

Experimental Challenges in Conventional Charmonium

(a provisional list)

Ryan Mitchell
Indiana University
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Outline

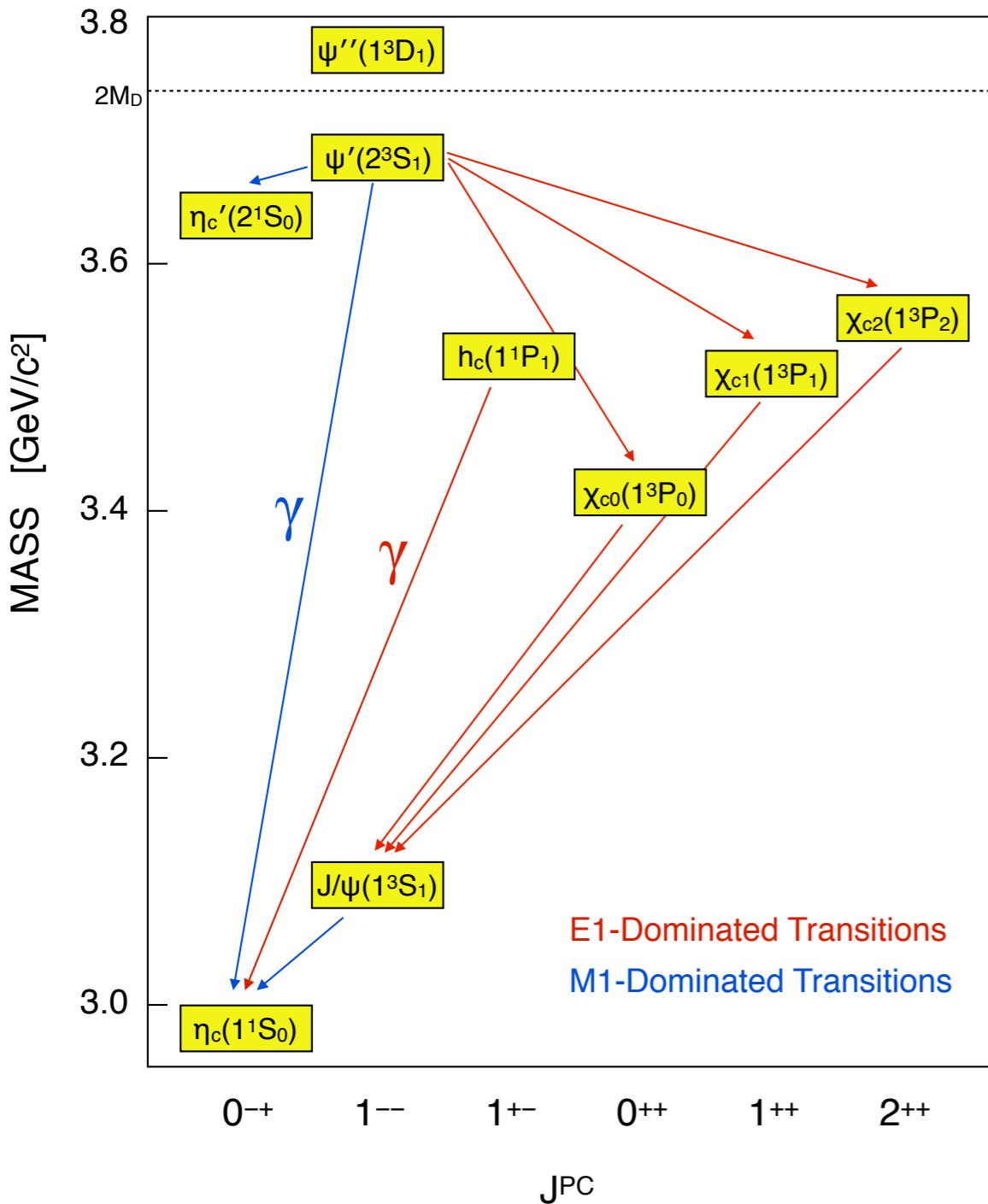
Experimental Challenges in Conventional Charmonium *(a provisional list)*

1. Make precision measurements of radiative transitions.
2. Probe differences between charmonium decays.
3. Untangle the excited ψ states.
4. Establish the $\chi_{cJ}(2P)$ and $h_c(2P)$ states.
5. Confirm the 3D_J states.

Plus a few notes on future prospects.

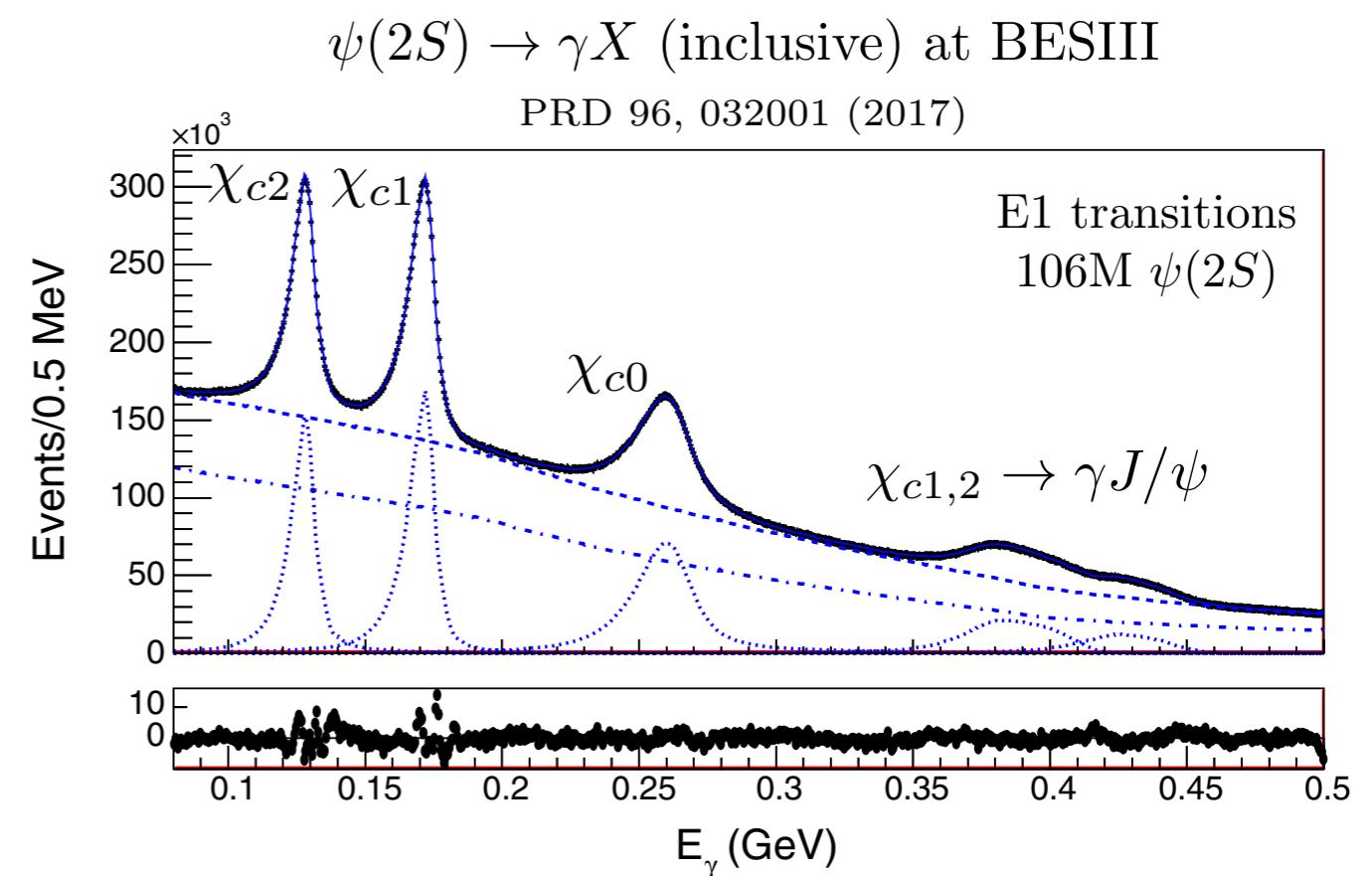
1. Make precision measurements of radiative transitions.

Radiative transitions are sensitive probes of meson wave functions.



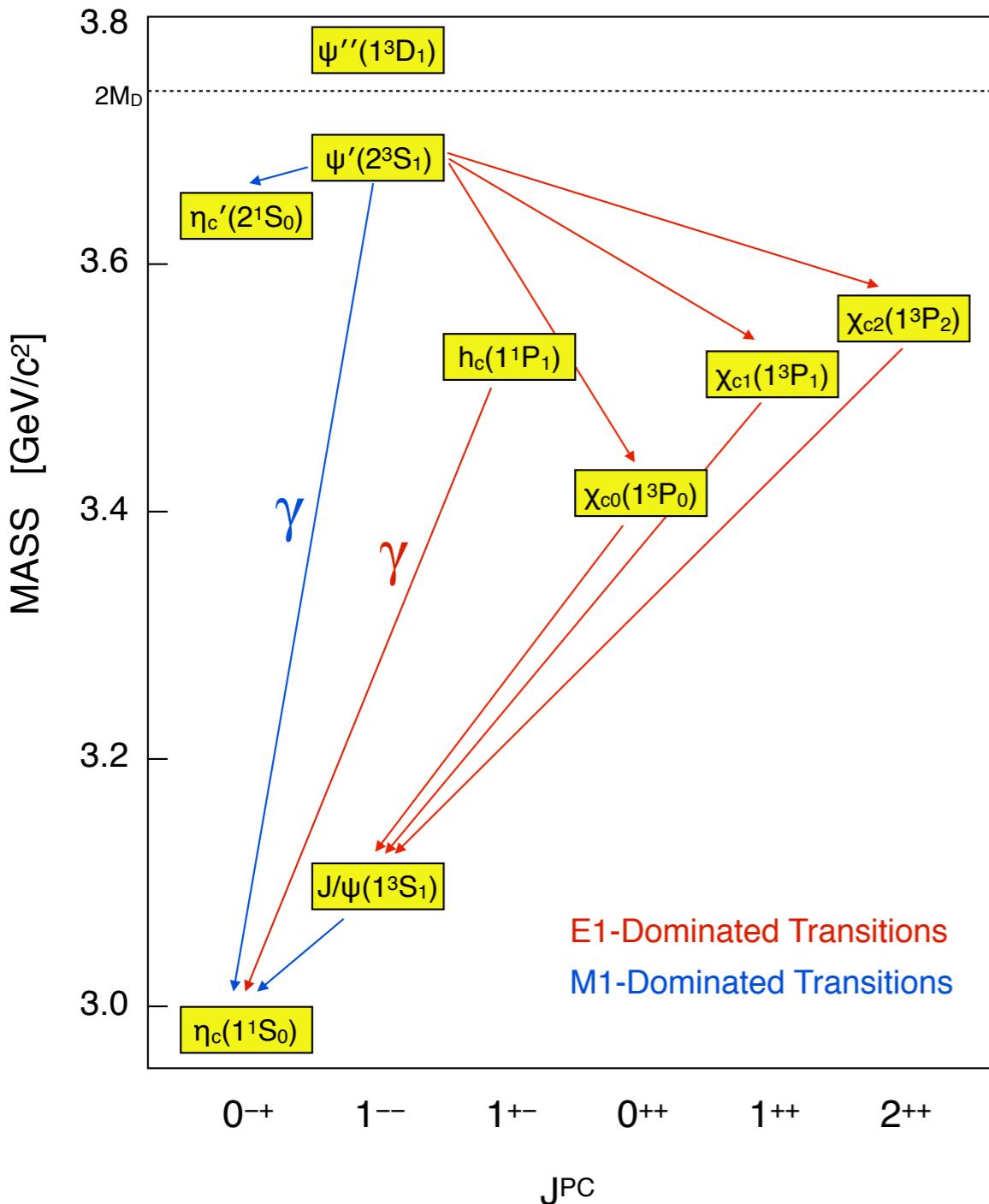
Absolute branching fractions require inclusive measurements.

Measurements are systematics limited [O(3%)] due to signal and background shapes.

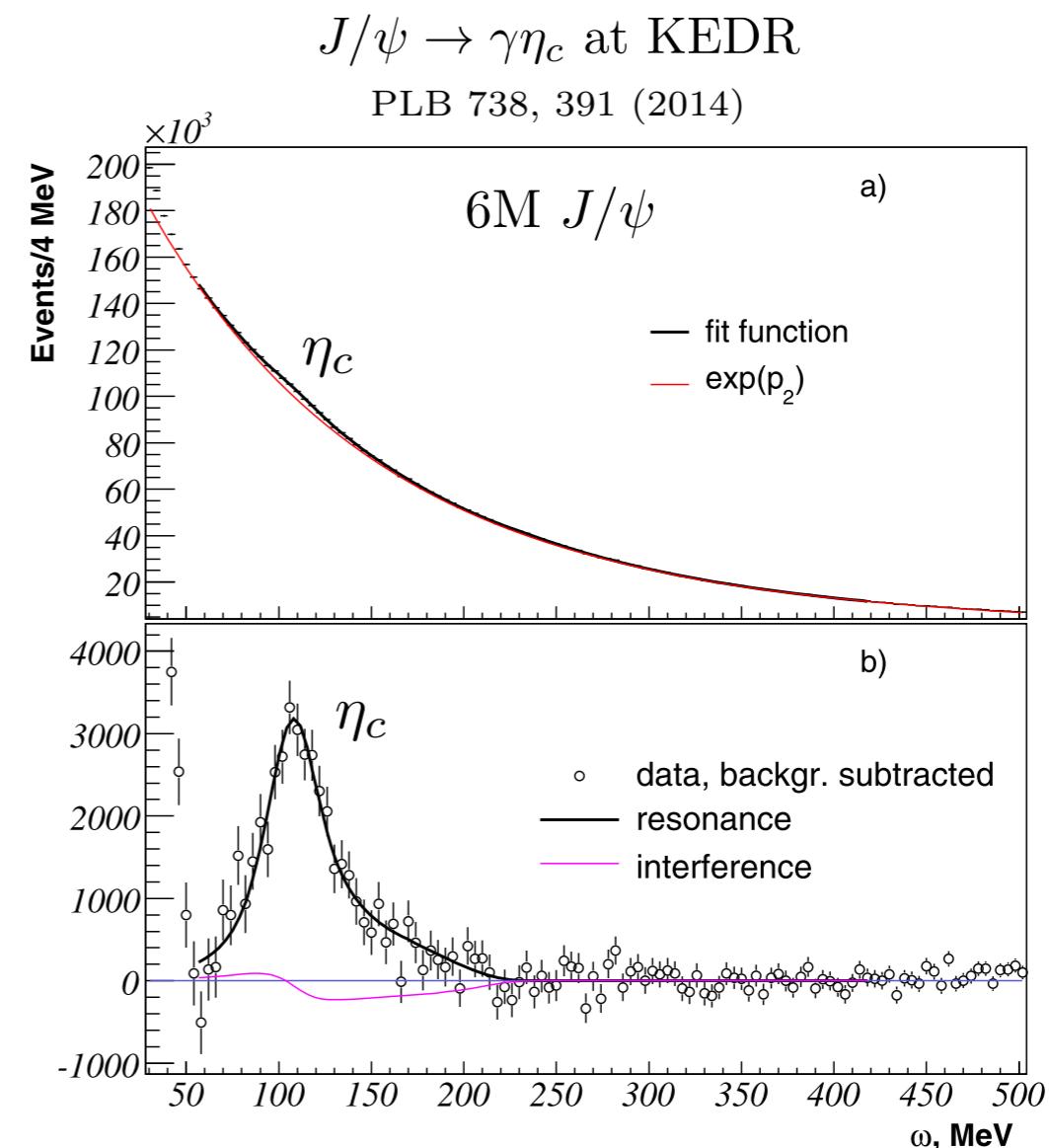


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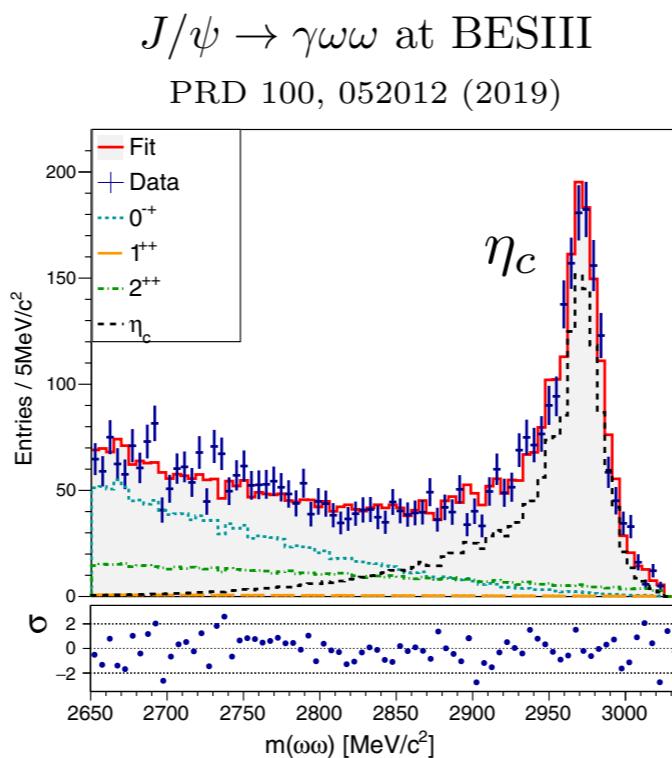
M1 transitions to the η_c are even harder.



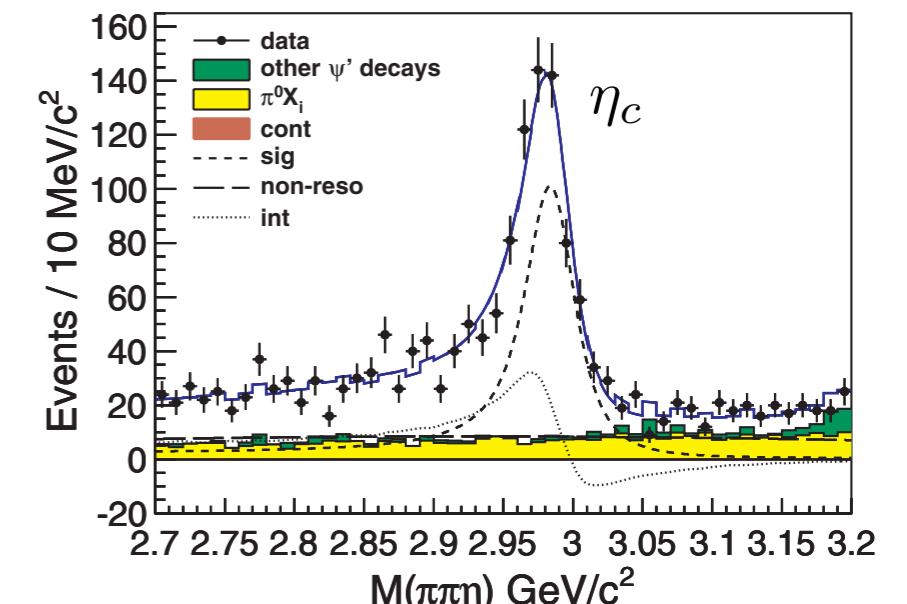
Systematic uncertainties are O(10%).

1. Make precision measurements of radiative transitions.

Exclusive radiative transitions can help better constrain the η_c shape.

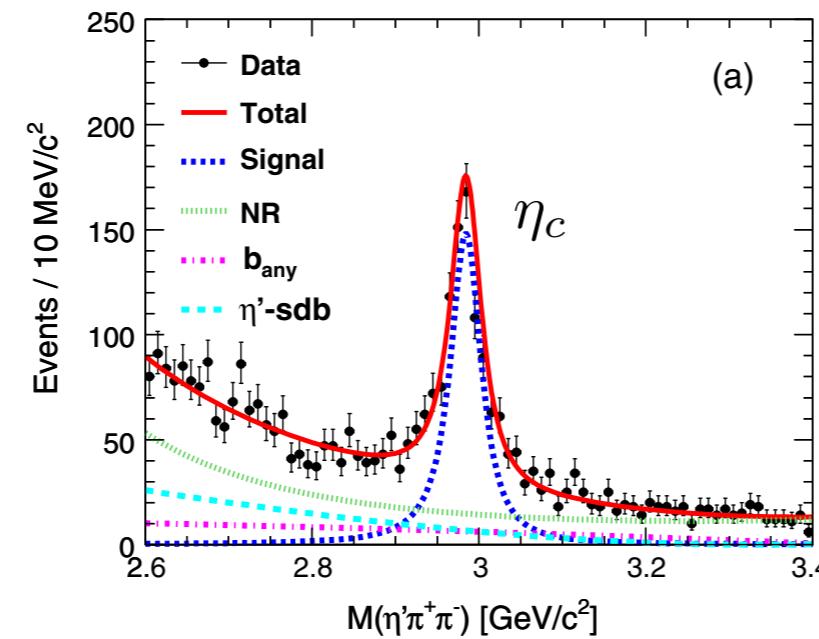


$\psi(2S) \rightarrow \gamma\eta\pi^+\pi^-$ at BESIII
PRL 108, 222002 (2012)

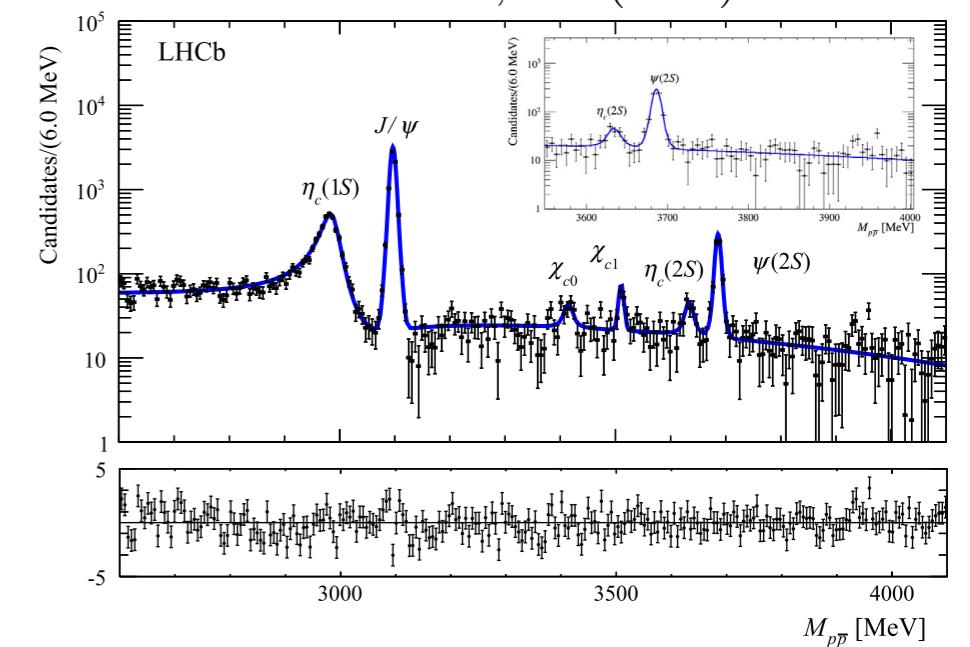


$\gamma\gamma \rightarrow \eta'\pi^+\pi^-$ at Belle
PRD 98, 072001 (2018)

And other processes also provide crucial input.



$B^+ \rightarrow p\bar{p}K^+$ at LHCb
PLB 769, 305 (2017)

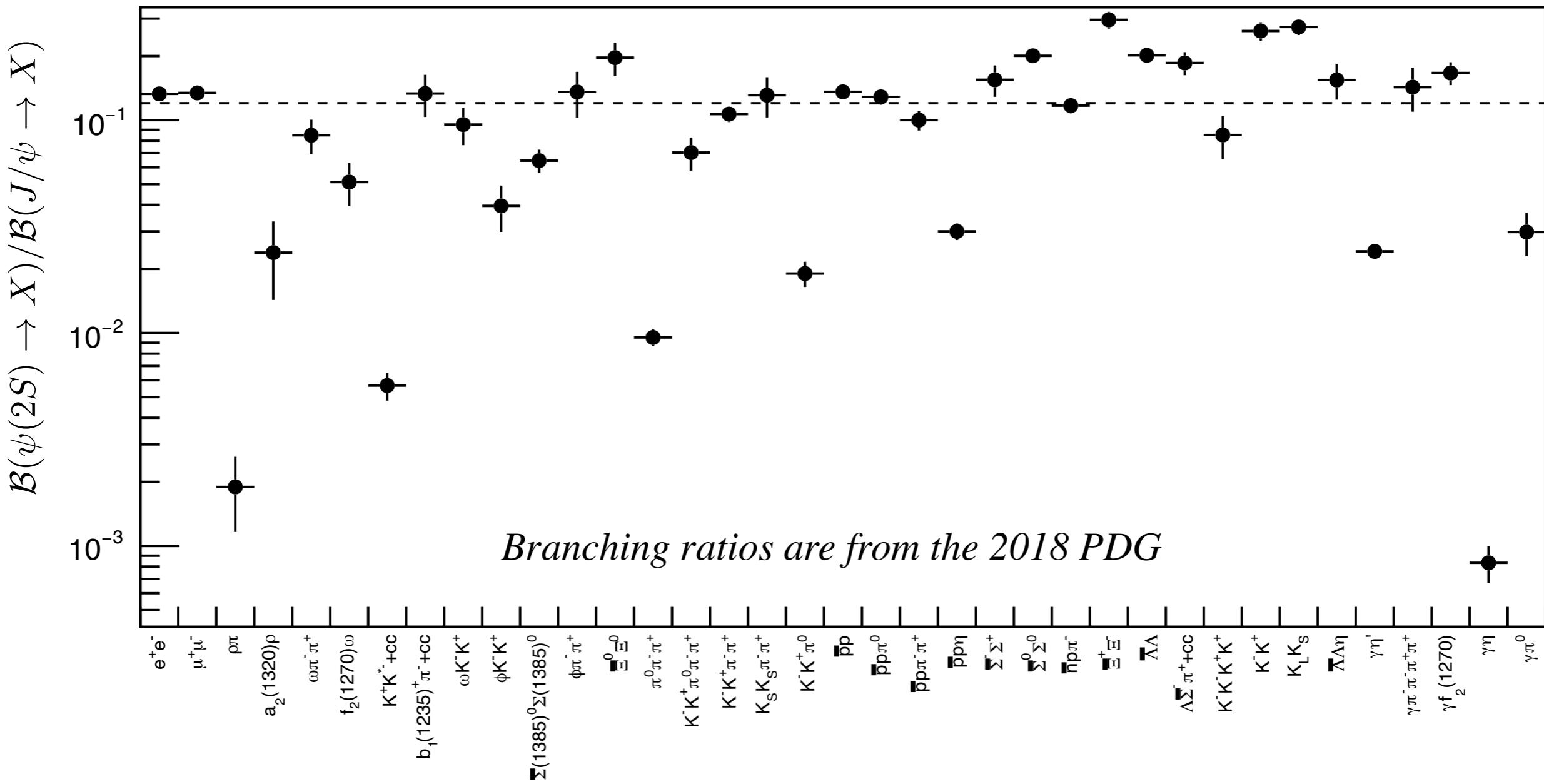


Keep improving our understanding of charmonium states below threshold.

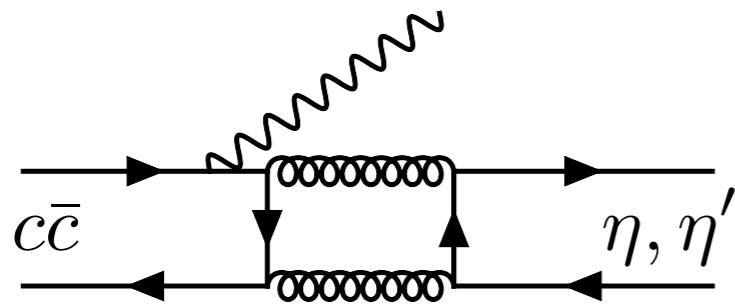
2. Probe differences between charmonium decays.

The “12% Rule”: If the charm quarks of the J/ψ and $\psi(2S)$ annihilate to gluons, and if the hadronization of the gluons is independent of their origin, then:

$$\frac{\mathcal{B}(\psi(2S) \rightarrow X)}{\mathcal{B}(J/\psi \rightarrow X)} \approx 12\%$$



2. Probe differences between charmonium decays.



implies:

$$\frac{\mathcal{B}(J/\psi \rightarrow \gamma\eta)}{\mathcal{B}(J/\psi \rightarrow \gamma\eta')} \approx \frac{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta)}{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta')}$$

but:

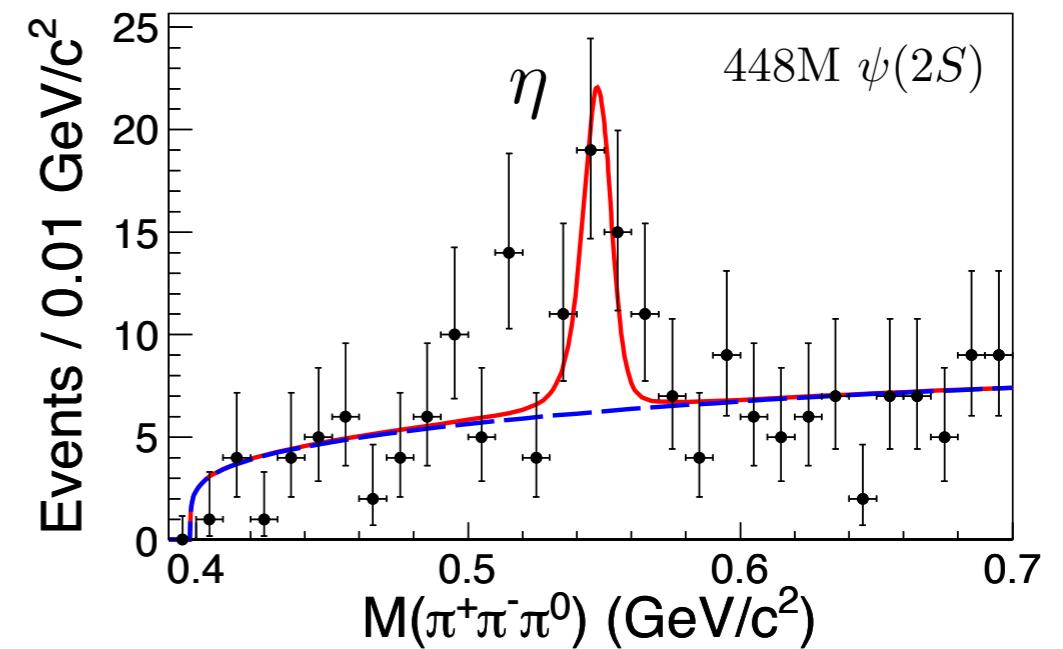
$$\frac{\mathcal{B}(J/\psi \rightarrow \gamma\eta)}{\mathcal{B}(J/\psi \rightarrow \gamma\eta')} = (21.4 \pm 0.9)\%$$

and:

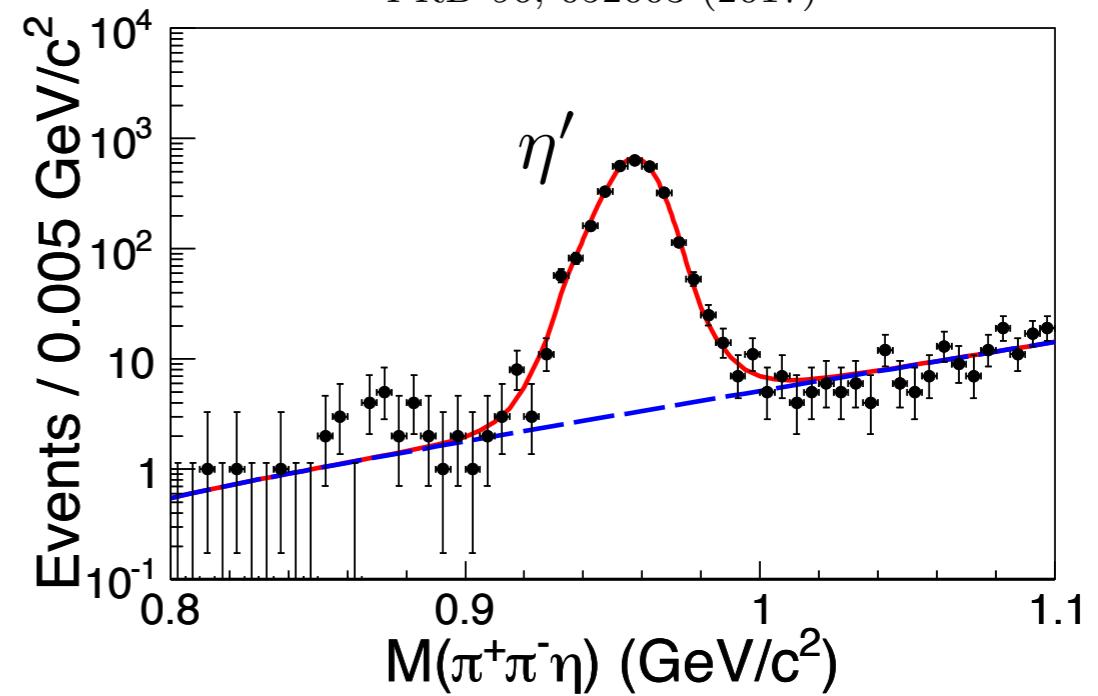
$$\frac{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta)}{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta')} = (0.66 \pm 0.13 \pm 0.02)\%$$

Establish decay patterns in other charmonia beyond the J/ψ and $\psi(2S)$.

$\psi(2S) \rightarrow \gamma\eta$ at BESIII
PRD 96, 052003 (2017)



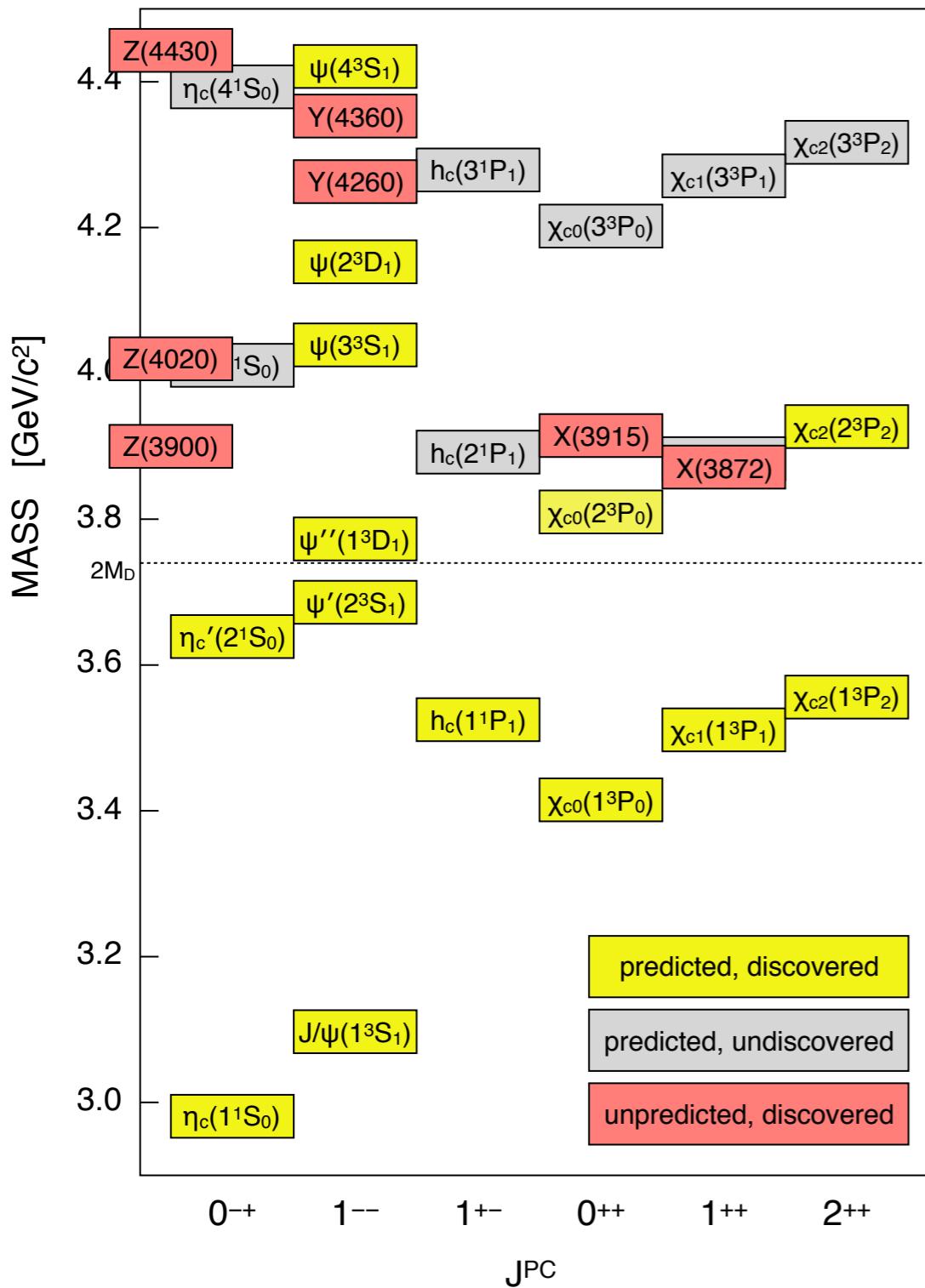
$\psi(2S) \rightarrow \gamma\eta'$ at BESIII
PRD 96, 052003 (2017)



3. Untangle the excited ψ states.

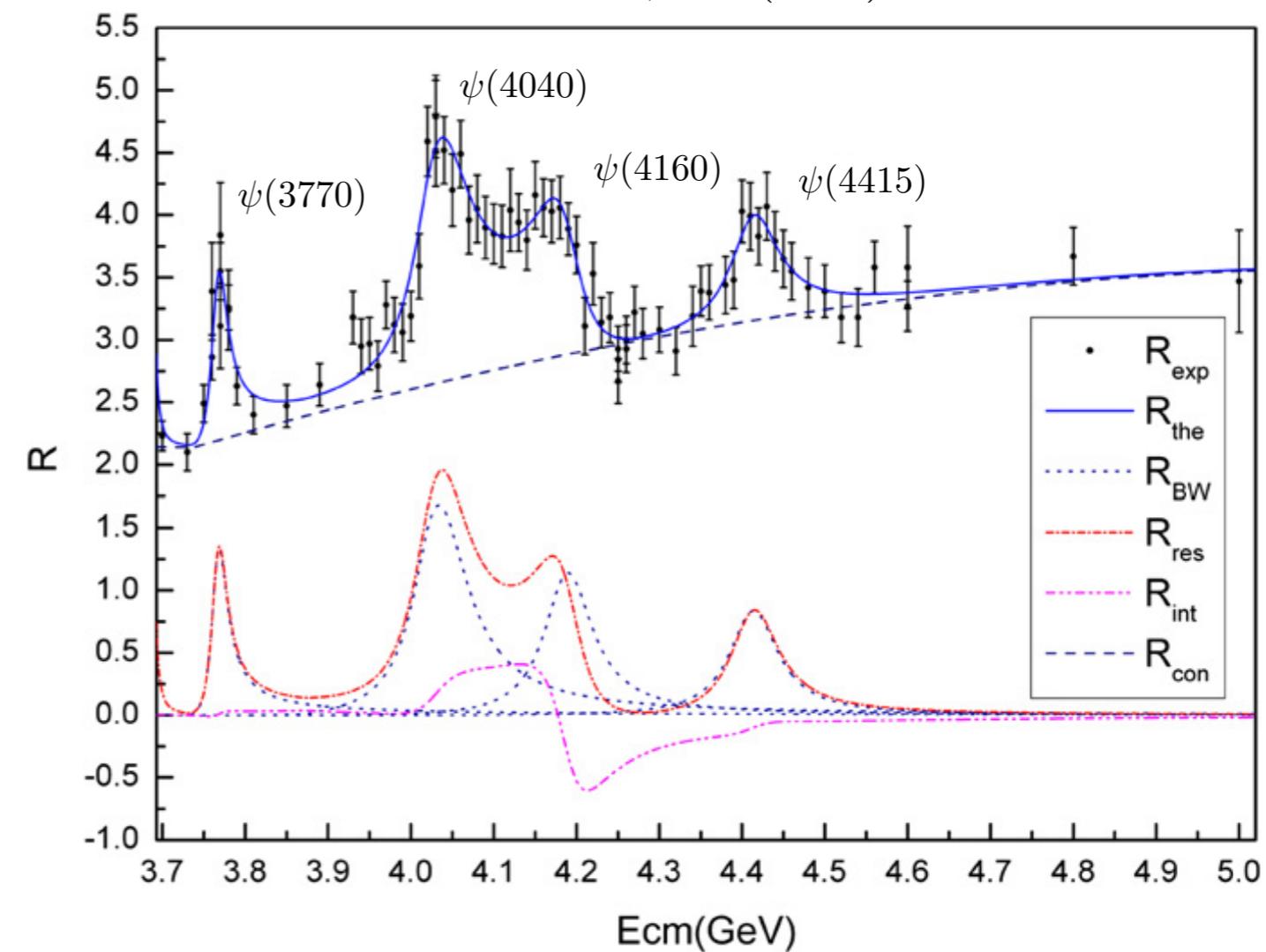
Charmonium Spectrum

*predictions based on PRD 72, 054026 (2005)
measurements from PDG 2018*



$e^+e^- \rightarrow \text{hadrons at BESII}$

PLB 660, 315 (2008)



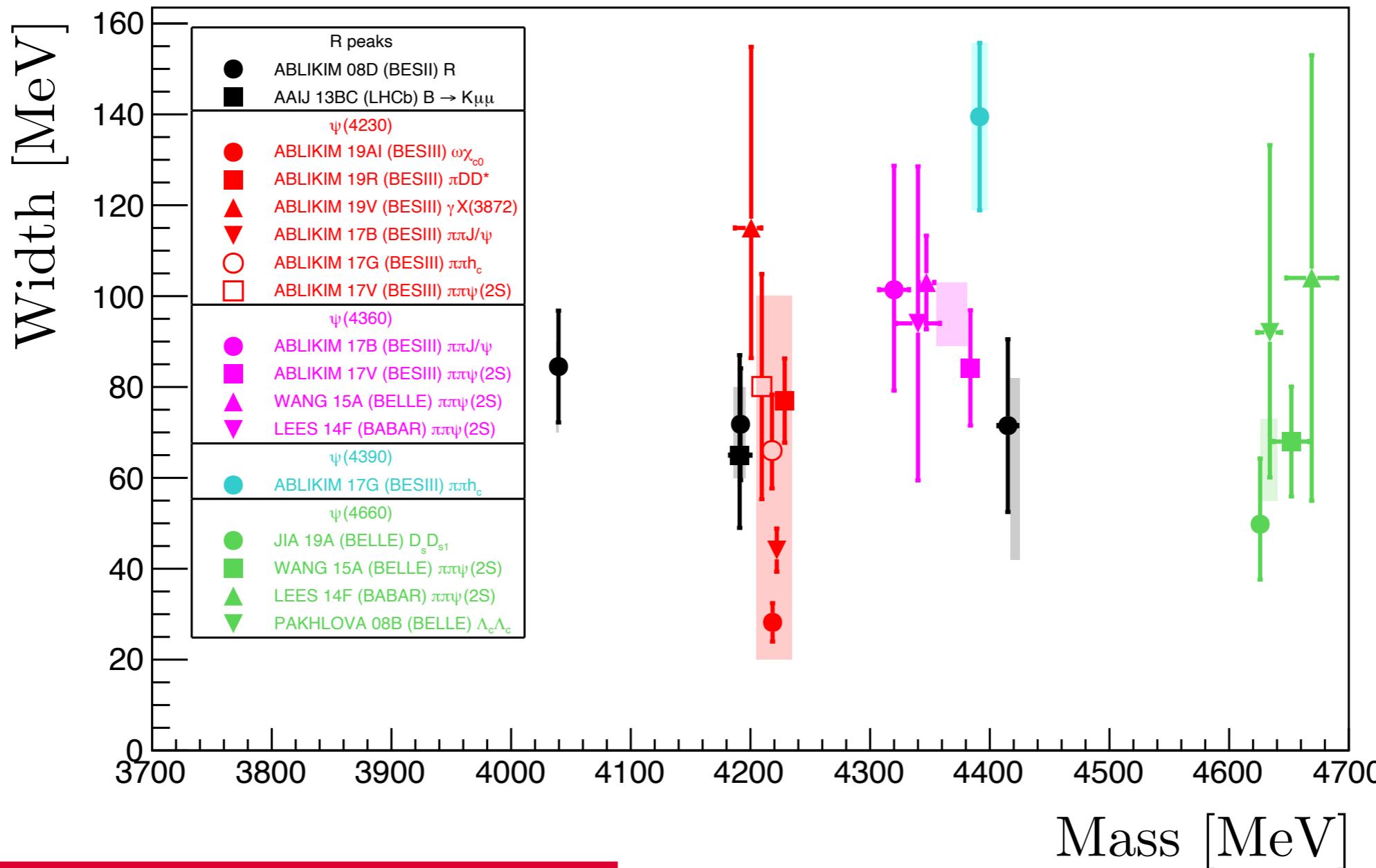
In R , all looks okay with the quark model:

$$\begin{array}{ll} \psi(3770) = 1^3D_1 & \psi(4160) = 2^3D_1 \\ \psi(4040) = 3^3S_1 & \psi(4415) = 4^3S_1 \end{array}$$

3. Untangle the excited ψ states.

In exclusive channels, things become much more complicated...

PDG 2020 ψ States



Measure more open-charm final states
and perform a more global analysis.

4. Establish the $\chi_{cJ}(2P)$ and $h_c(2P)$ states.

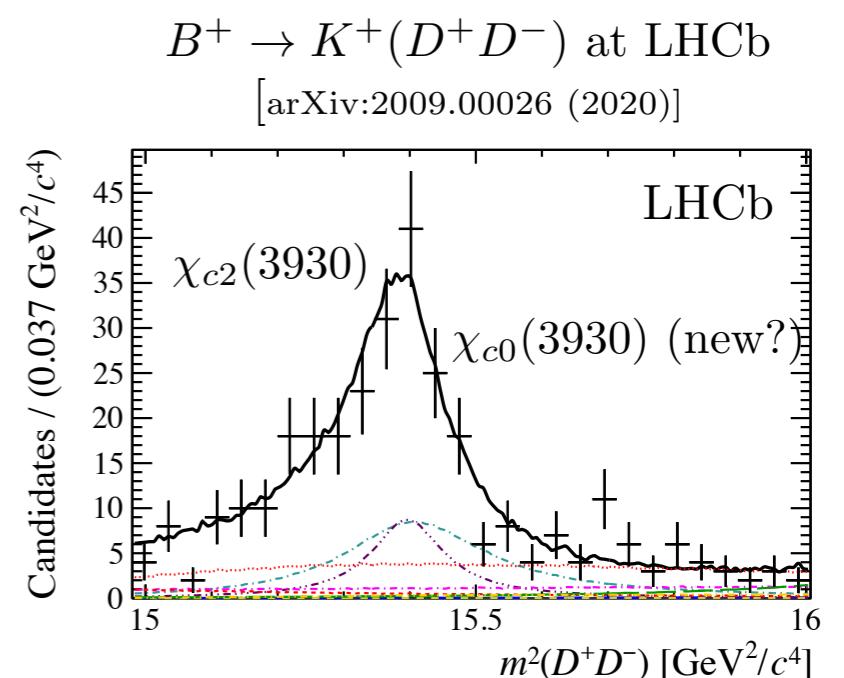
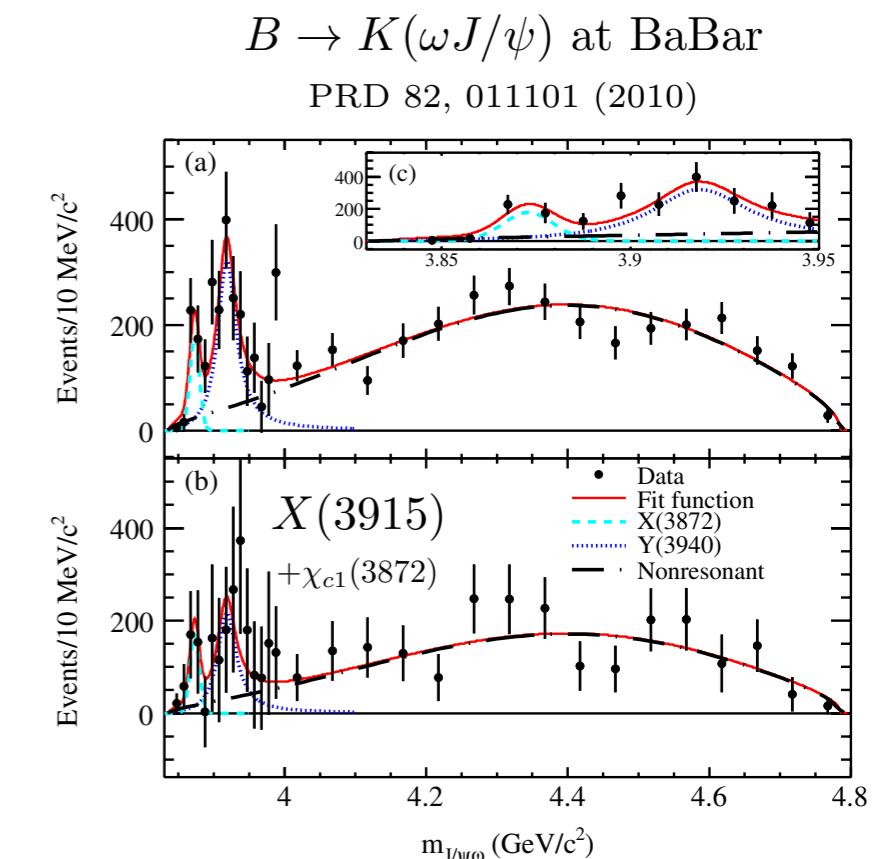
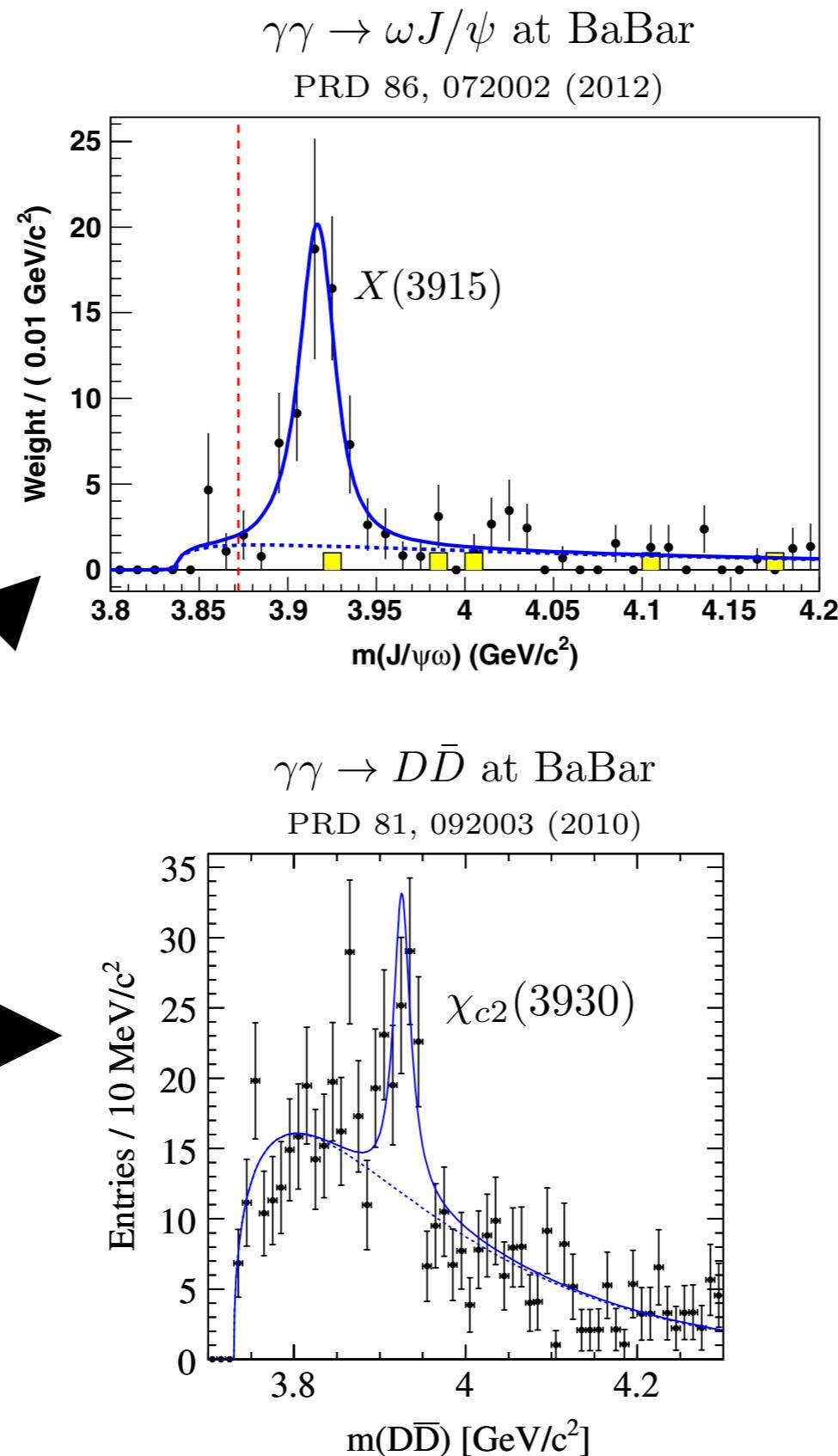
How are the $X(3915)$, $\chi_{c0}(3930)$, and $\chi_{c2}(3930)$ related?

And how do they relate to the $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$?

There's now a "square" of measurements...



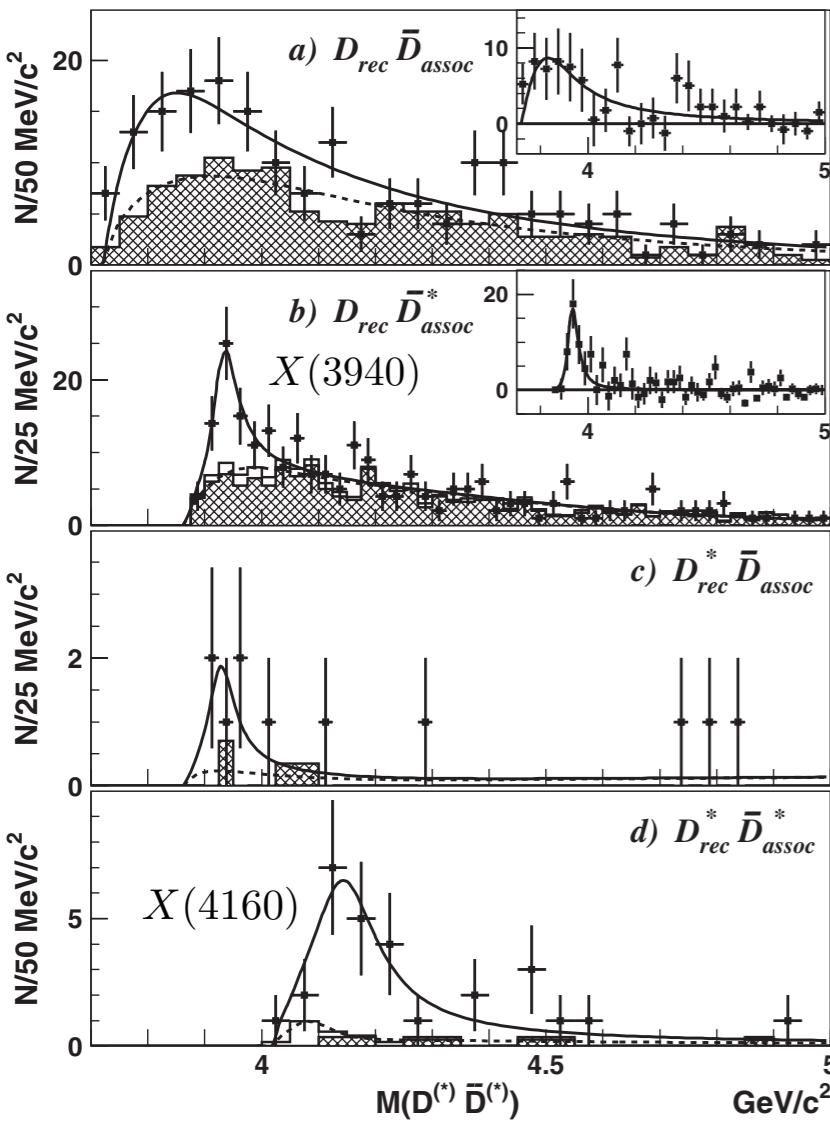
Pinning down these conventional states would help us understand the extra ones, hopefully...



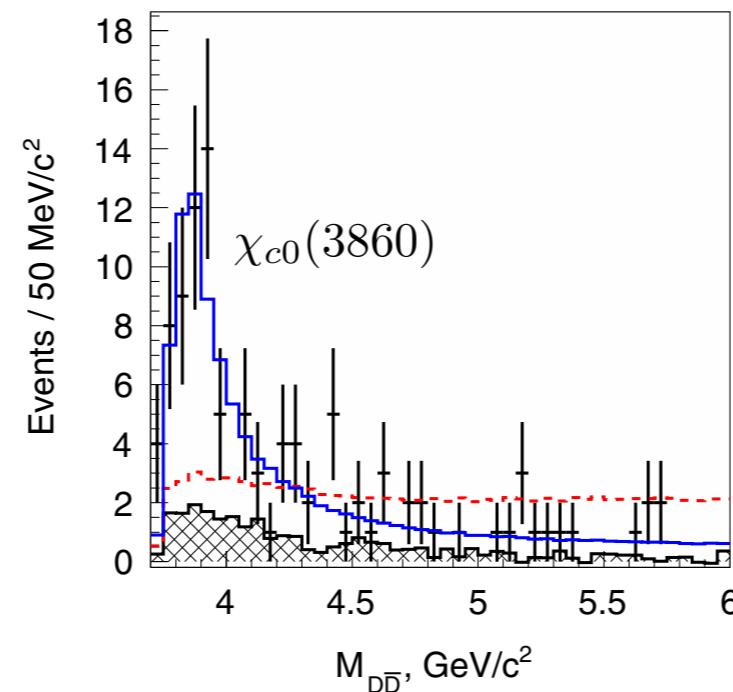
4. Establish the $\chi_{cJ}(2P)$ and $h_c(2P)$ states.

Extra pieces to the 2P puzzle...

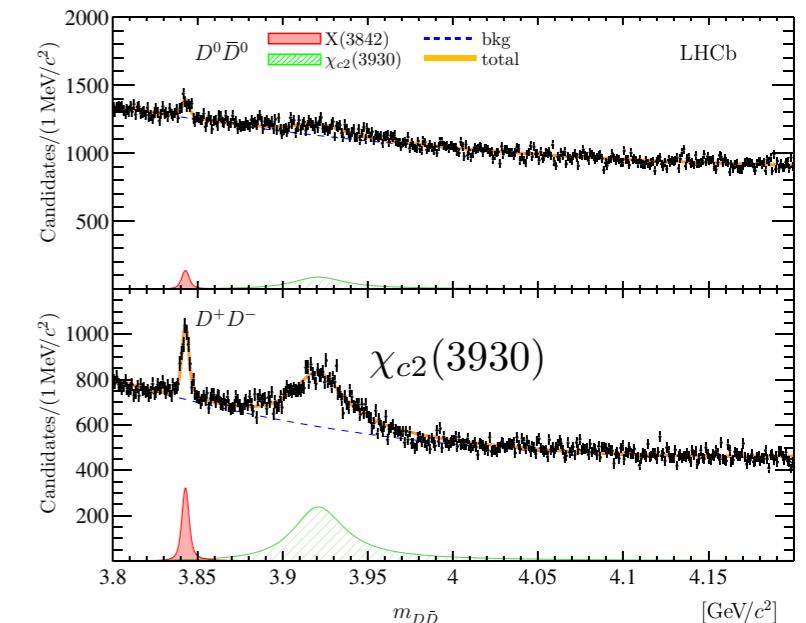
$e^+e^- \rightarrow J/\psi(D^{(*)}\bar{D}^{(*)})$ at Belle
PRL 100, 202001 (2008)



$e^+e^- \rightarrow J/\psi(D\bar{D})$ at Belle
PRD 95, 112003 (2017)



$pp \rightarrow D\bar{D}X$ (inclusive) at LHCb
JHEP 7, 35 (2019)



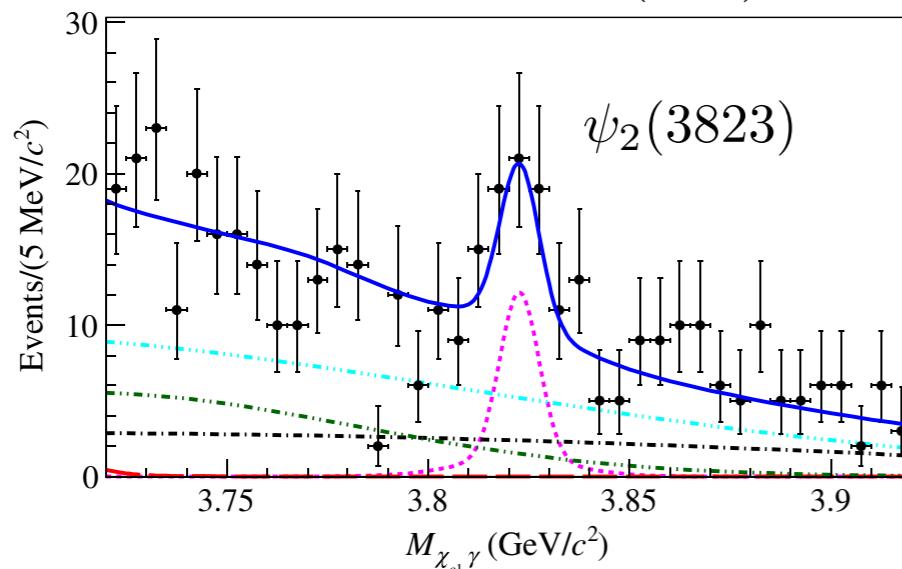
also look for:
 $e^+e^- \rightarrow J/\psi(J/\psi\omega)?$

Study all of these same processes with more data. Connect channels.
Also look for an $h_c(2P)$ candidate.

5. Confirm the 3D_J states.

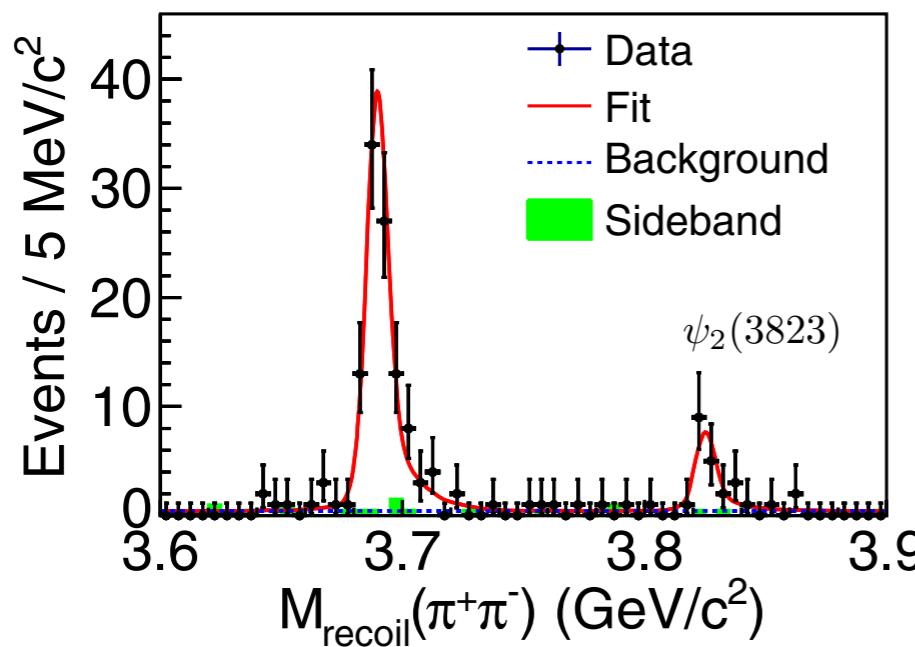
$B \rightarrow (\gamma\chi_{c1})K$ at Belle

PRL 111, 032001 (2013)



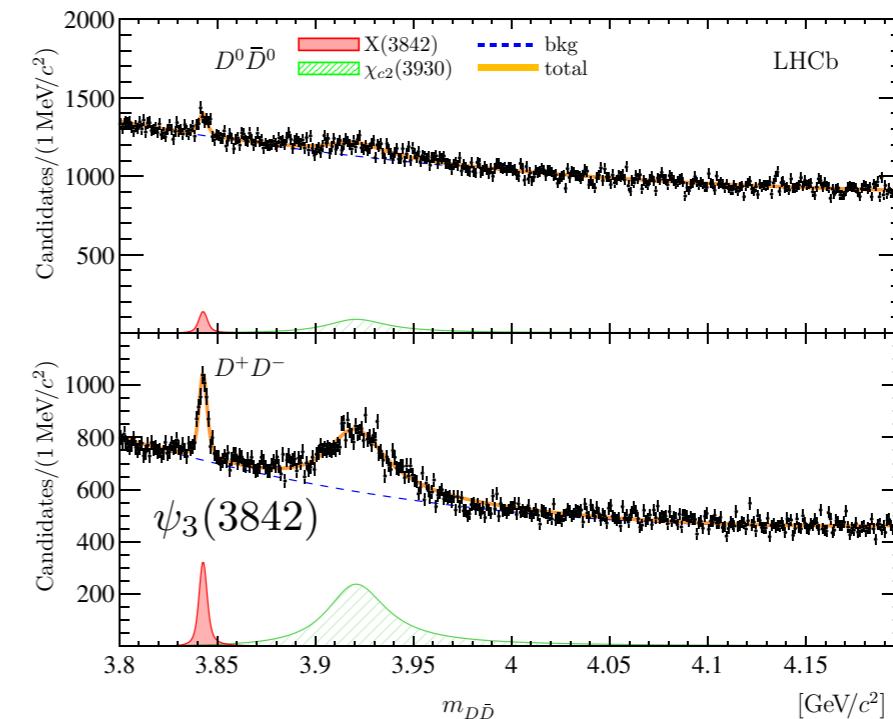
$e^+e^- \rightarrow (\gamma\chi_{c1})\pi^+\pi^-$ at BESIII

PRL 115, 011803 (2015)



$pp \rightarrow D\bar{D}X$ (inclusive) at LHCb

JHEP 7, 35 (2019)



The $\psi_2(1^3D_2)$ and $\psi_3(1^3D_3)$ states
(along with the $\psi(3770) = \psi_1(1^3D_1)$)
look good!

Confirm the 2^{--} and 3^{--} assignments.
Also look for the $\eta_{c2}(1^1D_2)$ partner.

Notes on Future Prospects

BESIII: e^+e^- in the charmonium region (current and future)

- charmonium in $\psi(2S)$ decays ($\times 5$ statistics expected soon)
- charmonium above $D\bar{D}$ threshold (now using energies ≥ 4.6 GeV)
- BEPC3 upgrade (very preliminary) could give $\times 3$ luminosity

Super tau-charm facility (STCF): e^+e^- in the charmonium region (future)

- advanced designs developed in Russia (BINP) and China (USTC)
- luminosity expected to be BESIII $\times 50$

BelleII: e^+e^- in the bottomonium region (just starting)

- expect 50ab^{-1} of data (Belle $\times 50$)
- charmonium in B decays, $\gamma\gamma$ collisions, ISR, against $J/\psi\dots$

LHCb, ATLAS, and CMS: pp at high energy (current and future)

- future upgrades planned (high-luminosity LHC)
- charmonium in B decays, inclusive pp production...

Panda: $p\bar{p}$ in the charmonium region (future)

- $p\bar{p}$ cross sections as interesting as e^+e^- ? Or more interesting?
- measure lineshapes for narrow resonances

EIC: high-energy electron-ion collisions (future)

- photoproduction of conventional and exotic charmonium