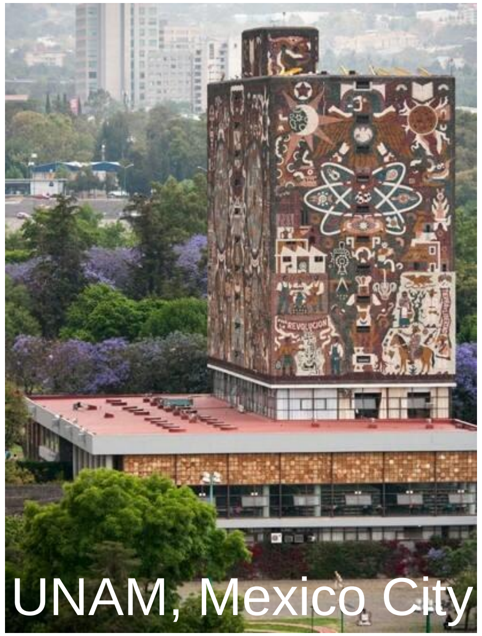
(Charm Hadron) Exotics

Tomasz Skwarnicki

Syracuse University, NY, USA

Exotic hadrons ≡ not $q\bar{q}, qqq$

Concentrate on developments since Charm 2018 (still selected topics)



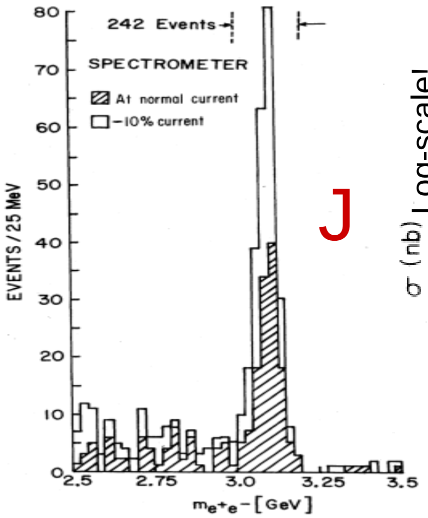
2021

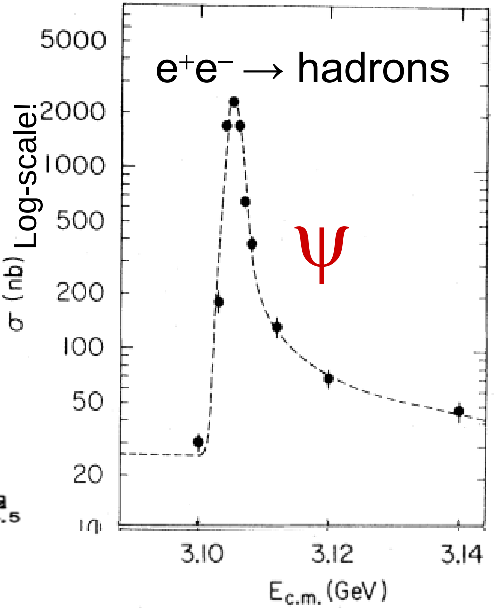
10th International Workshop on Charm Physics (CHARM 2020)

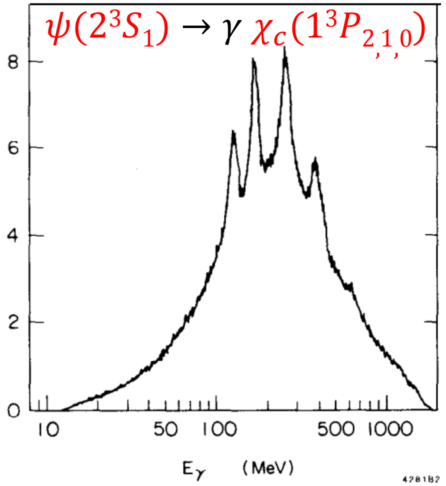
Initial charm revelation

November revolution of 1974

$pBe \to e^+e^- X$

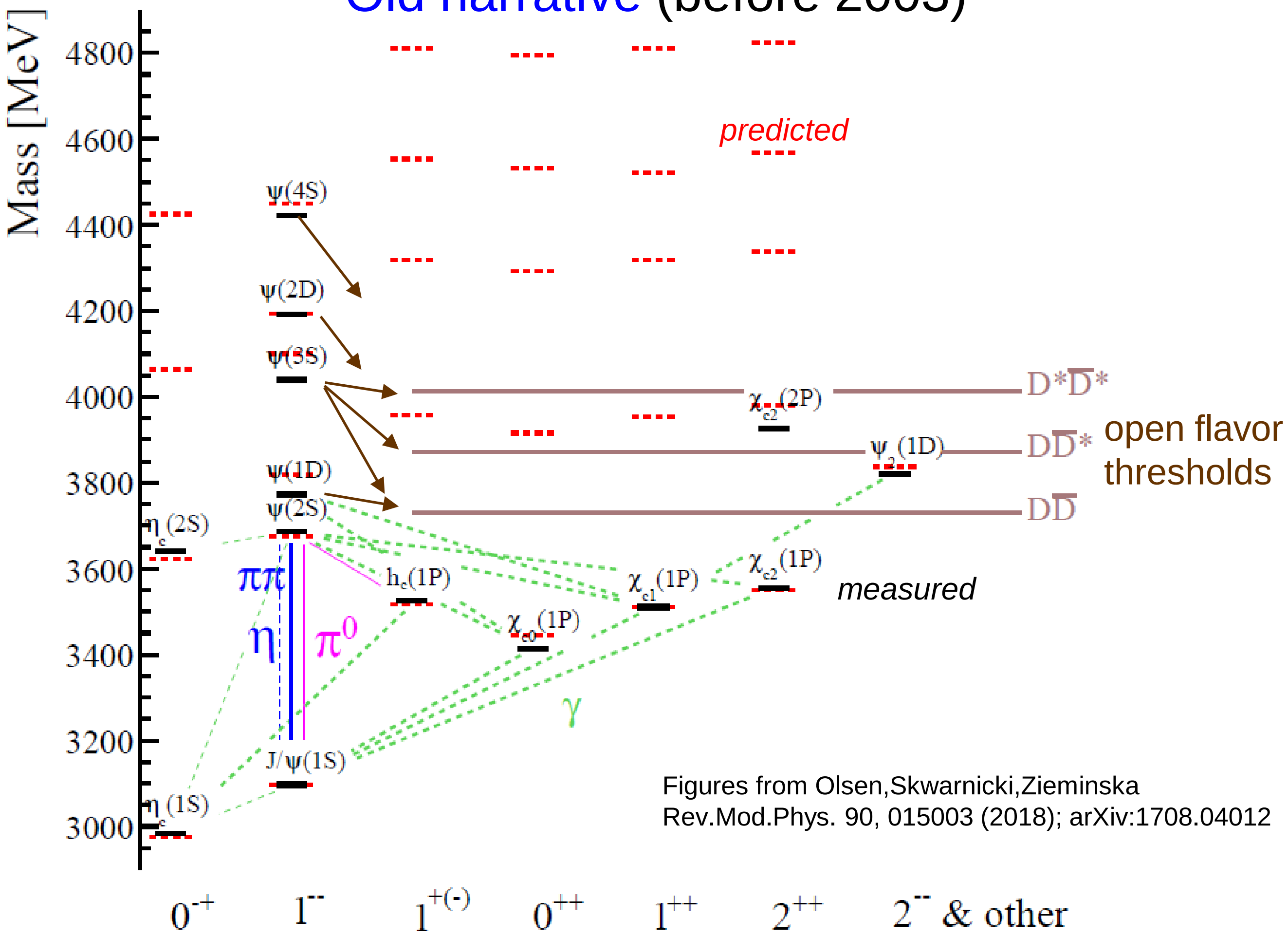






Crystal Ball SLAC-PUB-2887 (1982)

Old narrative (before 2003)

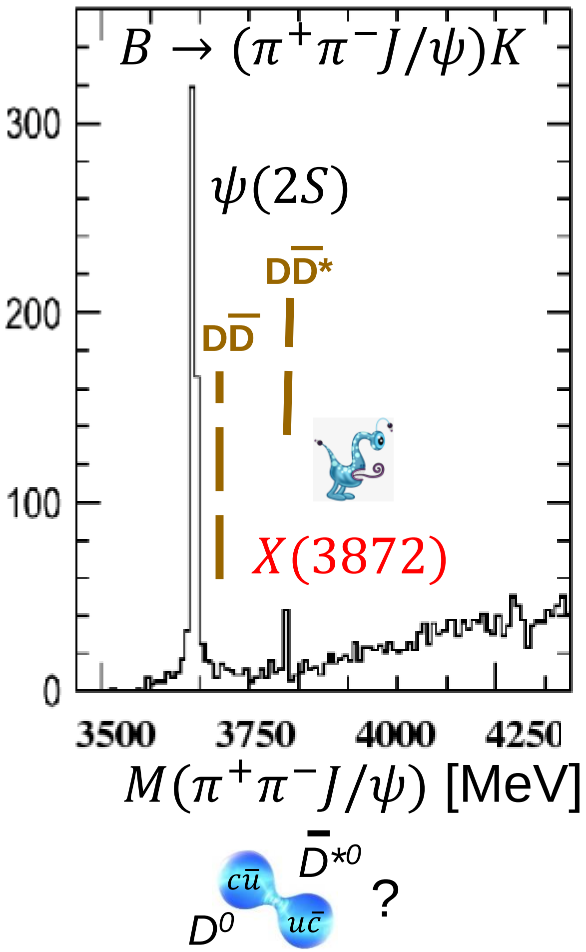


Figures from Olsen,Skwarnicki,Zieminska Rev.Mod.Phys. 90, 015003 (2018); arXiv:1708.04012

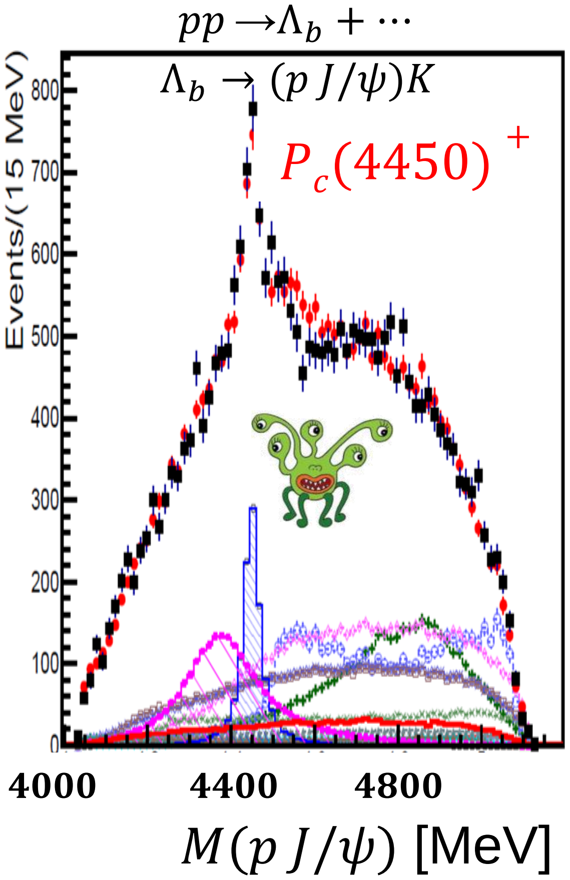
Mesons are $(q\bar{q})$ bound states.

Continuing charm revelations since 2003

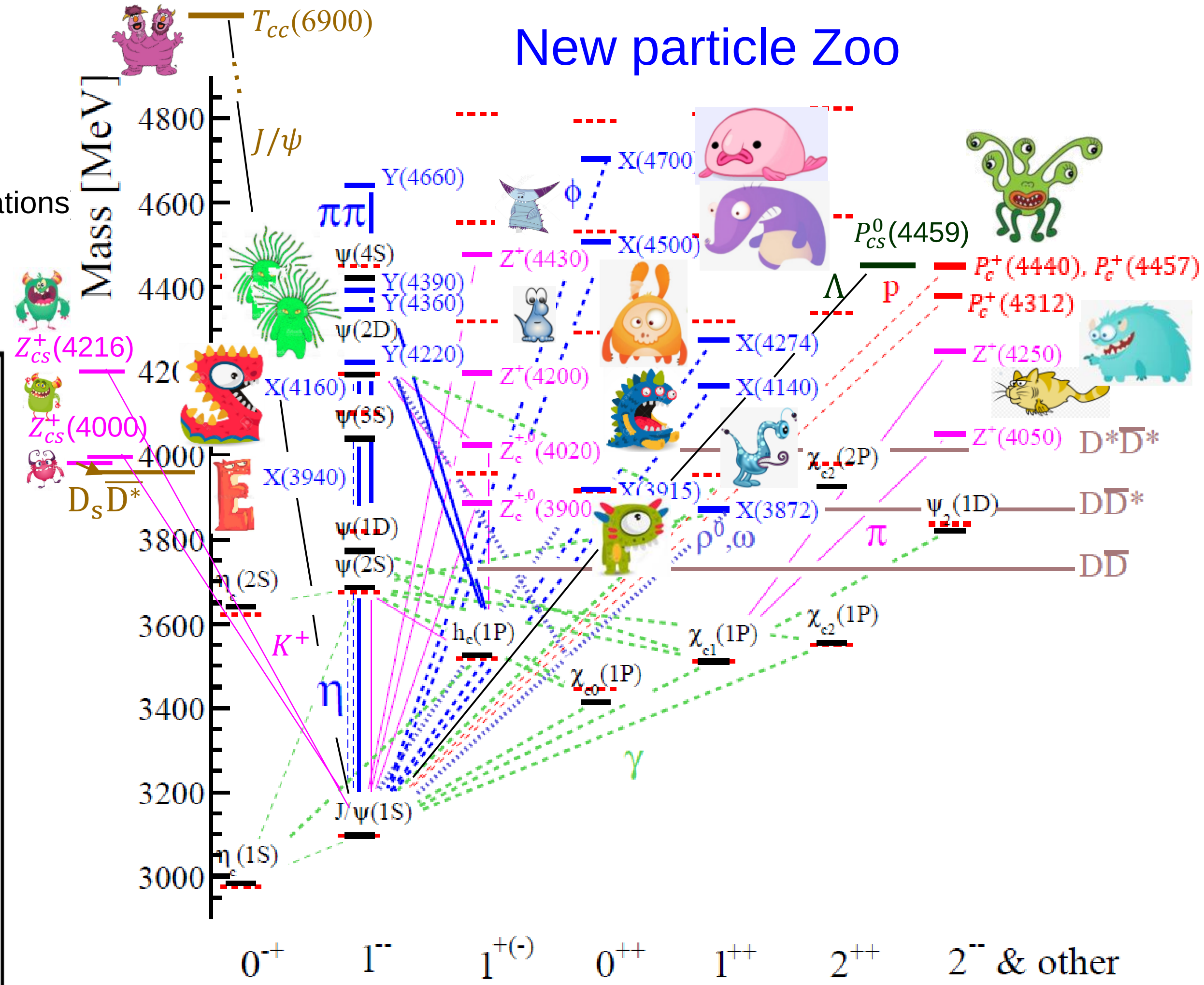
Belle 2003:
Discovery of X(3872)
PRL 91, 262001 (2003)
The most cited Belle paper (1947 citations)



LHCb 2015:
Discovery of Pc states
PRL 115, 07201 (2015)
The most cited LHCb paper (1218 citations



New particle Zoo

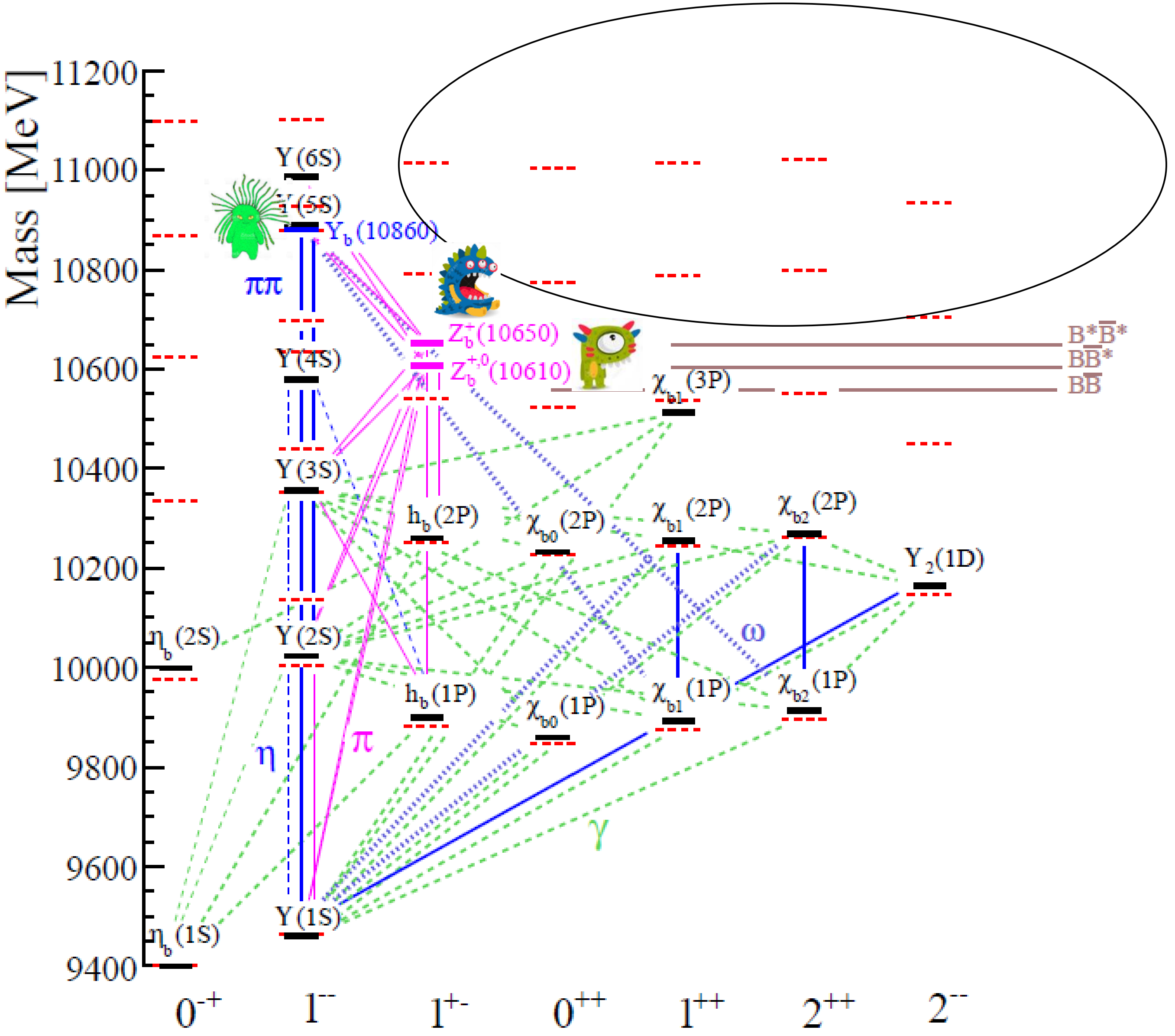


Mesons/baryons are **predominantly** $(q\bar{q}/qqq)$ bound states below the open flavor threshold.
They are more complex structures above it, and we have not yet understood them.

New particle Zoo: bottomonium above flavor threshold

Difficult to explore experimentally:

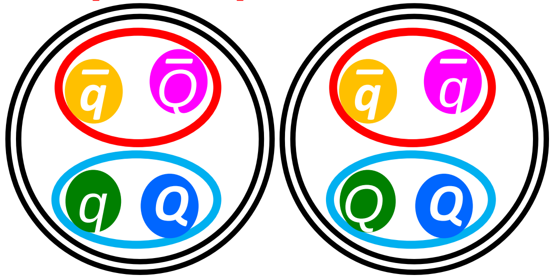
- Not accessible at e$^+$e$^-$ B-factories
- Prompt production at LHC more promising but comes with **suppressed cross-section** ($m_b > m_c$) and **very large combinatorial backgrounds** (huge particle multiplicities out of PV)
- $t \to bW$ at LHC does not produce secondary vertex unlike $b \to cW$ (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 → $b\bar{b}$)
  - Doubtful a dedicated high-luminosity e$^+$e$^-$ machine to scan above Υ(6S) would be built



Because of much easier experimental access, charm hadrons are a better goldmine!

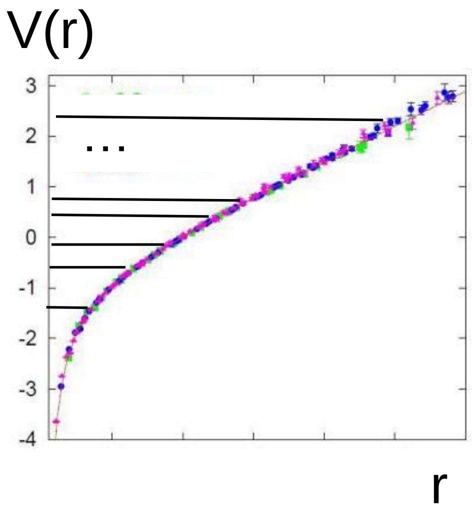
Types of exotic states expected

- 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**

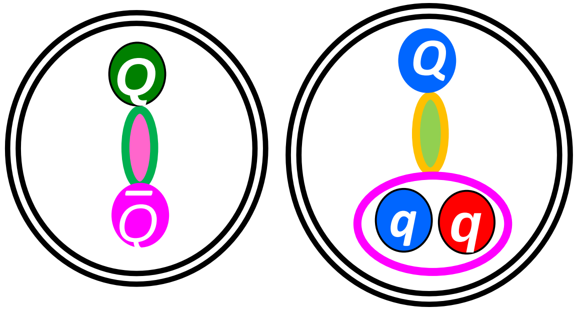


Very rich mass and J^P spectrum expected!

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

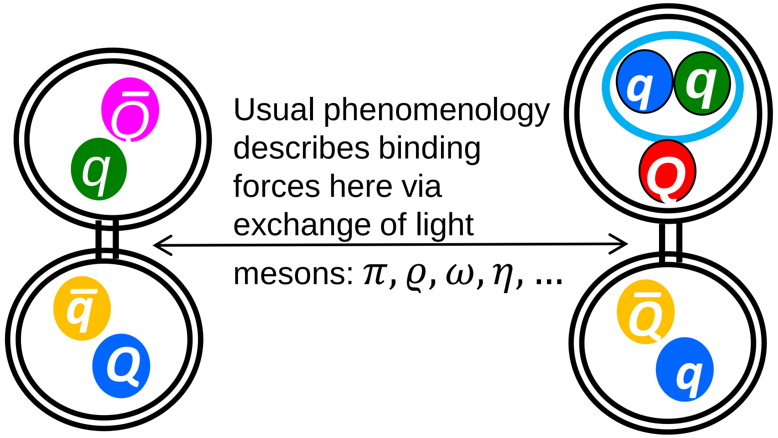


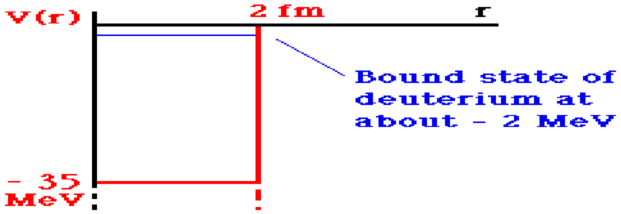
Mixing into higher mass excitation spectrum of mesons and baryons.

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"**





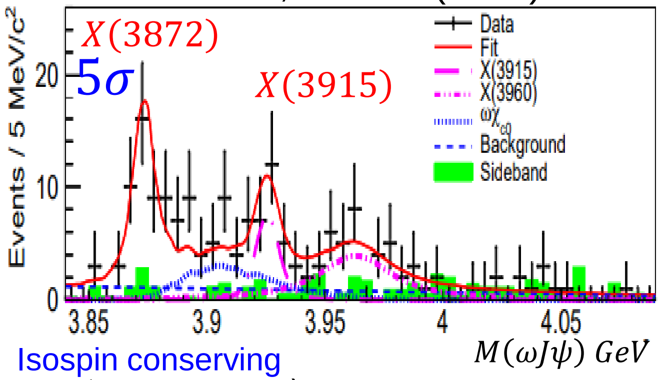
Typically expect only $n=1, L=0$ split by $\vec{S}_1 \cdot \vec{S}_2$

Mass and J^P fairly constrained from the constituents.

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

A lot of recent measurements on X(3872)

BESIII PRL 122, 232002 (2019)

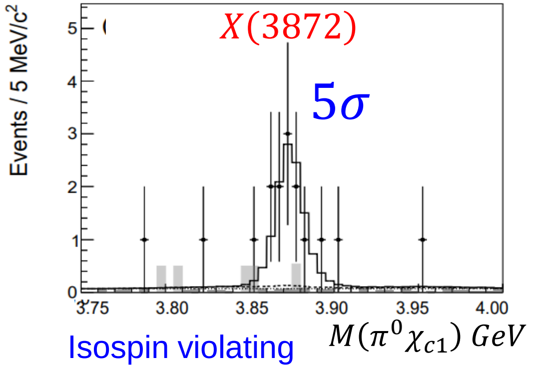


Isospin conserving

$$\frac{BR(X(3872)\to\omega J/\psi)}{BR(X(3872)\to\pi^+\pi^- J/\psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$$

in agreement with Belle (2005)
,and BaBar (2010)

BESIII PRL 122, 202001 (2019)



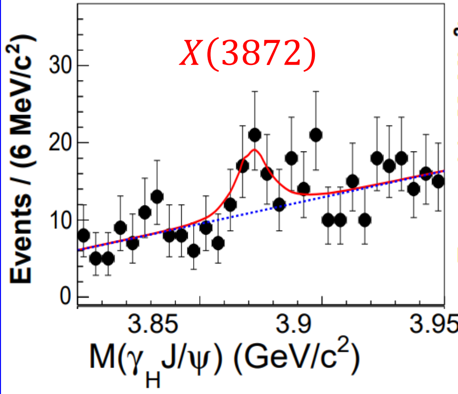
Isospin violating

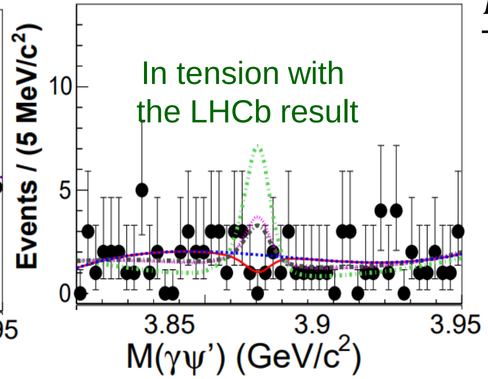
$$\frac{BR(X(3872)\to\pi^0\chi_{c1})}{BR(X(3872)\to\pi^+\pi^- J/\psi)} = 0.88^{+0.33}_{-0.27} \pm 0.10$$

Isospin violation in the denominator (ϱ^0)

Large isospin violations in X(3872) still the best evidence for it not being $c\bar{c}$. ($D^0\bar{D}^{*0}$?)

BESIII PRL 124, 242001 (2020)





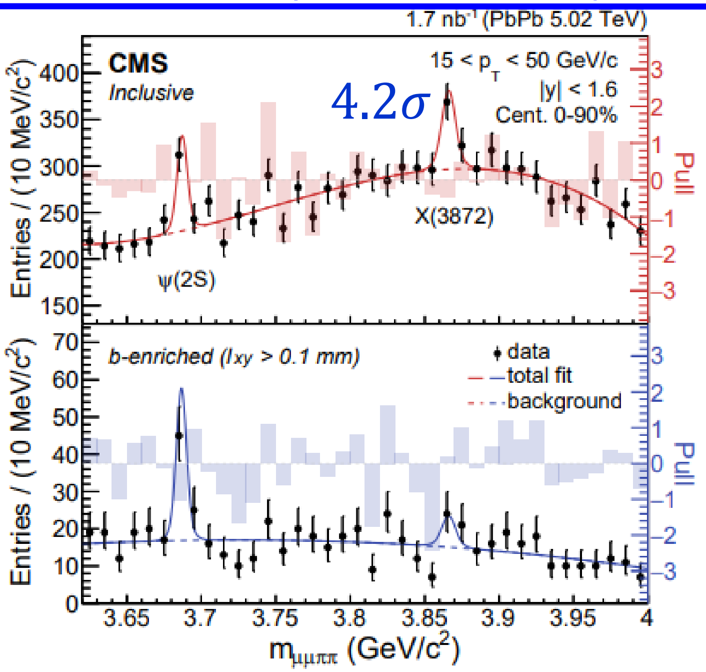
$$\frac{BR(X(3872)\to\gamma\psi(2S))}{BR(X(3872)\to\gamma J/\psi)} < 0.59\ (90\%\ CL)$$

All measurements statistically marginal.

$\chi_{c1}(2P)\to\gamma\psi(2S)$ favored E1 transition.

Important controversy to resolve

See the next talk by Feng-Kun Guo for more on X(3872)



$$\frac{\sigma(PbPb\to(X(3872)\to\pi^+\pi^- J/\psi))+\cdots)}{\sigma(PbPb\to(\psi(2S)\to\pi^+\pi^- J/\psi))+\cdots)} = 1.08 \pm 0.49 \pm 0.52$$

vs ~0.1 in pp collisions

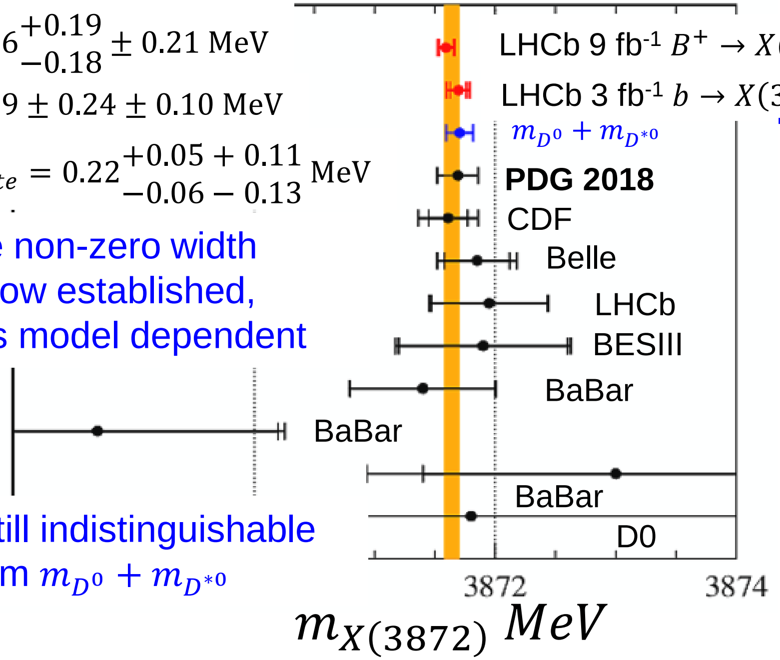
Need more data!

$\Gamma_{BW} = 0.96^{+0.19}_{-0.18} \pm 0.21$ MeV

$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10$ MeV

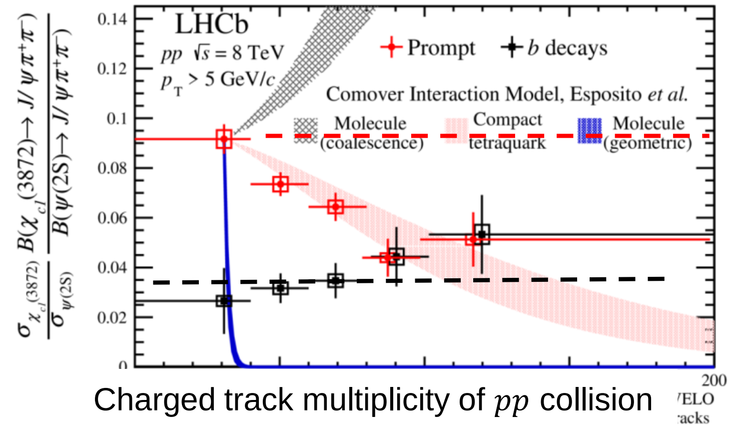
$FWHM_{Flatte} = 0.22^{+0.05\,+0.11}_{-0.06\,-0.13}$ MeV

The non-zero width is now established, but it is model dependent



Mass still indistinguishable from $m_{D^0}+m_{D^{*0}}$

LHCb 2 fb^{-1} PRL 126 , 092100 (2021)

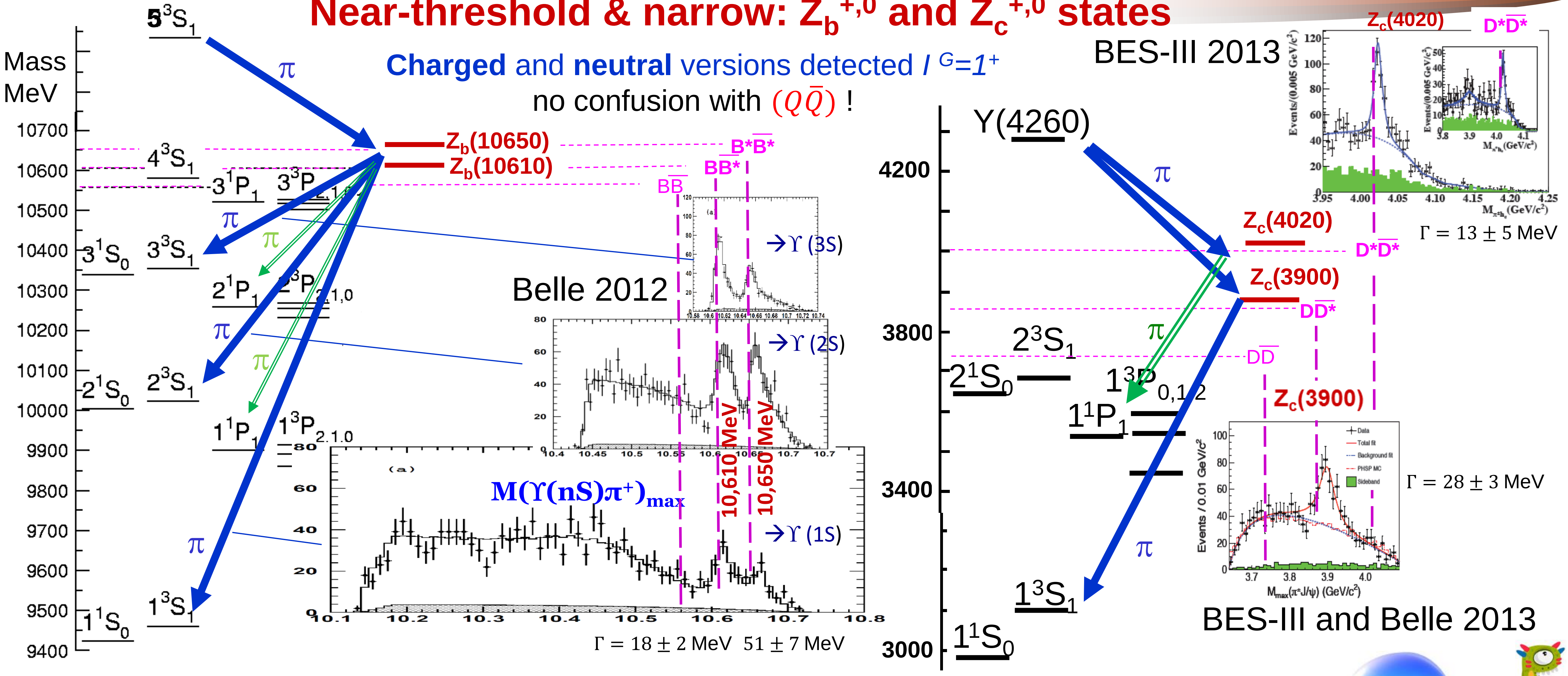


In prompt pp, production of X(3872) is suppressed with multiplicity relative to $\psi(2S)$

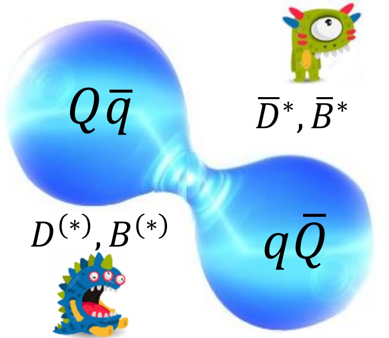
Near-threshold & narrow: $Z_b^{+,0}$ and $Z_c^{+,0}$ states

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

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



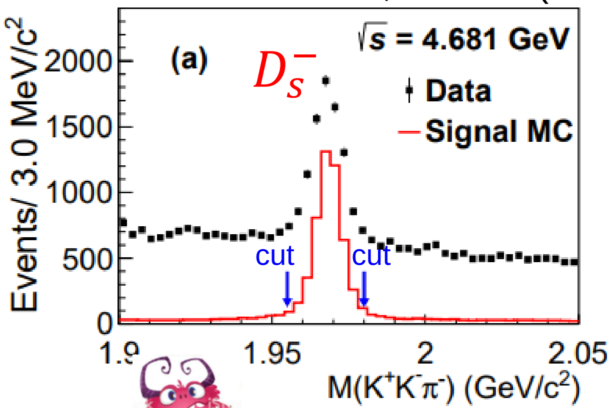
- Near thresholds, relatively narrow, large fall-apart modes, $J^P=1^+$ ⟶ molecular states $B\bar{B}^*$, $B^*\bar{B}^*$, $D\bar{D}^*$, $D^*\bar{D}^*$ (very weakly bound or virtual). No sign of such states at $D\bar{D}$ and $B\bar{B}$, hints at forces dominated by π exchange.
- Not everybody agrees: the 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.

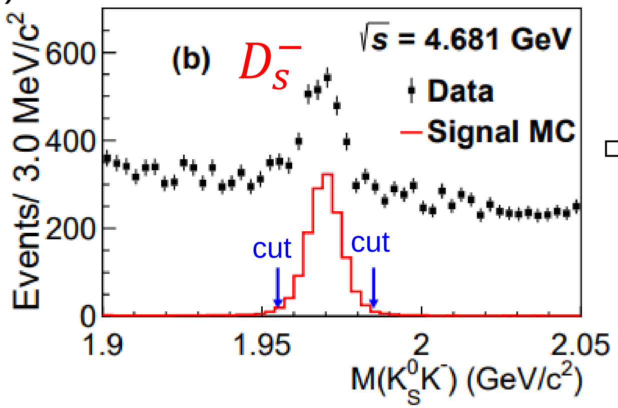


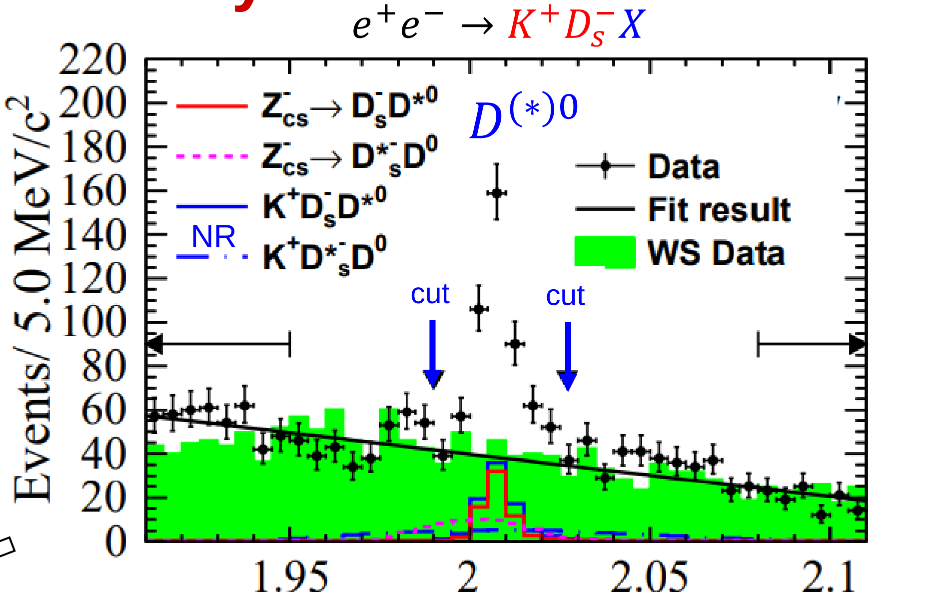
Observation of narrow $Z_{cs}^{-} \to D_s^- D^{*0}$, $D_s^{*-} D^0$ state by BESIII

Clever partial reconstruction technique

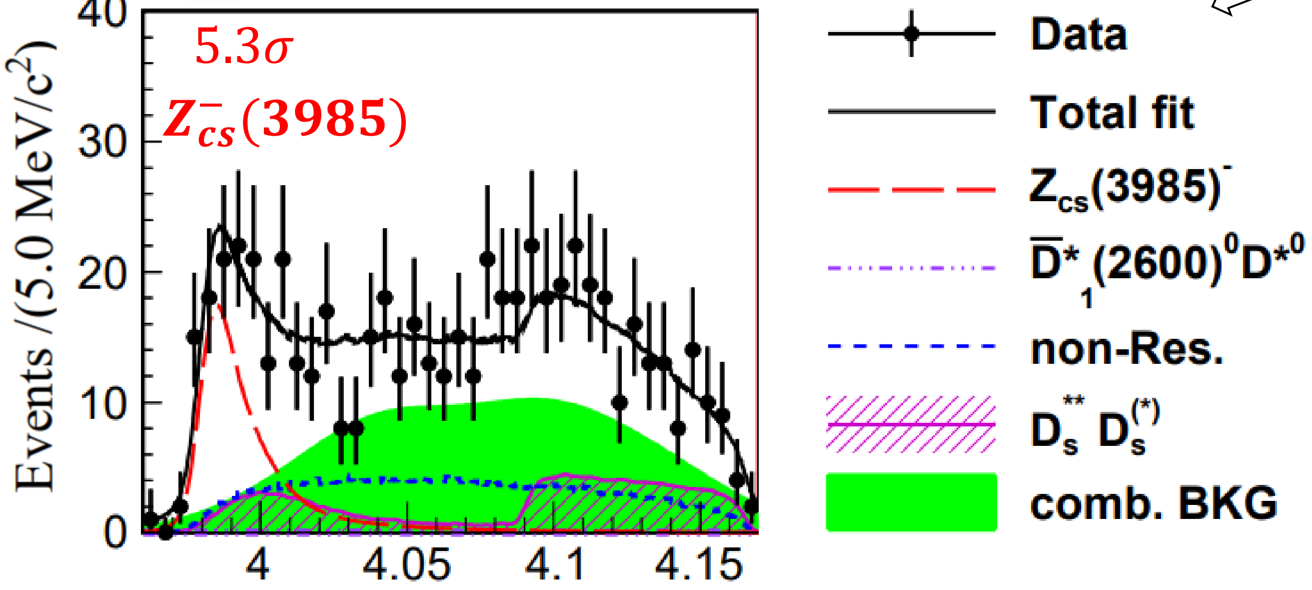
BESIII PRL 126, 102001 (2021)







$M(X)$ via Recoil Mass against $K^+ D_s^-$



$M(D_s^- D^{(*)0})$ via Recoil Mass against K^+

$$m_{Z_{cs}(3985)} = 3982.5^{+1.8}_{-2.6} \pm 2.1 \ MeV$$

$$m_{D_s^-} + m_{D^{*0}} = 3975.2 \pm 0.1 \ MeV$$

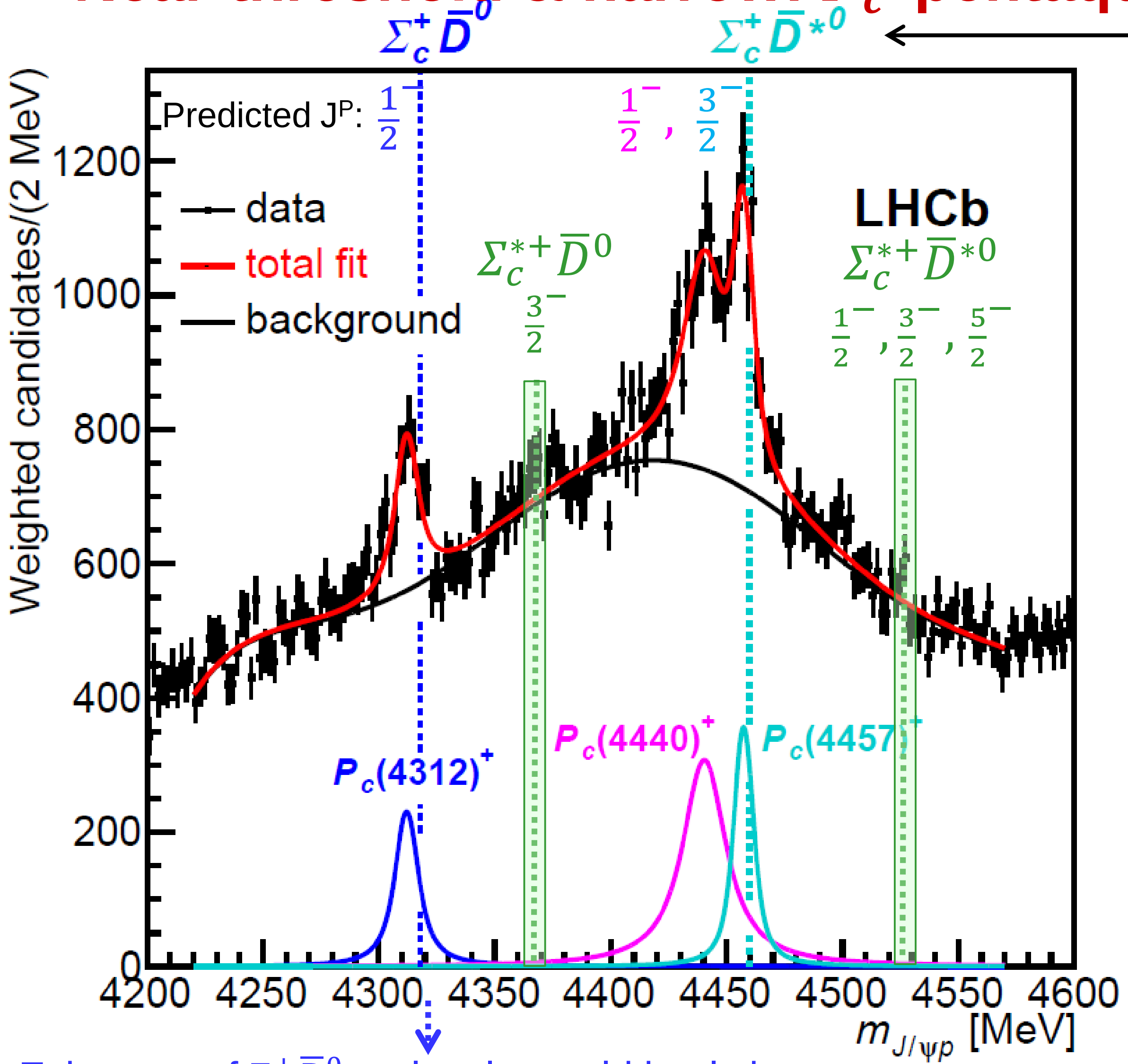
$$m_{D_s^{*-}} + m_{D^0} = 3977.0 \pm 0.4 \ MeV$$

$$\Gamma_{Z_{cs}(3985)} = 12.8^{+5.3}_{-4.4} \pm 3.0 \ MeV$$

Narrow, a few MeV above the threshold

SU(3)$_f$ partner of $Z_c^{\pm,0}(3900)$?

Near-threshold & narrow: P_c^+ pentaquark states

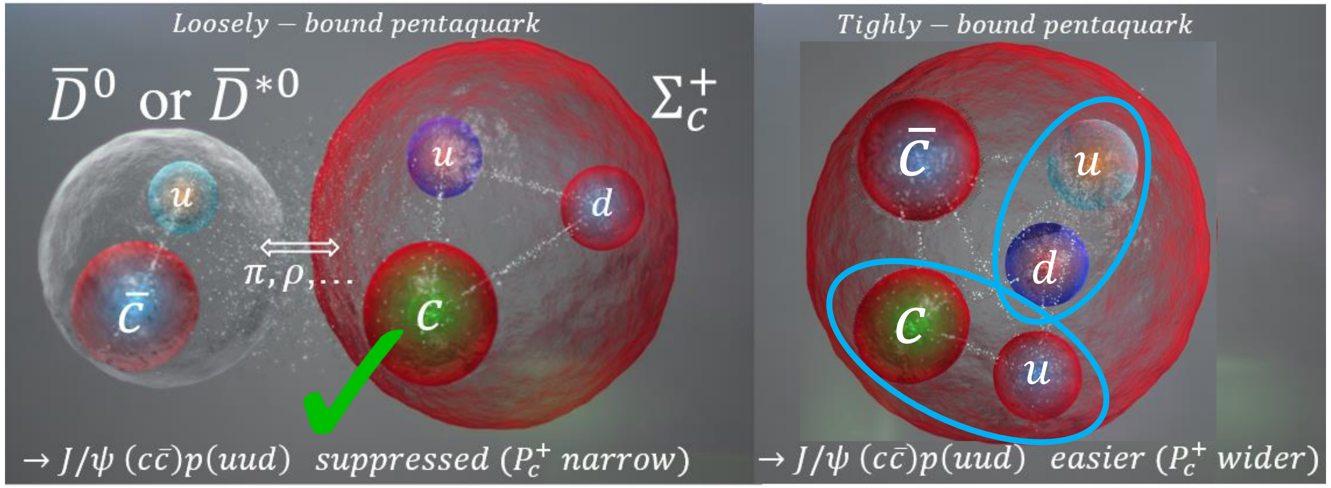


The **only** thresholds in this mass range below which molecular bound states of very-narrow hadrons are expected

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

9x more than in 2015

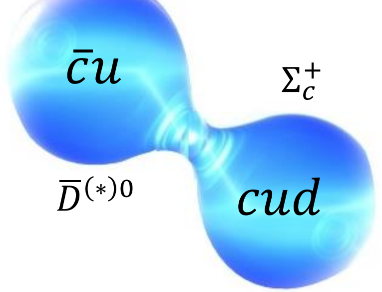
LHCb PRL 122, 222001 (2019)



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 $\Sigma_c^{*+}\bar{D}^{(*)0}$



?

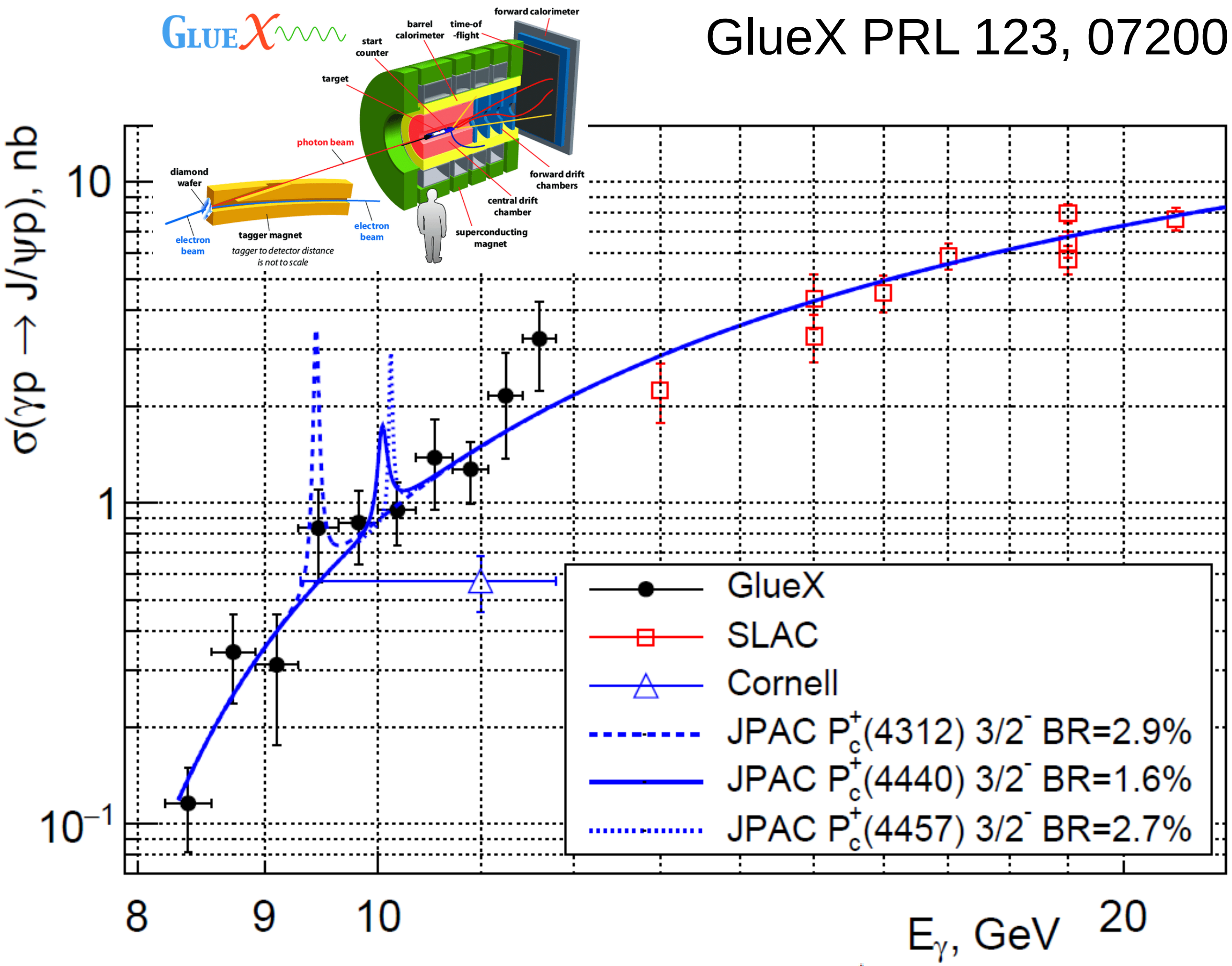
Existence of $\Sigma_c^+\bar{D}^0$ molecule would imply importance of $\pi\pi$ or ρ-exchanges

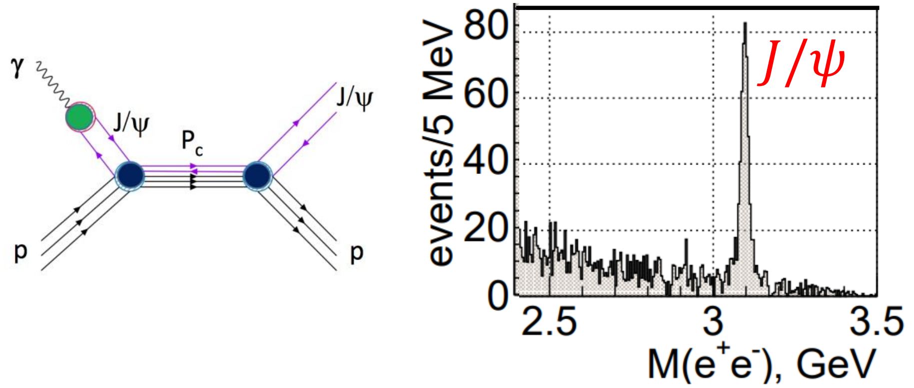
Narrow, near-threshold states!

$\Gamma < O(10^1)$ MeV

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

GlueX PRL 123, 072001 (2019)





No photo-produced P_c^+ states have been observed so far.
Expected cross-sections are model dependent.
More data will be analyzed.

<4.6nb
<1.8nb
<3.9nb

$$\sigma_{max}(\gamma \rightarrow P_c^+)BR(P_c^+ \rightarrow J/\psi p)$$

at 90% C.L.

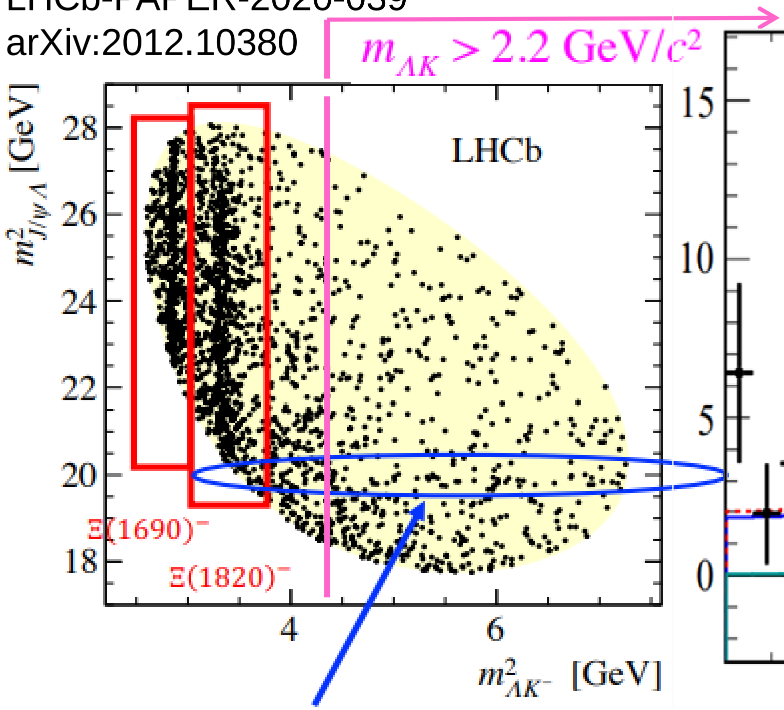
In Refs. [30–32] the partial widths of the $P_c^+ \to J/\psi p$ decays were calculated and shown to be orders of magnitude different for two pentaquark models, the hadrocharmonium and molecular models. Our upper limits on the branching fractions do not exclude the molecular model, but are an order of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

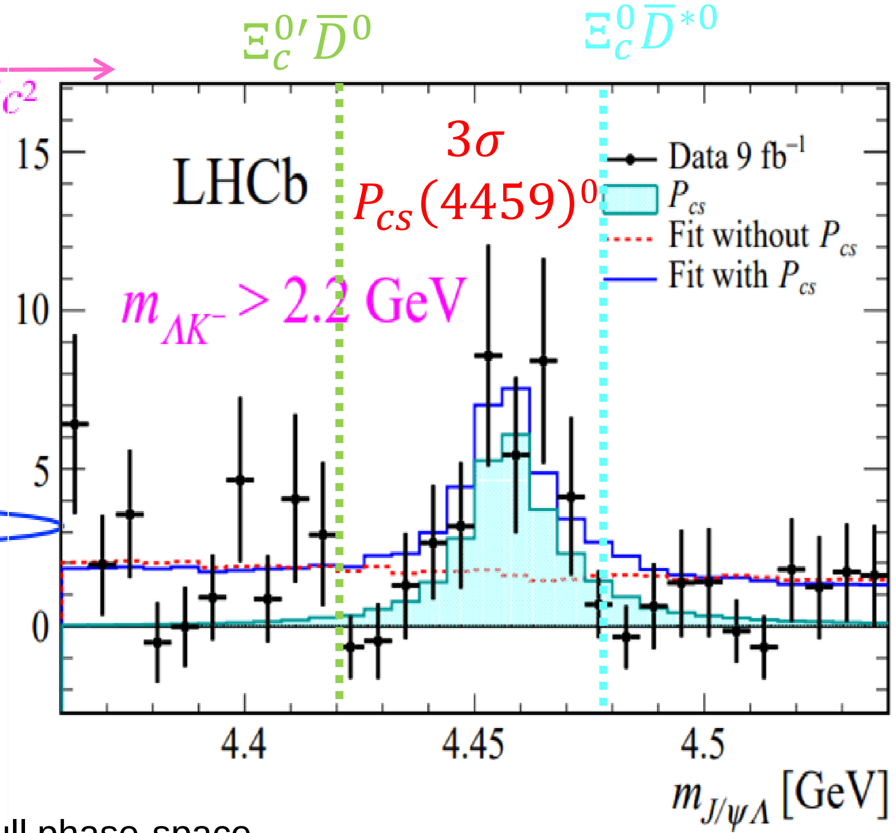
[30] M. I. Eides, V. Yu. Petrov, and M. V. Polyakov, Eur. Phys. J. **C78**, 36 (2018).
[31] M. I. Eides and V. Yu. Petrov, Phys. Rev. **D98**, 114037 (2018).
[32] M. I. Eides, V. Y. Petrov, and M. V. Polyakov, arXiv:1904.11616 (2019).

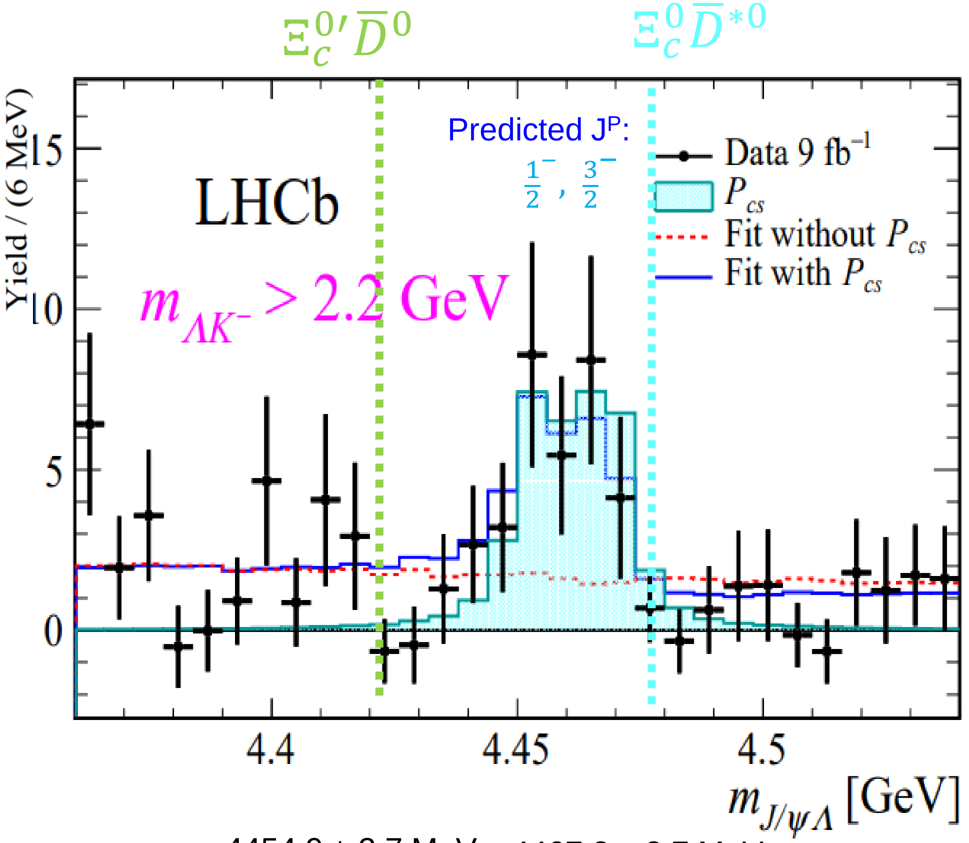
Near-threshold & narrow: P^0_{cs} pentaquark states?

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

LHCb-PAPER-2020-039
arXiv:2012.10380





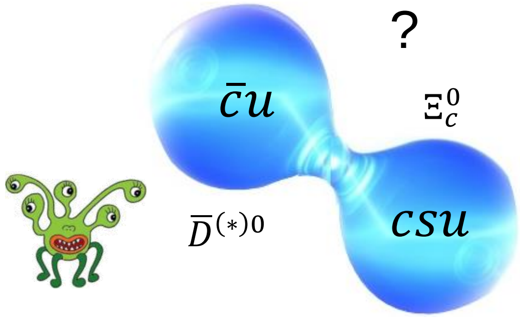


4454.9 ± 2.7 MeV
7.5 ± 9.7 MeV

4467.8 ± 3.7 MeV
5.2 ± 5.3 MeV

Amplitude analysis in full phase-space

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

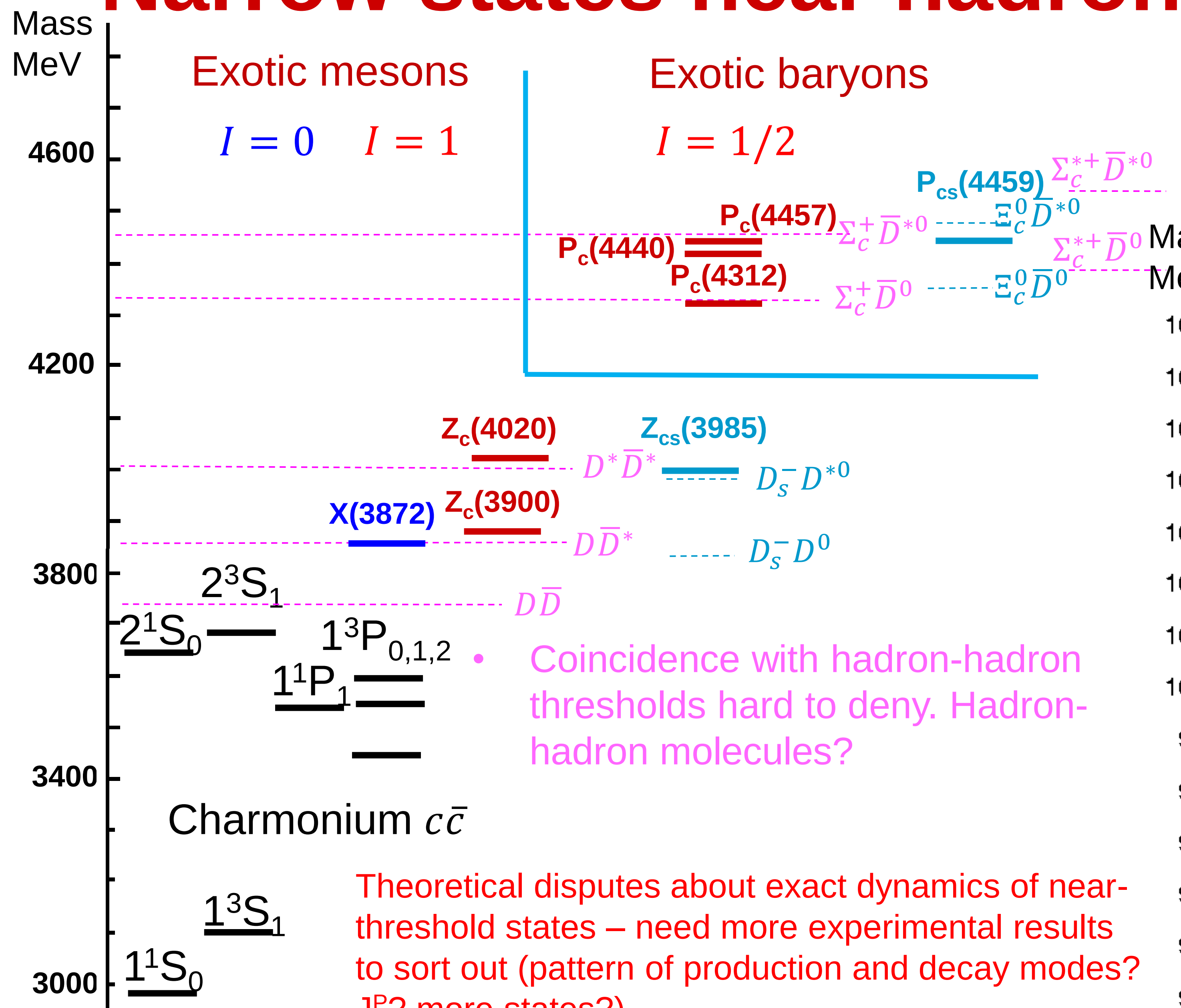


3σ evidence for
a $J/\psi\Lambda$ mass structure

one or two states?

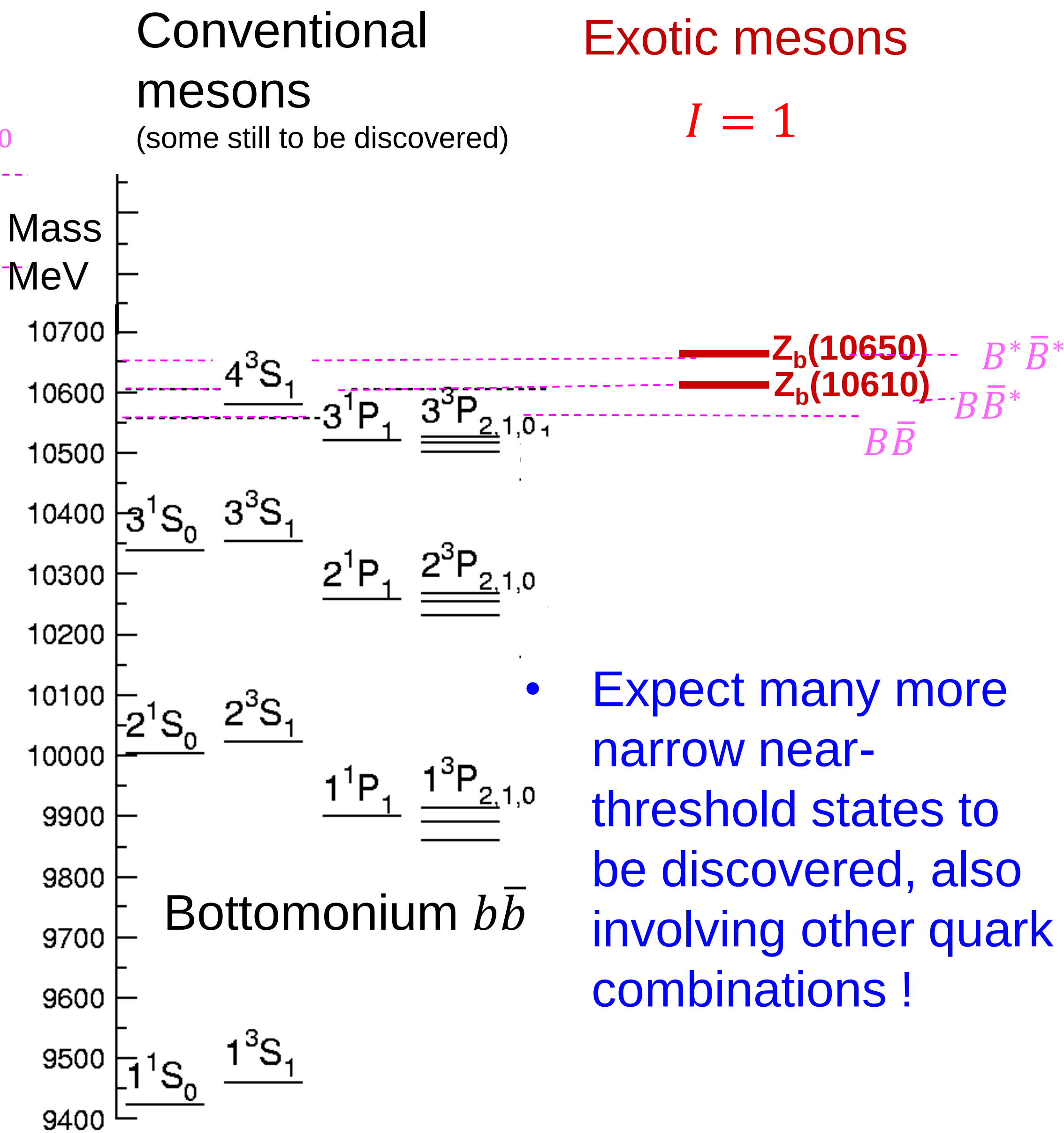
Need more data!

Narrow states near hadron-hadron thresholds



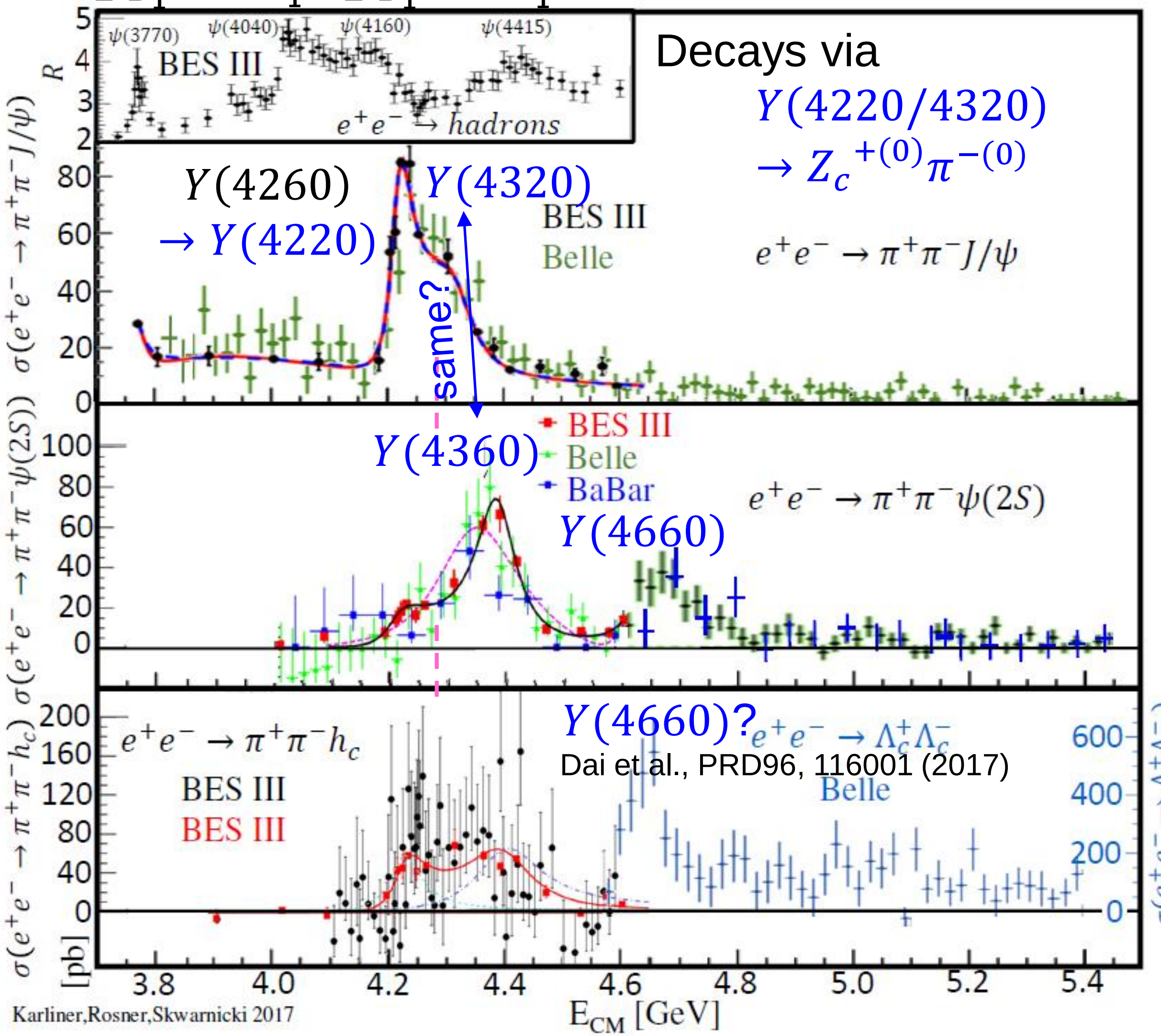
- Coincidence with hadron-hadron thresholds hard to deny. Hadron-hadron molecules?

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 !

Anomalous charmonium-like vector states

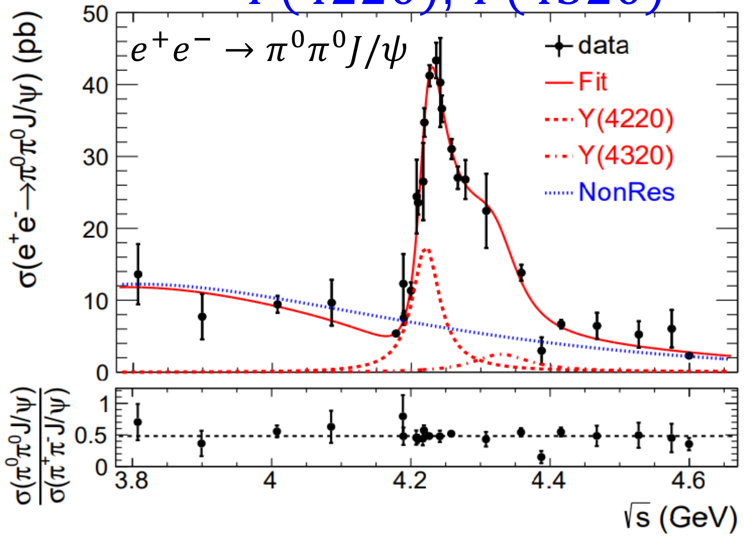


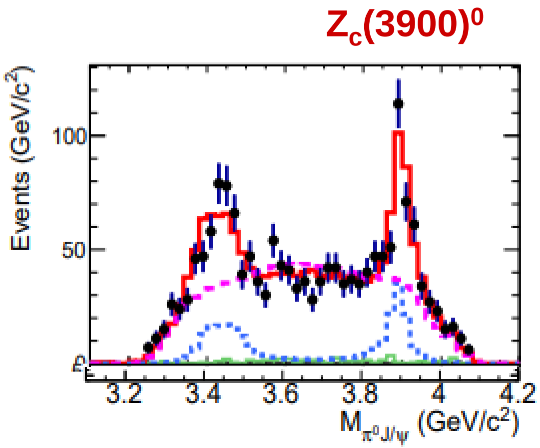
Decays via $Y(4220/4320) \to Z_c^{+(0)}\pi^{-(0)}$

$gc\bar{c}$ hybrid states?,
$(cd)(\bar{c}\bar{d})$ tetraquarks,…?

BESIII PRD 102, 012009 (2020)

$Y(4220)$, $Y(4320)$

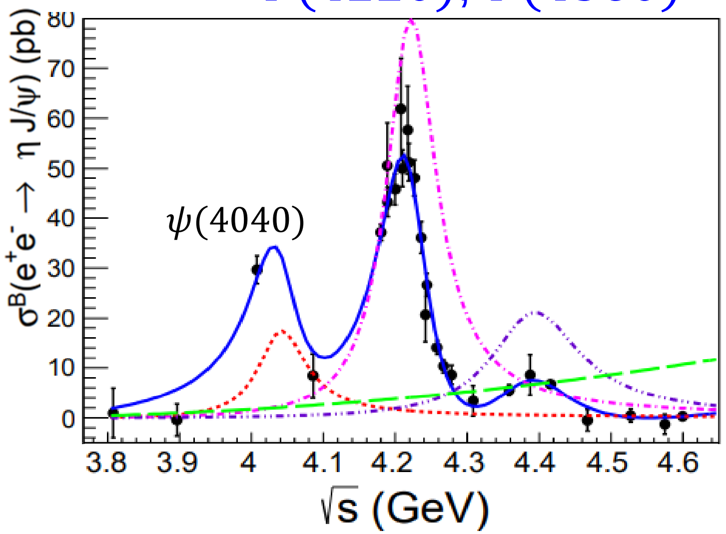


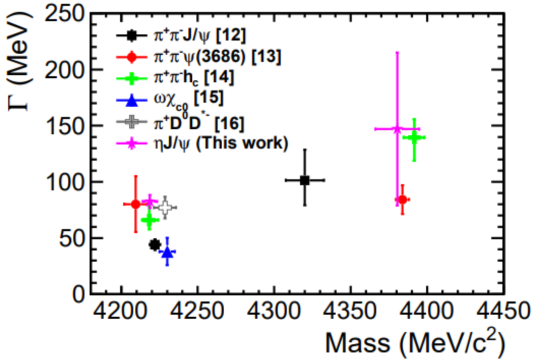


Good isospin symmetry between $\pi^0\pi^0 J/\psi$ and $\pi^+\pi^- J/\psi$

BESIII PRD 102, 031101 (2020)

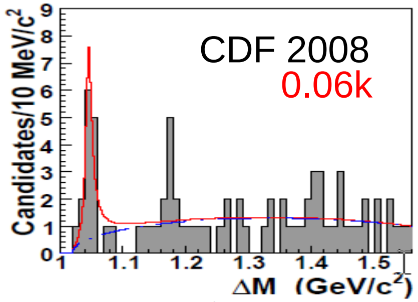
$Y(4220)$, $Y(4360)$

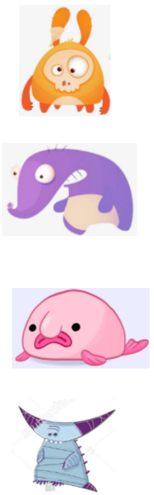


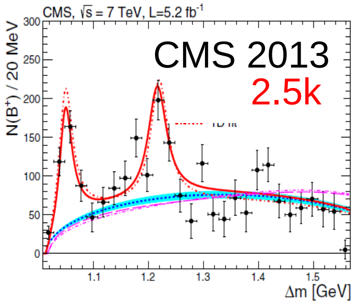


The channel that keeps giving: $B^+ \to J/\psi\phi K^+$

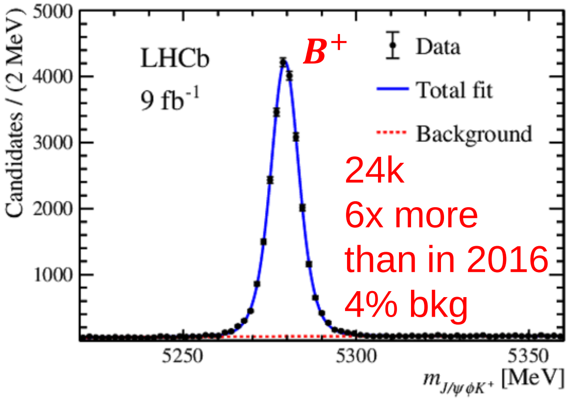
$B \to XK, X \to J/\psi\phi$



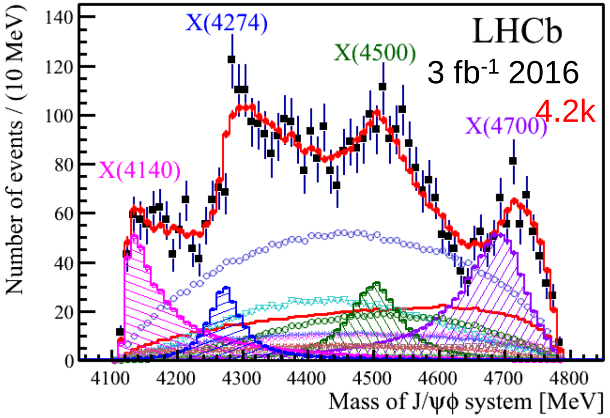


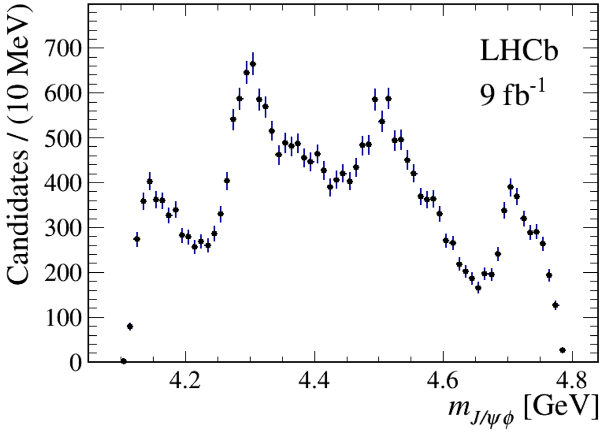


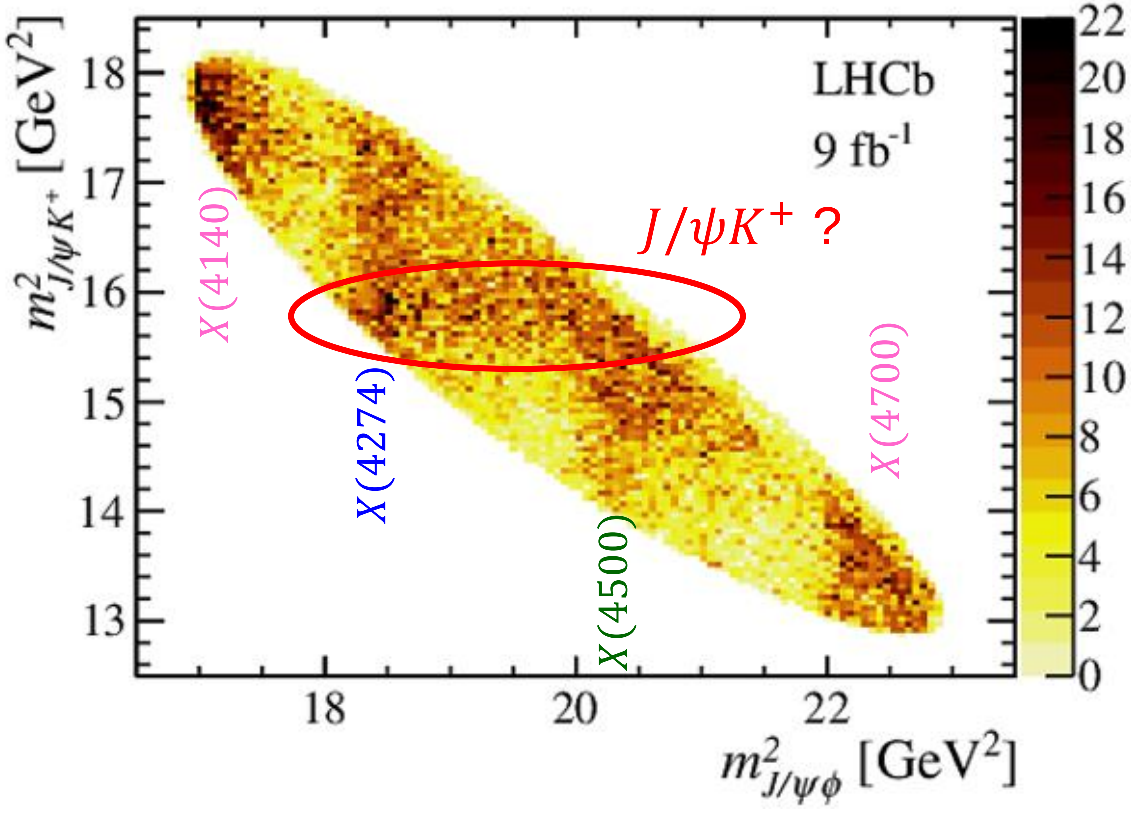
LHCb-PAPER-2020-044
arXiv:2103.01803 Mar 2021



Dramatic sign of new spectroscopy!







A whole family of $J/\psi\phi$ states! **Not so narrow and not near molecular thresholds.**

$J/\psi\omega$ spectra in $B^+ \to J/\psi\omega K^+$ are different ($c\bar{c}$ explanations not plausible).

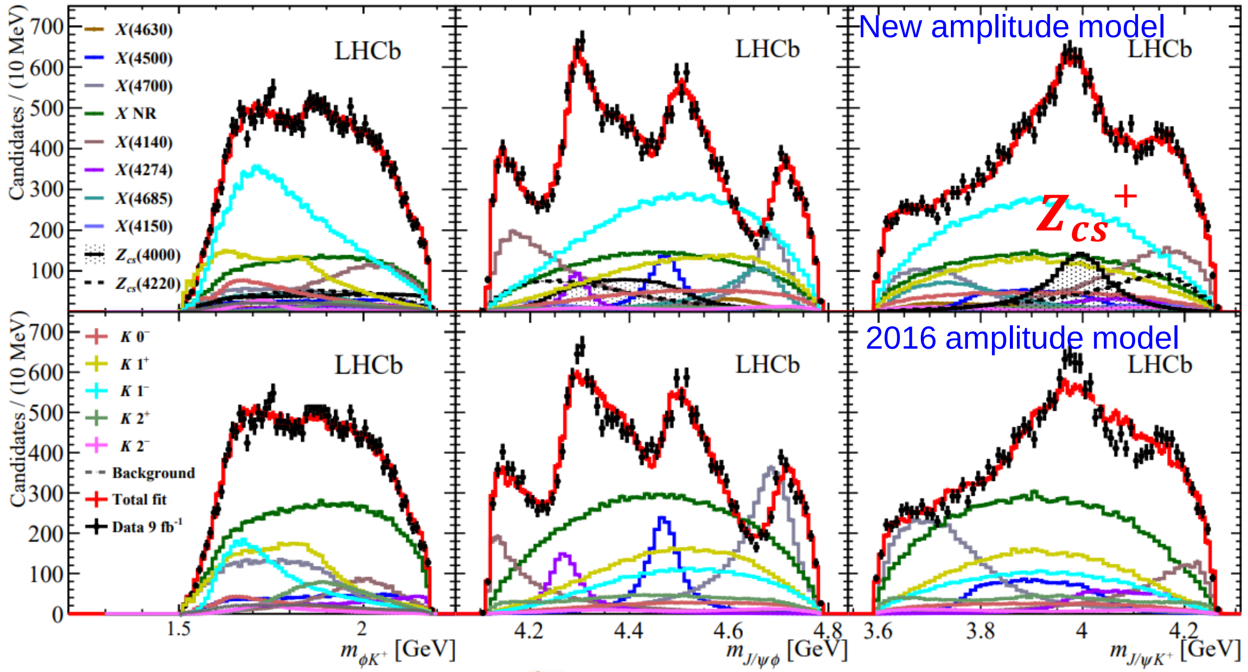
$(cs)(\bar{c}\bar{s})$ **tetraquarks?**

Observation of $Z_{cs}^{+} \to J/\psi K^{+}$ states

LHCb-PAPER-2020-044
arXiv:2103.01803 Mar 2021

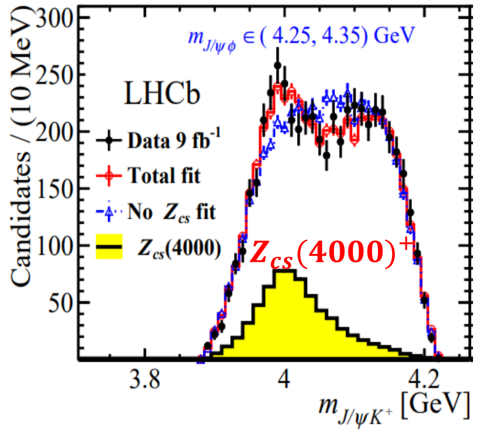
New amplitude analysis of $B^{+} \to J/\psi\phi K^{+}$

Contribution		Significance [$\times\sigma$]	M_0 [MeV]	Γ_0 [MeV]	FF [%]
	All $K(1^+)$				$25 \pm 4\,^{+\ 6}_{-15}$
2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10\,^{+16}_{-46}$	$149 \pm 41\,^{+231}_{-\ 23}$	
2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37\,^{+124}_{-\ 48}$	$276 \pm 50\,^{+319}_{-159}$	
1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3\,^{+\ 3}_{-11}$
	All $K(2^-)$				$2.1 \pm 0.4\,^{+2.0}_{-1.1}$
1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
	All $K(1^-)$				$50 \pm 4\,^{+10}_{-19}$
1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2\,^{+35}_{-\ 8}$
2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5\,^{+11}_{-17}$
	$K(2^+)$				
2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22\,^{+194}_{-\ 31}$	$318 \pm 82\,^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
	$K(0^-)$				
2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2\,^{+1.0}_{-3.8}$
	$X(2^-)$				
	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
	$X(1^-)$				
	$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+\ 18}_{-110}$	$174 \pm 27\,^{+134}_{-\ 73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
	All $X(0^+)$				$20 \pm 5\,^{+14}_{-\ 7}$
	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6\,^{+10}_{-\ 8}$	$5.6 \pm 0.7\,^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4\,^{+16}_{-\ 3}$	$87 \pm 8\,^{+16}_{-\ 6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
	All $X(1^+)$				$26 \pm 3\,^{+\ 8}_{-10}$
	$X(4140)$	13 (16)	$4118 \pm 11\,^{+19}_{-36}$	$162 \pm 21\,^{+24}_{-49}$	$17 \pm 3\,^{+19}_{-\ 6}$
	$X(4274)$	18 (18)	$4294 \pm 4\,^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5\,^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
	All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6\,^{+\ 4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-\ 7}$



Even more, less obvious, $J/\psi\phi$ states needed (rich spectroscopy)

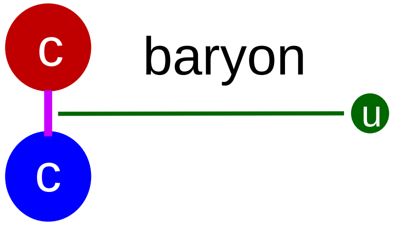
Previously claimed, dominant, $J/\psi\phi$ states confirmed



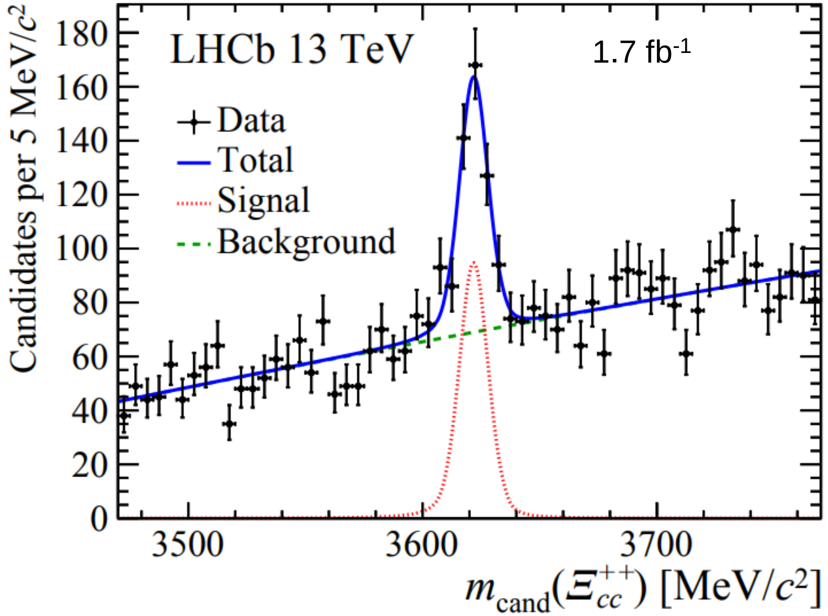
$Z_{cs}(4000)^{+}$ significantly wider than $Z_{cs}(3985)^{+}$ from BESIII.
Likely different states with different dynamics.

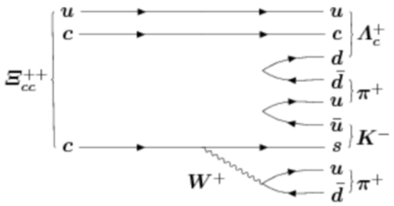
Two $J/\psi K^{+}$ states needed, $Z_{cs}(4000)^{+}$ with overwhelming significance

Doubly flavored baryons and stable (?) tetraquarks



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





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

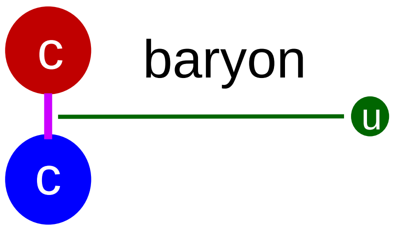
Karliner,Rosner PRD90,094007 (2014)

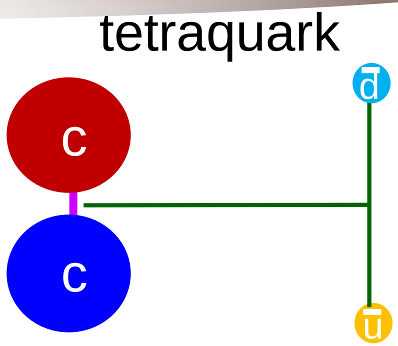
State	Quark content	$M(J=1/2)$	$M(J=3/2)$
$\Xi_{cc}^{(*)}$	ccq	3627 ± 12	3690 ± 12
$\Xi_{bc}^{(*)}$	$b[cq]$	6914 ± 13	6969 ± 14
Ξ'_{bc}	$b(cq)$	6933 ± 12	$\cdots$
$\Xi_{bb}^{(*)}$	bbq	10162 ± 12	10184 ± 12

LHCb: 3621 ± 1

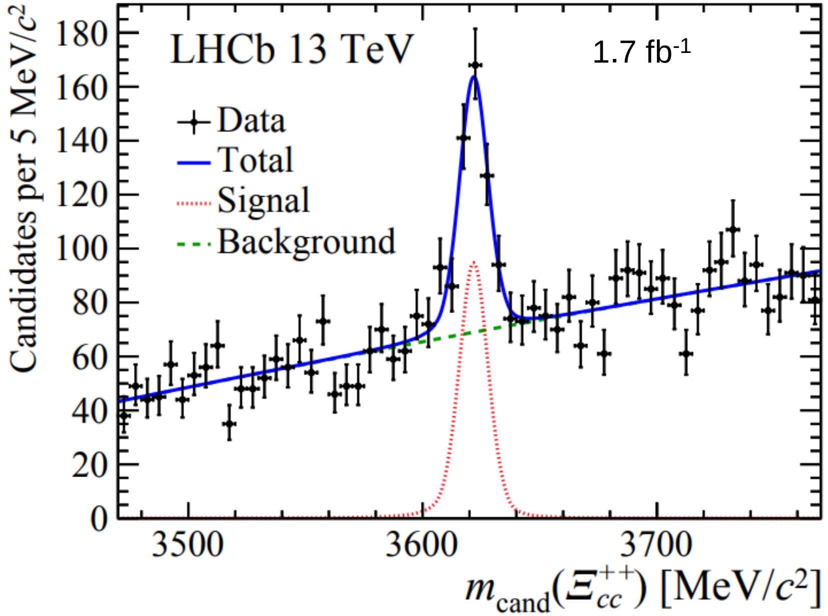
55

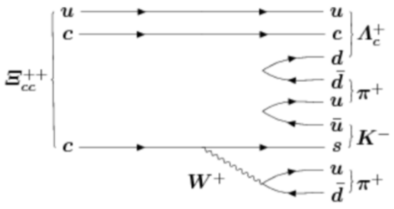
Doubly flavored baryons and stable (?) tetraquarks





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





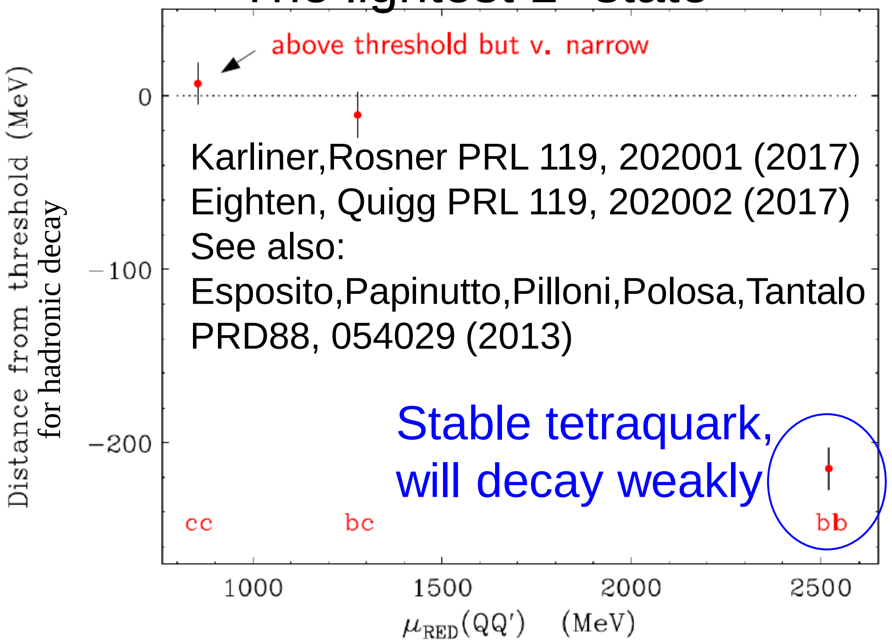
the same toolkit

<u>Karliner,Rosner PRD90,094007 (2014)</u>

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 55

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

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

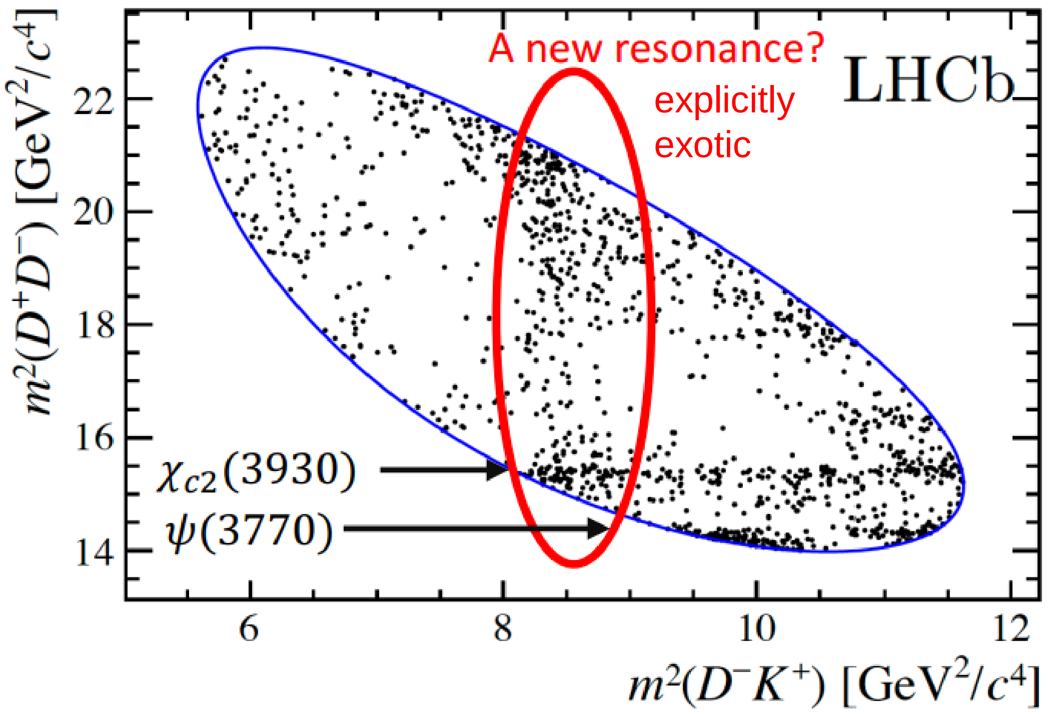
Future searches for such states above or below the $(Q\bar{q})(Q\bar{q})$ threshold will be very exciting

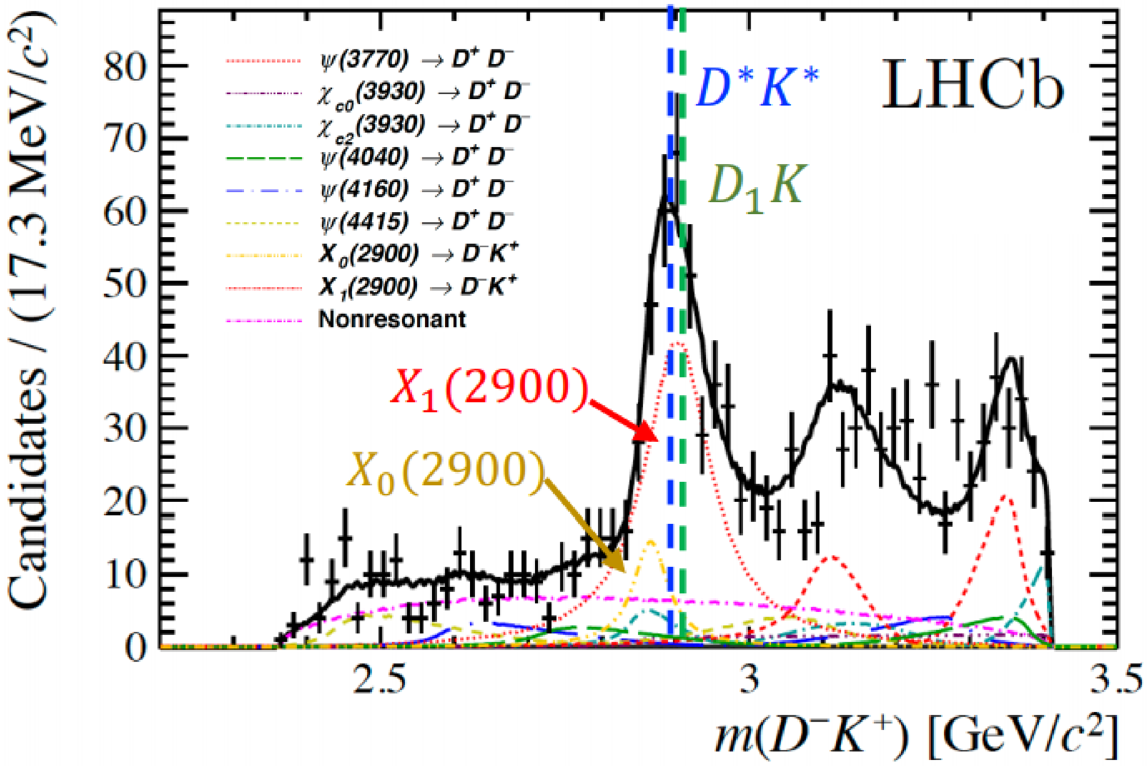
Charming and strange exotic state

LHCb 9 fb^{-1} PRD102, 112003 (2020) amplitude analysis
PRL 125, 242001 (2020) model-independent

$1.3k\ B^+ \to D^+ D^- K^+$

Amplitude analysis

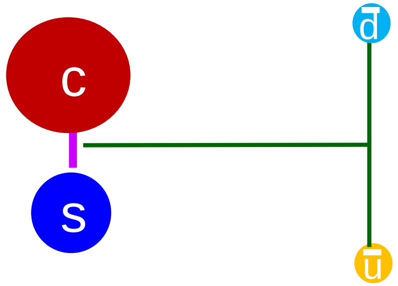




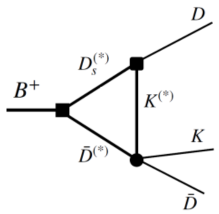
$X_0(2900)$: $M = 2.866 \pm 0.007 \pm 0.002$ GeV/c^2 , $\Gamma = 57 \pm 12 \pm 4$ MeV

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

- The 0^+ $X_0(2900)$ state is a good candidate for a "nearly"-doubly-heavy tetraquark

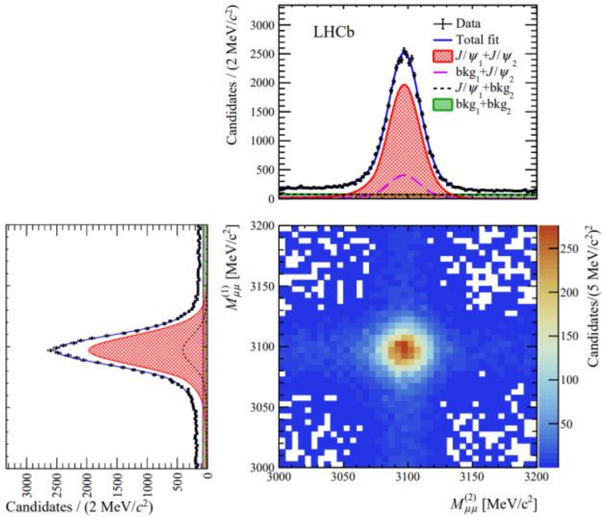


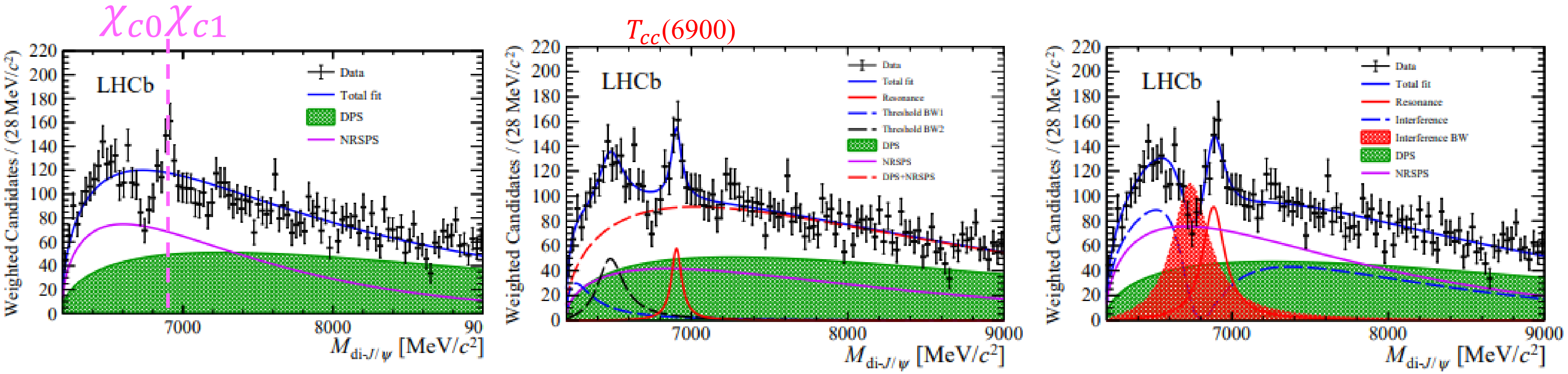
Proximity of the thresholds motivates other explanations - molecular or triangle diagrams



Hidden double charm tetraquarks ?

$pp \to (J/\psi \to \mu^+\mu^-)(J/\psi \to \mu^+\mu^-) + \cdots$ LHCb-PAPER-2020-011, Science Bulletin 65, 1983 (2020), arXiv:2006.16957

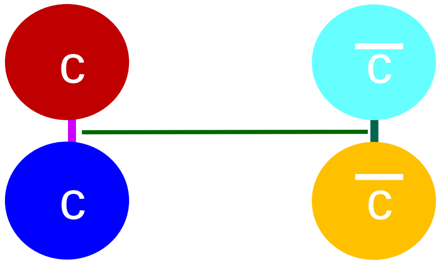




Structure	Significance	
	$p_T^{\text{di-}J/\psi}$-threshold	$p_T^{\text{di-}J/\psi}$-binned
Any structure beyond NRSPS plus DPS	$3.4\,\sigma$	$6.0\,\sigma$
Threshold enhancement plus $X(6900)$	$6.4\,\sigma$	$6.9\,\sigma$
Threshold enhancement	$6.0\,\sigma$	$6.5\,\sigma$
$X(6900)$	$5.1\,\sigma$	$5.4\,\sigma$

- 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 ?



Summary and outlook

- It is a jungle out there! More exotic states than conventional for the charmonium above the open flavor threshold. They keep coming.
- 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 $J/\psi\phi$, $J/\psi J/\psi$ mass structures.
  - 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!

More from LHC (pp at ≥13 TeV)

Future looks bright!

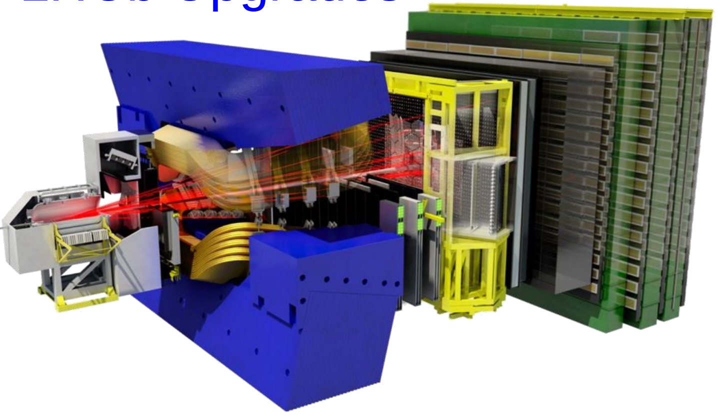
	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2022-24)	Run 4 (2027-30)	Run 5+ (2031+)
LHCb Int. Lumi.	3 fb^{-1}	6 fb^{-1}	⟶	50 fb^{-1}	*300 fb^{-1}

Inst. Lumi. 4×10^{32} $cm^{-2}s^{-1}$ — 2×10^{33} $cm^{-2}s^{-1}$ — 2×10^{34} $cm^{-2}s^{-1}$

upgrade in progress

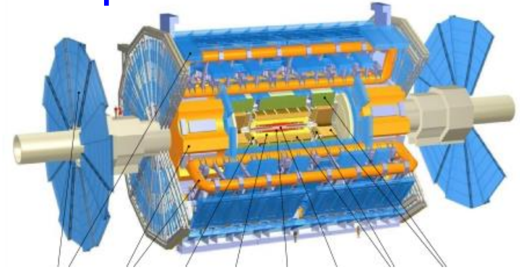
anticipated upgrade

LHCb Upgrades

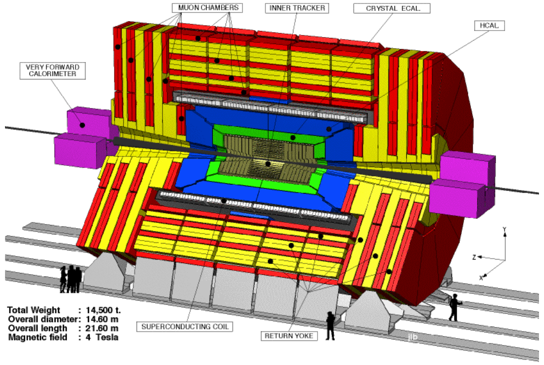


Even higher luminosity samples from:

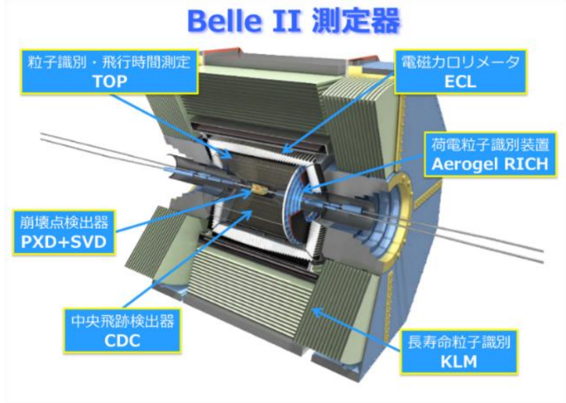
ATLAS



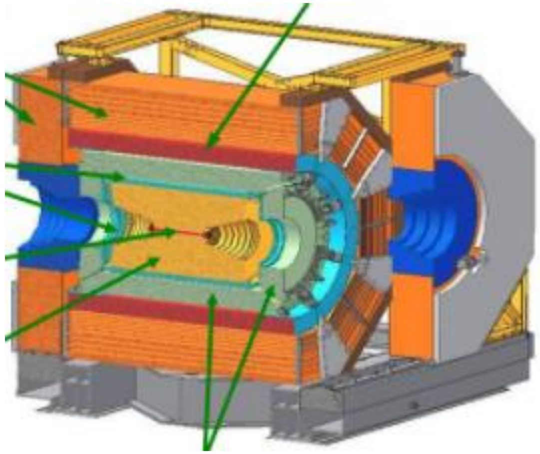
CMS



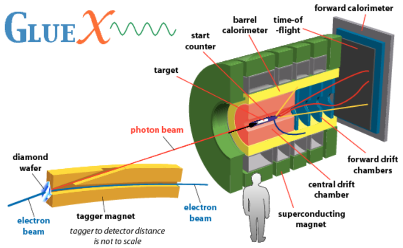
Belle II is ramping up (e^+e^- near $b\bar{b}$ threshold)



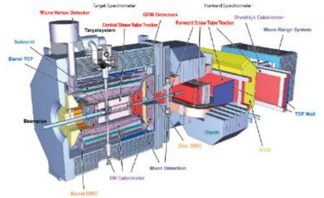
More data from BES III (e^+e^- near $c\bar{c}$ threshold) [new $\tau - c$ factories?]



More from JLAB [EIC?] (γp near $c\bar{c}$ threshold)



[PANDA] ($p\bar{p}$ near $c\bar{c}$ threshold)



and many more… including other future colliders!