Hadron Spectroscopy

Lecture 5 – XYZ, P and T

HUGS - June 2, 2025

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Jefferson Lab

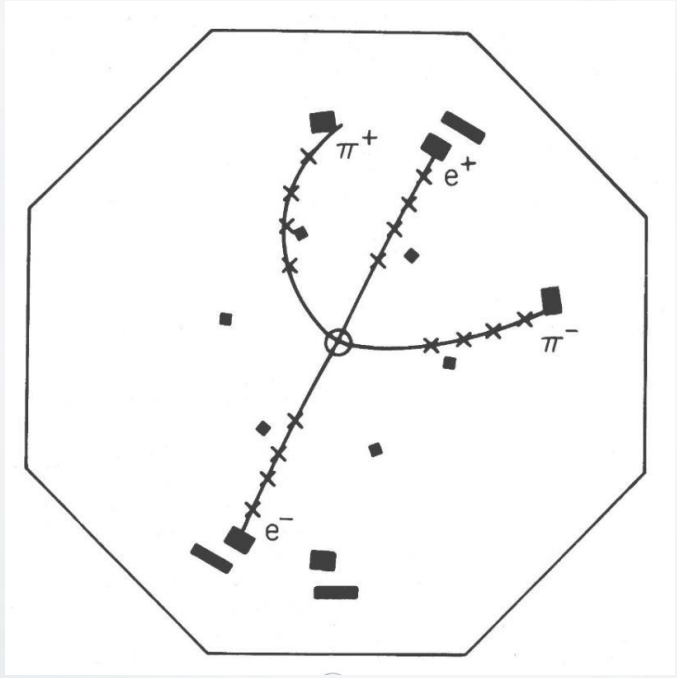
U.S. DEPARTMENT OF ENERGY

Outline

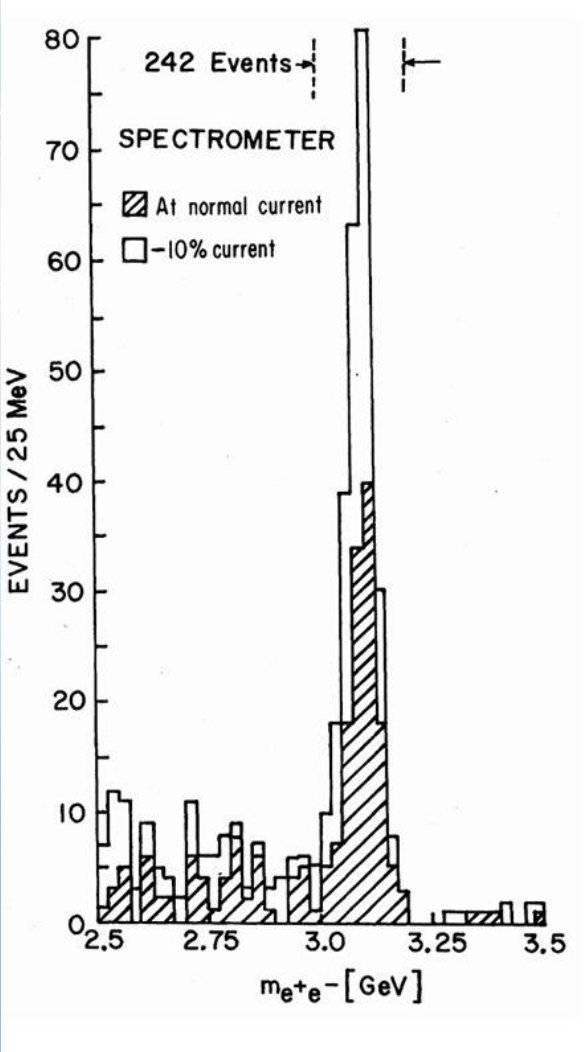
1. November Revolution and Charmonium
2. Unexpected States
3. Measurements of Charmonia at Jefferson Lab

Jefferson Lab

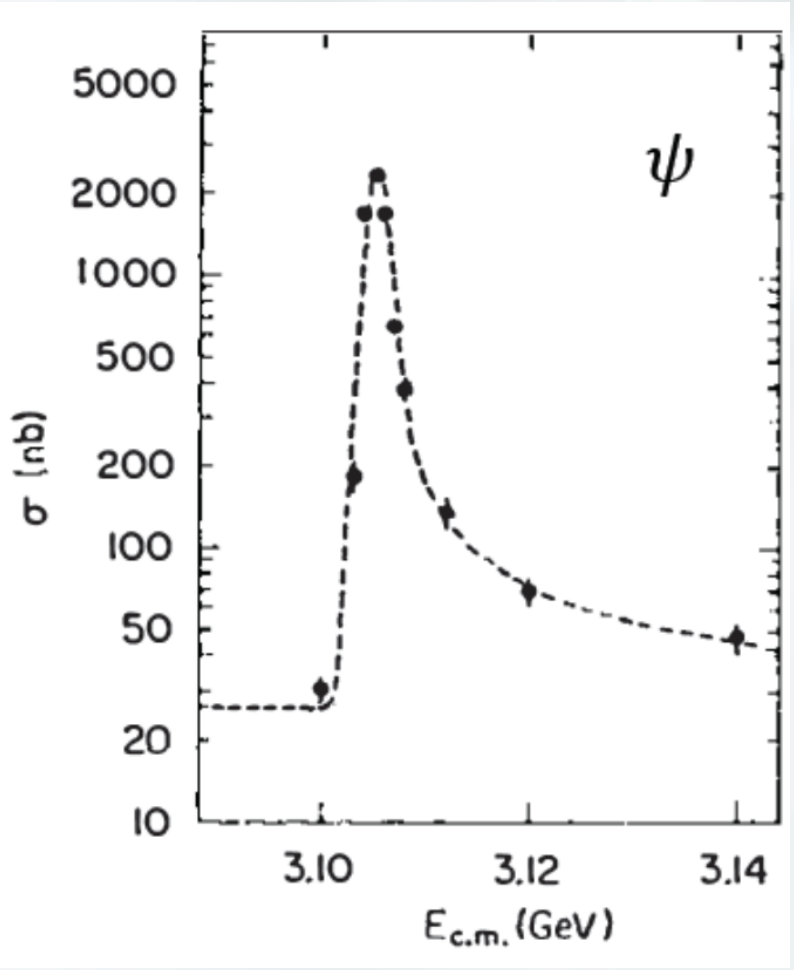
November Revolution



November Revolution (1974)

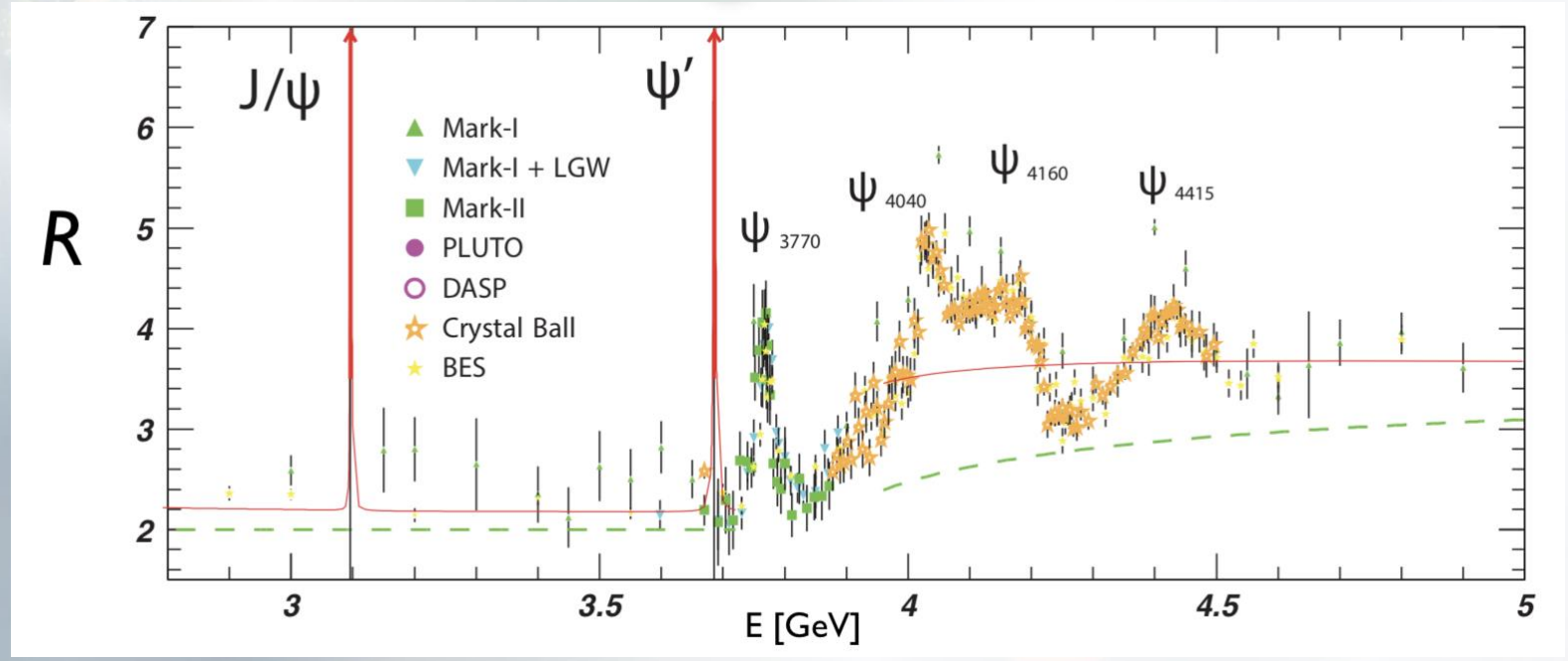


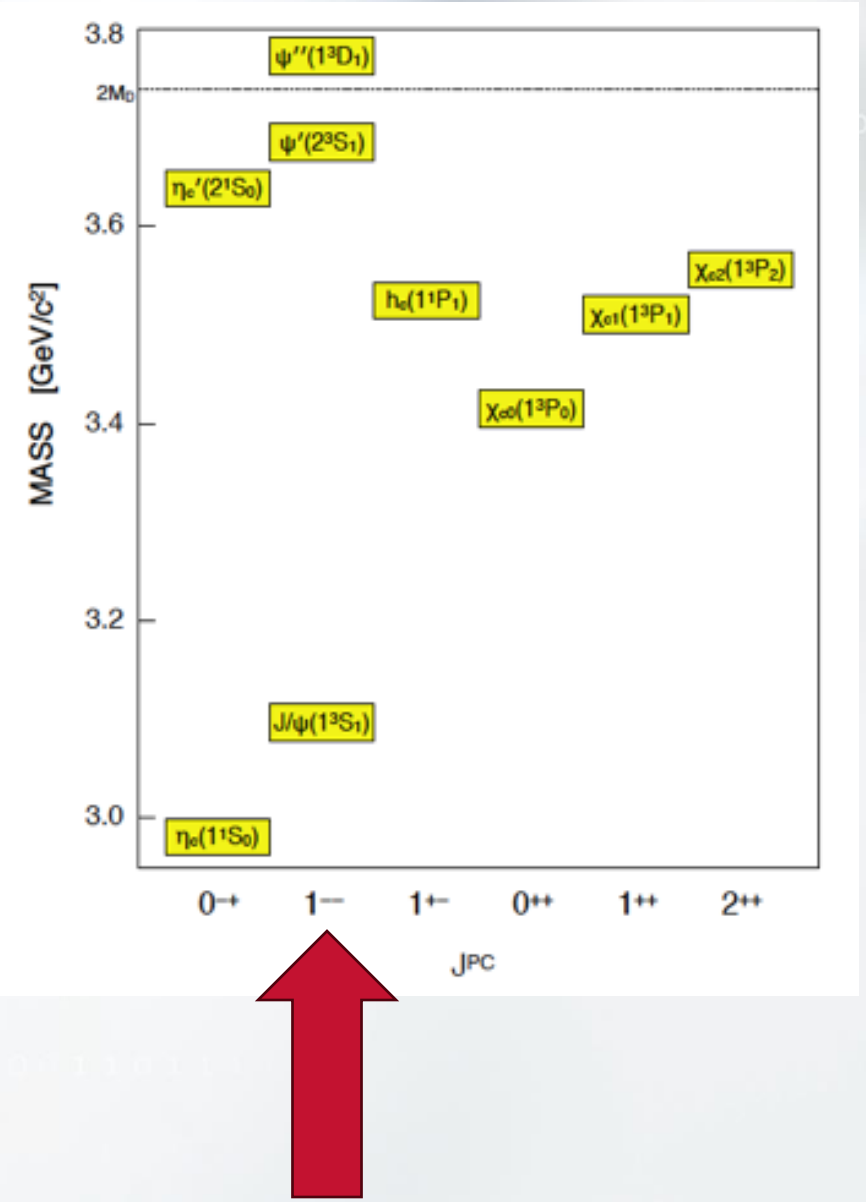
- 4th quark postulated by Glashow, Iliopoulos, and Maiani (1970)
- Samuel Ting (丁) and group from MIT analyzed data from BNL/AGS (p + Be)
- Burton Richter and team at SLAC hadronic cross section in e^+e^- collisions as function of CM energy
- Independently discovered J/ψ particle and confirmed charm quark
- Shared Nobel price 1976



Charmonium Spectrum

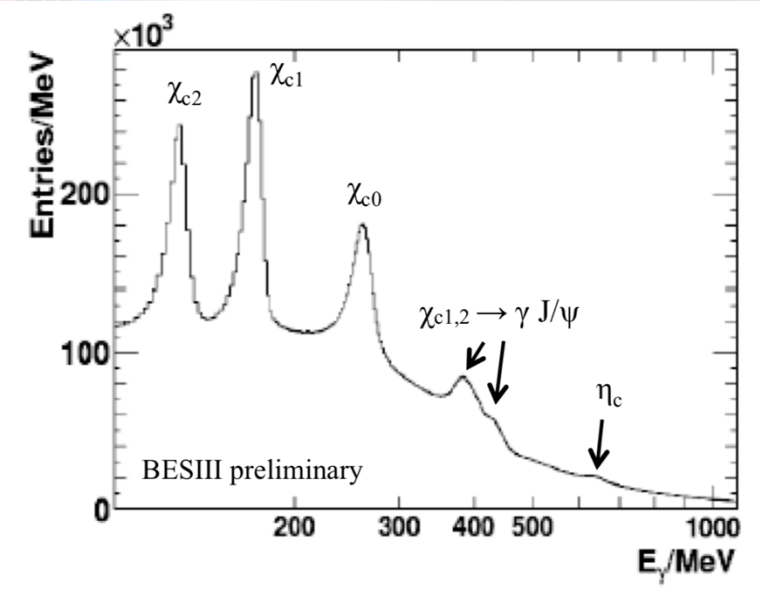
- Resonances appear as enhancements in cross section
- e^+e^- annihilation only produces vector mesons $J^{PC} = 1^{--}$
- Broad resonances above open charm ($D\bar{D}$) threshold

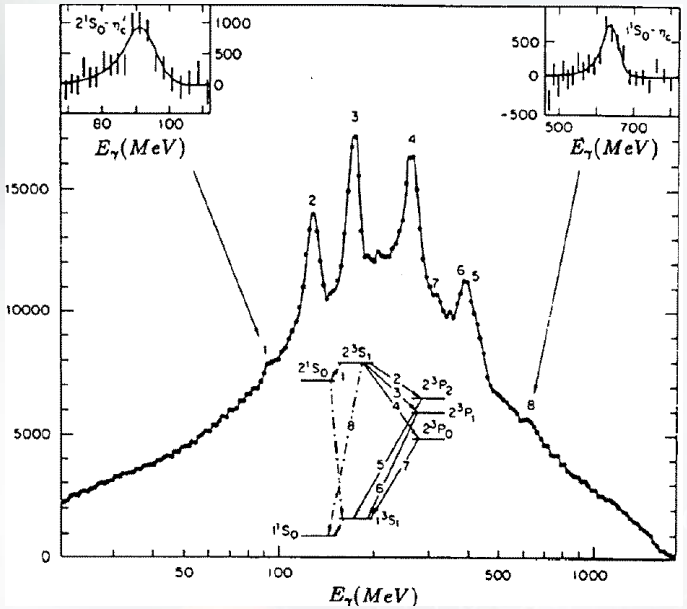


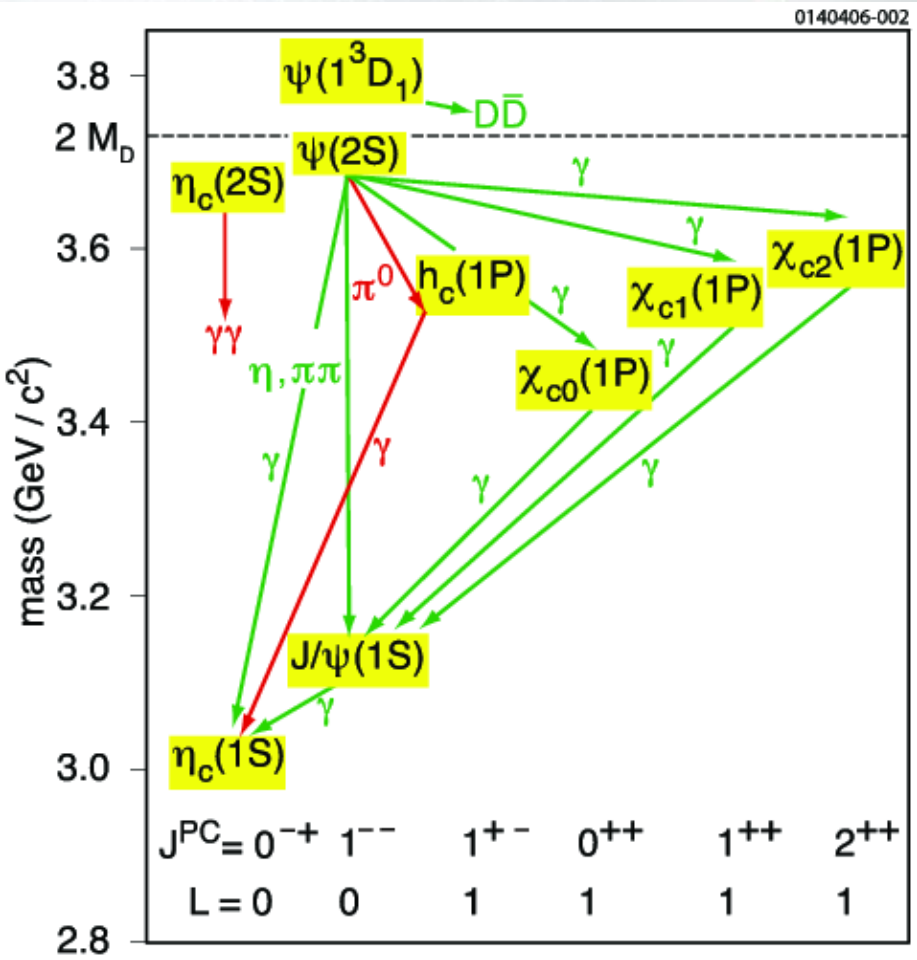


Charmonium Spectrum

- Resonances appear as enhancements in cross section
- e^+e^- annihilation only produces vector mesons $J^{PC} = 1^{--}$
- Broad resonances above open charm ($D\bar{D}$) threshold
- Other states accessed via decays

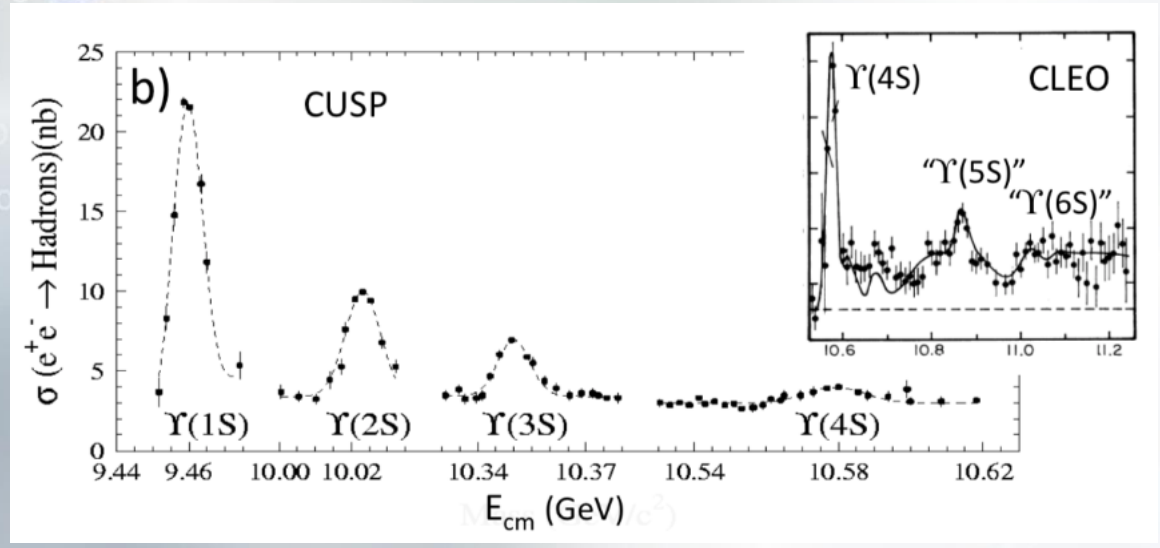


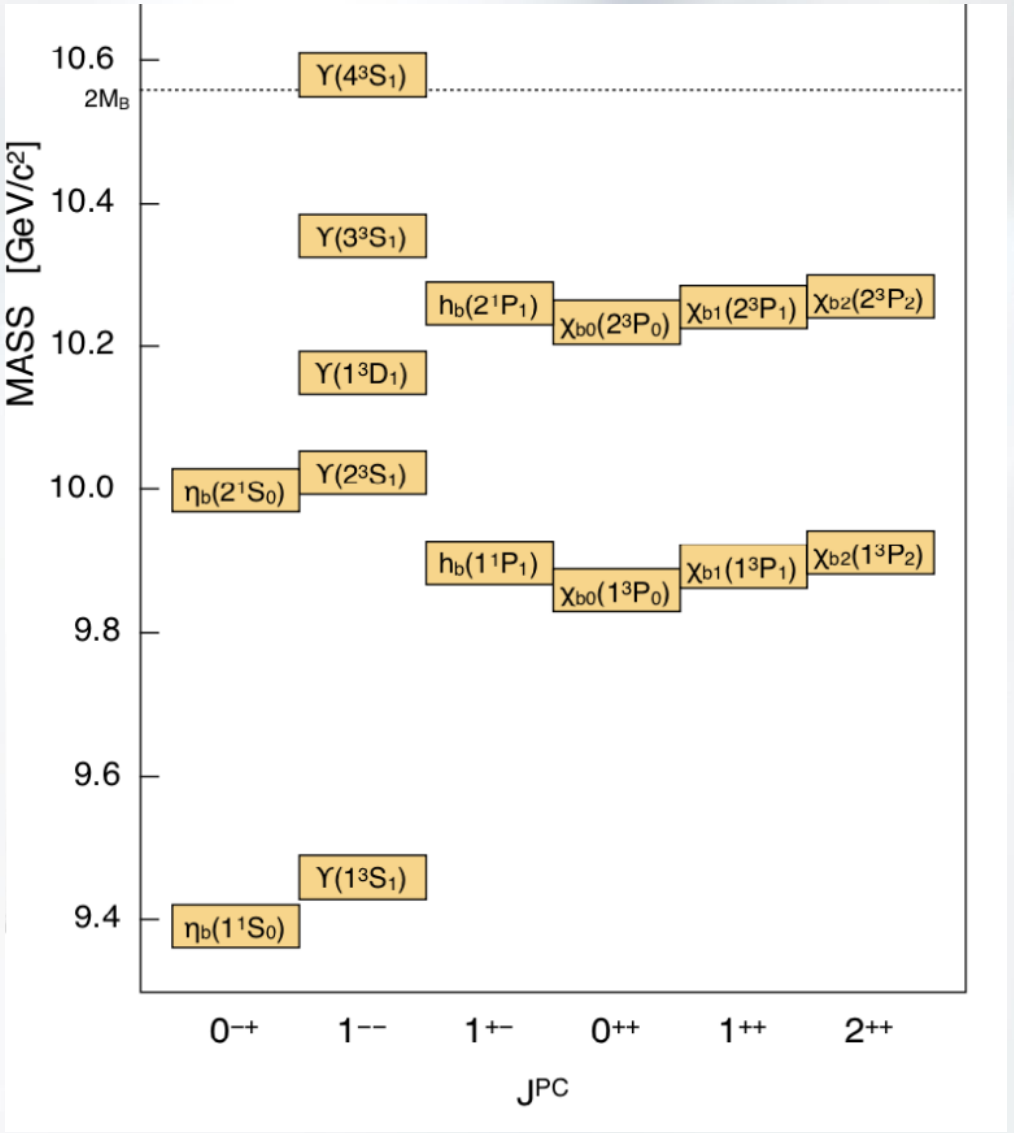




Bottomonium Spectrum

- Similar picture for Bottomonium below open bottom threshold
- Quark model works well, predicts approximate masses and widths

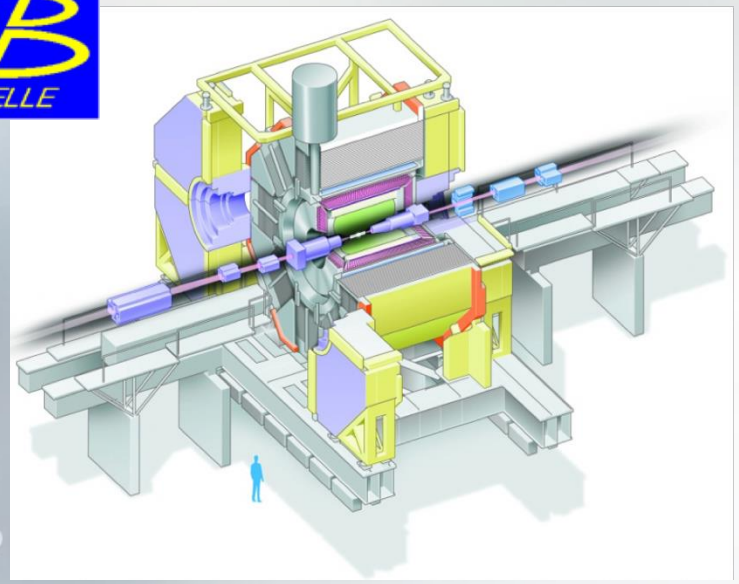


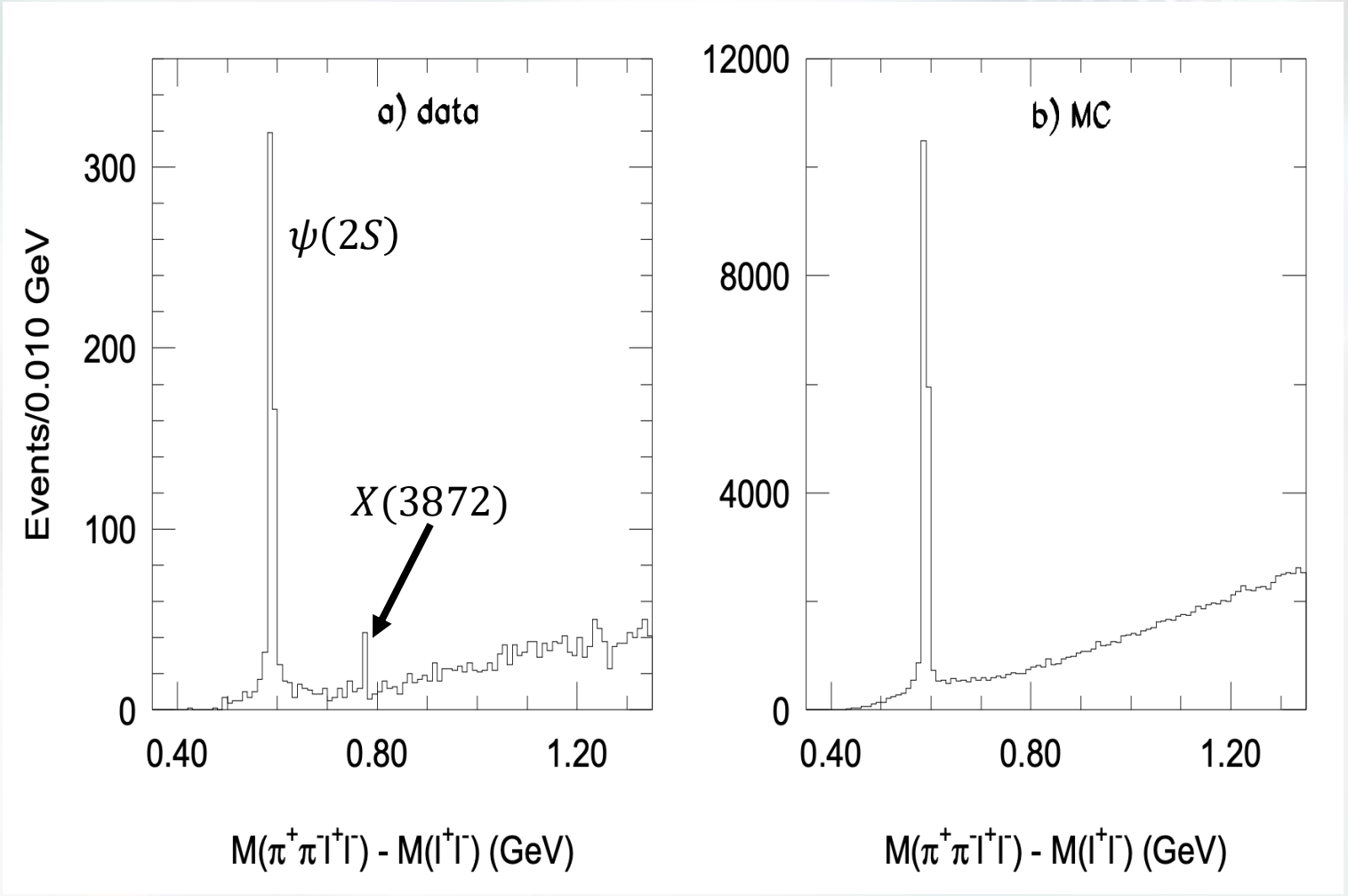


Unexpected States

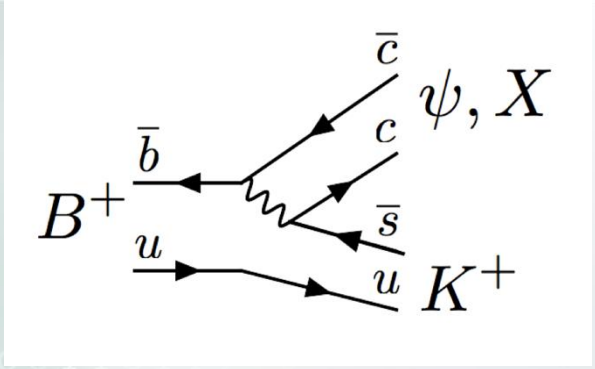
Unexpected discovery

- Belle at KEKB (Japan)
- Study CP violation
- $e^+e^- \to b\bar{b}$ at $\Upsilon(4S)$ mass
- $B \to K\pi^+\pi^- J/\psi$
- Narrow peak in $\pi^+\pi^- J/\psi$ reported in 2003

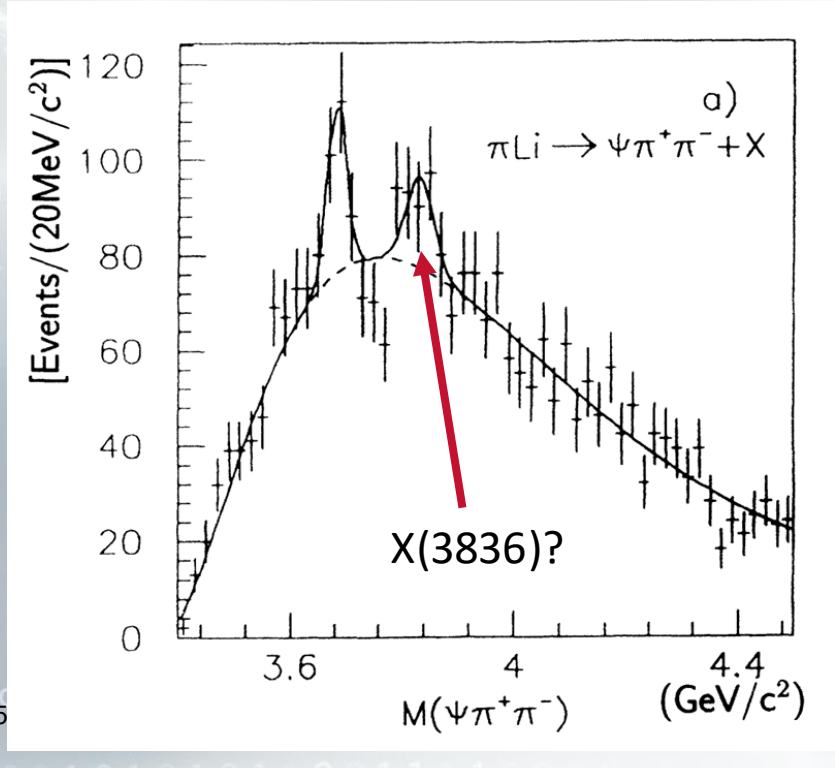


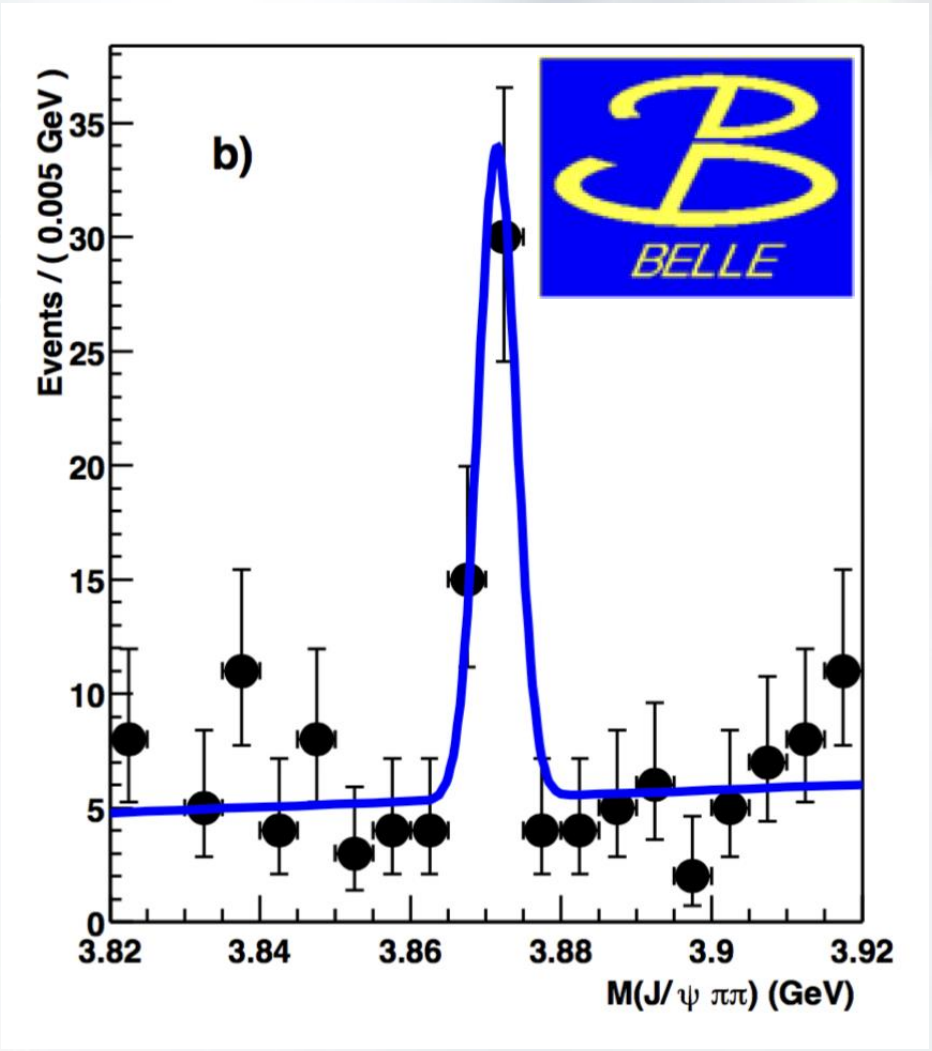


X(3872)



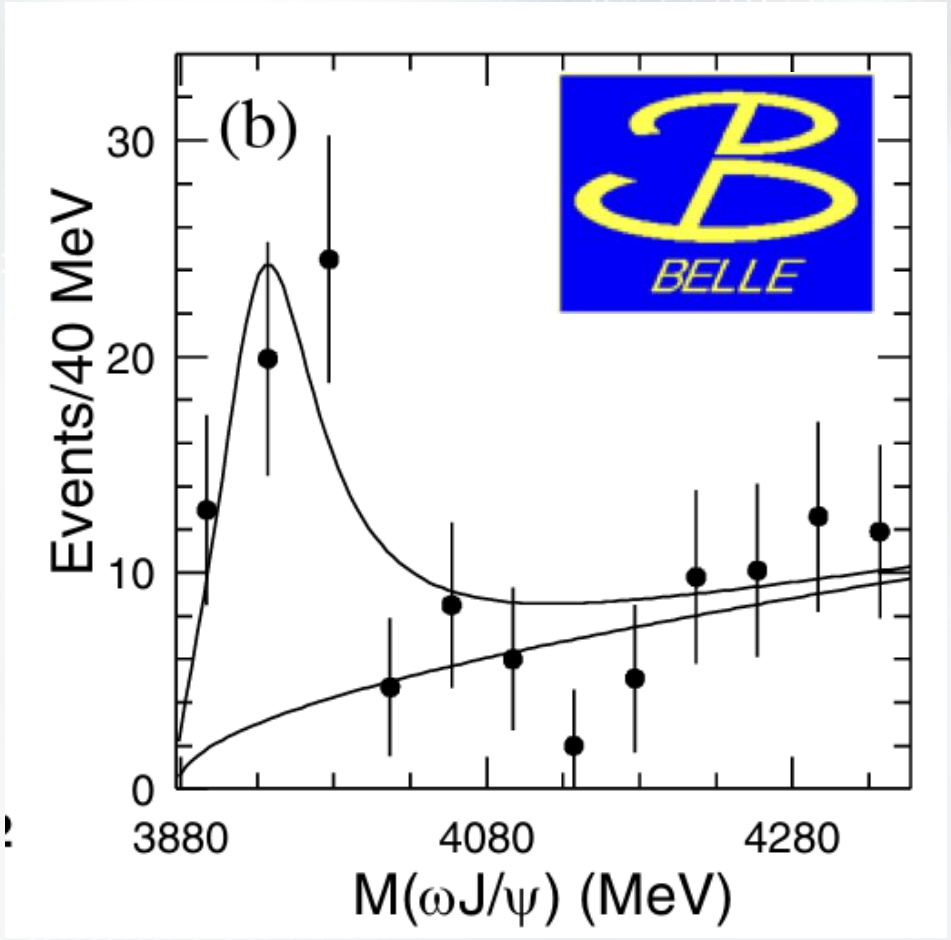
- $e^+e^- \to b\bar{b}$, $B \to K\pi^+\pi^- J/\psi$
- Mass and width do not fit quark model expectations
- Seen previously by E705 (FermiLab), but only with 2.8σ significance, low resolution



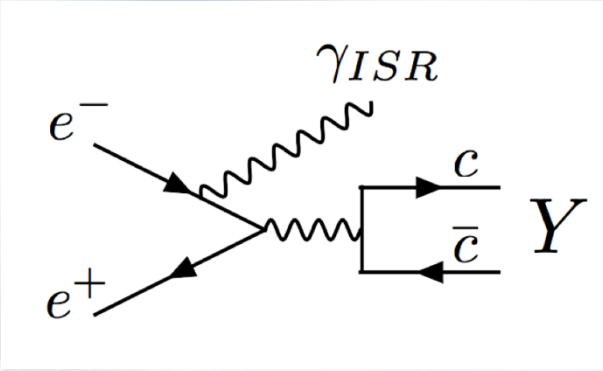


X(3872): Properties

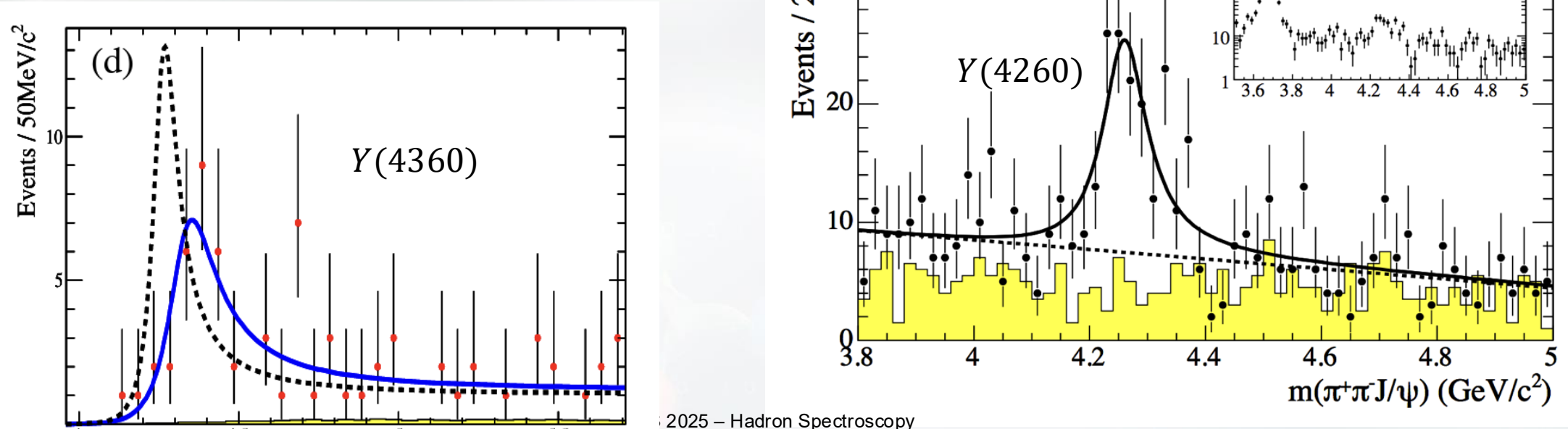
- $\pi^+\pi^-$ appear to originate from $\rho(770)$ (Isovector)
- Either: $X(3872)$ is isovector $I = 1$, cannot be $c\bar{c}$
- Or: Isoscalar $I = 0$, but decay violates isospin
- Search for isospin conserving decay: $\mathrm{X}(3872) \rightarrow \omega\, J/\psi$
- Instead, found broad peak: $Y(3940)$



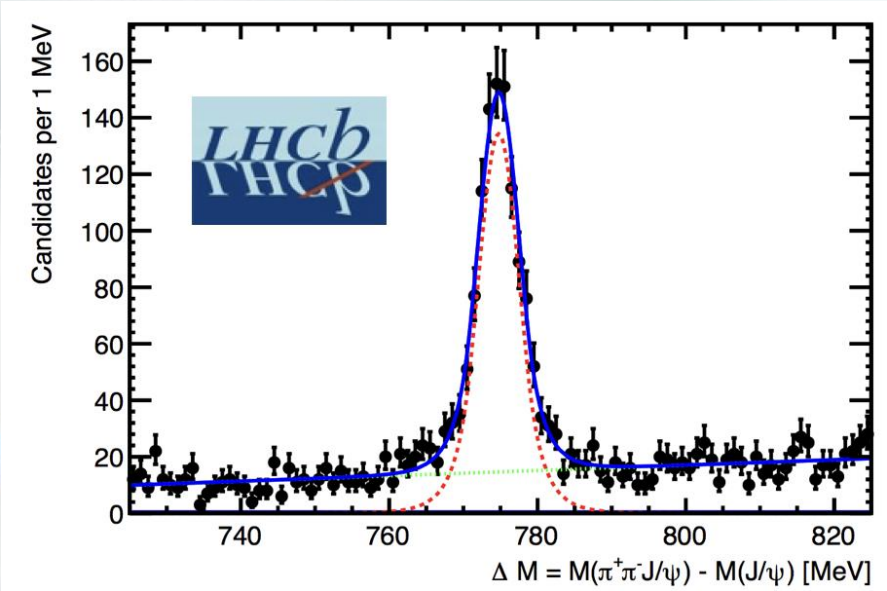
X(3872): Properties

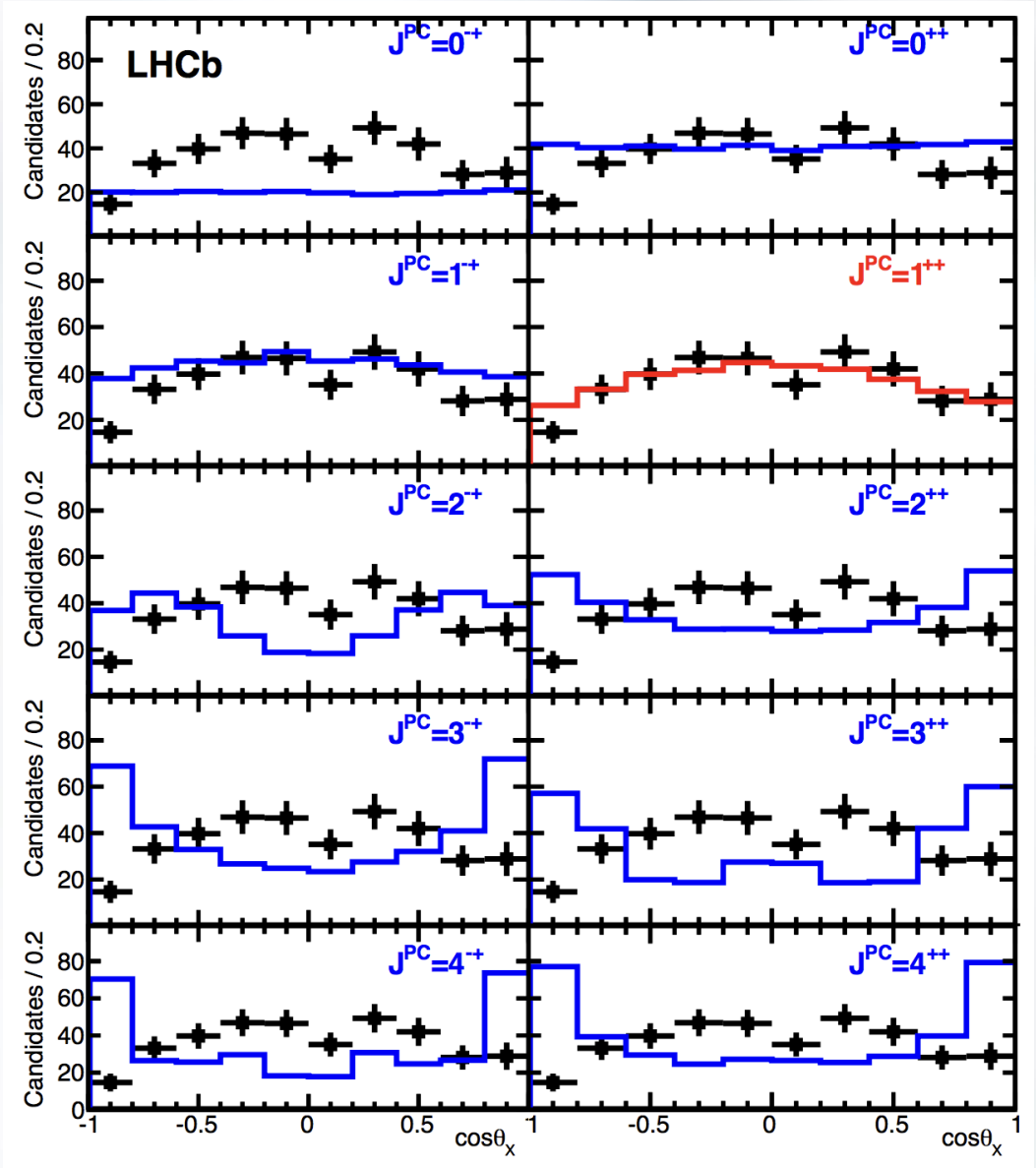


- Study different production mechanisms to determine quantum numbers
- Babar: $e^+e^- \to X(3872) \to \pi^+\pi^- J/\psi$ with Initial State Radiation (ISR)
- No signal, but different peak found: $Y(4260)$
- Same technique: $e^+e^- \to \pi^+\pi^-\psi(2S)$
  $\to$ another peak at higher mass: $Y(4360)$



Quantum Numbers

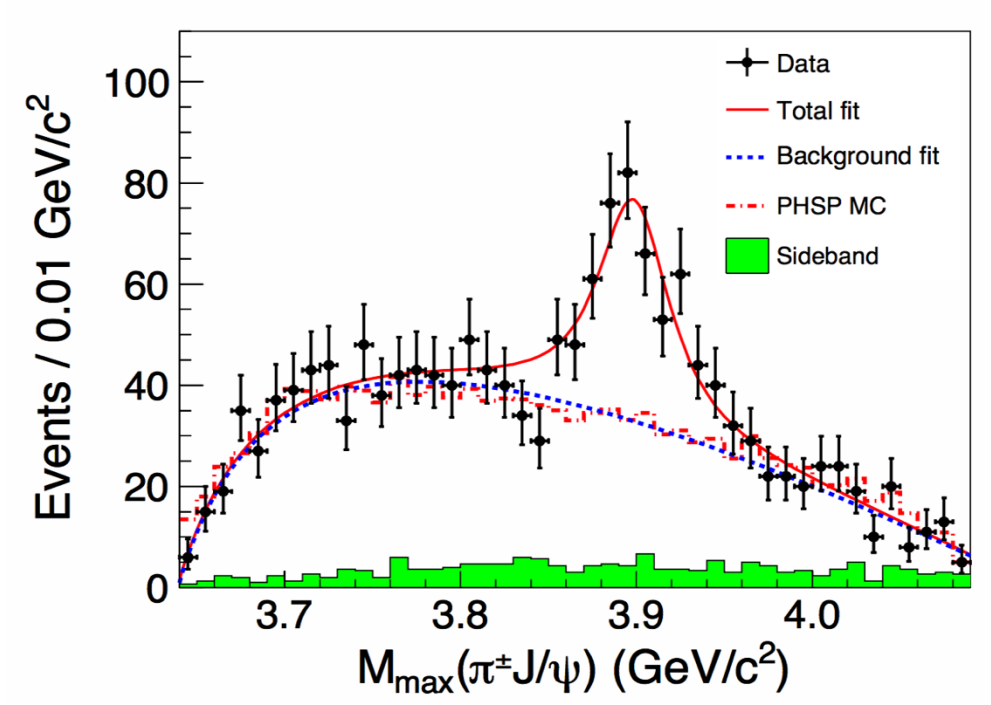


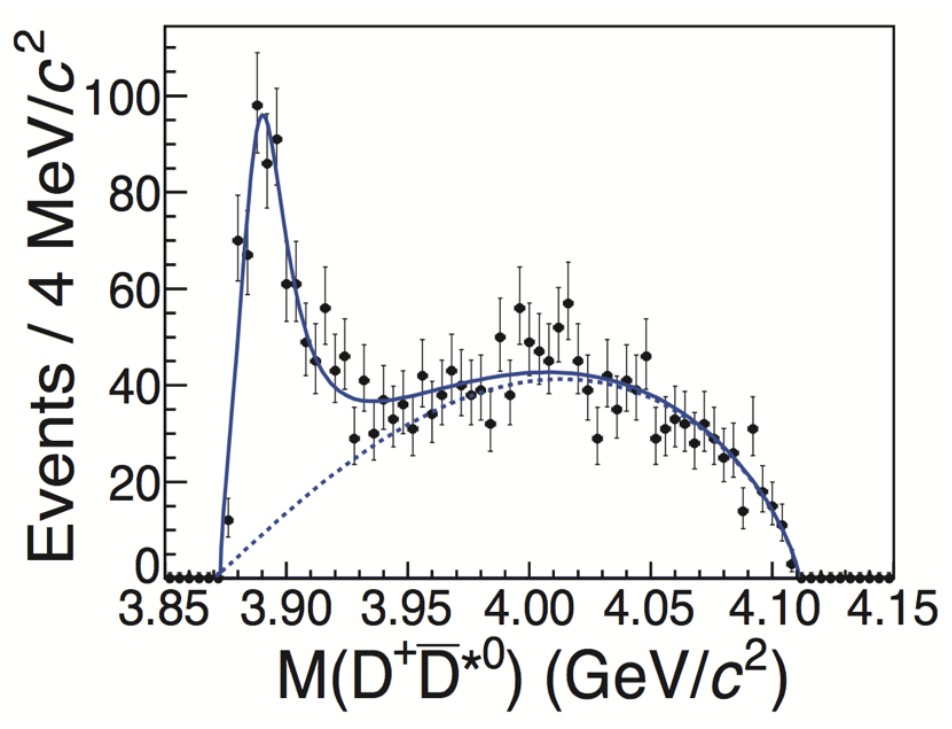


- Large data sets from LHCb
- 5-dimensional angular analysis
- $J^{PC} = 1^{++}$
- $\mathrm{X}(3872) \rightarrow \omega\, J/\psi$ measured in BaBar, but ratio ~0.8 $\rightarrow$ Isospin violation

Z(3900)

- BES-III: Another unexpected discovery in the decay of Y(4260)
- Peaks in $\pi^{\pm}J/\psi$ and $D\bar{D}^{*}$
- Charged charmonium $Z_c^{\pm}(3900)$: at least 4 quarks $c\bar{c}u\bar{d}$
- More states seen with $\mathrm{h_c(1P)}/\psi(2S)$ in final state: $Z_c^{\pm}(4020)$/ $Z_c^{\pm}(4430)$



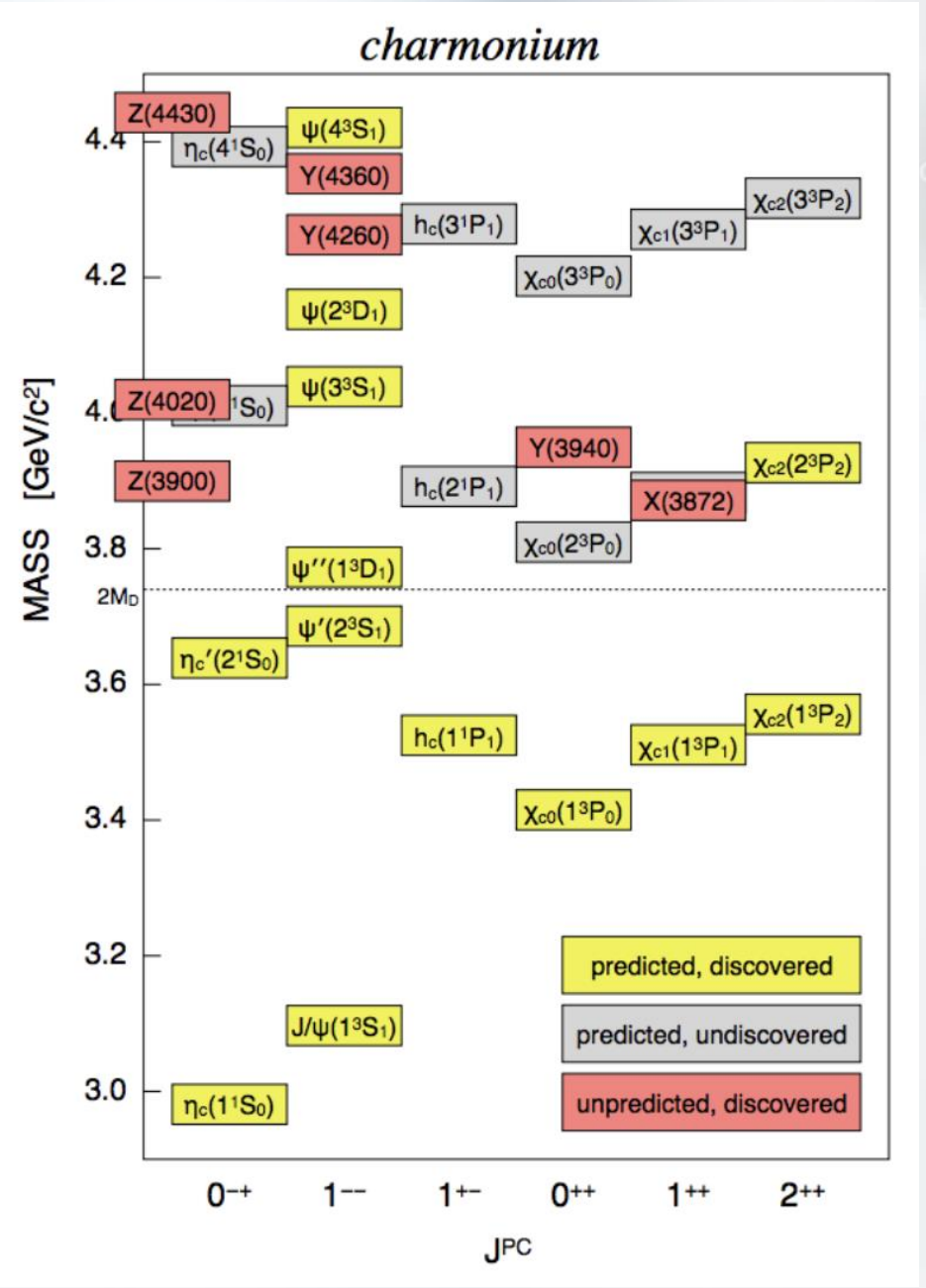


Notation

All X,Y and Z states do not fit the conventional quark model expectations

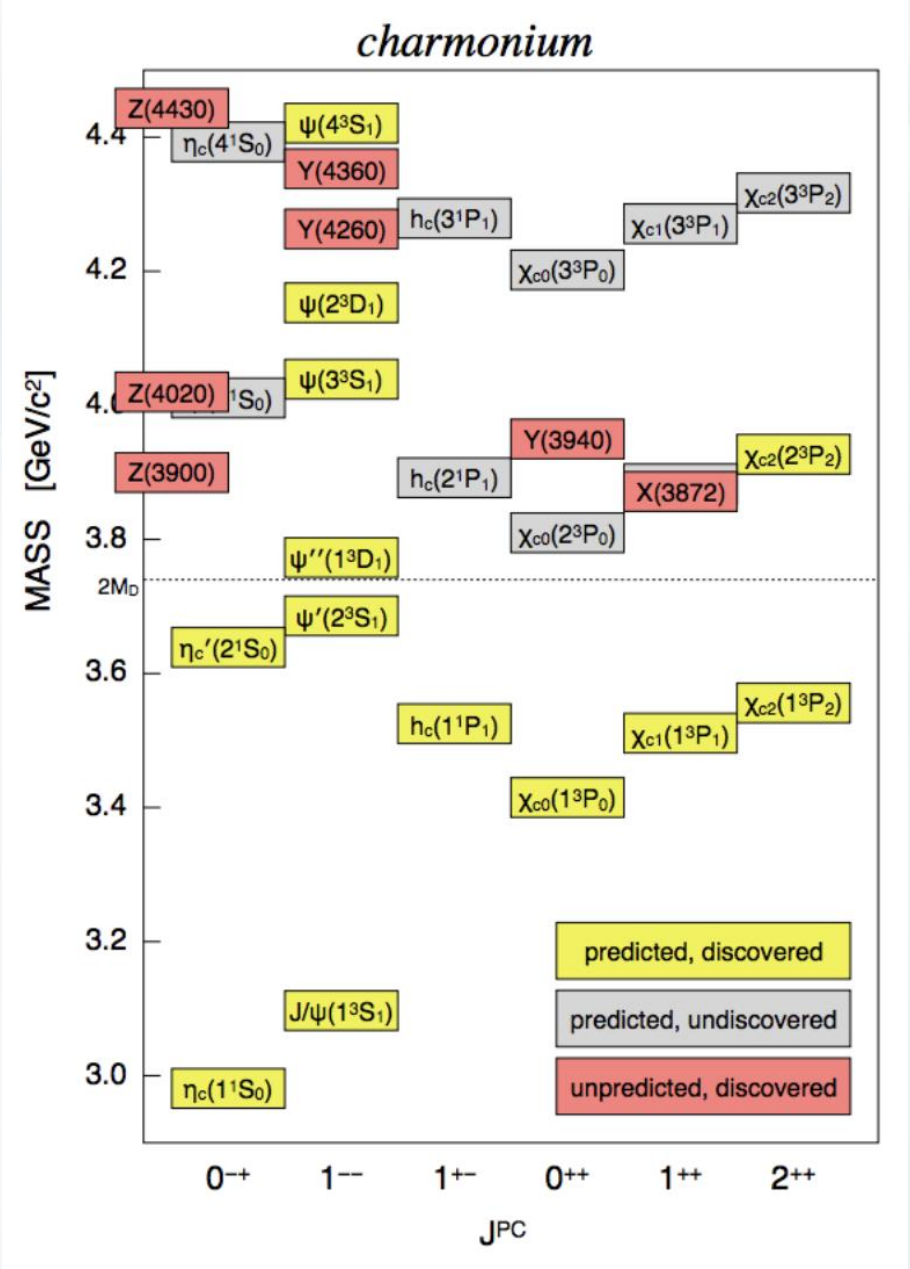
Naming scheme not entirely settled

- Z: electrically charged, do not fit into $c\bar{c}$ by definition
- Y: $J^{PC} = 1^{--}$ from e^+e^-, but not all
- X: Everything else unexpected



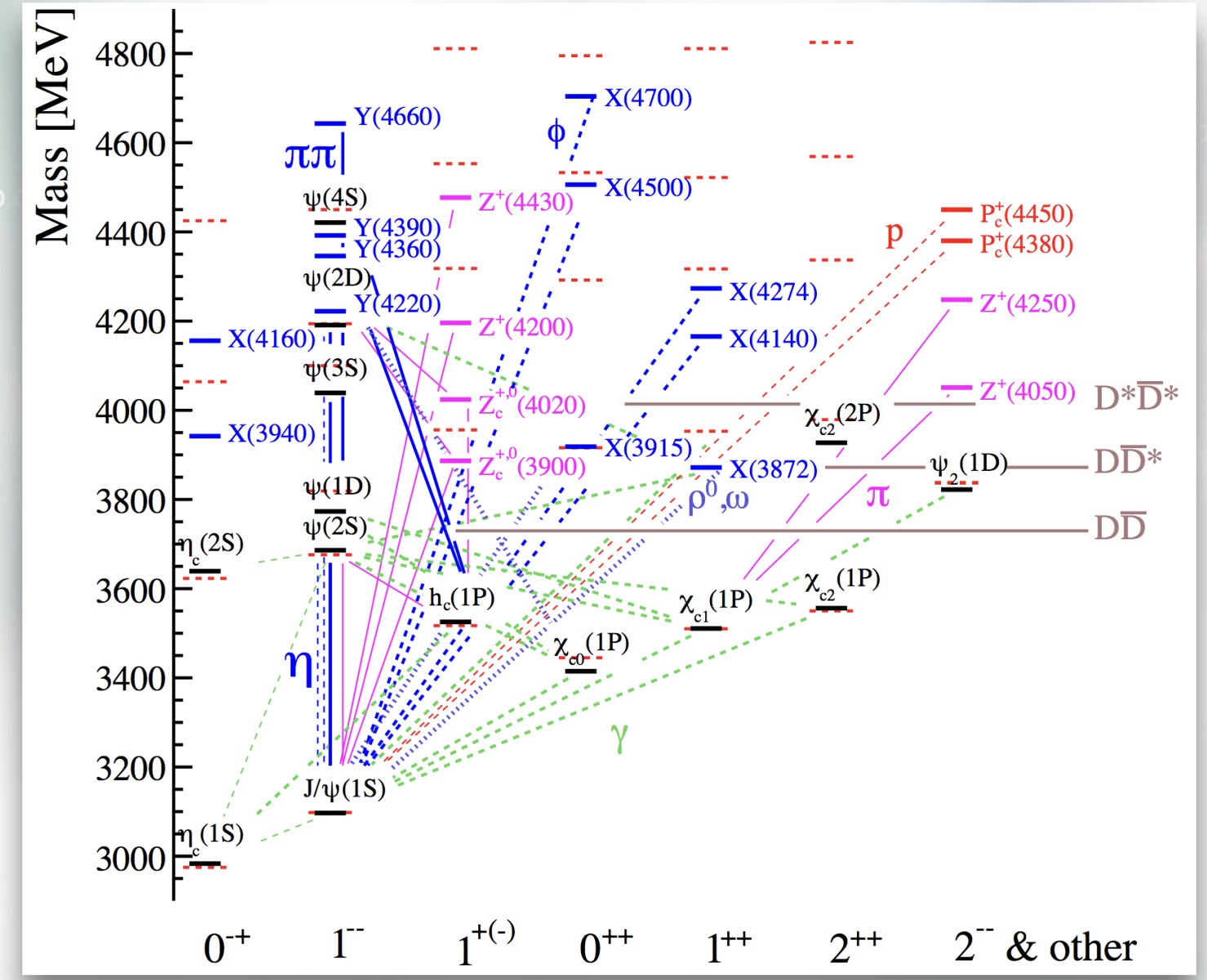
Interpretation

- Consensus: unexpected $c\bar{c}$ states
- Many lie remarkably close to two-meson thresholds, but not all
  → Very weakly bound hadron molecule?
  → Isospin dependence supports this
- Hadroquarkonium:
  Color-singlet $Q\bar{Q}$ core with light-quark cloud
- Tetraquarks?
- Hybrids?
- Kinematic effects?

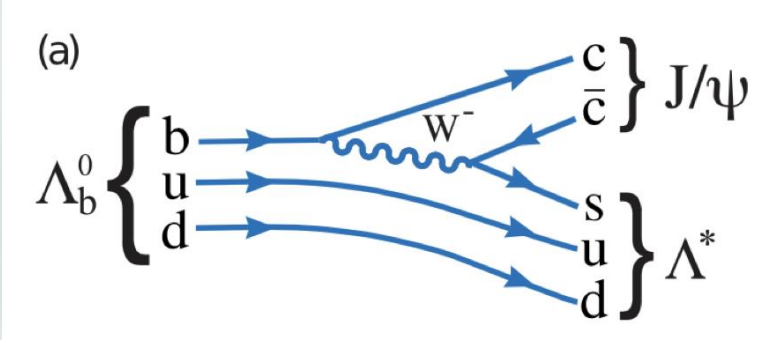


More states

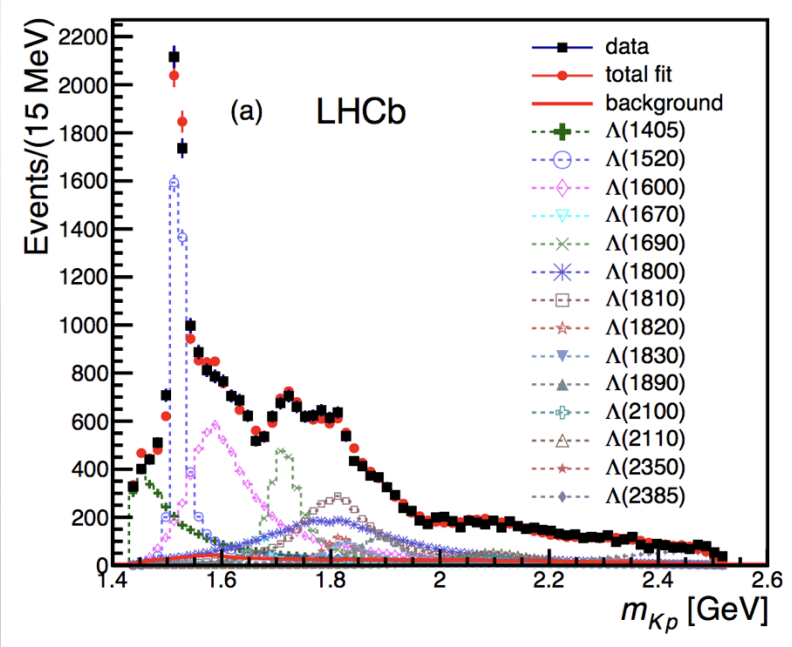
- Explosion of observations
- Large number of models
- Many-particle dynamics
- More understanding?

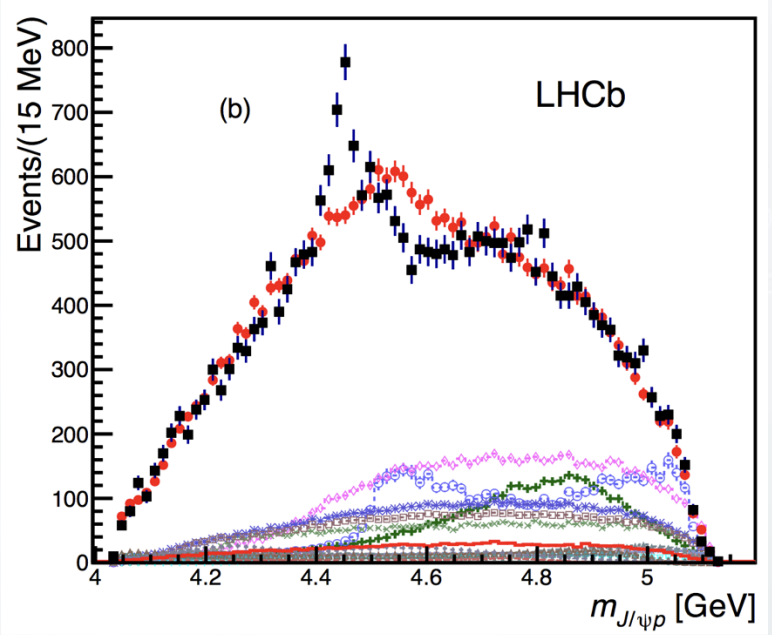


Exotic Baryons

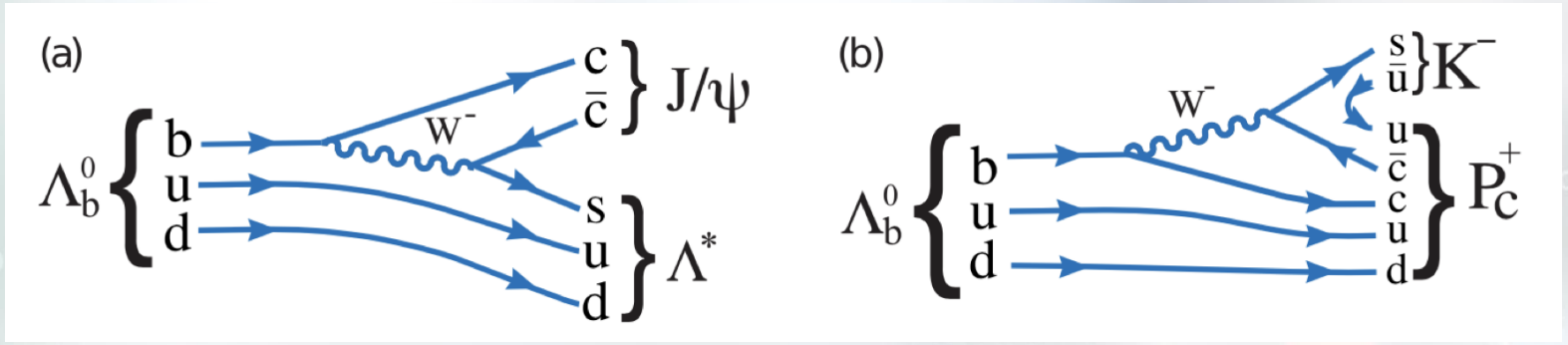


- LHCb (2015): $\Lambda_b \to K\, p\, J/\psi$
- Full amplitude analysis
- Excited Λ^* can describe Kp spectrum reasonably well

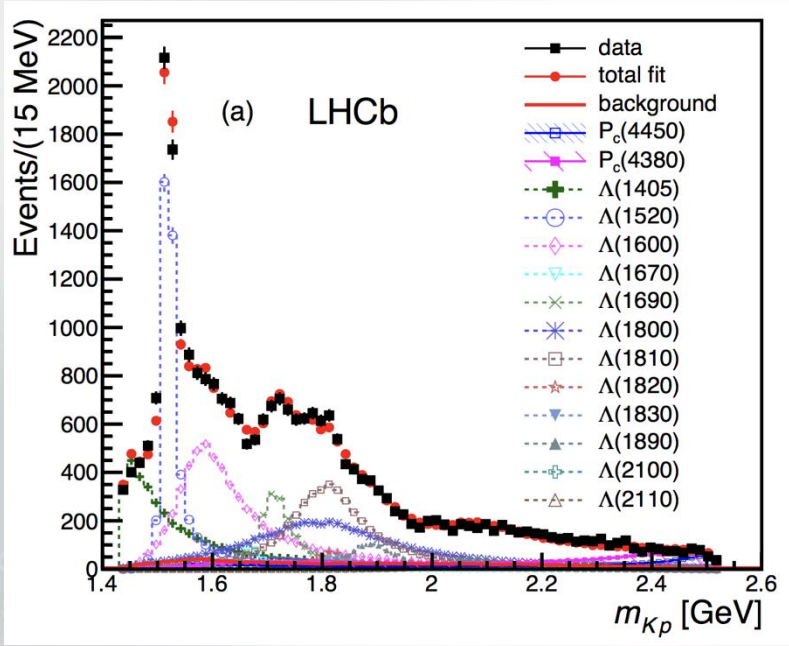


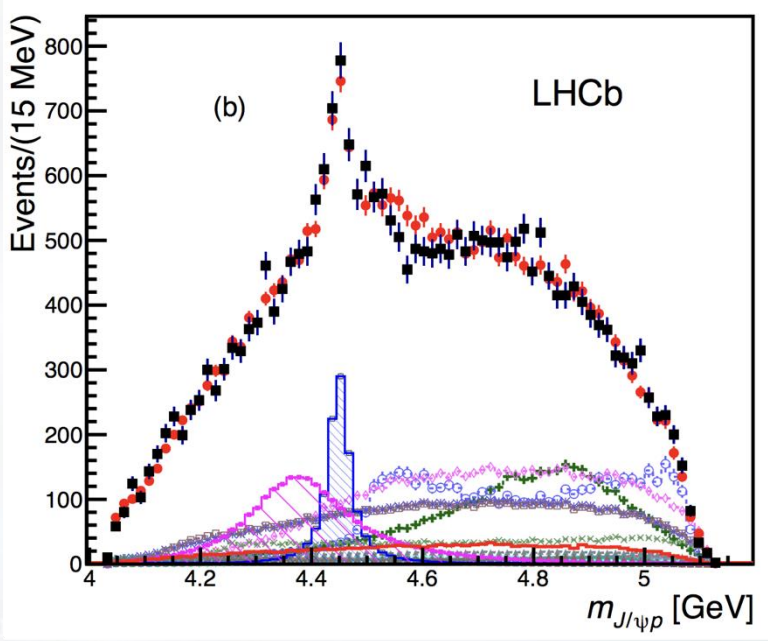


Exotic Baryons



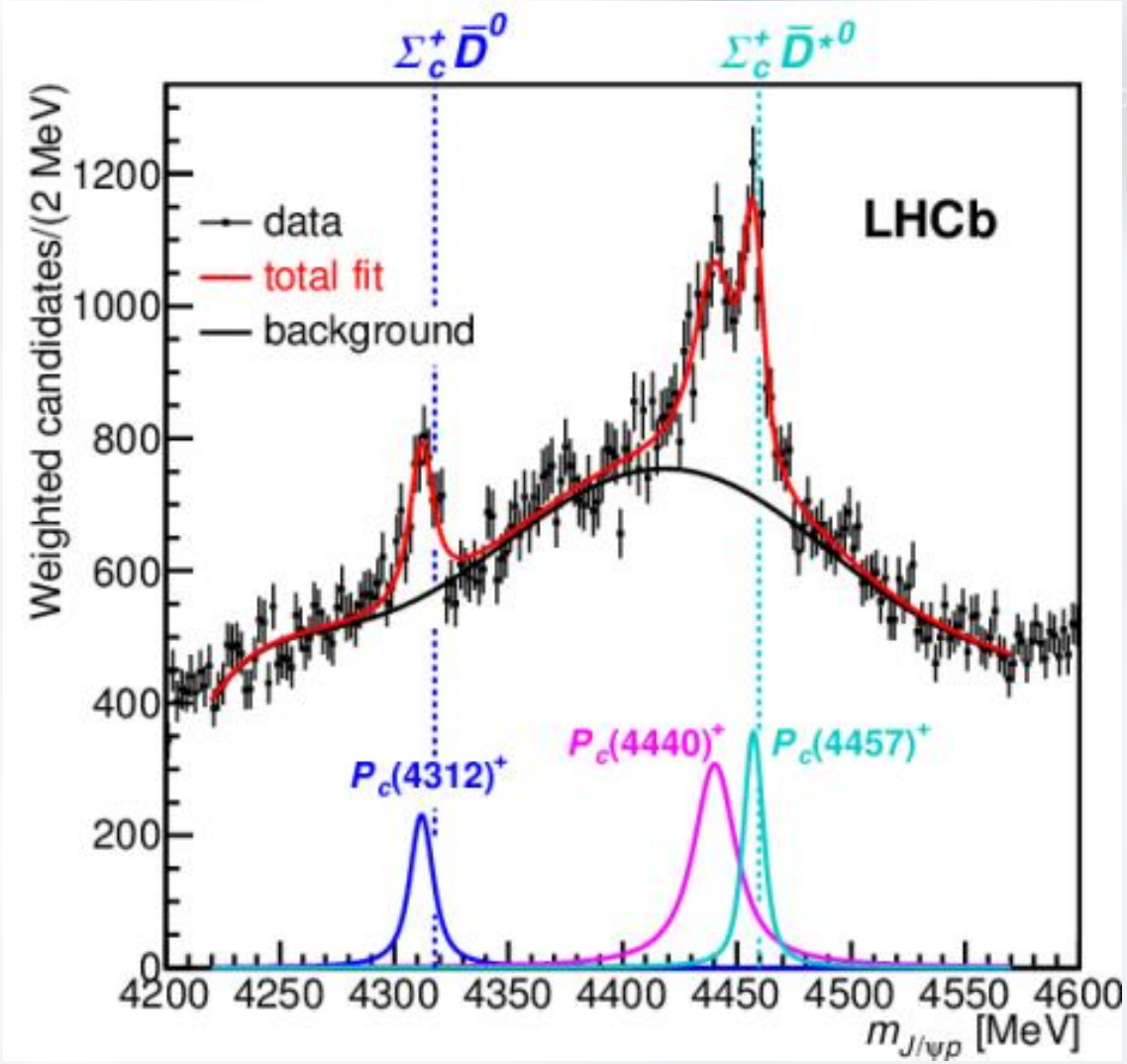
- LHCb (2015): $\Lambda_b \to K\, p\, J/\psi$
- Full amplitude analysis
- Excited Λ^* can describe Kp spectrum reasonably well
- Peaks in $\mathrm{p}\, J/\psi$ require contribution from P_c states





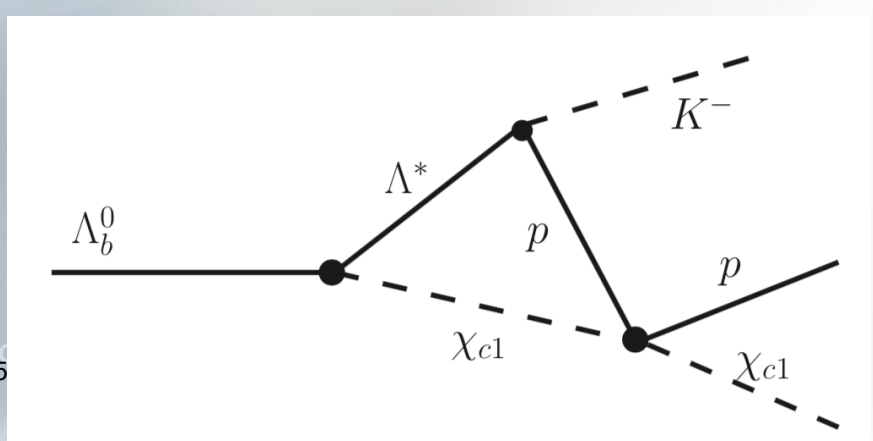
Pentaquark Update

- LHCb (2019): significantly larger data set
- Narrow peaks close to $\Sigma_c \bar{D}^{(*)}$ thresholds
- But no full amplitude analysis



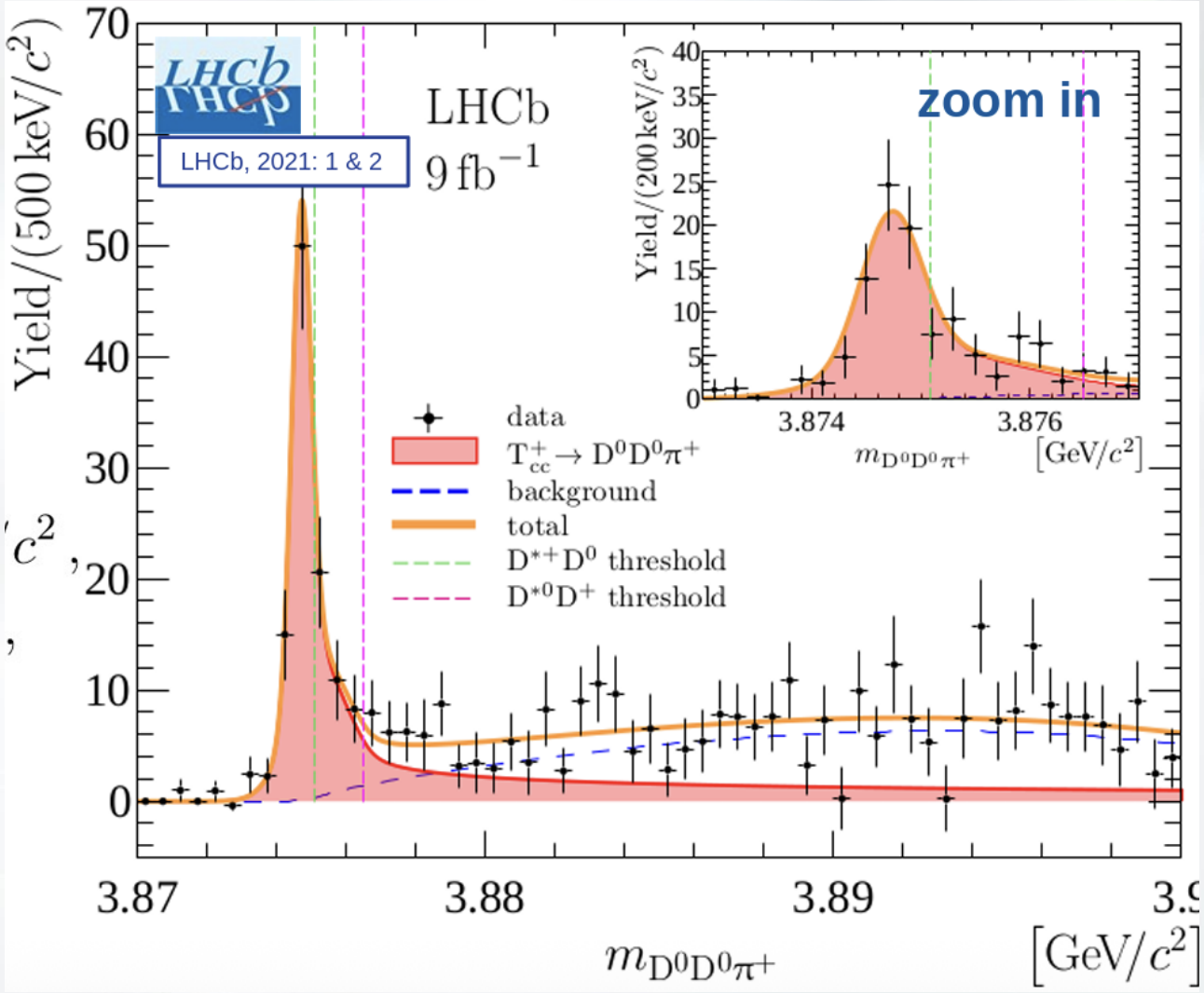
Interpretation:

- Hadronic molecules?
- Virtual state (see Lecture 4)
- Rescattering ("triangle singularity")?



Double-charmed Tetraquark

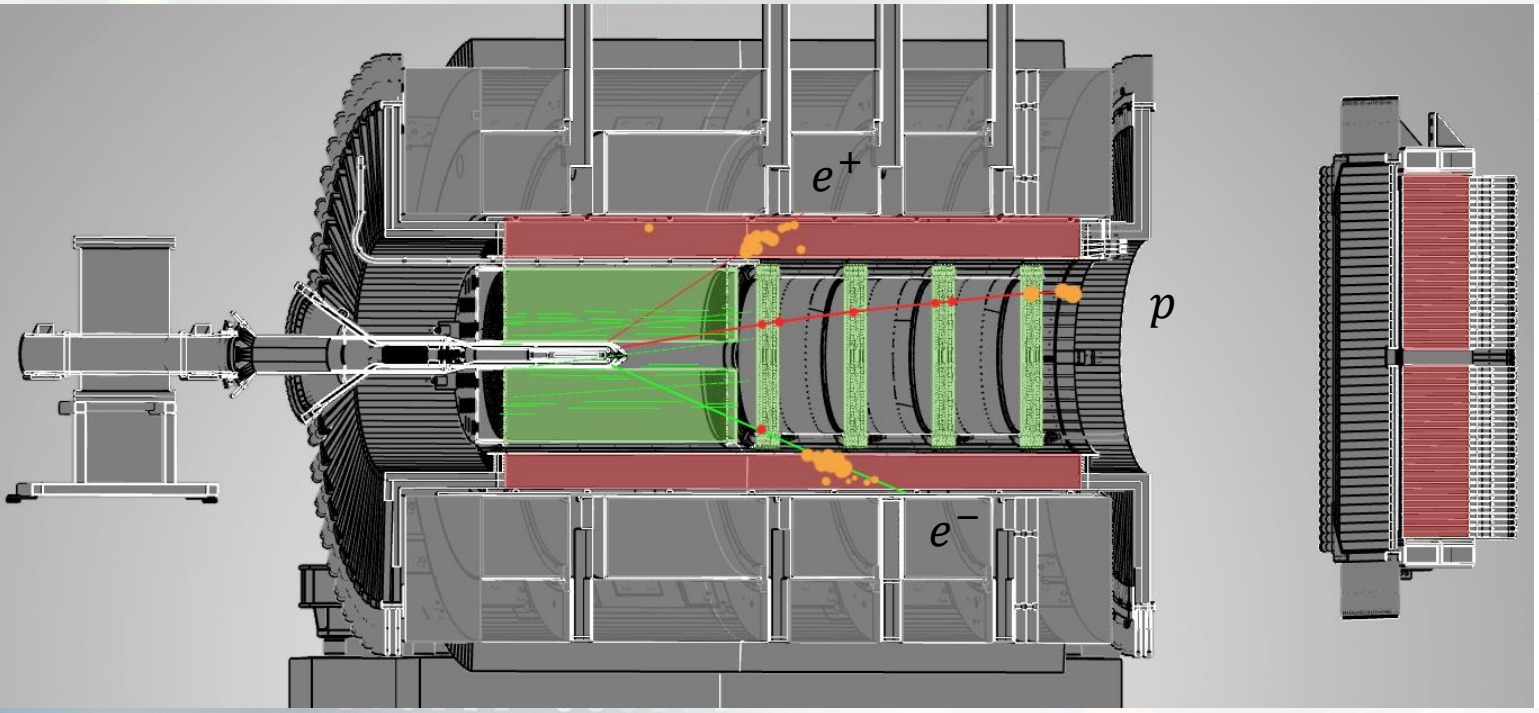
- Reported by LHCb in 2021
- T_{cc} $(cc\overline{ud})$ signal in $D^0D^0\pi^+$,
- Just below D^0D^{*+} threshold
- $I\ J^P = 0\ 1^+$
- Predictions for “stable” T_{bb}
- No known strange counterpart T_{ss}

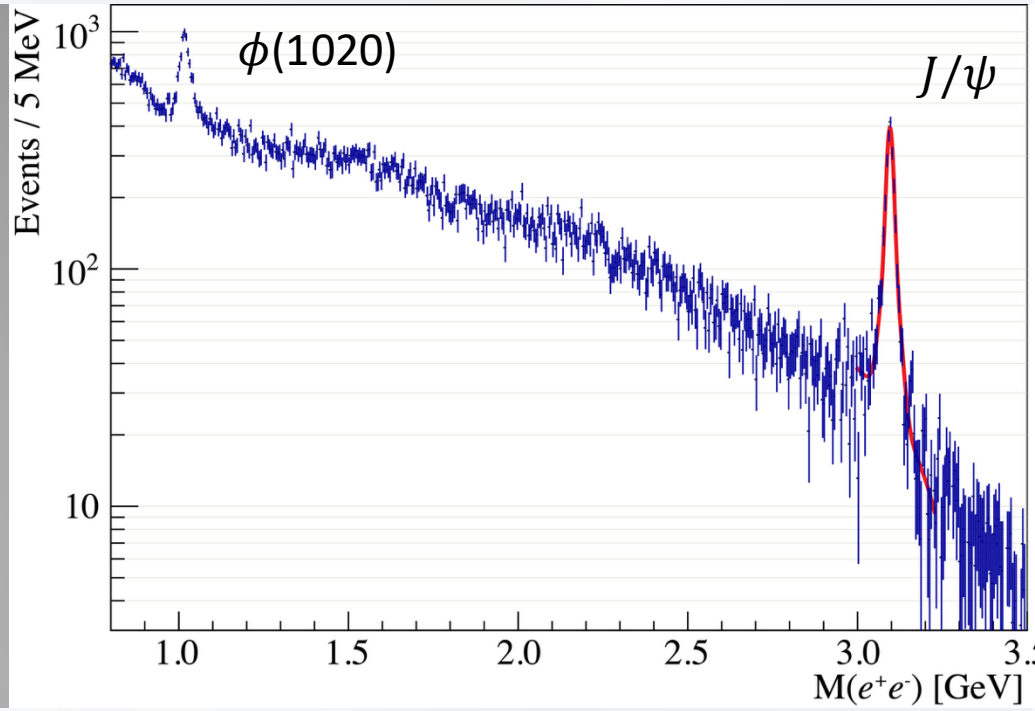


Charmonium at Jefferson Lab

Photoproduction with GlueX

- Reaction $\gamma p \rightarrow J/\psi p$
- Threshold for charmonium photo-production: 8.22 GeV
- Electron identification with calorimeters, pion suppression by 10^{-4}





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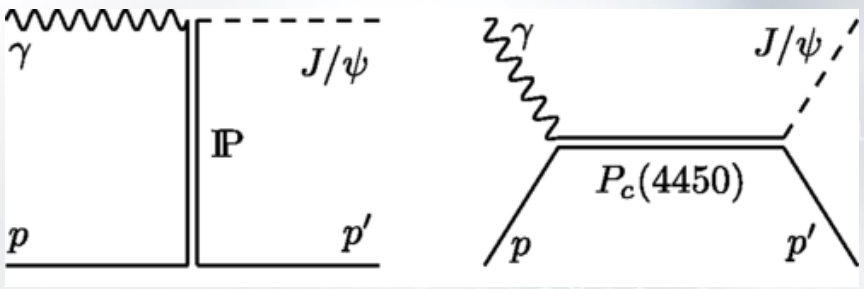
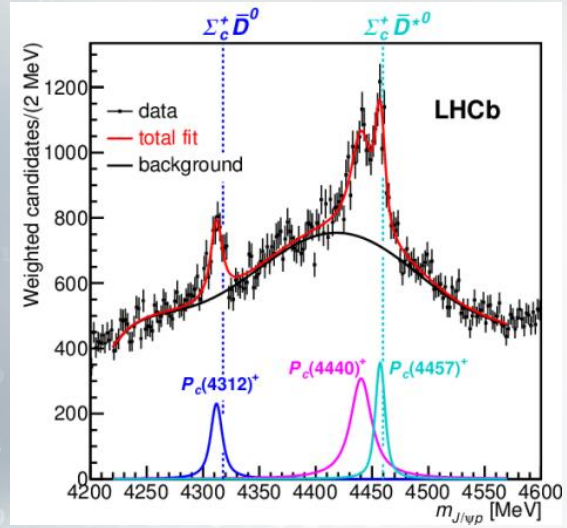
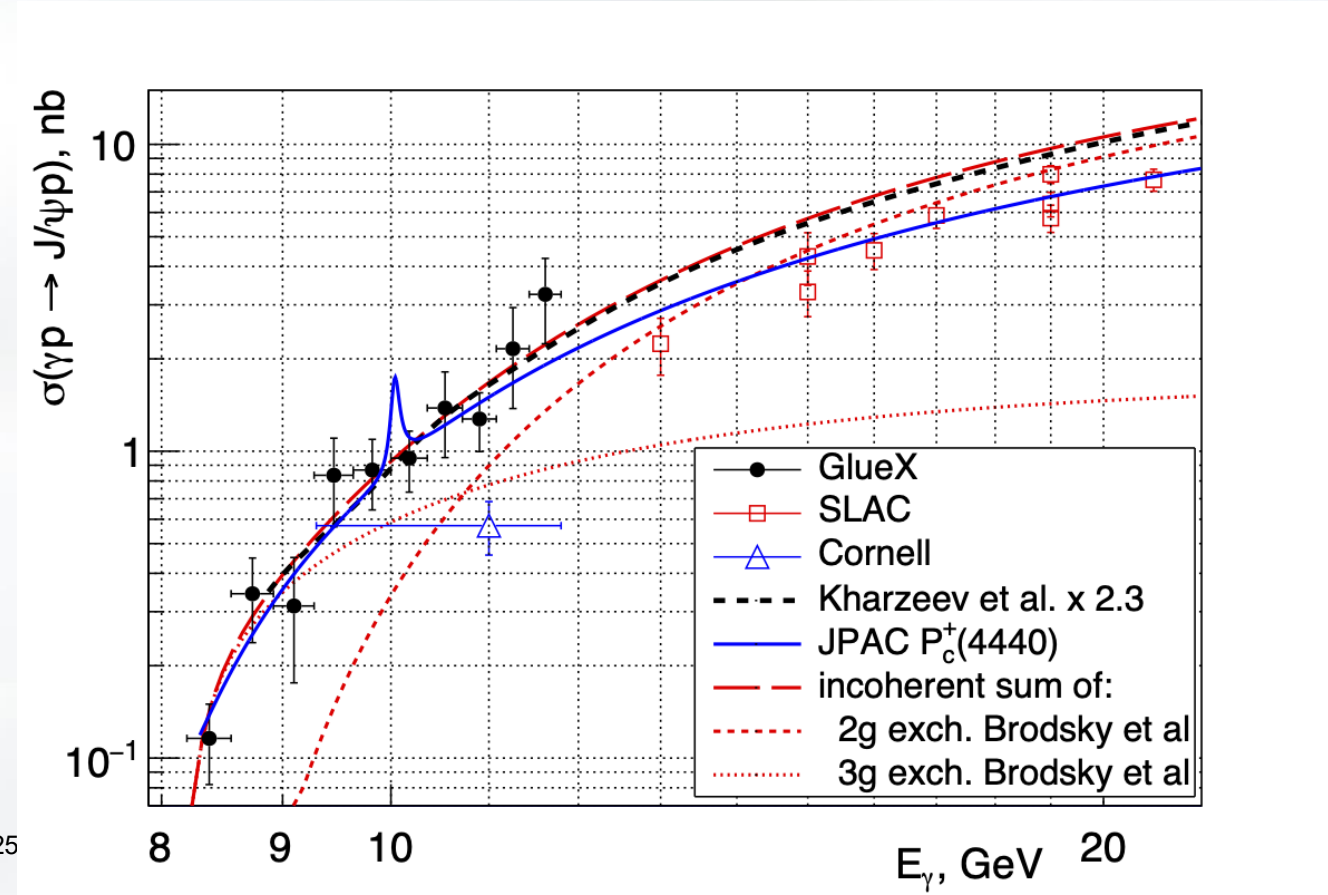


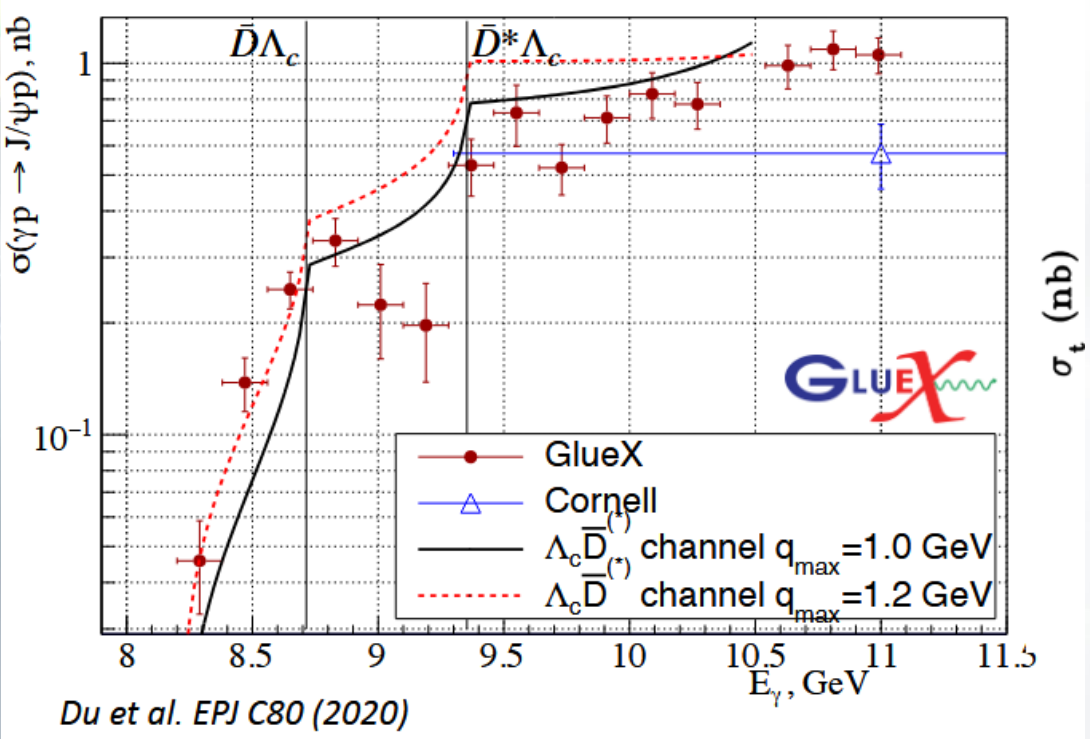
- Reaction $\gamma p \rightarrow J/\psi p$
- Energy-dependence of total cross section probes resonances in $J/\psi p$ system
- Advantage: no spectator particle
  → No rescattering effects
- No evidence for P_c states
  → Model-dependent upper limits (2019)

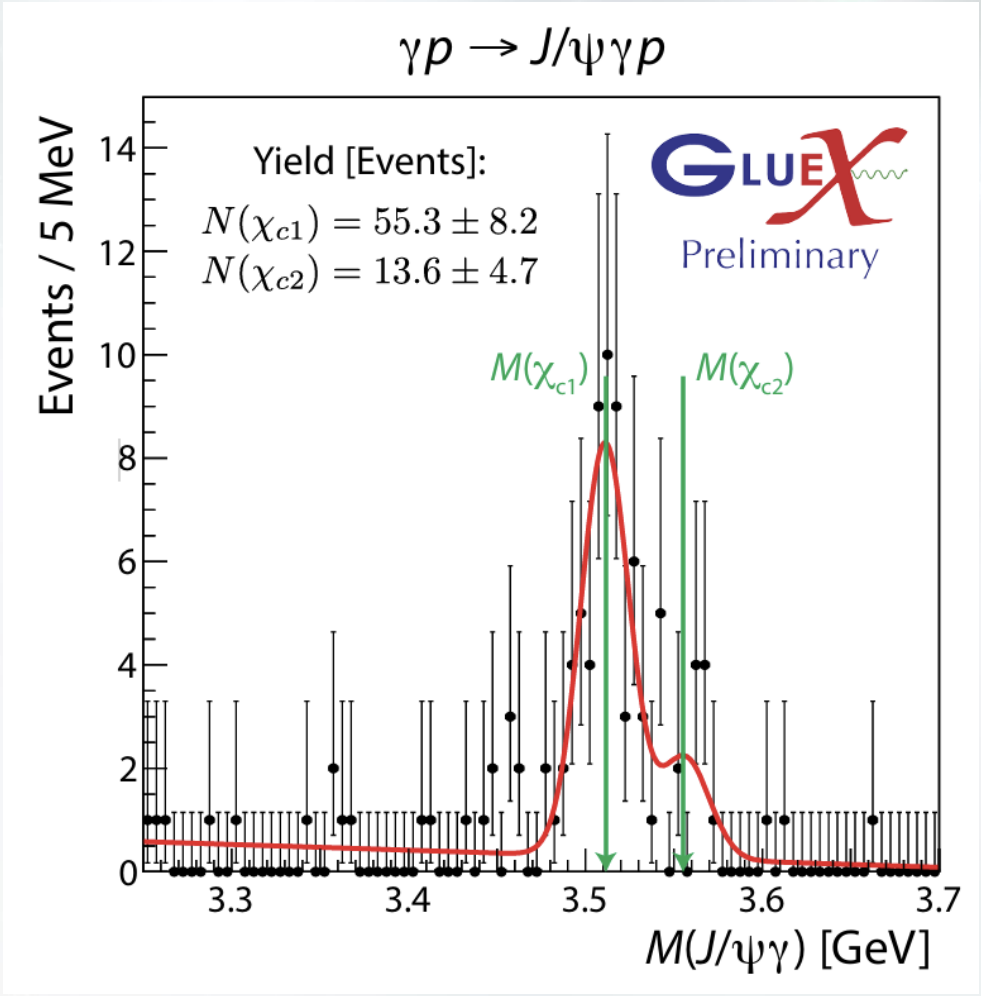




Photoproduction with GlueX

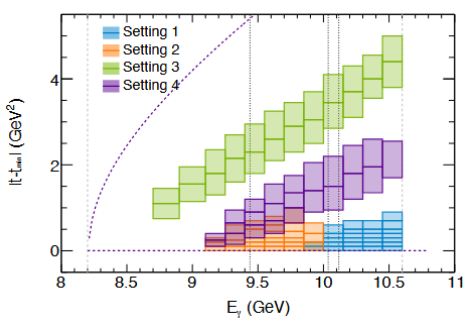
- 2023: 4 times more data
- Effects of open charm threshold ($\Lambda_c \bar{D}$) on cross section?
- First measurement of χ_{c1} and $\chi_{c2} \rightarrow \gamma J/\psi$ at Jefferson Lab

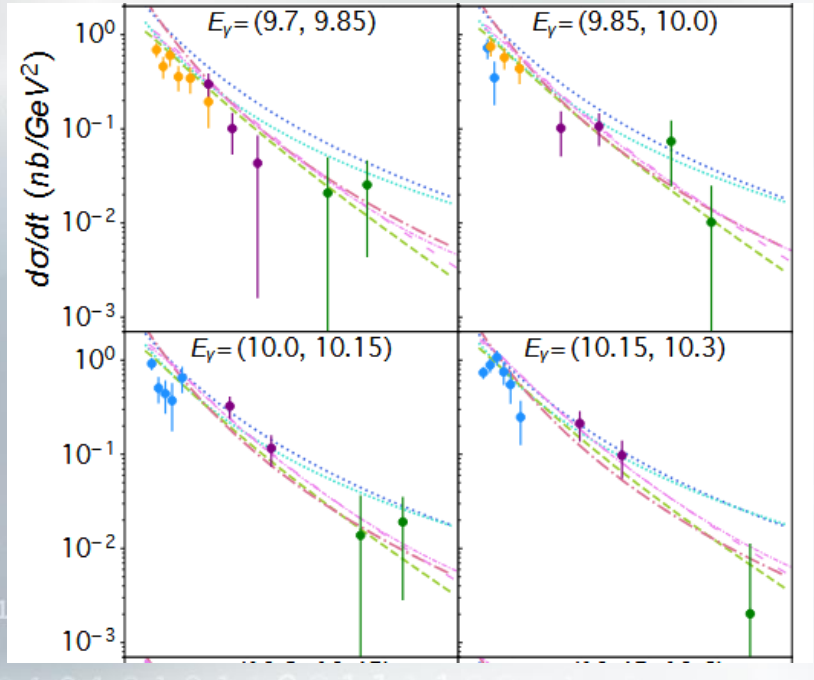




007 J/ψ

- Dedicated experiment to study J/ψ photo-production in Hall C (10.6 GeV)
- 4 discrete kinematic settings
- Results inconsistent with Pentaquark → Tight limits on models

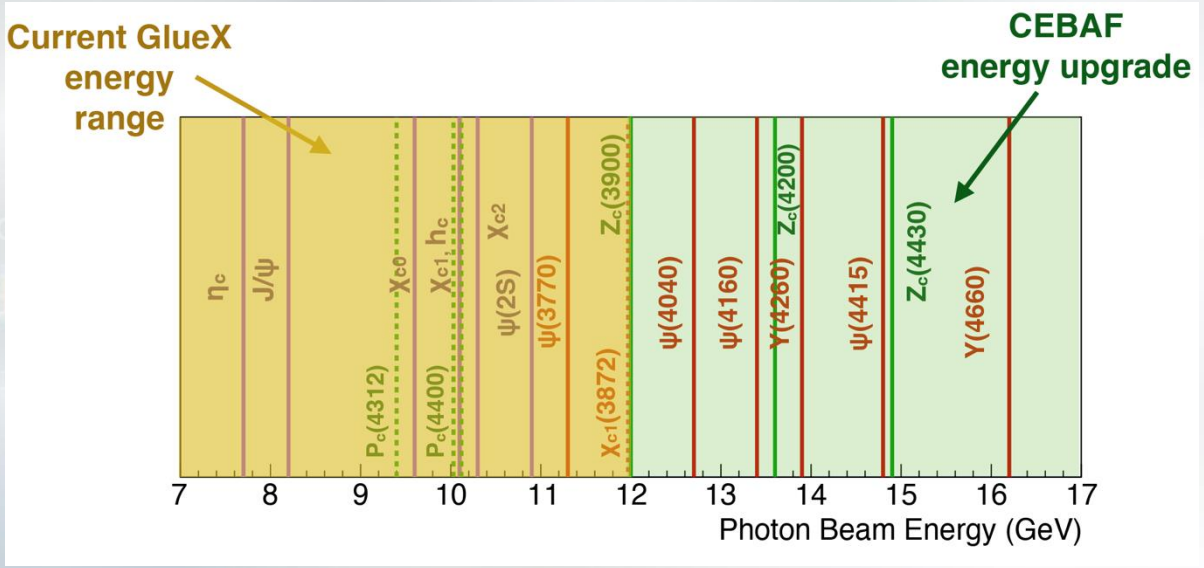


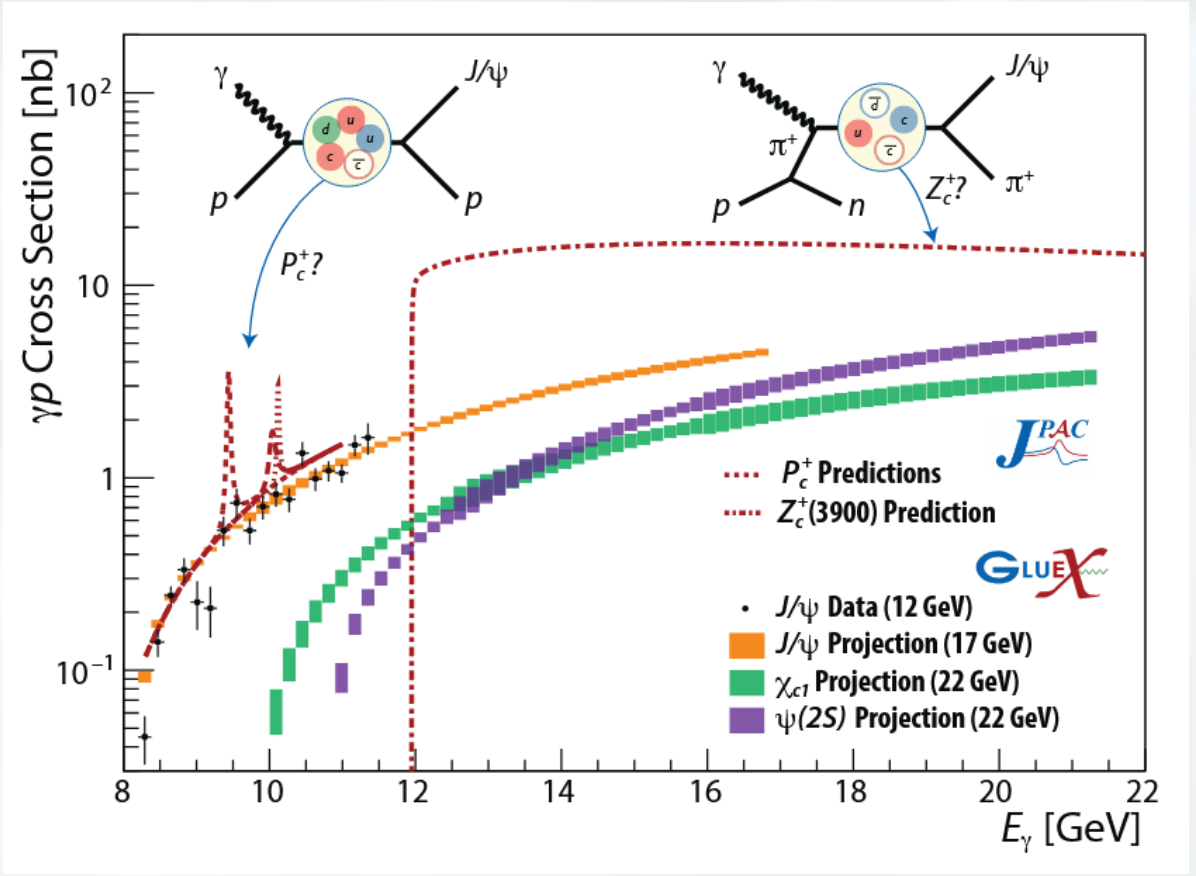


Exciting results on gluonic gravitational form factors [Nature 615, (2023) 813–816]

Jefferson Lab at 22 GeV

- Proposal to extend CEBAF energy range with Fixed-Field Alternating Gradient arcs
- Access to photoproduction of many more charmonium states, including XYZs





Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab
https://arxiv.org/abs/2306.09360

Want to know more?

- Heavy-Quark QCD Exotica
  Richard F. Lebed, Ryan E. Mitchell, Eric S. Swanson
  Prog. Part. Nucl. Phys. 93 (2017) 143
  https://arxiv.org/abs/1610.04528

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QUESTIONS?

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