Overview of Heavy Quark Exotics

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Exotic hadrons ≡ not $q\bar{q}, qqq$

Concentrate on the most recent discoveries

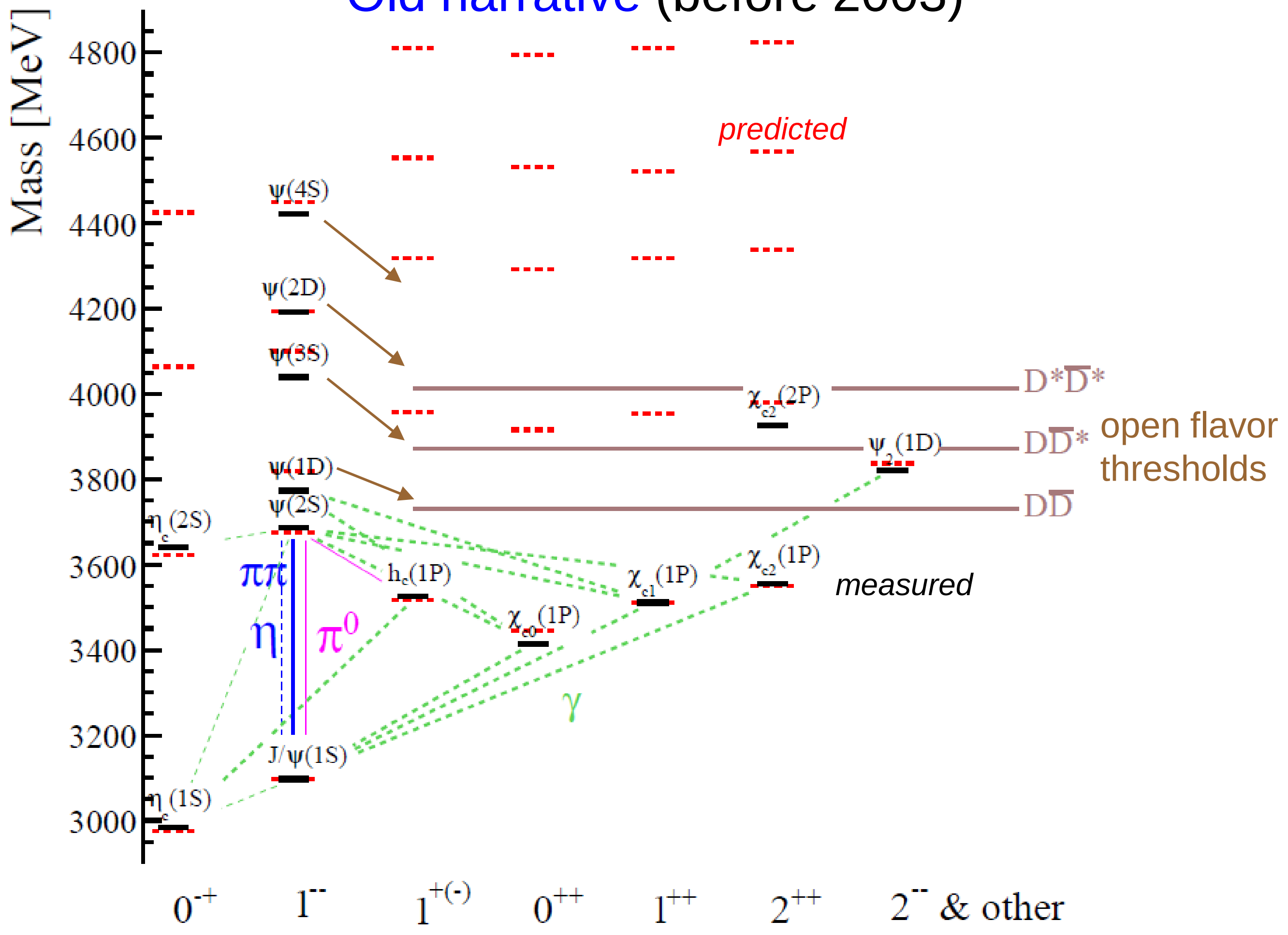
Opportunities with Heavy Flavor at the EIC - a CFNS Ad hoc Workshop

Center for Frontiers in Nuclear Science Workshop series

Nov. 5, 2020

New particle Zoo: charmonium above flavor threshold

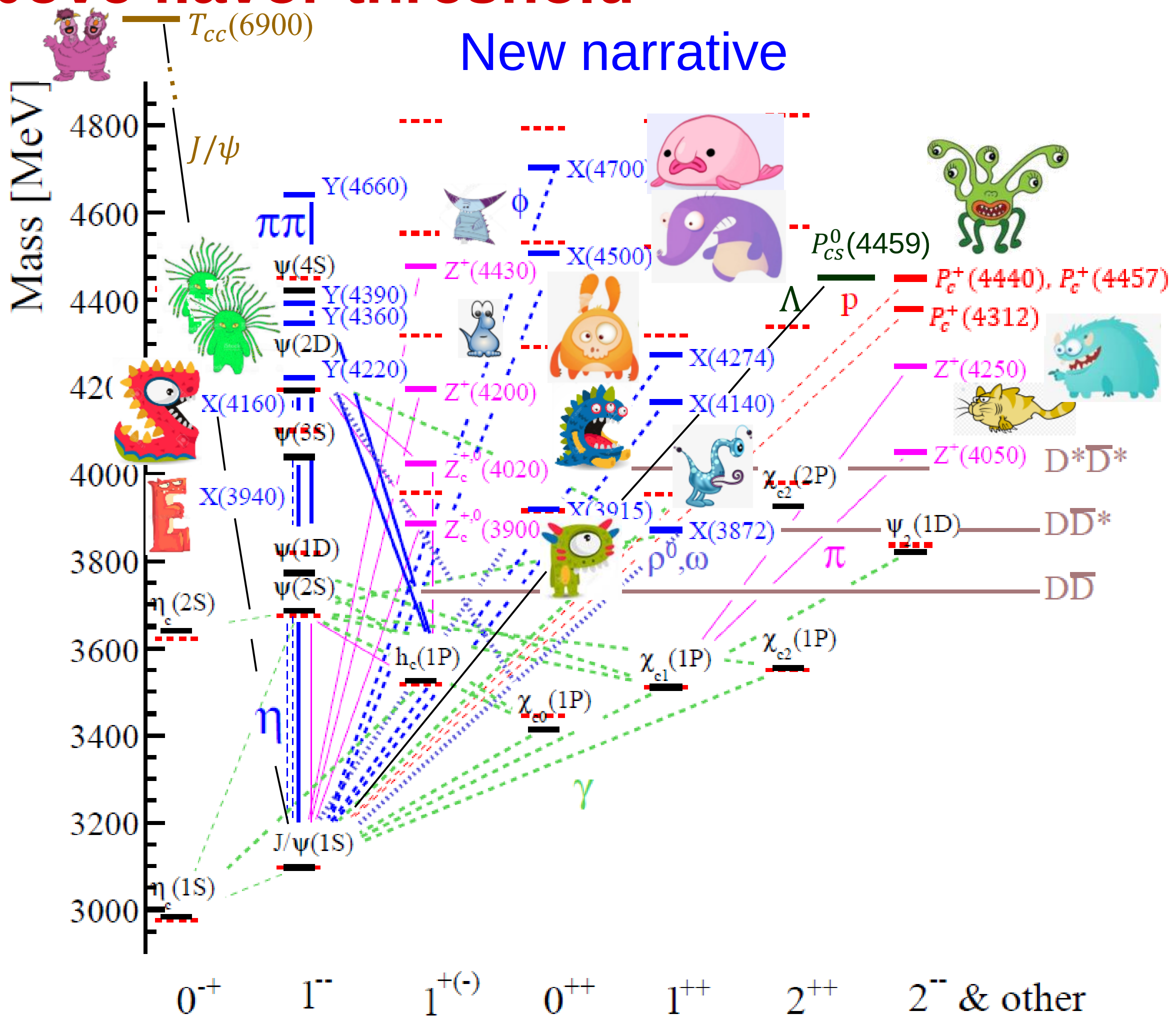
Old narrative (before 2003)



Figures from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

Mesons are $(q\bar{q})$ bound states.

New narrative



Mesons/baryons are **predominantly** $(q\bar{q}/qqq)$ bound states below the open flavor threshold. **They are more complex structures above it,** and we have not yet understood them.

All excited light hadrons are above "the open flavor threshold"!

New particle Zoo: bottomonium above flavor threshold

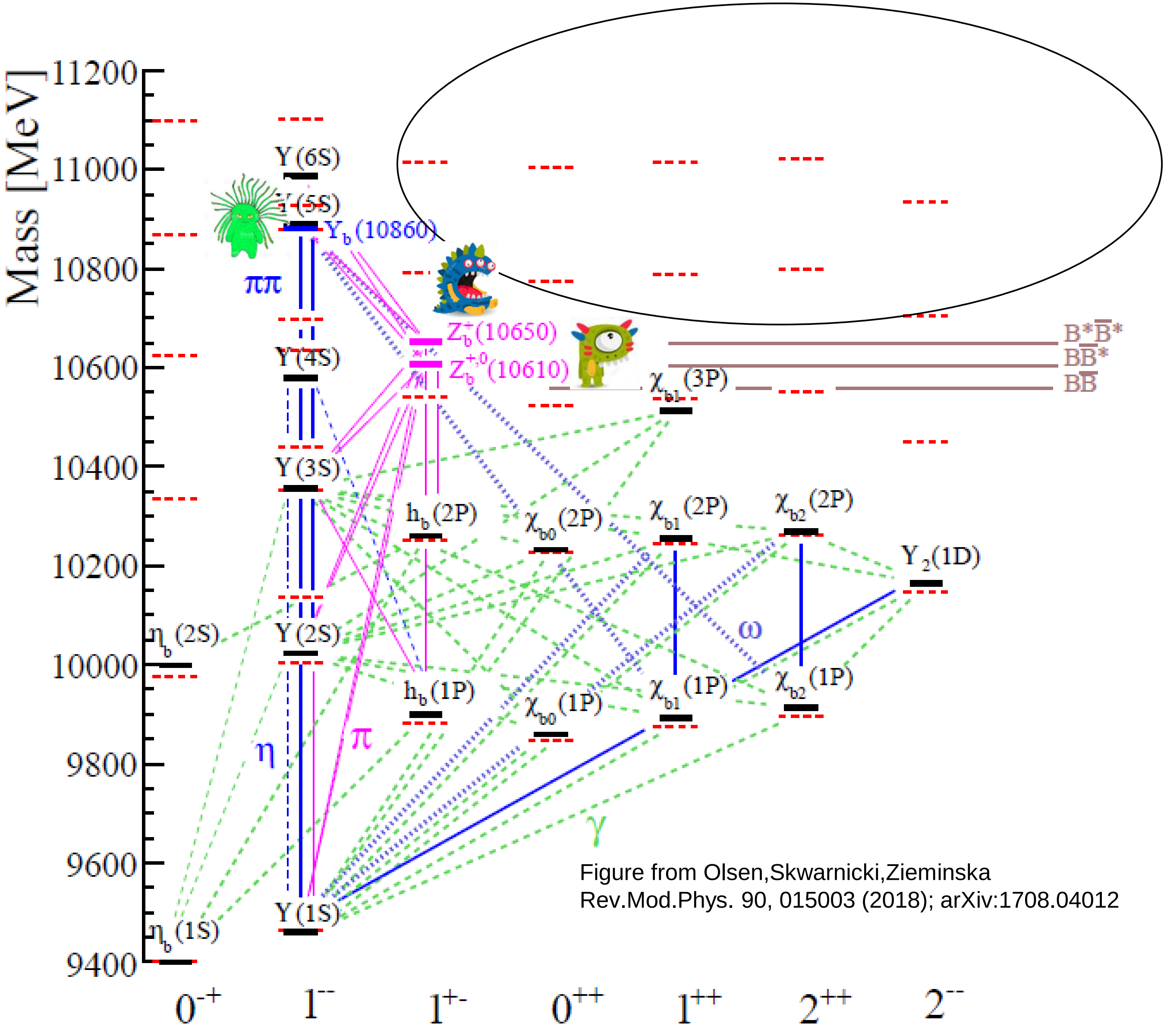


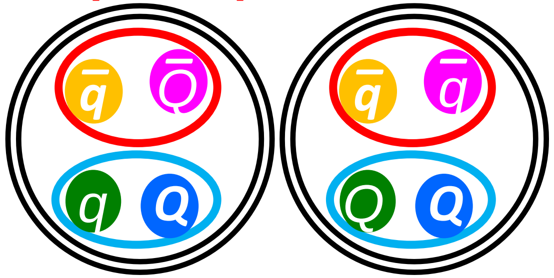
Figure from Olsen,Skwarnicki,Zieminska
Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

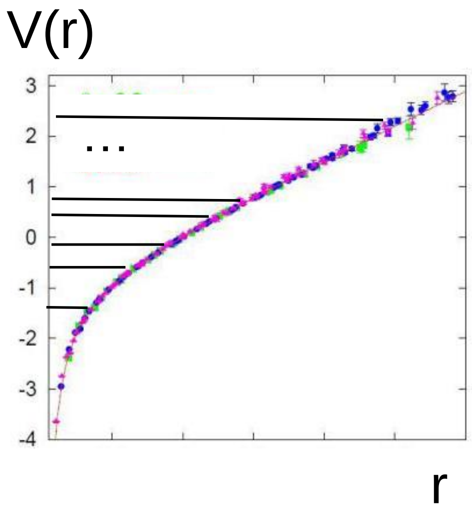
Difficult to explore experimentally:

- Not accessible at e^+e^- B-factories
- Prompt production at LHC more promising but comes with **suppressed cross-section** $(m_b > m_c)$ and **very large combinatorial backgrounds** (huge particle multiplicities out of PV)
- $t \to bW$ at LHC does not produce secondary vertex unlike $b \to cW$ (much smaller backgrounds) since top is too short-lived
- Future high-energy e^+e^- collider?
  - ISR production from Higgs factory?
  - Z^0 factory ($Z^0 \to b\bar{b}$)
  - Doubtful a dedicated high-luminosity e^+e^- machine to scan above Υ(6S) would be built
- EIC?

Types of exotic states expected

- In QCD, expect attractive force in a **diquark** in the color antitriplet configuration (charge of antiquark)
- Expect tightly-bound by color forces compact **tetraquarks** and **pentaquarks**

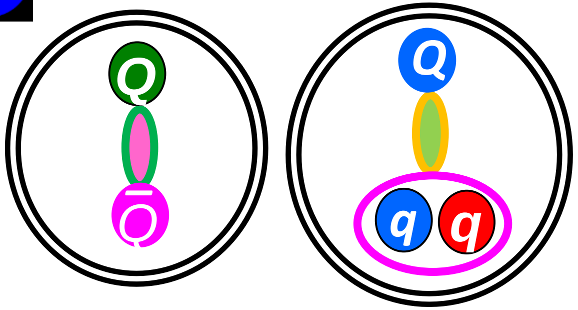




Very rich mass and J^P spectrum expected!

Could be broad. Does effective mechanism to suppress their fall-apart widths exist? This likely depends on specific quark masses and quantum numbers of the state.

- From QCD also expect compact **hybrid** states, in which a **gluon** acts as a valence constituent

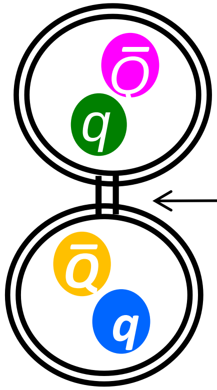


Mixing into higher mass excitation spectrum of mesons and baryons.

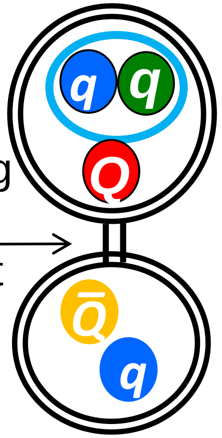
Different decay properties.

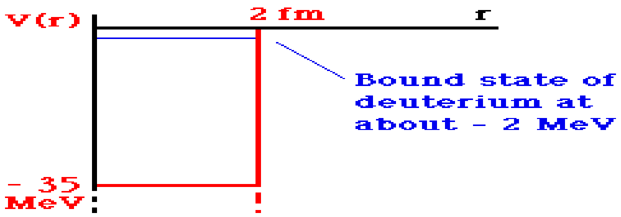
Some may have J^P not reachable by conventional mesons and baryons.

- From nuclear physics, expect weakly-bound, spatially extended states. Usually called **"molecular"**



Usual phenomenology describes binding forces here via exchange of light mesons: $\pi, \varrho, \omega, \eta, \ldots$





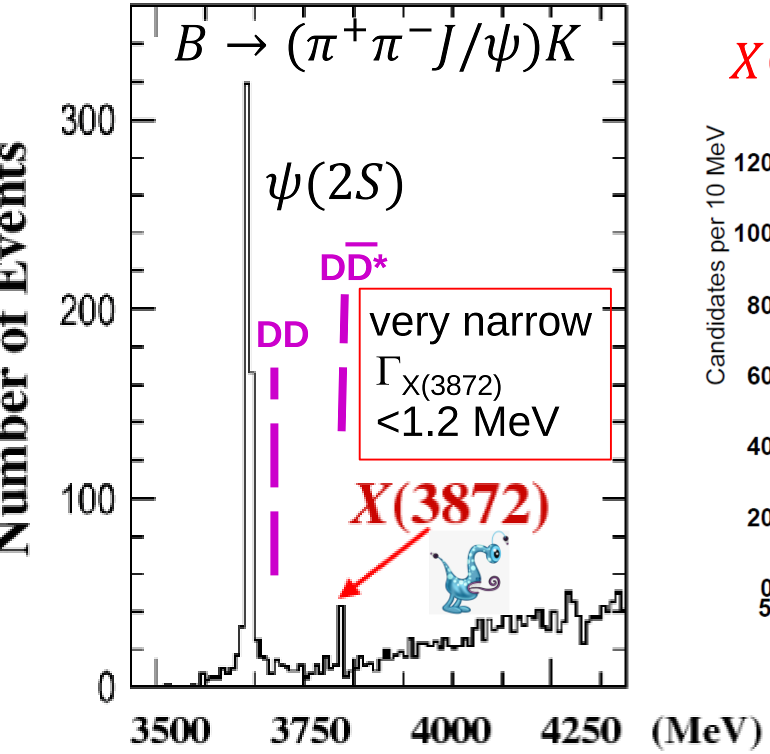
Typically expect only $n=1, L=0$ split by $\vec{S}_1 \cdot \vec{S}_2$

Mass and J^P fairly constrained from the constituents.

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

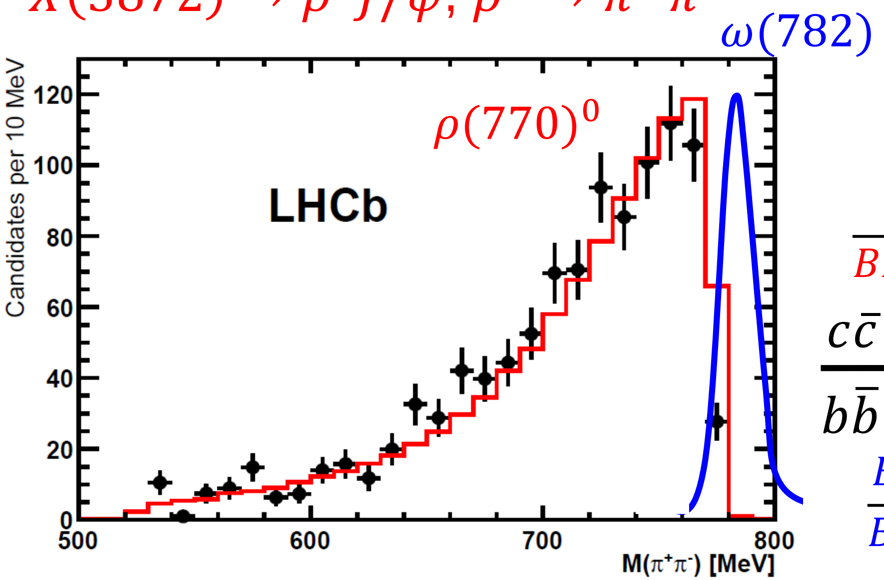
First weird state discovered in charmonium – X(3872)

Belle: Discovery of X(3872)
PRL 91, 262001 (2003)
The most cited Belle paper (1441 citations)



No charged partner found: *I=0*.

Isospin violating decay:
$X(3872) \to \rho^0 J/\psi,\ \rho^0 \to \pi^+\pi^-$



LHCb $J^{PC}=1^{++}$

$\chi_{c1}(2^3P_1)$?

$(\omega \to \pi^+\pi^-\pi^0)$

$$\frac{BR(X(3872) \to \omega J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 1.4 \pm 0.3$$

Suppression of isospin allowed $X(3872) \to \omega J/\psi$ can be blamed on phase-space $\Delta m = 774.8$ MeV

$$\frac{BR(X(3872) \to \gamma J/\psi(1^3S_1))}{BR(X(3872) \to \pi^+\pi^- J/\psi(1^3S_1))} = 0.27 \pm 0.08$$

$c\bar{c}$

$b\bar{b}$ $\Delta m = 795.2$ MeV

$$\frac{BR(\chi_{b1}(2^3P_1) \to \gamma \Upsilon(1^3S_1))}{BR(\chi_{b1}(2^3P_1) \to \omega \Upsilon(1^3S_1))} = 6.1 \pm 1.6$$

$\chi_{b1}(2^3P_1) \to \pi^+\pi^-\ \Upsilon(1^3S_1)$ not seen

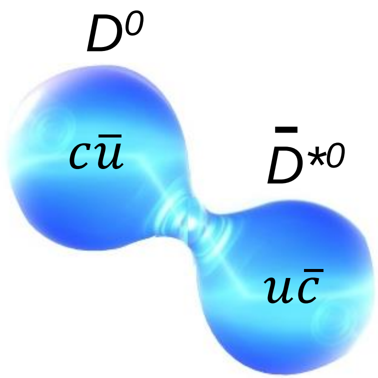
Enhancement of isospin violating $X(3872) \to \pi^+\pi^- J/\psi$ relative to radiative transitions rules out pure $\chi_{c1}(2^3P_1)$ interpretation

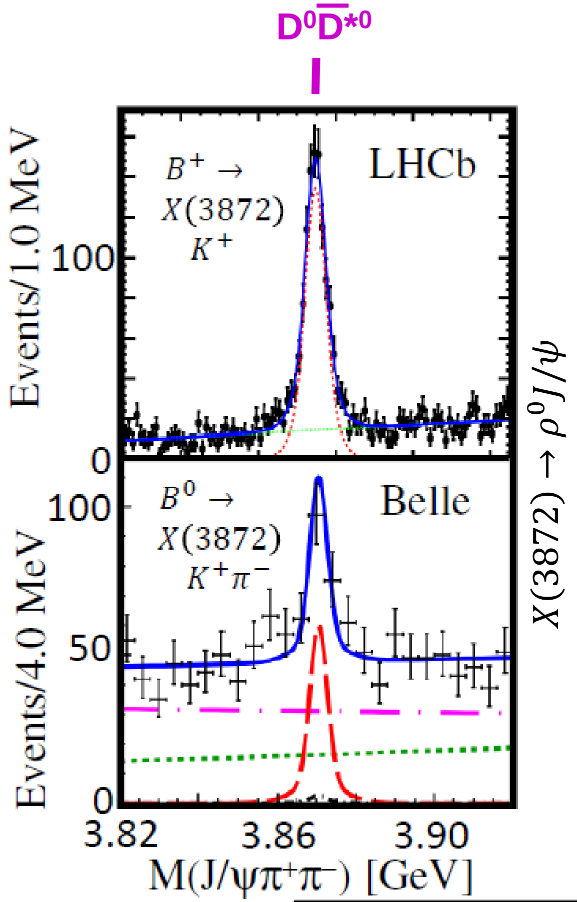
$m_{X(3872)} \approx m_{D^0} + m_{D^{*0}}$
indistinguishable within the errors

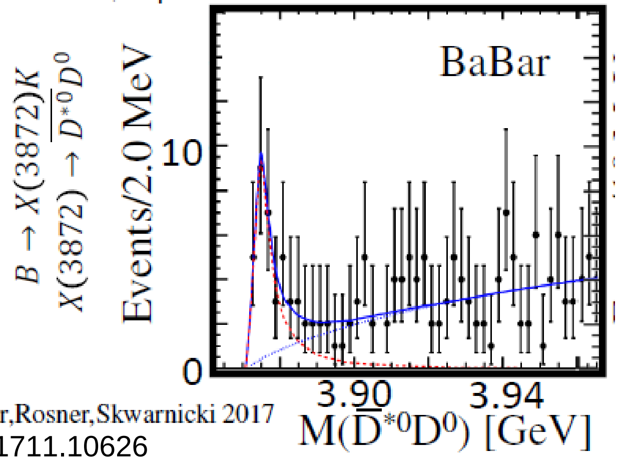
molecule ?

8.2 ± 0.2 MeV below $m_{D^\pm} + m_{D^{*\pm}}$ ⇨ natural source of isospin violation

X(3872): molecular features



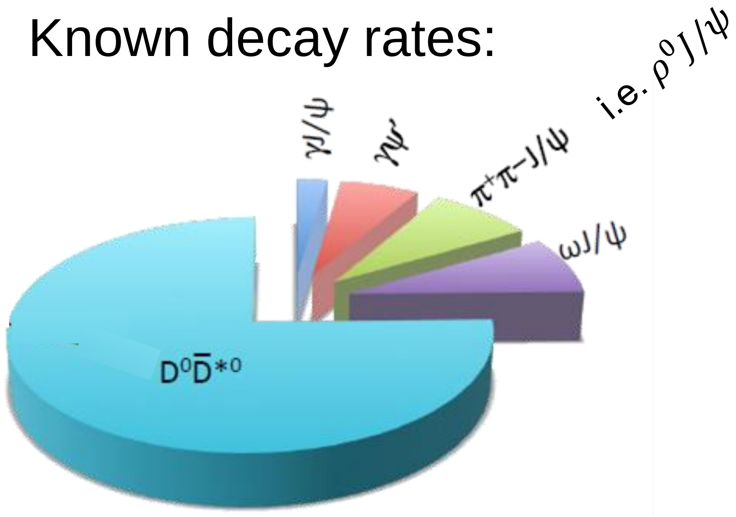




Karliner,Rosner,Skwarnicki 2017
arXiv:1711.10626

Narrow width in decays to $c\bar{c}$

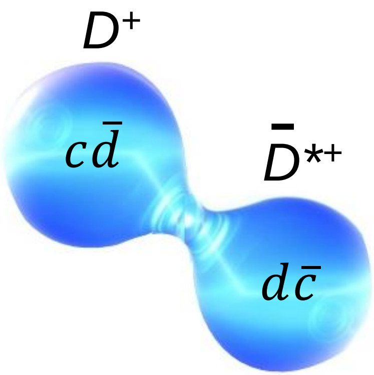
Known decay rates:



Huge fall-apart mode from the resonance tail above the $D^0\overline{D^{*0}}$ threshold

0^-1^- interacting in S-wave
compatible with $J^{PC}=1^{++}$

only small admixture of

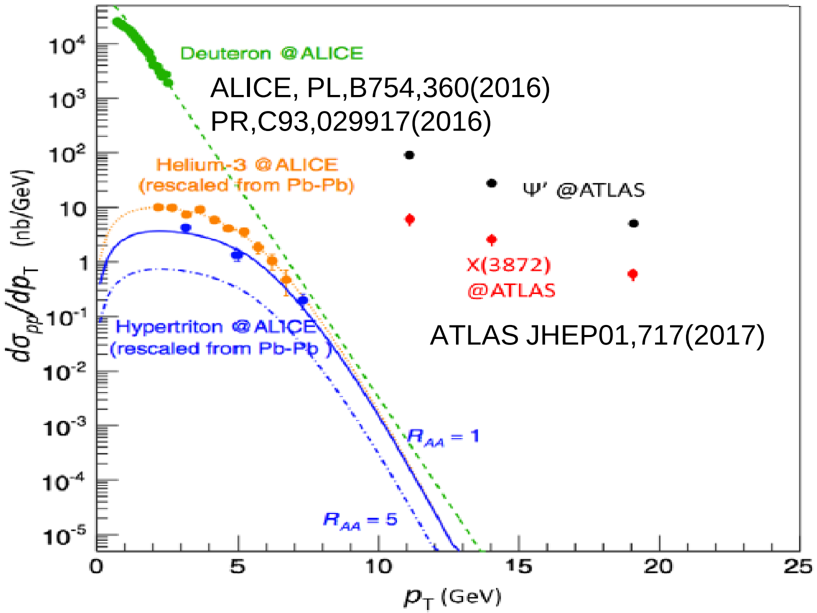


Enhanced isospin violating decays

$X(3872) \to \rho^0 J/\psi$

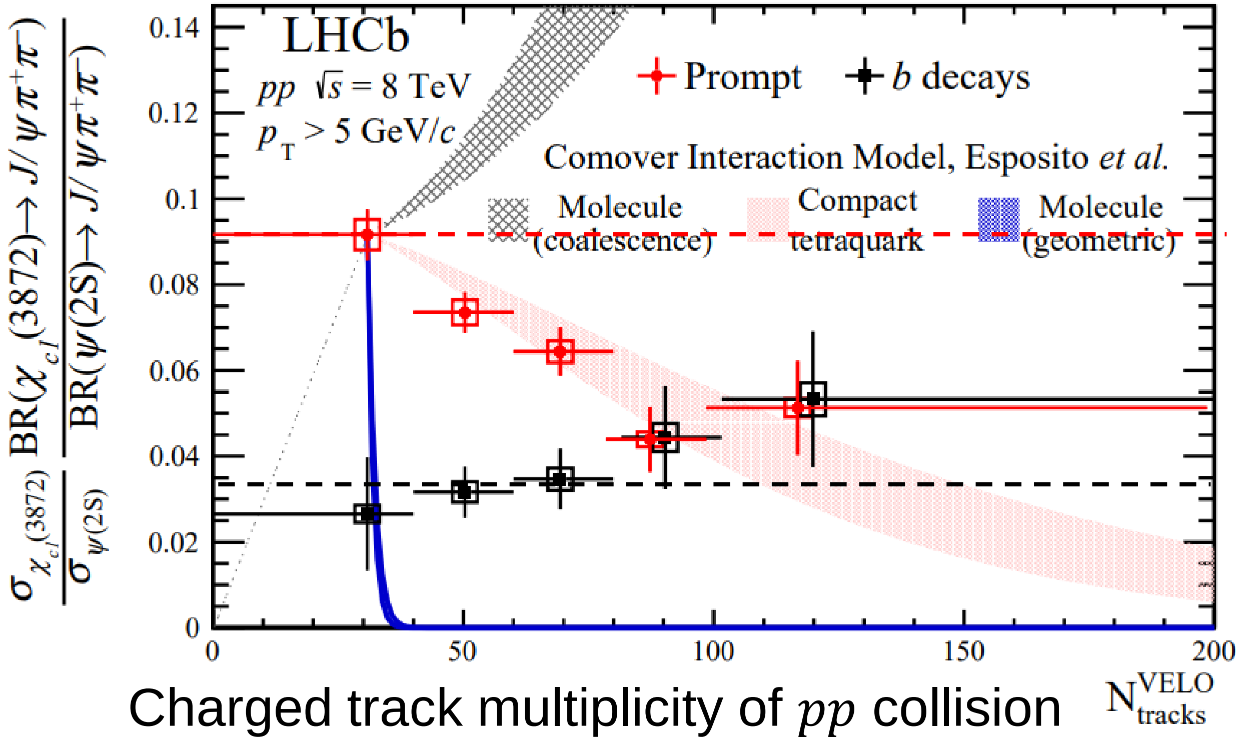
X(3872): compact state features

$pp \to X(3872) + \ldots$ @LHC



A. Esposito, et al. PRD92, 034028 (2015)
(ATLAS data inserted by S.Olsen)

LHCb-PAPER-2020-023



Charged track multiplicity of pp collision

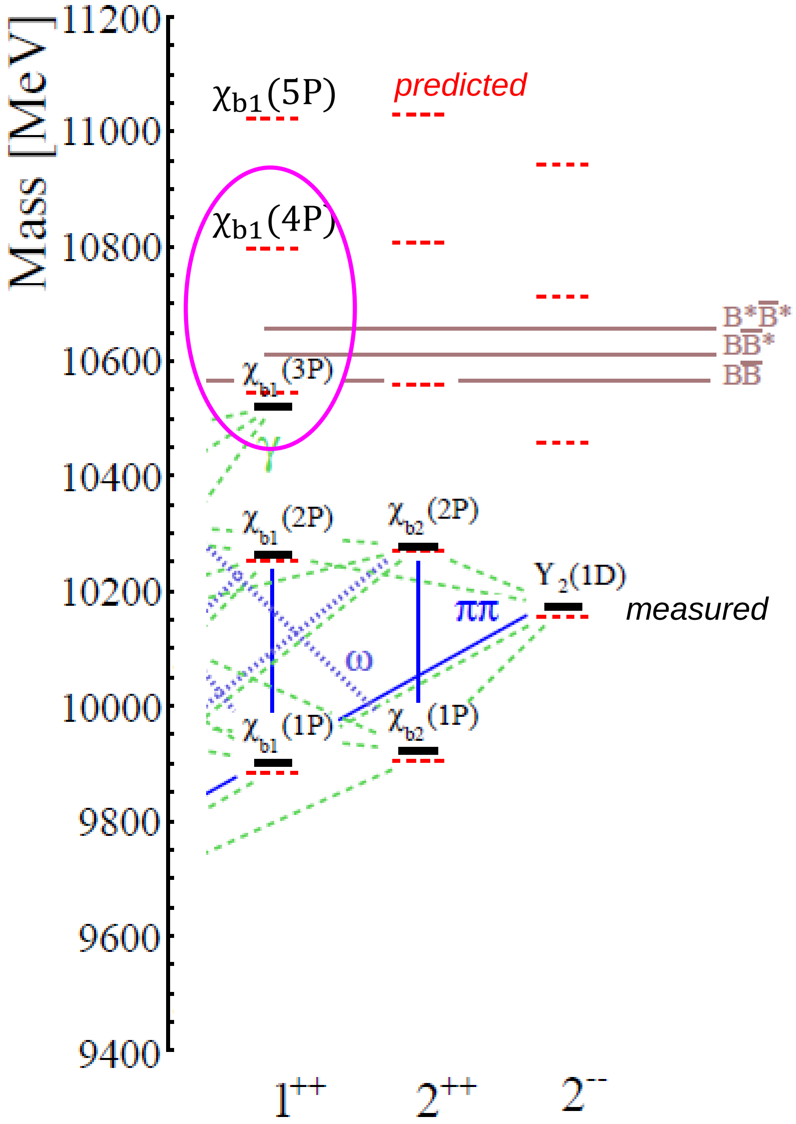
- X(3872) production rates in prompt processes and in B decays more like for a compact state than molecule (in magnitude and in p_T dependence)
- X(3872) behavior in between a **compact $c\bar{c}$ state**, and a molecule melted down by surrounding activity. Compact tetraquark?

Mixture of a compact state ($c\bar{c}, cu\bar{c}\bar{u}$) and a molecule?

Even after 17 years, and 1843 citations of the Belle X(3872) discovery paper, we keep arguing about the nature of this state. More experimental results is expected soon (LHCb, Belle II, …)

X(3872), so far, is unique!

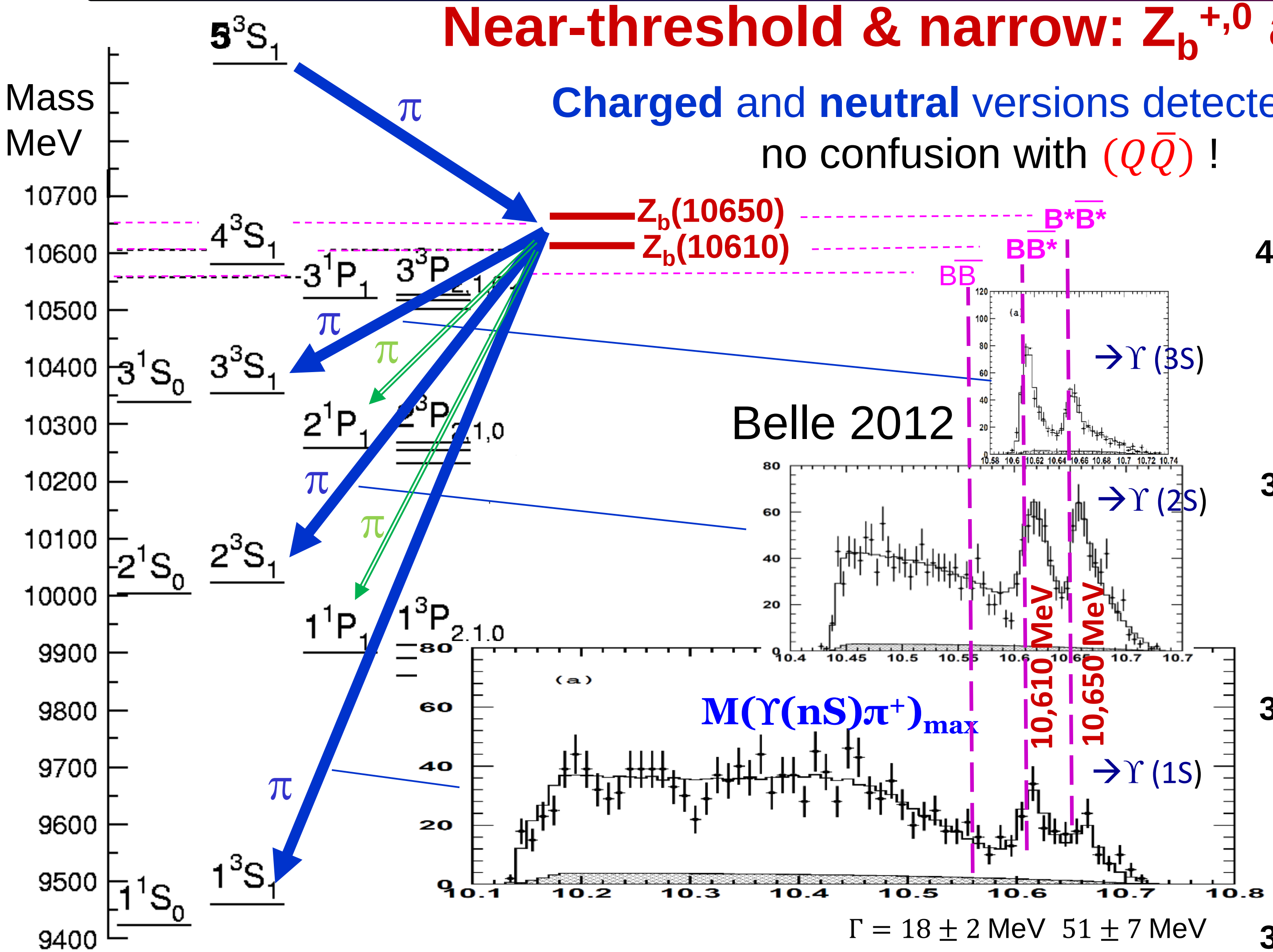
- The only exotic charmonium-like candidate which shows up consistently in many different productions mechanism, accompanying well-behaved $c\bar{c}$ state $-\ \psi(2S)$, and detected in many different decays modes
- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0\overline{D}^{0*}$ threshold is responsible for it, then there is no narrow analog of it in bottomonium
- Any other states like this, with conventional $q\bar{q}$ and exotic properties mixed in?

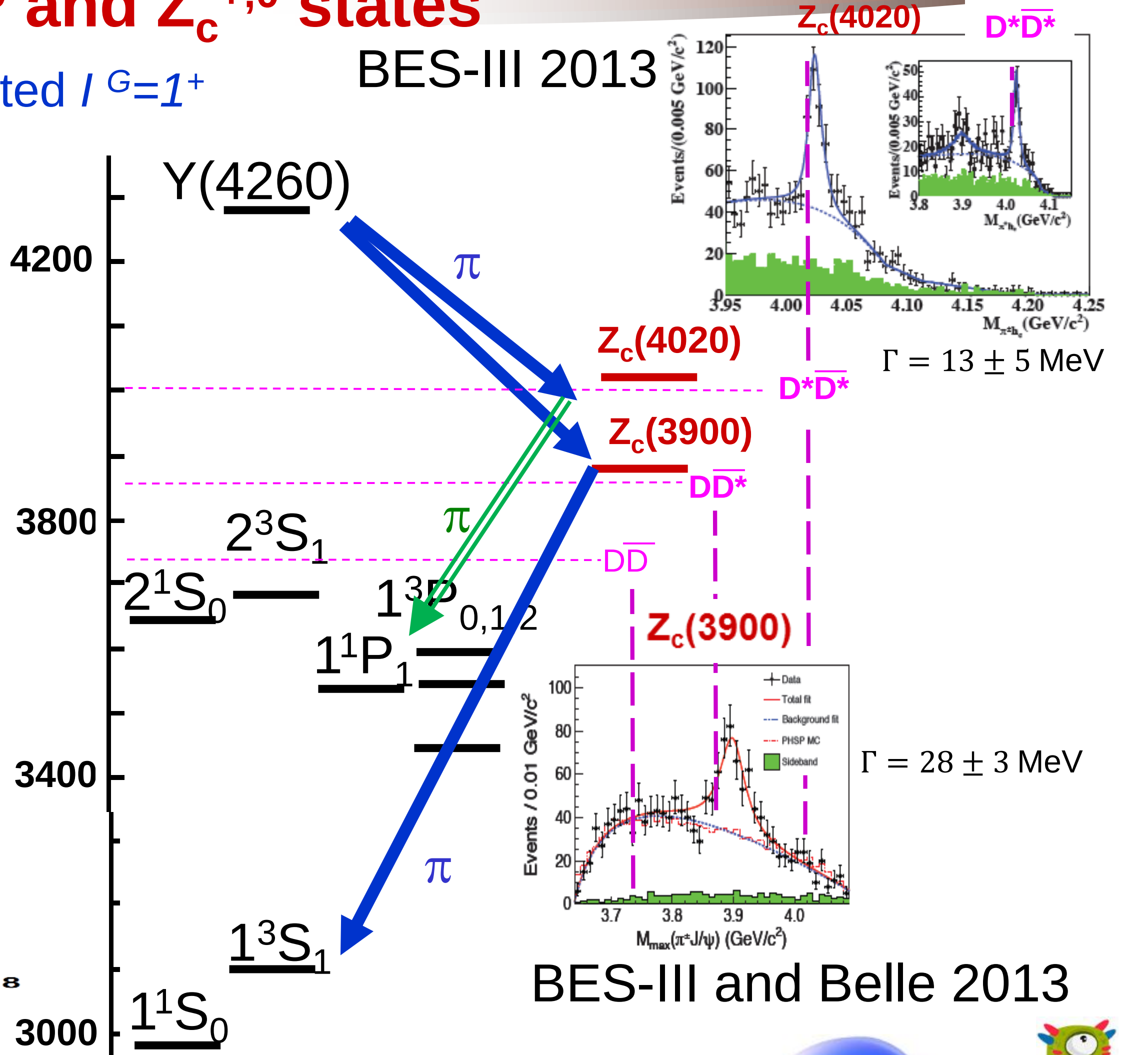


Near-threshold & narrow: $Z_b^{+,0}$ and $Z_c^{+,0}$ states

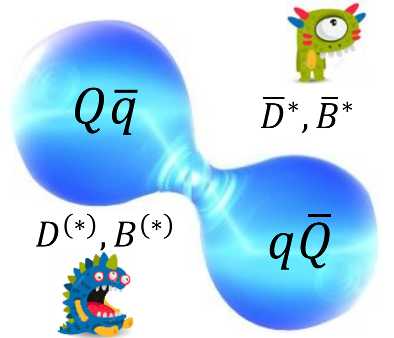
Charged and **neutral** versions detected $I^G=1^+$

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





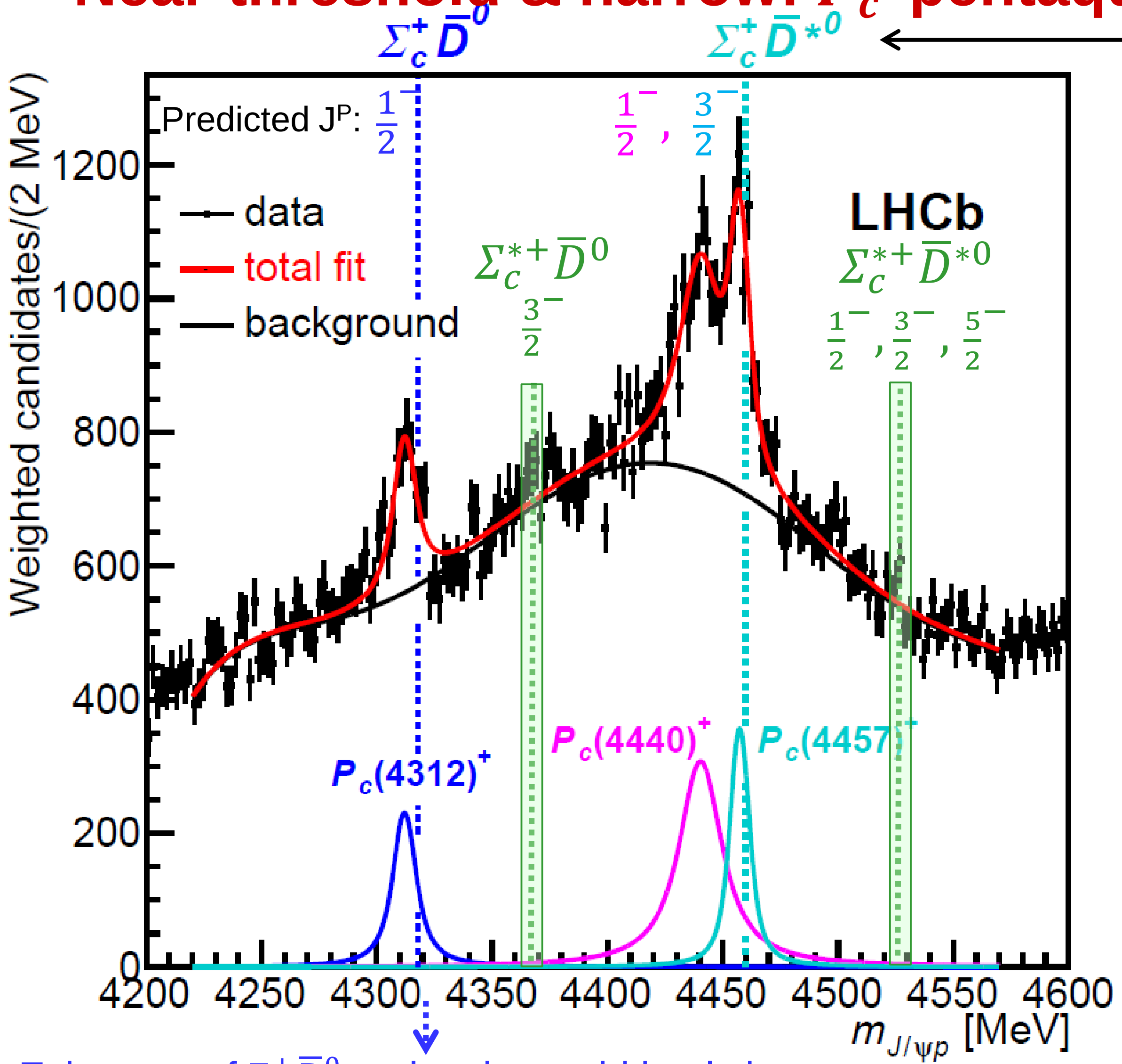
- Near thresholds, relatively narrow, large fall-apart modes, $J^P=1^+$ ⟶ molecular states $B\bar{B}^*$, $B^*\bar{B}^*$, $D\bar{D}^*$, $D^*\bar{D}^*$ (very weakly bound or virtual). No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange.
- Not everybody agrees: the states actually peak a few MeV above the thresholds. A. Ali, L. Maiani, A. Polosa, V. Riquer, PRD91, 017502 (2015) → $((qc)(\bar{q}\bar{c}))$ diquark tetraquarks.



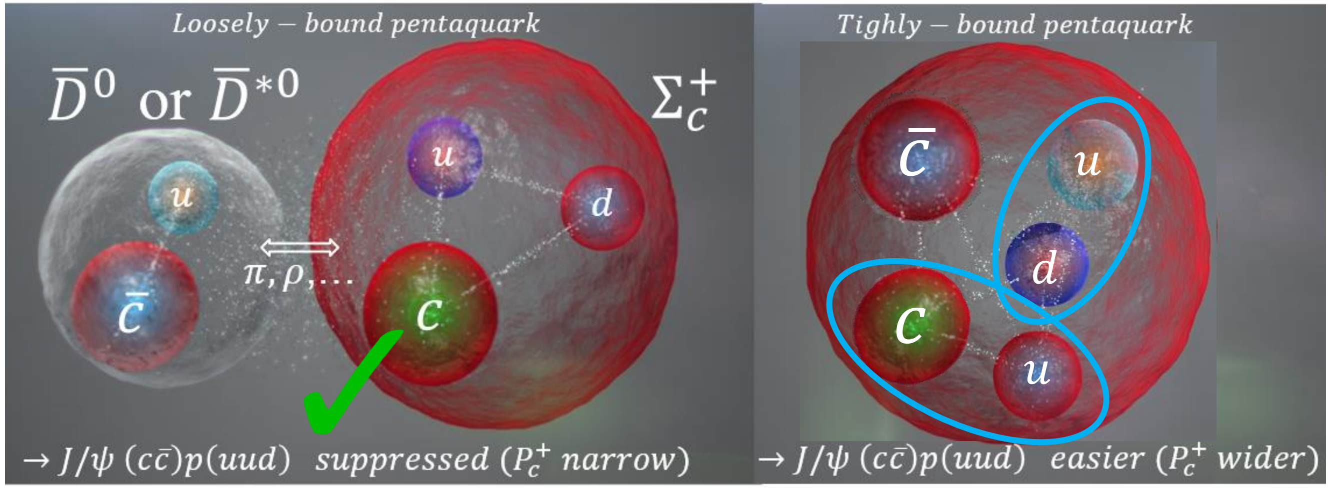
Near-threshold & narrow: P_c^+ pentaquark states

$246k\ \Lambda_b \to J/\psi p K^-$

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



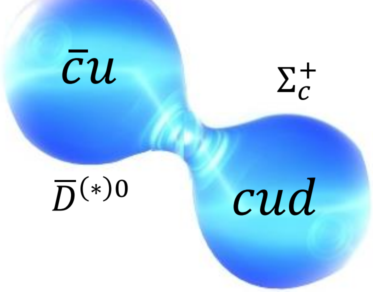
The **only** thresholds in this mass range below which molecular bound states of very-narrow hadrons are expected



However, to confirm baryon-meson hypothesis need to measure J^Ps, find isospin partners, other expected decay modes with predicted rate.

Difficulties in explaining narrow widths and the mass splitting between $P_c(4312)^+$ and $P_c(4440)^+$, $P_c(4457)^+$

Also expect 4 relatively narrow states $\Sigma_c^{*+}\bar{D}^{(*)0}$



Existence of $\Sigma_c^+\bar{D}^0$ molecule would imply importance of $\pi\pi$ or ρ-exchanges

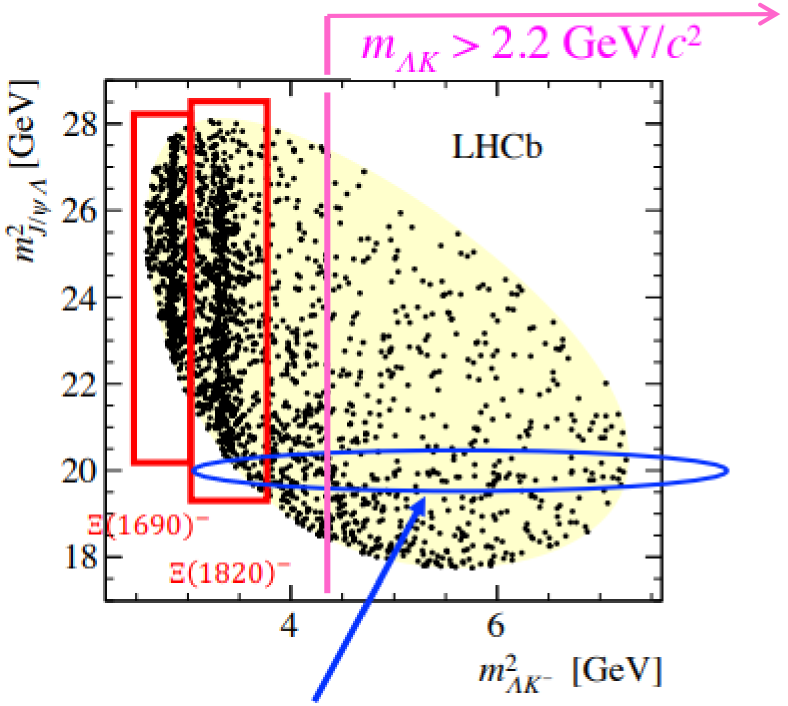
Narrow near-threshold states!
$\Gamma < O(10^1)$ MeV

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

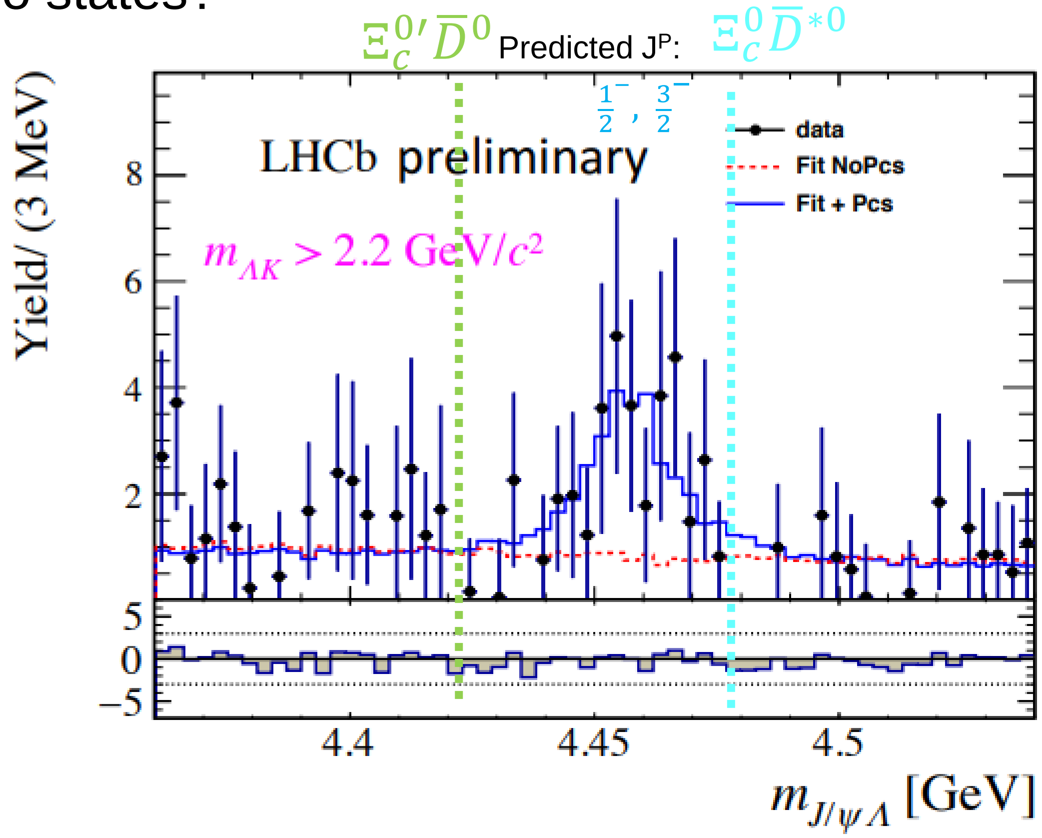
$1.8k\ \Xi_b^- \to J/\psi\Lambda K^-$

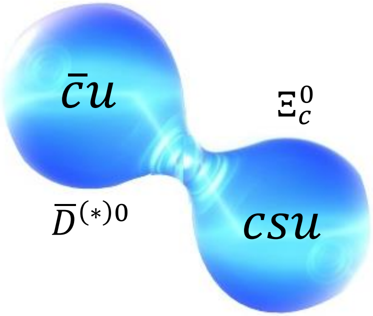
LHCb-PAPER-2020-039-001
In preparation

3.1σ evidence for a mass $J/\psi\Lambda$ structure
one or two states?



Potential P_{cs} contribution?



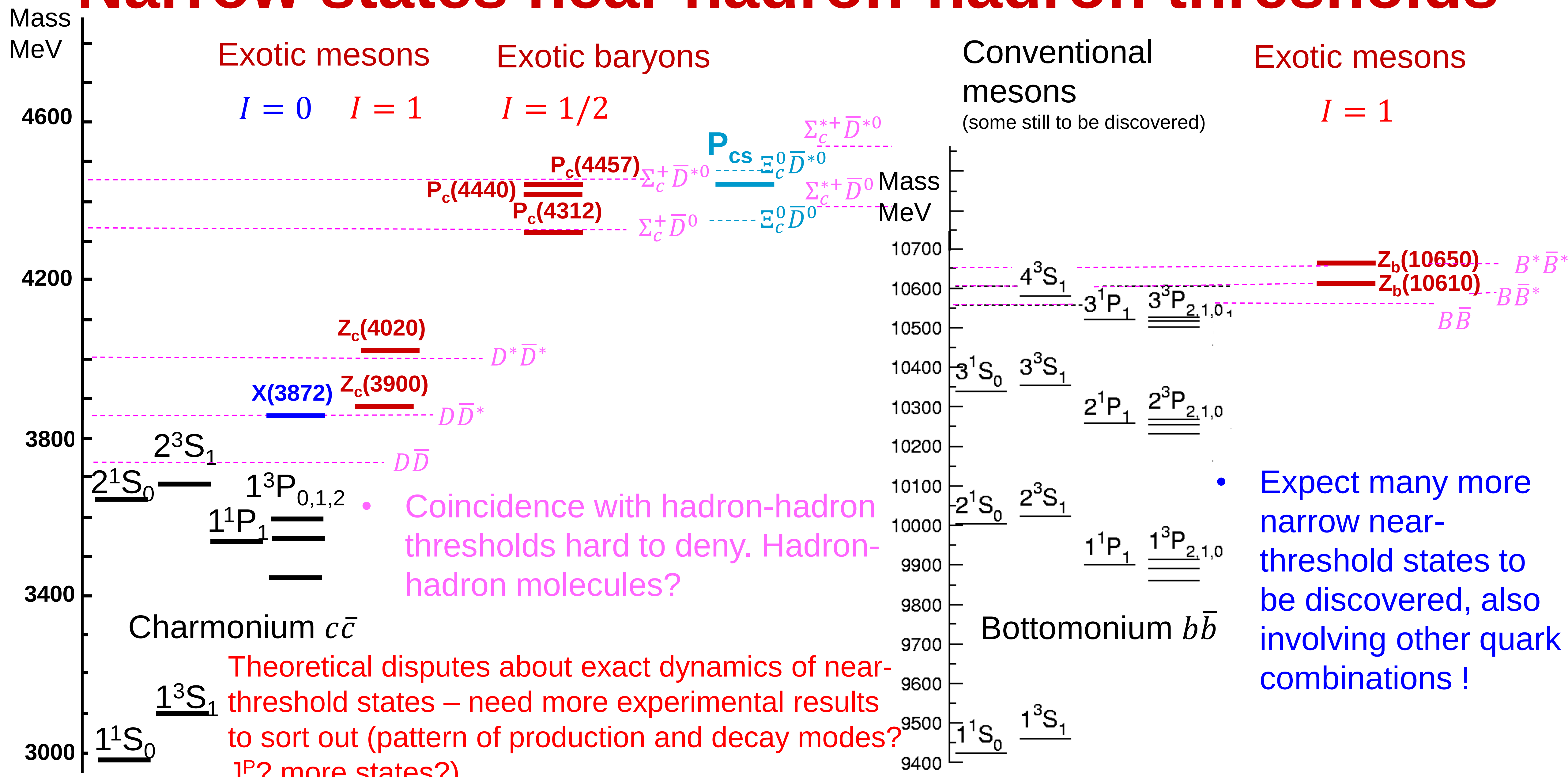


?

Mengzhen Wang
at Workshop on Implications of LHCb measurements and future prospects
Oct. 29, 2020

https://indico.cern.ch/event/857473/contributions/4062686/attachments/2132662/3591489/Implication_exotic_experiment.pdf

Narrow states near hadron-hadron thresholds



- Coincidence with hadron-hadron thresholds hard to deny. Hadron-hadron molecules?

Theoretical disputes about exact dynamics of near-threshold states – need more experimental results to sort out (pattern of production and decay modes? J^P? more states?)

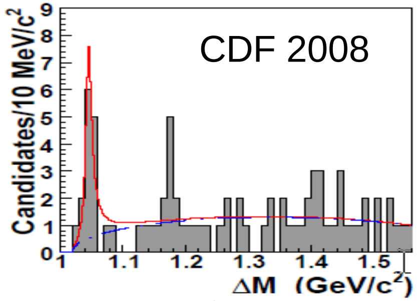
- Expect many more narrow near-threshold states to be discovered, also involving other quark combinations !

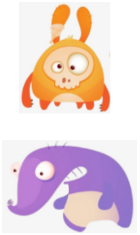
Many broader exotic states not near thresholds

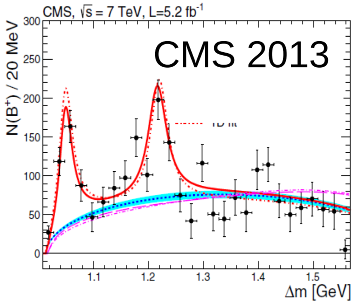
$B \to XK, X \to J/\psi\phi$

$(cs)(\bar{c}\bar{s})$ tetraquarks?

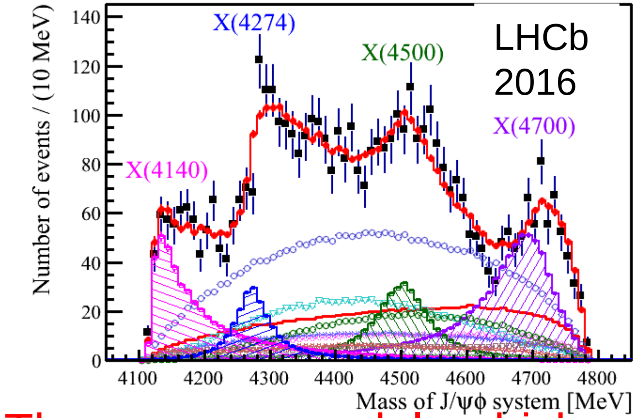
3,4^{3}P$_{1,0}$ $(c\bar{c})$ in the mix?





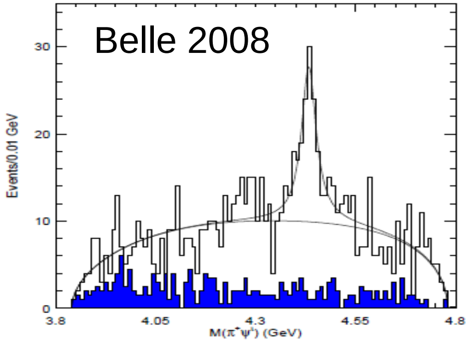


$\Gamma \sim 56 - 120$ MeV

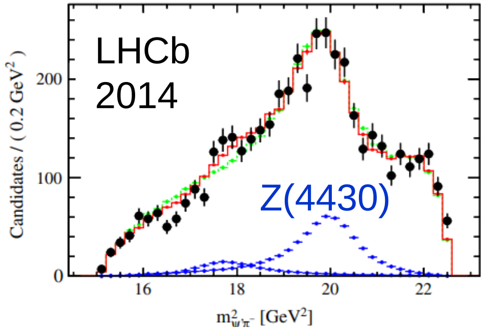


$B \to ZK, Z \to \psi(2S)\pi^{\pm}$

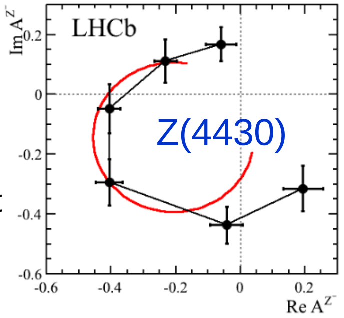
$(cu)(\bar{c}\bar{d})$ tetraquark?



$\Gamma \sim 181 \pm 31$ MeV



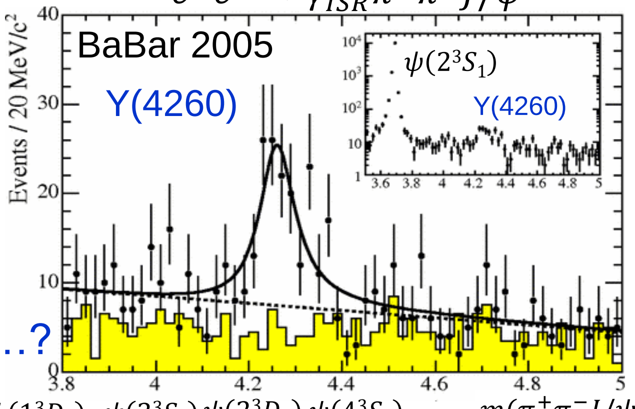
Resonant phase-shift

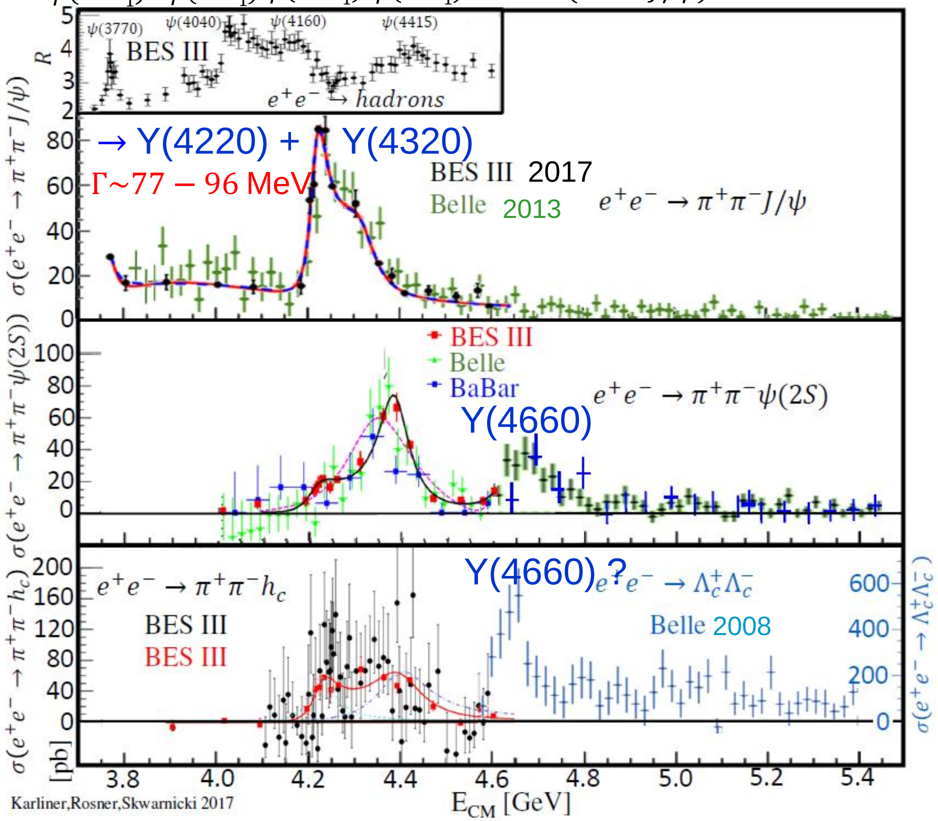


$gc\bar{c}$ hybrid states?,

$(cd)(\bar{c}\bar{d})$ tetraquarks,…?

$e^+e^- \to \gamma_{ISR}\pi^+\pi^-J/\psi$



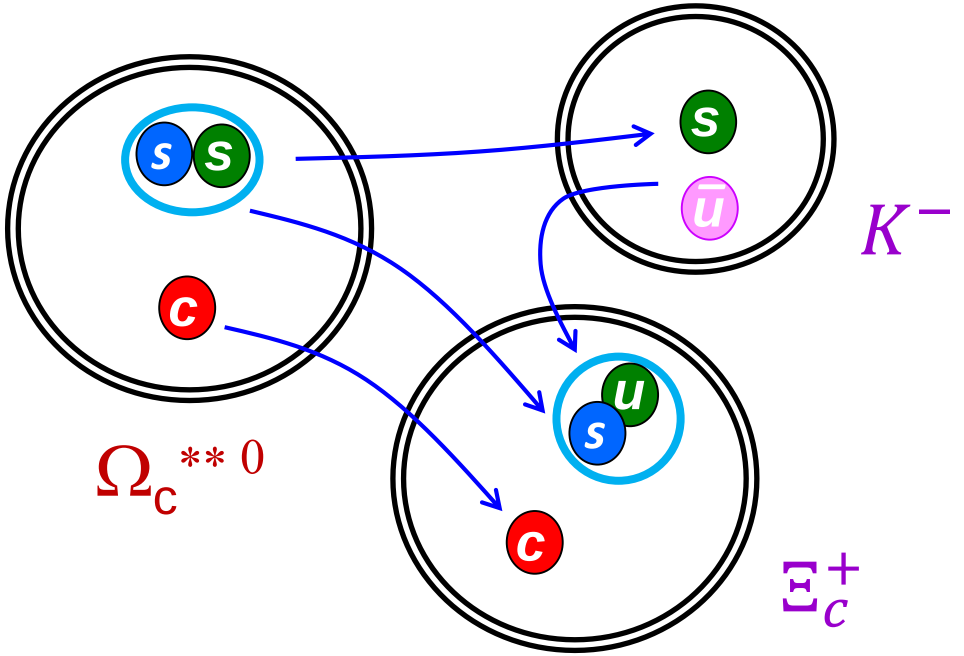


There are no models which can explain all these effects at the same time

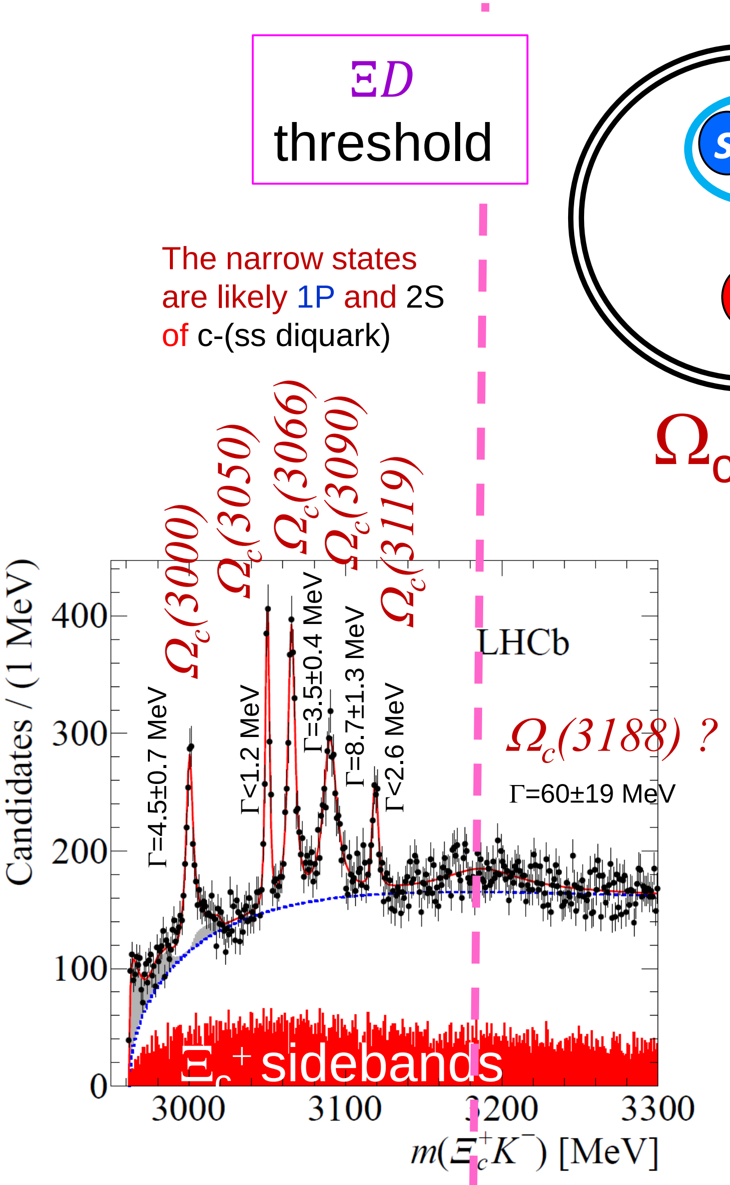
Conventional heavy baryons

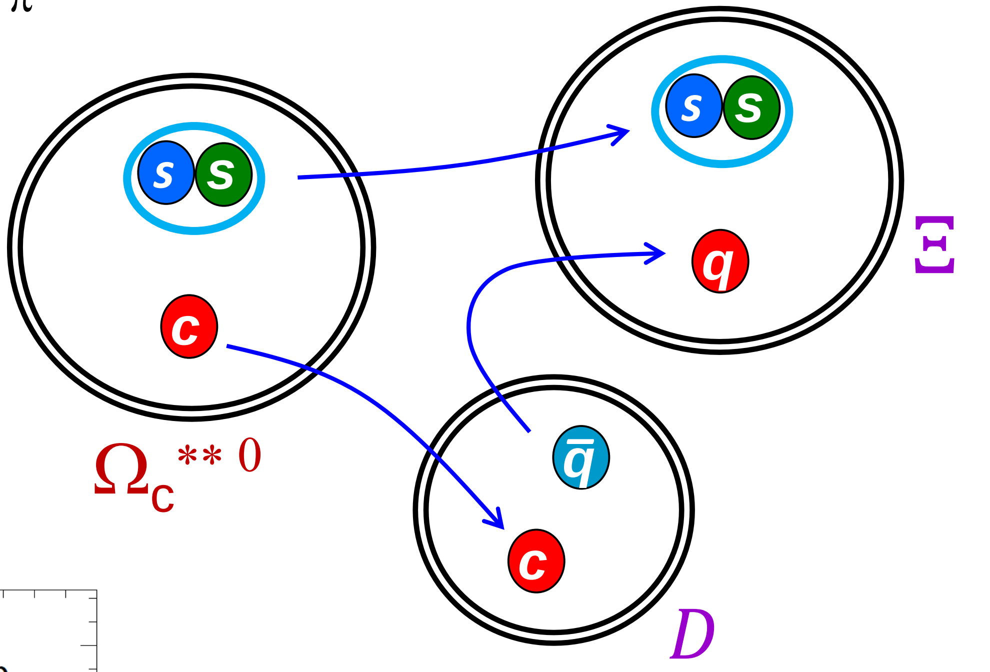
- A lots of new states are being discovered. Many contain nice evidence for diquark substructure e.g.

LHCb-PAPER-2017-002, PRL 118 (2017) 182001; 3.3 fb^{-1} $\Omega_c^{**0} \to \Xi_c^+ K^-$, $\Xi_c^+ \to pK^-\pi^+$



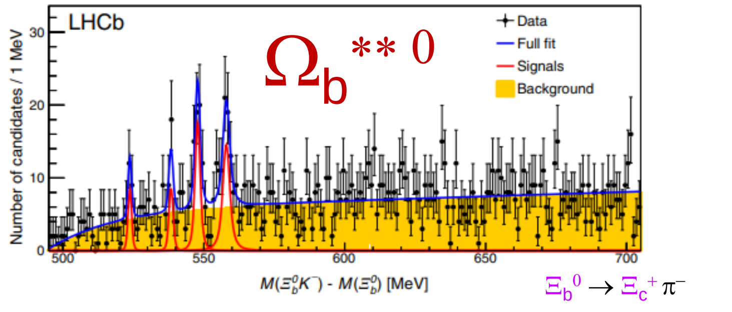
OZI allowed but rips the diquark apart
– suppressed (narrow states)





the diquark survives
– fast fall apart (wide states)

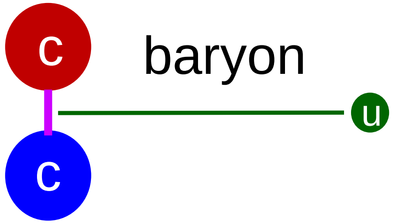
LHCb-PAPER-2019-042, PRL 124 (2020) 082002; 9 fb^{-1}



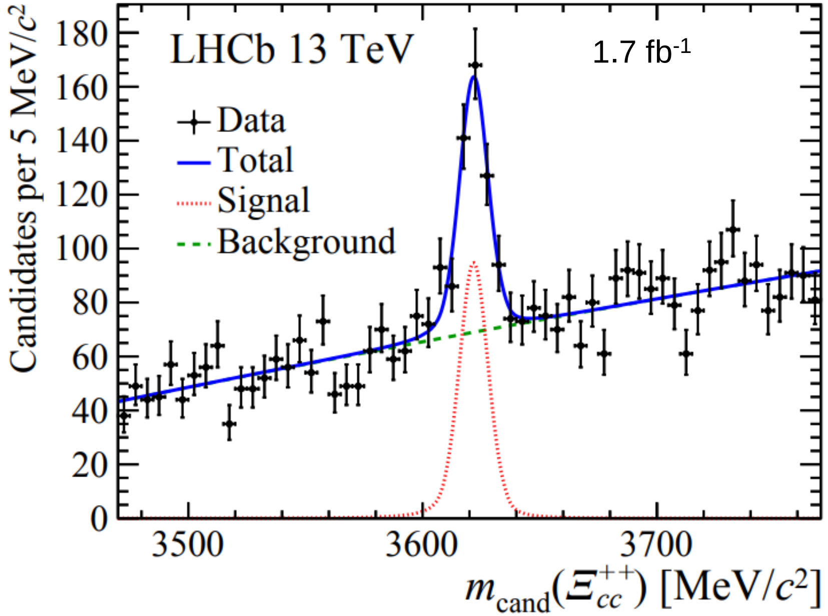
Future:

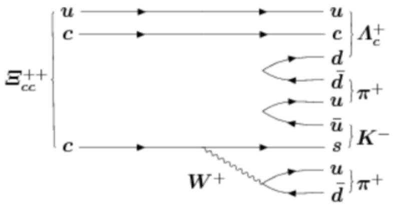
Many more charm and beauty baryons to discover
Study different decay modes of known baryons

Doubly flavored baryons and stable (?) tetraquarks



LHCb-PAPER-2017-018, LHCb PRL 119 (2017) 112001





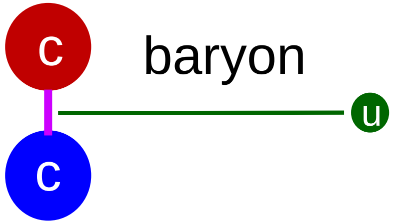
$\Lambda_c^+ \to pK^-\pi^+$

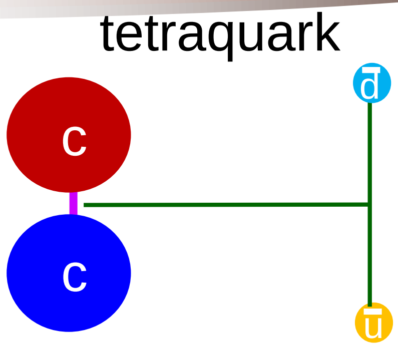
Karliner,Rosner PRD90,094007 (2014)

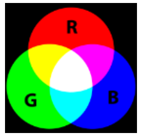
State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

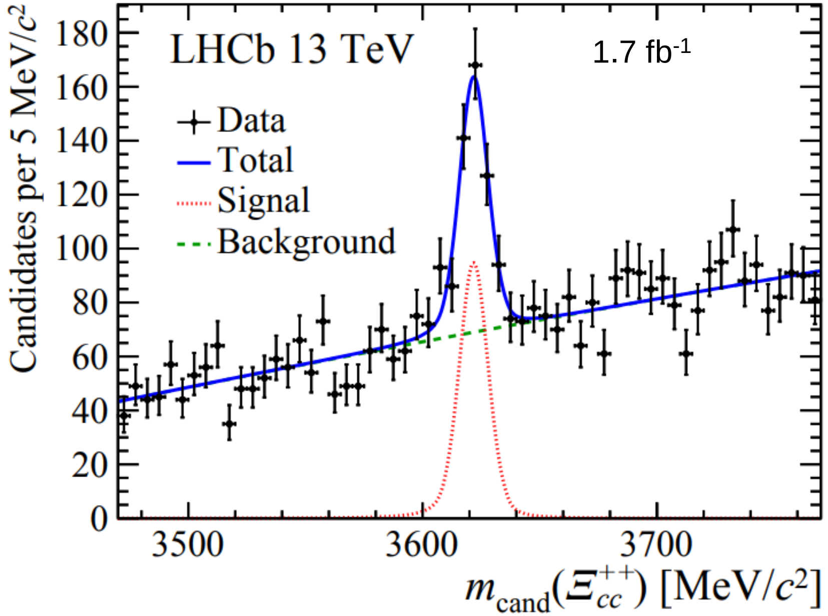
Doubly flavored baryons and stable (?) tetraquarks

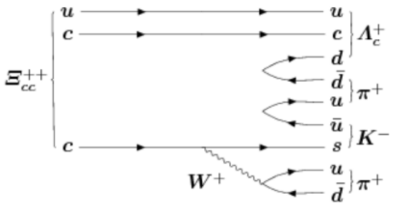






LHCb-PAPER-2017-018, LHCb PRL 119 (2017) 112001

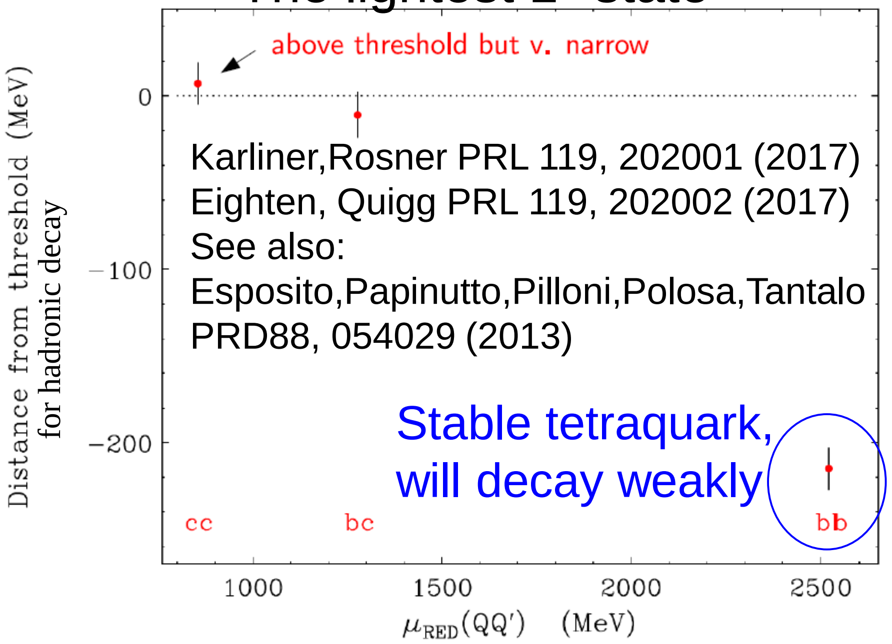




$\Lambda_c^+ \to pK^-\pi^+$

the same toolkit

The lightest 1^+ state



Karliner,Rosner PRL 119, 202001 (2017)
Eighten, Quigg PRL 119, 202002 (2017)
See also:
Esposito,Papinutto,Pilloni,Polosa,Tantalo PRD88, 054029 (2013)

Stable tetraquark, will decay weakly

Karliner,Rosner PRD90,094007 (2014)

State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

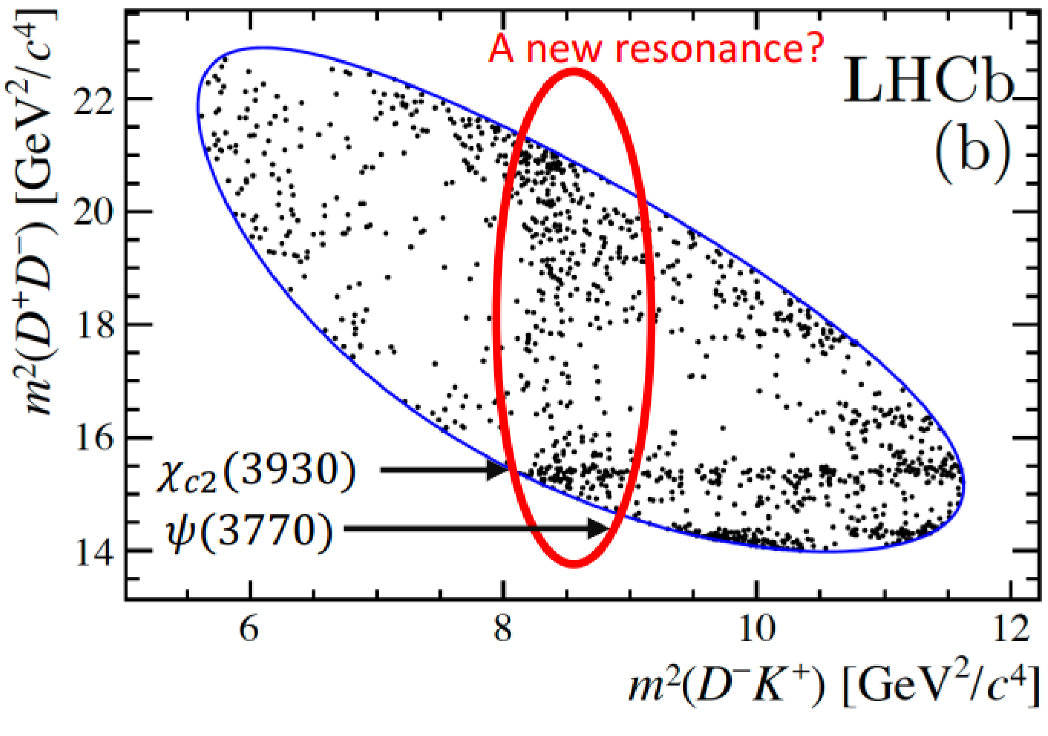
LHCb: 3621 ± 1

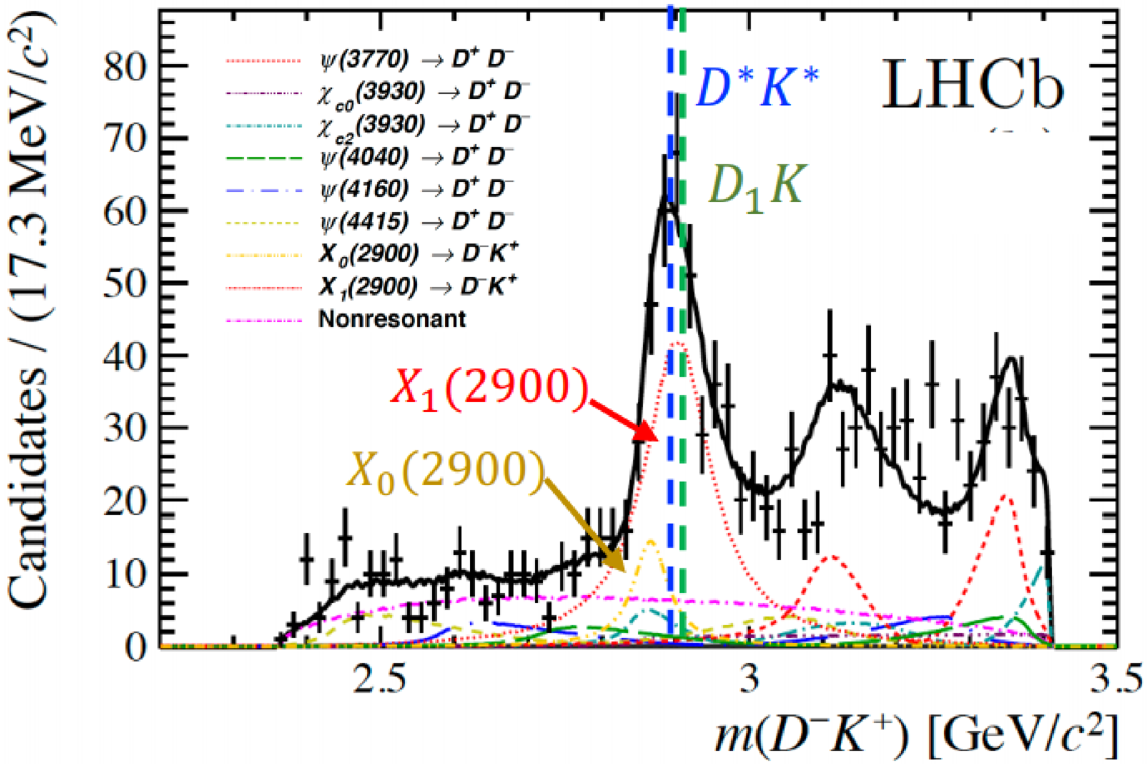
Consistent results predicted by LQCD: Francis,Hudspith,Lewis,Maltman PRL 1118,142001 (2017)

Future searches for such states above or below the $(Q\bar{q})(Q\bar{q})$ threshold will be very exciting

Charming and strange exotic state

$1.3k\ B^+ \to D^+D^-K^+$
arXiv:2009.00026 (accepted by PRD)
LHCb-PAPER-2020-025

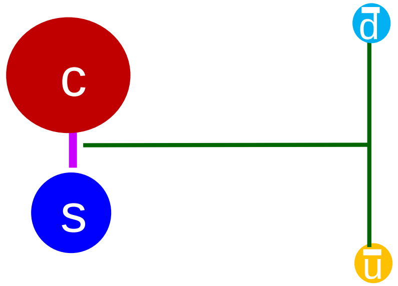




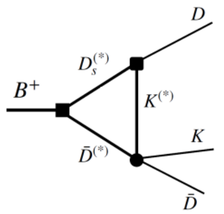
$X_0(2900)$: $M = 2.866 \pm 0.007 \pm 0.002\ \text{GeV}/c^2$, $\Gamma = 57 \pm 12 \pm 4\ \text{MeV}$

$X_1(2900)$: $M = 2.904 \pm 0.005 \pm 0.001\ \text{GeV}/c^2$, $\Gamma = 110 \pm 11 \pm 4\ \text{MeV}$

- The 0^+ state is a good candidate for a "nearly"-doubly-heavy tetraquark



Proximity of the thresholds motivates other explanations - molecular or triangle diagrams



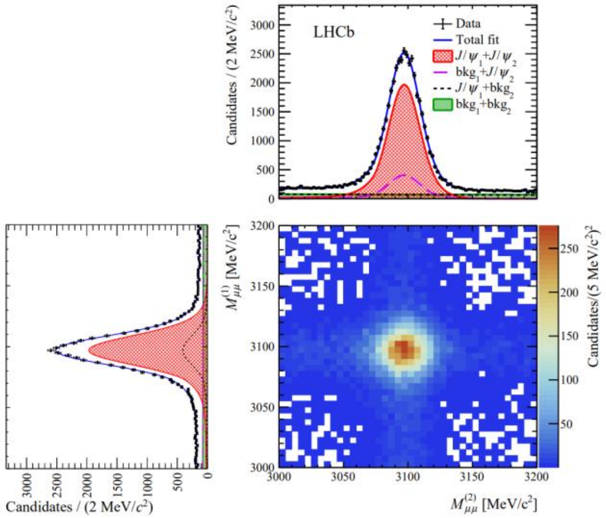
See Tim Burns
at Workshop on Implications of LHCb measurements and future prospects
Oct. 29, 2020

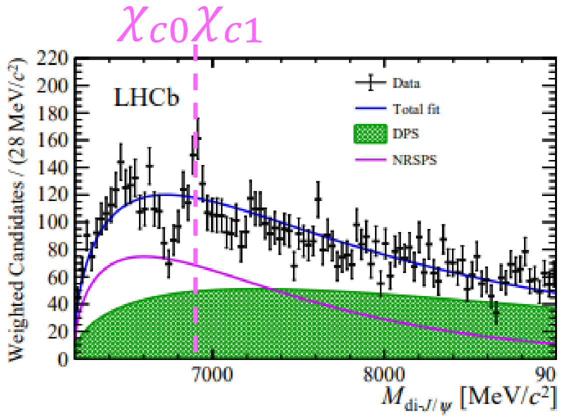
https://indico.cern.ch/event/857473/contributions/4062687/attachments/2132793/3591749/talk_IW2020_Burns.pdf

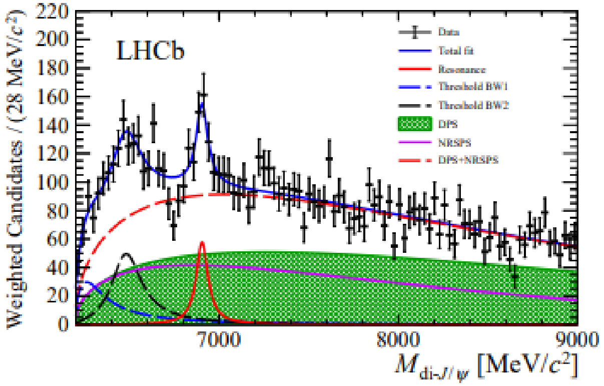
Hidden double charm tetraquarks ?

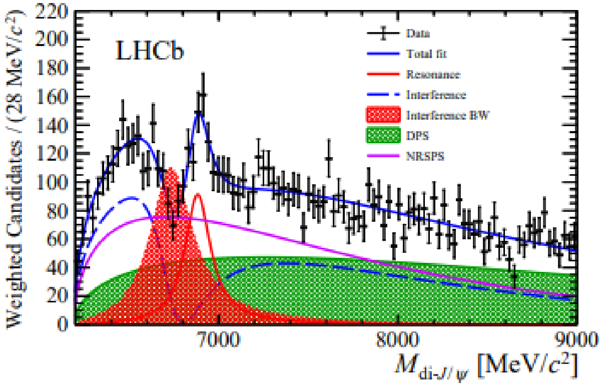
$pp \to (J/\psi \to \mu^+\mu^-)(J/\psi \to \mu^+\mu^-) + \cdots$

LHCb June 2020





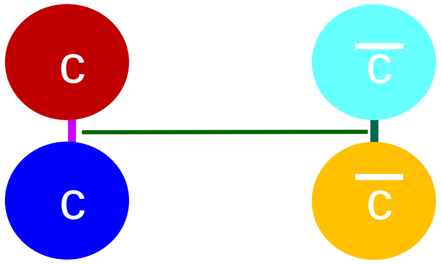




Structure	Significance: $p_T^{\text{di-}J/\psi}$-threshold	Significance: $p_T^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS plus DPS	$3.4\,\sigma$	$6.0\,\sigma$
Threshold enhancement plus $X(6900)$	$6.4\,\sigma$	$6.9\,\sigma$
Threshold enhancement	$6.0\,\sigma$	$6.5\,\sigma$
$X(6900)$	$5.1\,\sigma$	$5.4\,\sigma$

- Very significant structure in J/ψJ/ψ mass
- Interpretation of data is not clear:
  - One, or more (interfering?) resonances
  - possible effects due to nearby $\chi_{c0}\chi_{c0,1}$ thresholds, however, there are no known mechanism for binding forces between two charmonium states, and the X(6900) peak seems too wide to be a molecule (Γ~80 MeV or more)
  - likely theoretical interpretation: $(cc)(\bar{c}\bar{c})$ tetraquark state(s)
- Experimental questions to answer in the future:
  - How many states? J^Ps? Other decay modes e.g. $J/\psi\eta_c$

Tetraquark ?

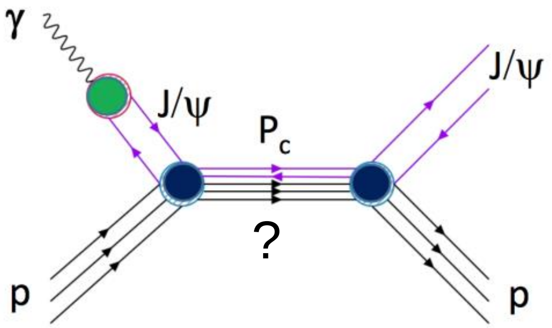


Experimental prospects at JLab and EIC

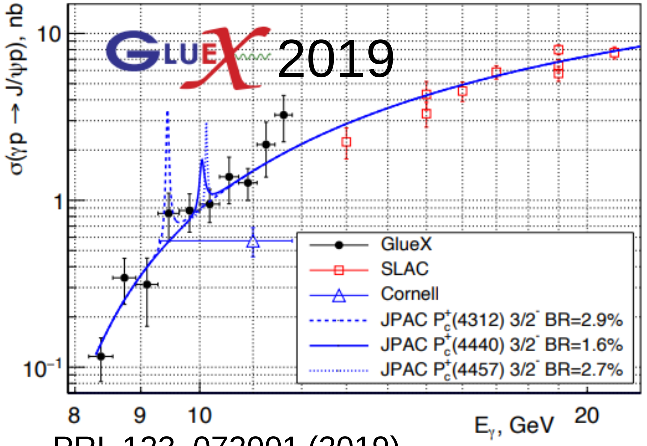
JLab: 12 GeV e^- beam (2017-…)

Electron Ion Collider e^-p, e^-A (2030-…)

Photoproduction of charm exotics

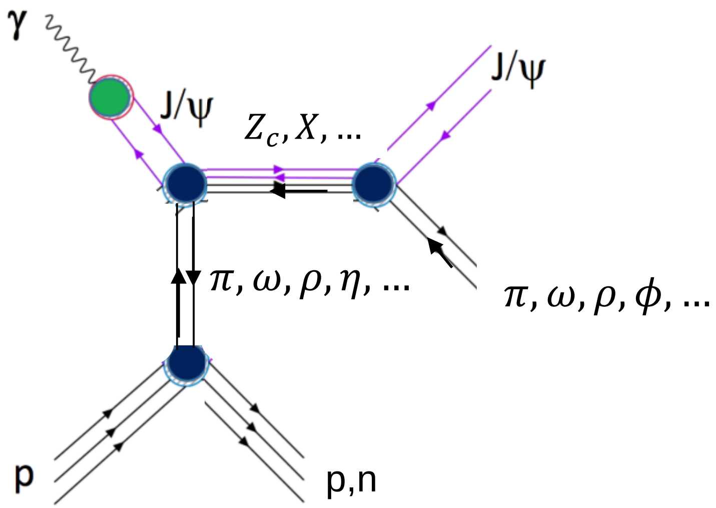


Search for Pc states



PRL 123, 072001 (2019)

Statistical errors will be improved



Summary and outlook

- It is a jungle out there! More exotic states than conventional for the charmonium above the open flavor threshold.
- Many relatively-narrow states at heavy meson-meson and meson-baryon thresholds.
  - Are they bound "molecular" states or something more complicated?
  - Quantitative and predictive theoretical model of such interactions?
- Tantalizing evidence for diquark hadrons. The strongest from $J/\psi J/\psi$ mass structure.
  - Experimental evidence needs to be solidified and provide more constraints on theoretical models.
  - How strong evidence for diquark is from conventional heavy baryons?
  - Stable diaquark tetraquarks?
- Any hybrid states in the mix?
- Do conventional heavy and light $q\bar{q}$, qqq states get modified by multiquark effects?
- A lot of work to do for both experimentalists and theorists!
  - EIC can contribute