Plans and ideas for charmonium spectroscopy with PANDA

Sean Dobbs
Florida State U.

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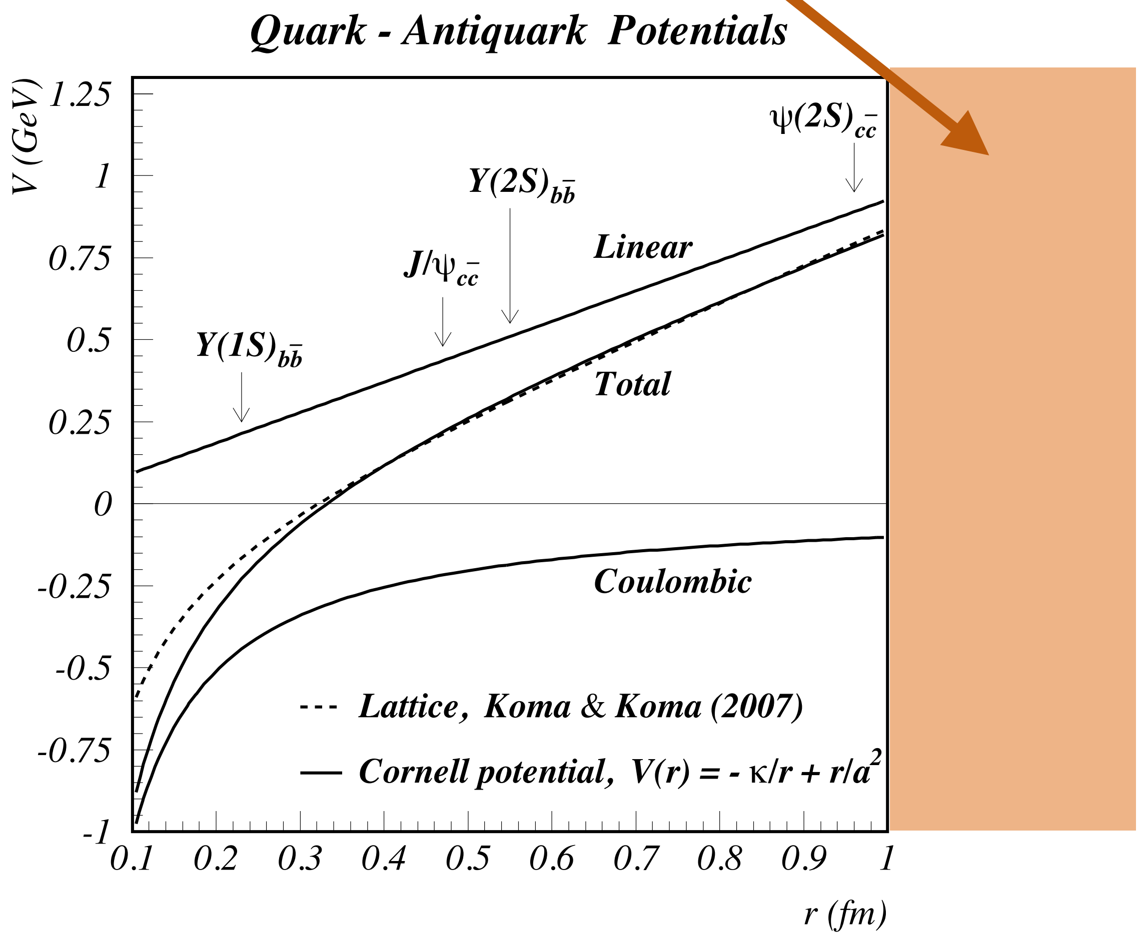
Introduction

- Charmonium: Hydrogen atom of QCD
  - Both experimentally and theoretically accessible
- Rich spectrum of excited states
  - Bound states give detailed information on spin structure of potential
  - More exciting over D$\bar{D}$ threshold:
    - Resonance properties dominated by confining interaction
    - Multiquark & other exotic states energetically allowed
- PANDA can make key contributions:
  - High-spin states
  - EM final states

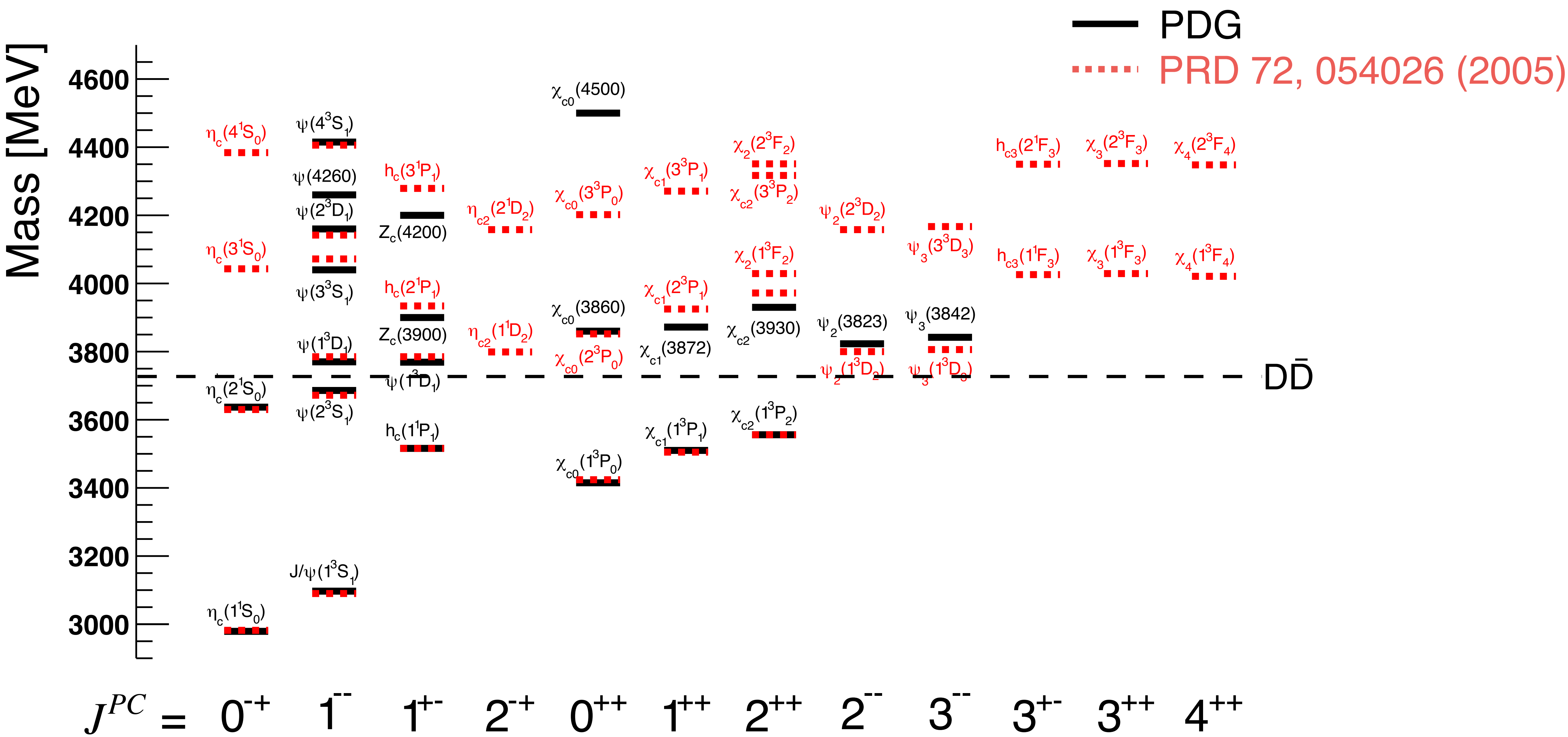
Cornell potential:

$$V(r) = -\frac{a}{r} + br$$

States above D$\bar{D}$ threshold

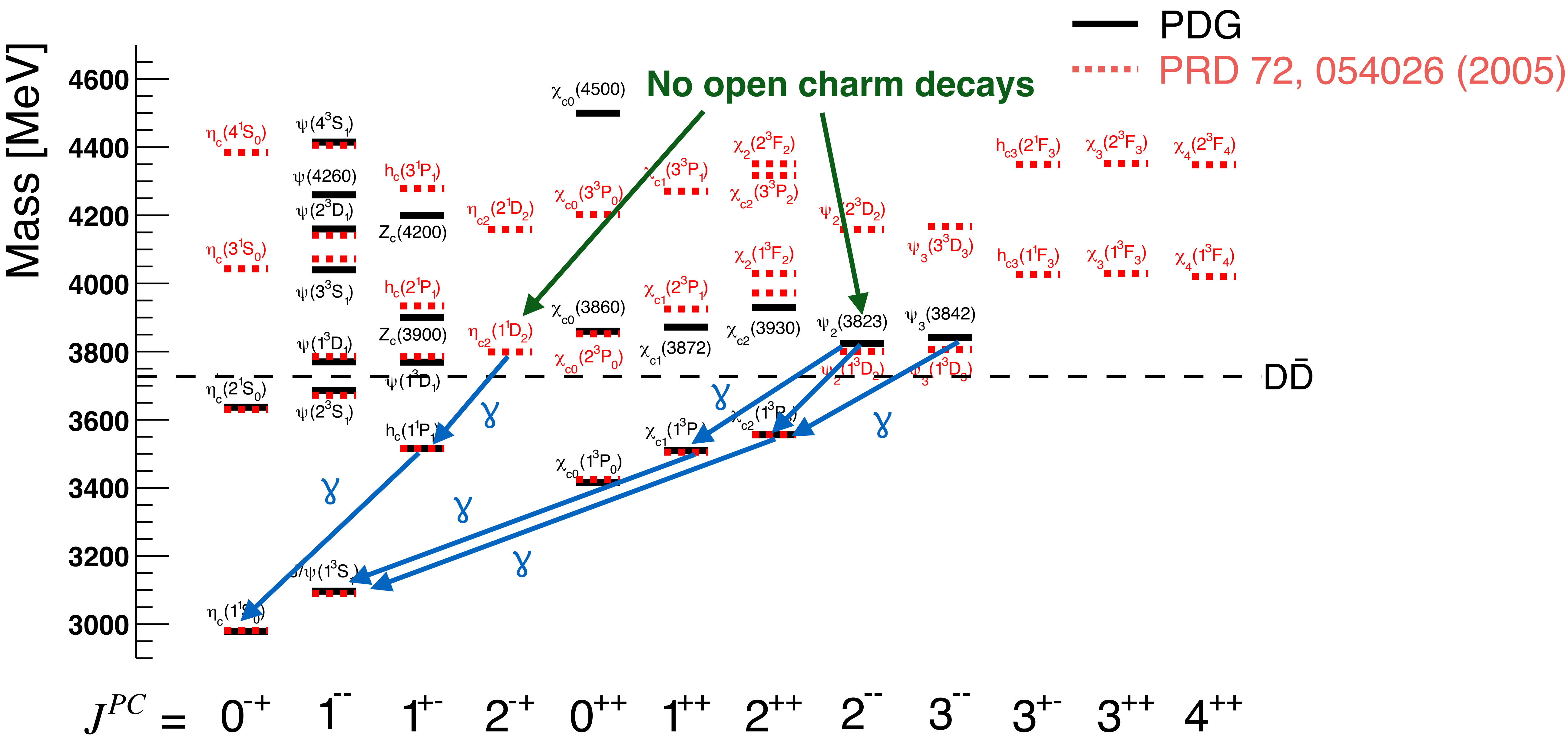


The Charmonium Spectrum



- Charmonia above $D\bar{D}$ are sensitive to confinement potential, loop contributions, opening of additional thresholds, …
  - Basis of our understanding of resonances in the “unbound” region

The Charmonium Spectrum: D-wave states

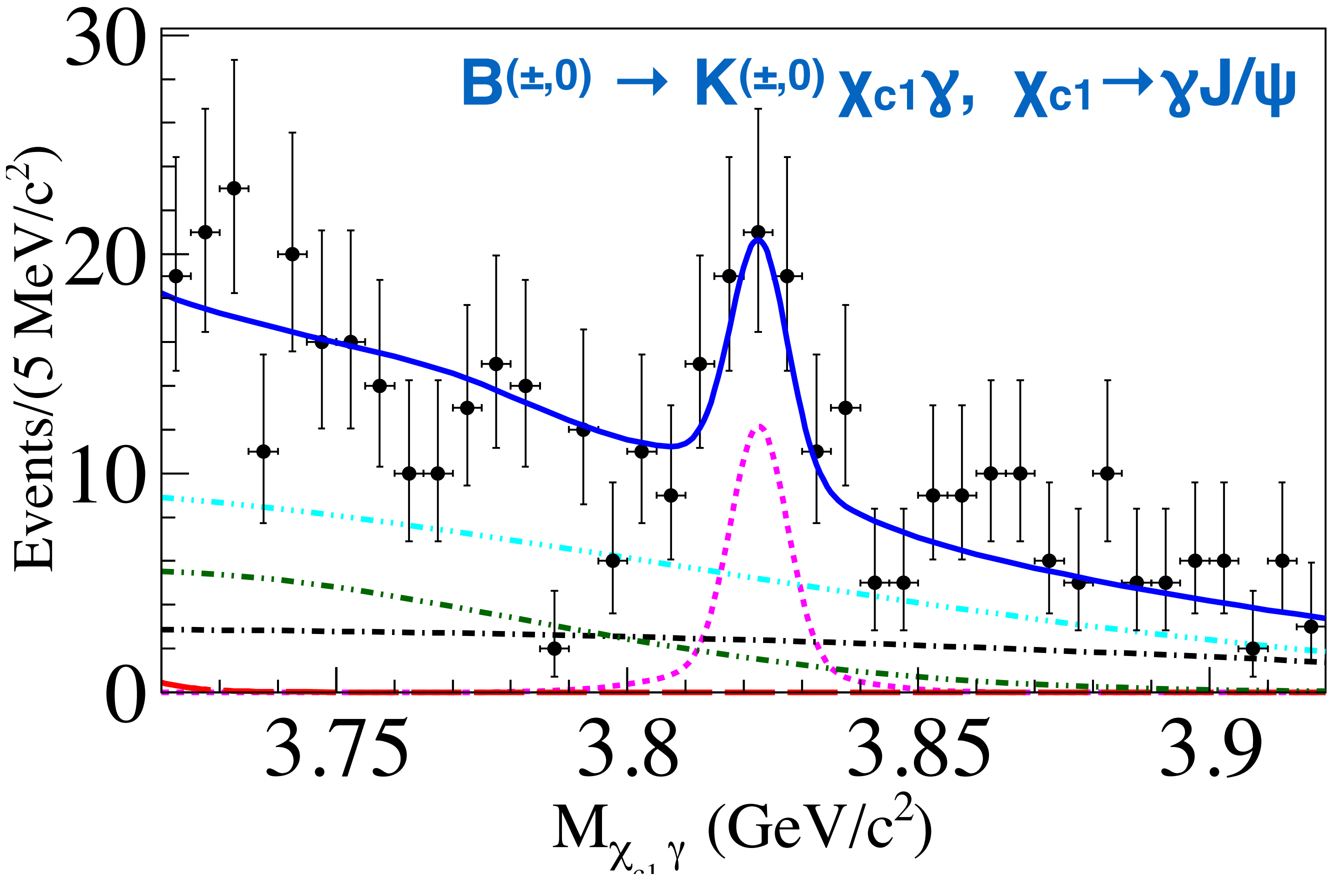


- Charmonia above $D\bar{D}$ are sensitive to confinement potential, loop contributions, opening of additional thresholds, …
  - Basis of our understanding of resonances in the “unbound” region

Higher-spin D-wave States: $\psi_2(1^3D_2)$

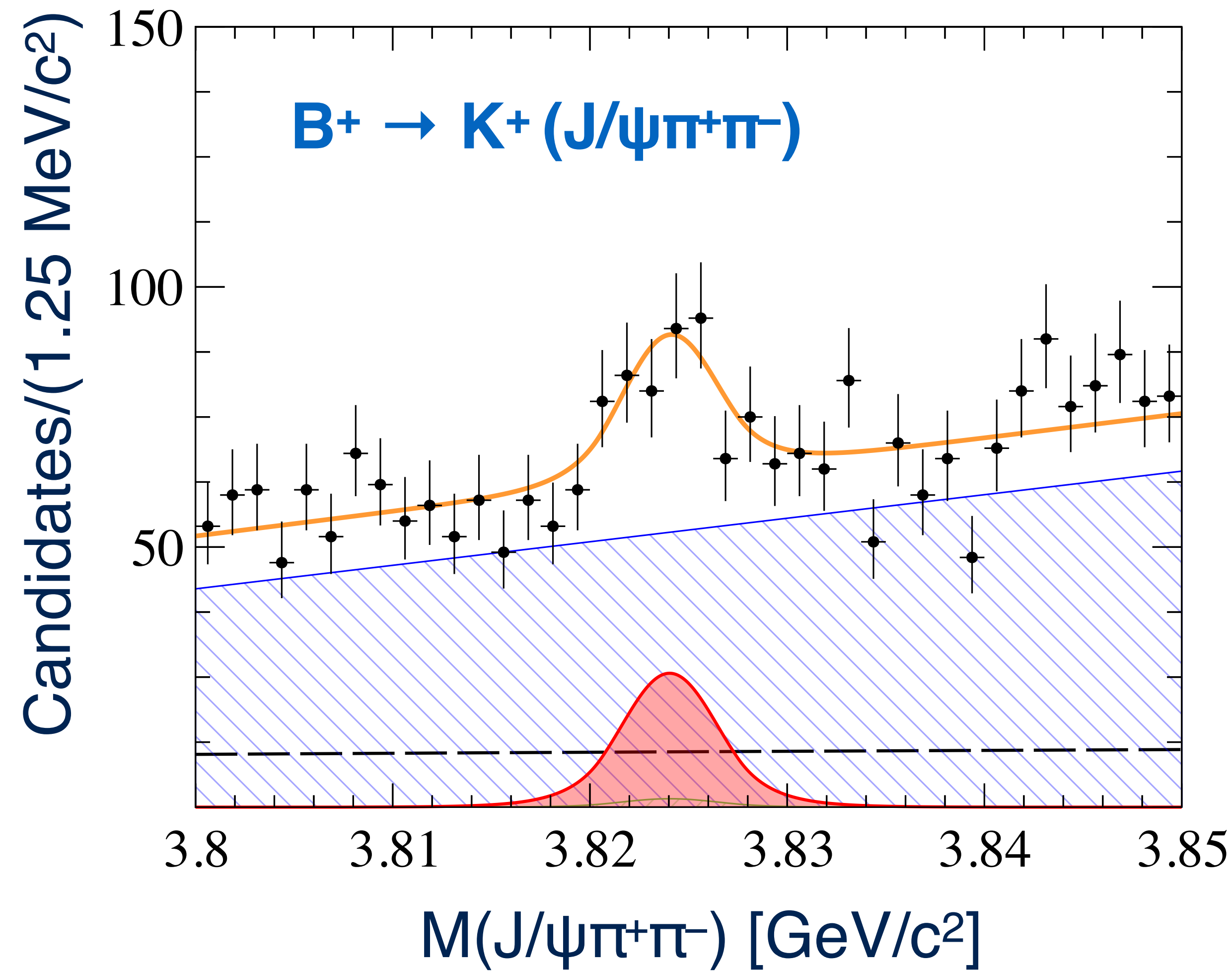
- $\psi_2(1^3D_2)$ expected to be narrow, no allowed open-charm decays, expected large decay to $\gamma\chi_{c1}$

Belle: PRL 111, 032001 (2013)



M = 3823.1 ± 1.9 MeV, Γ < 24 MeV

LHCb: arXiv:2005.13422



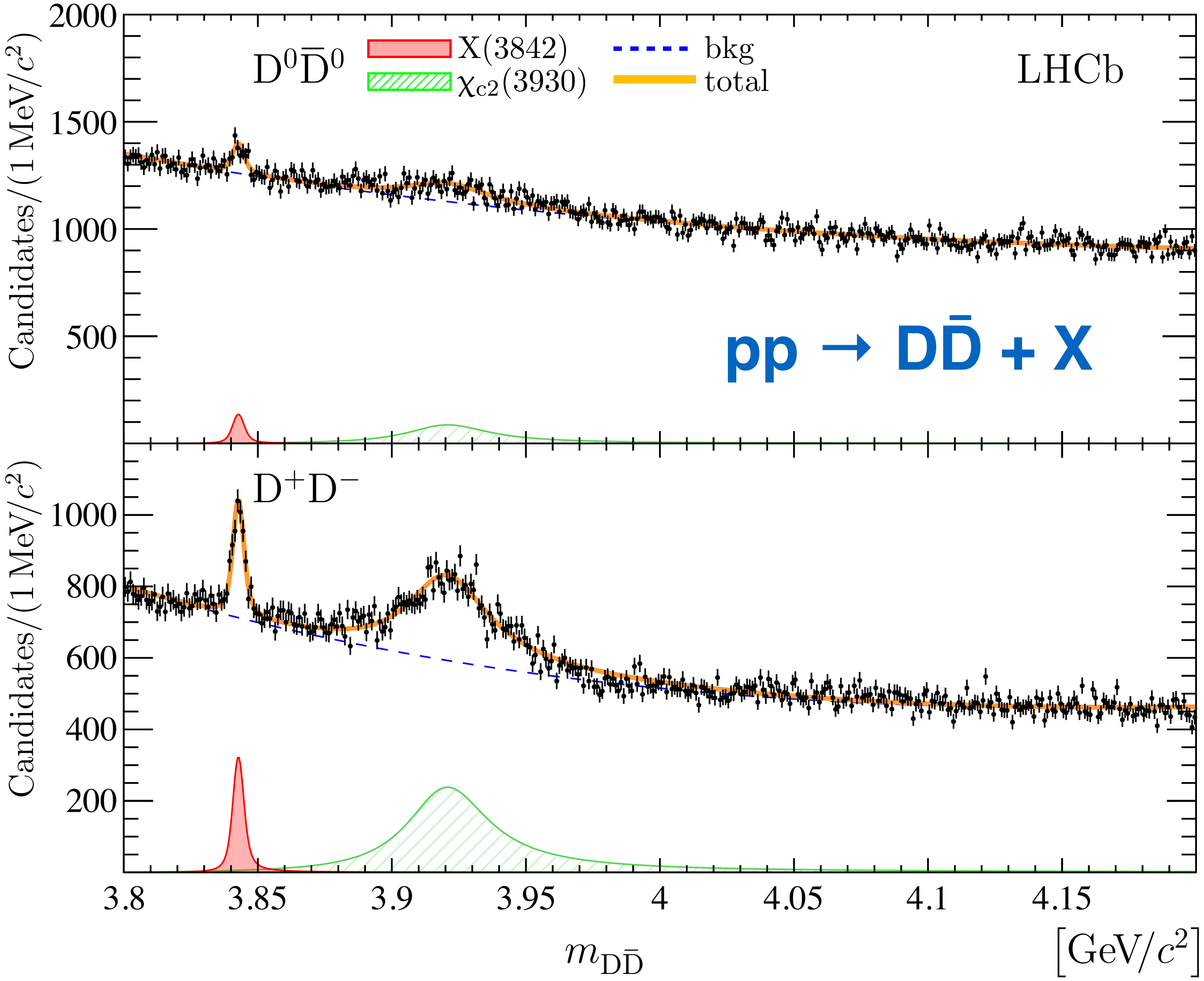
M = 3824.08 ± 0.55 MeV, Γ < 6.6 MeV

- Spin-parity should be measured, note $\gamma\chi_{c2}$ decay 4-5x smaller

Higher-spin D-wave States: $\psi_3(1^3D_3)$

- $\psi_3(1^3D_3)$ expected to be narrow, little phase space to $D\bar{D}$
  expected width ~ 1 MeV, $B(\psi_3 \to \gamma\chi_{c2})$ ~ 30–50%

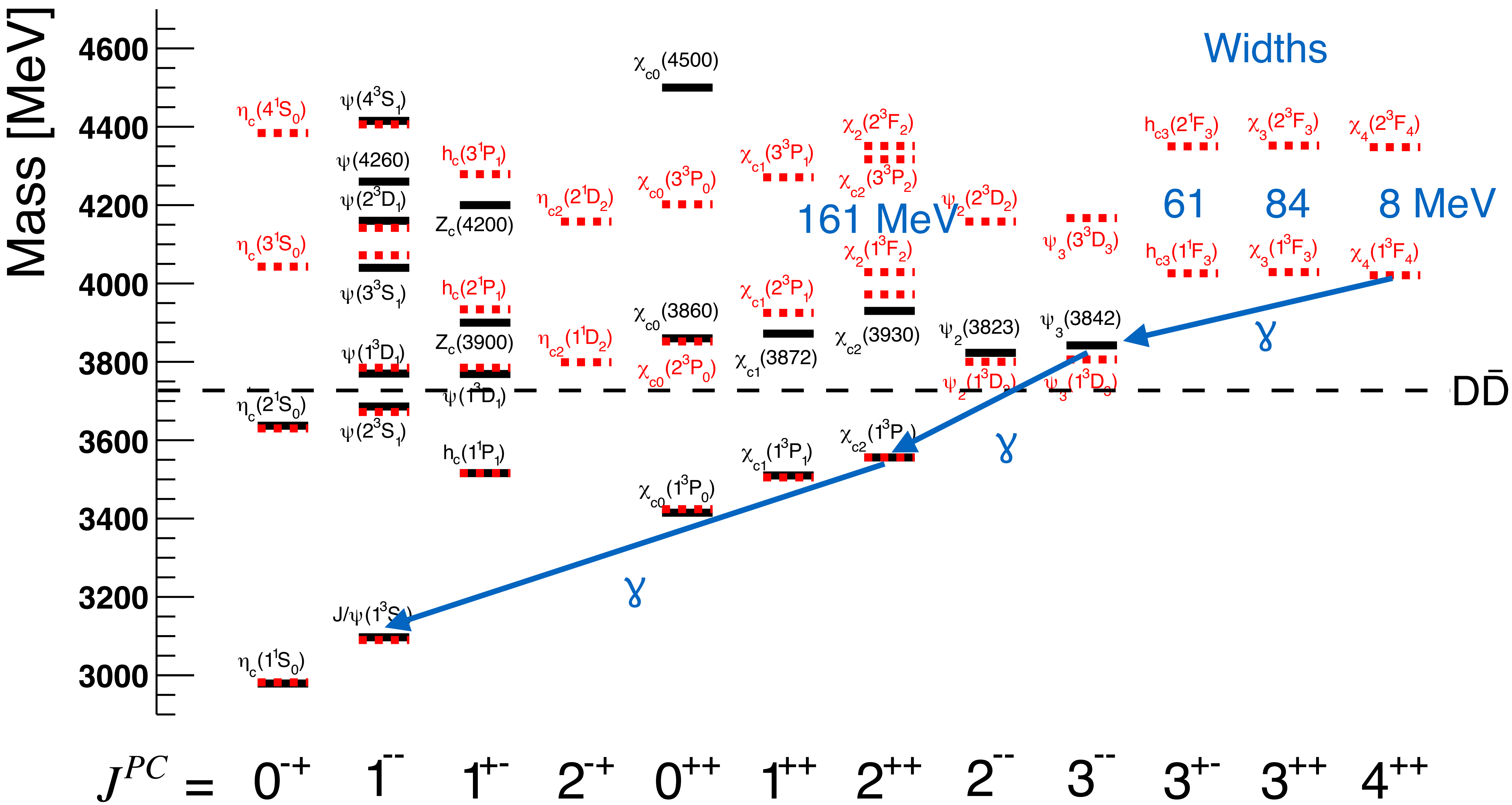
LHCb: JHEP 07, 035 (2019)



M = 3842.71 ± 0.20 MeV
Γ = 2.8 ± 0.6 MeV

- What is sensitivity at PANDA?
- Plan: Look for
  $p\bar{p} \to \psi_{2,3} \to \chi_{c1,2}\gamma$
  $\to (J/\psi\gamma)\gamma \to e^+e^-\gamma\gamma$
  - First, determine event selections
  - Then test angular distribution fitter
- Needs to be confirmed, spin-parity measured

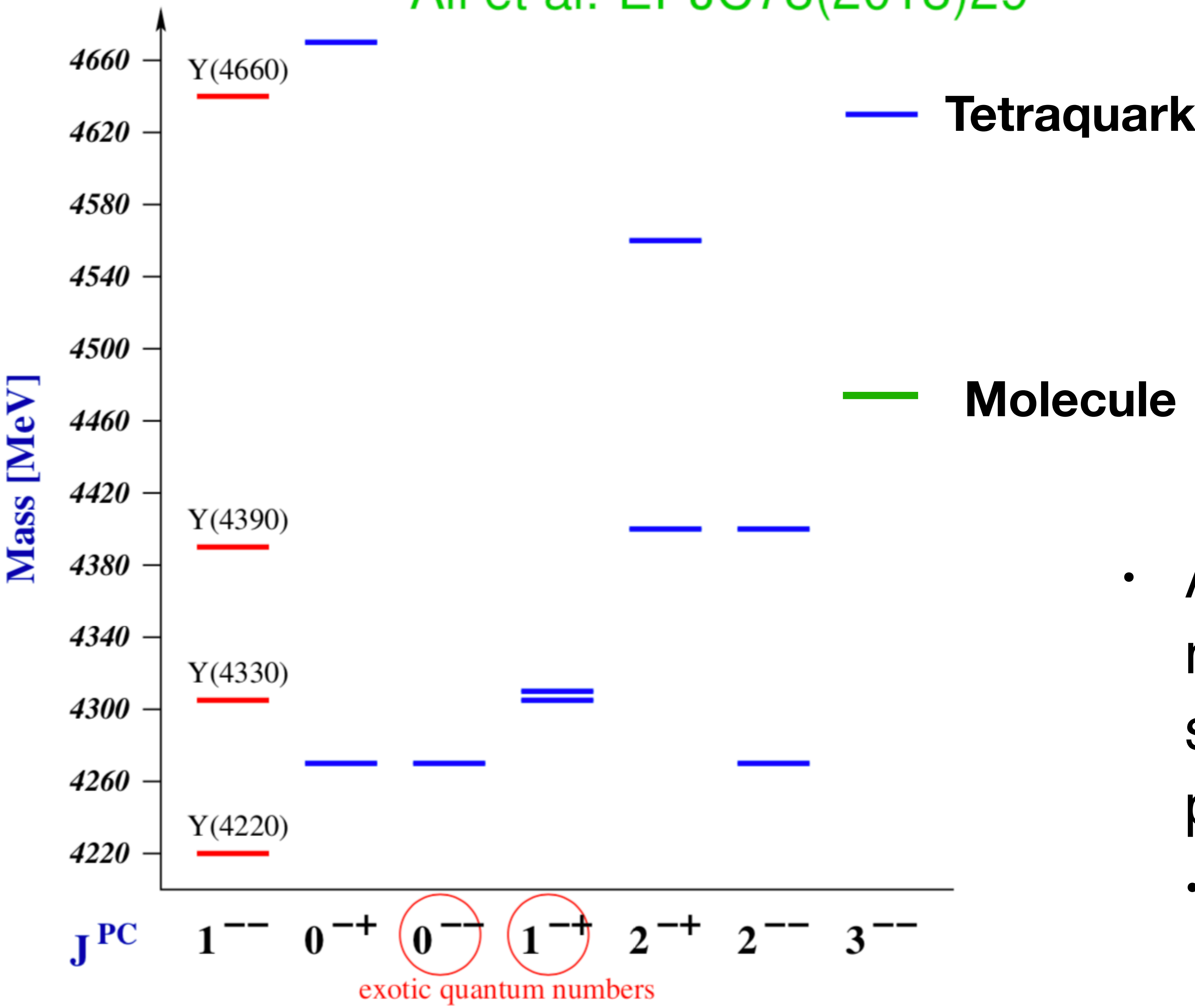
The Charmonium Spectrum: Higher-Spin States



- F- and G-wave states push our understanding of the cc̄ potential
- Most are wide, $\chi_{c4}(1^3F_4)$ is predicted to be narrow, possible to see in radiative cascade decay

High-Spin Exotic States

Ali et al. EPJC78(2018)29

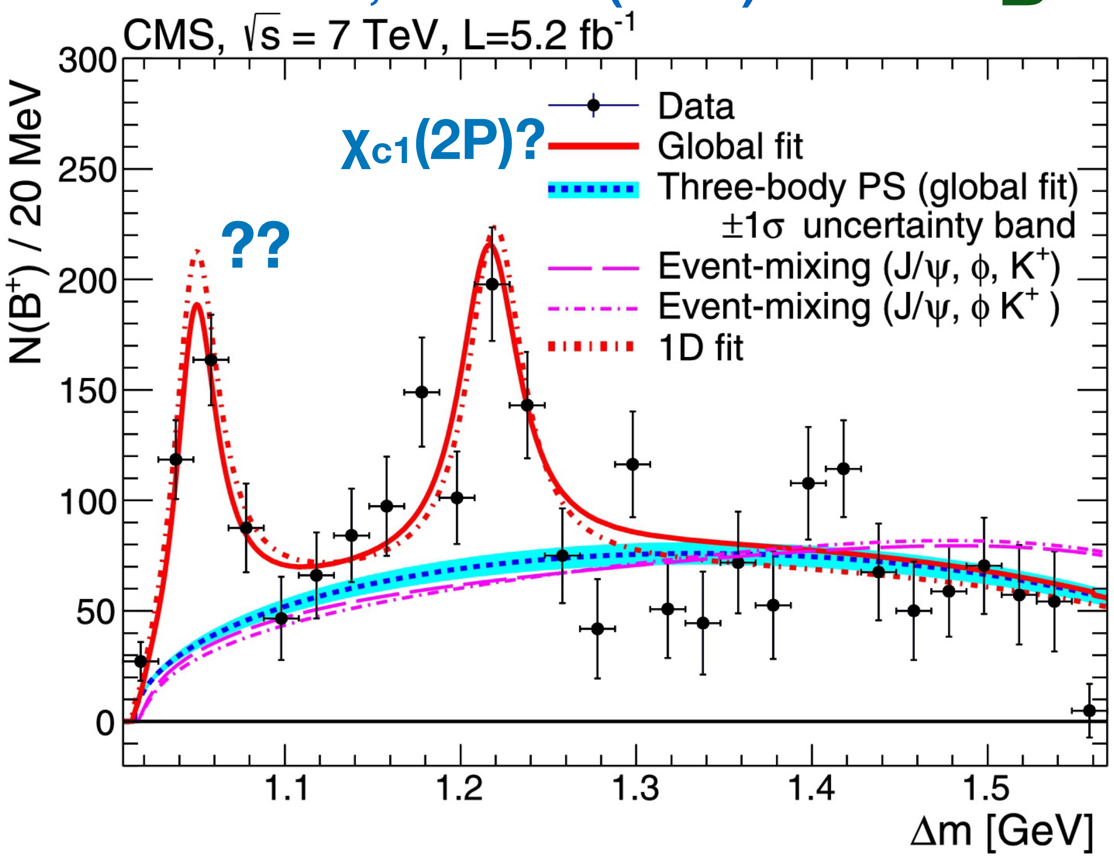


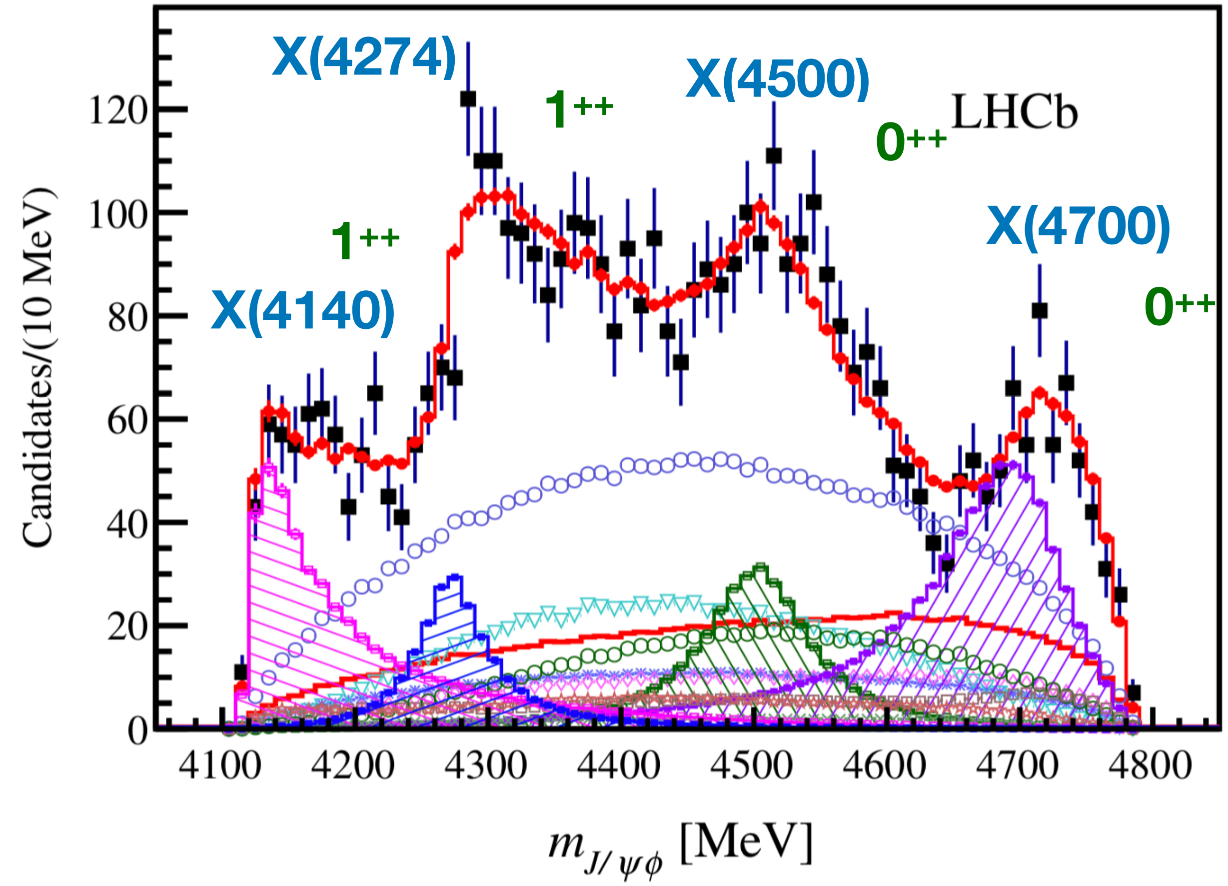
- At high spin, some models for exotic states give divergent predictions
  - Important test!

The Charmonium Spectrum: $J/\psi\phi$ Final States

- Heavier states may couple more strongly to $J/\psi\phi$ ($D_s D_s$ state?)
- LHCb amplitude analysis finds contributions from 4 (!) states

CMS: PLB, 734 261 (2014) **$B^+ \to K^+ J/\psi\ \phi$** **LHCb: PLB, PRL 118 022003 (2017)**





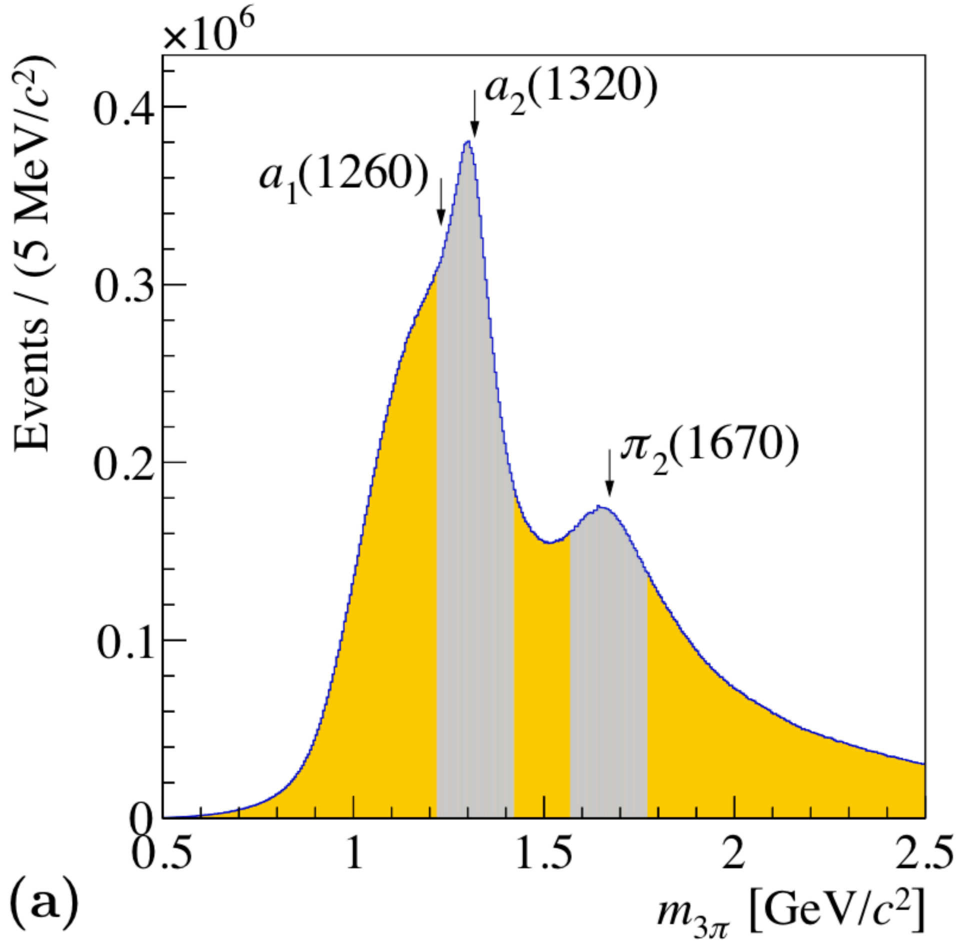
$M = 4148.0 \pm 6.7$ MeV
$\Gamma = 28 \pm 24$ MeV

2 1^{++} and 2 0^{++} states

- Study expected S/B at PANDA, think about optimizing scans over wide energy range

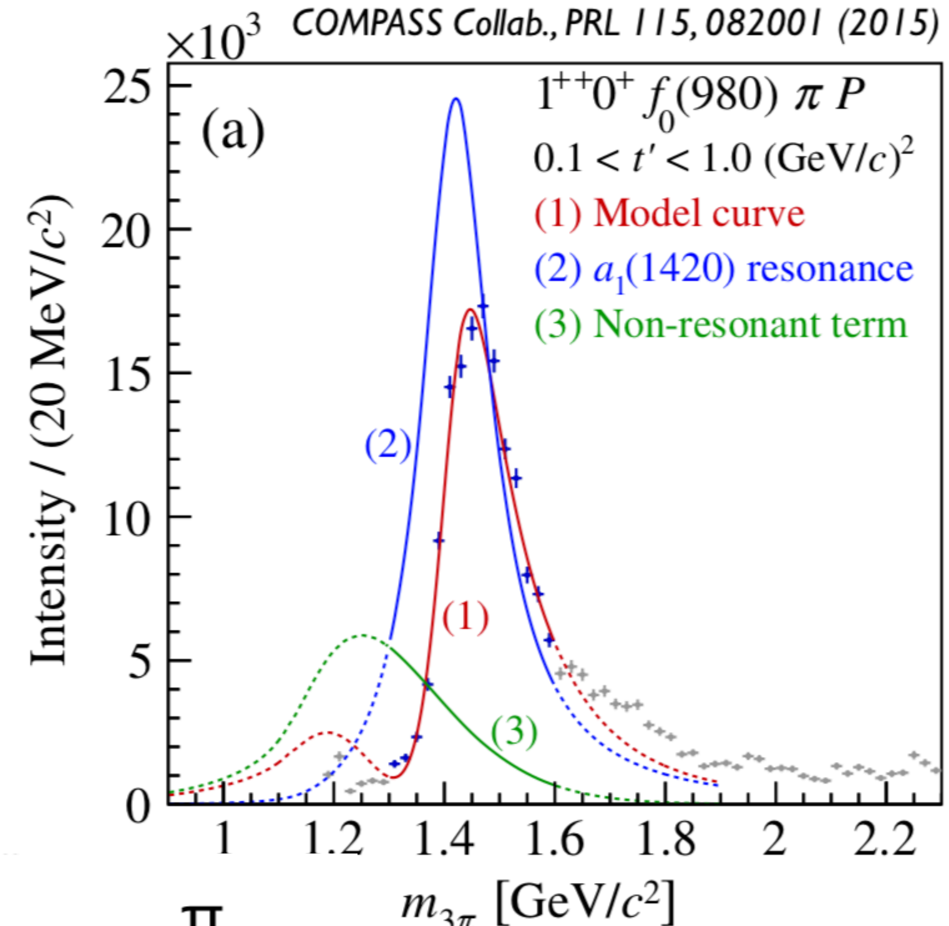
Why is searching for states in $p\bar{p}$ important?

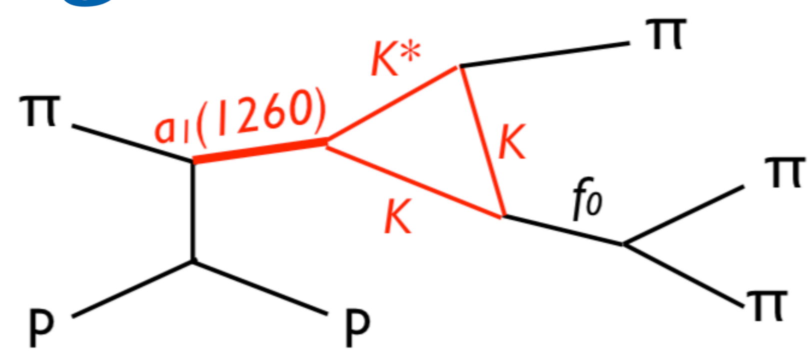
50M $\pi^-\pi^-\pi^+$ events



PRD 95, 032004 (2017)

$a_1(1420) \rightarrow f_0(980)\,\pi$?





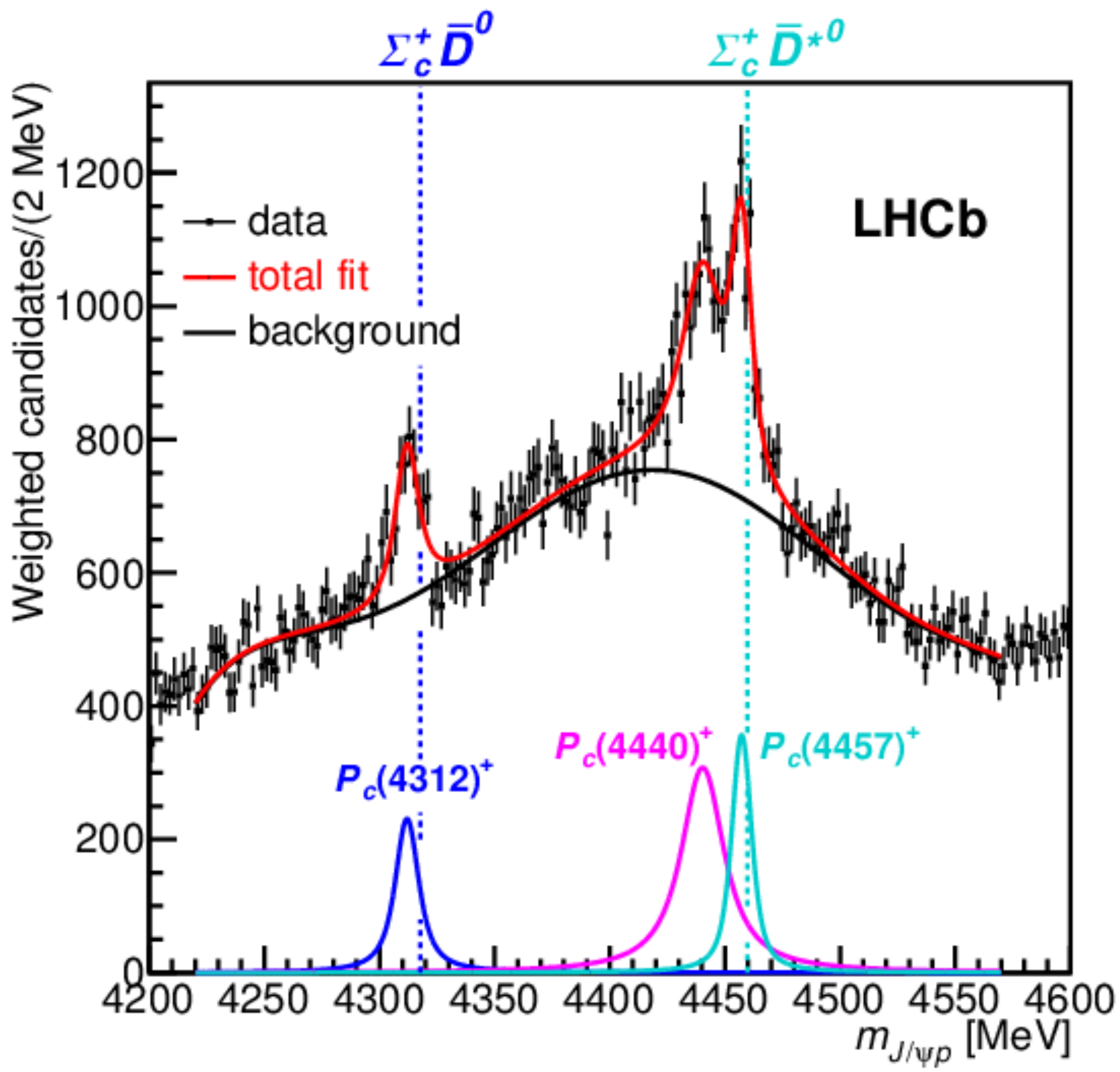
Describe non-$q\bar{q}$ candidate as triangle singularity

arXiv:2006.05342

- Many charmonium-like states have been seen in decay, with constrained kinematics

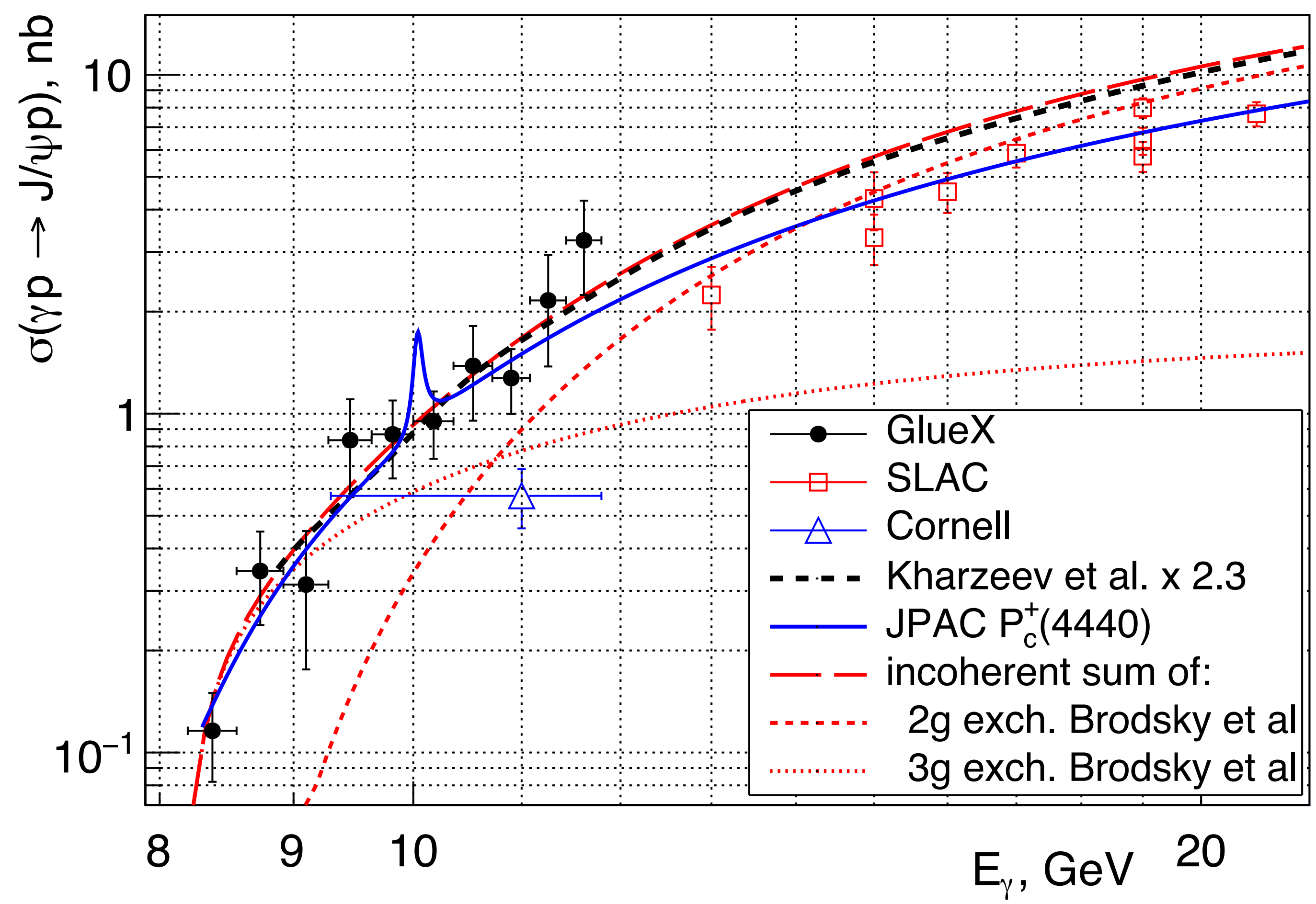
Why is searching for states in $p\bar{p}$ important?

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



LHCb, PRL 122, 222001 (2019)

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



GlueX: PRL 123, 072001 (2019)

- Rescattering and other kinematic effects ("triangle singularities) have been suggested as source of Z_c's among others

Summary

- PANDA has clear advantages in searching for high mass charmonium(-like) states
  - Formation in $p\bar{p}$ annihilation
  - Excellent PID
  - EM final states
- Plan to perform sensitivity studies and build analysis tools
  - High spin states and spin-parity determinations
  - Large energy range scans and $J/\psi\phi$
  - Hybrid searches
  - …