Recent Experimental Developments in Heavy Quarkonium

Quark Confinement and the Hadron Spectrum XI
St. Petersburg, Russia

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Indiana University

Heavy Quarkonium

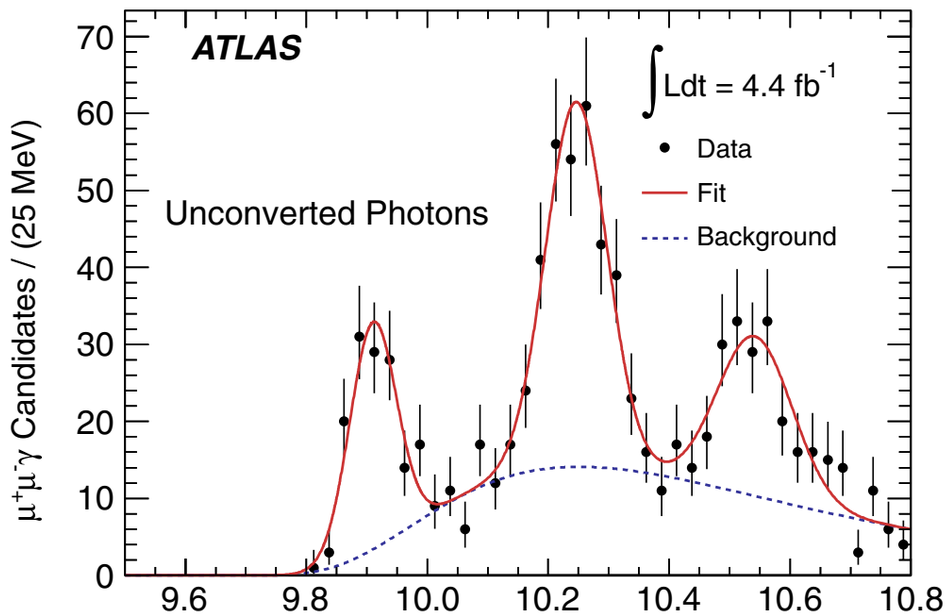
- <u>Heavy Quarkonium Spectroscopy:</u>
  present experimental focus is studying what might not be quarkonium (tetraquarks, molecules, hybrids, …)
  - study spectrum via e^+e^- collisions and *B* decay
  - very little recent experimental work on conventional quarkonium and transitions
- <u>Heavy Quarkonium Production:</u>
  a laboratory for testing QCD calculations that is now moving into the LHC era
  - total cross section in hadron collisions
  - polarization measurements
- Active field: many players with diverse goals and experimental approaches
  - my apologies in advance if your favorite result doesn't receive proper attention!

CLEO-c

Discovery of $X_b(3P)$ Multiplet

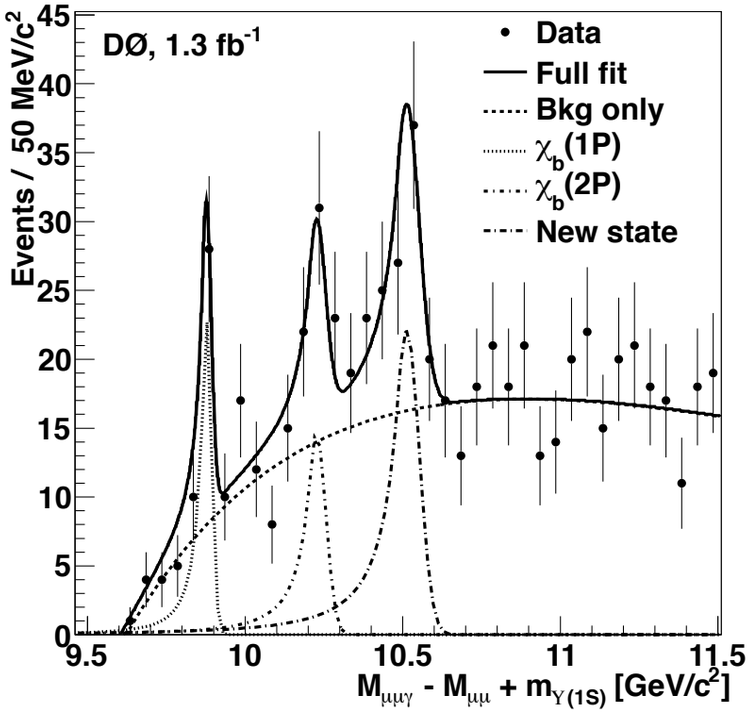
- Production in pp collisions
- Observed in radiative transitions to the $\Upsilon(1S)$ and $\Upsilon(2S)$
- Unable to resolve individual J=0,1,2 states
- Discovered by ATLAS and confirmed by D0

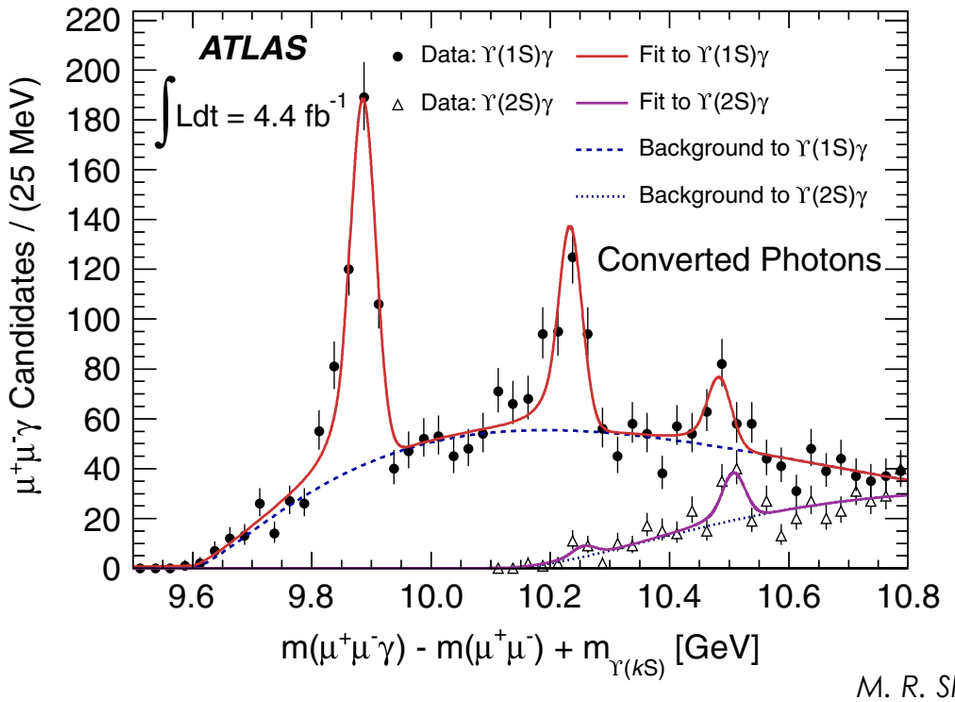
ATLAS Collaboration, PRL 108, 152001 (2012)



(a)

D0 Collaboration, PRD 86, 031103 (2012)





(b)

Heavy Quarkonium

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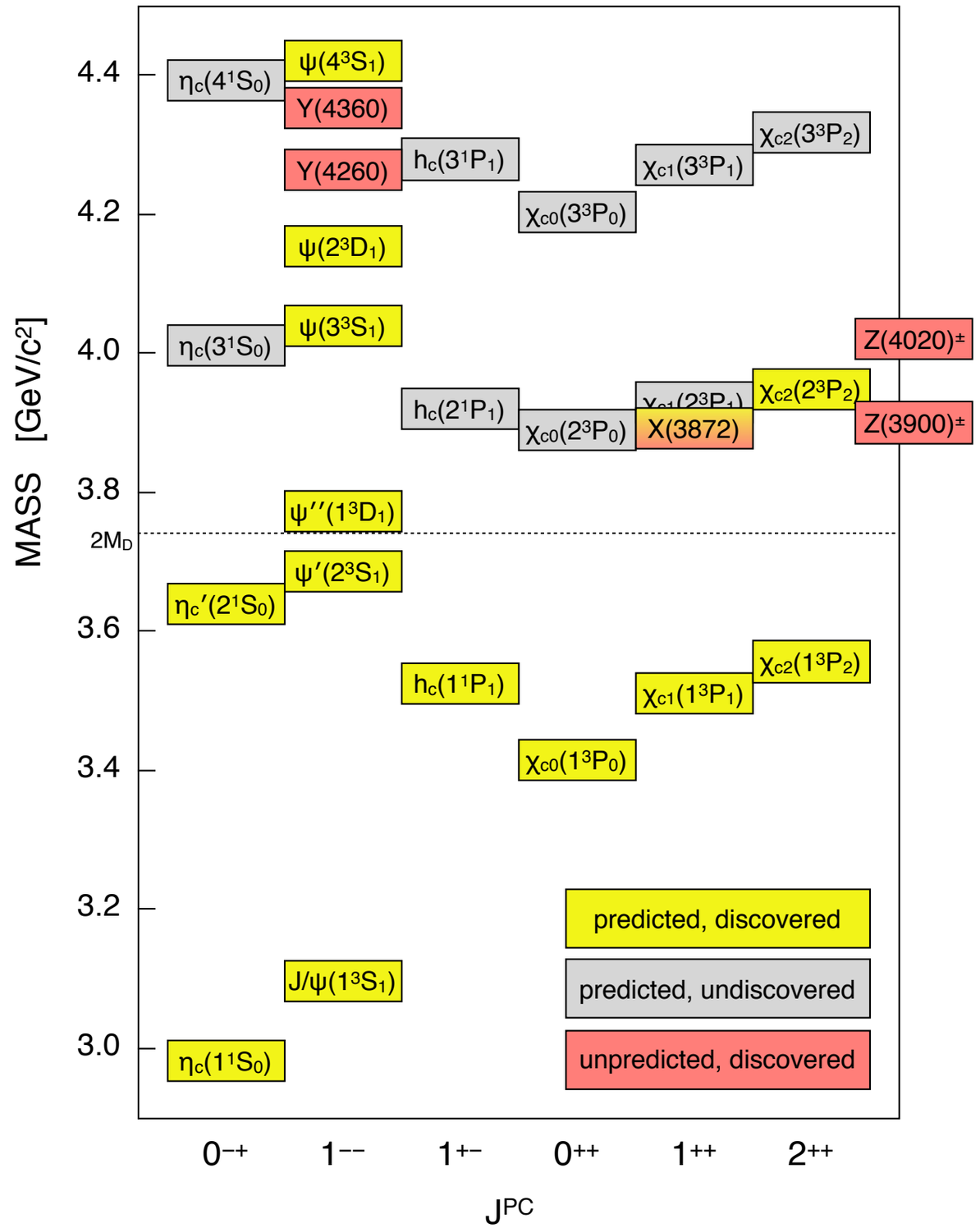
CLEO-c

Charmonium from e^+e^- Collisions

- Populate vector mesons directly
  - vector states are well studied
- Look for transitions to other states in the spectrum
- The attempt to study the unusual *Y*(4260) led to discovery of charged *Z* structures

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



Y(4260) and Y(4360)

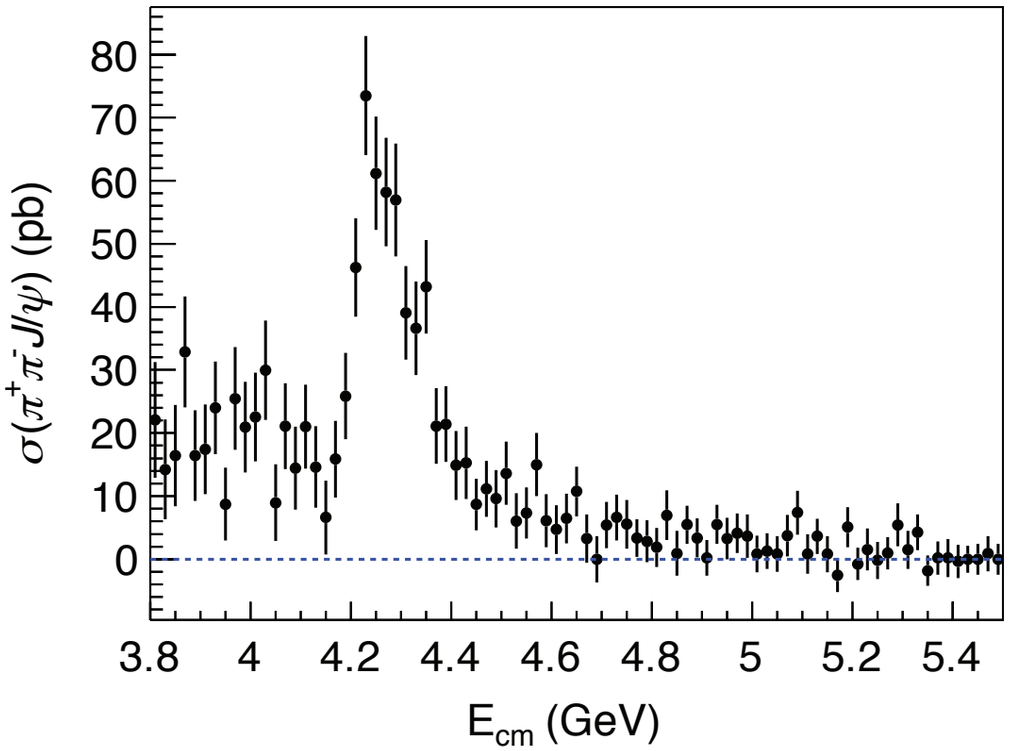
- Discovery in ISR by BaBar and Belle
- No clear assignment in quark models
- Strongly suppressed open charm decay modes
- Nature? Motivates study at BESIII

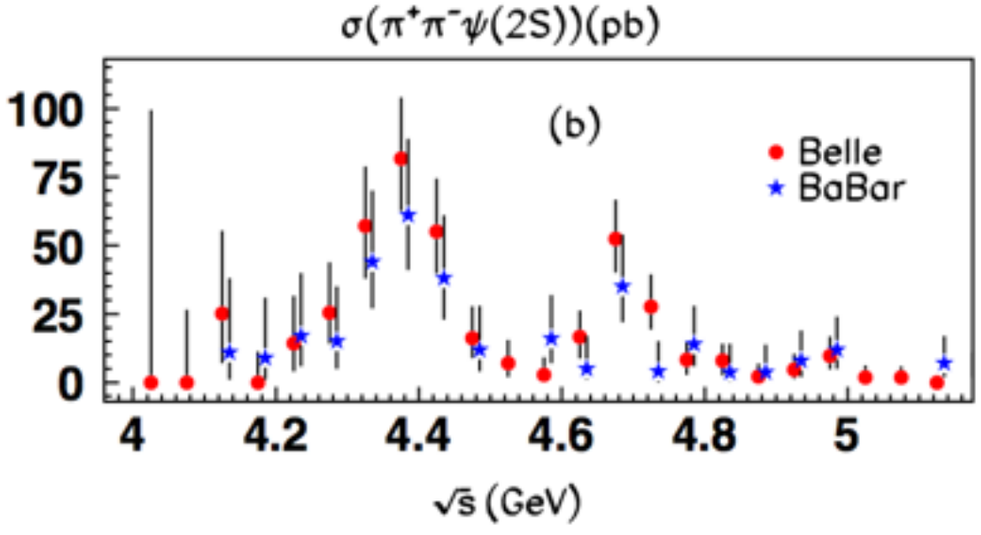
CLEO Collaboration, PRD 80, 072001 (2009)

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

compare with ≈500 for ψ(3770)

Belle Collaboration, PRL 110, 252002 (2013)

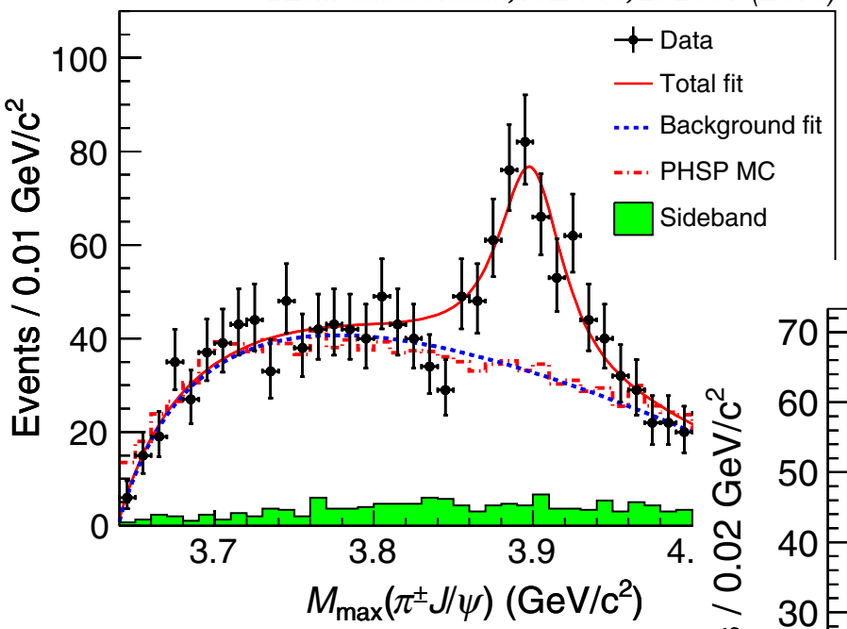




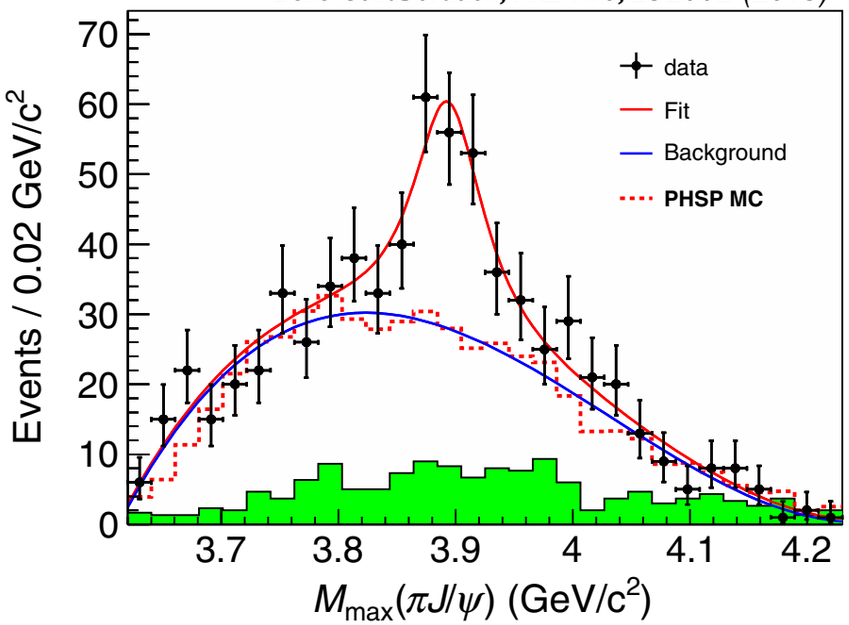
Liu, Qin, and Yuan, PRD 78, 014032 (2008) using data from:
BaBar Collaboration, PRL 98, 212001 (2007)
Belle Collaboration, PRL 99, 142002 (2007)

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

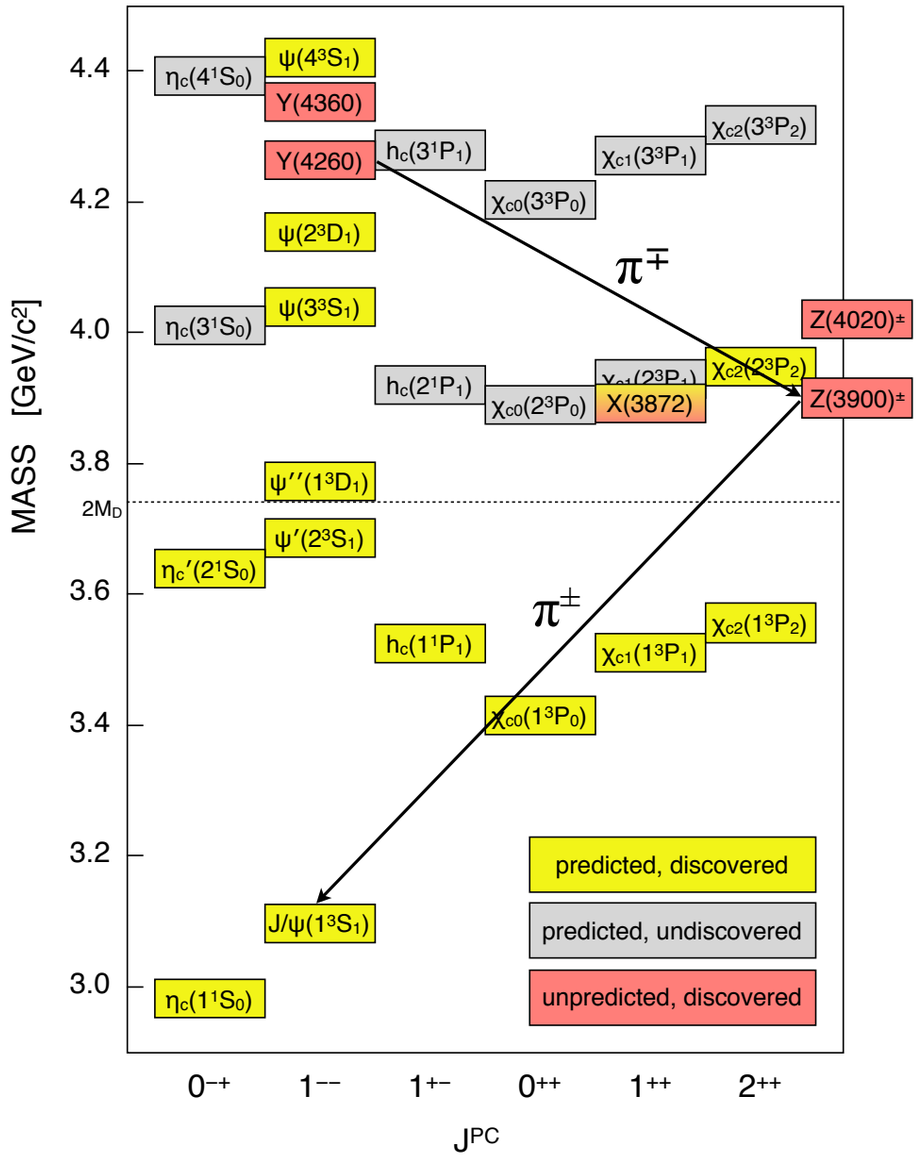
BESIII Collaboration, PRL 110, 252001 (2013)



Belle Collaboration, PRL 110, 252002 (2013)

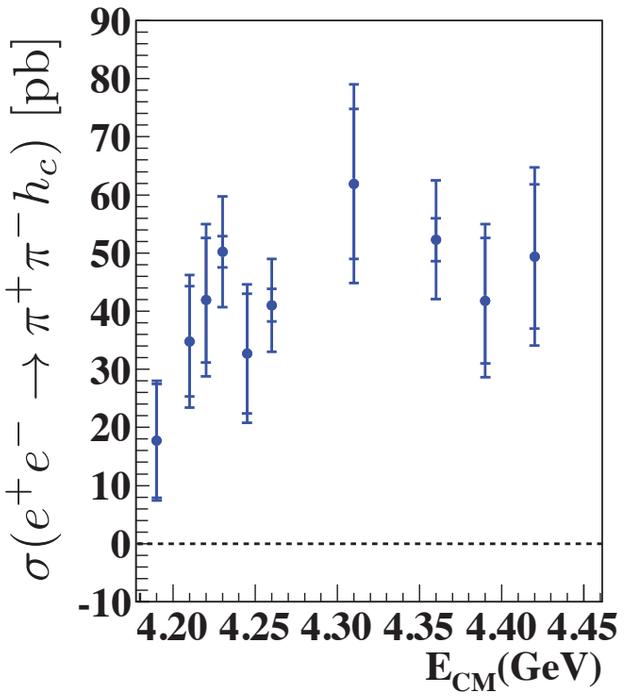


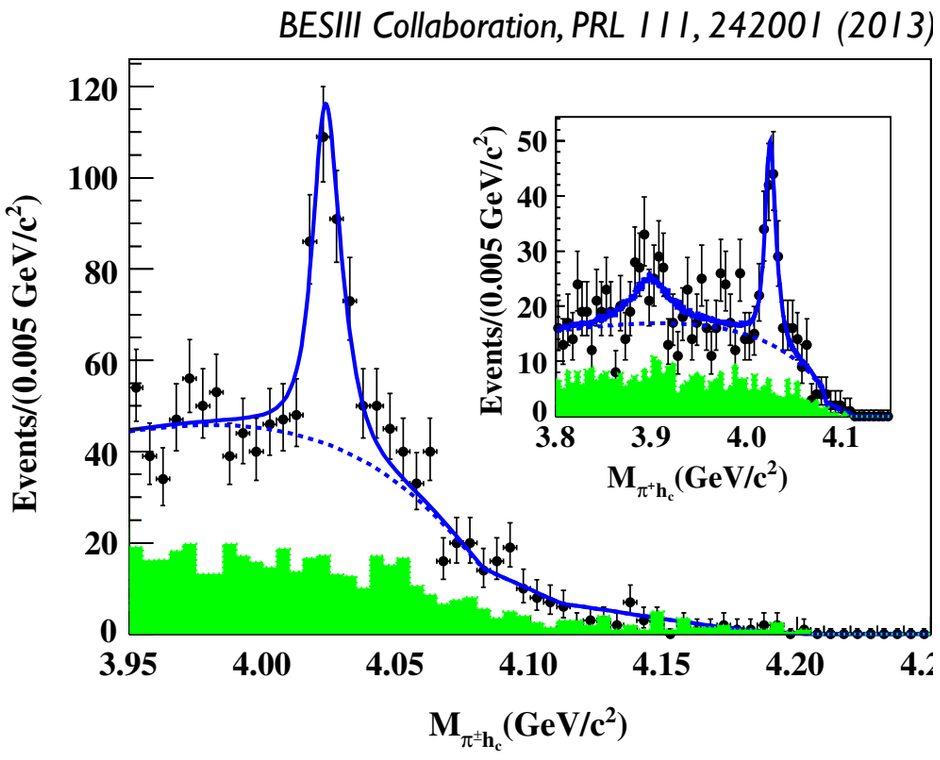
Study:
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$



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

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





Study:
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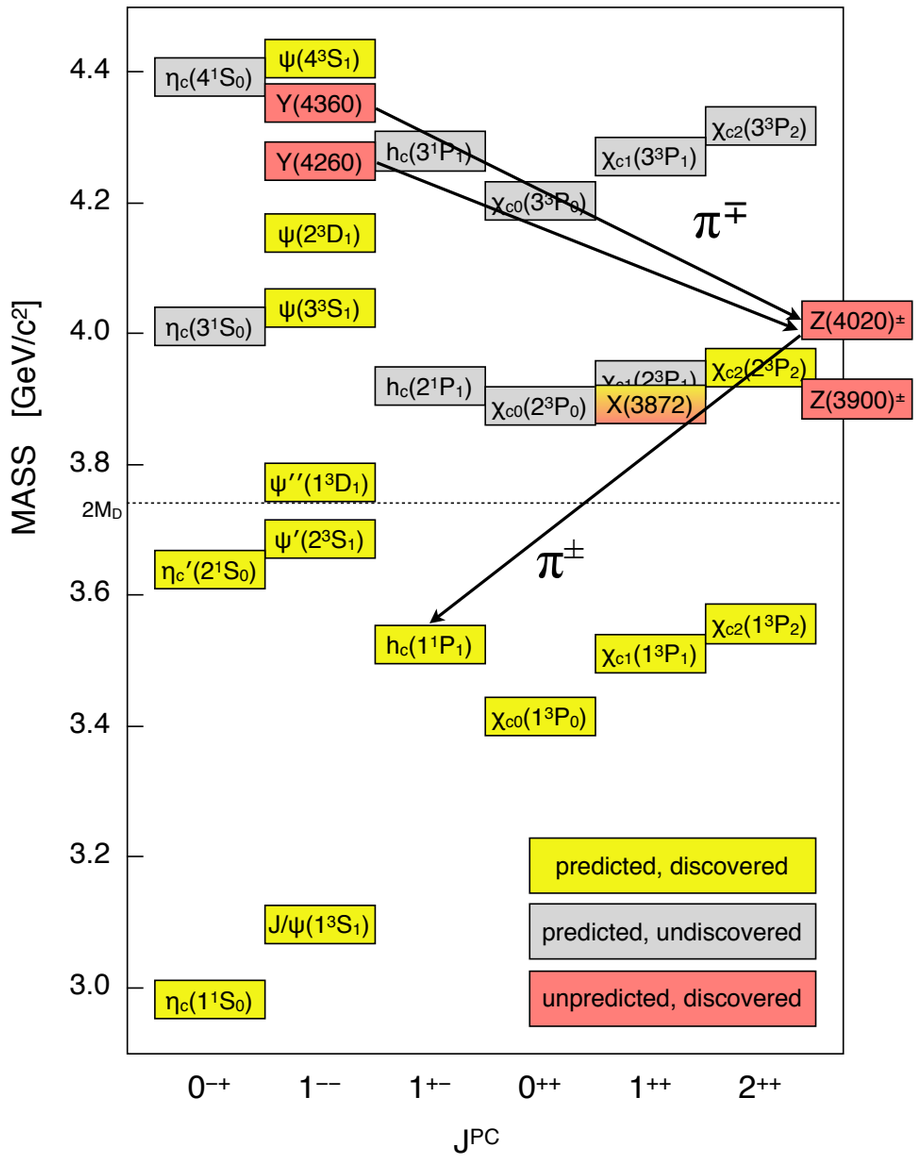


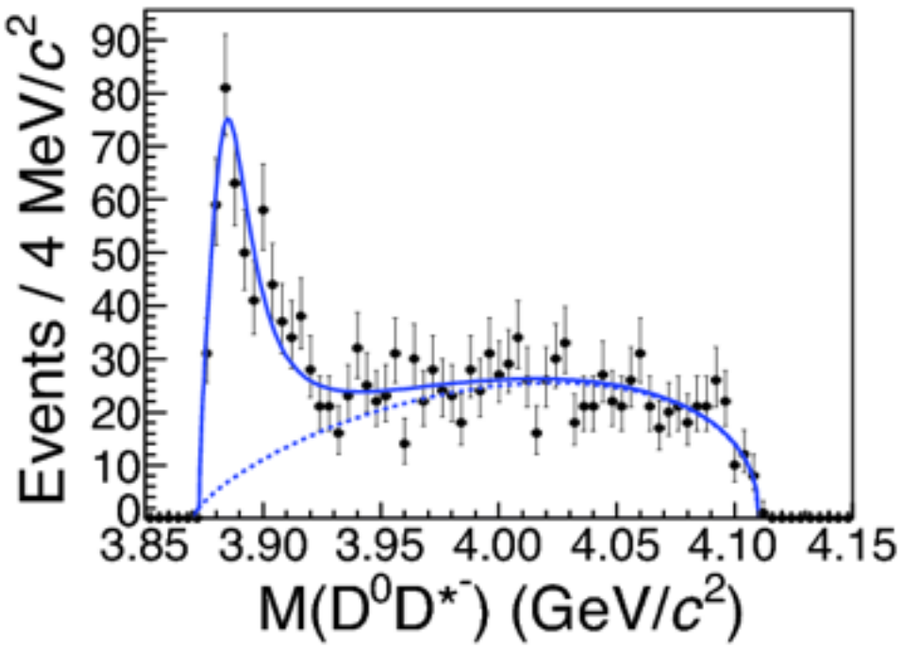
- No *Y*(4260)-like peaking structure in $\pi^+\pi^- h_c$ cross section, which is comparable to peak $\sigma(\pi^+\pi^- J/\psi)$
- Very narrow charged $\pi^{\pm} h_c$ structure
- Evidence for neutral partner
  (see W.M. Song's talk Parallel III:C3)

Couplings to Open Charm?

$Z(3900)^{\pm} \rightarrow DD^*$

$Z(4020)^{\pm} \not\rightarrow DD^*$

BESIII Collaboration, PRL 112, 022001 (2013)

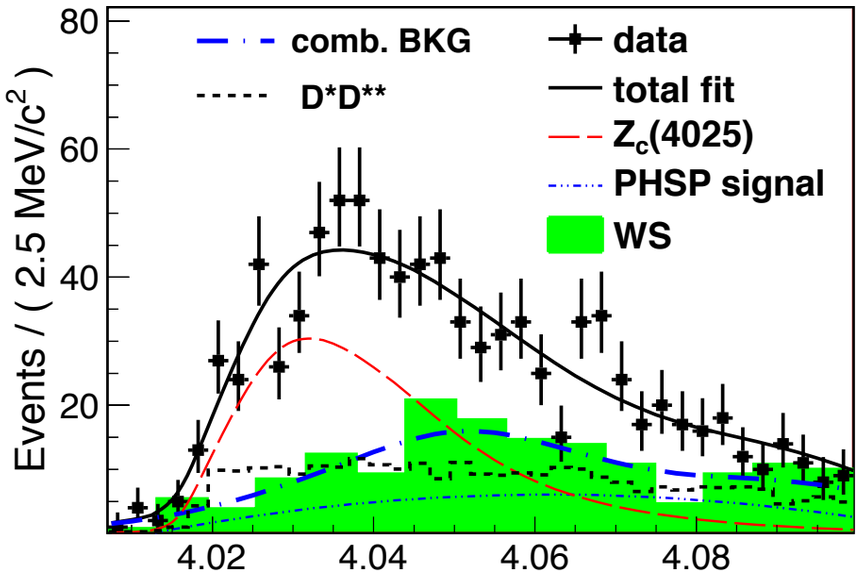


$$\frac{\Gamma(Z_c(3900) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 2.9$$

Angular analysis establishes $J^P = 1^+$
(the same as S-wave DD^*)

$Z(4020)^{\pm} \rightarrow D^*D^*$??

BESIII Collaboration. PRL 112. 132001 (2014)

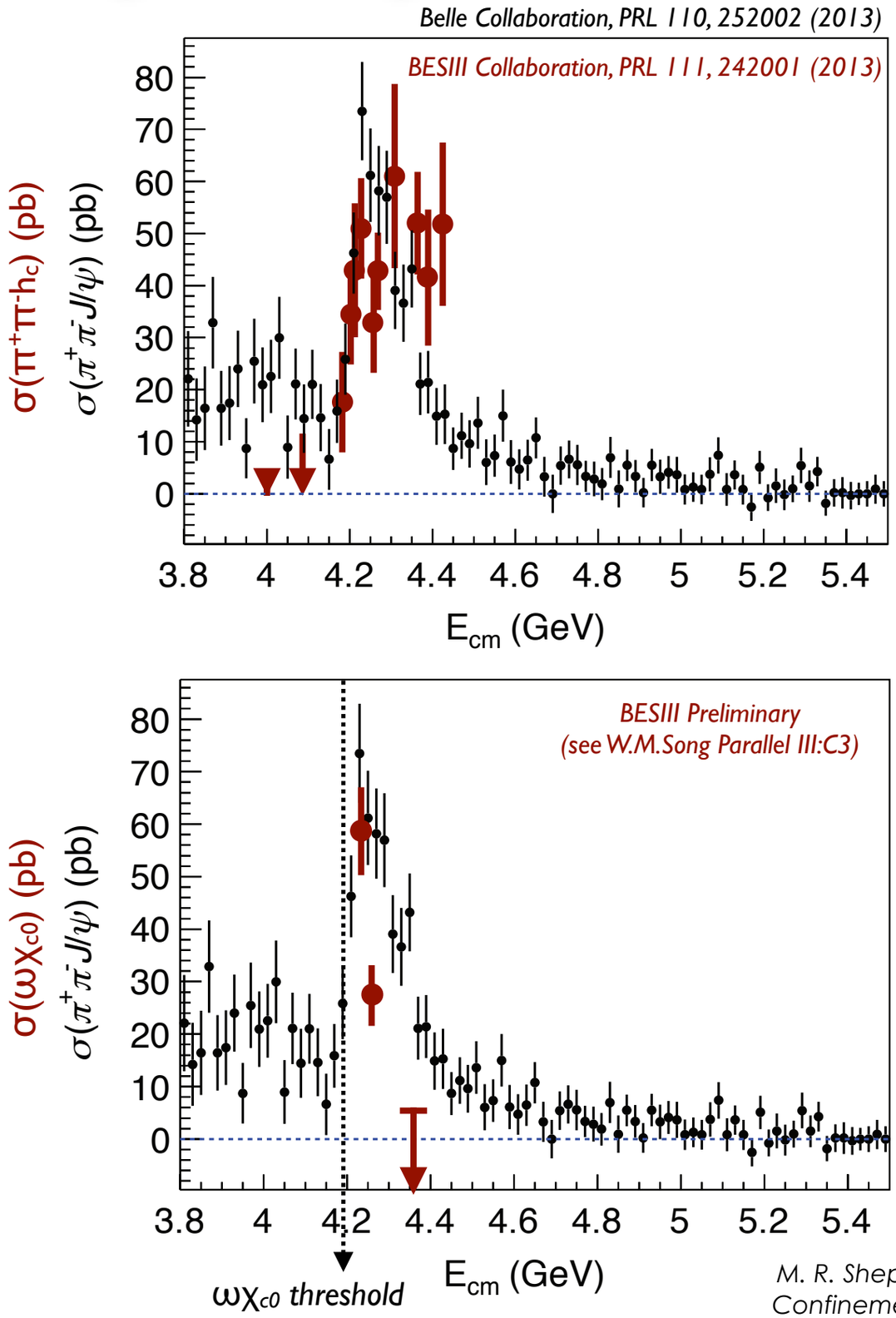


Deviation from phase space that can be fit with a resonance, if $Z(4020)$:

$$\frac{\Gamma(Z_c(4020) \to D^*\bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

What about *Y*(4260)?

- Production of *Z*(3900) correlated with decays of *Y*(4260), inconclusive for *Z*(4020)
- $\sigma(\pi^+\pi^- h_c)$ significant: too broad for *Y*(4260) only
- $\sigma(\omega\chi_{c0})$ significant: too narrow for *Y*(4260)
- Evidence for $e^+e^- \to \gamma X(3872)$ at 4260 MeV: may be a radiative transition of *Y*(4260)? *[BESIII, PRL 112, 092001 (2014)]*
  - *X(3872)* is 1^+ with radiative transitions consistent with mixture of $\chi_{c1}(2P)$ and bound *DD**
    [LHCb, PRL 110, 222001 (2013); LHCb, NP B886, 665 (2014)]



Parallels to Bottomonium

Bottomonium

Belle Collaboration, PRL 108, 032001 (2012)
Belle Collaboration, PRL 108, 122001 (2012)

- significant $\sigma(\pi\pi\Upsilon)$ and $\sigma(\pi\pi h_b)$ in e^+e^- collisions at 10.865 GeV
- "$\Upsilon(5S)$"$\rightarrow\pi\pi\Upsilon(nS)$ partial width two orders of magnitude greater than other Υ states
- $\sigma(\pi\pi h_b) \approx \sigma(\pi\pi\Upsilon)$ at 10.865 GeV
- $Z(10610)^{\pm}$ just above BB^* threshold
- $Z(10650)^{\pm}$ just above B^*B^* threshold

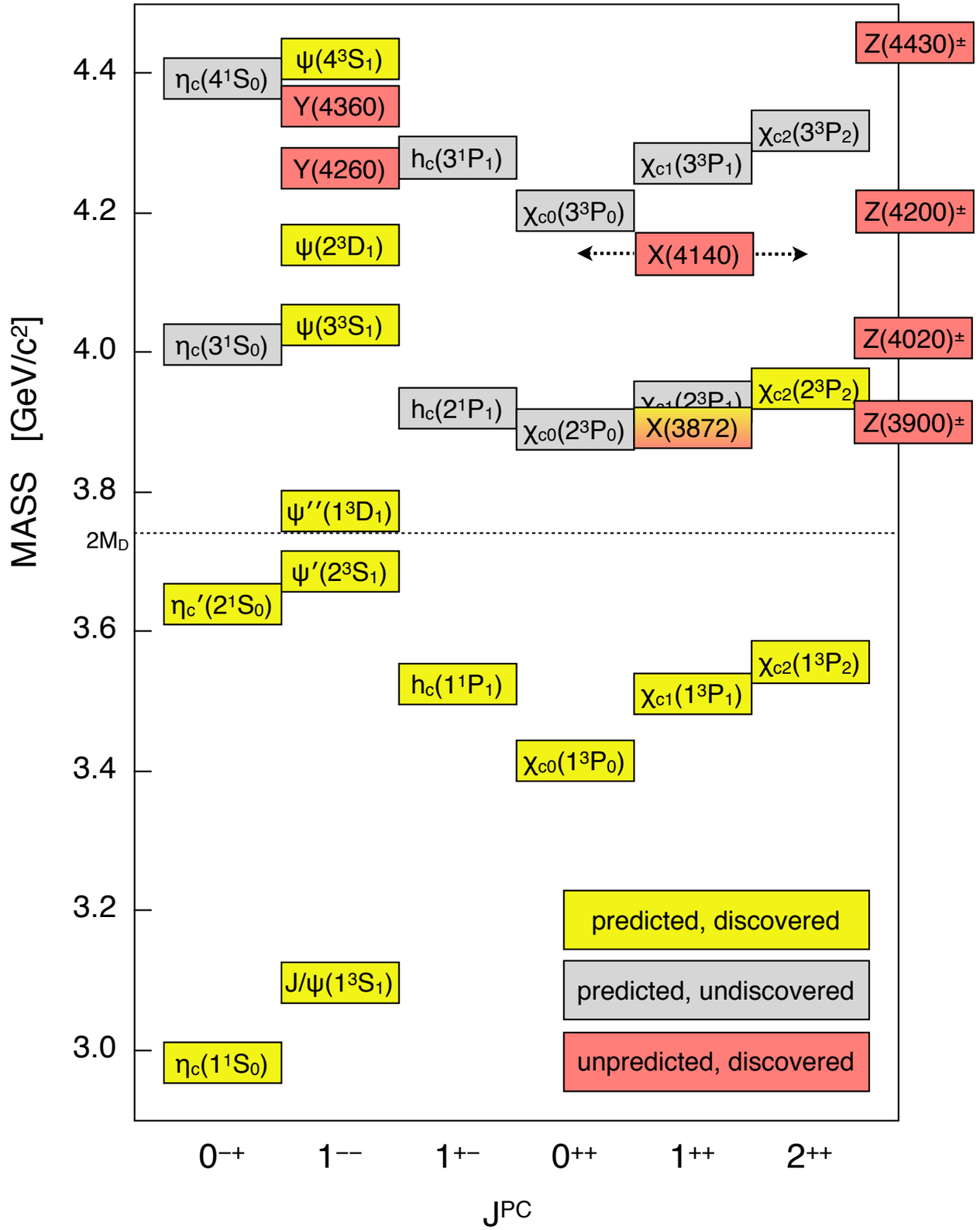
Charmonium

- peaking $\sigma(\pi\pi J/\psi)$ in e^+e^- collisions: $Y(4260)$; significant $\sigma(\pi\pi h_c)$
- $Y(4260)$ decay to $\pi\pi J/\psi$ enhanced with respect to open charm when compared to other ψ states
- $\sigma(\pi\pi h_c) \approx \sigma(\pi\pi J/\psi)$ at 4.2 - 4.4 GeV
- $Z(3900)^{\pm}$ just above DD^* threshold
- $Z(4020)^{\pm}$ just above D^*D^* threshold

Similar spectra of exotic "quarkonia" or similar heavy flavor meson dynamics?

Charmonium in *B* Decay

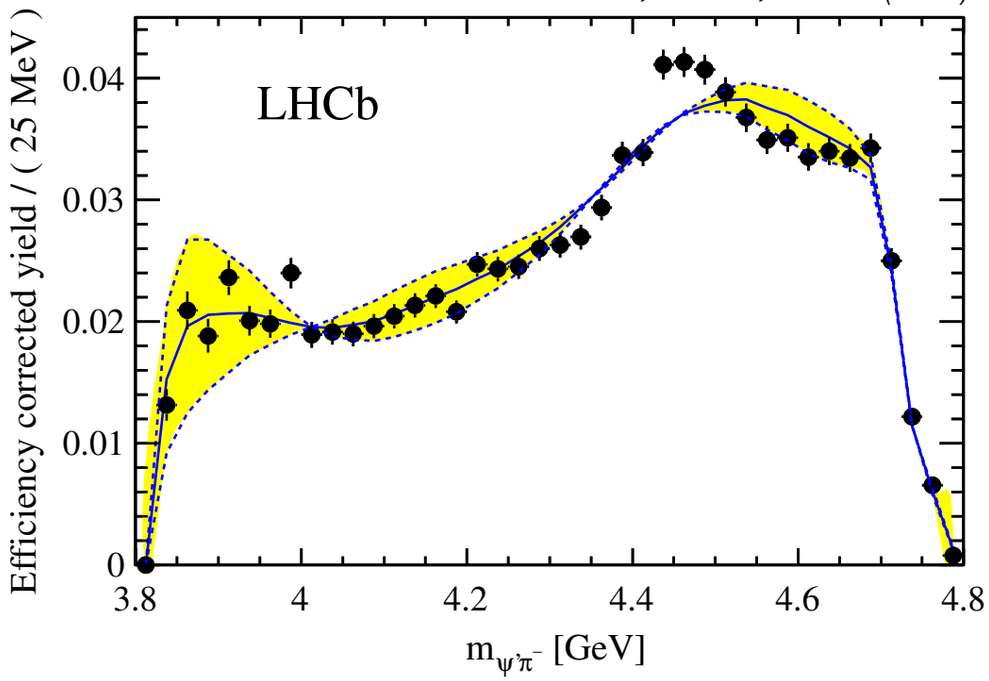
- Hadronic decays of the *B* meson (M(*B*) = 5.27 GeV) can be used to study the charmonium spectrum
  - useful tool at hadron colliders
- Recent hot topics:
  - charged states: *Z*(4430) and *Z*(4200) in $\pi^{\pm}\psi(')$
  - narrow neutral state: *X*(4140) in $\Phi J/\psi$

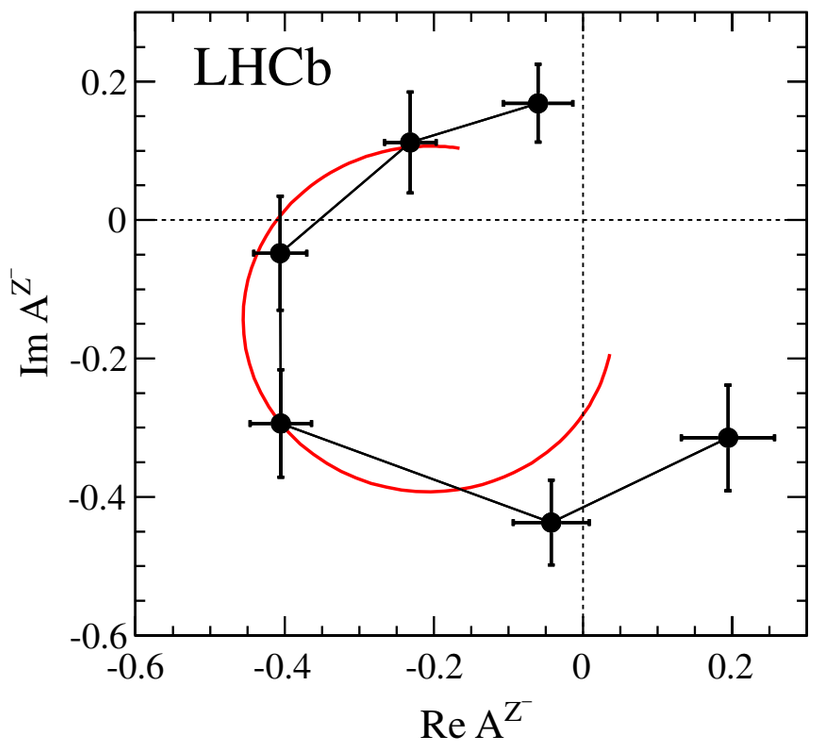


$Z(4430)^{\pm} \rightarrow \psi'\pi^{\pm}$

- Examine $\psi'\pi^{\pm}$ produced in $B \rightarrow \psi' K \pi^{\pm}$
  - need to understand $K\pi$ structure
- $Z(4430)$ reported initially by Belle [PRL 100, 142001 (2008)], but not confirmed by BaBar [PRD 79, 112001 (2009)]
- $Z(4430)$ recently confirmed with 10x more data at LHCb
- established $J^P = 1^+$
  - not S-wave $D^*(2007)D_1(2420)$ or $D^*(2007)D_2^*(2460)$
- Broad structure: $\Gamma_{tot} \approx 200$ MeV
- LHCb: second structure around 4200 at 6σ; resonant nature inclusive

LHCb Collaboration, PRL 112, 222002 (2014)

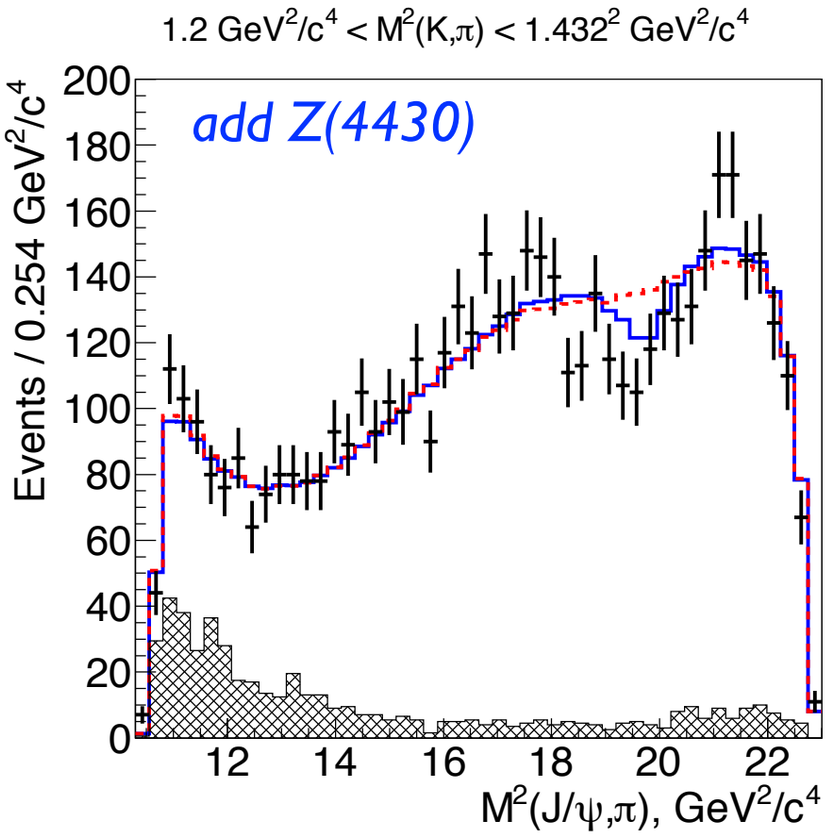


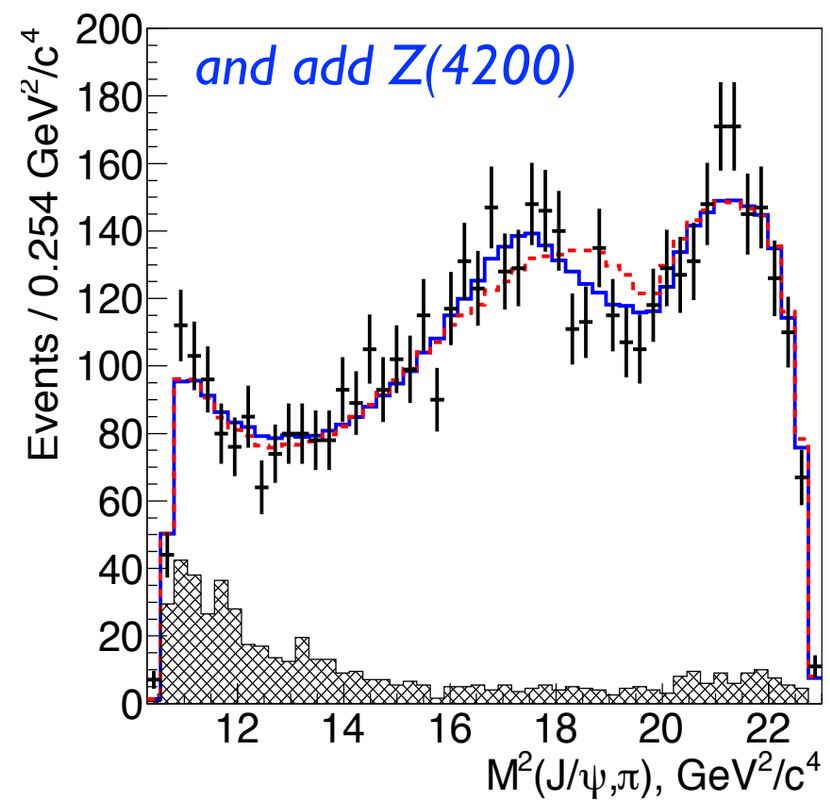


$B \to K\pi^{\pm}J/\psi$

- Belle reports evidence for $Z(4430) \to \pi^{\pm}J/\psi$
  - about 10x smaller than $Z(4430) \to \pi^{\pm}\psi'$
- Belle: $Z(4200)^{\pm} \to \pi^{\pm}J/\psi$ at 6.2σ
  - broad: $\Gamma_{tot} \approx 400$ MeV
  - $J^P = 1^+$ favored
    - compatible with "structure" in LHCb analysis of $\pi^{\pm}\psi'$
- No evidence for the $Z(3900)$ that is correlated with $Y(4260)$ decay
  - production mechanism dependence?
  - $Z(3900)$ is fundamentally different from $Z(4200)$ and $Z(4430)$?

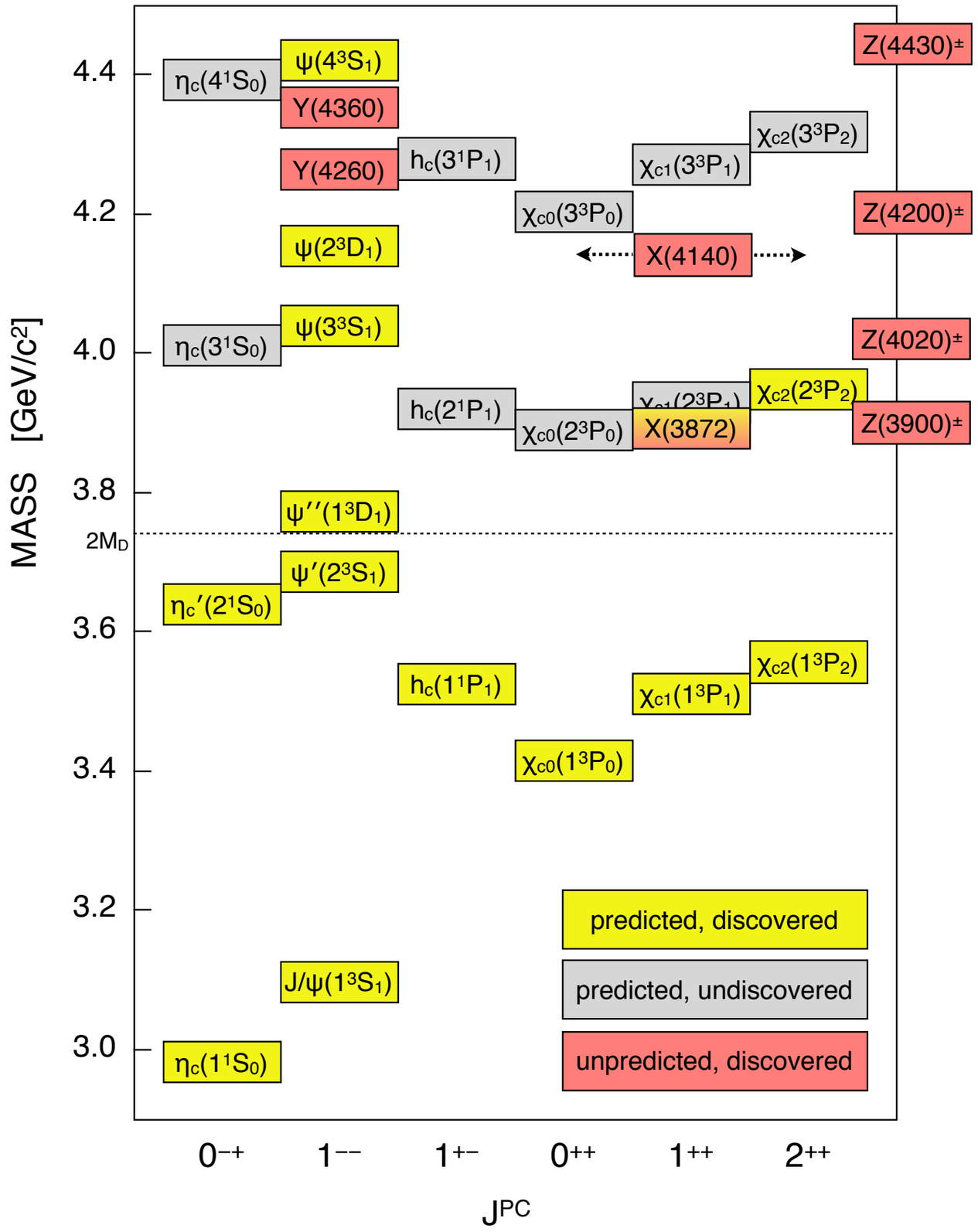
Belle Collaboration, arXiv:1408.6457 (2014)





Charged Z Recap

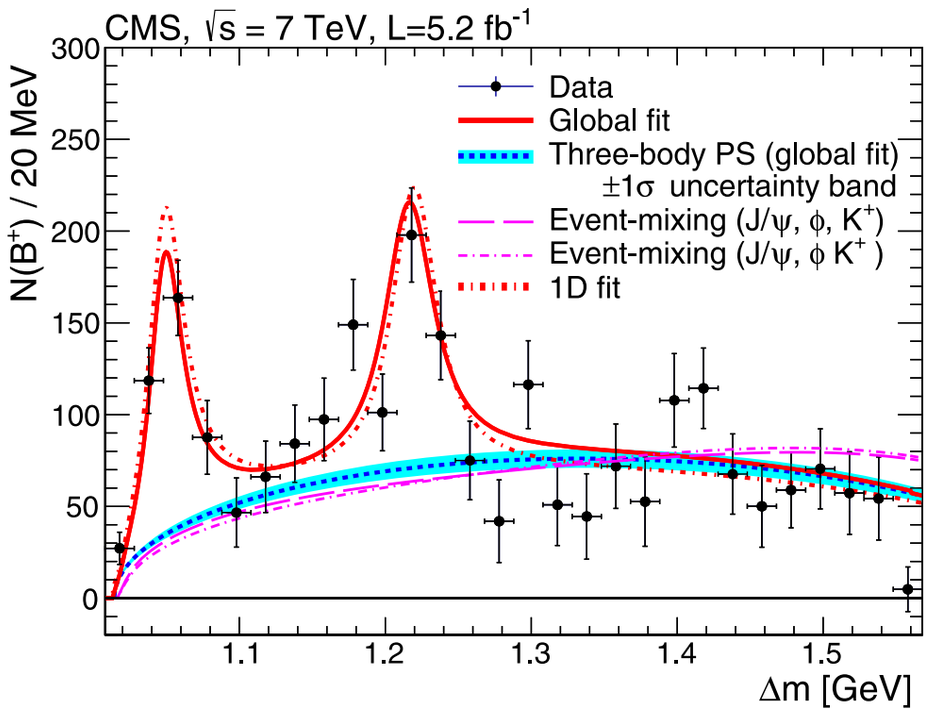
- $Z(3900)$ and $Z(4020)$
  - correlated with $Y(4260)$ and/or $Y(4360)$
  - narrow: tens of MeV
  - near DD^* and D^*D^* thresholds
  - similarities in the bottomonium system
  - not produced in hadronic B decay
- $Z(4200)$ and $Z(4430)$
  - produced in B decay
  - broad: hundreds of MeV
  - no apparent correlation with open charm thresholds?
- Other charged states in B decay: Z(4050) and Z(4250) ("older news" and not pictured)
  - reported in $\chi_{c1}\pi^{\pm}$ by Belle [PRD 78, 072004 (2008)]
  - not confirmed by BaBar [PRD 85, 052003 (2012)]



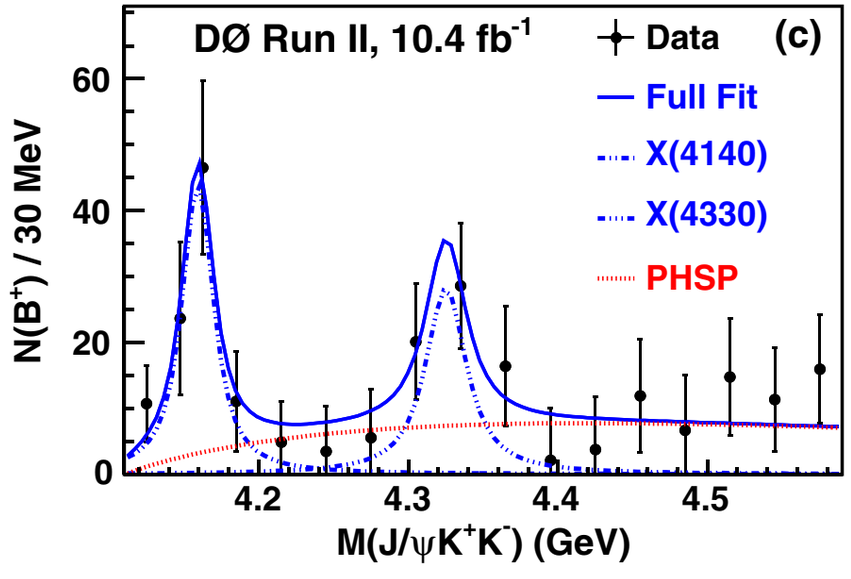
X(4140) → ΦJ/ψ

- Observed in $B^+ \to K^+ \Phi J/\psi$
- Neutral state with C=+
- Narrow: $\Gamma_{tot} \approx 30$ MeV
- No apparent charmonium candidate?
- State first discovered by CDF [PRL 102, 242002 (2009)]
- Not confirmed by LHCb [PRD 85, 091103 (2012)]
- BarBar: statistically limited - inconclusive [arXiv:1407.7244]
- Recently confirmed by CMS and D0 (seems consistent w/both CDF and LHCb)
- Significance of second peak uncertain due to potential kinematic reflections

CMS Collaboration, PLB 734, 261 (2014)

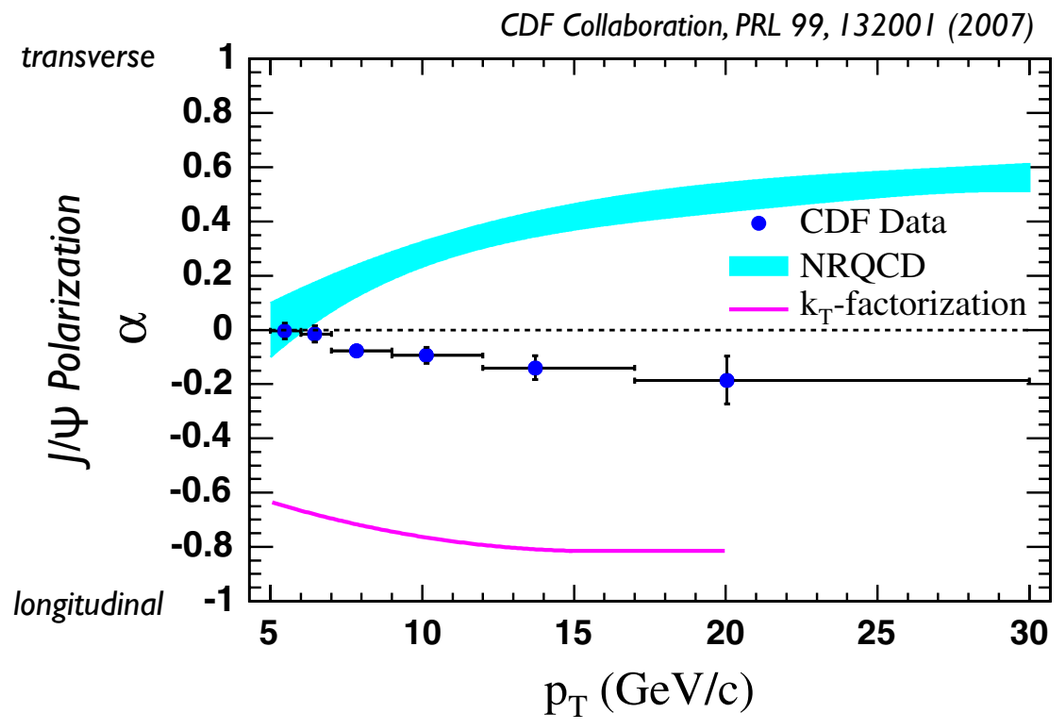


D0 Collaboration, PRD 89, 012004 (2014)



Quarkonium Production

- Production of heavy quarkonium is a hard process: at leading order, rates and polarization not affected by soft QCD
- Rates and polarization fractions calculable in effective field theory (e.g. NRQCD) — need phenomenological input:
  - universal matrix elements
  - fragmentation functions
- Use experiment to validate self-consistent theoretical formulation
- Experimental applicability
  - quarkonium production in hadron collisions and deep inelastic scattering
  - $e^+e^- \rightarrow J/\psi\, X(c\bar{c}$ or non-$c\bar{c})$
  - $\gamma\gamma \rightarrow J/\psi\, X$



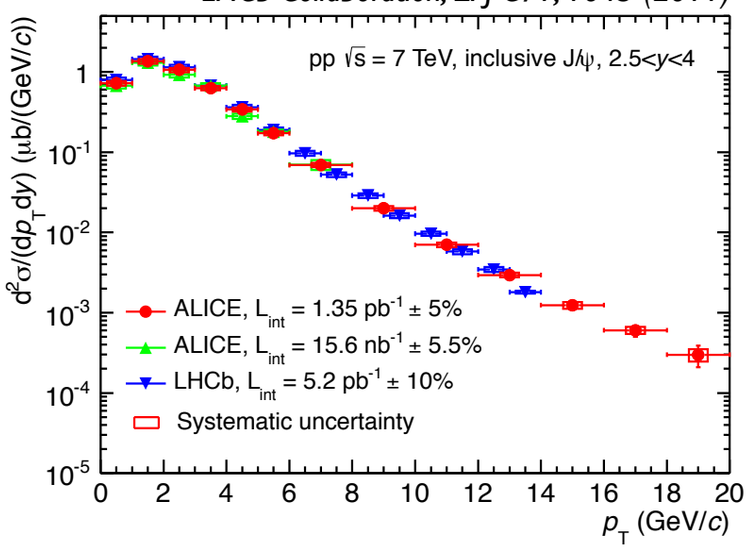
LHC-era experimental goals

- push measurement to higher p_T
- measure *bb* and *cc* species at high precision
- reduce experimental systematic errors: frame invariant analyses

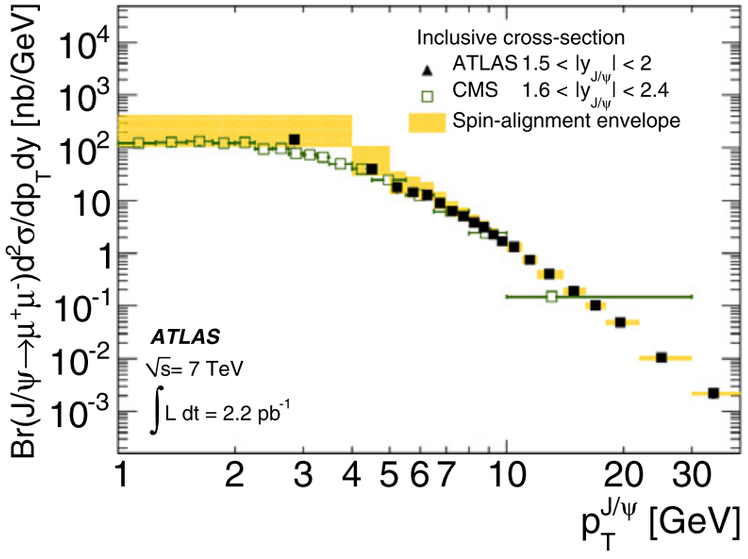
Charmonium Cross Sections

J/ψ

ALICE Collaboration, arXiv:1403.3648
LHCb Collaboration, EPJ C71, 1645 (2011)

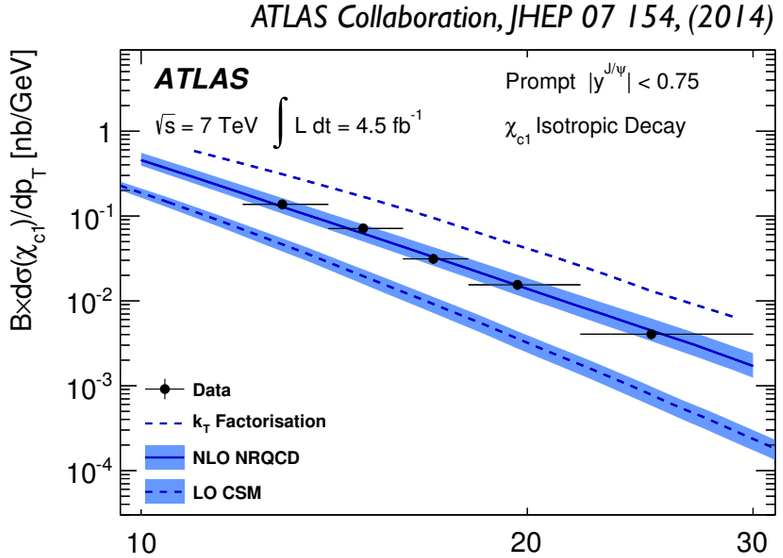


ATLAS Collaboration, NP B850, 387 (2011)
CMS Collaboration, EPJ C71, 1575 (2011)

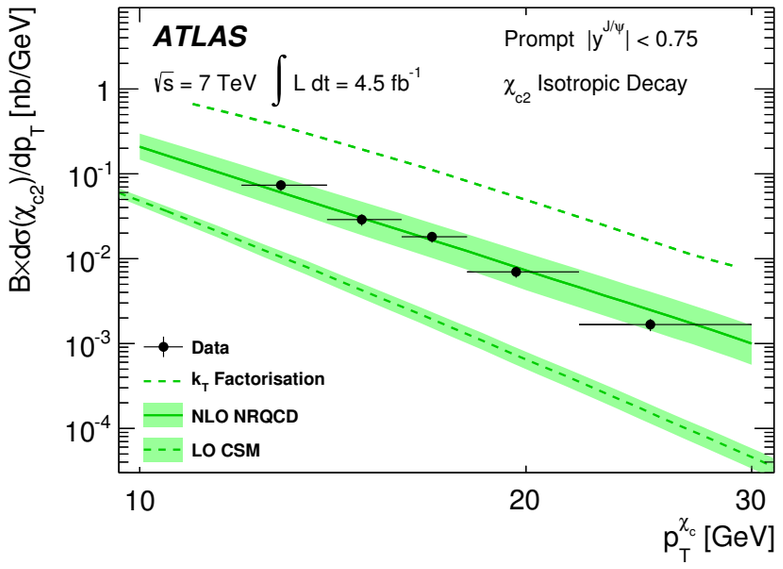


X_{c1}

ATLAS Collaboration, JHEP 07 154, (2014)

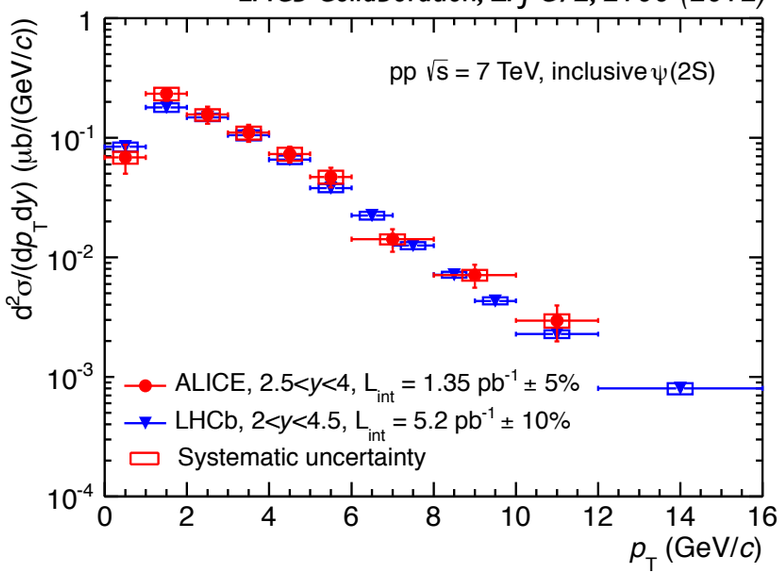


X_{c2}

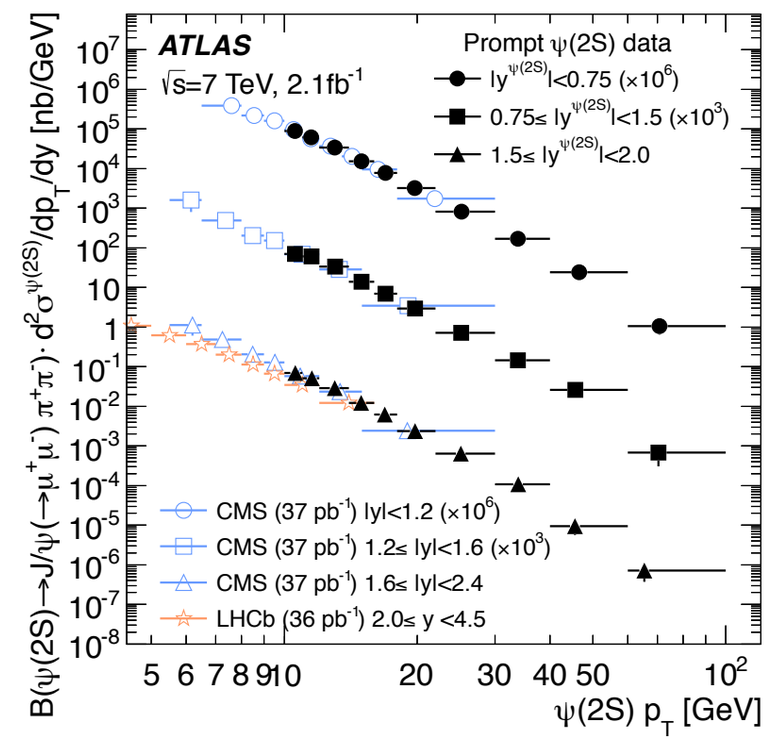


ψ(2S)

ALICE Collaboration, arXiv:1403.3648
LHCb Collaboration, EPJ C72, 2100 (2012)

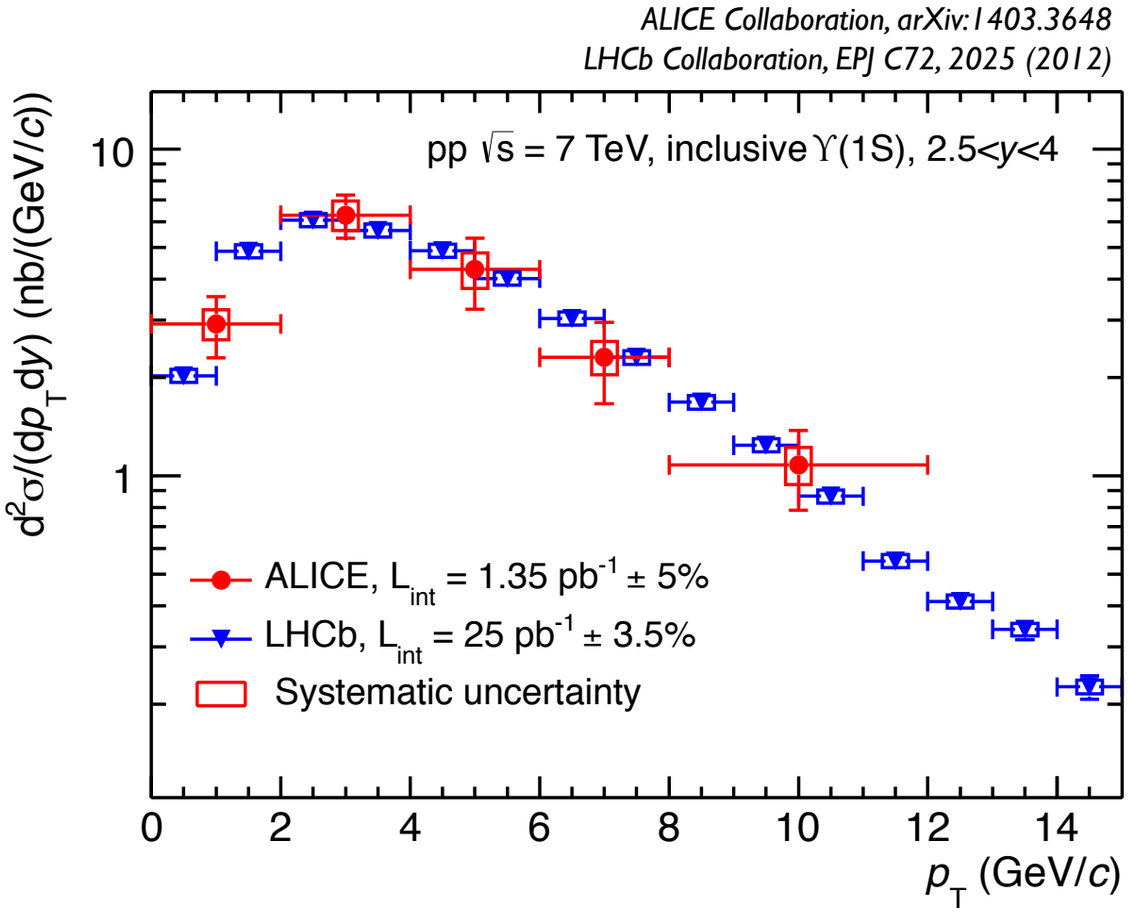


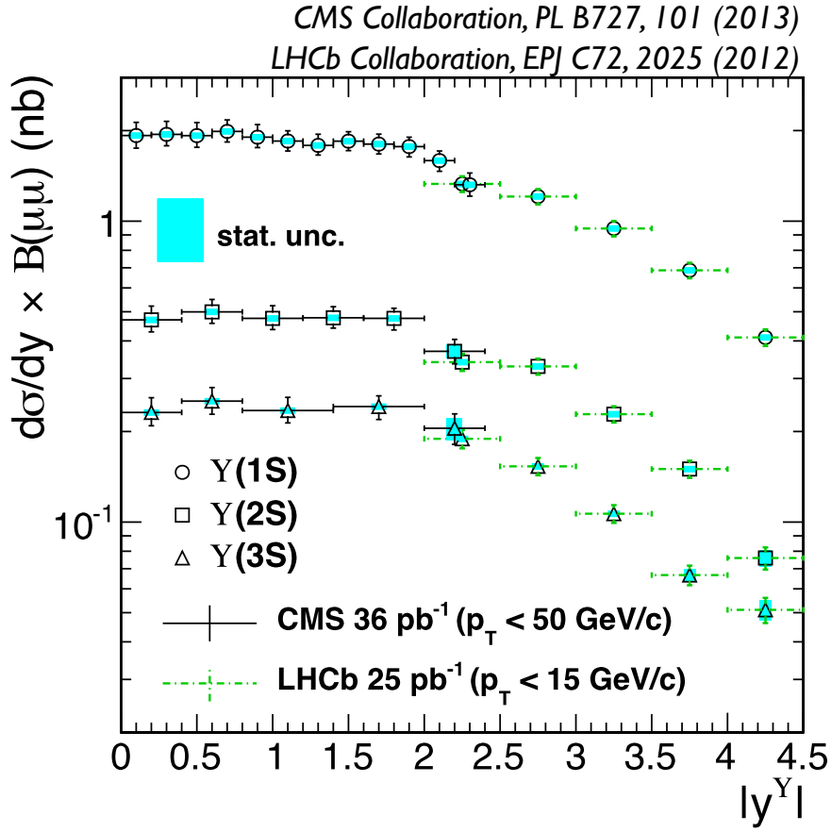
ATLAS Collaboration, arXiv:1407.5532
LHCb Collaboration, EPJ C72, 2100 (2012)
CMS Collaboration, JHEP 1202, 011 (2012)



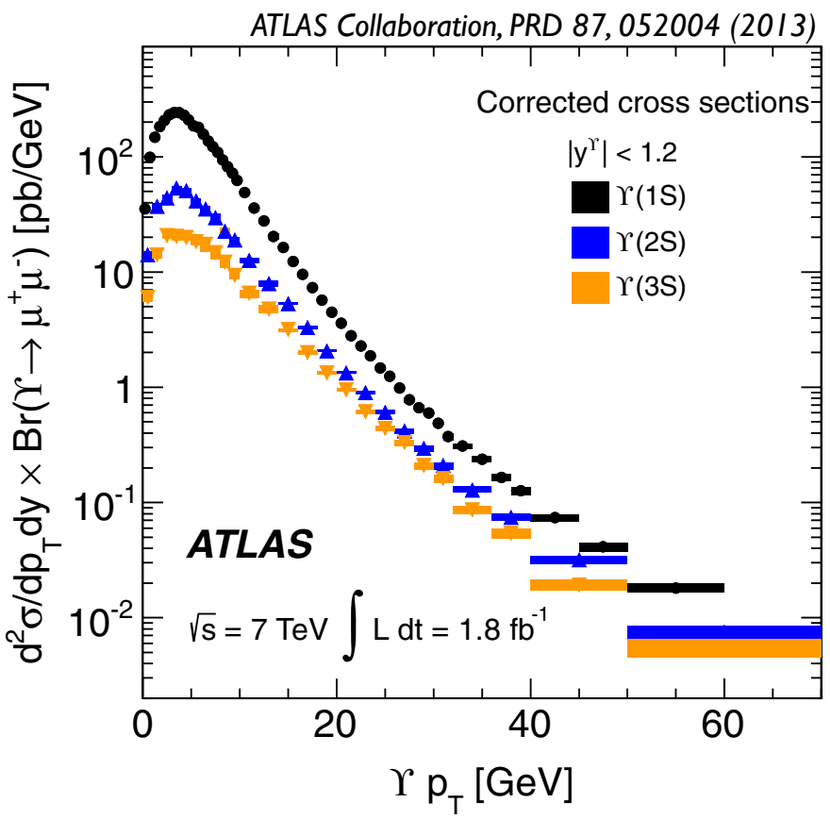
Bottomonium Cross Sections

Υ(1S)





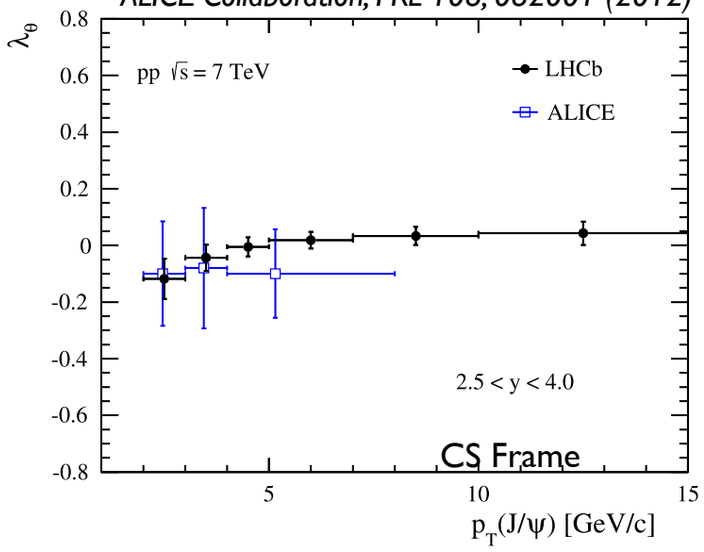
Υ(1S)
Υ(2S)
Υ(3S)



Quarkonium Polarization

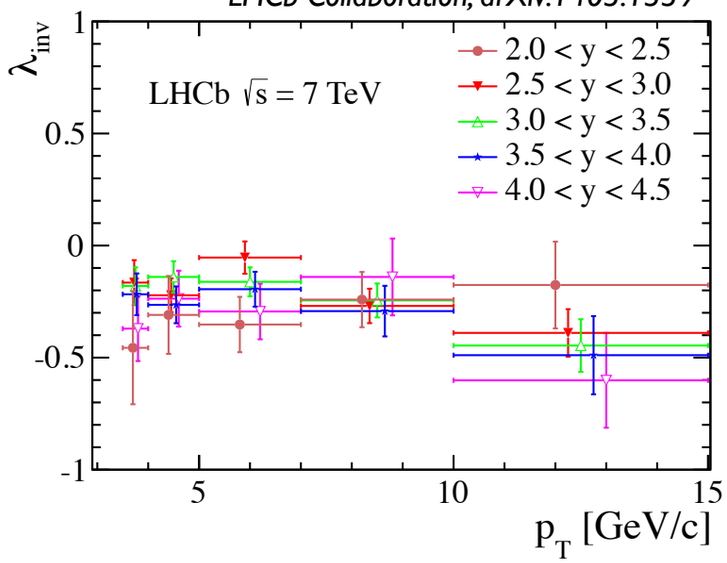
J/ψ

LHCb Collaboration, EPJ C73, 2631 (2013)
ALICE Collaboration, PRL 108, 082001 (2012)

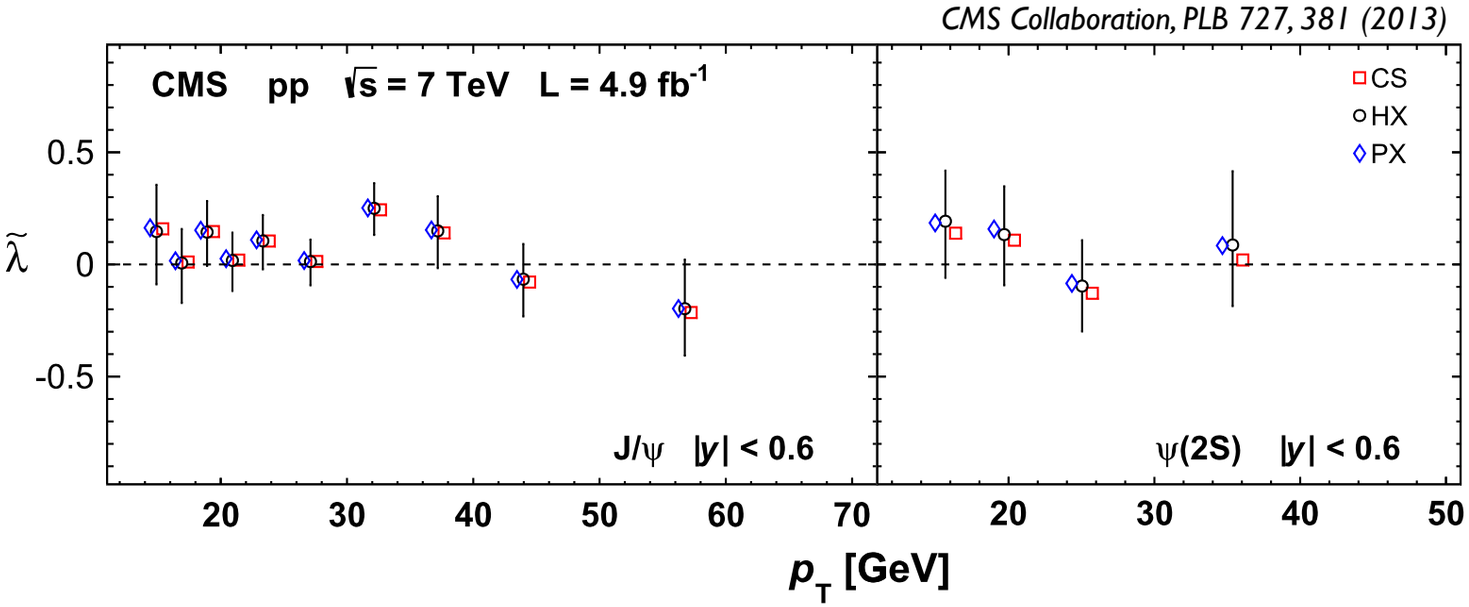


ψ(2S)

LHCb Collaboration, arXiv:1403.1339

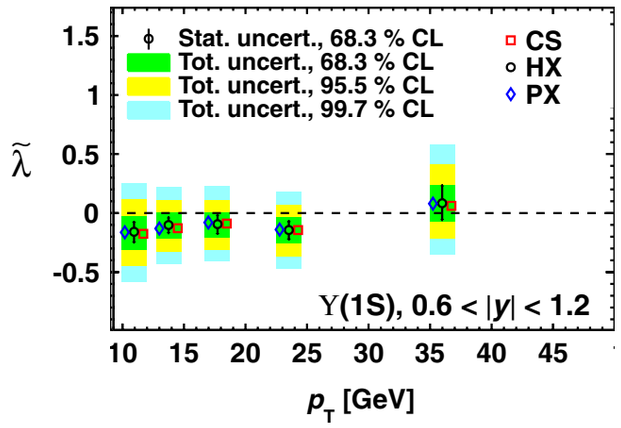


CMS Collaboration, PLB 727, 381 (2013)

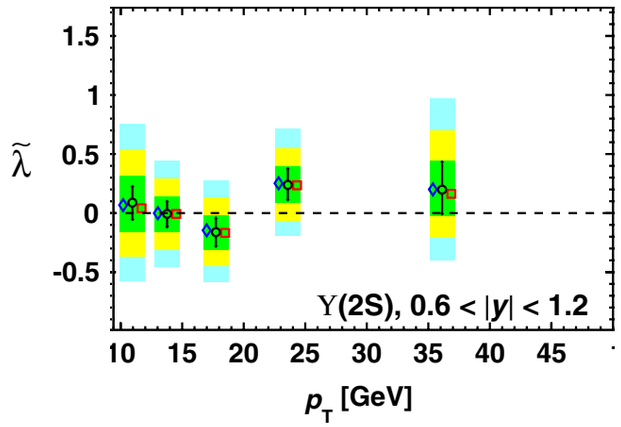


CMS Collaboration, PRL 110, 081802 (2013)

Υ(1S)



Υ(2S)



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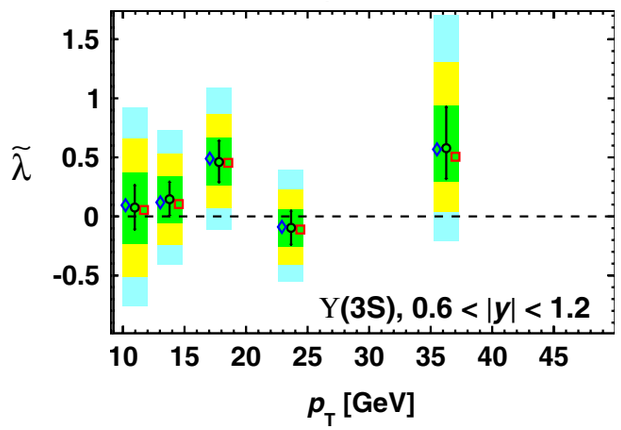

Summary

- Many diverse experimental studies of heavy quarkonia
  - central theme: understanding QCD
- Interesting structures in the *cc* and *bb* systems that appear to not be conventional quarkonium
  - common exotic spectra or common heavy meson dynamics?
  - no apparent connection between e^+e^- production and B decay
- The LHC has ushered in a new era of experiments in quarkonium production
  - no evidence of significant vector quarkonium polarization at high p_T
- There are many details to be discussed in the "Parallel III" sessions this week!