Recent Results in Hadron Spectroscopy

National Nuclear Physics Summer School
2021

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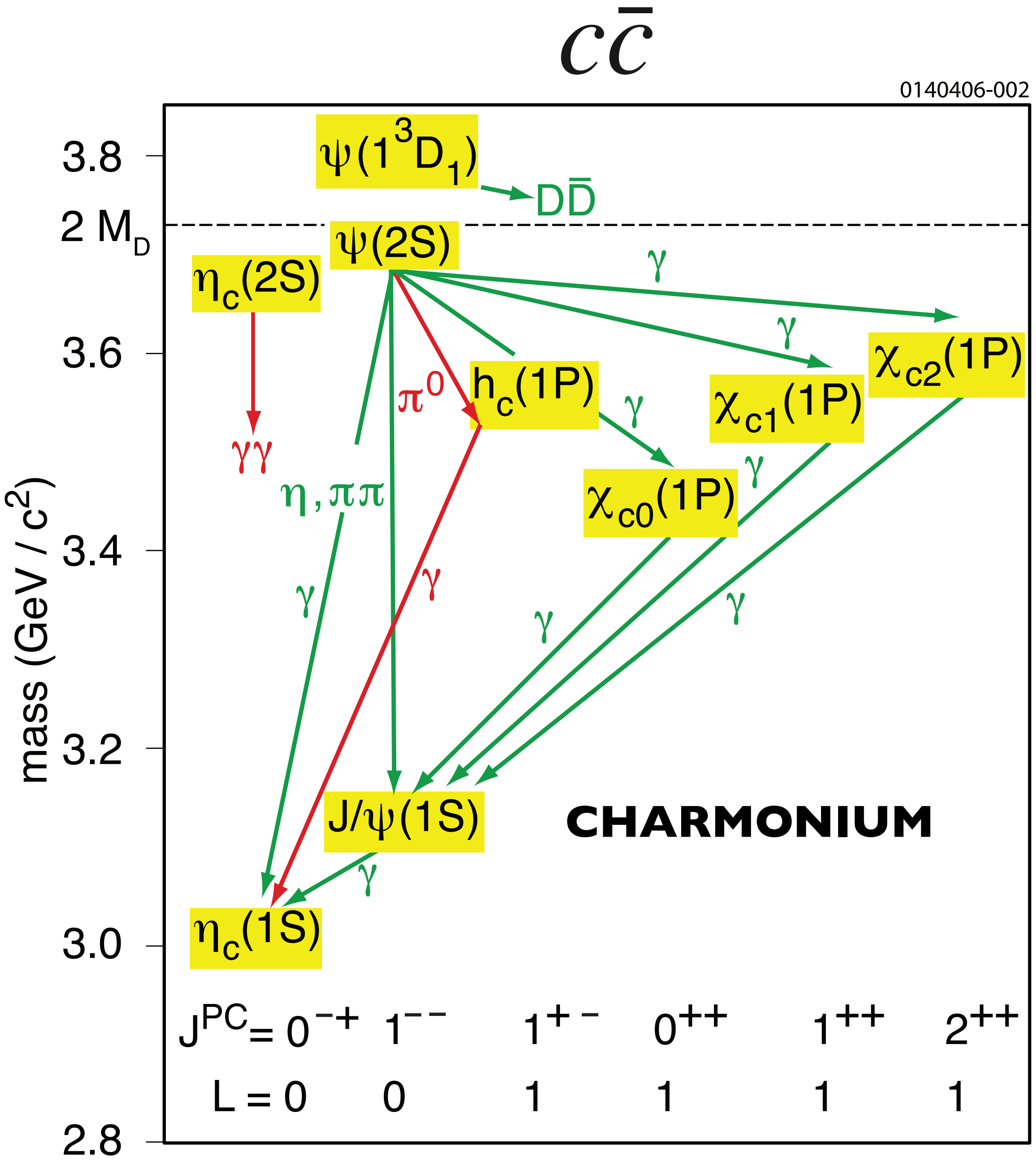
Indiana University

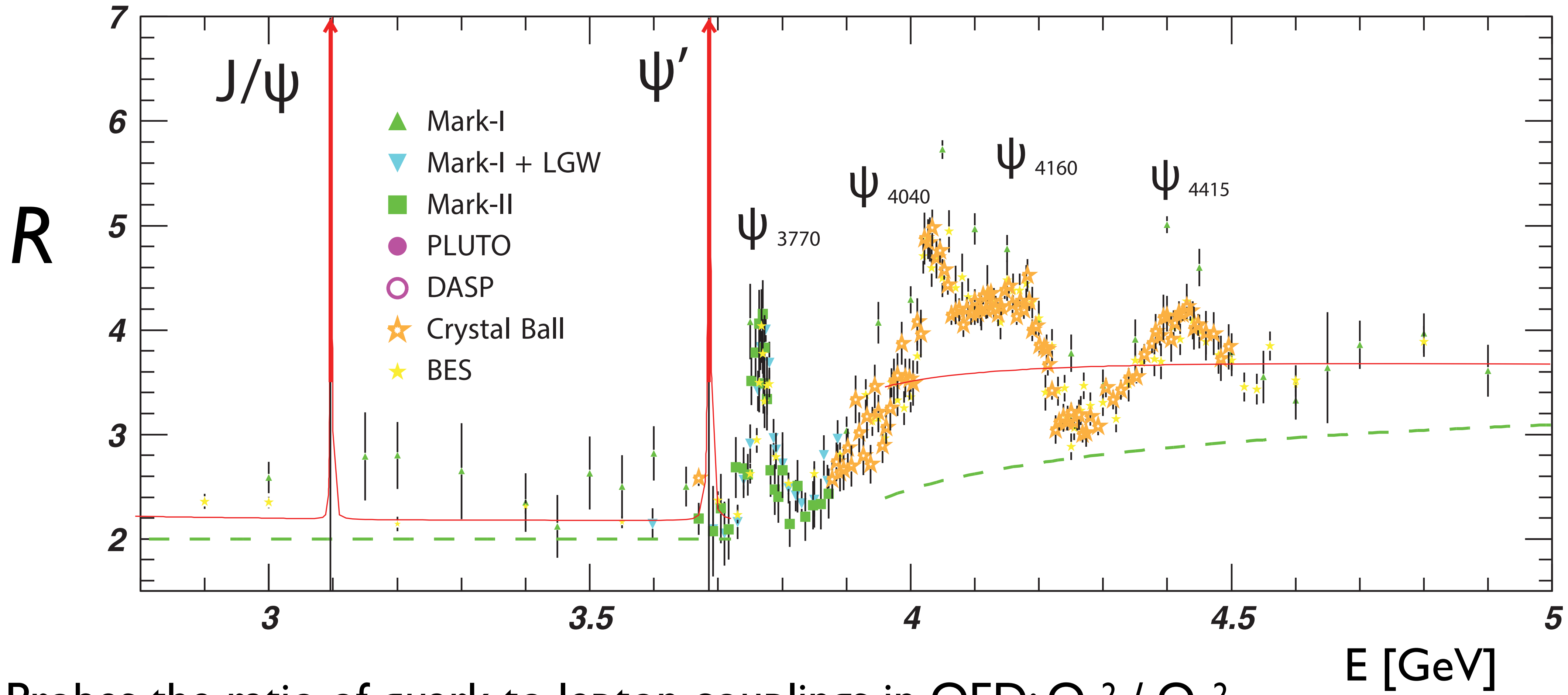
Outline

The charmonium spectrum

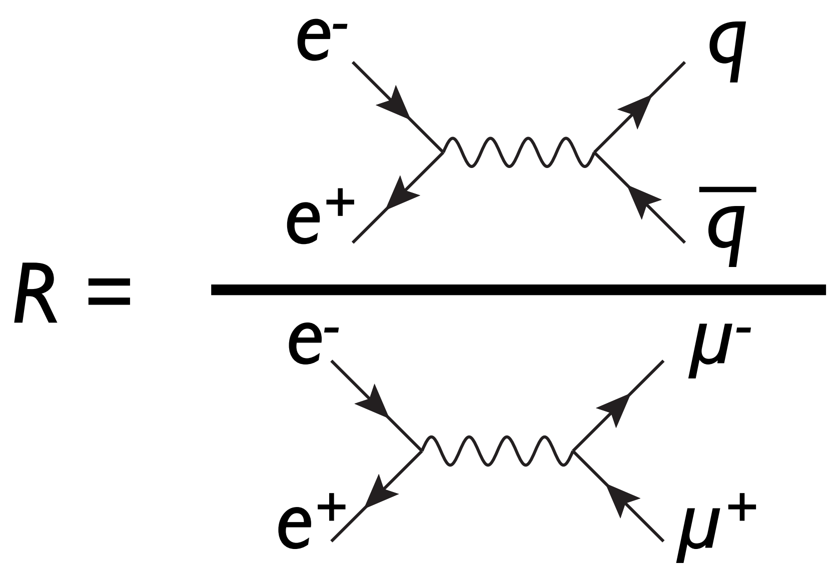
- Why do we believe this is a spectrum of charm anti-charm mesons?
- How can we study QCD through properties of the states?



Producing Charmonium



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



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

three colors

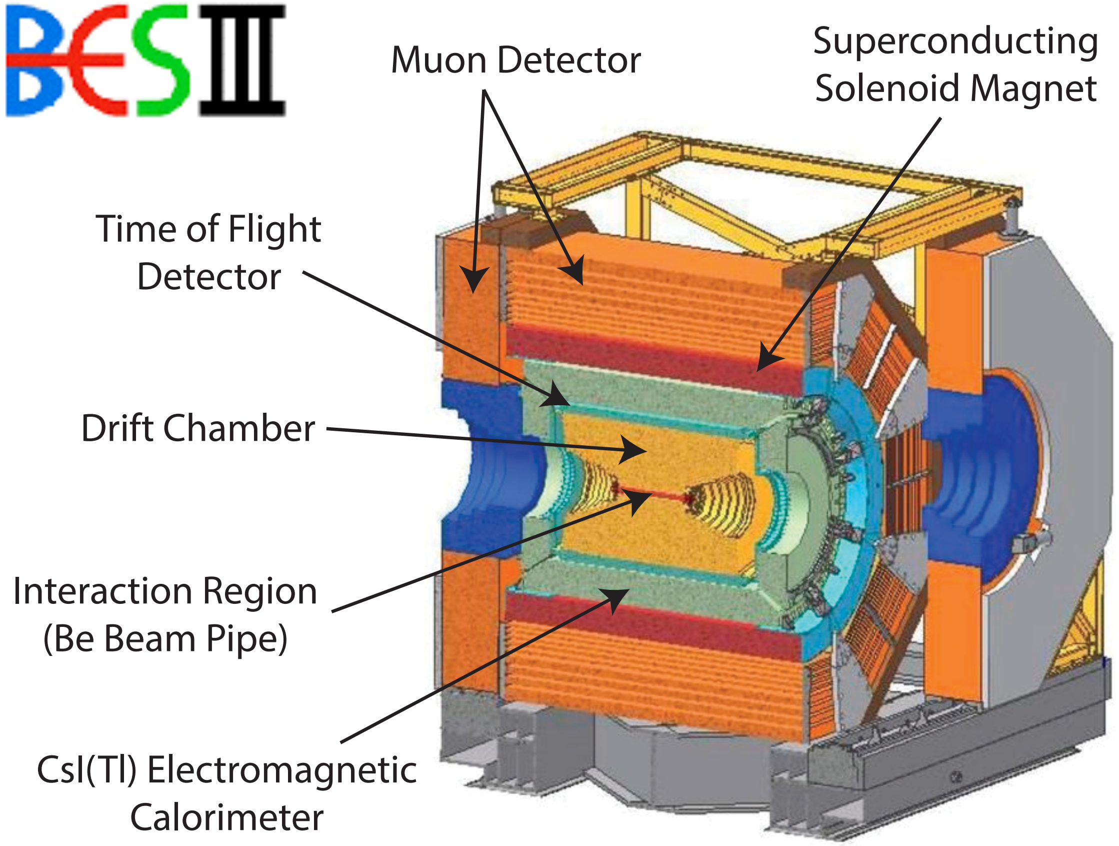
Expect:

$2 \rightarrow 10/3$

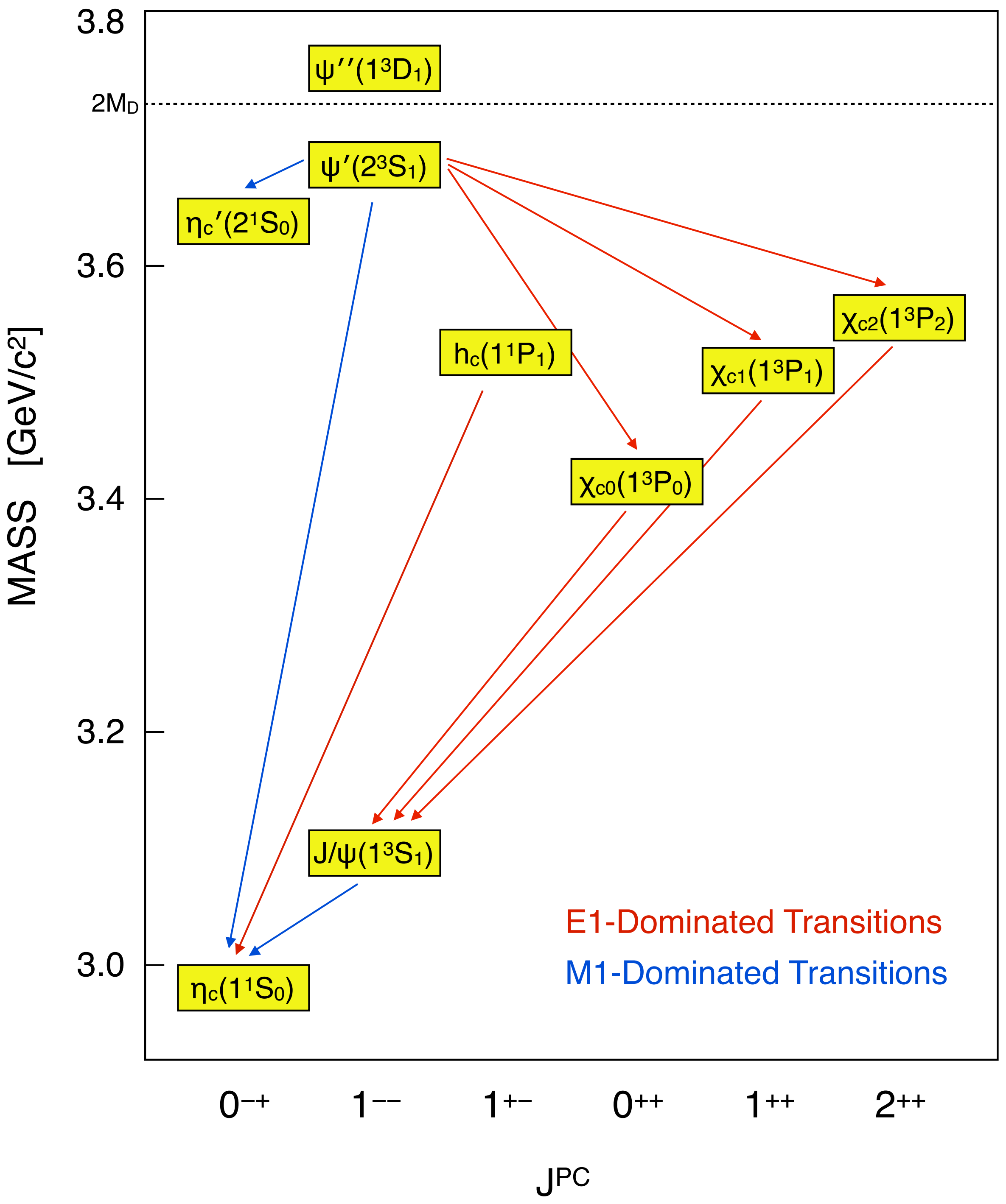
u,d,s u,d,s,c

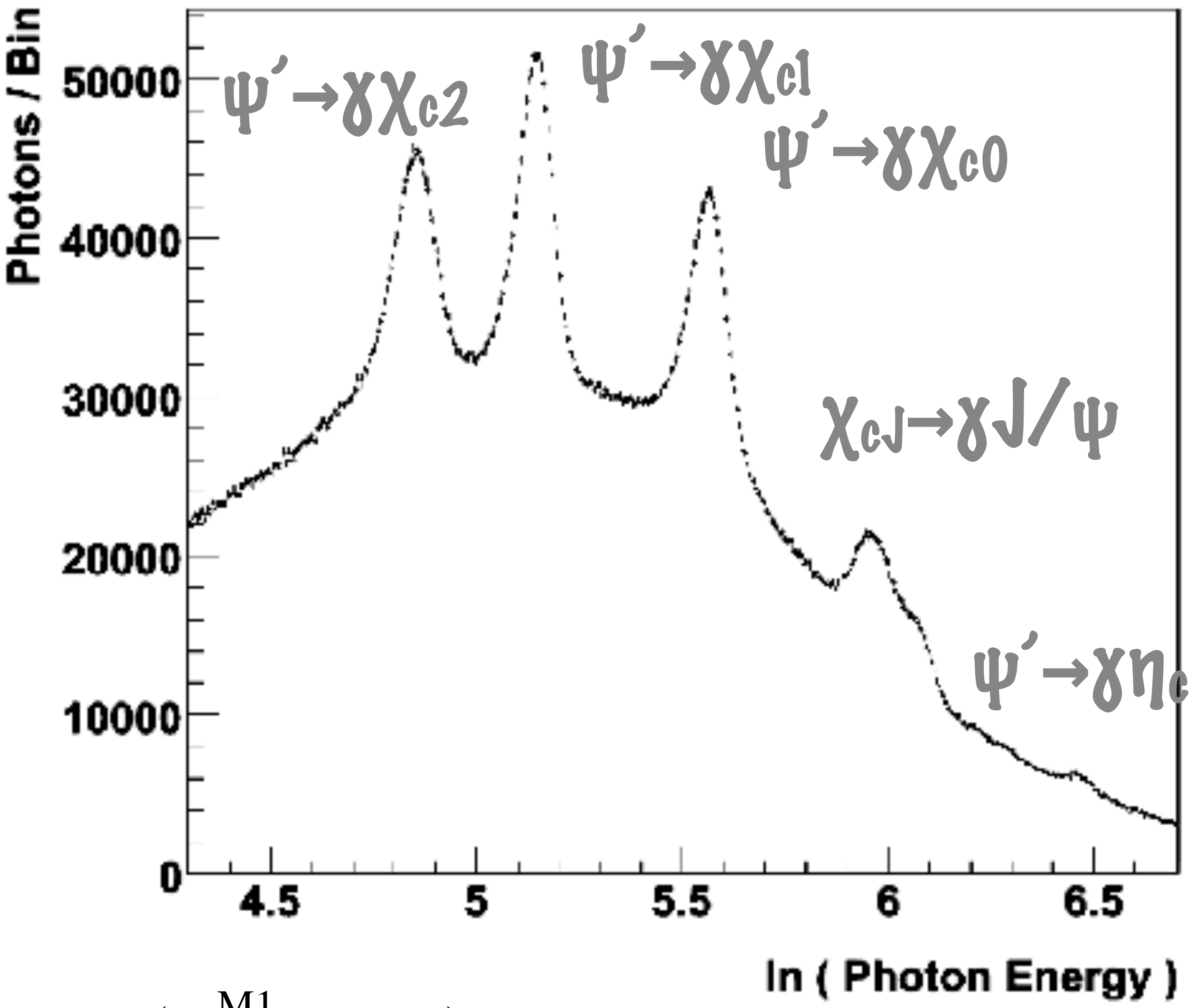
Producing Charmonium

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



Electromagnetic Transitions





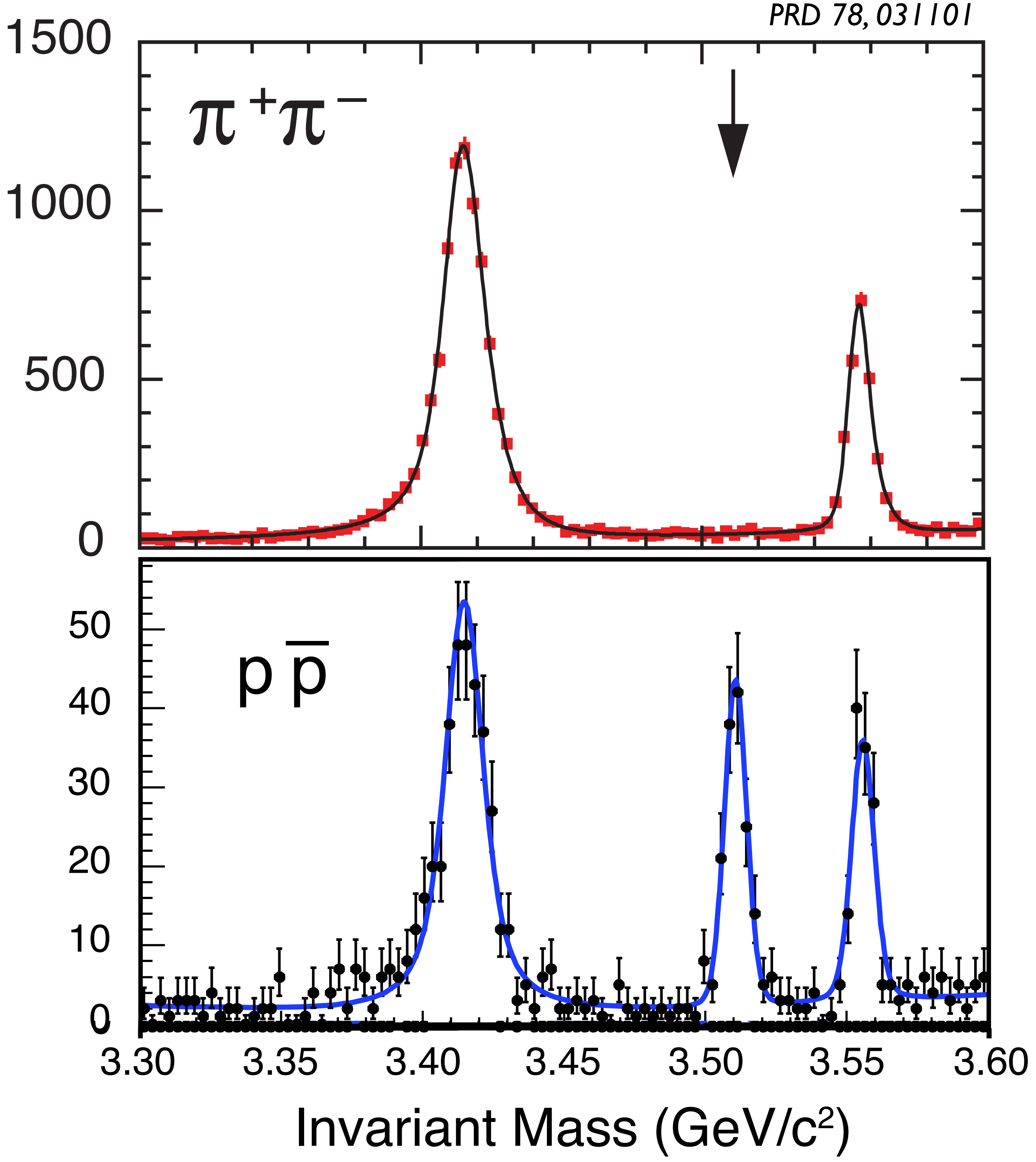
$$\Gamma\left(i \xrightarrow{\mathrm{M1}} \gamma + f\right) = \frac{16}{3}\alpha e_Q^2 \frac{E_\gamma^3}{m_i^2}(2J'+1)\mathrm{S}_{if}^{\mathrm{M}}|\mathcal{M}_{if}|^2$$

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

χ_{cJ} Decays to Hadrons

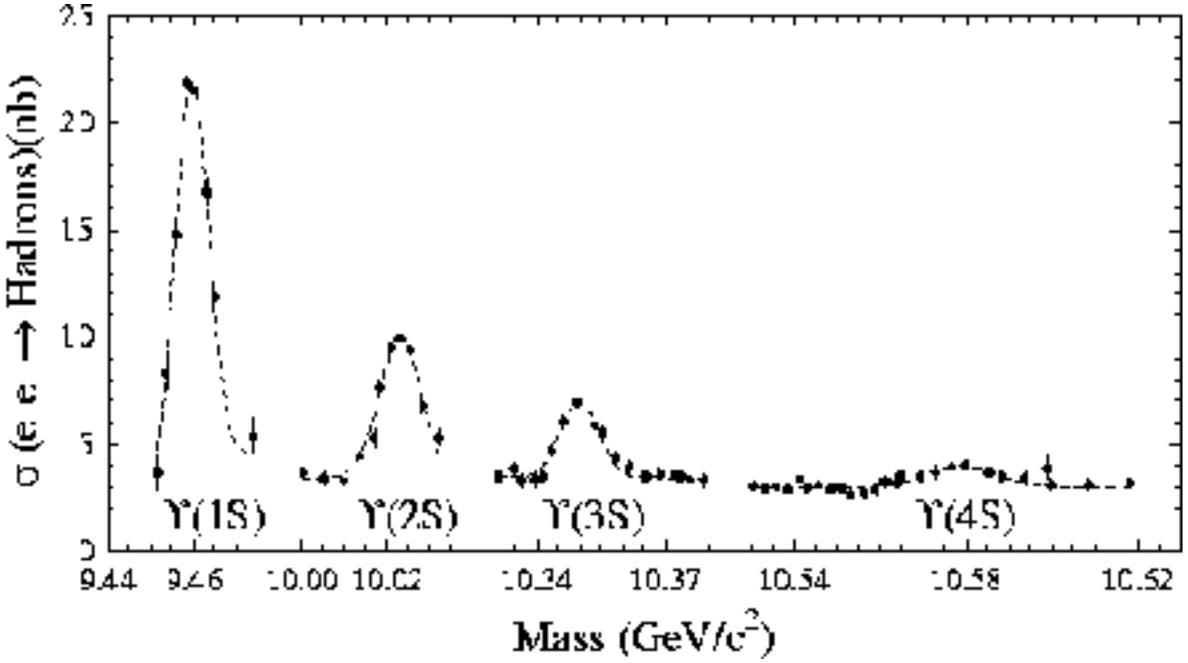
- Study:
  - $\psi' \to \gamma\pi^+\pi^-$
  - $\psi' \to \gamma p\bar{p}$
- *Quiz*: why does a third peak appear in $p\bar{p}$ but not $\pi^+\pi^-$?
  - J^P of a pion: 0^-
  - J^P of a proton: $\frac{1}{2}^-$
  - J^{PC} of the χ_{cJ}: $(0,1,2)^{++}$

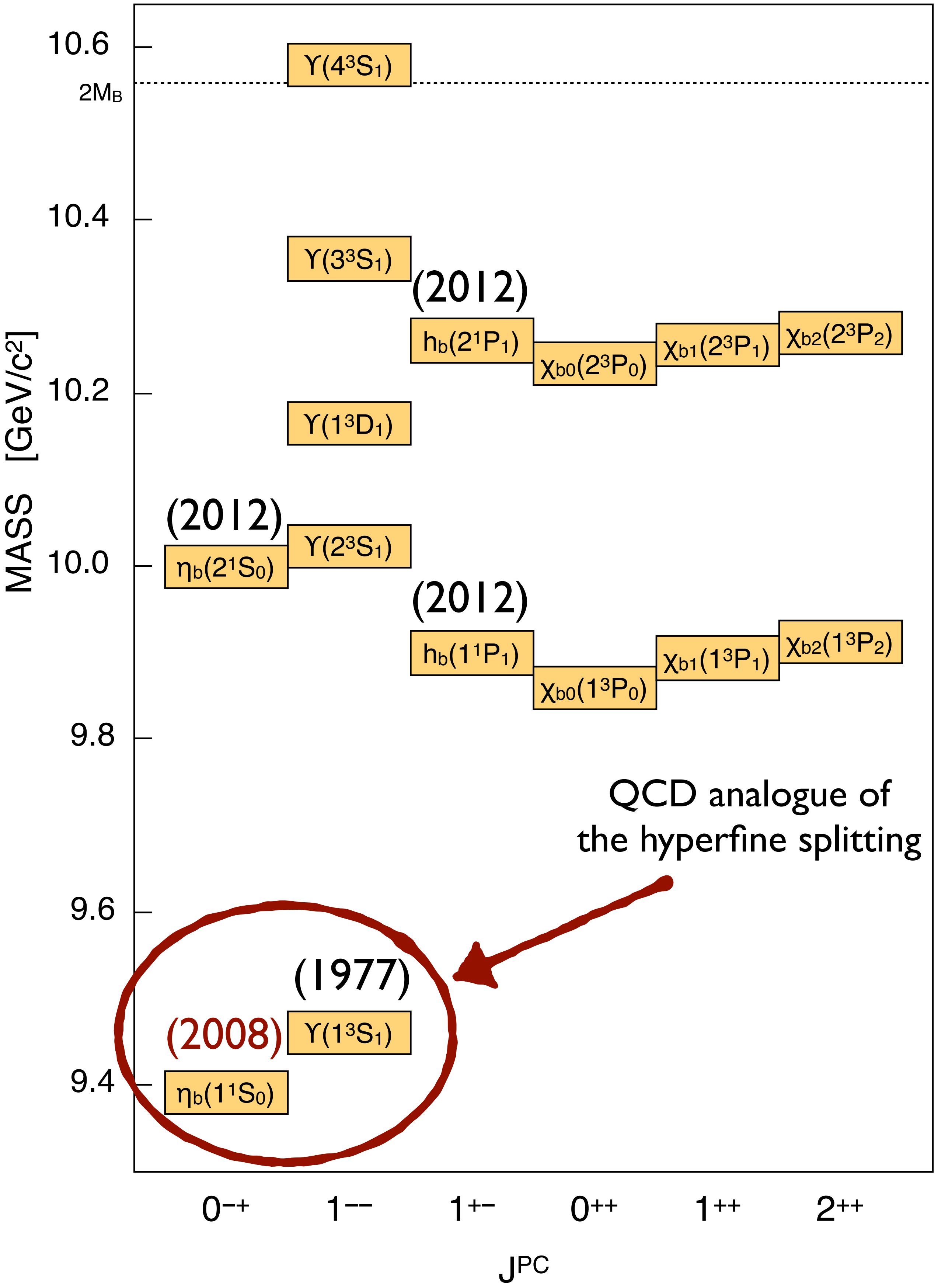
PRD 79, 072007
PRD 78, 031101



Bottom Quarks

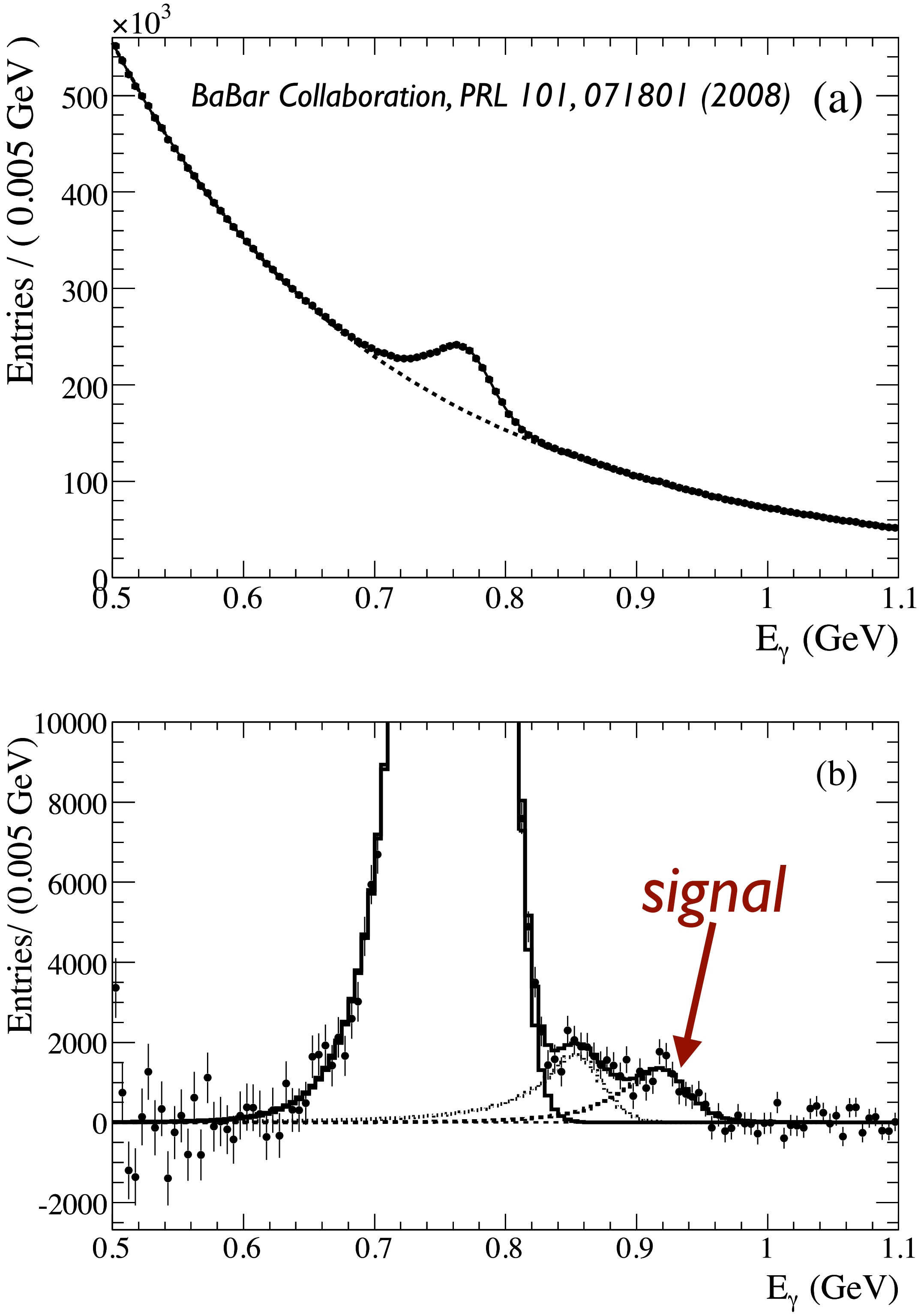
- Similar production
- All state below 2 M_B with $L \leq 1$ experimentally established (recently)
- Probe of QCD at different mass scale

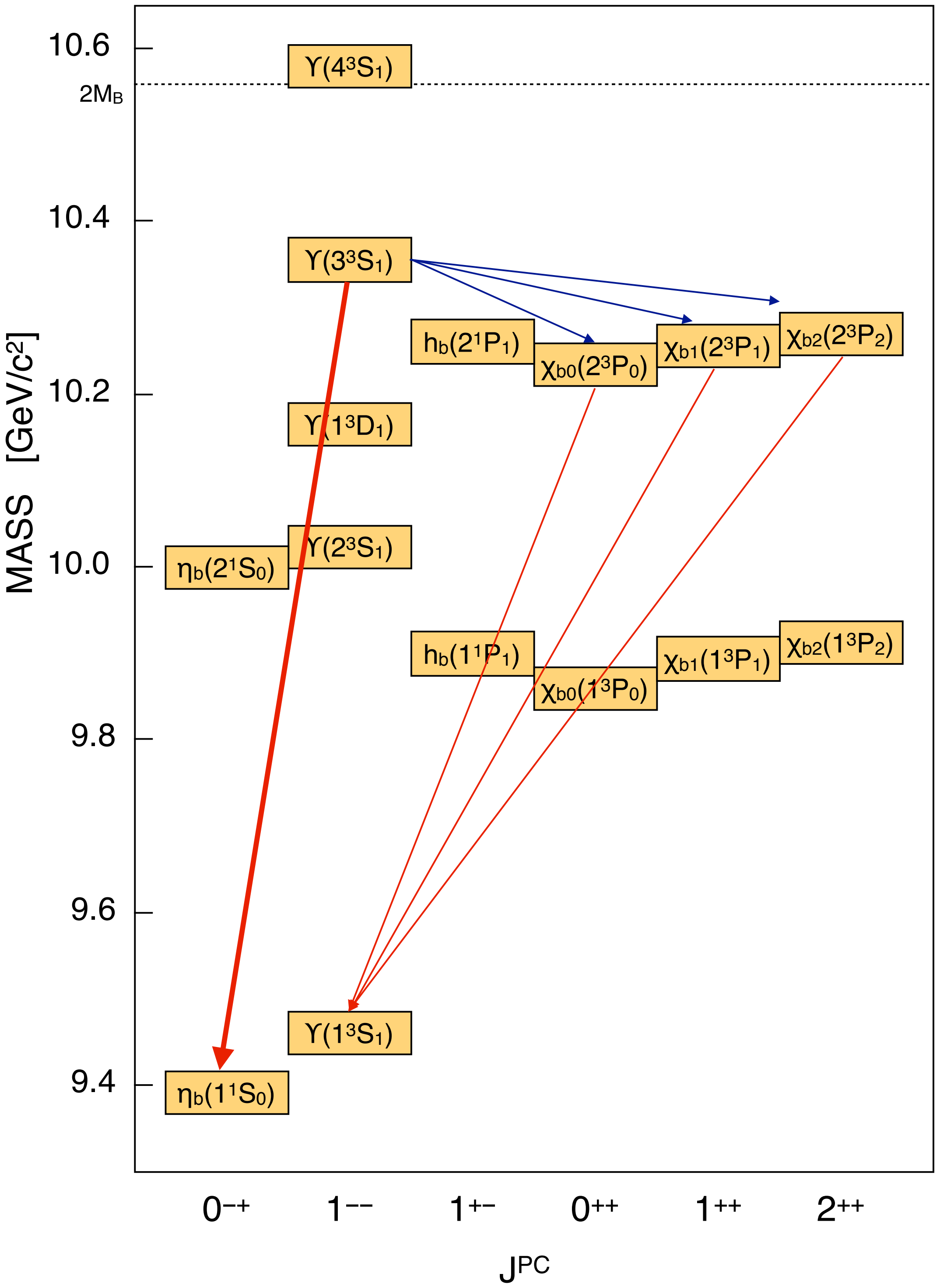




QCD analogue of the hyperfine splitting

Discovery of the η_b

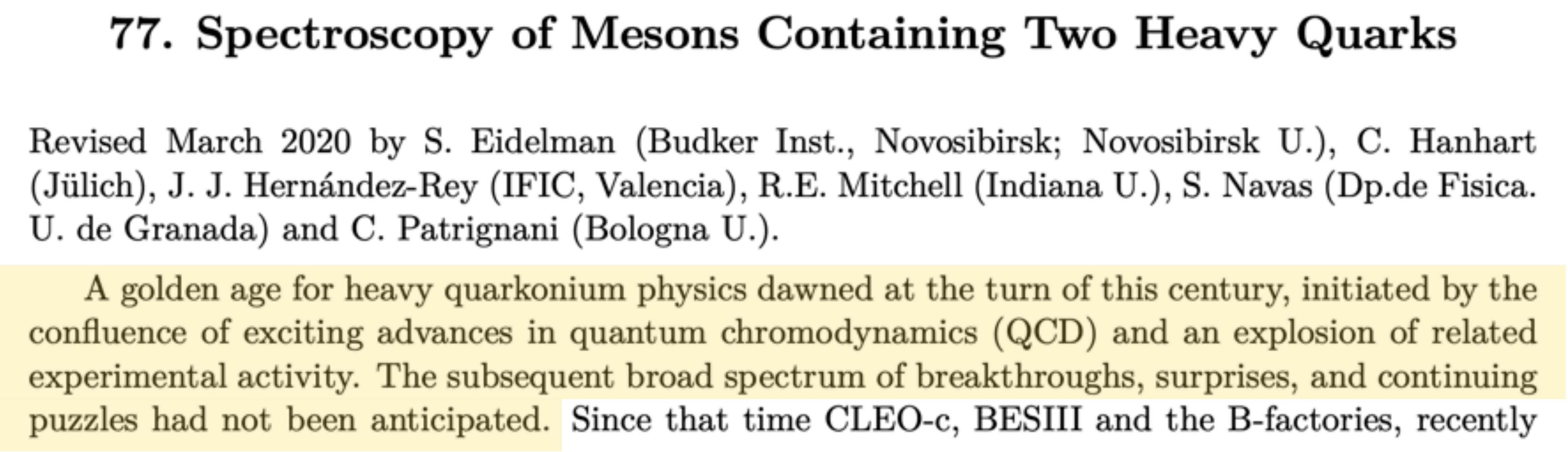




Things are not as simple as they seem...

- 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 -- almost all quark model states below open flavor threshold has been identified and they behave as expected

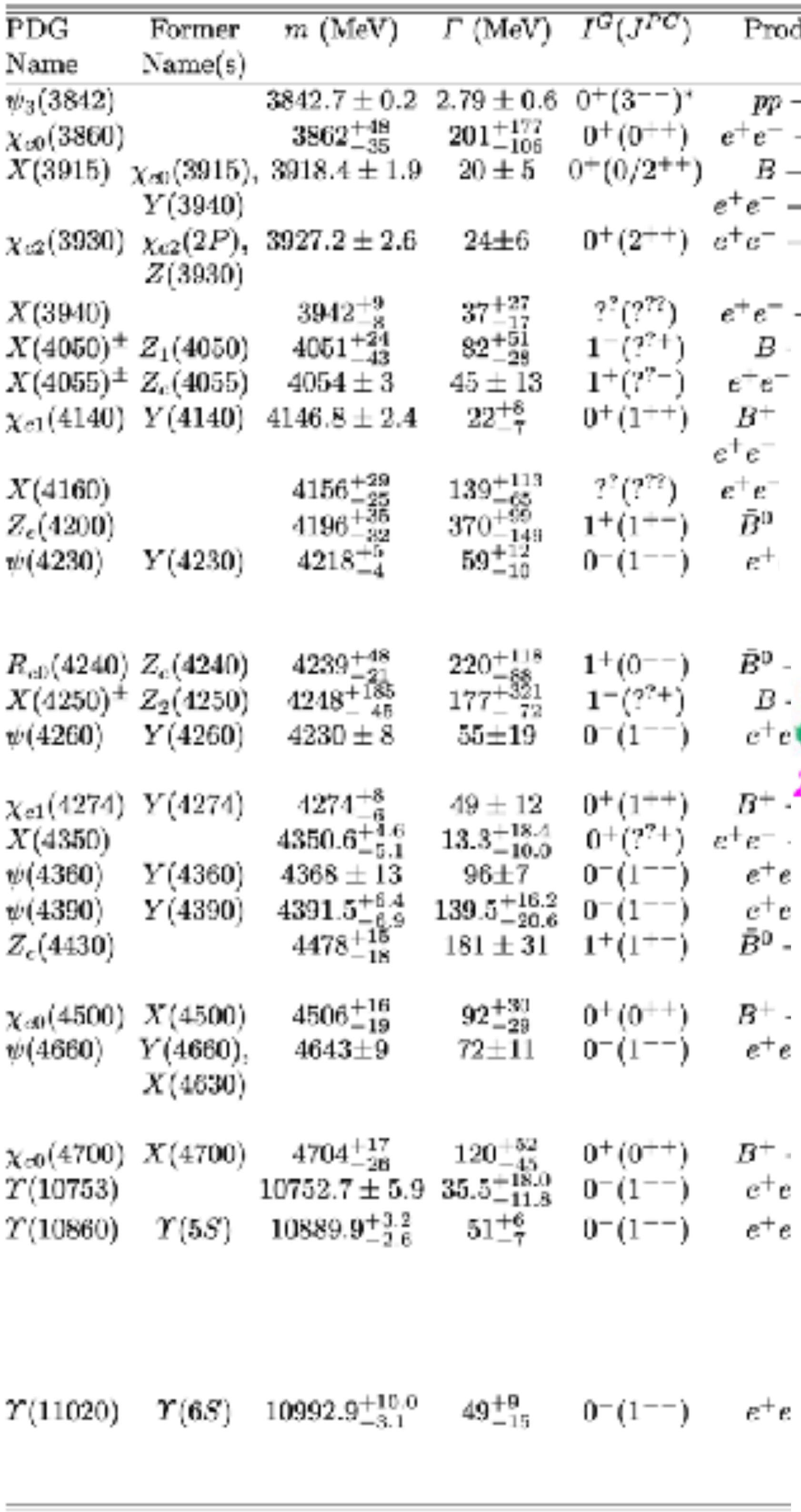
from the 2021 edition of the Review of Particle Physics:



77. Spectroscopy of Mesons Containing Two Heavy Quarks

Revised March 2020 by S. Eidelman (Budker Inst., Novosibirsk; Novosibirsk U.), C. Hanhart (Jülich), J. J. Hernández-Rey (IFIC, Valencia), R.E. Mitchell (Indiana U.), S. Navas (Dp.de Fisica. U. de Granada) and C. Patrignani (Bologna U.).

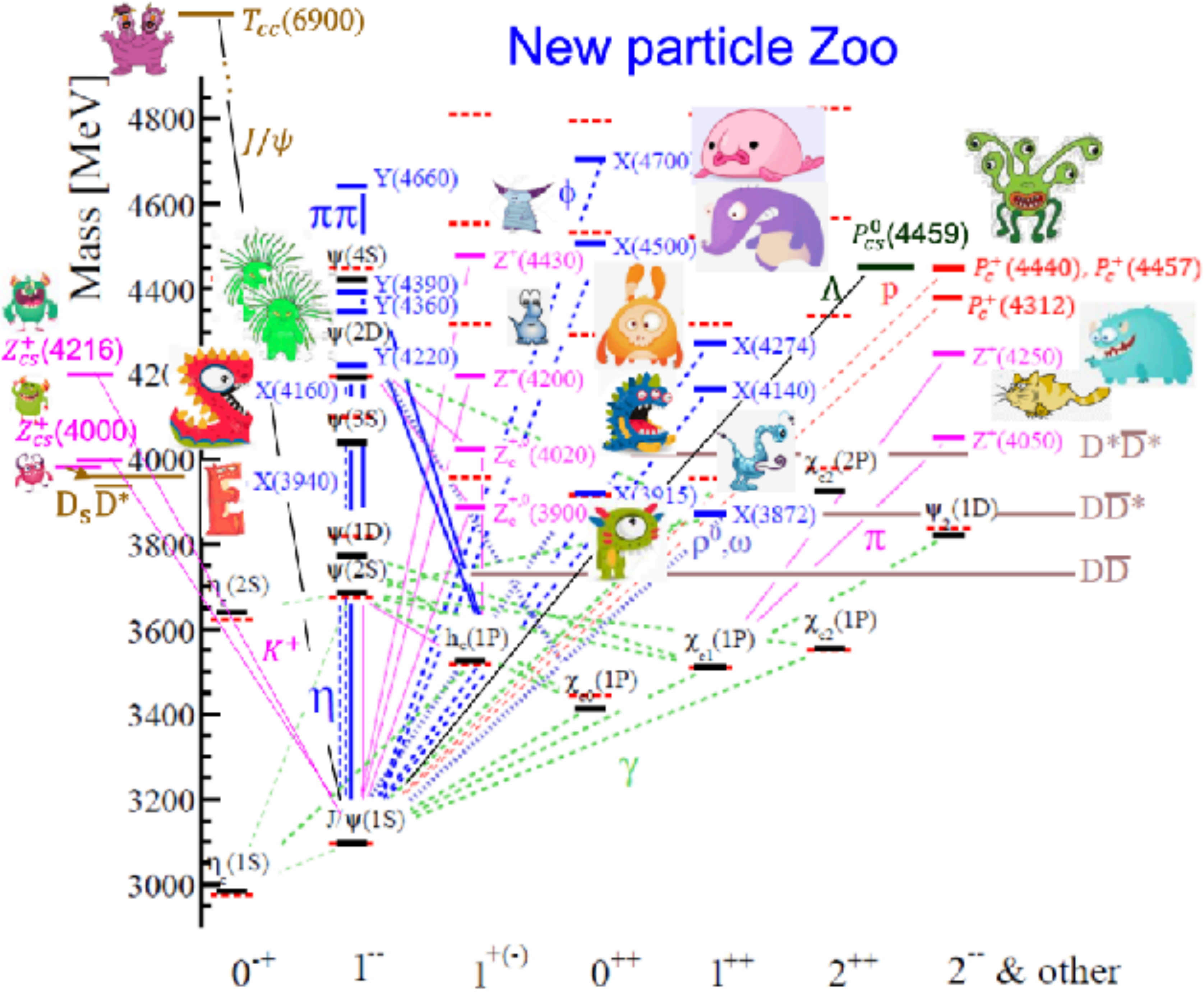
A golden age for heavy quarkonium physics dawned at the turn of this century, initiated by the confluence of exciting advances in quantum chromodynamics (QCD) and an explosion of related experimental activity. The subsequent broad spectrum of breakthroughs, surprises, and continuing puzzles had not been anticipated. Since that time CLEO-c, BESIII and the B-factories, recently



PDG Name	Former Name(s)	m (MeV)	Γ (MeV)	$I^G(J^{PC})$	Production	Decay	Discovery Year	Summary Table
$\psi_3(3842)$		3842.7 ± 0.2	2.79 ± 0.6	$0^+(3^{--})^*$	$pp \to X...$	$D\bar{D}$	2019	NO
$\chi_{c0}(3860)$		3862^{+48}_{-35}	201^{+177}_{-106}	$0^+(0^{++})$	$e^+e^- \to J/\psi X$	$D\bar{D}$	2017	NO
$X(3915)$	$\chi_{c0}(3915)$, $Y(3940)$	3918.4 ± 1.9	20 ± 5	$0^+(0/2^{++})$	$B \to KX$ $e^+e^- \to e^+e^-X$	$\omega J/\psi$	2004	YES
$\chi_{c2}(3930)$	$\chi_{c2}(2P)$, $Z(3930)$	3927.2 ± 2.6	$24{\pm}6$	$0^+(2^{++})$	$e^+e^- \to e^+e^-X$	$D\bar{D}$	2005	YES
$X(3940)$		3942^{+9}_{-8}	37^{+27}_{-17}	$?^?(?^{??})$	$e^+e^- \to J/\psi X$	$D\bar{D}^*$	2007	NO
$X(4050)^+$	$Z_1(4050)$	4051^{+24}_{-43}	82^{+51}_{-28}	$1^-(?^{?+})$	B			
$X(4055)^\pm$	$Z_c(4055)$	4054 ± 3	45 ± 13	$1^+(?^{?-})$	e^+e^-			
$\chi_{c1}(4140)$	$Y(4140)$	4146.8 ± 2.4	22^{+8}_{-7}	$0^+(1^{++})$	B^+ e^+e^-			
$X(4160)$		4156^{+29}_{-25}	139^{+113}_{-65}	$?^?(?^{??})$	e^+e^-			
$Z_c(4200)$		4196^{+35}_{-32}	370^{+99}_{-149}	$1^+(1^{+-})$	$\bar{B}^0$			
$\psi(4230)$	$Y(4230)$	4218^{+5}_{-4}	59^{+12}_{-10}	$0^-(1^{--})$	e^+			
$R_{c0}(4240)$	$Z_c(4240)$	4239^{+48}_{-21}	220^{+118}_{-88}	$1^+(0^{--})$	$\bar{B}^0$			
$X(4250)^+$	$Z_2(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$1^-(?^{?+})$	B			
$\psi(4260)$	$Y(4260)$	4230 ± 8	$55{\pm}19$	$0^-(1^{--})$	e^+e			
$\chi_{c1}(4274)$	$Y(4274)$	4274^{+8}_{-6}	49 ± 12	$0^+(1^{++})$	B^+			
$X(4350)$		$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0^+(?^{?+})$	e^+e^-			
$\psi(4360)$	$Y(4360)$	4368 ± 13	$96{\pm}7$	$0^-(1^{--})$	e^+e			
$\psi(4390)$	$Y(4390)$	$4391.5^{+6.4}_{-6.9}$	$139.5^{+16.2}_{-20.6}$	$0^-(1^{--})$	e^+e			
$Z_c(4430)$		4478^{+15}_{-18}	181 ± 31	$1^+(1^{+-})$	$\bar{B}^0$			
$\chi_{c0}(4500)$	$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	$0^+(0^{++})$	B^+			
$\psi(4660)$	$Y(4660)$, $X(4630)$	$4643{\pm}9$	$72{\pm}11$	$0^-(1^{--})$	e^+e			
$\chi_{c0}(4700)$	$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	$0^+(0^{++})$	B^+			
$\Upsilon(10753)$		10752.7 ± 5.9	$35.5^{+18.0}_{-11.3}$	$0^-(1^{--})$	e^+e			
$\Upsilon(10860)$	$\Upsilon(5S)$	$10889.9^{+3.2}_{-2.6}$	51^{+6}_{-7}	$0^-(1^{--})$	e^+e			
$\Upsilon(11020)$	$\Upsilon(6S)$	$10992.9^{+10.0}_{-3.1}$	49^{+9}_{-15}	$0^-(1^{--})$	e^+e			

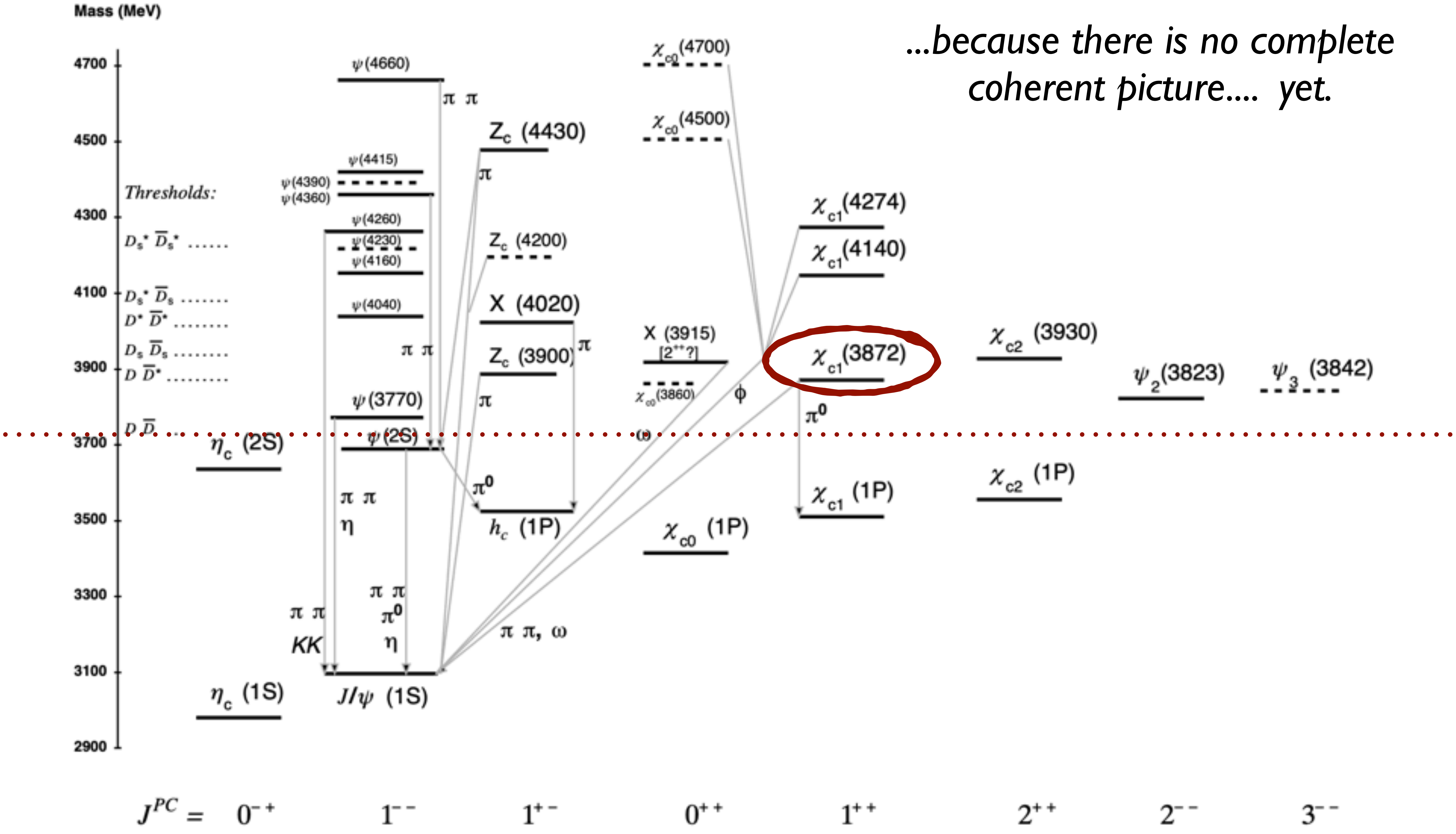
from T. Skwarnicki at Charm 2021:

New particle Zoo



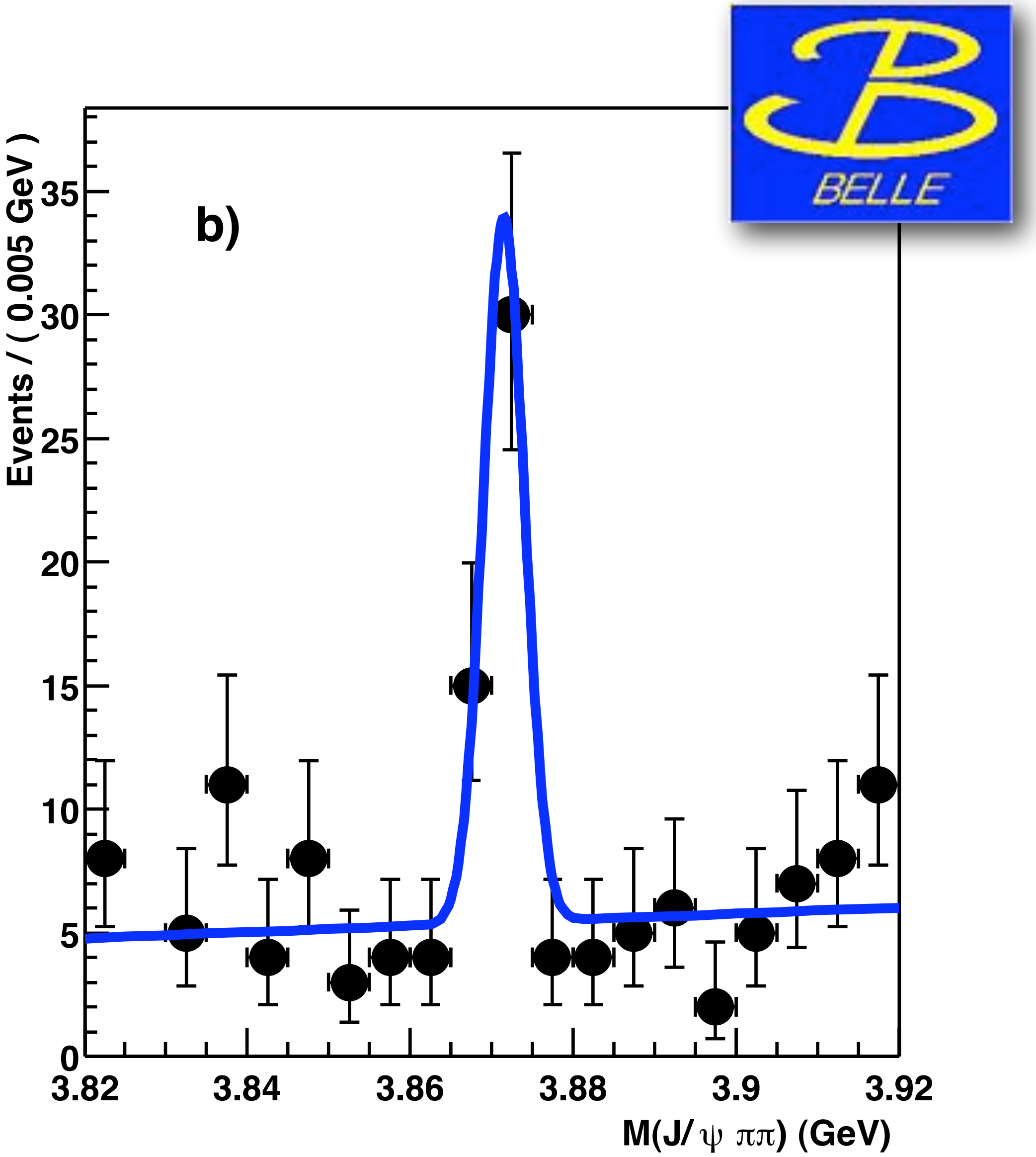
A very brief story...

...because there is no complete coherent picture.... yet.



Almost twenty years ago

- Discovery of $X(3872)$ in $B^+ \to K^+\pi^+\pi^- J/\psi$ decays, by Belle, an experiment built for studying CP-violation in B mesons
- Peculiar properties:
  - very narrow
  - right at DD^* mass threshold
  - not well-matched to potential model predictions of charmonium mesons
- At the time J^{PC} was unknown



PRL 91, 262001 (2003)

(1950+ citations as of this week,
the most cited Belle result
by a ~900 citation margin)

Now: $X(3872) \rightarrow \chi_{c1}(3872)$

- observed by multiple experiments in multiple production modes
- very narrow
  $\Gamma(\chi_{c1}(38720)) = 1\ \mathrm{MeV}$
  compare: $\Gamma(\psi(3770)) = 27\ \mathrm{MeV}$
- $J^{PC} = 1^{++}$
- behaves like $c\bar{c}$ in some ways but not in others
  - identify with radial excitation of the χ_{c1}?
- presence of DD* threshold seems more than just coincidence

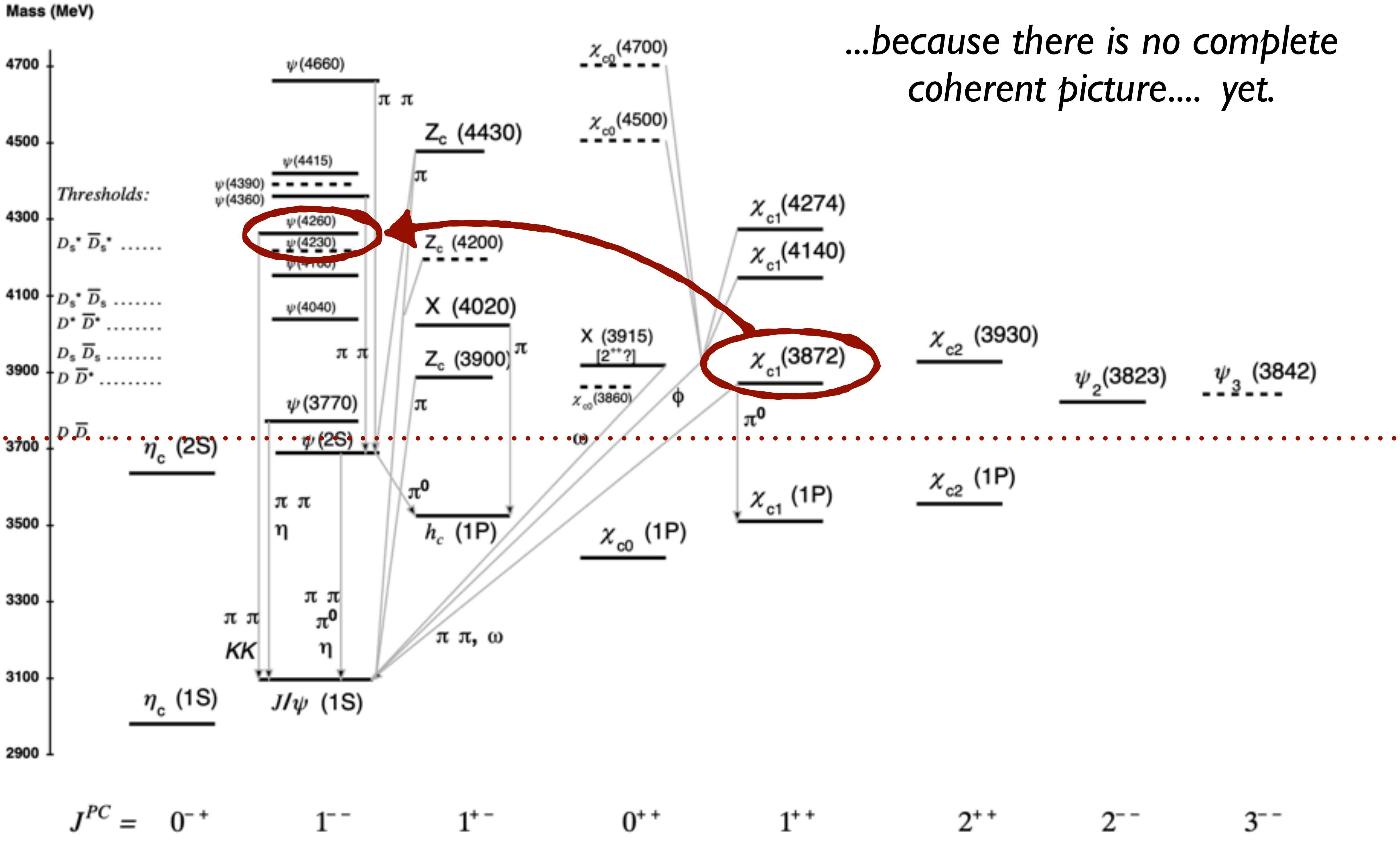
2021 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE

VALUE (MeV)	*EVTS*		*DOCUMENT ID*		*TECN*	*COMMENT*
3871.65 ± 0.06	**OUR AVERAGE**					
3871.64 ±0.06 ±0.01	19.8k	1	AAIJ	2020S	LHCB	$B^+ \to J/\psi\pi^+\pi^-K^+$
3871.9 ±0.7 ±0.2	20		ABLIKIM	2014	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
3871.95 ±0.48 ±0.12	0.6k		AAIJ	2012H	LHCB	$p\,p \to J/\psi\pi^+\pi^-X$
3871.85 ±0.27 ±0.19	170	2	CHOI	2011	BELL	$B \to K\pi^+\pi^-J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27	3	DEL-AMO-SANCH.	2010B	BABR	$B \to \omega J/\psi K$
3871.61 ±0.16 ±0.19	6k	4, 3	AALTONEN	2009AU	CDF2	$p\,\bar{p} \to J/\psi\pi^+\pi^-X$
3871.4 ±0.6 ±0.1	93.4		AUBERT	2008Y	BABR	$B^+ \to K^+J/\psi\pi^+\pi^-$
3868.7 ±1.5 ±0.4	9.4		AUBERT	2008Y	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.8 ±3.1 ±3.0	522	5, 3	ABAZOV	2004F	D0	$p\,\bar{p} \to J/\psi\pi^+\pi^-X$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
3871.695 ±0.067 ±0.068	15.5k	6	AAIJ	2020AD	LHCB	$p\,p \to J/\psi\pi^+\pi^-X$
3871.59 ±0.06 ±0.03	4.2k	7	AAIJ	2020S	LHCB	$B^+ \to J/\psi\pi^+\pi^-K^+$
3873.3 ±1.1 ±1.0	45	8	ABLIKIM	2019V	BES	$e^+e^- \to \gamma\omega J/\psi$
3860.0 ±10.4	13.6	9, 3	AGHASYAN	2018A	COMP	$\gamma^* N \to X\pi^\pm N'$
3868.6 ±1.2 ±0.2	8	10	AUBERT	2006	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.3 ±0.6 ±0.1	61	10	AUBERT	2006	BABR	$B^- \to K^-J/\psi\pi^+\pi^-$
3873.4 ±1.4	25	11	AUBERT	2005R	BABR	$B^+ \to K^+J/\psi\pi^+\pi^-$
3871.3 ±0.7 ±0.4	730	3, 12	ACOSTA	2004	CDF2	$p\,\bar{p} \to J/\psi\pi^+\pi^-X$
3872.0 ±0.6 ±0.5	36	13	CHOI	2003	BELL	$B \to K\pi^+\pi^-J/\psi$
3836 ±13	58	3, 14	ANTONIAZZI	1994	E705	$300\ \pi^\pm\ \mathrm{Li} \to J/\psi\pi^+\pi^-X$

$$M(D^0) + M(D^{*0}) = 3871.69 \pm 0.07\ \mathrm{MeV}$$

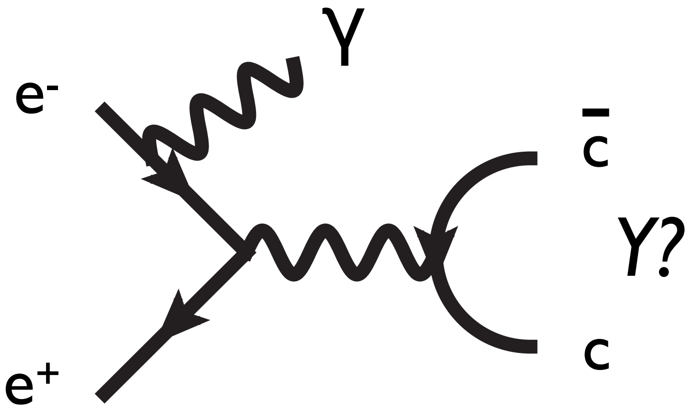
A very brief story...



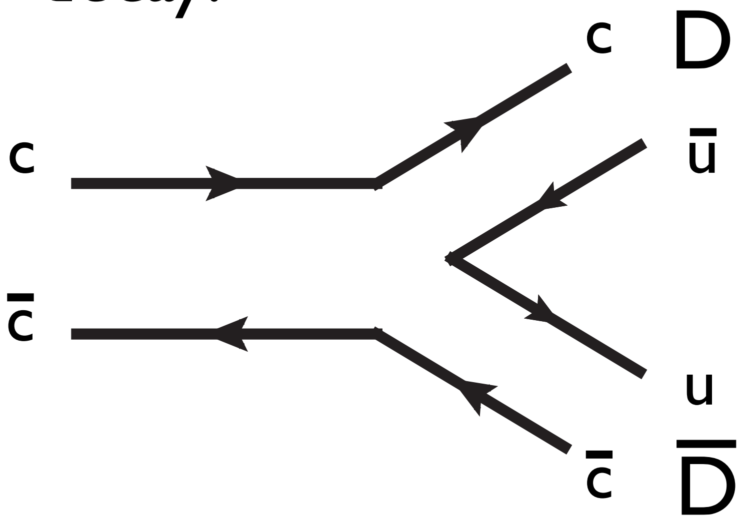
...because there is no complete coherent picture.... yet.

Looking for X(3872) uncovered the "Y(4260)"

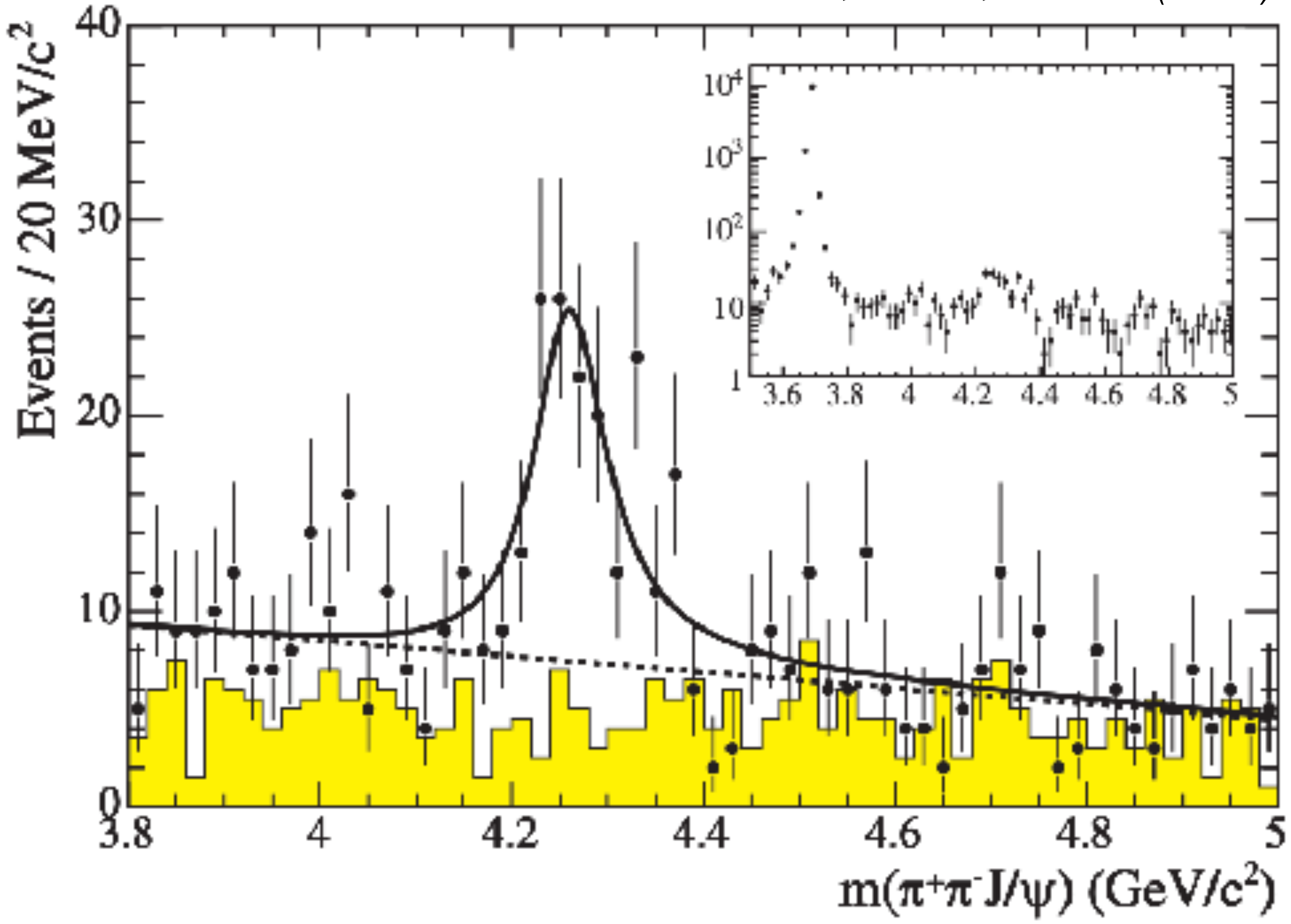
- 1^{--} state produced in e^+e^-



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



BaBar Collaboration, PRL 95, 142001 (2005)

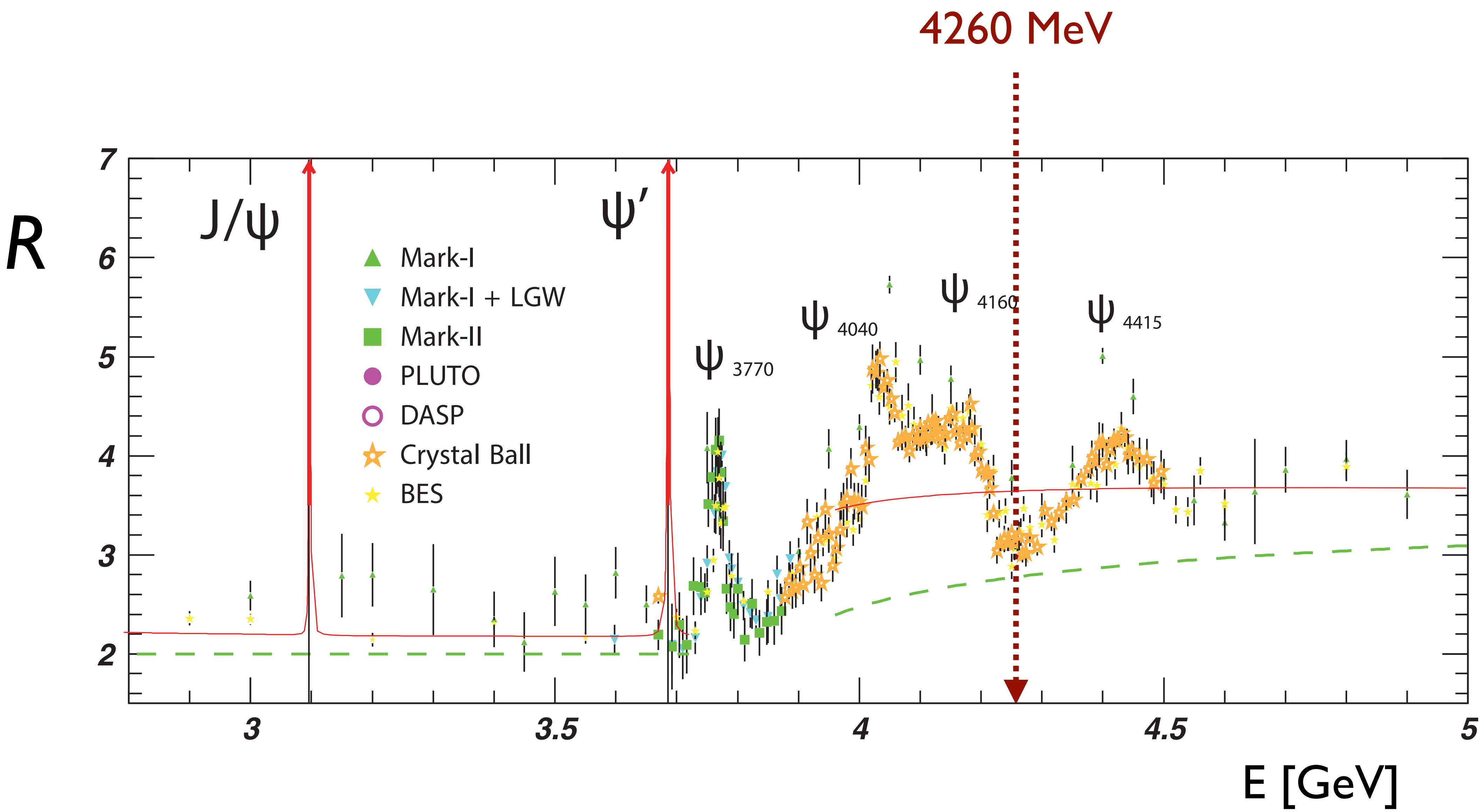


CLEO Collaboration, PRD 80, 072001 (2009)

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

compare with ≈500 for ψ(3770)

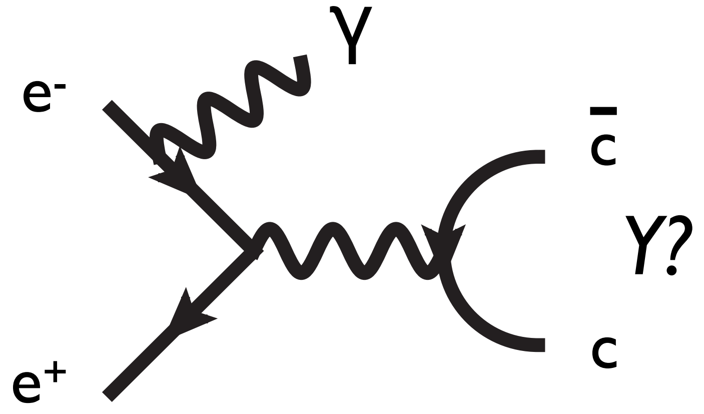
Production of 1^{--}Charmonia in e^+e^- Collisions



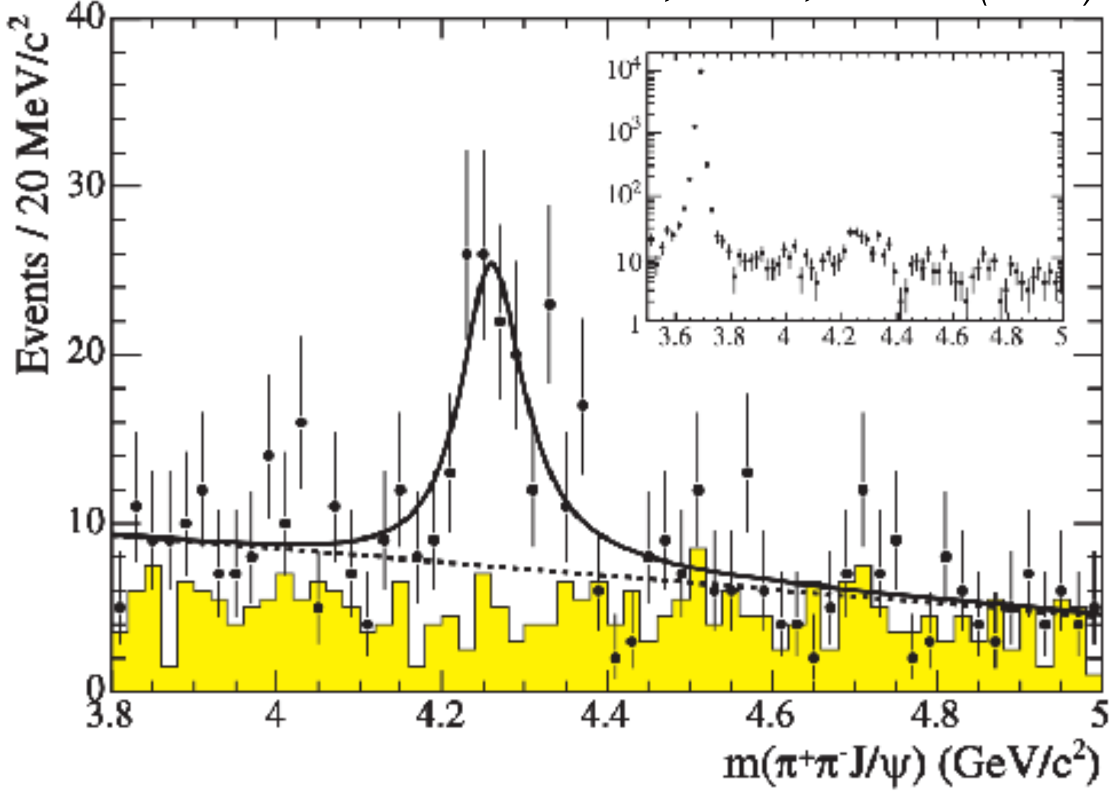
All 1^{--} quark model states have been identified.
No obvious place in the spectrum for the Y(4260).

Direct production of Y(4260)

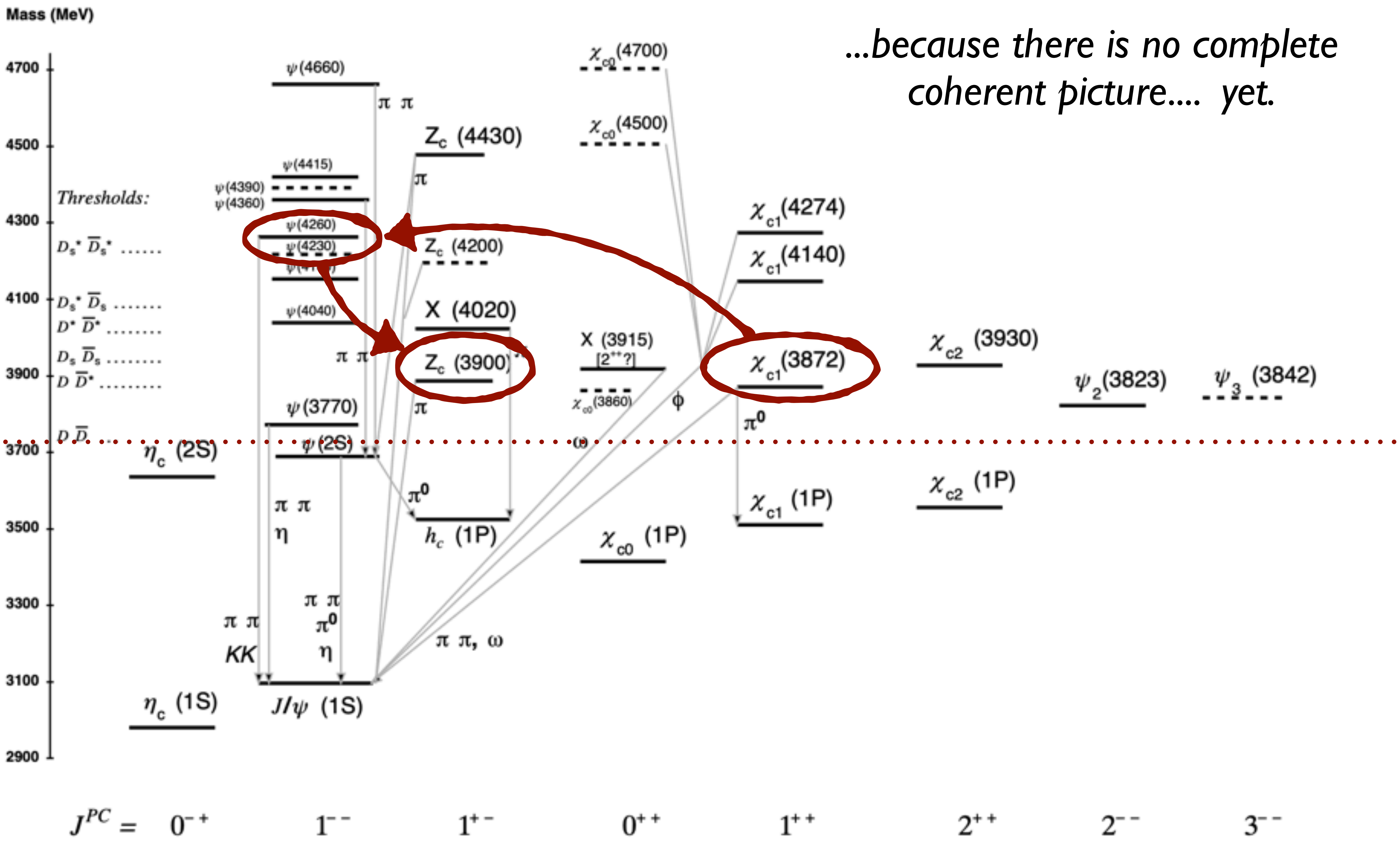
- Discovery of Y(4260) came via enormous samples of B meson data collected at $E_{cm} \approx 10\ \mathrm{GeV}$
- BESIII and BEPC could collide e^+e^- beams at $E_{cm} = 4.26\ \mathrm{GeV}$
  - higher Y(4260) statistics but
  - no easy "scanning" of Y(4260) shape
- In 2012, BESIII collects first data with machine tuned to produce Y(4260)
  - ...an interesting decade of discovery follows



BaBar Collaboration, PRL 95, 142001 (2005)

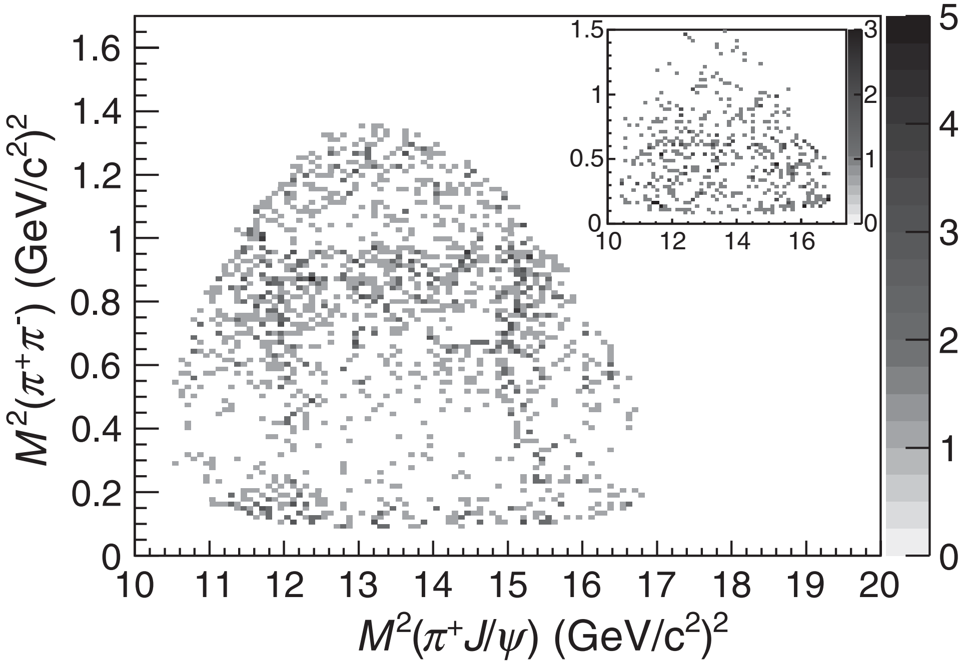


A very brief story...



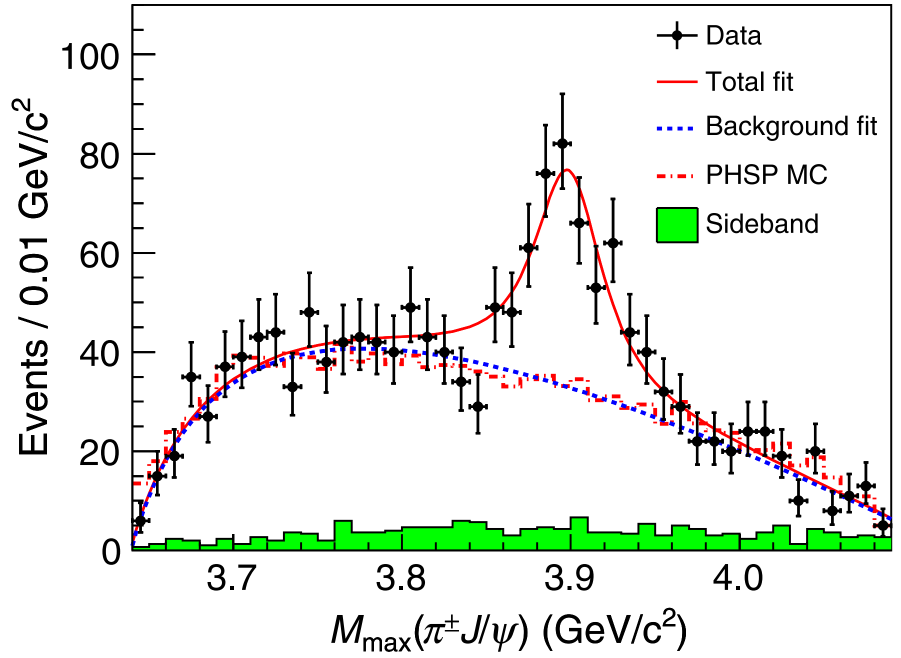
...because there is no complete coherent picture.... yet.

$e^+e^- \to \pi\pi J/\psi$ at $E_{cm} = 4260$ MeV uncovers the $Z_c^+(3900)$

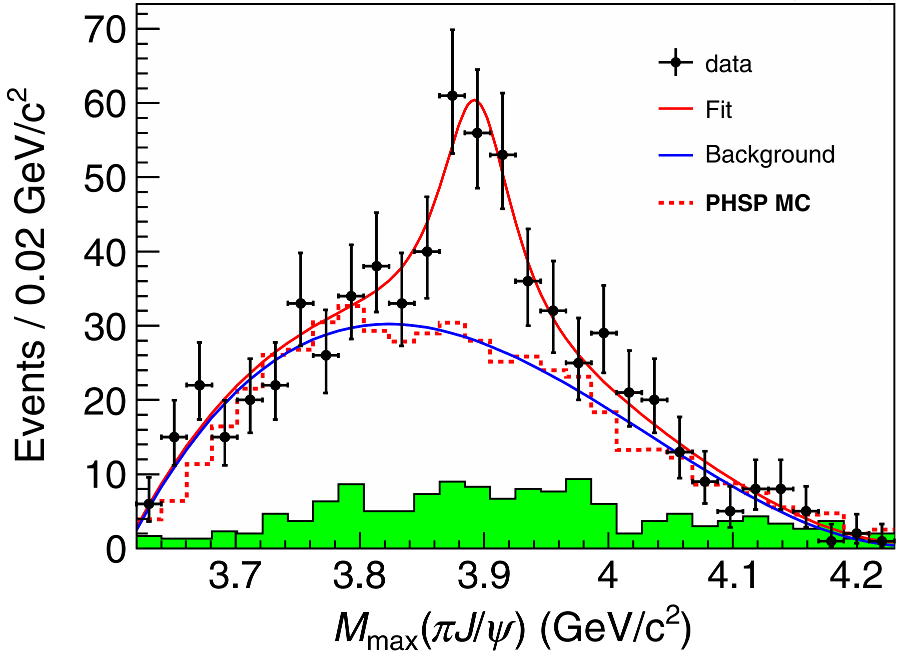


- Discovered at both BESIII and Belle
- Heavy, narrow (≈50 MeV) and *charged* suggests a minimal quark content of $c\bar{c}u\bar{d}$
- Not conventional charmonium: tetraquark?
- Evidence of neutral partner [*T. Xiao et al., PLB 727, 366 (2013)*]

BESIII Collaboration, PRL 110, 252001 (2013)

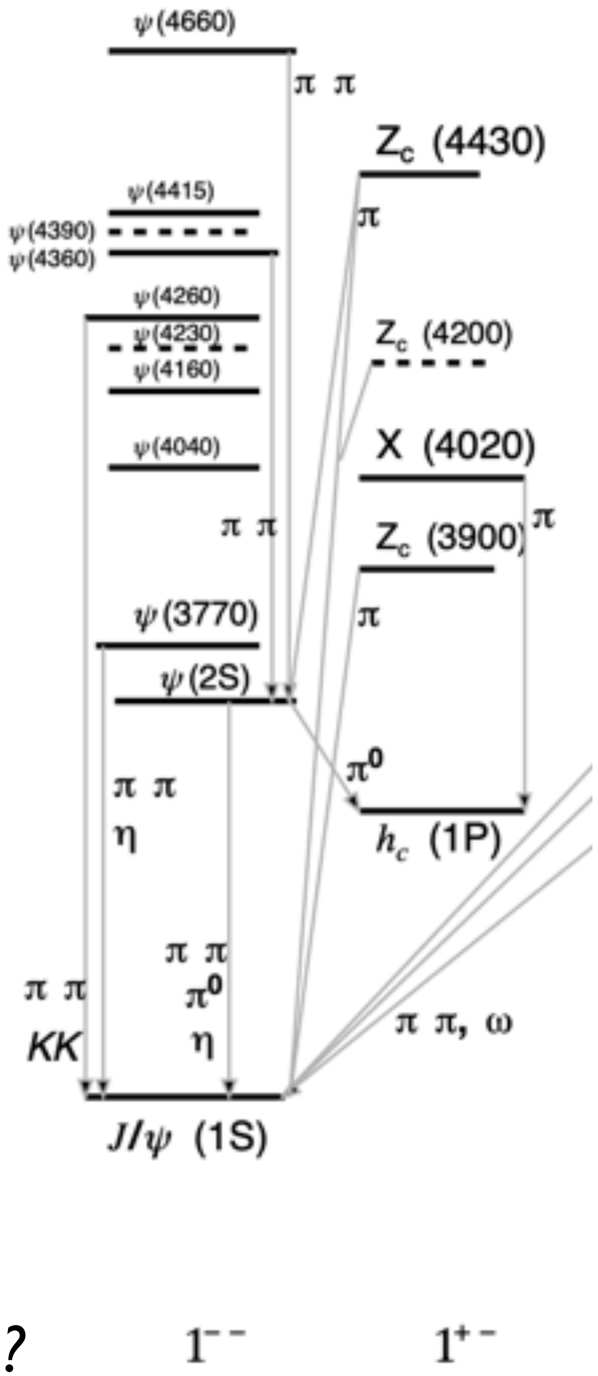


Belle Collaboration, PRL 110, 252002 (2013)



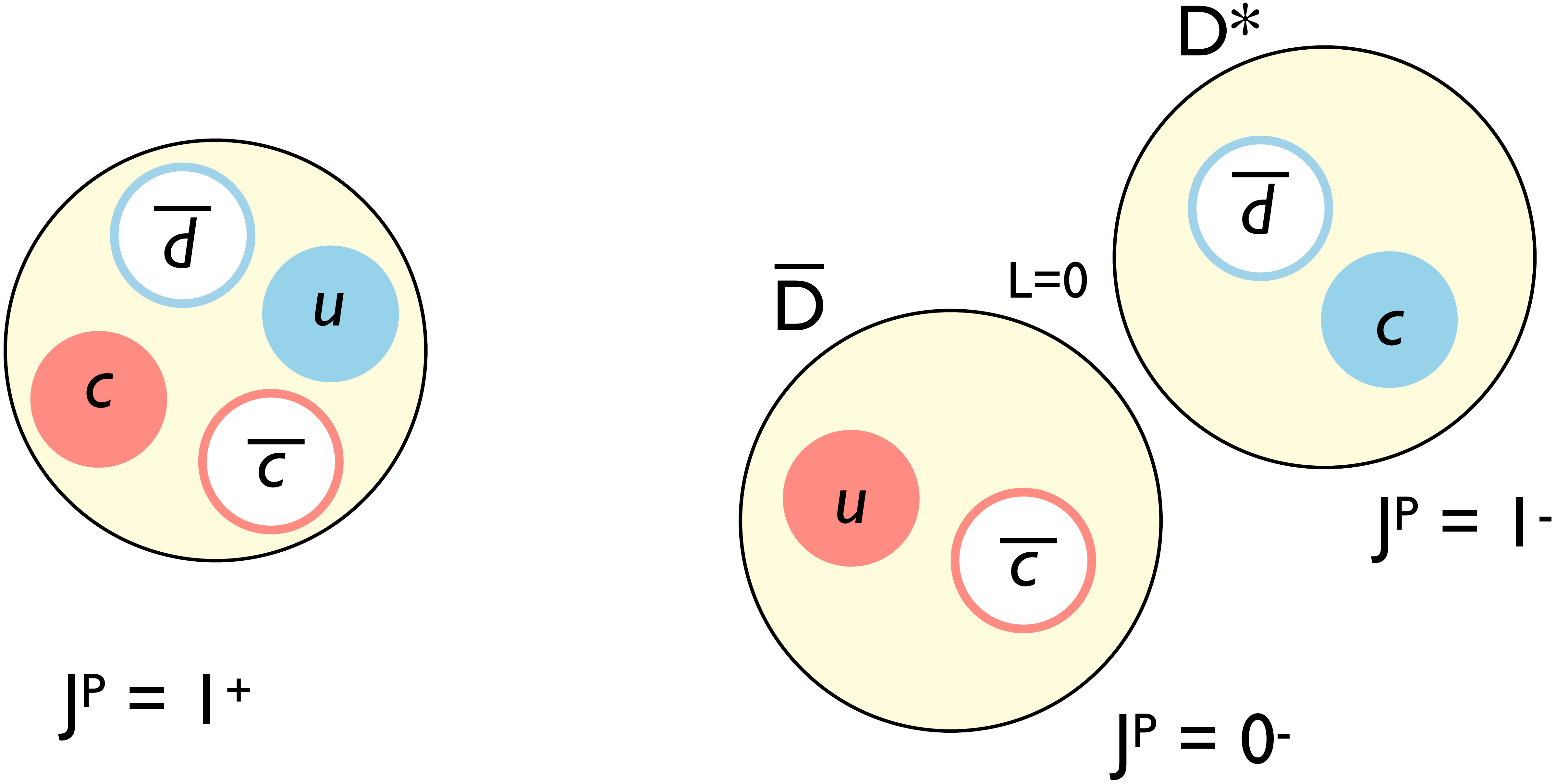
But there is much much more....

- Observation of the Z_c in open charm decays as well as $\pi J/\psi$ -- established: $J^P = 1^+$
- Analogous Z_c state at higher mass observed in πh_c
- Additional Z_c states observed in B decay
- A stranger version: $Z_{cs}(3985)$ was discovered this year
- Analogous states in the bottomonium system have been identified: Z_b, which couple to $\pi\Upsilon$ and πh_c



Spectroscopy! What is the underlying fundamental physics?

What is Z(3900)?

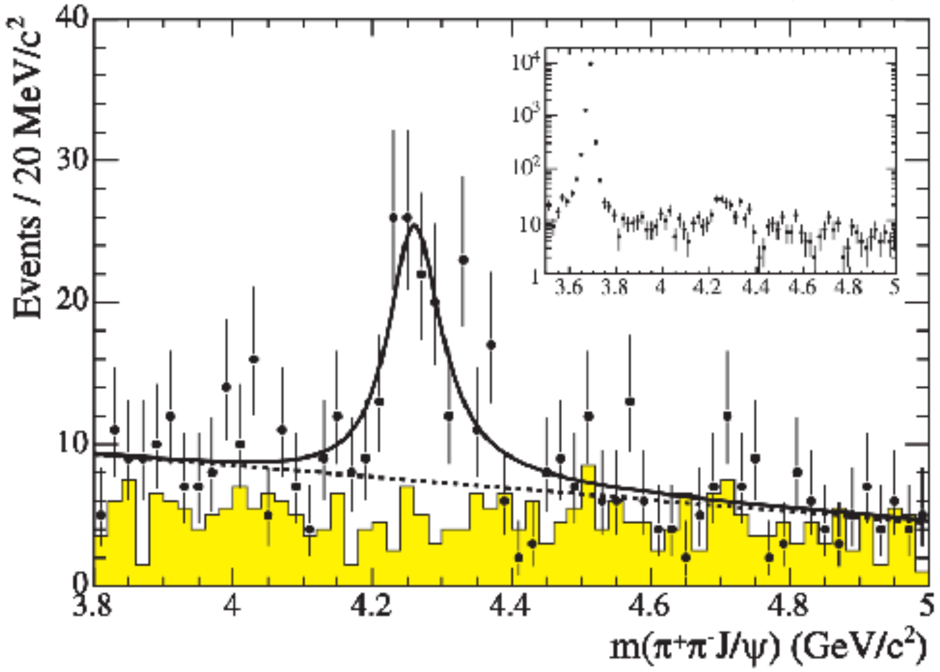


How is it connected to Y(4260)?

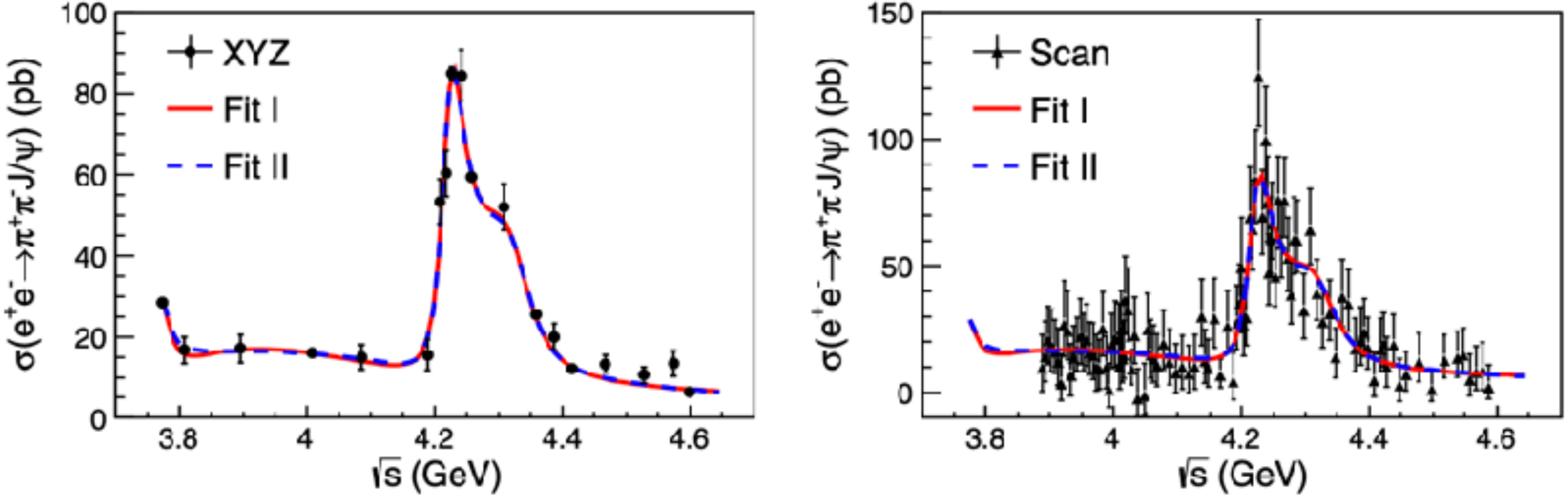
The "Y(4260)" is more complicated than it seems...

- Detailed scan of the Y(4260) indicates a lineshape that is not consistent with a single resonance
- About the $X(3872)$... BESIII observed $e^+e^- \to \gamma X(3872)$ at $E_{cm} = 4.26$ GeV

BaBar Collaboration, PRL 95, 142001 (2005)



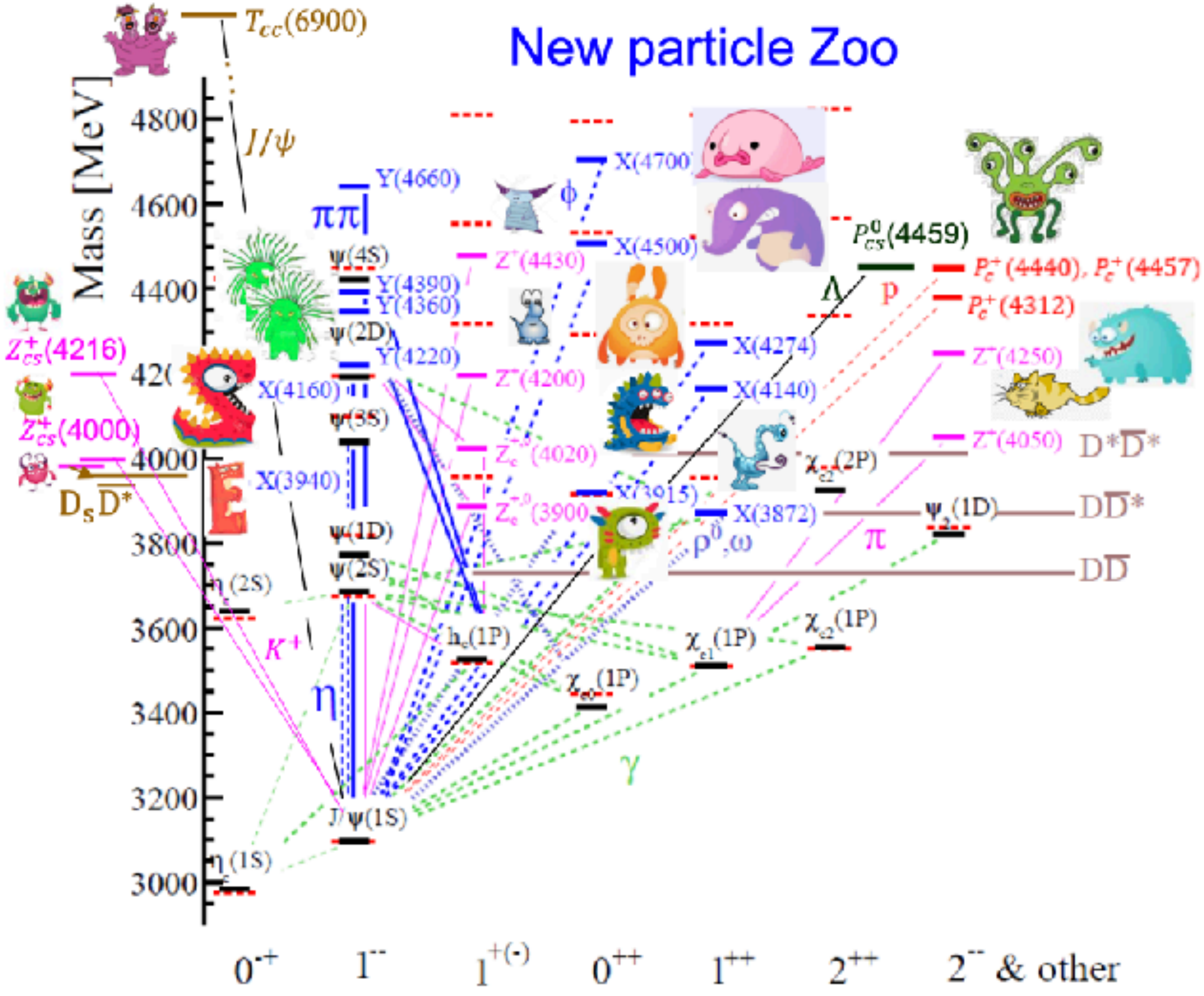
BESIII Collaboration, PRL 118, 092001 (2017)

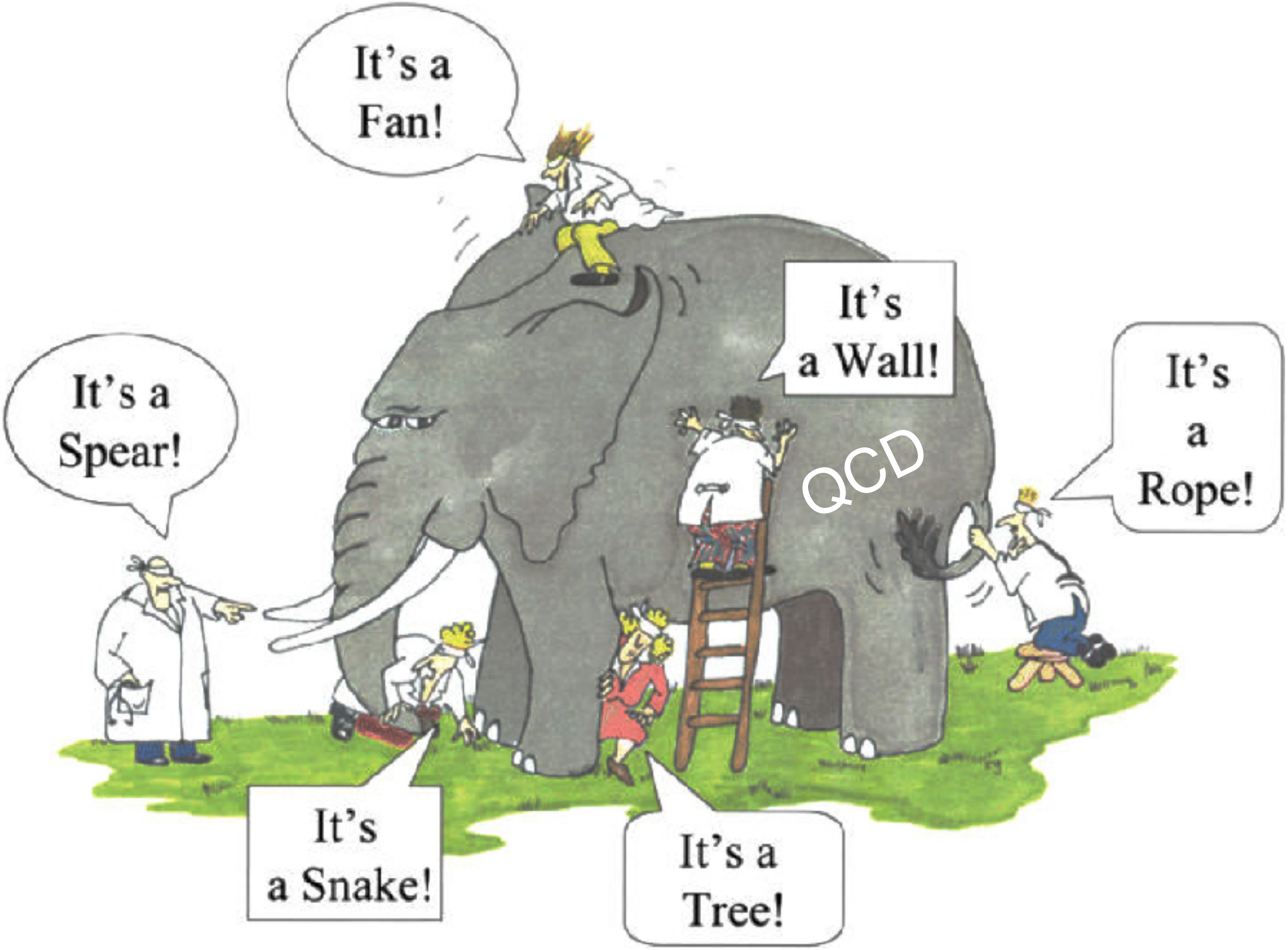


Heavy Quarks Recap

- exciting and confusing
- not experimental statistical fluctuations
- some patterns are emerging
    - similarities in different quark flavors
    - presence of hadron thresholds seems important
    - few states observed in multiple production environments (??)
- demands a better understanding of
    - experimental signatures for resonances
    - the particles generated by QCD
- *effort must be driven by the search for the simplest explanation for all observations*

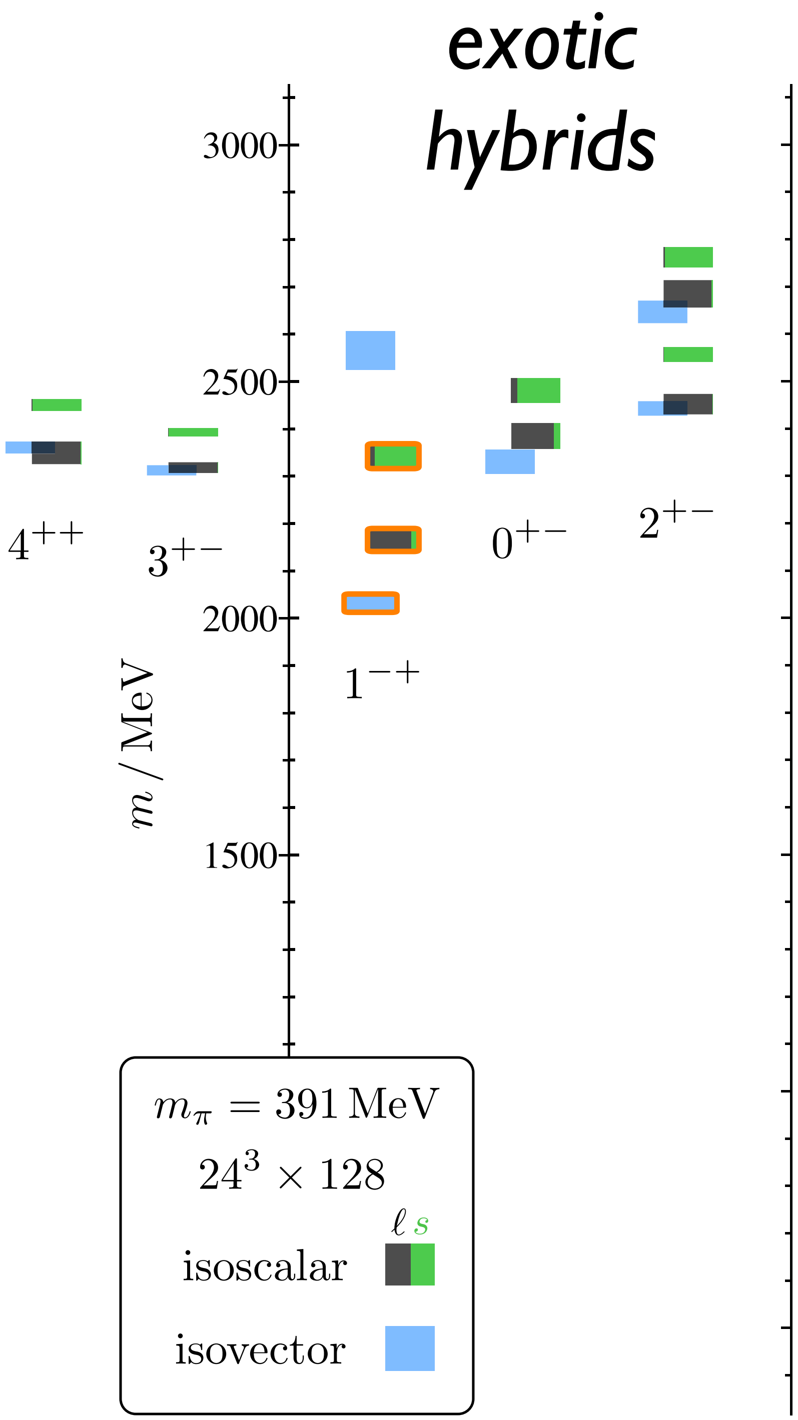
from T. Skwarnicki at Charm 2021:




It's a Fan!
It's a Spear!
It's a Wall!
QCD
It's a Rope!
It's a Snake!
It's a Tree!

Heavy and Light Systems and Hybrid Mesons

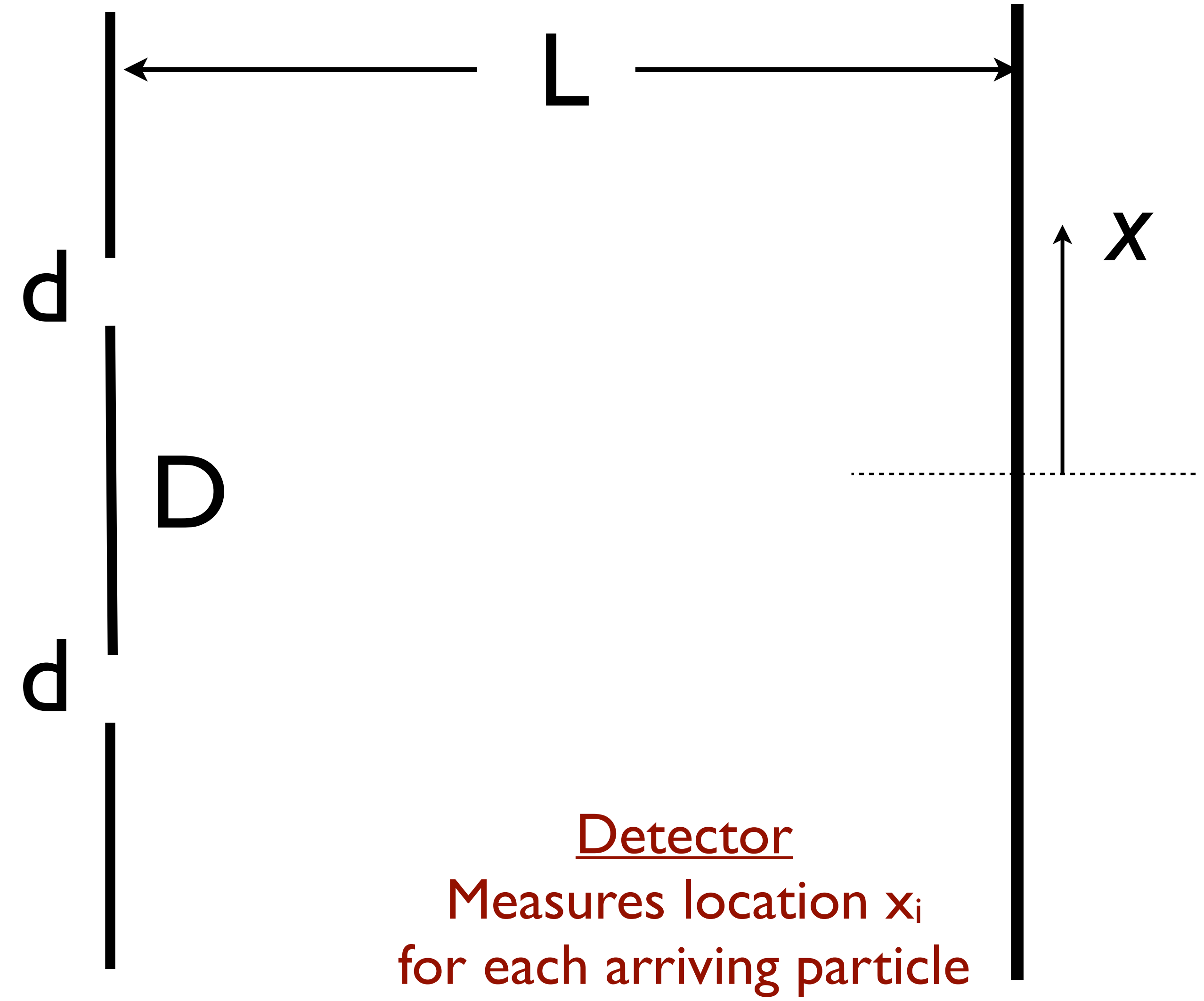
- Production of a heavy quark system with exotic J^{PC} seems challenging
  - no direct production in any annihilation process
- No evidence of exotic J^{PC} states in charmonium or bottomonium
- What about light quarks?
  - characterized by broad overlapping states
  - access to small amplitudes and phases through interference effects



A familiar analogy in one dimension

Physical System Under Study
Two Slits: width d, separation D

record the location *x*
where it was detected



Detector
Measures location x_i
for each arriving particle

shoot particles
at slits

Probe
Beam of Particles
wavelength λ

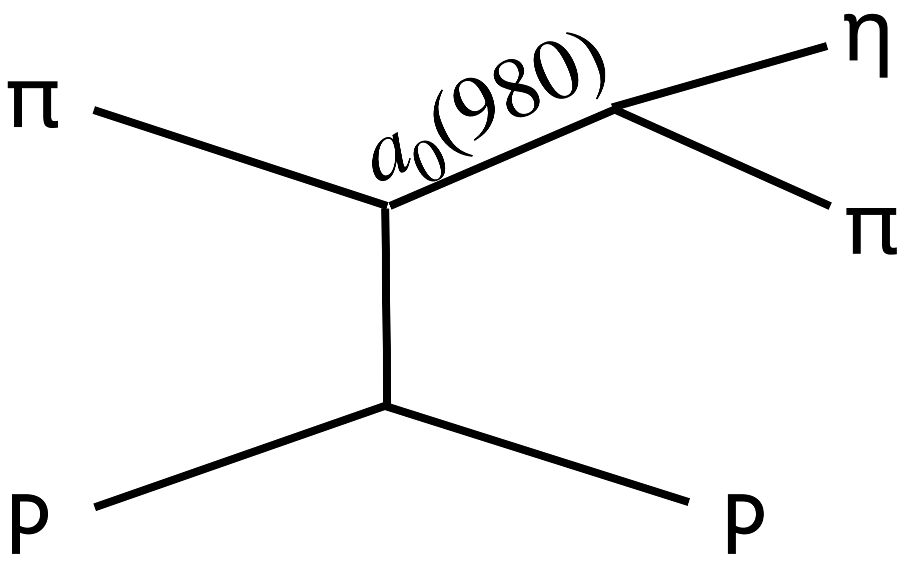
Goal: determine the values of *d* and *D*

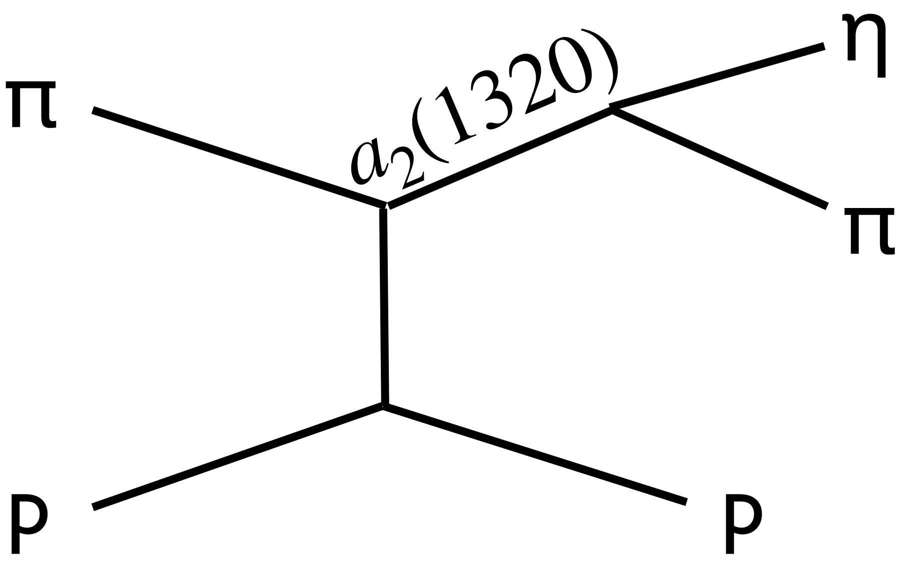
$$I(x) = I_0 \left(\frac{\sin(d\pi x/\lambda L)}{d\pi x/\lambda L} \right)^2 \cos^2(2D\pi x/\lambda L)$$

theoretical model with
parameters to optimized
based on data

Connecting to Spectroscopy

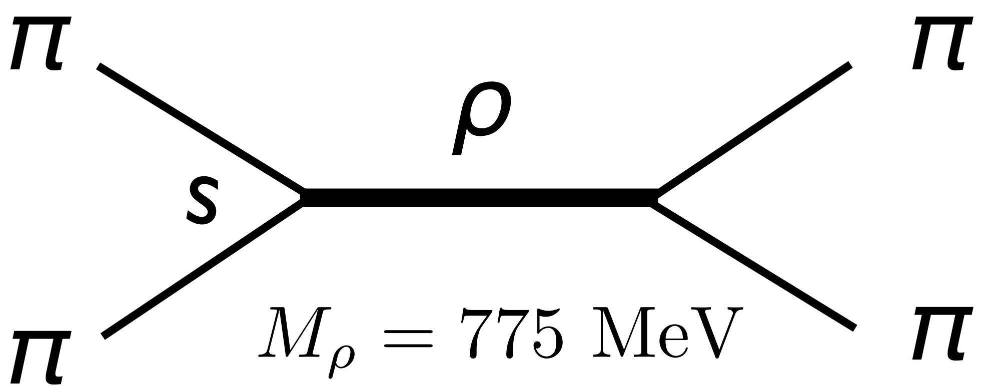
- Suppose we have $\pi p \rightarrow \eta\pi p$, and we produce two different resonances





- Each of these can be related to an independent quantum mechanical *amplitude* that, on its own, would generate a unique angular distribution
- Given any single event with fixed kinematic variables we do not know which process occurred -- they are indistinguishable

Signature of a resonance

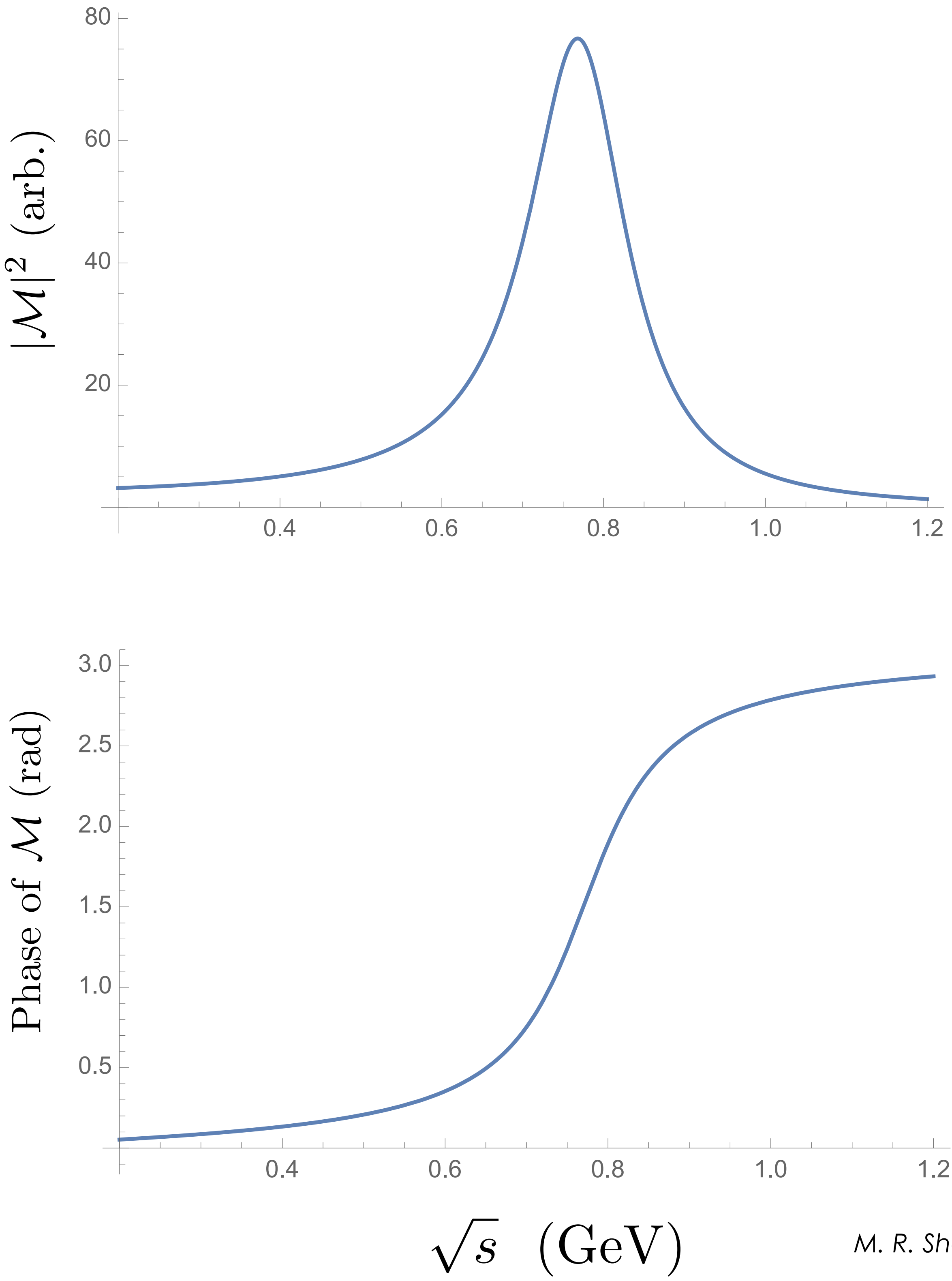


$$M_\rho = 775 \text{ MeV}$$
$$\Gamma_\rho = 148 \text{ MeV}$$

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

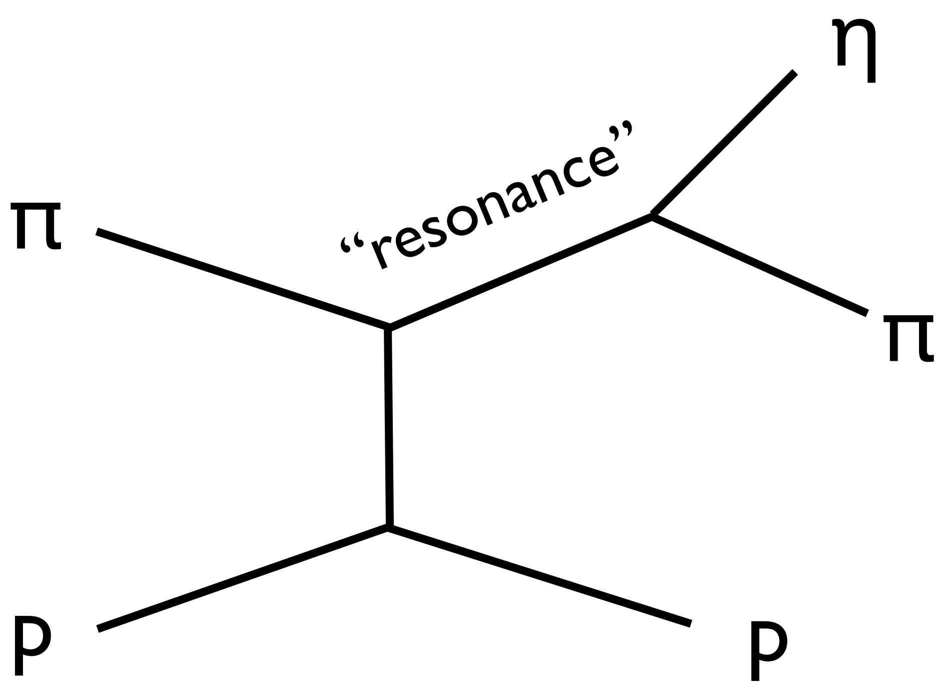
$$\text{pole}: \quad \sqrt{s} = M - i\Gamma/2$$

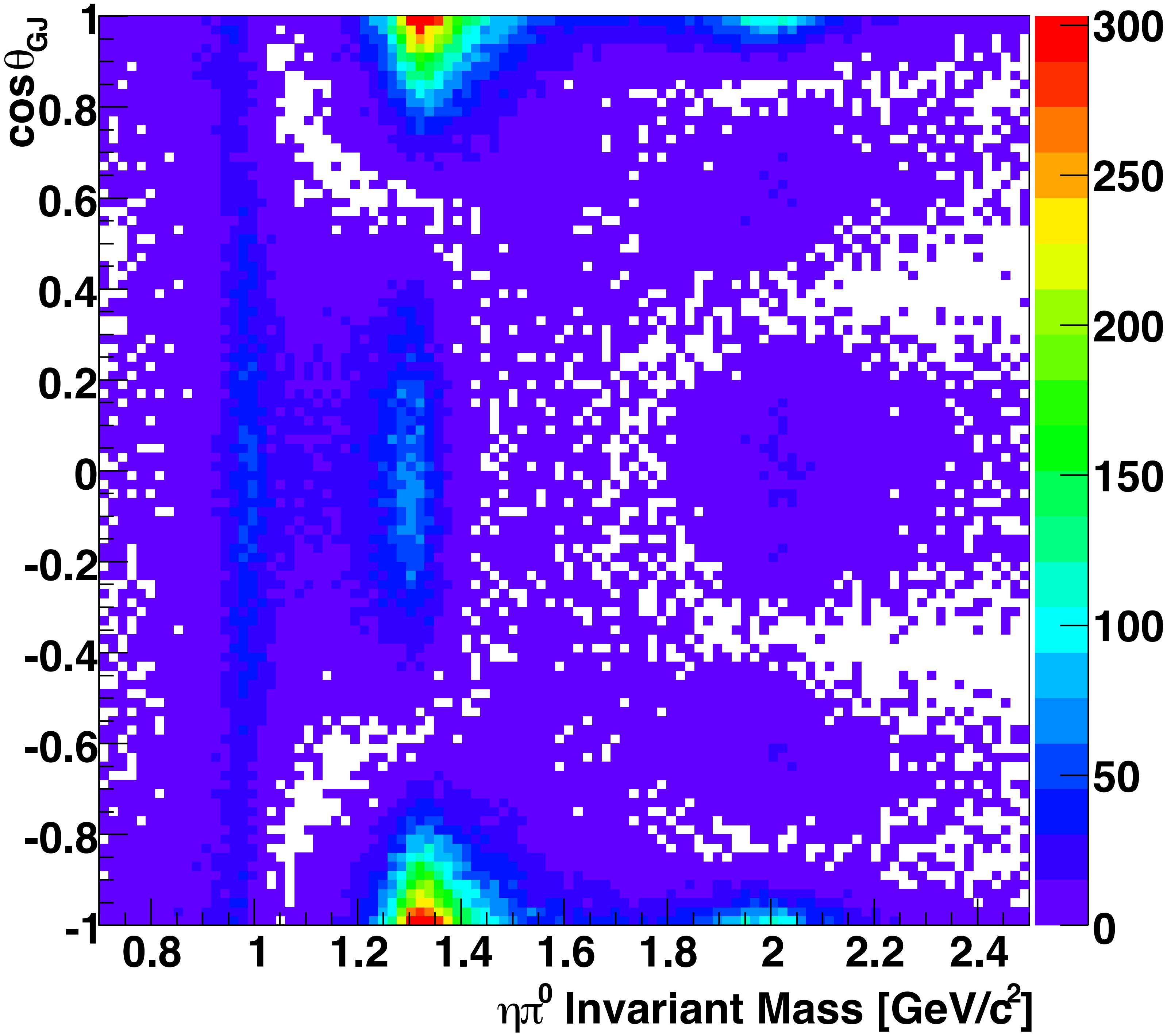
- Experiment:
  - s = [M(ππ)]^2 (real)
  - only sensitive to phase differences through interference



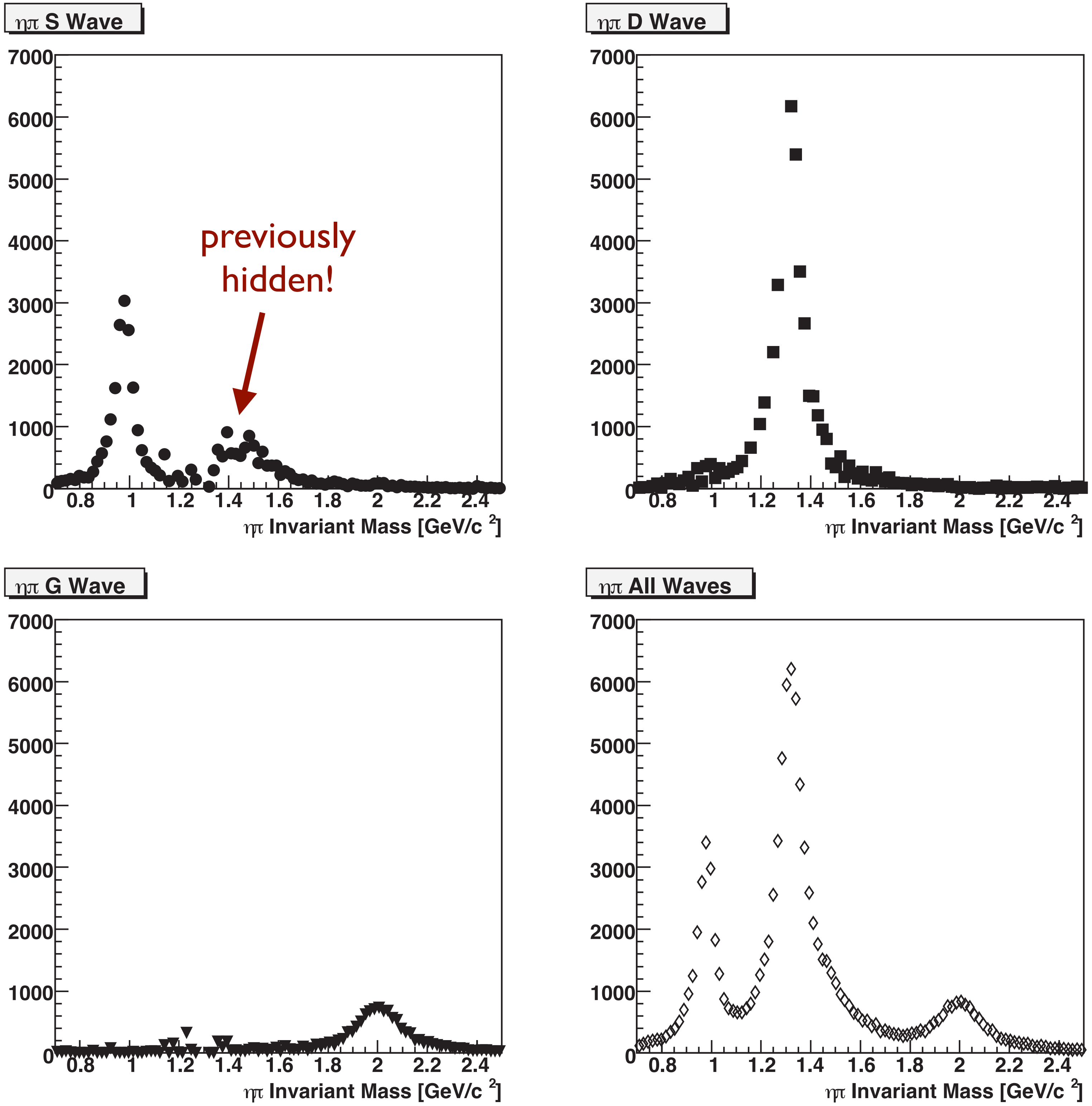
An example with simulated data

- Fake data:
  $\pi p \rightarrow \eta \pi p$
- How many resonances?
- What are their spins?





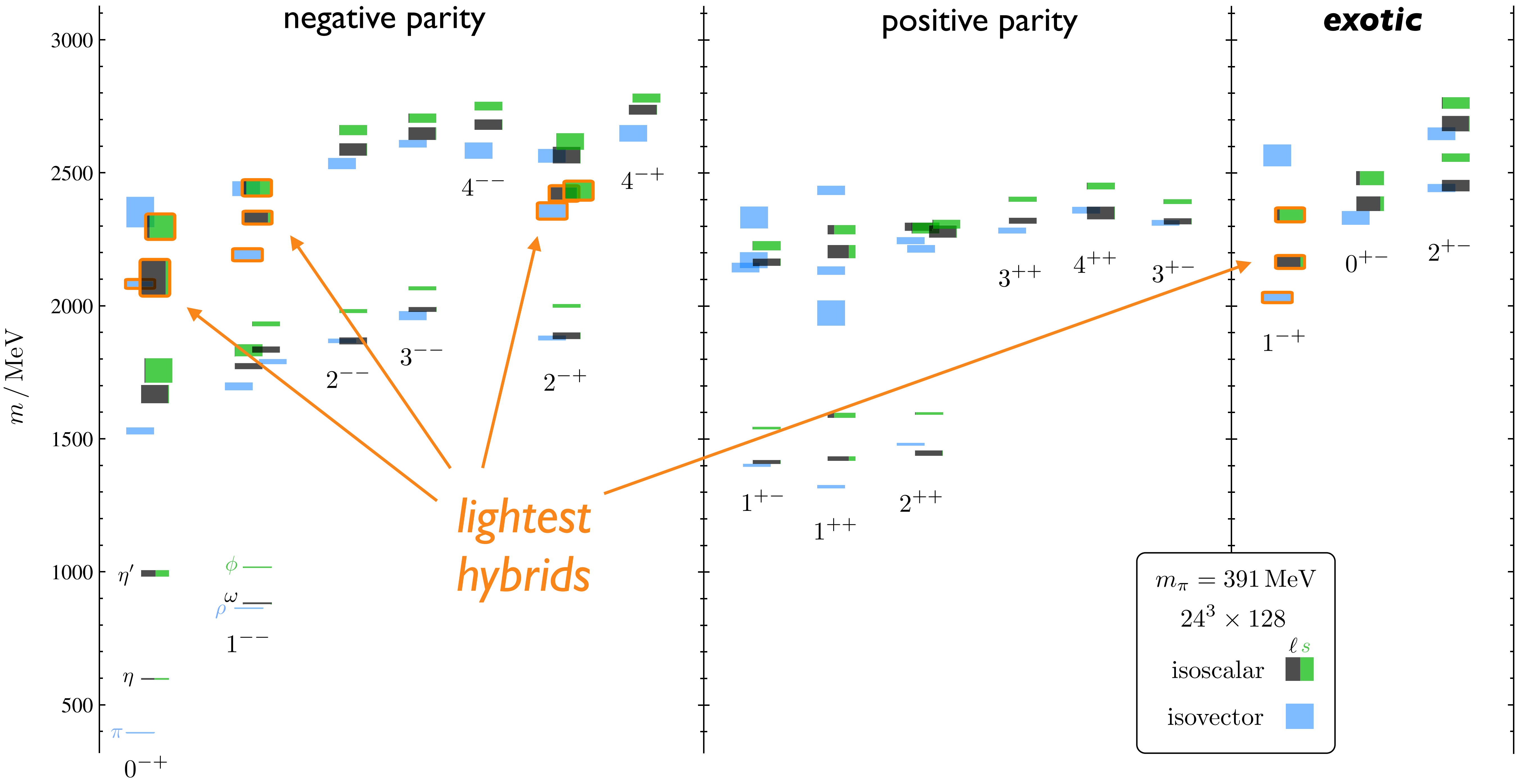
Partial Wave Decomposition



previously hidden!

Meson Spectrum from Lattice QCD

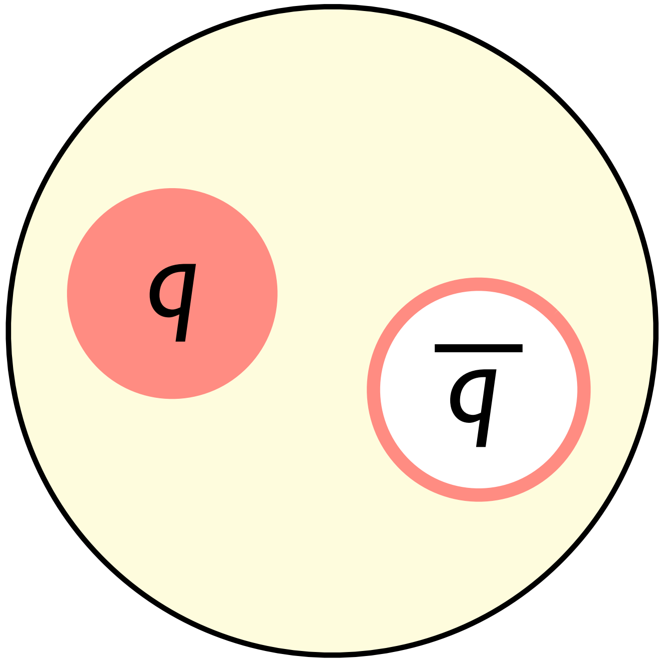
Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)



All states have strangeness = 0

Hybrid Mesons

color singlet
quark anti-quark

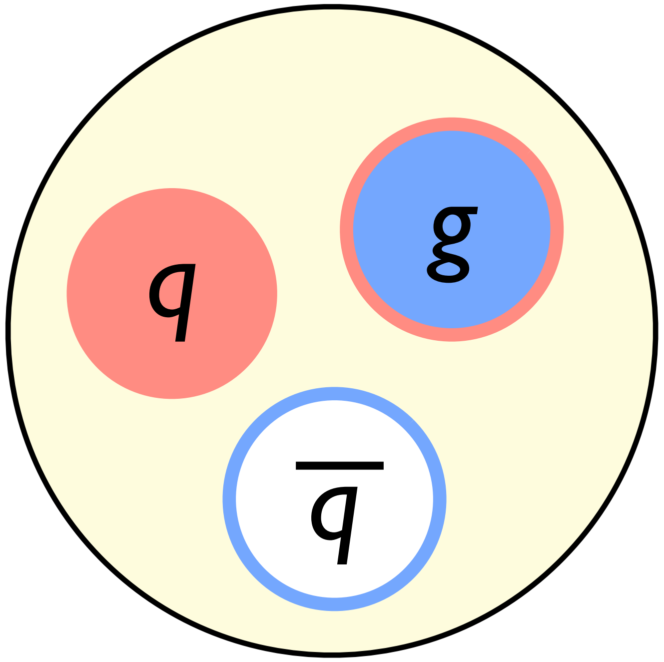


“constituent gluon”

$(J^{PC})_g = 1^{+-}$

mass ≈ 1.0-1.5 GeV

color-octet
$q\bar{q}$ pair



$J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S}$

Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

Forbidden J^{PC}: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

Lightest Hybrids

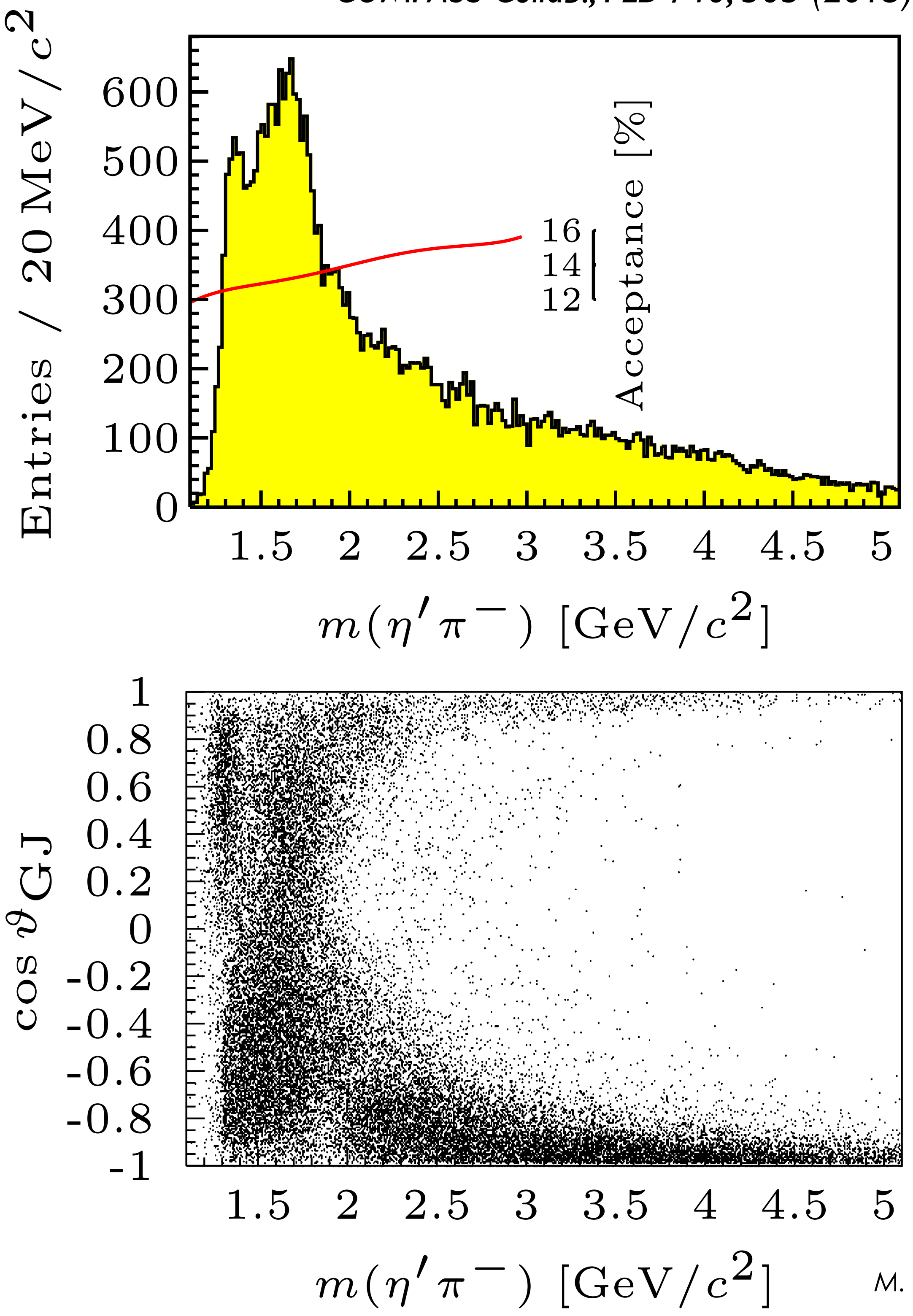
	$S_{q\bar{q}} = 1$	$S_{q\bar{q}} = 0$
J^{PC}:	$0^{-+}, 1^{-+}, 2^{-+}$	1^{--}

“exotic hybrid”

Where to find exotic quantum numbers?

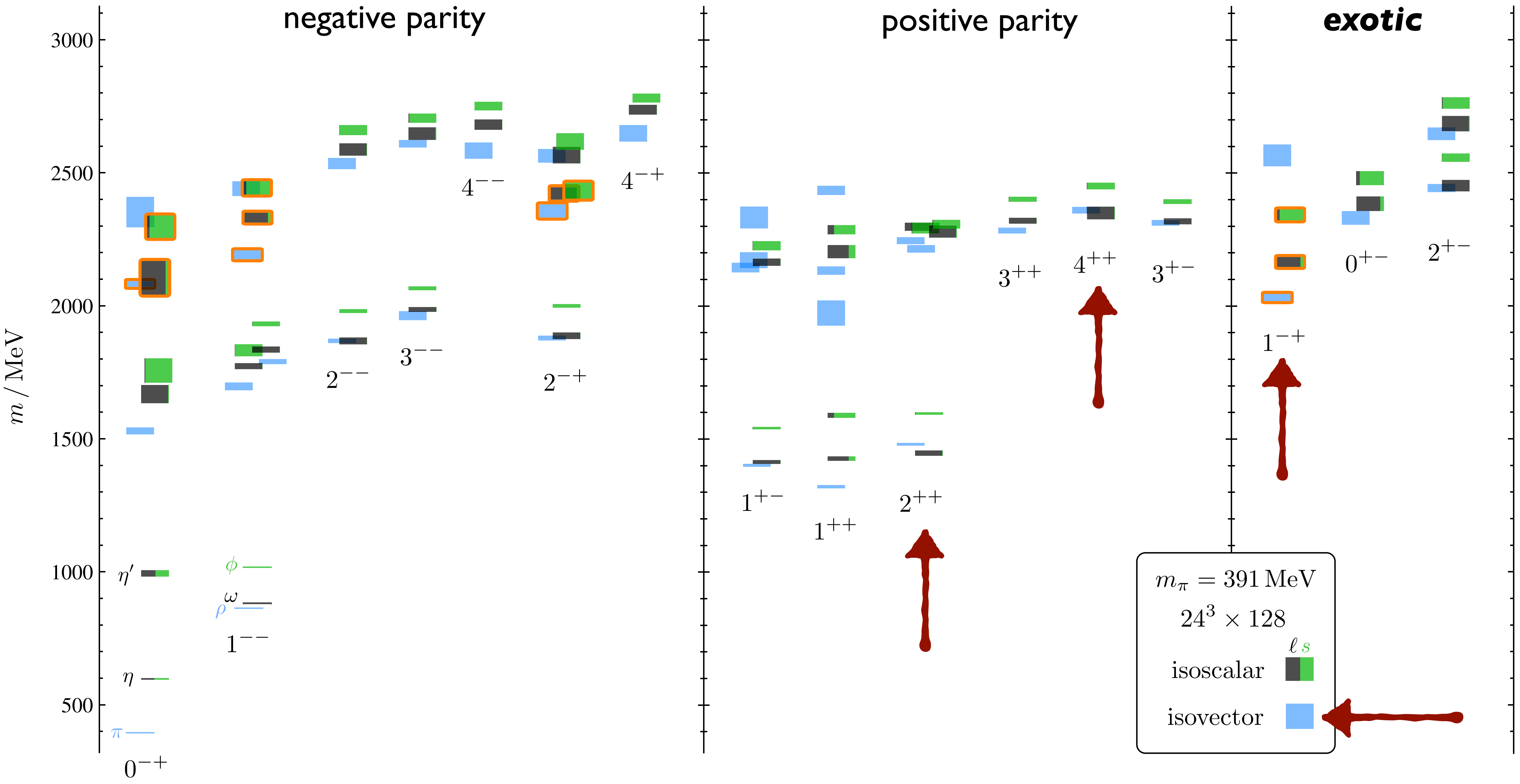
- Production of $\eta^{(\prime)}\pi$ studied by COMPASS using a 190 GeV pion beam: $\pi^- p \to \eta^{(\prime)}\pi^- p$
- consider $X \to \eta\pi^-$ where the two particles have relative orbital angular momentum L -- what are the properties of X?
    - total isospin $= 1$
    - both η and π have $J = 0$ so the spin of X obeys $J = L$
    - both η and π have $P = -$ so the parity of X depends only on L and is negative if L is odd
    - G-parity is $(+)(-) = -$
    - recall $C = G(-1)^I = +$
- For $L = 0,1,2,\ldots$, we have for X $J^{PC} = 0^{++}, 1^{-+}, 2^{++}, \ldots$
    - PDG nomenclature: $a_0, \pi_1, a_2, \ldots$

COMPASS Collab., PLB 740, 303 (2015)

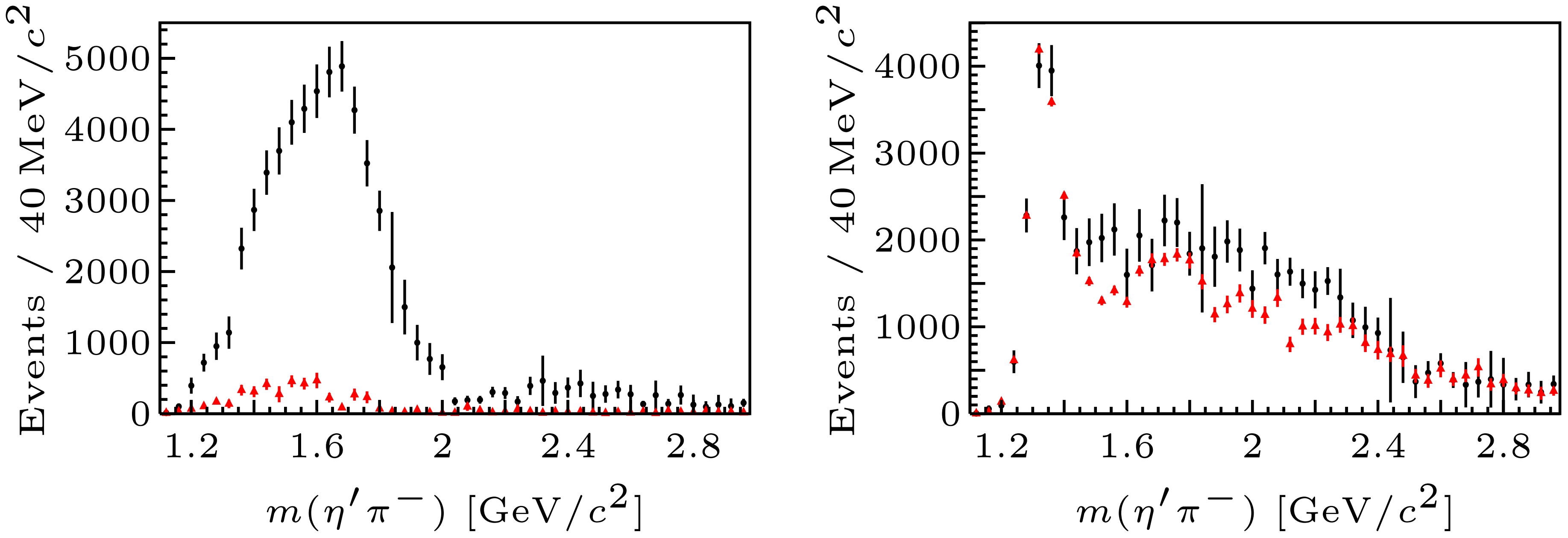


Meson Spectrum from Lattice QCD

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)

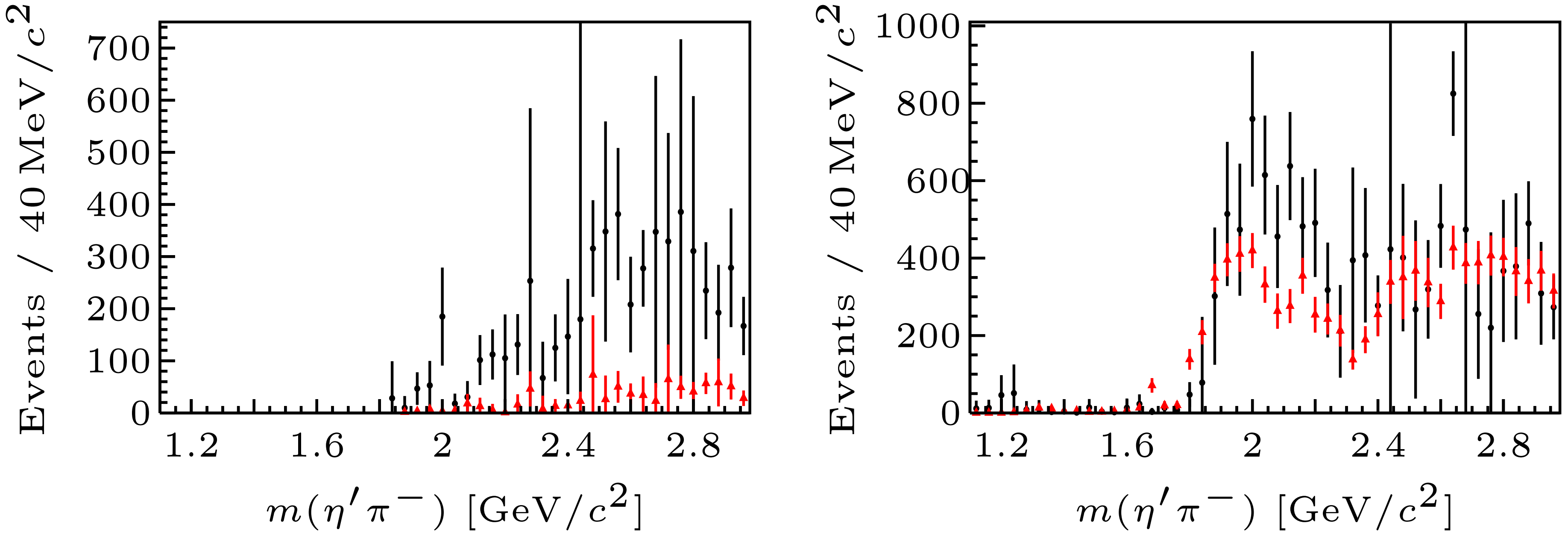


$\pi^- p \to \eta^{(\prime)}\pi^- p$



(a) P-wave, $L = 1$

(b) D-wave, $L = 2$



(c) F-wave, $L = 3$

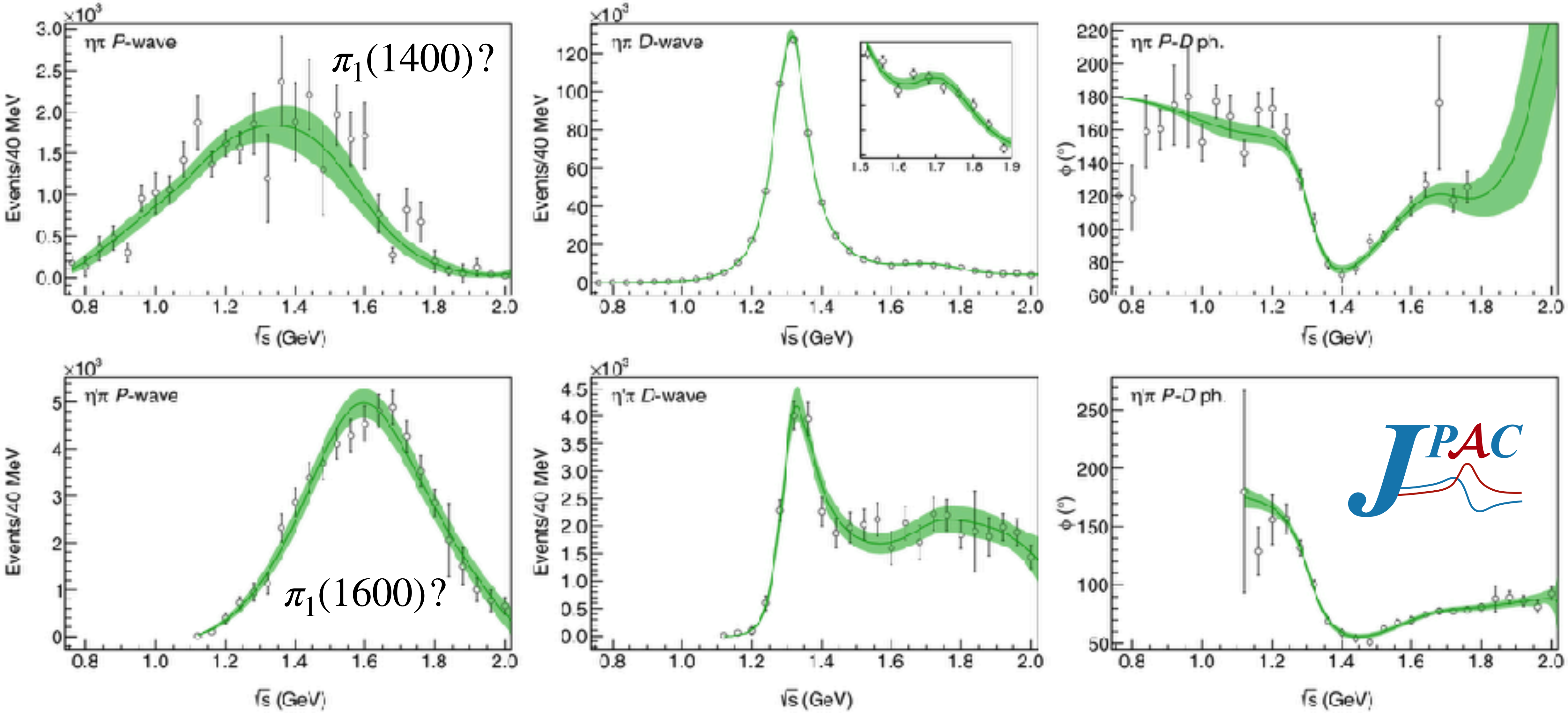
(d) G-wave, $L = 4$

COMPASS Collab., PLB 740, 303 (2015)

Resonances in $\eta^{(\prime)}\pi$

Coupled-channel analysis that enforces unitarity and analyticity of the S matrix.

A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)
[using data from COMPASS Collab., PLB 740, 303 (2015)]



Two π_1 states are reported in the literature (see PDG review),
but only one π_1 pole is needed in the JPAC analysis.
(And only one π_1 is predicted by Lattice QCD.)

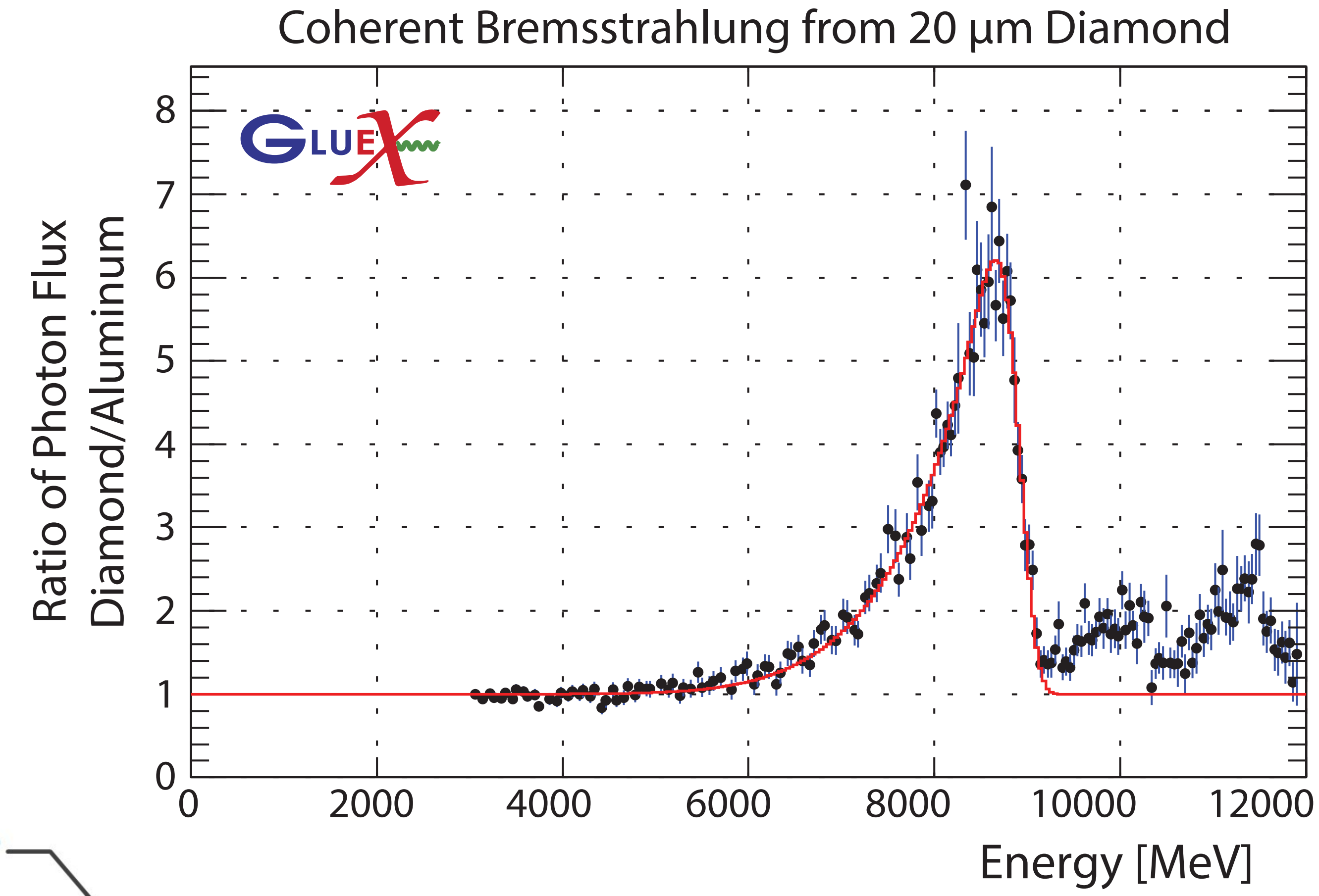
Light Quarks and Looking Forward

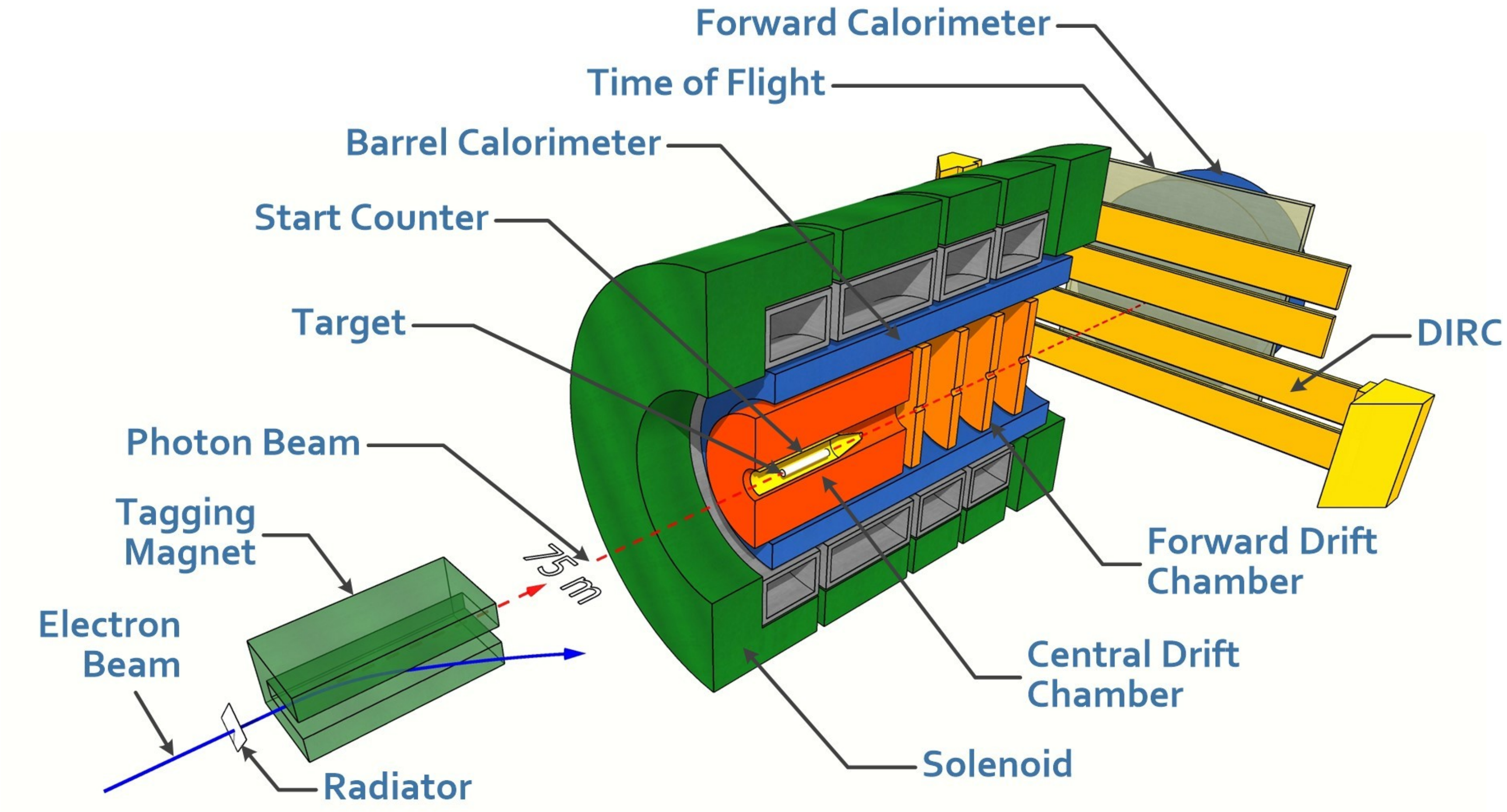
- Precision data has converged with precision theory
  - analysis of high-data benefits from rigorous theoretical constraints
  - emerging picture: experimental data support the existence of a single exotic $J^{PC} = 1^{-+}$ isovector hybrid, the π_1
- Need a spectrum of states to conclusively establish the existence of hybrids (exotic and non-exotic) -- *patterns of resonances are much more important than the idea of a single smoking gun*
- Primary goals of current and future experiments:
  - observing the π_1 in different production modes
  - searching for other states in the hybrid spectrum

Meson Spectroscopy: A Global Approach

	hadron probes		electromagnetic probes	
	completed/analysis	ongoing/future	ongoing/future	completed/analysis
colliding beam	CDF II DØ	ATLAS CMS LHCb	BESIII Belle II	BaBar BELLE
fixed target	COMPASS	panda	GlueX CLAS12	clas CEBAF Large Acceptance Spectrometer

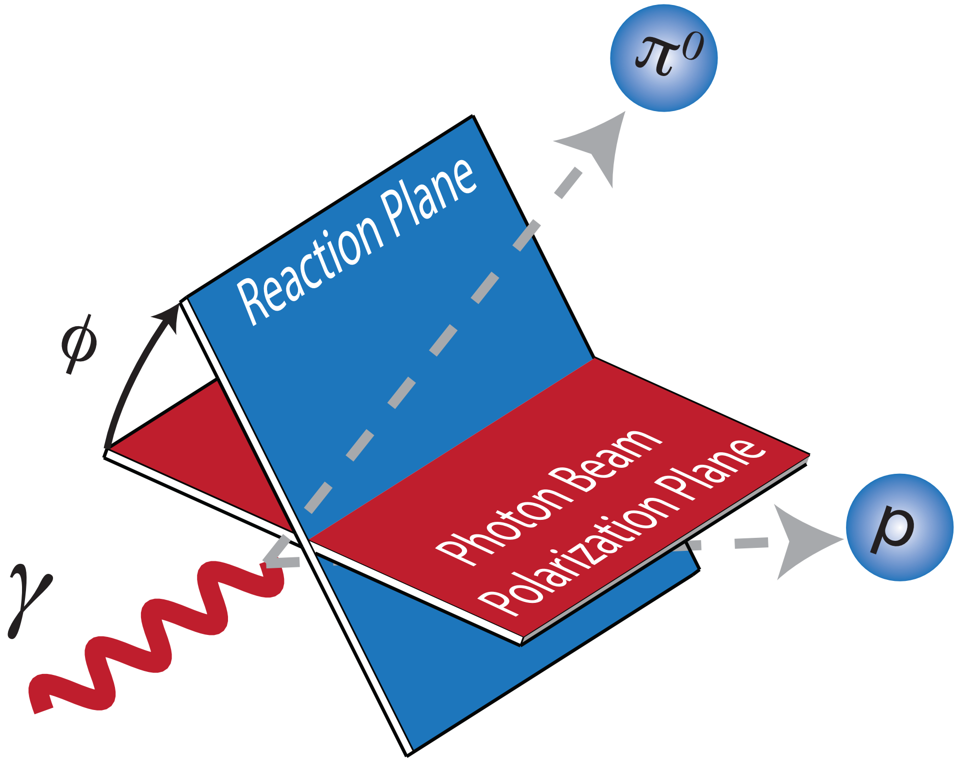
Question from yesterday: why use photons as a beam?

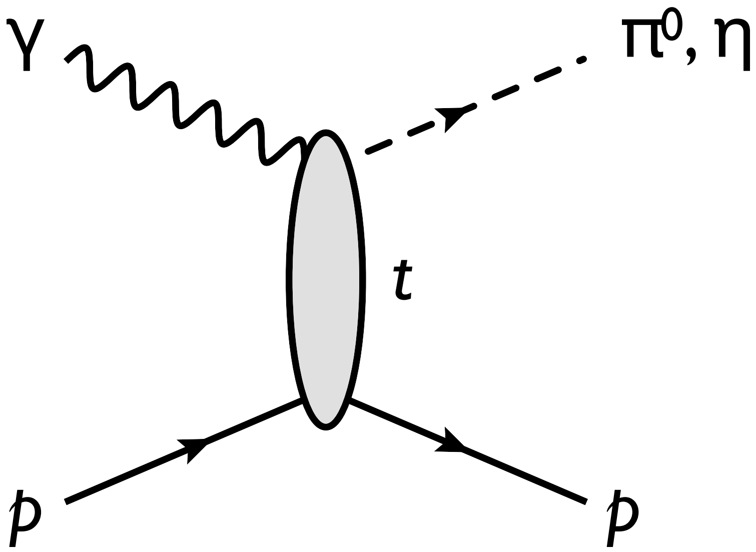




Asymmetry of Pseudoscalar Production

- Angle between beam polarization plane and reaction plane ϕ is sensitive to J^P of exchange
  - $\sigma(\phi) = \sigma_0[1 - P_\gamma \Sigma \cos(2\phi)]$
  - $\Sigma = +1 \implies 0^+, 1^-, 2^+, \ldots$
  - $\Sigma = -1 \implies 0^-, 1^+, 2^-, \ldots$
- Asymmetry Σ depends on a t in general
- Goal: understand and develop models for photoproduction of known mesons
  - learn about available production mechanisms
  - leverage in search for hybrid mesons





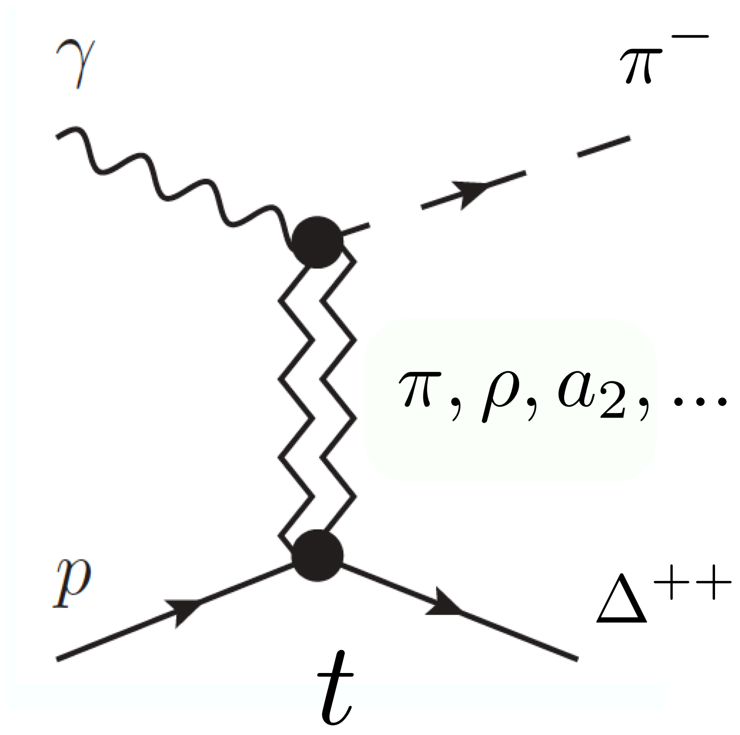
Exchange J^{PC}

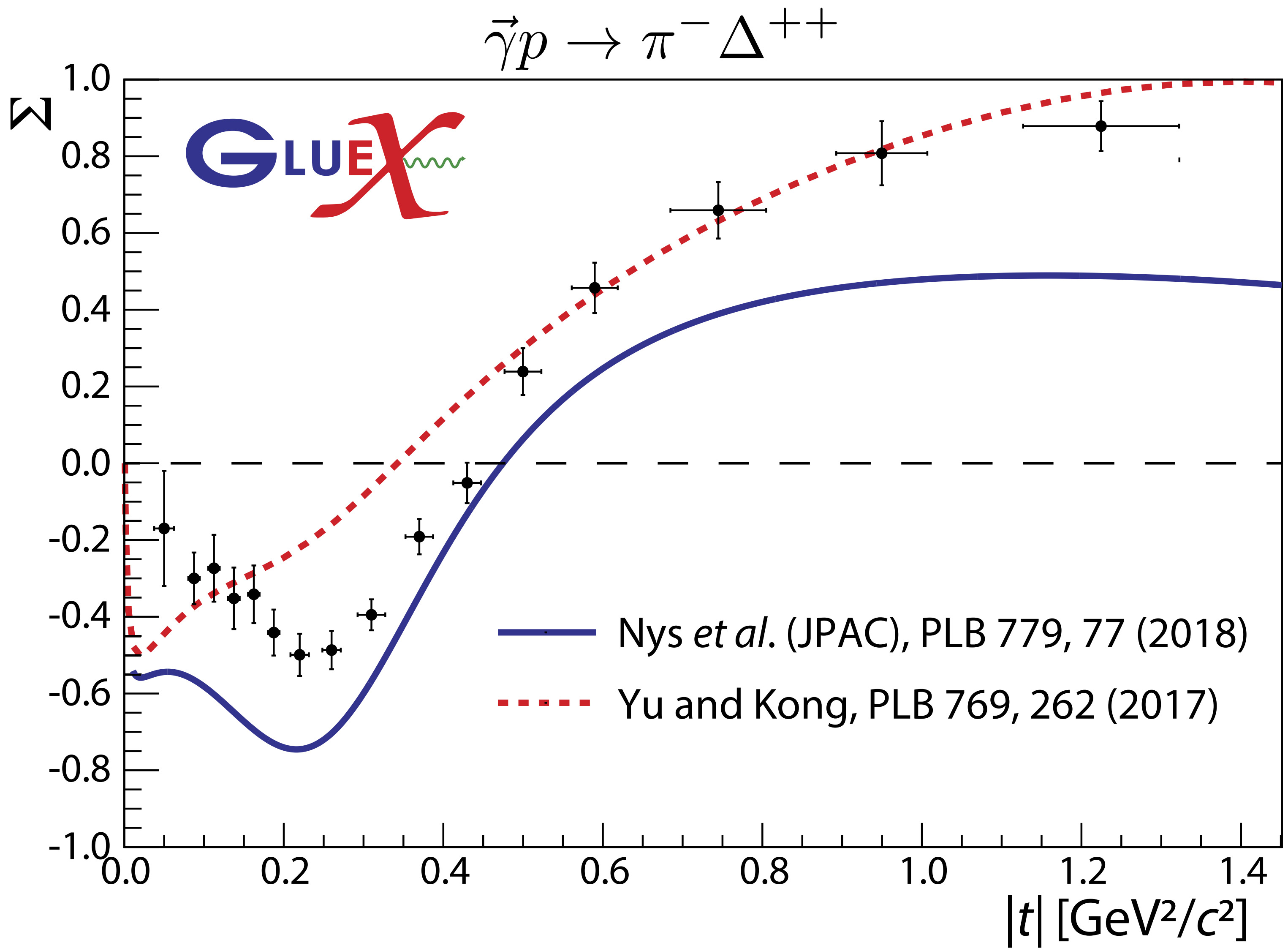
$1^{--}: \ \omega, \rho$

$1^{+-}: \ b, h$

Photoproduction of π⁻

- Charge exchange process
- Dominated by π exchange at low *t* and ρ or a_2 exchange at high *t*





GlueX Collaboration, PRC 103, L022201 (2021)

Final Thoughts

- Overarching goal: understand how the features of QCD leave their imprint on the spectrum of hadrons
- A very active field:
  - 10+ years of new additions to the "particle zoo" with no end in sight
  - tremendous advancement in theoretical techniques for data analysis
- A bright outlook:
  - expect new results from running experiments and future planned experiments
  - continued growth of theory/experiment collaboration on data analysis
  - new advances in lattice QCD enhance our ability to connect experimental results about the hadron spectrum to the fundamental theory of the strong interaction
- An exciting time for graduate students to get involved in the field!