European Nuclear Physics Conference 2022 (EuNPC 2022)

24–28 Oct 2022
University of Santiago de Compostela
Europe/Madrid timezone

Hadron Spectroscopy: an experimental overview

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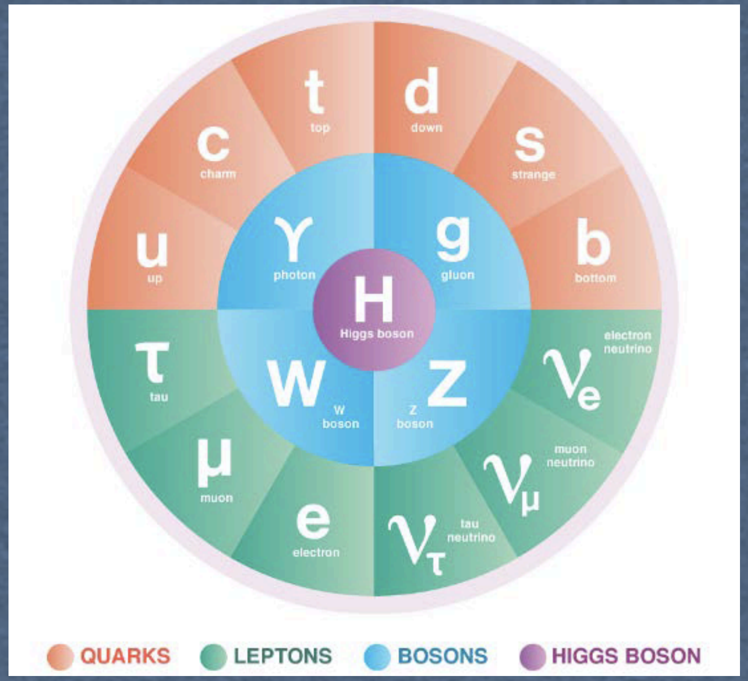
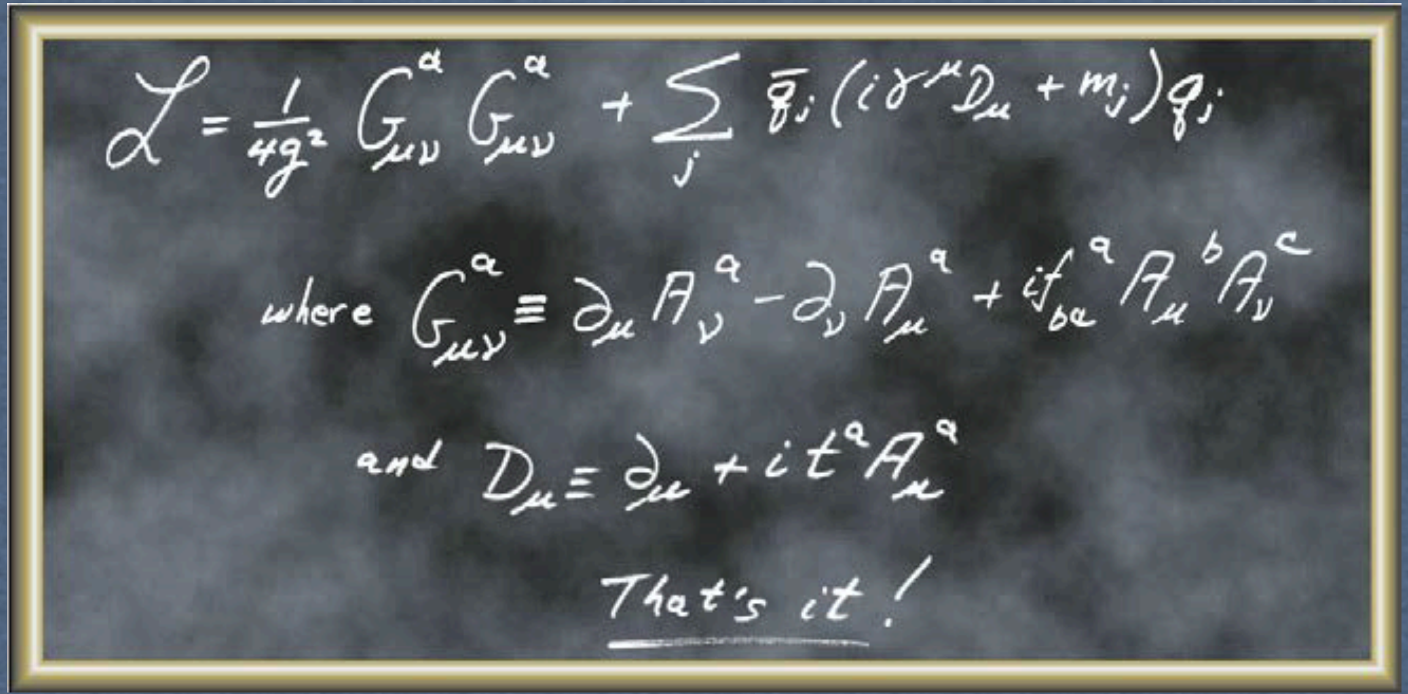
Hadrons and QCD

- Most of the mass of the matter that surrounds us is due to protons and neutrons that make up the atomic nuclei
- Quantum Chromo-Dynamics is the theory that describes the strong interaction
- Baryons and mesons are made of quarks and gluons, interacting by the strong force in a non-perturbative regime



Standard Model of particles and interactions



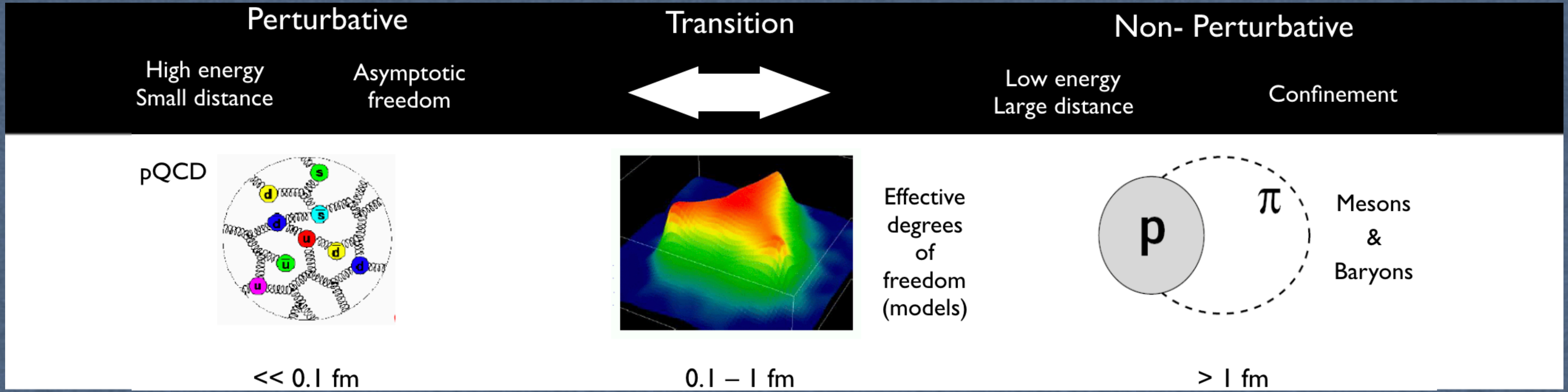
Frank Wilczek, Physics Today, August 2000

QCD (beauty) and non-perturbative QCD (the beast)

- To understand matter we NEED to deal with non-pQCD
- In spite of many years of studies, we still lack a full understanding of the dynamics of strong interaction and many open questions remain

What we do not know

1. **What is the nature of the mass of hadrons?**
   Quarks account for only a small fraction of the mass of the proton (m_u=1.7-3.3 MeV, m_d=4.1-5.8 MeV): what leads to the ~GeV mass?
2. **Which are the relevant degrees of freedom?**
   At high energy, phenomena can be described in terms of quarks and gluons; at low energy, we observed baryons and mesons: what are the real degrees of freedom, and how does the transition from small to large distances occur?
3. **What is the origin of confinement?**
   Are quarks confined within colorless objects? Can we prove and explain it?
4. **Do quark configurations beyond qqq and qq-bar exist?**
   The theory of strong interactions does not prohibit hadronic states with different quark configurations (*5q, gg, 2qg*). Can we find evidence of the existence of such states?



Studying the spectrum of hadrons is a fundamental step to understanding the characteristics of constituents and forces

Hadron Spectroscopy

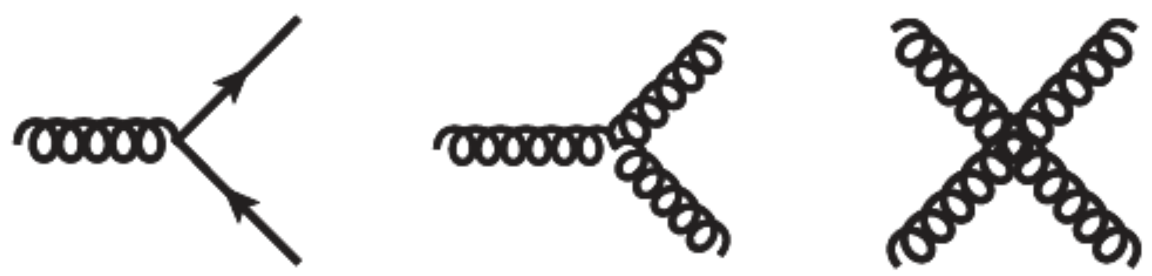
For decades, hadronic spectroscopy was the core of high-energy physics

- 1947: Discovery of $\pi^{\pm}$, $K^{\pm}$, K^{0}
- 1950 - 1965: The hadron zoo; strangeness; the Eightfold Way; the quark model; color charge
- 1974: Charmonium; evidence for asymptotic freedom & QCD
- 1977: Bottomonium; 3rd generation of quarks needed for CP violation
- 1983: First full reconstruction of B meson decays
- 1983: W & Z bosons. Look for the top quark! Look for Higgs! Look for BSM!!
- 1983– Hadron spectroscopy: Fill out the quark-model multiplets

The Quark Model

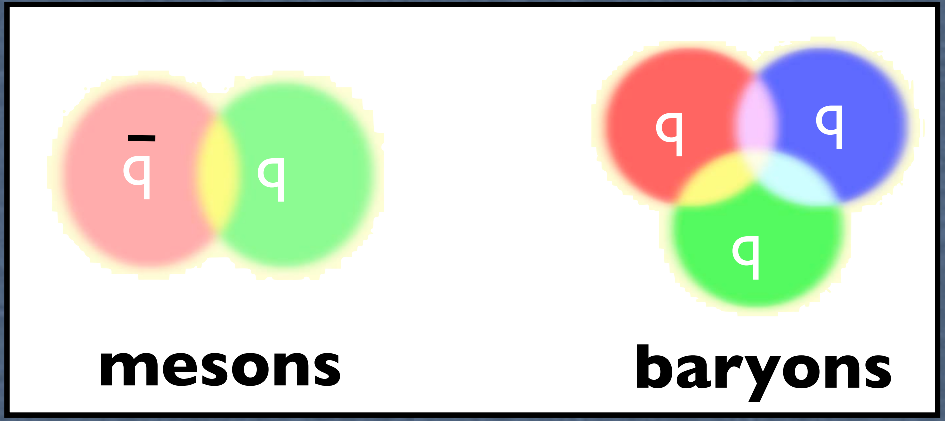
> anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.
>
> *Gell-Mann, Phys. Lett. 8, 1 (1964)*

QCD (gluons)



What we know

Observed mesons and baryons well described by 1st principles QCD



Quarks are confined inside colorless hadrons
they combine to 'neutralize' color force

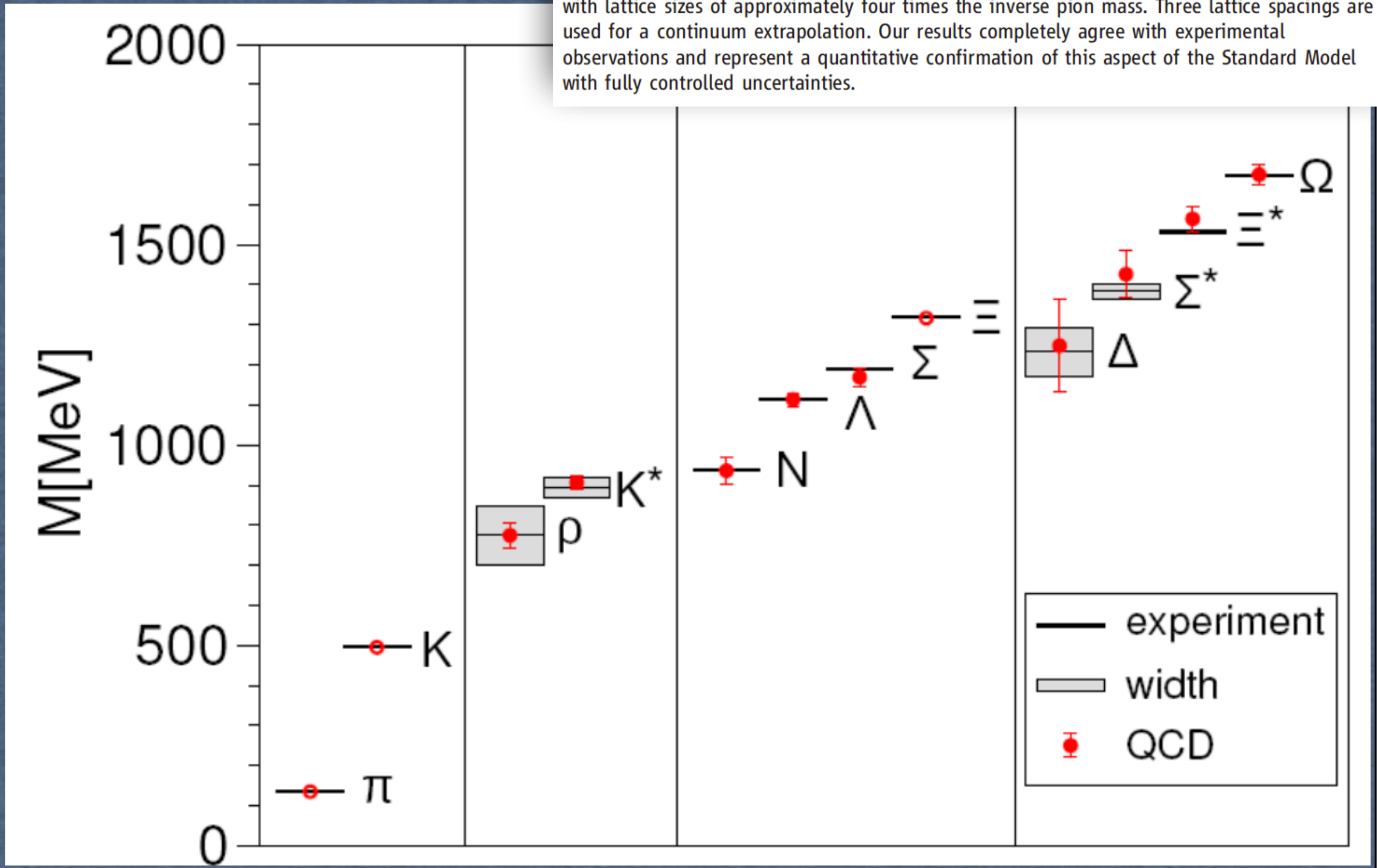
X	Experimental (28)	M_X (Ξ set)	M_X (Ω set)
ρ	0.775	0.775 (29) (13)	0.778 (30) (33)
K*	0.894	0.906 (14) (4)	0.907 (15) (8)
N	0.939	0.936 (25) (22)	0.953 (29) (19)
Λ	1.116	1.114 (15) (5)	1.103 (23) (10)
Σ	1.191	1.169 (18) (15)	1.157 (25) (15)
Ξ	1.318	1.318	1.317 (16) (13)
Δ	1.232	1.248 (97) (61)	1.234 (82) (81)
Σ*	1.385	1.427 (46) (35)	1.404 (38) (27)
Ξ*	1.533	1.565 (26) (15)	1.561 (15) (15)
Ω	1.672	1.676 (20) (15)	1.672

Science 21 Nov 2008:
Vol. 322, Issue 5905, pp. 1224-1227
DOI: 10.1126/science.1163233

Ab Initio Determination of Light Hadron Masses

S. Dürr,[1] Z. Fodor,[1,2,3] J. Frison,[4] C. Hoelbling,[2,3,4] R. Hoffmann,[2] S. D. Katz,[2,3] S. Krieg,[2] T. Kurth,[2] L. Lellouch,[4] T. Lippert,[2,5] K. K. Szabo,[2] G. Vulvert[4]

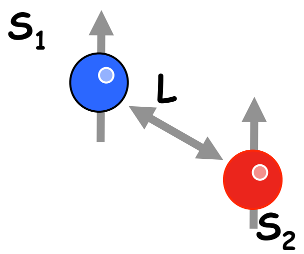
More than 99% of the mass of the visible universe is made up of protons and neutrons. Both particles are much heavier than their quark and gluon constituents, and the Standard Model o particle physics should explain this difference. We present a full ab initio calculation of the masses of protons, neutrons, and other light hadrons, using lattice quantum chromodynamics. Pion masses down to 190 mega–electron volts are used to extrapolate to the physical point, with lattice sizes of approximately four times the inverse pion mass. Three lattice spacings are used for a continuum extrapolation. Our results completely agree with experimental observations and represent a quantitative confirmation of this aspect of the Standard Model with fully controlled uncertainties.



What we know (light q)

Constituent Quark Model

- Quark-antiquark pairs with total spin S=0,1 and orbital angular momentum L



$S=S_1+S_2$ $J= L+S$

$P = (-1)^{L+1}$ $C= (-1)^{L+S}$

Not all the J^{PC} combinations are allowed:

0^{++} 0^{+-} 0^{-+} 0^{--} 1^{++} 1^{+-} 1^{-+} 1^{--} 2^{++} 2^{+-} 2^{-+} 2^{--} 3^{++} 3^{+-} 3^{-+} 3^{--} …

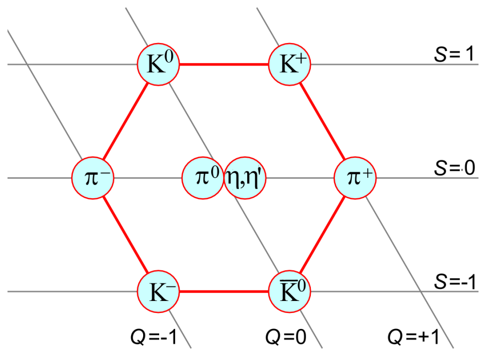
- SU(3) flavor symmetry → nonet (8⊕1) of degenerate states

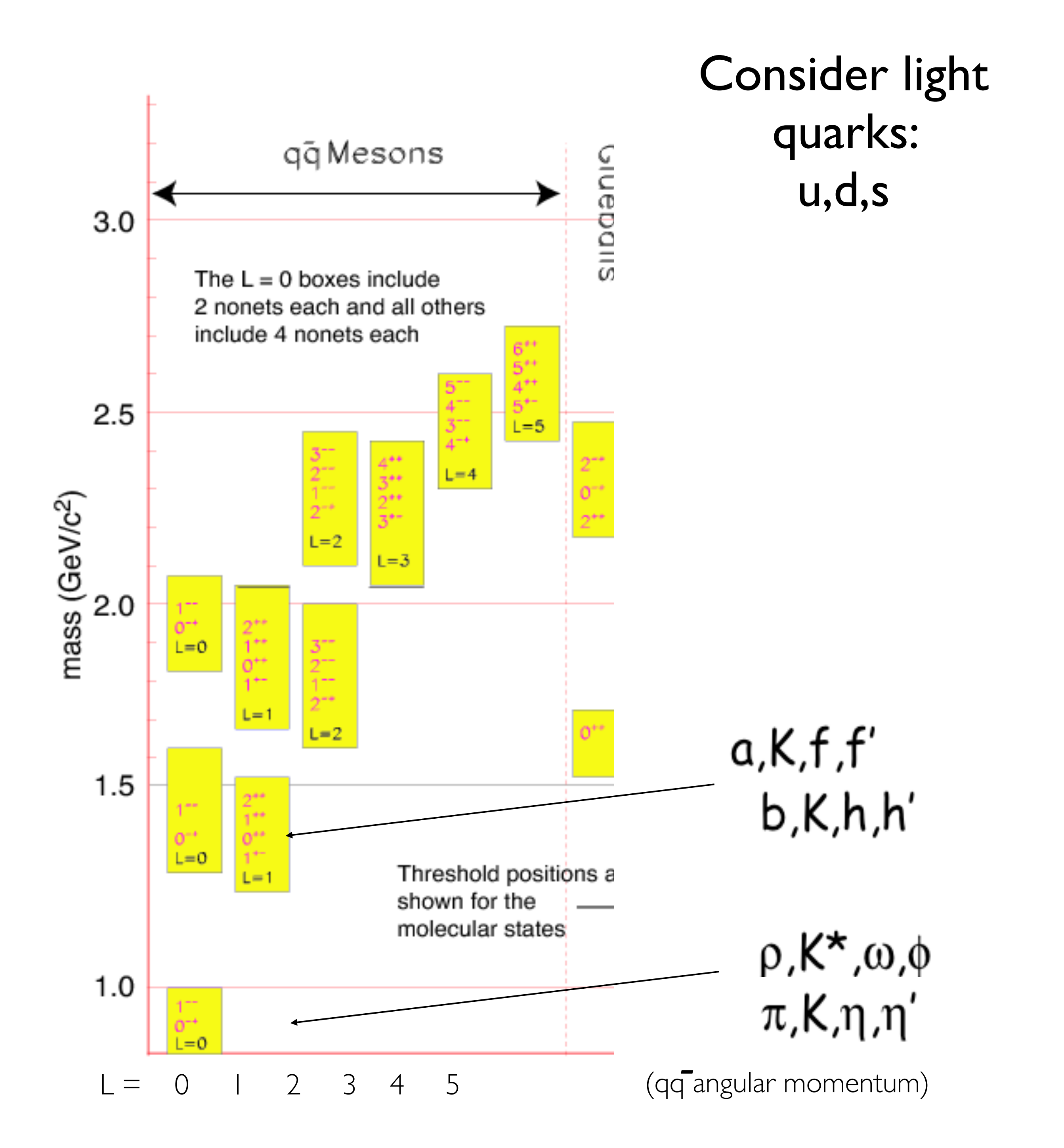
$J^{PC}= 0^{-+}$ ⇒ (π,K,η,η')

1^{--} ⇒ (ρ,K*,ω,Φ)

1^{+-} ⇒ (b_1,K_1,h_1,h_1')

…



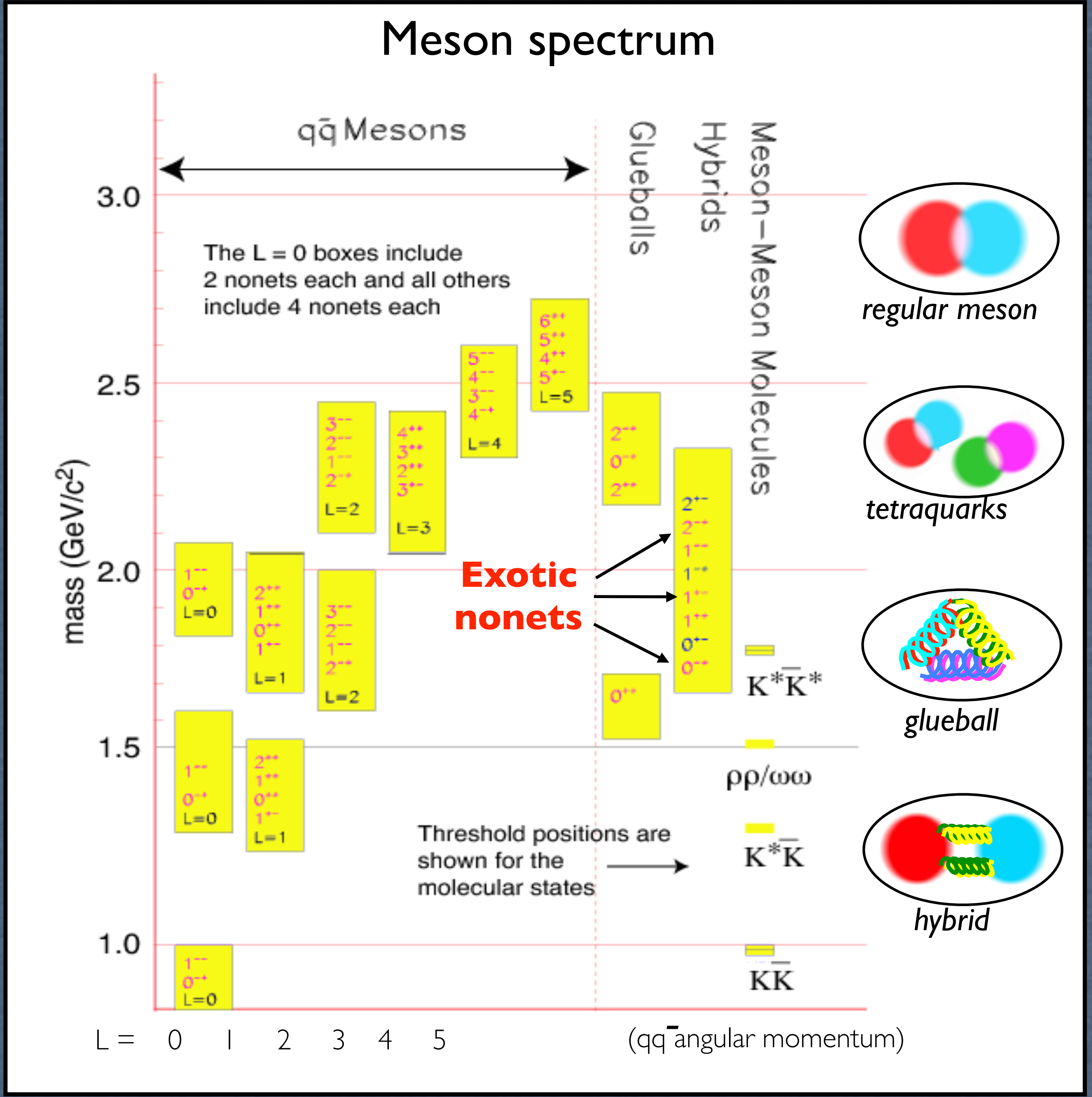


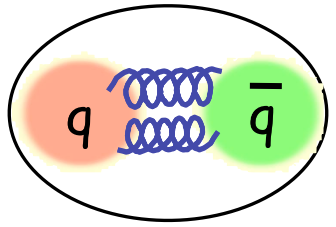
- Great success in describing the lower mass states
- …. but, a number of predicted states is not experimentally observed and assignments are uncertain

The gluons and the hadron spectrum

- Understanding gluonic excitations of mesons and the origin of confinement
- At high energy experimental evidence is found in jet production
- At lower energies the hadron spectrum carries information about the gluons that bind quarks
- Can we find hints of the glue in the meson spectrum?

Search for non-standard states with explicit gluonic degrees of freedom





hybrid mesons

Not-allowed J^{PC} = $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ ...

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

The gluons and the hadron spectrum

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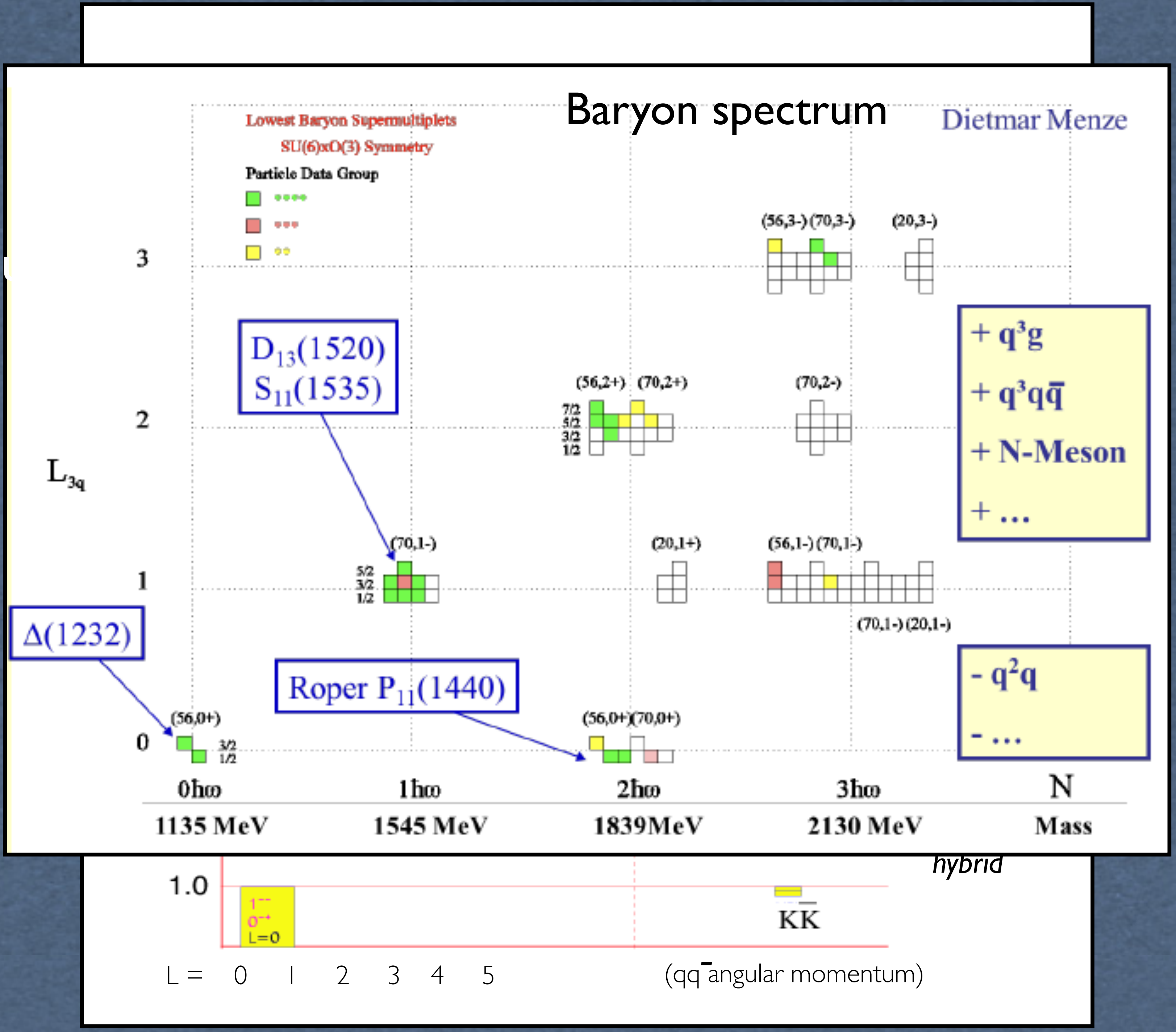
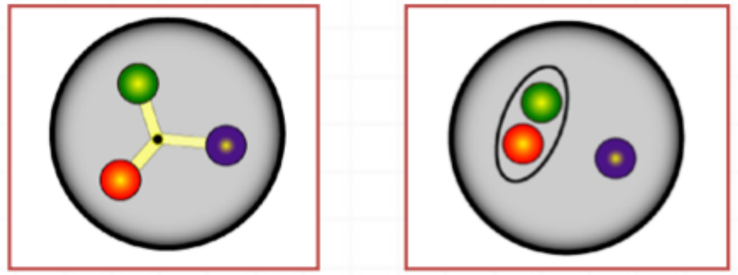
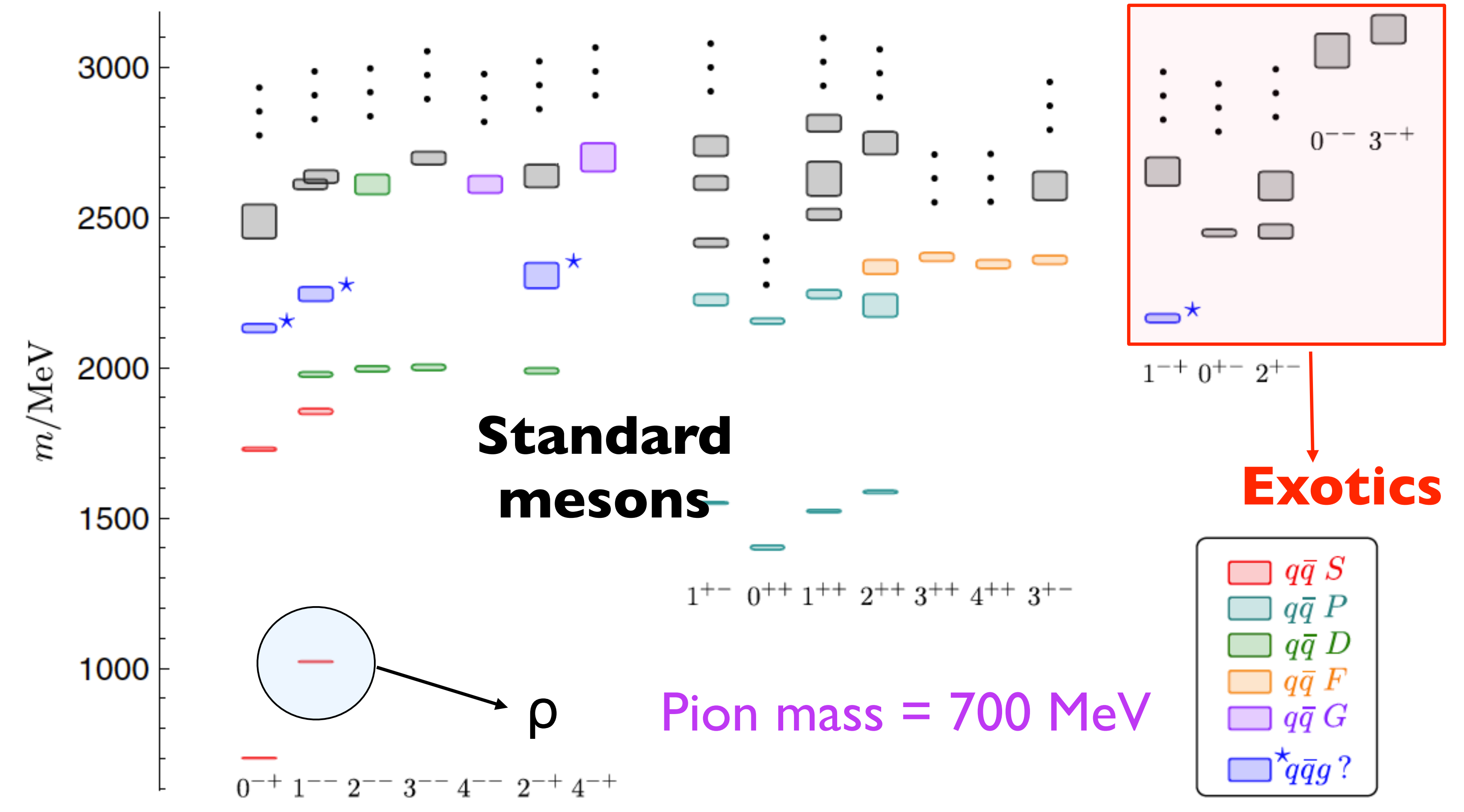


Search for non-standard states with explicit gluonic degrees of freedom

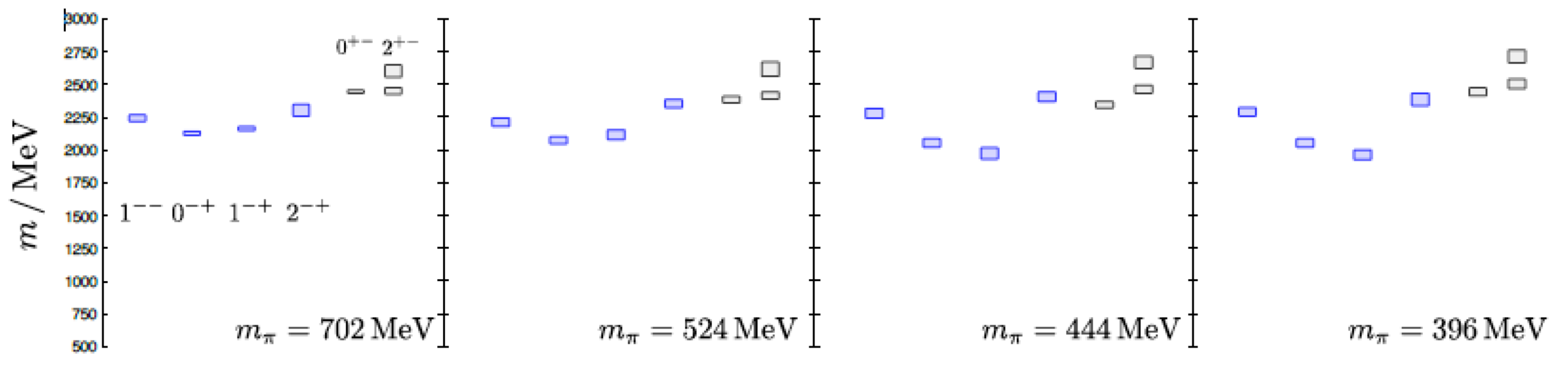
- QM qqq predicts less states than observed
- Missing baryon reconciled if assuming a more complex 3q structure (e.g. q-diquark)



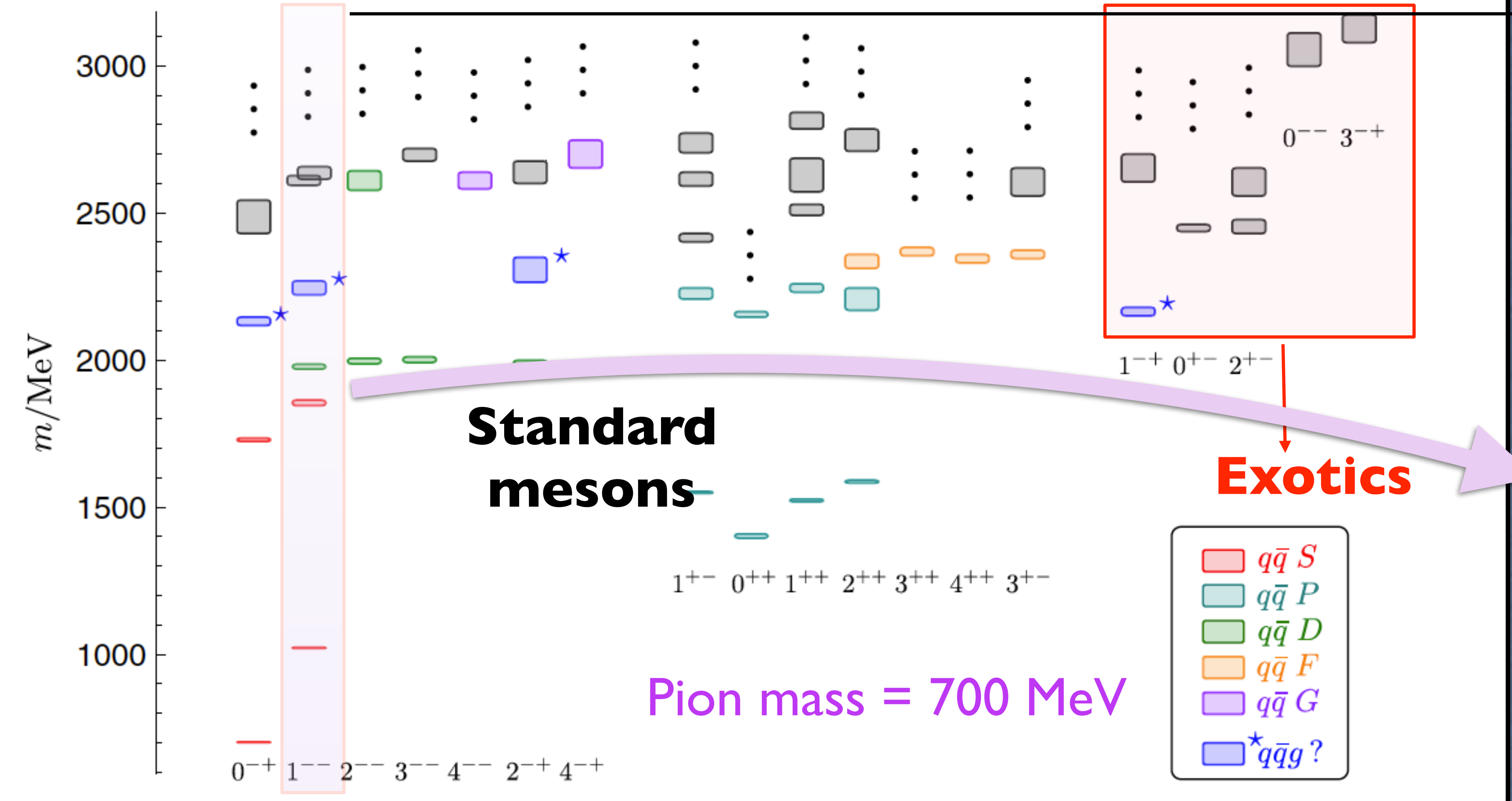
Light q spectrum from lattice QCD



J.Dudek et al Phys.Rev.D82 (2010) 034508   J.Dudek et al., Phys. Rev. D84, 074023 (2011)



Light q spectrum from lattice QCD



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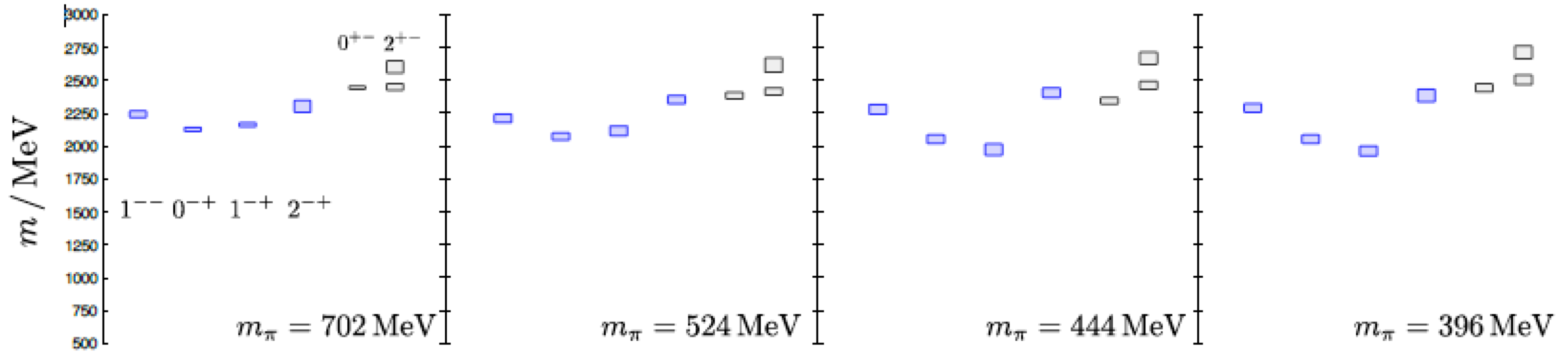
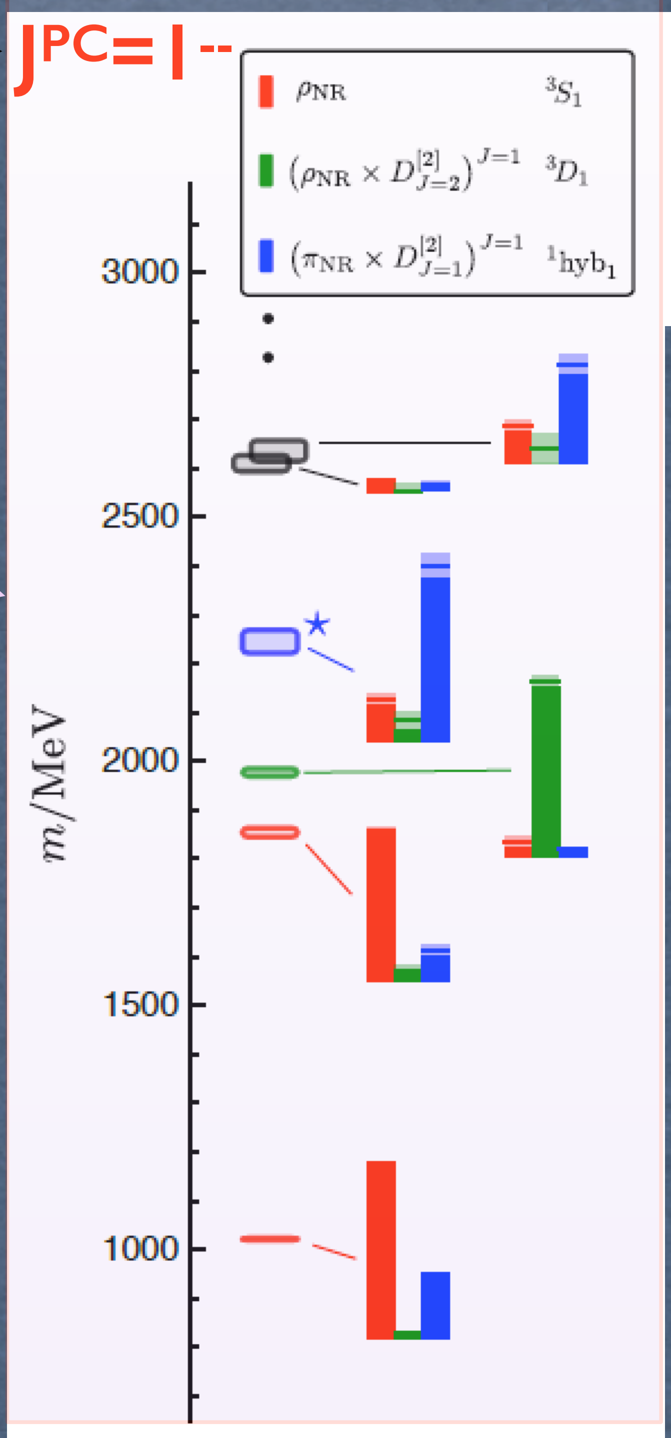
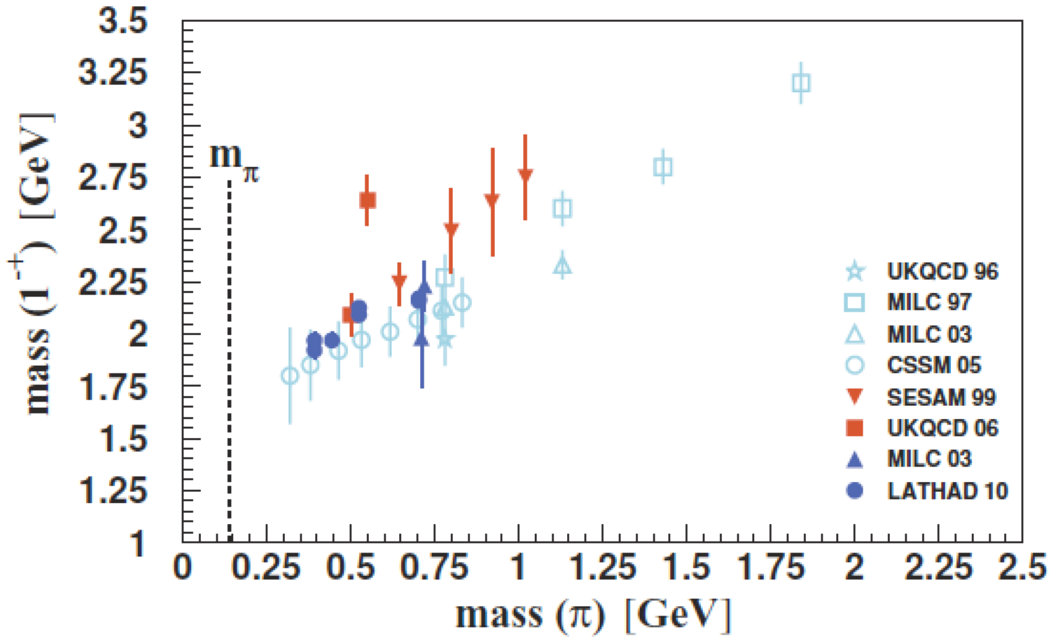


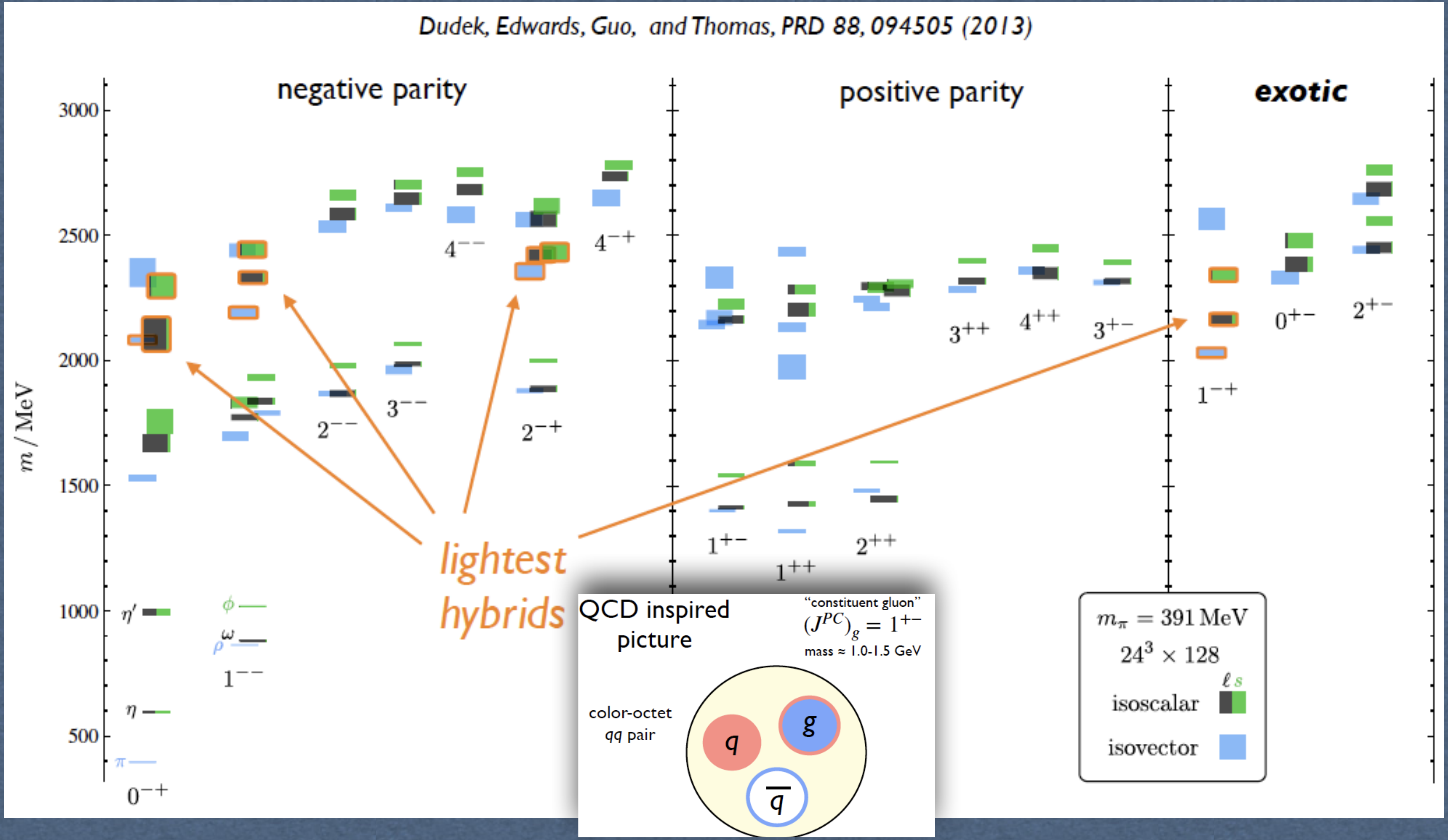


in blue: overlap with $J^{PC}=1^{-+}$ operator interpreted as qq-bar in S-wave + $J_g^{P_gC_g}=1^{+-}$ in P-wave

- Interpretation in term of CQM + Gluon field
- Dependence on Lattice size
- Dependence on pion mass



Light q spectrum from lattice QCD



Lattice-QCD predictions for the lowest hybrid states

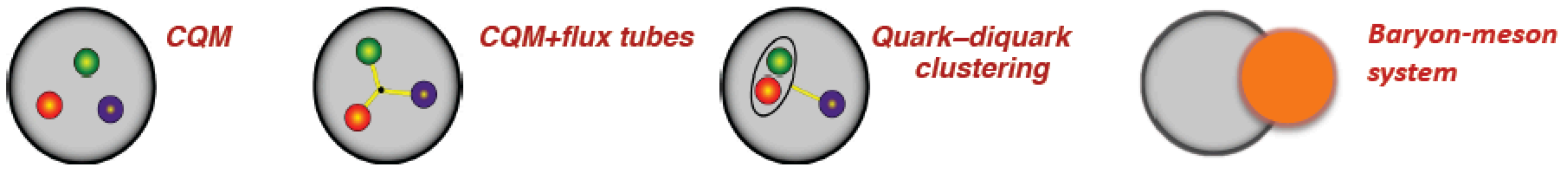
0^{+-} ~ 2.0 GeV
1^{-+} ~1.6 GeV

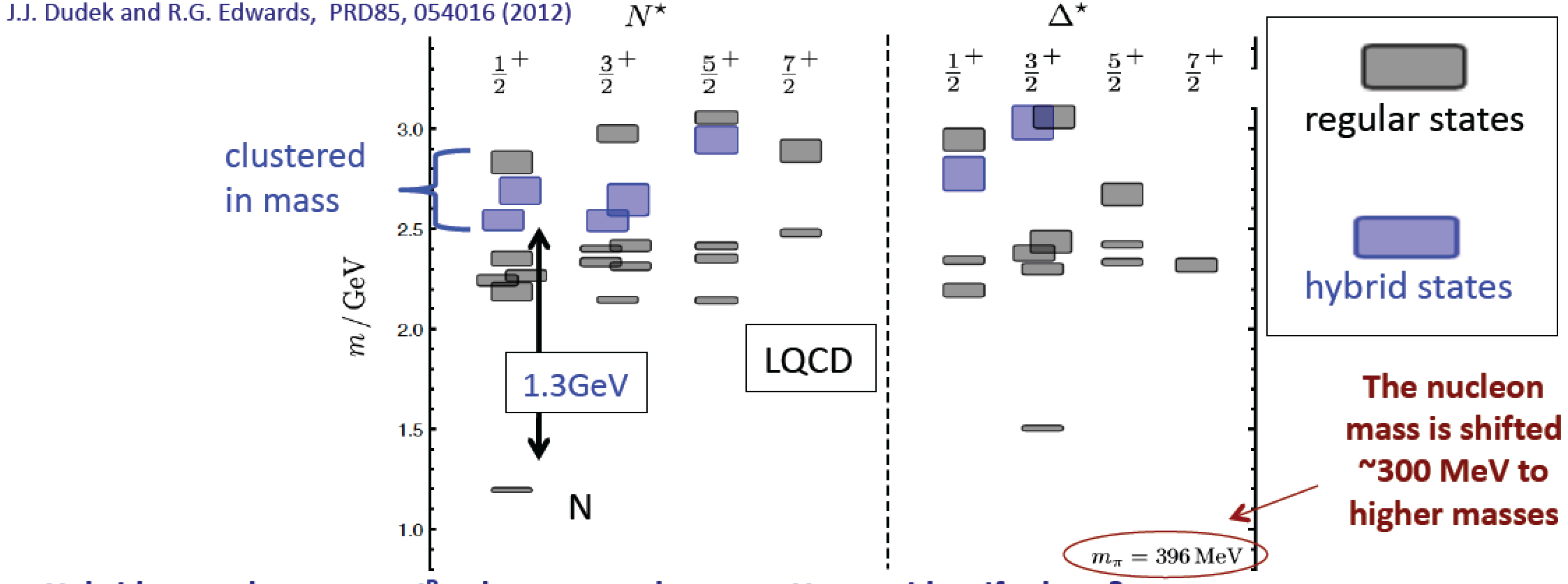
Hybrid mesons and glueballs mass range:

1.4 GeV - 3.0 GeV

This mass range is accessible in current experiments (e.g. GLUEX@JLab)

Hybrid baryons in Lattice QCD





Hybrid states have same J^P values as qqq baryons. How to identify them?

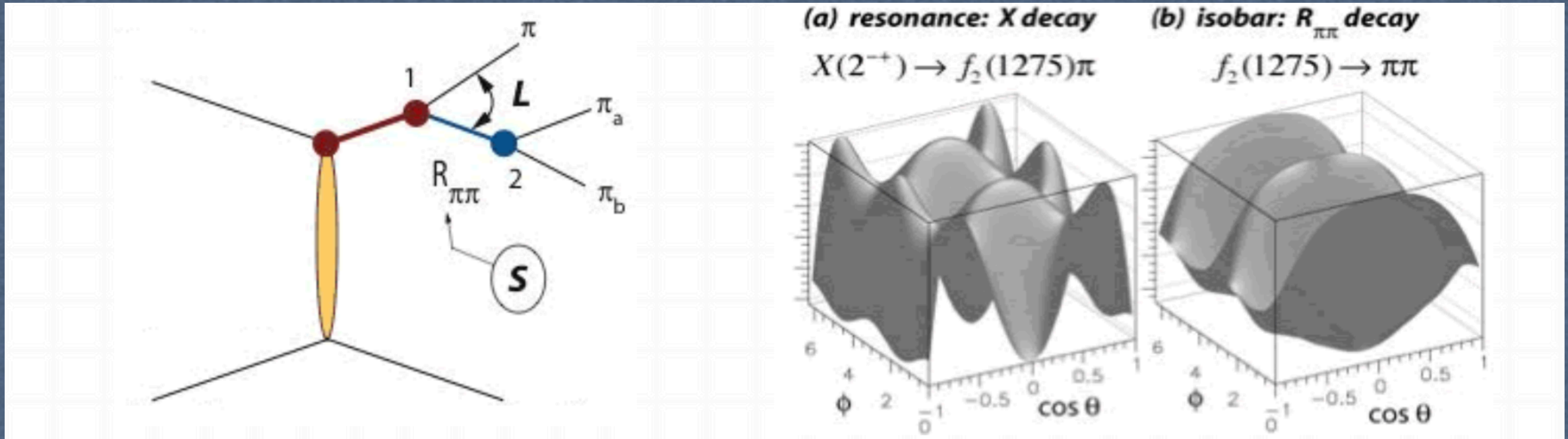
- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution. Can we do it?**

Resonance detection

Two main experimental approaches to identifying and studying a hadron resonance

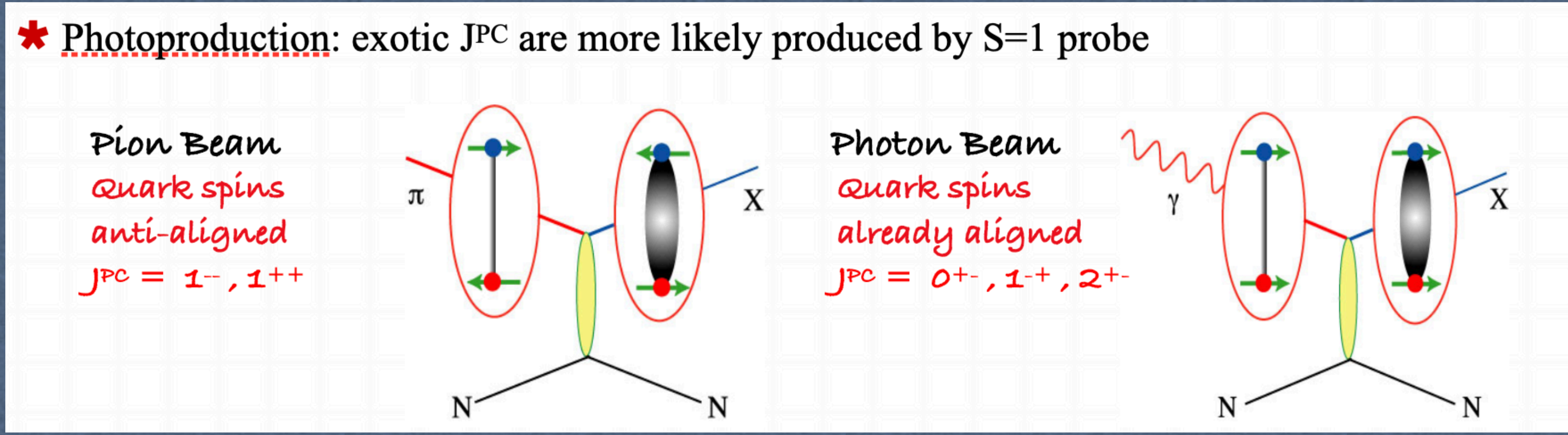
Decay

- Easier and straightforward
- Independent on production mechanisms
- Dalitz plot for 3-body decays
- Isobar Model for higher multiplicity



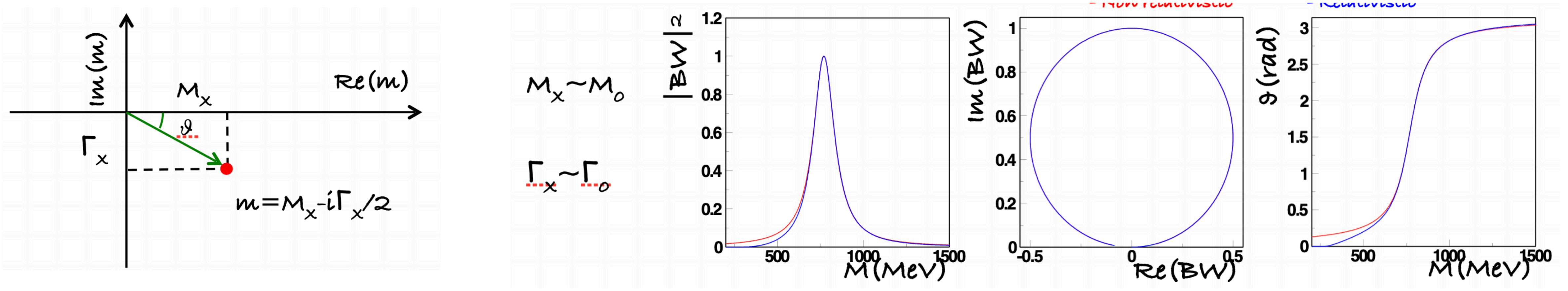
Production

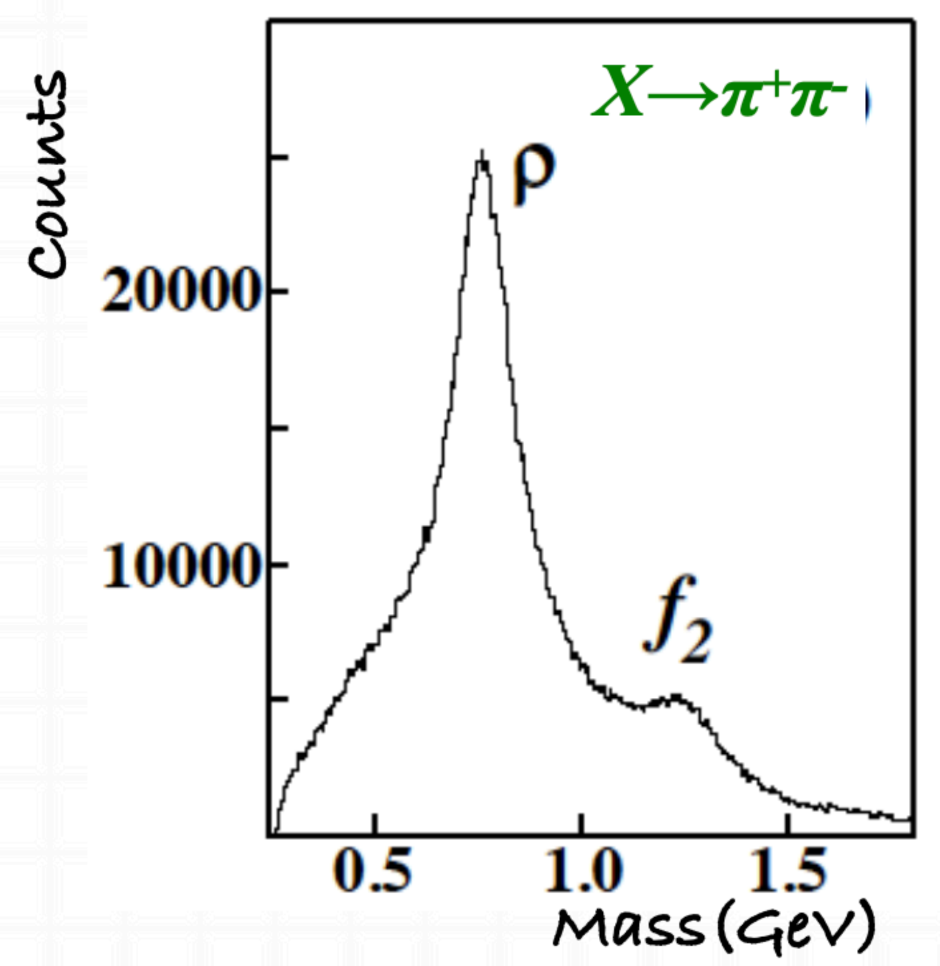
- Requires parametrisation of production vertex
- exclusive (or semi-inclusive) final state
- sensitive to the internal structure (nature)



From data to the spectrum

'resonance' is defined by the pole of the complex amplitude
… not every bump is a resonance and not every resonance is a bump!



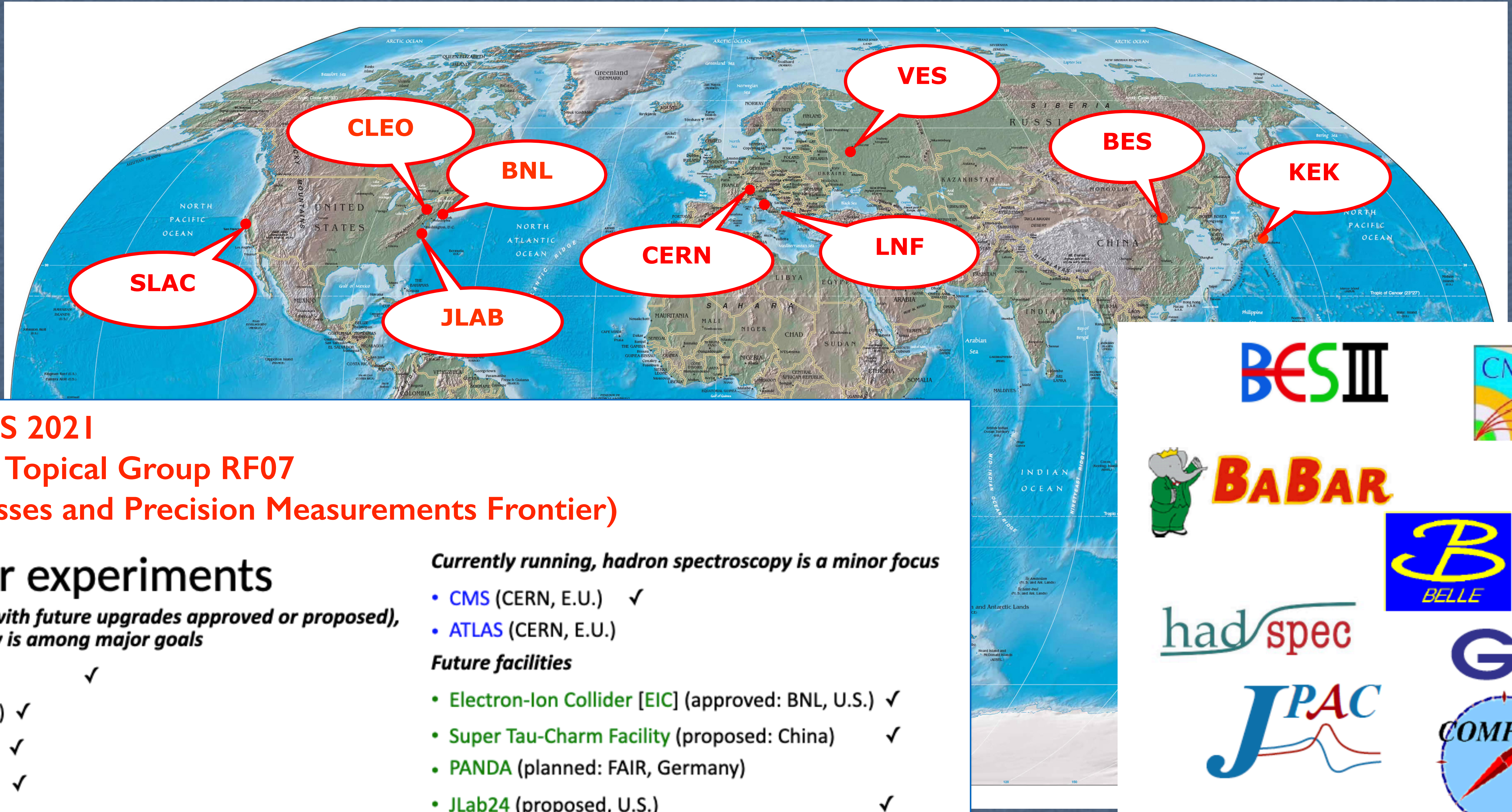


- A hadron resonance can be observed by studying the **invariant mass spectrum** of its decay product.
- In real life, resonances do not always appear so clearly in a mass spectrum because they are **not isolated**
- A resonance has specific quantum numbers with defined decay angular momentum
- Each partial wave only includes the corresponding resonances

Partial Wave Analysis (PWA)

- Goal: extract the intensity of the different angular waves as a function of the invariant mass of the final state particles
- Measure events for the process of interest
- Build a model that describes the process
- Fit the model to the data

Meson spectroscopy in the world



SNOWMASS 2021
Summary of Topical Group RF07
(Rare Processes and Precision Measurements Frontier)

The major experiments

Currently ongoing (with future upgrades approved or proposed), hadron spectroscopy is among major goals

- LHCb (CERN, E.U.) ✓
- Belle II (KEK, Japan) ✓
- BESIII (IHEP, China) ✓
- GlueX (JLab, U.S.) ✓

Currently running, hadron spectroscopy is a minor focus

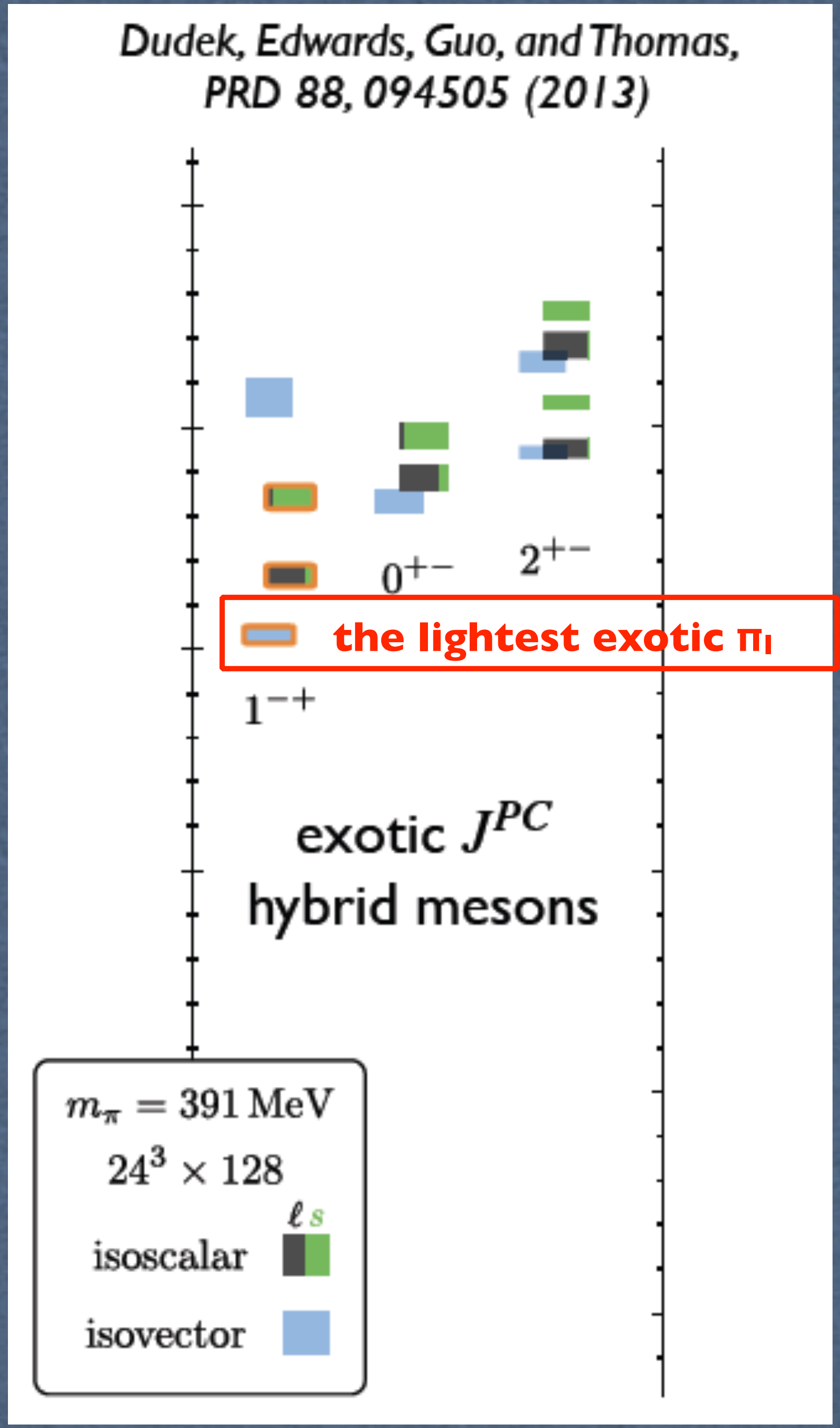
- CMS (CERN, E.U.) ✓
- ATLAS (CERN, E.U.)

Future facilities

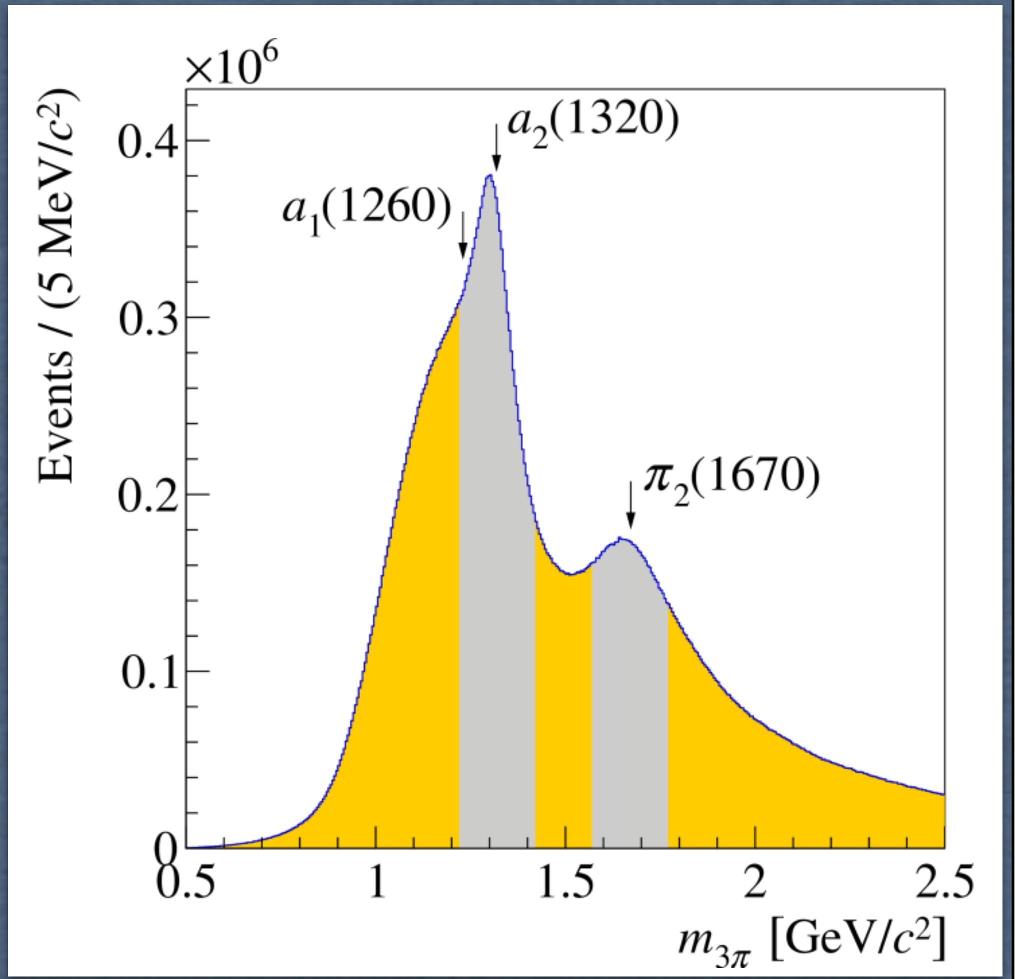
- Electron-Ion Collider [EIC] (approved: BNL, U.S.) ✓
- Super Tau-Charm Facility (proposed: China) ✓
- PANDA (planned: FAIR, Germany)
- JLab24 (proposed, U.S.) ✓

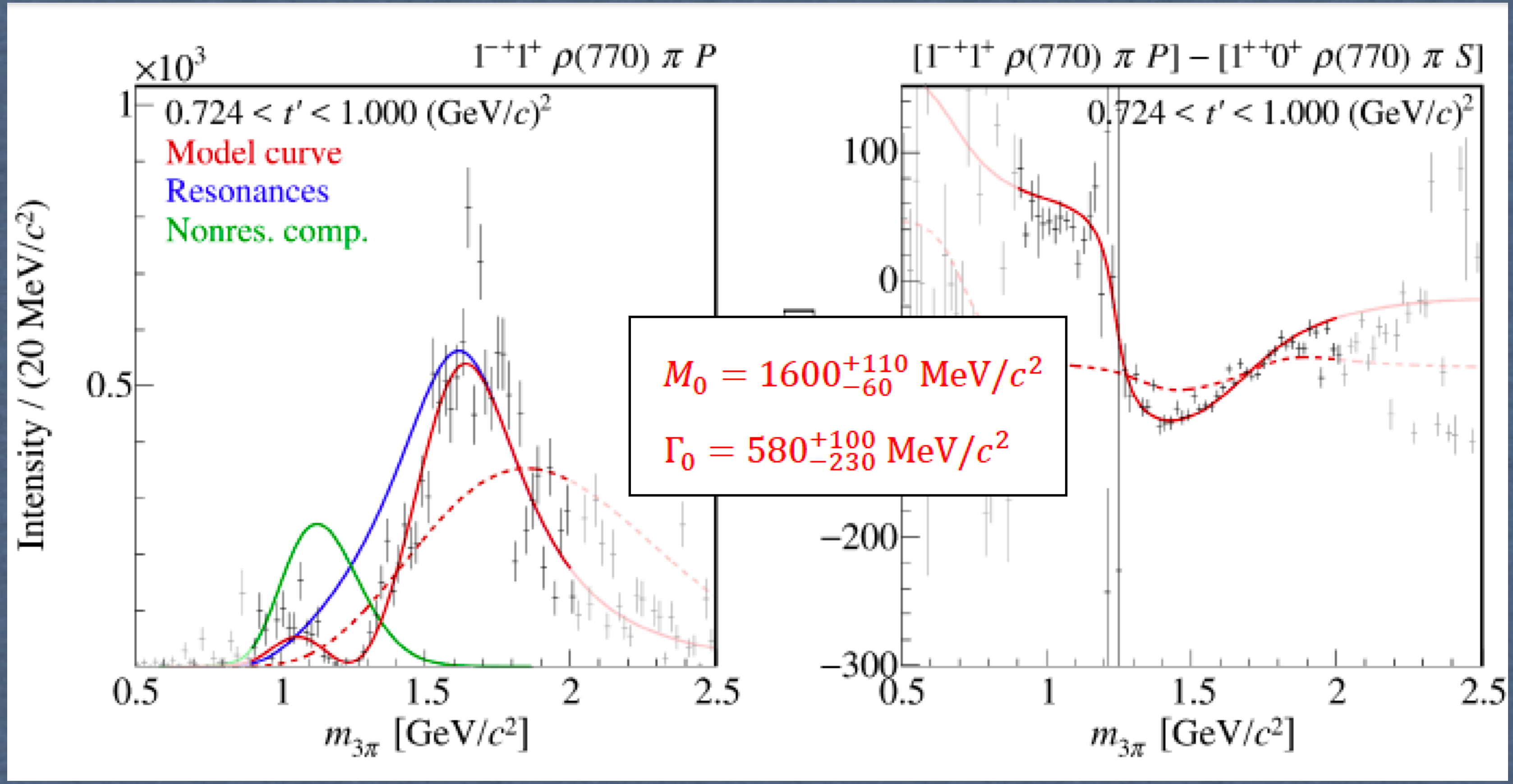
Light q hybrids

3π final state



- ✳ Possible evidence of exotic meson $\pi_1(1600)$ in $\pi^- p \to p\, \pi^- \pi^- \pi^+$ (E852-Brookhaven)
- ✳ Simple final state with low bg



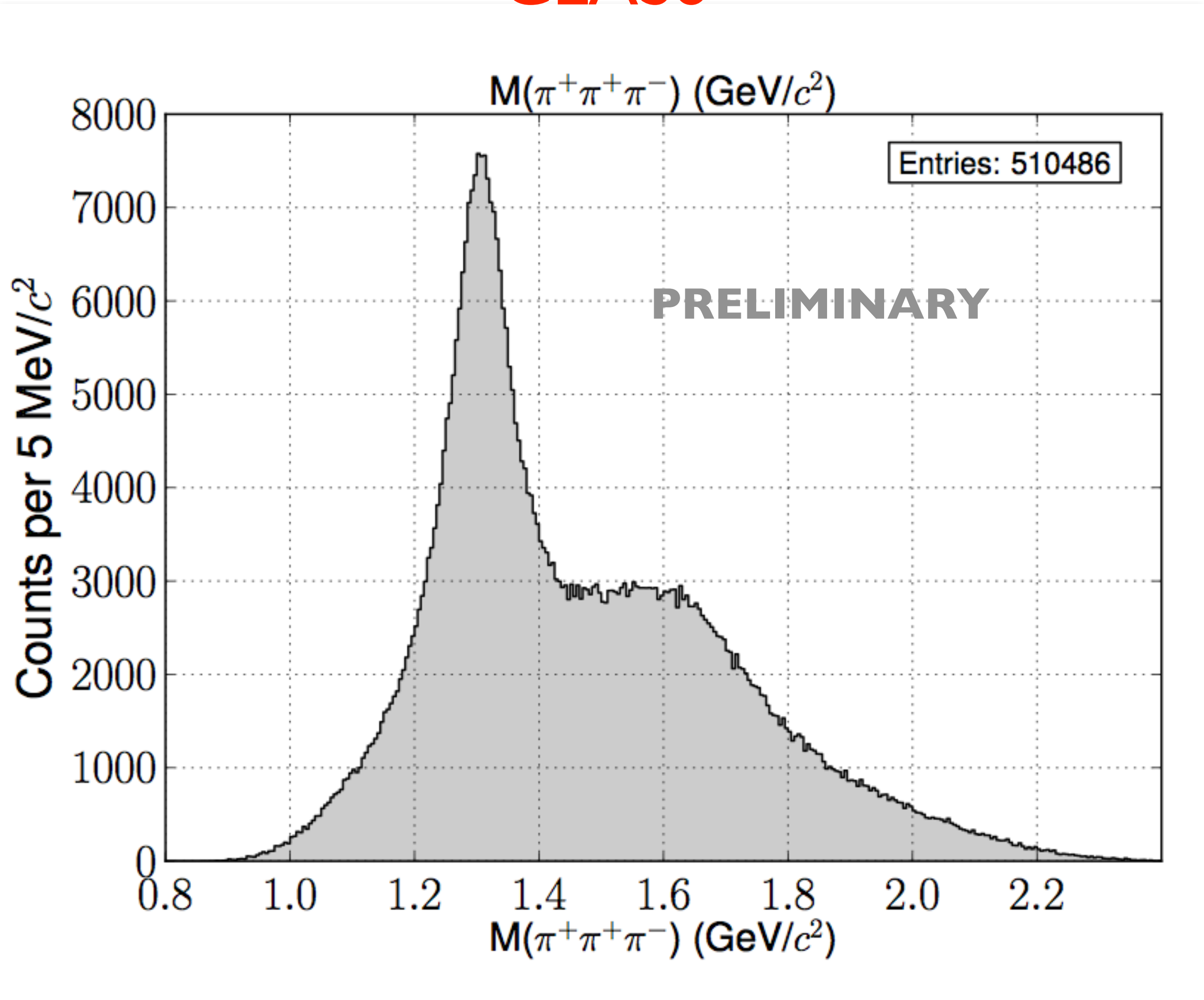


Bad description of data without resonance component
π1(1600) needed to describe data

nPQCD in action

A side note: invariant mass spectrum of (3π) system measured at:

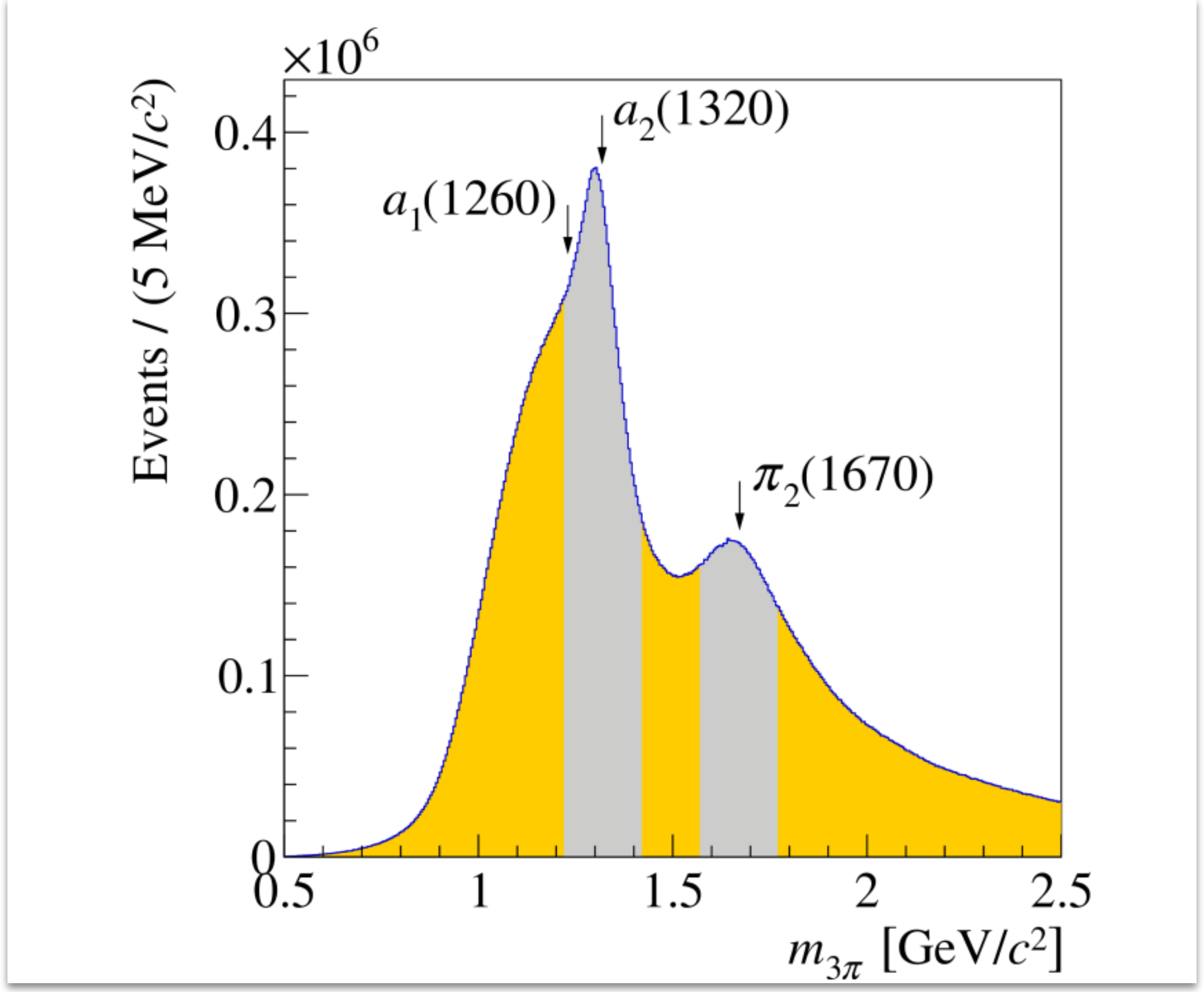
CLAS6



$\gamma\ p \rightarrow (n)\ \pi^+\ \pi^+\ \pi^-$

$E_\gamma = 5$ GeV

COMPASS



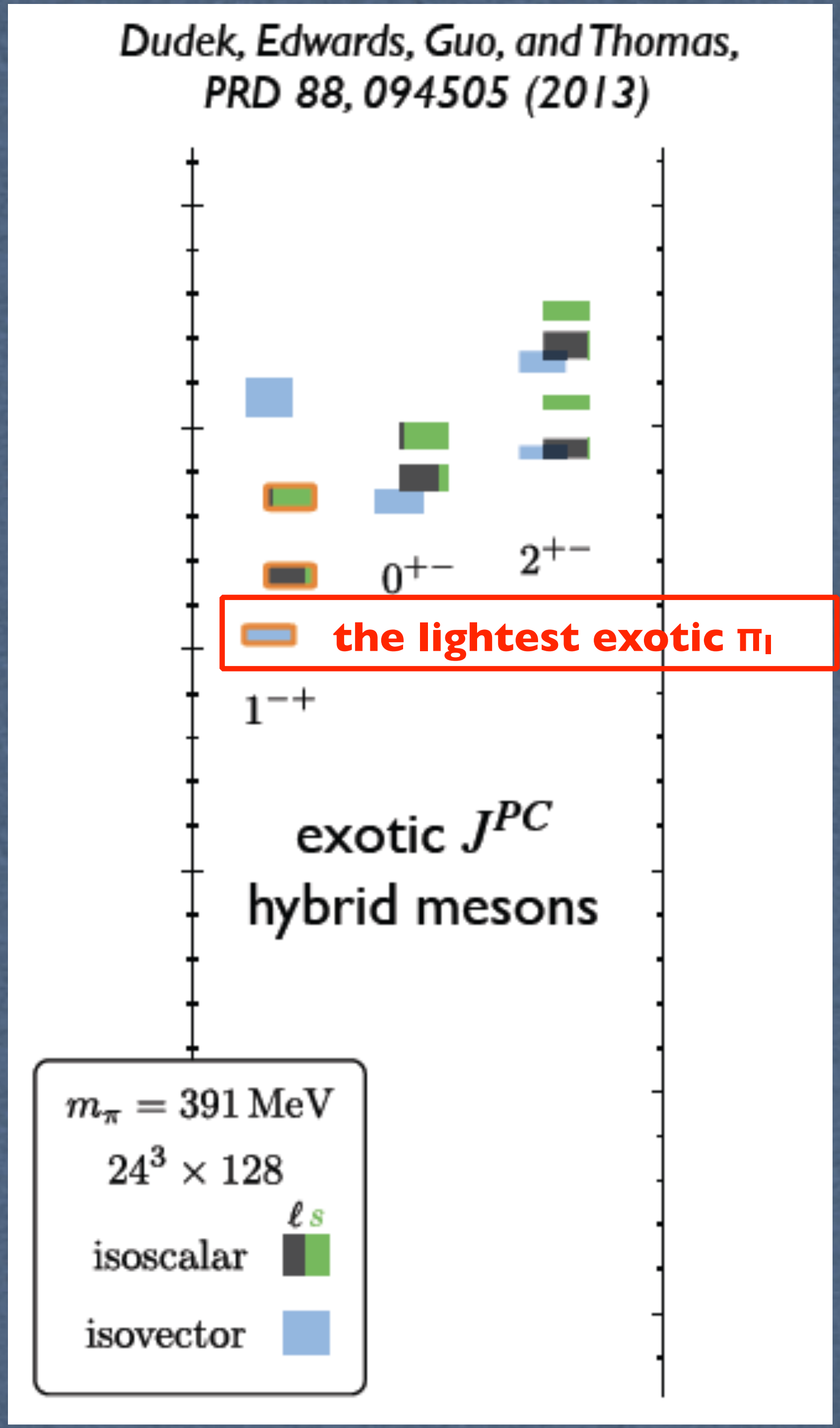
$\pi^-\ p \rightarrow (p)\ \pi^+\ \pi^-\ \pi^-$

$E_\pi = 191$ GeV

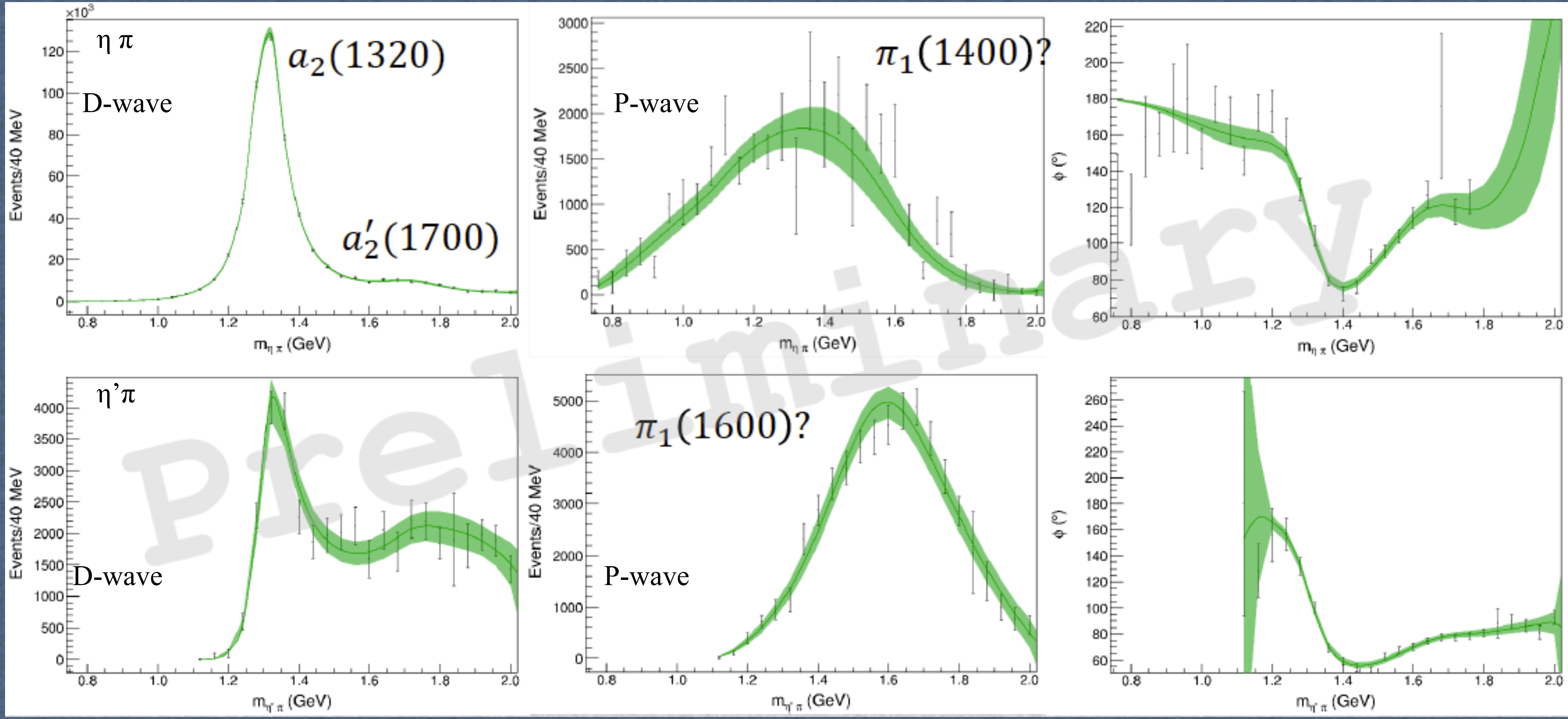
Despite the significant difference in beam energy, the two spectra are similar showing the resonances dominate the spectrum below 2 GeV (low energy → non-pQCD)

Light q hybrids

ηπ final state



- $\pi^- p \rightarrow p\eta\pi^-$ and $\pi^- p \rightarrow p\eta'\pi^-$ at 191 GeV
- $\pi_1(1400)$ exotic state (1^{-+} wave)

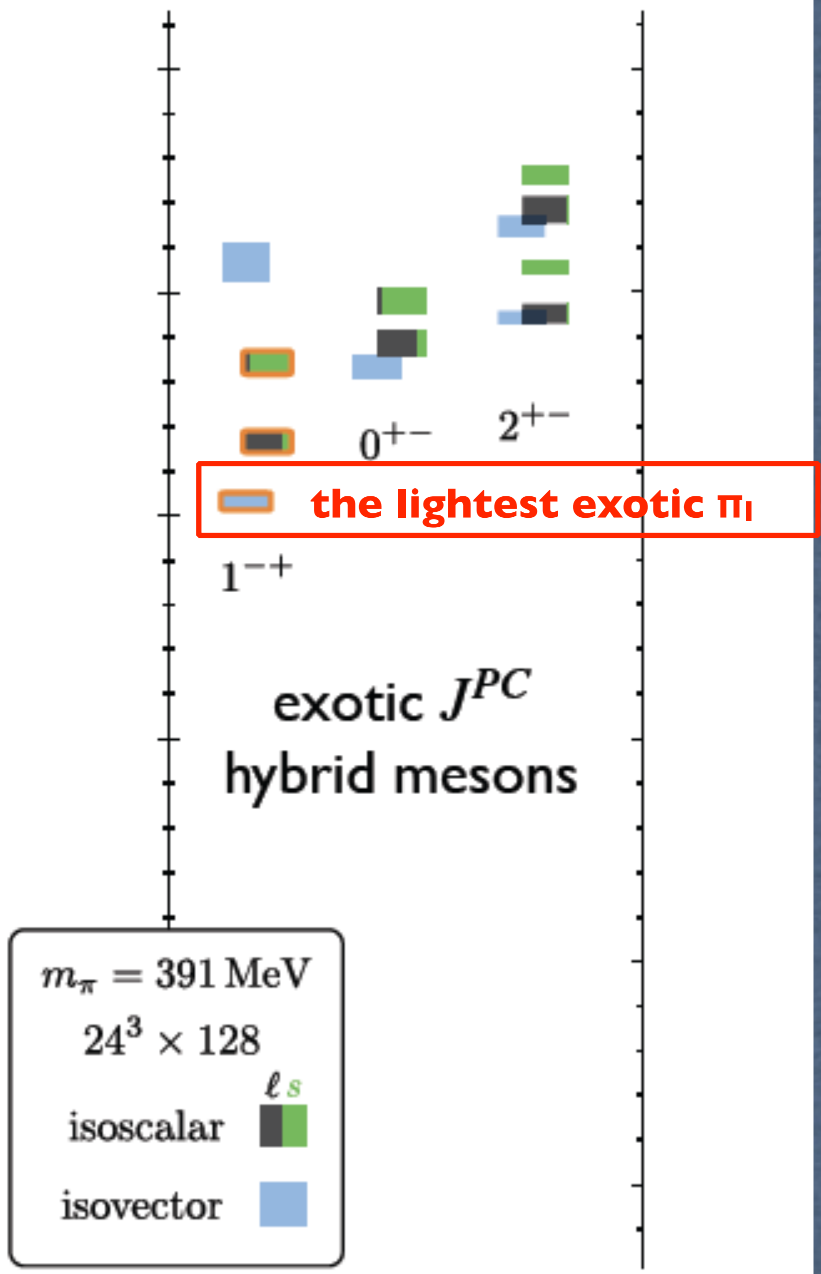


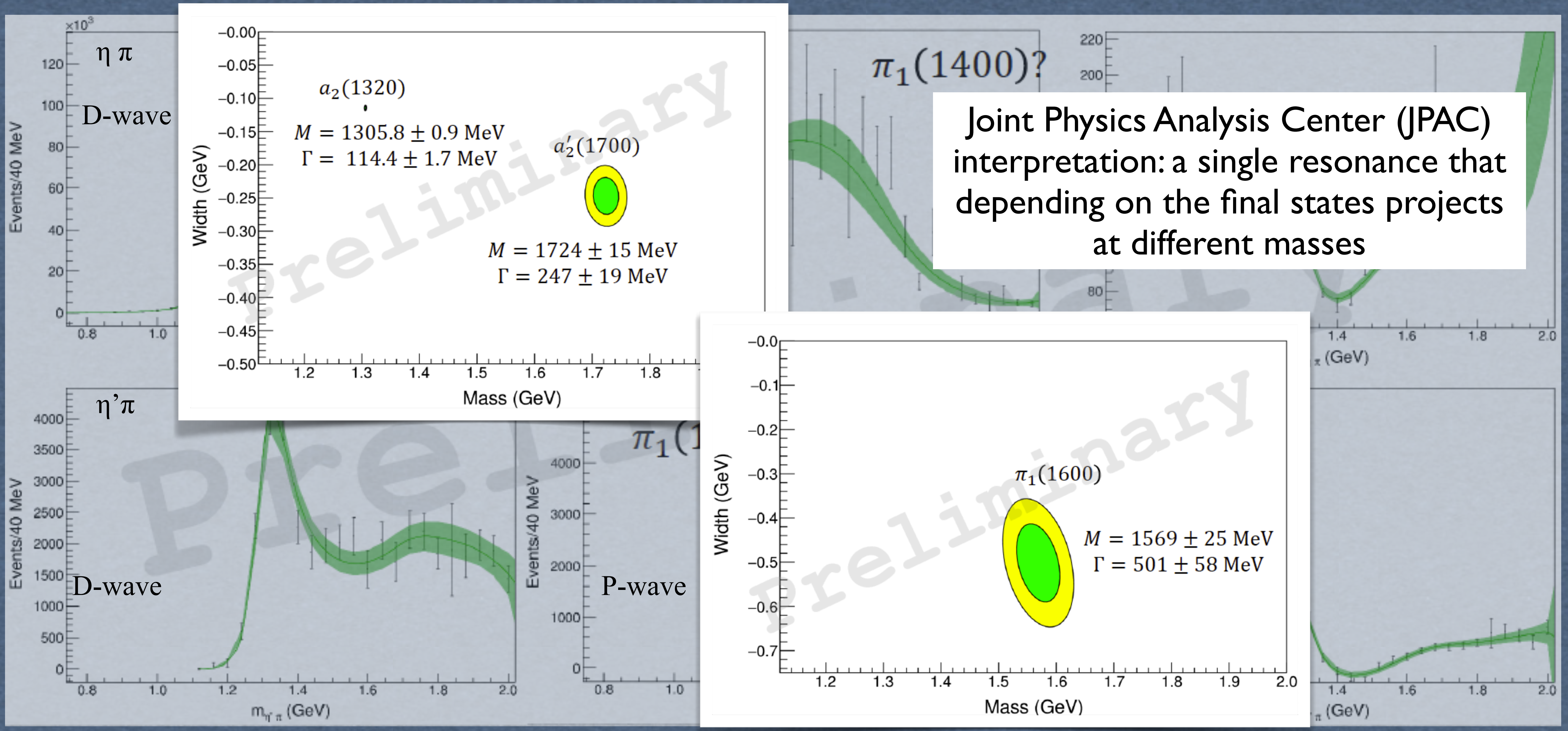
Light q hybrids

ηπ final state

- $\pi^- p \rightarrow p \eta \pi^-$ and $\pi^- p \rightarrow p \eta' \pi^-$ at 191 GeV
- $\pi_1(1400)$ exotic state (1^{-+} wave)

Dudek, Edwards, Guo, and Thomas, PRD 88, 094505 (2013)

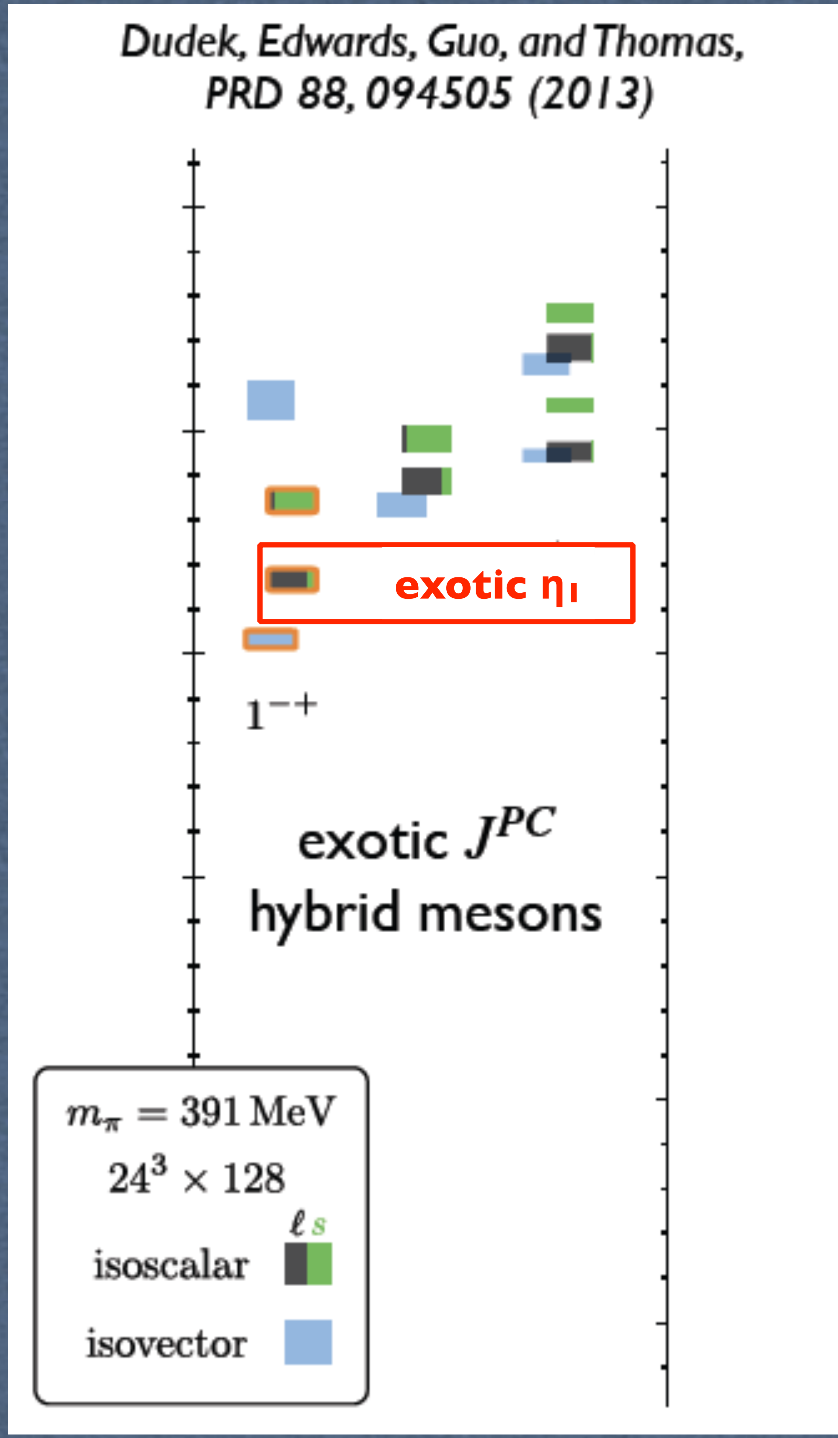


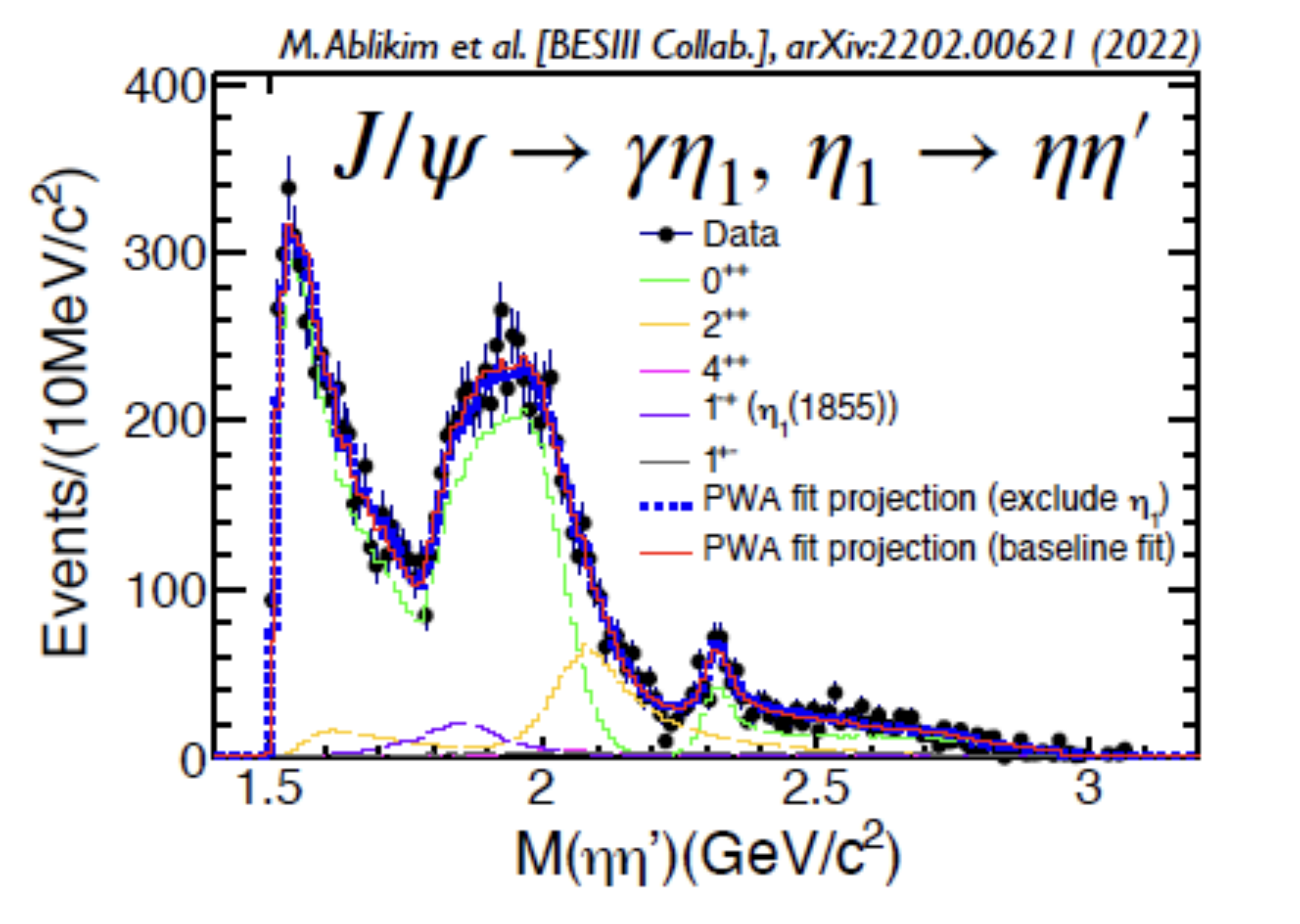


Joint Physics Analysis Center (JPAC) interpretation: a single resonance that depending on the final states projects at different masses

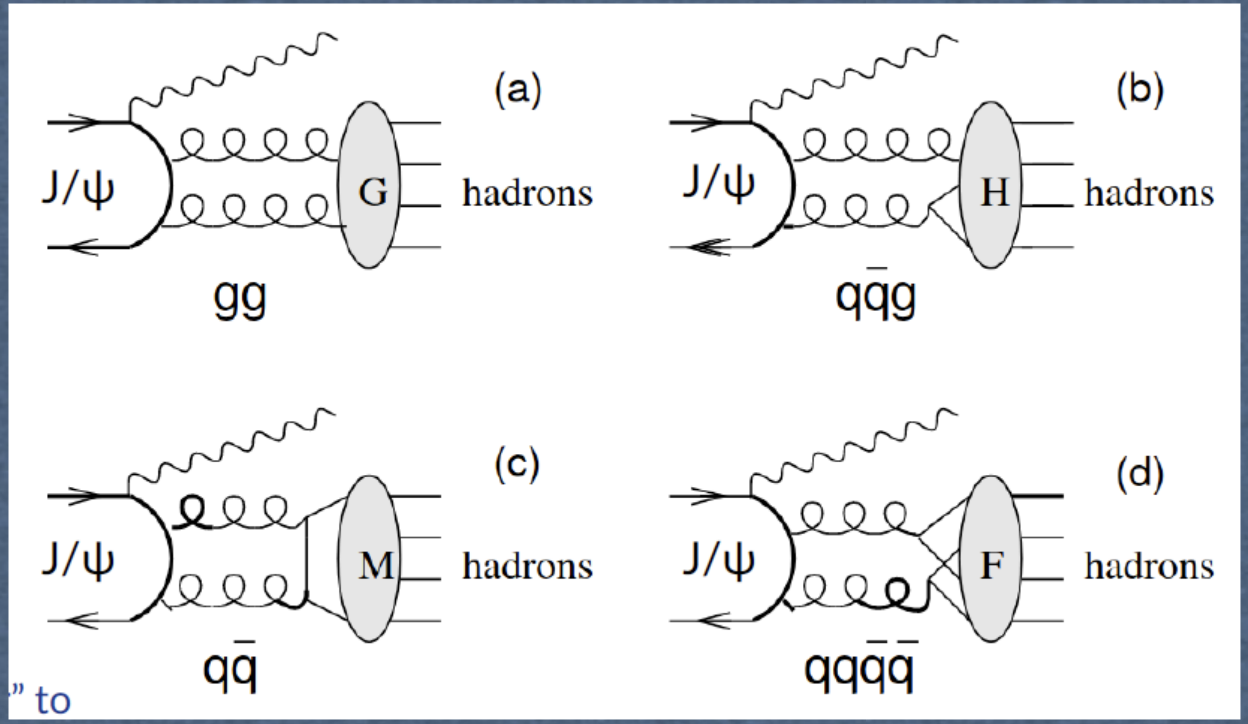
Light q hybrids

J/ψ radiative decay





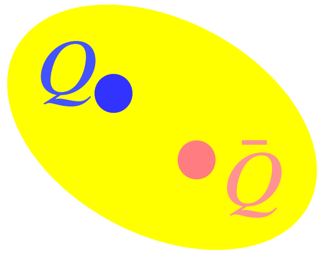
- J/ψ gluon-rich decays are an ideal laboratory
- Search for exotic "quantum-number" to separate from mixing effects



- ηη' final state
- η_1(1855) exotic state (1^{-+} wave)
- Determination of the scalar and tensor pole positions from J/psi radiative decays by JPA

The charmonium orthodoxy

Exotic configurations in the light quark sector are expected to a large width (identification via PWA)

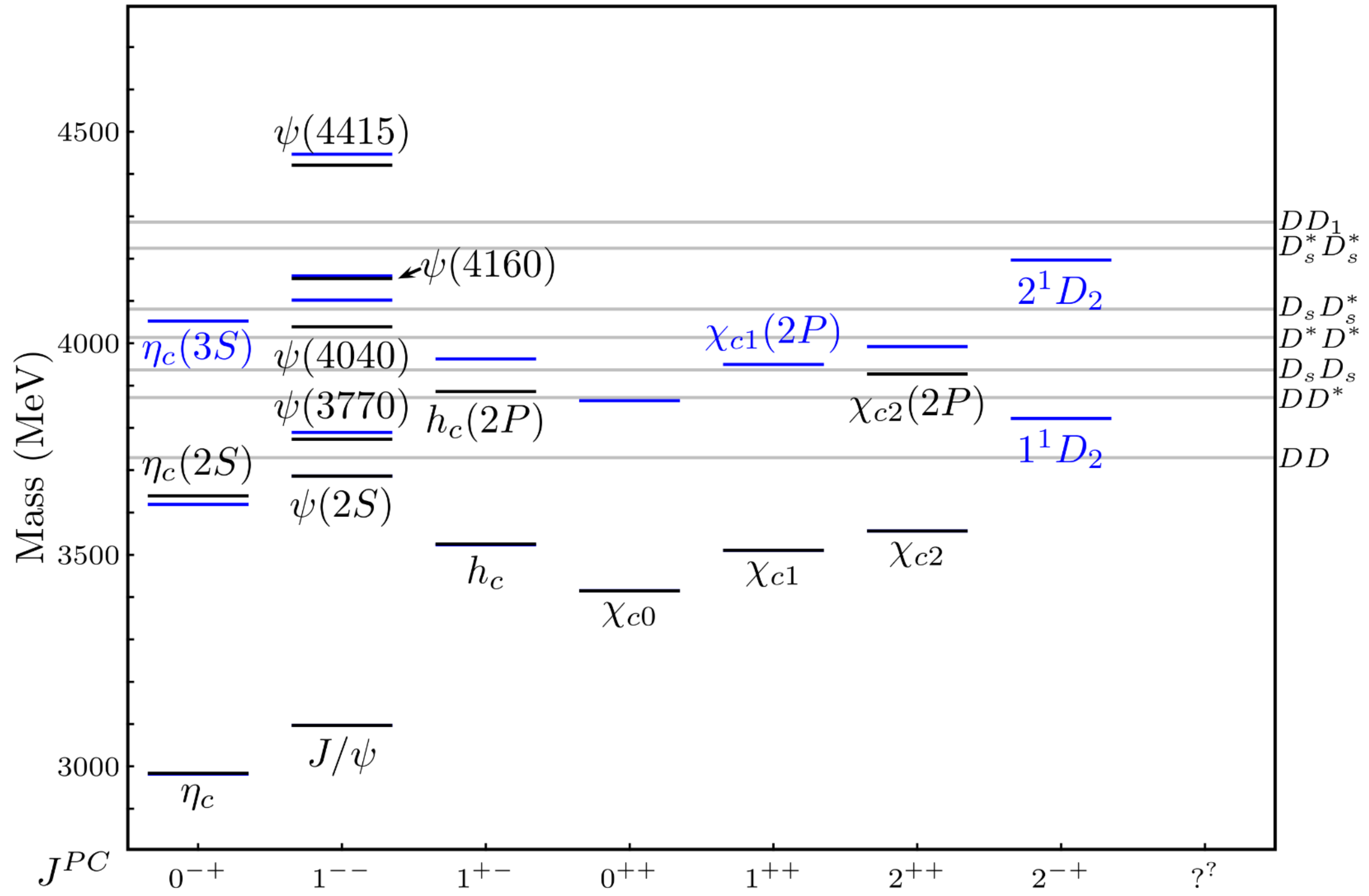


Potential models
(when)

$$V(r) = -\frac{C_F \alpha_s}{r} + \sigma r$$

Effective theories
(HQET, NRQCD, pNRQCD...)

Integrate out heavy DOF
↓
(spectrum), decay
& production rates



The charmonium orthodoxy

Exotic confi ... PWA)

Q

Poten
(

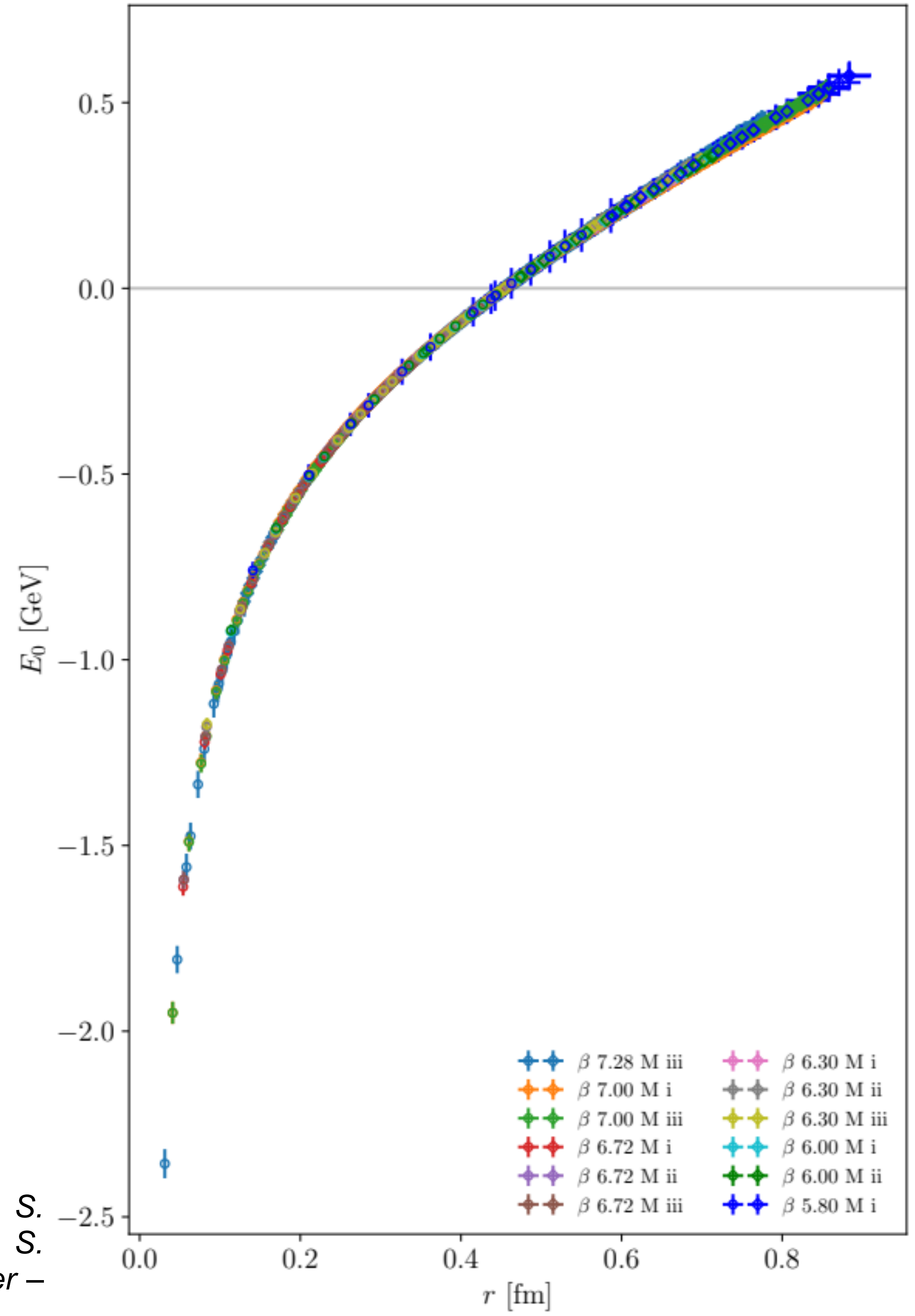
$V(r) = -$

Effecti
(HQET, NRQ

Integrate

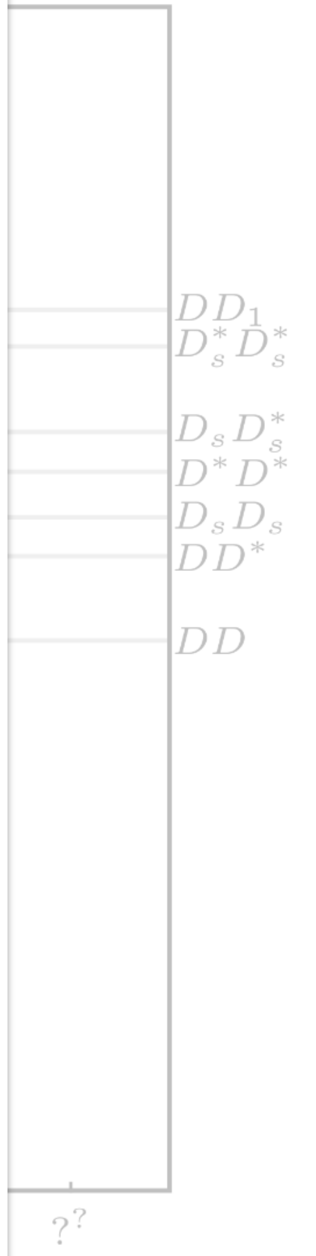
(spect
& proc

STATIC ENERGY IN 2+1+1 FLAVOR LATTICE QCD



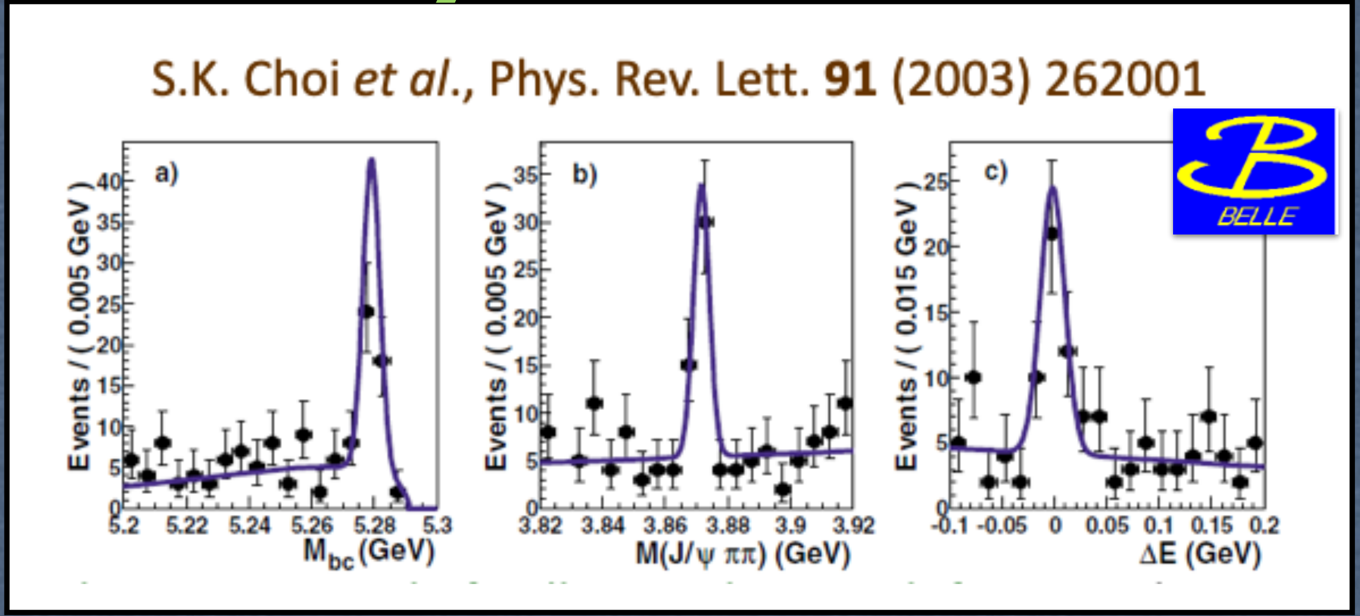
N. Brambilla, R. L. Delgado, A. S. Kronfeld, Viljami Leino, P. Petreczky, S. Steinbeißer, A. Vairo and J. H. Weber – arXiv:2206.03156 [hep-lat]

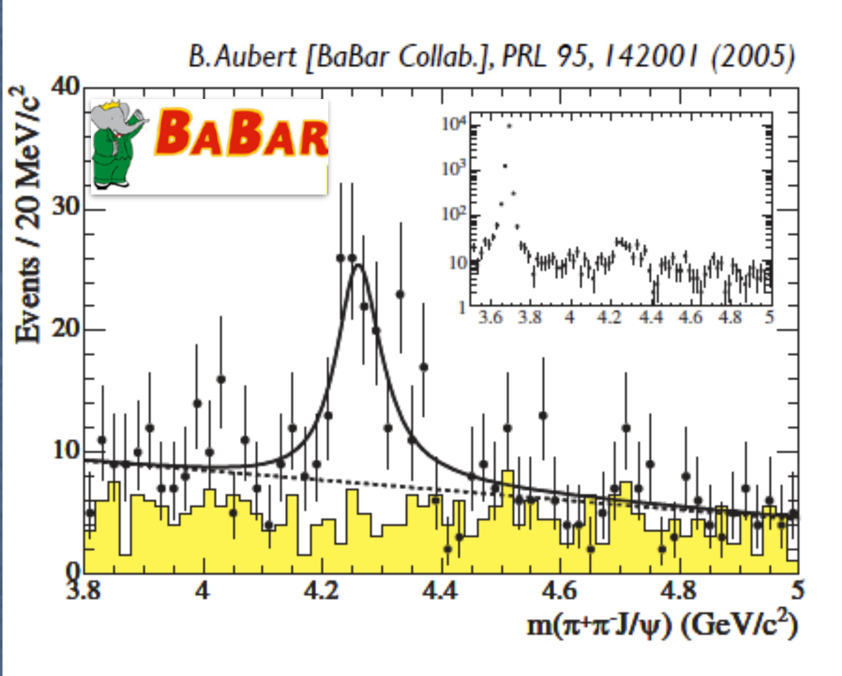
- Computed the static energy in 2+1+1 flavour lattice with several quark masses, including the physical one
- Static energy with dynamic charm measured from lattice QCD
- Can observe charm effects
- Precise determination of the lattice scales



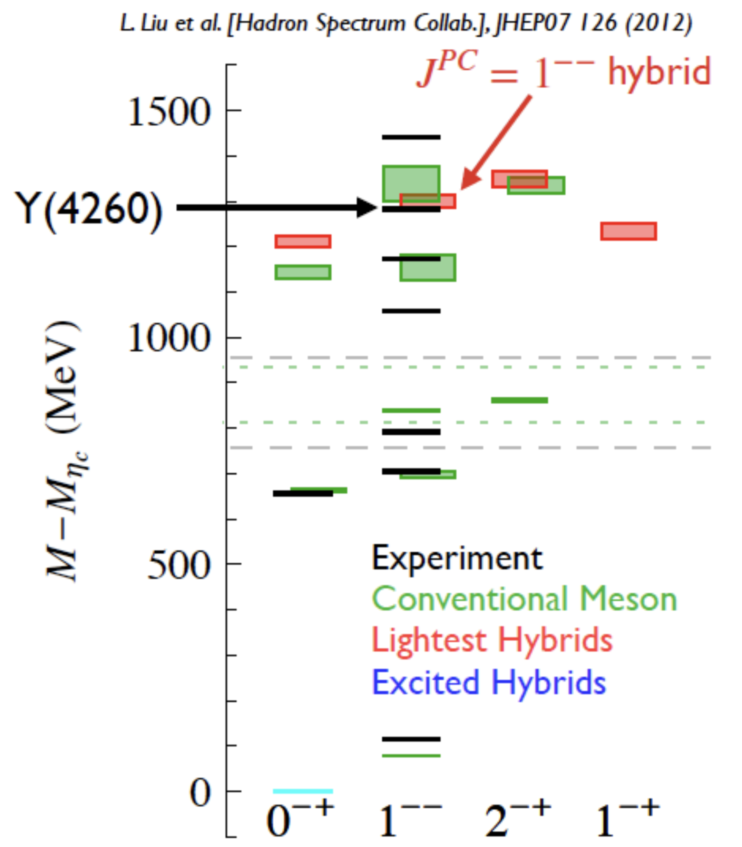
The charmonium (un)orthodoxy

- In 2003 The **Belle Collaboration** at KEK found evidence for a narrow new particle at 3872 MeV
- Mass is in the charmonium range
- … but *very unlike* a pure $c\bar{c}$ state, almost certainly a hadron of valence quark content $c\bar{c}q\bar{q}$
- Thew XYZ saga started …

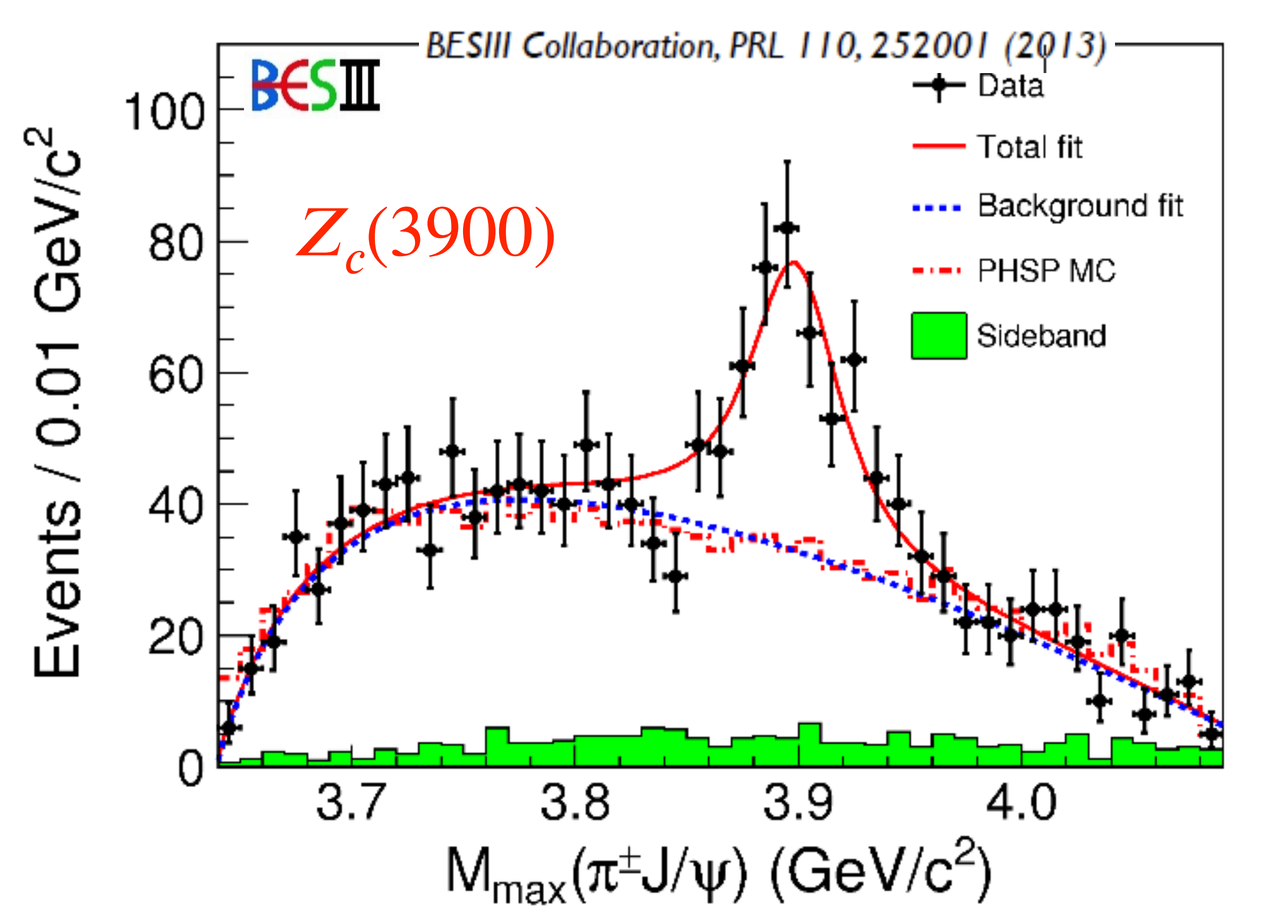




"Y(4260)" in $e^+e^- \to \pi\pi J/\psi$



- Few years later BaBar found another 'weird' state
- Interpretation consistent with a hybrid state

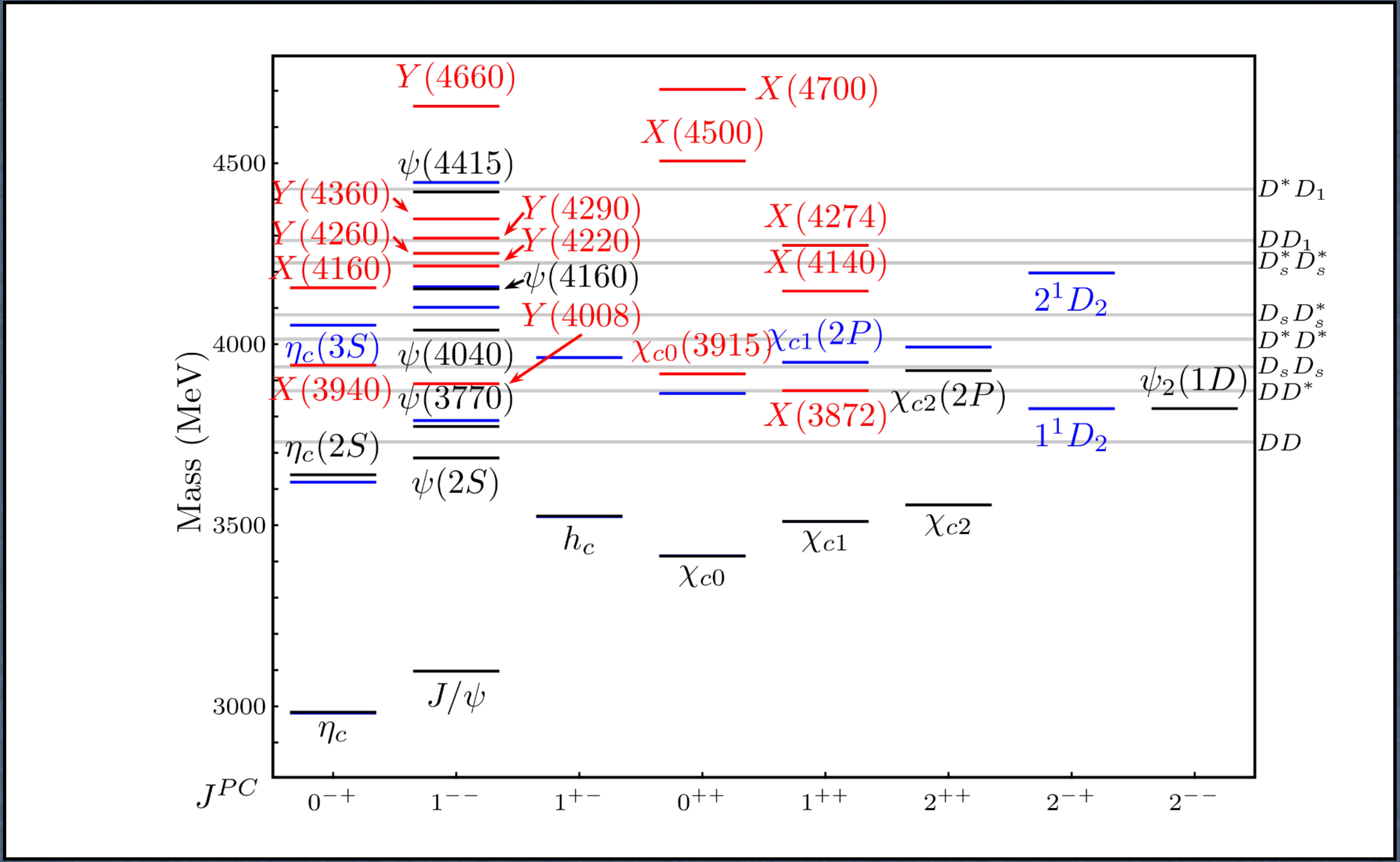


- BESIII observed a new charged state
- A charged charmonium state (???)
- Manifestly incompatible with a pure cc-bar state

…

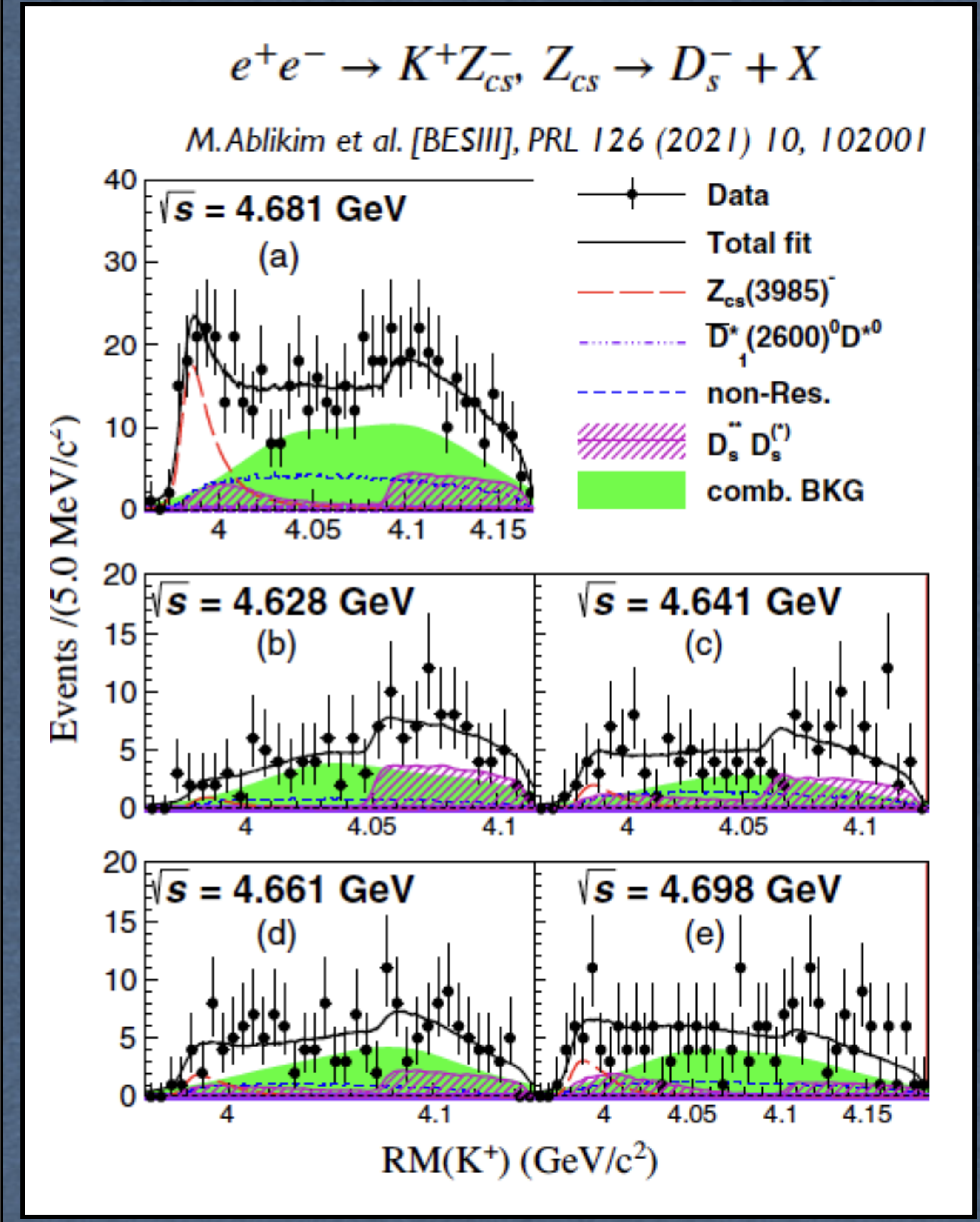
The charmonium (un)orthodoxy

- A host of new and unexpected resonances have appeared
- Preferred decay: charmonium + light
- Difficult to reconcile with charmonium-like interpretation

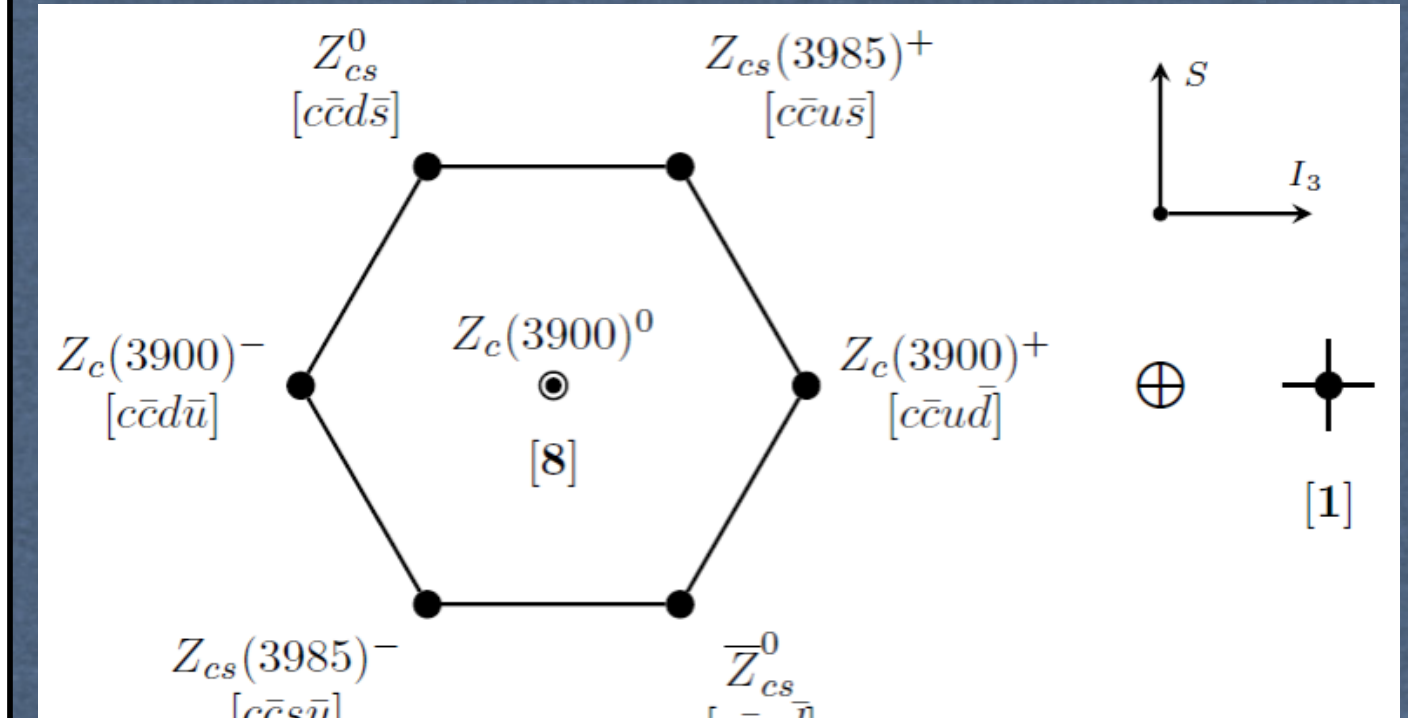


The *good old* times suddenly ended disclosing a realm populated by new and unknown states (multi-quarks? glue-rich? …)

Tetraquarks candidates

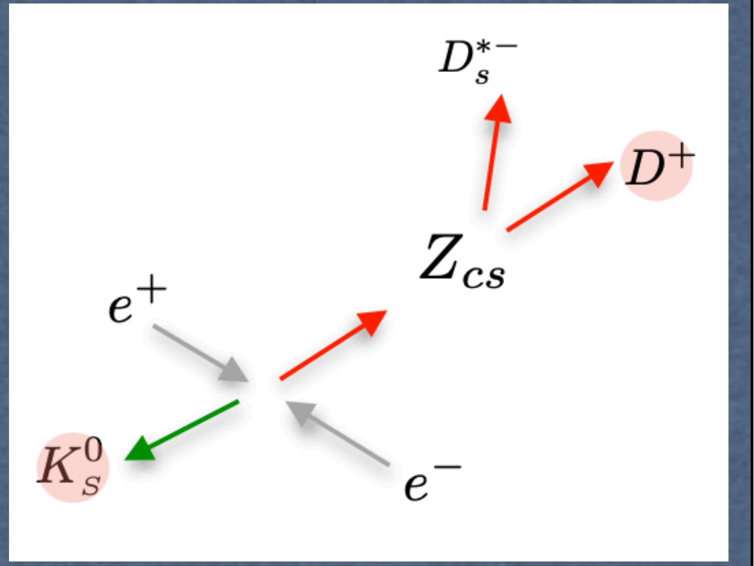


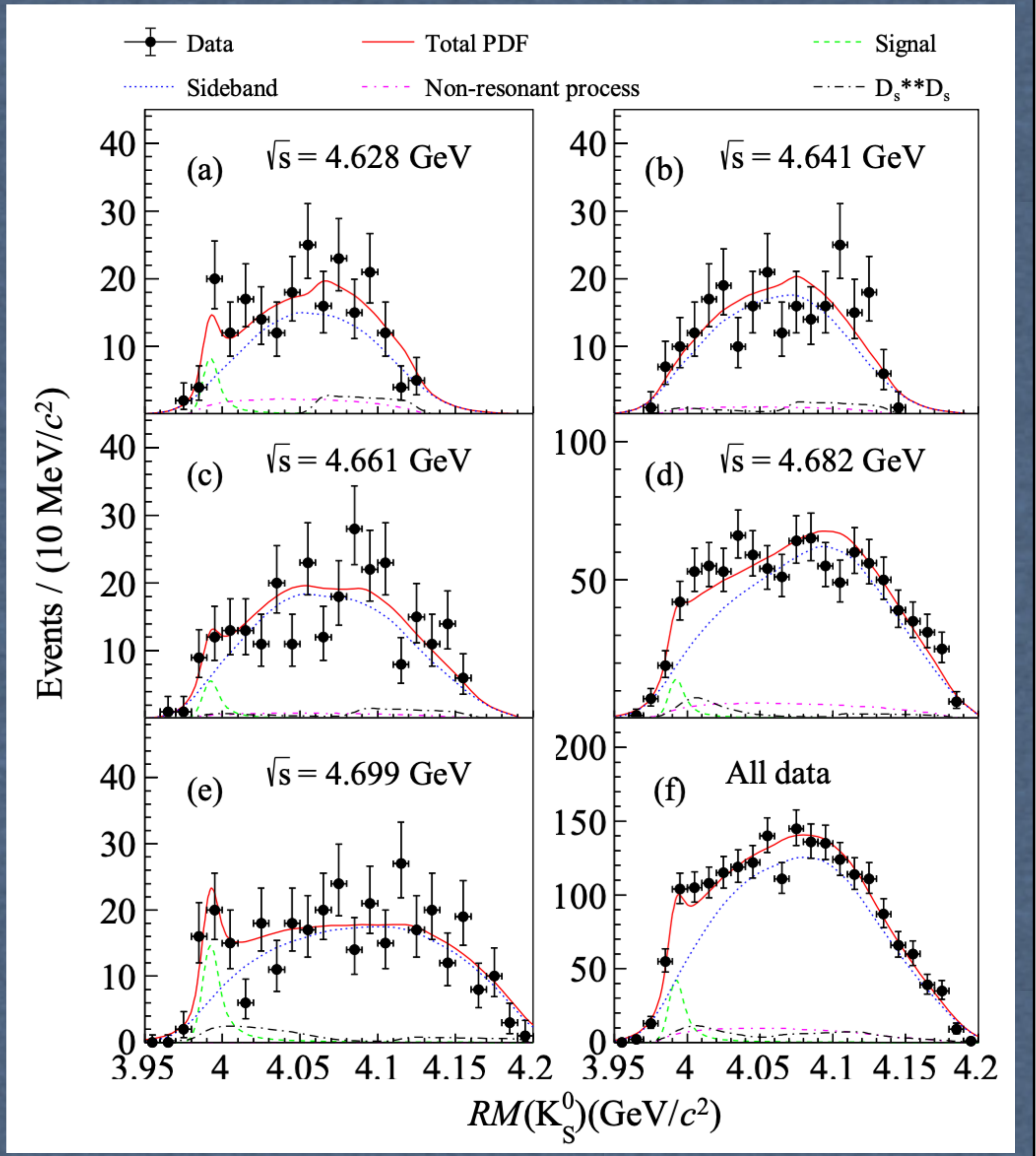
- Years after discovery of charged *Zc* states and analogous *Zb* the picture becomes stranger with the recent discovery of *Zcs* = $c\bar{c}s\bar{q}$
- Prediction of new exotic states based on SU(3) classification



arXiv: 2207.08563

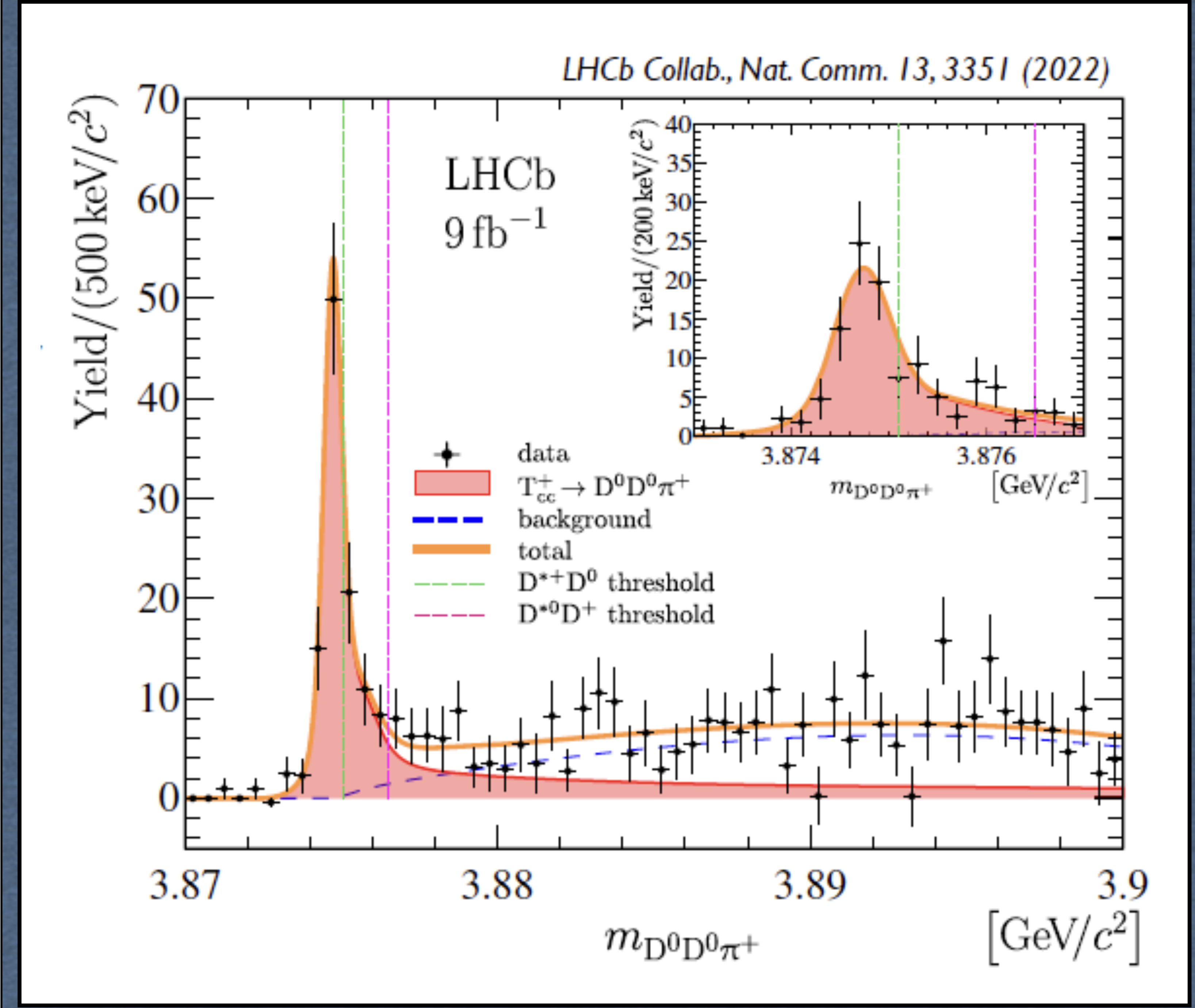
- Isospin partner found by BESIII in D*D+



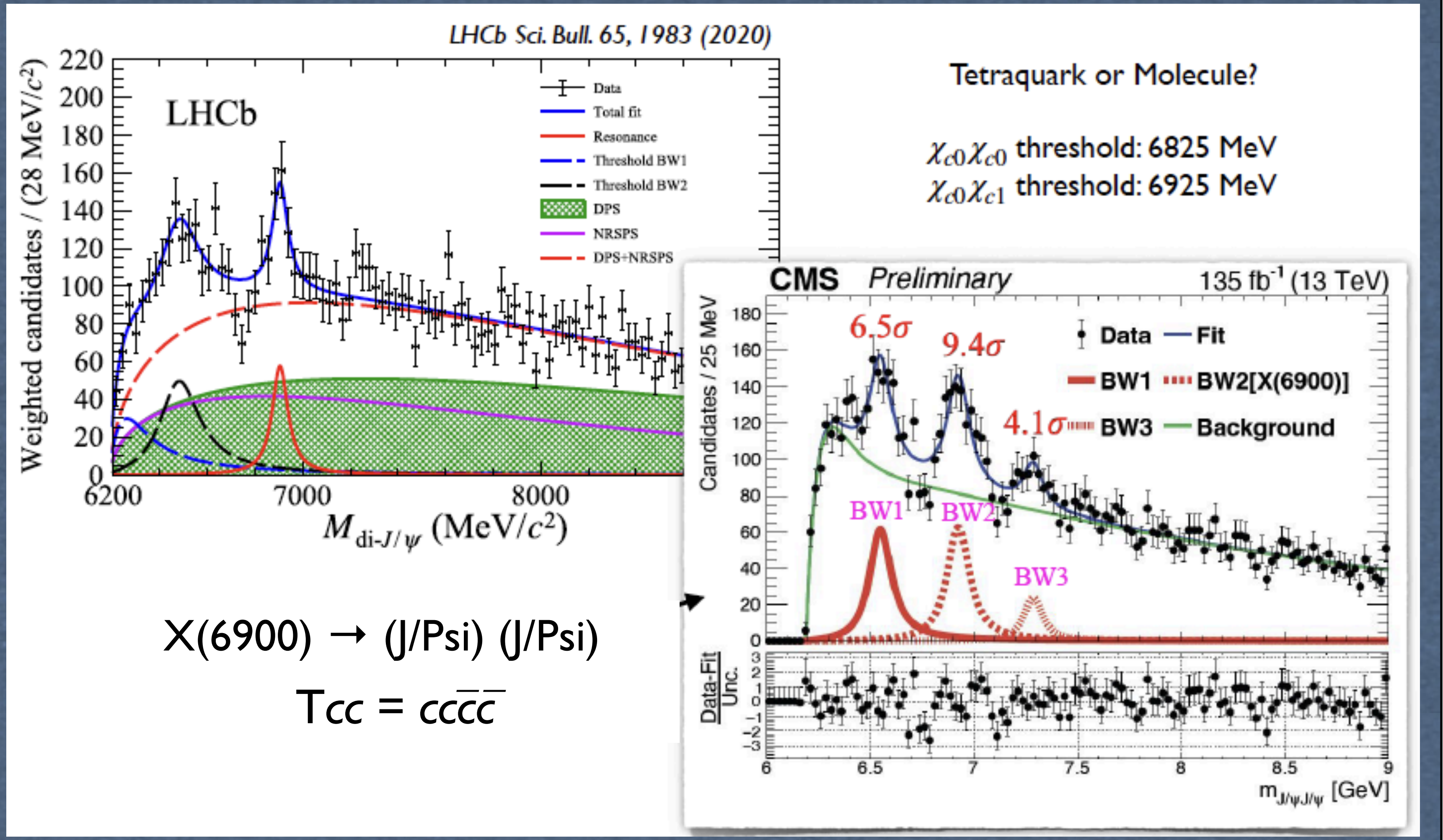


BESIII PRL129 (2022) 112003

Tetraquarks candidates



- Doubly charmed tetraquark: Tcc = $cc\bar{u}\bar{d}$
- Only known meson to be composed by two charm quarks
- Onlyf ew hundred keV below open-charm threshold
- Interpretation: compact tetraquark that decays strongly via an off-shell meson D*
- b-quark analogue (if it exists) should be deeply bound



X(6900) → (J/Psi) (J/Psi)

Tcc = $cc\bar{c}\bar{c}$

How a discovery does happen?

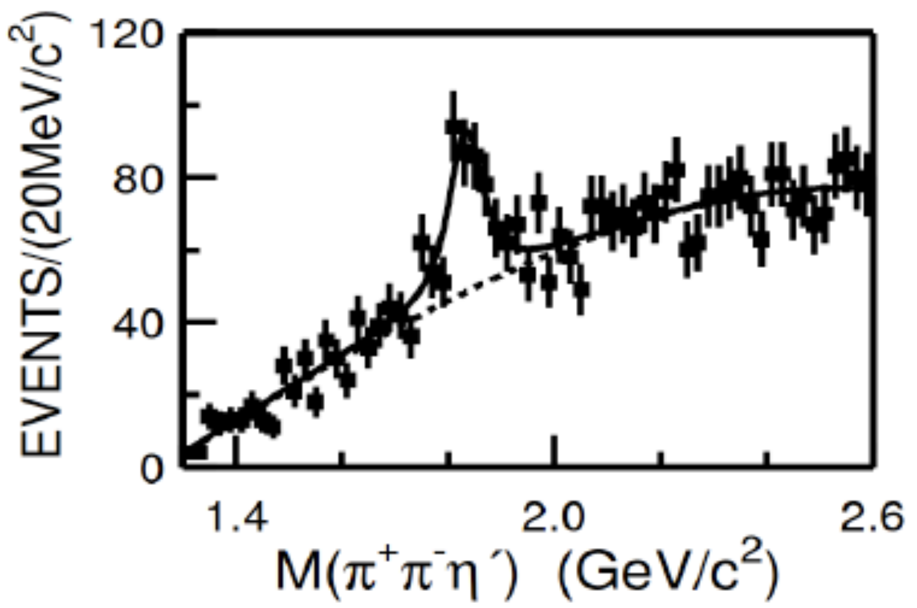
J/ψ radiative decay

Exotic X in J/ψ -> γππη'

Phys. Rev. Lett. 129 (2022) 042001

History of a decay full of surprises

PRL 95 (2005) 262001



58 Million J/psi

Clear signal of exotic X(1835)

presented by G.Mezzadri at STRON2020 Hadron Spectroscopy Workshop in Munich Sept 2022

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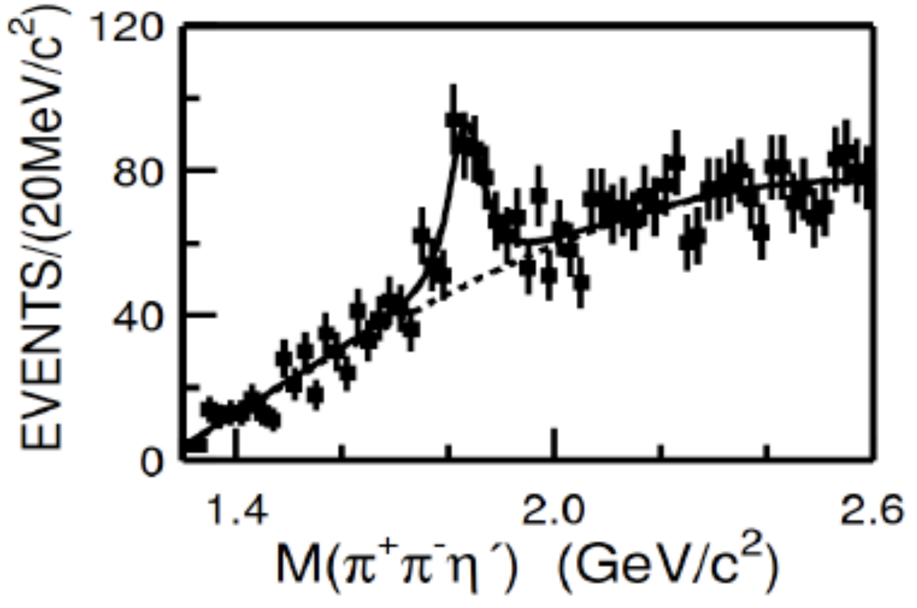

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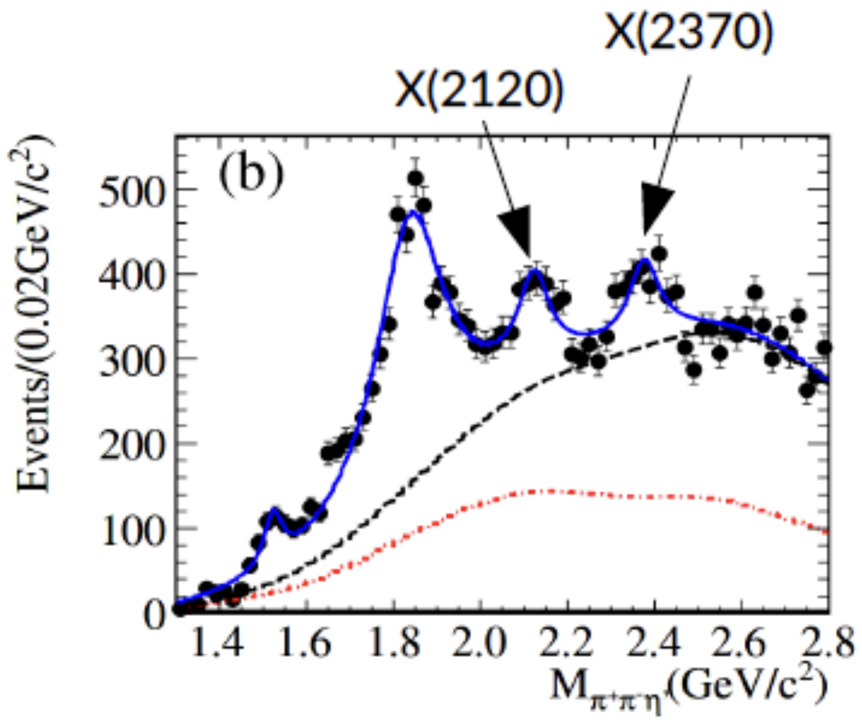

225 Million J/psi

X(1835) confirmed
other two structures emerge

presented by G.Mezzadri at STRON2020 Hadron Spectroscopy Workshop in Munich Sept 2022

How a discovery does happen?

J/ψ radiative decay

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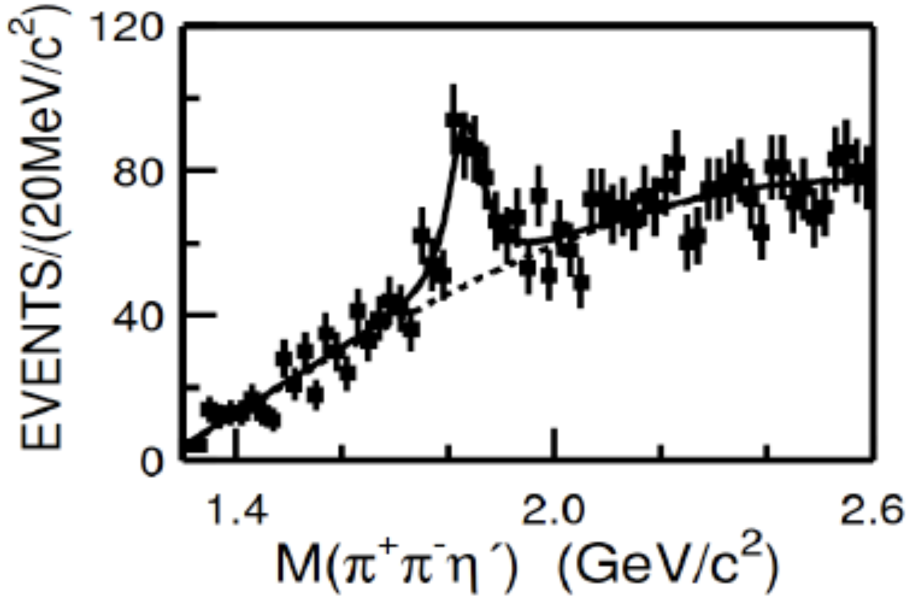

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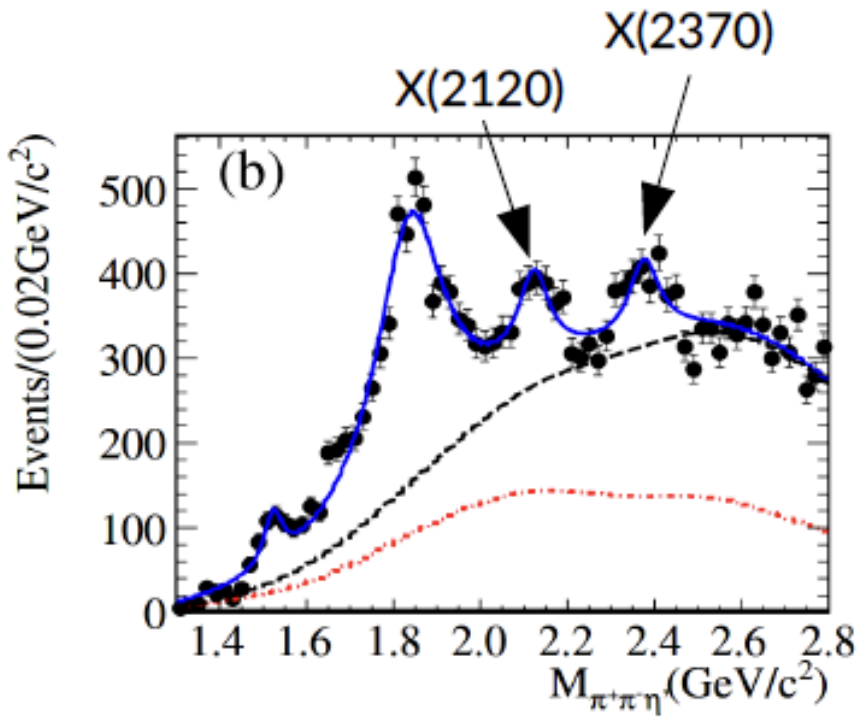
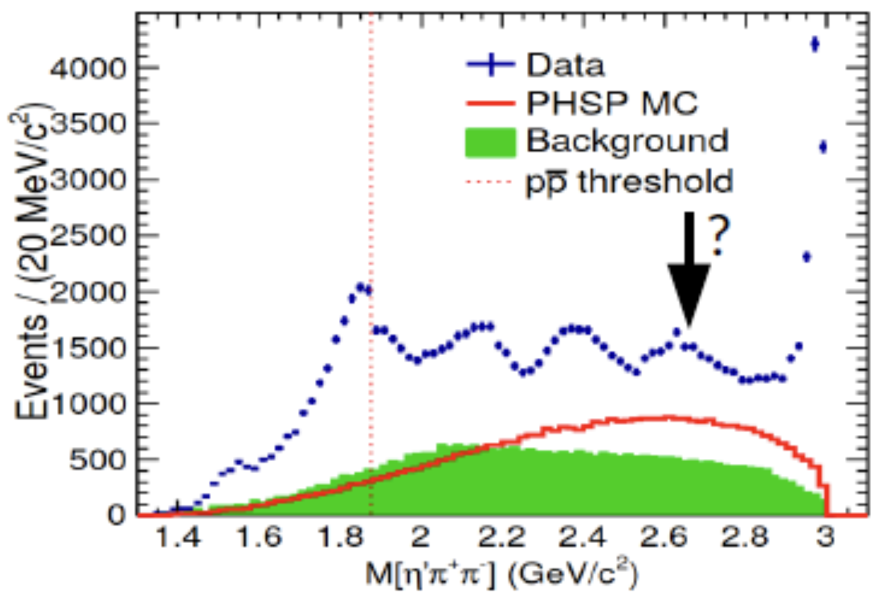


225 Million J/psi

X(1835) confirmed
other two structures emerge

PRL 117 (2016) 042002



1.3 Billion J/psi

@ 1835 MeV:
2 states or threshold effect?

presented by G.Mezzadri at STRON2020 Hadron Spectroscopy Workshop in Munich Sept 2022

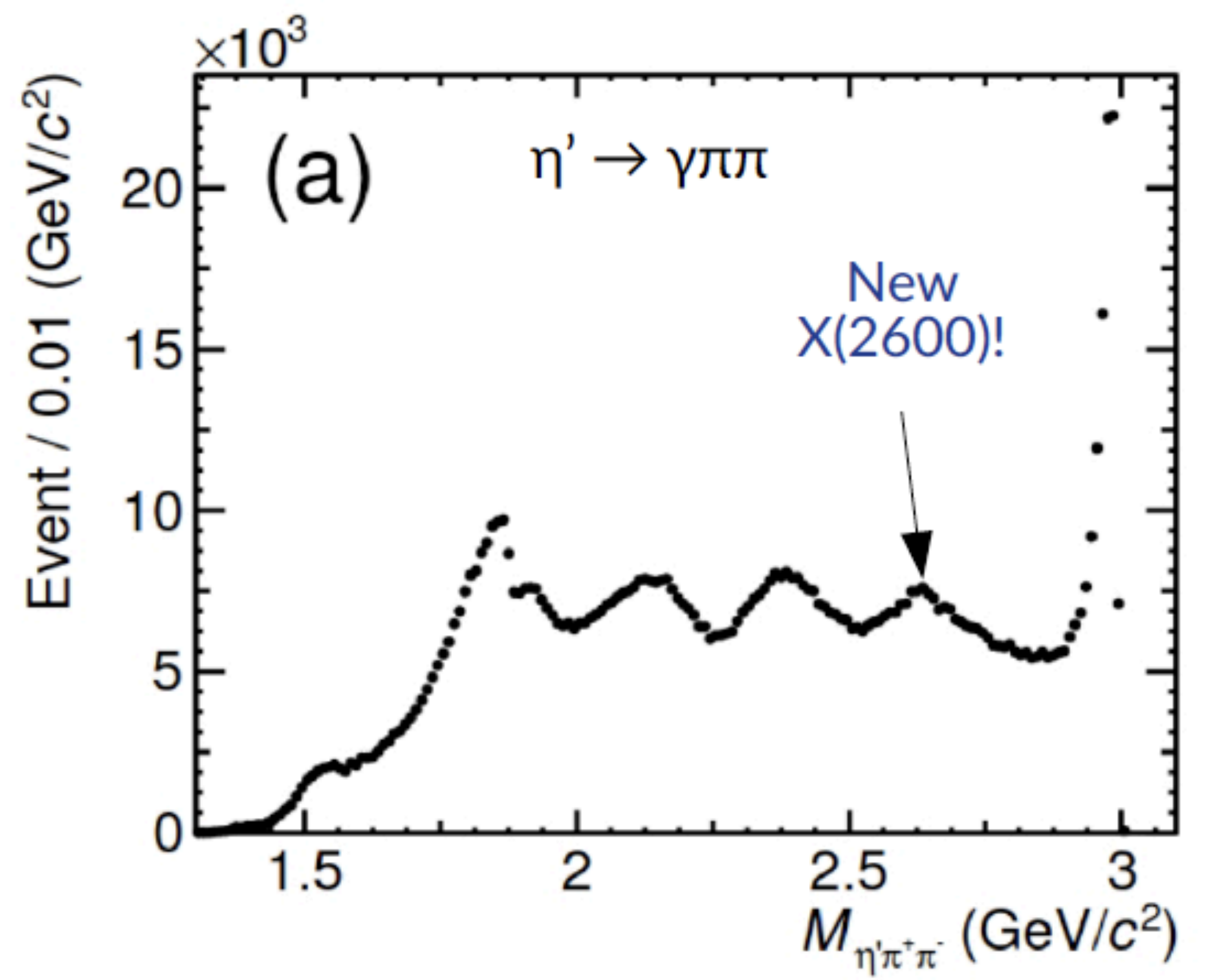
Light q hybrids

J/ψ radiative decay

History of a decay full of surprises

Exotic X in $J/\psi \to \gamma\pi\pi\eta'$

Phys. Rev. Lett. 129 (2022) 042001



X(2600)

Phys. Rev. Lett. 129 (2022) 042002

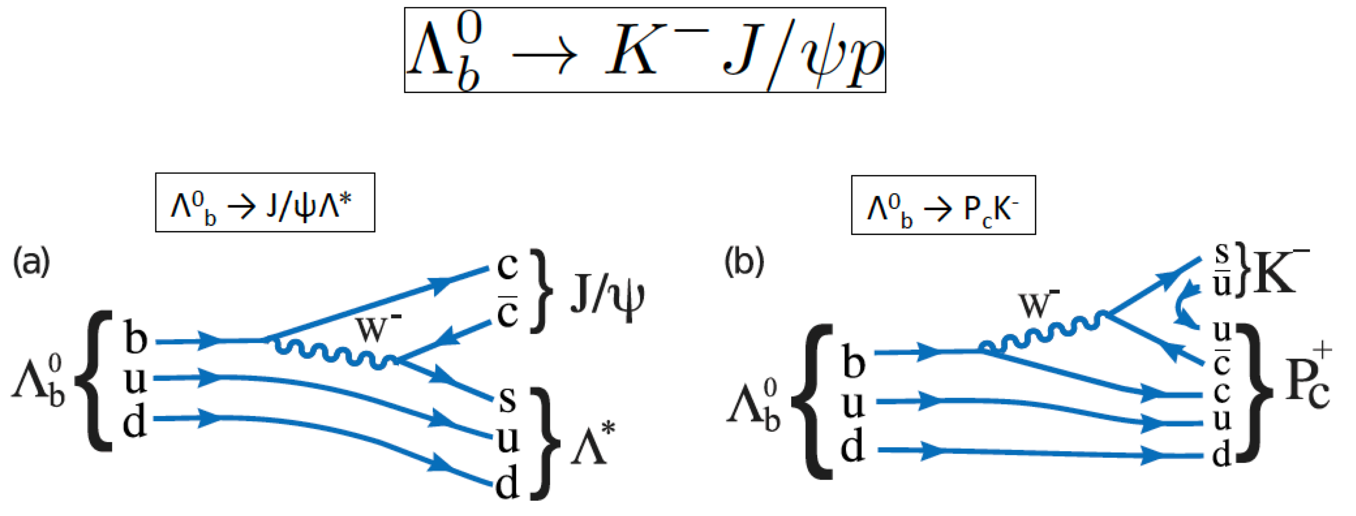
TABLE I. Masses and widths of the $f_0(1500)$, $X(1540)$, and $X(2600)$. The first uncertainties are statistical, and the second are systematic.

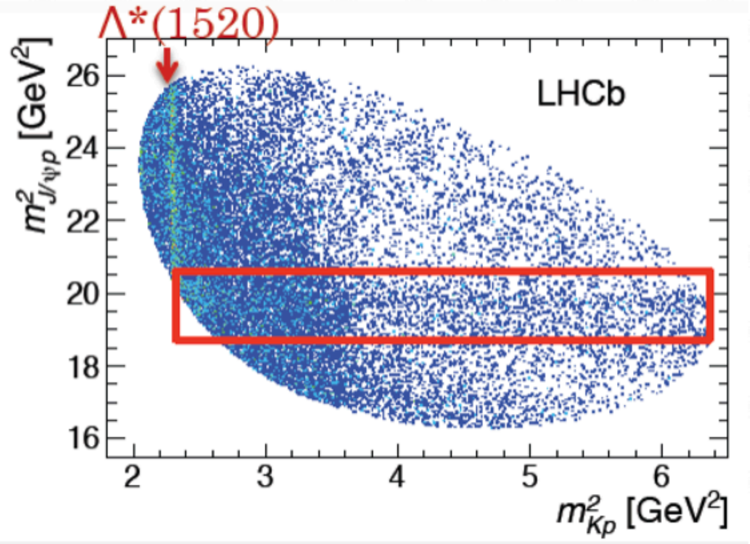
Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

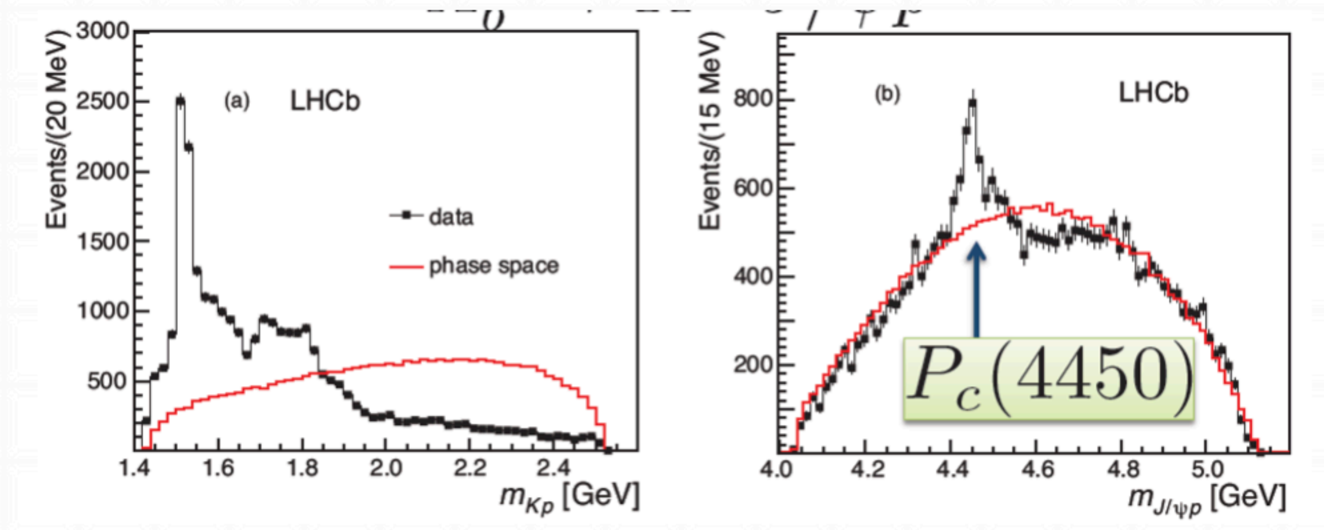
More than 20σ significance for the 3 resonances

presented by G.Mezzadri at STRON2020 Hadron Spectroscopy Workshop in Munich Sept 2022

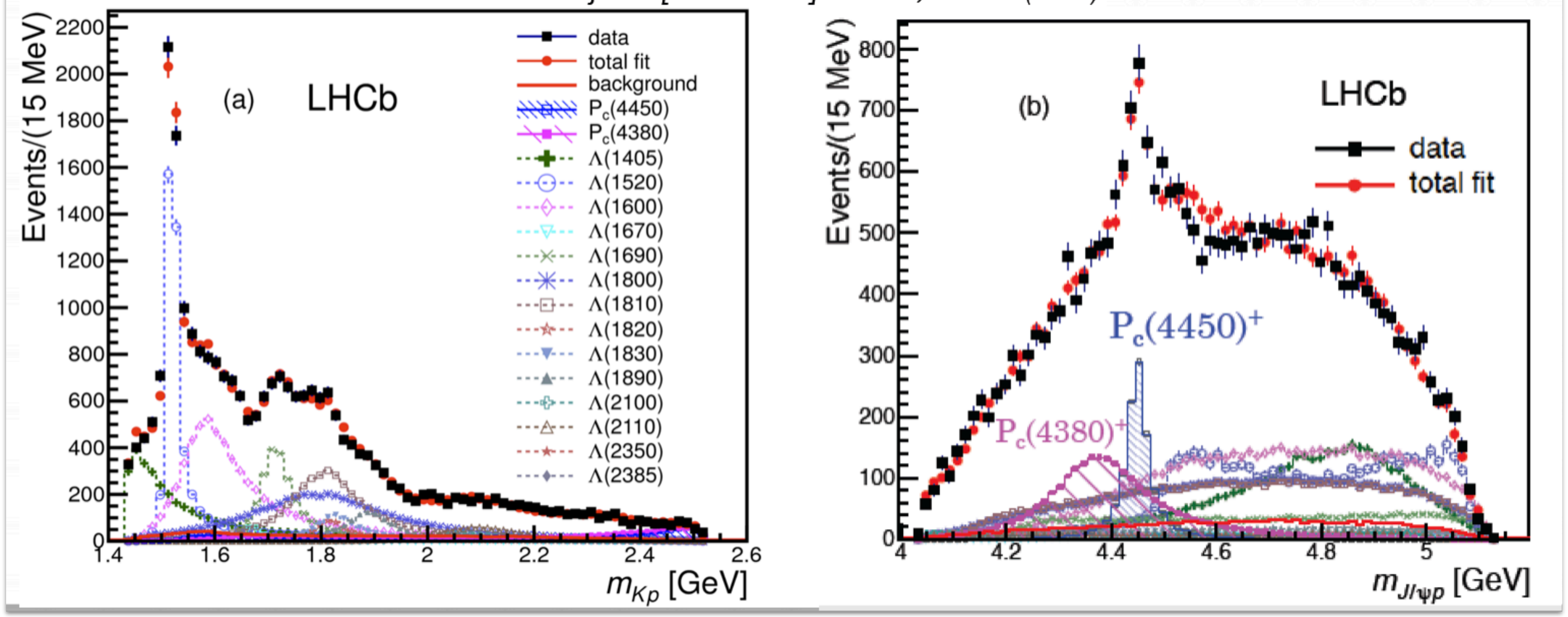
Pentaquark(s)





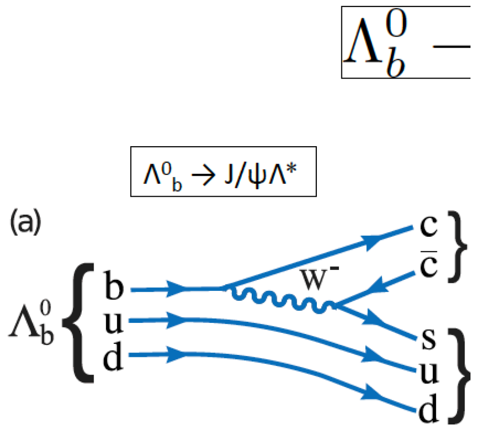


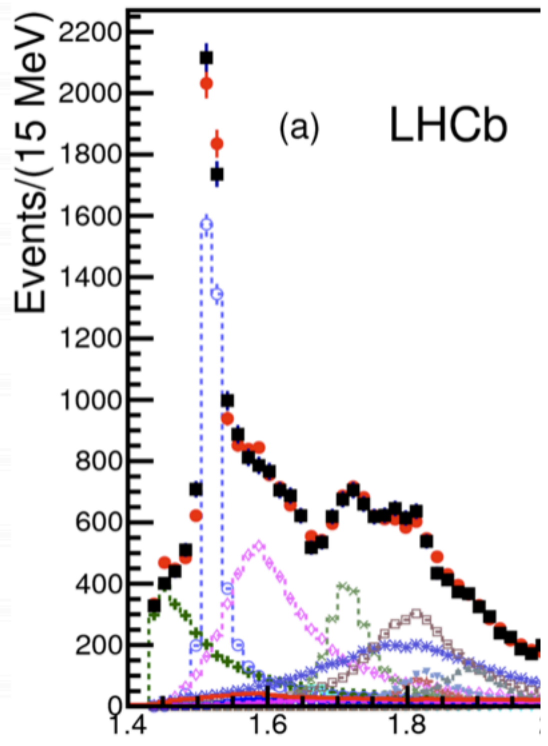
R.Aaij et al. [LHCb Collab.] PRL 115, 072001 (2015)



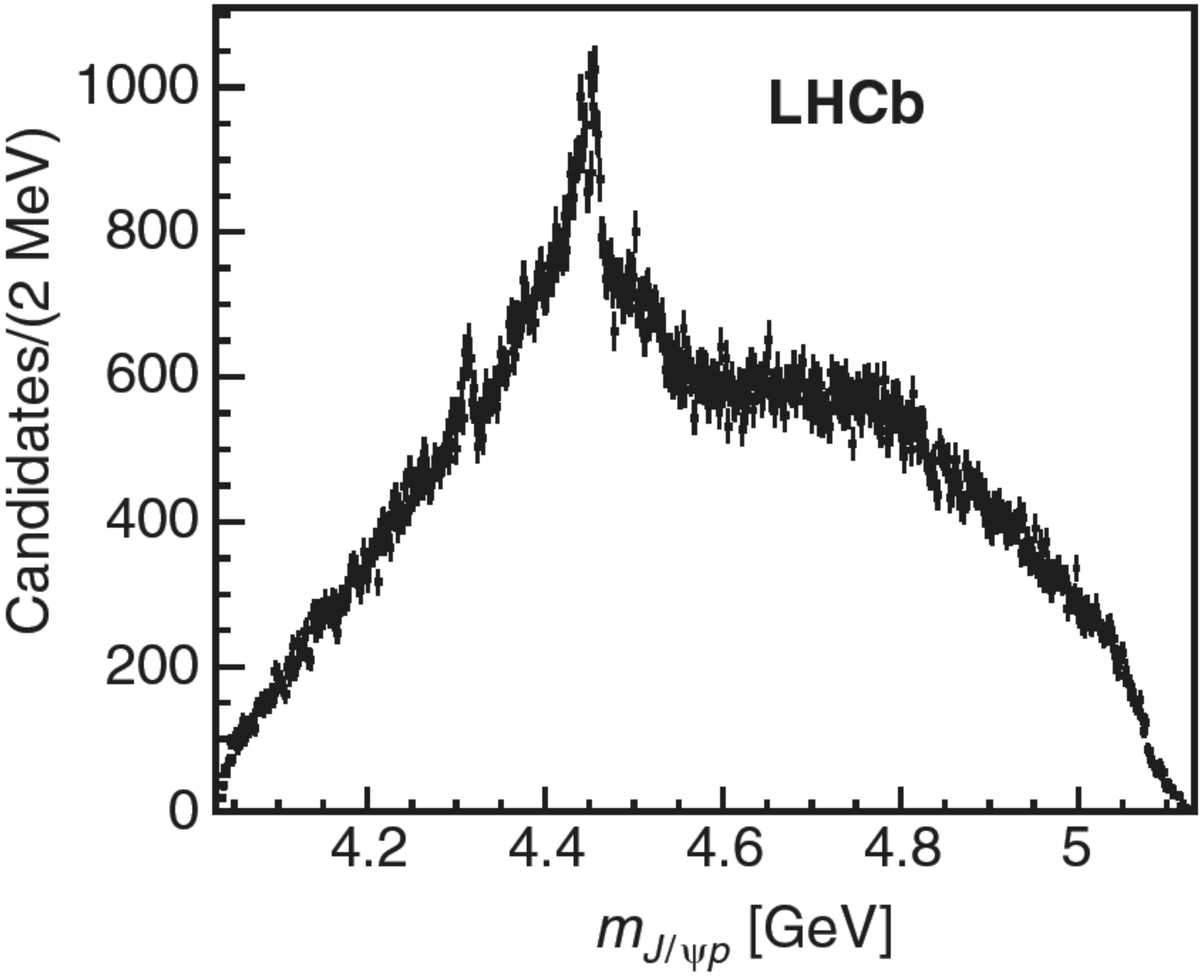
- Combination of quantum number incompatible with a qq-bar state
- sharp peak over smooth background
- narrow width
- The fit included all known Lambda's + phase space (background) + two new states: $P_c(4450)$ Γ=39MeV and $P_c(4380)$ Γ=2015MeV

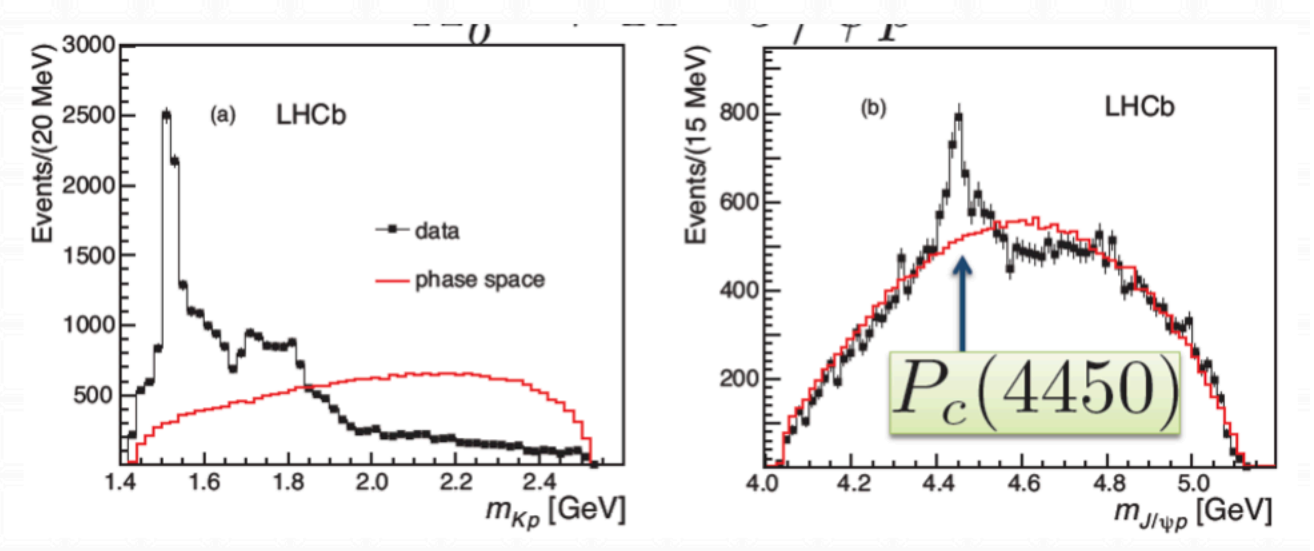
Pentaquark(s)





R.Aaij et al. [LHCb Collab.] PRL 122, 222001 (2019)





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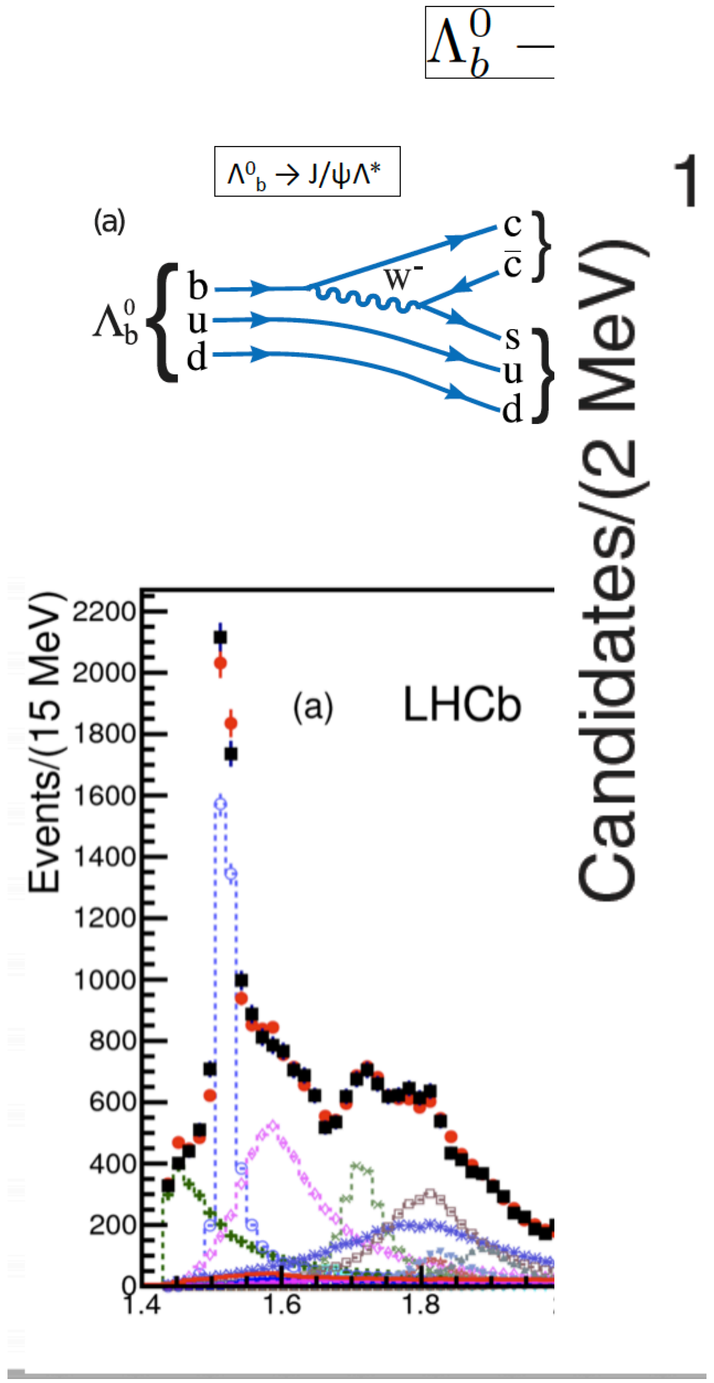
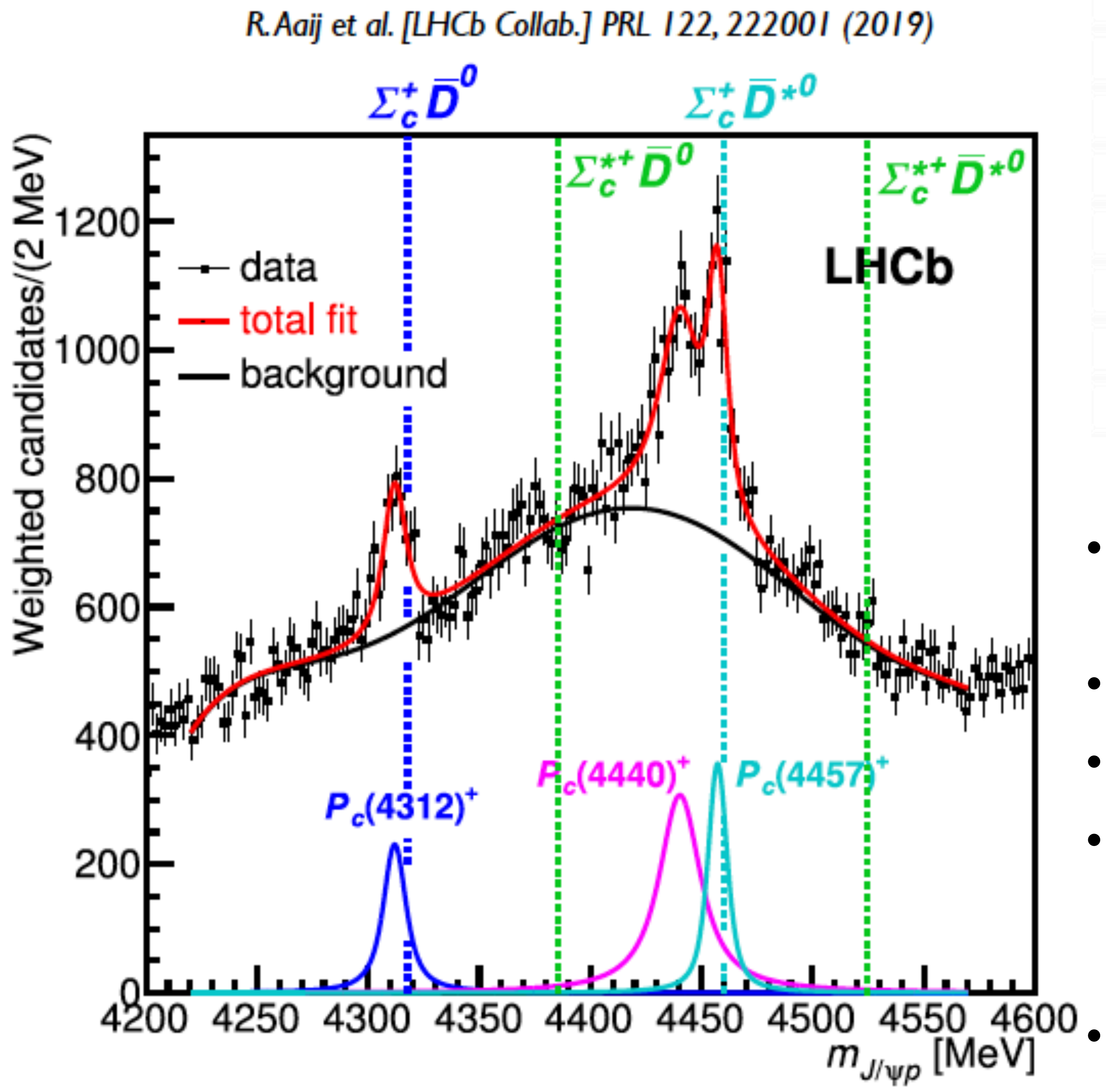
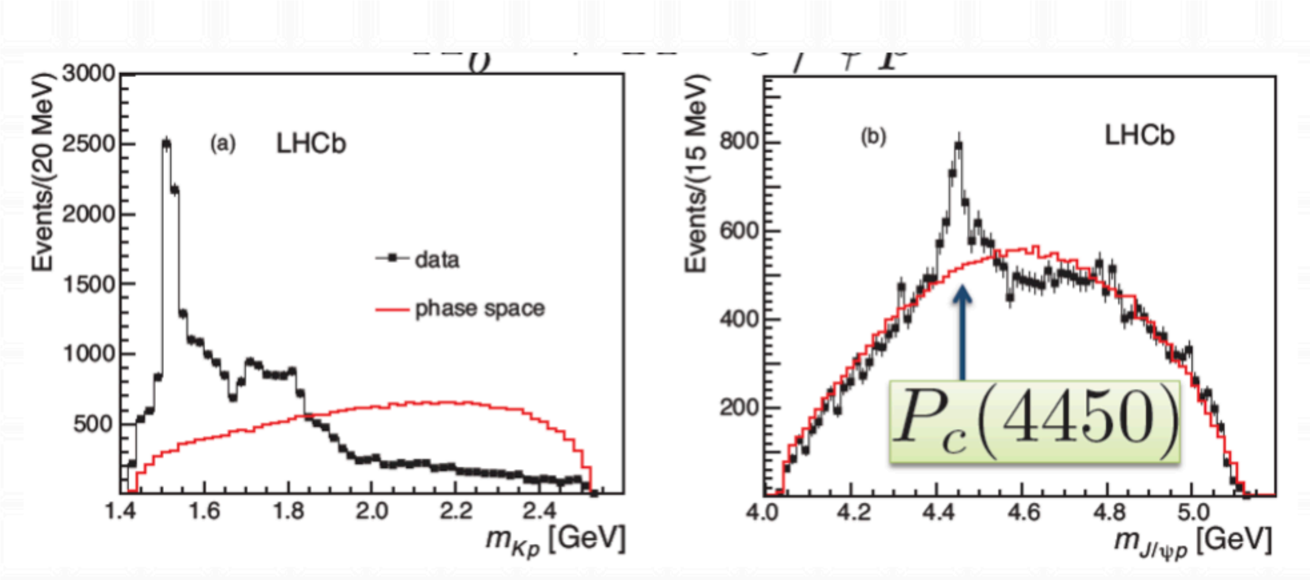
Pentaquark(s)







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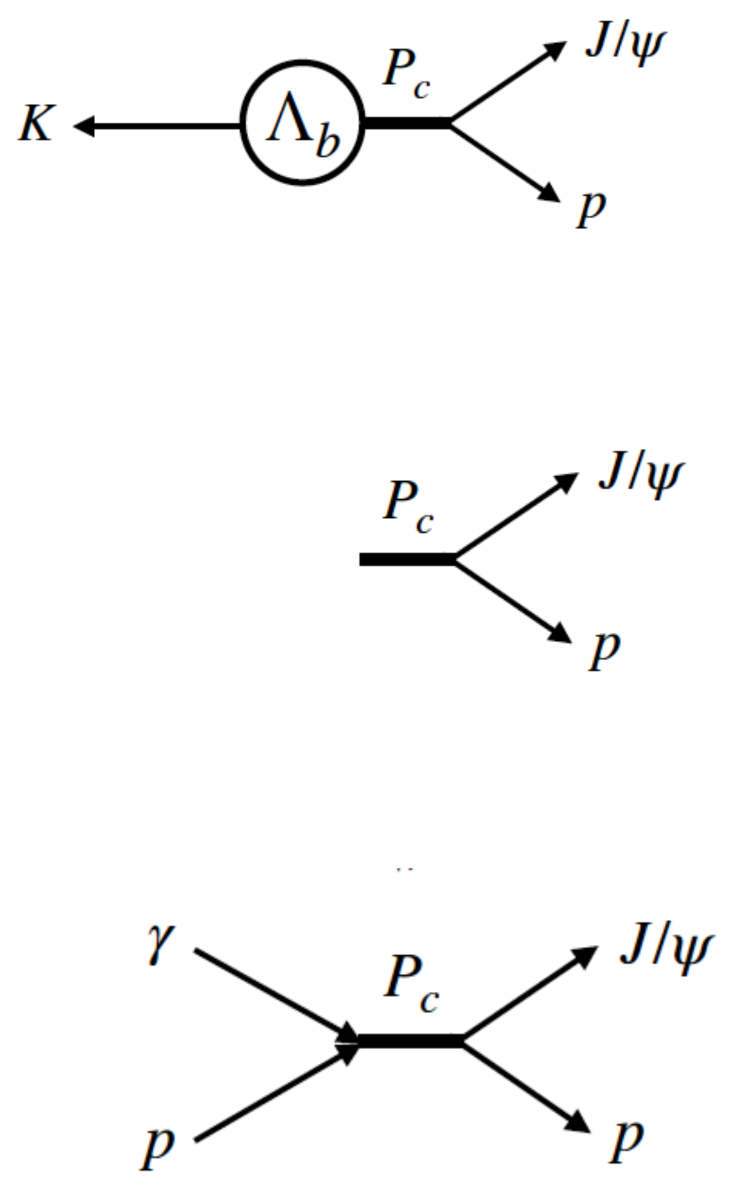
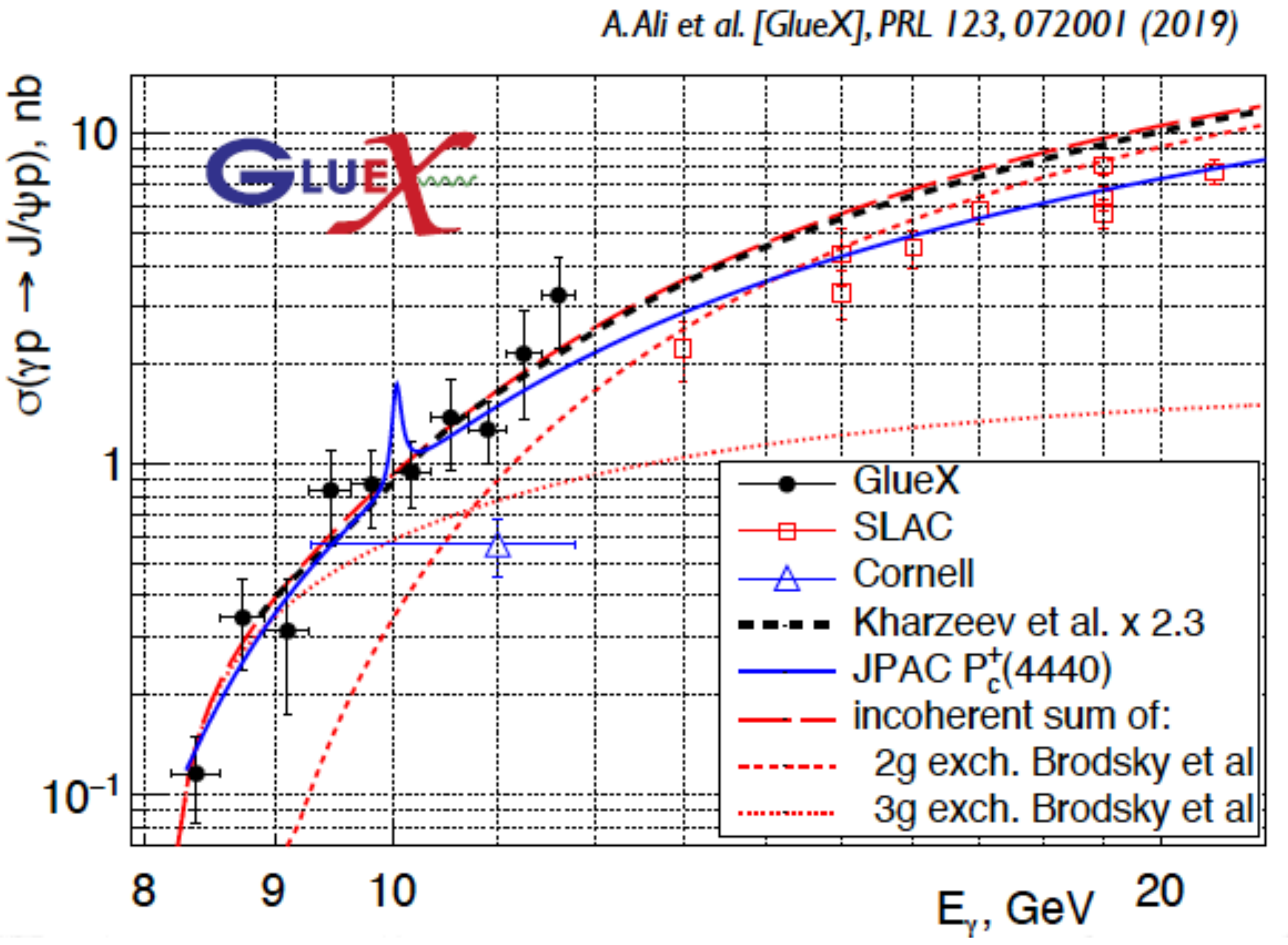
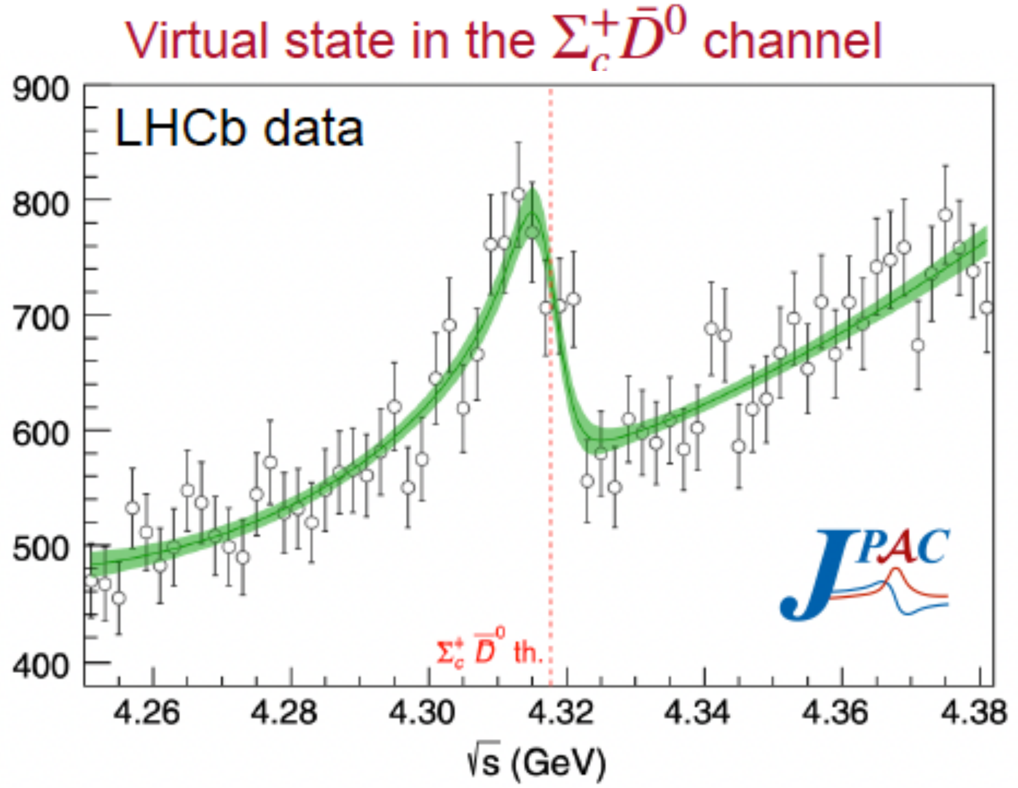
Pentaquark(s)





- Seeking for confirmation in other reaction channel
- No evidence found in s-channel photoproduction
- Doubts on genuine pentaquark nature

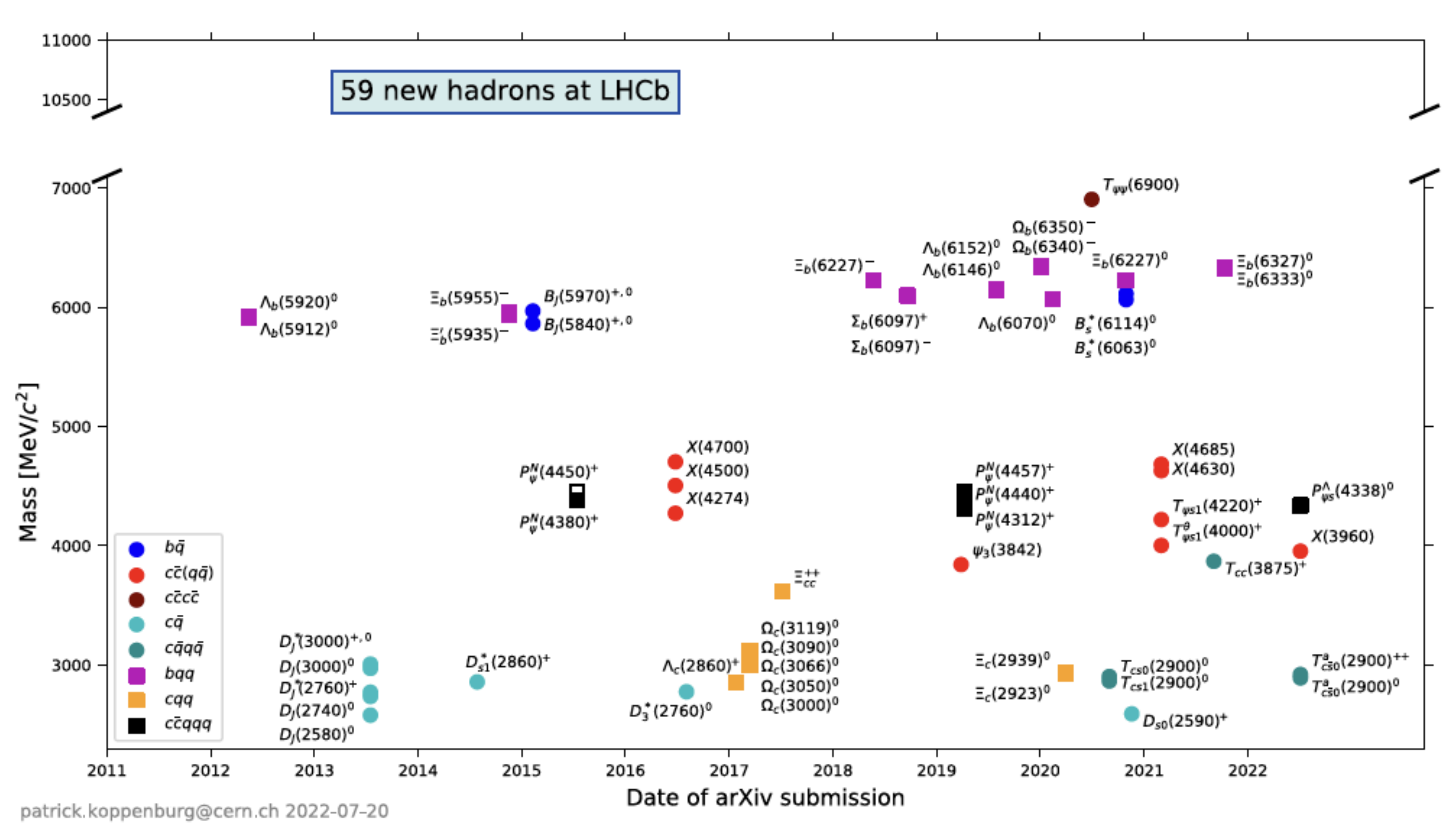
JPAC interpretation:



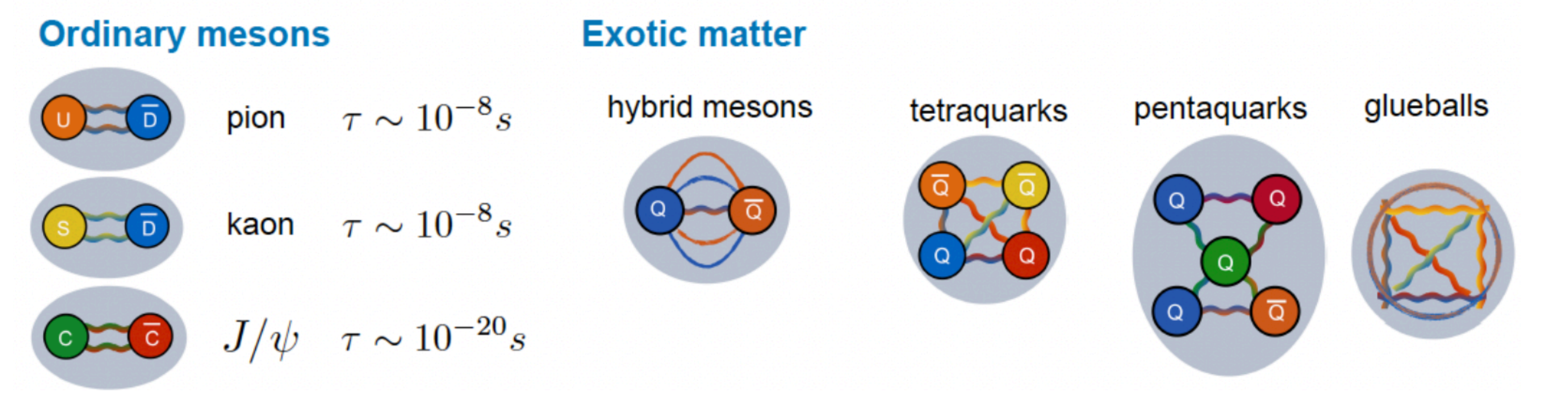
Where are we?

- On June 2022, 59 new exotics states were observed including tetra-quarks and pentaquark
- 44 in the charmonium sector, 5 in the bottomonium sector (less explored), few with a single flavour quark …
- From simple symmetry arguments, ~100 are expected

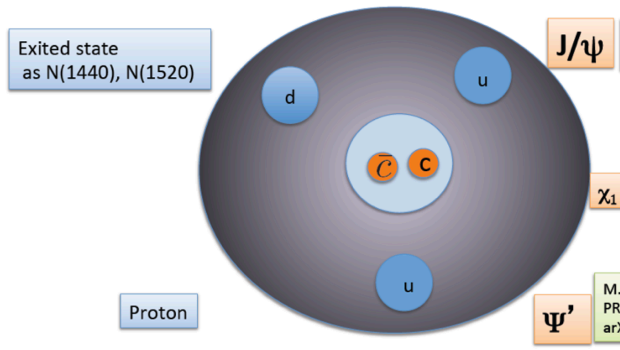
"That's it!"? not at all …



Exotic states interpretation



Baryocharmonium



V. K. and M.B. Voloshin, Phys.Rev. D 92, 3, 031502 (2015)

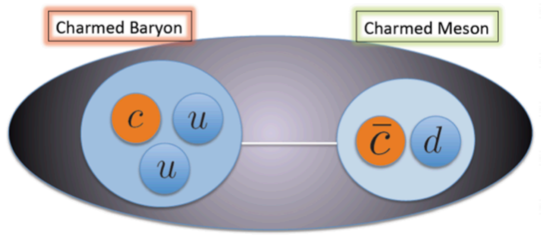
U.-G. Meisner and J. A. Oller, arXiv:1507.07478

M. I. Eides, V.Petrov,M.Polyakov PRD 93, 054039 (2016) arXiv:1709.09523 (2017)

Pentaquark

Pentaquark in this scenario looks like atomic system with a small nucleus whose role plays the heavy quarkonium state and light quarks that play the role of the atomic electrons.
The predicted Γ(P5->J/ψ+p)=11 MeV.

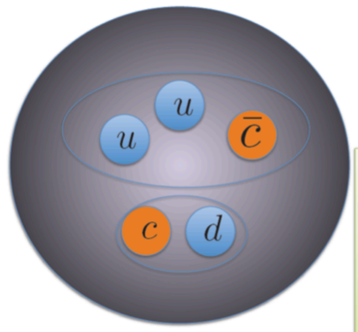
Hadronic molecule



- M. Karliner and J. L. Rosner, arXiv: 1506.06386
- L. Roca, J. Nieves, and E. Oset, arXiv: 1507.04249
- R. Chen, X. Liu, X.-Q. Li, and S.-L. Zhu, arXiv: 1507.03704
- H-X. Chen, W. Chen, X. Liu, T.G. Steele, and S-L. Zhu, arXiv:

These molecules made from a charmed baryon and charmed meson with week coupling. Such pentaquarks will decay predominantly to the charmed baryon and charmed meson.

Bag with color objects



tightly correlated **diquarks or colored baryon-like and meson-like constituents.**

- L. Maiani et al. Phys. Lett. B 749, 289 (2015)
- V. V. Anisovichet al., arXiv: 1507.07652
- A. Mironov and A. Morozov, JETP Lett. 102, no. 5, 271 (2015)
- R. F. Lebed, Phys. Lett. B 749, 454 (2015)

Pentaquarks made of highly correlated diquarks or colored baryon-like and mesonlike constituenents

Mesons depicted here, but each model has a baryonic analogue

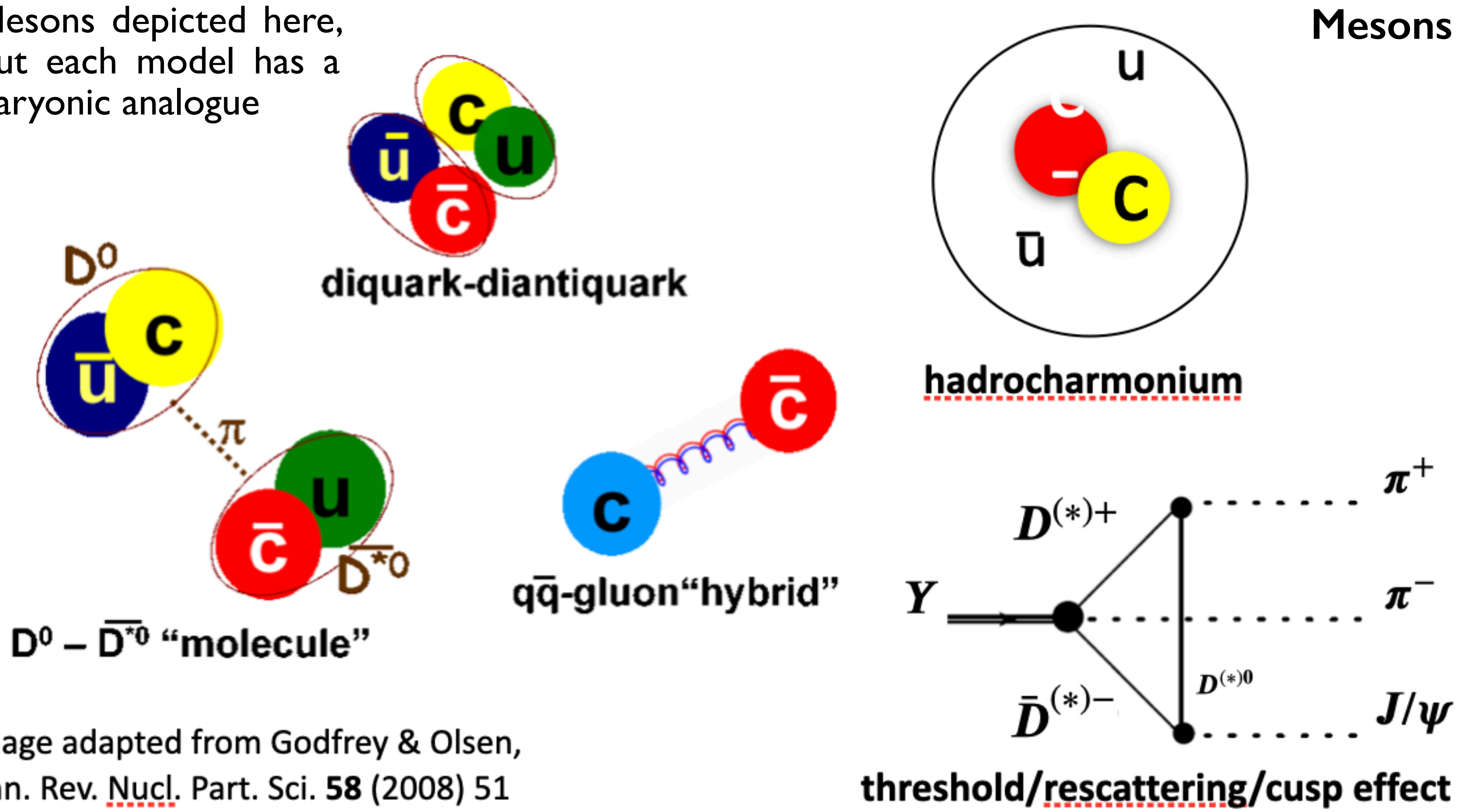


Image adapted from Godfrey & Olsen, Ann. Rev. Nucl. Part. Sci. **58** (2008) 51

Internal structure not yet resolved

Lesson learned and future perspectives

1) new high precision (statistics and systematics) experiments are needed to pin down new states

2) Complement decay studies with 'production'

3) No single model accommodates all new states

4) It's important to distinguish 'resonances' (poles) from 'virtual states' or 'bound states' or 'threshold rescattering effects'

5) Modern hadron spectroscopy requires collaborations between experimentalists and theorists

6) Lattice QCD is our reference but has some limitations: precise predictions are true for states stable against strong decay and NONE of the new states are …

7) Lattice should be used in coordination with phenomenological models

- ✳ Hadron spectroscopy (now as in the past) demonstrates to be an important tool to study strong forces
- ✳ Several new multi-quark states that do not fit into the Quark Model have been discovered
- ✳ Quark bound-states are genuine manifestation of non-perturbatibe regime of QCD
- ✳ The effort to un reveal the internal structure of new states will be payed off by progressing our understanding of the strong force
- ✳It is still a long way to go but in an exciting journey!