Hadron Spectroscopy Today

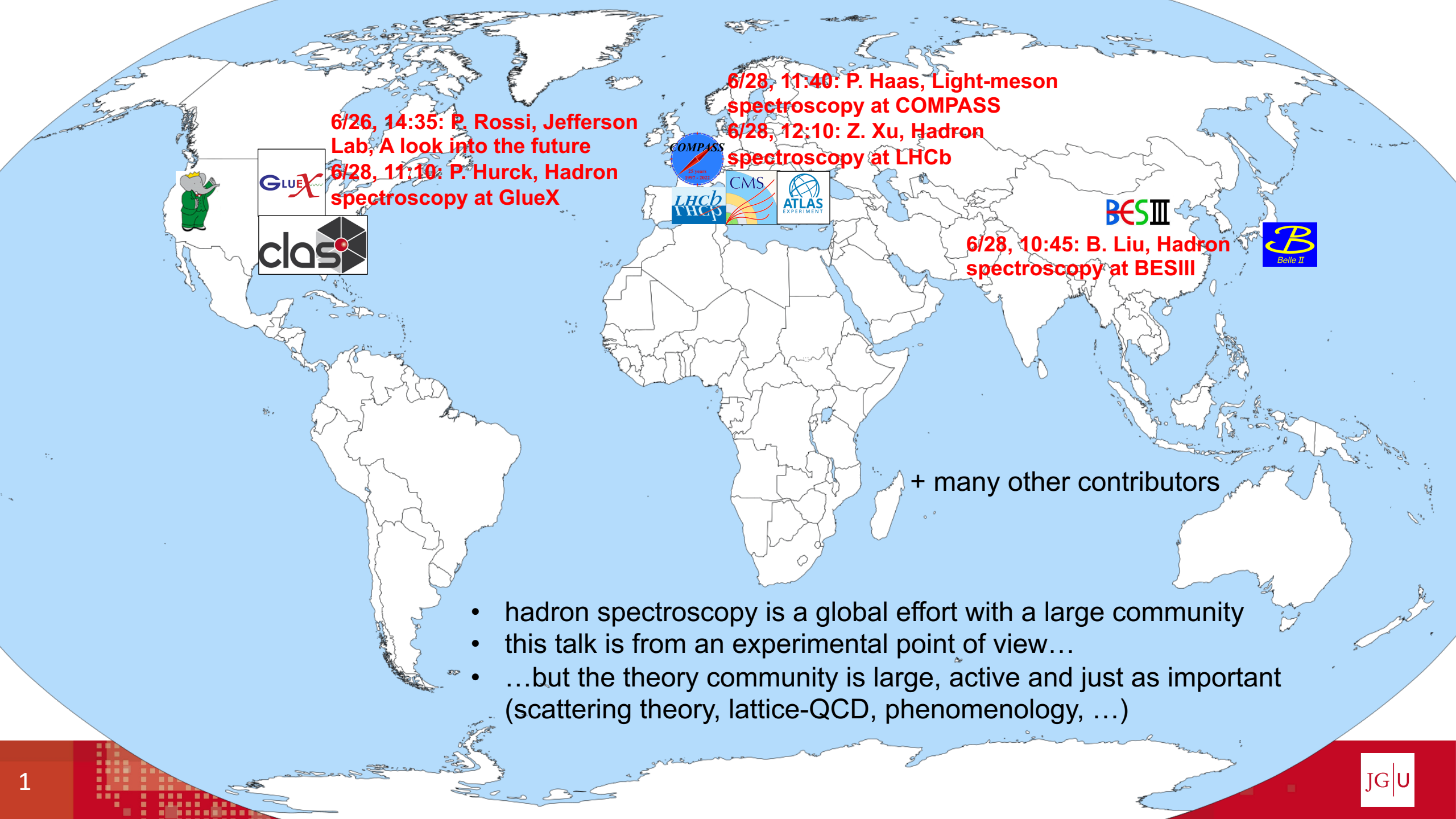
Nils Hüsken
Johannes Gutenberg-Universität Mainz

International Workshop on Hadron Structure and Spectroscopy 2023
Prague - June 26, 2023

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

MARIE CURIE ACTIONS

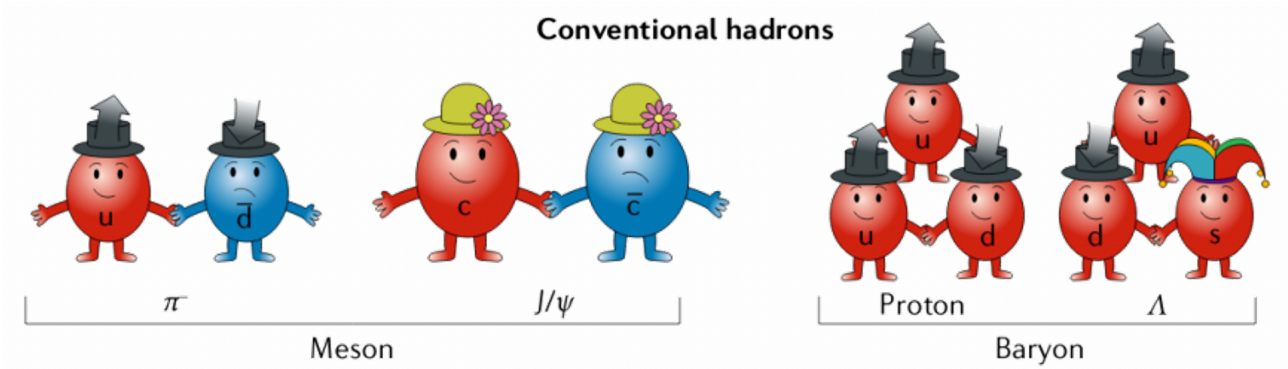


+ many other contributors

- hadron spectroscopy is a global effort with a large community
- this talk is from an experimental point of view…
- …but the theory community is large, active and just as important (scattering theory, lattice-QCD, phenomenology, …)

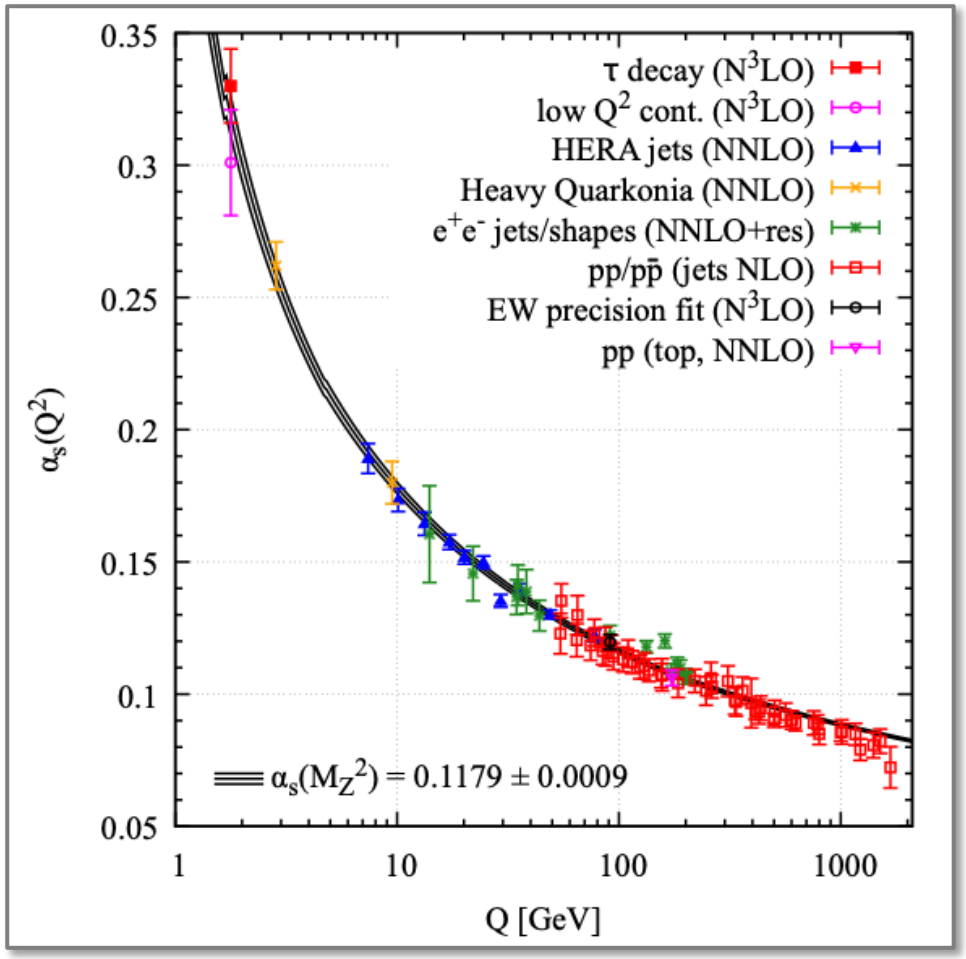
HADRONS...

- color charged quarks and gluons are the fundamental degrees of freedom of QCD
- confinement: quarks and gluons bind and form color-neutral hadrons



Nature Rev. Phys. 1 (2019) no.8, 480-494

- hadron spectrum is one access to study the strong interaction in the non-perturbative regime



Prog. Theor. Exp. Phys. 2020, 083C01 (2020) and 2021 update.

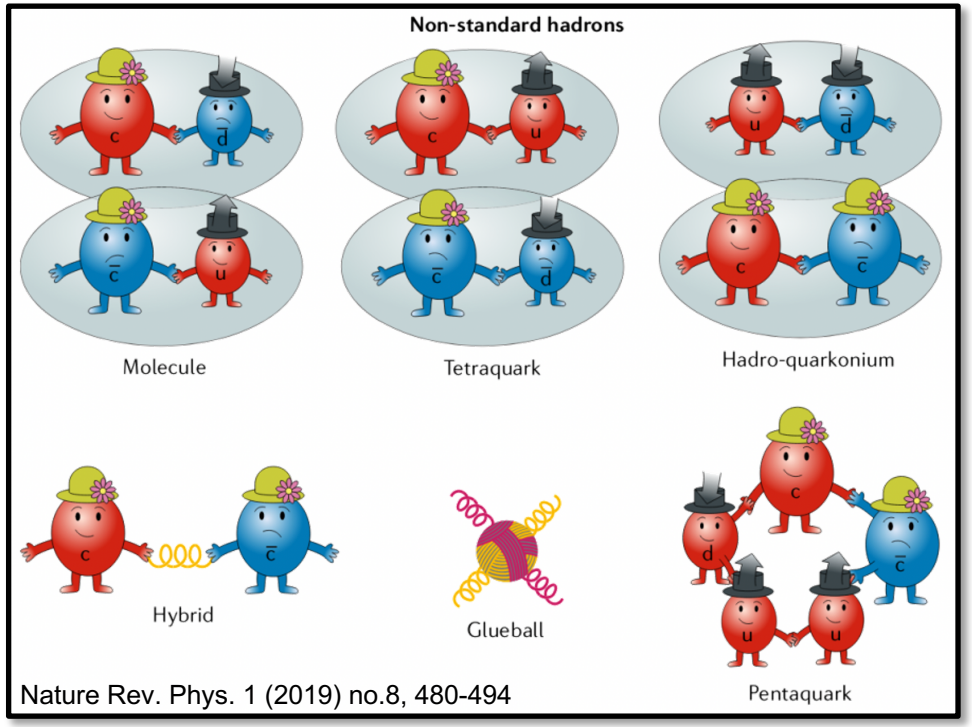
… AND EXOTIC HADRONS

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the 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**.



Nature Rev. Phys. 1 (2019) no.8, 480-494

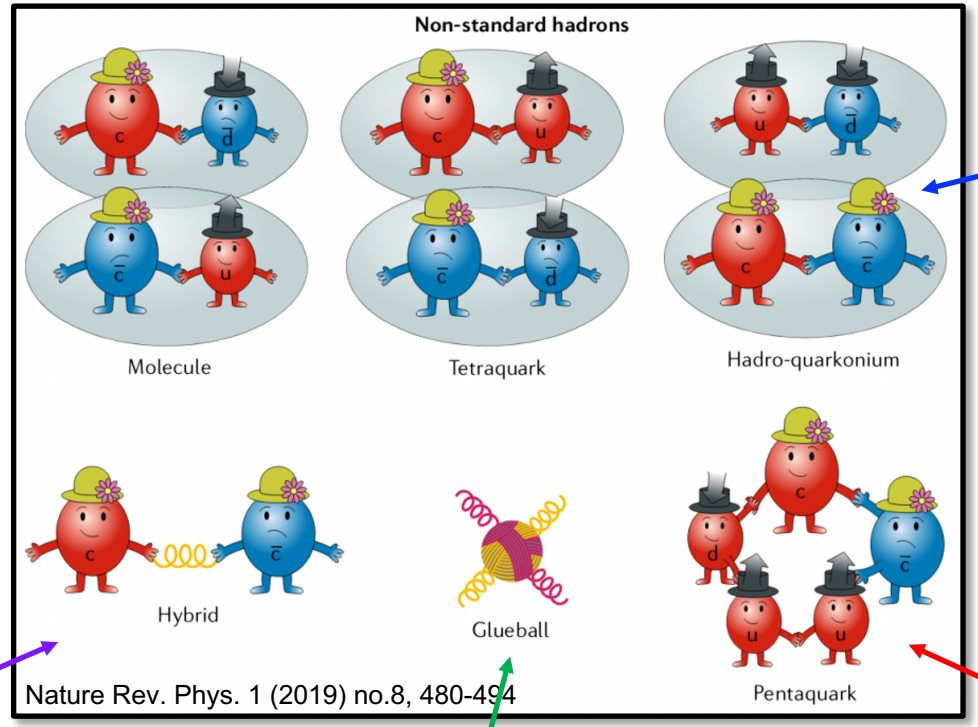
… AND EXOTIC HADRONS

A SCHEMATIC MODEL OF BARYONS AND MESONS *

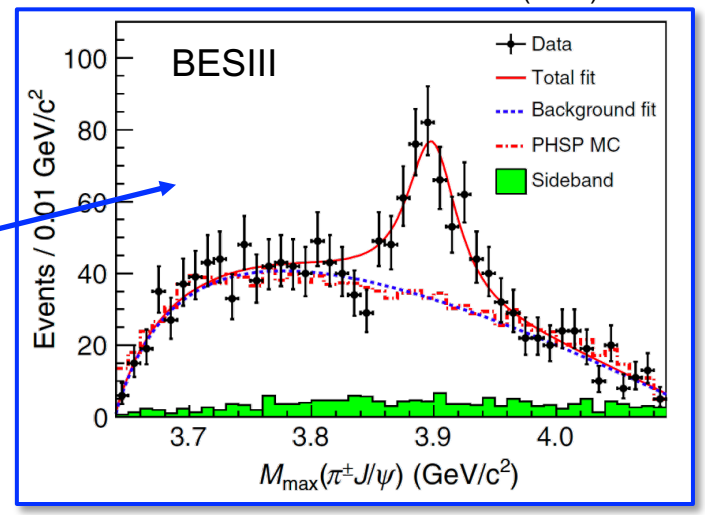
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

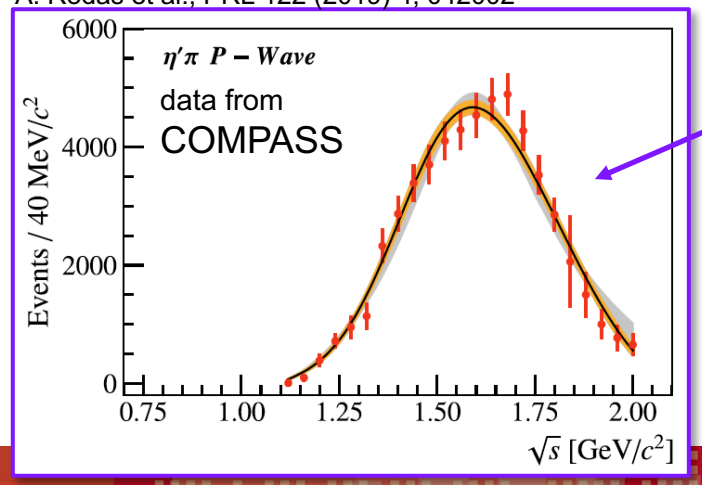
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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**.



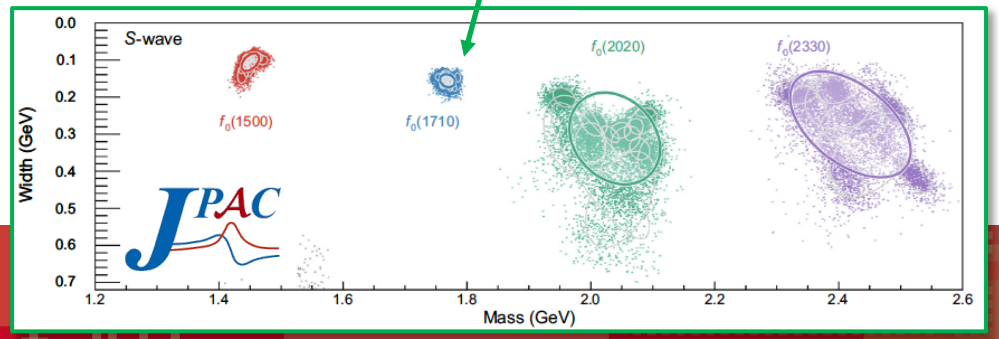
PRL 110 (2013) 252001



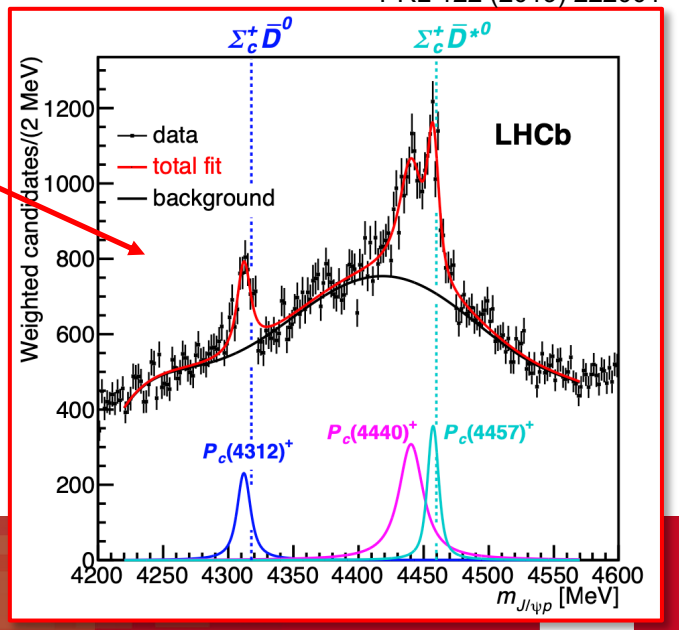
B. Kopf et al., EPJ C 81, 1056 (2021)
A. Rodas et al., PRL 122 (2019) 4, 042002



Rodas et al., EPJ C 82, 80 (2022)



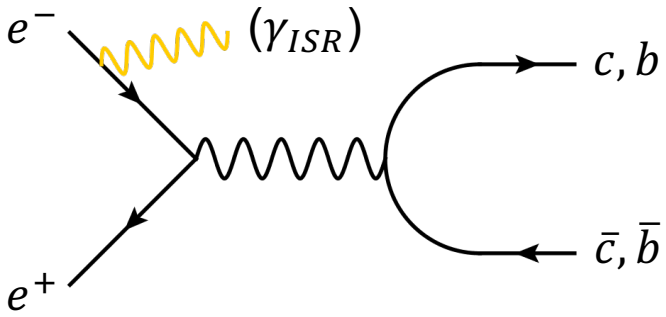
PRL 122 (2019) 222001



QUARKONIUM(-LIKE) STATES

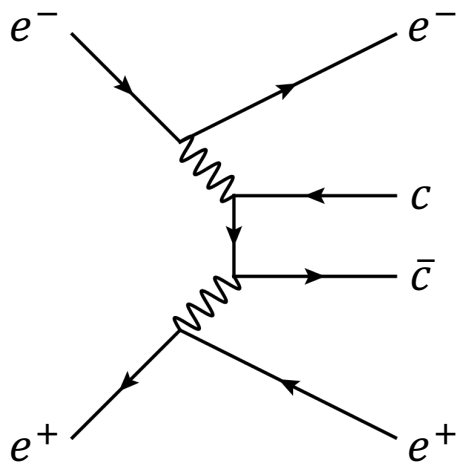
QUARKONIUM PRODUCTION

- in e^+e^- machines:



annihilation:

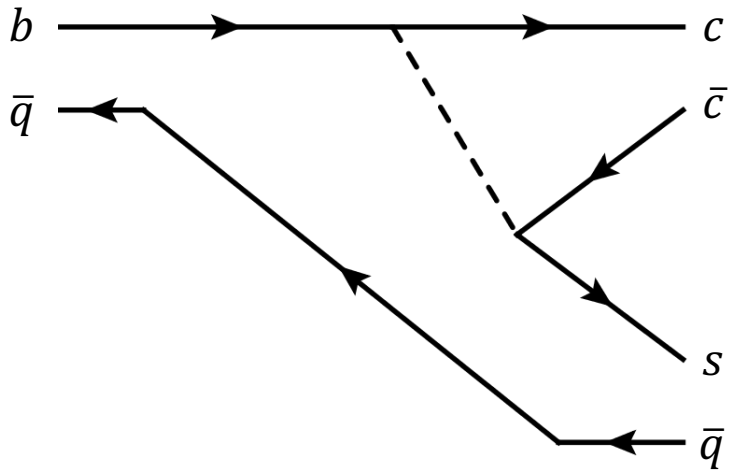
$J^{PC} = 1^{--}$



two-photon fusion:

$C = +1$

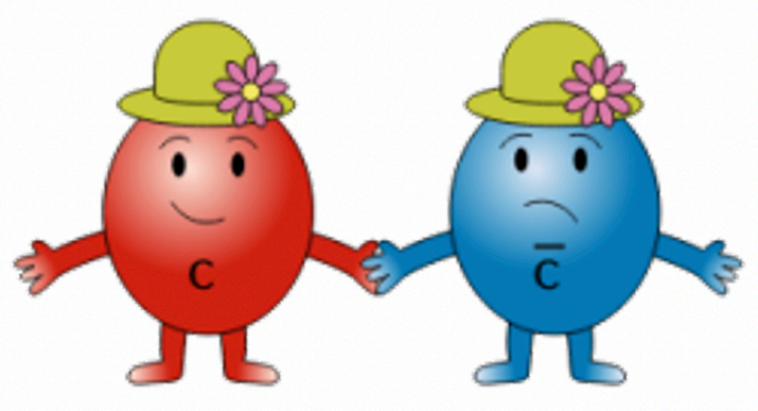
- in weak b decays:



from $B, B_s, \Lambda_b, \ldots$

+ prompt production
+ photo-production
…

QUARKONIUM



Nature Rev. Phys. 1 (2019) no.8, 480-494

- QCD-analogue to hydrogen atom / positronium
- spectrum from potential models:

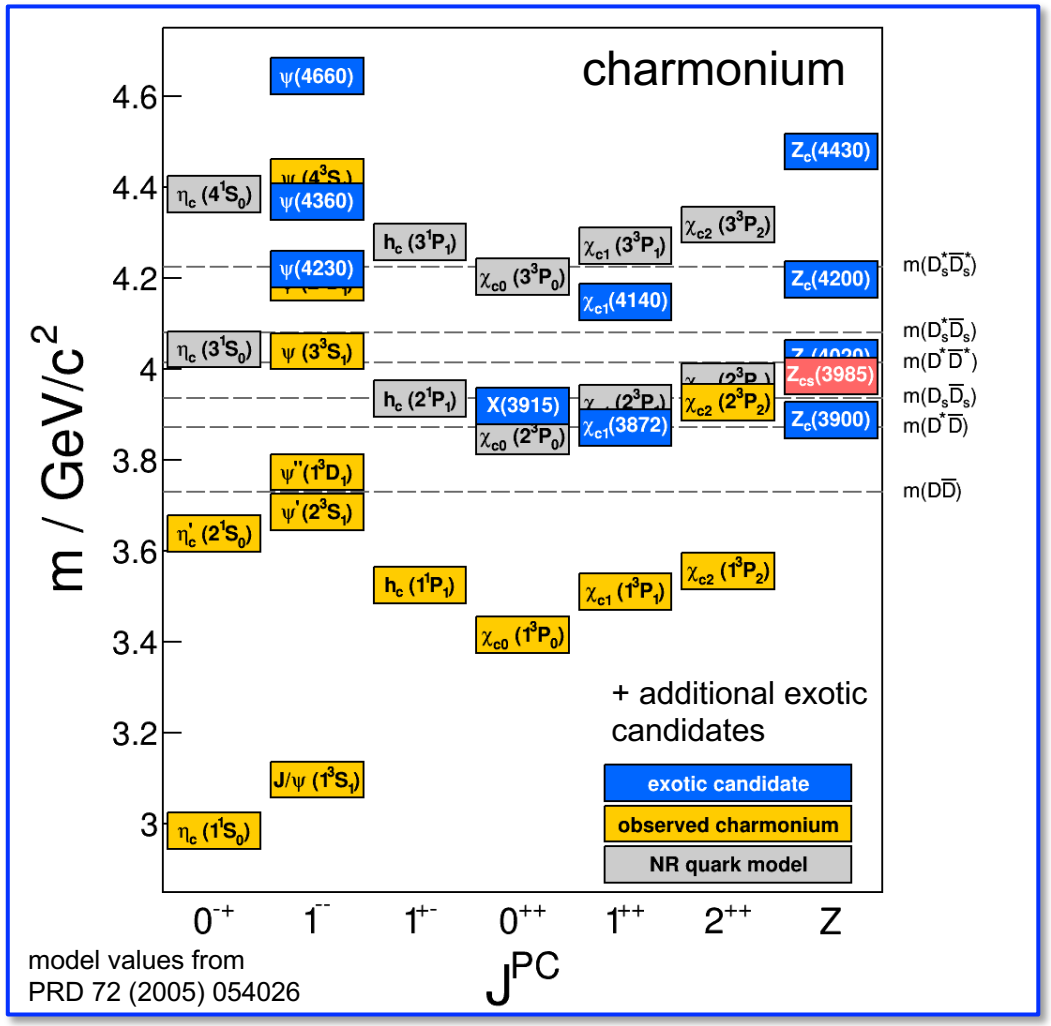
$$V_{q\bar{q}} = -\frac{4}{3} \cdot \frac{\alpha_s(r)}{r} + k \cdot r$$

+ spin-dependent terms

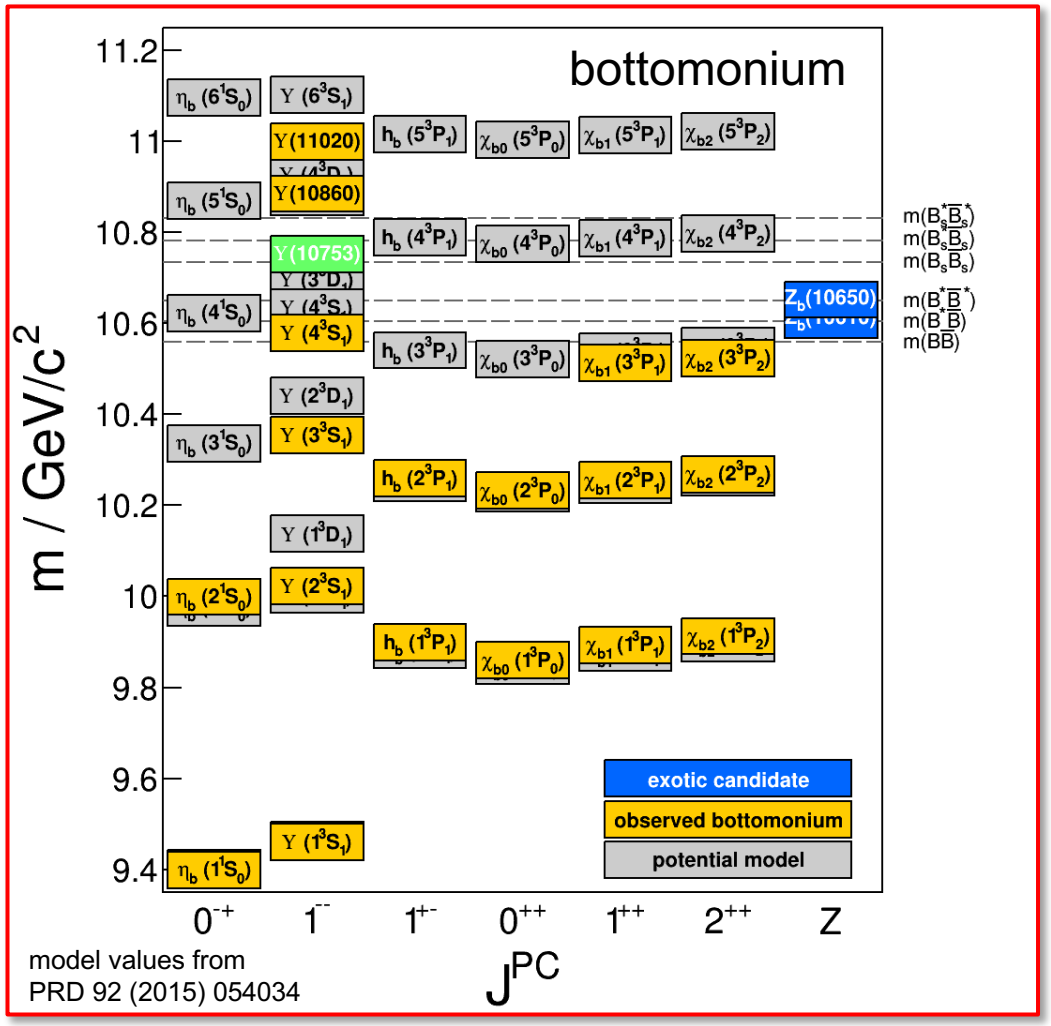
see e.g.: Godfrey & Isgur, PRD 32 (1985) 189-231
Barnes, Godfrey, Swanson, PRD 72 (2005) 054026
Godfrey & Moates, PRD 92 (2015) 054034

- good agreement with experiments (BaBar, Belle, BESIII, CLEO, …) for charmonium and bottomonium

QUARKONIUM

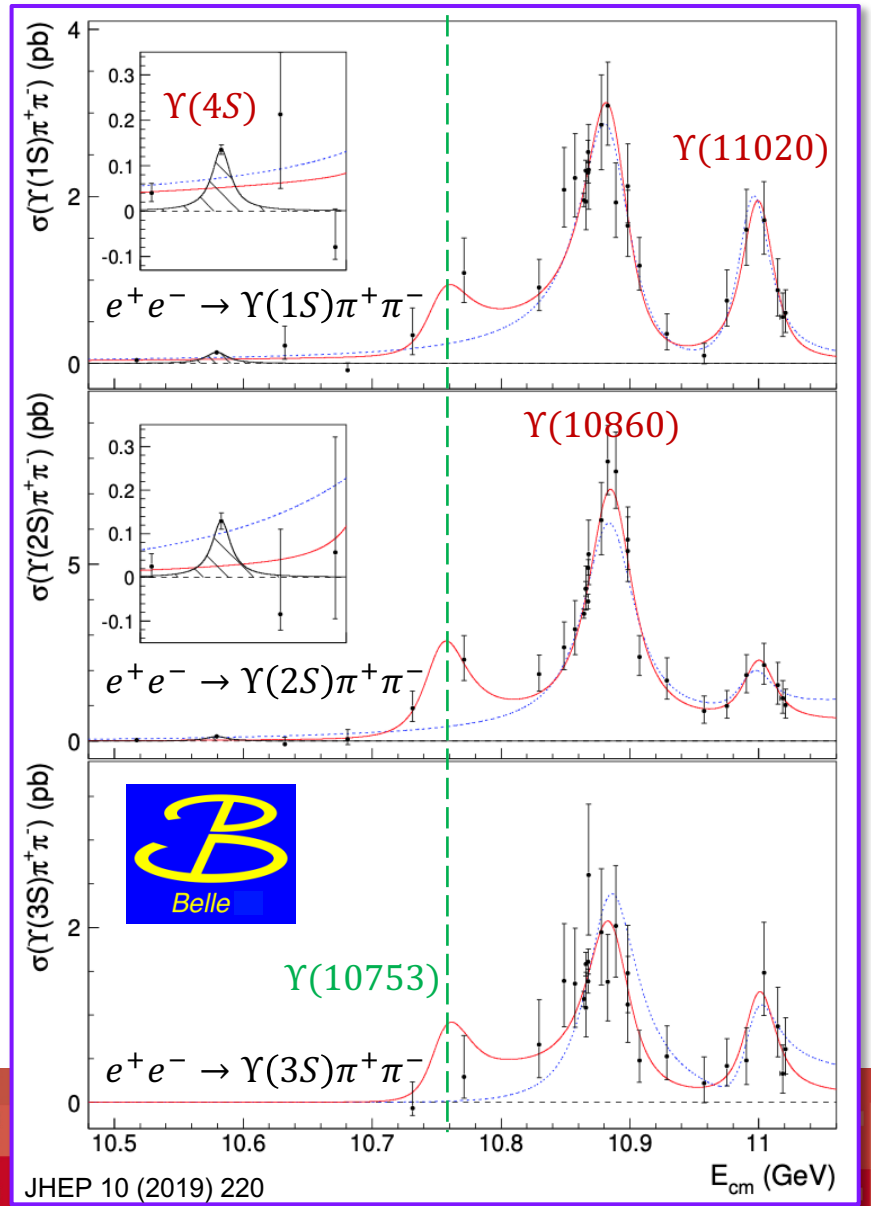


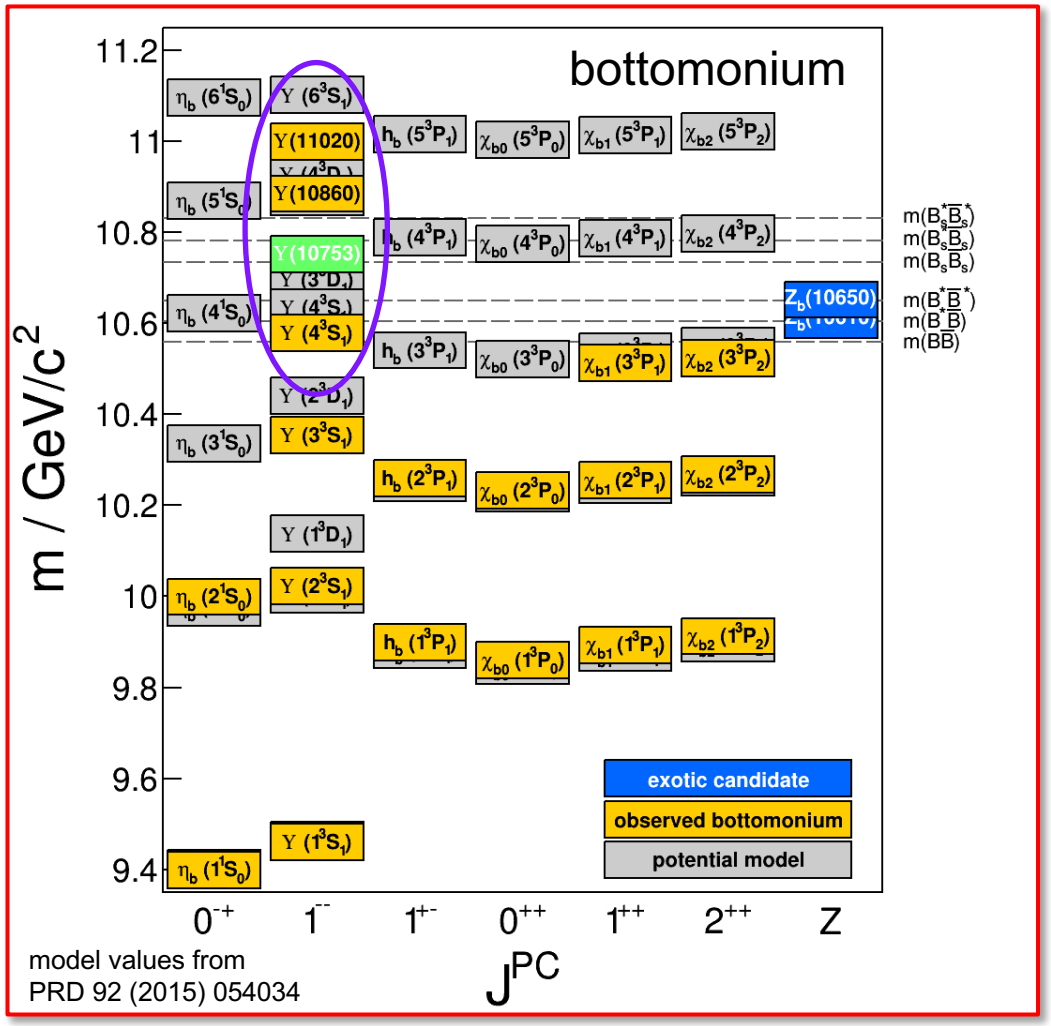
model values from
PRD 72 (2005) 054026



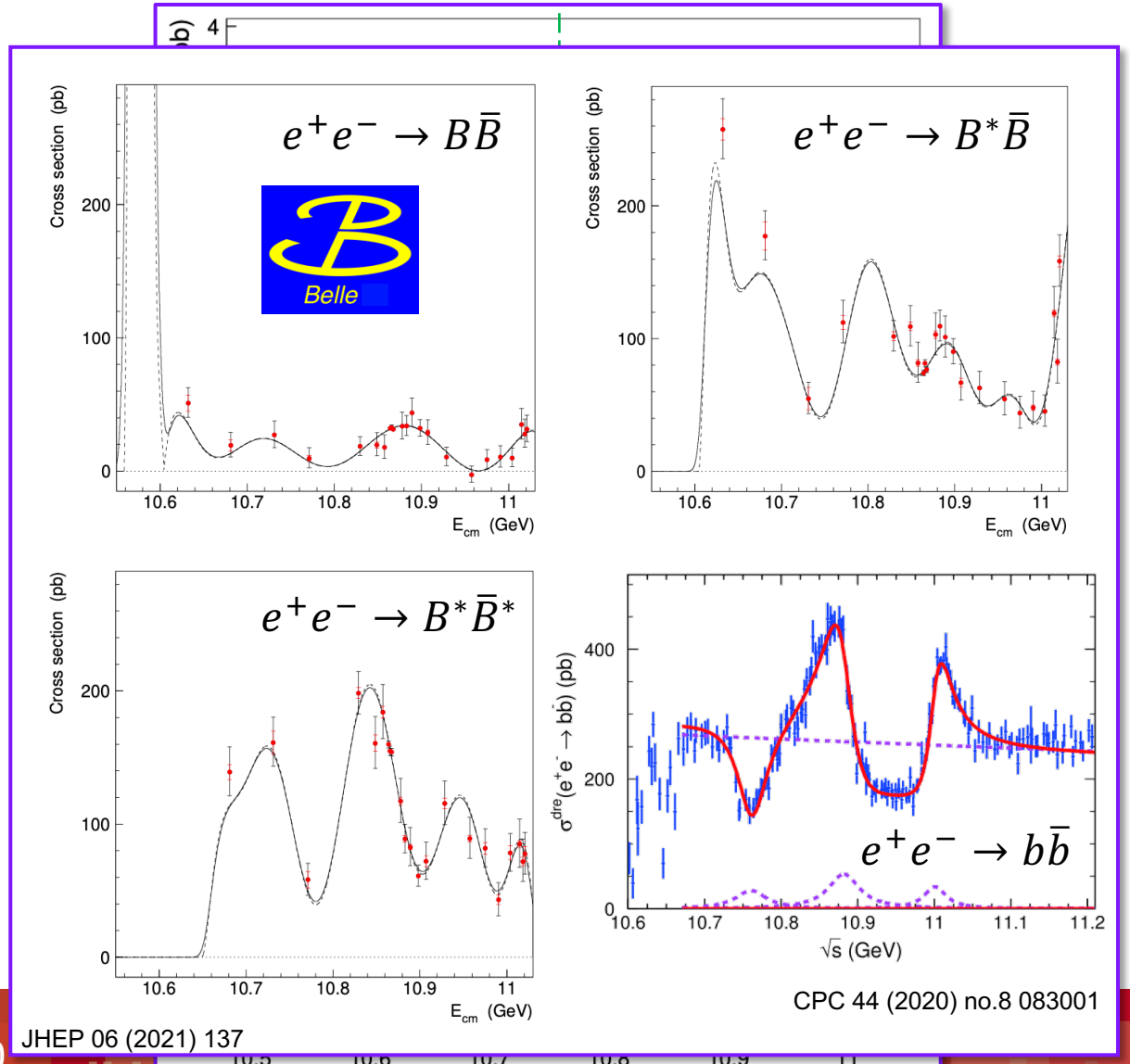
model values from
PRD 92 (2015) 054034

BOTTOMONIUM





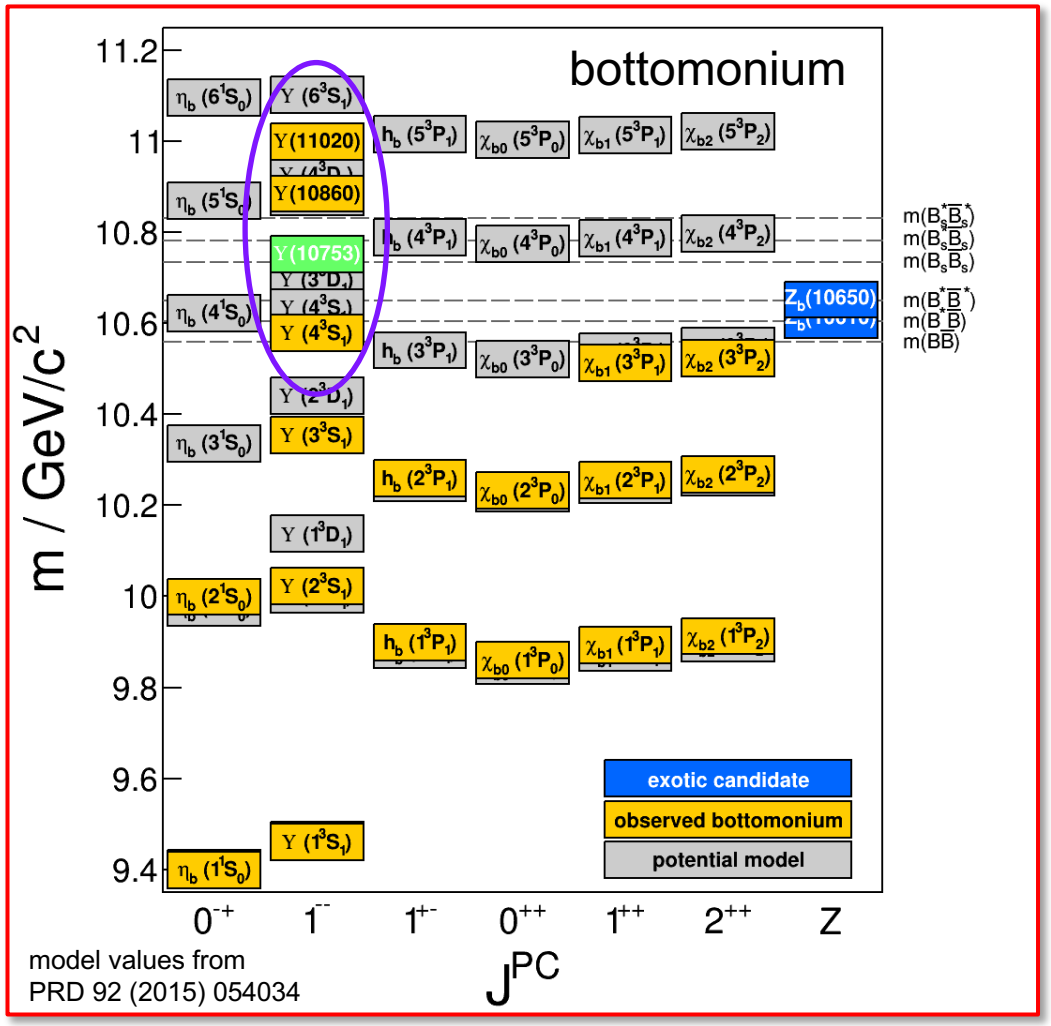
BOTTOMONIUM



JHEP 06 (2021) 137

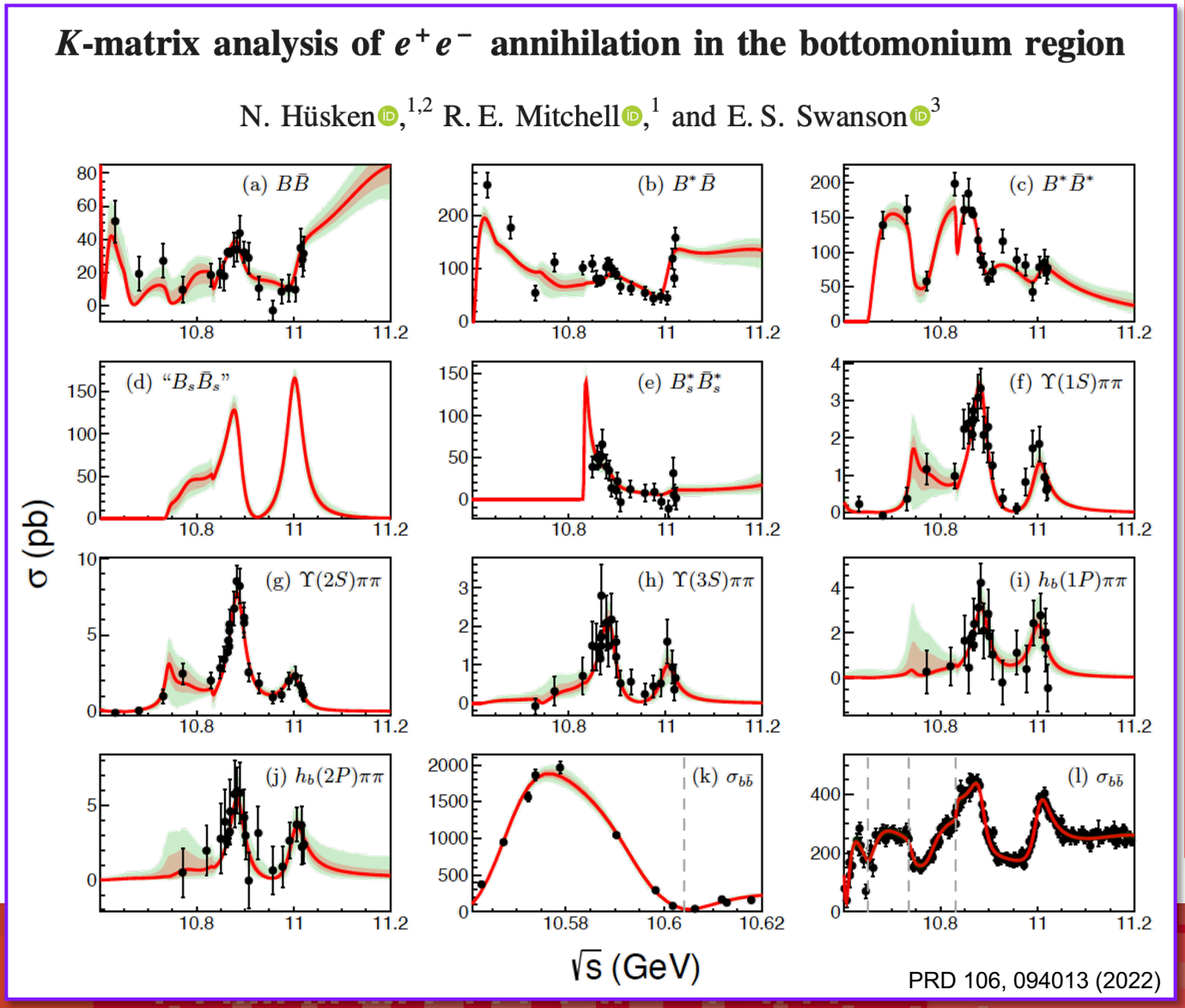
CPC 44 (2020) no.8 083001

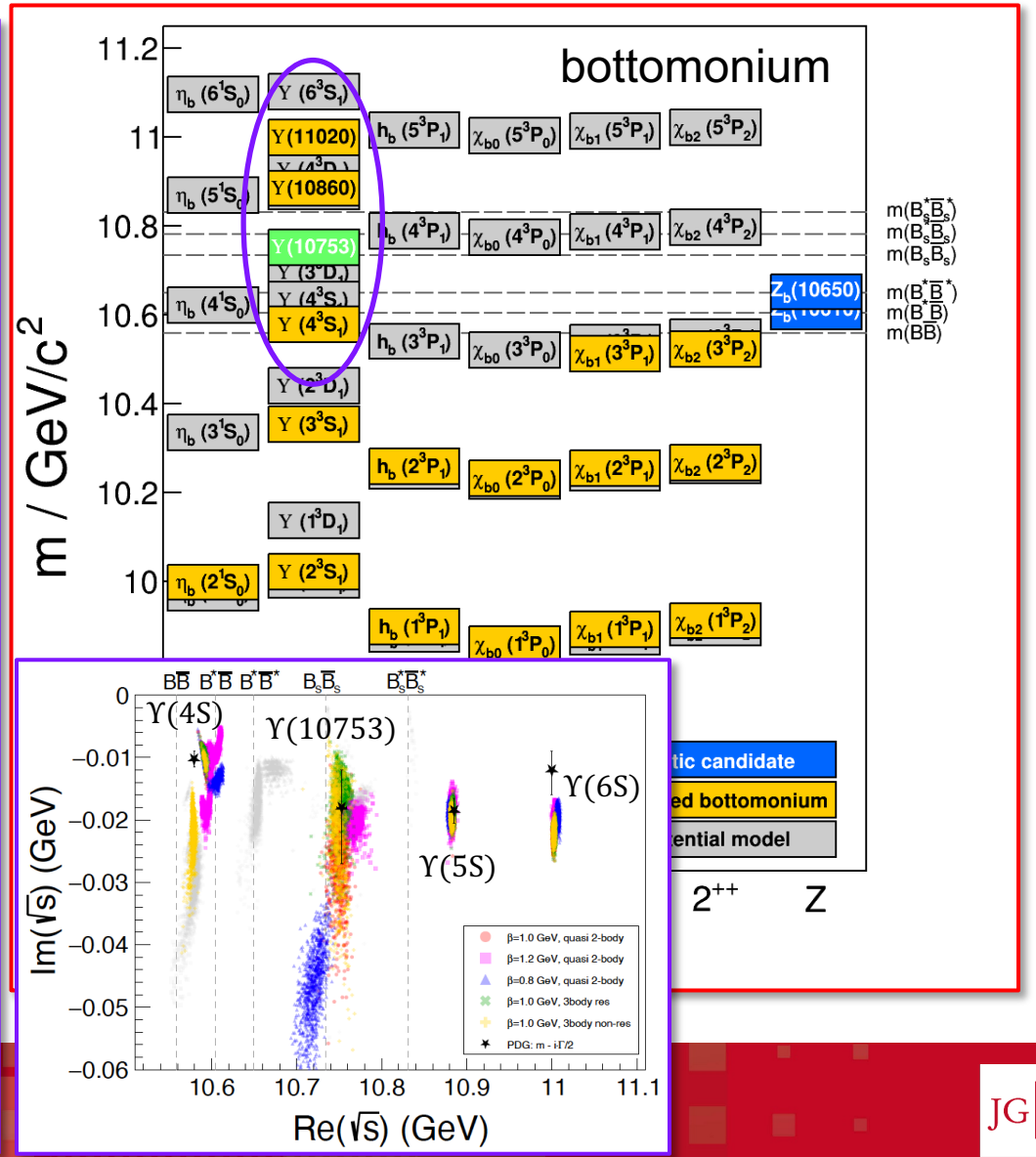
JHEP 10 (2019) 220



model values from
PRD 92 (2015) 054034

BOTTOMONIUM

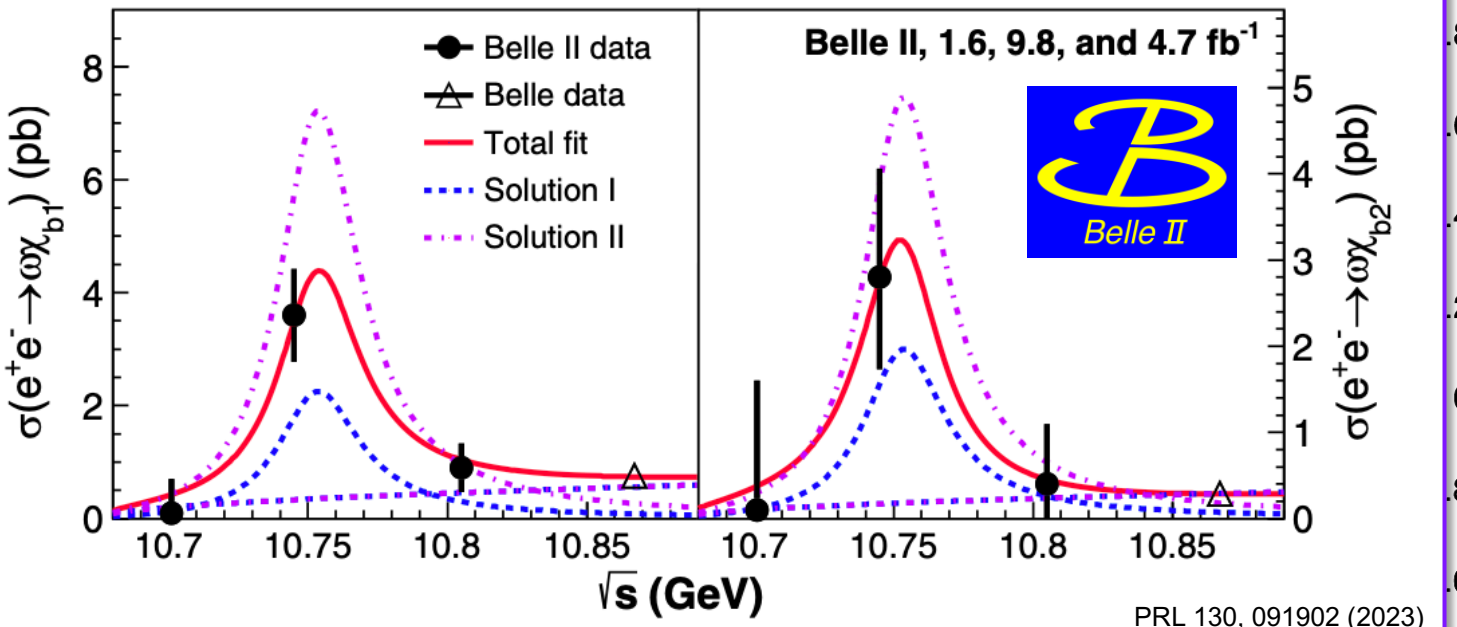




BOTTOMONIUM

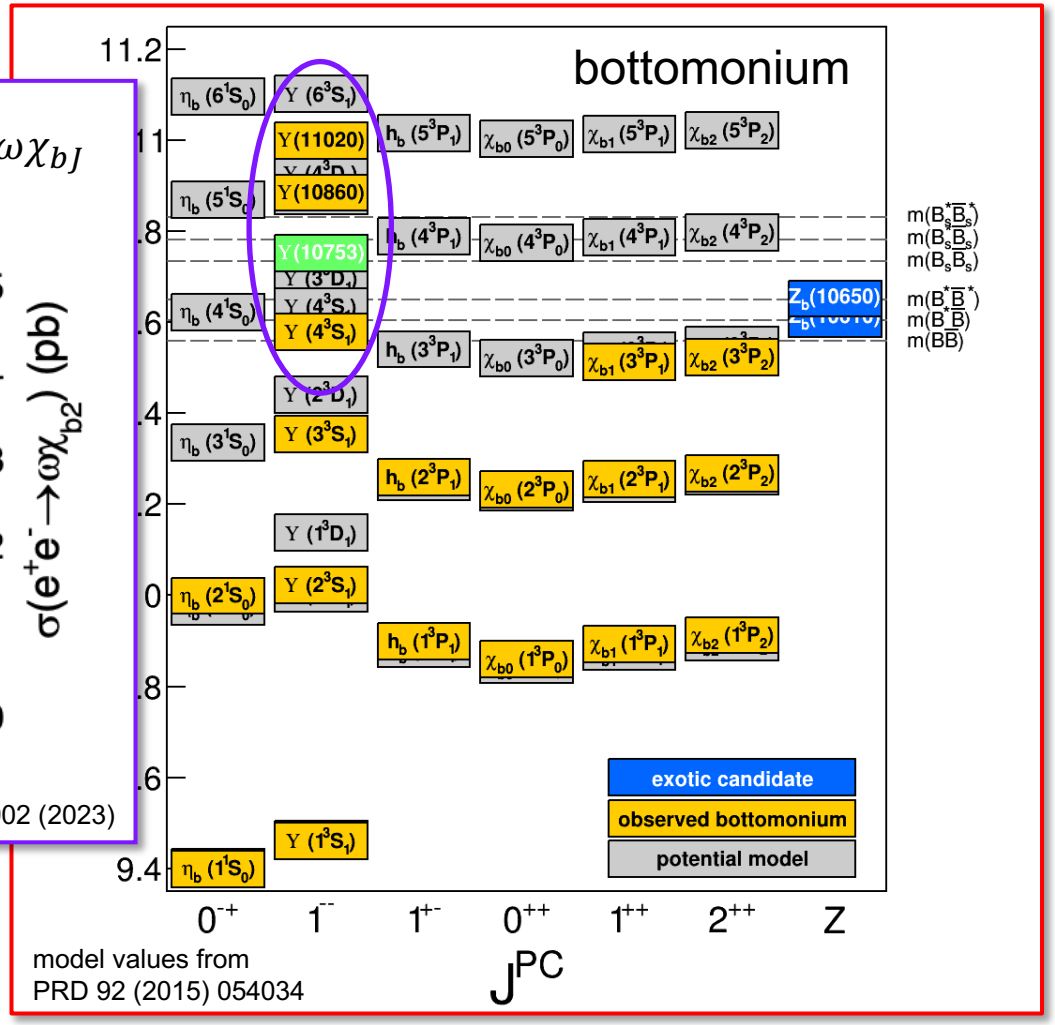
BelleII as a new contributor!

hint of $\Upsilon(10753)$ in $e^+e^- \to \omega\chi_{bJ}$

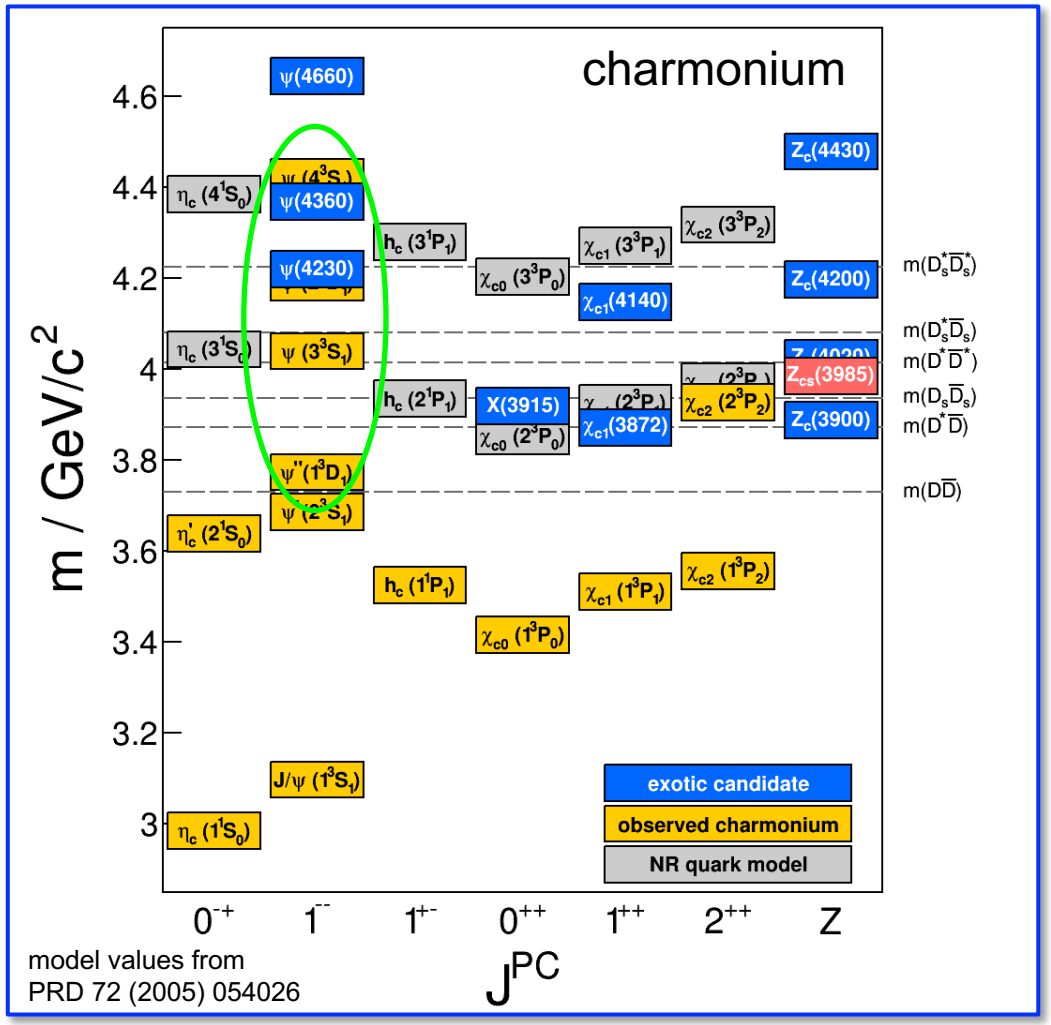


PRL 130, 091902 (2023)

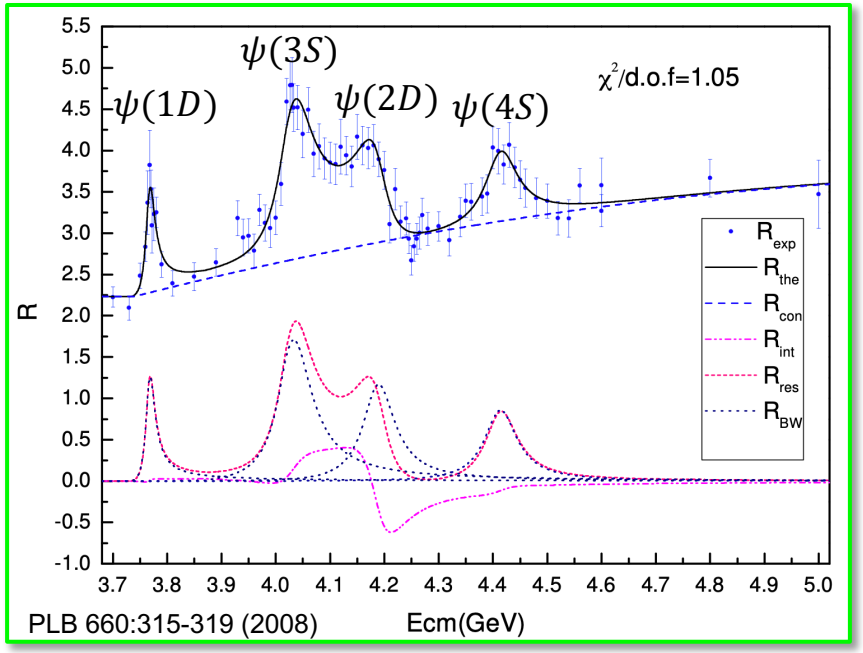
→ exciting times for bottomonium spectroscopy!



CHARMONIUM

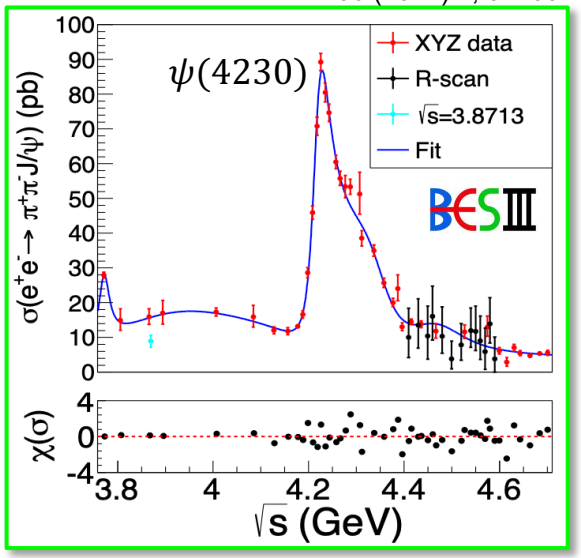


model values from
PRD 72 (2005) 054026

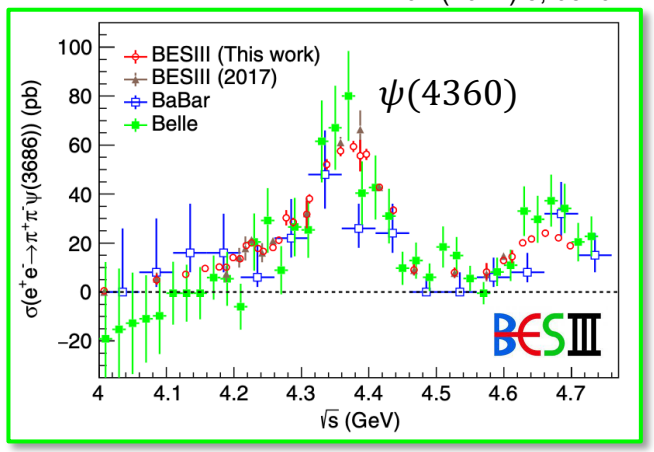


PLB 660:315-319 (2008)

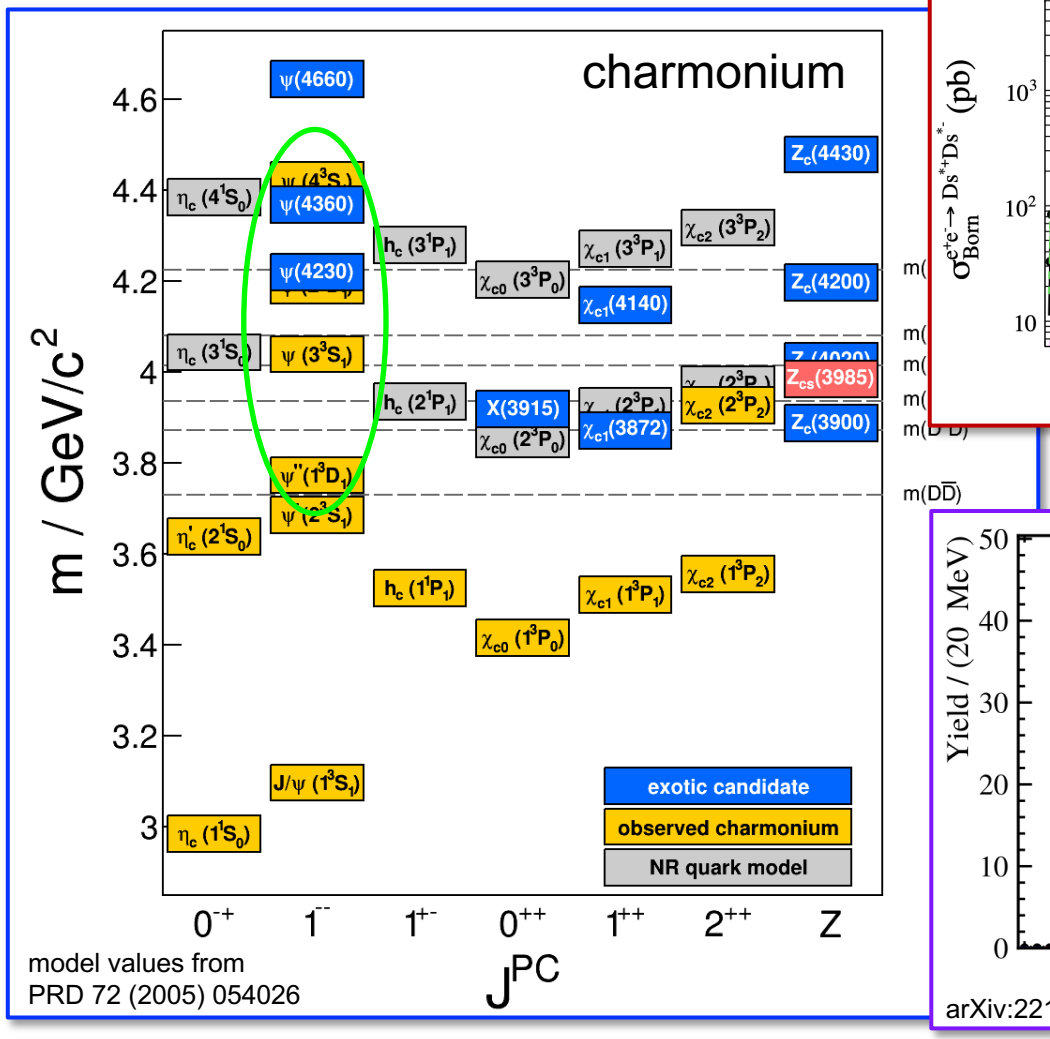
PRD 106 (2022) 7, 072001



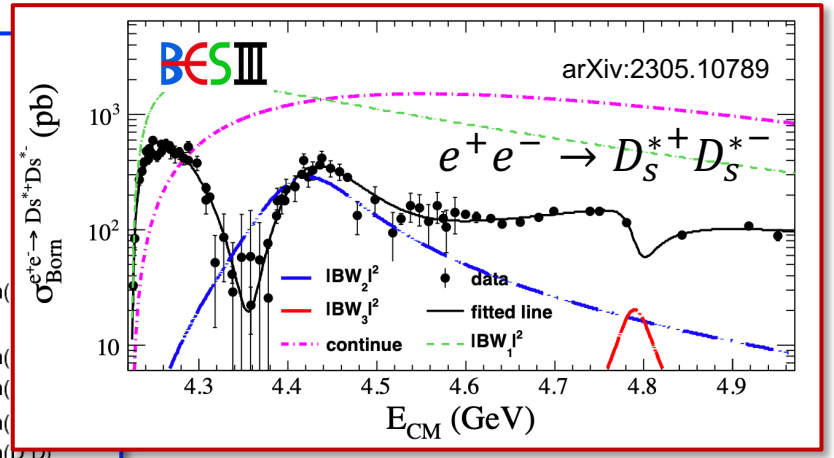
PRD 104 (2021) 5, 052012

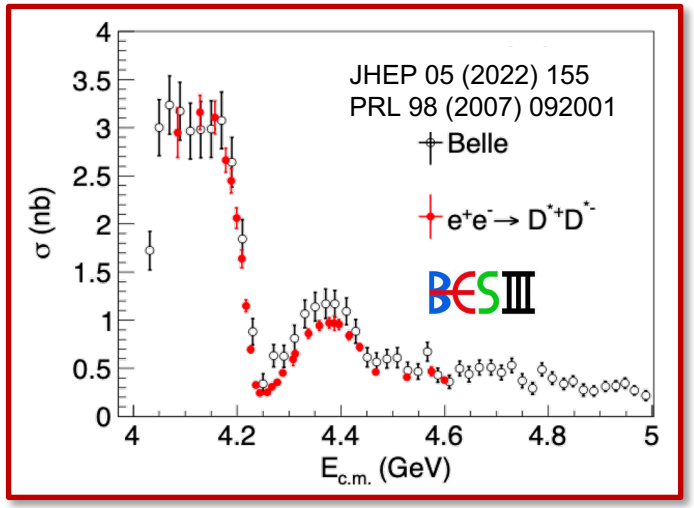


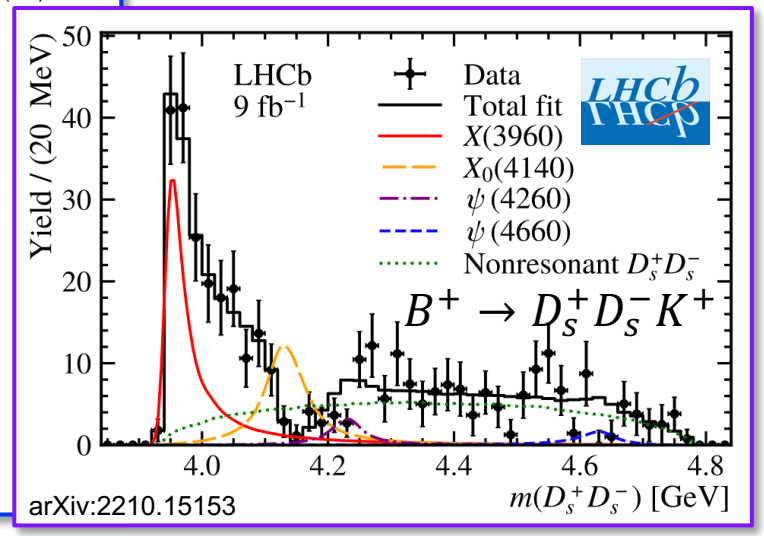
CHARMONIUM

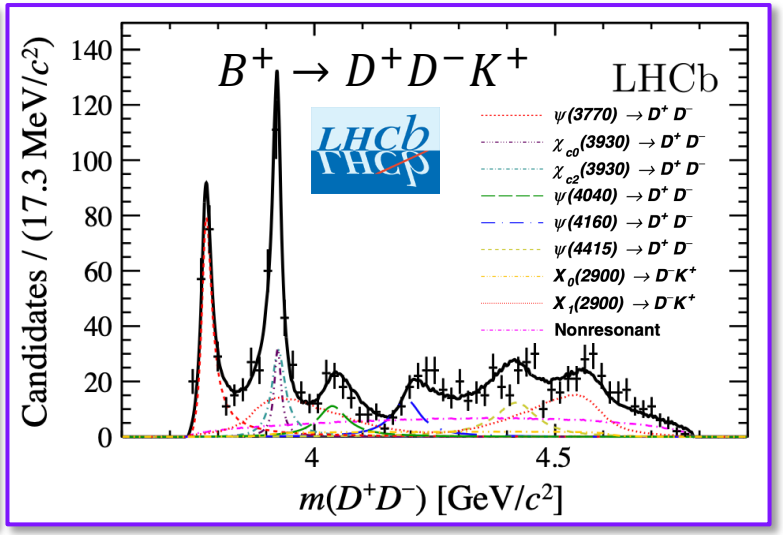


model values from
PRD 72 (2005) 054026





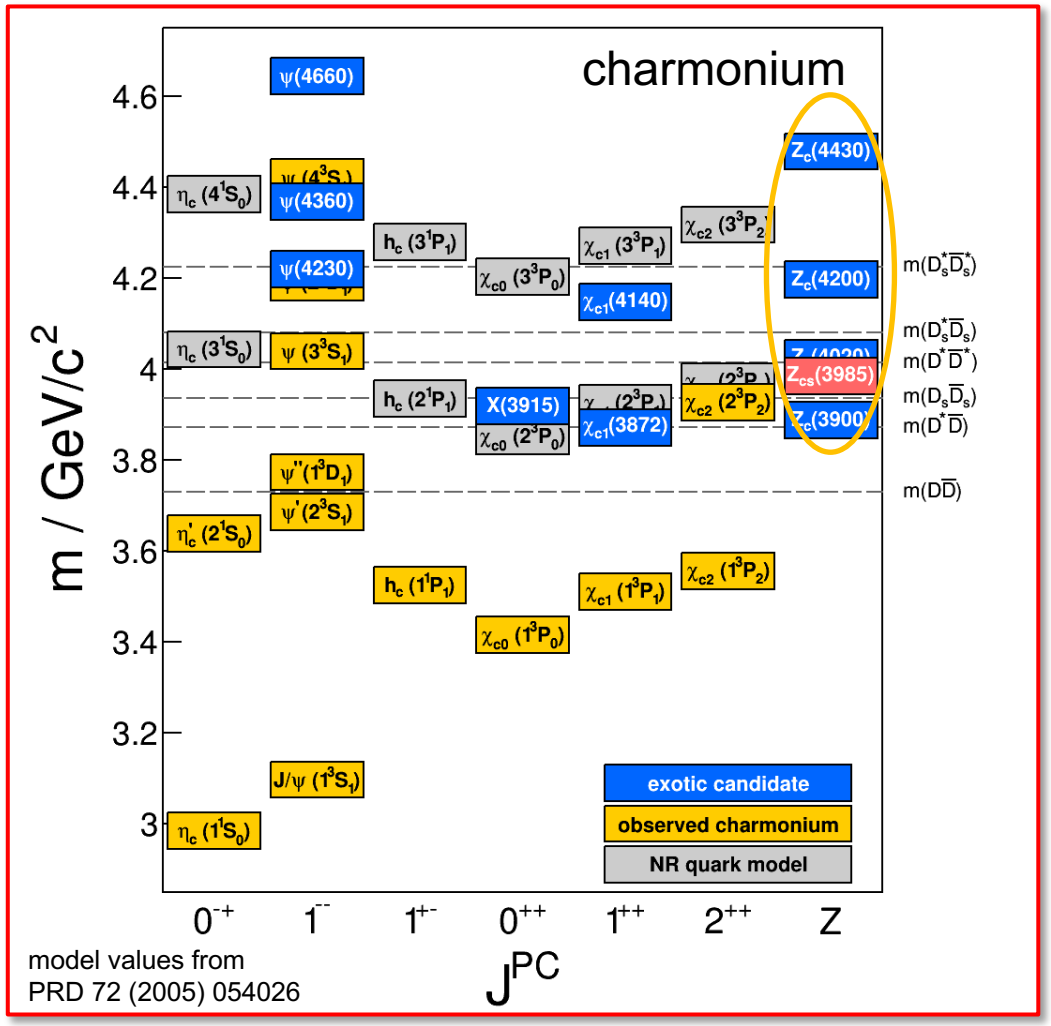




PRD 102, 112003 (2020)

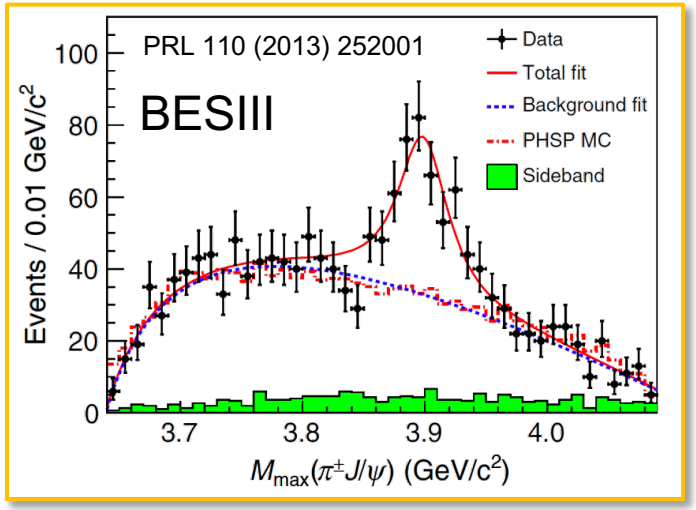
→ it will take a coordinated effort to understand vector charmonium(-like) states!

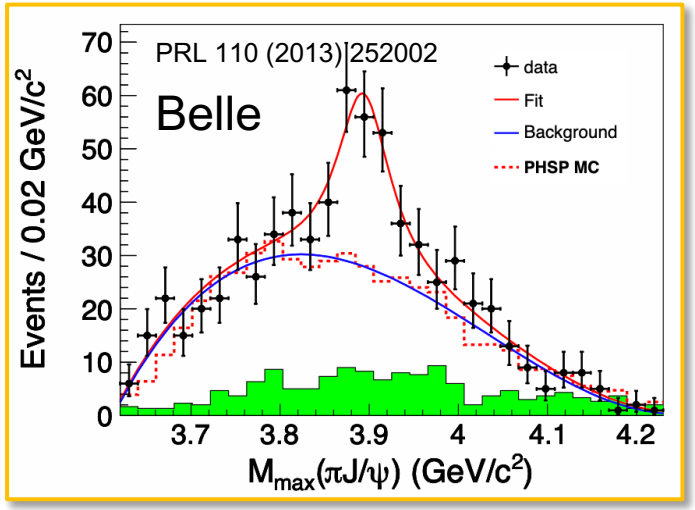
CHARMONIUM



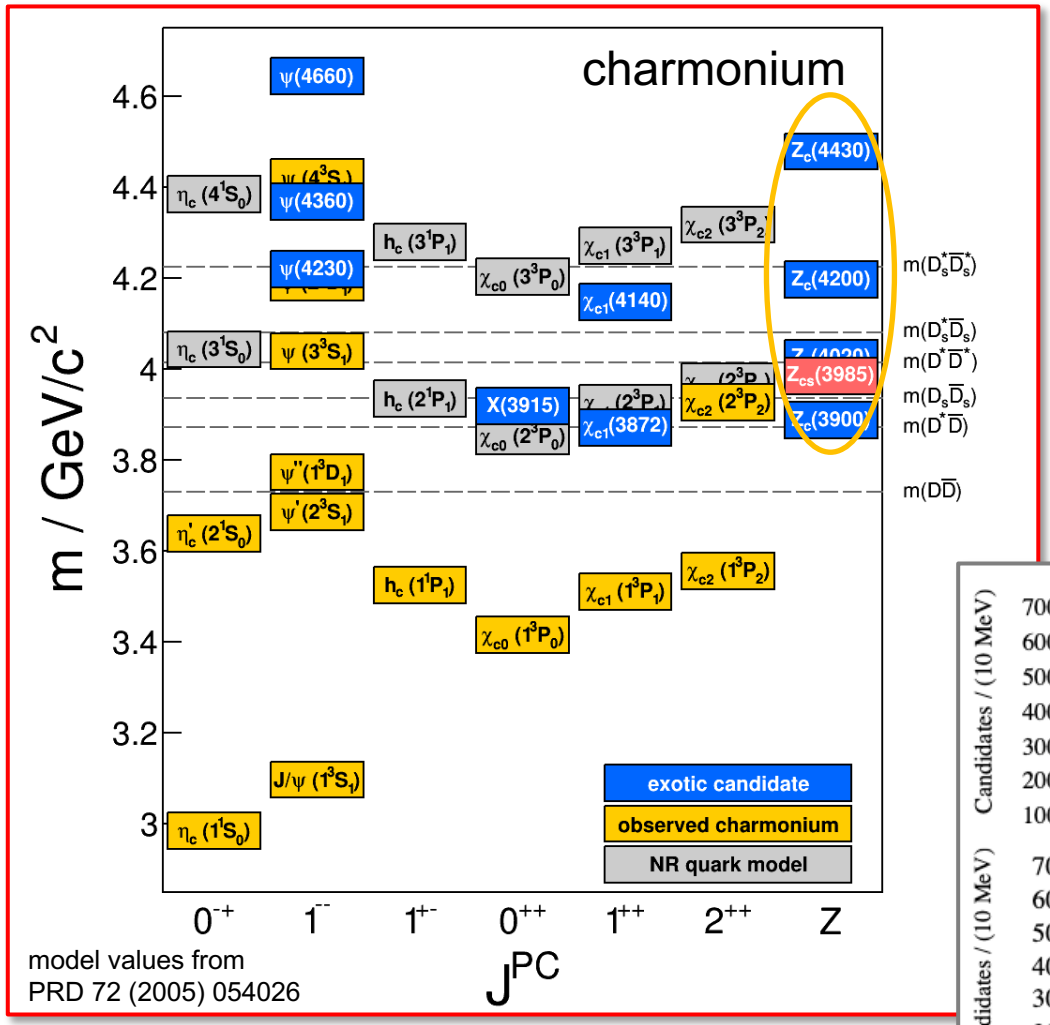
model values from
PRD 72 (2005) 054026

$Z_c(3900) \rightarrow J/\psi\pi$



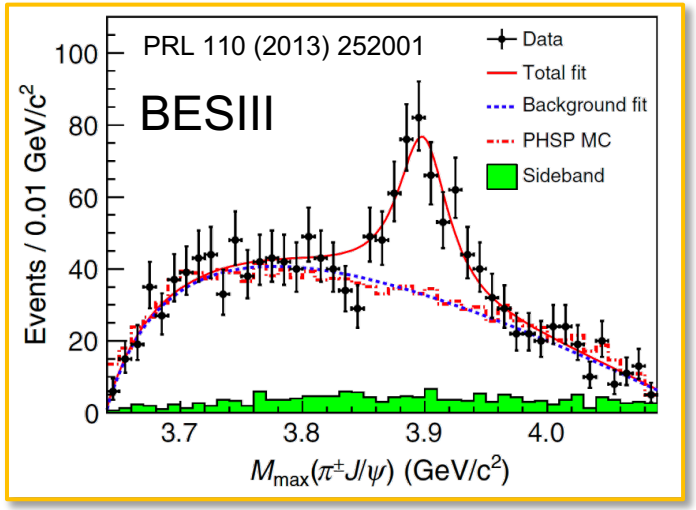


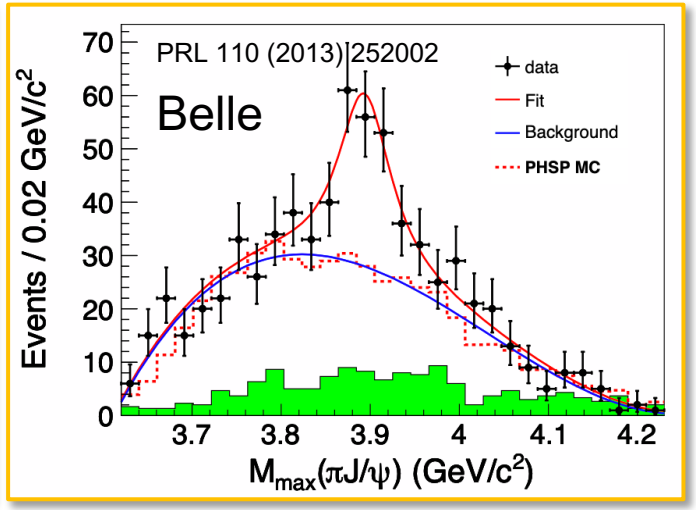
CHARMONIUM



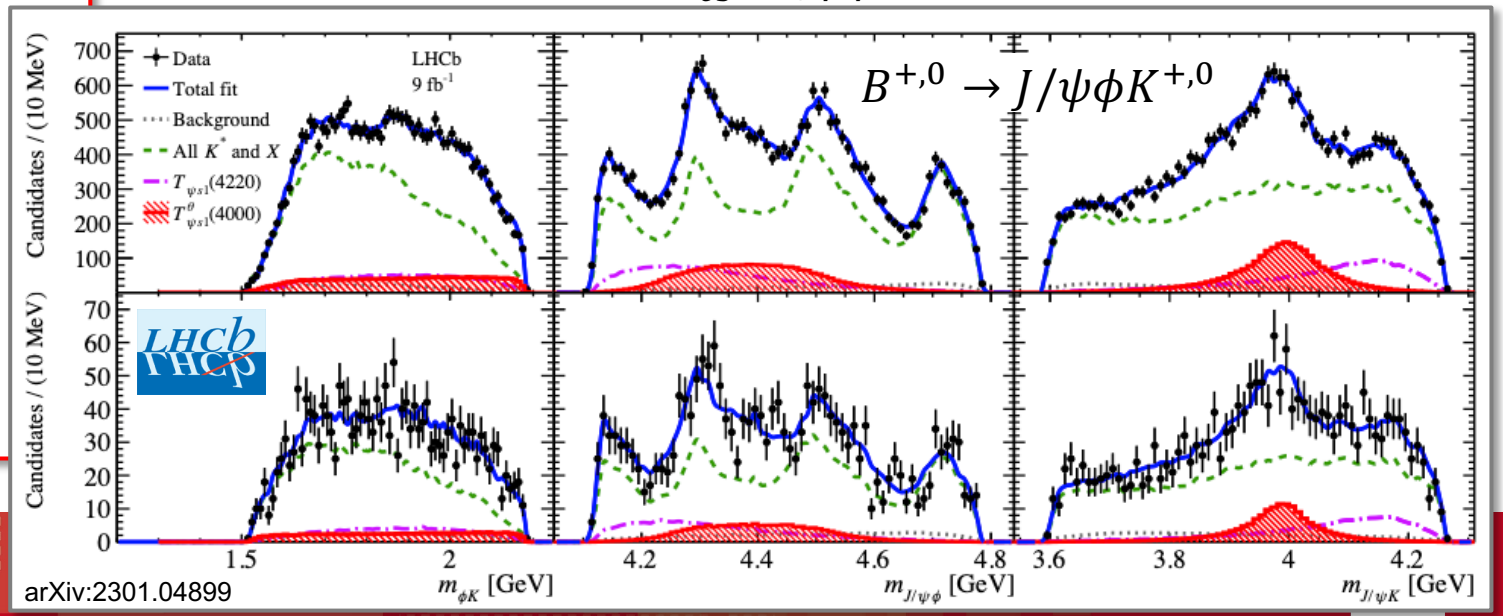
model values from
PRD 72 (2005) 054026

$Z_c(3900) \to J/\psi\pi$



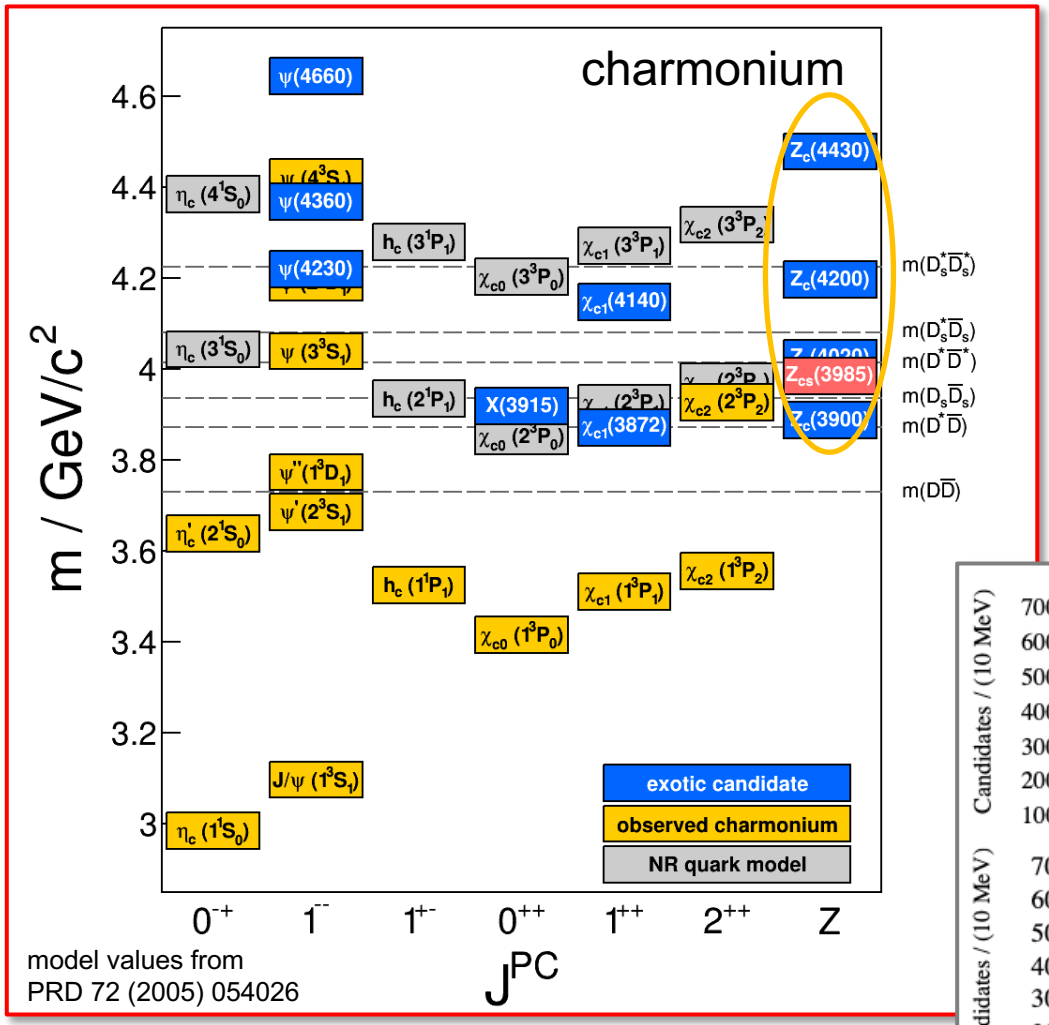


$Z_{cs} \to J/\psi K$



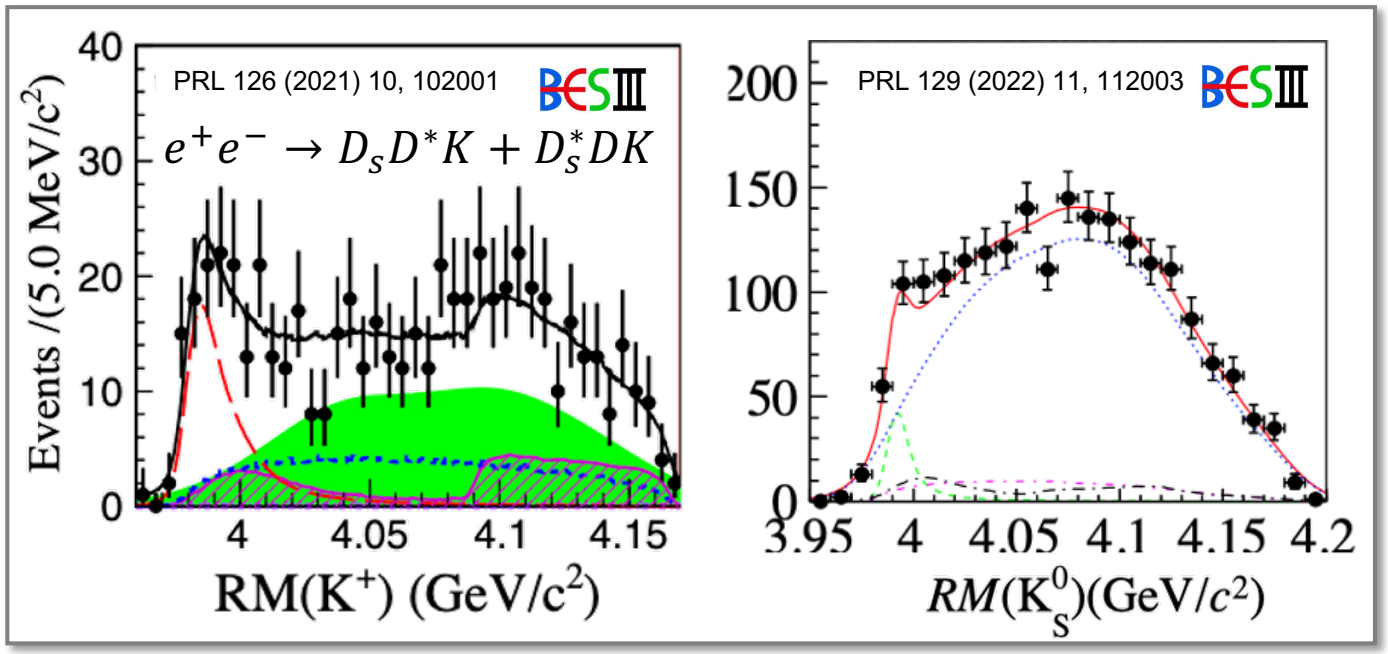
arXiv:2301.04899

CHARMONIUM



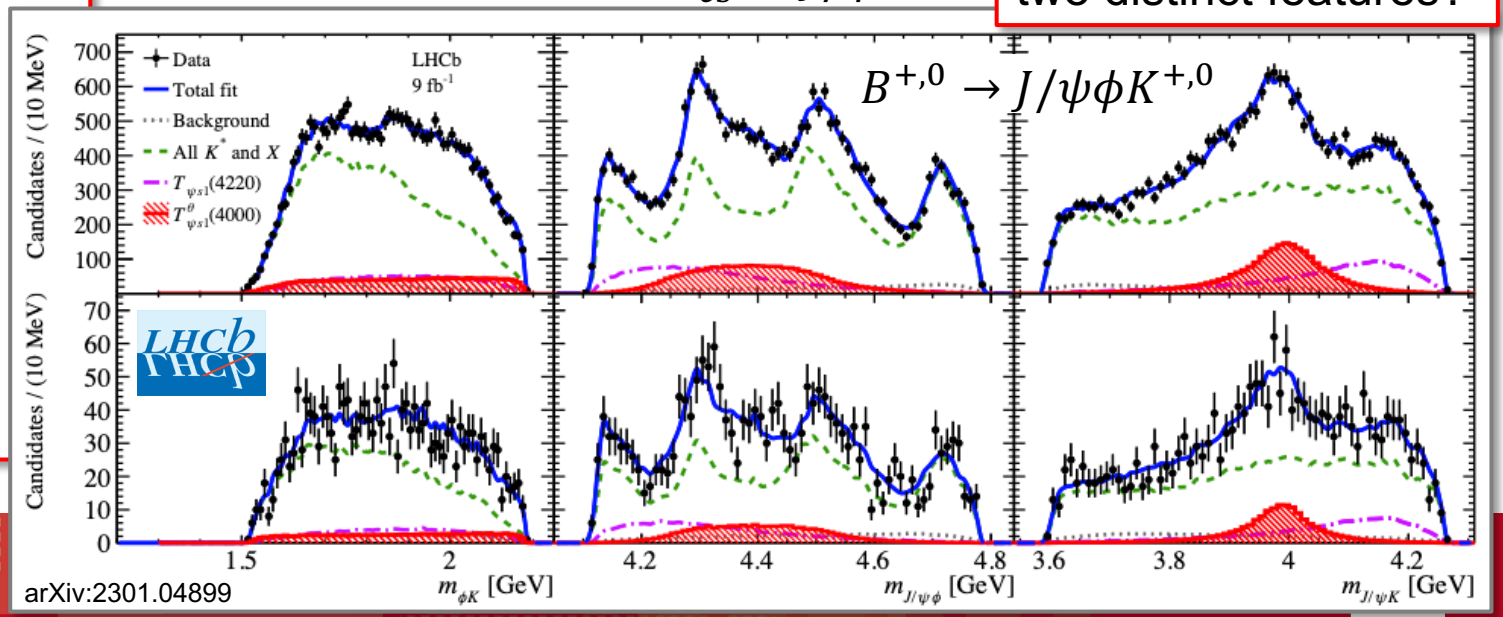
model values from
PRD 72 (2005) 054026

$Z_{cs} \to D_s D^* + D_s^* D$



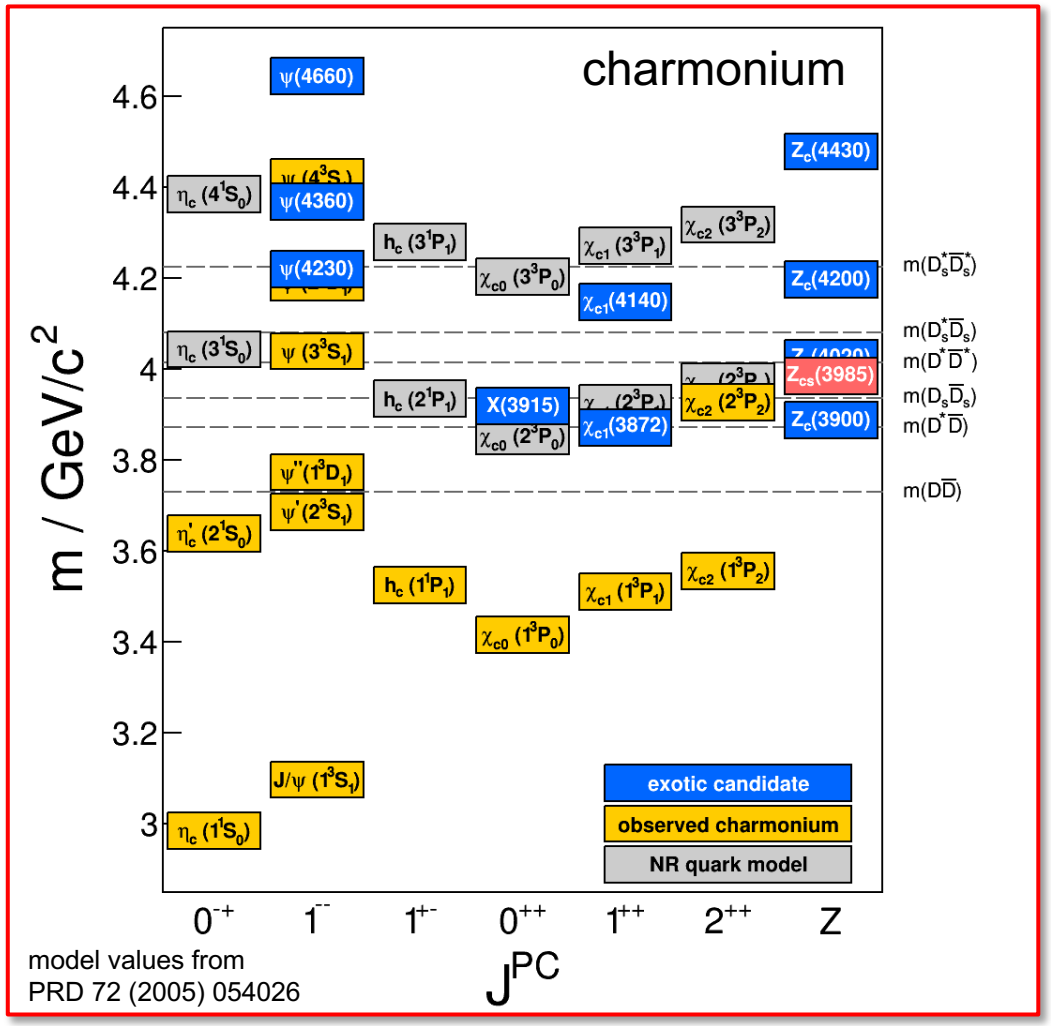
$Z_{cs} \to J/\psi K$

two distinct features?



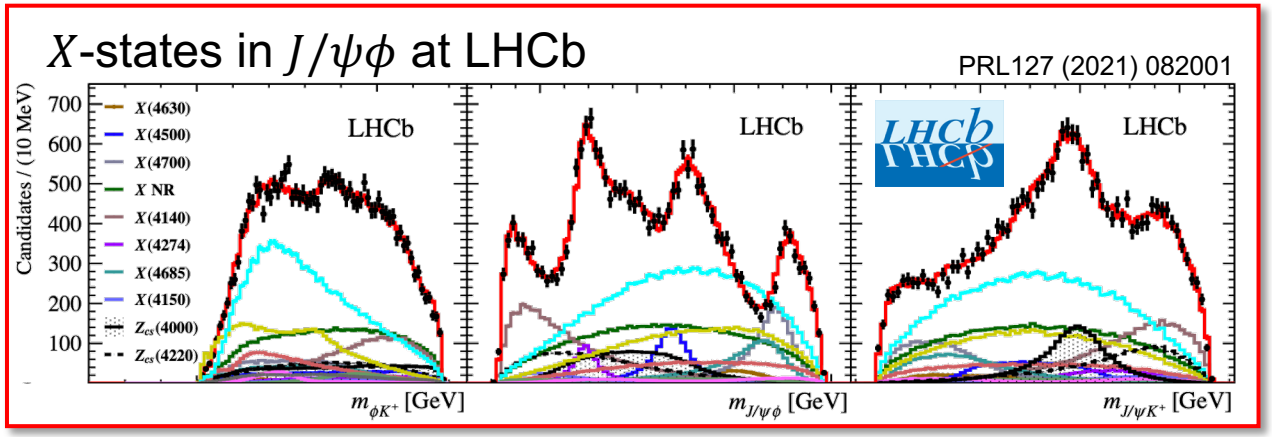
arXiv:2301.04899

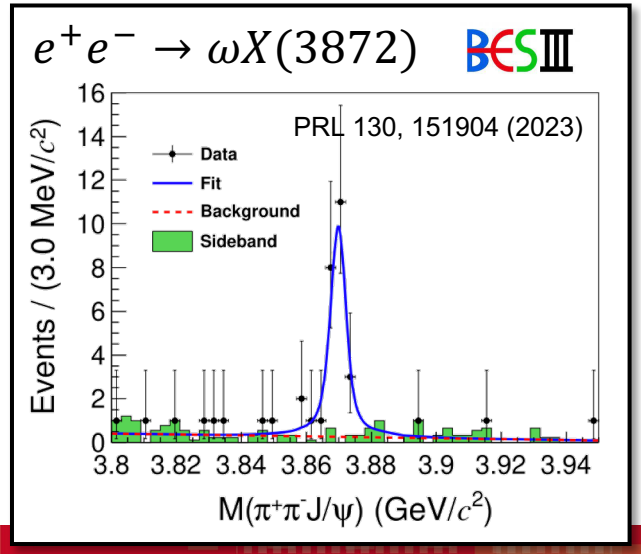
CHARMONIUM

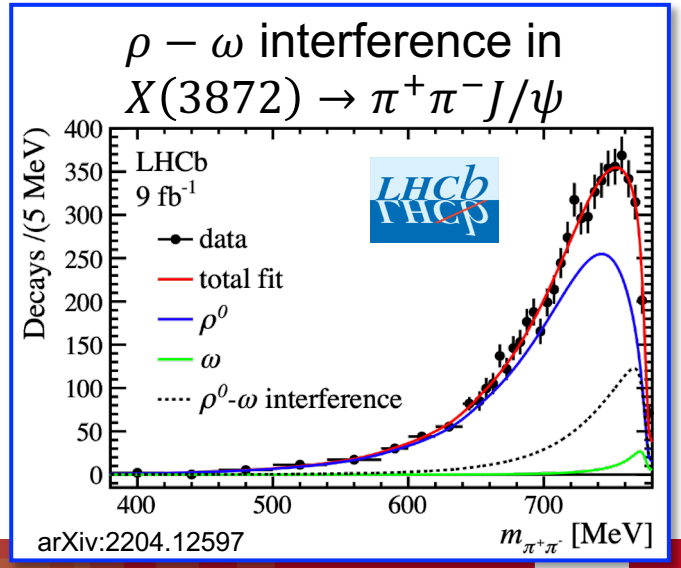


model values from
PRD 72 (2005) 054026

+ many other new, exciting results…



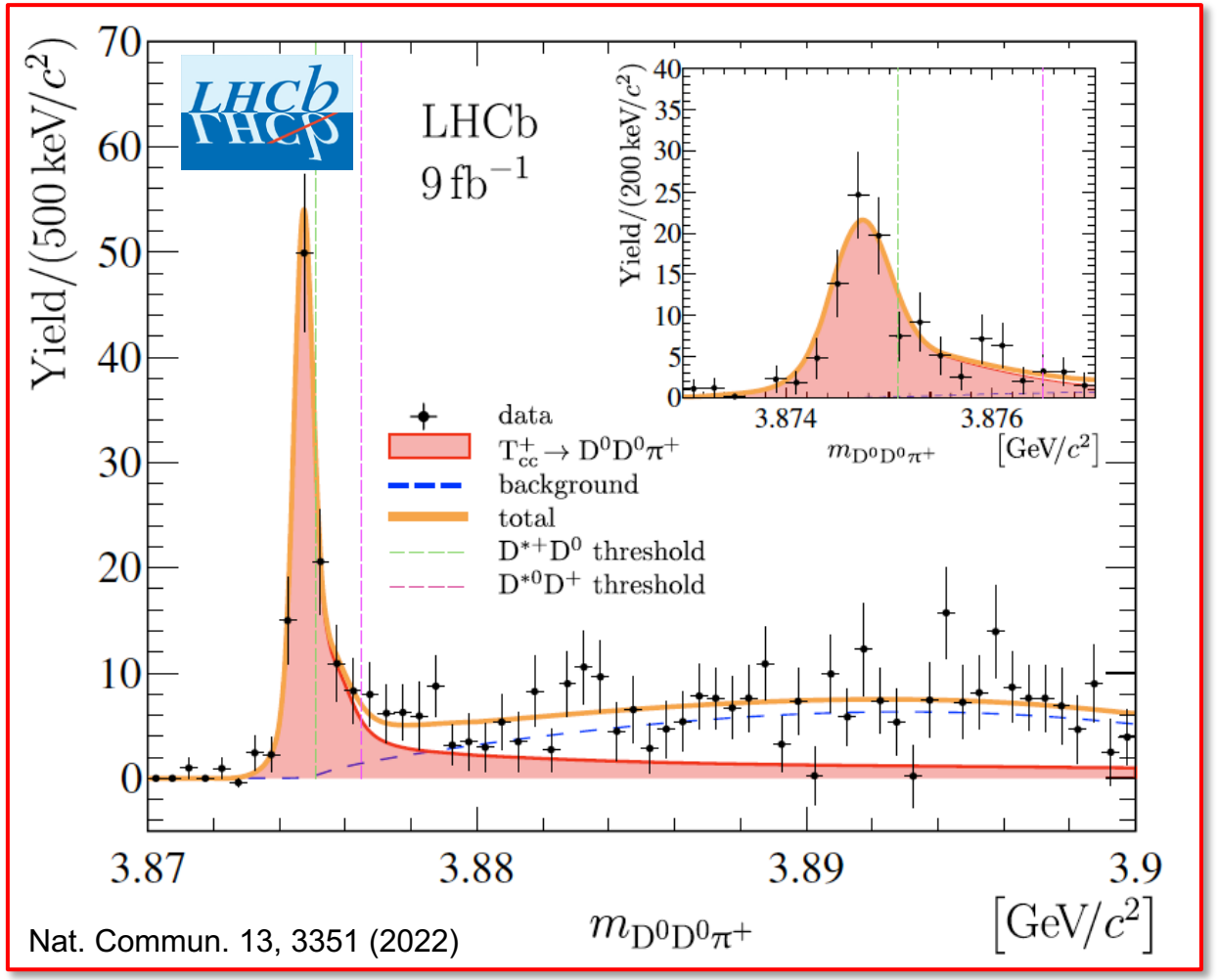




→ see dedicated LHCb, BESIII talks on Wed.

DOUBLY OPEN-CHARM TETRAQUARK T_{cc}

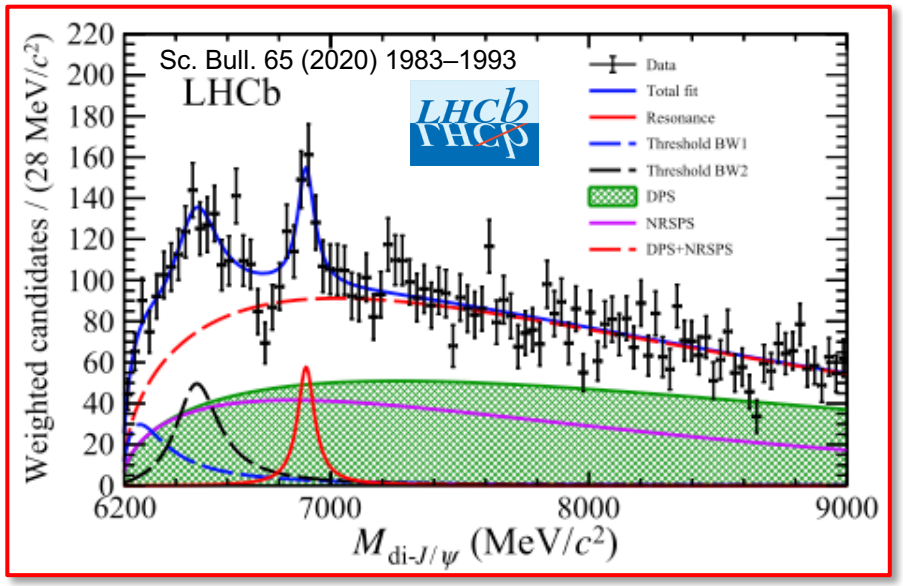
- LHCb observe narrow peak in $D^0D^0\pi^+$ just under $D^{*+}D^0$ threshold (in prompt production)
- minimal quark content $cc\bar{u}\bar{d}$
- no indication of isospin partners → isoscalar state
- decay via off-shell D^*
- first observation of a state of $QQ\bar{q}\bar{q}$ nature

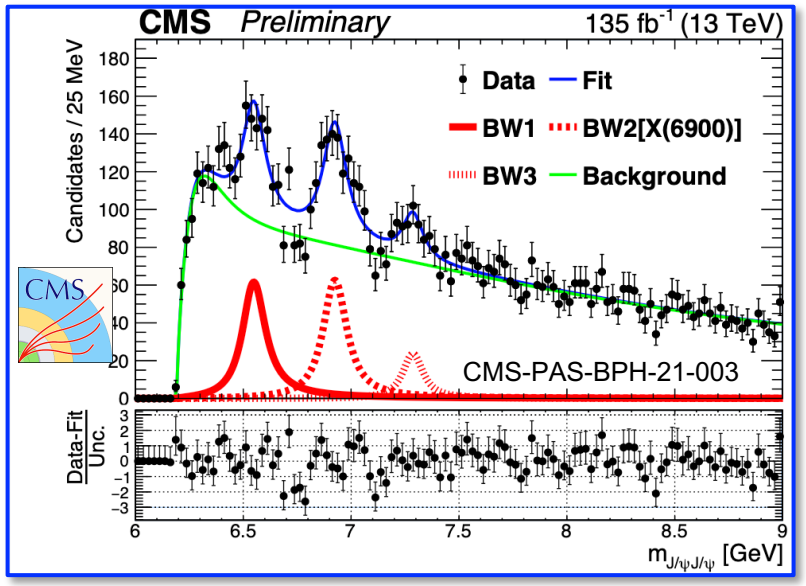


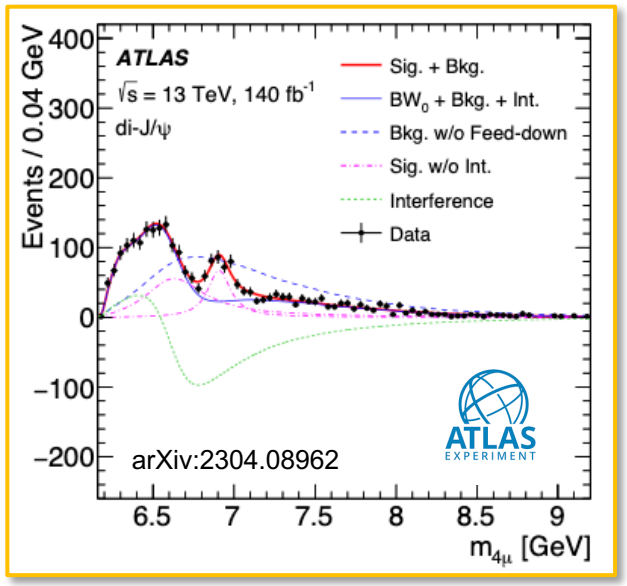
Nat. Commun. 13, 3351 (2022)

FULLY-CHARMED $T_{cc\bar{c}\bar{c}}$

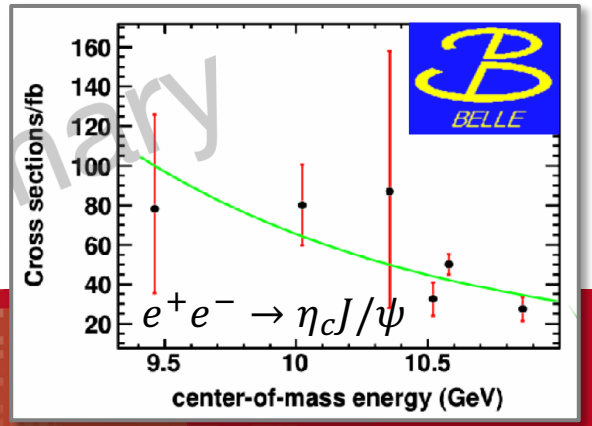
- fully-heavy tetraquark ($cc\bar{c}\bar{c}$) candidate $T_{cc\bar{c}\bar{c}}$ ($X(6900)$), first observed by LHCb in $T_{cc\bar{c}\bar{c}} \to J/\psi\, J/\psi$







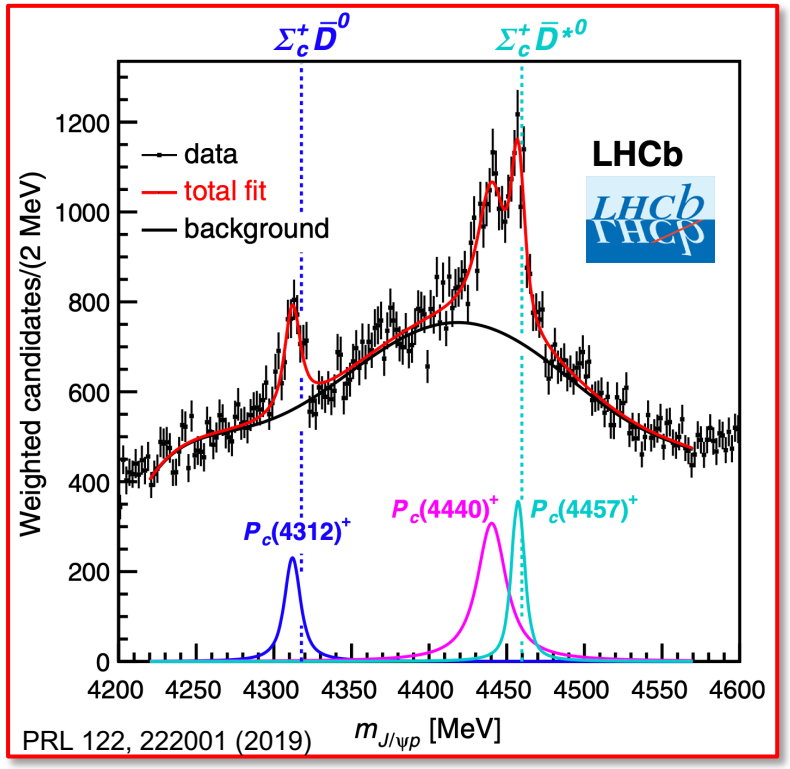
- since then: observation of similar structures in both CMS and ATLAS
- consistent with fully-charmed tetraquark interpretation



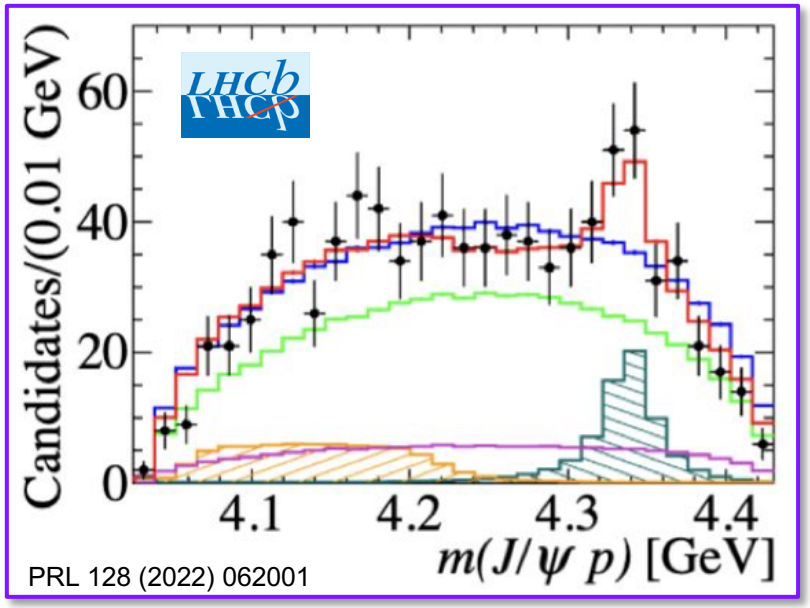
Junhao Yin, HADRON2023
(Belle preliminary)

PENTAQUARKS

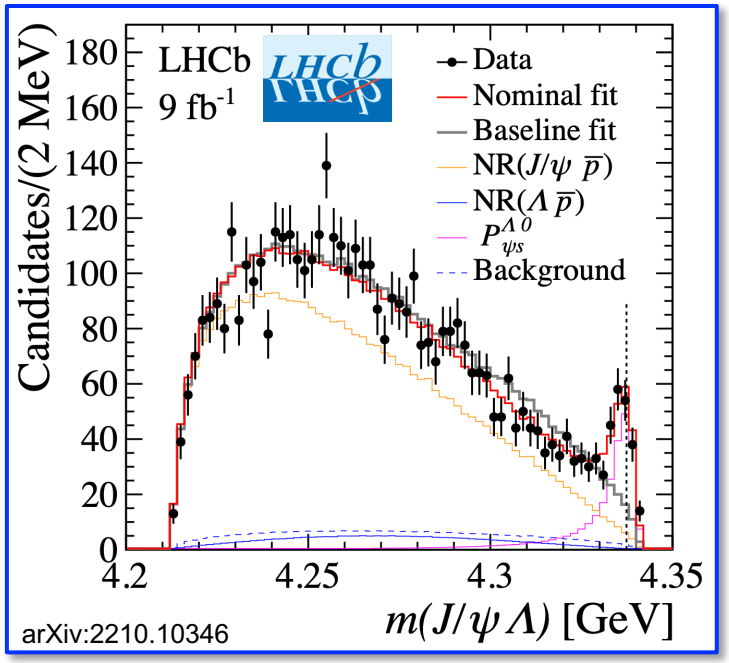
- 2015: first LHCb P_c in $\Lambda_b^0 \to J/\psi p K^-$



- another P_c in $B_s^0 \to J/\psi p \bar{p}$



- strange P_{cs} in $B^- \to J/\psi \Lambda \bar{p}$

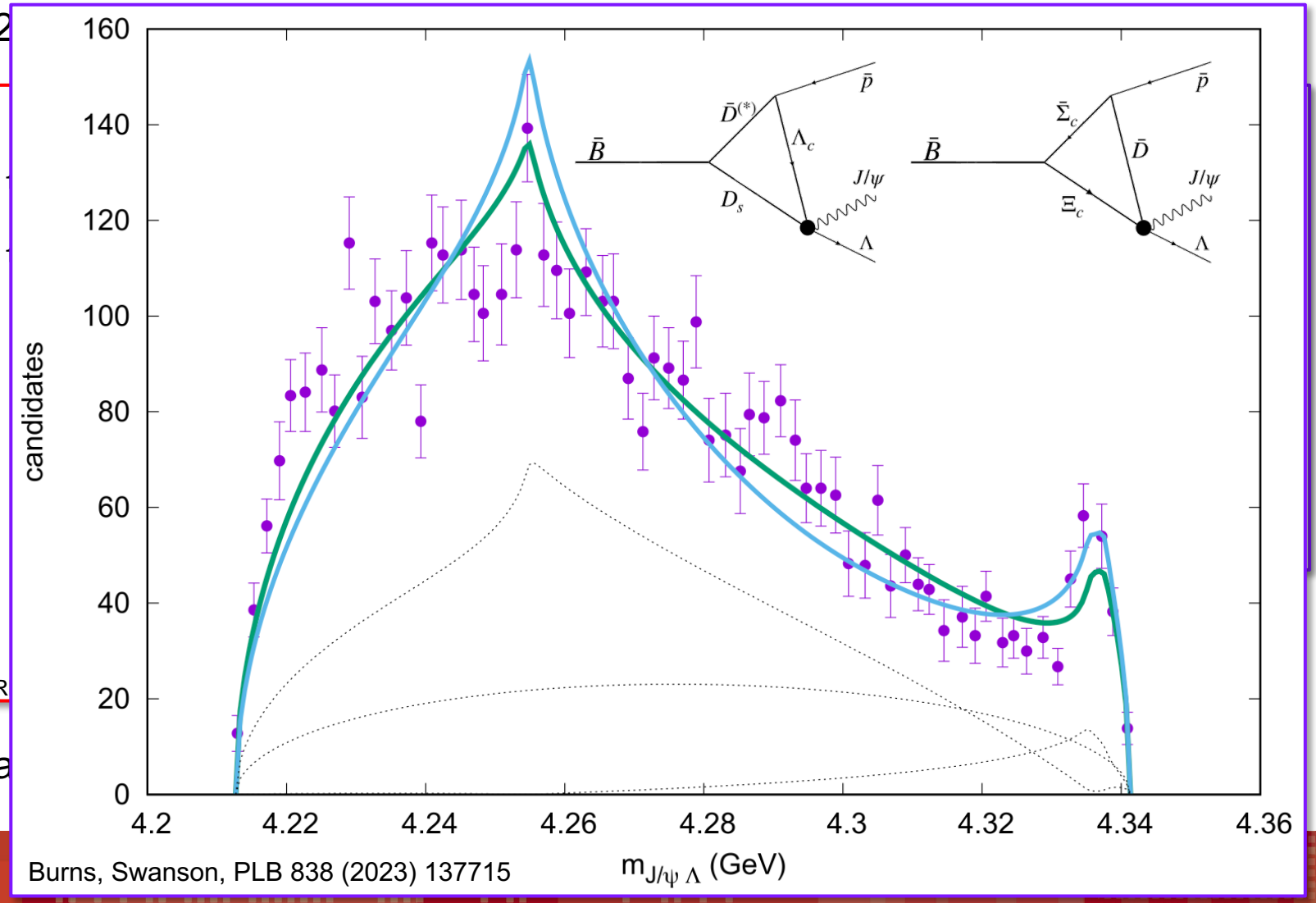


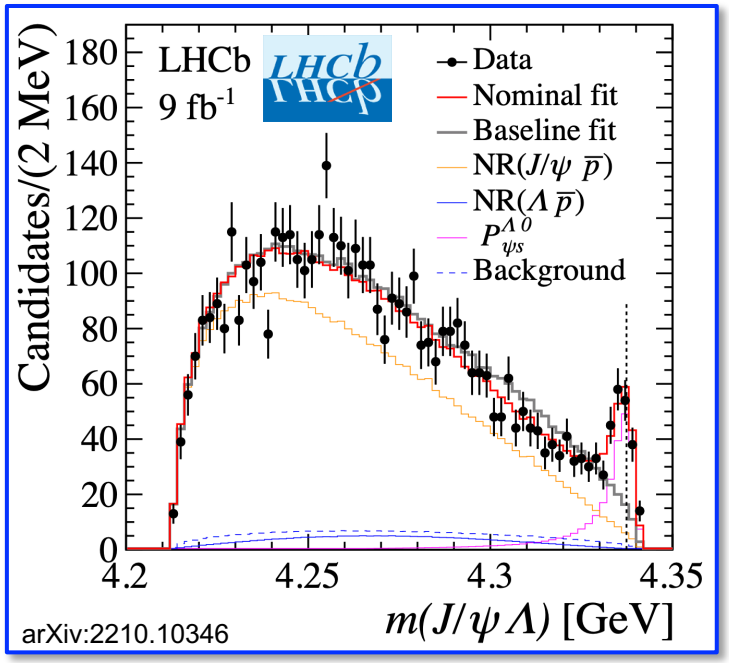
- are these genuine pentaquark states, cusp effects, caused by triangles?

PENTAQUARKS

- 2

- strange P_{cs} in $B^- \to J/\psi \Lambda \bar{p}$



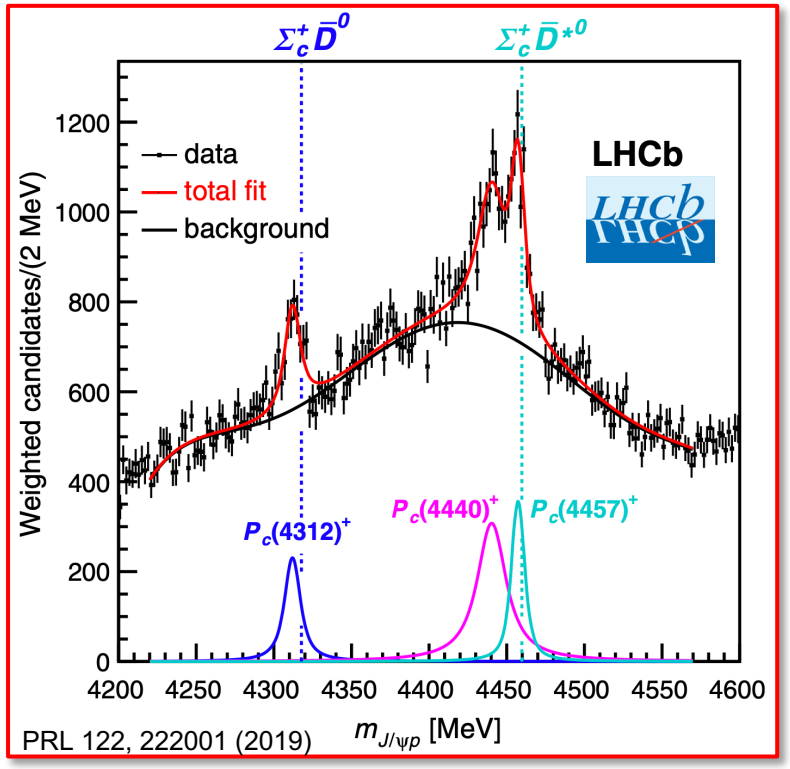


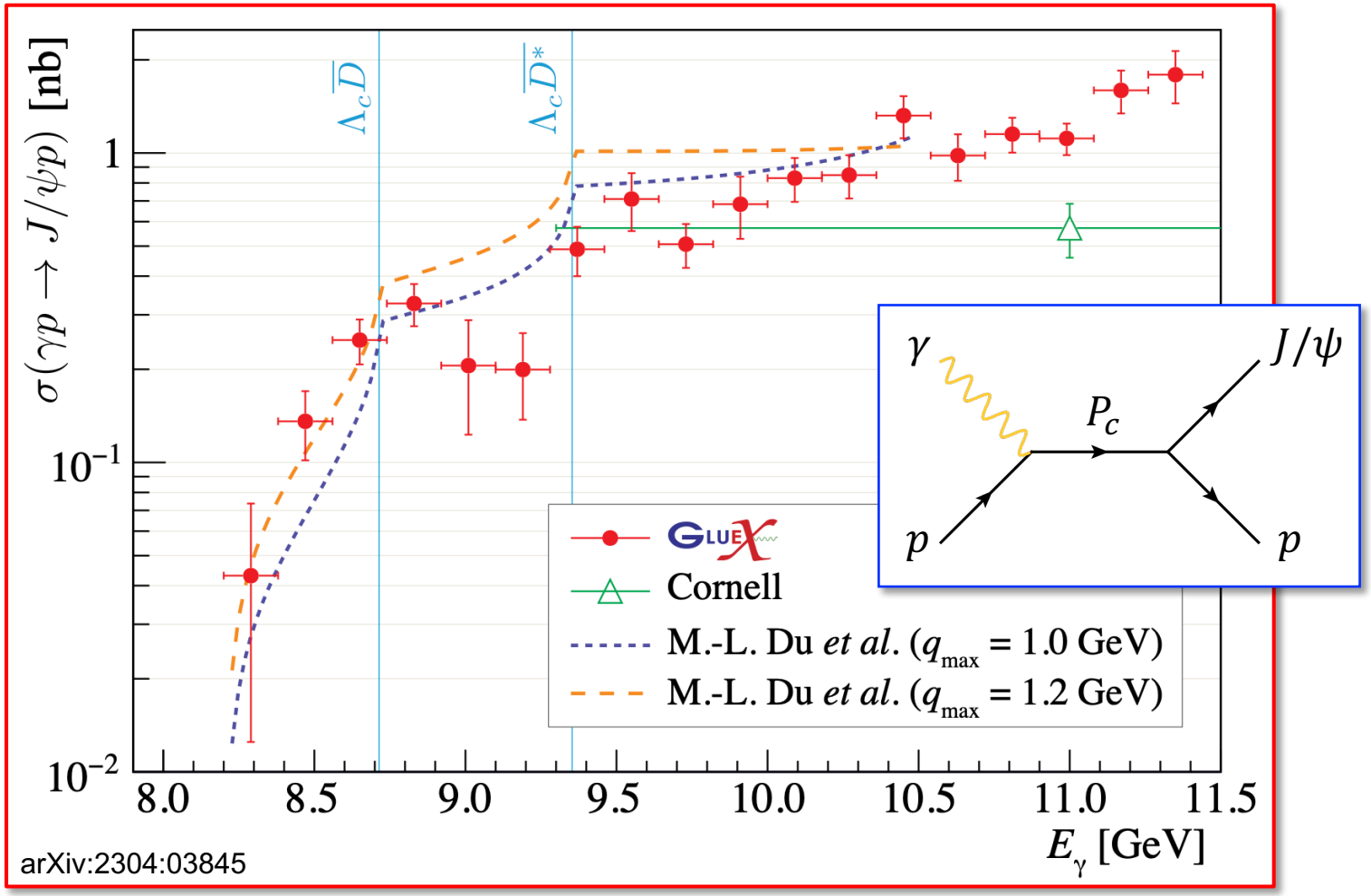
- a

disclaimer: this is one example of many, many theoretical works on pentaquarks!

PENTAQUARKS

- 2015: first LHCb P_c in $\Lambda_b^0 \to J/\psi p K^-$





- are these genuine pentaquark states, cusp effects, caused by triangles?

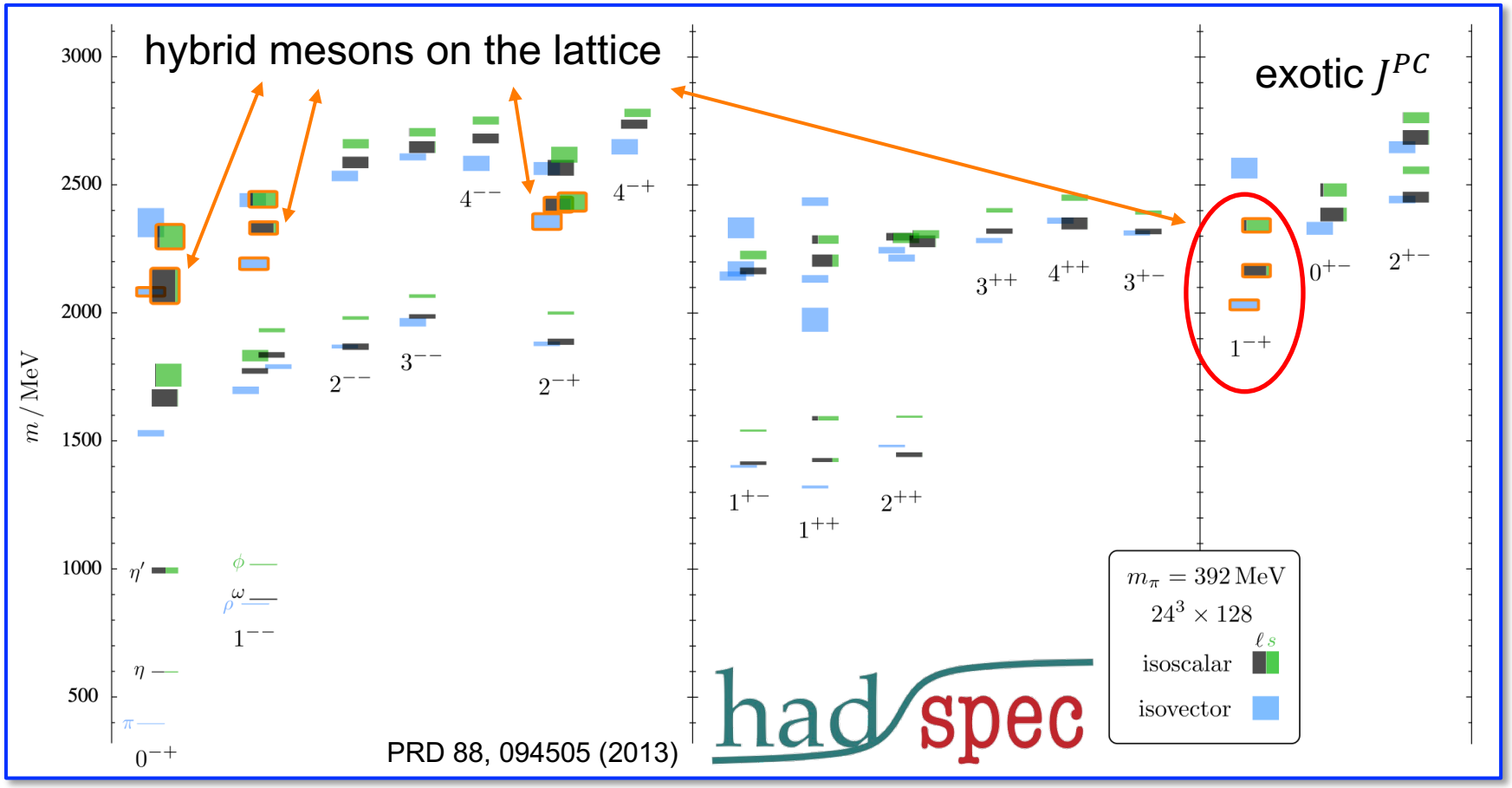
HYBRID MESONS

HYBRID MESONS

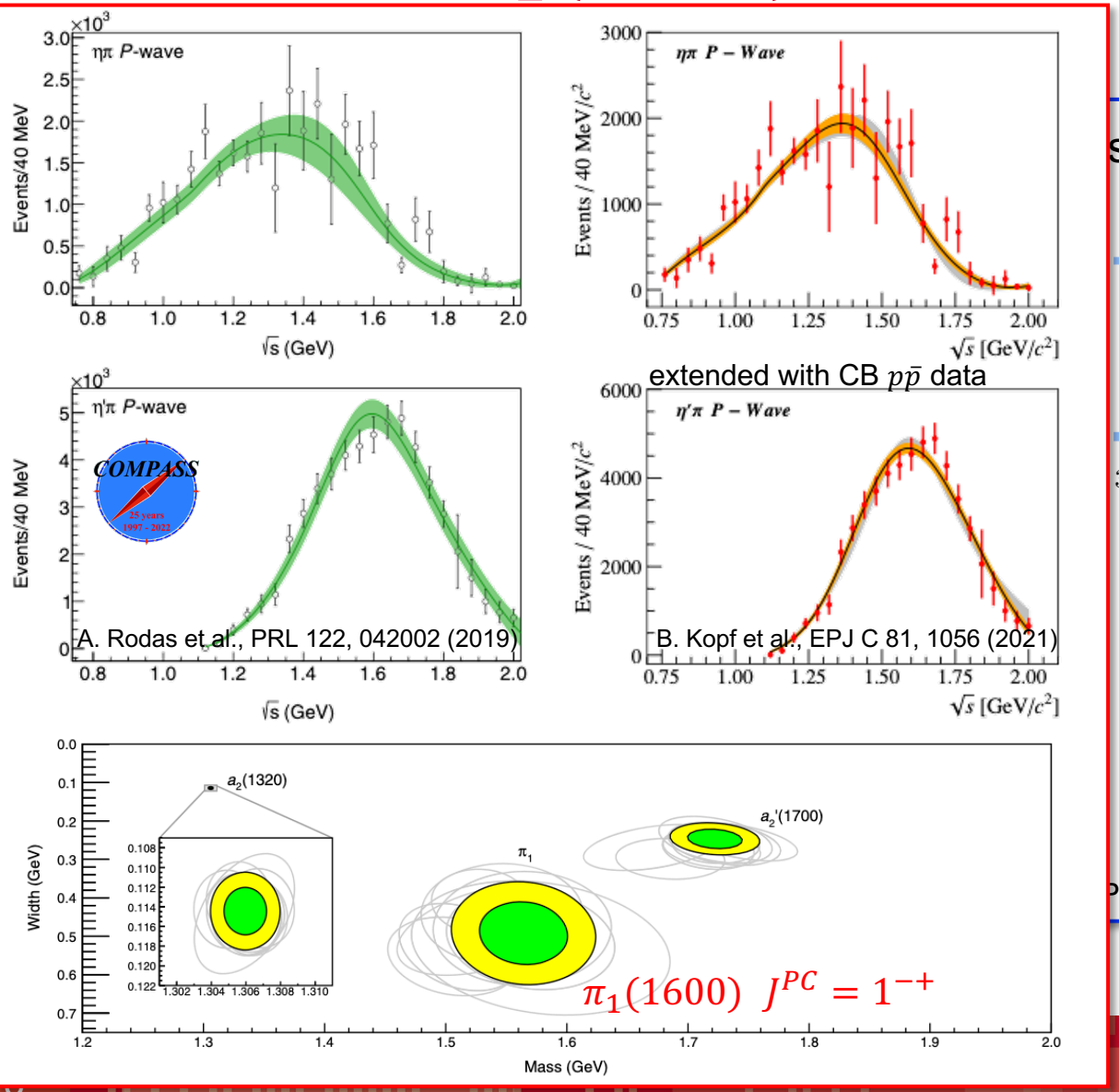
$q\bar{q}$ meson:

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

→ $J^{PC} = 0^{--}, odd^{-+}, even^{+-}$
not possible for $q\bar{q}$ mesons



ISOVECTOR $\pi_1(1600)$



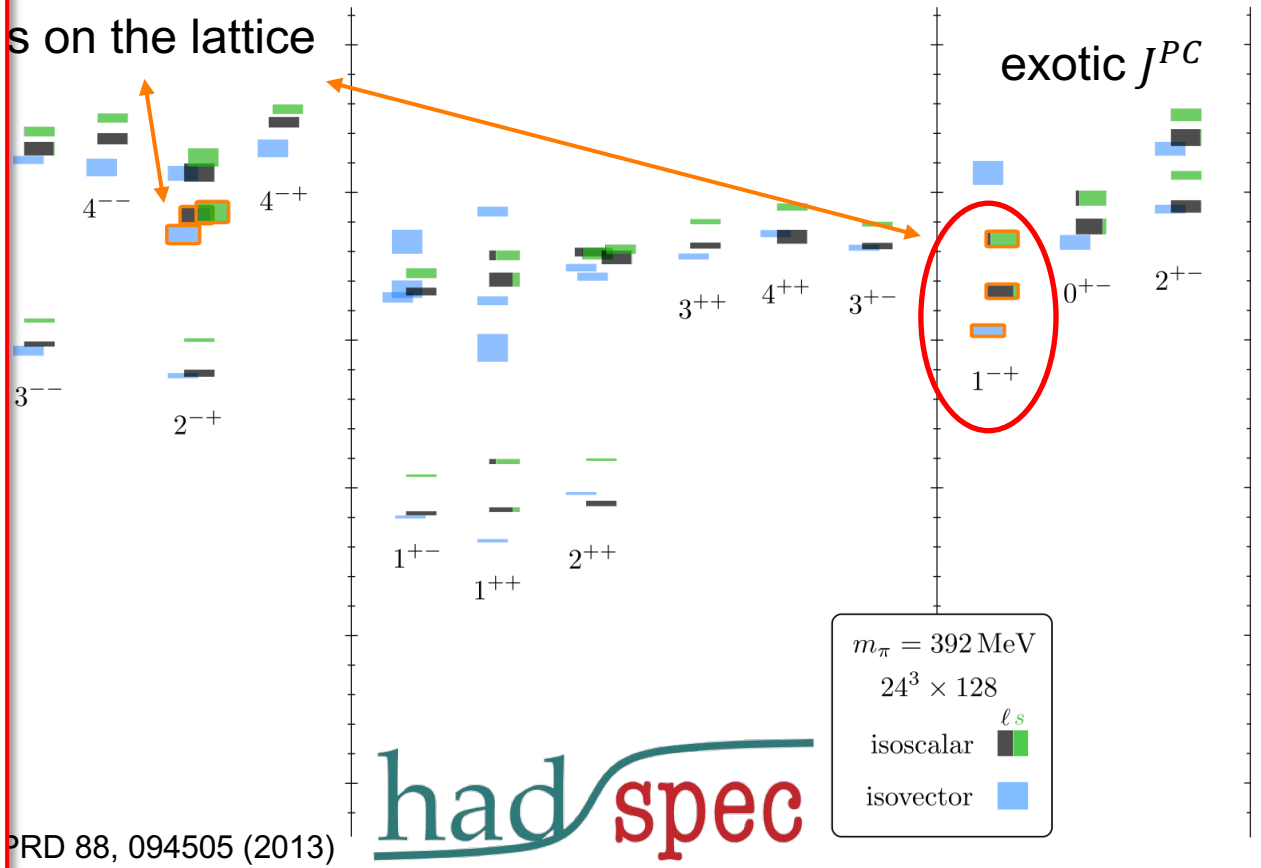
extended with CB $p\bar{p}$ data

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

B. Kopf et al., EPJ C 81, 1056 (2021)

$\pi_1(1600)$ $J^{PC} = 1^{-+}$

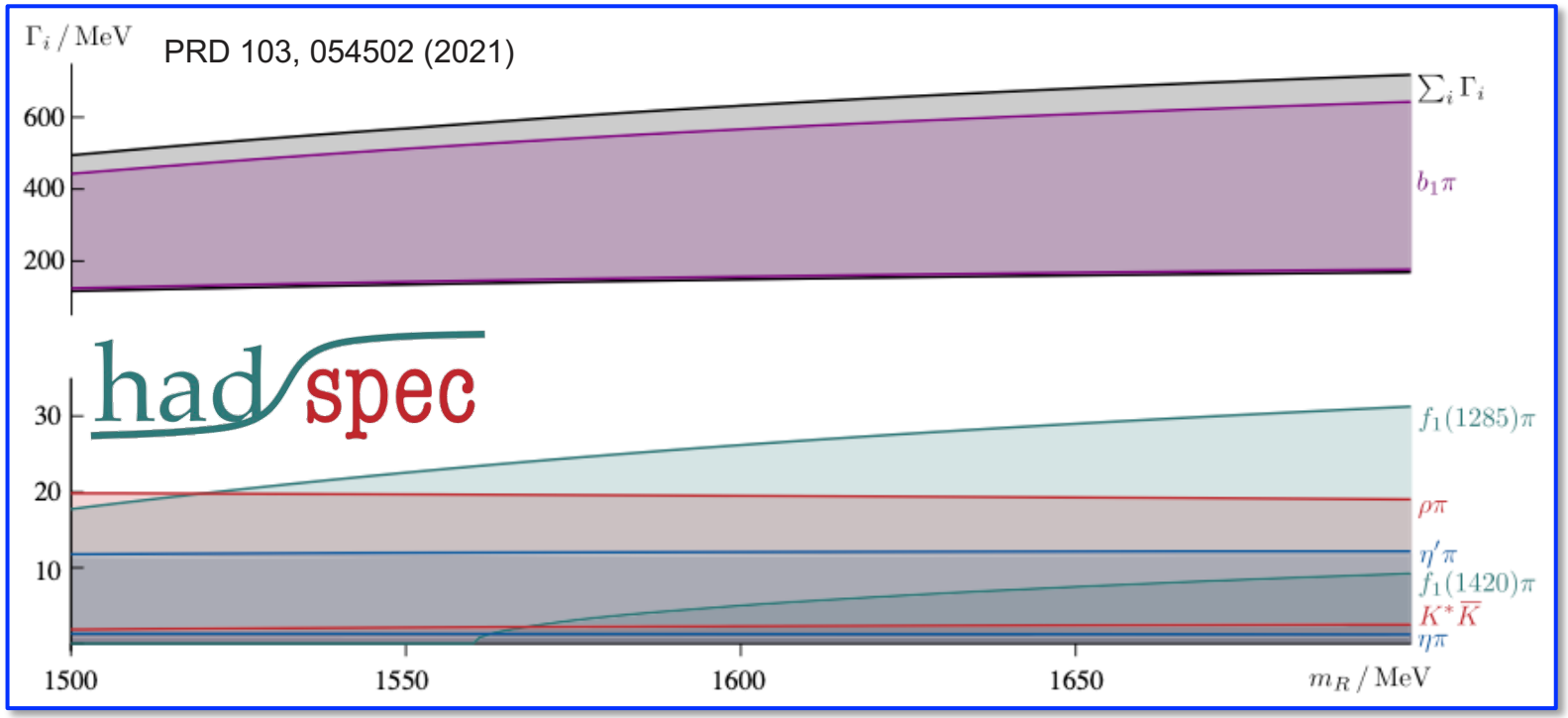
s on the lattice

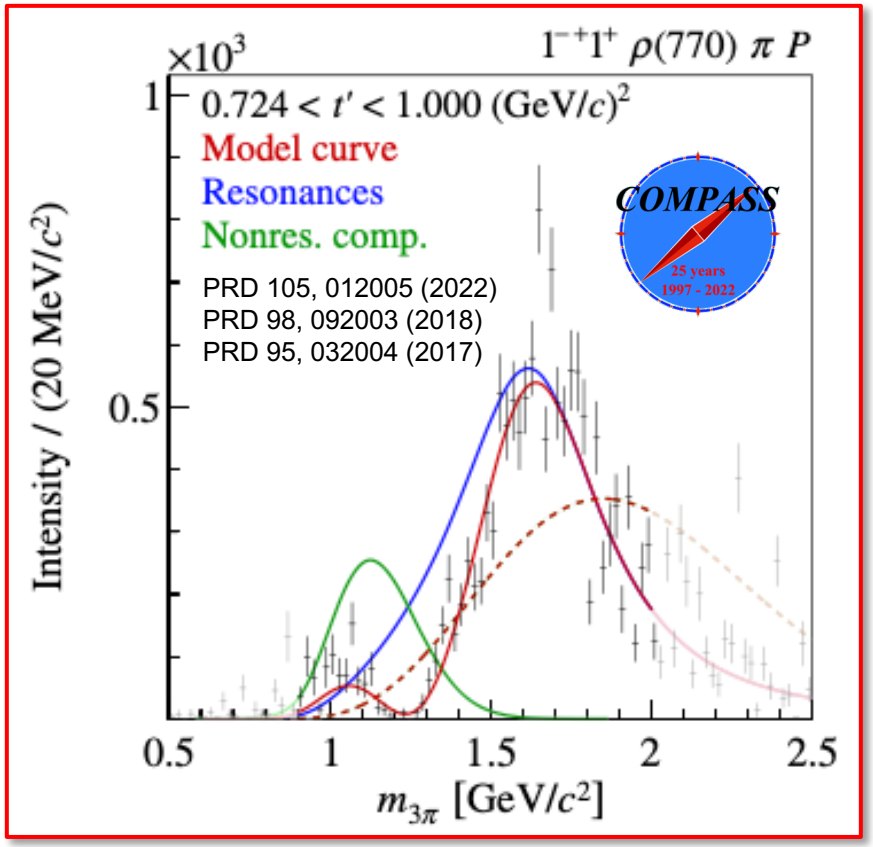


PRD 88, 094505 (2013)

ISOVECTOR $\pi_1(1600)$

- $\pi_1(1600)$ decays predicted from lattice-QCD

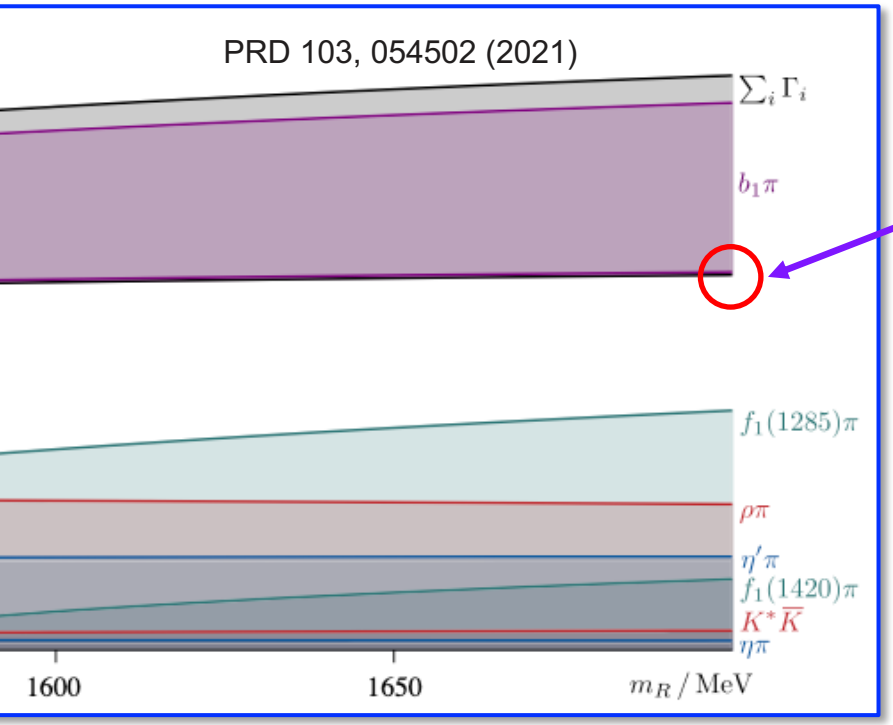


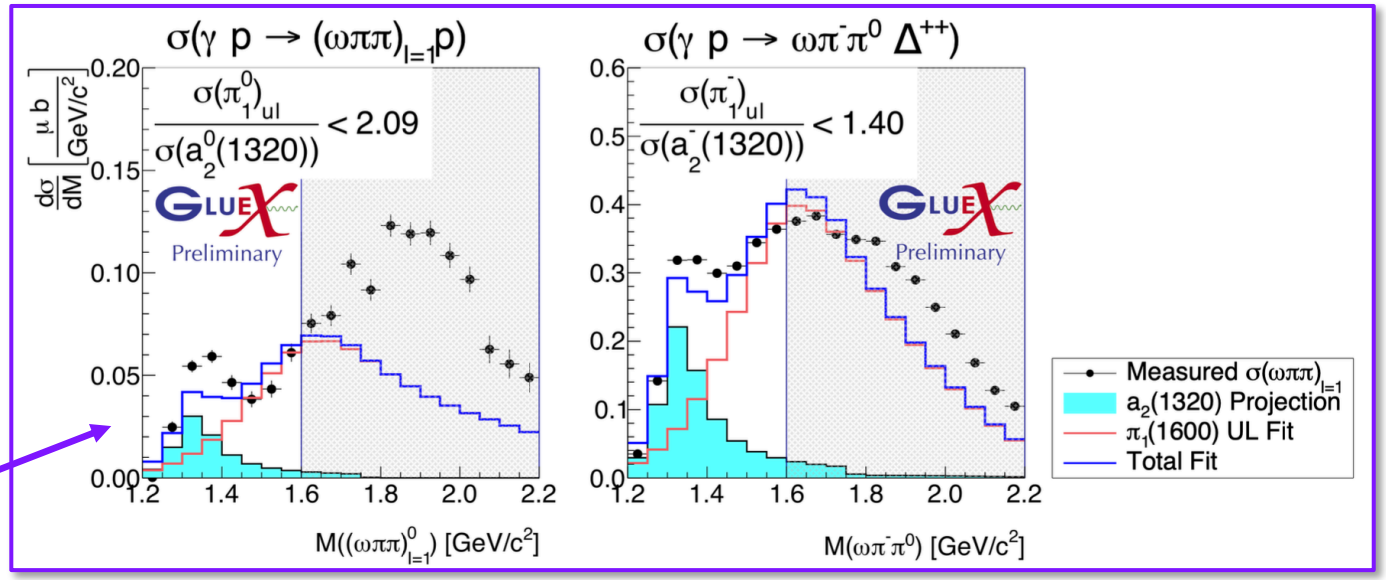


- dominantly to $b_1(1235)\pi$, discovery modes rather small
- COMPASS (and others) studying other decay modes

ISOVECTOR $\pi_1(1600)$

- $\pi_1(1600)$ decays predicted from lattice-QCD



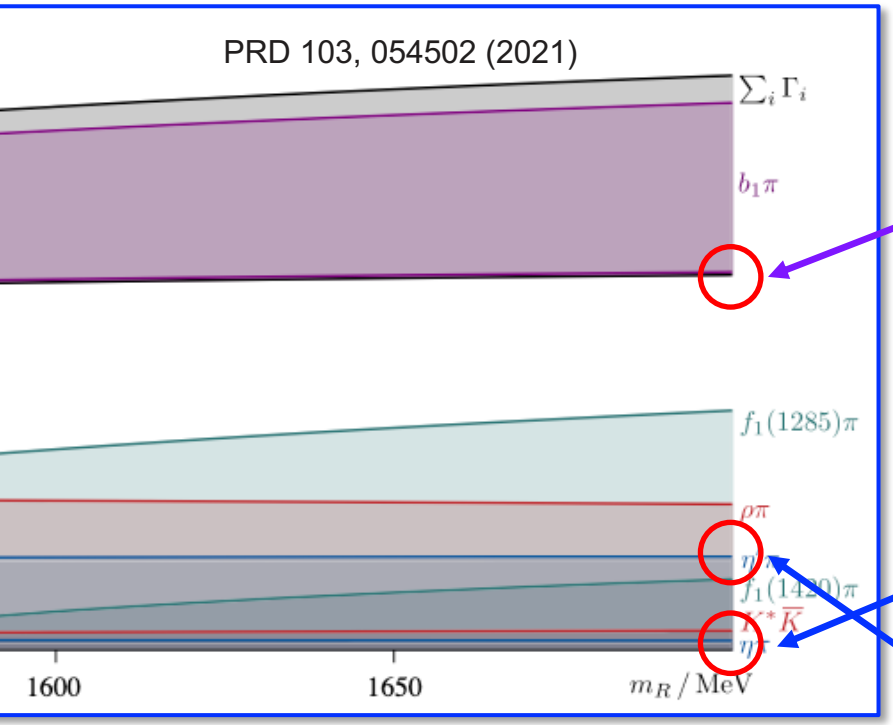


from M. Albrecht (GlueX), HADRON2023

- $\pi_1(1600)$ in photo-production?

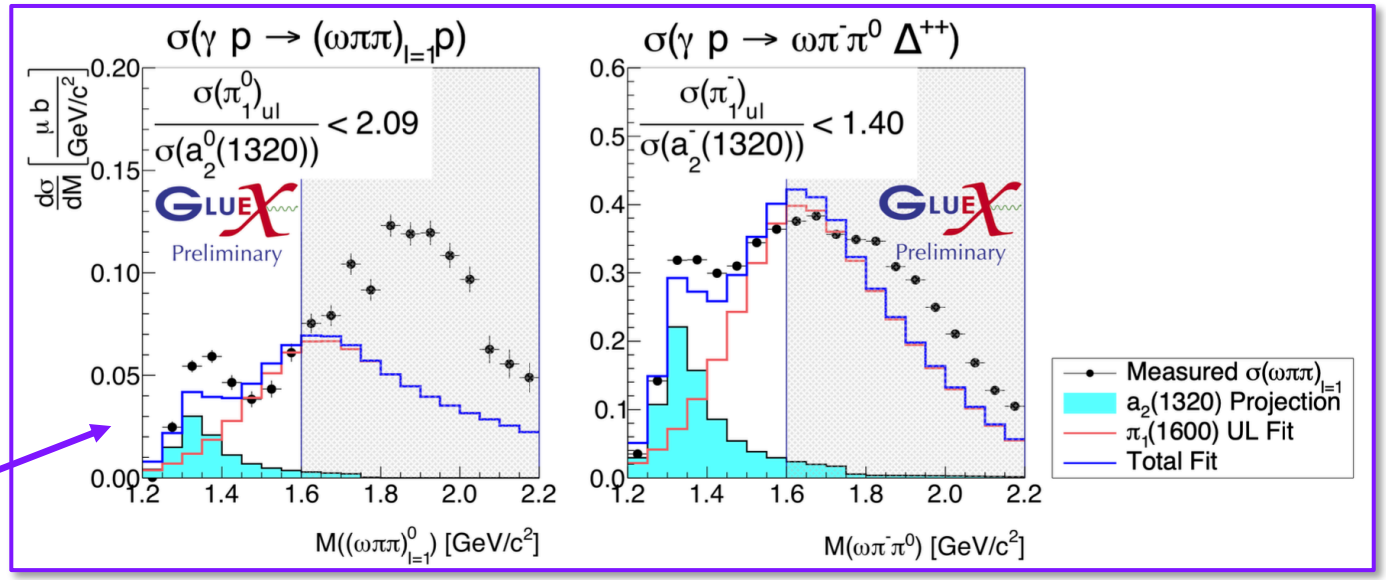
ISOVECTOR $\pi_1(1600)$

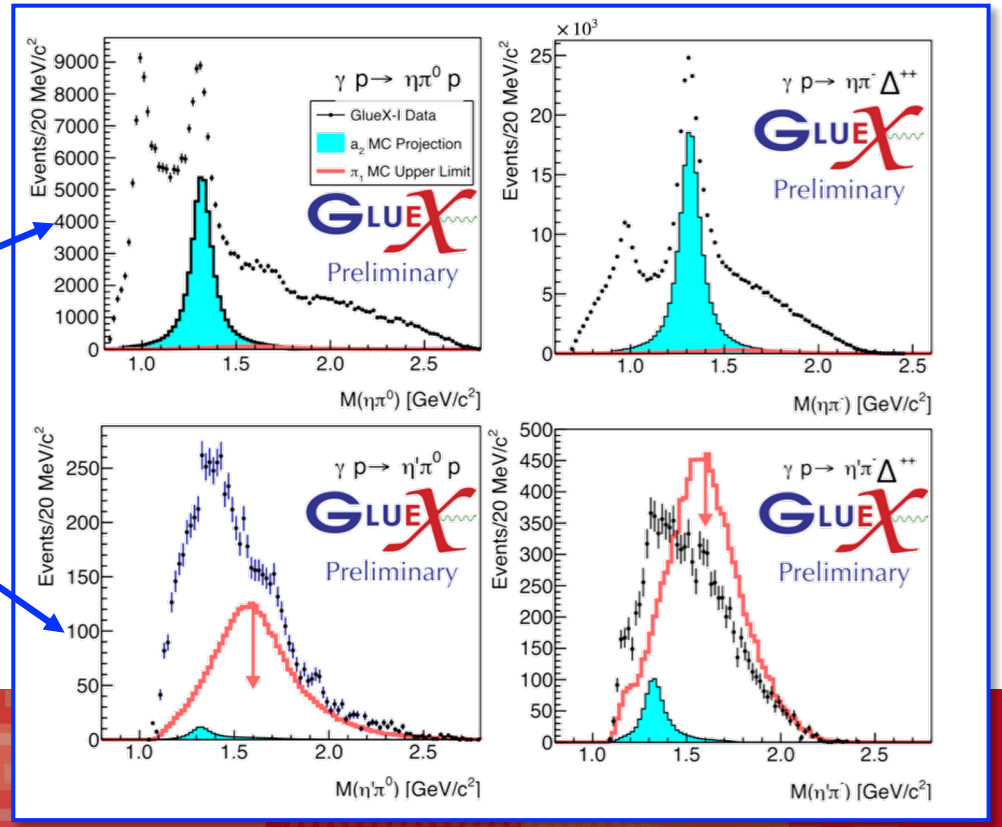
- $\pi_1(1600)$ decays predicted from lattice-QCD



- $\pi_1(1600)$ in photo-production?

→ strong potential for $\pi_1(1600) \to \eta'\pi$ in GlueX!

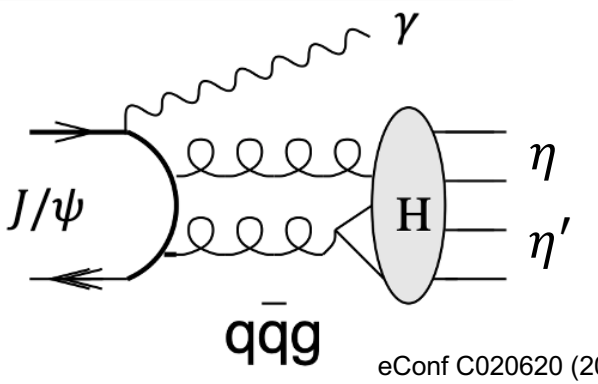




from M. Albrecht (GlueX), HADRON2023

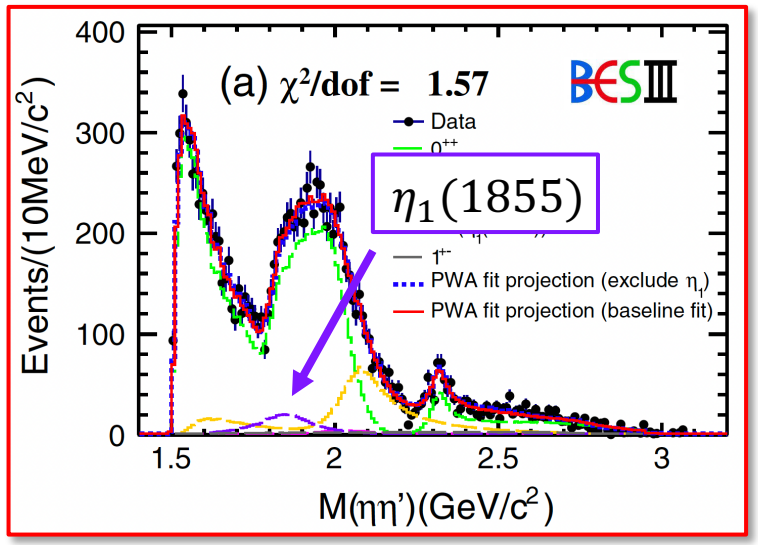
AN ISOSCALAR HYBRID $\eta_1(1855)$?

- study of $J/\psi \to \gamma\eta\eta'$ radiative decays using 10B J/ψ at BESIII

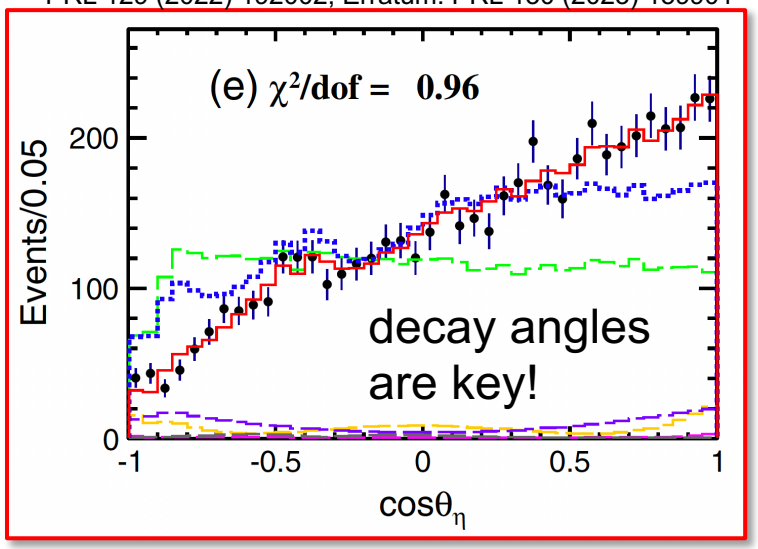


eConf C020620 (2002) THAT07

- observation of $J^{PC} = 1^{-+}$ $\eta_1(1855)$
- could be one of two iso-scalar partner states to the $\pi_1(1600)$



PRL 129 (2022) 192002, Erratum: PRL 130 (2023) 159901



for $1.7\ \text{GeV} \leq m(\eta\eta') \leq 2.0\ \text{GeV}$

- more information needed (decay modes, production processes, …)

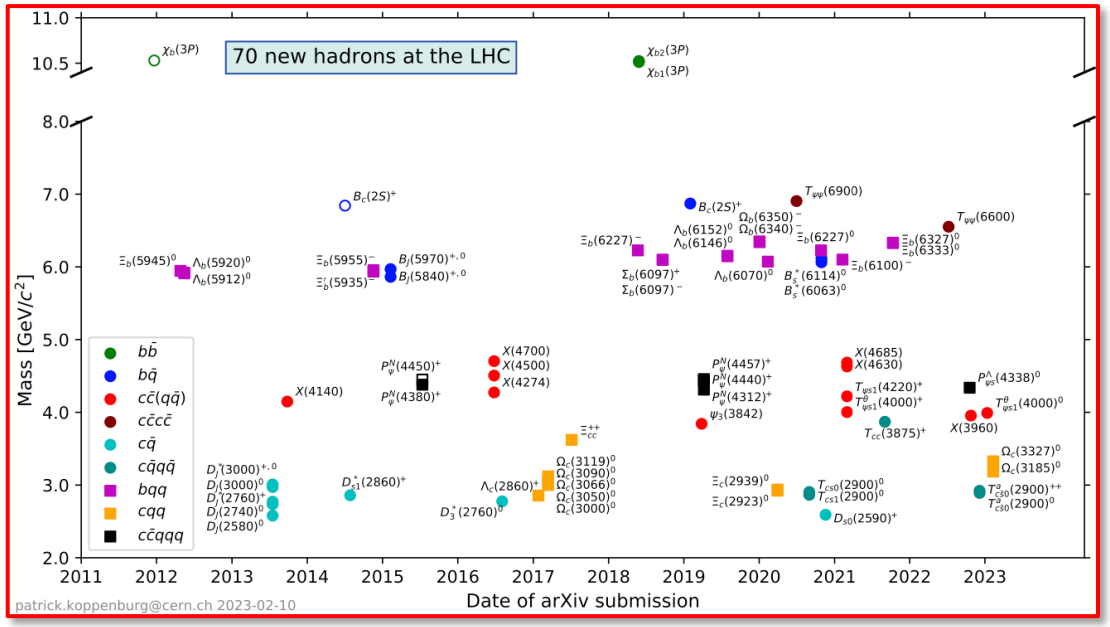
SO, WHERE DO WE STAND?

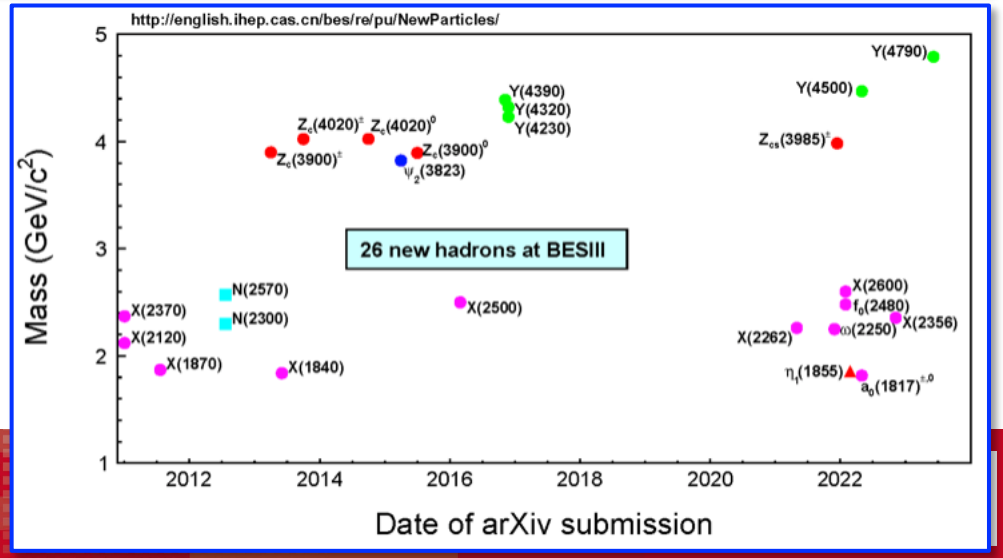
- modern, high statistics experiments reveal many new, interesting structures (hadrons?)
- some of them clearly go beyond the naive $q\bar{q}$, qqq picture of mesons and baryons
- complementarity of experiments around the world is important

→ try to confirm new states in different production processes or decay modes wherever possible!

- joint effort with theory is key!
  - Lattice-QCD predictions for masses, decay modes, …
  - rigorous theoretical frameworks to interpret data

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC, LHCb-FIGURE-2021-001, 2021, and 2023 updates





Thank you for your attention!

JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

JG|U