

# Hadron Spectroscopy at GlueX and Beyond (1)

**Justin Stevens**



**WILLIAM & MARY**

CHARTERED 1693

# Preliminaries

- ✱ **Goal:**

- ✱ A self-contained introduction to hadron spectroscopy and an overview of recent excitement in the field

- ✱ **Outline:**

- ✱ **Introduction to QCD and hadron spectroscopy**

- ✱ Why study spectroscopy through QCD?
- ✱ Classification of hadrons
- ✱ Heavy quark spectroscopy: “The XYZ story”
- ✱ Light quark spectroscopy (tomorrow)

# Standard Model

Coupling Strength:

$10^{-6}$

$1/137$

1



Generation

1

2

3

Up <b>u</b>	Charm <b>c</b>	Top <b>t</b>
Down <b>d</b>	Strange <b>s</b>	Bottom <b>b</b>
Electron <b>e</b>	Muon <b>μ</b>	Tau <b>τ</b>
e-Neutrino <b>ν<sub>e</sub></b>	μ-Neutrino <b>ν<sub>μ</sub></b>	τ-Neutrino <b>ν<sub>τ</sub></b>

Quarks

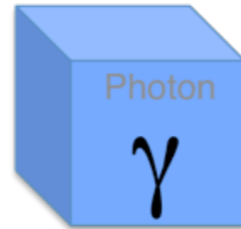
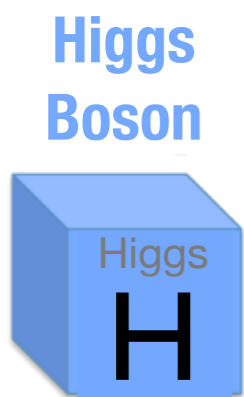
Leptons

All Particles

Charged Particles

Just Quarks

Increasing Mass



Force Carriers

Spin 1

Spin 1/2

# Standard Model

**Coupling Strength:**

$10^{-6}$

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**1**



Generation

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Quarks

Electron <b>e</b>	Muon $\mu$	Tau $\tau$
e-Neutrino $\nu_e$	$\mu$ -Neutrino $\nu_\mu$	$\tau$ -Neutrino $\nu_\tau$

Leptons

Increasing Mass

All Particles

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Higgs Boson



Force Carriers



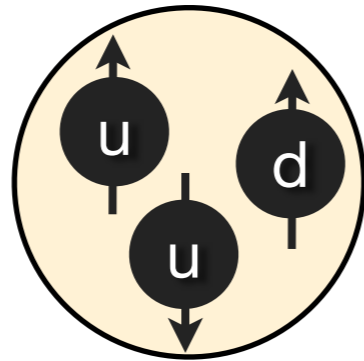
**Spin 1**

**Spin 1/2**

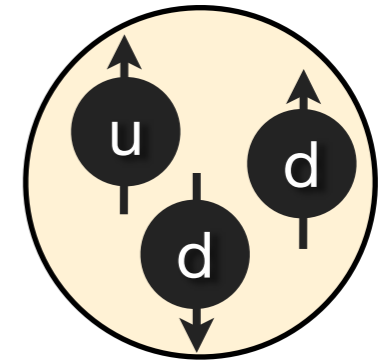
# Quarks and hadrons

- \* Proposed to explain proton structure and properties of other states observed at the time

*proton* =  $|uud\rangle$   
 $J = 1/2$



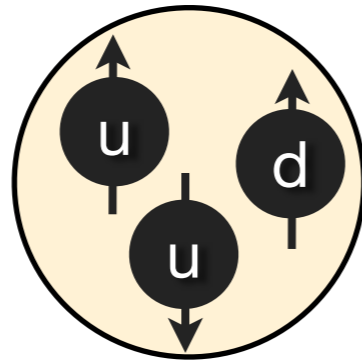
*neutron* =  $|udd\rangle$   
 $J = 1/2$



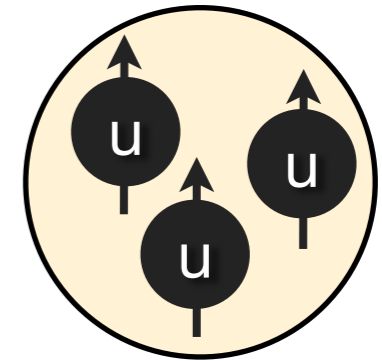
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$$\Delta^{++} = |uuu\rangle$$
$$J = 3/2$$

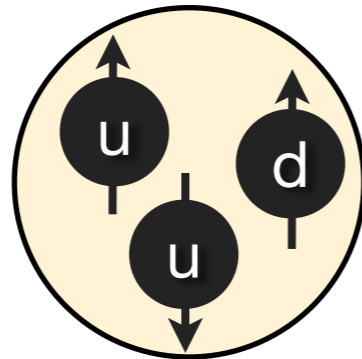


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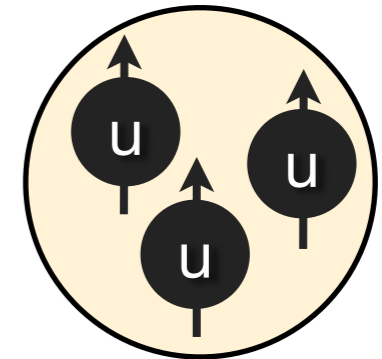
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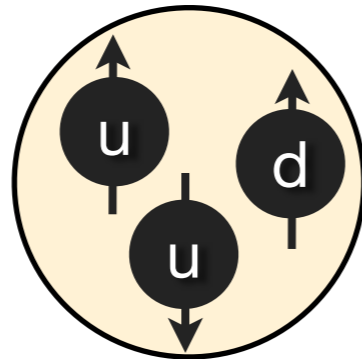
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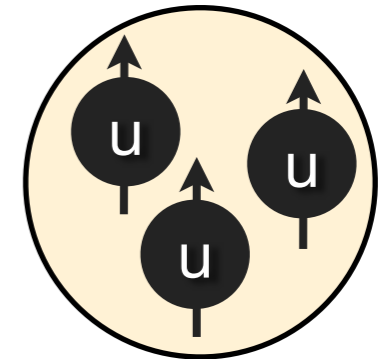
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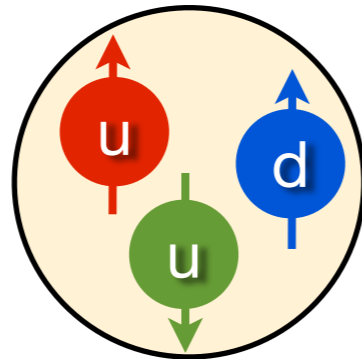
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$$\psi(\Delta^{++}) = \psi(r) \cdot \psi_{\text{spin}}(J) \cdot \psi_{\text{flavour}} \cdot \psi_{\text{colour}}$$

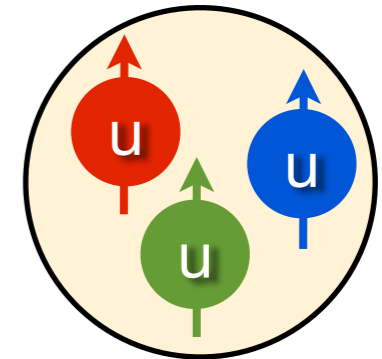
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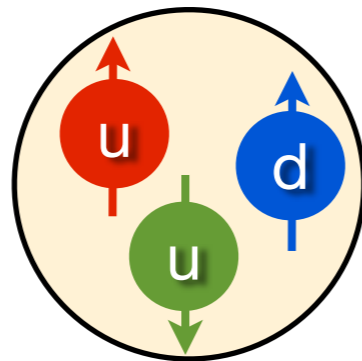
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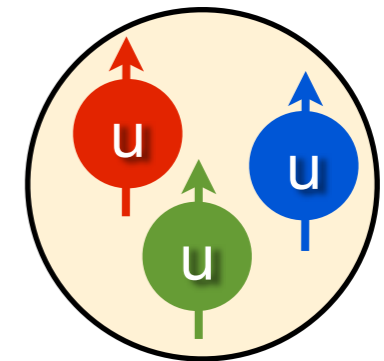
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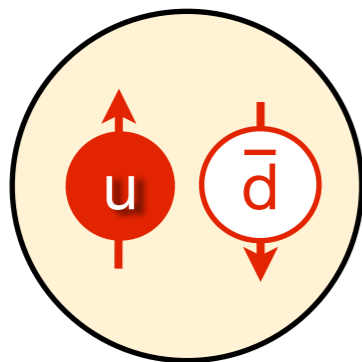


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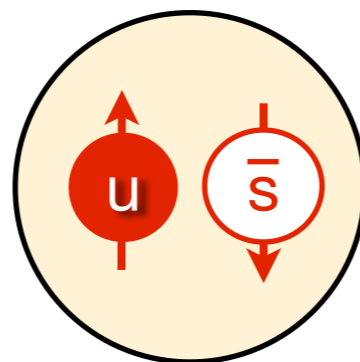
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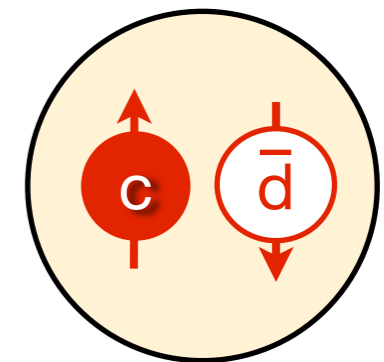
- \* Color charge analogous to electric charge: atoms are electrically neutral and hadrons are color neutral (or color singlets)
- \* And other quark flavors such as **strange** and **charm**



$$\pi^+ = |ud\bar{\phantom{d}}\rangle$$



$$K^+ = |us\bar{\phantom{s}}\rangle$$

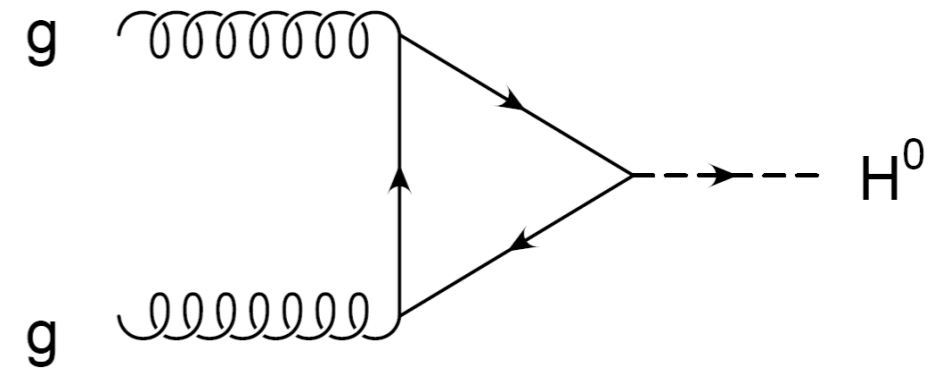


$$D^+ = |cd\bar{\phantom{d}}\rangle$$

# Color interactions in QCD

- \* **High energy (short distance) limit**

- \* Interactions are weak: quarks are “asymptotically free”
- \* QCD is calculable using perturbation theory, e.g. Higgs production at LHC



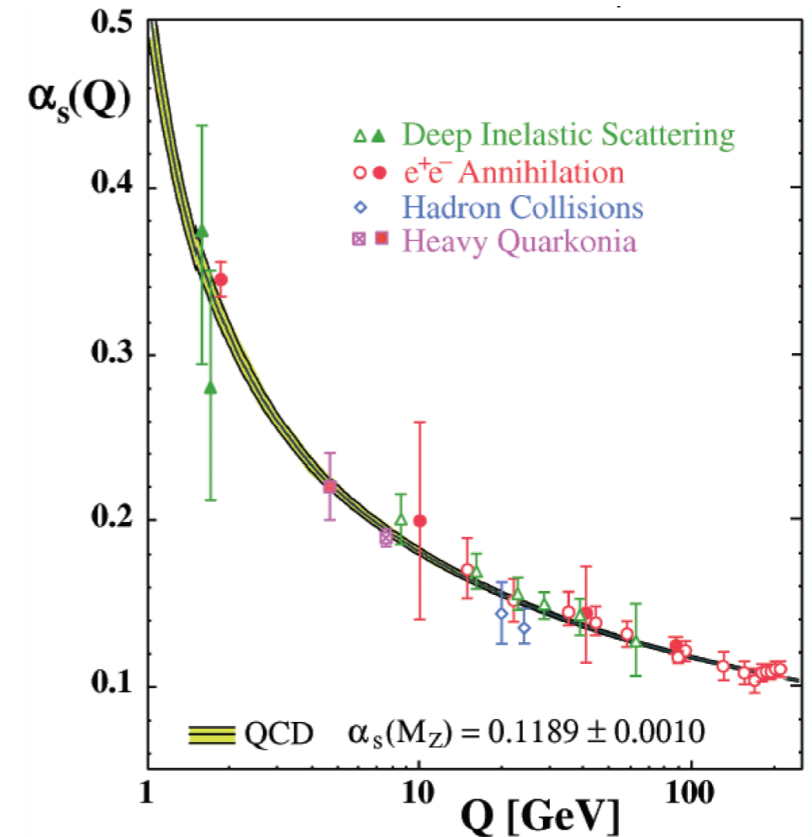
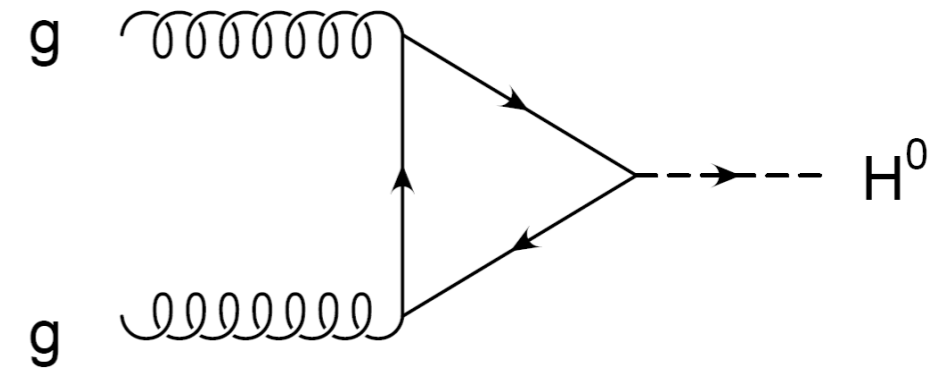
# Color interactions in QCD

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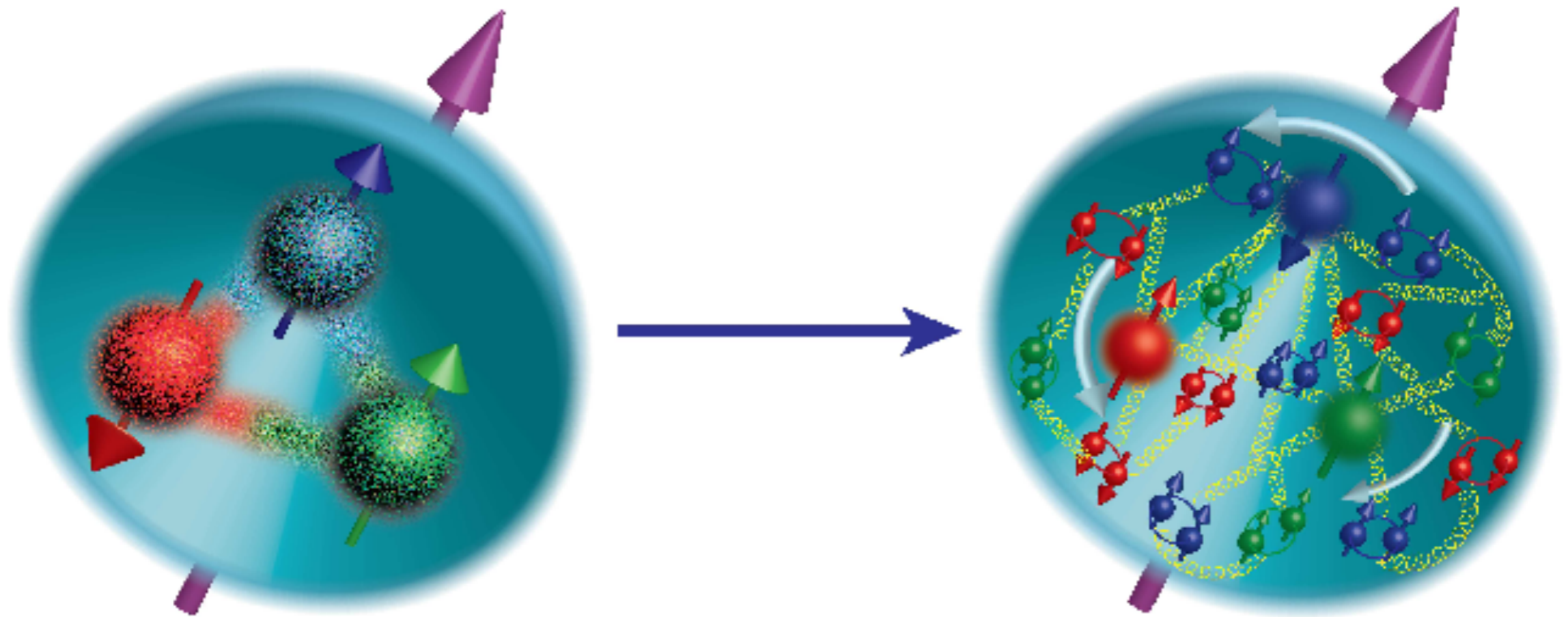
- \* Interactions are weak: quarks are “asymptotically free”
- \* QCD is calculable using perturbation theory, e.g. Higgs production at LHC

## \* Low energy (long distance) limit

- \* Interactions are strong and increase with distance, so quarks are **confined**
- \* QCD is **not** calculable perturbatively, but recent, dramatic progress in lattice QCD
- \* Opportunity to study QCD in strongly coupled bound states, *i.e.* hadrons



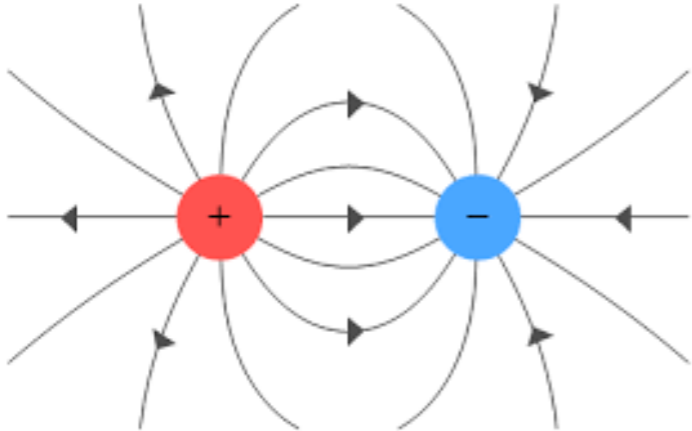
# Aside: what about nucleon structure?



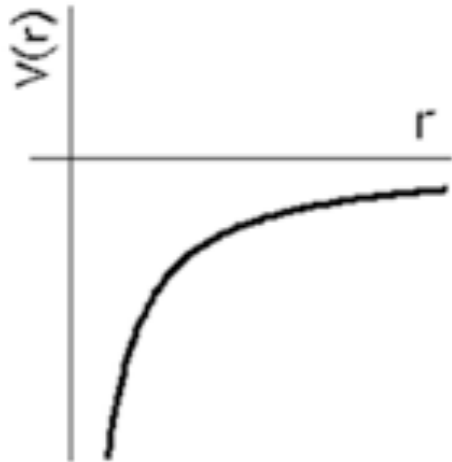
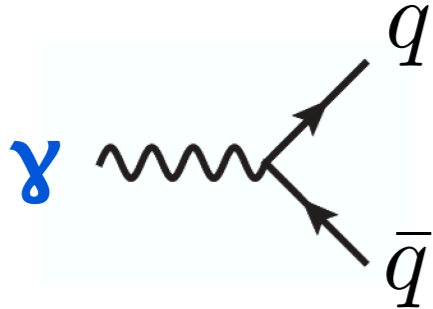
**See DIS lectures from  
Ming Li (yesterday)**

# Comparing E&M and QCD

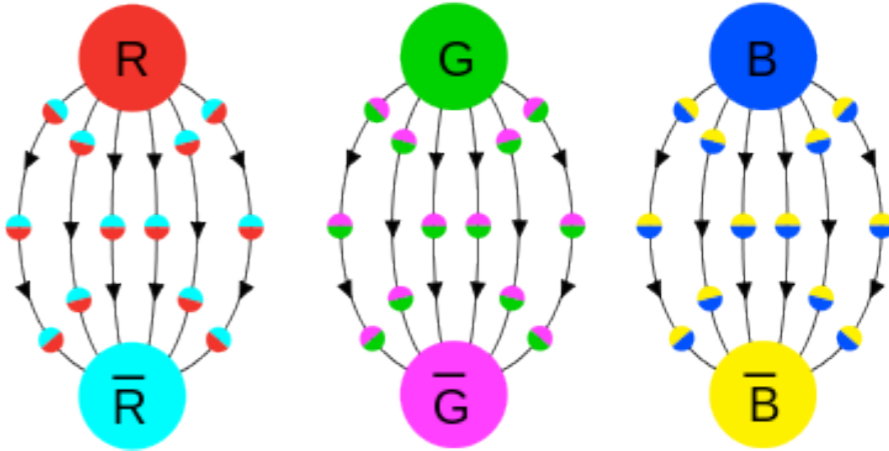
## E&M



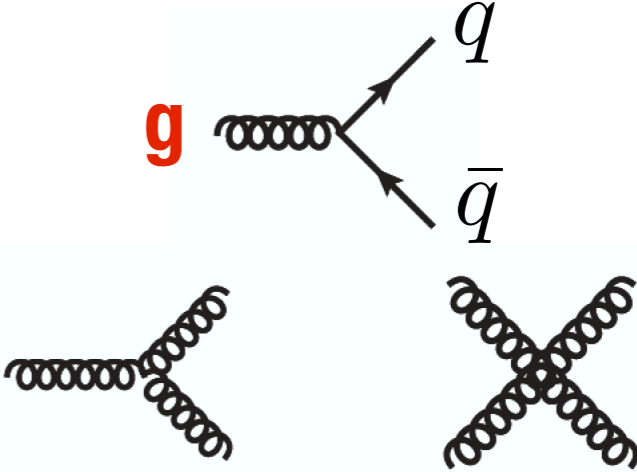
Photons (gluons) mediate forces between electric (color) charges



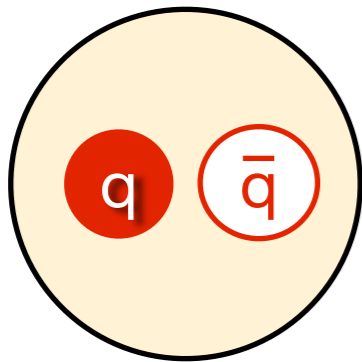
## QCD



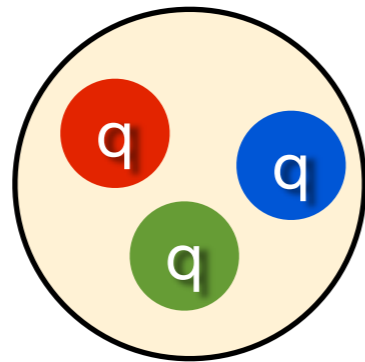
Gluon self-interaction produces a potential that grows  $\sim$ linearly with distance



# Confined states of quarks and gluons



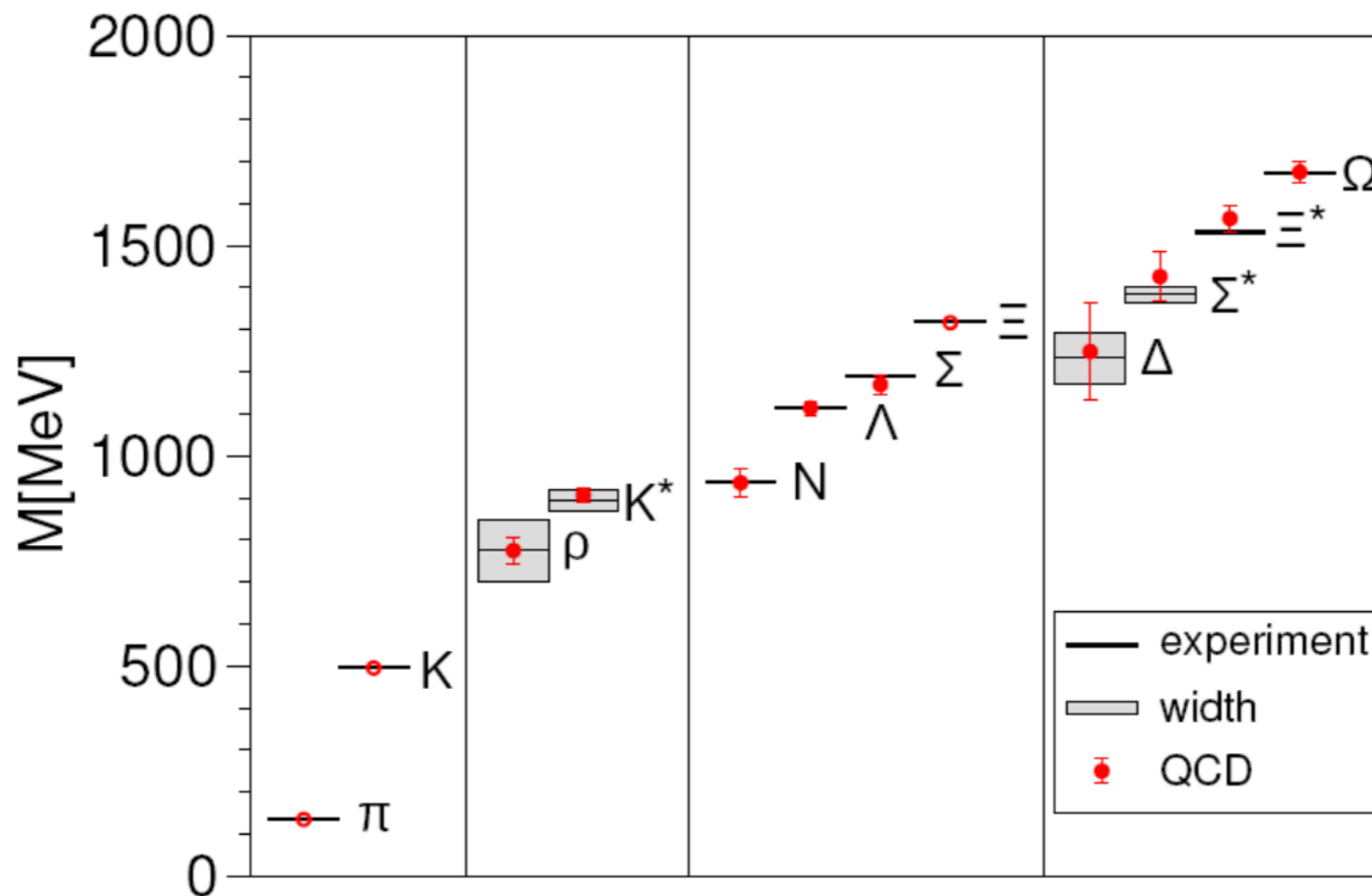
mesons



baryons

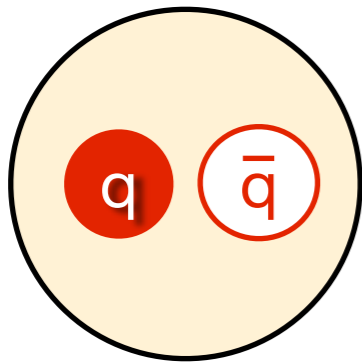
Observed mesons and baryons well described by 1<sup>st</sup> principles QCD

But these aren't the only states permitted by QCD

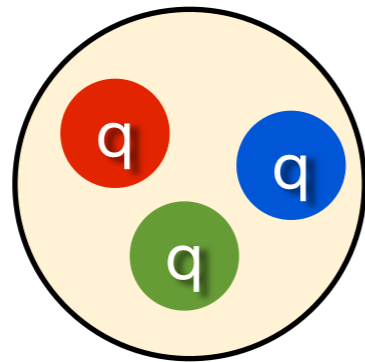


**Lattice QCD: Science (2008)**

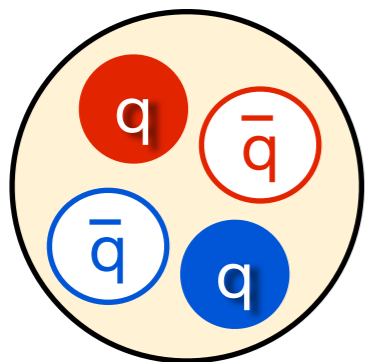
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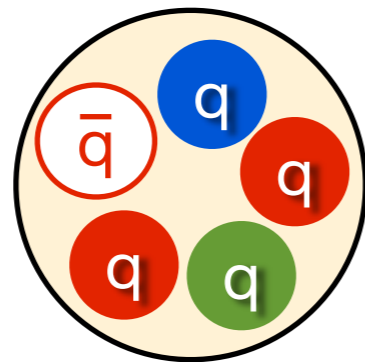
mesons



baryons



tetraquark



pentaquark

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A SCHEMATIC MODEL OF BARYONS AND MESONS \*

M. GELL-MANN

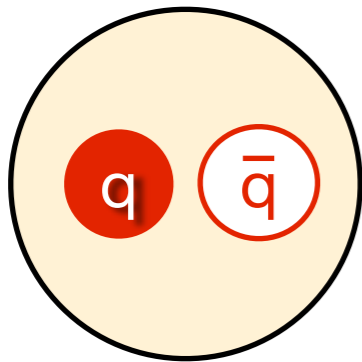
*California Institute of Technology, Pasadena, California*

... Baryons can now be constructed from quarks by using the combinations  $(qqq)$ ,  $(qqqq\bar{q})$ , etc., while mesons are made out of  $(q\bar{q})$ ,  $(qq\bar{q}\bar{q})$ , etc. ...

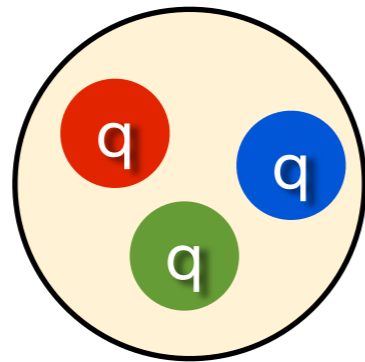
[Phys. Lett. 8 \(1964\) 214](#)



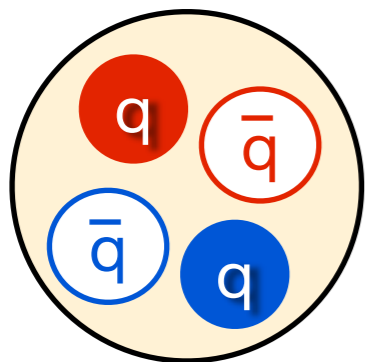
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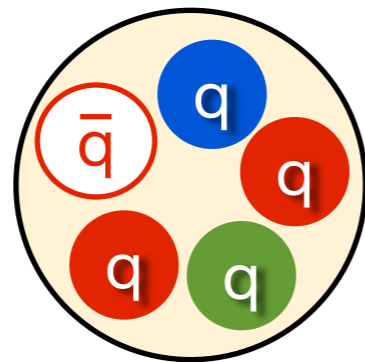
mesons



baryons



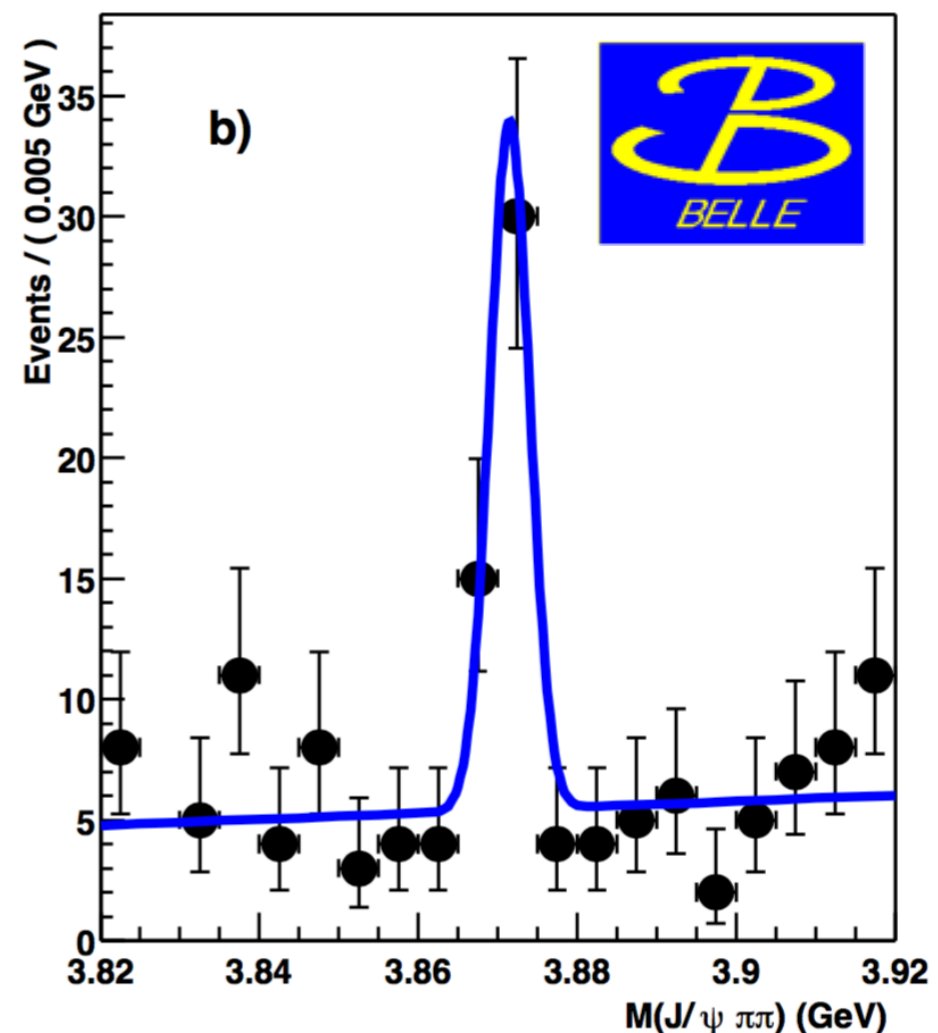
tetraquark



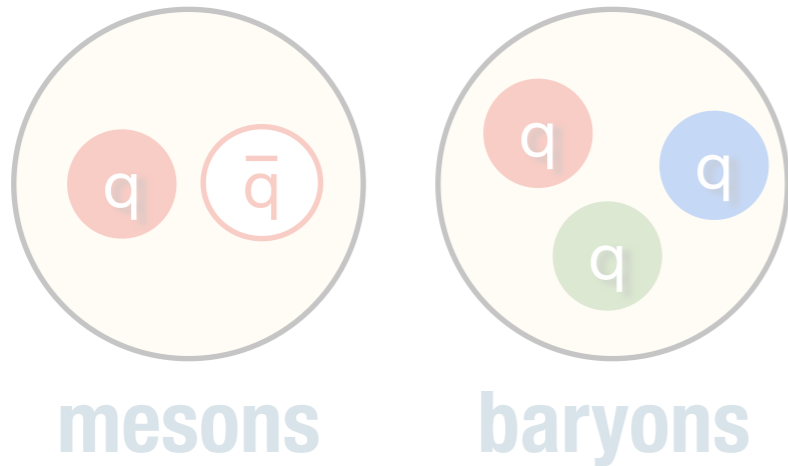
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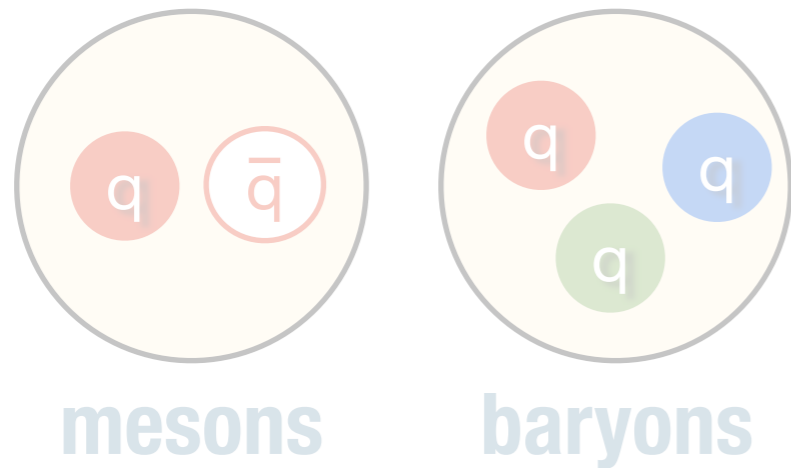
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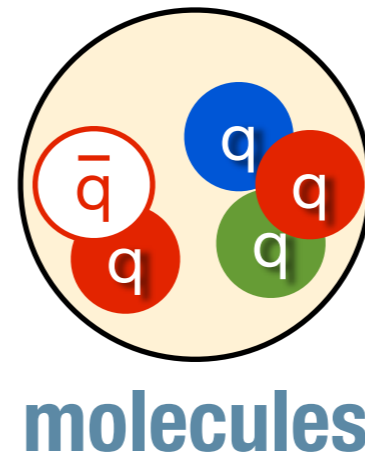
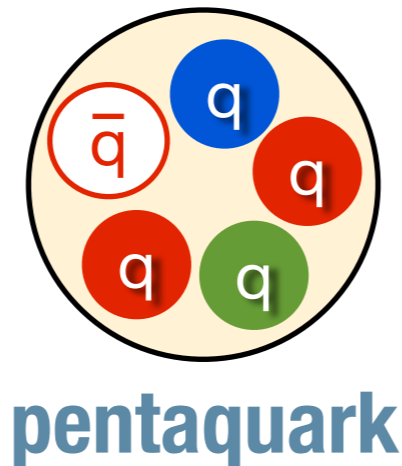
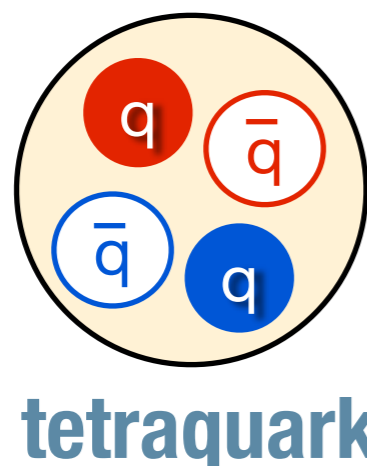
- \* Definition of **exotic hadron**: hadron not described by quark model
  - Extra (supernumerary) states in the spectrum: **X and Y**

# Confined states of quarks and gluons

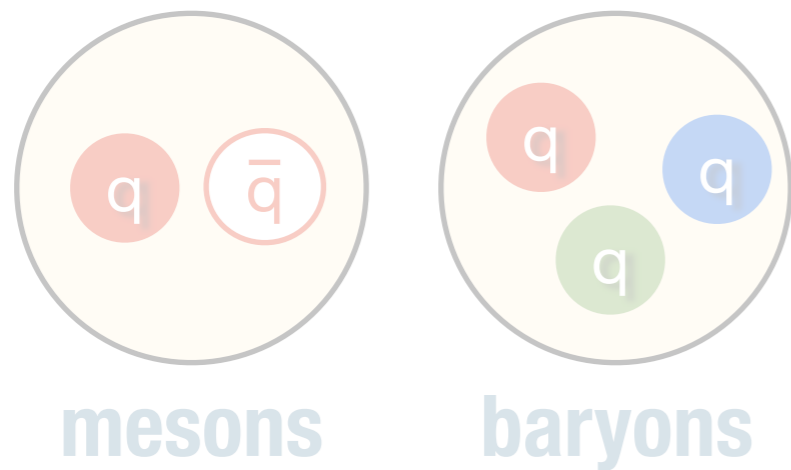


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  - Extra (supernumerary) states in the spectrum: **X and Y**
  - 4 or 5 quark states (charged with hidden charm): **Z and P<sub>c</sub>**

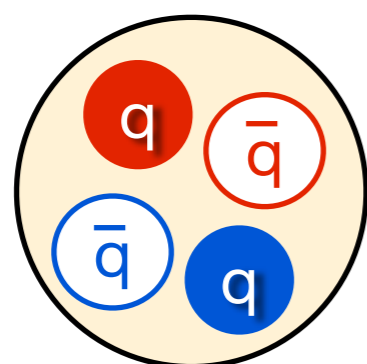


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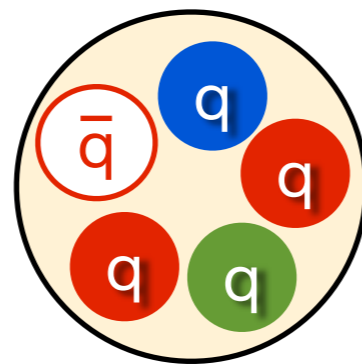


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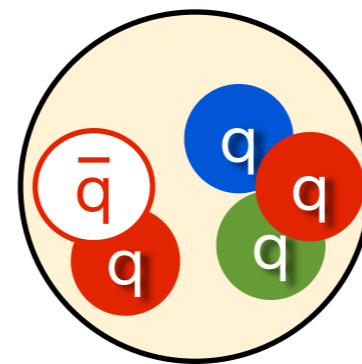
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  - Quantum numbers not allowed by  $q\bar{q}$ : **hybrid mesons**



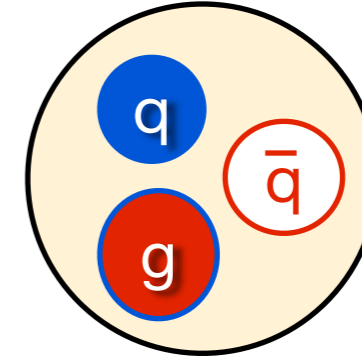
**tetraquark**



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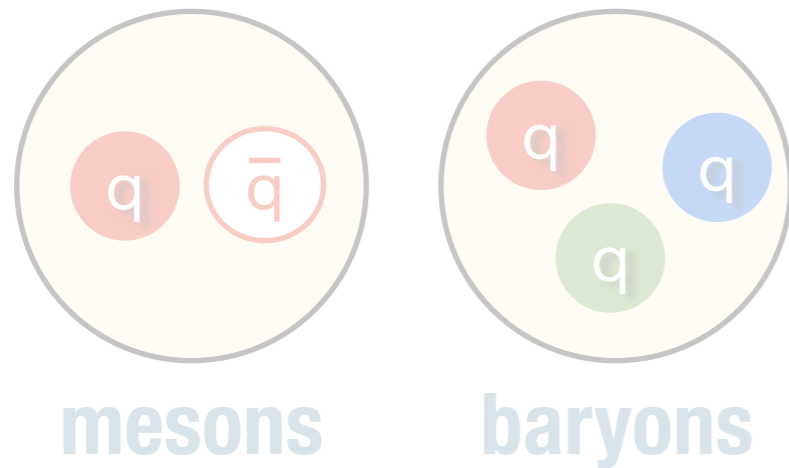


**molecules**



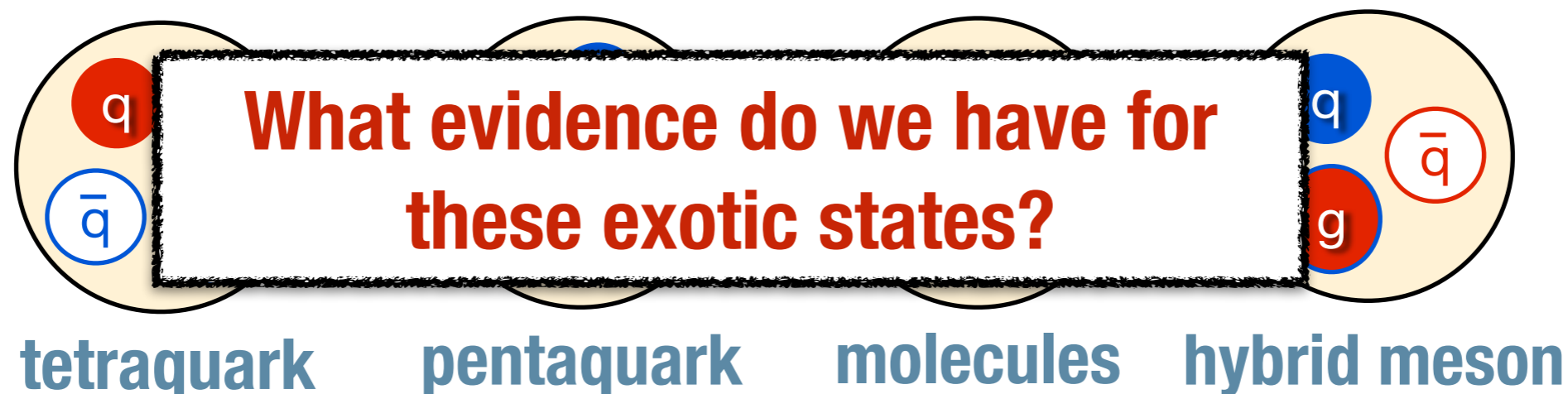
**hybrid meson**

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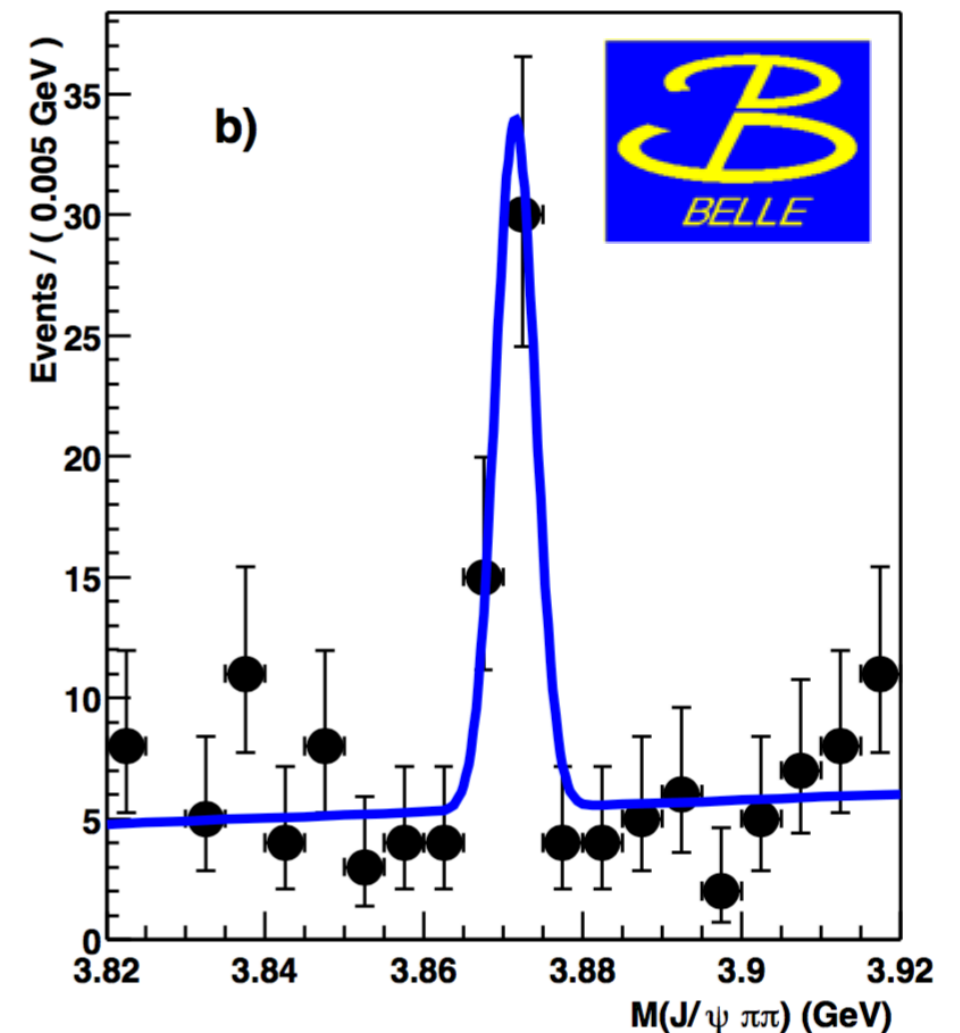
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# Experimental strategy

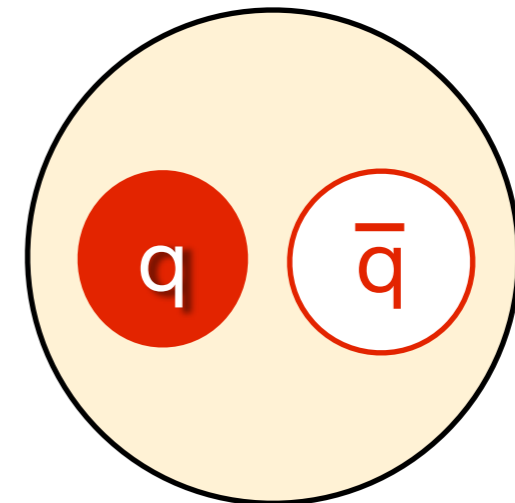
- \* **Search for new particles**
- \* Bumps in mass spectra
- \* Unique decay distributions
- \* **Next measure:**
  - \* mass and width
  - \* decay modes
  - \* quantum numbers:  $J^{PC}$
- \* Identify **patterns** and compare with QCD and models

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



# Classifying mesons

- \* General properties: mass, electric charge, quark flavor
- \* Grouped by quantum numbers in the “Quark Model”:  $J^{PC}$



- \* Angular momentum:  $\vec{J} = \vec{L} + \vec{S}$

- \* Parity: Invert spatial coordinates

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

- \* Charge conj.: particle  $\leftrightarrow$  antiparticle

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

**What combination of quantum numbers  $J^{PC}$  are allowed for these mesons?**

# Exercise #1: Particle Data Group

## Quark Model

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

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

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

### LIGHT UNFLAVORED MESONS ( $S = C = B = 0$ )

For  $I = 1$  ( $\pi, \rho, a$ ):  $u\bar{d}, (u\bar{u} - d\bar{d})/\sqrt{2}, d\bar{u}$ ;  
for  $I = 0$  ( $\eta, \eta', h, h', \omega, \phi, f, f'$ ):  $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

Form Factors for Semileptonic Kaon ( $K_{\ell 3}$ ), Radiative Pion ( $\pi_{\ell 2\gamma}$ ) and Kaon ( $K_{\ell 2\gamma}$ ) Decays [PDF](#)

Scalar Mesons below 1 GeV [PDF](#)

Spectroscopy of Light Meson Resonances [PDF](#)

• $\pi^\pm$	$1^-(0^-)$	• $\rho_3(1690)$	$1^+(3^{--})$
• $\pi^0$	$1^-(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\eta$	$0^+(0^{++})$	• $a_2(1700)$	$1^-(2^{++})$
• $f_0(500)$	$0^+(0^{++})$	$a_0(1710)$	$1^-(0^{++})$
aka $\sigma$ ; was $f_0(600), f_0(400 - 1200)$		• $f_0(1710)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$	$X(1750)$	$?^-(1^{--})$
• $\omega(782)$	$0^-(1^{--})$	$\eta(1760)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{++})$	$f_0(1770)$	$0^+(0^{++})$

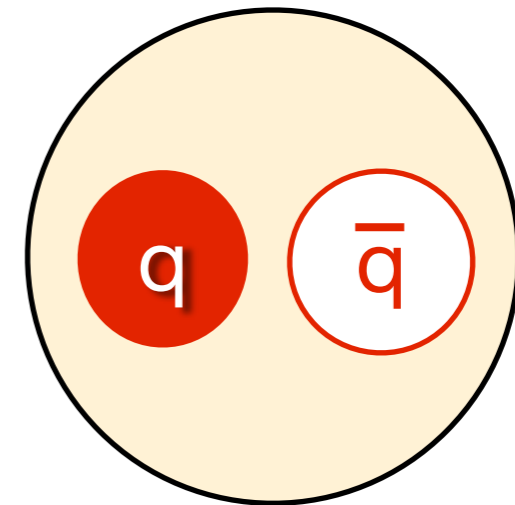
- \* Find one example of each allowed quantum number
- \* Are there also exotic ones?

<https://pdg.lbl.gov/>

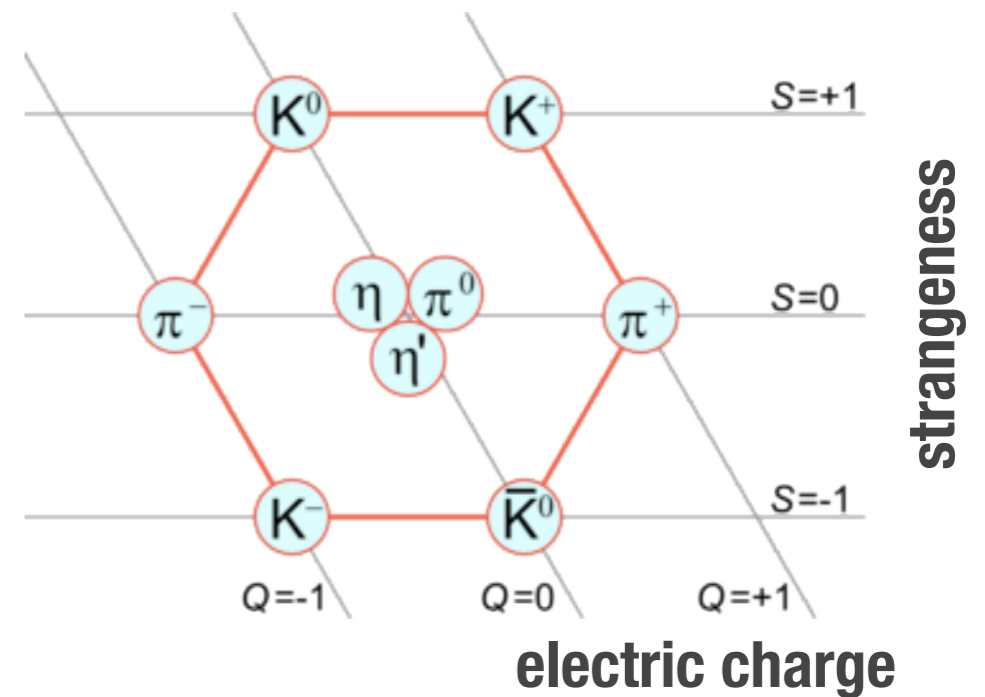
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$$P = (-1)^{L+1}$$
  - \* Charge conj.: particle  $\leftrightarrow$  antiparticle
 
$$C = (-1)^{L+S}$$
- \* Allowed  $J^{PC}$  for  $q\bar{q}$  mesons:

$$J^{PC} = \boxed{0^{-+}}, 1^{--}, 1^{+-}, 0^{++}, 2^{++} \dots$$



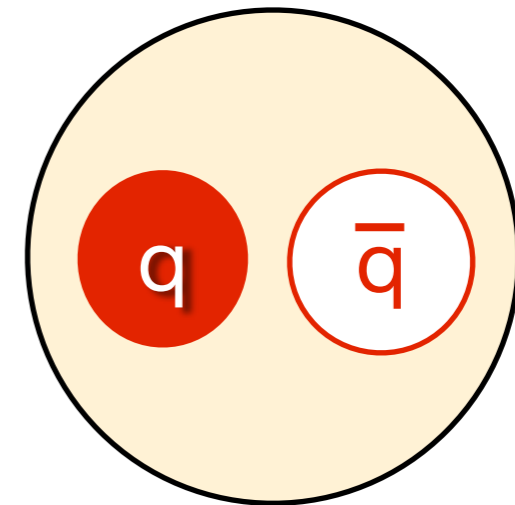
## Spin 0



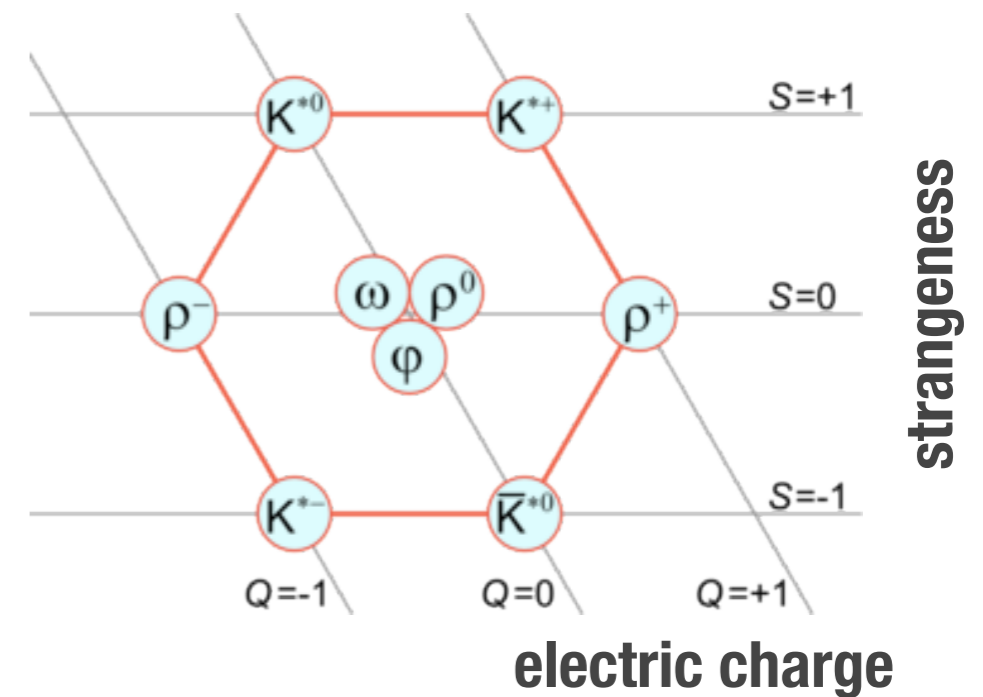
# Classifying mesons

- \* General properties: mass, electric charge, quark flavor
- \* Grouped by quantum numbers:  $J^{PC}$ 
  - \* Angular momentum:  $\vec{J} = \vec{L} + \vec{S}$
  - \* Parity: Invert spatial coordinates
 
$$P = (-1)^{L+1}$$
  - \* Charge conj.: particle  $\leftrightarrow$  antiparticle
 
$$C = (-1)^{L+S}$$
- \* Allowed  $J^{PC}$  for  $q\bar{q}$  mesons:

$$J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 2^{++} \dots$$

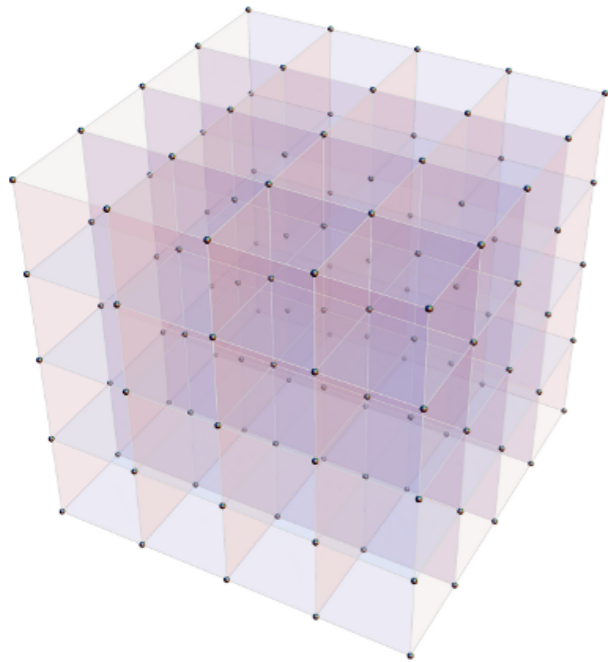


## Spin 1

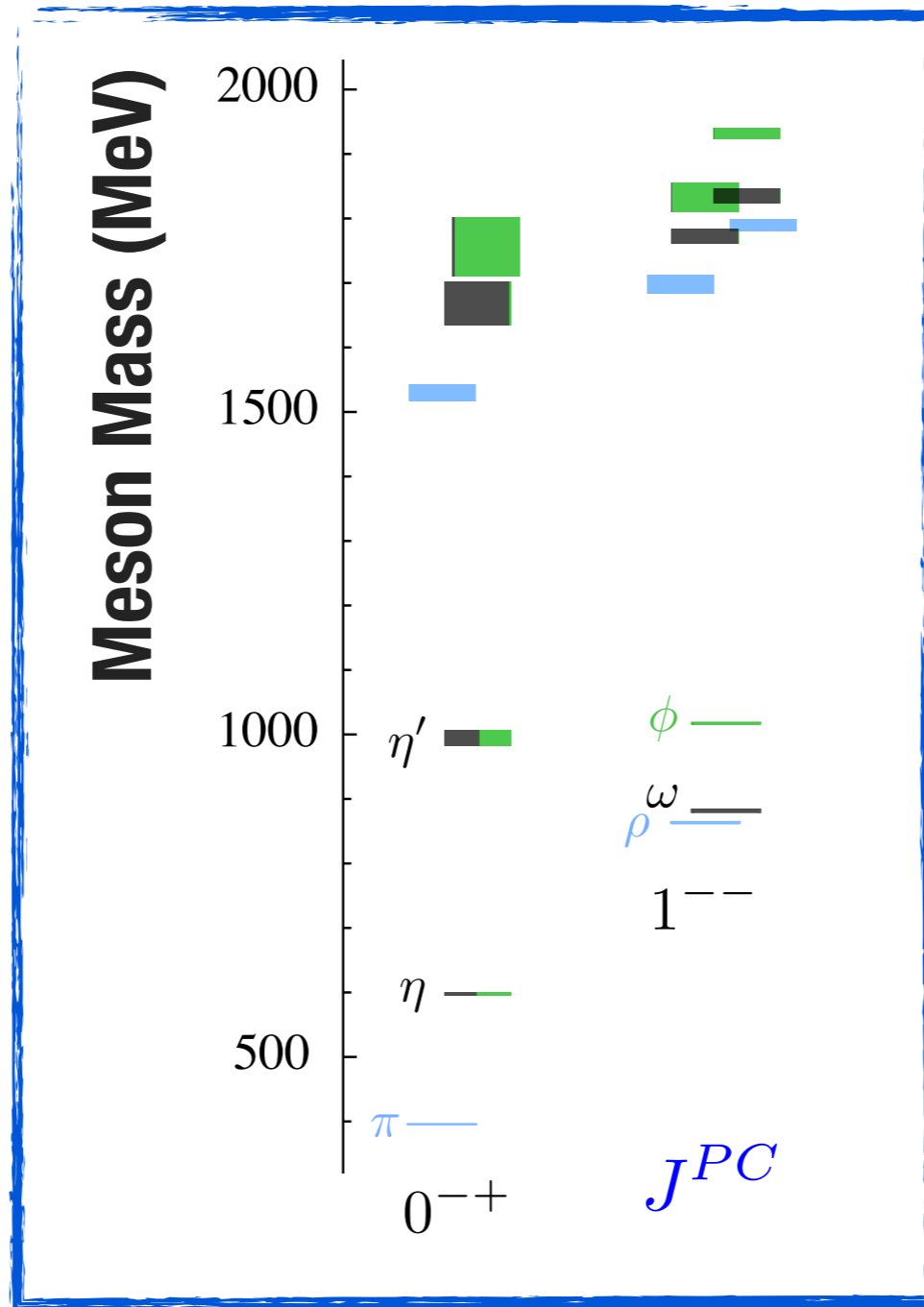


# Lattice QCD spectrum

Dudek et al. PRD 88 (2013) 094505



$$\pi^0 = |u\bar{u} - d\bar{d}\rangle$$



$$u\bar{u} + d\bar{d} \quad \blacksquare$$

$$s\bar{s} \quad \blacksquare$$















$$\phi = |s\bar{s}\rangle$$

$$\omega = |u\bar{u} + d\bar{d}\rangle$$











**Note:**  $m_\pi = 392 \text{ MeV}$

See lectures from  
Kostas Orginos

# Spectroscopy: a global endeavor

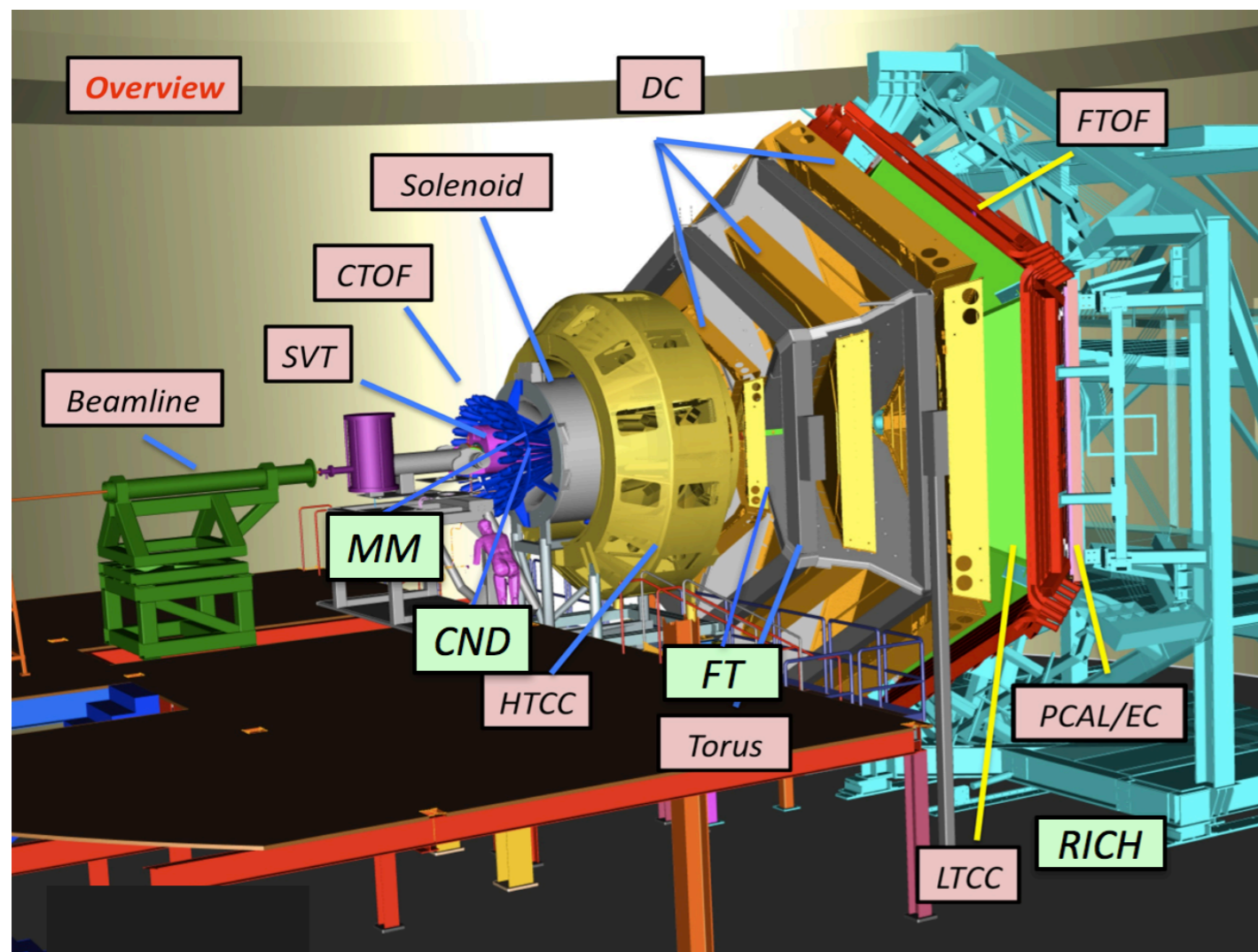
	Heavy quarks	Light quarks		
Electromagnetic probes	$e^+e^-$    	$\gamma p$   		
Hadronic probes	$\bar{p}p$  	$pp$   	$\bar{p}p$ 	$\pi p$ 

# Light quark experiments

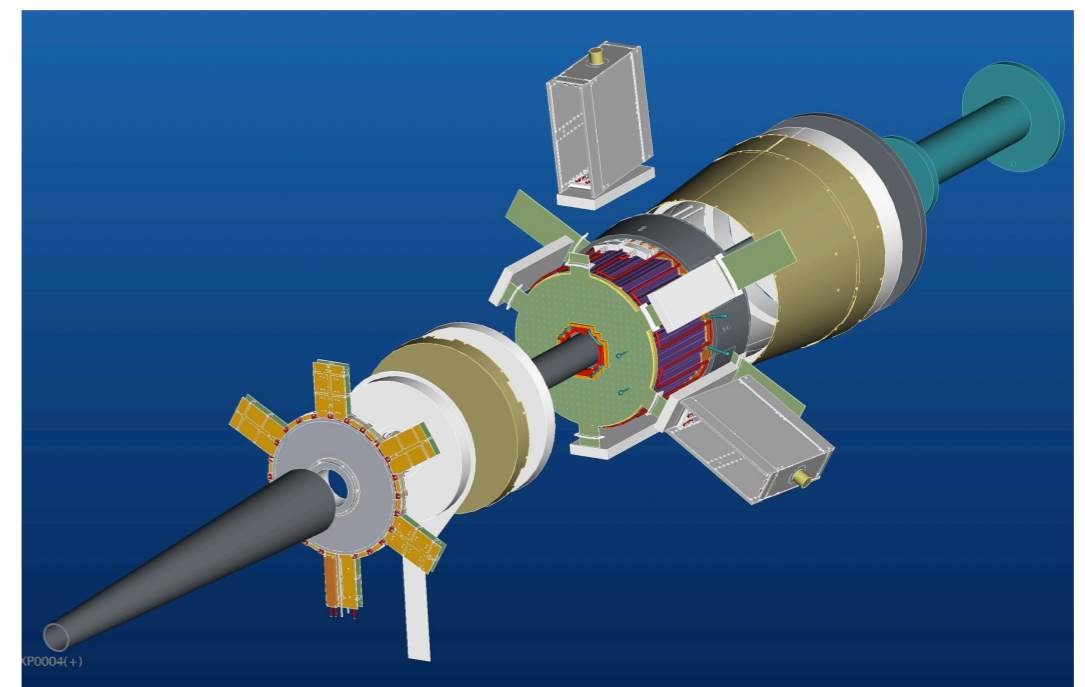
	Heavy quarks	Light quarks
Electromagnetic probes	$e^+e^-$    	$\gamma p$   
Hadronic probes	$\bar{p}p$   $pp$   	$\bar{p}p$  $\pi p$ 

# CLAS12 in Hall B

- \* CEBAF delivers 11 GeV electron beam to Hall B
- \* Linearly polarized photons through quasi-real photoproduction
- \* Electron scattering provides access to hybrid baryons

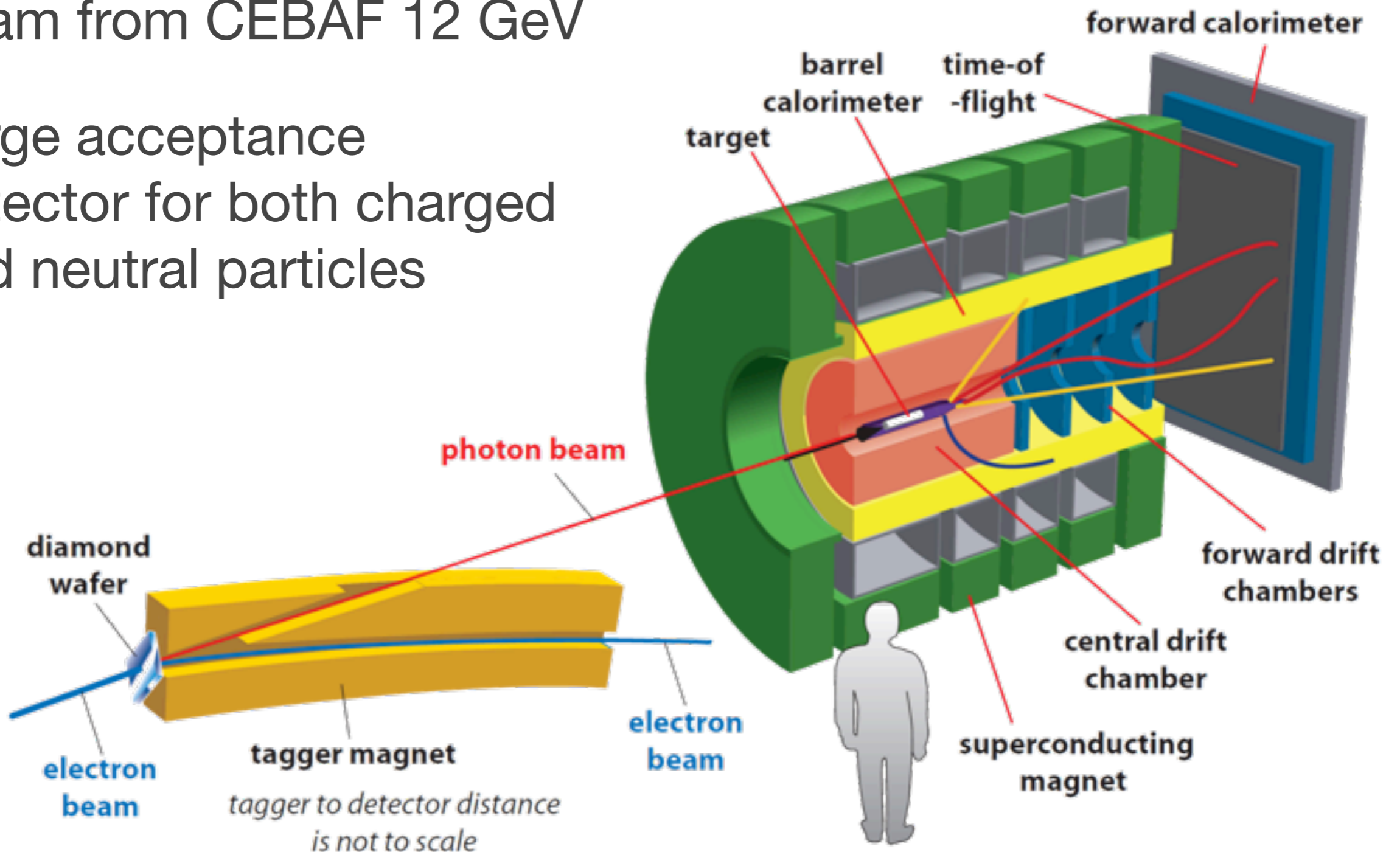


## Forward Tagger (FT)



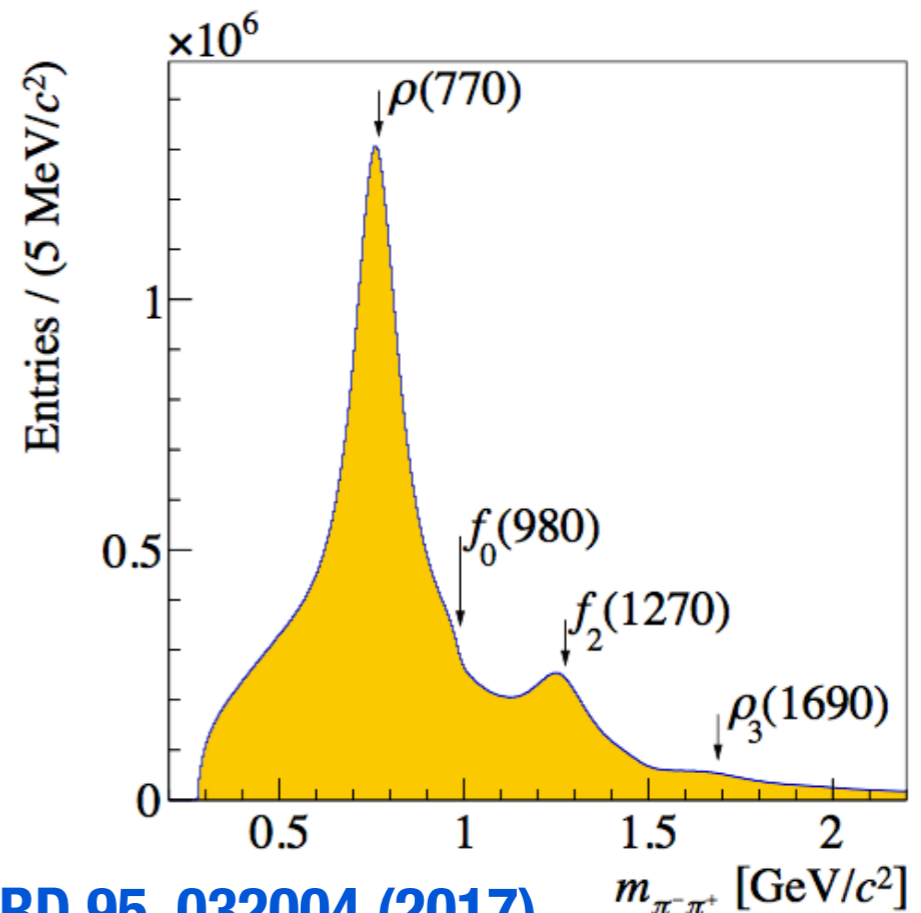
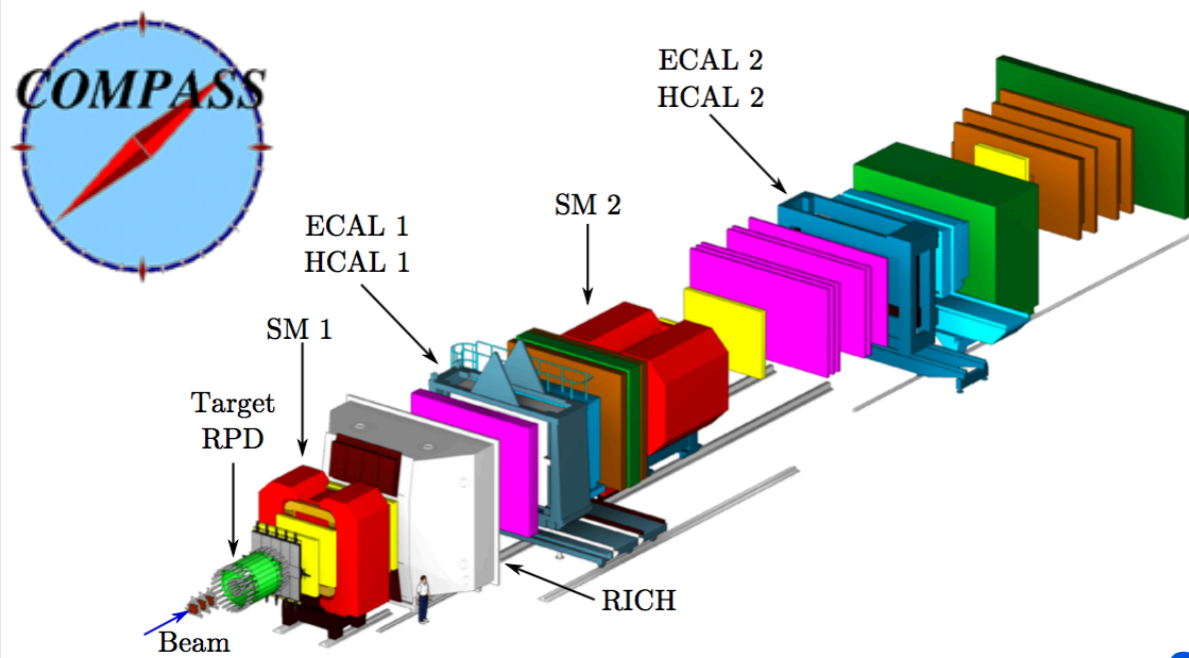
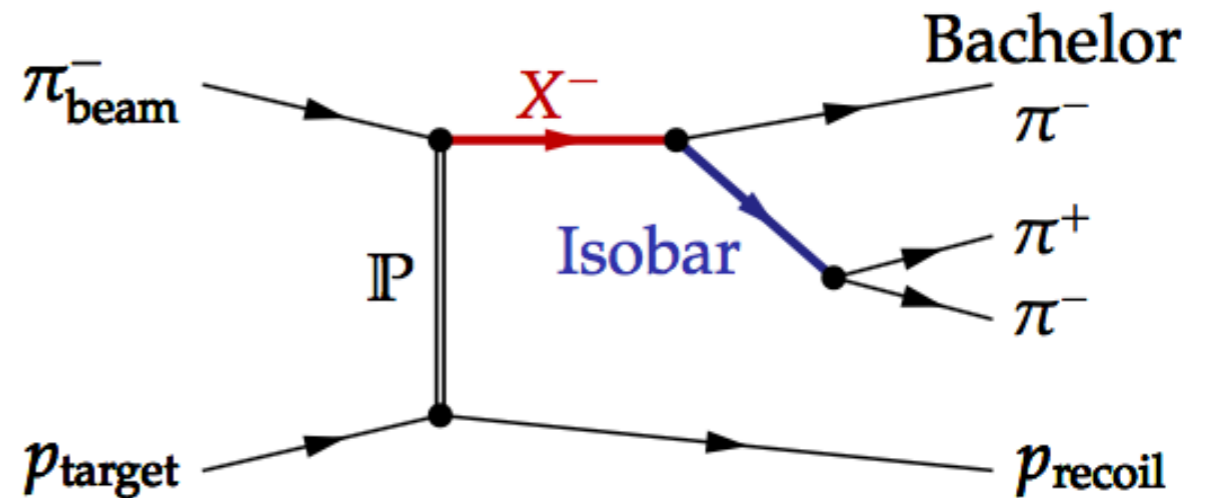
# GLUEX in Hall D

- \* Linearly polarized photon beam from CEBAF 12 GeV
- \* Large acceptance detector for both charged and neutral particles



# Compass: Diffractive $\pi p$ scattering

- \* Long history of hadron spectroscopy in pion production experiments
- \* Rich structure in  $\pi^-\pi^+\pi^-$  spectrum, modeled as intermediate resonances  $X^-$  and  $\pi^+\pi^-$  **Isobars**

















Compass: PRD 95, 032004 (2017)

# Exercise #2: Hadron Resonance

- \* Decay width:  $\Gamma_{tot} = \Sigma \Gamma_i$
  - \* Related to lifetime of particle:  $\Gamma_{tot} = h/\tau$
  - \* What can we measure?
    - \* Hadron resonance modeled as a complex-valued Breit-Wigner with mass  $m_0$  and width  $\Gamma$
- $$A(m) = \frac{1}{m_0^2 - m^2 - im_0\Gamma}$$
- \* However sometimes difficult to separate “natural” width from experimental resolution

[https://drive.google.com/file/d/1avV16YnboKA6hpsqE0UED3oKUDJCdU\\_f/view?usp=sharing](https://drive.google.com/file/d/1avV16YnboKA6hpsqE0UED3oKUDJCdU_f/view?usp=sharing)

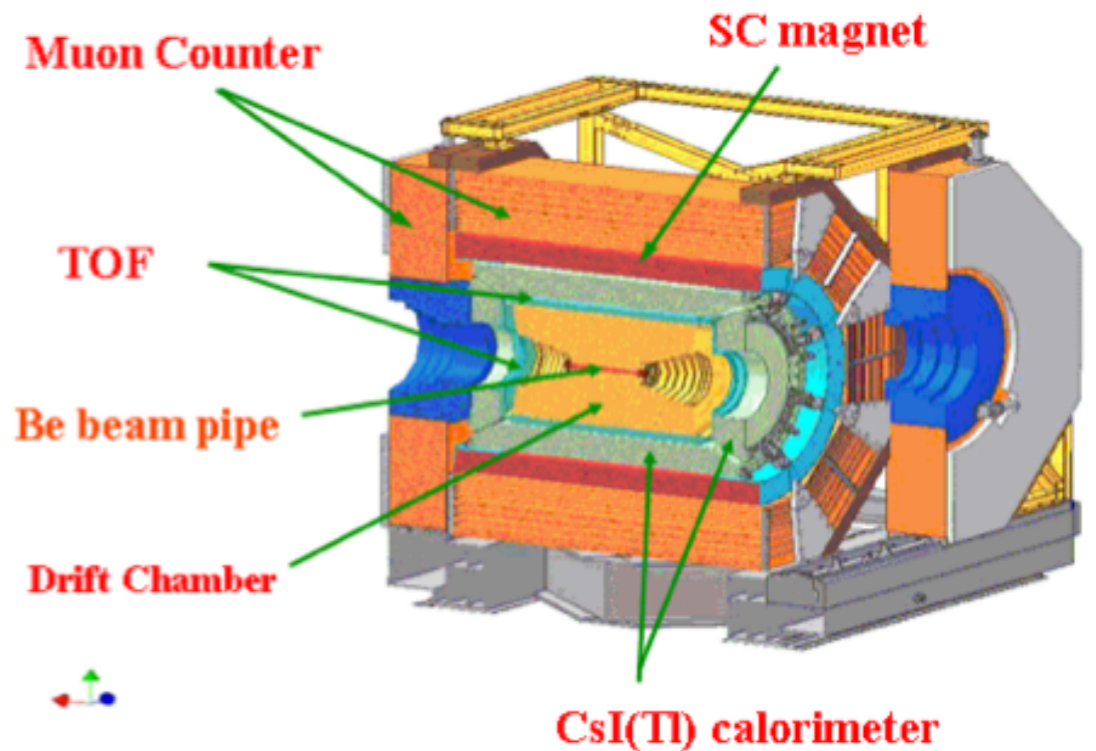
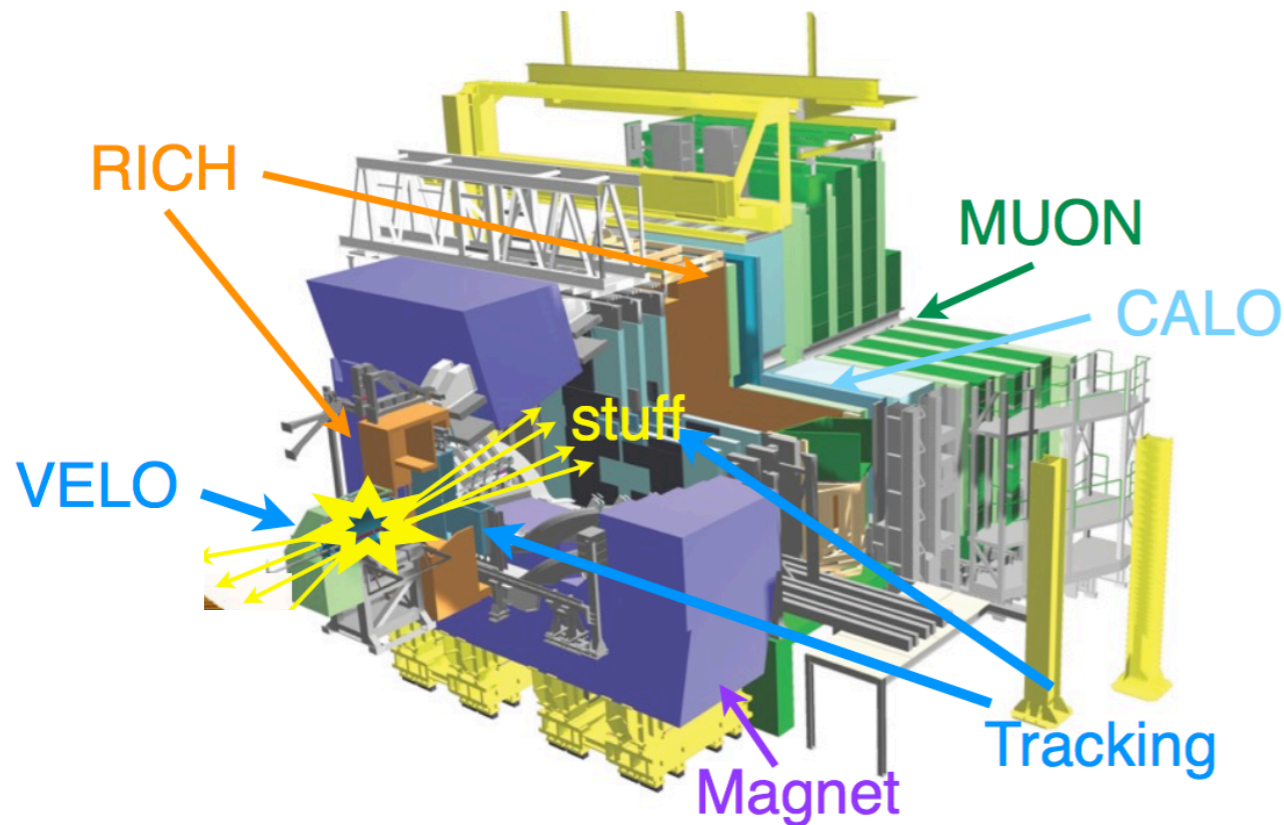
# Heavy quark experiments

	Heavy quarks	Light quarks
Electromagnetic probes	$e^+e^-$    	$\gamma p$   
Hadronic probes	$\bar{p}p$   $pp$   	$\bar{p}p$  $\pi p$ 

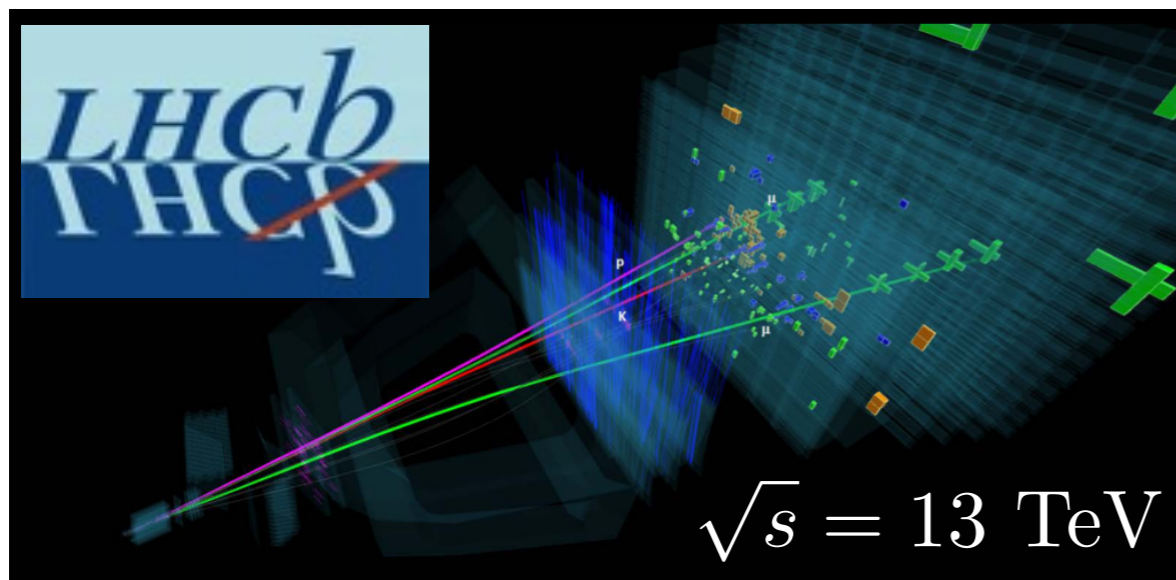
# Heavy quark production and detection

Inclusive:  $pp \rightarrow BX$  or  $\Lambda_B X$

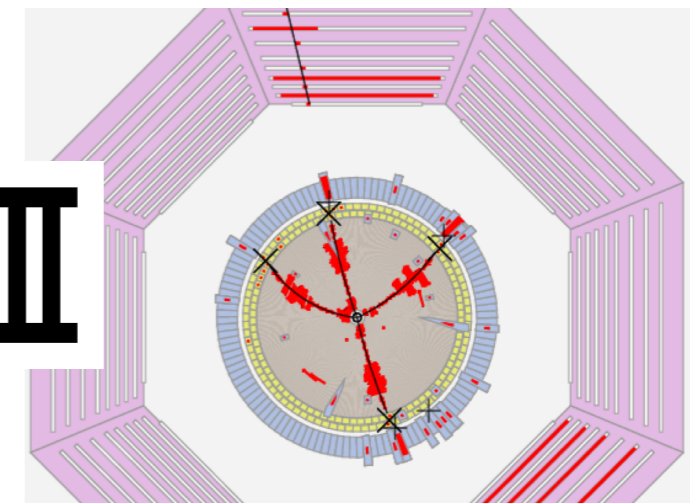
Exclusive:  $e^+e^- \rightarrow c\bar{c}$



$$\sqrt{s} = 2 - 4.6 \text{ GeV}$$



**BESIII**



**Pro: high rate**

**Con: messy**

**Pro: controlled**

**Con: statistics**

# Hadron Spectroscopy at GlueX and Beyond (2)

**Heavy Quark Spectroscopy: “The XYZ Story”**

**Justin Stevens**



**WILLIAM & MARY**

CHARTERED 1693

# Preliminaries

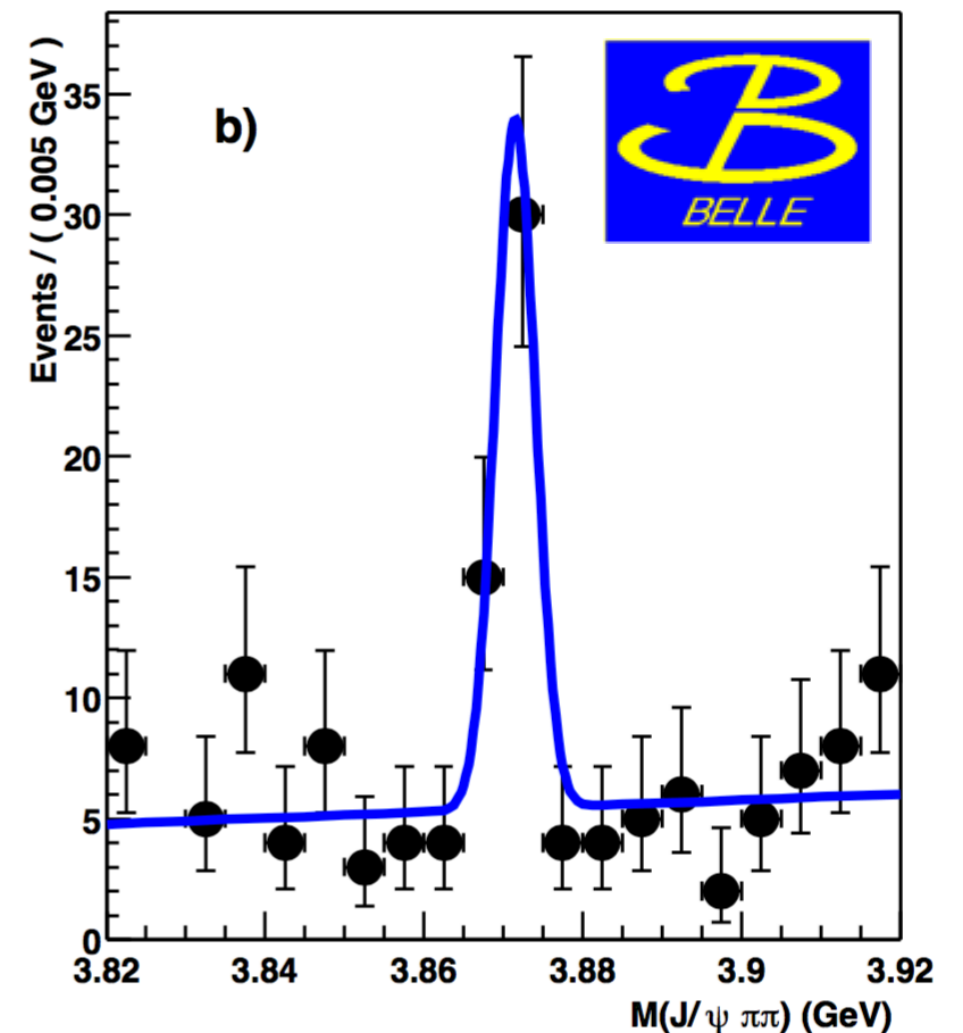
- ✱ **Outline:**

- ✱ Introduction to QCD and hadron spectroscopy
- ✱ **Heavy quark spectroscopy: “The XYZ story”**
  - ✱ “Conventional” charmonium and bottomonium
  - ✱ Observation of XYZs and possible interpretations
  - ✱ Future prospects
- ✱ Light quark spectroscopy (tomorrow)

# Experimental strategy

- \* **Search for new particles**
- \* Bumps in mass spectra
- \* Unique decay distributions
- \* **Next measure:**
  - \* mass and width
  - \* decay modes
  - \* quantum numbers:  $J^{PC}$
- \* Identify **patterns** and compare with QCD and models

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



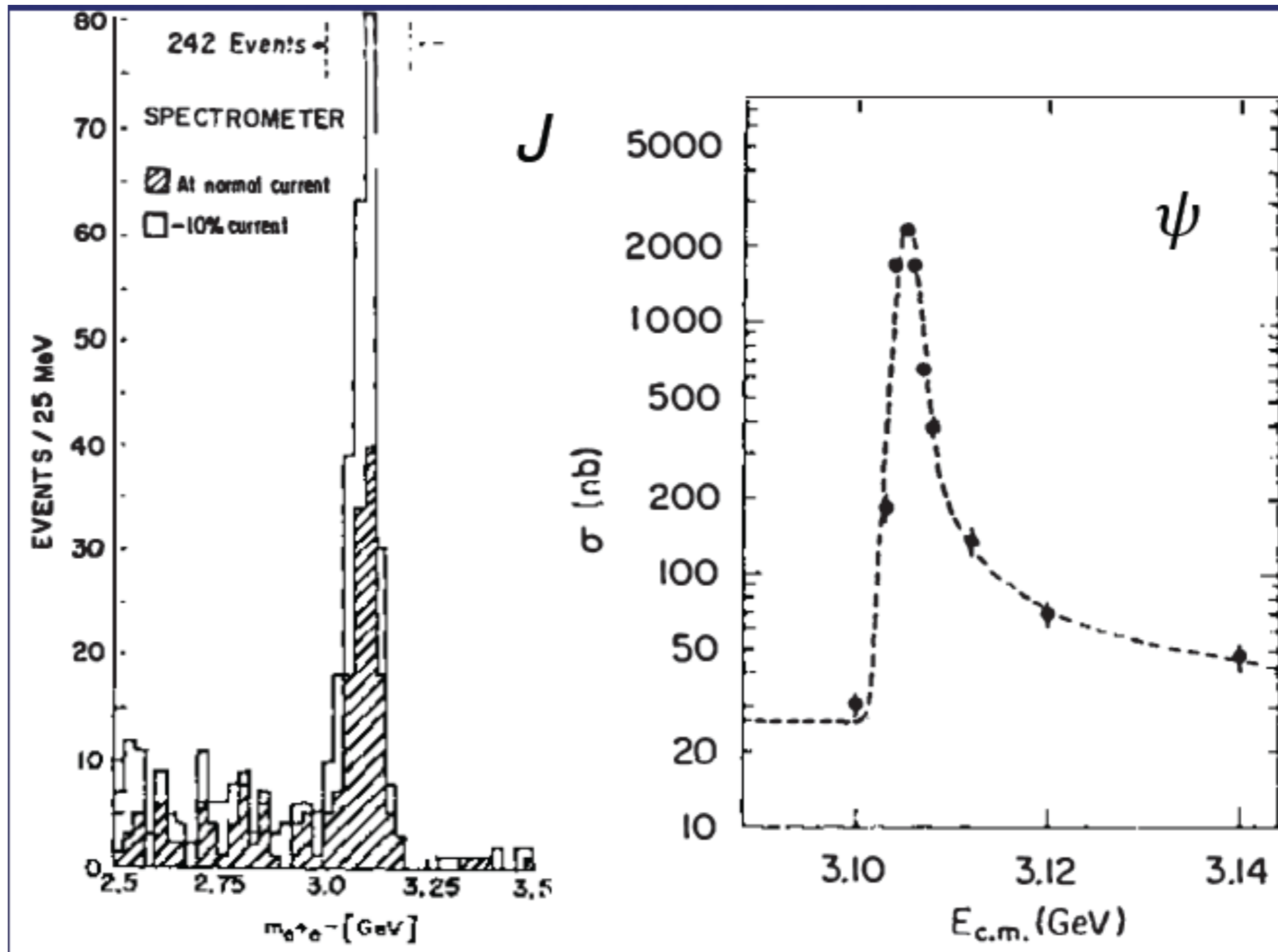
# Discovery of charm ( $J/\psi$ ) in 1974

**BNL/MIT**

$$p + Be \rightarrow e^+ e^- X$$

**SLAC**

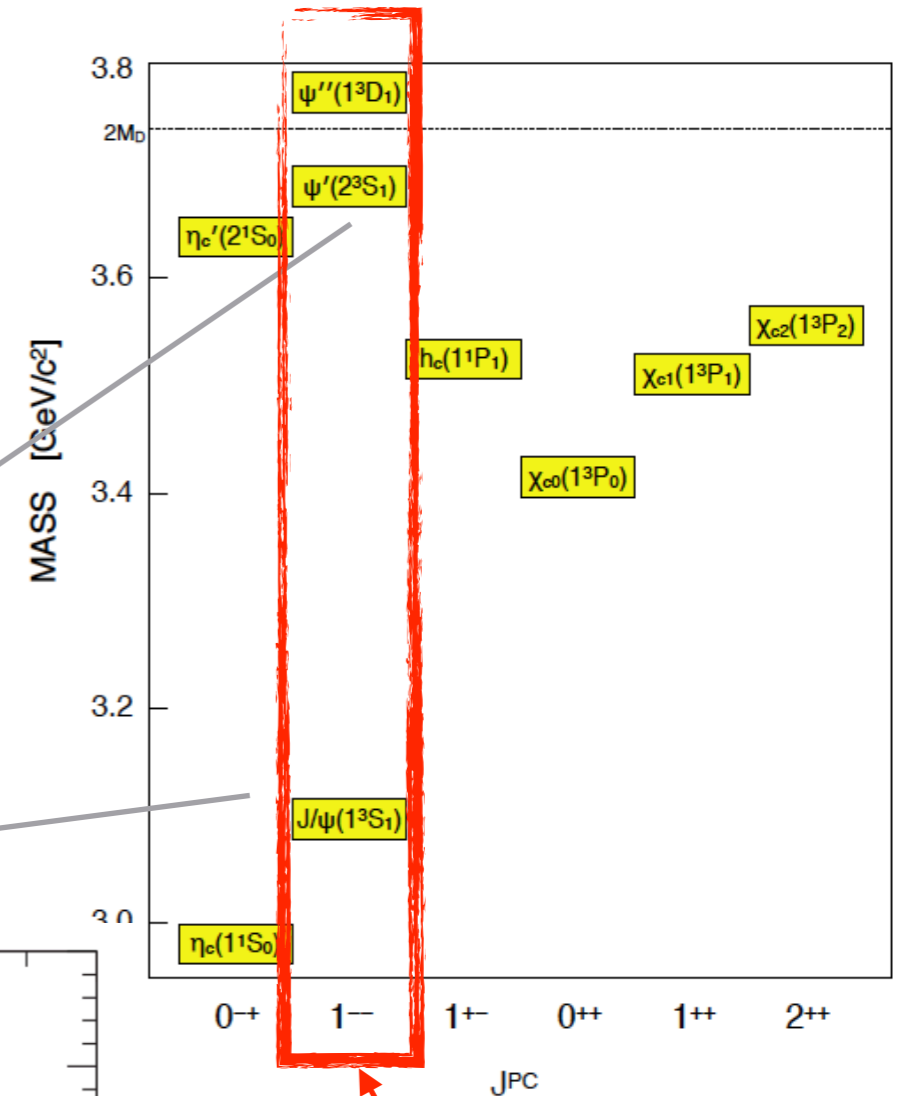
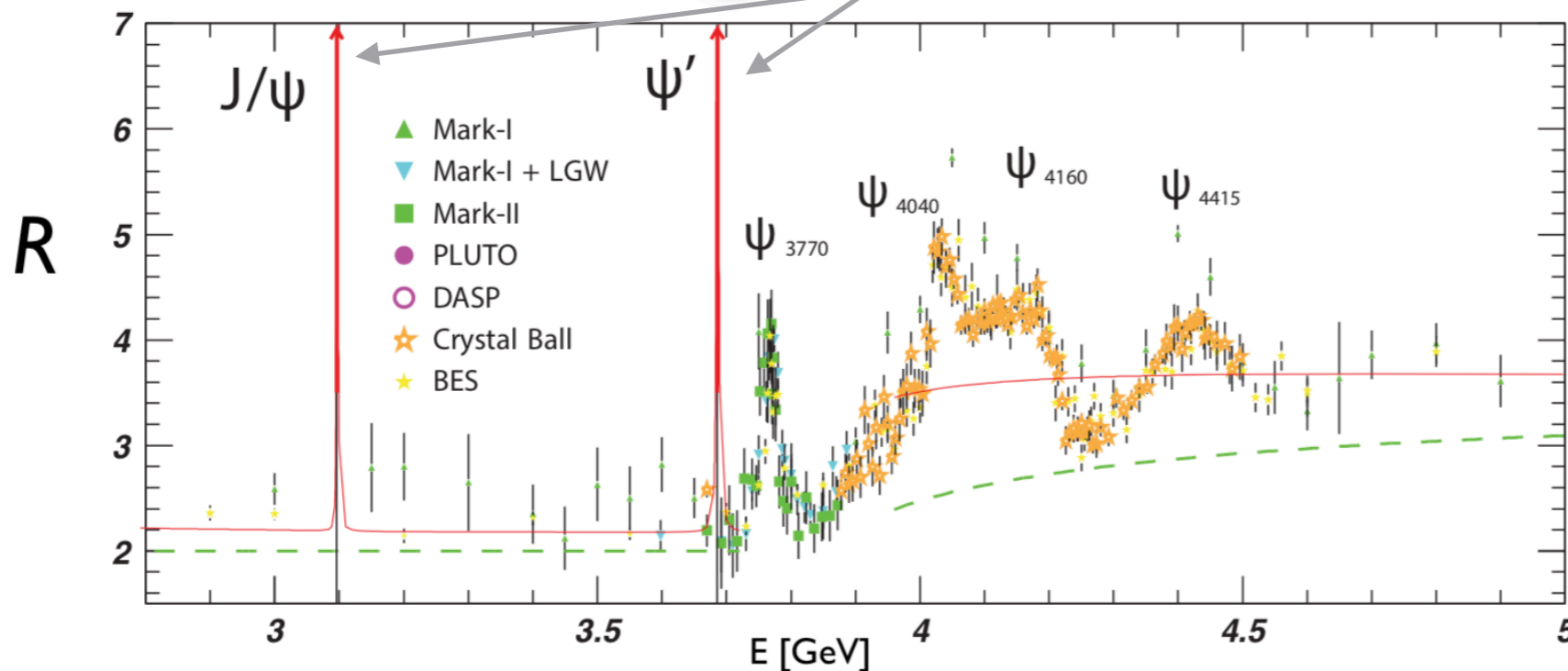
$$e^+ e^- \text{ collisions}$$



# “Conventional” charmonium

Resonances appear as enhancement  
in cross section at  $M = \sqrt{s}$

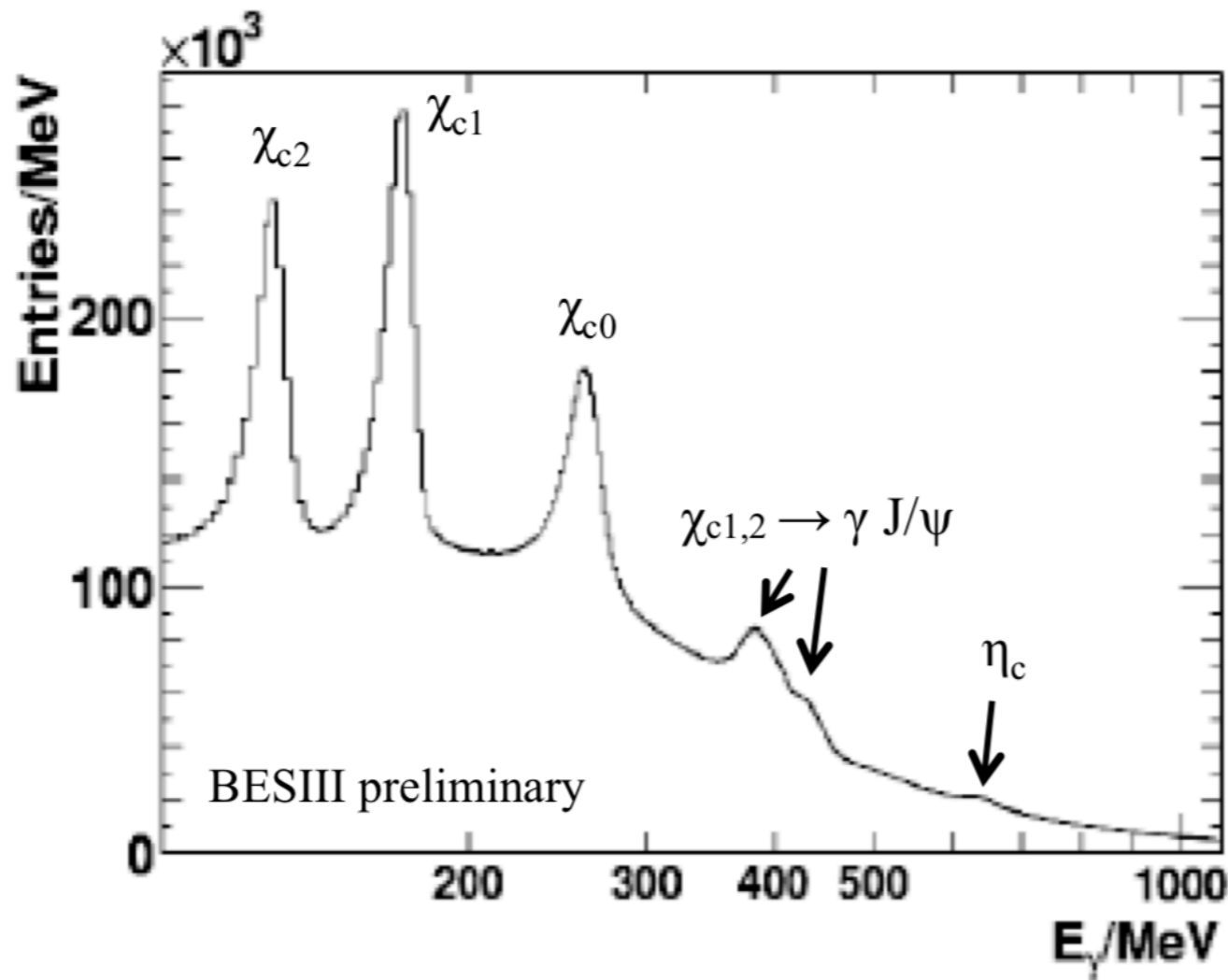
$$R = \frac{\begin{array}{c} e^- \\ \swarrow \\ \text{---} \\ \nearrow \\ e^+ \end{array} \begin{array}{c} q \\ \swarrow \\ \text{---} \\ \searrow \\ \bar{q} \end{array}}{\begin{array}{c} e^- \\ \swarrow \\ \text{---} \\ \nearrow \\ e^+ \end{array} \begin{array}{c} \mu^- \\ \swarrow \\ \text{---} \\ \searrow \\ \mu^+ \end{array}}$$



**Only  $J^{PC} = 1^{--}$   
produced in  $e^+e^-$**

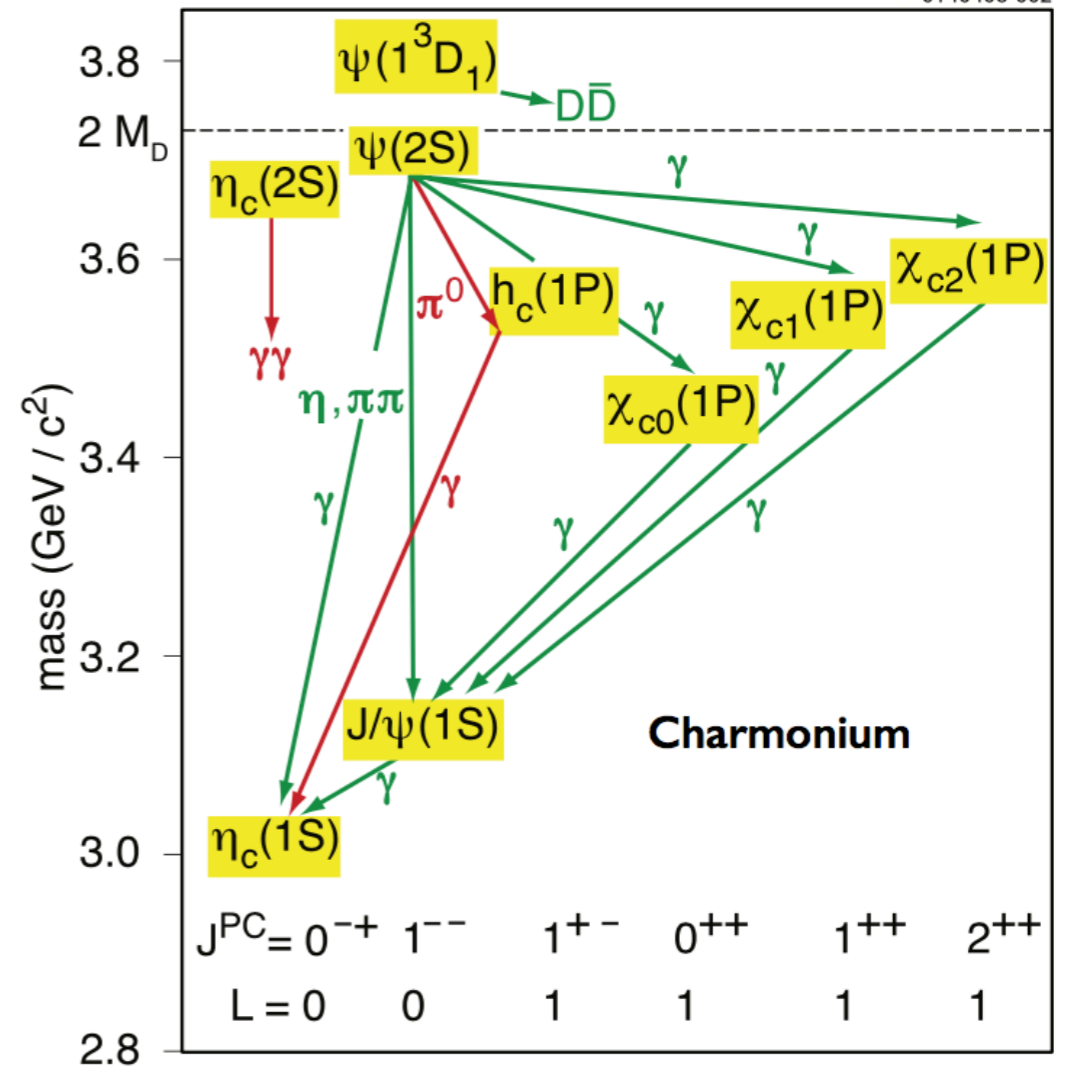
# “Conventional” charmonium

$$\psi(2s) \rightarrow \gamma X$$



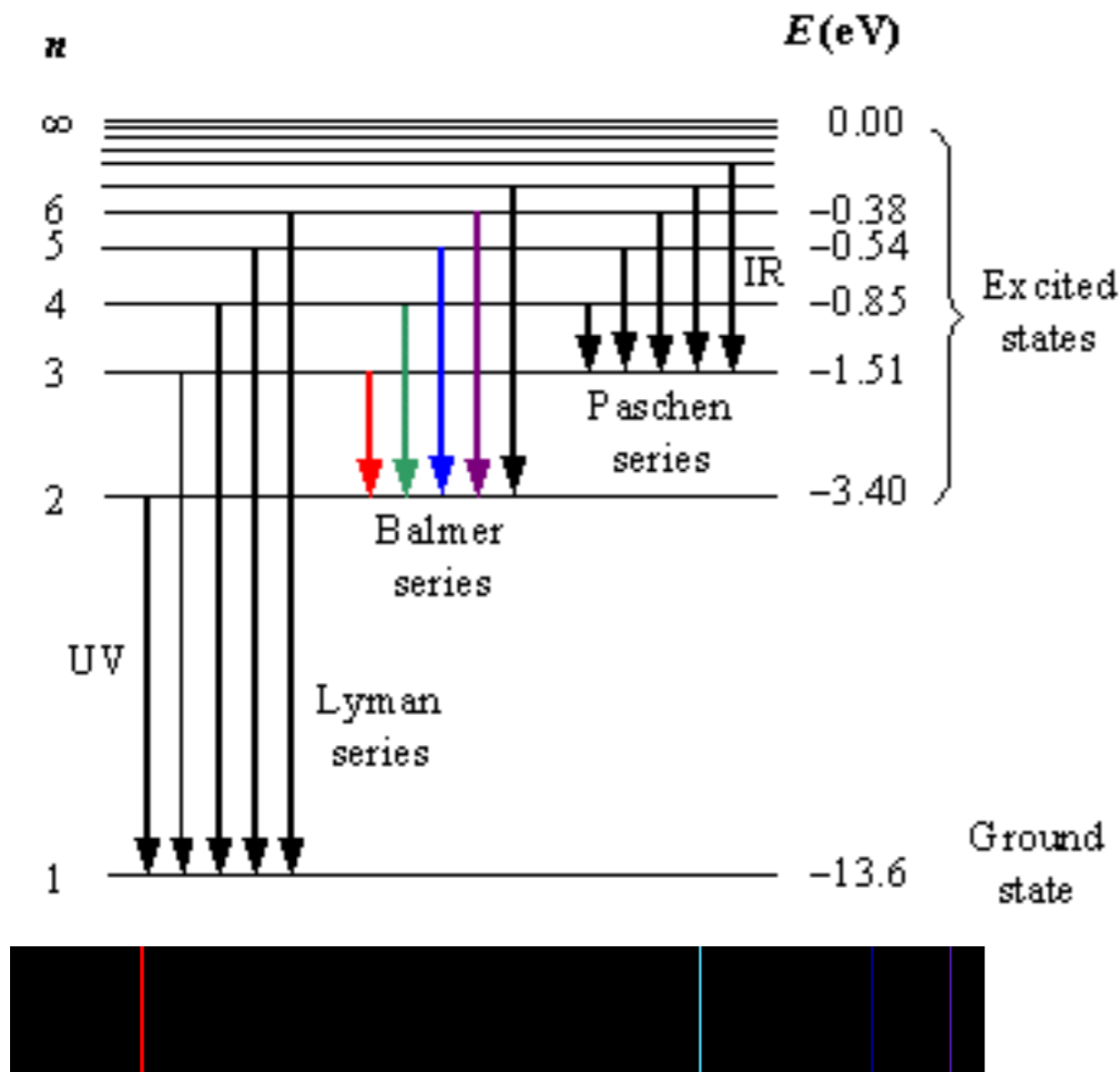
## Strong Force $c\bar{c}$

0140406-002



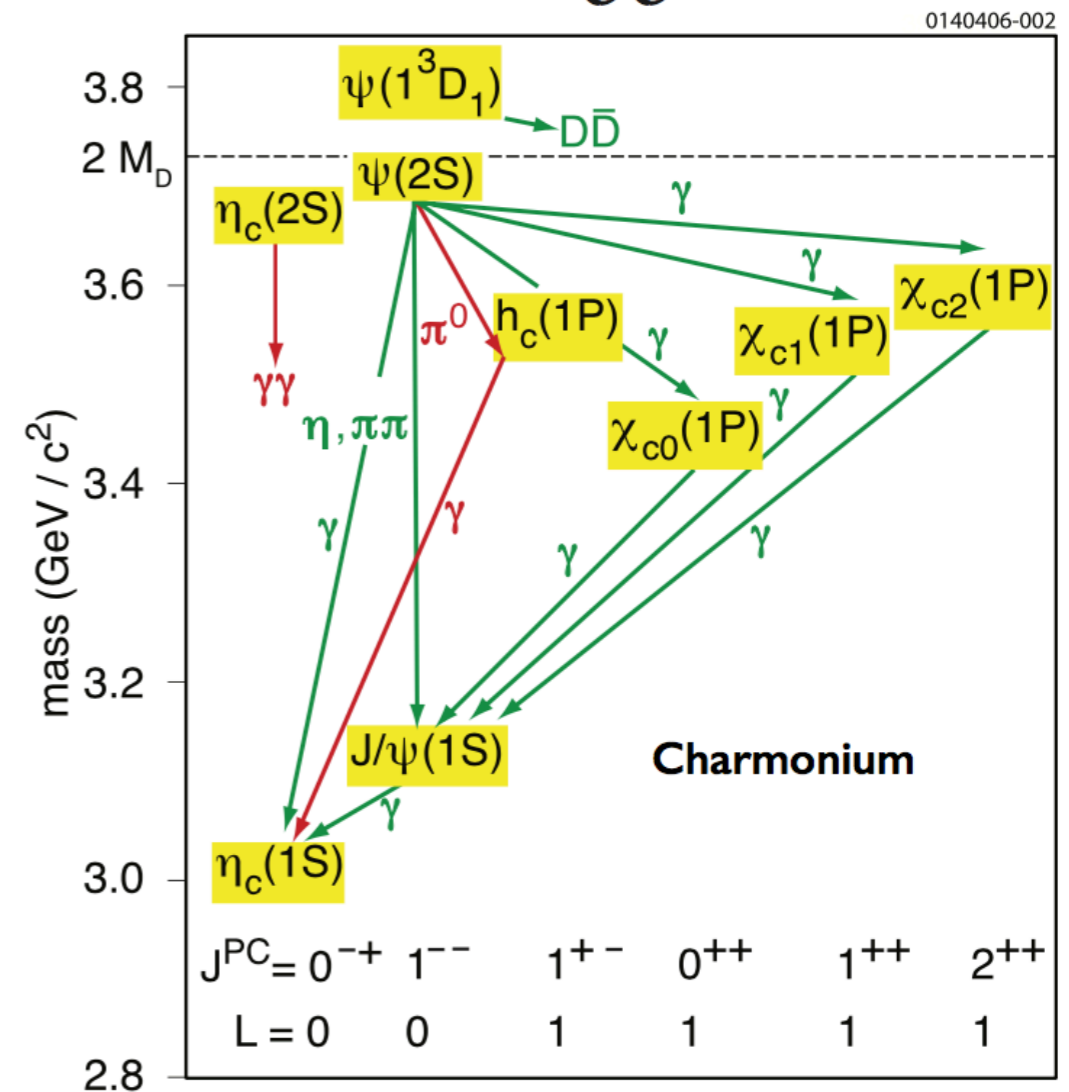
# “Conventional” charmonium

## Electromagnetic Force



## Strong Force

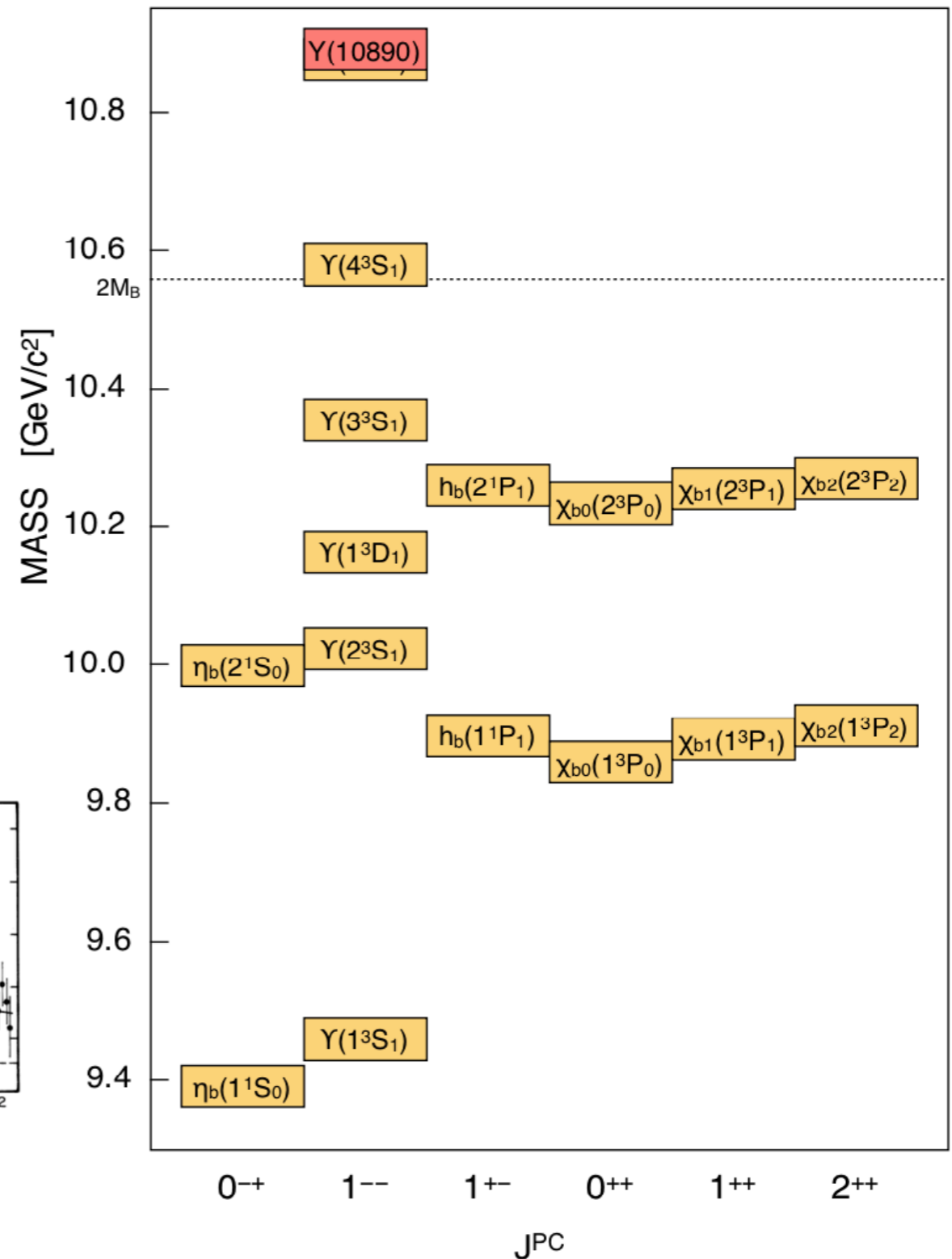
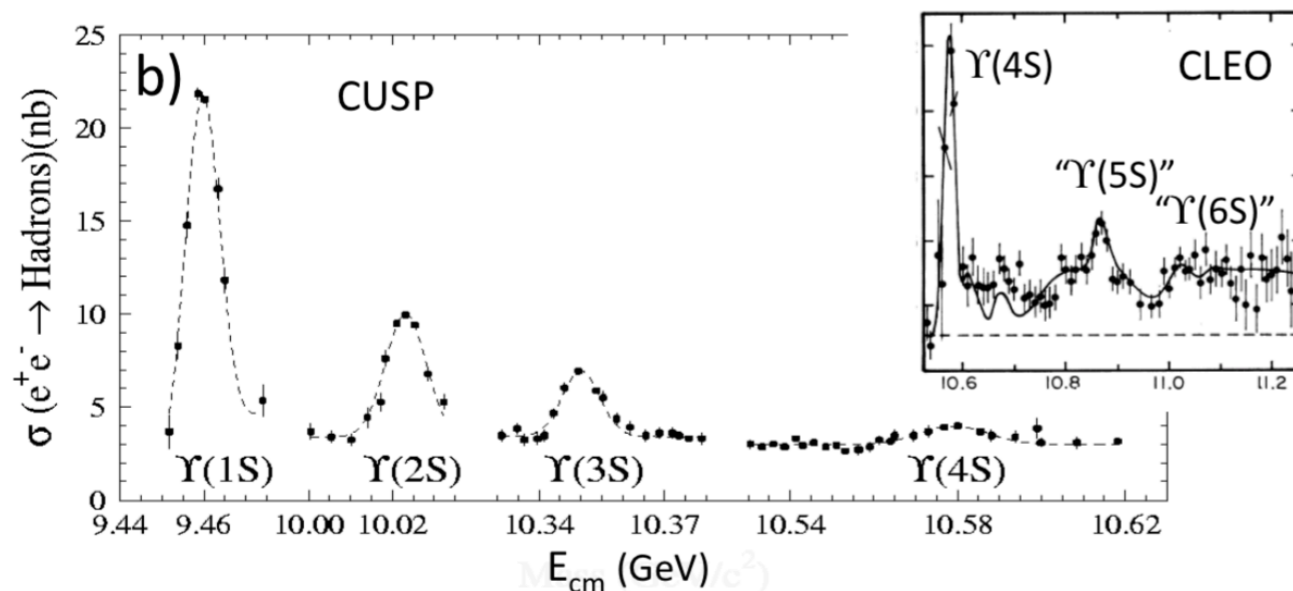
$c\bar{c}$



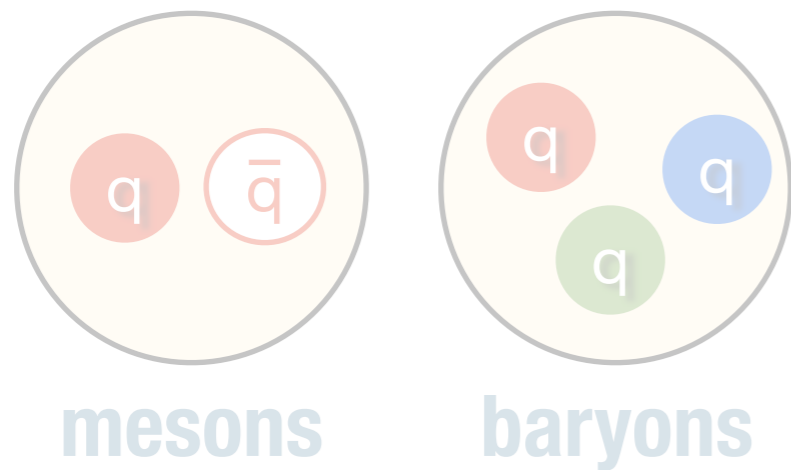
“Simple”  $c\bar{c}$  spectrum well described by quark model expectation with expected electromagnetic transitions

# “Conventional” bottomonium

- Similar picture for bottomonium states
- EM transitions at expected masses

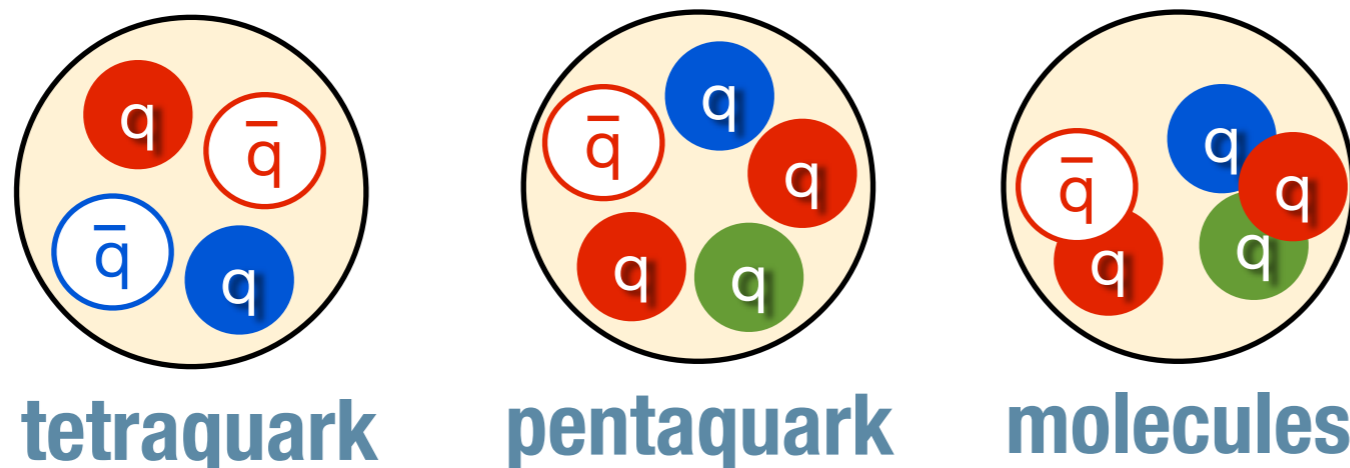


# Confined states of quarks and gluons

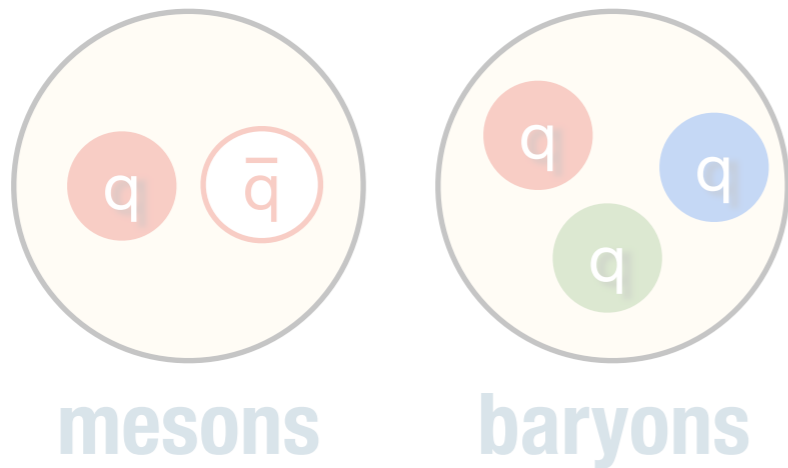


Observed mesons and baryons well described by the quark model and 1<sup>st</sup> principles QCD

- \* Definition of **exotic hadron**: hadron not described by quark model
  - Extra (supernumerary) states in the spectrum: **X and Y**
  - 4 or 5 quark states (charged with hidden charm): **Z and P<sub>c</sub>**

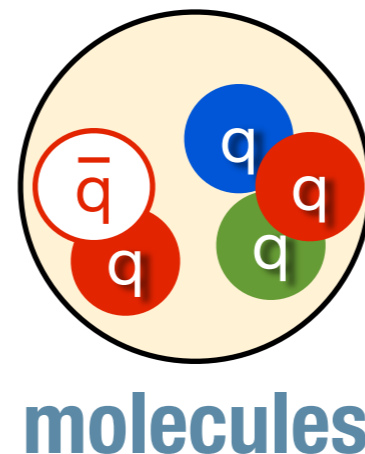
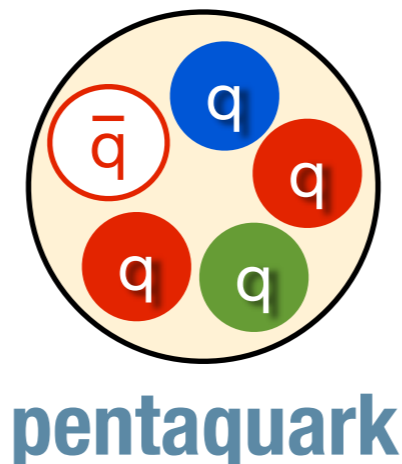
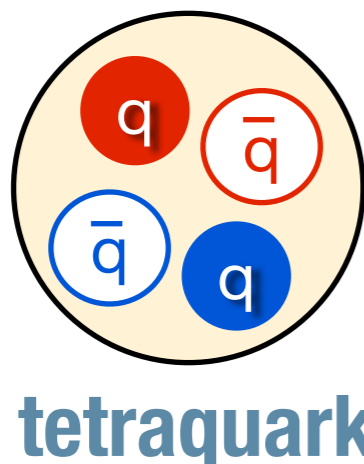


# Confined states of quarks and gluons



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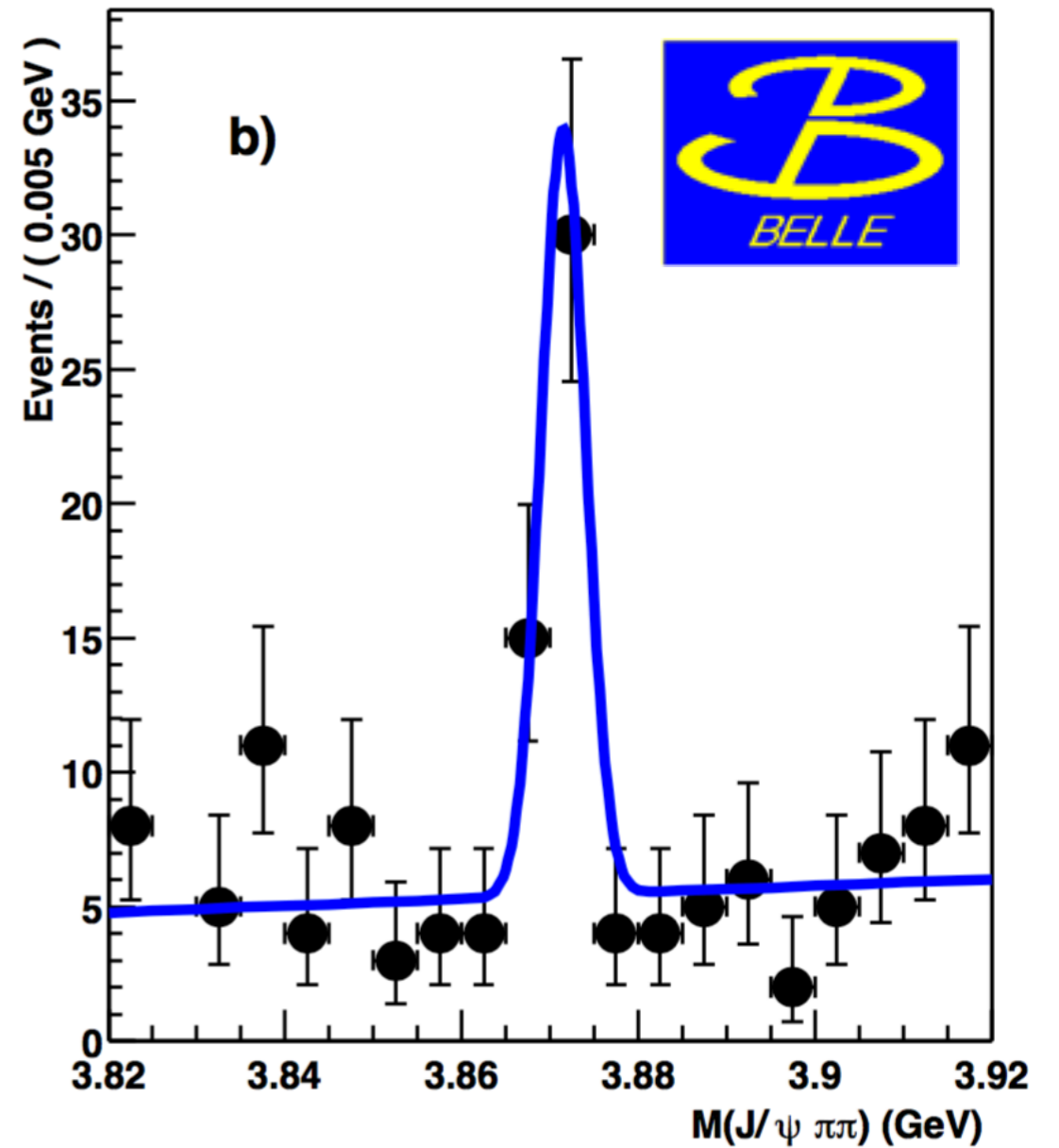
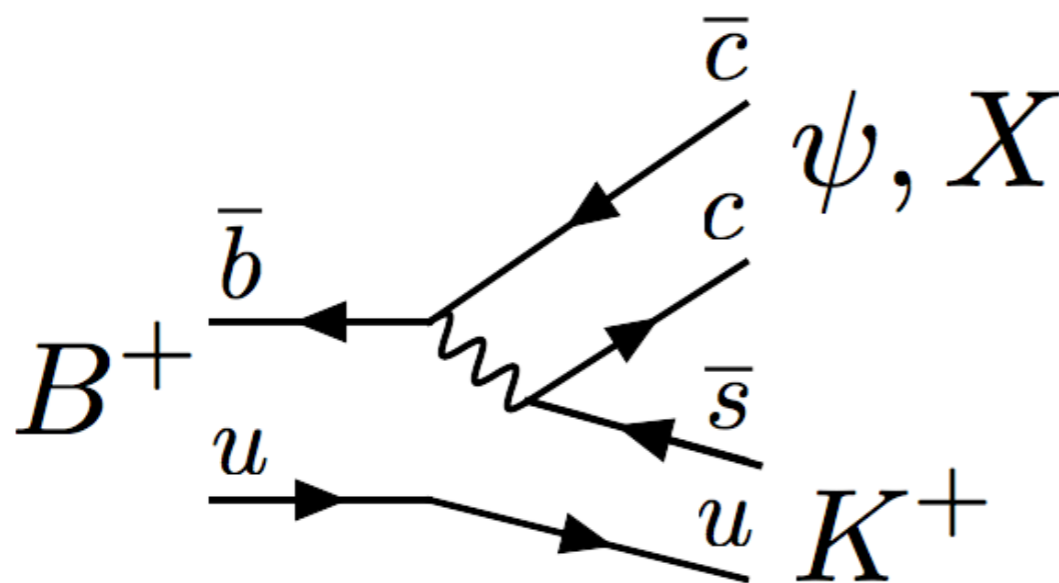
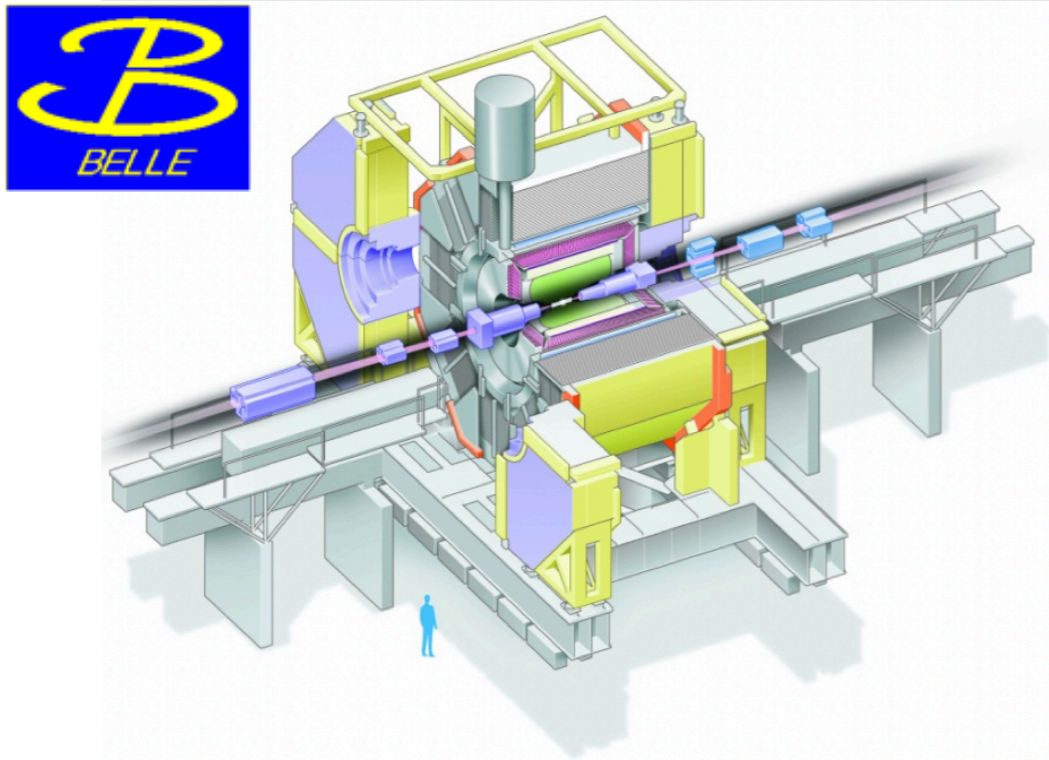


**What evidence do we have for these exotic states?**

# Where the XYZ odyssey began: **$X(3872)$**

$$e^+e^- \rightarrow b\bar{b}$$

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



**Belle (2003)**

# Introduction to XYZs

- \* **What are they?**

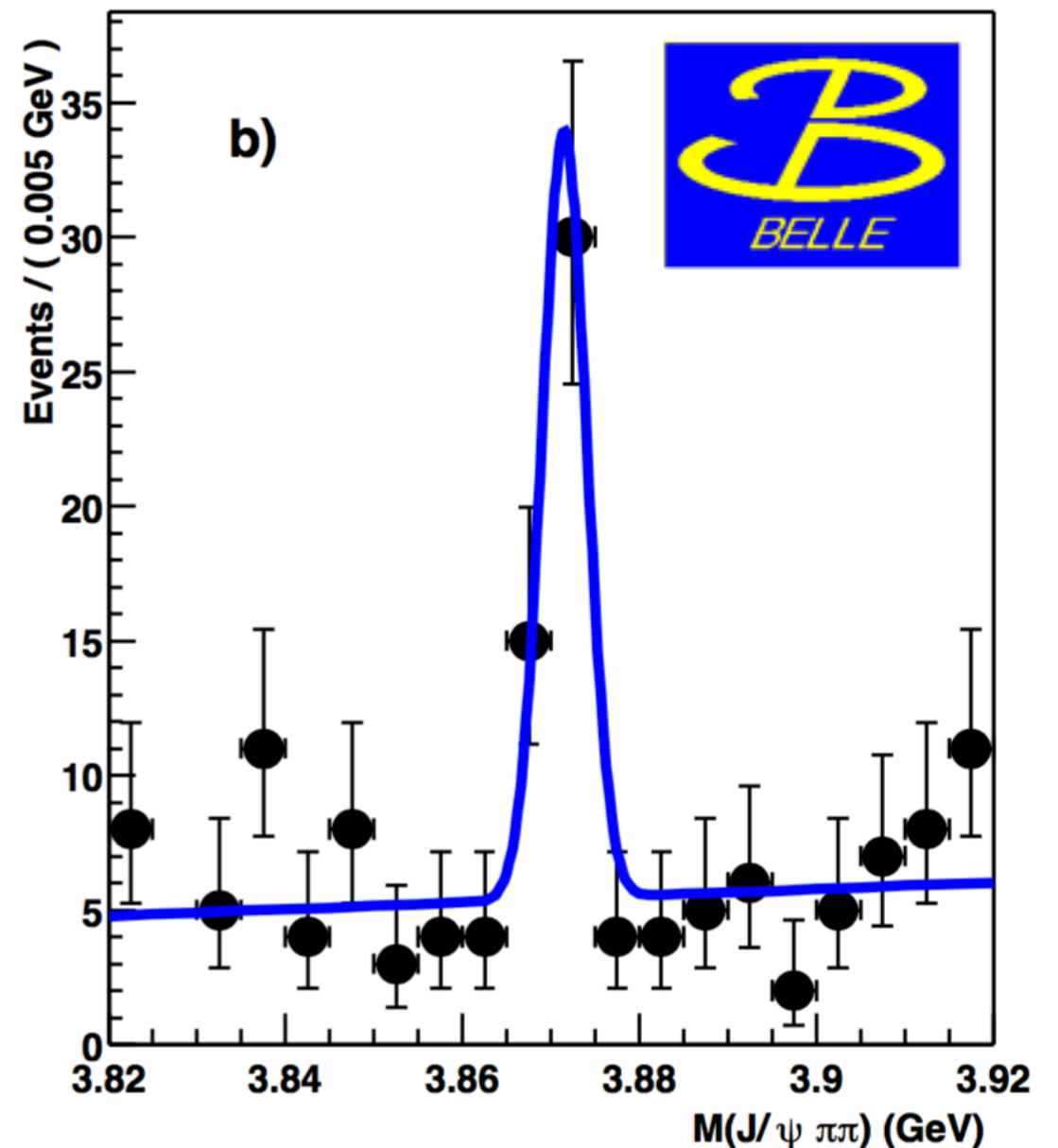
- \* Observations that don't fit with conventional quark model charmonium

- \* **Why called XYZ?**

- \* **X:** Everything else!
- \* **Y:**  $J^{PC}=1^{--}$  in  $e^+e^-$
- \* **Z:** Electrically charged

- \* **How many are there?**

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



**Belle (2003)**

# Introduction to XYZs

- \* **What are they?**

- \* Observations that don't fit with conventional quark model charmonium

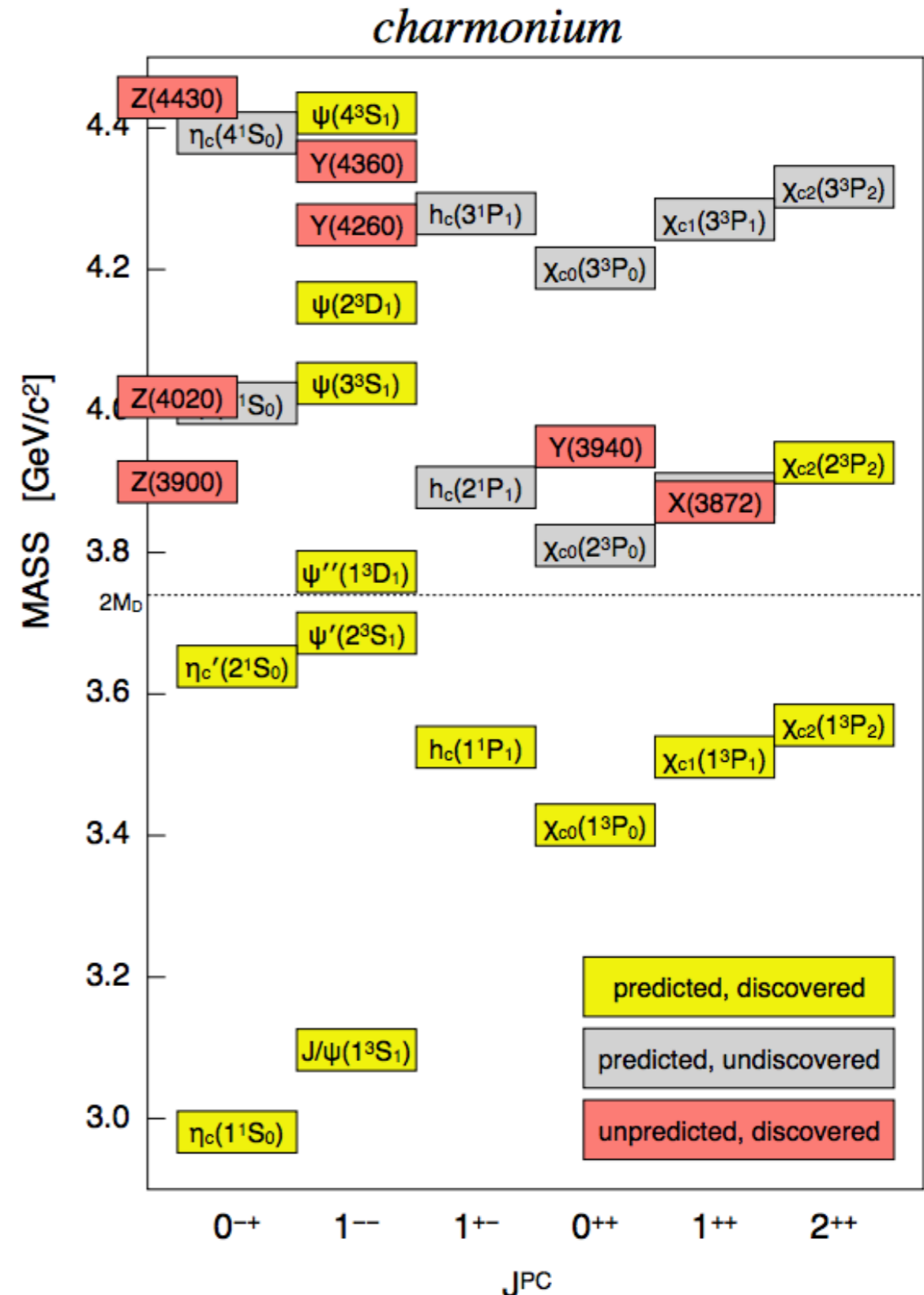
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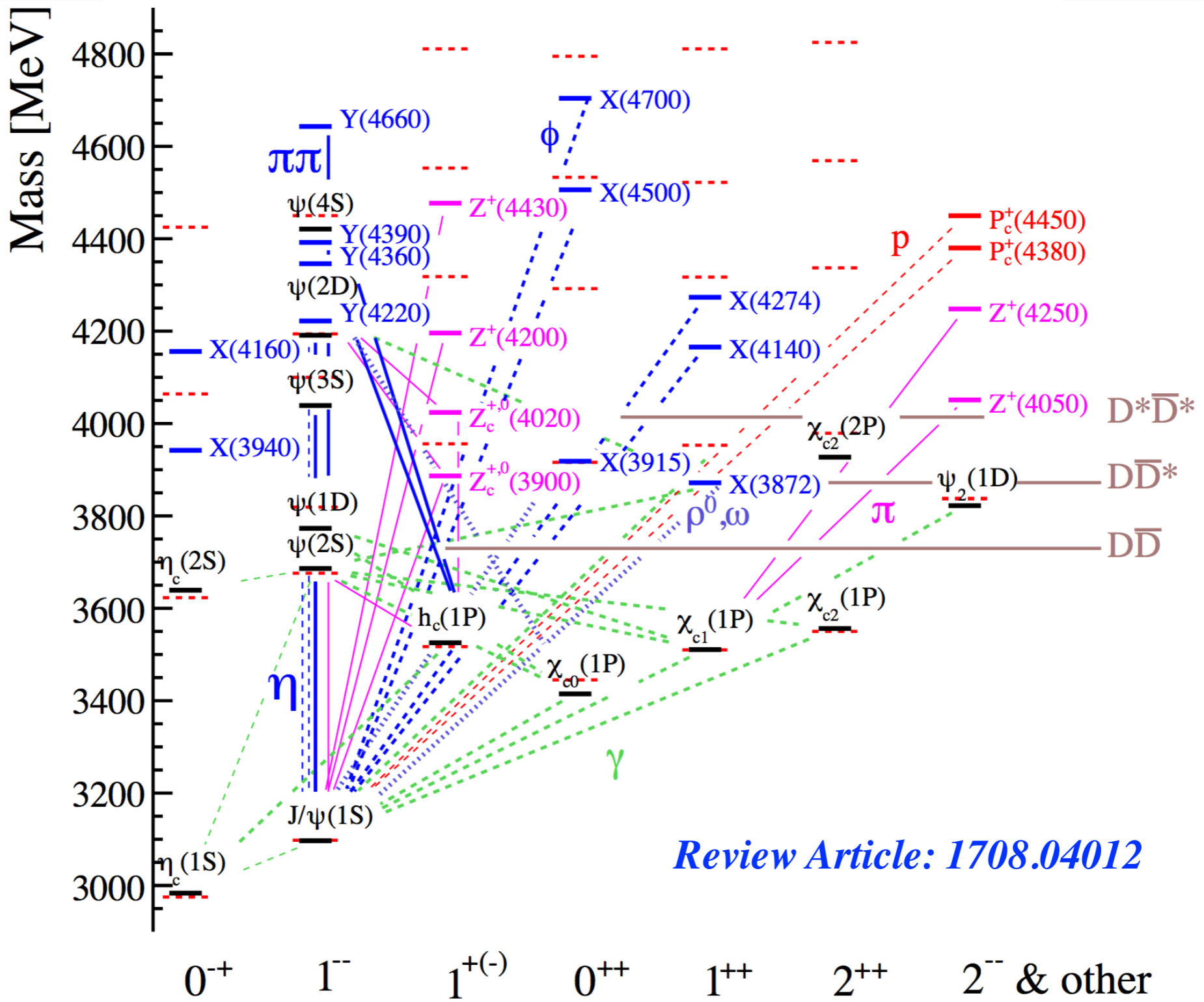
- \* **How many are there?**



# Introduction to XYZs

How many are there? **Lots!!!**

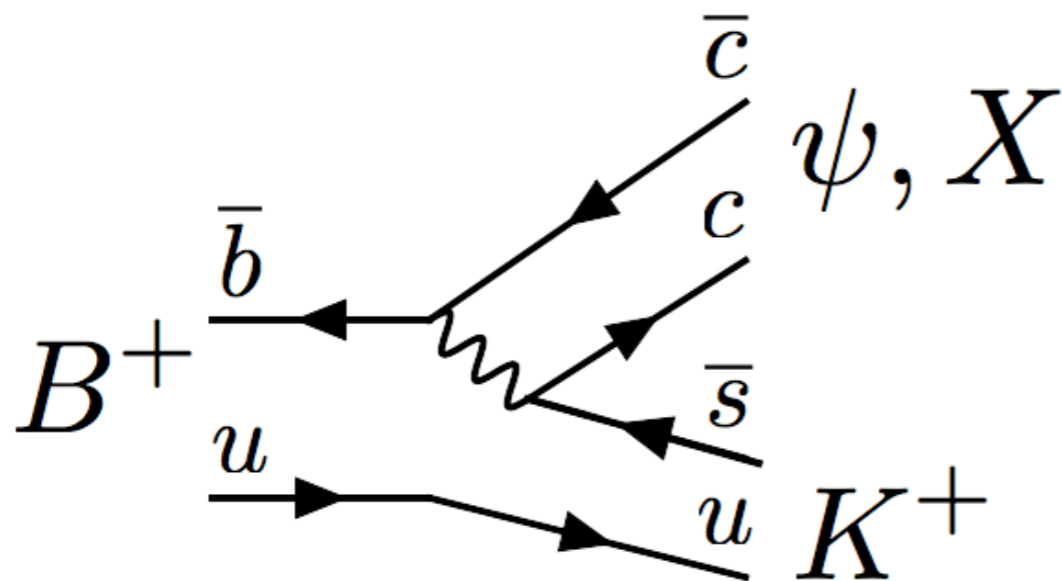
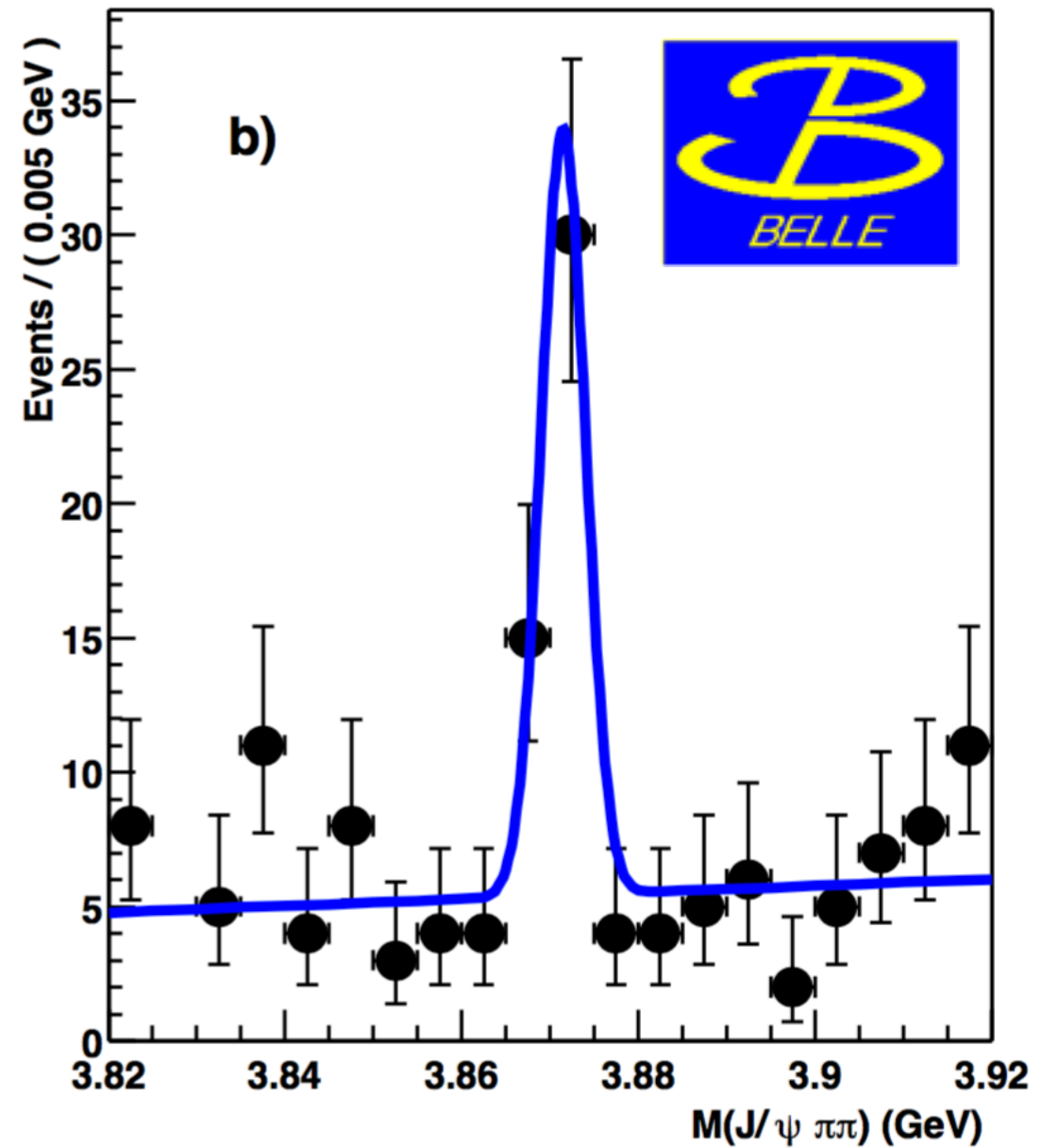
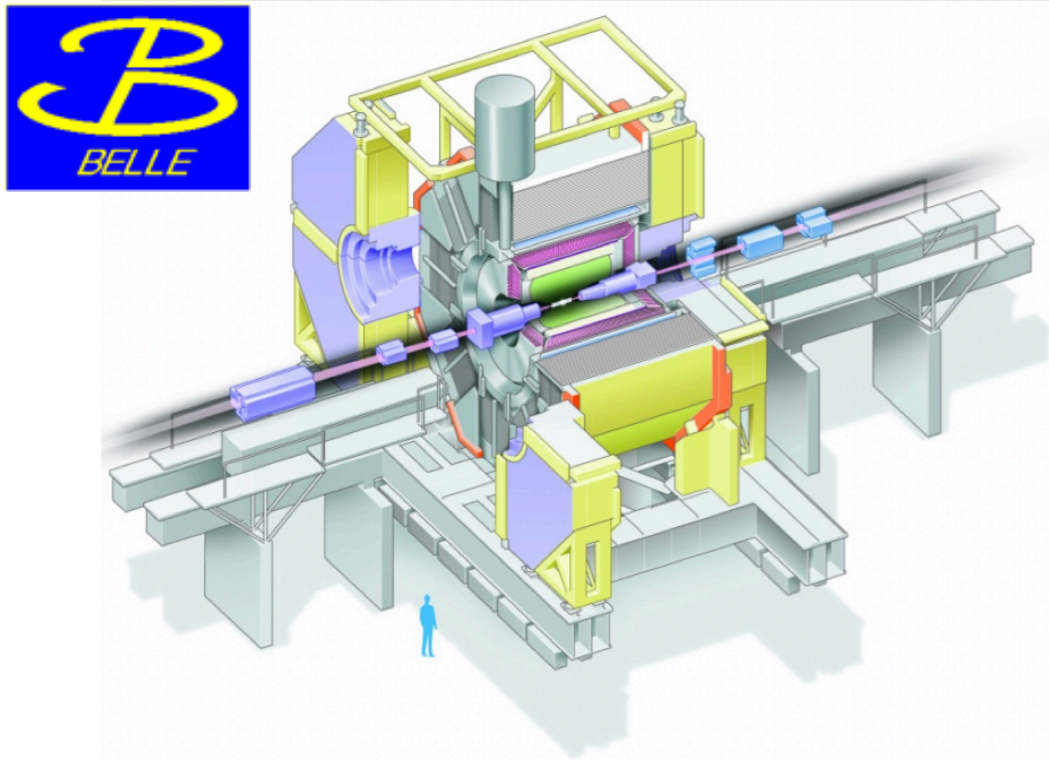
- \* What are they?
- \* Observed with confidence
- \* Why call them XYZs?
- \* Z: Electrically neutral
- \* Y: JPC = 1<sup>-</sup>0<sup>+</sup>0<sup>-</sup>
- \* X: Electrically charged
- \* How many are there?



# Where the XYZ odyssey began: **$X(3872)$**

$$e^+e^- \rightarrow b\bar{b}$$

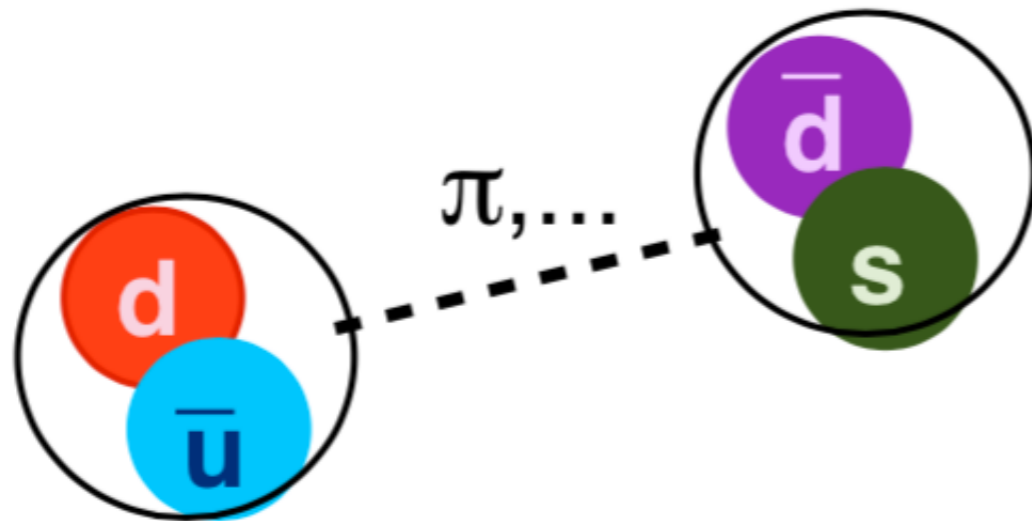
$$X \rightarrow \pi^+\pi^- J/\psi$$



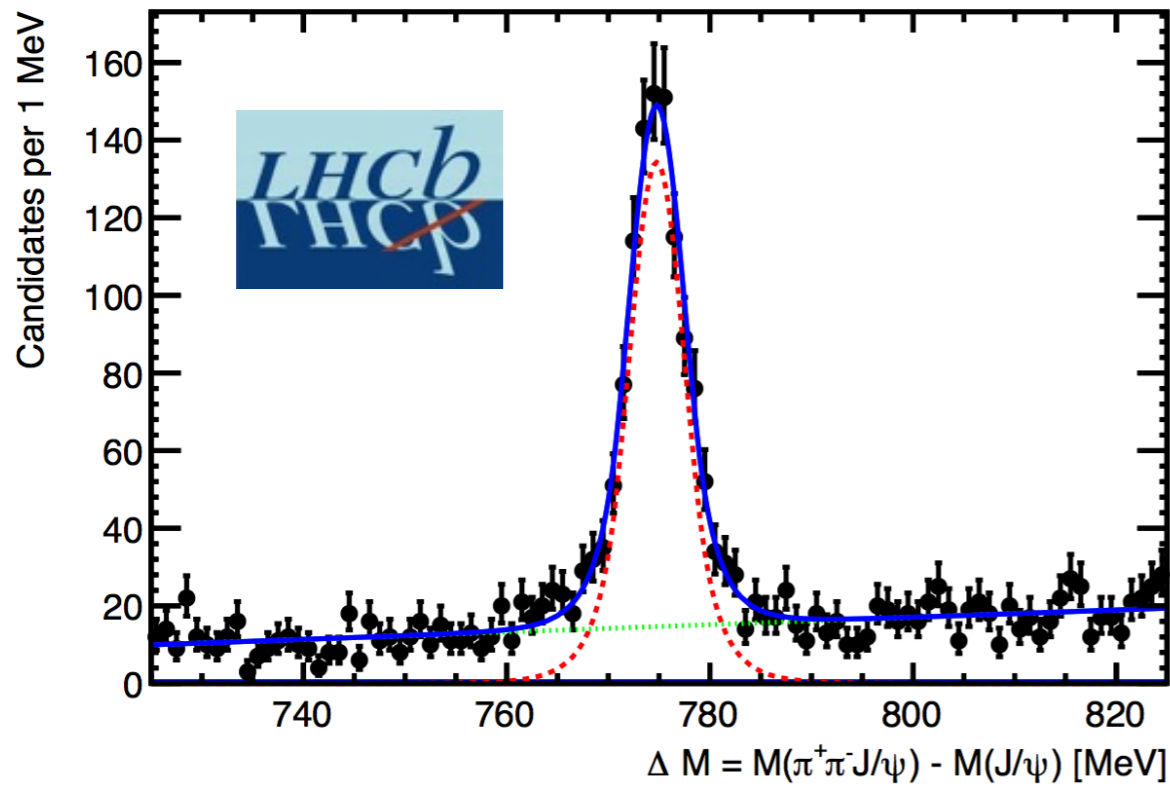
**Belle (2003)**

# Where the XYZ odyssey began: $X(3872)$

- \* Interpretations
  - \* Unexpected  $c\bar{c}$  state?
  - \* Hadron molecule?
  - \* Tightly bound “tetraquark”?



# Where the XYZ odyssey began: $X(3872)$



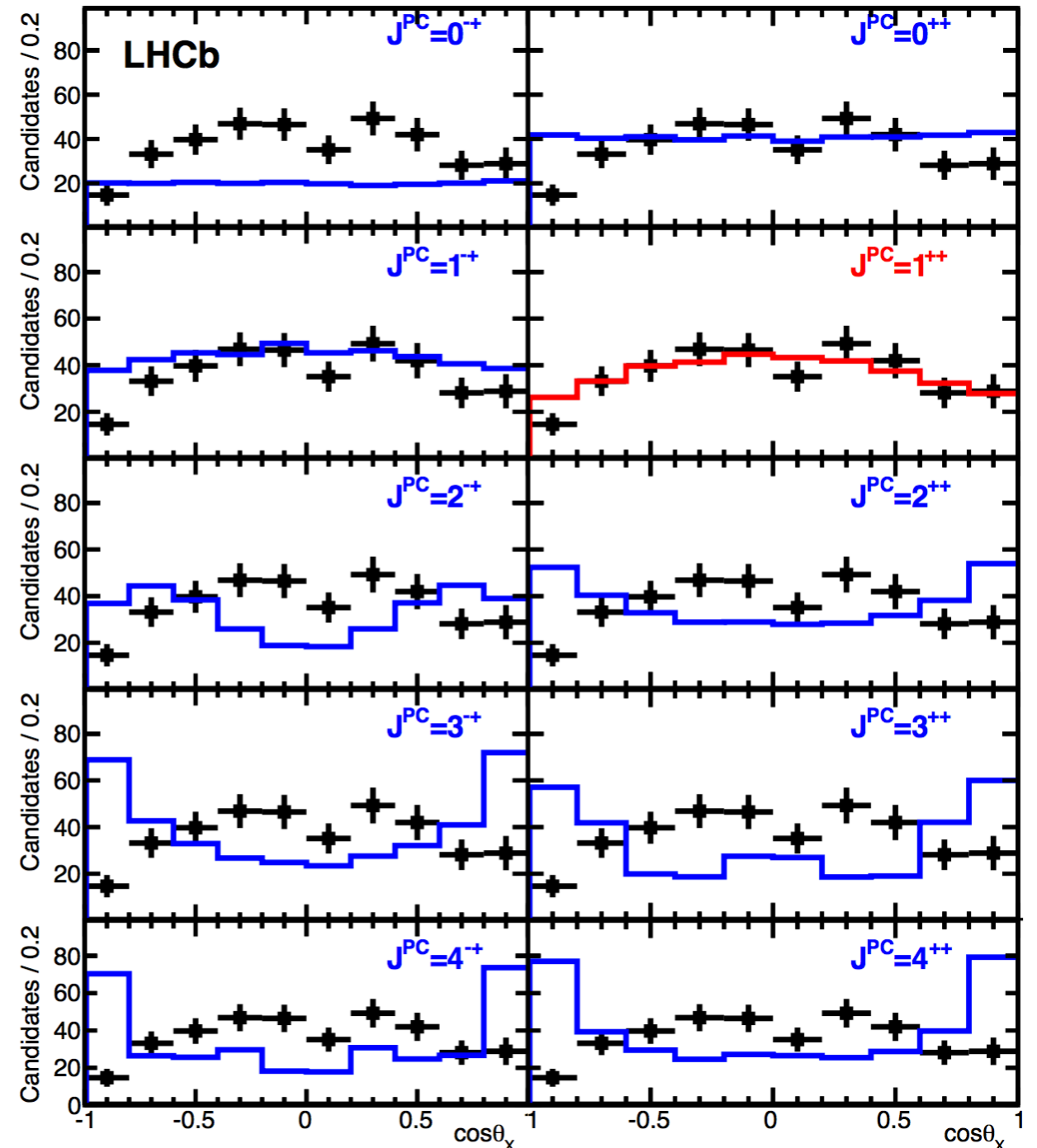
$$J^{PC} = 1^{++}$$

\* Higher statistics: more studies

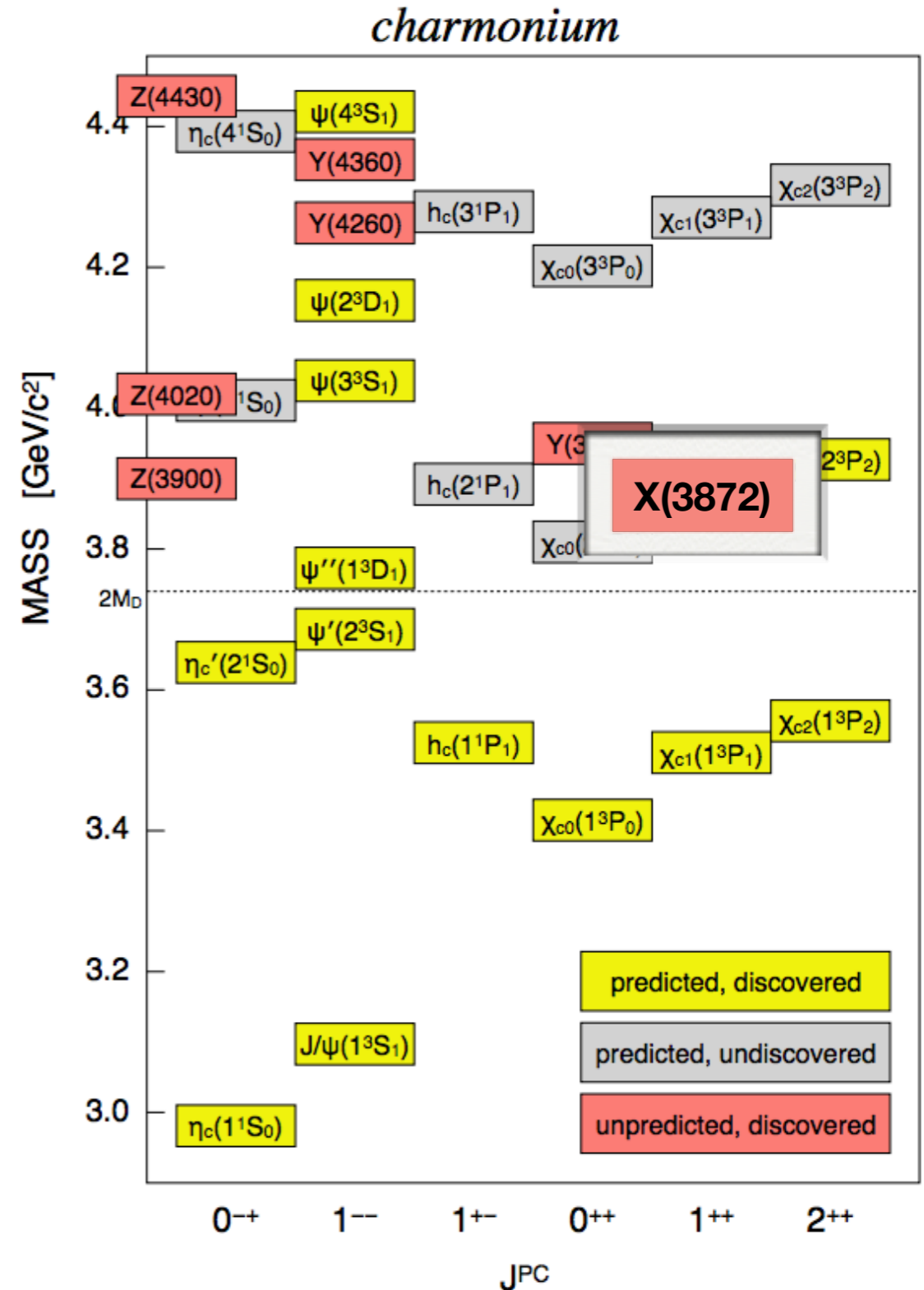
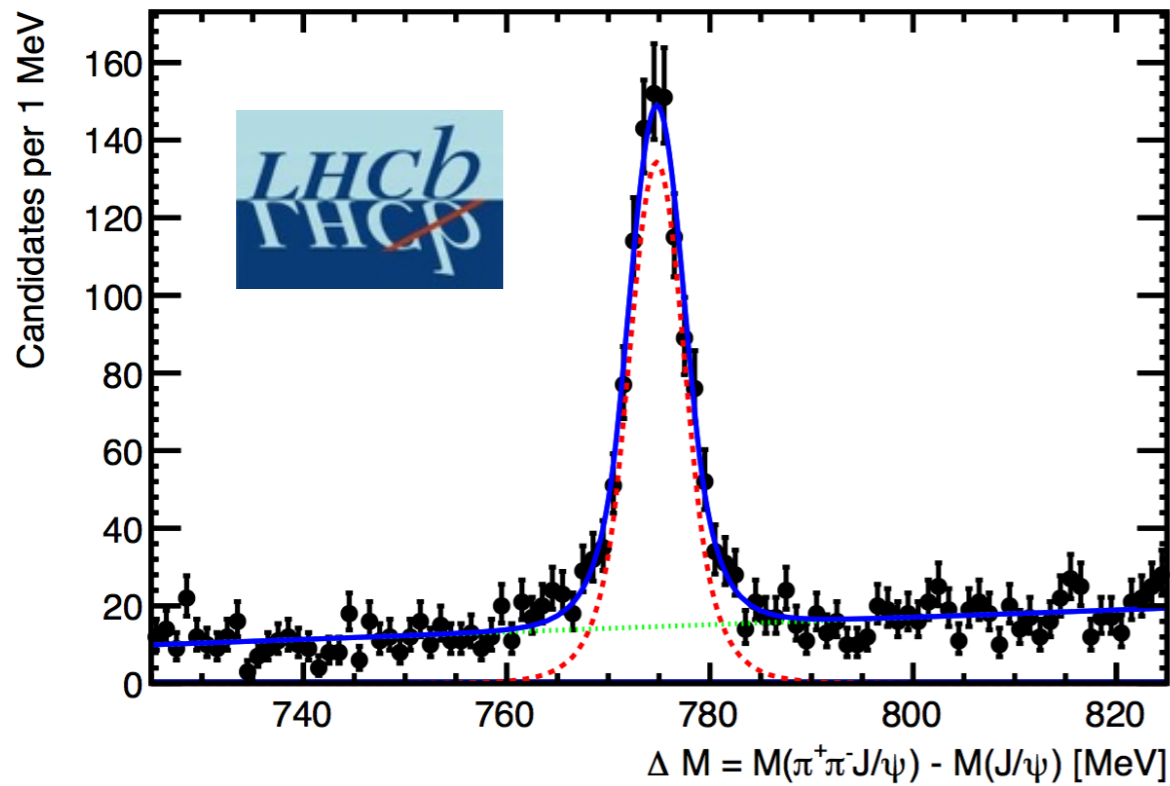
\* Quantum numbers

\*  $M_X \sim M_D + M_{D^*}$

\* Interpretation?

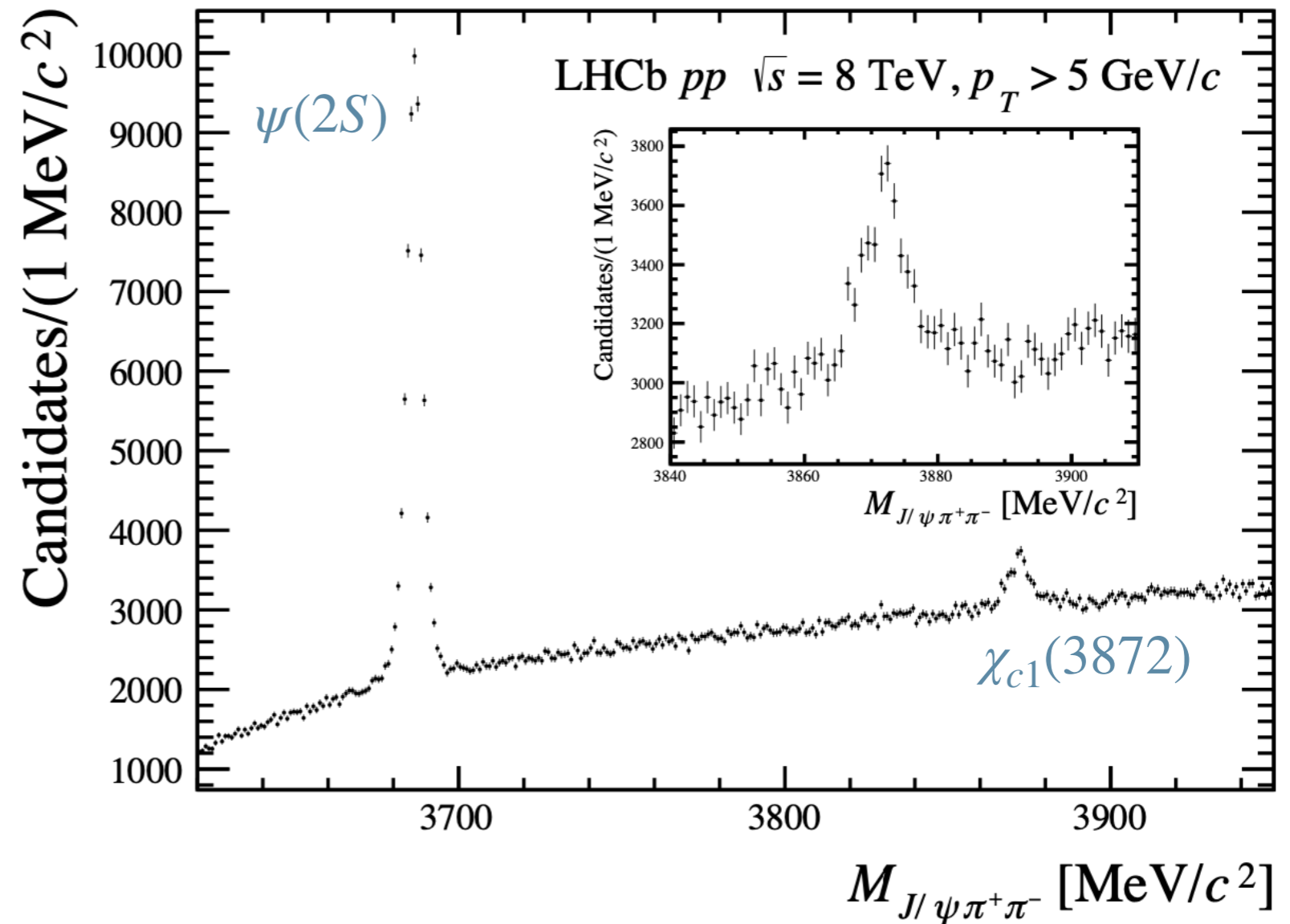


# Where the XYZ odyssey began: **X(3872)**



- \* Higher statistics: **more studies**
- \* Quantum numbers
- \*  **$M_X \sim M_D + M_{D^*}$**
- \* Interpretation?

# $\chi_{c1}(3872)$ compared to $\psi(2S)$



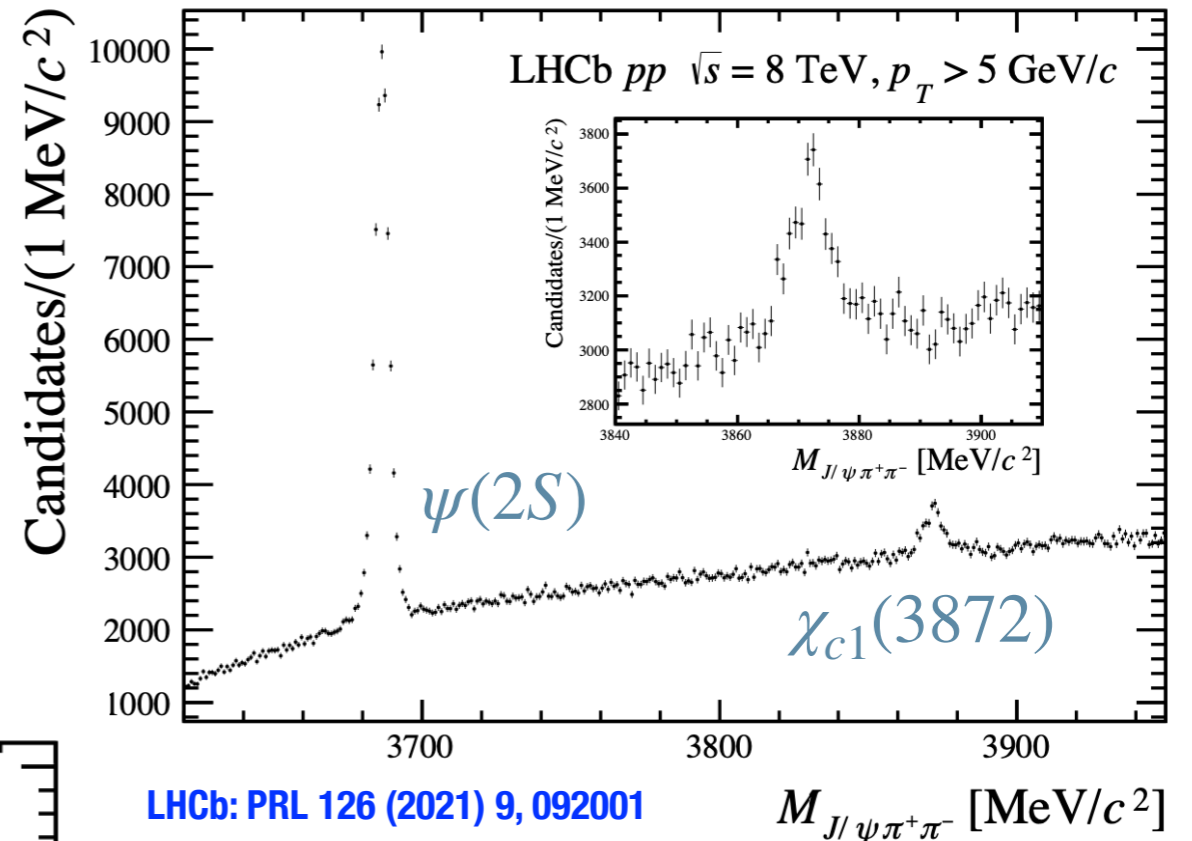
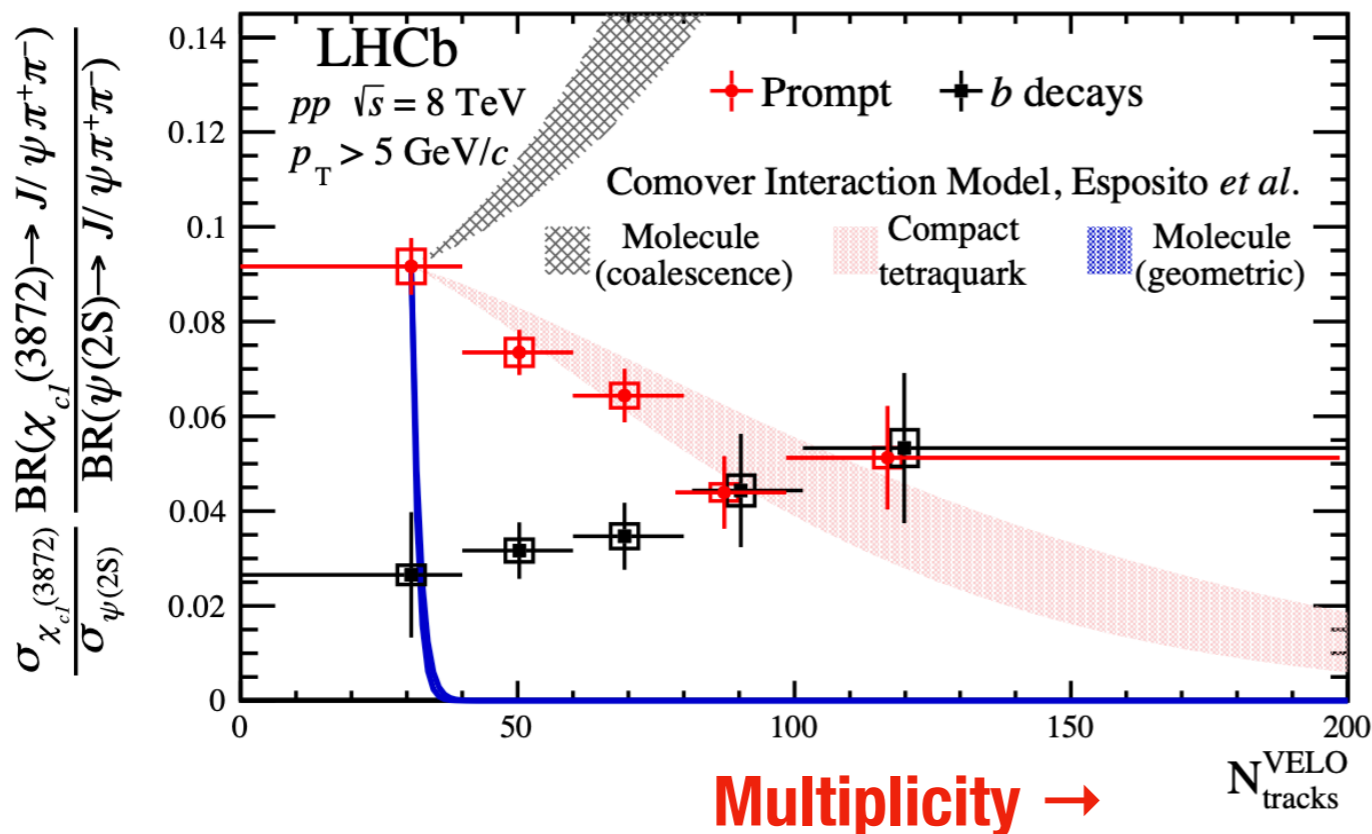
LHCb: PRL 126 (2021) 9, 092001

- \* LHCb results on “prompt”  $\chi_{c1}(3872)$  production demonstrate robust signal, not just from B-decays

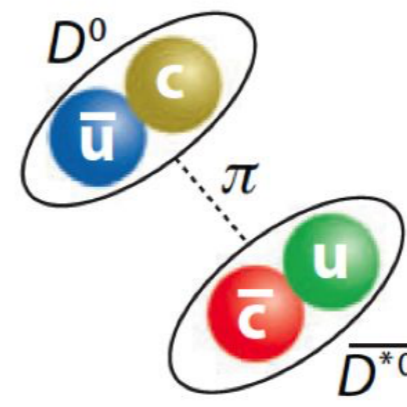
# $\chi_{c1}(3872)$ compared to $\psi(2S)$

- Recent LHCb results in pp show prompt  $\chi_{c1}(3872)$  decreases with multiplicity

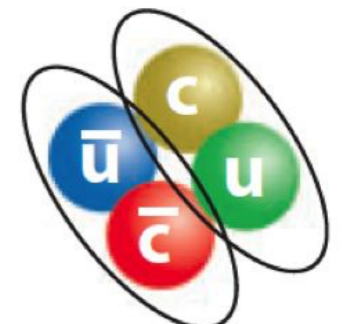
$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \frac{\text{BR}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\text{BR}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}$$



**Molecule**



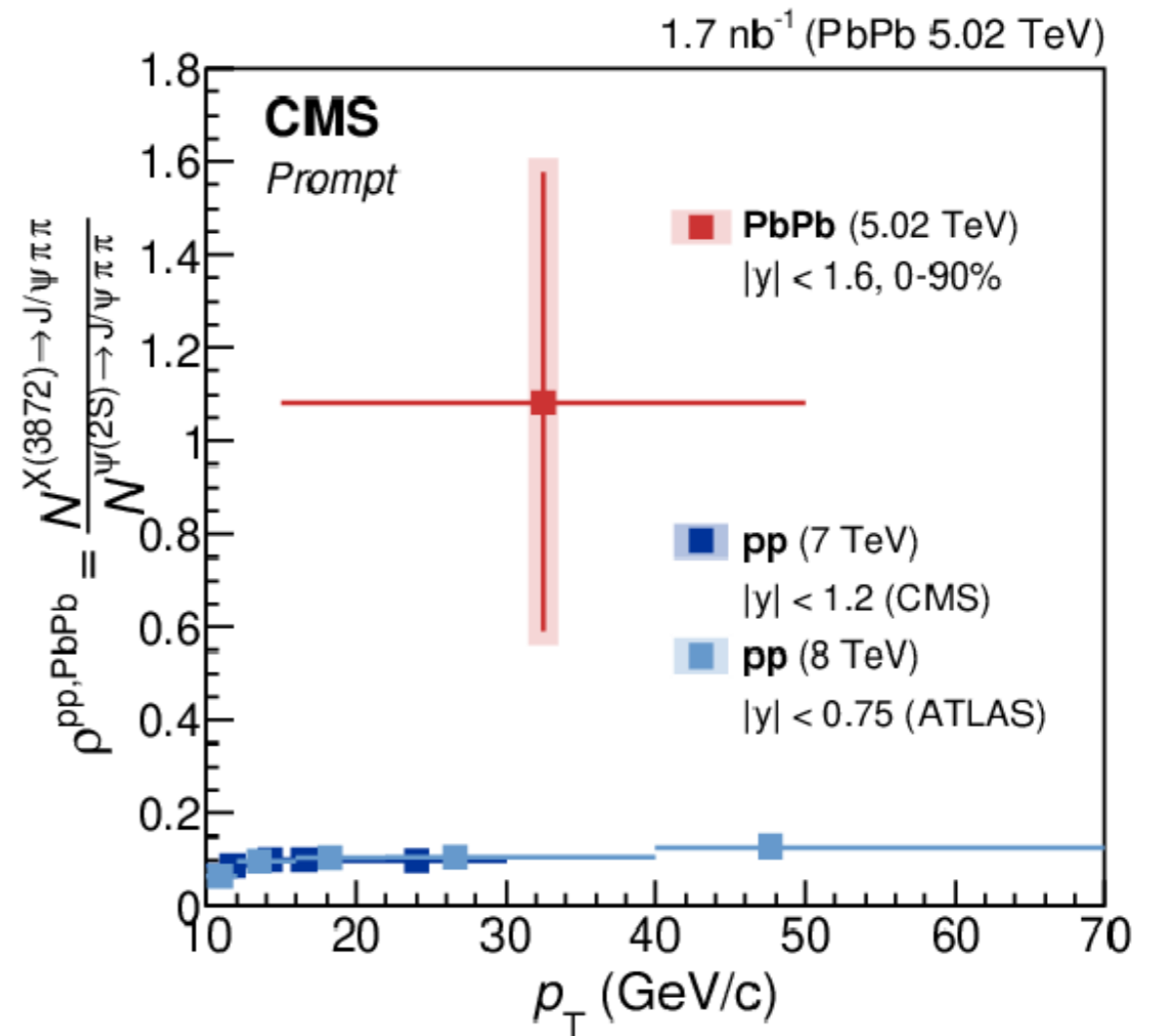
**Compact Tetraquark**



# $\chi_{c1}(3872)$ in heavy ion collisions

- \* Recent LHCb results in pp show prompt  $\chi_{c1}(3872)$  decreases with multiplicity
- \* First observation of prompt  $\chi_{c1}(3872)$  in PbPb at CMS not suppressed relative to  $\psi(2S)$

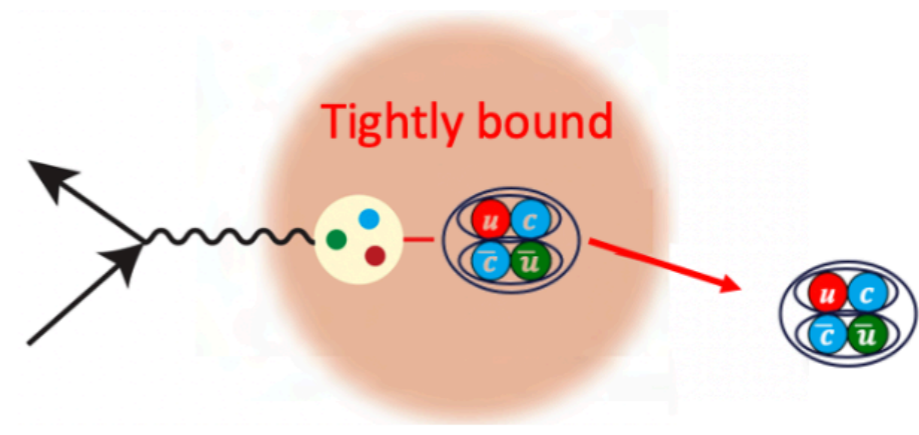
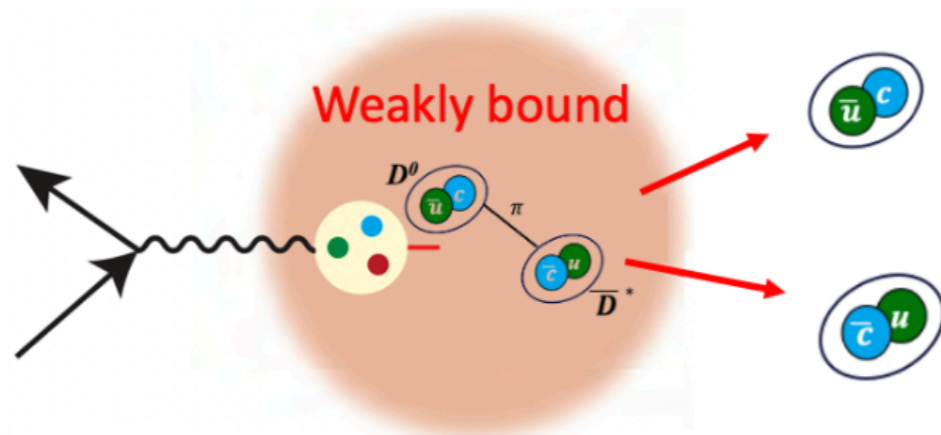
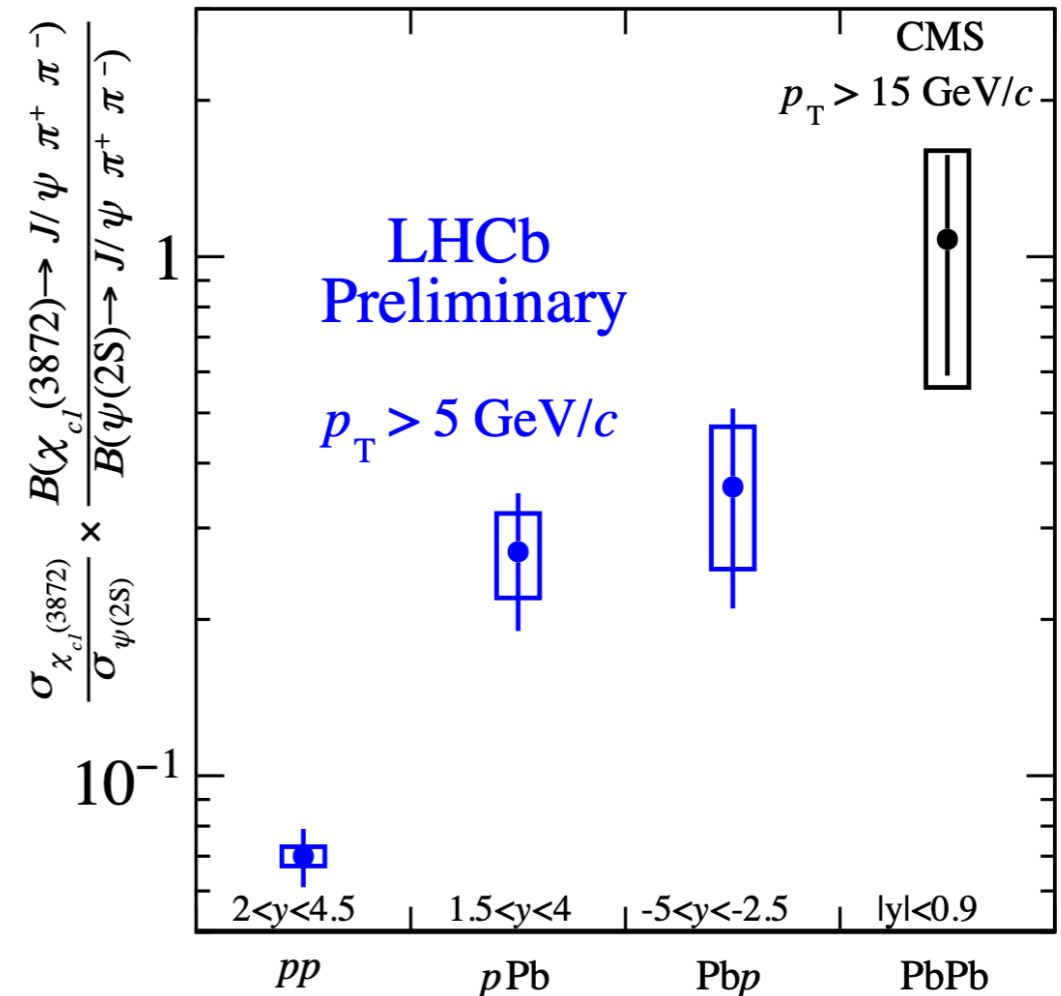
$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \frac{\text{BR}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\text{BR}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}$$



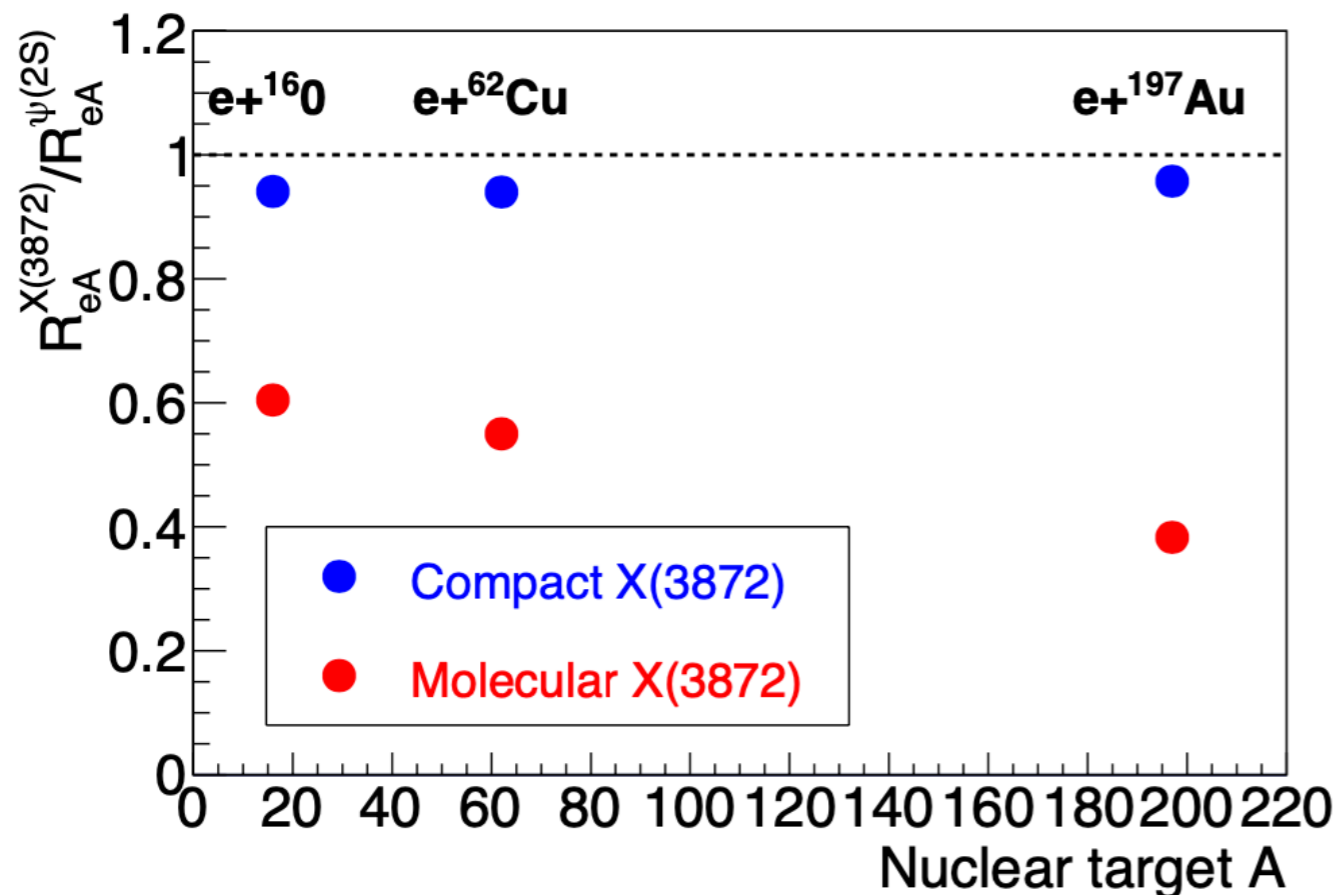
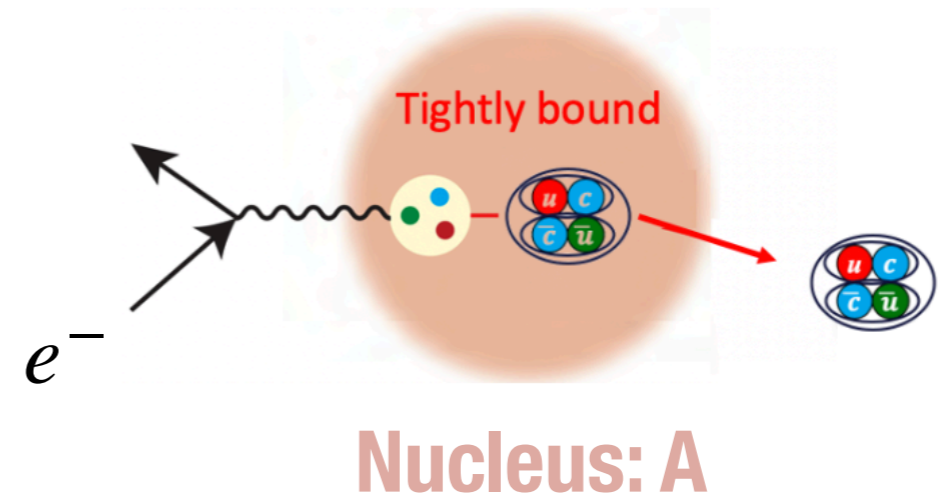
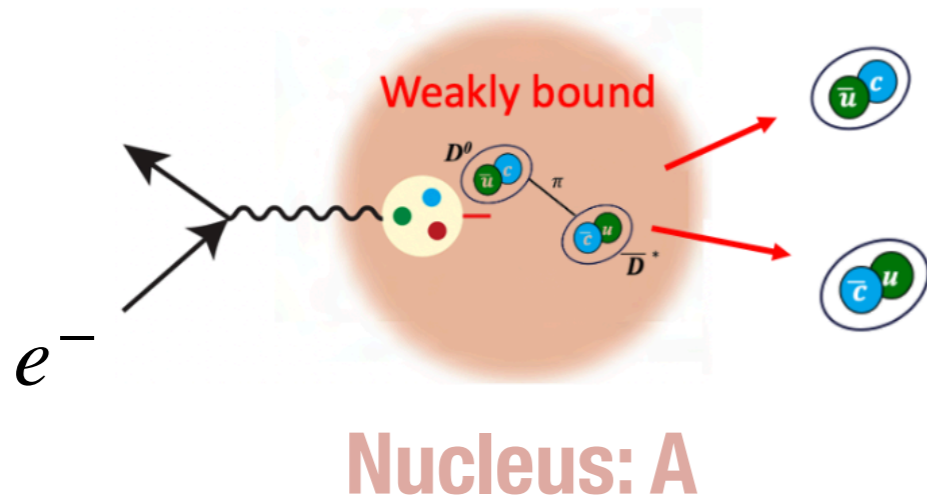
CMS: PRL 128 (2022) 3, 032001

# $\chi_{c1}(3872)$ in heavy ion collisions

- \* Recent LHCb results in pp show prompt  $\chi_{c1}(3872)$  decreases with multiplicity
- \* First observation of prompt  $\chi_{c1}(3872)$  in PbPb at CMS not suppressed relative to  $\psi(2S)$
- \* Enhancement in pPb relative to pp, increase with system size



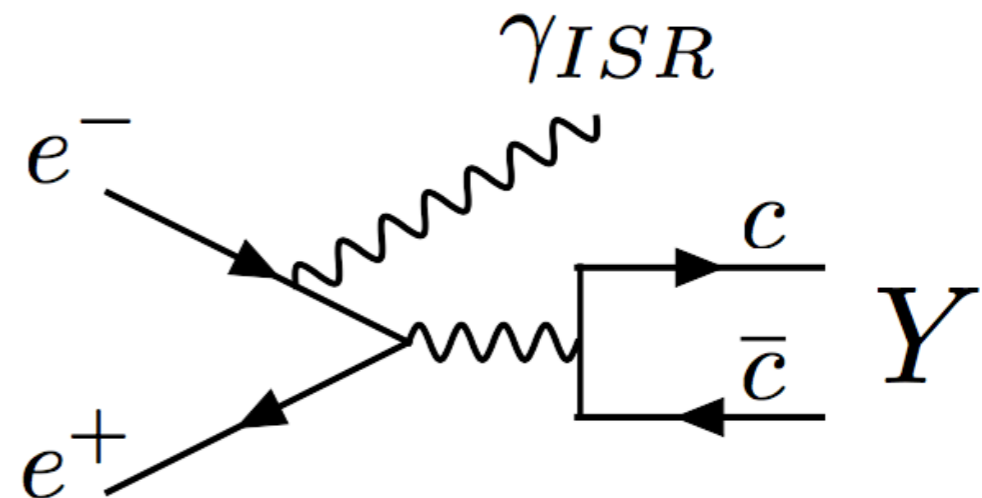
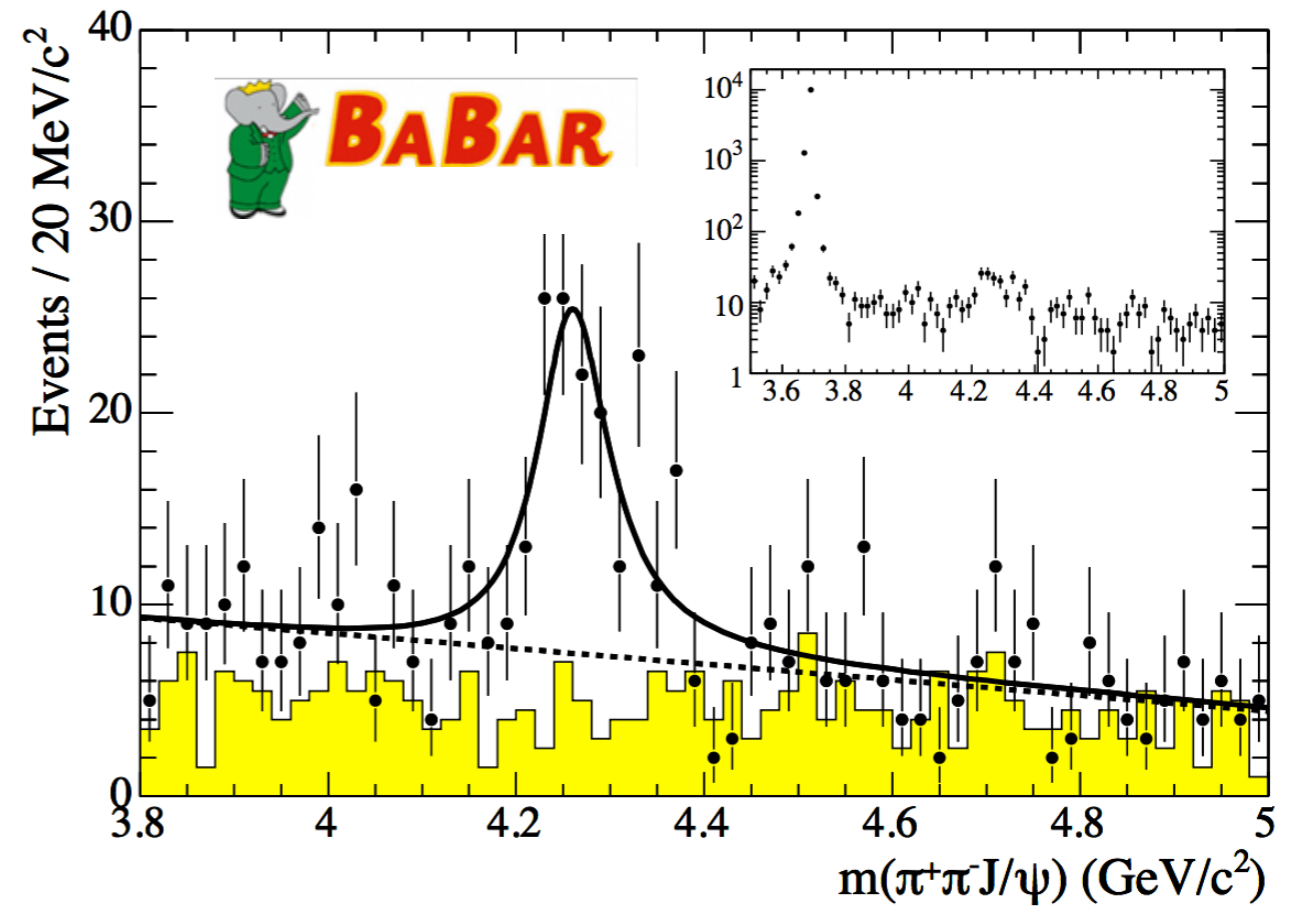
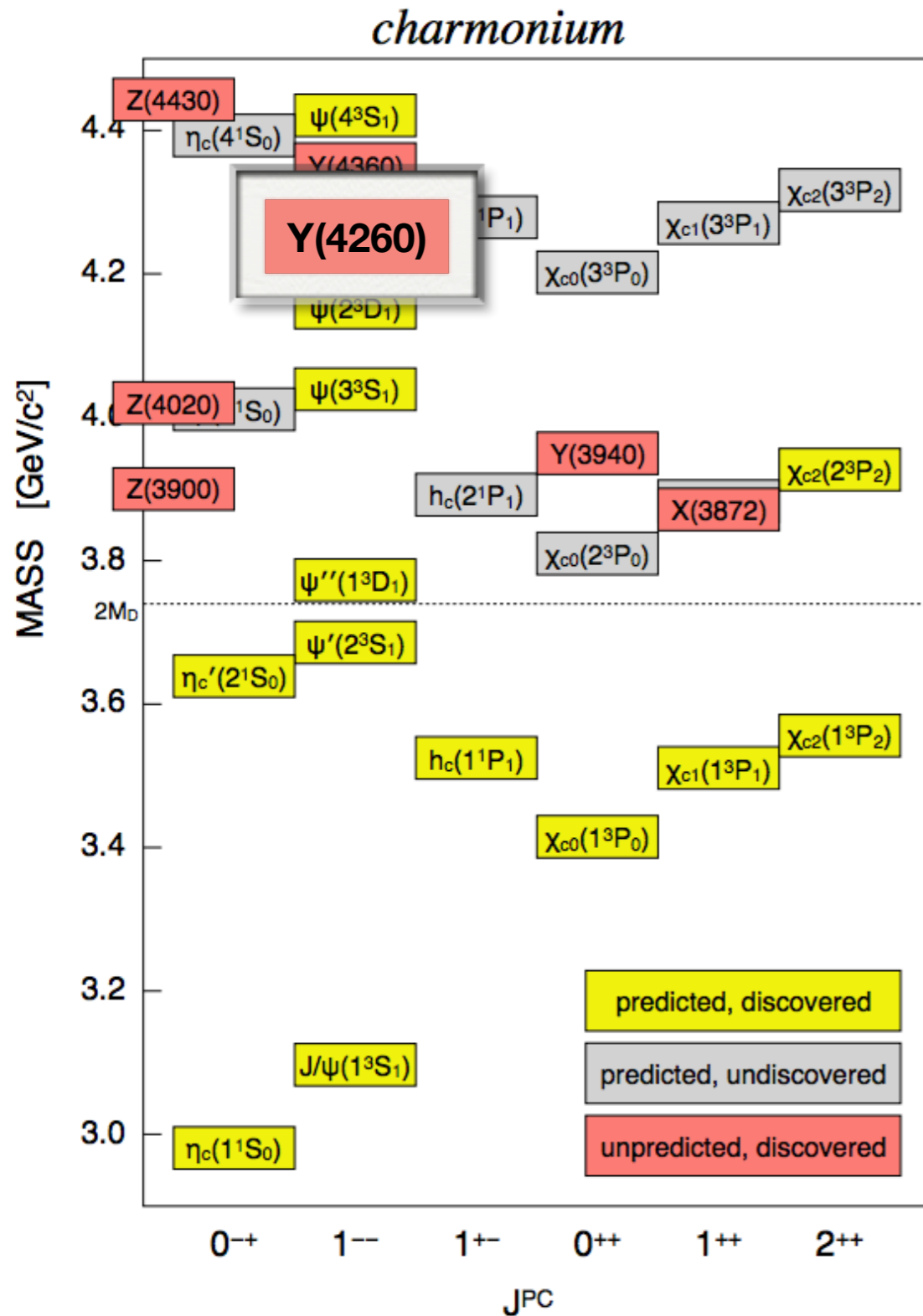
# Electroproduction of $X(3872)$ at the EIC



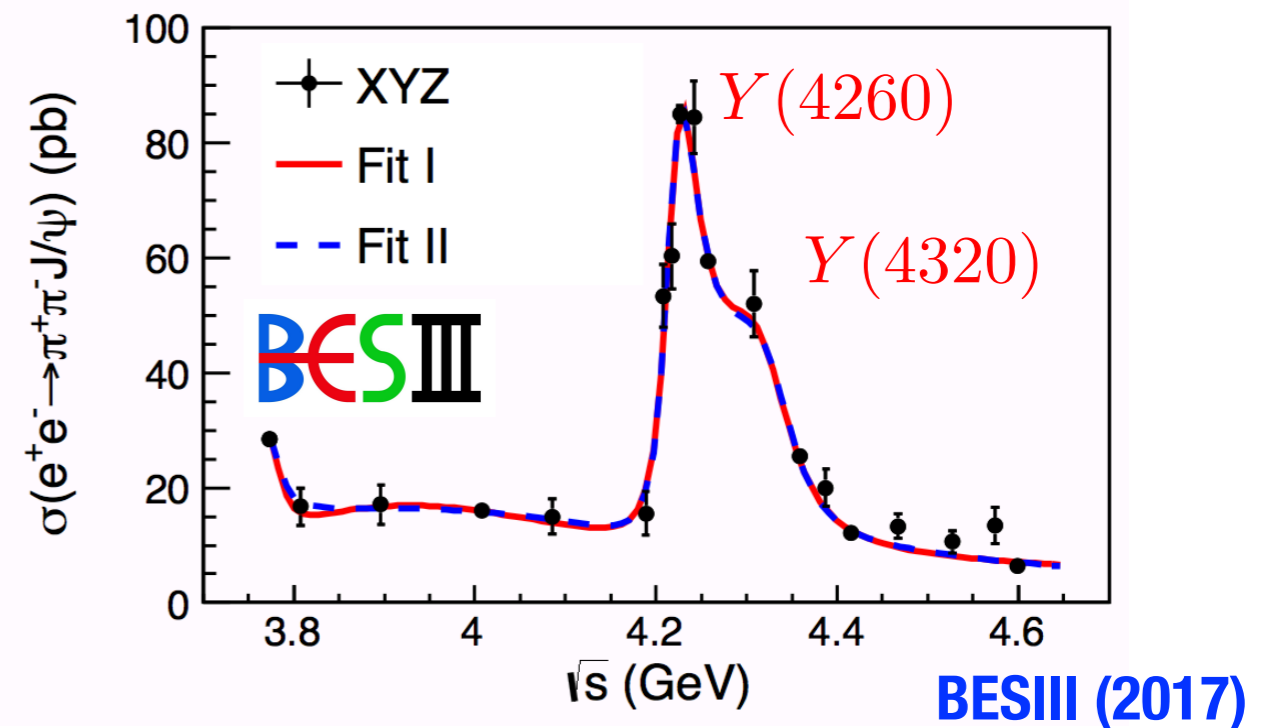
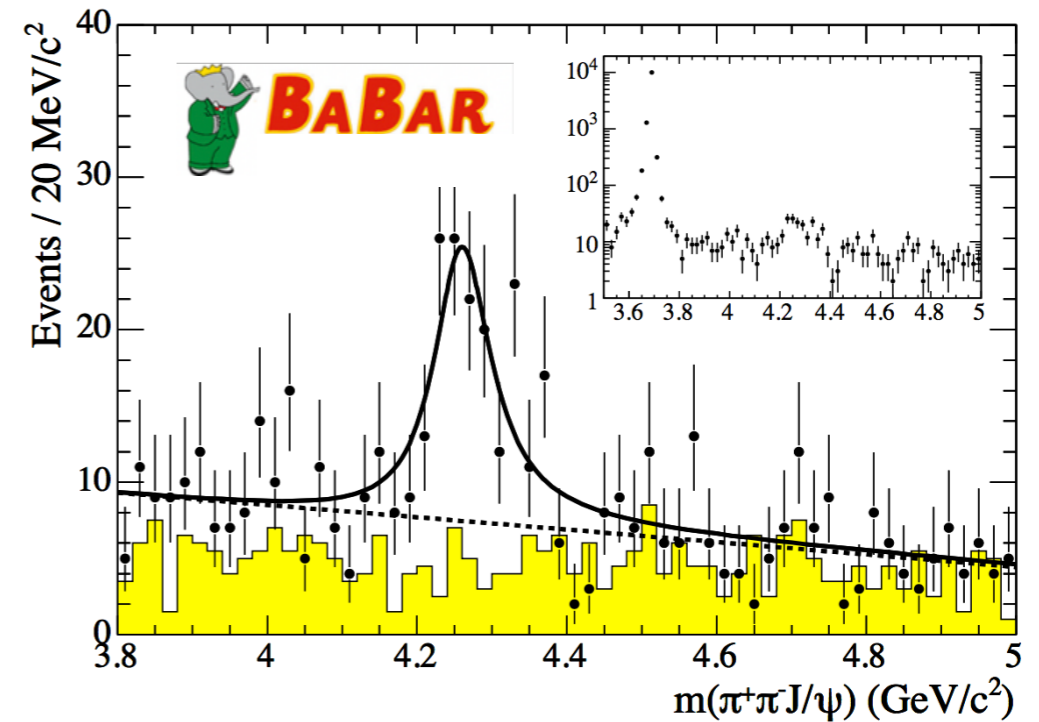
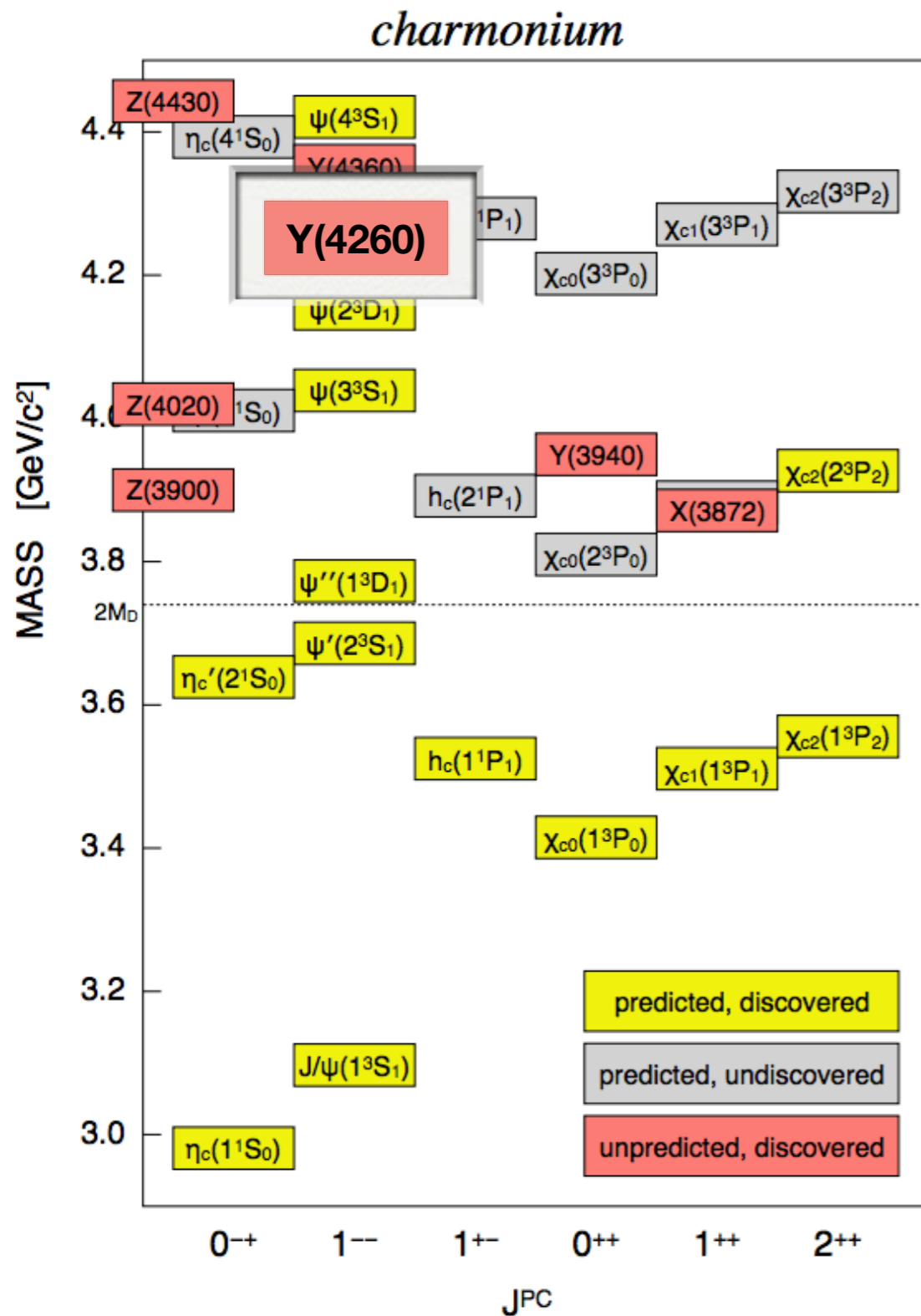
- \* Dependence on breakup of  $X(3872)$  in nuclei?
- \* Little suppression expected for compact tetraquark configuration
- \* Expect suppression of molecular (large size) configuration

# Discovery of the $Y(4260)$

BaBar (2003)

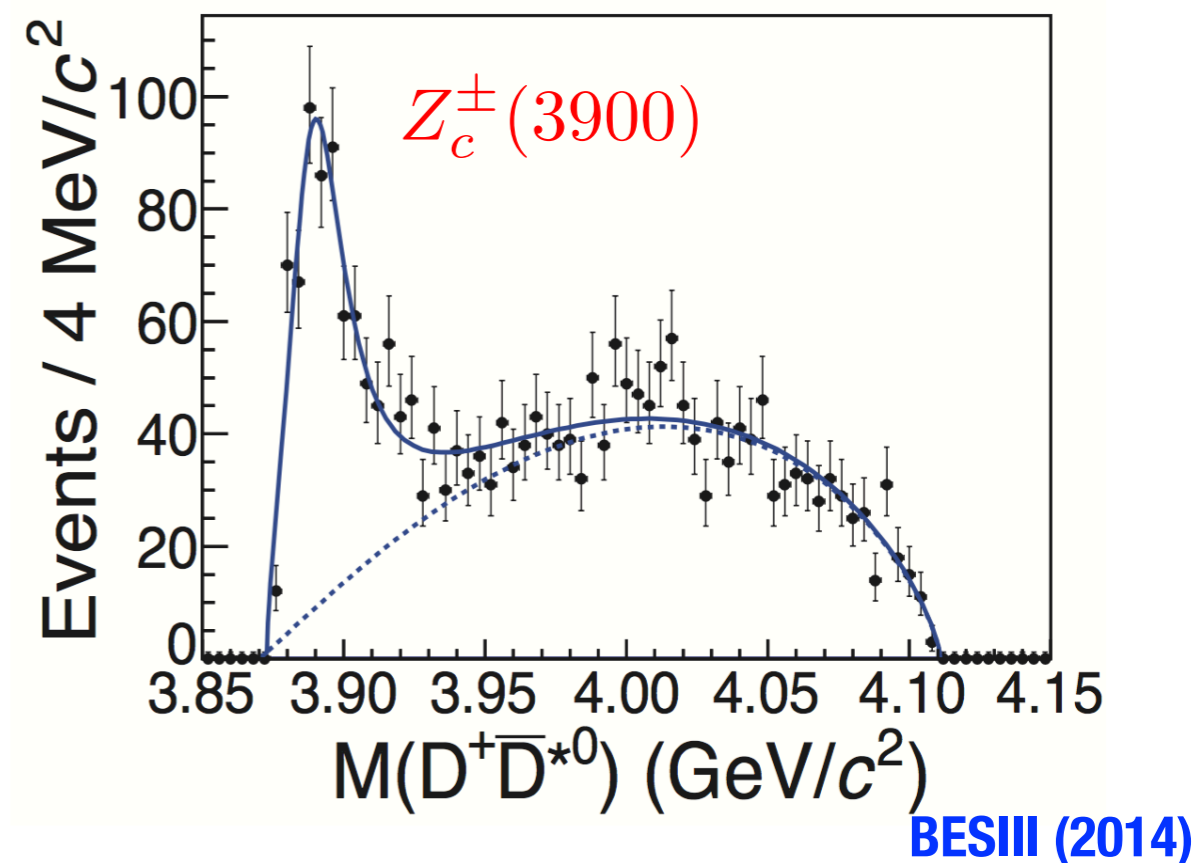
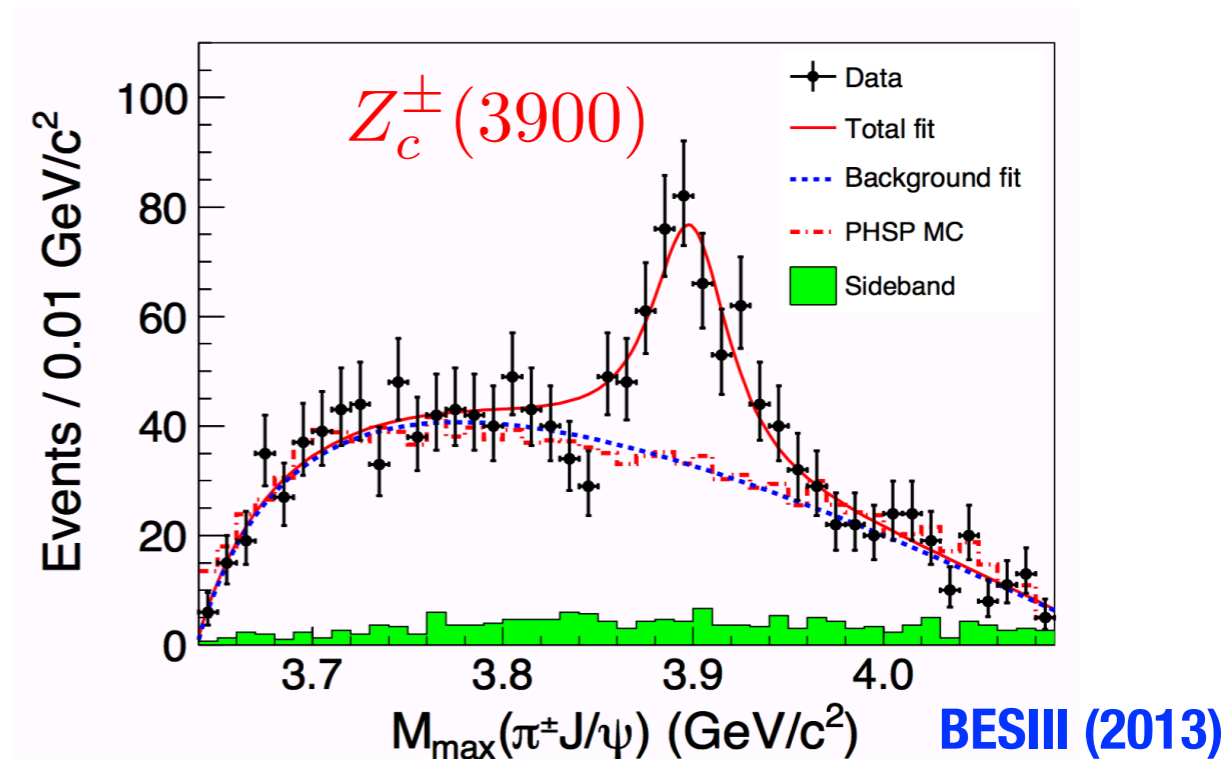
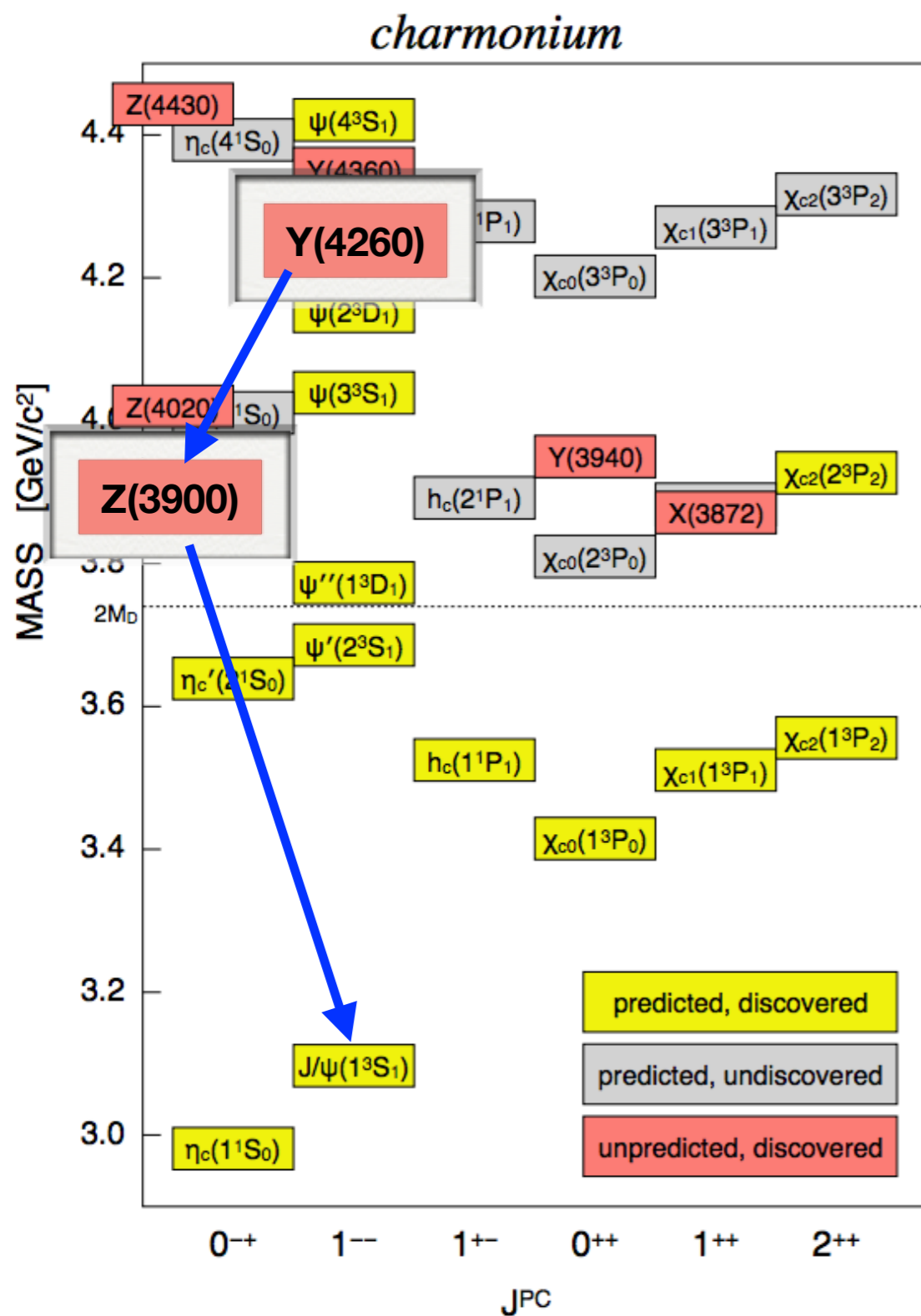


# Diving deeper into $Y(4260)$



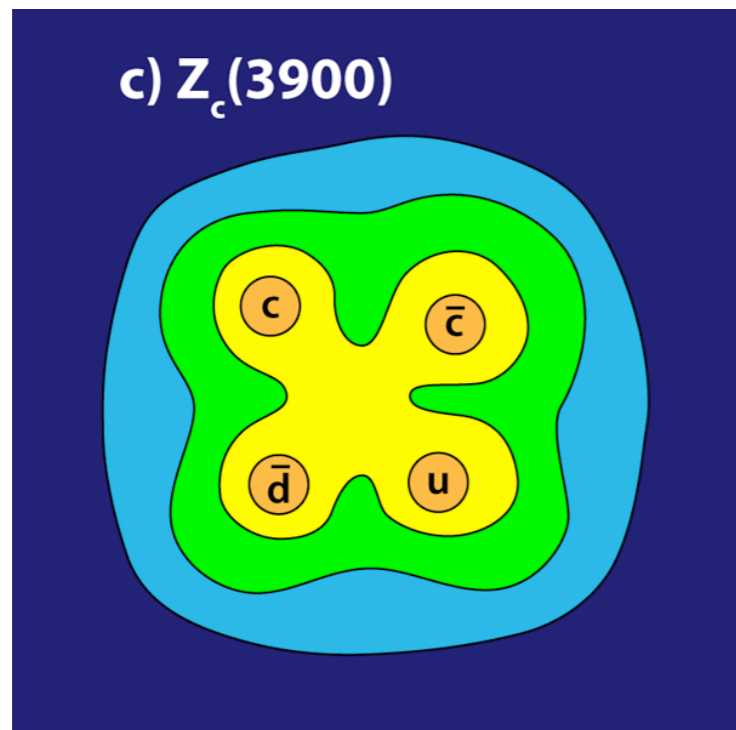
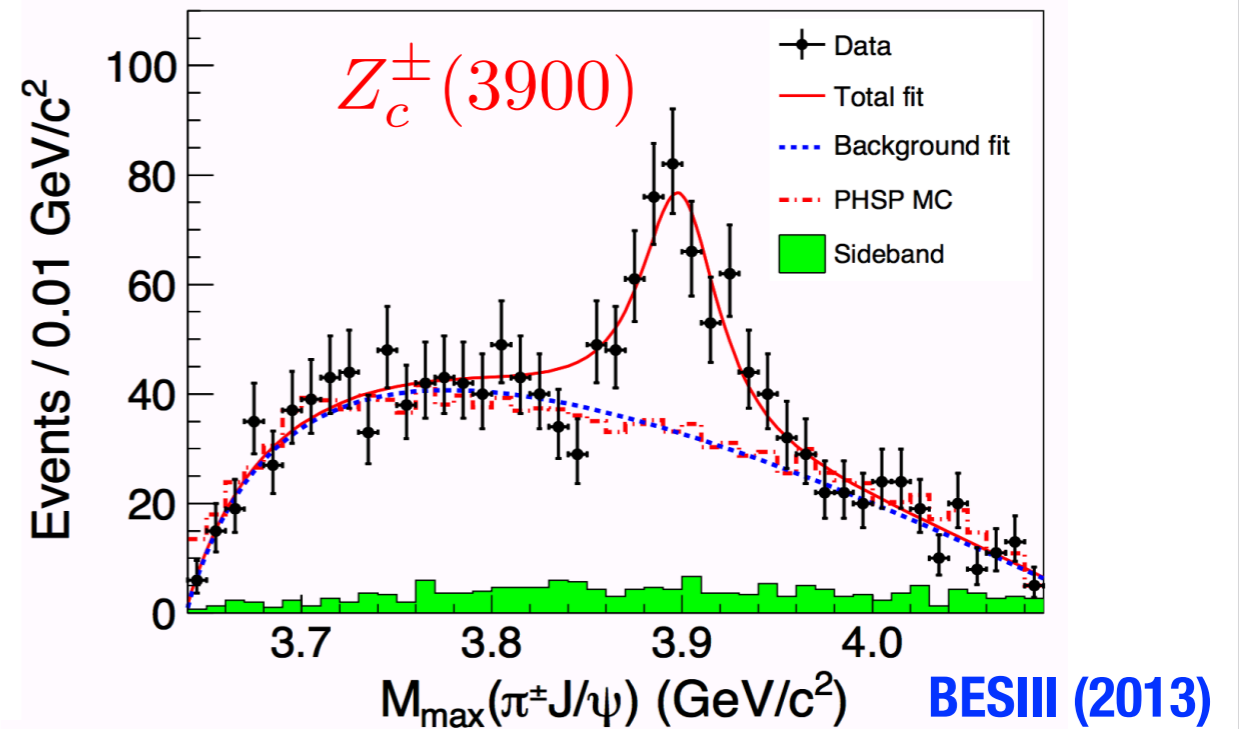
**More statistics: 2 peaks!**

# Diving deeper into $Y(4260)$

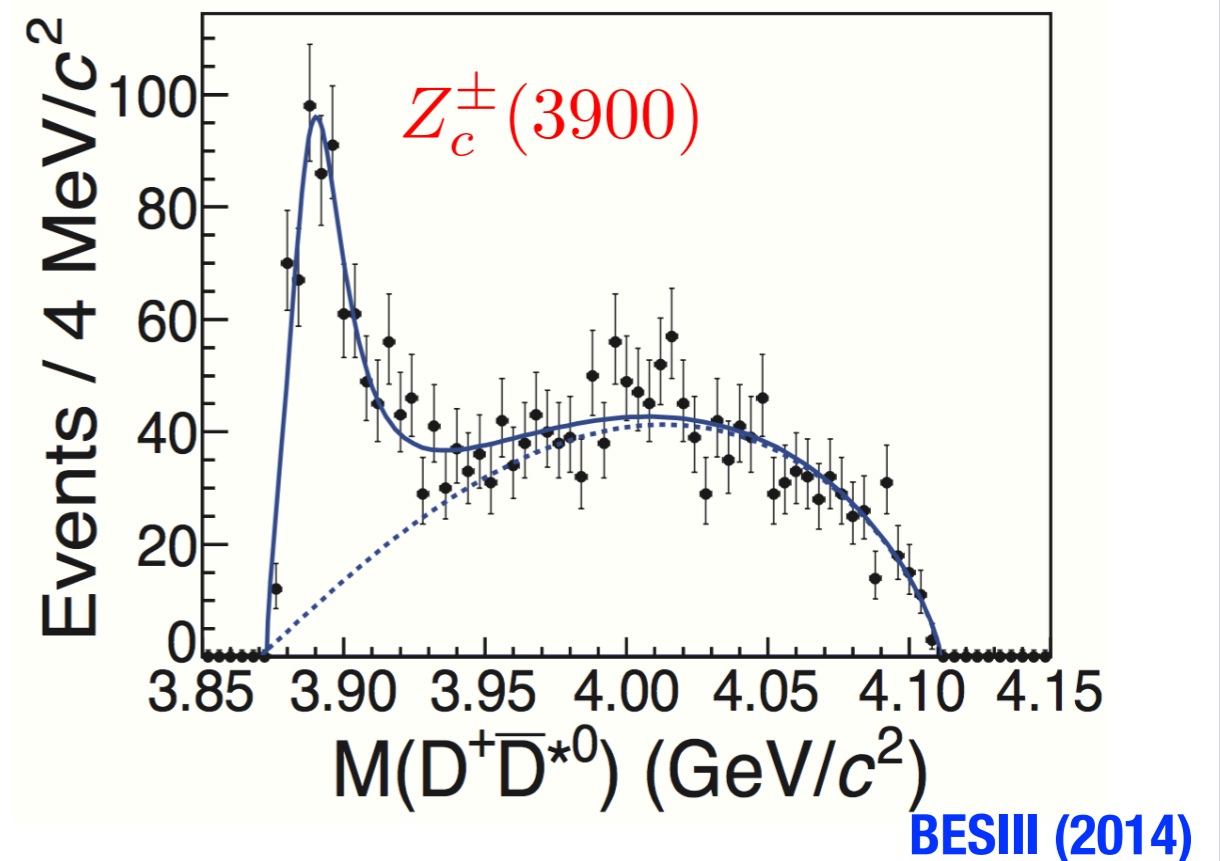


# Four quark state: $Z_c(3900)$

- \* Charged charmonium structure observed in decay of  $Y(4260)$
- \* 4-quark content ( $c\bar{c}u\bar{d}$ )
- \* Neutral partner observed: is it a **tetraquark?**

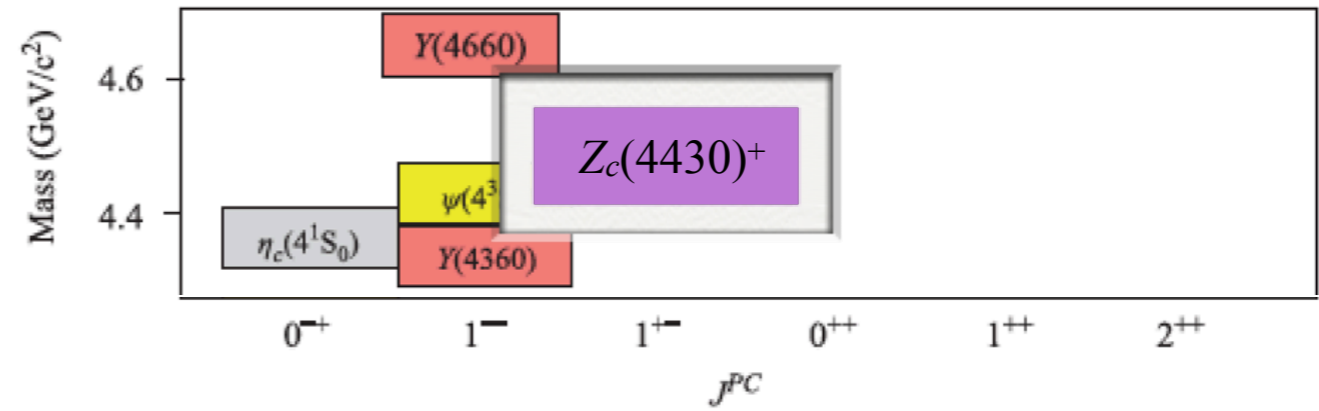
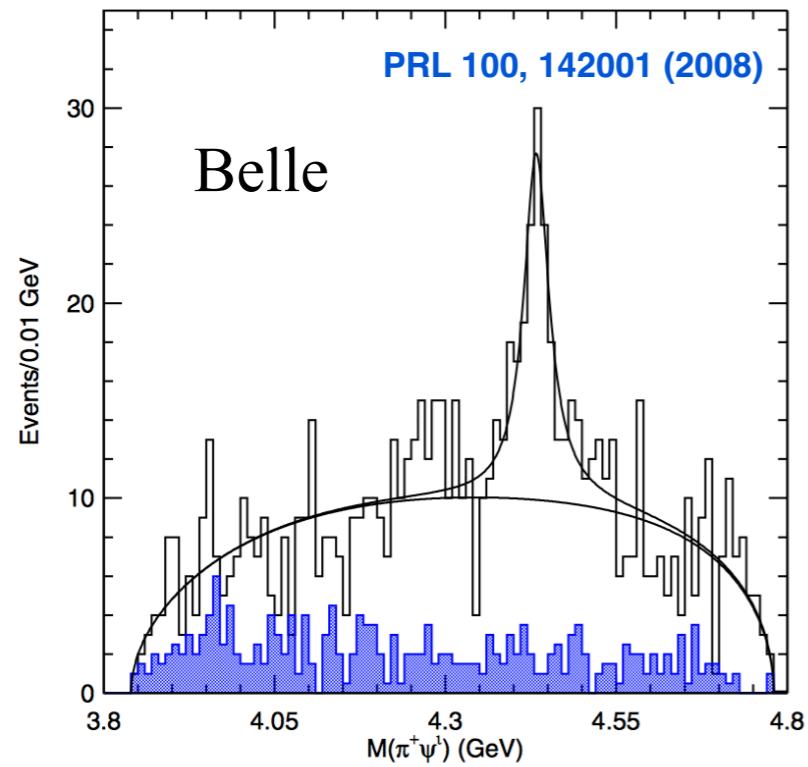


Physics Viewpoint 6, 69 (2013)



# $Z_c^+(4430)$

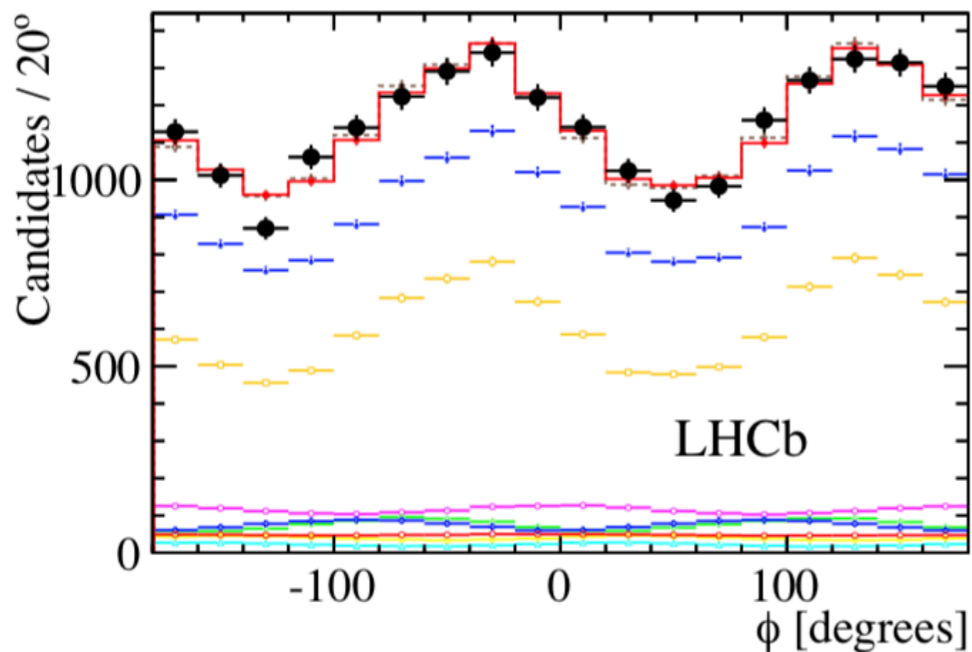
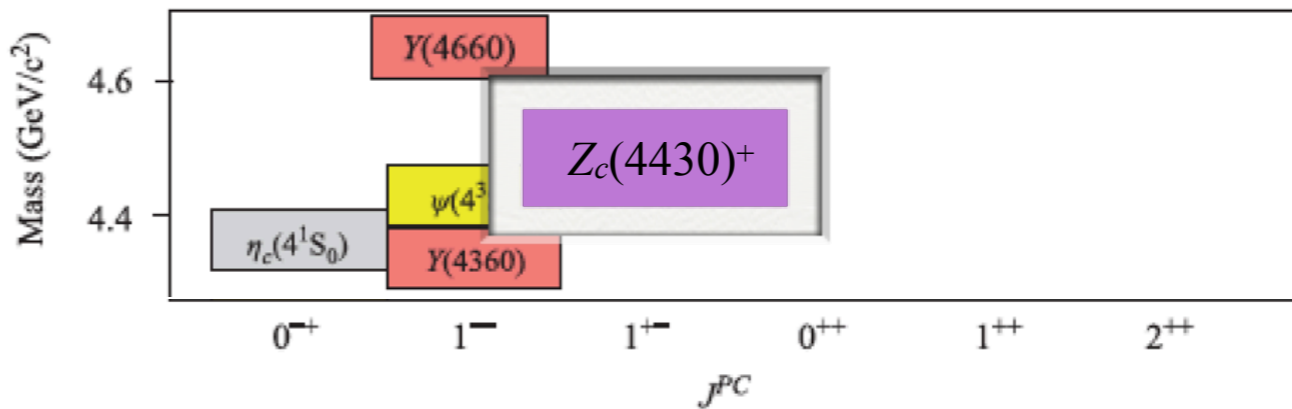
$$B \rightarrow K(\pi\psi')$$



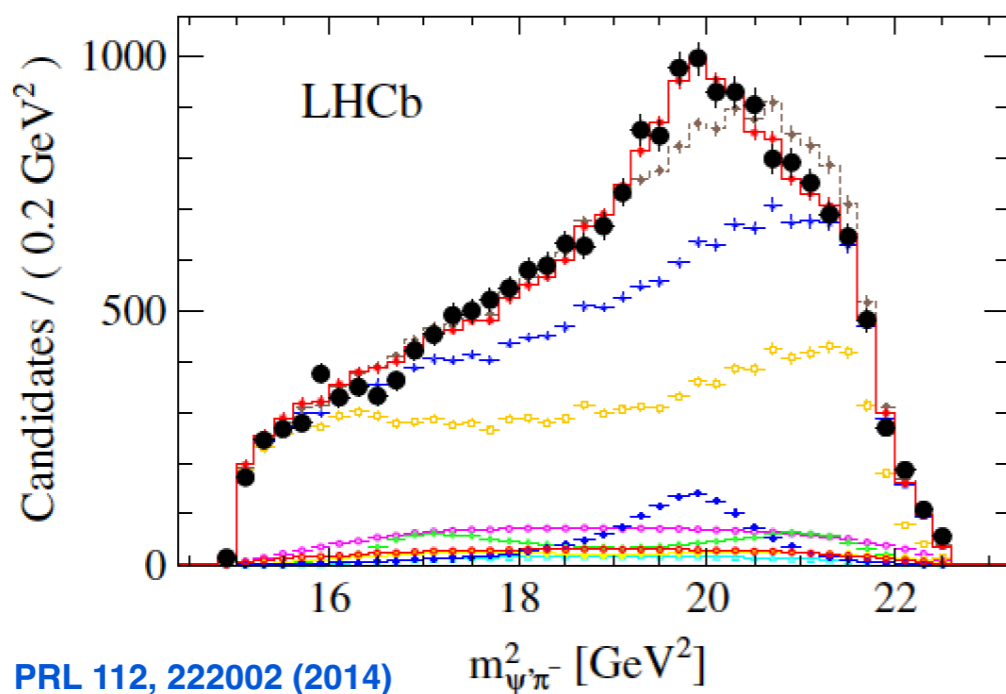
- \* Charged charmonium structure observed in 2008 by Belle

# $Z_c^+(4430)$

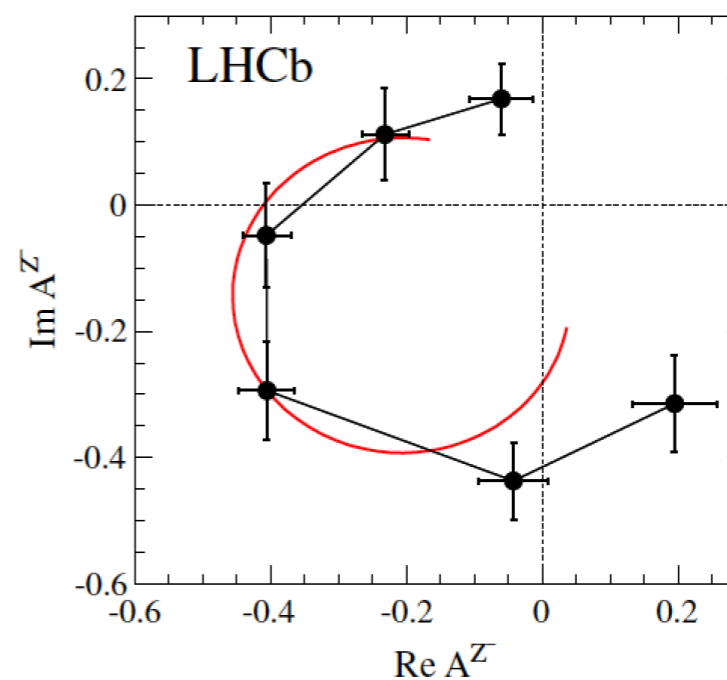
$$B \rightarrow K(\pi\psi')$$



- ✦ Charged charmonium structure observed in 2008 by Belle
- ✦ Recently emphatically confirmed by LHCb and resonant character observed

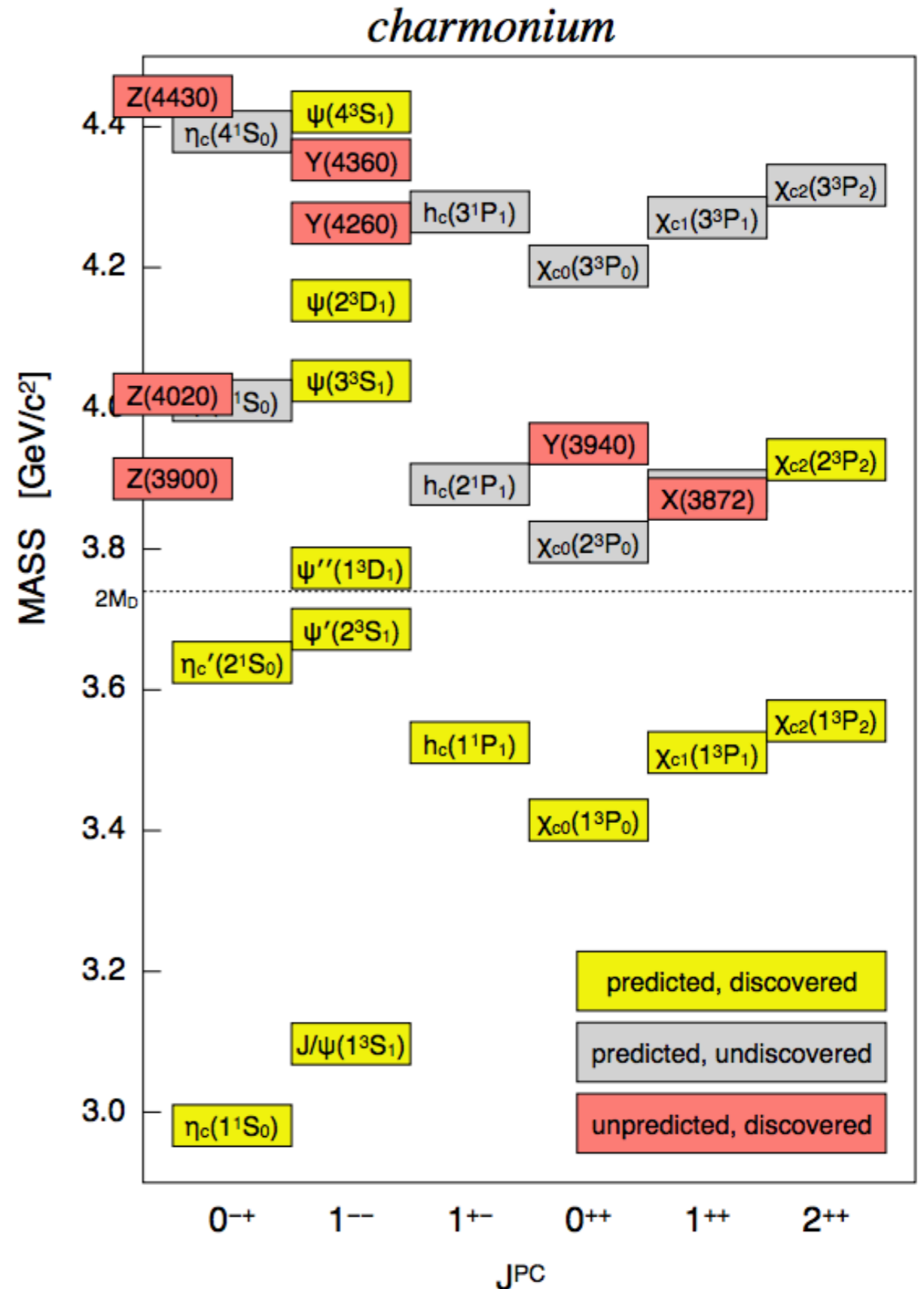


PRL 112, 222002 (2014)



# Heavy quark summary

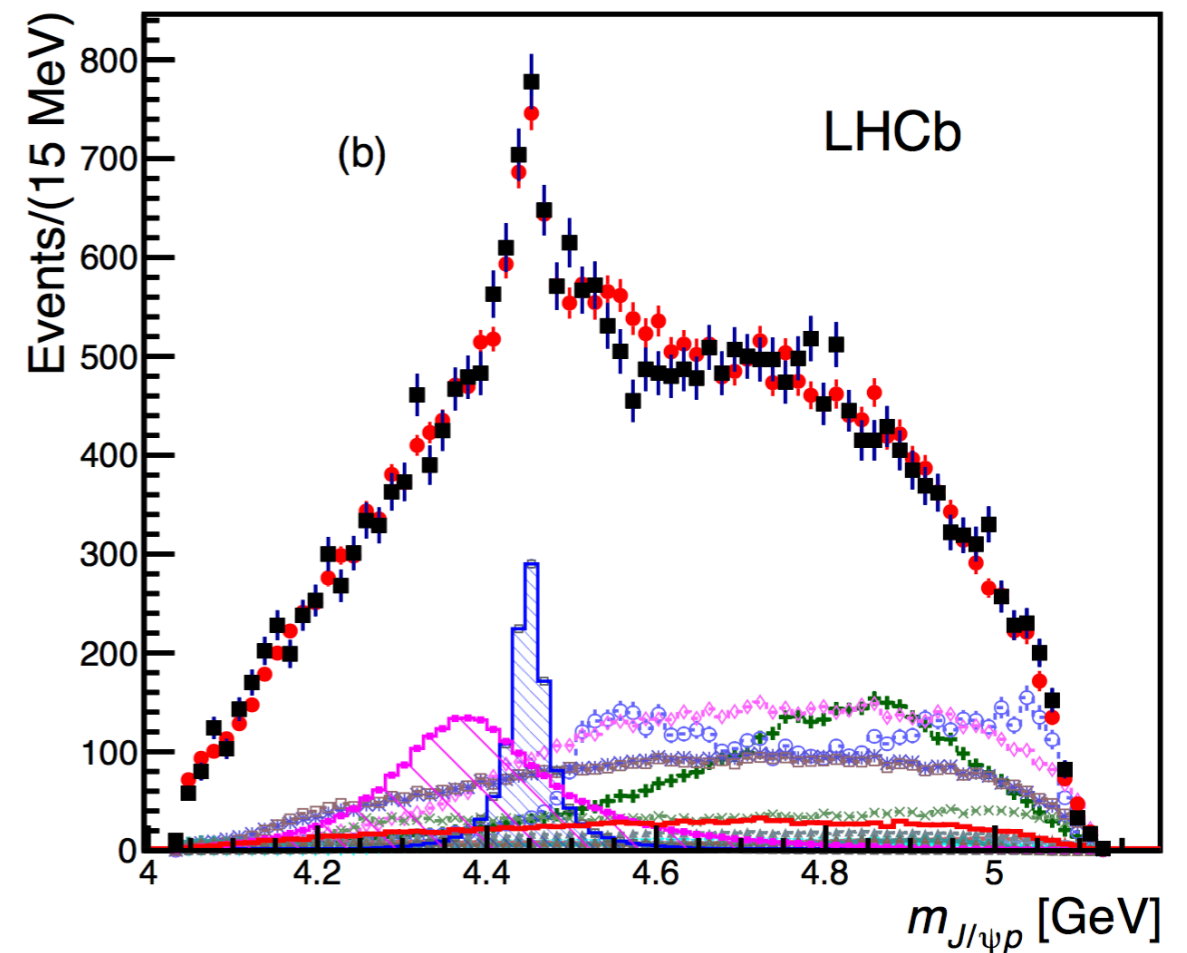
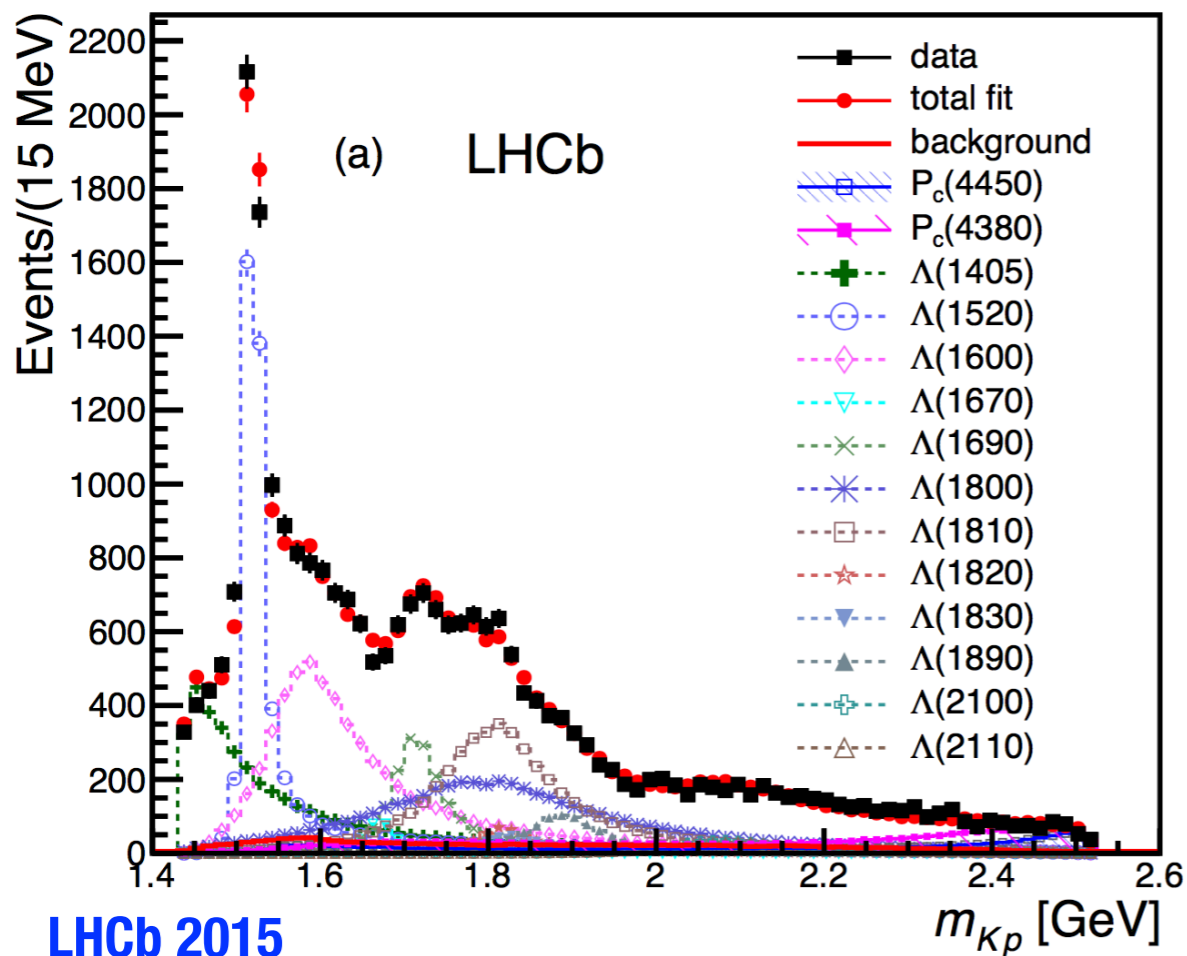
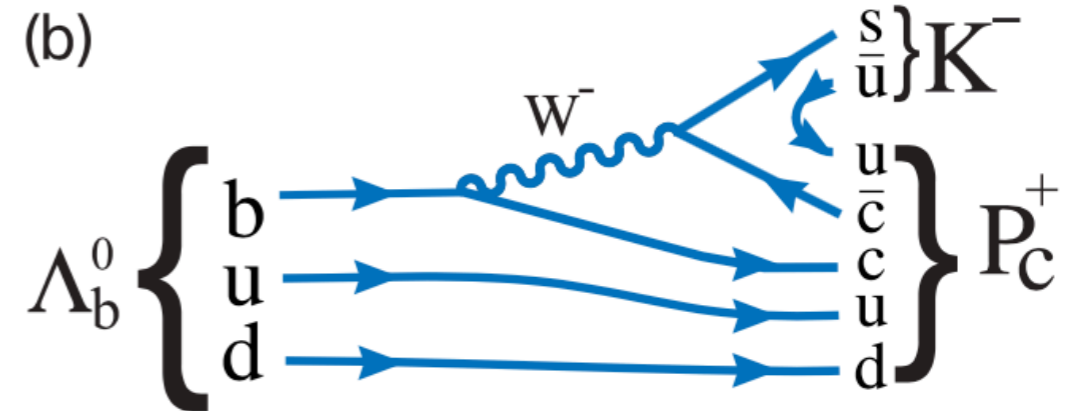
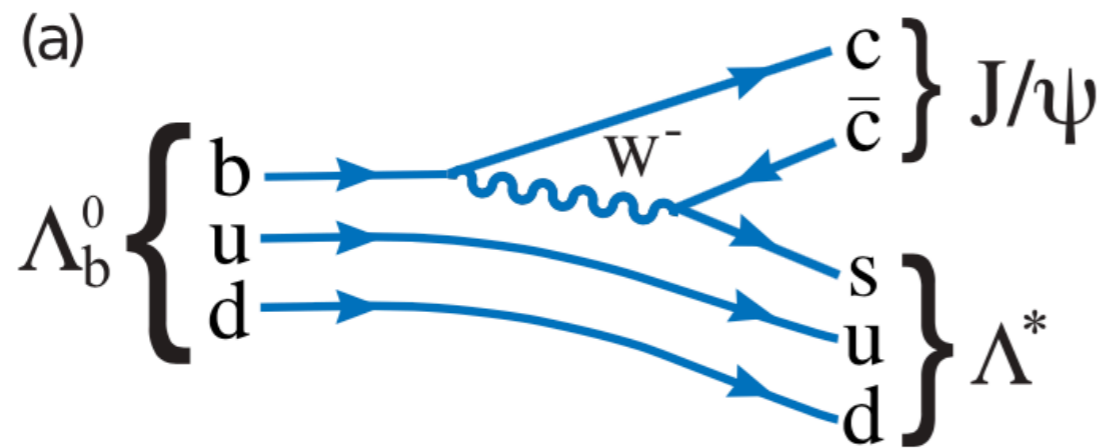
- \* Explosion of new heavy quark XYZ states
- \* No signs of slowing: more data from LHCb, BESIII, Belle II, and PANDA
- \* Models describing tightly bound resonances, molecules, rescattering...
- \* New decay modes and production mechanism shed new light



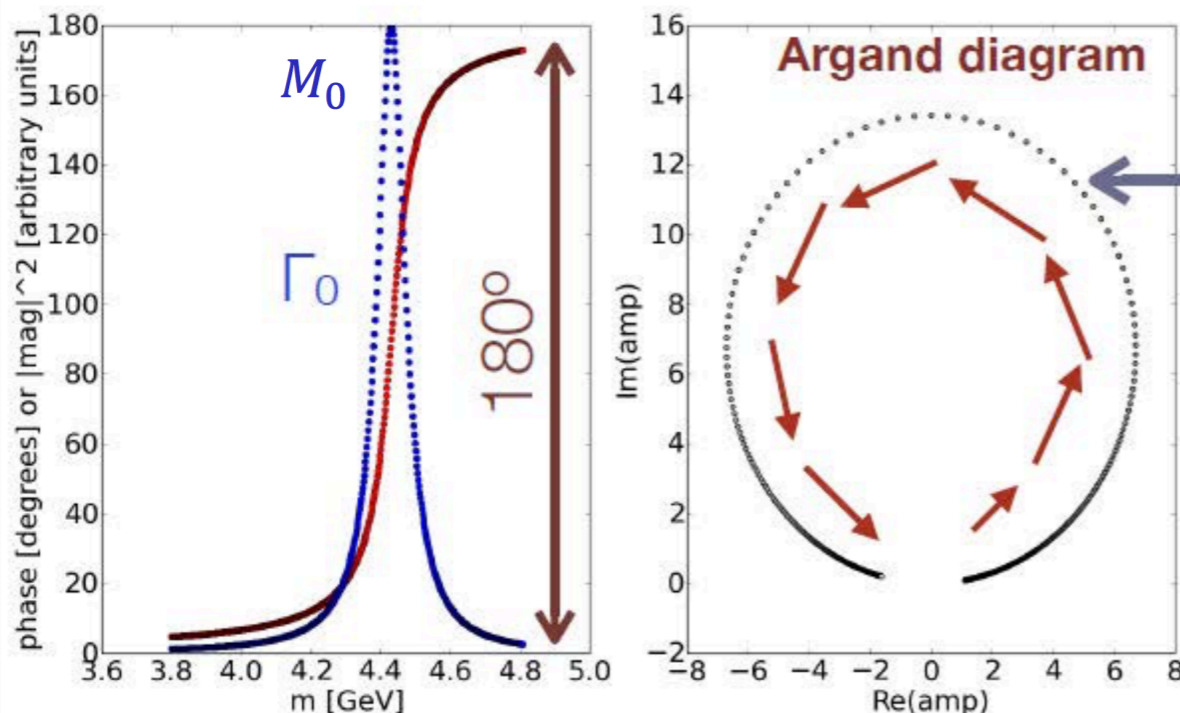
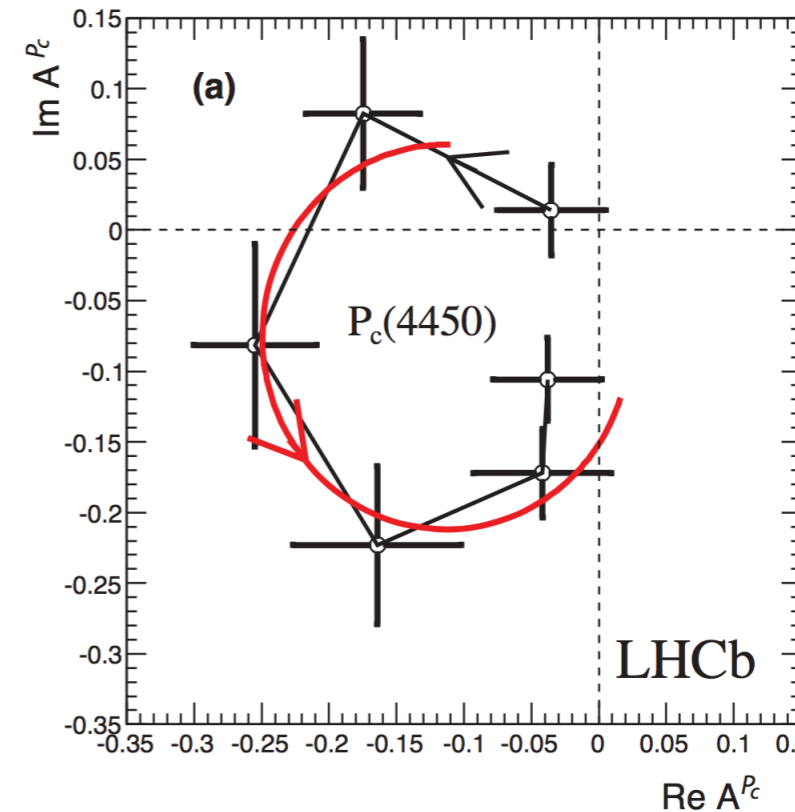
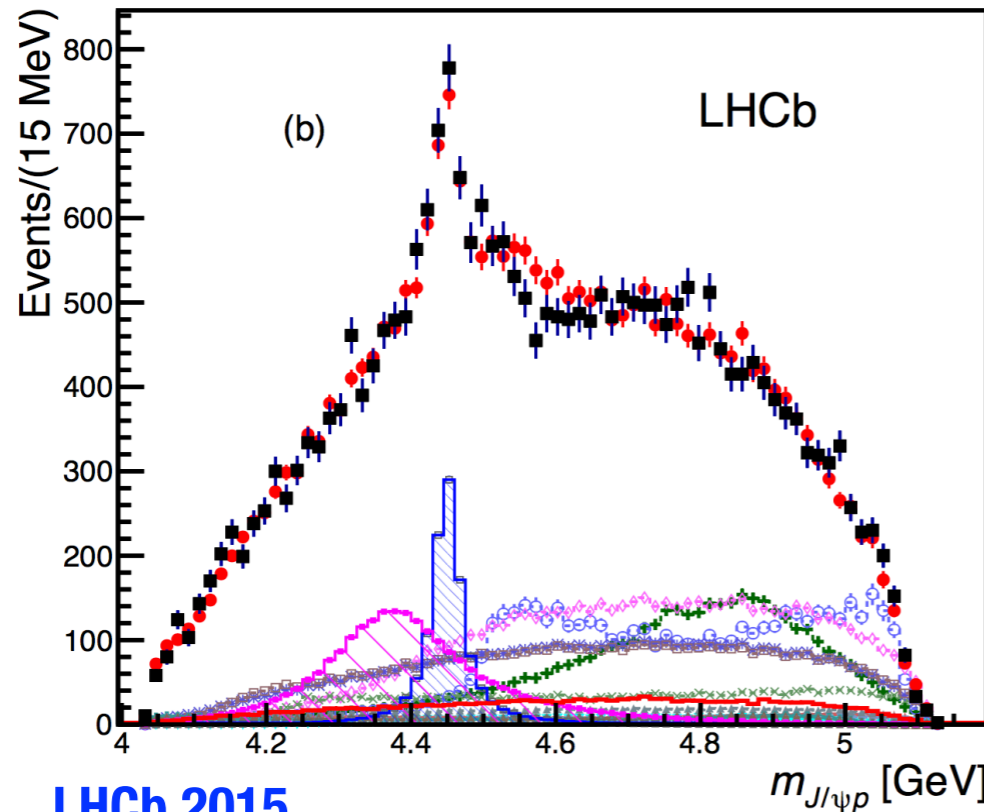
# Pentaquark surprise



$$\Lambda_b \rightarrow J/\psi p K^-$$



# Interpretation: phase motion

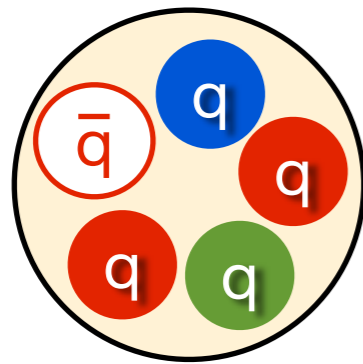
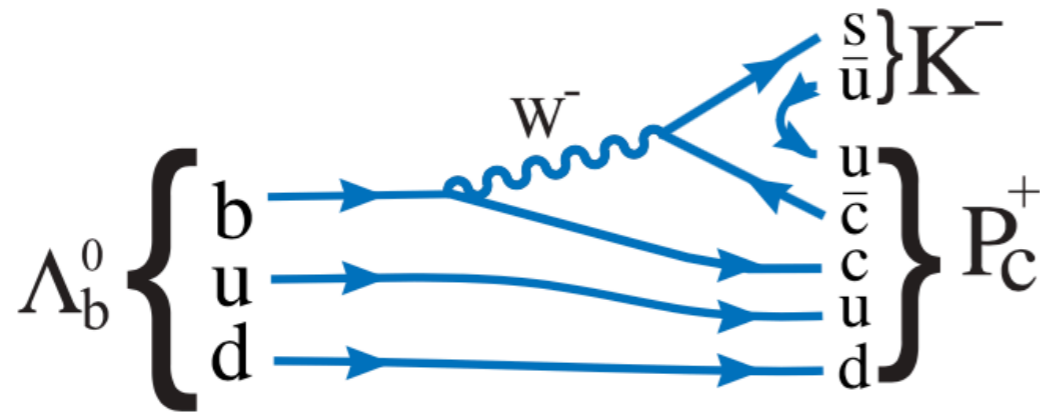


- \* **Breit-Wigner:** complex valued function of mass describing the “resonance”

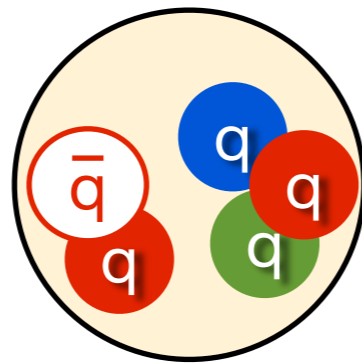
$$BW(m|M_0, \Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

- \* Expect circular trajectory in the complex plane: 180° phase change over the particle’s mass

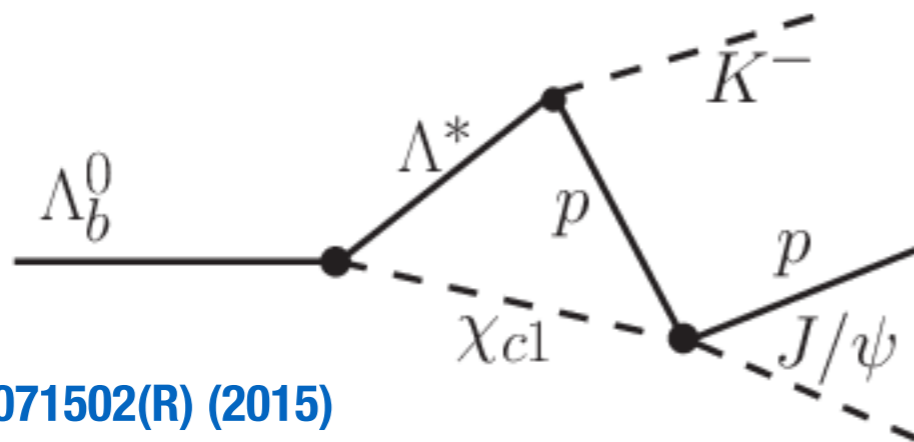
# Pentaquark observation and interpretation



**pentaquark**



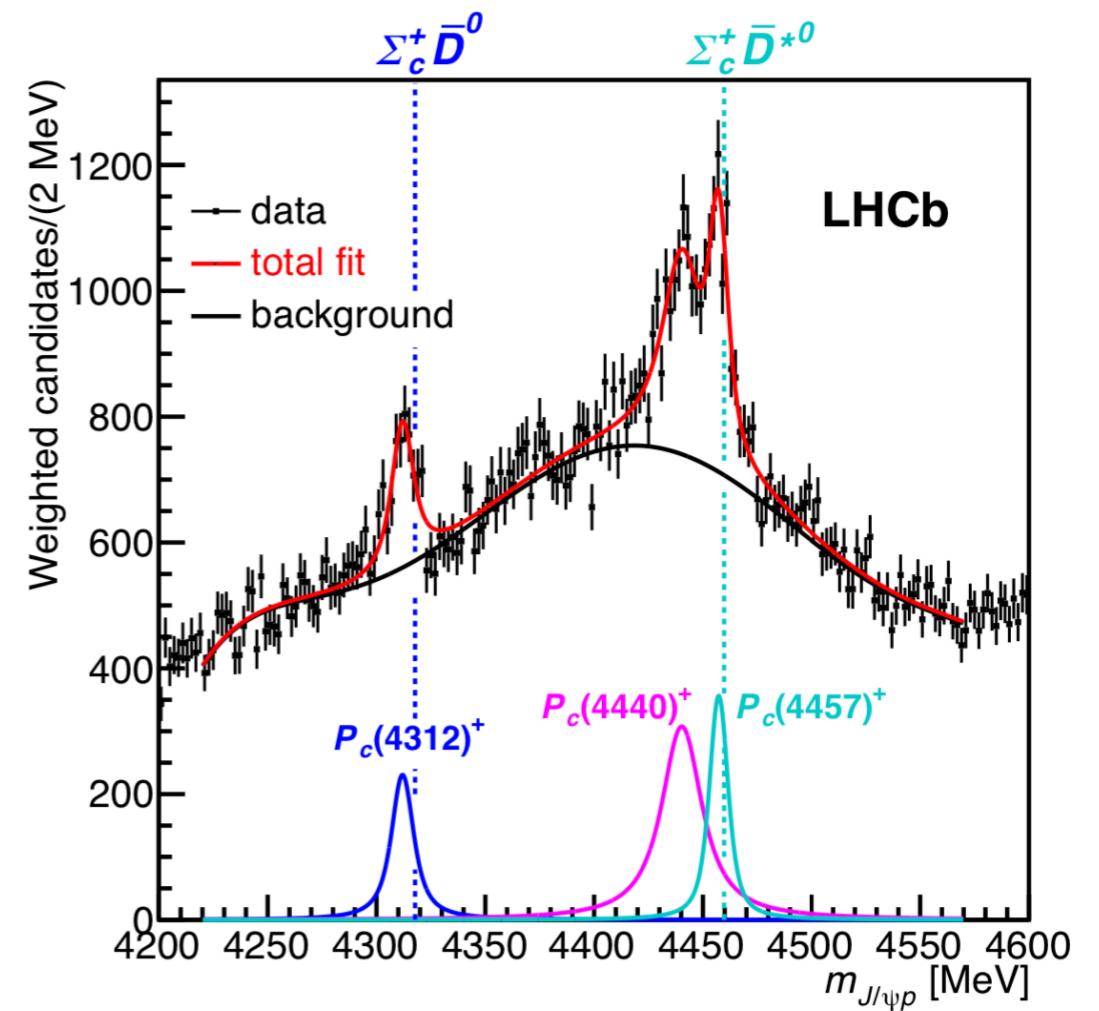
**molecular**



e.g. PRD 92, 071502(R) (2015)

**rescattering (triangle singularity)**

$$\Lambda_b \rightarrow J/\psi p K^-$$



**PRL 122, 222001 (2019)**

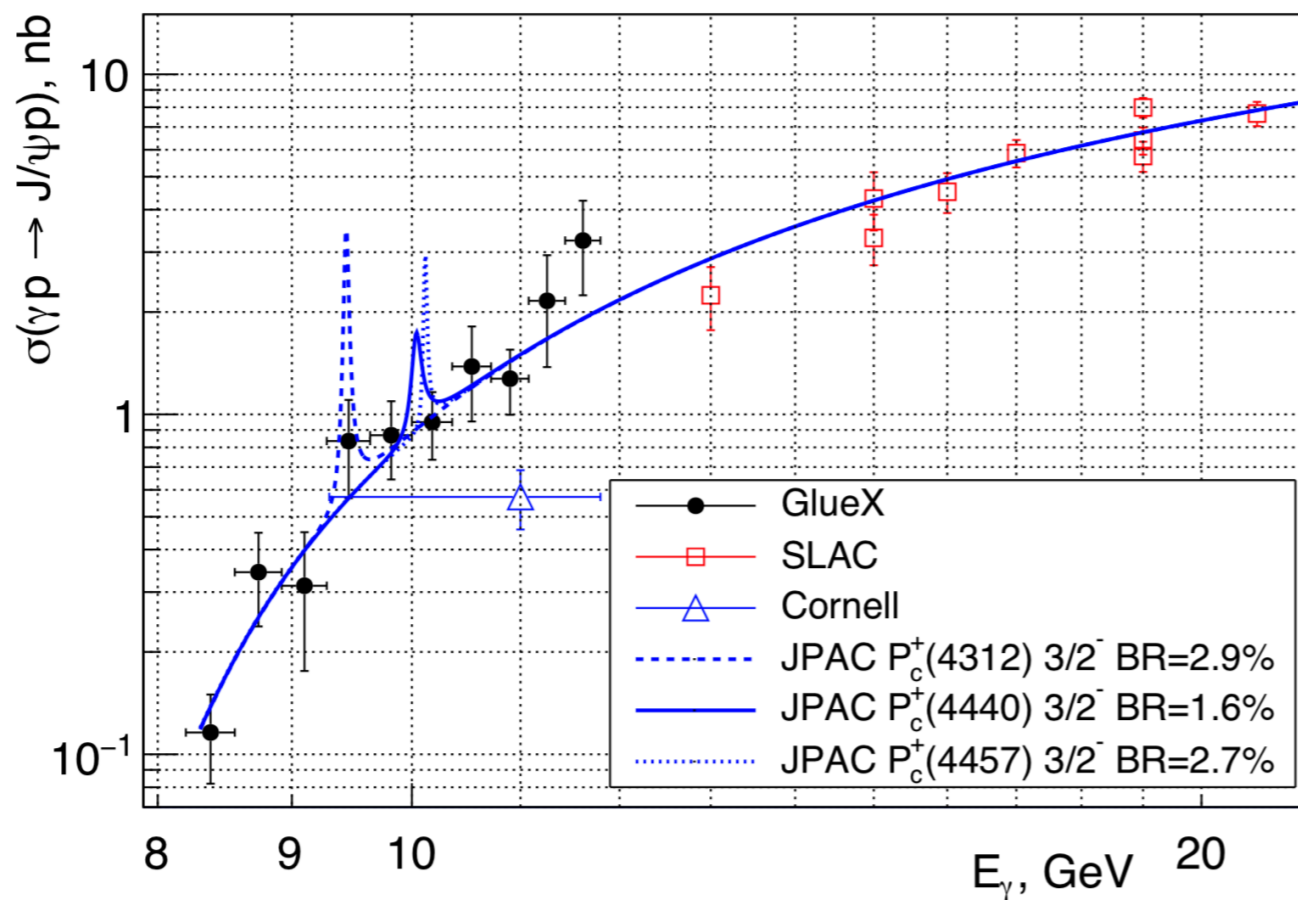


# Pentaquark photoproduction

$$\gamma p \rightarrow J/\psi p$$

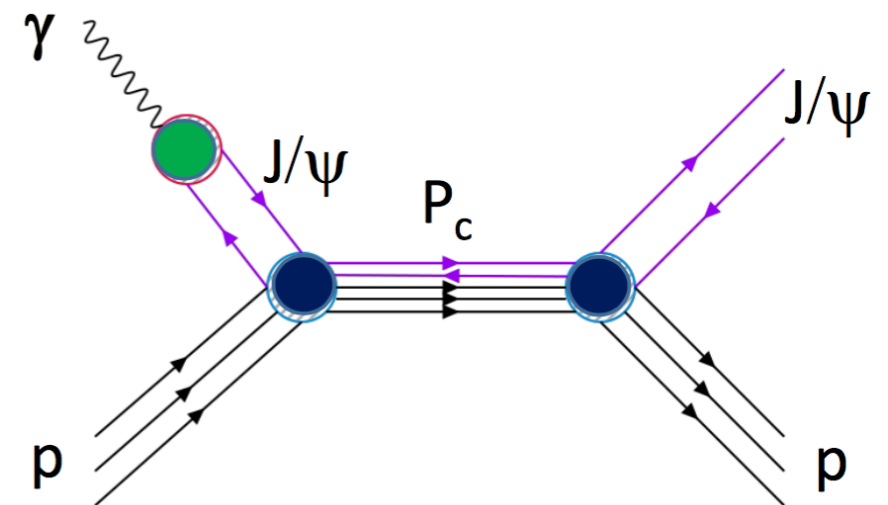
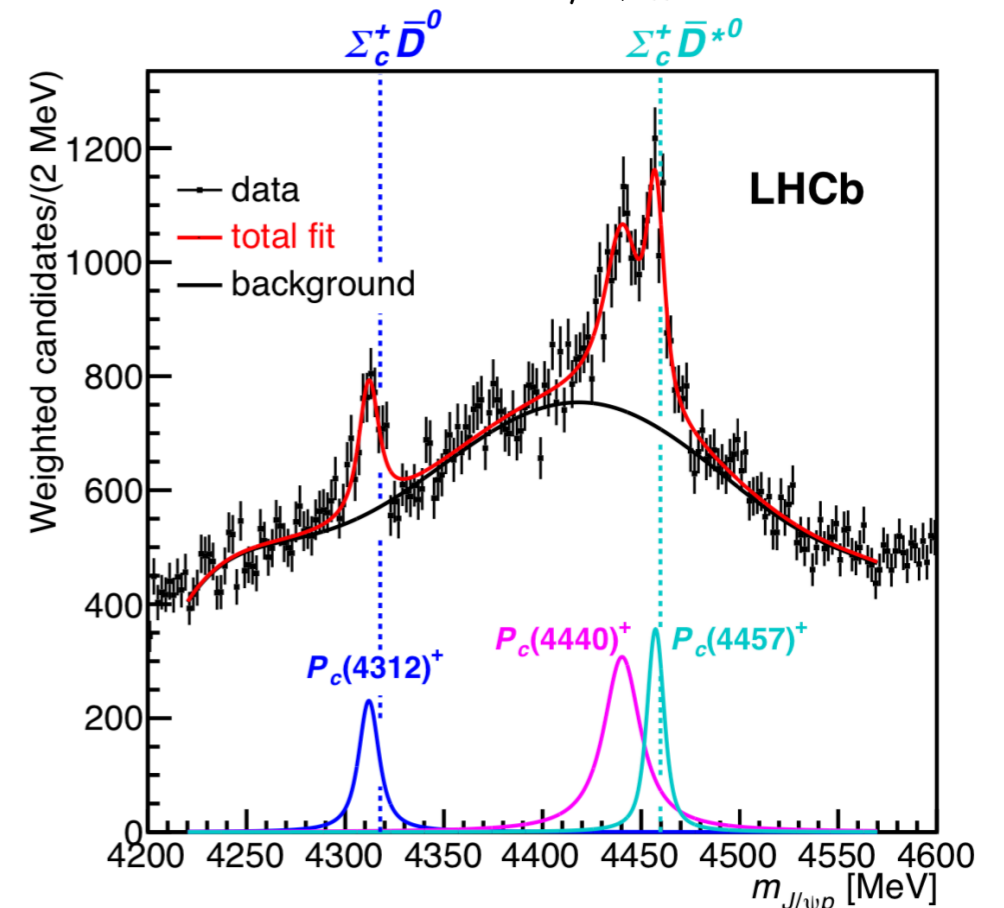


PRL 123, 072001 (2019)



**Model-dependent limits on**  
 $BR(P_c \rightarrow J/\psi p) < 2-4\%$

$$\Lambda_b \rightarrow J/\psi p K^-$$

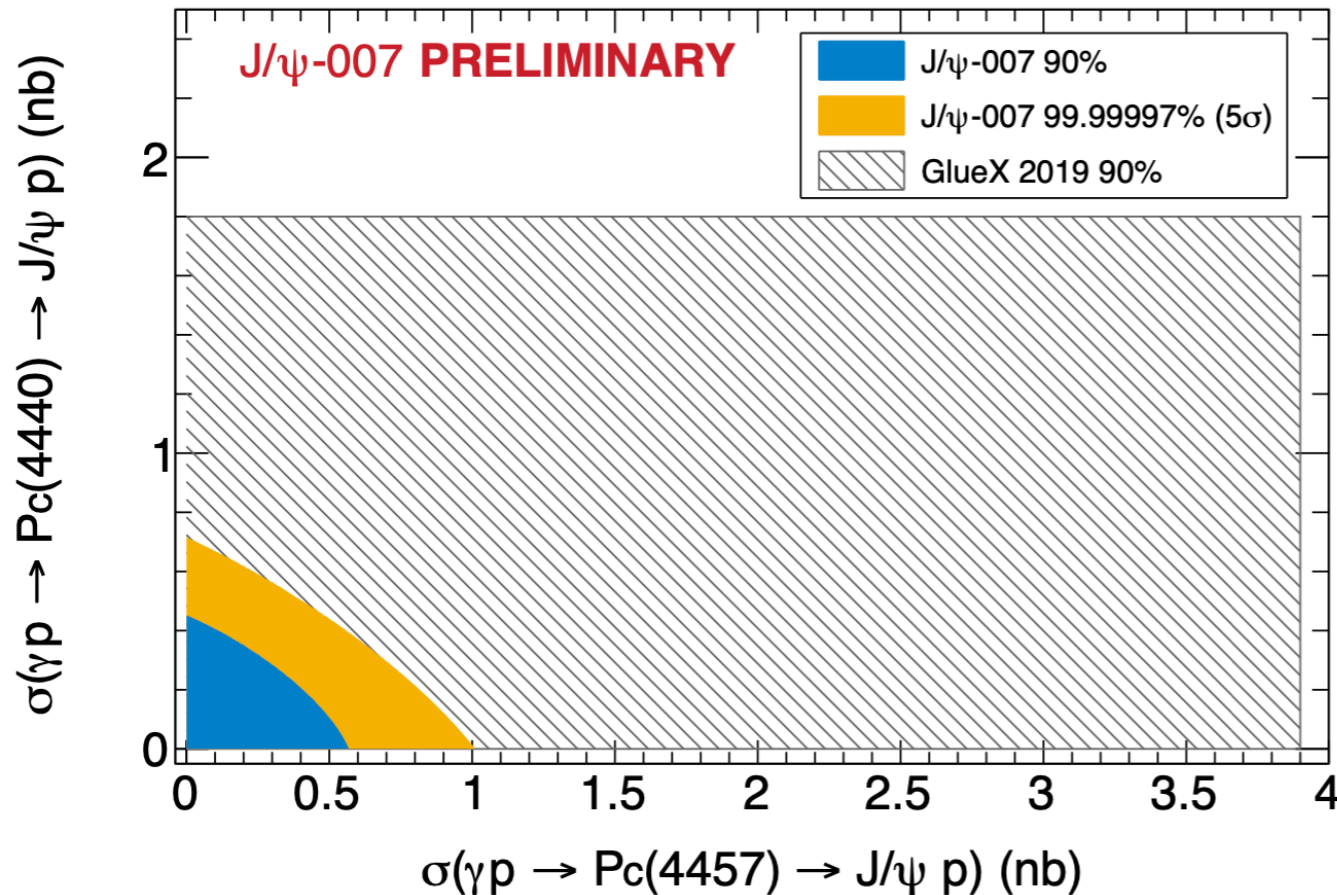


Proportional to  $BR(P_c \rightarrow J/\psi p)^2$

# Pentaquark photoproduction

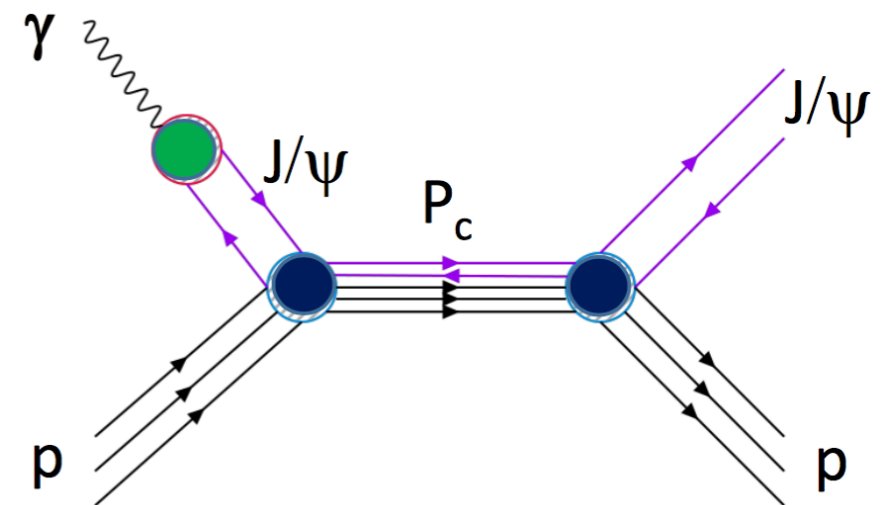
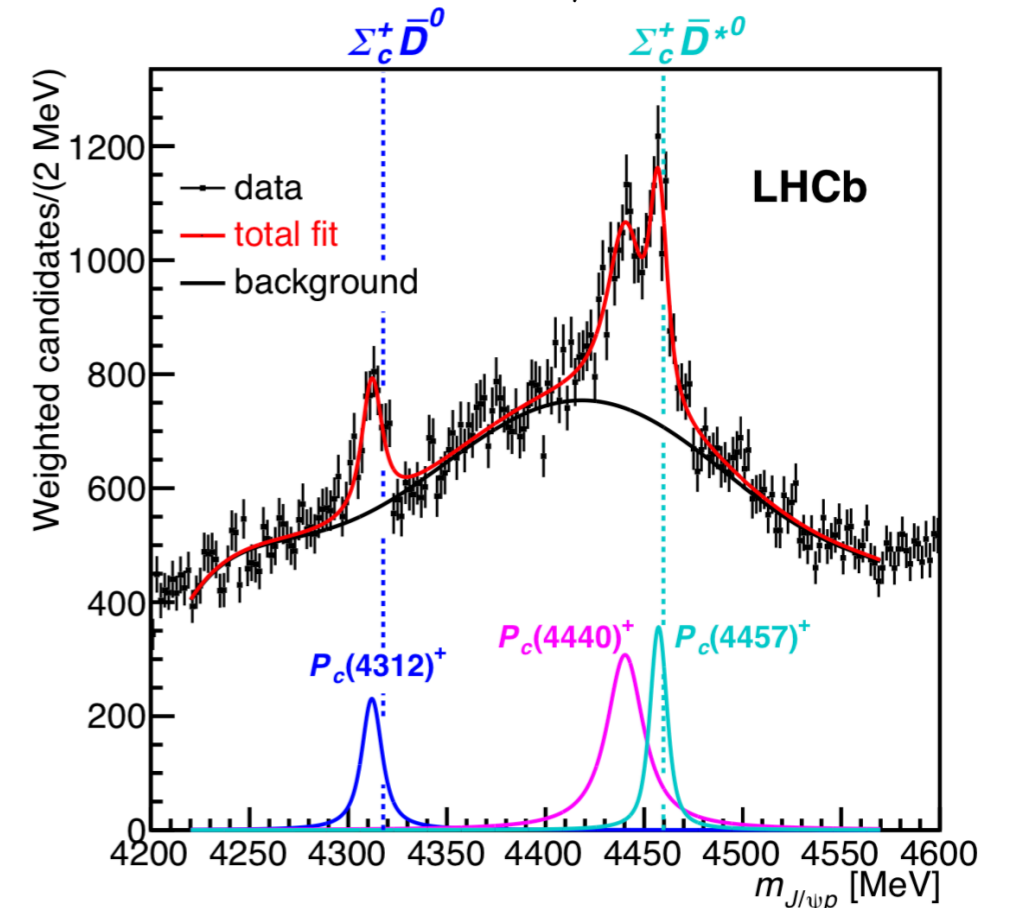
$$\gamma p \rightarrow J/\psi p$$

Hall C:  $J/\psi$ -007 experiment



**Even stricter limits on  $P_c$  production taking into account differential cross section  $d\sigma/dt$**

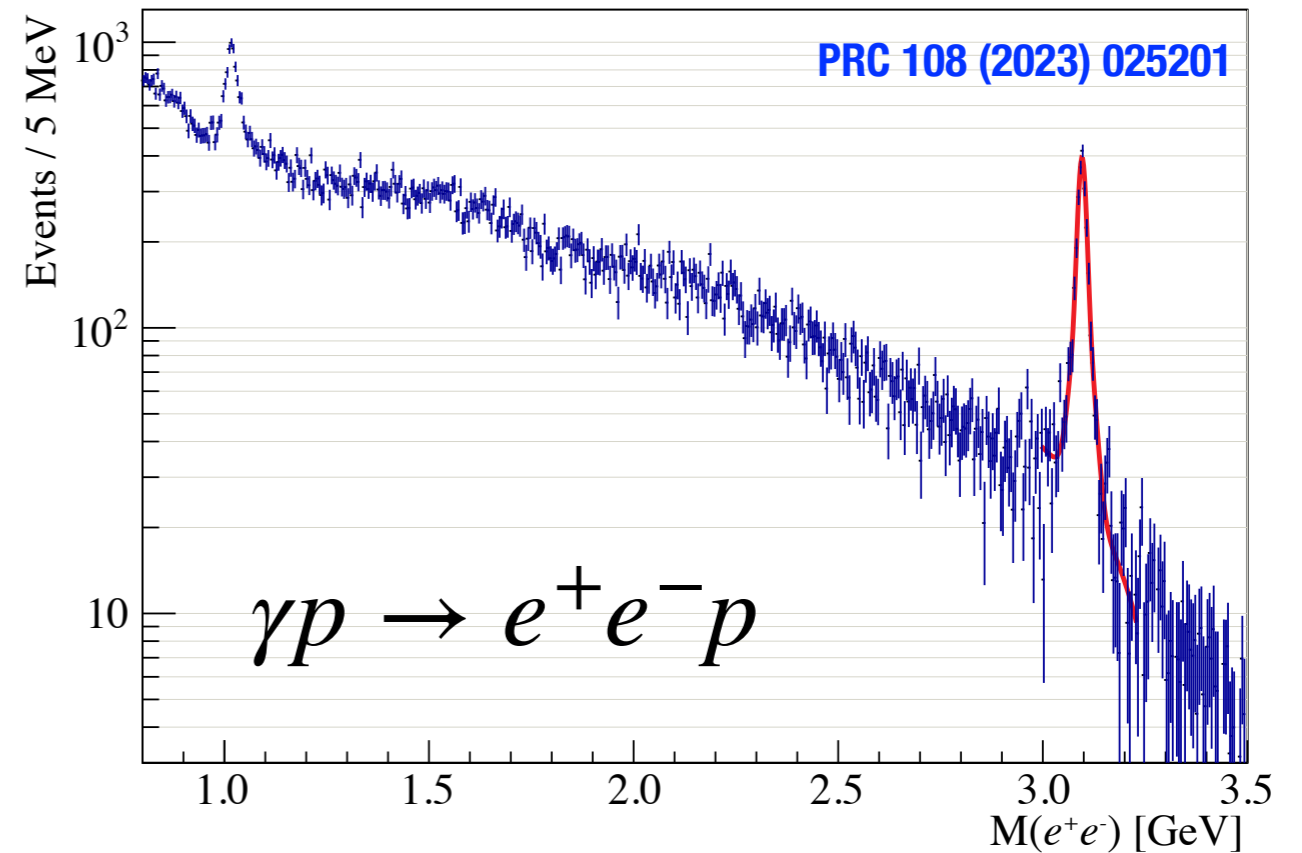
$$\Lambda_b \rightarrow J/\psi p K^-$$



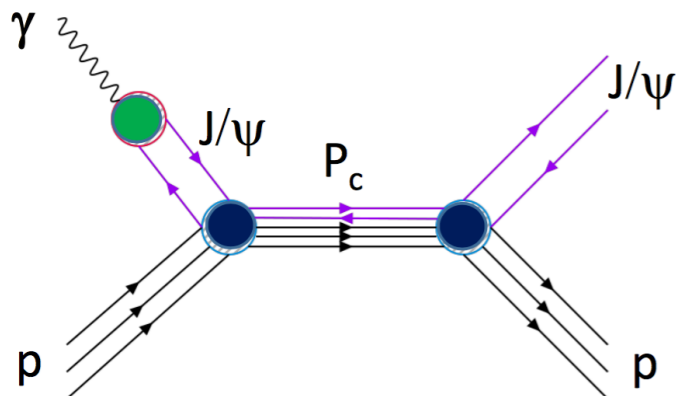
Proportional to  $\text{BR}(P_c \rightarrow J/\psi p)^2$

# J/ψ photoproduction at **GLUEX**

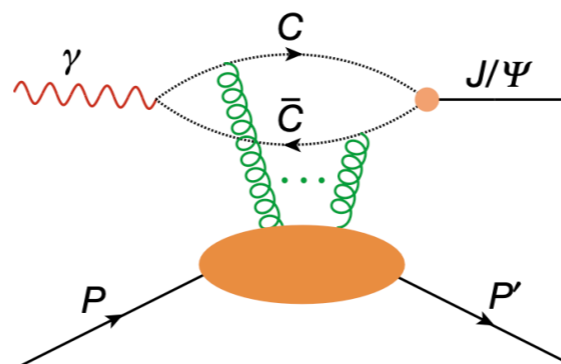
- ✱ Experimentally clean and rare probe with  $\sim 2.2\text{k } J/\psi$  observed in GlueX-I
- ✱ Broad physics program driven by different production mechanisms



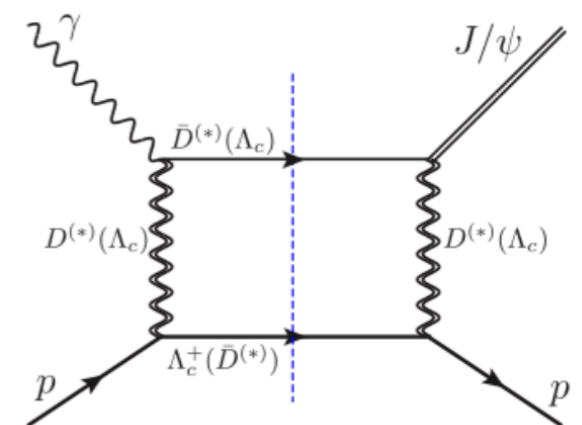
**s-channel:  
pentaquarks**



**t-channel:  
gluon GPDs, mass radius**



**open charm**

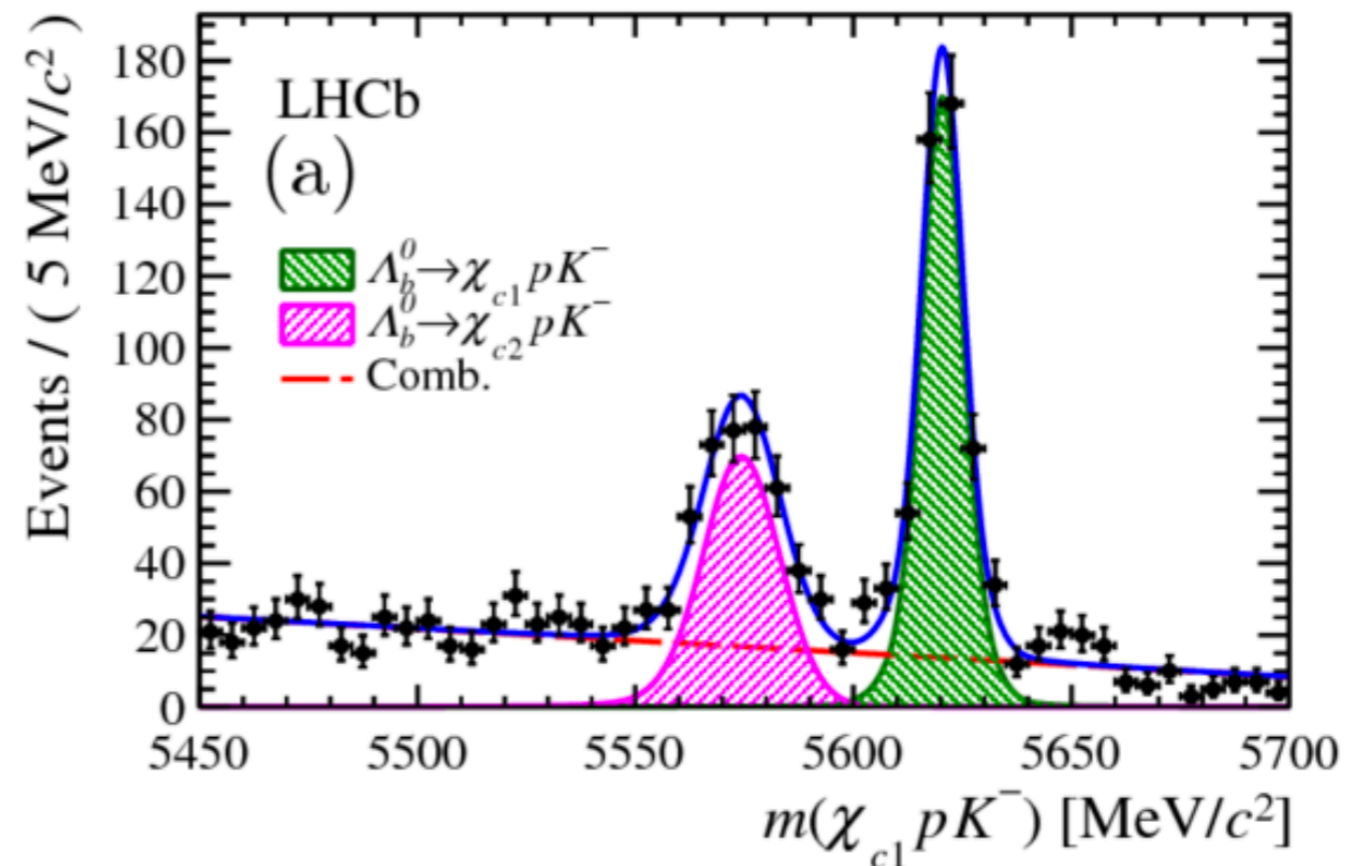
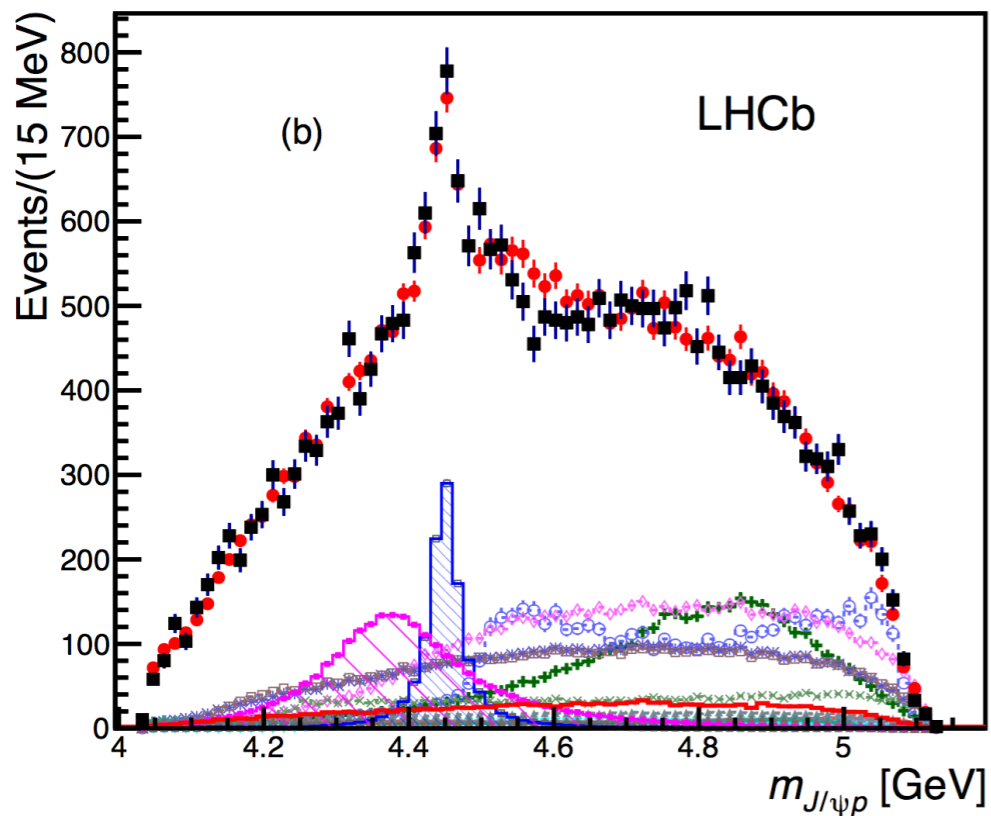
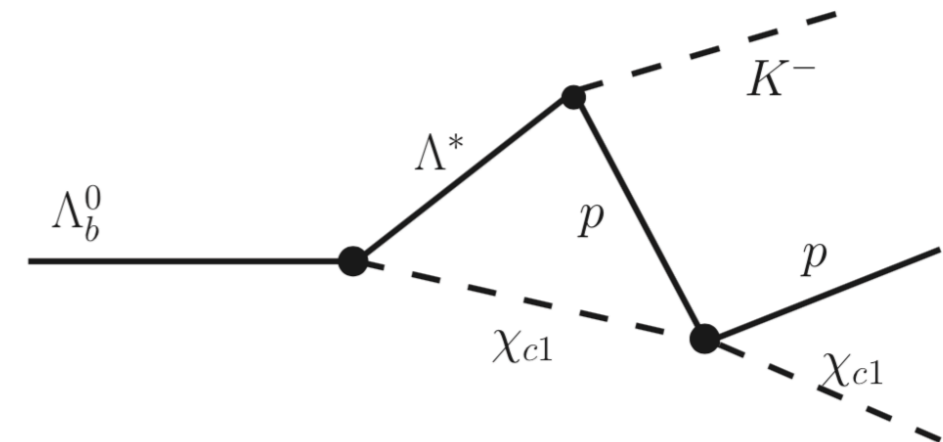


# Interpretation: molecules, rescattering

## Closeby thresholds

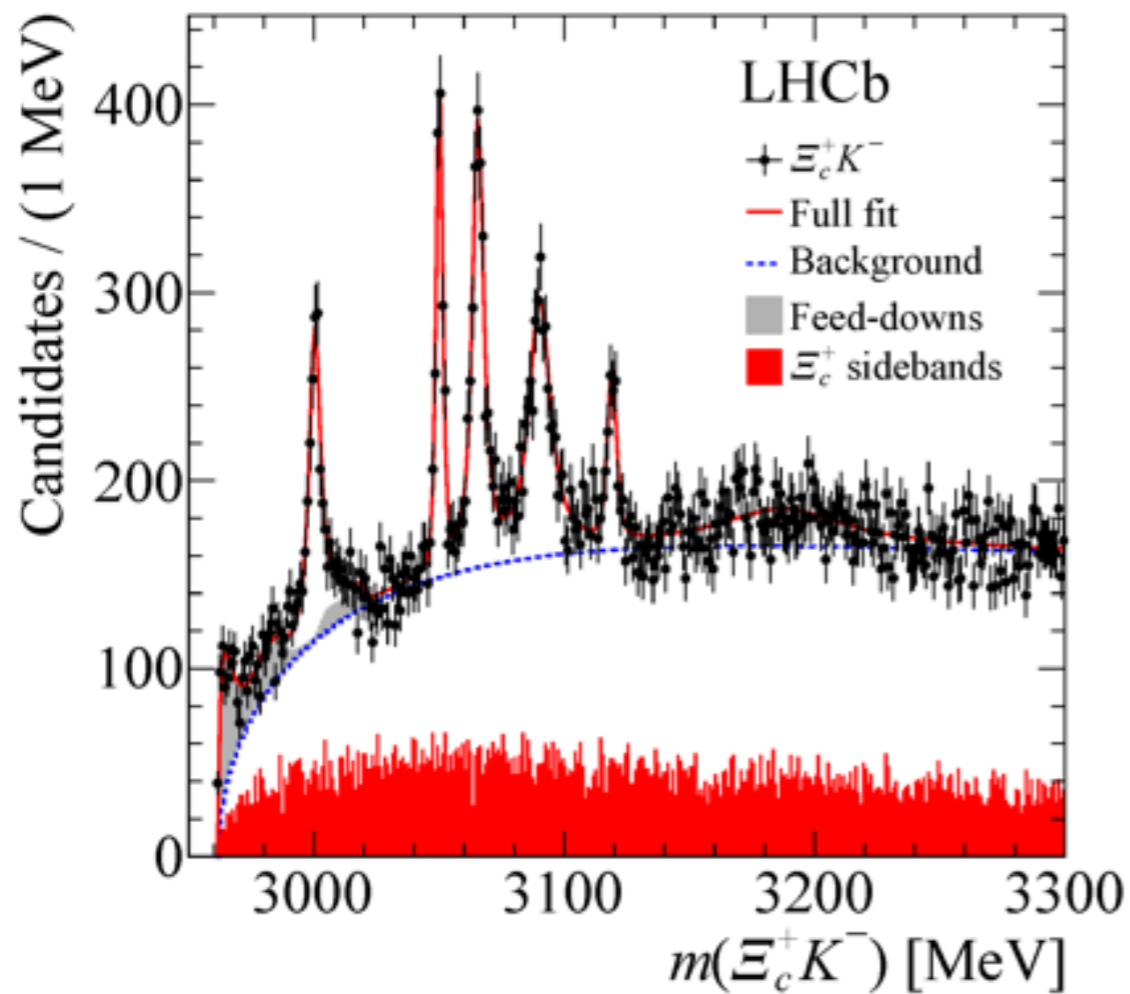
[MeV]	$P_c(4380)^+$	$P_c(4450)^+$
<b>Mass</b>	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
$\Sigma_c^{*+} \bar{D}^0$	$4382.3 \pm 2.4$	
$\chi_{c1}(1P)p$		$4448.93 \pm 0.07$
$\Lambda_c^{+*} \bar{D}^0$		$4457.09 \pm 0.35$
$\Sigma_c \bar{D}^{0*}$		$4459.9 \pm 0.5$
$\Sigma_c \bar{D}^0 \pi^0$		$4452.7 \pm 0.5$

[EPJ A51(2015)11,152]



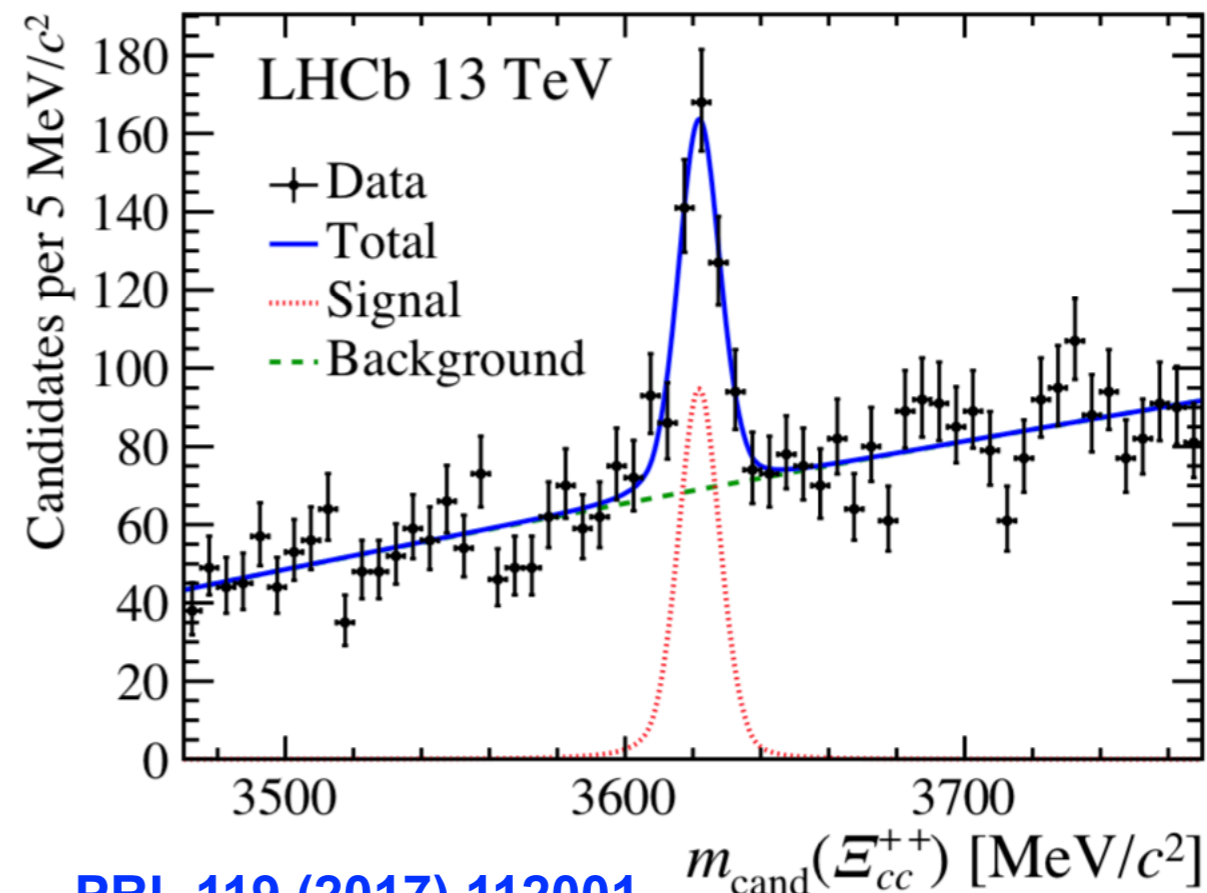
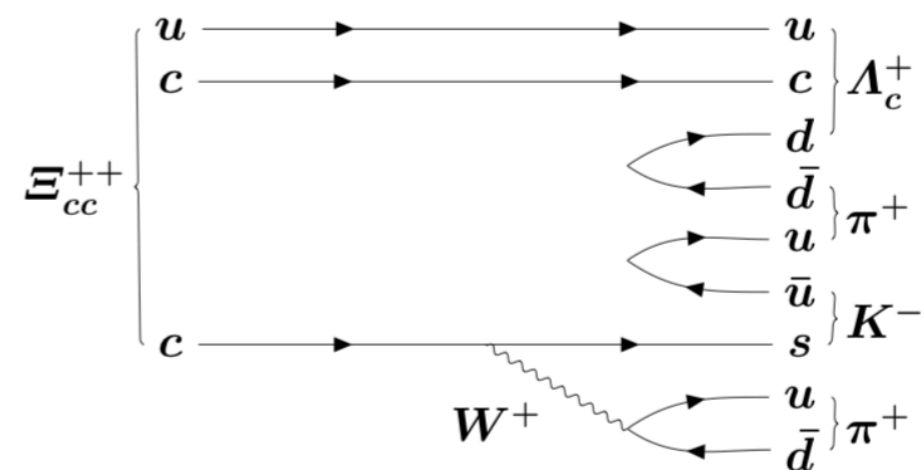
# Heavy quark baryons

## $\Omega_c$ baryons ( $css$ )



PRL 118 (2017) 182001

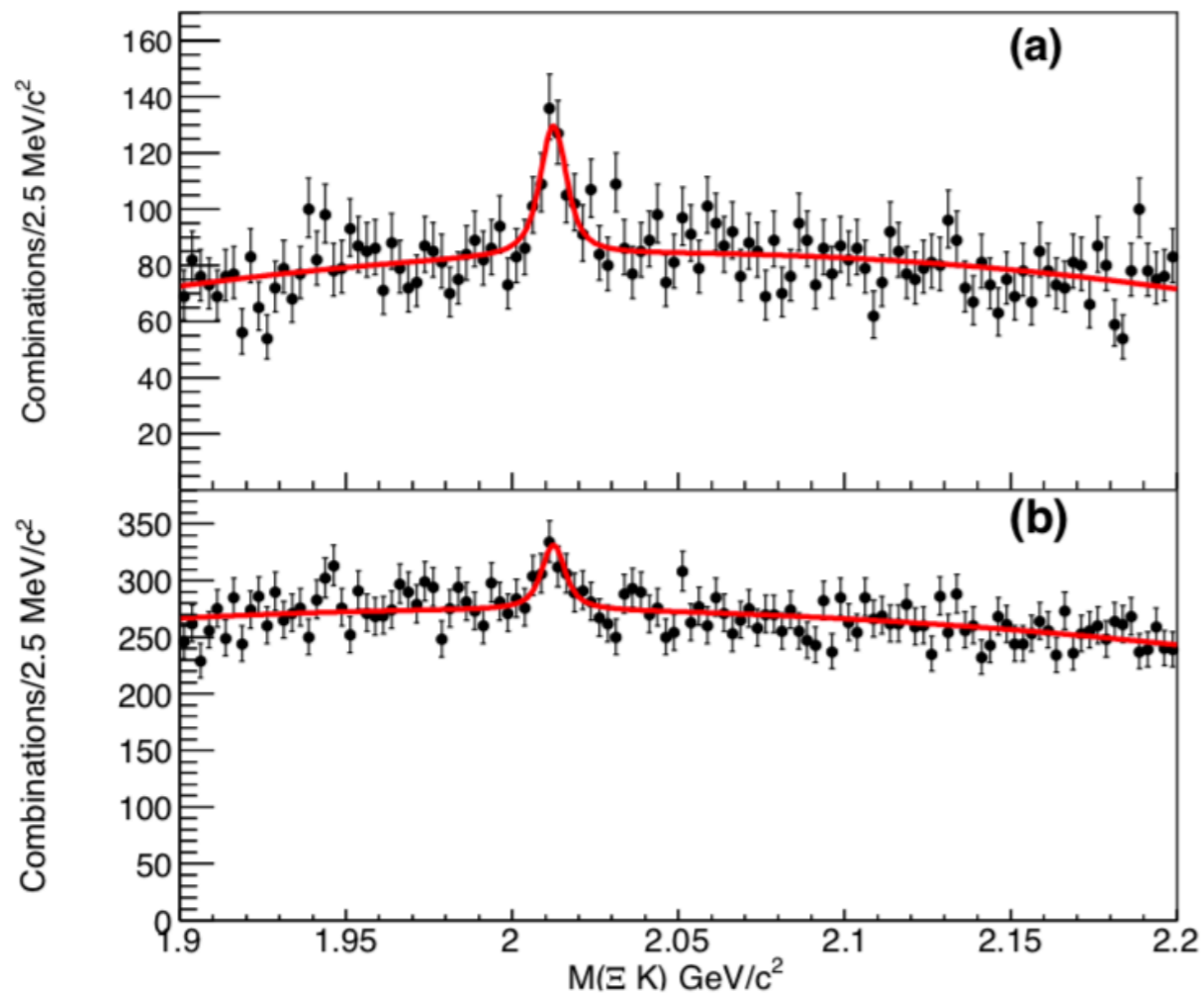
## Doubly charm baryon



PRL 119 (2017) 112001

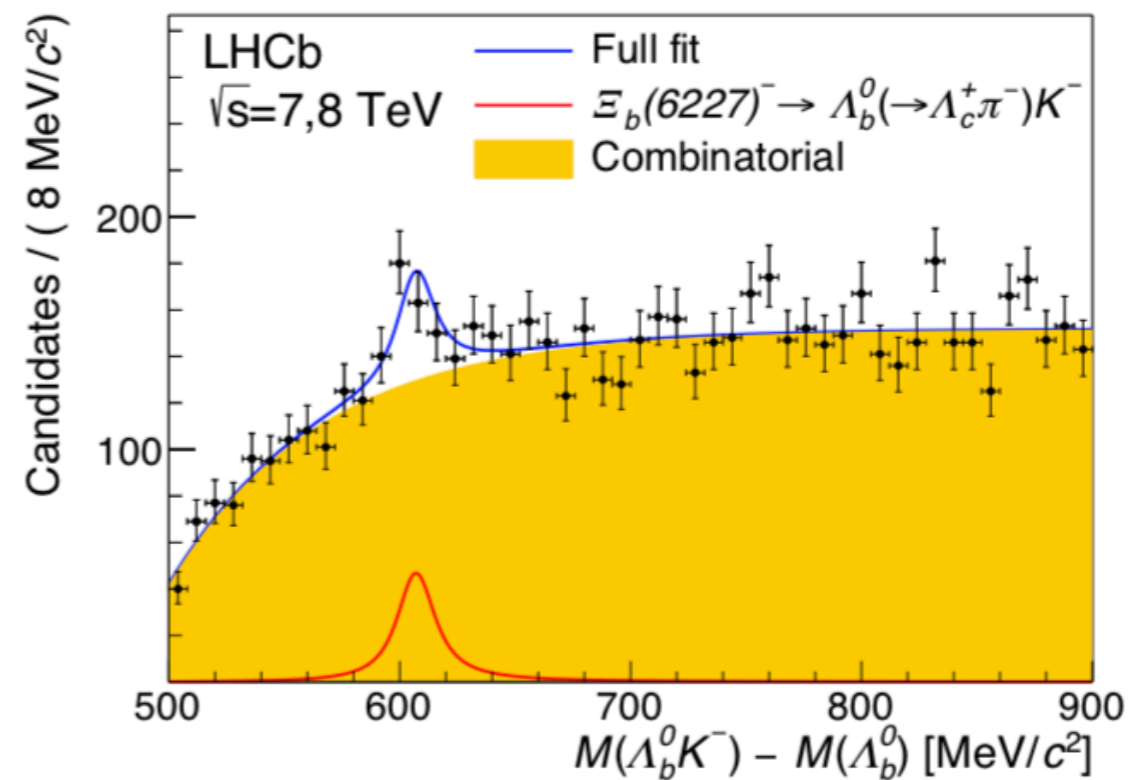
# Heavy quark baryons

## Excited $\Omega_s$ baryon ( $sss$ )



[arXiv:1805.09384](https://arxiv.org/abs/1805.09384)

## $\Xi_b$ baryon ( $bsq$ )



[arXiv:1805.09418](https://arxiv.org/abs/1805.09418)

# Summary: heavy quark spectroscopy

- \* Conventional charmonium and bottomonium well described by “simple” quark model
- \* Explosion of new XYZ states
  - \* Interesting connections between observed states
  - \* Higher precision brings new conclusions
- \* New baryonic states observed in charm and bottom decays at the LHC
  - \* Pentaquark not observed in photoproduction at JLab
  - \* Interest in connections to strange quarks (JLab)

# Further Reading

- \* **Heavy-Quark QCD Exotica**

Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson, *Progress in Particle and Nuclear Physics* 93, 143–194 (2017)

- \* **Non-Standard Heavy Mesons and Baryons, an Experimental Review**

Stephen Lars Olsen, Tomasz Skwarnicki, Daria Ziemska [*arXiv:1708.04012*]

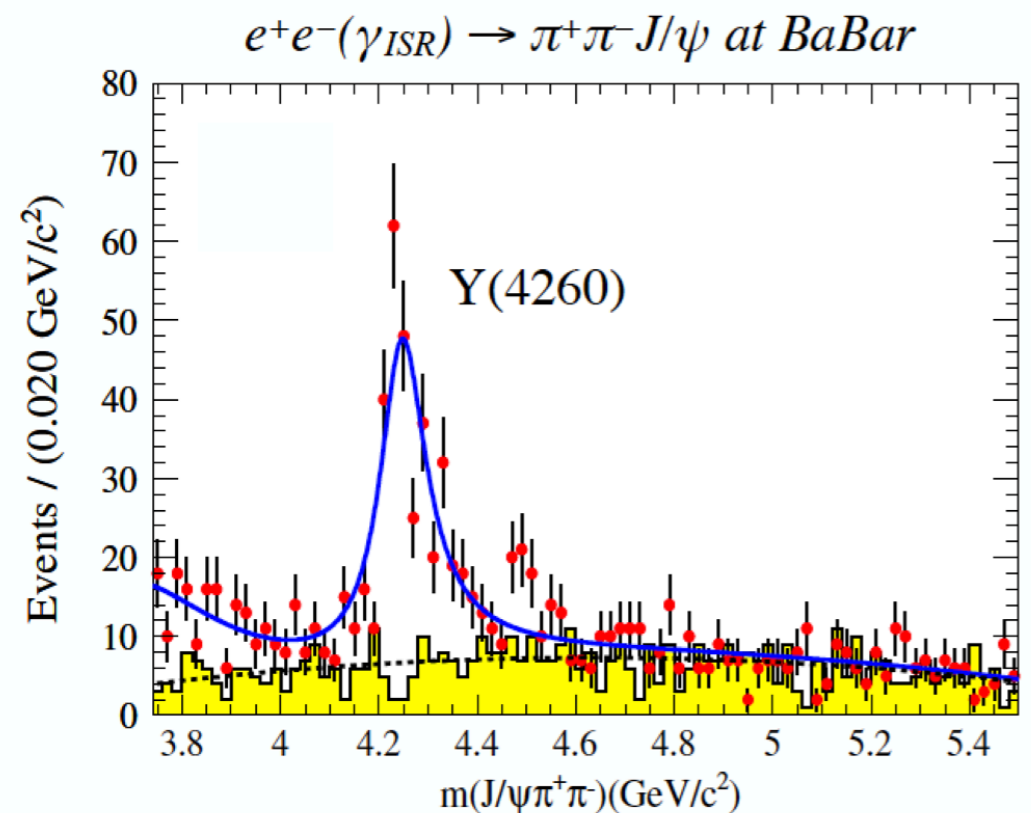
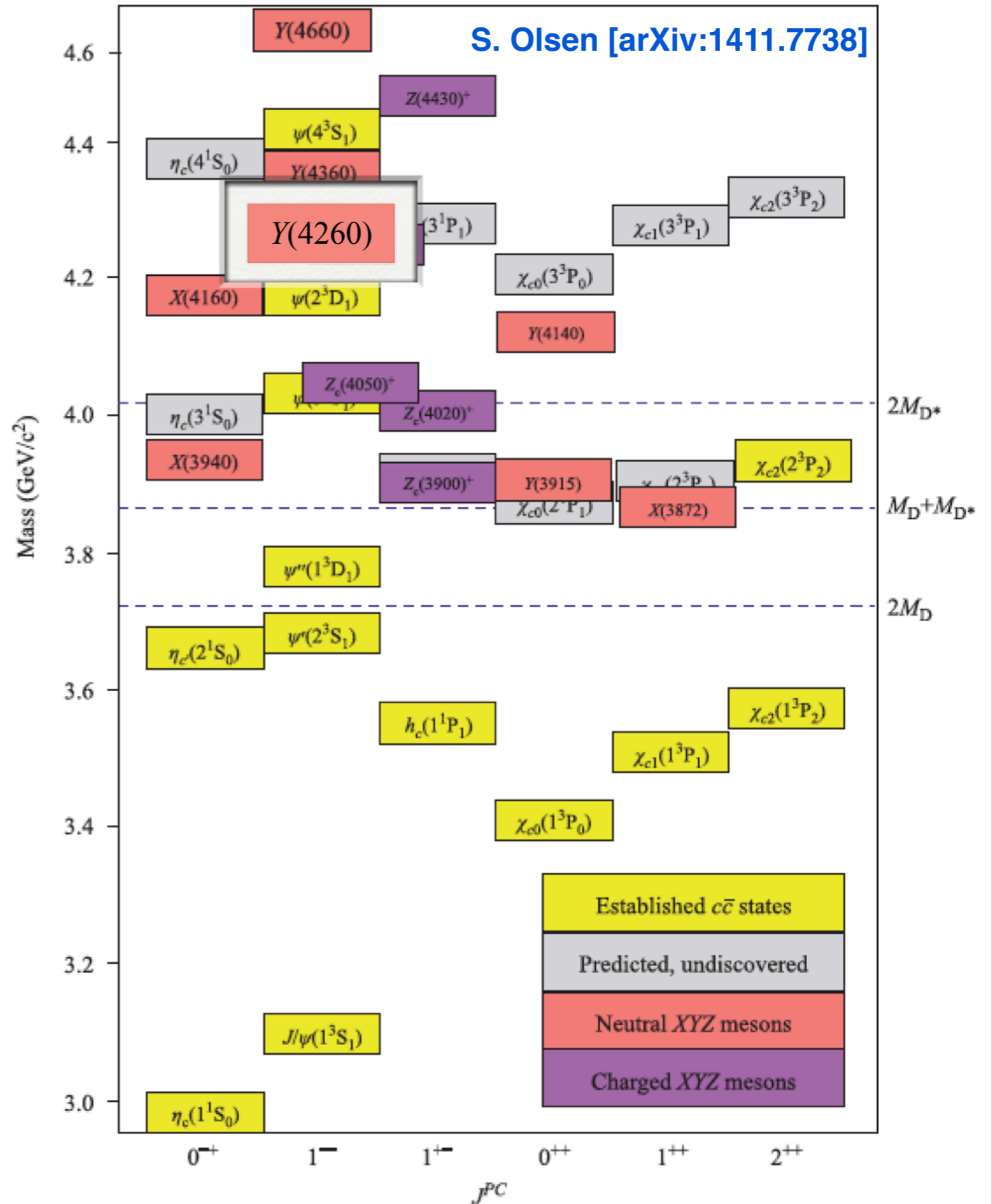
- \* **Hybrid mesons**

Curtis A. Meyer and Eric S Swanson, *Progress in Particle and Nuclear Physics* 82, 21-58 (2015)

# Backup

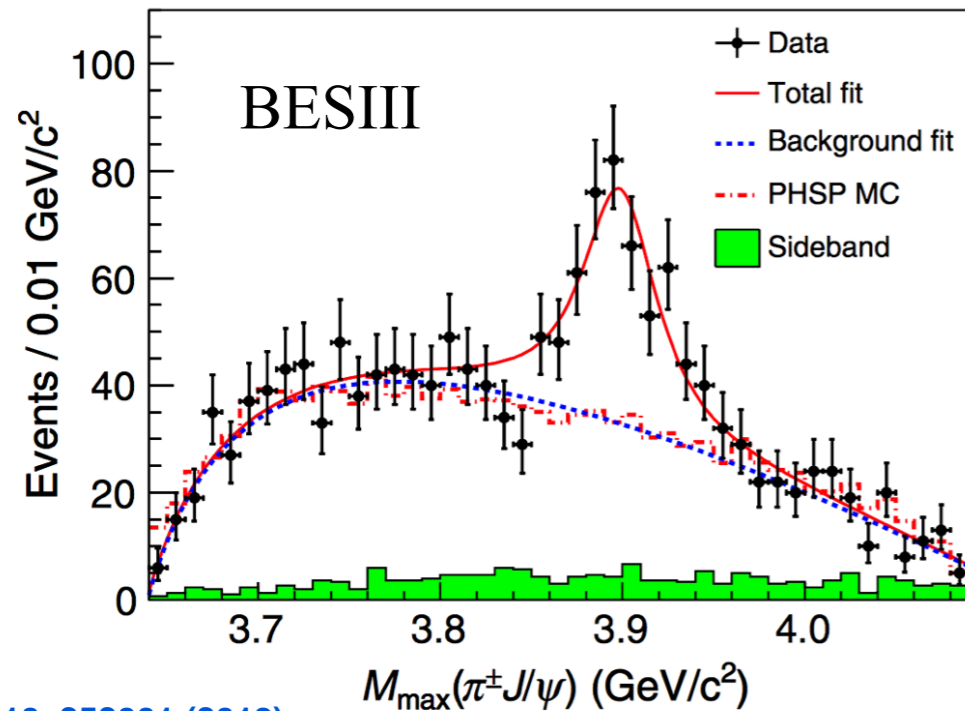
# XYZ states

- \* Recent discoveries of charmonium-like states at BaBar, Belle, BESIII, CLEO, LHCb, etc.
- \* So called “XYZ” mesons, not predicted by the standard charmonium models
- \* Many models for interpretation: resonant states, meson molecules, re-scattering effects, etc.

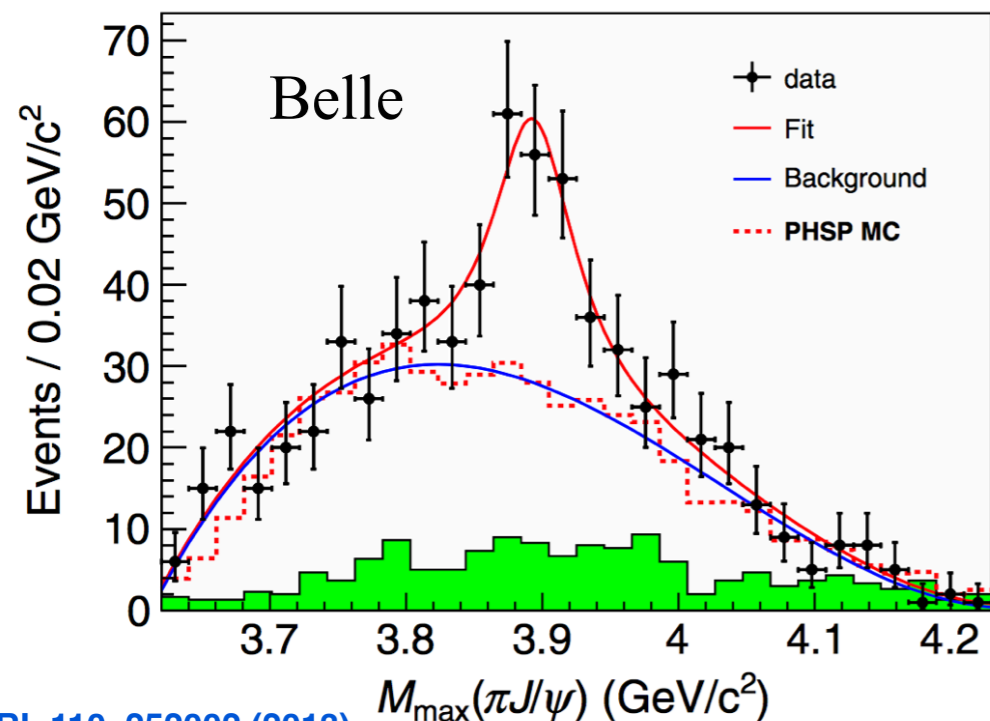


# $Z_c^+(3900)$

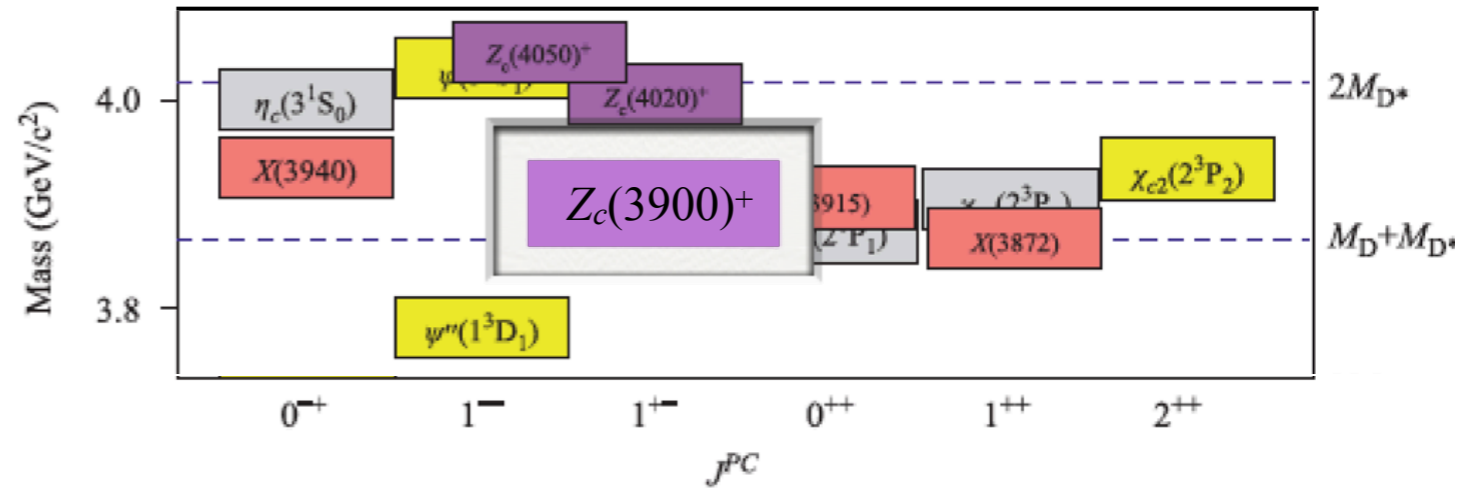
$$e^+e^- \rightarrow \pi^+\pi^- J/\psi \quad (4260 \text{ MeV})$$



PRL 110, 252001 (2013)

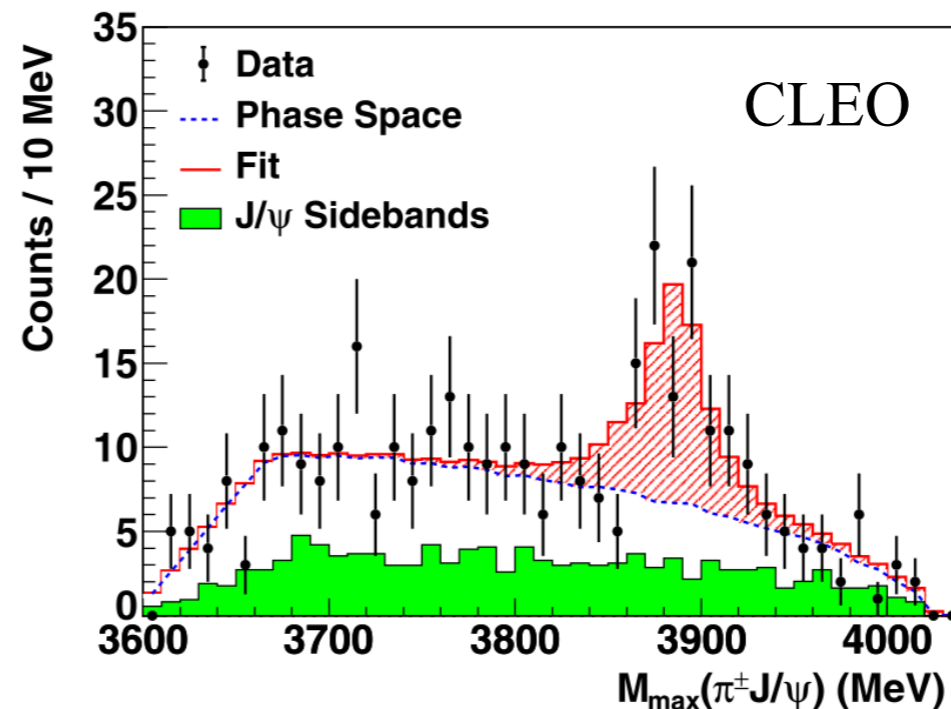


PRL 110, 252002 (2013)

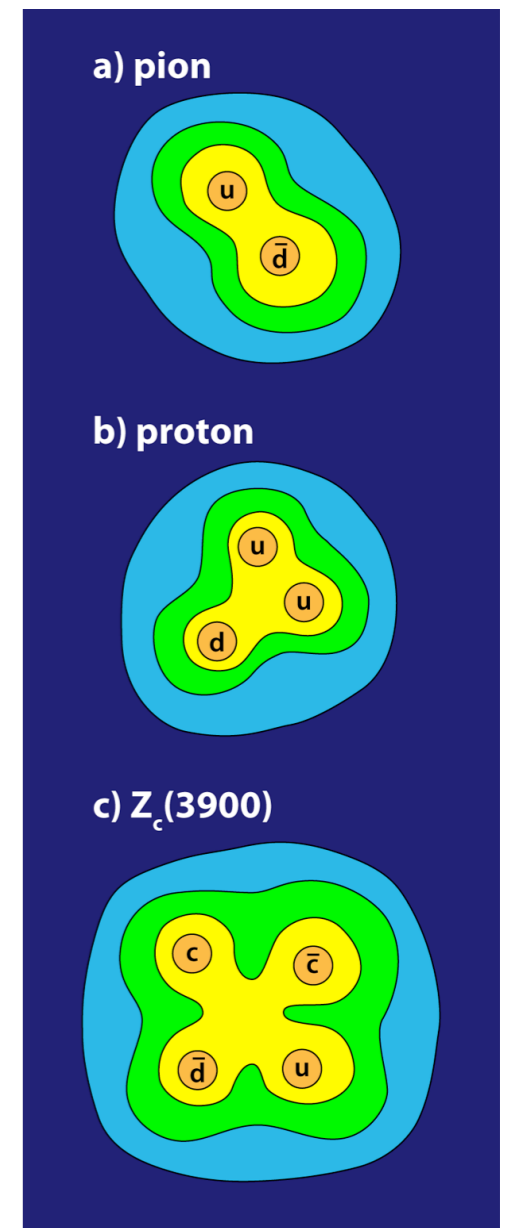


\* Charged charmonium structure observed by BESIII, Belle and CLEO in decay of  $Y(4260)$

\* 4-quark content ( $c\bar{c}u\bar{d}$ )



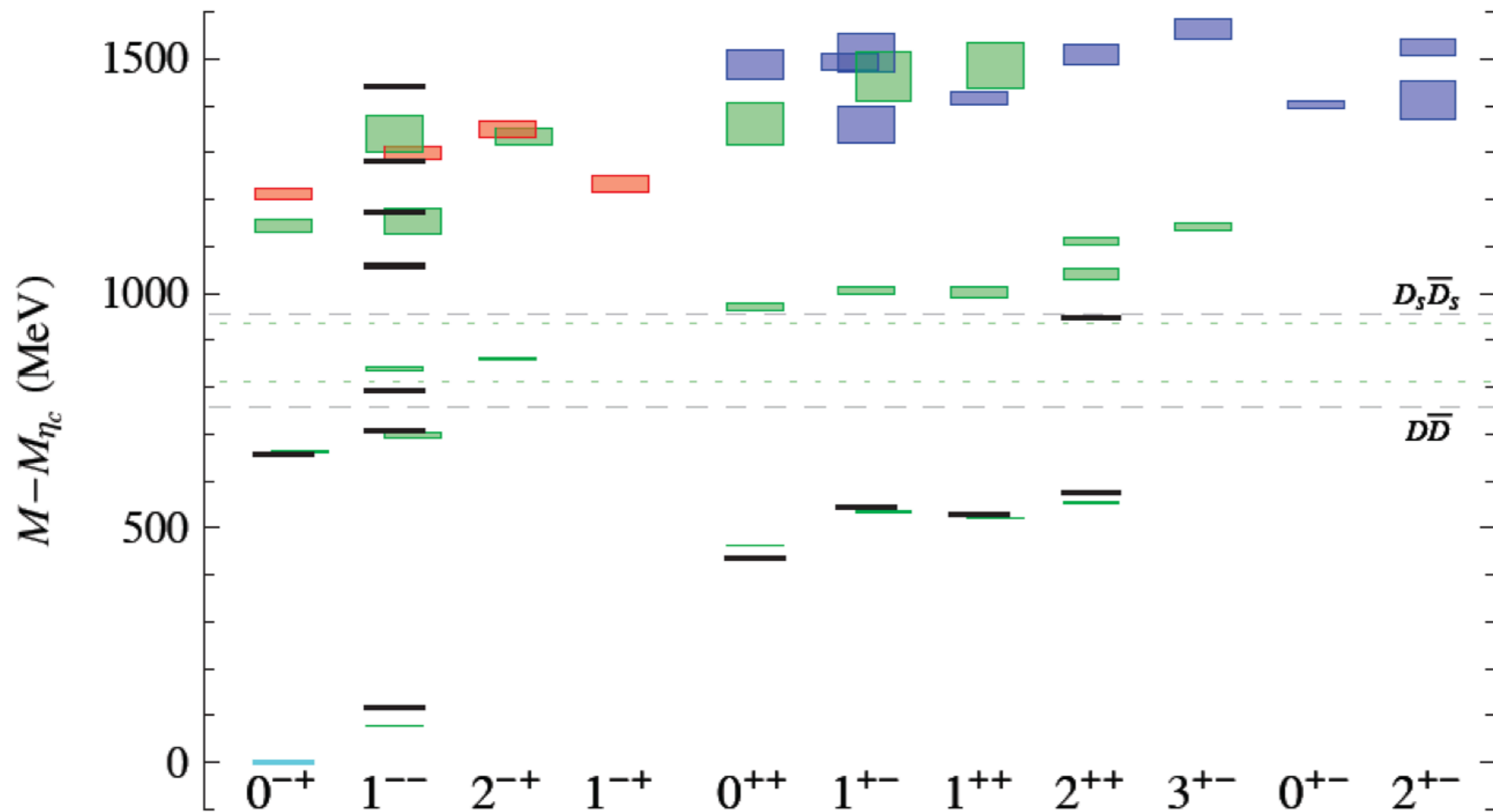
PLB 727 (2013) 366



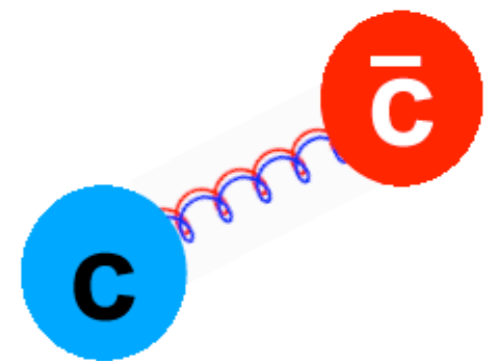
Physics Viewpoint 6, 69 (2013)

# Charmonium hybrids

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



$c\bar{c}g$  Hybrid



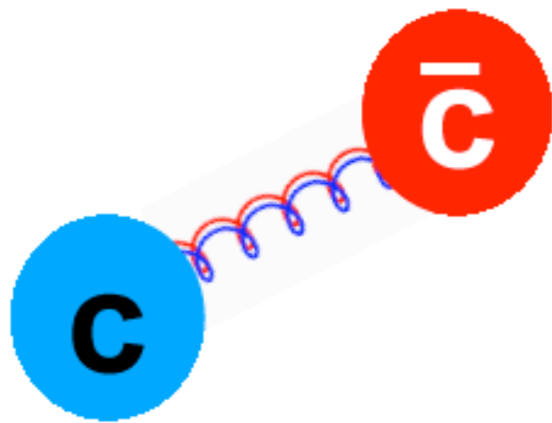
**Constituent Gluon:**  
**Mass ~ 1-1.5 GeV**  
 $J^{PC} = 1^{+-}$

- \* Lattice QCD predicts hybrid states charmonium states with gluonic contribution to their wavefunction including **exotic  $J^{PC} = 1^{-+}, 0^{+-}, 2^{+-}$**
- \* Exotic  $J^{PC}$  not accessible in  $e^+e^-$ , but could be studied through other mechanisms like photoproduction or  $p\bar{p}$  annihilation (eg. PANDA@GSI)

# Hybrid photoproduction

- \* Lattice QCD calculations of charmonium radiative decays
  - \* Conventional  $c\bar{c}$  mesons in reasonable agreement with experiment
  - \* Sizable radiative transitions predicted for hybrid charmonium

$c\bar{c}g$  Hybrid



**Y(4260)?**

**Exotic Hybrid**

transition	$\Gamma_{\text{lattice}}$ (keV)	$\Gamma_{\text{expt}}$ (keV)
$\chi_{c0} \rightarrow J/\psi\gamma$	199(6)	131(14)
$\psi' \rightarrow \chi_{c0}\gamma$	26(11)	30(2)
$\psi'' \rightarrow \chi_{c0}\gamma$	265(66)	199(26)
$c\bar{c}g(1^{--}) \rightarrow \chi_{c0}\gamma$	< 20	
$J/\psi \rightarrow \eta_c\gamma$	2.51(8)	1.85(29)
$\psi' \rightarrow \eta_c\gamma$	0.4(8)	0.95 – 1.37
$\psi'' \rightarrow \eta_c\gamma$	10(11)	
$c\bar{c}g(1^{--}) \rightarrow \eta_c\gamma$	42(18)	
$c\bar{c}g(1^{-+}) \rightarrow J/\psi\gamma$	115(16)	

PRD 79 (2009) 094504 and Review article 1502.07276