Hadron Spectroscopy
Lecture 2
Heavy Quark Spectroscopy

National Nuclear Physics Summer School
at MIT

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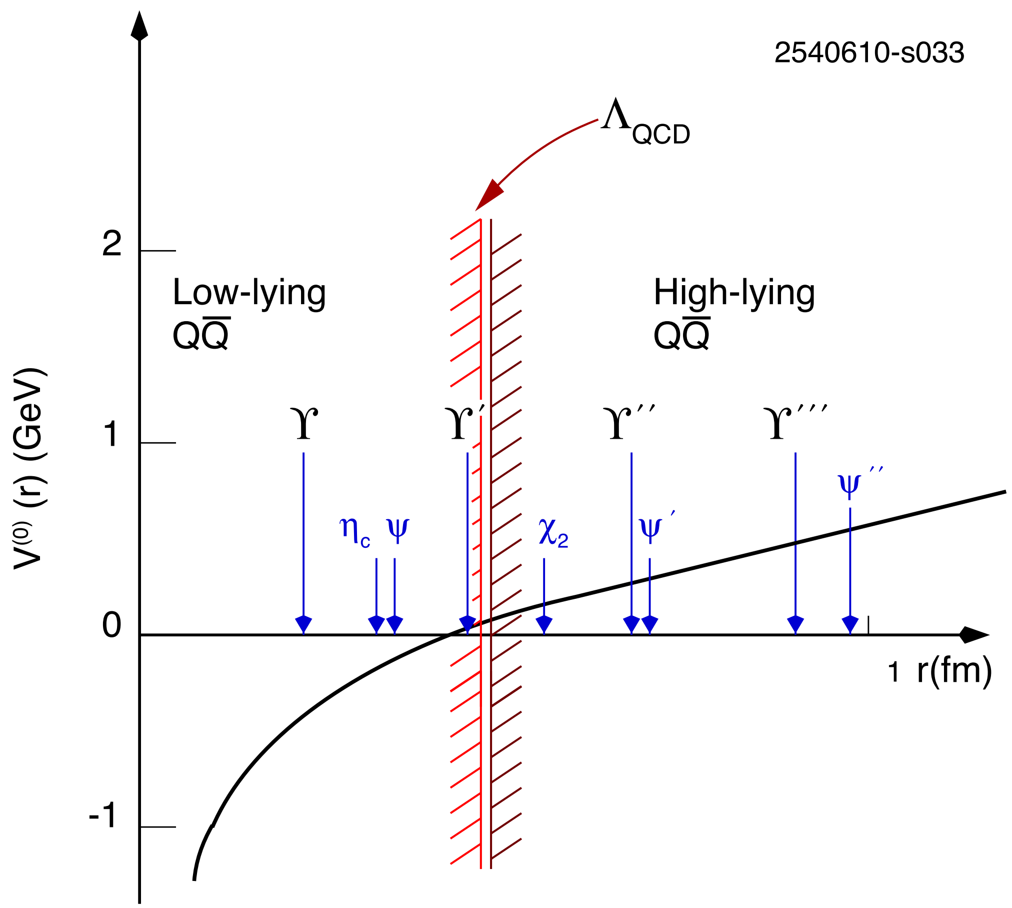
Indiana University

Outline

1. Overview and Motivation
2. Spectroscopy of Heavy Quark Systems
    2.1. Low lying heavy quarkonium: a QCD laboratory
    2.2. Excited heavy quarkonium: a QCD puzzle
3. Spectroscopy of Light Quark Systems
4. Summary and Outlook: Present and Future Facilities

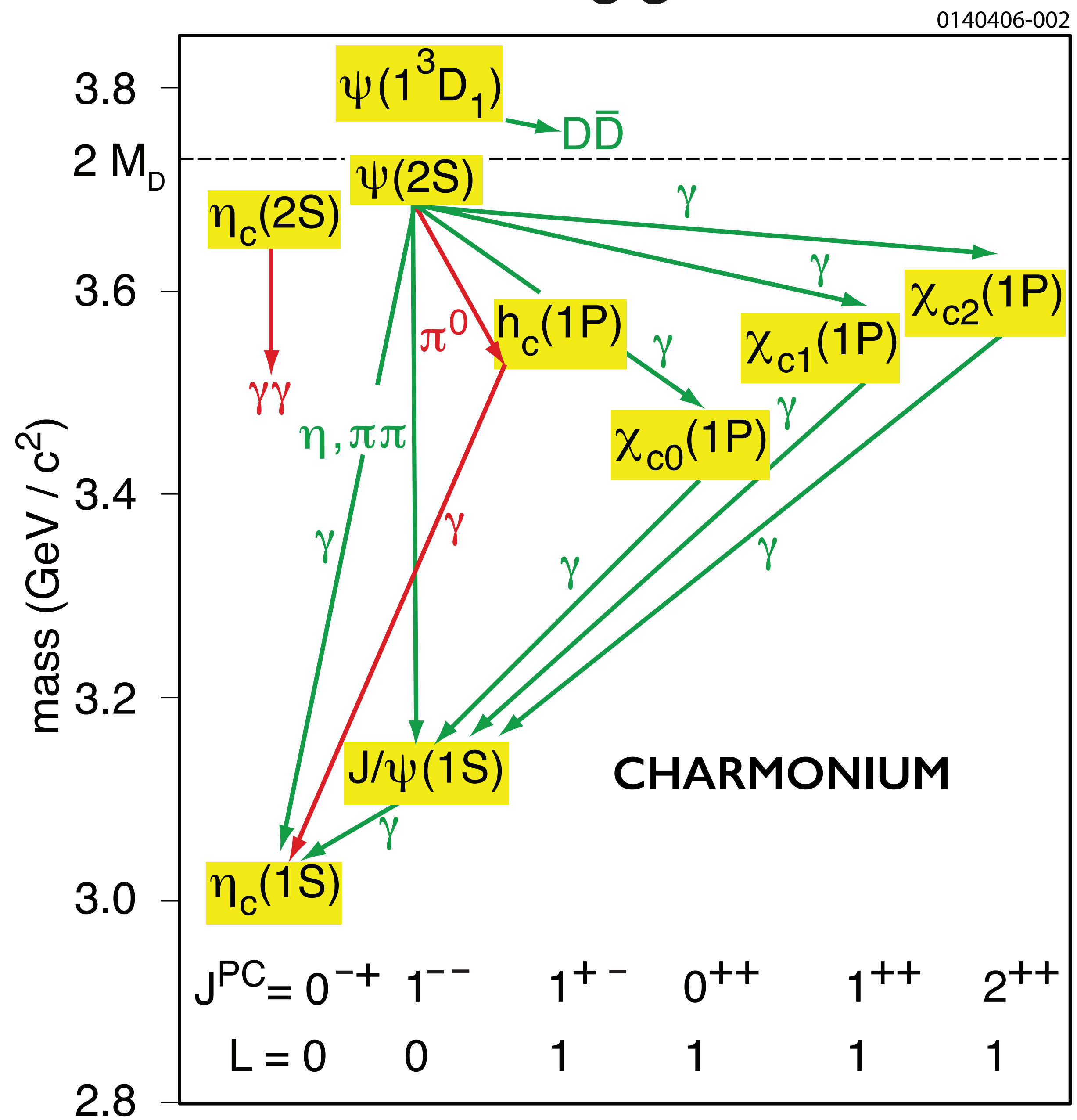
The charmonium system

- Why do we believe this is a spectrum of charm anti-charm?
- How can we study QCD through properties of the states?

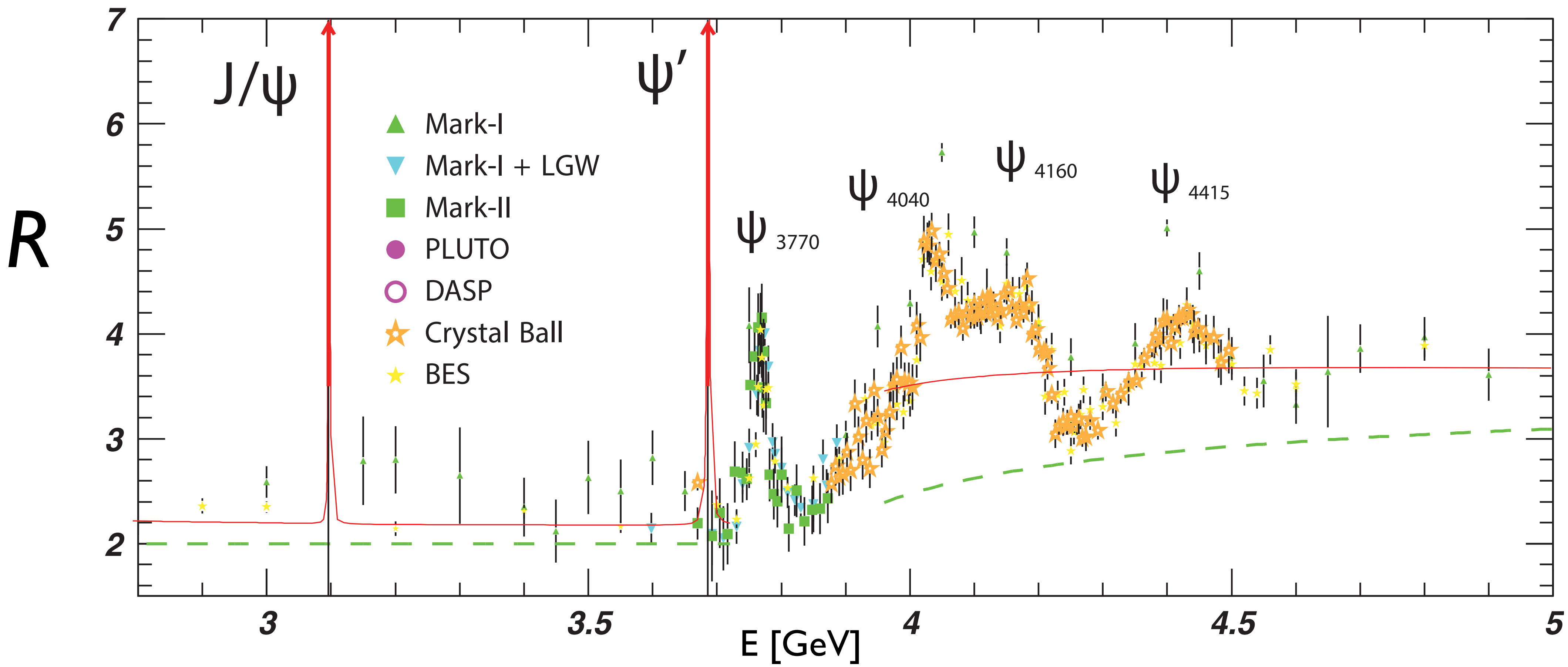


Strong Force

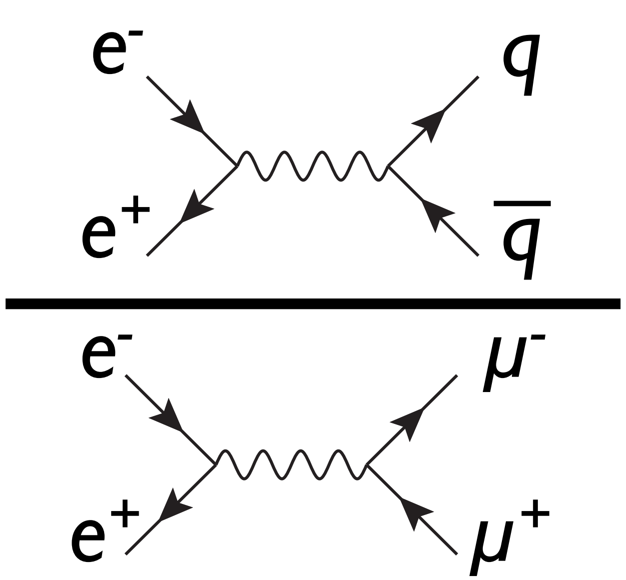
$c\bar{c}$



Producing Charmonium



- Probes the ratio of quark to lepton couplings in QED: Q_q^2 / Q_μ^2

$R =$ 

$$R = 3\sum_q Q_q^2$$

three colors

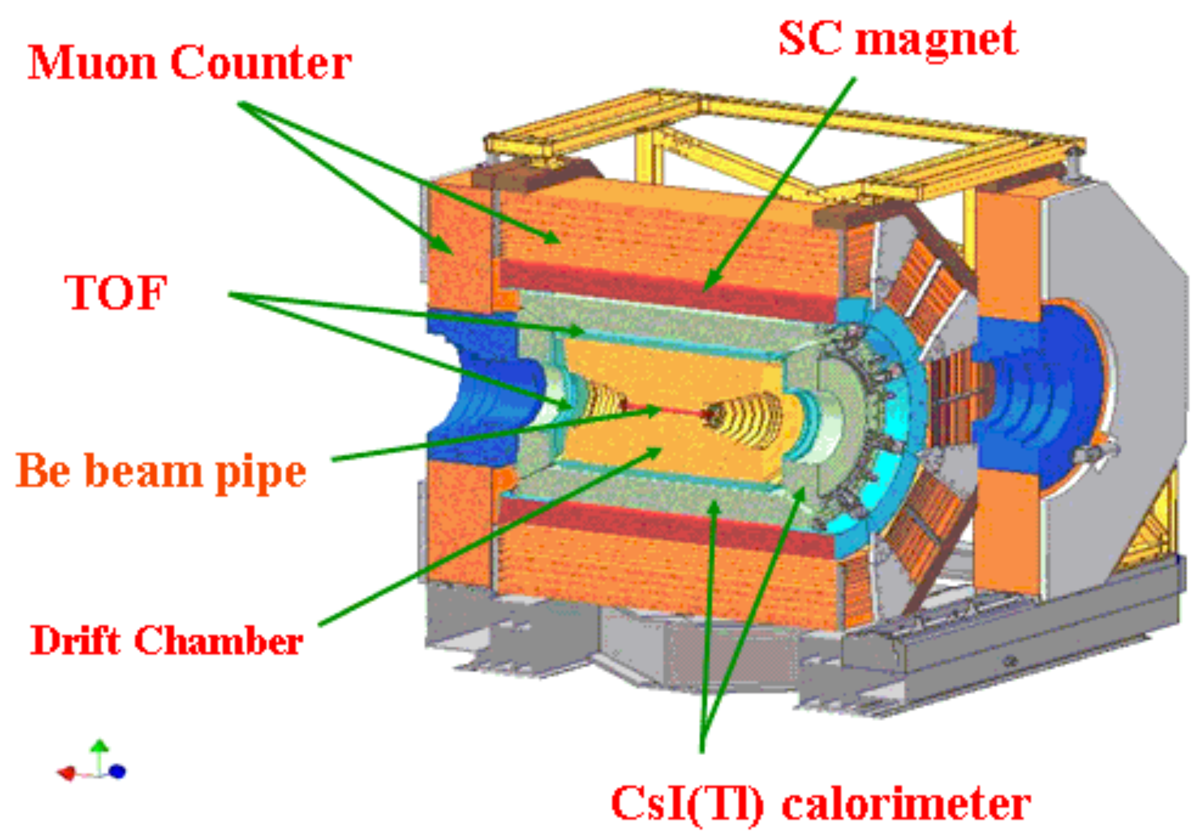
Expect:

$2 \rightarrow 10/3$

u,d,s u,d,s,c

Producing Charmonium

An ideal machine
for charmonium study:
e^+e^- collisions measured
with BESIII at BEPCII



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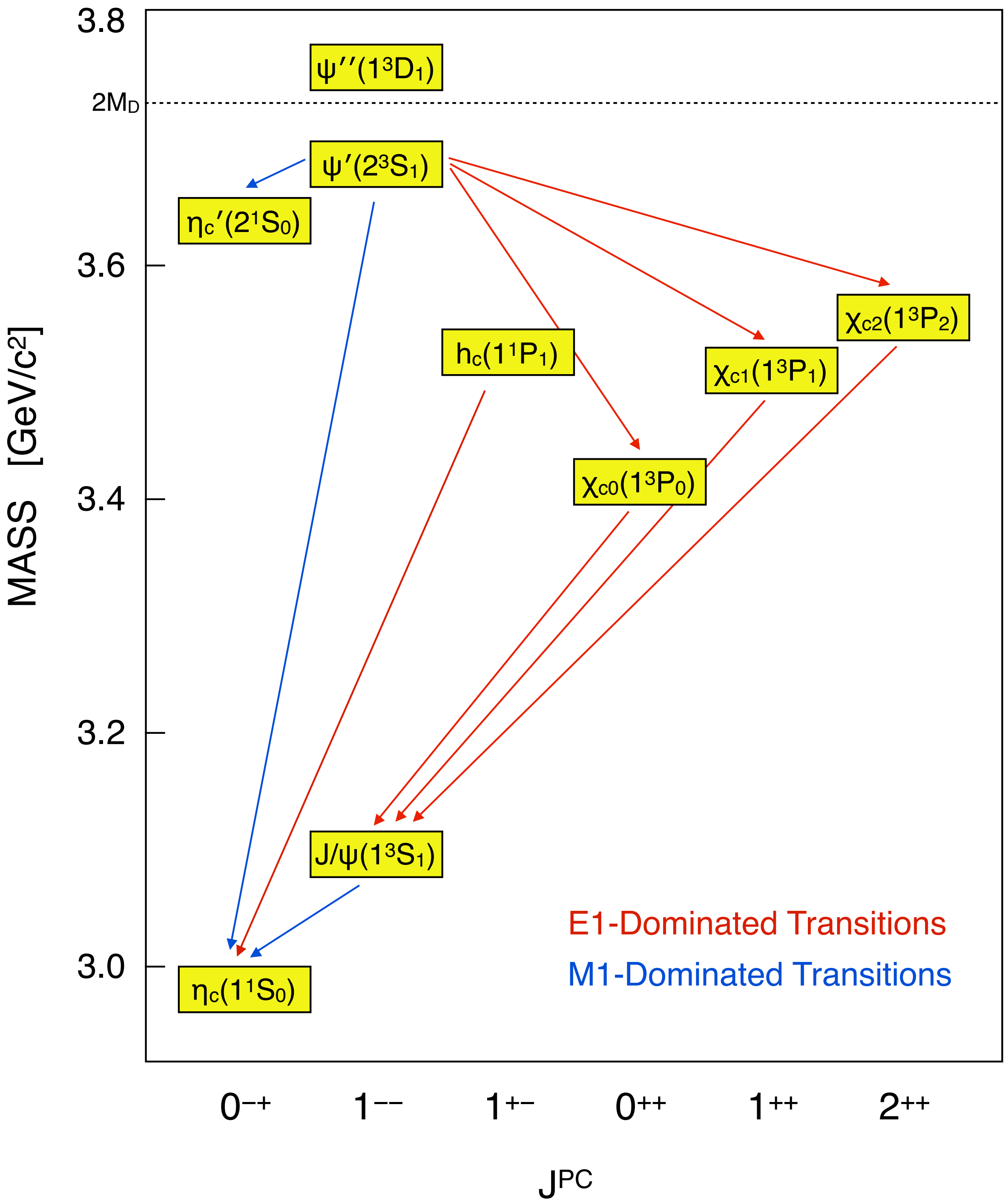
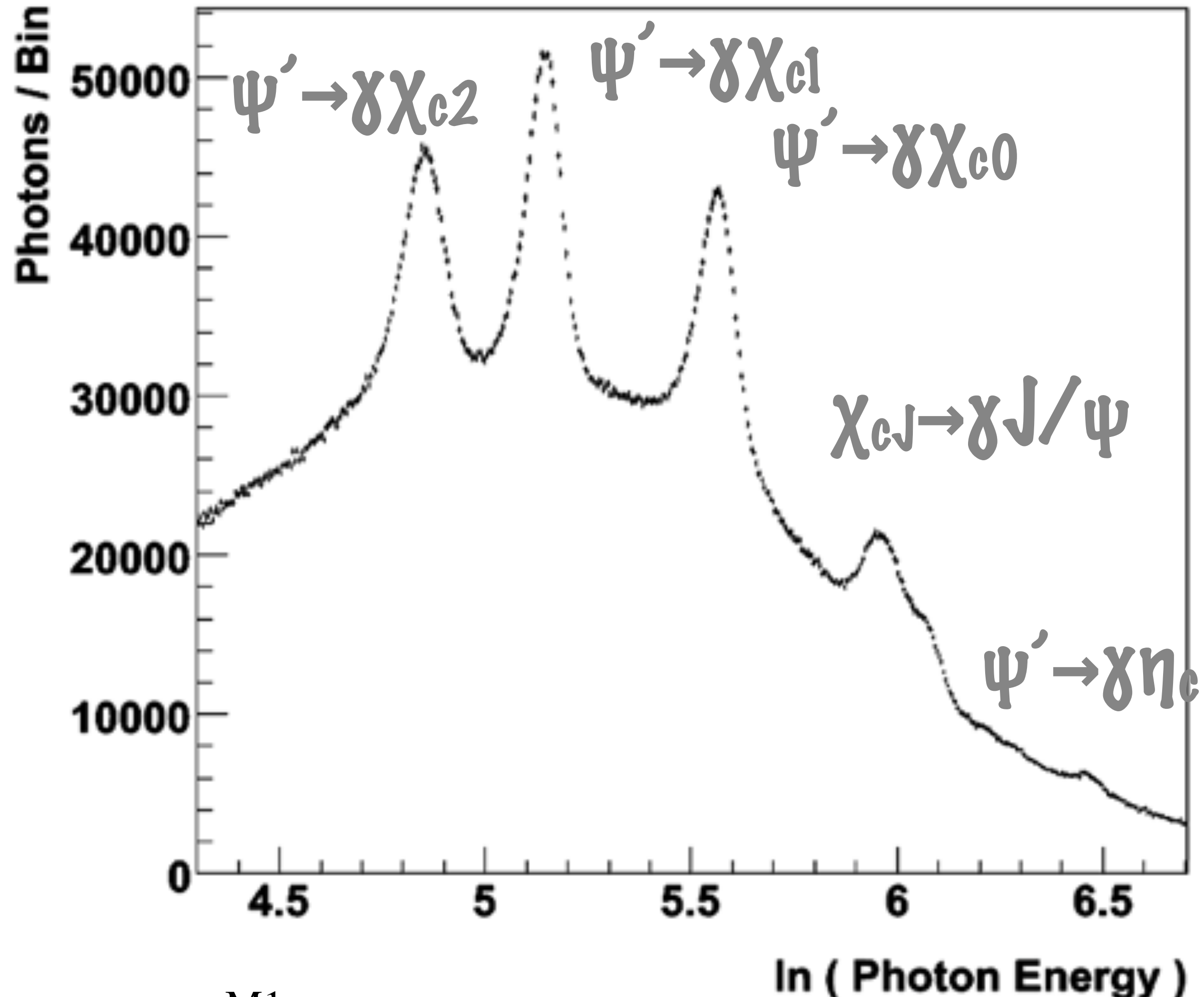
Electromagnetic Transitions





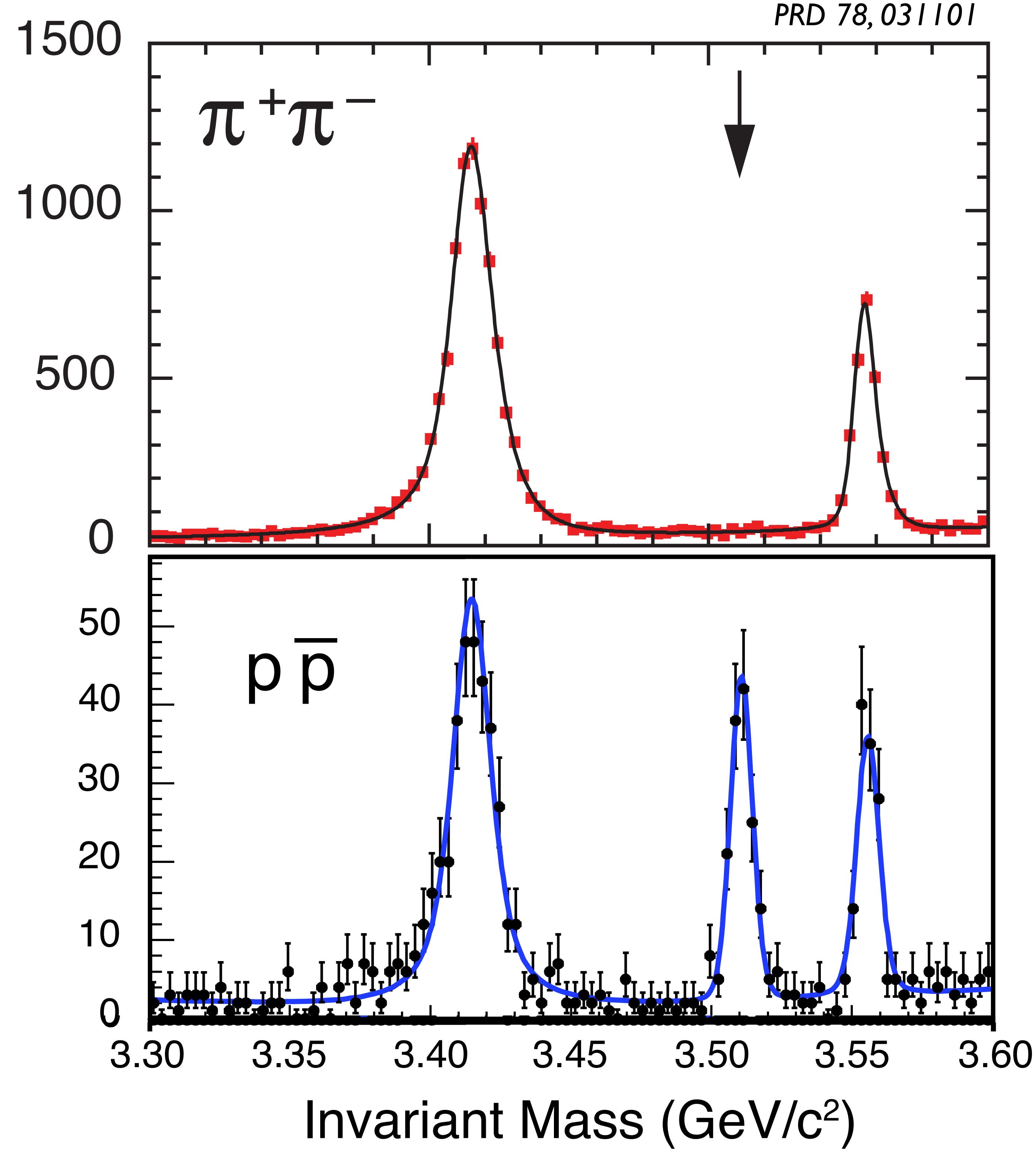
$$\Gamma\left(i \xrightarrow{\text{M1}} \gamma + f\right) = \frac{16}{3}\alpha e_Q^2 \frac{E_\gamma^3}{m_i^2}(2J'+1)\mathrm{S}_{if}^{\mathrm{M}}|\mathcal{M}_{if}|^2$$

$$\Gamma\left(i \xrightarrow{\text{E1}} \gamma + f\right) = \frac{4}{3}\alpha e_Q^2 E_\gamma^3 (2J'+1)\mathrm{S}_{if}^{\mathrm{E}}|\mathcal{E}_{if}|^2$$

χ_{cJ} Decays

- Study:
  - $\psi' \rightarrow \gamma\ \pi^+\pi^-$
  - $\psi' \rightarrow \gamma$ p anti-p
- Homework: why does a third peak appear in p anti-p but not ππ?
  - J^P of a pion: 0^-
  - J^P of a proton: $1/2^-$

PRD 79, 072007
PRD 78, 031101



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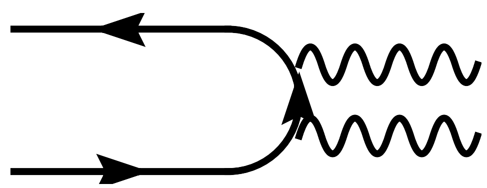
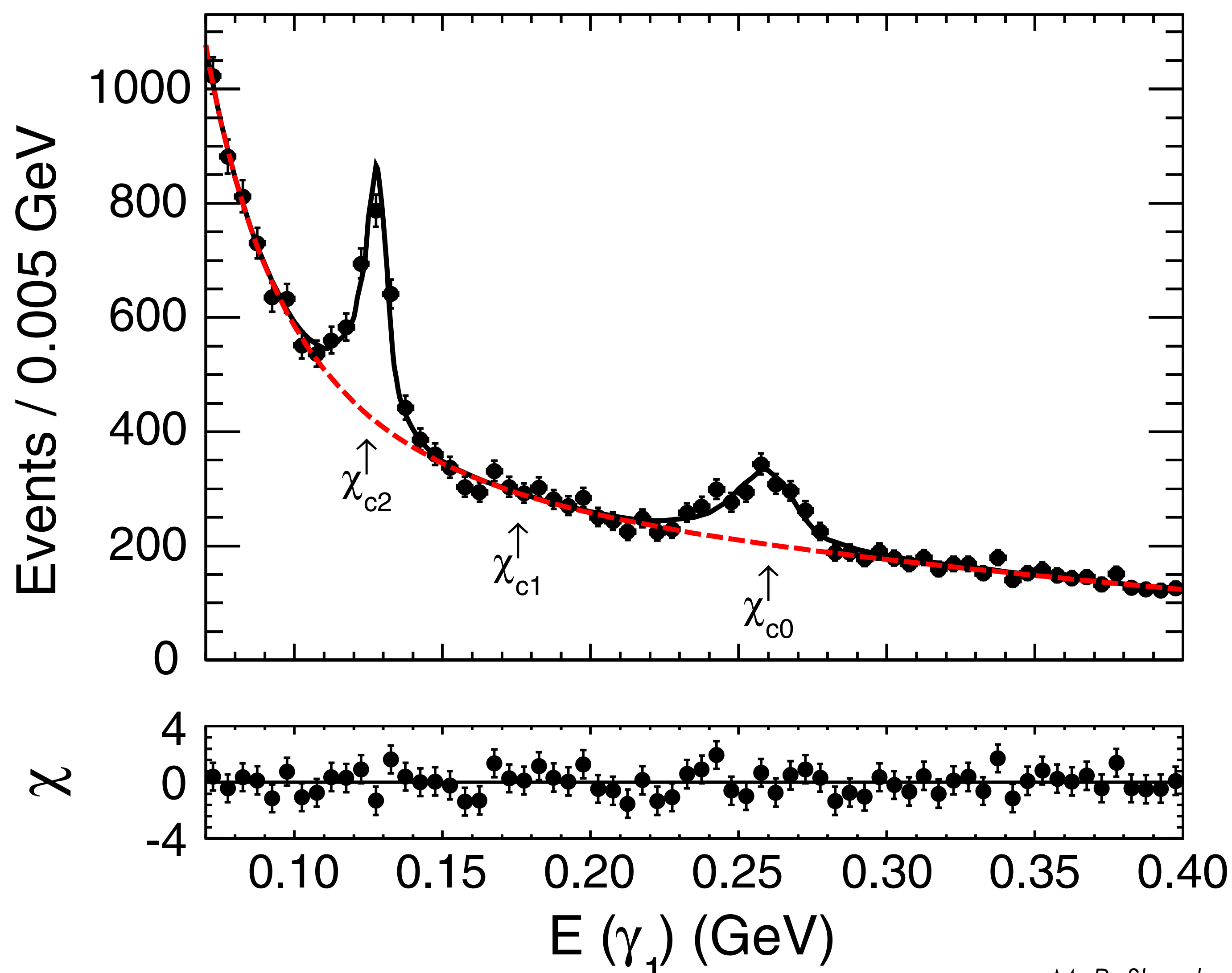
χ_{cJ} Decays to $\gamma\gamma$

$$R = \frac{\Gamma_{\gamma\gamma}(\chi_{c2}) = 4(|\Psi'(0)|^2\alpha_{EM}^2/m_c^4) \times [1 - 1.70\alpha_S + \ldots]}{\Gamma_{\gamma\gamma}(\chi_{c0}) = 15(|\Psi'(0)|^2\alpha_{EM}^2/m_c^4) \times [1 + 0.06\alpha_S + \ldots]} = (4/15)\,[\,1 - 1.76\alpha_S + \ldots]$$

$\chi_{c(0,2)}$  $\gamma\gamma$

BESIII, PRD 85, 112008 (2012)



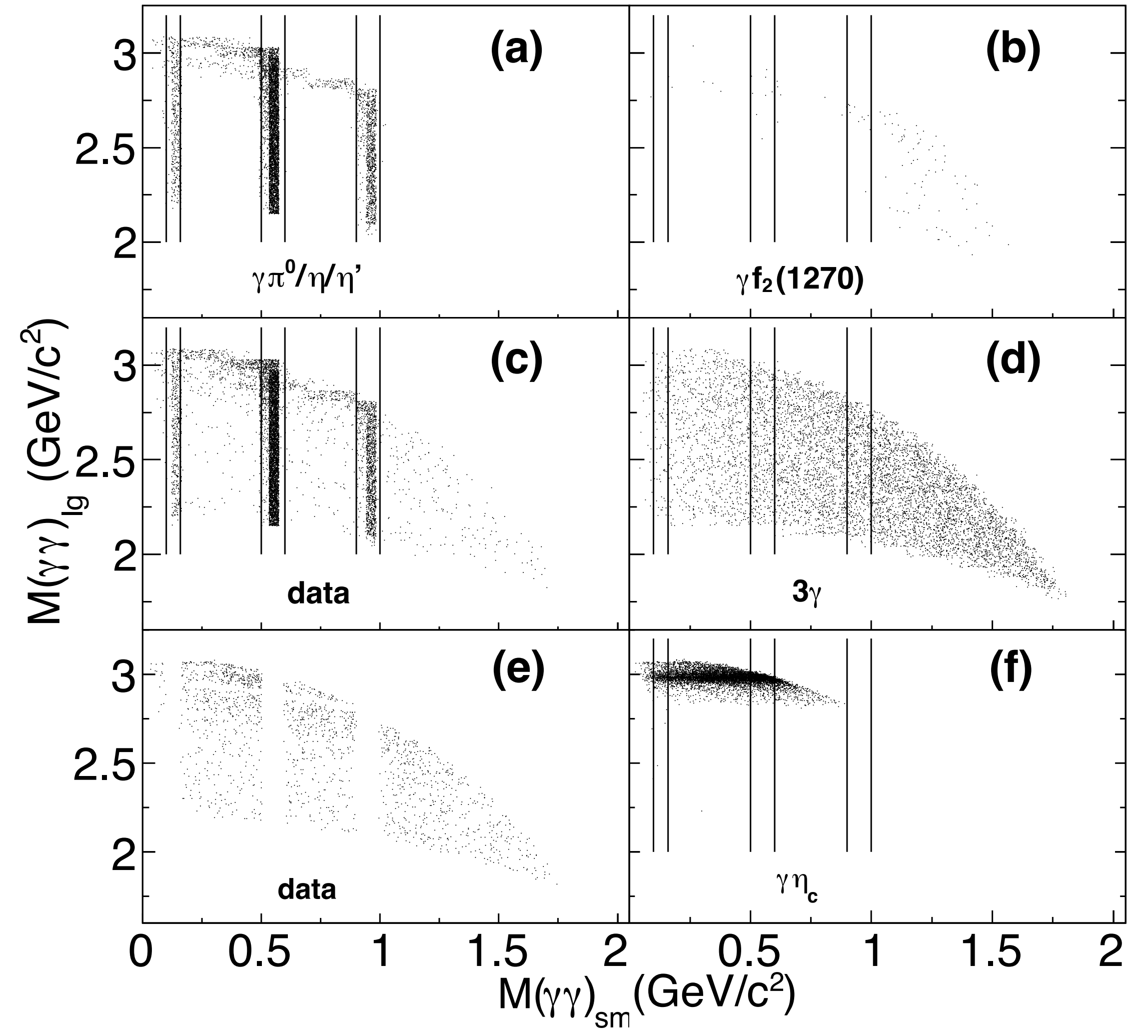
prediction:
$\alpha_s = 0.32 \rightarrow R = 0.12$

Expt: R = 0.27 ± 0.04

Higher order corrections significant!

$J/\psi \to \gamma\gamma\gamma$

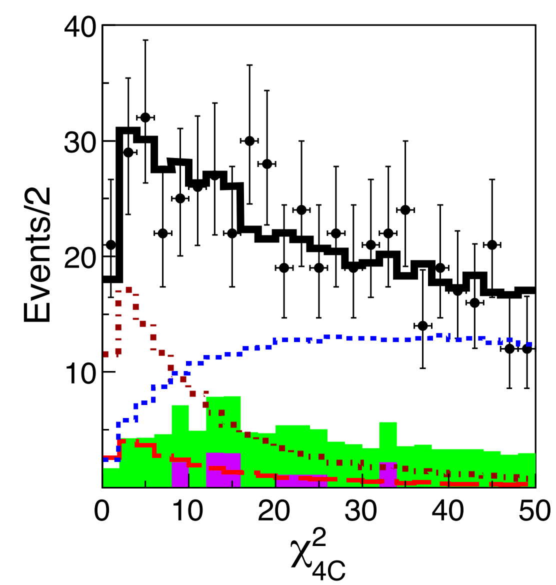
BESIII, PRD 87, 032003 (2013)

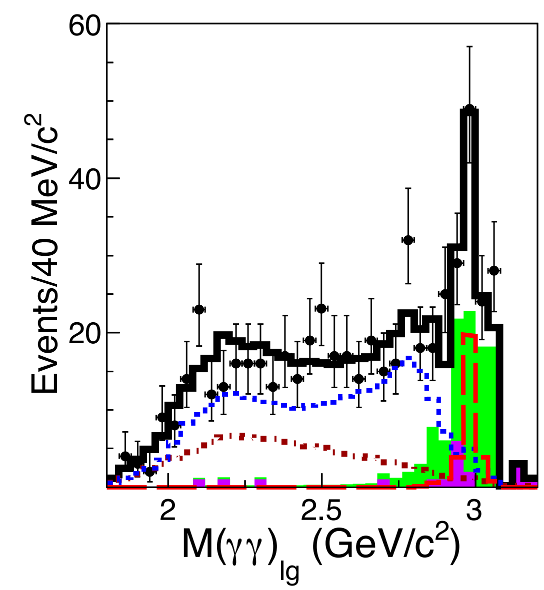


- Test of non-perturbative QCD corrections to a QED process (at first order):

$$\mathcal{R} \equiv \frac{\mathcal{B}(J/\psi \to 3\gamma)}{\mathcal{B}(J/\psi \to e^+e^-)} = \frac{64(\pi^2-9)}{243\pi}\alpha(1-7.3\frac{\alpha_s(r)}{\pi})$$

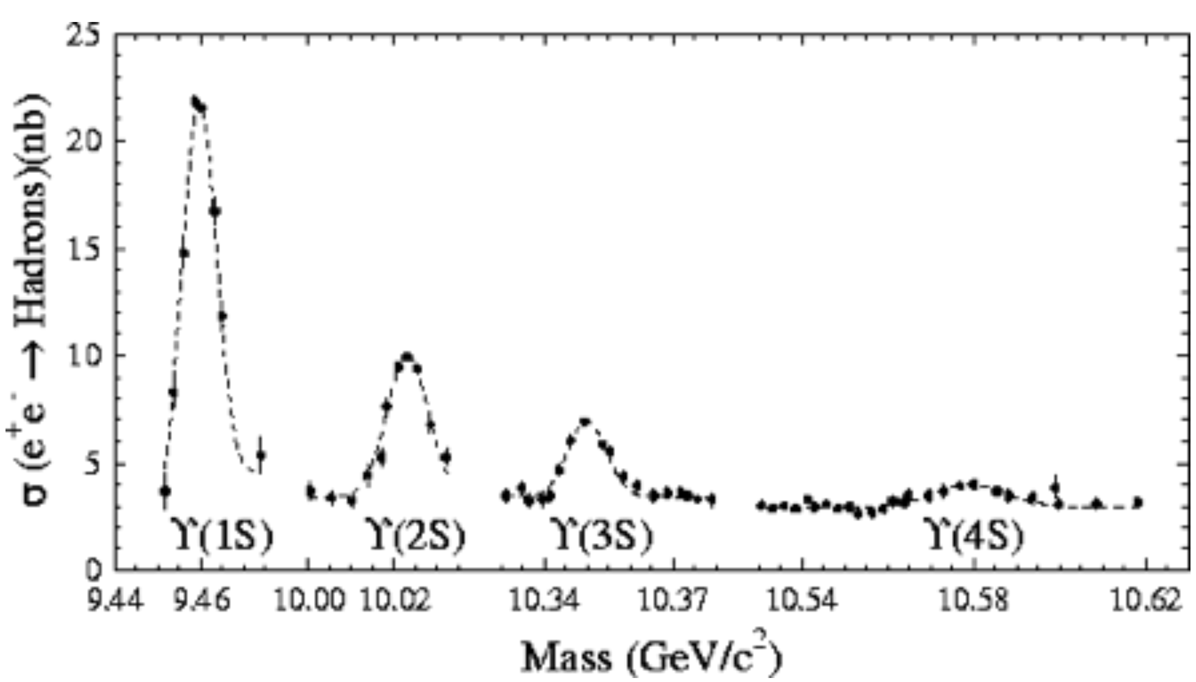
- Leading order: $R = 5.3 \times 10^{-4}$;
  Using $\alpha_s = 0.19$: $R = 3.0 \times 10^{-4}$
- Suppress EM bkg. by using J/ψ from $\psi' \to \pi\pi J/\psi$
  Measure: $B(J/\psi \to \gamma\gamma\gamma) = (11.3 \pm 1.8 \pm 2.0) \times 10^{-6}$
- Combine w/CLEO-c [PRL 101, 101801 (2008)]
  From experiment: $R = (1.95 \pm 0.37) \times 10^{-4}$

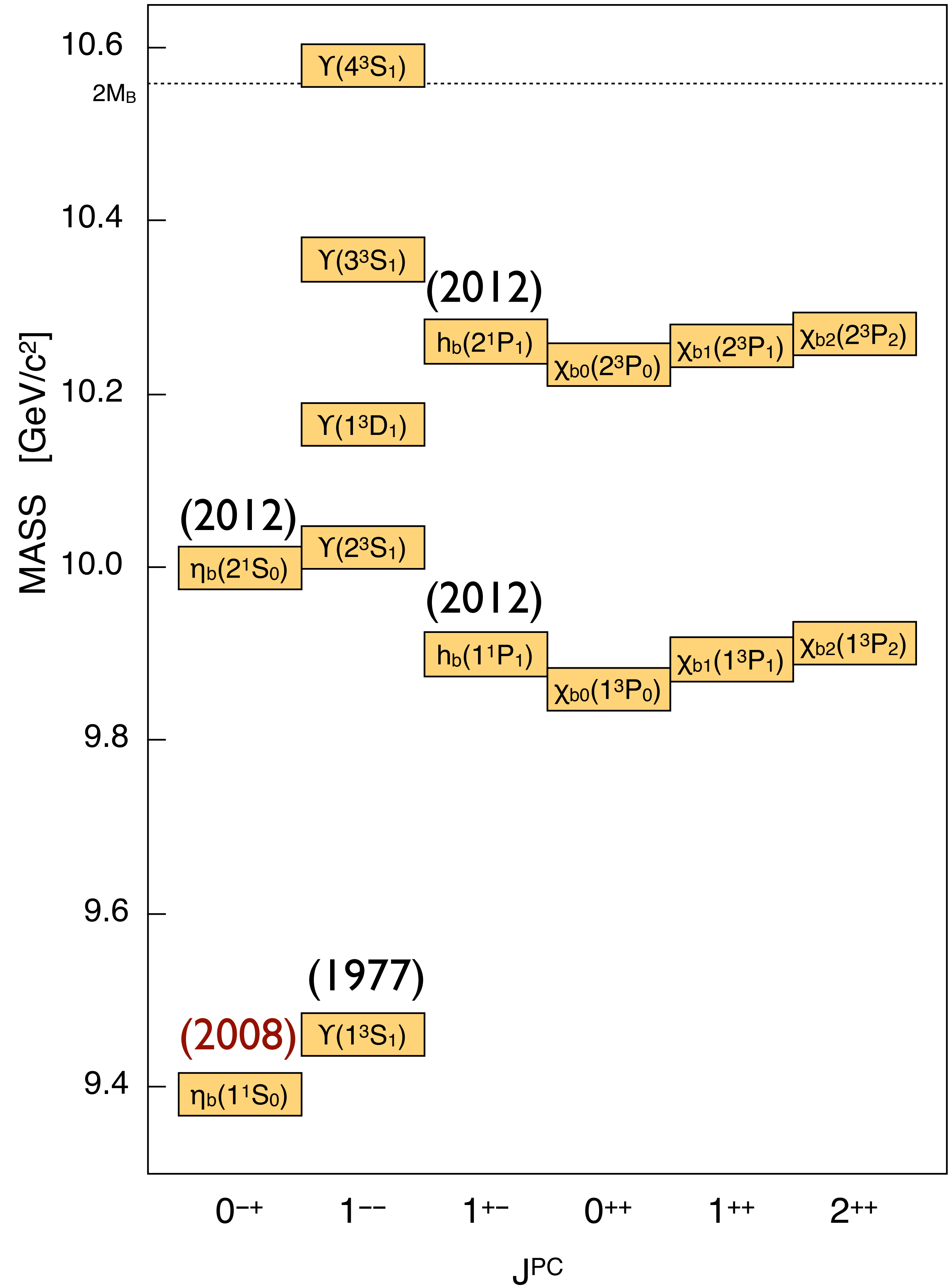




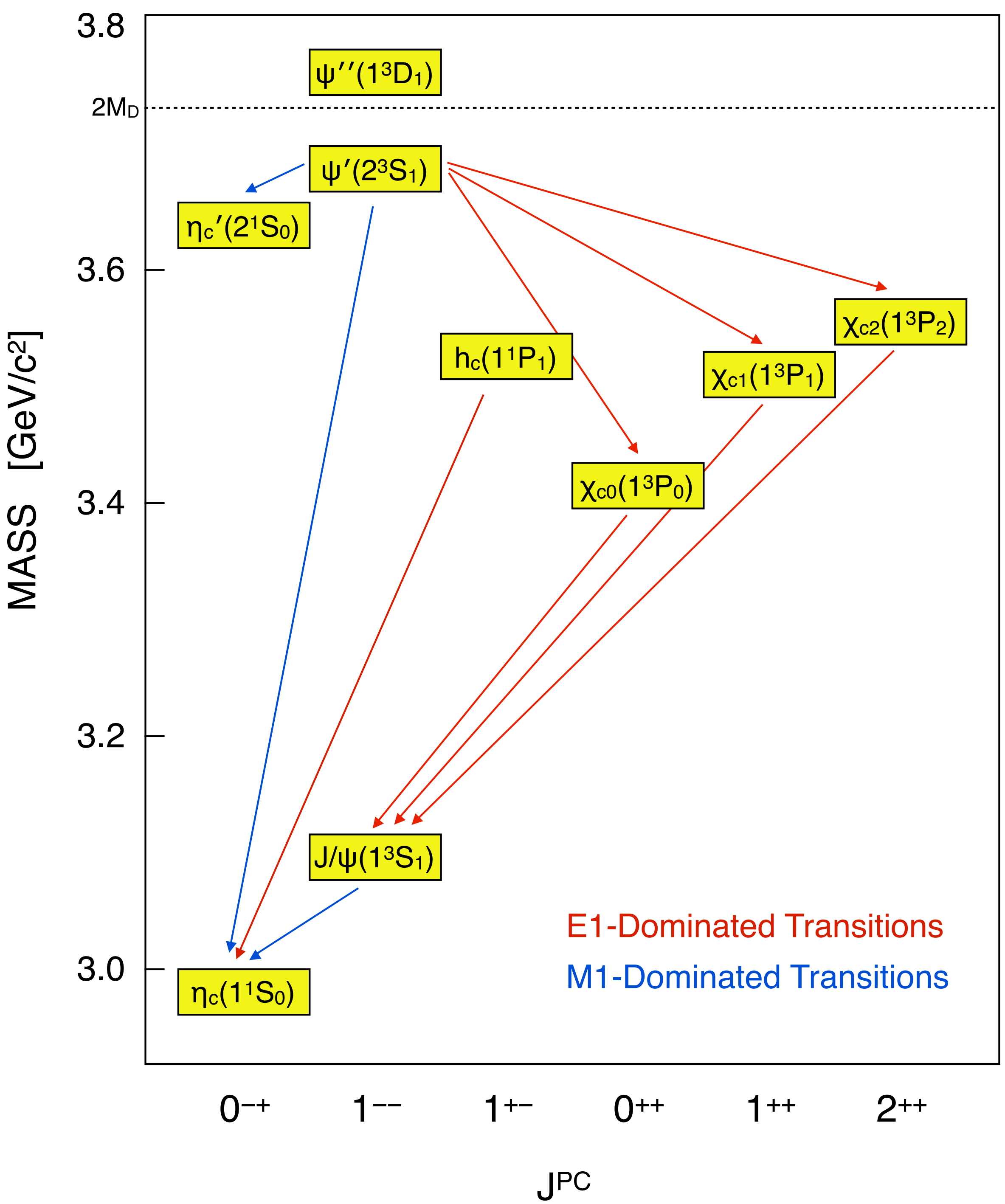
Bottom Quarks

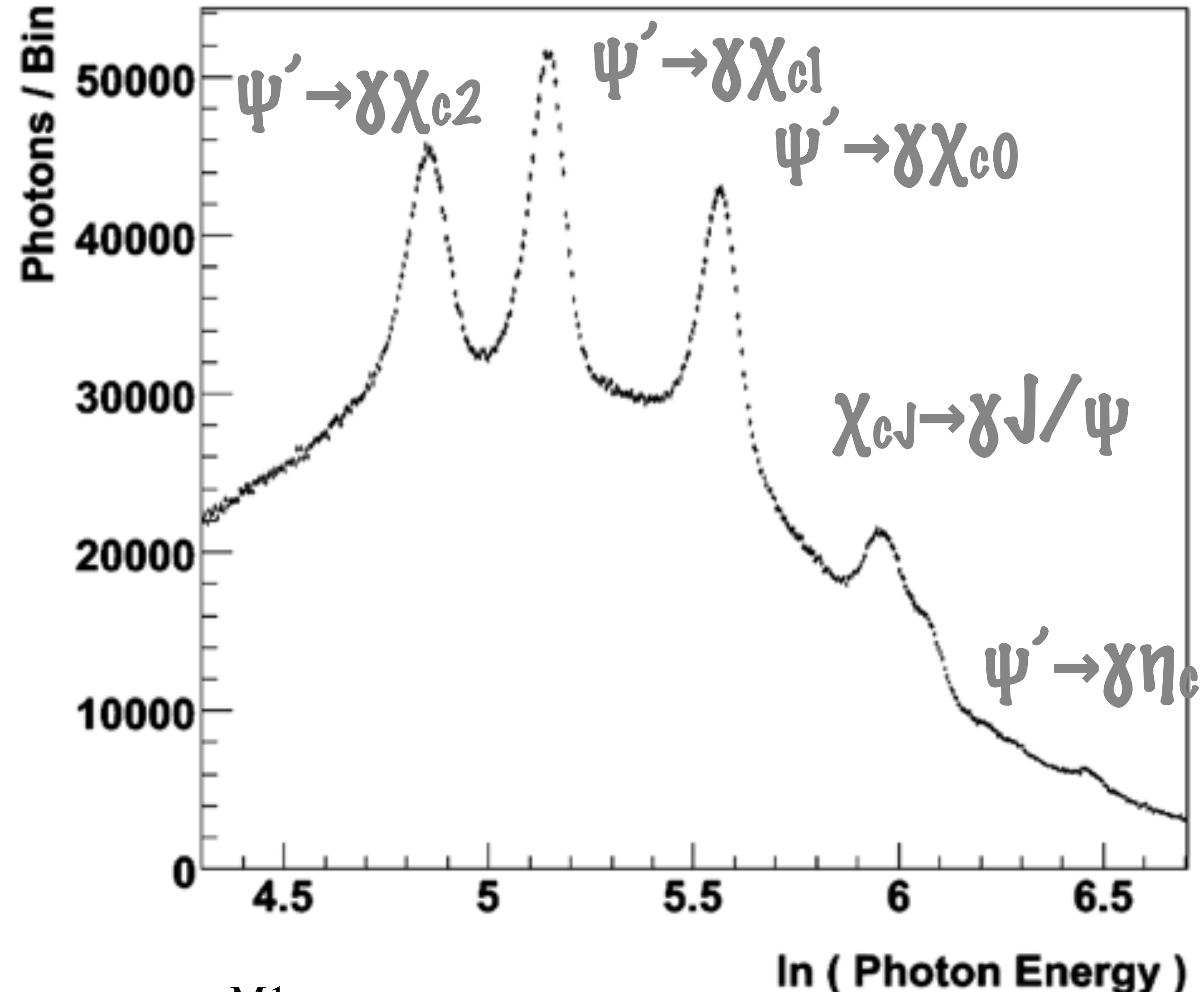
- Similar production
- All state below 2 M_B with $L \leq 1$ experimentally established (recently)
- Probe of QCD at different mass scale





Electromagnetic Transitions

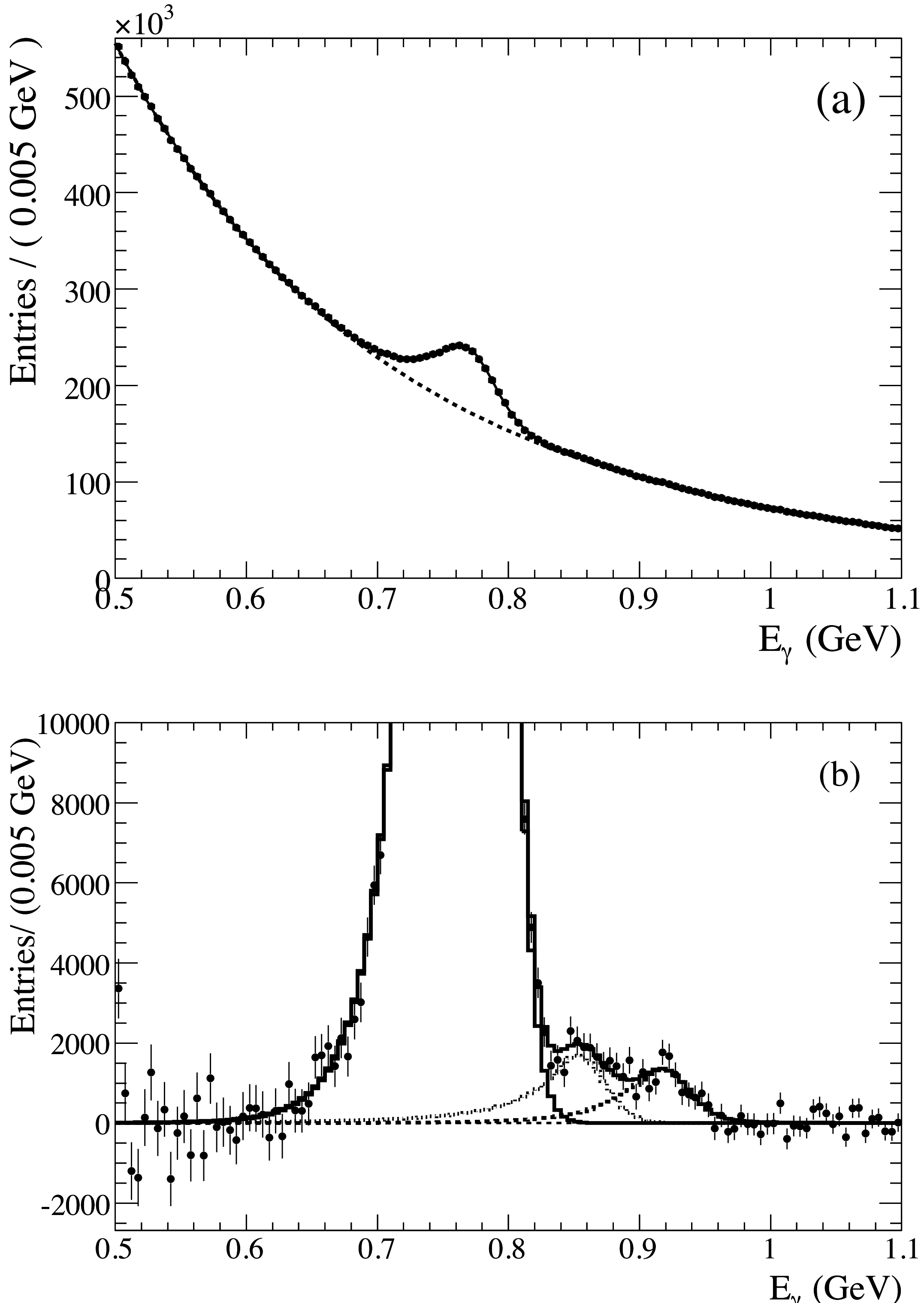




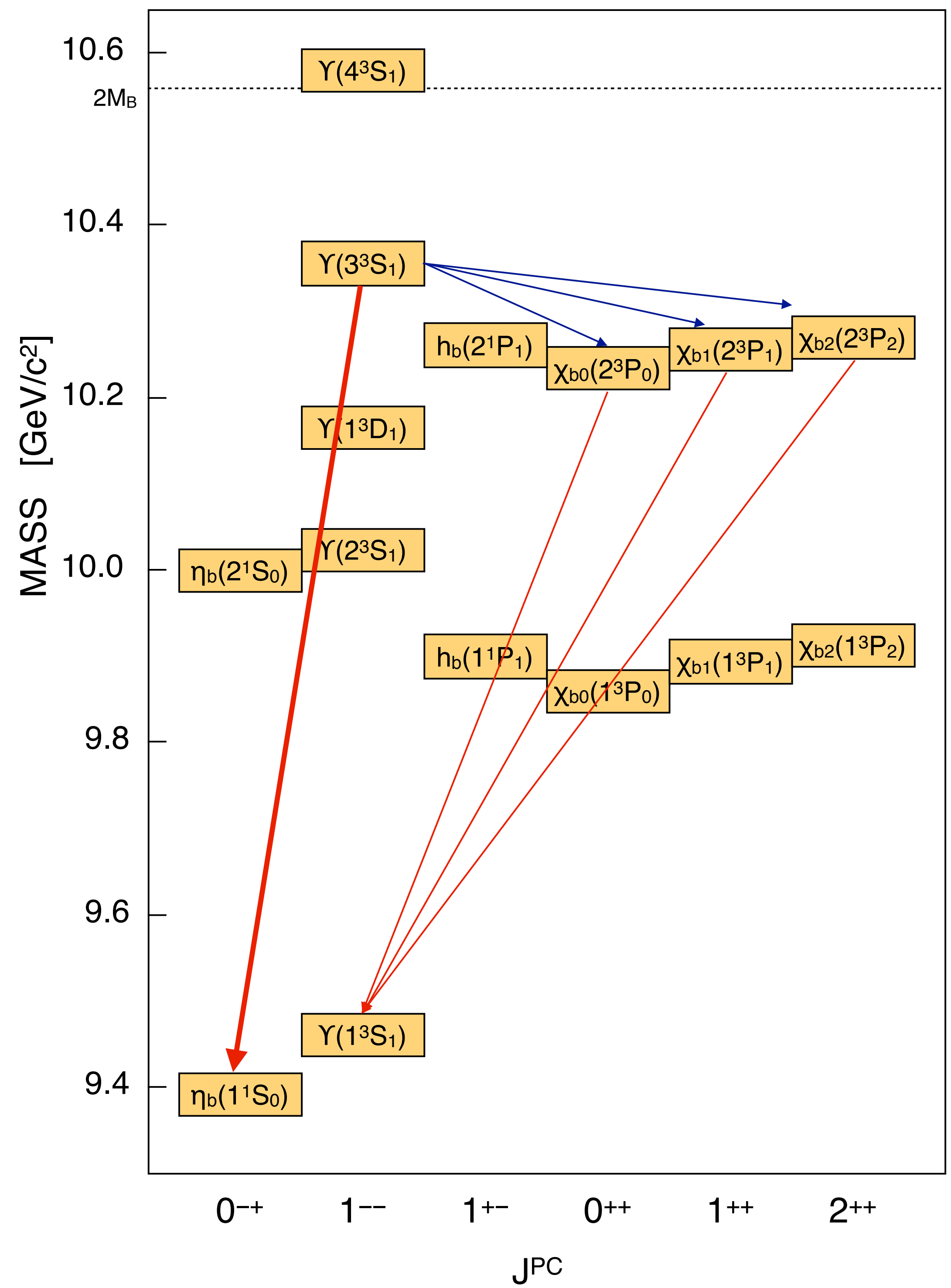
$$\Gamma\left(i \xrightarrow{\text{M1}} \gamma + f\right) = \frac{16}{3}\alpha e_Q^2 \frac{E_\gamma^3}{m_i^2}(2J'+1)\mathrm{S}_{if}^{\mathrm{M}}|\mathcal{M}_{if}|^2$$

$$\Gamma\left(i \xrightarrow{\text{E1}} \gamma + f\right) = \frac{4}{3}\alpha e_Q^2 E_\gamma^3 (2J'+1)\mathrm{S}_{if}^{\mathrm{E}}|\mathcal{E}_{if}|^2$$

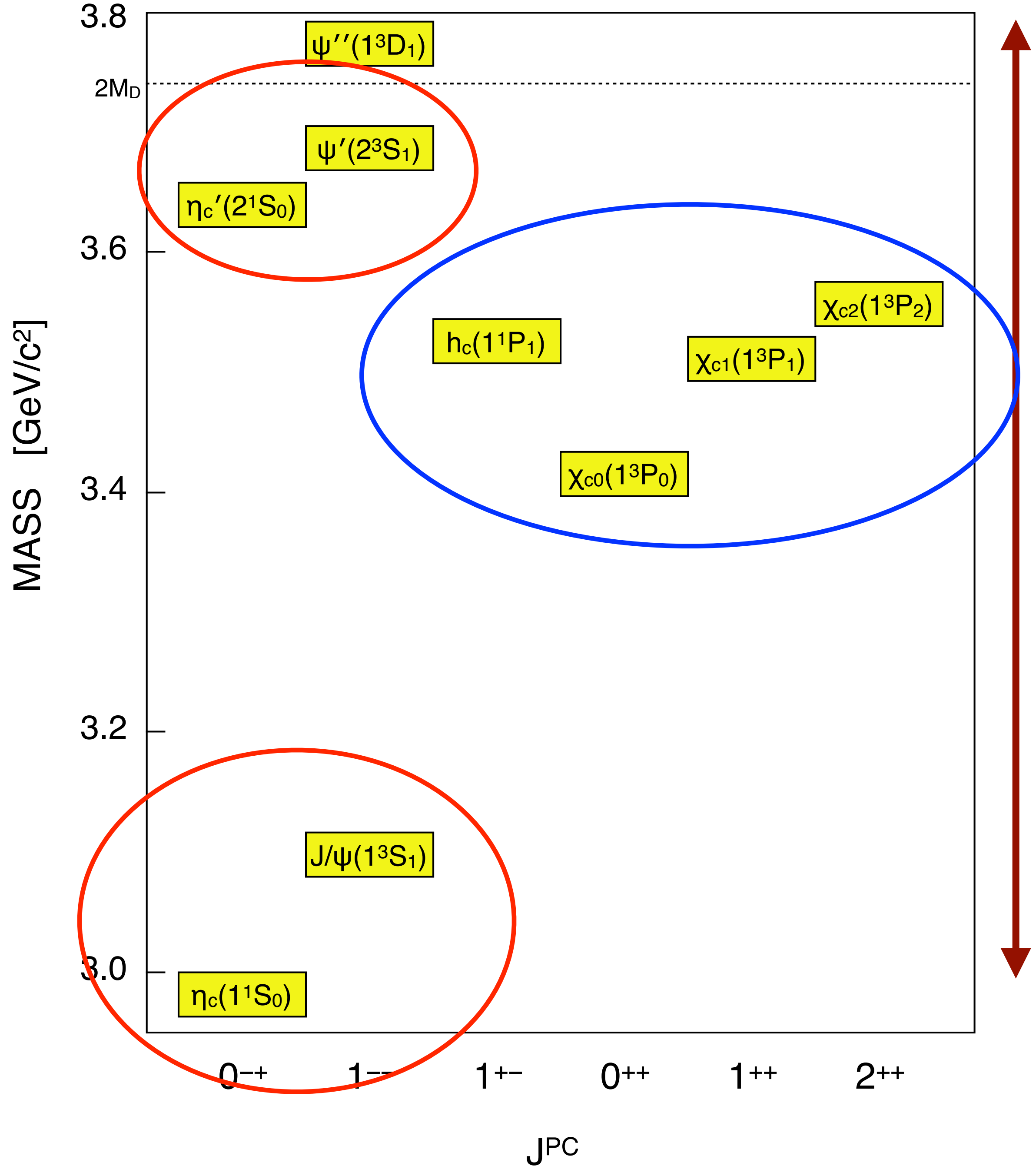
Discovery of η_b

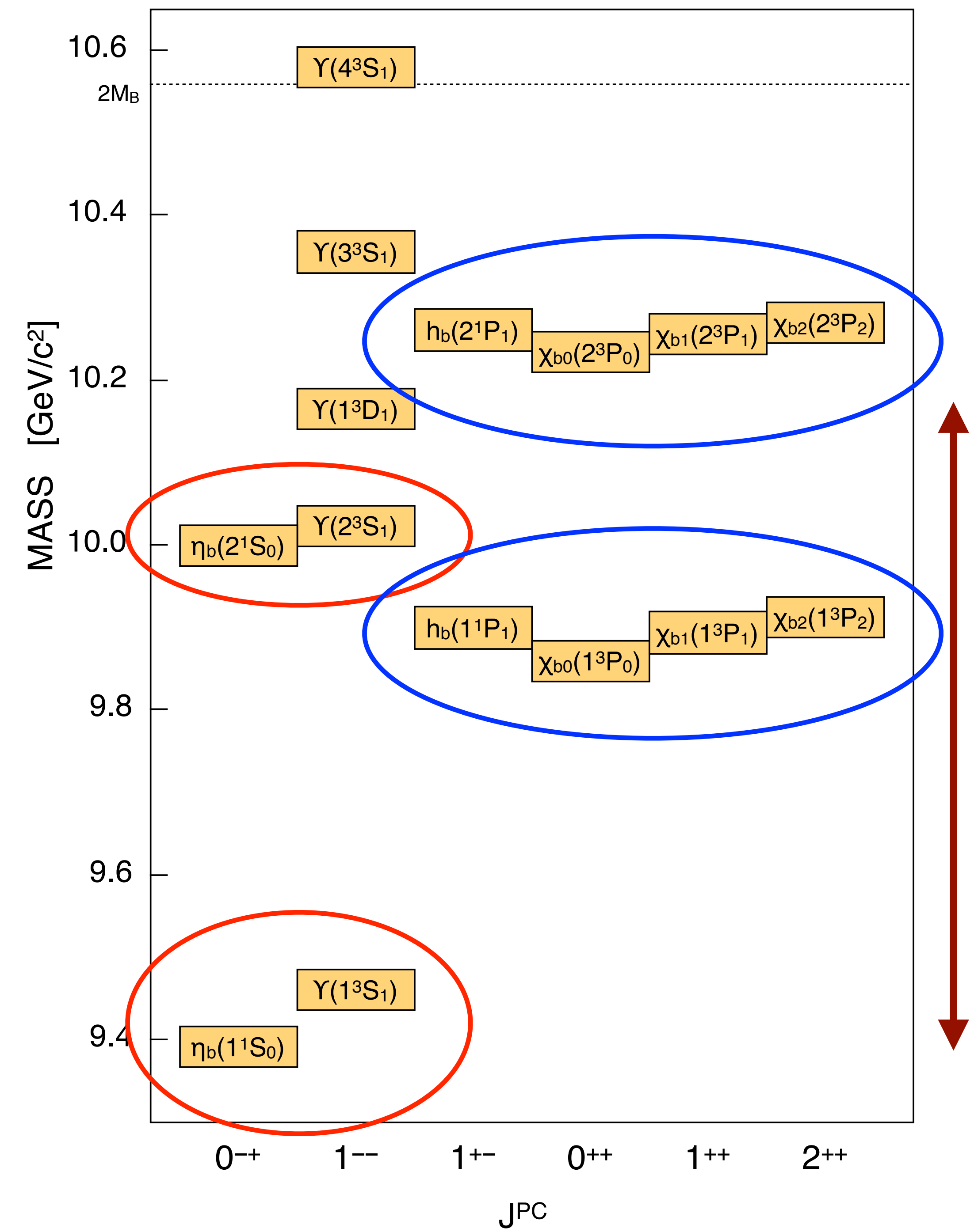


BaBar Collaboration, PRL 101, 071801 (2008)



Hyperfine Structure





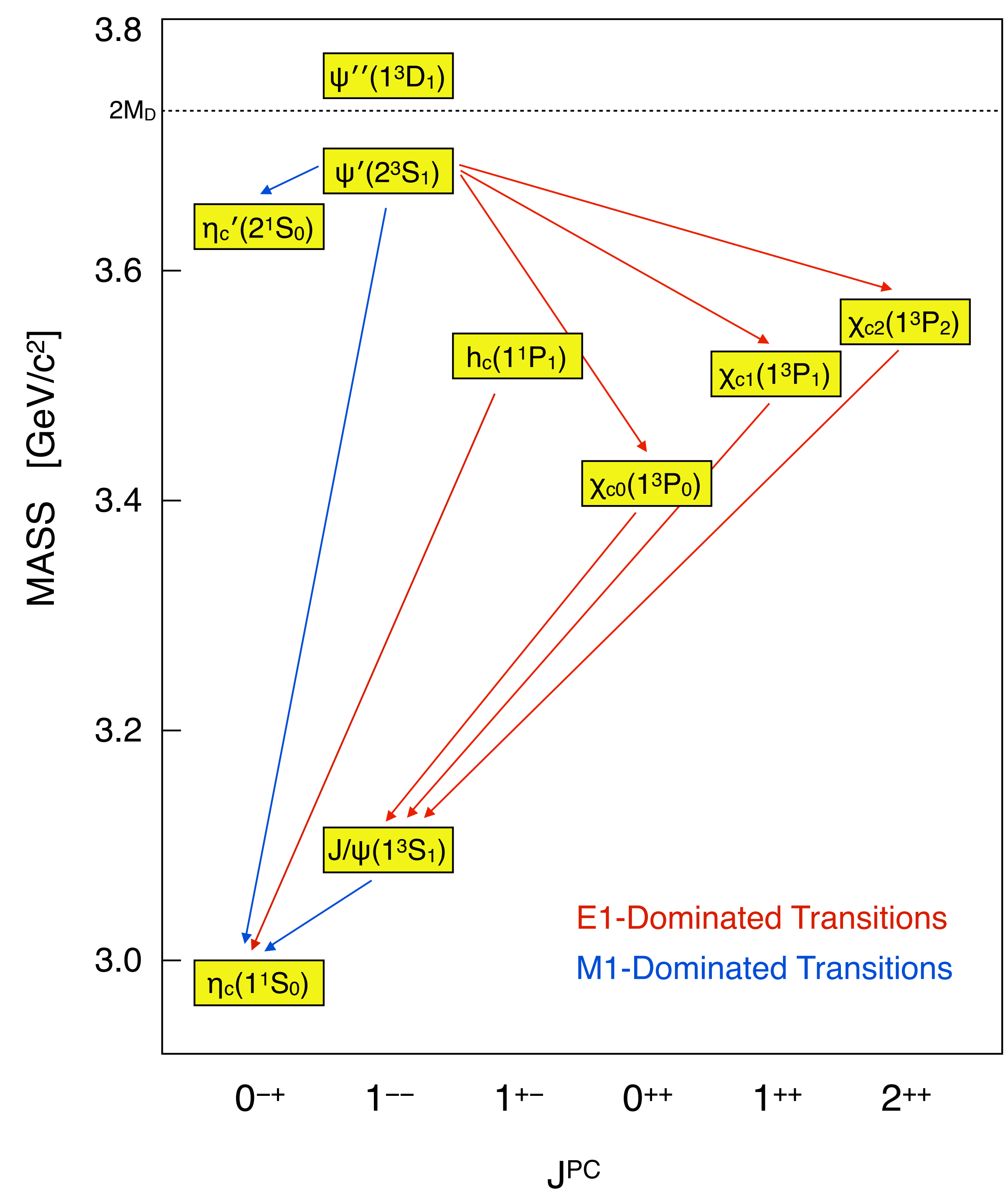
Emerging Message

- Heavy quarkonia systems provide an opportunity to study the QCD interaction between two quarks
- There is little debate about the quark content and spin configuration of the lowest lying heavy quarkonium states

- Puzzles:
  - Strong decays of quarkonium to light quarks
  - Excited spectrum of quarkonium

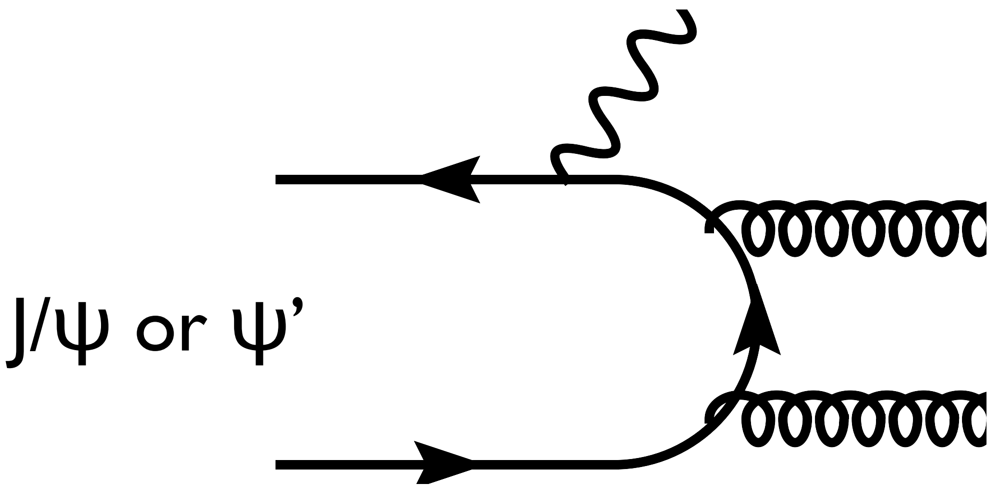
Charmonium

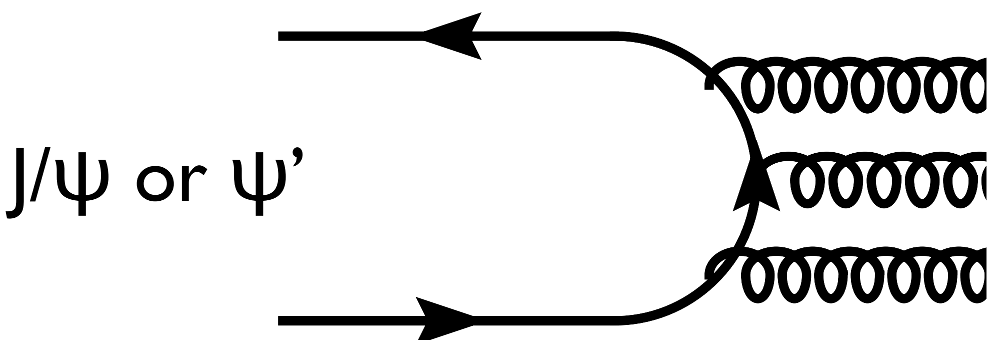
- Directly produce J/ψ or ψ' in e^+e^- collisions
  - study spectrum and transitions
  - spectrum of low-lying charmonium states and transitions between them seem understandable
- Surprises:
  - decays to light quarks
  - excited charmonium spectrum
- Handling light quark degrees of freedom in QCD is challenging



Surprises in Strong Decays

- Naive picture of strong decay
- J/ψ and ψ' are very similar
  - same J^{PC}
  - ψ' is a radial excitation of J/ψ
- How does the initial state influence which light quark hadrons are produced in the final state?



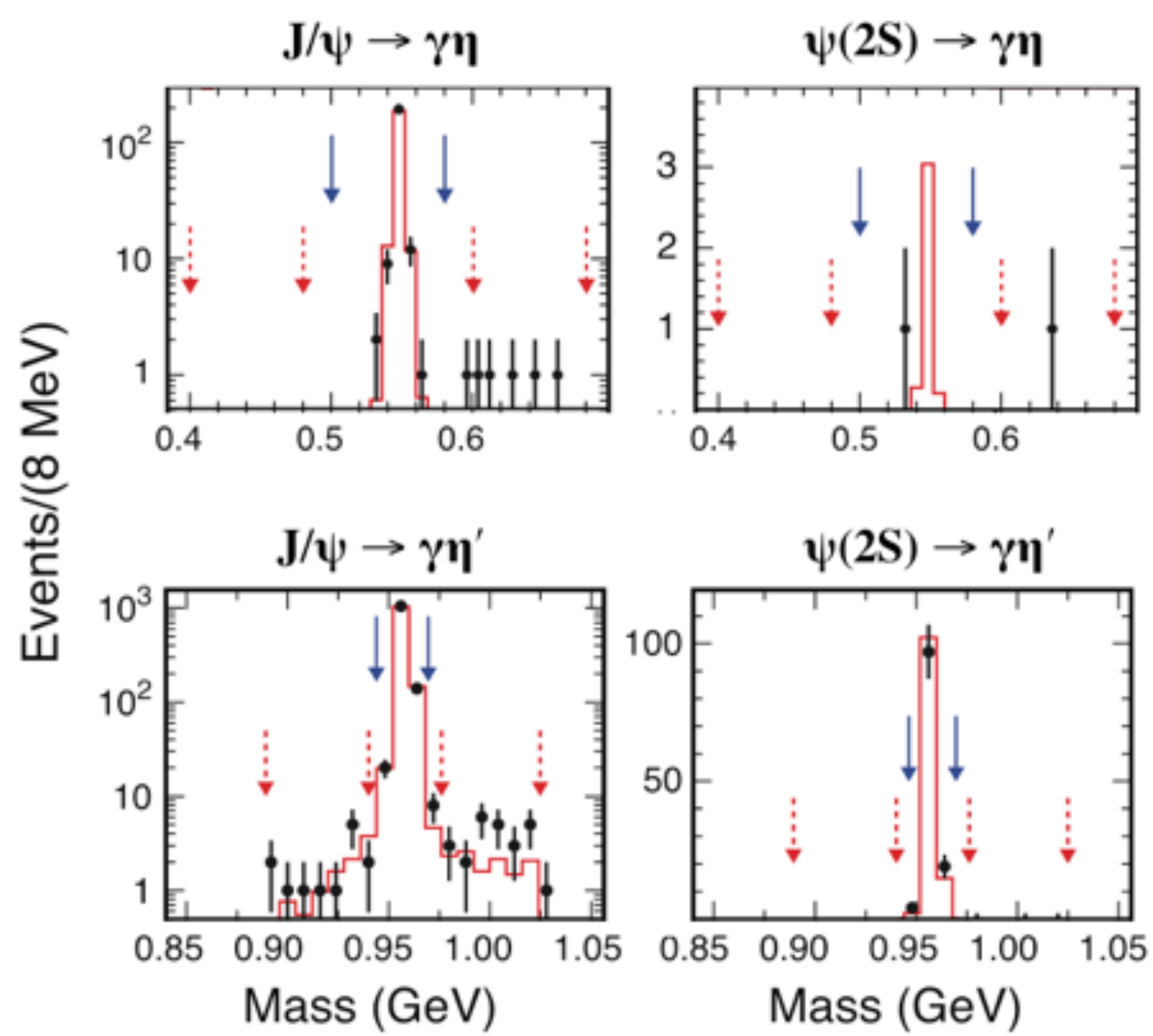


J/ψ,ψ'→γ(η, η')

- Measure:

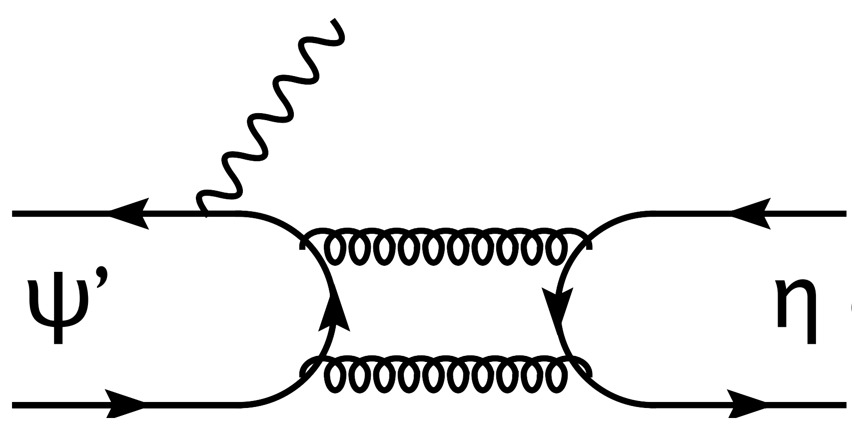
$$R_n \equiv \frac{\mathcal{B}(\psi(nS) \to \gamma\eta)}{\mathcal{B}(\psi(nS) \to \gamma\eta')}$$

- Existing measurements of R_1 consistent with expected mechanism and known η/η' mixing
- *R_2 expected to be equal to R_1*



"Cut and count" analysis in region of meson mass

J/ψ or ψ'



η or η'

CLEO Collaboration
PRD 79, 111101(R) (2009)

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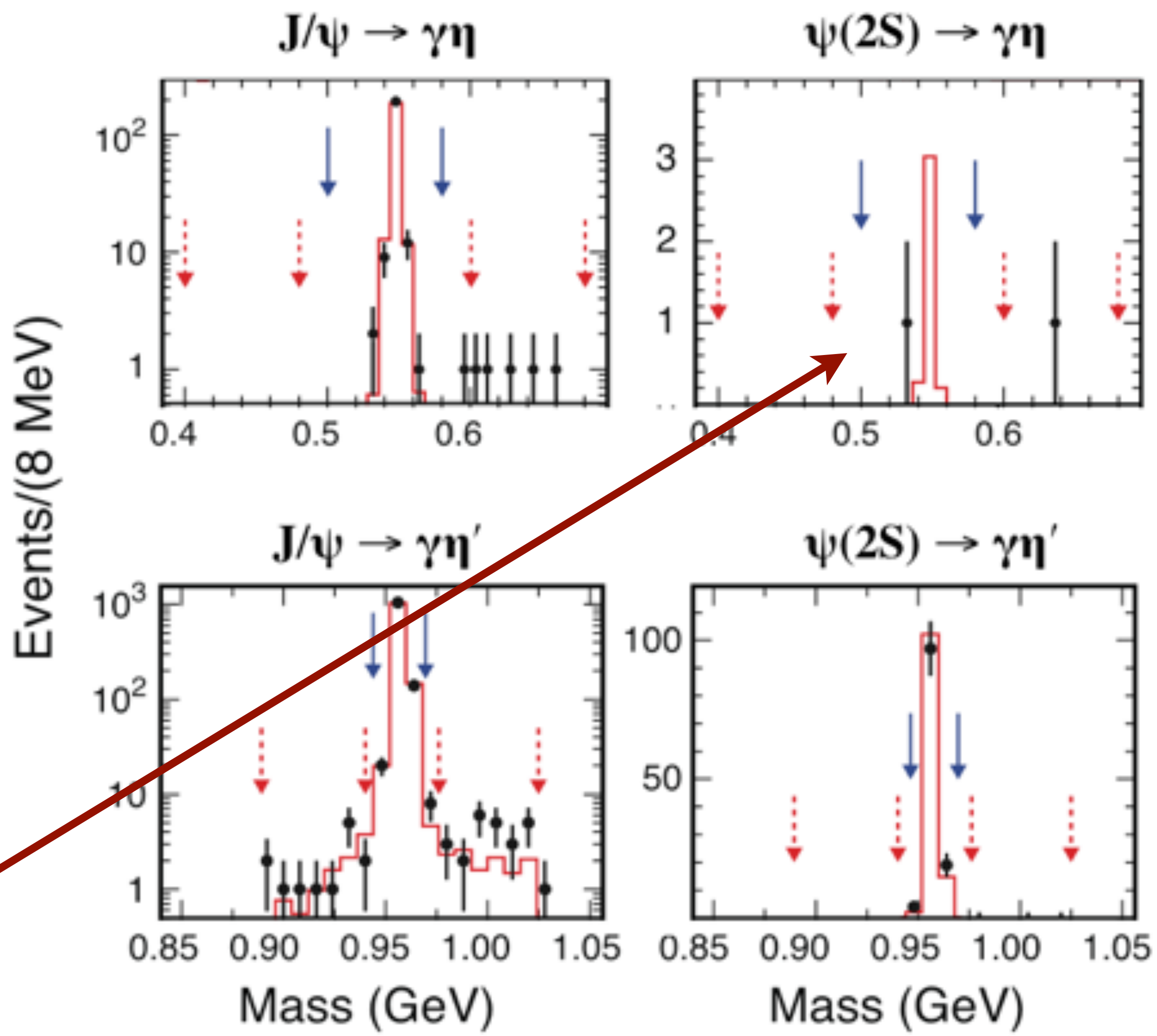
J/ψ,ψ’→γ(η, η’)

Results:

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

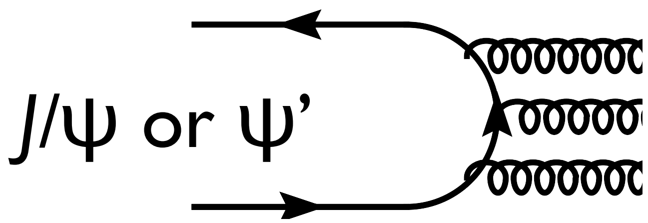
$$\frac{B(\psi(2S) \to \gamma\eta)}{B(\psi(2S) \to \gamma\eta')} < 1.8\%$$



Why is ψ(2S)→γη strongly suppressed?

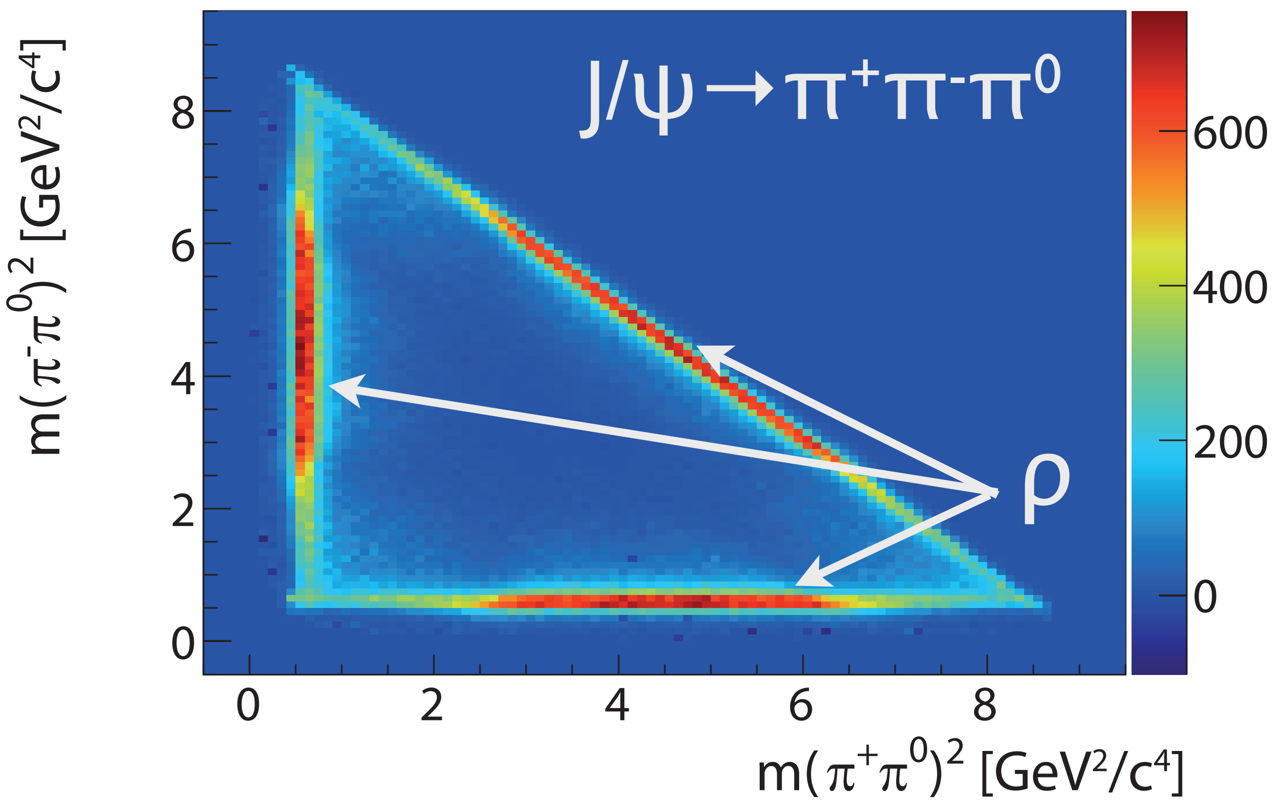
CLEO Collaboration
PRD 79, 111101(R) (2009)

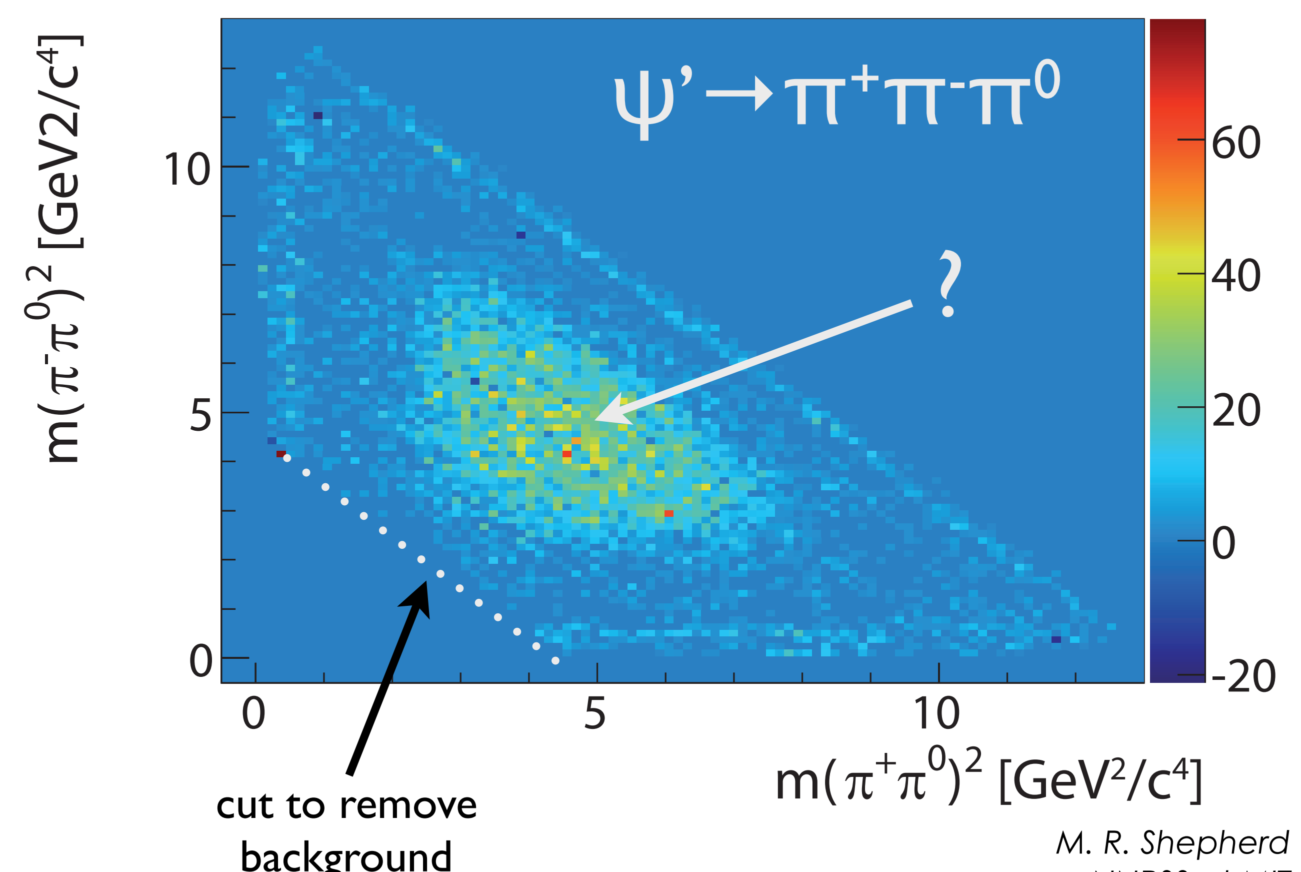
3π Decays of J/ψ and ψ’



- In the naive picture both decays should be very similar
  - *cc* annihilation
  - same parent J^{PC}
  - hadronization into 3π at about the same energy scale
- The two Dalitz plots couldn’t look any more different!
  - *J*/ψ is dominated by ρ
  - ψ’ is strongly populated by higher mass states absent in J/ψ decay

BESIII, PLB 710, 594 (2012)





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Excited Charmonium Spectrum

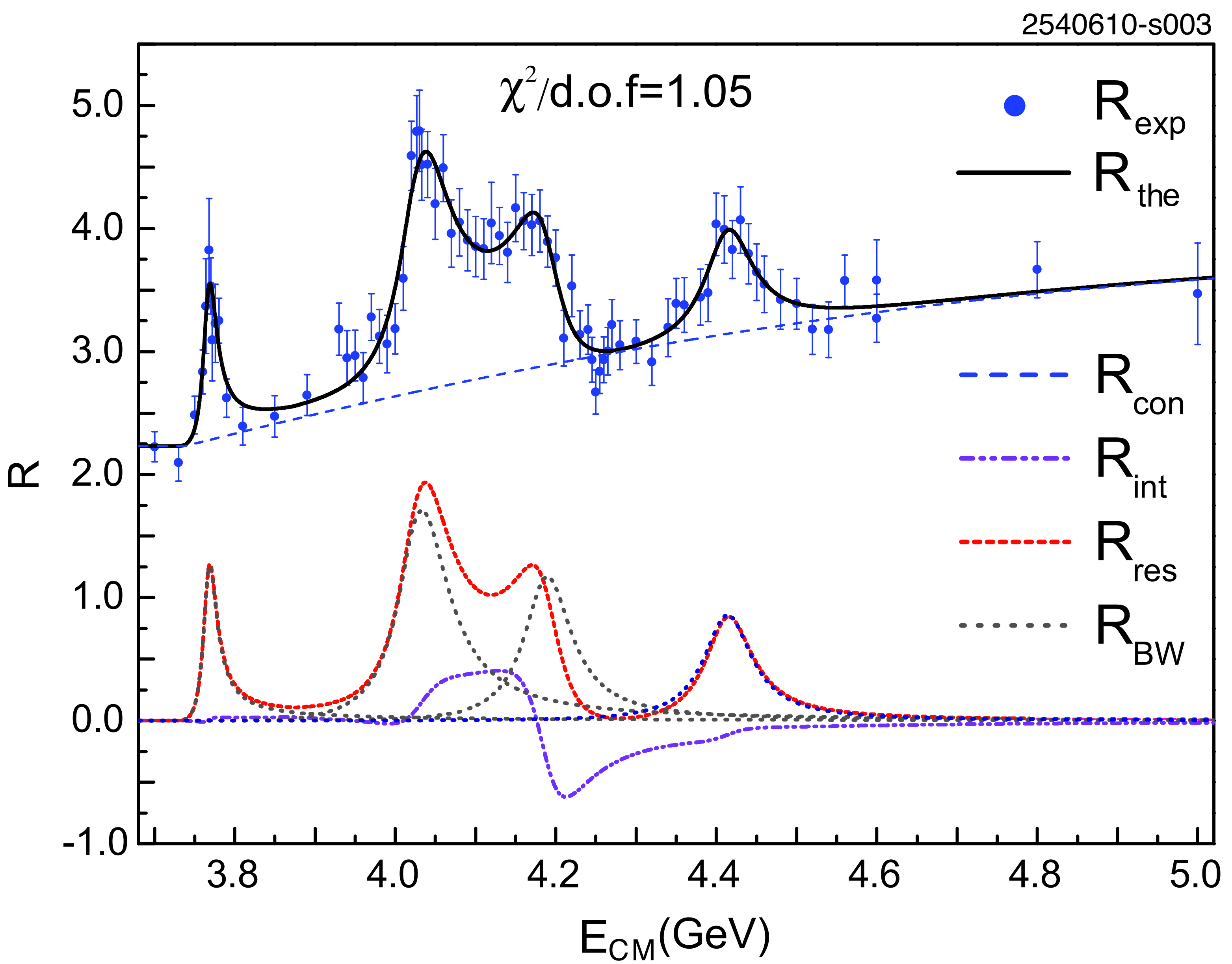
- Center of spectroscopy activity in the last decade
- Simplicity of charmonium system makes it easy to notice unusual states

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

EPJ, C71 1534 (2011)

Vector (1^{--}) Charmonia

Resonance	m (MeV)	Γ_{tot} (MeV)	δ (°)	Ref.
$\psi(3770)$	3769.9 ± 2.5	23.6 ± 2.7		PDG04 [17]
	3771.1 ± 2.4	23.0 ± 2.7		Seth [14]
	3772.0 ± 1.9	30.4 ± 8.5	0	BES [15]
	3772.92 ± 0.35	27.3 ± 1.0		PDG08 [18]
$\psi(4040)$	4040 ± 1	52 ± 10		PDG04 [17]
	4039 ± 1.0	80 ± 10		Seth [14]
	4039.6 ± 4.3	84.5 ± 12.3	130 ± 46	BES [15]
$\psi(4160)$	4159 ± 20	78 ± 20		PDG04 [17]
	4153 ± 3	103 ± 8		Seth [14]
	4191.7 ± 6.5	71.8 ± 12.3	293 ± 57	BES [15]
$\psi(4415)$	4415 ± 6	43 ± 15		PDG04 [17]
	4421 ± 4	62 ± 20		Seth [14]
	4415.1 ± 7.9	71.5 ± 19.0	234 ± 88	BES [15]

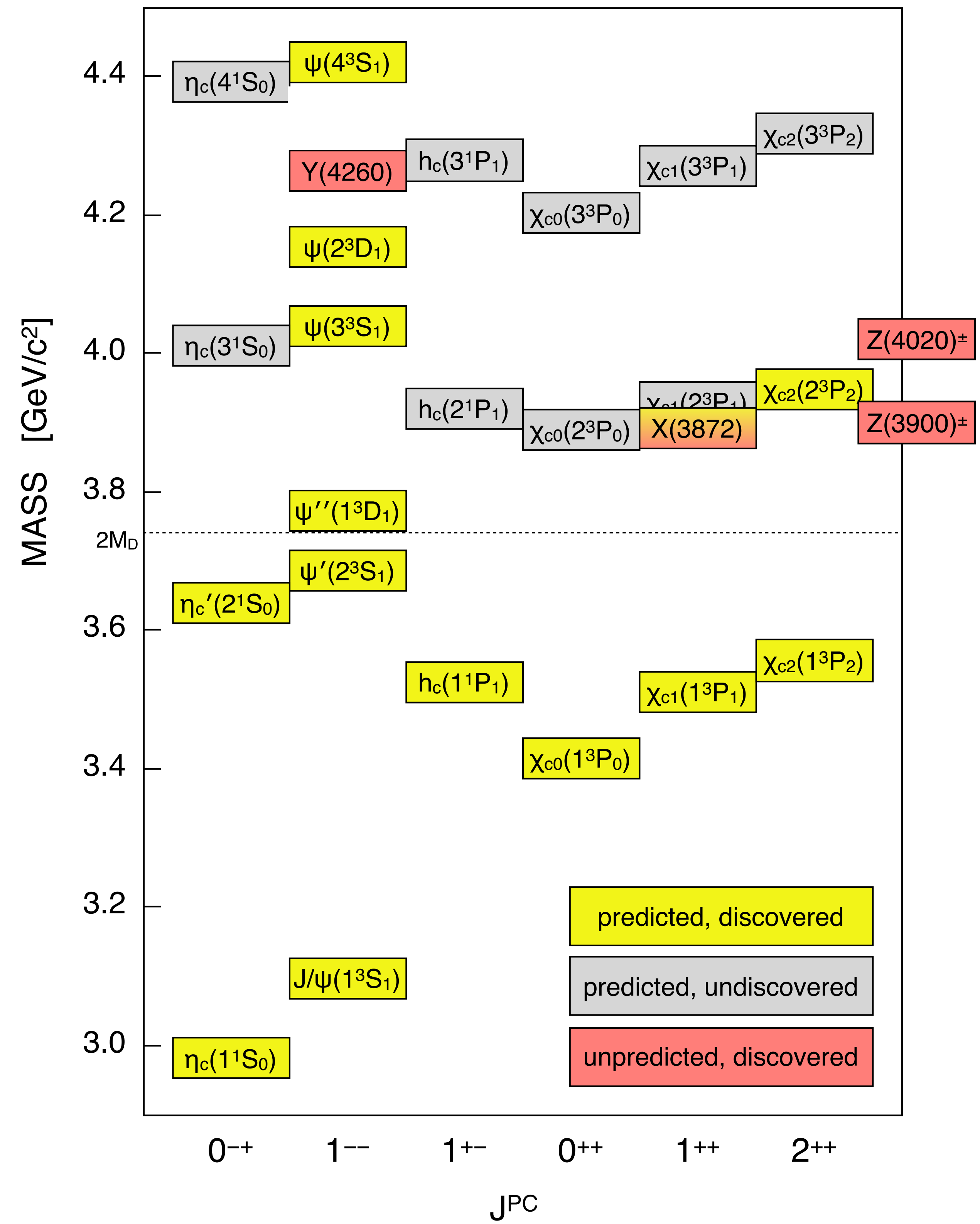


See EPJ, C71 1534 (2011) for details

Charmonium Landscape

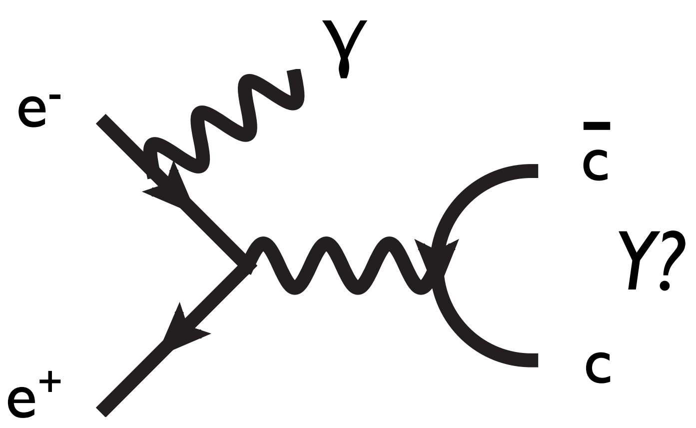
- Key players:
  - Y(4260): ???
  - J/ψ: S_q=1 L=0, J^{PC} = 1⁻ ⁻
  - h_c: S_q=0 L=1, J^{PC} = 1⁺⁻
- Key transitions:
  - Y→ππJ/ψ
  - Y→ππh_c
- Study of Y(4260) led to discovery of charged $Z(3900)^{\pm}$ and $Z(4020)^{\pm}$ structures

Quark Model Prediction:
Barnes *et al.*, PRD 72, 054026 (2005)
(approximate — not all XYZ candidates shown!)

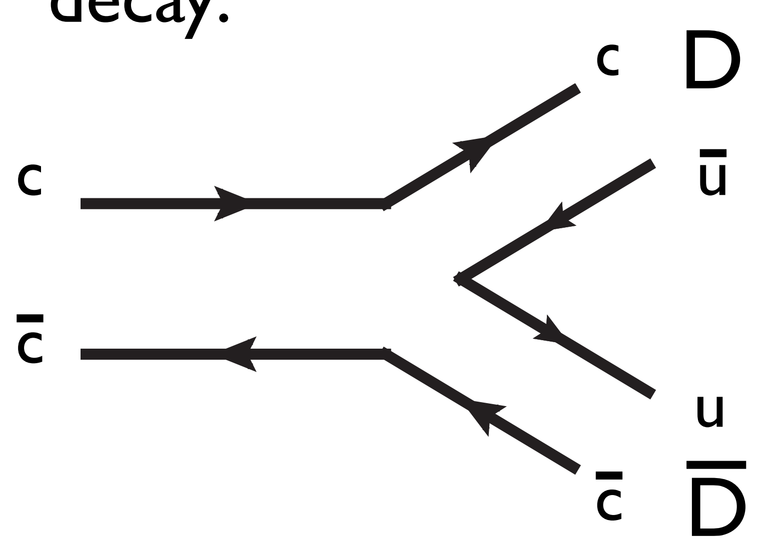


The Y(4260)

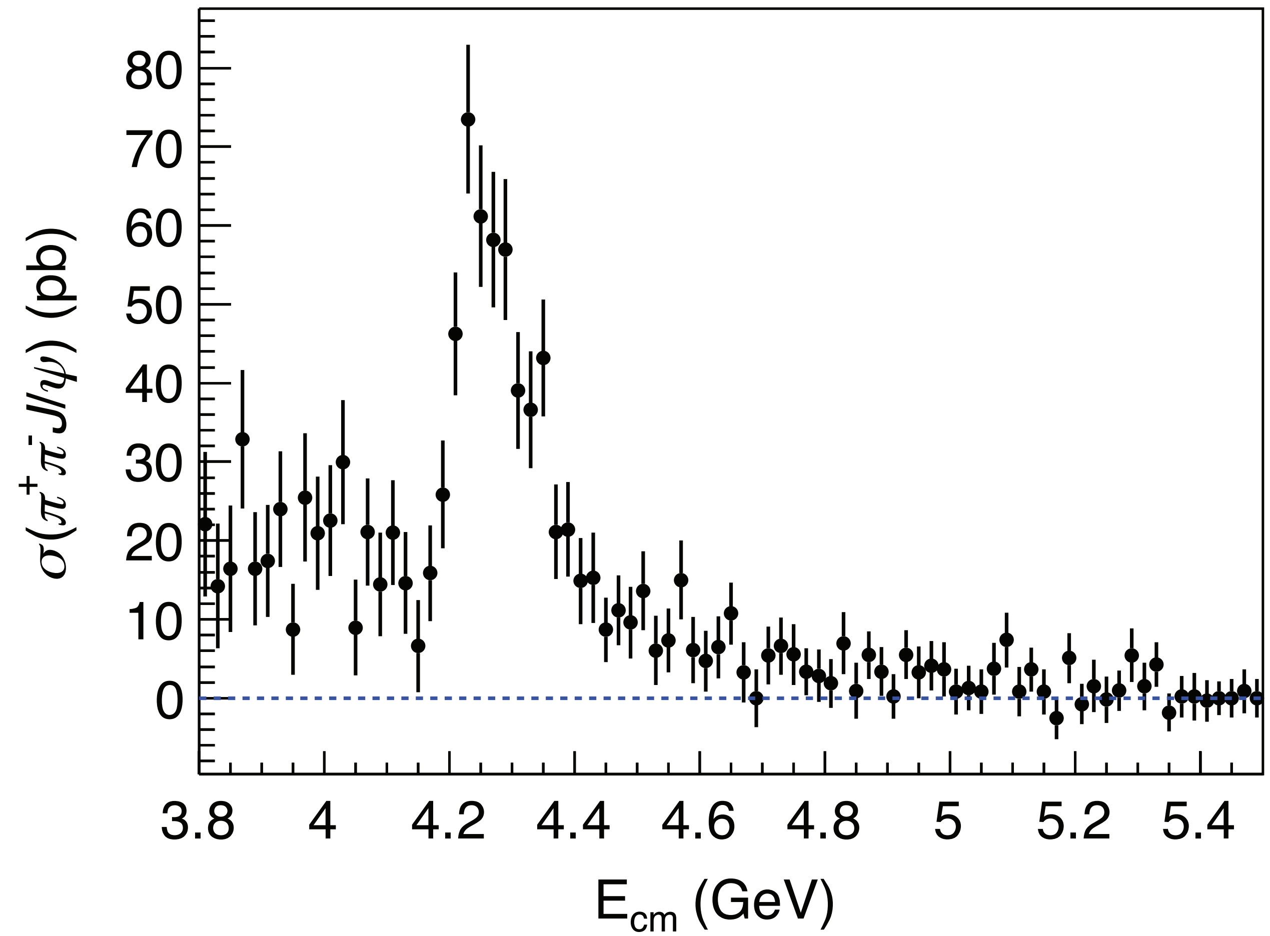
- 1^{--} state produced in e^+e^-



- mass greater than 2M(D) so we expect OZI favored decay:



Belle Collaboration, PRL 110, 252002 (2013)



CLEO Collaboration, PRD 80, 072001 (2009)

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi\pi J/\psi)} < 4$$

compare with ≈500 for ψ(3770)

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Exercise: Y(4260)→ππJ/ψ

What do the first two lines of this table *suggest* about the isospin of Y(4260)? Could Y(4260) be the neutral member of an isotriplet of tetraquarks?

TABLE I: For each mode $e^+e^- \to X$, for three center-of-mass regions: the detection efficiency, ϵ; the number of signal [background] events in data, N_s [N_b]; the cross-section $\sigma(e^+e^- \to X)$; and the branching fraction of $\psi(4040)$ or $\psi(4160)$ to X, $\mathcal{B}$. Upper limits are at 90% CL. '–' indicates that the channel is kinematically or experimentally inaccessible.

from CLEO-c, PRL 96, 162003 (2003)

Channel	$\sqrt{s} = 3970 - 4060$ MeV					$\sqrt{s} = 4120 - 4200$ MeV					$\sqrt{s} = 4260$ MeV			
	ϵ (%)	N_s	N_b	σ (pb)	$\mathcal{B}$ (10^{-3})	ϵ (%)	N_s	N_b	σ (pb)	$\mathcal{B}$ (10^{-3})	ϵ (%)	N_s	N_b	σ (pb)
$\pi^+\pi^- J/\psi$	37	12	3.7	$9^{+5}_{-4}\pm 2$	< 4	38	13	3.7	$8^{+4}_{-3}\pm 2$	< 4	38	37	2.4	$58^{+12}_{-10}\pm 4$
$\pi^0\pi^0 J/\psi$	20	1	1.9	< 8	< 2	21	5	0.9	$6^{+5}_{-3}\pm 1$	< 3	22	8	0.3	$23^{+12}_{-8}\pm 1$
$K^+K^- J/\psi$			–			7	1	0.07	< 20	< 5	21	3	0.07	$9^{+9}_{-5}\pm 1$

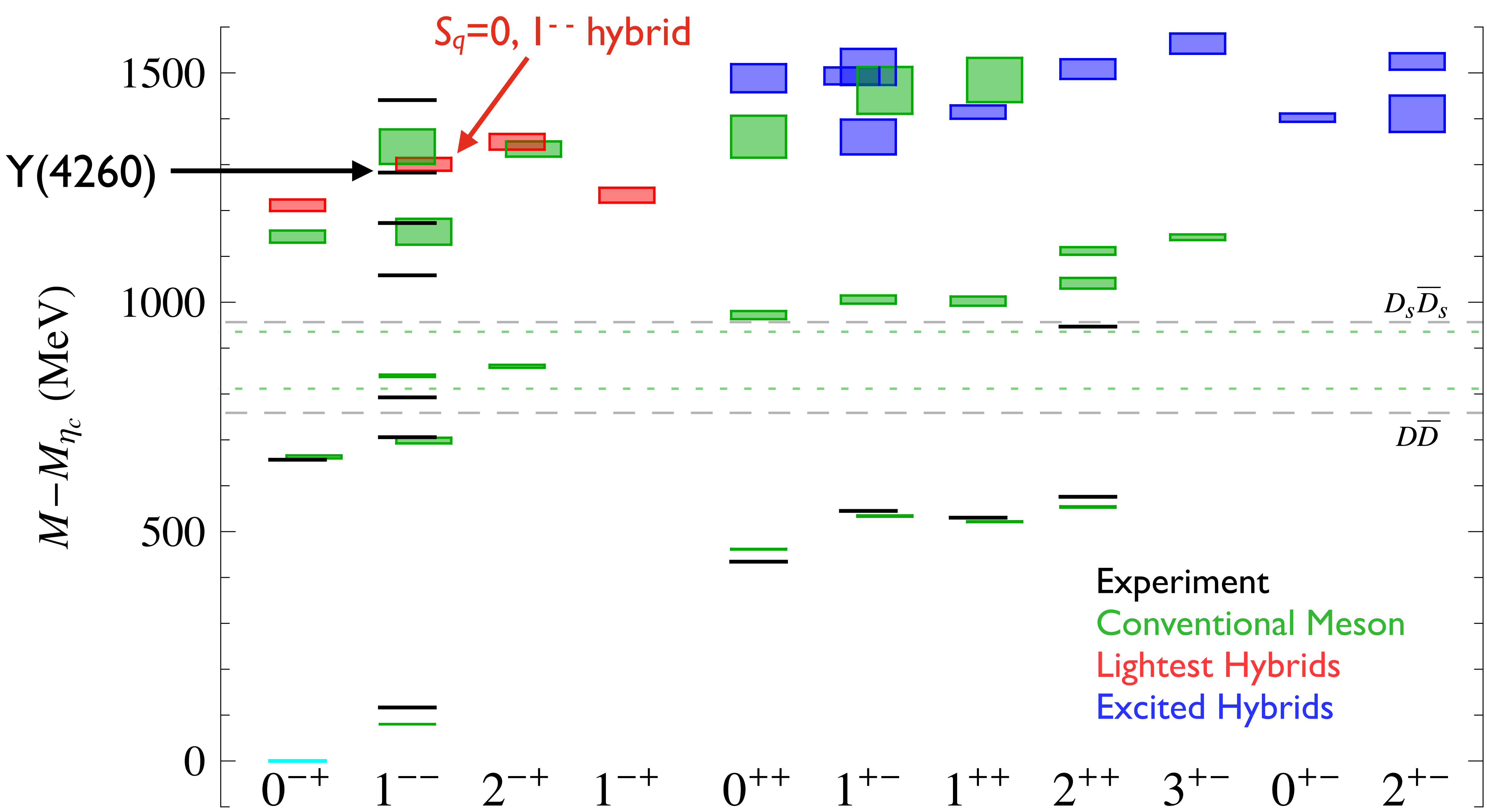
Notation:

		J	J	...
		M	M	...
m_1	m_2	Coefficients		
m_1	m_2			
.	.			
.	.			
.	.			

		2	1	0
		0	0	0
+1	−1	1/6	1/2	1/3
0	0	2/3	0	−1/3
−1	+1	1/6	−1/2	1/3

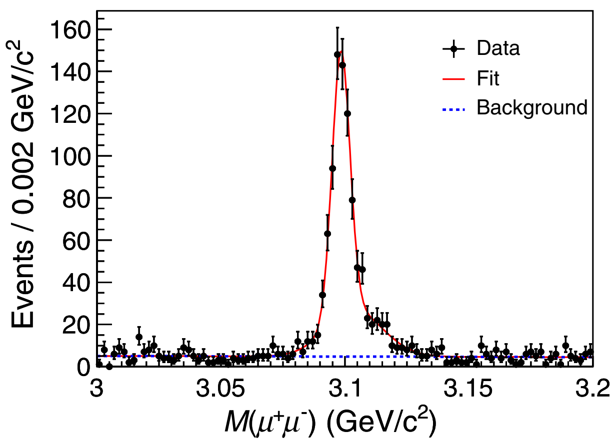
Charmonium from Lattice QCD

L. Liu *et al.* [Hadron Spectrum Collab.], JHEP07 126 (2012)



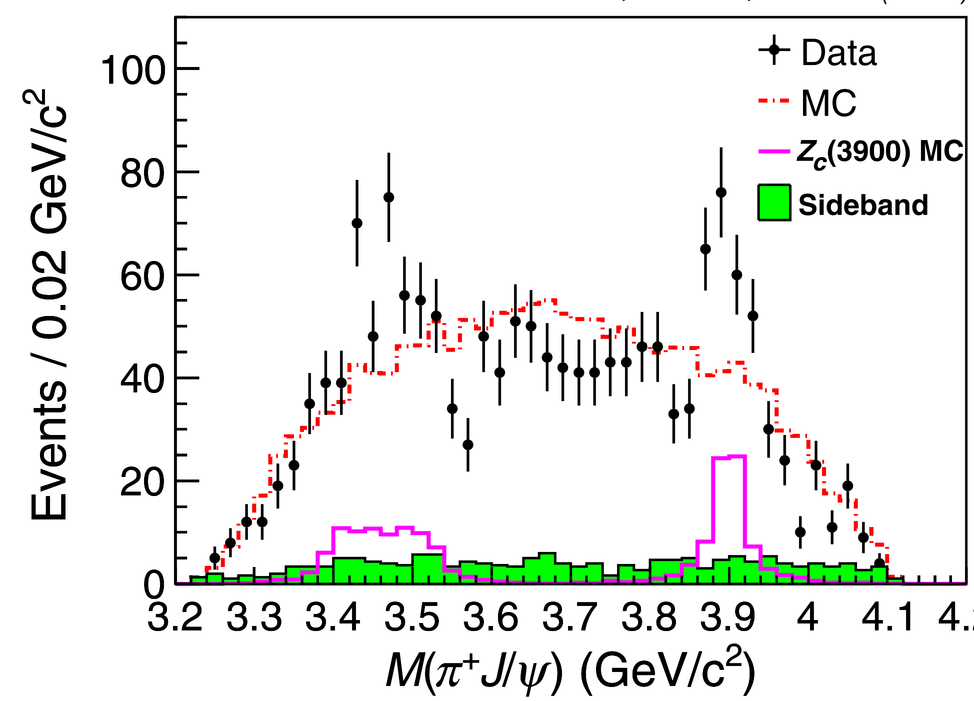
$e^+e^- \to \pi^+\pi^- J/\psi$ at E_{cm} = 4260 MeV

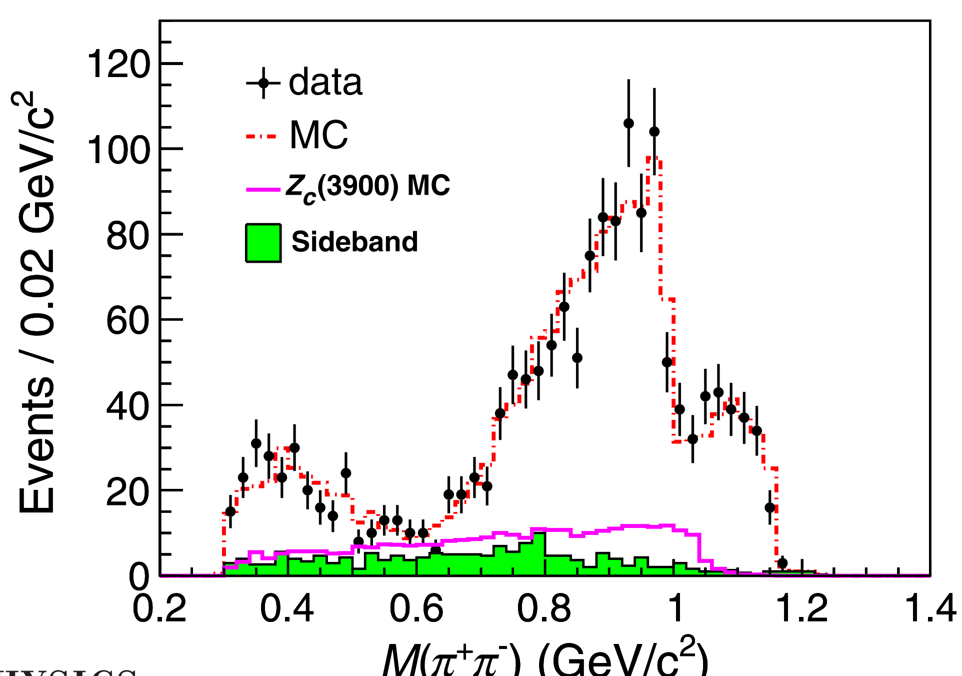
- J/ψ is cleanly identified in dilepton decay modes

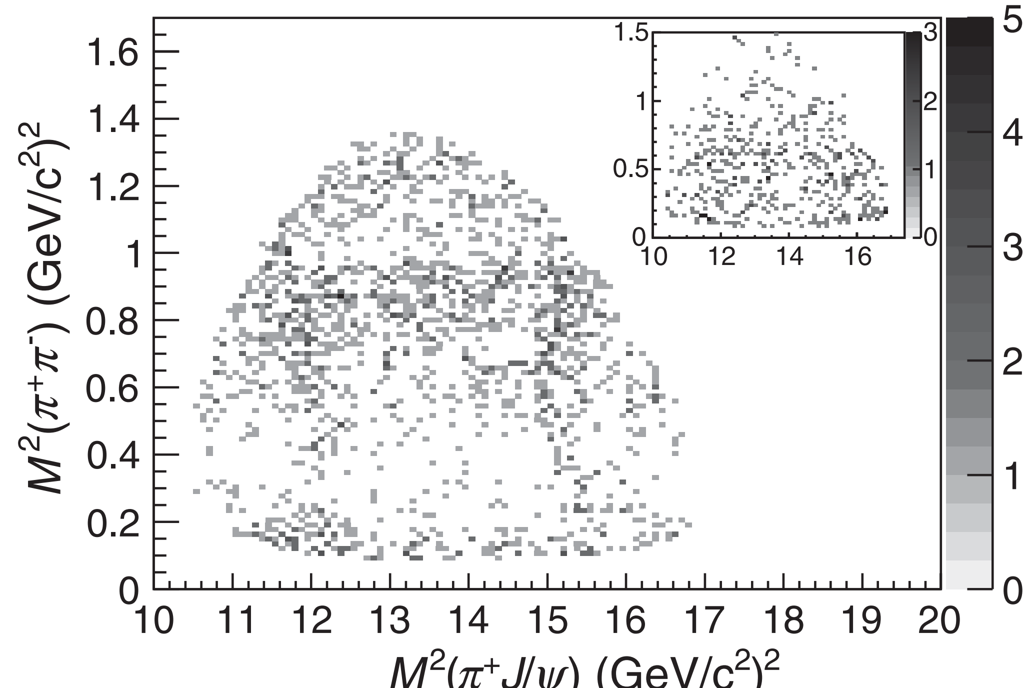


- Structure in π^+J/ψ mass that does not arise from $\pi^+\pi^-$ interactions

BESIII Collaboration, PRL 110, 252001 (2013)

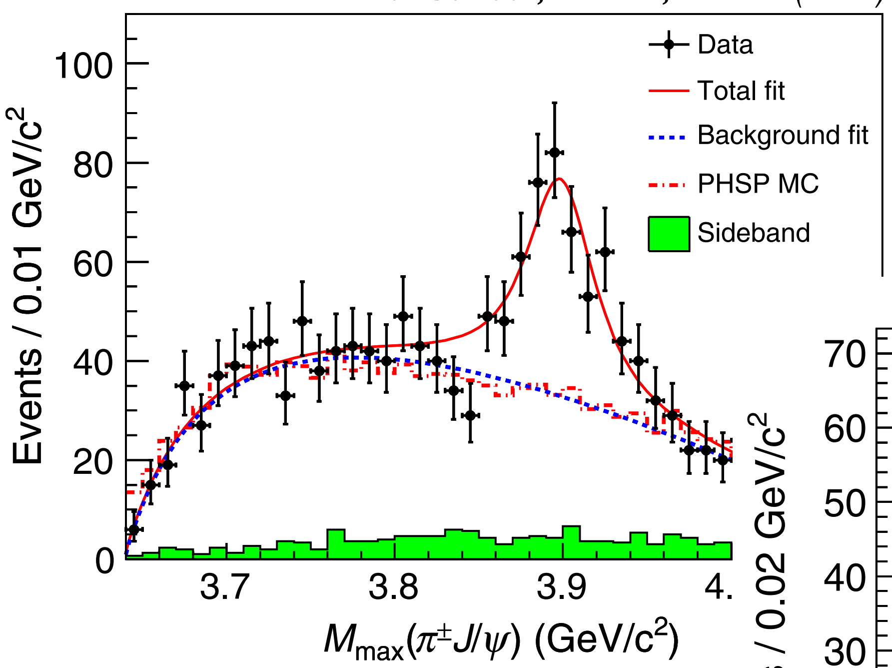




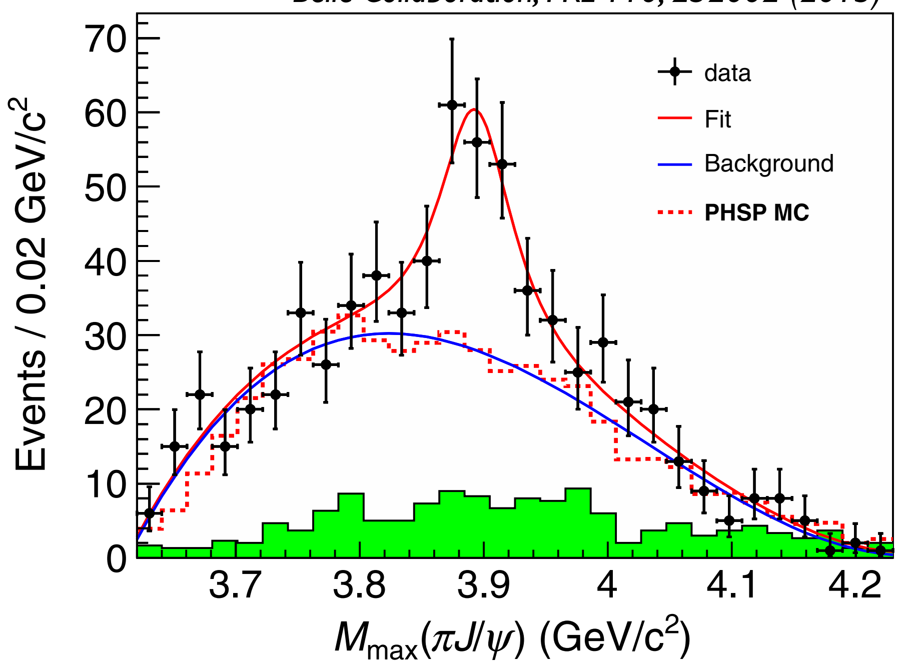


$Z(3900)^{\pm} \to \pi^{\pm} J/\psi$

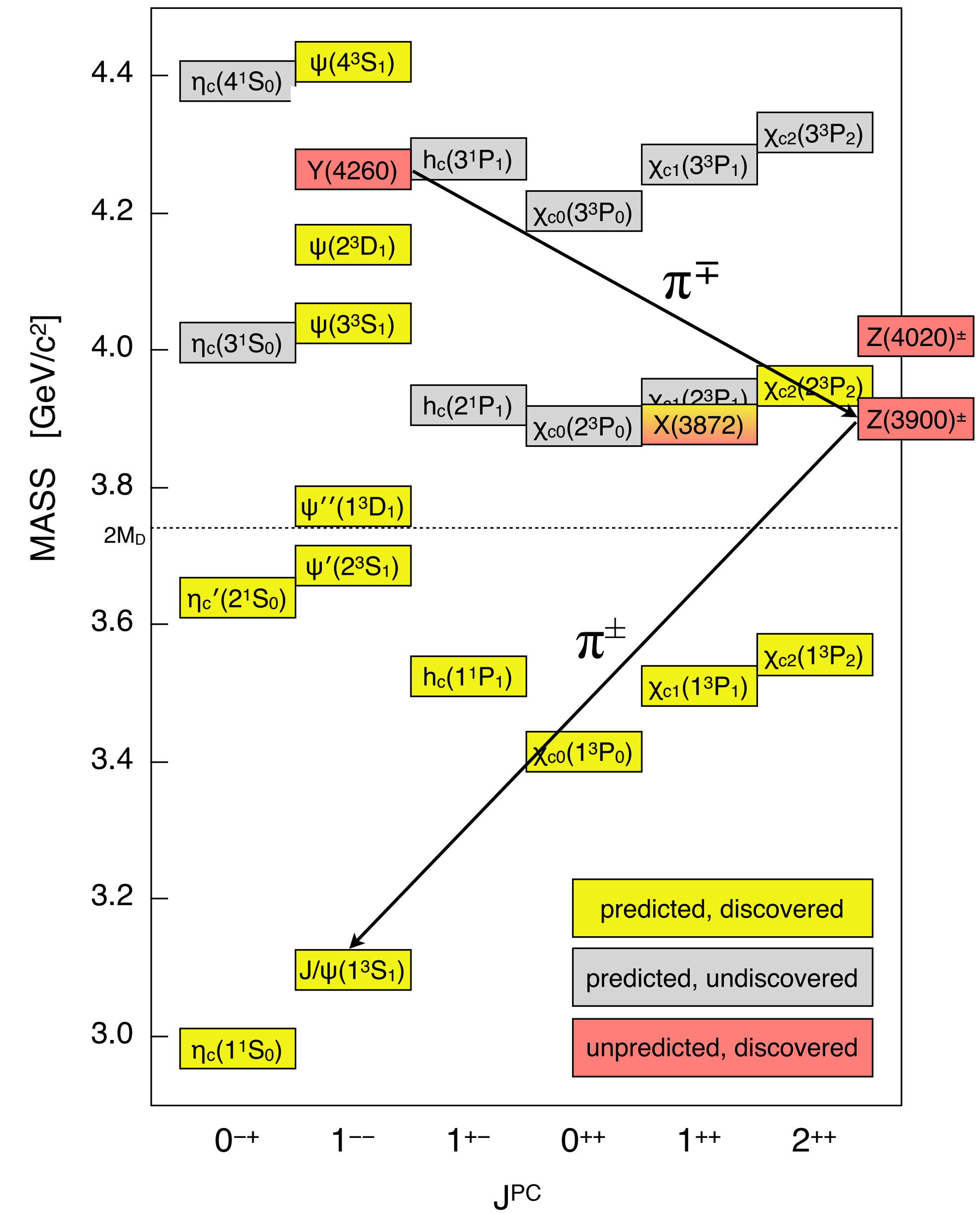
BESIII Collaboration, PRL 110, 252001 (2013)



Belle Collaboration, PRL 110, 252002 (2013)



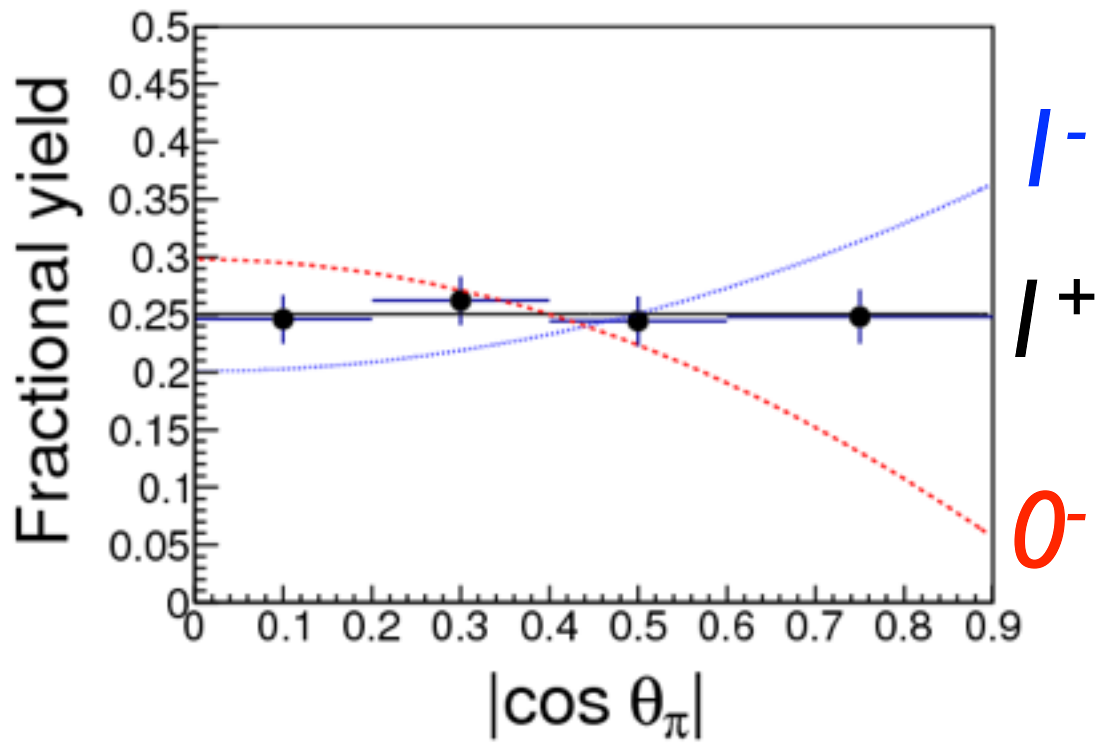
Study:
$e^+e^- \to \pi^+\pi^- J/\psi$



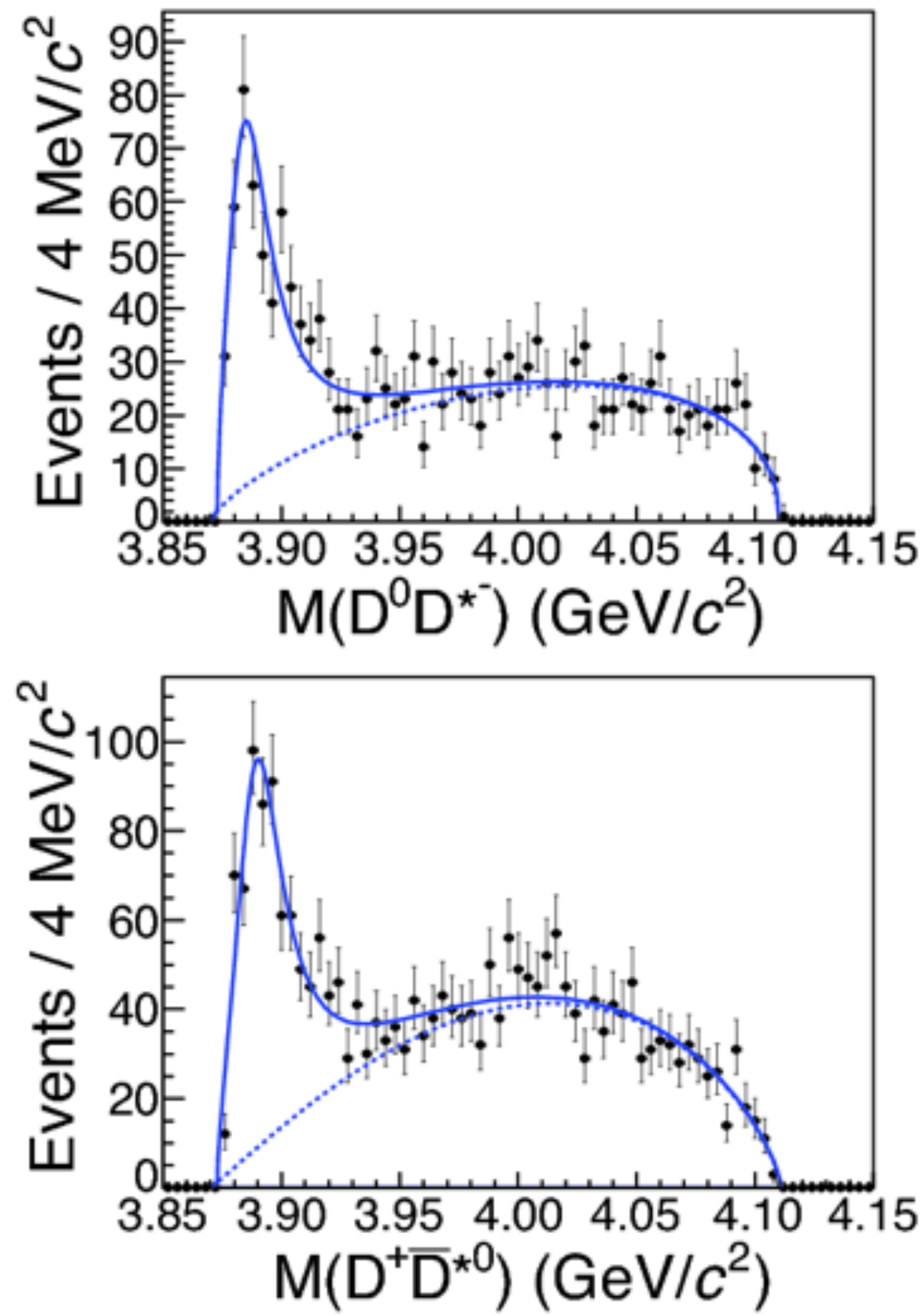
- Narrow (≈50 MeV) and *charged*
- Not conventional charmonium: tetraquark?
- Evidence of neutral partner
  [*T. Xiao et al., PLB 727, 366 (2013)*]

$e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$ at E_{cm} = 4260 MeV

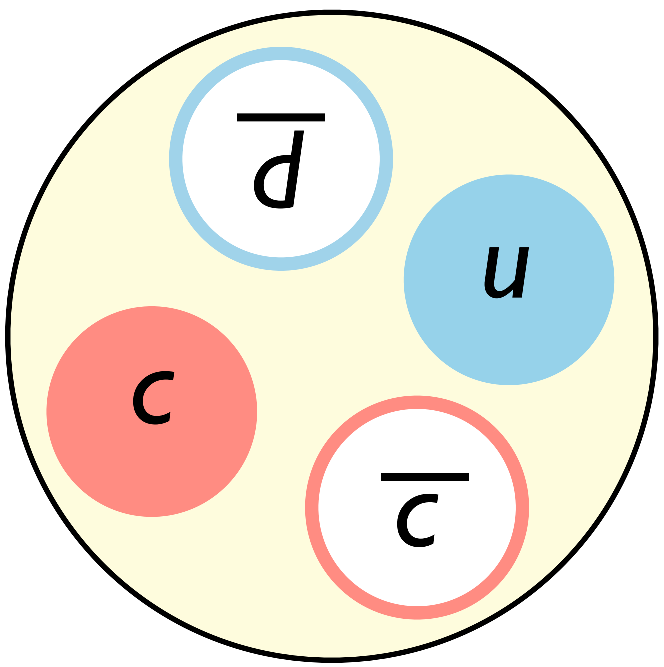
- π angular distribution establishes $J^P = 1^+$



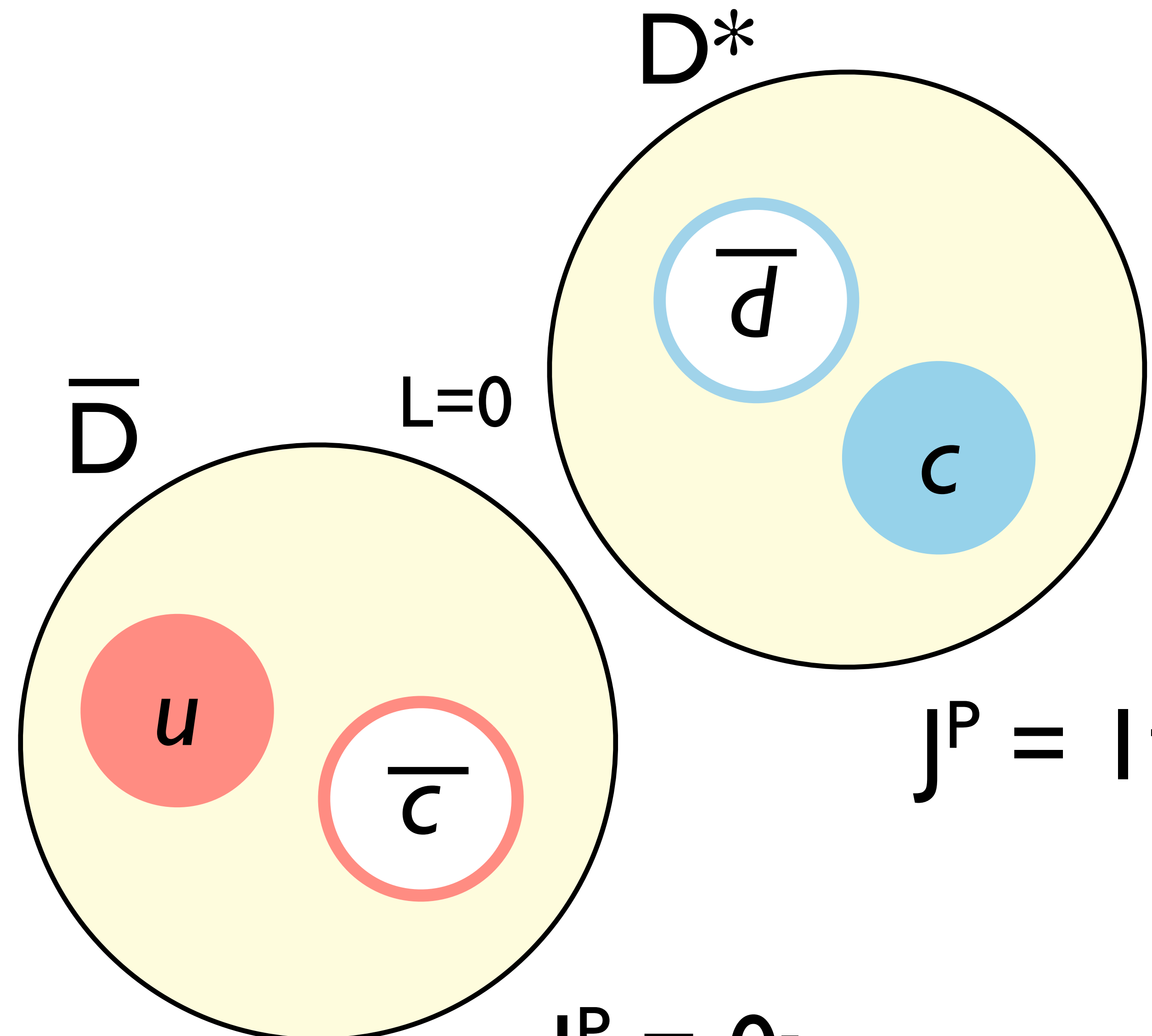
BESIII Collaboration, PRL 112, 022001 (2013)



What is Z(3900)?



$J^P = 1^+$

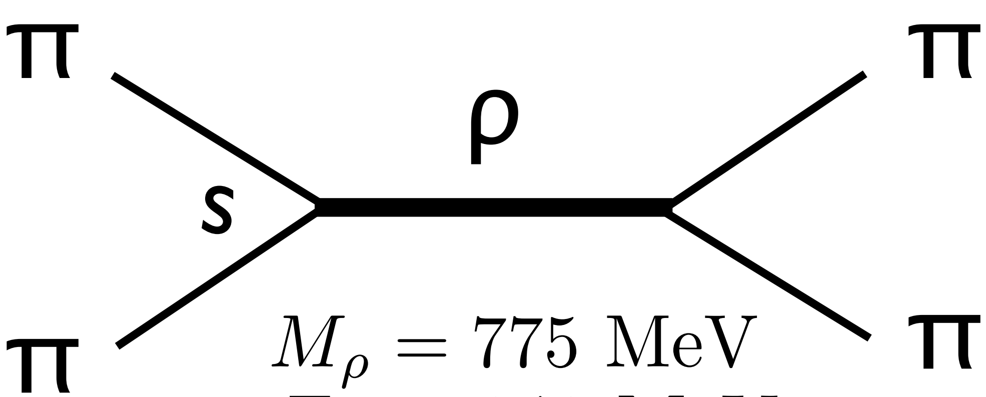


$J^P = 1^-$

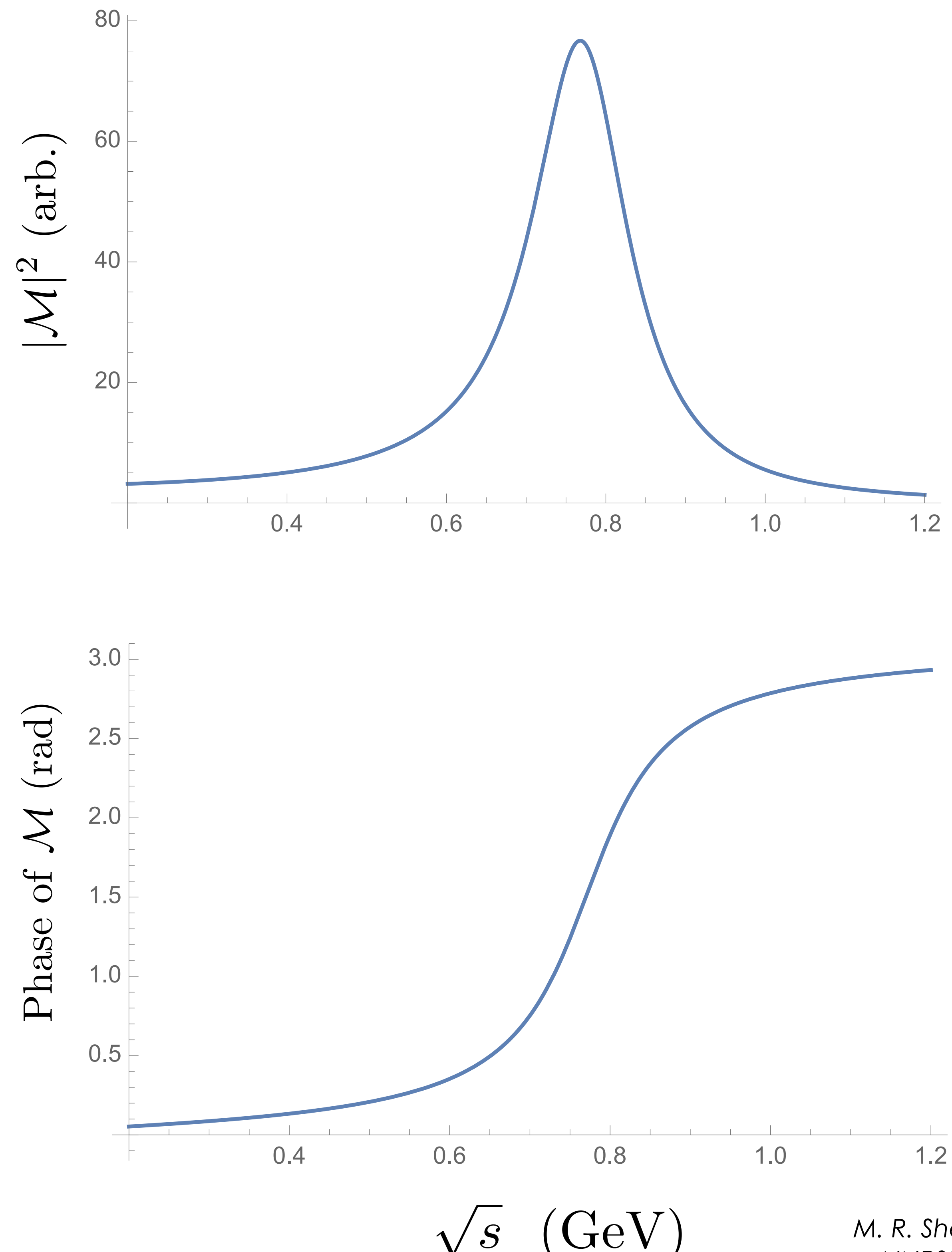
$J^P = 0^-$

How is it connected to Y(4260)?

What is a Resonance?



$$M_\rho = 775\ \text{MeV}$$
$$\Gamma_\rho = 148\ \text{MeV}$$



$$\mathcal{M} \propto \frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

$$\text{pole}: \quad \sqrt{s} = M - i\Gamma/2$$

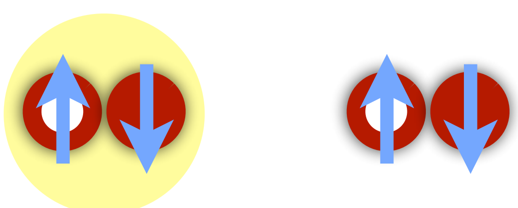
Expt.: $s = [M(\pi\pi)]^2$ (real)

Y(4260) hybrid test?

- Lattice QCD predicts the hybrid 1^{--} state to have spin $S = 0$

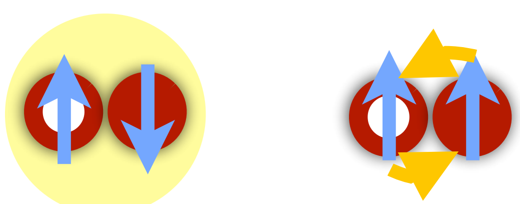
Using LQCD Dudek *et al.* predict [PRD 79, 094504 (2009)]

$$Y_{\text{hybrid}} \to \gamma\eta_c$$



rate is comparable or larger than

$$Y_{\text{hybrid}} \to \gamma\chi_{c0}$$



Potential "hybrid test" for *Y*(4260), but no experimental sensitivity…yet

Two decays that we can attempt to compare instead:

$$Y(4260) \to \pi\pi h_c$$

??

$$Y(4260) \to \pi\pi J/\psi$$

??

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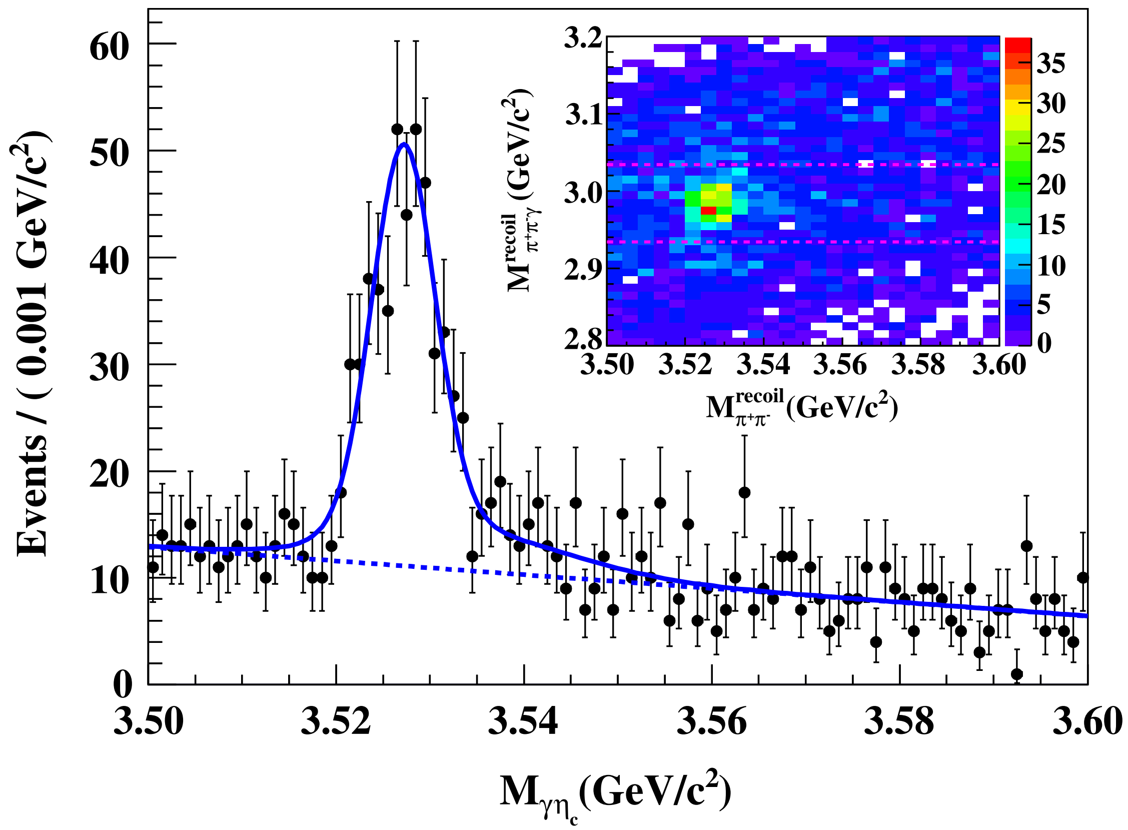
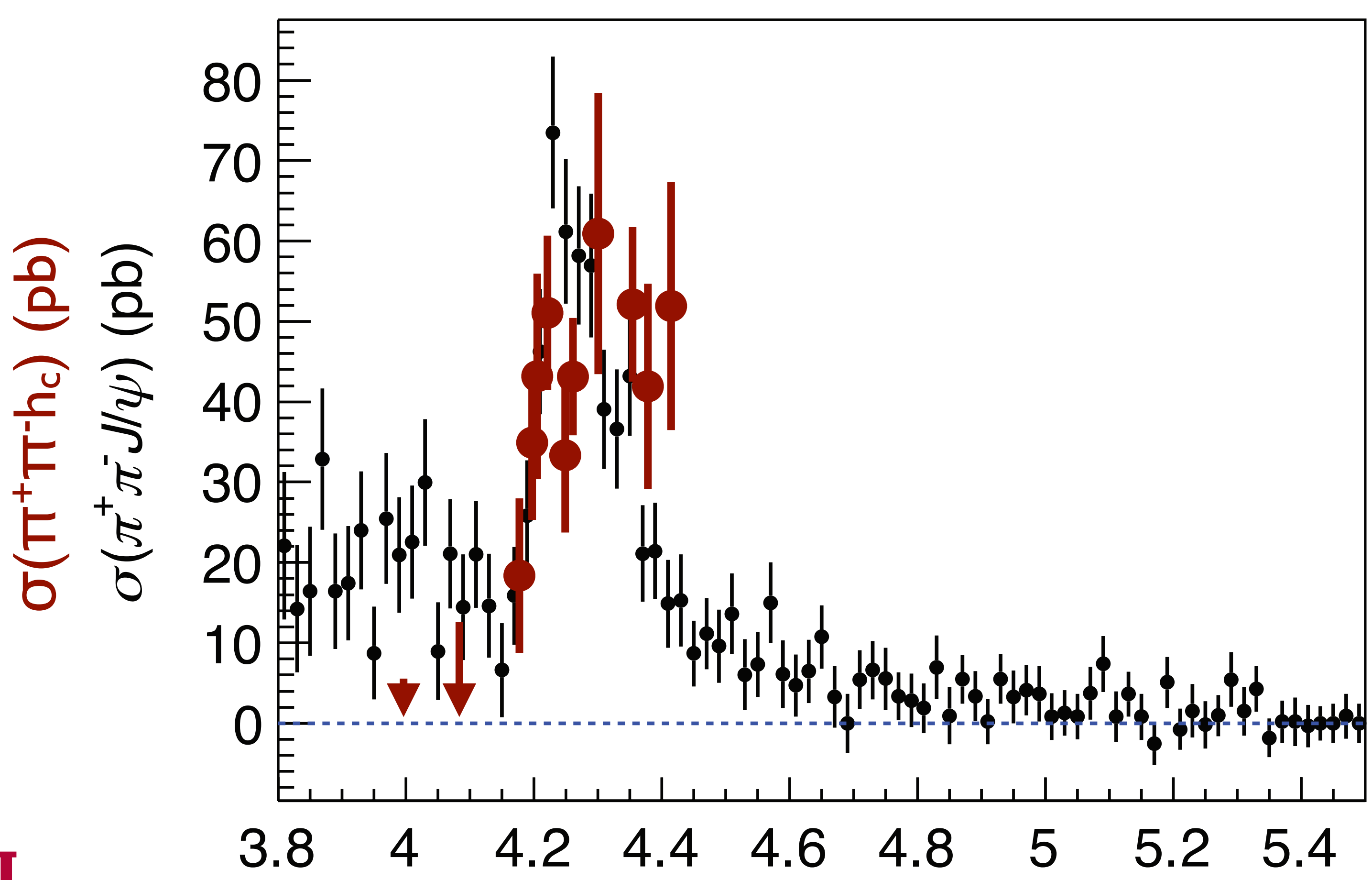
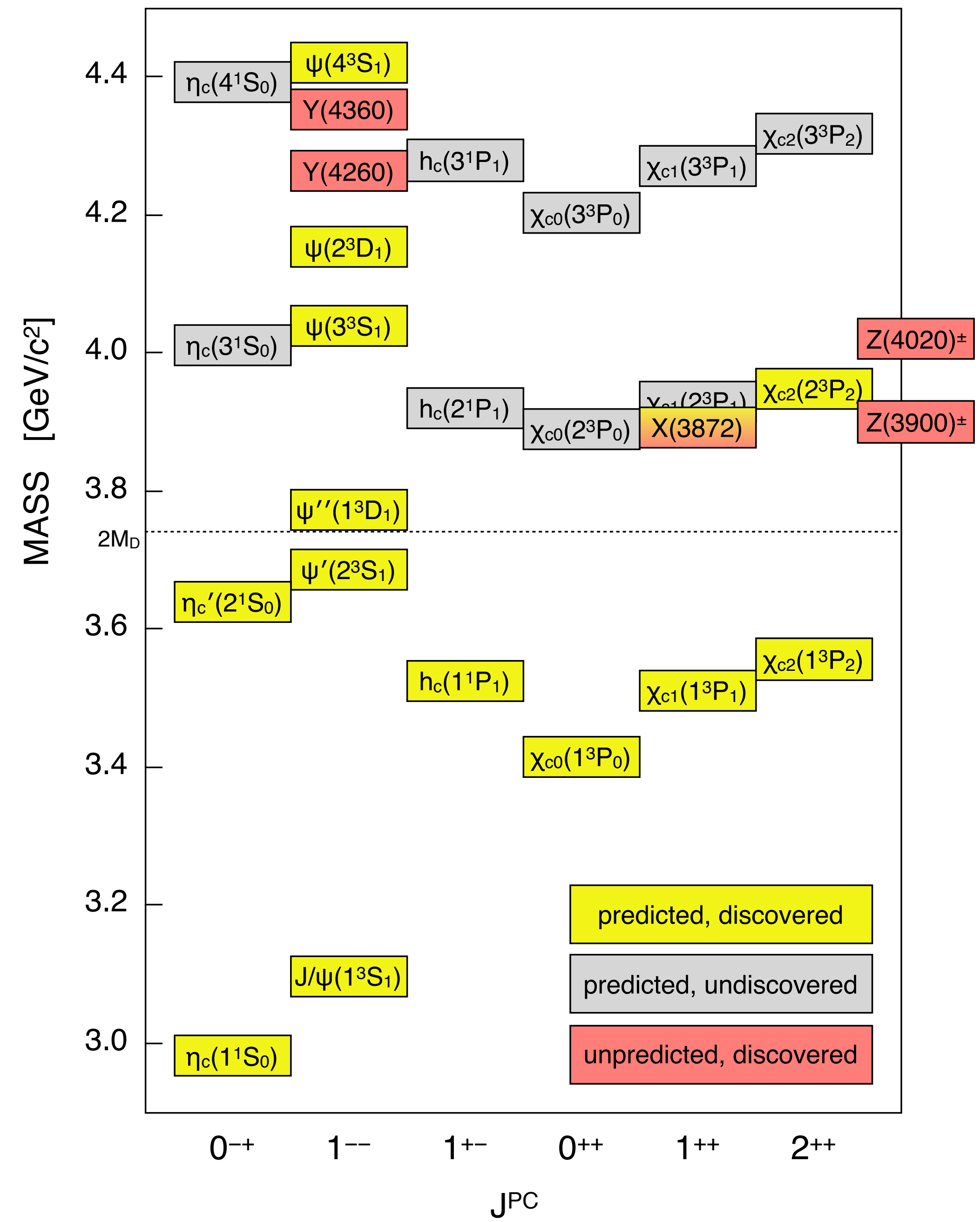
$e^+e^- \to \pi^+\pi^- h_c$



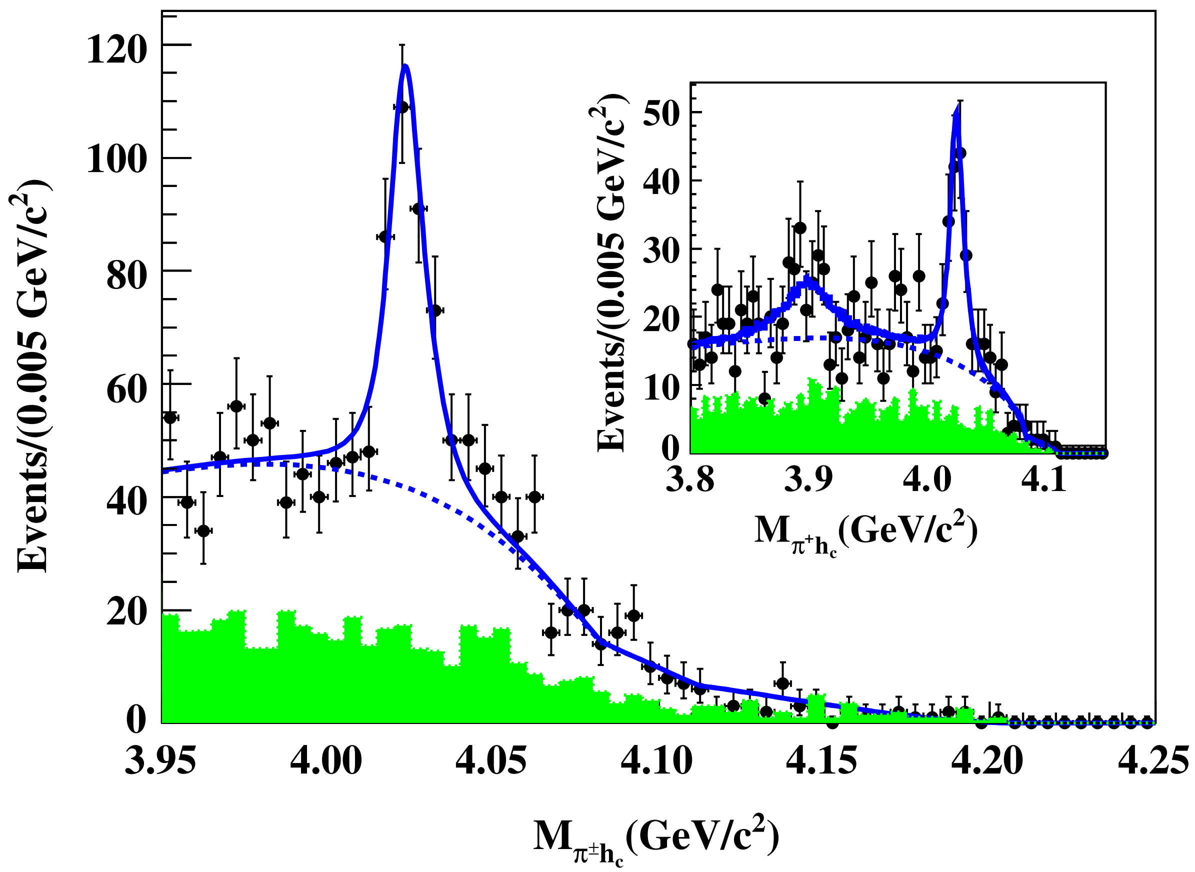
BESIII Collaboration, PRL 111, 242001 (2013)



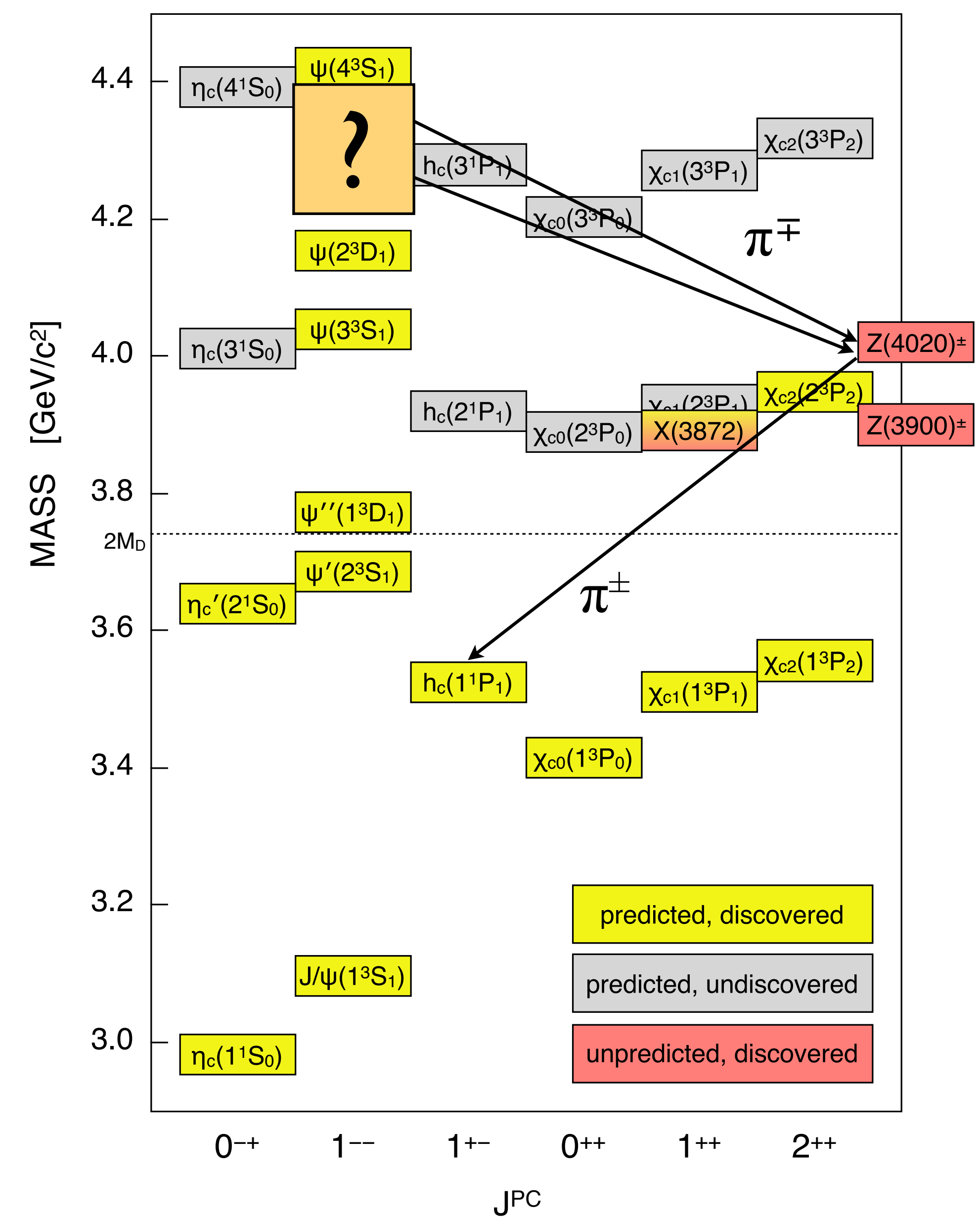


$Z(4020)^{\pm} \to \pi^{\pm} h_c$

BESIII Collaboration, PRL 111, 242001 (2013)



Study:
$e^+e^- \to \pi^+\pi^- h_c$



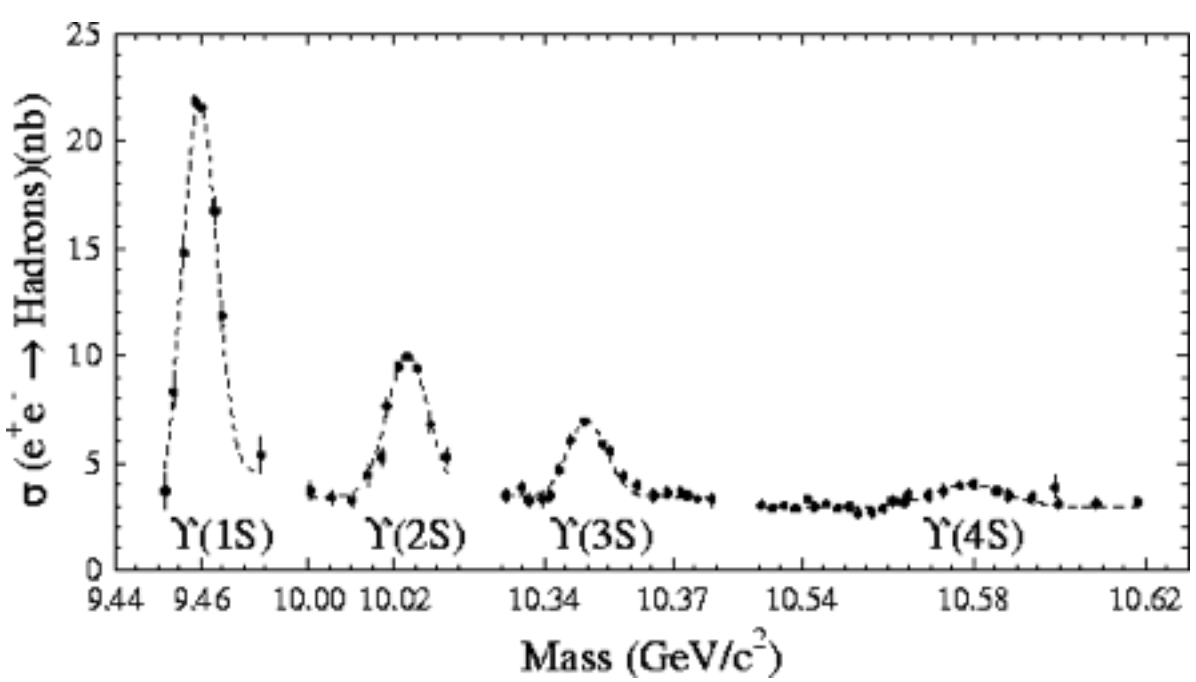
- No *Y*(4260)-like peaking structure in $\pi^+\pi^- h_c$ cross section, which is comparable to peak in $\sigma(\pi^+\pi^- J/\psi)$
- Very narrow charged $\pi^{\pm} h_c$ structure near DD^* threshold
- Not conventional charmonium

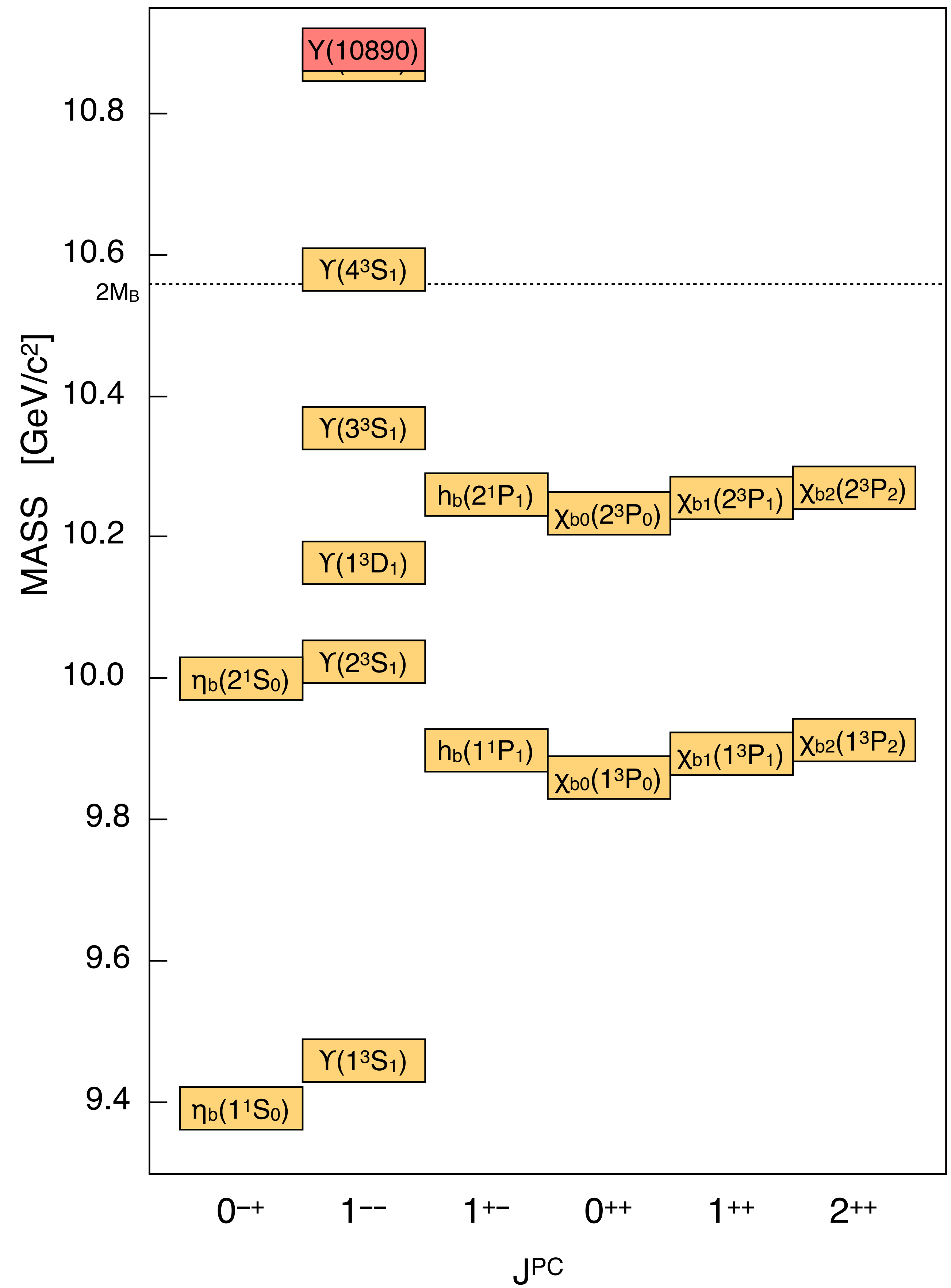
Questions

- Have we discovered some new bound state of QCD?
- What does it tell us about the state we set out to study: Y(4260)?
- Can we observe similar physics in other systems?

b-quark system

- Do we see similar physics for a different set of heavy quarks?

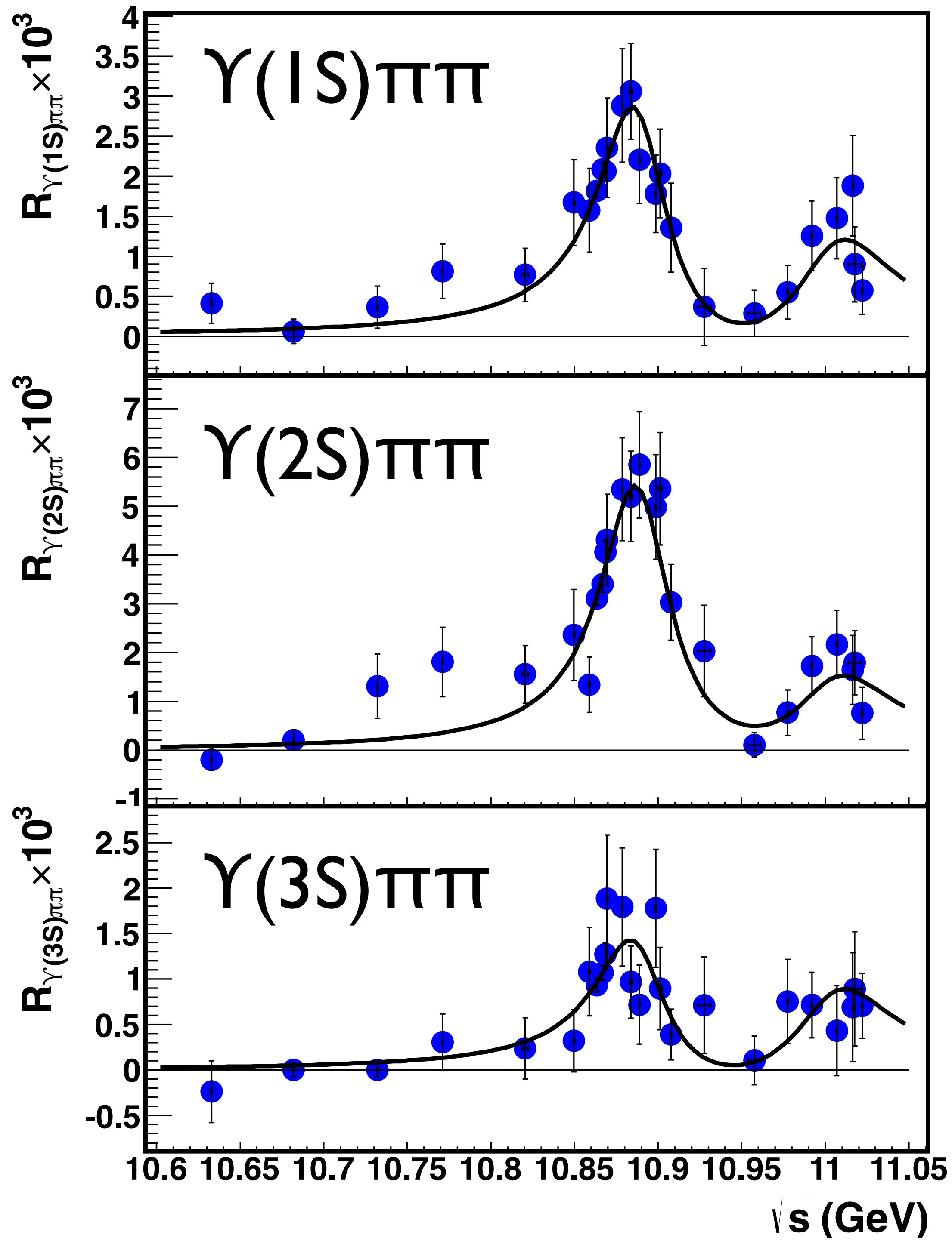




What about *b* quarks?

- Same story, heavier characters
  - $Y(4260) \rightarrow \Upsilon$ or $\Upsilon(10860)$
  - $J/\psi \rightarrow \Upsilon$
  - $h_c \rightarrow h_b$
- at 10890 MeV: peak in $\pi\pi$ transitions to $\Upsilon(nS)$ states
- Study $\pi\Upsilon$ and πh_b structure in transitions

Belle Collaboration, arXiv:1501.01137



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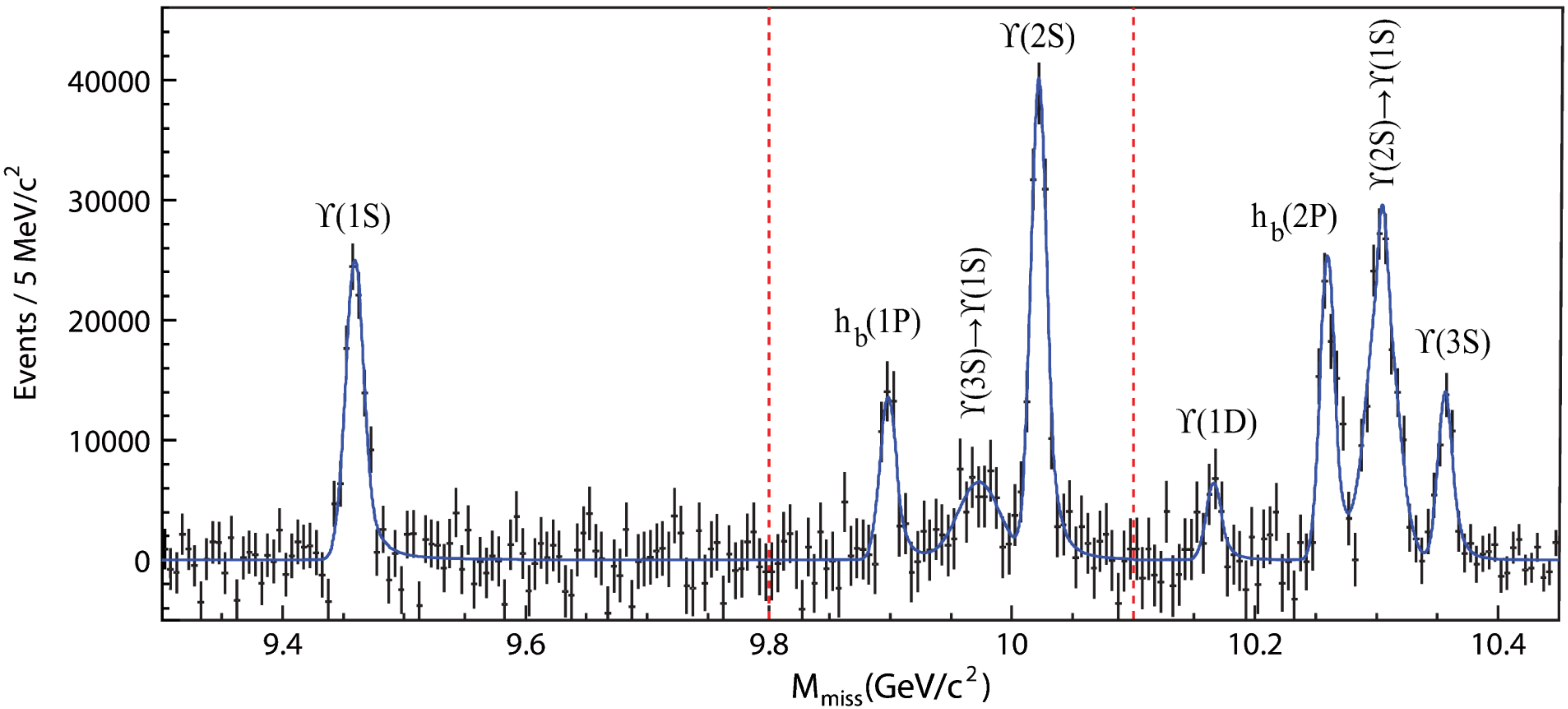
M. R. Shepherd
NNPSS at MIT
July 2016

Production of ππϒ(nS) and ππh_b(mP)

Belle Collaboration, PRL 108, 032001 (2012)



Why are production of h_b (S=0) and ϒ (S=1) of the same scale?
Seems impossible starting from vector bottomonium (S=1).

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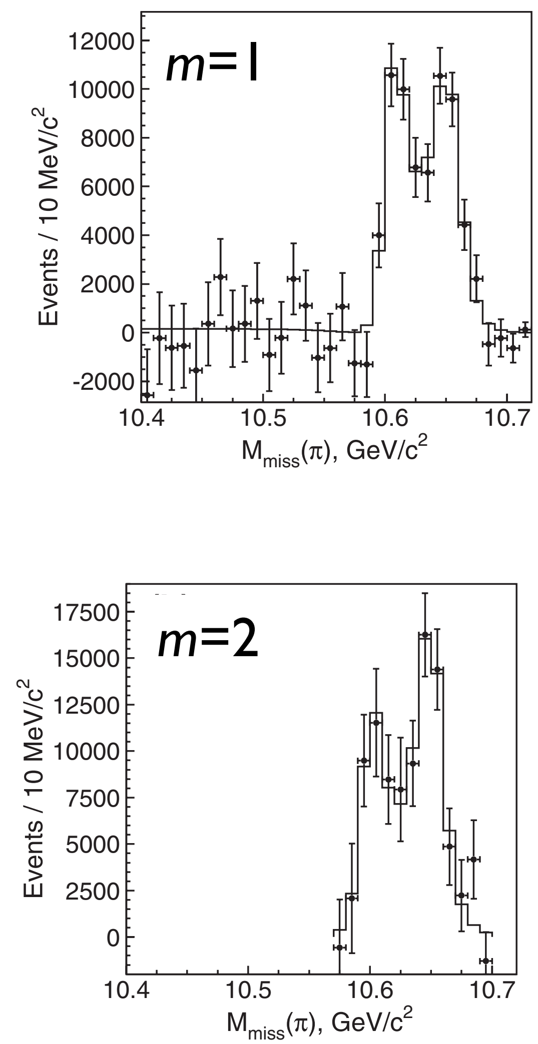
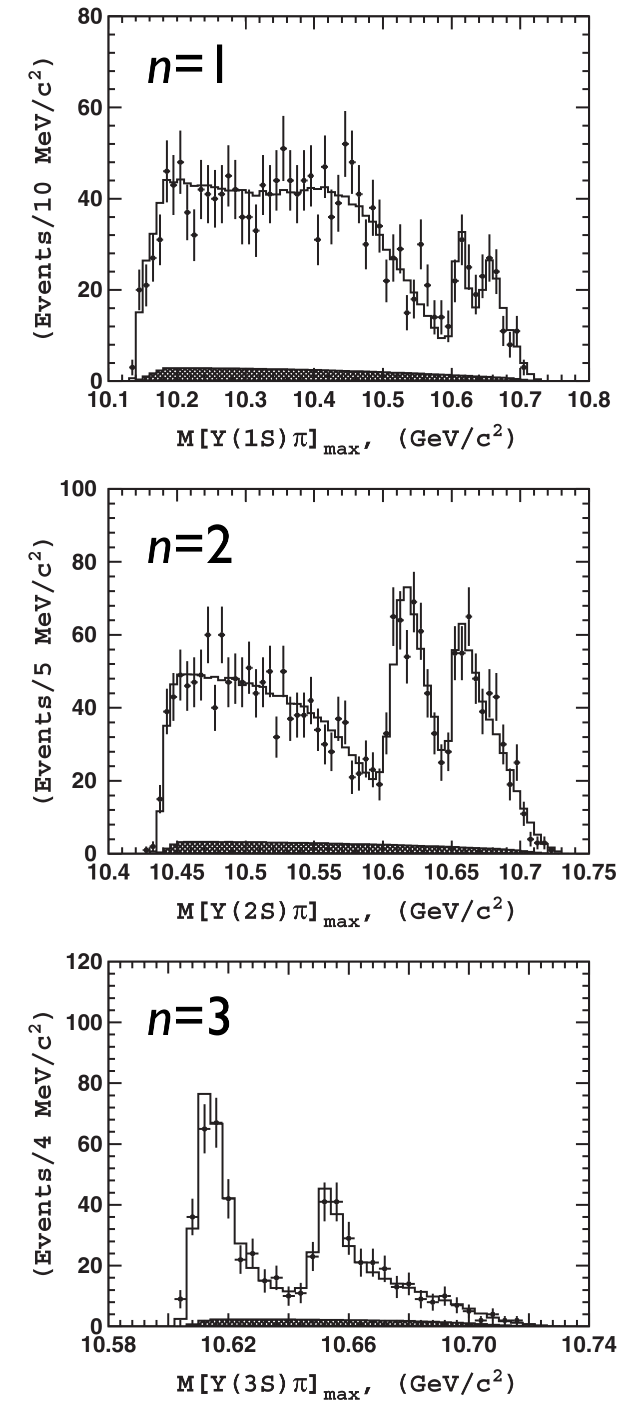
Observation of $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$

- Belle observes two charged states in the bottomonium spectrum
  - couple to $\pi^{\pm}h_b$ and $\pi^{\pm}\Upsilon$
- consistent masses and widths *in five different decay modes*
- masses at or just above BB^* and B^*B^* thresholds
- decays to $B^{(*)}\overline{B}^*$: *[Belle Collaboration arXiv:1209.6450]*

$\pi^{\pm}h_b(mP)$



$\pi^{\pm}\Upsilon(nS)$



Belle Collaboration, PRL 108, 122001 (2012)

Summary

- Similar unconventional spectroscopy (?) in both bottom and charm systems
    - Signs of new states bound of QCD?
    - Meson meson interactions? Complications from light quark degrees of freedom?
    - (Many more results from more experiments than shown here, including candidates for unconventional baryons.)
- Need tools to try to probe the complete scattering amplitude: magnitude and phase
    - more about this tomorrow