

LHCb RESULTS ON EXOTICS AND PENTAQUARK STATES

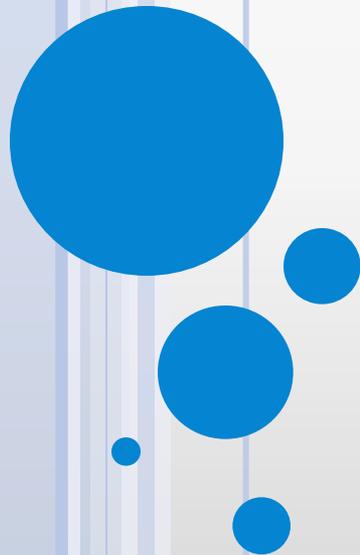
Marco Pappagallo

University of Bari & INFN

on behalf of LHCb collaboration

QCD@Work

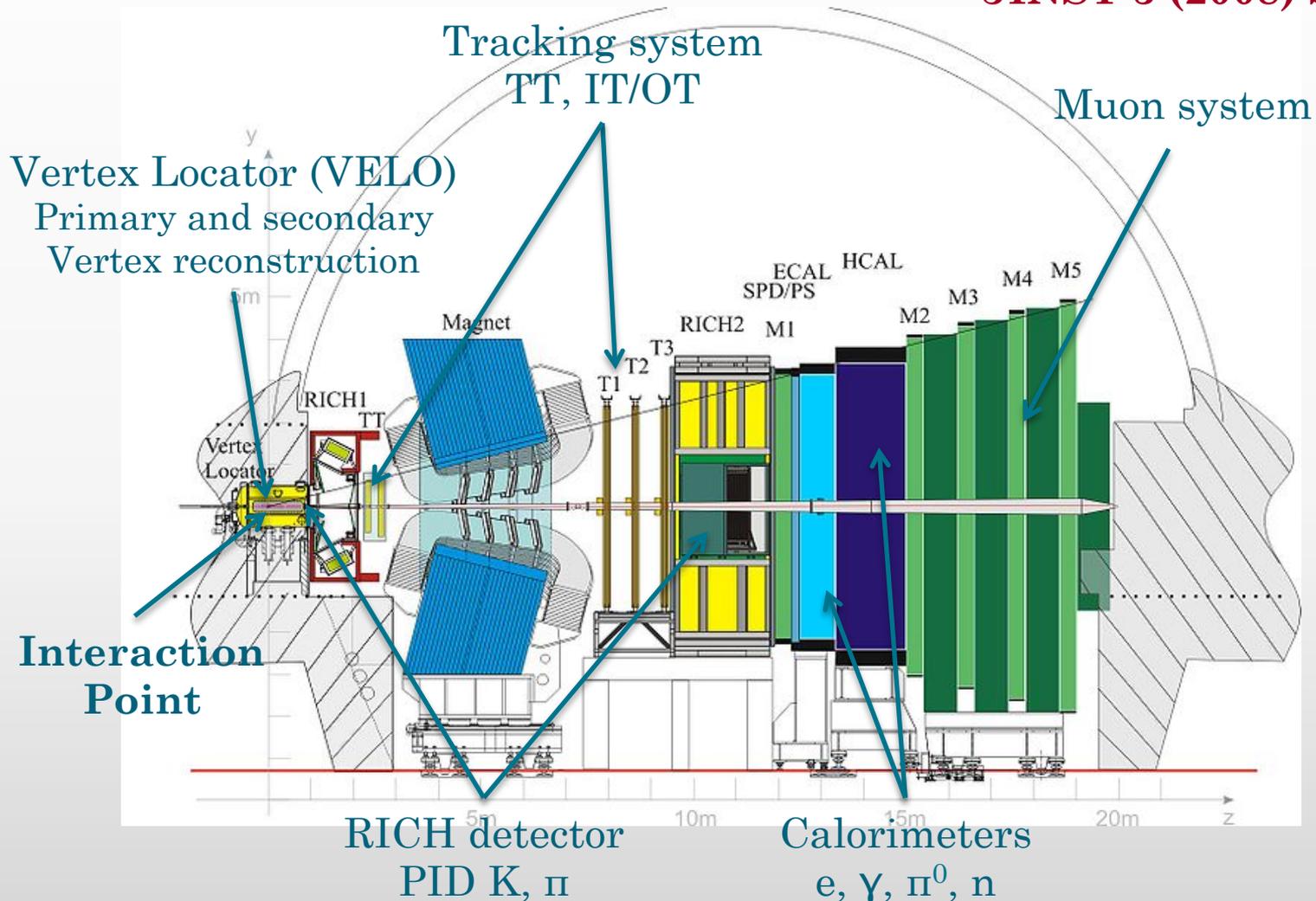
27-30 June 2016, Martina Franca, Italy



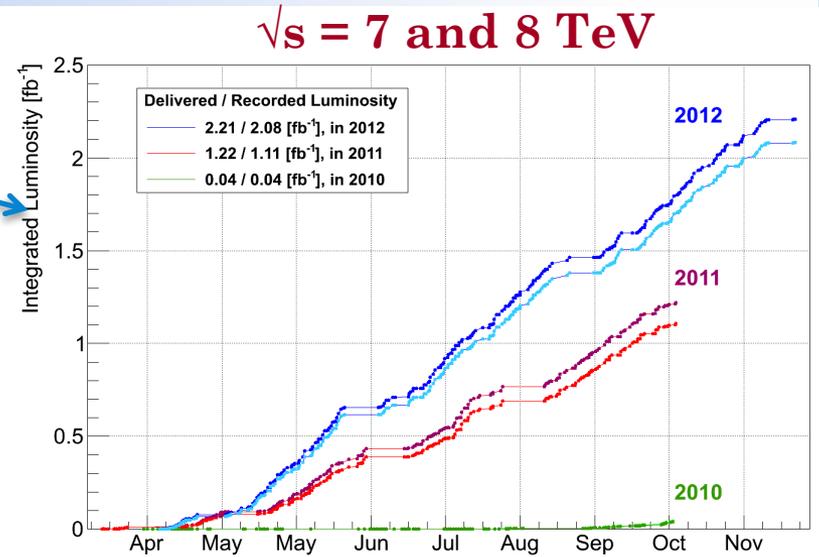
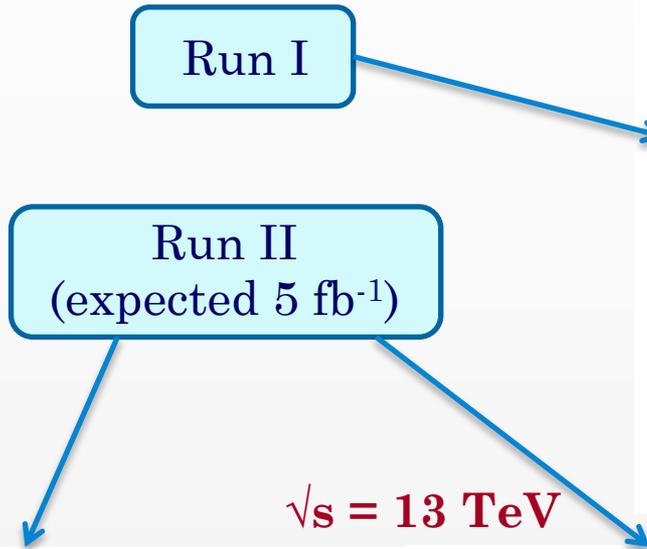
- LHCb Experiment
- Search for Pentaquarks $P_c^+ \rightarrow J/\psi p$
 - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p K^-$ Decays
 - Model Independent Analysis of $\Lambda_b \rightarrow J/\psi p K^-$ Decays
 - Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p \pi^-$ Decays
- Search for a tetraquark $X(5568)^\pm \rightarrow B_s \pi^\pm$
- Amplitude Analysis of $B^+ \rightarrow J/\psi \phi K^+$ Decays

THE LHCb DETECTOR

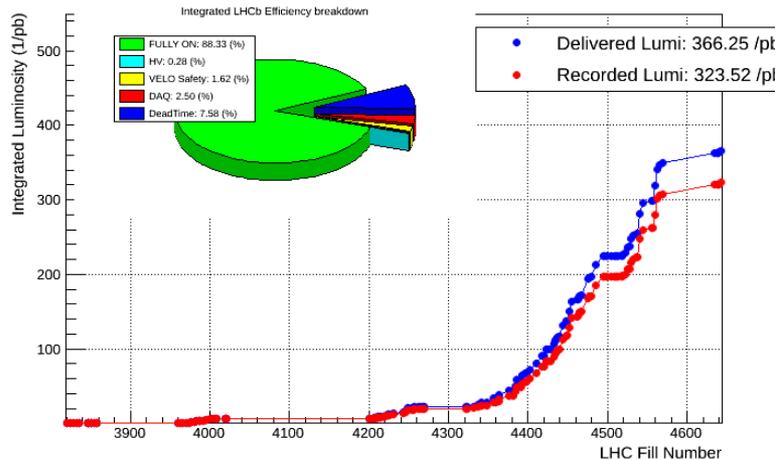
JINST 3 (2008) S08005



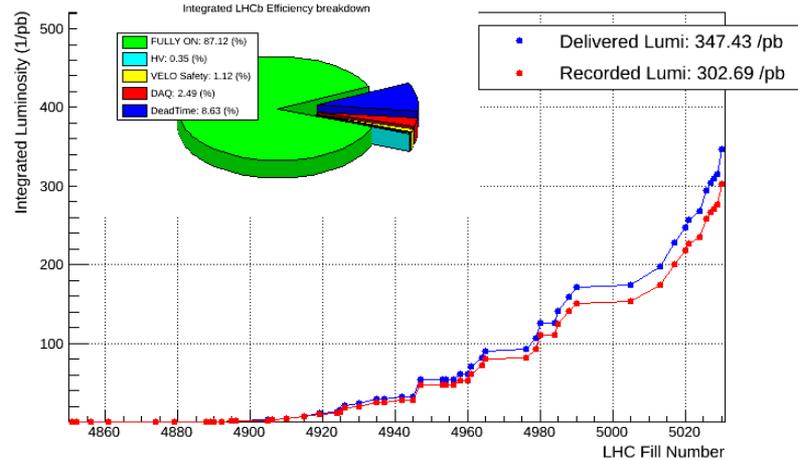
DATASET

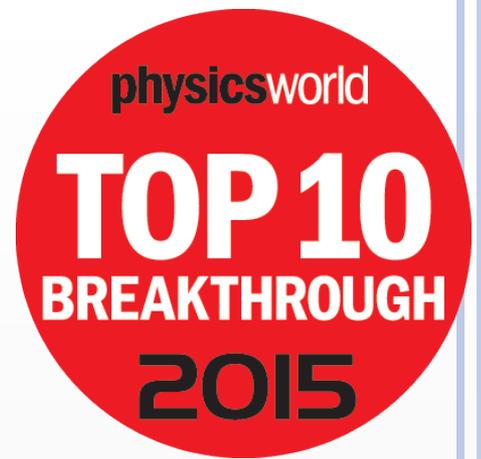


LHCb Integrated Luminosity at p-p in 2015



LHCb Integrated Luminosity at p-p in 2016





Observation of J/ψ p resonances consistent with pentaquark states in $\Lambda_b \rightarrow J/\psi$ p K^- decays

[LHCb: PRL 111 (2013) 102003]

FIRST OBSERVATION OF $\Lambda_b \rightarrow J/\psi K^- p$

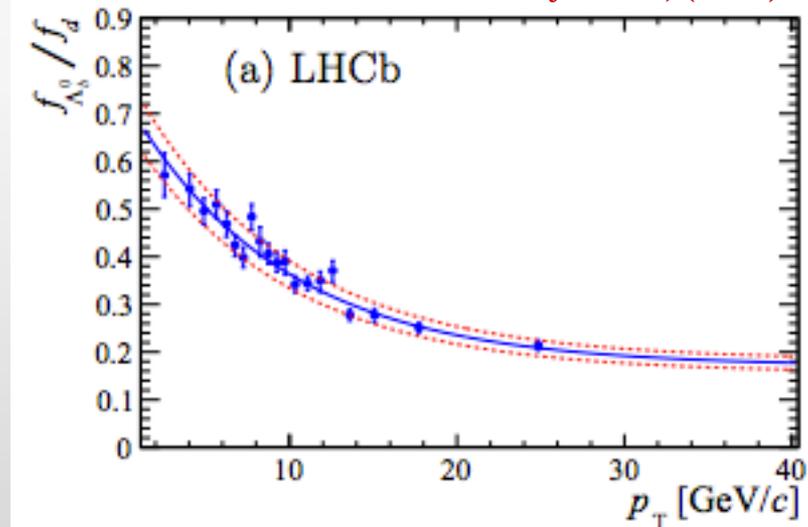
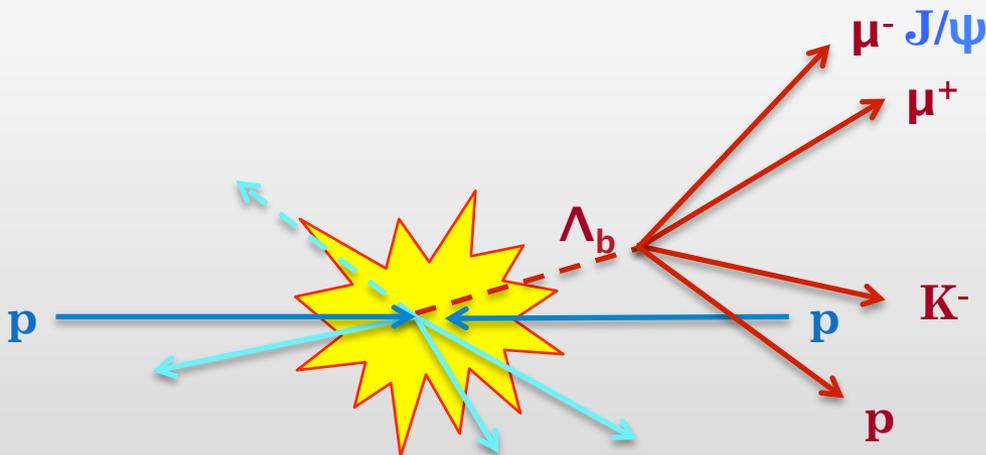
[LHCb: PRL 111 (2013) 102003]

Why did LHCb arrive first? The decay was not observed before!

- ✓ $J/\psi \rightarrow$ Large trigger efficiency
- ✓ 4 Tracks \rightarrow Large detection efficiency
- ✓ Large Λ_b production

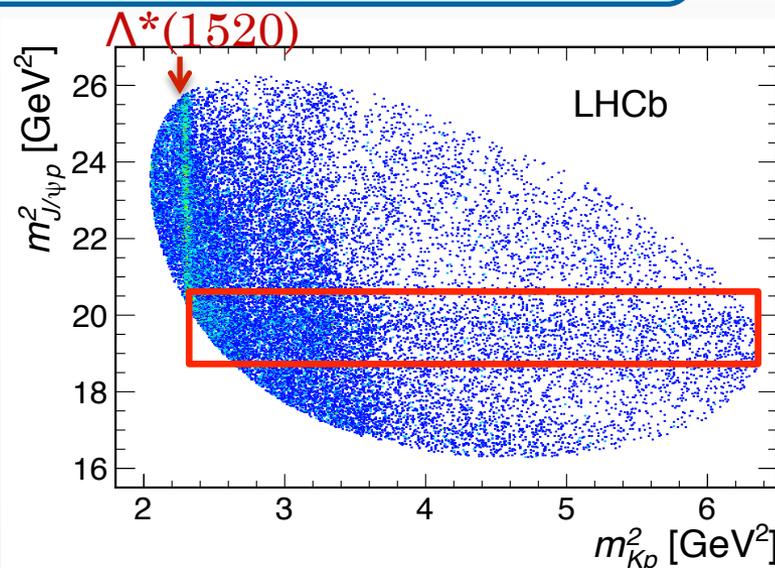
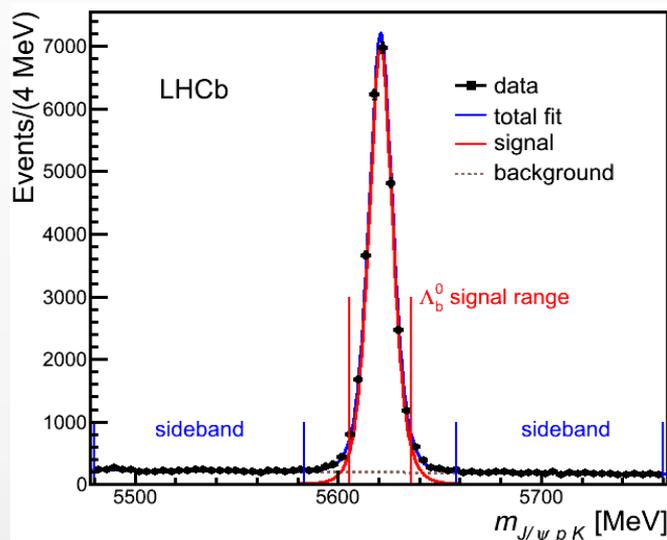
LHCb: JHEP 08(2014)143

LHCb: Chin. Phys. C40, (2016) 011001



OBSERVATION OF A NARROW BAND IN THE Λ_b DALITZ PLANE

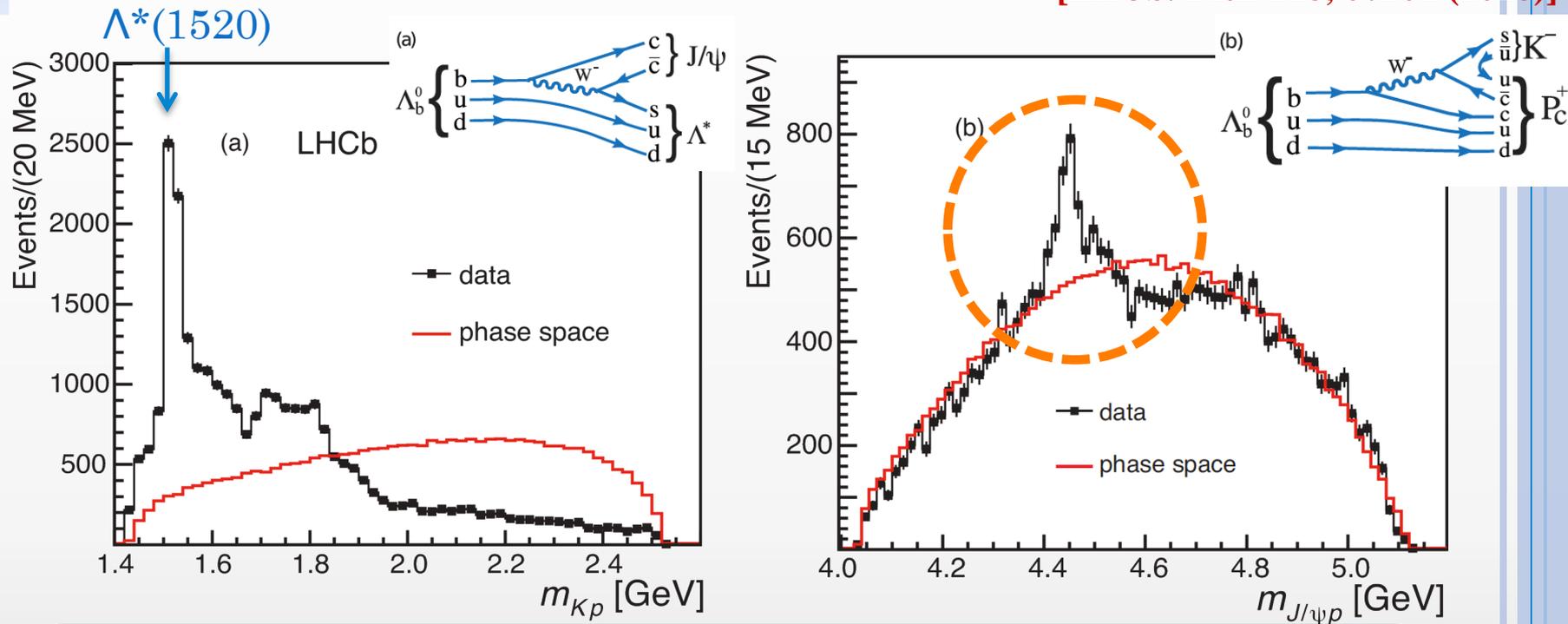
Selection updated with the full Run I dataset (3fb^{-1})
26k Λ_b^0 candidates. Background $\sim 5.4\%$



- Efficiency flat over the “Dalitz” plot
- Cross checks:
 - ✓ Veto $B_s \rightarrow J/\psi KK$ & $B^0 \rightarrow J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters: $p \leftrightarrow K$ or $p \leftrightarrow \pi$
 - ✓ Clone and ghost tracks carefully removed
 - ✓ Not a partially reconstructed Ξ_b decay

UNEXPECTED NARROW PEAK IN $m(J/\psi p)$

[LHCb: PRL 115, 07201 (2015)]

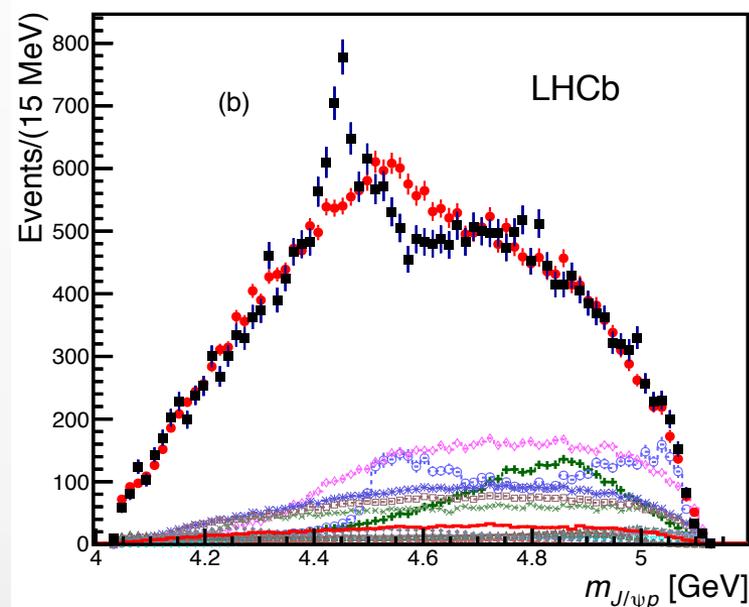
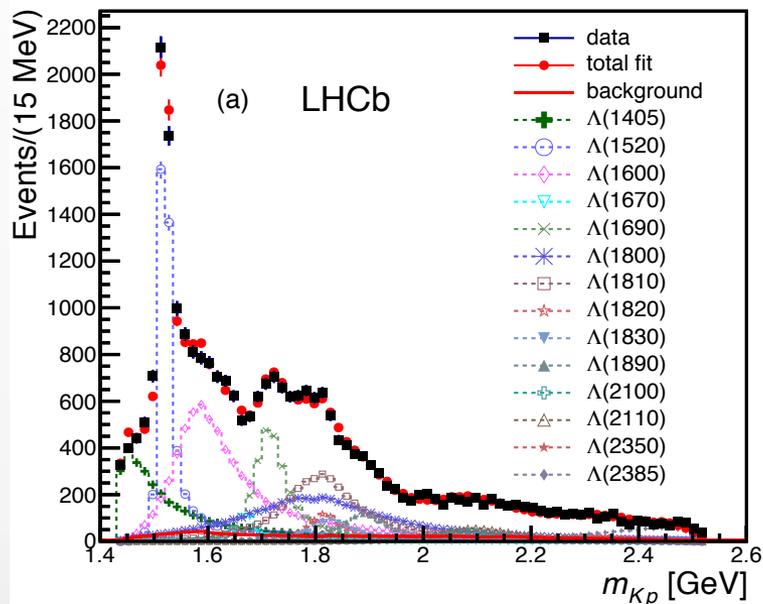


- A lot of structures in $m(pK^-)$!
- Could it be a reflection of the interfering Λ^* 's \rightarrow pK^- ?

6D Amplitude analysis

FIT WITH $\Lambda^* \rightarrow pK$ STATES ONLY

[LHCb: PRL 115, 07201 (2015)]



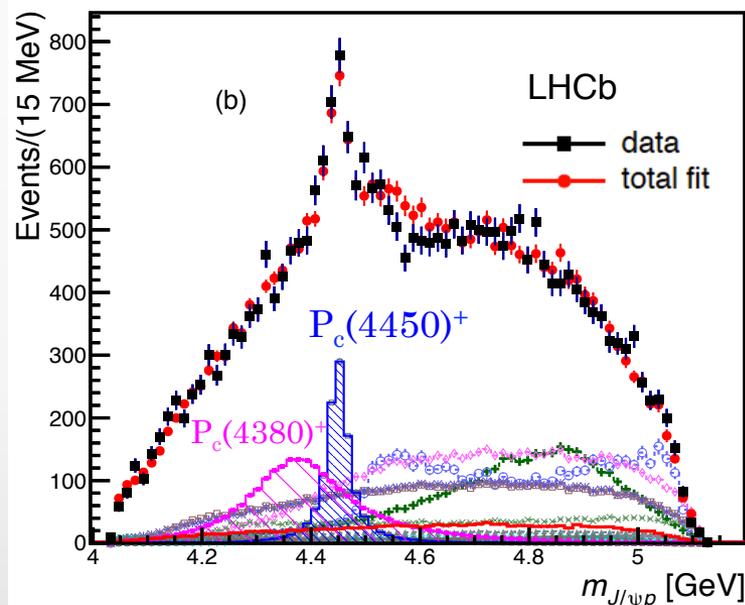
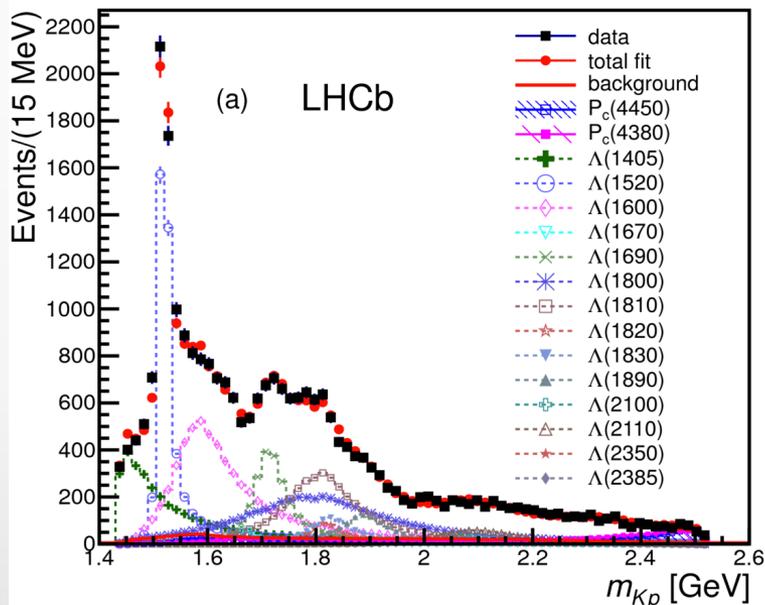
Use of extended model, so all possible known Λ^* amplitudes:
 m_{Kp} projection looks fine, but the fit projection can't reproduce the
 peaking structure in $J/\psi p$

ADDING $P_c \rightarrow J/\psi p$ AMPLITUDES

[LHCb: PRL 115, 07201 (2015)]

Reduced Λ^* model + 2 states decaying to $J/\psi p$

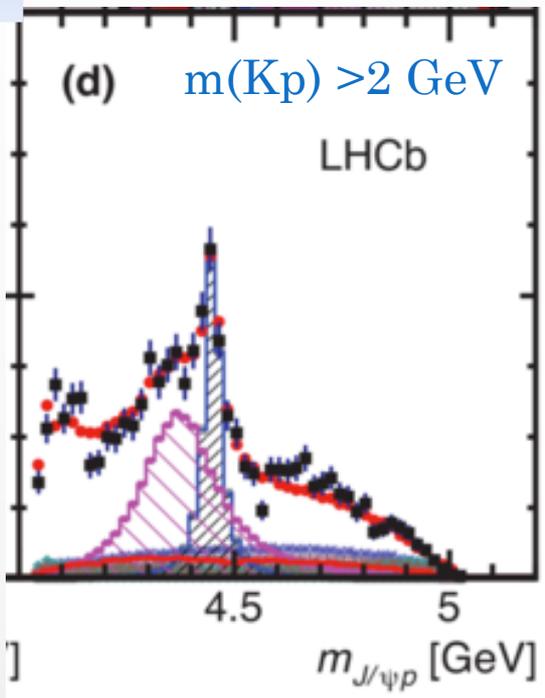
Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred



State	Mass (MeV)	Width (MeV)	Fit fraction (%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$

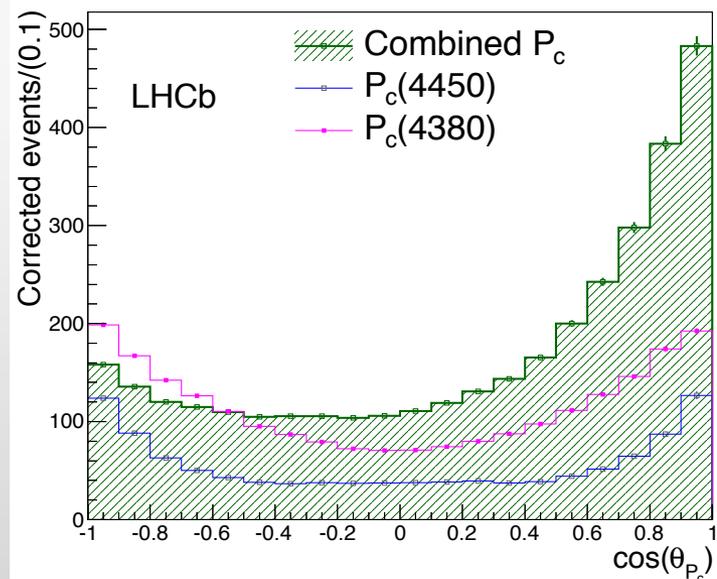
DO WE REALLY NEED 2 P_c^+ 'S? YES

[LHCb: PRL 115, 07201 (2015)]



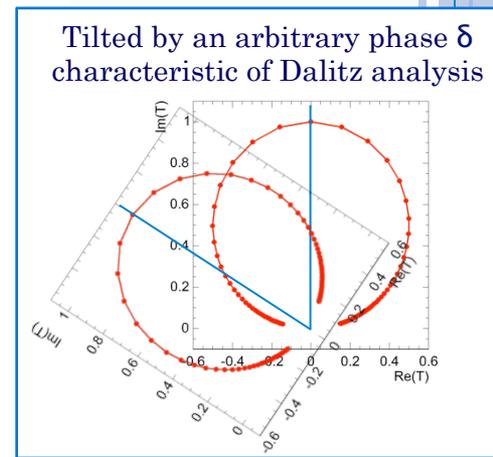
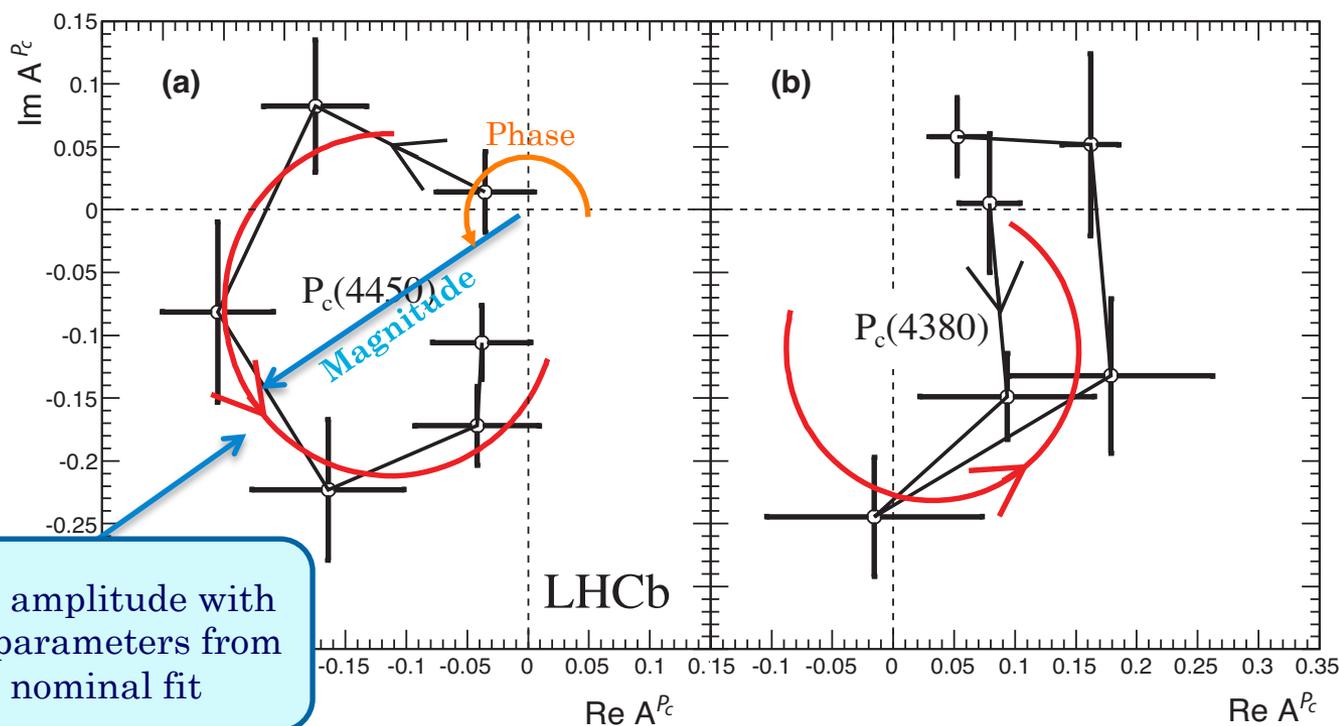
Clear need for the 2nd broad P_c^+ where the $\Lambda^* \rightarrow pK^-$ contribution is the smallest

Evidence of an interference pattern in the angular distribution



ARGARD DIAGRAMS

[LHCb: PRL 115, 07201 (2015)]



BW amplitude with P_c^+ parameters from nominal fit

- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive

Model-independent evidence for J/ψ p contributions to $\Lambda_b \rightarrow J/\psi$ p K^- decays

[LHCb: arXiv:1604.05708]

MODEL INDEPENDENT ANALYSIS

[LHCb: arXiv:1604.05708]

- Amplitude analyses are powerful tools but they are intrinsically model dependent:
 - How many Λ^* should be taken in account? How to deal with unknown/not observed states predicted by the quark model?
 - Not trivial to model NR components. Any mass dependence?
 - Possible 3-body contribution?
 - Isobar model has well known limitation: unitarity violation when adding broad overlapping states. K-matrix formalism? How to deal with the couplings to the exotic sector?

Can the reflections of the structures in $m(pK)$ and $\cos \vartheta_{\Lambda^}$ reproduce the $m(J/\psi p)$ distribution?*

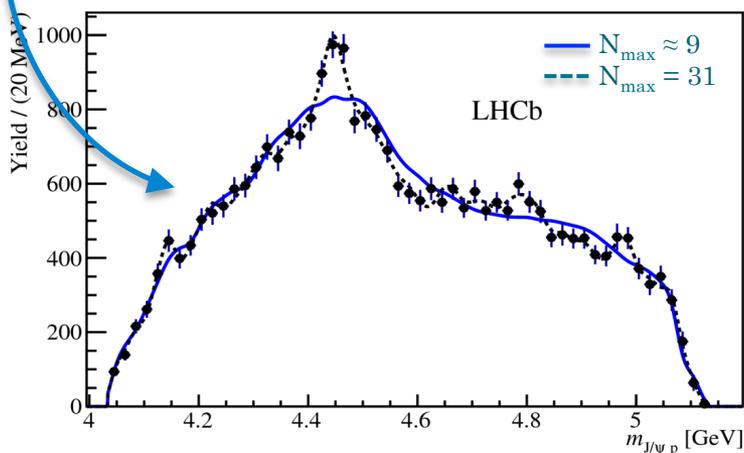
RESULTS FROM MODEL INDEPENDENT APPROACH

[LHCb: arXiv:1604.05708]

Decompose angular distribution into Legendre moments

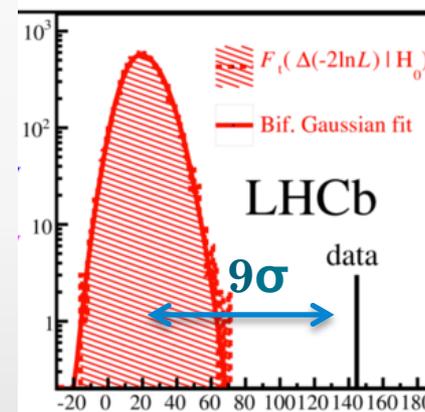


Recombine the “meaningful” moments up to a certain order (driven by physics arguments)



Test significance of implausible $N_{max} < N < 31$ moments using the log-likelihood ratio:

$$\Delta(-2\text{NLL}) = -2\ln \frac{\mathcal{L}_{N_{max}}}{\mathcal{L}_{31}} = -2\ln \frac{\prod_i \mathcal{F}_{N_{max}}(m_{\psi'\pi}^i)}{\prod_i \mathcal{F}_{31}(m_{\psi'\pi}^i)}$$



Explanation of the data with plausible Λ^* contributions is ruled at high significance without assuming anything about Λ^* resonance shapes or their interference patterns!



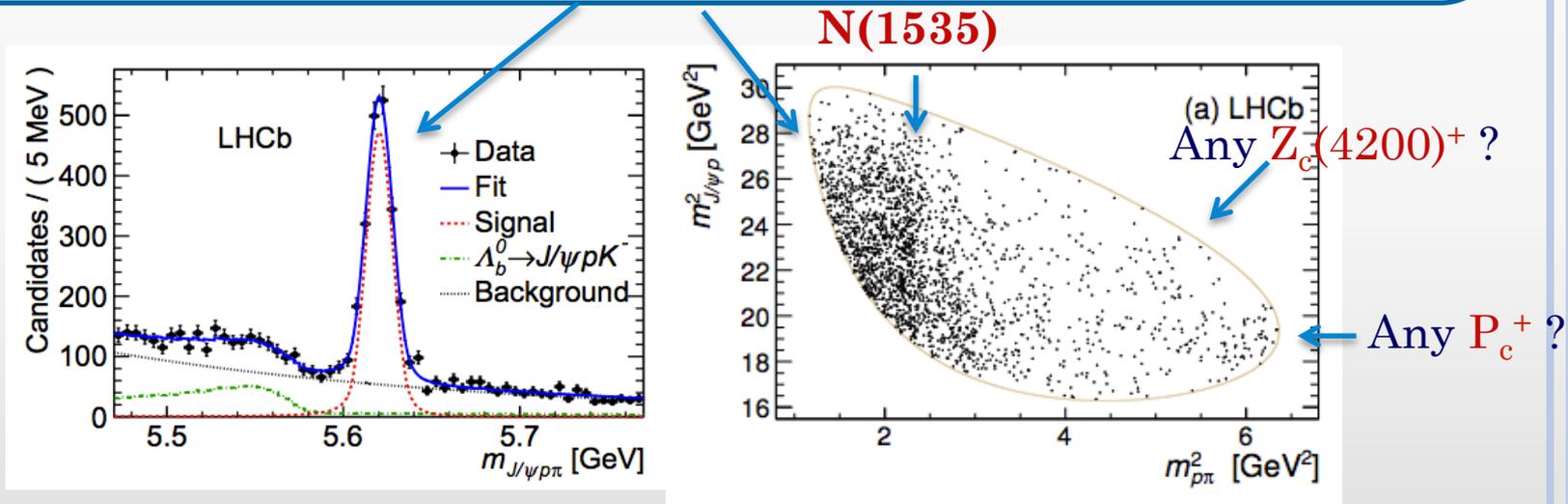
Evidence for the Exotic Hadron Contributions to $\Lambda_b \rightarrow J/\psi p \pi^-$ decays

[arXiv:1606.06999]

HOW TO INVESTIGATE THE P_c^+ STATES FURTHER?

The confirmation of a new state passes through:

- Observation of a different decay:
 - $P_c^+ \rightarrow \chi_{c1} p$ (neutrals are involved)
 - $P_c^+ \rightarrow \Lambda_c D$ (long-lived hadrons \rightarrow low efficiency, small BR's)
- Observation in a different environment:
 - Prompt production $pp \rightarrow P_c^+ + X$ (large track multiplicity at LHC)
 - $\Lambda_b \rightarrow J/\psi p \pi$: Cabibbo suppressed but feasible

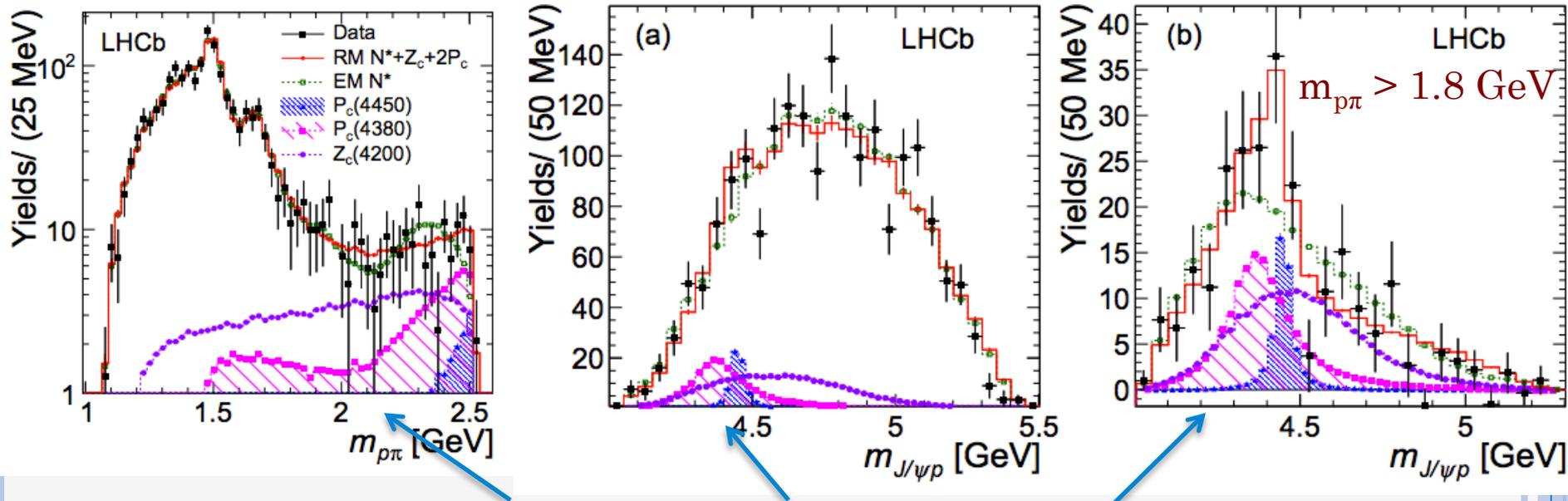


Dataset: 3 fb^{-1}

$N_{\text{events}} = 1885 \pm 50$ (10x smaller than $\Lambda_b \rightarrow J/\psi p K$)

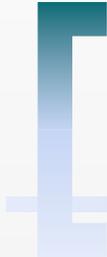
Background $\sim 20\%$ (3x larger than $\Lambda_b \rightarrow J/\psi p K$)

AMPLITUDE ANALYSIS OF $\Lambda_B \rightarrow J/\psi p \pi$ DECAY FIT RESULTS



$P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ overlap each other

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ (including systematic uncertainty) \rightarrow Evidence for exotic hadrons.
- Individual exotic hadron contributions are not significant.
- Fit fractions consistent with what expected for the Cabibbo suppressed decay



Search for structure in the $B_s^0\pi^\pm$ invariant mass spectrum

[LHCb-CONF-2016-004]

<http://cds.cern.ch/record/2140095/>

A NEW $B_s^0 \pi^\pm$ STATE CLAIMED BY DØ

[DØ: arXiv:1602.07588]

Claimed observation/evidence of an exotic state

✓ $X(5568)^\pm \rightarrow B_s^0 \pi^\pm$, $B_s^0 \rightarrow J/\psi \phi$, $J/\psi \rightarrow \mu^+ \mu^-$, $\phi \rightarrow K^+ K^-$

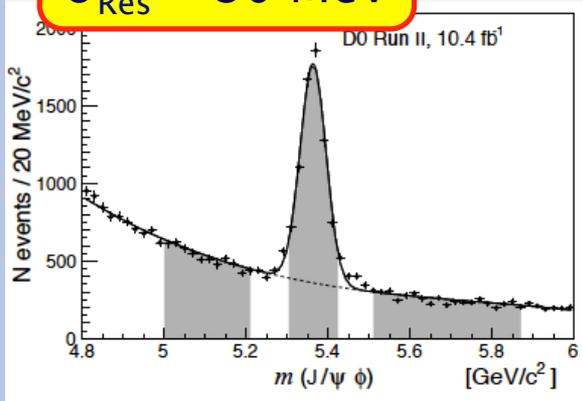
$$M = 5567.8 \pm 2.9_{-1.9}^{+0.9} \text{ MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4_{-2.5}^{+5.0} \text{ MeV}/c^2$$

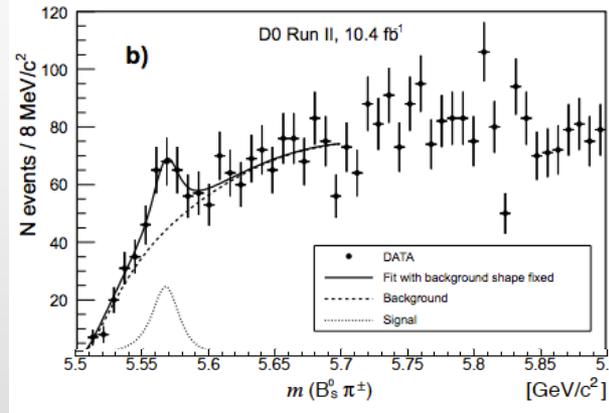
✓ Fraction of B_s^0 from X^\pm decay: $\rho_X^{DØ} = (8.6 \pm 1.9 \pm 1.4) \%$

“Cone” cut: $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$

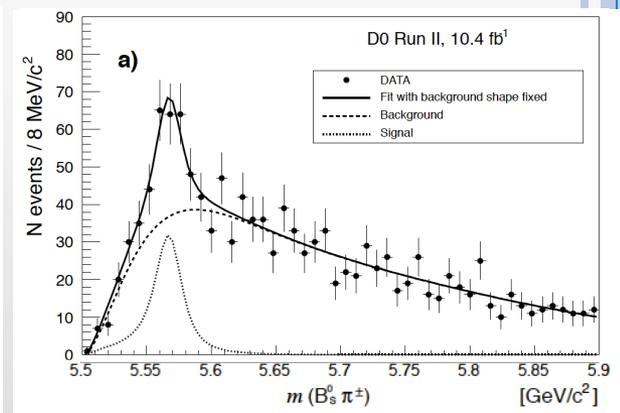
$N(B_s) \sim 5500$
 $\sigma_{\text{Res}} \sim 30 \text{ MeV}$



$N(X) = 106 \pm 23$



$N(X) = 133 \pm 31$



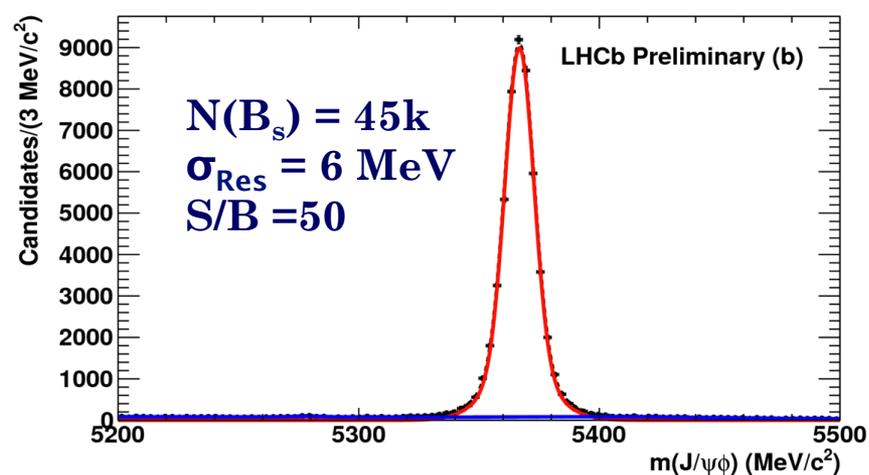
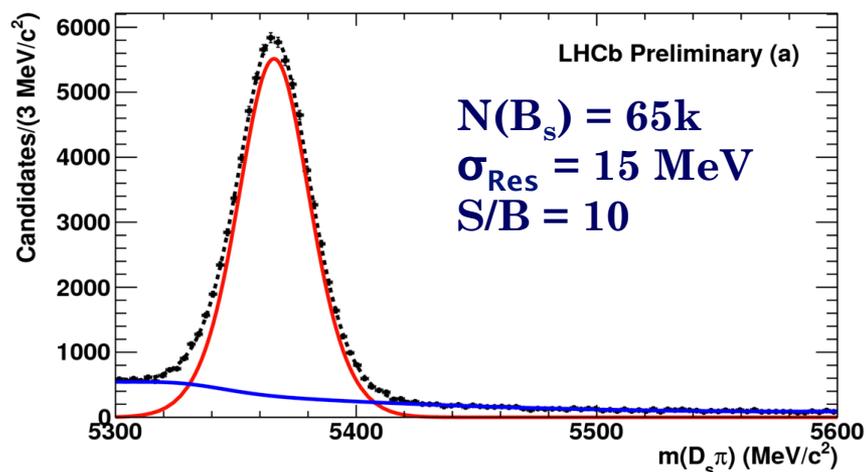
3.9σ

5.1σ

Signal significance

B_s SELECTION

- RUN I data (3 fb⁻¹)
- Cut-based selections aiming to very clean B_s⁰ samples
 - ✓ Both B_s⁰ → D_s⁻π⁺ and J/ψ φ (Mass constraints on the D_s and J/ψ)
 - ✓ Stick closely to tried and trusted analysis methods:
B^{} → Bπ and B_s^{**} → BK**
 - ✓ p_T(π) > 500 MeV/c
 - ✓ Baseline: p_T(B_s⁰) > 5 GeV/c; Tight: p_T(B_s⁰) > 10 GeV/c to match the DØ selection



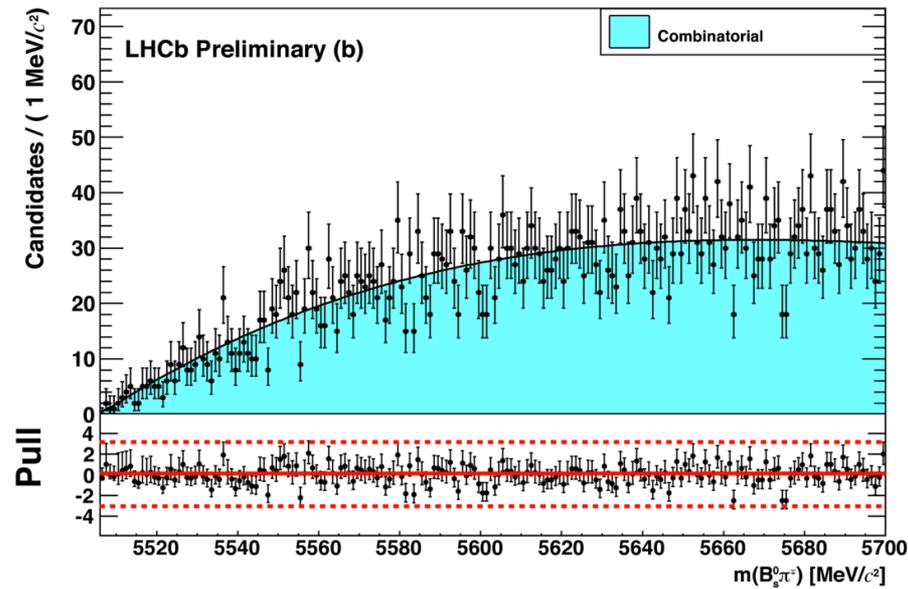
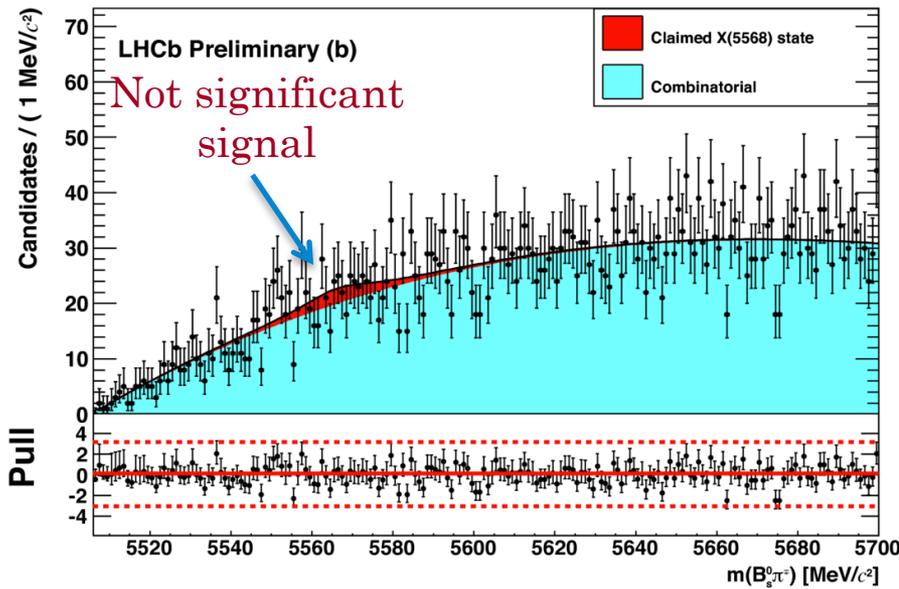
B_s sample 20x larger and much cleaner than DØ

FIT RESULT

Both modes combined (no “Cone” cut applied):
 $p_T(B_s) > 10 \text{ GeV}/c$

Fit with signal component

Fit without signal component



$$\rho_X^{\text{LHCb}}(B_s^0, p_T > 5 \text{ GeV}/c) < 0.009 (0.010) @ 90 (95) \% \text{ CL}$$

$$\rho_X^{\text{LHCb}}(B_s^0, p_T > 10 \text{ GeV}/c) < 0.016 (0.018) @ 90 (95) \% \text{ CL}$$



Amplitude analysis of $B^+ \rightarrow J/\psi \phi K^+$ decays

[LHCb: arXiv: 1606.07895]

[LHCb: arXiv: 1606.07898]

X(4140): A BIT OF HISTORY

CDF: Evidence/“Observation” in $B^+ \rightarrow J/\psi \phi K^+$
 [PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)

$$m = 4143.0^{+2.9}_{-3.0} \pm 0.6 \text{ MeV}$$

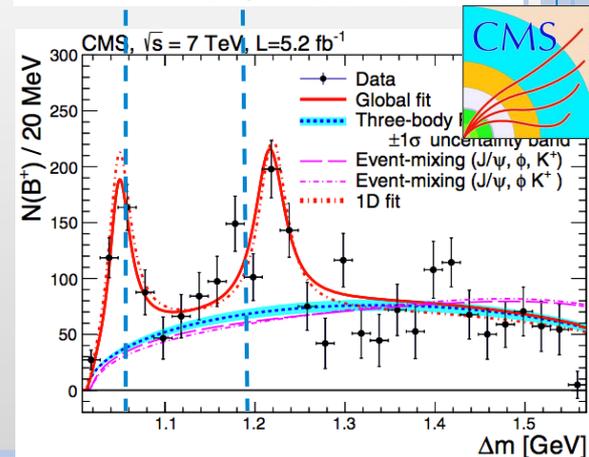
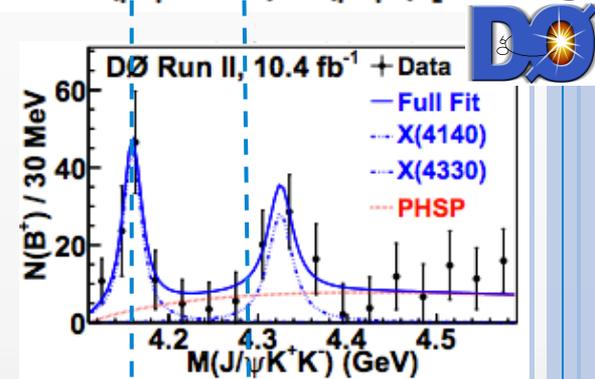
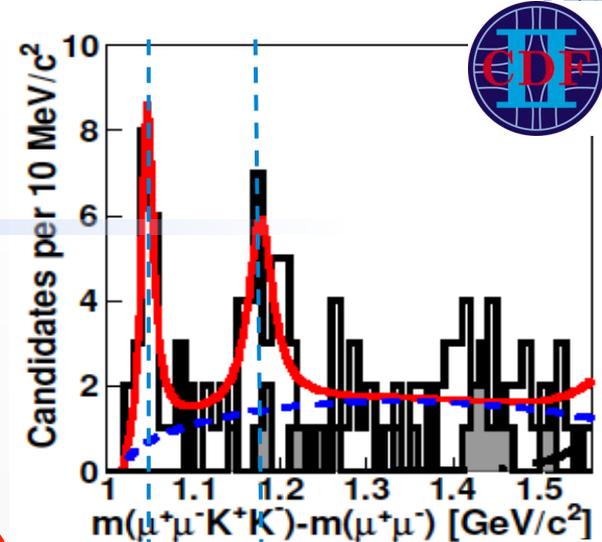
$$\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5 \text{ MeV}$$

X(4274)

$$m = 4274.4^{+8.4}_{-6.7} \pm 1.9 \text{ MeV}$$

$$\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6 \text{ MeV}$$

- Belle: No evidence of X(4140) in $\gamma\gamma \rightarrow J/\psi \phi$. Observation of a new state X(4350) [PRL 104, 112004 (2010)]
- LHCb: No evidence of X(4140)/X(4274) in B decays but UL’s don’t disprove them [PRD 85, 091103(R) (2012)]
- D0: “Threshold enhancement consistent with the X(4140) (3.1σ) ... Second structure consistent with X(4350)” [PRD89 012004 (2014)]
- CMS: Peak in $J\psi \phi$ consistent with X(4140). Evidence of a 2nd peak affected by reflections [PLB 734 (2014) 261]
- BaBar: No evidence of X(4140)/X(4274) [PRD 91, 012003 (2015)]
- D0: Evidence of X(4140) in prompt production [PRL 115, 232001 (2015)]

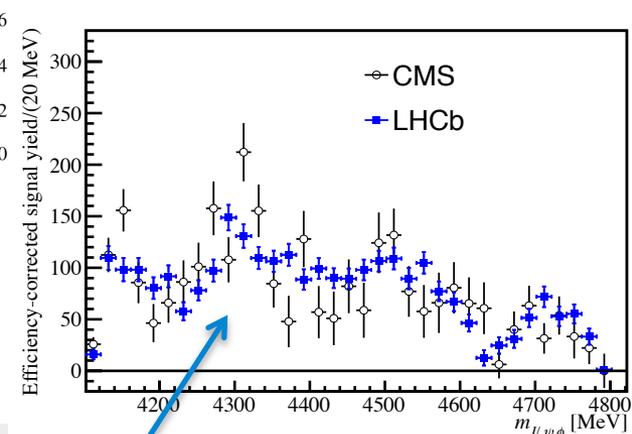
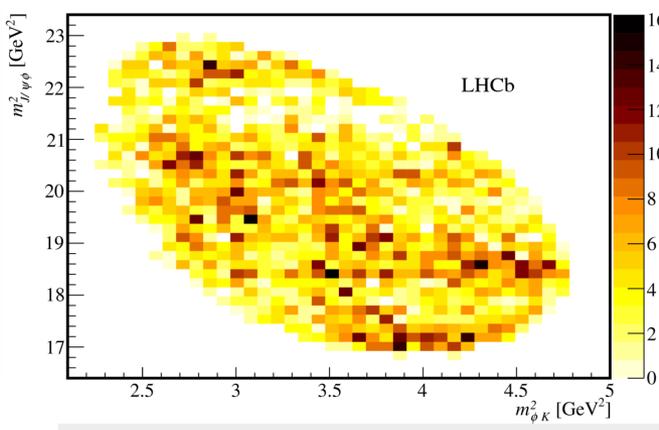
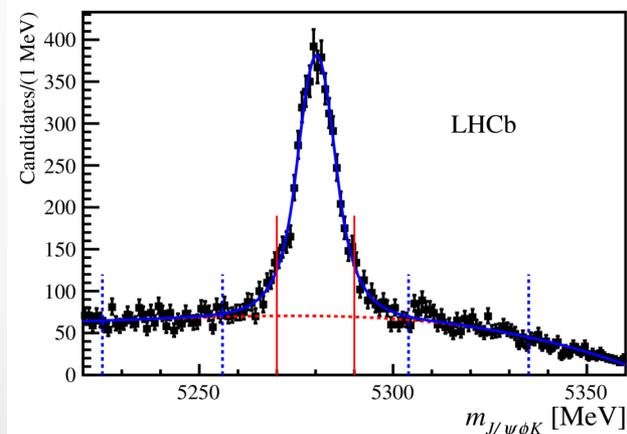


THE $B^+ \rightarrow J/\psi \phi K^+$ SAMPLE

[LHCb: arXiv: 1606.07895]

[LHCb: arXiv: 1606.07898]

Run I data (3 fb^{-1})
 $N_{\text{Events}} = 4289 \pm 151$
Background $\sim 20\%$

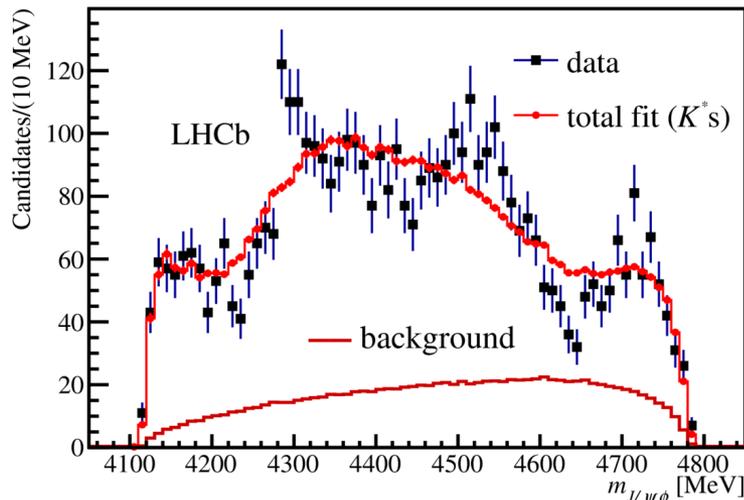


Qualitative agreement over the full mass range

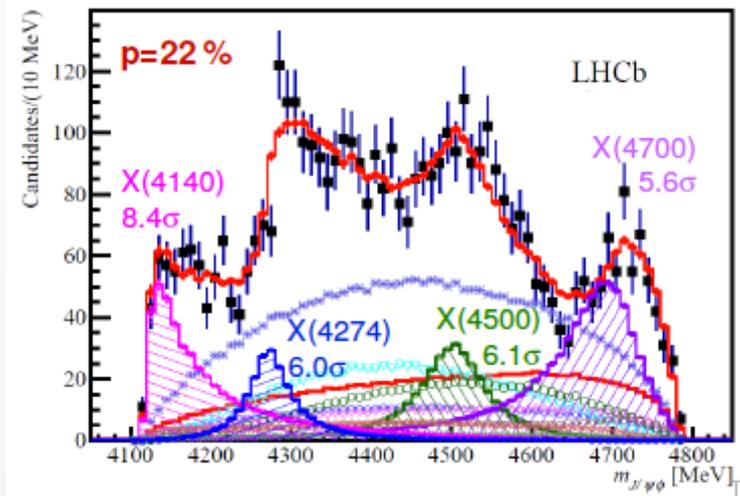
- Statistically, the most powerful $B^+ \rightarrow J/\psi \phi K$ sample analyzed so far
- First 6D amplitude analysis

FIT RESULTS

Fit with K^* only



Fit with $K^* + 4 X$'s!



$X(4140)$ ($J^{PC} = 1^{++}$)

- Mass consistent with the previous measurements but the width substantially larger

$X(4274)$ ($J^{PC} = 1^{++}$)

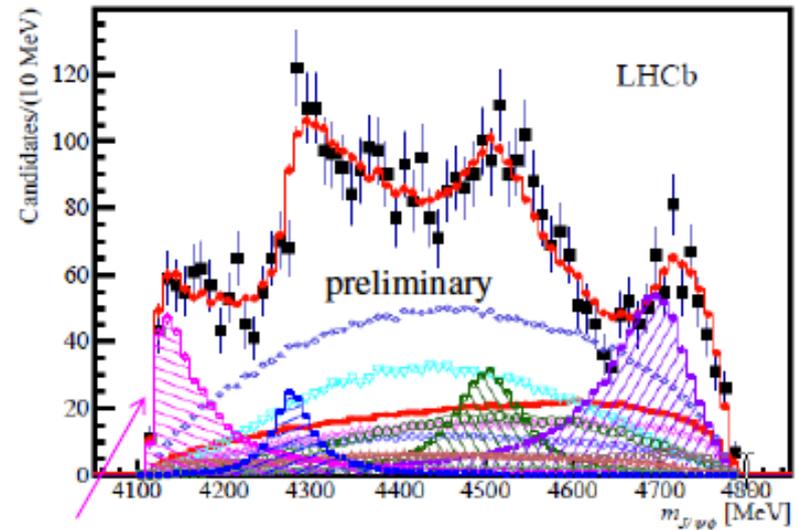
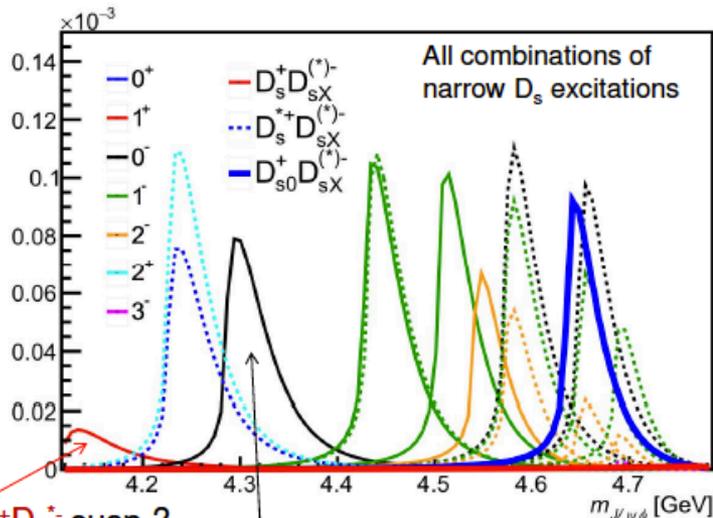
- Consistent with the unpublished CDF results.

Two new states : $X(4500)$ and $X(4700)$ with ($J^{PC} = 0^{++}$)

IS THE X(4140) A $D_s D_s^*$ CUSP?

Results of alternate fit where the X(4140) parameterized by a $D_s D_s^*$ cusp

E.S.Swanson: arXiv:1504.07952
Phys. Rev. D91 034009, 2015



Is X(4140) a $D_s^+ D_s^{*-}$ cusp ?

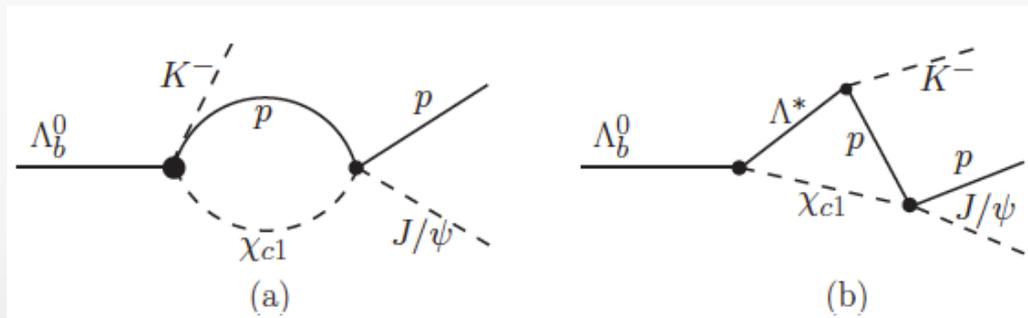
Right $J^P = 1^+$

Is X(4274) a $D_s^+ D_{s0}^{*-}$ cusp ?
Wrong $J^P = 0^-$

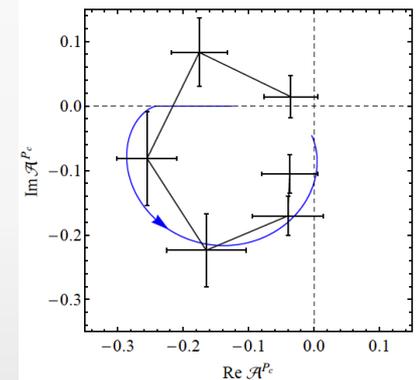
The cusp is preferred over the Breit-Wigner amplitude for X(4140) from the fit likelihood ratio

SUMMARY

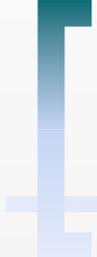
- *The number of exotic hadrons keeps growing up*
 - LHC experiments, Belle II, BES will play a fundamental role into measuring the properties: masses, widths, production, J^P
 - Possible explanation for the X(4140) as a cusp (why we don't observe them at every threshold?)
 - Cusps can also mimic the circle in the Argand diagram



PRD 92 (2015) 7, 071502



- *The two Pentaquarks P_c^+ observed in $\Lambda_b \rightarrow J/\psi p K$ are getting support*
 - Model independent analysis of $\Lambda_b \rightarrow J/\psi p K$ decay and amplitude analyses of $\Lambda_b \rightarrow J/\psi p \pi$ suggest the presence of exotic
 - More data required to determine J^P



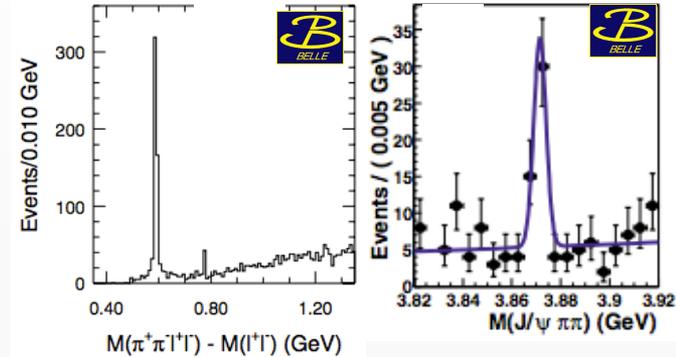
Back-up slides

THE X(3872) STATE

Discovered in 2003 by the Belle collaboration in the $B \rightarrow K X(3872)$ decay where $X(3872) \rightarrow J/\psi \pi^+ \pi^-$

- ⊗ Mass is roughly equal to $m(D^0) + m(D^{*0})$
- ⊗ Width is surprisingly narrow (< 1.2 MeV)
- ⊗ Large production rate in $p\bar{p}$ collisions

[Belle: PRL 91, 262001 (2003)]



LHC experiments are largely contributing to shed light on the nature of the X(3872) state

- Determination of the quantum numbers [PRL 110, 222001 (2013)][PRD92, 011102 (2015)]
- Measurement of $B(X(3872) \rightarrow \psi(2S) \gamma) / B(X(3872) \rightarrow J/\psi \gamma)$ [Nucl.Phys.B886 (2014) 665]
- Precise mass measurement [EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]
 $E_B = m(D^0 \bar{D}^{*0}) - m(X(3872)) = 3 \pm 192 \text{ keV}/c^2 \rightarrow$ *Loosely bound in the molecule scenario*
- Production cross-section in pp collisions at $\sqrt{s} = 7$ TeV [EPJC 72 (2012) 1972, JHEP 1304, 154 (2013)]
- Search for $X(3872) \rightarrow p\bar{p}$ [EPJC 73 (2013) 2462]

$$\frac{BR(X(3872) \rightarrow p\bar{p})}{BR(X(3872) \rightarrow J/\psi \pi^+ \pi^-)} < 2.0 \times 10^{-3}$$

Λ^* DECAY MODELS

[LHCb: PRL 115, 07201 (2015)]

Two models: Reduced and Extended
 L = angular momentum between J/ψ and Λ^*

No high- J^P high-mass states, limited L All states, all L

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$?	≈ 2585	200	0	6

of fit parameters: 64 146

All known
 Λ^* states

MODEL INDEPENDENT APPROACH

[LHCb: arXiv:1604.05708]

H1: If no exotics in $J/\psi K$ and $J/\psi p$



$$(m_{pK}, \theta_{\Lambda b}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu) \rightarrow (m_{pK}, \theta_{\Lambda^*})$$

Decompose angular distribution into Legendre moments

Legendre Polynomials

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0 \rangle P_0 + \langle P_1 \rangle P_1 + \langle P_2 \rangle P_2 + \langle P_3 \rangle P_3 + \langle P_4 \rangle P_4 + \langle P_5 \rangle P_5 + \langle P_6 \rangle P_6 + \dots$$

where the moments $\langle P_l \rangle$ determined from data:
$$\langle P_l \rangle = \sum_{i=1}^{N_{data}} \frac{1}{\epsilon_i} P_l(\cos \theta_{K^*}^i)$$

Recombine the “meaningful” moments up to a certain order

(driven by physics arguments)

MODEL INDEPENDENT APPROACH

[LHCb: arXiv:1604.05708]

H2: (e.g.) If only Λ^* resonances up to $J = 3/2$



$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0 \rangle P_0 + \langle P_1 \rangle P_1 + \langle P_2 \rangle P_2 + \langle P_3 \rangle P_3 + \langle P_4 \rangle P_4 + \langle P_5 \rangle P_5 + \langle P_6 \rangle P_6 + \dots$$

Sum of the terms up to $P_{N_{\max}}$, where $N_{\max} = 2 * J(\Lambda^*)$,
has to describe the data projections

Should it not happen →

There are Λ^* resonances with $J > 3/2$

OR

There are exotic(s) which make the
high order terms non-zero!

AMPLITUDE ANALYSIS OF $\Lambda_B \rightarrow J/\psi p \pi$ DECAY FIT MODEL

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

$N^* \rightarrow p \pi$

- Reduced model (RM) for central values, extended (EM) for systematics and significances
- Neglecting higher orbital angular momenta for most of the N^* states

$P_c^+ \rightarrow J/\psi p$

- Masses, widths and $J^P = (3/2^-, 5/2^+)$ fixed. Not possible to float them with the current statistic

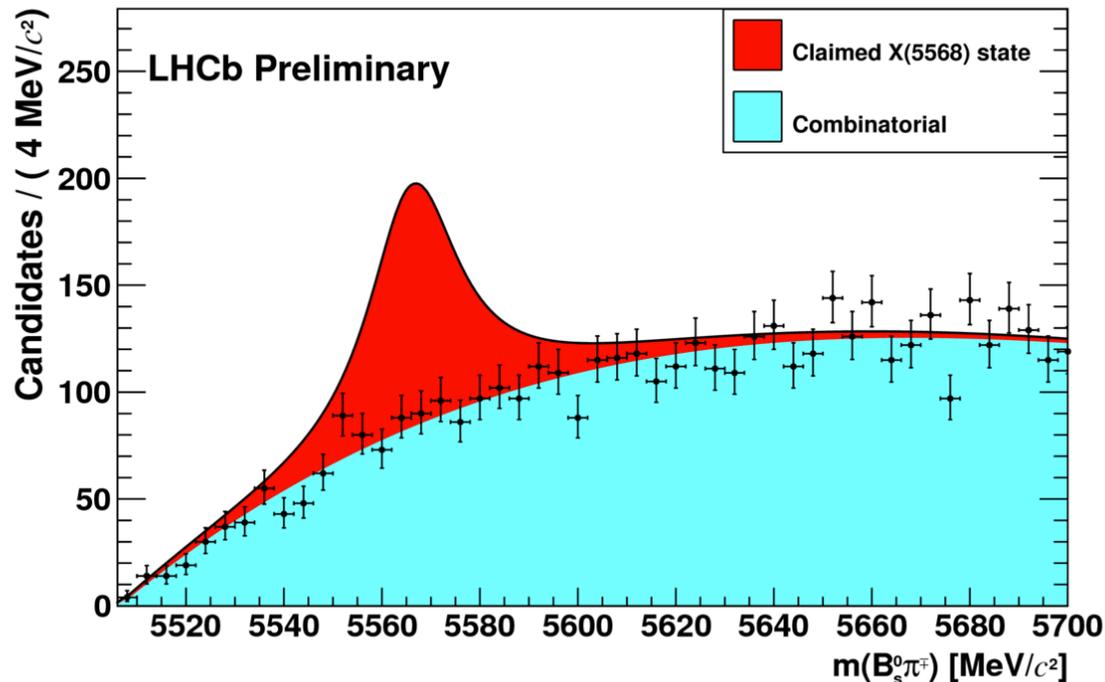
$Z_c(4420)^+ \rightarrow J/\psi \pi$

- Observed by Belle [PRD, 90, 112009]
- Mass, width and $J^P = 1^+$ fixed

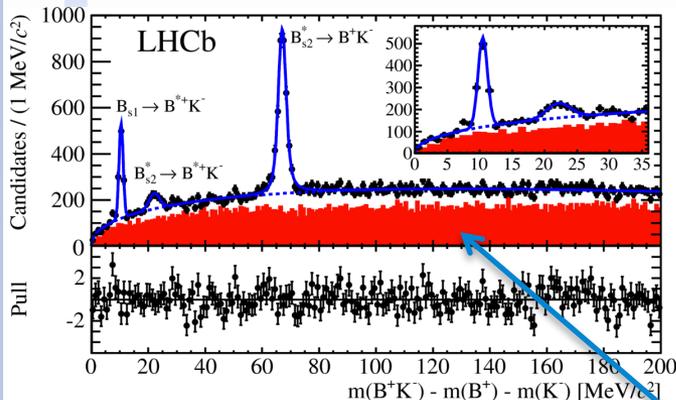
JUST FOR CURIOSITY...

If $\rho_X^{\text{LHCb}} = \rho_X^{\text{DØ}} = 8.6\%$, how would the X(5568) signal look like?

(Both modes combined: $p_T(\text{B}_s) > 10 \text{ GeV}/c$)

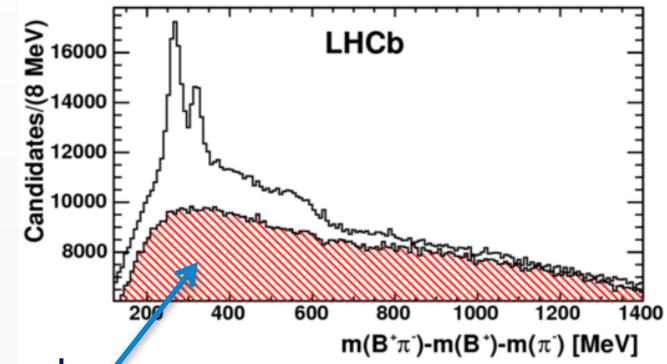


OTHER "IMPLICIT" SEARCHES



PRL 110 (2013) 151803

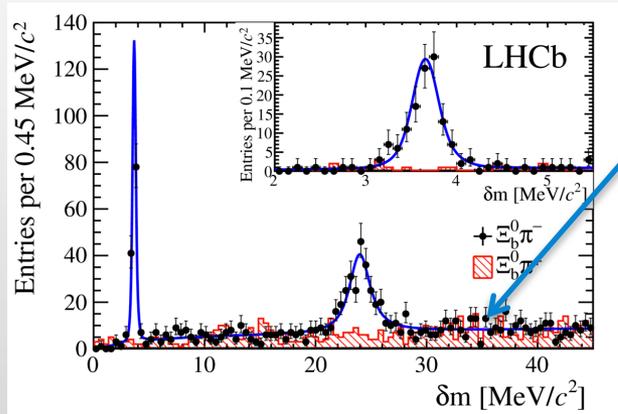
B^+K^+



JHEP 1504 (2015) 024

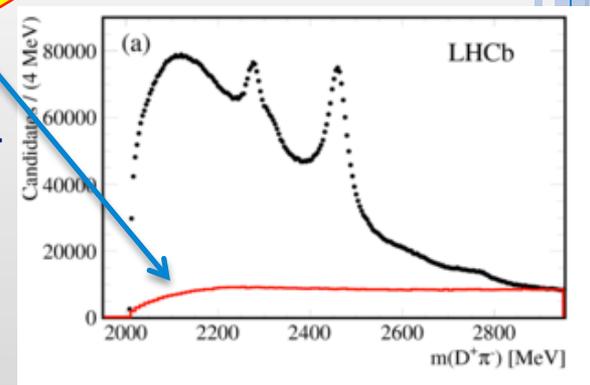
$B^+\pi^+$

The red histograms, referred as Wrong Sign plots, are implicitly searches for tetra/pentaquark



PRL 114 (2015) 062004

$\Xi_b^0 \pi^+$



JHEP 09 (2013) 145

$D^+\pi^+$