Hadron Spectroscopy, exotics and B_c physics at LHCb

Biplab Dey

on behalf of the LHCb collaboration

BEACH 2016, Fairfax, VA

Introduction: exotics

- Tetra/pentaquarks were predicted by Gell-Mann/Zweig in 1964

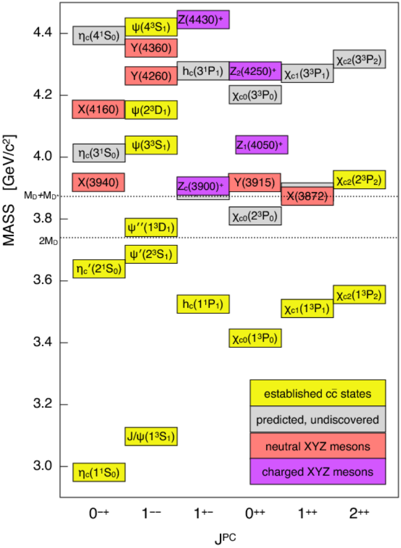
> A SCHEMATIC MODEL OF BARYONS AND MESONS *
>
> M. GELL-MANN
>
> *California Institute of Technology, Pasadena, California*
>
> Received 4 January 1964
>
> We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the 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

- Yet, only a handful seen, only in the heavy-quark sector.

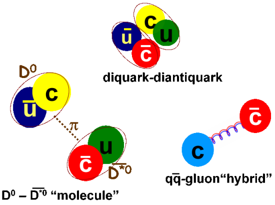
- LHCb: first dedicated b/c-physics detector at a hadron collider. Excellent vertexing and PID. $B : \Lambda_b^0 : B_s \sim 4 : 2 : 1$ within acceptance.

THE CHARMONIA *XYZ* STATES AND EXOTICS

Olsen 1403.1254



- Exotics revolution in mesonic sector since Belle discovery of $X(3872)$ in 2003.
- Several *XYZ* states @ BESIII, Belle/BaBar, CDF/D0, LHCb/CMS.
- No clear organising principle yet.



The charmonia *XYZ* states and exotics

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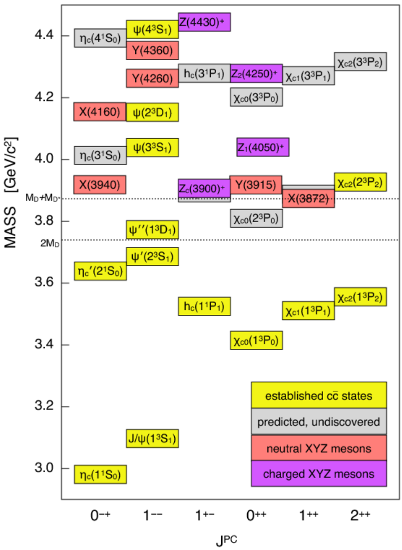

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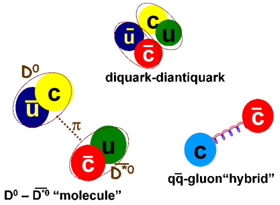


- Baryonic sector: LHCb discovery of two pentaquarks in 2015.

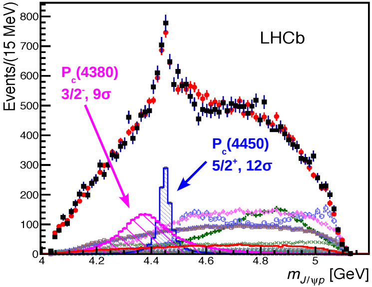
Some selected results @ LHCb

- Pentaquarks in $\Lambda_b^0 \to J/\psi\, pK$: "model-independent" evidence NEW!
- Pentaquark evidence in $\Lambda_b^0 \to J/\psi\, p\pi$ NEW!
- Exotic structures in $B^+ \to X(\to J/\psi\,\phi)K^+$ NEW!
- LHCb non-confirmation of D0 tetraquark $X(5568)^+ \to B_s\pi^+$

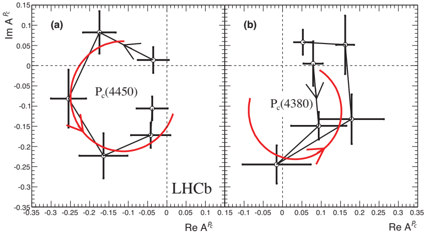
Pentaquarks in $\Lambda_b^0 \to J/\psi\, pK^-$ PRL 115, 072001

- 2015: LHCb discovers two pentaquark states $P_c \to J/\psi\, p$.

- Amplitude fit in full 6d. 9 σ and 12 σ evidence for two P_c states.



- Phase-motion distinctive of a resonant structure (for $P_c(4450)$).



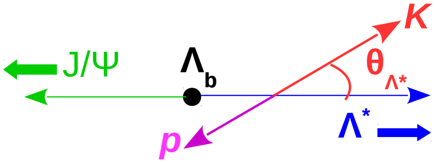
- However, the large number of poorly known Λ^* states makes the amplitude fits inherently model-dependent.

Model-independent P_c evidence (NEW!) 1604.05708

- Test null hypothesis H_0: no P_c's are needed and Λ^* resonances can alone explain data.
- Signature of each spin-J $\Lambda^{*J} \to pK$: moments expansion in $\cos\theta_{\Lambda^*}$.

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

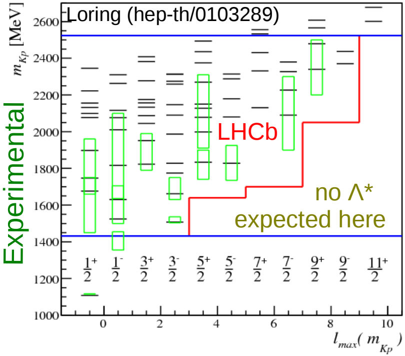
$$\langle P_l^U \rangle^k = \sum_{i=0}^{n^k_{\text{cand}}} (w_i/\epsilon_i) P_l(\cos\theta^i_{\Lambda^*})$$



- If $J_{\max}$ is the highest Λ^{*J} spin in the k^{th} m_{pK} bin, $l_{\max} = 2J_{\max}$.
- Since the Legendre polynomials P_l forms an orthonormal complete basis; $l_{\max} \to \infty$ can describe any distribution.
- Data model: hypothesis H_1 with "large" $l_{\max} = 31$.

Testing the "Λ^*-only" hypothesis H_0 1604.05708

- For a given m_{pK} bin, limit $J_{\max}$.
- High spins not expected at low Λ^* masses. $l_{\max} = 2J_{\max}$
- Higher moments can only be produced by P_c reflections.
- Λ^*-only model H_0: $l_{\max}(m_{pK})$.

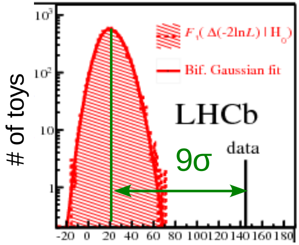


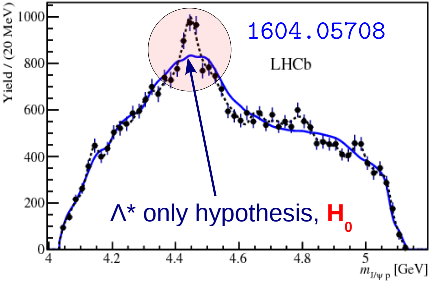
- Test statistic for compatibility check between $l_{\max} = 31$ (H_1) and $l_{\max}(m_{pK})$ (H_0), determined using toys:

$$\Delta(-2lnL) \equiv -2 \sum_{i=1}^{N_{\text{events}}} w_i \ln \left[\frac{PDF(m_{J/\psi\, p}|H_0)/I_{H_0}}{PDF(m_{J/\psi\, p}|H_1)/I_{H_1}} \right]$$

Quantitative test of the null hypothesis H_0

- Toys generated with $l_{\max}(m_{pK})$ (H_0) show a 9σ deviation wrt Data.
- Null hypothesis rejected with minimal assumption on the Λ^*'s.
- Consistent with the P_c evidence from amplitude fits.

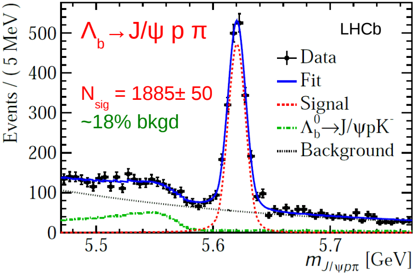


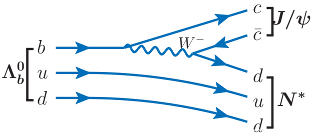


- Same analysis for $Z_c(4200)^+$ claimed by Belle in $B^0 \to J/\psi\, K^+\pi^-$ is in the pipeline.

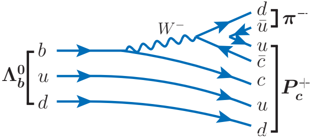
PENTAQUARKS IN $\Lambda_b^0 \to J/\psi\, p\pi^-$ (NEW!) LHCb-PAPER-2016-015

- Observation in a new mode: genuine resonances and not kinematic effects.
- Cabibbo-suppressed mode: $\times 15$ less statistics, $\times 3$ more background.
- Additional "internal" W-exchange, compared to $\Lambda_b^0 \to J/\psi\, pK^-$.

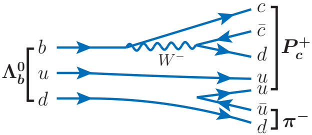




N^* resonances



"external" W ex.



"internal" W ex.

$\Lambda_b^0 \to J/\psi\, p\pi^-$: AMPLITUDE MODELS LHCb-PAPER-2016-015

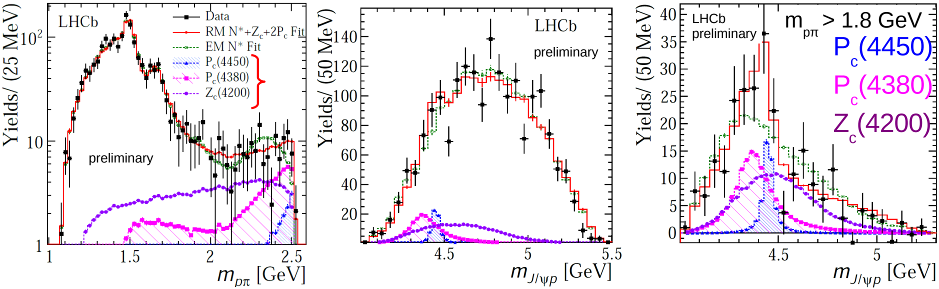
- No obvious structure in $m(J/\psi\, p)$. Need full amplitude analysis.
- Breit-Wigners for all resonances; Flatte for $N(1535)$
- Significant $p\pi$ S-wave at threshold: non-resonant component.
- Check consistency with the two P_c states from $\Lambda_b^0 \to J/\psi\, pK^-$.
- $\Lambda_b^0 \to Z_c(4200)^-(\to J/\psi\, \pi^-)p$ also considered from Belle (1408.6457).

- 15 established N^* states.
- Reduced (RM): central values. Extended (EM): syst. + signif.

State	J^P	M_0 (MeV)	Γ_0 (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
$N(2220)$	$9/2^+$	2250	400	-	-
$N(2250)$	$9/2^-$	2275	500	-	-
$N(2600)$	$11/2^-$	2600	650	-	-
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

Fit results LHCb-PAPER-2016-015

- $N^* + 2P_c + Z_c$ gives good fit. Exotic significance is 3.1σ (EM' N^*'s).



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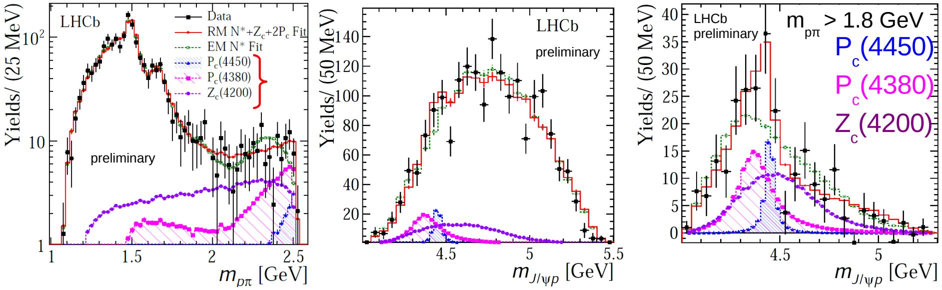
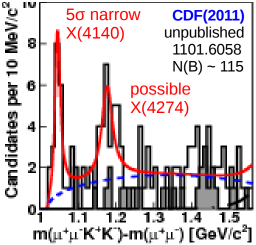
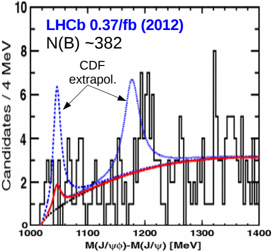


- $R_{\pi/K} \equiv \dfrac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)}$ tests P_c^+ production mechanism.
- $R_{\pi/K} \sim 0.05(4380)$, $R_{\pi/K}(4450) \sim 0.033$. Consistent w/ Cabibbo suppression (Cheng, 1509.03708): 0.07-0.08.
- Overall outlook: $J/\psi\, p\pi$ data is *consistent* with P_c's seen in $J/\psi\, pK$.

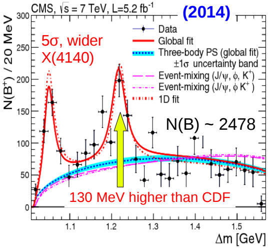
The $X(4140)$ chronology

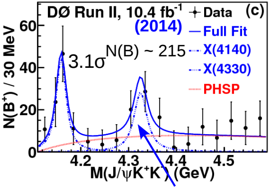


PRD 85, 091103R



PLB 734, 261



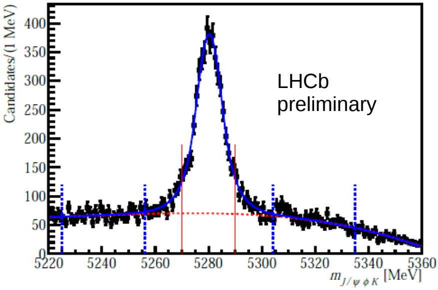


2^{nd} peak not significant

Also 4.7σ in prompt p $\bar{p}$ **(2015)**

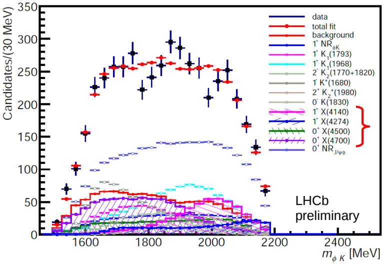
- $X(4140)$: some disagreements over the years from hadron colliders.
- Also some results from the B-factories. Not too significant, but neither in contradiction with hadron colliders.

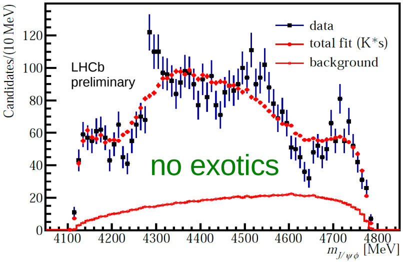
X states in 3/fb LHCb (NEW!) LHCb-Paper-2016-018



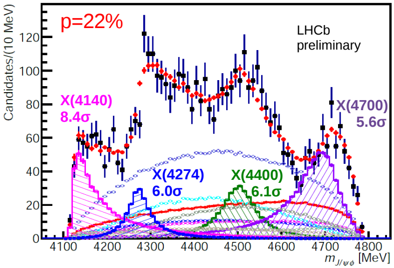
- Selection similar to 0.37/fb analysis, with some re-optimization.
- $N_{\rm sig} = 4289 \pm 151$, background fraction $23 \pm 6\%$ inside signal band.
- Largest world dataset for this mode.
- First amplitude analysis in 6d: $m_{\phi K}$ and 5 angular variables
- Three contributing amplitudes that can interfere:
  - $B^+ \to J/\psi\, K^{*+}(\to \phi K^+)$ (poorly understood K^* states)
  - $B^+ \to X(\to J/\psi\, \phi)K^+$ ("exotic" X states)
  - $B^+ \to Z_c^+(\to J/\psi\, K^+)\phi$ ("exotic" Z states)

Fit results LHCb-Paper-2016-018

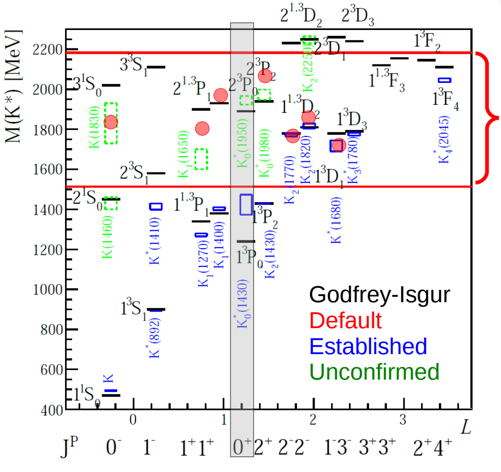




- No obvious peaking structure in $m_{\phi K}$, but rich K^* structure underneath.
- Adding $Z^+ \to J/\psi\, K^+$ doesn't have much effect. Only adding X states improves fit.



Fit results for $K^* \to \phi K$ LHCb-Paper-2016-018



- K^*: within kinematic limits, red circles are the LHCb fit results.
- 1^+: NR + 1793(1900) + 1968(1930). FF is 42%.
- 2^-: 1777(1770) + 1853(1820). FF is 11%.
- 1^-: 1717(1680). FF is 6.7%.
- 2^+: 2073(1980). FF is 2.9%.
- 0^-: consistent with unconfirmed 1874(1830). FF is 2.6%.

- Good agreement with both theory (Godfrey-Isgur) and previous experiments.

Fit results for $X \to J/\psi\,\phi$ LHCb-Paper-2016-018

- $X(4140)$ mass consistent with previous measurements. Width larger.
- $X(4274)$ mass/width consistent with unpub. CDF results.
- $X(4140)$ and $X(4274)$: $J^{PC} = 1^{++}$ determined for the 1st time. $X(4140)$ can be a possible $D_s^{\pm} D_s^{*\mp}$ "cusp" (rescattering).
- High $m_{J/\psi\,\phi}$ mass region probed for the 1st time. Dominated by 0^-. NR + new $X(4500)$ and $X(4700)$ resonances.

State	J^{PC}	signif.	Mass	Width	fit frac.
$X(4140)$	1^{++}	8.4σ	$4165 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	$13.0 \pm 3.2^{+4.8}_{-2.0}$
$X(4274)$	1^{++}	6.0σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	$7.1 \pm 2.5^{+3.5}_{-2.4}$
$X(4500)$	0^{++}	6.1σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	$6.6 \pm 2.4^{+2.5}_{-2.3}$
$X(4700)$	0^{++}	6.1σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	$12 \pm 5^{+9}_{-5}$

INTERPRETATIONS ALREADY...

postdiction: 1606.03179

Understanding the internal structures of the $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$

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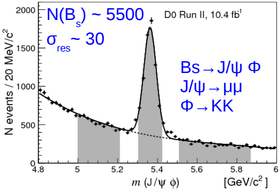
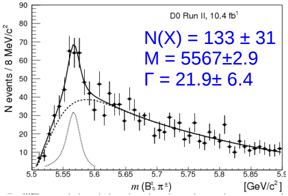
[2]*Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, Saskatchewan, S7N 5E2, Canada*
[3]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[4]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[5]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[6]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[7]*Center of High Energy Physics, Peking University, Beijing 100871, China*

We investigate the newly observed $X(4500)$ and $X(4700)$ based on the diquark-antidiquark configuration within the framework of QCD sum rules. Both of them may be interpreted as the D-wave $cs\bar{c}\bar{s}$ tetraquark states of $J^P = 0^+$, but with opposite color structures, which is remarkably similar to the result obtained in Ref. [1] that the $X(4140)$ and $X(4274)$ can be both interpreted as the S-wave $cs\bar{c}\bar{s}$ tetraquark states of $J^P = 1^+$, also with opposite color structures. However, the extracted masses and these suggested assignments to these X states do depend on these running quark masses where $m_s(2\text{ GeV}) = 95 \pm 5$ MeV and $m_c(m_c) = 1.23 \pm 0.09$ GeV. As a byproduct, the masses of the hidden-bottom partner states of the $X(4500)$ and $X(4700)$ are extracted to be both around 10.64 GeV, which can be searched for in the $\Upsilon\phi$ invariant mass distribution.

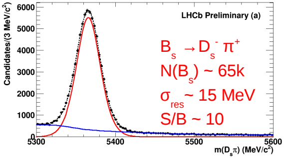
D0 CLAIM OF $X(5568)^{\pm} \to B_s\pi^{\pm}$ 1602.07588

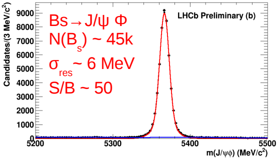
- D0: 5 σ evidence for new "4-flavored" $(\bar{b}su\bar{d})$ exotic $X(5568)$.
- Fraction of B_s's from X decay: $\rho_X^{\rm D0} = (8.6 \pm 1.9 \pm 1.4)\%$





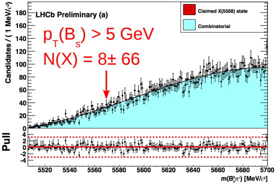
- LHCb should see this. Large and clean samples.

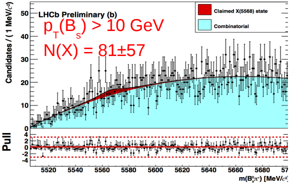




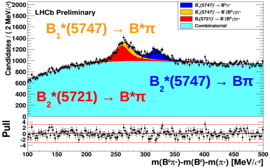
LHCb $X(5568)$ non-confirmation LHCb-CONF-2016-004

- B_s and π from the same PV. Mass-constrained $\{B_s, D_s, J/\psi\}$.
- No significant signal seen in full Run I. $\rho_X^{\rm LHCb} < 0.018$ @ 95% CL





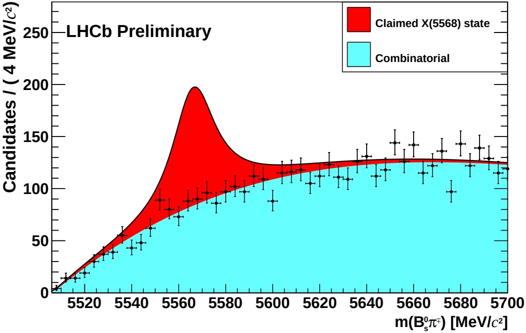
- Checks done in bins of rapidity. Expected B^{**} structures seen w/ similar analysis chain for B^0.



- D0 structure remains yet to be confirmed by another experiment.

LHCb $X(5568)$ non-confirmation LHCb-CONF-2016-004

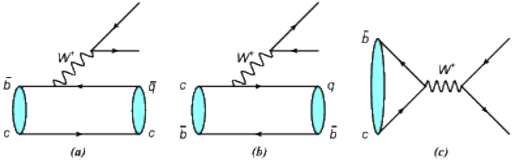
- Expected signal if 8.6% of B_s's came from $X(5568)$:



B_c^+ physics @ LHCb

- Lowest bound state of $\bar{b}$ and c quarks. Unlike $\bar{b}b$, $\bar{c}c$; decays *only* weakly. Unique, flavor asymmetry: t is too heavy.

- Either the $\bar{b}$ or c can decay:
  (a) $\bar{b} \to cW^+$: $J/\psi\,\ell^+\nu$, $J/\psi\,\pi^+$
  (b) $c \to sW^+$: $B_s\ell^+\nu$, $B_s\pi^+$
  (c) Weak annihilation (WA), $\bar{b}c \to W^+$: $\tau^+\nu_\tau$, $\bar{K}^{*0}K^+$



- Experimentally, $b \to c$ is clearer (due to the J/ψ) but Cabibbo suppressed.

- $c \to s$ is challenging but Cabibbo favored ($\mathcal{B} \sim 70\%$). First seen in $B_c^+ \to B_s^0\pi^+$ by LHCb (1308.4544)

- WA is sensitive to H^+. CF over B^+ by $|\frac{V_{cb}}{V_{ub}}|^2 \sim 100$

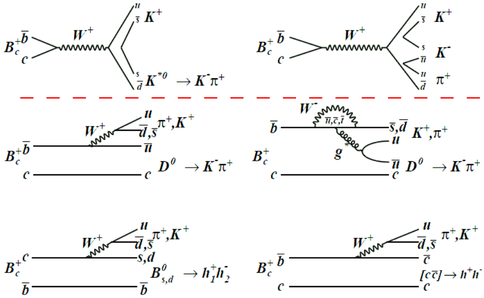
B_c^+ physics @ LHCb

- LHCb results dominate many of the measurements, including the world's best measurements on B_c^+ mass and lifetime.

Physics	mode	$\mathcal{L}$ (fb^{-1})
Production, Mass	$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}{\sigma(B^+)\mathcal{B}(B^+\to J/\psi\,K^+)}$	0.37 PRL 109 232001, 2 PRL 114 132001
Production	$\frac{\sigma(B_c^+)}{\sigma(B^+)}\mathcal{B}(B_c^+ \to B_s^0\pi^+)$	3 PRL 111 181801
Production	$\frac{\mathcal{B}(B_c^+\to\psi(2S)\pi^+)}{\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}$	1 PRD 87 071103, 3 PRD 92 072007
Decay, Mass	$B_c^+ \to J/\psi\, D_s^{(*)+}$	3 PRD 87 112012
Decay, Mass	$B_c^+ \to J/\psi\, p\bar{p}\pi^+$	3 PRL 113 152003
Decay	$B_c^+ \to J/\psi\,\pi^+\pi^-\pi^+$	0.8 PRL 108 251802
Decay	$B_c^+ \to J/\psi\, K^+$	1 JHEP 09 075
Decay	$B_c^+ \to J/\psi\, K^+K^-\pi^+$	3 JHEP 11 094
Decay	$B_c^+ \to J/\psi\, 3\pi^+3\pi^-$	3 JHEP05(2014)148
Decay	$\frac{\mathcal{B}(B_c^+\to J/\psi\,\pi^+)}{\mathcal{B}(B_c^+\to J/\psi\,\mu^+\nu_\mu)}$	1 PRD 90 032009
Lifetime	$B_c^+ \to J/\psi\,\mu^+\nu_\mu$	2 EPJC, 74 2839
Lifetime	$B_c^+ \to J/\psi\,\pi^+$	3 PLB 742 29-37

WA studies via charmless $B_c \to h^+ h^- h'$

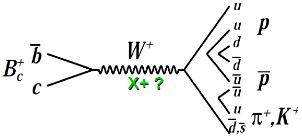
- B_c decays to charmless states proceeds only via $\bar{b}c \to W^+ \to u\{d, s\}$. $|V_{ud}| > |V_{us}|$ implies $\Delta S = 0$ dominates over $\Delta S = 1$.
- LHCb is studying $B_c \to \{KKK, \pi\pi\pi, KK\pi, p\bar{p}K, p\bar{p}\pi\}$.
- Large available phase-space!
- Intermediate D^0, $B_{s,d}$ and $c\bar{c}$ also contribute.



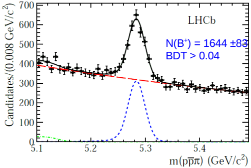
- Some theory (0907.2256) estimates for (quasi) 2-body decays. $\mathcal{B} < 10^{-6}$. Expect few events in Run I.
- Utlimately, Dalitz analysis, $\mathcal{A}_{CP}$, ...

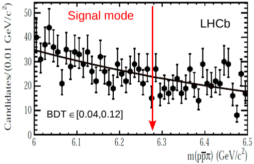
Search for $B_c^+ \to p\bar{p}\pi^+$ (NEW!) LHCb-PAPER-2016-001

- $m(p\bar{p}) < 2.85$ GeV: near-threshold $p\bar{p}$ production expected. Also $[2.85, 3.15]$ GeV for the J/ψ region.



- Measured $R_p \equiv \frac{f_c}{f_u} \times \mathcal{B}(B_c^+ \to p\bar{p}\pi^+)$, with $B^+ \to p\bar{p}\pi^+$ as norm. mode
- No signal detected. UL's for 95% CL set as: $R_p < 3.6 \times 10^{-8}$ and $R_p^{J/\psi} < 8.4 \times 10^{-6}$.
- Compatible with LHCb $\mathcal{B}(B_c^+ \to J/\psi\,\pi^+)$. Hoping for some signal with Run II data.
- $B_c^+ \to K^+K^-\pi^+$ in the immediate pipeline.





Summary: exotics @ LHCb

- $\Lambda_b^0 \to J/\psi\, pK^-$: "model-independent" approach confirms Λ^* reflections can't explain data. Exotics present.
- $\Lambda_b^0 \to J/\psi\, p\pi^-$: P_c's consistent with the $J/\psi\, pK^-$ mode. $R_{\pi/K}$ consistent with Cabibbo suppression.
- $X \to J/\psi\, \phi$: confirms 1^+ for $X(4140)$ and $X(4274)$. $X(4140)$ width larger than CDF. Two new high-mass 0^+ resonances.
- LHCb does *not* confirm D0 $X(5568)$. Inputs from ATLAS/CMS?

Summary: B_c^+ physics @ LHCb

- LHCb has performed many measurements in B_c^+ physics in Run I
- Most precise mass and lifetime measurements.
- Many decay modes observed: $J/\psi\,3\pi$, $J/\psi\,K^-$, $\psi(2s)\pi$, $J/\psi\,D_s^{(*)+}$, $J/\psi\,2K\pi$, $J/\psi\,3\pi 2\pi$, $B_s\pi$, ...
- New modes being investigated, especially charmless weak annihilation types.
- Searches for excited B_c states ongoing as well.

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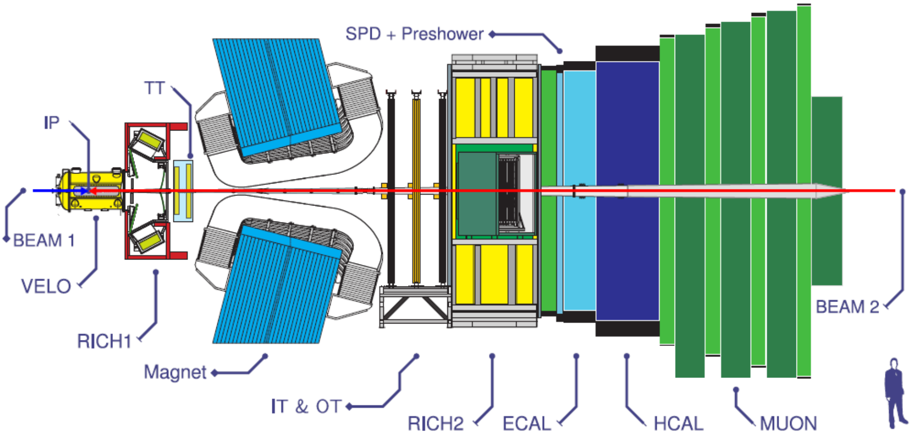
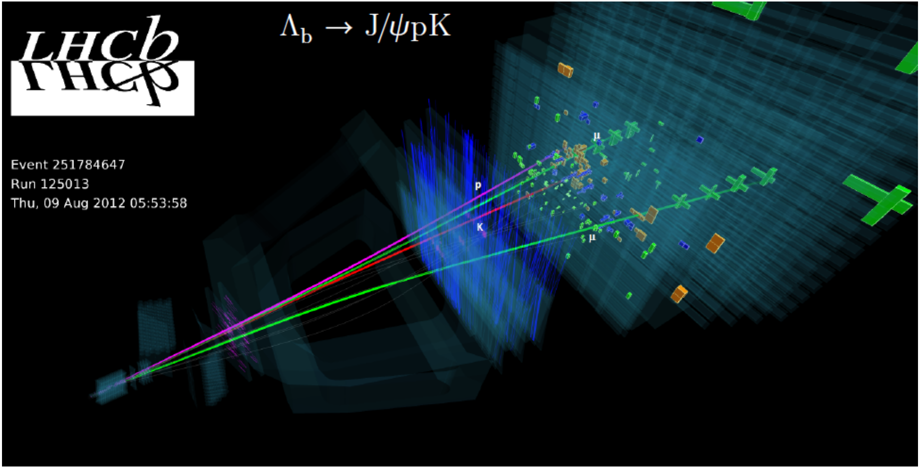
$\times 5$ statistics after Run II (end-2018). Much more data coming!.

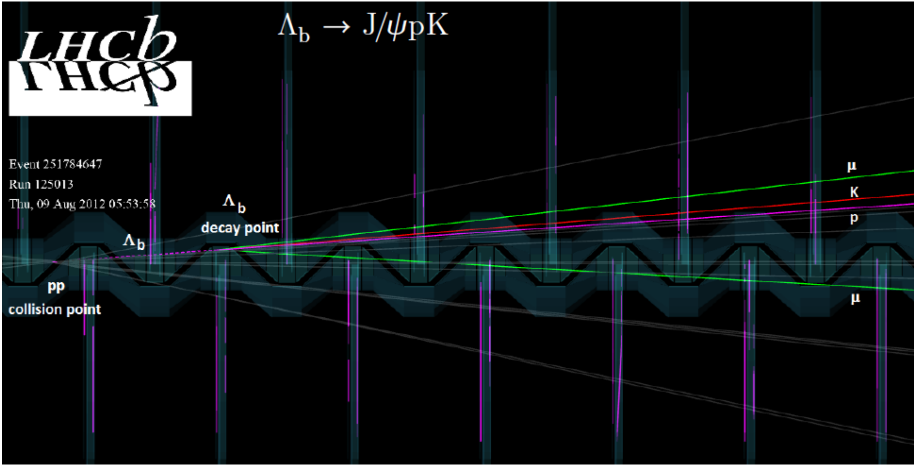
The LHCb Detector components



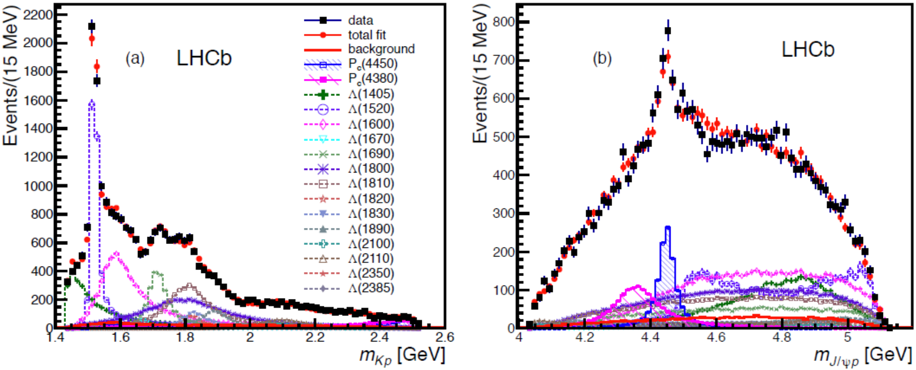
A $\Lambda_b^0 \to J/\psi\, pK^-$ EVENT



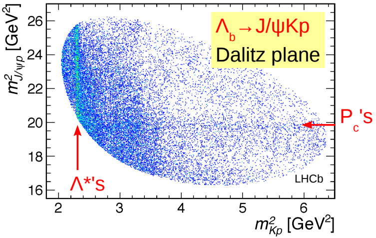
A $\Lambda_b^0 \to J/\psi pK^-$ event in the VeLo

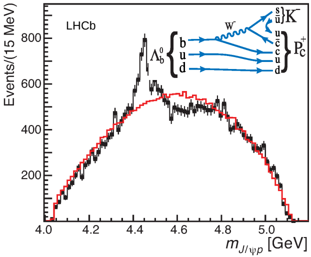


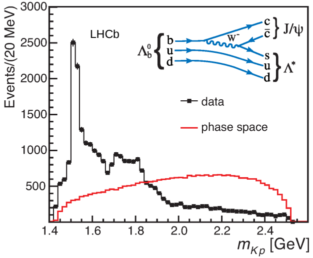
The LHCb Detector components



PENTAQUARKS IN $\Lambda_b^0 \to J/\psi\, pK^-$ PRL 115, 072001

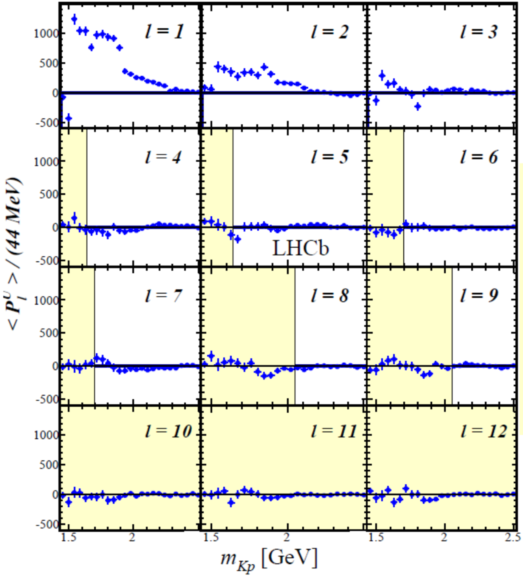






- Original goal was precise measurement of the Λ_b^0 lifetime (PRL 111 102003)
- Unexpected structure seen in $m(J/\psi\, p)$.
- Λ^* reflections or true resonance(s)?

The extracted moments in the data



filter out maximum spin depending depending on m_{Kp} bin

$\Lambda_b^0 \to J/\psi\, p\pi^-$: N^* resonance models LHCb-PAPER-2016-015

- $N(1535)$ is a Flatte for $n\eta$ opening
- All others are Breit-Wigners with masses and widths fixed to PDG (varied in systematic studies).
- NR S-wave $p\pi^-$ for threshold enhancement. $1/m^2$ mass-dependence.
- K-matrix model for $\frac{1}{2}^-$ S-wave from Bonn-Gatchina (1112.4937).
- $\Lambda_b^0 \to J/\psi\, \Delta^*(\to p\pi^-)$ is isospin violating and supressed is $[ud]$ in Λ_b^0 is spectator $I = 0$ diquark. Not considered.

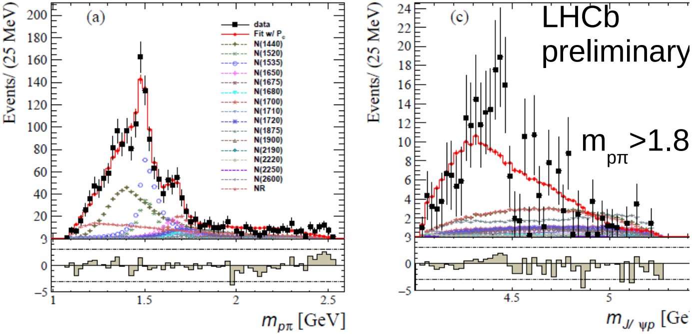
- 15 N^* states.
- Reduced (RM): central values. Extended (EM): syst. + signif.

State	J^P	M_0 (MeV)	Γ_0 (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
$N(2220)$	$9/2^+$	2250	400	-	-
$N(2250)$	$9/2^-$	2275	500	-	-
$N(2600)$	$11/2^-$	2600	650	-	-
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

$\Lambda_b^0 \to J/\psi\, p\pi^-$: RESONANCE MODELS LHCb-PAPER-2016-015

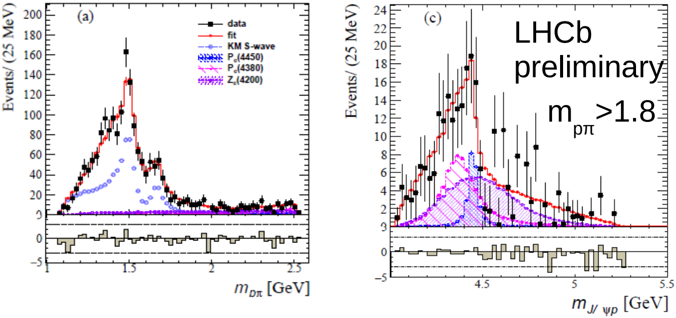
- Each N^* has 4(6) individual LS coupling for spin 1/2(higher)
- "Extended Model": all 15 3-star and 4-star resonances and maximal LS couplings. Used for quoting minimum significances and systematics.
- "Reduced model": 6 well-established N^*'s and L's that are significant. Used for nominal results.
- P_c and $Z_c(4200)$: mass, widths and couplings to $J/\psi\, p / J/\psi\, \pi$ fixed from previous higher statistics analyses.
- $Z_c(4300)$: only 0.6σ significant and goes into systematics.

$\Lambda_b^0 \to J/\psi\, p\pi^-$: only N^* states LHCb-PAPER-2016-015



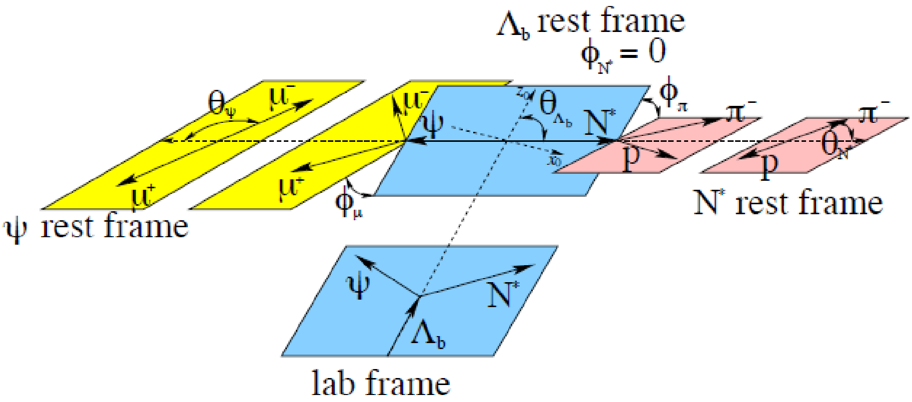
- Extended model, only N^* states.
- 6.6σ exotic significance if only established states are used.

$\Lambda_b^0 \to J/\psi\, p\pi^-$: K-matrix S-wave LHCb-PAPER-2016-015

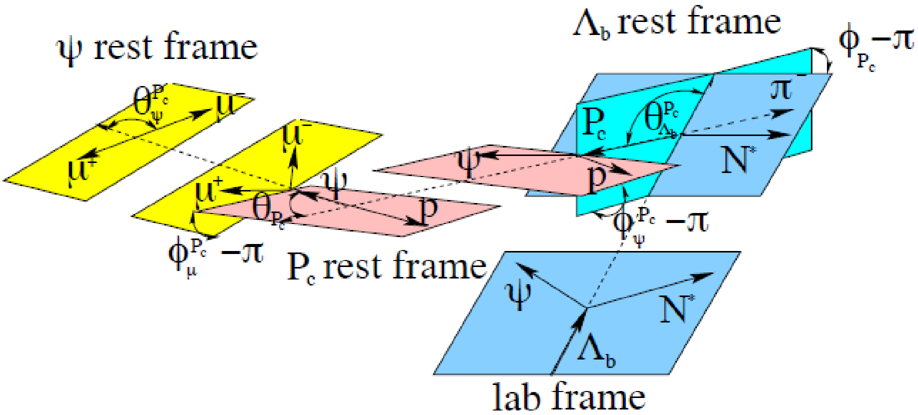


- Instead of isobar model, K-matrix model for the dominant S-wave from Bonn-Gatchina.
- Conclusions invariant on significances. Goes into systematics.

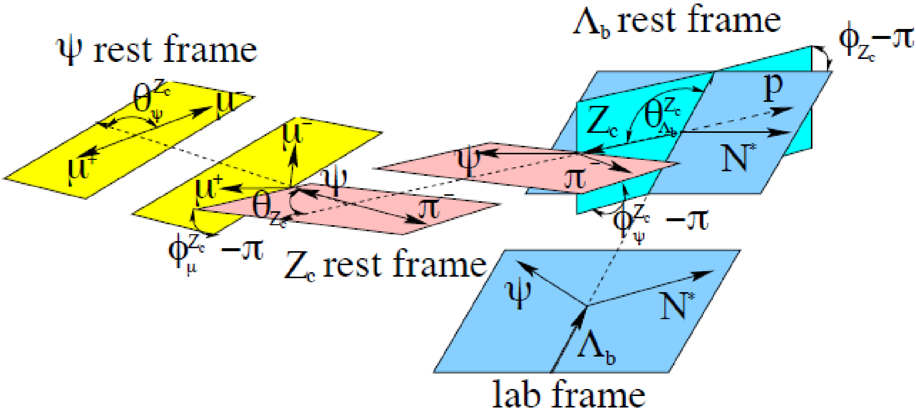
$\Lambda_b^0 \to J/\psi\, p\pi^-$: N^* angles LHCb-PAPER-2016-015



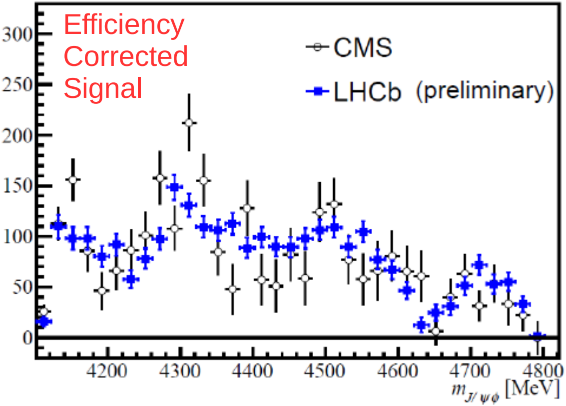
$\Lambda_b^0 \to J/\psi\, p\pi^-$: P_c^+ ANGLES LHCb-PAPER-2016-015



$\Lambda_b^0 \to J/\psi\, p\pi^-$: Z_c^- ANGLES LHCb-PAPER-2016-015



$\Lambda_b^0 \to J/\psi\, p\pi^-$: Z_c^- ANGLES LHCb-PAPER-2016-015

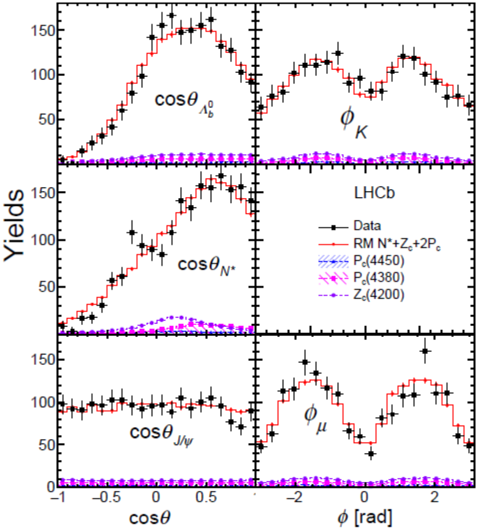


$\Lambda_b^0 \to J/\psi\, p\pi^-$: Fit fractions LHCb-PAPER-2016-015

Fit fraction in percentage for the fits with the RMN^*

Components	$N^* + 2P_c + Z_c$	$N^* + Z_c$	$N^* + 2P_c$
$N(1440)$	34.0 ± 4.9	33.3 ± 5.0	30.9 ± 4.6
$N(1520)$	7.6 ± 2.2	4.7 ± 2.0	5.3 ± 2.0
$N(1535)$	25.4 ± 5.9	31.5 ± 6.4	29.4 ± 5.6
$N(1650)$	10.5 ± 5.1	11.5 ± 4.7	12.3 ± 4.3
$N(1675)$	$3.4^{+2.2}_{-1.0}$	4.3 ± 1.7	$2.3^{+2.0}_{-0.8}$
$N(1720)$	$3.9^{+1.8}_{-1.3}$	6.3 ± 2.3	$3.7^{+2.4}_{-0.9}$
NR $p\pi$	18.6 ± 3.2	17.6 ± 3.5	19.6 ± 3.2
$P_c(4380)$	5.1 ± 1.5	-	6.7 ± 1.4
$P_c(4450)$	$1.6^{+0.8}_{-0.6}$	-	$1.5^{+0.8}_{-0.5}$
$Z_c(4200)$	7.7 ± 2.8	17.2 ± 3.5	-

$\Lambda_b^0 \to J/\psi\, p\pi^-$: FIT QUALITY LHCb-PAPER-2016-015

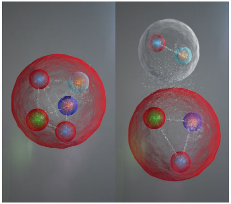


$\Lambda_b^0 \to J/\psi\, p\pi^-$: SIGNIFICANCES LHCb-PAPER-2016-015

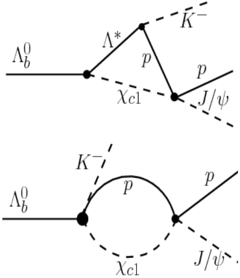
State	$N^* + 2P_c$		$N^* + 2P_c + Z_c$	
	EM	EM'	EM	EM'
Z_c	-	-	1.8	0.4
$P_c(4380)$	5.0	2.4	0.0	1.4
$P_c(4450)$	1.2	1.5	1.6	1.7
$2P_c$	6.7	3.3	2.5	0.9
$2P_c + Z_c$	-	-	6.6	3.1

- EM': includes two high mass, low-spin N^* states observed by BES III (PRL 110 (2013), 022001), but excludes spin $> 9/2$, which are suppressed at high $m_{p\pi}$.

Pentaquark interpretations and outlook



- Tightly bound quarks? Colored diquark-triquark (Lebed), colored diquark+anti-quark (Maiani).
- Meson-baryon molecules with meson-exchange binding? Karliner-Rosner: narrow $P_c(4450)$ very close to $\Sigma_c \bar{D}^*$.

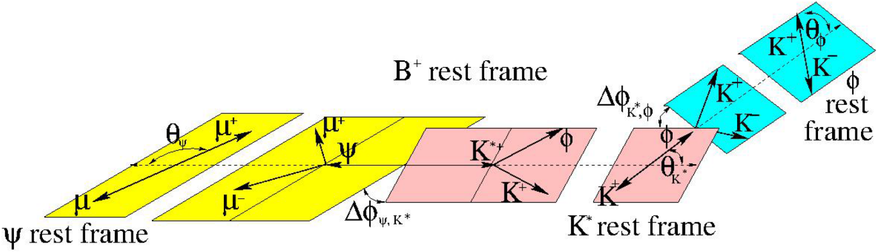


- Rescattering effects: $P_c(4450)$ just above $[\chi_{c1} p]$ threshold (Guo).
- Reproduces phase-motion of $P_c(4450)$, but what about $P_c(4380)$?

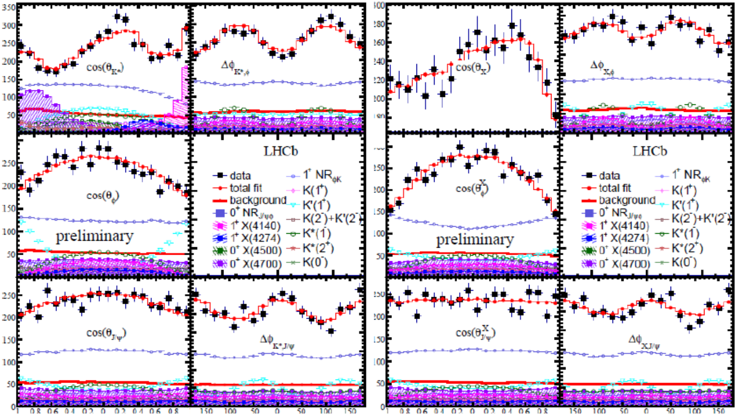
Pentaquark outlook (cntd.)

- Experimental program: new decay modes and production mechanisms. Confirmation by other experiments. Where are the ground states?
- Different final states: $\Upsilon \to J/\psi\, p\bar{p}$, $B^0 \to J/\psi\, p\bar{p}$, $\Lambda_b^0 \to J/\psi\, p\pi K_S^0$.
- New open-charm and charmless decay modes of P_c:
  $\Lambda_b^0 \to \chi_{c1}(1P) pK$, $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$, $\Lambda_b^0 \to \Sigma_c^+ D^0 K^-$
- Pentaquark multiplets: $\Lambda_b^0 \to J/\psi\, p\pi K_S^0$. $\Lambda_b^0 \to J/\psi\, \Lambda\phi$

$B^+ \to J/\psi\,\phi K^+$ ANGLES

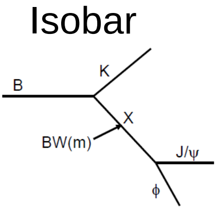


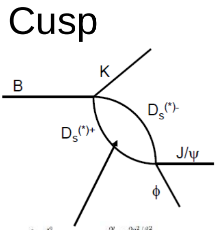
$B^+ \to J/\psi \phi K^+$ fit quality in the angles



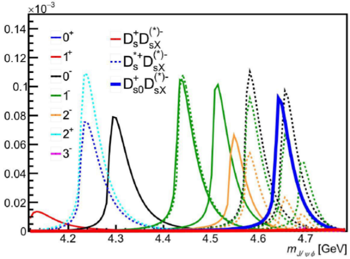
$B^+ \to J/\psi\,\phi K^+$: CUSPS

- Opening of threshold, not necessary bound molecular states can cause "peaking"-like structures.
- Coupled-channel cusp models, Swanson: 1504.07952, 1409.3291. Internal $L = 0$, so





$$\Pi(m) = \int \frac{d^3q}{(2\pi)^3} \frac{q^{2l}\, e^{-2q^2/\beta_{AB}^2}}{m - M_A - M_B - \frac{q^2}{2\mu_{AB}} + i\,\epsilon}$$



K^{*+} summary for $B^+ \to J/\psi\,\phi K^+$

- Robust tapestry of K^* states from amplitude analysis
- 1^+: dominant, w/ $K_1(1650)$ at 7.6σ.
- 2^-: two resonances consistent w/ $K_2(1770)$ and $K_2(1820)$
- 1^-: First observation of $K^*(1680) \to \phi K$
- 2^+: 5.4σ evidence for a broad resonance consistent w/ $K^*(1980)$
- 0^-: 3.5σ evidence for the earlier observed $K_0^*(1830)$