

Experimental Hadron Spectroscopy

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Indiana University*



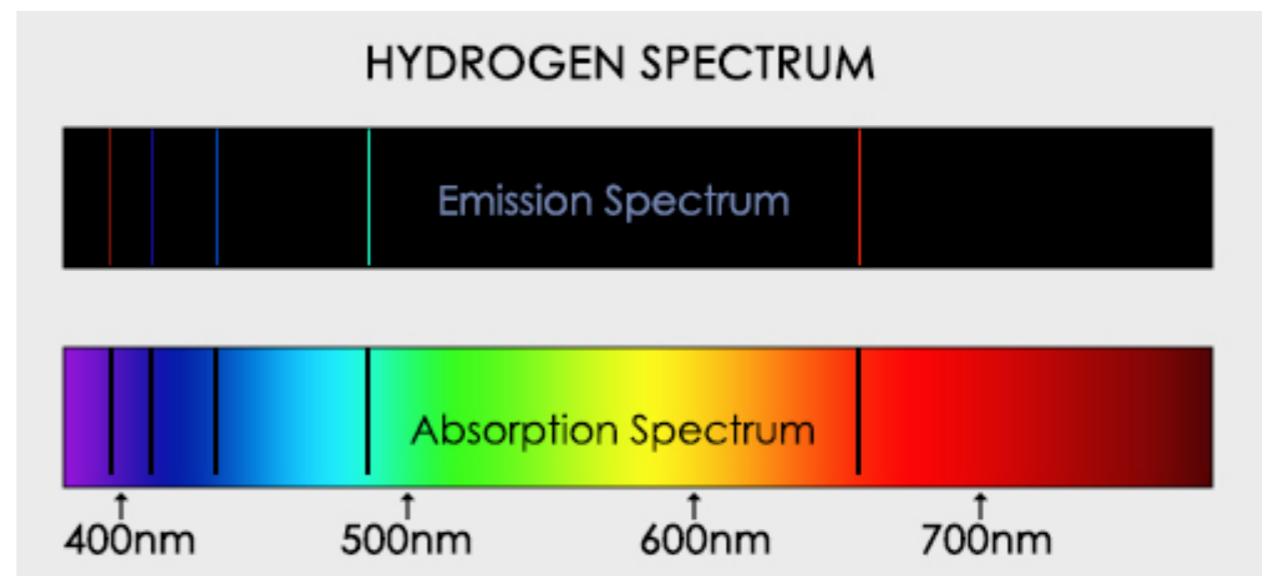
*International Symposium on Multiparticle Dynamics
ISMD 2021*

07 / 14 / 2021

Why Spectroscopy?

- **Atomic spectroscopy:**

- Famous example: Hydrogen absorption / emission spectrum
- Enabled study of electromagnetic processes

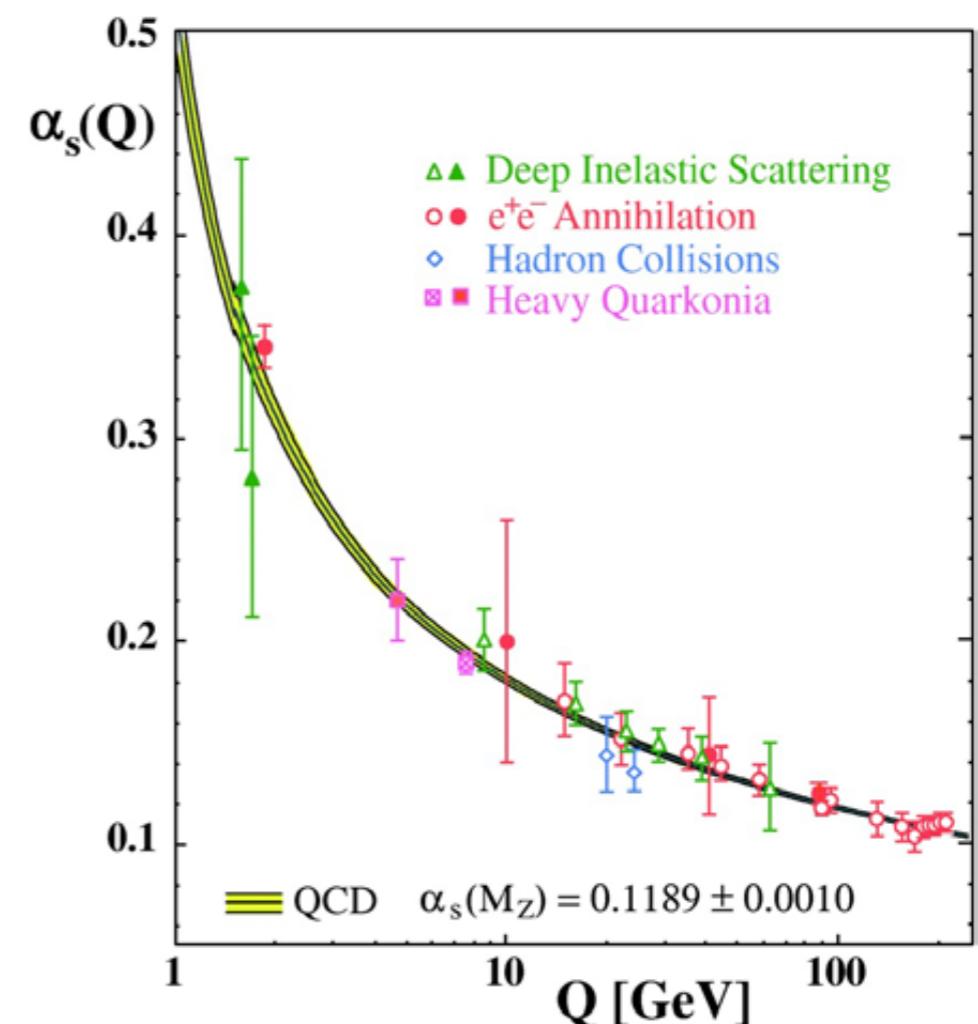


- **Hadron spectroscopy:**

- Study QCD through the excitation spectrum of strong interaction
- What are the correct degrees of freedom?
- What are the effective forces?
- What is the role of gluons?

Will discuss two *selected* topics:

- 1) Charmonium-like tetraquark candidates
- 2) Light hybrid meson candidates

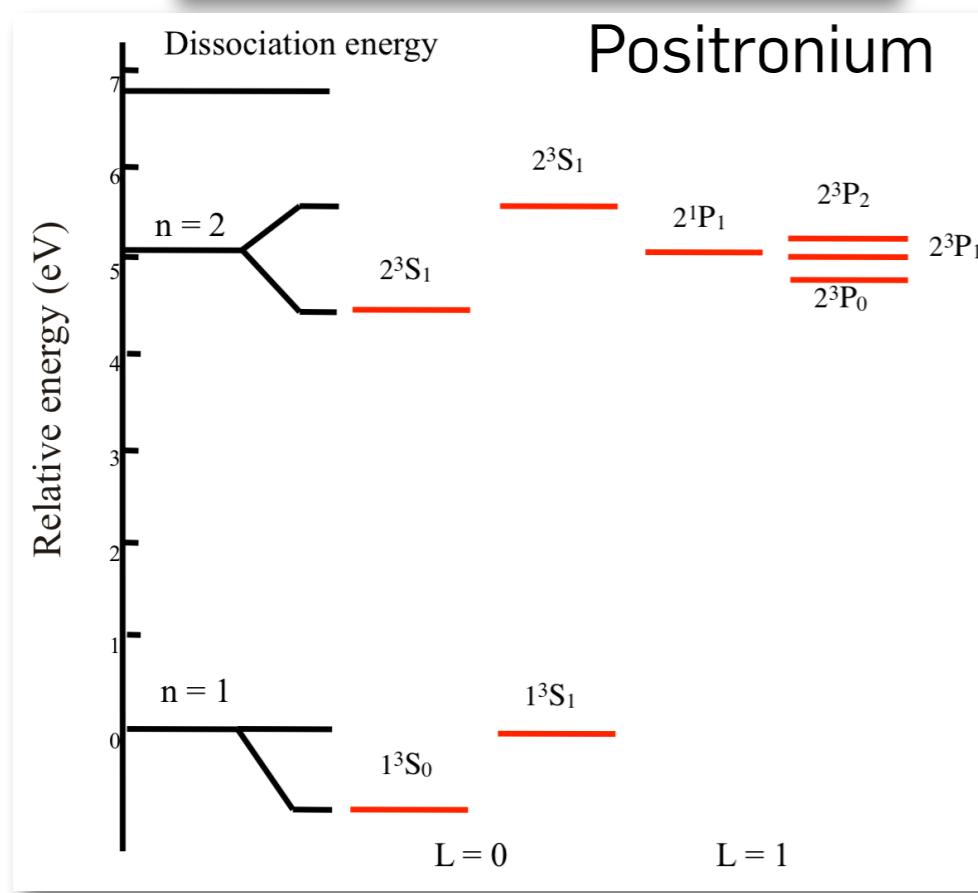
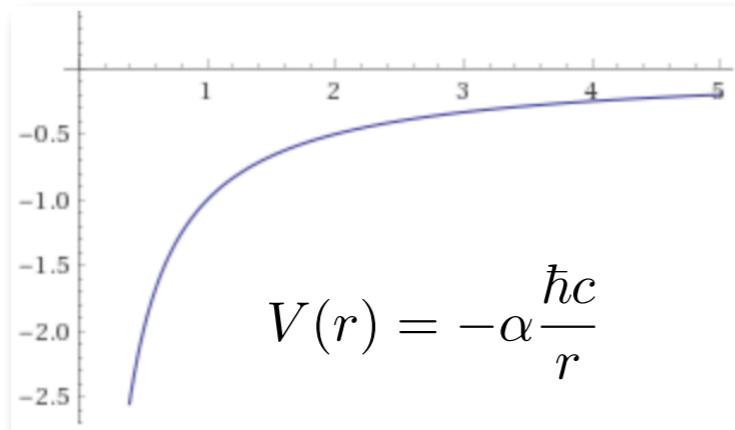


[S.Bethke, Prog.Part.Nucl.Phys. 58, 351 (2007)]

(Hadron) Spectroscopy

QED

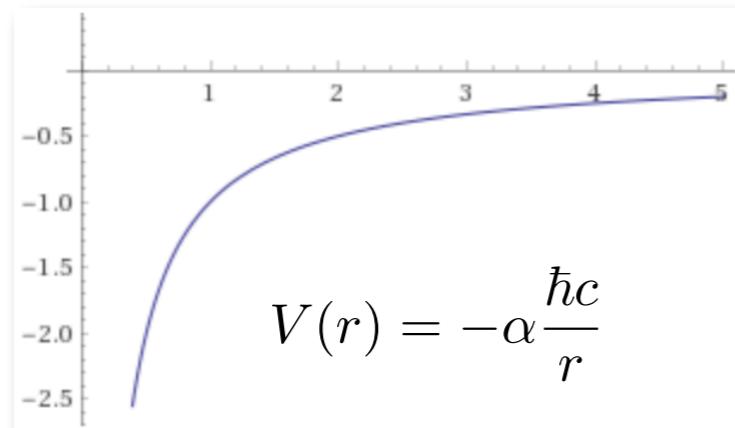
- Coulomb potential for e^+e^- system



(Hadron) Spectroscopy

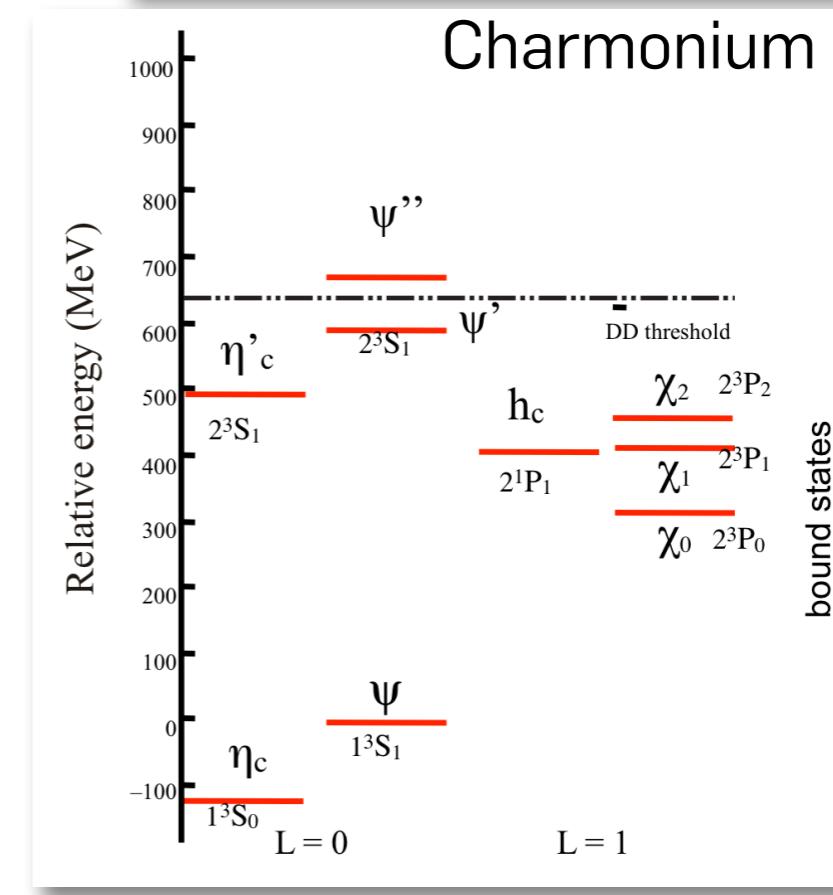
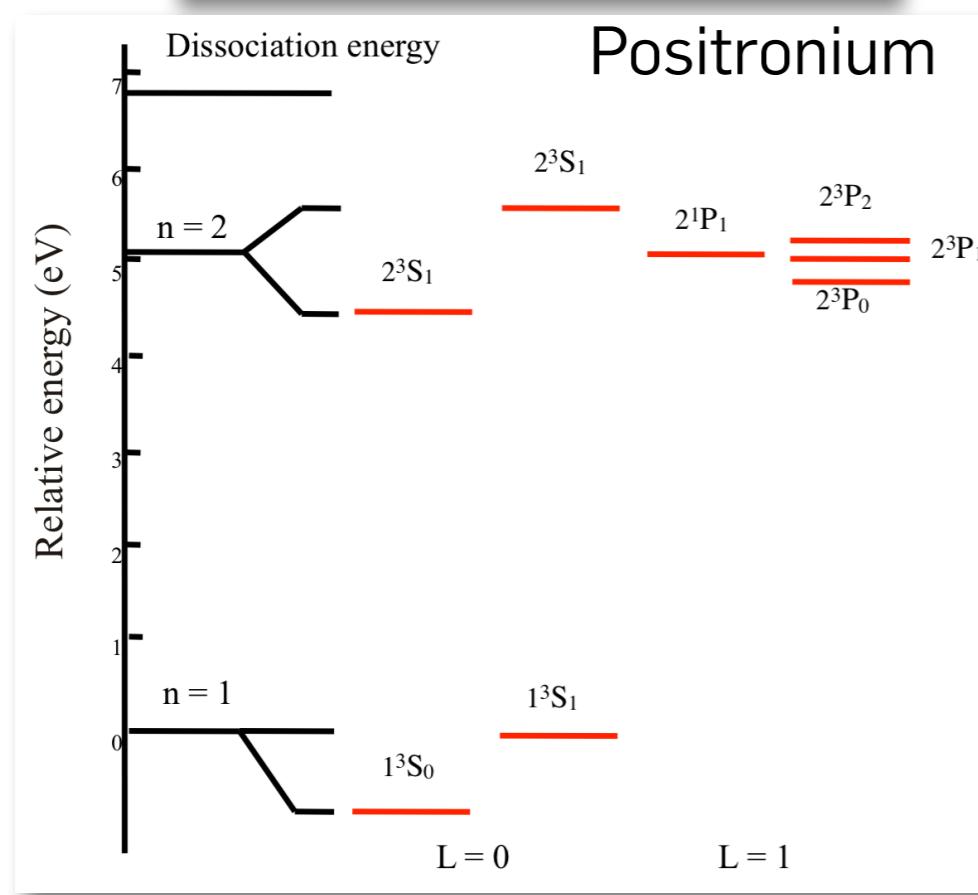
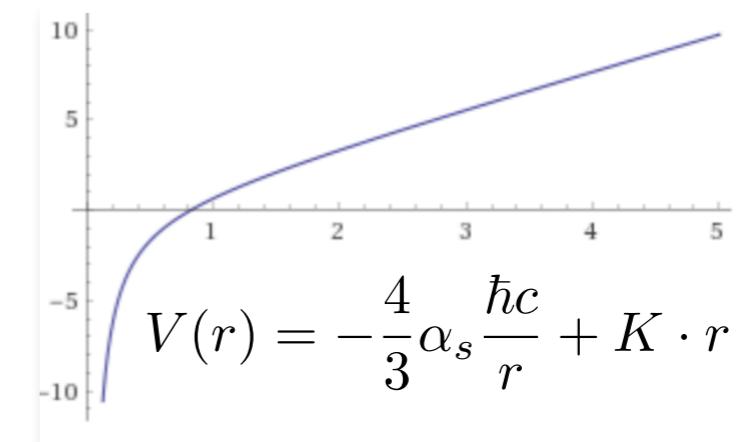
QED

- Coulomb potential for e^+e^- system



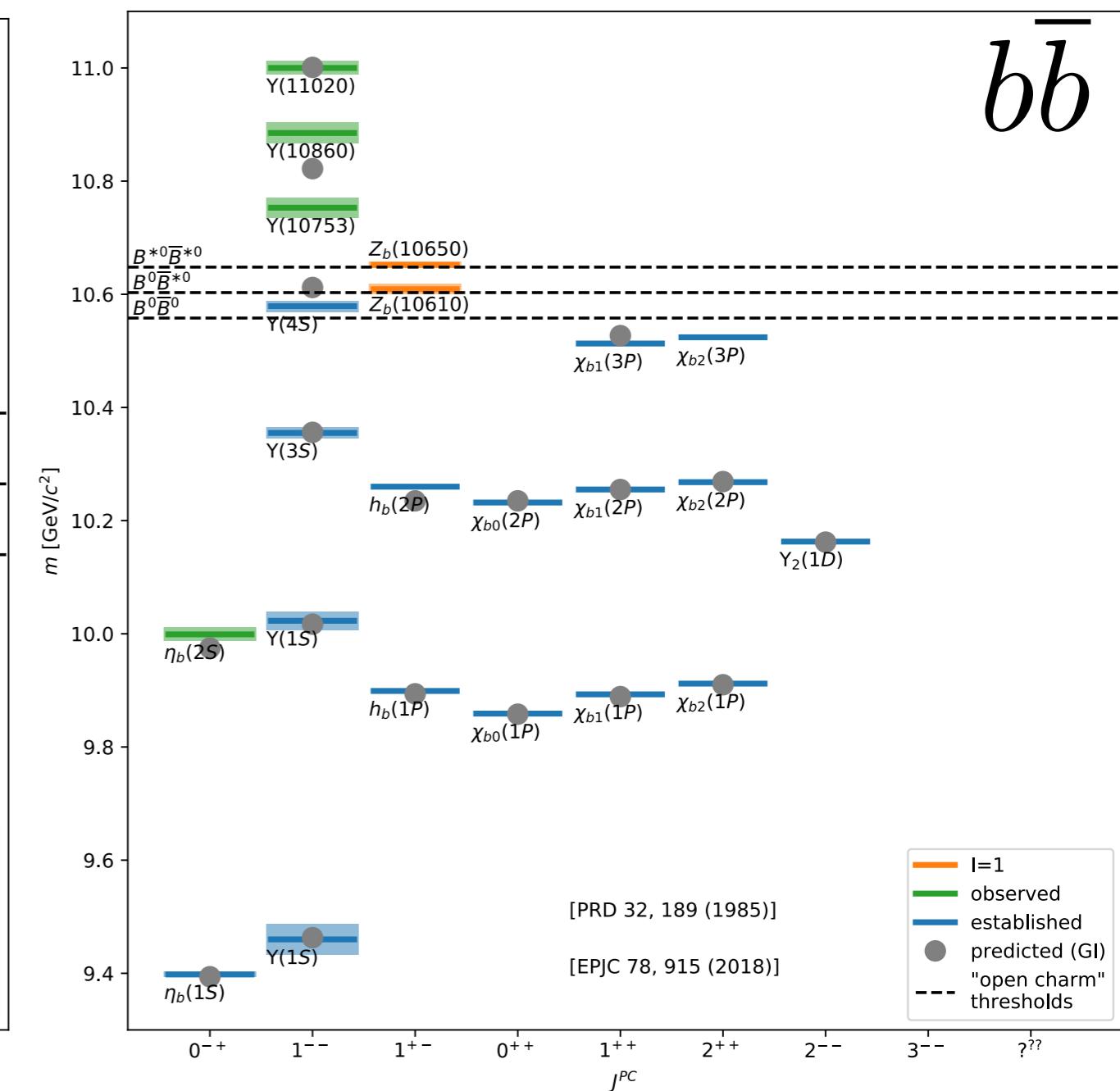
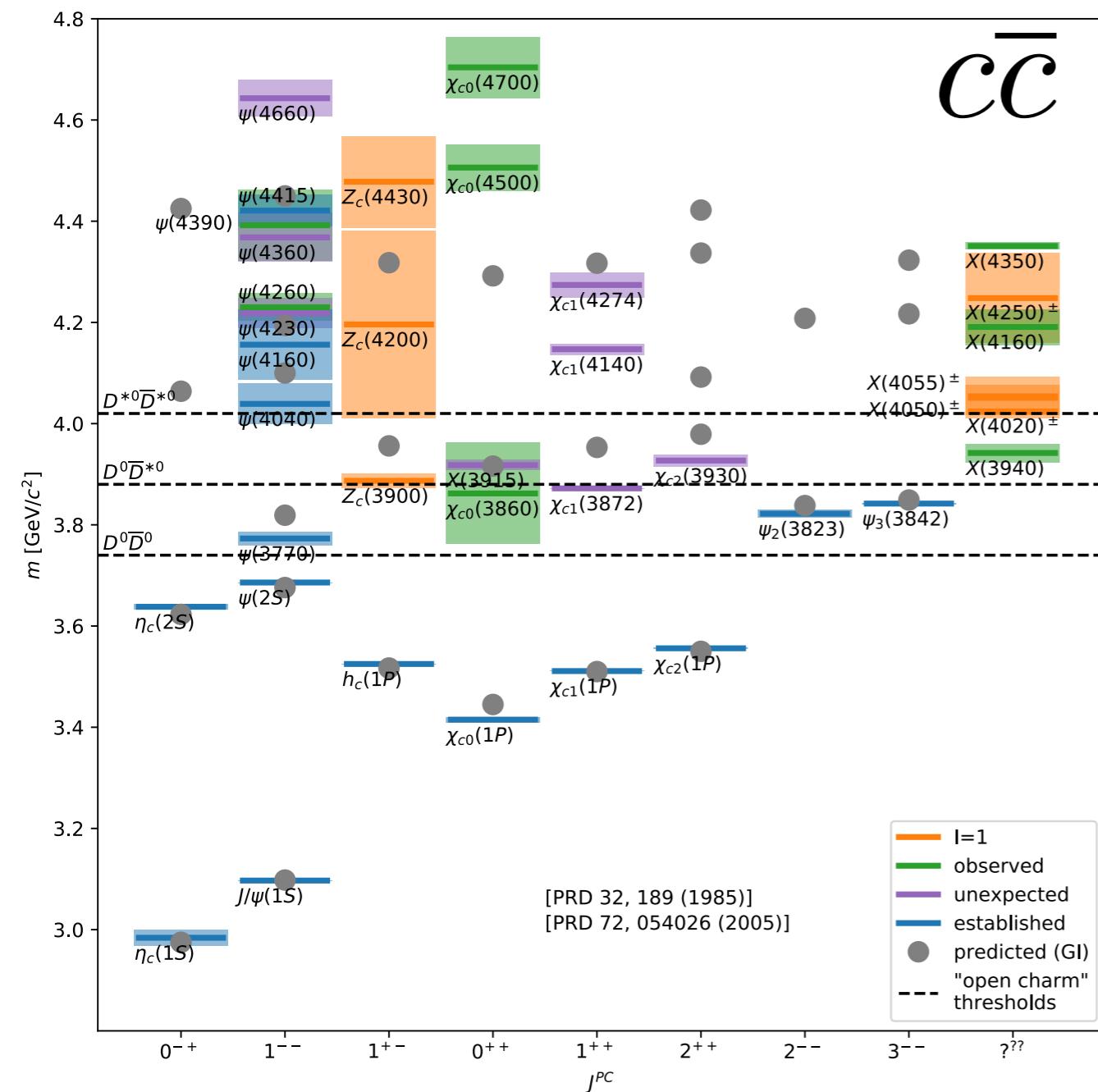
QCD

- Confinement potential for $c\bar{c}$ system



Heavy Quarkonia

- Potential model: Reasonable results below open-flavor thresholds
- Surprises: BaBar (SLAC, USA) and Belle (KEK, Japan), BESIII (IHEP, China) find unpredicted states



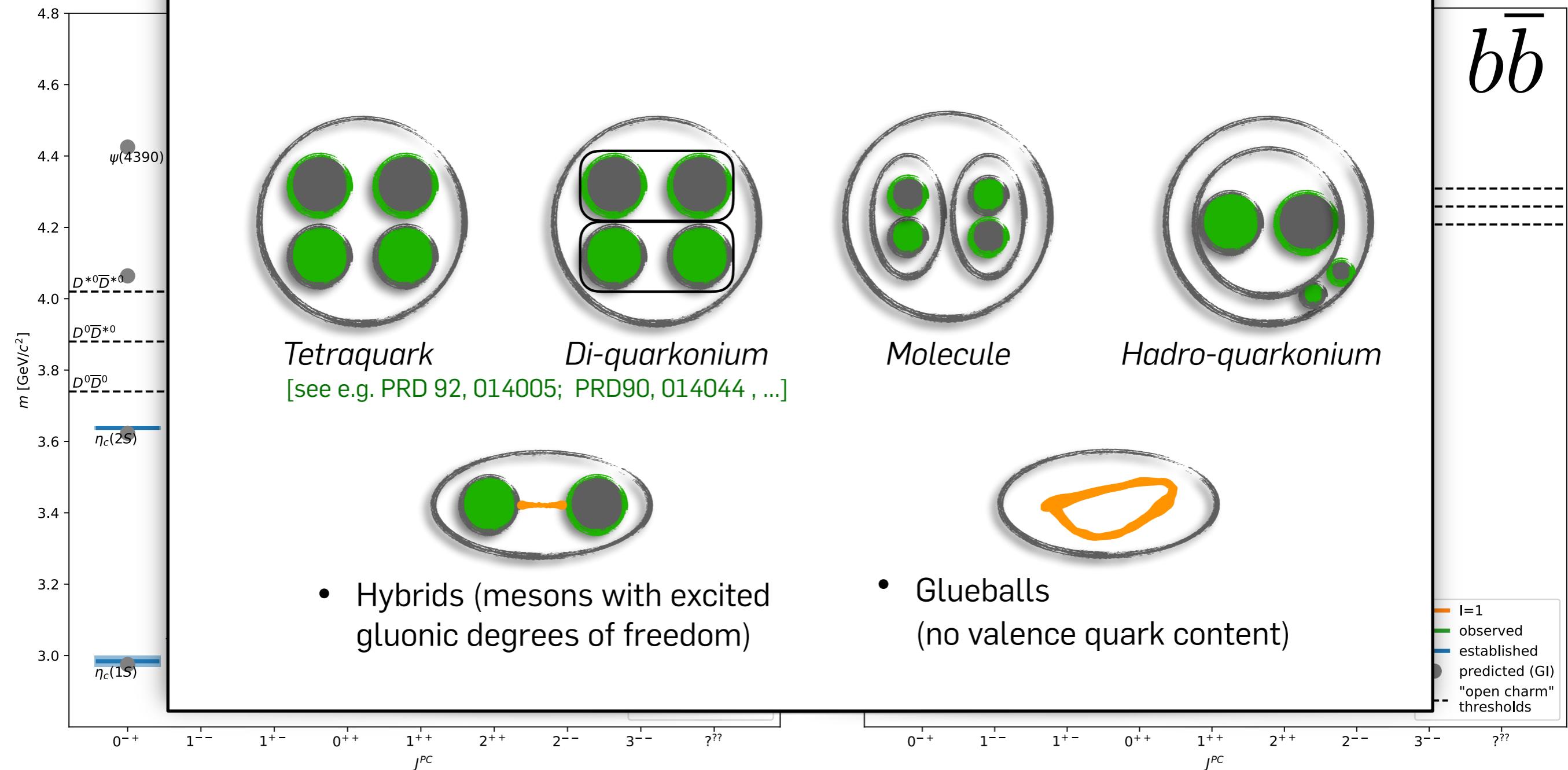
Heavy Quarkonia

- Potential model: Reasonable results below open flavor thresholds

- Surprisingly few exotic states found

China)

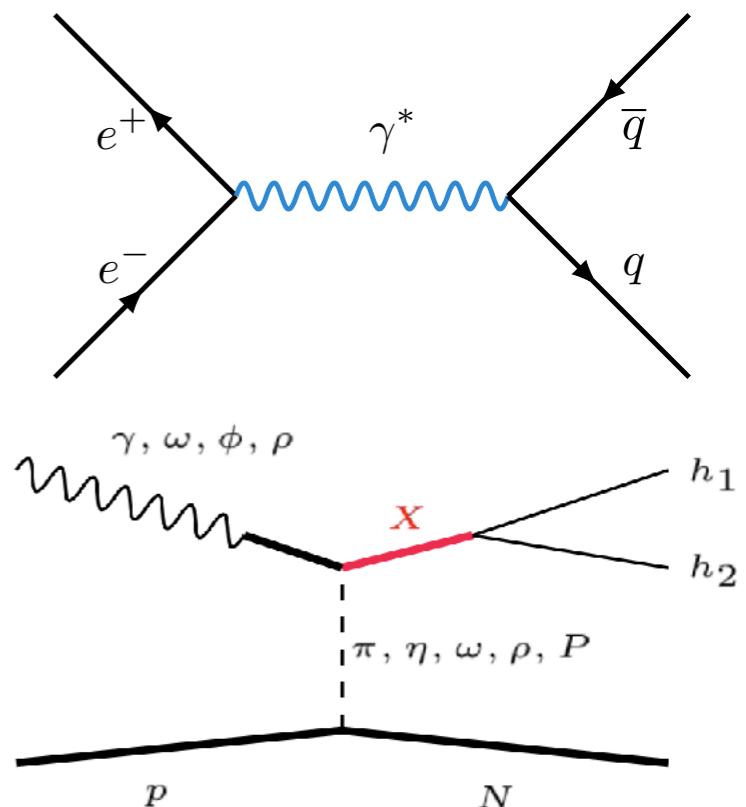
Possible configurations for inner structure:



Production of Hadrons

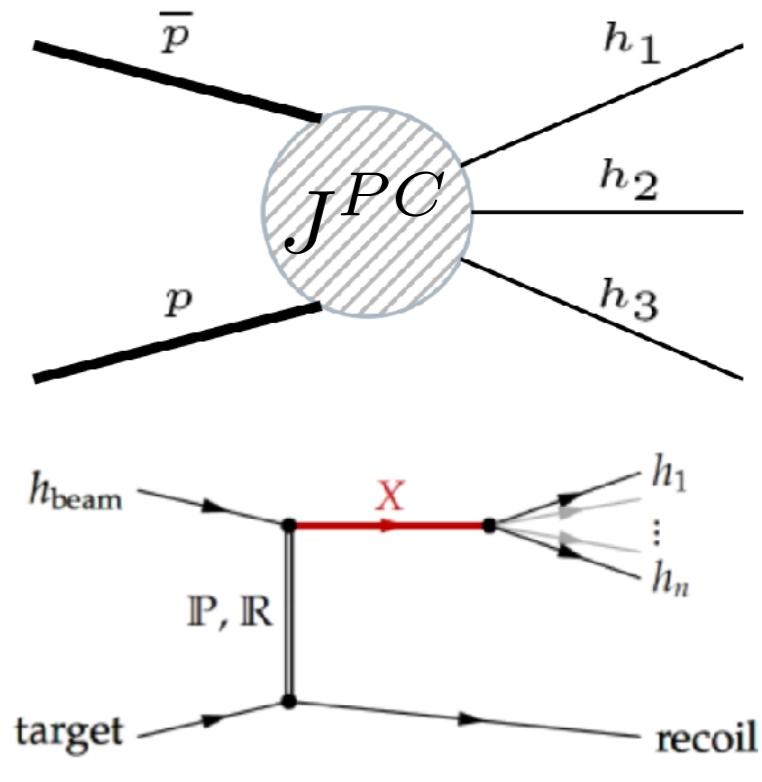
- **Electromagnetic probes:**

- e^+e^- annihilation
(CLEO, BaBar, Belle(2), BESIII, ...)
- Only direct production of $J^{PC} = 1^{--}$
- γN Photoproduction
(GlueX, CLAS, CBELSA, ...)



- **Hadronic probes:**

- pp collisions (ATLAS, CMS, LHCb, ...) = multiple quark-gluon collisions
- $\bar{p}p$ annihilation (CB/LEAR, E835, PANDA) = annihilation of quark-antiquark pairs → All non-exotic J^{PC} directly accessible
- πN collisions (COMPASS, VES, ...)

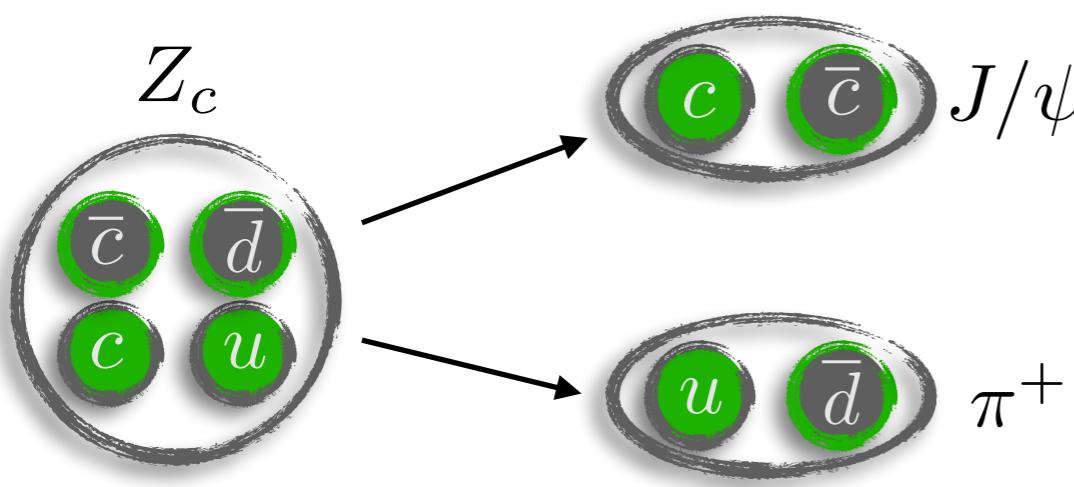


New Discoveries at BESIII/Belle

- New state found in e^+e^- annihilations

The charged Z_c :

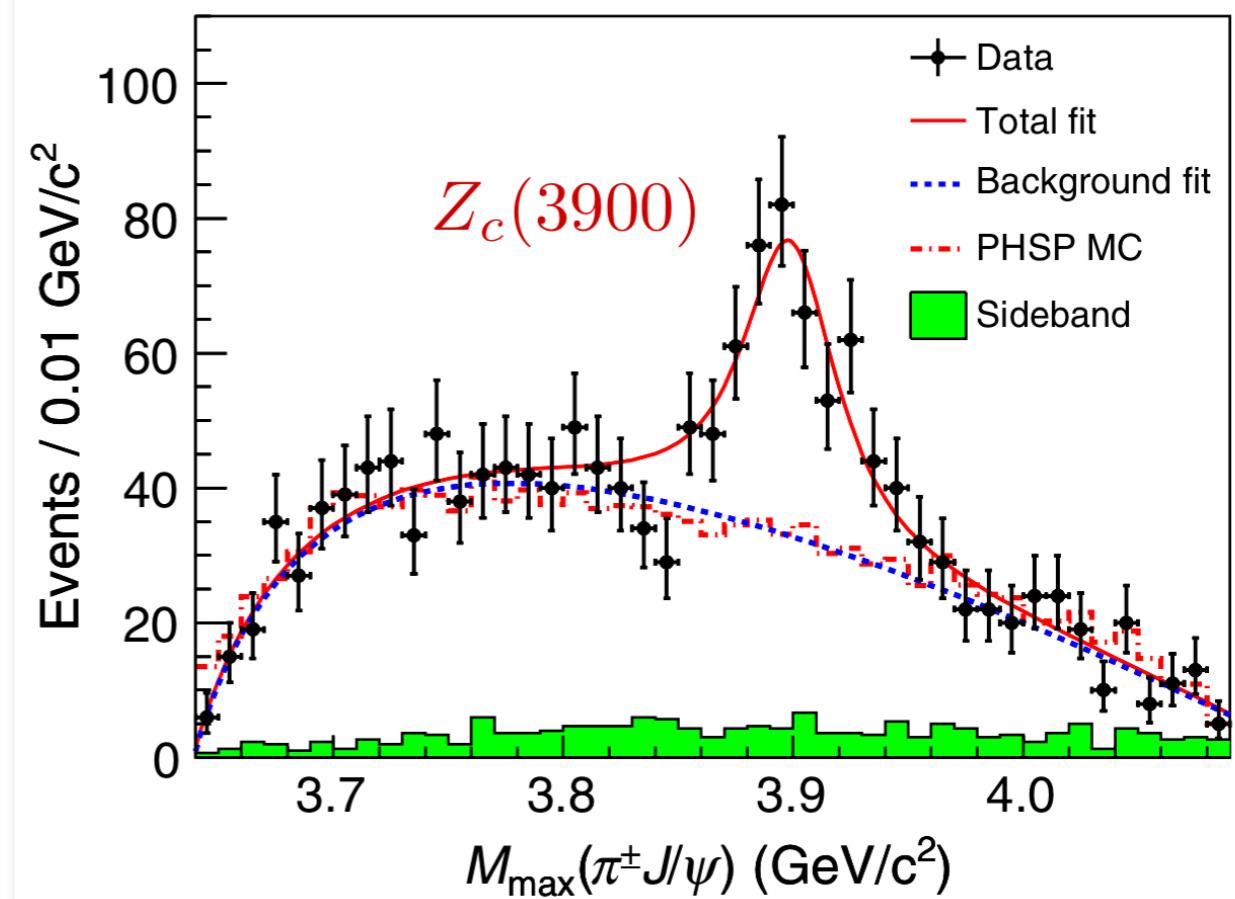
- Observed state decays into charmonium + charged light meson



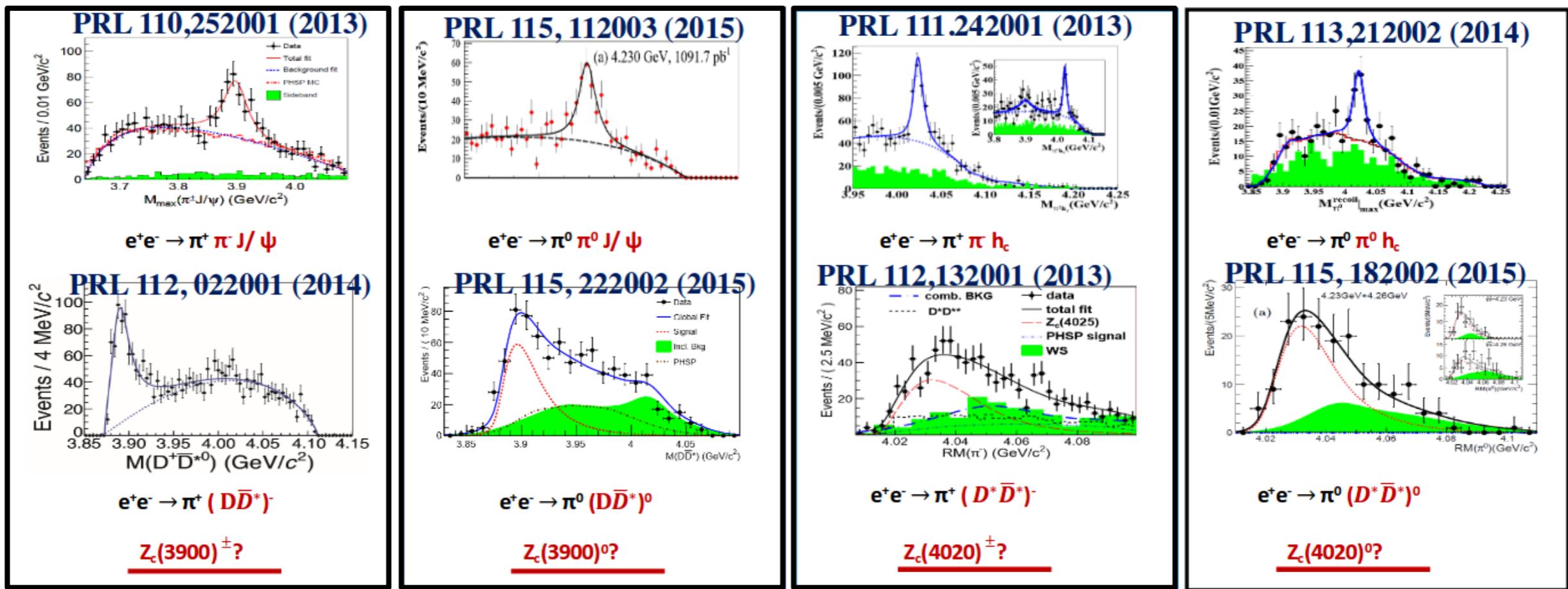
→ If it is a resonance, minimum quark content is $c\bar{c}u\bar{d}$

Obviously exotic!

$e^+e^- \rightarrow \pi^\pm Z^\mp; Z^\mp \rightarrow \pi^\mp J/\psi$ at BESIII
PRL110,252001 (2013)



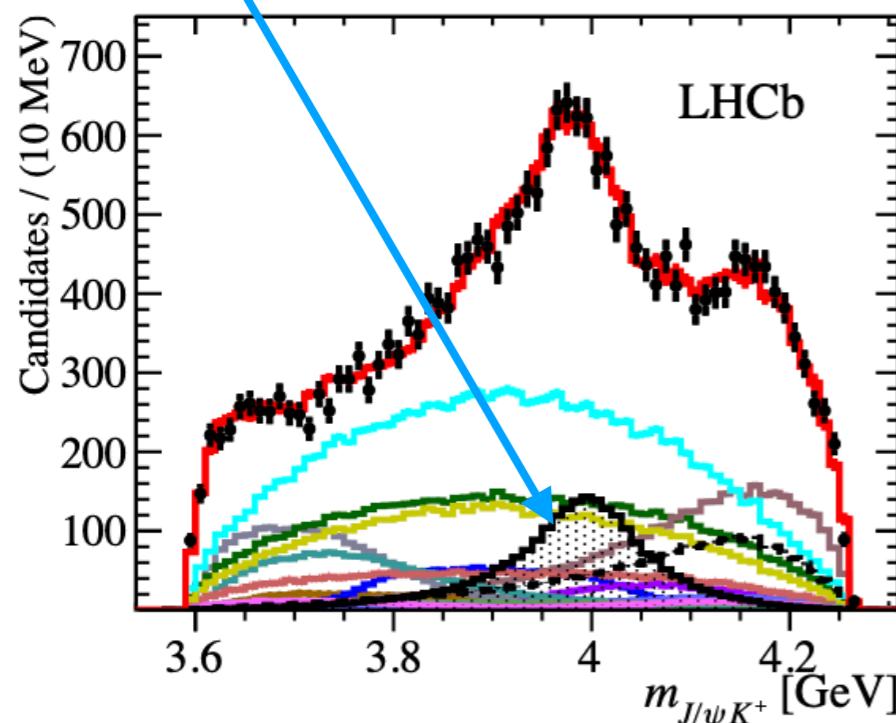
New Discoveries at BESIII/Belle



- Two isospin triplets of charged charmonium-like states established?
- $Z_c(3900)$: close to DD^* threshold
- $Z_c(4020)$: close to D^*D^* threshold

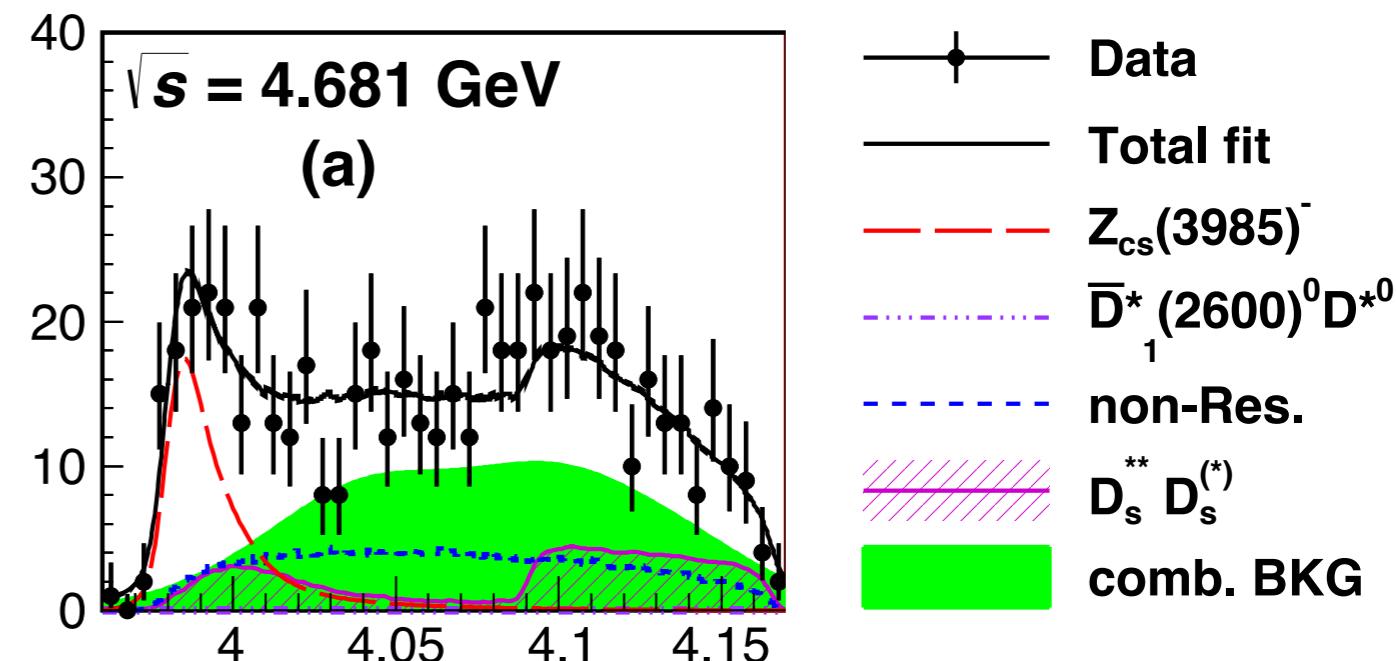
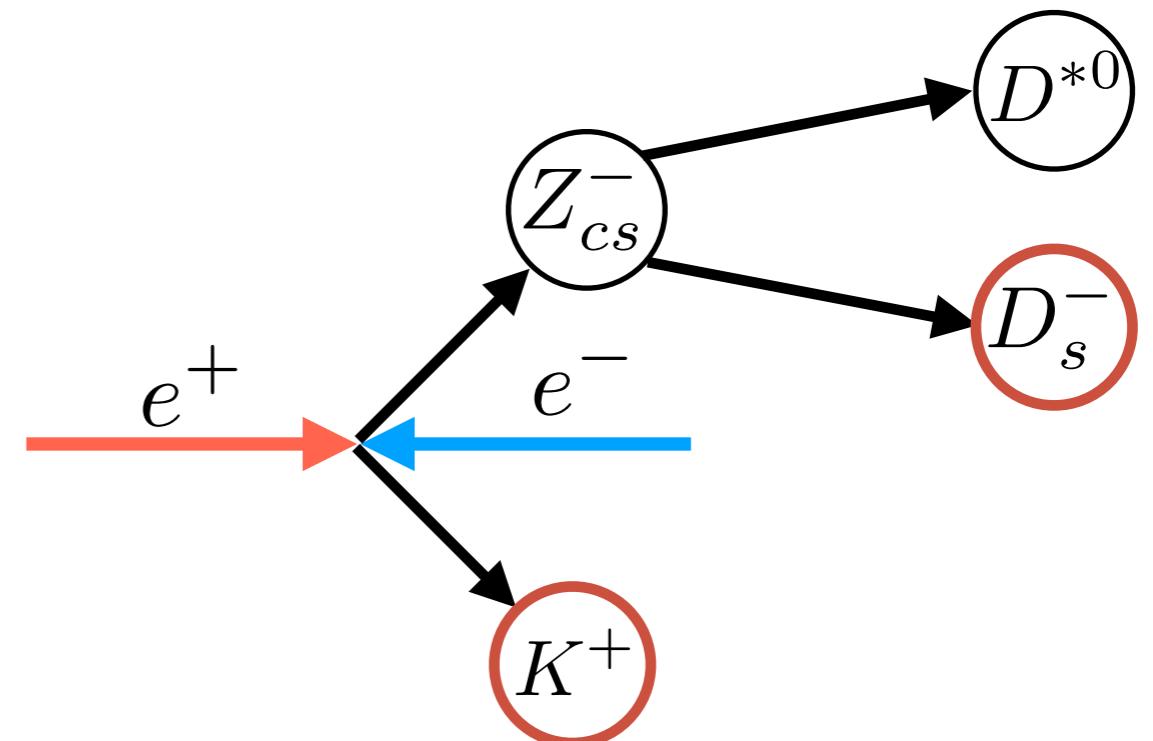
A new member of the Family: $Z_{cs}(c\bar{c}s\bar{u})$

- Partial reconstruction: Tag K^+ and D_s^-
- Observation of structure at threshold in K^+ recoil spectrum
- Enhancement can not be explained by non-resonant process
- Connection to $Z_{cs}(4000)^-$ observed by LHCb in $J/\psi K^+$?



[LHCb, arXiv:2103.01803]

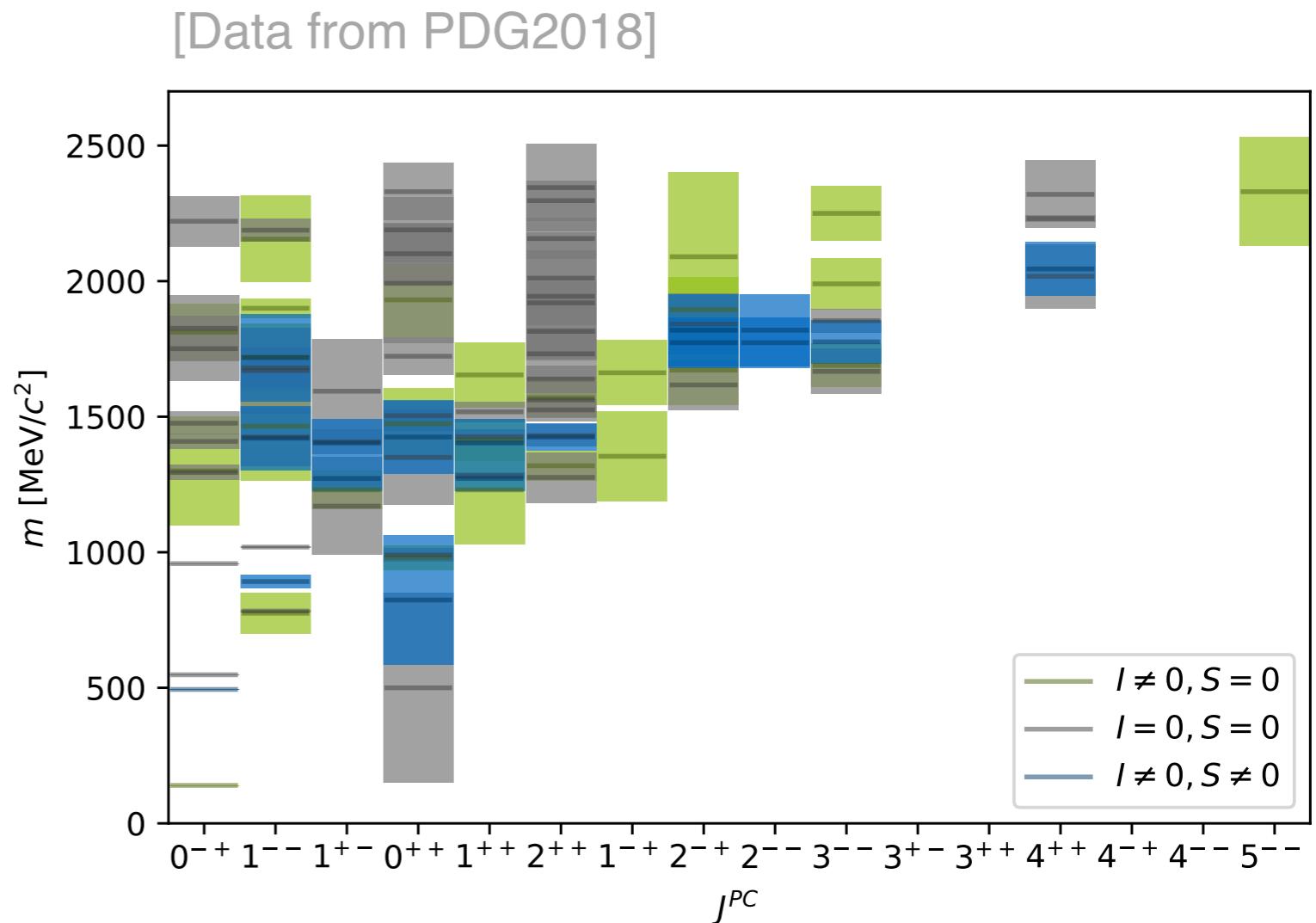
$$e^+ e^- \rightarrow K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$$



[BESIII, PRL126.102001(2021)]

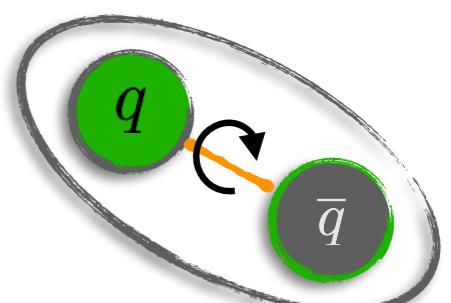
The Light Meson Sector

- Many broad and overlapping states discovered
- Assignment to multiplets ambiguous
- Fundamental to gain deeper understanding of strong interaction
- Ideally: Combine different **production and decay modes**

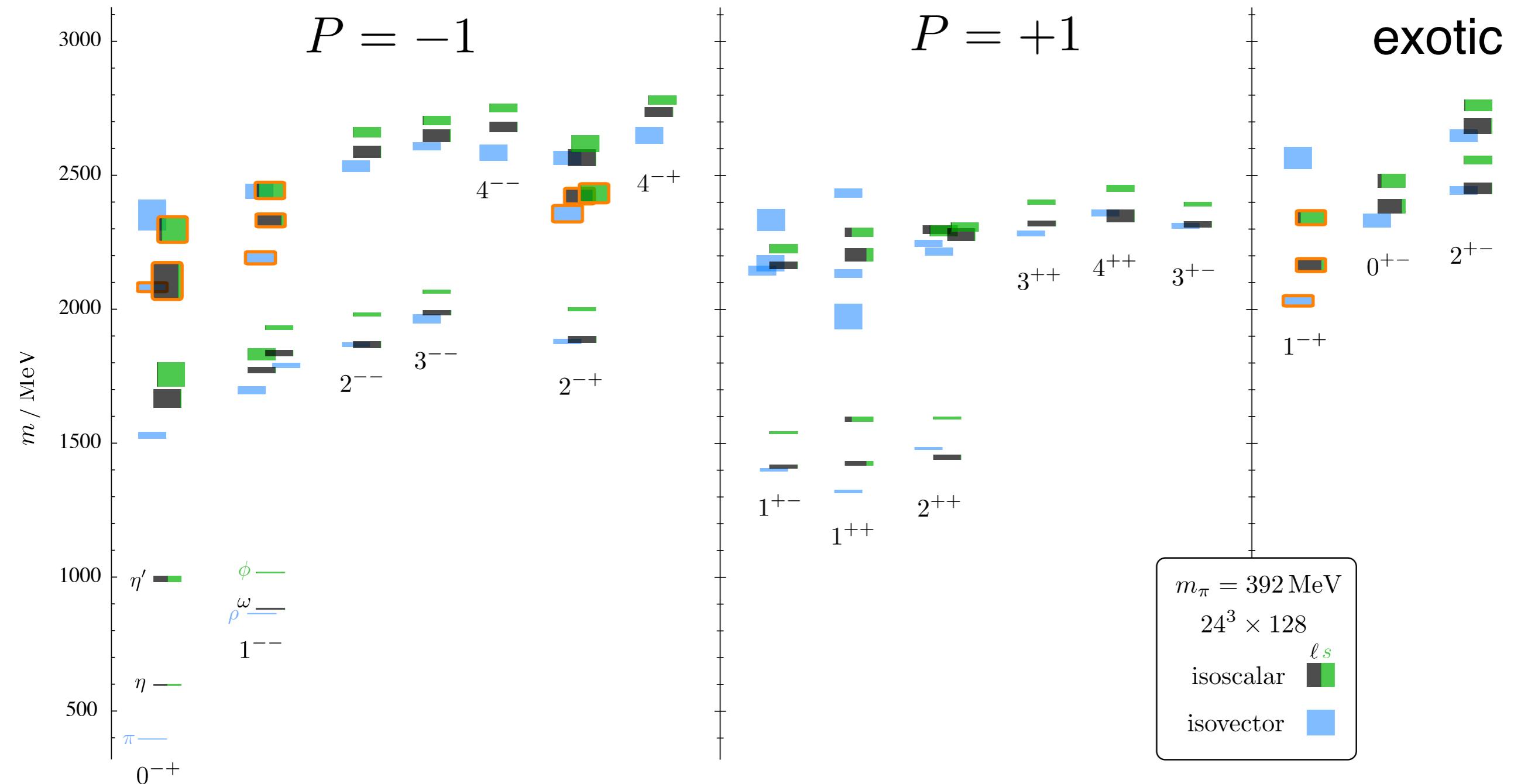


- Hunting ground for mesons with explicit gluonic degrees of freedom (“hybrids”)
- “Smoking gun”: J^{PC} quantum numbers not allowed for $q\bar{q}$

$$P = (-1)^{L+1} \quad C = (-1)^{L+S} \Rightarrow J^{PC} = 0^{-+}, 0{++}, 1{--}, 1{+-}, 2{++}, \dots$$



Light Quark Mesons from Lattice QCD

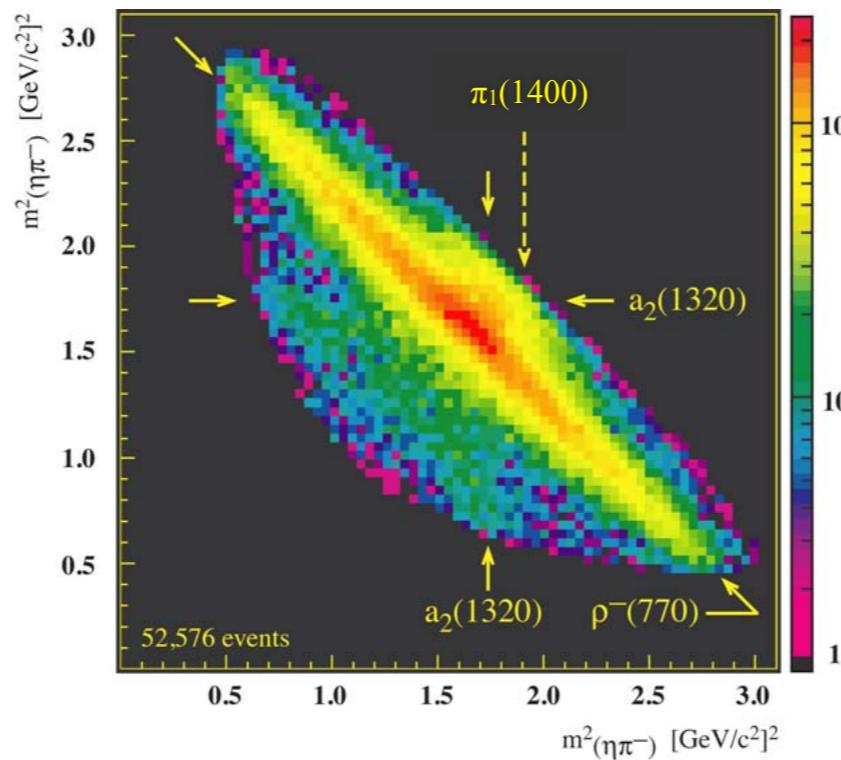
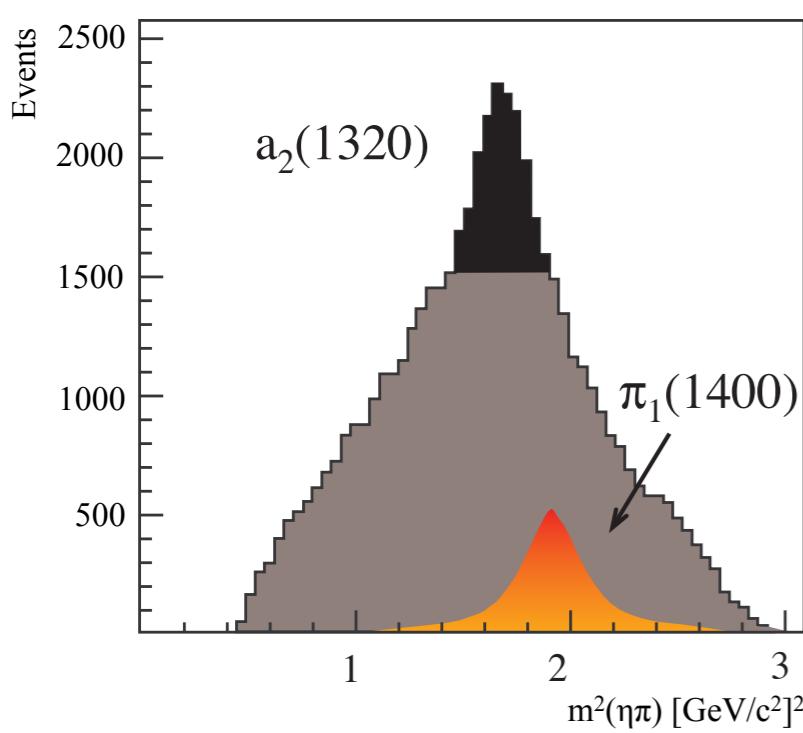


[J.Dudek, R.Edwards, P.Guo, C.Thomas, PRD **88** 094505(2013)]

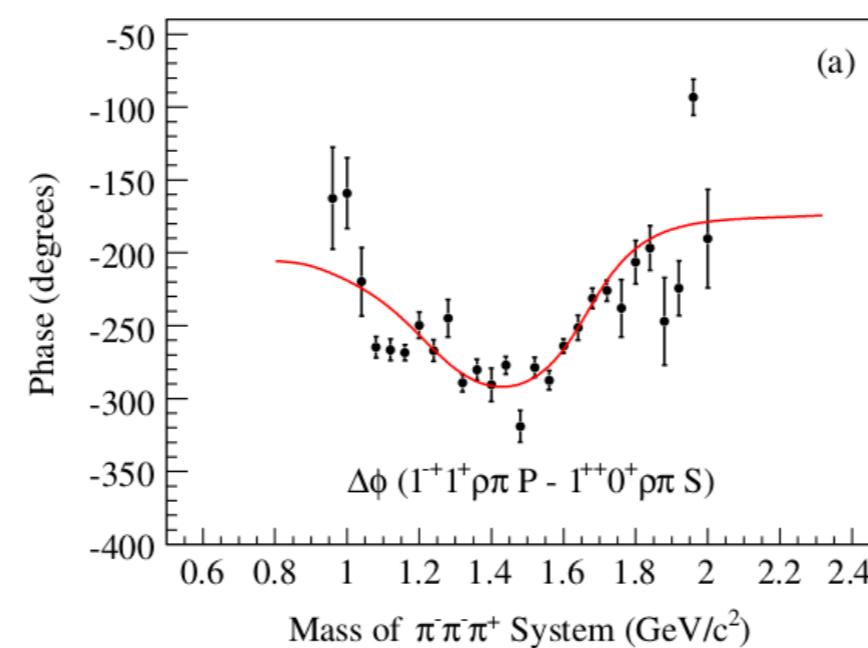
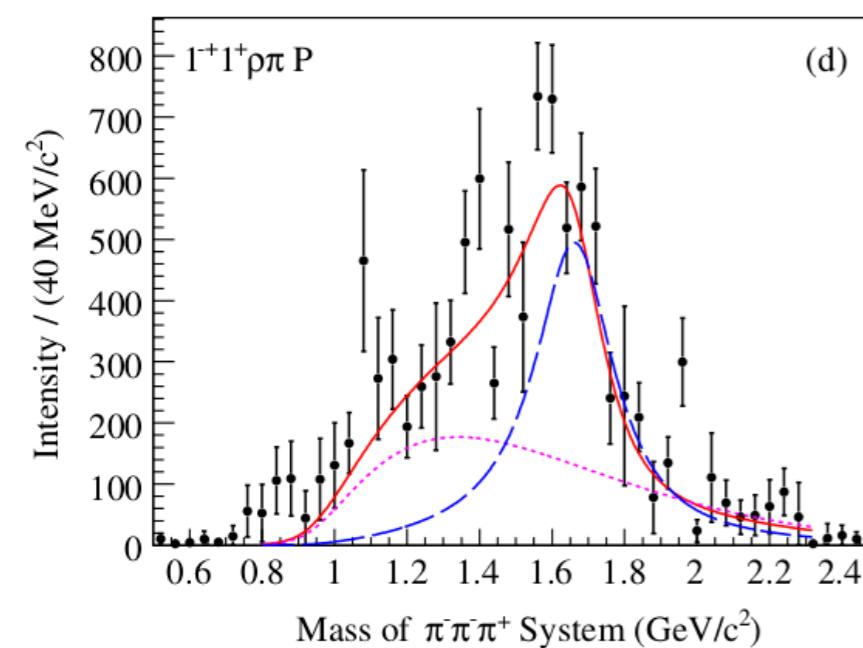
- Lightest spin-exotic state: $J^{PC} = 1^{-+}$, $M \approx 2 \text{ GeV}/c^2$
- Recent calculations: Large coupling of 1^{-+} state to axial vector – pseudoscalar channels
[A.Woss, J.Dudek, R.Edwards, C.Thomas, D.Wilson, PRD **103** (2021) 054502]

Hybrid Mesons

PLB 423, 175-184 (1998), Crystal Barrel

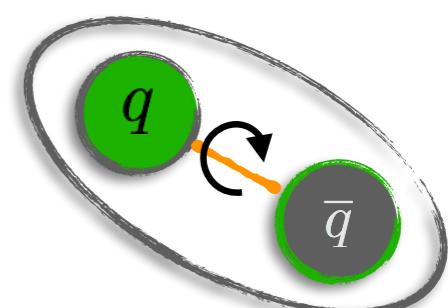


PRL 104, 241803 (2010), COMPASS



- Hints for spin-exotic states already in 1980s
- Observed at various experiments
- From PWA: $J^{PC} = 1^{-+}$
 - $\pi_1(1400)$ in $\eta\pi$
 - $\pi_1(1600)$ in $\eta'\pi, \rho\pi$

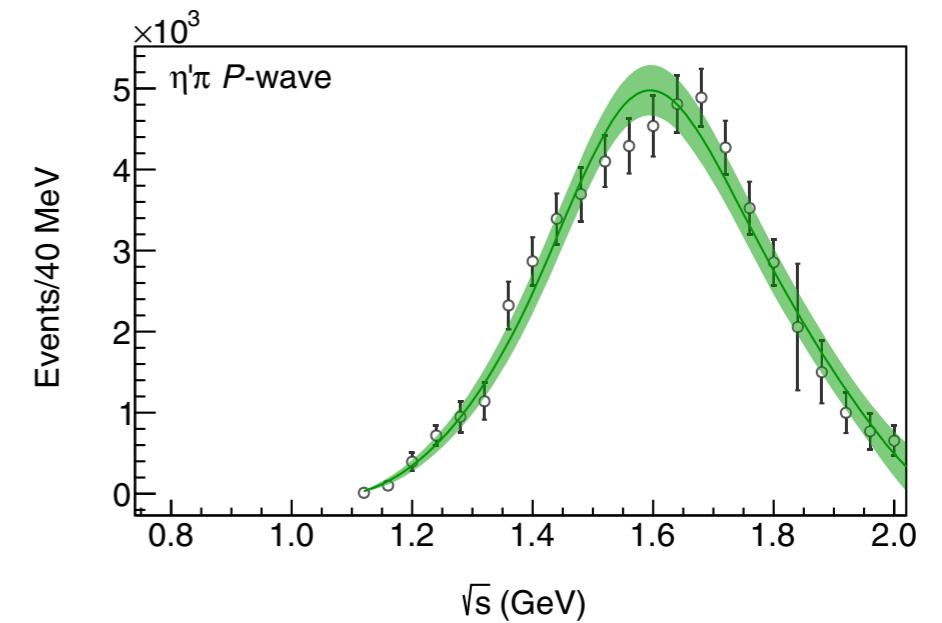
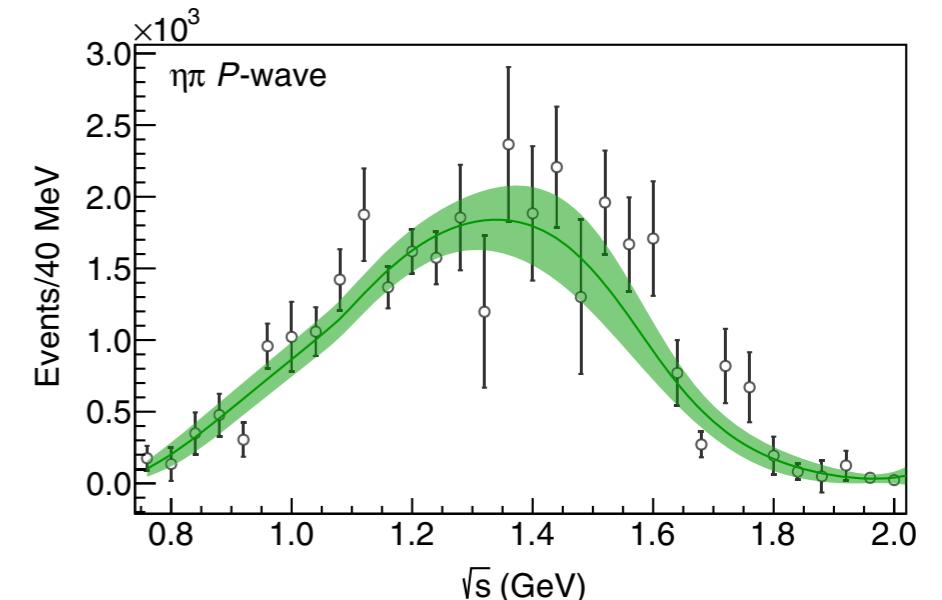
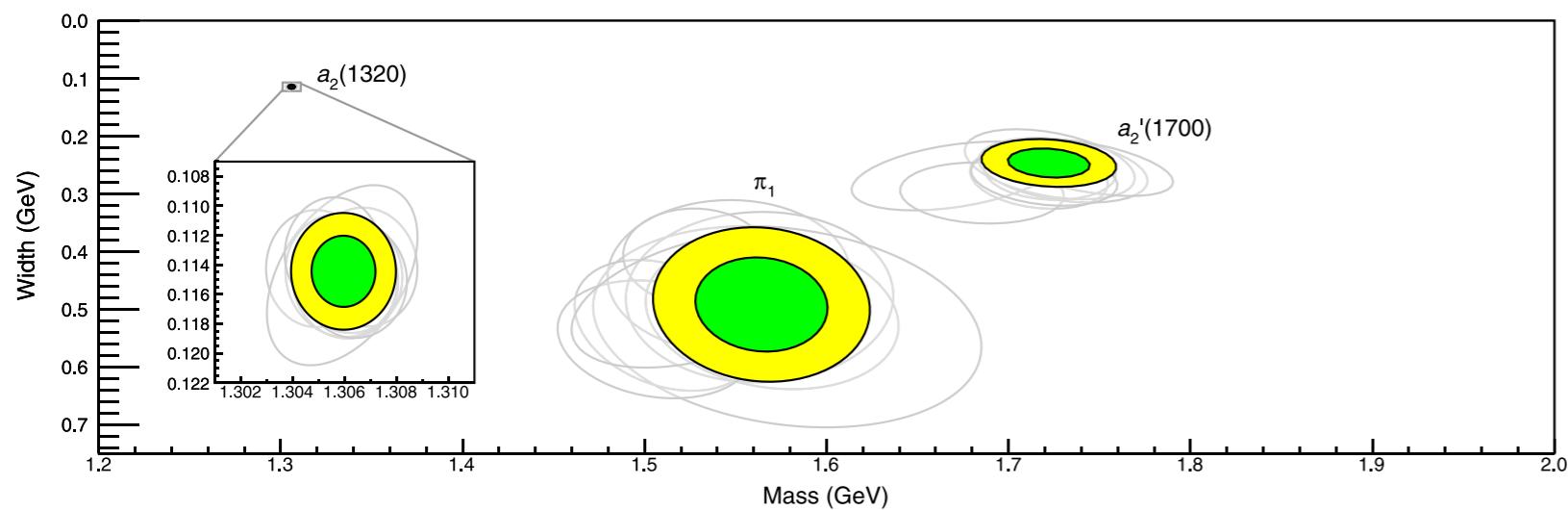
- Clear contribution of exotic wave
- Two genuine resonances?



Two Hybrid Mesons?

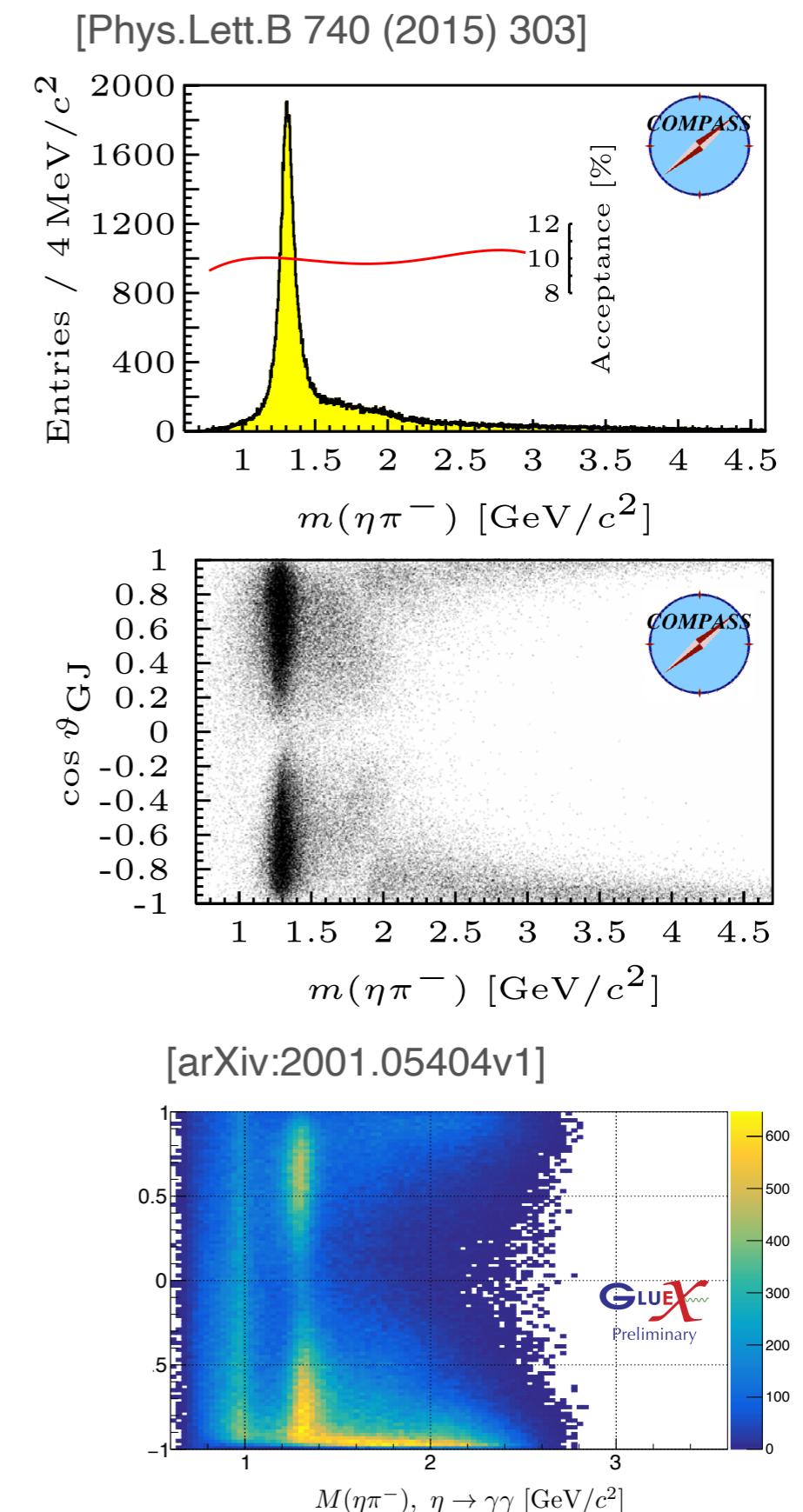
- Recent analysis of COMPASS data in $\eta\pi$, $\eta'\pi$ channels from Joint Physics Analysis Center
- Sophisticated description of 1^{-+} wave with 1-pole, 2-channel K-Matrix
- Enhancements at 1.4GeV in $\eta\pi$, 1.6GeV in $\eta'\pi$ can be described by a single pole!
- $\pi_1(1400)$ and $\pi_1(1600)$ are the same?

[A.Rodas et.al. PRL 122, 042002 (2019)]



The $\eta^{(')}\pi$ System

- Strongest evidence for π_1 contribution in $\eta\pi$, $\eta'\pi$ and $\rho\pi$ channels in πN and $\bar{p}p$ reactions
- Important to study in different production processes
- GlueX Experiment at Jefferson Lab:
 - Photoproduction experiment using 9 GeV linearly polarized photon beam
 - Analyses of $\eta^{(')}\pi$ channels underway
 - Multiple charge combinations and decay modes accessible
- Extend search for exotics beyond π_1 candidates
- Map out spectrum of light hybrids



Summary & Conclusion

- Hadron spectroscopy is entering precision era
 - Systematic investigations have proven necessary
 - Hadron spectroscopy is a worldwide endeavor
- The Future of (Meson) Spectroscopy - What do we expect?
 - Higher statistics and better resolution
 - New accelerators and experiments



- What do we need?
 - Complete and unambiguous knowledge of all multiplets
 - Close collaborations between experiments and theory
 - Sophisticated analysis methods