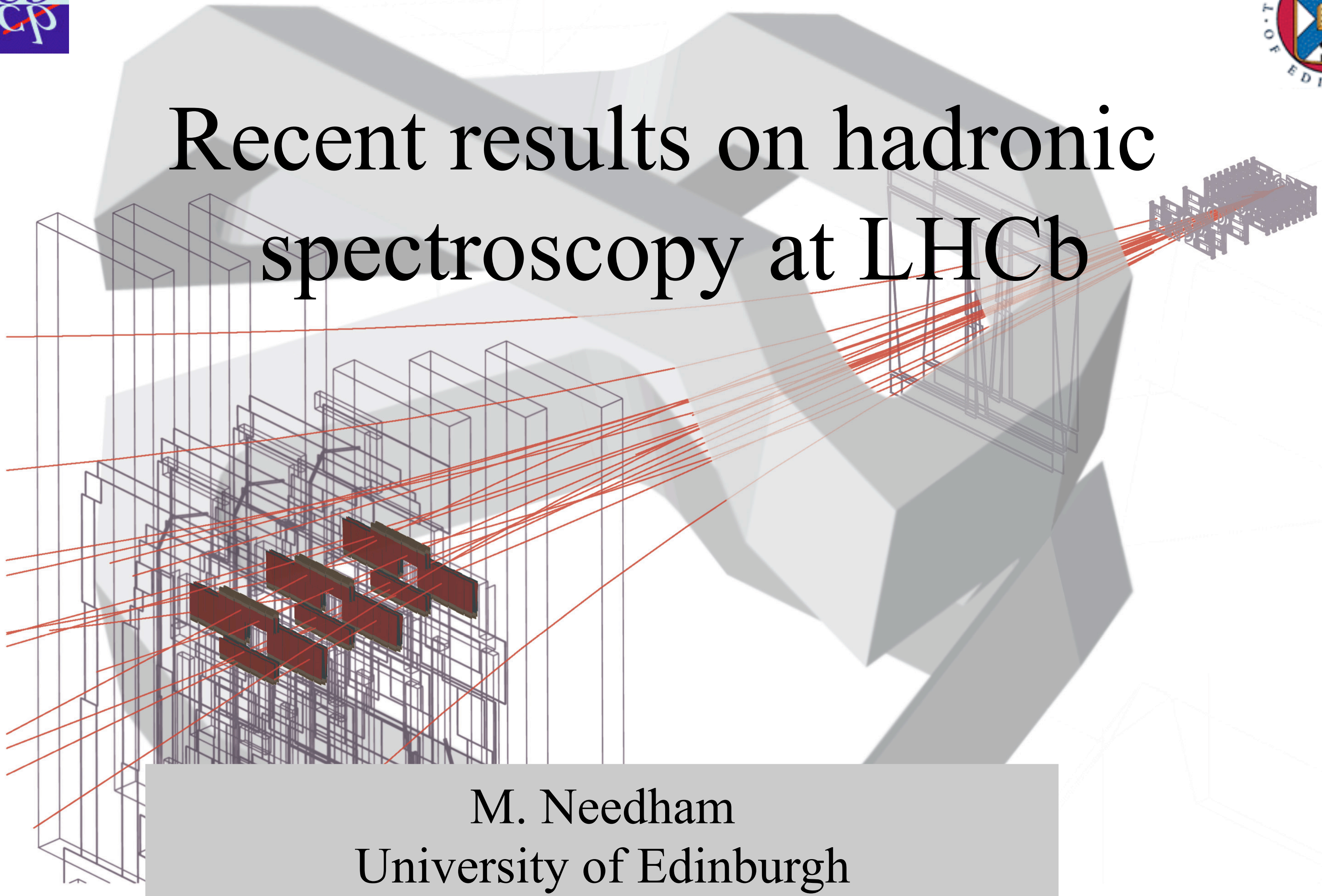
Recent results on hadronic spectroscopy at LHCb



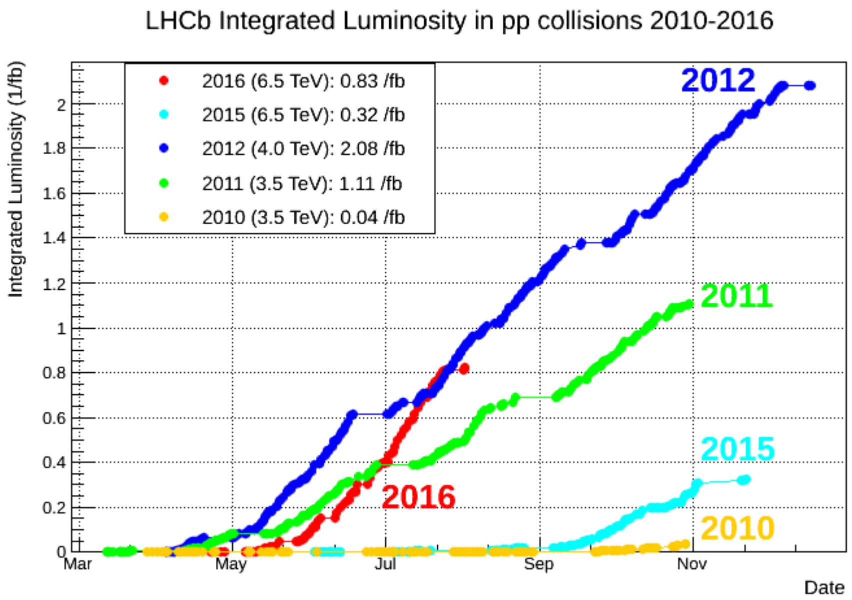
M. Needham
University of Edinburgh
Mainz, 28th June 2017
On behalf of the LHCb collaboration

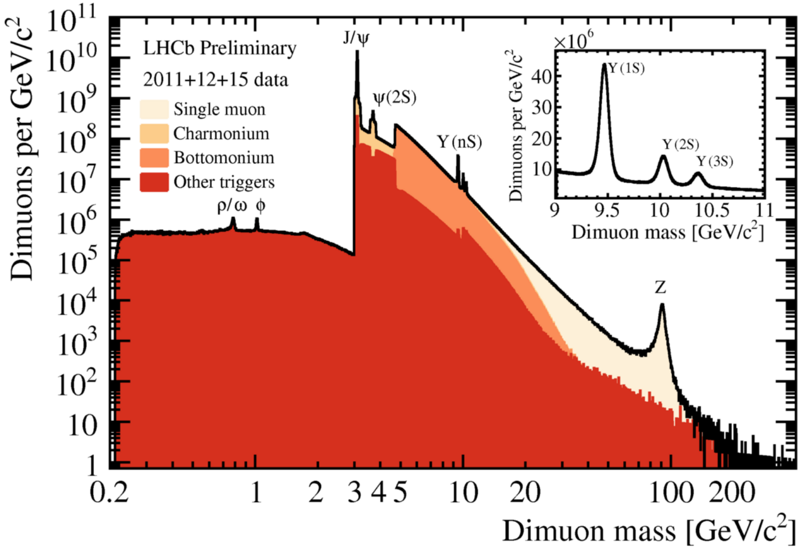
Outline

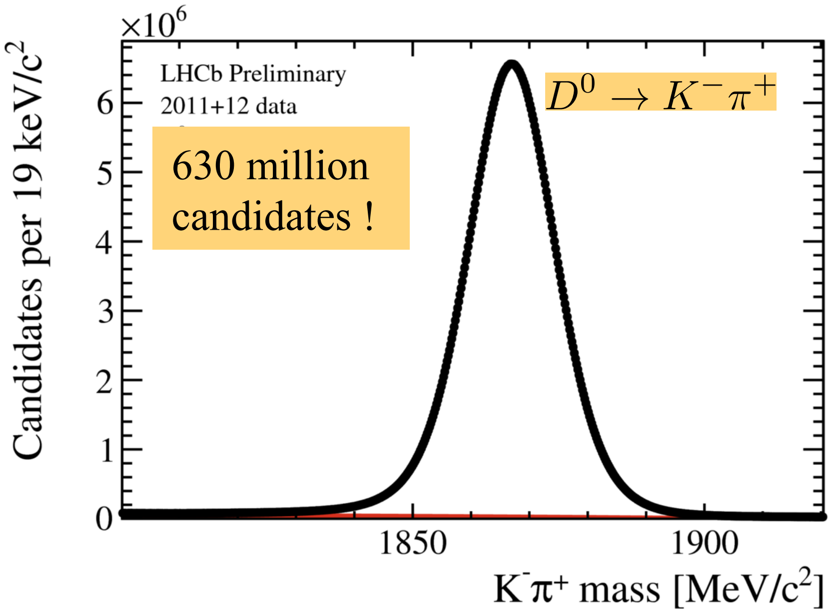
- Introduction
- Quarkonia production in b ➔ΦΦX decays New
- XYZ states: pentaquarks and tetraquarks
- Observation of excited Ω_c baryons
- Summary and outlook

Impossible to present everything in 25 minutes hence focus on more recent results + XYZ states

Introduction







LHCb-CONF-2016-005

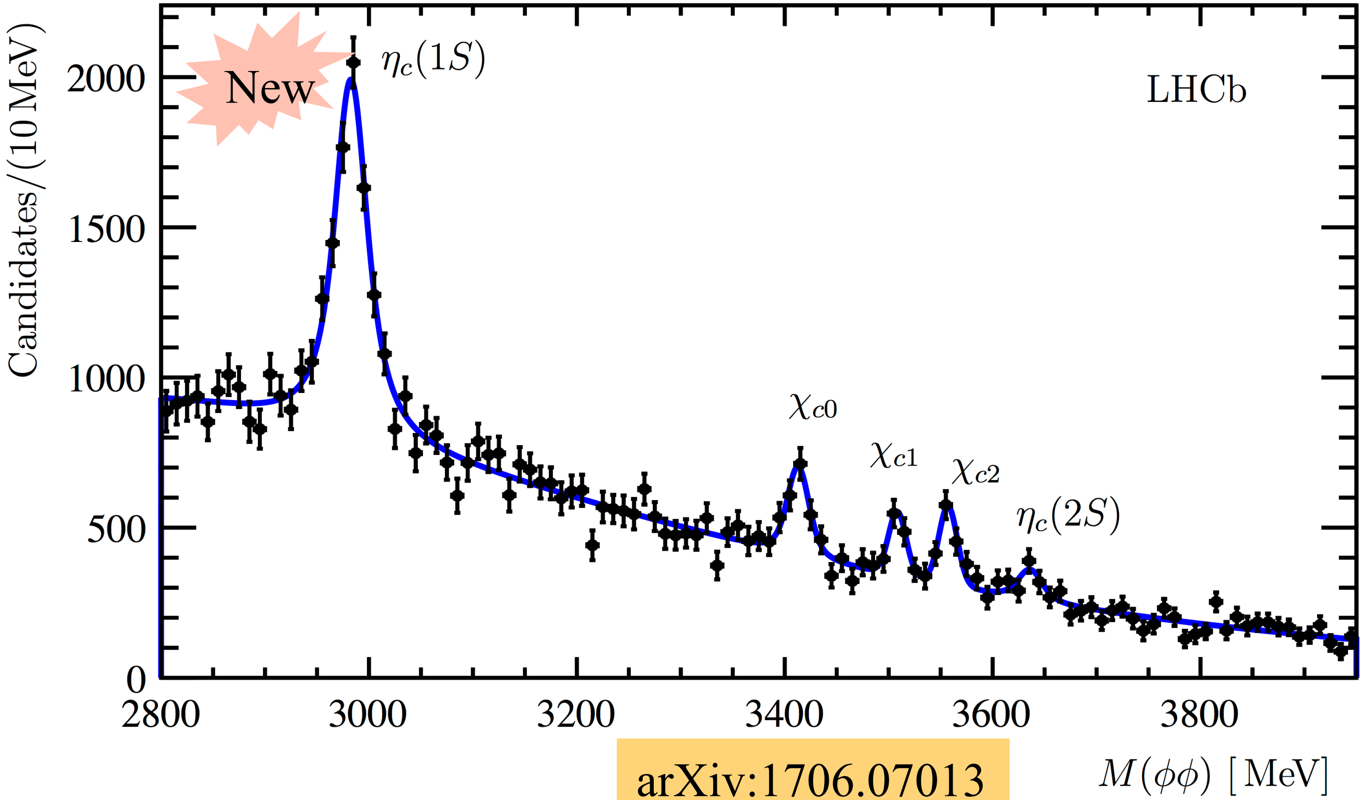
- World largest heavy flavour dataset ! 3 fb^{-1} Run 1, 2 fb^{-1} Run2
- Precision tracking
- Excellent PID using RICH
- Trigger for fully hadronic decays

Charmonia production in b → $\phi\phi$X decays

Quarkonia with b ➔ ϕϕX decays

Studies of inclusive quarkonia production in b-hadron decays allows to probe QCD production models and to make spectroscopic measurements

Many charmonia states decay to ϕϕ final state



arXiv:1706.07013

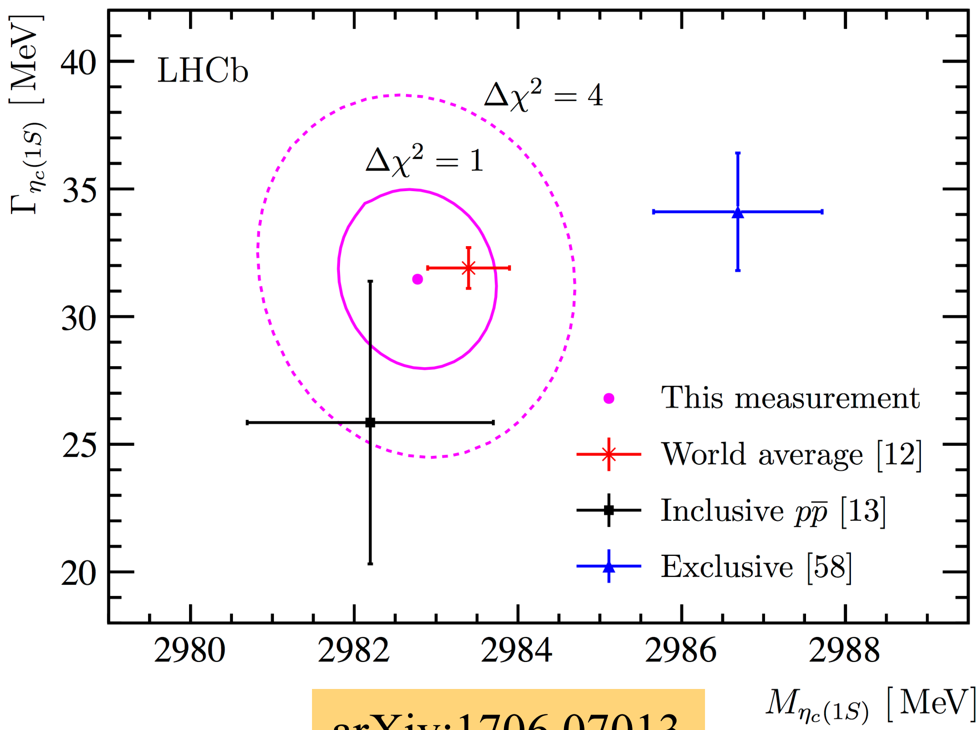
Run 1 dataset

Hadronic trigger to select displaced ϕϕ final state

No evidence for X(3872), X(3915), χ_{c2}(2P), limits set

Quarkonia with b ➔ $\phi\phi X$ decays

- Measured charmonium masses in agreement with world averages
- Precision of $\eta_c(1S)$ mass comparable to/in agreement with world average



$$M_{\eta_c(1S)} = 2982.81 \pm 0.99 \pm 0.45\,\mathrm{MeV}/c^2$$

$$\Gamma_{\eta_c(1S)} = 31.35 \pm 3.51 \pm 2.01\,\mathrm{MeV}$$

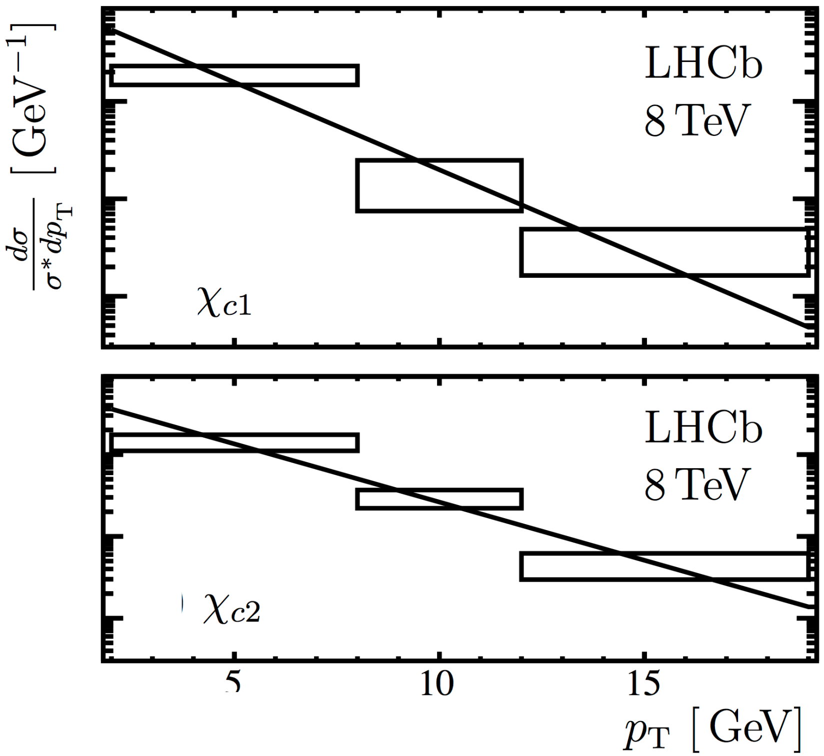
arXiv:1706.07013

EPJC 75 (2015) 311

Phys Lett B769 (2017) 305

[LHCb]

Quarkonia with b ➔ φφX decays

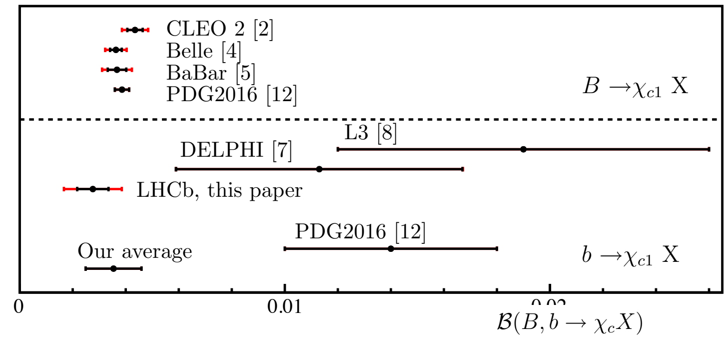


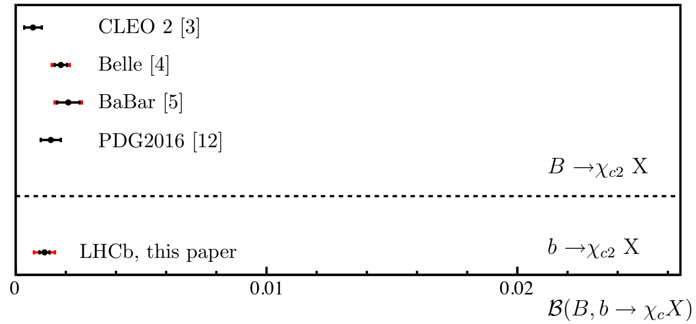
Differential cross-section versus pt studied

Various branching ratios quoted, LHCb measurement of b ➔ η_cX inclusive BF in EPJC 75 (2015) 311 used for normalization

$$\mathcal{B}(b \to \chi_{c0} X) = (3.02 \pm 0.47 \pm 0.23 \pm 0.94_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c1} X) = (2.76 \pm 0.59 \pm 0.23 \pm 0.89_{\mathcal{B}}) \times 10^{-3}$$
$$\mathcal{B}(b \to \chi_{c2} X) = (1.15 \pm 0.20 \pm 0.07 \pm 0.36_{\mathcal{B}}) \times 10^{-3}$$

(Factorization: χ_{c0} and χ_{c2} suppressed. Spin counting χ_{c0} suppressed to χ_{c2} arxiv 9808360)





arXiv:1706.07013

Exotic Spectroscopy

Exotic Spectroscopy

Why do quarks seem to come in twos or threes ?

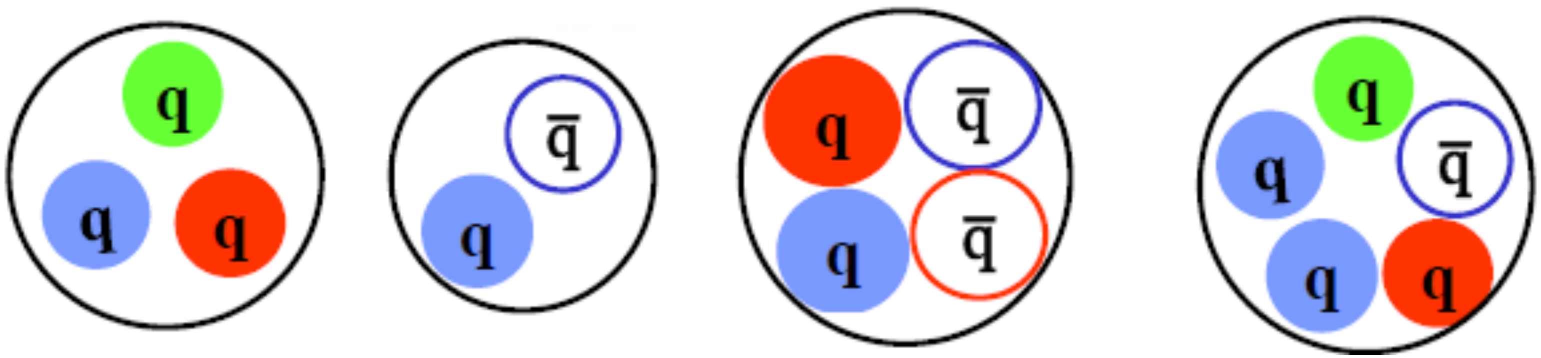
A puzzle since earliest days of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest



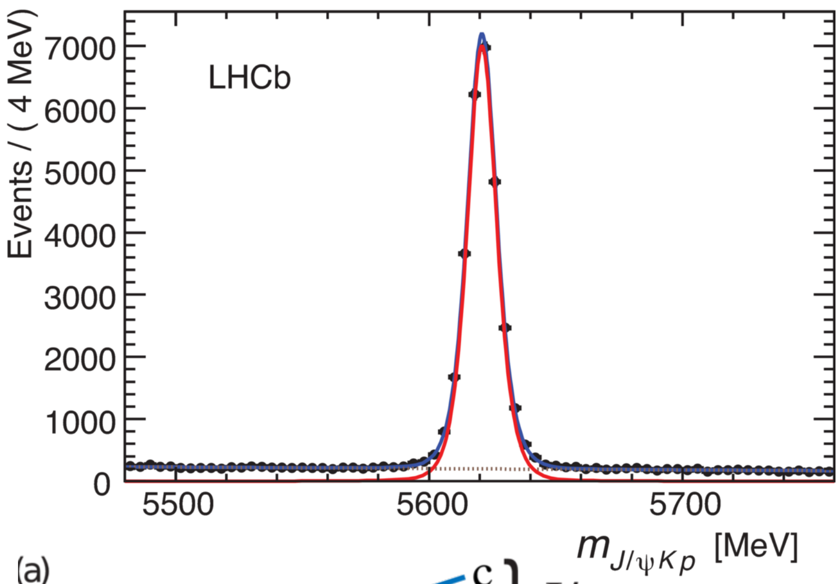
Baryon | Meson | Tetraquark | Pentaquark

Hot topic in recent years. Many candidates claimed

Pentaquarks

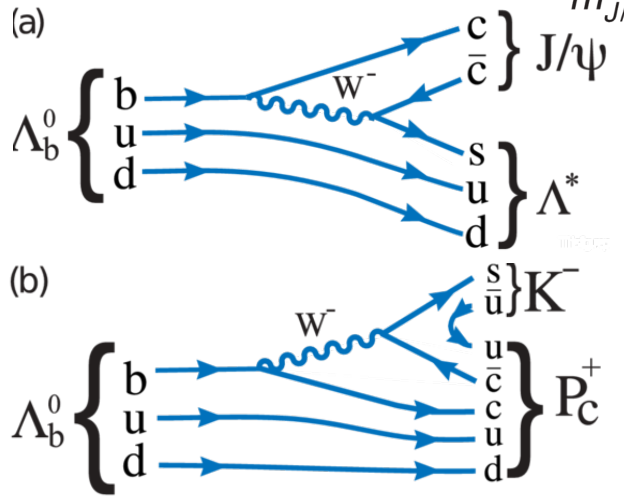
Summer 2015 LHCb observed two pentaquark candidates in Λ_b ➔ J/ψpK

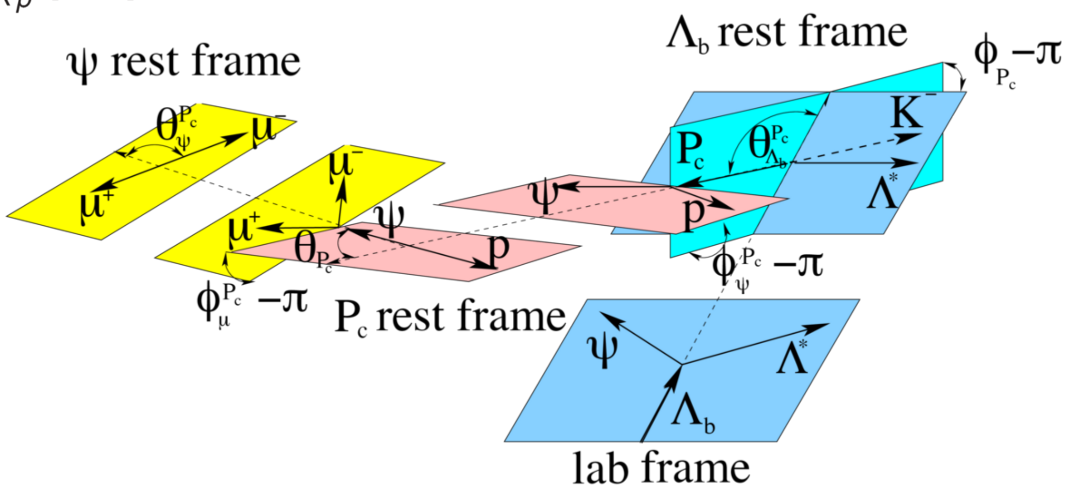
Phys. Rev. Lett 115 (072001) 2015



Contributions from both Λ^*
And pentaquark states possible

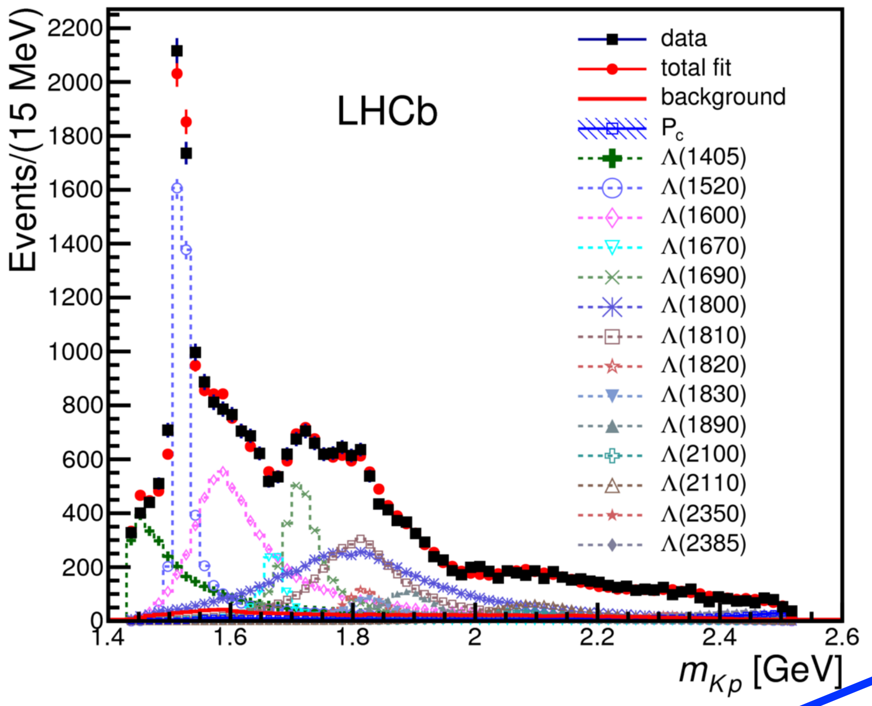
Disentangle with angular analysis

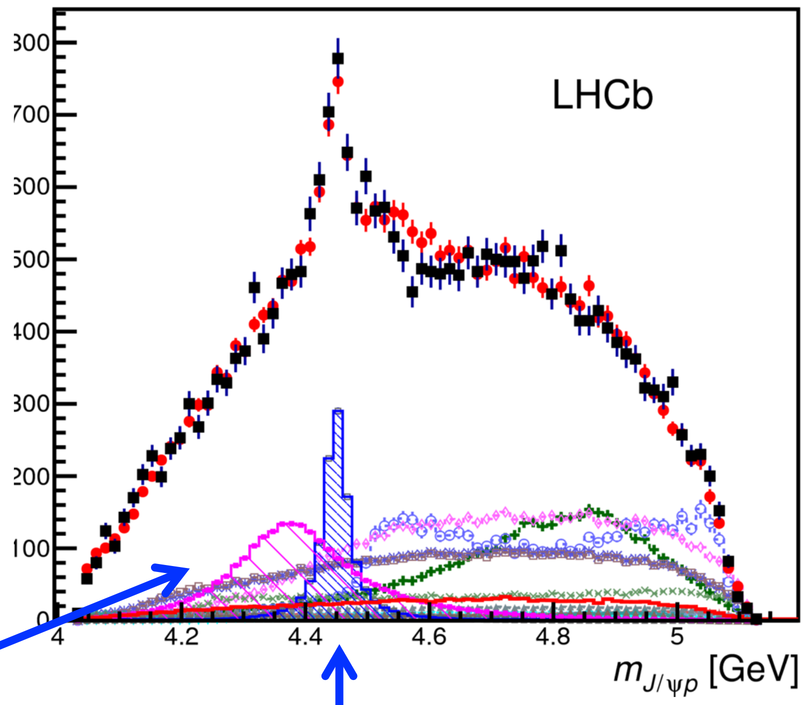




Pentaquarks

Phys. Rev. Lett 115 (072001) 2015





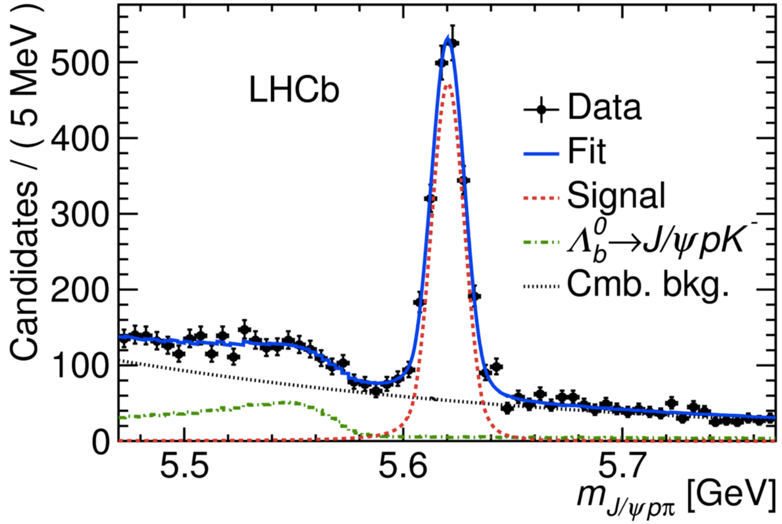
$P_c(4380)$ $P_c(4450)$

Width 200 MeV, spin 3/2 ? Width 40 MeV, spin 5/2 ?

Confirmed with model independent approach PRL 117, 082003 (2016)

Important to confirm these observations in other channels + search for other pentaquarks

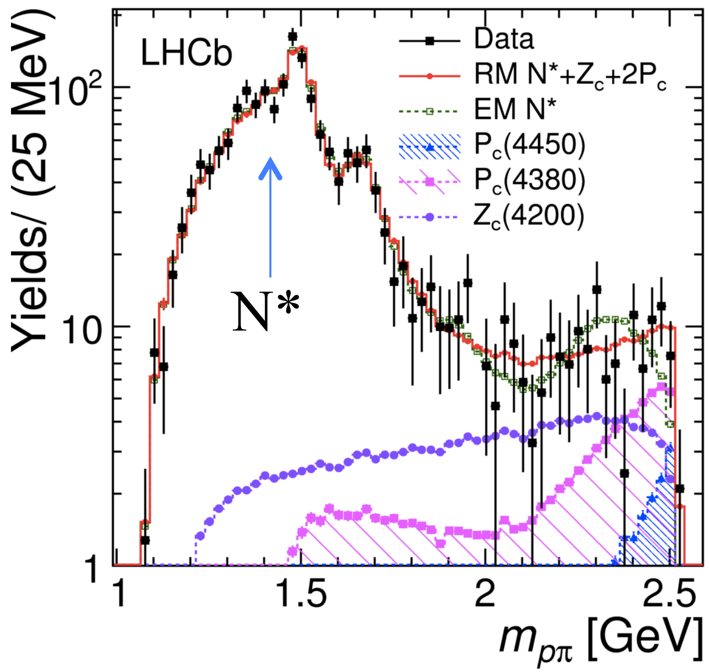
Study of $\Lambda_b \rightarrow J/\psi p \pi$



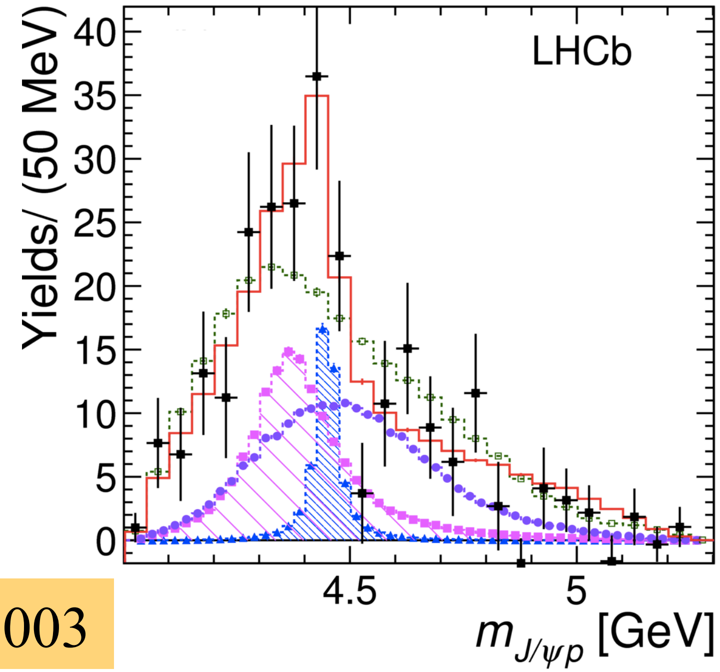
Cabibbo suppressed mode (less statistics)

Can be exotic Z contributions in J/ψ p

Fit with 2 pentaquarks + $Z_c(4200)$ favoured by 3σ compared to no exotic contributions



$m_{p\pi} > 1.8\,\mathrm{GeV}$

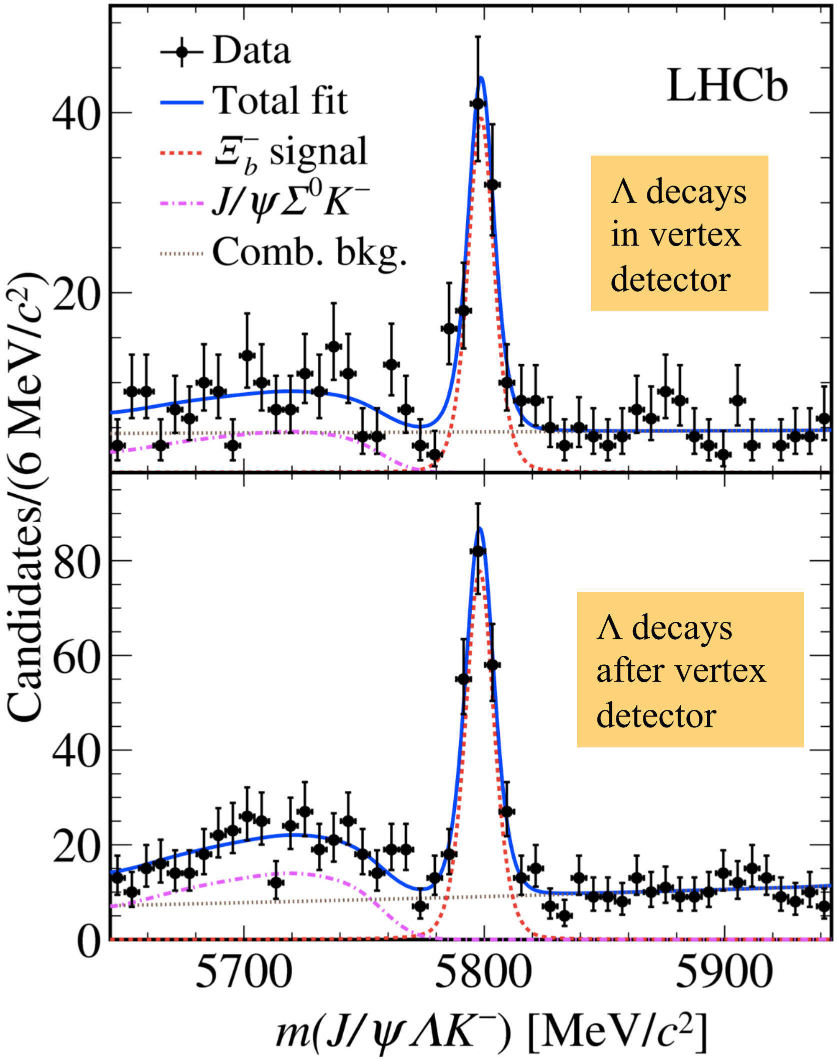


PRL 117 082003

Observation of $\Xi_b^- \rightarrow J/\psi \Lambda K^-$

Suggested in arxiv: 1604.03769 to look for uds$\bar{c}$c pentaquark in this mode

arxiv:1701.05274



Mode observed for first time with Run 1 data

Around 300 Ξ_b^- candidates seen. BF fraction and Ξ_b^- mass measured

$$m(\Xi_b^-) - m(\Lambda_b) = 177.08 \pm 0.47 \pm 0.16\,\mathrm{MeV}/c^2$$

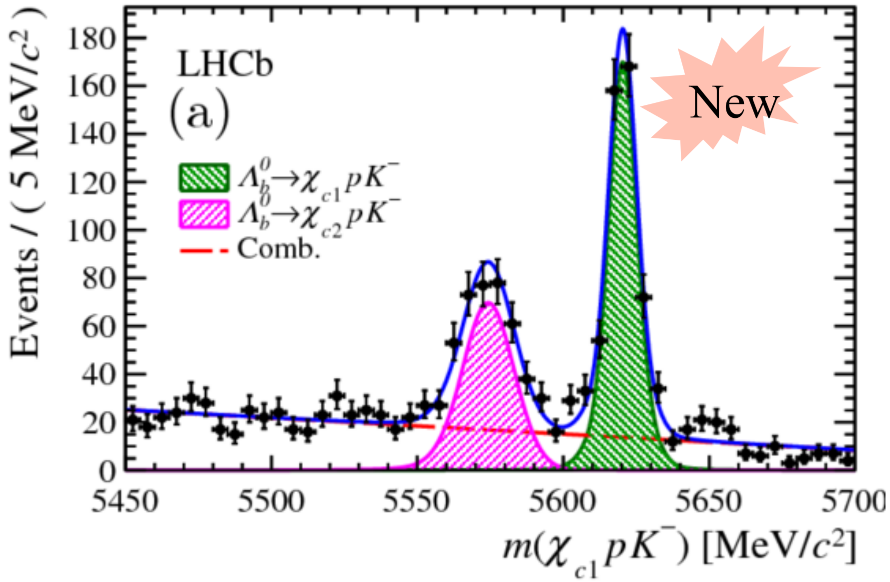
In agreement with previous LHCb Measurements [Slight tension with CDF]

Including Run 2 data full amplitude analysis can be performed

Observation of $\Lambda_b \rightarrow \chi_{c1,2} pK$

$P_c(4450)^+$ very close to $\chi_{c1}p$ threshold: Triangle singularity ? (PRD92 071502 (2015)).
Motivates studies in this mode

arxiv: 1704.07900



Study with radiative χ_{cJ} decays

Mass constraint on χ_{c1} mass to improve resolution

Forces χ_{c2} signal to lower mass

First study observation of this mode
Measure BF, Λ_b mass

Next step angular analysis adding
Run 2 data

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

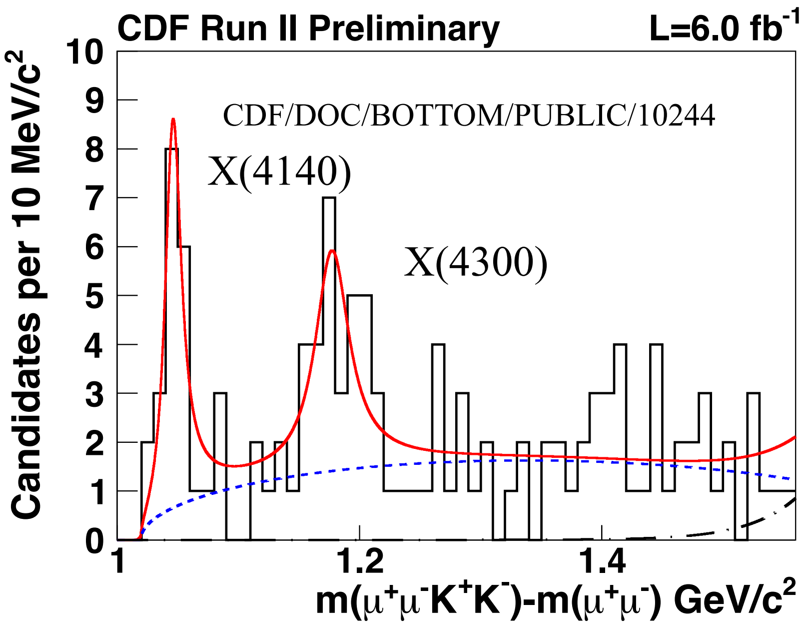
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

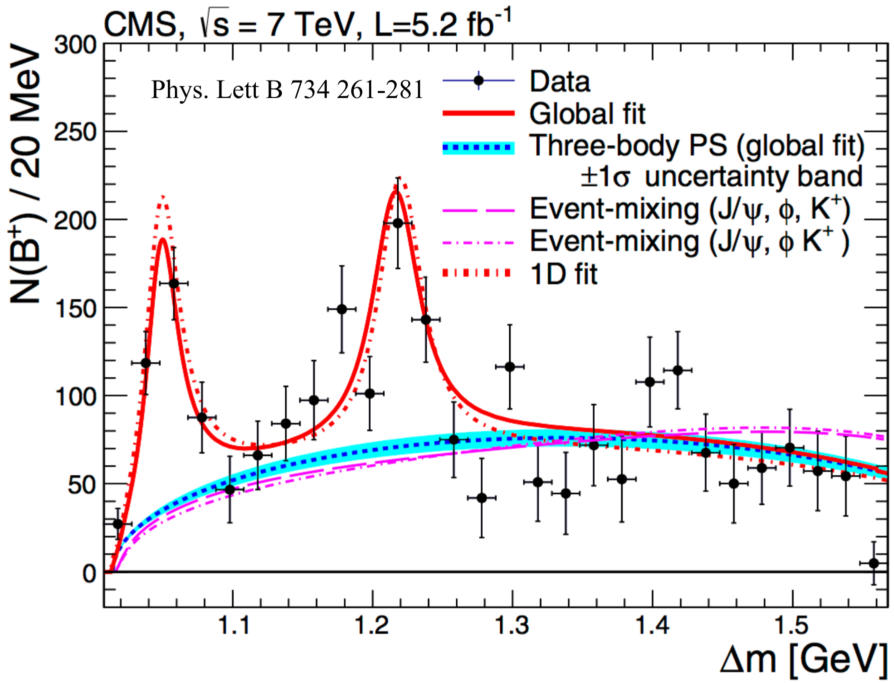
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05,$$

Λ_b mass $5619.44 \pm 0.28 \pm 0.26\ \mathrm{MeV}/c^2$

The puzzle of the X(4140)

- CDF observed a narrow structure at threshold in $B^+ \rightarrow (J/\psi\phi) K^+$
- CMS also saw this and confirmed hint of structure at X(4300)
  - CMS and CDF parameters not in best of agreement
- Early LHCb analysis: no narrow structure (PRD 85 091103(R) 2012)

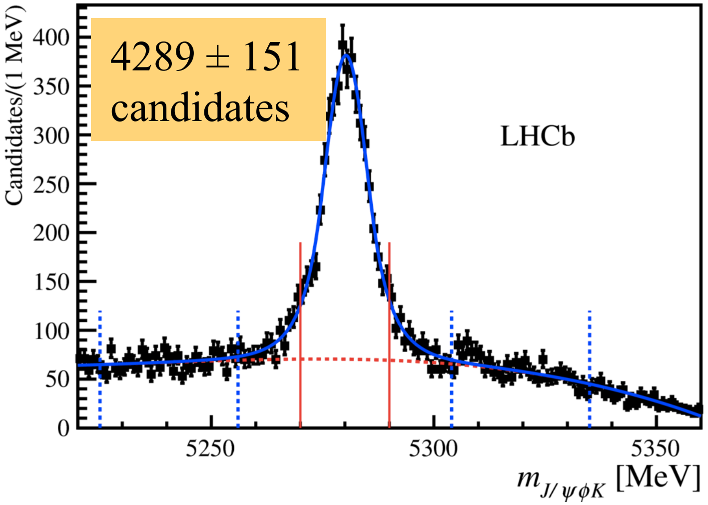


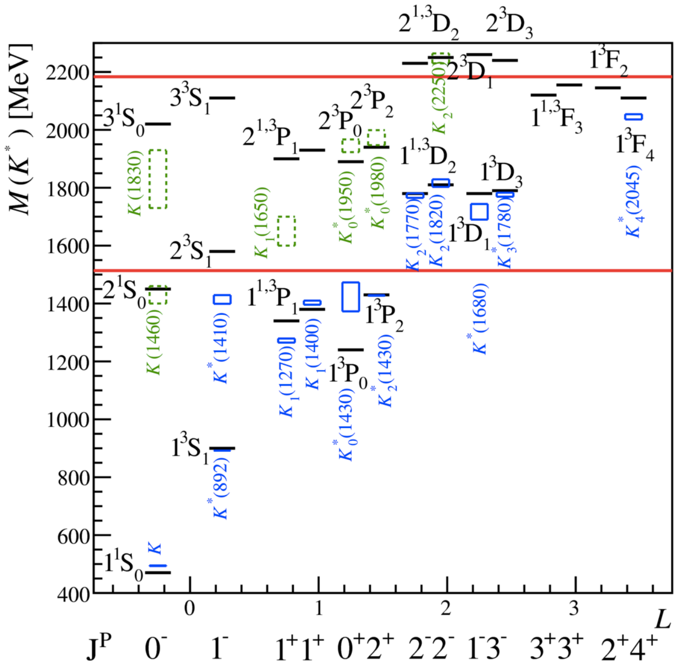


Exotic quarkonia candidates: Tetraquarks ? molecules ? cusps ?

The puzzle of the X(4140)

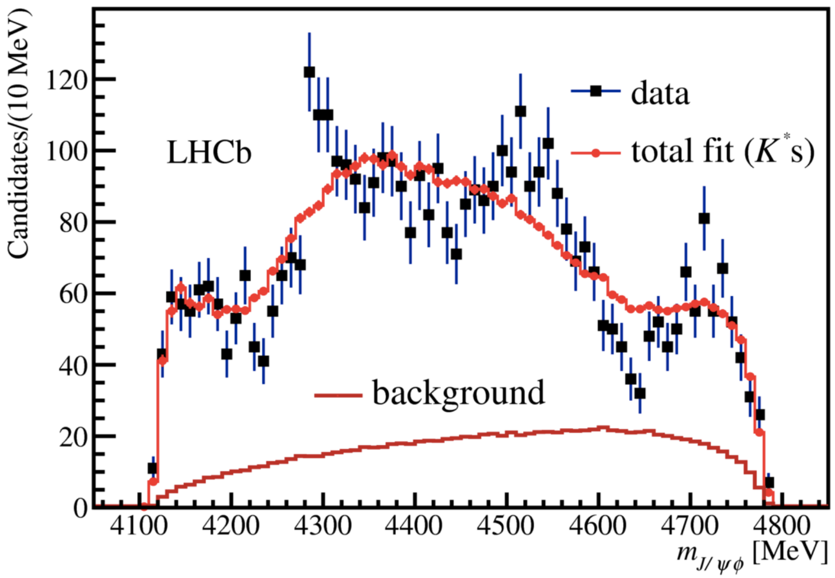
Phys. Rev. D95 (2017) 012002
Phys Rev. Lett 118 (2017) 022003





First full amplitude analysis using LHCb Run 1 dataset $B^+ \rightarrow (J/\psi\phi) K^+$

Complication: have to deal with decays of excited K^* to ϕK^+

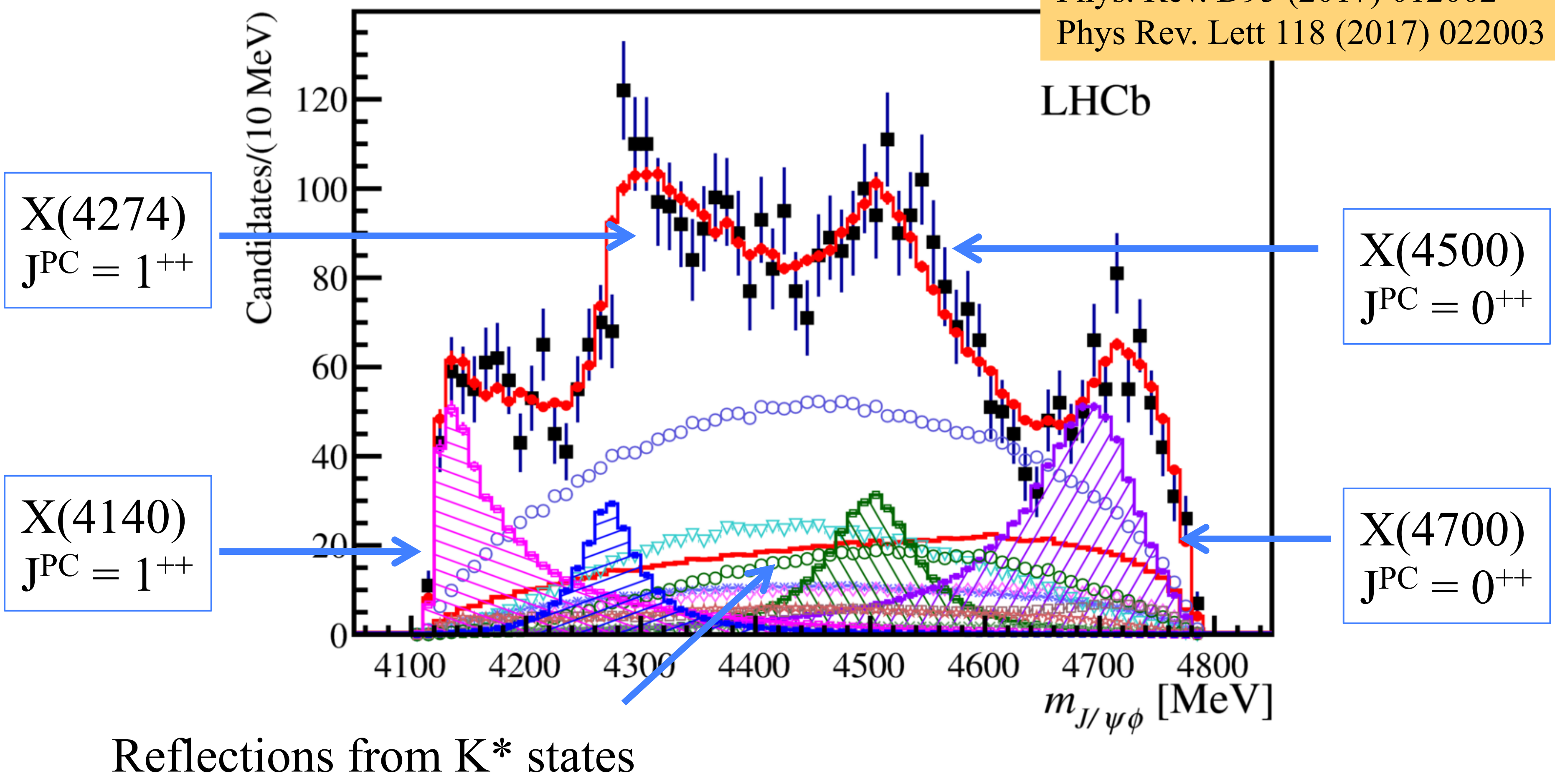


Model with excited K^* alone cannot describe the data

The puzzle of the X(4140)

Data well described by inclusion of four broad exotic resonances found

Phys. Rev. D95 (2017) 012002
Phys Rev. Lett 118 (2017) 022003



The puzzle of the X(4140)

Phys. Rev. D95 (2017) 012002
Phys Rev. Lett 118 (2017) 022003

Contri-bution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				$16\pm3\,^{+\,6}_{-\,2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.8}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\,3.6}$	$56\pm11\,^{+\,8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[29]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\,\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\,9}_{-\,5}$

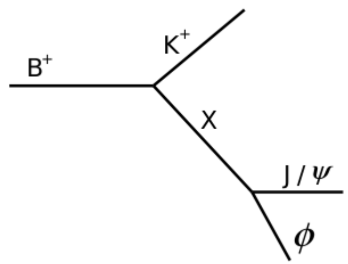
Measured width of X(4140) bigger than previous experiments

Analysis also provides precise information on excited K* states

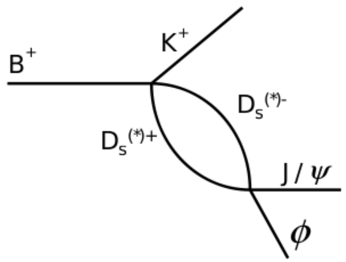
What are the observed states ? Molecules, cusps, tetraquarks ?

X(4140) fits D_sD_s* cusp predicted by Swanson (Int. J Mod Phys E25 1652010 16)

X(4274) quantum numbers rules out cusp + molecule assignments



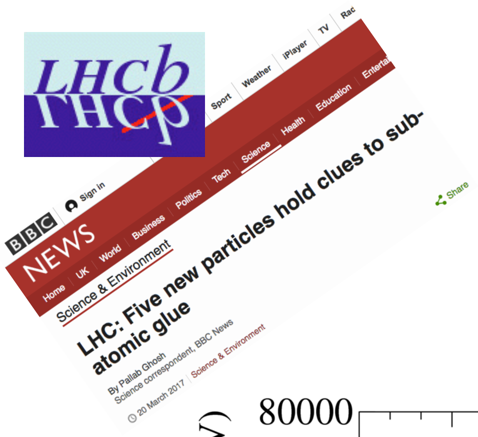
Resonance



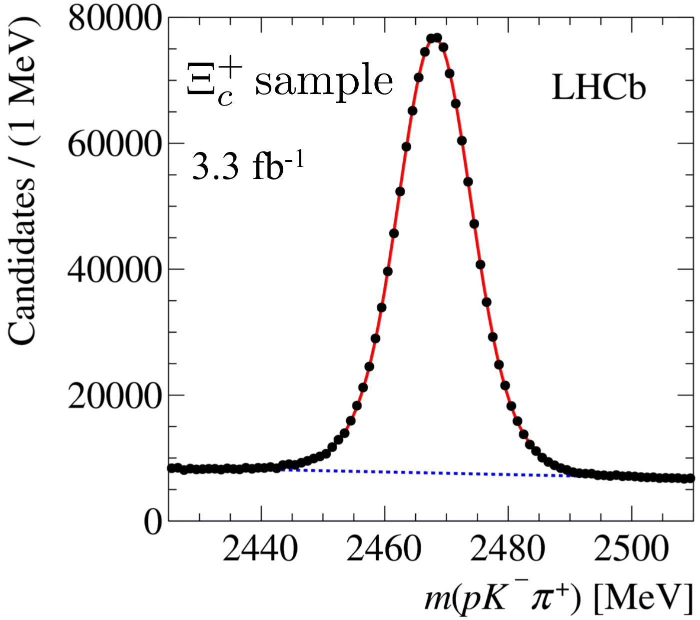
Cusp

Charm baryons

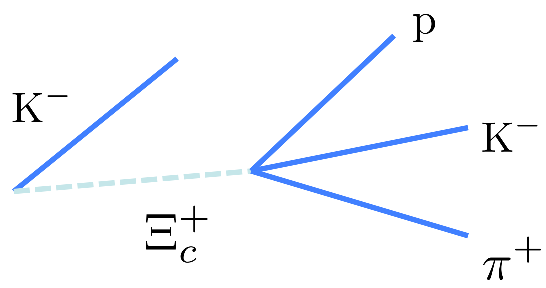
Excited Ω_c states

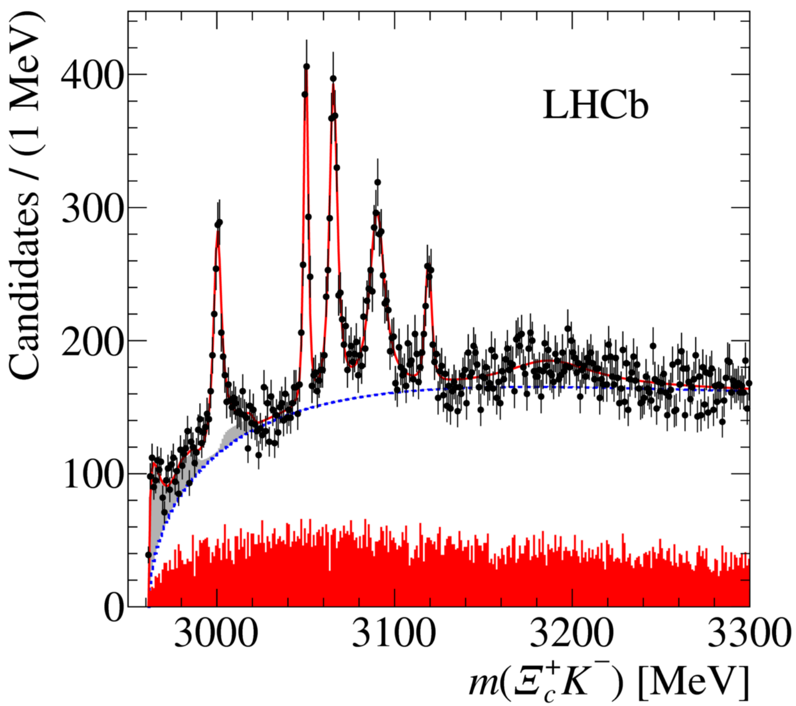


P R L 118, 182001 (2017)



Add K^- to reconstructed Ξ_c^+ candidates





5 new narrow Ω_c states clearly observed

Very spectacular spectrum and demonstration of power of LHC !

Excited Ω_c states

PRL 118, 182001 (2017)

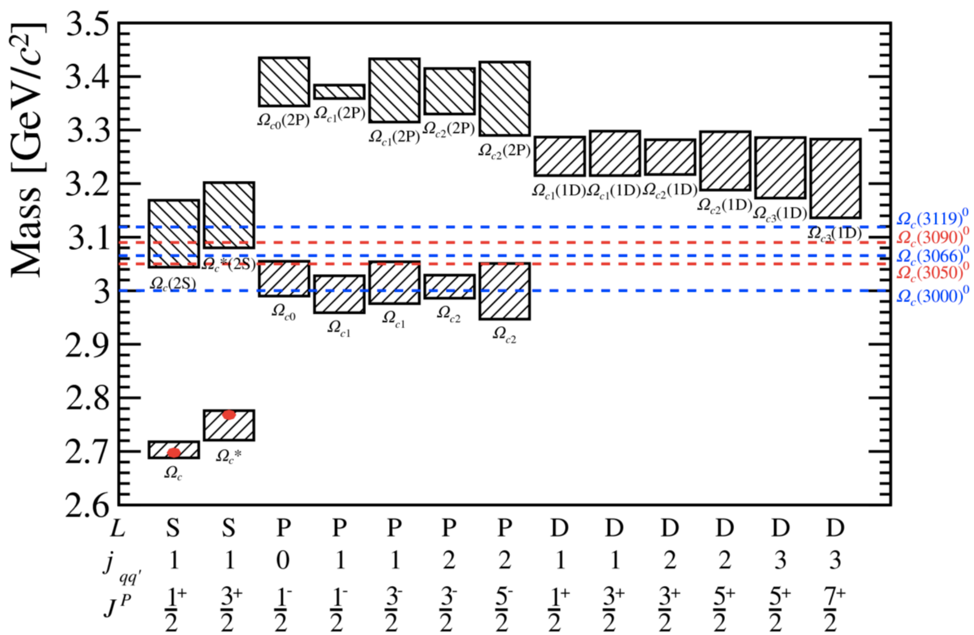
Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL		
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	

5 narrow states evidence for sixth broader state at high mass

More measurements needed to match observed states to theory predictions

One puzzle is narrowness of states

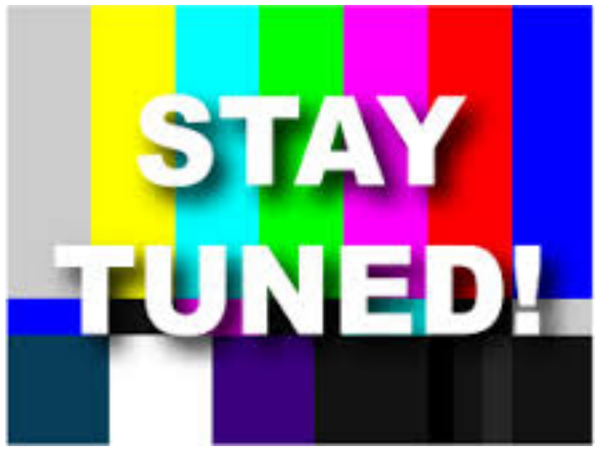
Paper has 23 citations so far



Summary + Outlook

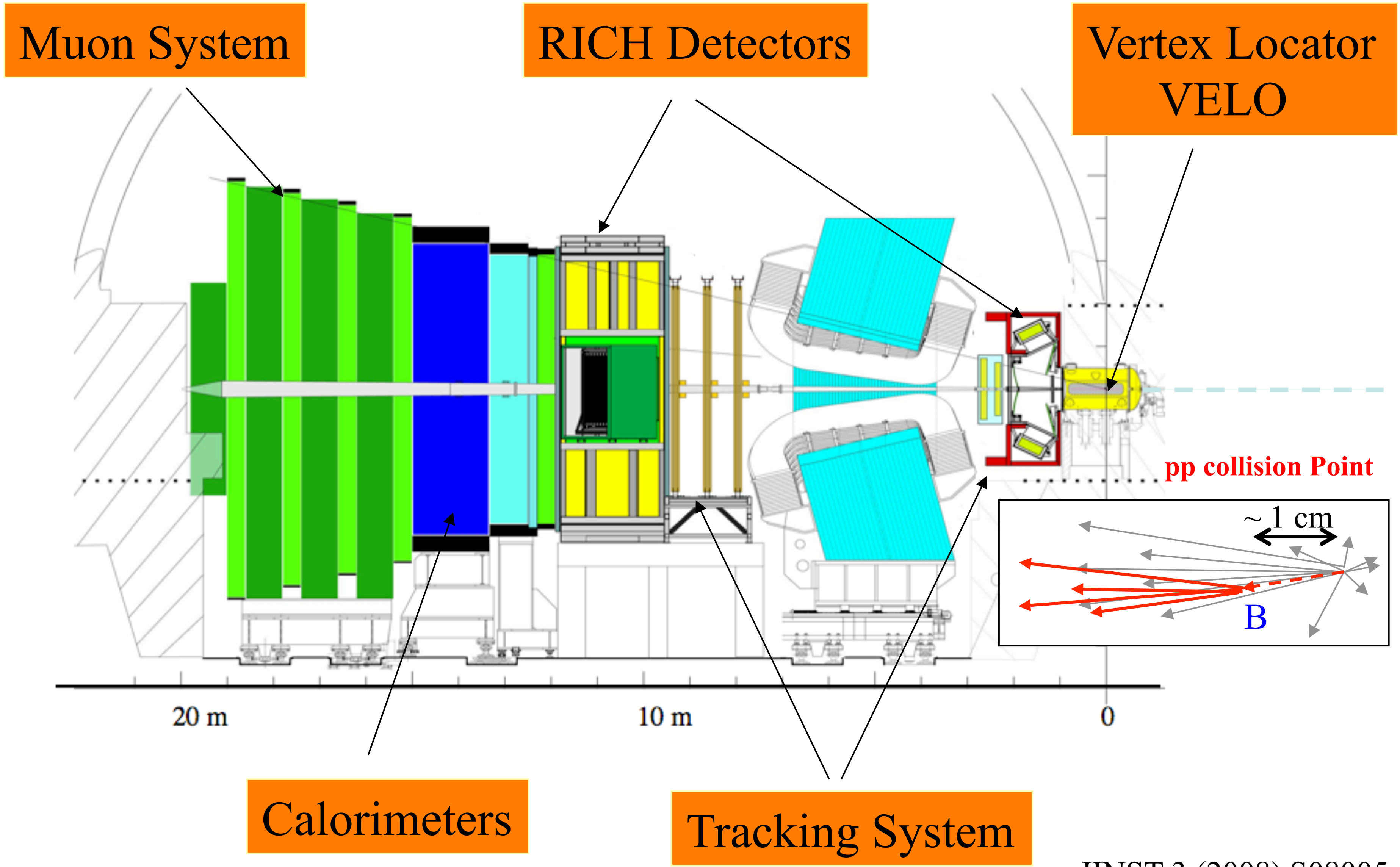
LHCb has made many important contributions to hadronic spectroscopy

- Studies of quarkonia production and properties
- Observation of Pentaquark/tetraquark candidates
- Observation of new charm baryons
- A lot more to come exploiting large Run 2 dataset !



Backup

The LHCb Detector



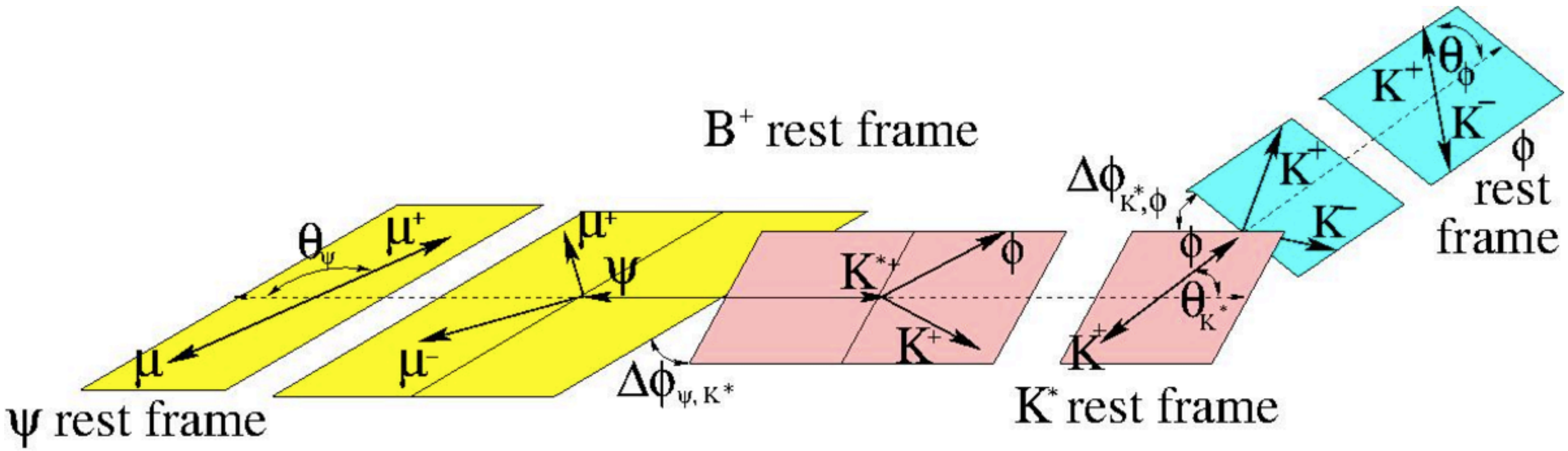
JINST 3 (2008) S08005

Quarkonia with b ➔ φφX decays

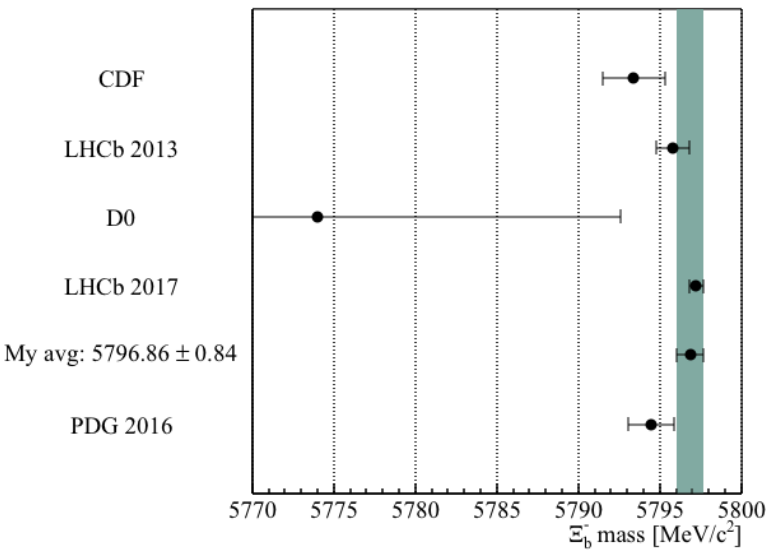
$$M_{\eta_c(1S)} = 2982.81 \pm 0.99 \pm 0.45\,\mathrm{MeV}/c^2,$$
$$M_{\chi_{c0}} = 3412.99 \pm 1.91 \pm 0.62\,\mathrm{MeV}/c^2,$$
$$M_{\chi_{c1}} = 3508.38 \pm 1.91 \pm 0.66\,\mathrm{MeV}/c^2,$$
$$M_{\chi_{c2}} = 3557.29 \pm 1.71 \pm 0.66\,\mathrm{MeV}/c^2,$$
$$M_{\eta_c(2S)} = 3636.35 \pm 4.06 \pm 0.69\,\mathrm{MeV}/c^2,$$
$$\Gamma_{\eta_c(1S)} = 31.35 \pm 3.51 \pm 2.01\,\mathrm{MeV}.$$

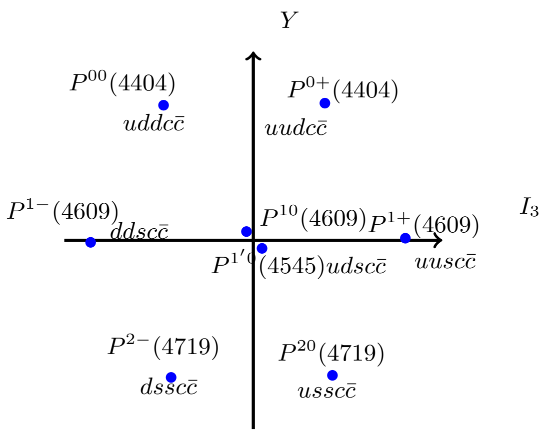
$$\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi) < 4.5(3.9) \times 10^{-7}$$
$$\mathcal{B}(b \to X(3915)X) \times \mathcal{B}(X(3915) \to \phi\phi) < 3.1(2.7) \times 10^{-7}$$
$$\mathcal{B}(b \to \chi_{c2}(2P)X) \times \mathcal{B}(\chi_{c2}(2P) \to \phi\phi) < 2.8(2.3) \times 10^{-7}$$

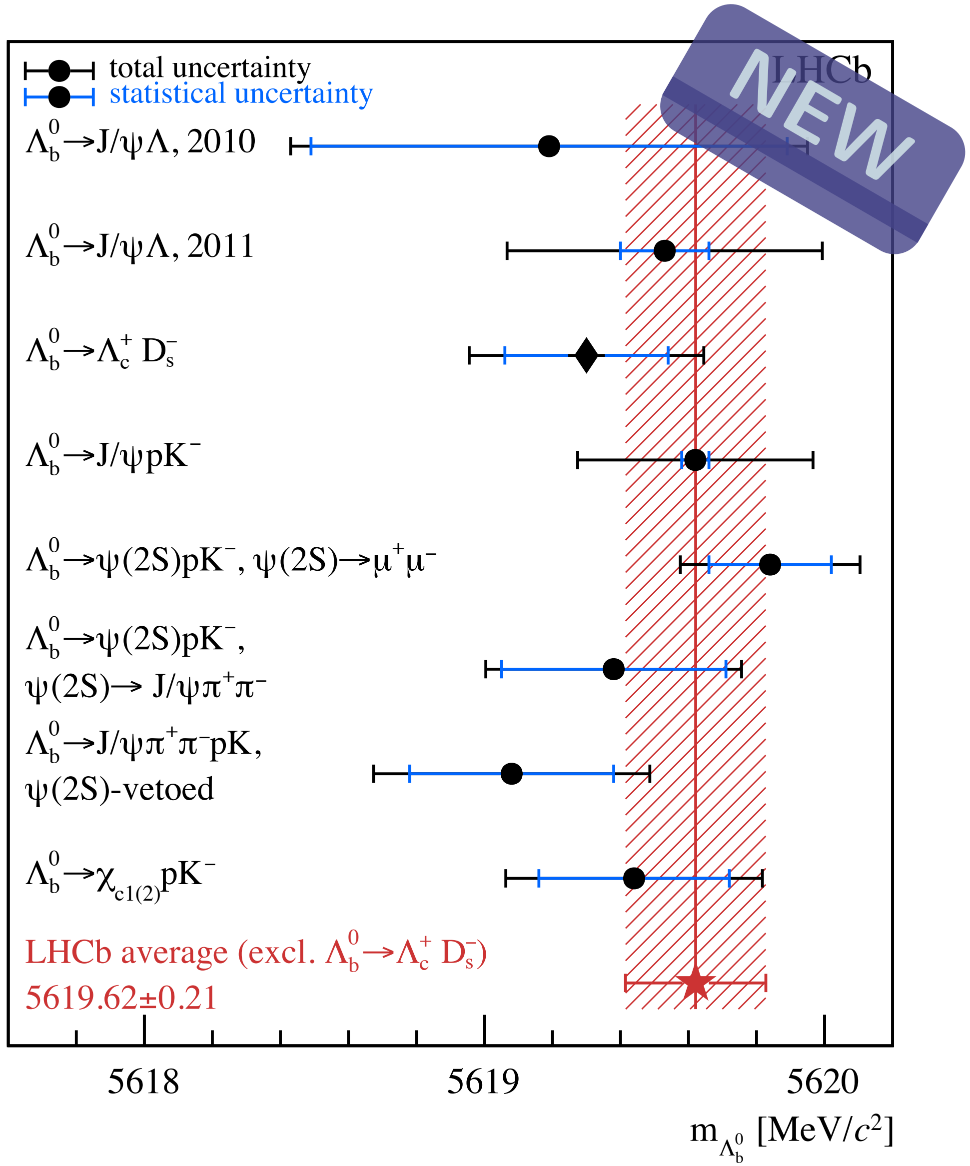
The puzzle of the X(4140)



Mass measurements + Pentaquarks







The puzzle of the X(4140)

sign.			Fit results		
: Ref.	M_0 [MeV]	Γ_0 [MeV]	FF %	f_L	$f_\perp$
8.0σ			$42\pm\ 8^{+\ 5}_{-\ 9}$		
			$16\pm13^{+35}_{-\ 6}$	0.52 ± 0.29	0.21 ± 0.16
7.6σ	$1793\pm59^{+153}_{-101}$	$365\pm157^{+138}_{-215}$	$12\pm10^{+17}_{-\ 6}$	0.24 ± 0.21	0.37 ± 0.17
[53]	1900				
[37]	1650 ± 50	$150\pm\ 50$			
1.9σ	$1968\pm65^{+\ 70}_{-172}$	$396\pm170^{+174}_{-178}$	$23\pm20^{+31}_{-29}$	0.04 ± 0.08	0.49 ± 0.10
[53]	1930				
5.6σ			$11\pm\ 3^{+\ 2}_{-\ 5}$		
5.0σ	$1777\pm35^{+122}_{-\ 77}$	$217\pm116^{+221}_{-154}$		0.64 ± 0.11	0.13 ± 0.13
[53]	1780				
[37]	$1773\pm\ 8$	$188\pm\ 14$			
3.0σ	$1853\pm27^{+\ 18}_{-\ 35}$	$167\pm\ 58^{+\ 83}_{-\ 72}$		0.53 ± 0.14	0.04 ± 0.08
[53]	1810				
[37]	1816 ± 13	$276\pm\ 35$			
8.5σ	$1722\pm20^{+\ 33}_{-109}$	$354\pm\ 75^{+140}_{-181}$	$6.7\pm1.9^{+3.2}_{-3.9}$	0.82 ± 0.04	0.03 ± 0.03
[53]	1780				
[37]	1717 ± 27	322 ± 110			
5.4σ	$2073\pm94^{+245}_{-240}$	$678\pm311^{+1153}_{-\ 559}$	$2.9\pm0.8^{+1.7}_{-0.7}$	0.15 ± 0.06	0.79 ± 0.08
[53]	1940				
[37]	1973 ± 26	$373\pm\ 69$			
3.5σ	$1874\pm43^{+\ 59}_{-115}$	$168\pm\ 90^{+280}_{-104}$	$2.6\pm1.1^{+2.3}_{-1.8}$	1.0	
[53]	2020				
[37]	~ 1830	~ 250			
			$16\pm3\ ^{+\ 6}_{-\ 2}$		
8.4σ	$4146.5\pm4.5^{+4.6}_{-2.8}$	$83\pm21^{+21}_{-14}$	$13.0\pm3.2^{+4.8}_{-2.0}$		
ble 1	4147.1 ± 2.4	15.7 ± 6.3			
6.0σ	$4273.3\pm8.3^{+17.2}_{-\ 3.6}$	$56\pm11^{+\ 8}_{-11}$	$7.1\pm2.5^{+3.5}_{-2.4}$		
[29]	$4274.4^{+8.4}_{-6.7}\pm1.9$	$32^{+22}_{-15}\pm8$			
[25]	$4313.8\pm5.3\pm7.3$	$38^{+30}_{-15}\pm16$			
			$28\pm\ 5\pm\ 7$		
6.4σ			$46\pm11\ ^{+11}_{-21}$		
6.1σ	$4506\pm11^{+12}_{-15}$	$92\pm21^{+21}_{-20}$	$6.6\pm2.4^{+3.5}_{-2.3}$		
5.6σ	$4704\pm10^{+14}_{-24}$	$120\pm31^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$		