

Experimental review of heavy pentaquarks

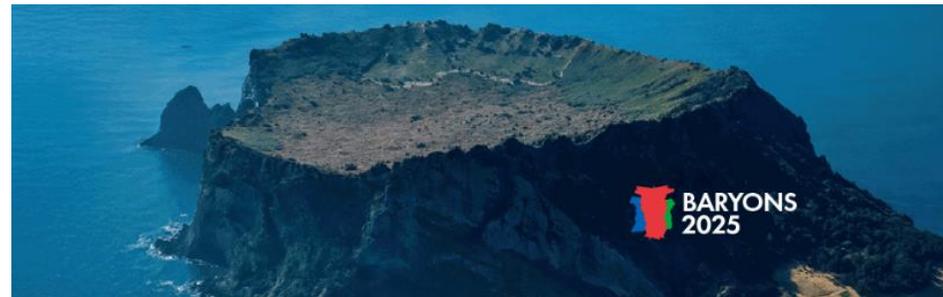
Tomasz Skwarnicki

Syracuse University, NY, USA

Apology for:

- Using older notation: P_c , P_{c_s} instead of presently recommended $P_{c\bar{c}}$, $P_{c\bar{c}s}$
- Cartoon-like treatment of theoretical interpretations

Nov 10, 2025



Baryons 2025, Jeju Island, South Korea, Nov 10-14, 2025

“Exotic” multiquark states conceived already at the birth of Quark Model

Volume 8, number 3

PHYSICS LETTERS

1 February 1964

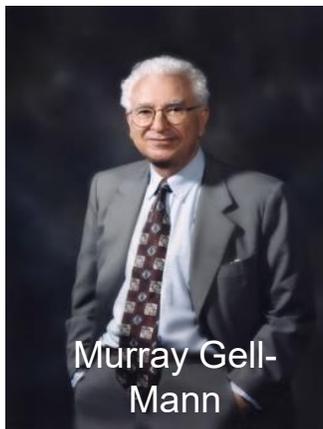
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 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) , $(qqq\bar{q})$ etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assumed that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



Murray Gell-Mann

8419/TH.412

21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

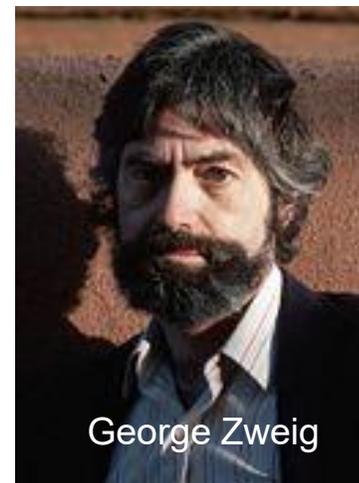
II *)

G. Zweig

CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

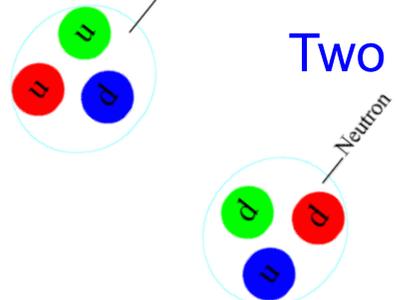
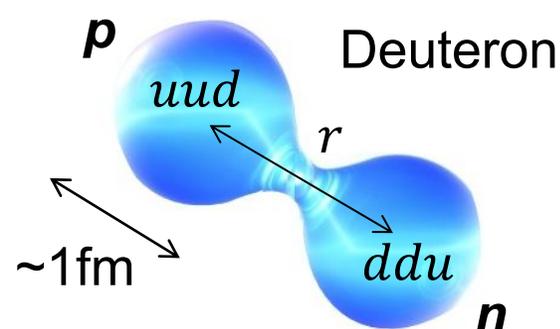
- 6) In general, we would expect that baryons are built not only from the product of three aces, AAA , but also from $\bar{A}AAA$, $A\bar{A}AAA$, etc., where \bar{A} denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $A\bar{A}A$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA , that is, "deuces and treys".



George Zweig

Tetraquarks: $(qq\bar{q}\bar{q})$ – mesons, **Pentaquarks** $(qqqq\bar{q})$ - baryons, ...

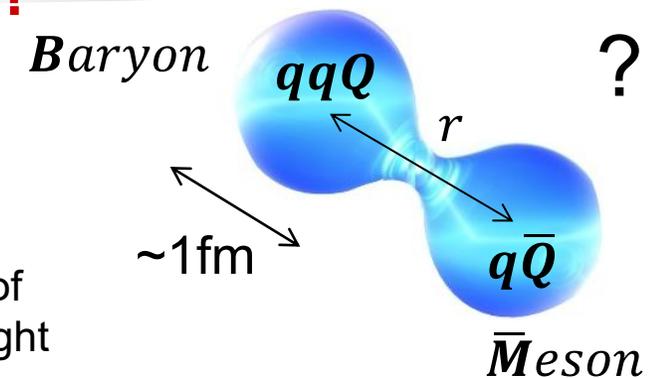
Deuteron and “molecular” $((qqQ) - (q\bar{Q}))$ pentaquarks?



Two almost-distinct confinement volumes.

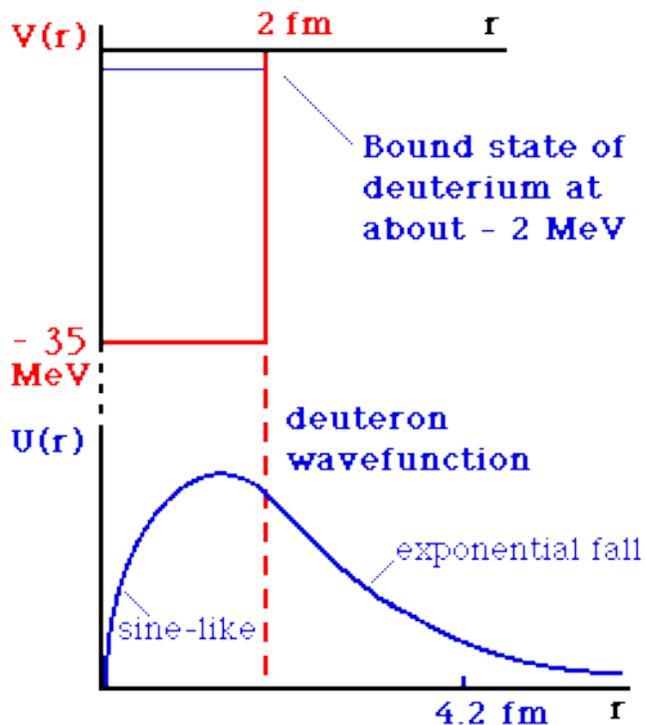
Residual strong force.

Phenomenologically modelled by exchange of light mesons $\pi, \rho, \pi\pi, \omega, \eta, \dots$, (exchange of light quarks like exchange of outer electrons in a molecular forces)



No excitations, just a ground state $(n = 1, l = 0, S = 0)$!

The simplest $V(r)$ model



A large range of ad hoc assumptions – qualitative rather than quantitative predictions.

Hadrons as constituents in a shallow binding \rightarrow very restrictive spectroscopy:

- **Masses at or just below the threshold** for disintegration to the constituent hadrons (“loosely bound”)
 - $\triangleright M = m_B + m_{\bar{M}} - \Delta E; \Delta E \sim O(10) \text{ MeV}$
- **Constrained spin-parity:** $\vec{J} = \vec{S}_B + \vec{S}_{\bar{M}}, P = P_B P_{\bar{M}}$ (since $L = 0$)
- **Hyperfine interactions** ($\vec{S}_B \cdot \vec{S}_{\bar{M}}$) can generate **closely spaced multiplet** with up to $|S_B + S_{\bar{M}}| - |S_B - S_{\bar{M}}| + 1$ states (since $S_B, S_{\bar{M}}$ small – 1,2, or 3 states)
- For narrow constituents **expect narrow states**, since decays to a charmonium/bottomonium ($Q\bar{Q}$) + light baryon (qqq) suppressed by Q and \bar{Q} confined in nearly-separate volumes
- Such states can be very **extended in size** $\langle r \rangle \sim 1/\Delta E$
 - \triangleright The states closest to the threshold can be the narrowest

No universal production coupling.

Difficult to relate observation in one reaction to expected rate in another.

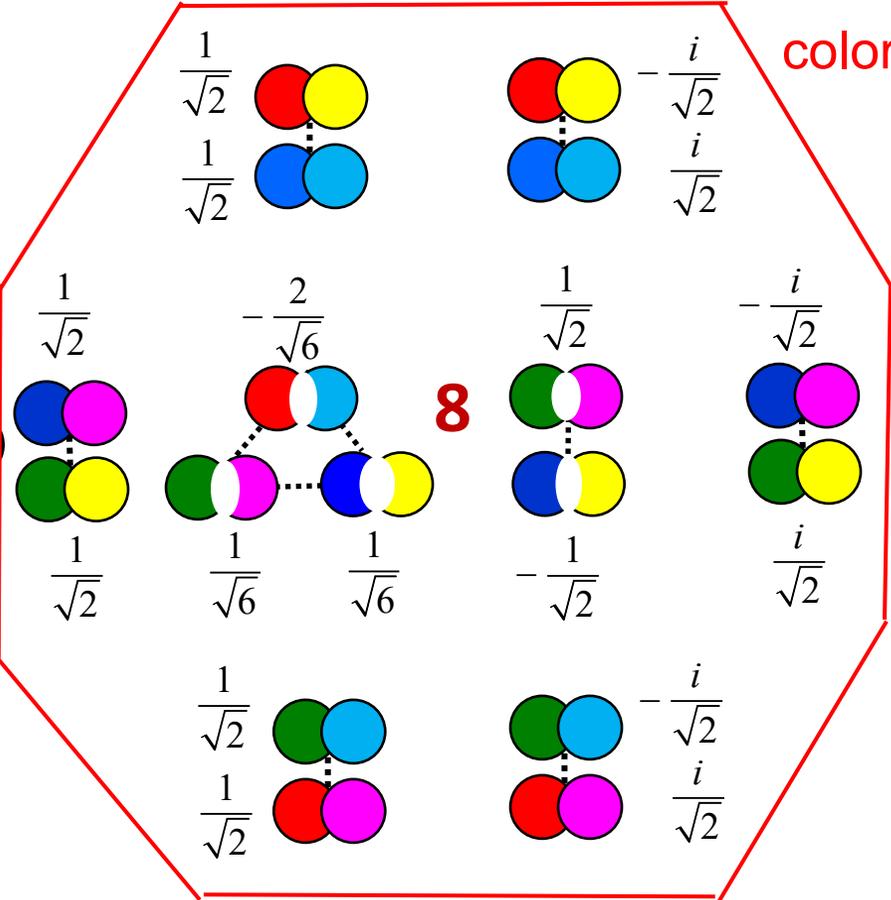
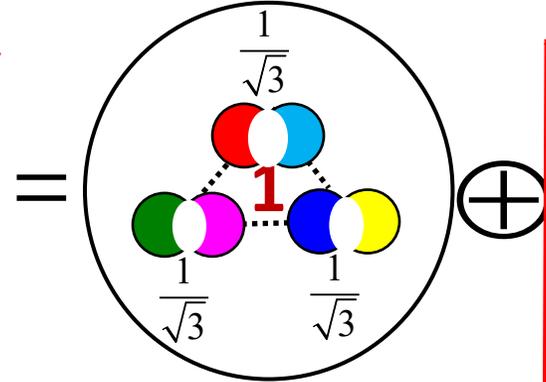
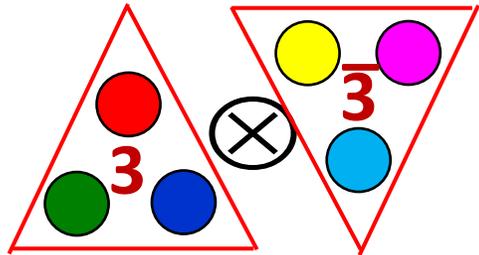


Quark – antiquark interactions in perturbative QCD

color triplet

color antitriplet

color singlet



color octet

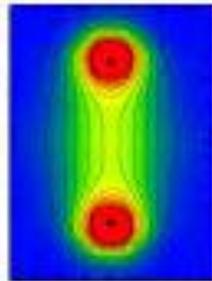
quark q antiquark \bar{q}

Perturbative QCD (small r):
attractive color force

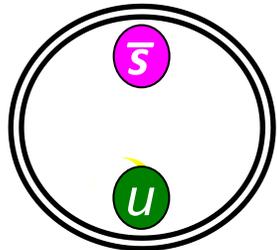
$$V(r) \sim -\frac{4\alpha_s}{3r}$$

($q\bar{q}$) meson
e.g. K^+

Long distance model (supported by LQCD):
color flux tube stretched between quark and antiquark with attractive potential



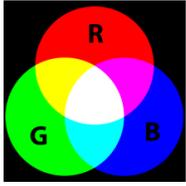
$$V(r) \sim r$$



Perturbative QCD:
repulsive color force

$$V(r) \sim +\frac{1\alpha_s}{6r}$$

Cannot build a meson in this configuration but this can be a building block in more complicated hadron e.g. hybrid meson $((q\bar{q})g)$, as gluons belong to color octet configuration, or pentaquarks $((q\bar{q})(qqq))$ – see later



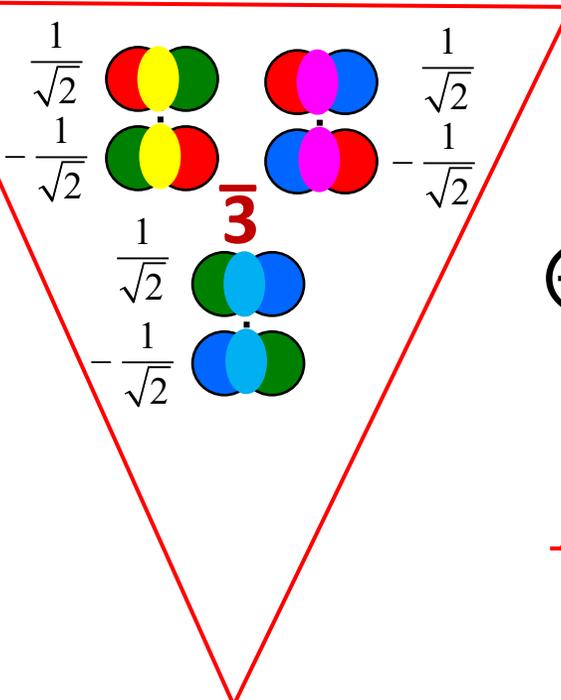
Colored diquarks in QCD

(antisymmetric)
color
antitriplet

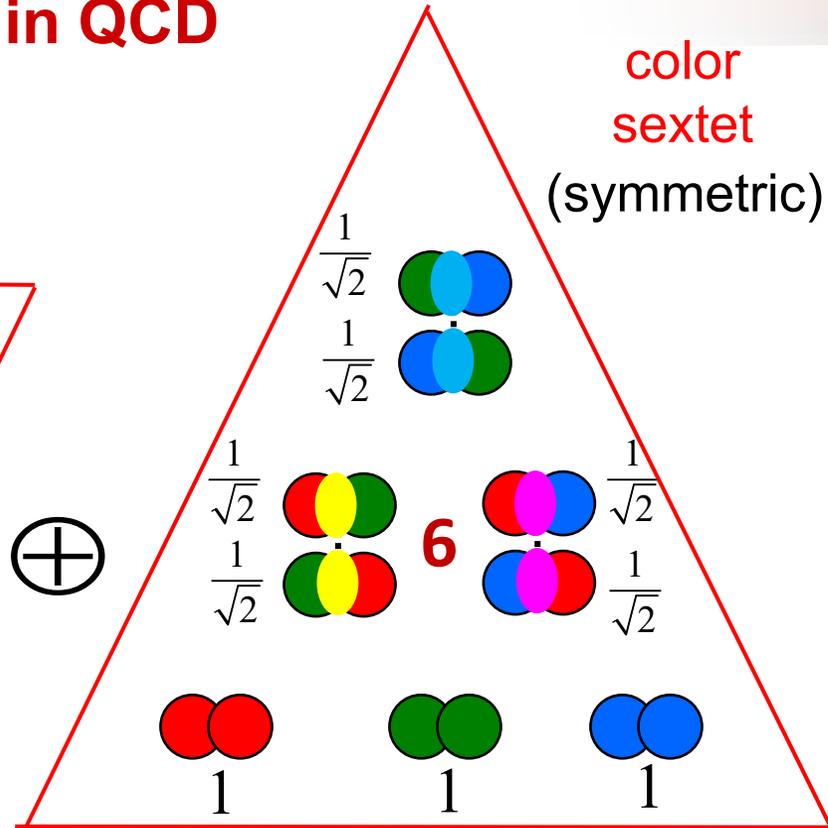
color
sextet
(symmetric)

color
triplet

color
triplet



⊕



quark
q

quark
q

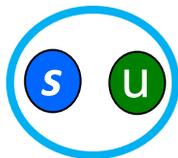
repulsive color force at short r

$$V(r) \sim + \frac{1}{3} \frac{\alpha_s}{r}$$

attractive color force for small r : $V(r) \sim - \frac{2}{3} \frac{\alpha_s}{r}$

(perturbatively: half as strong as in the meson)
(qq) diquark

**sextet-diquark can build
((qq)((qq)q̄)) pentaquarks**

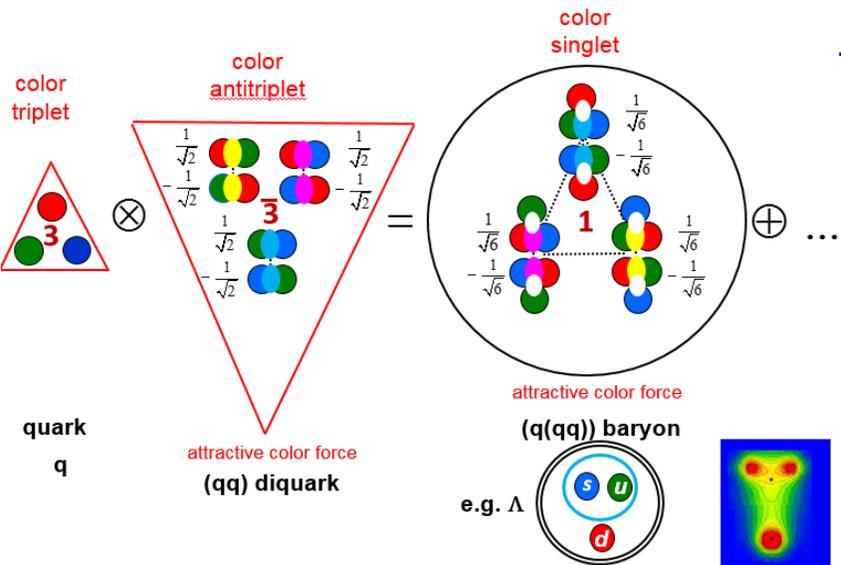


Not a particle, just a
building block in
QCD

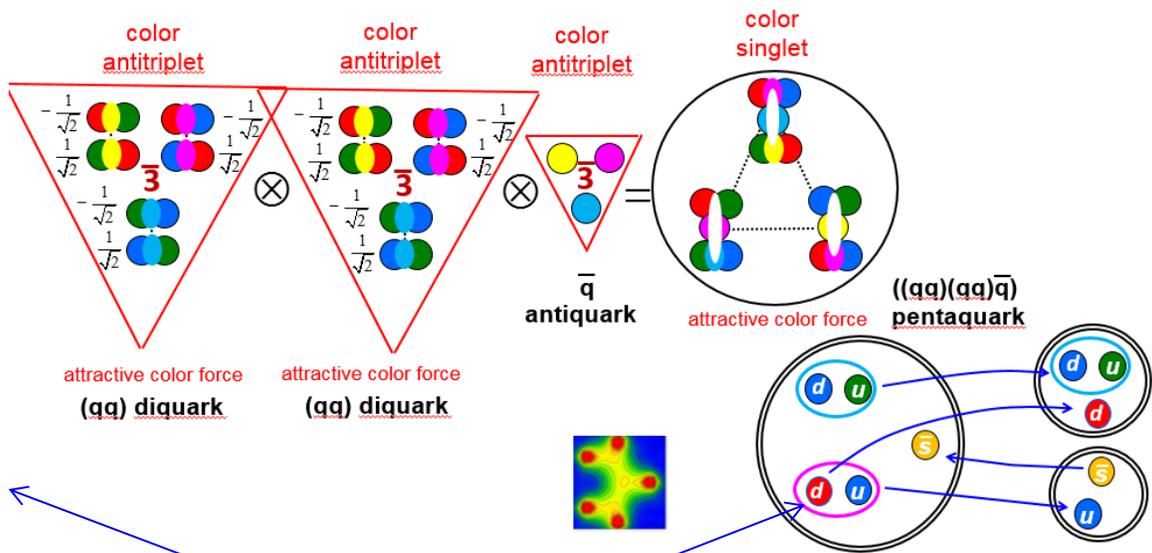
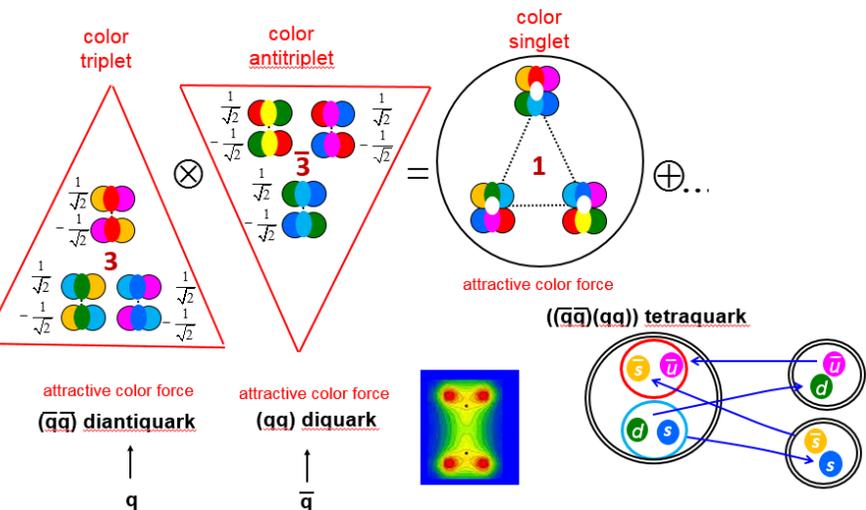
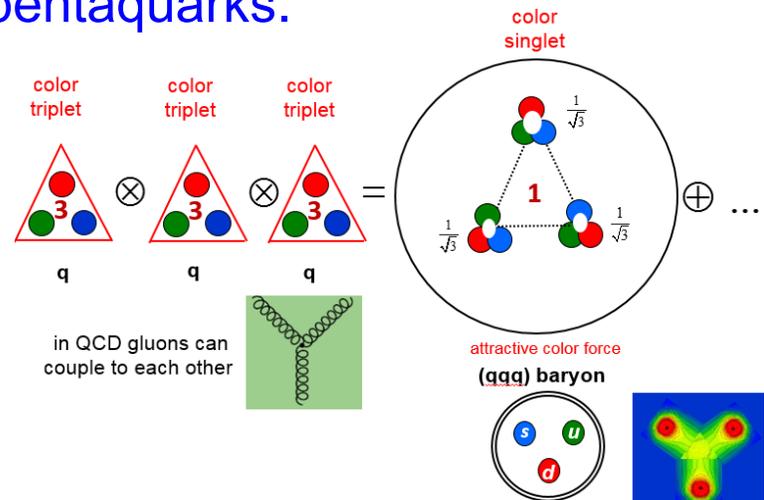
**antitriplet-diquark can go in a place of antiquark in a hadron
(triplet-antidiquark in place of a quark)**

Hadrons from diquarks?

Historically, diquarks provided additional motivation for existence of tetra- and pentaquarks.



VS.

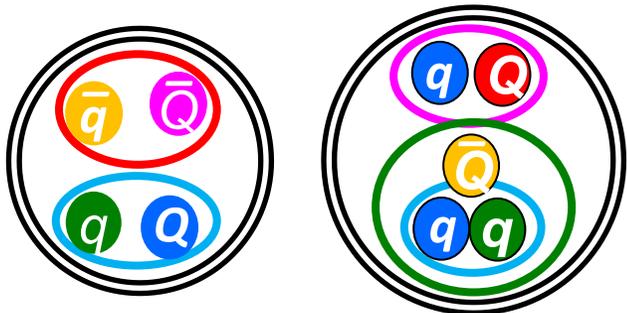


Does effective mechanism to suppress rapid fall-apart exist?

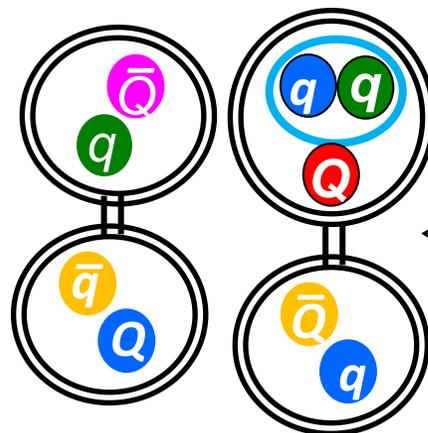
Tightly bound diquark vs “molecular” tetra/pentaquark spectroscopy

- The same quark content can, in principle, create a spatially extended, loosely bound hadron-hadron molecule or a compact, strongly bound diquark tetra/penta-quark
- However, mass spectrum (“spectroscopy”) from these two types of bindings are expected to be very different

$((\bar{Q}\bar{q})(Qq))$, $((Qq)((qq)\bar{Q})$
compact diquark tetra/penta-quark



$(\bar{Q}q)-(\bar{q}Q)$, $(Qqq)-(\bar{Q}q)$
Extended hadron-hadron molecule



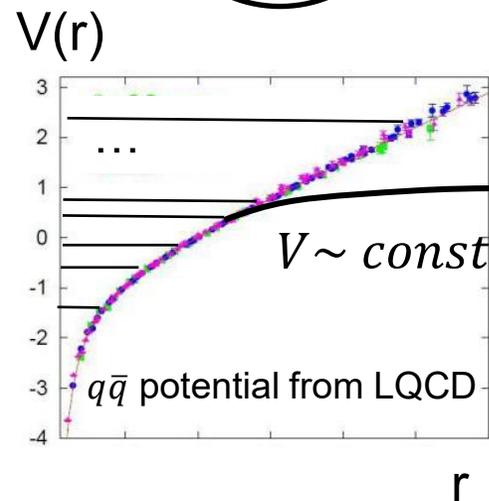
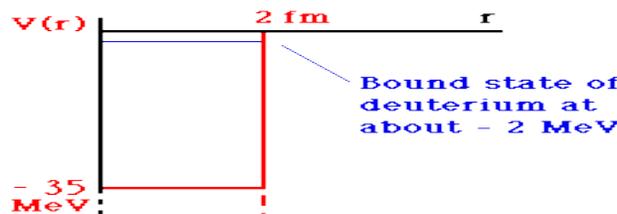
Usual phenomenology describes binding forces here via exchange of light mesons:

$\pi, \rho, \omega, \eta, \dots$

Typically expect only $n=1, L=0$ split by small hyperfine $\vec{S}_1 \cdot \vec{S}_2$

Mass and J^P fairly constrained from the constituents.

Fall apart prevented by spatial separation – **narrow states** are expected.



Very rich mass and J^P spectrum expected from various radial, orbital momentum and spin excitations!

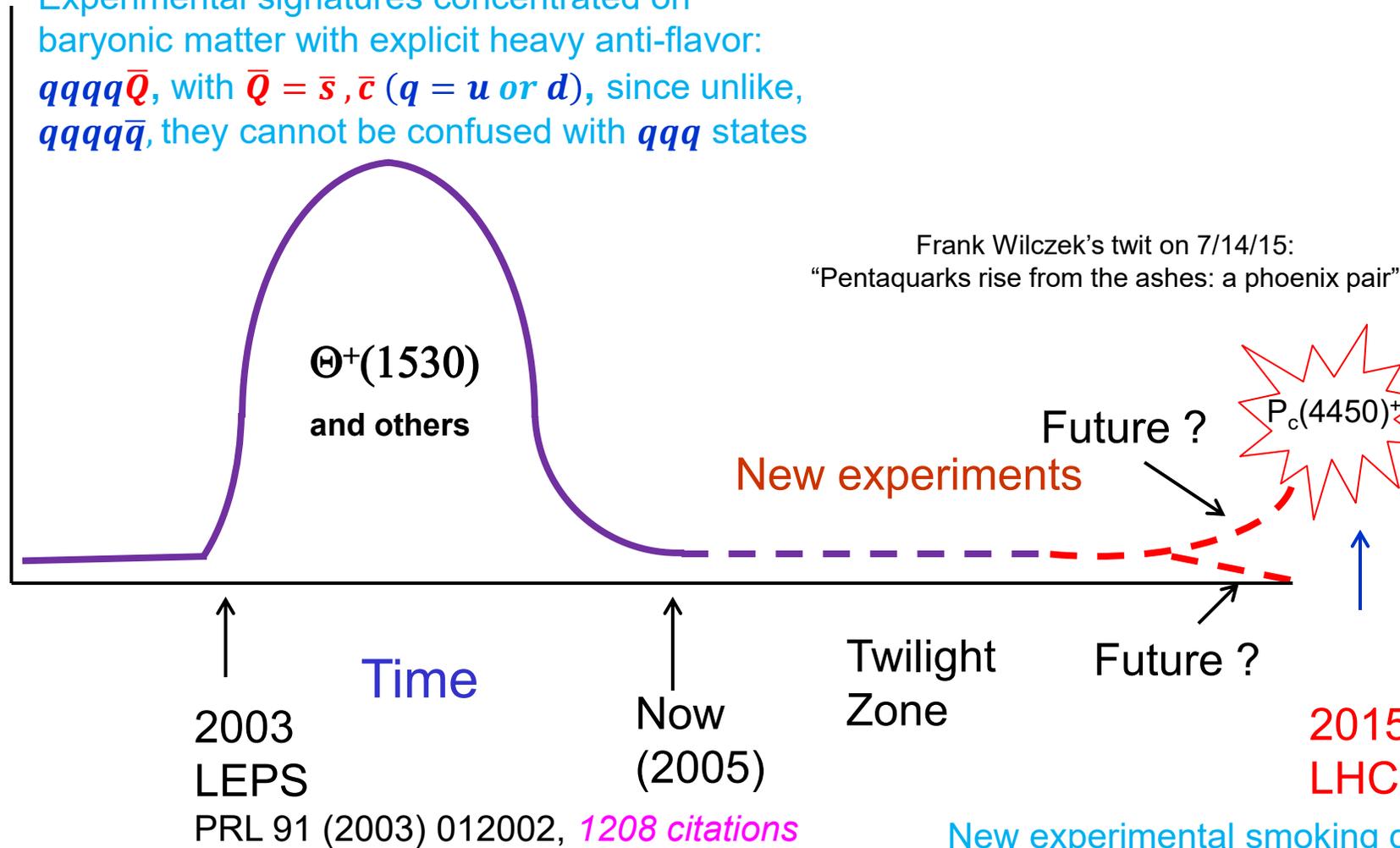
Could be broad. Does effective mechanism to suppress their fall-apart widths exist?

Adopted from Wolfgang Lorenzon's slide from his talk "Pentaquarks" on Oct 2005:

Pentaquark Vital Signs

Experimental signatures concentrated on baryonic matter with explicit heavy anti-flavor: $qqqq\bar{Q}$, with $\bar{Q} = \bar{s}, \bar{c}$ ($q = u$ or d), since unlike, $qqqq\bar{q}$, they cannot be confused with qqq states

Excitement Level

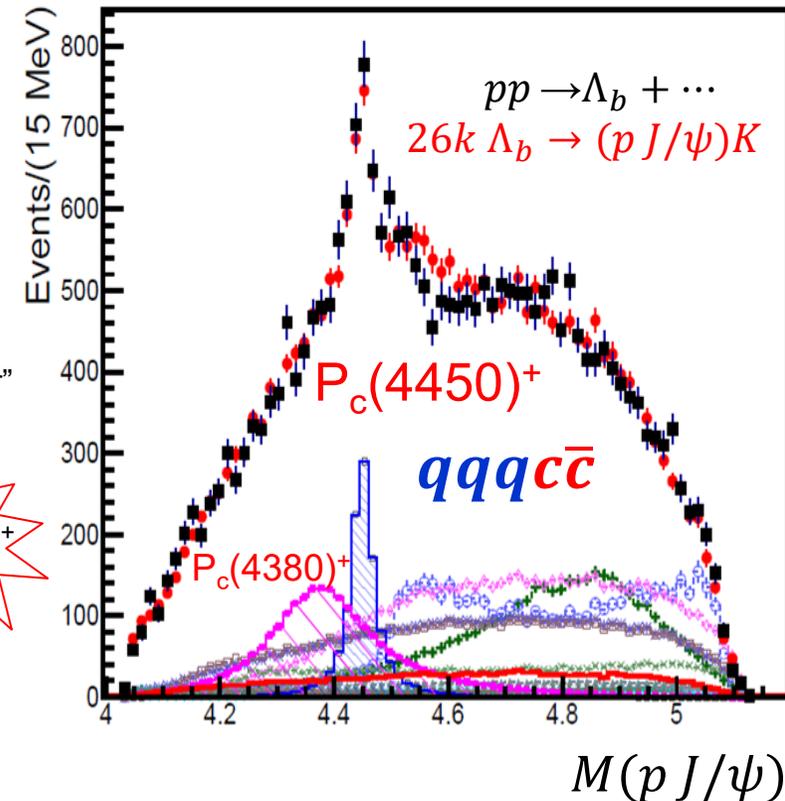


Evidence for $\Theta^+(1530)$ went away with better measurements

New experimental smoking gun for pentaquark - baryonic matter with hidden heavy flavor: $qqqQ\bar{Q}$, since they also cannot be confused with $qqq(Q\bar{Q})$ - too heavy to pop out in decays of latter)

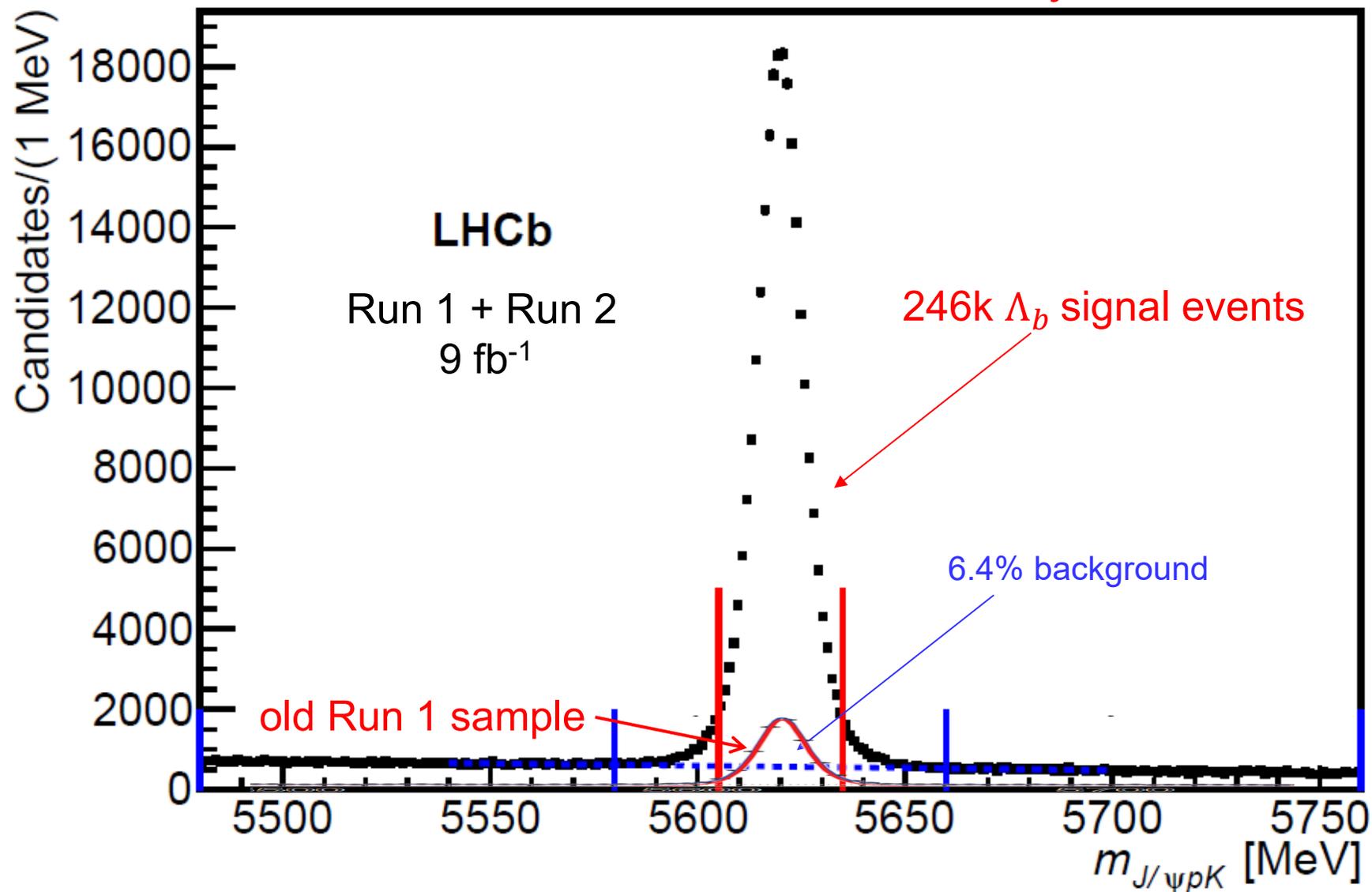
Heavy quarks save the day!

PRL 115, 072001 (2015) 2034 citations



Full LHCb $\Lambda_b \rightarrow J/\psi p K^-$ data sample – results published in 2019

9x more than used in the Run 1 analysis

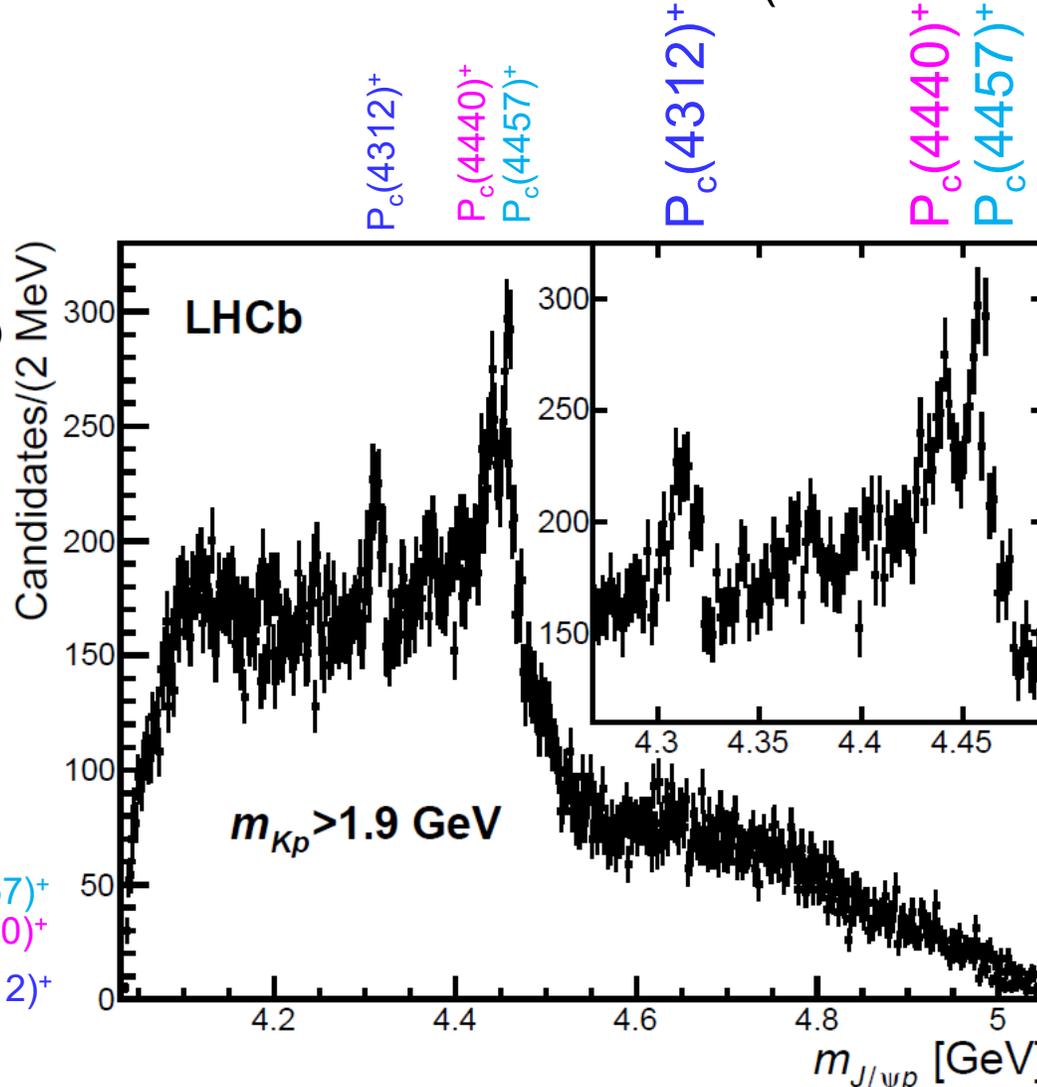
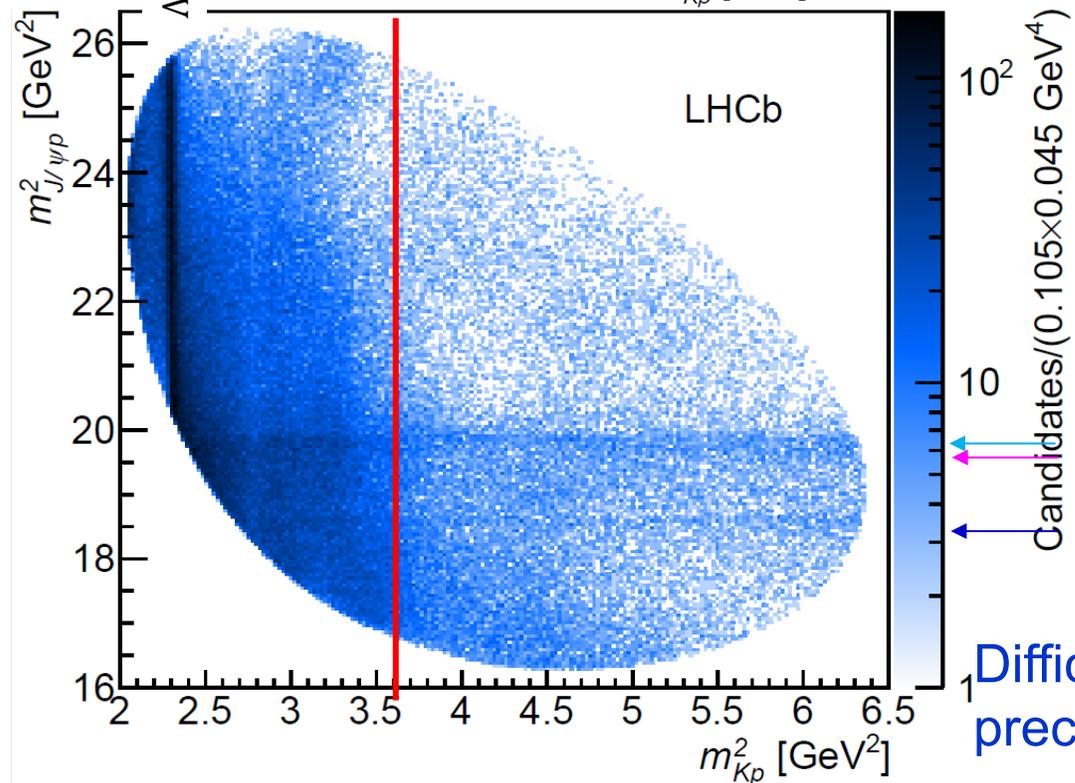
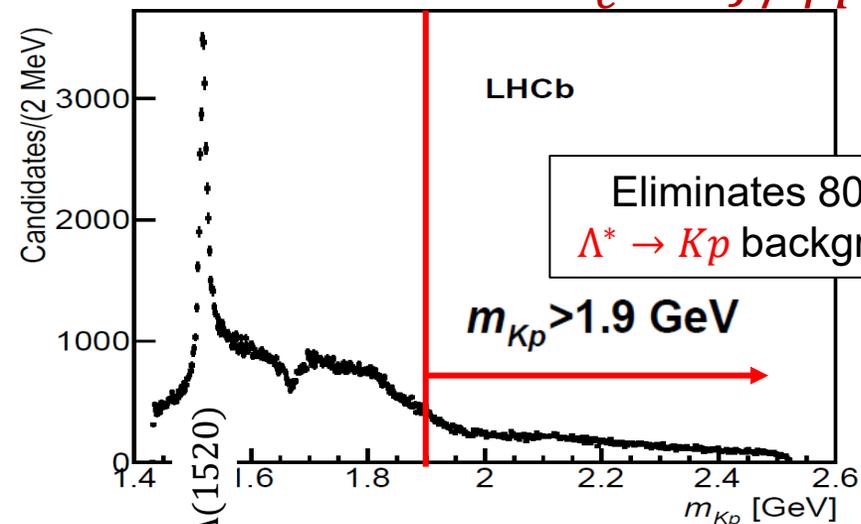


arXiv:1904.03947
LHCb-PAPER-2019-014
PRL **122**, 222001 (2019)

Improvements in the data selection (x 2), integrated luminosity (x 3) and cross-section ($\sqrt{s} = 13$ TeV vs 7-8 TeV)

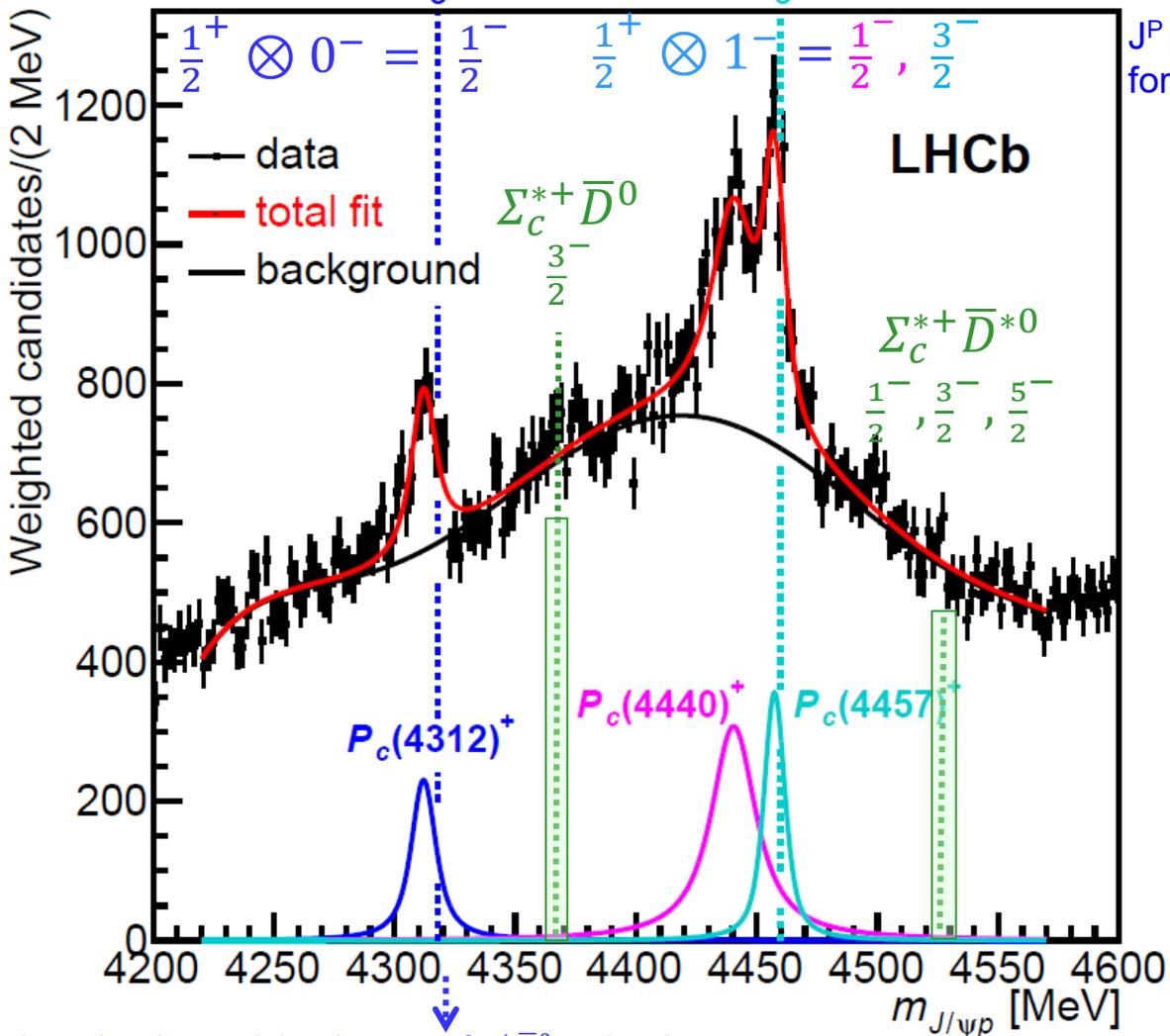
Narrow $P_c^+ \rightarrow J/\psi p$ peaks with Λ^* suppression

Mass resolution $\sigma=2.3-2.7$ (FWHM 5.4-6.4) MeV



Difficult to construct amplitude model of $\Lambda_b \rightarrow J/\psi \Lambda^*, \Lambda^* \rightarrow Kp$ with precision required to study very small peaks due to the narrow P_c^+

2019 pentaquark results and molecular model



J^P predicted for molecules

The **only** thresholds in this mass range made from very narrow $I \neq 0$ baryon - $I \neq 0$ meson pairs

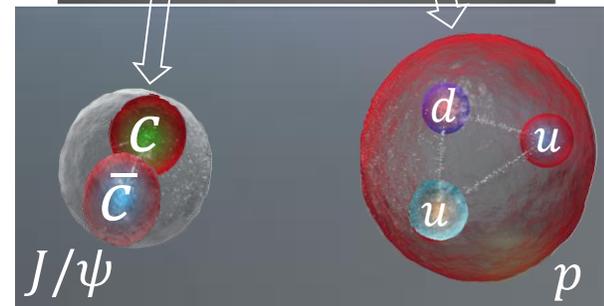
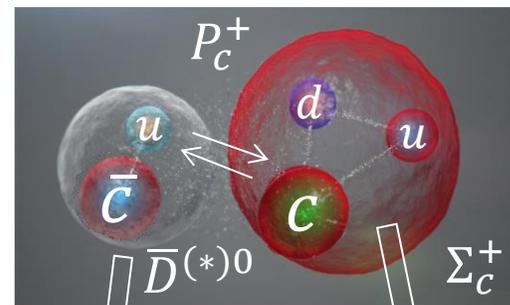
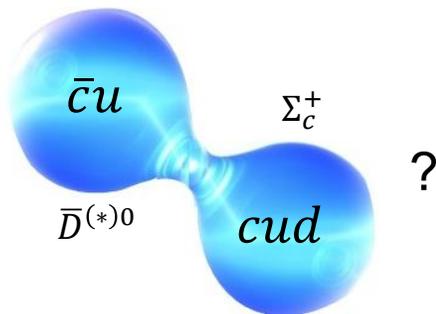
Simple mass fits (no amplitude analysis)

State	M [MeV]	Γ [MeV] (95% CL)	\mathcal{R} [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$ (< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$ (< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$ (< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

7.3σ

Three narrow near-threshold states!
 $\Gamma < O(10^1)$ MeV

Masses, number of states and small widths fit the molecular model



Wu, Molina, Oset, Zou, PRL105 (2010) 232001
Wang, Huang, Zhang, Zou, PR C84 (2011) 015203
Karliner, Rosner, PRL 115 (2015) 122001
and others

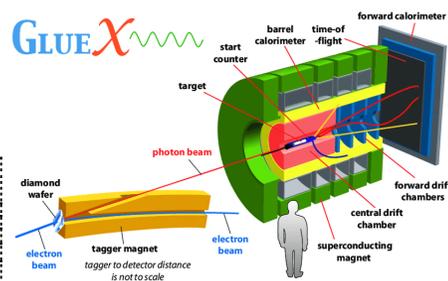
$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400 \text{ MeV}$
 $M_{P_c^+} = M_{\bar{D}^{*0}} + M_{\Sigma_c^+} - \sim \text{few MeV}$
Fast fall-apart prevented

In molecular model, existence of $\Sigma_c^+ \bar{D}^0$ molecule would imply importance of $\pi\pi$ or ρ -exchanges

Also expect 4 relatively narrow states $\Sigma_c^{*+} \bar{D}^{(*)0}$ ($\Gamma_{\Sigma_c^{*+}} \sim 17 \text{ MeV}$)

However, to confirm baryon-antimeson molecular hypothesis need to measure J^P s, find other expected decay modes with predicted rate, find $\Sigma_c^{*+} \bar{D}^{(*)0}$ states.

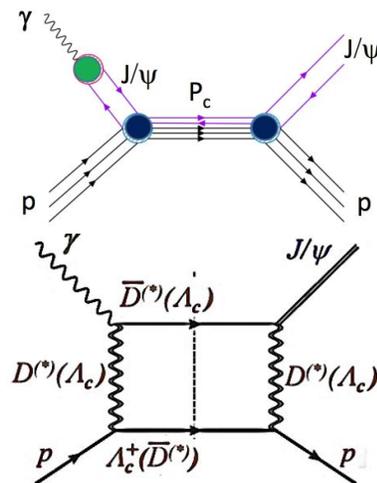
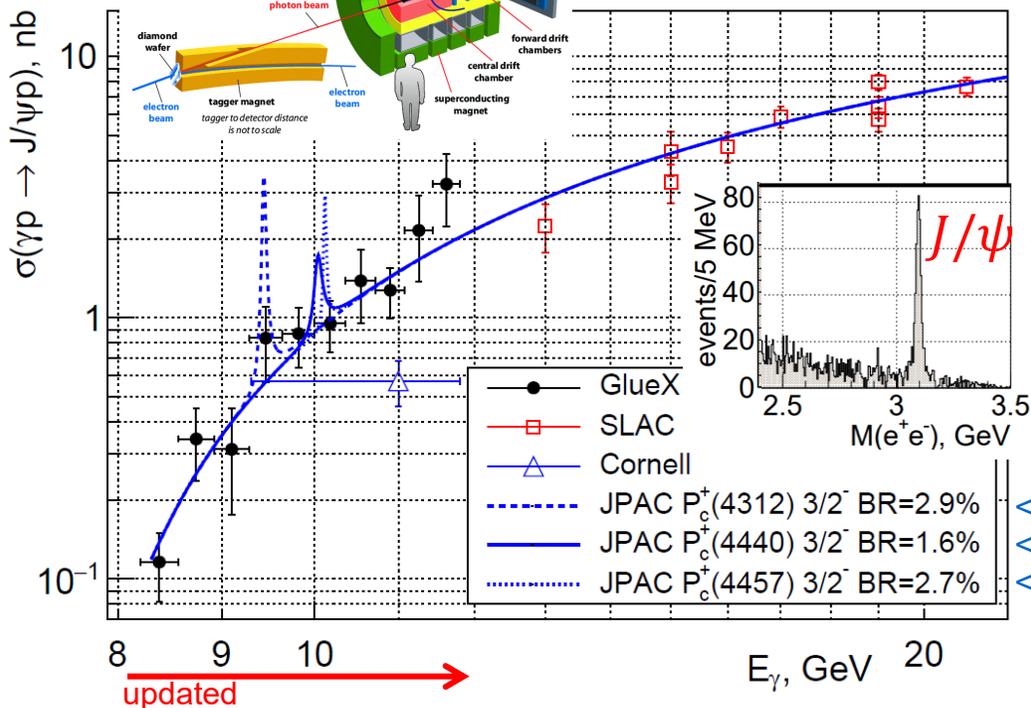
Search for P_c^+ states in photo-production at JLab



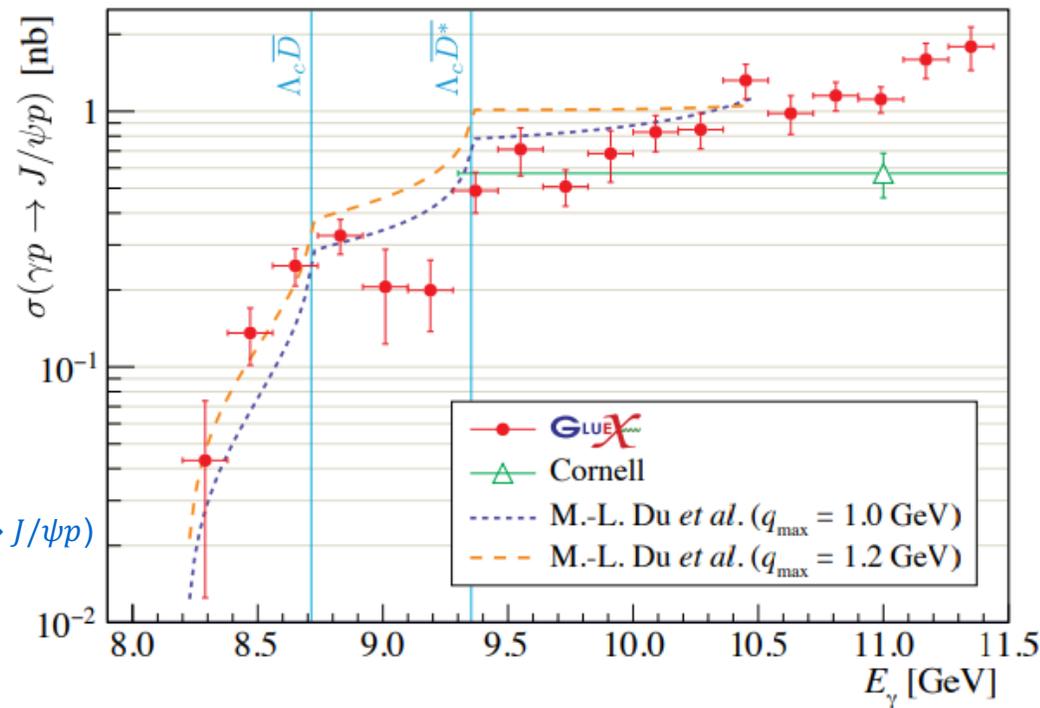
GlueX PRL 123, 072001 (2019)

GlueX, PRC 108, 025201 (2023)

Igor Starkovsky @Baryons2025 will cover this topic in detail



$\sigma_{max}(\gamma \rightarrow P_c^+) BR(P_c^+ \rightarrow J/\psi p)$
 at 90% C.L.
 < 4.6 nb
 < 1.8 nb
 < 3.9 nb



No photo-produced P_c^+ states have been observed so far. Expected cross-sections are very model dependent, thus no strong phenomenological implications.

The updated measurement points to possible effects from exchange of charmed baryon-meson pairs.

In Refs. [30-32] the partial widths of the $P_c^+ \rightarrow J/\psi p$ decays were calculated and shown to be orders of magnitude different for two pentaquark models, the hadrocharmonium and molecular models. Our upper limits on the branching fractions do not exclude the molecular model, but are an order of magnitude lower than the predictions in the hadrocharmonium scenario.

[30] M. I. Eides, V. Yu. Petrov, and M. V. Polyakov, Eur. Phys. J. **C78**, 36 (2018).
 [31] M. I. Eides and V. Yu. Petrov, Phys. Rev. **D98**, 114037 (2018).
 [32] M. I. Eides, V. Y. Petrov, and M. V. Polyakov, arXiv:1904.11616 (2019).

See also
 Sun-Young Ryu@Baryons2025 for
 P111 $\pi^- p \rightarrow J/\psi n$ proposal at J-Parc

Near-threshold & narrow: P_{cs}^0 pentaquark states?

LHCb-PAPER-2020-039,
 Science Bulletin 66, 1278 (2021),
 arXiv:2012.10380

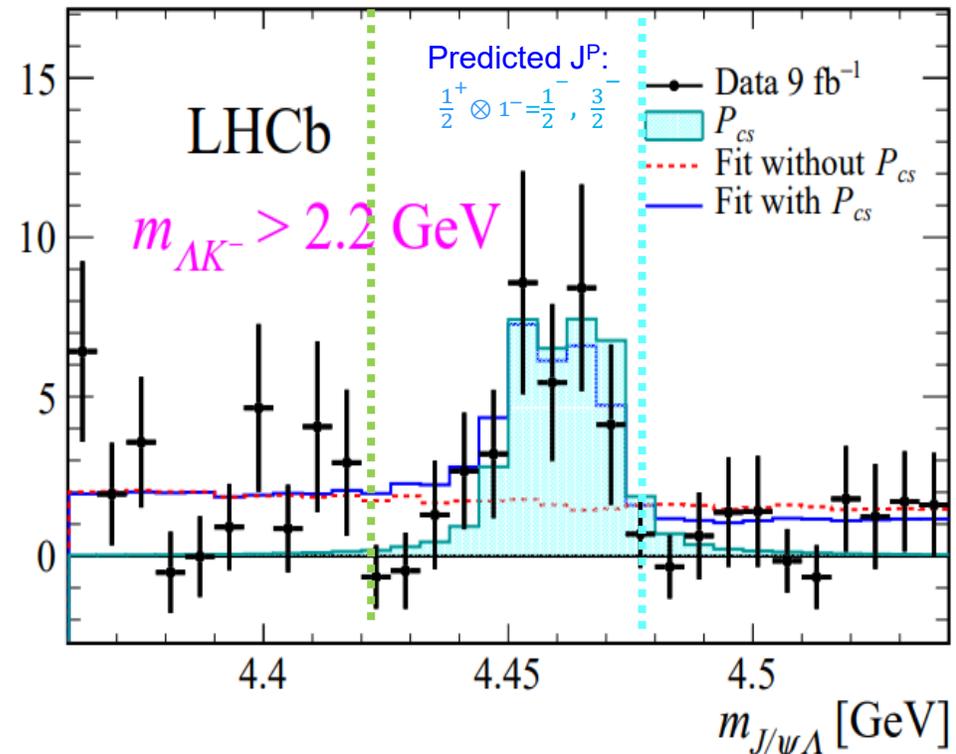
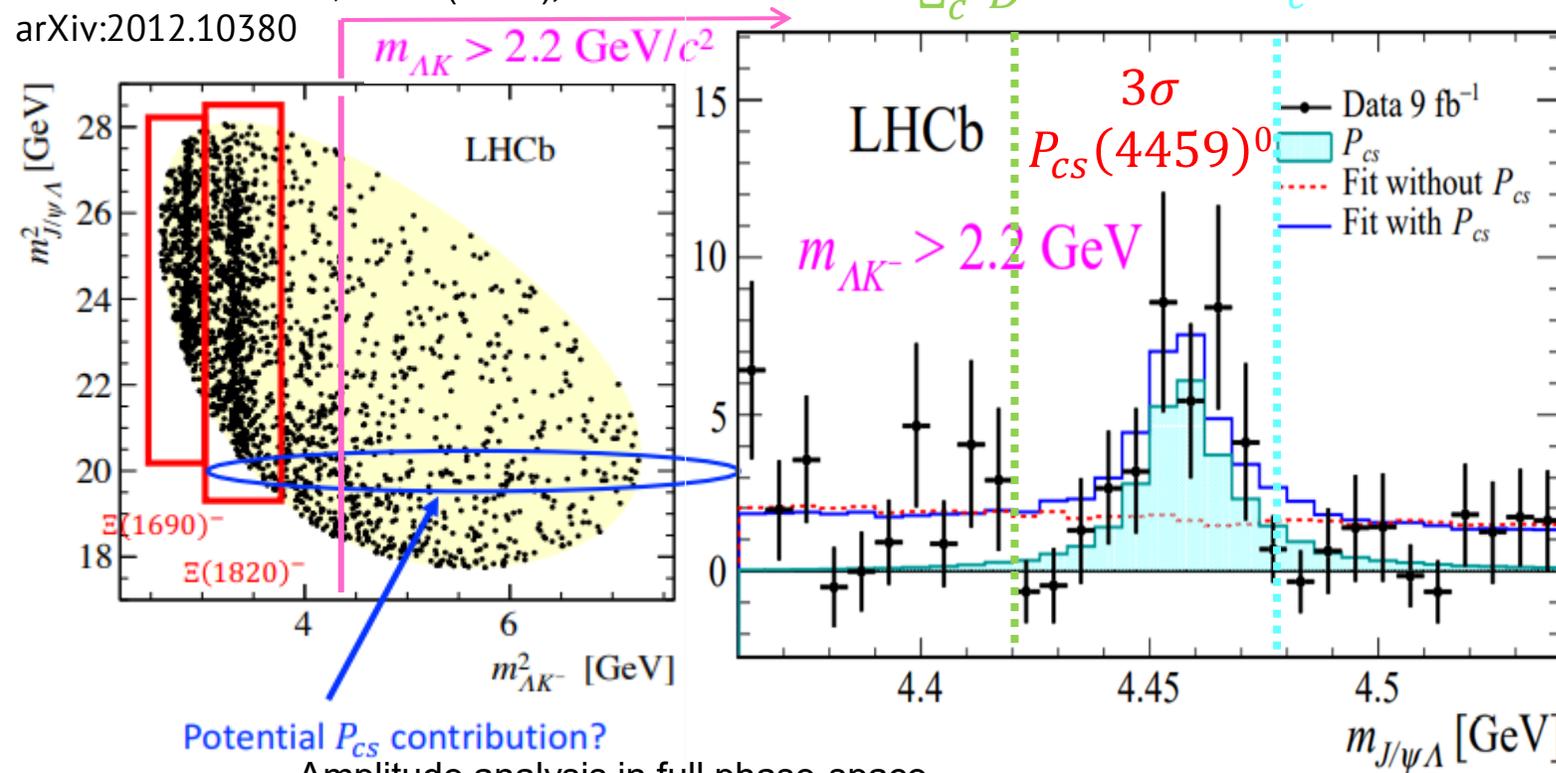
$$1.8k \Xi_b^- \rightarrow J/\psi \Lambda K^-$$

$$\Xi_c^{0'} \bar{D}^0$$

$$\Xi_c^0 \bar{D}^{*0}$$

$$\Xi_c^{0'} \bar{D}^0$$

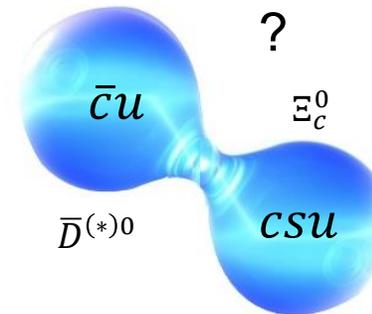
$$\Xi_c^0 \bar{D}^{*0}$$



M_0	4454.9 ± 2.7 MeV	4467.8 ± 3.7 MeV
Γ_0	7.5 ± 9.7 MeV	5.2 ± 5.3 MeV

Amplitude analysis in full phase-space

State	M_0 [MeV]	Γ_0 [MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$
$\Xi(1690)^-$	$1692.0 \pm 1.3^{+1.2}_{-0.4}$	$25.9 \pm 9.5^{+14.0}_{-13.5}$	$22.1^{+6.2+6.7}_{-2.6-8.9}$
$\Xi(1820)^-$	$1822.7 \pm 1.5^{+1.0}_{-0.6}$	$36.0 \pm 4.4^{+7.8}_{-8.2}$	$32.9^{+3.2+6.9}_{-6.2-4.1}$
$\Xi(1950)^-$	1910.6 ± 18.4	105.7 ± 23.2	$11.5^{+5.8+49.9}_{-3.5-9.4}$
$\Xi(2030)^-$	2022.8 ± 4.7	68.2 ± 8.5	$7.3^{+1.8+3.8}_{-1.8-4.1}$
NR	—	—	$35.8^{+4.6+10.3}_{-6.4-11.2}$



3 σ evidence for
 a $J/\psi \Lambda$ mass structure

one or two states?

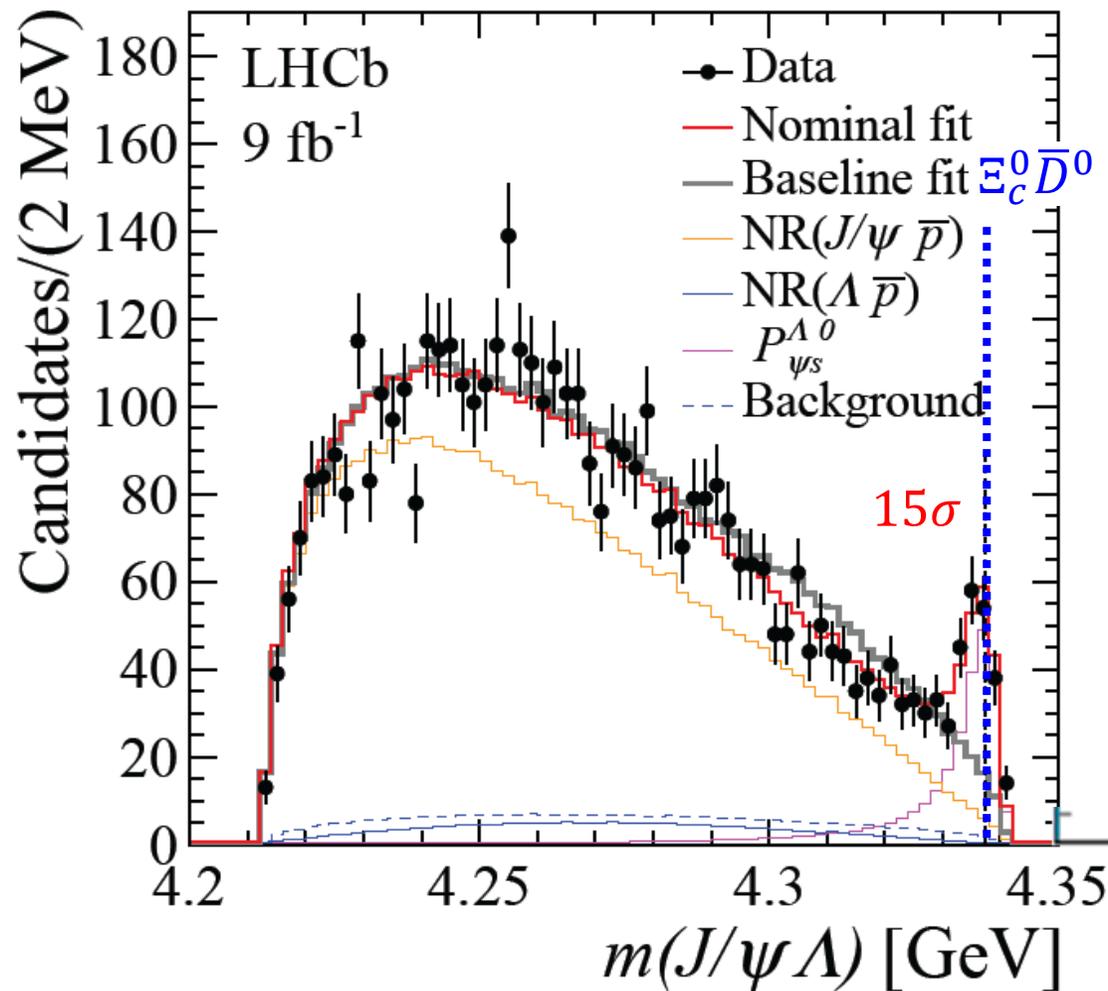
Need more data!

Another narrow P_{cs}^0 state

6D amplitude analysis of masses and decay angles

4.6k $B^- \rightarrow J/\psi \Lambda \bar{p}$

LHCb-PAPER-2022-031, arXiv:2210.10346
PRL131, 031901 (2023)



$$m_{P_{cs}^0} = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$

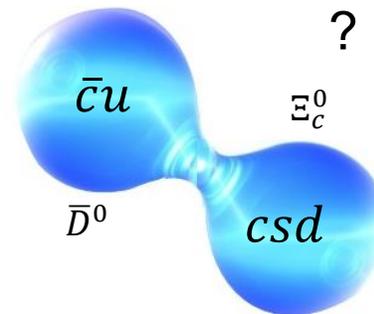
$$\Gamma_{P_{cs}^0} = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

$$J^P = \frac{1}{2}^- \text{ favored}$$

($J = \frac{3}{2}$ rejected at 3σ , $J^P = \frac{1}{2}^+$ rejected at 90% CL)

$$m_{\Xi_c^0} + m_{D^0} = 4335.3 \pm 0.3 \text{ MeV}$$

P_{cs}^0 state(s)
from $\Xi_b^- \rightarrow J/\psi \Lambda K^-$



Predicted J^P :
 $\frac{1}{2}^+ \otimes 0^- = \frac{1}{2}^-$

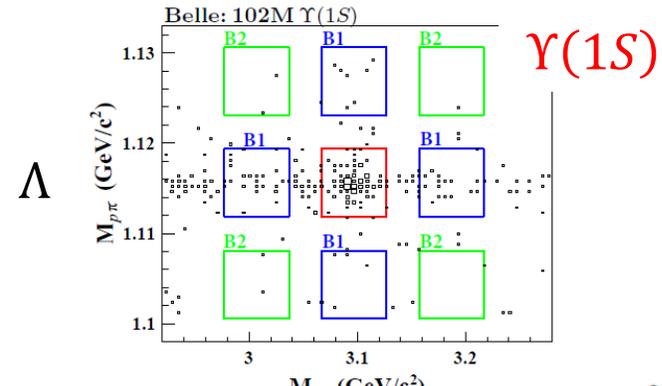
Evidence for P_{cs}^0 state in Belle data

$\Xi_c^0 \bar{D}^0$ $\Xi_c^0 \bar{D}^{*0}$

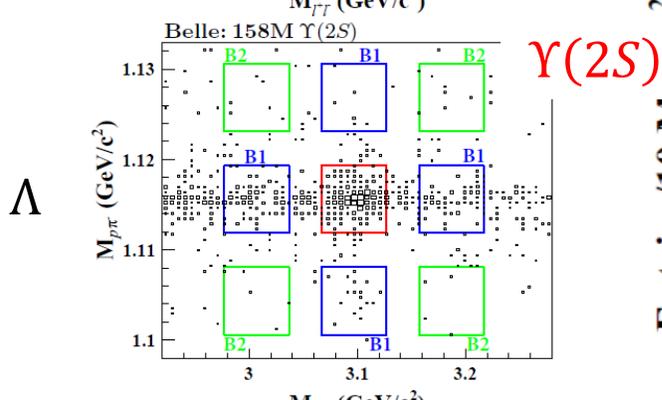
Belle arXiv:2502.09951

$$e^+e^- \rightarrow \Upsilon(1,2S) \rightarrow J/\psi\Lambda + \dots$$

$\Xi_c^0 \bar{D}^0$ $\Xi_c^0 \bar{D}^{*0}$



$\Upsilon(1S)$



$\Upsilon(2S)$

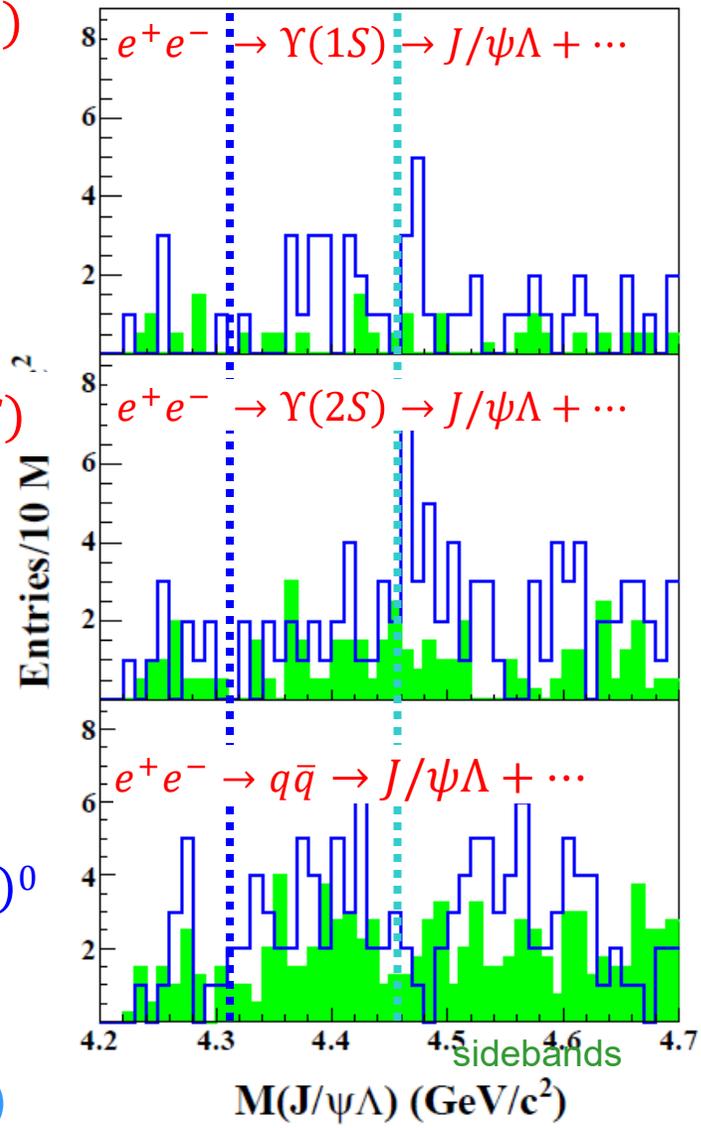
J/ψ

No evidence for $P_{cs}(4338)^0$ at the $\Xi_c^0 \bar{D}^0$ threshold

Need more data!

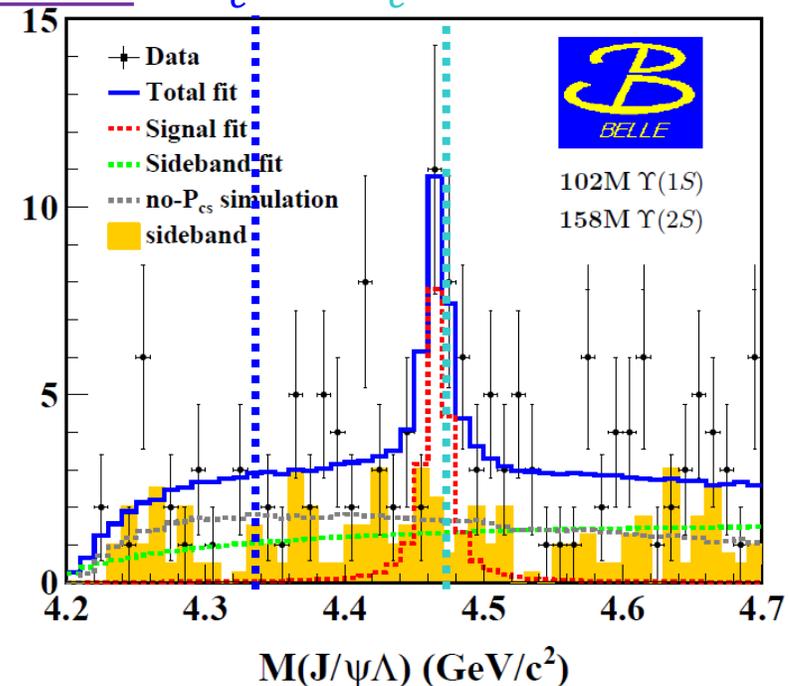
Belle JHEP 09,048 (2025)

No $P_c^+ \rightarrow J/\psi p$ signals found in $\Upsilon(1,2S)$ decays



+

Entries/10 MeV/c²



$$m_{P_{cs}^0} = 4471.7 \pm 4.8 \pm 0.6 \text{ MeV}$$

$$\Gamma_{P_{cs}^0} = 22 \pm 13 \pm 3 \text{ MeV}$$

3.8 σ local significance; 2.8 σ global [no sys.err.]

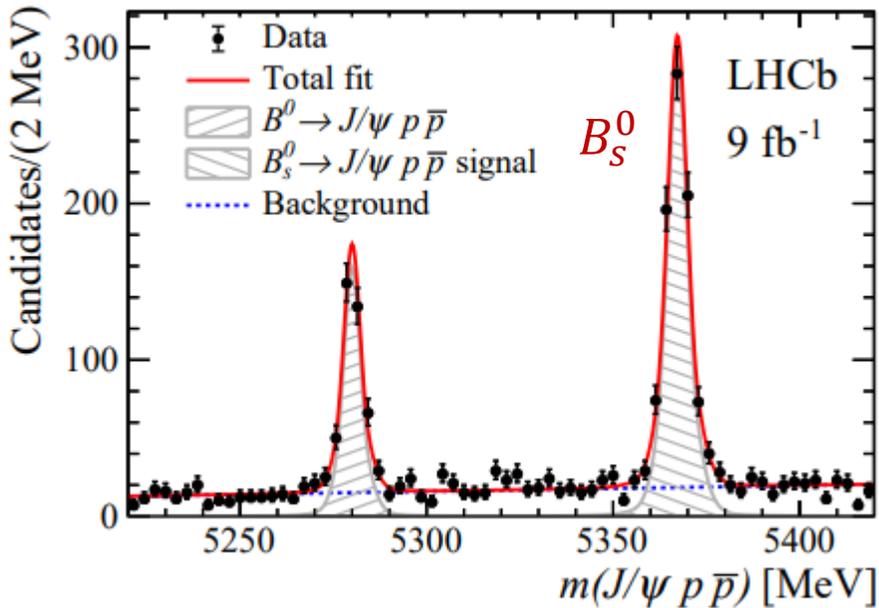
3.3 σ significance [including systematics] when constrained to LHCb's $P_{cs}(4459)^0$ [consistent with it at 1.8 σ in mass]

Coincides with $P_{cs}(4468)^0$ in 2-peak fit to LHCb data

If confirmed, important also because of new production mechanisms

Pentaquark state not near baryon-antimeson thresholds?

LHCb-PAPER-2021-018, arXiv:2108.04720, PRL 128, 062001 (2022)



- ⊕ Data
- Total fit
- Baseline fit
- ▨ NR decay
- ▨ P_c^+
- ▨ P_c^-
- ▨ Background

Significance is 3.1σ

$$m_{P_c^+} = 4337^{+7}_{-4} \pm 2 \text{ MeV}$$

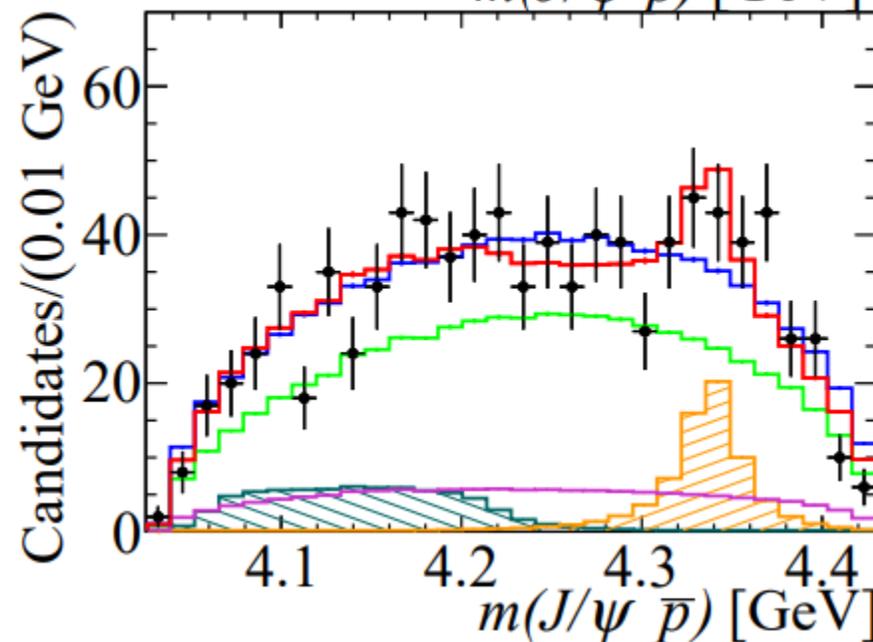
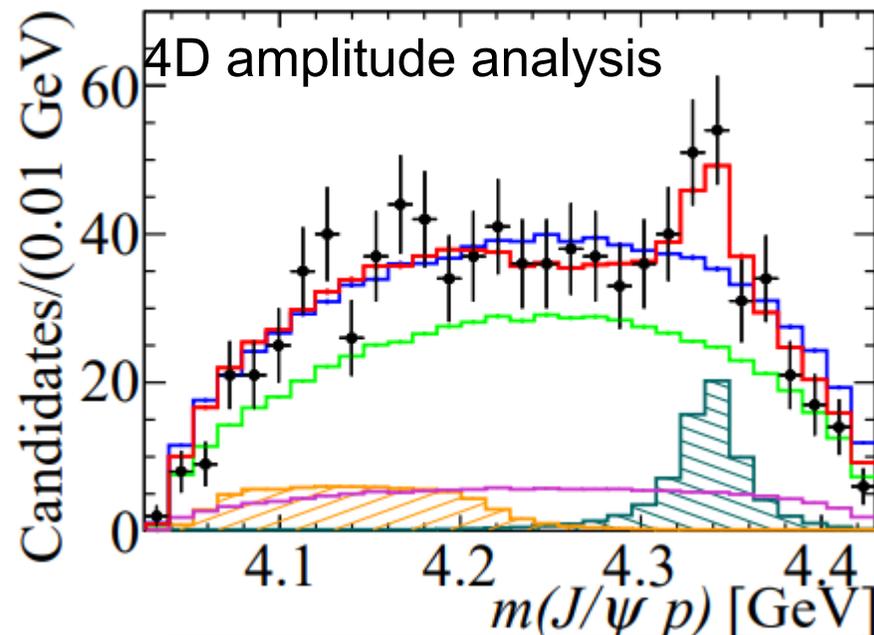
$$\Gamma_{P_c^+} = 29^{+26}_{-12} {}^{+14}_{-14} \text{ MeV}$$

Very weak evidence for claiming a new particle at random mass value.

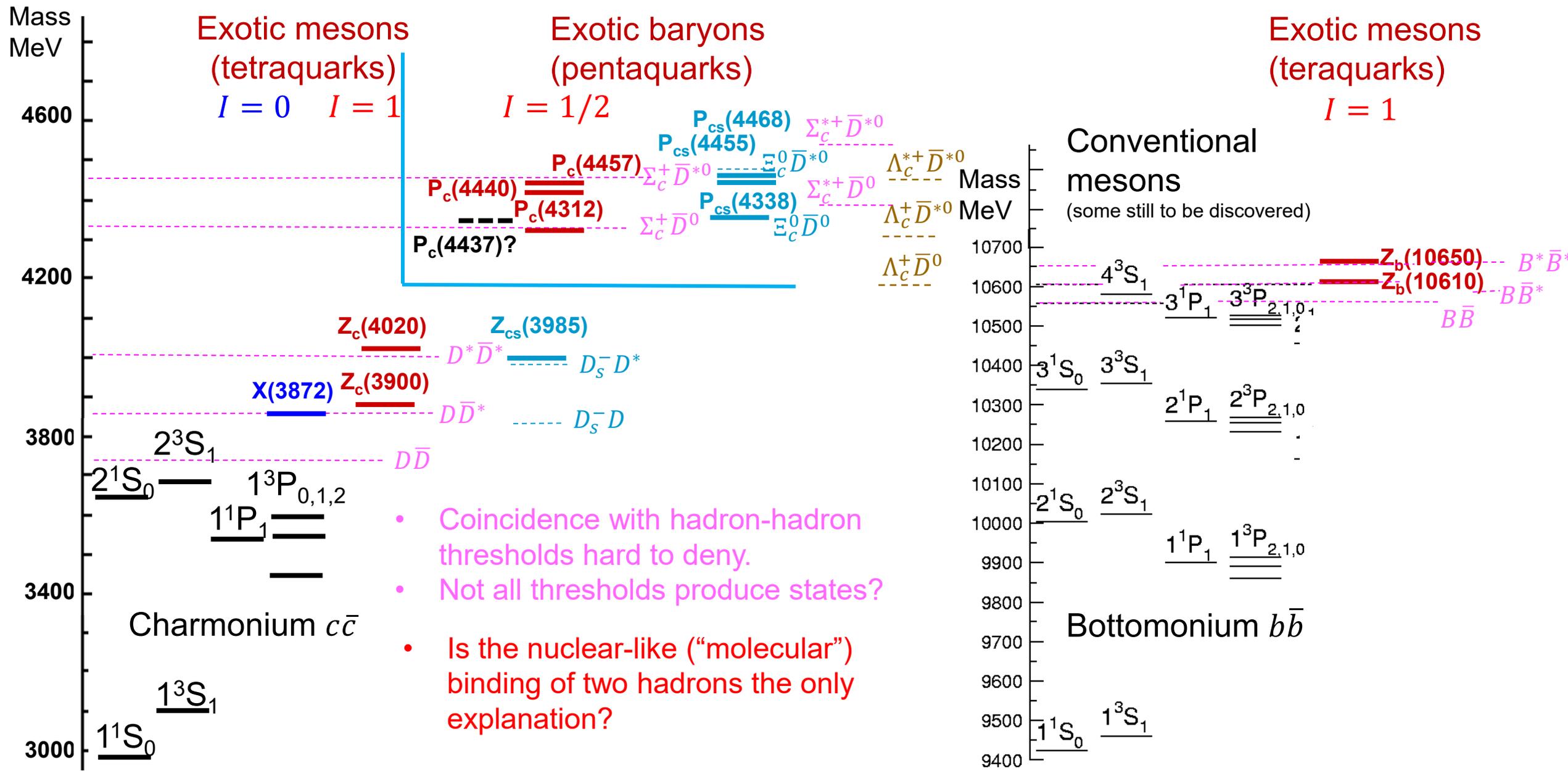
Need more data!

Significantly above (below) $\Sigma_c^+ \bar{D}^0$ ($\Sigma_c^{*+} \bar{D}^0$) thresholds

More than one mechanism to bind pentaquarks?



New period table of narrow hidden charm/bottom tetraquarks or pentaquarks

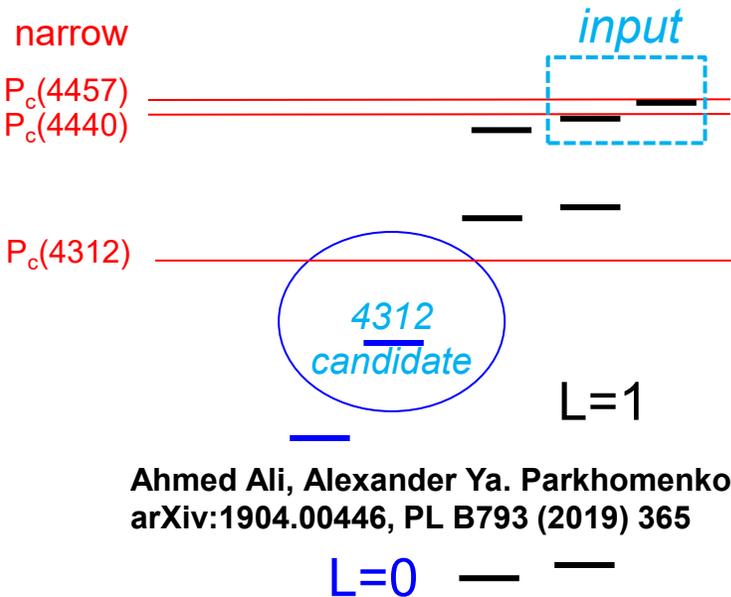


Difficulties of diquark compact tetraquark models

Diaquark model

$$((uc)_{S=1}(ud)_{S=0}\bar{c})_{L=0}$$

$$((uc)_{S=1}(ud)_{S=0}\bar{c})_{L=1}$$



Ahmed Ali, Alexander Ya. Parkhomenko
arXiv:1904.00446, PL B793 (2019) 365

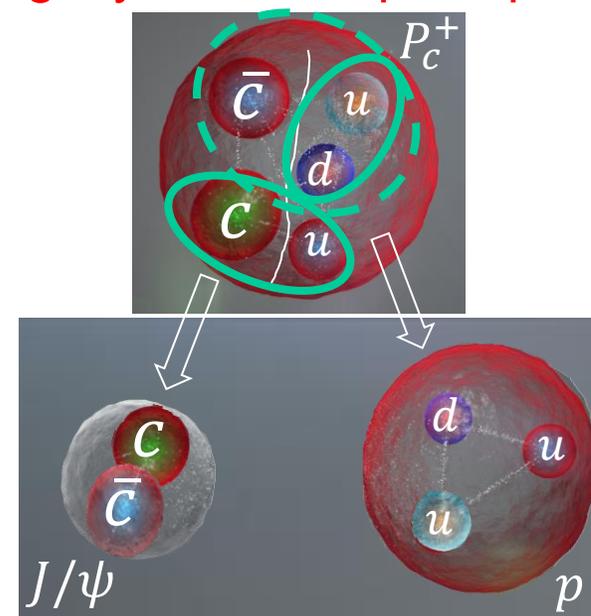
$\Delta L = 1$ splitting taken from baryons does not fit the narrow P_c states

1^-	3^-	1^+	3^+	5^+
$\frac{1}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{5}{2}$

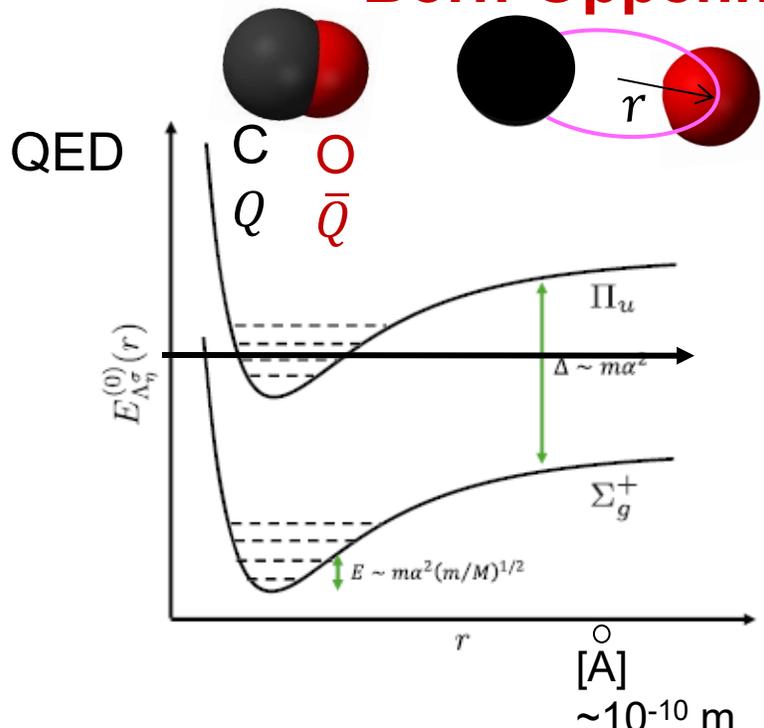
- The P_c^+ mass splitting is not reproduced
- The model predicts a large number of pentaquark states from direct color couplings which are not observed
- Coincidence with the meson-baryon thresholds not explained
- No particularly good mechanism to prevent fast fall apart (large width)

Tightly-bound diquark pentaquark

$$M_{P_c^+} = M_{J/\psi} + M_p + \sim 400\text{MeV}$$

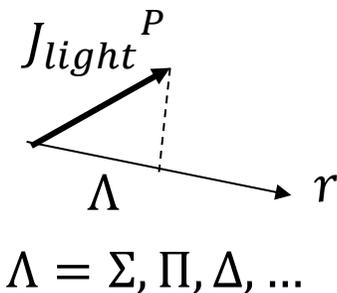


Born-Oppenheimer potentials

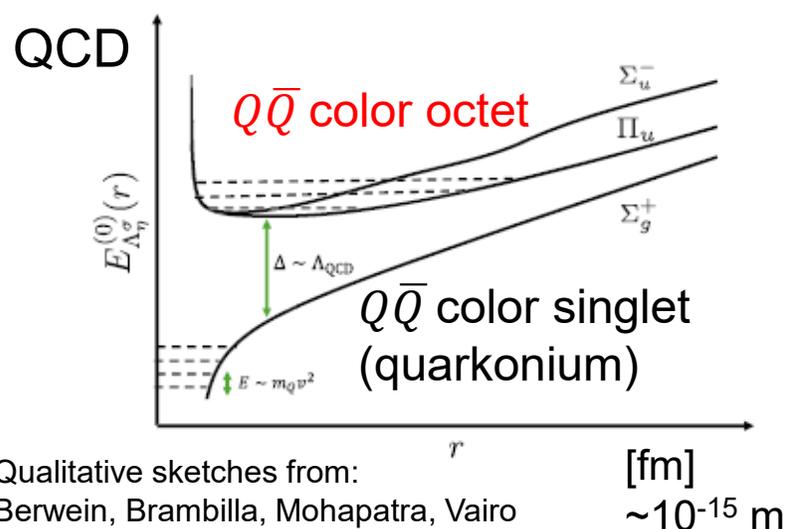


Heavy nuclei ($Q\bar{Q}$) pair slowly moving in electric (color) potential set up by fast moving light electrons (qqq) quarks

Projections of total angular momentum of electrons (light quarks) onto molecular (heavy quarks) axis



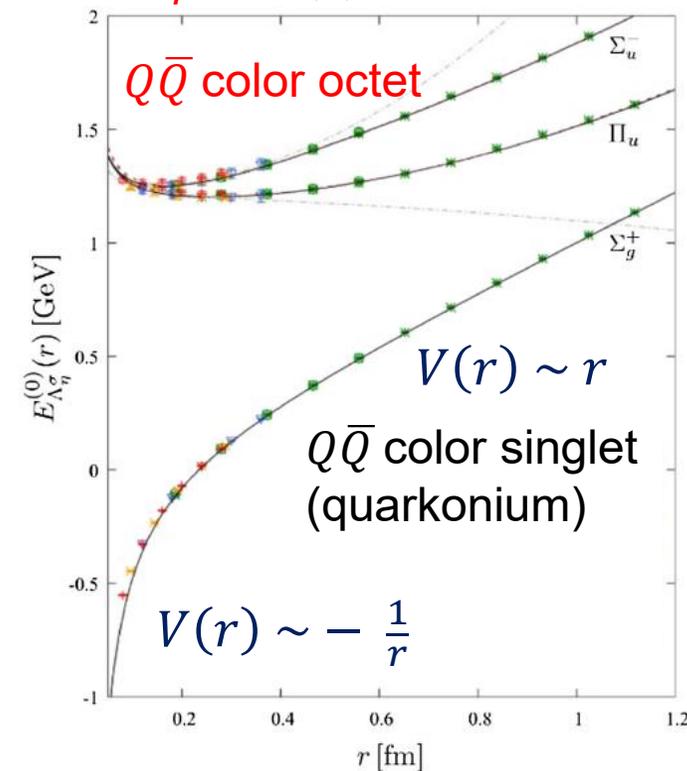
The $c\bar{c}$ pair must be in **color octet state at short distances** (repulsive $V(r)$), otherwise would be a color singlet and not feel strong forces from the light uud quarks (also easily form charmonium state and decouple)



Qualitative sketches from: Berwein, Brambilla, Mohapatra, Vairo PRD110, 094040 (2024)

Lattice QCD calculations for $Q\bar{Q}g$ hybrids
C. Schlosser, M. Wagner PRD105, 054503 (2022)

$V(r) \sim \frac{1}{r}$ $V(r) \sim r^2$



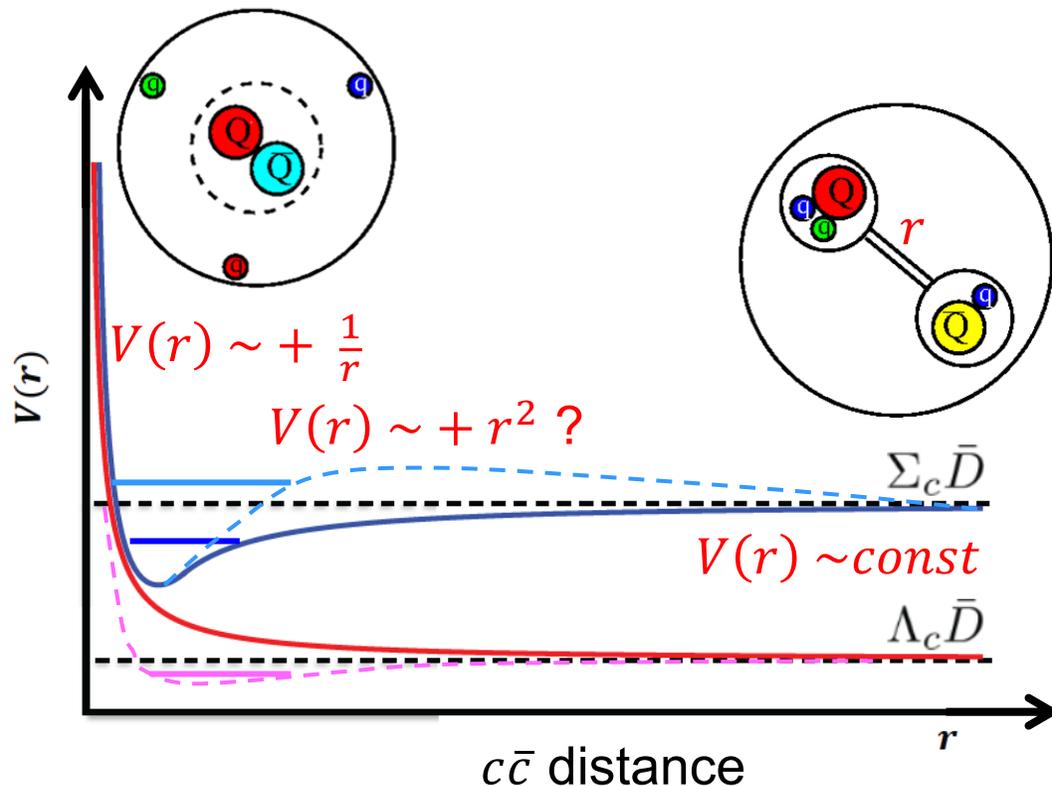
This picture stabilizes $Q\bar{Q}qqq$ pentaquarks, since decay to a quarkonium $Q\bar{Q}$ plus a light baryon qqq proceeds via emission of a relatively hard ($\sim \Lambda_{QCD}$) gluon changing octet to a singlet state. Still predict a lot of states because of the confinement.

Born-Oppenheimer models – recent developments

N. Brambilla, A. Mohapatra, A. Vairo, arxiv:2508.13050 [also: Berwein, Brambilla, Mohapatra, Vairo PRD110, 094040 (2024)]

F. Alasiri, E. Braaten, R. Bruschini, arxiv:2507.06991 [tetraquarks: Braaten, Bruschini PLB863, 139386 (2025)]

- At large $c\bar{c}$ distances light quarks will be forced to split between c and \bar{c} to form non-interacting heavy-light charmed baryon $c(ud)$ and anticharmed meson $\bar{c}u$ ($V(r) \sim \text{const}$).
- Short distance quantum numbers J_{light}^P, Λ must match long distance $J_{light B}^P \otimes J_{light \bar{M}}^P$



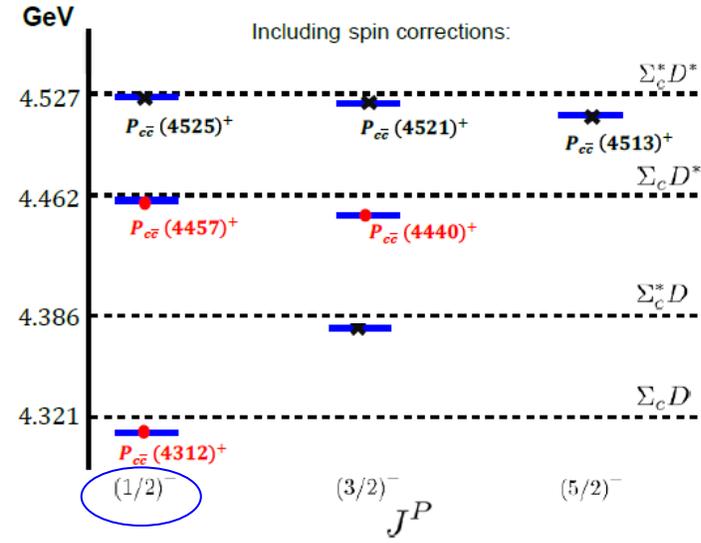
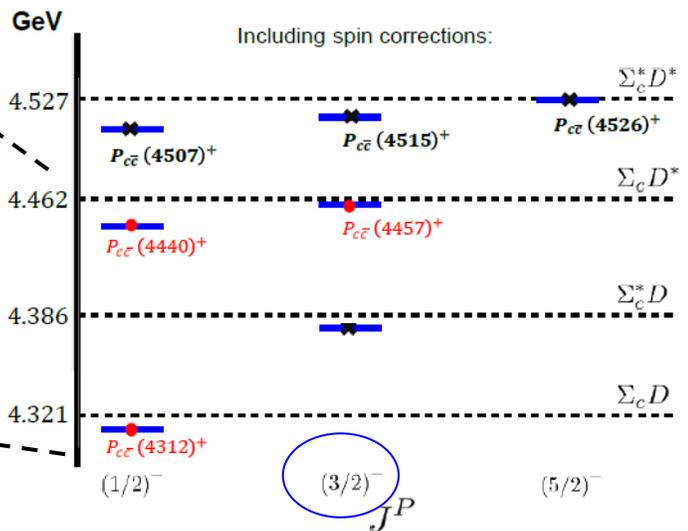
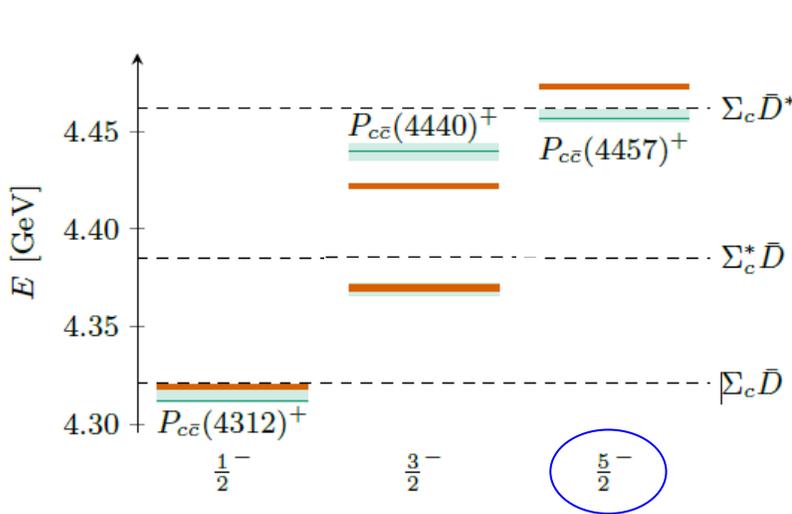
- Very attractive features:

- Explains why there is a very limited number of states
- Explains why some thresholds (e.g. $\Lambda_c \bar{D}$) may not produce bound states, while some others (e.g. $\Sigma_c \bar{D}$) do – depends on exact transition
- Explains why masses of pentaquark states are near charmed baryon-meson thresholds
- Can generate states slightly above thresholds (needed for narrow Z_b, Z_c)
- There is a mechanism to suppress fast fall apart to a charmonium and a light baryon.
- Prescription of how to do quantitative phenomenology:
 - non-relativistic Schrodinger equation: $v_Q \ll c$
 - coupling of heavy quark spins as hyperfine structure: $\Delta m_B \vec{S}_Q \cdot \vec{J}_{qq} + \Delta m_M \vec{S}_{\bar{Q}} \cdot \vec{J}_q$
- Opportunity to connect potential modelling to Lattice QCD
- Differs from naïve molecular model (colored heavy/light quarks vs neutral hadrons as constituents)

Born-Oppenheimer models vs data

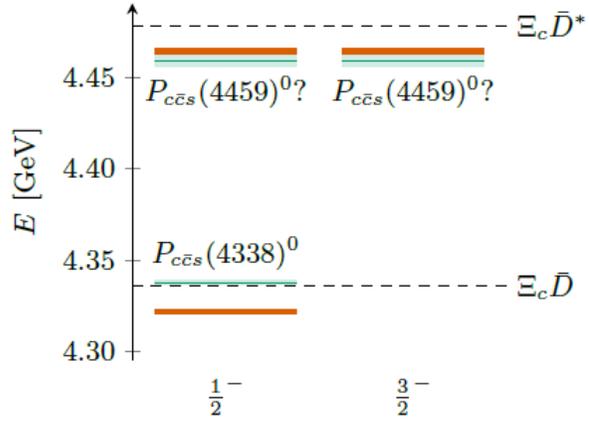
F. Alasiri, E. Braaten, R. Bruschini, arxiv:2507.06991
 (only $J_{light}^P = 3/2^+$ binds)

N. Brambilla, A. Mohapatra, A. Vairo, arxiv:2508.13050
 ($J_{light}^P = 1/2^+, 3/2^+$ bind)



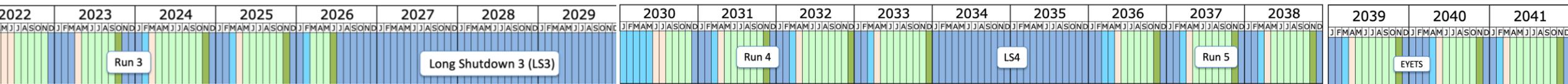
(T.S.: I removed comparisons to the broad $P_c(4380)$, which is not established experimentally)

[reproduced molecular J^P]



- The models differ in the assumptions how to match short- and long-distance behaviors, and which configurations will bind.
- **Both take input from spin-averaged measured masses (averaged differently).**
- Their predictions differ by the number of P_c^+ states (4 vs 7) and J^P of $P_c(4457)^+$
- **More data needed to sort out different scenarios.**

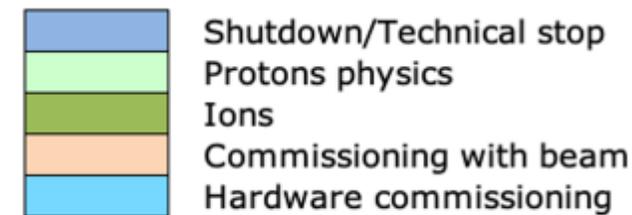
LHCb schedule and accumulated luminosity



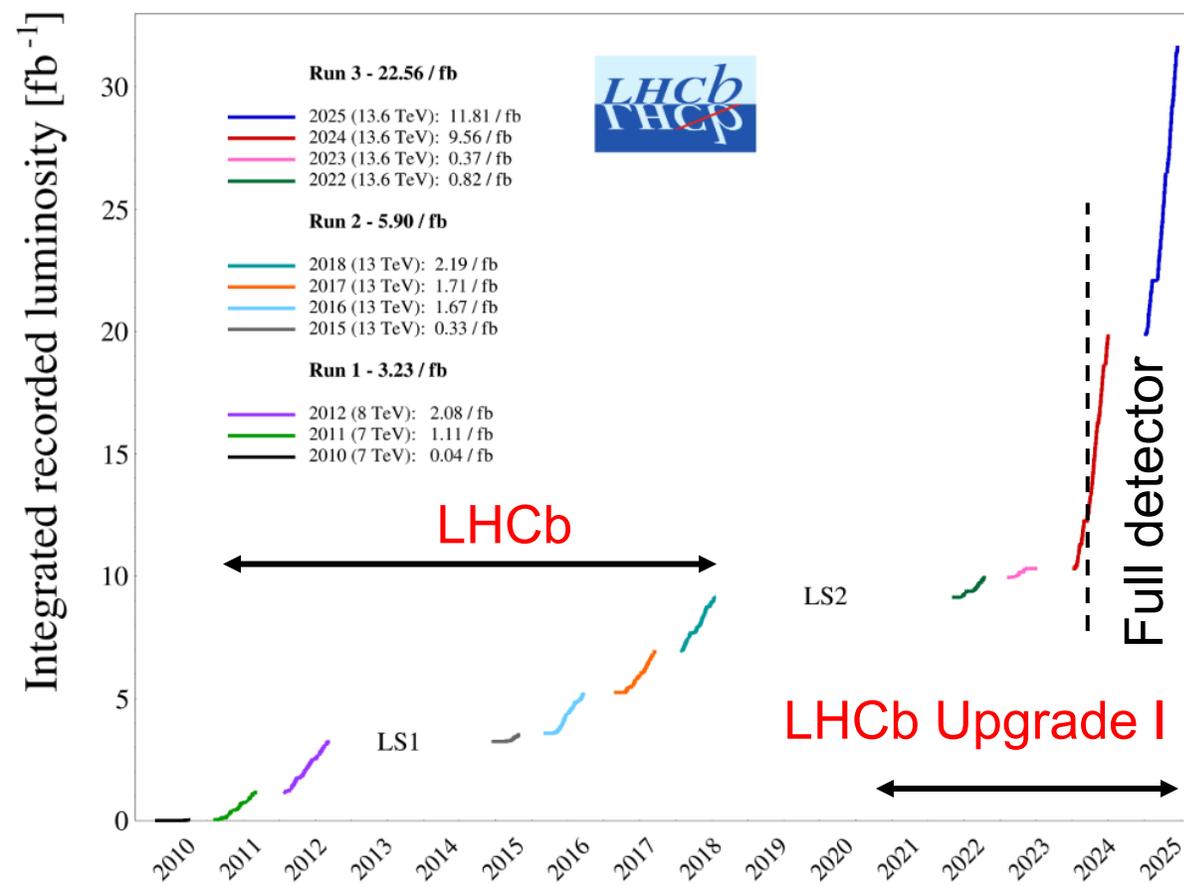
LHCb upgrade I

ATLAS/CMS upgrade

LHCb upgrade II



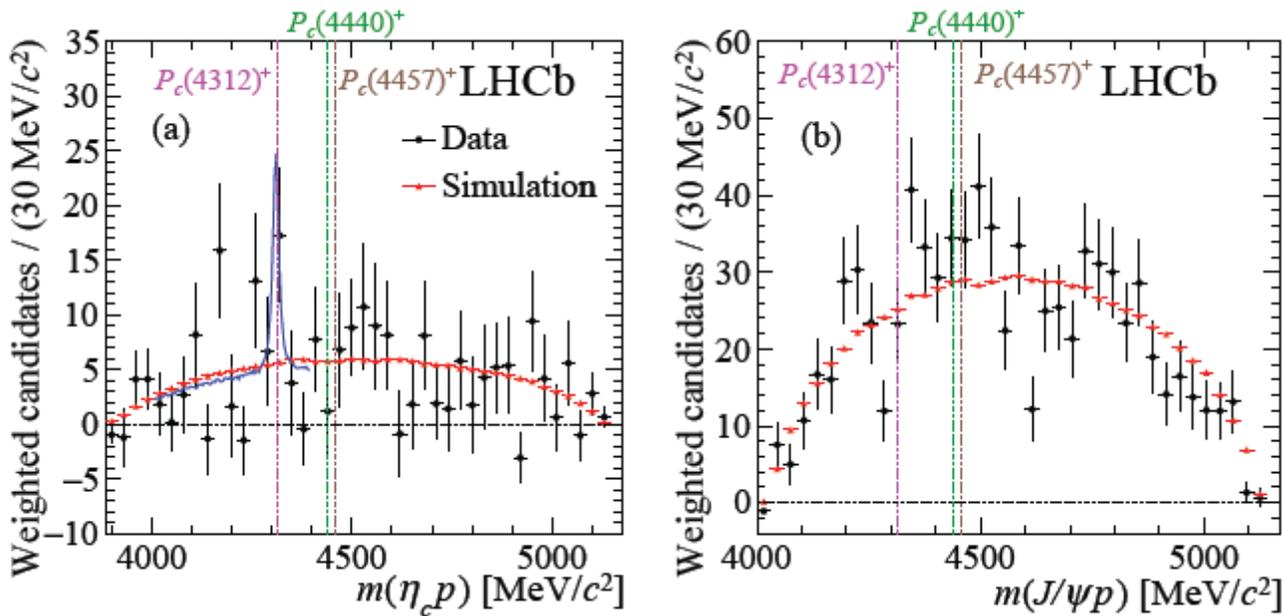
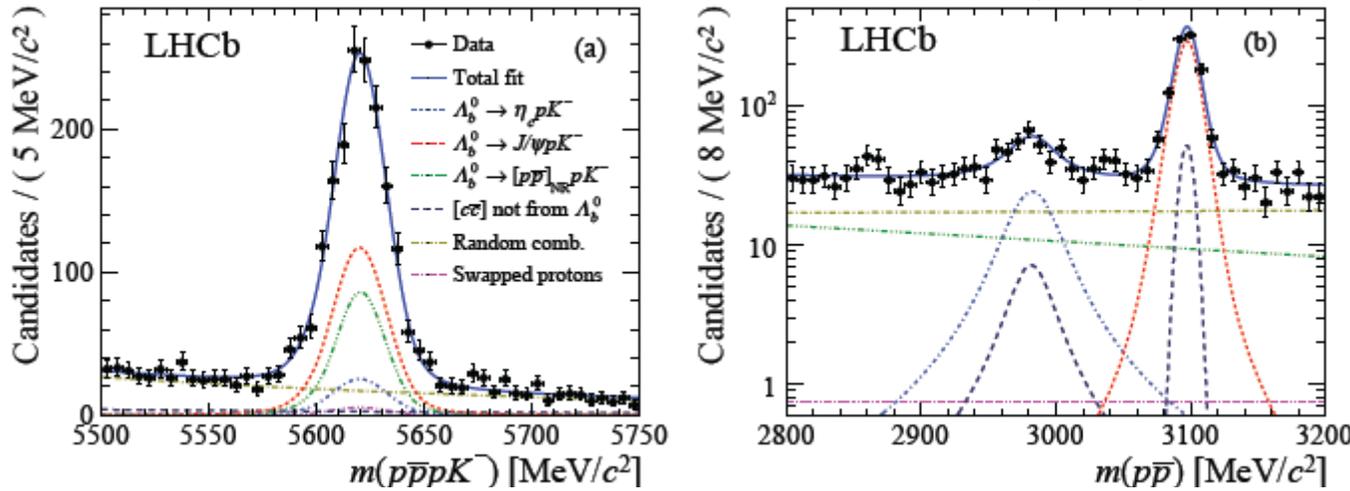
Total recorded luminosity – pp – 31.7 fb^{-1}



- LHCb
 - Run 1-2 sample **9 fb^{-1}**
- LHCb Upgrade I with full detector:
 - Run 3
 - 2024-25 **$\sim 18 \text{ fb}^{-1}$**
 - 2026 **$\sim 5 \text{ fb}^{-1} ?$**
 - Run 4 2030-33 **$\sim 35 \text{ fb}^{-1} ?$**
 - All **$> 50 \text{ fb}^{-1}$ goal**
- LHCb Upgrade II:
 - Run 5 2036-2041 **$\sim 300 \text{ fb}^{-1}$ goal**

Search for P_c^+ states in $\Lambda_b \rightarrow \eta_c(1S)pK^-$

LHCb-PAPER-2020-012 PRD 102, 112012 (2020)



No meaningful sensitivity with present statistics.

Theoretical predictions:

$$B(P_c^+ \rightarrow \eta_c(1S)p)/B(P_c^+ \rightarrow J/\psi p) \sim 0(0.1 - 5)$$

$$173 \pm 25 \text{ events } \Lambda_b \rightarrow \eta_c(1S)pK^-$$

$$804 \pm 31 \text{ events } \Lambda_b \rightarrow J/\psi pK^- \quad 5.5 \text{ fb}^{-1}$$

$$\eta_c(1S), J/\psi \rightarrow p\bar{p}$$

$$246,000 \text{ events } \Lambda_b \rightarrow J/\psi pK^- \quad 9 \text{ fb}^{-1}$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

$$\frac{B(\eta_c(1S) \rightarrow p\bar{p})}{B(J/\psi \rightarrow \mu^+ \mu^-)} \sim \frac{1}{45}$$

Additional loss $\sim 1/8$ due to hadronic vs $\mu^+ \mu^-$ triggers and p vs μ particle ID

Hadronic triggers improved in Upgrade I $\sim 2x$

Rough expectations for $\Lambda_b \rightarrow \eta_c(1S)pK^-$ yield:

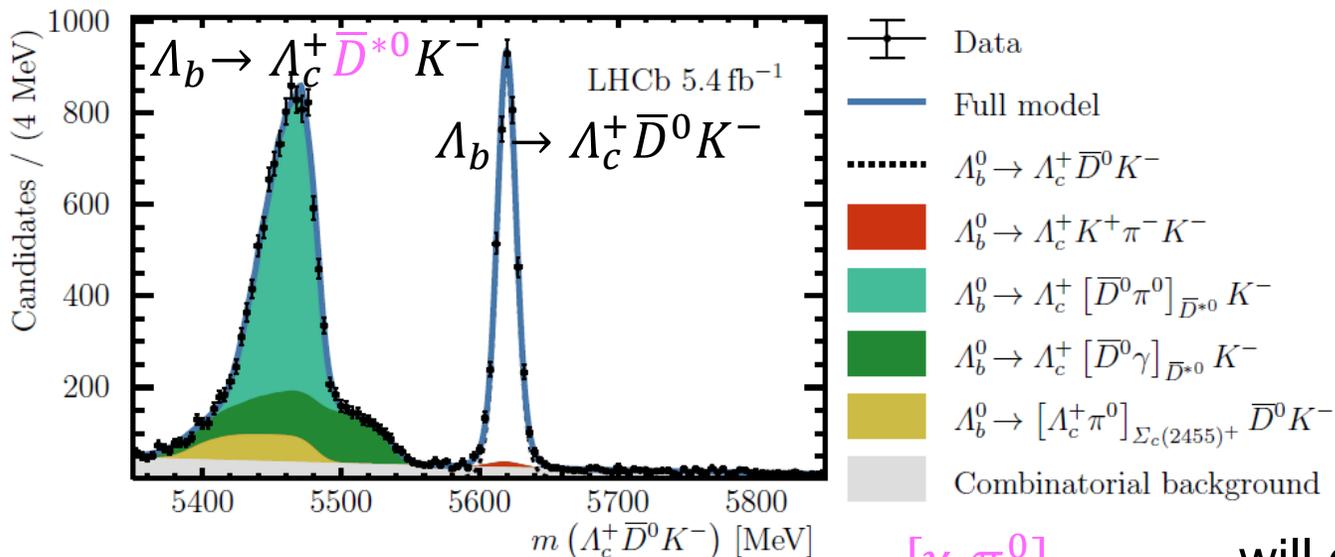
Upgrade I $50 \text{ fb}^{-1} \sim 10k$

Upgrade II $300 \text{ fb}^{-1} \sim 60k$

LHCb Upgrades will reach meaningful sensitivity!

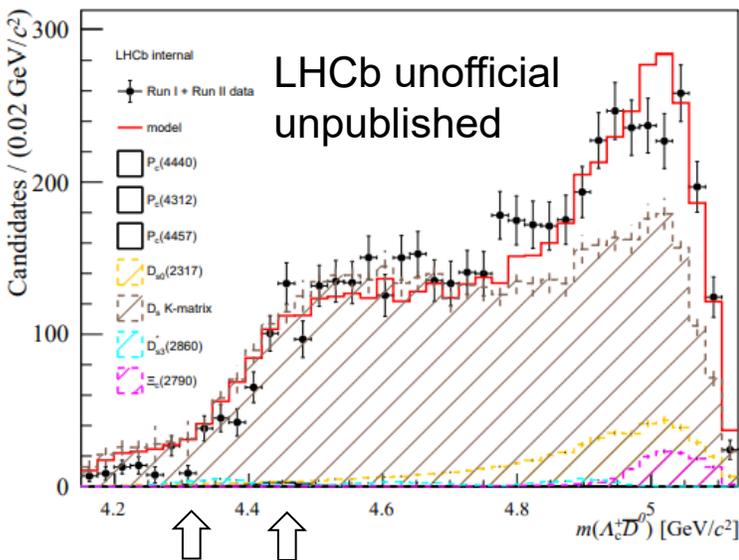
P_c^+ states in $\Lambda_b \rightarrow \Lambda_c^+ \bar{D}^{(*)0} K^-$?

LHCb-PAPER-2023-034 EPJ C84, 575 (2024)



Amplitude analysis of $\Lambda_b \rightarrow \Lambda_c^+ \bar{D}^0 K^-$
 A. Piucci, PhD thesis, Heidelberg U., 2019.

$[\gamma, \pi^0]_{\text{undetected}}$ will dilute sensitivity to $P_c^+ \rightarrow \Lambda_c^+ \bar{D}^{*0}$



No evidence for $P_c^+ \rightarrow \Lambda_c^+ \bar{D}^0$ was found

Theoretical predictions:

$$B(P_c^+ \rightarrow \Lambda_c^+ \bar{D}^{(*)0})/B(P_c^+ \rightarrow J/\psi p) \sim O(0 - 10)$$

In many models zero or very small

$$4,010 \pm 70 \text{ events } \Lambda_b \rightarrow \Lambda_c^+ \bar{D}^0 K^- \quad 5.4 \text{ fb}^{-1}$$

$$10,560 \pm 300 \text{ events } \Lambda_b \rightarrow \Lambda_c^+ \bar{D}^{*0} K^-$$

$$\Lambda_c^+ \rightarrow p K^- \pi^+$$

$$\bar{D}^0 \rightarrow K^+ \pi^-$$

$$\bar{D}^{*0} \rightarrow \bar{D}^0 [\gamma, \pi^0]_{\text{undetected}}$$

$$246,000 \text{ events } \Lambda_b \rightarrow J/\psi p K^- \quad 9 \text{ fb}^{-1}$$

$$J/\psi \rightarrow \mu^+ \mu^-$$

$$\frac{B(\Lambda_c^+ \rightarrow p K^- \pi^+) B(\bar{D}^0 \rightarrow K^+ \pi^-)}{B(J/\psi \rightarrow \mu^+ \mu^-)} \sim \frac{1}{24}$$

Additional large losses due to Hadronic vs $\mu^+ \mu^-$ triggers and 6 vs 4 charged tracks

Rough expectations for $\Lambda_b \rightarrow \Lambda_c^+ \bar{D}^0 K^-$ yield:

Upgrade I 50 fb⁻¹ ~70k

Upgrade II 300 fb⁻¹ ~440k

LHCb Upgrades will reach meaningful sensitivity!

P_c⁺ states in $\Lambda_b \rightarrow \Sigma_c^{(*)++} \bar{D}^{(*)-} K^-$?

LHCb-PAPER-2023-044 PRD110, L031104 (2024)

$B(P_c^+ \rightarrow \Sigma_c^{(*)++} \bar{D}^{(*)-})/B(P_c^+ \rightarrow J/\psi p)$
Ought to be large for P_c⁺ states

above $\Sigma_c^{(*)++} \bar{D}^{(*)-}$ thresholds

480 ± 25 events $\Lambda_b \rightarrow \Sigma_c^{++} \bar{D}^- K^-$ 6 fb⁻¹

279 ± 26 events $\Lambda_b \rightarrow \Sigma_c^{*++} \bar{D}^- K^-$

100 % $\Sigma_c^{(*)++} \rightarrow \Lambda_c^+ \pi^+$

$\Lambda_c^+ \rightarrow p K^- \pi^+$

$\bar{D}^- \rightarrow K^+ \pi^- \pi^-$

$$\frac{B(\Lambda_c^+ \rightarrow p K^- \pi^+) B(\bar{D}^- \rightarrow K^+ \pi^- \pi^-)}{B(J/\psi \rightarrow \mu^+ \mu^-)} \sim \frac{1}{10}$$

243 ± 17 events $\Lambda_b \rightarrow \Sigma_c^{++} \bar{D}^{*-} K^-$ 9 fb⁻¹

116 ± 15 events $\Lambda_b \rightarrow \Sigma_c^{*++} \bar{D}^{*-} K^-$

$$\frac{B(\Lambda_c^+ \rightarrow p K^- \pi^+) B(\bar{D}^{*-} \rightarrow \bar{D}^0 \pi^-) B(\bar{D}^0 \rightarrow K^+ \pi^-)}{B(J/\psi \rightarrow \mu^+ \mu^-)} \sim \frac{1}{36}$$

$\bar{D}^{*-} \rightarrow \bar{D}^0 \pi^-$

$\bar{D}^0 \rightarrow K^+ \pi^-$

246,000 events $\Lambda_b \rightarrow J/\psi p K^-$
 $J/\psi \rightarrow \mu^+ \mu^-$

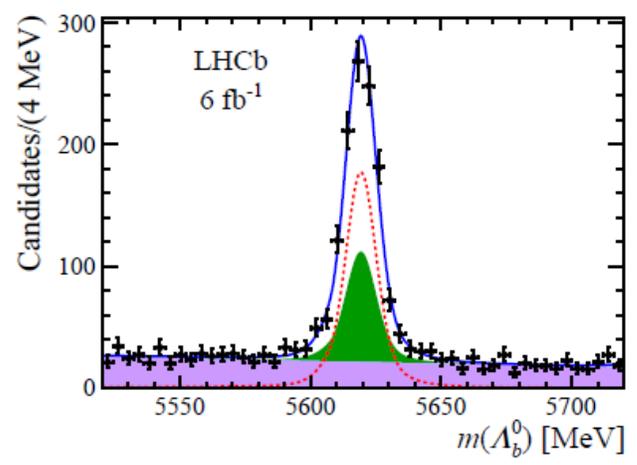
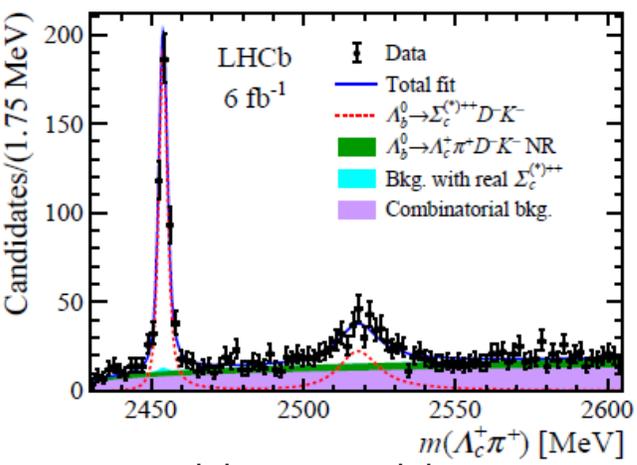
Additional large losses due to Hadronic vs $\mu^+ \mu^-$ triggers and 7 vs 4 charged tracks

Rough expectations for $\Lambda_b \rightarrow \Lambda \Sigma_c^{++} \bar{D}^- K^-$ yield:

Upgrade I 50 fb⁻¹ ~8k

Upgrade II 300 fb⁻¹ ~48k

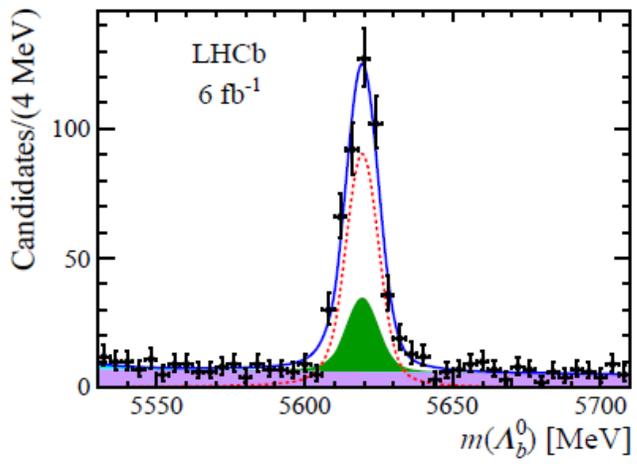
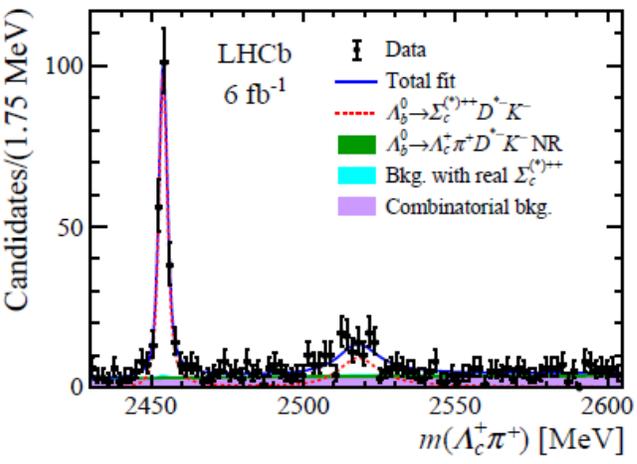
LHCb Upgrades will reach meaningful sensitivity!



Σ_c^{++}

Σ_c^{*++}

Λ_b



No meaningful sensitivity with present statistics

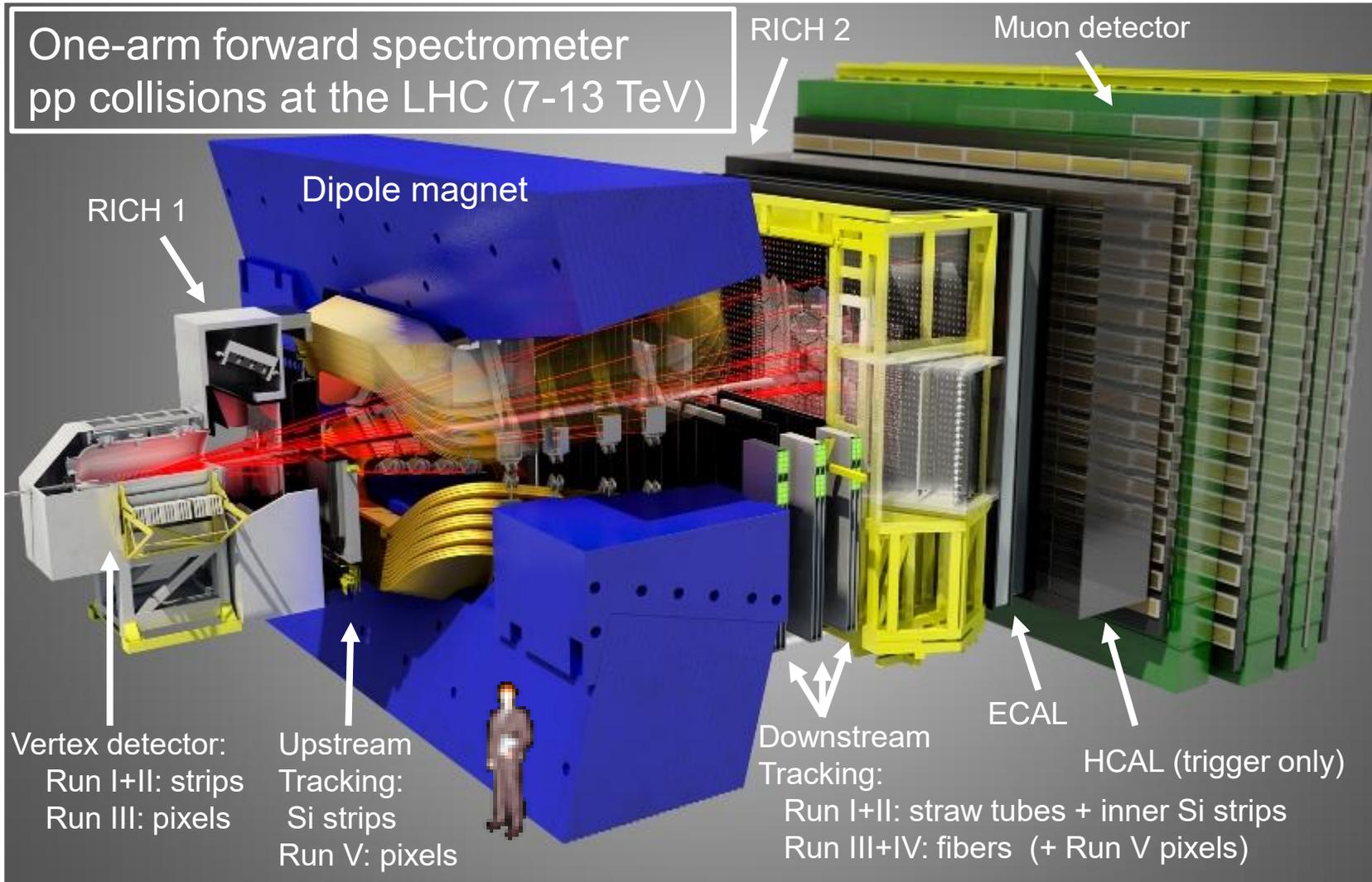
LHCb-PAPER-2023-018, PRD 110, 032001 (2024) 5.7 fb⁻¹

No promptly produced $P_c^+ \rightarrow \Lambda_c^+ \bar{D}, \Sigma_c \bar{D}$ signals have been found

- After 10 years since the discovery of hidden-charm pentaquarks by LHCb, more Run 1-2 data confirmed the existence of hidden-charm pentaquarks but also clarified their nature.
- **By now, it is firmly established that there are 3 narrow $P_{c\bar{c}}^+$ pentaquarks decaying to $J/\psi p$ with masses at or below the $\Sigma_c^+ \bar{D}^0(1)$ and $\Sigma_c^+ \bar{D}^{*0}(2)$ thresholds. A highly significant narrow hidden-charm and strange $P_{c\bar{c}s}^0$ pentaquark was also observed by LHCb in decay to $J/\psi \Lambda$ with the mass at the $\Xi_c^0 \bar{D}^0$ threshold.**
- There is a good evidence for 1-2 additional narrow $P_{c\bar{c}s}^0$ states decaying to $J/\psi \Lambda$ with masses just below the $\Xi_c^0 \bar{D}^{*0}$ threshold from LHCb and Belle (produced in strong decays of $b\bar{b}$!). These observations require confirmation and clarification with more data.
- There may be a relatively narrow $P_{c\bar{c}}^+ \rightarrow J/\psi p$ state in between the $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^{*+} \bar{D}^0$ mass thresholds, but its significance is marginal and badly needs verification with more data.
- **Emerging pattern of narrow hidden-charm pentaquarks with masses near charmed baryon – anticharmed meson thresholds, is reminiscent of the several narrow hidden-charm and hidden-bottom tetraquarks observed near charmed meson – anticharmed meson thresholds.**
- This pattern fits the predictions of “molecular” model, and not compact states made from heavy-light diquark models.
- **However, models based on Born-Oppenheimer approximation describing heavy hidden-charm quark pair as being in repulsive color-octet state at short distances, transitioning to a pair of non-interacting charmed hadron – anticharmed hadron pairs also reproduce the observed pattern of states, and offer more attractive phenomenology with connection to the fundamental QCD.**
- Expect more of narrow pentaquark states near baryon-meson thresholds.
- So far, all evidence at LHC via weak decays of b –quark hadrons: $b \rightarrow c(\bar{c}s)$. No prompt production of pentaquarks at LHC established so far. This could be a gateway for observation of pentaquarks in different heavy quark configurations in the future (lower cross-sections, higher backgrounds). Doubly-charmed baryons, super-narrow $T_{cc}(3875)^+ \rightarrow D^0 D^0 \pi^+$ and broader $T_{c\bar{c}c\bar{c}} \rightarrow \psi\psi$ tetraquarks have been discovered in prompt $p\bar{p}$ production.
- If broader pentaquark states exist is still an open question. Good evidence for broad tetraquarks exist.
- **This field is still strongly data driven (one of the last frontiers within the SM?). More data (some already recorded!) will allow to develop this phenomenology further.**

BACKUP SLIDES

LHCb detector



- First hadron-collider experiment optimized to heavy flavor (b,c-quarks) physics
- Run I 2011-2012 3 fb⁻¹ of data
- Run II 2015-2018 6 fb⁻¹ of data
- **LHCb Upgrade Run III+IV: 2024-33**
 - Fully software trigger at 40 MHz; luminosity $4 \times 10^{32} \rightarrow 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$; $9 \rightarrow 50 \text{ fb}^{-1}$
 - Finer segmentation of tracking detectors to deal with 5 times higher pile-up (1.5 \rightarrow 5.3 visible interactions per crossing)
- **LHCb Upgrade II (~2036-41, Run V):**
 - Further luminosity upgrade; $\rightarrow 1\text{-}2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$; $\rightarrow 300 \text{ fb}^{-1}$
 - Need timing in tracking detectors and finer segmentation to deal with ~ 40 visible interactions per crossing

Status of broad $P_c(4380)^+$: defunct

84. Pentaquarks

Revised March 2024 by M. Karliner (Tel Aviv U.) and T. Skwarnicki (Syracuse U.).

The fit chosen by the LHCb for the central mass and width values is displayed in Fig. 84.2. The $P_{c\bar{c}}(4312)^+$ state (formerly known as $P_c(4312)^+$) peaks right below the $\Sigma_c^+ \bar{D}^0$ threshold and has statistical significance over 7.6σ . The $P_{c\bar{c}}(4457)^+$ state peaks right below the $\Sigma_c^+ \bar{D}^{*0}$ threshold, while the $P_{c\bar{c}}(4440)^+$ state peaks about 20 MeV below it. The significance of the two-peak versus one-peak hypothesis for the 4450 MeV structure is over 5.4σ , rendering the single peak interpretation of this region obsolete. The six-dimensional amplitude analysis reported in Ref. [8], which in addition to the structure near 4450 MeV, provided also evidence for the broad $P_{c\bar{c}}(4380)^+$ state, is obsolete since it used the single $P_{c\bar{c}}(4450)^+$ state and it lacked the $P_{c\bar{c}}(4312)^+$ state. Furthermore, it used the helicity formalism in which the half-integer spin of the proton was not aligned properly between the different Λ_b^0 decay chains [11, 12]. The newer one-dimensional analysis by LHCb [10] was not sensitive to wide $P_{c\bar{c}}^+$ states. The LHCb result from the six-dimensional amplitude analysis of the Cabibbo suppressed channel $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ [13], which contains a statistically marginal evidence for the sum of the $P_{c\bar{c}}^+$ and the $T_{c\bar{c}1}^-$ (formerly known as $Z_c(4200)^-$) contributions, took extensive input from Ref. [8] and, like the $P_{c\bar{c}}(4380)^+$ state, should be treated with caution until the both amplitude analyses are completed on the enlarged data sets with the modified helicity formalism.

S. Navas *et al.* (Particle Data Group), Phys. Rev. D **110**, 030001 (2024)

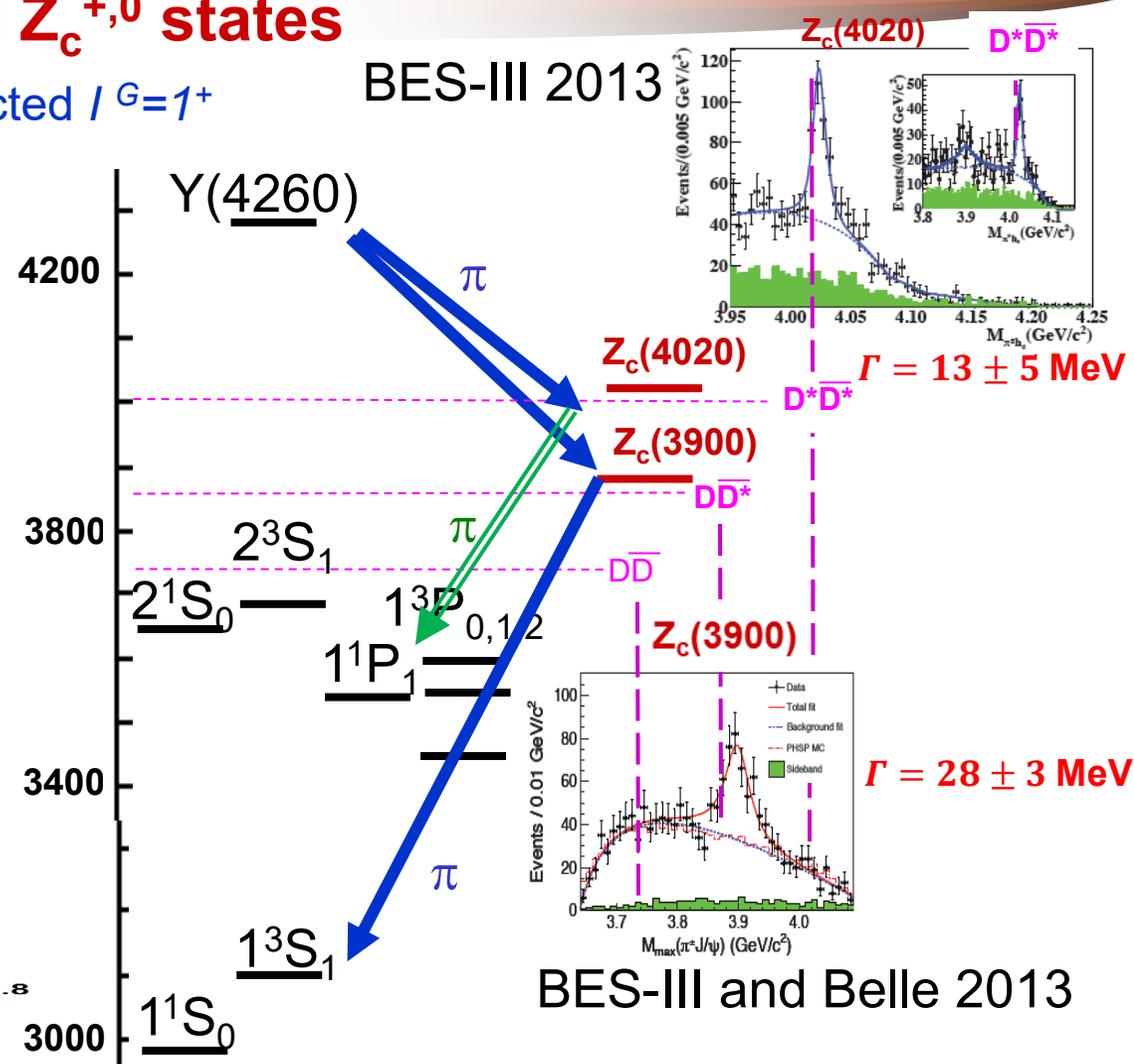
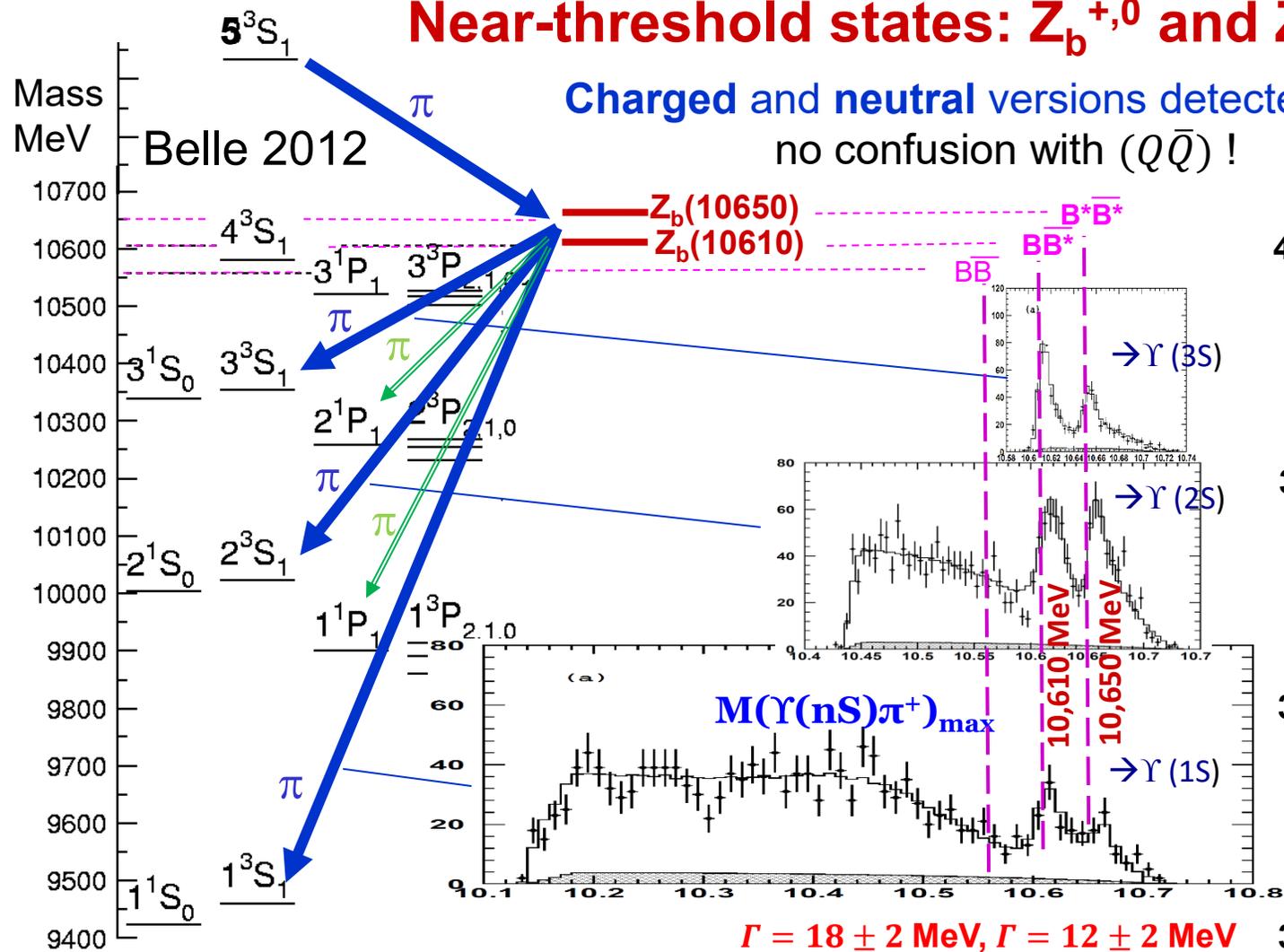
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At this point we don't know if broad $P_{c\bar{c}}$ states exist

Near-threshold states: $Z_b^{+,0}$ and $Z_c^{+,0}$ states

Charged and neutral versions detected / $G=1^+$

no confusion with $(Q\bar{Q})$!



- Near charmed meson – anticharmed meson thresholds, relatively narrow, large fall-apart branching fractions, $J^P=1^+$.
- Molecular states $B\bar{B}^*$, $B^*\bar{B}^*$, $D\bar{D}^*$, $D^*\bar{D}^*$? (No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange).
- The states actually peak a few MeV above the thresholds. Compact tetraquark states $(q\bar{q}c\bar{c})$?