Exotic Hadrons at LHCb

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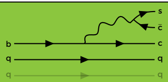
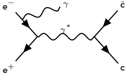
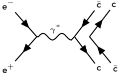
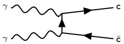
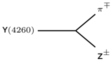
Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

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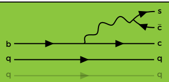
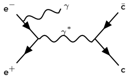
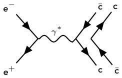
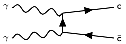
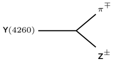
$\chi_{c1}(1P)\,\pi$	Z(4051) Z(4248)						
$h_c(1P)\,\pi$					Z(4020)		
$D\overline{D}$				Z(3930)			
$D\overline{D}^*$	X(3872)		X(3940)		Z(3885)		
$D^*\overline{D}^*$			X(4160)		Z(4025)		
$J/\psi\,p$	$P_c(4380)$ $P_c(4430)$						

LHCb contributions

						$p\overline{p}$ incl.	pp incl.
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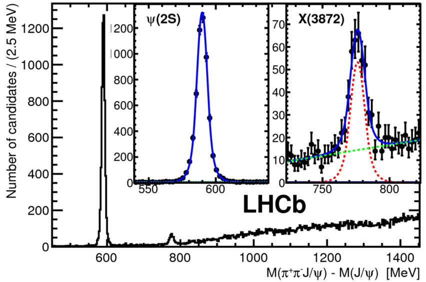
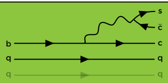
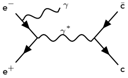
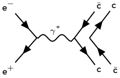
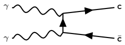
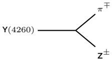


LHCb contributions

	 	 	 	 	 	$p\overline{p}$ incl.	pp incl.
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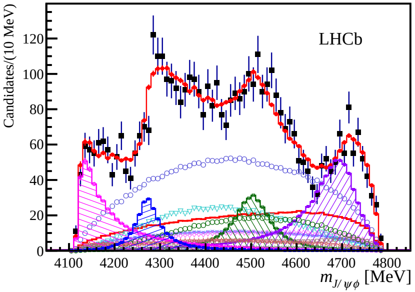
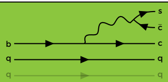
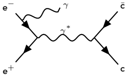
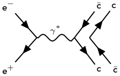
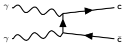
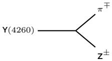


LHCb contributions

						$p\bar{p}$ incl.	pp incl.
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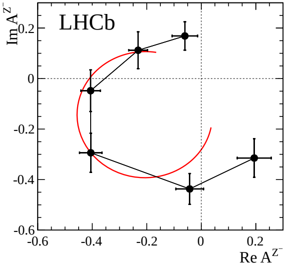
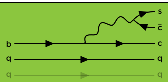
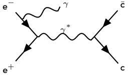
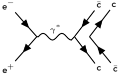
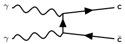
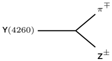


LHCb contributions

						$p\bar{p}$ incl.	pp incl.
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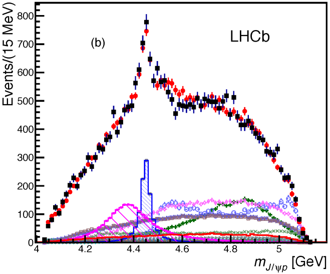
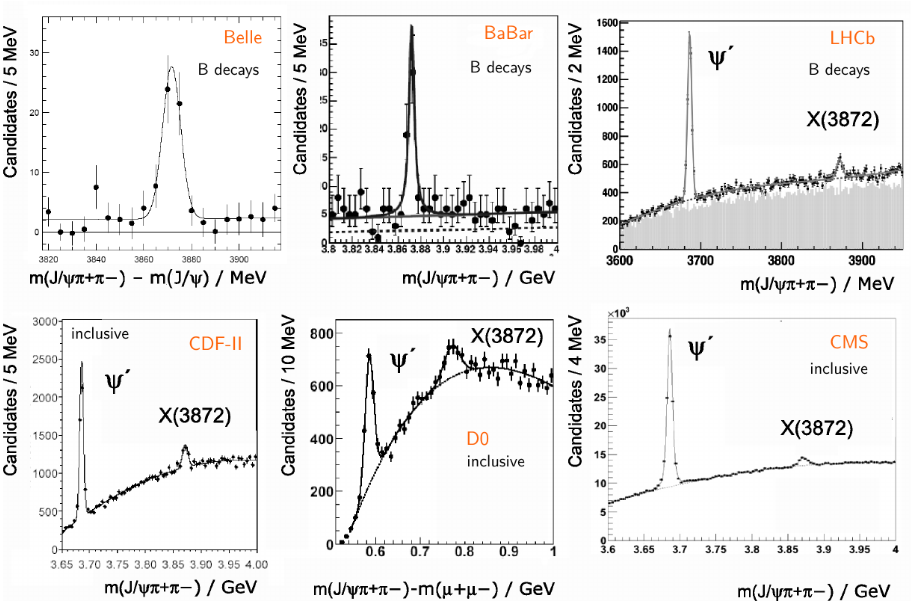


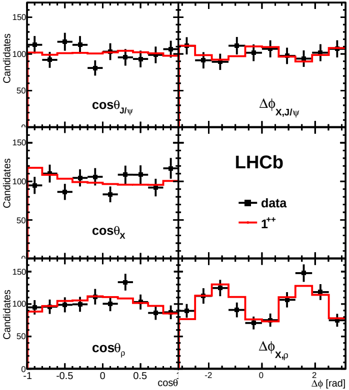
LHCb contributions

The X(3872)


Belle
B decays
Candidates / 5 MeV
m(J/ψπ+π−) − m(J/ψ) / MeV
BaBar
B decays
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
LHCb
ψ´
B decays
X(3872)
Candidates / 2 MeV
m(J/ψπ+π−) / MeV
inclusive
CDF-II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
ψ´
X(3872)
D0
inclusive
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
ψ´
CMS
inclusive
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

Experimental Status of the $\mathrm{X}(3872)$

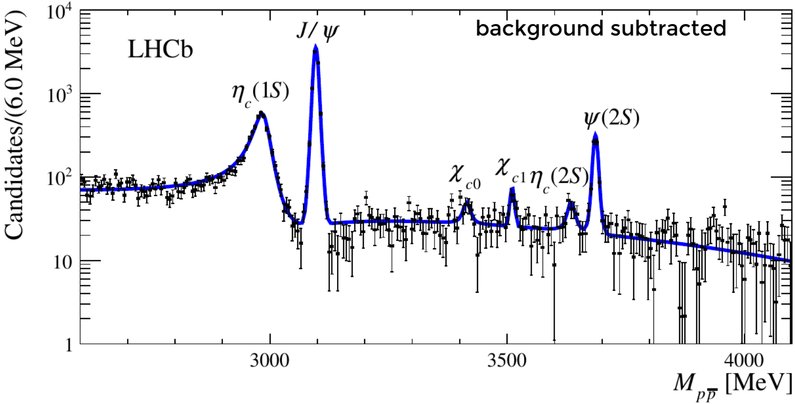
- $J^{PC} = 1^{++}$ established at LHCb
  [PRL110(2013)222001][PRD92(2015)011102]



- Mass m $= 3871.69 \pm 0.17$ MeV
  (in $\mathrm{X}(3872) \to J/\psi$ X decays)
- $D\bar{D}^*$ threshold: 3871.81 ± 0.09 MeV
- Very narrow Width $\Gamma < 1.2$ MeV
  Belle [PRD84(2011)052004]
- Observed in Charmonium-like decay modes:
  $D^{*0}\overline{D}^0$, $J/\psi\pi\pi$, $J/\psi\omega$, $J/\psi\gamma$, $\psi(2S)\gamma$
- Mass and (partial) width disfavour pure $c\bar{c}$ state.
- No charged partner, no C $= -1$ partner found
  - Small coupling to $J/\psi\rho^+$? No bound state?

Search for $X(3872)$ in $p\bar{p}$

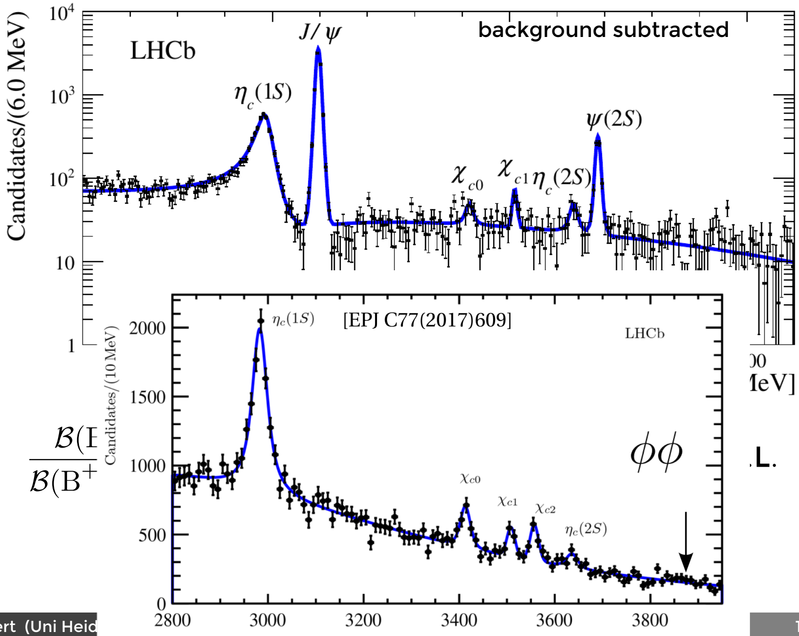
[PLB769(2017)10]



$$\frac{\mathcal{B}(B^+ \to \mathbf{X}K^+) \times \mathcal{B}(\mathbf{X} \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2} \, @ \, 95\% \text{ C.L.}$$

Search for $X(3872)$ in $p\bar{p}$

[PLB769(2017)10]



$X(3872)$ Plans at LHCb

Location of resonance
relative to $D\overline{D}^*$ threshold

- Precision measurement $\Delta m = m(X(3872)) - m(\psi(2S))$
- Needs to take into account coupled channels

Explore other decay channels,

- $D\overline{D}^*$ threshold region

Differential production cross section

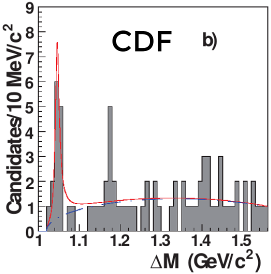
- Theory prediction in (NLO) NRQCD [PRD96(2017)074014]
- CMS and ATLAS data well described [JHEP04(2013)154][JHEP01(2017)117]
- misses LHCb total cross section by factor ~ 2 [[EPJ C72(2012)1972]

Resonances decaying to $J/\psi\phi$

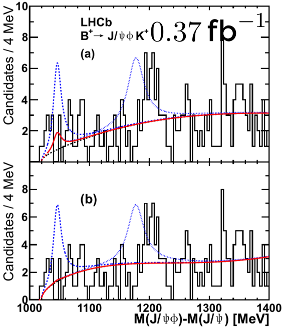
$c\bar{c}s\bar{s}$ Tetraquarks?

Narrow resonances in $J/\psi\phi$ (from B-decays)

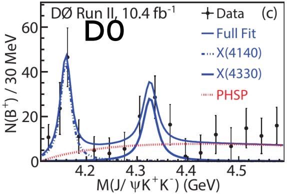
[PRL102(2009)242002]

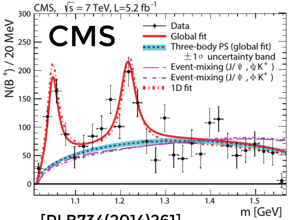


LHCb [PRD85(2012)091103]



[PRD89(1)(2014)012004]





[PLB734(2014)261]

- Narrow structures in $J/\psi\phi$ discovered by CDF in 2008
- Subsequent observations by D0 and CMS
- BaBar, Belle and LHCb $(0.37\,\text{fb}^{-1})$: no significant signal

[PRL104(2010)112004][PRD91(2015)012003][PRD85(2012)091103]

Averages	M [MeV]	Γ [MeV]
X(4140)	4143.4 ± 1.9	15.7 ± 6.3
X(4274)	4293 ± 20	35 ± 16

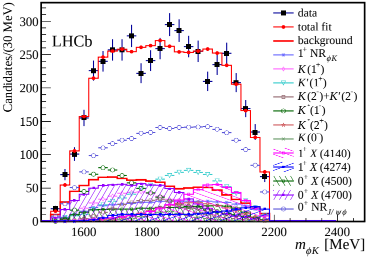
- No amplitude analysis so far
- CDF/CMS X(4274) mass measurements disagree at 3.16σ

LHCb: $B^+ \to J/\psi \phi K^+$ amplitude analysis

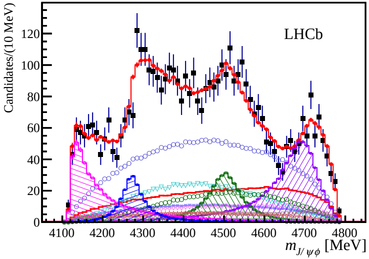
[PRL118(2017)022003]
[PRD95(2017)012002]

χ^2_{1D}/ndof $= 37.9/22$

ϕ K

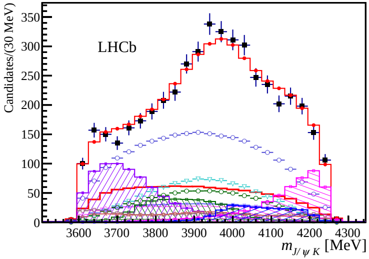


χ^2_{1D}/ndof $= 71.5/67$



$J/\psi\ \phi$

- 3 fb^{-1} yield 4289 ± 151 $B^+ \to J/\psi \phi K^+$ candidates
- 7 K^* resonances + non-resonant ϕ K amplitude
- 4 exotic resonances in $J/\psi\ \phi$
- Fit quality on Dalitz-Plot: $p_{2D} = 17\%$
- No J/ψ K resonances needed



J/ψ K

χ^2_{1D}/ndof $= 21.1/23$

Results for X(4140), X(4274), X(4500) & X(4700)

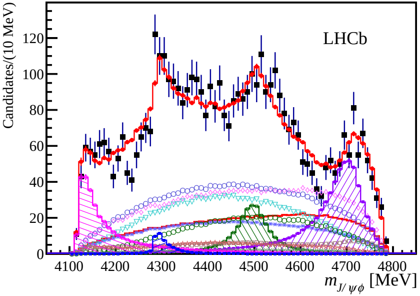
[PRL118(2017)022003][PRD95(2017)012002]

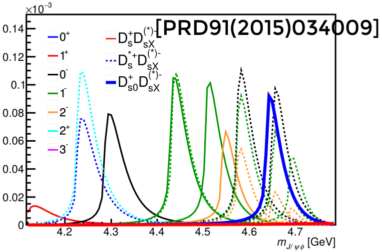
State	M [MeV]	Γ [MeV]	signi	J^{PC}	J^{PC} signi
X(4140)	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	1^{++}	5.7σ
X(4274)	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	6.0σ	1^{++}	5.8σ
X(4500)	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	6.1σ	0^{++}	4.0σ
X(4700)	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	5.6σ	0^{++}	4.5σ

- X(4140) & X(4274) confirmed but with larger width than previous analyses
- First evidence of two new states X(4500) and X(4700)

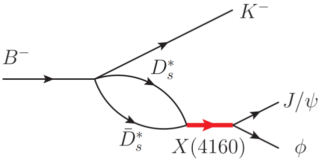
- Large contribution from K^* resonances, including first observation of $K^*(1680) \to K^+\phi$
- non-resonant contribution in 0^{++} amplitude.

Close-by two body thresholds: cusps?





- First fits with $D_s^{(*)} D_s^{(*)}$ cusp-amplitudes included in fit
- Many cusps to consider, needs future investigation (and more data)



Detailed coupled channel models becoming available

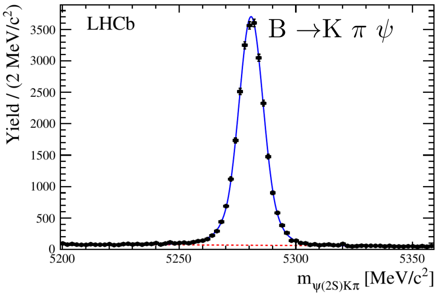
↪ arXiv:1710.02061

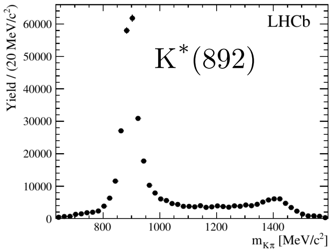
The charged exotic meson Z$^+(4430)$

- Z$(4430)^-$ has first been claimed by Belle in $\mathrm{B} \to \mathrm{K}(\pi^-\psi(2\mathrm{S}))$
- Minimal quark content: $\mathrm{c\bar{c}d\bar{u}}$
- BaBar could explain this through reflections of the $\mathrm{K}\pi$ system (K^*)
- Amplitude analysis by Belle confirms new state (assuming a resonant shape)

$B \to K\pi^- \psi(2S)$ at LHCb

[PRD92(2015)112009]





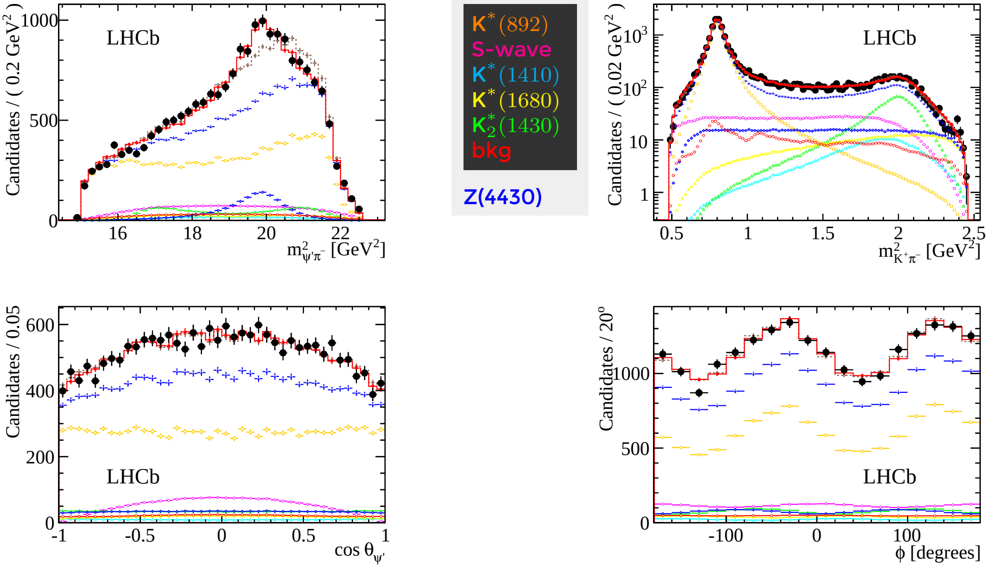
Data sample:

- $\sim 25\,000$ $B \to K\pi^- \psi(2S)$ candidates in $3\,\mathrm{fb}^{-1}$ at LHCb with $\sim 3\%$ residual background

2 Analysis methods:

- 4D amplitude analysis a'la Belle
  model the decay matrix element
  extract resonant phase
- Moments analysis a'la BaBar
  model independent
  confirms existence of Z(4430)

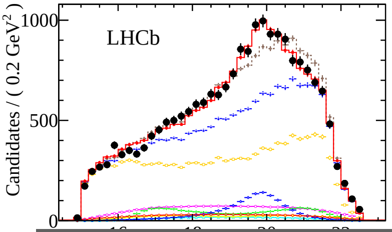
Amplitude Analysis of $B \to K(\pi^- \psi(2S))$ [PRL112(2014)222002]



$K^*(892)$
S-wave
$K^*(1410)$
$K^*(1680)$
$K^*_2(1430)$
bkg

Z(4430)

Amplitude Analysis of $B \to K(\pi^- \psi(2S))$ [PRL112(2014)222002]



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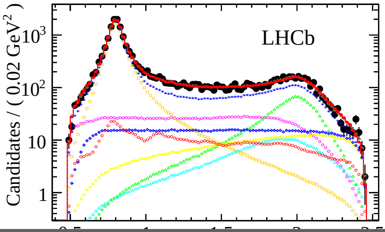
Z(4430)



Results

Mass [MeV]	Width [MeV]	J^P	Significance
4475 ± 7	172 ± 13	1^+	$18.9\sigma (> 13.9)$

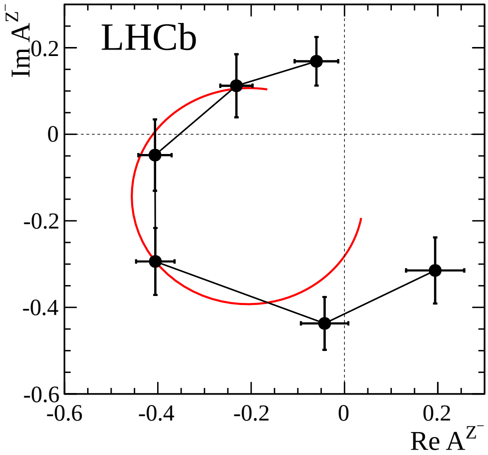
- D-wave contribution negligible (1.3σ using Wilks' theorem)
- Biggest systematic: inclusion of $K_3^*(1780)$ resonance

Candidates / 0.05 6 4 2

cos $\theta_{\psi'}$ φ [degrees]

Extracting Resonant Phase Motion of Z(4430)

- Replace the Breit-Wigner amplitude in the model with a complex valued cubic spline A$(m_{\pi\psi})$ in 6 bins of m$(\pi^- \psi(2S))$



- Argand plot: amplitude in complex plane
- Circular shape corresponds to resonant phase motion (anti-clockwise)
- Model amplitude (Breit-Wigner) overlaid in red
- Note: Offset in phase from reference amplitude(s)

Modelindependent analysis of Z(4430)

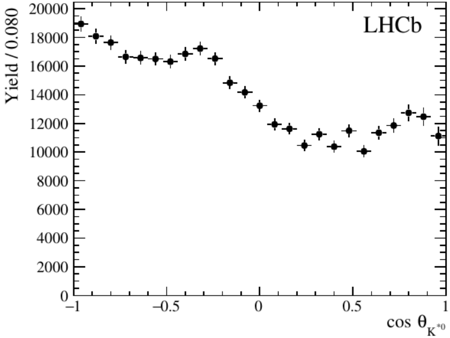
[PRD92(2015)112009]

- Extract the angular structure of the $K\,\pi$ system by moments:

$$\frac{dN}{d\cos\theta_{K^*}} = \sum_{k=0}^{l_{max}} \langle P_k^U \rangle P_k(\cos\theta_{K^*})$$

- with Legendre polynomials P_k
- Moments are determined in bins of $m_{K\pi}$:

$$\langle P_k^U \rangle = \sum_{i=0}^{N_{events}} \frac{W_i}{\epsilon_i} P_k(\cos\theta^i_{K^*})$$



Resonance	Mass (MeV/c^2)	Γ (MeV/c^2)	J^P
$K^*(892)^0$	895.81±0.19	47.4±0.6	1^-
$K^*(1410)^0$	1414±15	232±21	1^-
$K_0^*(1430)^0$	1425±50	270±80	0^+
$K_2^*(1430)^0$	1432.4±1.3	109±5	2^+
$K^*(1680)^0$	1717±27	322±110	1^-
$K_3^*(1780)^0$	1776±7	159±21	3^-

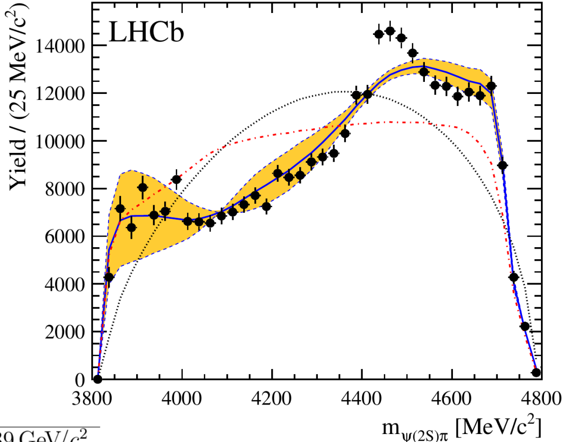
Reflections from K^* Resonances not sufficient

- Higher spin K^* resonances are heavier

$$l_{\max} = \begin{cases} 2 & m_{K\pi} < 836\,\mathrm{MeV}/c^2 \\ 3 & 836\,\mathrm{MeV}/c^2 < m_{K\pi} < 1000\,\mathrm{MeV}/c^2 \\ 4 & m_{K\pi} > 1000\,\mathrm{MeV}/c^2. \end{cases}$$

- $K_3^*(1780)$ is outside the Dalitz plot
- Hypothesis that K^* reflections alone cause $\psi(2S)\,\pi$ shape rejected:

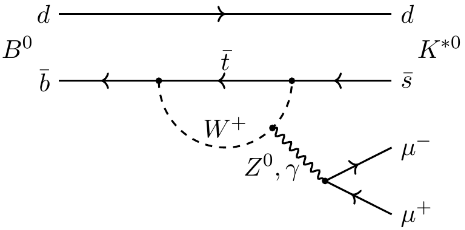
	S, whole $m_{K\pi}$ spectrum	S, $1.0 < m_{K\pi} < 1.39\,\mathrm{GeV}/c^2$
$l_{\max} = 4$	13.3σ	18.2σ
$l_{\max} = 6$	8.0σ	14.1σ
$l_{\max}(m_{K\pi})$	15.2σ	17.3σ



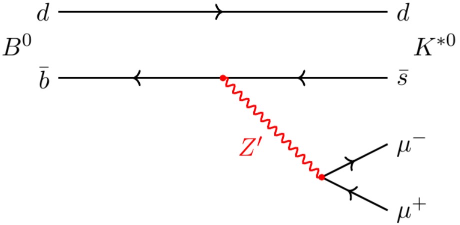
Higher moments are reflections of Z(4430) into $\mathrm{K}\ \pi$!

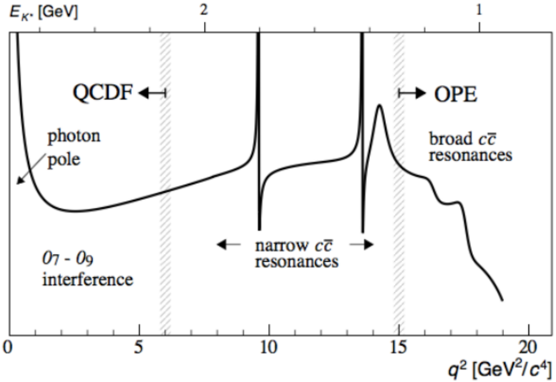
Side remark on connection to $\mathrm{B} \to \mathrm{K}^{*}\mu^{+}\mu^{-}$

SM penguin



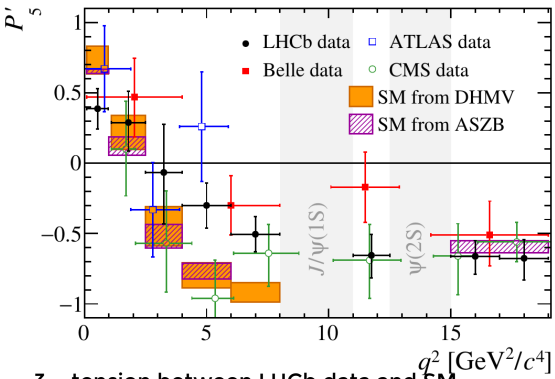
Possible NP





Exotic $\psi\pi$ resonances and $B \to K^*\mu^+\mu^-$

Angular analysis of $B \to K^*\mu^+\mu^-$ in low $q^2 = m^2_{\mu\mu} \in [1,6]$ GeV^2
[JHEP02(2016)104]



$\sim$ 3 σ tension between LHCb data and SM

Major theory uncertainty from hadronic contributions in charmonium region

Long distance effects from analyticity:
$\hookrightarrow$ `arXiv:1707.07305`

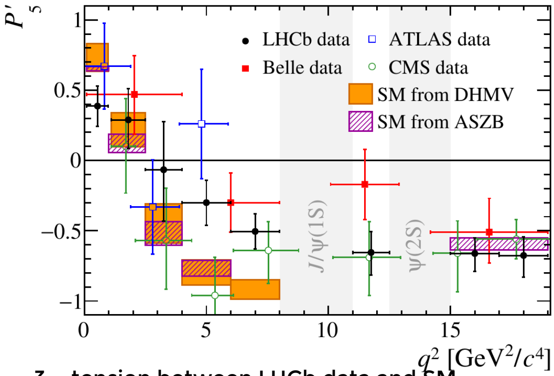
- analyticity constraint to "bridge" SM calculation through charmonium region
- Uses input from $B \to \psi K^*$
- Caveat: neglects $\psi\pi$ resonances

"More recent results for the full angular distributions, stemming from amplitude analyses that take into account tetra-quark contributions, are not used here. The ansatz involving tetra-quark amplitudes is incompatible with the basis of our analysis. Although we expect to be able to use these additional results in future studies, this requires further dedicated work."

Exotic $\psi\pi$ resonances and $B \to K^* \mu^+ \mu^-$

Angular analysis of $B \to K^* \mu^+ \mu^-$ in low $q^2 = m^2_{\mu\mu} \in [1, 6]$ GeV^2

[JHEP02(2016)104]



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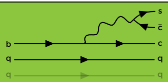
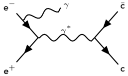
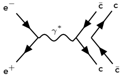
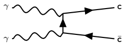
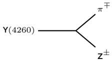
Reaching sensitivities where multiquark hadronic effects will need to be taken into account in NP searches.

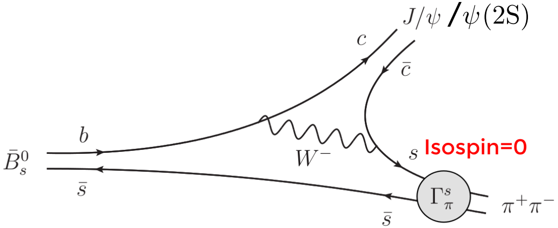
Future avenues to Exotic Mesons at LHCb

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

LHCb contributions

The B_s^0 as a source of Exotic Mesons??

Z(4430) in $B^0_{(s)} \to \psi(2S)\pi\pi$



(see also [JHEP1602(2016)009])

- Compare exotic contributions in both channels!

Y(4260) in B-decays?

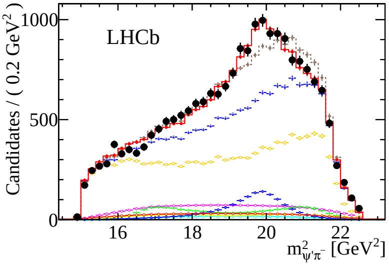
- Limit from BaBar:
  $\mathcal{B}(B \to Y(4260)K \to J/\psi\pi\pi K) < 2.9 \times 10^{-5}$
  [PRD73(2006)011101]
- QCD sum rules:
  $3.0 \times 10^{-8} < \mathcal{B} < 1.8 \times 10^{-6}$
  ↪ arXiv:1502.00119
- Could also be produced in
  $B_s^0 \to Y(4260)\phi$
- Isolate strangeness in well defined state (ϕ)

Prompt prod. of charged mesons with hidden charm?

Challenge: all known $Z^{\pm}$ states have significant widths ~ 150 MeV

$B \rightarrow \psi(2S)K\pi$

no narrow peak



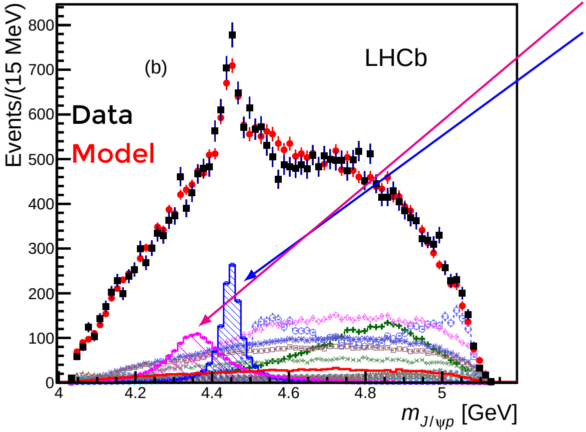
- Extraction of resonances depends on observation of interference effects in three body B-decay.
- We would need another signature to isolate the states
  clever ideas welcome!
- Are there more narrow charged exotics?

Extremely challenging measurement.

Exotic Baryons

Two resonances decaying to $J/\psi p$ [PRL115(2015)072001]

6D Amplitude analysis allows to measure resonance parameters

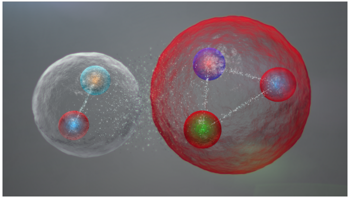


State	Mass [MeV]	Width [MeV]	J^P
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$

- Spin parity assignment not unique
- Excluded: same parity solution
- Exotic contributions needed in two subsequent analyses
  - $\Lambda_b \to J/\psi pK$ moments analysis [PRL117(2016)082002]
  - $\Lambda_b \to J/\psi p\pi$ amplitude analysis [PRL117(2016)082003]

Models overview

- Proximity of thresholds suggests two-body contributions



Closeby thresholds

[MeV]	$P_c(4380)^+$	$P_c(4450)^+$
Mass	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
$\Sigma_c^{*+}\overline{D}^0$	4382.3 ± 2.4	
$\chi_{c1}(1P)p$		4448.93 ± 0.07
$\Lambda_c^{+*}\overline{D}^0$		4457.09 ± 0.35
$\Sigma_c\overline{D}^{0*}$		4459.9 ± 0.5
$\Sigma_c\overline{D}^0\pi^0$		4452.7 ± 0.5

[EPJ A51(2015)11,152]

Rescattering	Hadronic molecules	Tightly bound states
kinematic effect	loosely bound system of color-singlets	constituents carrying color (di-quarks)
above threshold	below threshold	no association
–	S-wave binding restricts J^P	large multiplets

Models overview

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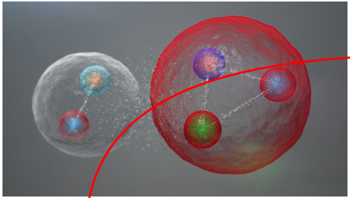

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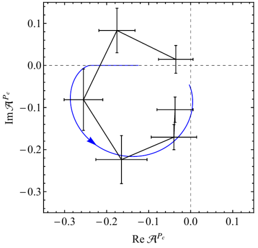
Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)\ p\ K$

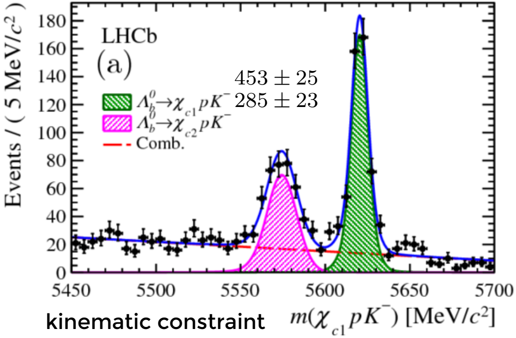
- Cusps need to be taken into account in amplitude analyses
- phase motion: resonance vs cusp



- Add complementary data: investigate near threshold region in the channel $\chi_{c1}(1P)\ p$

[PRL119(2017)062001]

First observation of $\Lambda_b \to \chi_{c1(2)} pK$



kinematic constraint $\chi_c = \chi_{c1} \to J/\psi\gamma$

Testing Rescattering Models: $\Lambda_b \to \chi_{c1}(1P)\ p\ K$

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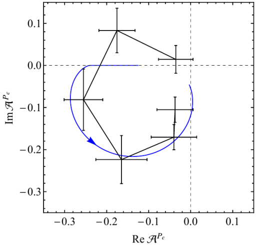

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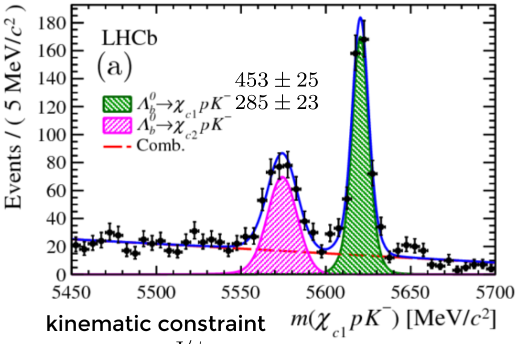
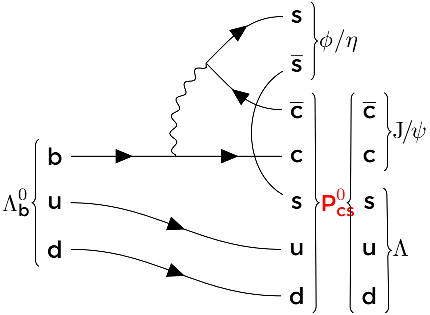


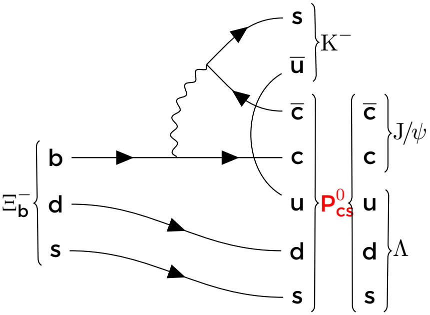
kinematic constraint $\chi_c = \chi_{c1} \to J/\psi\gamma$

Next: amplitude analysis

Pentaquarks with Strangeness?

Both final states provide access to strange pentaquarks usdc$\bar{c}$





- [EPJ C76(2016)446]
- $J/\psi\phi$ system accessible

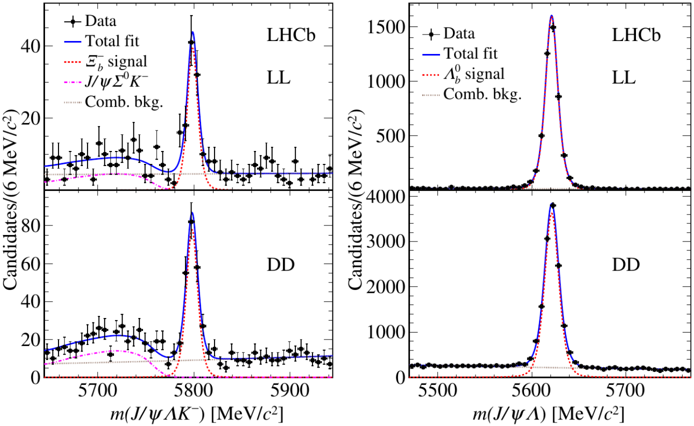
- Discussed in [PRC93(2016)065203]

First Observation of $\Xi_b^- \to J/\psi \Lambda K^-$ [PLB772(2017)265]

$$\frac{f_{\Xi_b}\mathcal{B}(\Xi_b \to J/\psi \Lambda K)}{f_{\Lambda_b}\mathcal{B}(\Lambda_b \to J/\psi \Lambda)}$$
$$= (4.19 \pm 0.29 \pm 0.14) \times 10^{-2}$$

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

- Need Run II data set to study $J/\psi \Lambda K^-$ amplitudes

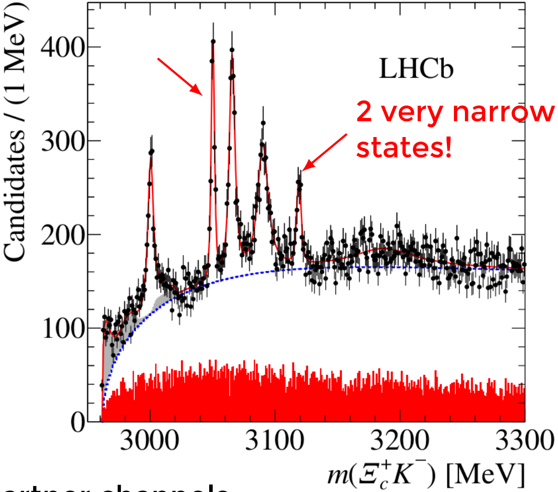


More Exotic Baryons?

Five new Ω_c states in the decay $\Xi_c^+ K^-$ [PRL118(2017)182001]

M. Pappagallo
Tuesday morning

Resonance	Γ (MeV)
$\Omega_c(3000)^0$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$0.8 \pm 0.2 \pm 0.1$
	$< 1.2\,\text{MeV}, 95\%\ \text{CL}$
$\Omega_c(3066)^0$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$1.1 \pm 0.8 \pm 0.4$
	$< 2.6\,\text{MeV}, 95\%\ \text{CL}$



- **Pentaquarks?** [PRD96(2017)014009]
- **Meson-baryon molecules?**

↪ arXiv:1709.08737

→ Need quantum numbers and isospin partner channels

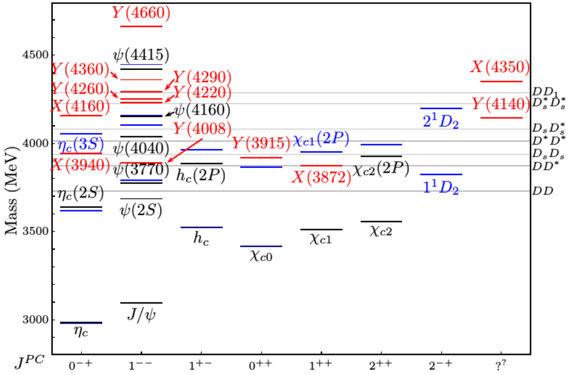
Summary and Outlook

- LHCb is making key discoveries
  - Charmonium-like exotics
  - Charged exotic mesons with hidden charm
  - Exotic heavy baryons
  - Non-exotic spectroscopy extremely important information
- Lively interaction with phenomenologists
  - New ideas what measurements to perform
  - Progress on analytic amplitude structure
  - Improved analysis methods (eg. coupled channel effects)
- RUN II set will enable amplitude analyses of more complicated final states

Backup

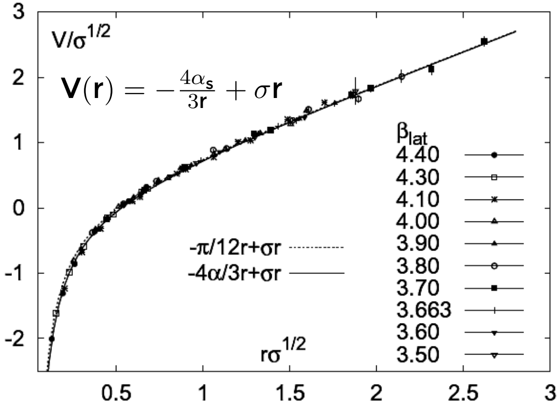
Charmonium: The $c\bar{c}$ spectrum

↪ arXiv:1411.5997



Cornell potential vs lattice QCD

[PRD71(2005)114510]



Observed charmonium

Potential model

↪ arXiv:hep-ph/0701117

Exotic states

X(3872) decays

Approx. product branching fractions	
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to D^{*0}\overline{D}^0)$	$\sim 1 \times 10^{-4}$
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi \underbrace{\pi\pi}_{\rho})$	$\sim 1 \times 10^{-5}$
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi\omega)$	0.6×10^{-5}
$\mathcal{B}(B \to K\mathbf{X}) \times \mathcal{B}(\mathbf{X} \to J/\psi\gamma)$	$\sim 2 \times 10^{-6}$
$\frac{\mathcal{B}(\mathbf{X}\to\psi(2S)\gamma)}{\mathcal{B}(\mathbf{X}\to J/\psi\gamma)}$	$\sim 2 - 3$
$\frac{\mathcal{B}(B^+\to\mathbf{X}K^+)\times\mathcal{B}(\mathbf{X}\to p\overline{p})}{\mathcal{B}(B^+\to J/\psi K^+)\times\mathcal{B}(J/\psi\to p\overline{p})}$	$< 0.25 \times 10^{-2}$ @95%C.L.
$\mathcal{B}(B^+ \to \mathbf{X}K^+) \times \mathcal{B}(\mathbf{X} \to p\overline{p})$	$< 6 \times 10^{-9}$

Allowed in molecule picture [PLB742(2015)394] [EPJ C75(2015)26]

[PLB 769(2017)10]

for a more details and precise values see the review ↪ arXiv:1601.02092

Search for narrow charmonia: $p\bar{p}$ fit model [PLB769(2017)10]

State	Parametrisation	Signal Yield	
$\eta_c(1S)$+non res.	rel. BW+gaussian + interference	11246 ± 119	
J/ψ	double gaussian	6721 ± 93	
$\chi_{c0}(1P)$	rel. BW+gaussian	84 ± 22	
$\chi_{c1}(1P)$	gaussian	95 ± 16	
η_c (2S)	rel. BW+gaussian	106 ± 22	first obs. 6.0σ
ψ (2S)	double gaussian	588 ± 30	
ψ (3770)	rel. BW+gaussian	-6 ± 9	
X(3872)	gaussian	-14 ± 8	

- $\eta_c(1S)$ allowed to interfere with $\ell = 0$ $p\bar{p}$ non-resonant component (phase-space distribution)
- $\chi_{c0}(1P)$,$\chi_{c1}(1P)$,X(3872) and ψ (3770) masses fixed to PDG values

$$\Delta M_{J/\psi,\eta_c(1S)} = 110.2 \pm 0.5 \pm 0.9 \text{ MeV}$$

$$\Gamma_{\eta_c(1S)} = 34.0 \pm 1.9 \pm 1.3 \text{ MeV}$$

$$\Delta M_{\psi(2S),\eta_c(2S)} = 52.5 \pm 1.7 \pm 0.6 \text{ MeV}$$

Status of $J/\psi\phi$ resonances

State	M [MeV]	Γ [MeV]	M^{LHCb} [MeV]	Γ^{LHCb} [MeV]	J^{PC}
X(4140)	4143.4 ± 1.9	15.5 ± 6.3	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	1^{++}
X(4274)	4293 ± 20	35 ± 16	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	1^{++}
X(4350)	$4350.6^{+4.6}_{-5.1} \pm 0.7$	$13^{+18}_{-9} \pm 4$			0^{+} or 2^{+}
X(4500)			$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	0^{++}
X(4700)			$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	0^{++}

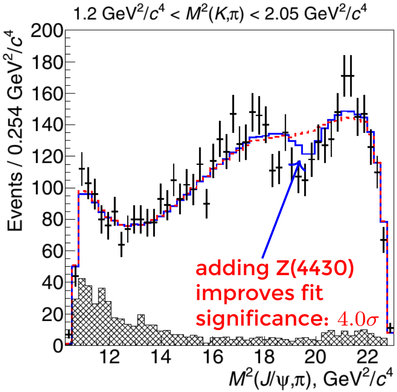
- $J^PC = 1^{++}$ assignment of X(4140) and X(4274) consistent with non-observation in $\gamma\gamma$ fusion
- Are X(4350) and X(4500) the same state? masses and widths don't match well
- X(4140) consistent with $D_sD_s{}^*$ cusp

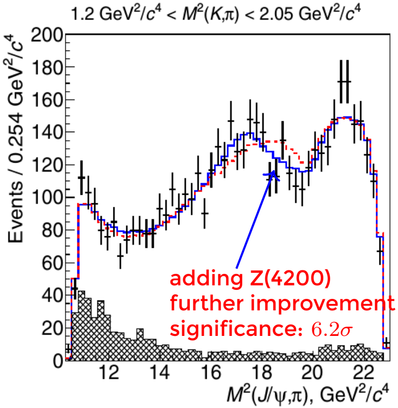
Charged Exotic Hadrons with Hidden Charm

$\overline{B} \rightarrow K^-\pi^+J/\psi$ at Belle

[PRD90(2014)112009]

- $30\,000\ \overline{B} \rightarrow K^-\pi^+J/\psi$ decays (711 fb^{-1})
- 4D amplitude analysis





- Z(4430) with J$^P = 1^+$ confirmed
- Z(4200) with J$^P = 1^+$ observed

Ongoing analyses on charged Exotics in LHCb

$\overline{B} \to K^- \pi^+ J/\psi$

- LHCb Run I: $\sim 20\times$ Belle statistics
- 3 analysis techniques:
  - Amplitude analysis
  - Moments analysis
  - Novel 3D moments analysis

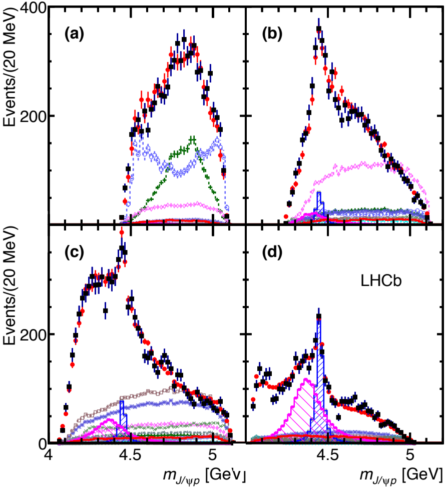
$\overline{B} \to K^- \pi^+ \chi_c$

- Amplitude analysis well advanced

COMING SOON!

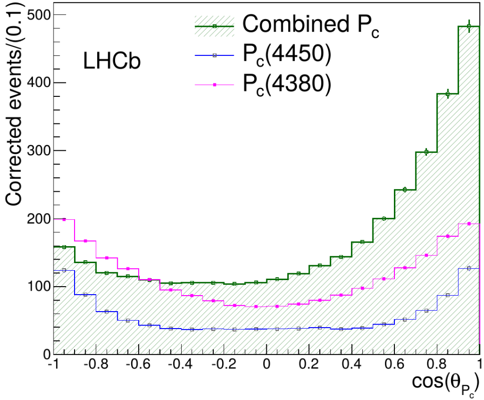
Why a second state with opposing parity?

$m_{Kp} < 1.55$ GeV $\quad 1.55 < m_{Kp} < 1.70$ GeV



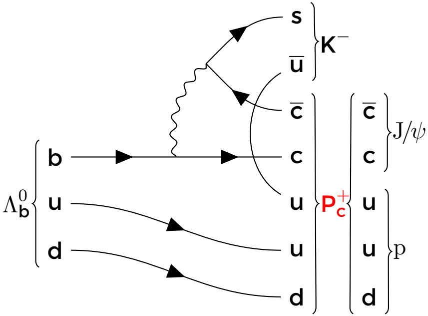
$1.70 < m_{Kp} < 2.00$ GeV $\quad 2.00$ GeV $< m_{Kp}$

- The peaking structure in $m_{J/\psi p}$ is asymmetric as a function of cos θ_{P_c})
- This can be explained by interference of two states with opposing parity



Decay of the P_c to Open Charm

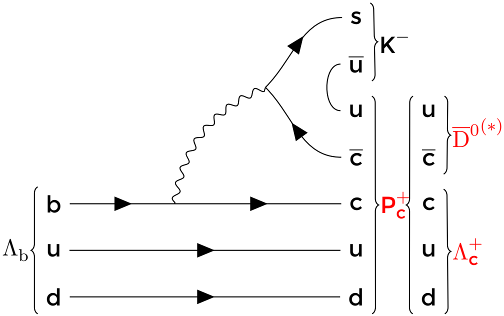
P_c discovery in $\Lambda_b \to J/\psi p K^-$



Molecular-Models:

$P_c^+ \to \Lambda_c^+ \overline{D}^{0(*)}$ favoured decay mode

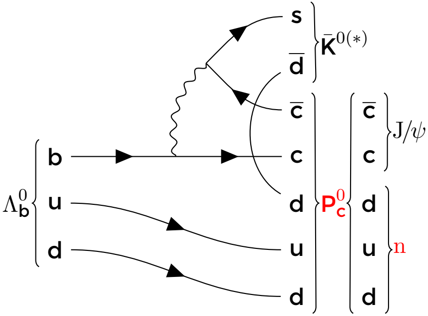
[PRC85(2012)044002][PRD95(2017)114017]



c and c̄ in meson/baryon pair

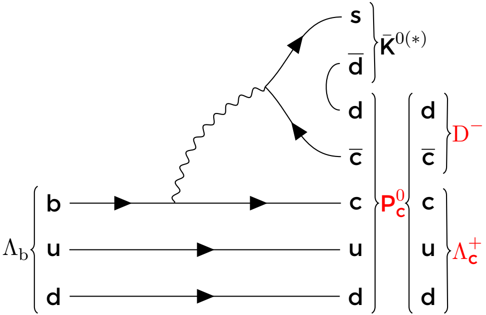
A neutral Pentaquark?

Are there isospin partners to the P_c^+? uudc$\bar{c}$ $\leftrightarrow$ uddc$\bar{c}$



Neutron not detectable in LHCb

Decay into open charm hadrons accessible



Combined Analysis $\Lambda_b \to \Lambda_c^+ \overline{D}^0 K$ and $\Lambda_b \to \Lambda_c^+ \overline{D}^{0*} K$

- Predictions on relative widths ↪ arXiv:1703.01045

Mode	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
$\bar{D}^*\Lambda_c$	131.3	41.6	80.5	22.6
$J/\psi p$	3.8	8.4	8.3	2.0
$\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8

- Possible spin-parity combinations for the $\Lambda_c^+ \overline{D}^{0(*)}$ system

ℓ	$\Lambda_c^+ \overline{D}^0$	$\Lambda_c^+ \overline{D}^*$	pJ/ψ
S	$\frac{1}{2}^-$	$\frac{1}{2}^-, \frac{3}{2}^-$	$\frac{1}{2}^-, \frac{3}{2}^-$
P	$\frac{1}{2}^+, \frac{3}{2}^+$	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$	$\frac{1}{2}^+, \frac{3}{2}^+, \frac{5}{2}^+$
D	$\frac{3}{2}^-, \frac{5}{2}^-$	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$	$\frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-, \frac{7}{2}^-$

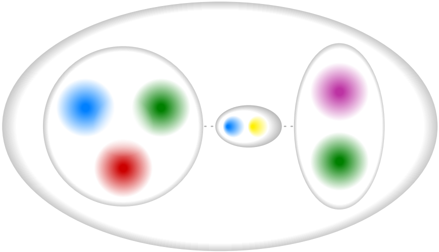
favoured quantum numbers highlighted

- Complementary information on quantum numbers

Meson-Baryon Molecules

Building color-neutral objects from color-neutral constituents

- Small binding energy
  $\rightarrow$ state just below 2-body thresholds
- Different parametrisations
  of the binding force available
- Predictions from coupled channel dynamics
  [Nucl.Phys.A776(2006)17][PRC 85 (2012) 044002]
- Constituents in S-wave
  Opposite parity problematic to explain



Channel	$\Sigma_c^* \overline{D} / \Sigma_c \overline{D}^*$	$J/\psi N(1440/1520)$
Features	Pion exchange	opposite parity with S-wave for both states
Exp.Sign.	Isospin $I = \frac{3}{2}$	150 MeV binding?

considered here: $J^P \in \left\{ \frac{3}{2}^{\pm}, \frac{5}{2}^{\pm} \right\}$

Pentaquarks in the Di-Quark Picture

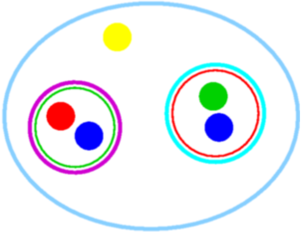
[PLB749(2015)289]

$$P = \{\bar{c}[cq]_s[qq]_s, \ell\}$$

Diquark color configuration:
$3 \otimes 3 \to \bar{3}$

- Opposite parity understood: additional orbital angular momentum ℓ
- One unit ℓ costs:
  $\delta m \approx m(\Lambda(1405)) - m(\Lambda(1116)) \approx 300\,\text{MeV}$
- Coupling spins to $s = 1$ in the light-light di-quark:
  $\delta m \approx m(\Sigma_c(2455)) - m(\Lambda_c(2286)) \approx 200\,\text{MeV}$

$P_c(4380)$	$\frac{3}{2}^-$	$\{\bar{c}[cq]_{s=1}[qq]_{s=1}, \ell = 0\}$
$P_c(4450)$	$\frac{5}{2}^+$	$\{\bar{c}[cq]_{s=1}[qq]_{s=0}, \ell = 1\}$



- Can explain the small mass gap!
- Predicts a large multiplet of states

Pentaquark program at LHCb

Amplitude analyses will leverage Run II data

What are they?

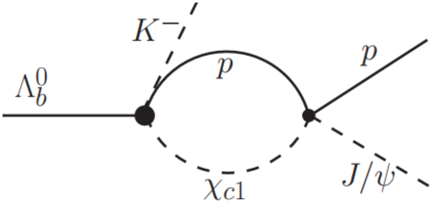
- Observe $P_c \to J/\psi p$ as subsystems in different final states
  - $\Lambda_b \to J/\psi\ p\ \pi$ — DONE
  - $\Upsilon \to J/\psi\ p\ \overline{p}$ — in progress
  - $\Lambda_b \to J/\psi\ p\ \pi\ K^0_S$ — in progress
- Search for new decay modes of P_c
  - $\Lambda_b \to \chi_{c1}(1P)\ p\ K$ — observed Λ_b-decay mode
  - $\Lambda_b \to \Lambda_c^+ \overline{D}^{0(*)} K$ — in progress

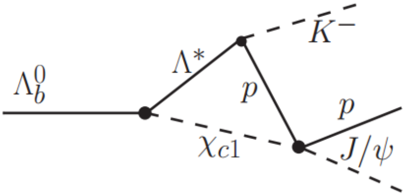
Are there more of their kind?

- Explore a possible multiplet of pentaquarks
  - $\Lambda_b \to J/\psi\ p\ \pi\ K^0_S$ — in progress
  - $\Lambda_b \to \Lambda_c^+ D^- K^*$ — in preparation
  - $\Xi_b \to J/\psi \Lambda K$ — observed Ξ_b decay-mode
  - $\Lambda_b \to J/\psi\ \Lambda\ \phi$ — in progress

Rescattering: hadronic loops

[PRD92(2015)071502]





Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^2 f_\Lambda(\vec{q}^2)}{E - m_1 - m_2 - \vec{q}^2/2\mu}$$

with a form factor $f_\Lambda(\vec{q}^2)$.

Triangle Singularity given by Landau-equation

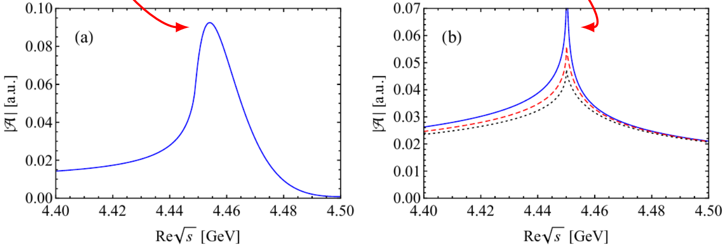
$$1 + 2y_{12}y_{23}y_{13} = y_{12}^2 + y_{23}^2 + y_{13}^2$$

$$y_{ij} = \left(m_i^2 + m_j^2 - (p_i + p_j)^2\right)/2m_im_j$$

Rescattering: hadronic loops

[PRD92(2015)071502]

Cusps just above threshold



But: no cusp in elastic channel here: $p\chi_{c1}$

Nonrelativistic loop integral:

$$G_\Lambda(E) = \int \frac{d^3q}{(2\pi)^3} \frac{\vec{q}^{\,2} f_\Lambda(\vec{q}^{\,2})}{E - m_1 - m_2 - \vec{q}^{\,2}/2\mu}$$

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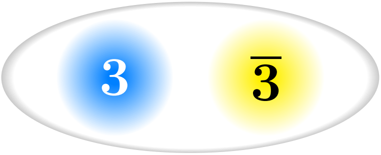
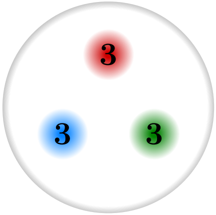
The Di-Quark Model

Building color-neutral objects from coloured constituents



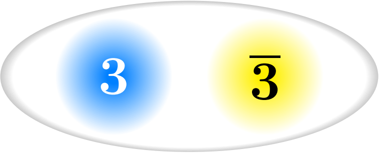


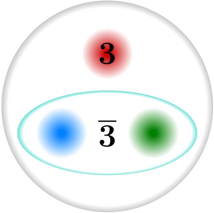
- $q\bar{q}$ mesons are bound through attractive $\mathbf{3}\bar{\mathbf{3}}$ color coupling

- qqq is also bound $\Rightarrow$ $\mathbf{3} \otimes \mathbf{3} \rightarrow \bar{\mathbf{3}}$
- At short distances the $\bar{3}$ qq binding is still half as strong as the color singlet binding
- $\Rightarrow$ qq di-quark correlations

The Di-Quark Model

Building color-neutral objects from coloured constituents





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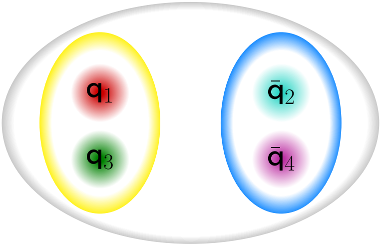
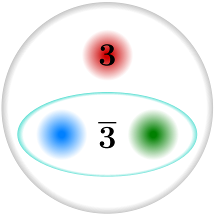




- Tetraquark in the di-quark model
- Qualitatively explains relations between X(3872), Z(3900), Z(4430) and Y(4260) exotic mesons

  e.g. ↪ arXiv:1405.1551

- qqq is also bound ⇒ $\mathbf{3} \otimes \mathbf{3} \rightarrow \bar{\mathbf{3}}$
- At short distances the $\bar{3}$ qq binding is still half as strong as the color singlet binding
- ⇒ qq di-quark correlations

Predictions from low-energy QCD?

Crypto-Exotic Baryons in Coupled-Channel Dynamics

Few predictions for states with hidden charm are available.

M. Lutz and J. Hofmann [Nucl.Phys.A776(2006)17]

- Building baryon resonances from coupled-channel dynamics within ground state multiplets
- 16-plet 0^- mesons $\times$ 20-plet $\frac{3}{2}^+$ baryons
- $\Rightarrow$ narrow octet of $J^P = \frac{3}{2}^-$ crypto-exotics

(I, S)	M[MeV]	Γ[MeV]
$(\frac{1}{2}, 0)$	3430	0.50
$(0, -1)$	3538	0.63
$(1, -1)$	3720	0.83
$(\frac{1}{2}, -2)$	3752	1.1

- No tuning
- Resonant states predicted!
- Very narrow width

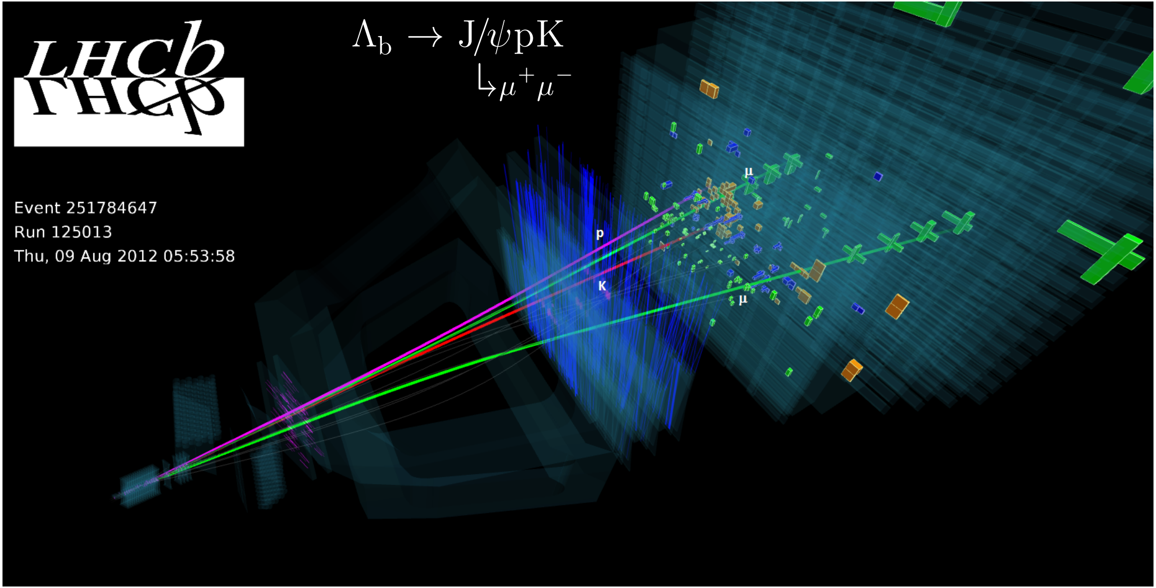
Dynamically Generated N^* with Hidden Charm

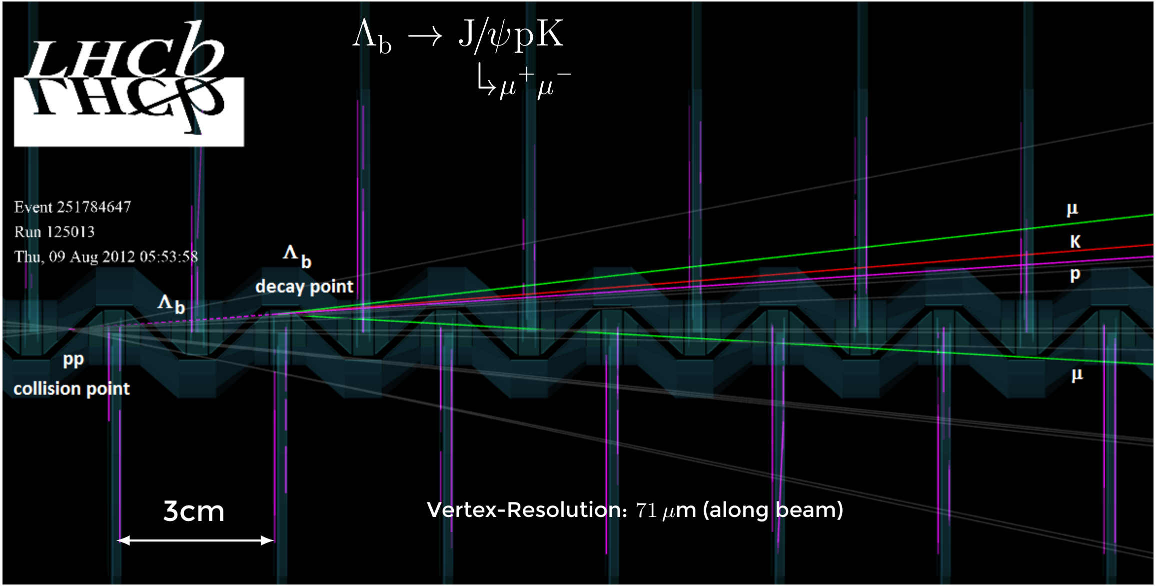
- Meson-Baryon interaction with vector exchange force
- Vector forces from local hidden gauge formalism
- Coupled channels $\overline{D}\ \Lambda_c^+$, $\overline{D}\ \Sigma_c$, $\overline{D}^*$,Λ_c^+,$\overline{D}^*\Sigma_c$,$\overline{D}\Sigma^*$, $\overline{D}^*\Sigma_c$ (η_c N,π N,η N,η'N,K Σ,K Λ)
- tuned to reproduce Λ_c^+ (2592) and Λ_c^+ (2625)
- $\Rightarrow$6 Nucleon resonances with hidden charm

Several similar models:
[PRC 84 (2011) 015202]
[PRC 85 (2012) 044002]
[EPJ A52 (2016) 43]

Main channel	J^P	M ± 20 MeV	Γ [MeV]	Main decay
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c + \overline{D}\Sigma_c)$	$1/2^-$	4228	21-51	$\overline{D}\ \Lambda_c^+$
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c - \overline{D}\Sigma_c)$	$1/2^-$	4295	11-41	$\overline{D}\ \Lambda_c^+$
$\overline{D}^*\Sigma_c$	$3/2^-$	4218	103	$\overline{D}\ \Lambda_c^+$
$\overline{D}^*\Sigma_c{}^*$	$1/2, 5/2^-$	4344	0	-
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c{}^* + \overline{D}\Sigma_c{}^*)$	$3/2^-$	4325	0	-
$\frac{1}{\sqrt{2}}(\overline{D}^*\Sigma_c{}^* - \overline{D}\Sigma_c{}^*)$	$3/2^-$	4378	0	-

- Only negative parity


LHCb
$\Lambda_b \to J/\psi p K$
$\hookrightarrow \mu^+\mu^-$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
p
K
μ
μ


LHCb
$\Lambda_b \to J/\psi p K$
$\hookrightarrow \mu^+\mu^-$
Event 251784647
Run 125013
Thu, 09 Aug 2012 05:53:58
Λ_b decay point
Λ_b
pp collision point
μ
K
p
μ
3cm
Vertex-Resolution: $71\ \mu$m (along beam)