Hadron spectroscopy at the LHC

- QCD
- Beauty baryons
- Pentaquarks
- Tetraquarks
- The $\chi_{c1}(3872)$ state

On behalf of the LHCb collaboration, with input from ATLAS and CMS

07/07/2021 — LISHEP C
[indico]

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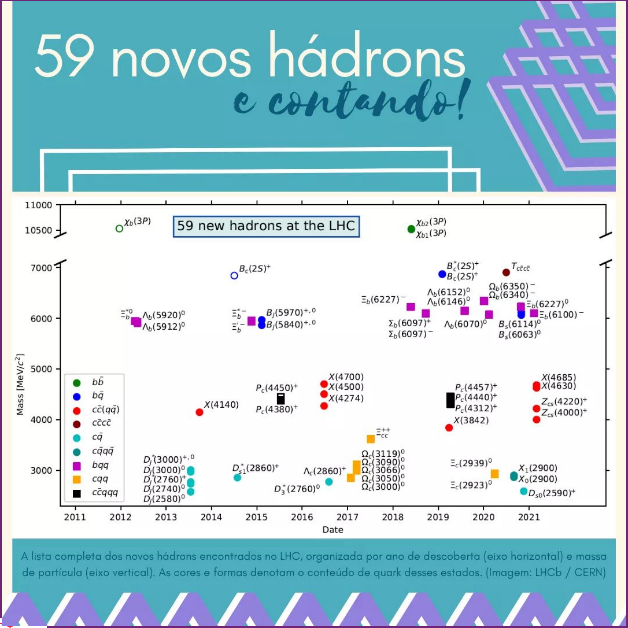
Nikhef



59 novos hádrons
e contando!
59 new hadrons at the LHC
Mass [MeV/c^2]
Date
11000
10500
7000
6000
5000
4000
3000
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
$b\bar{b}$
$b\bar{q}$
$c\bar{c}(q\bar{q})$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{c\bar{c}c\bar{c}}$
Ξ_b^{*0}
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
Ξ_b^{*-}
$\Xi_b'^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Xi_b(6227)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Xi_b(6227)^0$
$\Xi_b(6100)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s(6114)^0$
$B_s(6063)^0$
$X(4140)$
$P_c(4450)^+$
$P_c(4380)^+$
$X(4700)$
$X(4500)$
$X(4274)$
$P_c(4457)^+$
$P_c(4440)^+$
$P_c(4312)^+$
$X(3842)$
$X(4685)$
$X(4630)$
$Z_{cs}(4220)^+$
$Z_{cs}(4000)^+$
Ξ_{cc}^{++}
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D_{s1}^*(2860)^+$
$D_3^*(2760)^0$
$\Lambda_c(2860)^+$
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$X_1(2900)$
$X_0(2900)$
$D_{s0}(2590)^+$
A lista completa dos novos hádrons encontrados no LHC, organizada por ano de descoberta (eixo horizontal) e massa de partícula (eixo vertical). As cores e formas denotam o conteúdo de quark desses estados. (Imagem: LHCb / CERN)

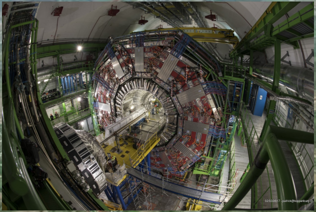
[B]

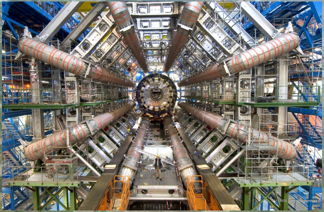
The Large Hadron Collider at CERN

See Ignacio De Bediaga, Richard Hawkings, Luca Malgeri, Luciano Musa

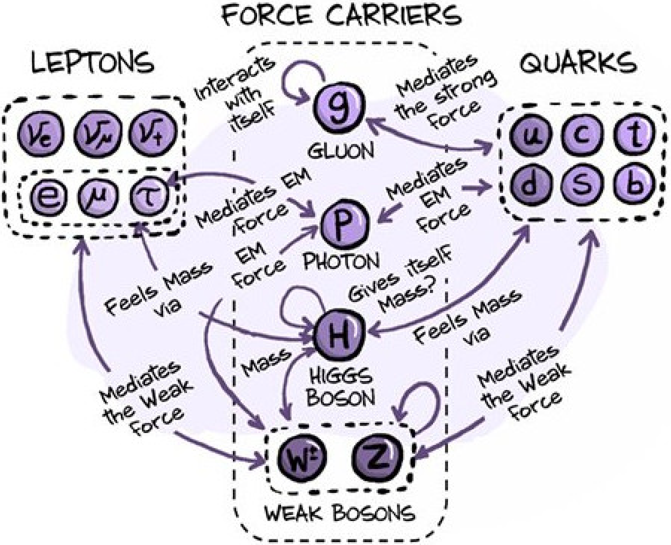
The Large Hadron Collider at CERN

See Ignacio De Bediaga, Richard Hawkings, Luca Malgeri, Luciano Musa



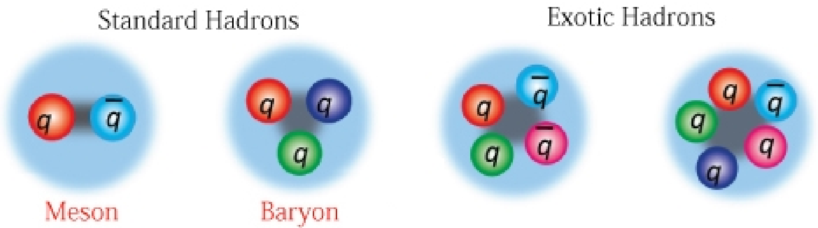


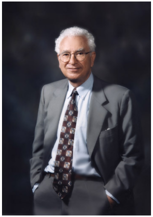
Standard Model



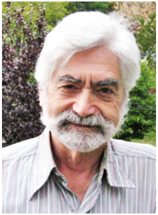
[Gell-Mann, Phys.Lett. 8 (1964) 214] [Zweig, CERN-TH-401] [Petermann, Nucl.Phys. 63 (1965) 349]

QUARKS





Murray Gell-Mann

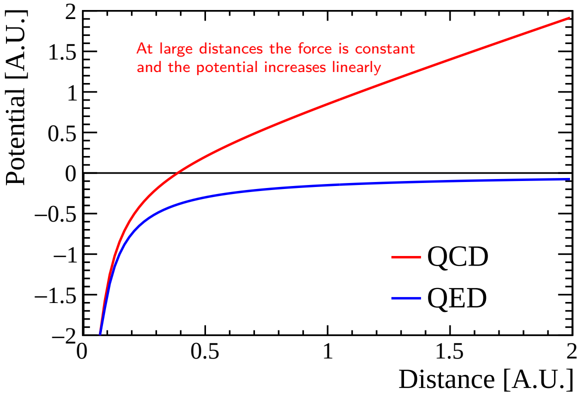


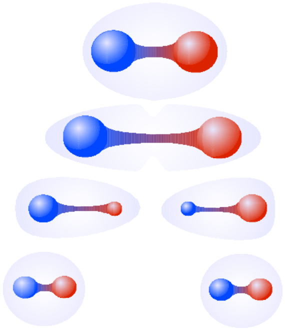
George Zweig

André Petermann

See also [Petrov, arXiv:1412.8681]

Confinement

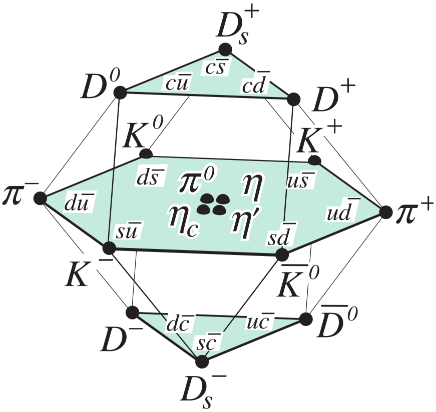




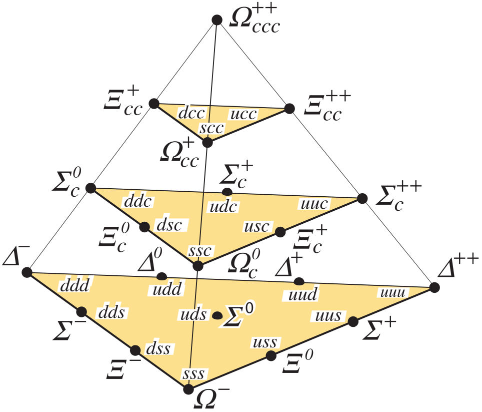
The QCD potential is **postulated**. The mathematical proof that QCD produces such a potential is an unsolved problem. Solve it and claim your $1M prize with the Clay Mathematics Institute [Millenium problems].

[PDG]

Bound states with d,u,s,c quarks

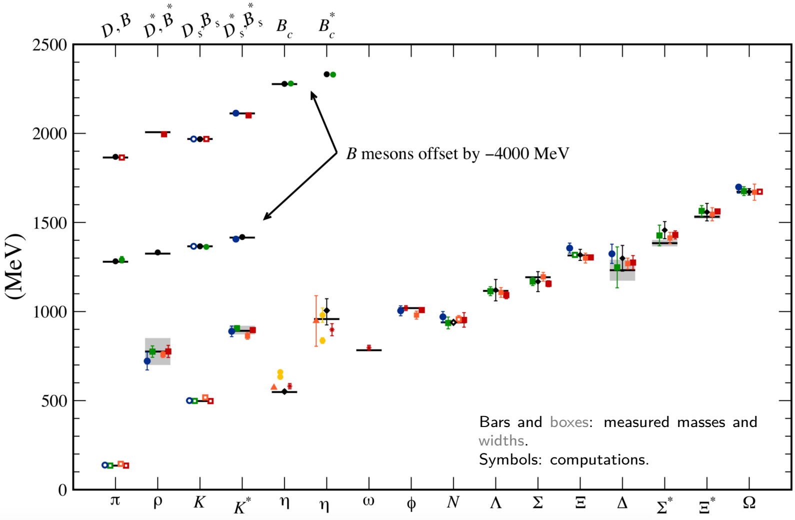


The meson 4-quark multiplet

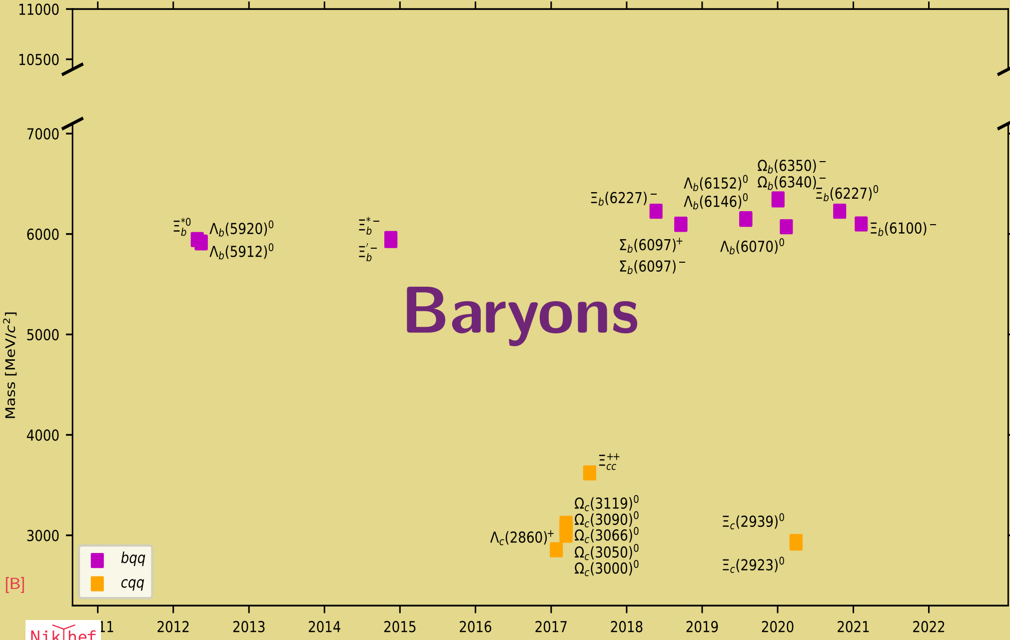


The baryon 4-quark multiplet

Masses of Ground States

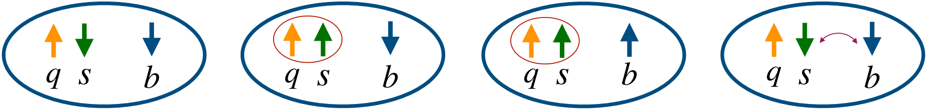


Bars and boxes: measured masses and widths.
Symbols: computations.

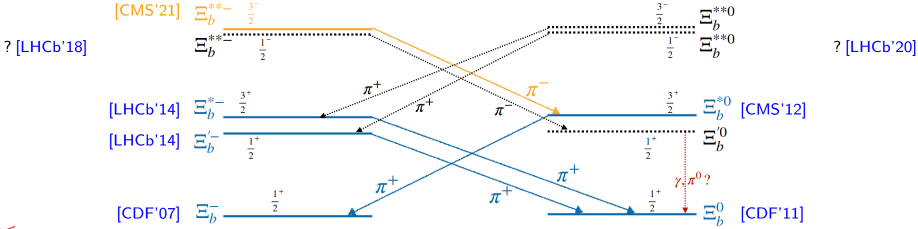

Baryons
Mass [MeV/c^2]
11000
10500
7000
6000
5000
4000
3000
Ξ_b^{*0}
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
Ξ_b^{*-}
$\Xi_b^{'-}$
$\Xi_b(6227)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Lambda_b(6070)^0$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Xi_b(6227)^0$
$\Xi_b(6100)^-$
Ξ_{cc}^{++}
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Lambda_c(2860)^+$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
bqq
cqq
[B]
11
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022

Isodoublet of Ξ_b^0 (bsu) and Ξ_b^- (bsd)

Ξ_b	Ξ_b'	Ξ_b^*	Ξ_b^{**}



Ξ_b	Ξ_b'	Ξ_b^*	Ξ_b^{**}
$j_{qs}=0$	$j_{qs}=1$	$j_{qs}=1$	$j_{qs}=1$
$J^P=\frac{1}{2}^+$	$J^P=\frac{1}{2}^+$	$J^P=\frac{3}{2}^+$	$J^P=\frac{1}{2}^-$ or $\frac{3}{2}^-$
			$L=1$

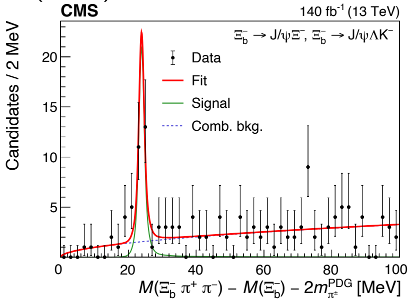


Observation of the $\Xi_b(6100)^-$ resonance

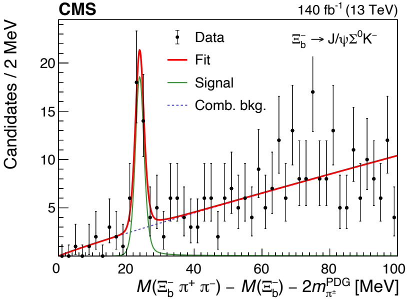
Using 130 fb^{-1} 2016–18 data, CMS study $\Xi_b^-\pi^+\pi^-$ combinations.

➜ new baryon $\Xi_b(6100)^-$ with mass $6100.3 \pm 0.2 \pm 0.1 \pm 0.6\,\text{MeV}/c^2$

Consistent with the orbitally excited $J^P = \frac{3}{2}^-$ state with $j_{ds} = 1$, as the $\Xi_c(2815)$.



$\Xi_b(6100)^- \to \Xi_b^-\pi^+\pi^-$ with fully reconstructed Ξ_b^-



Also visible with partially reconstructed $\Xi_b^- \to J/\psi\Sigma^0K^-$

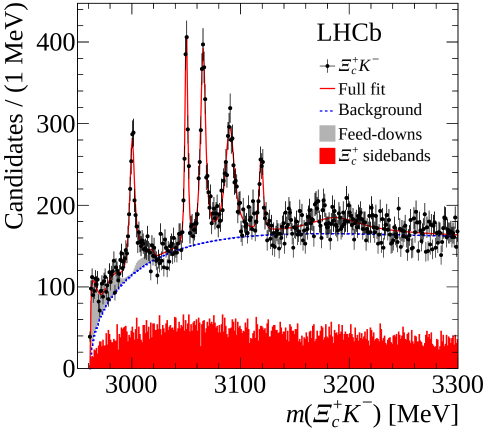
Five new Ω_c^0 resonances in $\Xi_c^+ K^-$

Using $3.3\,\text{fb}^{-1}$ at 7, 8 and 13TeV search for Ω_c^0 (css) states

- Reconstruct $\Xi_c^+ \to pK^-\pi^+$
- Combine with prompt K^-

➜ Wow-effect: **Five peaks!**

- Clearly five narrow states, two of which are very narrow.
- Maybe there is a sixth wider state

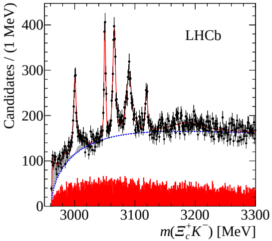


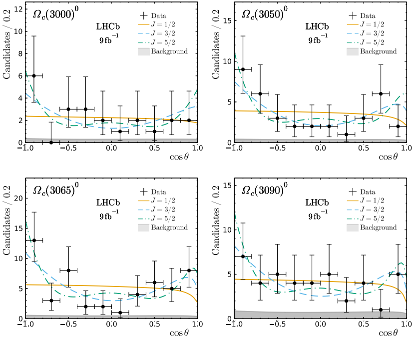
[LHCb, LHCb-PAPER-2021-012, in preparation]

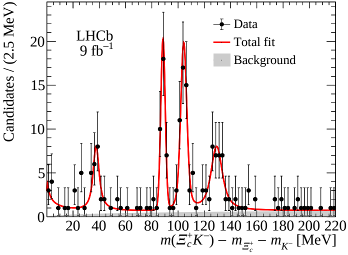
Excited Ω_c^0 in $\Omega_b^- \to \Xi_c^+ K^- \pi^+$

Using $9\,\mathrm{fb}^{-1}$ 2011–18 data reconstruct $\Omega_b^- \to \Xi_c^+ K^- \pi^+$ and study Ω_c^0 in $\Xi_c^+ K^-$

- See 4 of the 5 states of [PRL 118 (2017) 182001]
  - ➜ Angular fit to determine quantum numbers







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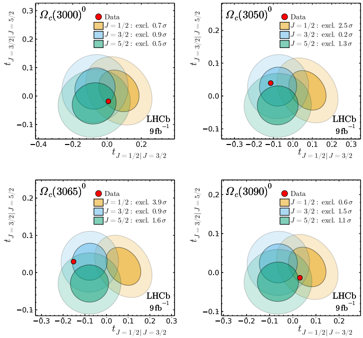
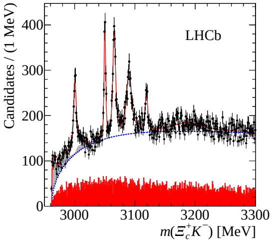
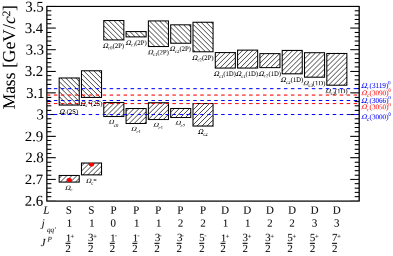
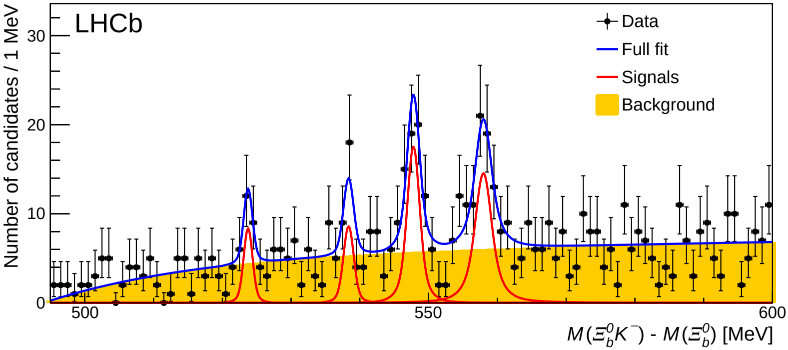


Spin assignments inconclusive. $\Omega_c(3050)^0$ and $\Omega_c(3065)^0$ are not $J = \frac{1}{2}$ ($2\sigma, 3\sigma$ resp.)





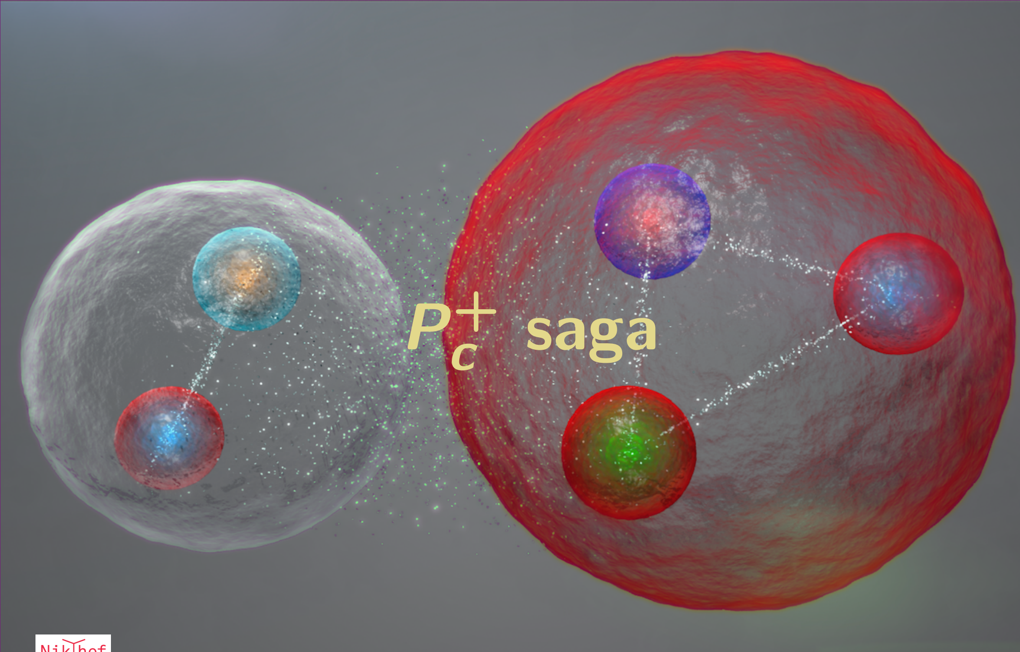
Observation of excited Ω_b^-



4 new states are seen at masses of 6316, 6330, 6340 and 6350 MeV/c^2

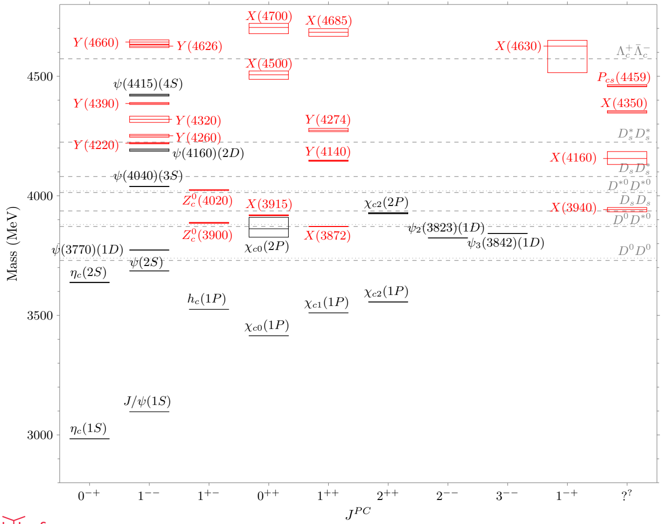
- Karliner and Roser argue they are excitations of the spin-1 $s\bar{s}$ diquark with $J^P = 1/2^-, 1/2^-, 3/2^-, 3/2^-$. A $5/2^-$ is missing. [PRD 102 (2020) 014027]
- Liang and Oset argue for molecules [PRD 101 (2020) 554033]

P_c^+ saga



[Lebed, Mitchell, Swanson, Progress in Particle and Nuclear Physics 93 (2017) 143, arXiv:1610.04528]

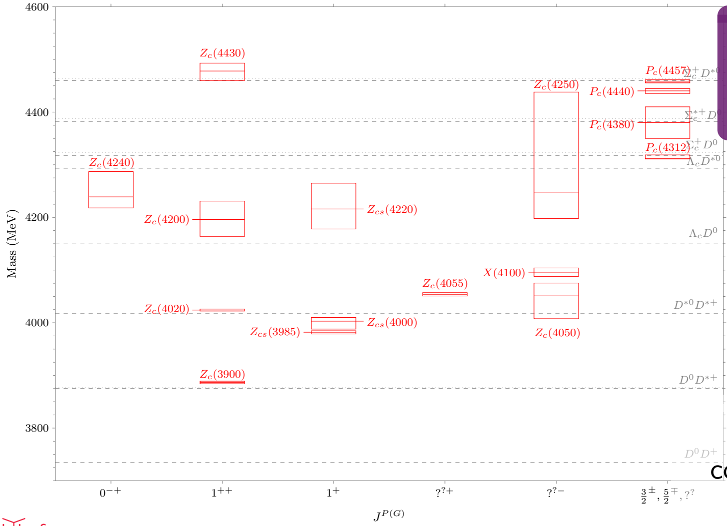
Energy Levels: neutral charmonium states



Observed conventional $c\bar{c}$, exotic states

[B]

Energy Levels: charged charmonium states

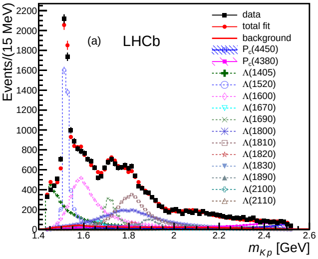


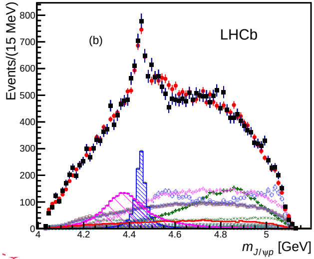
Must be tetra- or pentaquarks!

Observed conventional $c\overline{c}$, exotic states

[B]

2015 Pentaquark observation



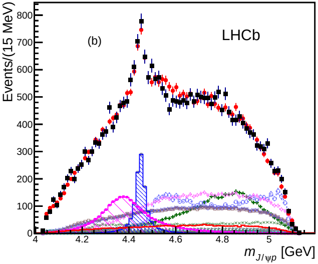


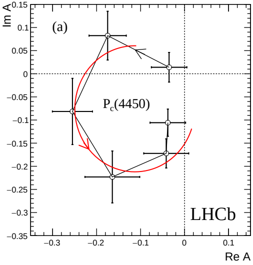
Using $3\,\mathrm{fb}^{-1}$ 2011–12 data find 26000 ± 170 $\Lambda_b^0 \to J/\psi p K^-$ decays.
A 6-dimensional angular analysis needs two exotic contributions:

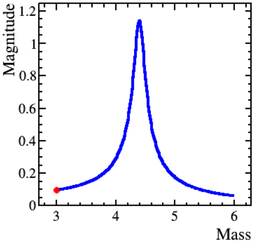
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

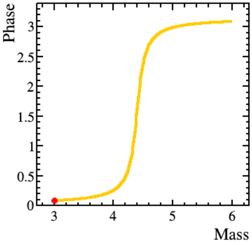
Also $> 3\sigma$ evidence for P_c^+ in Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ [PRL 117 (2016) 082003]

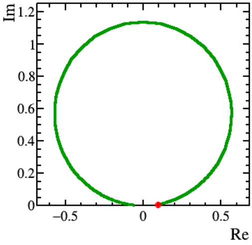
Breit-Wigner behaviour of pentaquarks







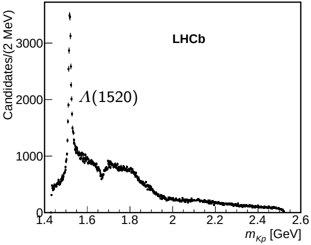


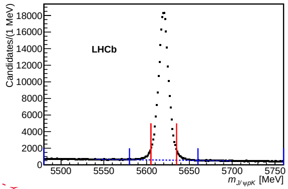


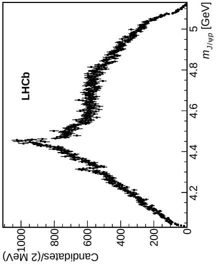
Observation of narrow pentaquarks

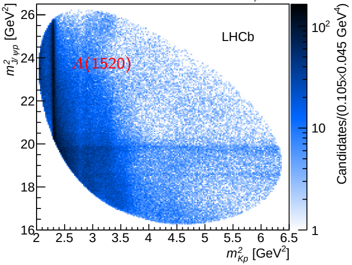
Update of Run 1 analysis [PRL 115 (2015) 072001]

- ➜ Revisit this channel with an updated BDT: 246 000 $\Lambda_b^0 \to J/\psi p K^-$ decays (10 times Run 1) and 6.4% background.
  - Reflections from B_s^0 vetoed
  - Re-optimised BDT including PID (new)
- Only 2 dimensions used: $J/\psi p$ and $\cos\theta$
  - ➜ No sensitivity to Argand diagram









[B]

Observation of narrow pentaquarks

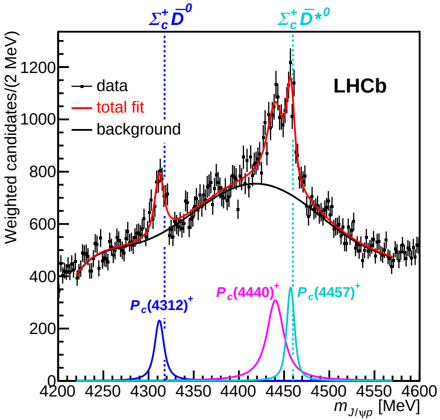
Three states are observed:

$P_c(4312)^+$ $\Gamma \sim 10\,\text{MeV}$ (7σ), which we could not see with $3\,\text{fb}^{-1}$

$P_c(4440)^+$ $\Gamma \sim 20\,\text{MeV}$ and

$P_c(4457)^+$ $\Gamma \sim 6\,\text{MeV}$. The significance of the 2-peak structure is 5.4σ

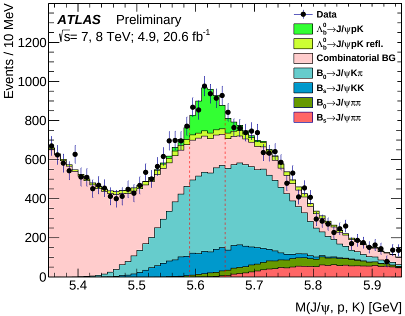
✗ No sensitivity to the wide $P_c(4380)^+$

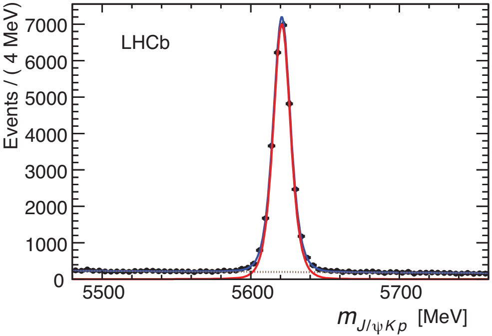


It is striking that the $P_c(4312)^+$ and the $P_c(4457)^+$ sit at the $\Sigma_c D$ and $\Sigma_c D^*$ thresholds

[B]

P_c^+ states at ATLAS





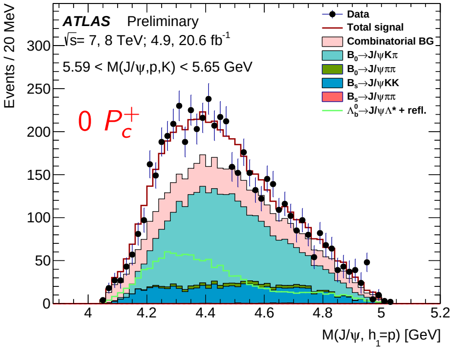
With Run 1 data, ATLAS find 2270 ± 300 $\Lambda_b^0 \to J/\psi p K^-$ decays

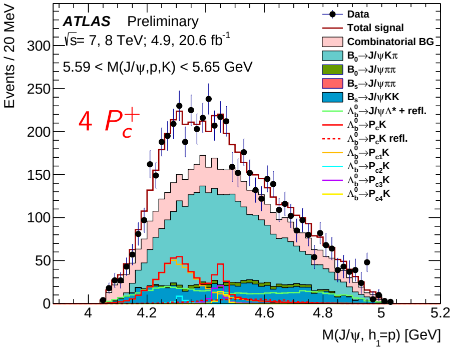
- With the same data, LHCb see $26\,000 \pm 170$ with hardly any background

[LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

[B]

P_c^+ states at ATLAS





With Run 1 data, ATLAS find 2270 ± 300 $\Lambda_b^0 \to J/\psi p K^-$ decays

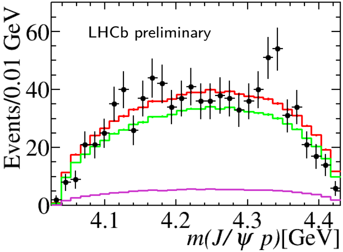
- Good fits with 4 P_c^+ LHCb states of [PRL 122 (2019) 222001] ($p \sim 69\%$)
  - (also with 2 P_c^+ of [PRL 115 (2015) 072001], excluded by LHCb, $p \sim 56\%$)
- Fit with only Λ is not ($p \sim 9 \times 10^{-3}$)

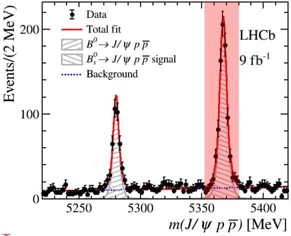
[B]

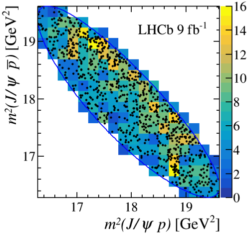
Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$

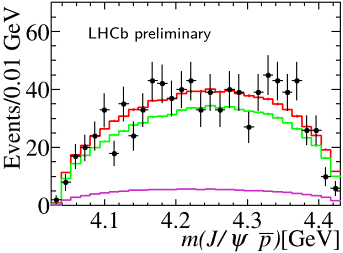
With $9\,\text{fb}^{-1}$ 2011–18 data, find 800 $B_s^0 \to J/\psi p\bar{p}$ with 15% background. Flavour is untagged.

- ✗ Some structure at 4.3 GeV









[B]

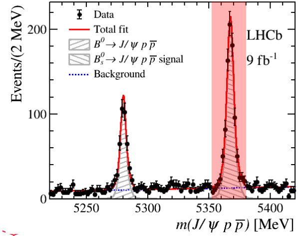
Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$

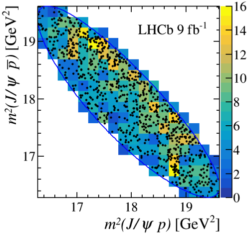
With $9\,\mathrm{fb}^{-1}$ 2011–18 data, find 800 $B_s^0 \to J/\psi p\bar{p}$ with 15% background. Flavour is untagged.

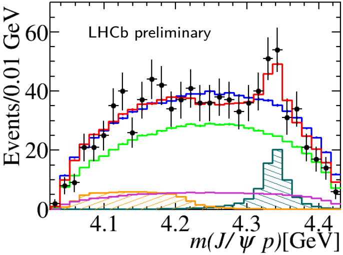
- ✔ Good fit with a P_c^+ state (3.1σ)

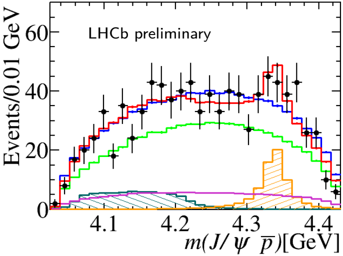
$$M = 4337\,^{+7}_{-4} \pm 2\,\mathrm{MeV}$$

$$\Gamma = 29\,^{+26}_{-12} \pm 14\,\mathrm{MeV}$$



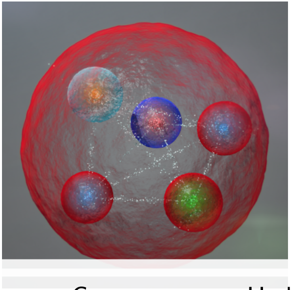


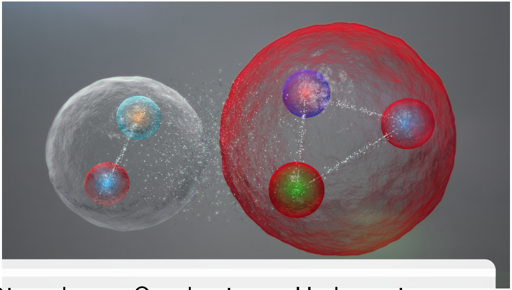


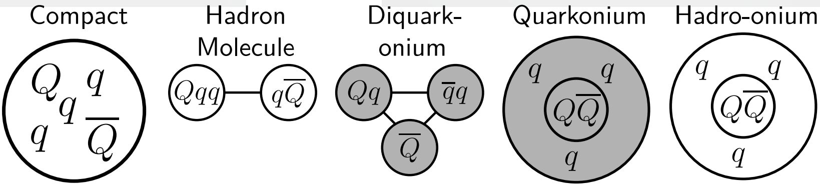


[B]

What is a Pentaquark?

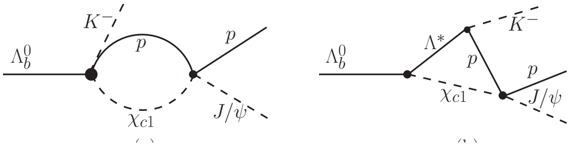




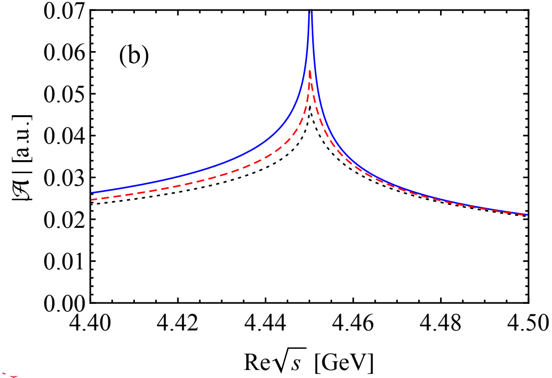


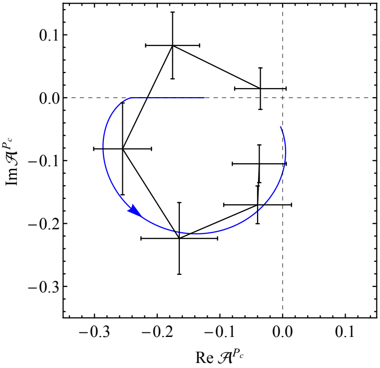
1200 papers citing the 1st P_c^+ paper, with many possible interpretations.

Pentaquarks as triangle diagrams



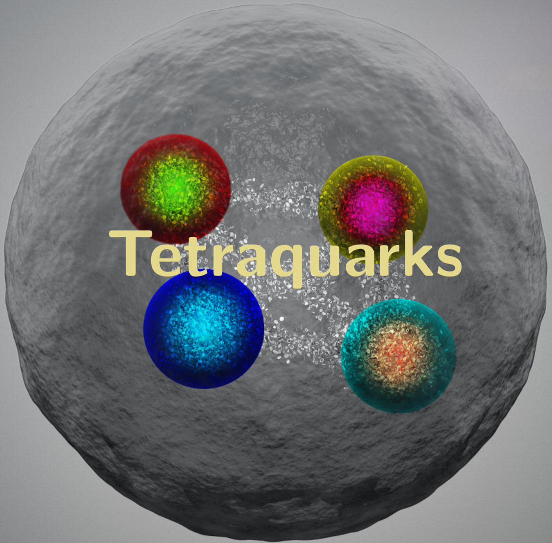
P_c^+ enhacements could be caused by triangle singularities



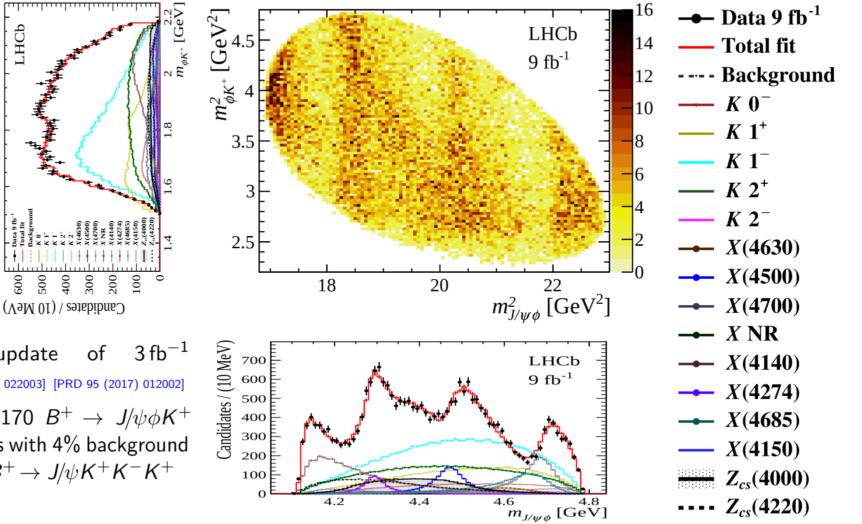


[B]

Tetraquarks



Strange tetraquarks in $B^+ \to J/\psi\phi K^+$



9 fb^{-1} update of 3 fb^{-1}

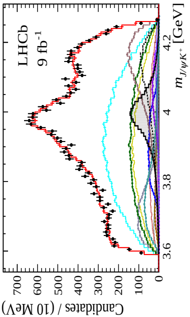
[PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

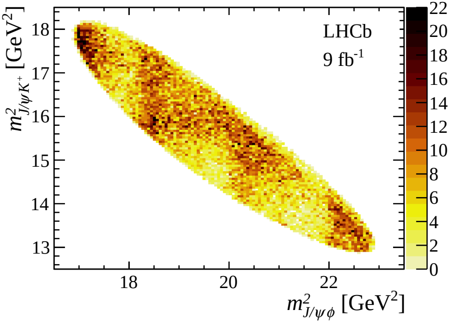
24 220 ± 170 $B^+ \to J/\psi\phi K^+$ candidates with 4% background and 2% $B^+ \to J/\psi K^+ K^- K^+$

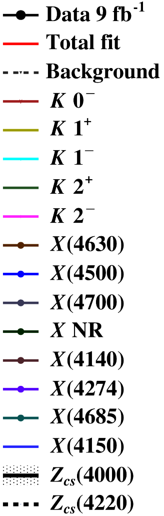
[B]

[LHCb, arXiv:2103.01803, submitted to PRD]

STRANGE TETRAQUARKS IN $B^+ \to J/\psi\phi K^+$







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[PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

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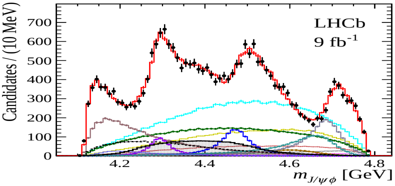
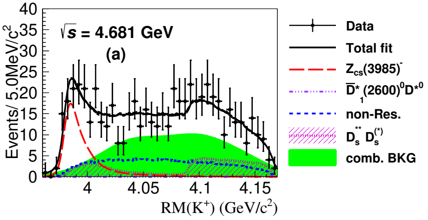


[B]

[LHCb, arXiv:2103.01803, submitted to PRD]

$Z_{cs}(3985)^+$ versus $Z_{cs}(4000)^+$



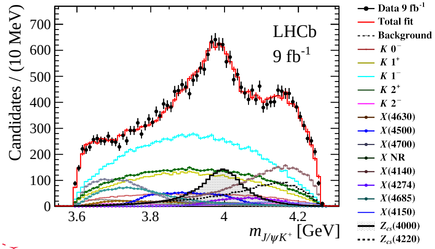
State seen in $D_s^- D^{*0}$ and $D_s^{*-} D^0$

$$m(Z_{cs}^-) = 3982.5\,^{+1.8}_{-2.6} \pm 2.1\,\text{MeV}/c^2$$

$$\Gamma(Z_{cs}^-) = 12.8\,^{+5.3}_{-4.4} \pm 3.0\,\text{MeV}$$

See Yifang Wang

[PRL 126 (2021) 102001]



State seen in $J/\psi K^+$

$$m(Z_{cs}^-) = 4003 \pm 6\,^{+4}_{-41}\,\text{MeV}/c^2$$

$$\Gamma(Z_{cs}^-) = 131 \pm 15 \pm 26\,\text{MeV}$$

[LHCb, arXiv:2103.01803, submitted to PRD]

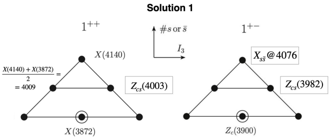
[B]

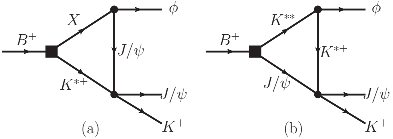
$Z_{cs}(3985)^+$ versus $Z_{cs}(4000)^+$

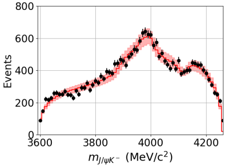
Multiplet: For [Maiani, Polosa, Riquer, arXiv:2103.08331] they are an $SU(3)$ multiplet

Threshold effects: For [Ge, Liu, Ke, arXiv:2103.05282] they are threshold effects

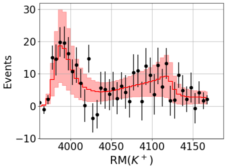
Virtual states: For [Ortega, Entem, Fernandez, arXiv:2103.07871] the Z_{cs} are the same virtual state in different coupled-channels environment.







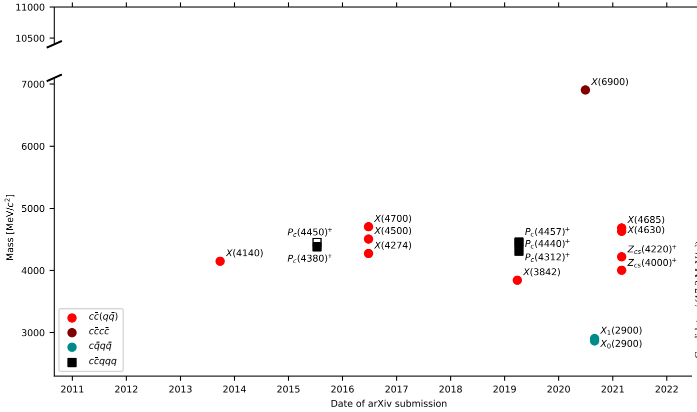
Description of LHCb data [arXiv:2103.01803]

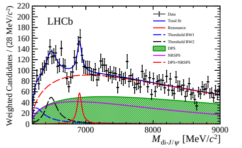


Description of BESIII data [PRL 126 (2021) 102001]

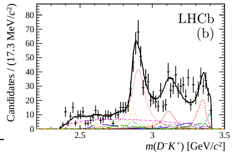
[B]

All exotic hadrons found at the LHC





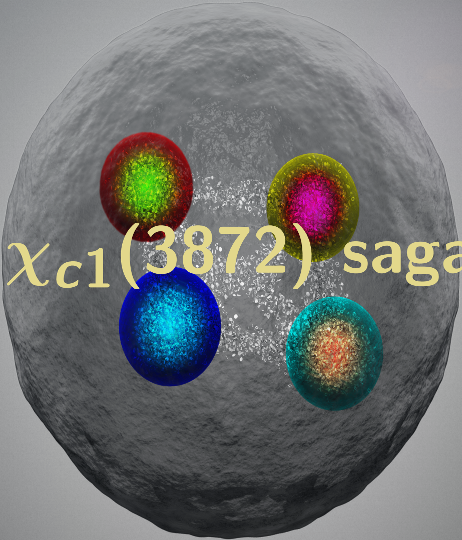
[Science Bulletin 65 (2020) 1983]



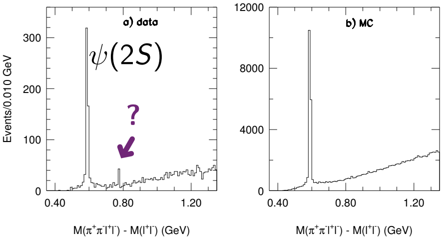
[PRL 125 (2020) 242001]

All exotic resonances observed at the LHC in a mass versus submission date plot. Hollow markers indicate superseded states.

$\chi_{c1}(3872)$ saga



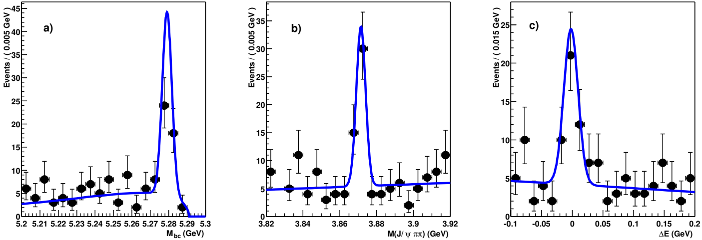
Observation of the $X(3872)$ Resonance



Belle reported a clear peak in the $J/\psi\pi^+\pi^-$ mass spectrum above the $\psi(2S)$ in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays (36 ± 7 events)

$$M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}/c^2$$
$$\Gamma < 2.3 \text{ MeV}$$

close to the $\bar{D}^0 D^{*0}$ threshold



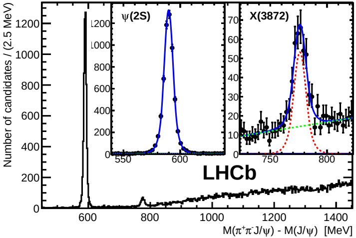
Moon-Mars

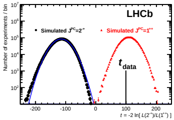
[B]

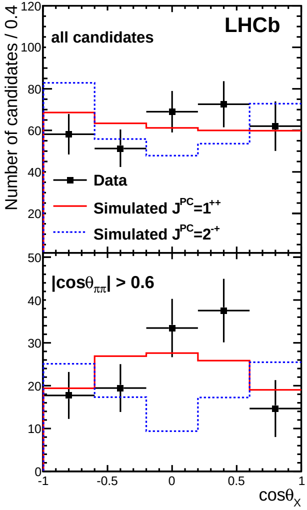
$X(3872)$ QUANTUM NUMBERS

- Five-dimensional angular analysis of $B^+ \to X(3872)K^+$ with $X(3872) \to J/\psi\pi^+\pi^-$ using 2011 data
  - ➜ 313 ± 26 decays in 38 000 $B^+ \to J/\psi\pi^+\pi^-K^+$ candidates

✔ Unambiguous assignment $J^{PC} = 1^{++}$ at 8σ. This rules out the η_{c2} (1^1D_2) hypothesis.



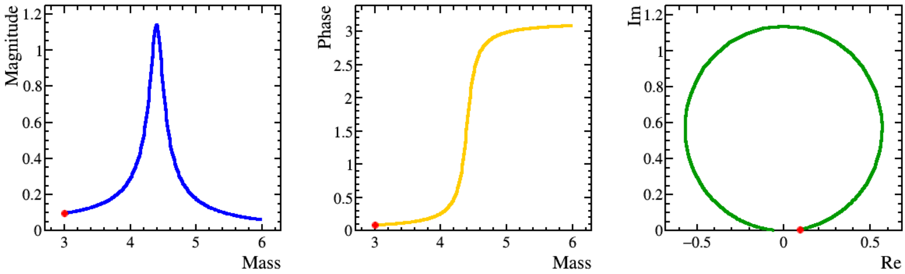




[B]

[Cowan, Gershon]

Breit-Wigner



For narrow resonances far away from the threshold, the Breit-Wigner parametrisation is suitable

$$\mathcal{A}(s) = \frac{\alpha}{M_{\mathrm{BW}}^2 - s - i\sqrt{s}\,\Gamma_{\mathrm{BW}}} \simeq \frac{\alpha}{M_{\mathrm{BW}}^2 - s - i\,M_{\mathrm{BW}}\,\Gamma_{\mathrm{BW}}}$$

[PDG]

Lineshape of the $\chi_{c1}(3872)$ meson

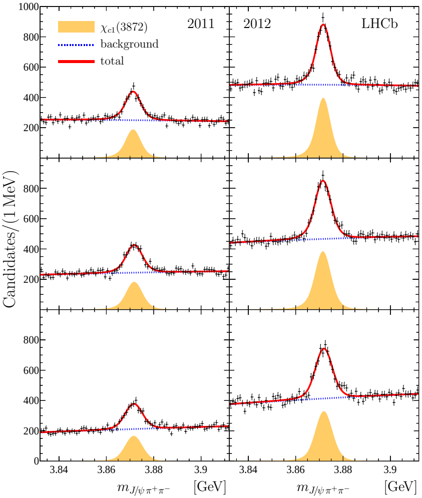
Using $3\,\mathrm{fb}^{-1}$ 2011–12 detached $J/\psi\pi^+\pi^-$ data, study the $\chi_{c1}(3872)$ lineshape (15k signal). $\psi(2S)$ is used as control.

$$m = 3871.70 \pm 0.07 \pm 0.07 \pm 0.01\,\mathrm{MeV}$$
$$\Gamma = 1.39 \pm 0.24 \pm 0.10\,\mathrm{MeV}$$

First measurement of the BW width!

Is the $\chi_{c1}(3872)$ above or below $D^{*0}\overline{D}$ threshold?

$$m(D^{*0}\overline{D}) = 3871.69 \pm 0.06\,\mathrm{MeV}$$



[B]

Lineshape of the $\chi_{c1}(3872)$ meson

For a resonance near threshold with coupled channels, the Flatté parametrisation is to be used [Yu, Kalashnikova, Nefediev, PRD80 (2009) 074004]

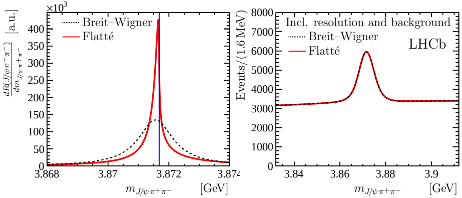
$$\frac{dR(J/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{\left|E - E_f + \frac{i}{2}\left[g\left(k_1 + k_2\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right]\right|^2}$$

$$E_f = m_0 - \left(m_{D^0} + m_{D^{*0}}\right)$$

Γ_f : various decay modes

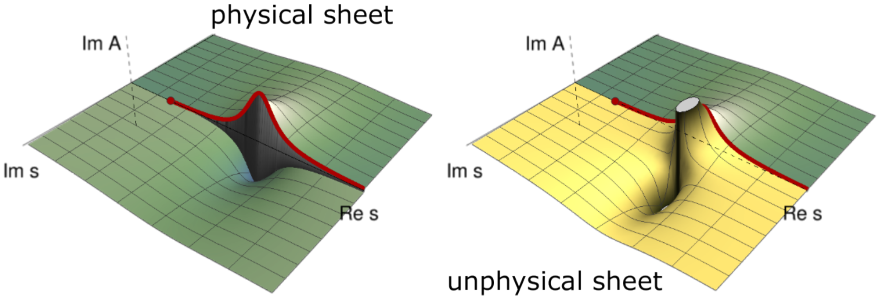
$$\text{mode} = 3871.69\,^{+0.00}_{-0.04}\,^{+0.05}_{-0.13}\ \text{MeV}$$

$$\text{FWHM} = 0.22\,^{+0.07}_{-0.06}\,^{+0.11}_{-0.13}\ \text{MeV}$$



[B]

Resonances



The physical states appear as poles of the S-matrix as a

Bound state on the real axis below threshold, on the physical sheet

Virtual state on the real axis above threshold, on the physical sheet

Resonance off the real axis, on the unphysical sheet.

➜ Real part: m, imaginary part: $\Gamma/2$

LINESHAPE OF THE $\chi_{c1}(3872)$ MESON

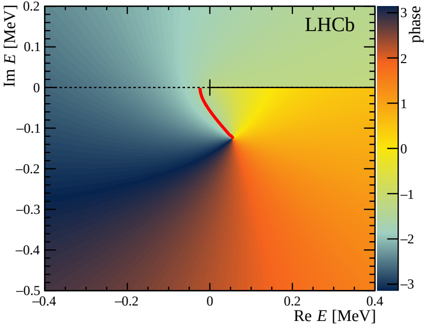
Analytic continuation of Flatté function in complex space.

Poles found:

$$\text{Sheet II}: (0.0569 - 0.1256\,i)\ \text{MeV}$$
$$\text{Sheet III}: (-3.5780 - 1.2165\,i)\ \text{MeV}$$

$\chi_{c1}(3872)$ looks like a quasi-bound* state of $D^{*0}\overline{D}$ with binding energy of 24 keV ($E_b < 100$ keV at 90% CL)

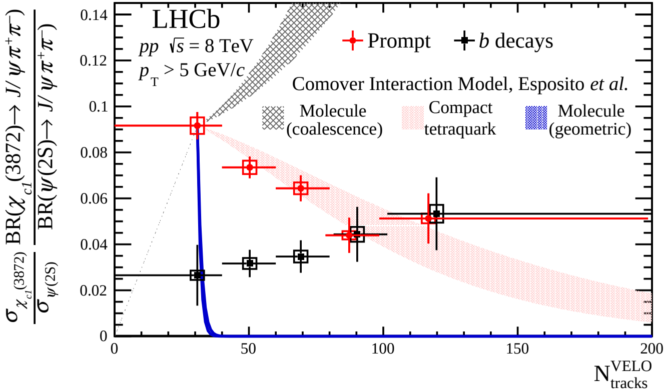
* In the limit of all other couplings being switched off



Phase on complex E plane, with trajectory when other couplings are moved to 0.

[B]

$\chi_{c1}(3872)$ production versus multiplicity



Ratio of $\psi(2S)$ and $\chi_{c1}(3872)$ production, for prompt and b decays.

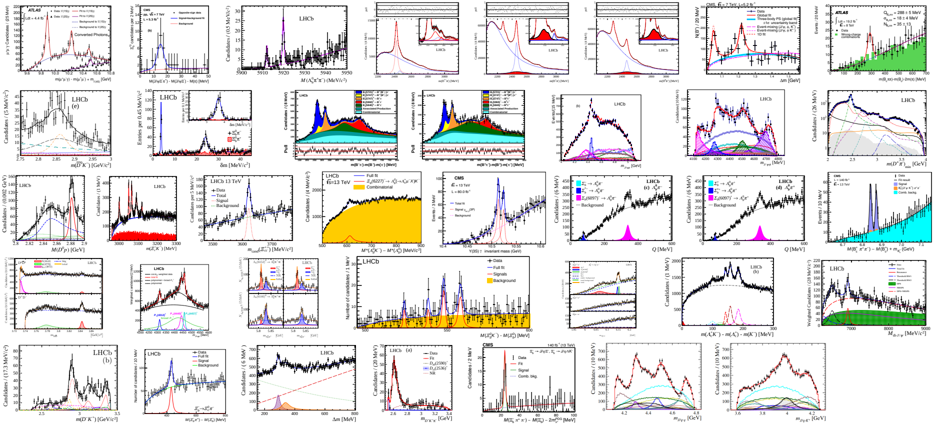
The from-b ratio is consistent with being flat. 5σ slope for prompt, compared with predictions from [Esposito, Ferreiro, Pilloni, Polosa, Salgado, arXiv:2006.15044].

[B]

Outlook

[LHCb-FIGURE-2021-001] [Updates here]

New hadrons found at the LHC



59 hadrons found so far, and still counting

Conclusion

- The LHC is a hadron discovery machine: 59 new hadrons to date
- 17 exotic hadrons discovered, but their nature is uncertain
- Study of baryons helps understanding diquarks
- Detailed study of $\chi_{c1}(3872)$ indicates it has a bound $D^{*}\overline{D}^{0}$ component

Contact: [@pkoppenburg] [patrick.koppenburg@nikhef.nl]


THE OTHER SIDE
Why do you need a reason?
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Backup

LHCb Upgrade

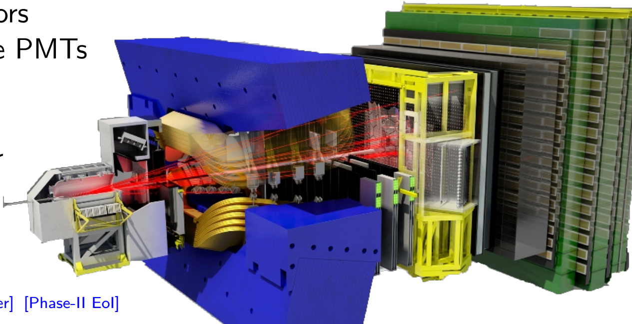
$\mathcal{L} = 2 \cdot 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ requires some new detectors and 40 MHz read-out clock new electronics

Velo: New pixel vertex detector

Trackers: New scintillating fibre tracker.
The upstream tracker is also replaced

PID: Hybrid photodetectors
replaced by multi-anode PMTs

➜ 50 fb^{-1} by Run 4.

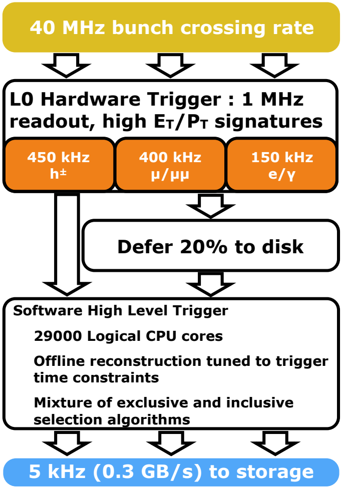


✔ We are preparing another upgrade for Run 5
➜ 300 fb^{-1}

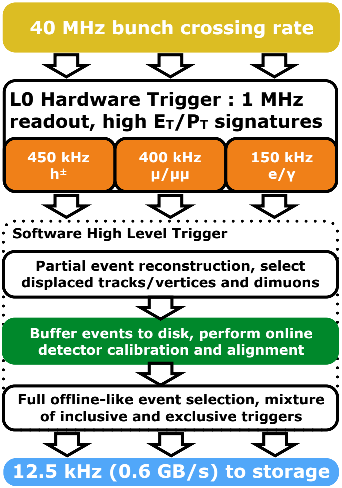
[Upgrade TDR] [Velo] [PID] [Sci-Fi] [Trigger] [Phase-II EoI]

LHCb Trigger in Run 2

LHCb 2012 Trigger Diagram



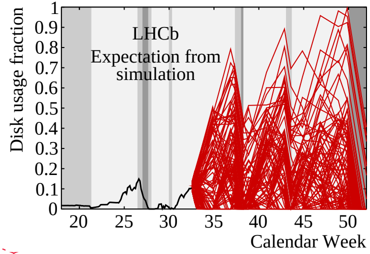
LHCb Run 2 Trigger Diagram

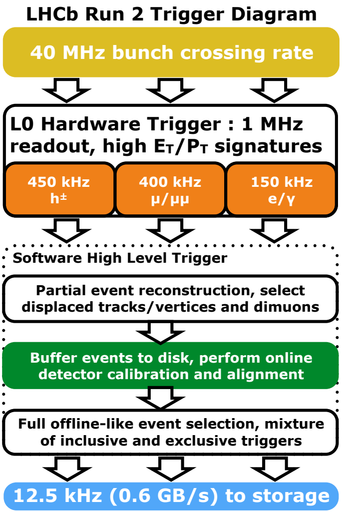


LHCb Trigger in Run 2

Events are buffered on disk (10 PB) while calibrations are being run.

- ➜ Offline-quality trigger objects available for analysis.
  - Disk ➜ more CPU. The full reconstruction can also be run during LHC downtime.





LHCb Trigger in Run 2

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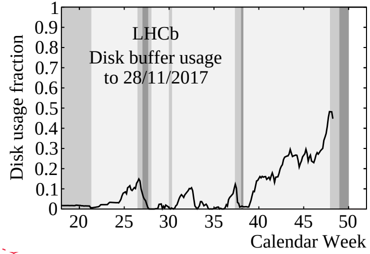
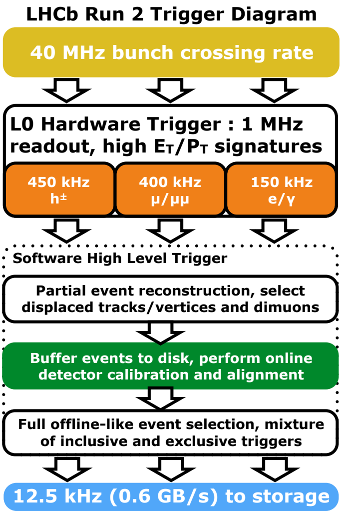
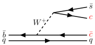
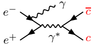
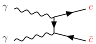
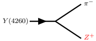




Tetraquarks

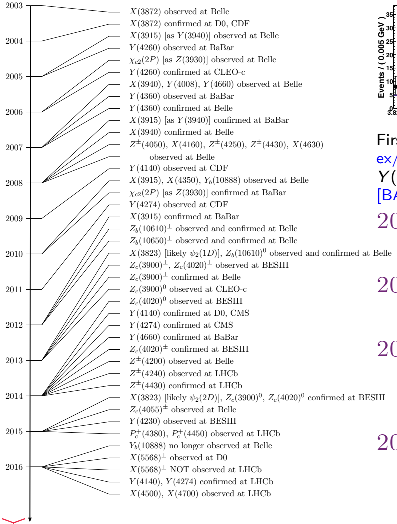
[B]

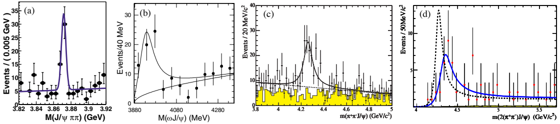
Production mechanism of exotic charmonia

Channel						In $p\bar{p}$	In pp
$J/\psi\pi^+\pi^-$	$X(3872)$	$Y(4008)$ $Y(4260)$				$X(3872)$	$X(3872)$
$\psi(2S)\pi^+\pi^-$		$Y(4360)$ $Y(4660)$					
$\Lambda_c^+\bar{\Lambda}_c^-$		$Y(4630)$					
$\psi(2S)\gamma$	$X(3872)$						
$\chi_{c1}(1P)\gamma$	$X(3832)$						
$\chi_{c1}(1P)\omega$				$Y(4220)$			
$J/\psi\omega$	$X(3872)$ $X(3940)$			$X(3915)$			
$J/\psi\phi$	$X(4140)$ $X(4274)$ $X(4500)$ $X(4700)$			$X(4350)$		$X(4140)$	
$J/\psi\pi^+$	$Z(4200)$ $Z(4240)$ $Z(4430)$				$Z(3900)$		
$\psi(2S)\pi^+$	$Z(4430)$						
$\chi_{c1}(1P)\pi^+\pi^+$	$Z(4051)$ $Z(4248)$						
$h_c(1P)\pi^+$					$Z(4020)$		
$D\bar{D}$				$Z(3930)$			
$D\bar{D}^*$			$X(3940)$		$Z(3885)$		
$D^*\bar{D}^*$			$X(4160)$		$Z(4025)$		
$J/\psi p$	$P_c^+(4380)$ $P_c^+(4450)$						

Colour coding: neutral — charged

Exotic Charmonia Timeline





First observations of $X(3872)$ [Belle, PRL 91 262001 (2003), arXiv:hep-ex/0309032], $Y(3940)$ [Belle, PRL 94 182002 (2005), arXiv:hep-ex/0408126], $Y(4260)$ [BABAR, PRL 95 142001 (2005), arXiv:hep-ex/0506081], $Y(4360)$ [BABAR, PRL 98 212001 (2007), arXiv:hep-ex/0610057]

2003 Belle sees $X(3872)$ by accident in $B^+ \to J/\psi K^+ \pi^+ \pi^-$ [Belle, PRL 91 262001 (2003), arXiv:hep-ex/0309032]

2005 Belle then searched for it in $B^+ \to J/\psi K^+ \omega$ but found the $Y(3940)$ [Belle, PRL 94 182002 (2005), arXiv:hep-ex/0408126]

2005 BaBar searched for it in $e^+e^- \to X(3872)$ with ISR but did not find it. They found the $Y(4260)$ instead. [BABAR, PRL 95 142001 (2005), arXiv:hep-ex/0506081]

2006 BaBar then looked whether the $Y(4260)$ decayed to $\psi(2S)\pi^+\pi^-$ with ISR. Instead they found the $Y(4360)$. [BABAR, PRL 98 212001 (2007), arXiv:hep-ex/0610057]

[B]

Exotic Charmonia Timeline

2003
- $X(3872)$ observed at Belle
- $X(3872)$ confirmed at D0, CDF

2004
- $X(3915)$ [as $Y(3940)$] observed at Belle
- $Y(4260)$ observed at BaBar
- $\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle

2005
- $Y(4260)$ confirmed at CLEO-c
- $X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
- $Y(4360)$ observed at BaBar

2006
- $Y(4360)$ confirmed at Belle
- $X(3915)$ [as $Y(3940)$] confirmed at BaBar
- $X(3940)$ confirmed at Belle

2007
- $Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
- $Y(4140)$ observed at CDF

2008
- $X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
- $\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
- $Y(4274)$ observed at CDF

2009
- $X(3915)$ confirmed at BaBar
- $Z_b(10610)^{\pm}$ observed and confirmed at Belle
- $Z_b(10650)^{\pm}$ observed and confirmed at Belle

2010
- $X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observed and confirmed at Belle
- $Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
- $Z_c(3900)^{\pm}$ confirmed at Belle

2011
- $Z_c(3900)^0$ observed at CLEO-c
- $Z_c(4020)^0$ observed at BESIII
- $Y(4140)$ confirmed at D0, CMS

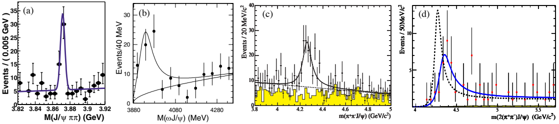
2012
- $Y(4274)$ confirmed at CMS
- $Y(4660)$ confirmed at BaBar
- $Z_c(4020)^{\pm}$ confirmed at BESIII

2013
- $Z^{\pm}(4200)$ observed at Belle
- $Z^{\pm}(4240)$ observed at LHCb
- $Z^{\pm}(4430)$ confirmed at LHCb

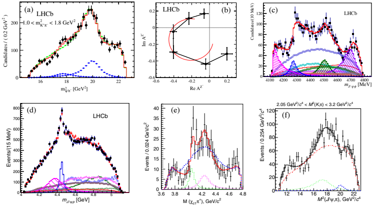
2014
- $X(3823)$ [likely $\psi_2(2D)$], $Z_c(3900)^0$, $Z_c(4020)^0$ confirmed at BESIII
- $Z_c(4055)^{\pm}$ observed at Belle
- $Y(4230)$ observed at BESIII

2015
- $P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
- $Y_b(10888)$ no longer observed at Belle
- $X(5568)^{\pm}$ observed at D0

2016
- $X(5568)^{\pm}$ NOT observed at LHCb
- $Y(4140)$, $Y(4274)$ confirmed at LHCb
- $X(4500)$, $X(4700)$ observed at LHCb



First observations of $X(3872)$ [Belle, PRL 91 262001 (2003), arXiv:hep-ex/0309032], $Y(3940)$ [Belle, PRL 94 182002 (2005), arXiv:hep-ex/0408126], $Y(4260)$ [BABAR, PRL 95 142001 (2005), arXiv:hep-ex/0506081], $Y(4360)$ [BABAR, PRL 98 212001 (2007), arXiv:hep-ex/0610057]



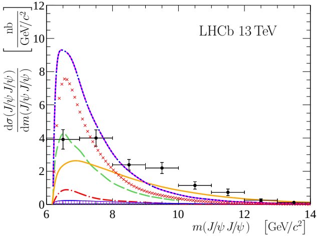
First observations of $Z_c(4200)$, $Z_c(4430)$ [PRL 112 (2014) 222002] $Y(4140)$, $Y(4274)$, $X(4500)$, $X(4700)$ [PRL 118 (2017) 022003] $P_c(4380)$, $P_c(4450)$ [PRL 115 (2015) 072001] $Z_1(4050)$, $Z_2(4250)$ [Belle, PRD 78 072004 (2008), arXiv:0806.4098], $Z_c(4200)$, $Z_c(4430)$ [Belle, PRD 90 112009 (2014),

[B]

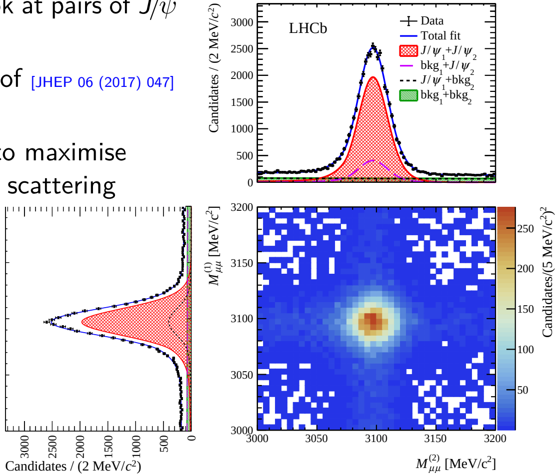
Structure in $J/\psi J/\psi$

Using $9\,\mathrm{fb}^{-1}$ Run 1+2 data look at pairs of J/ψ mesons.

- ➜ Revisit mass distribution of [JHEP 06 (2017) 047] ($280\,\mathrm{pb}^{-1}$)
- Require $p_{\mathrm{T}} > 5.2\,\mathrm{GeV}/c$ to maximise single over double parton scattering

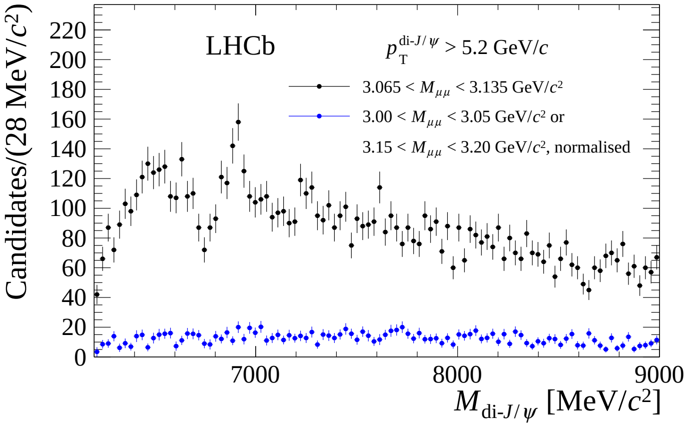


[JHEP 06 (2017) 047]



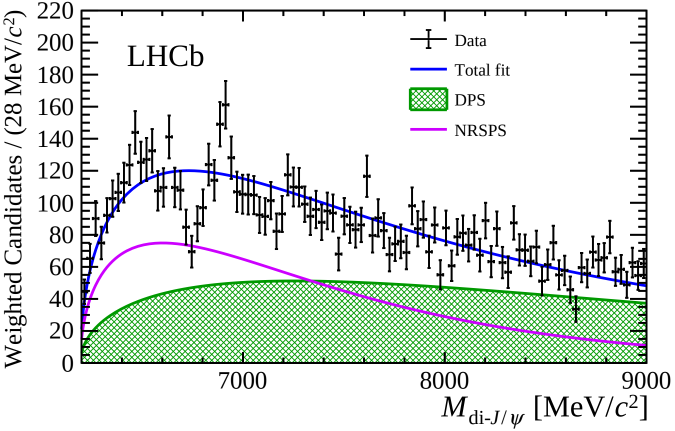
[LHCb, Science Bulletin 65 (2020) 1983, arXiv:2006.16957]

Structure in $J/\psi J/\psi$



Peaks seen at 6.9 GeV/c^2 and at threshold

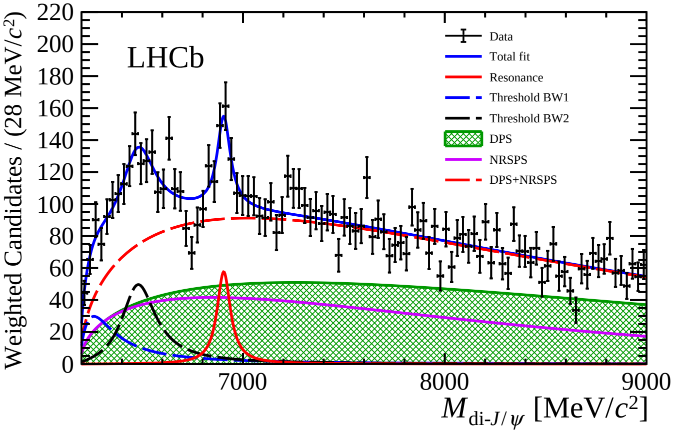
Structure in $J/\psi J/\psi$



Background-only fit. There is a peak at 6900 MeV/c^2.

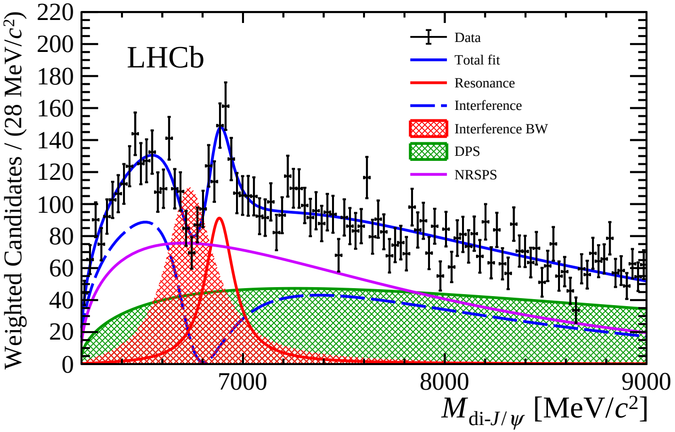
How to fit the low-mass region?

Structure in $J/\psi J/\psi$



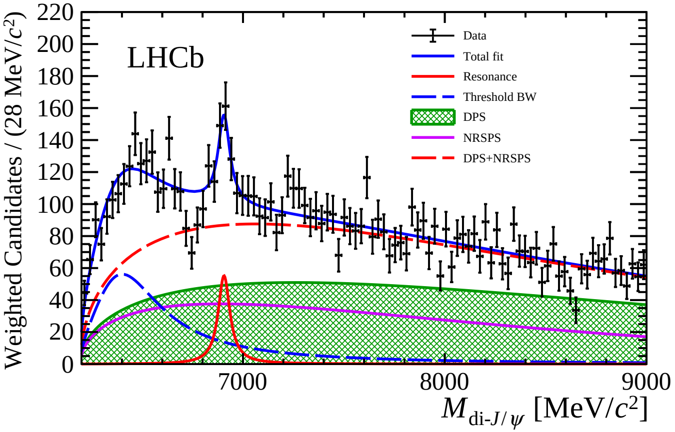
Model I: Two Breit–Wigner shapes for threshold,
$\chi^2/\mathrm{ndf} = 112.7/89$, $p = 4.6\%$

Structure in $J/\psi J/\psi$



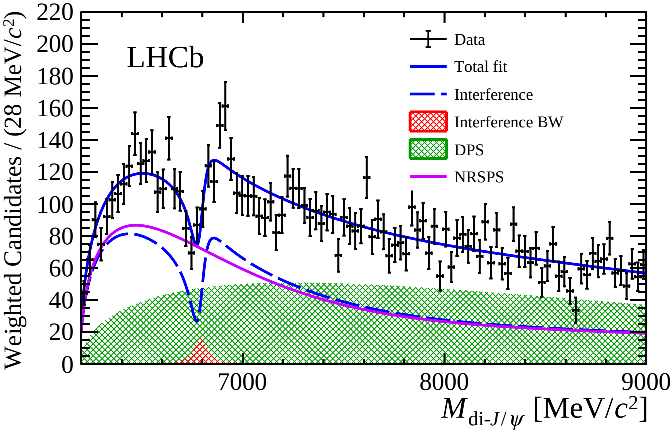
Model II: BW interfering with NRSPS, $p = 15.5\%$

Structure in $J/\psi J/\psi$



Or parametrise with a single BW

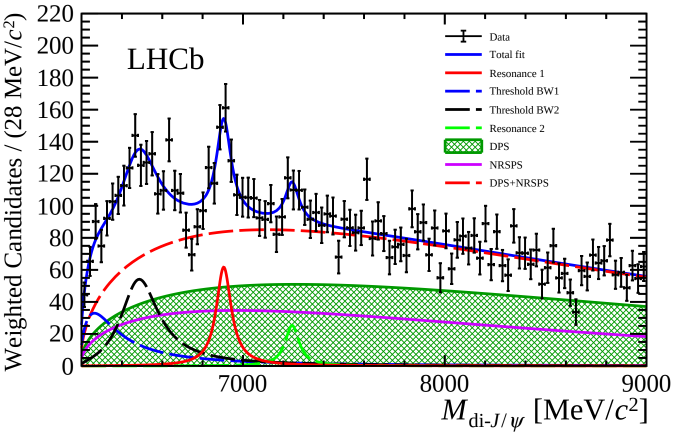
Structure in $J/\psi J/\psi$



BW interfering with SPS continuum

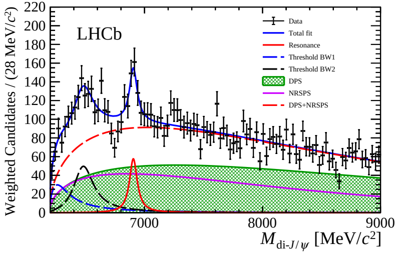
[LHCb, Science Bulletin 65 (2020) 1983, arXiv:2006.16957]

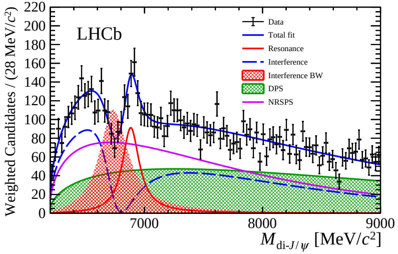
Structure in $J/\psi J/\psi$



Model I with another BW at 7.2 GeV/c^2

Structure in $J/\psi J/\psi$





In all cases a new state $T_{cc\overline{c}\overline{c}}(6900)$ is observed.

Mass and width, and cross-section $\mathcal{R}$ relative to $J/\psi J/\psi$, based on the no-interference fit:

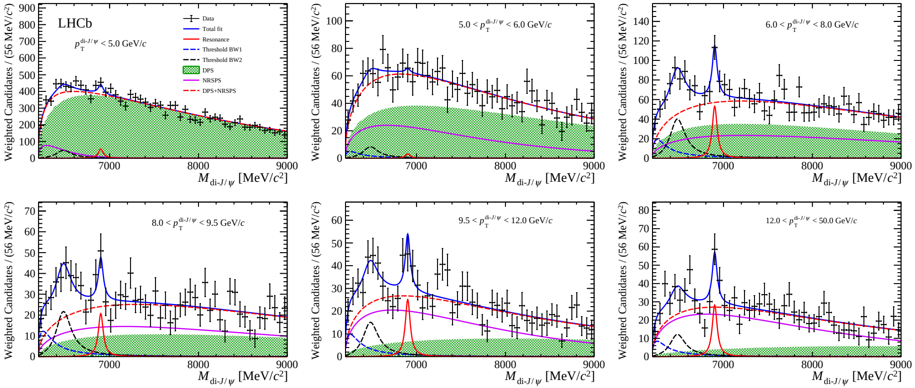
$$M = 6905 \pm 11 \pm 7\,\text{MeV}/c^2$$
$$\Gamma = 80 \pm 19 \pm 33\,\text{MeV}/c^2$$
$$\mathcal{R} = 2.6 \pm 0.6 \pm 0.8\%$$

And with an interfering resonance:

$$M = 6886 \pm 11 \pm 11\,\text{MeV}/c^2$$
$$\Gamma = 168 \pm 33 \pm 69\,\text{MeV}/c^2$$

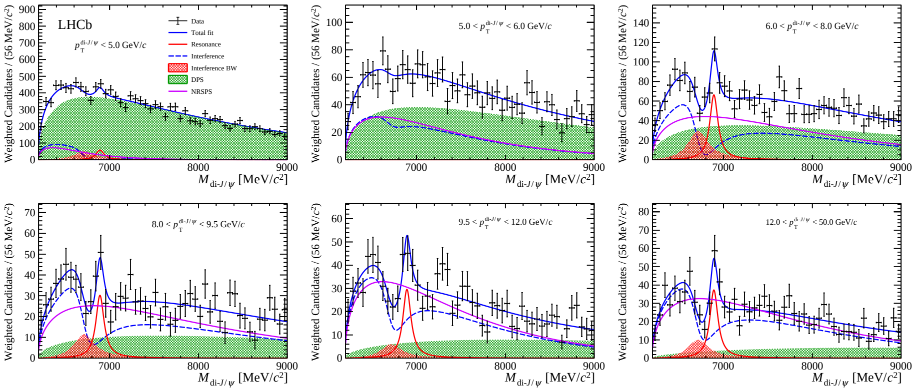
[LHCb, Science Bulletin 65 (2020) 1983, arXiv:2006.16957]

Structure in $J/\psi J/\psi$



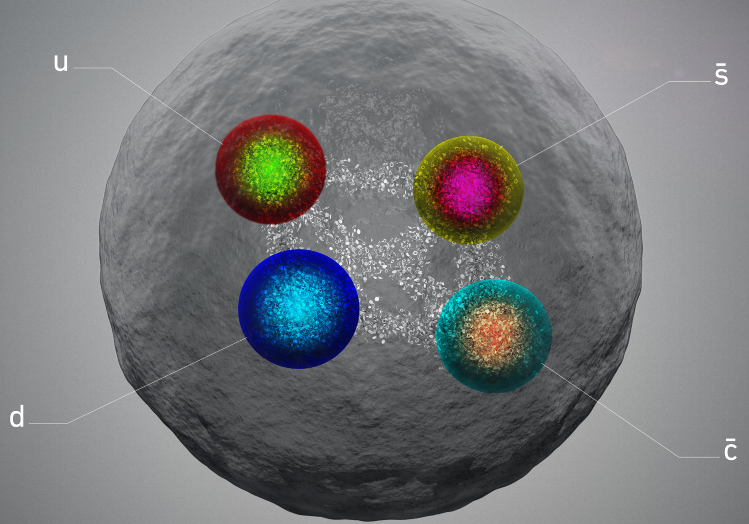
Model I fit in bins of p_{T}.

STRUCTURE IN $J/\psi J/\psi$



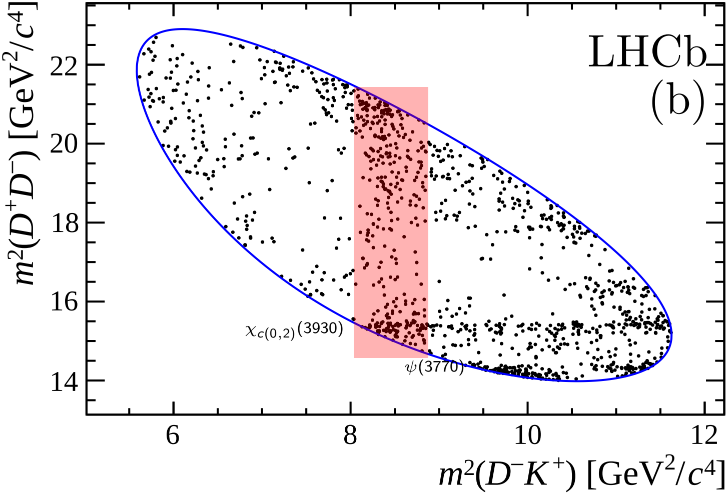
Model II fit in bins of p_T.

Amplitude analysis of $B^+ \to D^- D^+ K^-$



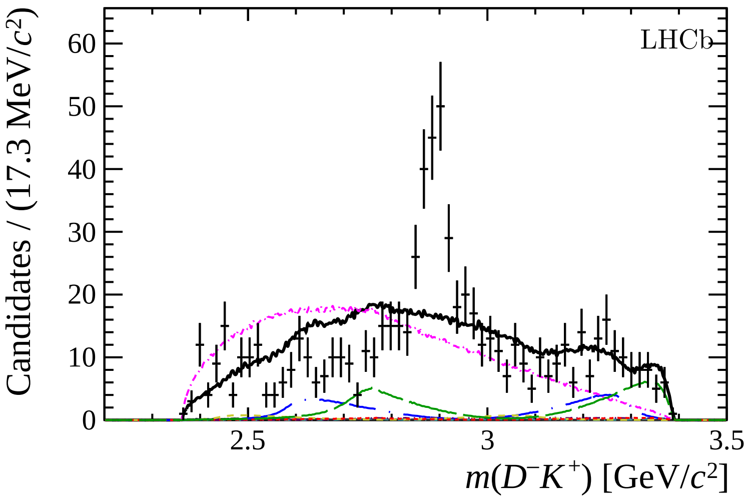
[LHCb, PRD 102 (2020) 112003, arXiv:2009.00026]

Amplitude analysis of $B^+ \to D^- D^+ K^-$



[LHCb, PRD 102 (2020) 112003, arXiv:2009.00026]

Amplitude analysis of $B^+ \to D^- D^+ K^-$



AMPLITUDE ANALYSIS OF $B^+ \to D^- D^+ K^-$

New $\overline{c}\overline{s}du$ states

$X_0(2900): M = 2866 \pm 7 \pm 2\,\text{MeV}/c^2$

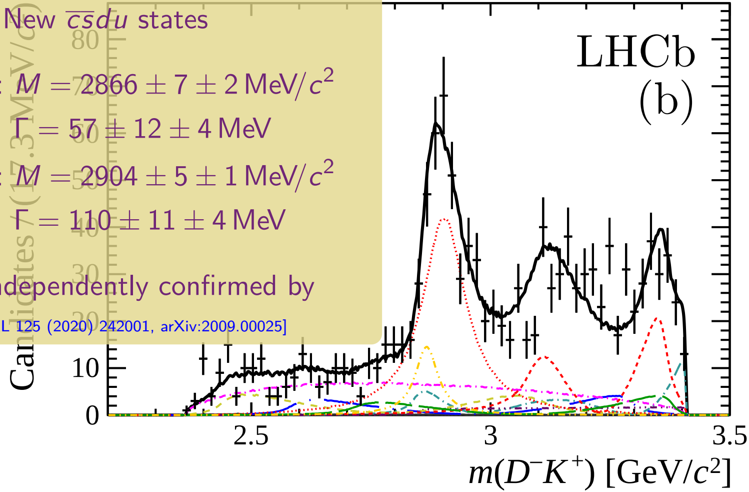
$\Gamma = 57 \pm 12 \pm 4\,\text{MeV}$

$X_1(2900): M = 2904 \pm 5 \pm 1\,\text{MeV}/c^2$

$\Gamma = 110 \pm 11 \pm 4\,\text{MeV}$

Model-independently confirmed by

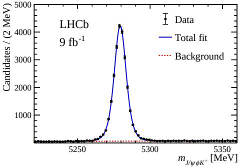
[LHCb, PRL 125 (2020) 242001, arXiv:2009.00025]

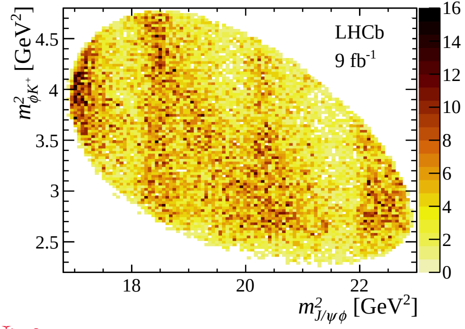


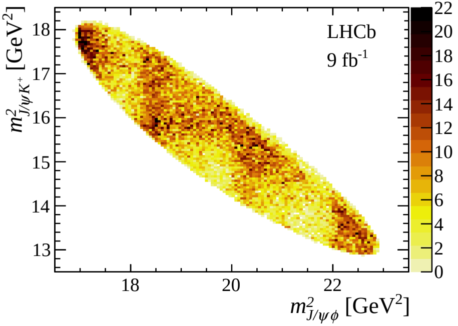
Strange tetraquarks in $B^+ \to J/\psi\phi K^+$

9 fb^{-1} update of 3 fb^{-1} [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

- $24\,220 \pm 170$ $B^+ \to J/\psi\phi K^+$ candidates with 4% background and 2% $B^+ \to J/\psi K^+K^-K^+$





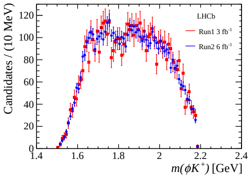


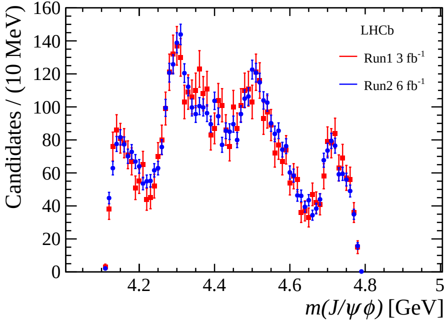
[B]

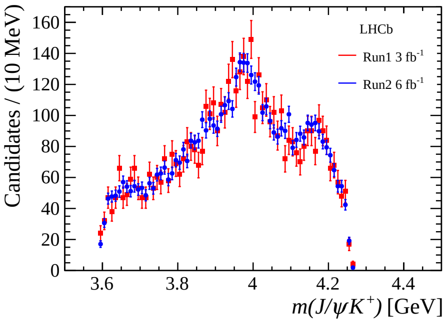
Strange tetraquarks in $B^+ \to J/\psi\phi K^+$

9 fb^{-1} update of 3 fb^{-1} [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

- $24\,220 \pm 170$ $B^+ \to J/\psi\phi K^+$ candidates with 4% background and 2% $B^+ \to J/\psi K^+ K^- K^+$
  - ➜ Run 2 almost 5 times Run 1 sample







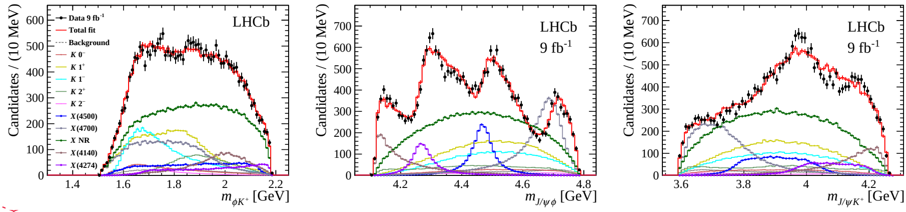
[B]

[LHCb, arXiv:2103.01803, submitted to PRD]

Strange tetraquarks in $B^+ \to J/\psi\phi K^+$

$9\,\mathrm{fb}^{-1}$ update of $3\,\mathrm{fb}^{-1}$ [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

- Try run-1 model with 5 $K^+\phi$ and 4 $J/\psi\phi$ resonances
  - ➜ $J/\psi K^+$ distribution poorly modelled

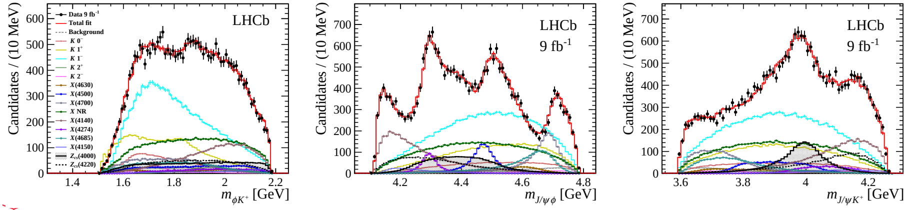


[B]

Strange tetraquarks in $B^+ \to J/\psi \phi K^+$

$9\,\mathrm{fb}^{-1}$ update of $3\,\mathrm{fb}^{-1}$ [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

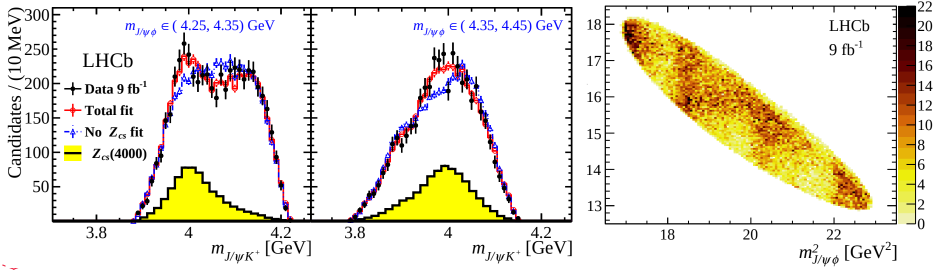
- Try run-1 model with 5 $K^+\phi$ and 4 $J/\psi\phi$ resonances
- Add more resonances: lower-mass kaons, two Z_{cs} and two more X.



Strange tetraquarks in $B^+ \to J/\psi\phi K^+$

$9\,\mathrm{fb}^{-1}$ update of $3\,\mathrm{fb}^{-1}$ [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

- Try run-1 model with 5 $K^+\phi$ and 4 $J/\psi\phi$ resonances
- Add more resonances: lower-mass kaons, two Z_{cs} and two more X.
- Clear need of $J/\psi K^+$ tetraquarks: $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$



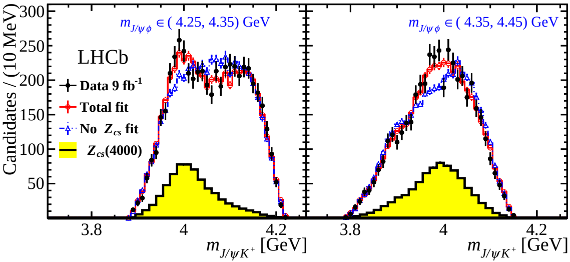
[B]

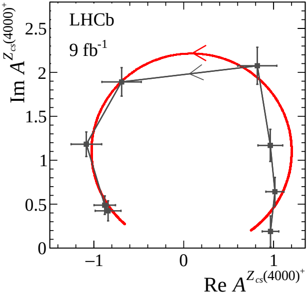
[LHCb, arXiv:2103.01803, submitted to PRD]

Strange tetraquarks in $B^+ \to J/\psi\phi K^+$

$9\,\text{fb}^{-1}$ update of $3\,\text{fb}^{-1}$ [PRL 118 (2017) 022003] [PRD 95 (2017) 012002]

- Try run-1 model with 5 $K^+\phi$ and 4 $J/\psi\phi$ resonances
- Add more resonances: lower-mass kaons, two Z_{cs} and two more X.
- Clear need of $J/\psi K^+$ tetraquarks: $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$
  - ✔ Resonant behaviour of $Z_{cs}(4000)^+$

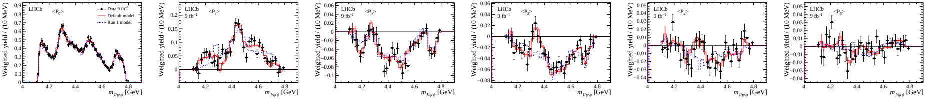




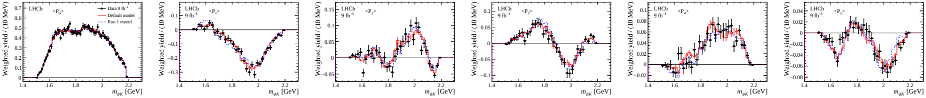
[B]

Strange tetraquarks in $B^+ \to J/\psi \phi K^+$

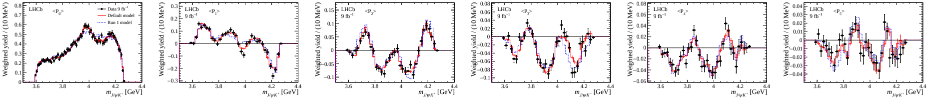
Angular moments of $J/\psi\phi$ helicity angle versus $J/\psi\phi$ mass



Angular moments of ϕK^+ helicity angle versus ϕK^+ mass



Angular moments of $J/\psi K^+$ helicity angle versus $J/\psi K^+$ mass

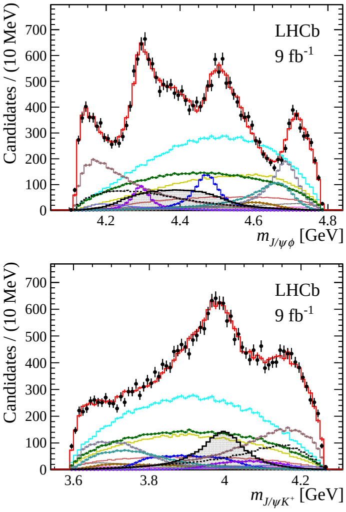


$$\left\langle P_\ell^U \right\rangle = \sum_{i=1}^{N_{\text{decays}}} \frac{1}{\eta_i} P_\ell(\cos\theta)$$

[B]

Strange tetraquarks in $B^+ \to J/\psi \phi K^+$

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)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-\ 7}$



[B]

Tetraquarks interpretation

Some comments by Richard Lebed:

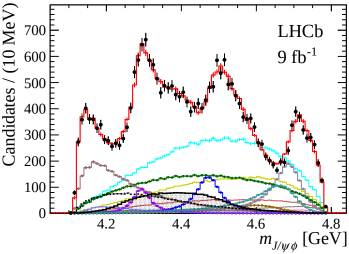
$Z_{cs}(4000)$ could be the strange SU(3) partner of $Z_c(3900)$ [BESIII, PRL 110 (2013) 252001]

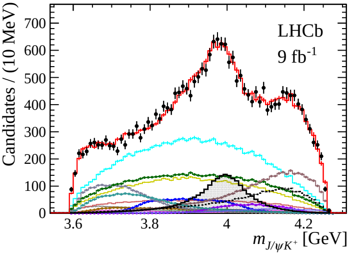
$Z_{cs}(4220)$ could be the strange SU(3) partner of $Z_c(4020)$ [BESIII, PRL 111 (2013) 242001]

- However these states are not seen in B decays and wider

$X(4630)$ is close in mass to $Y(4626)$ seen in $D^+ D_s(2536)^-$ [Belle, PRD 100 (2019) 111103]

$X(4150)$ is below 5σ. It could be the $\eta_{c2}(2D)$. The mass is predicted to be 4158 MeV [Barnes, Godfrey, Swanson, PRD 72 (2005) 054026]



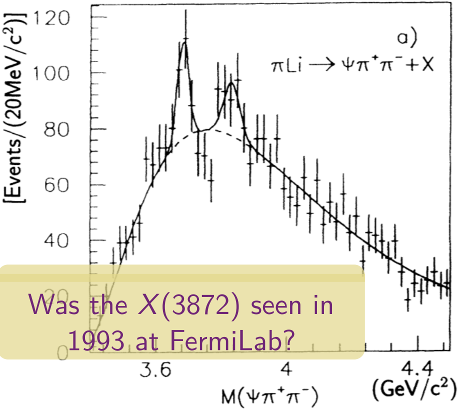


[B]

$\chi_{c1}(3872)$ saga

[B]

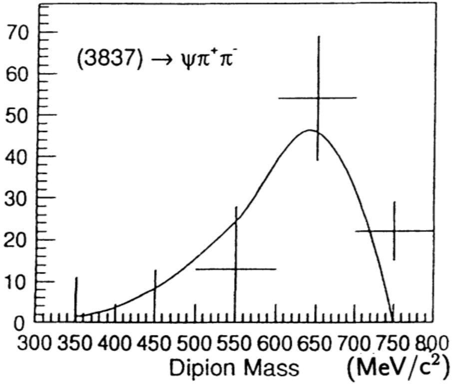
Hidden charm states decaying to $J/\psi\pi^+\pi^-$



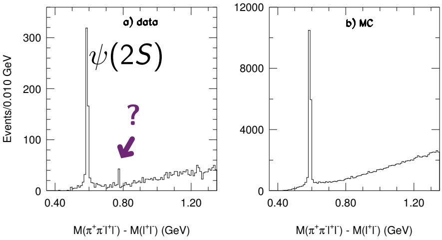
Was the $X(3872)$ seen in 1993 at FermiLab?

$J/\psi\pi^+\pi^-$ in 10 GeV/$c\pi^\pm$Li interactions

If the enhancement at 3.836 GeV/c^2 is confirmed by future experiments, then the most likely interpretation is that it is due to a $c\bar{c}$ charmonium state. A more speculative interpretation would be that it is due to a $c\bar{c}q\bar{q}$ state. The lack of a signal in the $J/\psi\,\pi^\pm\pi^0$ mass spectrum, shown in Fig. 8, and in the $J/\psi\,\pi^\pm\pi^\pm$ spectra



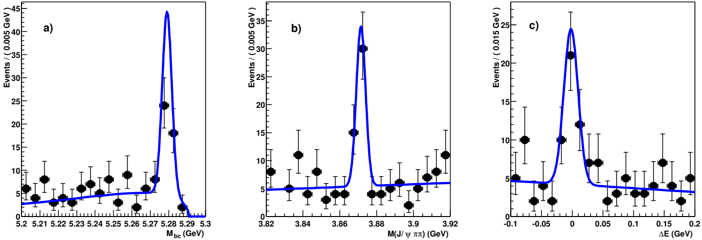
Observation of the $X(3872)$ Resonance



Belle reported a clear peak in the $J/\psi\pi^+\pi^-$ mass spectrum above the $\psi(2S)$ in $B^+ \to J/\psi\pi^+\pi^-K^+$ decays (36 ± 7 events)

$$M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV}/c^2$$
$$\Gamma < 2.3 \text{ MeV}$$

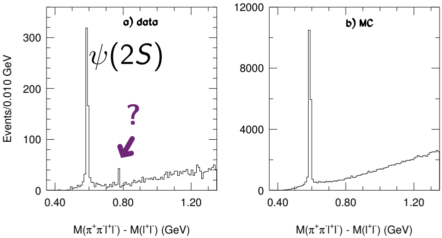
close to the $\bar{D}^0 D^{*0}$ threshold



Moon-Mars

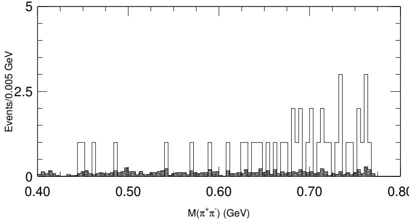
[B]

Observation of the $X(3872)$ Resonance

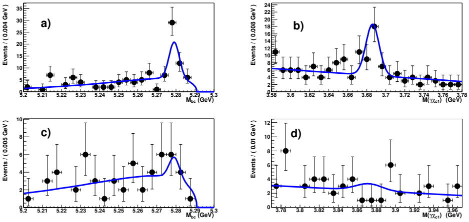


Belle reported a clear peak in the $J/\psi\pi^+\pi^-$ mass spectrum above the $\psi(2S)$ in $B^+ \to J/\psi\pi^+\pi^- K^+$ decays (36 ± 7 events)

$\pi^+\pi^-$ spectrum consistent with ρ^0



A search in $B^+ \to \gamma\chi_{c1} K^+$ yields no signal, contradicting a $^3D_{c2}$ explanation



[B]

$\chi_{c1}(3872)$ production at 7 TeV

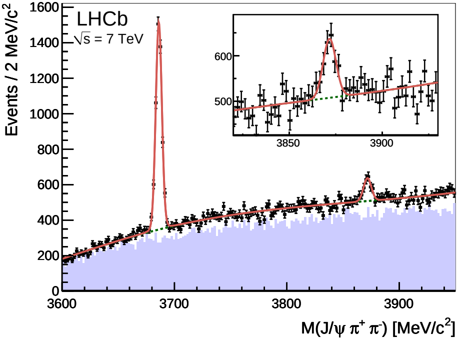
LHCb was first to observe the $\chi_{c1}(3872)$ meson in pp collisions (CDF saw it in $p\overline{p}$ [PRL96 (2016) 102002])

- Using 2010 data corresponding to $35\,\text{pb}^{-1}$, see 500 $\chi_{c1}(3872)$ and 4000 $\psi(2S)$ in $J/\psi\pi^+\pi^-$.

- Cross-section times BF in $25 < y < 4.5$ and $5 < p_\mathrm{T} < 20\,\text{GeV}/c$ is

$$5.4 \pm 1.3 \pm 0.8 \text{ nb}$$

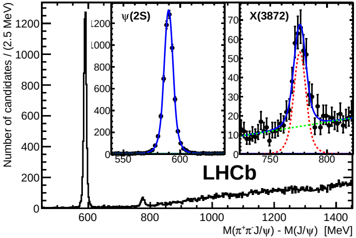
- The mass is also measured to be $3871 \pm 0.48 \pm 0.12\,\text{MeV}/c^2$

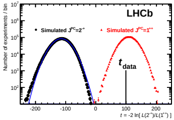


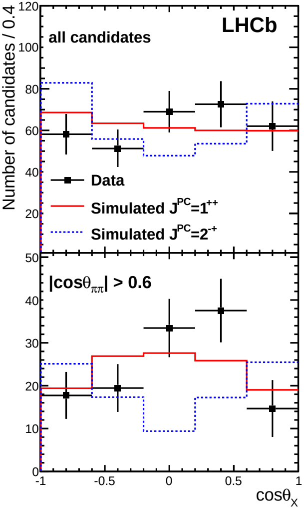
$X(3872)$ quantum numbers

- Five-dimensional angular analysis of $B^+ \to X(3872)K^+$ with $X(3872) \to J/\psi\pi^+\pi^-$ using 2011 data
  - ➜ 313 ± 26 decays in 38 000 $B^+ \to J/\psi\pi^+\pi^-K^+$ candidates

✔ Unambiguous assignment $J^{PC} = 1^{++}$ at 8σ. This rules out the η_{c2} (1^1D_2) hypothesis.

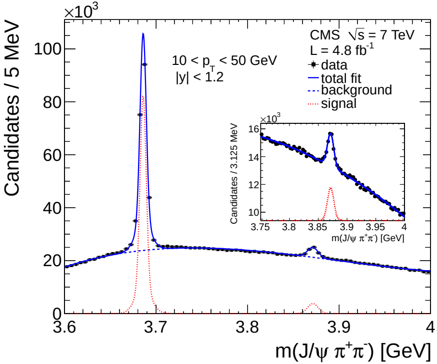


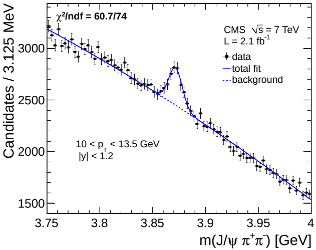


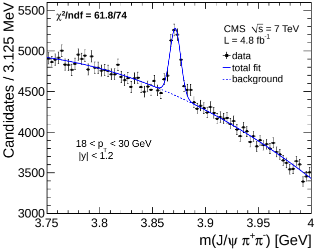


[B]

$\chi_{c1}(3872)$ production at 7 TeV



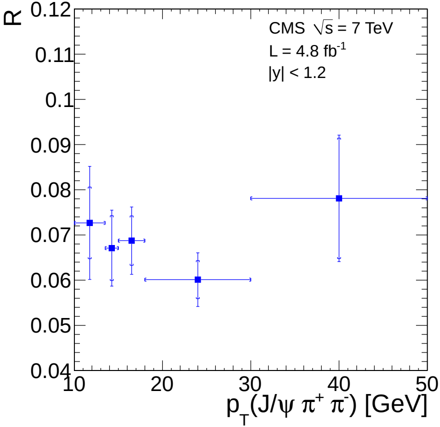




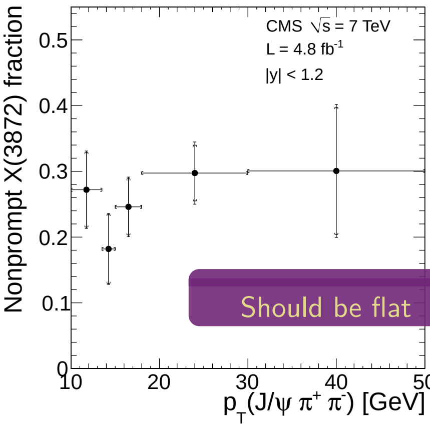
CMS see $\chi_{c1}(3872)$ with 2011 data ($4.8\,\text{fb}^{-1}$).

- They bin in p_{T}
- And determine the non-prompt fraction, defined as $\ell_{xy} > 100\,\mu\text{m}$

$\chi_{c1}(3872)$ production at 7 TeV



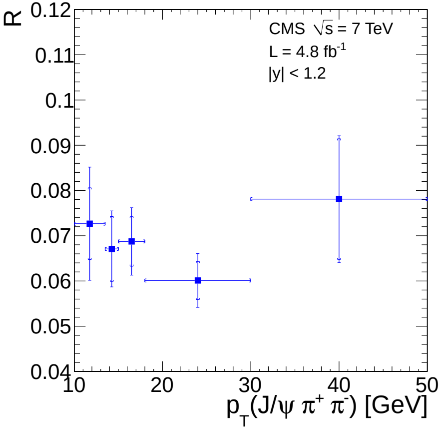
Ratio of $\sigma \times \mathcal{B}$ of $\chi_{c1}(3872)$ and $\psi(2S)$ versus p_{T}



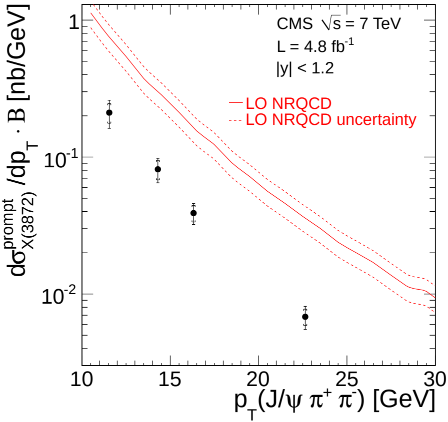
Should be flat

Non-prompt fraction of $\chi_{c1}(3872)$ versus p_{T}

$\chi_{c1}(3872)$ production at 7 TeV



Ratio of $\sigma \times \mathcal{B}$ of $\chi_{c1}(3872)$ and $\psi(2S)$ versus p_{T}

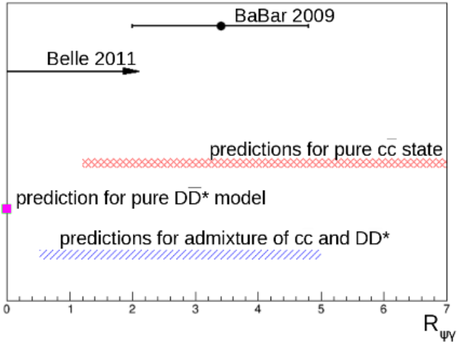


Prompt production of $\chi_{c1}(3872)$ versus p_{T}

[LHCb, Nucl. Phys. B886 (2014) 665, arXiv:1404.0275]

Evidence for $X(3872) \to \psi(2S)\gamma$

- The nature of the $X(3872)$ is not clear. The ratio $R_{\psi\gamma}$ of decay widths to $\psi(2S)\gamma$ and $J/\psi\gamma$ is expected to be very different for a $c\overline{c}$ state or a pure DD^* molecule
- BaBar and Belle results were not conclusive



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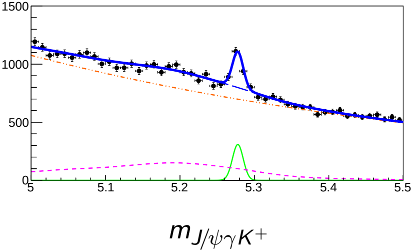
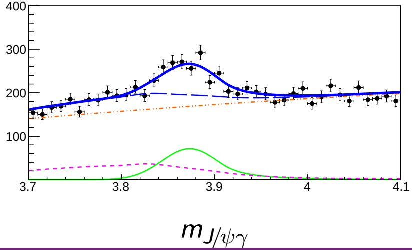
- We reconstruct $B^+ \to J/\psi\gamma K^+$ and fit for the X





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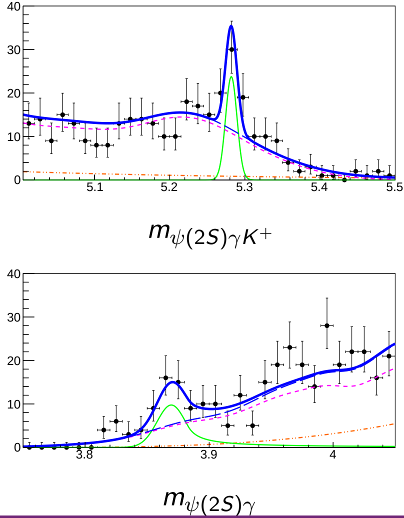
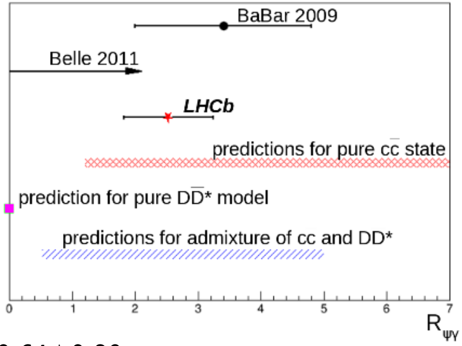
- We reconstruct $B^+ \to J/\psi\gamma K^+$ and fit for the X
- Same for $B^+ \to \psi(2S)\gamma K^+$: 4.4σ evidence



Evidence for $X(3872) \to \psi(2S)\gamma$

- The nature of the $X(3872)$ is not clear. The ratio $R_{\psi\gamma}$ of decay widths to $\psi(2S)\gamma$ and $J/\psi\gamma$ is expected to be very different for a $c\bar{c}$ state or a pure DD^* molecule
- We reconstruct $B^+ \to J/\psi\gamma K^+$ and fit for the X
- The ratio is measured to be



$$\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

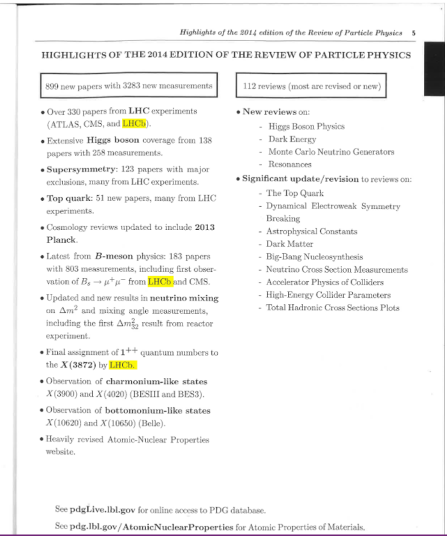
This disfavours the DD^* molecule at 4.4σ

[LHCb, PRD 92 (2015) 011102(R), arXiv:1504.06339]

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

- The $X(3872)$ state was observed by Belle [PRL 91 (2013) 26001] in $B \to XK$ and $X \to \pi^+\pi^- J/\psi$. Its nature is unknown.
- CDF determined the quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+} [PRL 98 (2007) 132002]
- LHCb determined $J^{PC} = 1^{++}$ [PRL 110 (2013) 222001] ($1\ \text{fb}^{-1}$)
  - ➜ One of the PDG highlights of the 2014 edition

✗ Both assumed the decay to be dominated by the lowest angular momentum L_{min}.



Highlights of the 2014 edition of the Review of Particle Physics 5

HIGHLIGHTS OF THE 2014 EDITION OF THE REVIEW OF PARTICLE PHYSICS

899 new papers with 3283 new measurements

- Over 330 papers from **LHC** experiments (ATLAS, CMS, and LHCb).
- Extensive **Higgs boson** coverage from 138 papers with 258 measurements.
- **Supersymmetry**: 123 papers with major exclusions, many from LHC experiments.
- **Top quark**: 51 new papers, many from LHC experiments.
- Cosmology reviews updated to include **2013 Planck**.
- Latest from ***B*-meson** physics: 183 papers with 803 measurements, including first observation of $B_s \to \mu^+\mu^-$ from LHCb and CMS.
- Updated and new results in **neutrino mixing** on Δm^2 and mixing angle measurements, including the first Δm^2_{32} result from reactor experiment.
- Final assignment of 1^{++} quantum numbers to the $X(3872)$ by LHCb.
- Observation of **charmonium-like states** $X(3900)$ and $X(4020)$ (BESIII and BES3).
- Observation of **bottomonium-like states** $X(10620)$ and $X(10650)$ (Belle).
- Heavily revised Atomic-Nuclear Properties website.

112 reviews (most are revised or new)

- **New reviews** on:
  - Higgs Boson Physics
  - Dark Energy
  - Monte Carlo Neutrino Generators
  - Resonances
- **Significant update/revision** to reviews on:
  - The Top Quark
  - Dynamical Electroweak Symmetry Breaking
  - Astrophysical Constants
  - Dark Matter
  - Big-Bang Nucleosynthesis
  - Neutrino Cross Section Measurements
  - Accelerator Physics of Colliders
  - High-Energy Collider Parameters
  - Total Hadronic Cross Sections Plots

See **pdgLive.lbl.gov** for online access to PDG database.

See **pdg.lbl.gov/AtomicNuclearProperties** for Atomic Properties of Materials.

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

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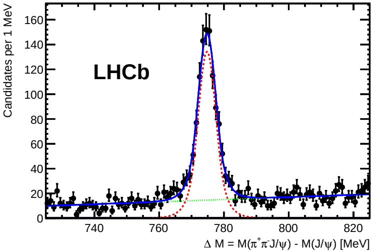
- CDF determined the quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+} [PRL 98 (2007) 132002]
- LHCb determined $J^{PC} = 1^{++}$ [PRL 110 (2013) 222001] (1 fb^{-1})
  - ➜ One of the PDG highlights of the 2014 edition
- ✗ Both assumed the decay to be dominated by the lowest angular momentum L_{min}.
- Here we present a re-analysis using 3 fb^{-1} without this assumption.

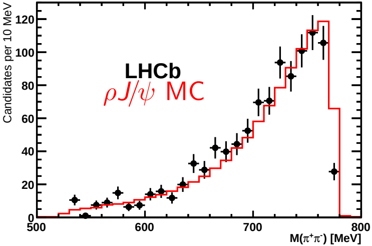
	B_{LS}	
J^{PC}	Any L value	Minimal L value
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

Parity-allowed LS couplings in $X \to \rho^0 J/\psi$

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

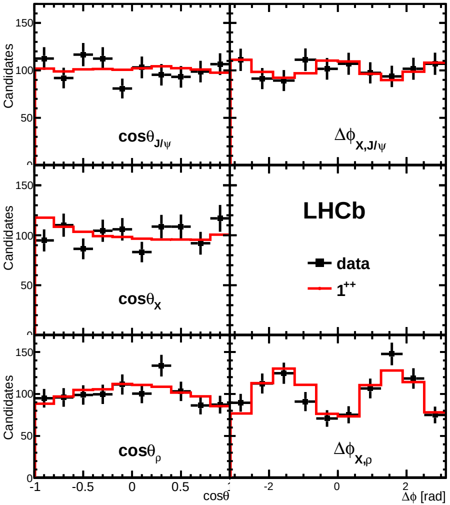
- Here we present a re-analysis using 3 fb^{-1} without this assumption.
- Use 1011 ± 38 $B^+ \to X K^+$, $X \to \rho^0 J/\psi$ decays
- The phase space is limited





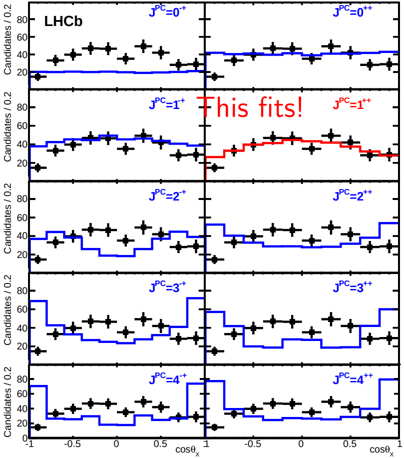
$X(3872)$ QN with $X(3872) \to \rho^0 J/\psi$

- Here we present a re-analysis using 3 fb^{-1} without this assumption.
- Use 1011 ± 38 $B^+ \to XK^+$, $X \to \rho^0 J/\psi$ decays
- The phase space is limited
- Use helicity formalism to fit 5-dimensional angular distributions



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

- Here we present a re-analysis using 3 fb^{-1} without this assumption.
- Use 1011 ± 38 $B^+ \to XK^+$, $X \to \rho^0 J/\psi$ decays
- The phase space is limited
- Use helicity formalism to fit 5-dimensional angular distributions
- Only $J^{PC} = 1^{++}$ fits and the fraction of D-wave is found to be less than 4%

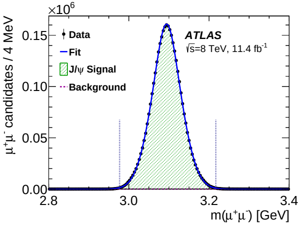


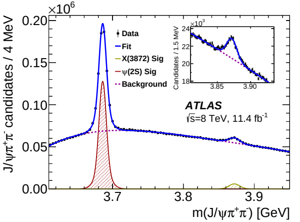
→ Compatible with tetraquark, molecule or $\chi_{c1}(2^3P_1)$ hypotheses (possibly mixed). It excludes any other charmonium state.

$\psi(2S)$ and $\chi_{c1}(3872)$ at 8 TeV

Study of $\psi(2S)$ and $X(3872)$ production using the final state $J/\psi(\mu^+\mu^-)\pi^+\pi^-$ with 8 TeV data.

- Prompt and non-prompt components disentangled by pseudo-lifetime fits





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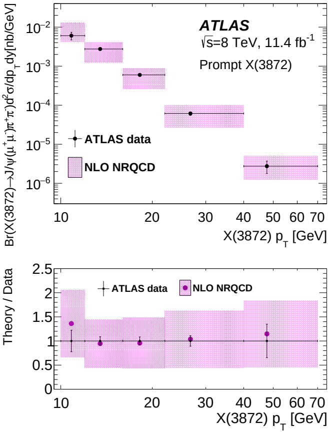
Study of $\psi(2S)$ and $X(3872)$ production using the final state $J/\psi(\mu^+\mu^-)\pi^+\pi^-$ with 8 TeV data.

- Prompt and non-prompt components disentangled by pseudo-lifetime fits
- Prompt $X(3872)$ production consistent with NLO NRQCD predictions [Artoisenet and Braaten, PRD81 114018, arXiv:0911.2016]. Also consistent with CMS [JHEP 04 (2013) 154, arXiv:1302.3968].

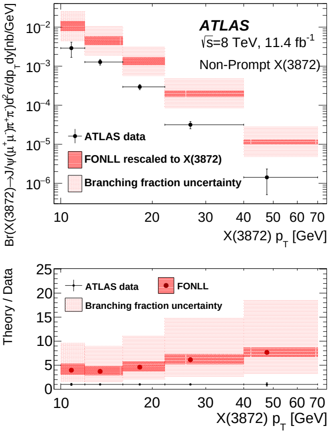


$\psi(2S)$ AND $\chi_{c1}(3872)$ AT 8 TEV

Study of $\psi(2S)$ and $X(3872)$ production using the final state $J/\psi(\mu^+\mu^-)\pi^+\pi^-$ with 8 TeV data.

- Prompt and non-prompt components disentangled by pseudo-lifetime fits
- Non-prompt $X(3872)$ production consistently low compared to predictions

  [Cacciari et al.,JHEP 10 (2012) 137, arXiv:1205.6344]



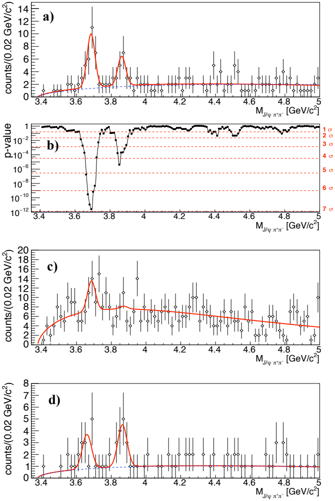
Ratio assuming same mix of b-hadrons:

$$\frac{\mathcal{B}(b\to X(3872)(\mu^+\mu^-)\text{any})}{\mathcal{B}(b\to \psi(2S)(\mu^+\mu^-)\text{any})} = (3.95 \pm 0.32 \pm 0.08)\%$$

But if B_c^+ component is fitted, it is found that $(25 \pm 13 \pm 2 \pm 5\,(\text{spin}))\%$ of non-prompt $X(3872)$ come from B_c^+ ➜ Puzzling!

$X(3872)$ muoproduction

- Placeholder



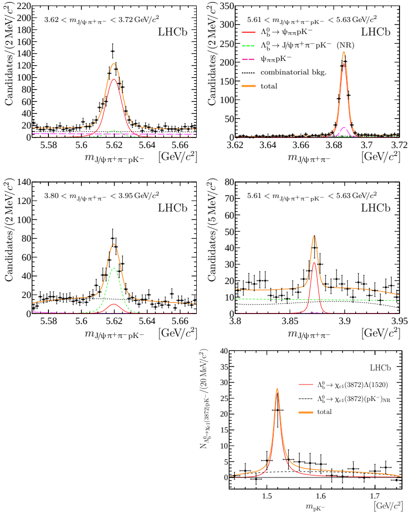
Observation of $\Lambda_b^0 \to \chi_{c1}(3872) p K^-$

The $X(3872)$ is now called $\chi_{c1}(3872)$.

Find 55 ± 11 (7σ) $\Lambda_b^0 \to \chi_{c1}(3872) p K^-$ with $\chi_{c1}(3872) \to \psi(2S)\pi^+\pi^-$

$$R_{\psi(2S)} = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872) p K^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S) K^-)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi \pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$

The combined BF is $(1.2 \pm 0.3 \pm 0.2) \times 10^{-6}$



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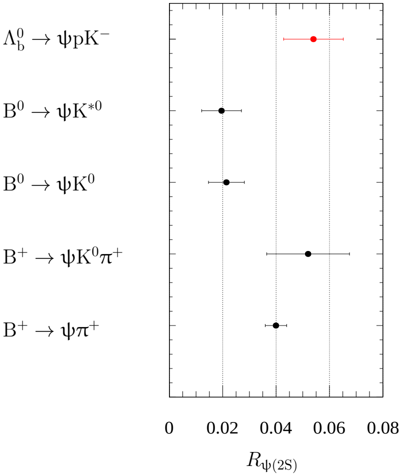
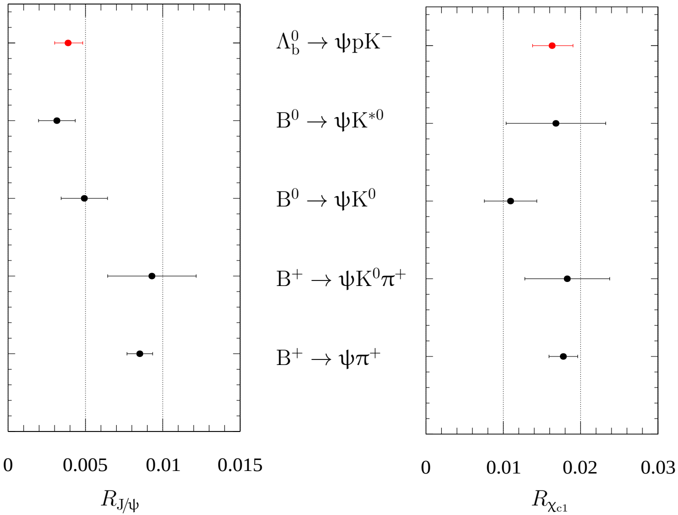


Compared with PDG averages

Observation of $\Lambda_b^0 \to \chi_{c1}(3872) p K^-$



[LHCb, PRD 102 (2020) 092005, arXiv:2005.13419]

Lineshape of the $\chi_{c1}(3872)$ meson

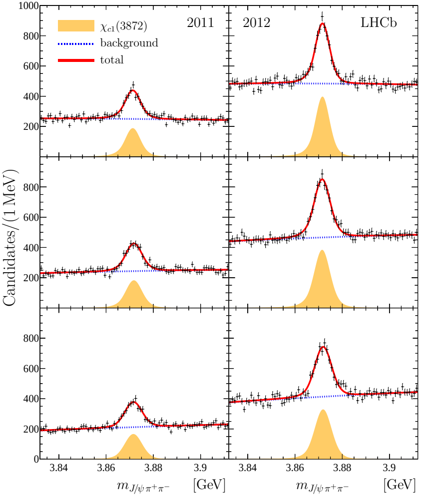
Using $3\,\text{fb}^{-1}$ 2011–12 detached $J/\psi\pi^+\pi^-$ data, study the $\chi_{c1}(3872)$ lineshape (15k signal). $\psi(2S)$ is used as control.

$$m = 3871.70 \pm 0.07 \pm 0.07 \pm 0.01\,\text{MeV}$$
$$\Gamma = 1.39 \pm 0.24 \pm 0.10\,\text{MeV}$$

First measurement of the BW width!

Is the $\chi_{c1}(3872)$ above or below $D^{*0}\overline{D}$ threshold?

$$m(D^{*0}\overline{D}) = 3871.69 \pm 0.06\,\text{MeV}$$



[B]

Lineshape of the $\chi_{c1}(3872)$ meson

For a resonance near threshold with coupled channels, the Flatté parametrisation is to be used [Yu, Kalashnikova, Nefediev, PRD80 (2009) 074004]

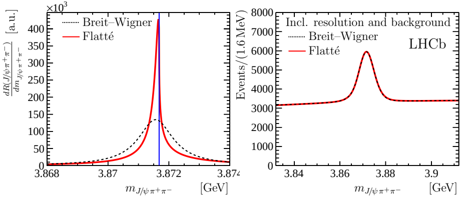
$$\frac{dR(J/\psi\pi^+\pi^-)}{dE} \propto \frac{\Gamma_\rho(E)}{\left|E - E_f + \frac{i}{2}\left[g\left(k_1 + k_2\right) + \Gamma_\rho(E) + \Gamma_\omega(E) + \Gamma_0\right]\right|^2}$$

$$E_f = m_0 - \left(m_{D^0} + m_{D^{*0}}\right)$$

Γ_f : various decay modes

$$\text{mode} = 3871.69\,^{+0.00}_{-0.04}\,^{+0.05}_{-0.13}\ \text{MeV}$$

$$\text{FWHM} = 0.22\,^{+0.07}_{-0.06}\,^{+0.11}_{-0.13}\ \text{MeV}$$



[B]

Lineshape of the $\chi_{c1}(3872)$ meson

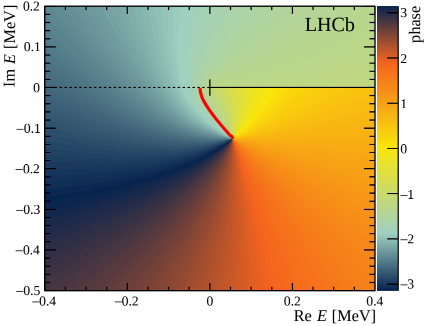
Analytic continuation of Flatté function in complex space.

Poles found:

$$\text{Sheet II}: (\ \ 0.0569 - 0.1256\,i)\ \text{MeV}$$
$$\text{Sheet III}: (-3.5780 - 1.2165\,i)\ \text{MeV}$$

$\chi_{c1}(3872)$ looks like a quasi-bound* state of $D^{*0}\bar{D}$ with binding energy of 24 keV ($E_b < 100$ keV at 90% CL)

* In the limit of all other couplings being switched off



Phase on complex E plane, with trajectory when other couplings are moved to 0.

[B]

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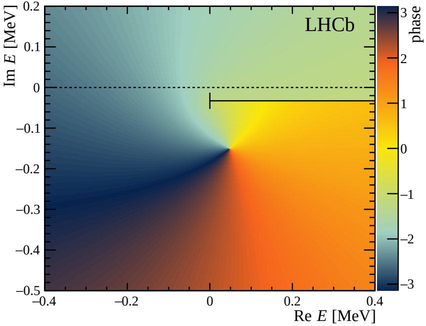

Phase on complex E plane, with width of D^{*0} taken into account

[B]

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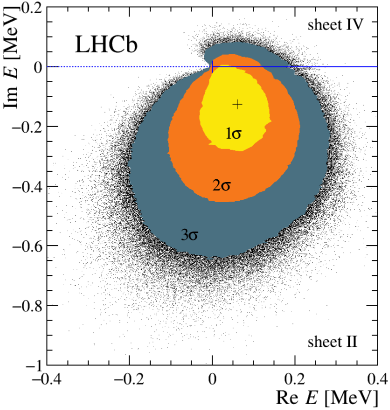
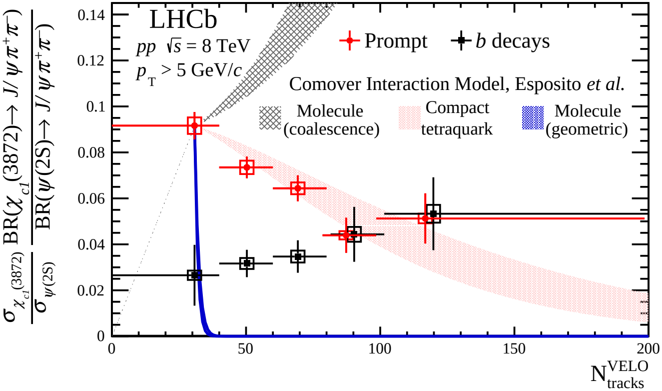


* In the limit of all other couplings being switched off

[B]

$\chi_{c1}(3872)$ production versus multiplicity



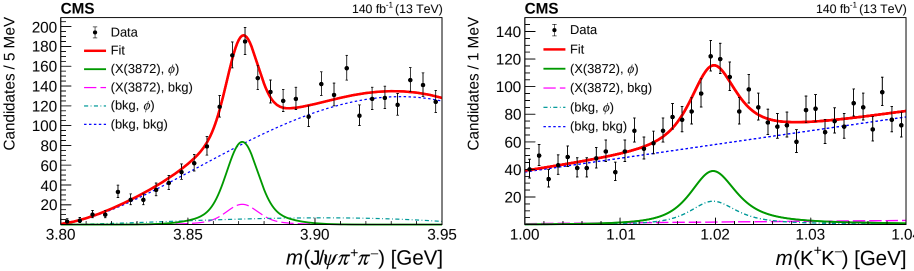
Ratio of $\psi(2S)$ and $\chi_{c1}(3872)$ production, for prompt and b decays.

The from-b ratio is consistent with being flat. 5σ slope for prompt, compared with predictions from [Esposito, Ferreiro, Pilloni, Polosa, Salgado, arXiv:2006.15044].

[B]

[CMS, PRL 125 (2020) 152001, arXiv:2005.04764]

Observation of $B_s^0 \to \chi_{c1}(3872)\phi$



Using 140 fb^{-1} 13 TeV data, find 300 $\pm$ 40 $B_s^0 \to \chi_{c1}(3872)\phi$

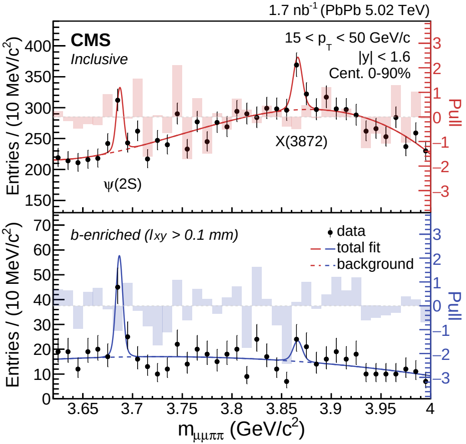
$$\frac{\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)\,\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\phi)\,\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29 \pm 0.17)\%$$

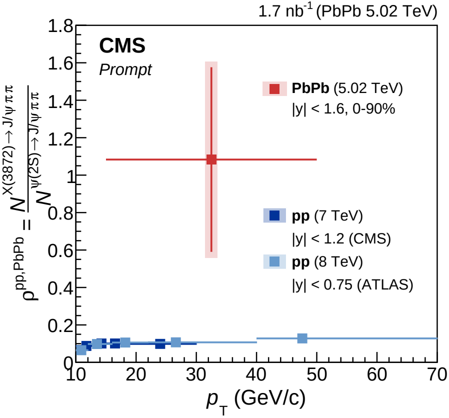
$$\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)\,\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-) = (4.14 \pm 0.54 \pm 0.32 \pm 0.46\,(\mathcal{B})) \times 10^{-6}$$

$$\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)/\mathcal{B}(B^+ \to \chi_{c1}(3872)K^+) = 0.482 \pm 0.063 \pm 0.037 \pm 0.070\,(\mathcal{B})$$

Which may indicate a different production mechanism in B_s^0 and B^+ (B_s^0 is consistent with B^0)

$\chi_{c1}(3872)$ production in PbPb





Evidence for very enhanced $\chi_{c1}(3872)$ production in PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV.

P_c^+ saga

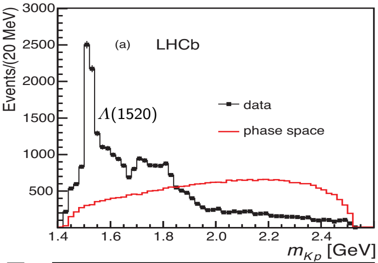
[B]

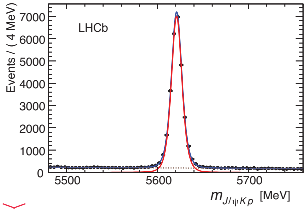
Observation of two pentaquarks

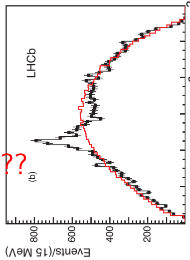
We knew there was something strange in $\Lambda_b^0 \to J/\psi p K^-$ [JHEP 07 (2014) 103] [PLB 734 (2014) 122] [PRL 111 (2013) 102003]

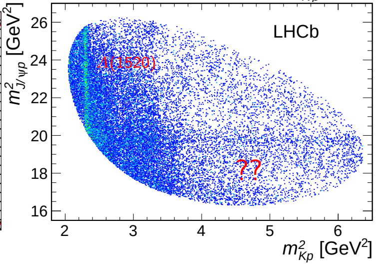
➜ Revisit this channel with a clean selection: 26000 ± 170 decays

- Reflections from B_s^0 vetoed
- Smooth efficiencies and backgrounds over Dalitz plane









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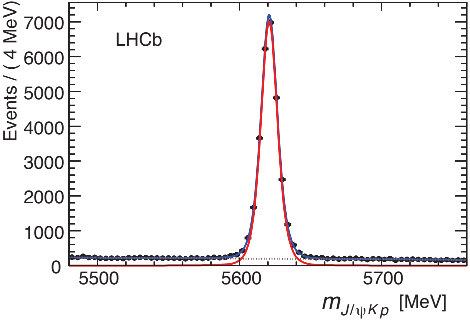
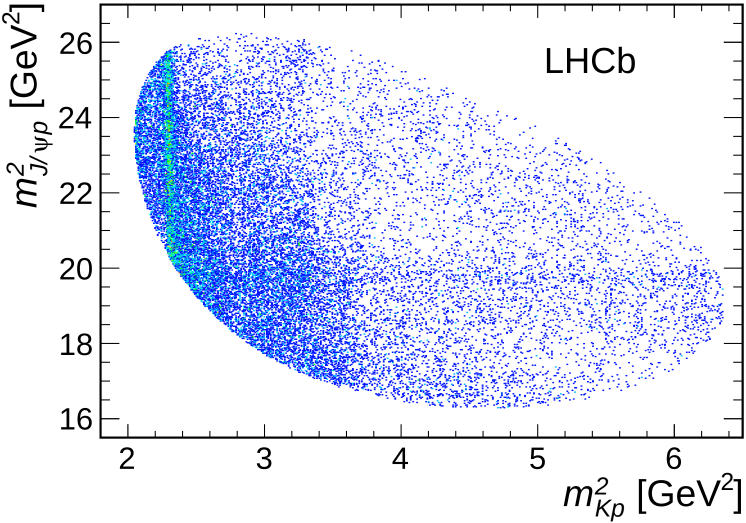
- Reflections from B_s^0 vetoed
- Re-optimised boosted decision tree trained on simulated signal and data background.

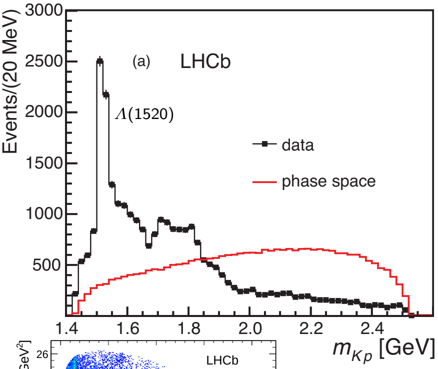


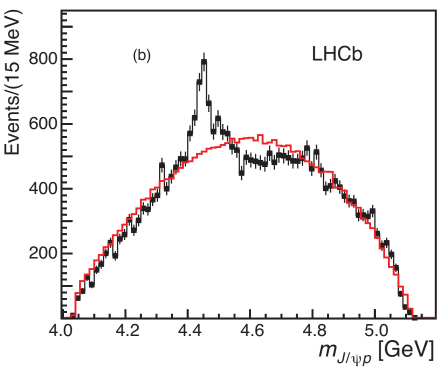
Observation of two pentaquarks

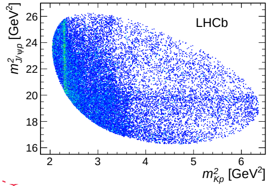


[LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

Observation of two pentaquarks



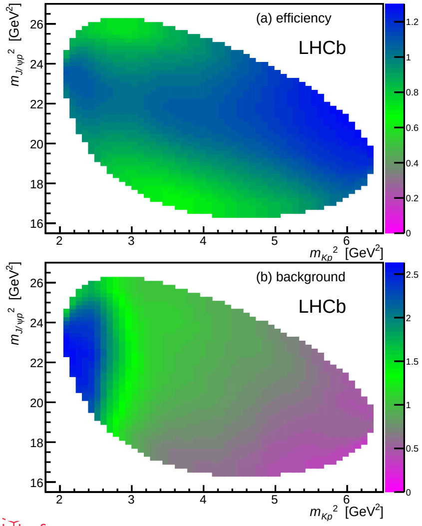




Clear difference with respect to phase-space

- In m_{K^-p} it is due to excited Λ resonances
- In $m_{J/\psi p}$ it is very puzzling

Observation of two pentaquarks



Efficiencies? Can it be sculpted by efficiencies?

- Efficiencies vary smoothly by a factor two over Dalitz
- Modelled using phase-space Simulation. Our detector response is well validated in many similar analyses.

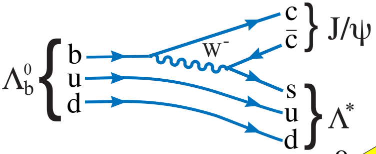
Background? We look in the sidebands and find nothing peaking.

- Peaking B^0 and B_s^0 are vetoed.
- Reconstruction artefacts are investigated.

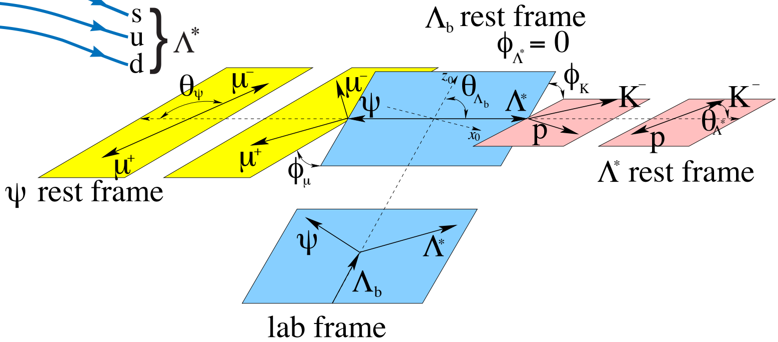
Observation of two pentaquarks

If it is not an artefact, it must be physics.

→ Can it be a conspiracy of interfering Λ resonances? See also [PRL 117 (2016) 082002].



Perform 6D amplitude analysis in $\theta_{\Lambda_b^0}$, θ_{Λ^*}, θ_ψ, ϕ_K, ϕ_μ, and m_{Kp}. But not $m_{J/\psi p}$.



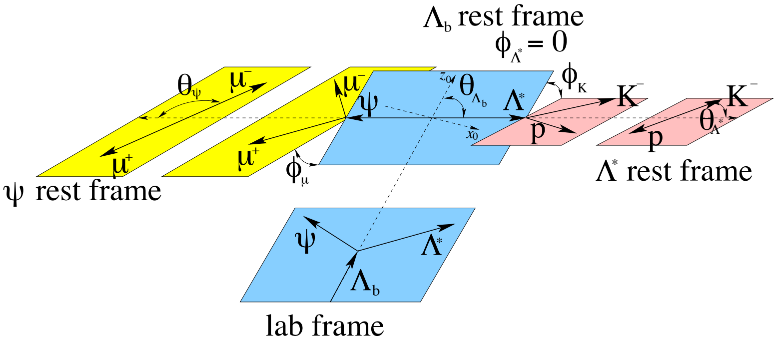
[LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

Observation of two pentaquarks

Matrix Elements with only Λ^* resonances:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^*$$

$$\mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_{\Lambda_n^*}(m_{Kp})\, D^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*,$$

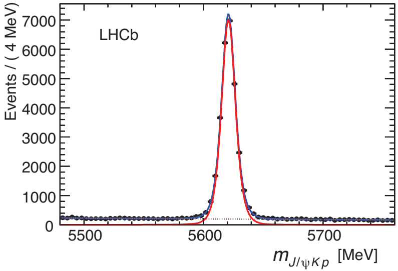


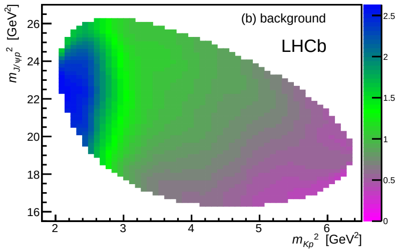
Observation of two pentaquarks

Two different implementations of the fitter, done by two groups on two continents. They differ by the background treatment

- cFit: Sideband data are used to construct 6D model of background shape.
- sFit: Background is statistically subtracted using *sPlot* weights from mass fit [Le Diberder, Pivk, NIM A 555 356 (2005)].

It is common practice in LHCb to have these two approaches.





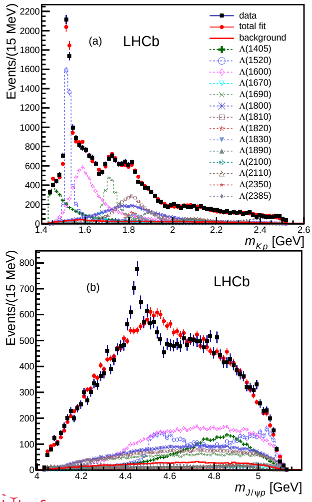
Observation of two pentaquarks

State	J^P	M_0 (MeV)	Γ_0 (MeV)	Red.	Ext.
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150		6
$\Lambda(2585)$	?	$\approx$2585	200		6
				64	146

Last columns show number of parameters are left free. Masses and Width are fixed.
Red.: Reduced model (fast). Ext.: Allows for more helicity (LS) couplings.

Observation of two pentaquarks

Extended Model — ■ data — ● fit



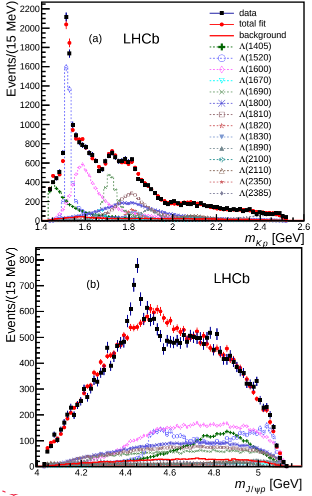
All known Λ^* resonances get the pK^- mass right, but not the $J/\psi p$ mass.

- We use the extended model in this fit
  - ➜ Adding more Λ resonances does not help [PRL 117 (2016) 082002]
- Letting the width and masses float does not help
- Adding $\Delta I = \frac{1}{2}$-suppressed Σ^{*0} ($I = \frac{3}{2}$) resonances does also not help

When you have eliminated the impossible, whatever remains, however improbable, must be the truth

Observation of two pentaquarks

Extended Model — ■ data — ● fit



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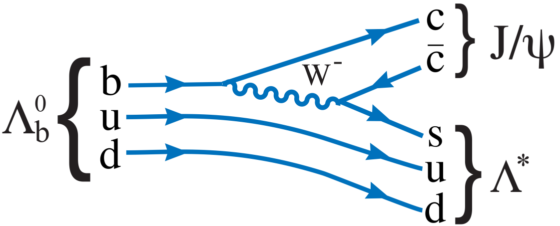

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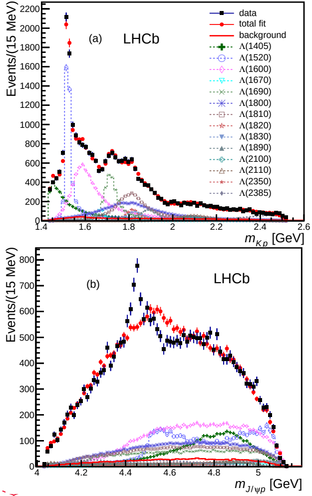

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$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150		6
$\Lambda(2585)$	?	≈2585	200		6
				64	146

Last columns show number of parameters are left free. Masses and Width are fixed.

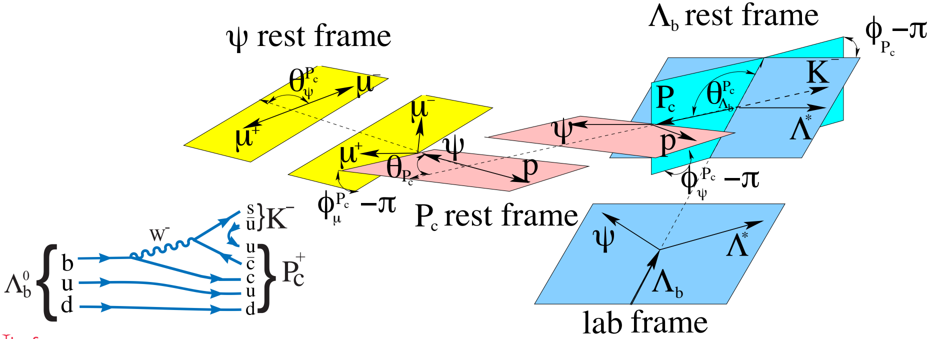
Red.: Reduced model (fast). Ext.: Allows for more helicity (LS) couplings.

Observation of two pentaquarks

Matrix Elements with a Pentaquark:

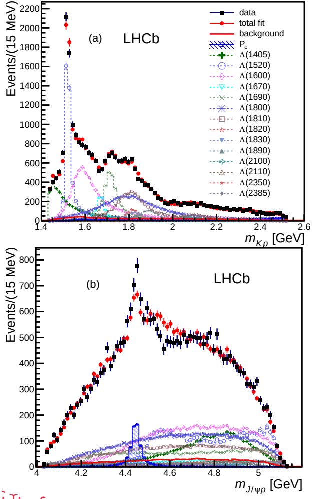
$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^*$$

$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_{P_{cj}}(m_{\psi p}) \quad D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*,$$

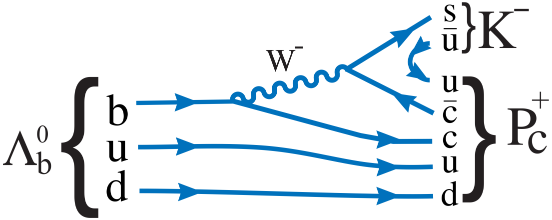


Observation of two pentaquarks

Reduced Model — ■ data — ● fit

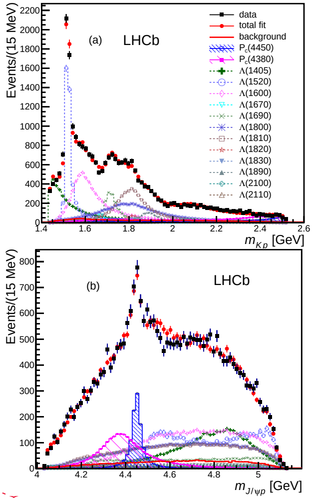


- There is an obvious peak at $m_{J/\psi p} = 4.45\ \text{GeV}/c^2$: Add one P_c^+ state with free J^P.
  - ✗ Unsatisfactory fit. $J^P = \frac{5}{2}^+$.



Observation of two pentaquarks

Reduced Model — ■ data — ● fit



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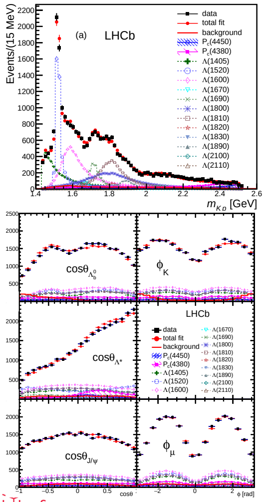
- Add another P_c^+
  - ✔ Good fit

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

Observation of two pentaquarks

Reduced Model — ■ data — ● fit



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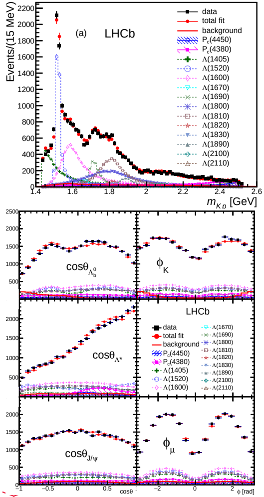
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

✔ The angular distributions are well reproduced

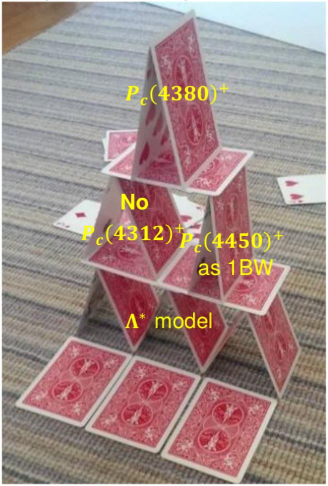
- Also OK: $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$
  - ➜ In any case opposite parities
- **Minimal quark content: $c\bar{c}uud$**

Observation of two pentaquarks

Reduced Model — ■ data — ● fit

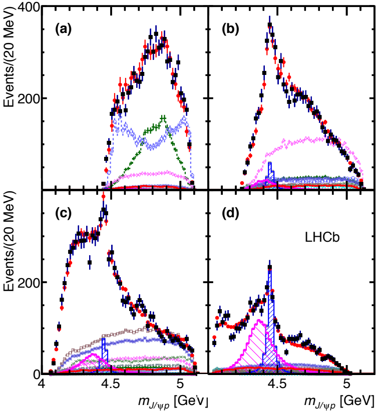


Amplitude analysis:



Observation of two pentaquarks

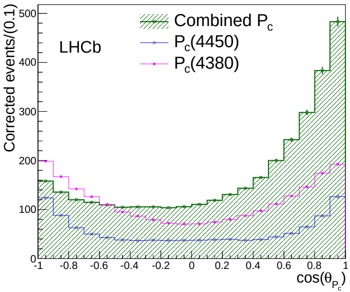
Reduced Model — ■ data — ● fit



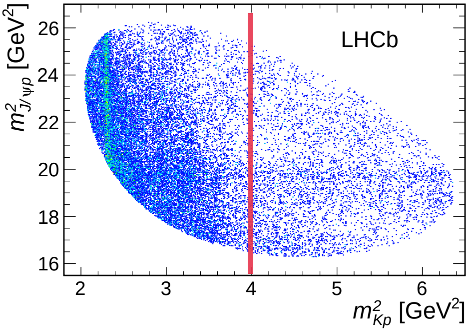
$K^- p$ mass ranges: a) $m_{Kp} < 1.55$
b) $1.55 < m_{Kp} < 1.7$ c) $1.7 < m_{Kp} < 2$
d) $2 < m_{Kp}$

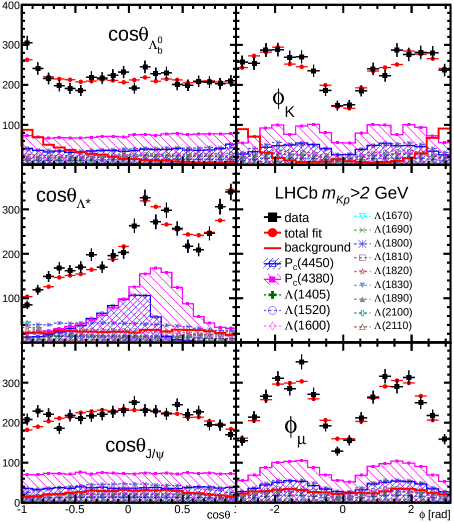
The interference pattern confirms the opposite parities:

- At $\cos\theta_{P_c^+} \sim -1$, low m_{Kp}: negative interference.
- At $\cos\theta_{P_c^+} \sim +1$, high m_{Kp}: positive interference.



Observation of two pentaquarks



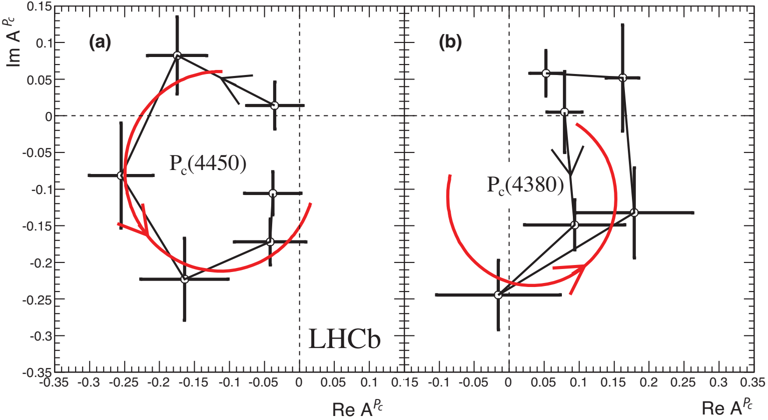


- Cutting at $m_{Kp} > 2$ GeV/c^2 enhances P_c^+ fraction

➜ Should be visible in other LHC experiments

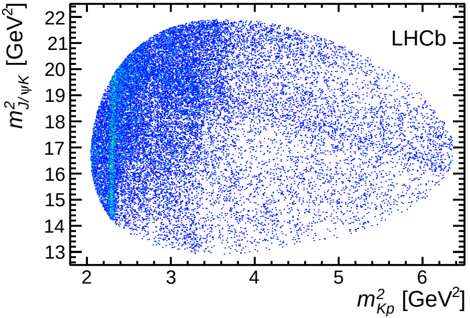
[LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

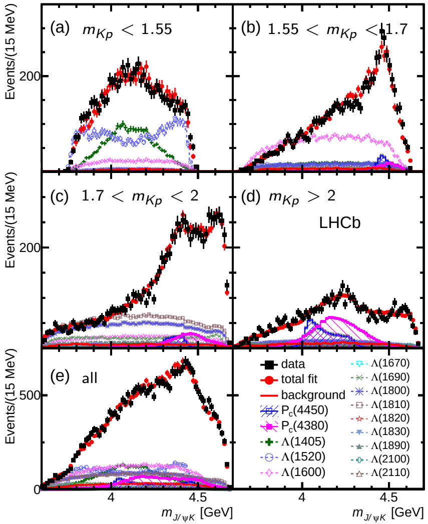
Observation of two pentaquarks



The Argand diagram shows the typical phase motion of a resonance for the $P_c(4450)^+$. For the $P_c(4380)^+$, one point is off by 2σ.

Observation of two pentaquarks





There are no known $J/\psi K^+$ tetraquarks, but there are the Z_c states decaying to $J/\psi \pi^+$

- ✔ No need to add $J/\psi K^+$ tetraquarks

Observation of two pentaquarks

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	4380	4450	4380	4450	4380	4450	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	**21**	0.2	**54**	**10**	**3.14**	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	**2.45**
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	**1.2**	1	1	0.09	0.03	0.31	0.01
Non-resonant	3	0.3	34	2	2.35	0.13	**3.28**	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$	10	**1.2**	34	**10**	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+(4380/4450)K^-$	6	0.7	4	8	0.37	0.16		
L_{P_c} $P_c^+(4380/4450) \to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	**0.53**	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Uncertainties added in quadrature. "4380": $P_c(4380)^+$, "4450": $P_c(4450)^+$

Observation of two pentaquarks

State	J^P	Mass [MeV/c^2]	Width [MeV]	Fit Fraction [%]
$P_c(4380)^+$	$\frac{3}{2}^-$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$\frac{5}{2}^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$				$15 \pm 1 \pm 6$
$\Lambda(1520)$				$19 \pm 1 \pm 4$

These fit fractions are converted into branching fractions

[LHCb, Chin. Phys. C40 (2016) 011001, arXiv:1509.00292]

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-) \times \mathcal{B}(P_c^+ \to J/\psi p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+0.46}_{-0.36}\right) \times 10^{-5}$$

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-) \times \mathcal{B}(P_c^+ \to J/\psi p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+0.22}_{-0.18}\right) \times 10^{-5}$$

	$\Delta(-2\ln\mathcal{L})$	Significance
$0 \to 1P_c^+$	14.7^2	12σ
$1 \to 2P_c^+$	11.6^2	9σ
$0 \to 2P_c^+$	18.7^2	15σ

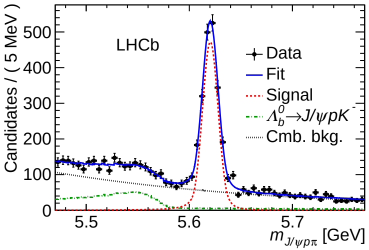
The significances are determined using the extended model.

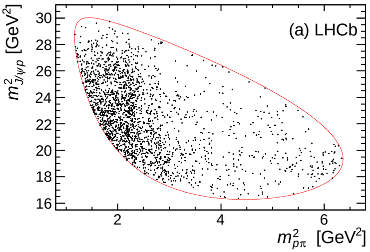
Exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

$\Lambda_b^0 \to J/\psi p \pi^-$ re-analysed after 2014 observation [JHEP 07 (2014) 103] with full angular fit, as in [PRL 115 (2015) 072001].

Need to describe all N resonances (Δ negligible)

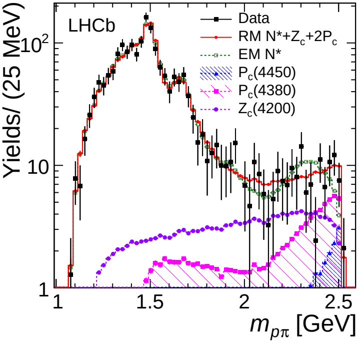
State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106





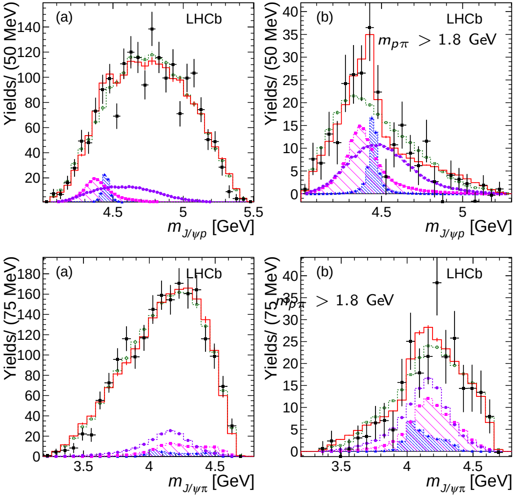
[LHCb, PRL 117 (2016) 082003, arXiv:1606.06999]

Exotics in $\Lambda_b^0 \to J/\psi p \pi^-$



Two fits:

- Only N states
- Add P_c^+ and $Z_c(4200)^- \to J/\psi \pi^-$



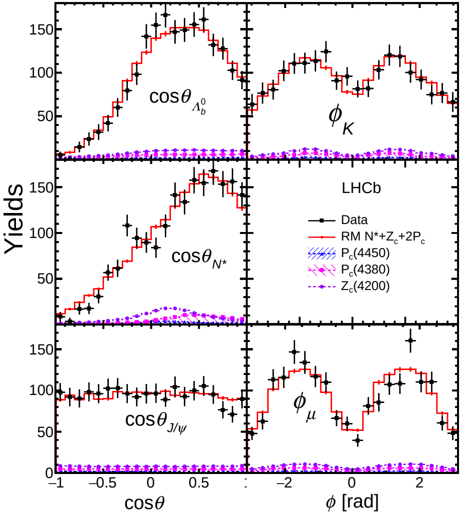
Exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

The fit fractions are

$$P_c(4380) : 5.1 \pm 1.5\,^{+2.1}_{-1.6}\,\%$$
$$P_c(4450) : 1.6\,^{+0.8}_{-0.6}\,^{+0.6}_{-0.5}\,\%$$
$$Z_c(4200) : 7.7 \pm 2.8\,^{+3.4}_{-4.0}\,\%$$

There is a 3.3σ significance for the presence of exotic states. The fit does not allow to say which.

No P_c^+ would require $(17.2 \pm 3.5)\%$ $Z_c(4200)$, which is much more than in $B^0 \to J/\psi K^+ \pi^-$ [Belle, PRD 90 (2014) 112009]



Exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

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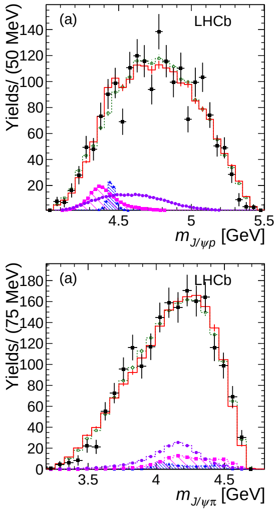
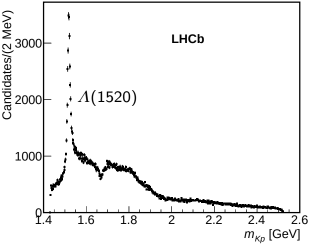
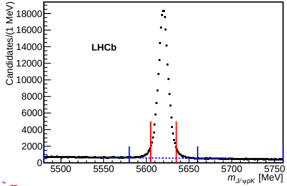


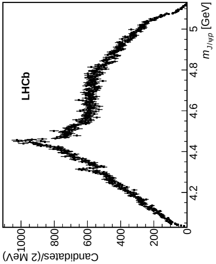
Observation of narrow pentaquarks

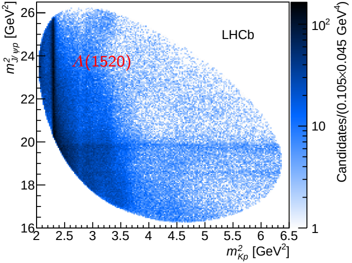
Update of Run 1 analysis [PRL 115 (2015) 072001]

- ➜ Revisit this channel with an updated BDT: 246 000 $\Lambda_b^0 \to J/\psi p K^-$ decays (10 times Run 1) and 6.4% background.
  - Reflections from B_s^0 vetoed
  - Re-optimised BDT including PID (new)









Observation of narrow pentaquarks

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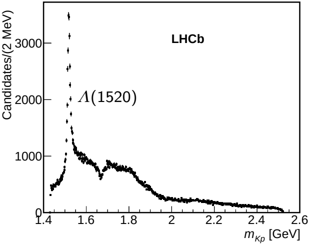
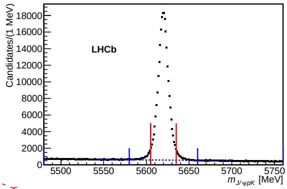
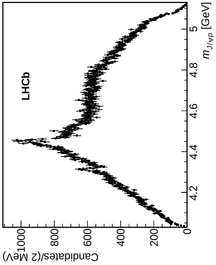
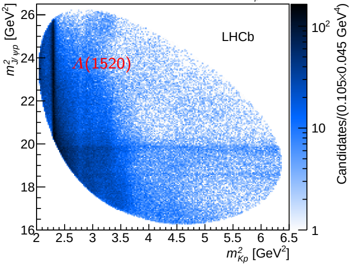
  - Re-optimised BDT including PID (new)
- Only 2 dimensions used: $J/\psi p$ and $\cos\theta$
  - ➜ No sensitivity to Argand diagram

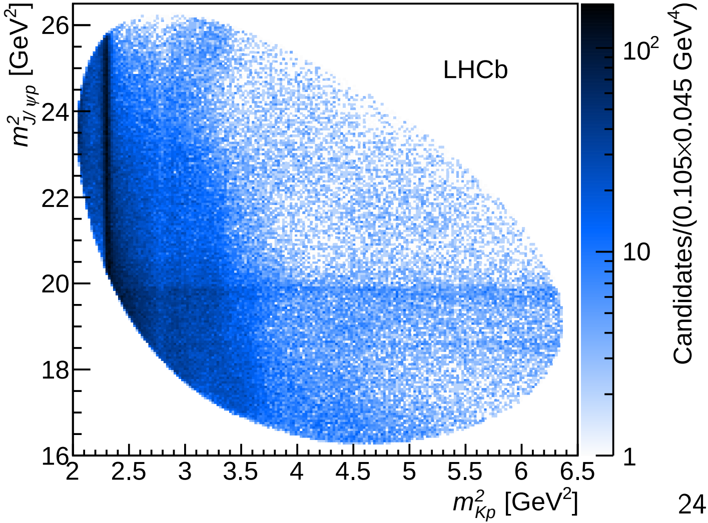








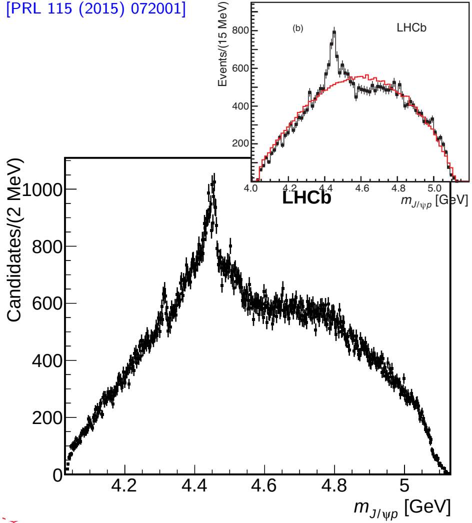
Observation of narrow pentaquarks

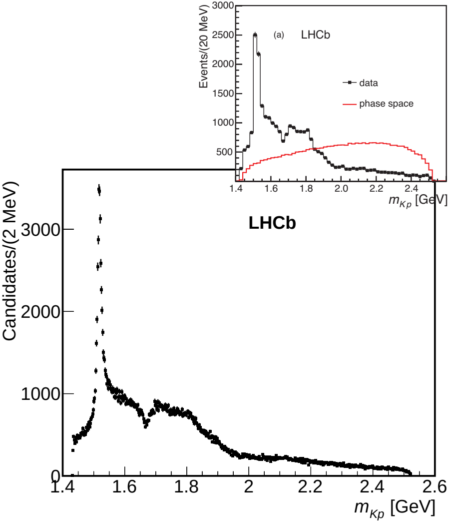


246 000 Λ_b^0

Observation of narrow pentaquarks

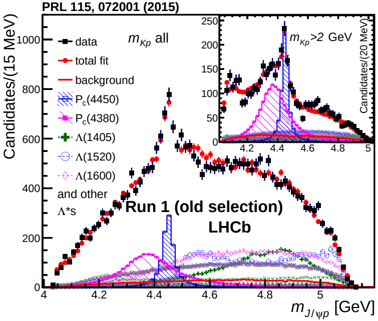
[PRL 115 (2015) 072001]

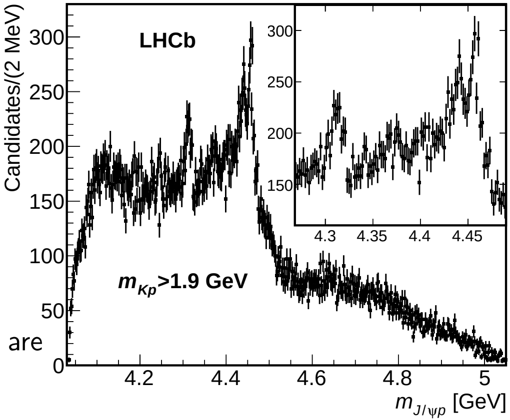




[LHCb, PRL 122 (2019) 222001, arXiv:1904.03947]

Observation of narrow pentaquarks

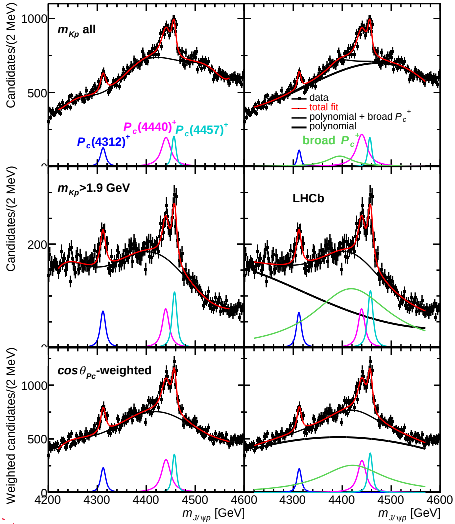




With the new data, more structures are visible:

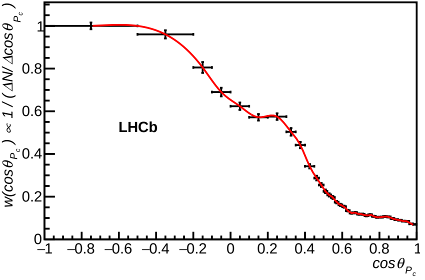
- Peak at 4312 MeV/c^2
- The $P_c(4450)^+$ is composed of two structures

Observation of narrow pentaquarks



To maximise the sensitivity, the data is weighted as function of $\cos\theta_{P_c^+}$, as Λ^* resonances are at positive $\cos\theta_{P_c^+}$.

The default fit uses these weights. Other fits are used for systematic studies.



[LHCb, PRL 122 (2019) 222001, arXiv:1904.03947]

Observation of narrow pentaquarks

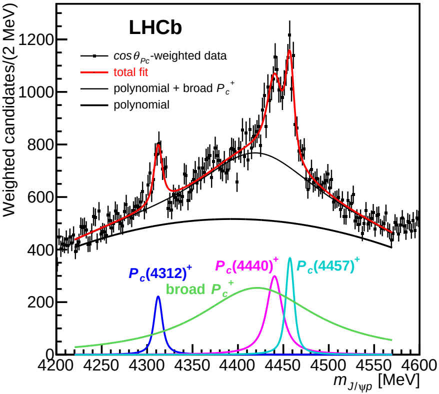
Three states are observed:

$P_c(4312)^+$ $\Gamma \sim 10$ MeV (7σ), which we could not see with 3 fb^{-1}

$P_c(4440)^+$ $\Gamma \sim 20$ MeV and

$P_c(4457)^+$ $\Gamma \sim 6$ MeV. The significance of the 2-peak structure is 5.4σ

✗ No sensitivity to the wide $P_c(4380)^+$

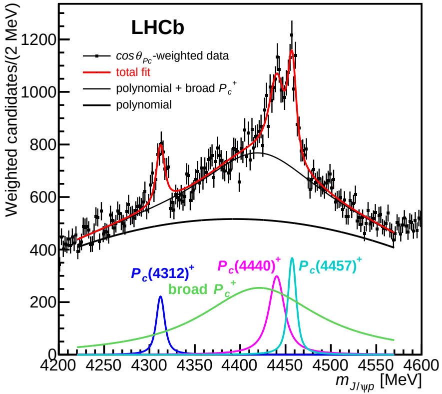


State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7\,^{+6.8}_{-0.6}$	$9.8 \pm 2.7\,^{+3.7}_{-4.5}$	(< 27)	$0.30 \pm 0.07\,^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3\,^{+4.1}_{-4.7}$	$20.6 \pm 4.9\,^{+8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33\,^{+0.22}_{-0.10}$
$P_c(4457)^+$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

Observation of narrow pentaquarks

Systematic uncertainties:

- **Interference:** The $m_{J/\psi p}$ fit has no sensitivity, thus several combinations are tried. The default is incoherent.
- **Background model:** Polynomial versus polynomial plus BW (default)
- **Data selection:** the fits for full, $m_{pK} > 1.9\,\text{GeV}$ and weighted (default) samples are compared.



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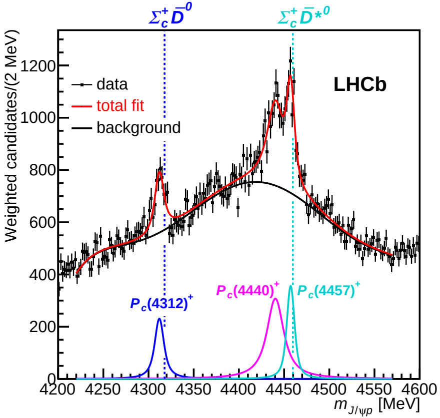
$P_c(4457)^+$	$4457.3 \pm 0.6\,^{+4.1}_{-1.7}$	$6.4 \pm 2.0\,^{+5.7}_{-1.9}$	(< 20)	$0.53 \pm 0.16\,^{+0.15}_{-0.13}$

Observation of narrow pentaquarks

Three states are observed:

- $P_c(4312)^+$ $\Gamma \sim 10\,\text{MeV}$ (7σ), which we could not see with $3\,\text{fb}^{-1}$
- $P_c(4440)^+$ $\Gamma \sim 20\,\text{MeV}$ and
- $P_c(4457)^+$ $\Gamma \sim 6\,\text{MeV}$. The significance of the 2-peak structure is 5.4σ

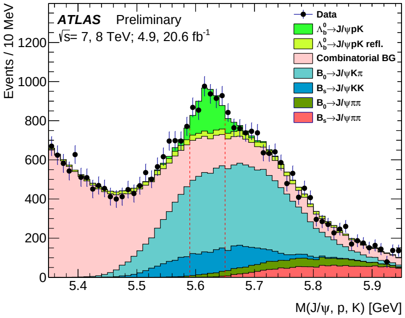
✗ No sensitivity to the wide $P_c(4380)^+$

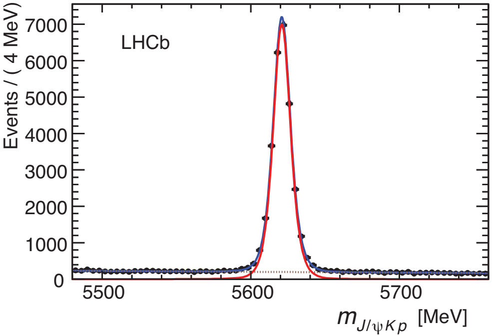


It is striking that the $P_c(4312)^+$ and the $P_c(4457)^+$ sit at the $\Sigma_c D$ and $\Sigma_c D^*$ thresholds

[ATLAS-CONF-2019-048]

P_c^+ states at ATLAS





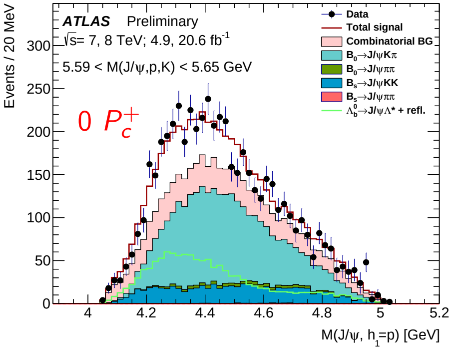
With Run 1 data, ATLAS find 2270 ± 300 $\Lambda_b^0 \to J/\psi p K^-$ decays

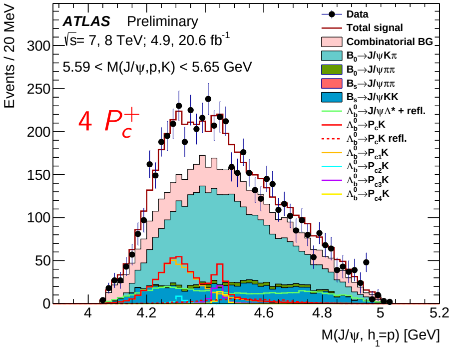
- With the same data, LHCb see $26\,000 \pm 170$ with hardly any background

[LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

[B]

P_c^+ states at ATLAS



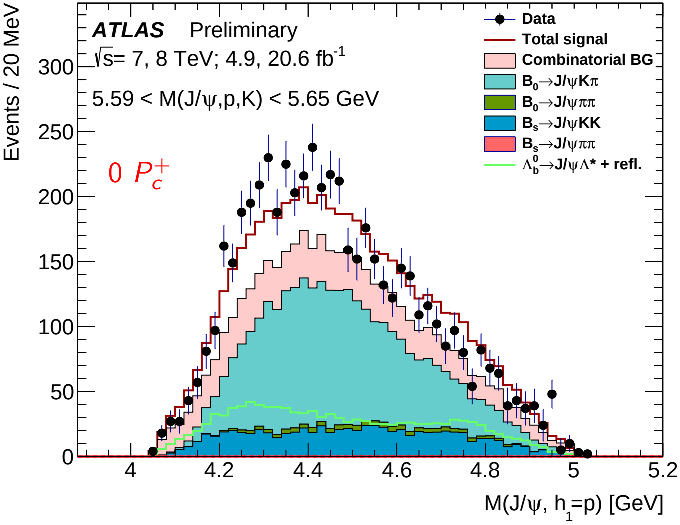


With Run 1 data, ATLAS find 2270 ± 300 $\Lambda_b^0 \to J/\psi p K^-$ decays

- Good fits with 4 P_c^+ LHCb states of [PRL 122 (2019) 222001] ($p \sim 69\%$)
  - (also with 2 P_c^+ of [PRL 115 (2015) 072001], excluded by LHCb, $p \sim 56\%$)
- Fit with only Λ is not ($p \sim 9 \times 10^{-3}$)

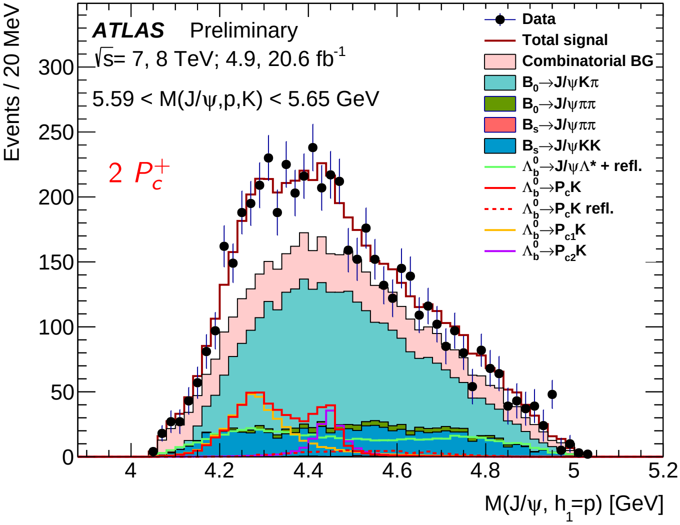
[B]

P_c^+ states at ATLAS



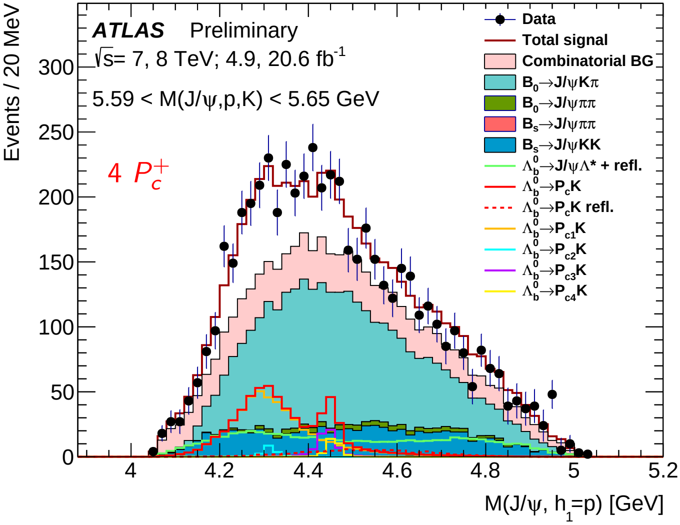
[B]

P_c^+ states at ATLAS



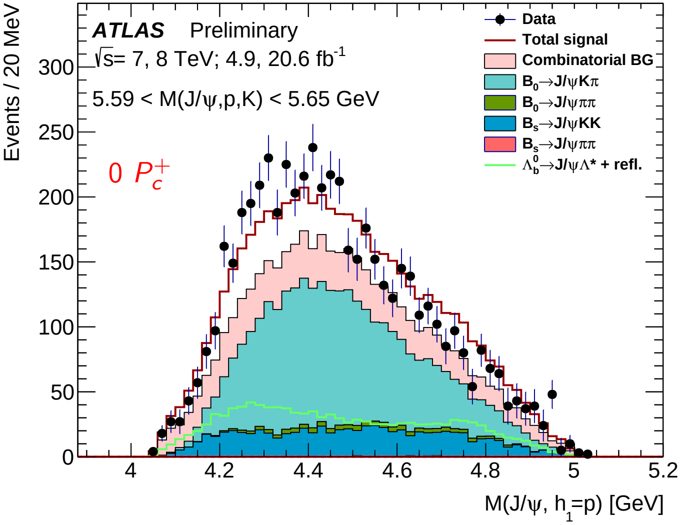
[B]

P_c^+ states at ATLAS



[B]

P_c^+ states at ATLAS

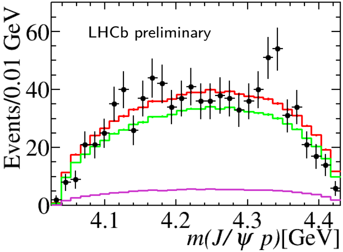


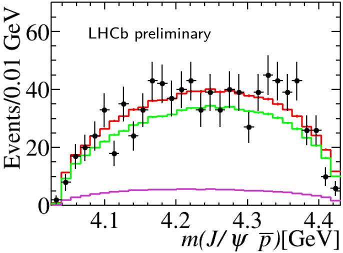
[B]

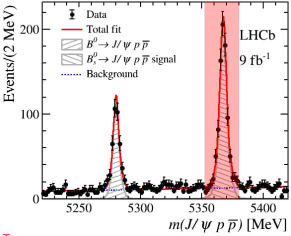
Amplitude analysis of $B_s^0 \to J/\psi p\overline{p}$

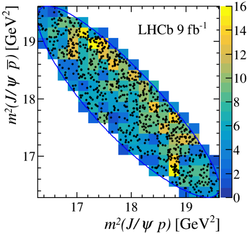
With 9 fb^{-1} 2011–18 data, find 800 $B_s^0 \to J/\psi p\overline{p}$ with 15% background. Flavour is untagged.

- ✗ Some structure at 4.3 GeV









[B]

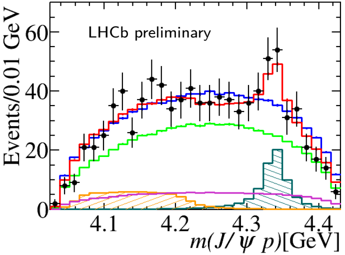
Amplitude analysis of $B_s^0 \to J/\psi p\overline{p}$

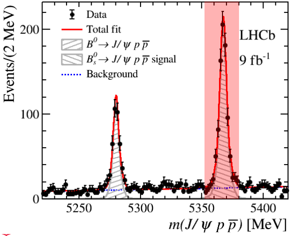
With $9\,\text{fb}^{-1}$ 2011–18 data, find 800 $B_s^0 \to J/\psi p\overline{p}$ with 15% background. Flavour is untagged.

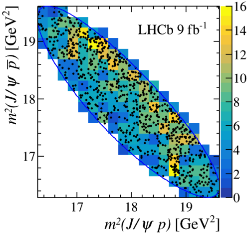
- ✔ Good fit with a P_c^+ state (3.1σ)

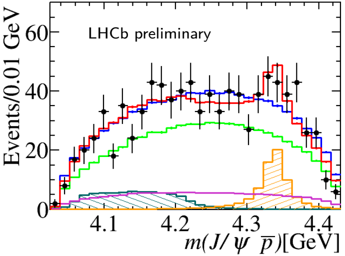
$$M = 4337\,^{+\,7}_{-\,4} \pm 2\,\text{MeV}$$

$$\Gamma = 29\,^{+\,26}_{-\,12} \pm 14\,\text{MeV}$$



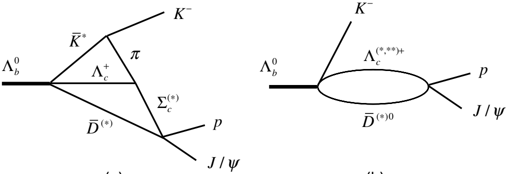




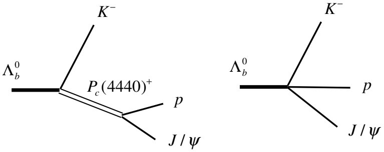


[B]

P_c^+ AS KINEMATICAL EFFECT



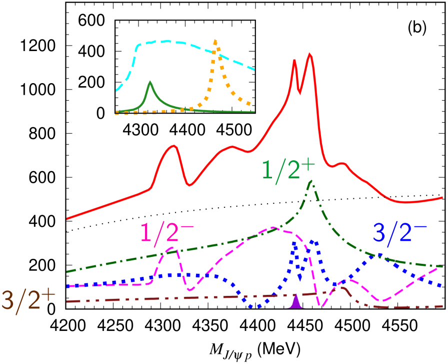
(a) (b)



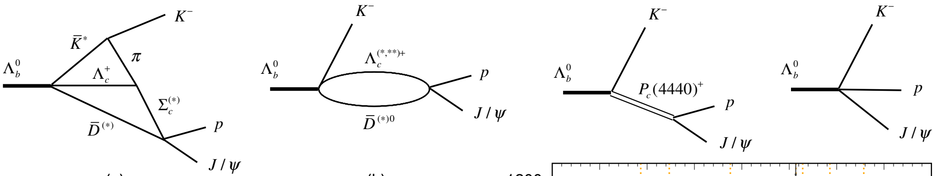
Double triangle singularities can cause the bumps

Various thresholds are at play

Not everyone is convinced



P_c^+ AS KINEMATICAL EFFECT



(a) (b)

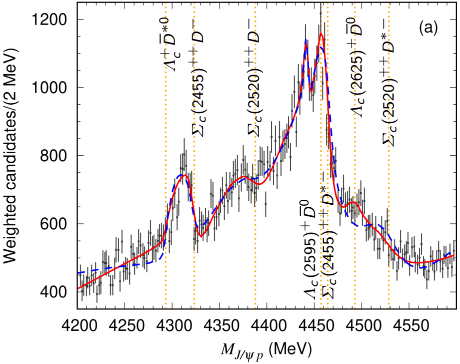
Double triangle singularities can cause the bumps

Various thresholds are at play

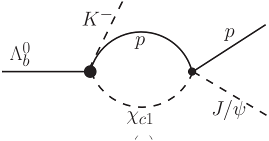
Good fit of the data

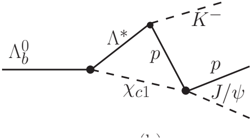
[PRL 122 (2019) 222001]

Not everyone is convinced

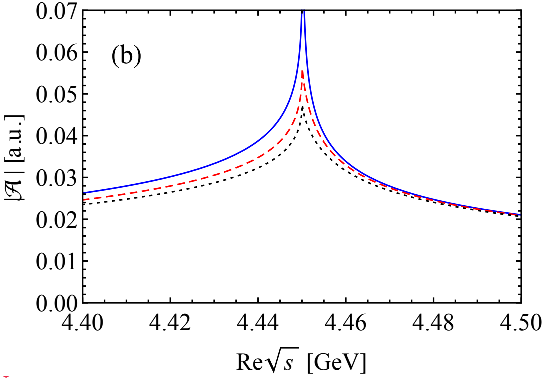


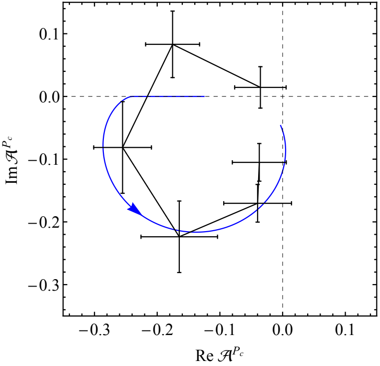
Pentaquarks as triangle diagrams





P_c^+ enhacements could be caused by triangle singularities





[B]

P_c^+ REFIT

Du et al. redo the fit to LHCb data [LHCb, PRL 122 (2019) 222001, arXiv:1904.03947] and find a 1.3σ excess at 4380 MeV/c^2, where a missing $\Sigma_c^* \overline{D}$ state is expected.