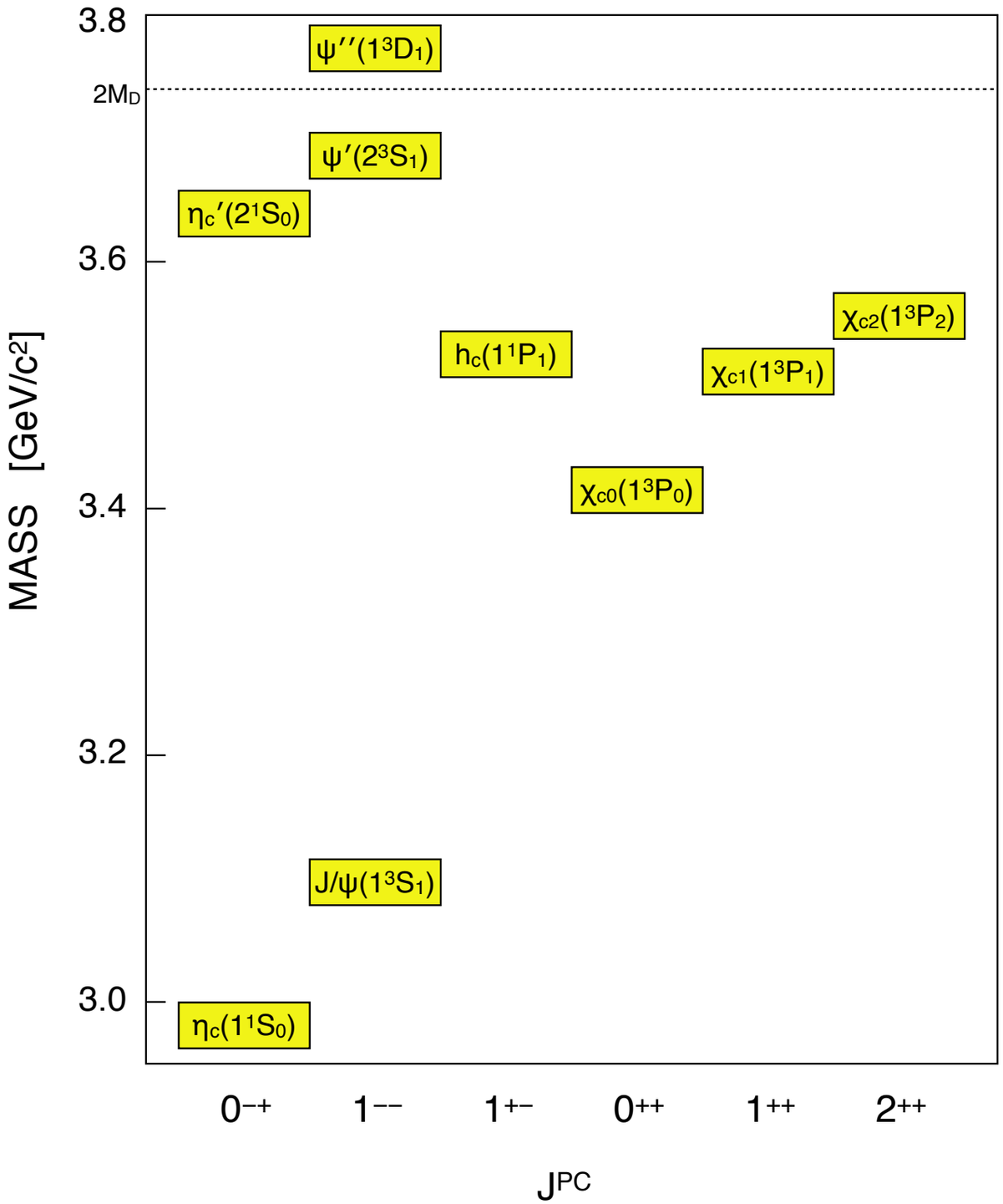
# Charmonium Spectroscopy, the "XYZ" States, and the Role of BESIII

Ryan Mitchell
Indiana University
SLAC Seminar
October 15, 2013

# Charmonium Spectroscopy and the Role of BESIII

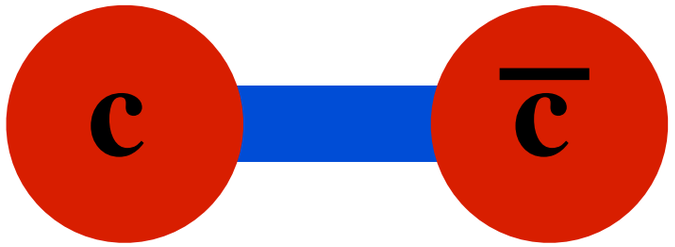



I. An Introduction to Charmonium

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

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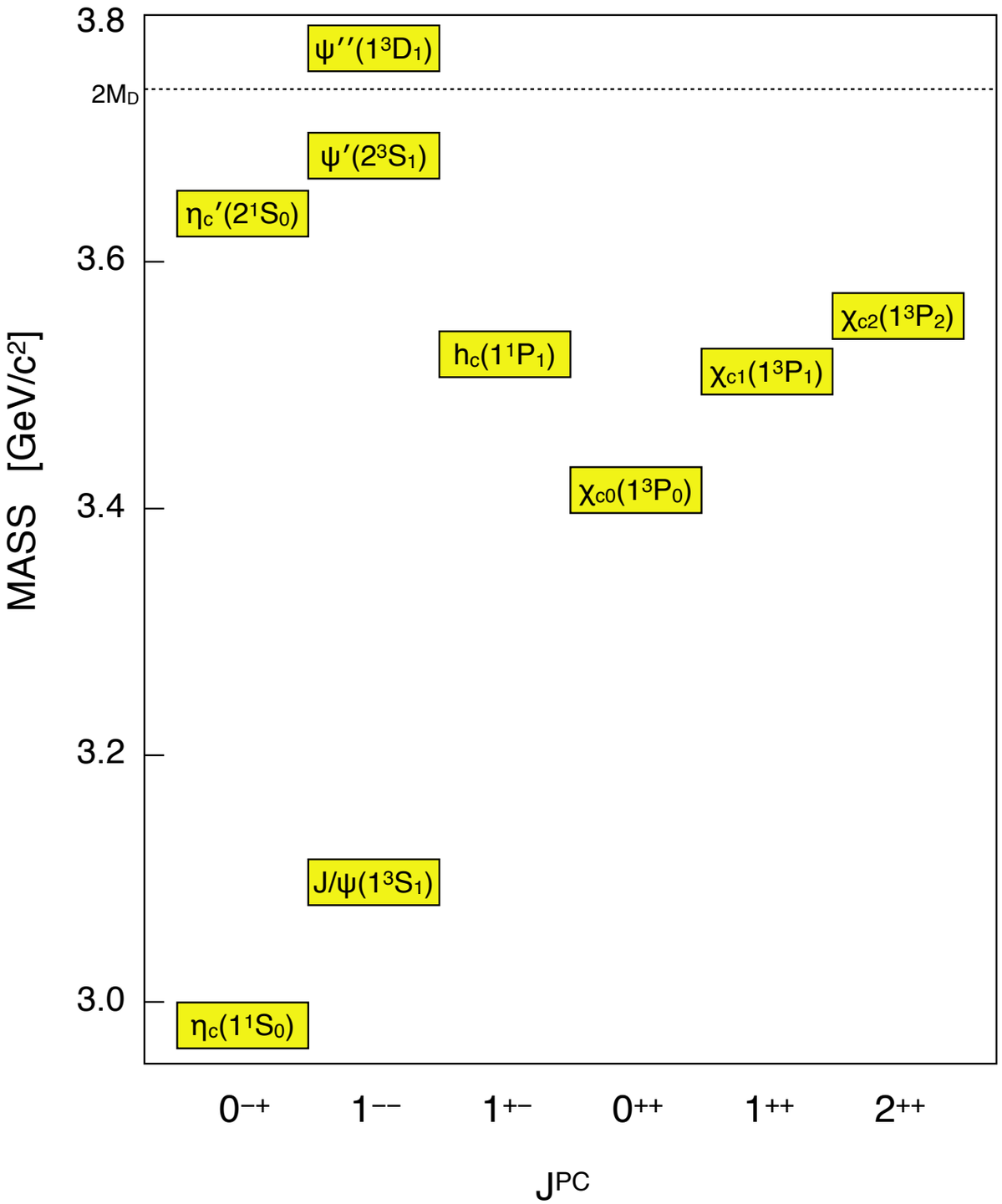


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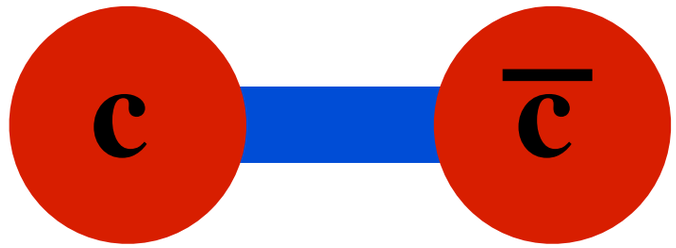


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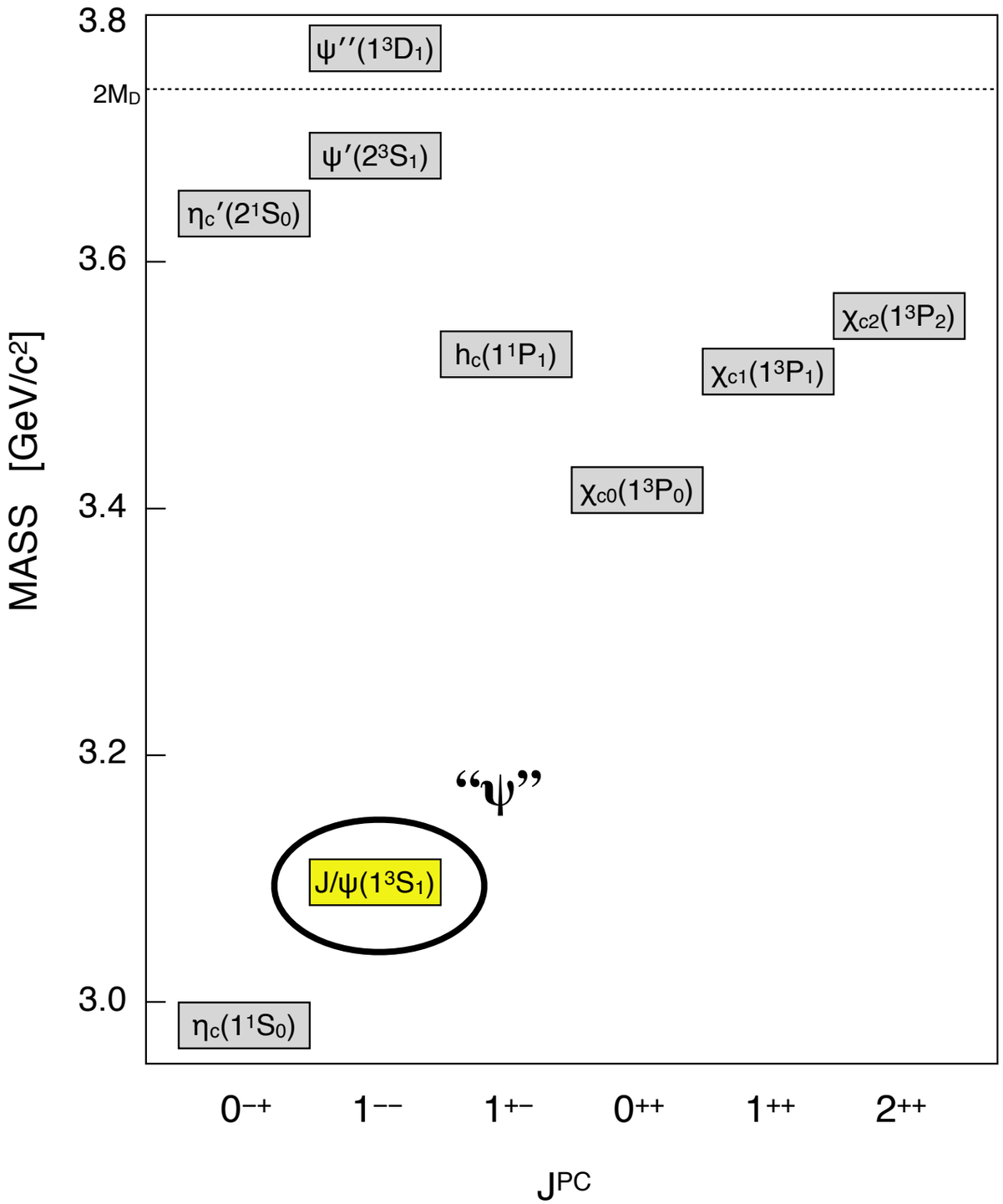


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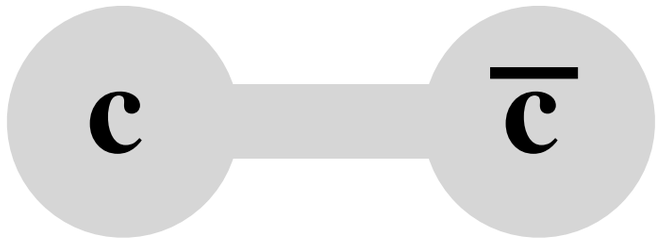


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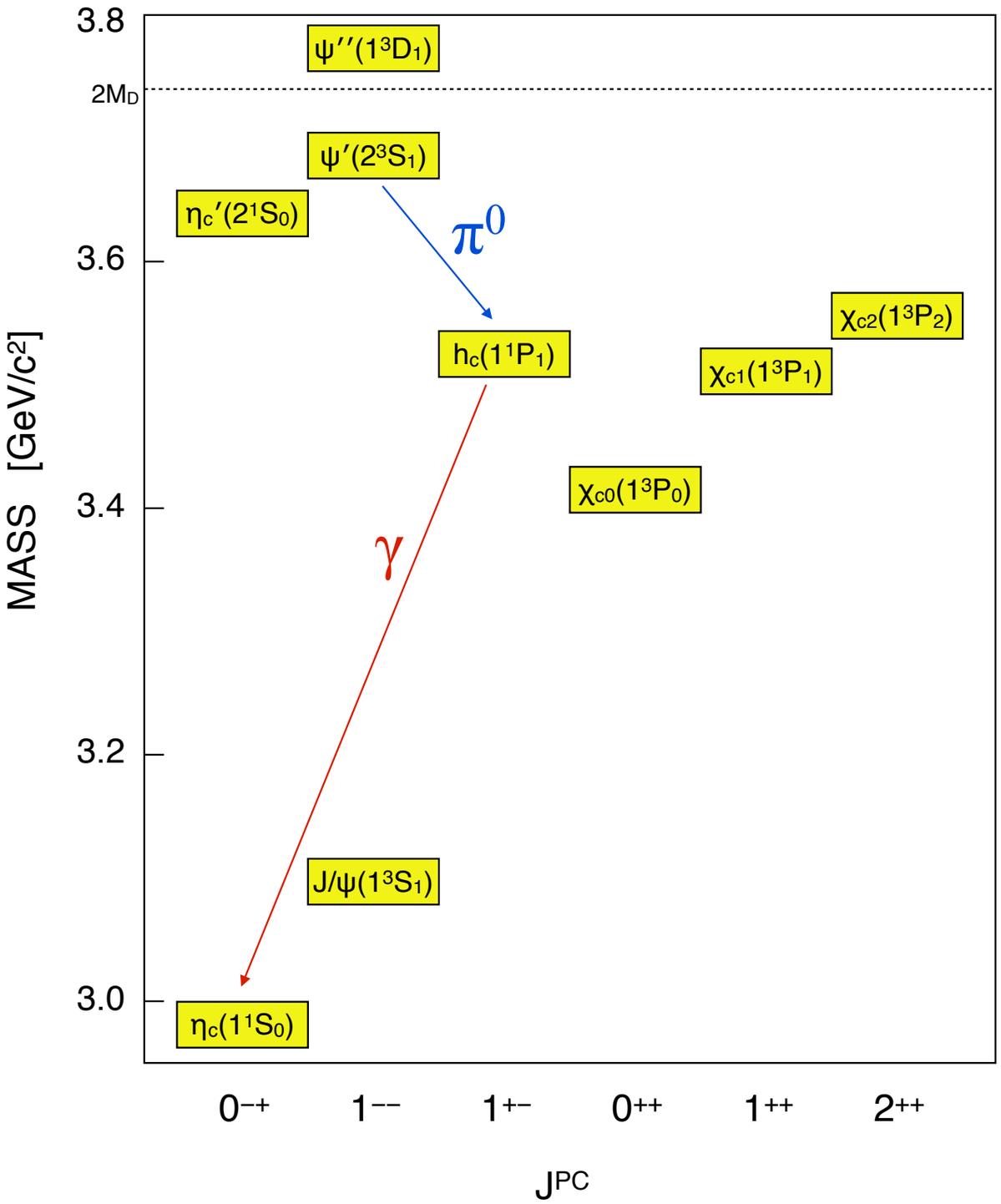


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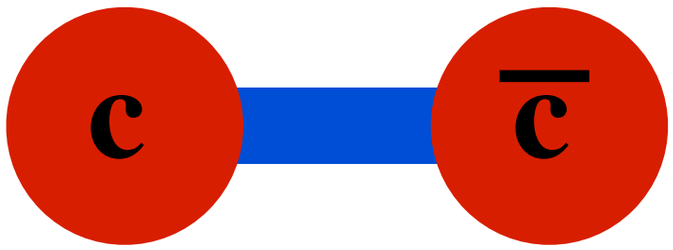


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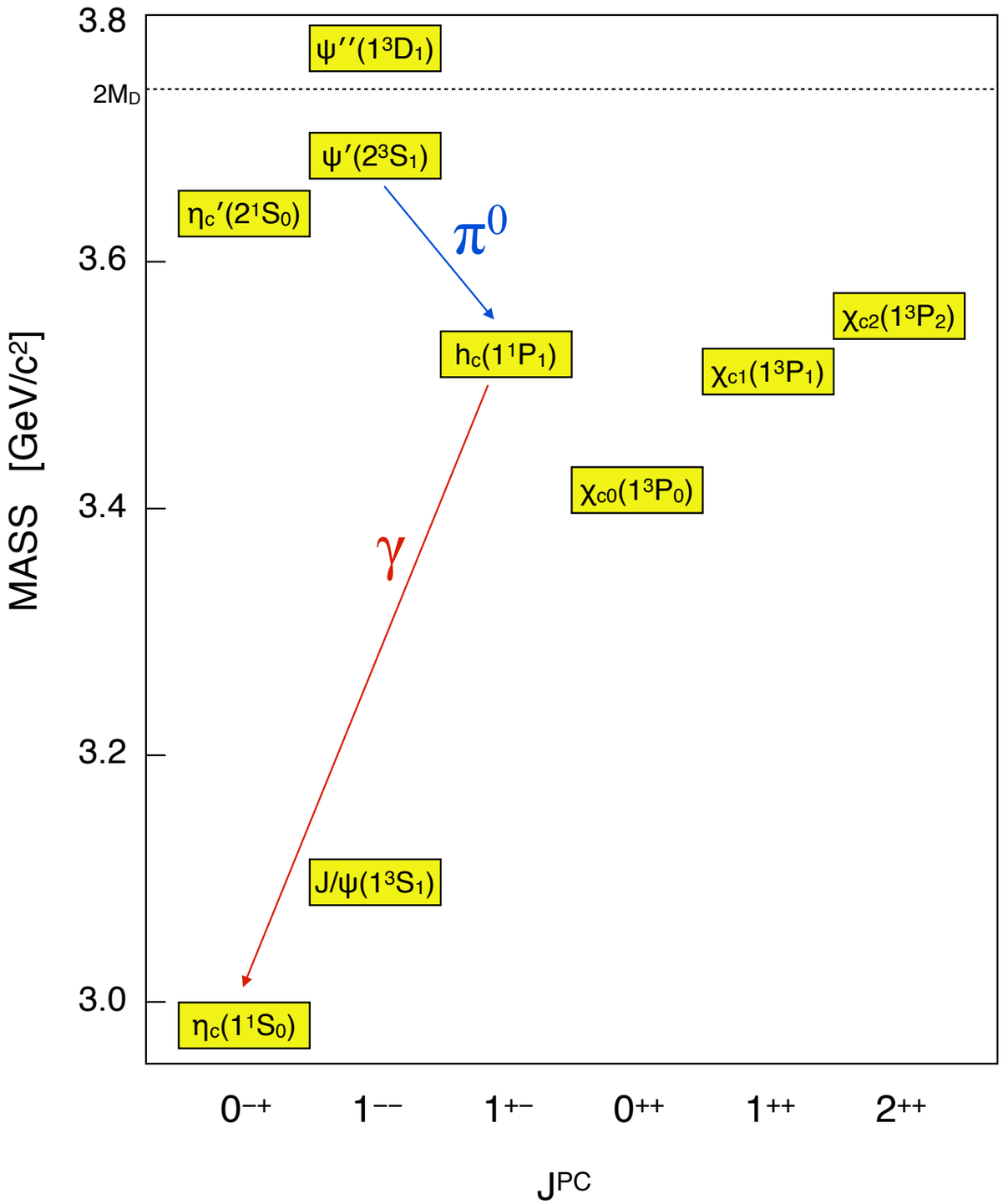


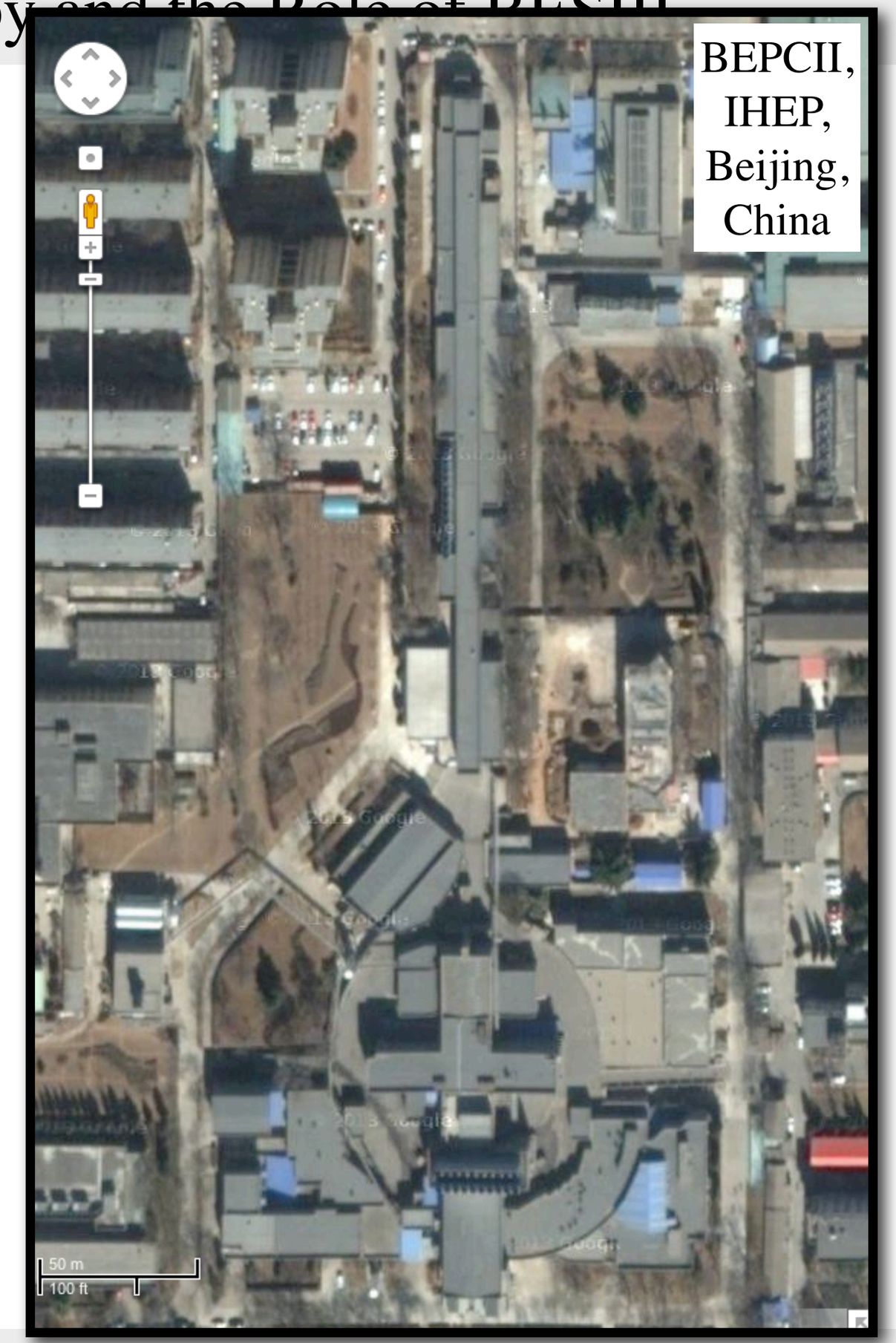


*Google satellite image of BEPC-II*

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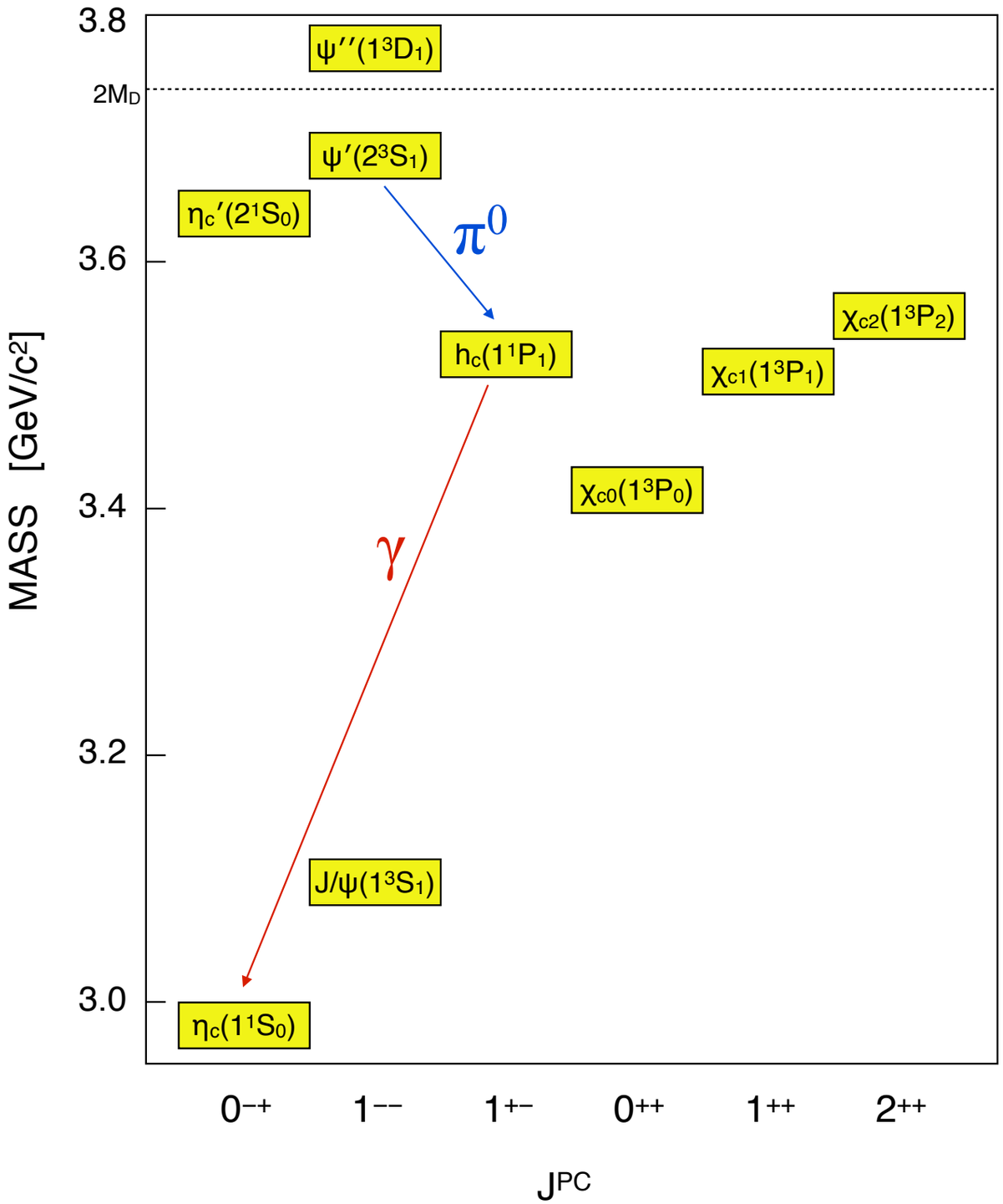



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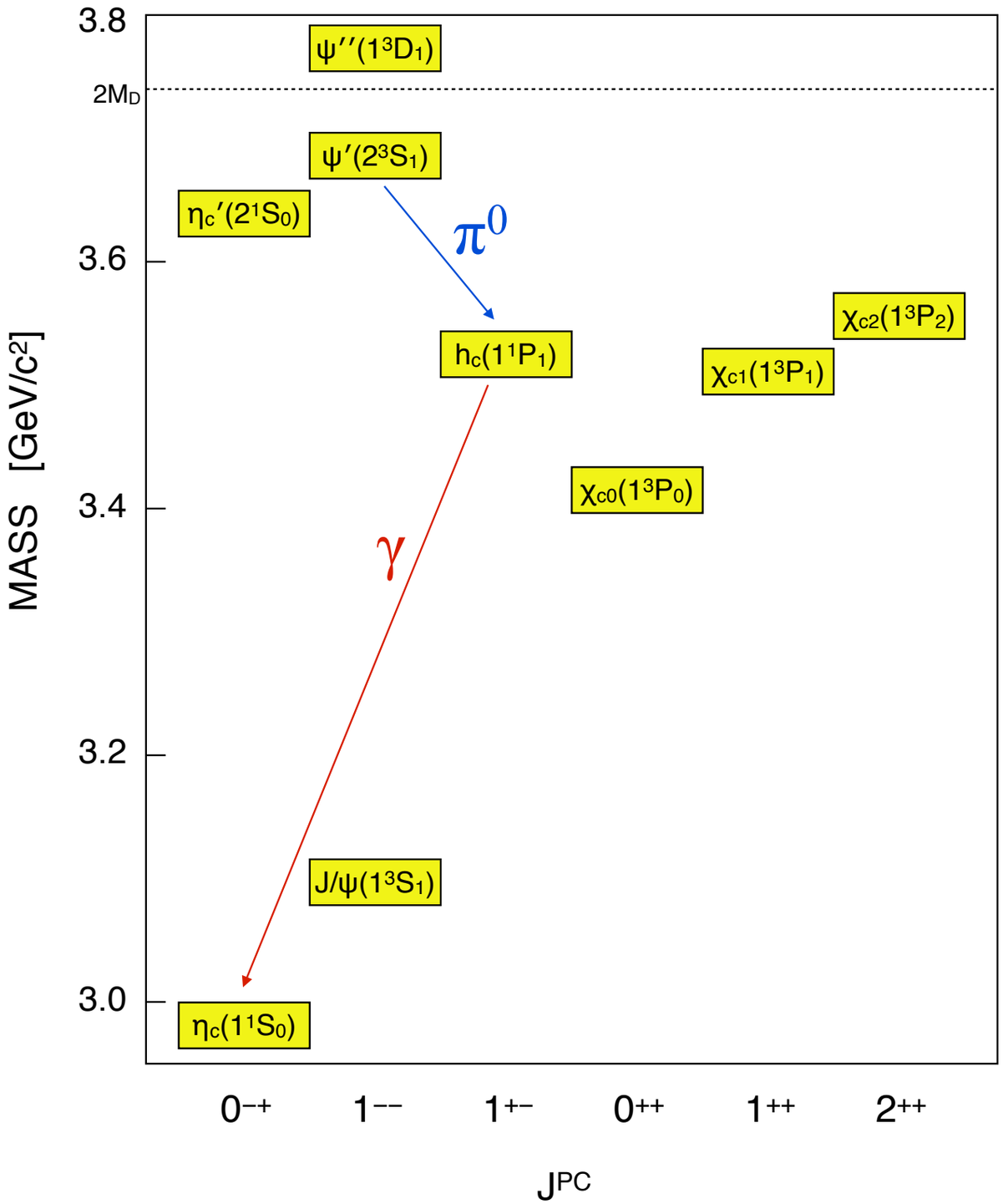



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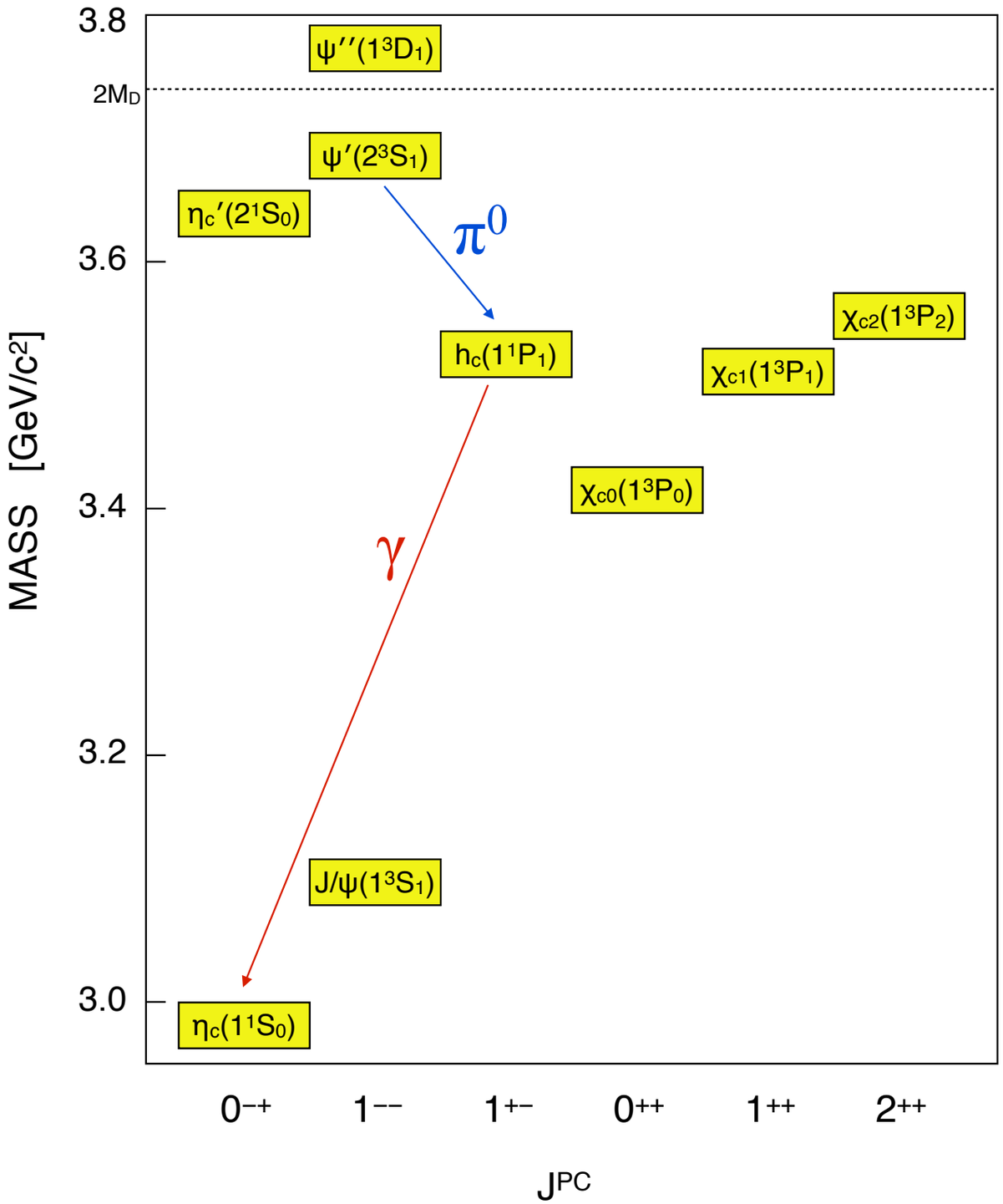



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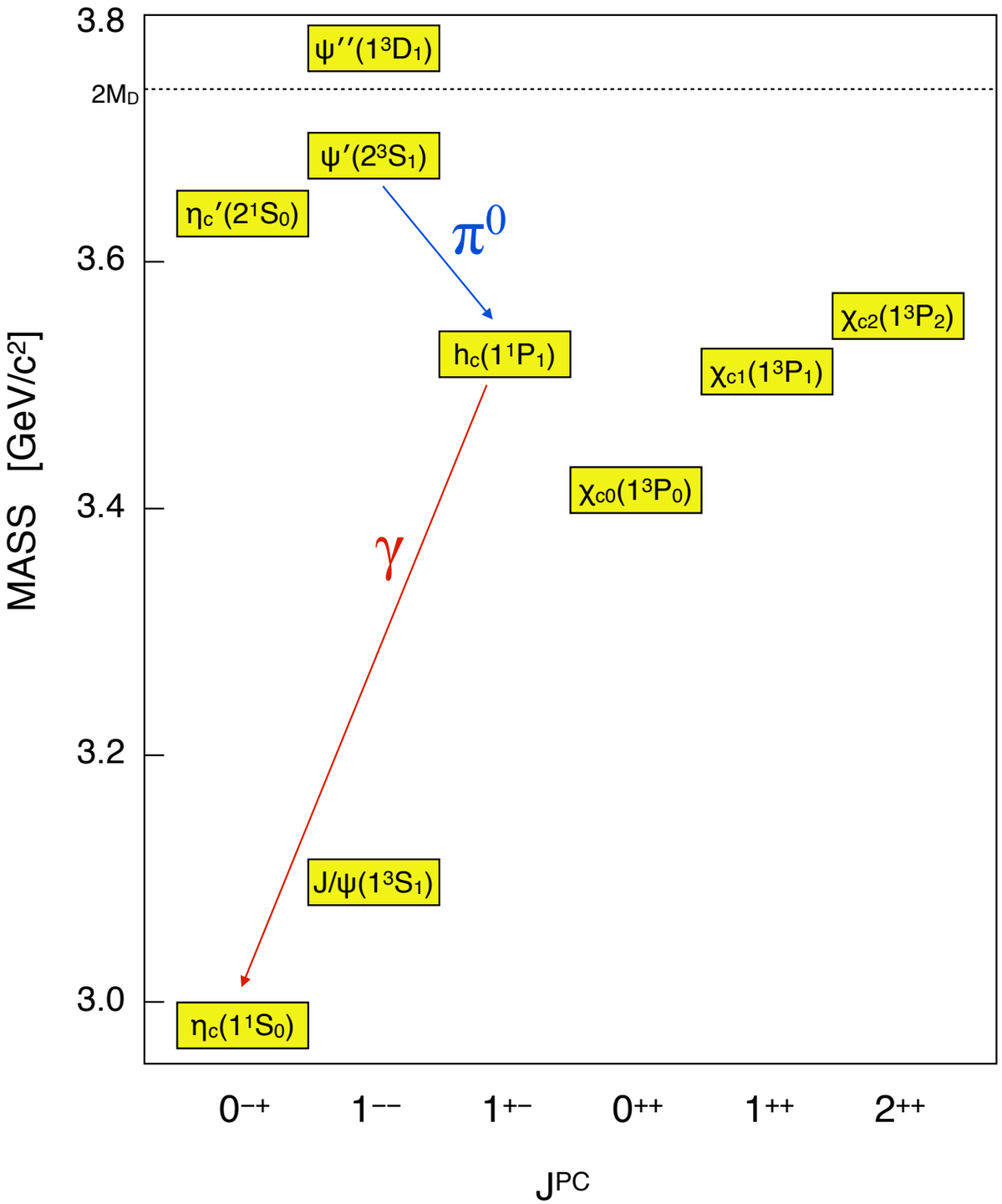


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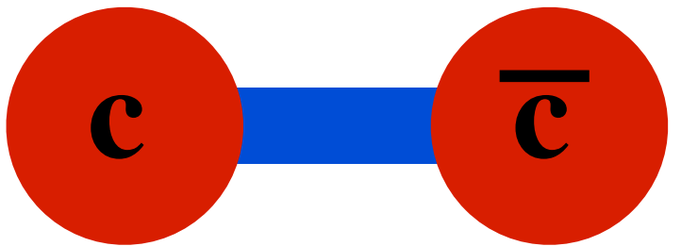


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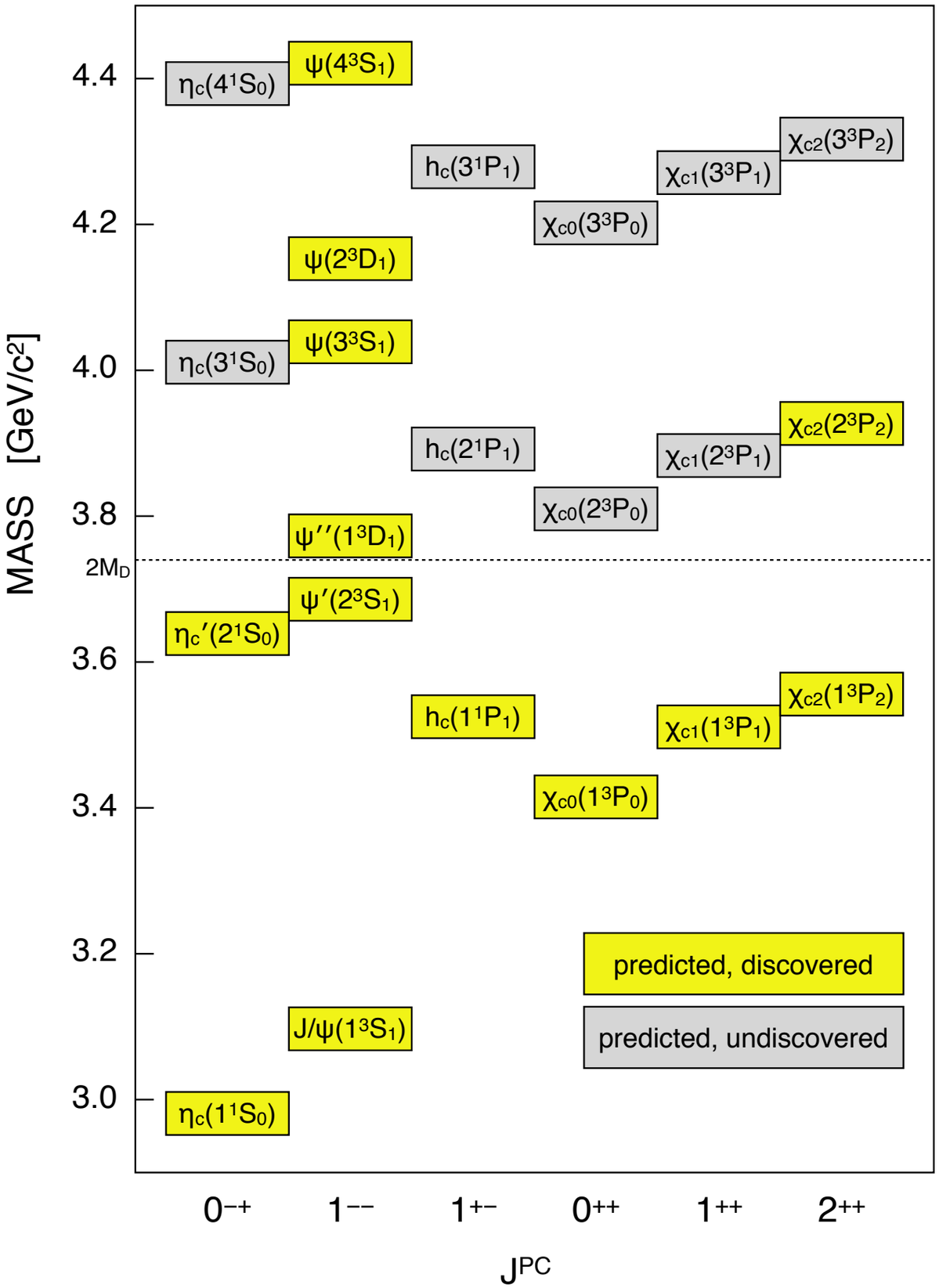


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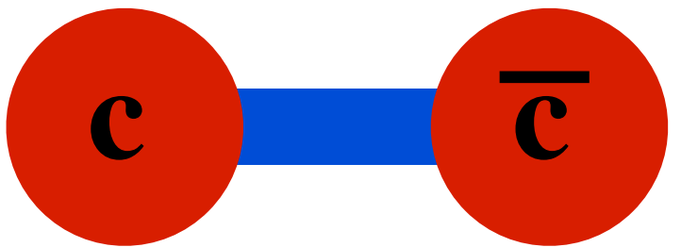


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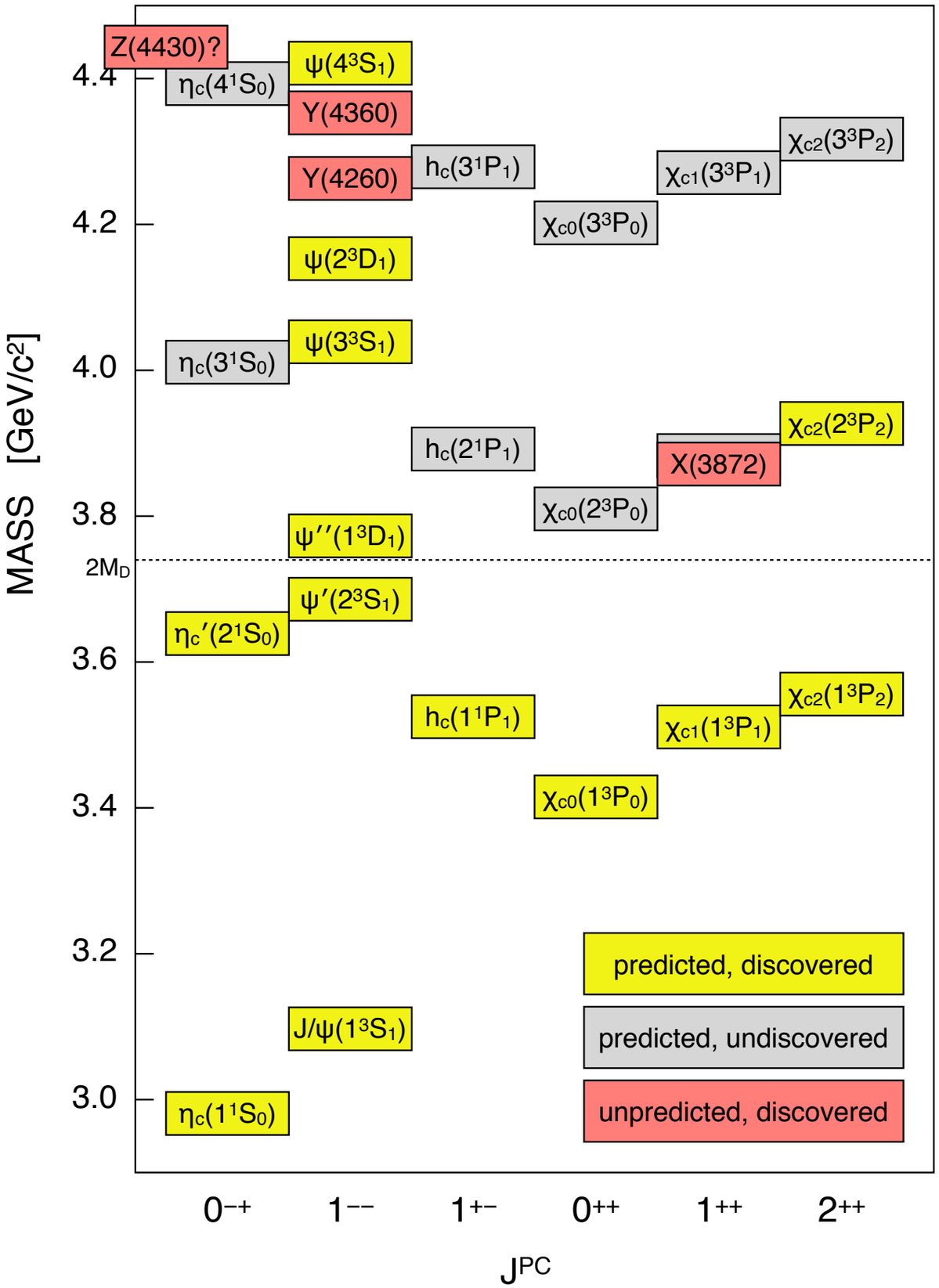


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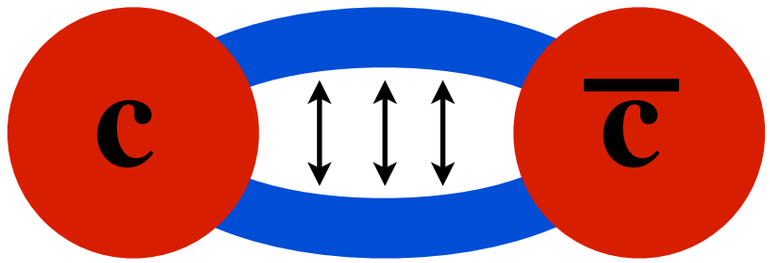
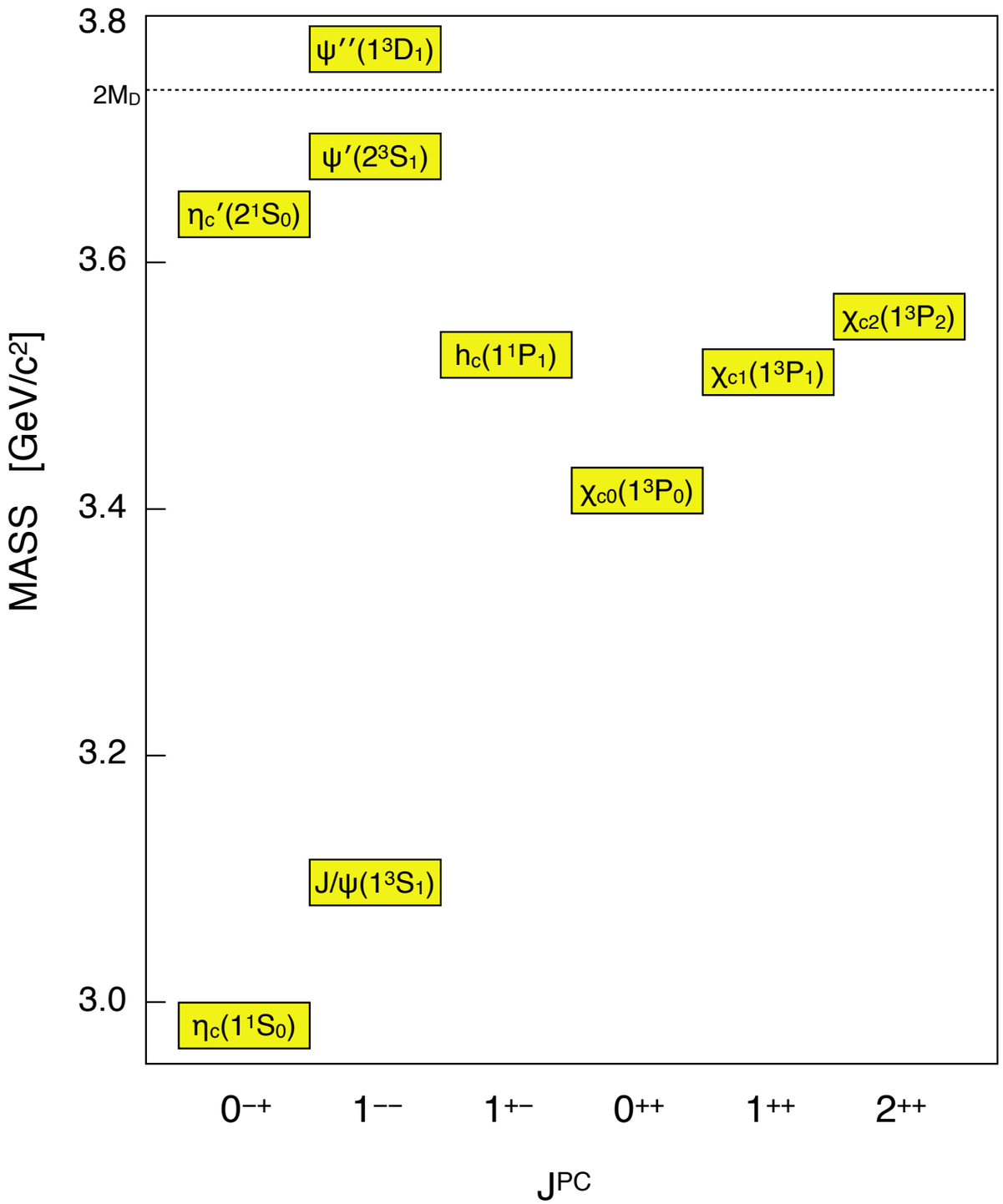
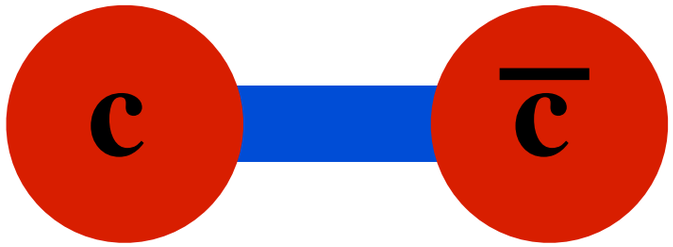



HYBRID CHARMONIUM?



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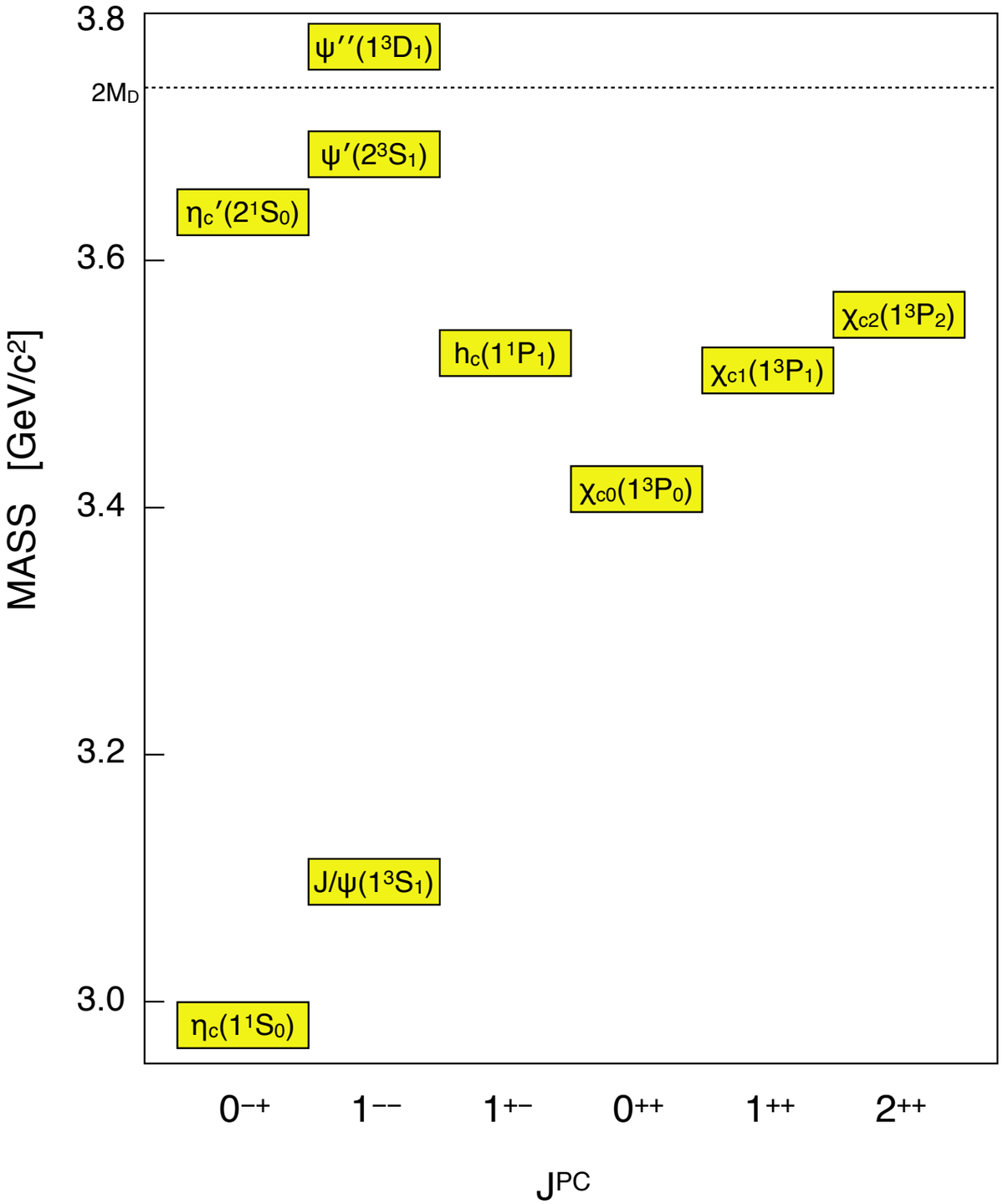
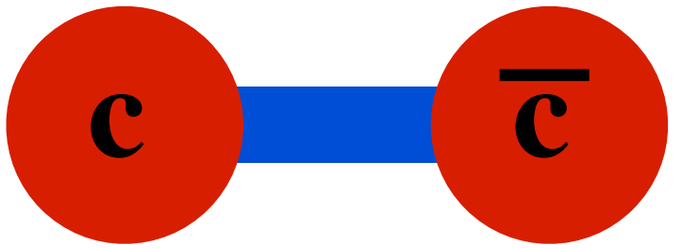



**Why charmonium?**

It is one of the simplest bound states of QCD.

*(like positronium or Hydrogen in QED)*

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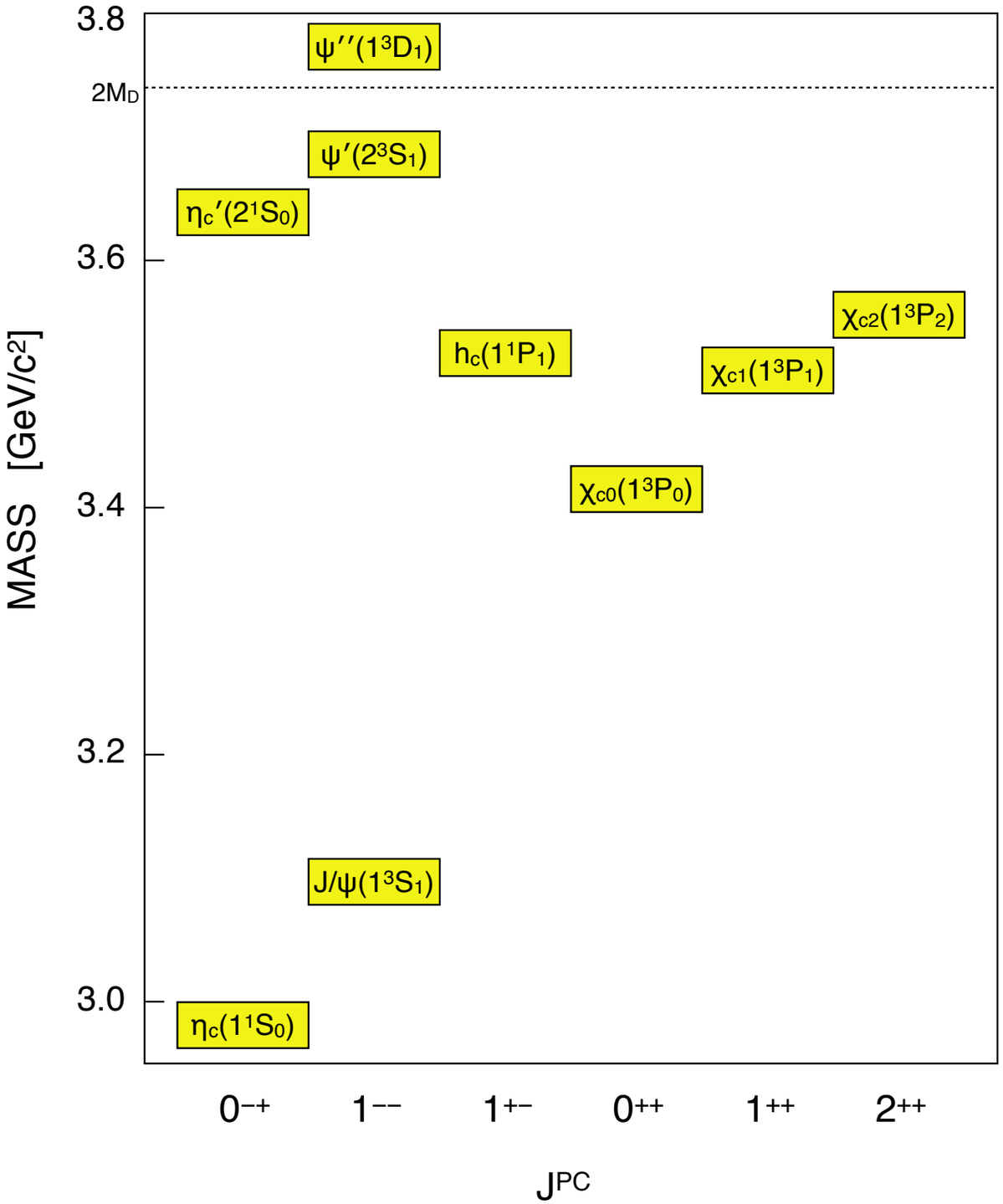
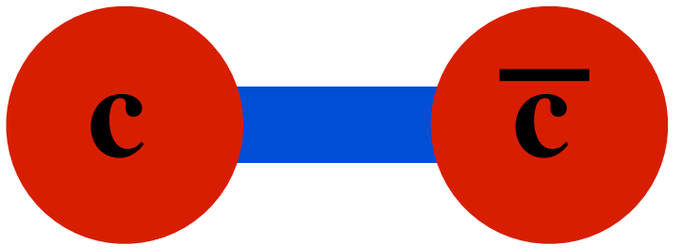



Classify using $\mathbf{J^{PC}}$

*(experimentally determined)*

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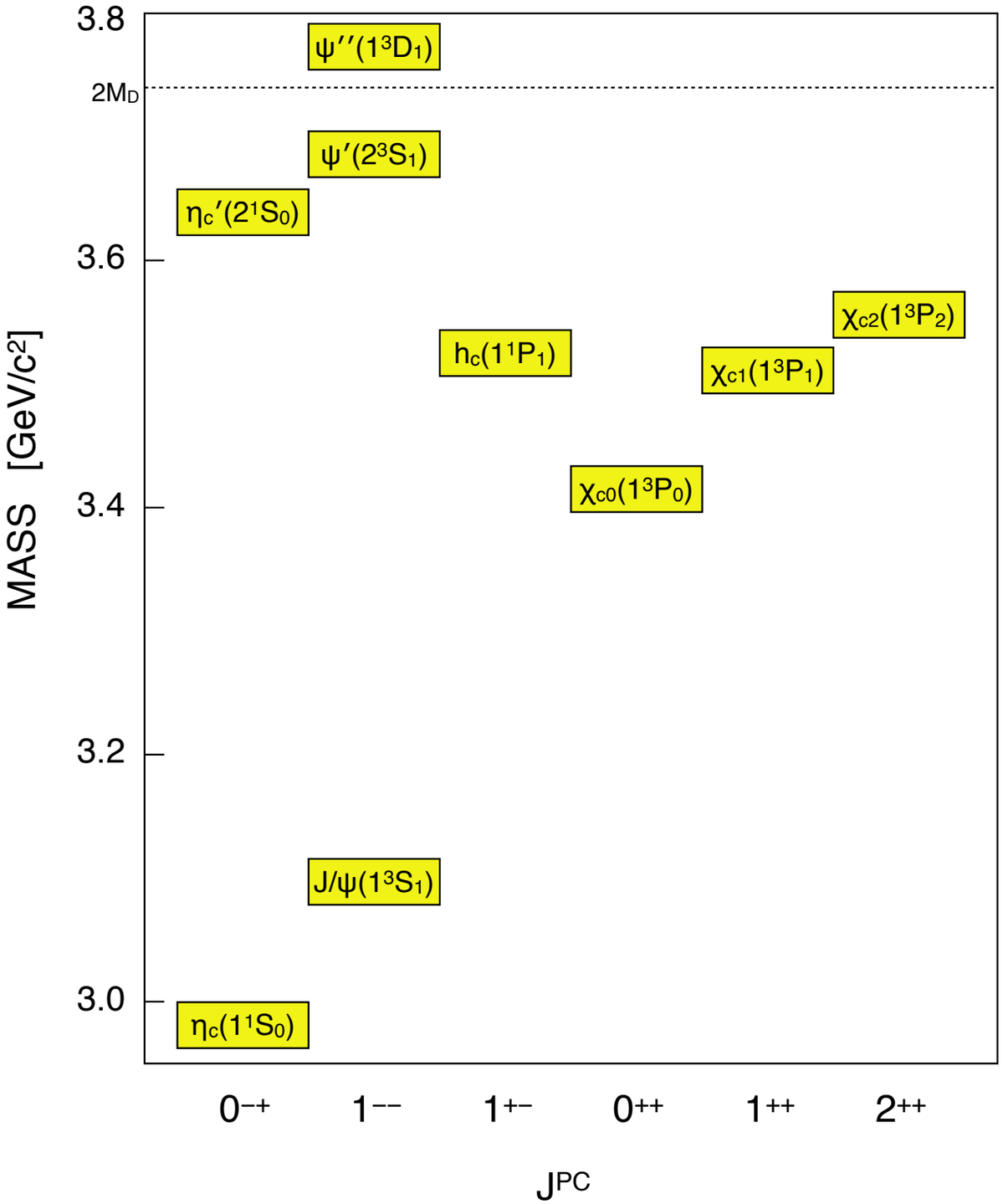
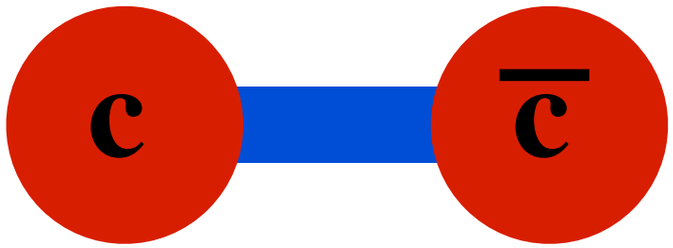



Match to $\mathbf{n^{2S+1}L_J}$
quark model states

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

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

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

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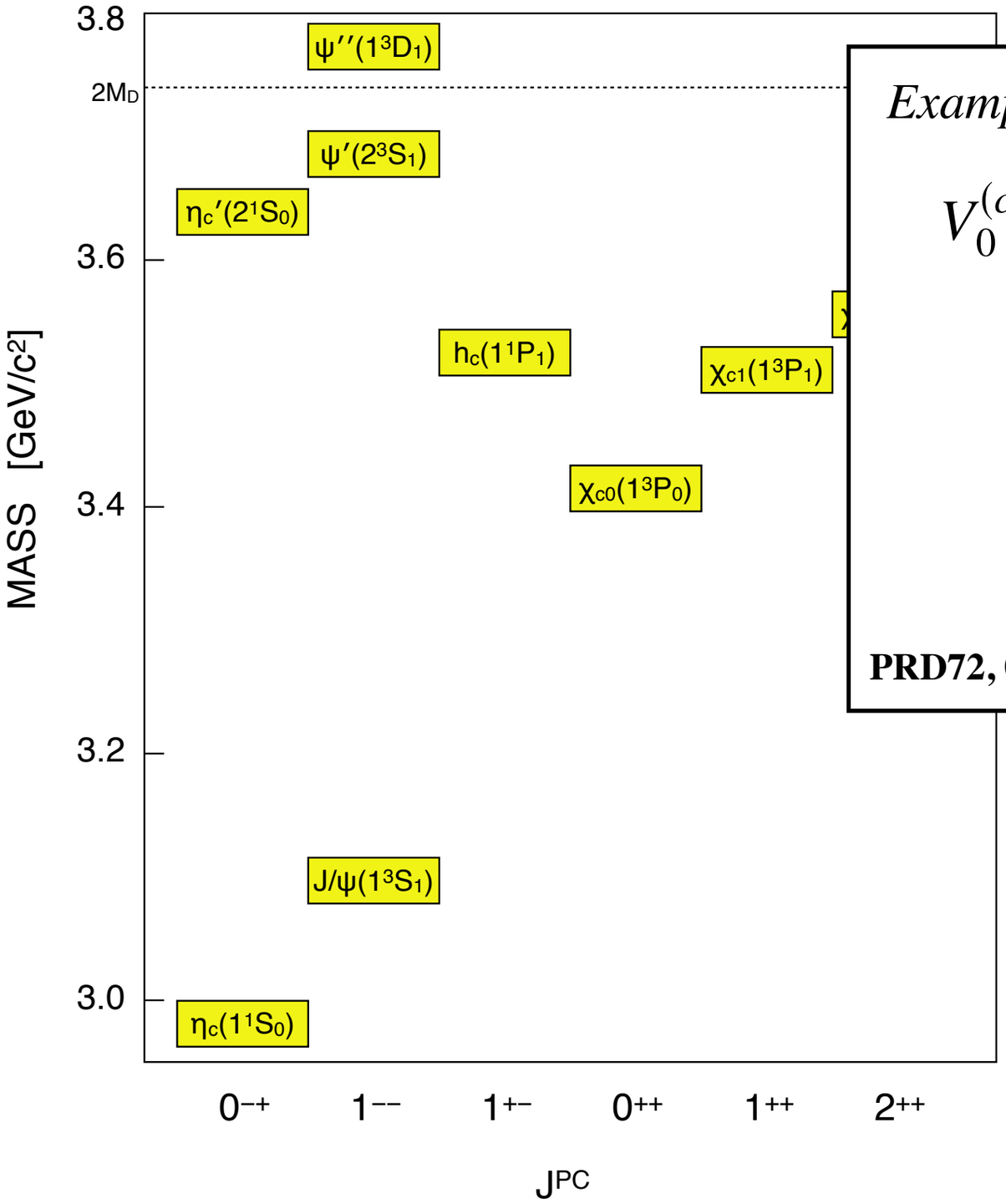



## Potential models:

*Example from Barnes, Godfrey, Swanson:*

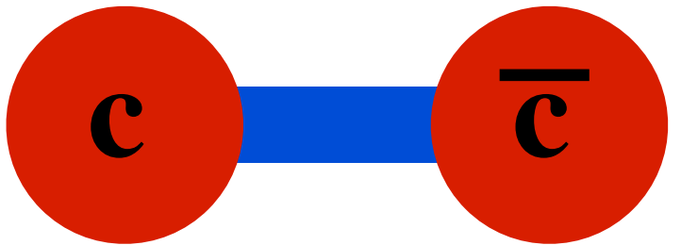
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(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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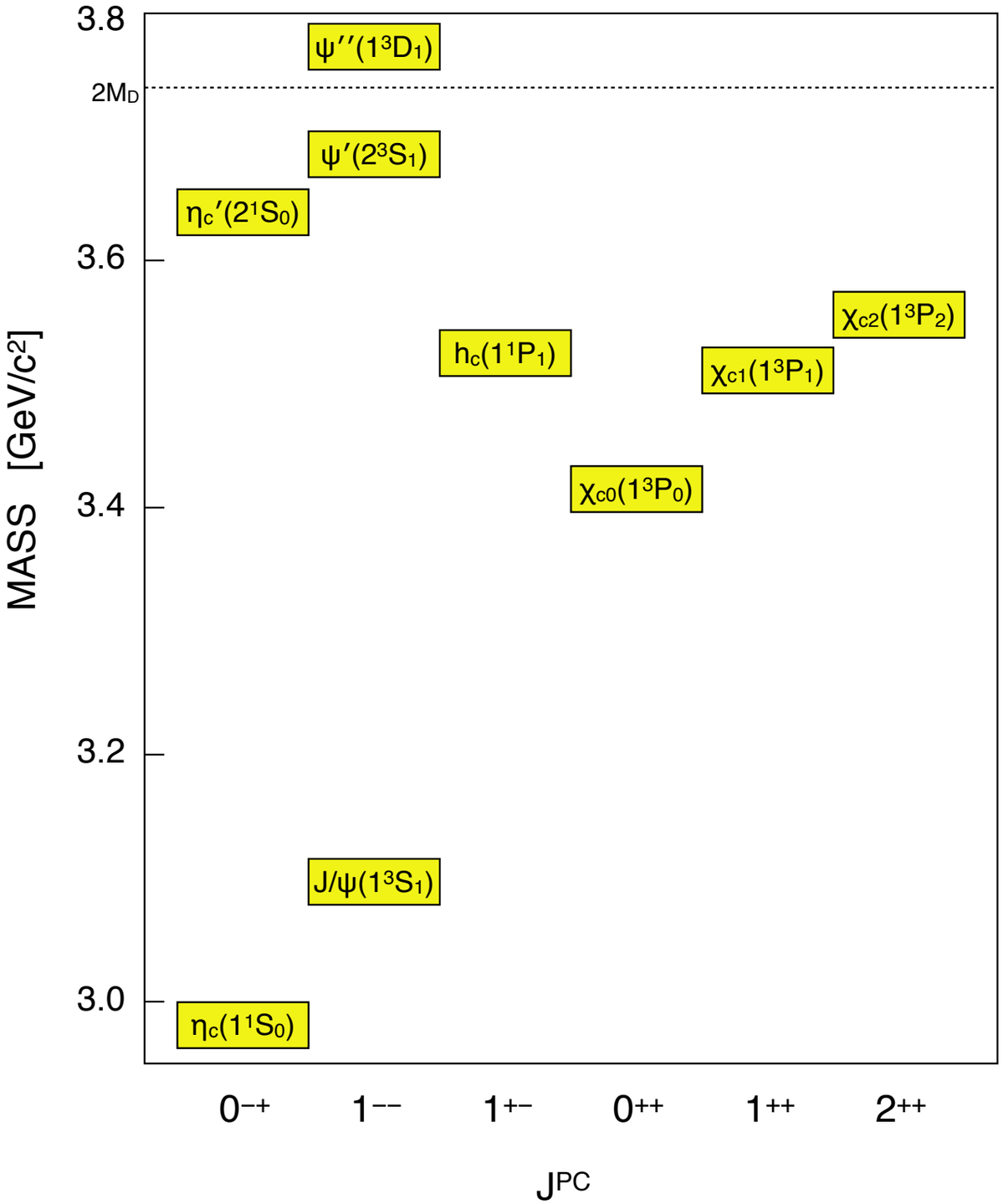


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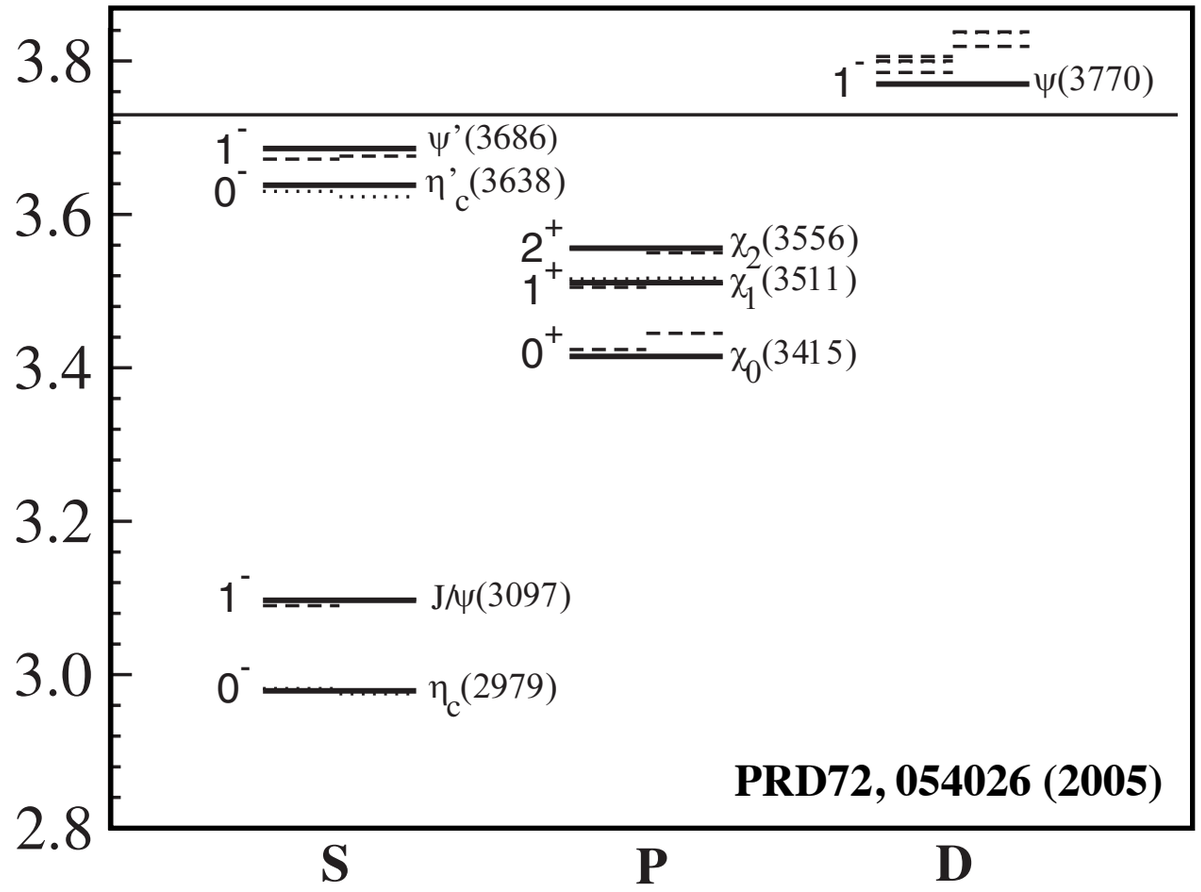


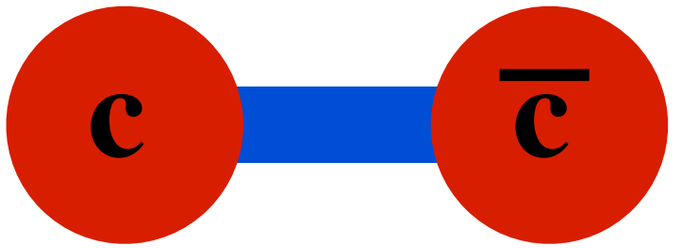


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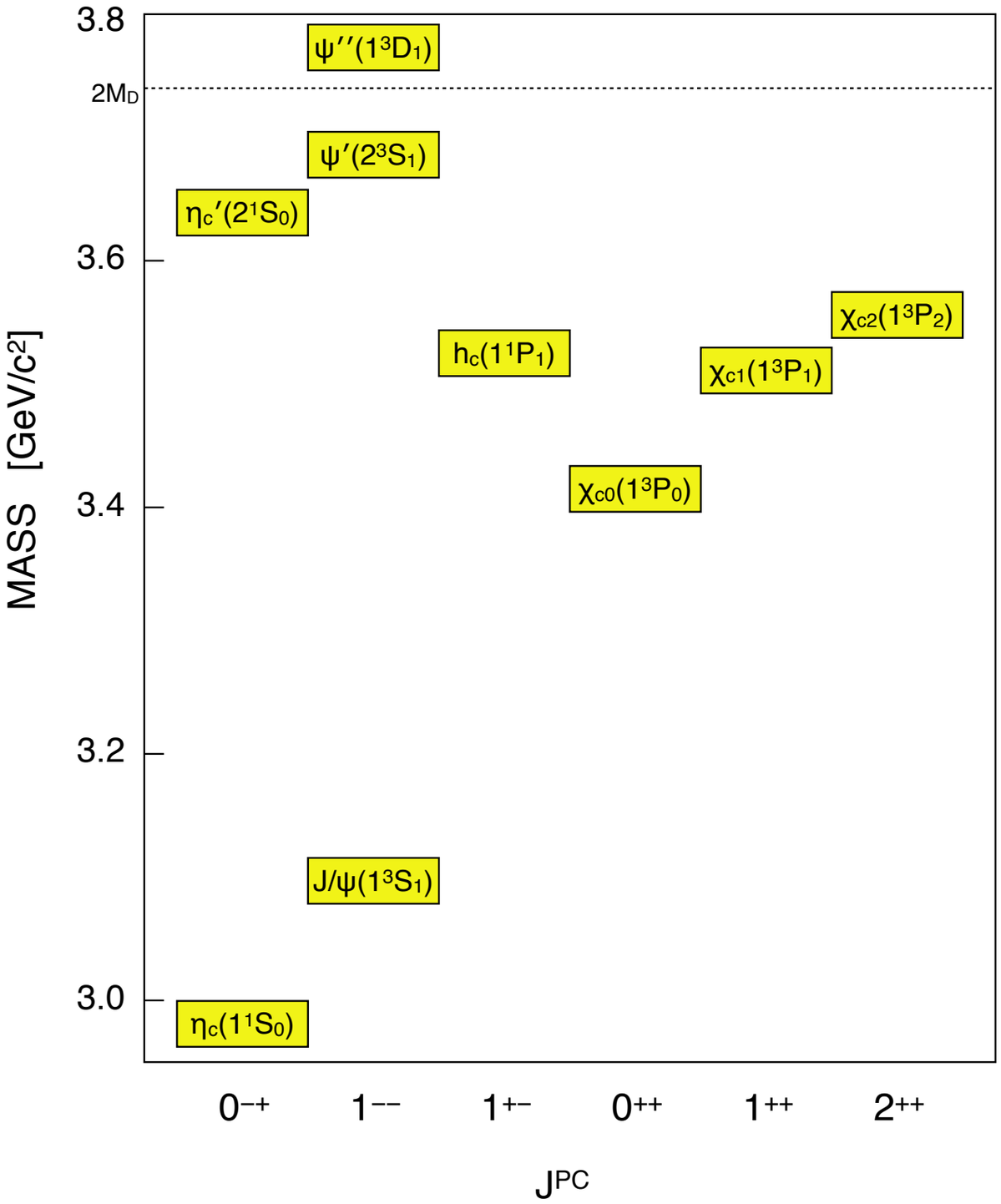
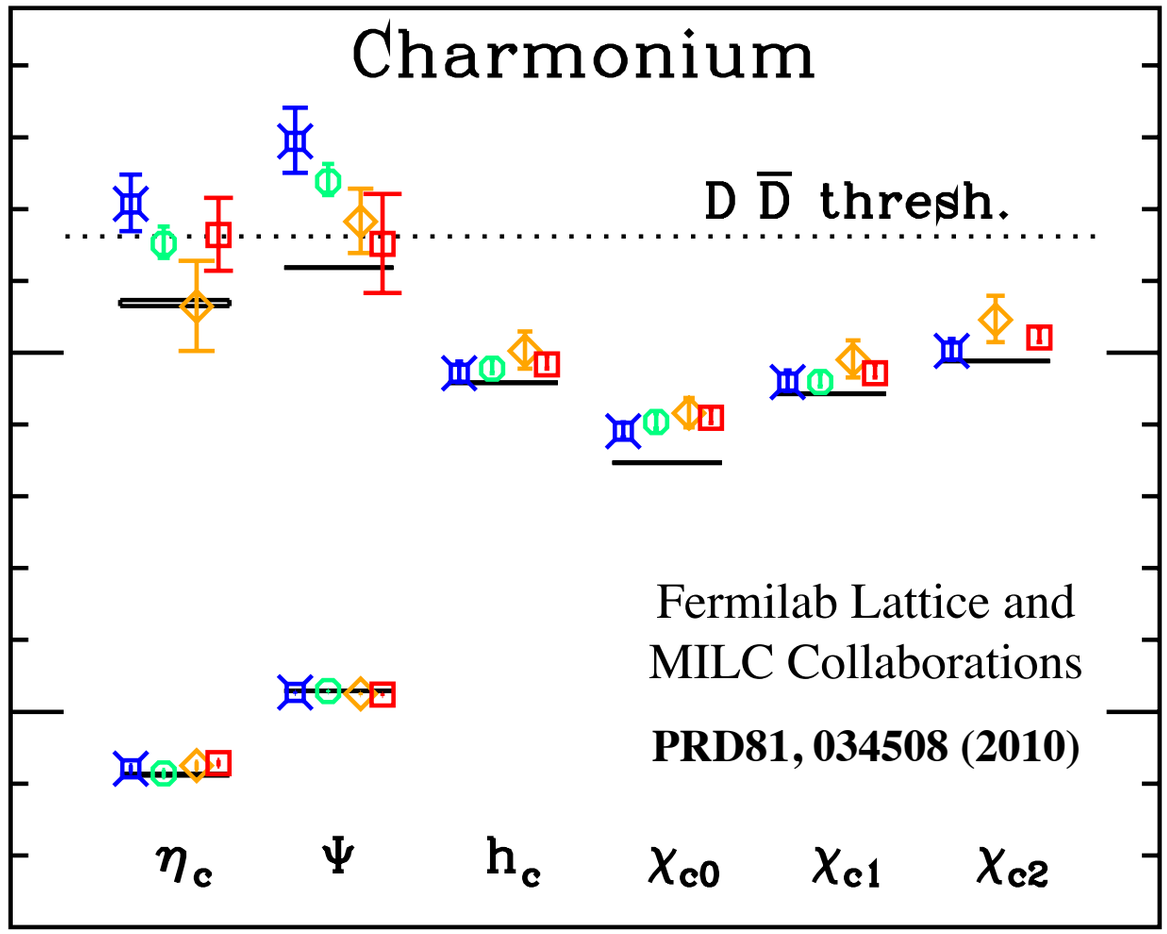



*A more fundamental approach,*
Lattice QCD:



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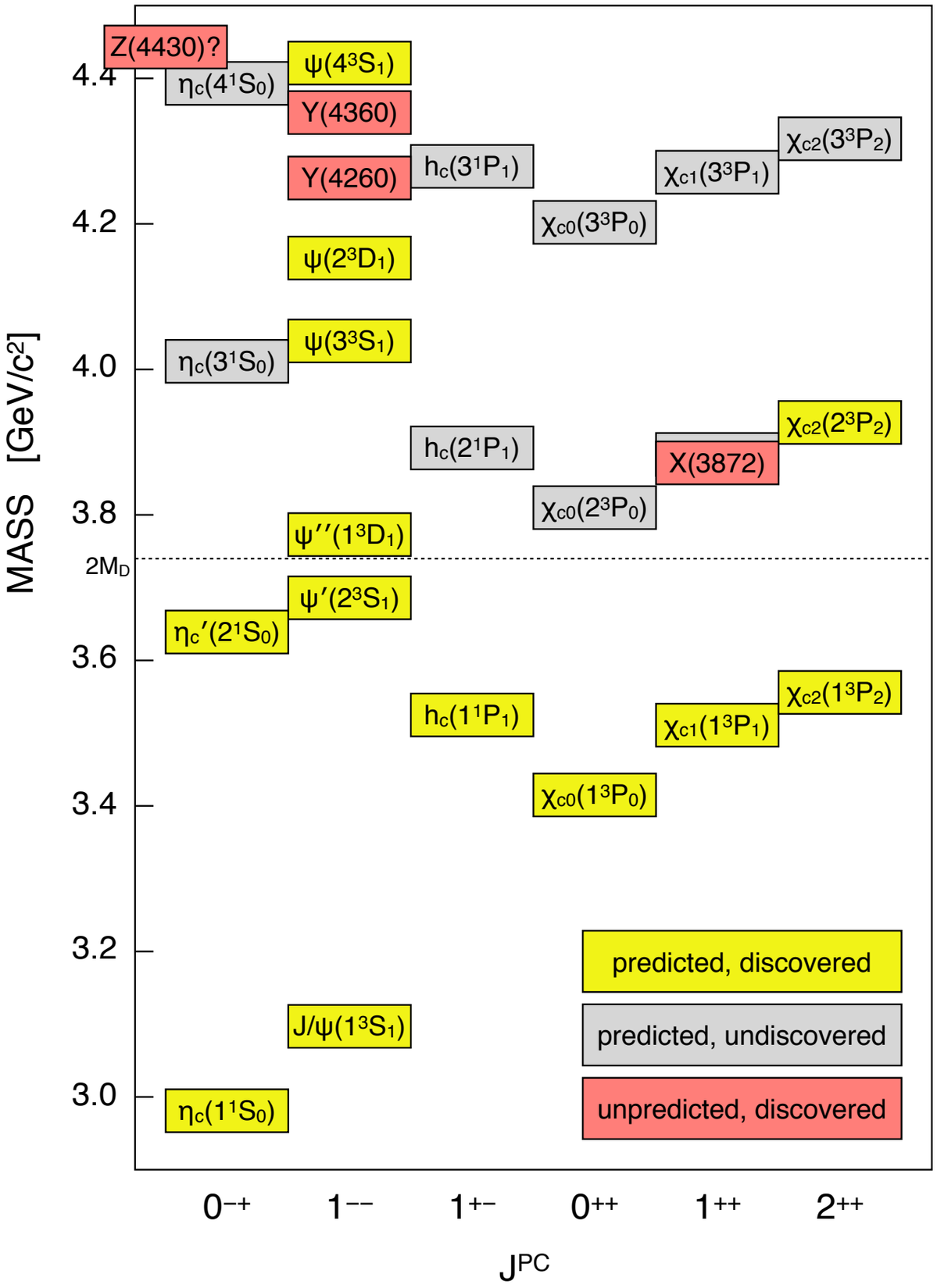


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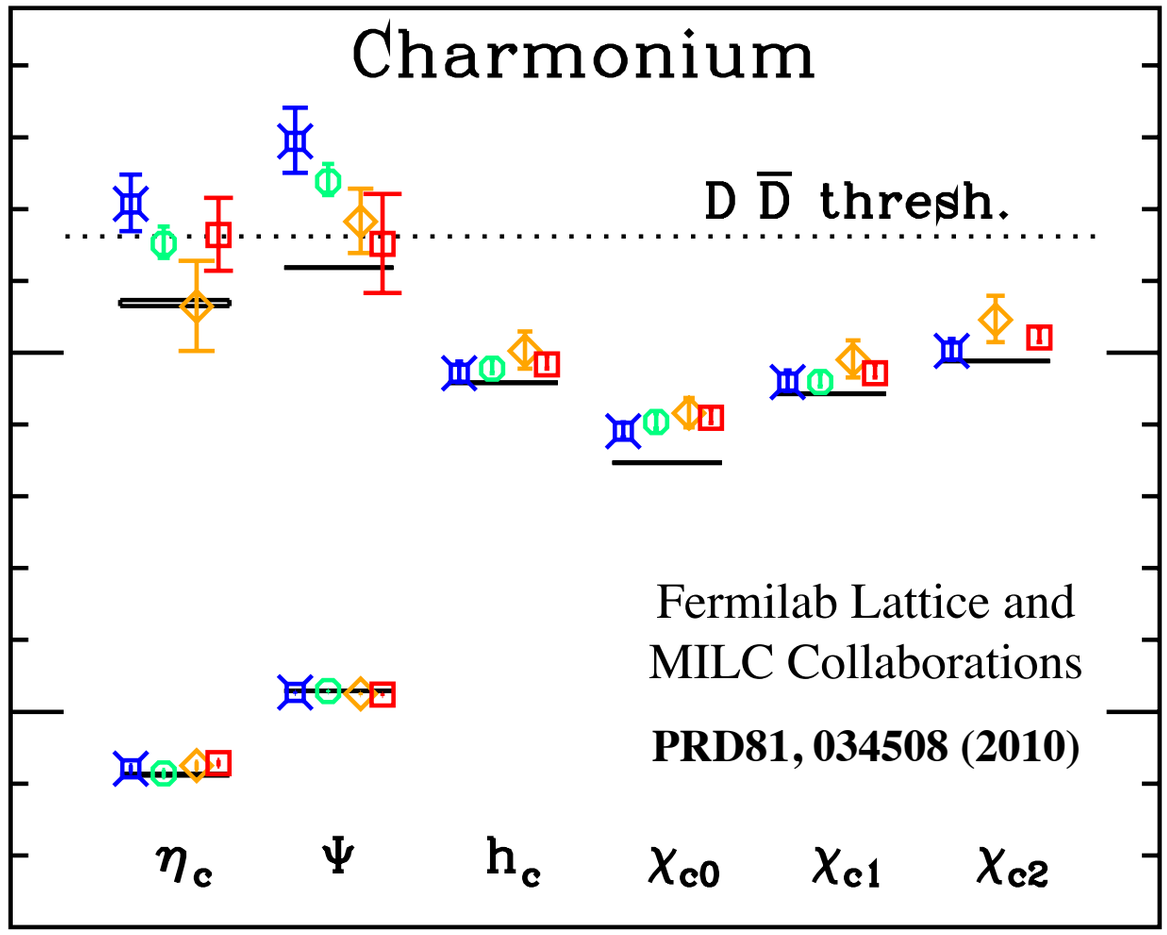

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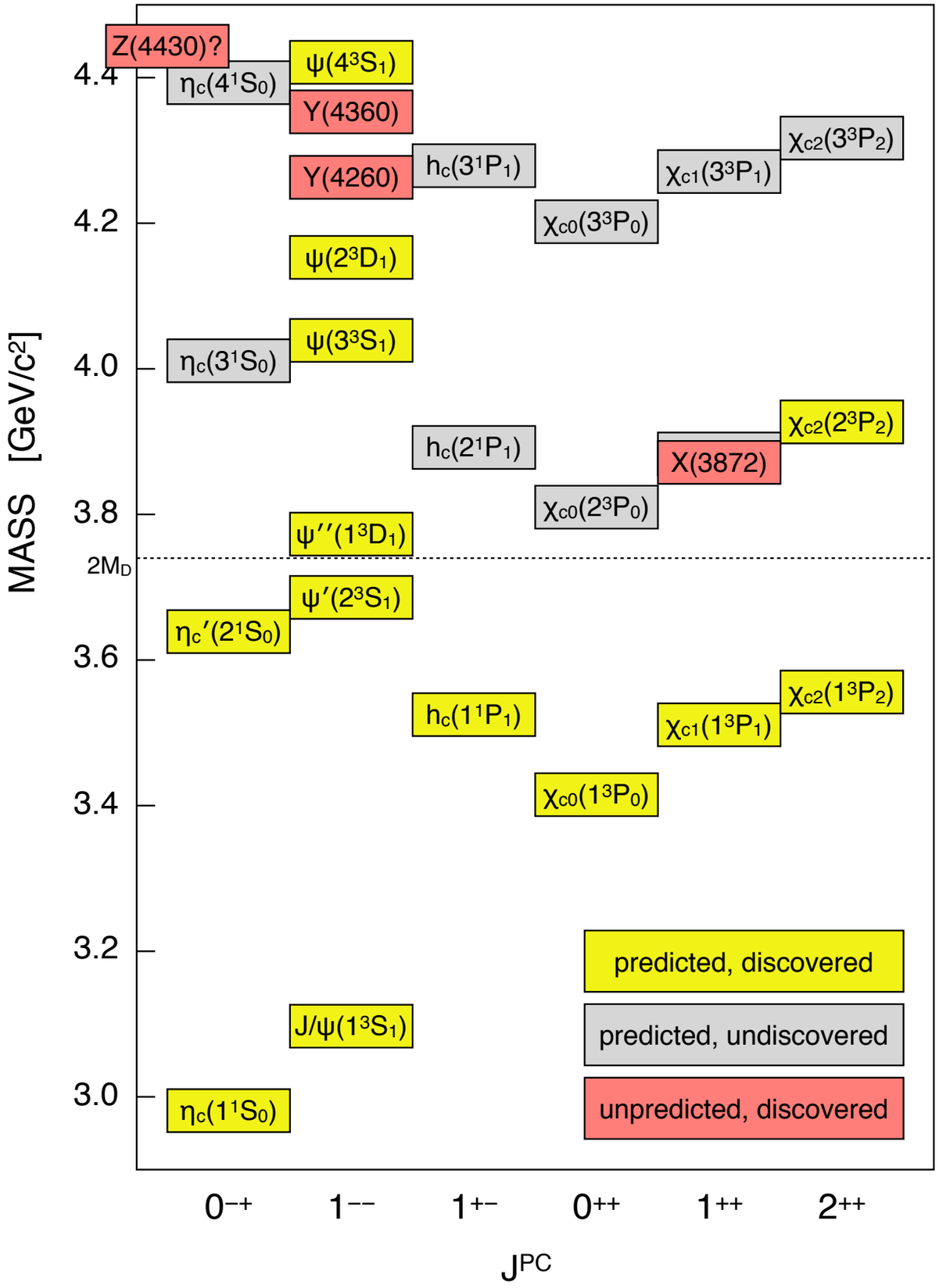


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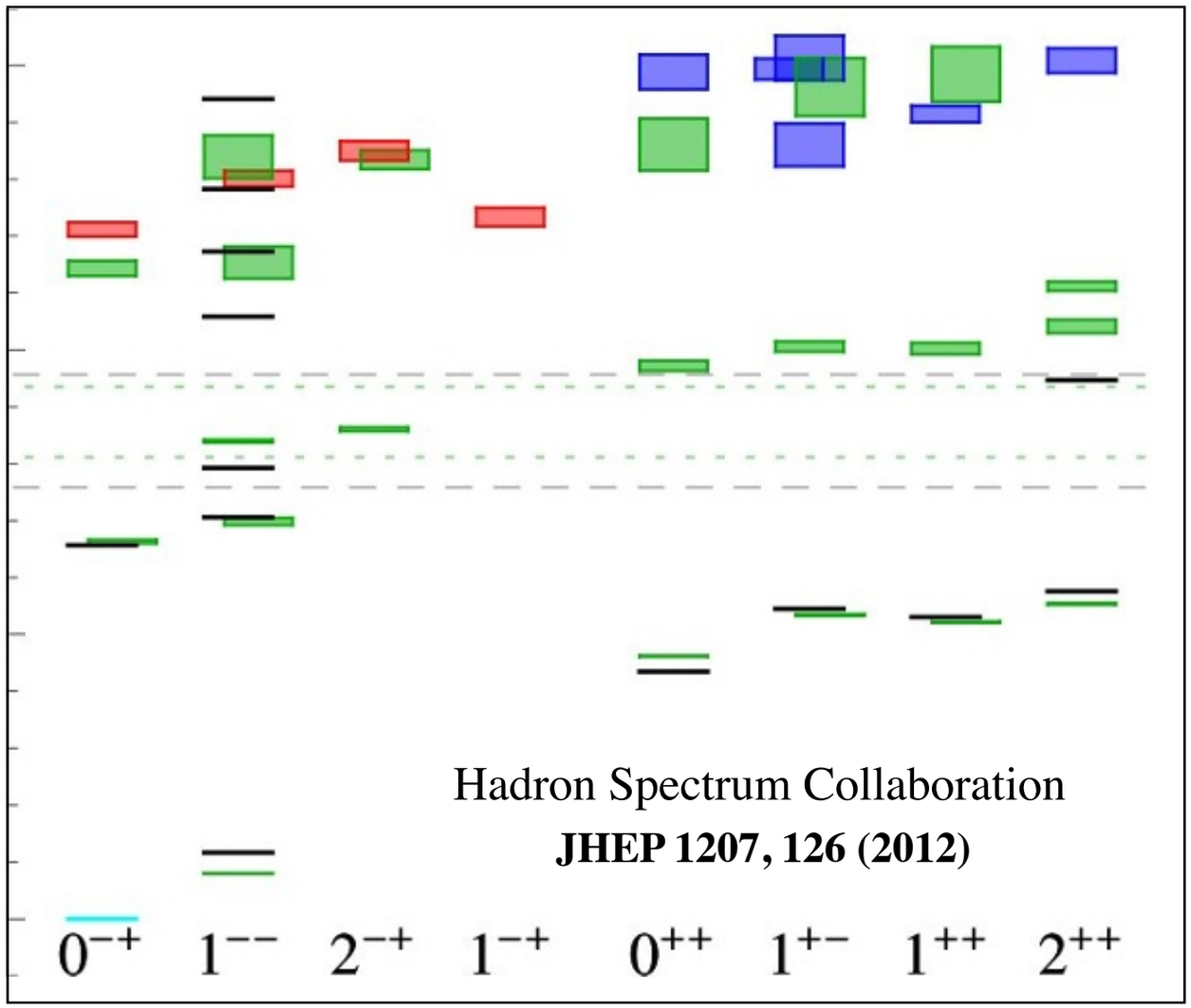


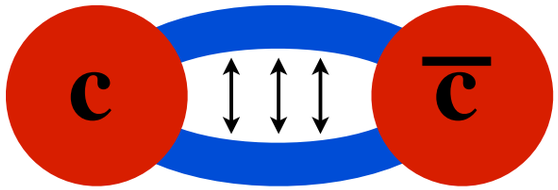


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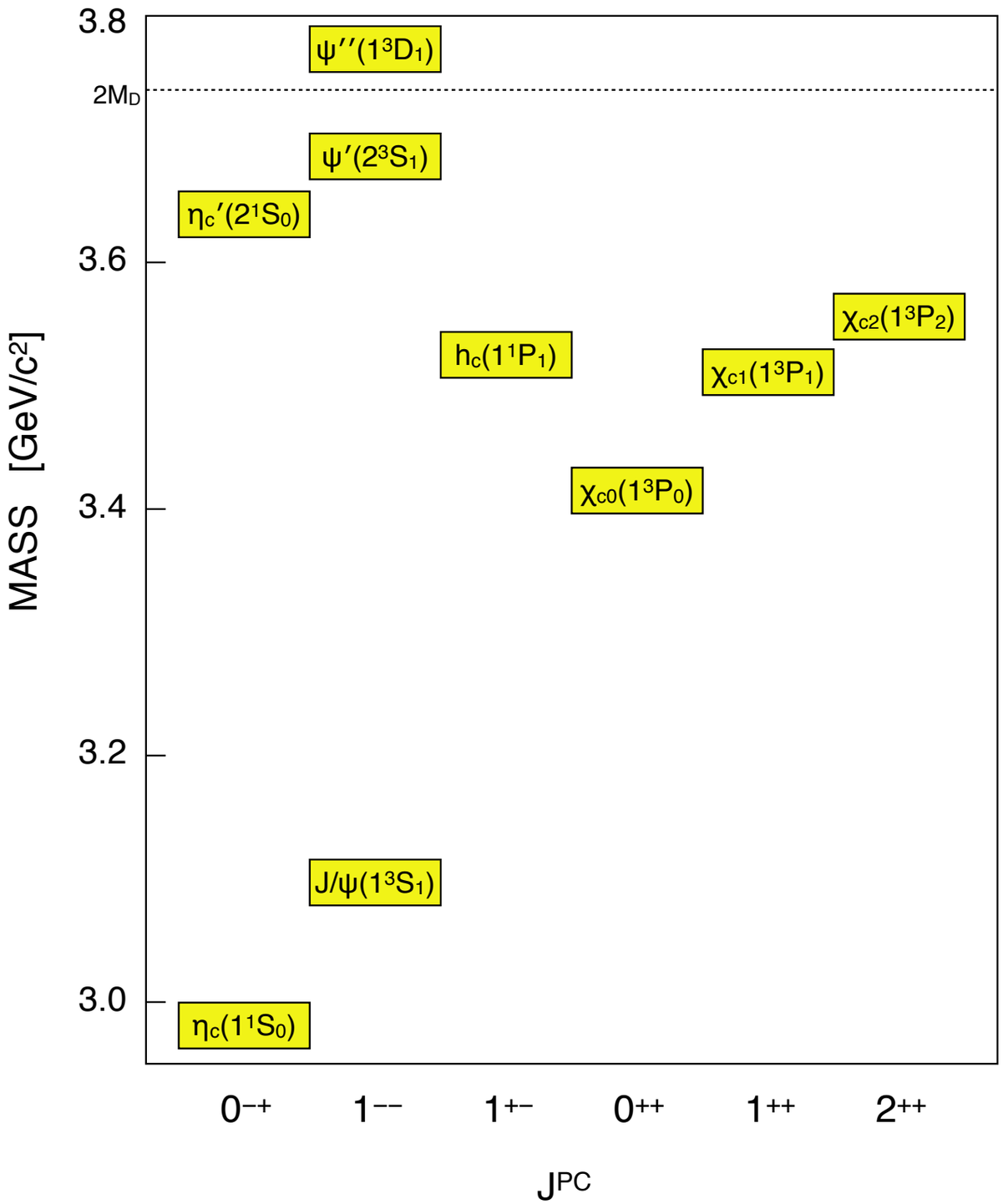




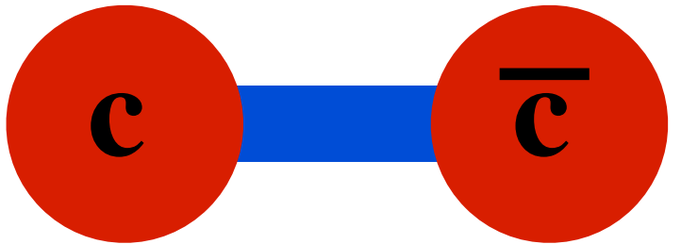


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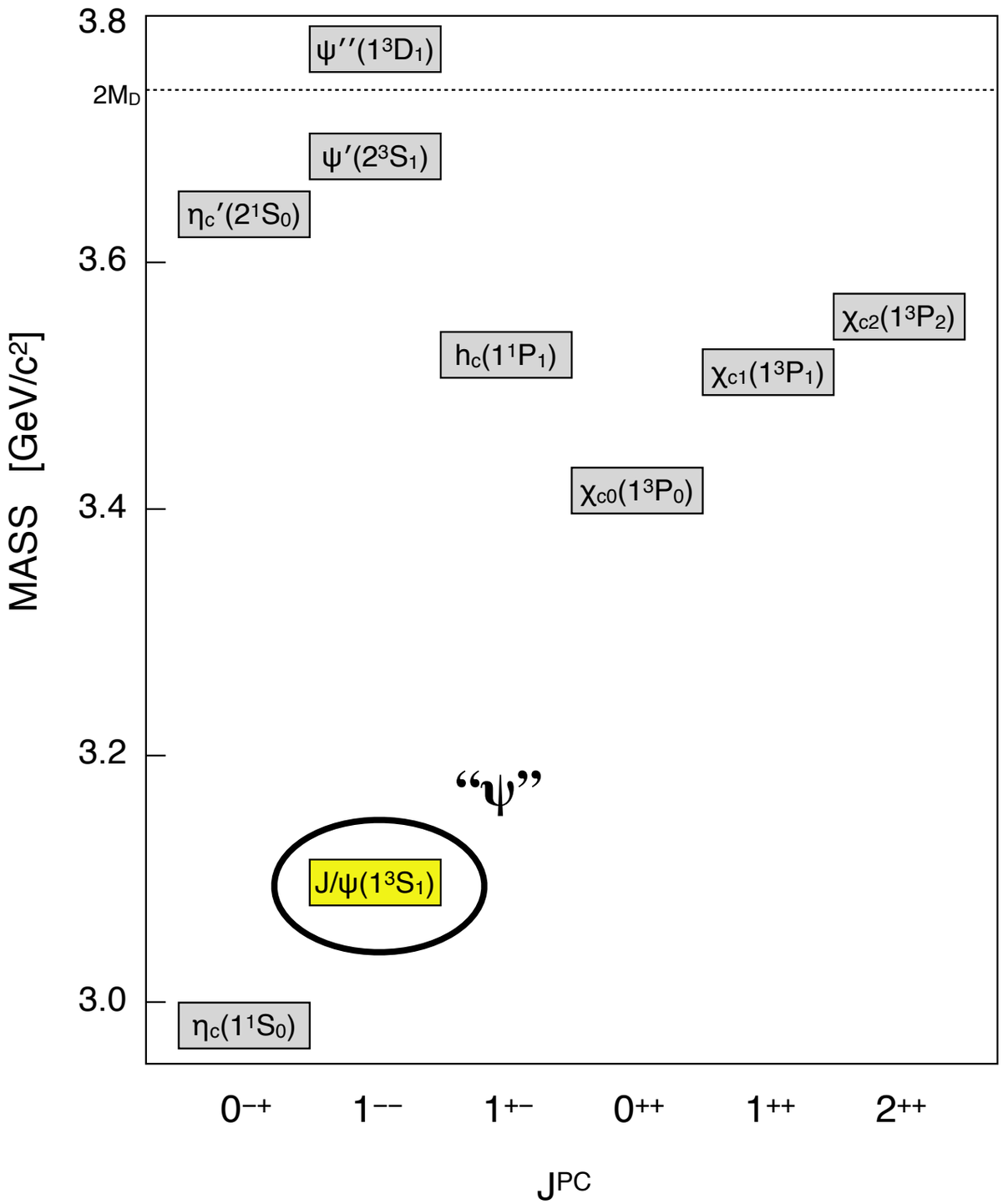




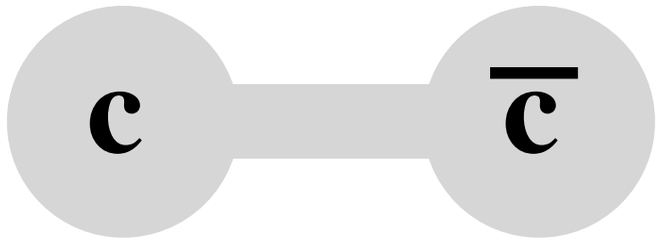


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# I. The "Quark Model" States of Charmonium: Discovery

summer 1974 preprint, published later as **RMP 47, 277 (1975)**

## Search for charm


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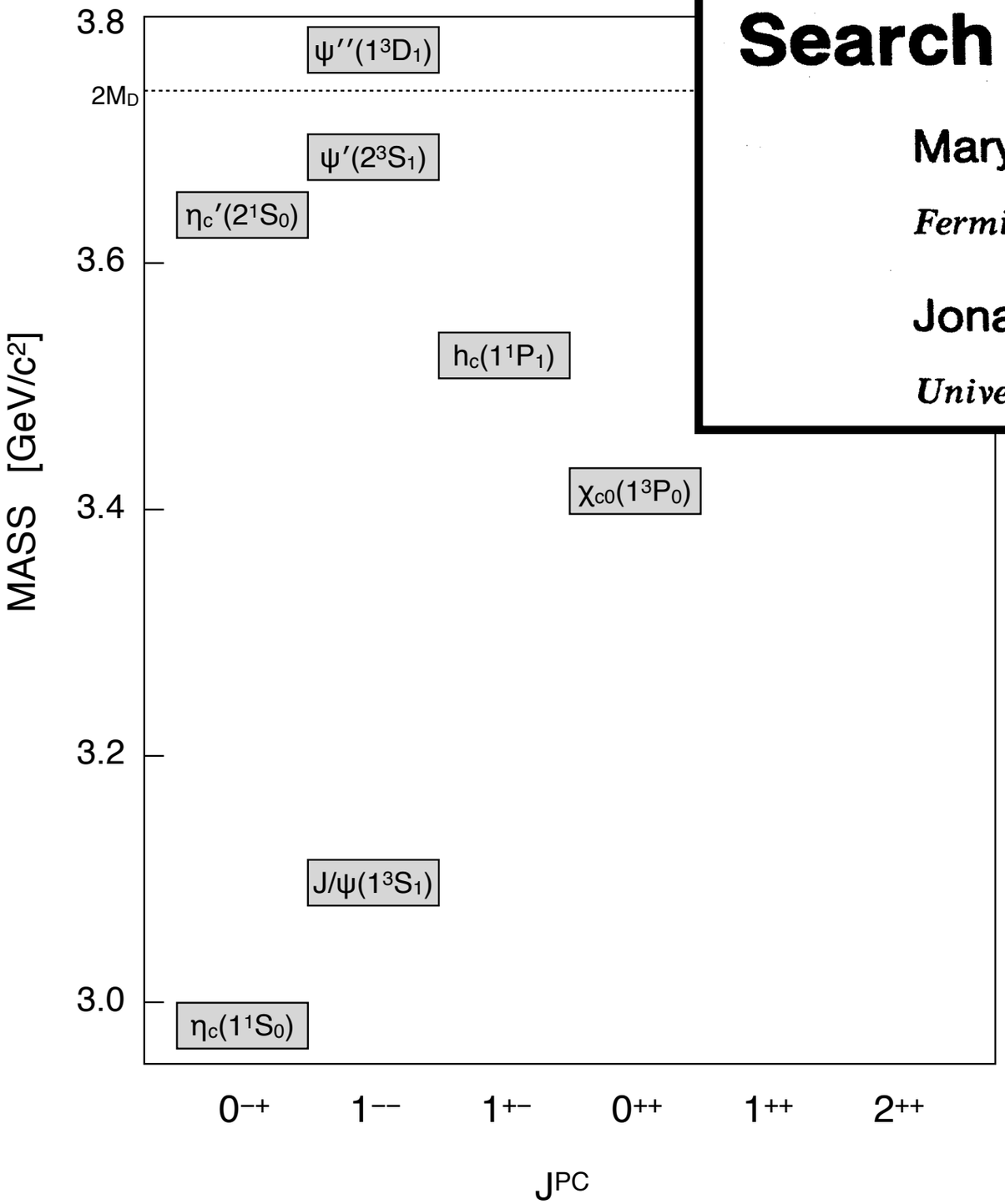
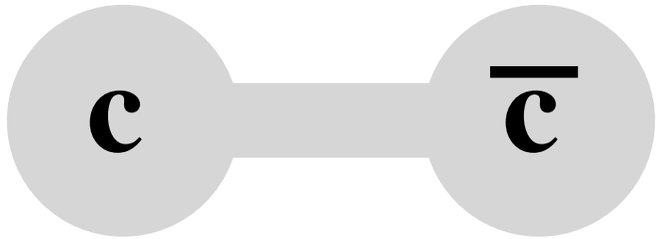
Jonathan L. Rosner

*University of Minnesota, Minneapolis, Minnesota 55455*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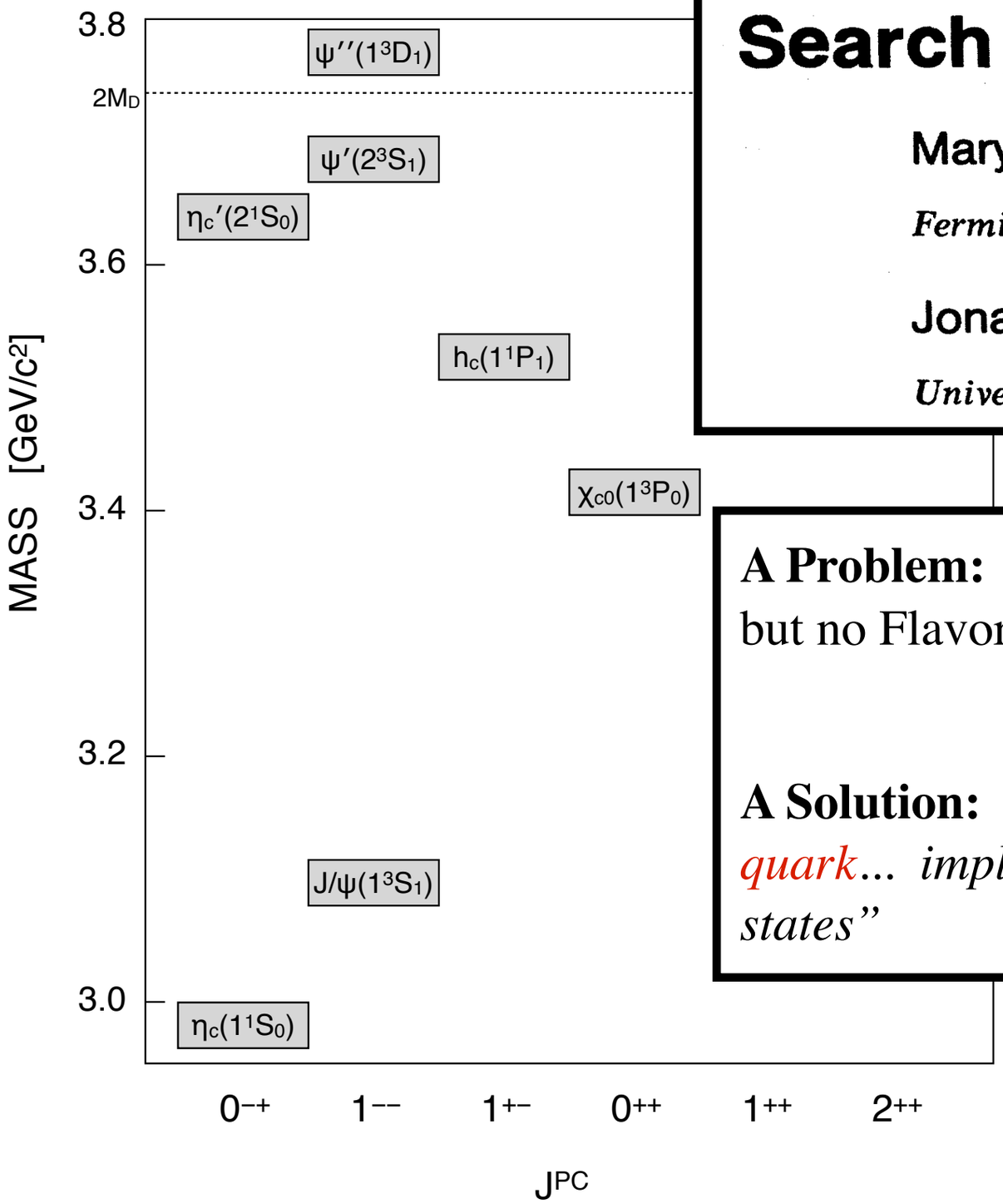
*University of Minnesota, Minneapolis, Minnesota 55455*


**A Problem:** Flavor-Changing Charged Currents ($K^+ \to \mu^+\nu_\mu$) but no Flavor-Changing Neutral Currents ($K^0_L \to \mu^+\mu^-$)

**A Solution:** *"... one possibility involves a fourth "charmed" quark... implying the existence of a new spectrum of hadron states"*

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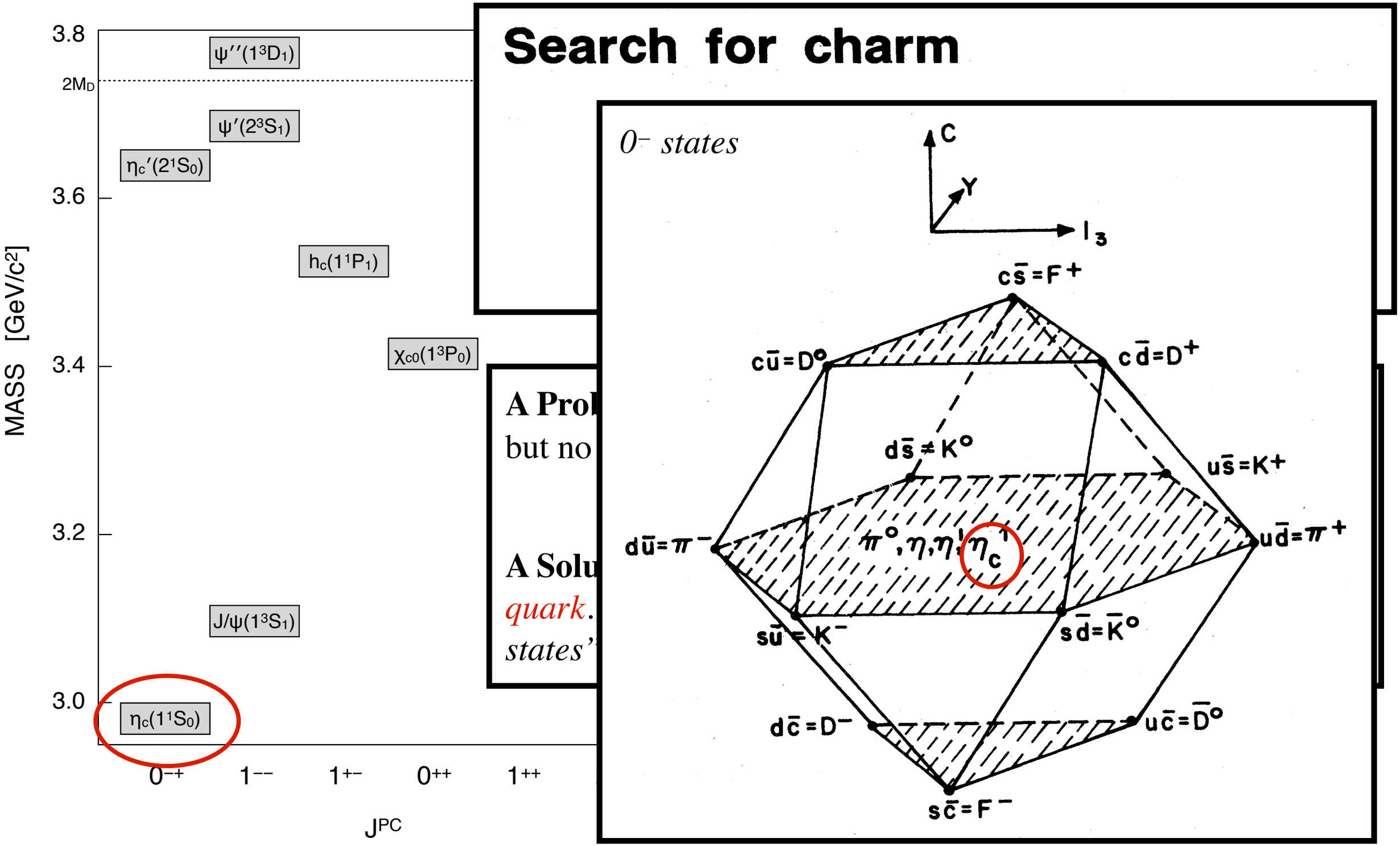

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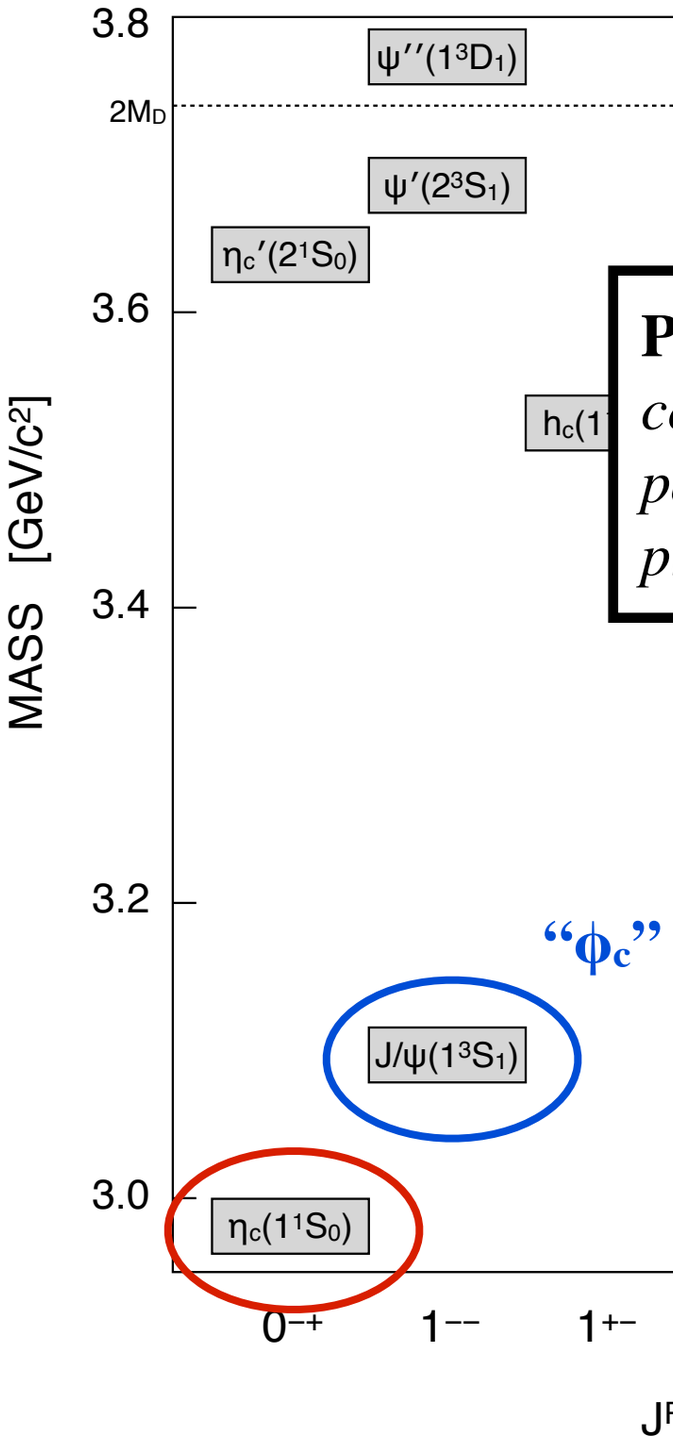
## Search for charm

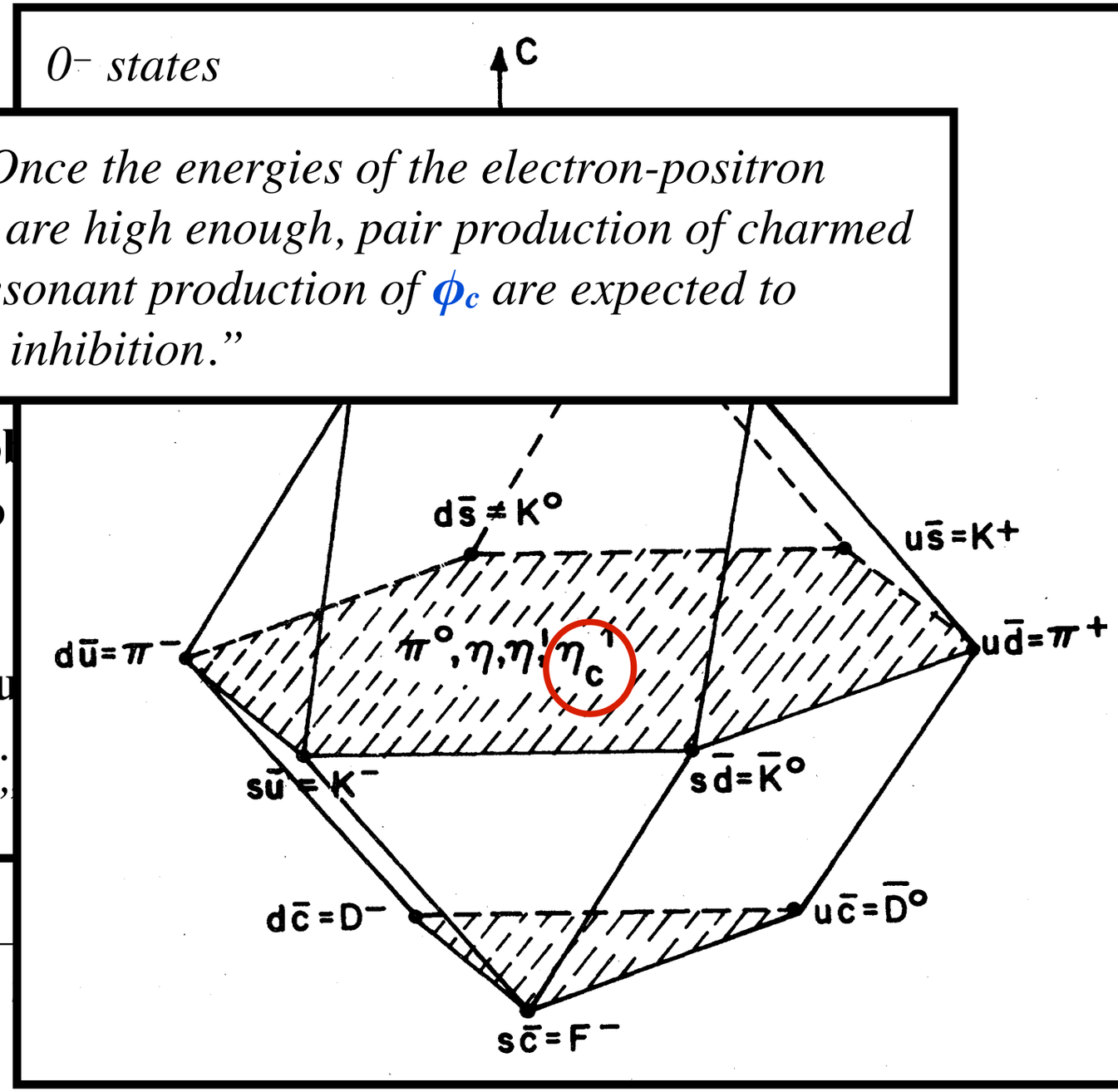
*0⁻ states*

**Production:** *"Once the energies of the electron-positron colliding beams are high enough, pair production of charmed particles, and resonant production of $\phi_c$ are expected to proceed without inhibition."*

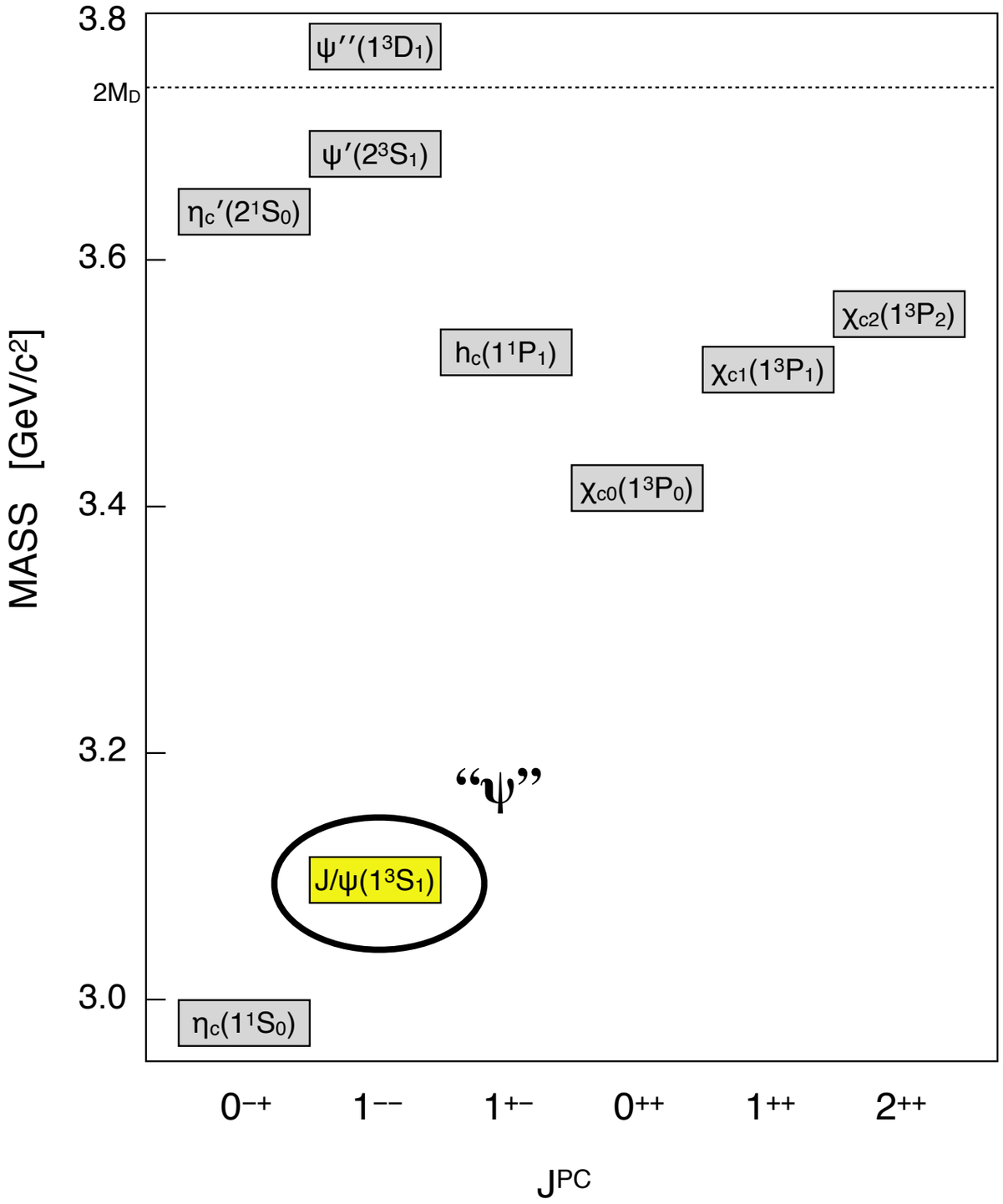
**A Prol**
but no

**A Solu**
*quark.*
*states'*

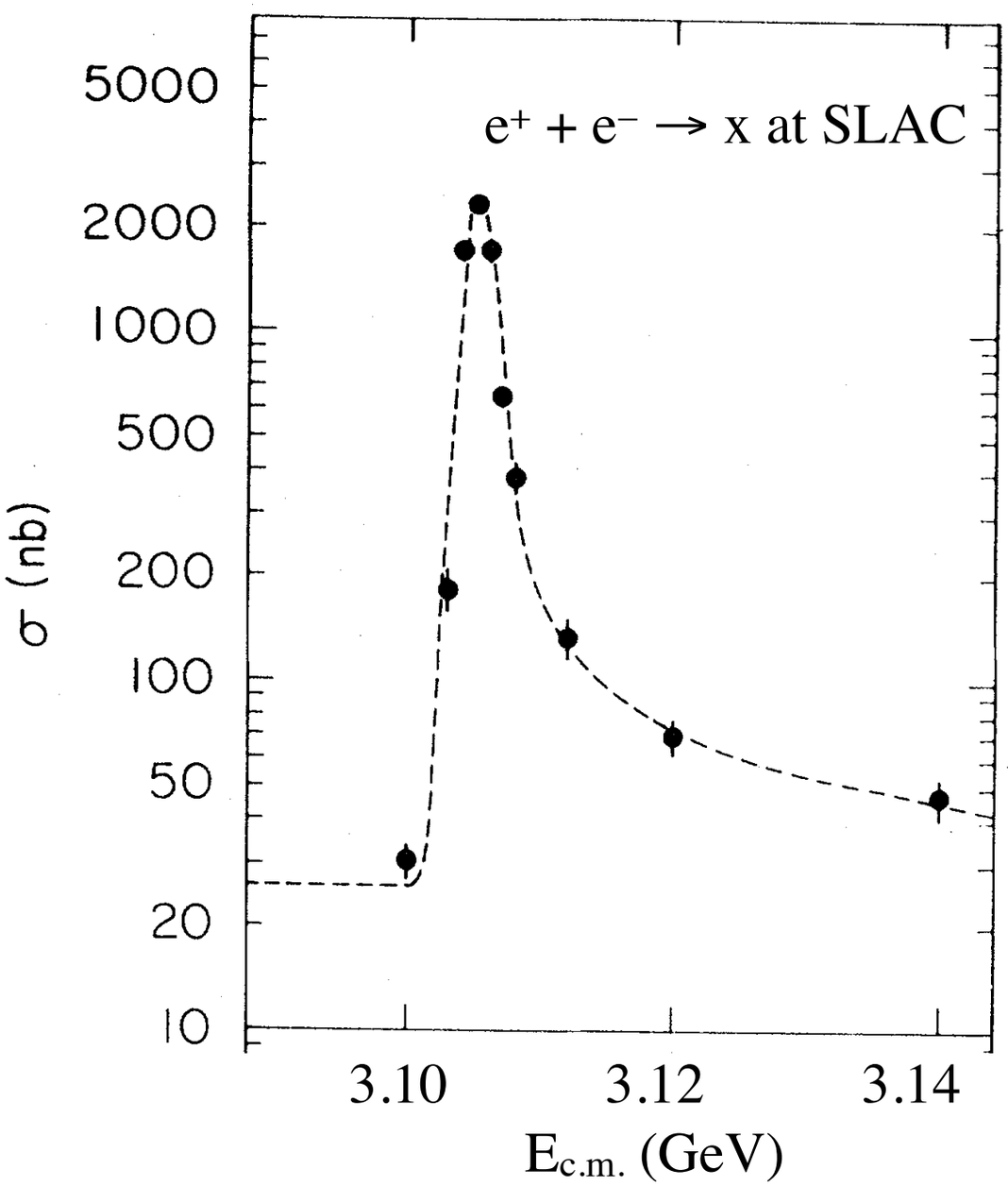


# II. The Original Era of Discovery



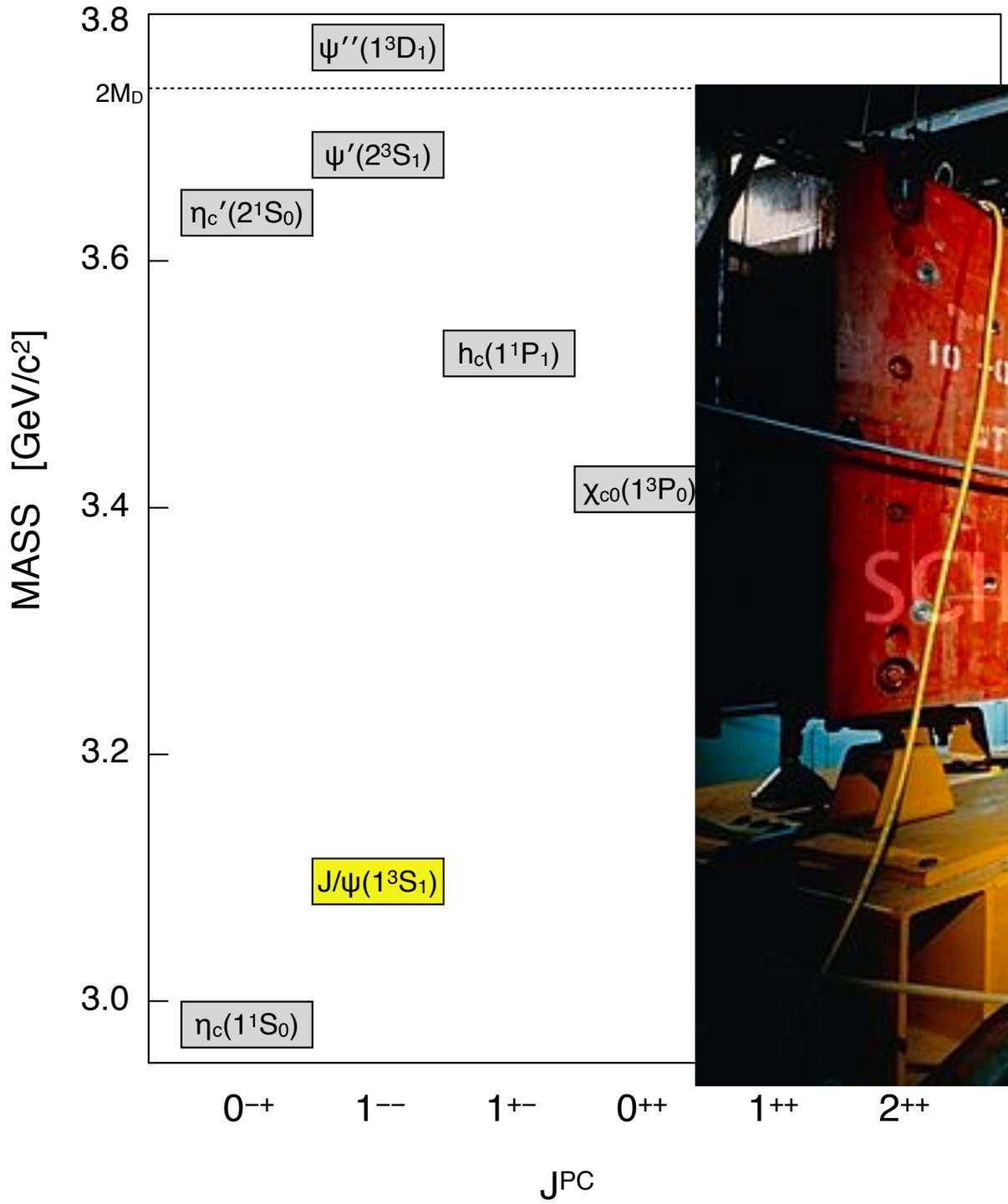

**November (1974) Revolution**



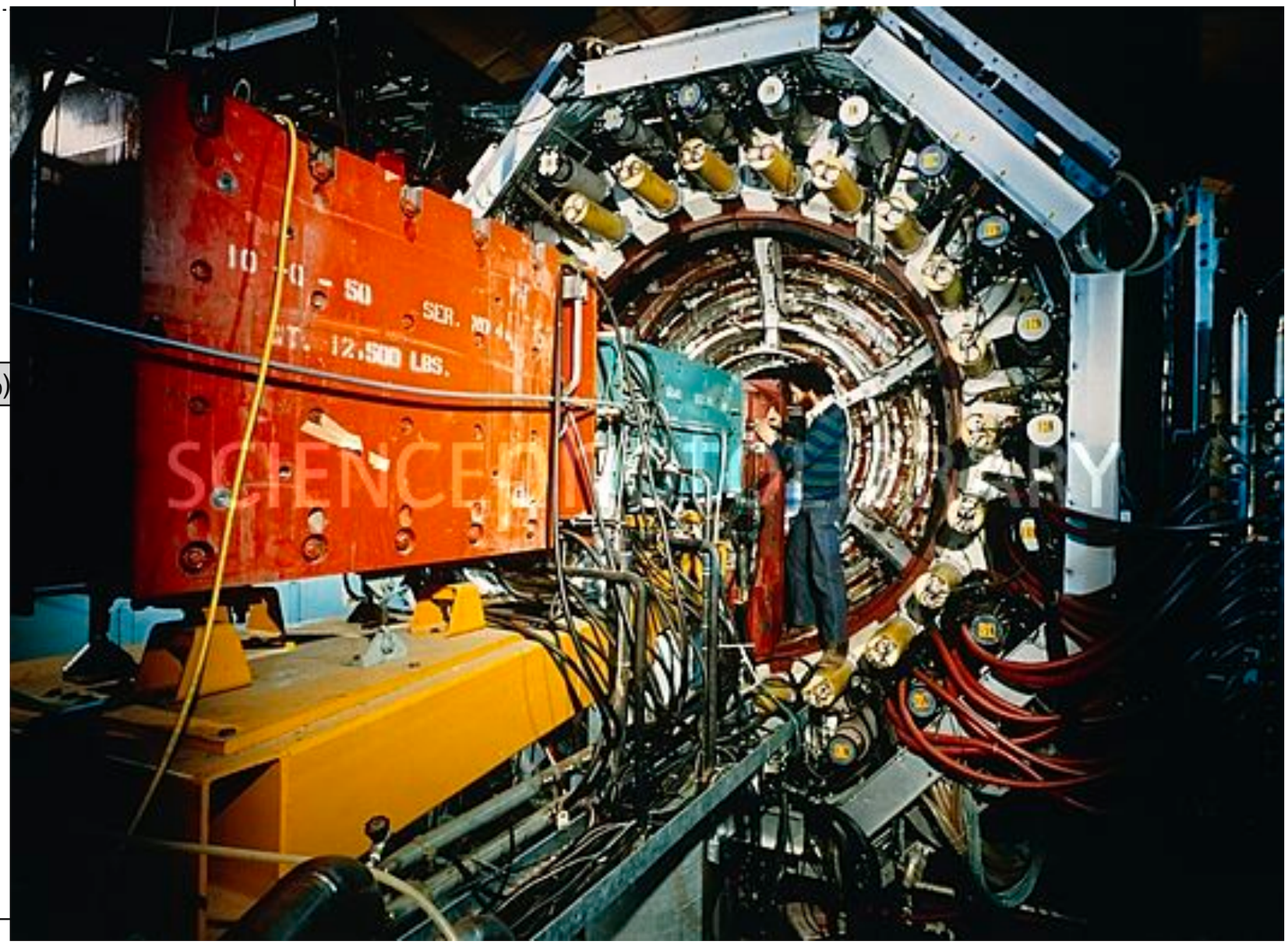

**PRL33, 1406 (1974)**

# II. The Original Era of Discovery

**November (1974) Revolution**




Mark I Detector at SLAC



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

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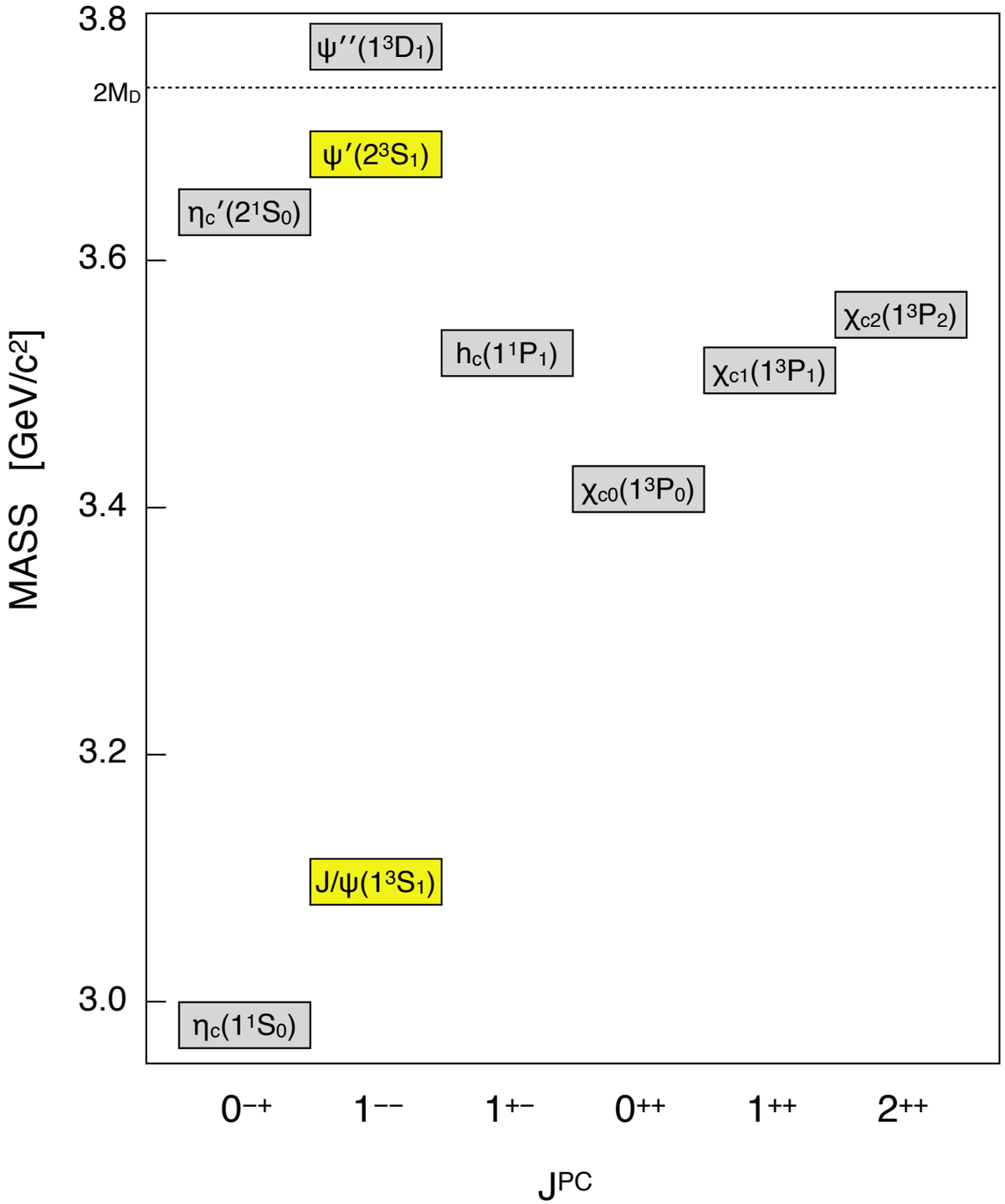
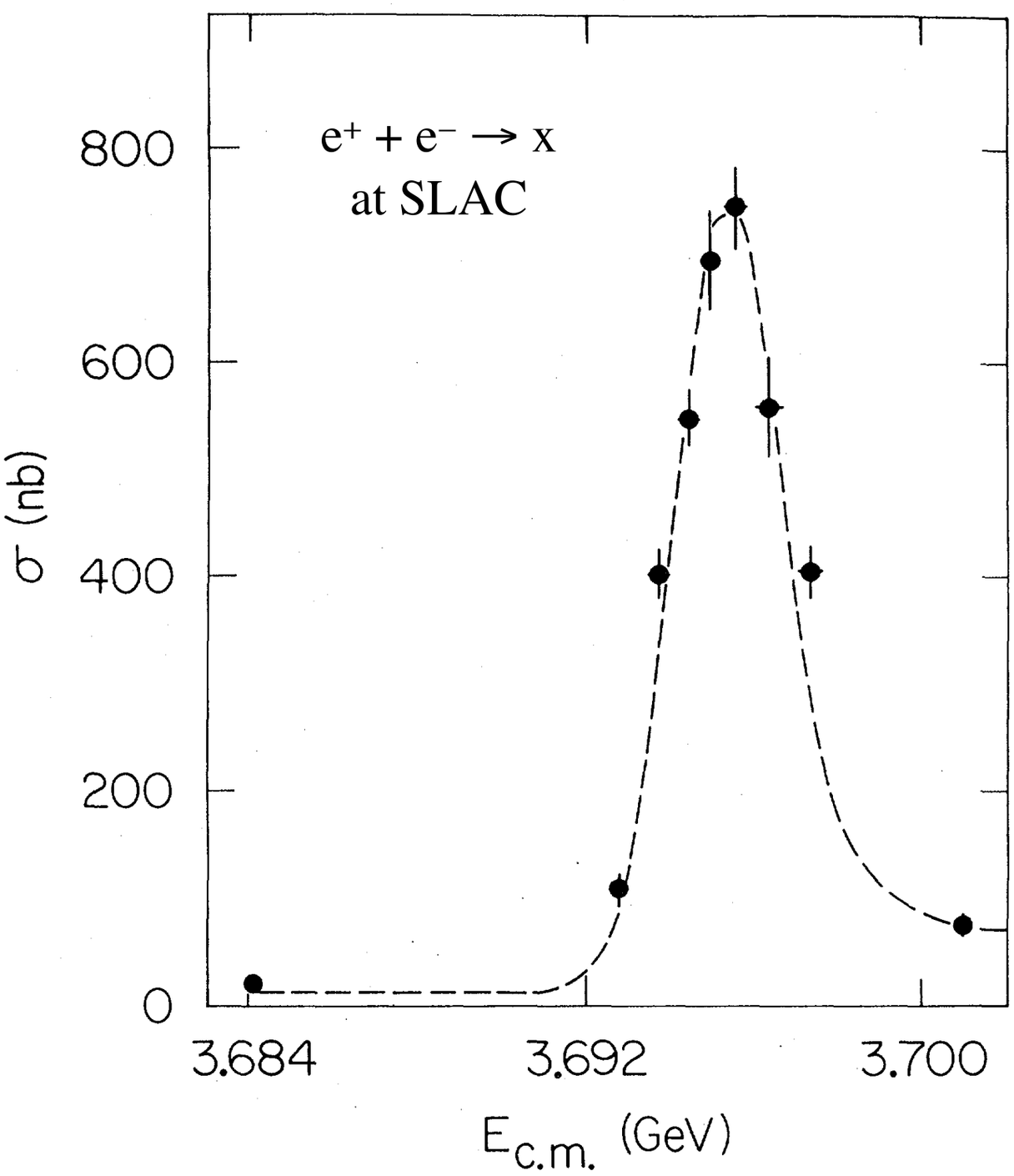



**November (1974) Revolution**




**PRL33, 1453 (1974)**

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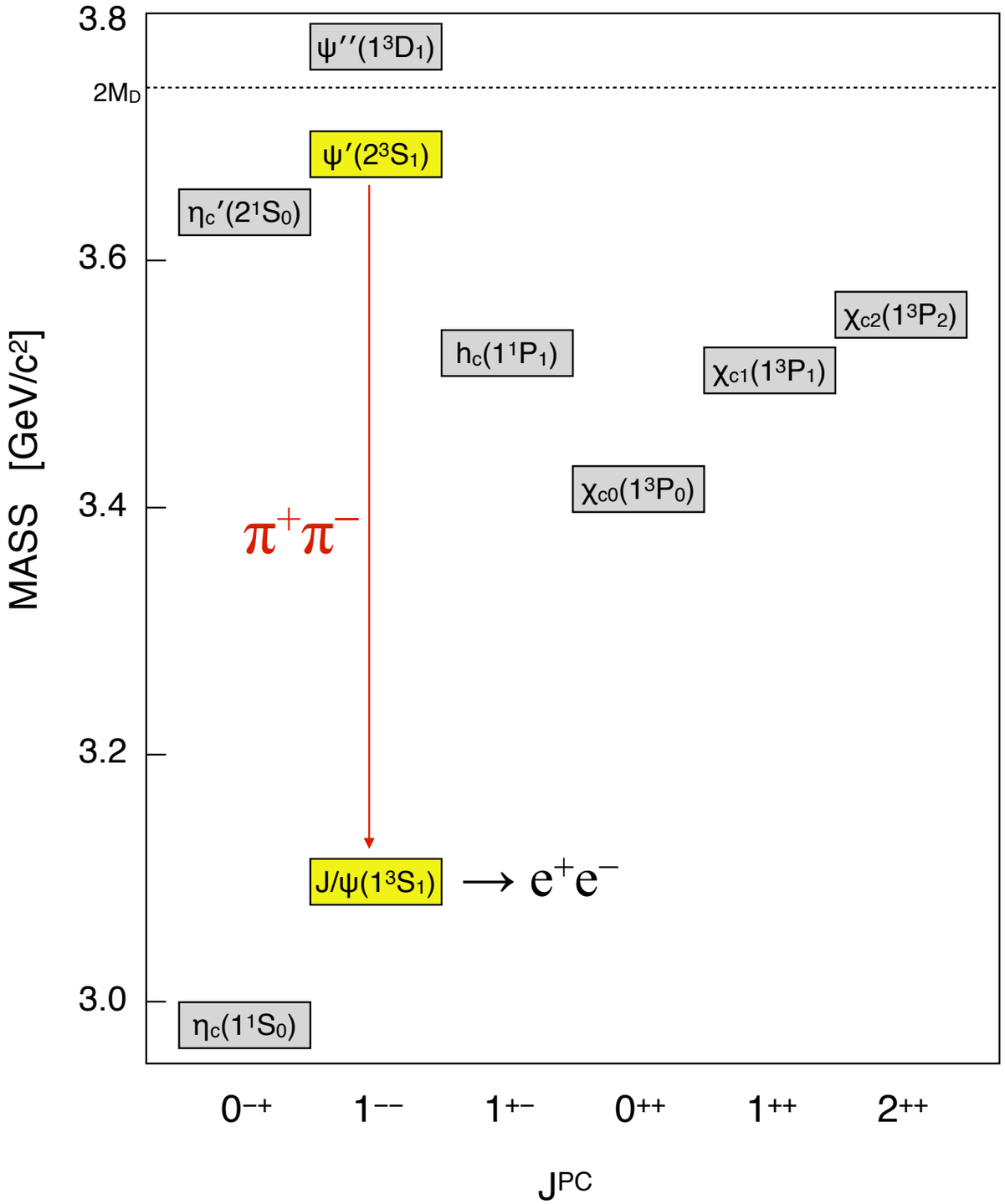
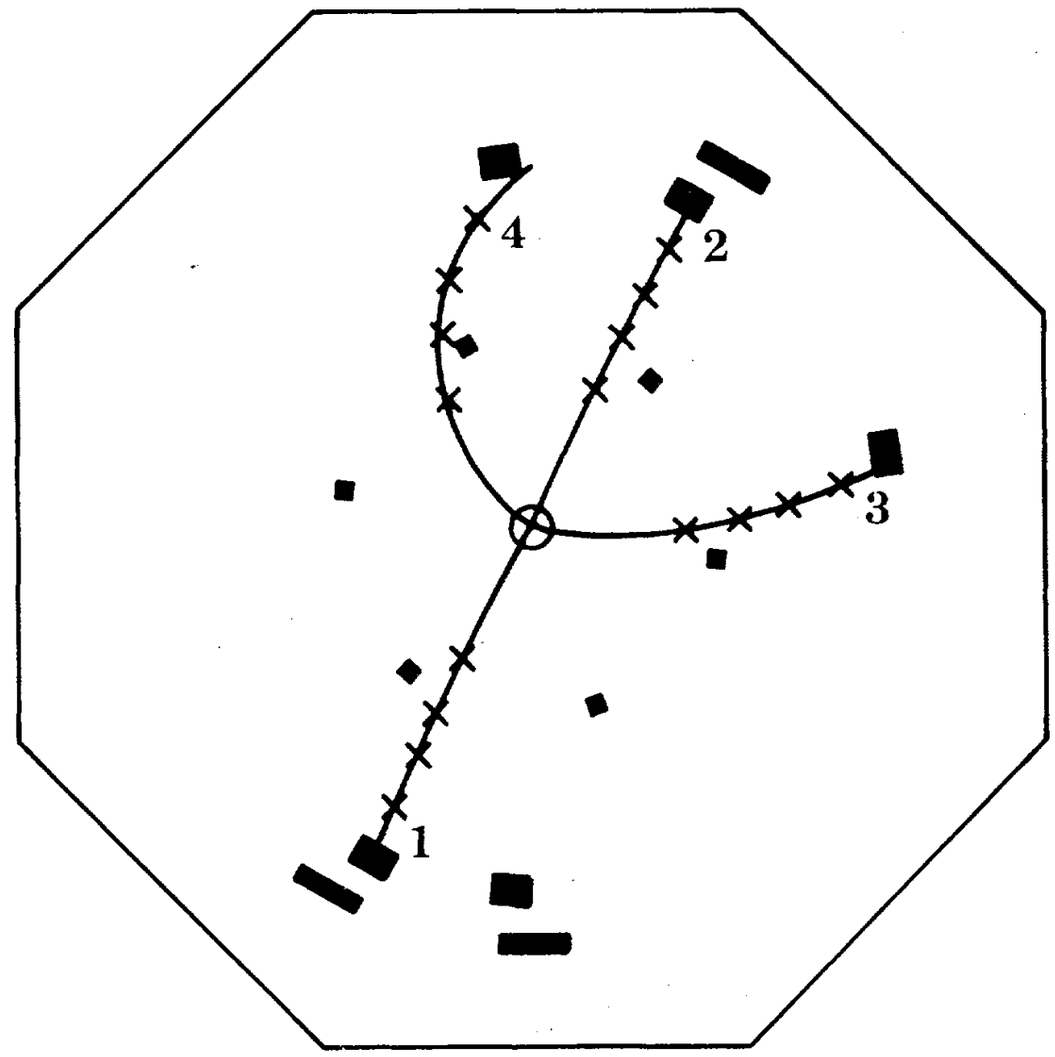
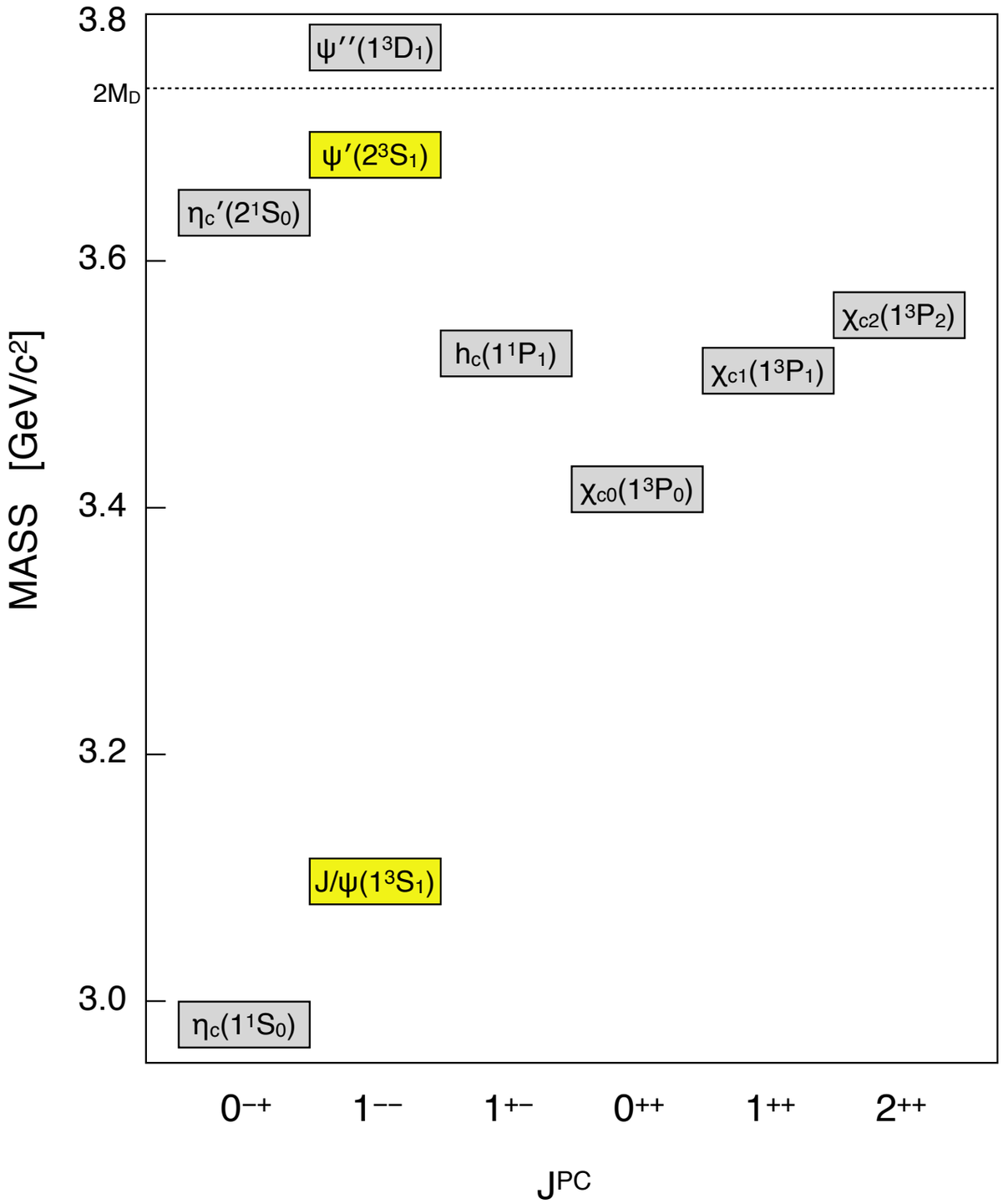



$\psi(2S) \rightarrow \pi^+\pi^- J/\psi$
at SLAC




**PRL34, 1181 (1975)**

# II. The Original Era of Discovery




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

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

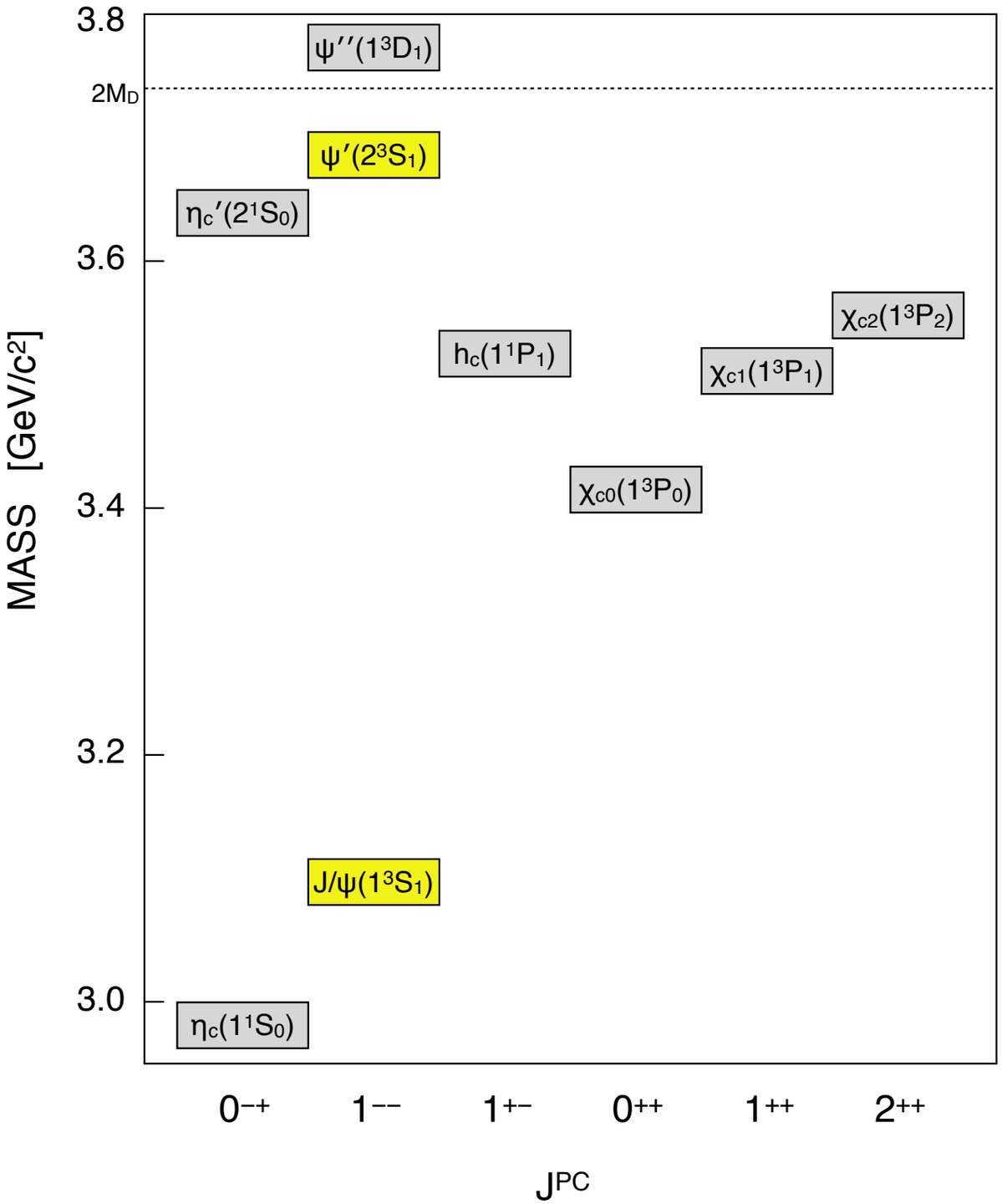
Spin-1 meson alternative to GIM
**(PRL34, 37 (1975))**

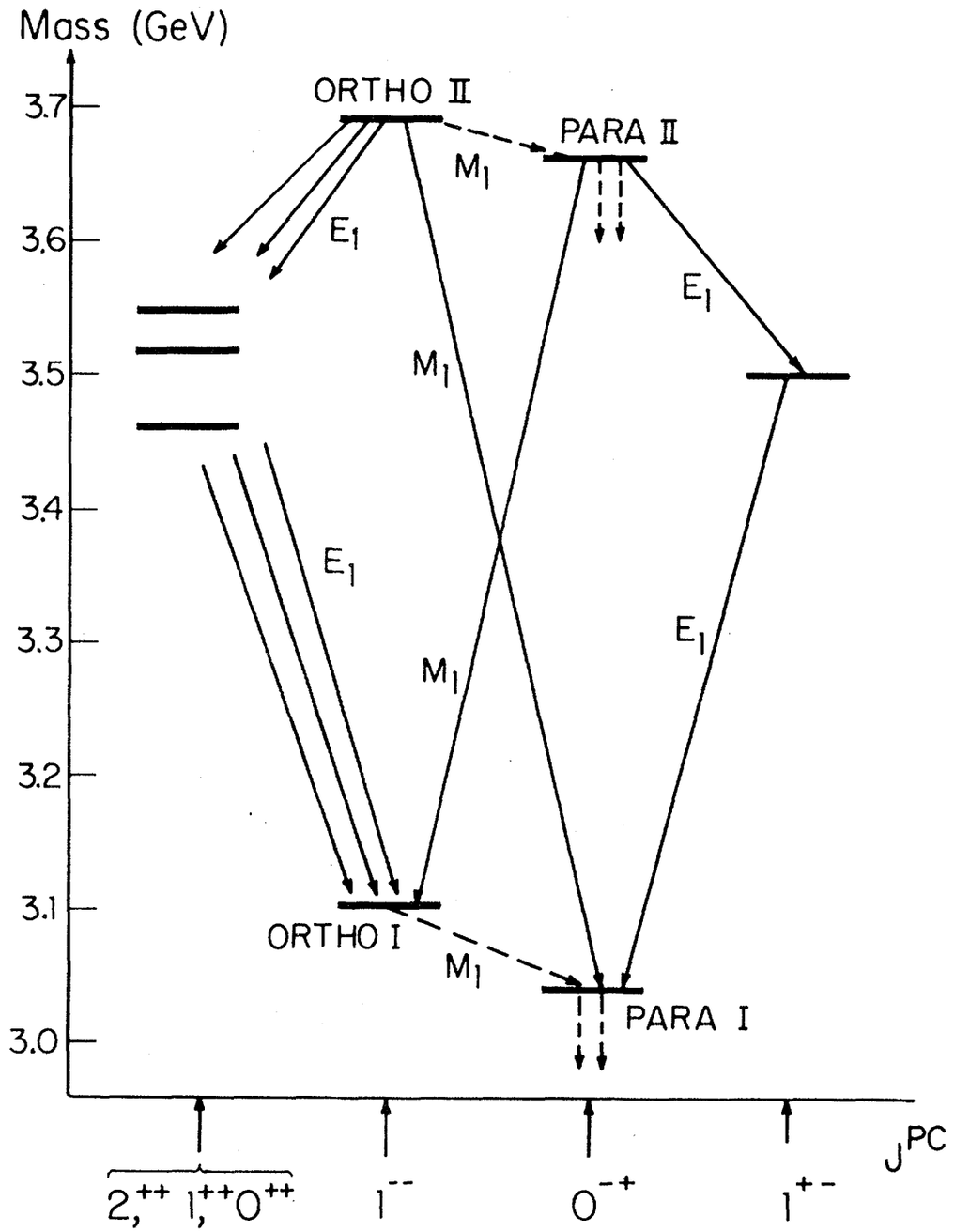
Three charm quarks (partners to u, d, s)
**(PRL34, 41 (1975))**

Lighter $Z_0$
**(PRL34, 56 (1975))**

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

# II. The Original Era of Discovery




**PRL34, 365 (1975)**

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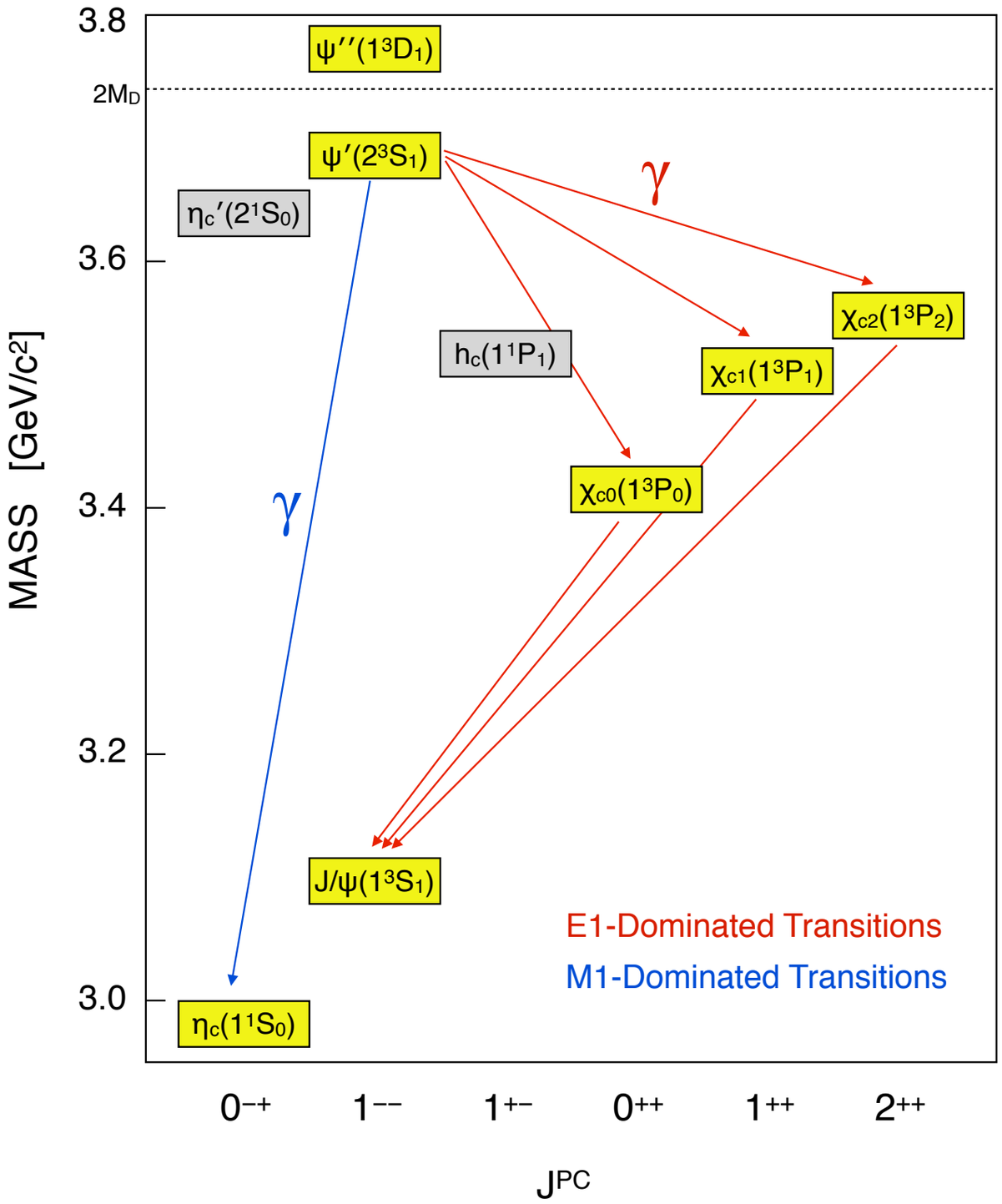
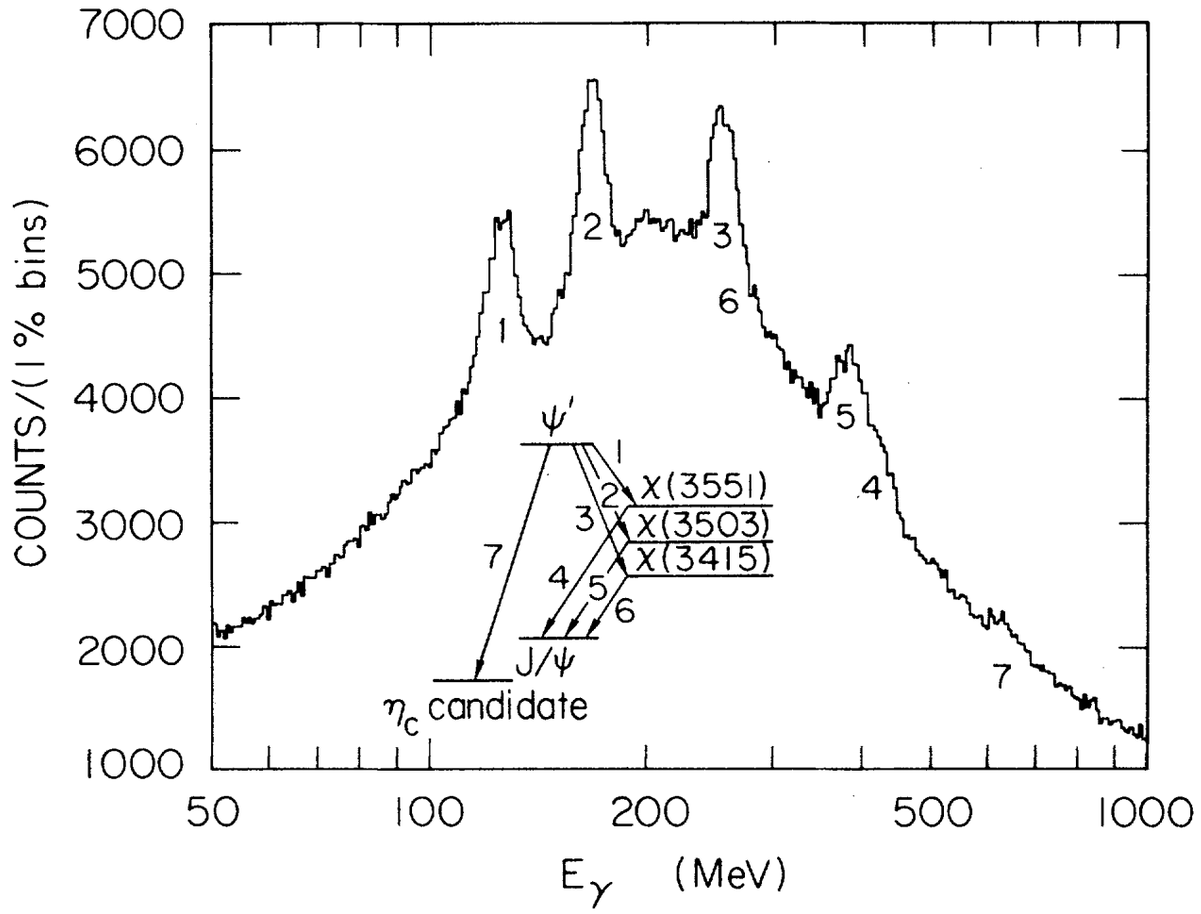



Crystal Ball at SLAC
*(discovery of $\eta_c$)*




**PRL45, 1150 (1980)**

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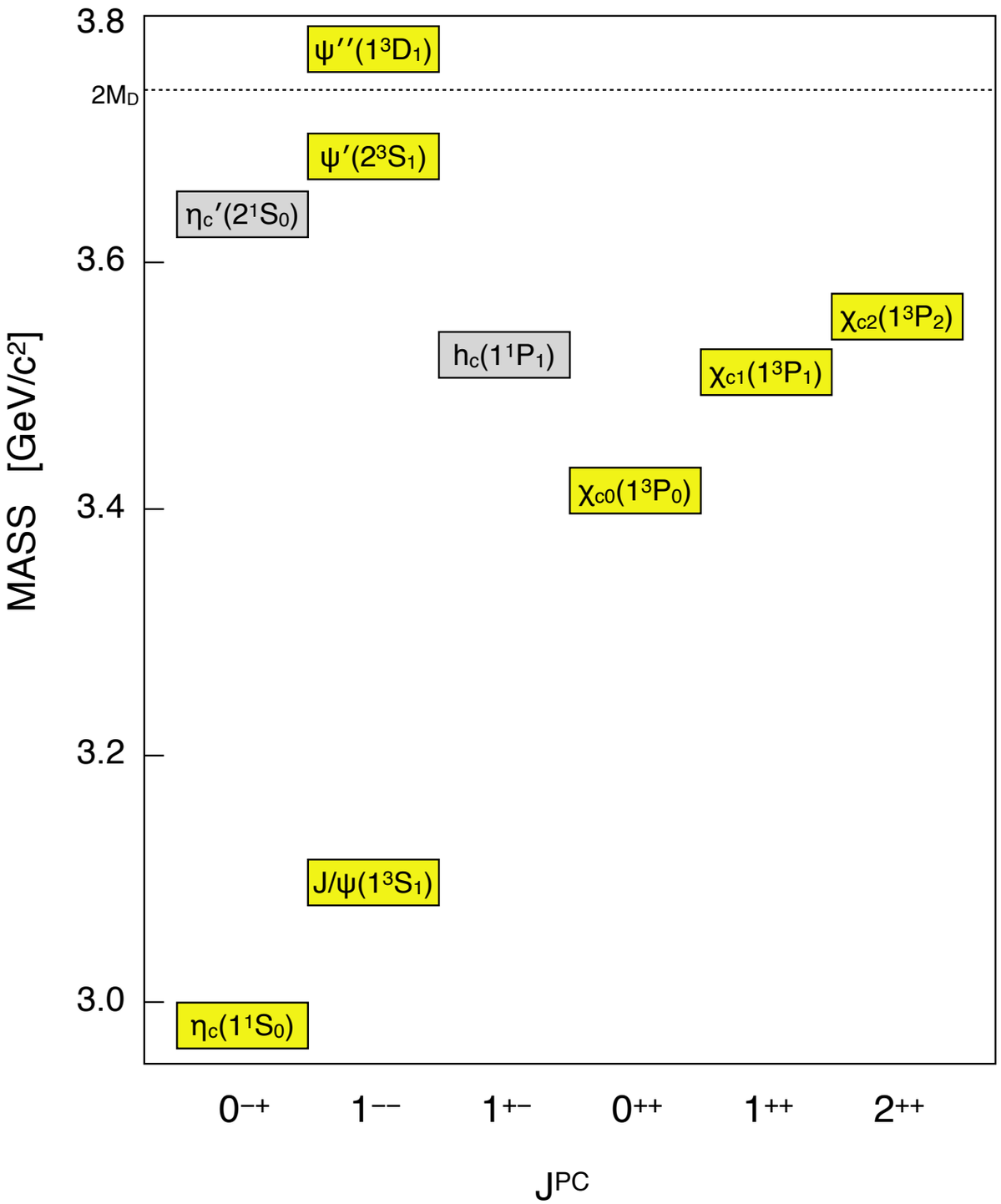
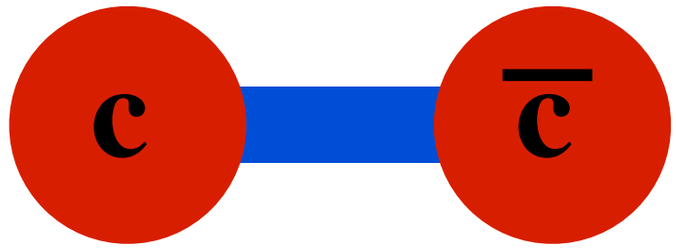
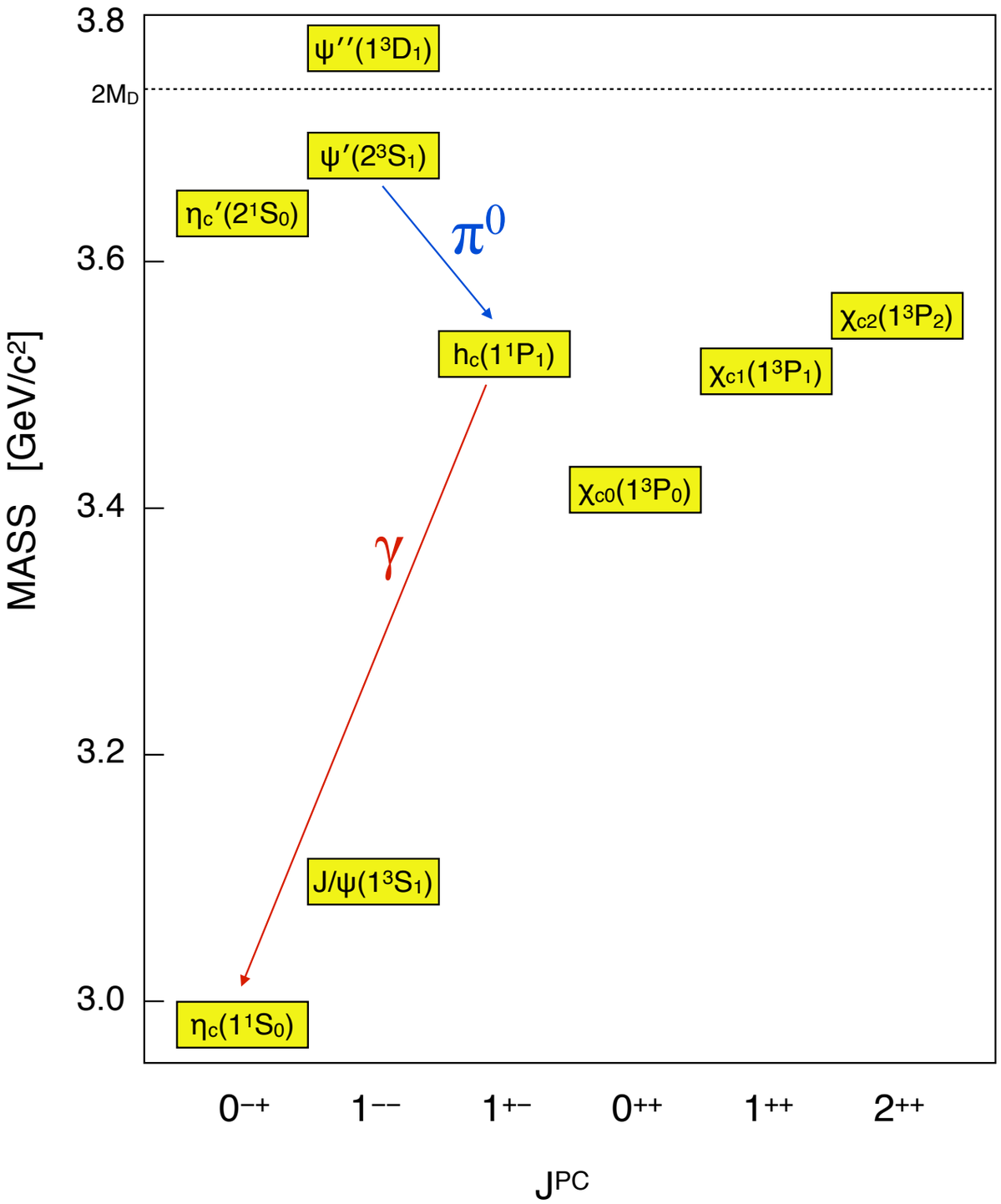





CHARMONIUM

# III. From Discovery to Precision

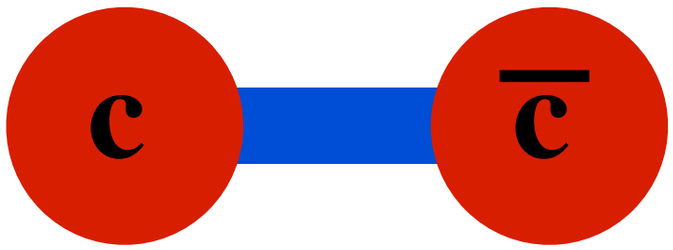



I. An Introduction to Charmonium

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

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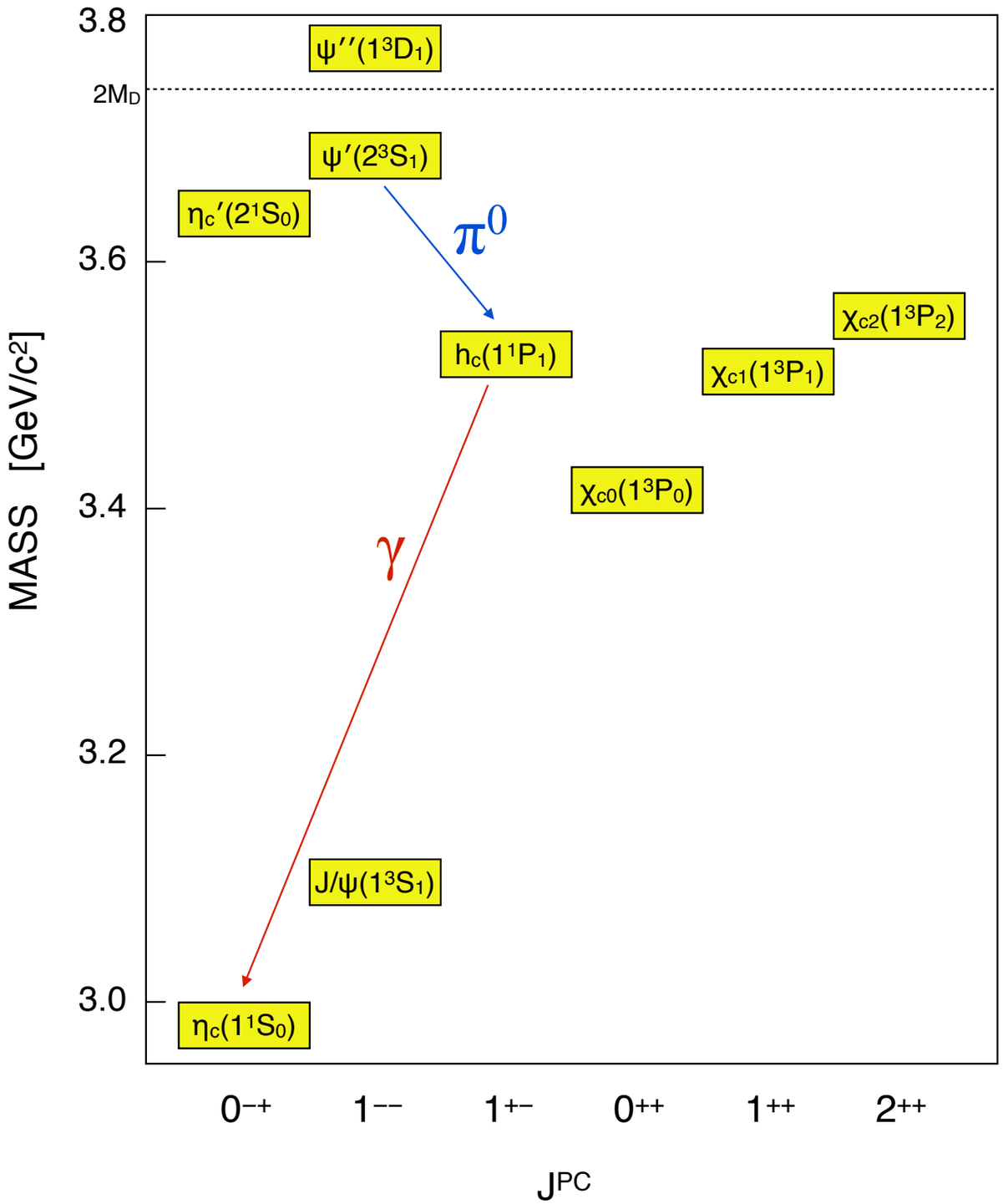


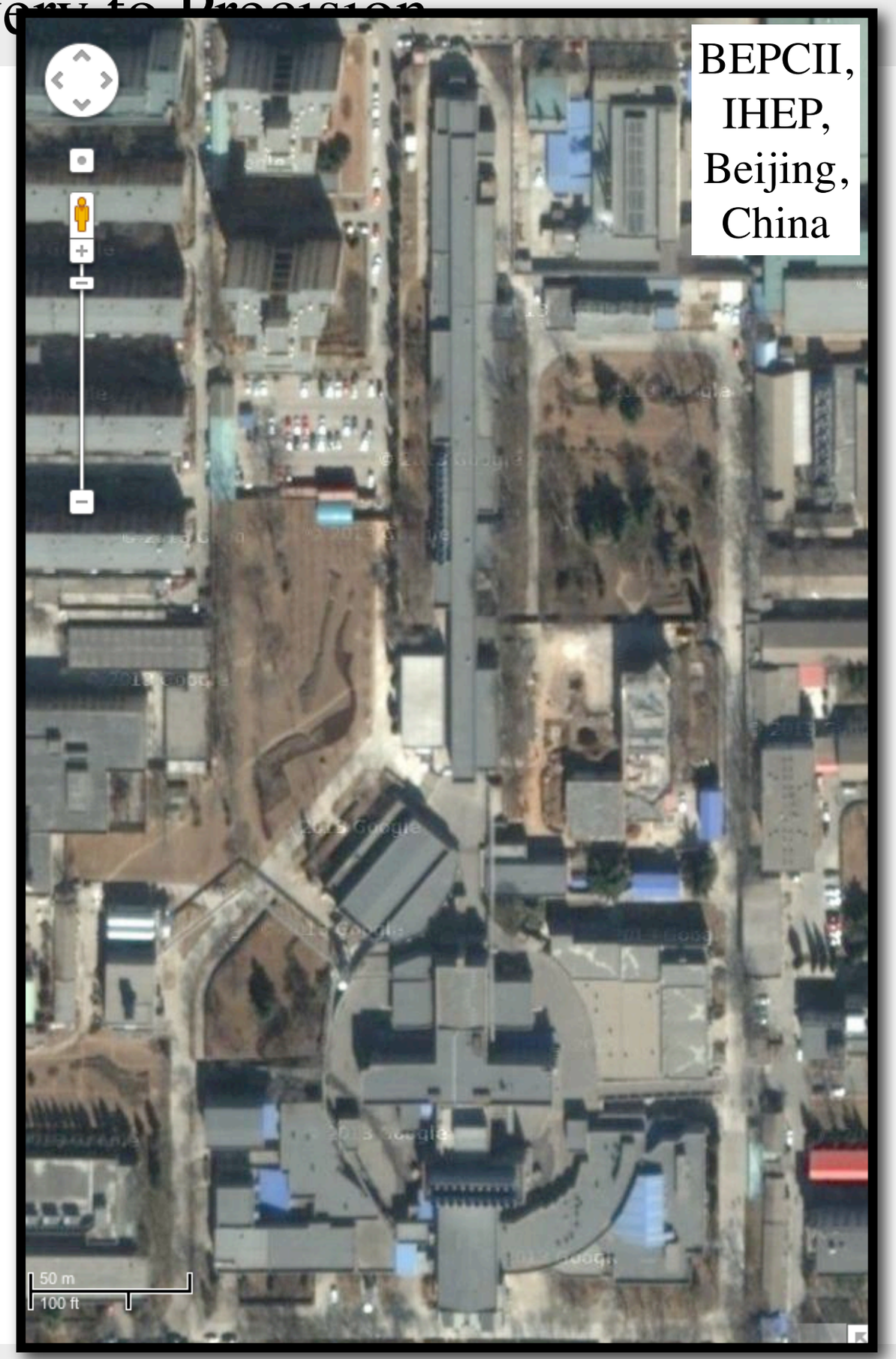


*Google satellite image of BEPC-II*

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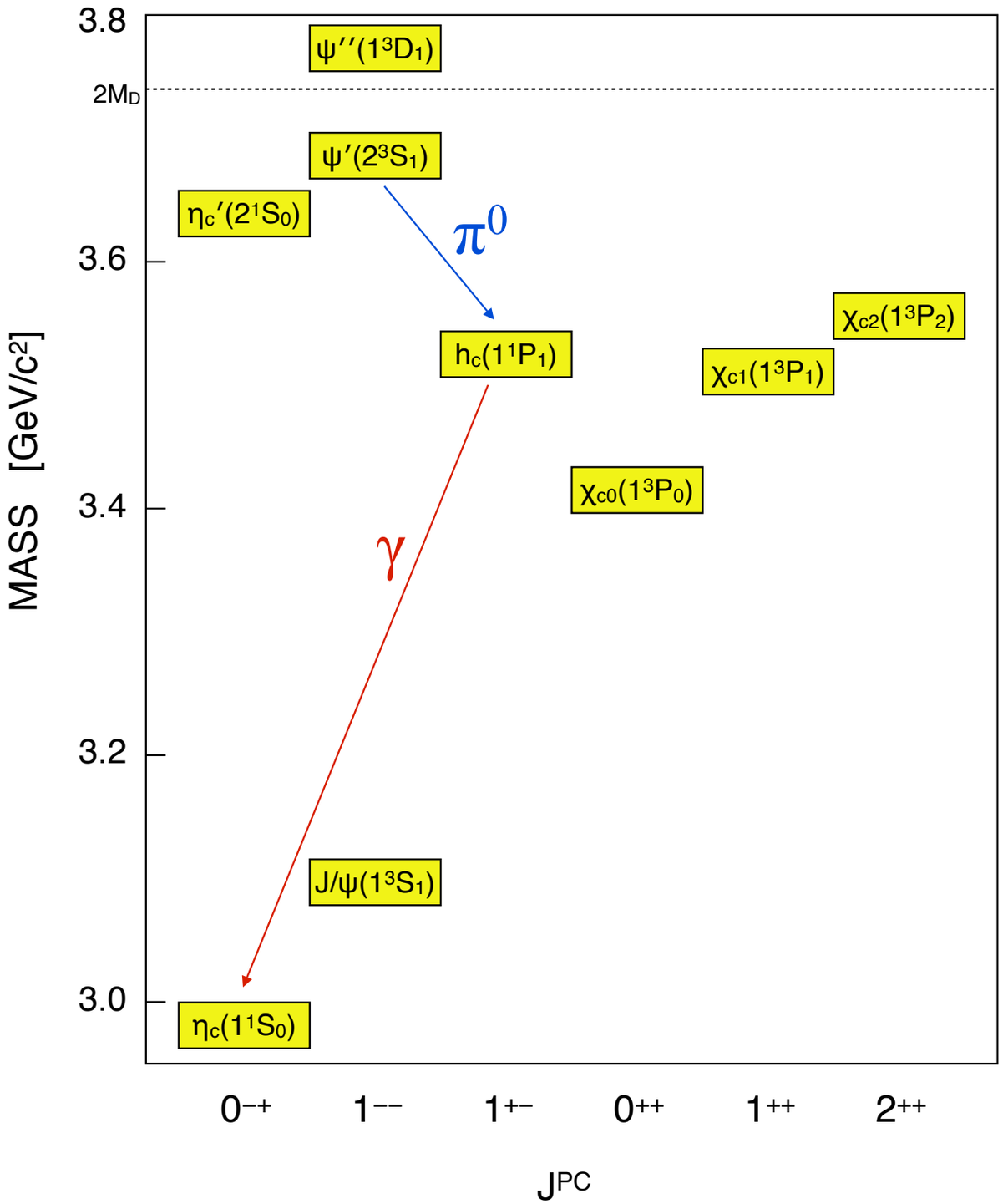


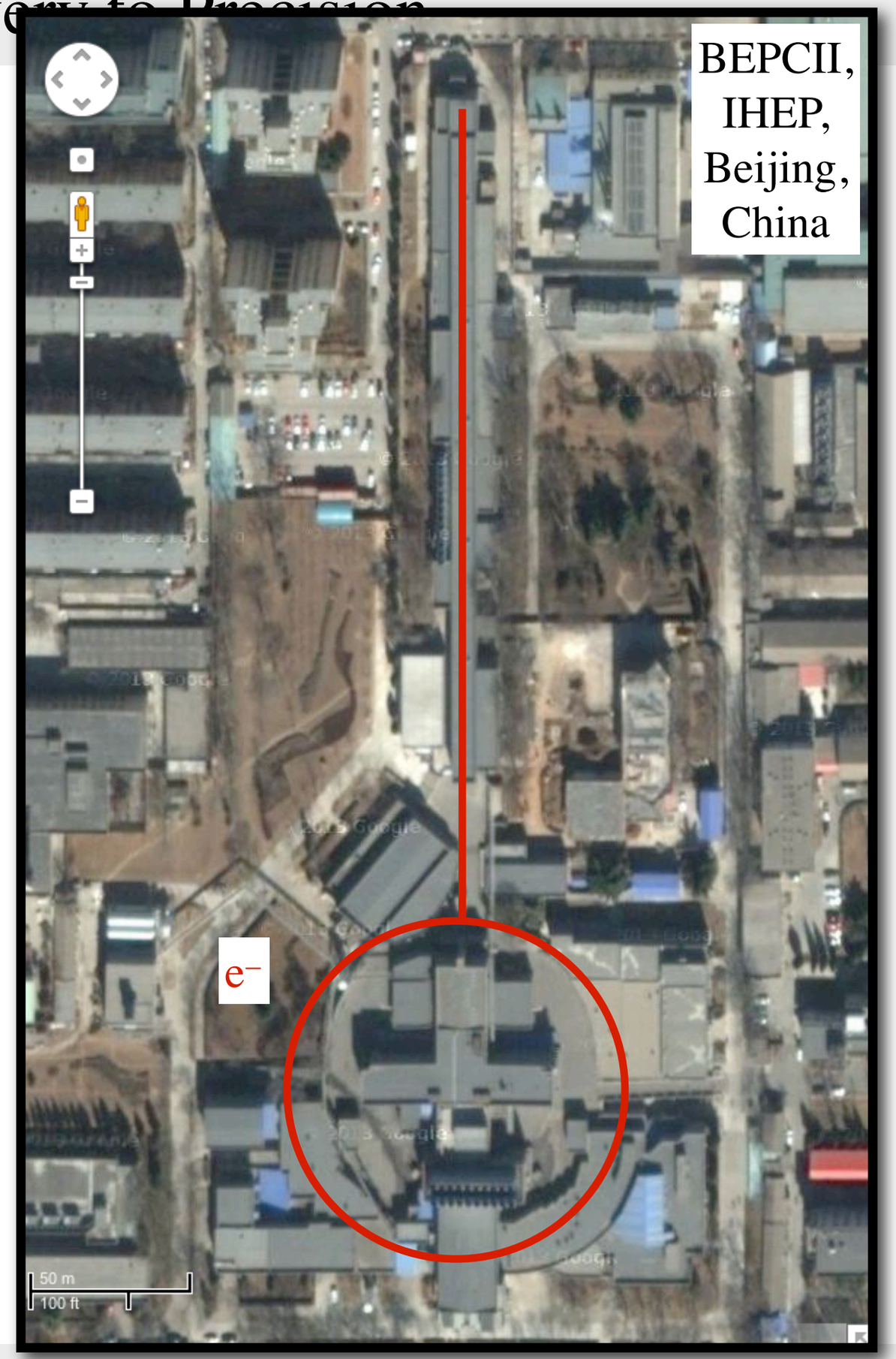


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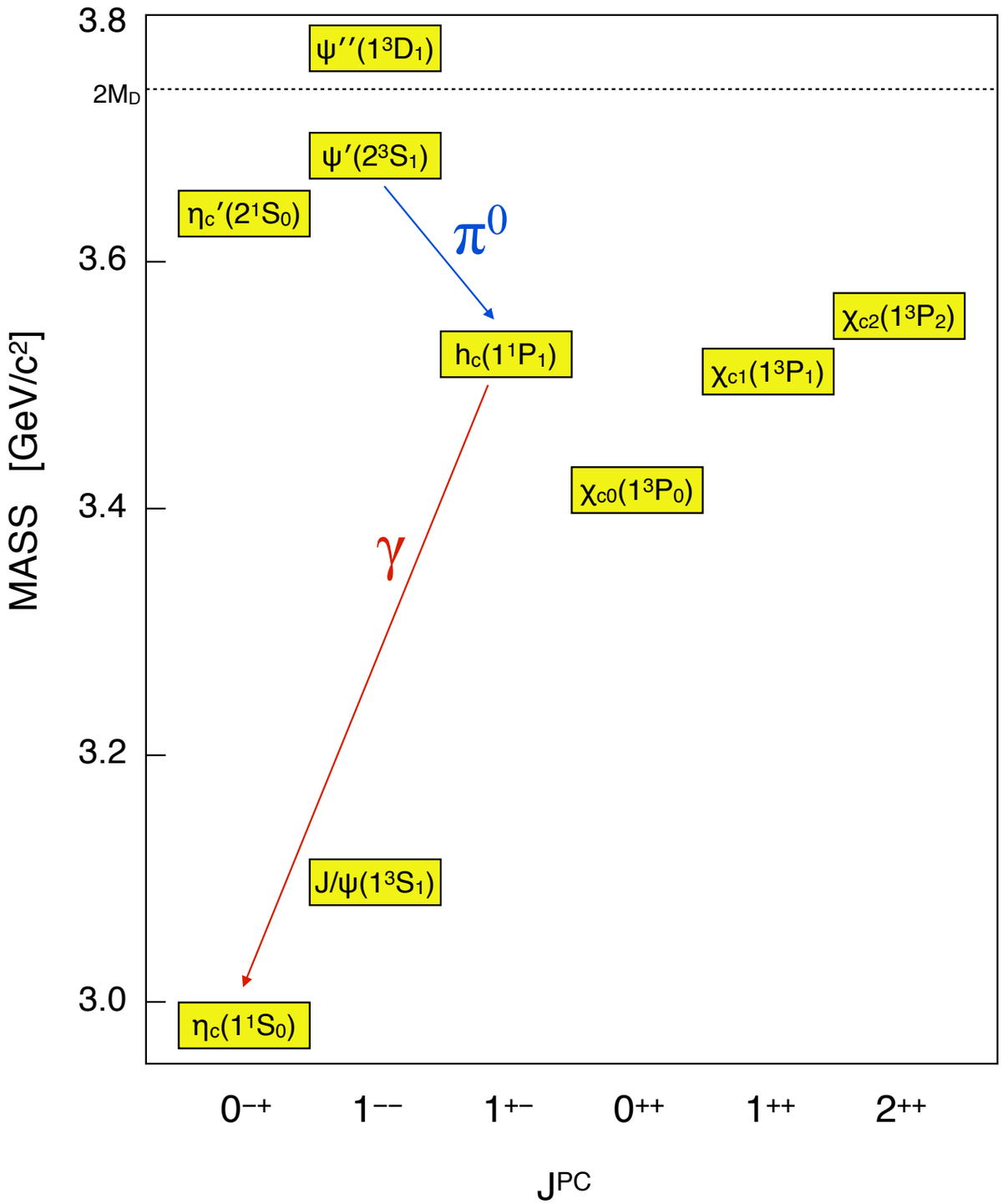



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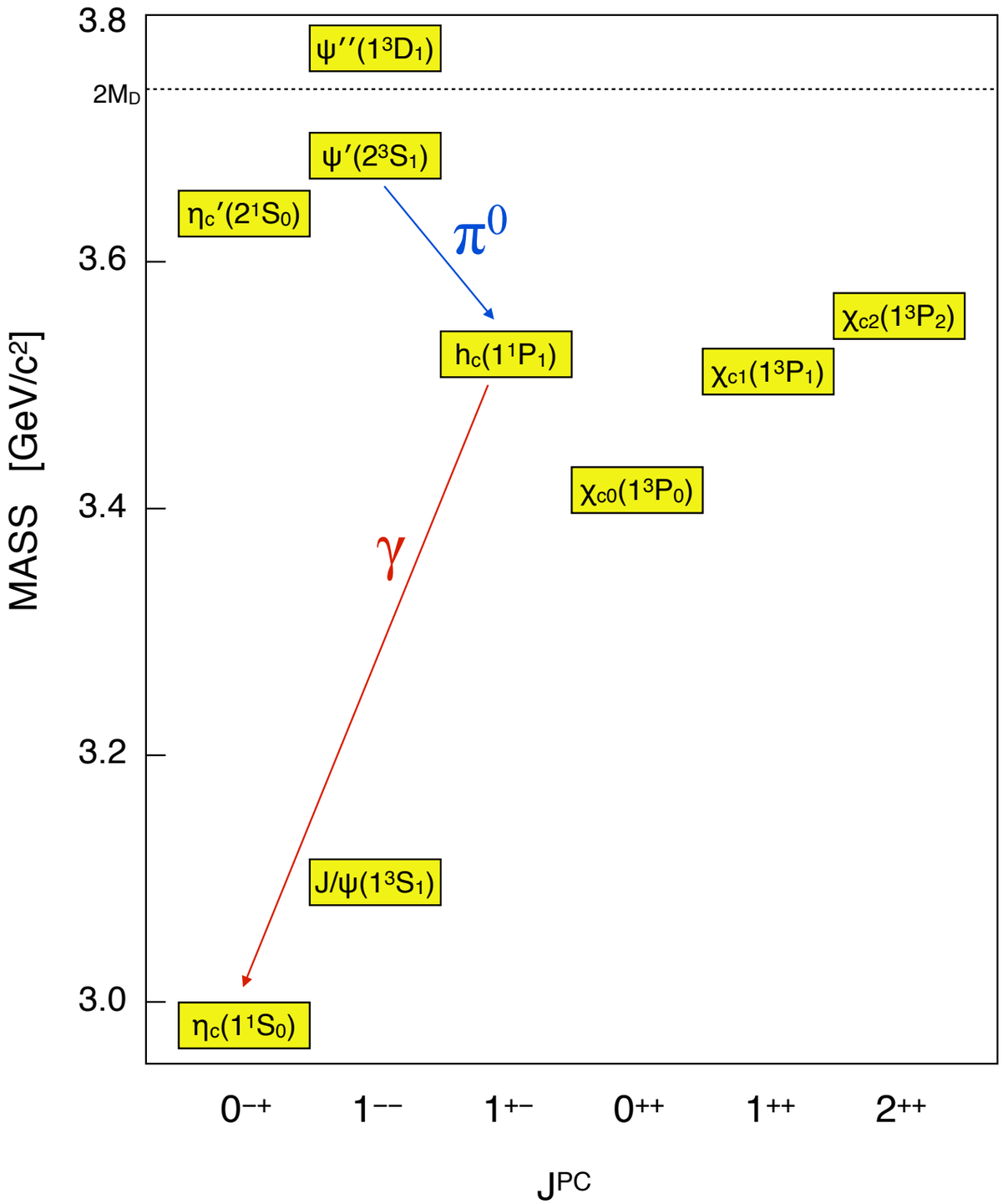


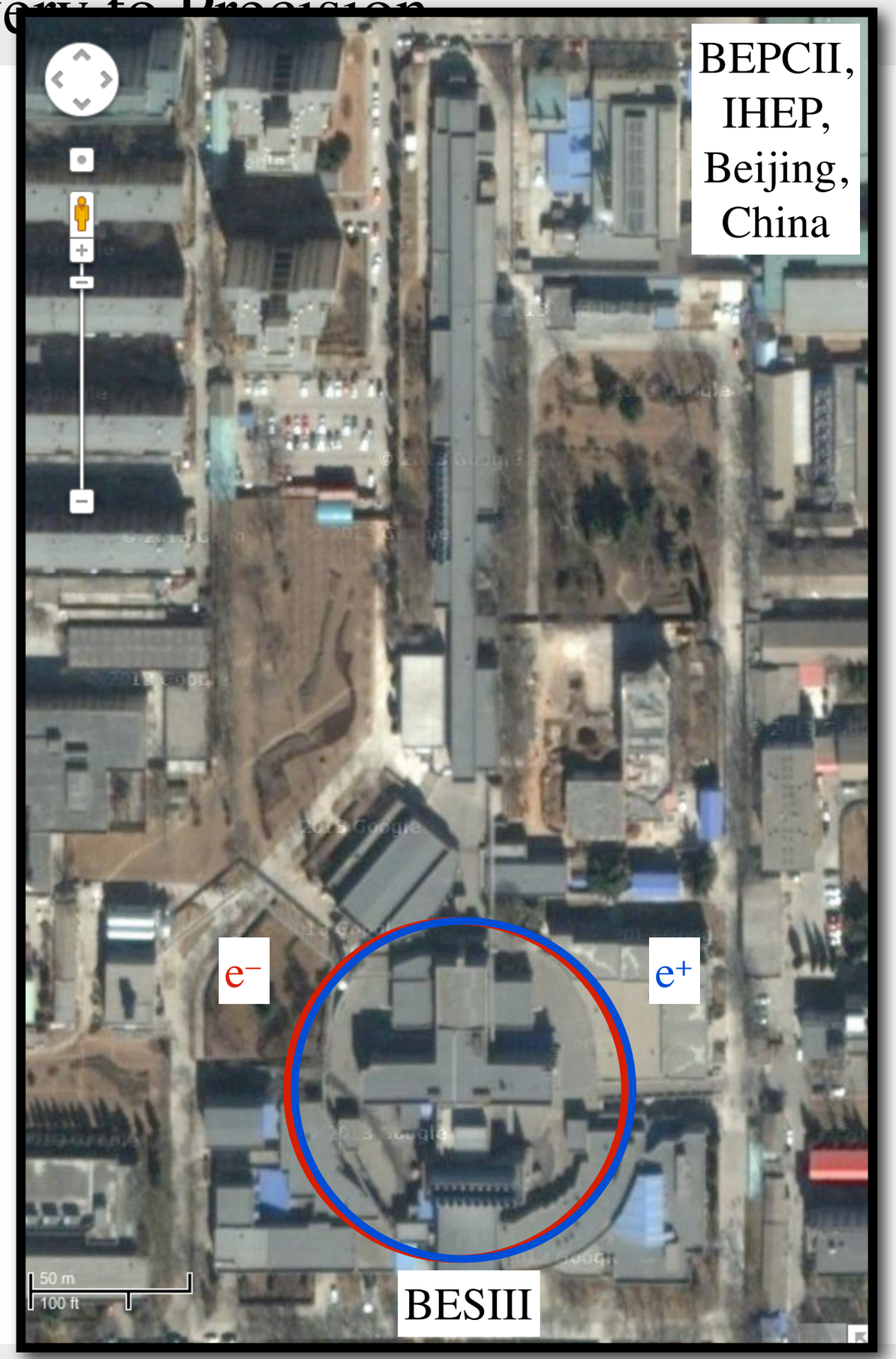


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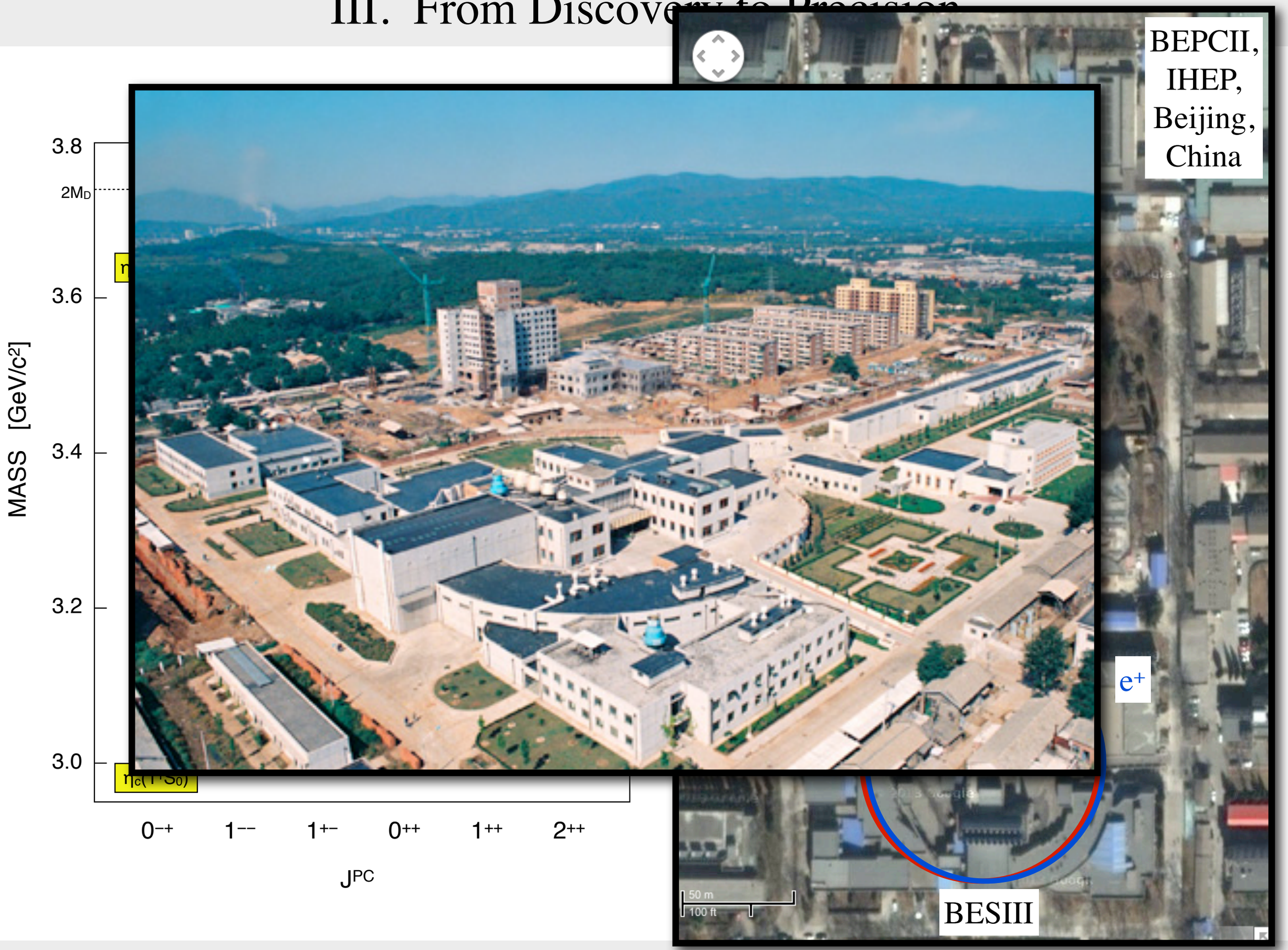

# III. From Discovery to Precision


*Google satellite image of BEPC-II*

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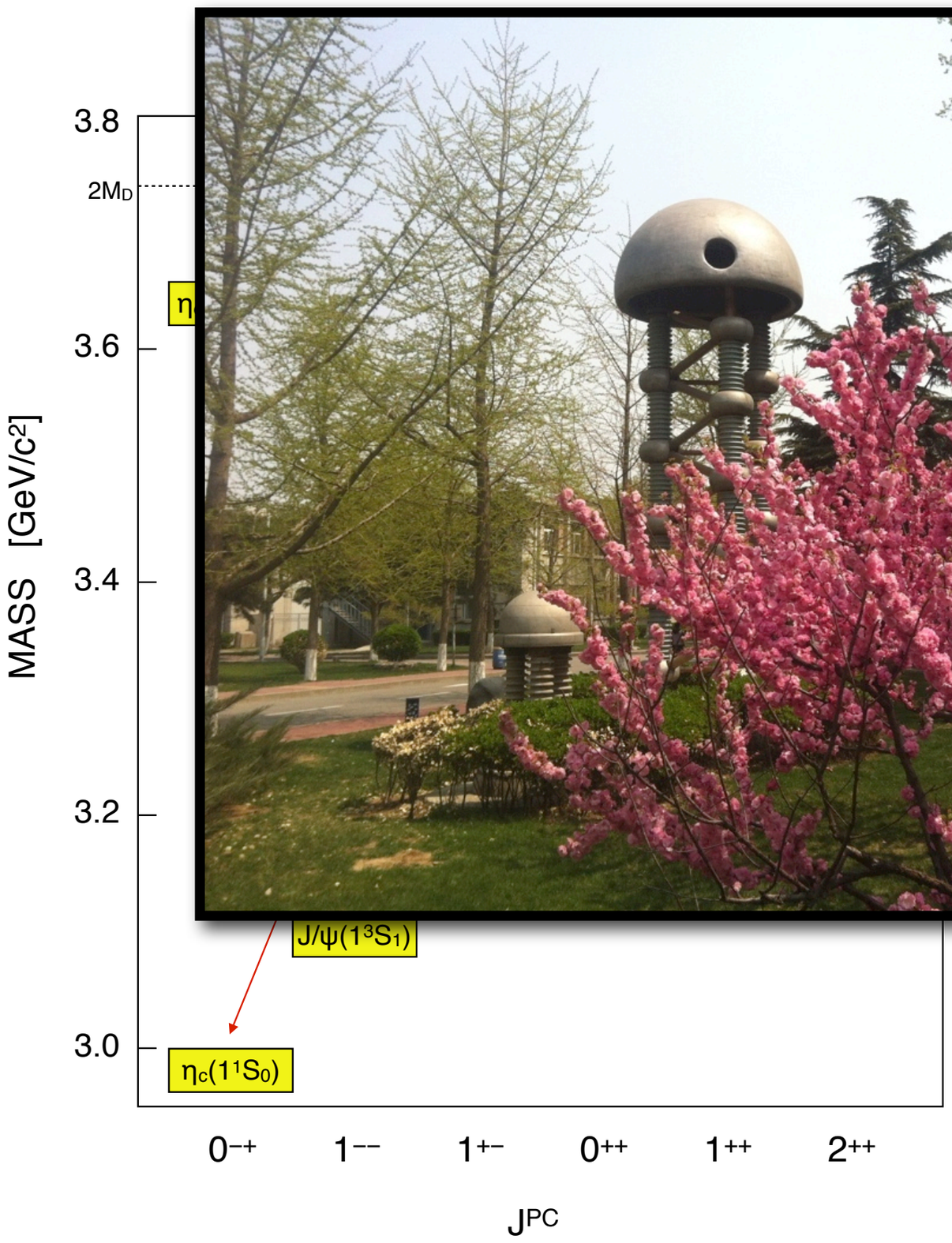





*Google satellite image of BEPC-II*

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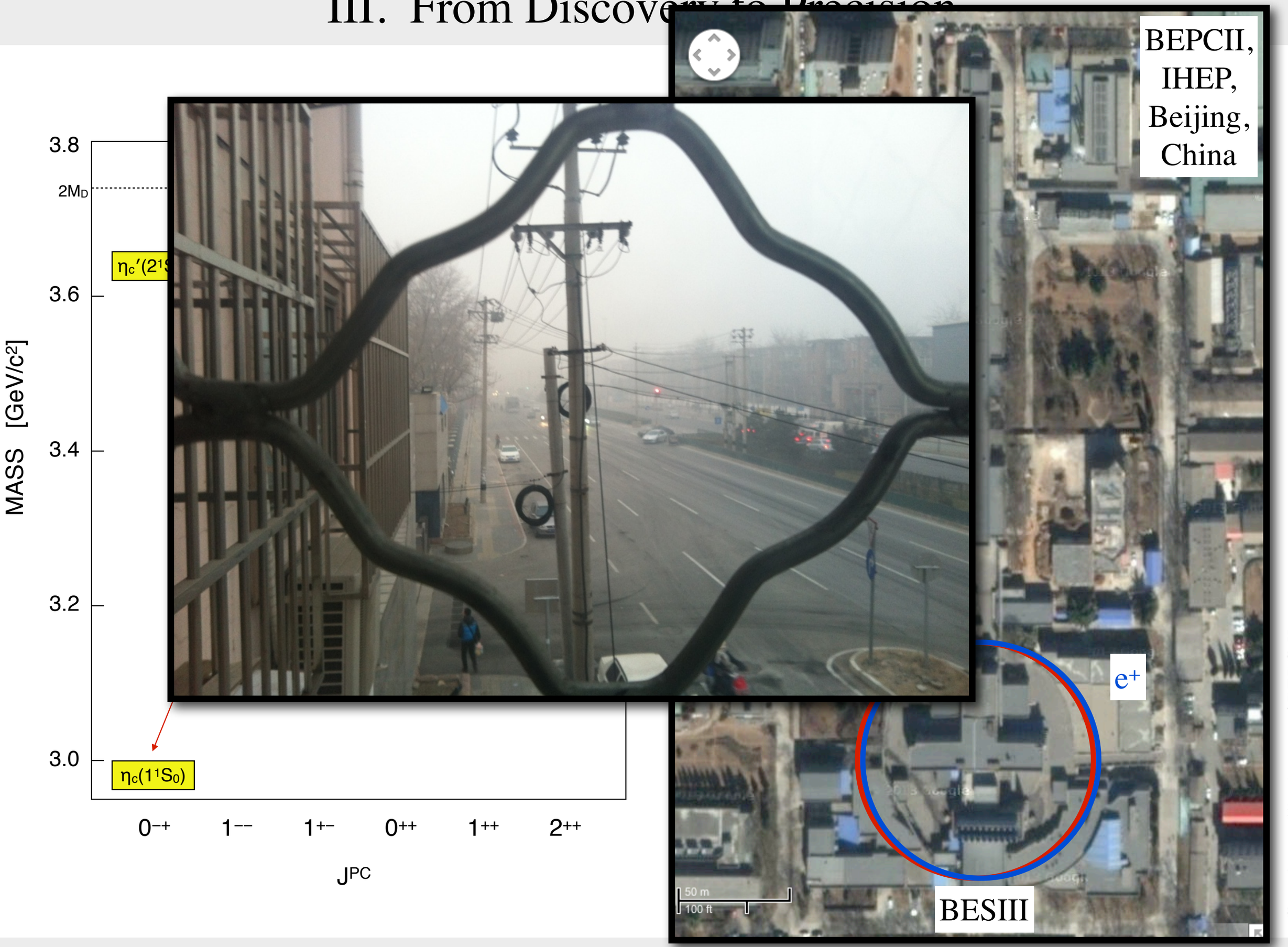

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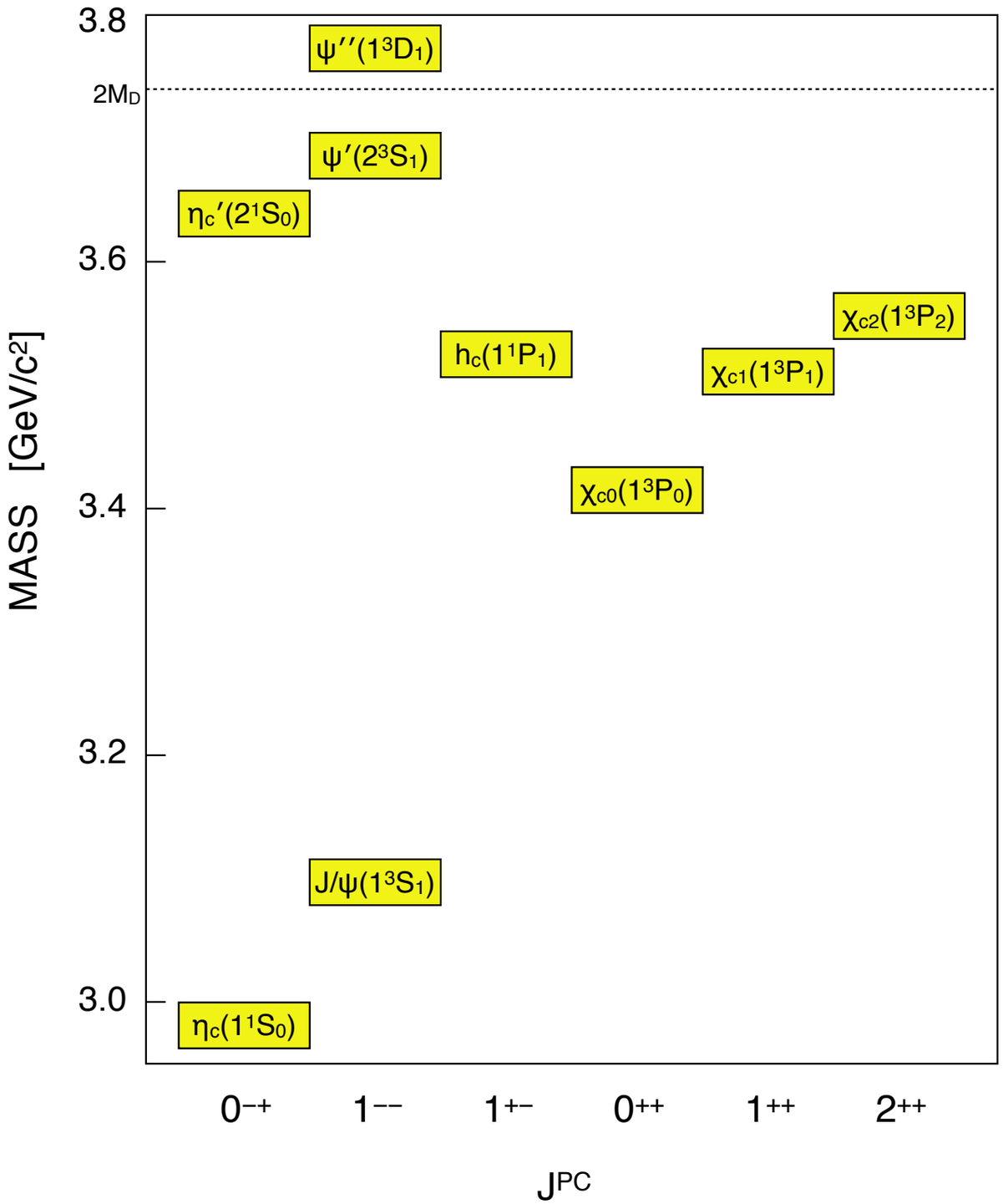


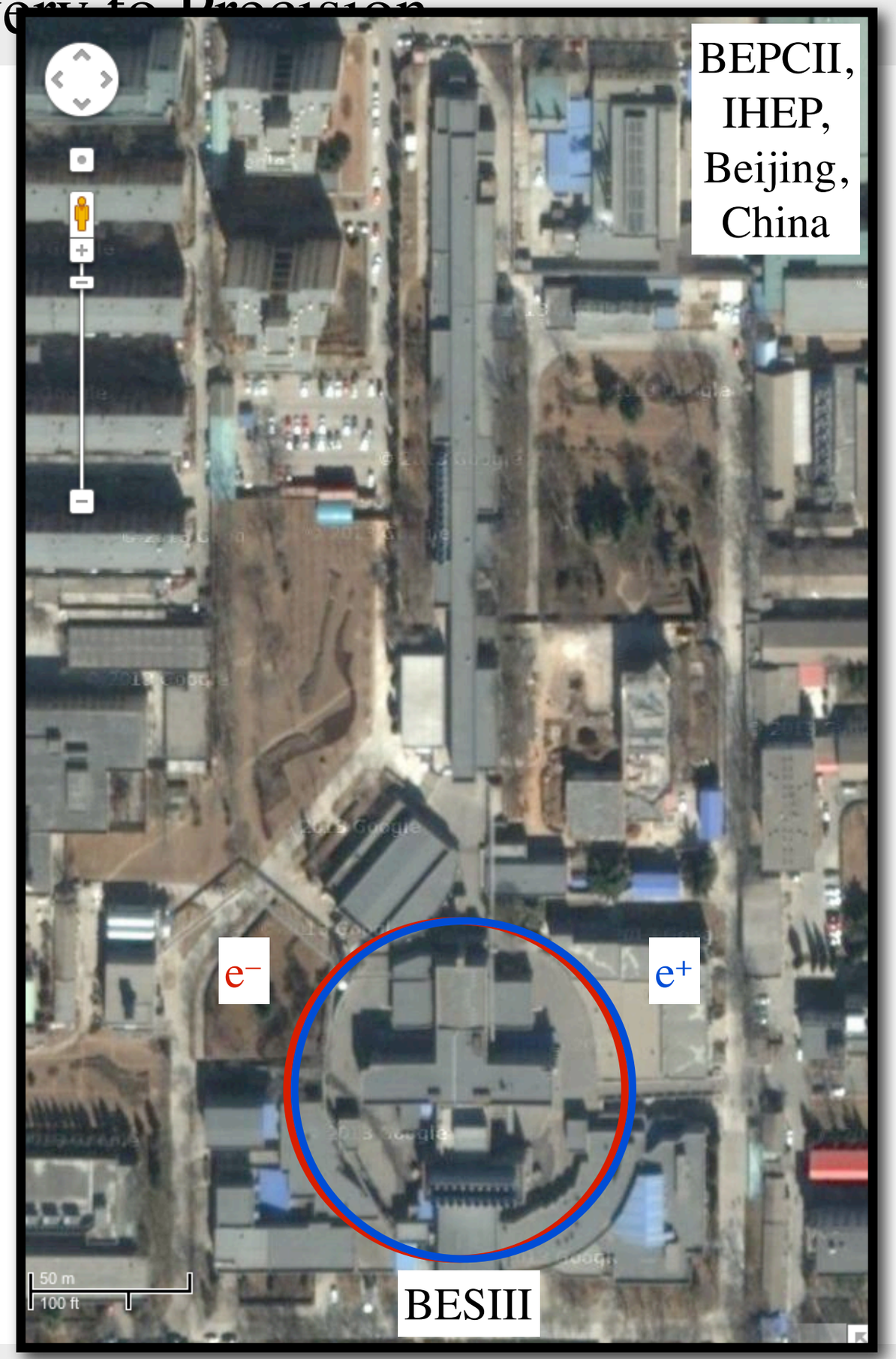


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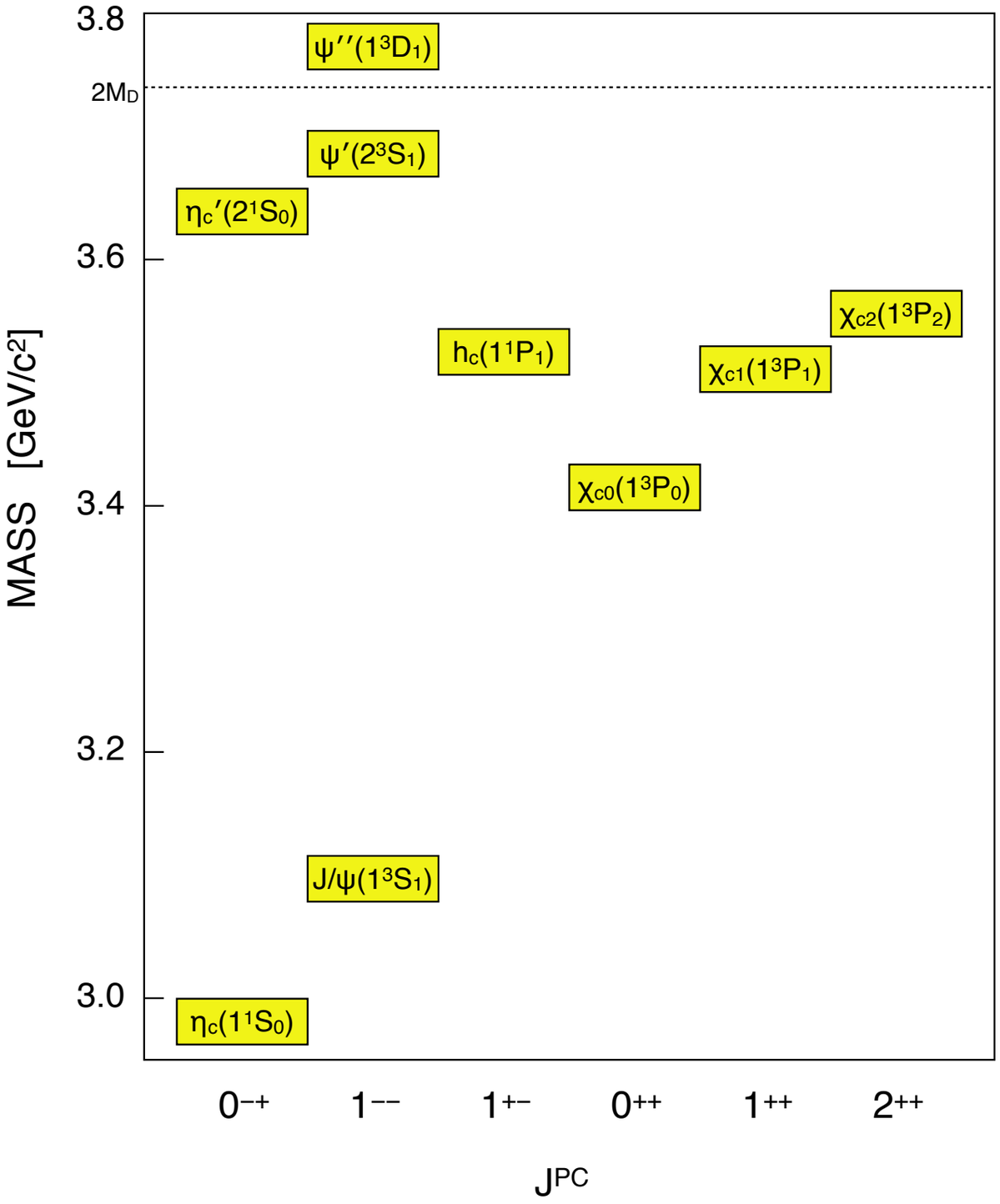
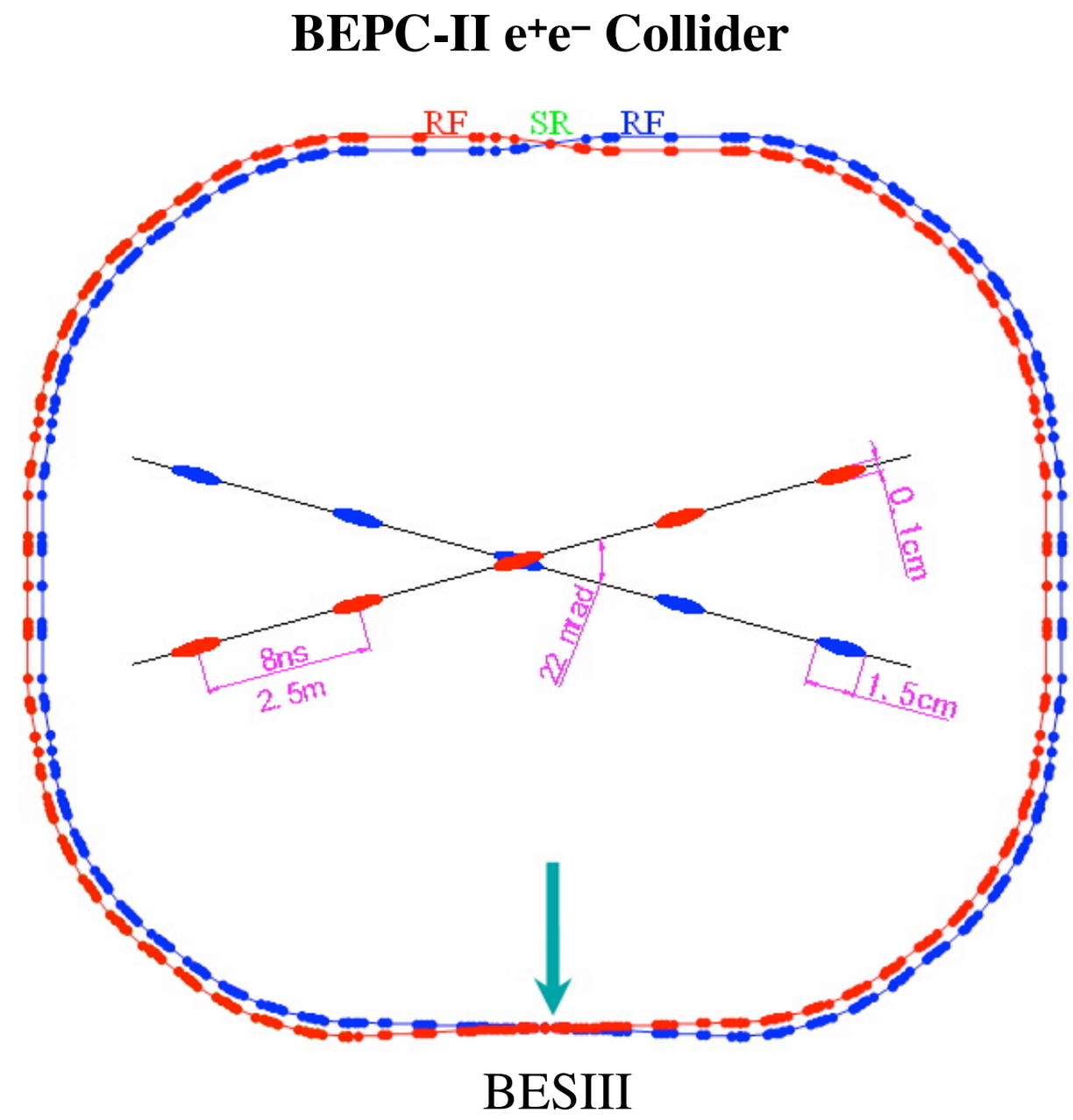
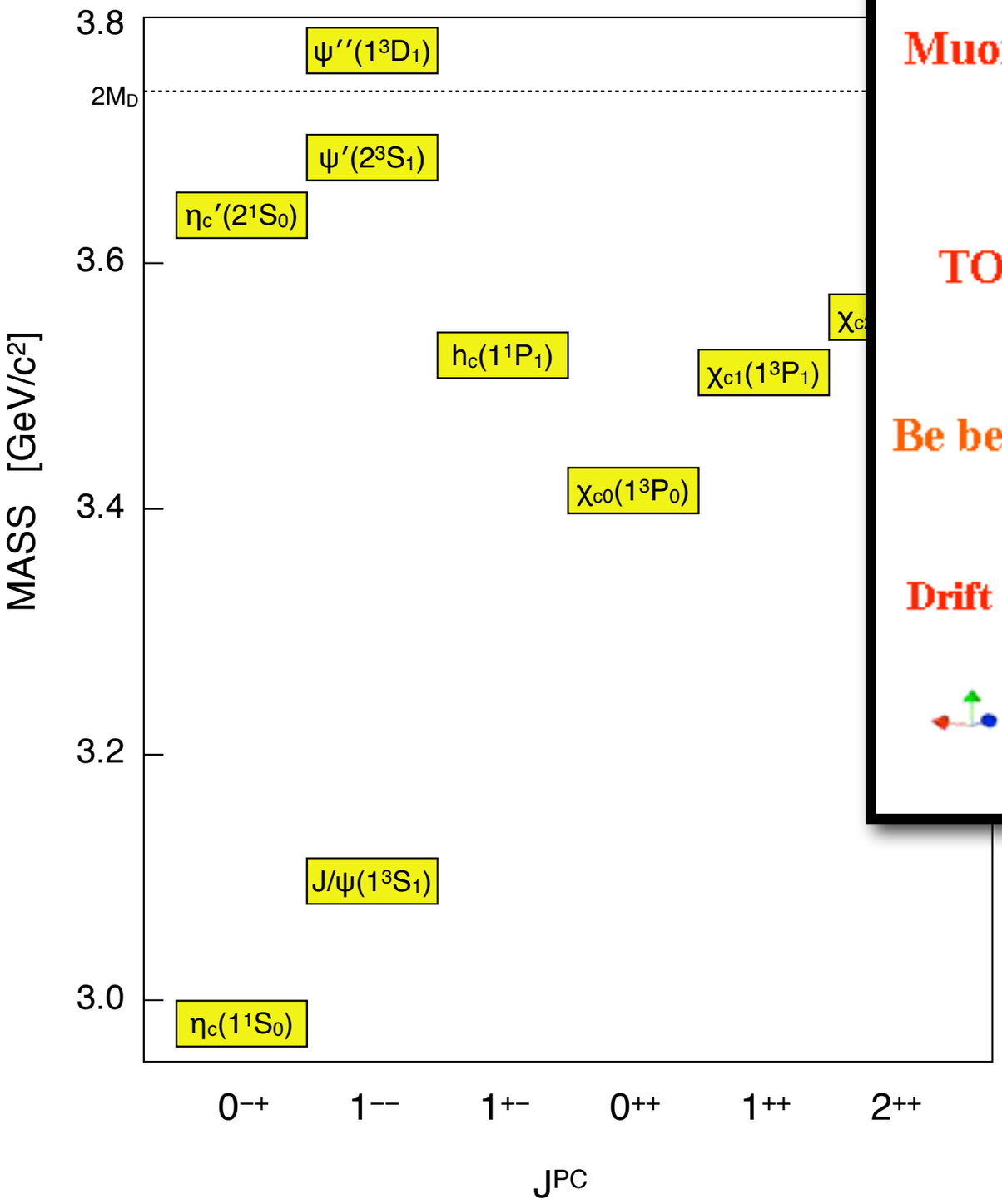


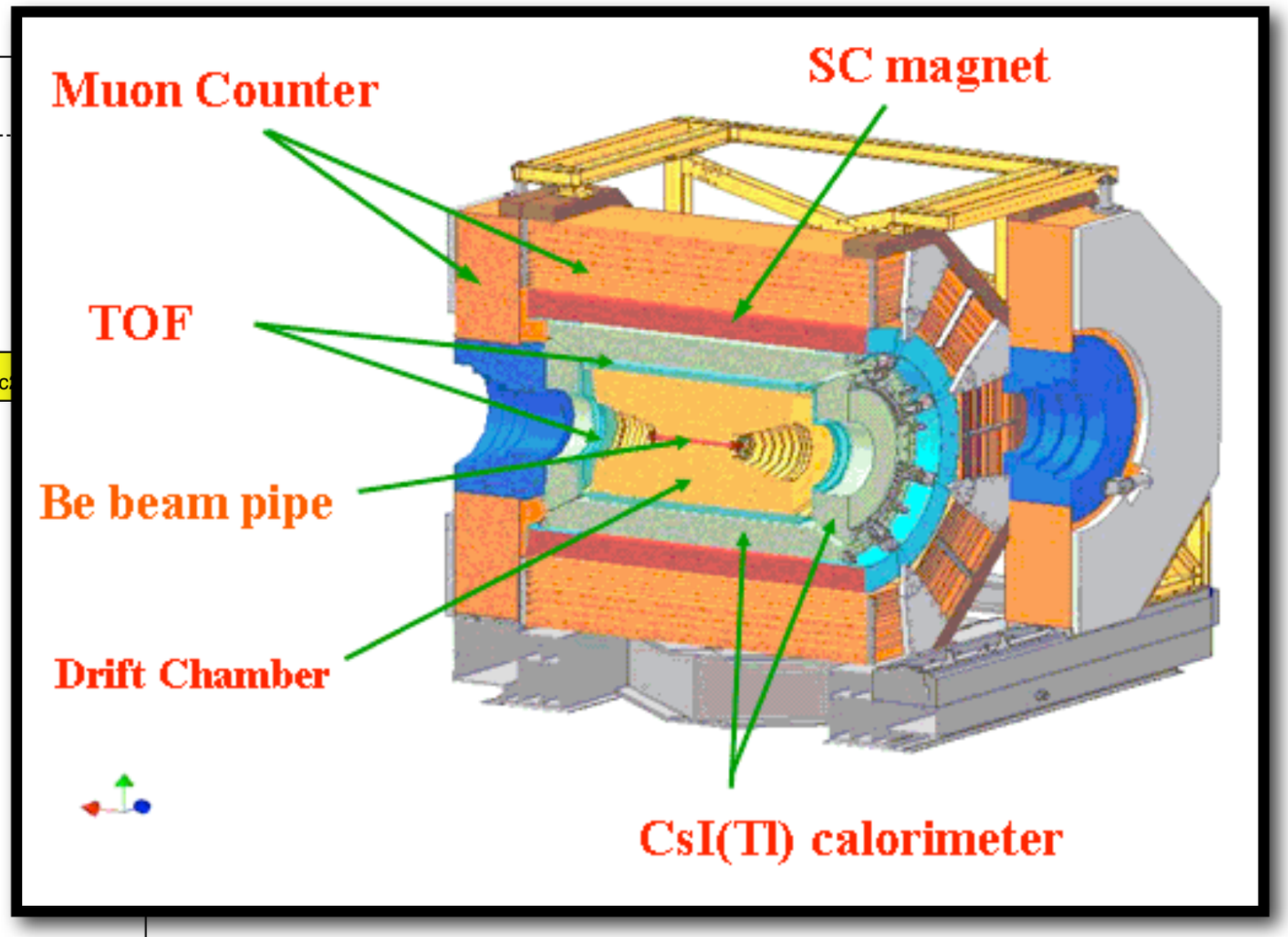




e⁺e⁻ collisions in the charmonium region

*(about 2 – 5?? GeV center of mass energies)*

# III. From Discovery to Precision

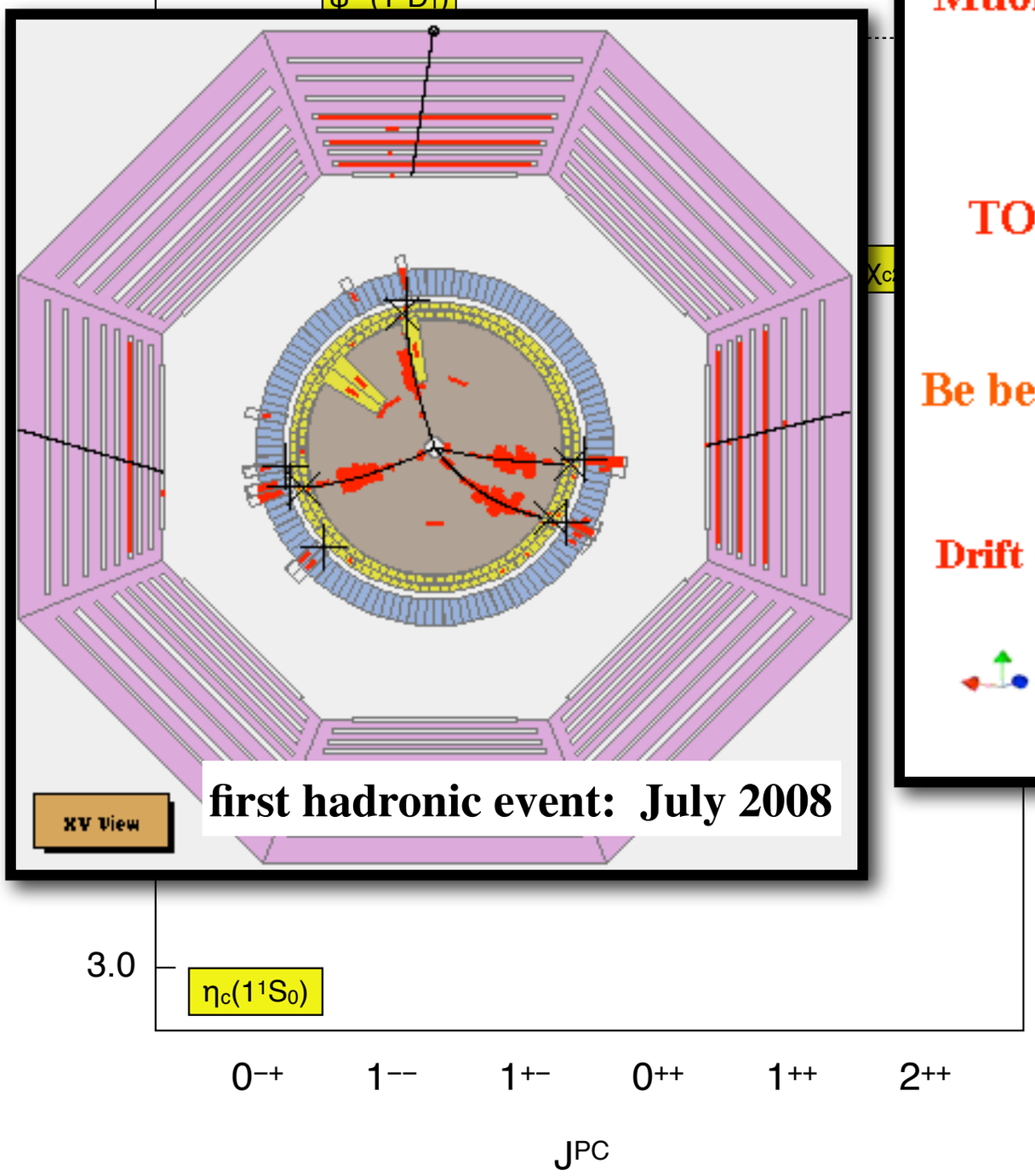


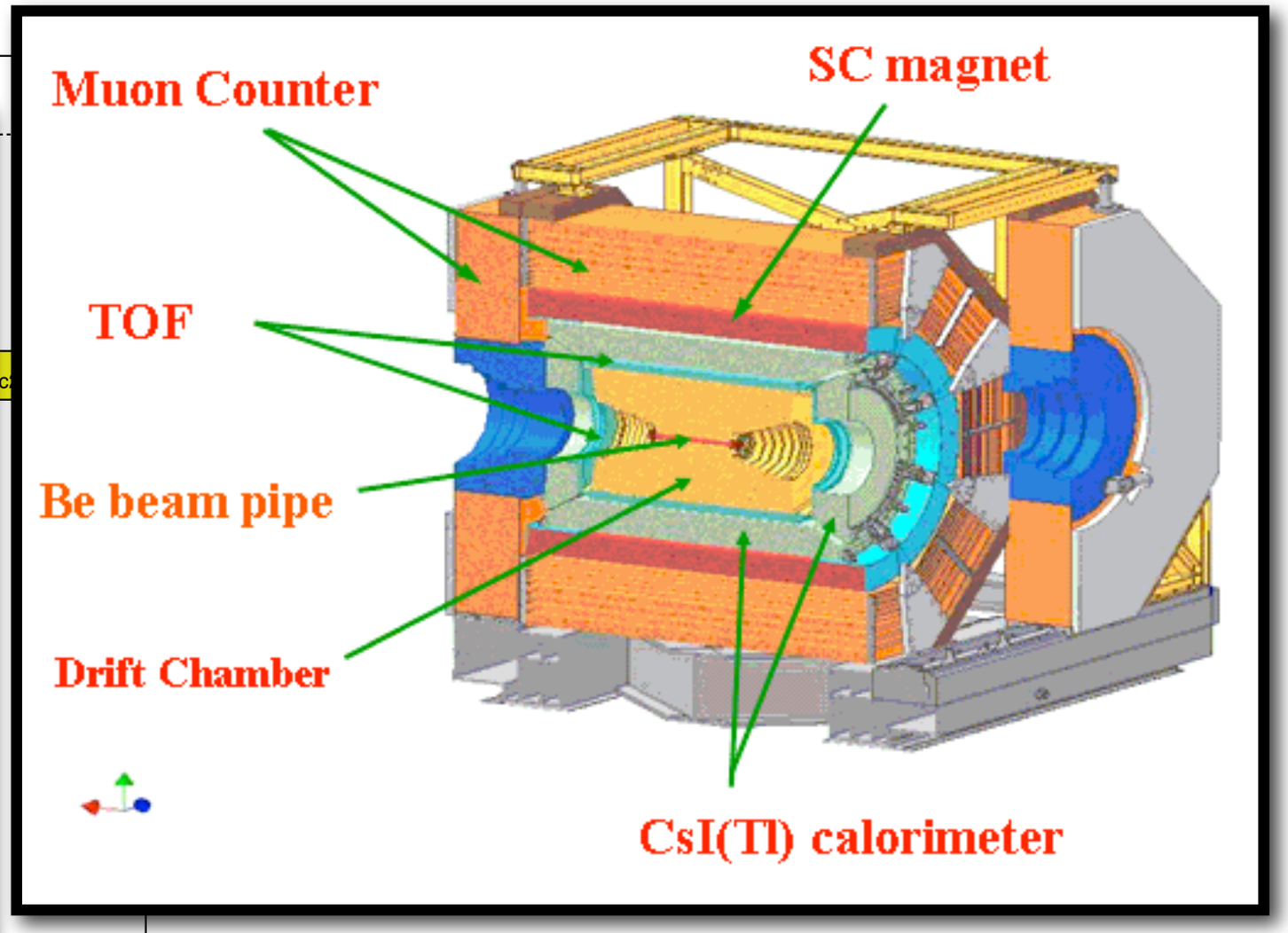

**Select data samples (2008-present):**

* more than a billion J/ψ decays
* 106 million ψ(2S) decays (+ more)
* ~2.9 fb$^{-1}$ at ψ''
* ~500 pb$^{-1}$ at 4.009 GeV
* ***XYZ data***

# III. From Discovery to Precision




**BES III Detector**

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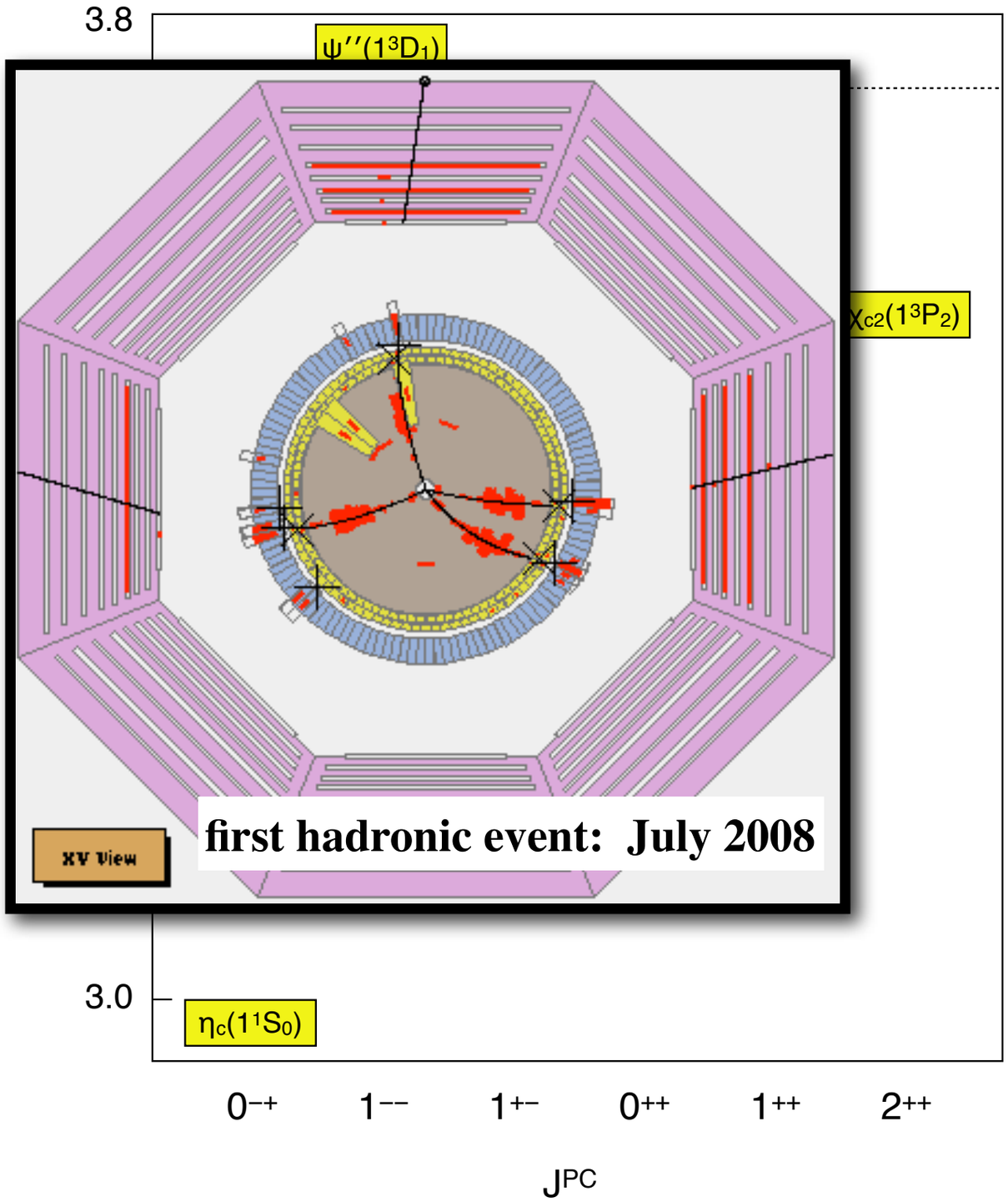


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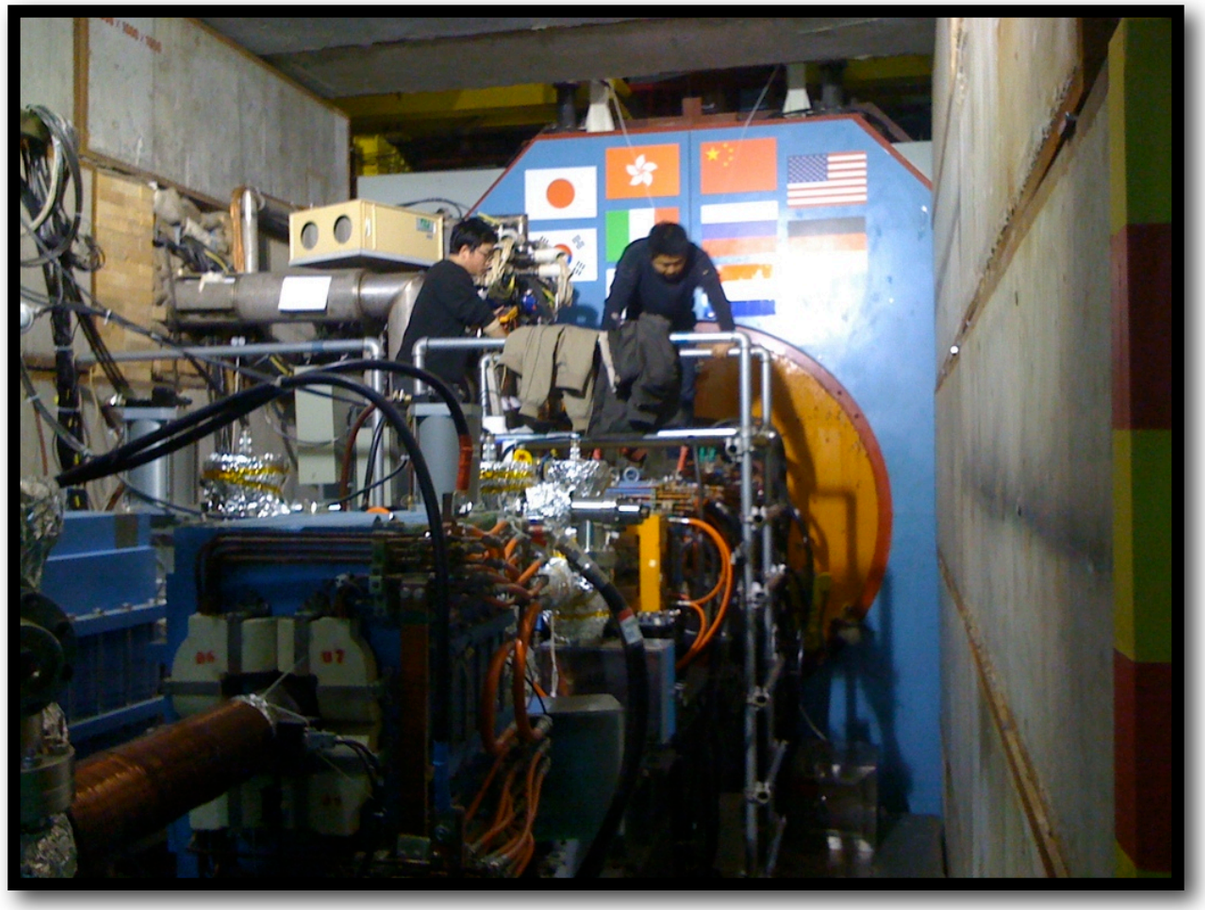

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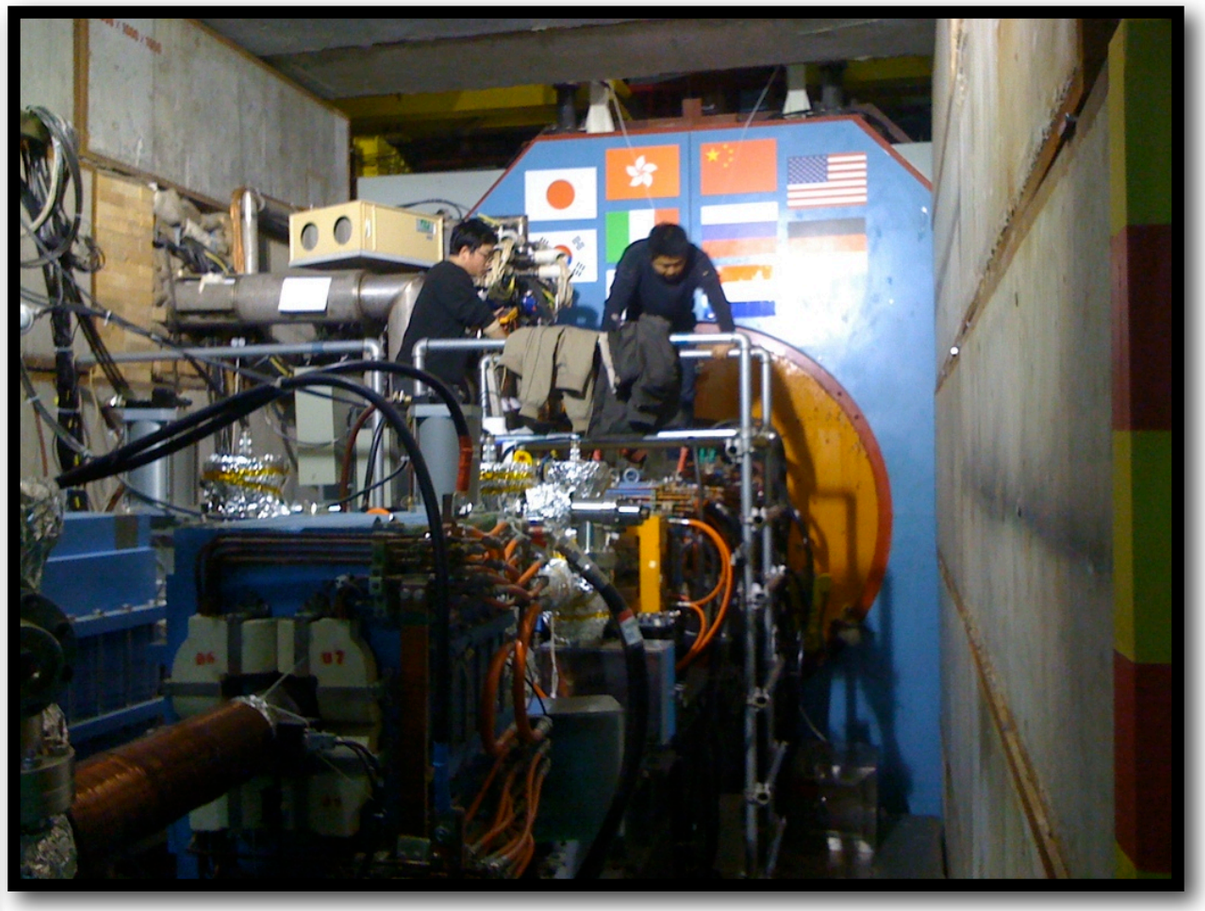
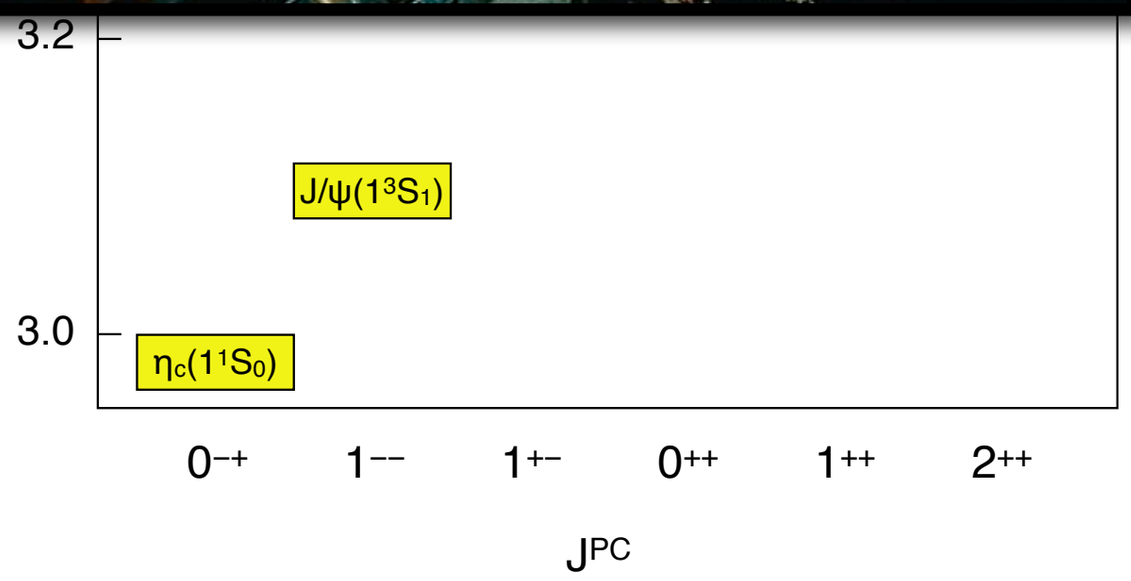
# III. From Discovery to Precision

**MARK I Detector**


**BES III Detector**



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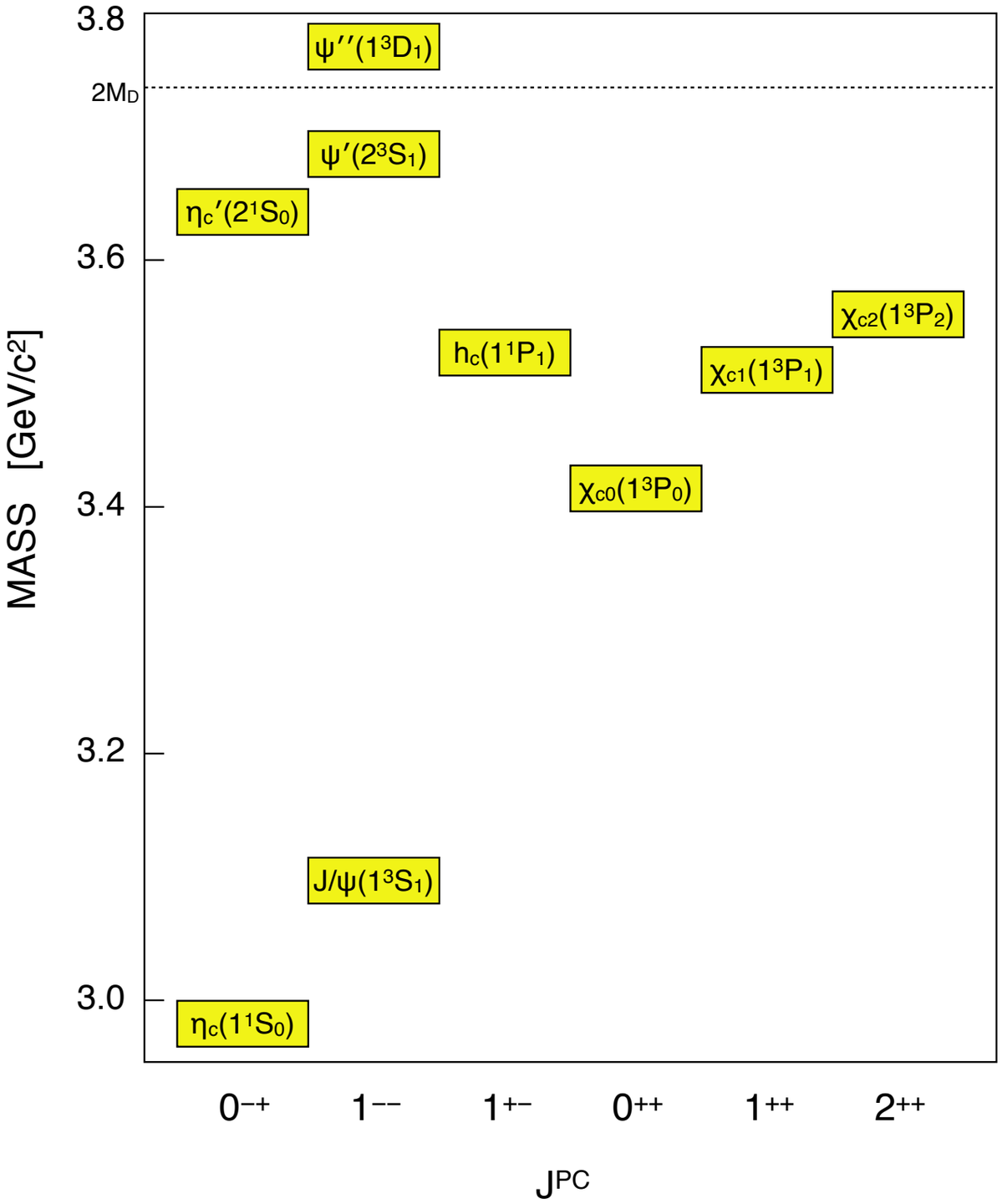


**A few BESIII charmonium results from 2012:**

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)**

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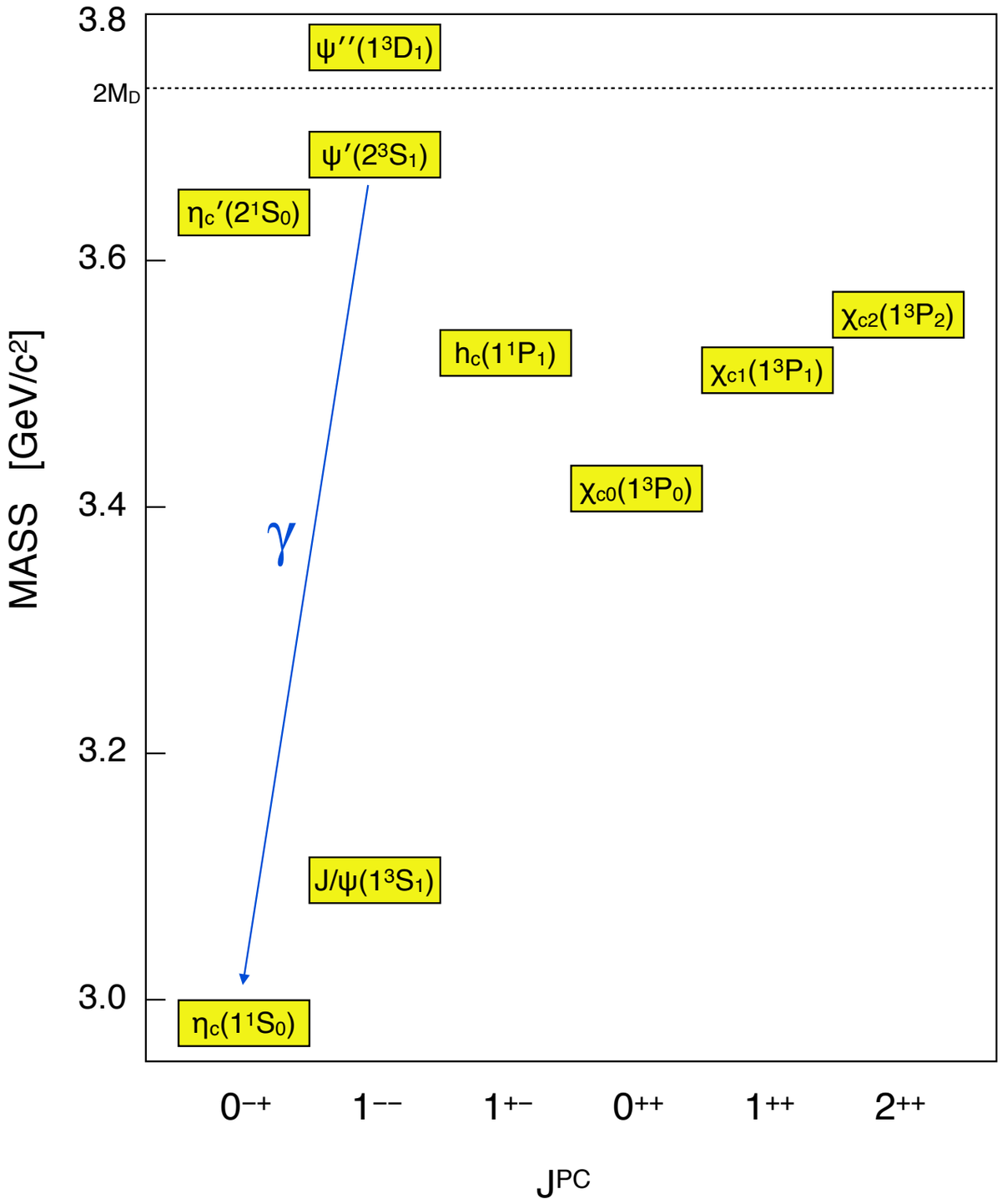


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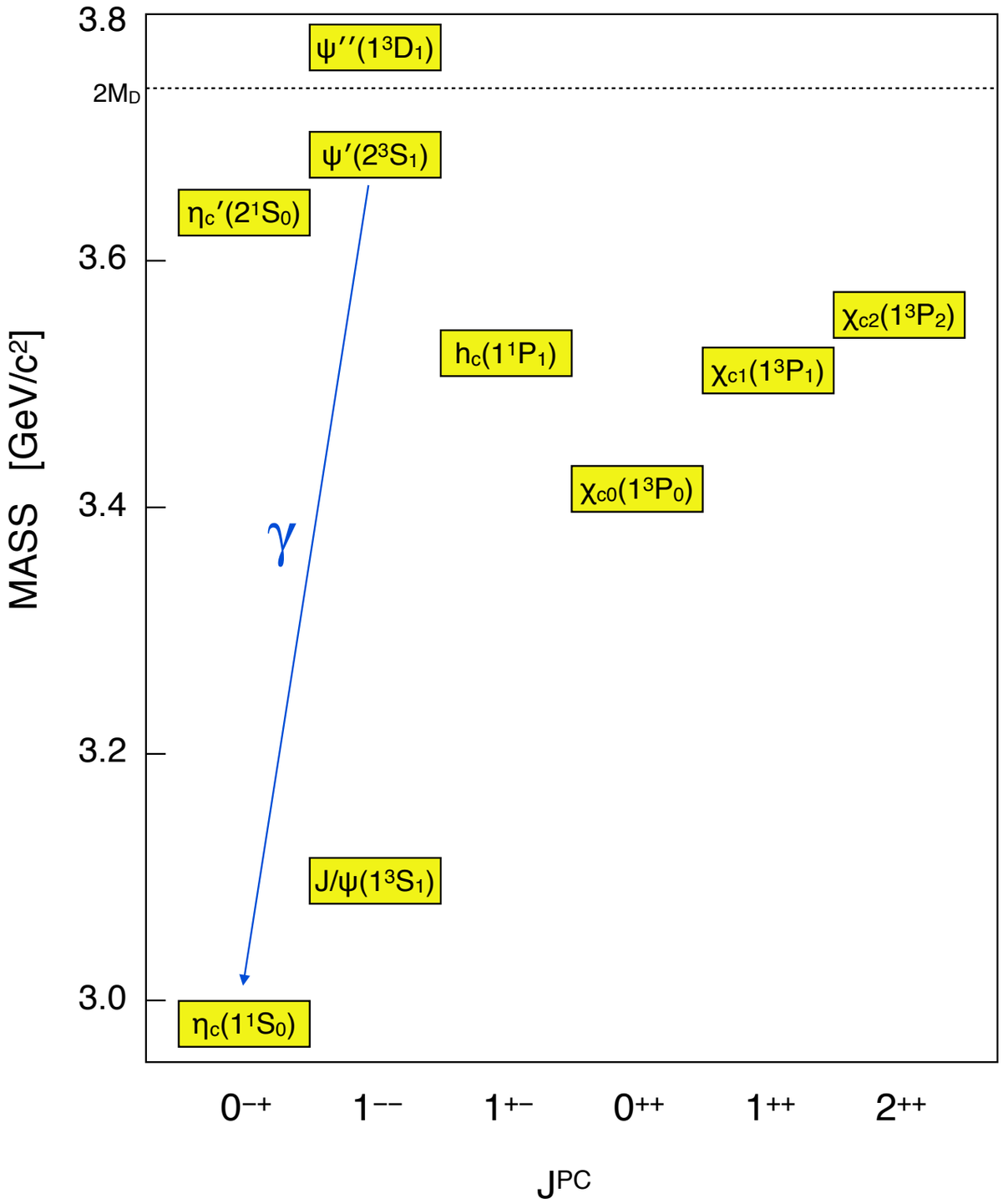
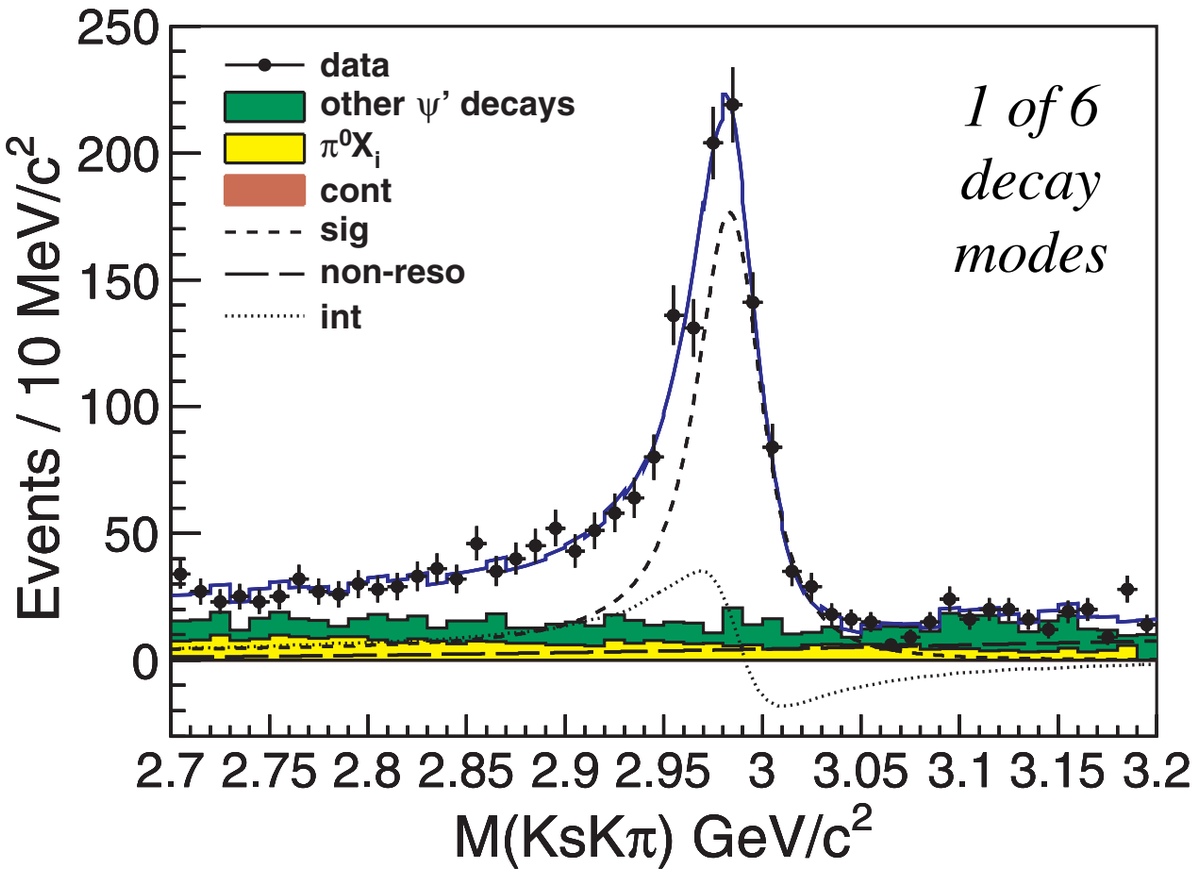



## Mass and Width of the $\eta_c(1S)$




⇒ 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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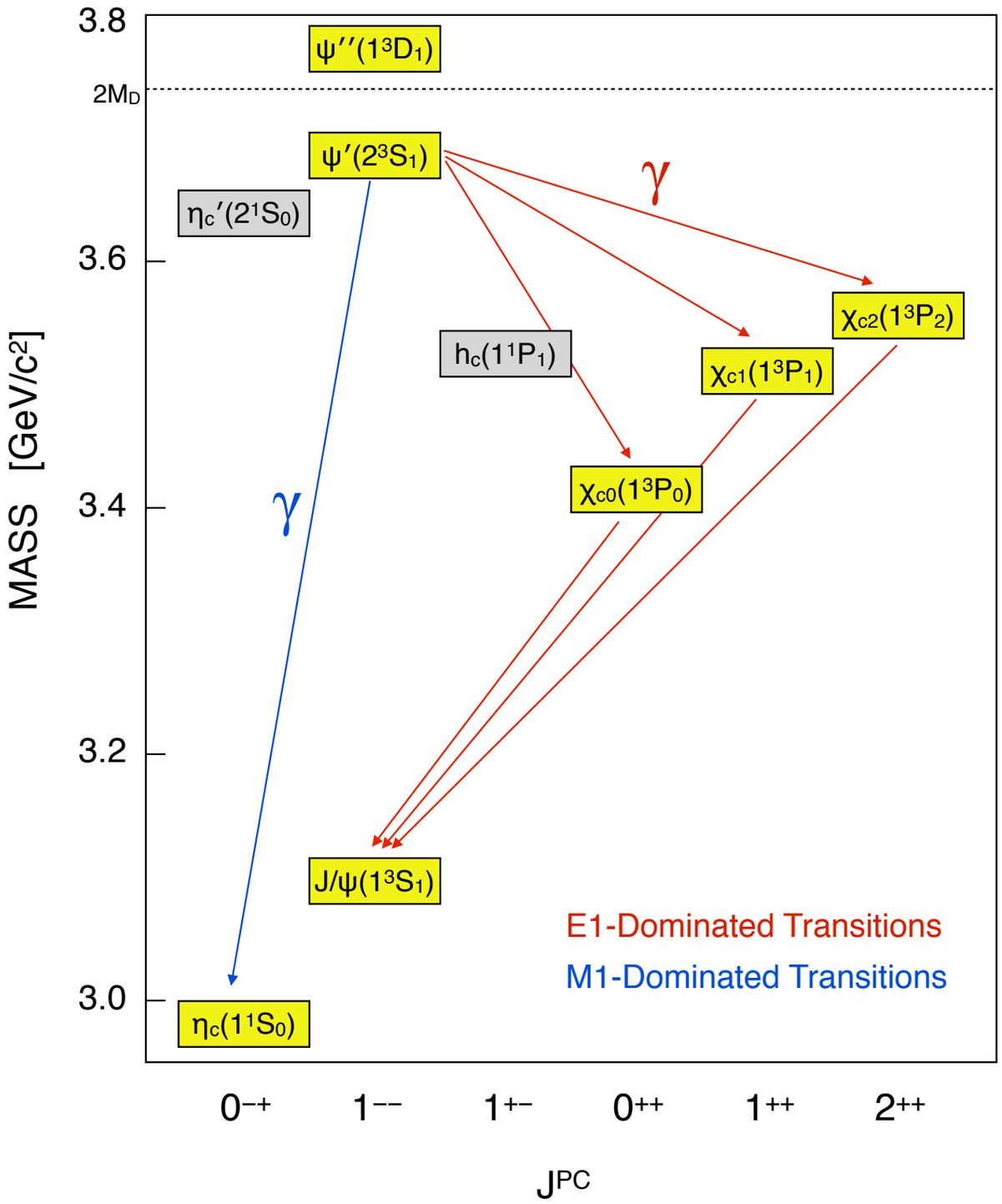


Crystal Ball at SLAC
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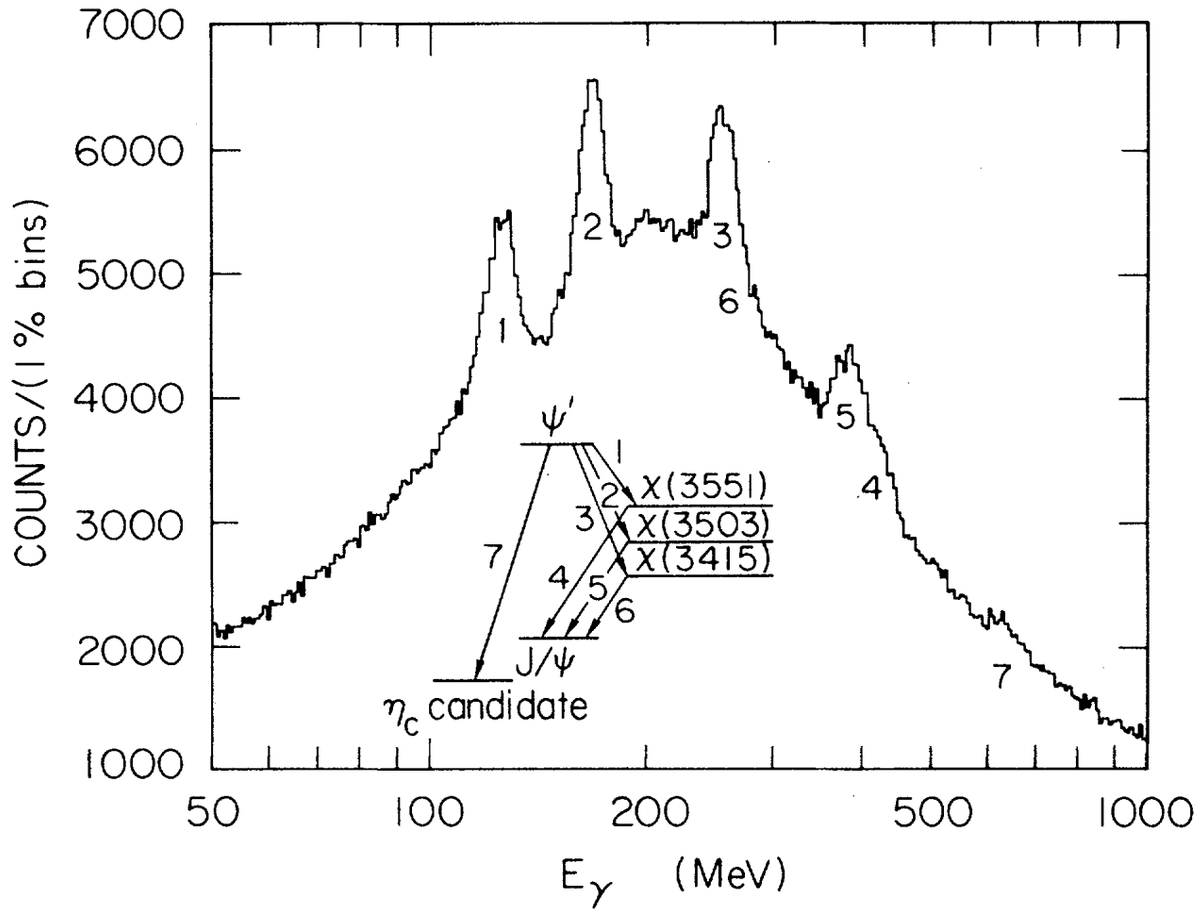


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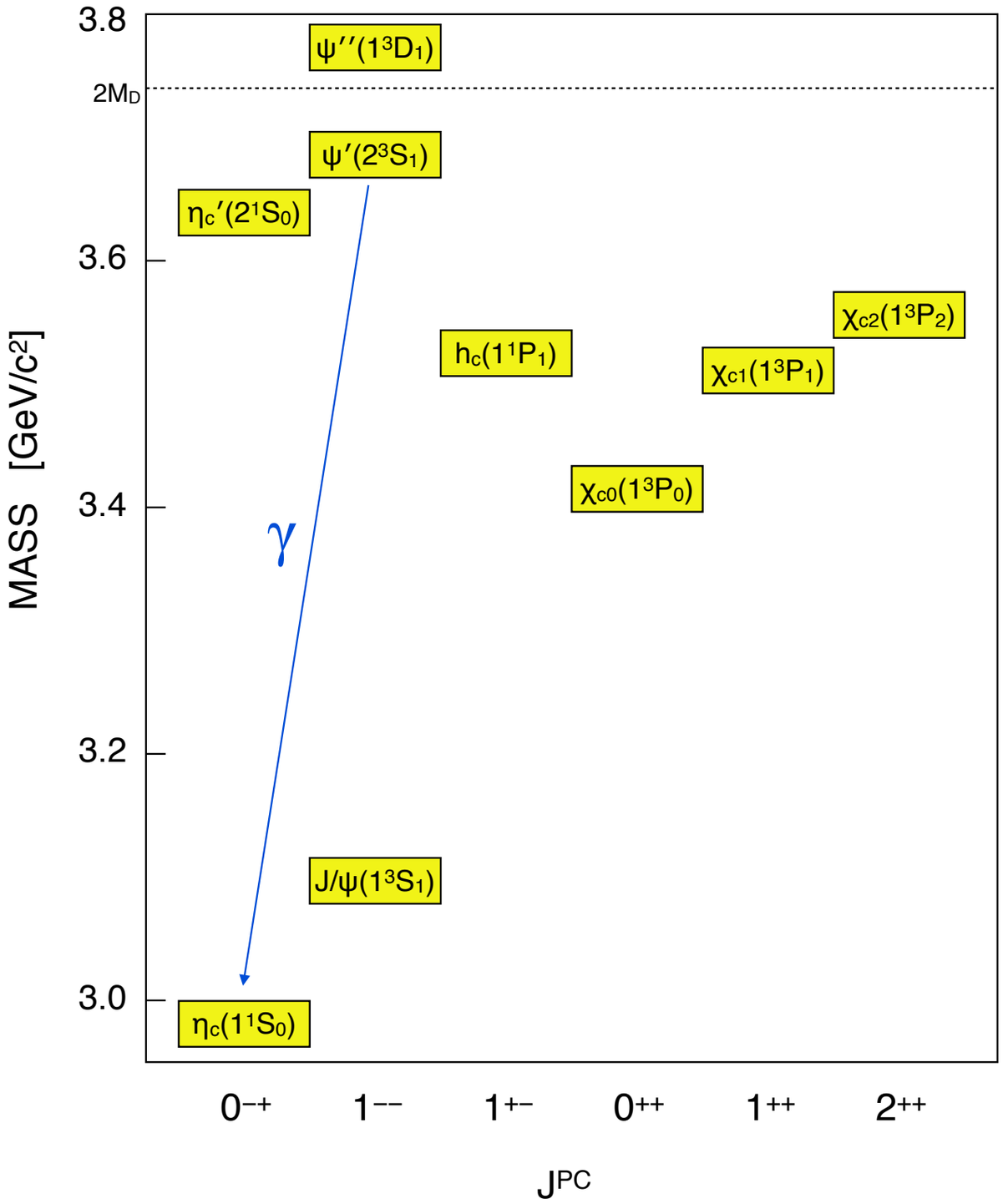


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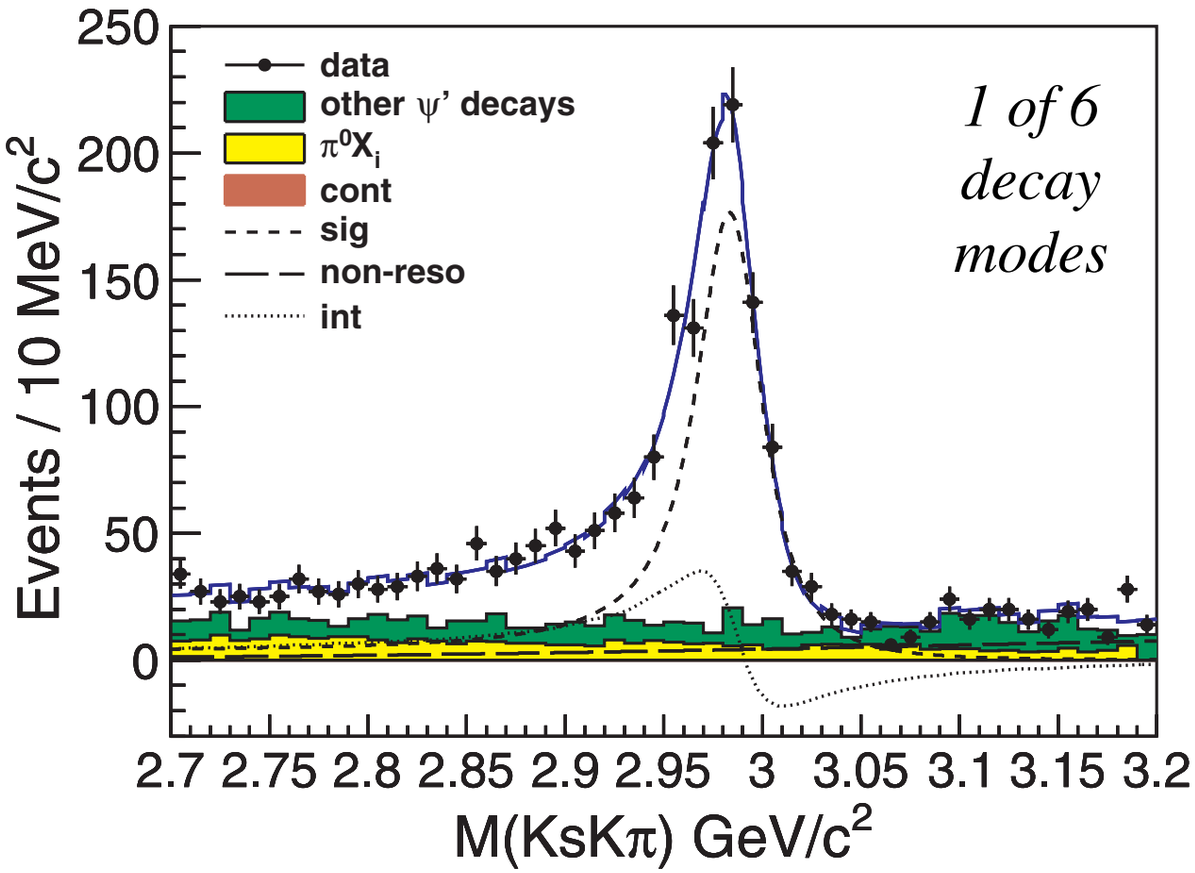


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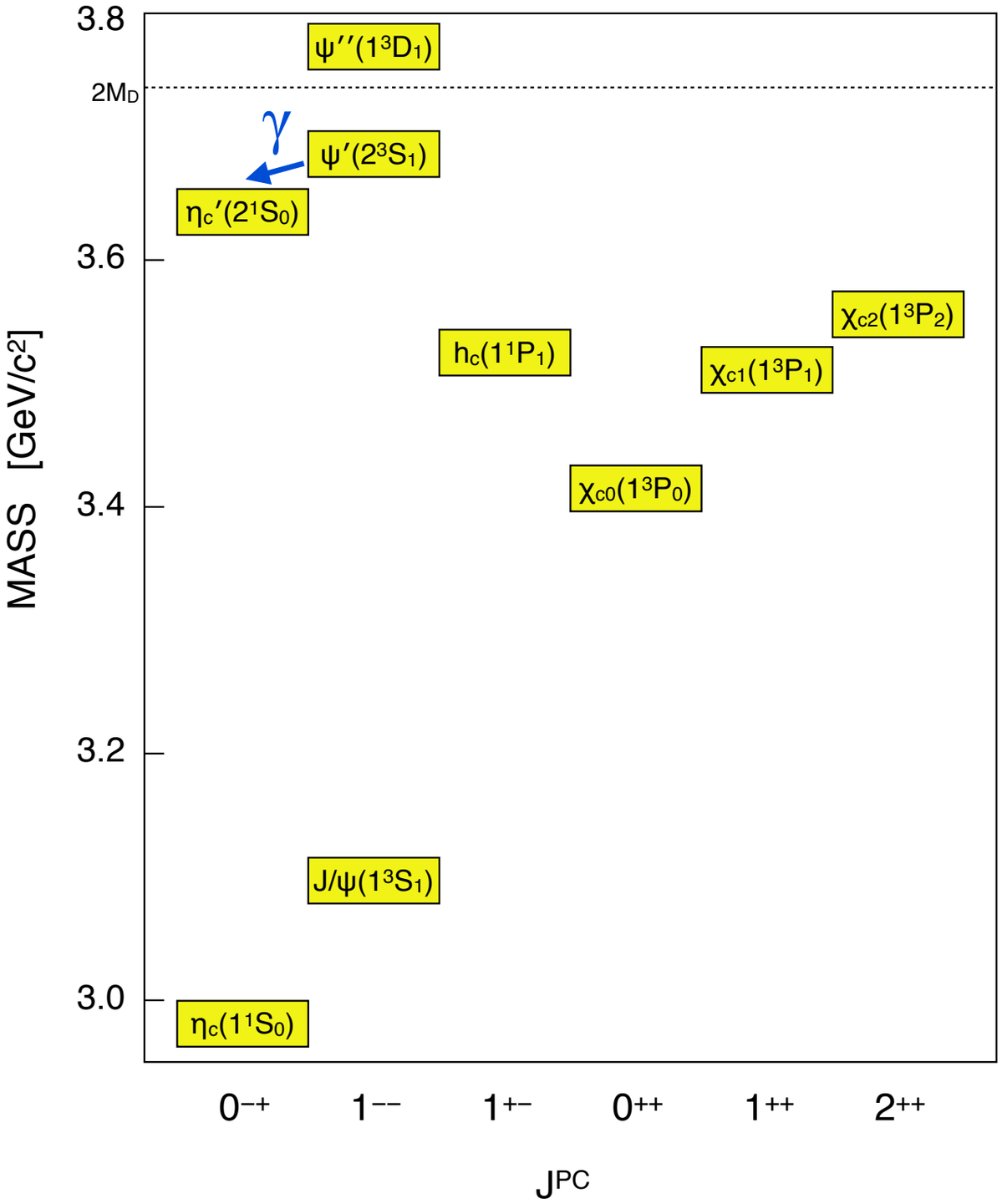


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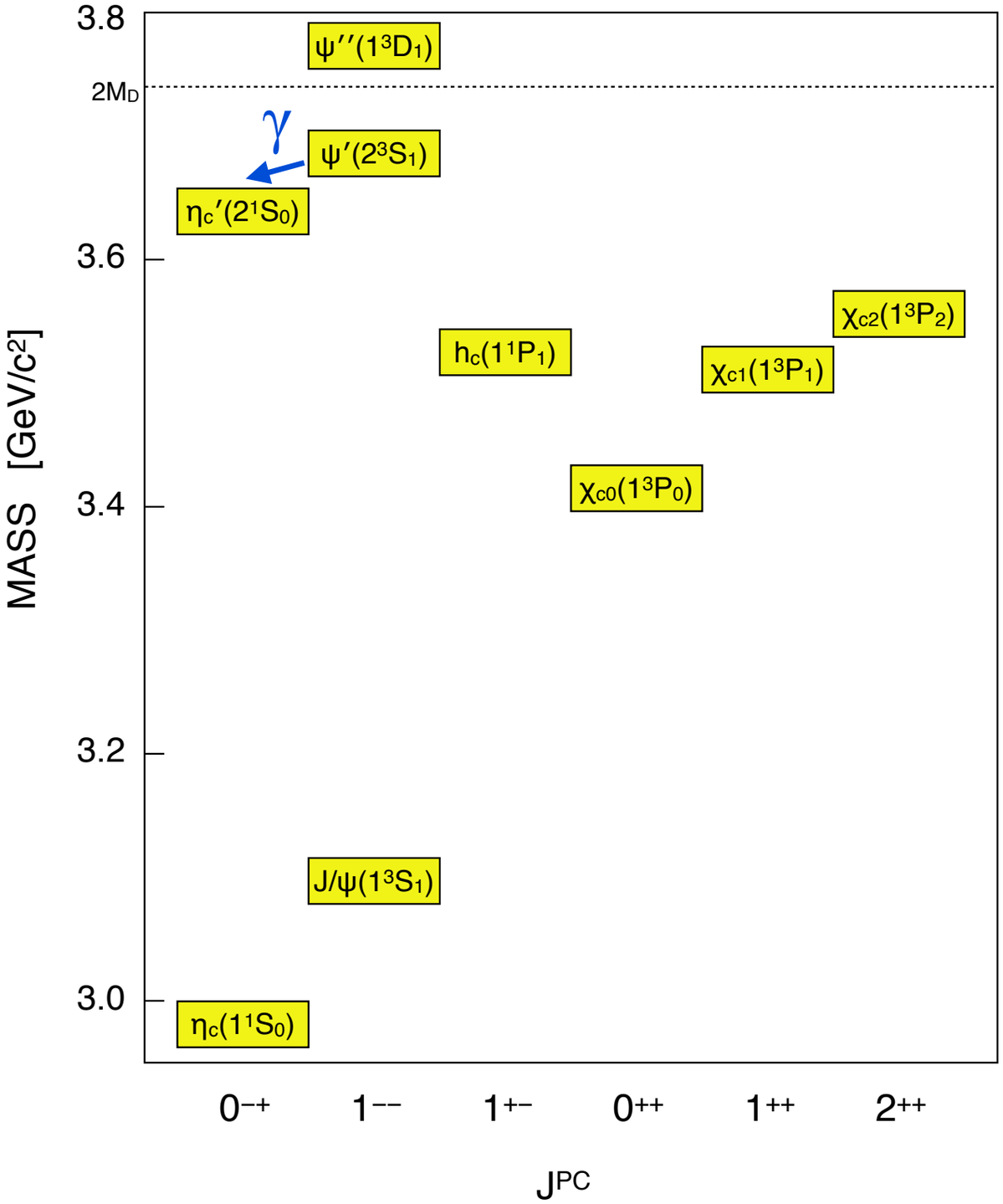
**2. First observation of the M1 transition $\psi(2S) \rightarrow \gamma\eta_c(2S)$**

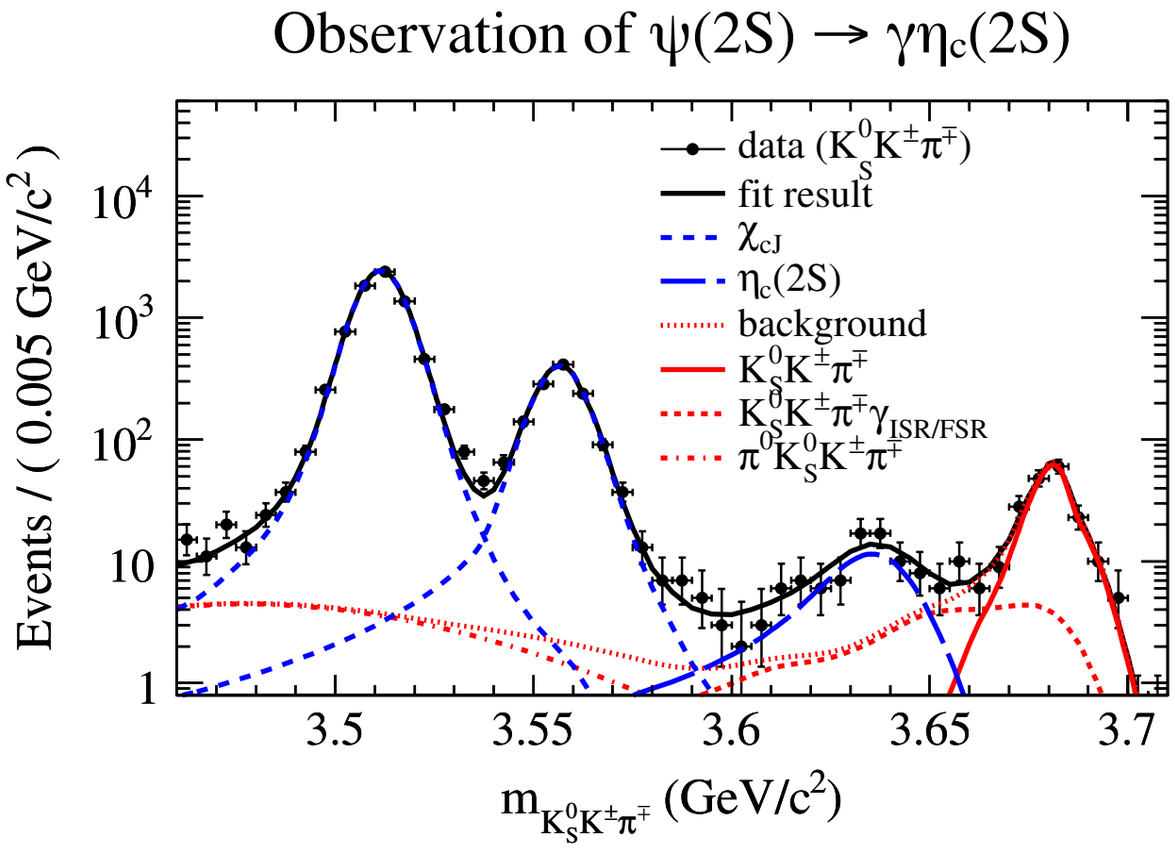
**PRL 109, 042003 (2012)**

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)**

# III. From Discovery to Precision



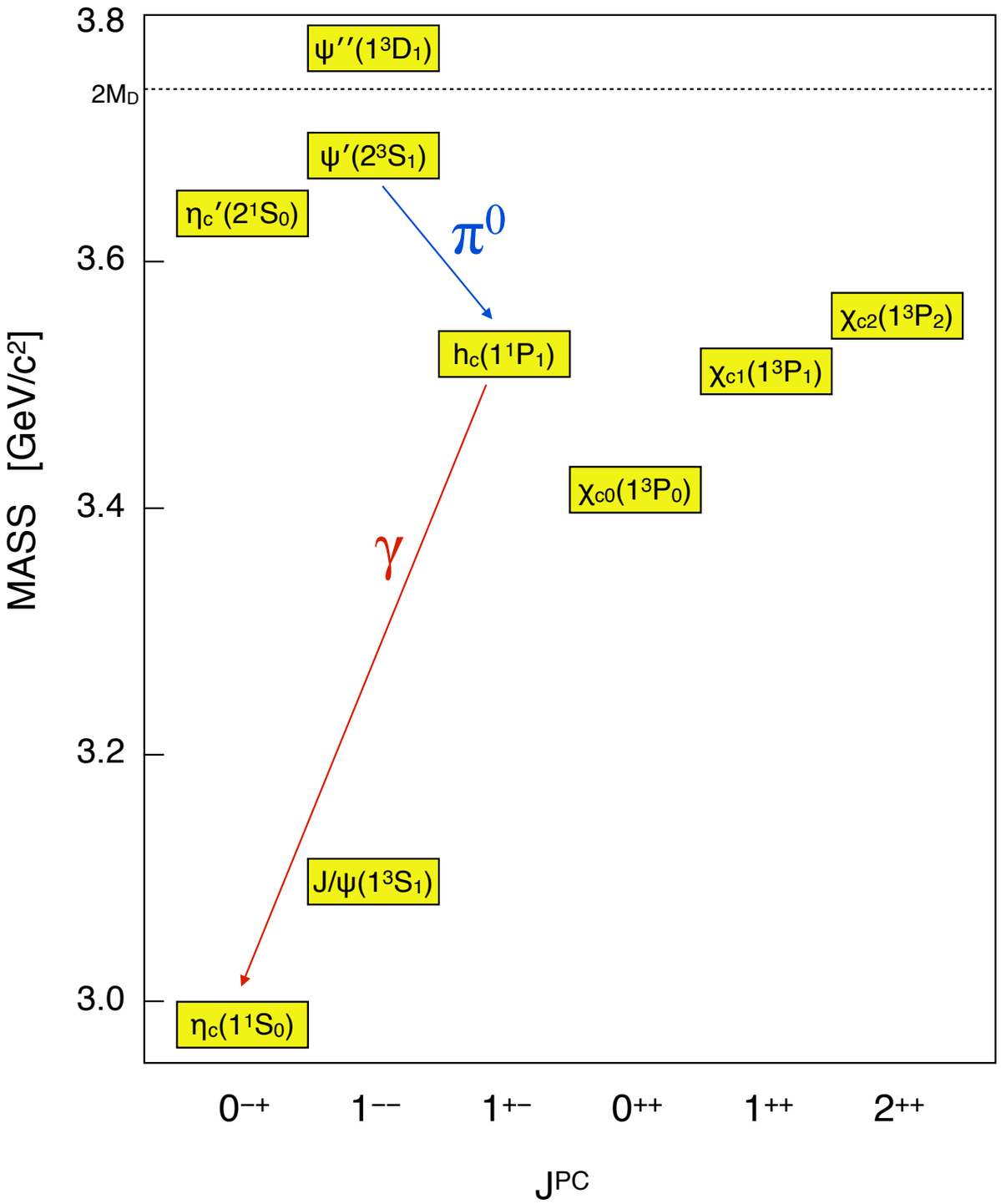

$M = 3637.6 \pm 2.9 \pm 1.6$ MeV

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

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

*BESIII discovered this transition after 18 years of searching!*

# III. From Discovery to Precision




**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)**

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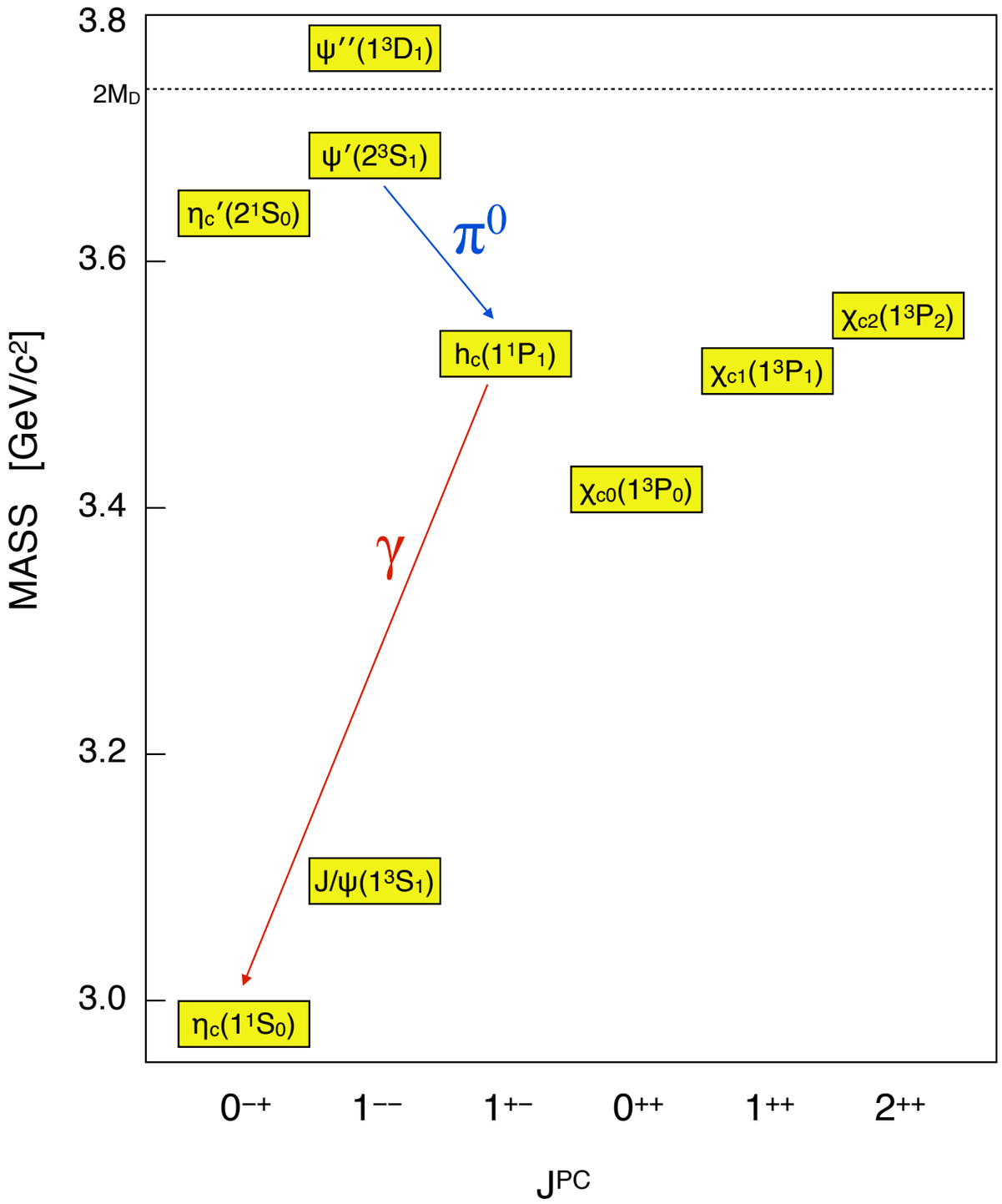
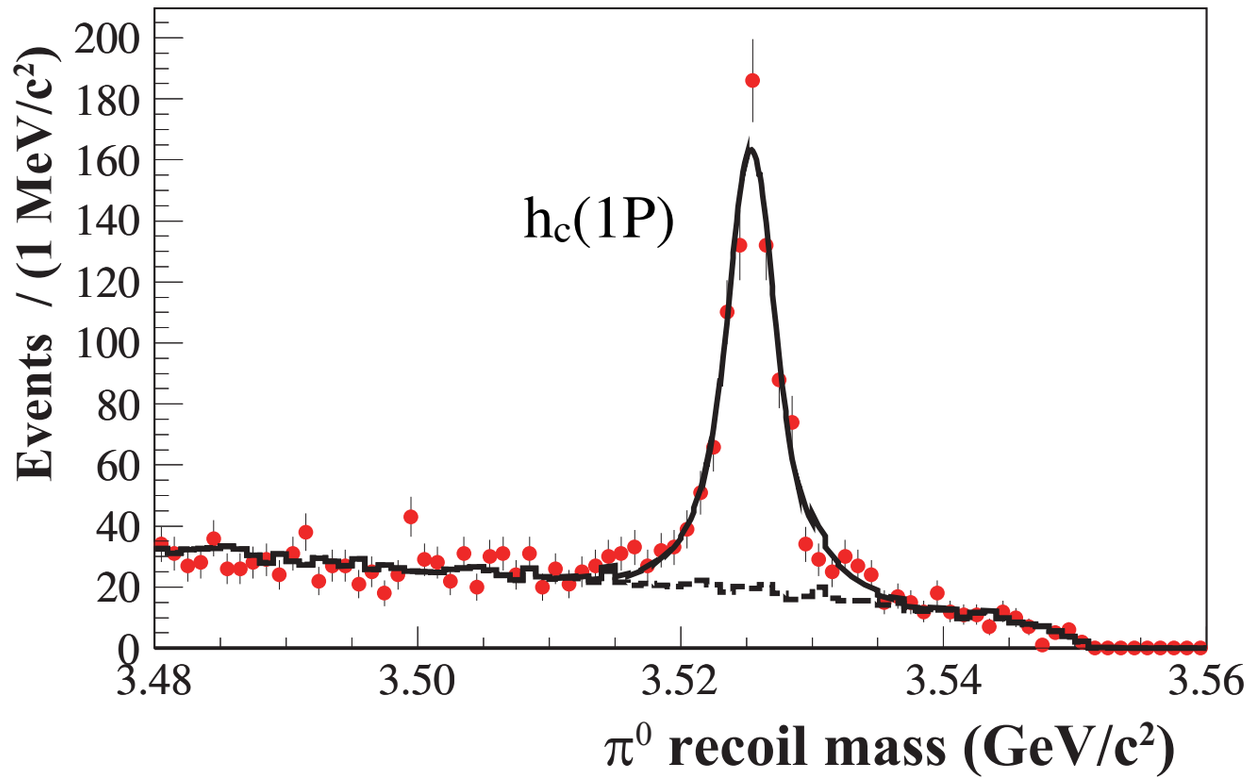


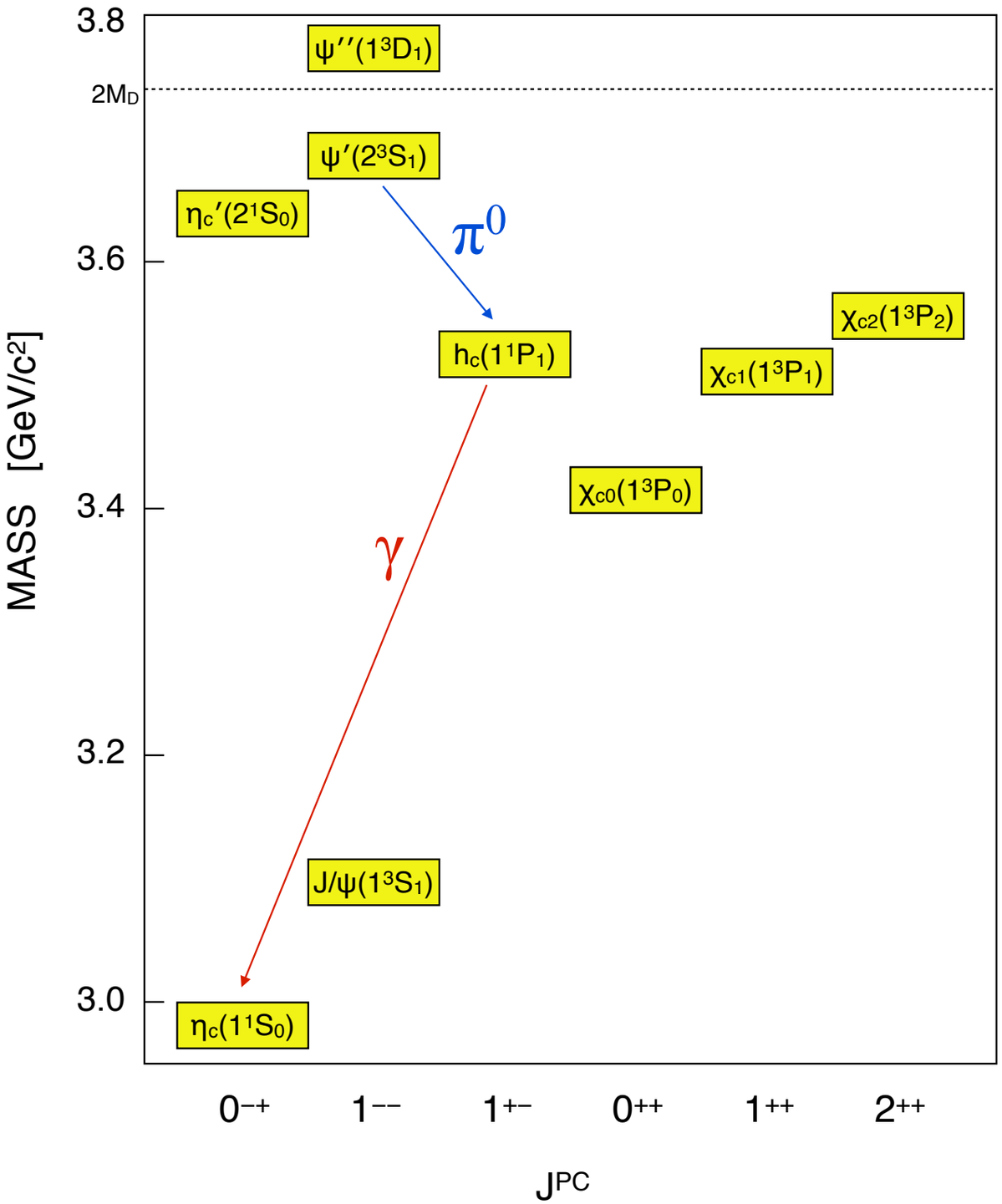

## Precision Measurements of the Mass and Width of the $h_c(1P)$




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

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

# III. From Discovery to Precision

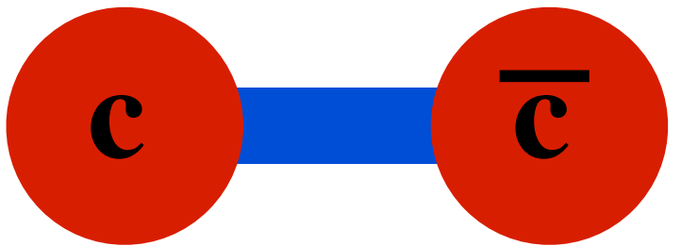



I. An Introduction to Charmonium

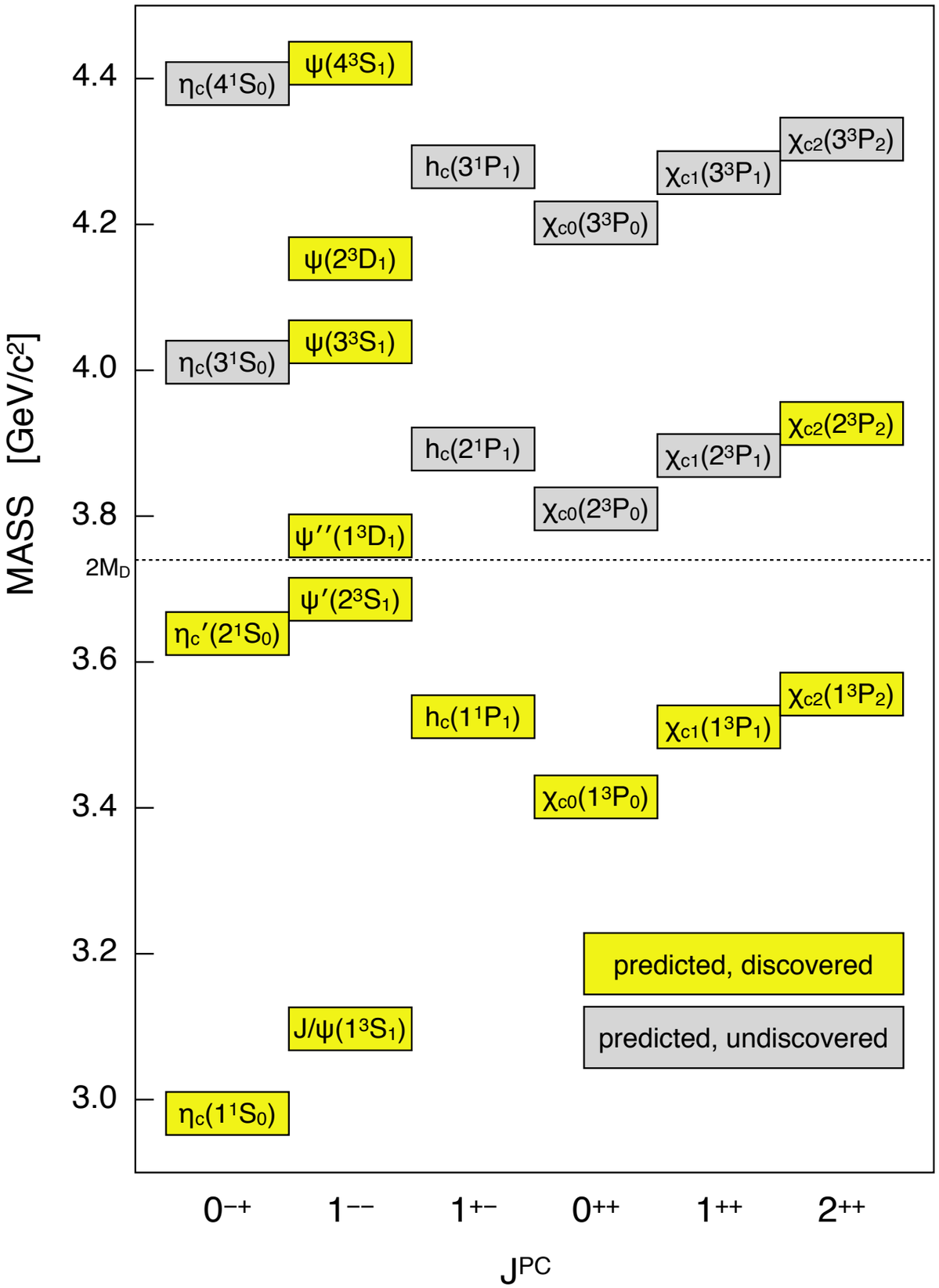
II. The Original Era of Discovery:
*establishing the quark model states*

**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

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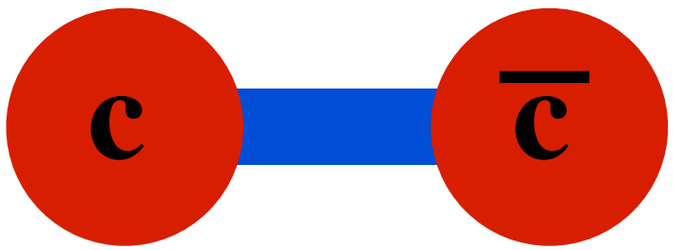
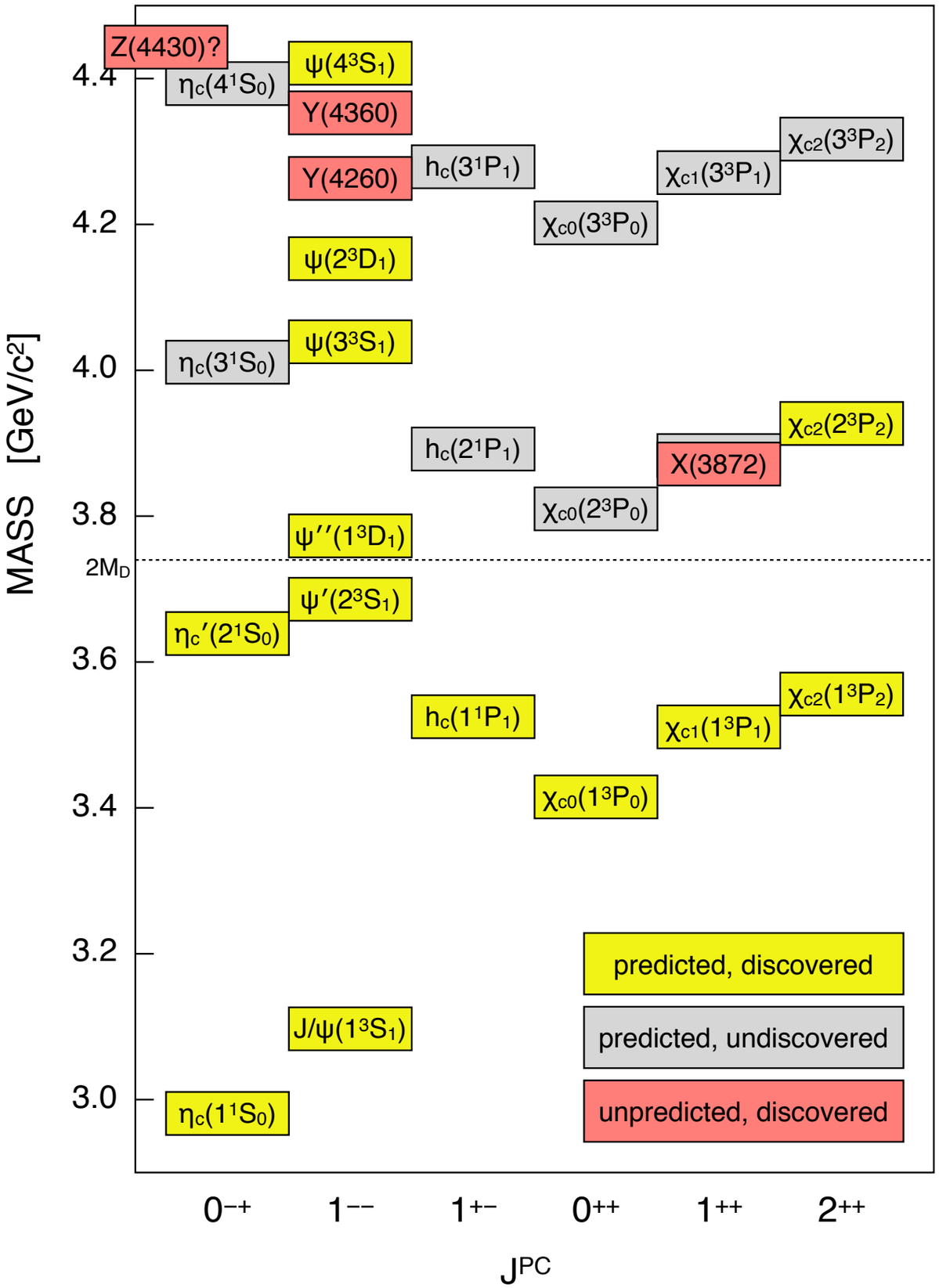



CHARMONIUM

# IV. A New Era of Discovery

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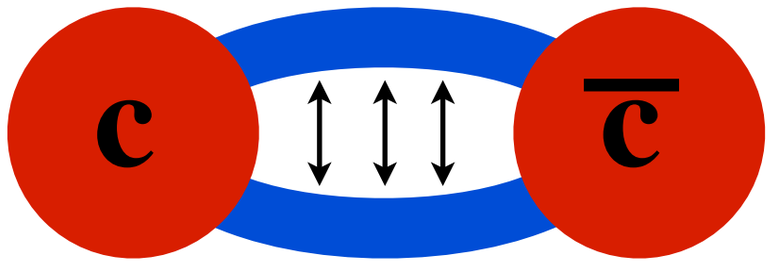
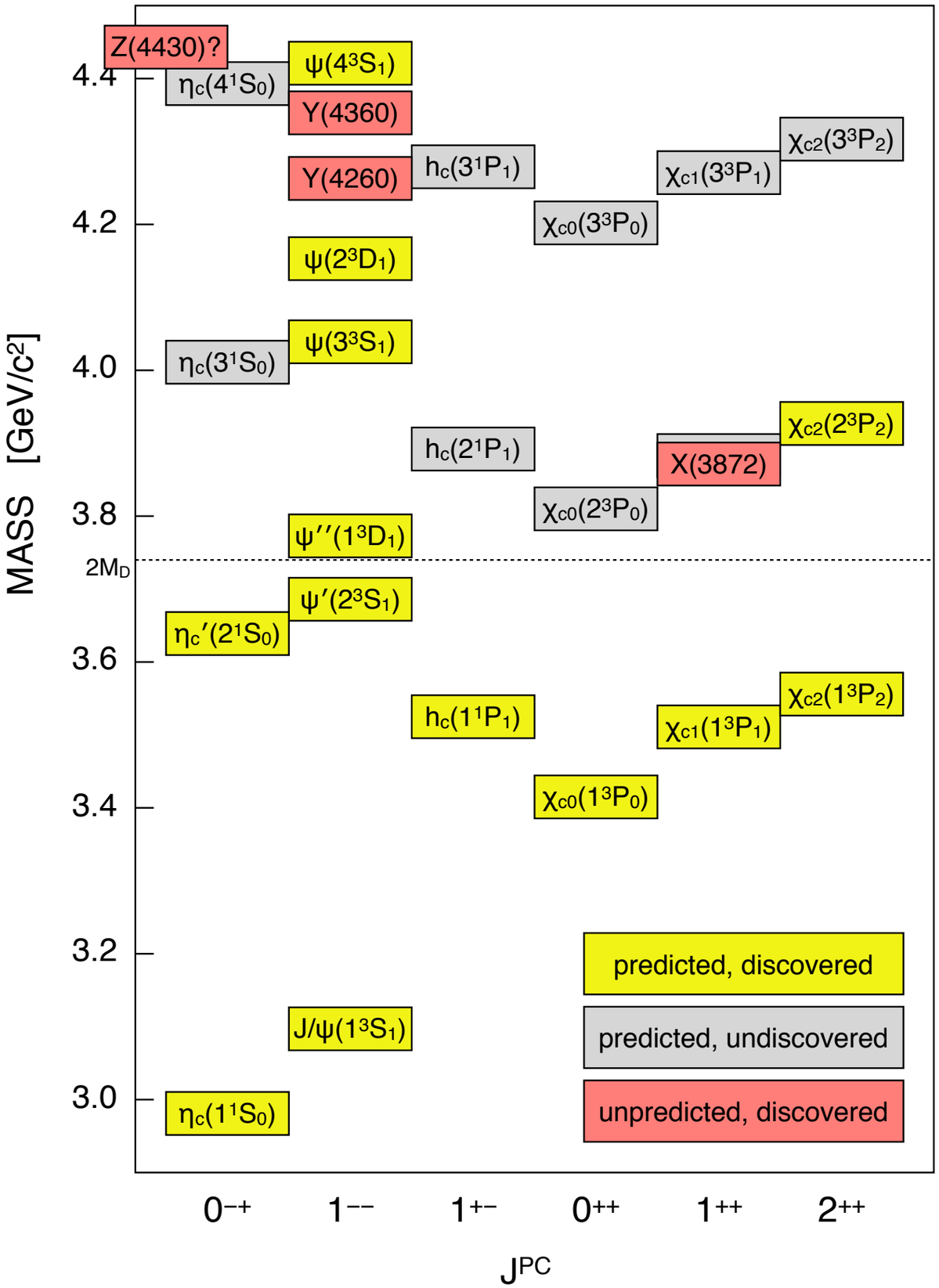



HYBRID CHARMONIUM?

# IV. A New Era of Discovery

| State | $m$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode) | Experiment (#$\sigma$) | Year | Status |
|---|---|---|---|---|---|---|---|
| $X(3872)$ | $3871.52 \pm 0.20$ | $1.3 \pm 0.6$ | $1^{++}/2^{-+}$ | $B \to K(\pi^+\pi^- J/\psi)$ | 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) | | |
| $X(3915)$ | $3915.6 \pm 3.1$ | $28 \pm 10$ | $0/2^{?+}$ | $B \to K(\omega J/\psi)$ | 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) | | |
| $G(3900)$ | $3943 \pm 21$ | $52 \pm 11$ | $1^{--}$ | $e^+e^- \to \gamma(D\bar{D})$ | *BABAR* [27] (np), Belle [21] (np) | 2007 | OK |
| $Y(4008)$ | $4008^{+121}_{-\ 49}$ | $226 \pm 97$ | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | 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! |
| $Y(4140)$ | $4143.4 \pm 3.0$ | $15^{+11}_{-\ 7}$ | $?^{?+}$ | $B \to K(\phi J/\psi)$ | 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! |
| $Y(4260)$ | $4263 \pm 5$ | $108 \pm 14$ | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ | *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! |
| $Y(4360)$ | $4353 \pm 11$ | $96 \pm 42$ | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | *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! |
| $Y(4660)$ | $4664 \pm 12$ | $48 \pm 15$ | $1^{--}$ | $e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$ | Belle [114] (5.8) | 2007 | NC! |
| $Y_b(10888)$ | $10888.4 \pm 3.0$ | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$ | Belle [37, 117] (3.2) | 2010 | NC! |

**EPJ C71, 1534 (2011)**

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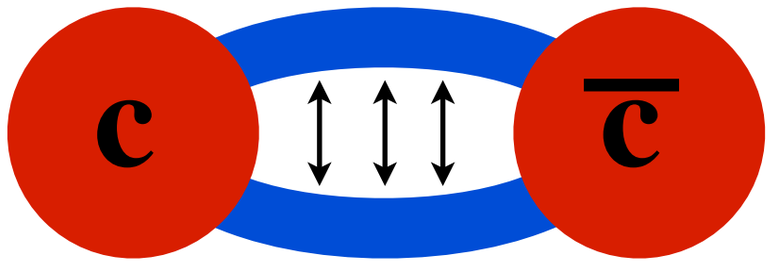
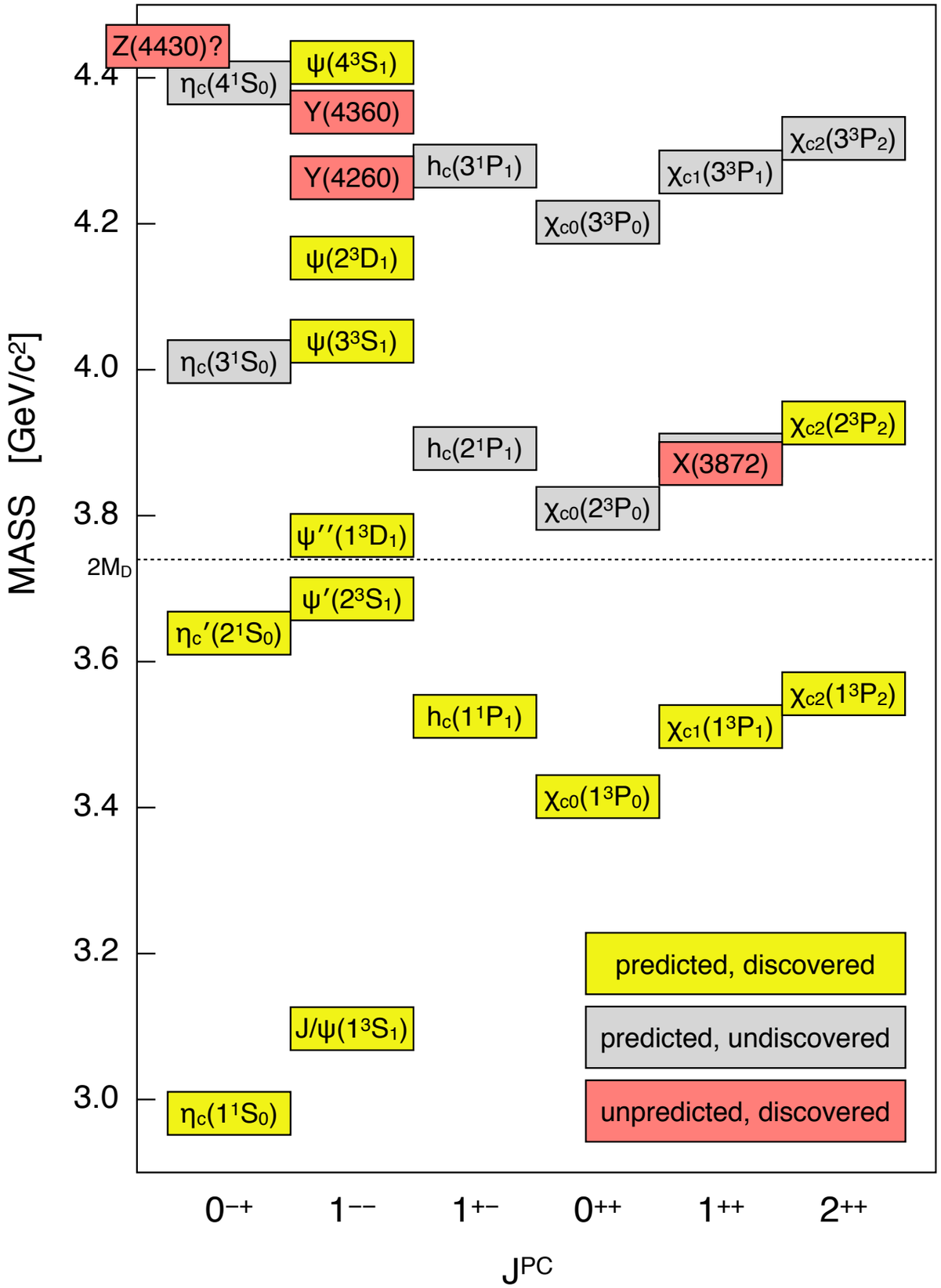


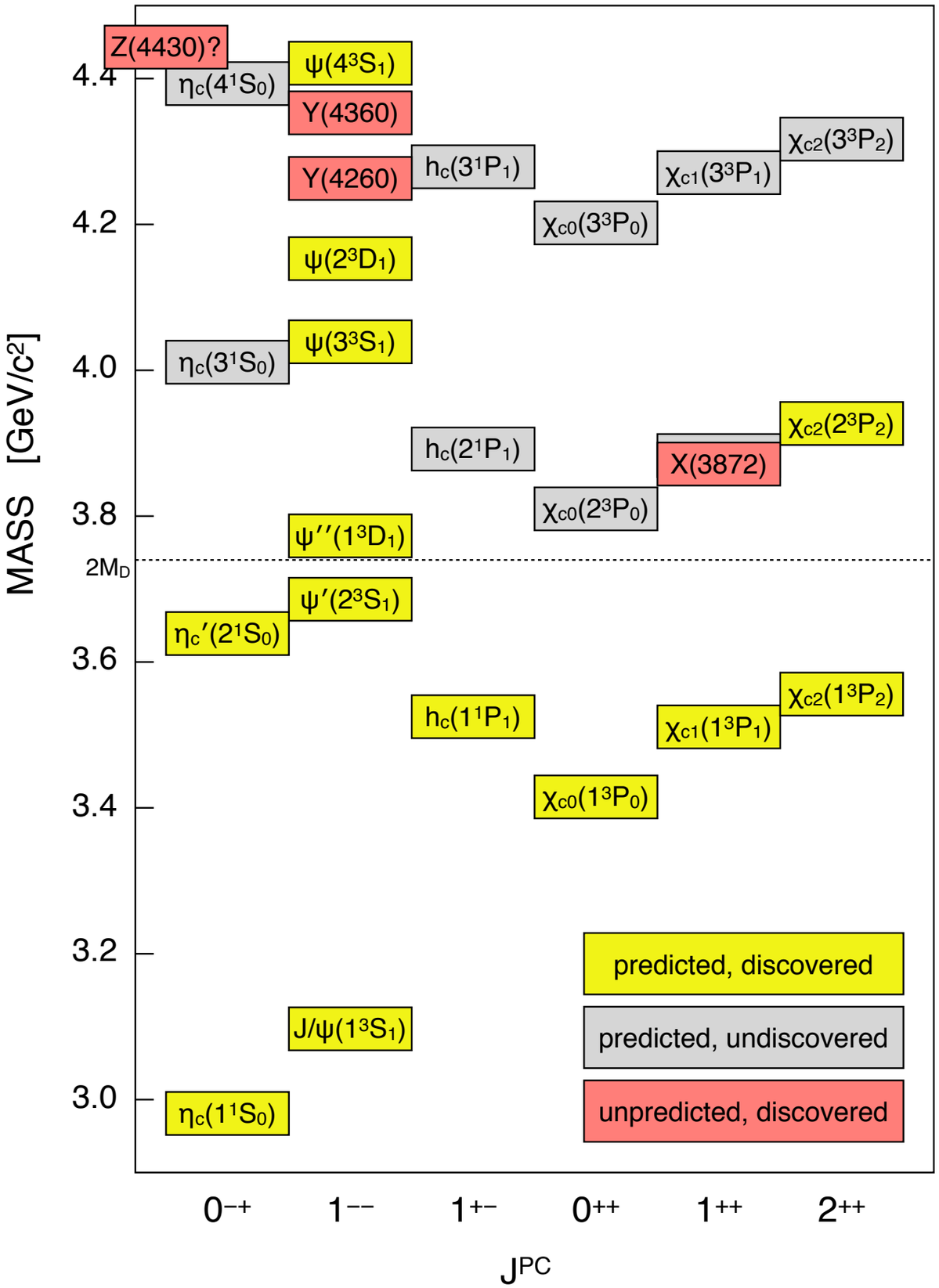

HYBRID CHARMONIUM?

# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

# IV. A New Era of Discovery

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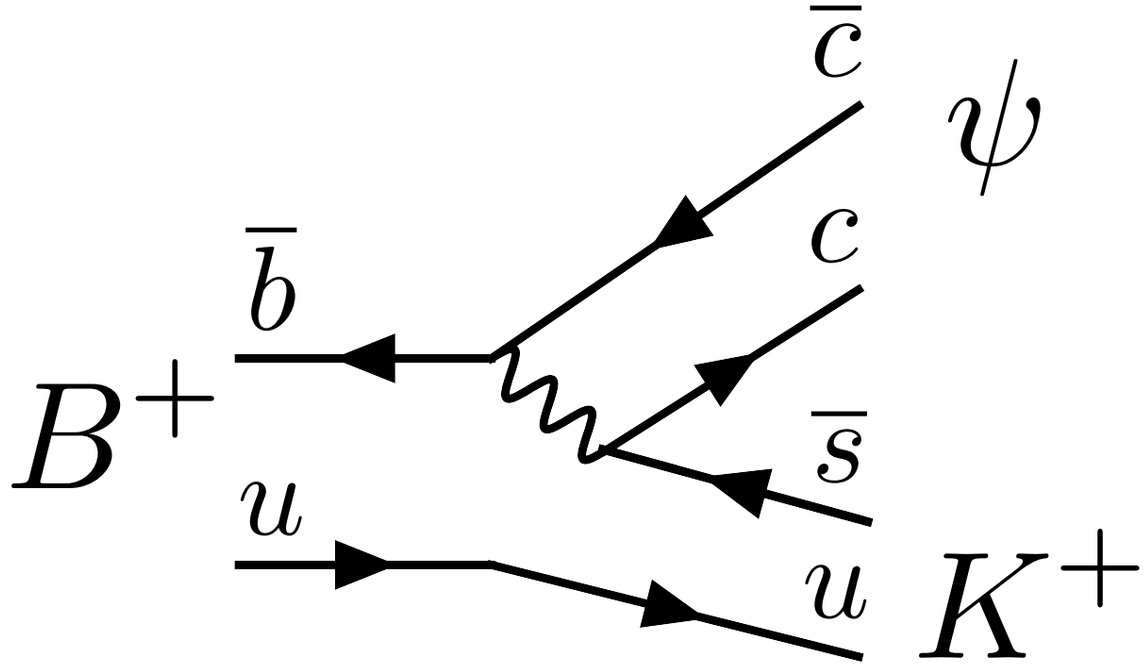
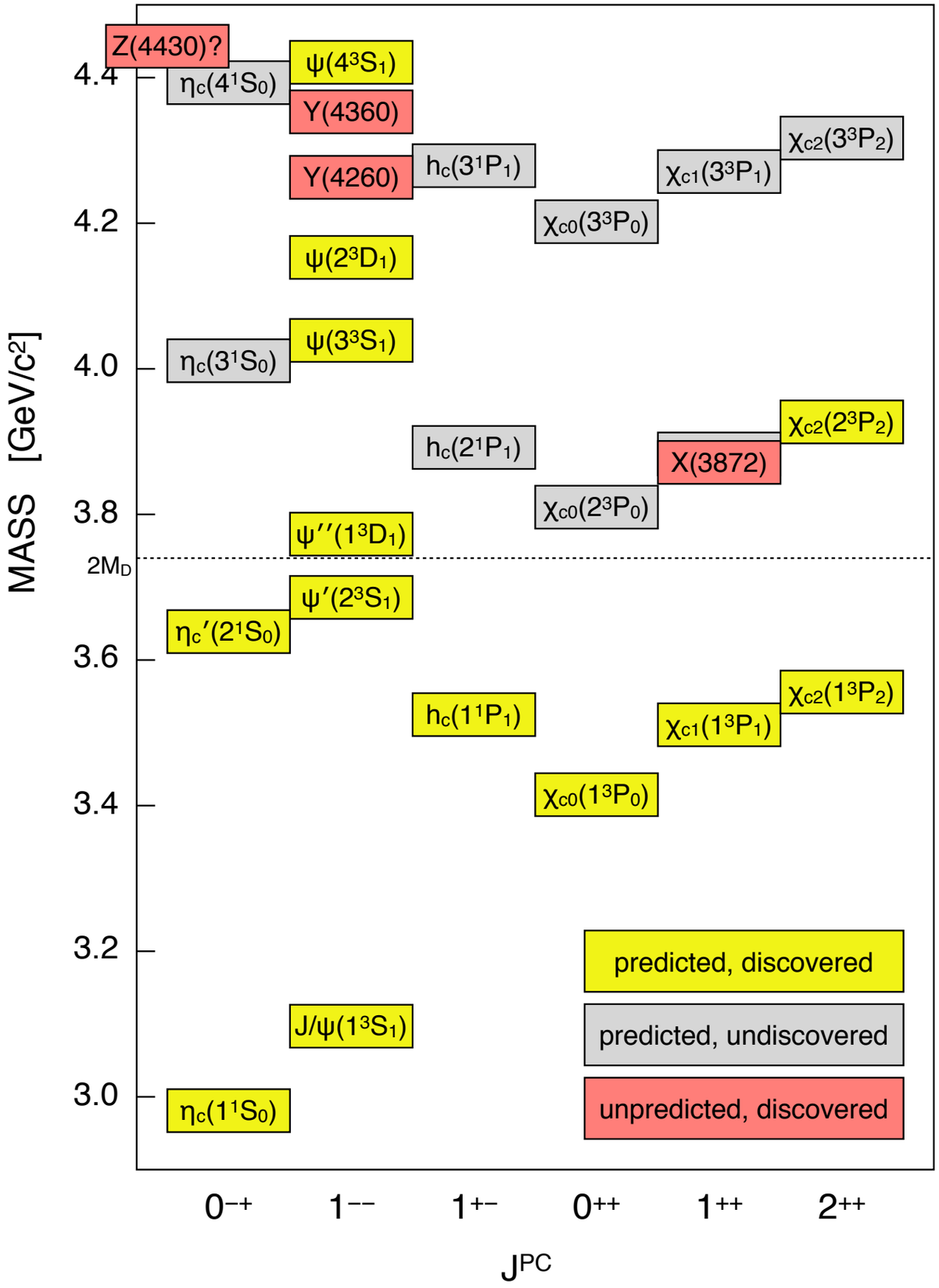
For example in B decays...



# IV. A New Era of Discovery

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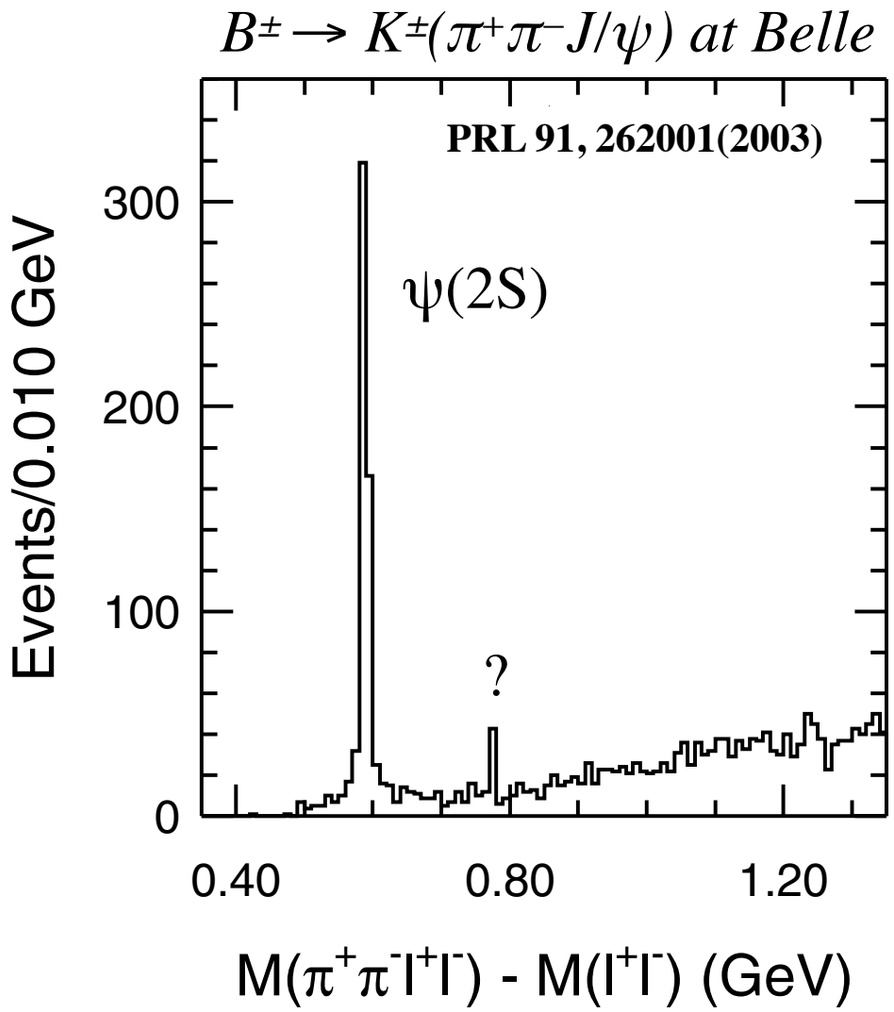

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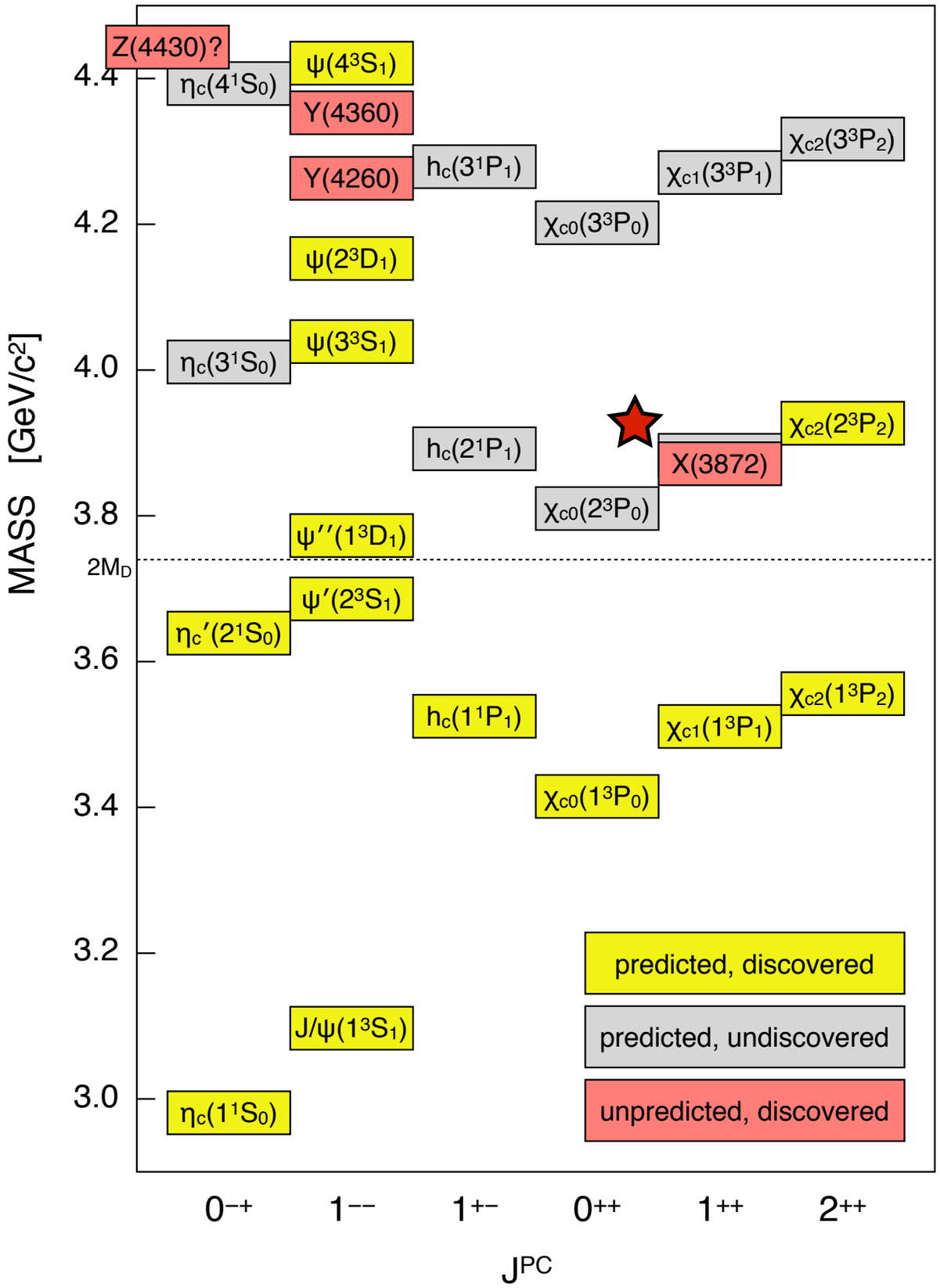


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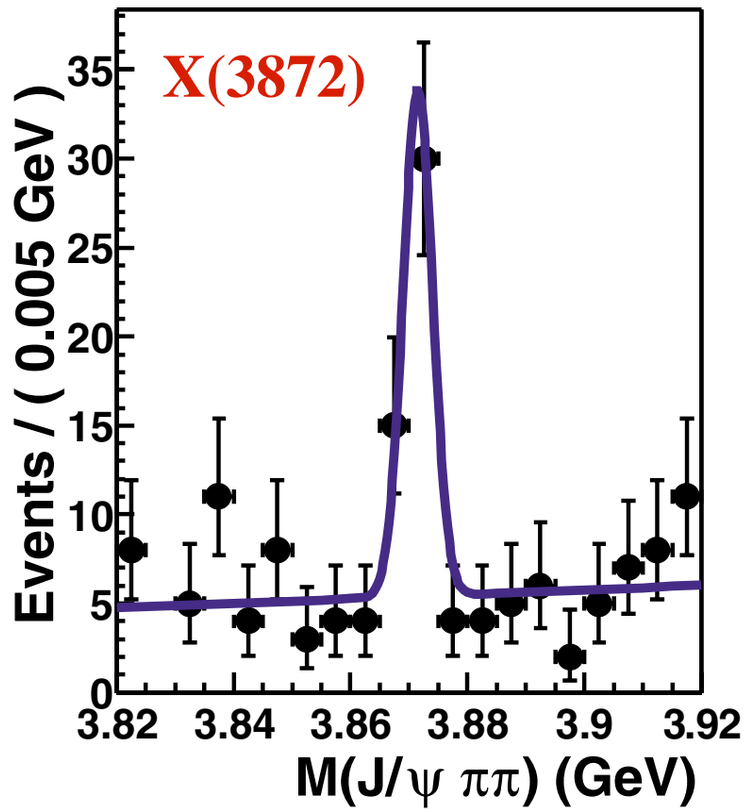
For example in B decays...

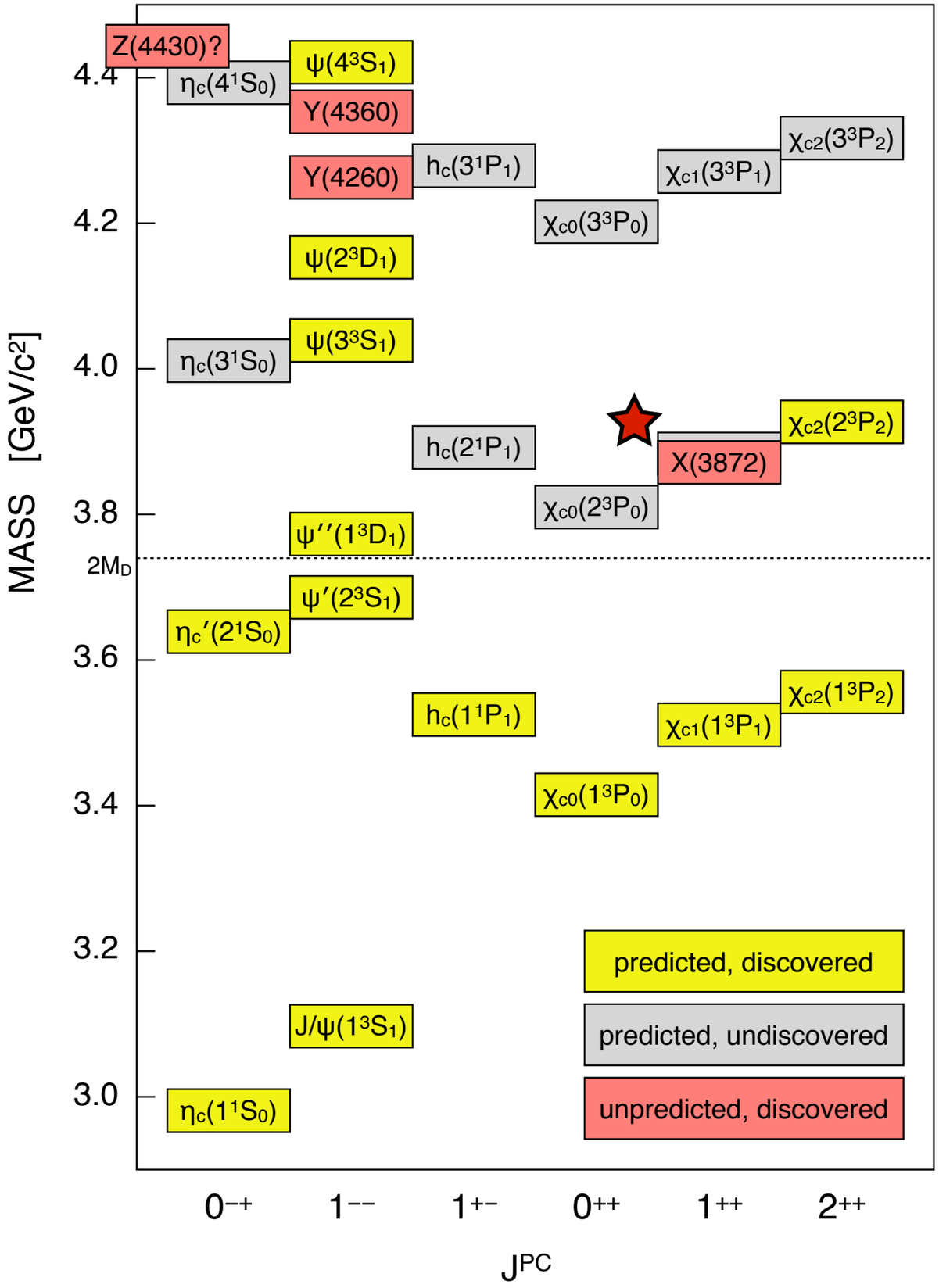
$B^\pm \to K^\pm(\pi^+\pi^- J/\psi)$ *at Belle*




$M = 3871.68 \pm 0.17$ MeV

$\Gamma < 1.2$ MeV (PDG 2012)

# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

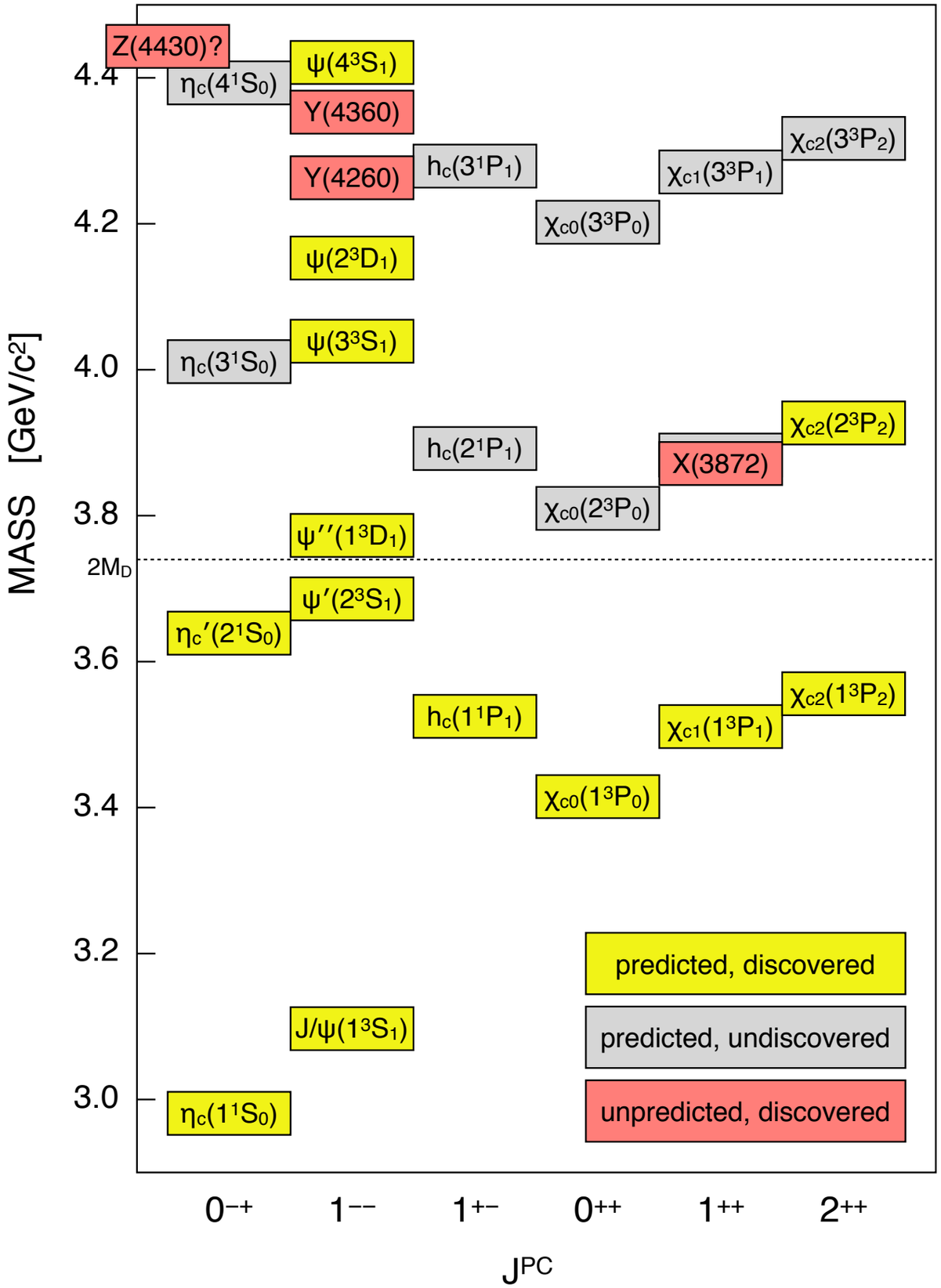
For example in B decays...

X(3872) Properties:

* very narrow (< 1.2 MeV)
* has $J^{PC} = 1^{++}$ (LHCb)
* too light to be the $\chi_{c1}(2P)$
* confirmed by many experiments
* mass is right at D*D mass

***D*D molecule?***

# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

For example in B decays...

Other B decays:

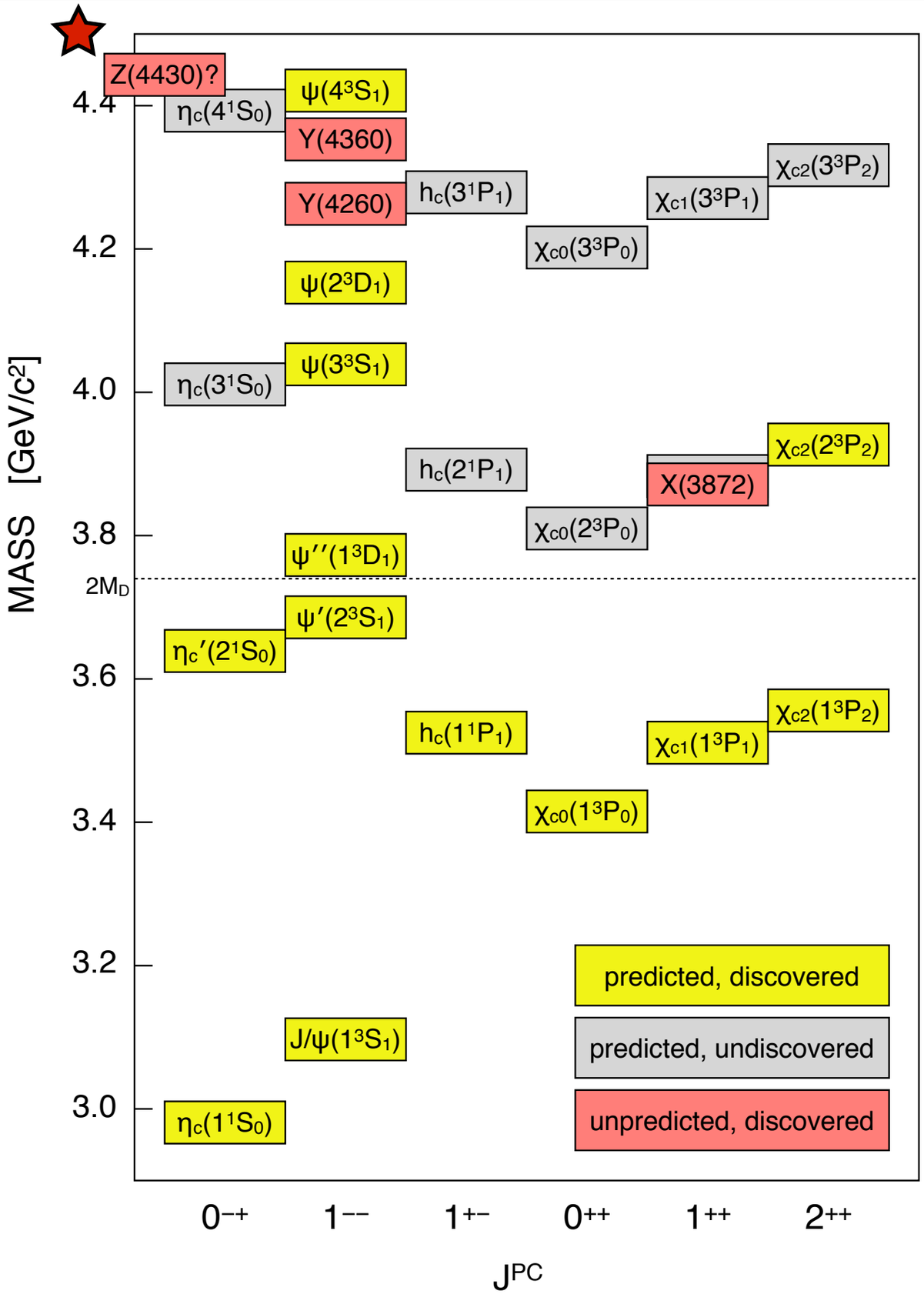
$$B^{\pm} \to K^{\pm}(\pi^+\pi^- J/\psi)$$

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

$$B \to K(\pi^+\chi_{c1}(1P))$$

$$B \to K(\pi^+\psi(2S))$$

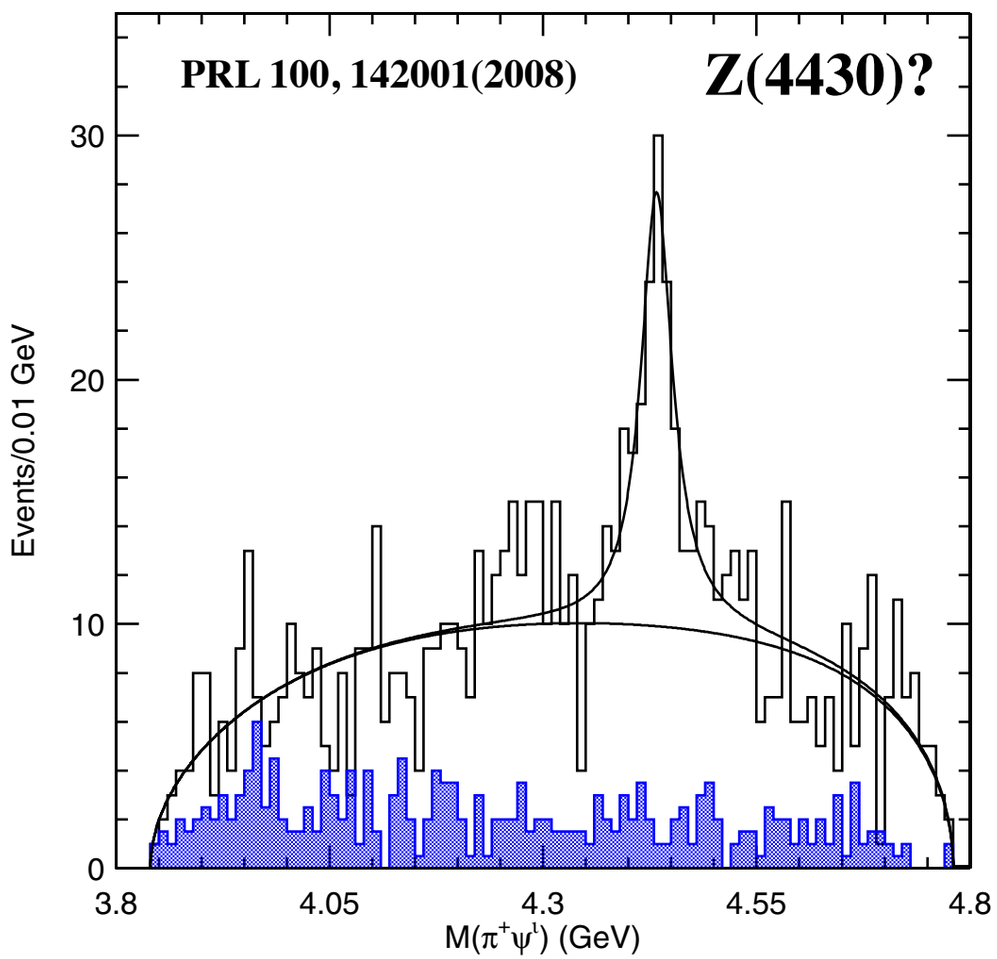
# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

For example in B decays...

*$B \to K(\pi^+\psi(2S))$ at Belle*



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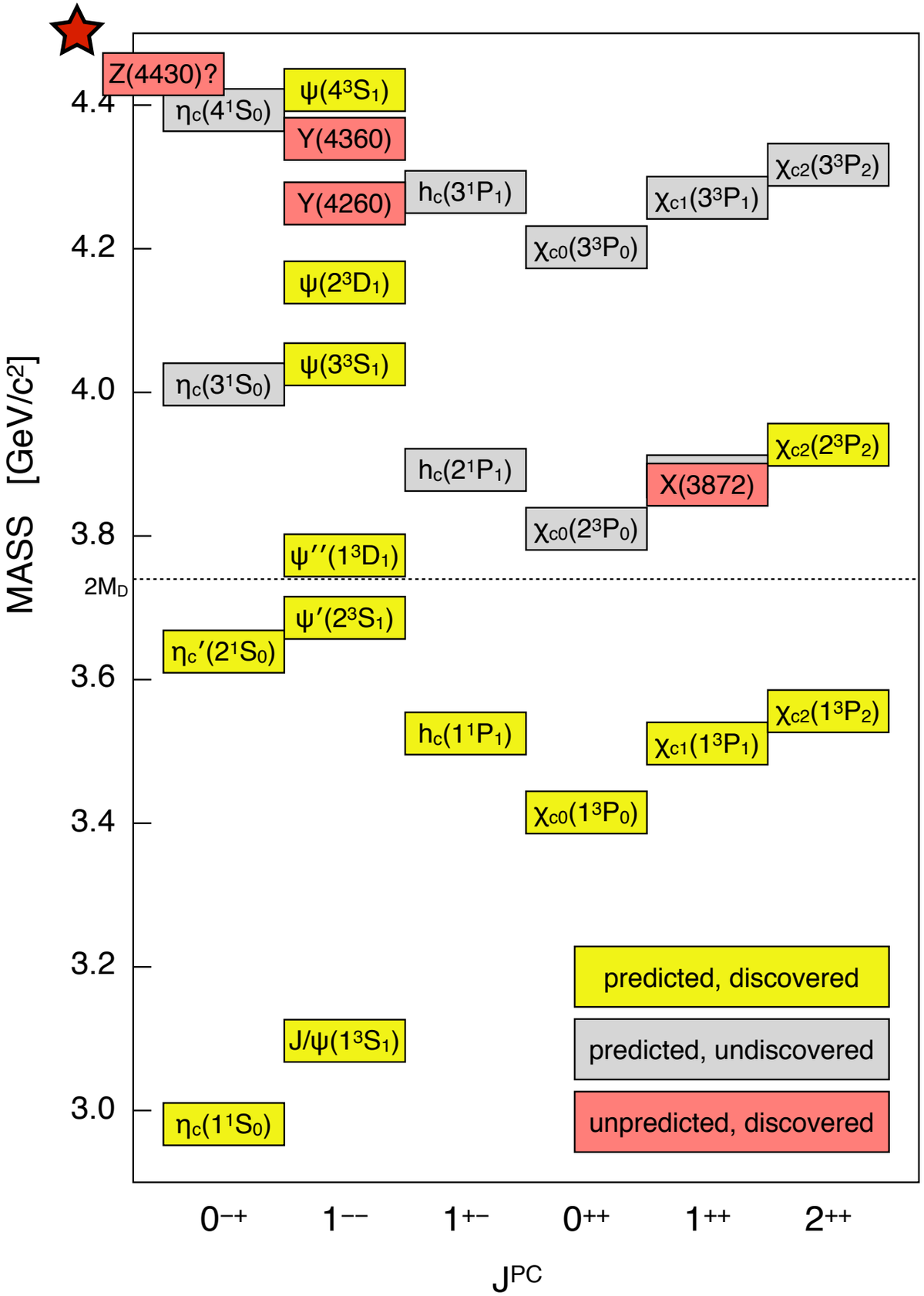



Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

For example in B decays...

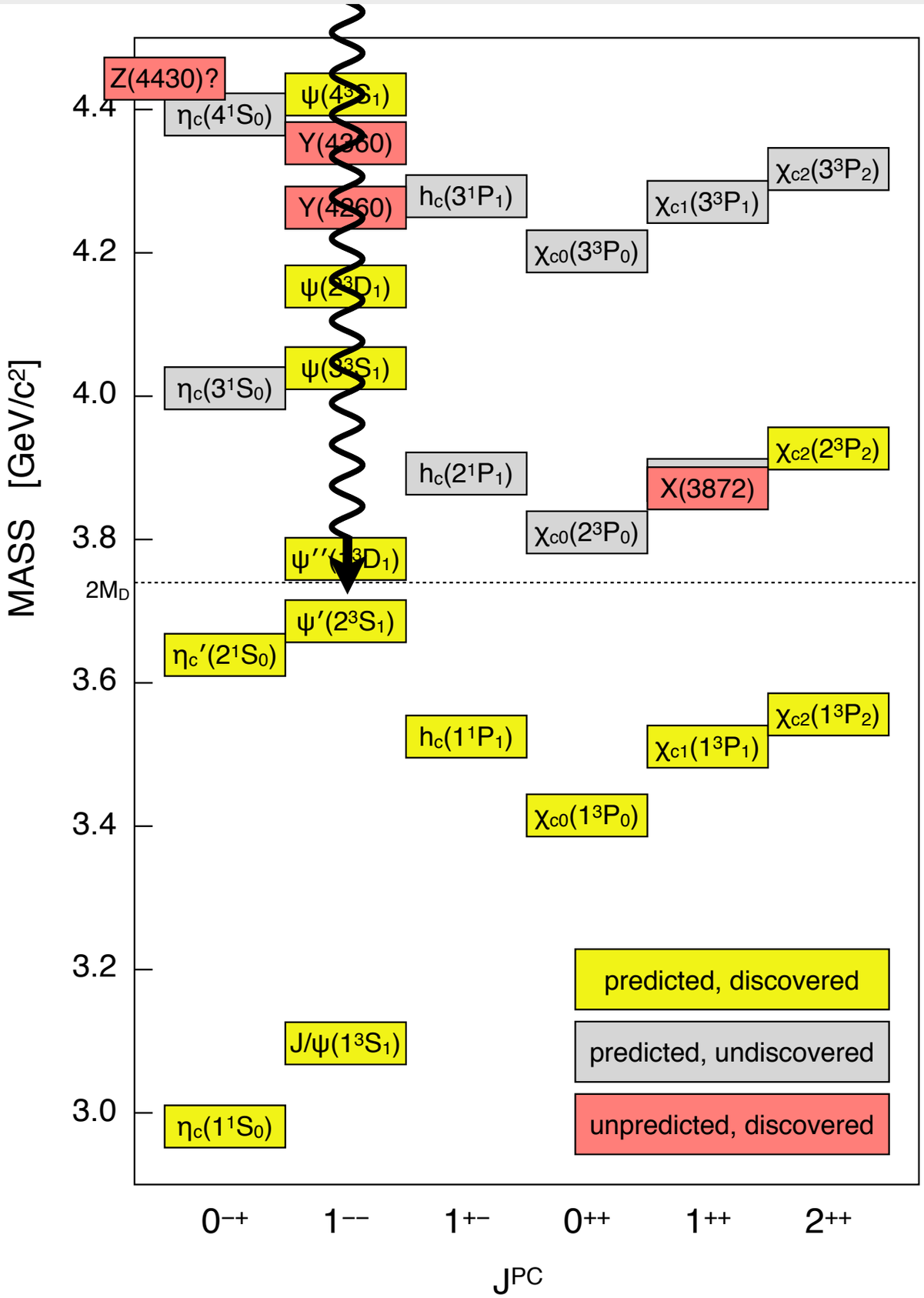
Z(4430) Properties:

* has an electric charge

  ⇒ **needs at least four quarks!**

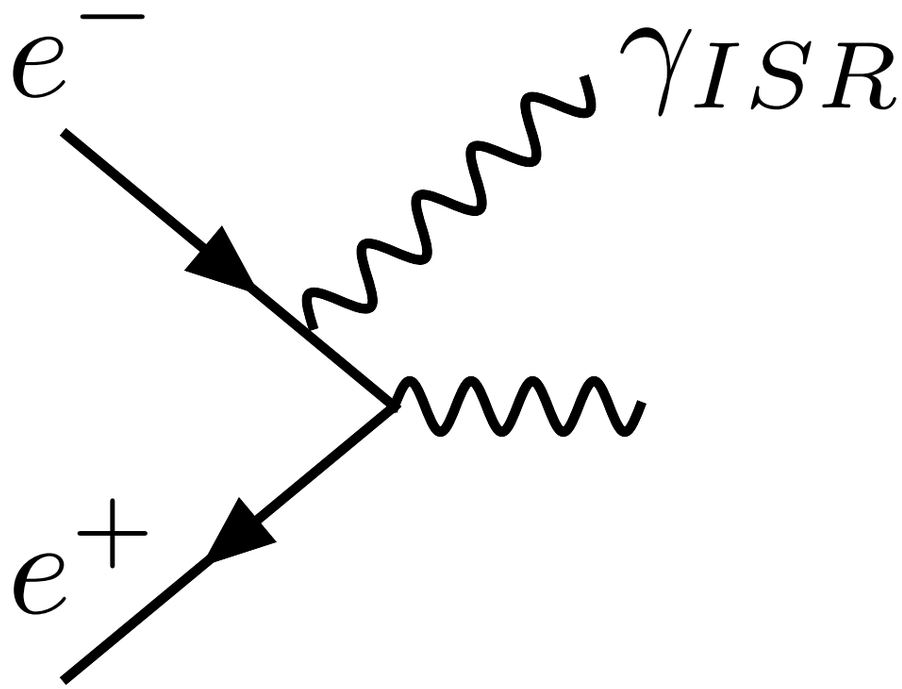
* *(not confirmed by BaBar)*

# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...



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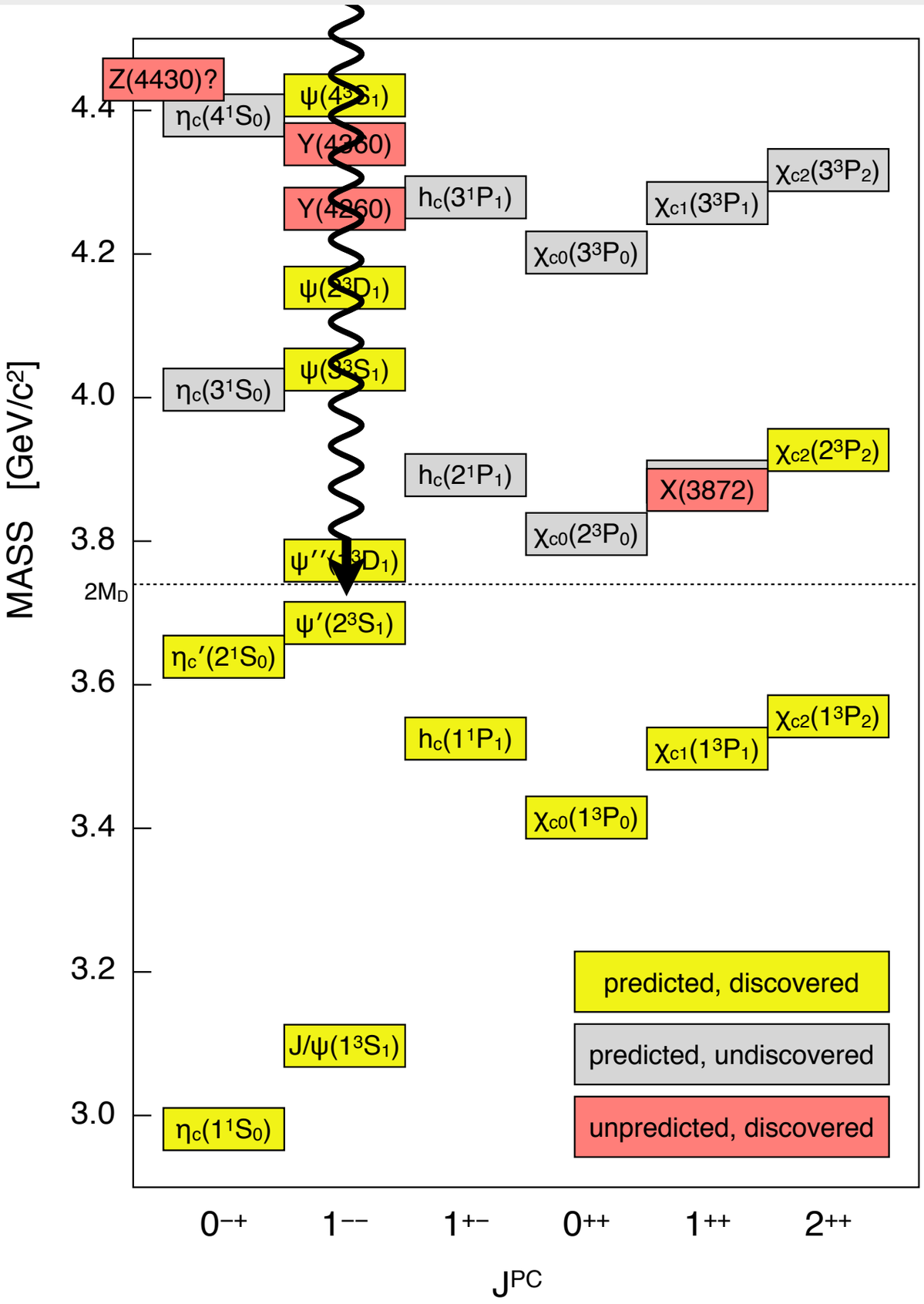


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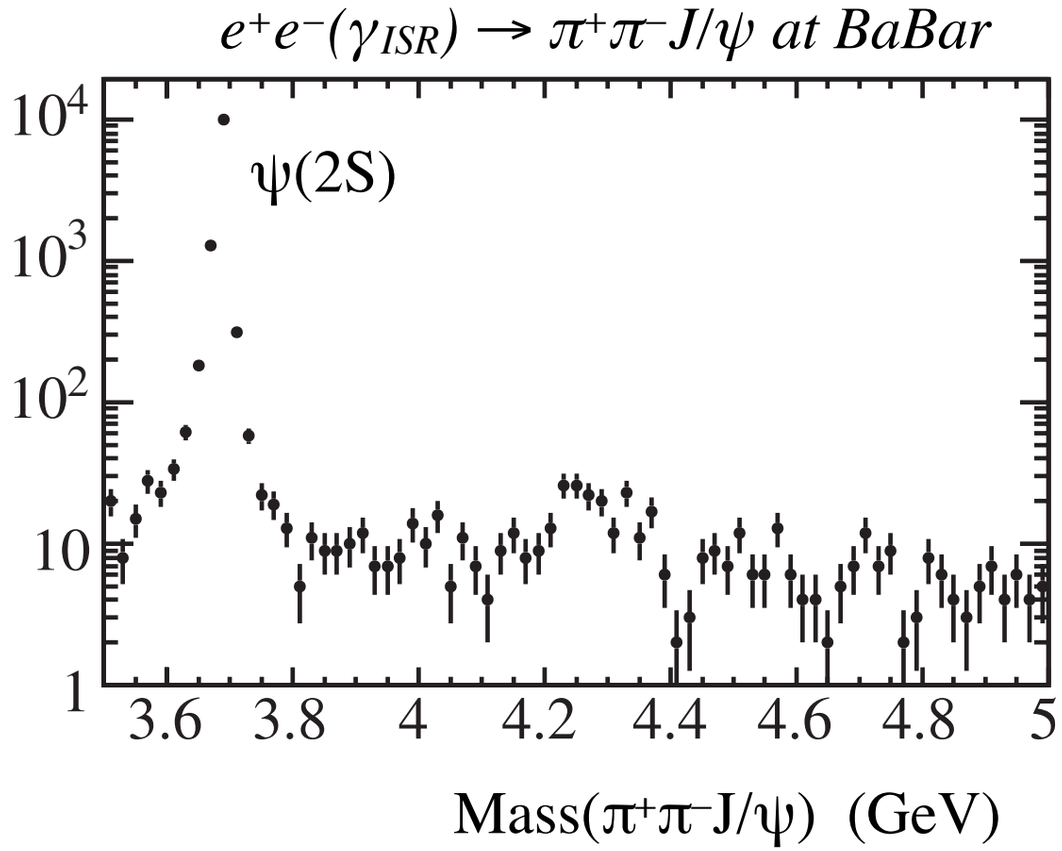


**PRL 95, 142001 (2005)**

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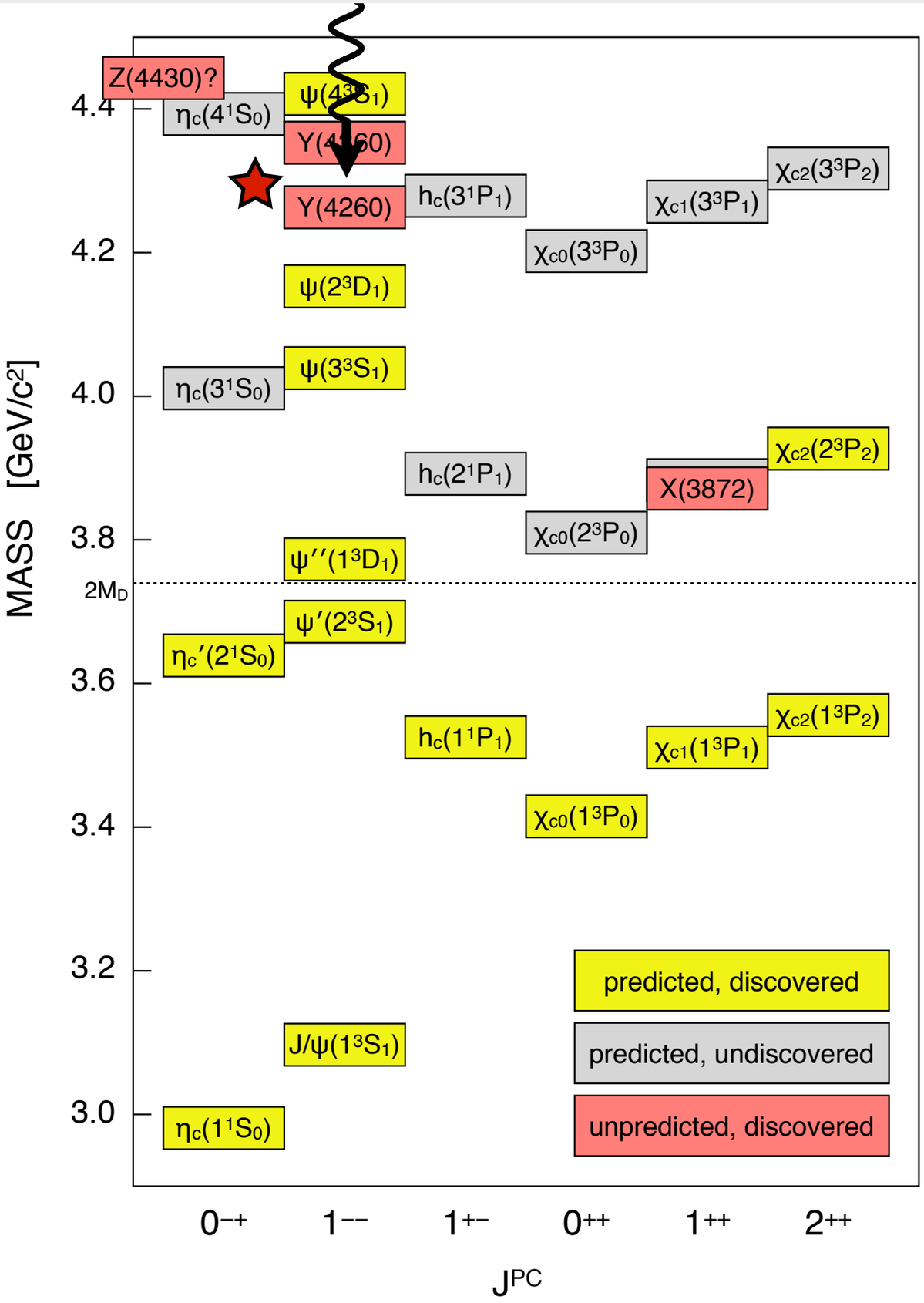


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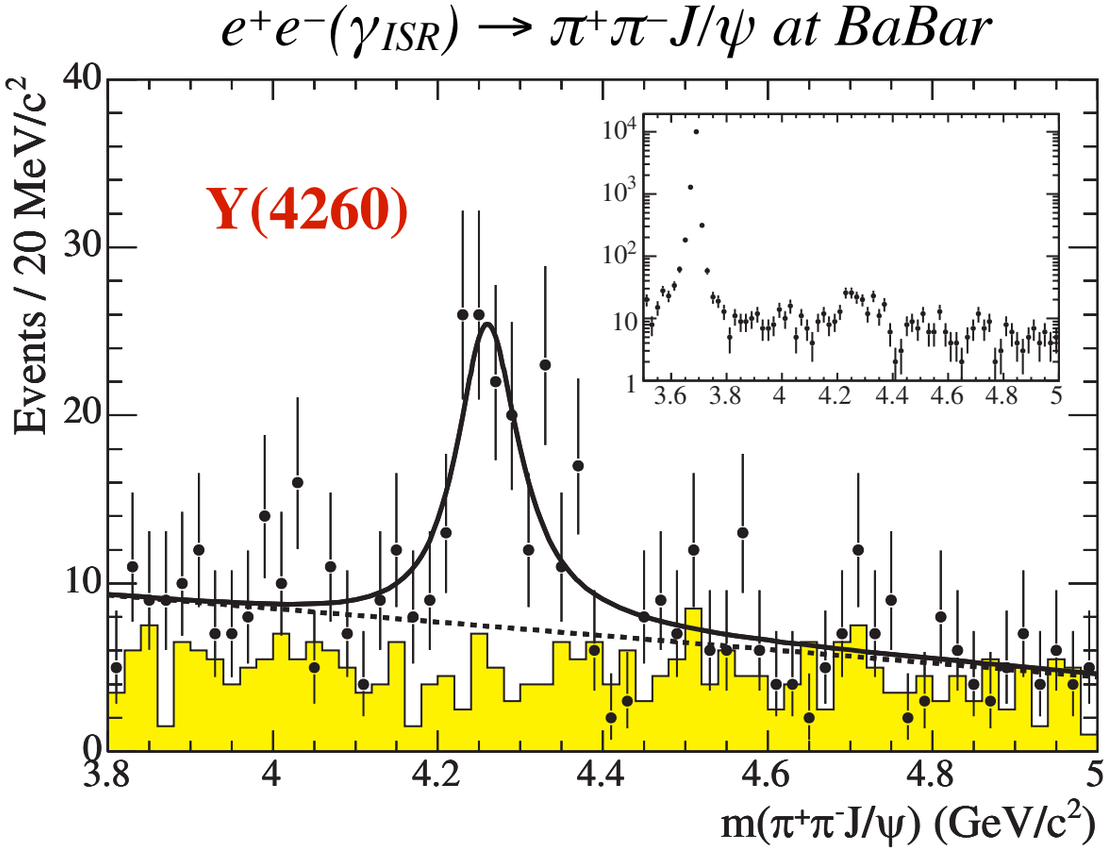
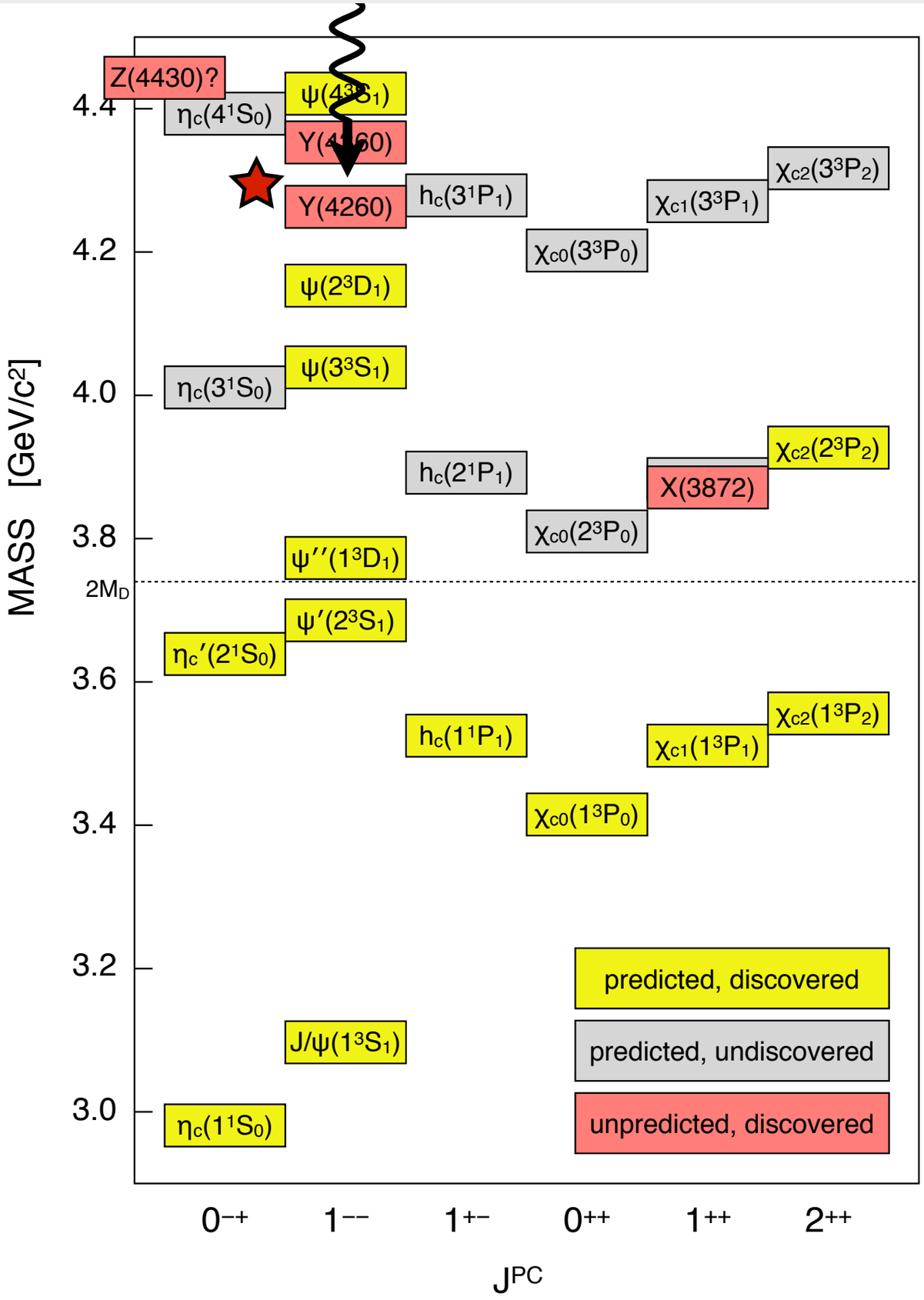


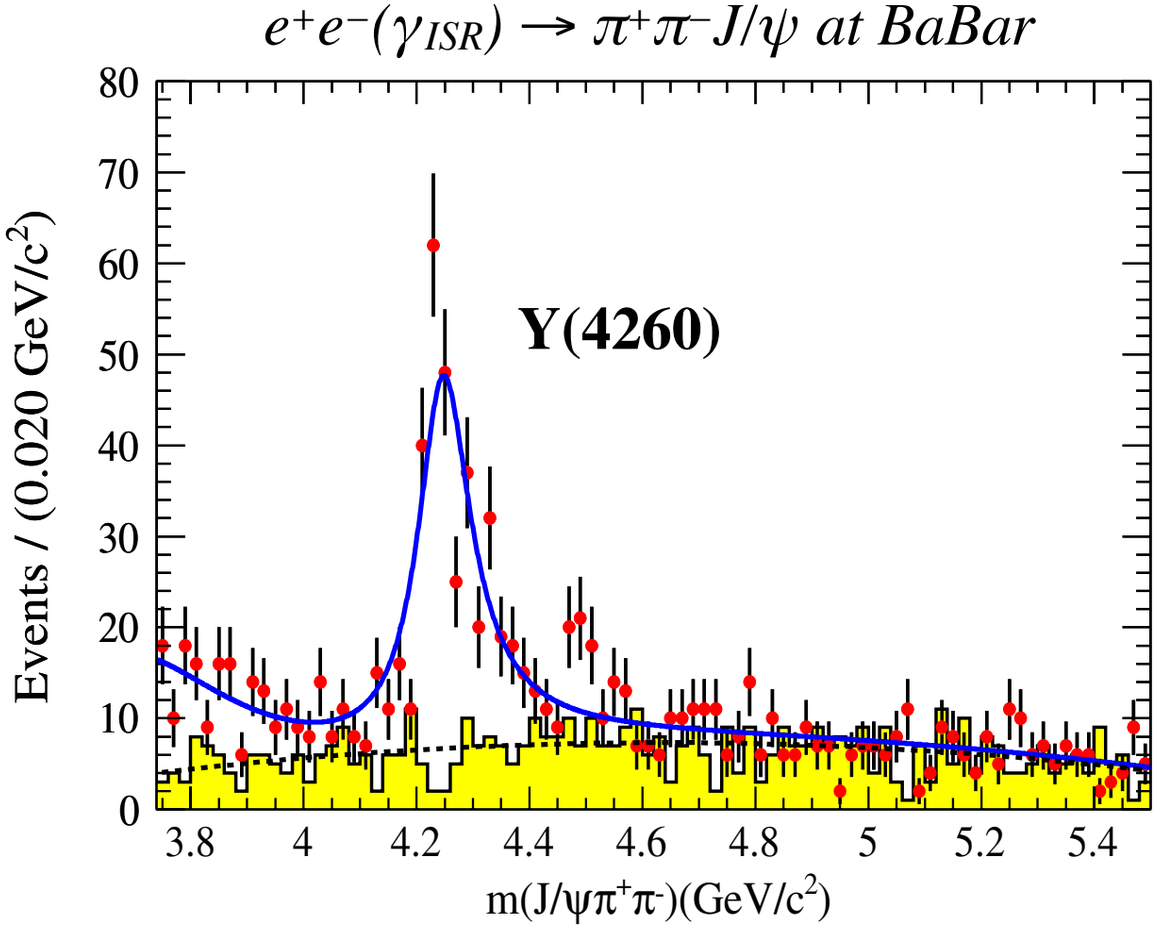

**PRL 95, 142001 (2005)**

# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...




**PRD 86, 051102(R) (2012)**

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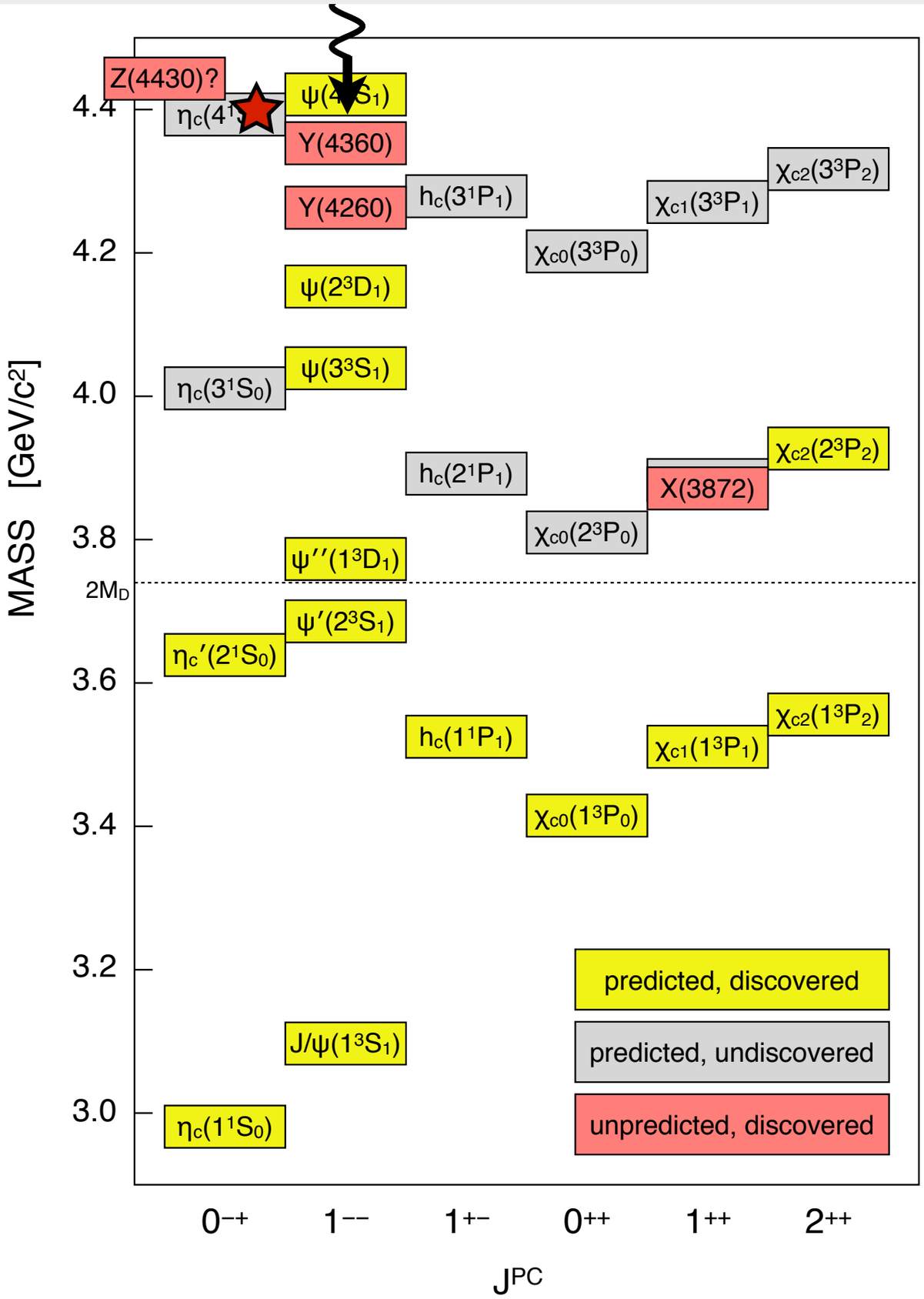
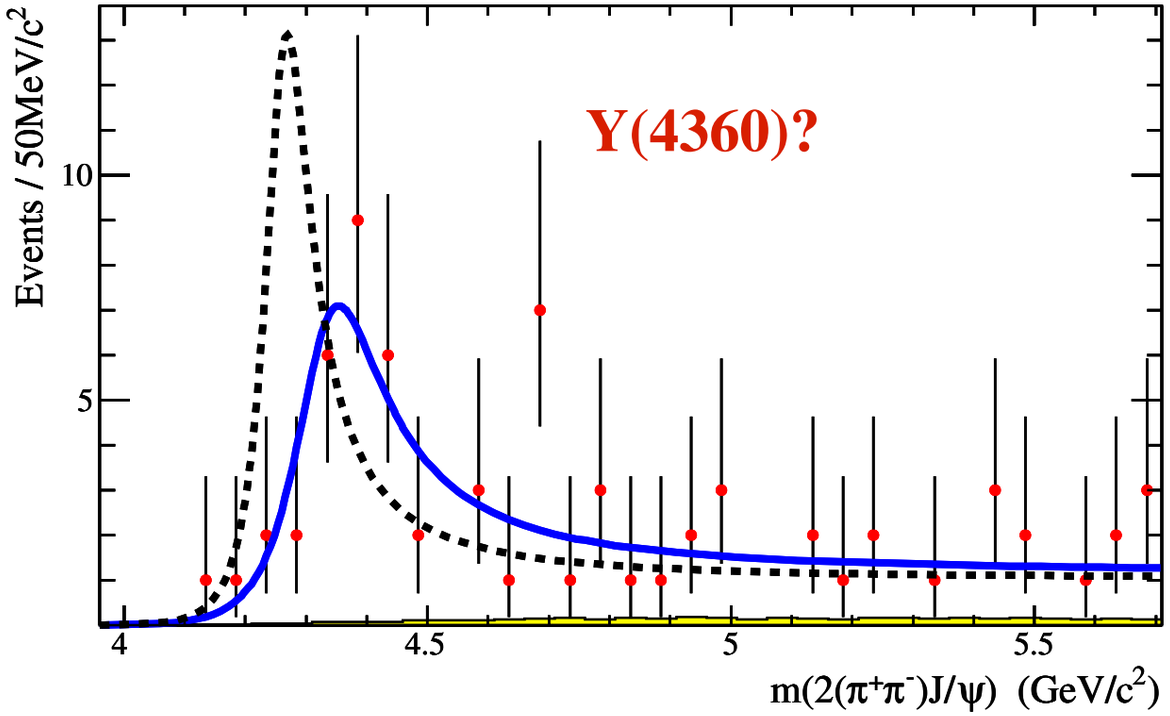



Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

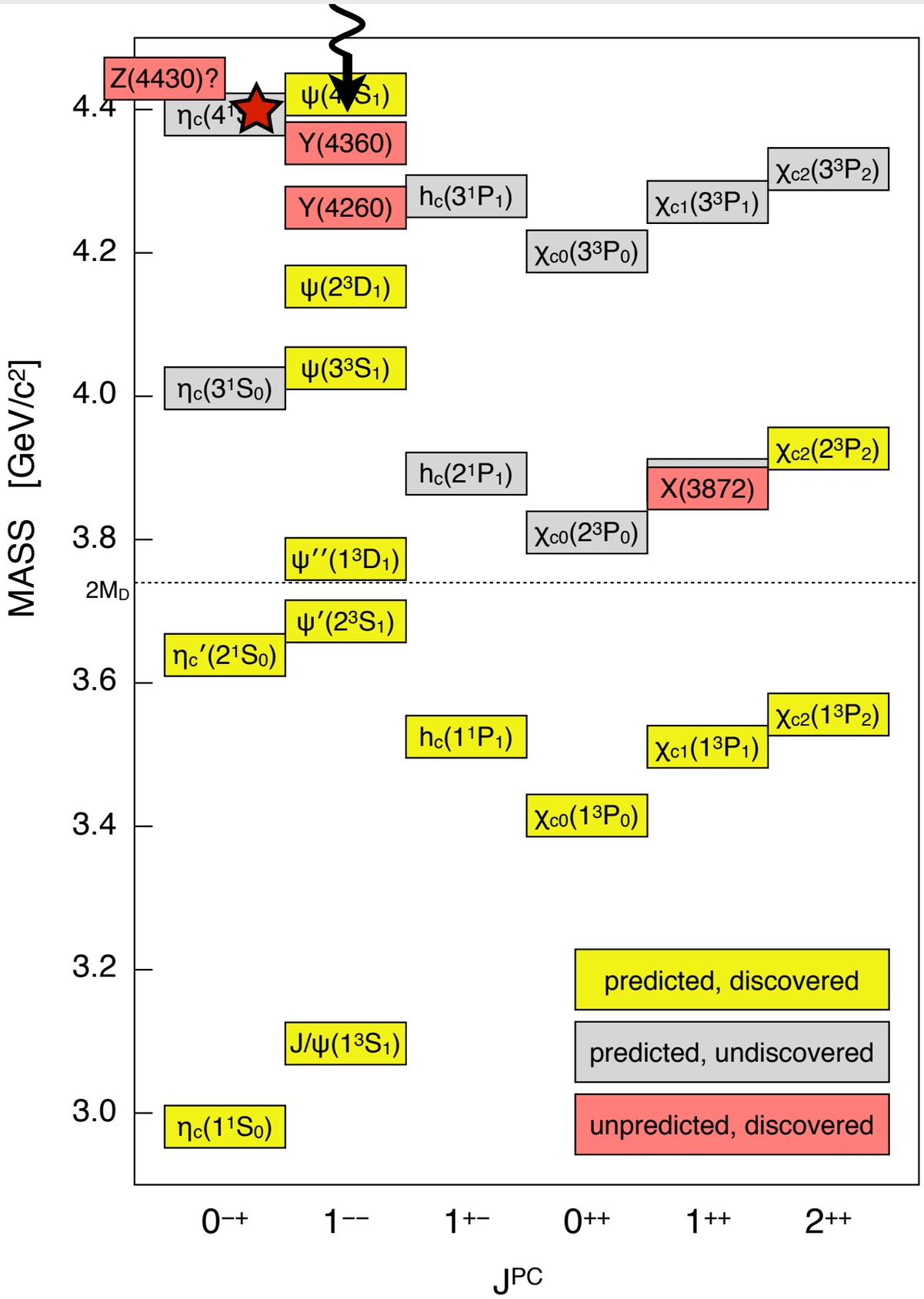
And in Initial State Radiation (ISR)...

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




**PRL 98, 212001 (2007)**

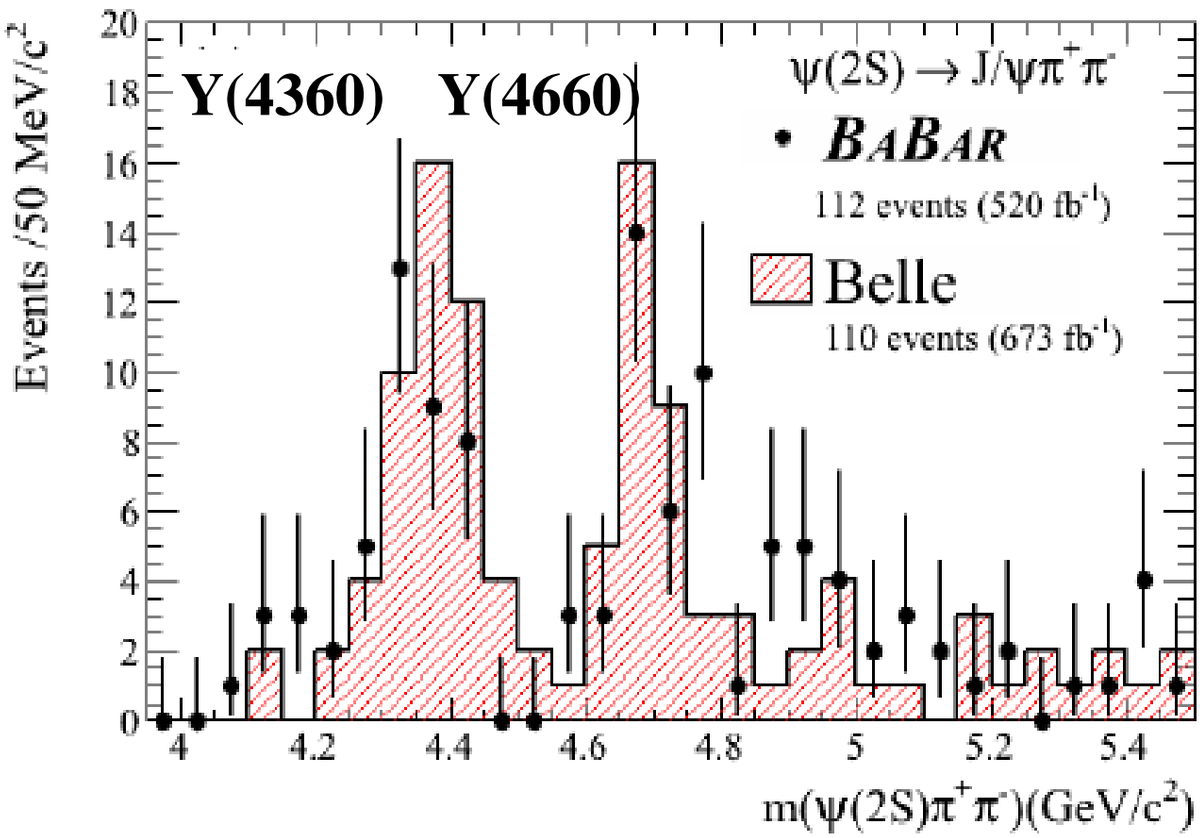
# IV. A New Era of Discovery




Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

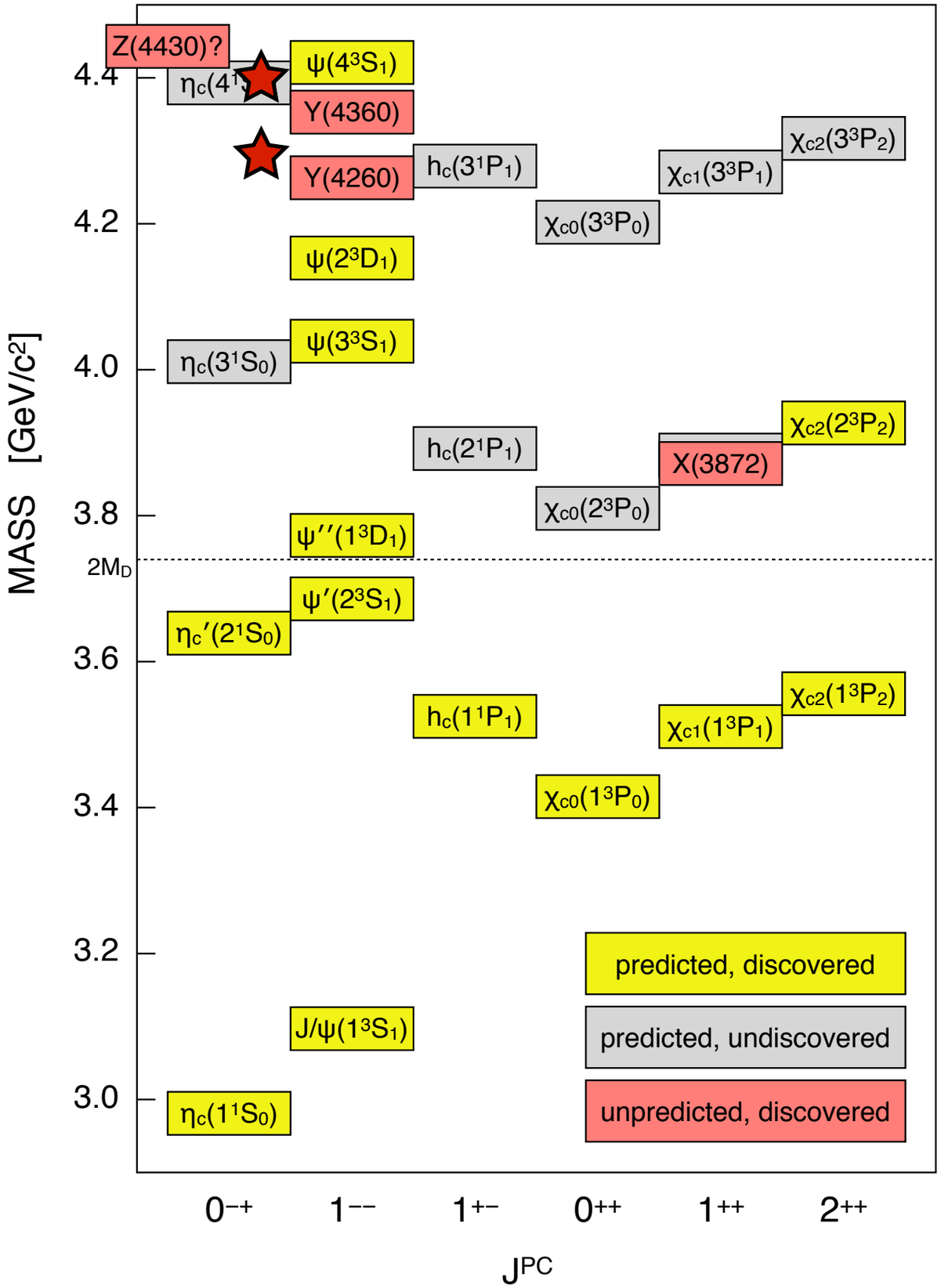
And in Initial State Radiation (ISR)...

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




**arXiv:1211.6271 and CHARM 2012**

# IV. A New Era of Discovery



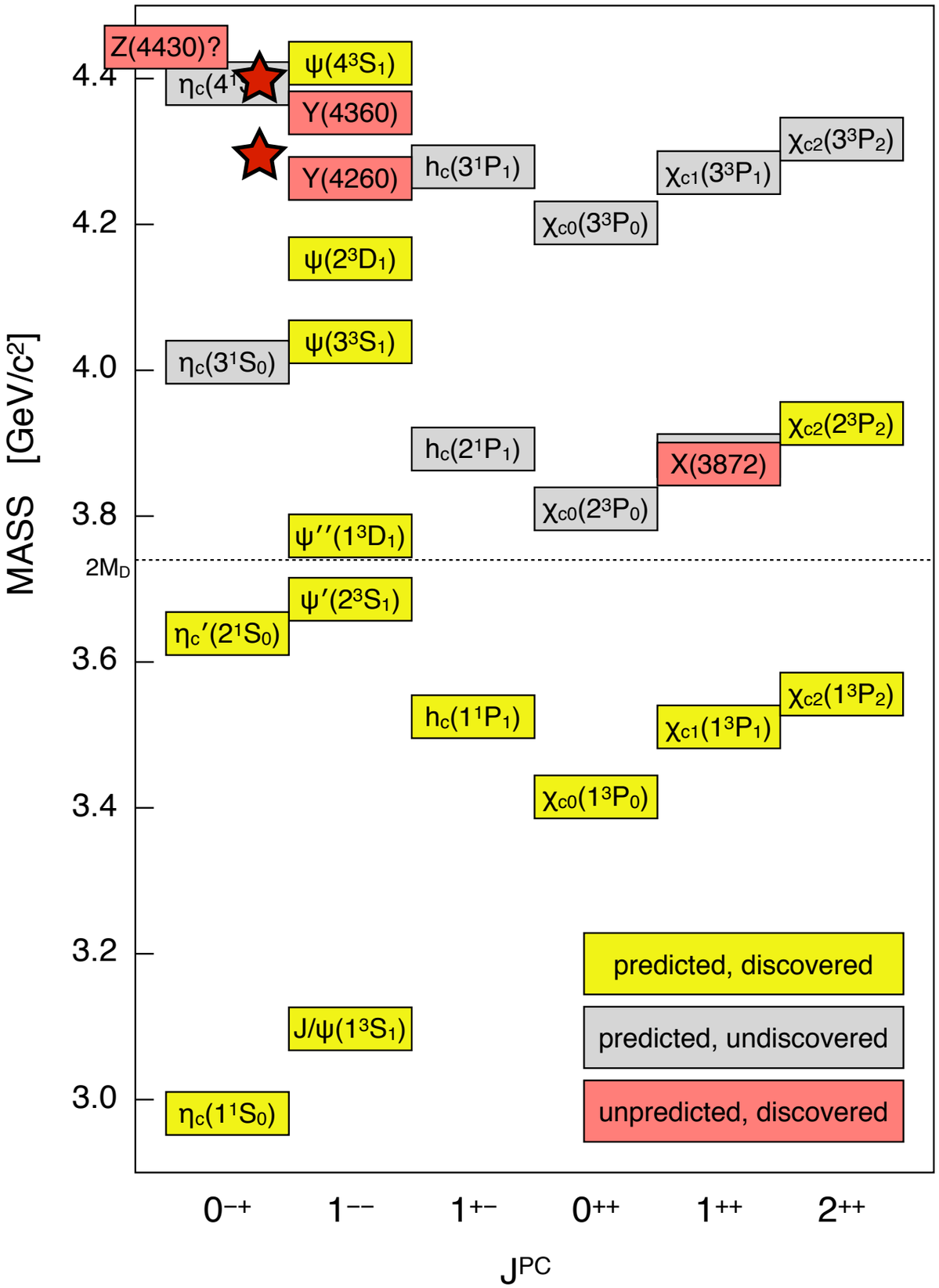

Most XYZ states were discovered at **Belle** and **BaBar** using $e^+e^-$ collisions in the bottomonium region...

And in Initial State Radiation (ISR)...

Y(4260), Y(4360) Properties:

* not predicted in the quark model
* tight upper limits on open charm decays

# IV. A New Era of Discovery




**<u>Theoretical Ideas on Y(4260), Y(4360):</u>**

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

**(NPA815, 53 (2009))**

J/ψ$f_0$ bound state (with KK → ππ)

**(PRD80, 094012 (2009))**

Tetraquarks (or two diquarks)

**(PRD72, 031502(R) (2005))**

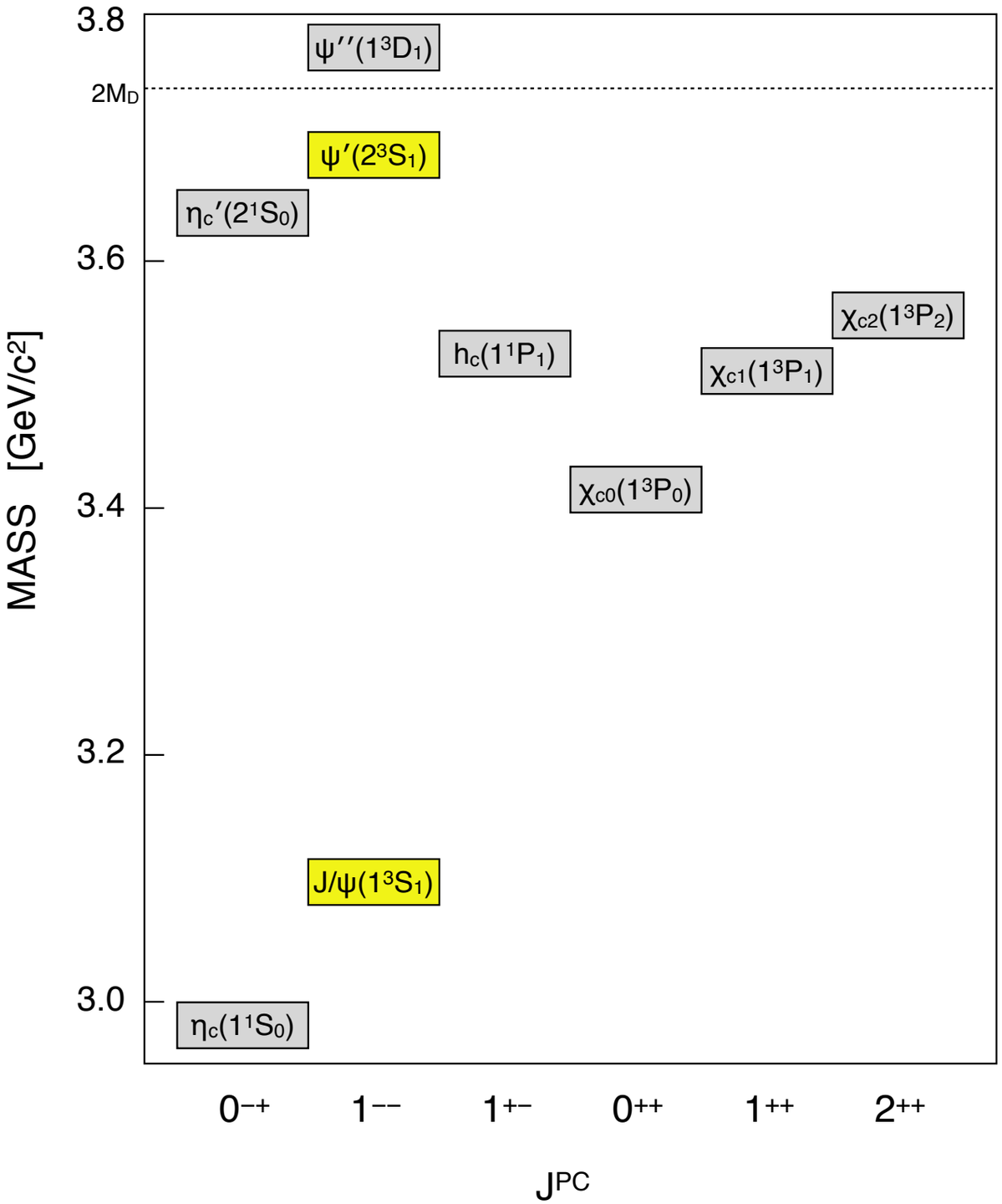
Hadrocharmonium

**(PLB666, 344 (2008))**

Hybrid Charmonium

**(PLB628, 215 (2005), PRD78, 094504 (2008), PLB625, 212 (2005))**

# II. The Original Era of Discovery




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

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

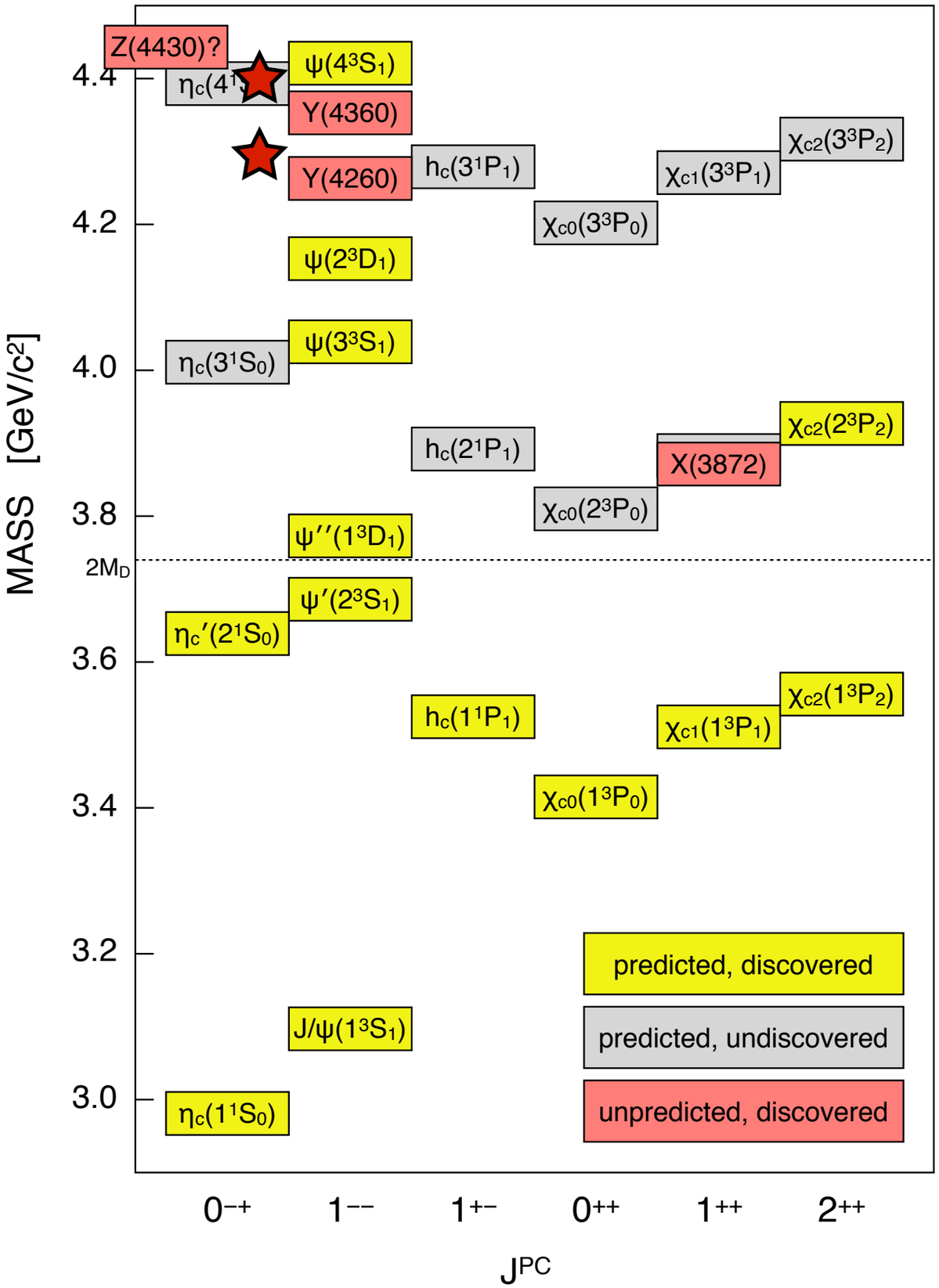
Spin-1 meson alternative to GIM
**(PRL34, 37 (1975))**

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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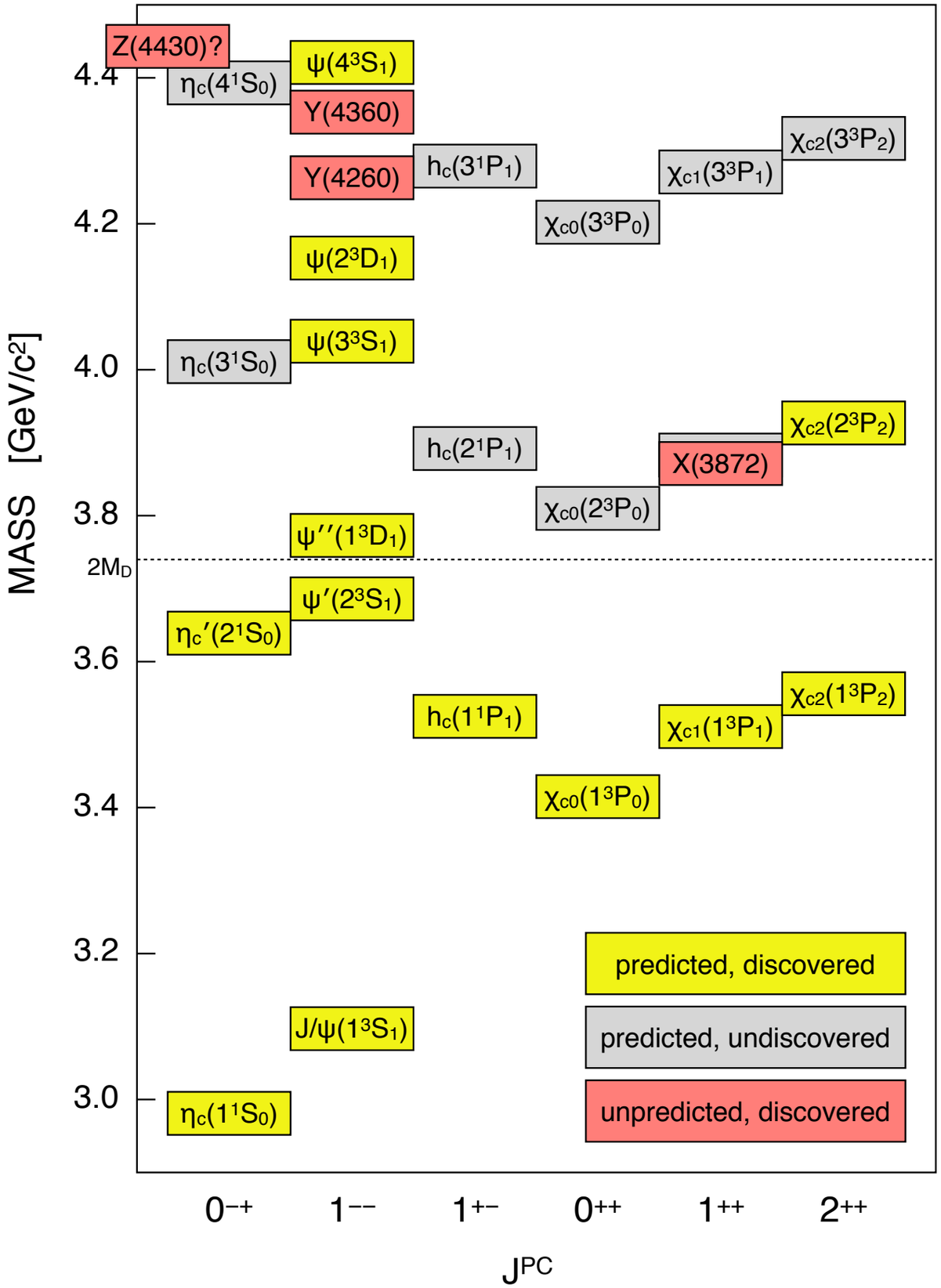
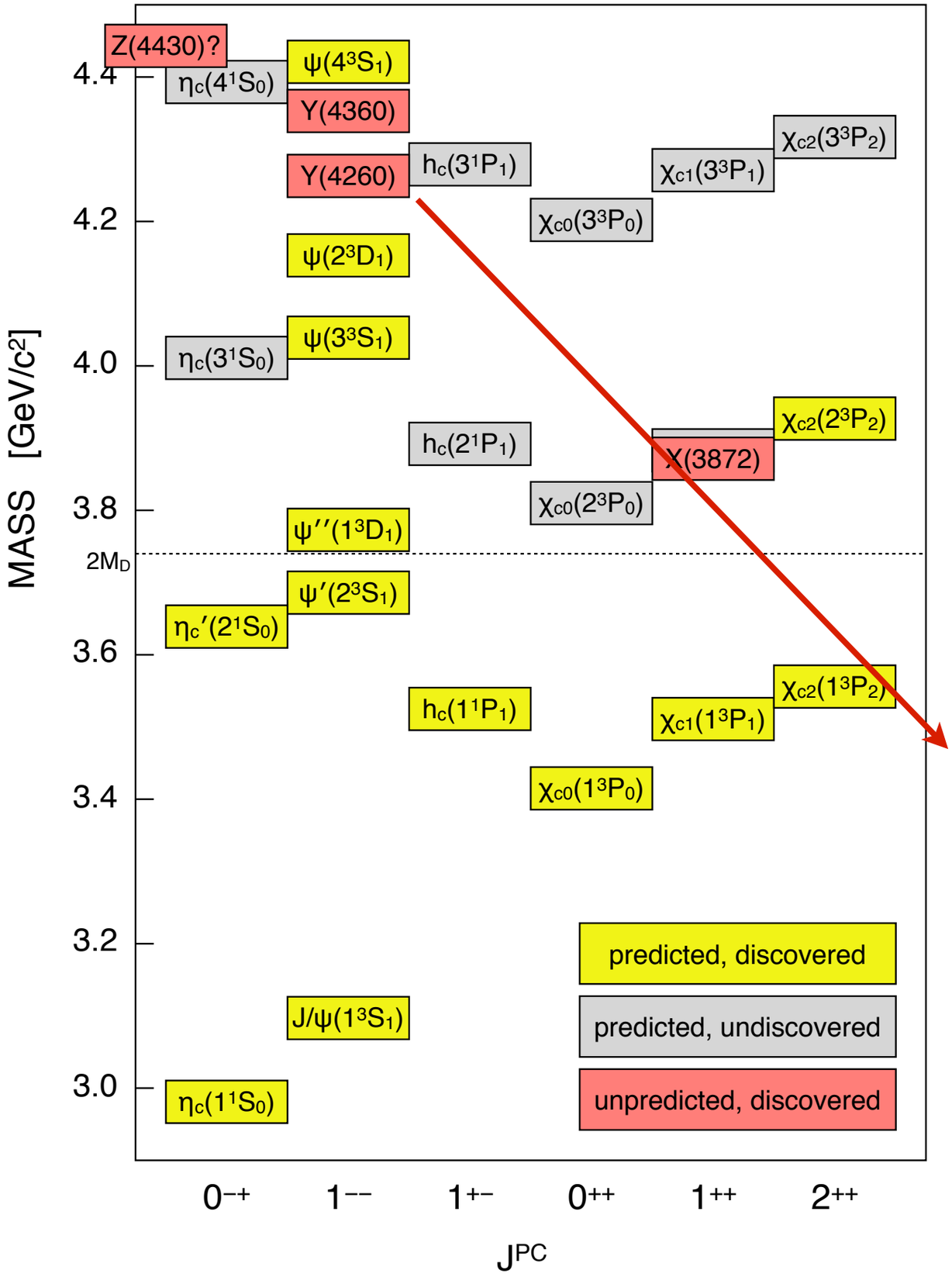
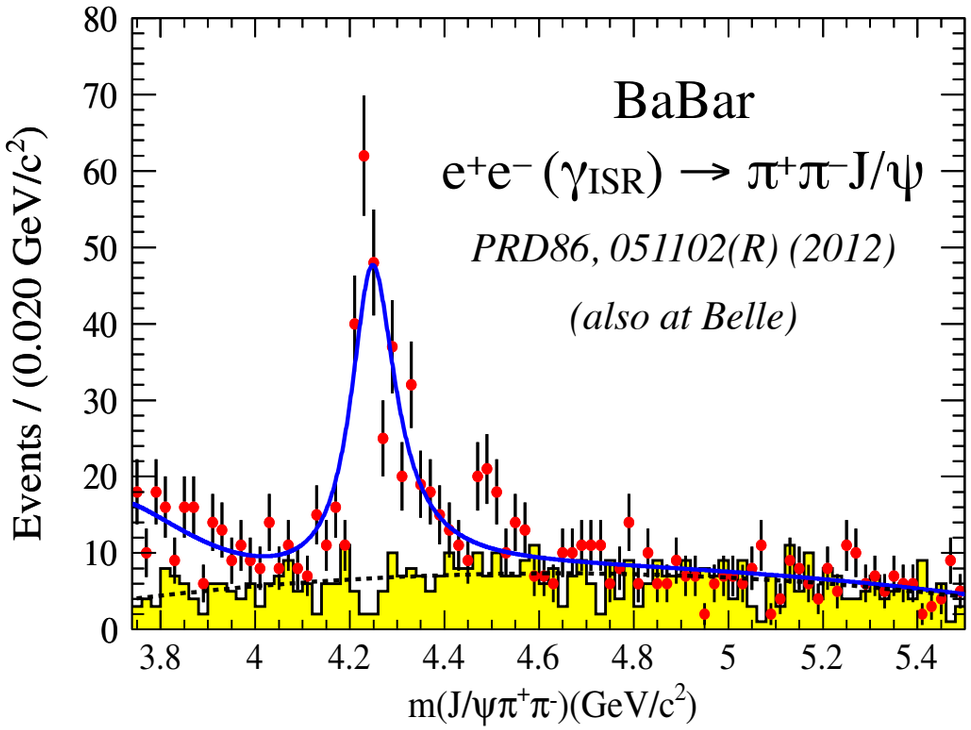



## How can BESIII contribute?

⇒ tune the $e^+e^-$ collision energies to directly produce large samples of **Y(4260)** and **Y(4360)** decays!

# IV. A New Era of Discovery



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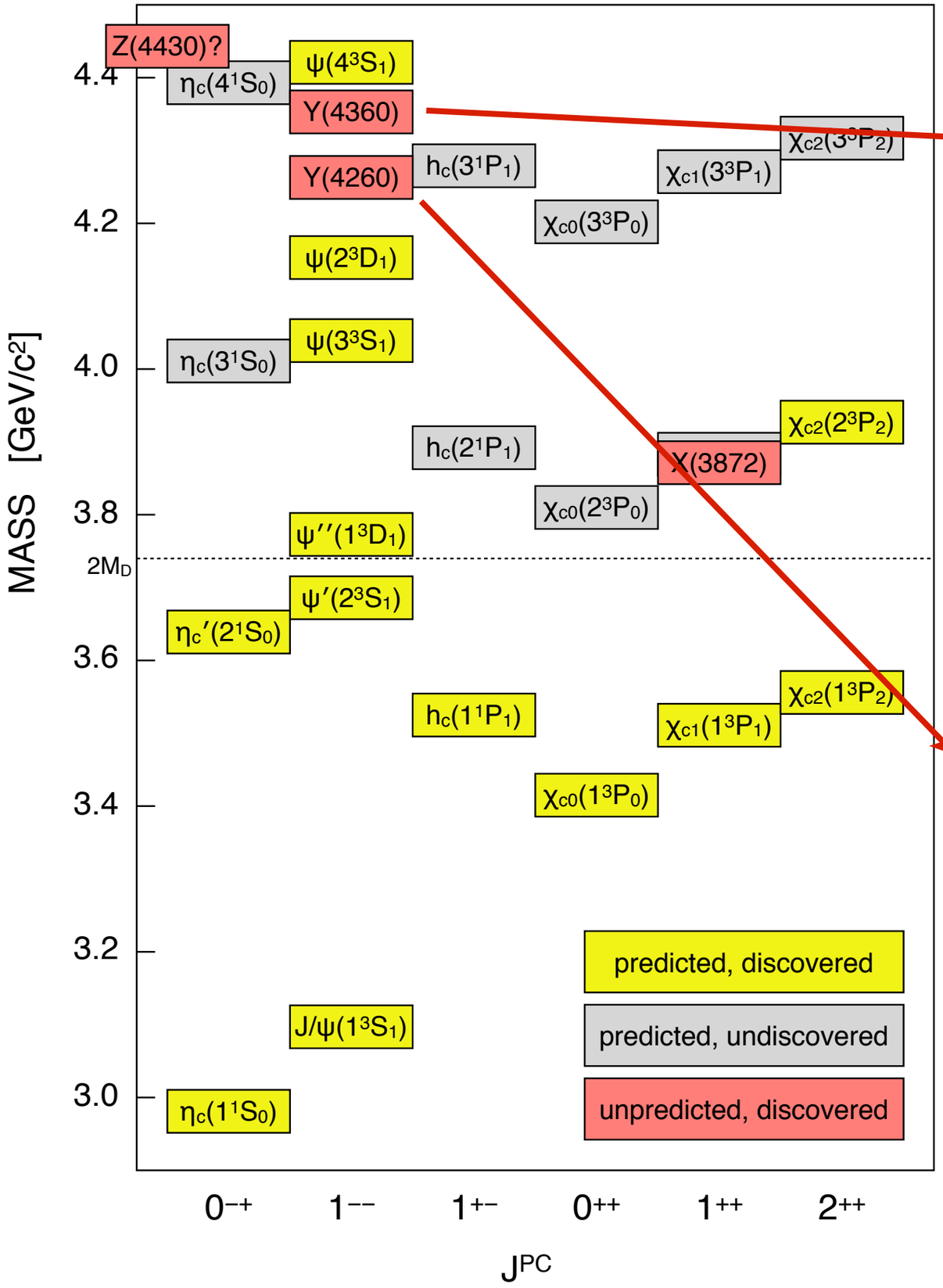


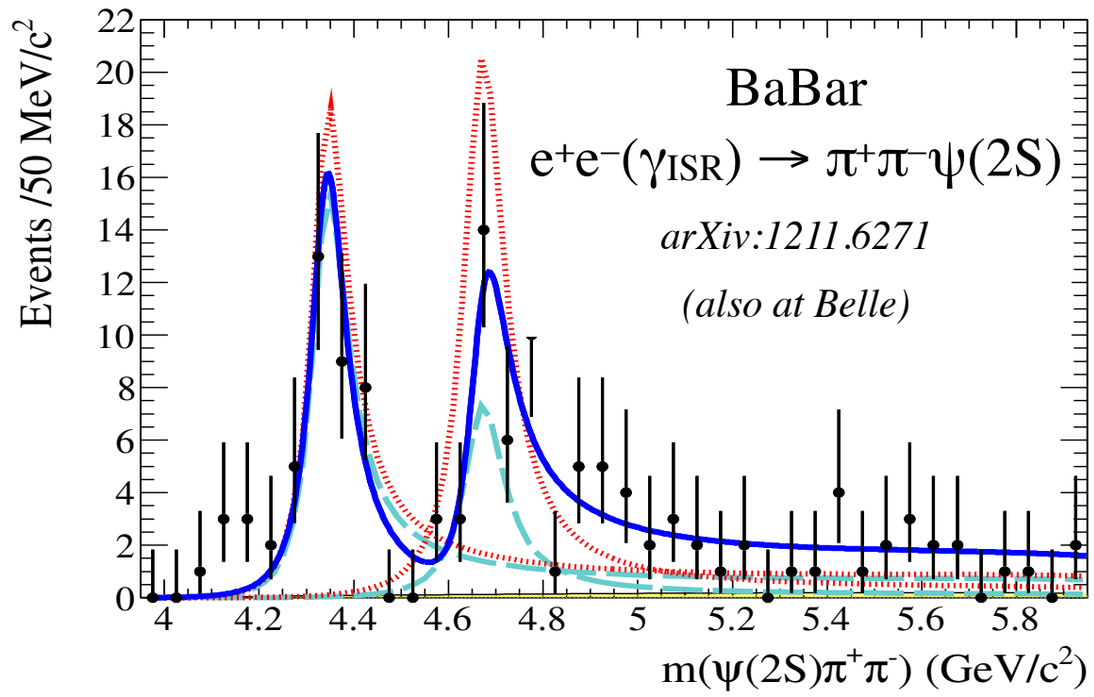


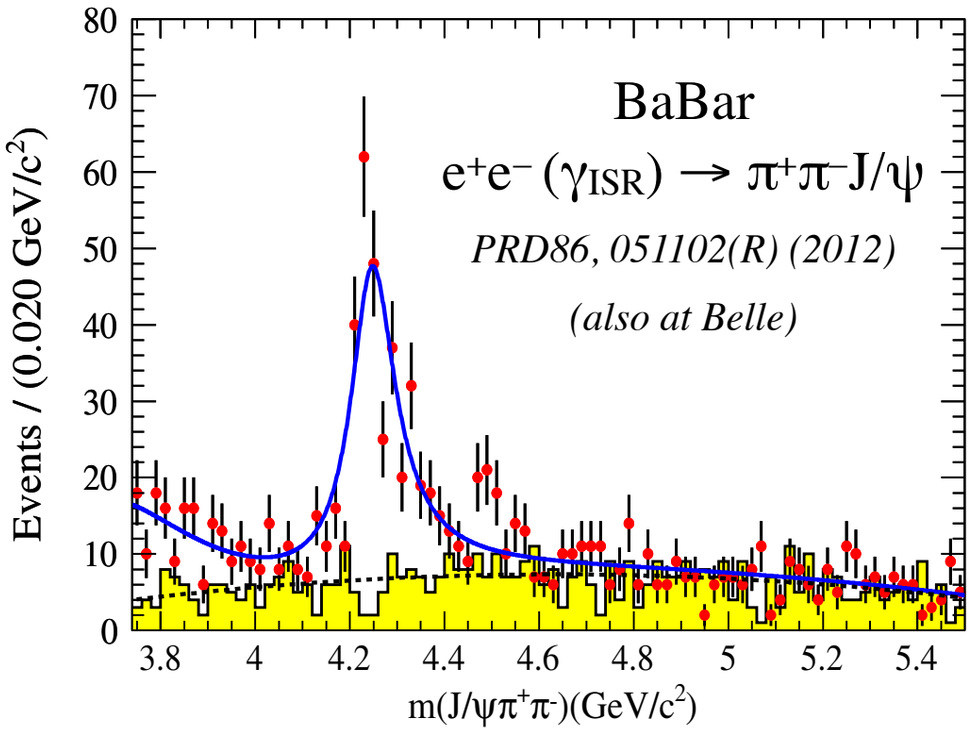

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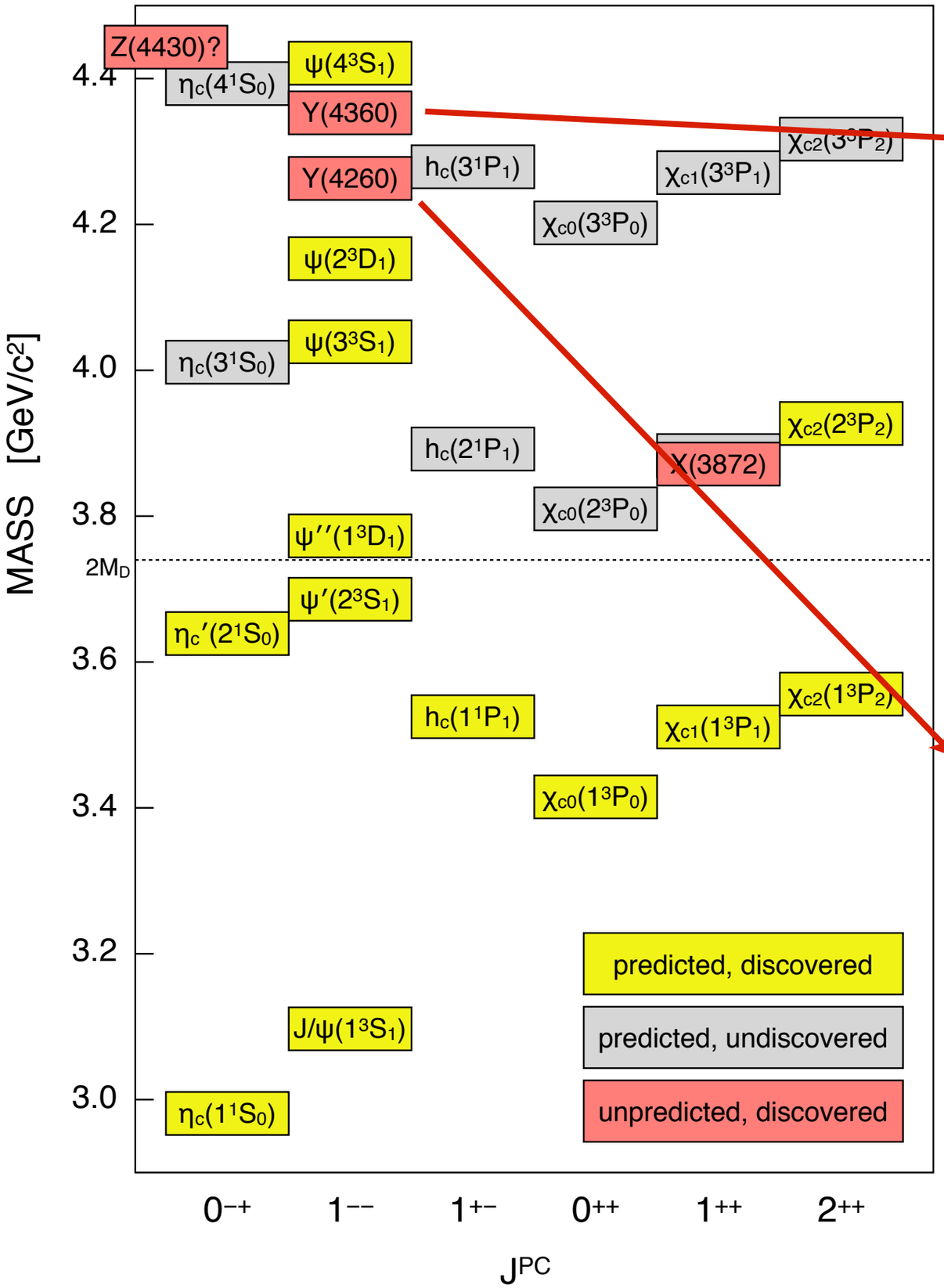
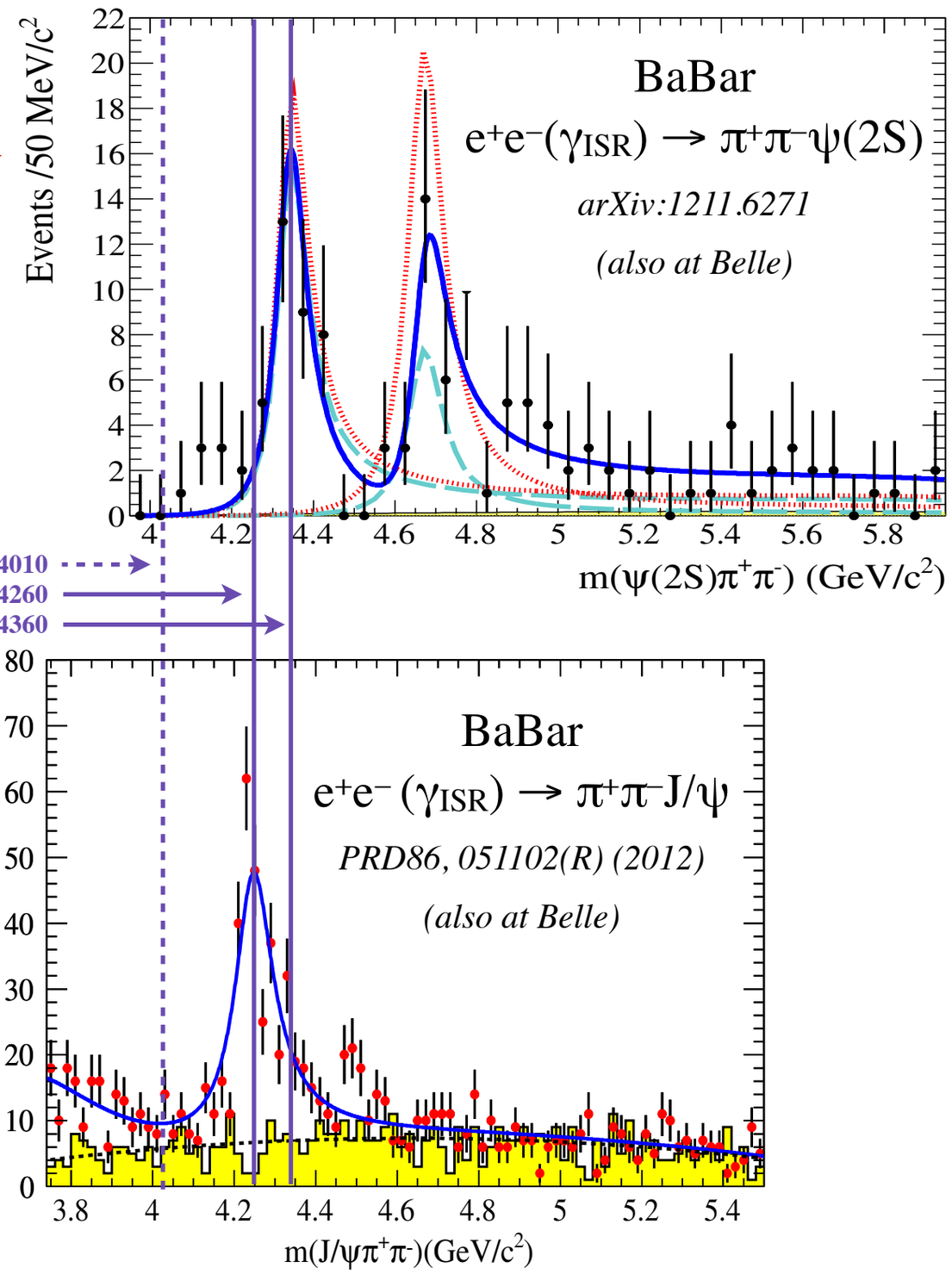
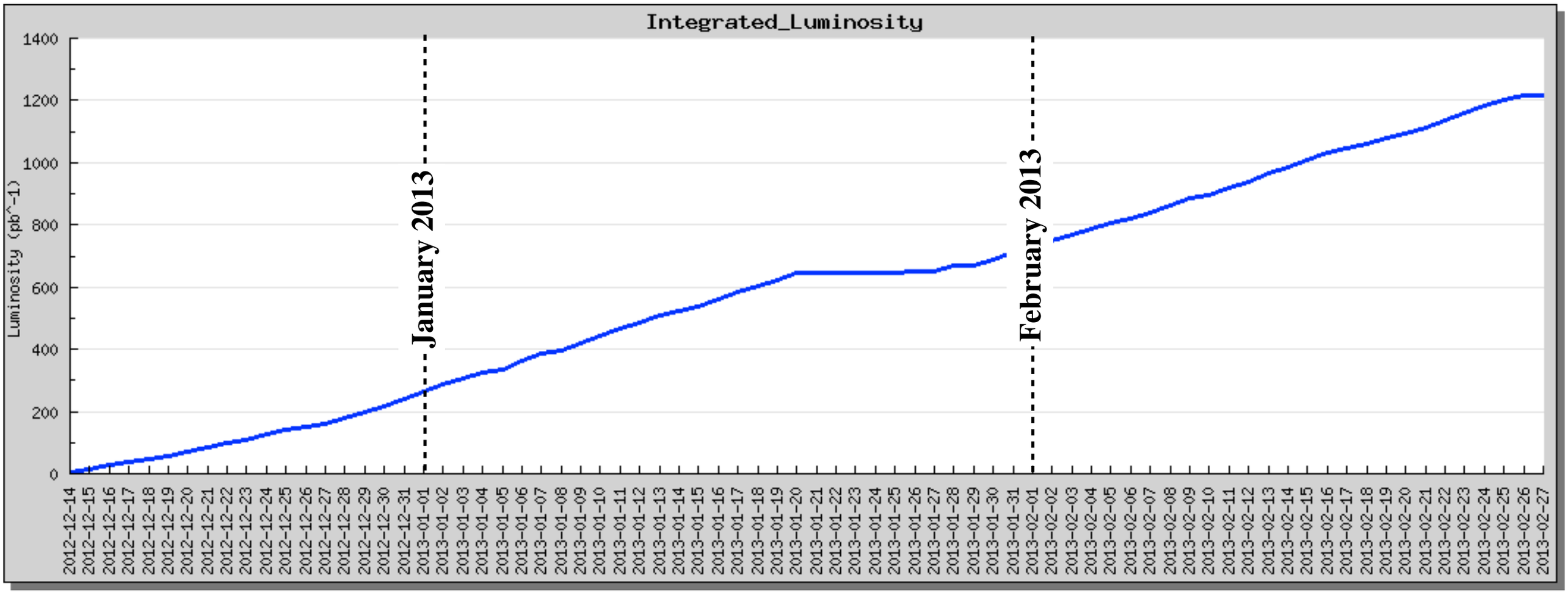



**BESIII: Take data at 4260 and 4360 MeV to study Y(4260) and Y(4360) decays.**

## BESIII Initial Round of Data-taking




**4260** (515 pb$^{-1}$)

***(world's largest sample of Y(4260) by ~2×)***

**4190** (42 pb$^{-1}$)

**4230** (43 pb$^{-1}$)

**4310** (44 pb$^{-1}$)

**4360** (523 pb$^{-1}$)

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**4420** (43 pb$^{-1}$)

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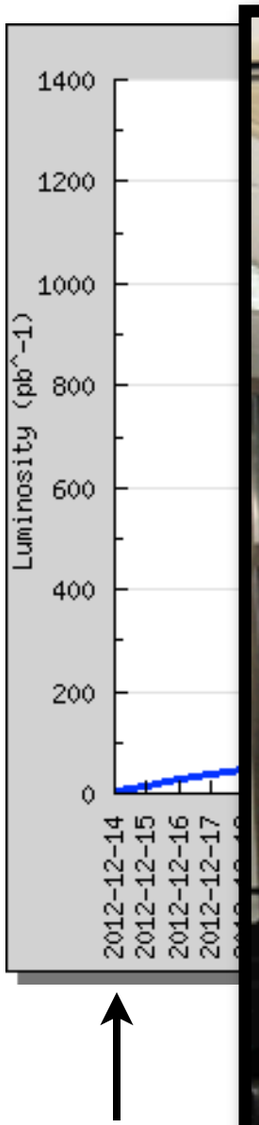



53 pb$^{-1}$)

43 pb$^{-1}$)

# IV. A New Era of Discovery

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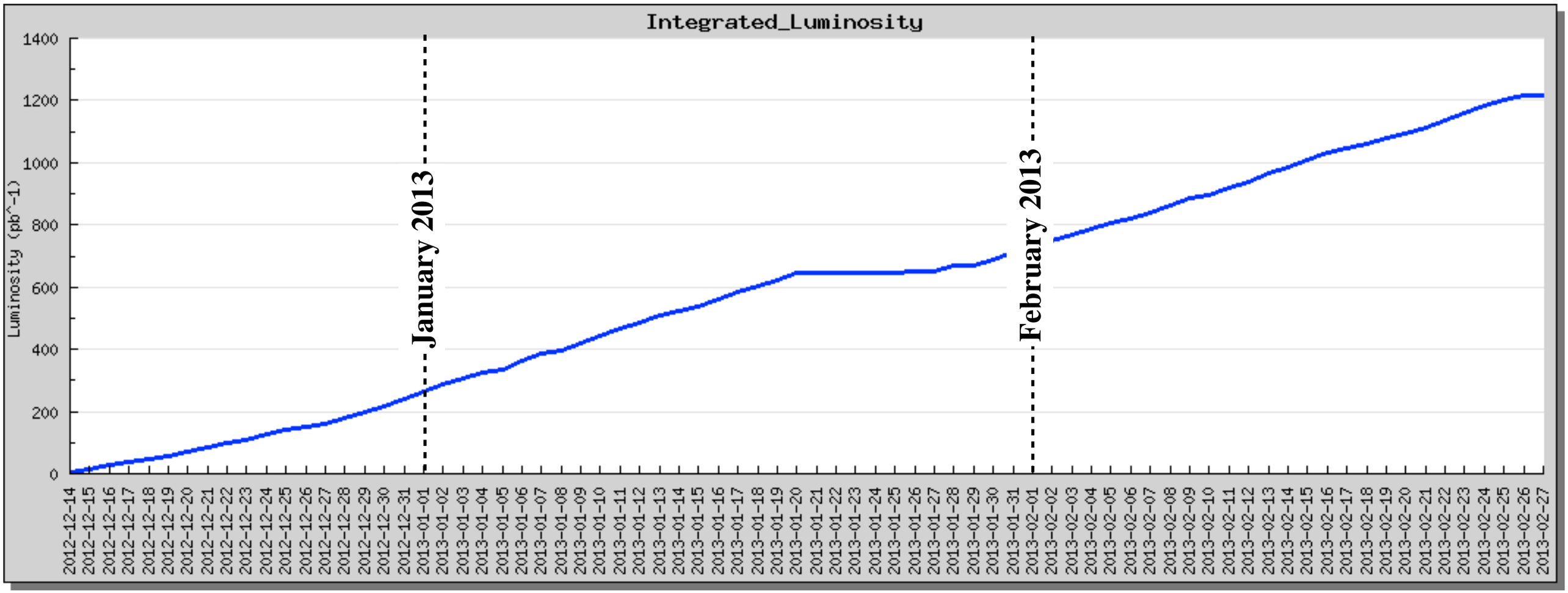


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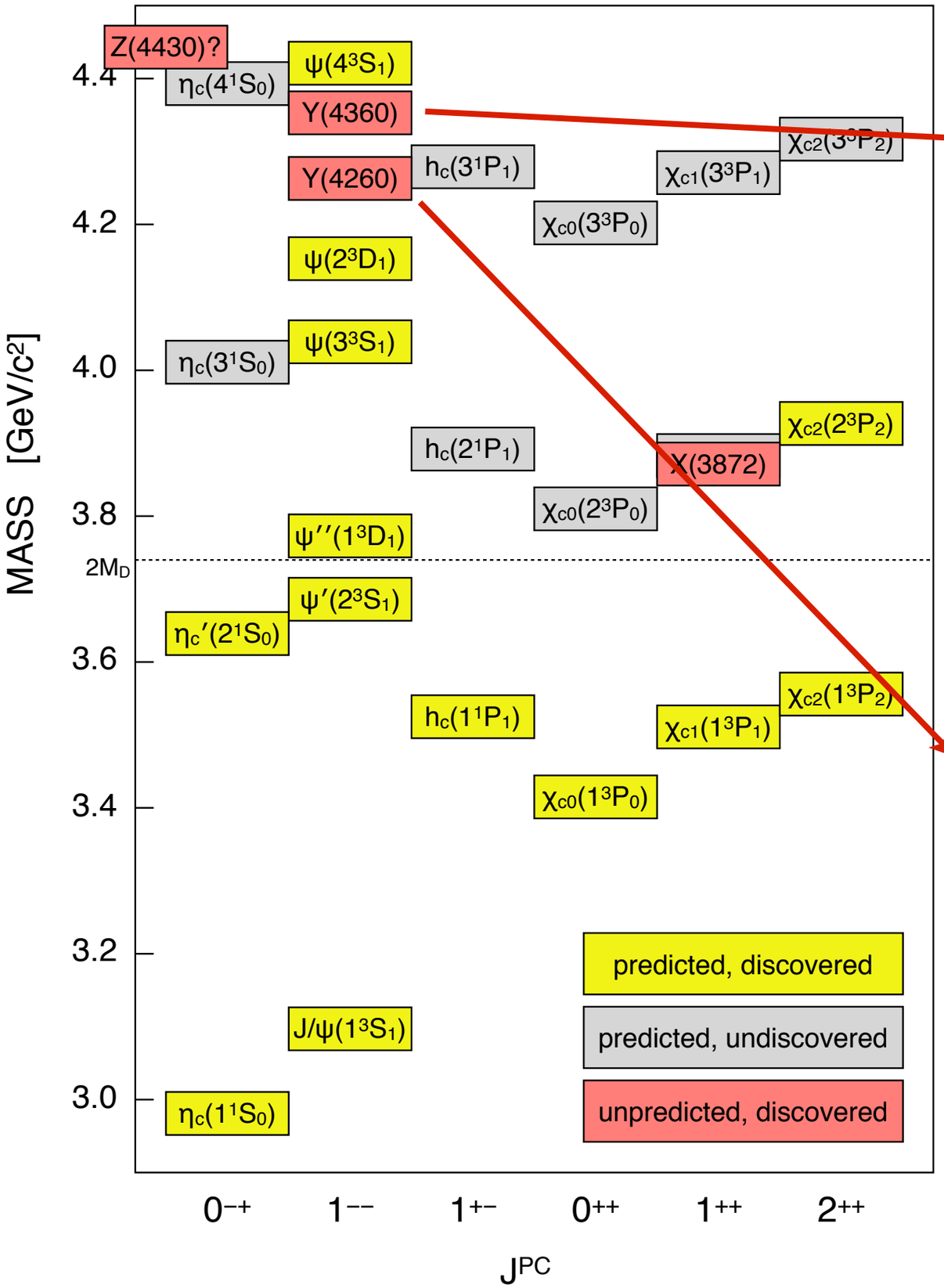


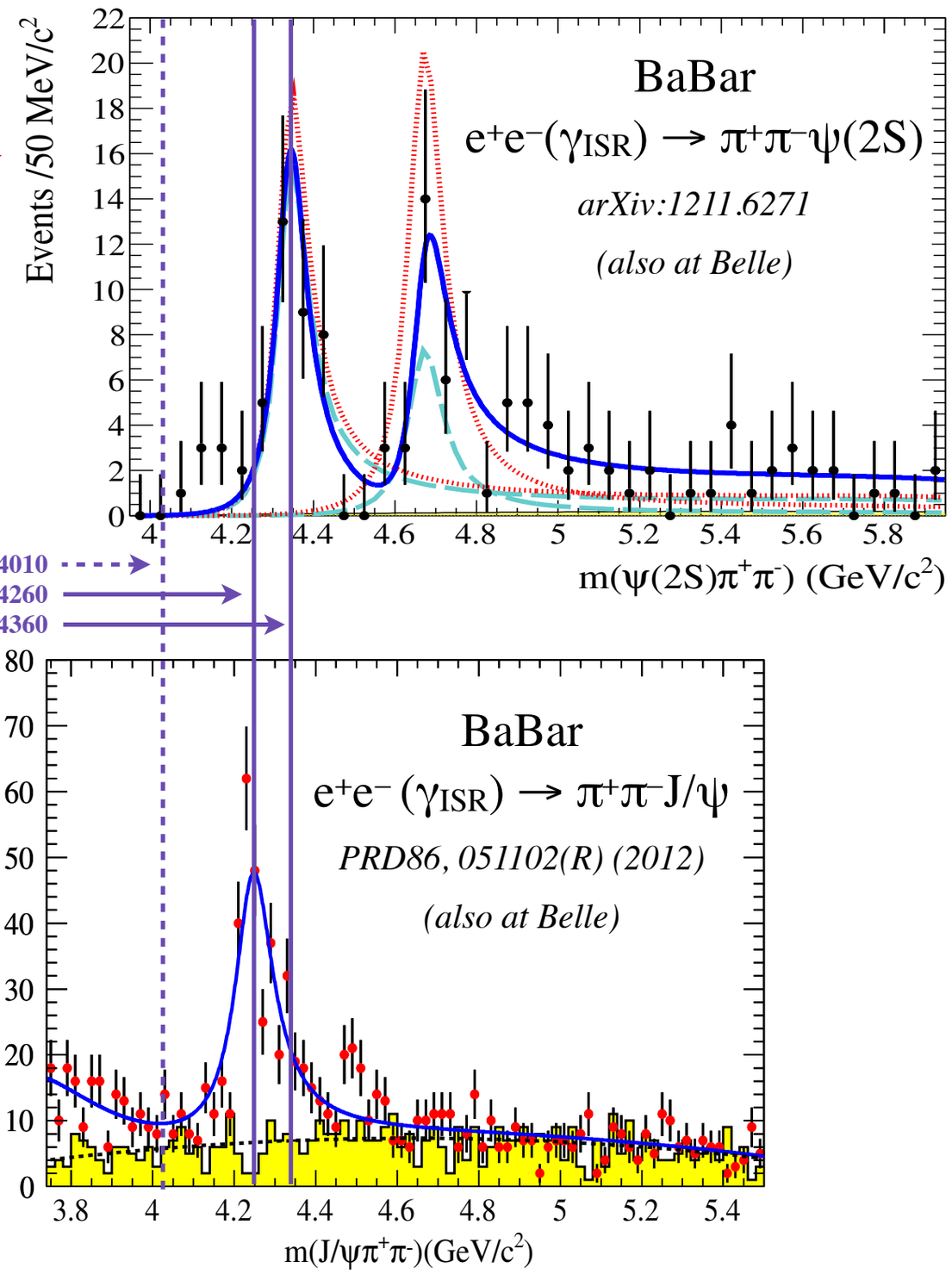


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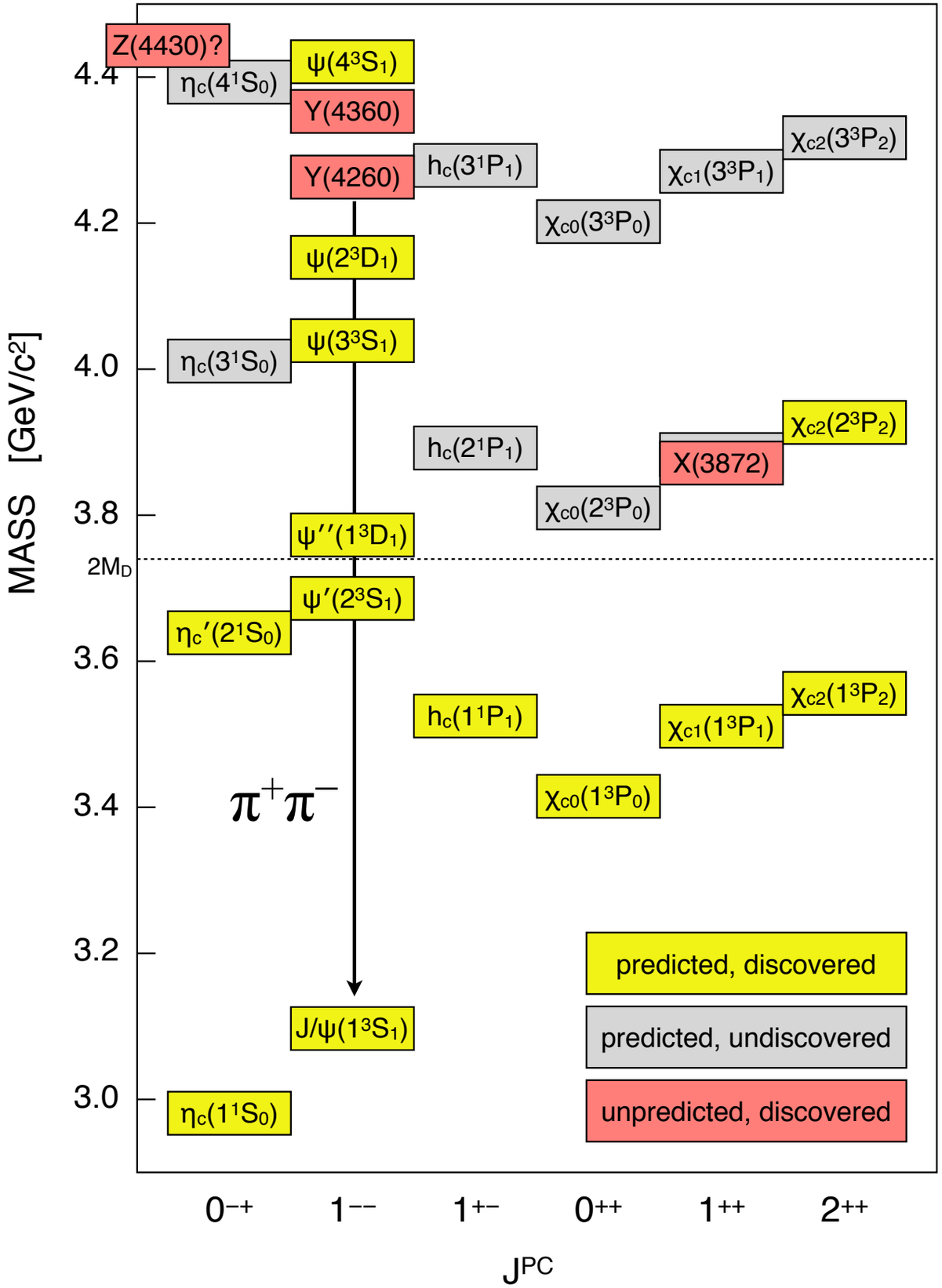
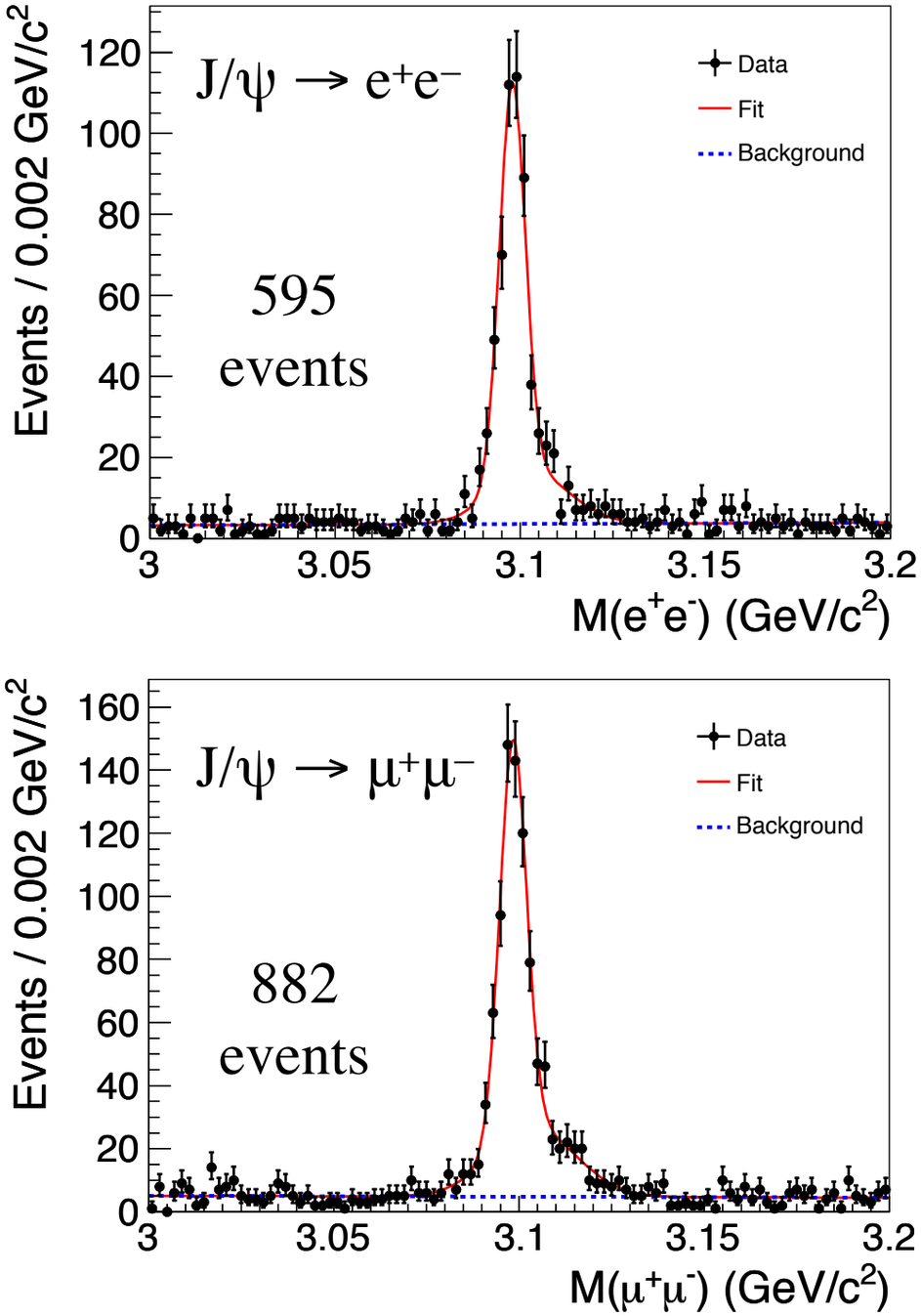


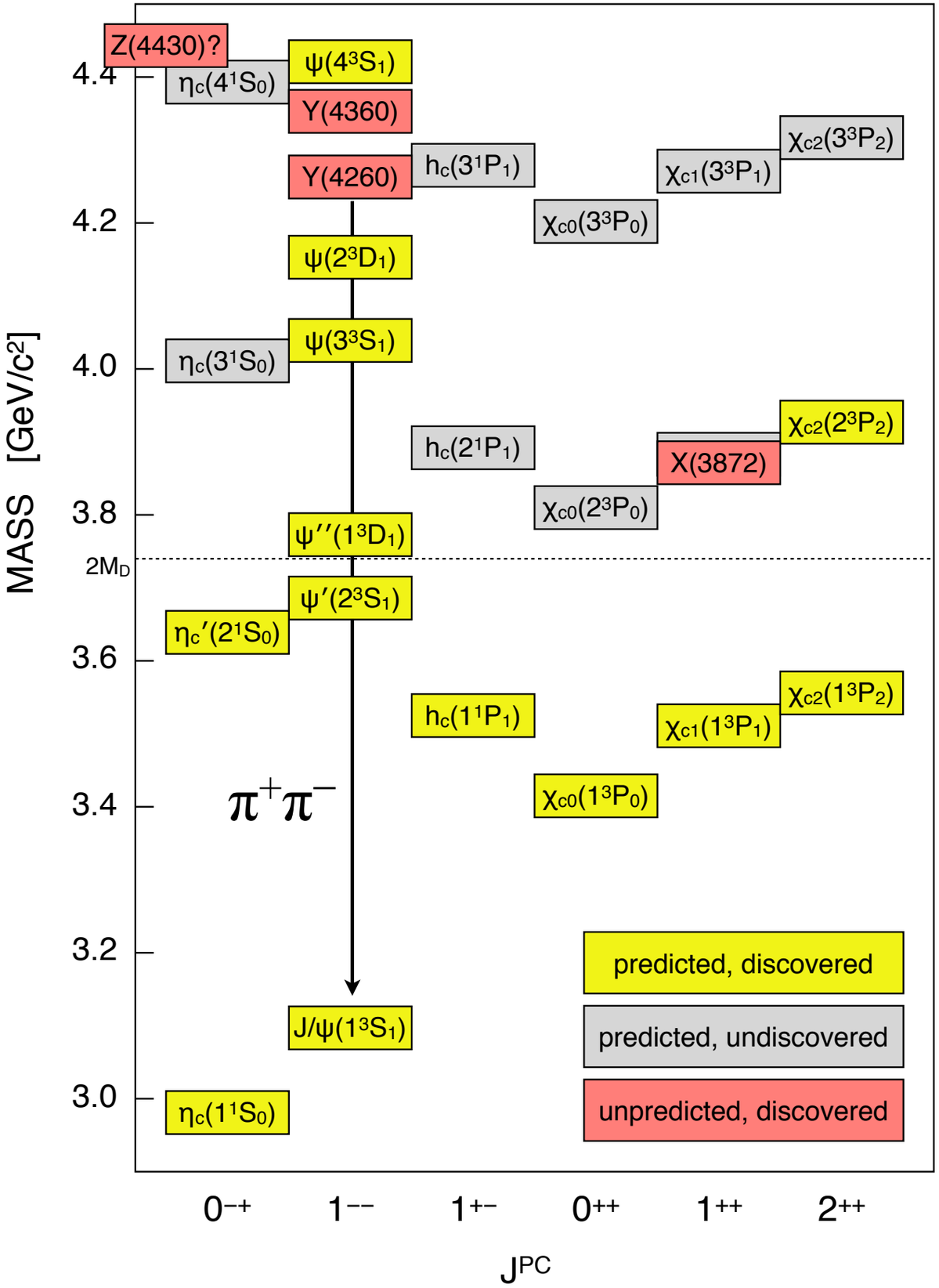

*$e^+e^-$ (at 4260 MeV) → $\pi^+\pi^- J/\psi$ at BESIII*



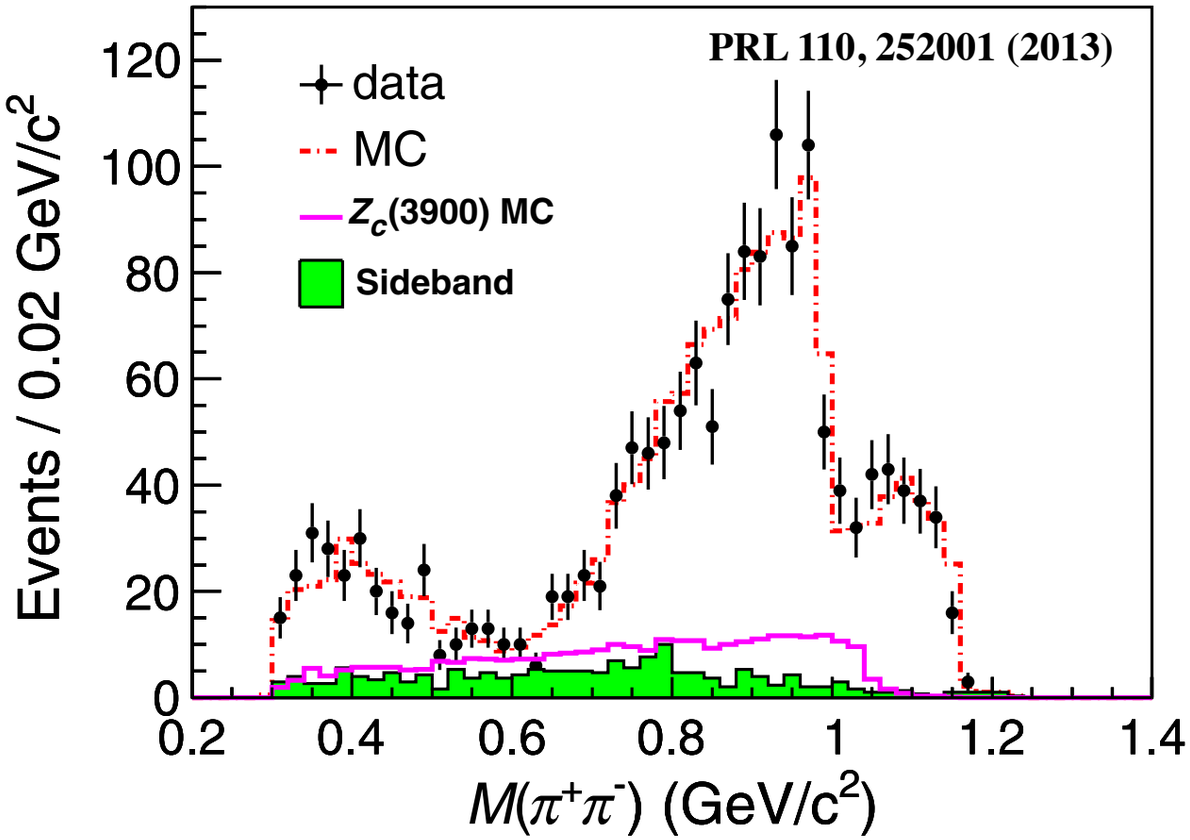

**PRL 110, 252001 (2013)**

*(cross section consistent with Belle and BaBar)*

# IV. A New Era of Discovery




$e^+e^-$ *(at 4260 MeV)* $\rightarrow \pi^+\pi^- J/\psi$ *at BESIII*




non-trivial substructure in $\pi^+\pi^- J/\psi$

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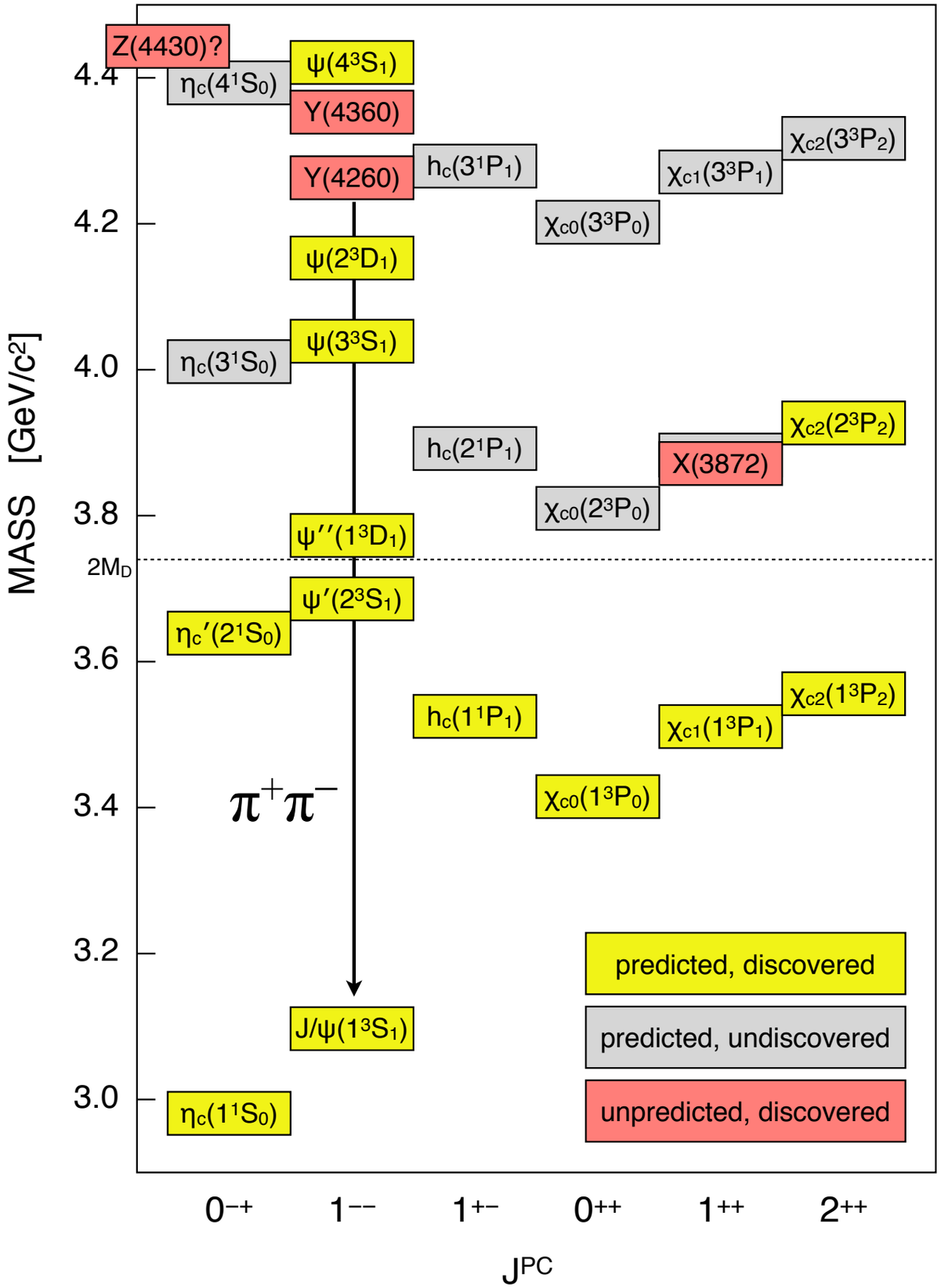


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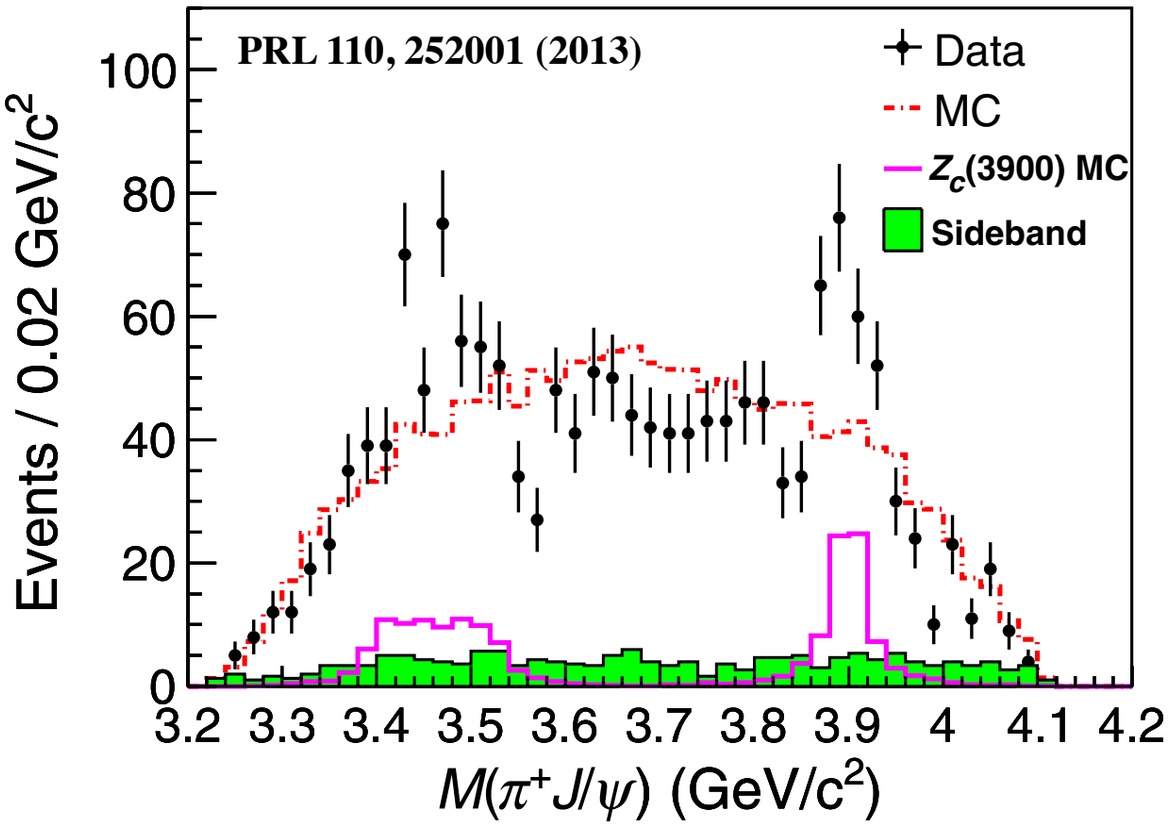


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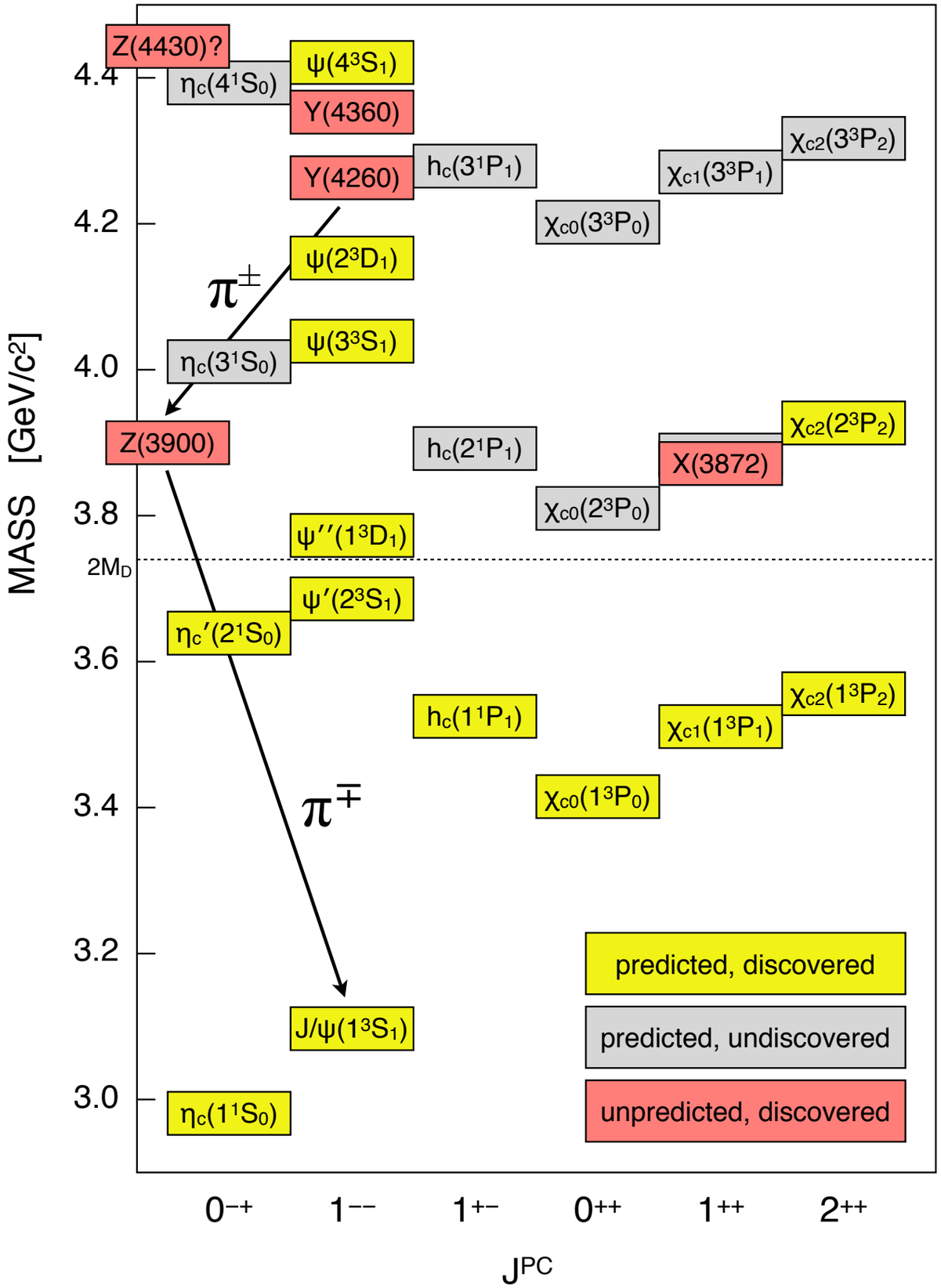


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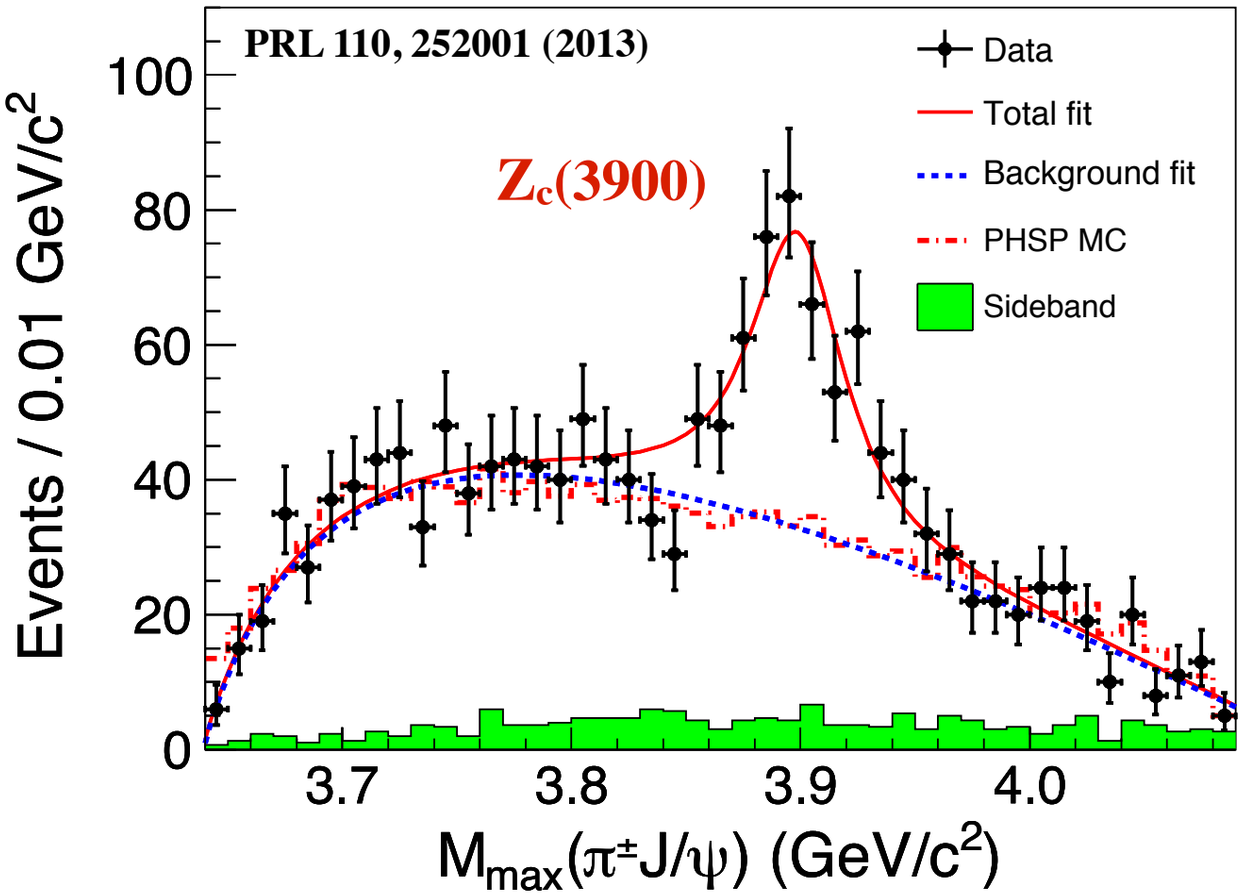


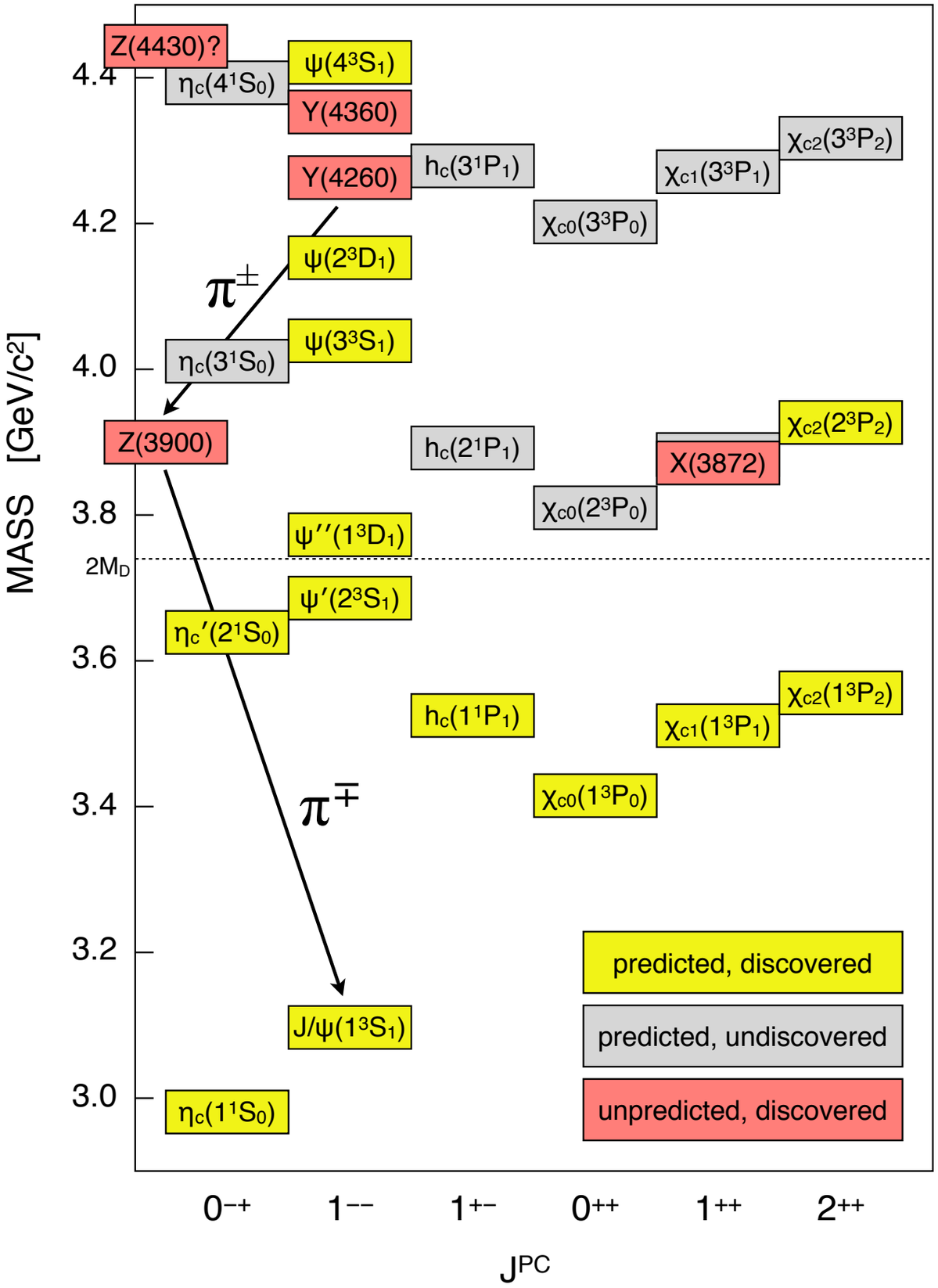

M = 3899.0 ± 3.6 ± 4.9 MeV
Γ = 46 ± 10 ± 20 MeV

**⇒ "Charged Charmoniumlike Structure"**

*(Confirmed by Belle and CLEO data.)*

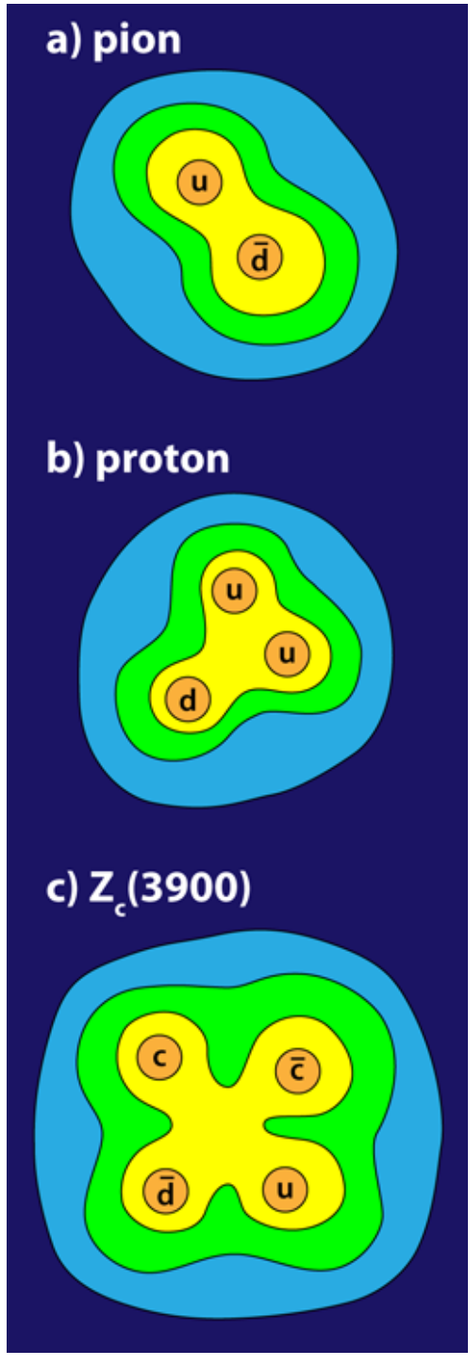
*(Many theoretical ideas -- close to D*D threshold.)*

# IV. A New Era of Discovery




## Viewpoint: New Particle Hints at Four-Quark Matter

Eric Swanson, University of Pittsburgh, Pittsburgh, PA 15260, USA
Published June 17, 2013 | Physics **6**, 69 (2013) | DOI: 10.1103/Physics.6.69



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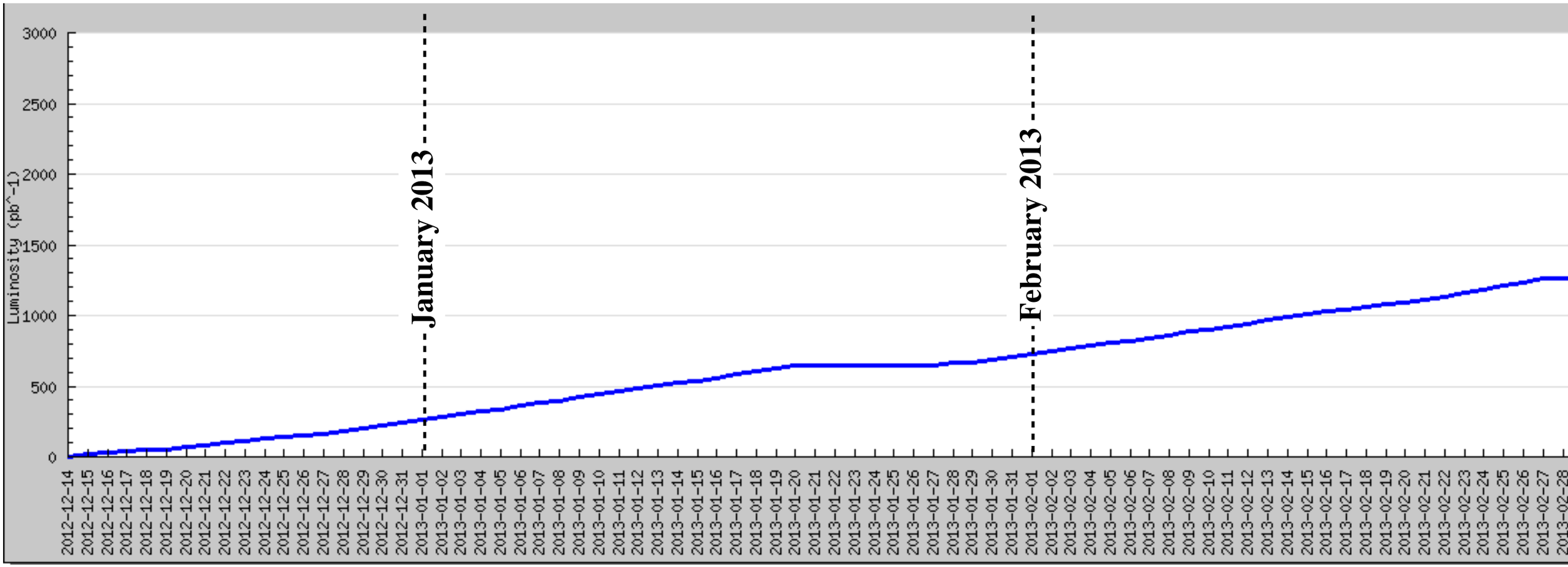


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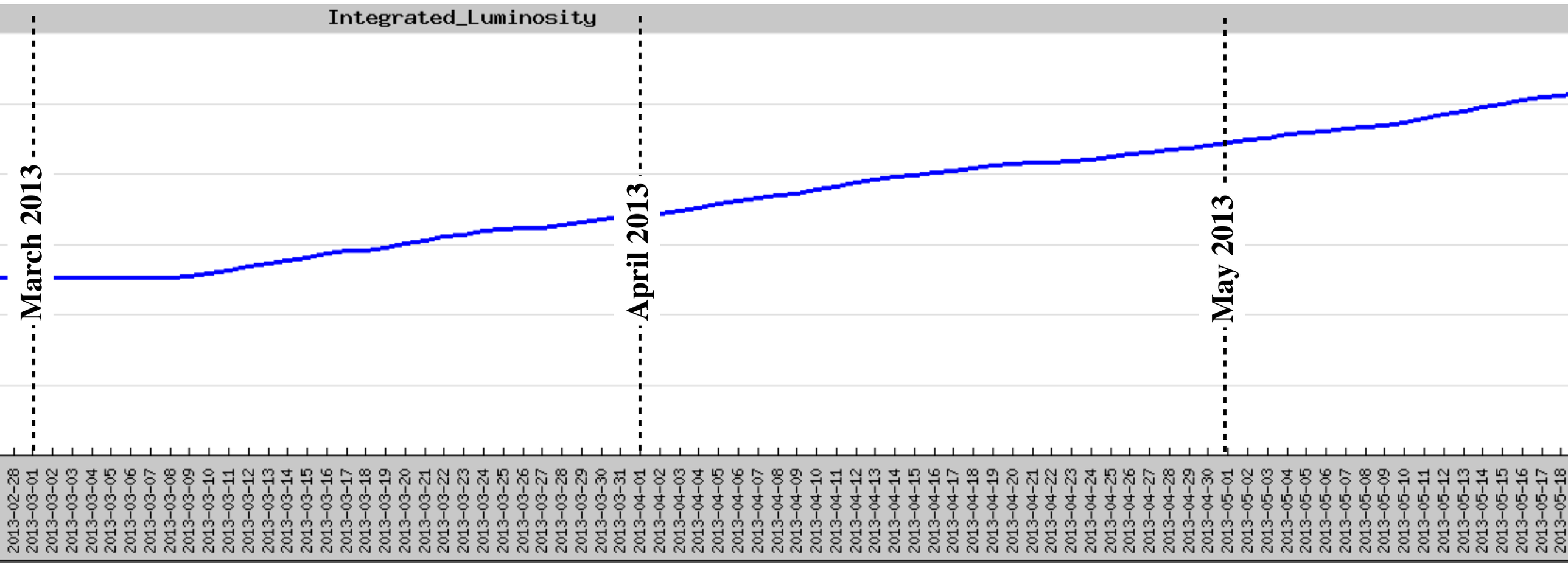



*BESIII meeting*

**4260** (291 pb$^{-1}$)

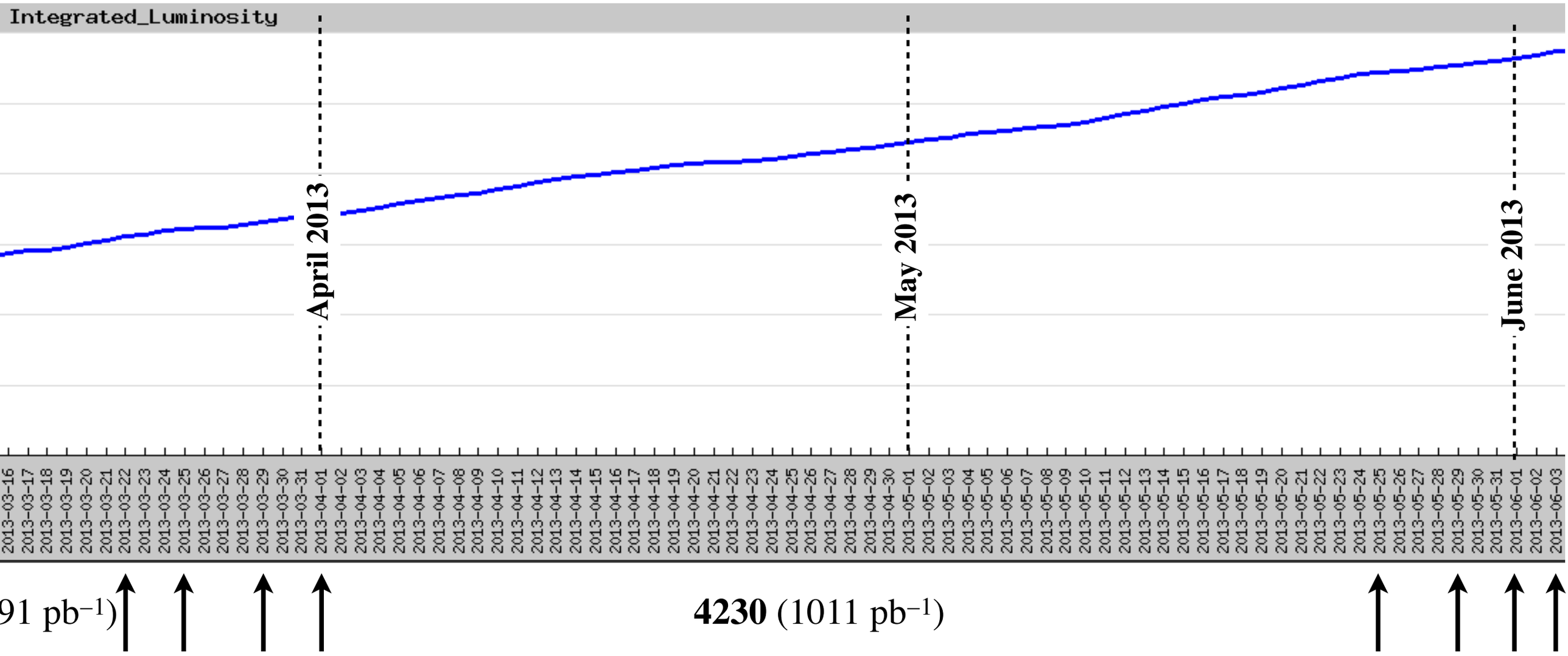
**4210** (52 pb$^{-1}$)

**4220** (52 pb$^{-1}$)

**4245** (53 pb$^{-1}$)

**4230** (1011 pb$^{-1}$)

## BESIII Additional Round of Data-taking




91 pb$^{-1}$)

**4230** (1011 pb$^{-1}$)

**4210** (52 pb$^{-1}$)

**4220** (52 pb$^{-1}$)

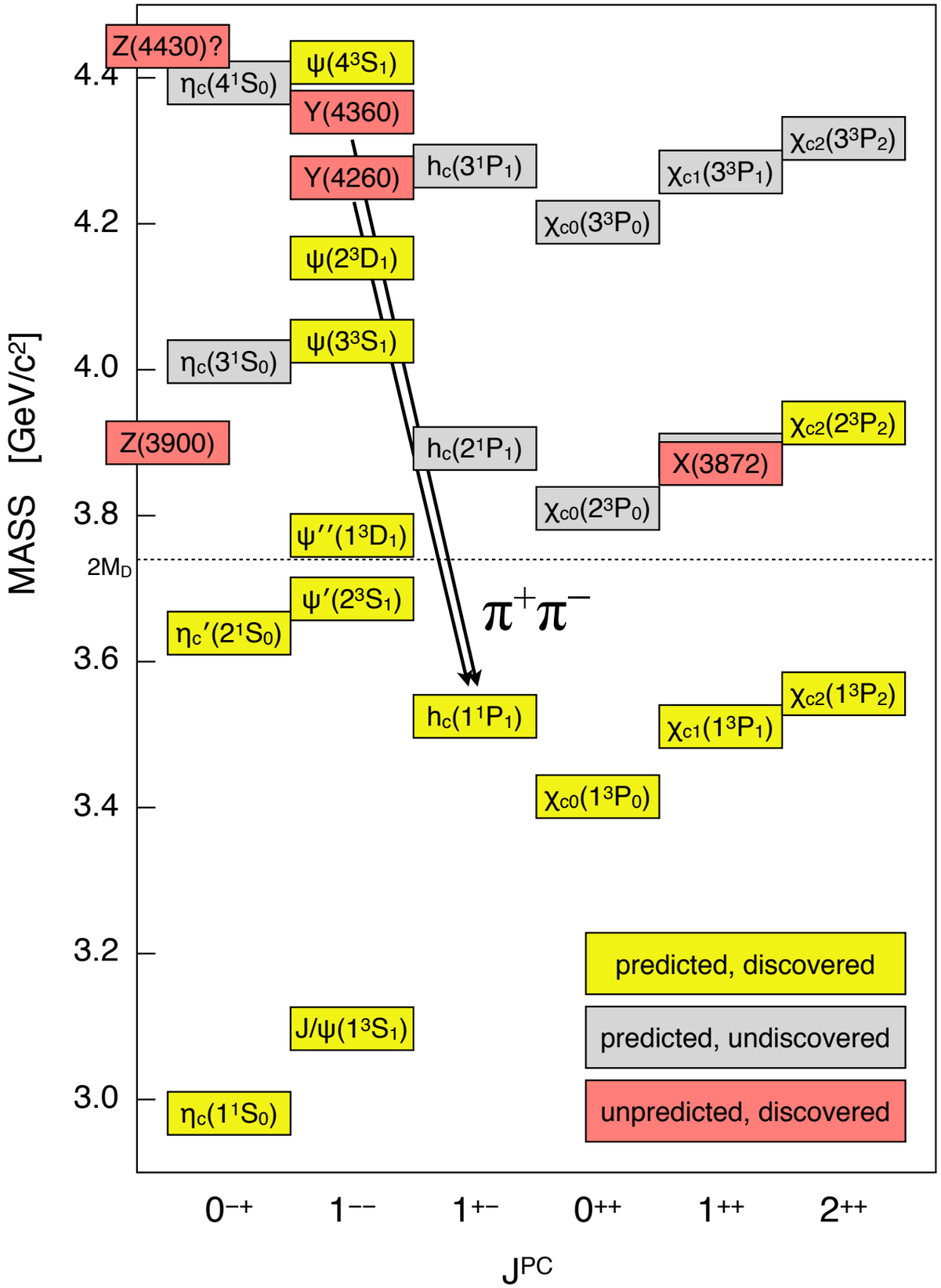
**4245** (53 pb$^{-1}$)

**3810** (48 pb$^{-1}$)

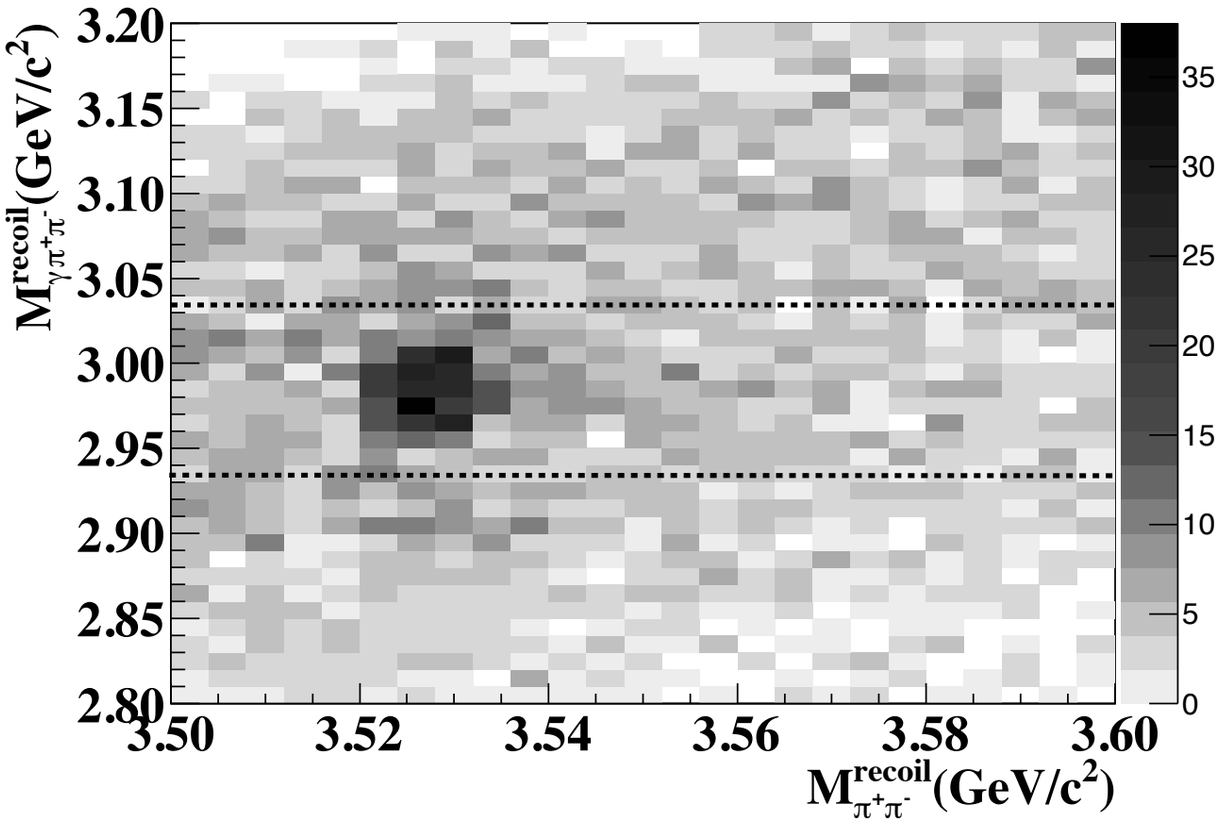
**3900** (50 pb$^{-1}$)

**4090** (50 pb$^{-1}$)

# IV. A New Era of Discovery




*$e^+e^-$ (at 4260 MeV) → $\pi^+\pi^- h_c(1P)$ at BESIII*




**arXiv:1309:1896**

Exclusively reconstruct the process:

$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

$h_c(1P) \rightarrow \gamma\eta_c(1S)$

$\eta_c(1S) \rightarrow$ **16 decay channels**

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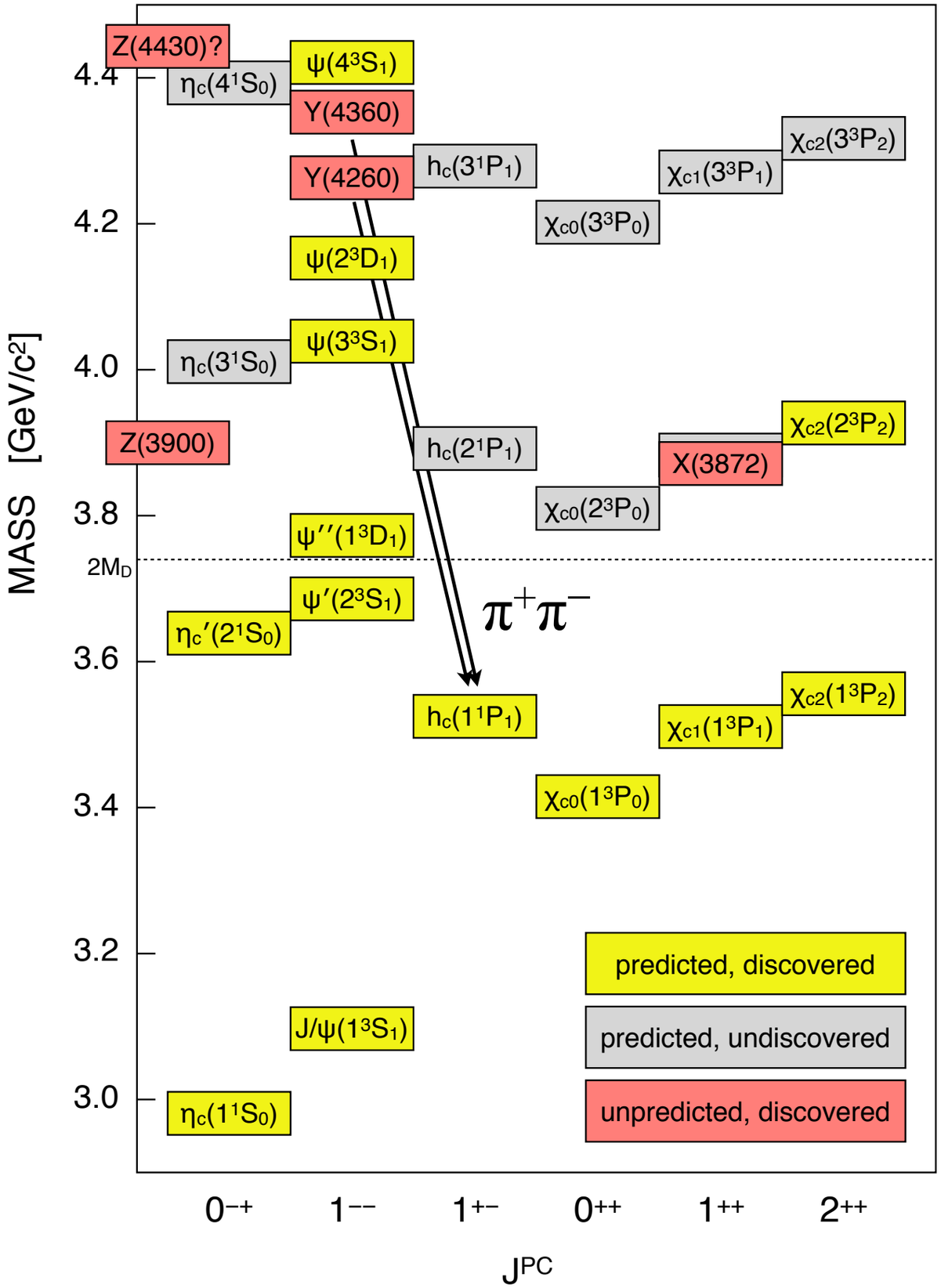


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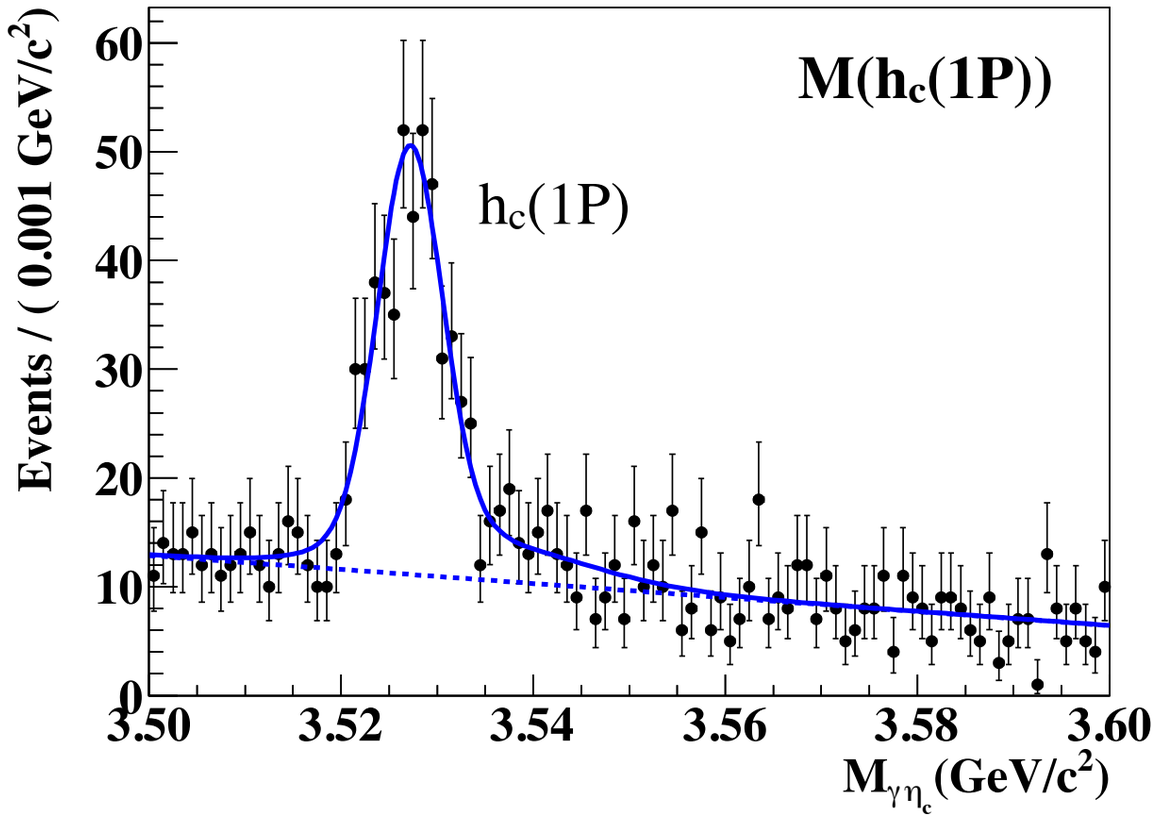


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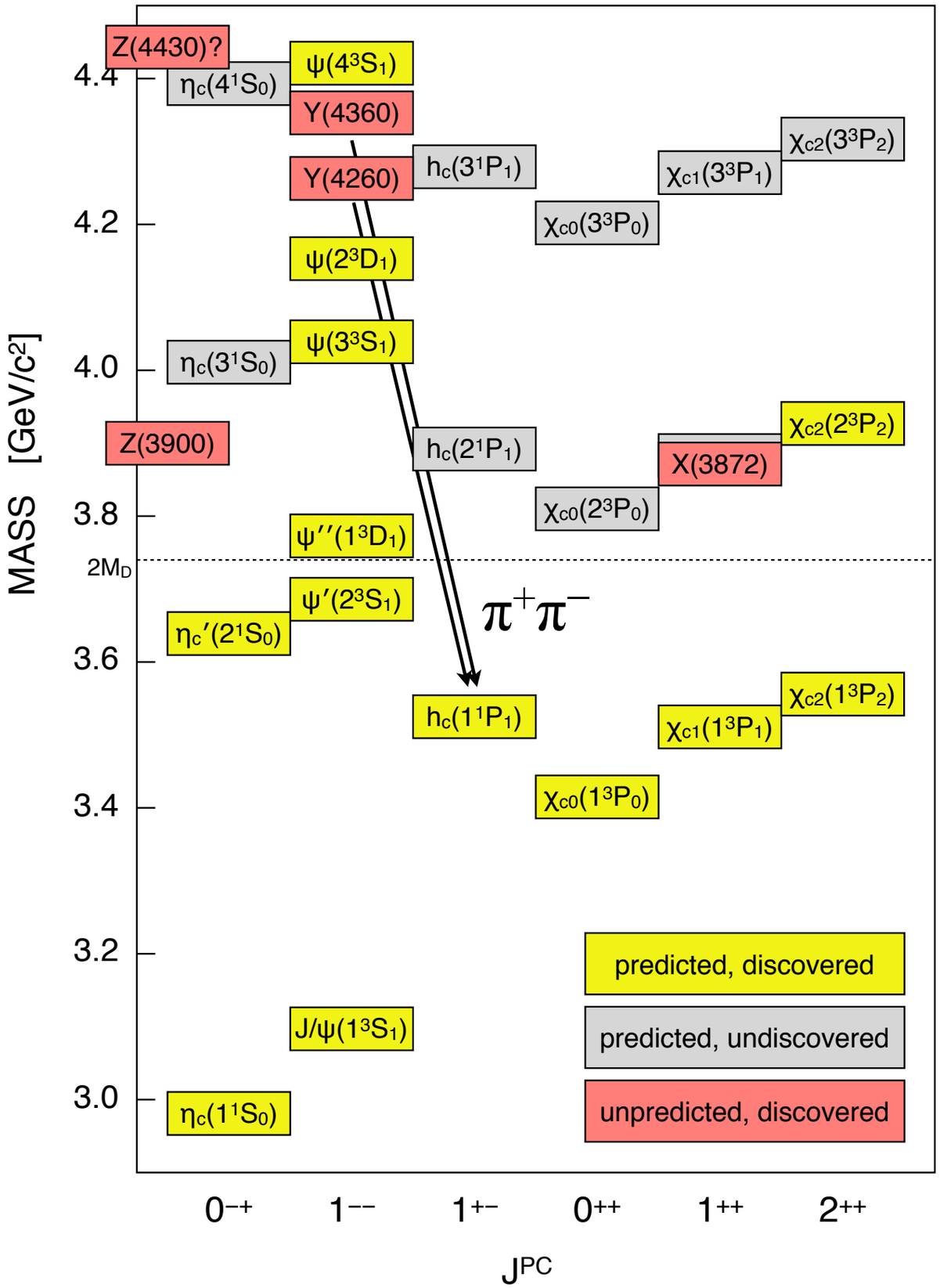


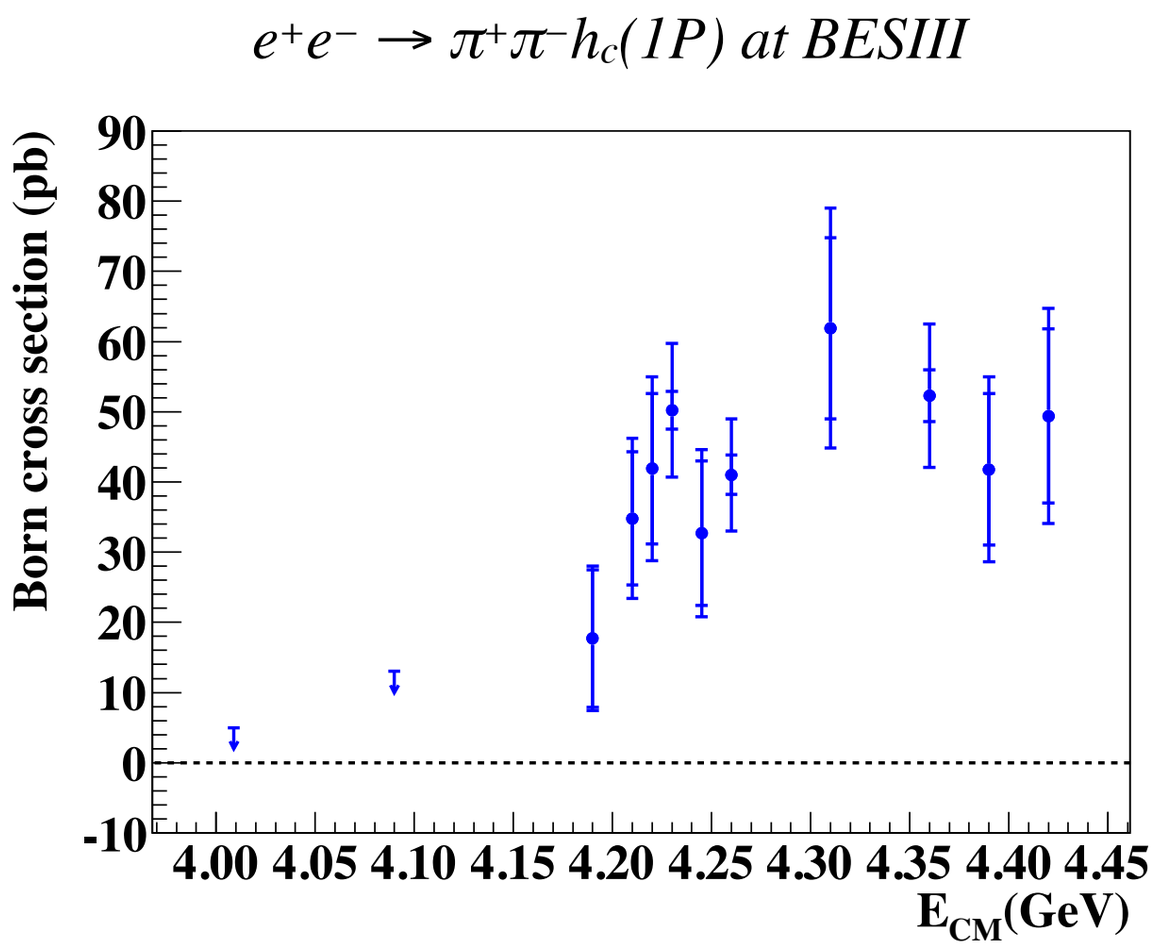


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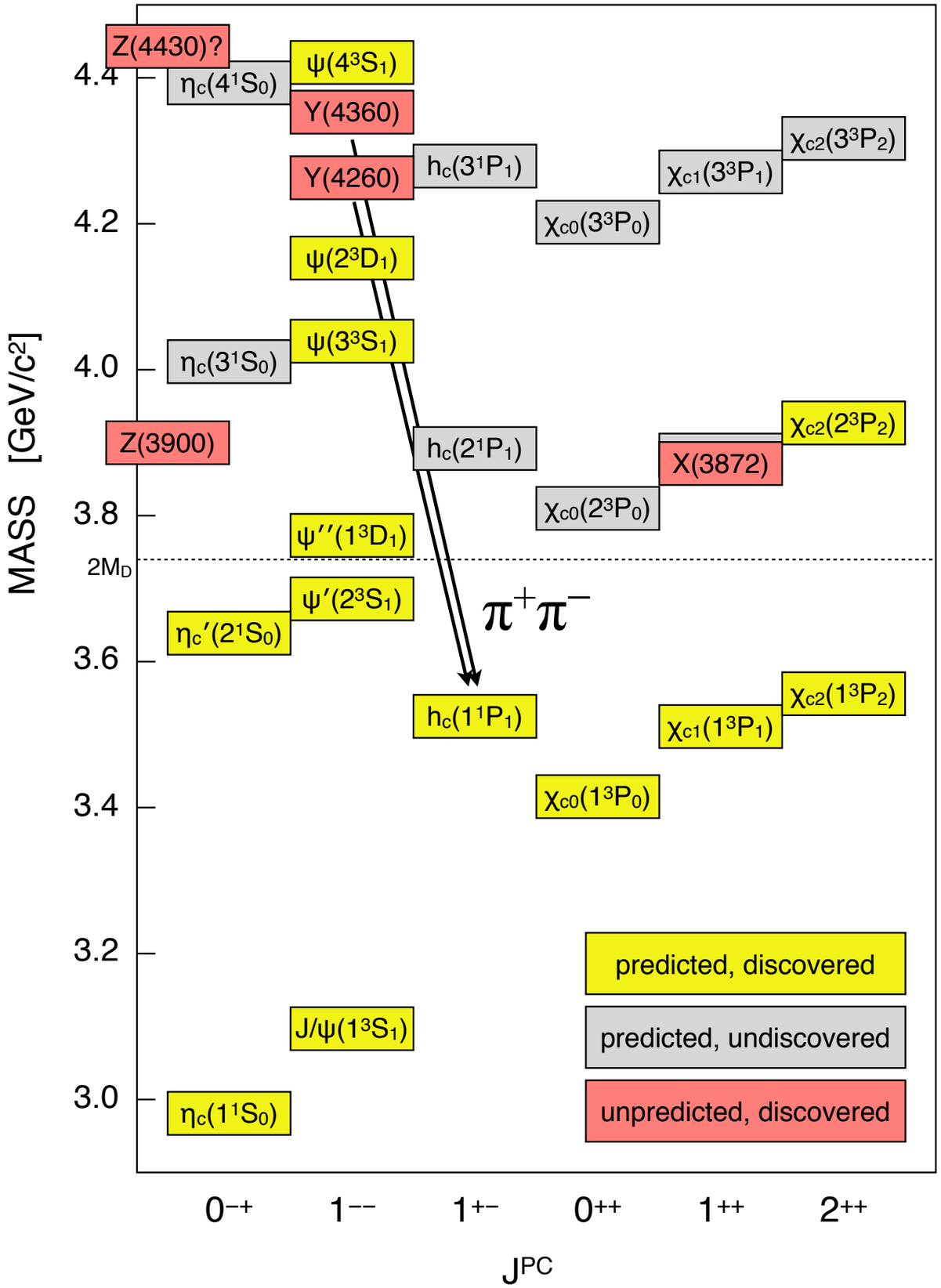


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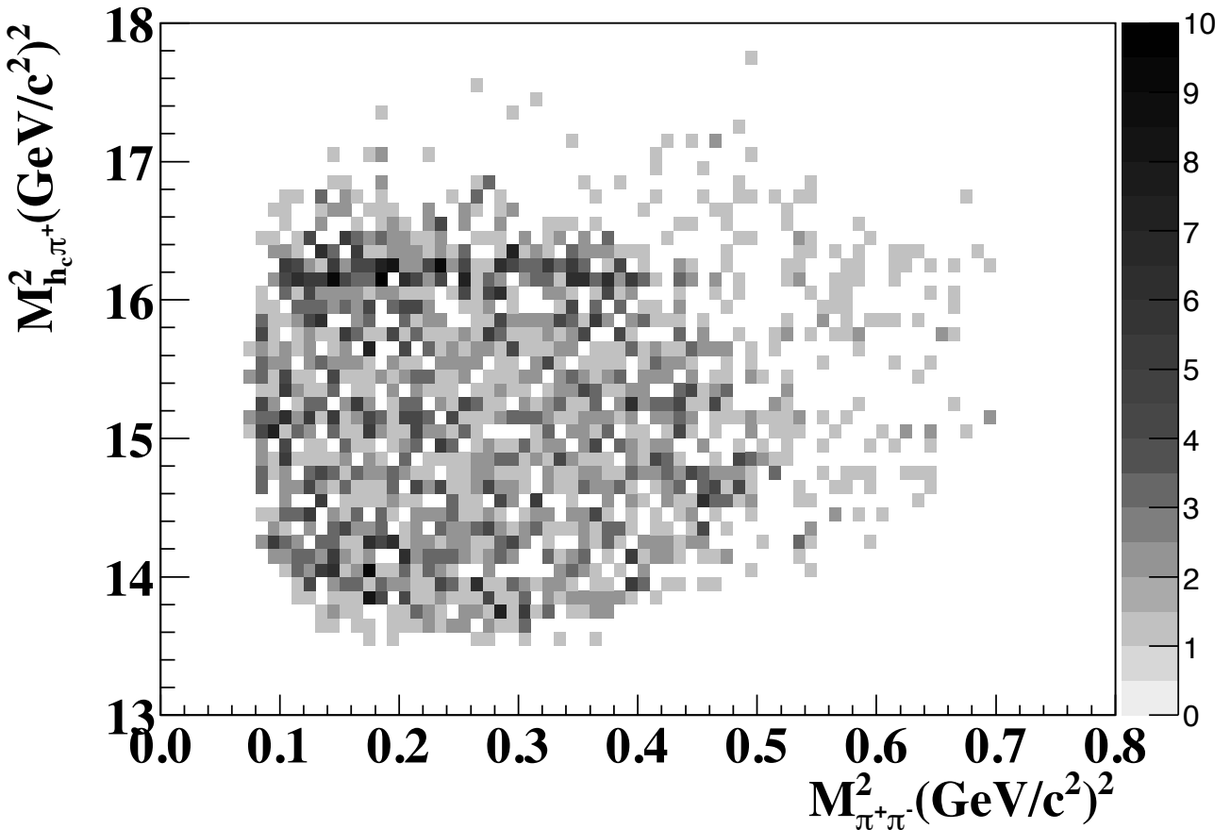


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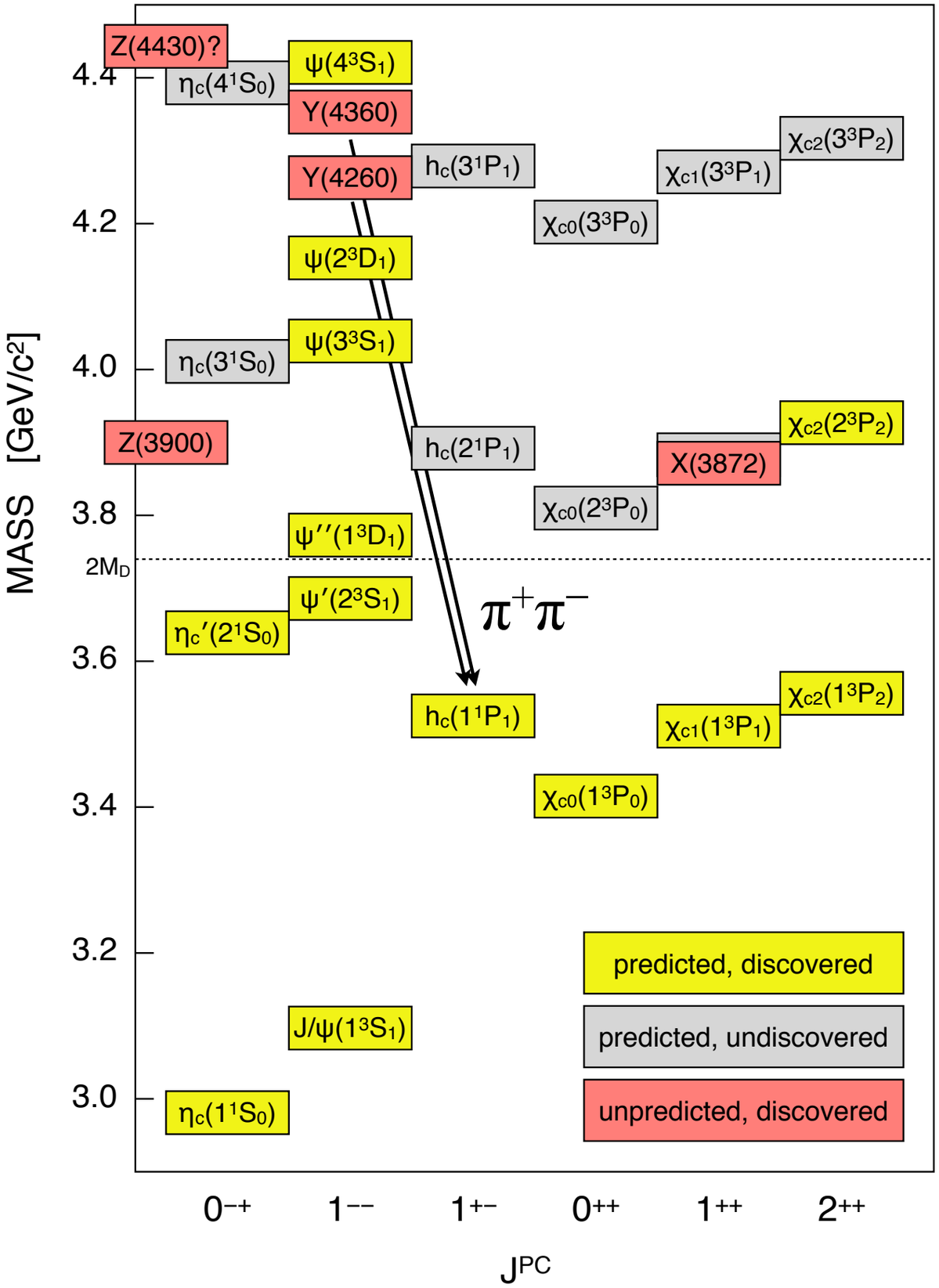


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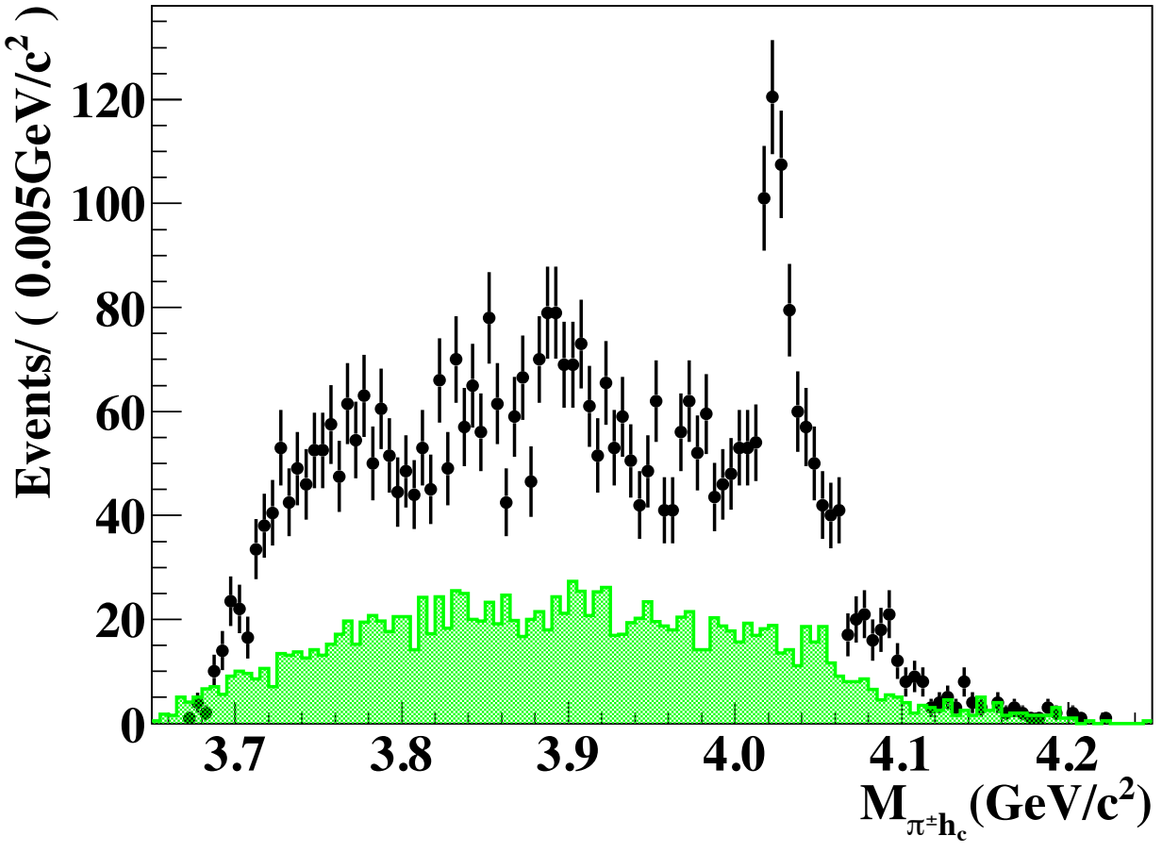


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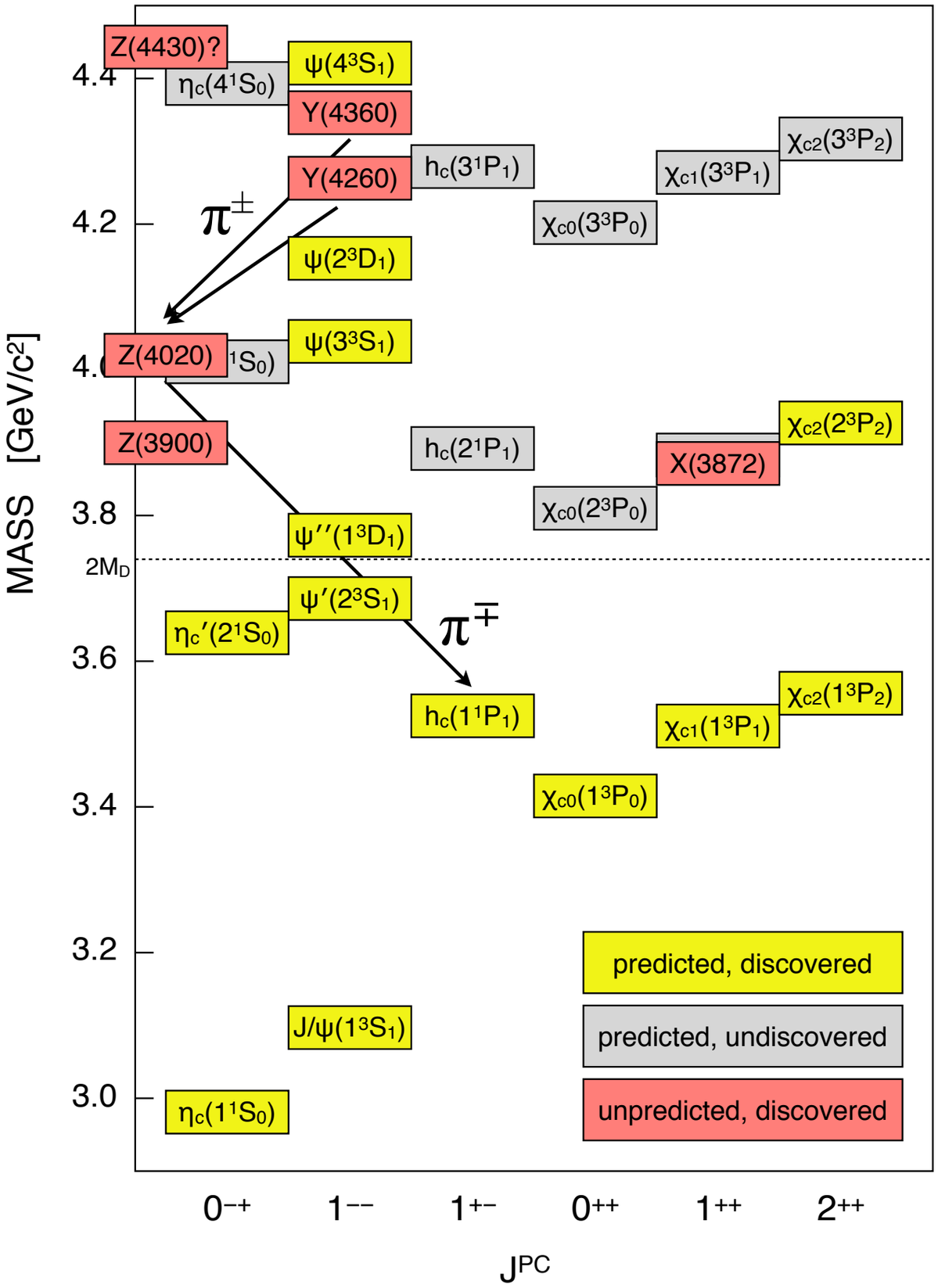


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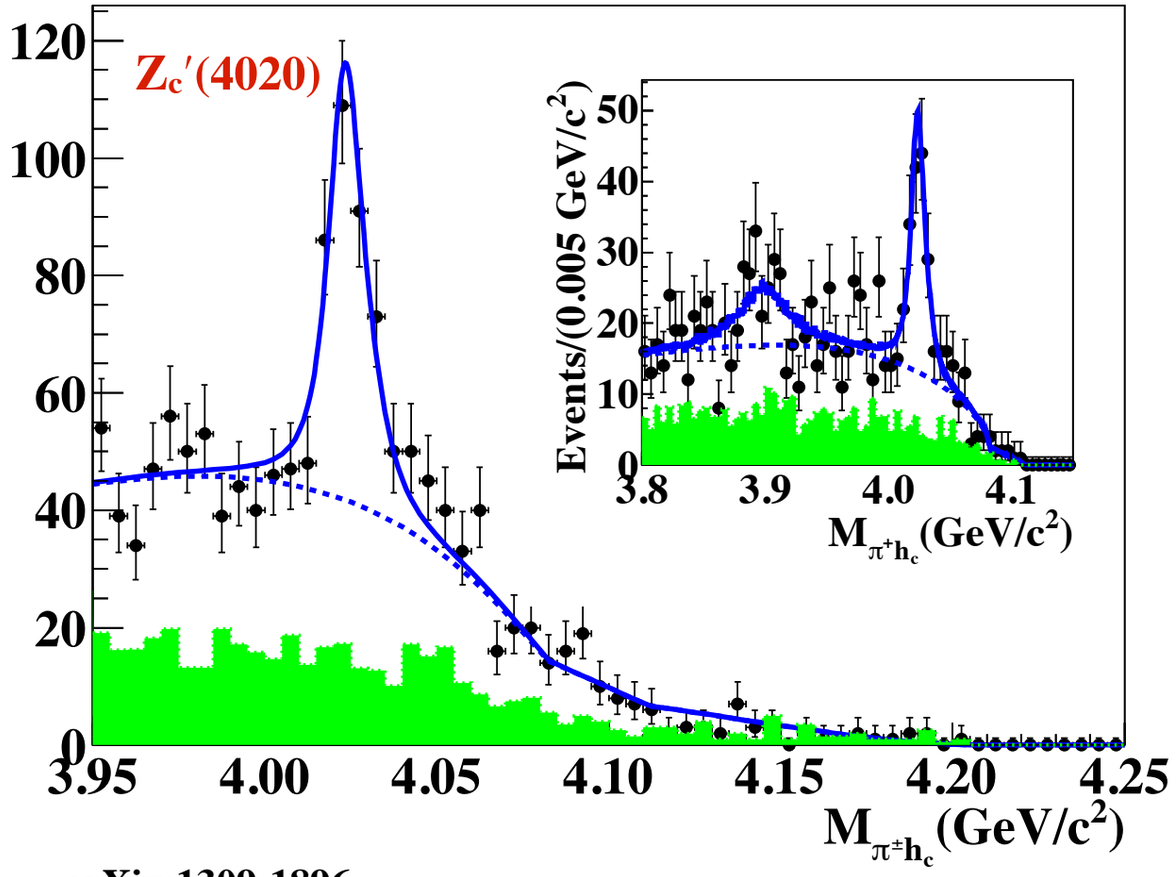



arXiv:1309:1896

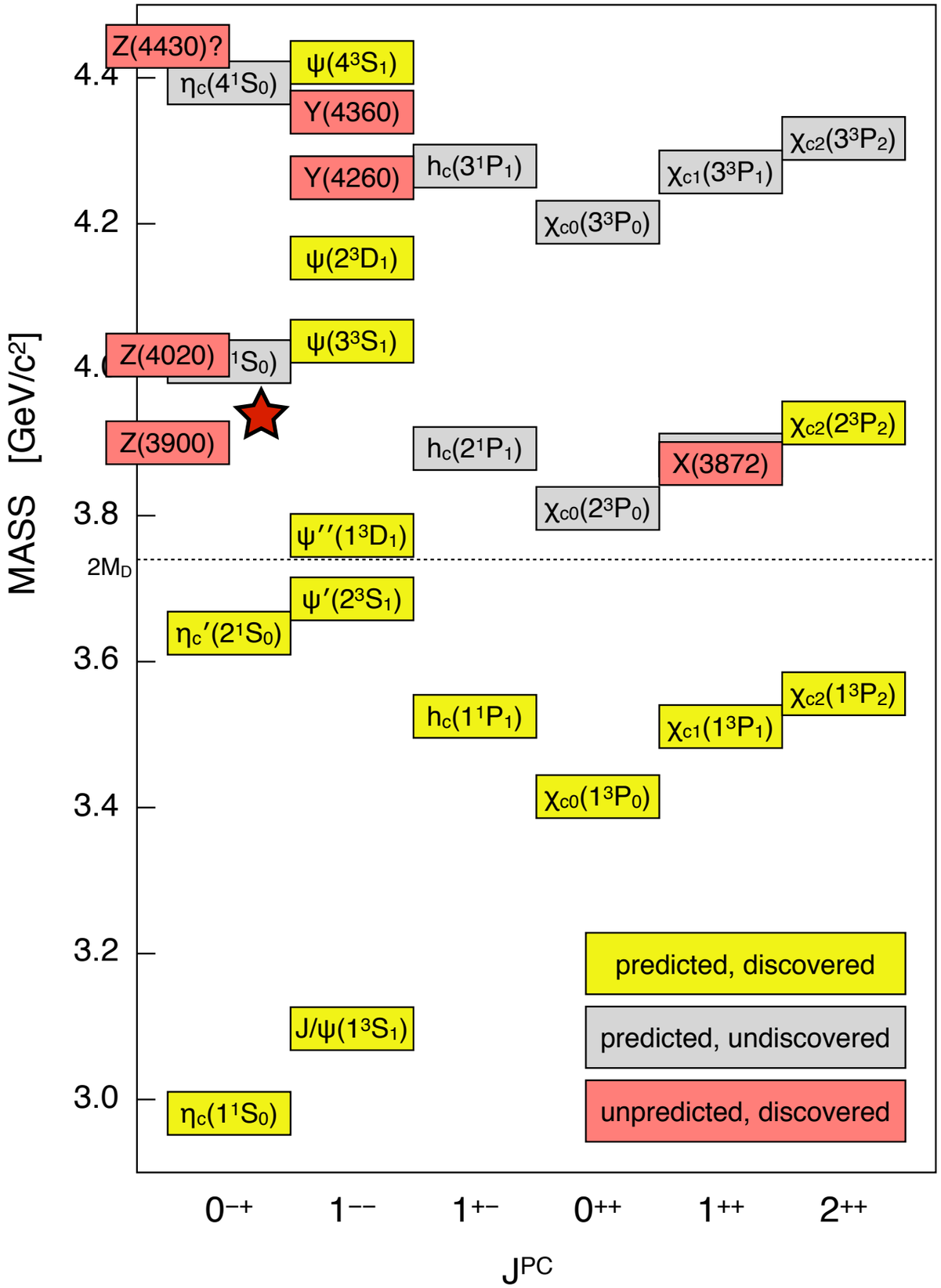
⇒ **"Charged Charmoniumlike Structure"**

*(this time close to D*D* threshold)*

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

# IV. A New Era of Discovery




The $Z_c(3900)$ is close to $DD^*$ threshold...

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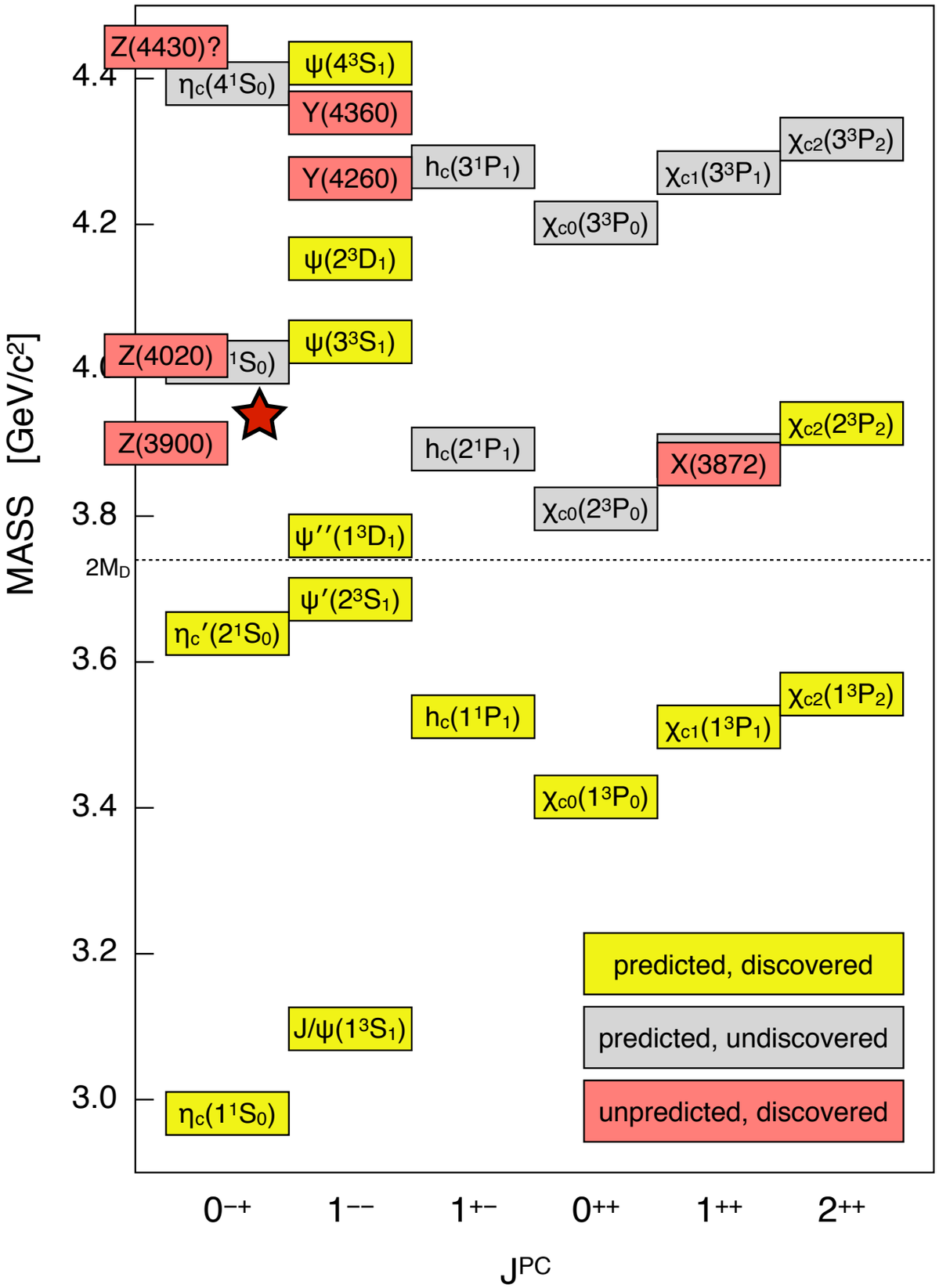
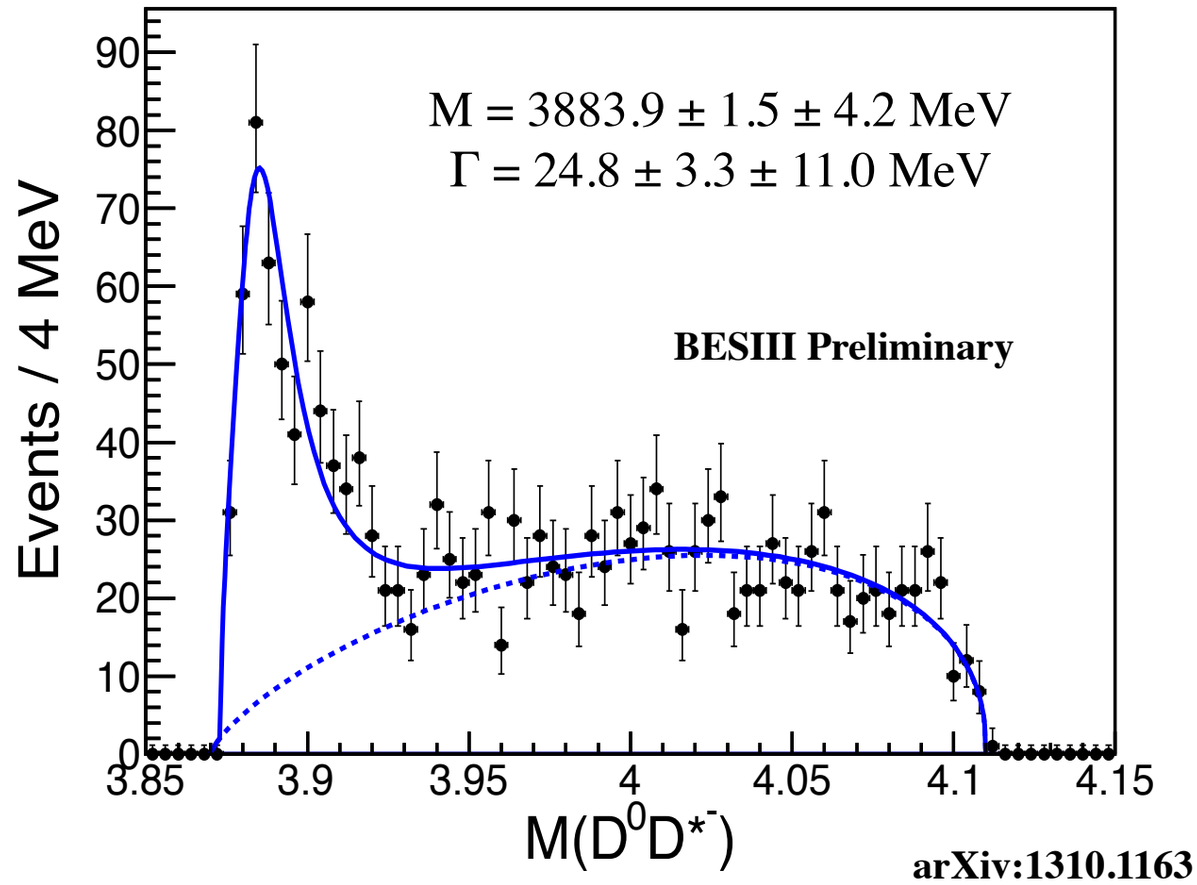



The $Z_c(3900)$ is close to $DD^*$ threshold...

$e^+e^- \to \pi^+ D^0 D^{*-}$ *at BESIII*




... and BESIII sees structure in $DD^*$.

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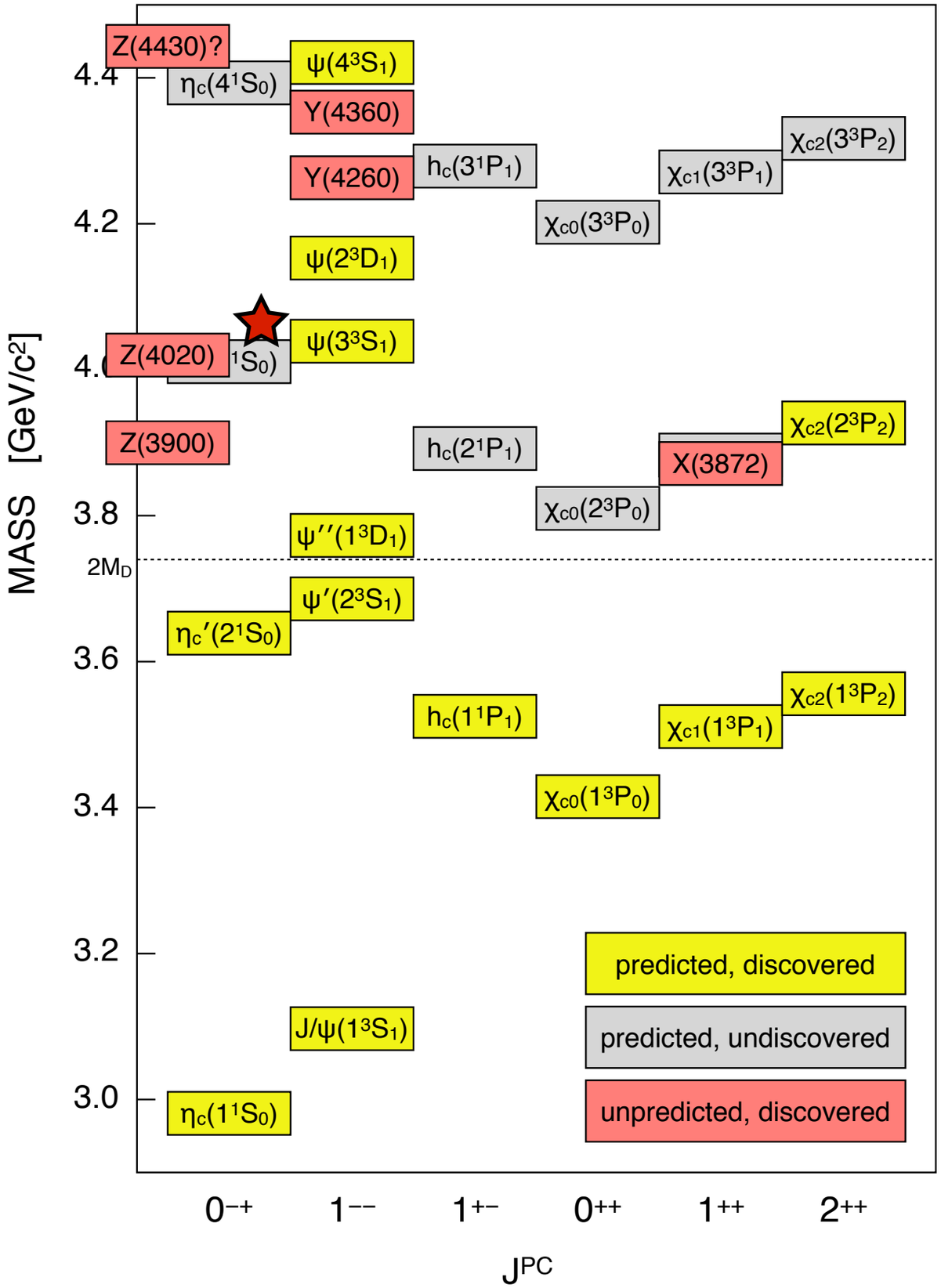


The $Z_c'(4020)$ is close to $D^*D^*$ threshold...

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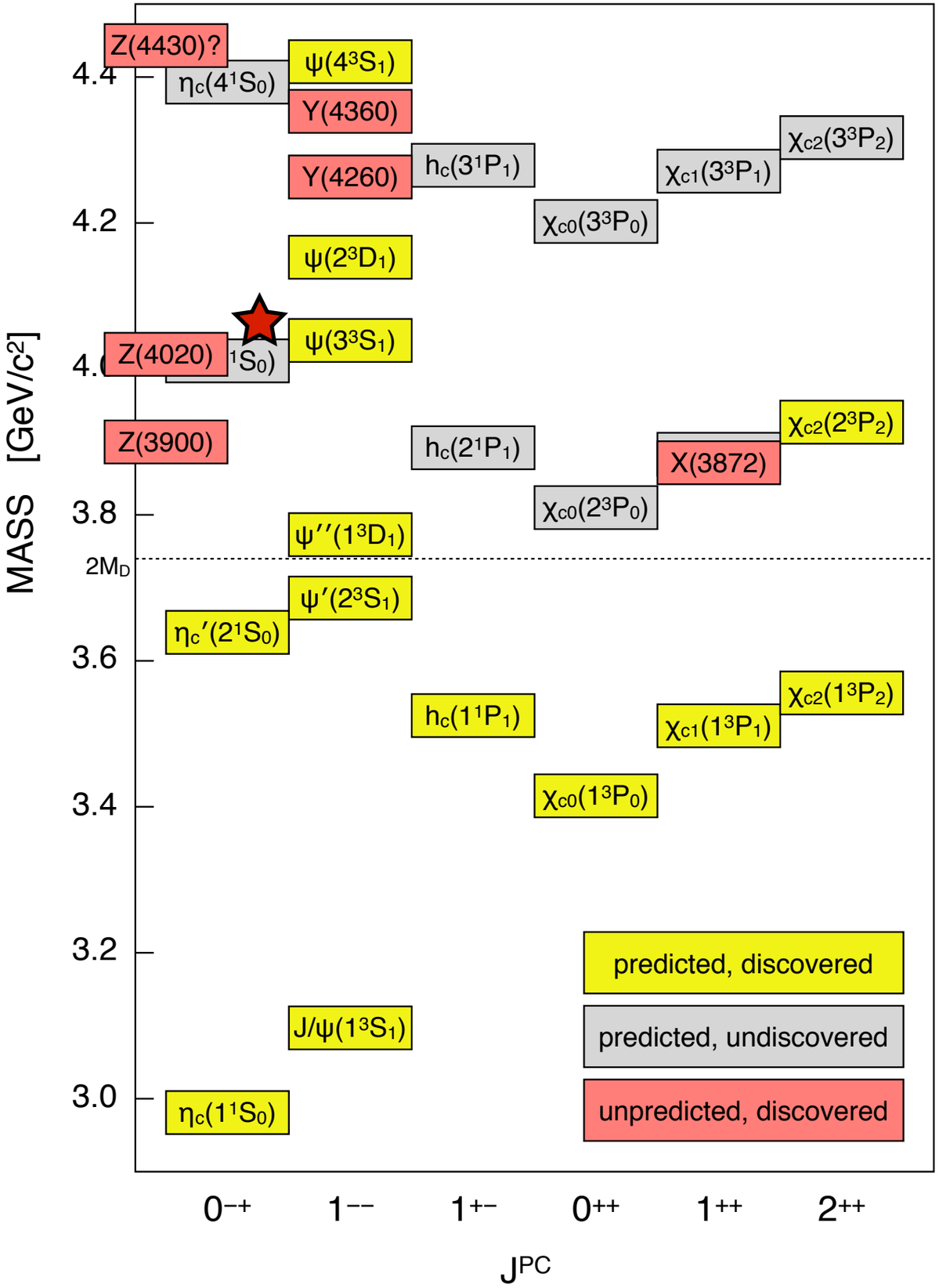
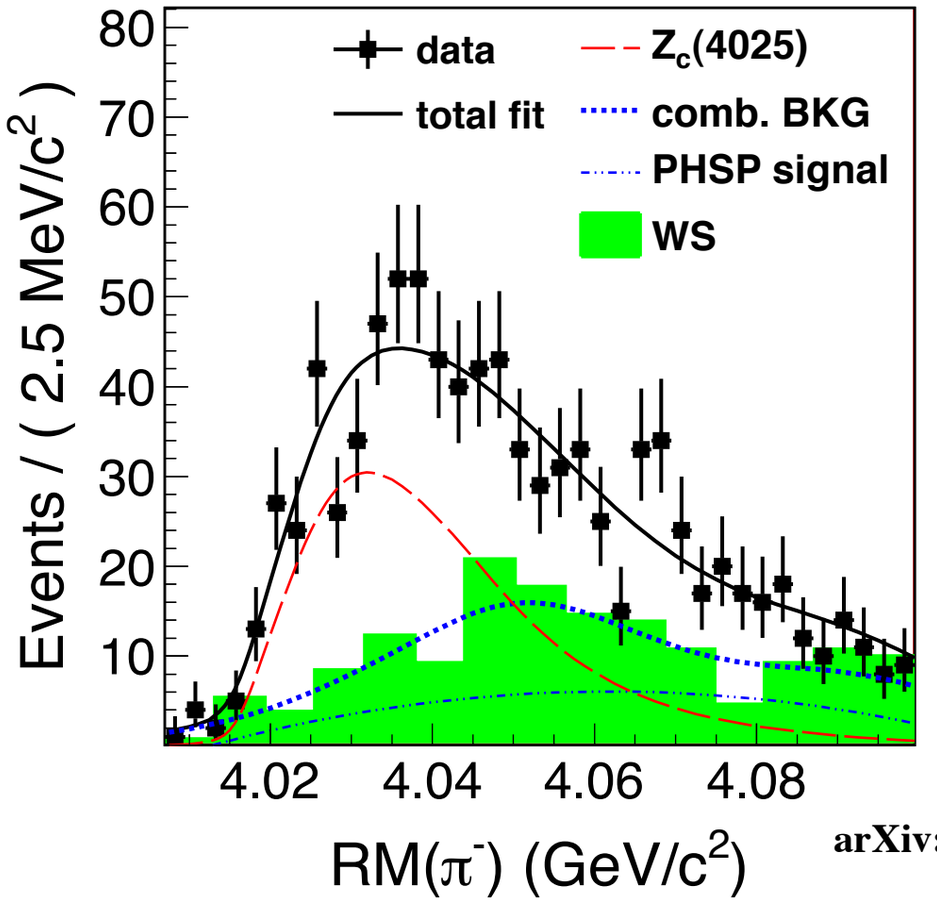



The $Z_c'(4020)$ is close to $D^*D^*$ threshold...

$e^+e^- \to \pi^\pm(D^*D^*)^\mp$ *at BESIII*

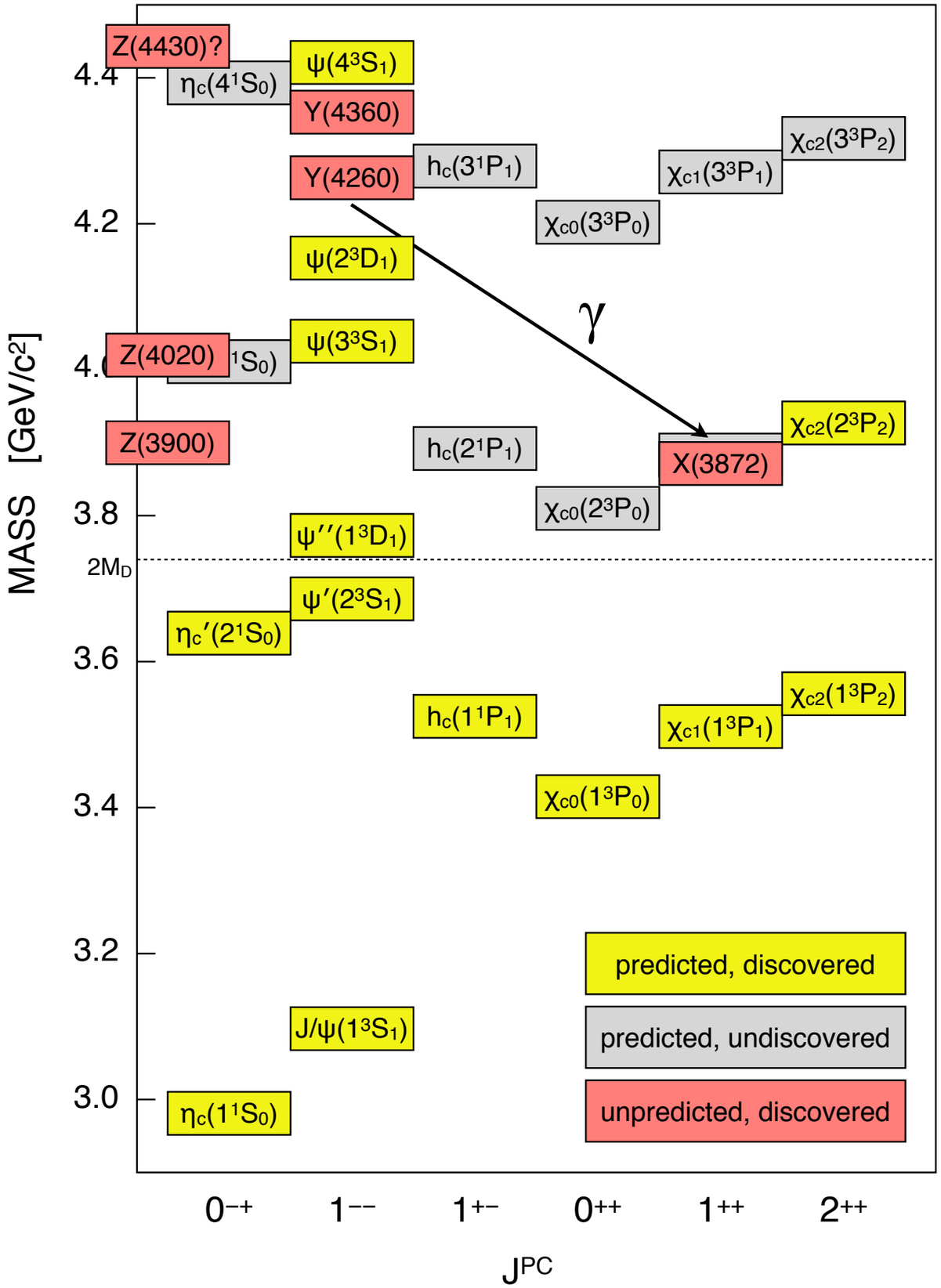



arXiv:1308.2760

... and BESIII sees structure in $D^*D^*$.

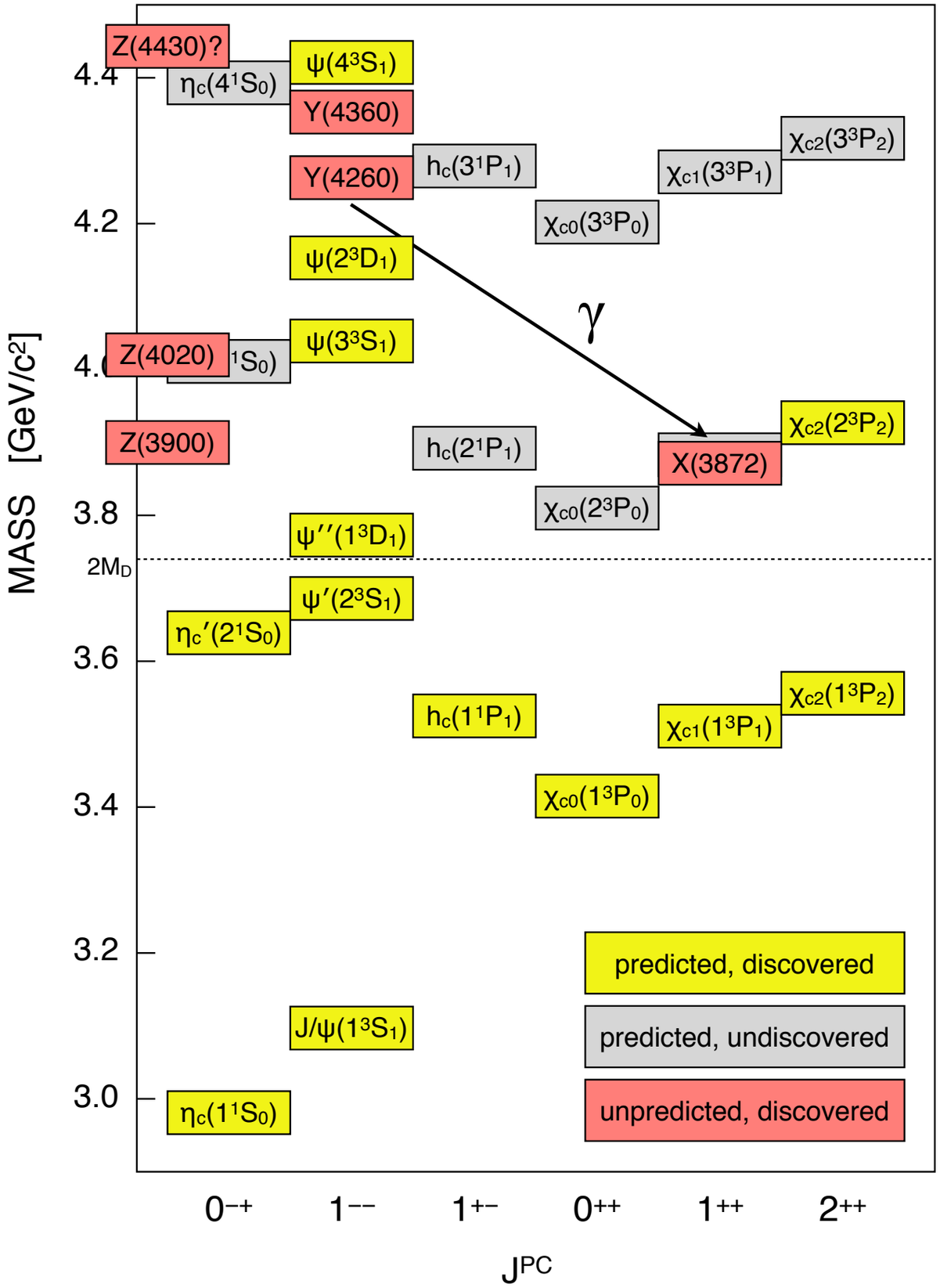
$M = 4026.3 \pm 2.6 \pm 3.7$ MeV
$\Gamma = 24.8 \pm 5.6 \pm 7.7$ MeV

# IV. A New Era of Discovery

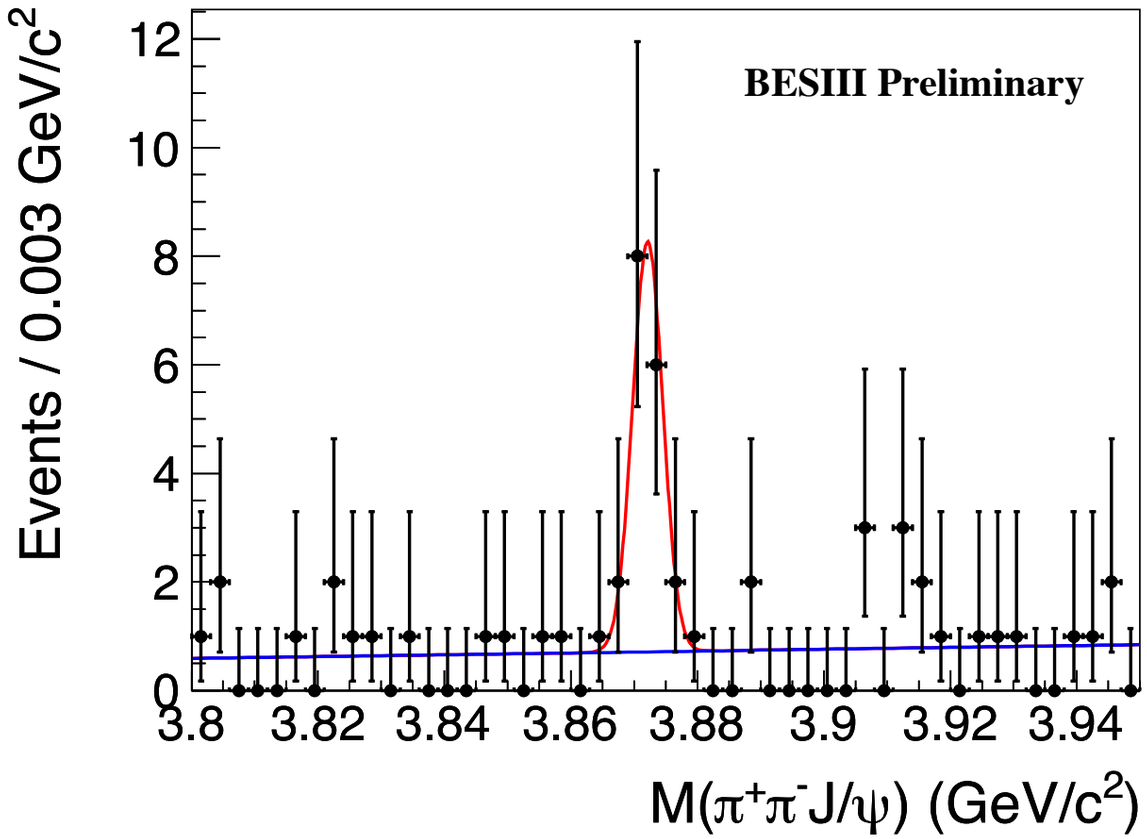



One more: Search for Y(4260) → γX(3872)...

# IV. A New Era of Discovery




$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ *at BESIII*




**⇒ "Observation of the X(3872)"**

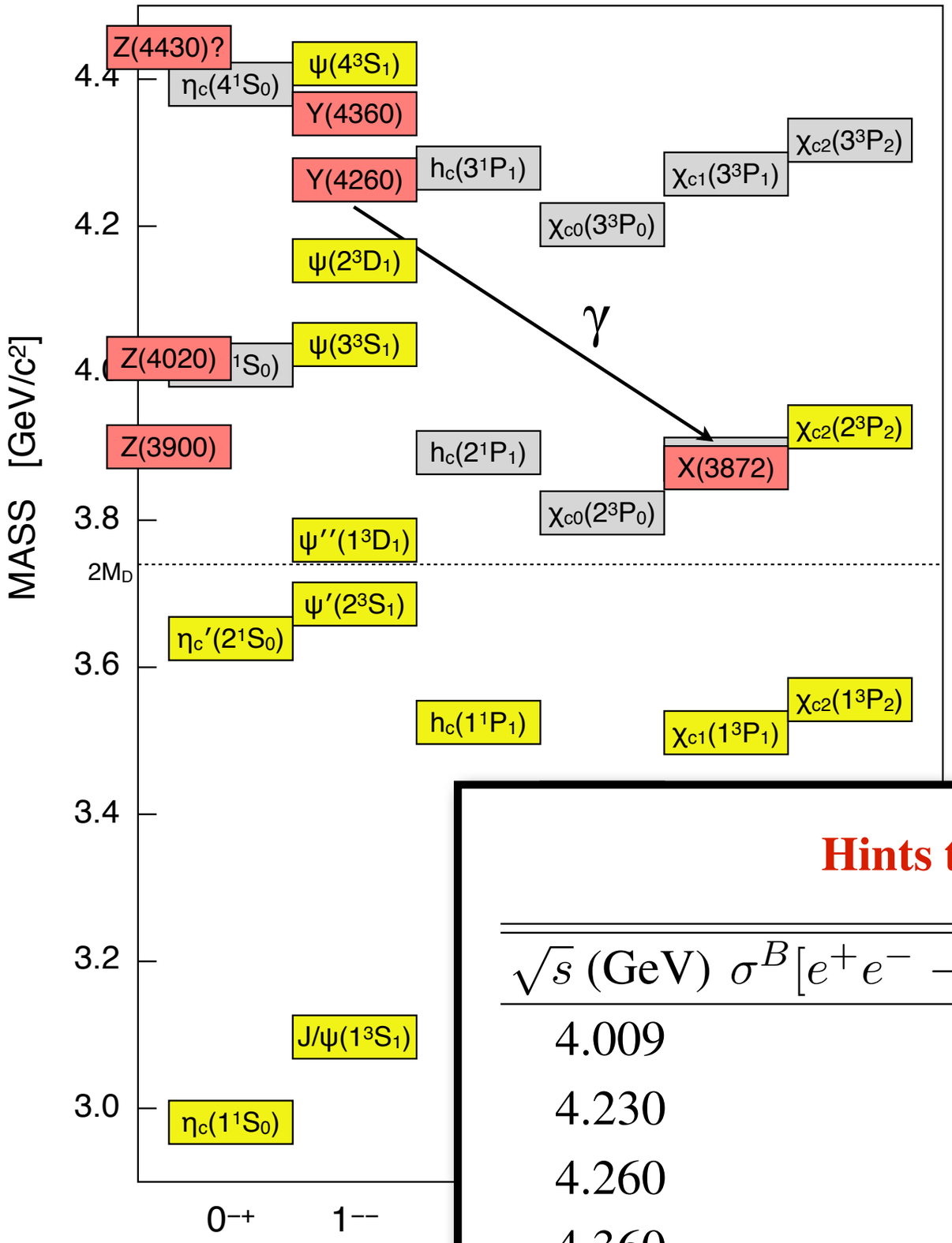
significance = 5.3σ

N = 15.0 ± 3.9 events

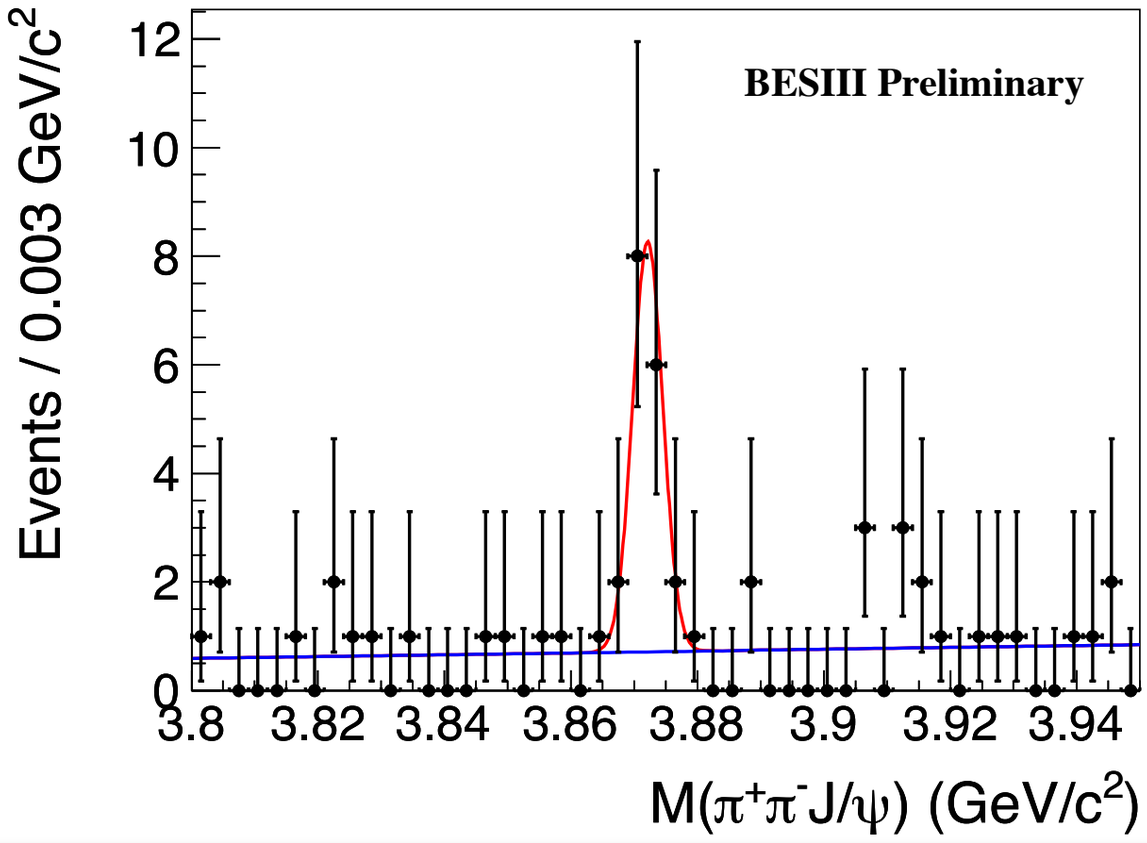
M = 3872.1 ± 0.8 ± 0.3 MeV

Γ consistent with resolution

# IV. A New Era of Discovery




$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ *at BESIII*

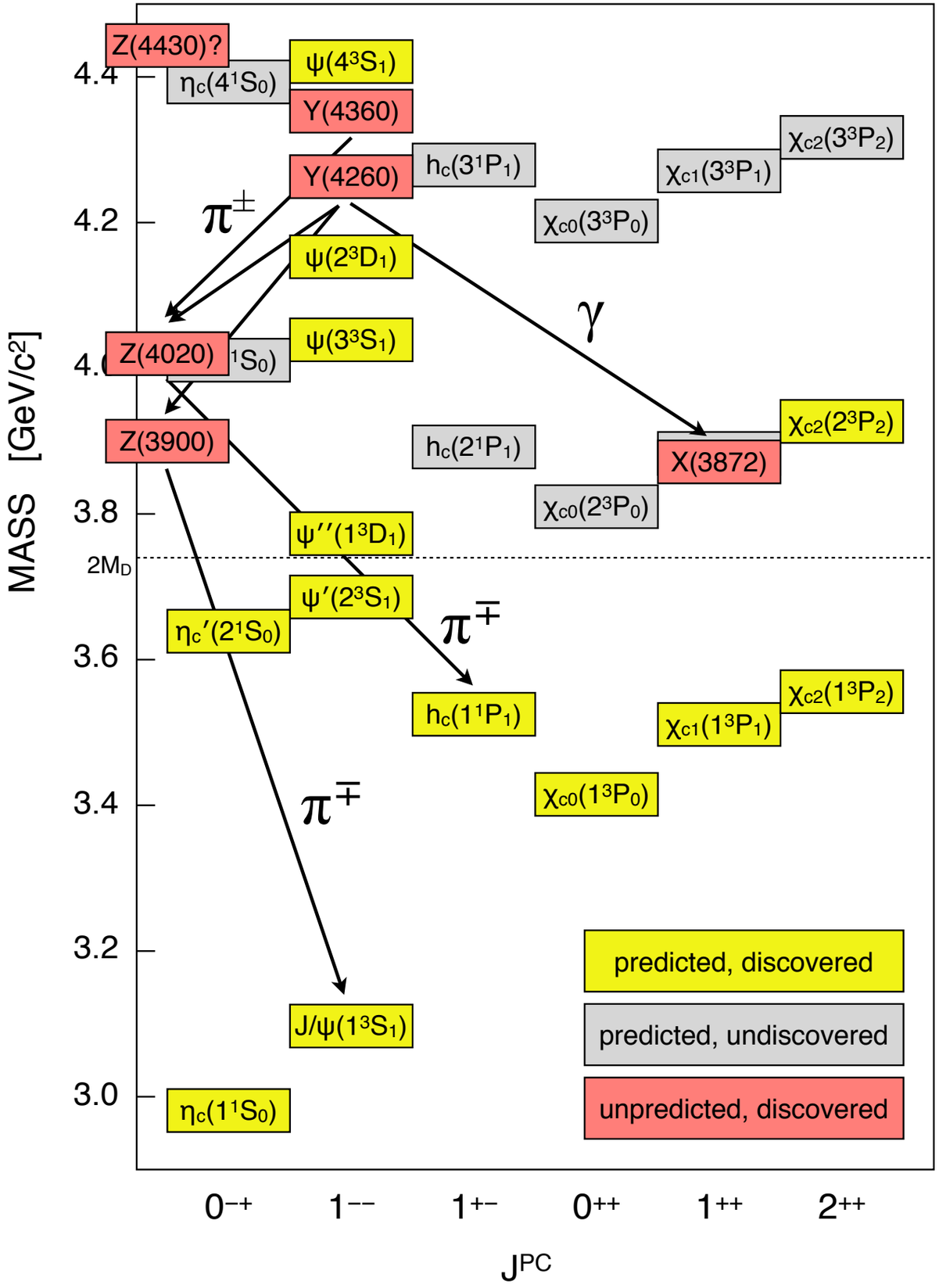



**Hints that this is Y(4260) → γX(3872)**

| $\sqrt{s}$ (GeV) | $\sigma^B[e^+e^- \to \gamma X(3872)] \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (pb) |
|---|---|
| 4.009 | $< 0.13$ at 90% C.L. |
| 4.230 | $0.32 \pm 0.15 \pm 0.02$ |
| 4.260 | $0.34 \pm 0.12 \pm 0.02$ |
| 4.360 | $< 0.39$ at 90% C.L. |

**BESIII Preliminary**

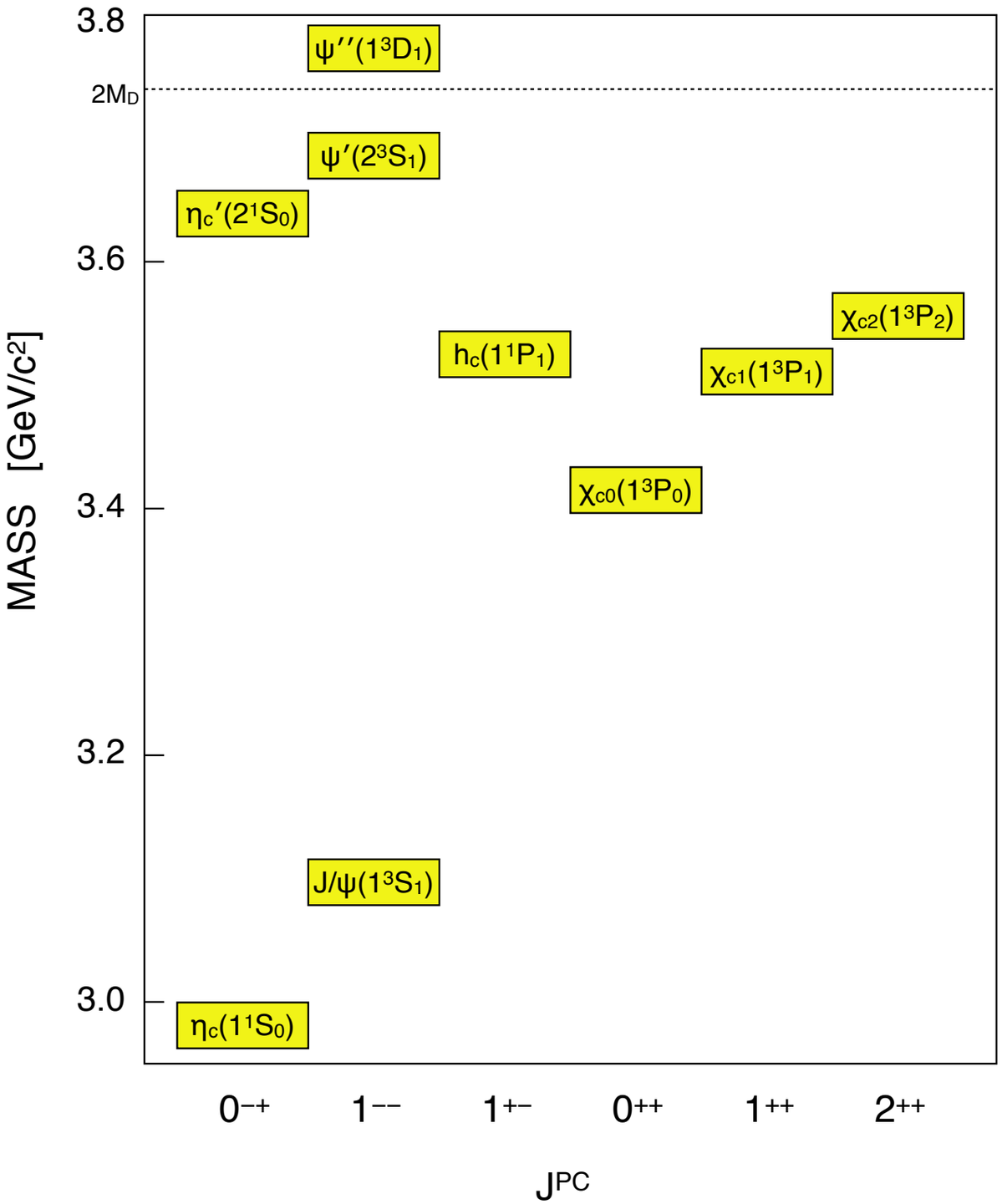
# IV. A New Era of Discovery




The role of **BESIII**:

**We are working on connections!**

# Charmonium Spectroscopy and the Role of BESIII

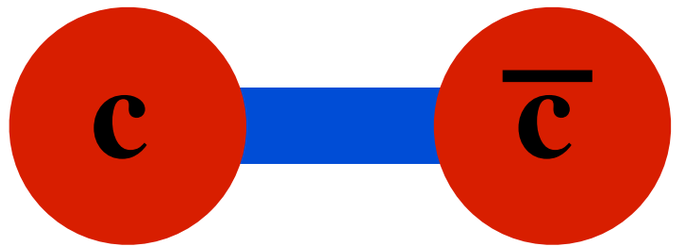



**I. An Introduction to Charmonium**

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

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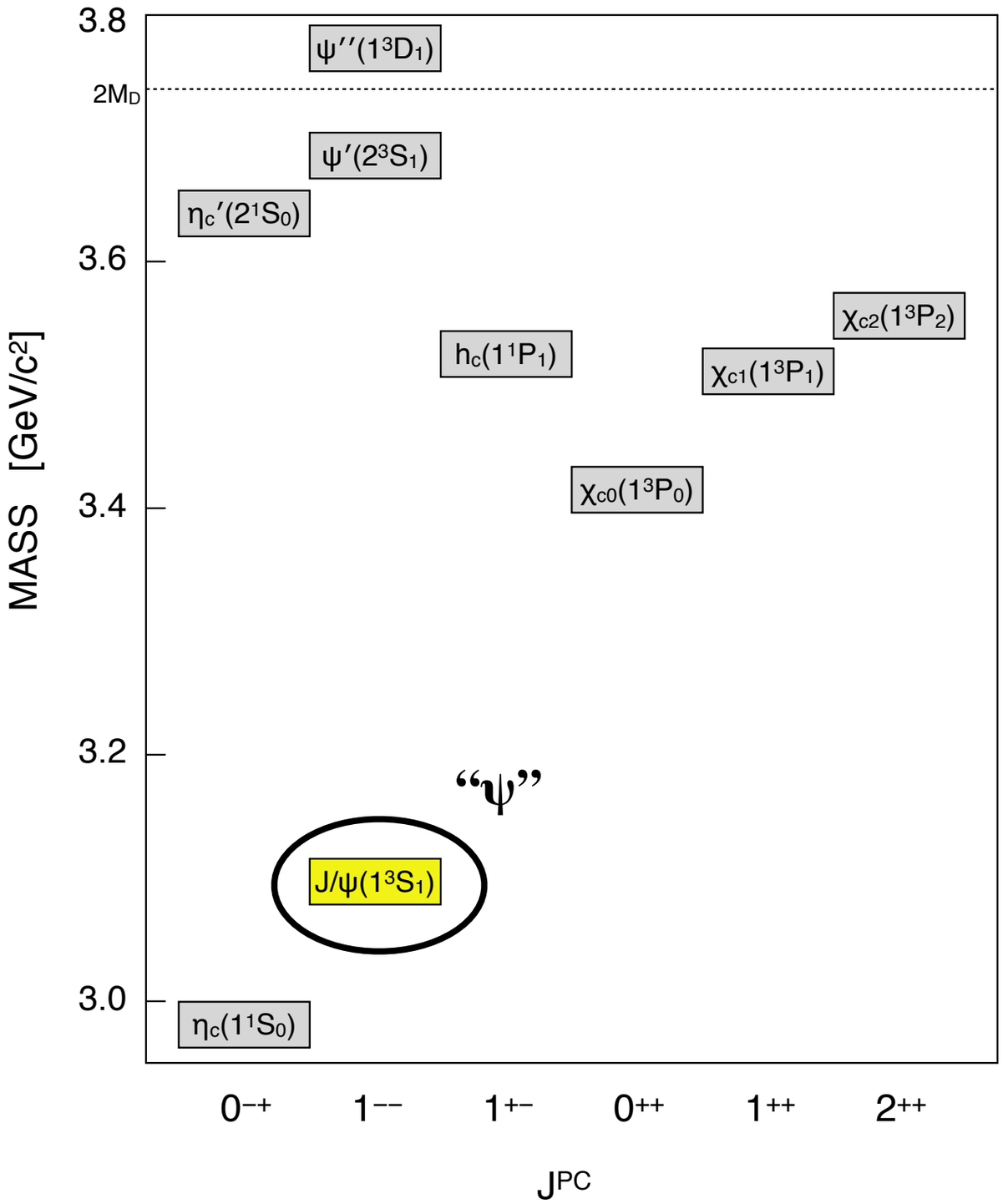


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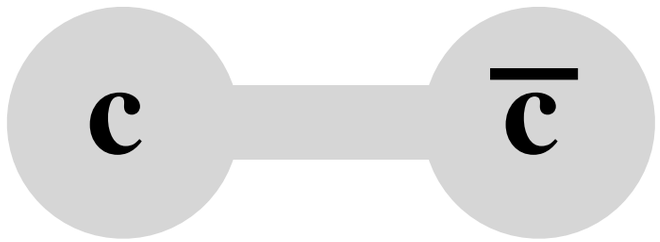


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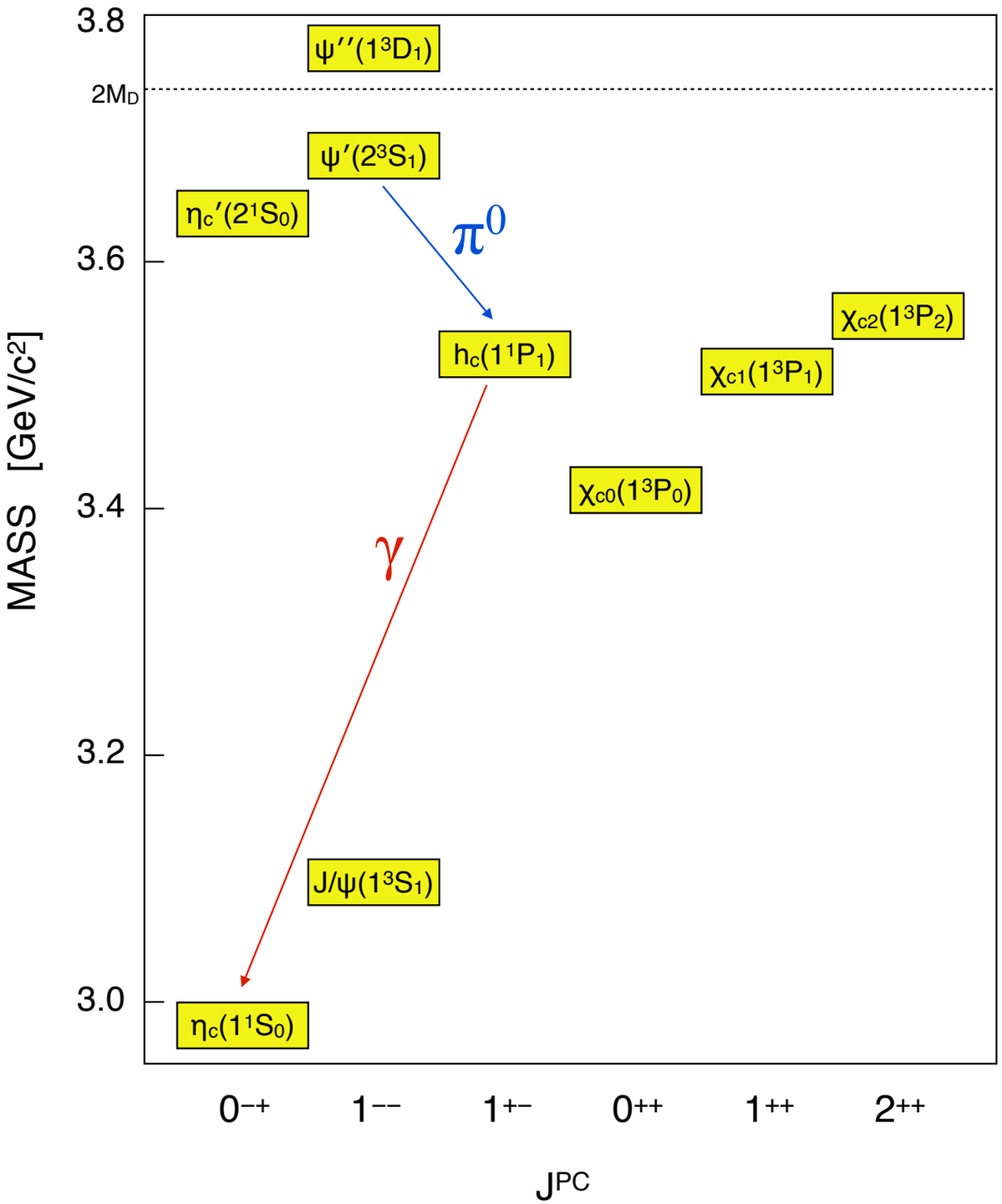


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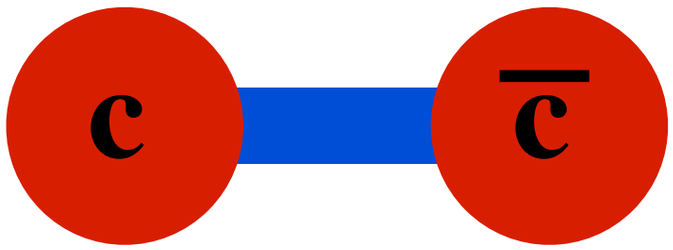


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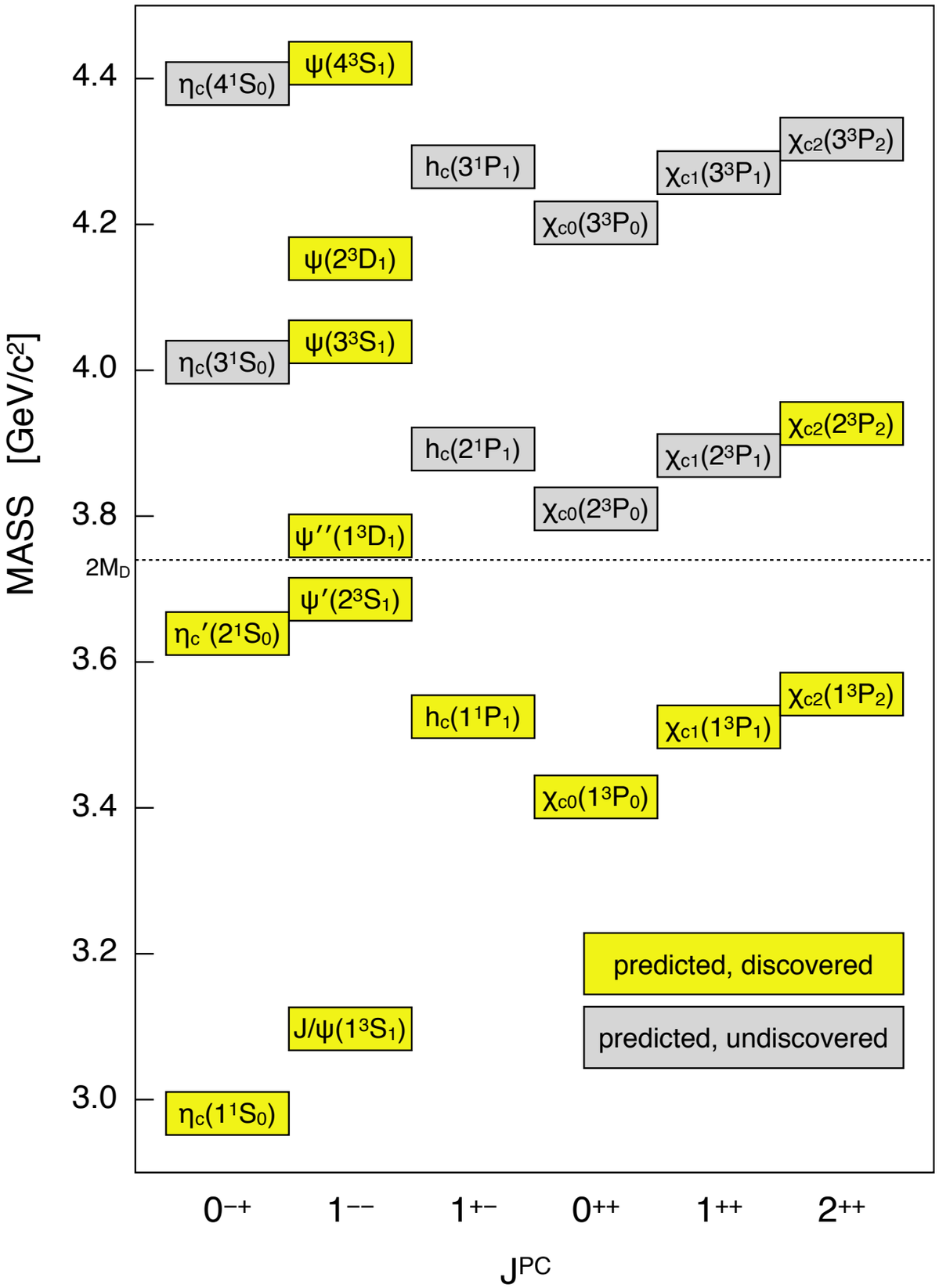


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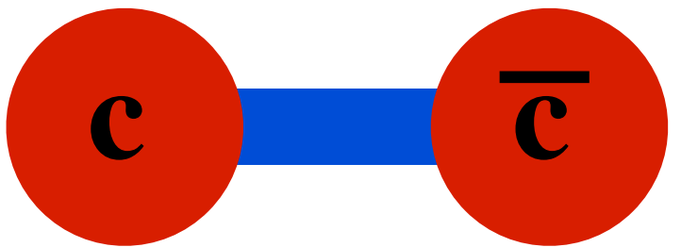


CHARMONIUM

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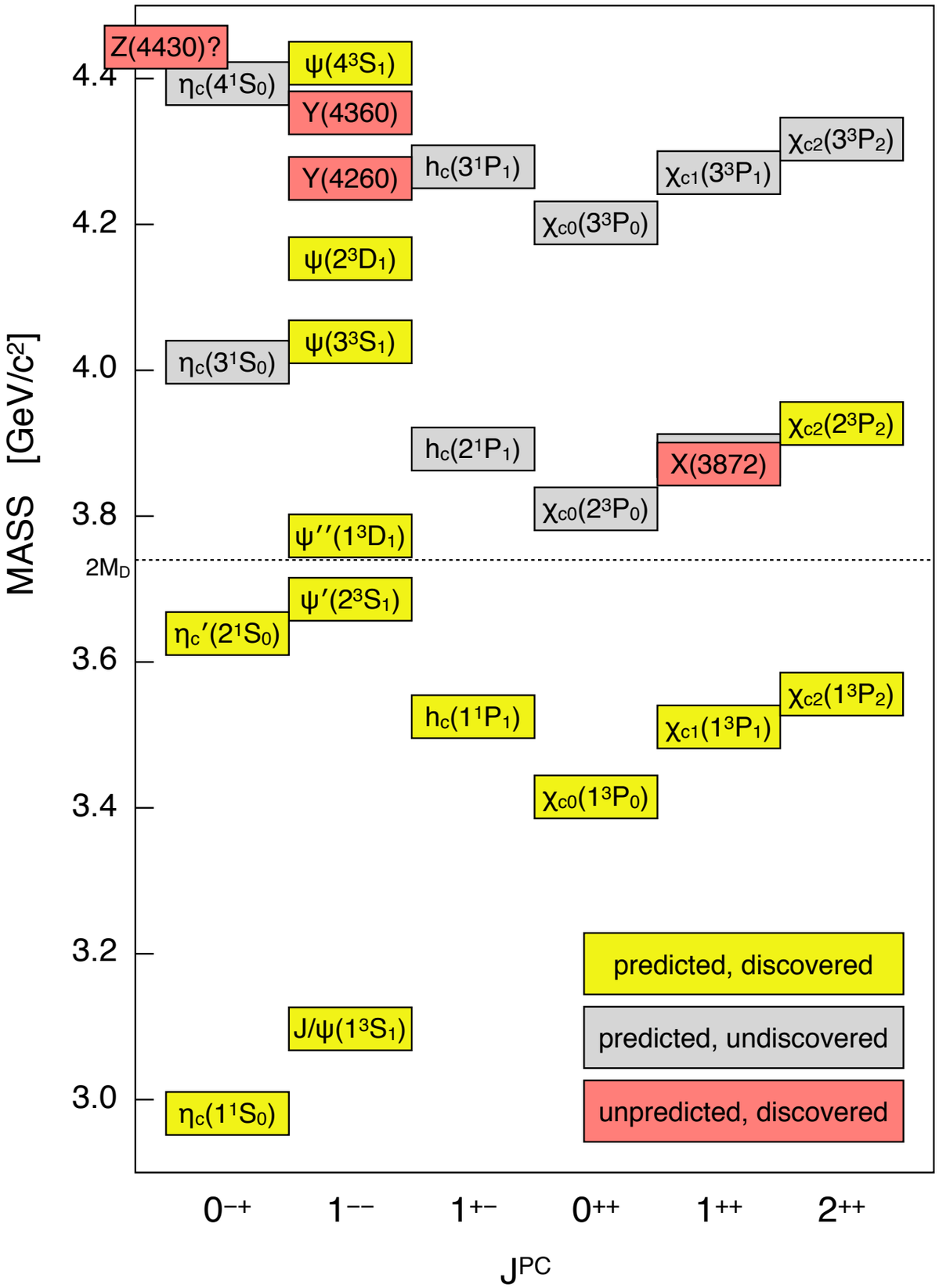


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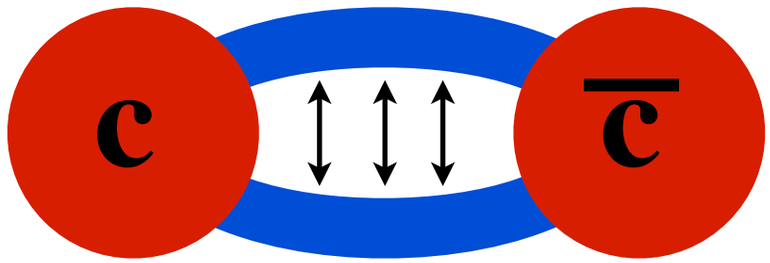
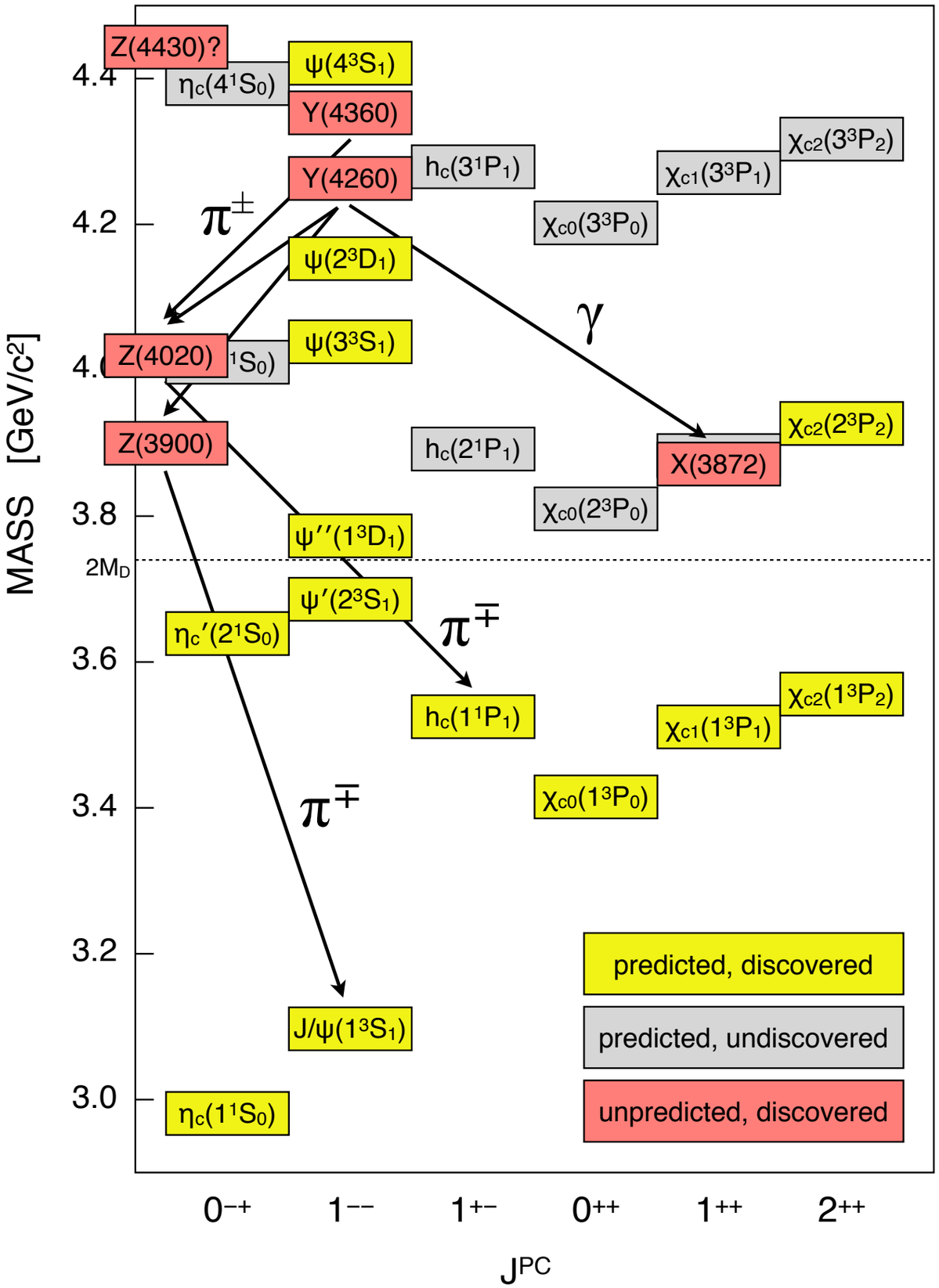



HYBRID CHARMONIUM?

# Charmonium Spectroscopy and the Role of BESIII

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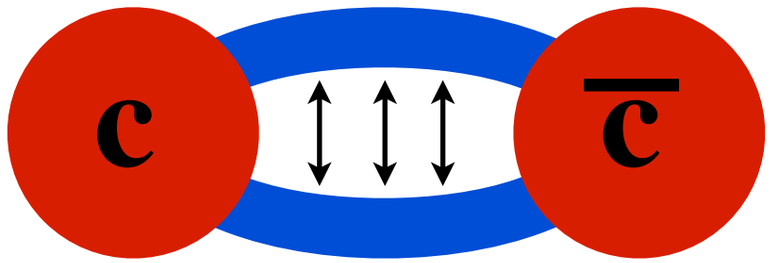


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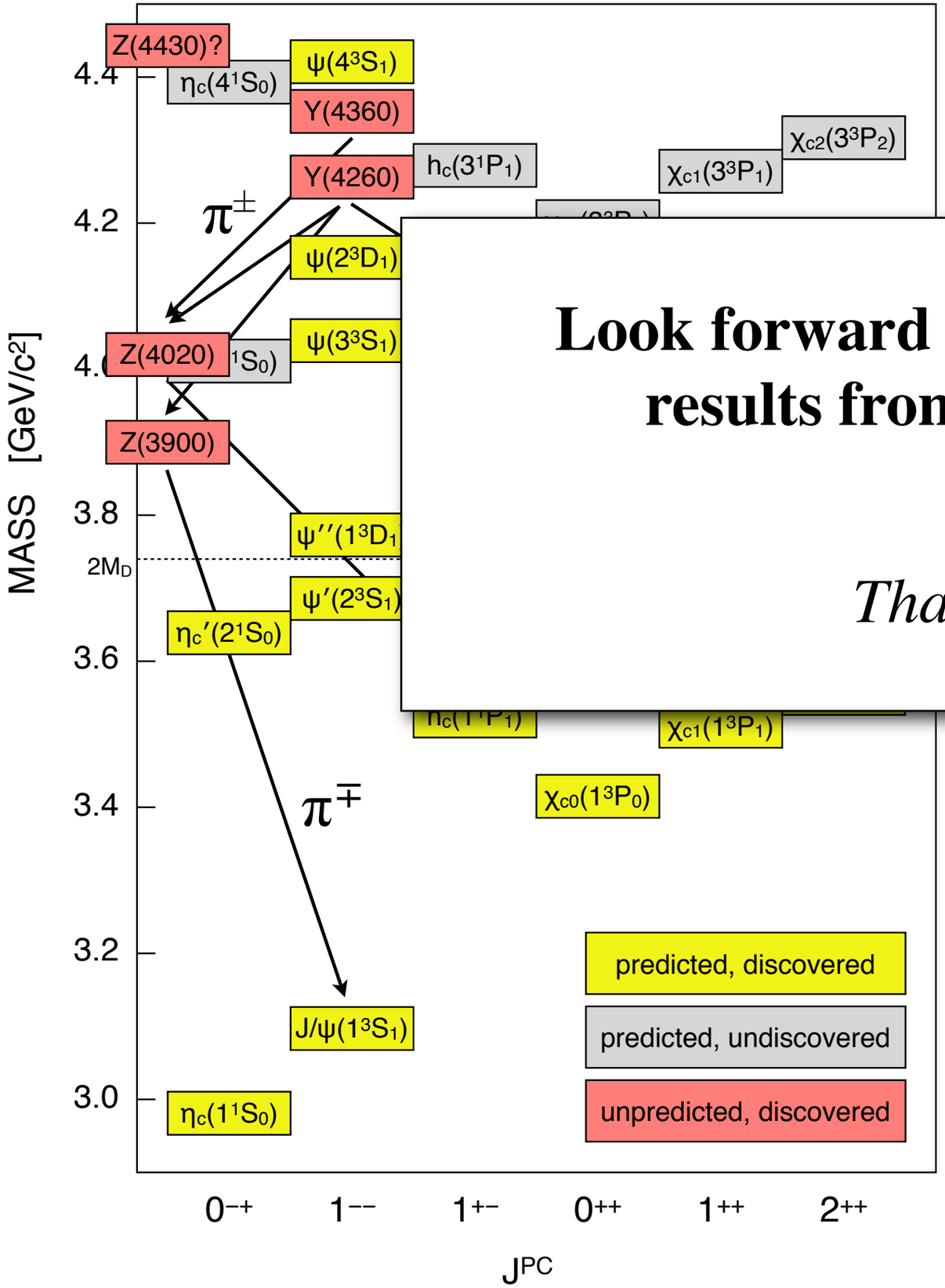


**Look forward to many new results from BESIII!**

*Thanks!*

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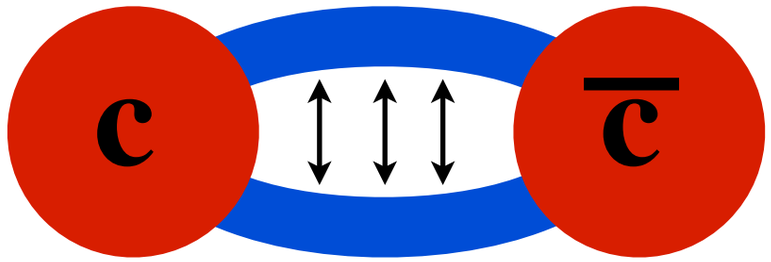


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