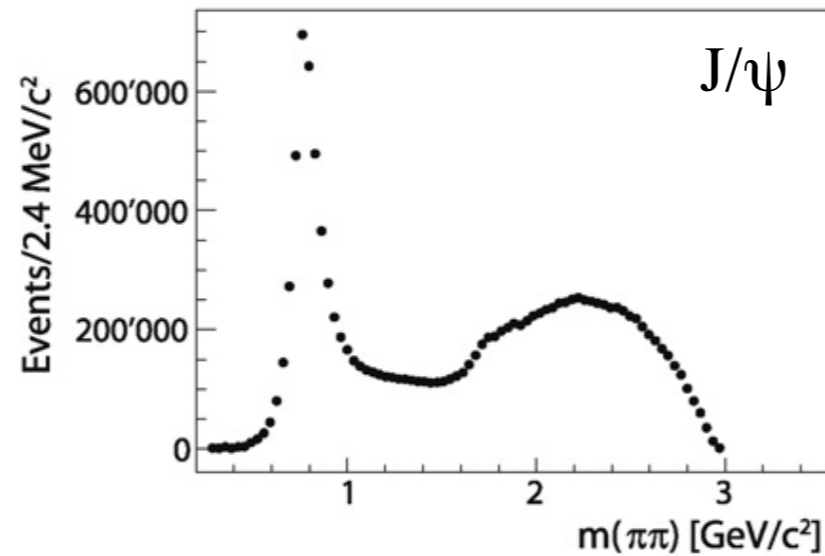
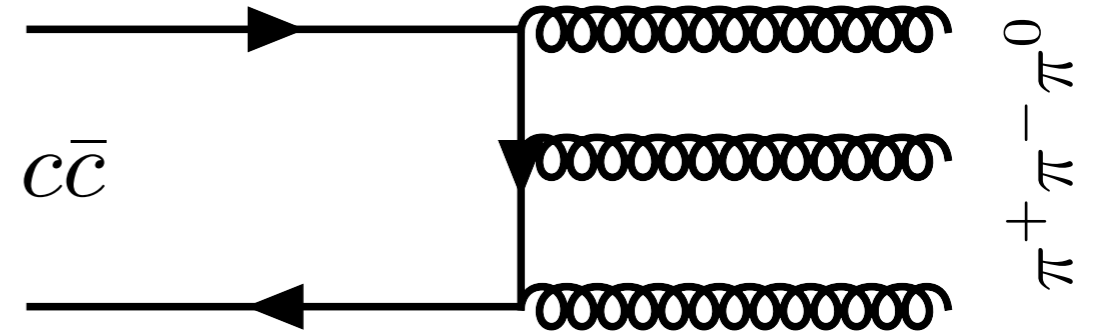




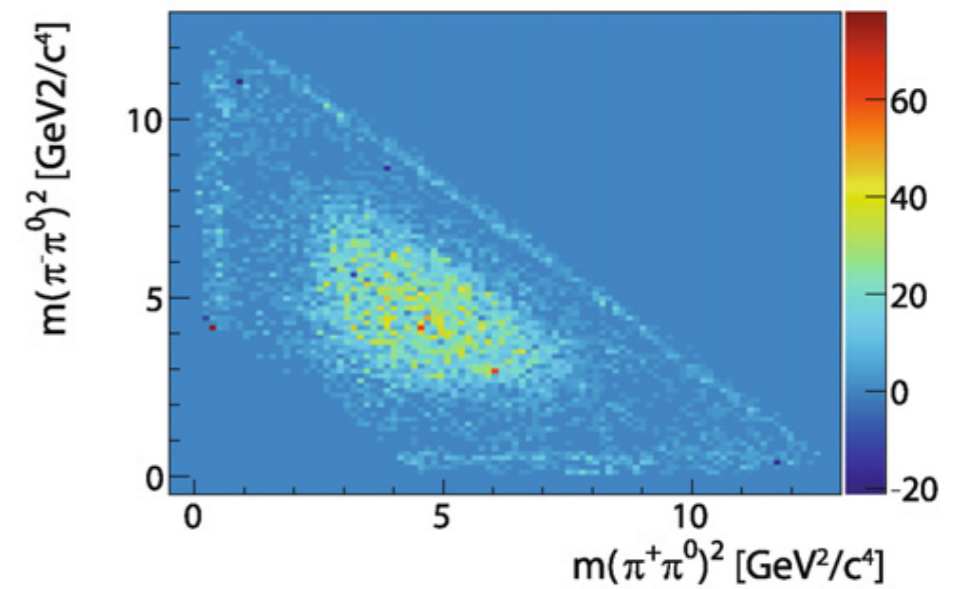
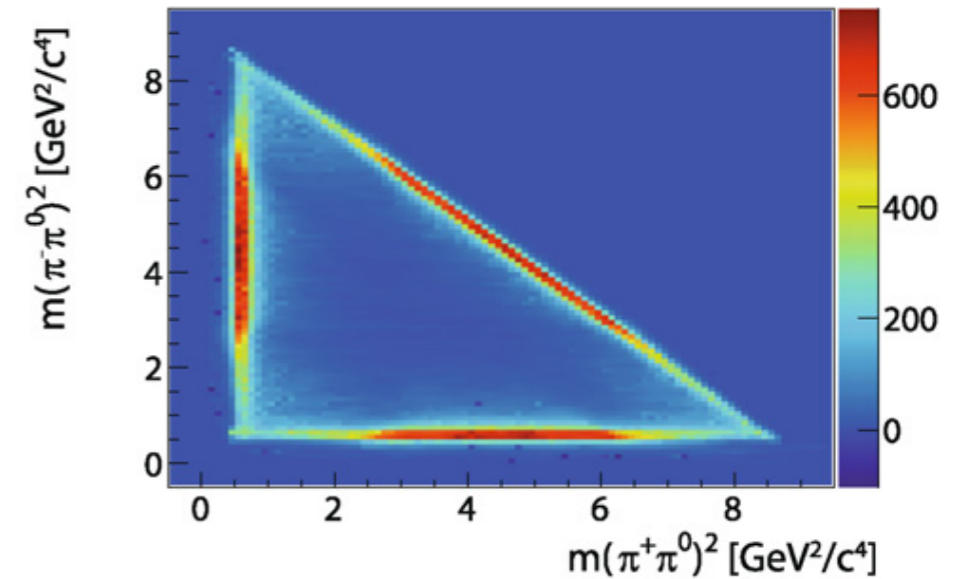
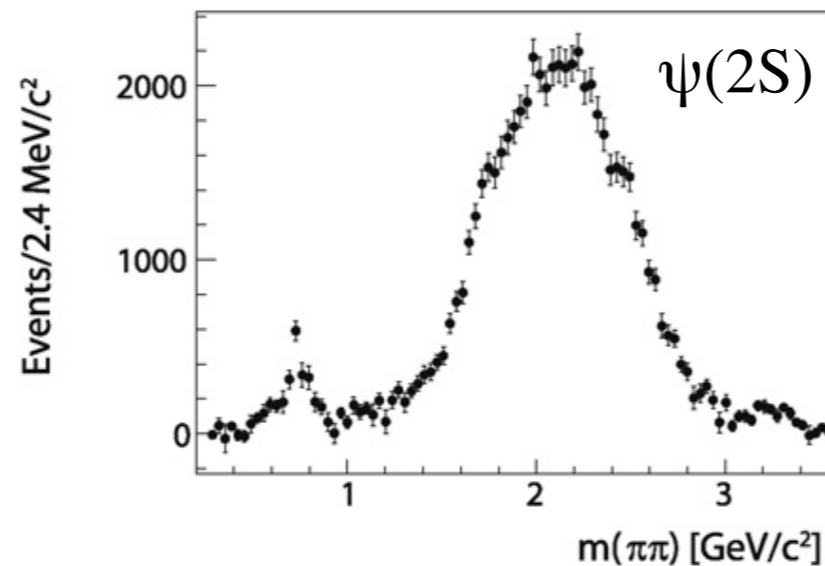
# I. Charmonium: the Hydrogen atom of the strong force



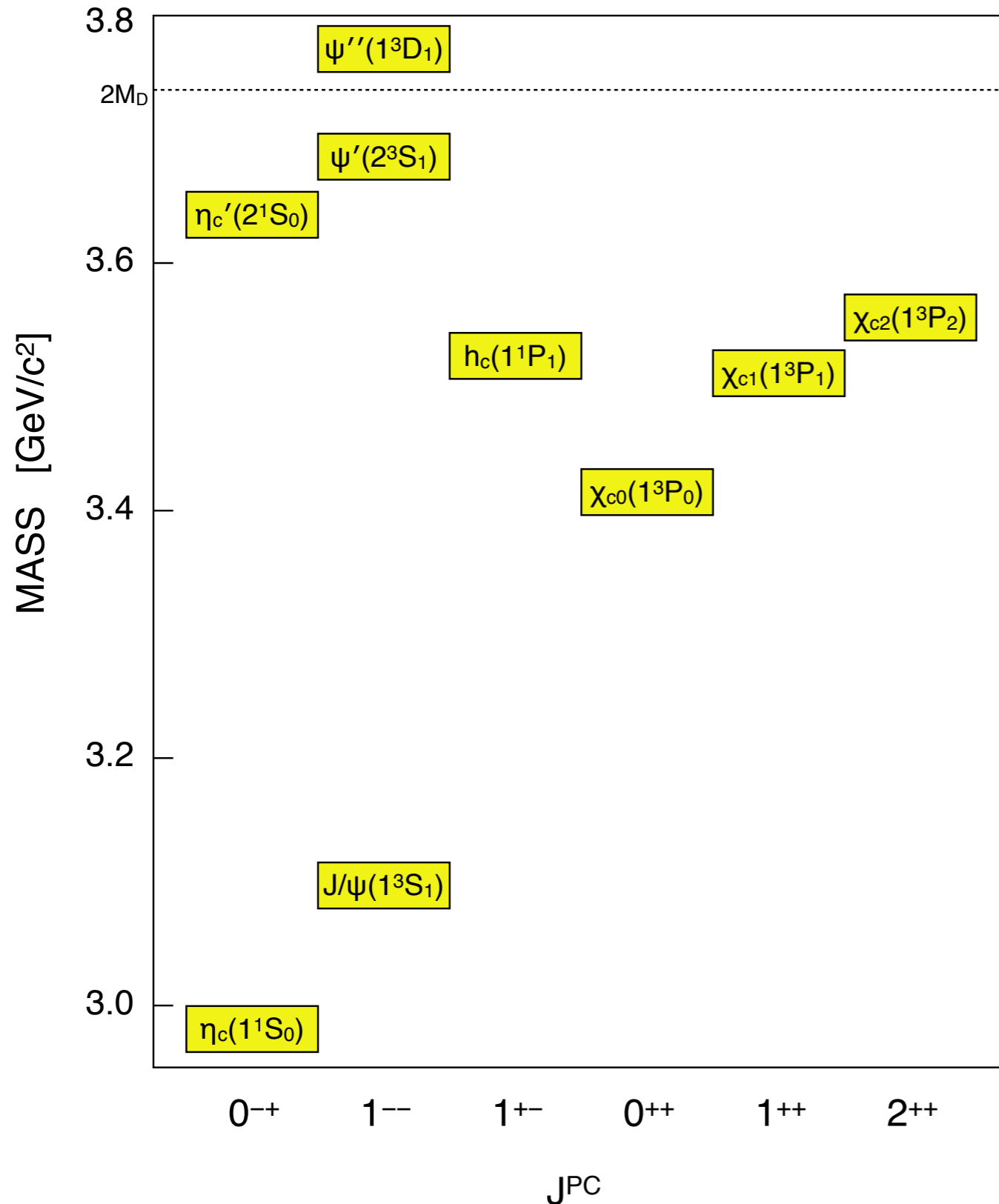
Hadronic decays of the  $J/\psi$  and  $\psi(2S)$ :



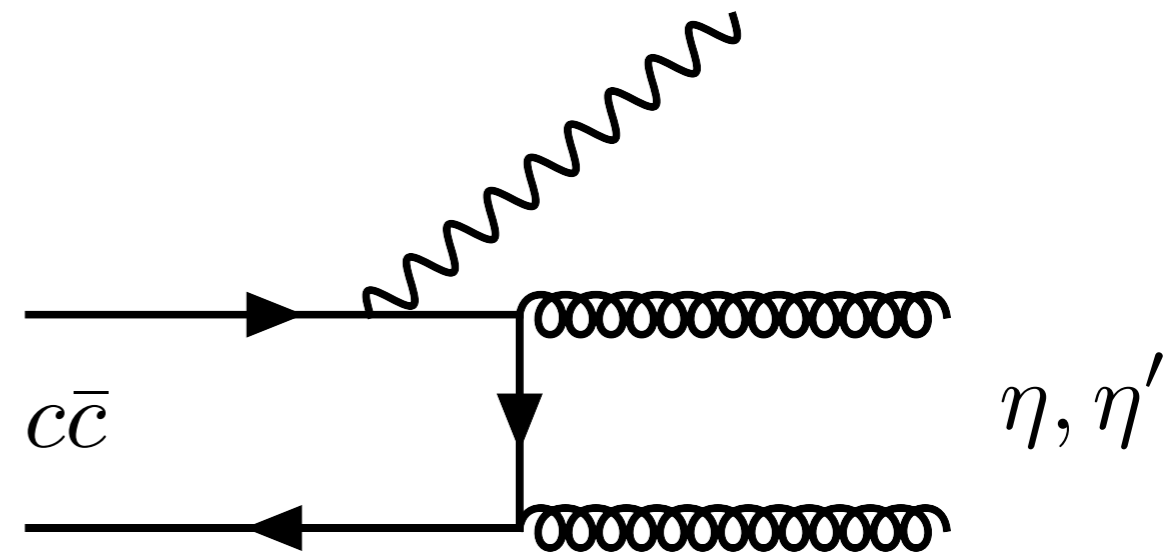
PLB 710, 294 (2012)



# I. Charmonium: the Hydrogen atom of the strong force



Radiative decays of the  $J/\psi$  and  $\psi(2S)$ :



$$\frac{\mathcal{B}(J/\psi \rightarrow \gamma\eta)}{\mathcal{B}(J/\psi \rightarrow \gamma\eta')} = (21.1 \pm 0.9)\%$$

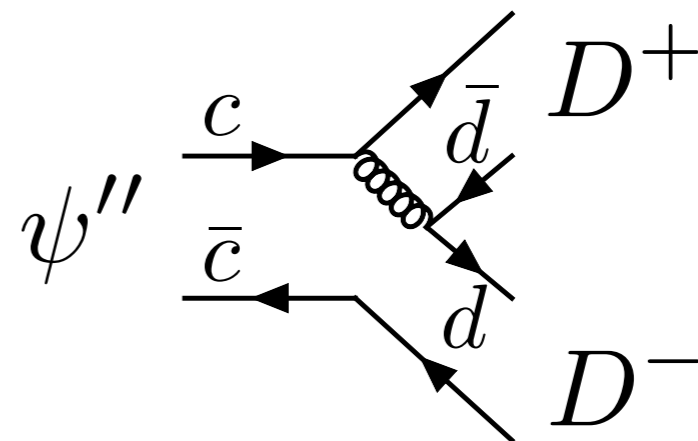
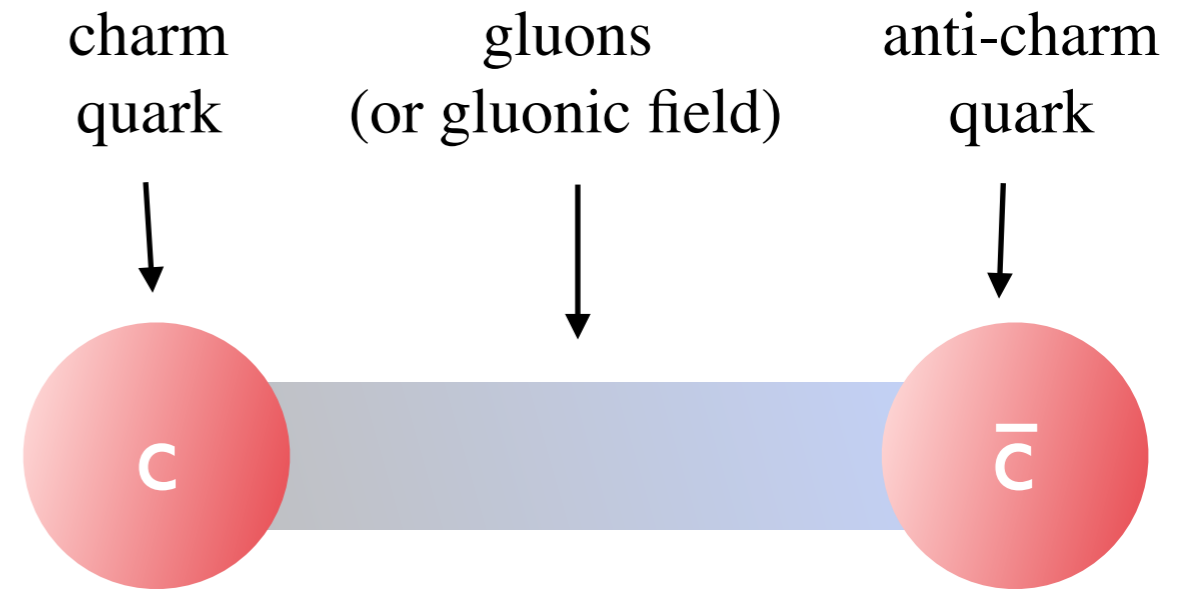
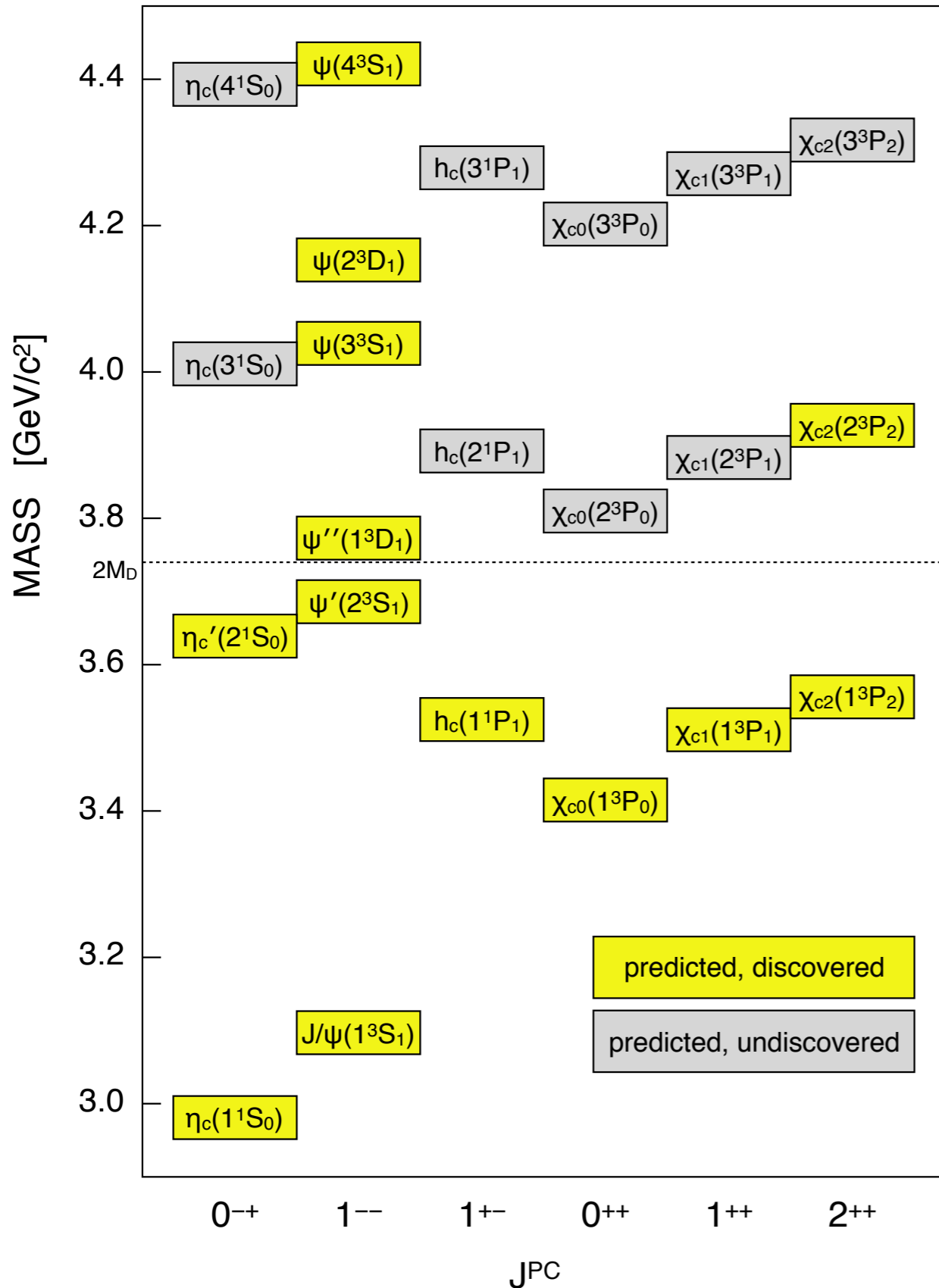
$$\frac{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta)}{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta')} = (1.1 \pm 0.4)\%$$

I. Charmonium

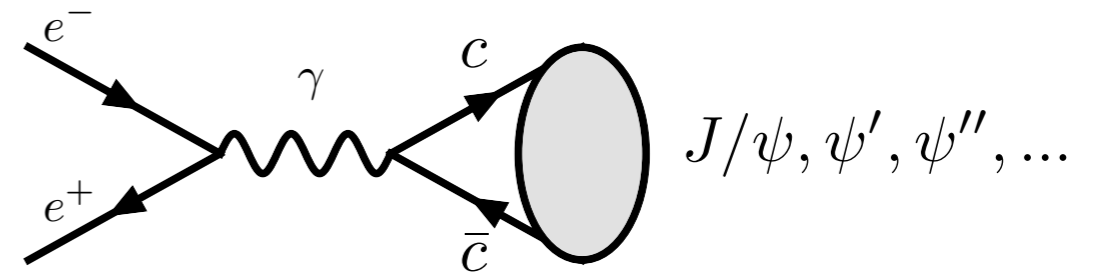
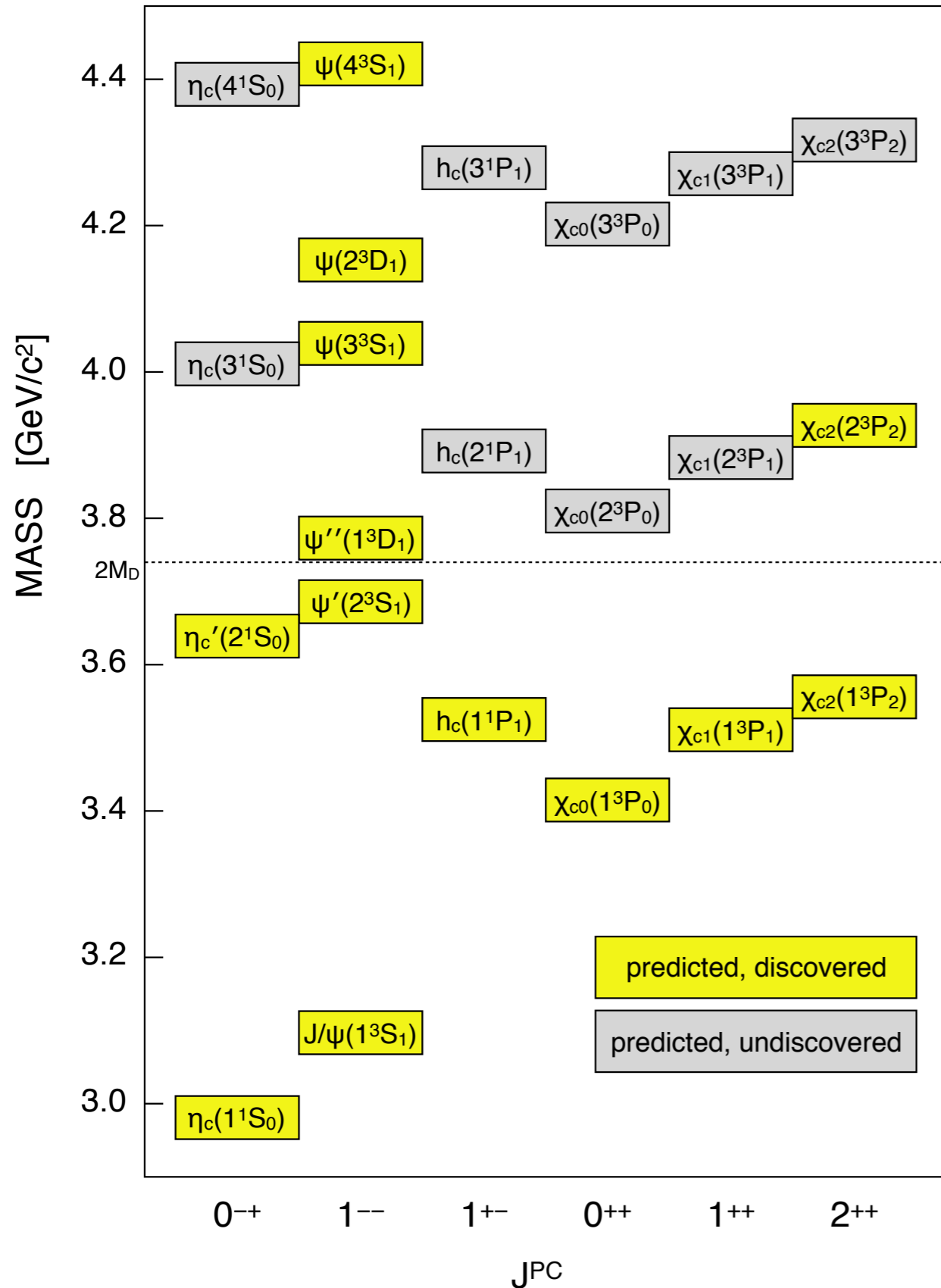
II. “Charmonium”

III. “Charmonium” at BESIII

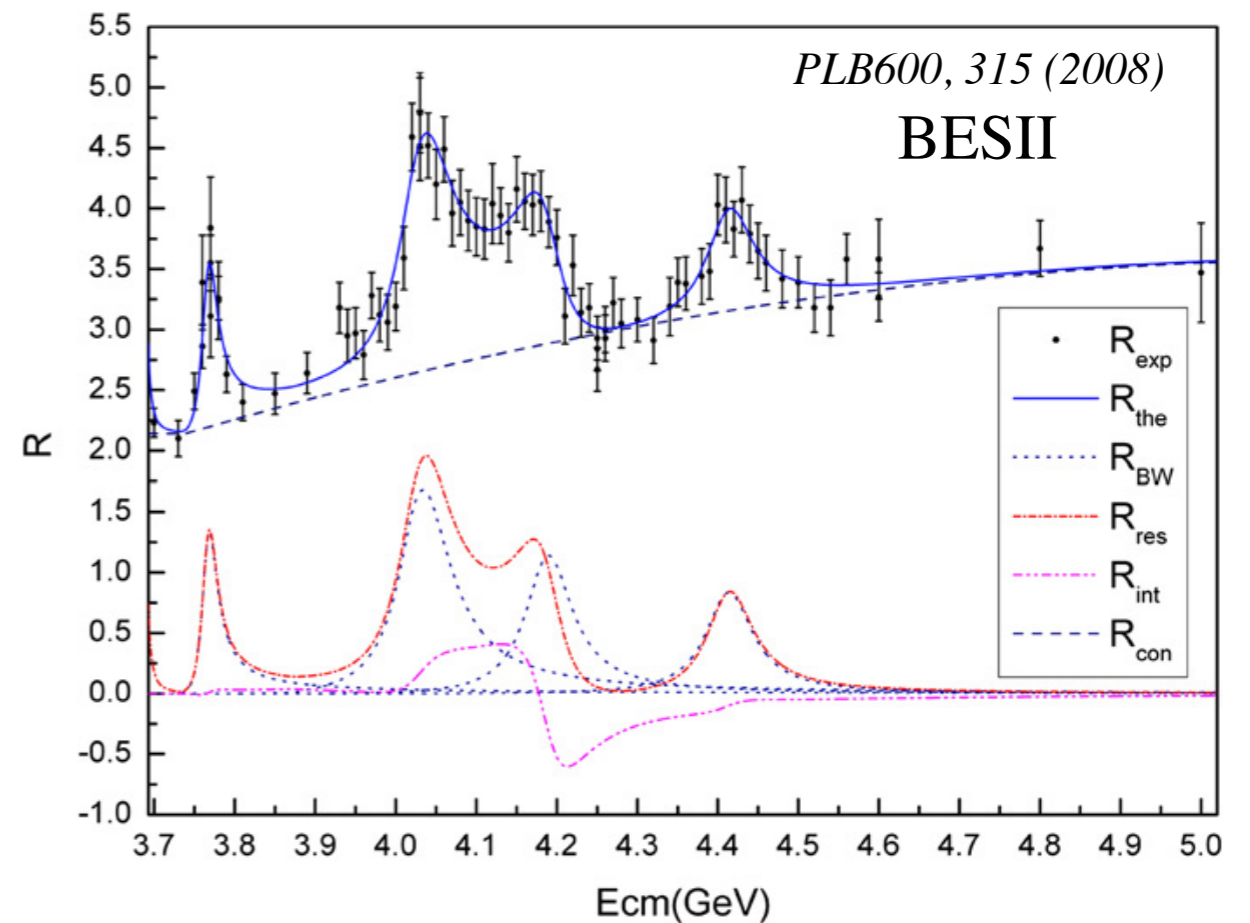
## II. Charmonium: problems and mysteries



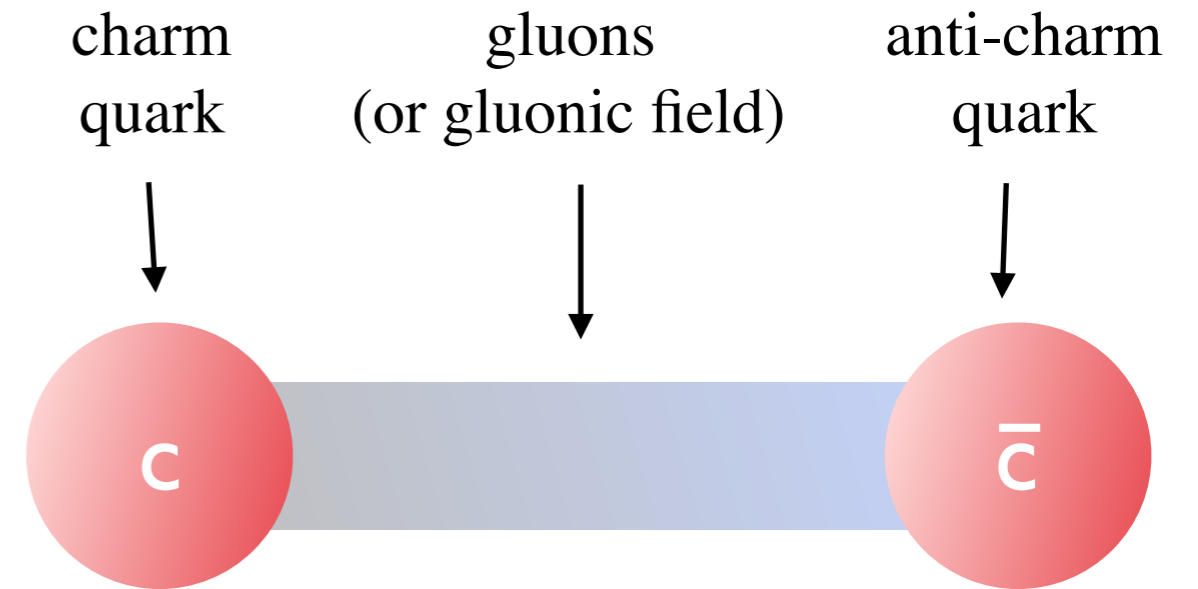
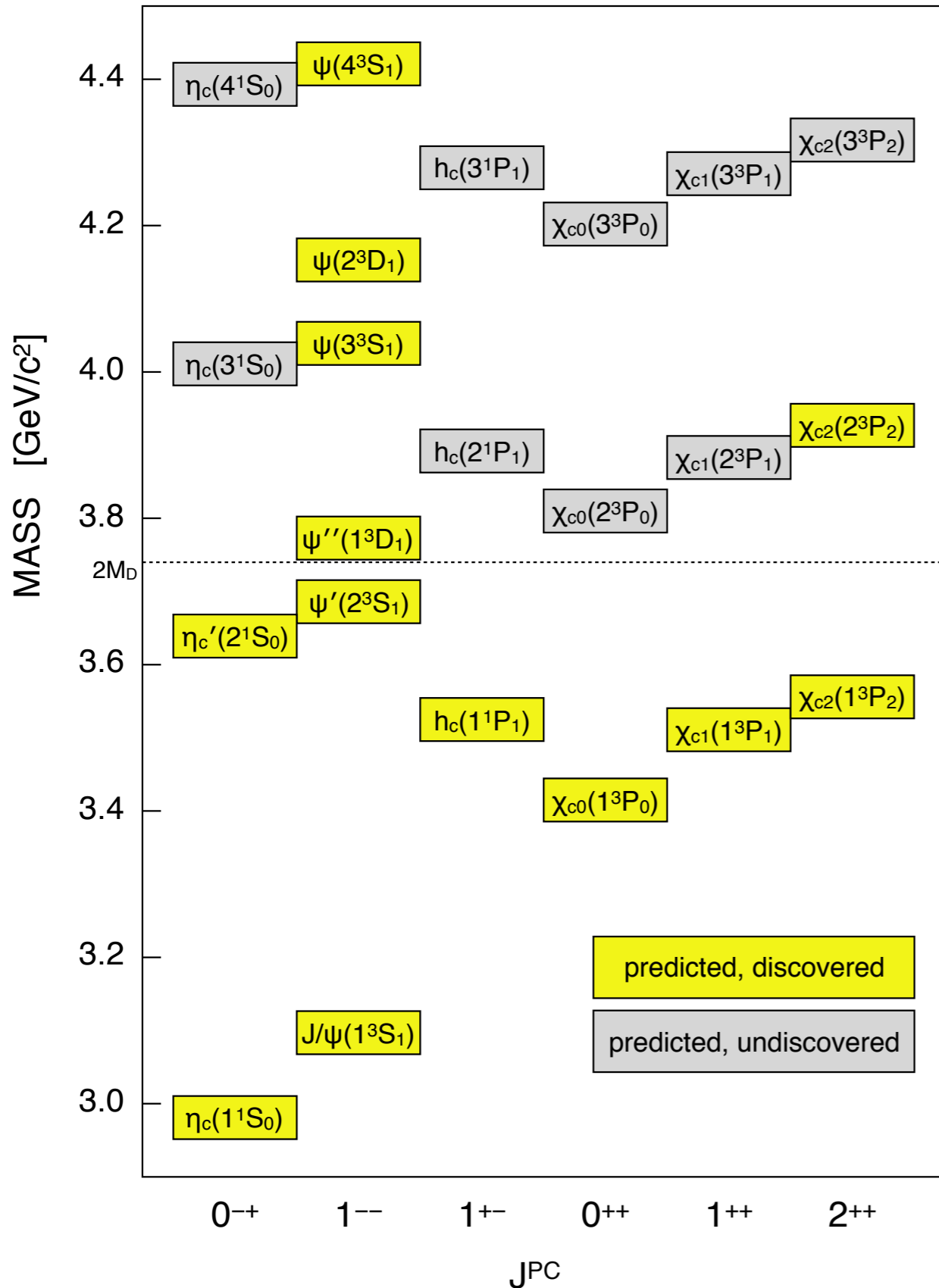
## II. Charmonium: problems and mysteries



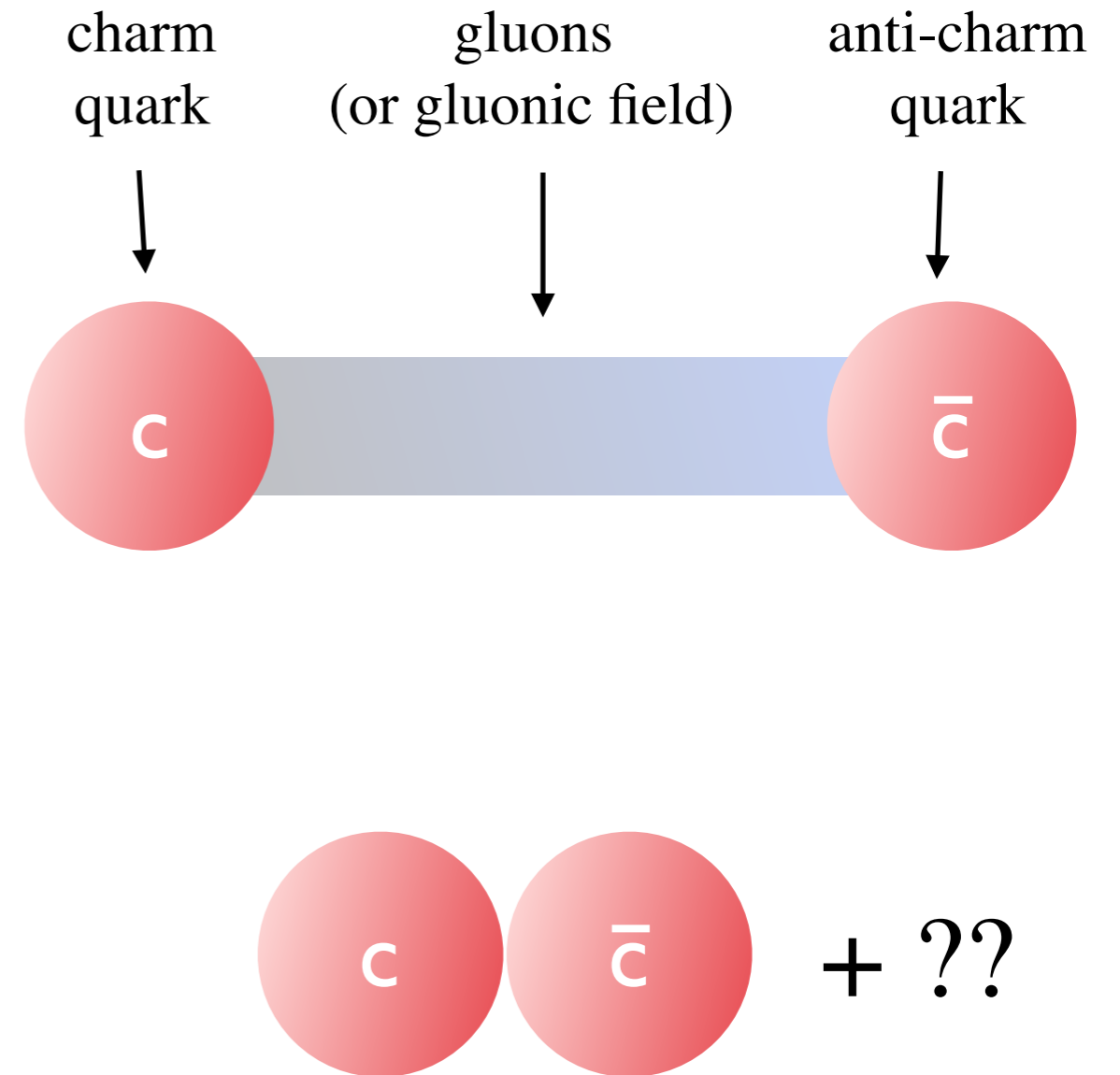
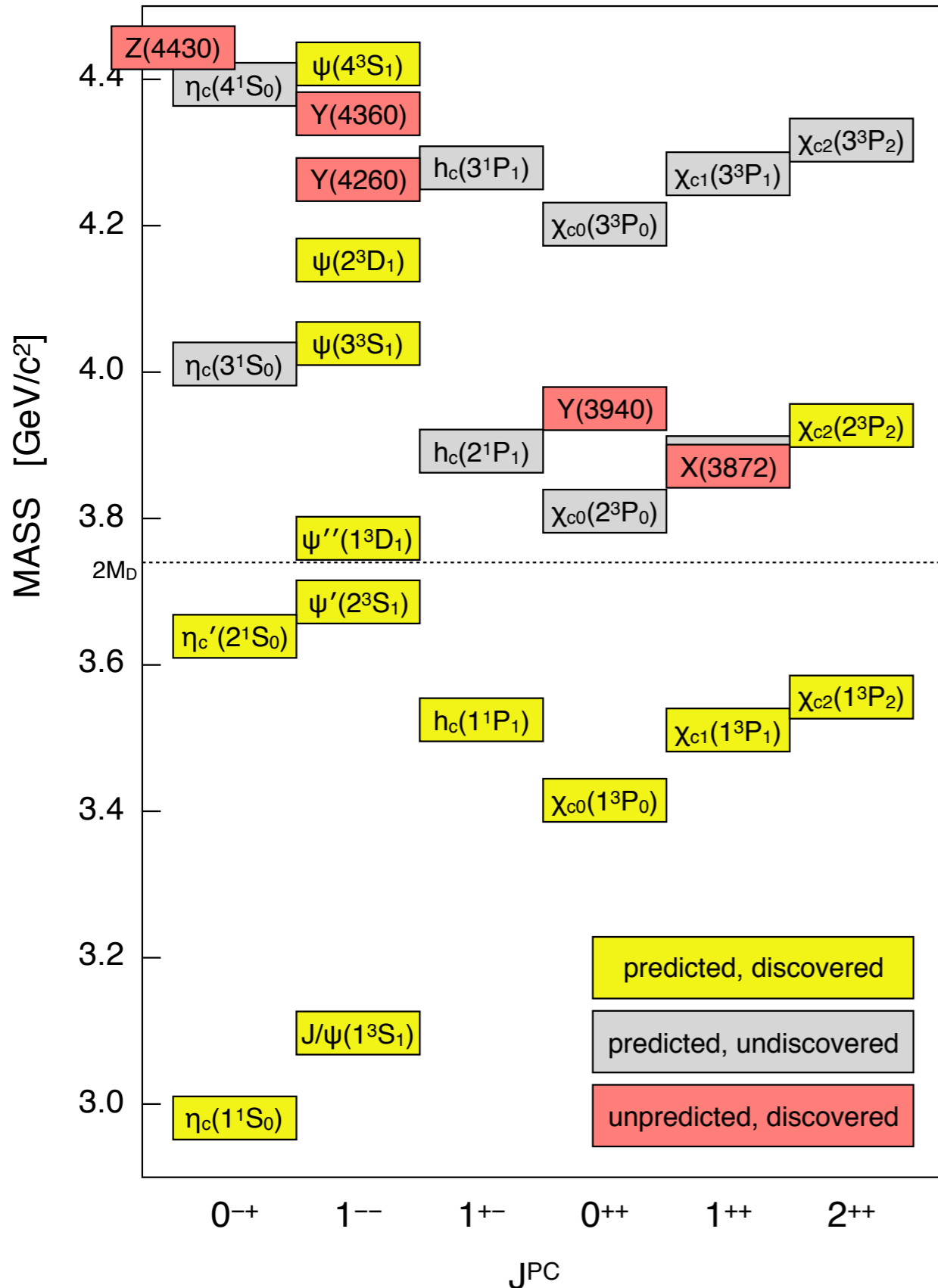
$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$



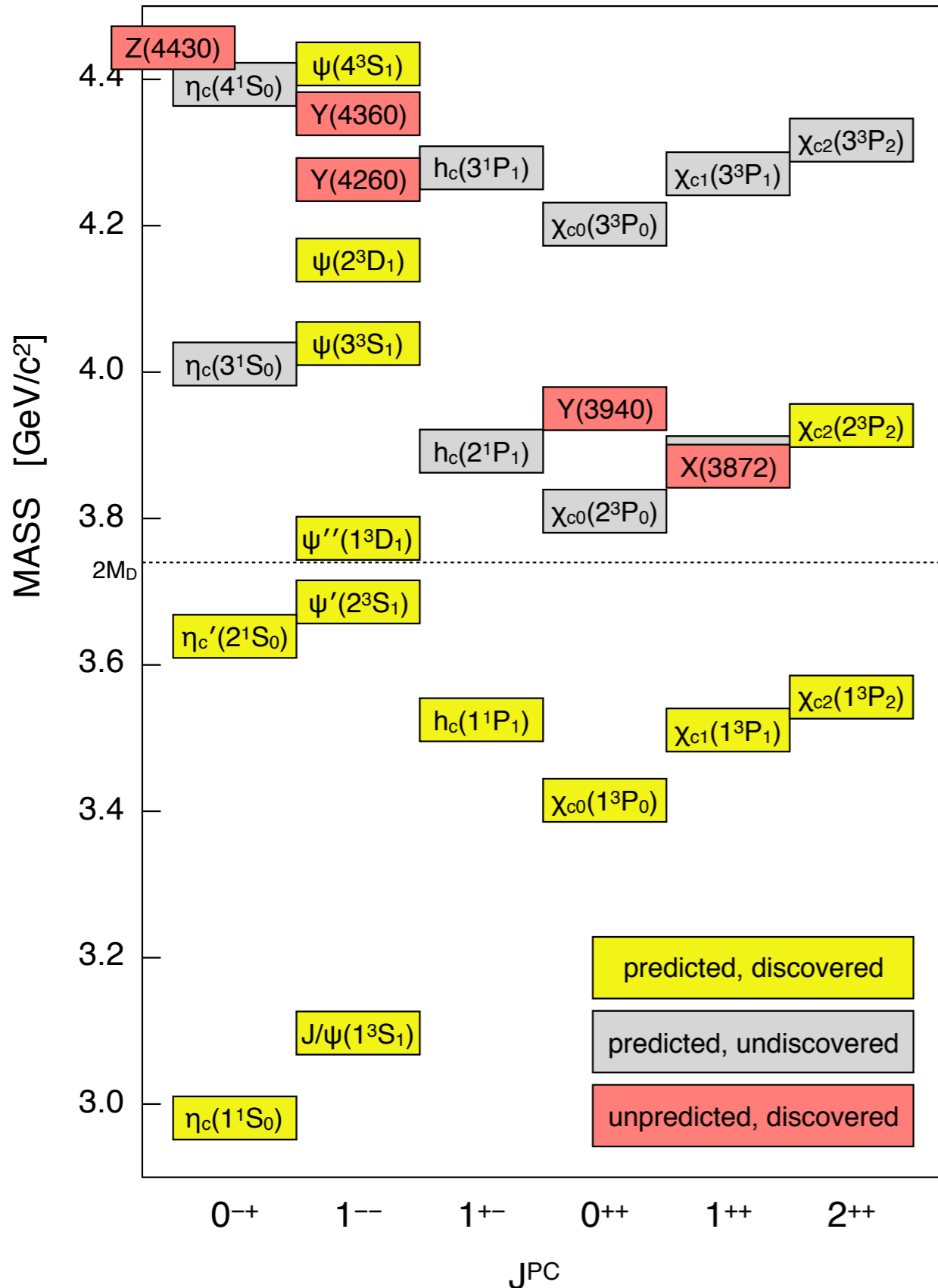
## II. Charmonium: problems and mysteries



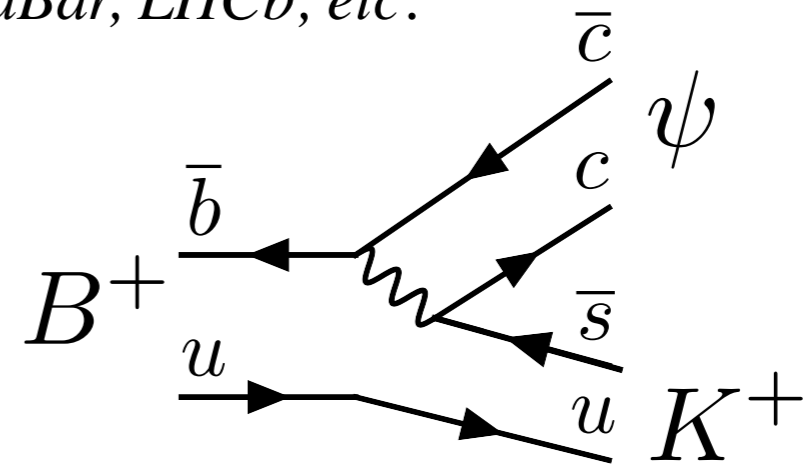
## II. Charmonium: problems and mysteries



## II. Charmonium: problems and mysteries

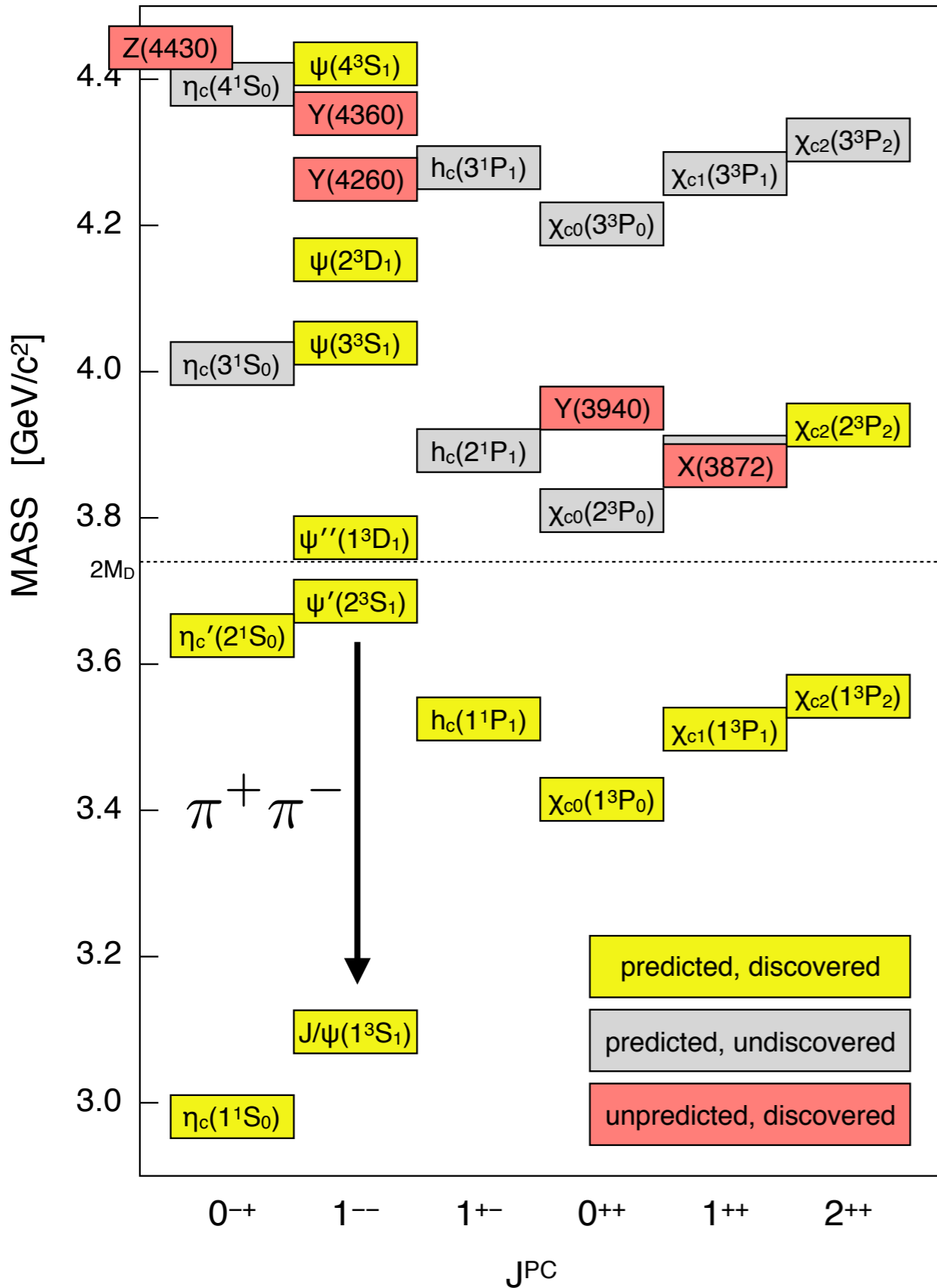


*Belle, BaBar, LHCb, etc.*

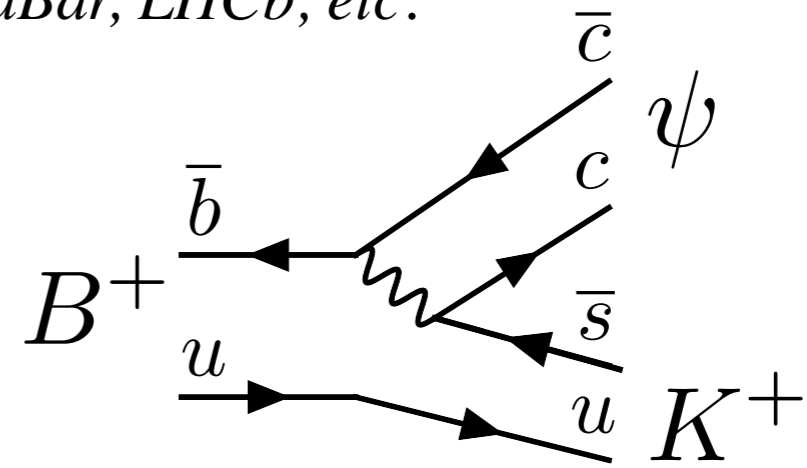




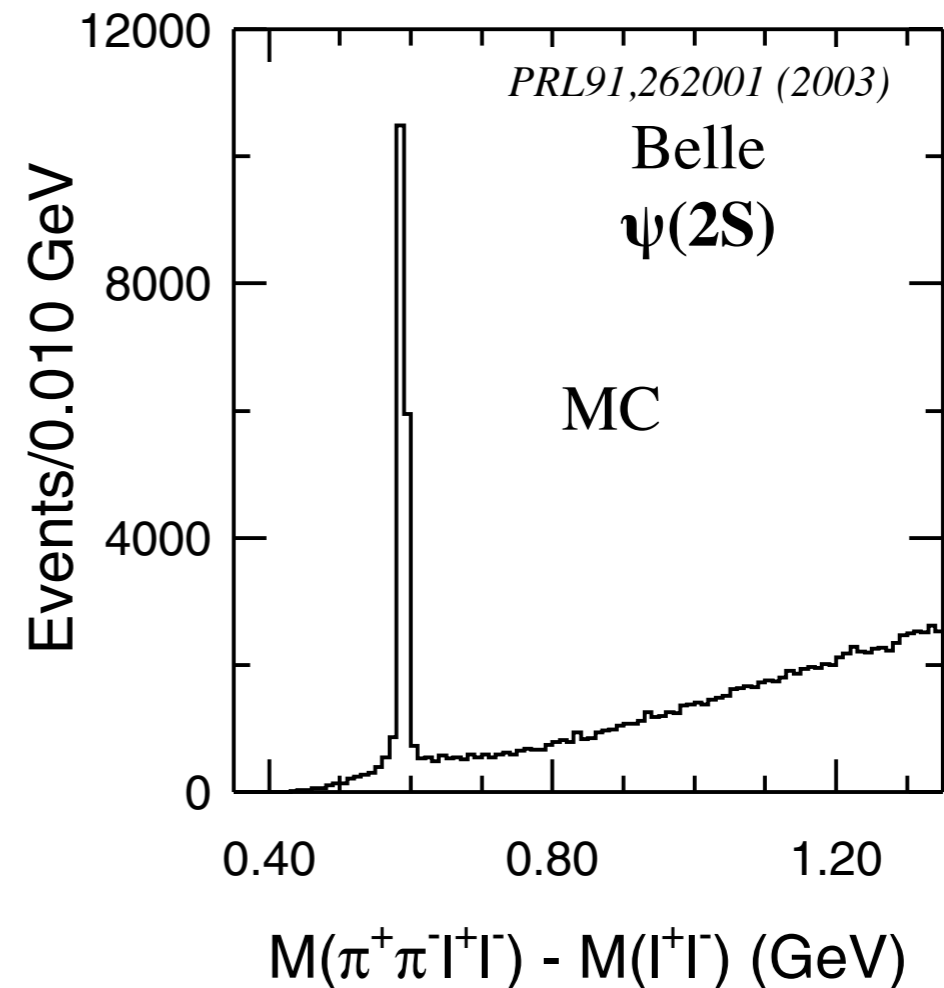
# II. Charmonium: problems and mysteries



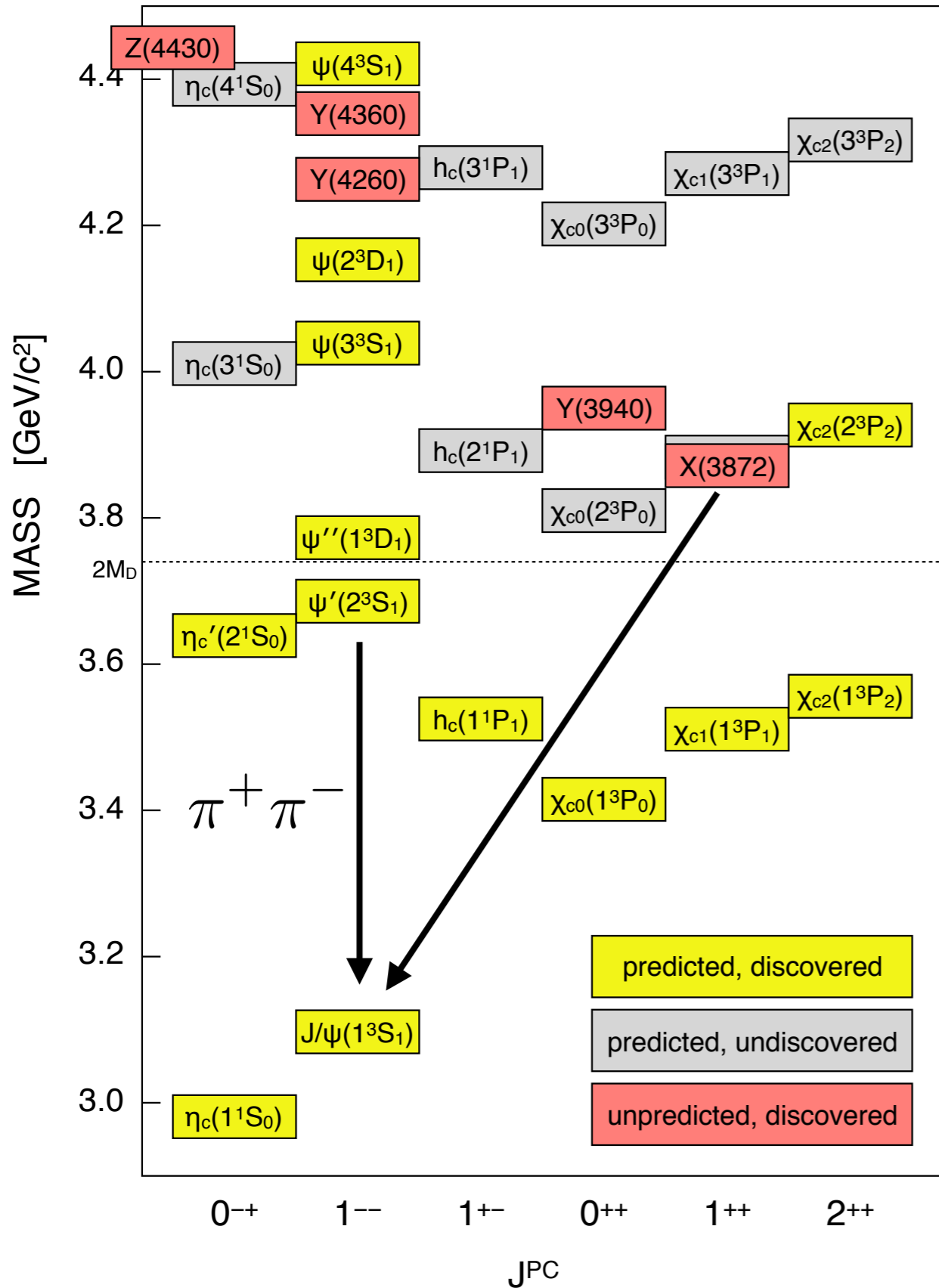
*Belle, BaBar, LHCb, etc.*



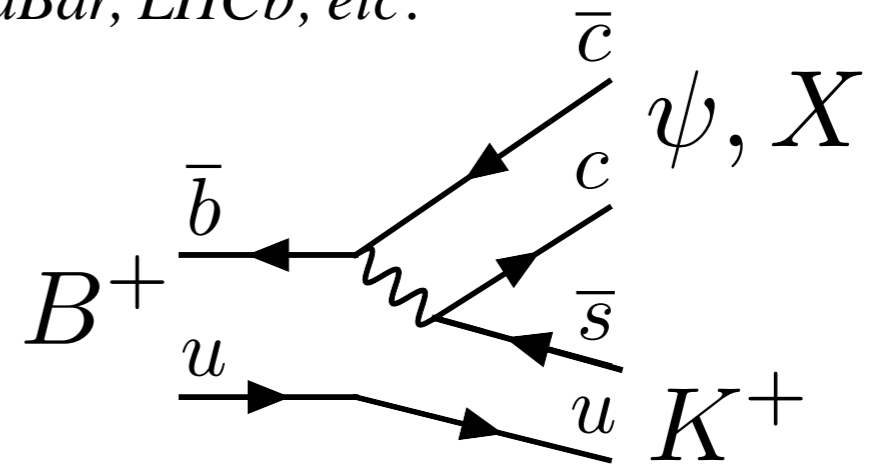
$$B \rightarrow K(\pi^+\pi^- J/\psi)$$



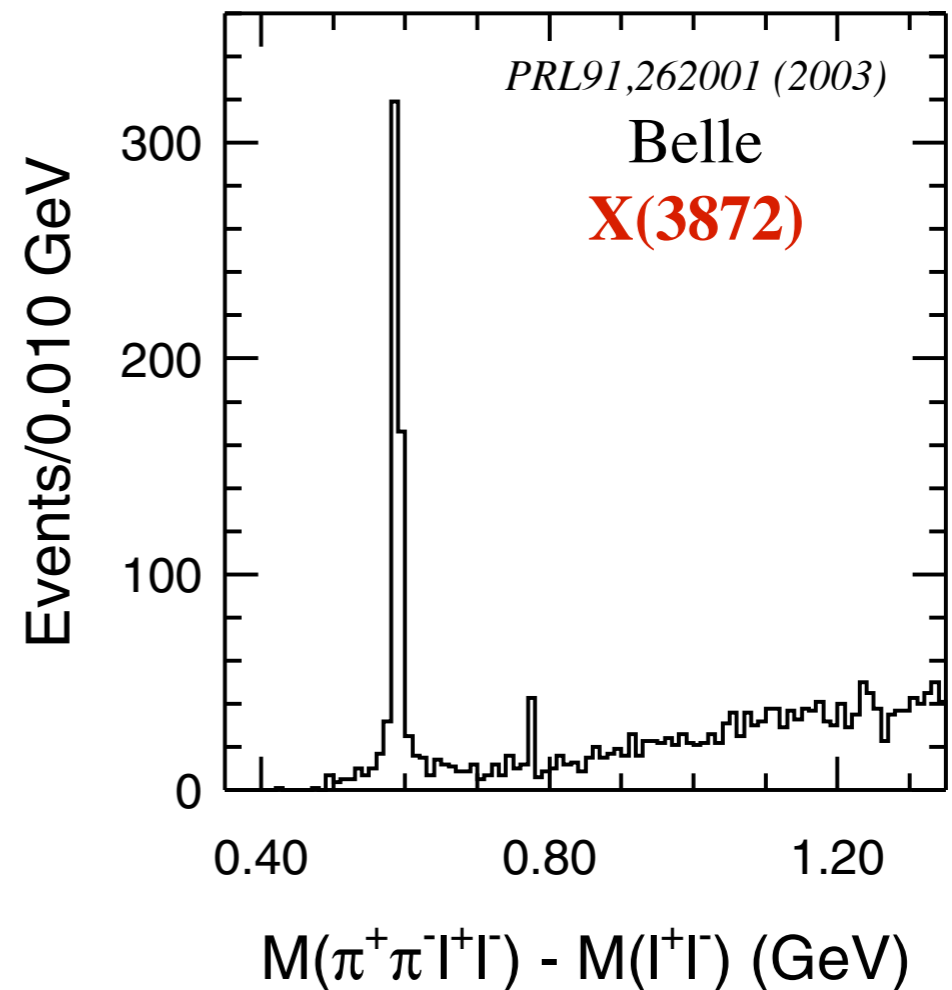
# II. Charmonium: problems and mysteries



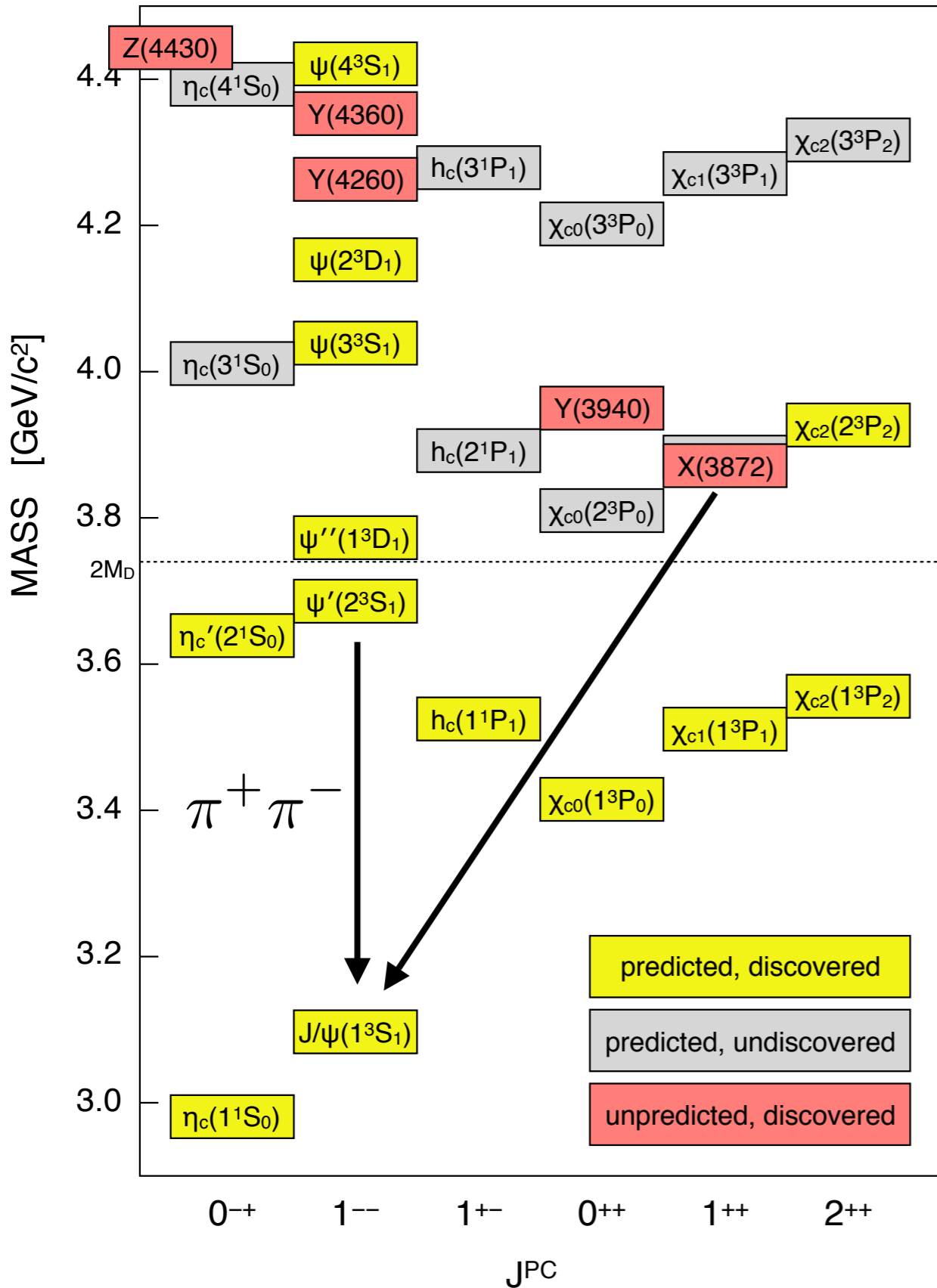
Belle, BaBar, LHCb, etc.



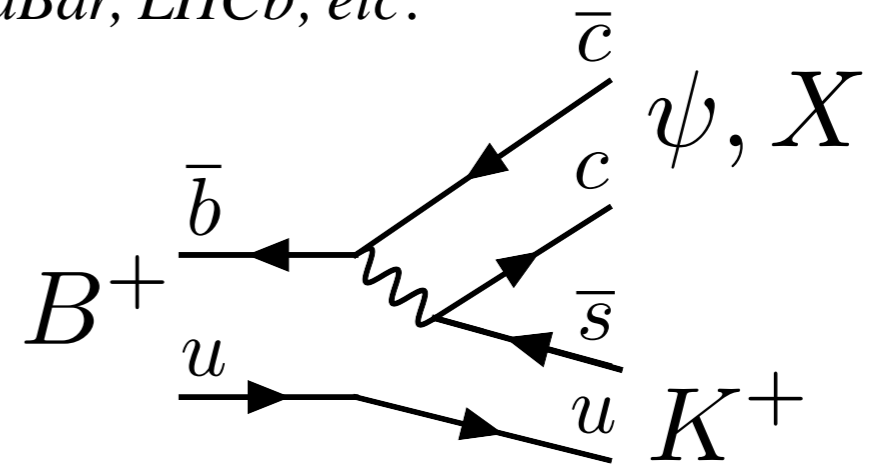
$B \rightarrow K(\pi^+ \pi^- J/\psi)$



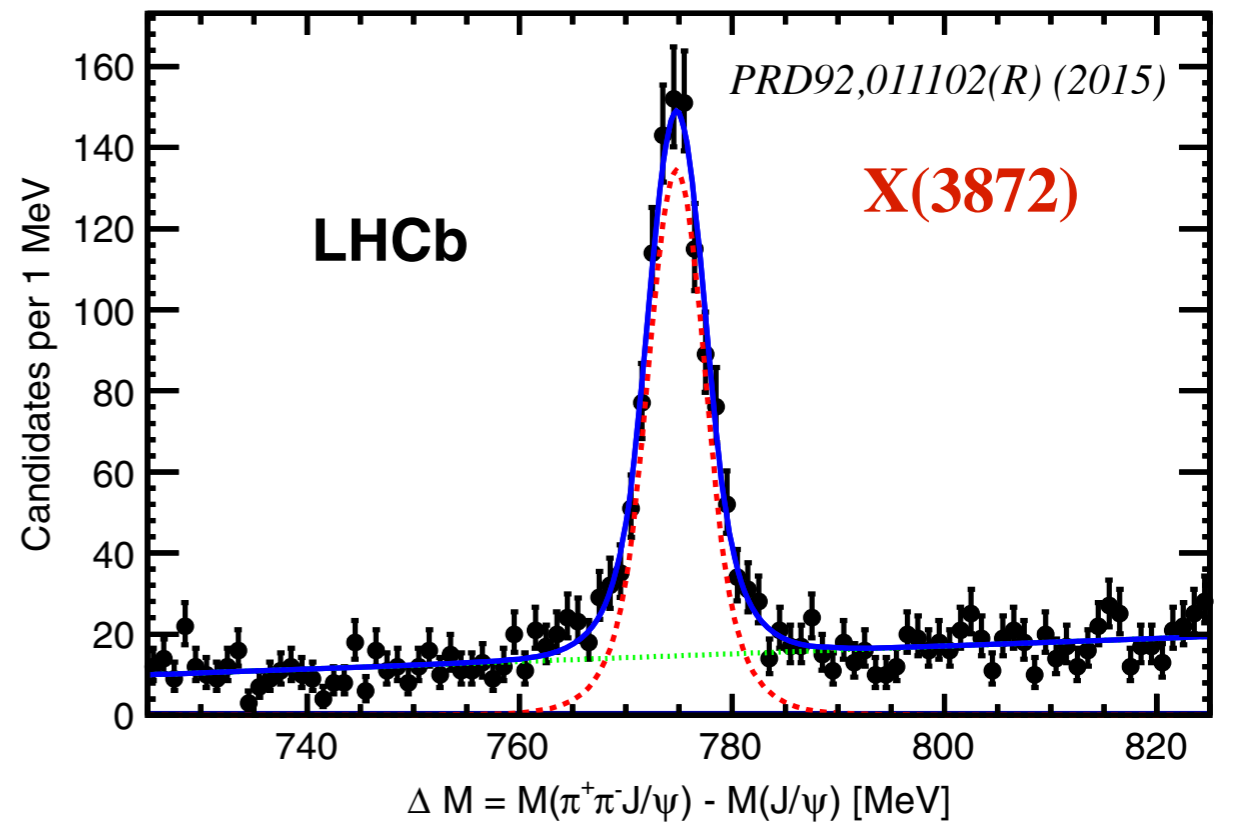
# II. Charmonium: problems and mysteries



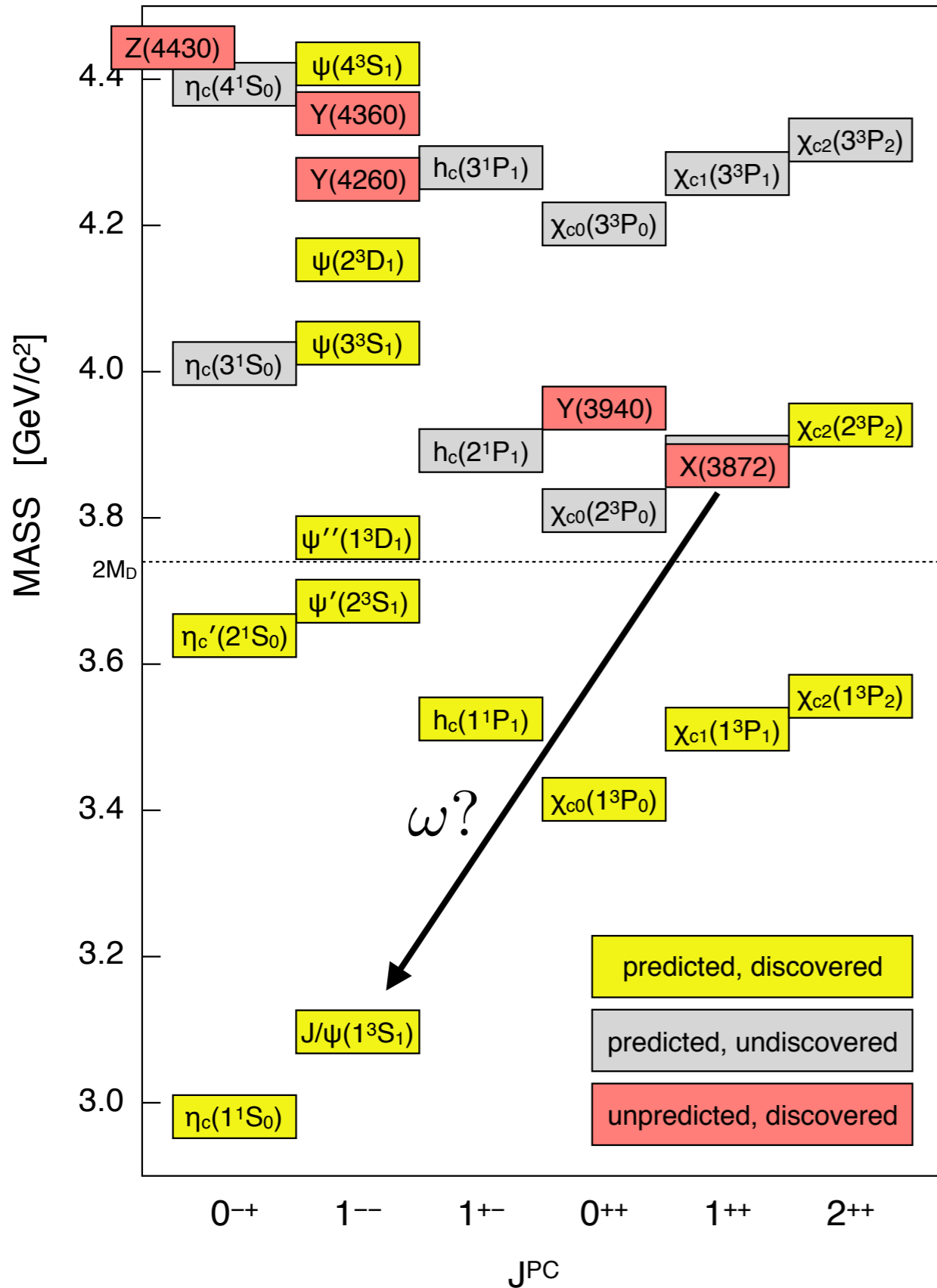
*Belle, BaBar, LHCb, etc.*



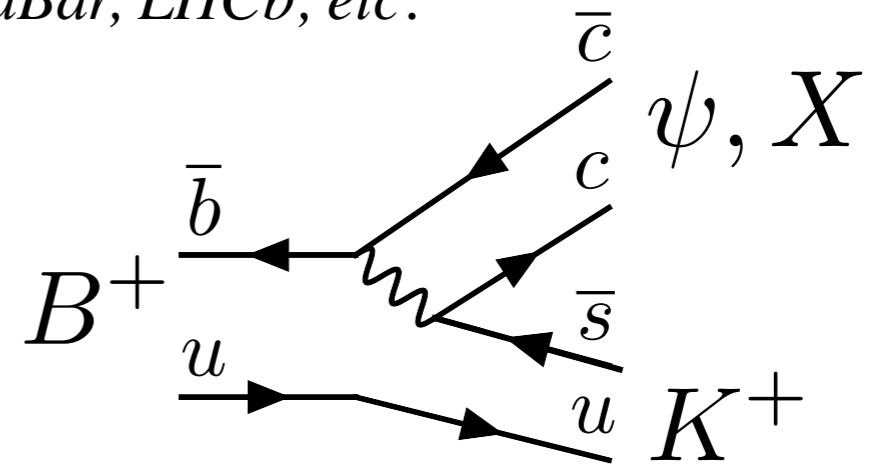
$$B \rightarrow K(\pi^+\pi^- J/\psi)$$



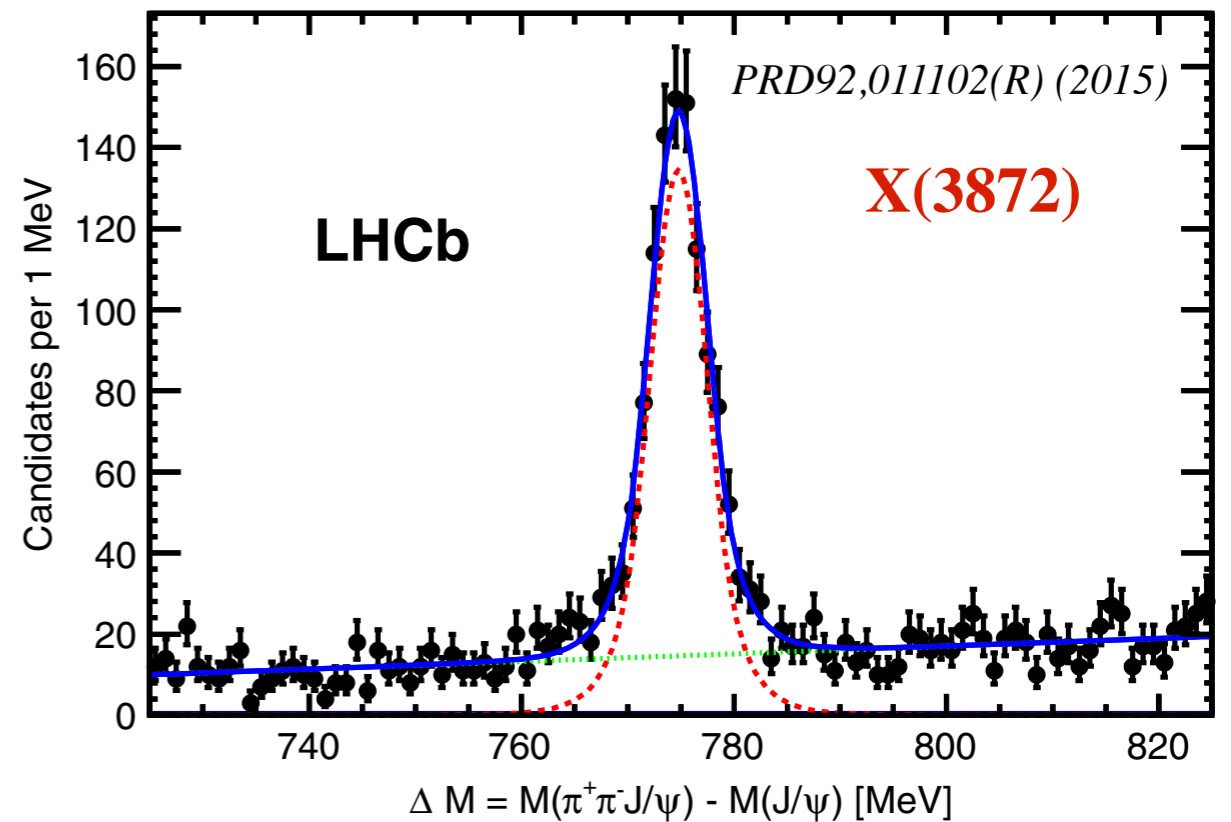
# II. Charmonium: problems and mysteries



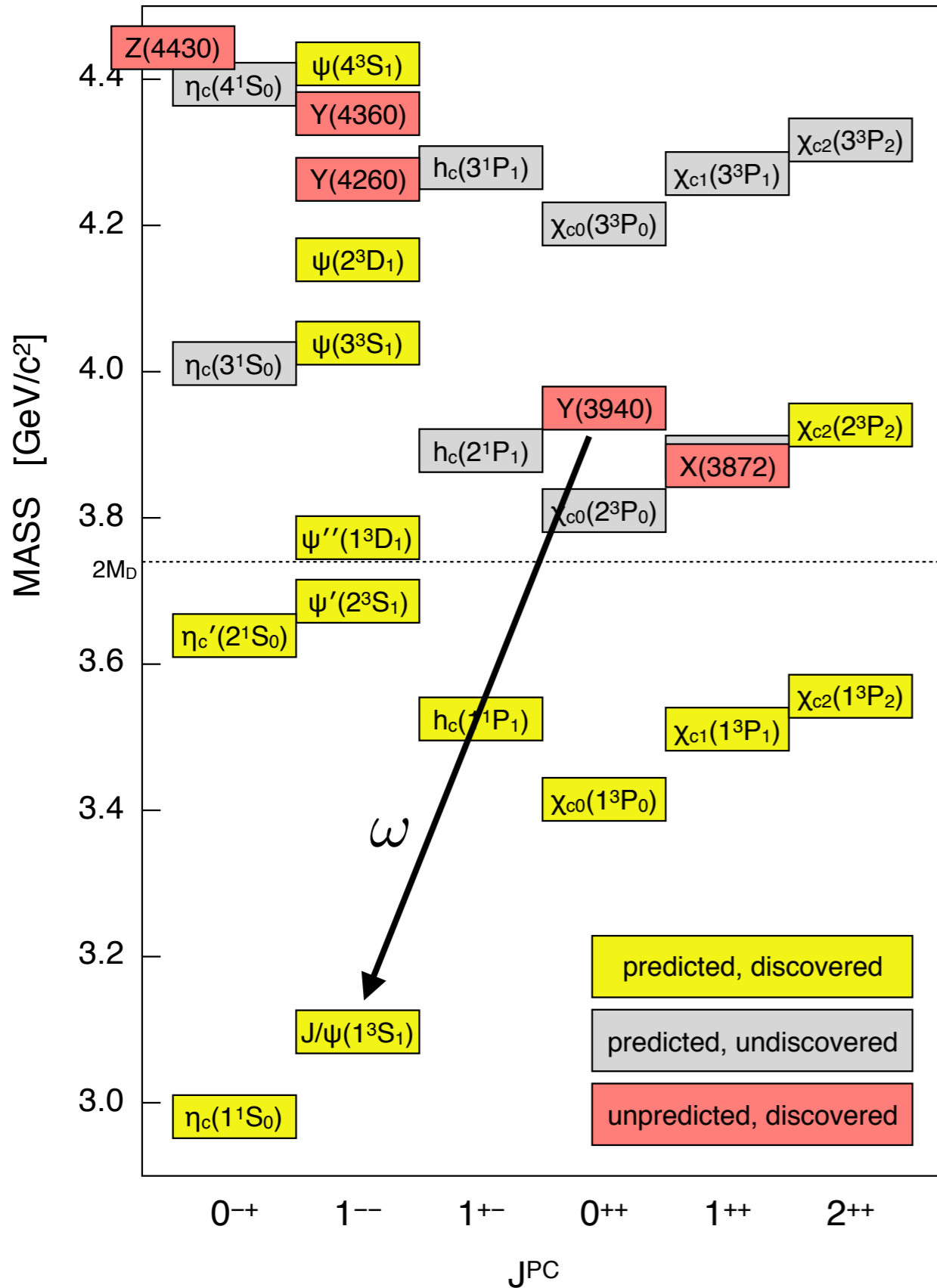
Belle, BaBar, LHCb, etc.



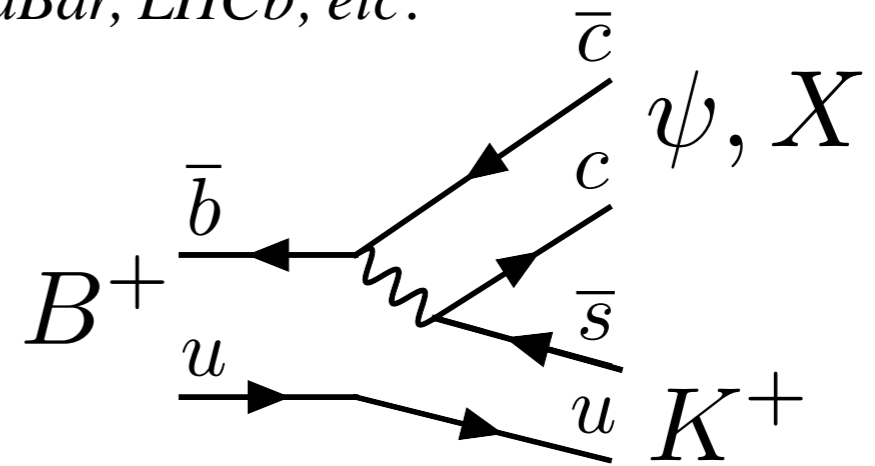
$$B \rightarrow K(\pi^+ \pi^- J/\psi)$$



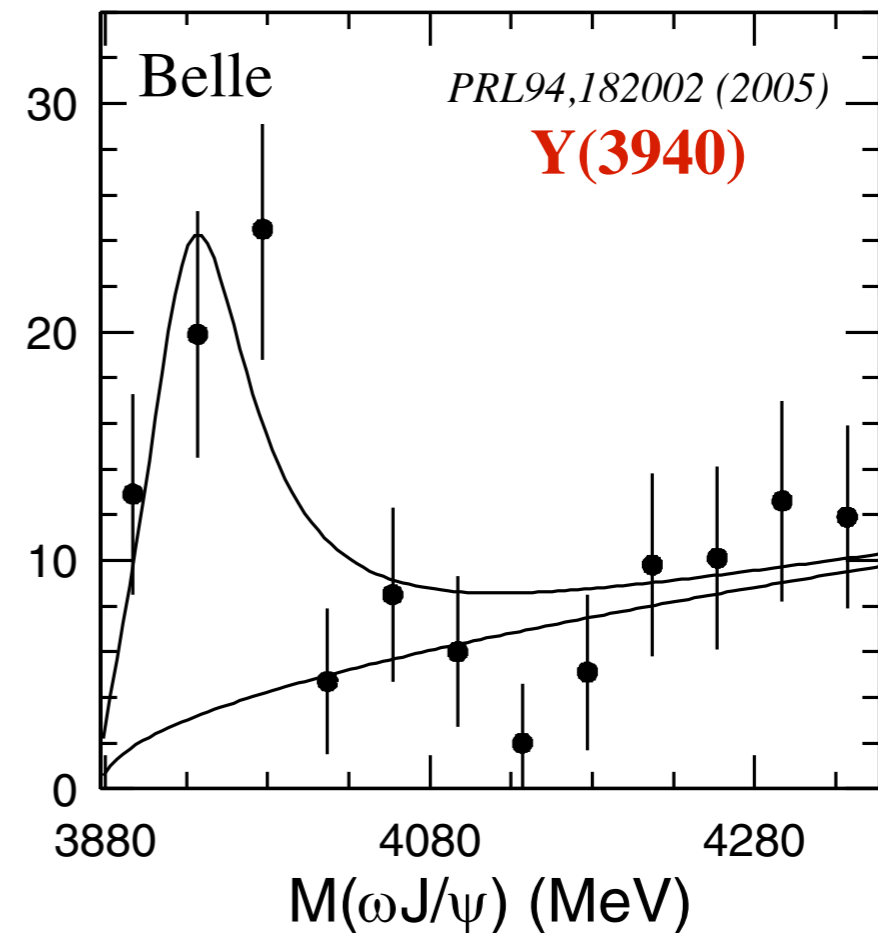
# II. Charmonium: problems and mysteries



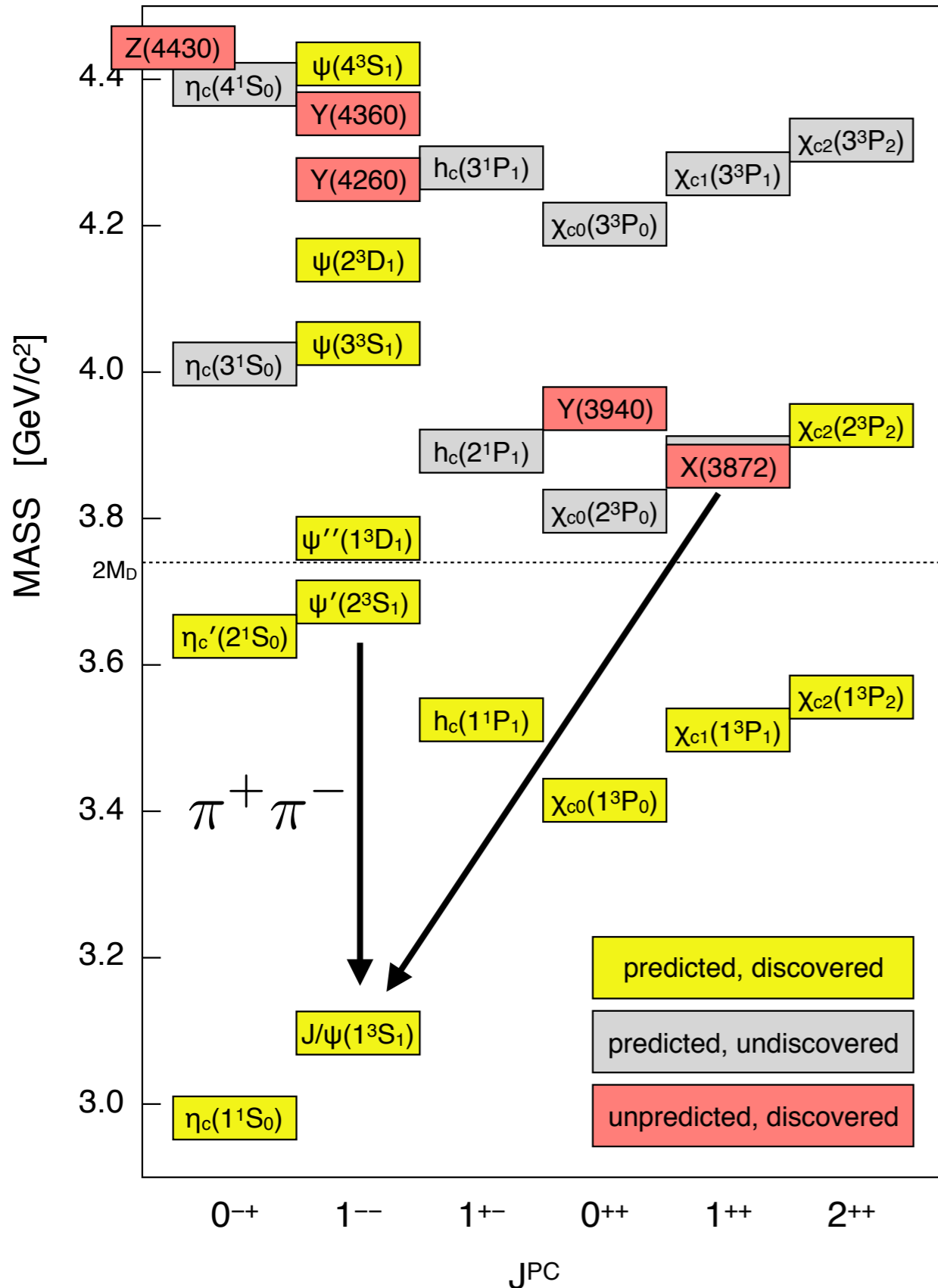
Belle, BaBar, LHCb, etc.



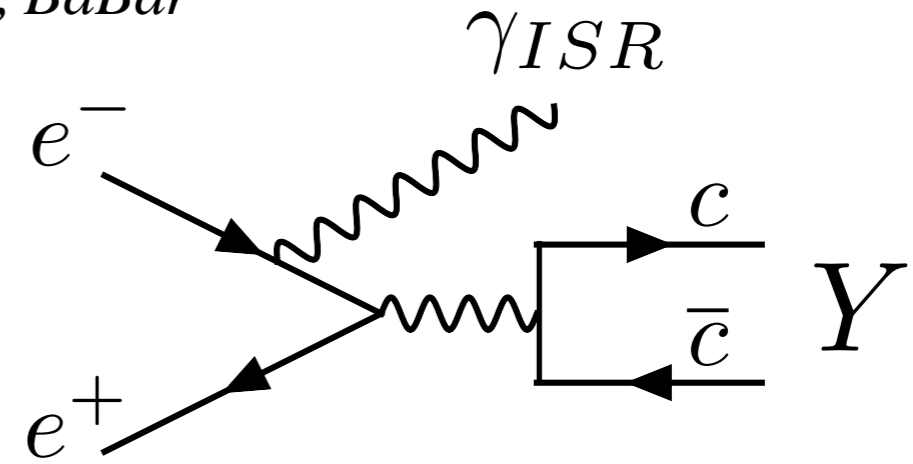
$B \rightarrow K(\omega J/\psi)$



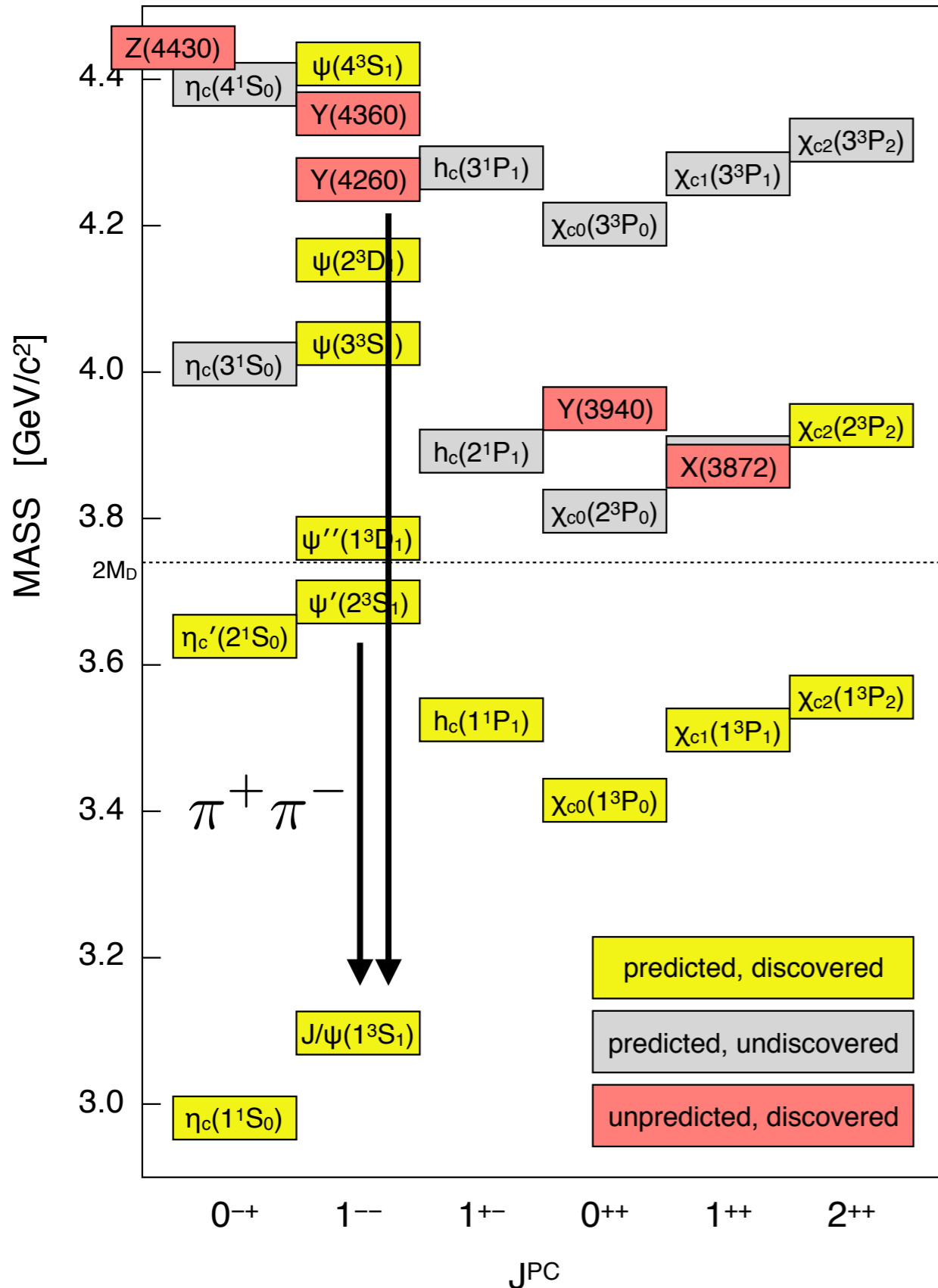
## II. Charmonium: problems and mysteries



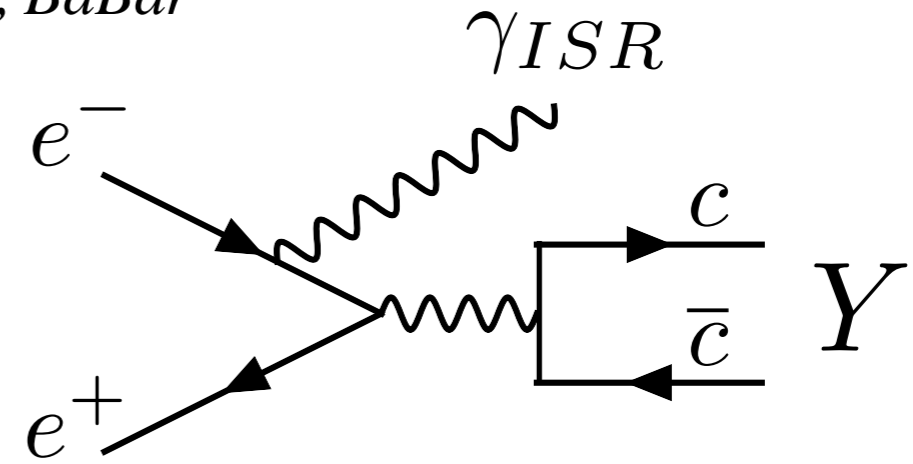
*Belle, BaBar*



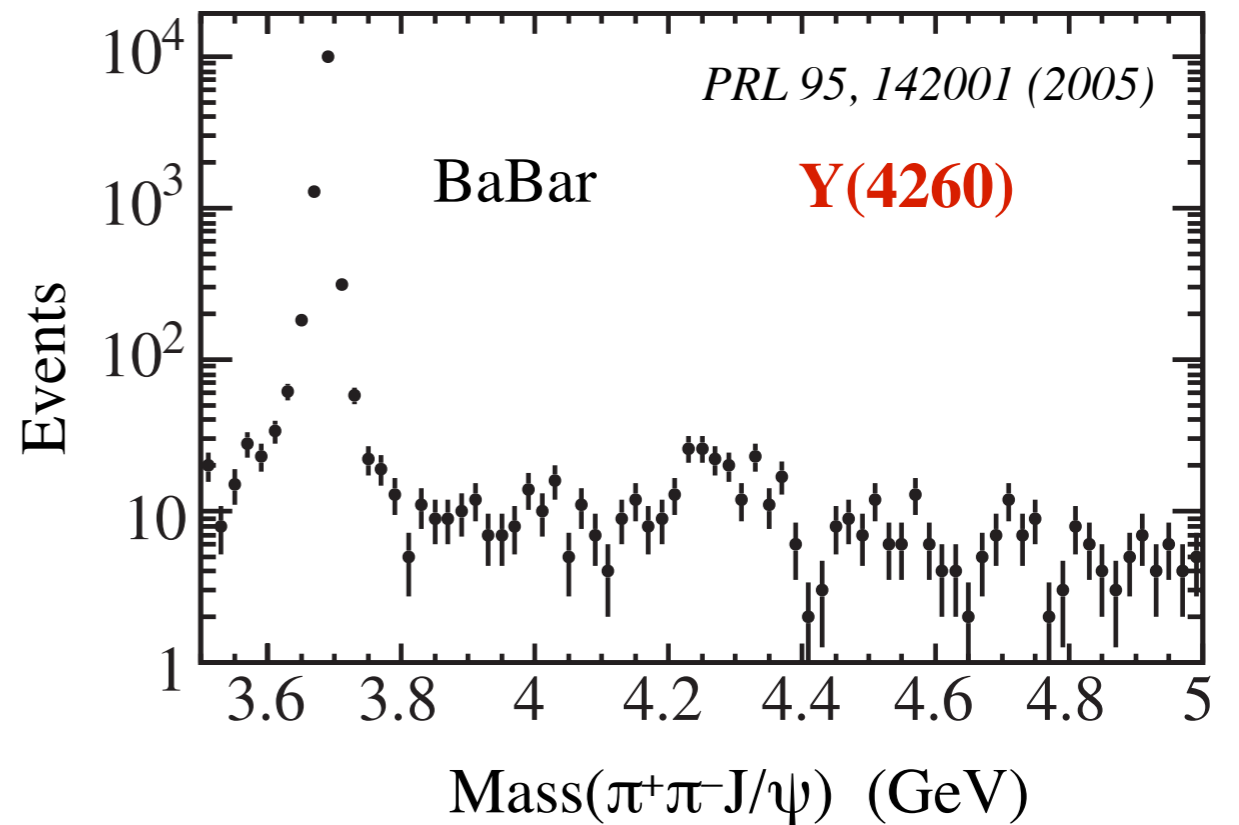
## II. Charmonium: problems and mysteries



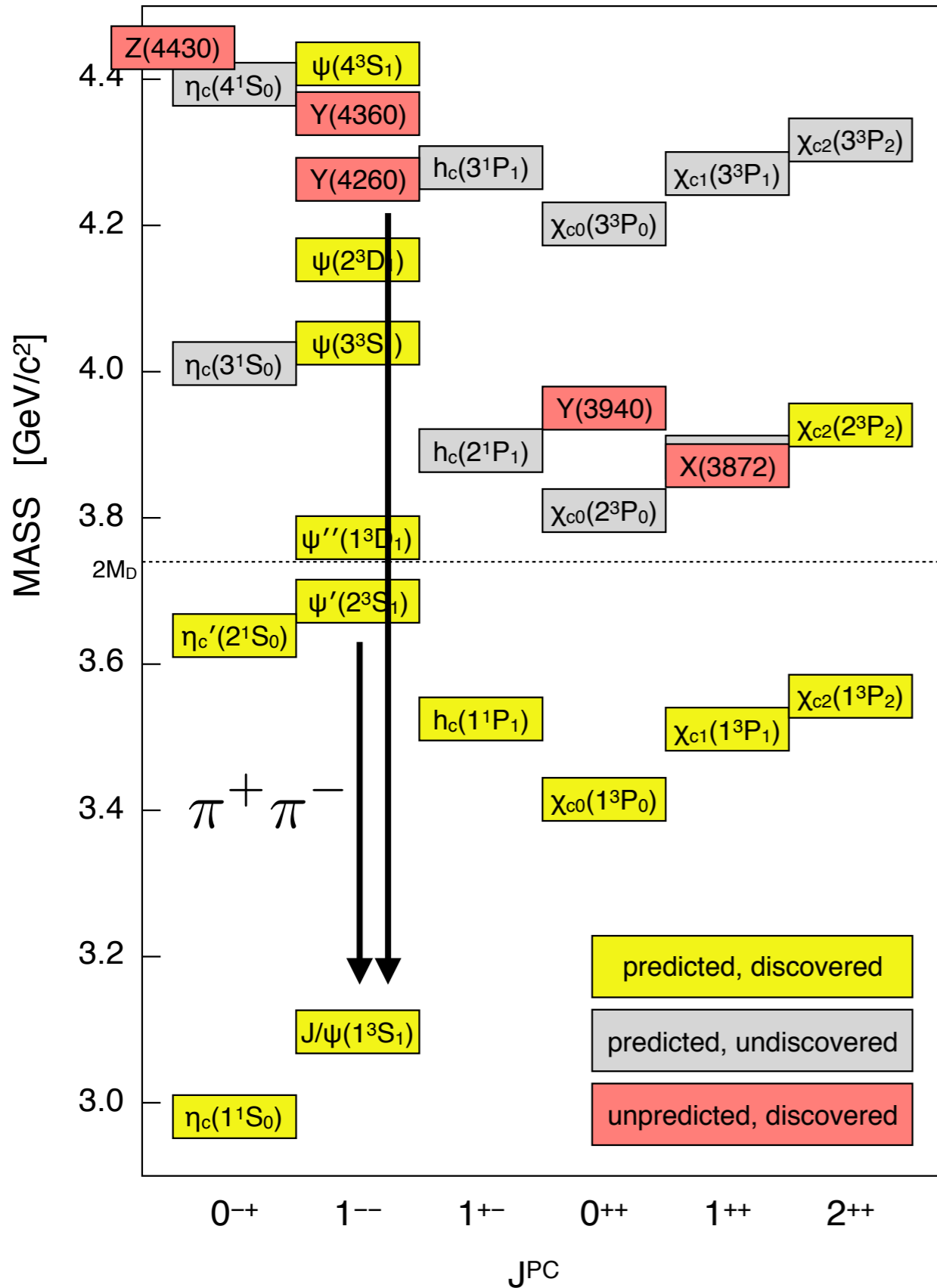
Belle, BaBar



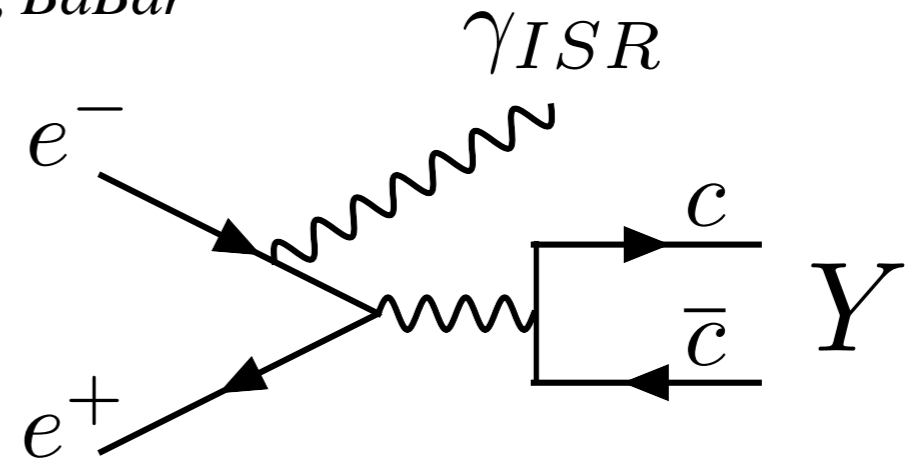
$$e^+e^- \rightarrow \pi^+\pi^- J/\psi$$



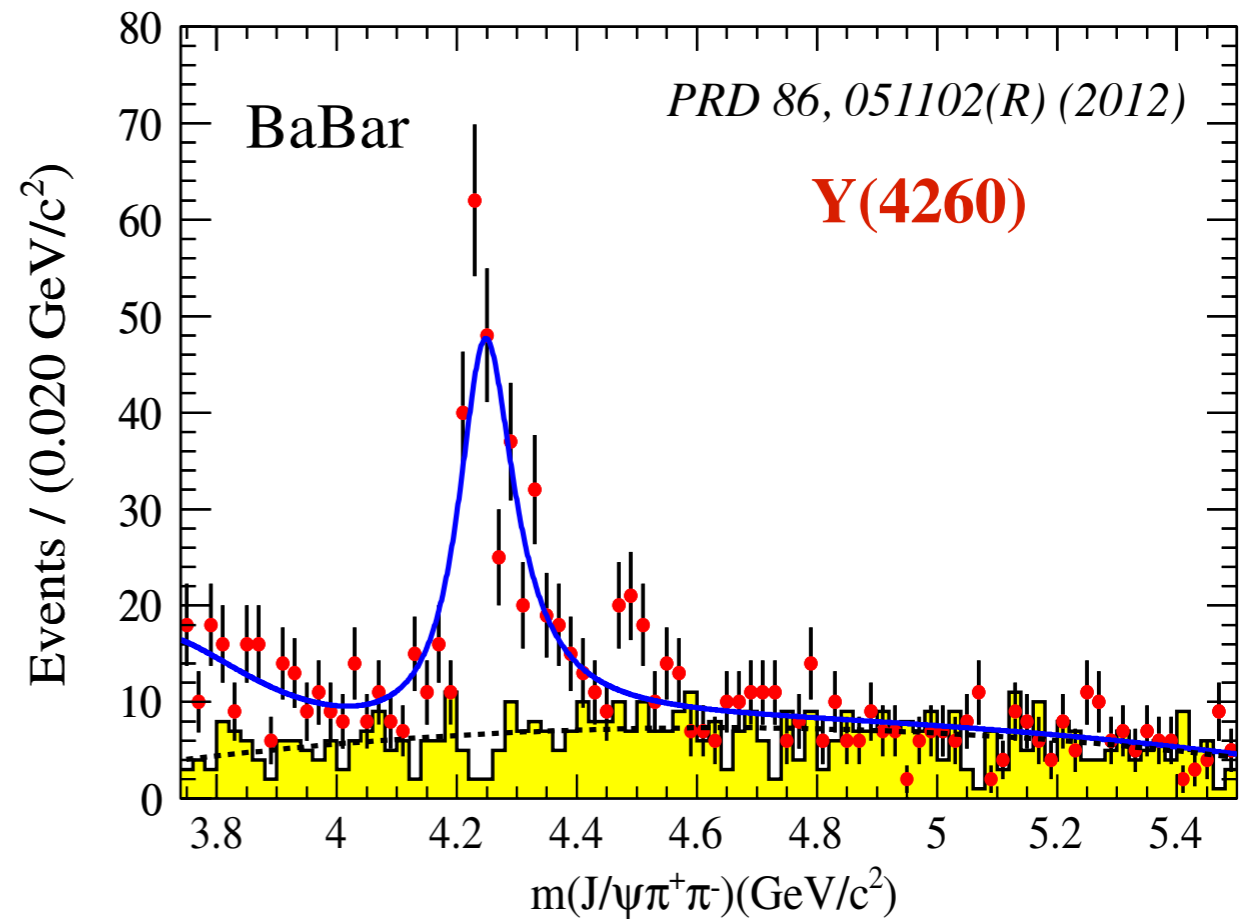
# II. Charmonium: problems and mysteries



Belle, BaBar

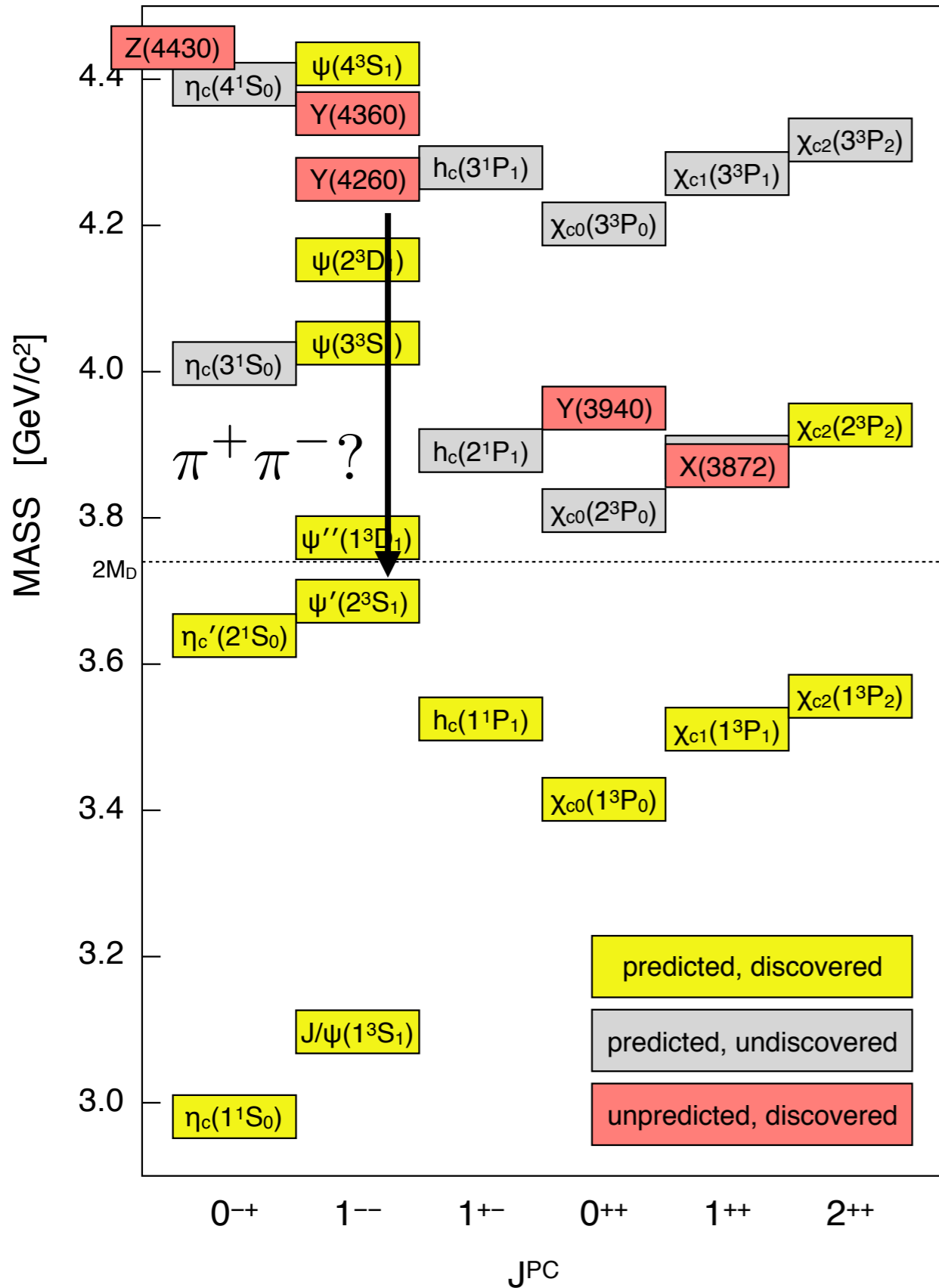


$$e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$$

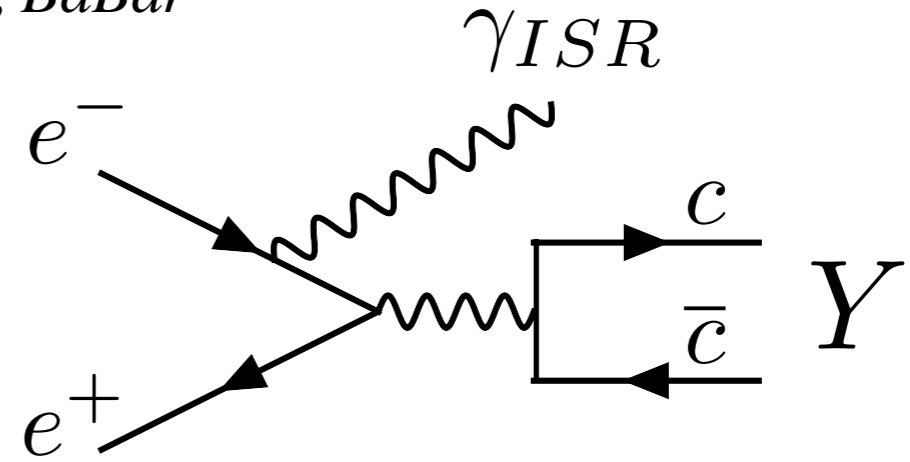




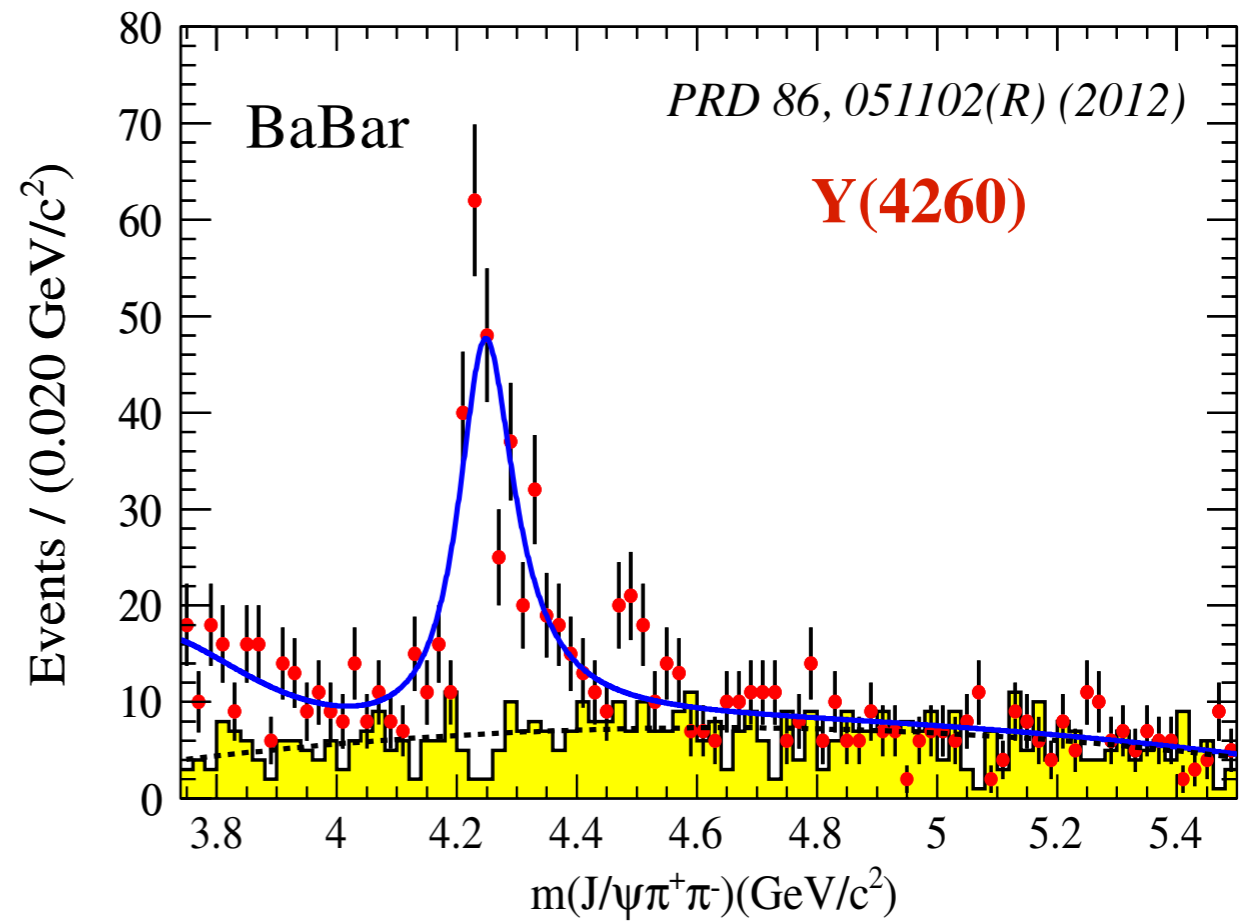
# II. Charmonium: problems and mysteries



Belle, BaBar



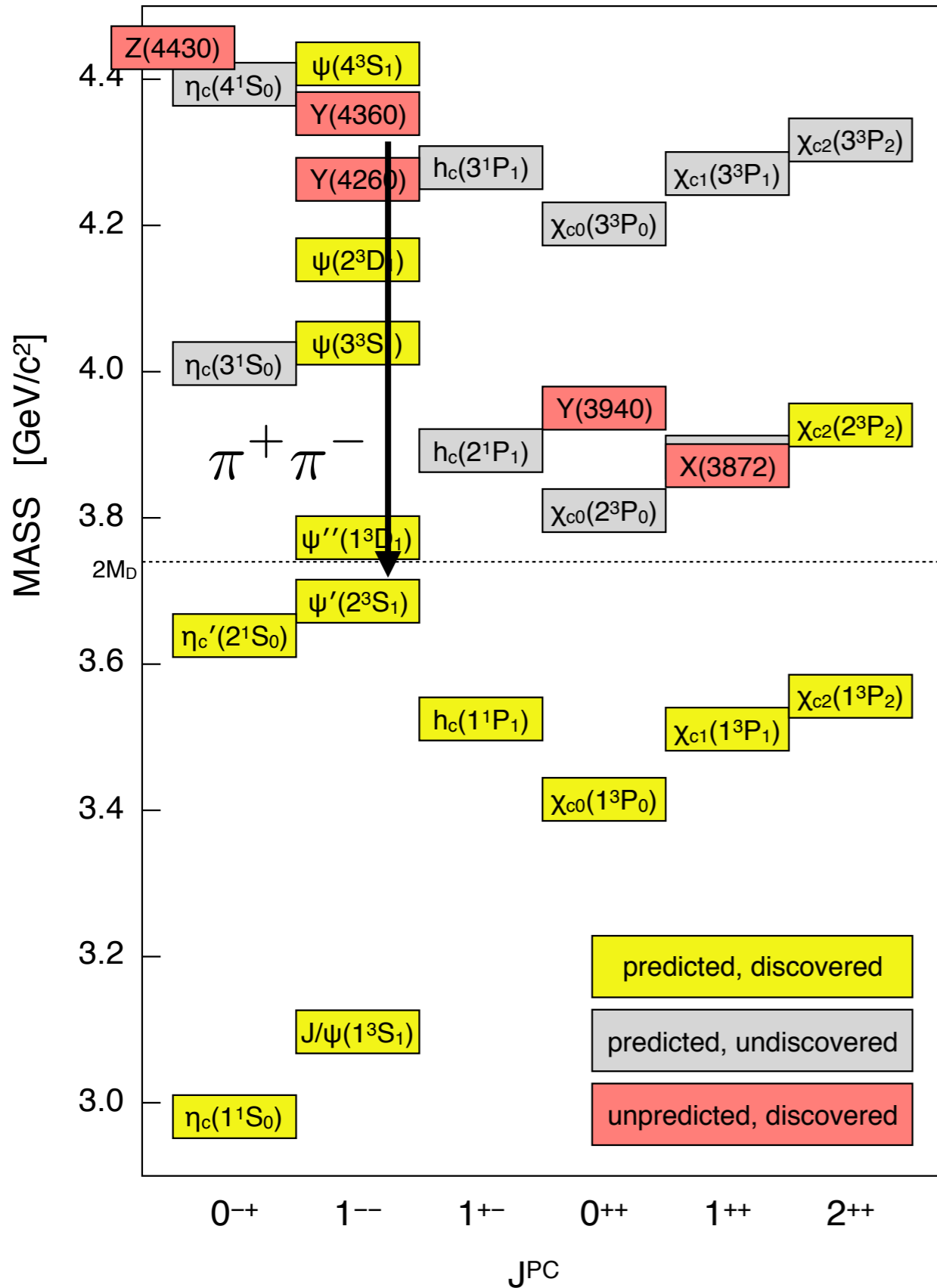
$$e^+e^- \rightarrow \pi^+\pi^- J/\psi$$



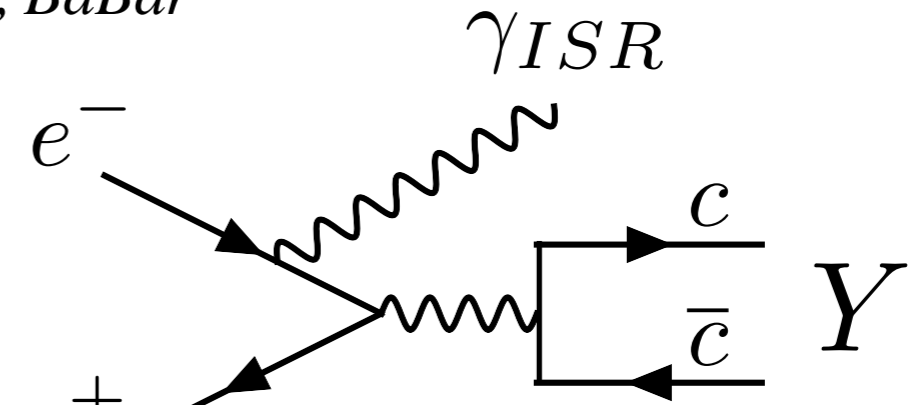
PRD 86, 051102(R) (2012)

**Y(4260)**

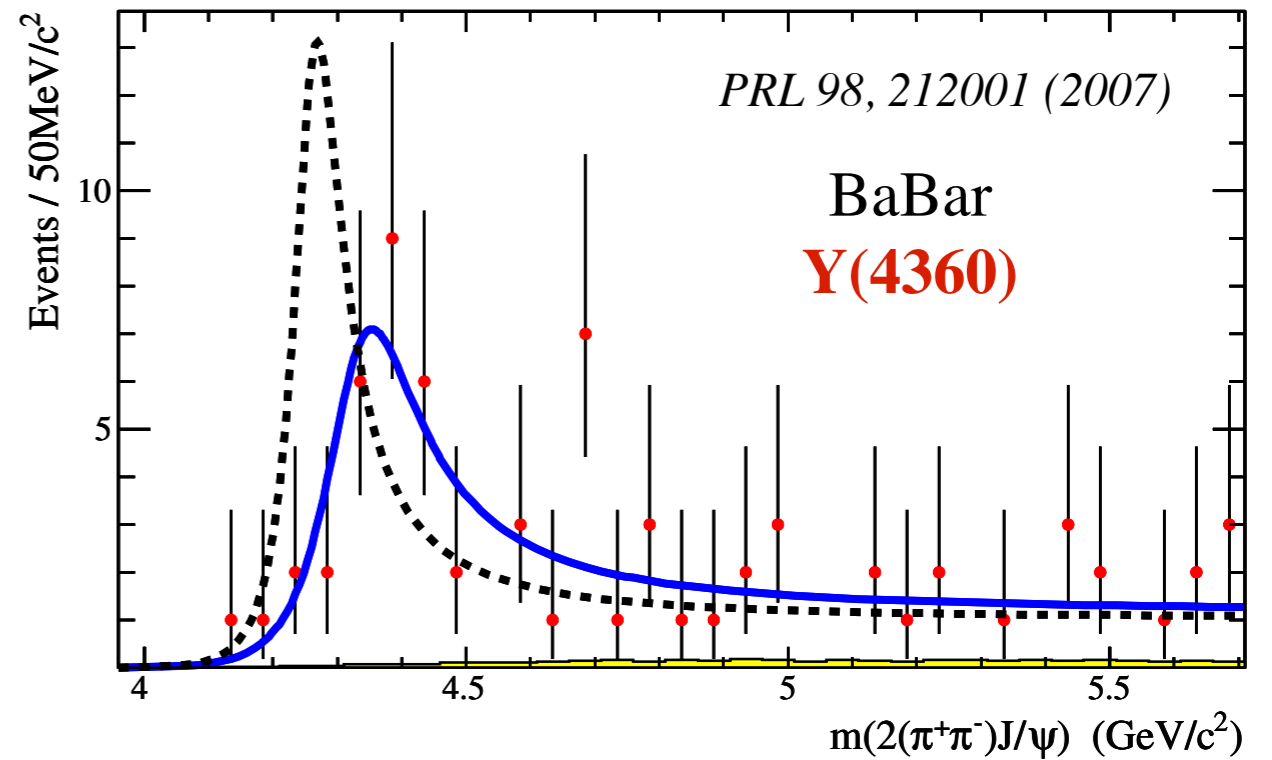
## II. Charmonium: problems and mysteries



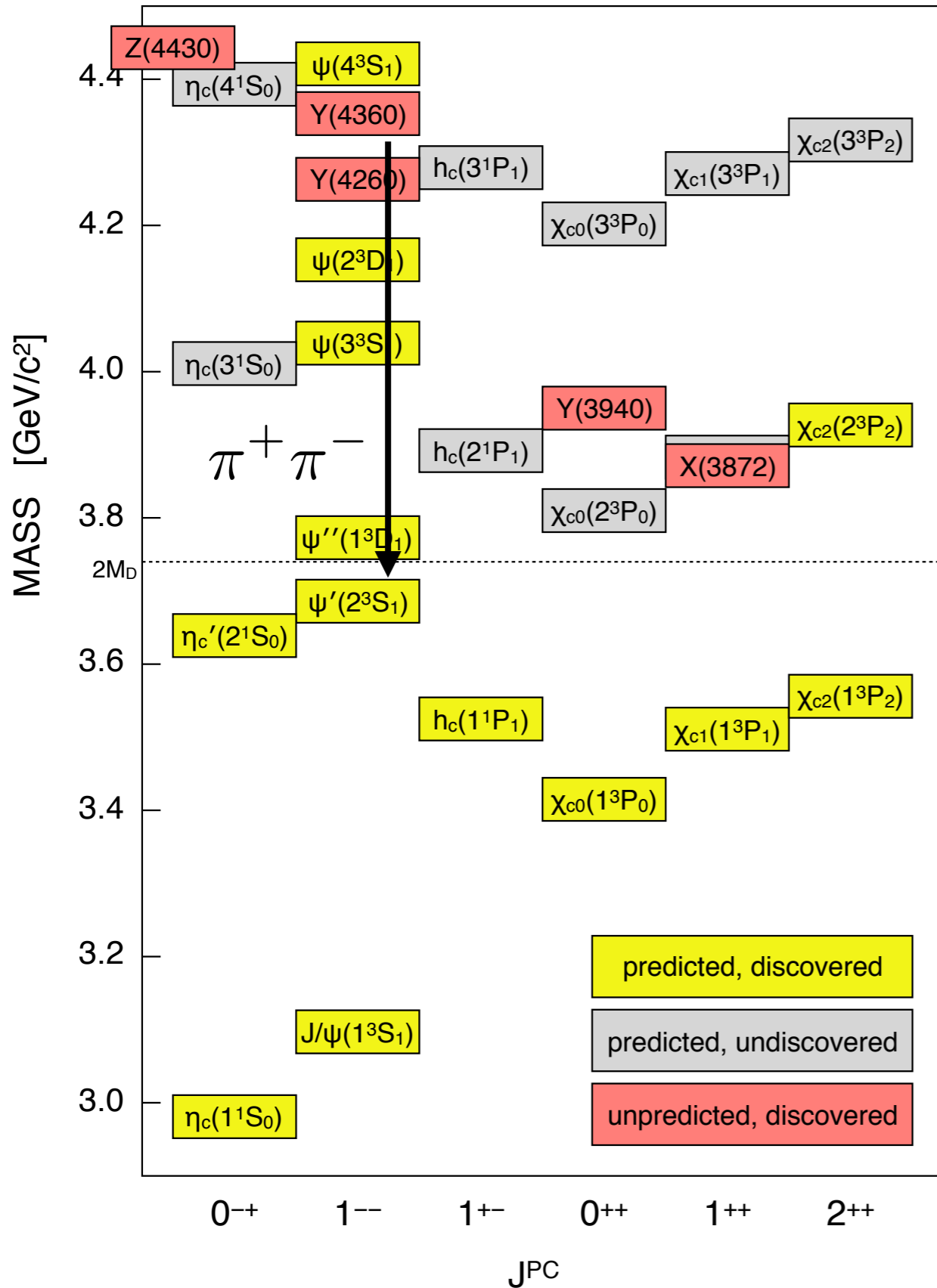
Belle, BaBar



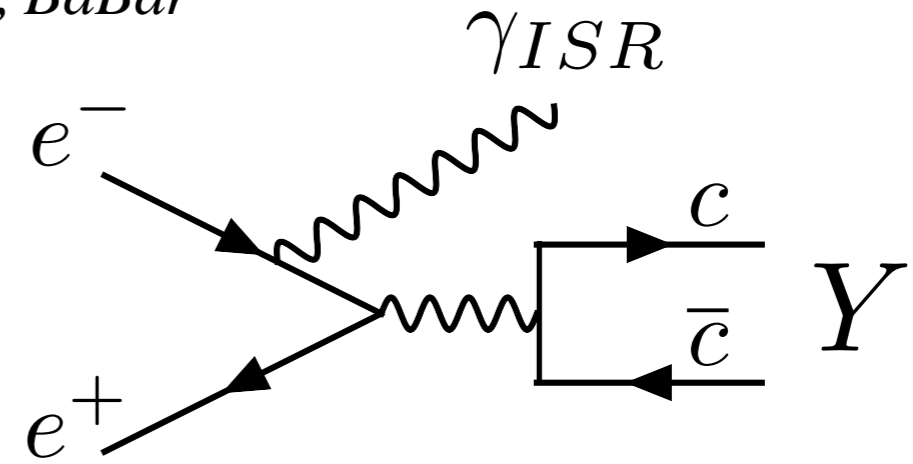
$$e^+ e^- \rightarrow \pi^+ \pi^- \psi(2S)$$



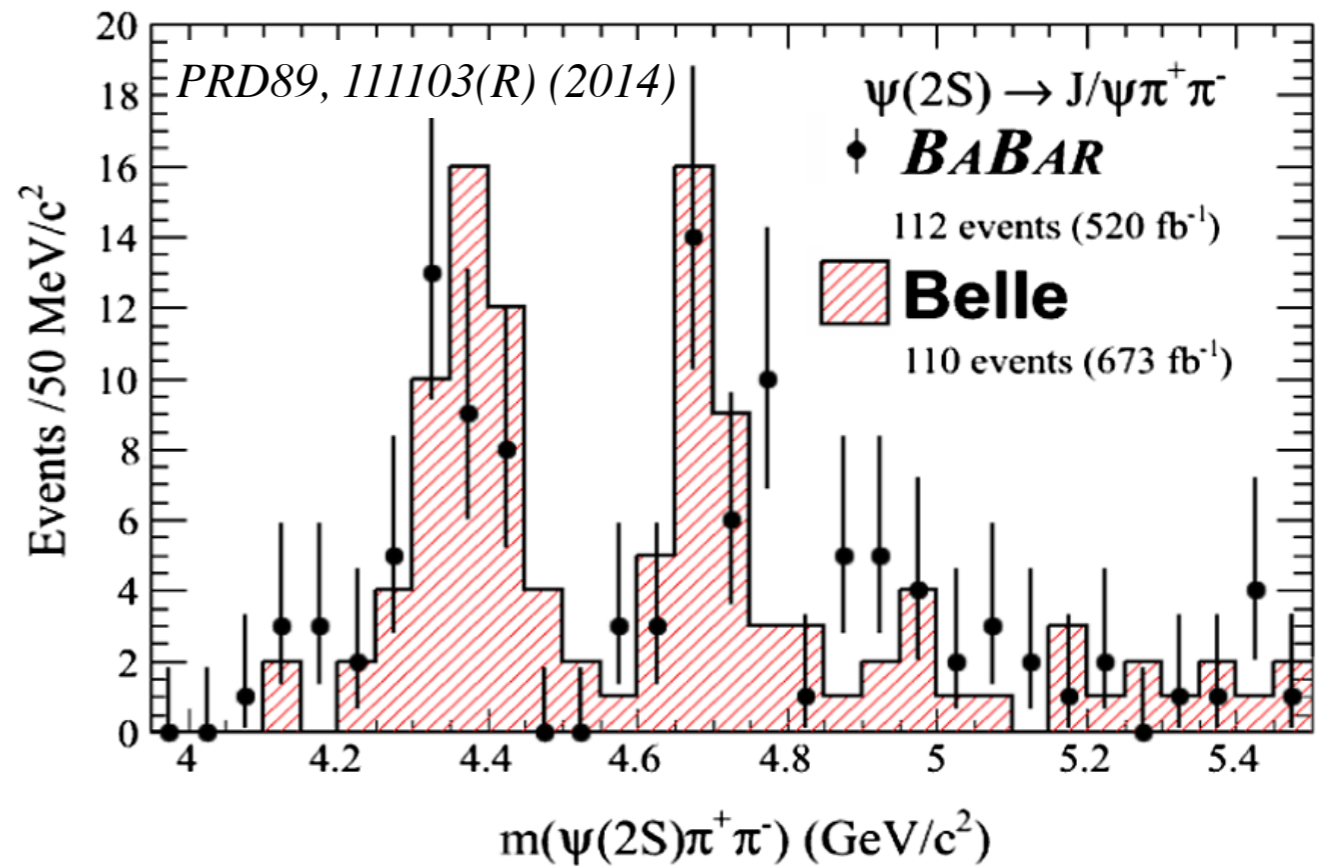
## II. Charmonium: problems and mysteries



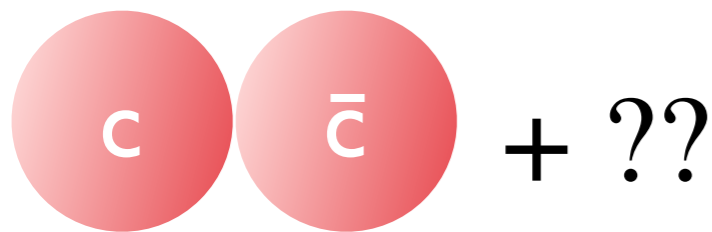
Belle, BaBar



$$e^+ e^- \rightarrow \pi^+ \pi^- \psi(2S)$$



# II. Charmonium: problems and mysteries



hybrid charmonium  
tetraquarks  
meson molecules  
hadrocharmonium

•  
•  
•

Lebed, Mitchell, Swanson,  
*Heavy-Quark QCD Exotica*,  
PPNP 93, 143 (2017)

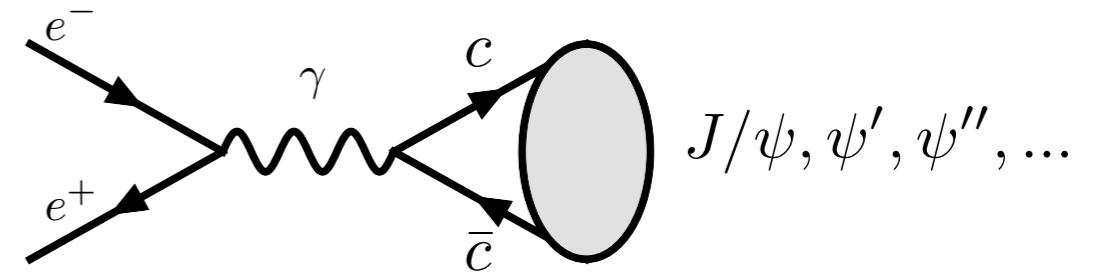
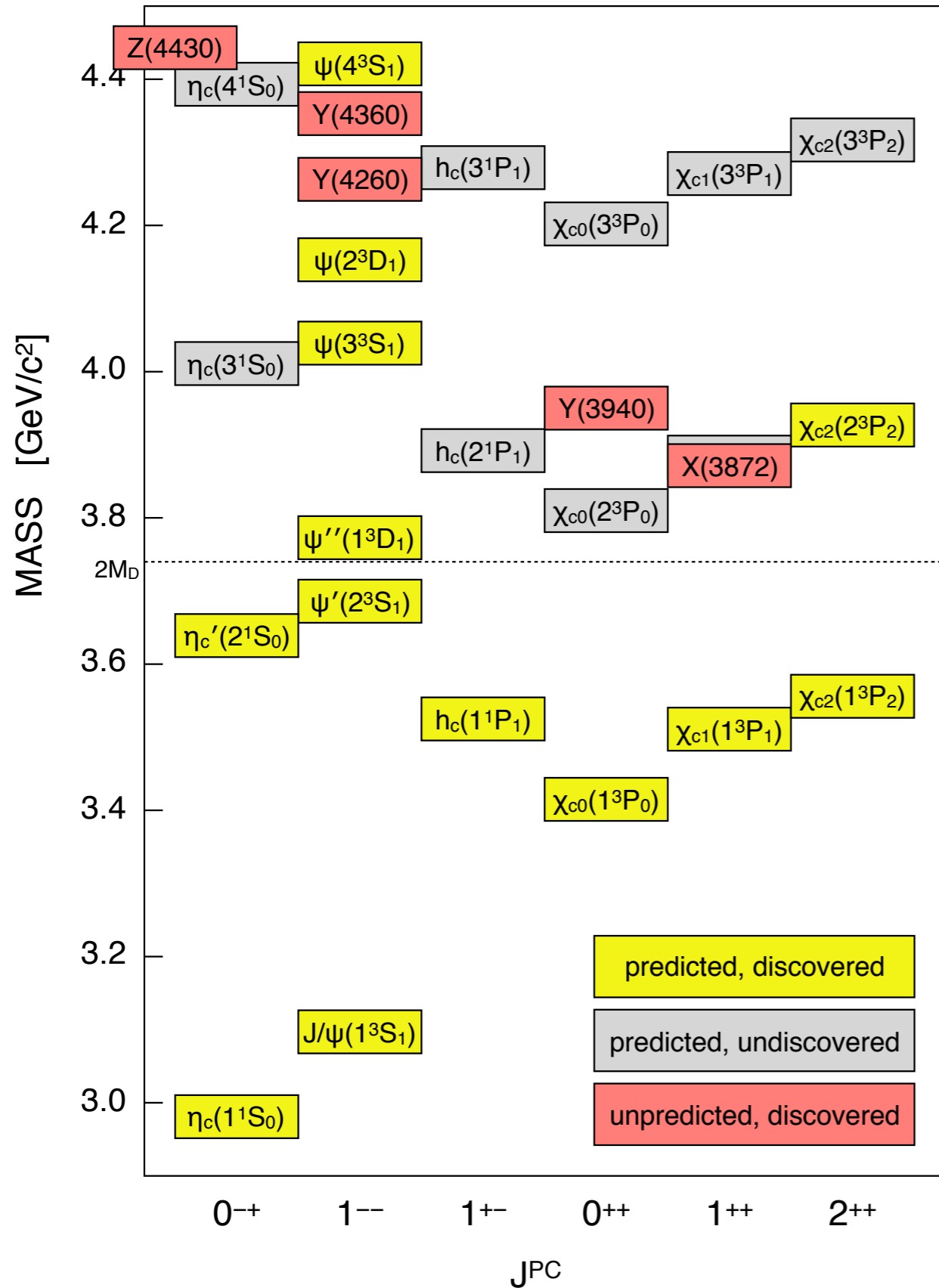
Particle	$I^G J^{PC}$	Mass [MeV]	Width [MeV]	Production and Decay
$X(3823)$ ( $\psi_2(1D)$ )	$(0^- 2^{--})$	$3822.2 \pm 1.2$ [176]	$< 16$	$B \rightarrow KX; X \rightarrow \gamma\chi_{c1}$ $e^+e^- \rightarrow \pi^+\pi^-X; X \rightarrow \gamma\chi_{c1}$
$X(3872)$	$0^+ 1^{++}$	$3871.69 \pm 0.17$ [176]	$< 1.2$	$B \rightarrow KX; X \rightarrow \pi^+\pi^-J/\psi$ $B \rightarrow KX; X \rightarrow D^{*0}\bar{D}^0$ $B \rightarrow KX; X \rightarrow \gamma J/\psi, \gamma\psi(2S)$ $B \rightarrow KX; X \rightarrow \omega J/\psi$ $B \rightarrow K\pi X; X \rightarrow \pi^+\pi^-J/\psi$ $e^+e^- \rightarrow \gamma X; X \rightarrow \pi^+\pi^-J/\psi$ $pp$ or $p\bar{p} \rightarrow X + \text{any.}; X \rightarrow \pi^+\pi^-J/\psi$
$Z_c(3900)$	$1^+ 1^{+-}$	$3886.6 \pm 2.4$ [176]	$28.1 \pm 2.6$	$e^+e^- \rightarrow \pi Z; Z \rightarrow \pi J/\psi$ $e^+e^- \rightarrow \pi Z; Z \rightarrow D^*\bar{D}$
$X(3915)$	$0^+ 0^{++}$	$3918.4 \pm 1.9$ [176]	$20 \pm 5$	$\gamma\gamma \rightarrow X; X \rightarrow \omega J/\psi$
$Y(3940)$				$B \rightarrow KX; X \rightarrow \omega J/\psi$
$Z(3930)$ ( $\chi_{c2}(2P)$ )	$0^+ 2^{++}$	$3927.2 \pm 2.6$ [176]	$24 \pm 6$	$\gamma\gamma \rightarrow Z; Z \rightarrow DD$
$X(3940)$		$3942_{-6}^{+7} \pm 6$ [41]	$37_{-15}^{+26} \pm 8$	$e^+e^- \rightarrow J/\psi + X; X \rightarrow D\bar{D}^*$
$Y(4008)$	$1^{--}$	$3891 \pm 41 \pm 12$ [23]	$255 \pm 40 \pm 14$	$e^+e^- \rightarrow Y; Y \rightarrow \pi^+\pi^-J/\psi$
$Z_c(4020)$	$1^+ ?^{? -}$	$4024.1 \pm 1.9$ [176]	$13 \pm 5$	$e^+e^- \rightarrow \pi Z; Z \rightarrow \pi h_c$ $e^+e^- \rightarrow \pi Z; Z \rightarrow D^*\bar{D}^*$
$Z_1(4050)$	$1^- ?^{? +}$	$4051 \pm 14_{-41}^{+20}$ [133]	$82_{-17-22}^{+21+47}$	$B \rightarrow KZ; Z \rightarrow \pi^\pm\chi_{c1}$
$Z_c(4055)$	$1^+ ?^{? -}$	$4054 \pm 3 \pm 1$ [148]	$45 \pm 11 \pm 6$	$e^+e^- \rightarrow \pi^\mp Z; Z \rightarrow \pi^\pm\psi(2S)$
$Y(4140)$	$0^+ 1^{++}$	$4146.5 \pm 4.5_{-2.8}^{+4.6}$ [125]	$83 \pm 21_{-14}^{+21}$	$B \rightarrow KY; Y \rightarrow \phi J/\psi$ $pp$ or $p\bar{p} \rightarrow Y + \text{any.}; Y \rightarrow \phi J/\psi$
$X(4160)$		$4156_{-20}^{+25} \pm 15$ [41]	$139_{-61}^{+111} \pm 21$	$e^+e^- \rightarrow J/\psi + X; X \rightarrow D^*\bar{D}^*$
$Z_c(4200)$	$1^+ 1^{+-}$	$4196_{-29-13}^{+31+17}$ [46]	$370_{-70-132}^{+70+70}$	$B \rightarrow KZ; Z \rightarrow \pi^\pm J/\psi$
$Y(4230)$	$0^- 1^{--}$	$4230 \pm 8 \pm 6$ [149]	$38 \pm 12 \pm 2$	$e^+e^- \rightarrow Y; Y \rightarrow \omega\chi_{c0}$
$Z_c(4240)$	$1^+ 0^{--}$	$4239 \pm 18_{-10}^{+45}$ [138]	$220 \pm 47_{-74}^{+108}$	$B \rightarrow KZ; Z \rightarrow \pi^\pm\psi(2S)$
$Z_2(4250)$	$1^- ?^{? +}$	$4248_{-29-35}^{+44+180}$ [133]	$177_{-39-61}^{+54+316}$	$B \rightarrow KZ; Z \rightarrow \pi^\pm\chi_{c1}$
$Y(4260)$	$0^- 1^{--}$	$4251 \pm 9$ [176]	$120 \pm 12$	$e^+e^- \rightarrow Y; Y \rightarrow \pi\pi J/\psi$
$Y(4274)$	$0^+ 1^{++}$	$4273.3 \pm 8.3_{-3.6}^{+17.2}$ [125]	$52 \pm 11_{-11}^{+8}$	$B \rightarrow KY; Y \rightarrow \phi J/\psi$
$X(4350)$	$0^+ ?^{? +}$	$4350.6_{-5.1}^{+4.6} \pm 0.7$ [170]	$13_{-9}^{+18} \pm 4$	$\gamma\gamma \rightarrow X; X \rightarrow \phi J/\psi$
$Y(4360)$	$1^{--}$	$4346 \pm 6$ [176]	$102 \pm 10$	$e^+e^- \rightarrow Y; Y \rightarrow \pi^+\pi^-\psi(2S)$
$Z_c(4430)$	$1^+ 1^{+-}$	$4478_{-18}^{+15}$ [176]	$181 \pm 31$	$B \rightarrow KZ; Z \rightarrow \pi^\pm J/\psi$ $B \rightarrow KZ; Z \rightarrow \pi^\pm\psi(2S)$
$X(4500)$	$0^+ 0^{++}$	$4506 \pm 11_{-15}^{+12}$ [125]	$92 \pm 21_{-20}^{+21}$	$B \rightarrow KX; X \rightarrow \phi J/\psi$
$X(4630)$	$1^{--}$	$4634_{-7-8}^{+8+5}$ [150]	$92_{-24-21}^{+40+10}$	$e^+e^- \rightarrow X; X \rightarrow \Lambda_c\bar{\Lambda}_c$
$Y(4660)$	$1^{--}$	$4643 \pm 9$ [176]	$72 \pm 11$	$e^+e^- \rightarrow Y; Y \rightarrow \pi^+\pi^-\psi(2S)$
$X(4700)$	$0^+ 0^{++}$	$4704 \pm 10_{-24}^{+14}$ [125]	$120 \pm 31_{-33}^{+42}$	$B \rightarrow KX; X \rightarrow \phi J/\psi$

I. Charmonium

II. “Charmonium”

III. “Charmonium” at BESIII

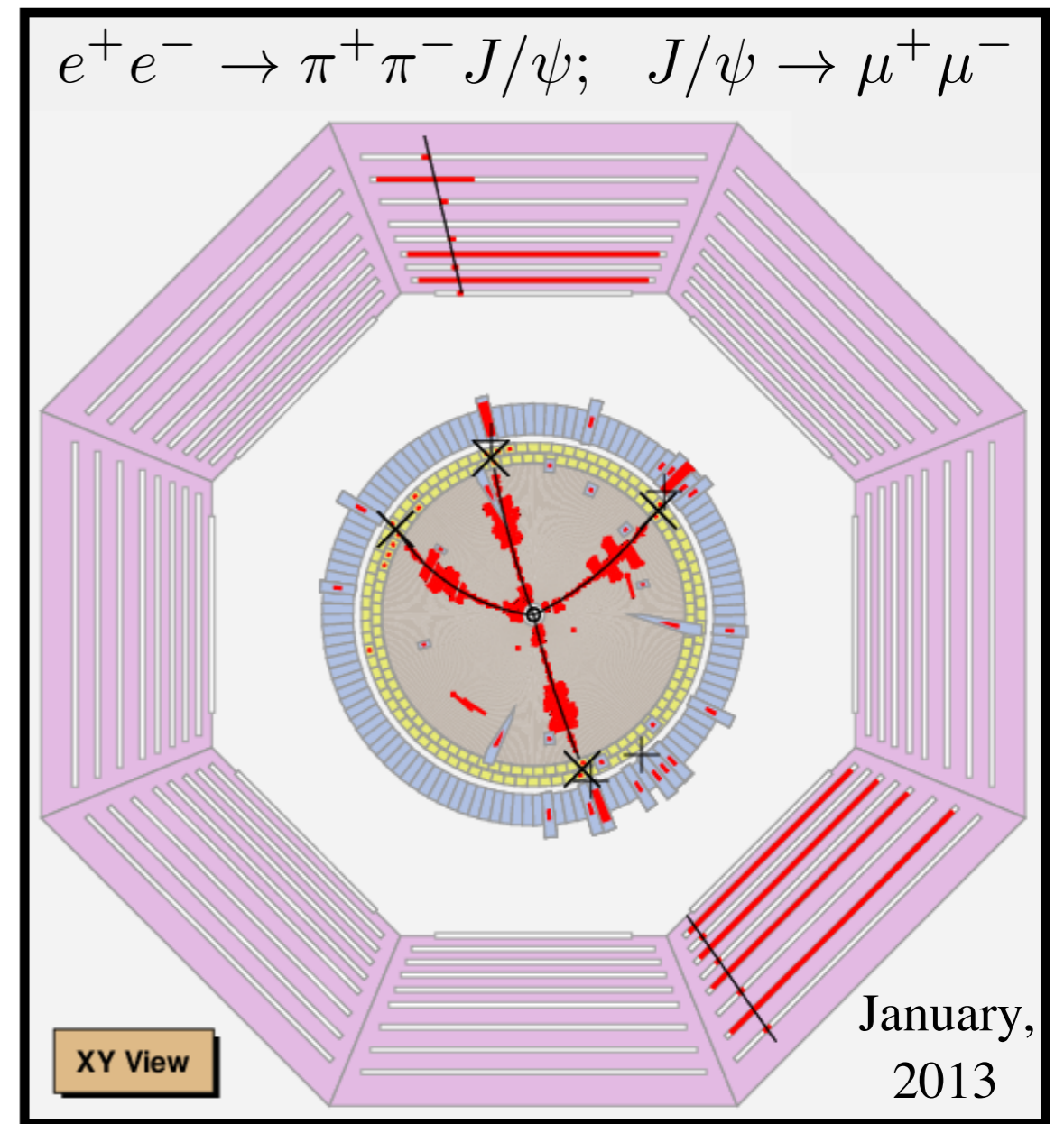
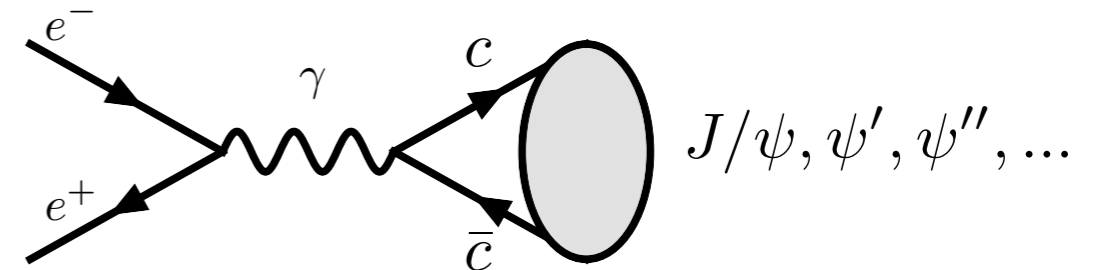
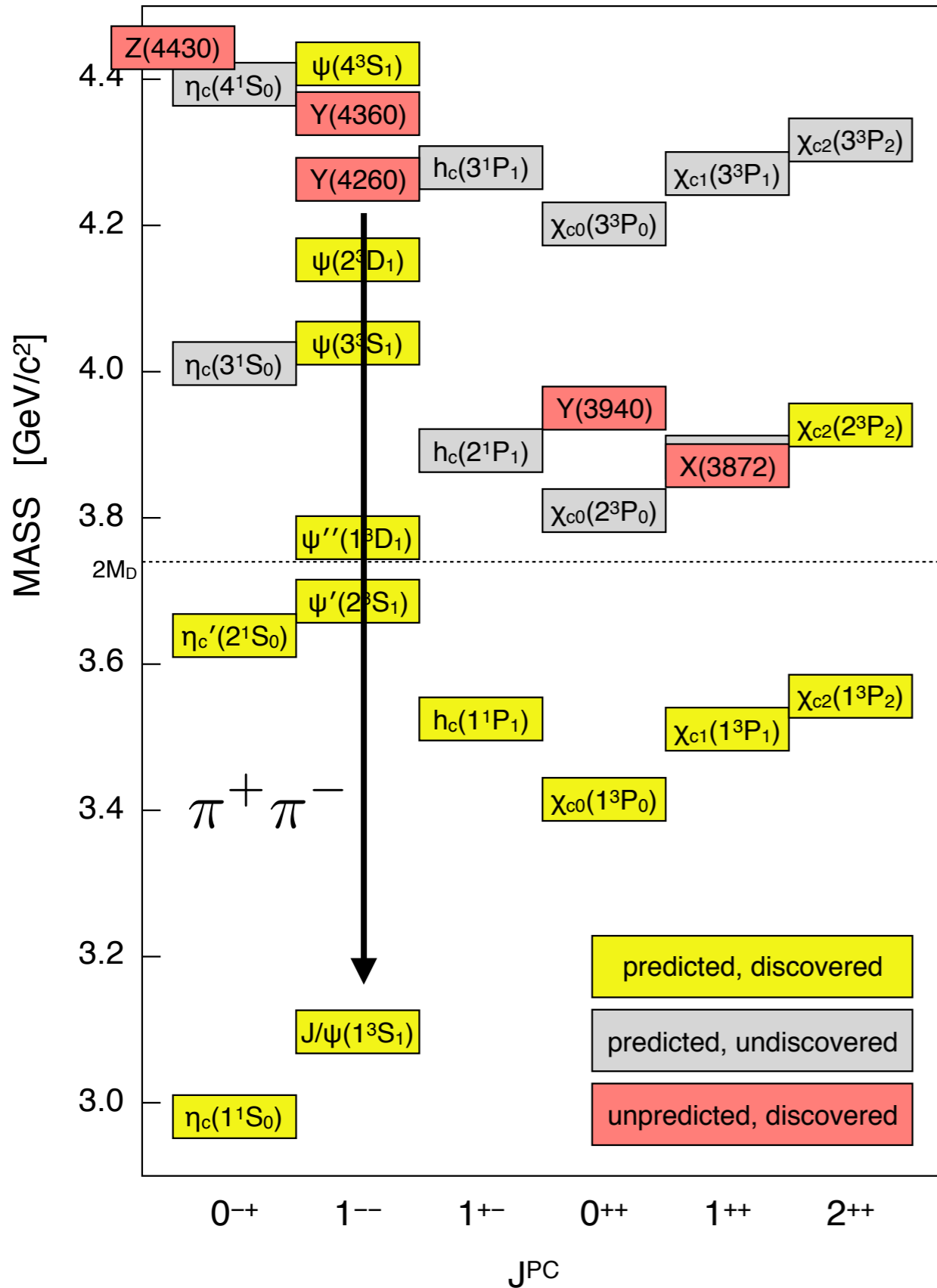
# III. The BESIII Experiment



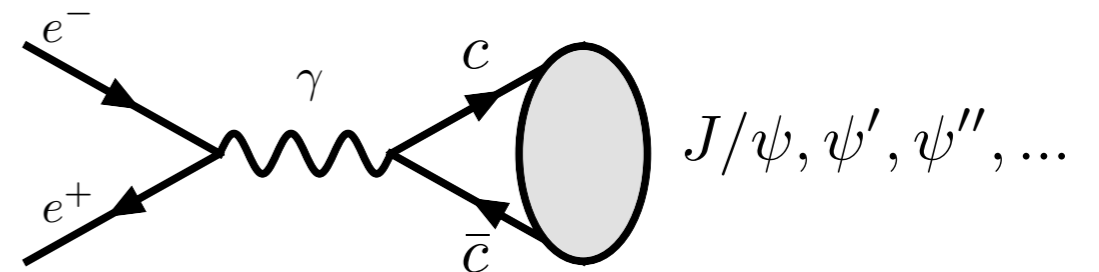
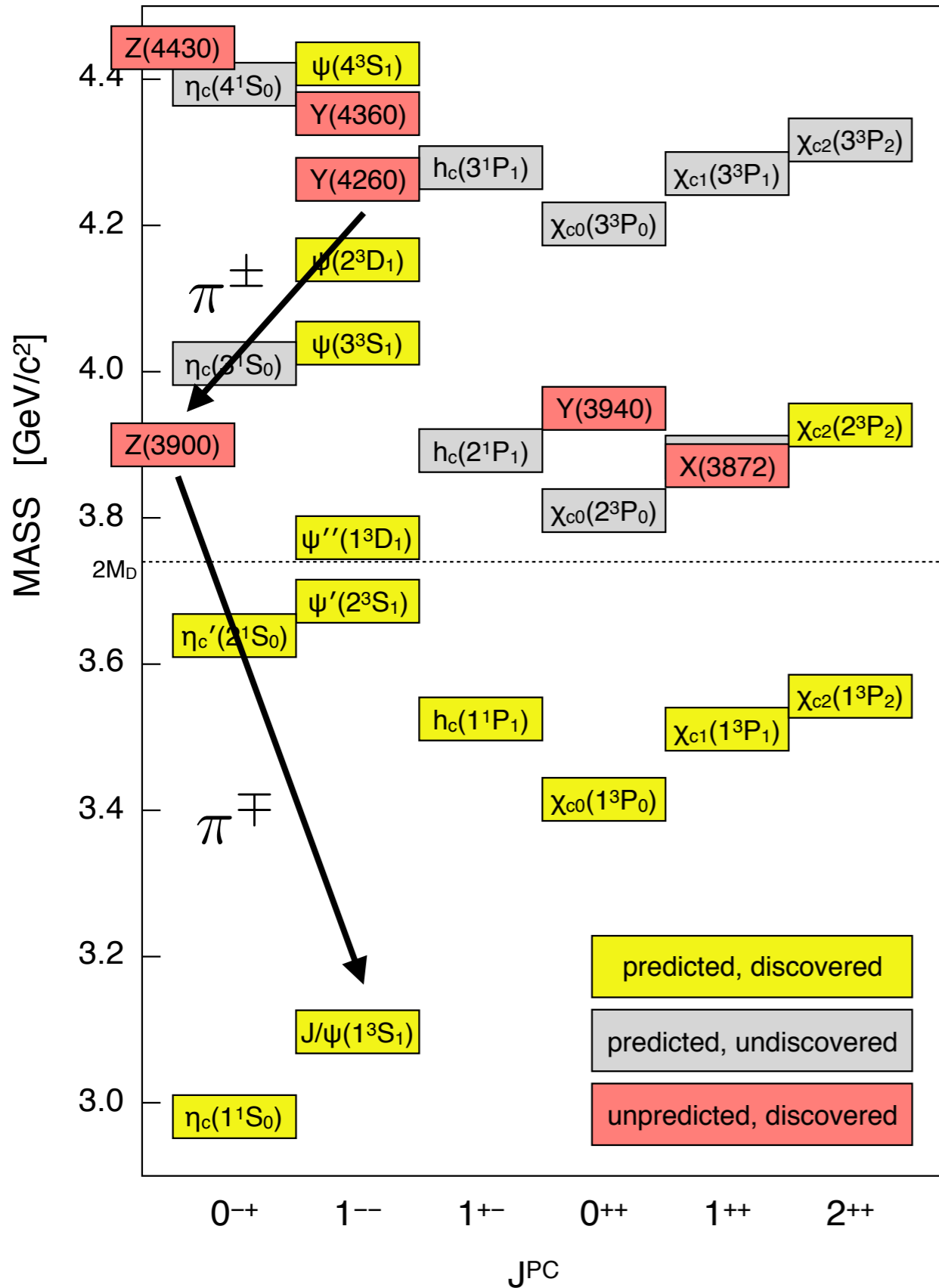
**Run at 4.26 GeV to produce the Y(4260)!**

We did this in 2013...

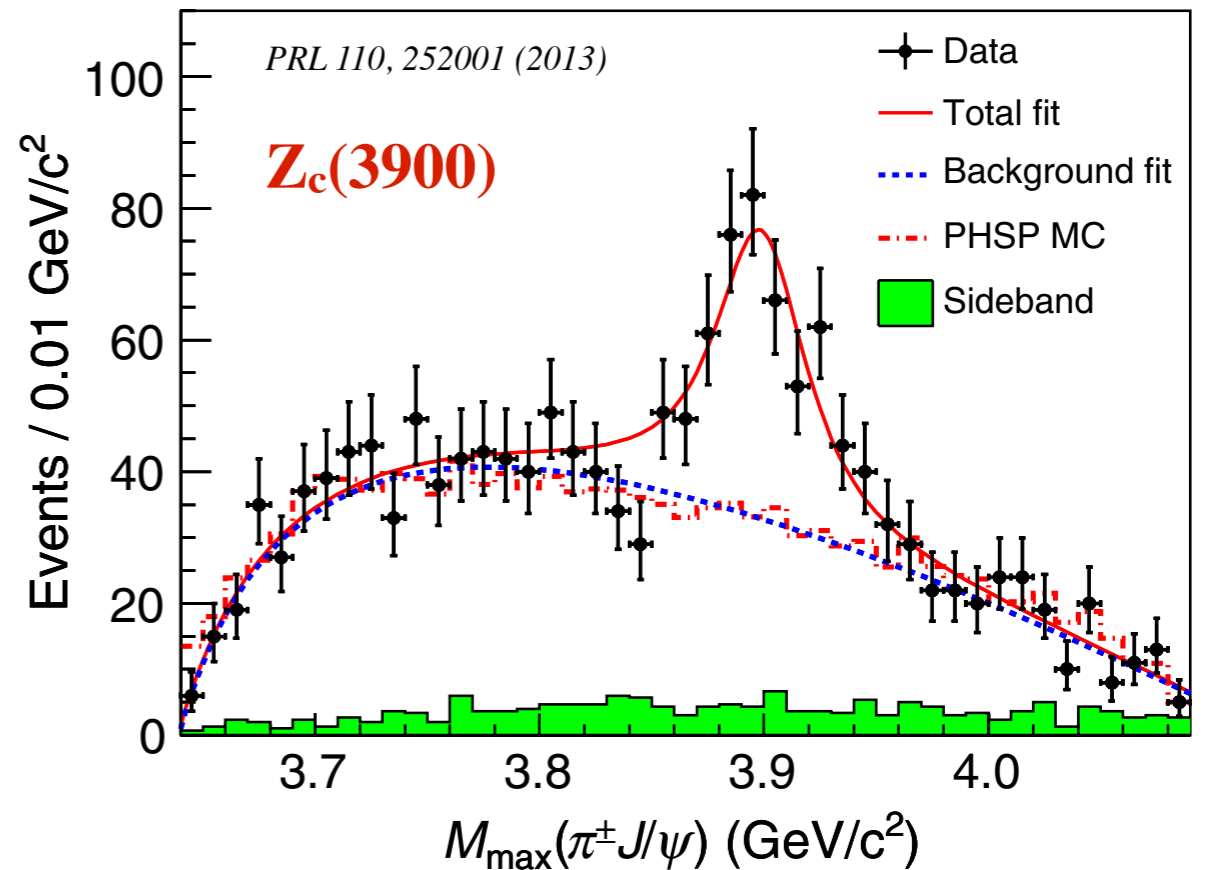
# III. The BESIII Experiment



# III. The BESIII Experiment

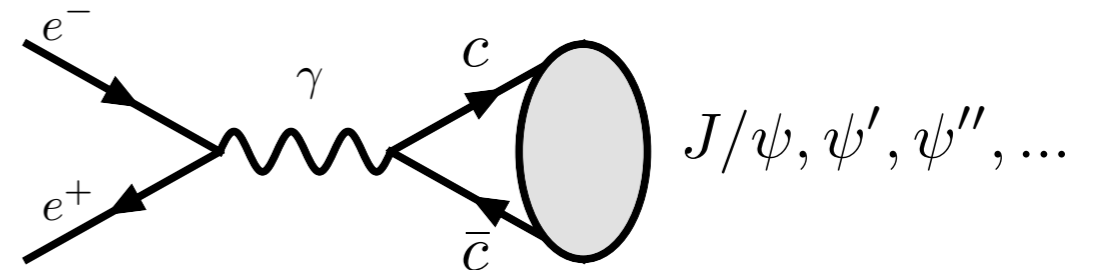
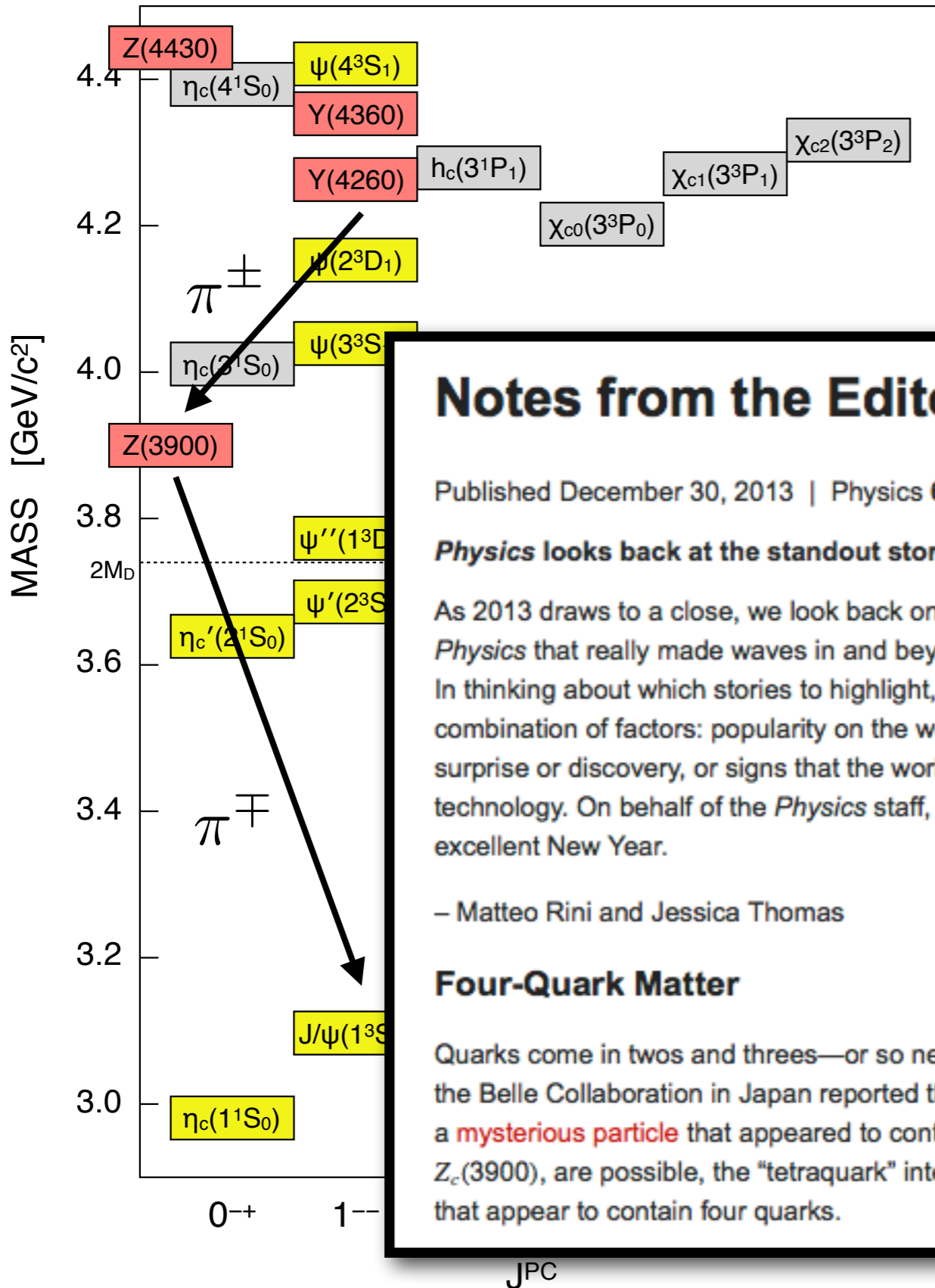


$$e^+ e^- \rightarrow \pi^+ \pi^- J/\psi$$





# III. The BESIII Experiment



## Notes from the Editors: Highlights of the Year

Published December 30, 2013 | *Physics* 6, 139 (2013) | DOI: 10.1103/Physics.6.139

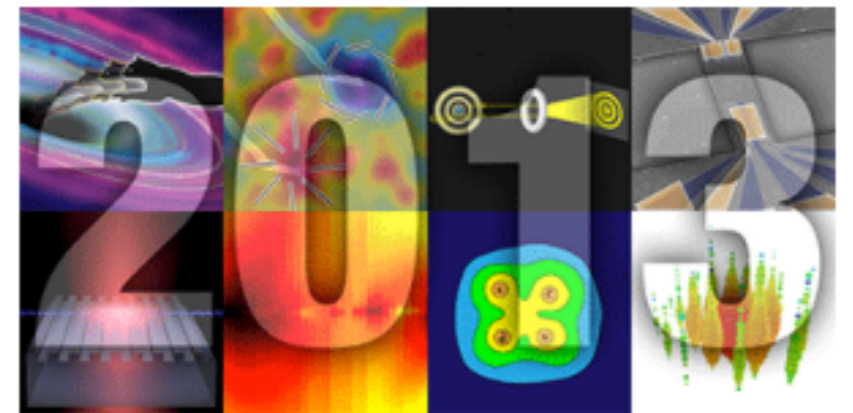
**Physics looks back at the standout stories of 2013.**

As 2013 draws to a close, we look back on the research covered in *Physics* that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the *Physics* staff, we wish everyone an excellent New Year.

— Matteo Rini and Jessica Thomas

### Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a **mysterious particle** that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed  $Z_c(3900)$ , are possible, the “tetraquark” interpretation may be gaining traction: BESIII has since **seen** a series of other particles that appear to contain four quarks.

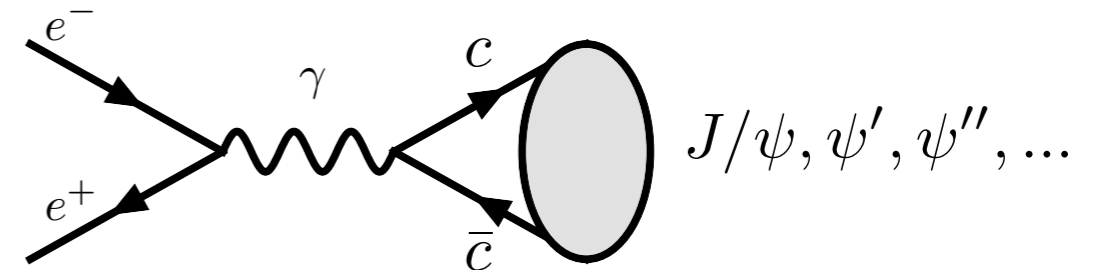
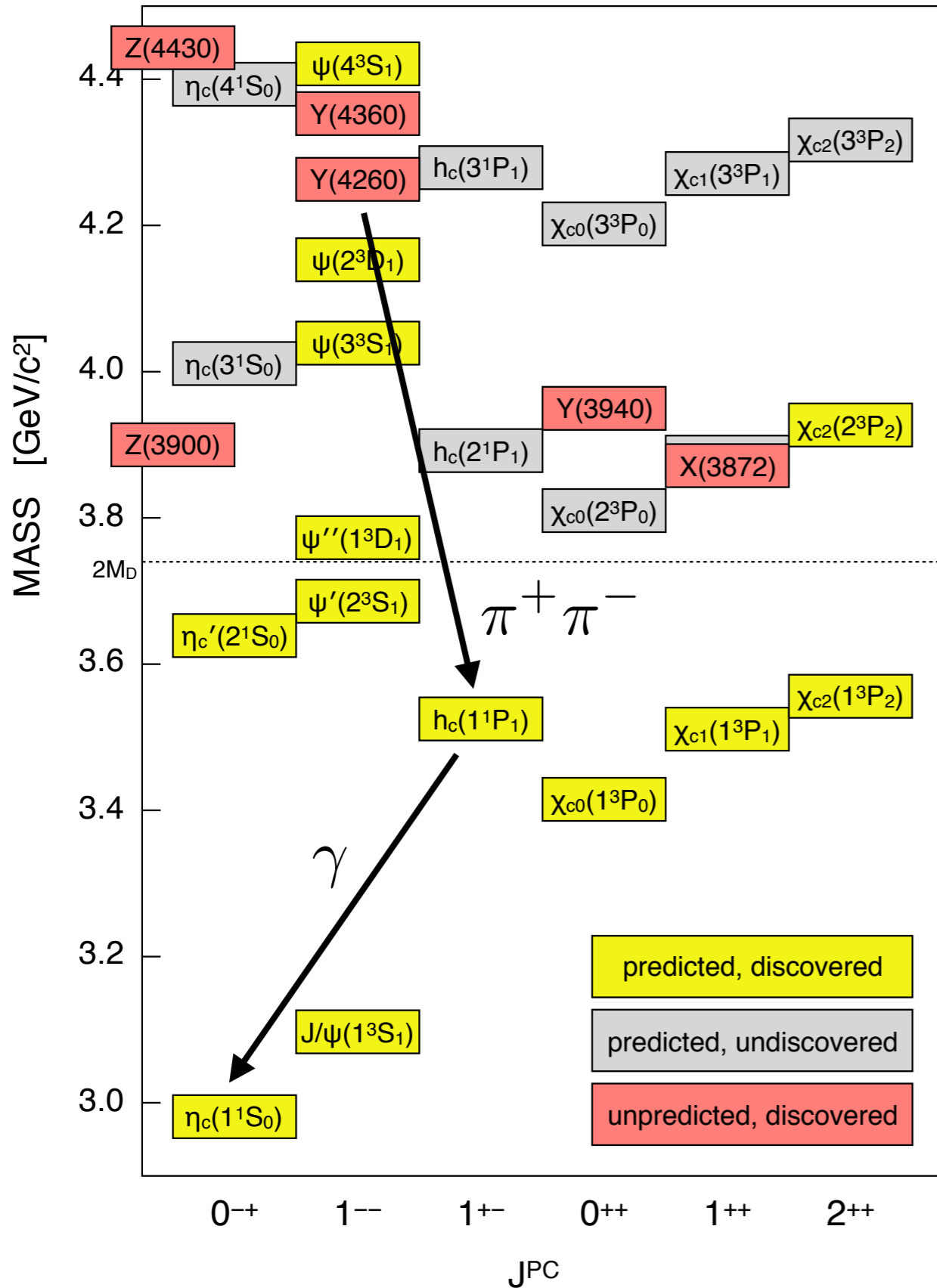


Images from popular *Physics* stories in 2013.

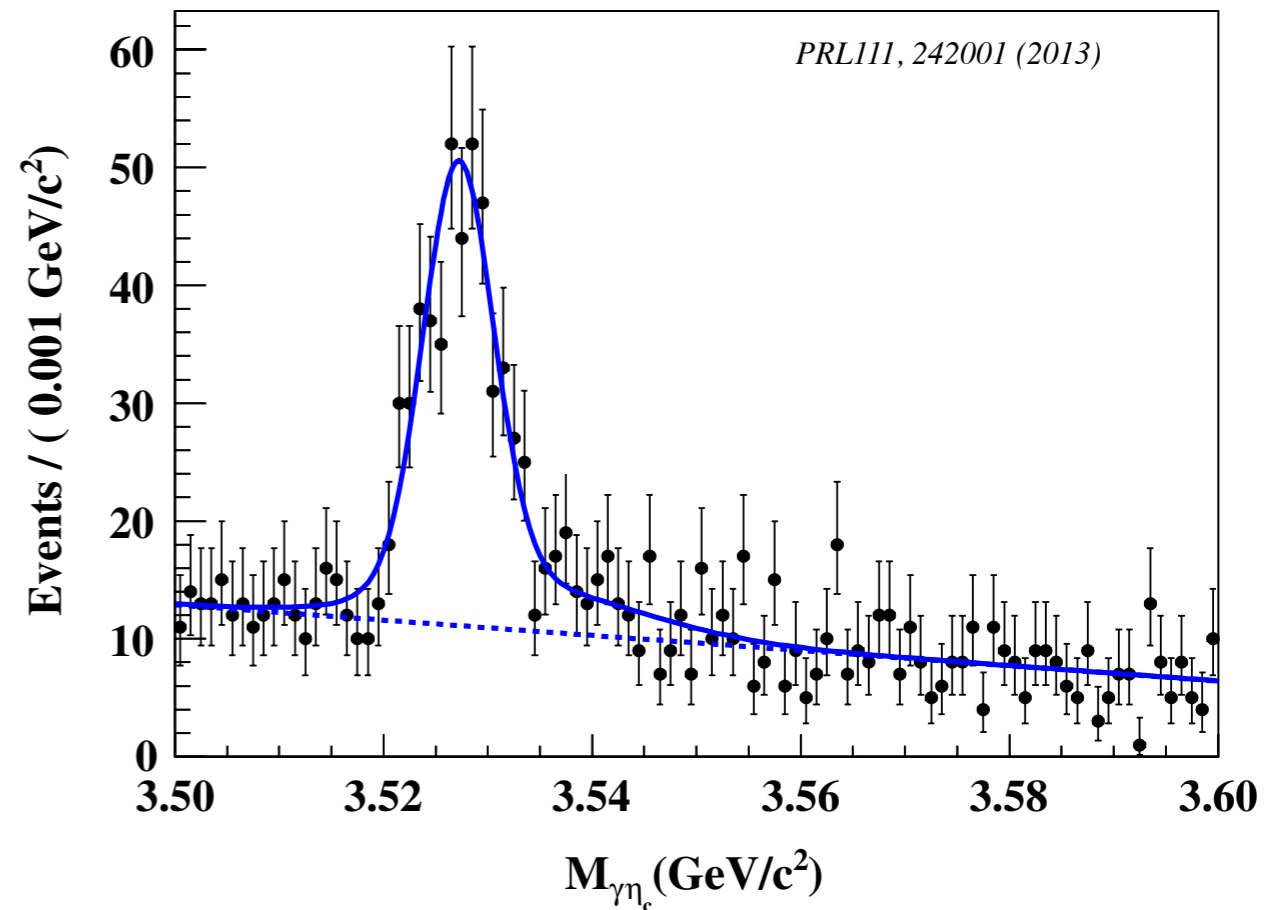
# III. The BESIII Experiment



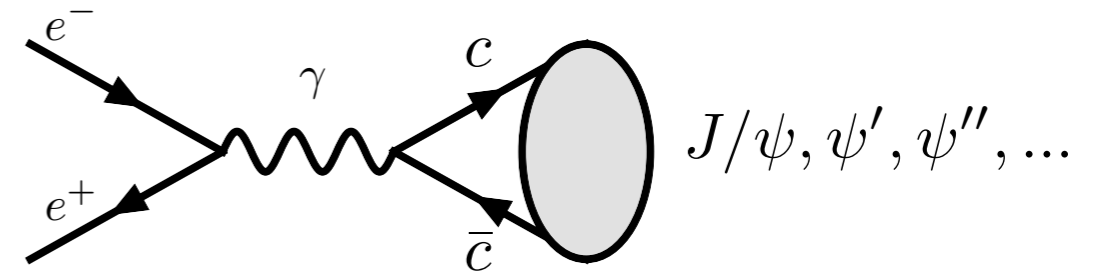
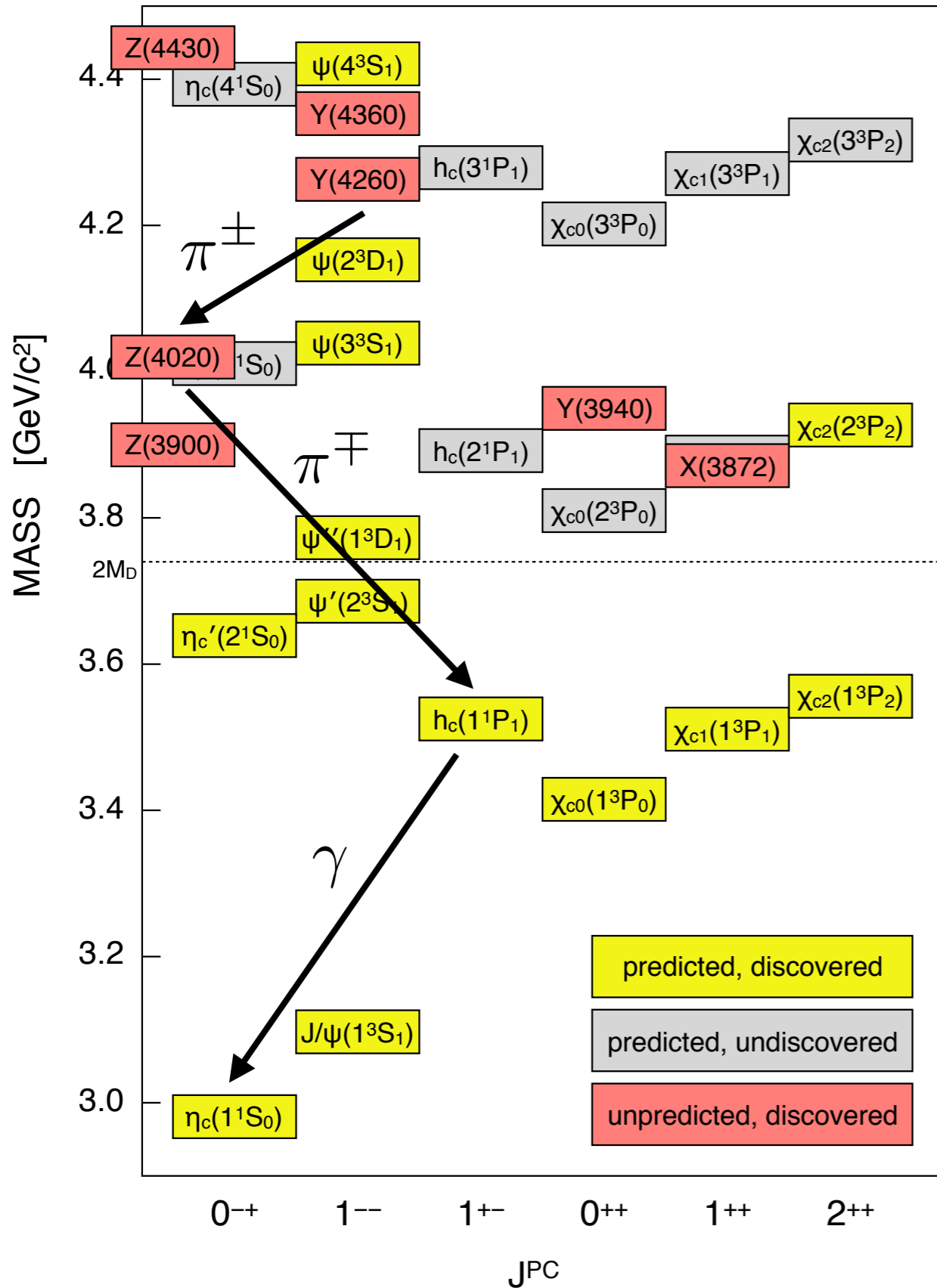
# III. The BESIII Experiment



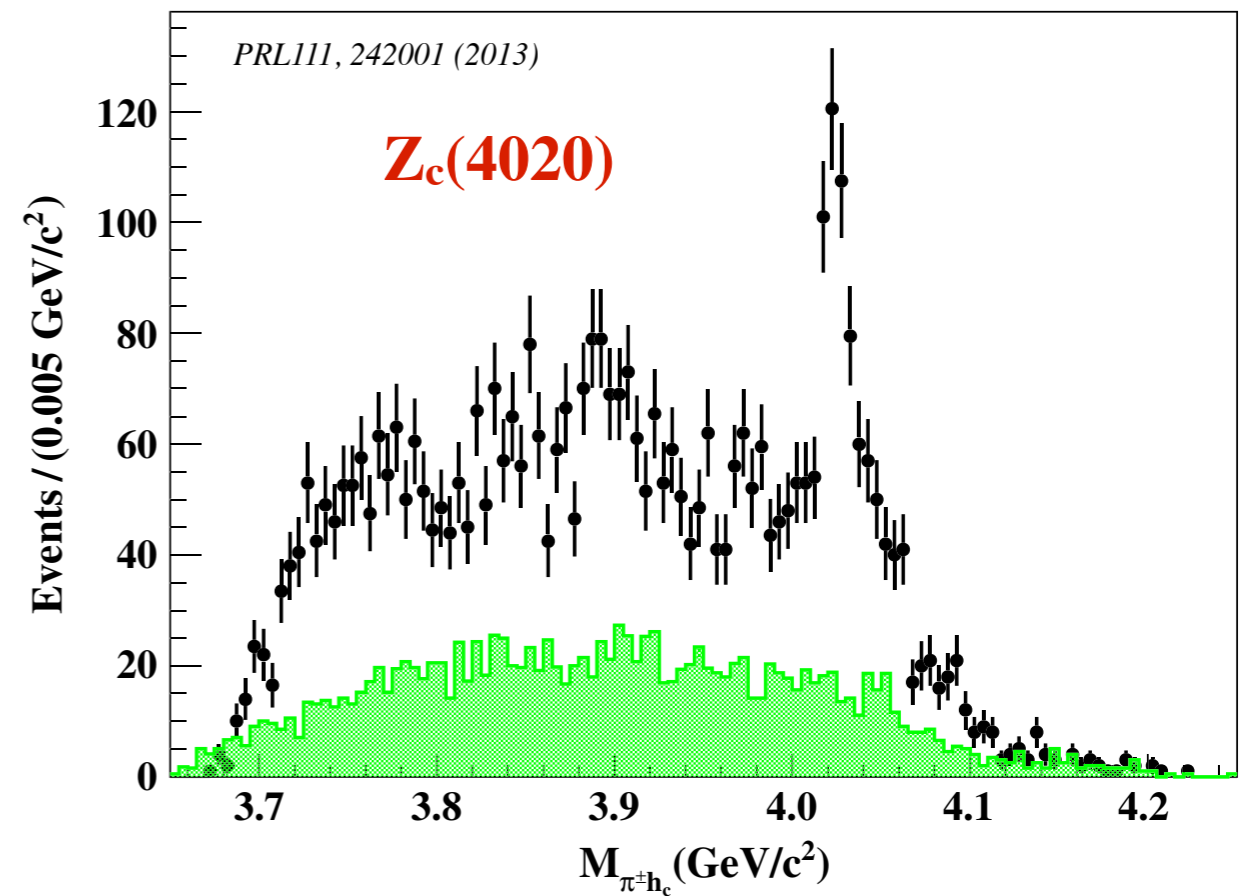
$$e^+e^- \rightarrow \pi^+\pi^-h_c$$



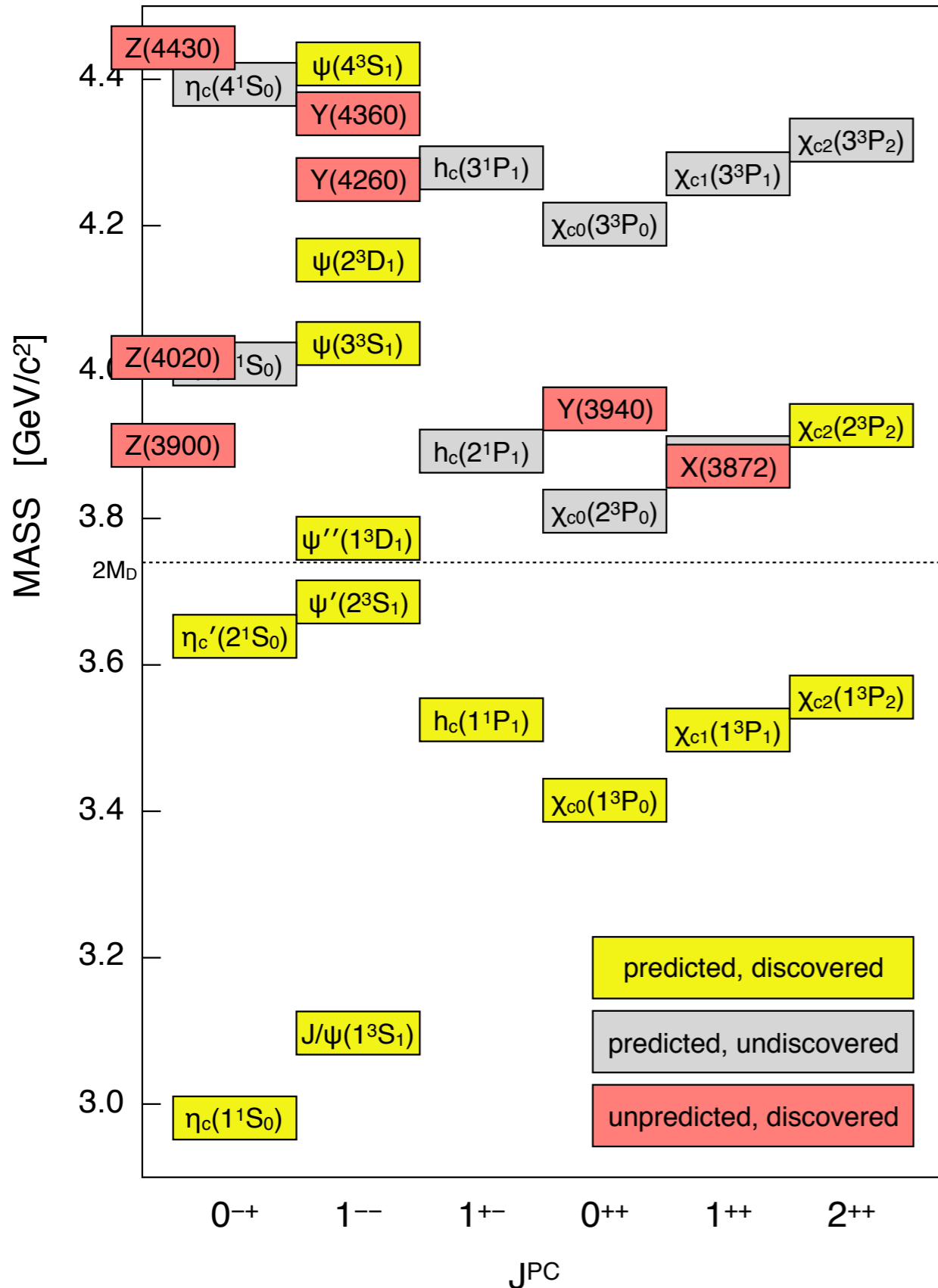
# III. The BESIII Experiment



$$e^+e^- \rightarrow \pi^+\pi^-h_c$$



# III. The BESIII Experiment



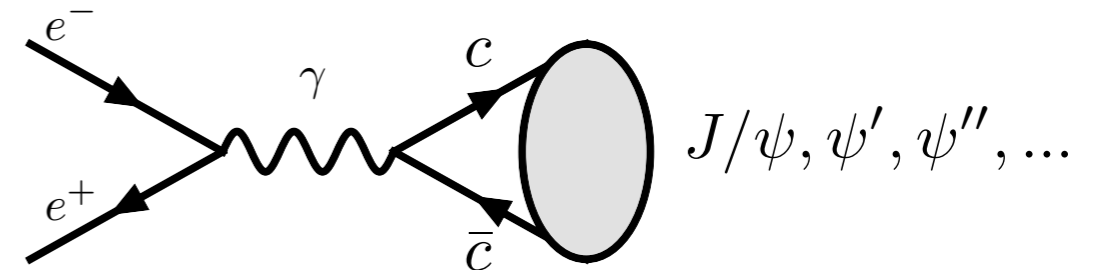
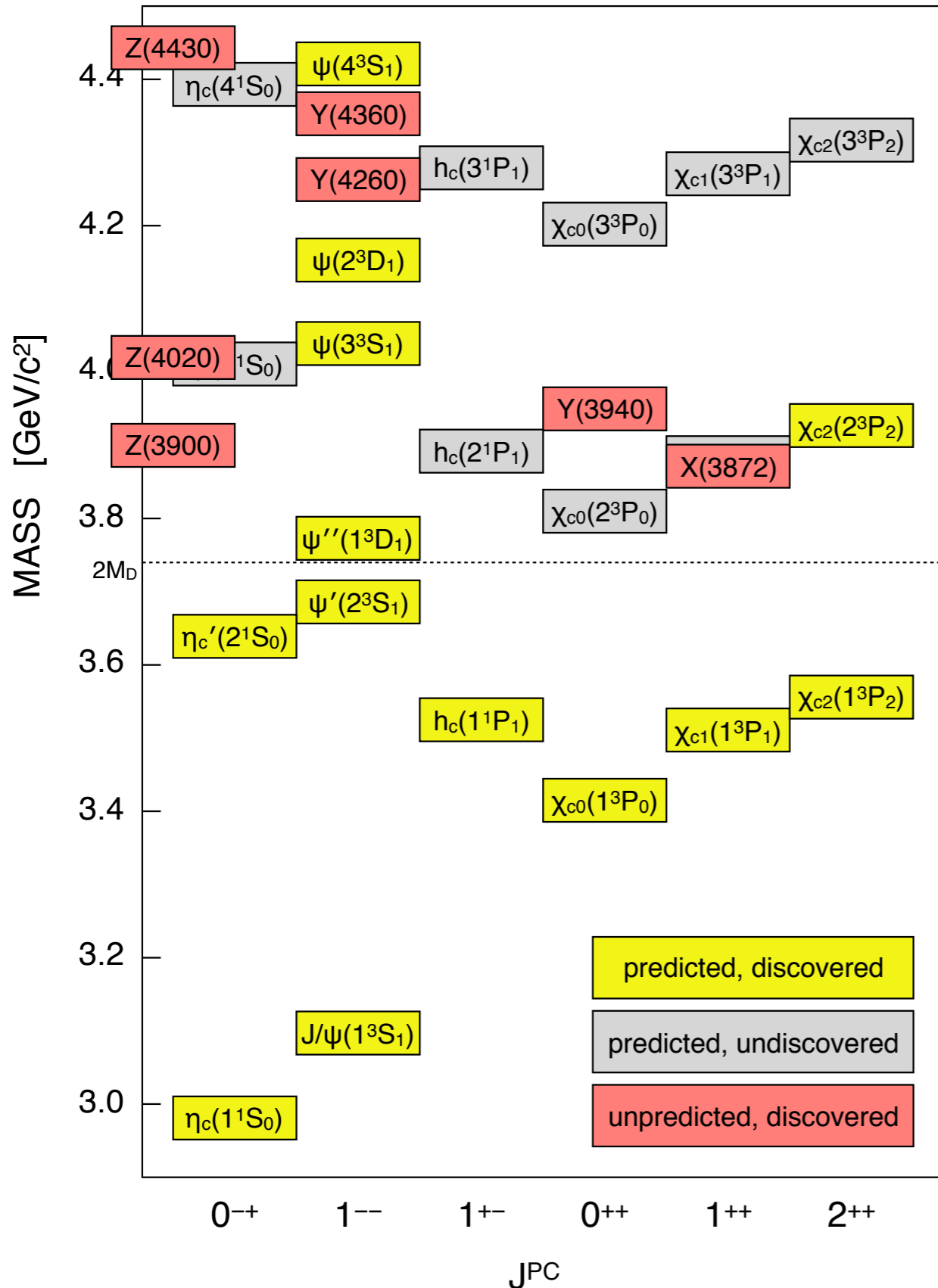
## Current status of the Z<sub>c</sub> states:

*(Good)* The Z<sub>c</sub>(3900) and Z<sub>c</sub>(4020) have clear analogues in the bottomonium system.

*(Interesting)* There are also Z<sub>c</sub> states seen in B decays (e.g. the Z<sub>c</sub>(4430)) that have not yet been found in e<sup>+</sup>e<sup>-</sup> annihilation.

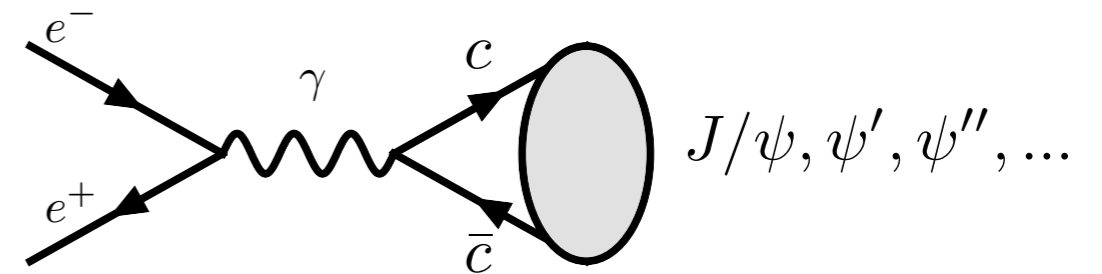
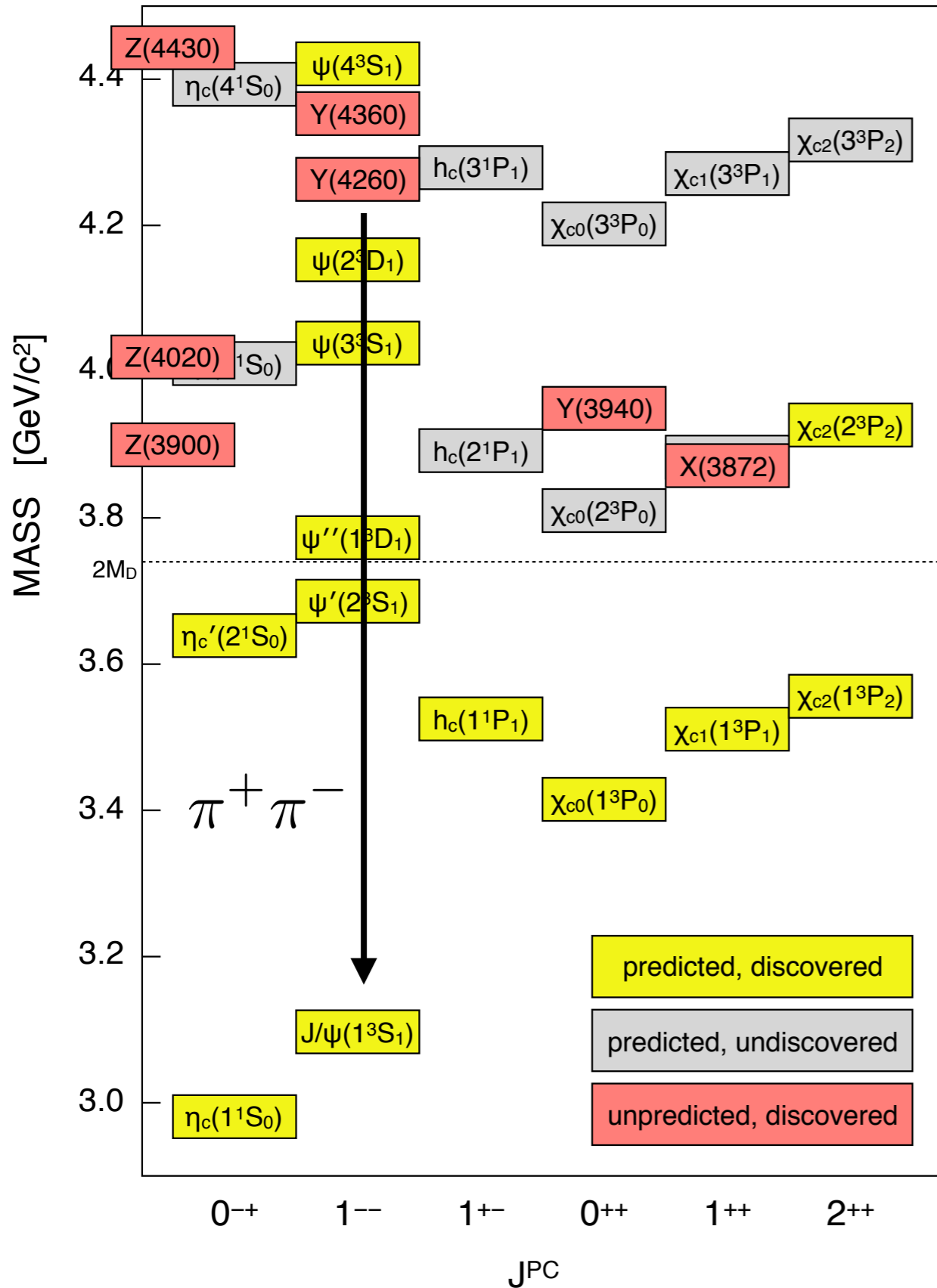
*(Confusing)* The Z<sub>c</sub>(3900) and Z<sub>c</sub>(4020) have not been found in B decays.

# III. The BESIII Experiment

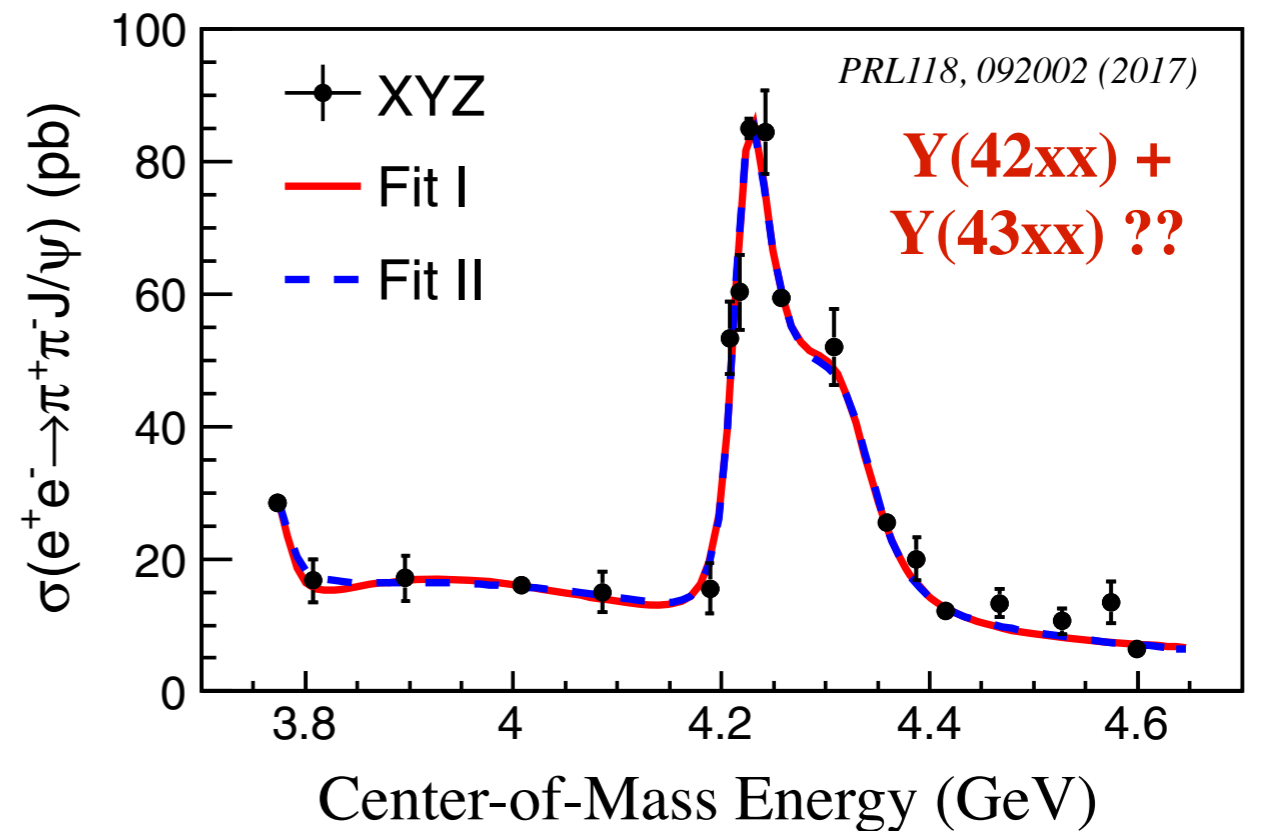


Later in 2013, 2014, and 2016, we collected data at many more energies...

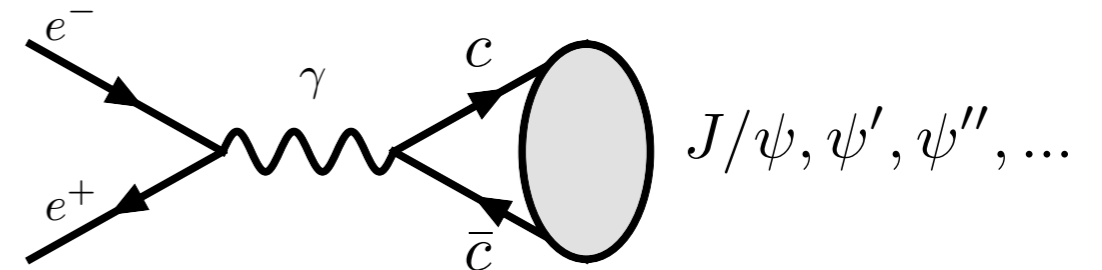
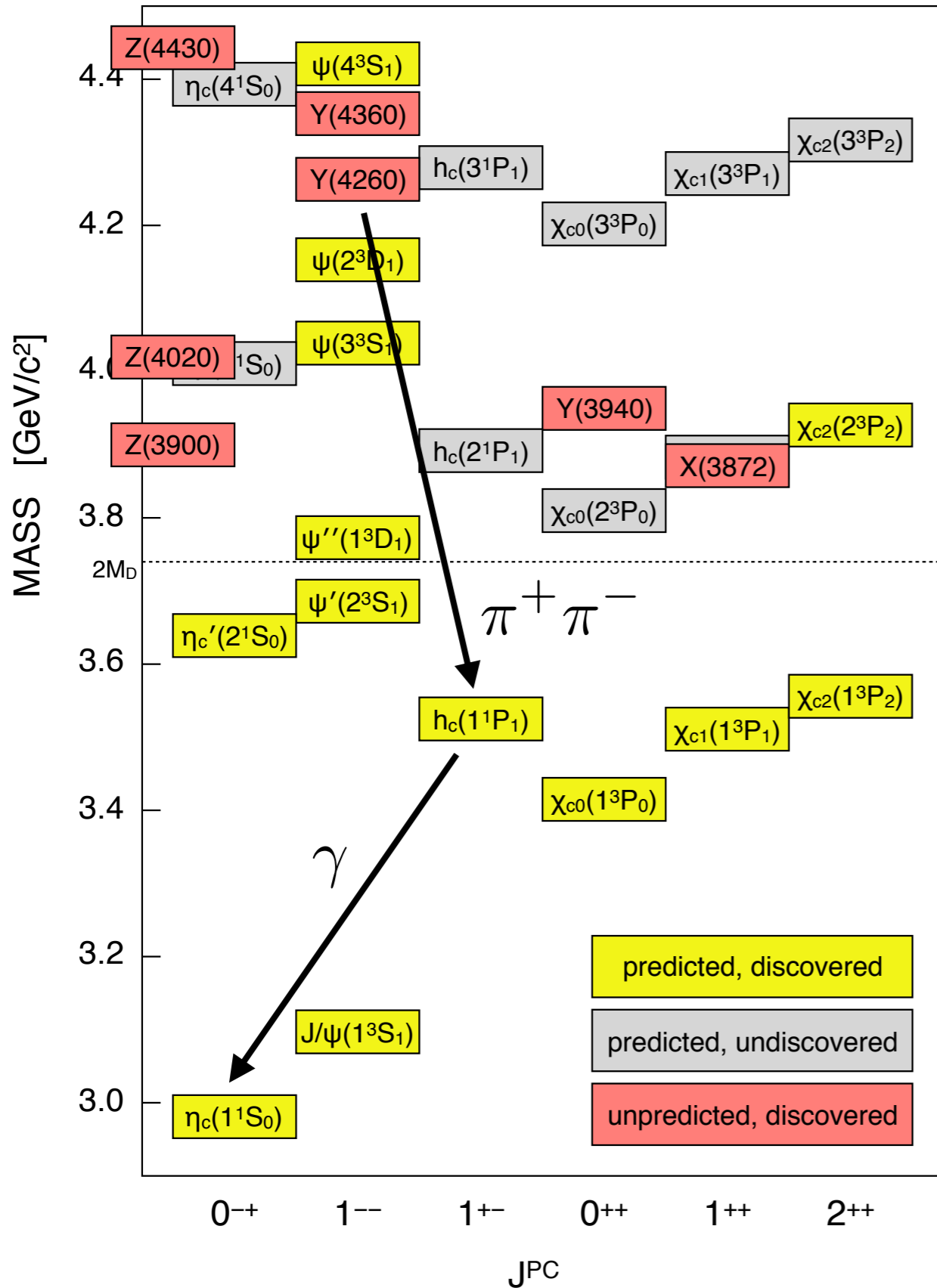
# III. The BESIII Experiment



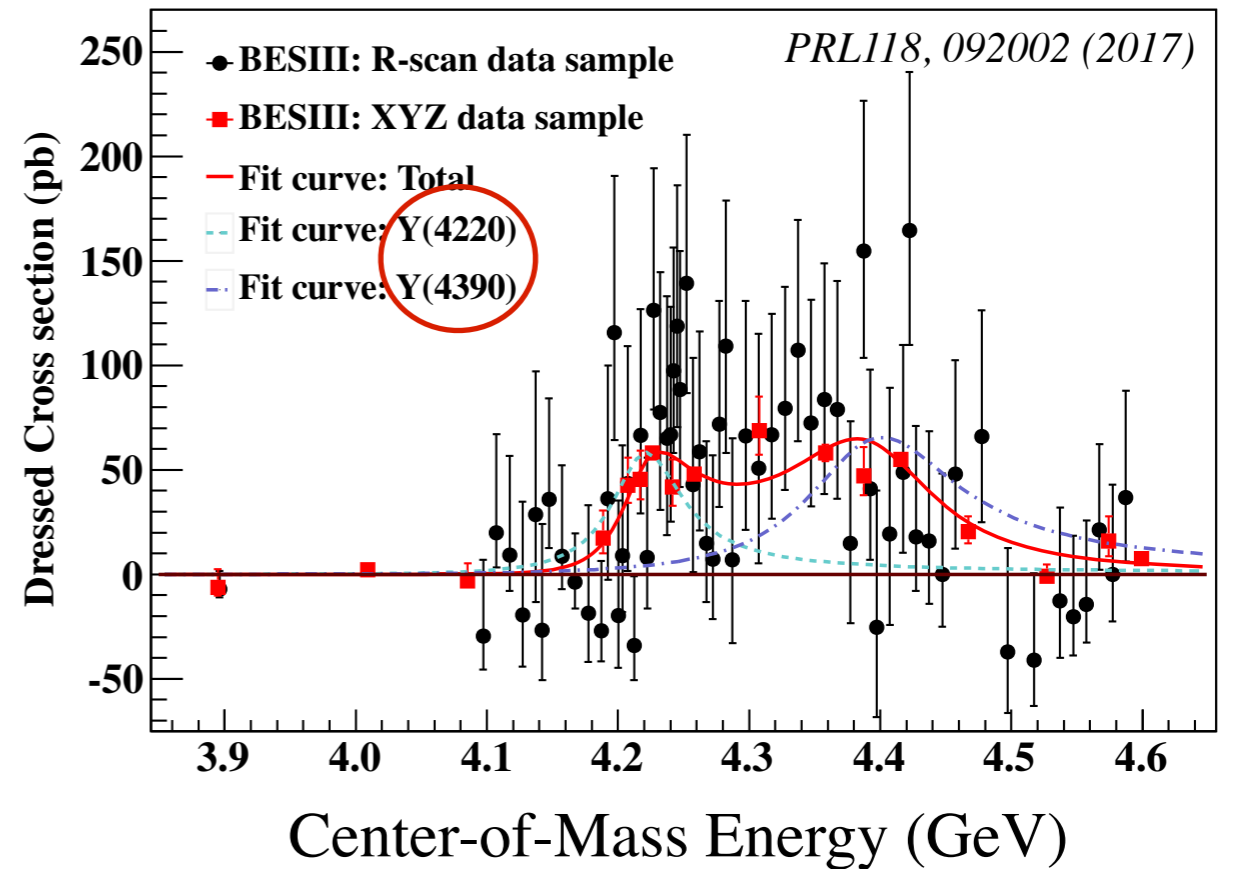
$$e^+e^- \rightarrow \pi^+\pi^- J/\psi$$



# III. The BESIII Experiment

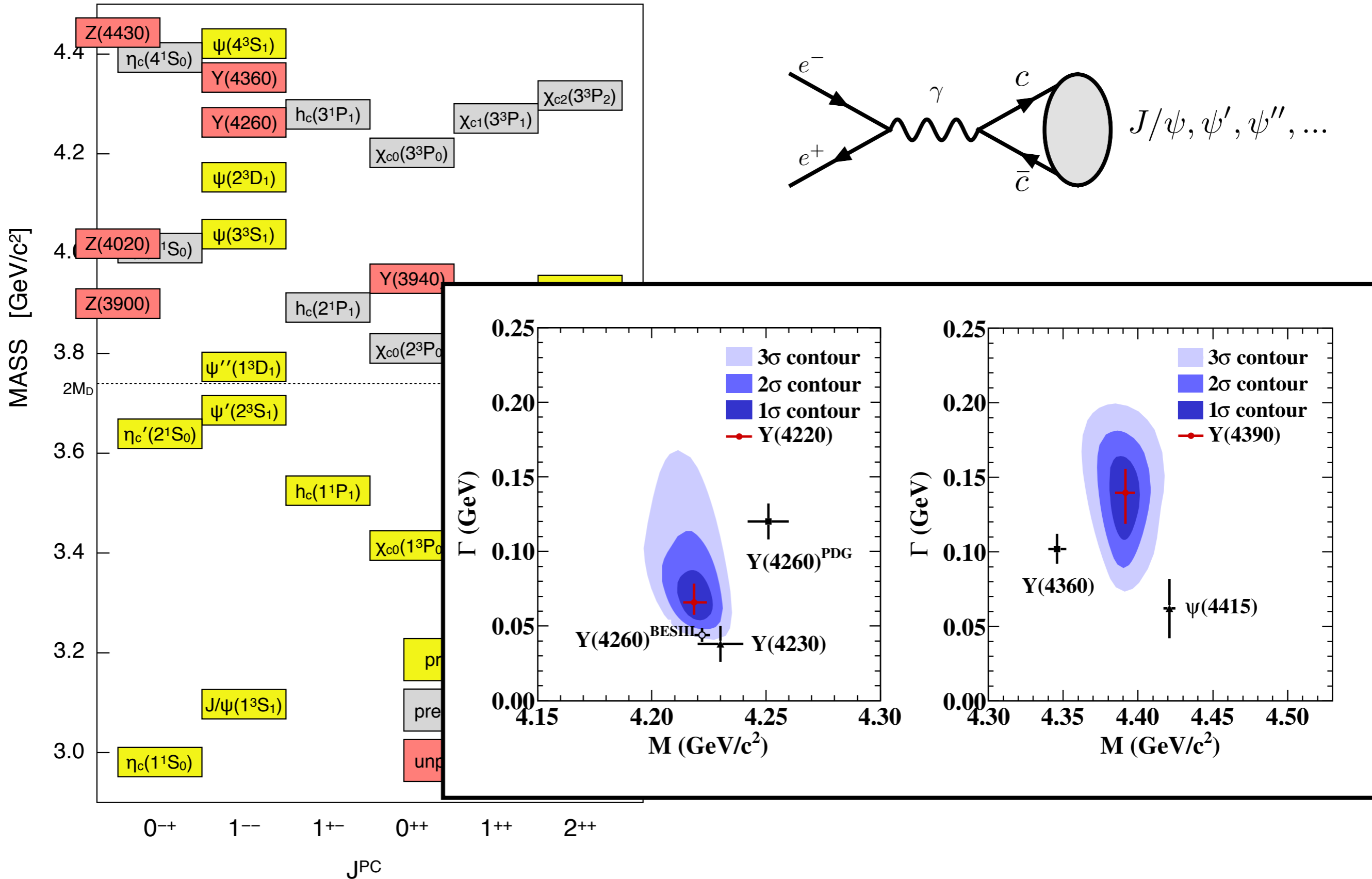


$$e^+e^- \rightarrow \pi^+\pi^-h_c$$

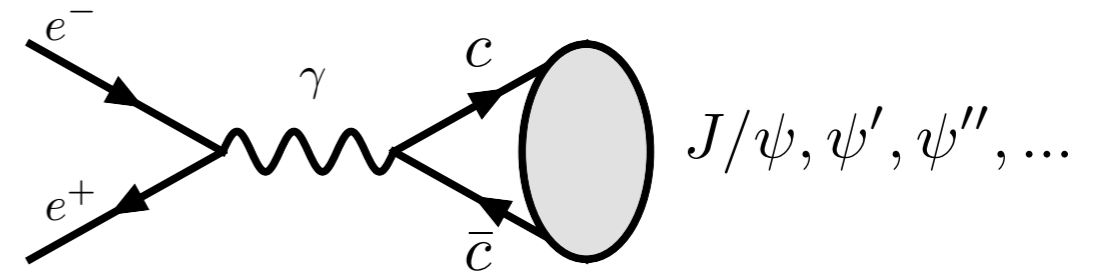
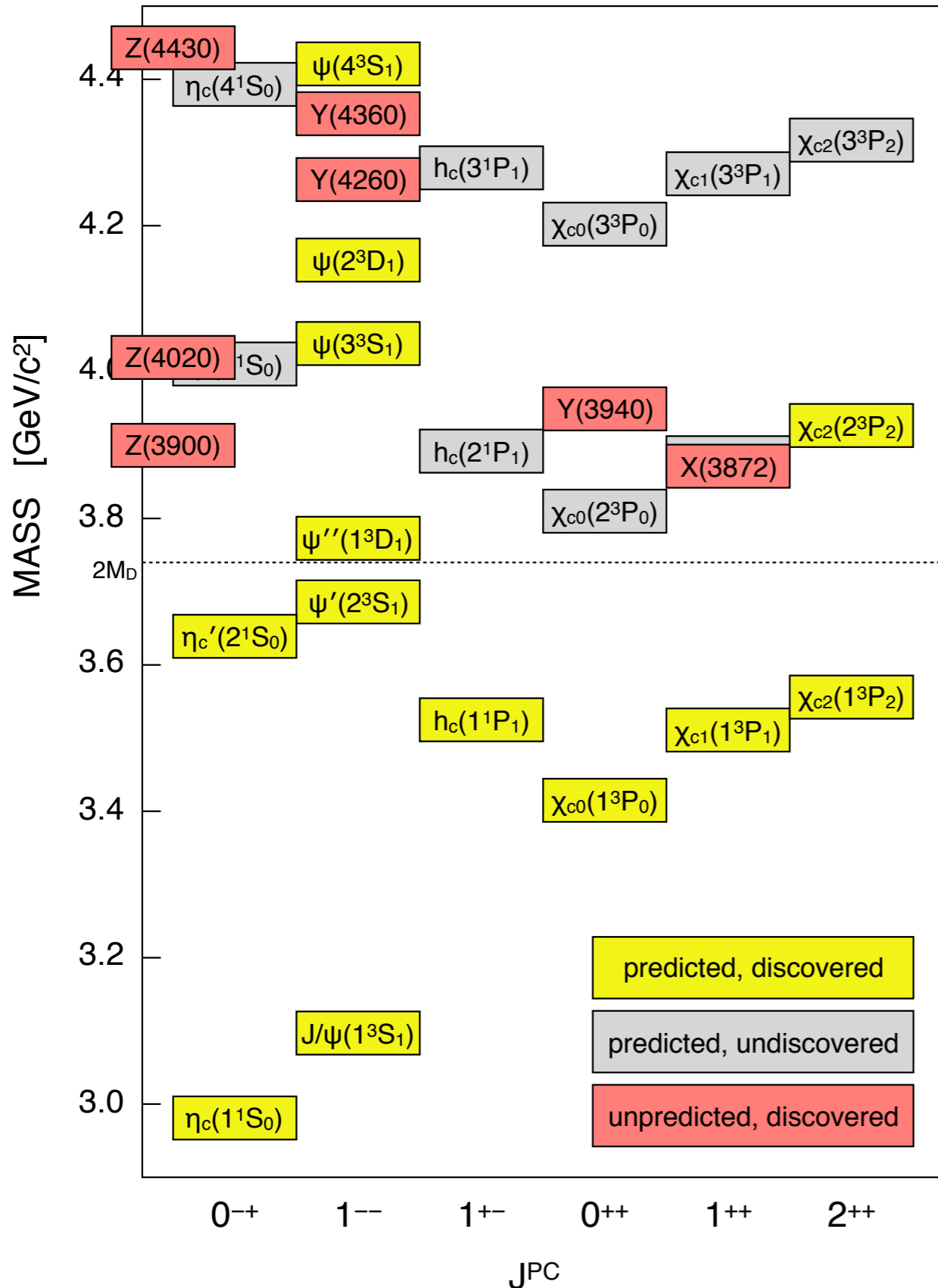




# III. The BESIII Experiment



# III. The BESIII Experiment

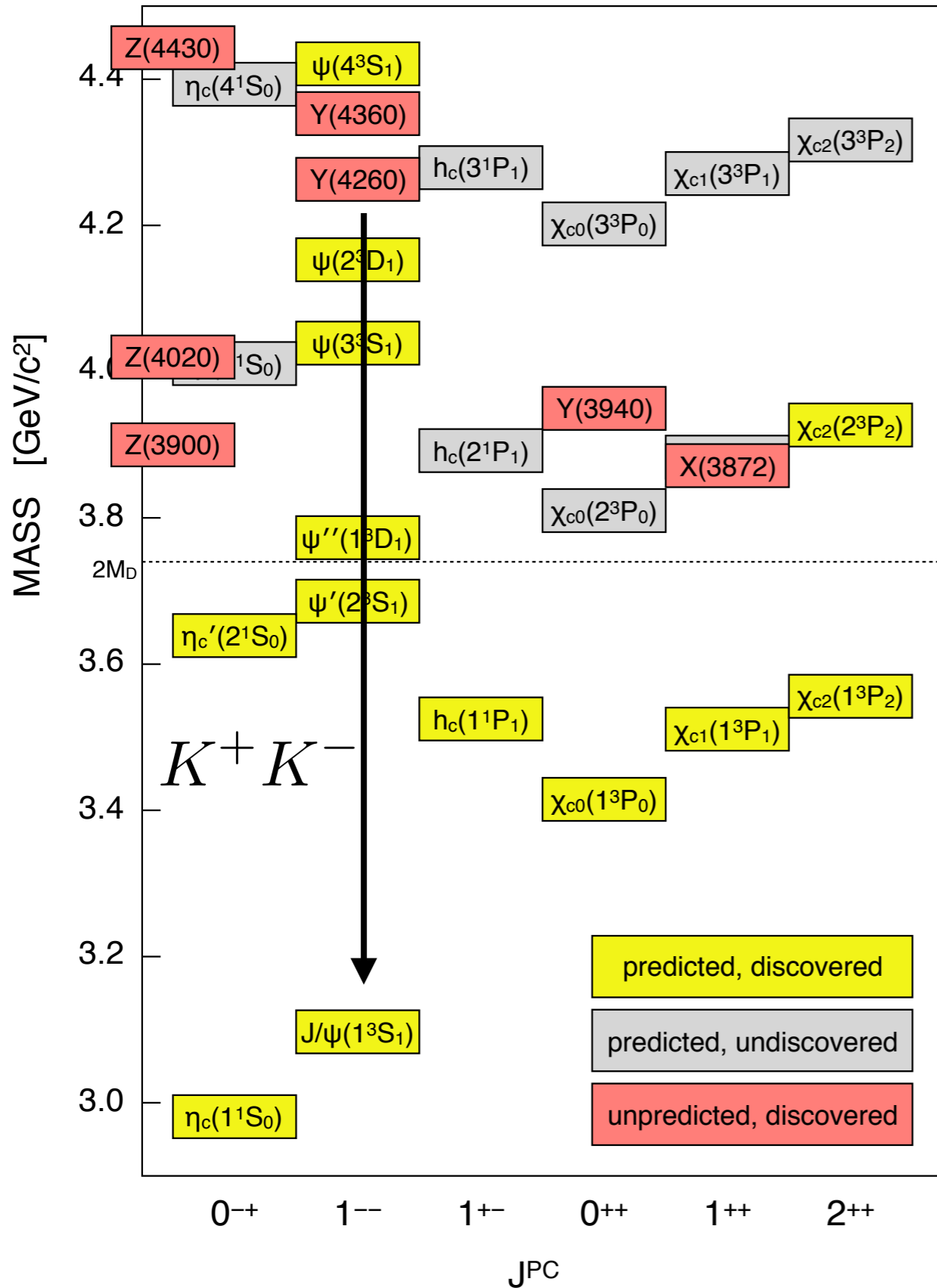


A few studies from IU graduate students:

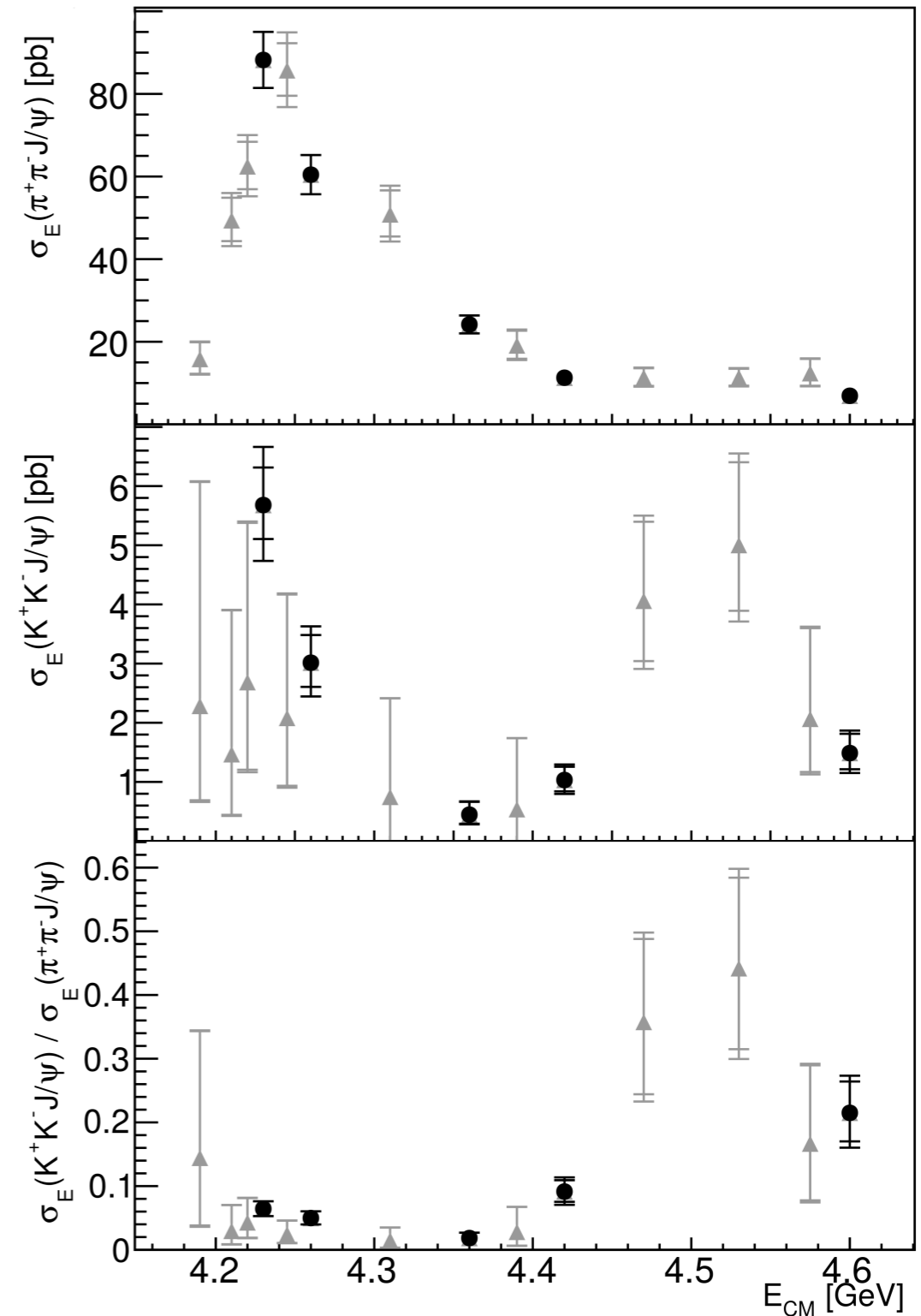
Dan Bennett: What about  $e^+e^- \rightarrow K^+K^-J/\psi$ ?

Manuel Lara: What about  $e^+e^- \rightarrow \gamma\eta_c$ ?

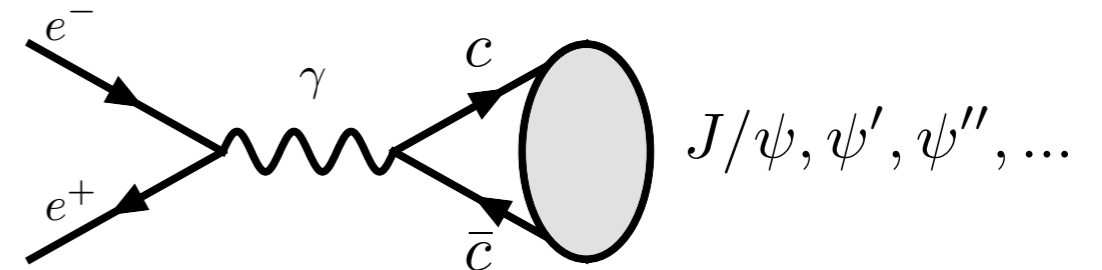
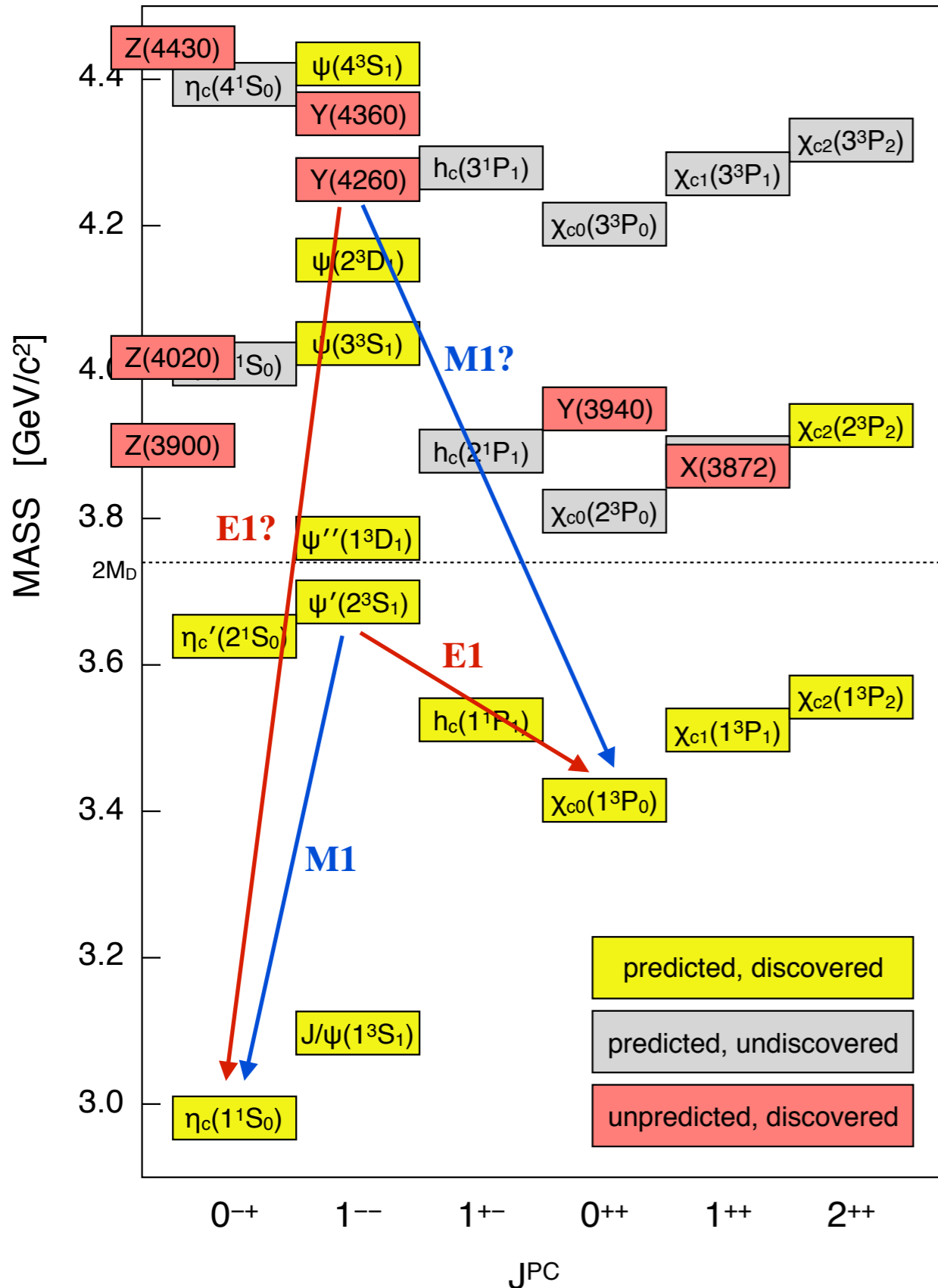
# III. The BESIII Experiment



$$e^+e^- \rightarrow \pi^+\pi^- J/\psi, K^+K^- J/\psi$$



# III. The BESIII Experiment

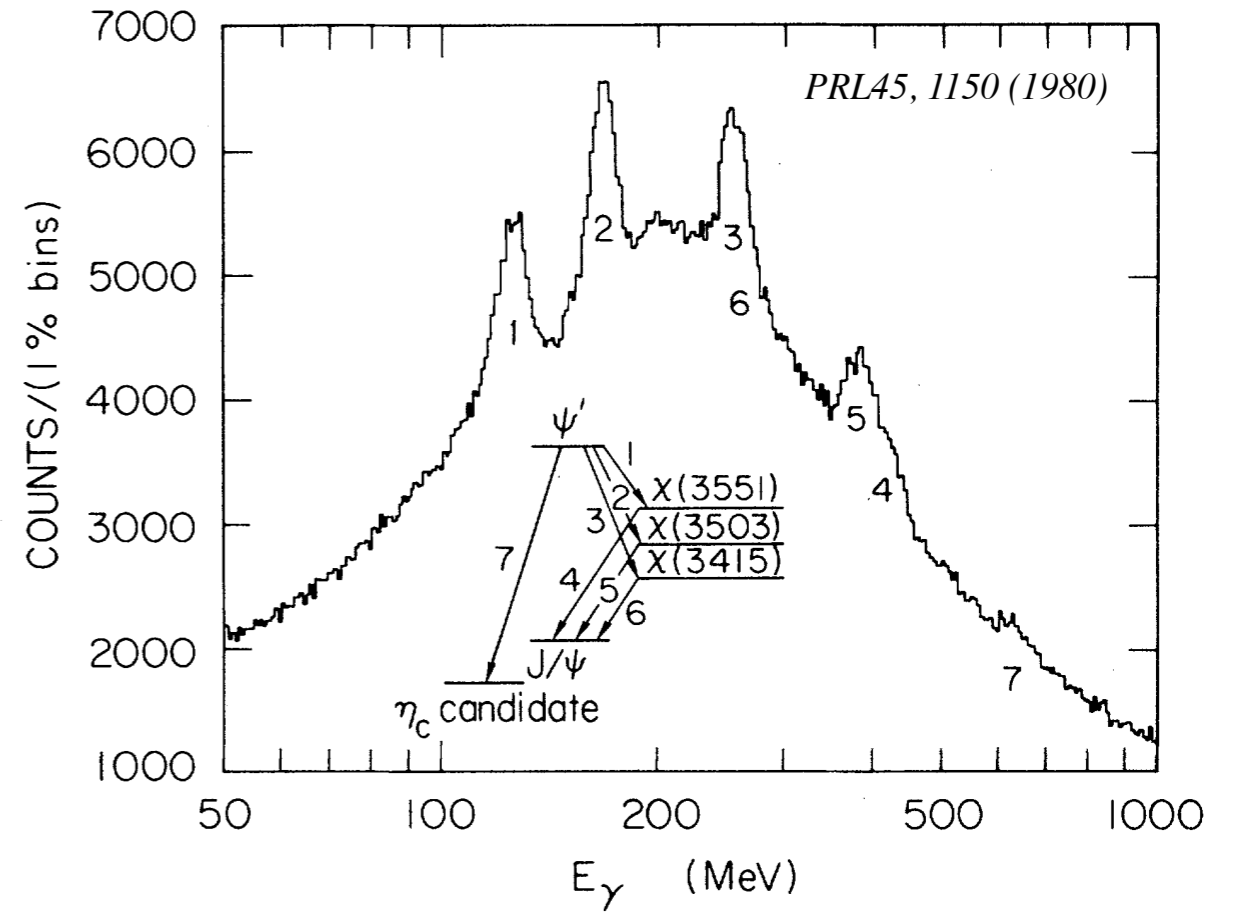
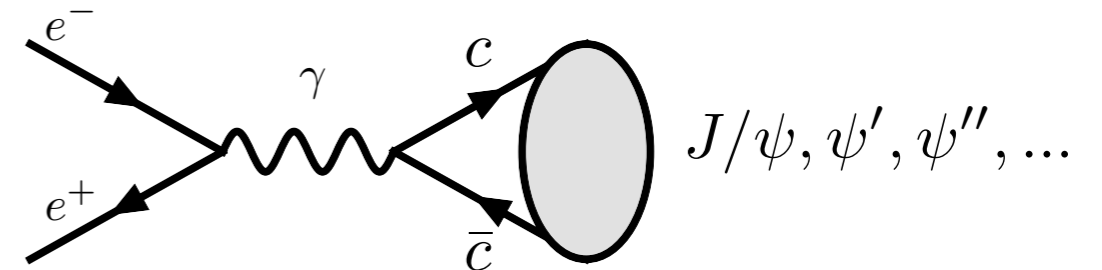
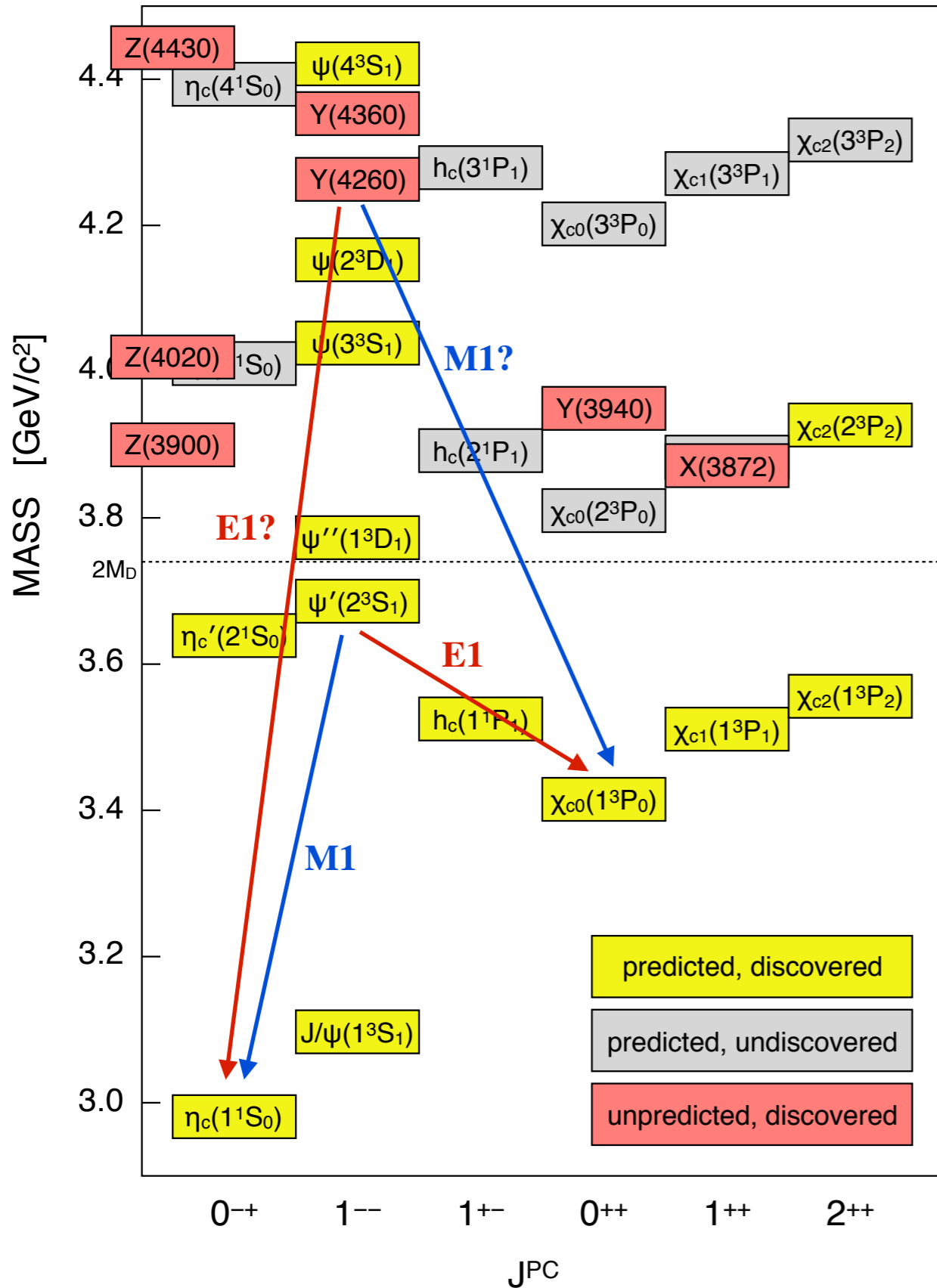


A few studies from IU graduate students:

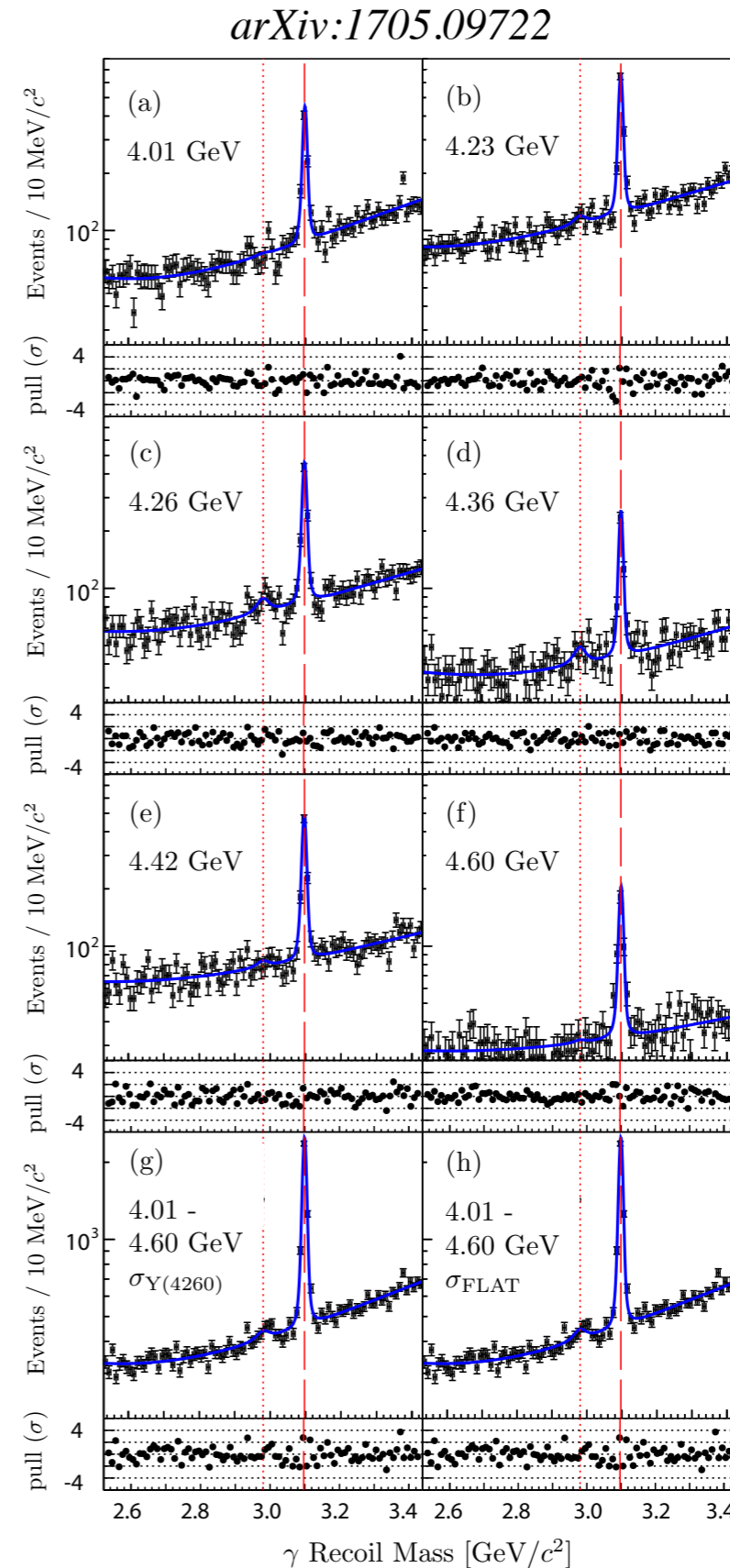
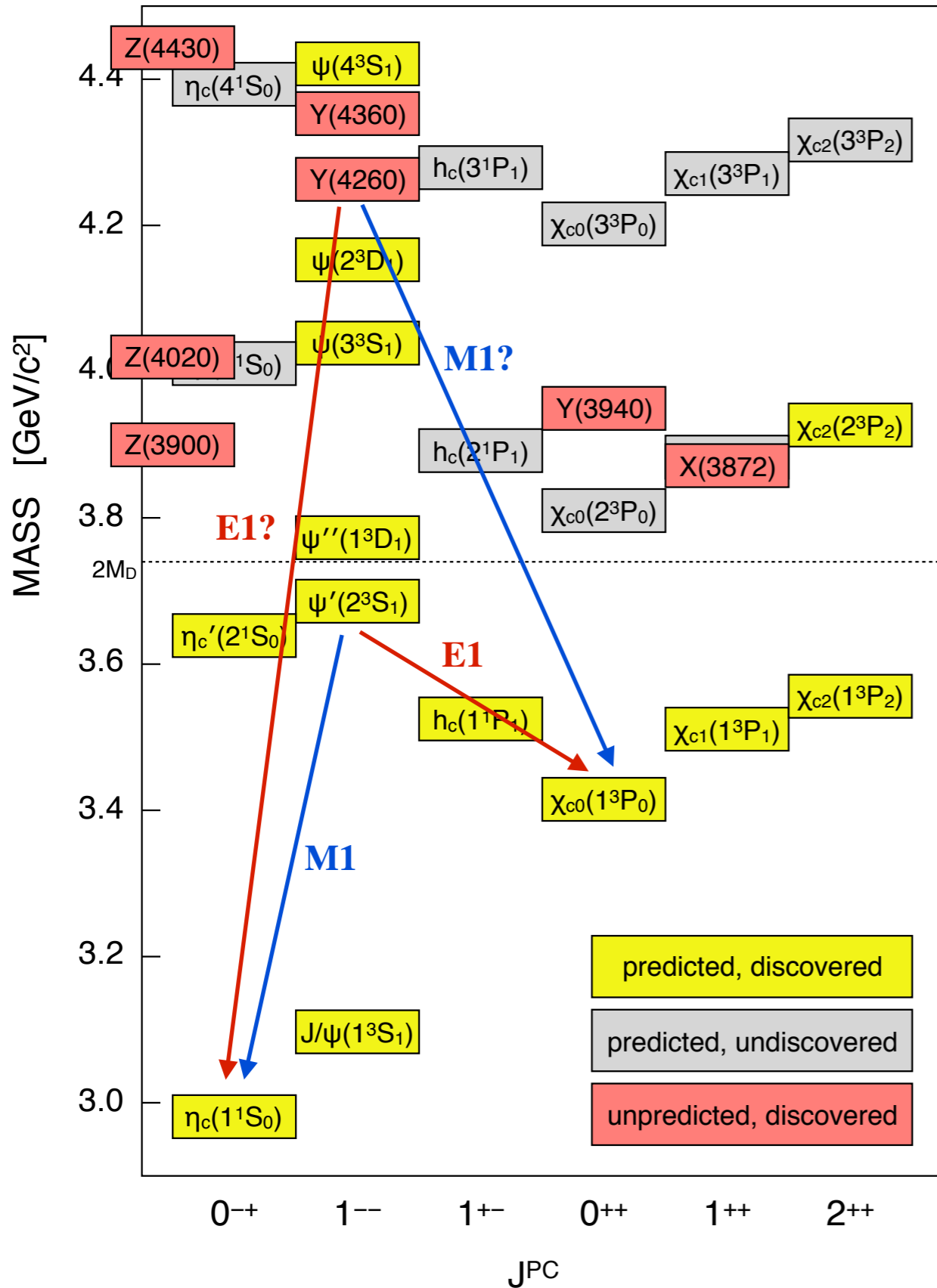
Dan Bennett: What about  $e^+e^- \rightarrow K^+K^-J/\psi$ ?

Manuel Lara: What about  $e^+e^- \rightarrow \gamma\eta_c$ ?

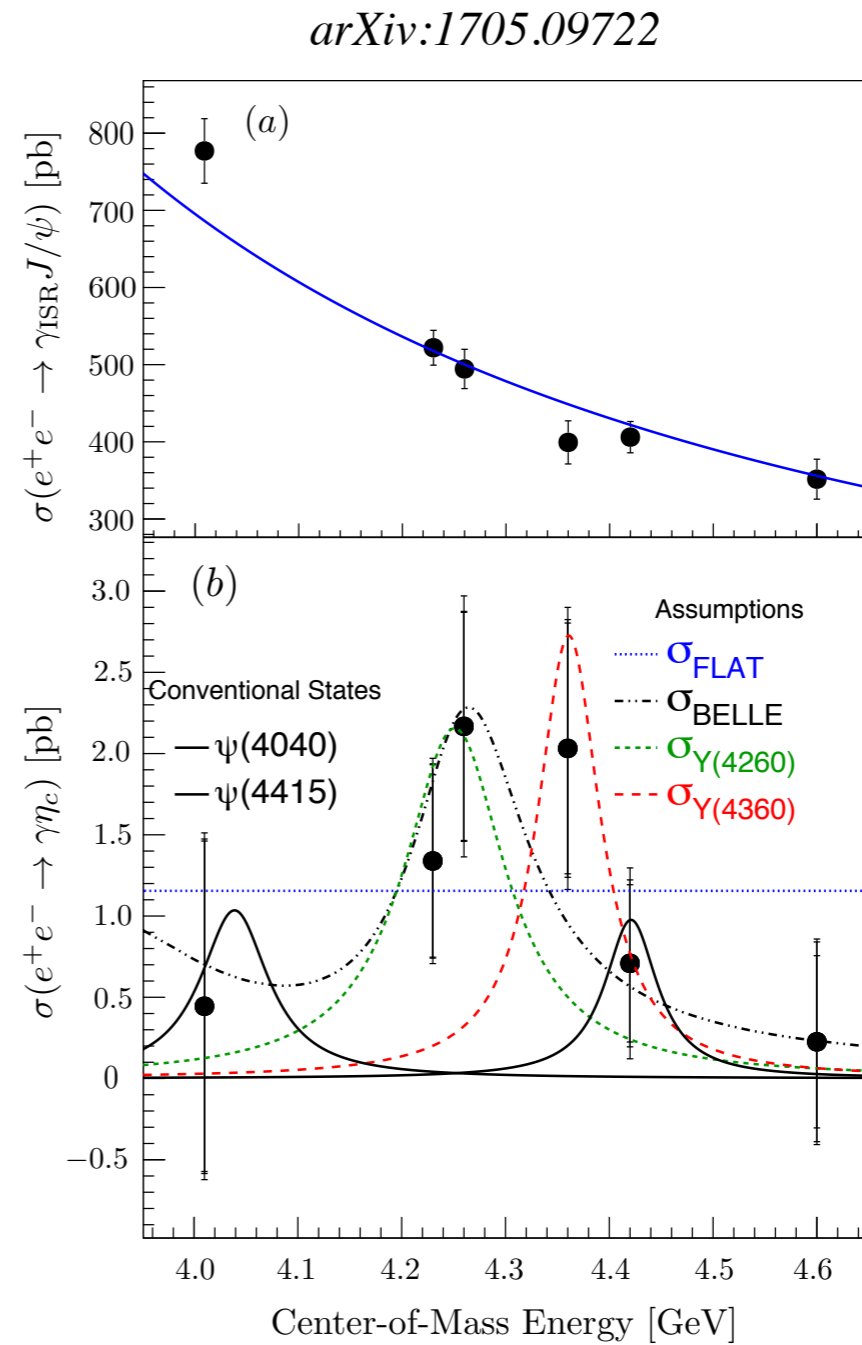
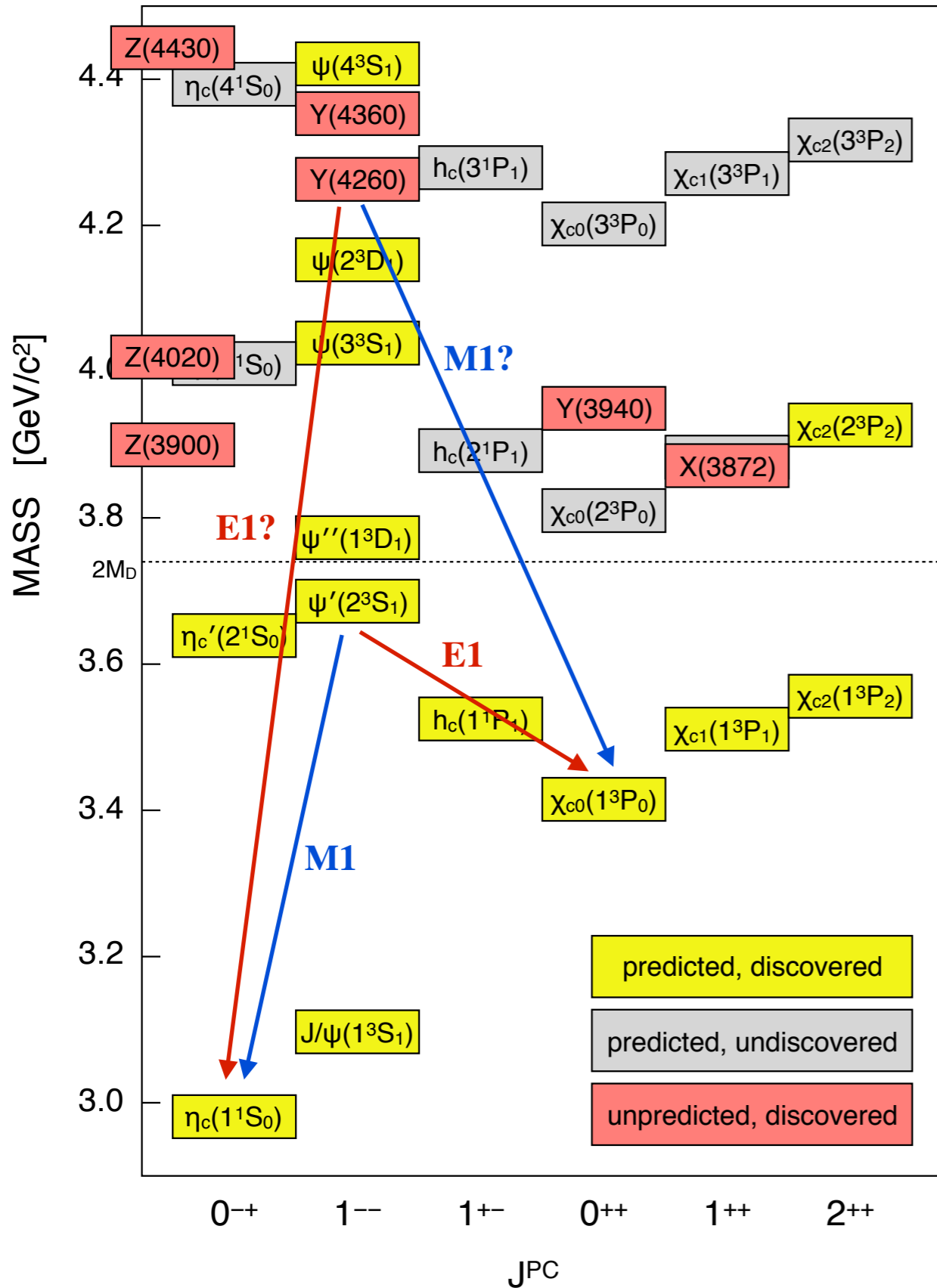
# III. The BESIII Experiment



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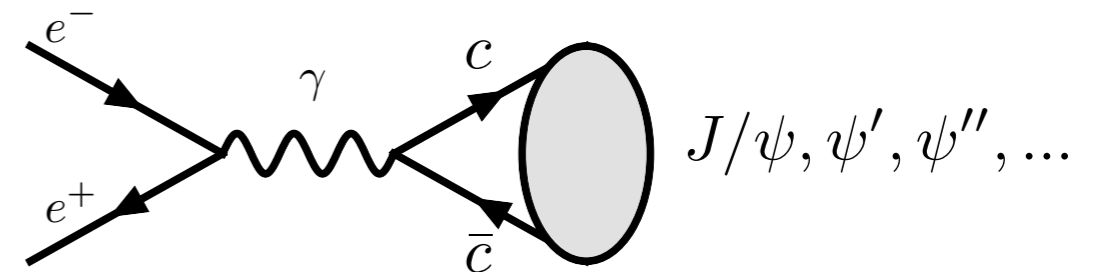
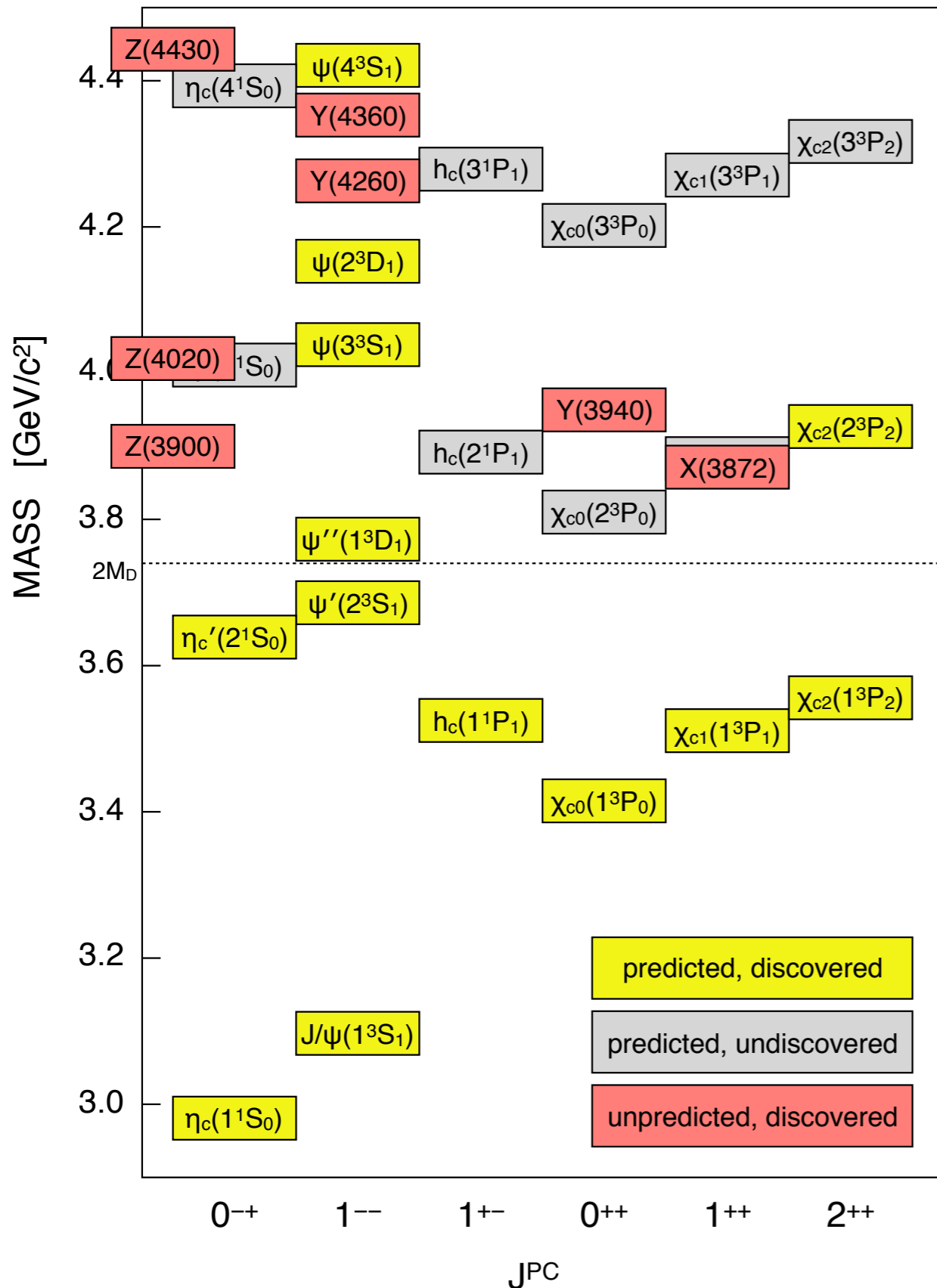
# III. The BESIII Experiment



> 4  $\sigma$   
evidence for  
 $e^+e^- \rightarrow \gamma \eta_c$

no sign of  
 $e^+e^- \rightarrow \gamma \chi_{c0}$

# III. The BESIII Experiment



Next Plan: Do a fine scan (*every ~10 MeV*) of the XYZ region with  $\sim 500 \text{ pb}^{-1}$  per point.

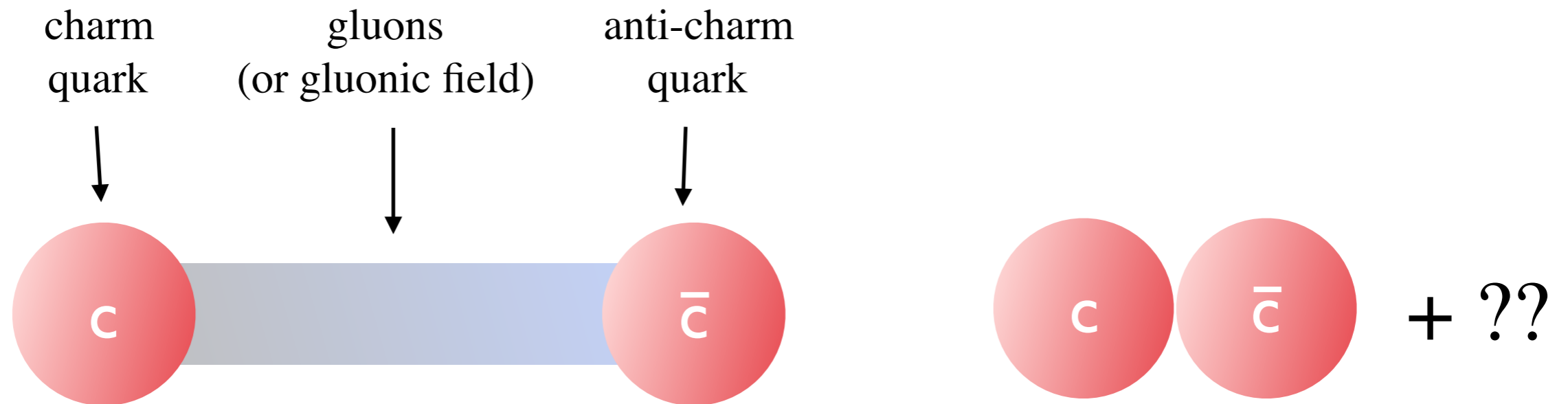
2017: 4190, 4200, 4210, 4230, 4240, 4250, 4270, 4280

Next: 4290, 4300, 4310, ..... MeV

Do a more systematic analysis of  $e^+e^-$  cross sections and substructure.



- There is still much to understand about the charmonium system:



- It is an exciting chance to learn more about the strong force.
- Progress is being made, but the destination is not clear...