Hadron Spectroscopy at GlueX and Beyond (2)

Heavy Quark Spectroscopy: “The XYZ Story”

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

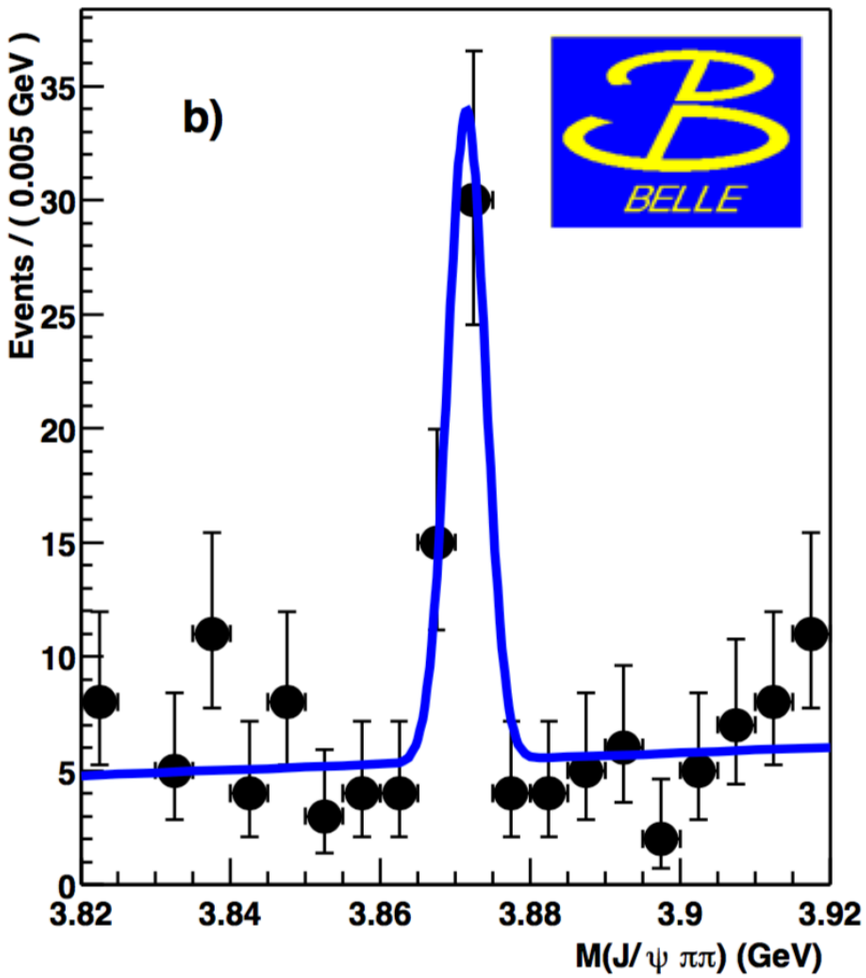
Preliminaries

- **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 and Wednesday)

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

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



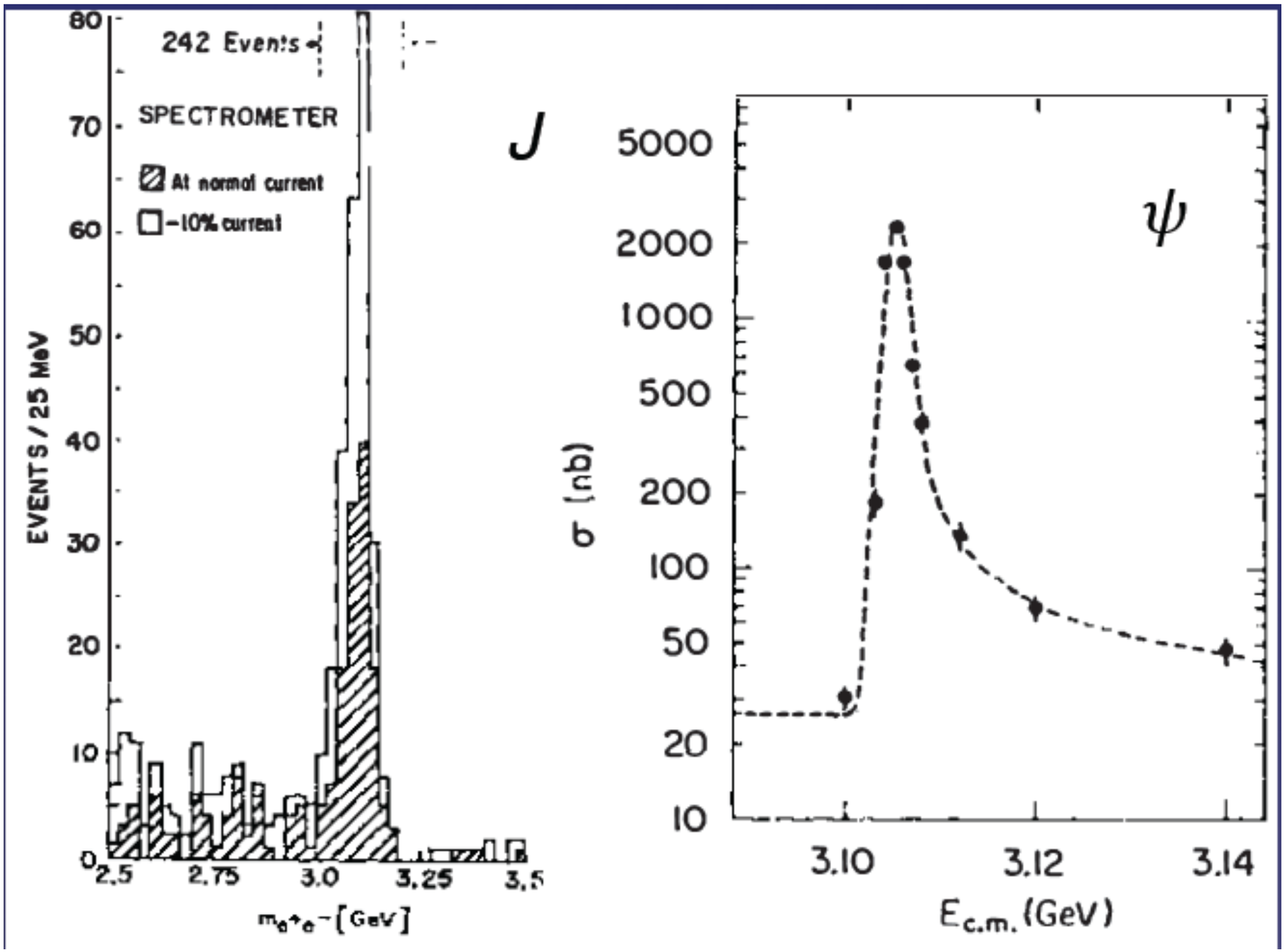
Discovery of charm (J/ψ) in 1974

BNL/MIT

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

SLAC

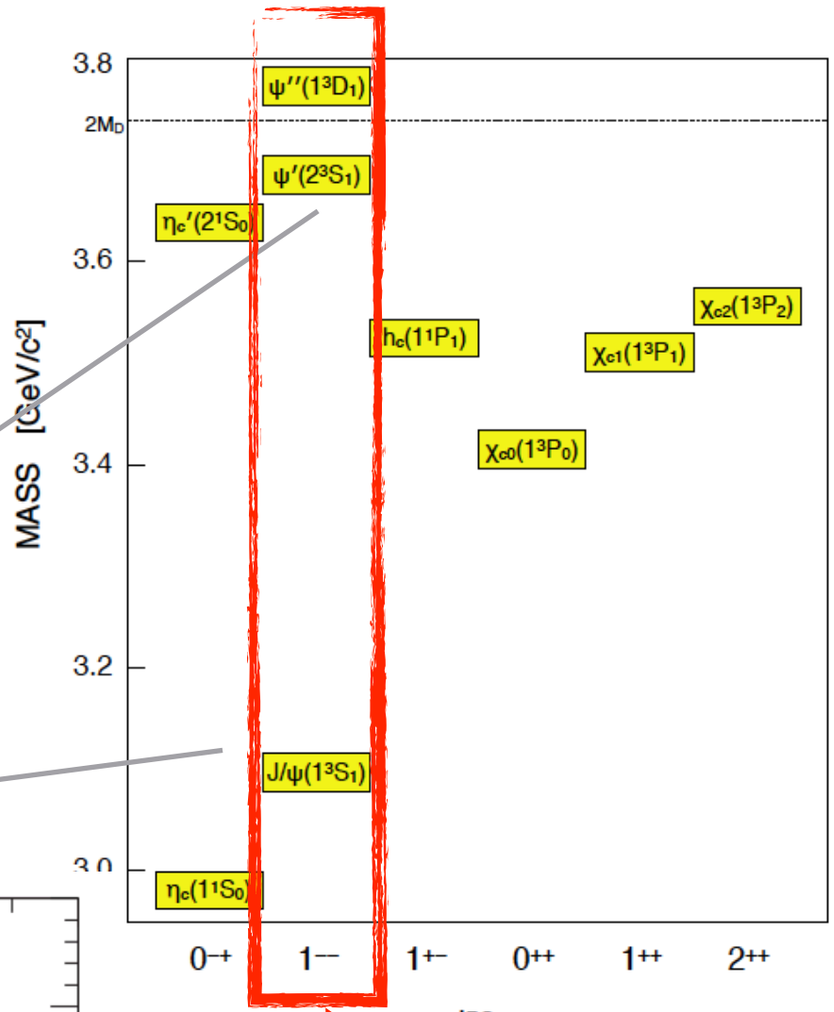
e^+e^- collisions

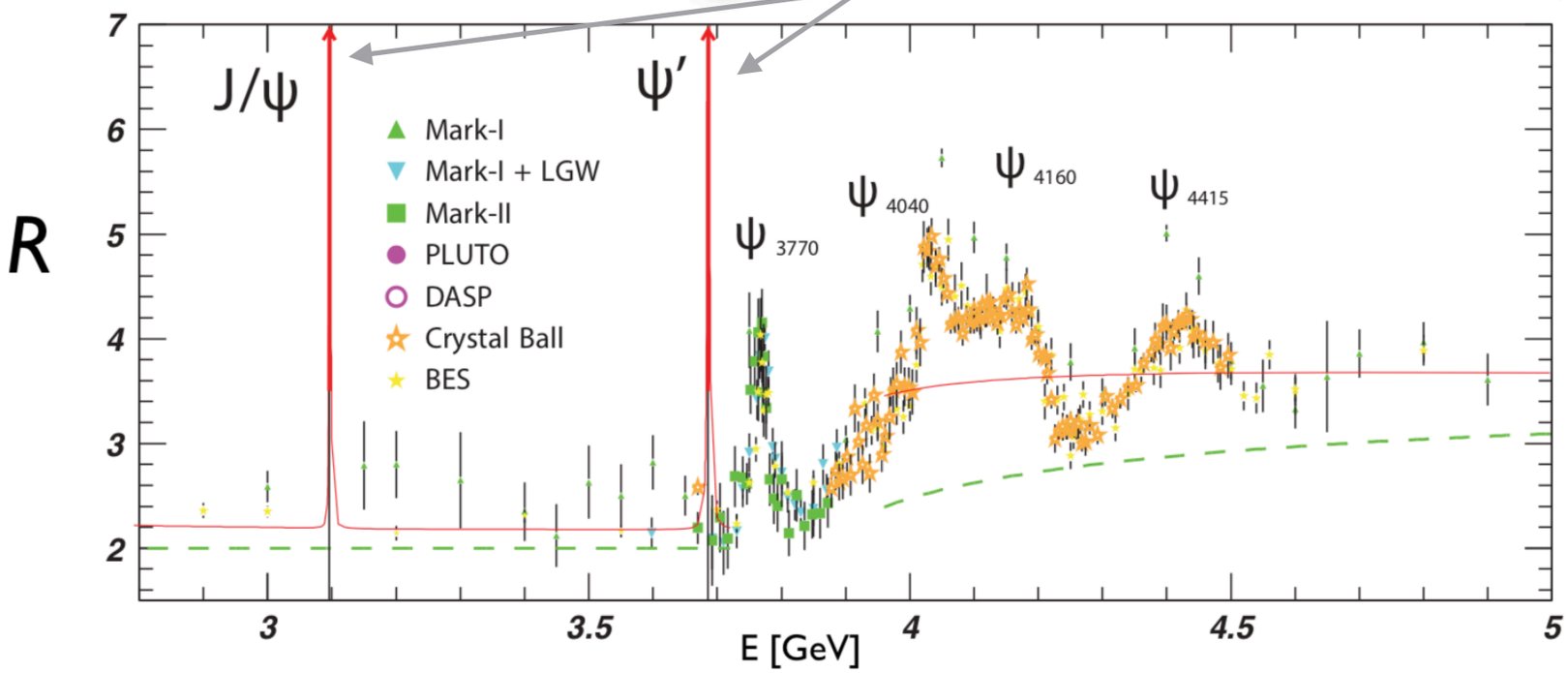


“Conventional” charmonium

Resonances appear as enhancement in cross section at M = √s

$$R = \frac{e^+e^- \to q\bar{q}}{e^+e^- \to \mu^+\mu^-}$$

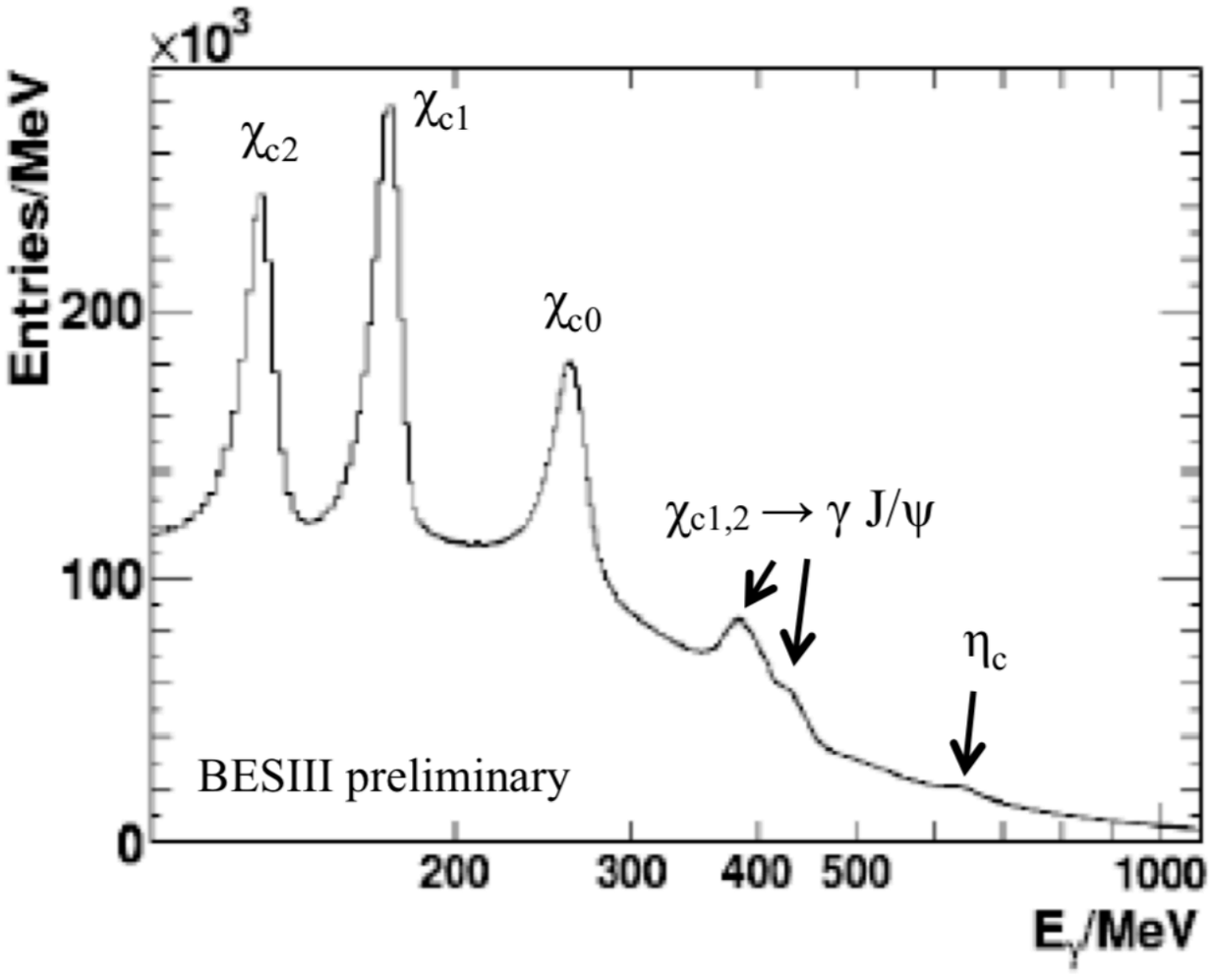


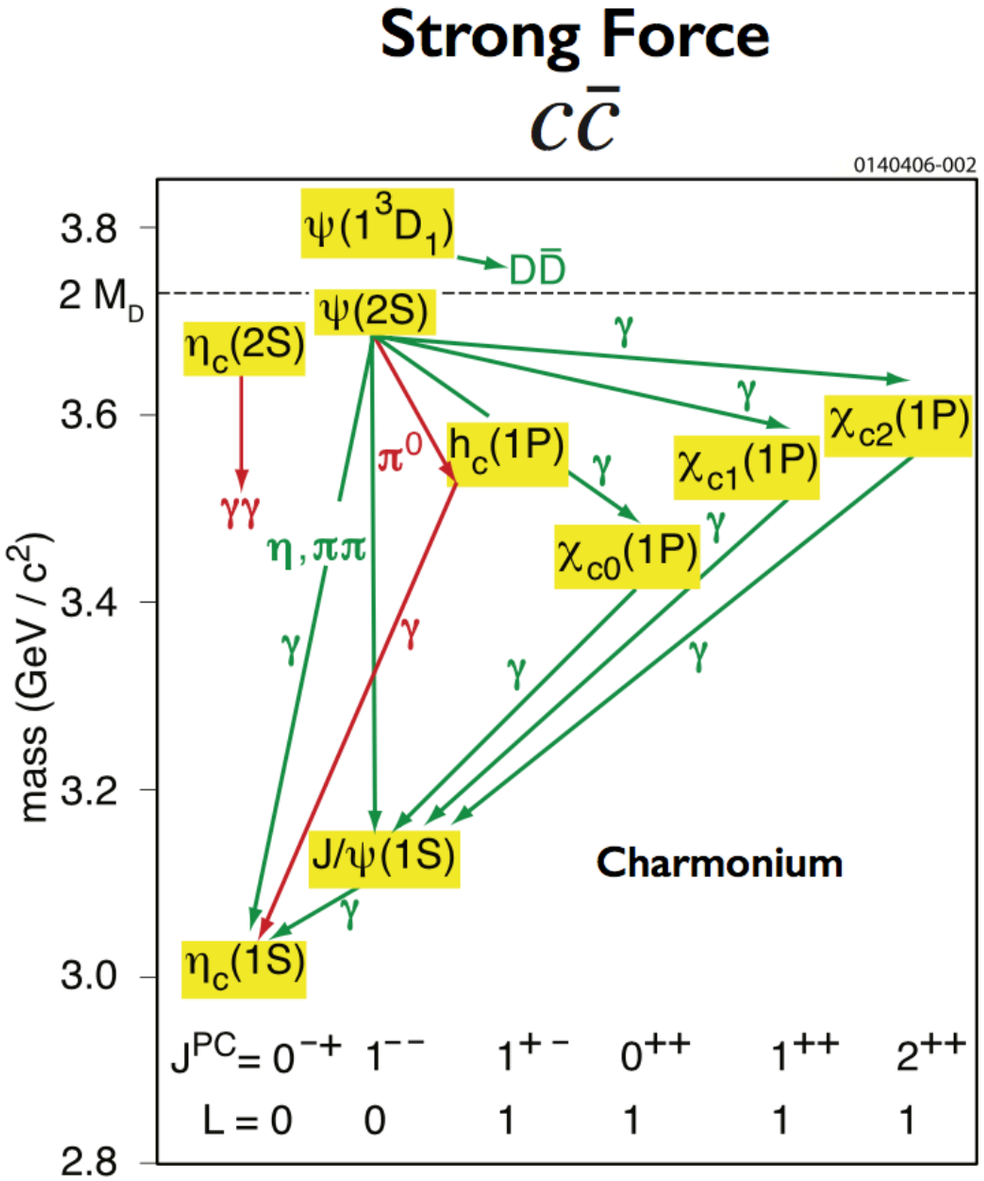


Only $J^{PC} = 1^{--}$ produced in e^+e^-

“Conventional” charmonium

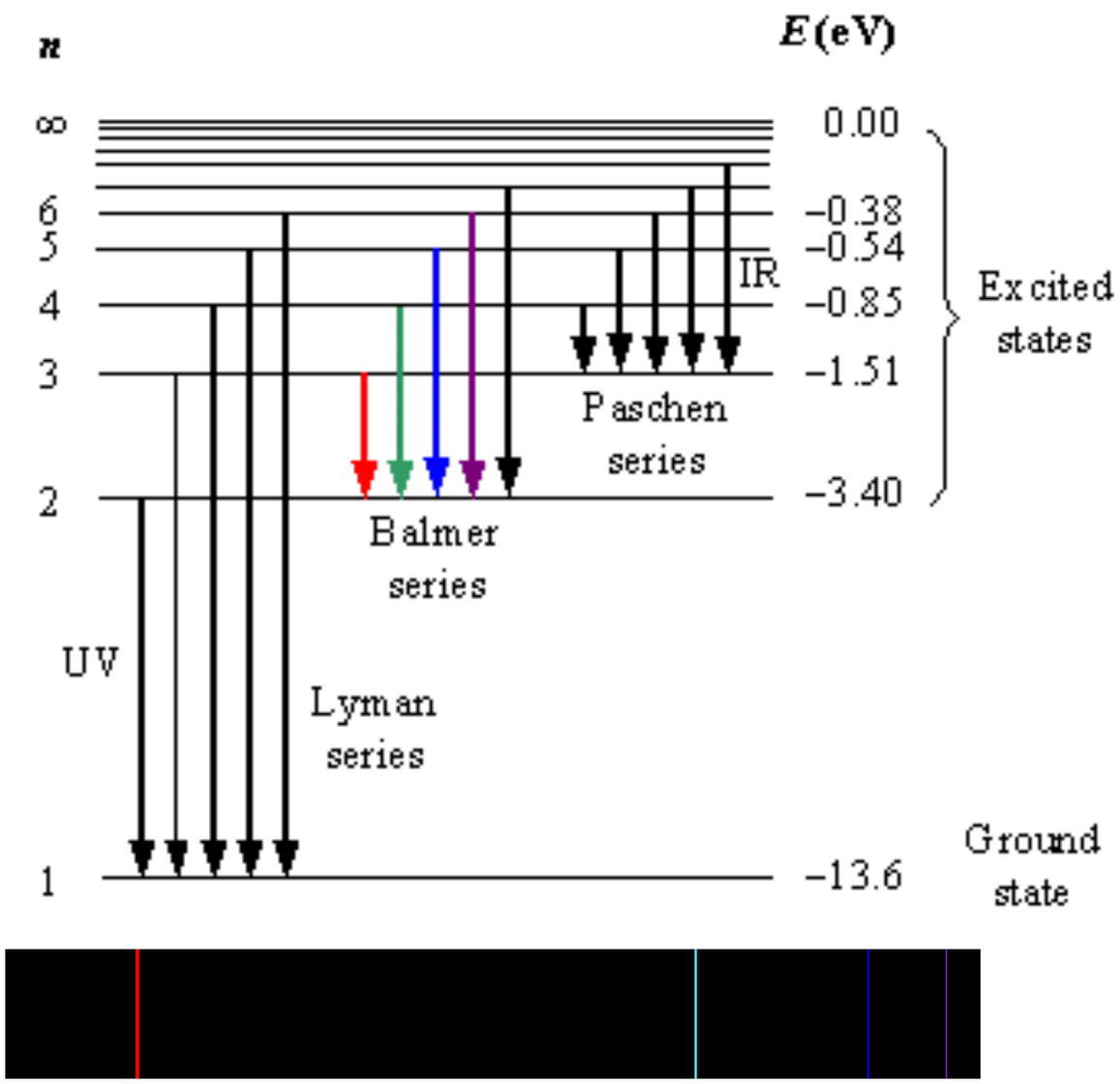
$$\psi(2s) \to \gamma X$$





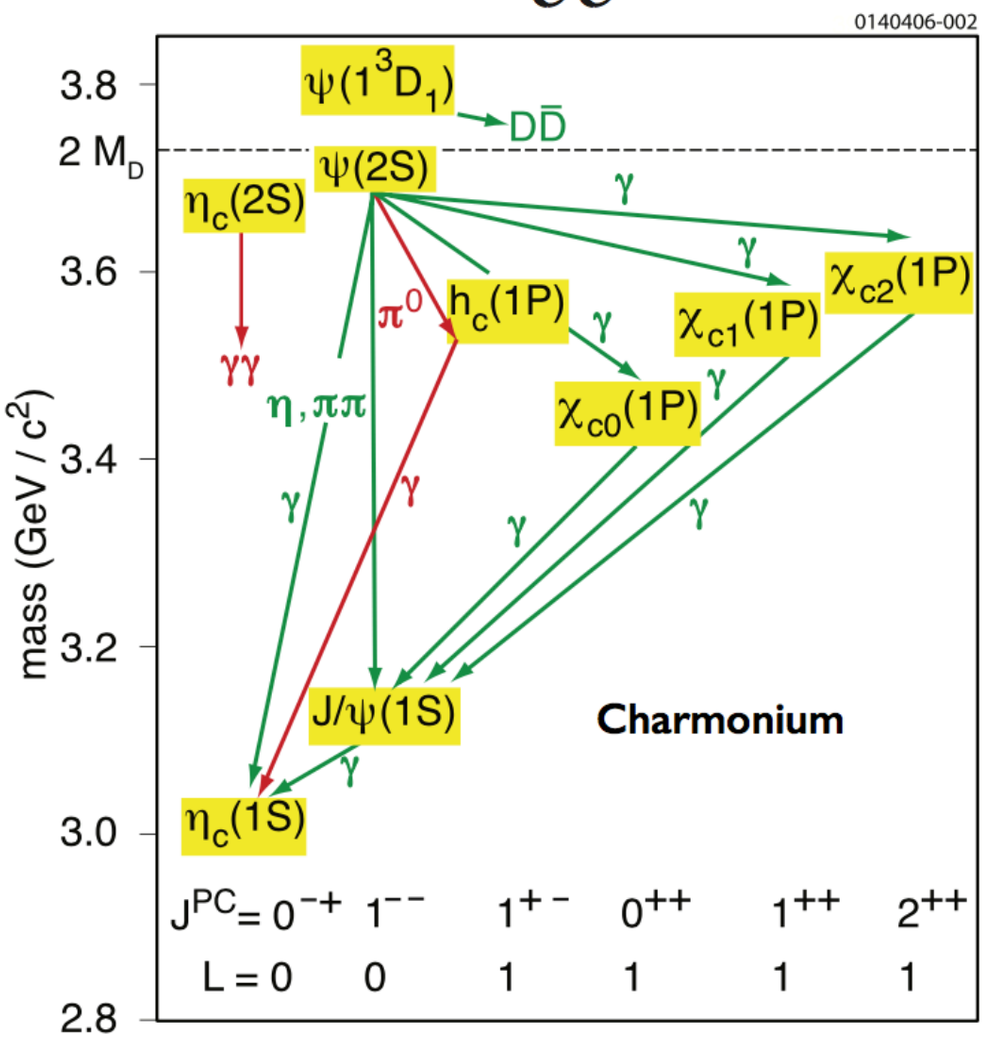
“Conventional” charmonium

Electromagnetic Force



Strong Force

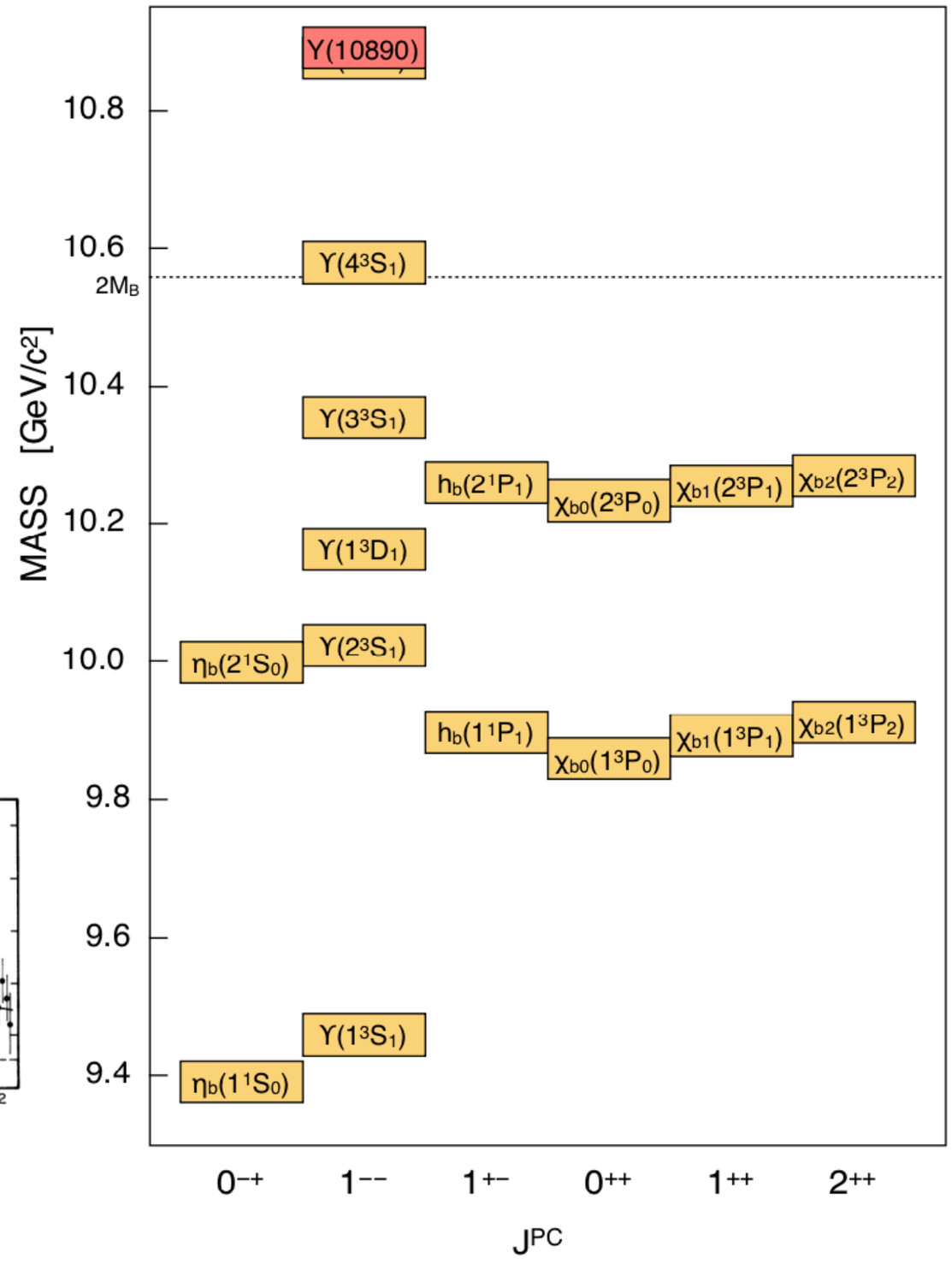
$c\bar{c}$

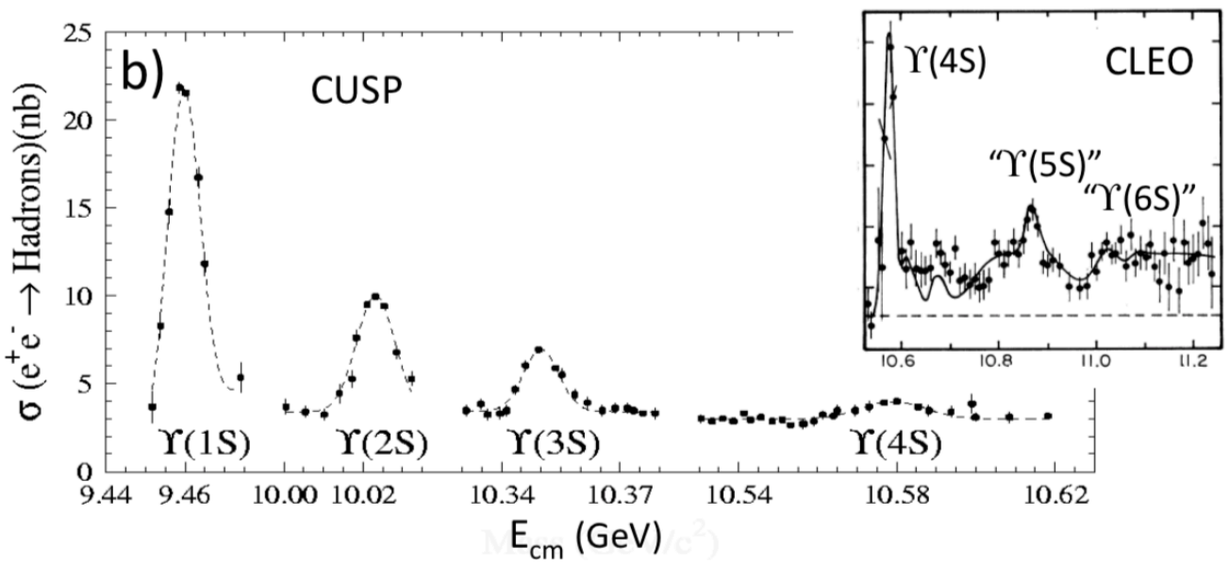


“Simple” $c\bar{c}$ spectrum well described by quark model expectation with expected electromagnetic transitions

“Conventional” bottomonium

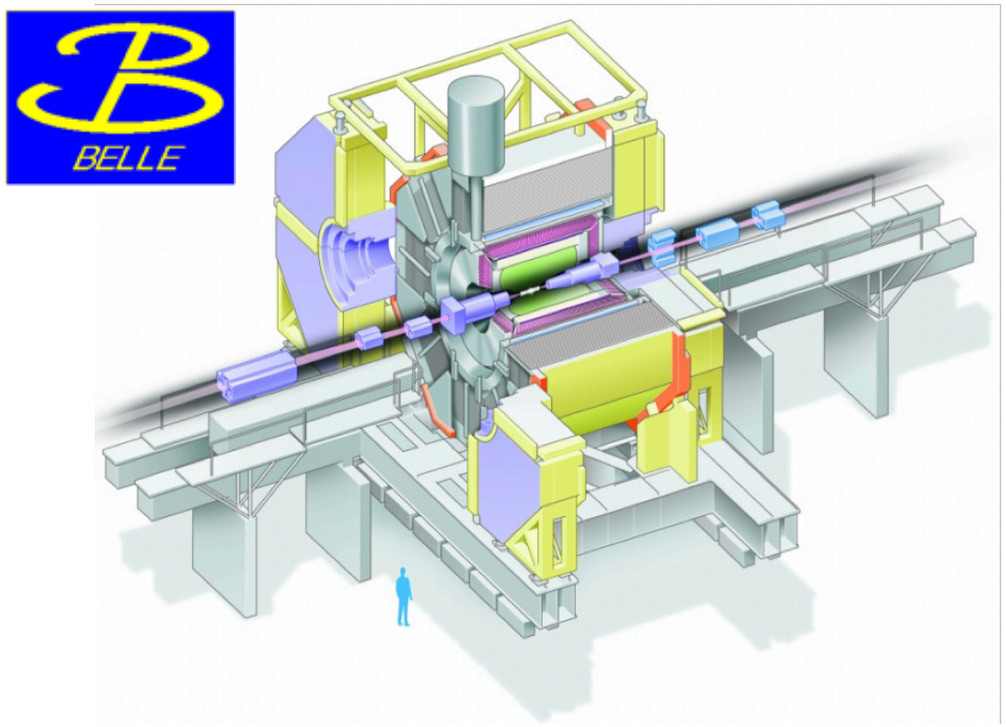
- Similar picture for bottomonium states
- EM transitions at expected masses

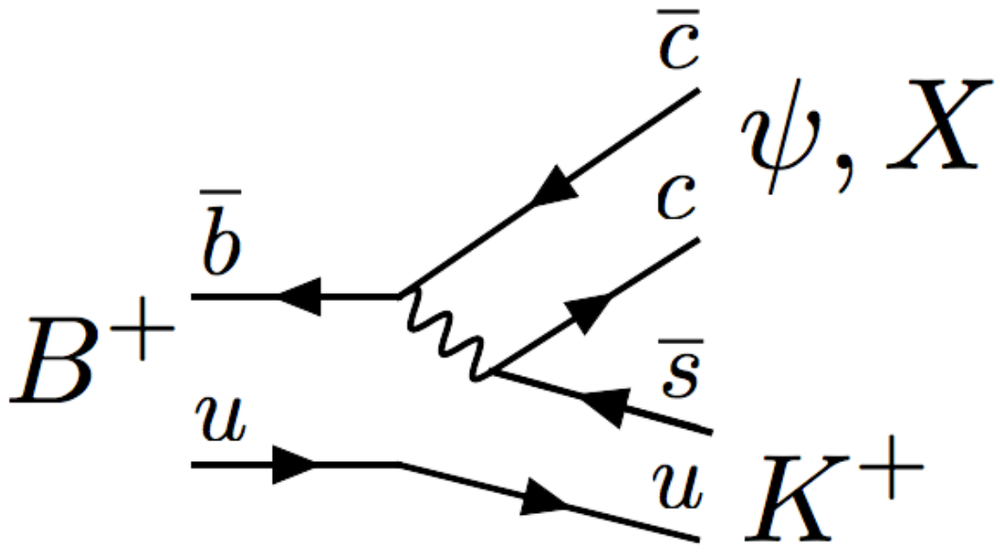




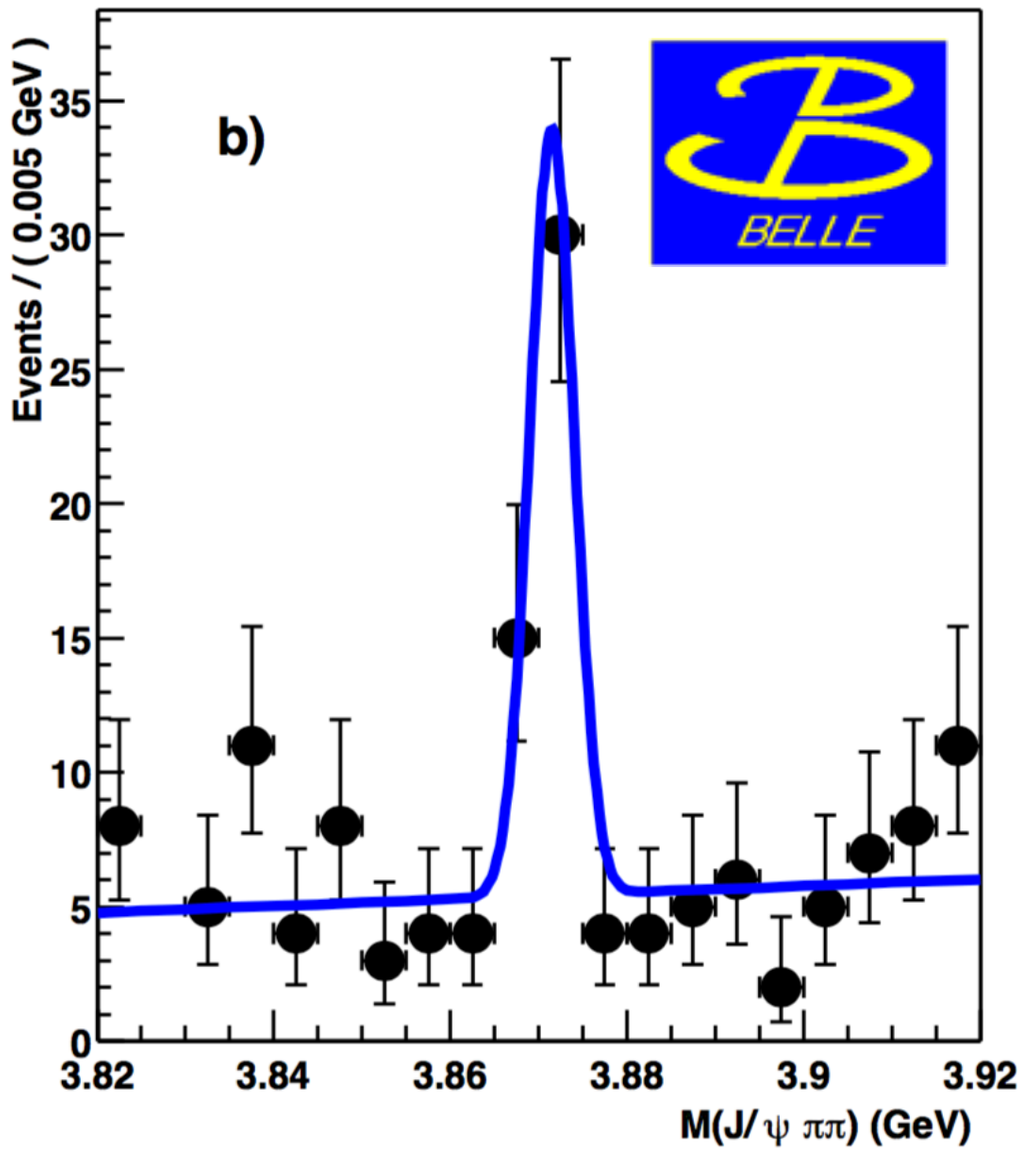
Where the XYZ odyssey began: *X*(3872)

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





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

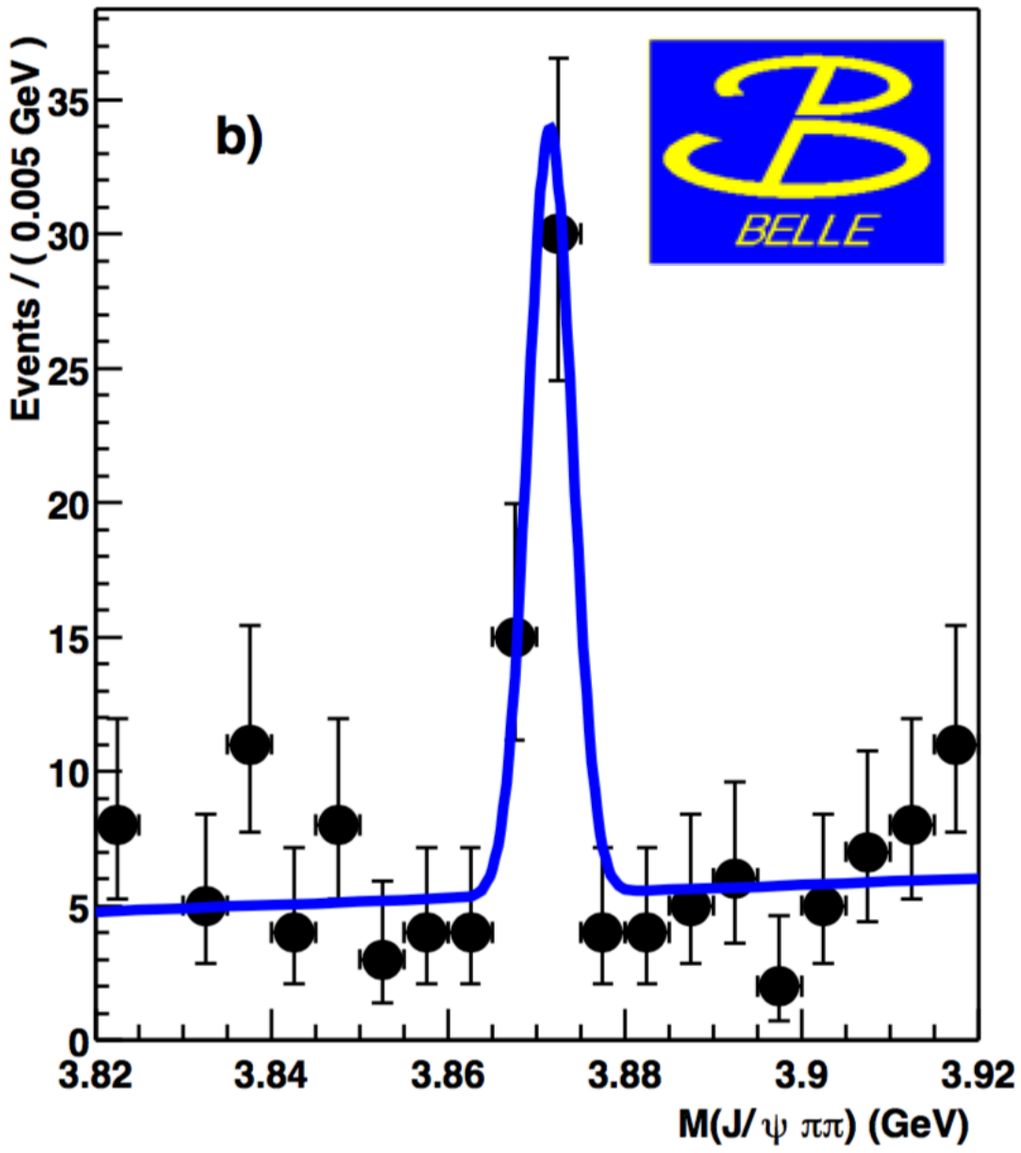


Belle (2003)

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?**

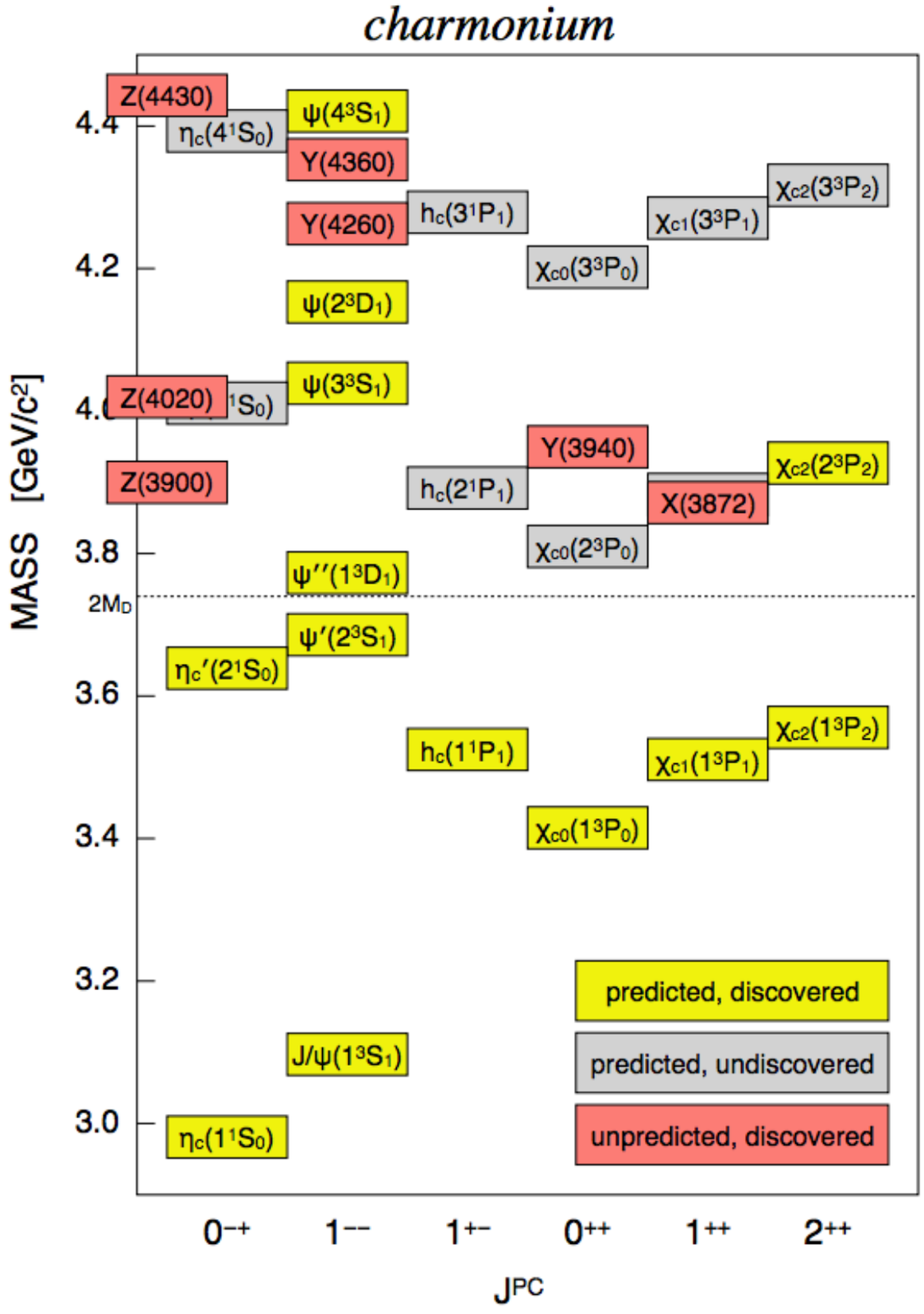
$$X \to \pi^+\pi^- J/\psi$$



Belle (2003)

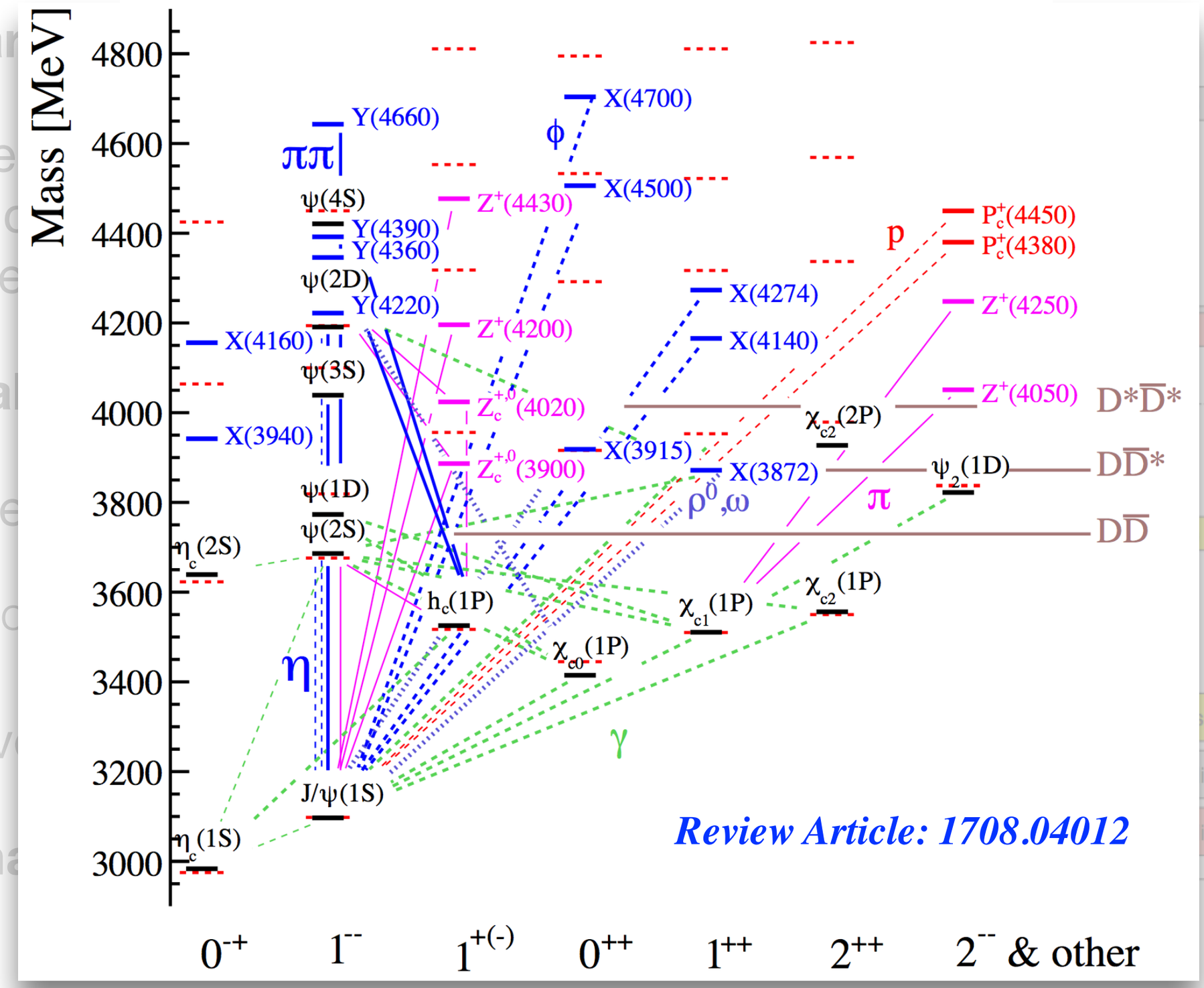
Introduction to XYZs

- **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?**



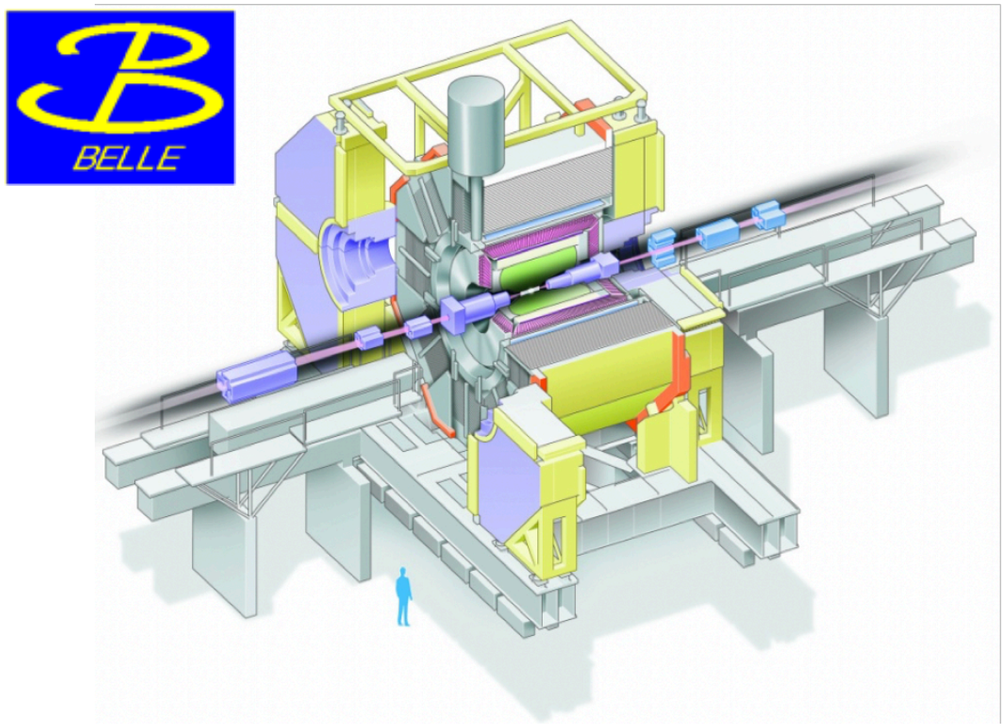
Introduction to XYZs

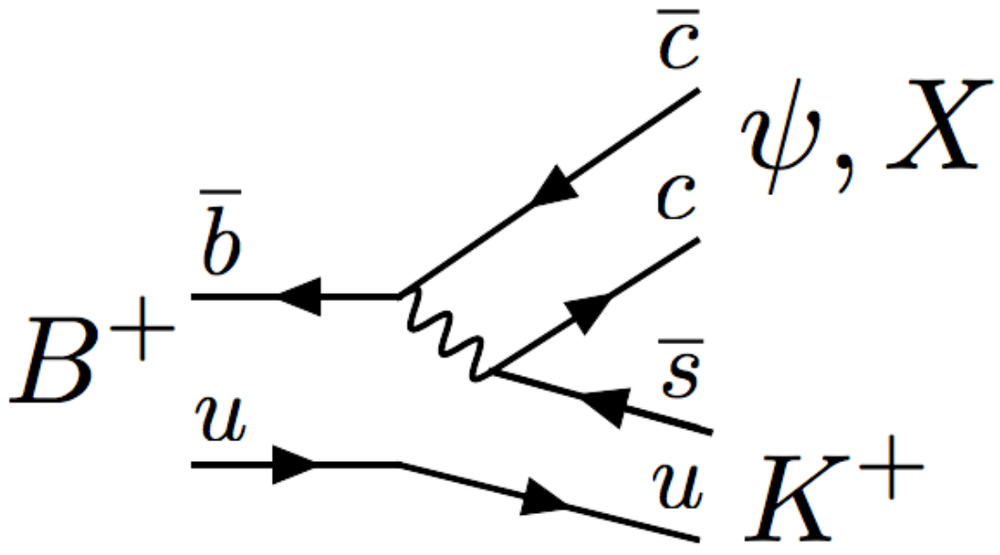
How many are there? Lots!!!



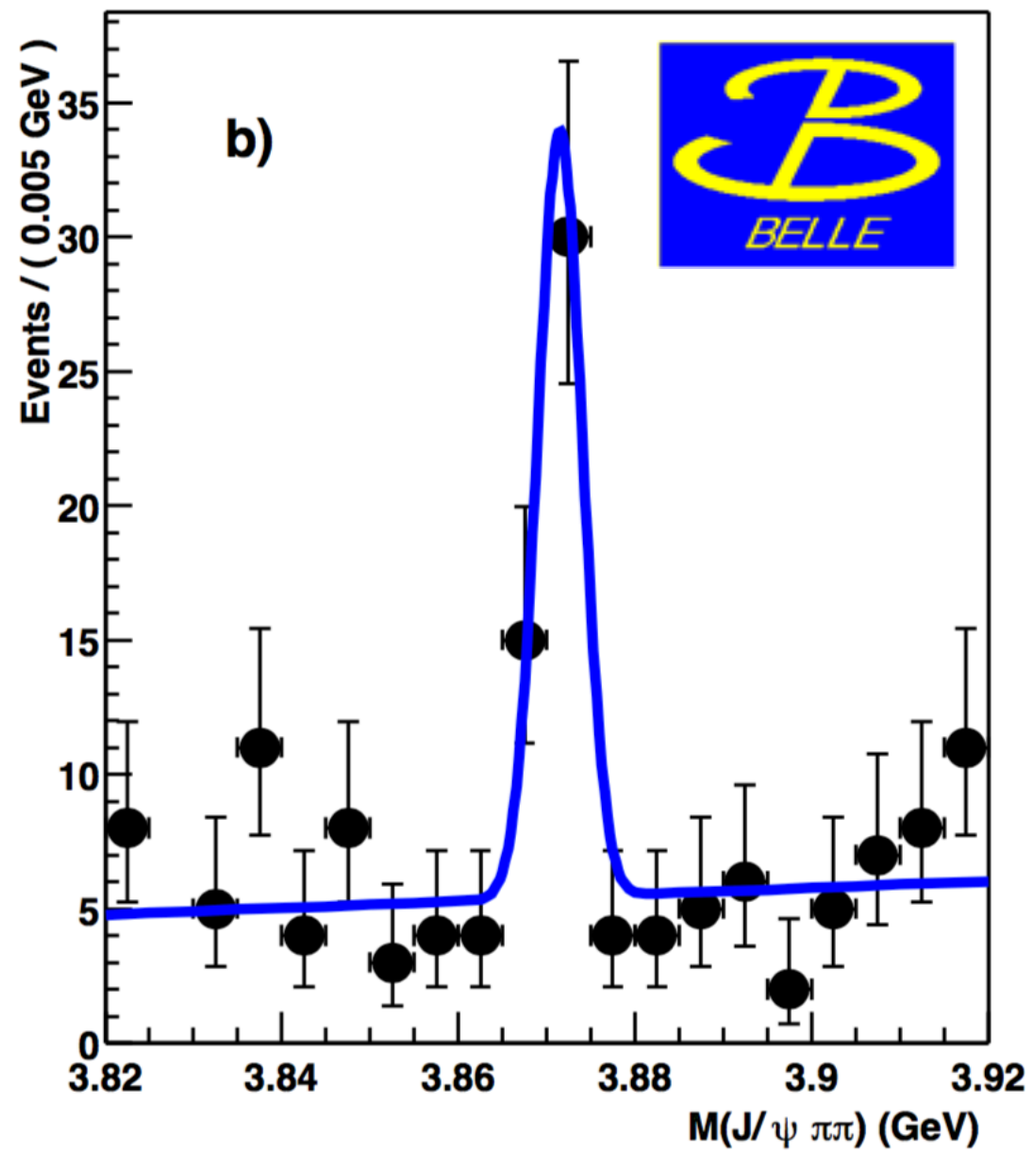
Where the XYZ odyssey began: *X*(3872)

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





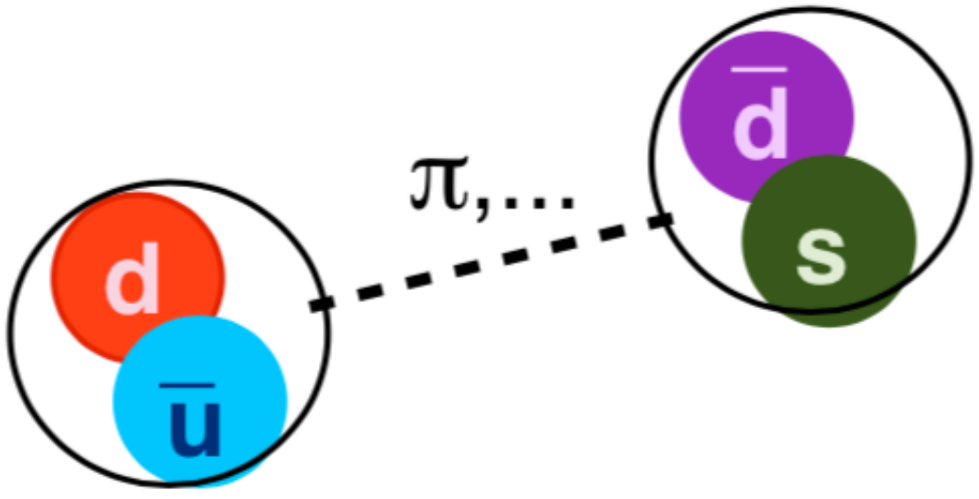
$X \to \pi^+\pi^- J/\psi$



Belle (2003)

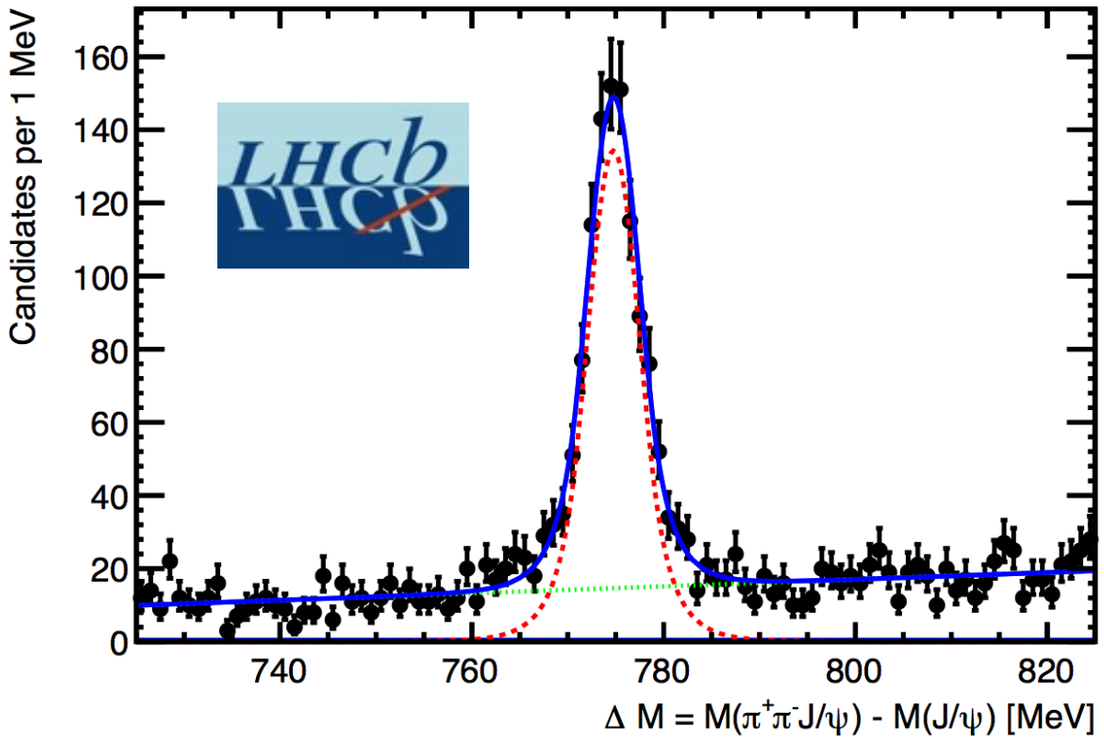
Where the XYZ odyssey began: $X(3872)$

- Interpretations
  - Unexpected cc state?
  - Hadron molecule?
  - Tightly bound “tetraquark”?

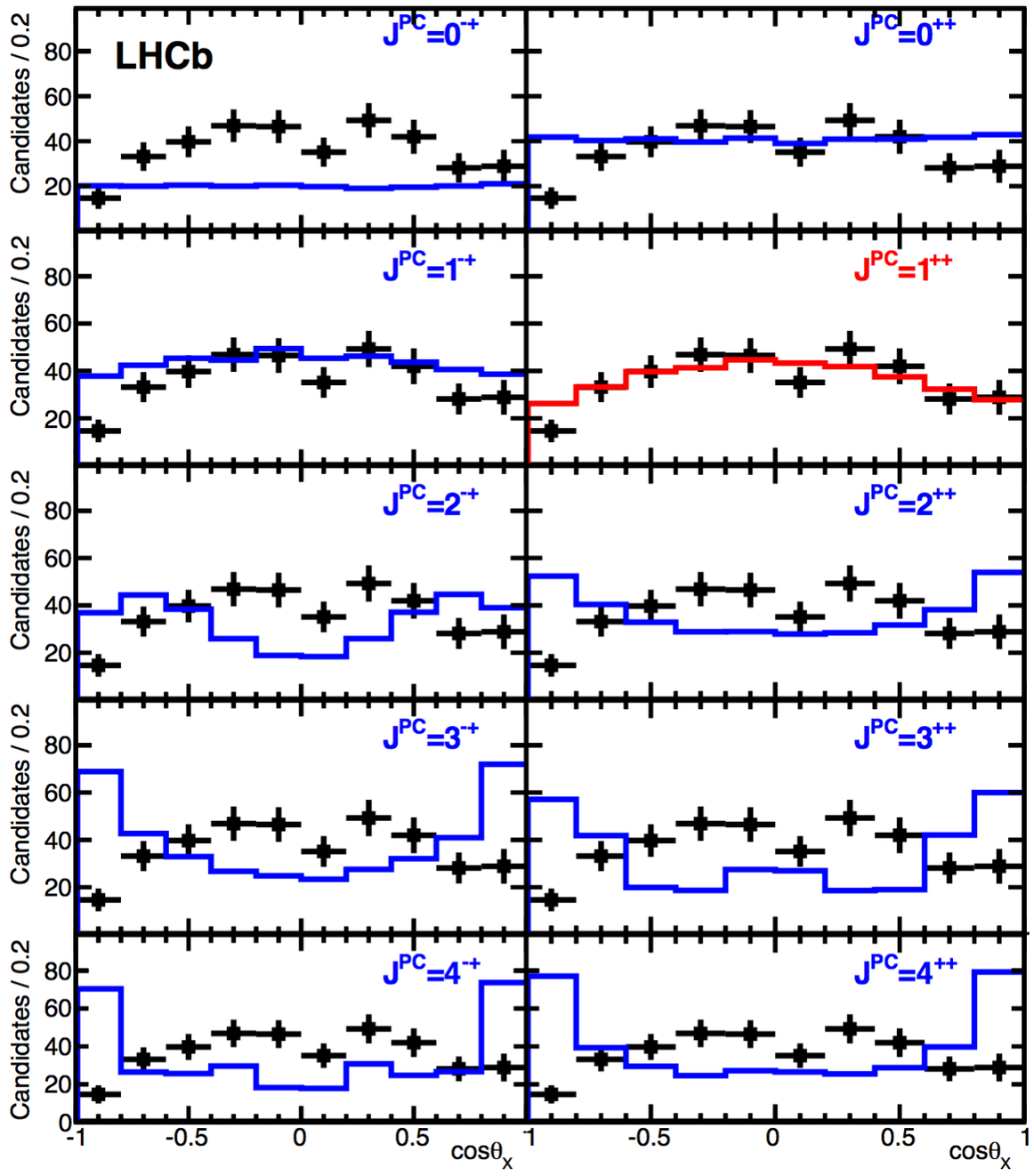


diquark-diantiquark

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

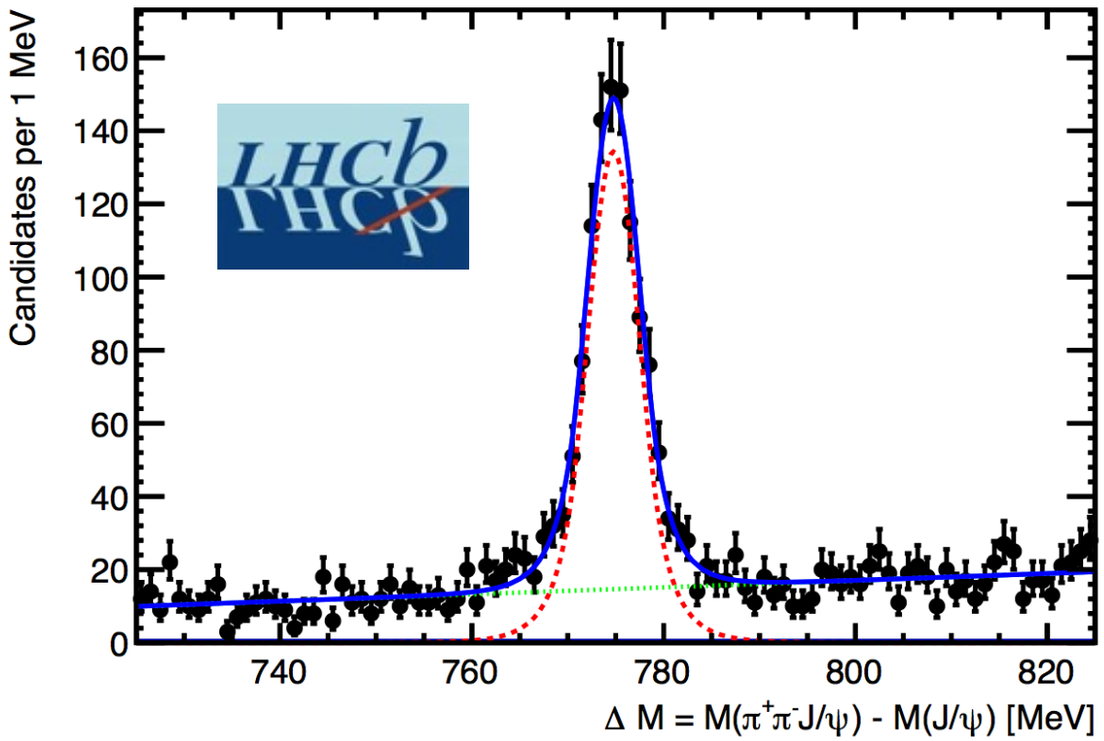


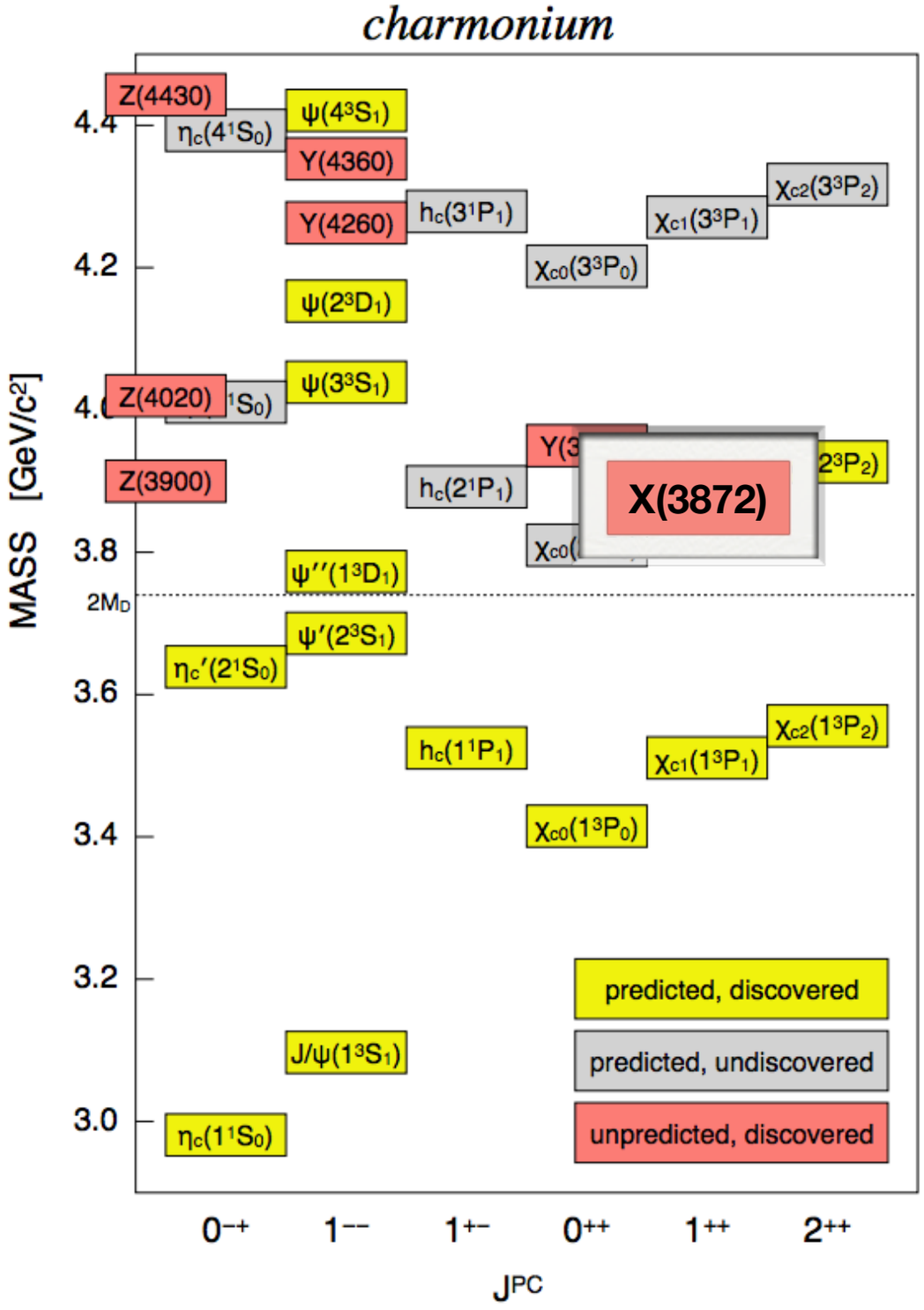
$$J^{PC} = 1^{++}$$



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

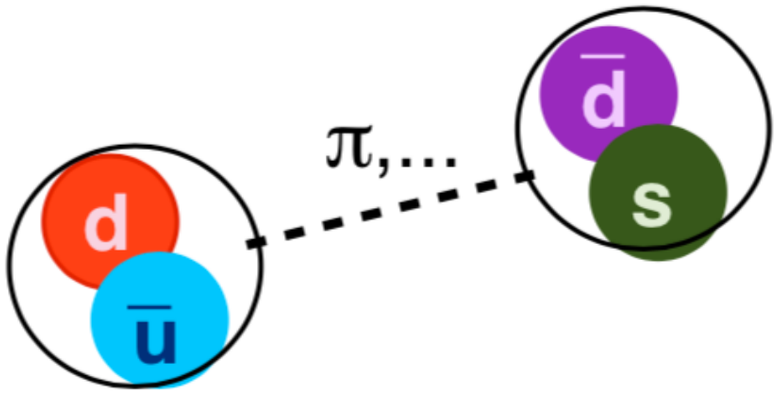
Where the XYZ odyssey began: *X*(3872)





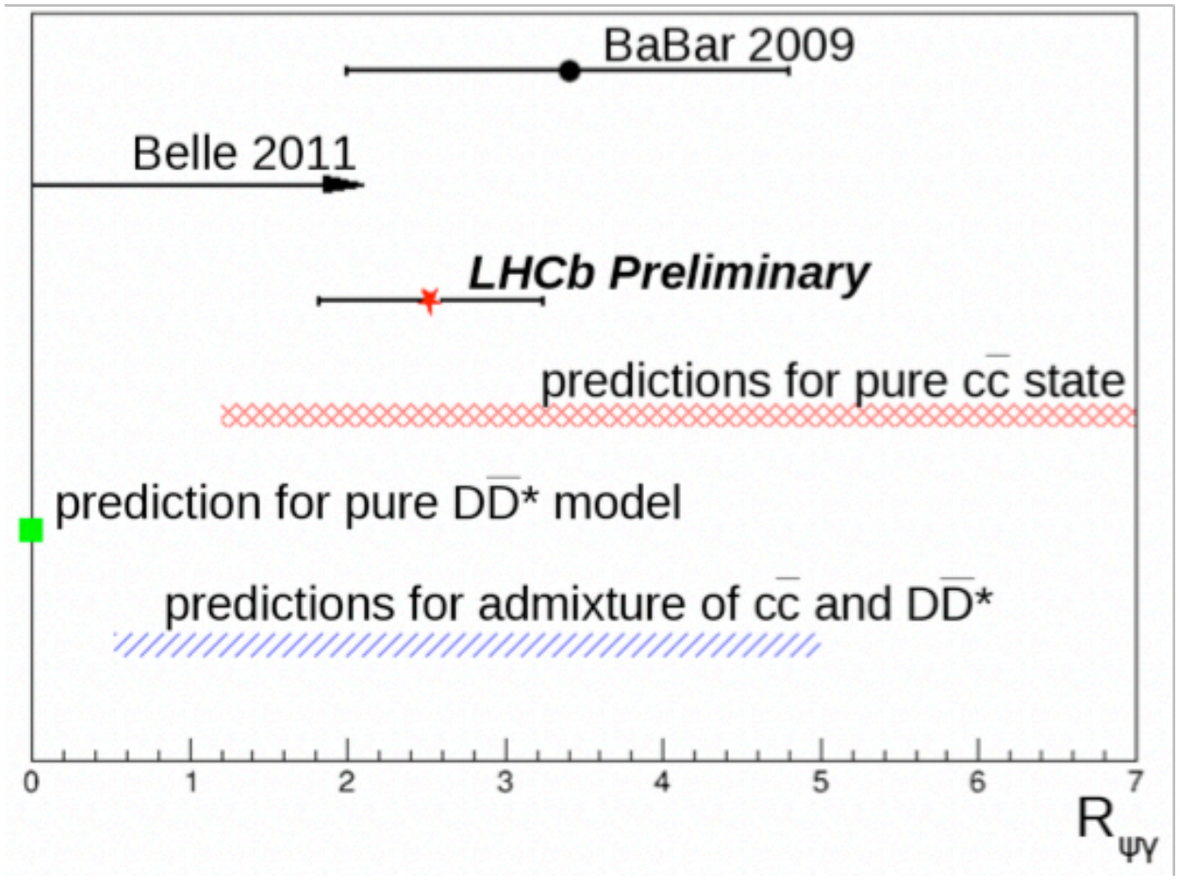
- Higher statistics: **more studies**
  - Quantum numbers
  - **$M_X \sim M_D + M_{D^*}$**
  - Interpretation?

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



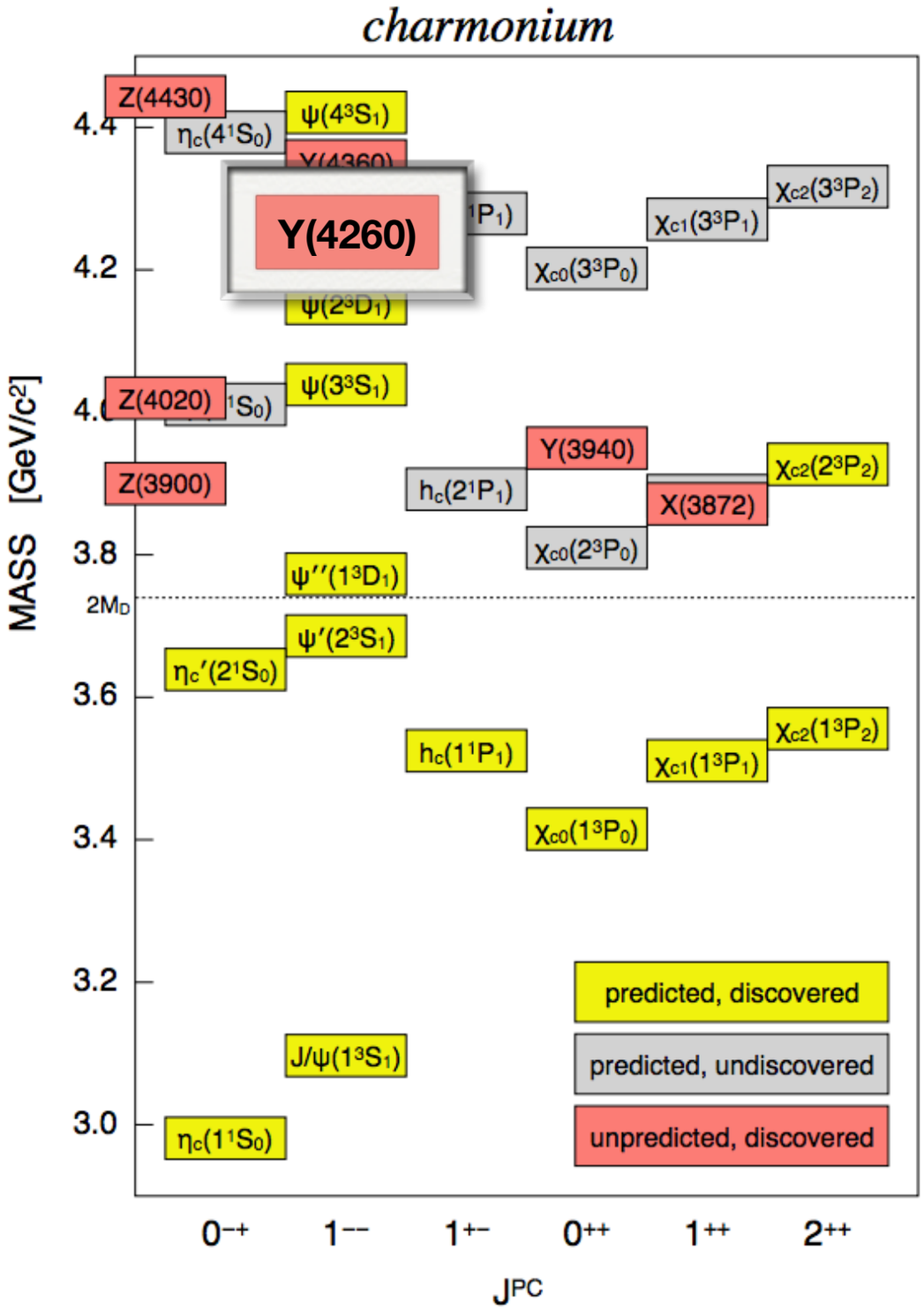
Radiative decay measurement

$$R_{\psi\gamma} = \frac{\mathcal{B}(\mathrm{X}(3872) \to \psi(2\mathrm{S})\gamma)}{\mathcal{B}(\mathrm{X}(3872) \to \mathrm{J}/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

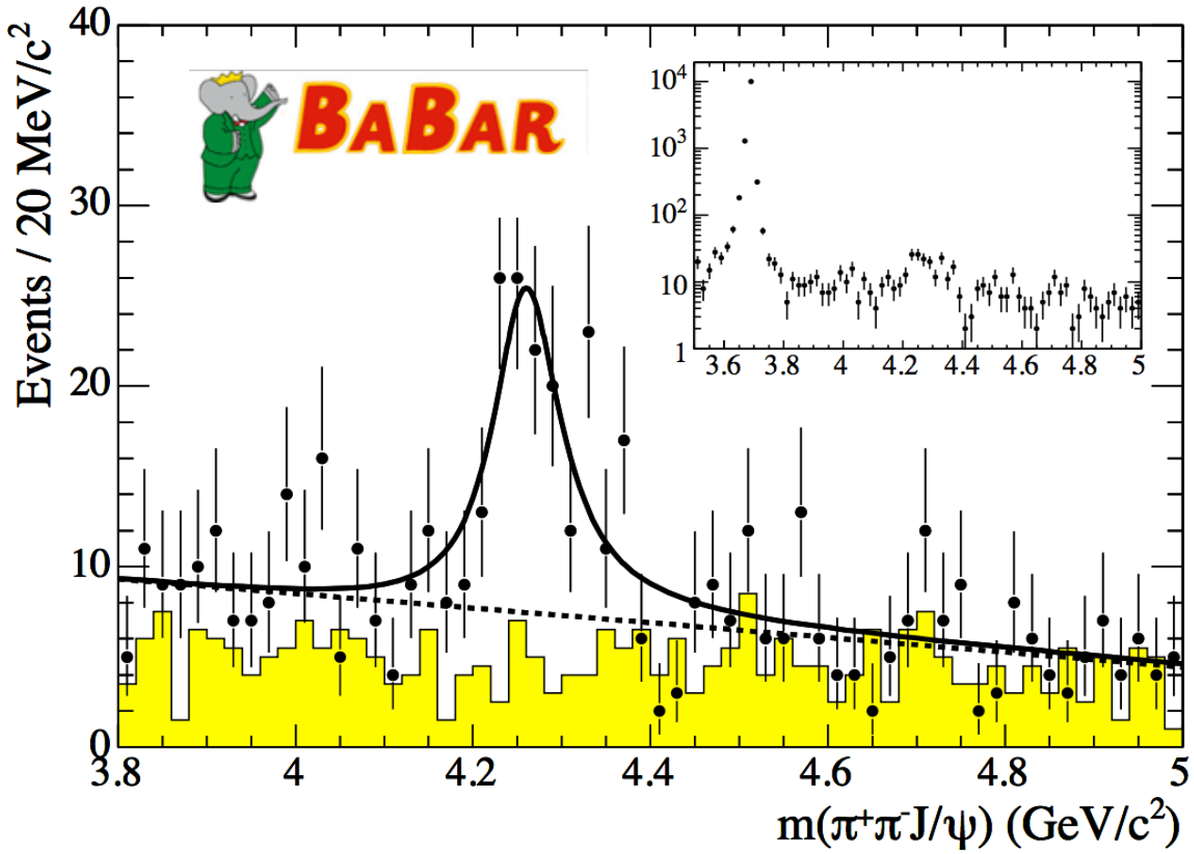


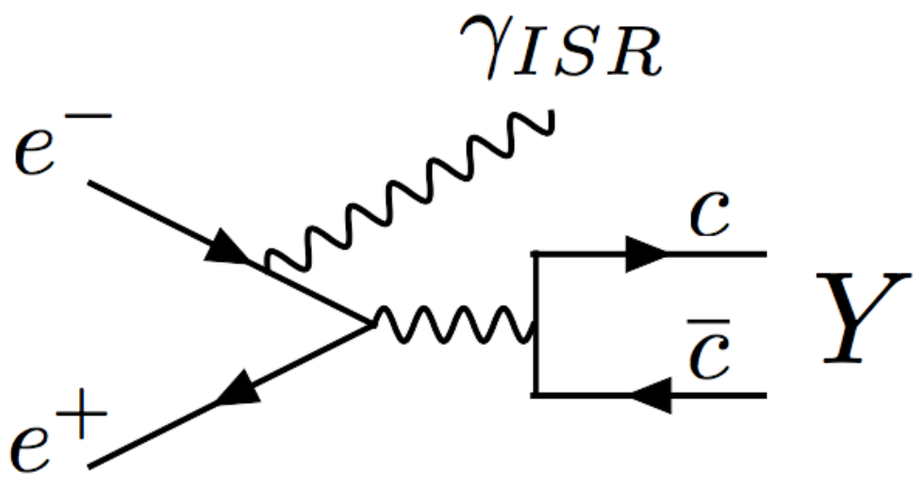
- Higher statistics: **more studies**
  - Quantum numbers
  - $M_X \sim M_D + M_{D^*}$
  - **Interpretation?**

Discovery of the *Y*(4260)

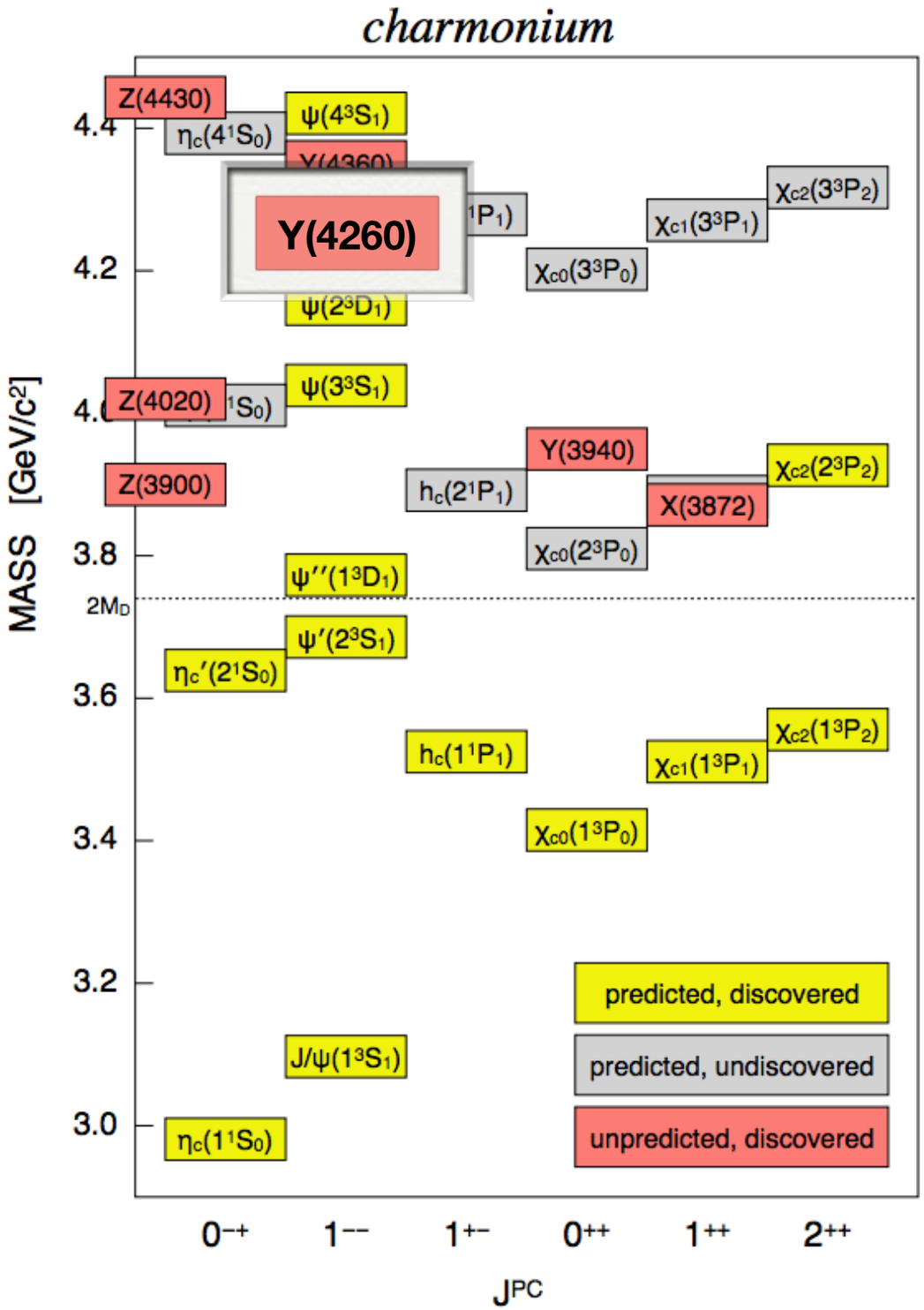


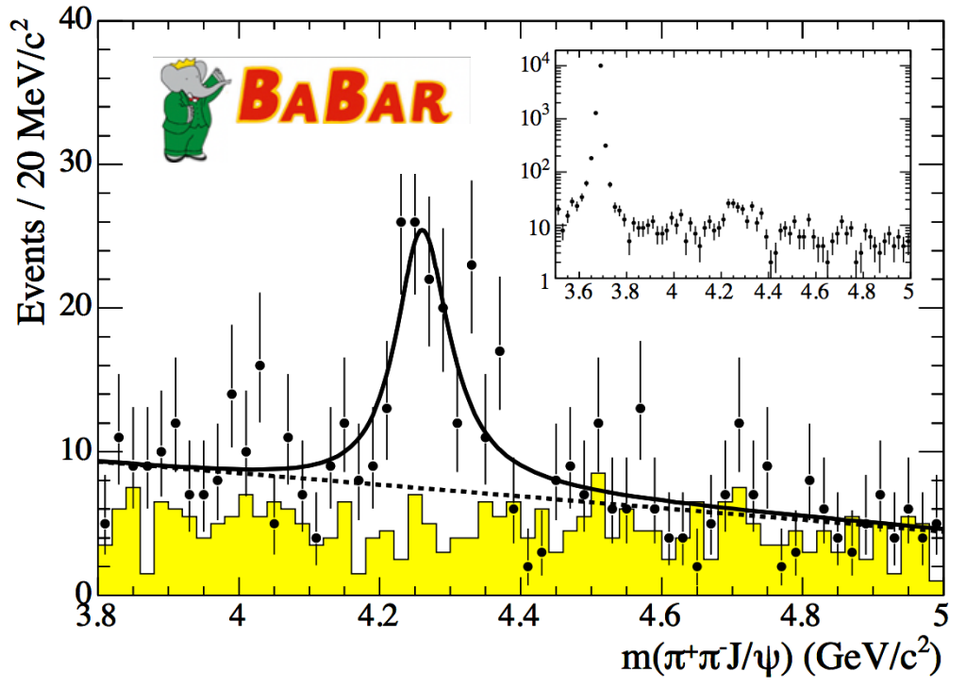
BaBar (2003)

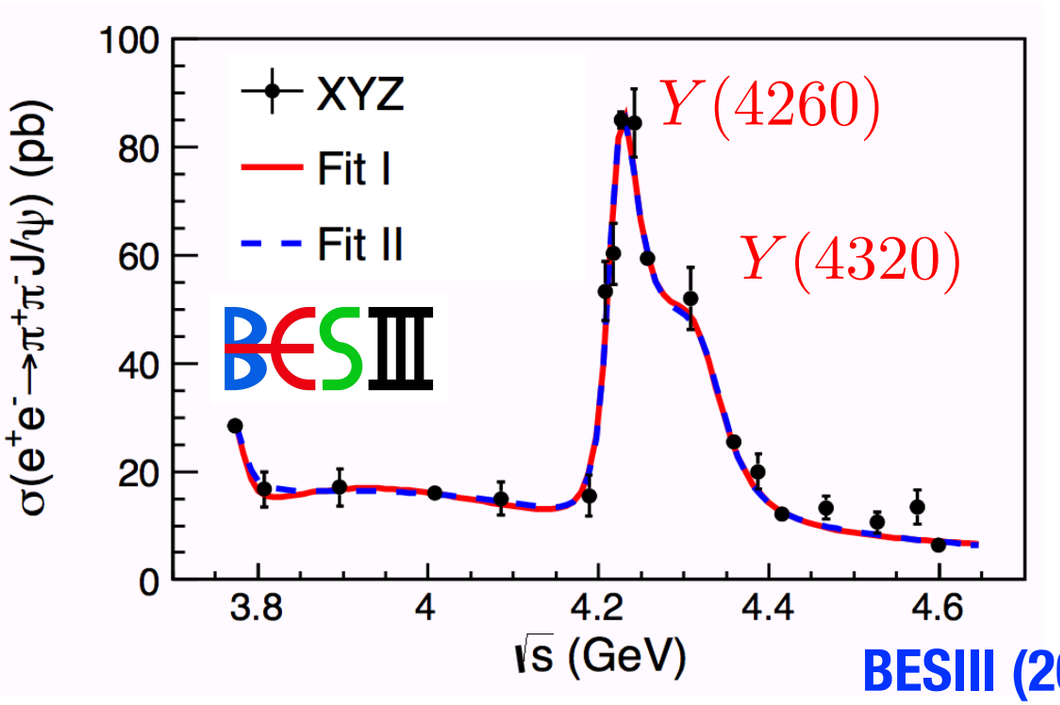




Diving deeper into *Y*(4260)



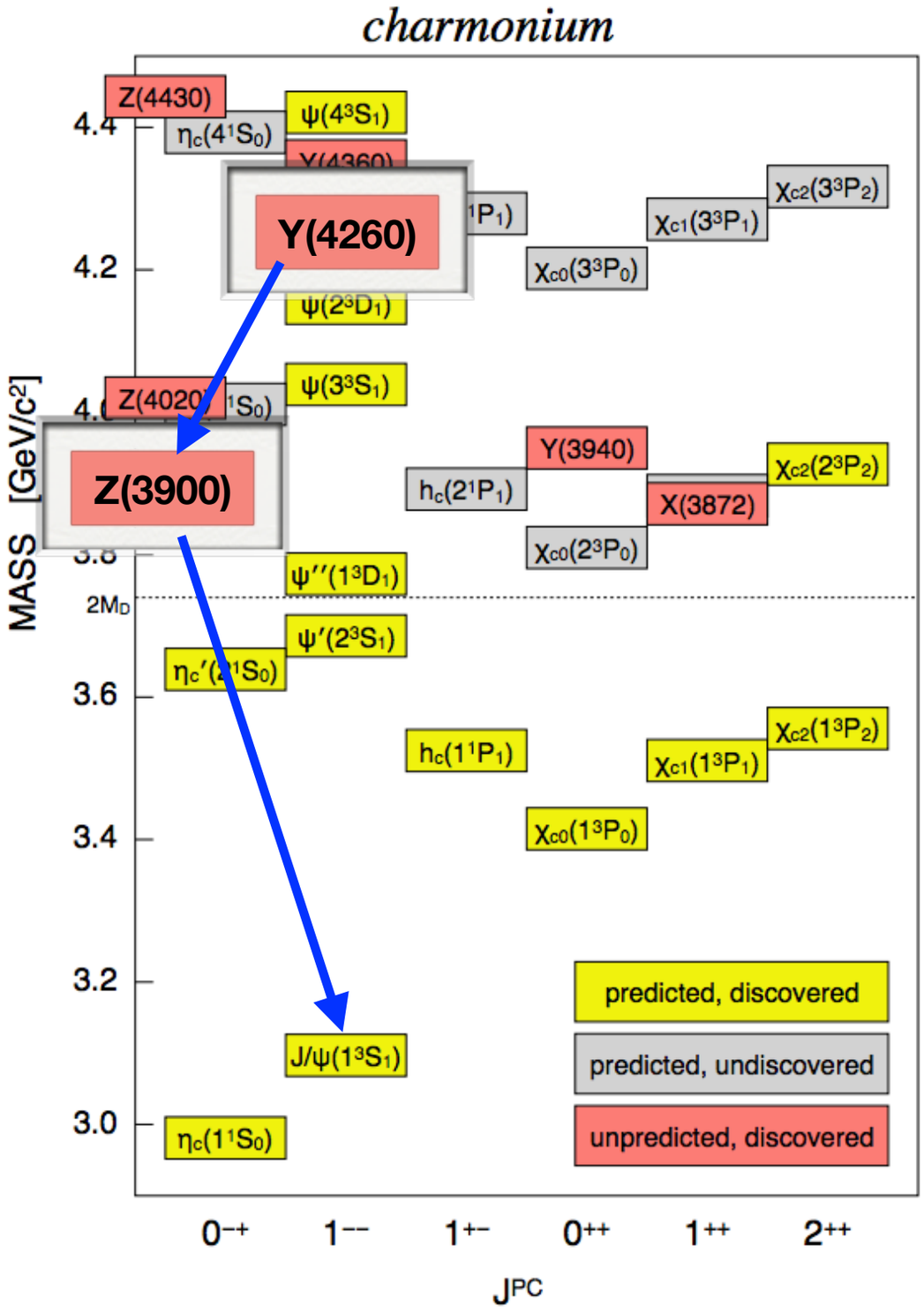


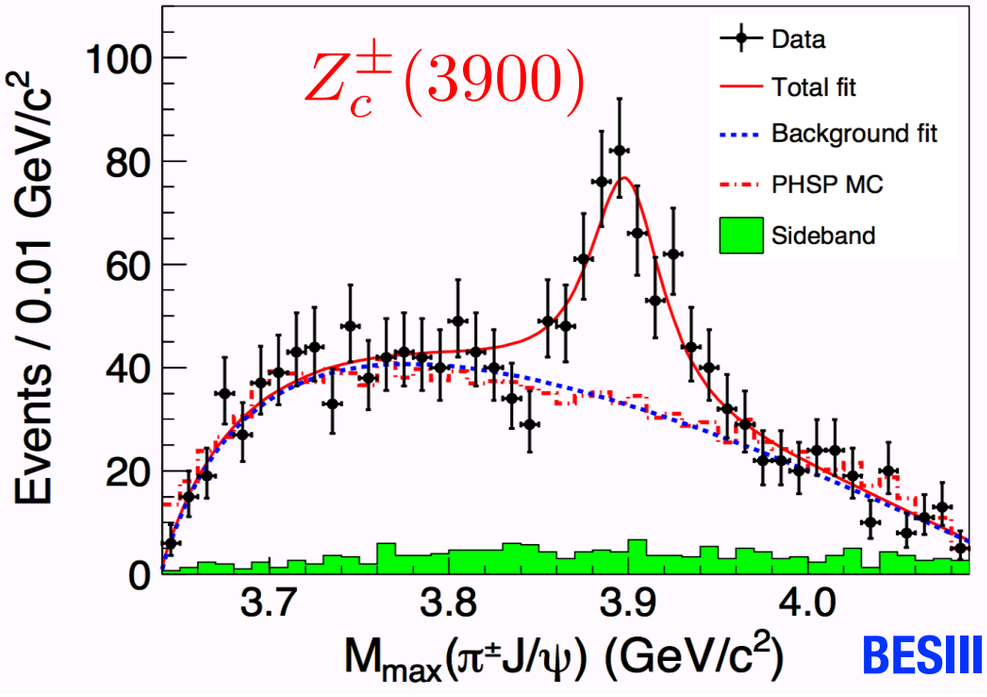


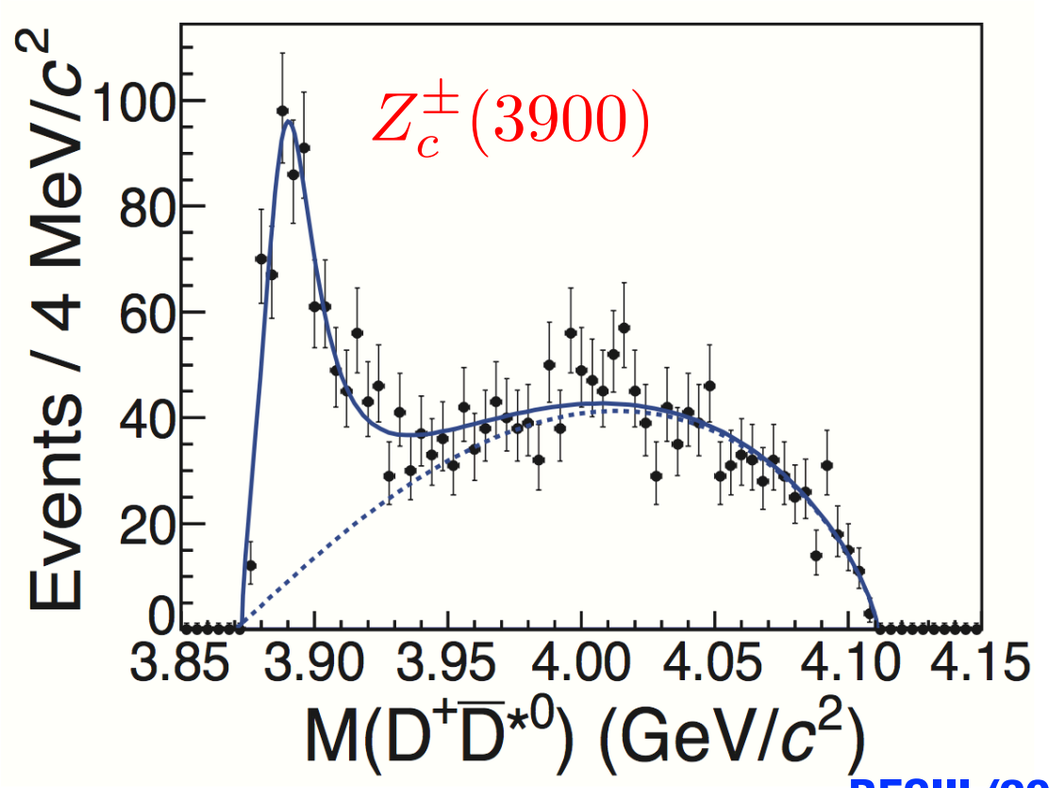
BESIII (2017)

More statistics: 2 peaks!

Diving deeper into *Y*(4260)

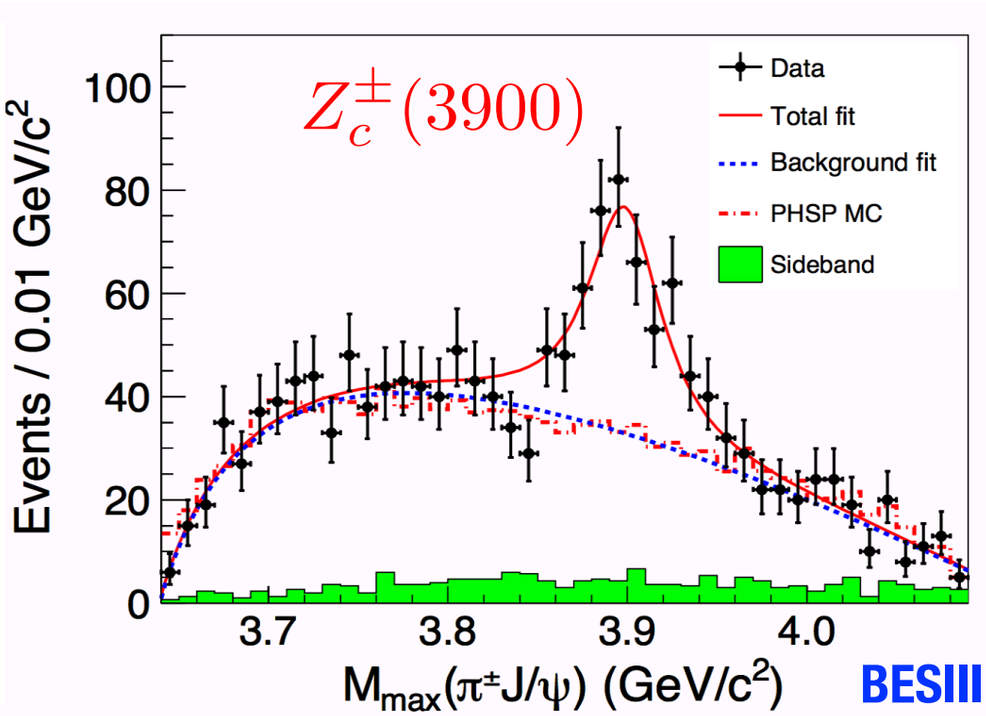


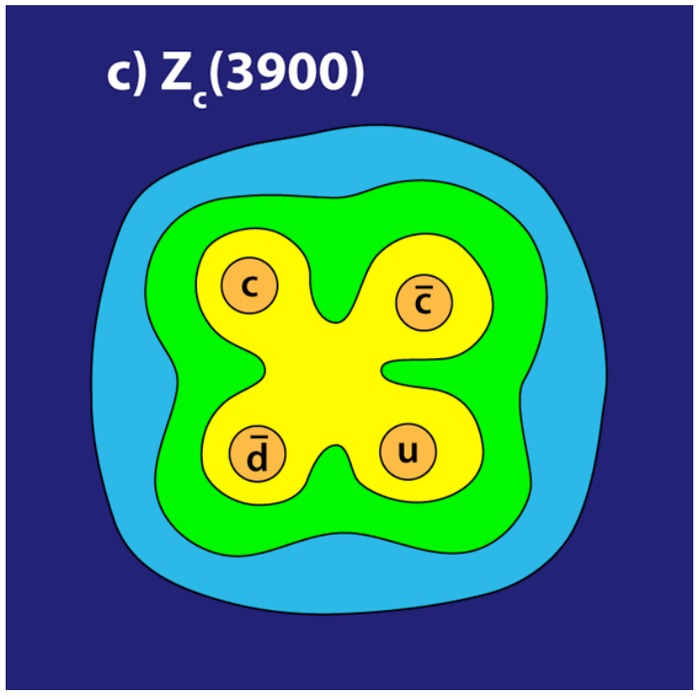




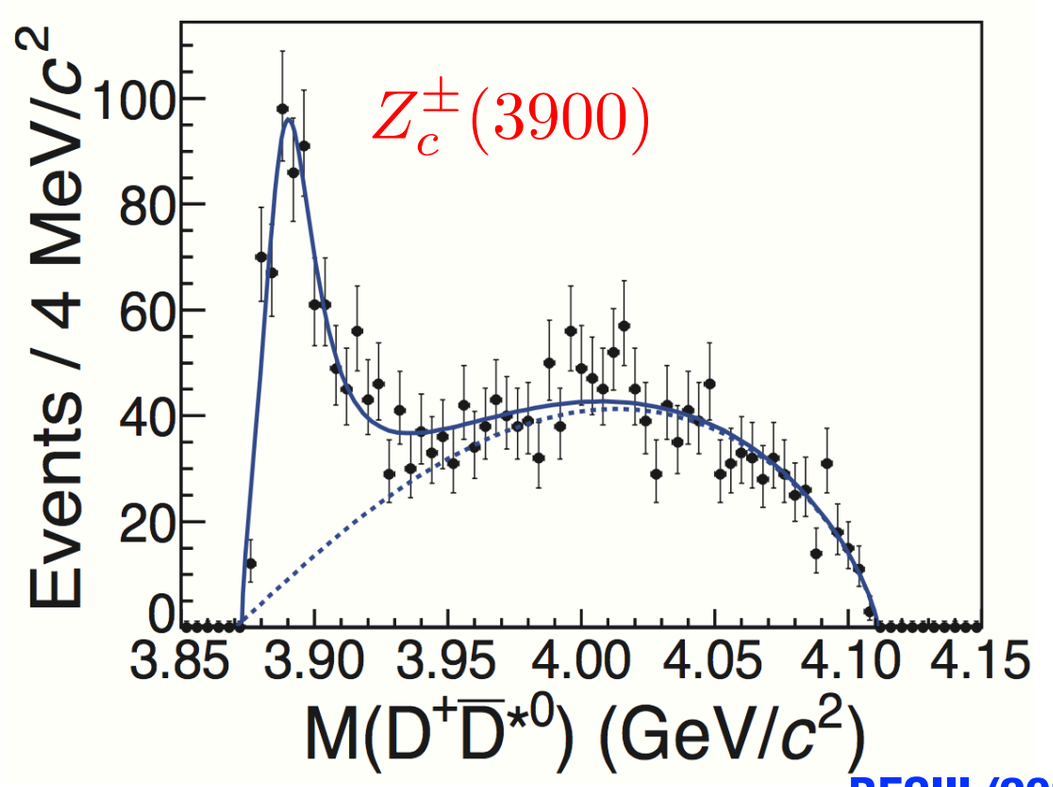
Four quark state: $Z_c(3900)$

- 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?**



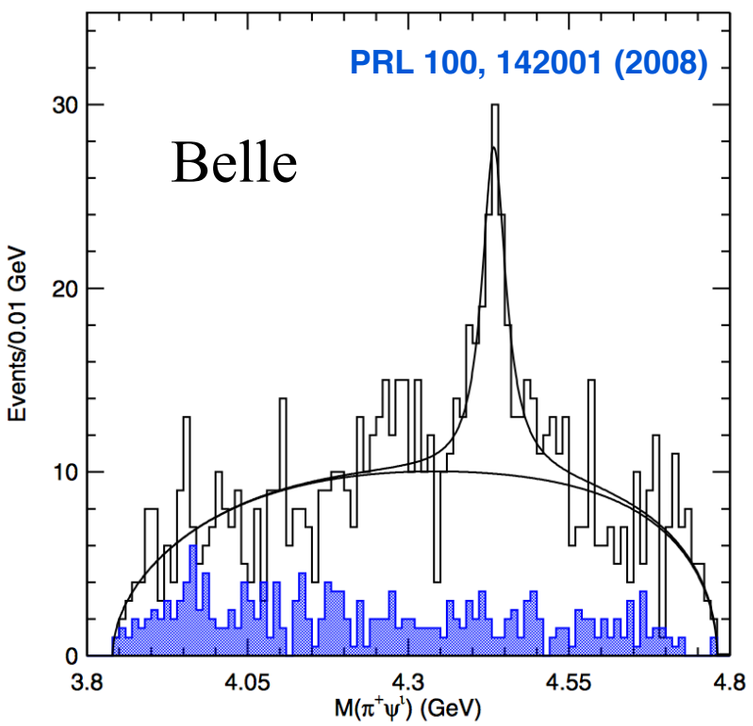


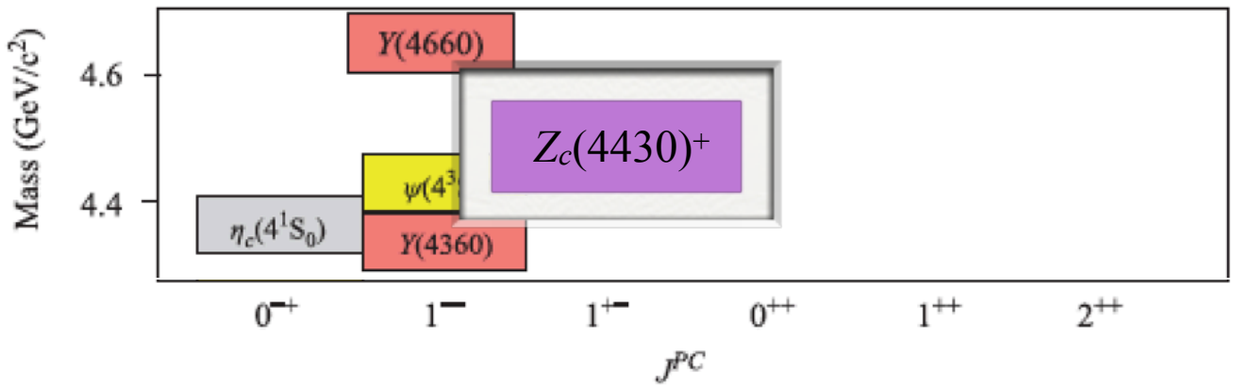
Physics Viewpoint 6, 69 (2013)



$Z_c^+(4430)$

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

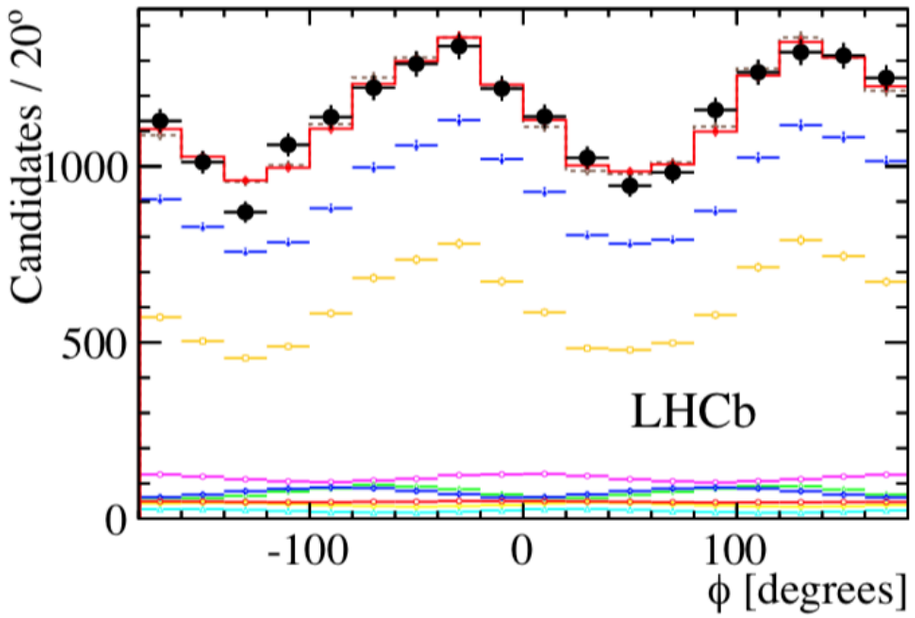


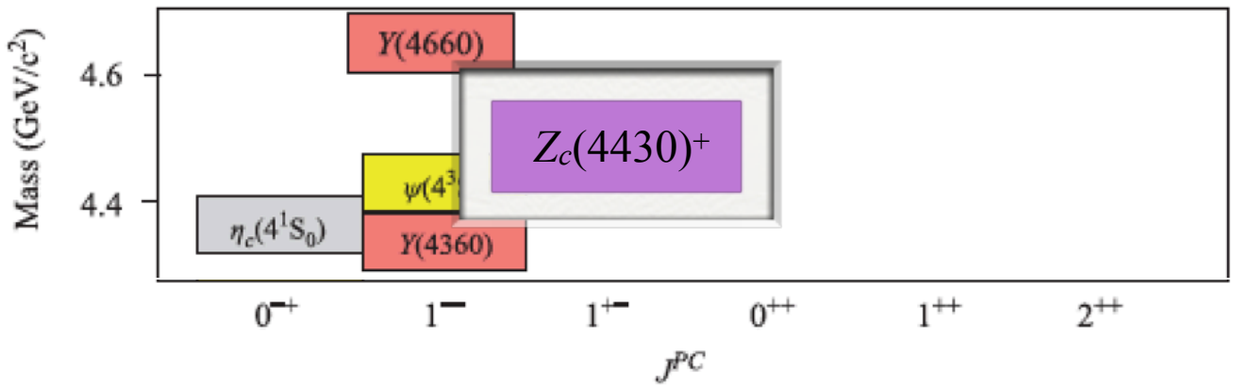


- Charged charmonium structure observed in 2008 by Belle

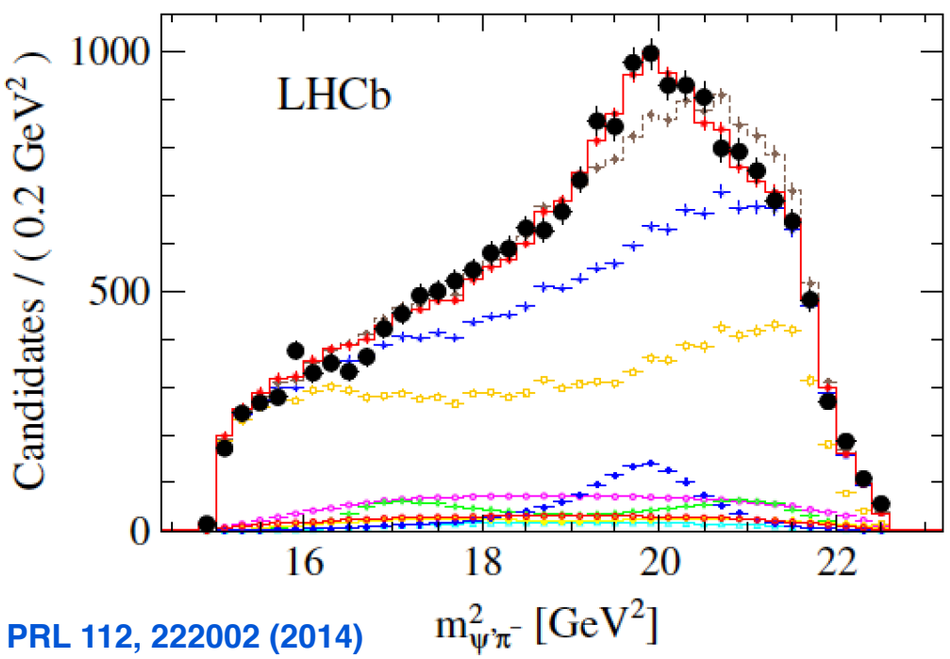
$Z_c^+(4430)$

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

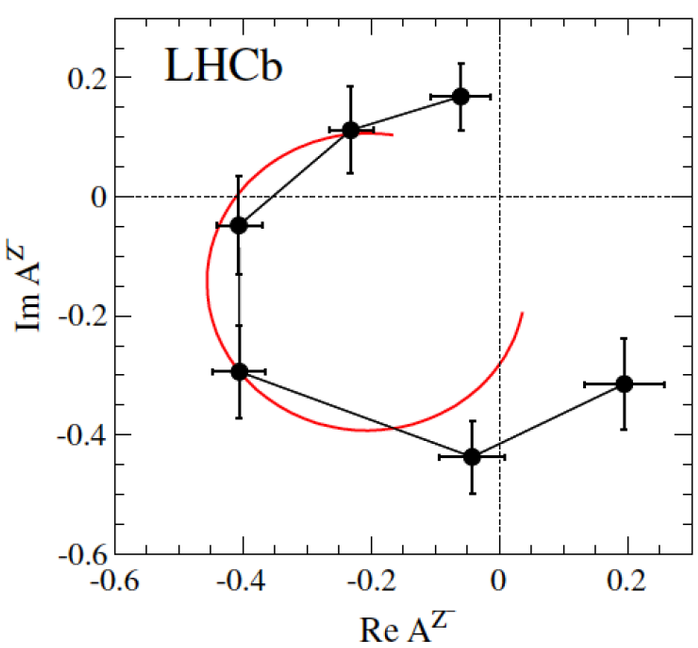




- Charged charmonium structure observed in 2008 by Belle
- Recently emphatically confirmed by LHCb and resonant character observed

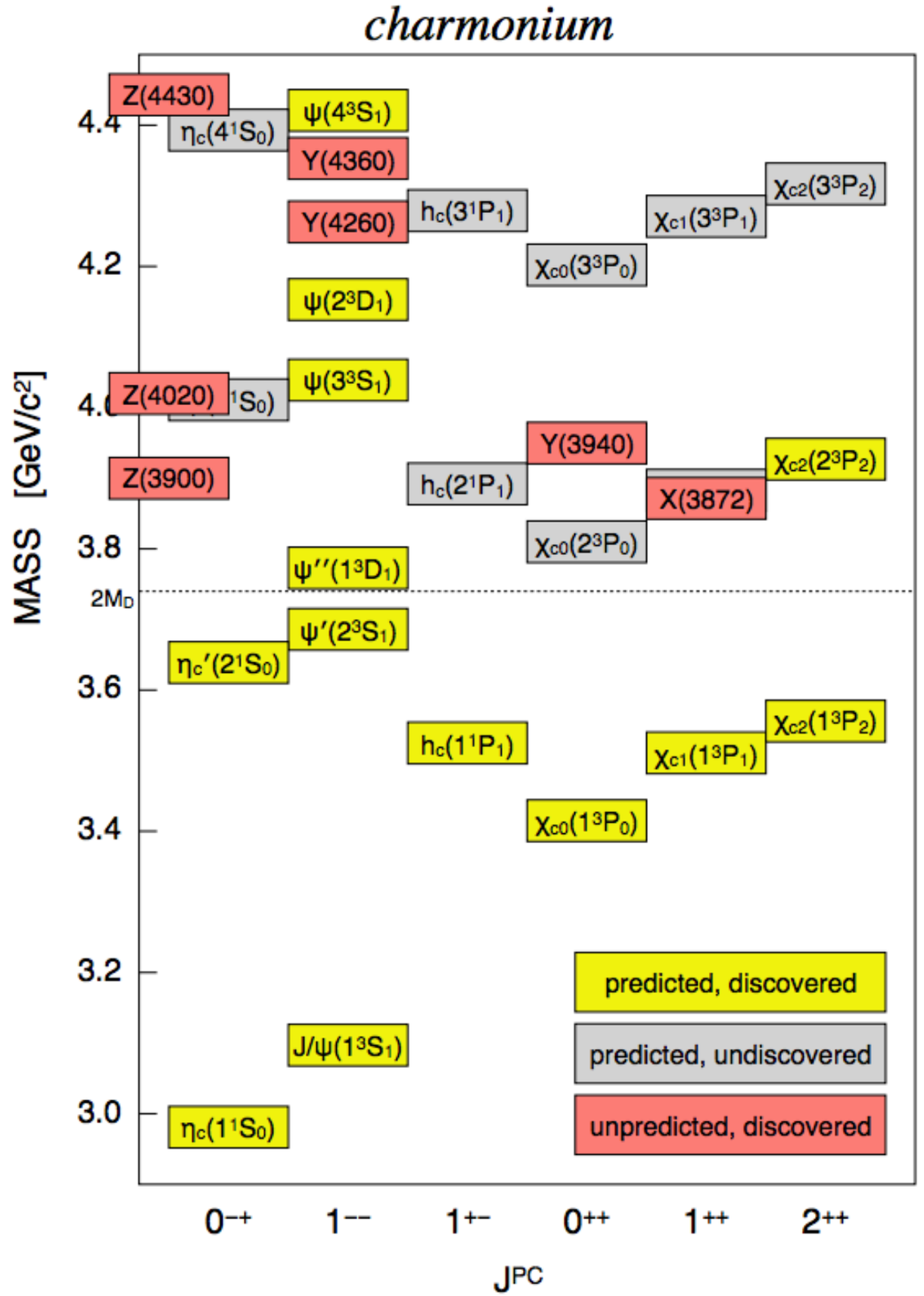


PRL 112, 222002 (2014)



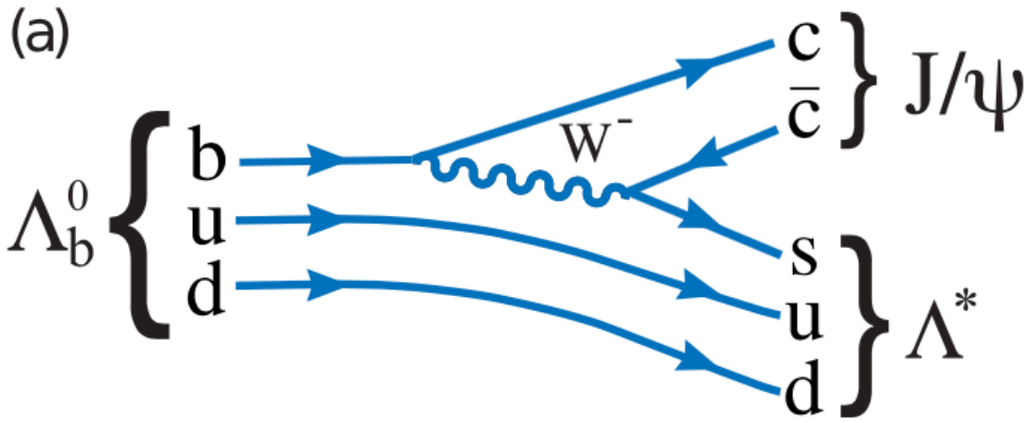
Heavy quark summary

- 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

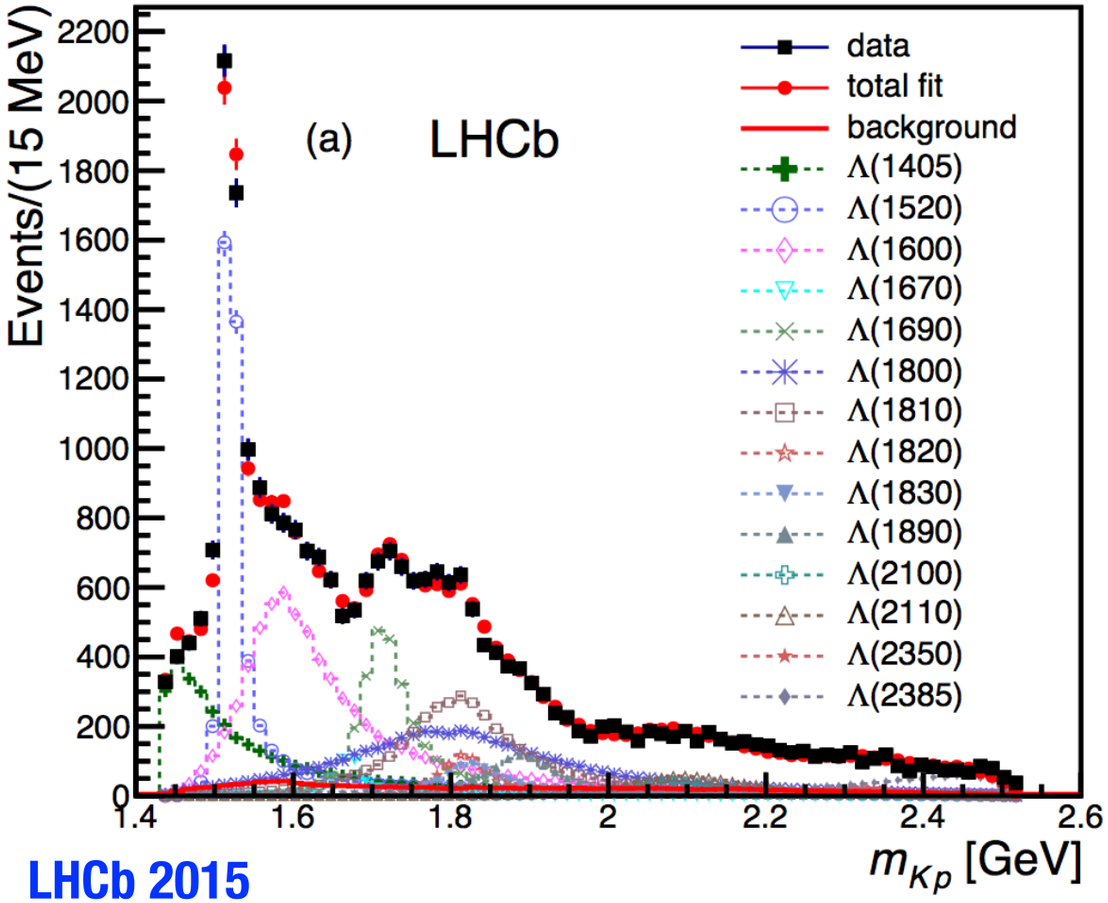


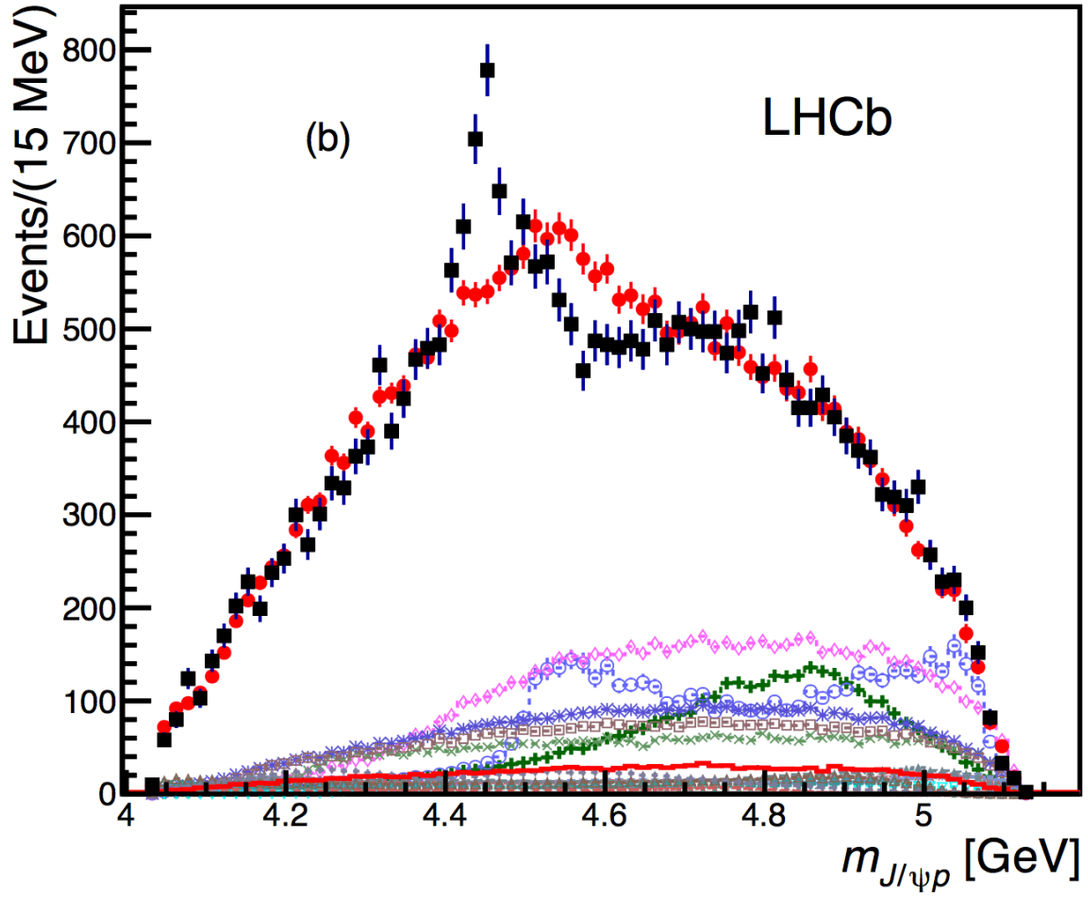
Pentaquark surprise

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



Excited Λ* reasonably reproduces ***Kp*** spectrum well, but not ***J/ψp***

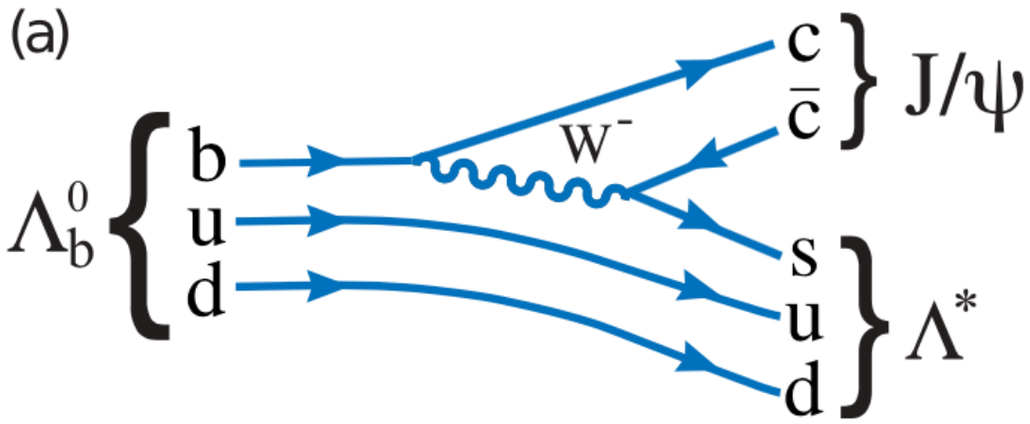


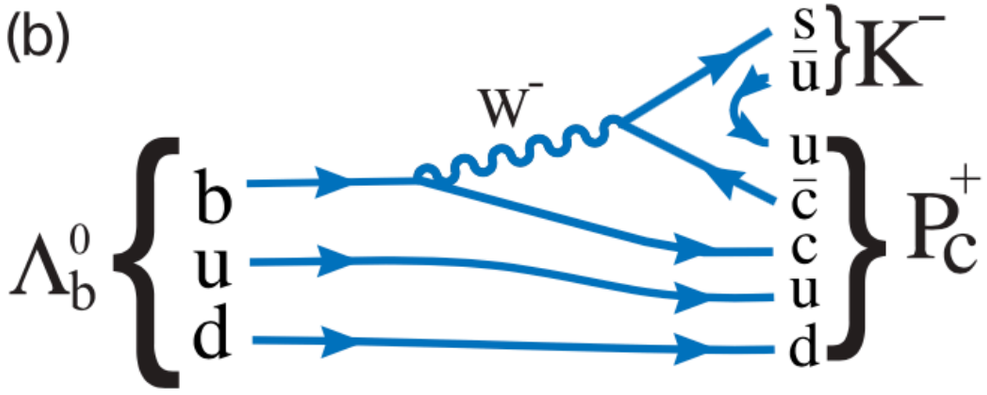


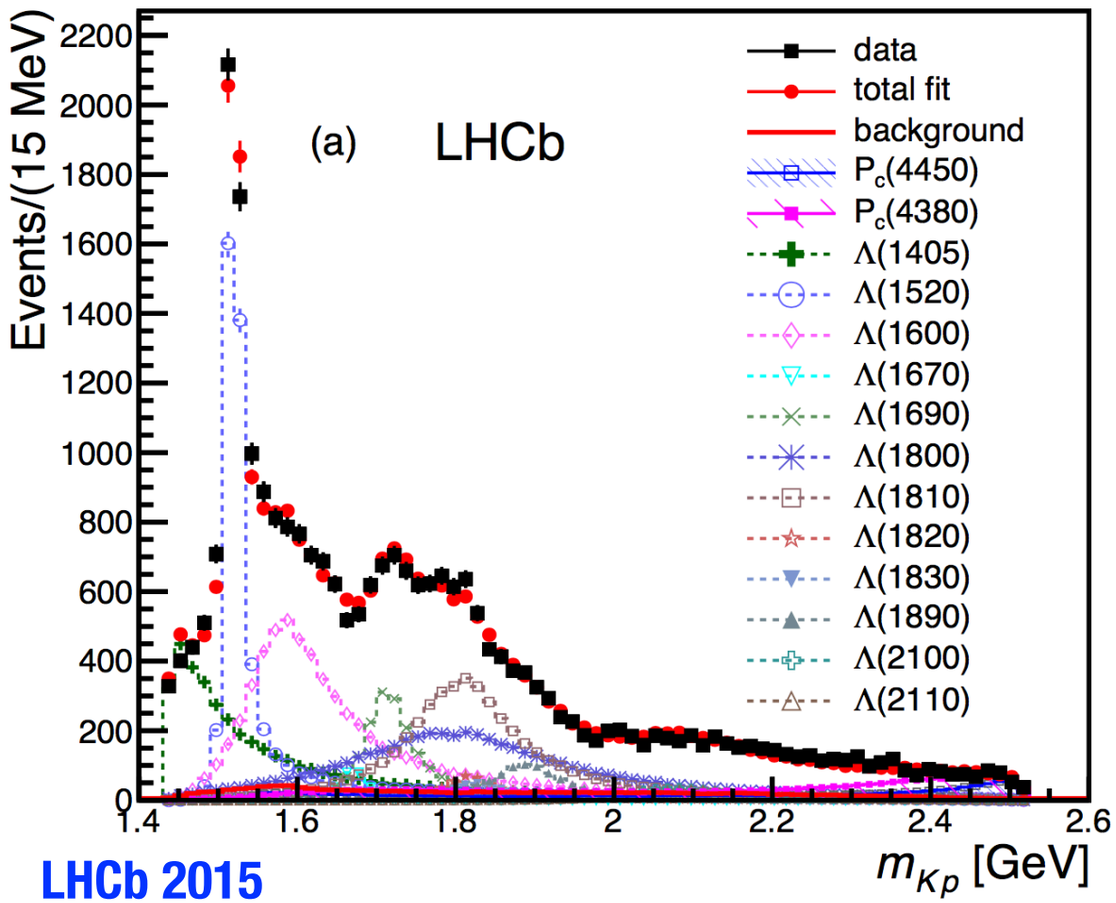
LHCb 2015

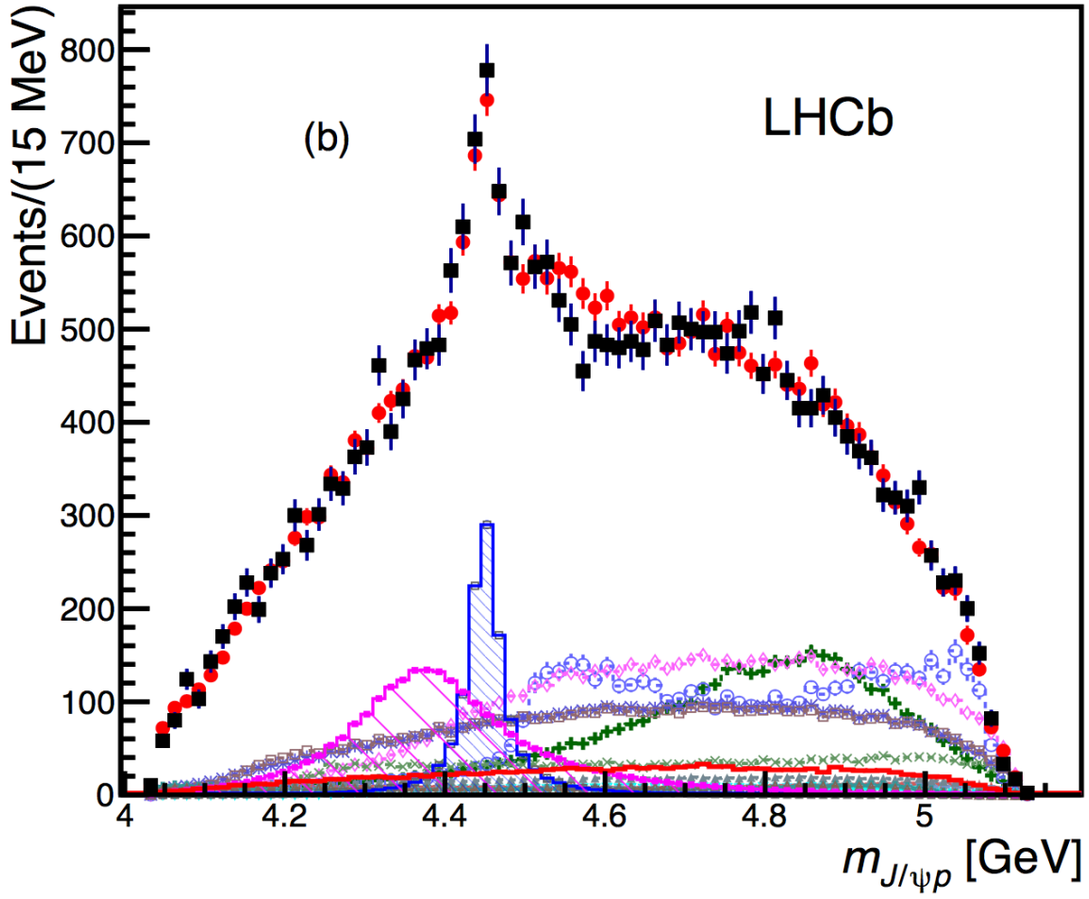
Pentaquark surprise

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



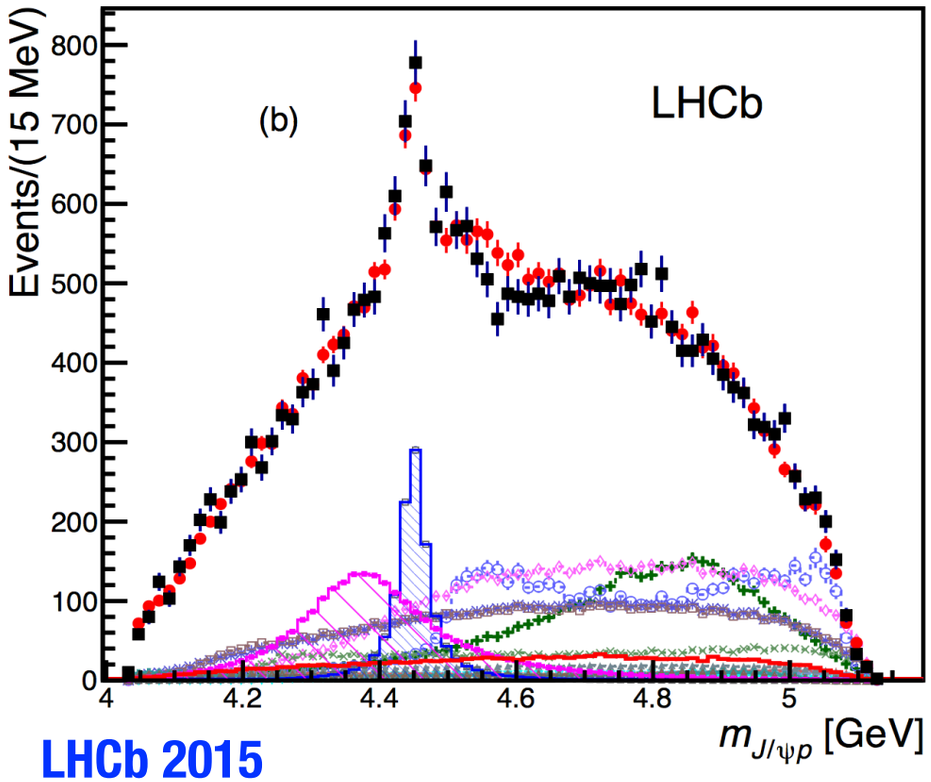




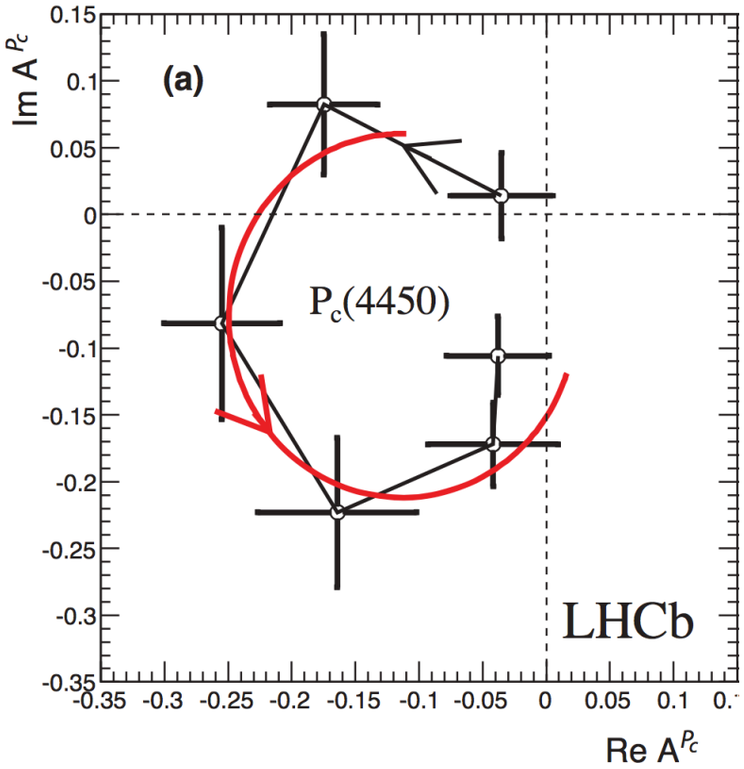


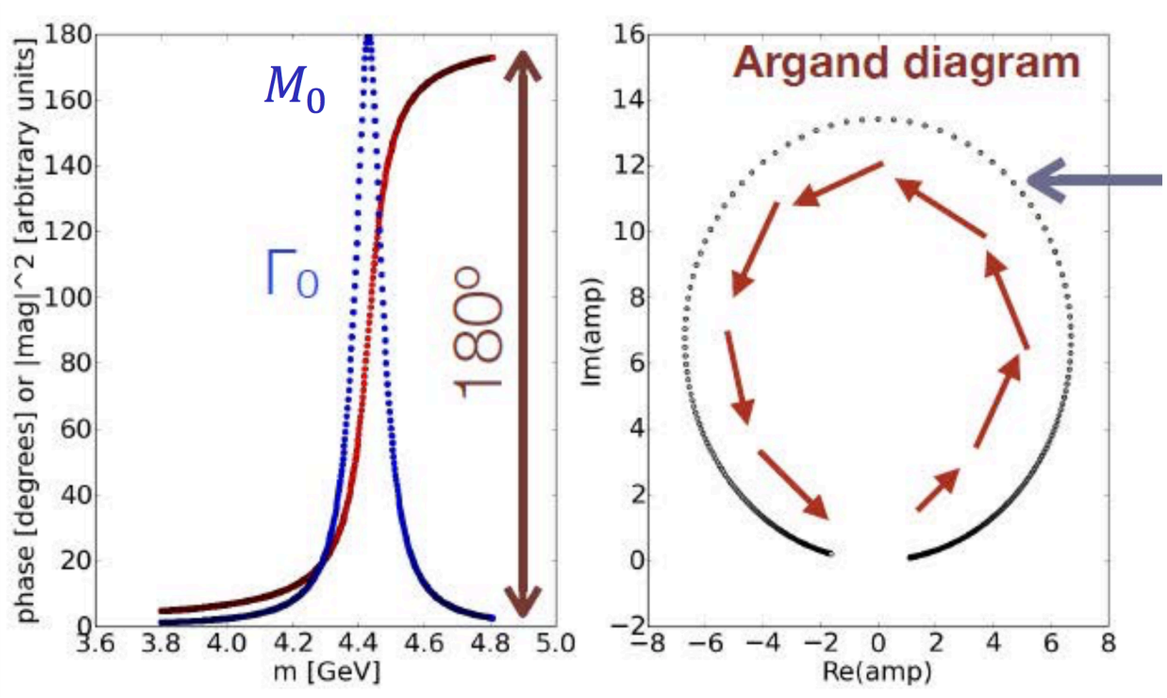
LHCb 2015

Interpretation: phase motion



LHCb 2015





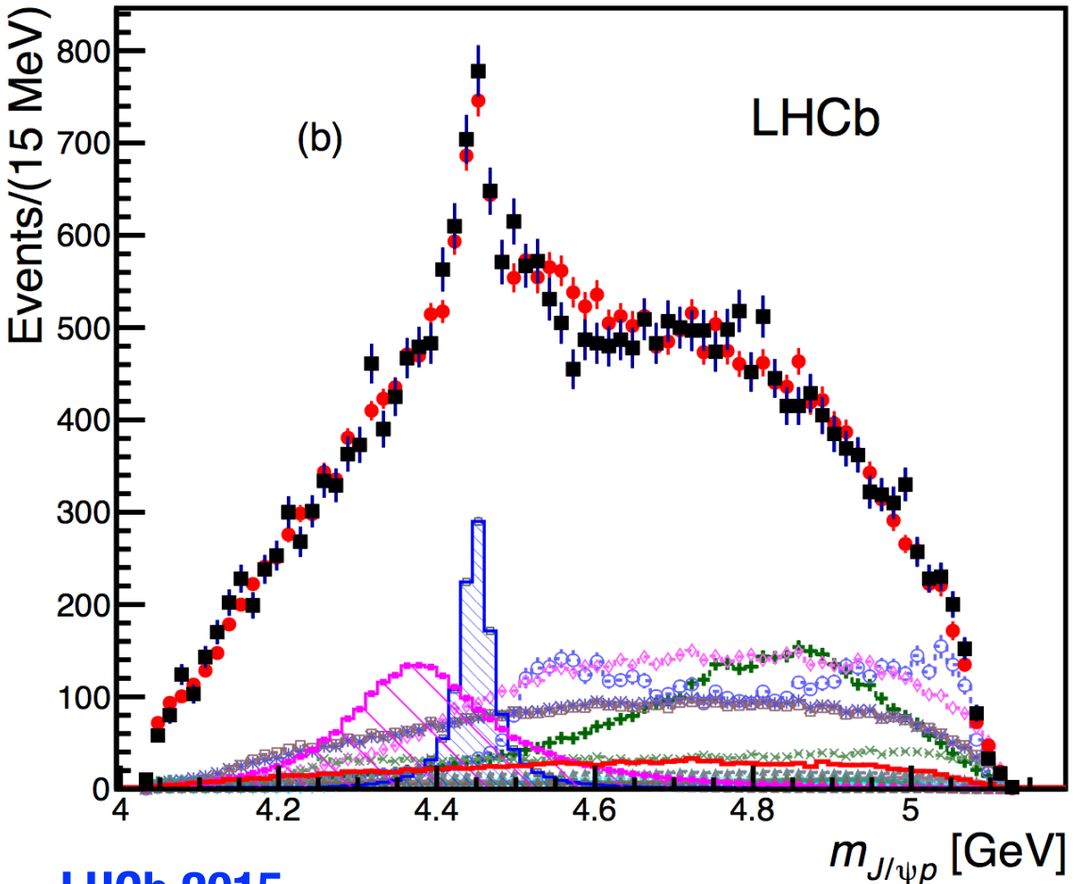
- **Breit-Wigner:** complex valued function of mass describing the "resonance"

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

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

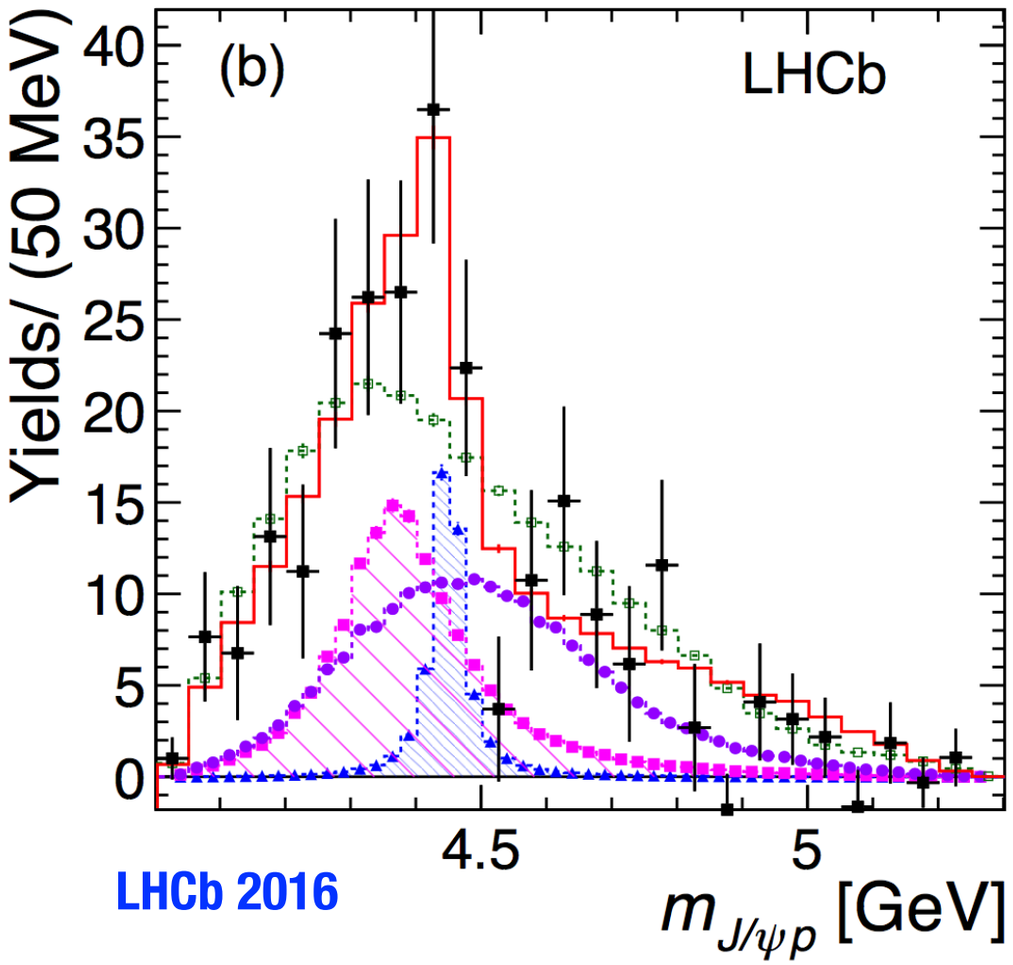
Interpretation: decay modes

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



LHCb 2015

$$\Lambda_b \to J/\psi p \pi^-$$



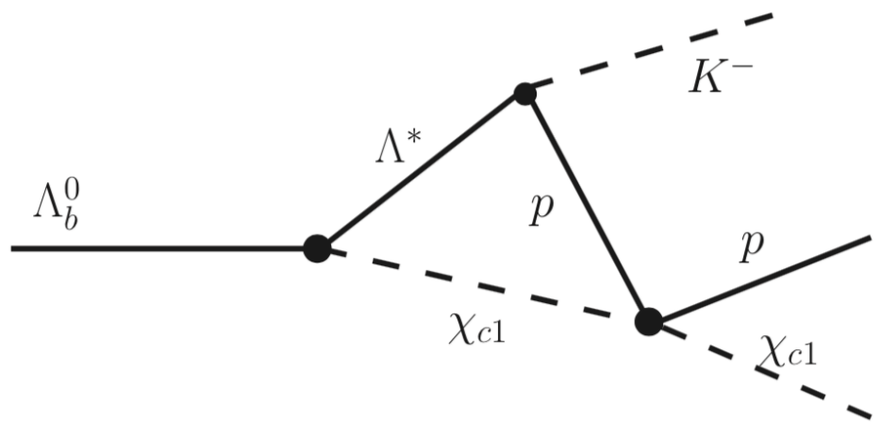
LHCb 2016

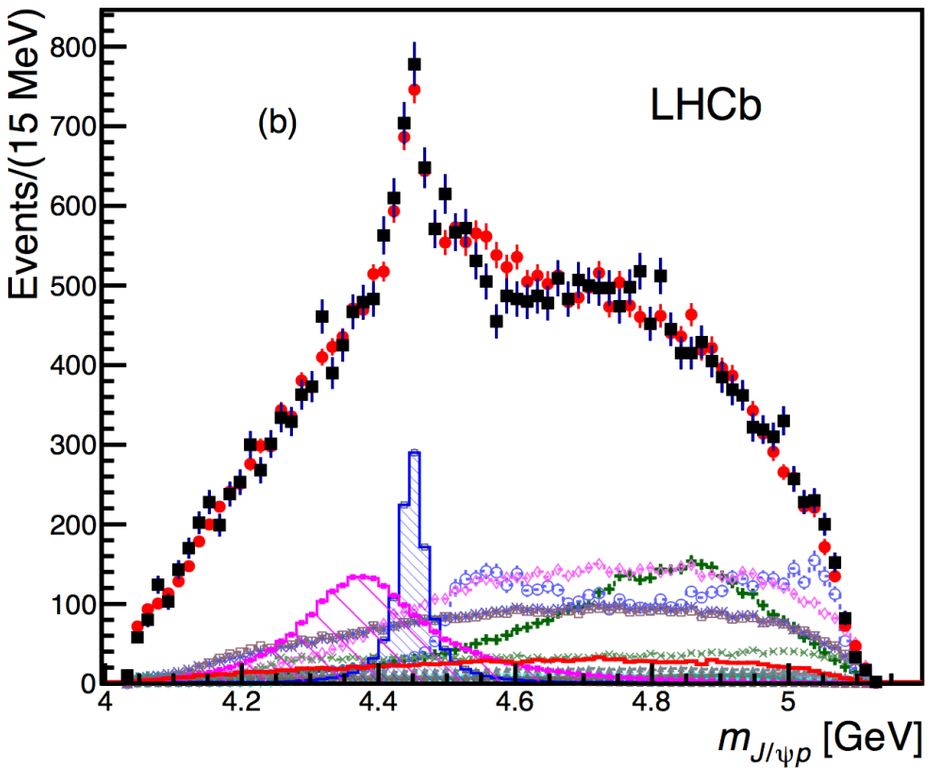
Interpretation: molecules, rescattering

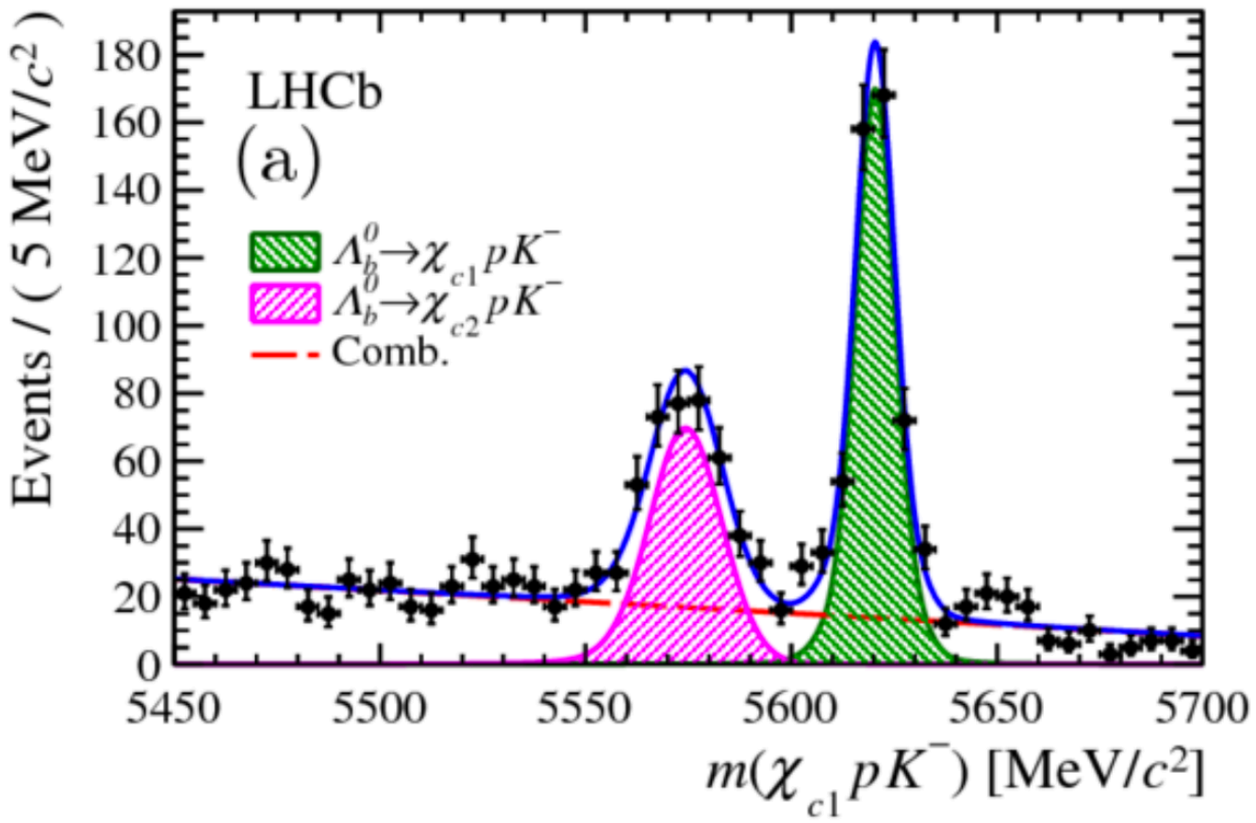
Closeby thresholds

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

[EPJ A51(2015)11,152]

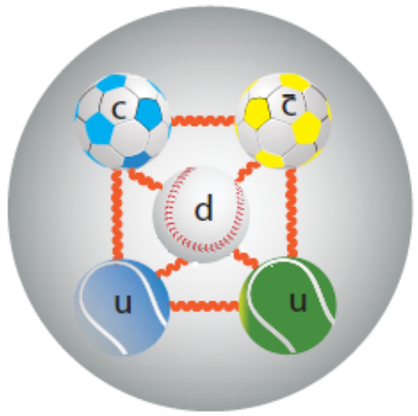




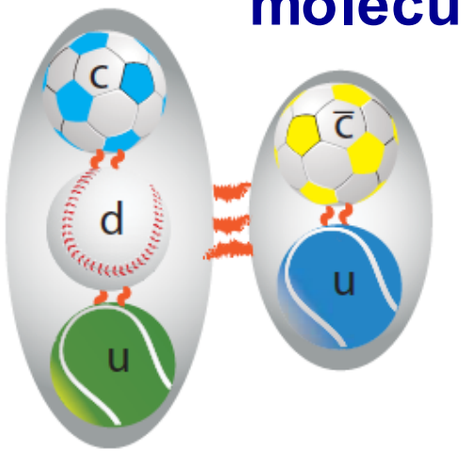


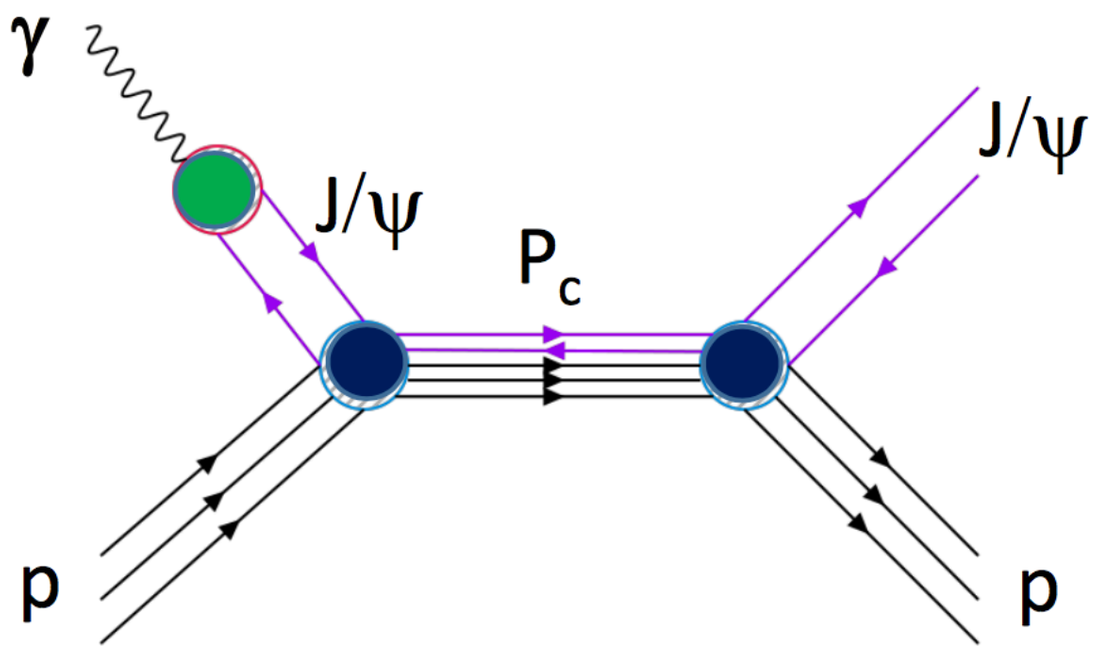
Charm Quarks at JLab

5-quark bound state

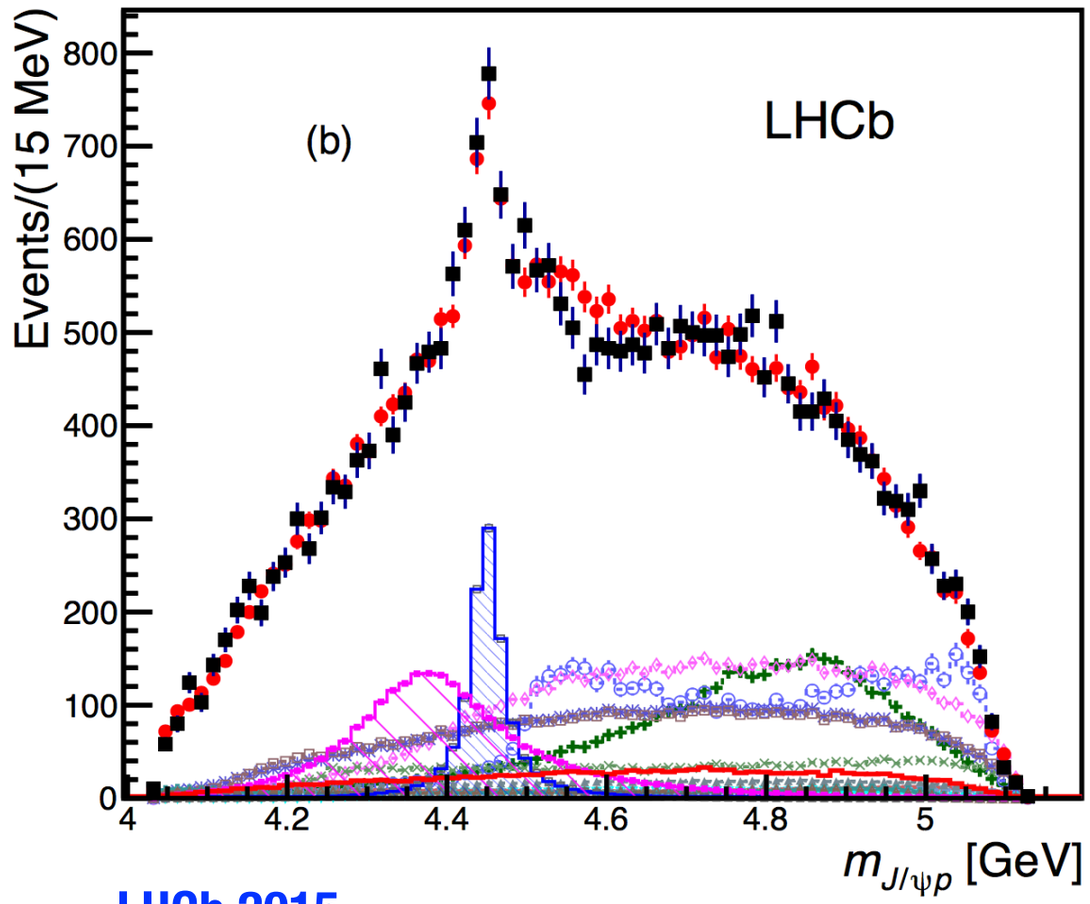


Hadronic molecule





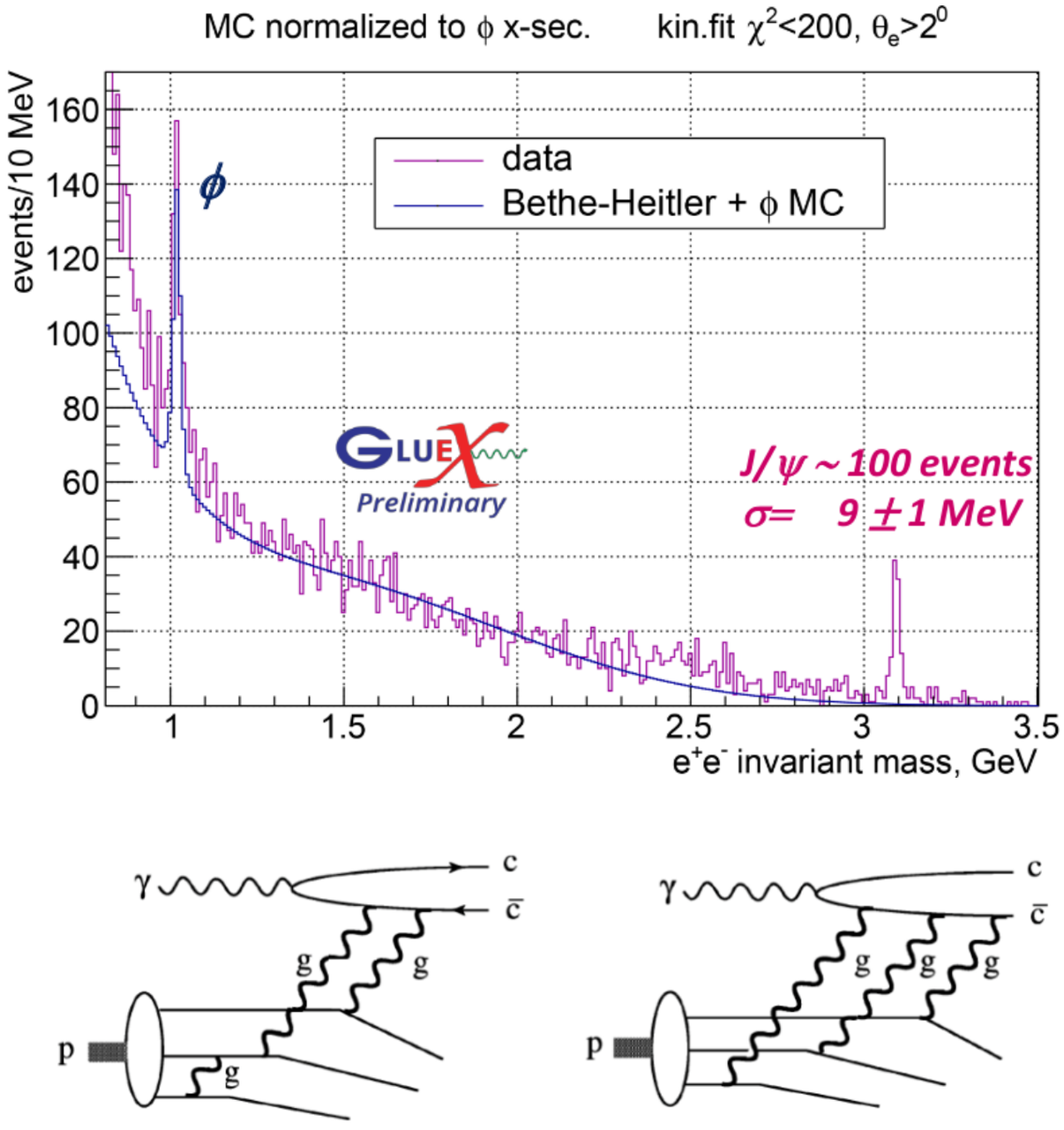
$$\Lambda_b \to J/\psi p K^-$$

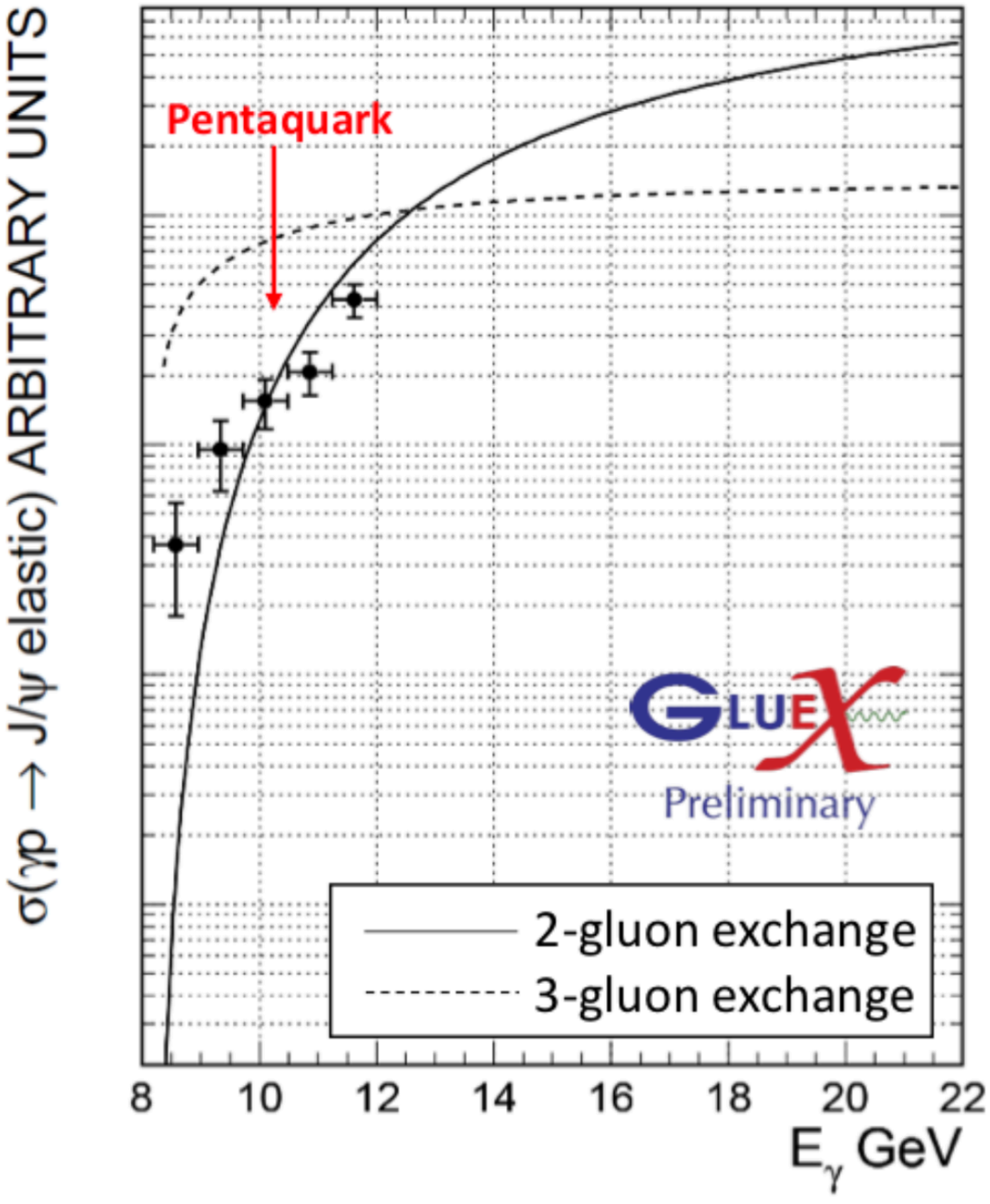


LHCb 2015

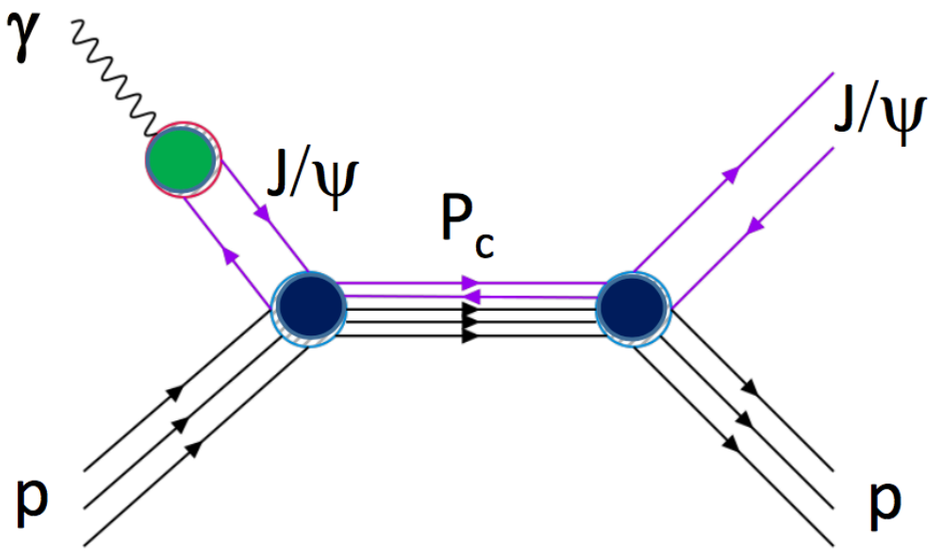
J/ψ photoproduction at GlueX

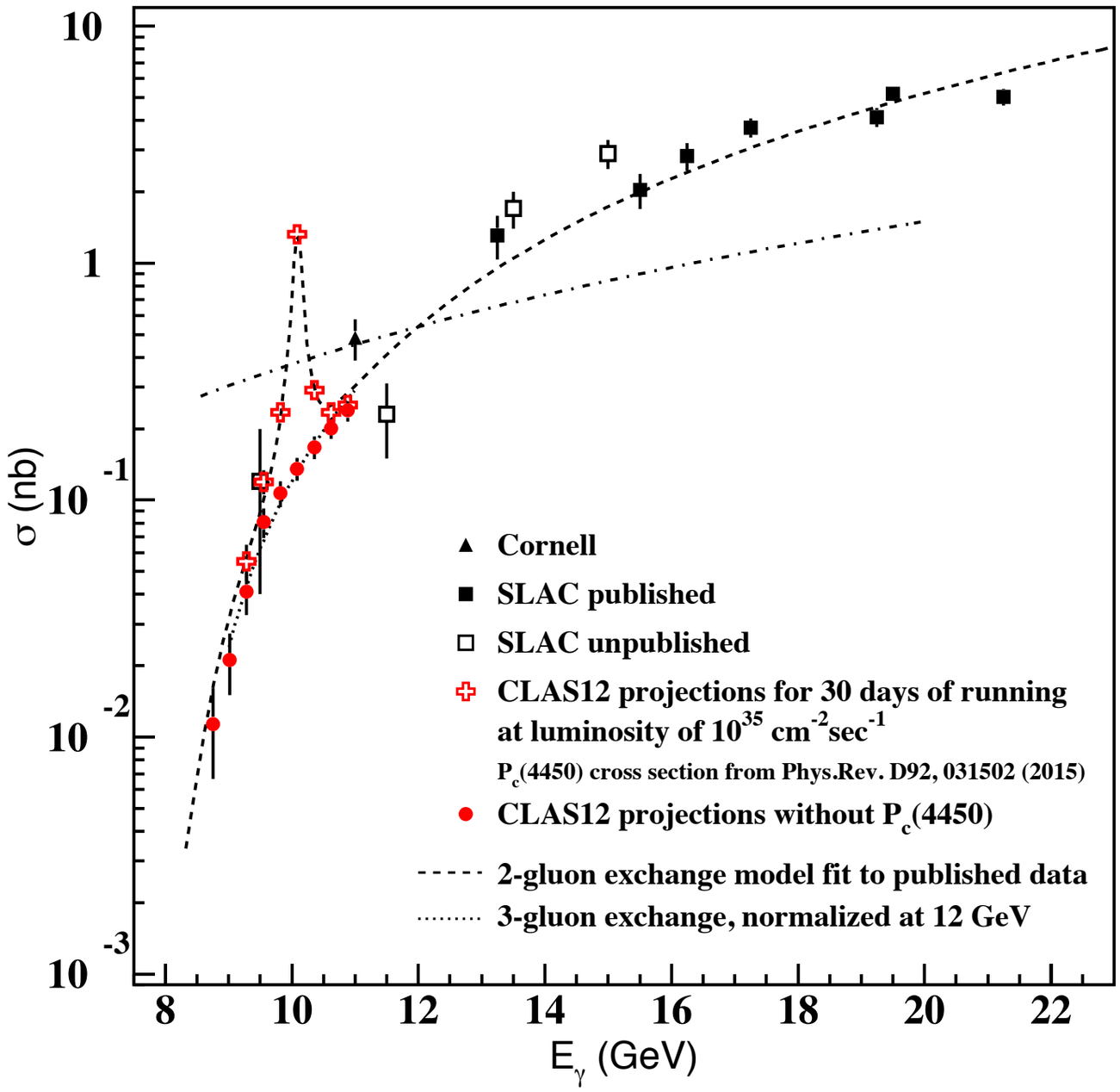
$$\gamma p \to p e^+ e^-$$





J/ψ photoproduction at CLAS12



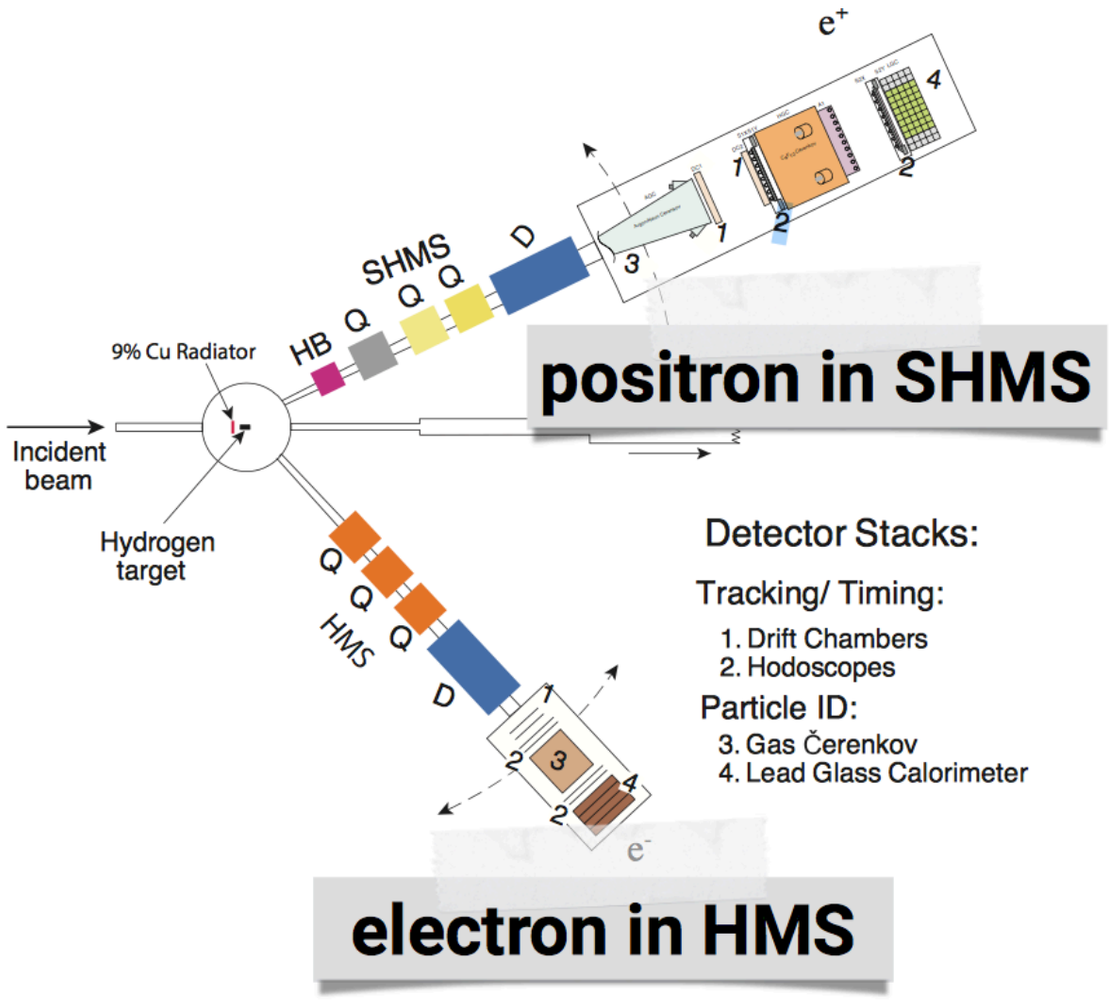


- Projected sensitivity for CLAS12 experiment
- Cross section assumes **$BR(P_c \rightarrow J/\psi p) = 1\%$**
- First data in 2018

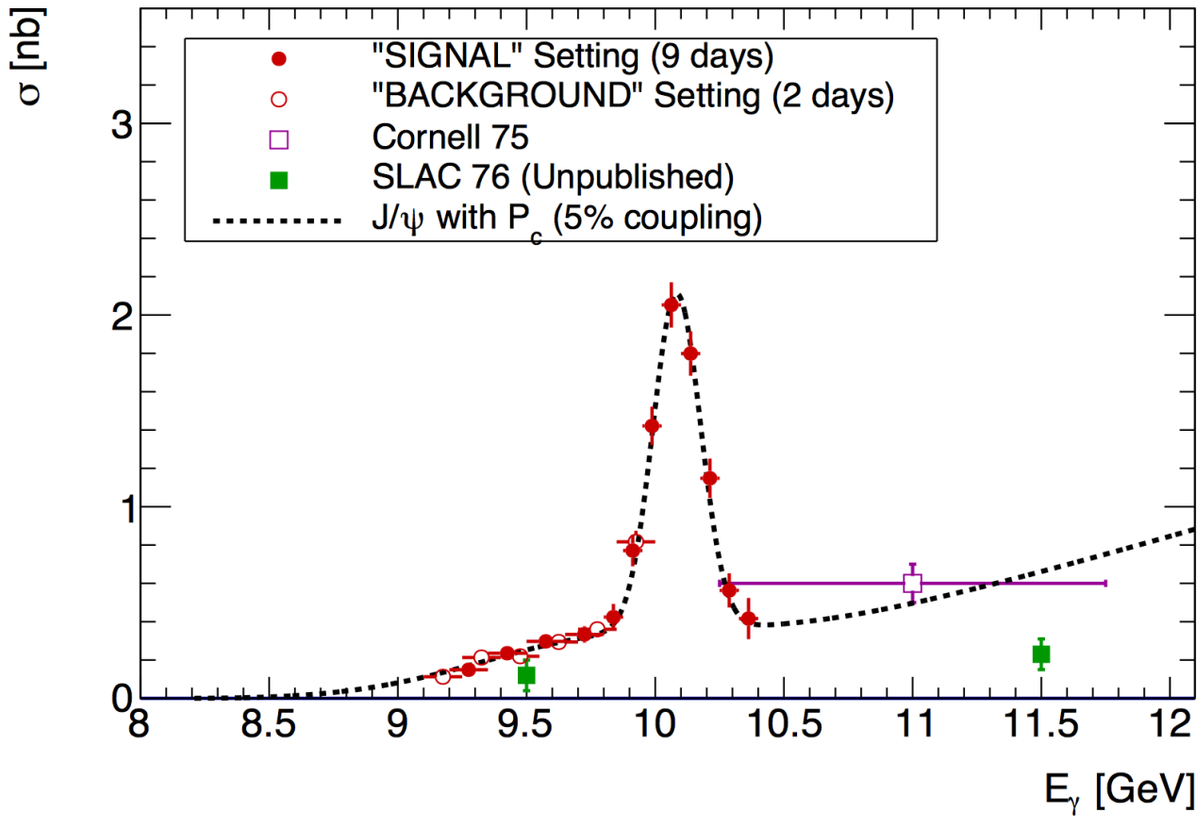
LHCb Pentaquark Search in Hall C

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

$$J/\psi \to e^+ e^-$$



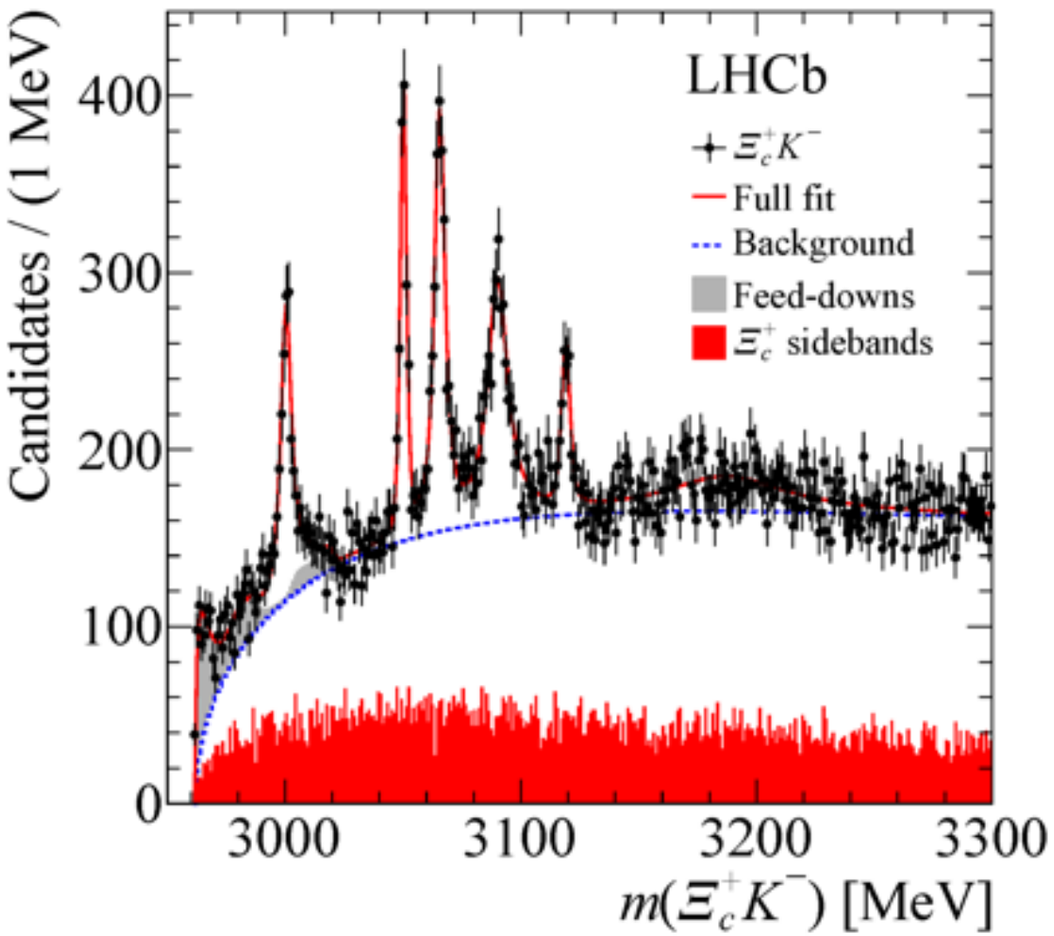
E12-16-007



- Elastic J/ψ production using Hall C standard equipment
- Short experiment (11 days) with high impact

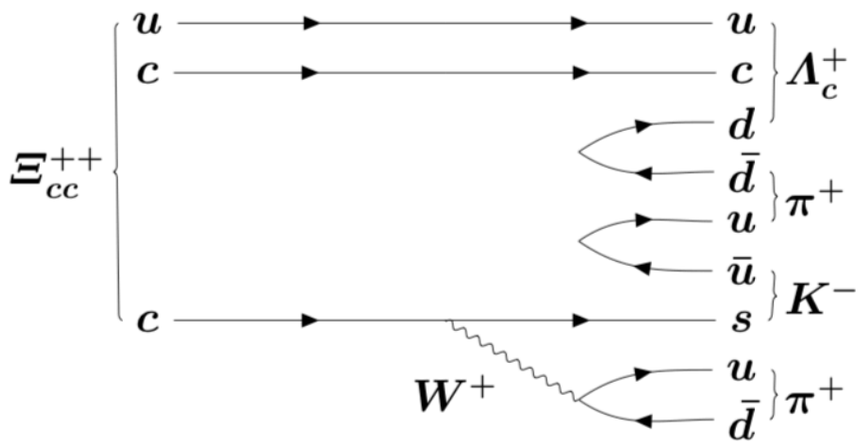
Heavy quark baryons (very recent)

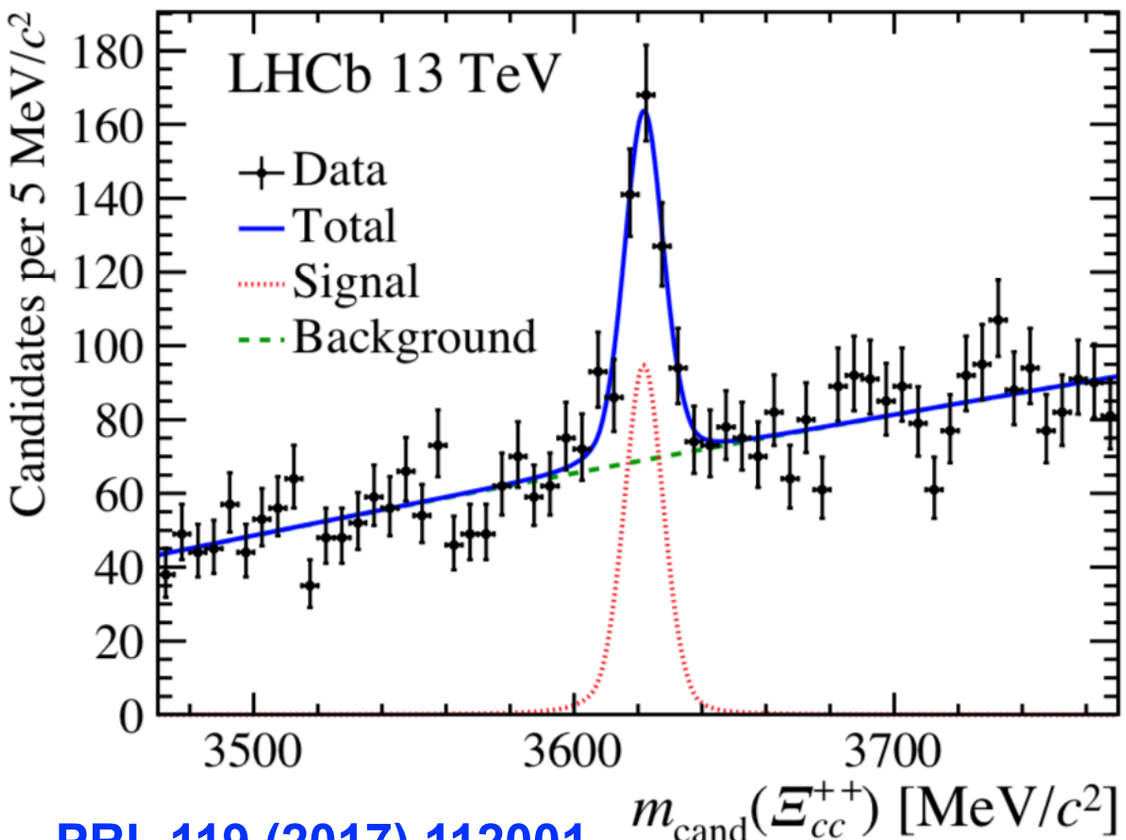
Ω_c baryons (css)



PRL 118 (2017) 182001

Doubly charm baryon

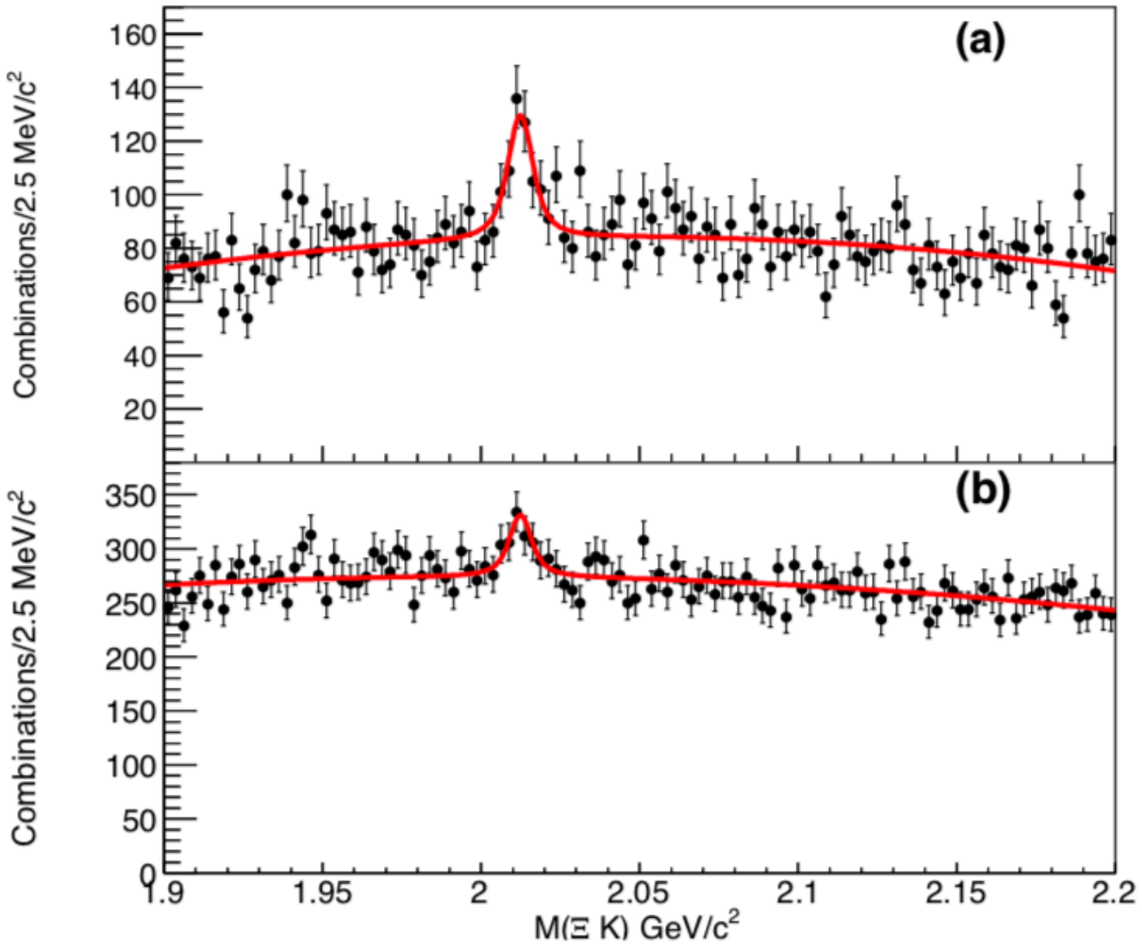




PRL 119 (2017) 112001

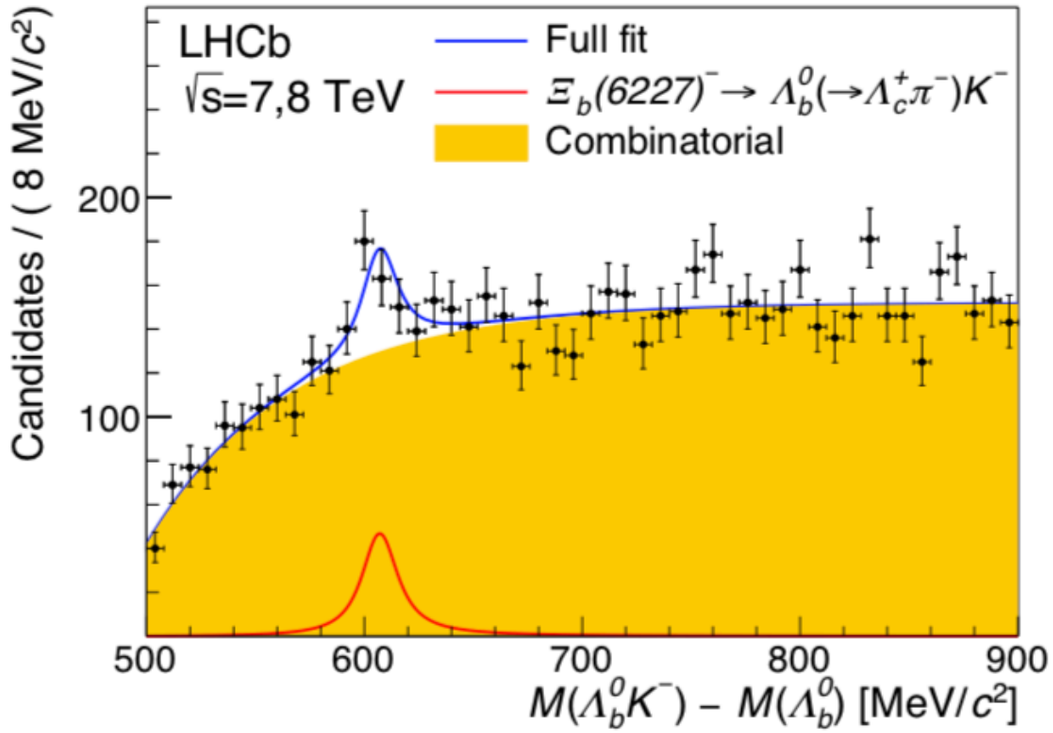
Heavy quark baryons (very recent)

Excited Ω_s baryon (sss)



arXiv:1805.09384

Ξ_b baryon (bsq)



arXiv:1805.09418

Summary: heavy quark spectroscopy

- Conventional charmonium and bottomonium well described by “simple” quark model
- Explosion of new XYZ states
  - Interesting connections between observe states
  - Higher precision brings new conclusions
- New baryonic states observed in charm and bottom decays at the LHC
  - Pentaquark search underway 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)

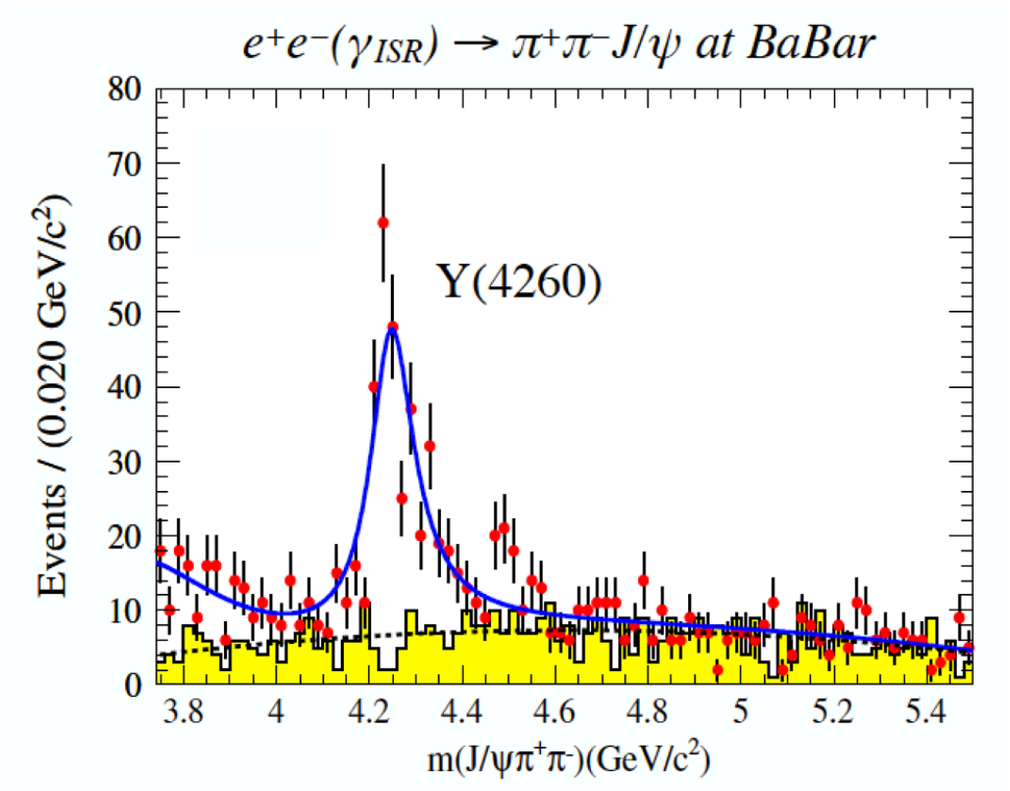
- **Non-Standard Heavy Mesons and Baryons, an Experimental Review**
  Stephen Lars Olsen, Tomasz Skwarnicki, Daria Zieminska *[arXiv:1708.04012]*

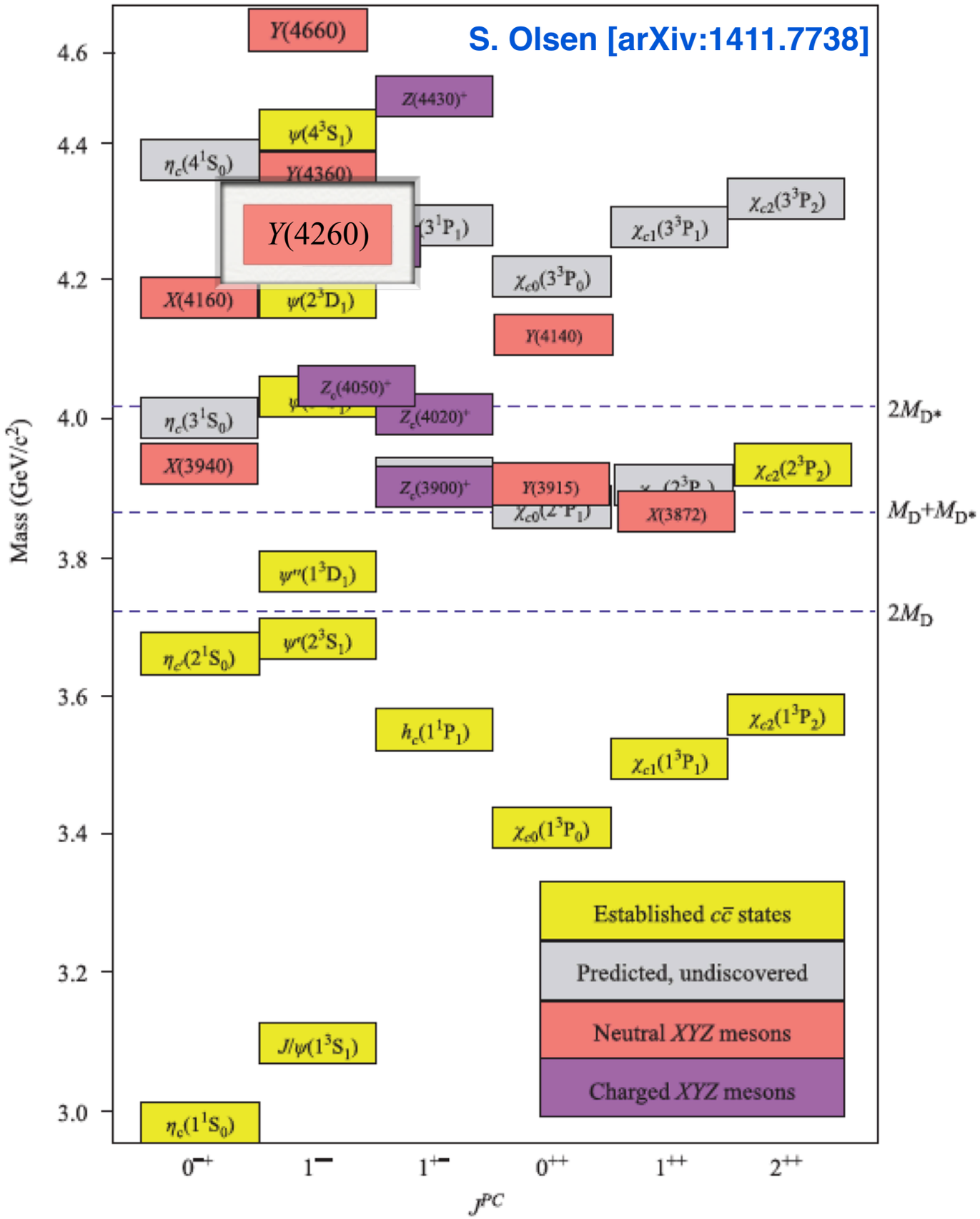
- **Hybrid mesons**
  Curtis A. Meyer and Eric S Swanson, Progress in Particle and Nuclear Physics 82, 21-58 (2015)

Backup

XYZ states

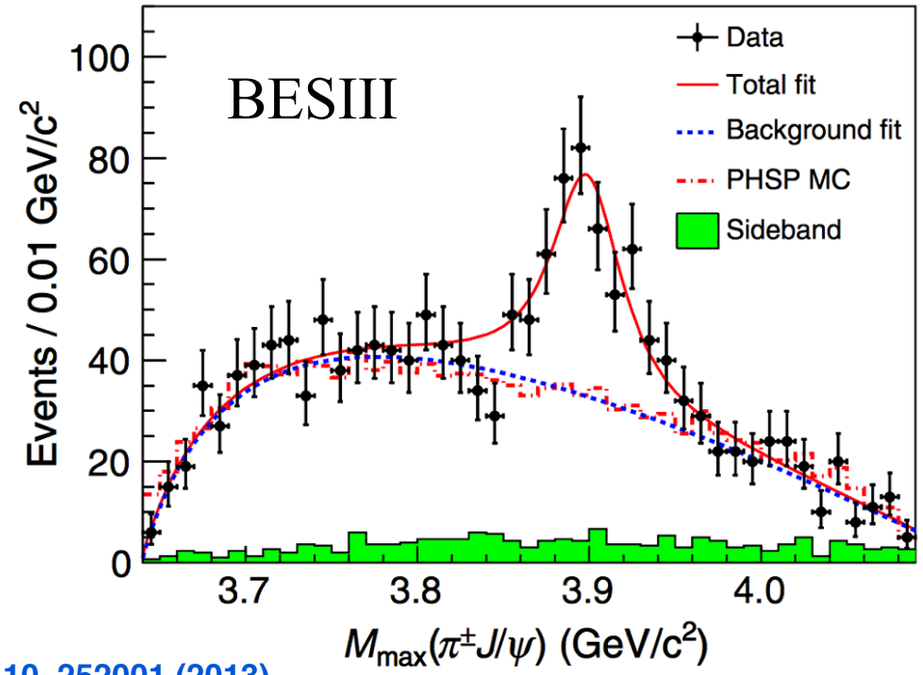
- Recent discoveries of charmonium-like states at BaBar, Belle, BESIII, CLEO, LHCb, etc.
- So called “XYZ” mesons, not predicted by the standard charmonium models
- Many models for interpretation: resonant states, meson molecules, re-scattering effects, etc.



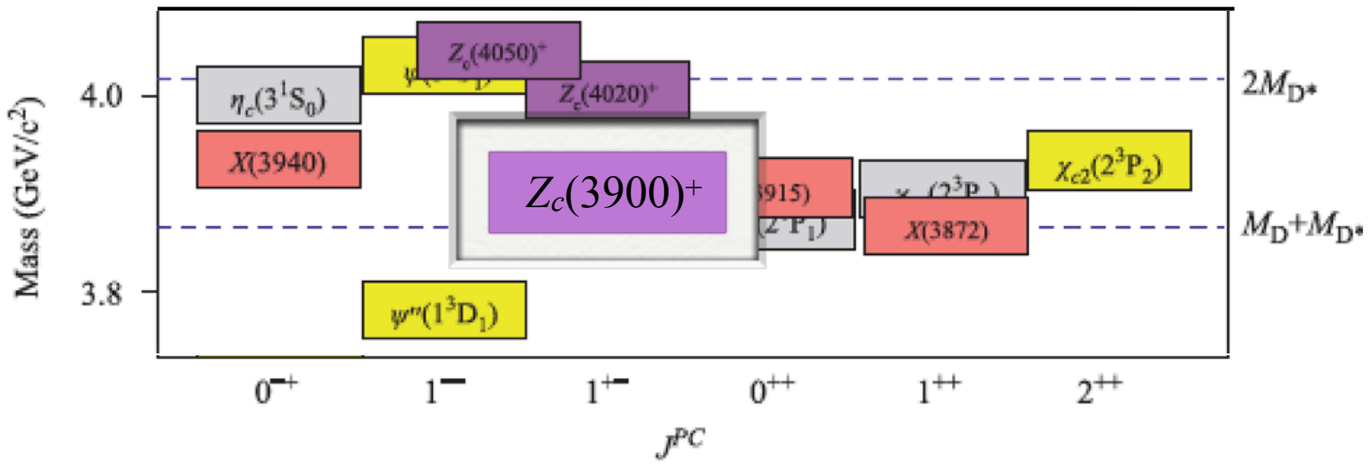


$Z_c^+(3900)$

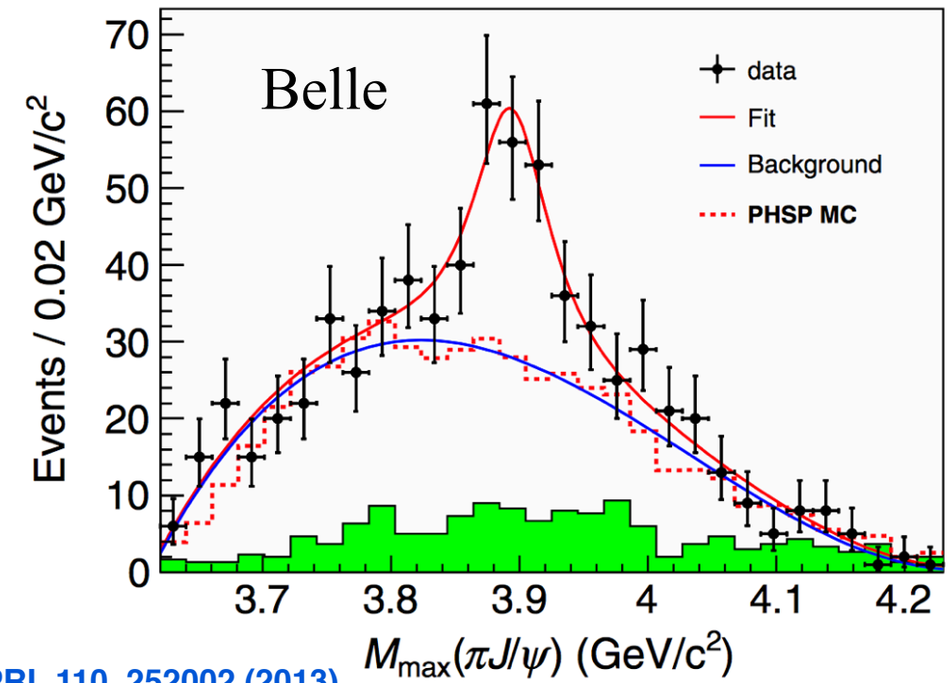
$$e^+e^- \to \pi^+\pi^- J/\psi \text{ (4260 MeV)}$$



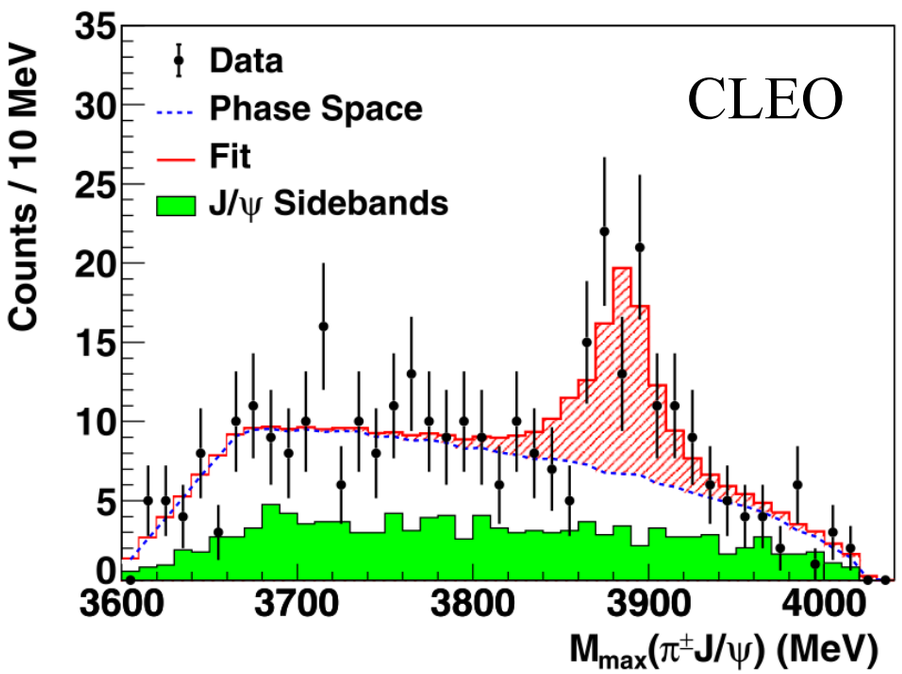
PRL 110, 252001 (2013)



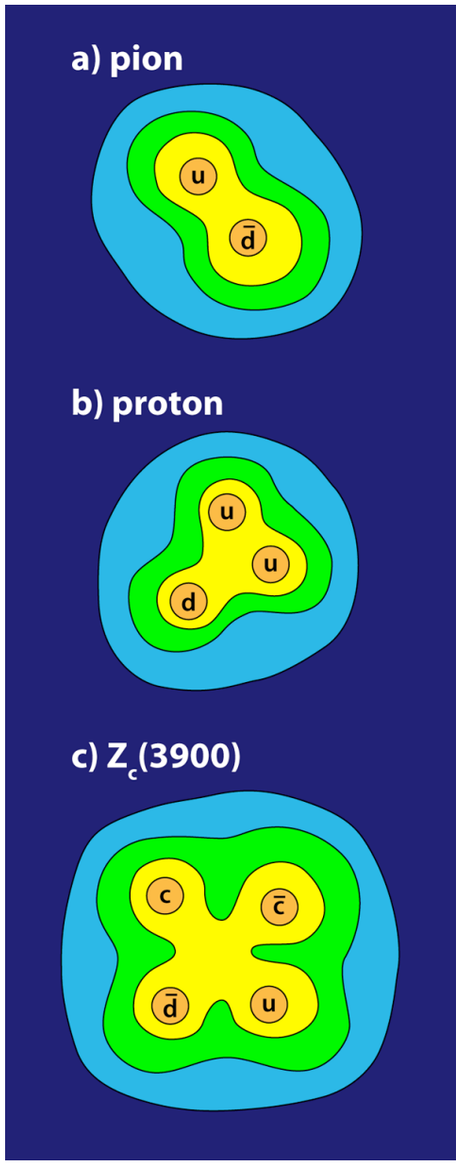
- Charged charmonium structure observed by BESIII, Belle and CLEO in decay of Y(4260)
- 4-quark content ($c\bar{c}u\bar{d}$)



PRL 110, 252002 (2013)



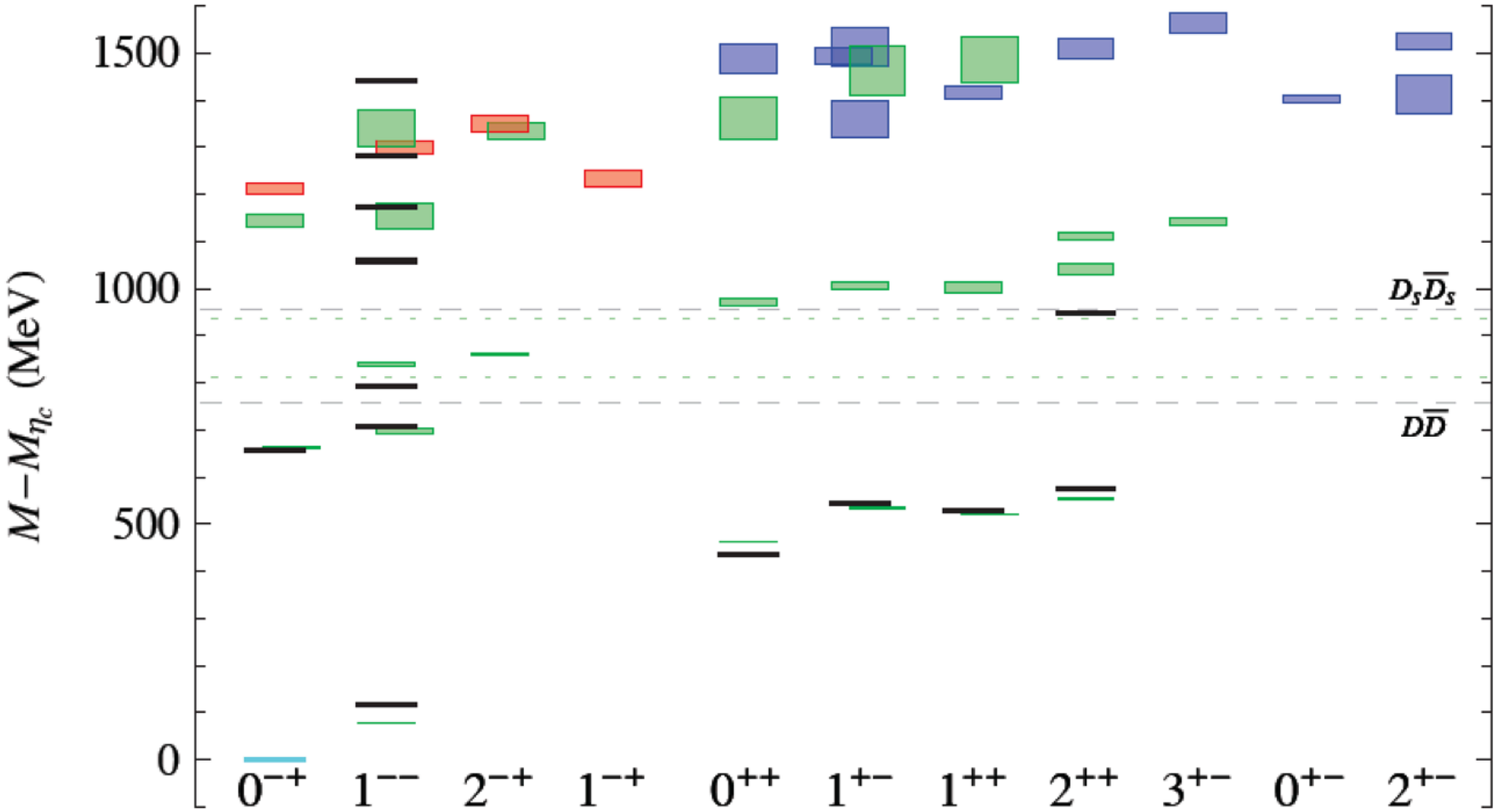
PLB 727 (2013) 366



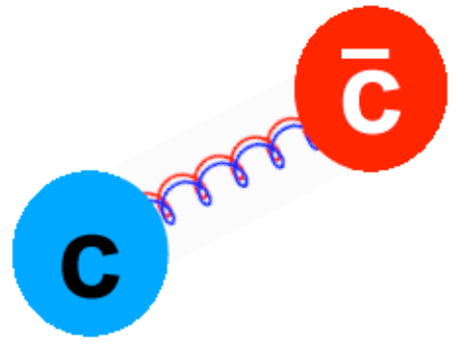
Physics Viewpoint 6, 69 (2013)

Charmonium hybrids

Hadron Spectrum Collaboration: JHEP 1207 (2012) 126



$c\bar{c}g$ Hybrid



Constituent Gluon:

Mass ~ 1-1.5 GeV

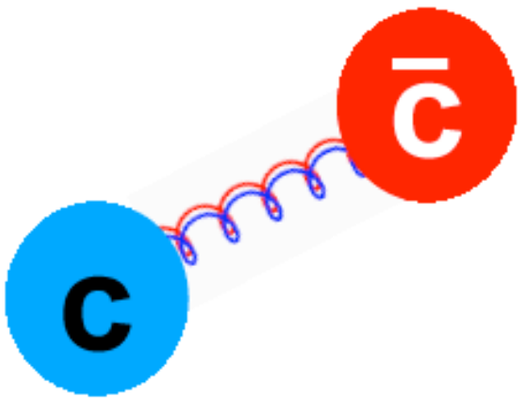
$J^{PC} = 1^{+-}$

- 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



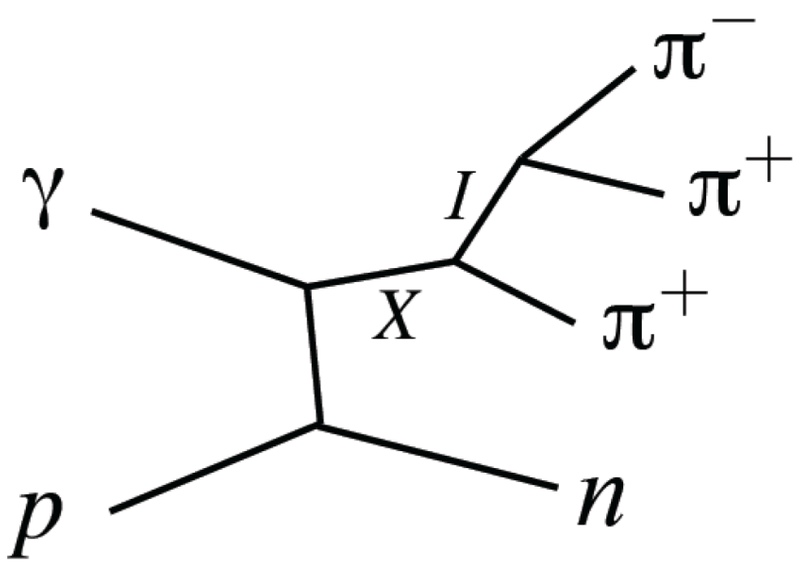
transition	Γ_{lattice} (keV)	Γ_{expt} (keV)
$\chi_{c0} \to J/\psi\gamma$	199(6)	131(14)
$\psi' \to \chi_{c0}\gamma$	26(11)	30(2)
$\psi'' \to \chi_{c0}\gamma$	265(66)	199(26)
$c\bar{c}g(1^{--}) \to \chi_{c0}\gamma$	< 20	
$J/\psi \to \eta_c\gamma$	2.51(8)	1.85(29)
$\psi' \to \eta_c\gamma$	0.4(8)	0.95 –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

Y(4260)?

Exotic Hybrid

PRD 79 (2009) 094504 and Review article 1502.07276

Amplitude Analysis



- **Goal:** Identify J^{PC} of $X \longrightarrow \pi^+\pi^-\pi^+$
- Model the intensity of events at the level of QM amplitudes (allow for interference)

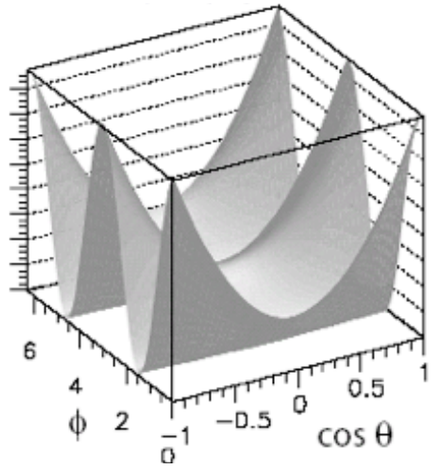
$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

- 5-dimensional problem: two new angles at each decay step (X and I)

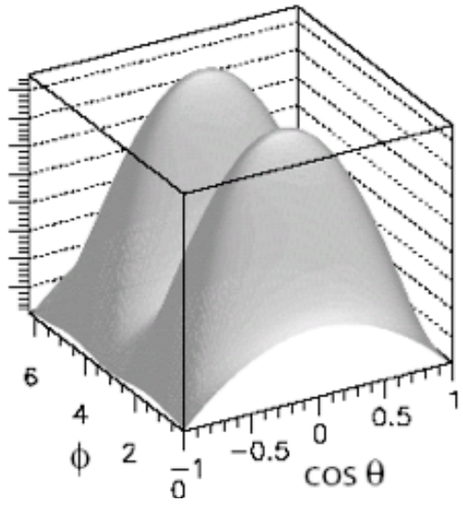
Example Intensity:

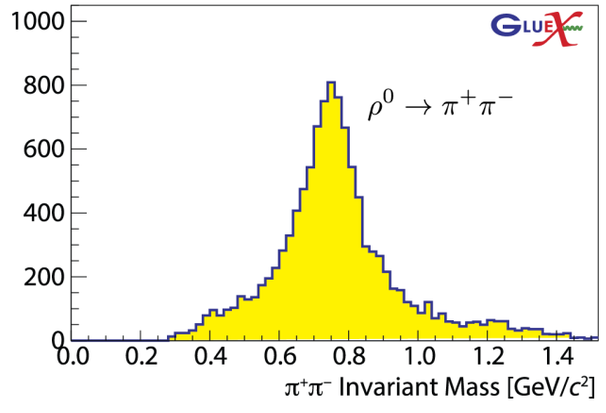
$$X(1^{++}) \rightarrow \rho\pi^+ \text{ (S wave)}$$

$X \rightarrow \rho\pi^+$



$\rho \rightarrow \pi^+\pi^-$





Amplitude Analysis

$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

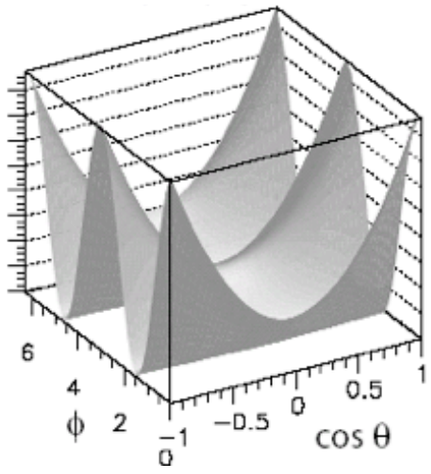
- Expand set of possible amplitudes over many X and I, and determine V_α via maximum likelihood fit
- Good angular acceptance critical for disentangling J^{PC}

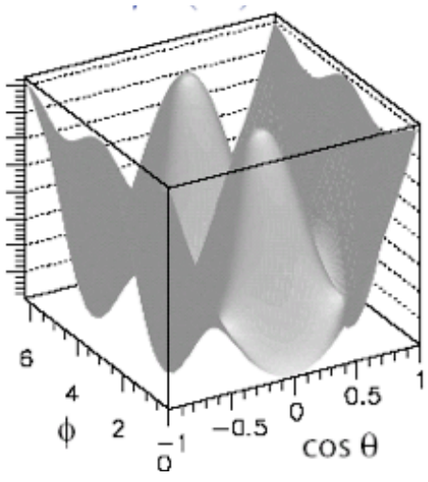
Example Intensities:

$X(1^{++})$
$\rightarrow \rho\pi^+$ (S wave)

$X(2^{++})$
$\rightarrow \rho\pi^+$ (D wave)

$X \rightarrow \rho\pi^+$





$\rho \rightarrow \pi^+\pi^-$