



# LHCb results on exotic spectroscopy

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**QCD @ LHC 2016,  
August 22-26, Zurich**

## Outline

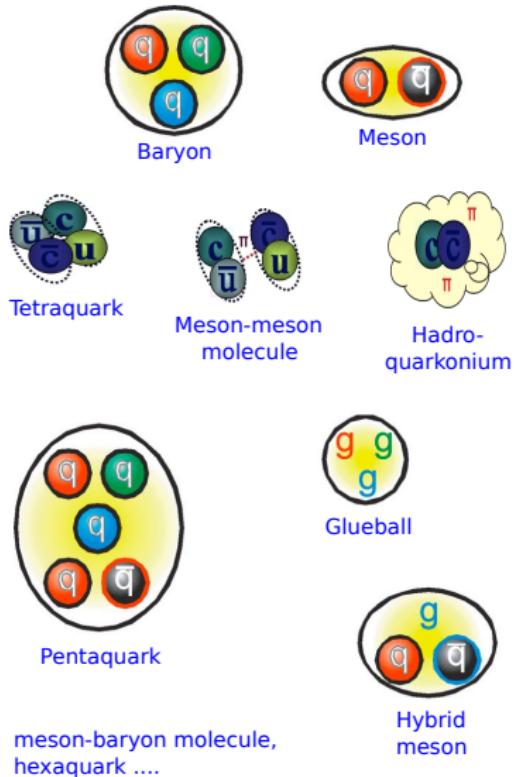
- exotic states overview
- study of  $B_s^0\pi^-$  system  
[arXiv:1608.00435]
- observation of pentaquark states at LHCb  
[PRL 115 (2015) 072001] , [PRL 117 (2016) 082002] , [arXiv:1606.06999]
- observation of exotic contributions in  $B^+ \rightarrow J/\psi\Phi K^+$  decays  
[arXiv:1606.07895], [arXiv:1606.07898]

all the presented analyses used the  $3\text{ fb}^{-1}$  sample collected by LHCb in Run 1

# Conventional and exotic hadrons

- exotic states are hadrons with more than the minimal quark content of mesons and baryons
- color-singlet configurations  $\Rightarrow$  not forbidden by QCD
- from Gell-Mann's "A schematic model of Baryons and Mesons"

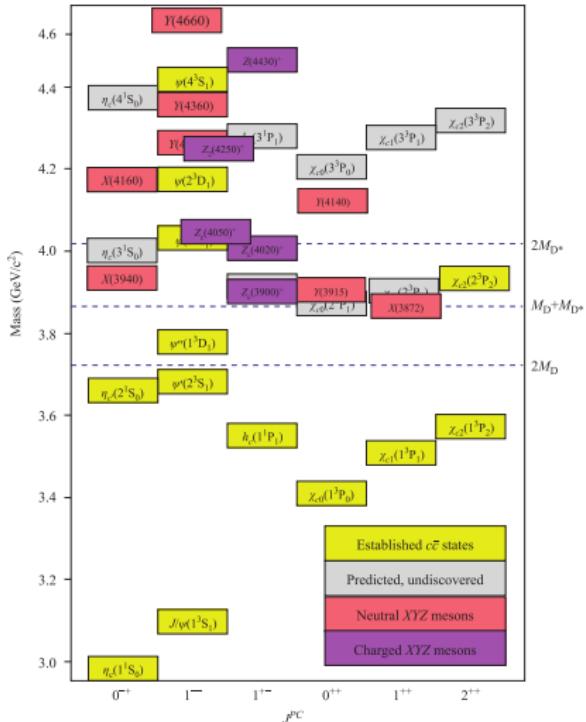
We then refer to the members  $u^{\pm}$ ,  $d^{\pm\frac{1}{2}}$ , and  $s^{\pm\frac{1}{2}}$  of the triplet as "quarks" and the members of the anti-triplet as anti-quarks  $\bar{q}$ . Baryons can now be constructed from quarks by using the combinations  $(qqq)$ ,  $(qqq\bar{q}\bar{q})$ , etc., while mesons are made out of  $(q\bar{q})$ ,  $(q\bar{q}\bar{q}\bar{q})$ , etc. It is assuming that the lowest baryon configuration  $(qqq)$  gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration  $(q\bar{q})$  similarly gives just 1 and 8.



no evidences for almost 40 years  $\Rightarrow$  **exotic states**

# Exotic states: first evidences and observations

- since 2003 many different exotic (**X****Y****Z**) candidates have been seen in  $c\bar{c}$  and  $b\bar{b}$  spectra at  $B$  and  $c$  factories
- they don't fit to conventional quarkonia states well predicted by QCD-motivated potential models
- their production and bound mechanism are still not clear
- $\Rightarrow$  **they need experimental and theoretical studies**



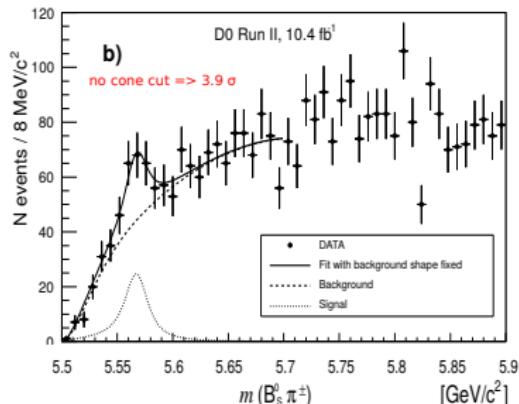
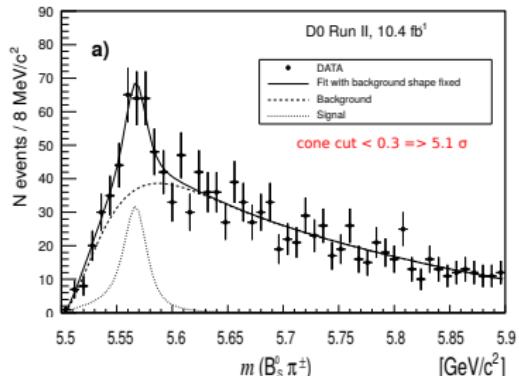
[arXiv:1411.7738v1]

# Search for structure in the $B_s^0\pi^-$ spectrum

# $X(5568)^- \rightarrow B_s^0 \pi^-$ state claimed by D0

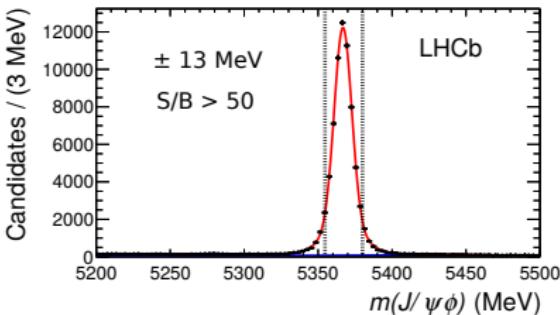
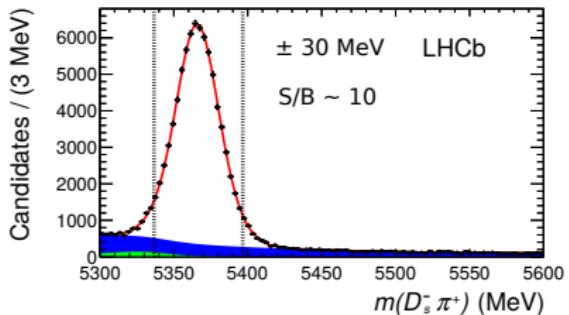
- observation/evidence of a new exotic state [PRL 117, 022003 (2016)]
- $X(5568)^- \rightarrow B_s^0 \pi^-$ ,  $B_s^0 \rightarrow J/\psi \phi$ ,  $J/\psi \rightarrow \mu^+ \mu^-$ ,  $\phi \rightarrow K^+ K^-$
- only take into account pions in a cone  $\sqrt{\Delta\eta^2 + \Delta\phi^2}$  around the  $B_s^0$  direction
- it would be unique with 4 different flavours:  $|X(5568)^-\rangle_f = |\bar{b} s \bar{u} d\rangle$

$M$ [MeV]	$\Gamma$ [MeV]	$\rho$ [%]
$5567.8 \pm 2.9^{+0.9}_{-1.9}$	$21.9 \pm 6.4^{+5.0}_{-2.5}$	$8.6 \pm 1.9 \pm 1.4$



# LHCb data sample and selection of the candidates

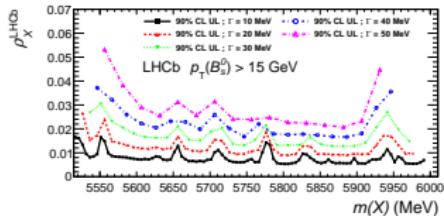
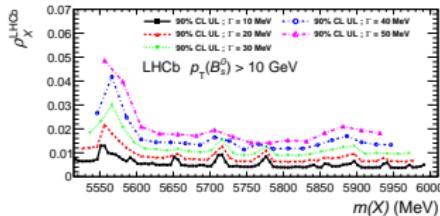
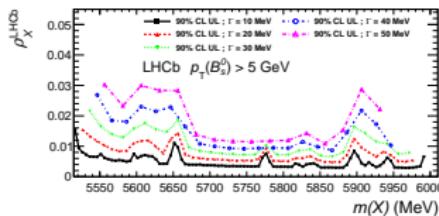
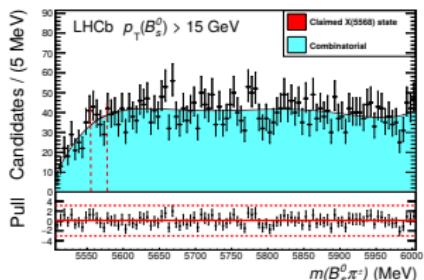
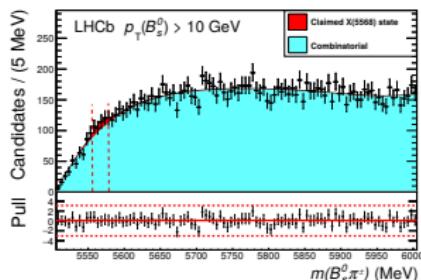
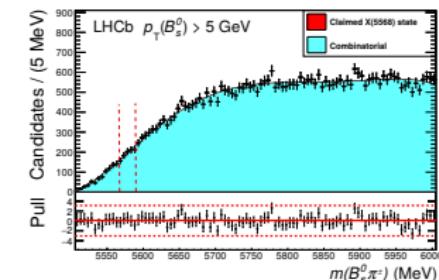
- $B_s^0 \rightarrow J/\psi\phi$ ,  $J/\psi \rightarrow \mu^+\mu^-$ ,  $\phi \rightarrow K^+K^-$ , D0-like
- $B_s^0 \rightarrow D_s^-\pi^+$ ,  $D_s^- \rightarrow K^+K^-\pi^-$
- well known selection criteria first used in studies for  $B^+K^-$  [PRL 110 (2013) 151803],  $B^+\pi^-$  and  $B^0\pi^+$  [JHEP 04 (2015) 024] (cross-check channels)
- sample  $\sim 20$  times larger than that used by the D0 collaboration, much cleaner,  $B_s^0$  resolution from 2 to 5 times better than D0 one



[arXiv:1608.00435]

# Results: no significant $X(5568)^-$ state

greater cut on  $p_T(B_s^0) \Rightarrow X(5568)^-$  produced in a harder process



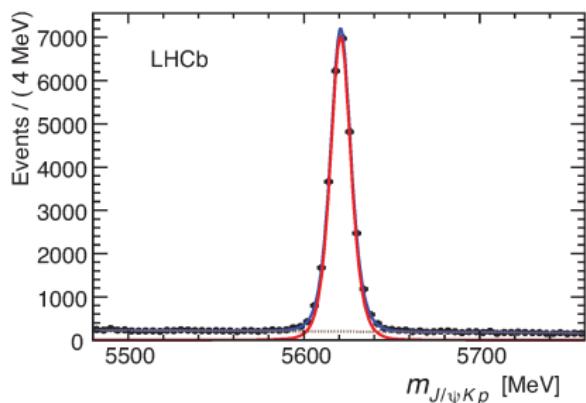
- $\rho_X^{LHCb}(p_T(B_s^0) > 5 \text{ GeV}) < 0.011 \text{ (0.012)} @ 90\% \text{ (95\%) CL}$
- $\rho_X^{LHCb}(p_T(B_s^0) > 10 \text{ GeV}) < 0.021 \text{ (0.024)} @ 90\% \text{ (95\%) CL}$
- $\rho_X^{LHCb}(p_T(B_s^0) > 15 \text{ GeV}) < 0.018 \text{ (0.020)} @ 90\% \text{ (95\%) CL}$

[arXiv:1608.00435]

# Search for pentaquark states: $\Lambda_b^0 \rightarrow J/\psi K^- p$ amplitude analysis

# $\Lambda_b^0 \rightarrow J/\psi K^- p$ decay channel

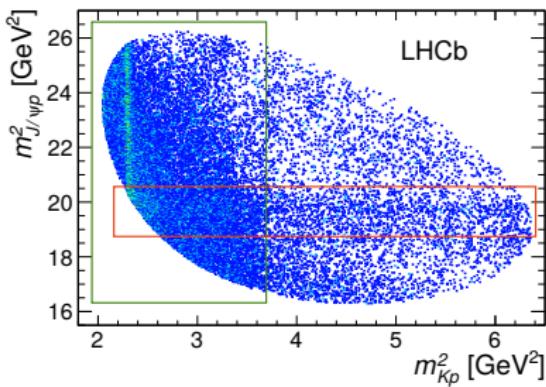
decay mode with unexpected large yield and low background rate, first used to measure  $\tau_{\Lambda_b}$  with  $1 \text{ fb}^{-1}$  sample collected in 2011 [PRL 111 (2013) 102003]



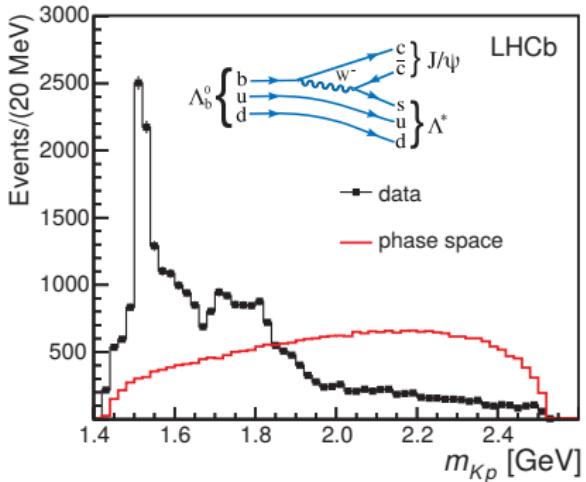
- decay is expected to be dominated by  $\Lambda^* \rightarrow K^- p$  interfering resonances
- unexpected and distinct horizontal band near  $19.5 \text{ GeV}^2$

[PRL 115 (2015) 072001]

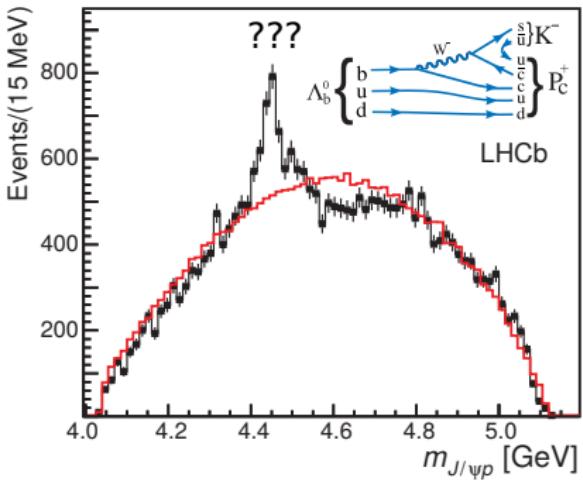
- $\sim 26000$  events
- pure sample with 5.4% of combinatorial background within  $\pm 2\sigma$  ( $\sigma = 7.5 \text{ MeV}/c^2$ ) of the peak



# Dalitz plot projections



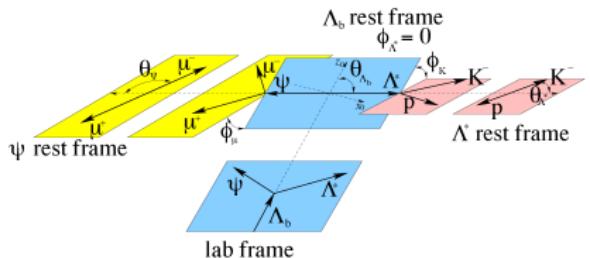
- expected  $\Lambda^*$  contributions above the phase space



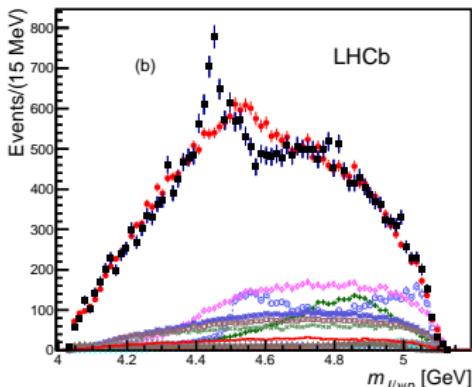
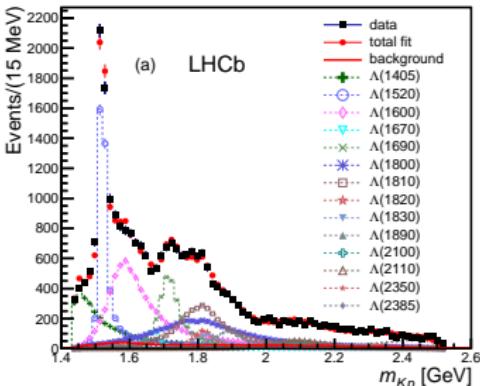
- reflections from  $m_{Kp}$ ?
- $|P_c^+\rangle_f = |uudcc\bar{c}\rangle$  resonance(s)?

[PRL 115 (2015) 072001]

# Amplitude fit with $\Lambda^* \rightarrow K^- p$ only

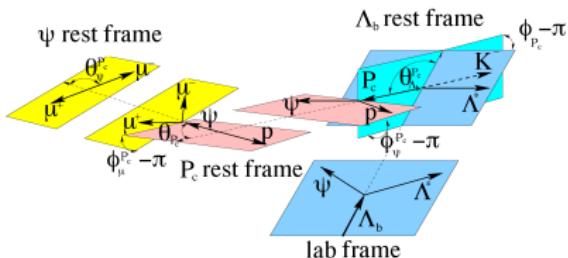


- helicity formalism to perform the full 6D amplitude fit
- $m_{Kp}, \theta_{\Lambda_b}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu$
- dynamical amplitudes given by relativistic Breit-Wigners plus the Flatté parametrization for the  $\Lambda(1405)$
- all possible known  $\Lambda^*$  states and decay amplitudes allowed

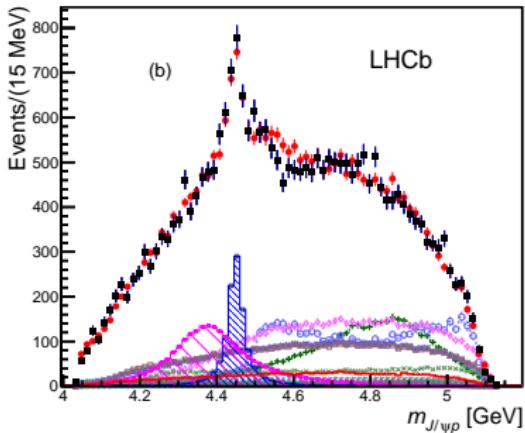


[PRL 115 (2015) 072001]

# Introduction of $P_c^+$ contributions



- new  $\Lambda_b^0 \rightarrow P_c^+ K^-$  decay sequence allowed to interfere with  $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$  chain
- reduced model of  $K^- p$  states keeping only well motivated 12  $\Lambda^*$  states



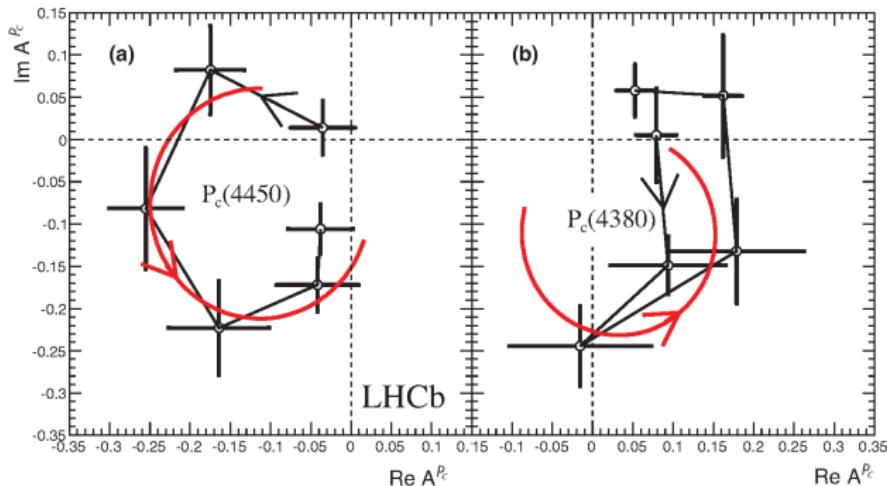
two interfering  $P_c^+$  states with opposite parities are necessary to obtain acceptable fits

State	$M_0$ [MeV]	$\Gamma_0$ [MeV]	$J^P$
$P_c(4380)^+ @ 9\sigma$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^- (\frac{3}{2}^+, \frac{5}{2}^+)$
$P_c(4450)^+ @ 12\sigma$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+ (\frac{5}{2}^-, \frac{3}{2}^-)$

[PRL 115 (2015) 072001]

## Check for resonant character

- additional fit representing each  $P_c^+$  amplitude as combination of 6 independent complex amplitudes in the  $[M_0 - \Gamma_0, M_0 + \Gamma_0]$  range
- $P_c(4450)^+$  Argand diagram consistent with the rapid counterclockwise change of phase when the magnitude reaches the maximum expected for a resonance
- not conclusive for the  $P_c(4380)^+$



[PRL 115 (2015) 072001]

# Search for pentaquark states: $\Lambda_b^0 \rightarrow J/\psi K^- p$ model independent analysis

## Motivations

- $\Lambda^*$  spectroscopy is a complex problem from both the theoretical and experimental point of views
- high density of predicted states, probably with large widths, would make it difficult to identify them experimentally
- nonresonant contributions with non-trivial  $K^- p$  mass dependence may also be present

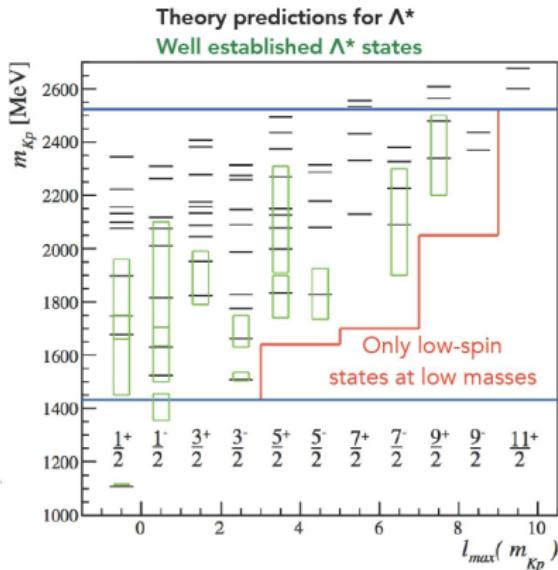
⇒ inspect data with a model independent approach with respect to  $K^- p$  contributions

strategy: assess level of consistency of data with  $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$  hypothesis ( $H_0$ )

[PRL 117 (2016) 082002]

# Moments analysis

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

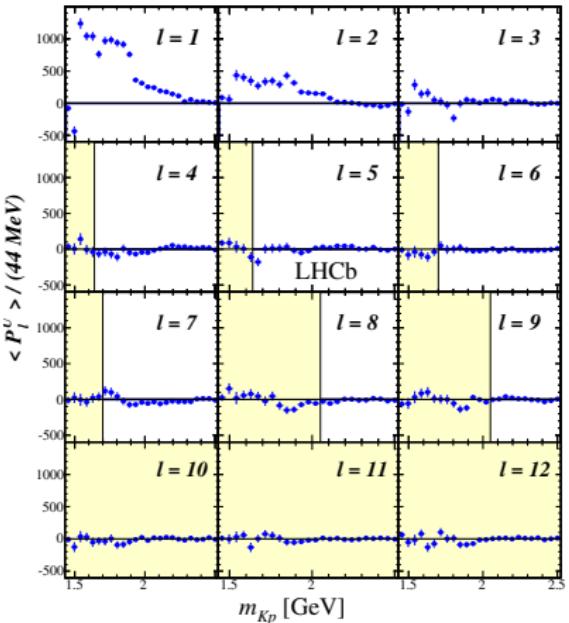


$$l_{max} = 2J_{max} \Rightarrow l_{max}(m_{Kp})$$

[PRL 117 (2016) 082002]

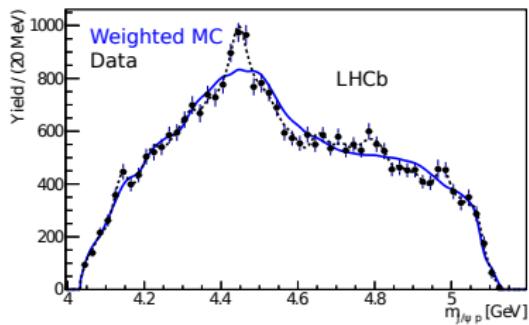
non zero values in the yellow shaded areas means non- $\Lambda^*$  activity

$$\langle P_l^U \rangle^k = \sum_{i=1}^{N^k} \frac{w_i}{\epsilon_i} P_l(\cos\theta_{\Lambda^*}^i)$$

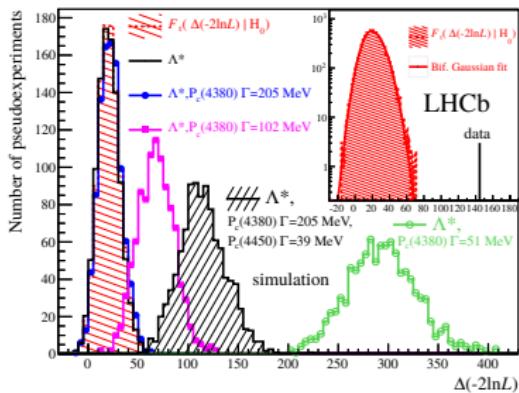


## Results

- phase space  $\Lambda_b^0 \rightarrow J/\psi K^- p$  weighted by  $m_{Kp}$  and moments



- hypothesis test through likelihood ratio using pseudoexperiments



- $\Rightarrow \Lambda^*$  reflections alone cannot describe the decay dynamics

**demonstrates at more than  $9 \sigma$  that  $\Lambda_b^0 \rightarrow J/\psi K^- p$  decays cannot be described with  $K^- p$  contributions alone**

[PRL 117 (2016) 082002]

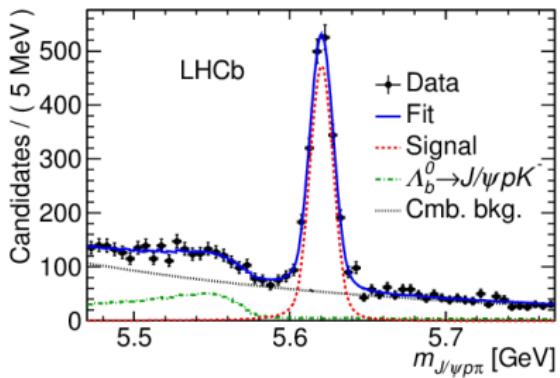
# Search for pentaquark states: $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ amplitude analysis

# $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ analysis

- independent check of  $m_{J/\psi p}$  amplitudes
- could indicate the  $P_c^+$  structures are really resonances [[arXiv:1512.01959](#)] and not just some kinematical effects [[arXiv:1507.04950](#)]
- Cabibbo suppressed partner of  $\Lambda_b \rightarrow J/\psi K^- p$  decay mode

$$\frac{\mathcal{B}(\Lambda_b \rightarrow J/\psi p\pi^-)}{\mathcal{B}(\Lambda_b \rightarrow J/\psi K^- p)} = 0.0824 \pm 0.0024 \pm 0.0042$$

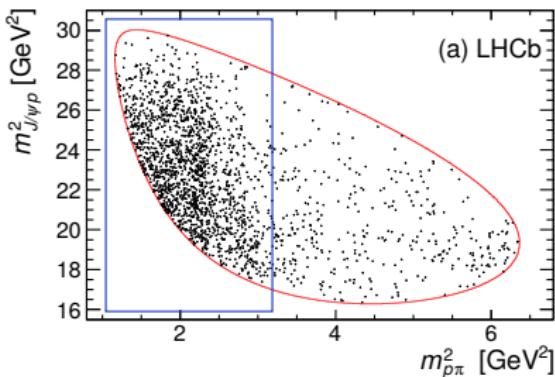
⇒ more than a factor of 10 lower statistics [[JHEP 07 \(2014\) 103](#)]



- candidates selection analogue to the  $\Lambda_b \rightarrow J/\psi K^- p$  one
- vetoes for  $B_d \rightarrow J/\psi K^+\pi^-$ ,  $B_s \rightarrow J/\psi K^+K^-$  and  $\Lambda \rightarrow K^+\pi^-$  backgrounds
- ~ 1885 events in Run1 data

[[arXiv:1606.06999](#)]

## $\Lambda_b^0 \rightarrow J/\psi p\pi^-$ amplitude models



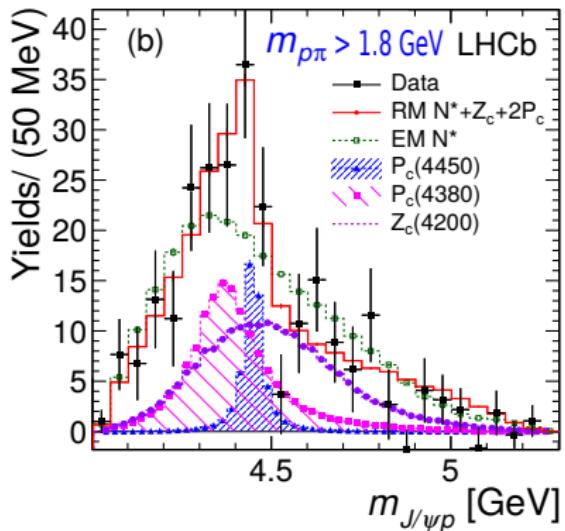
- $\Lambda_b \rightarrow J/\psi N^*$  dominant contributions
- $\Lambda_b \rightarrow P_c^+ \pi^-$
- possible  $Z_c(4200)^- \rightarrow J/\psi \pi^-$  contribution, observed first by the Belle collaboration  
**PRD 90 (2014) 112009**
- $\Rightarrow \Lambda_b \rightarrow Z_c(4200)^- p$

- matrix elements for the three decay sequences are analogue to the ones used in  $\Lambda_b \rightarrow J/\psi K^- p$
- since the sample statistics is limited,  $P_c^+$  and  $Z_c^-$  parameters have been fixed when their amplitudes are included in the model

[arXiv:1606.06999]

## Results

exotic contributions (two  $P_c^+$  or  $Z_c^-$ , or both) are required to obtain an acceptable fit in the  $M_{p\pi} > 1.8 \text{ GeV}$  region



- the significance for the model with 2  $P_c^+$  and no  $Z_c^-$  is  $3.3\sigma$
- the significance for the model with 2  $P_c^+ + Z_c^-$  is  $3.1\sigma$

[arXiv:1606.06999]

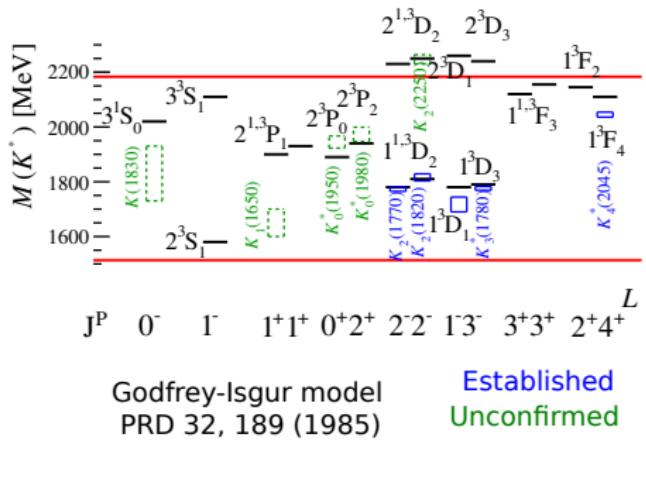
# Search for exotic contributions in $B^+ \rightarrow J/\psi \phi K^+$ decays

## X → J/ψφ structures

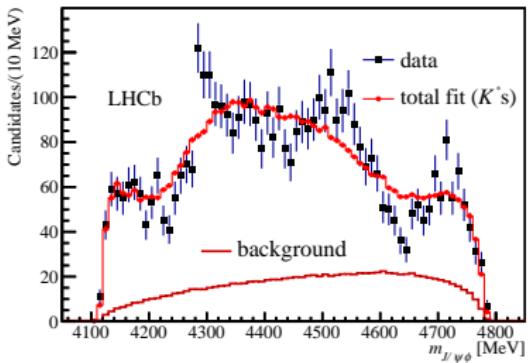
- CDF observation of a **narrow** near threshold structure: **X(4140)**  
[PRL 102, 24002 (2009)]
- manifestly exotic since it is above  $D_s^+ D_s^-$  threshold but narrow
- evidence for a second structure: **X(4274)**
- not confirmed by B-factories and LHCb with  $0.37 \text{ fb}^{-1}$  data
- **all previous results based on 1D fits to  $m_{J/\psi\phi}$**
- LHCb performed the first full 6D amplitude fit thanks to the largest sample of  $B^+ \rightarrow J/\psi\phi K^+$  decays so far

[arXiv:1606.07895], [arXiv:1606.07898]

# Amplitude fit with $K^* \rightarrow \phi K^+$ only



- 12  $K^* + \text{NR } \phi K^+$   $1^+$  S-wave
- BW resonances parametrization,  
floating  $M_0$  and  $\Gamma_0$

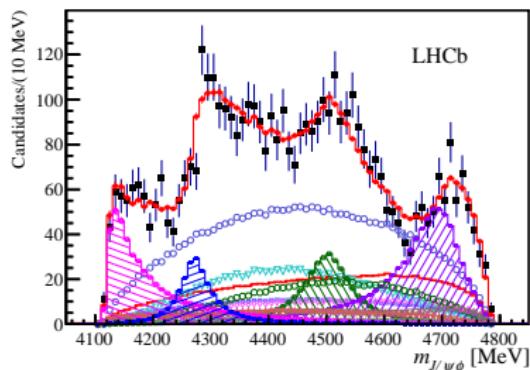
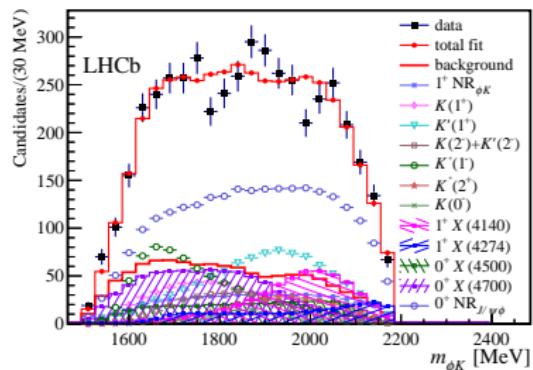


model fails to describe  $m_{J/\psi\phi}$  spectrum:  $p\text{-value} < 10^{-7}$

[arXiv:1606.07895], [arXiv:1606.07898]

## Exotic contributions and default amplitude model

- added  $B^+ \rightarrow XK^+$  and  $B^+ \rightarrow Z^+\phi$  decay chains
- only  $B^+ \rightarrow XK^+$  provides significant improvements in the description of data
- **7  $K^*$  + 4 X +  $\phi K^+$  +  $J/\psi\phi$  nonresonant components**

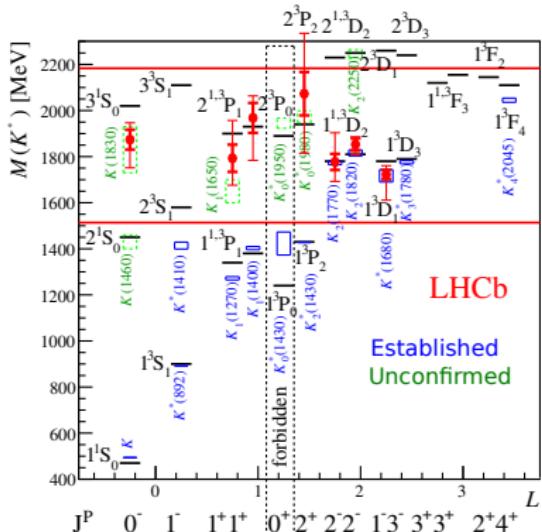


**successful description of  $m_{J/\psi\phi}$  spectrum: p-value = 22%**

[arXiv:1606.07895], [arXiv:1606.07898]

# Results [arXiv:1606.07895], [arXiv:1606.07898]

State	$M_0$ [MeV]	$\Gamma_0$ [MeV]	$J^{PC}$
$X(4140)$ @ 8.4 $\sigma$	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{21}_{-14}$	$1^{++}$ @ 5.7 $\sigma$
$X(4274)$ @ 6.0 $\sigma$	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{8.4}_{-11.1}$	$1^{++}$ @ 5.8 $\sigma$
$X(4500)$ @ 6.1 $\sigma$	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{21}_{-20}$	$0^{++}$ @ 4.0 $\sigma$
$X(4700)$ @ 5.6 $\sigma$	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{42}_{-33}$	$0^{++}$ @ 4.5 $\sigma$



- excellent agreement of  $X(4140)$  mass with previous observations, but width is much larger  
 $M_{CDF} = 4143.4 \pm 3.0 \pm 0.6$  MeV,  
 $\Gamma_{CDF} = 15.3^{+10.4}_{-6.1} \pm 2.5$  MeV
- confirmation of  $X(4274)$  state, first observation of two  $0^{++}$  states
- $K^{*+}$  spectroscopy: excellent agreement with theory and previous experiments

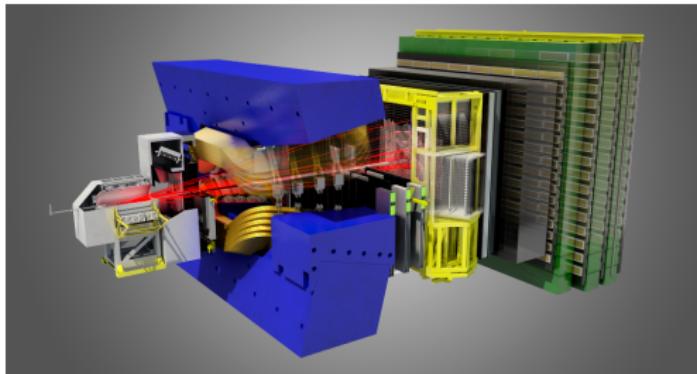
## Conclusions

- no visible  $X(5568)^-$  signal at LHCb, contradicting D0 claim(s)
- pentaquark observations in the  $\Lambda_b^0 \rightarrow J/\psi K^- p$  amplitude analysis is strongly supported by the same decay model independent analysis and by the  $\Lambda_b^0 \rightarrow J/\psi p\pi^-$  amplitude analysis
  - resonant behaviour of  $P_c(4380)^+?$
  - evidences  $\rightarrow$  observations in  $\Lambda_b^0 \rightarrow J/\psi p\pi^-?$
- 4  $J/\psi\phi$  structures observed
  - nature of  $X(4140)$ . Cusp interpretation is slightly preferred versus BW (1.6  $\sigma$ ): resonance or cusp?
- exceptional LHC performance in 2016 following 13 TeV commissioning in 2015 is very promising to answer the questions left open and to find new exotic states

Thanks and stay tuned!

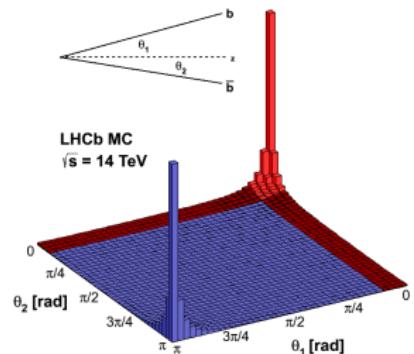
**Extra slides**

# The LHCb detector



- precise primary and secondary vertex reconstruction:  $\sigma_{IP} = (15 + 29/p_T) \mu\text{m}$
- excellent momentum resolution:  $\Delta p/p = 0.5\%$  at low momentum to 1.0 % at 200 GeV/c
- very good separation of charged  $\pi$ , K and p and excellent muon identification over the  $2 < p < 100 \text{ GeV}/c$  range

- $2 < \eta < 5$  range:  $\sim 25\%$  of  $b\bar{b}$  pairs inside LHCb acceptance

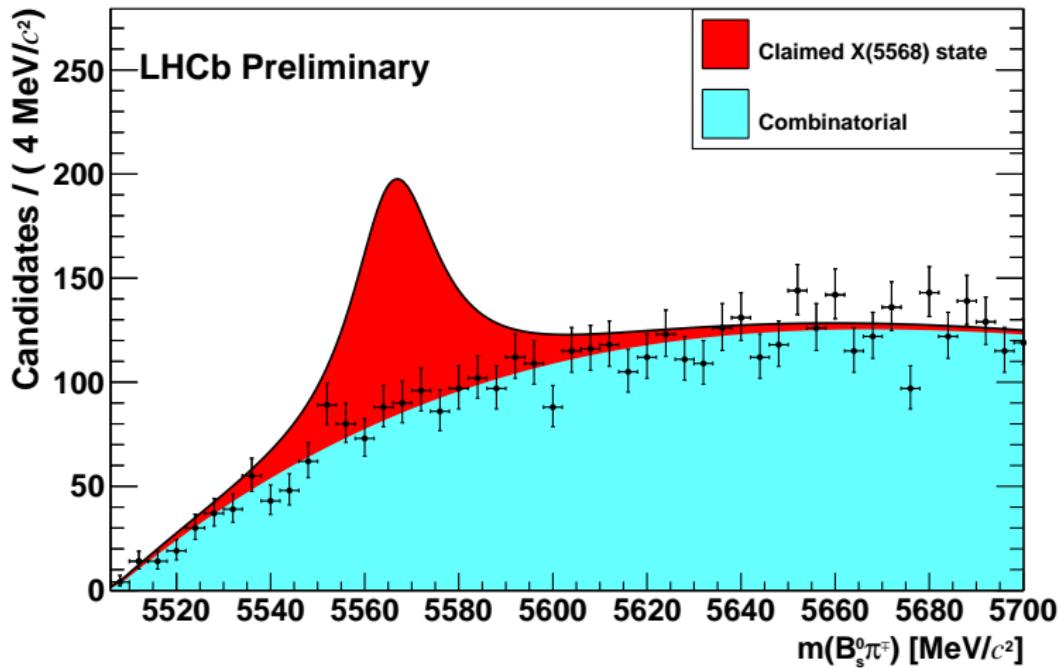


- $\mathcal{L} = 3 \text{ fb}^{-1}$  in 2011+2012 data taking  $\Rightarrow \sim 10^{12} b\bar{b}$  pairs
- data taking restarted in 2015: at the end of 2016 we expect to double the statistics

## Summary of LHCb results on exotic states

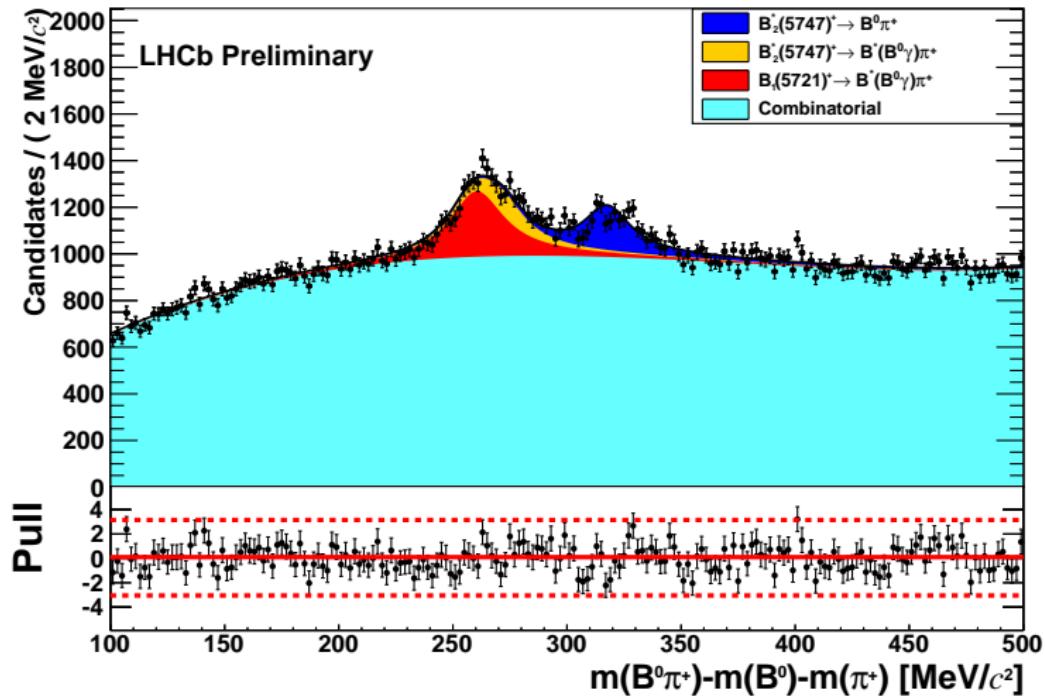
- search for  $X(5568)^- \rightarrow B_s\pi^-$  [[arXiv:1608.00435](#)]
- observation of exotic hadrons in  $B^+ \rightarrow J/\psi\Phi K^+$  [[arXiv:1606.07895](#)], [[arXiv:1606.07898](#)]
- evidence for exotic hadrons in  $\Lambda_b \rightarrow J/\psi p\pi^-$  [[arXiv:1606.06999](#)]
- observation of pentaquarks in  $\Lambda_b \rightarrow J/\psi K^- p$ 
  - model independent analysis [[arXiv:1604.05708v1](#)]
  - amplitude analysis and resonant character [[PRL 115 \(2015\) 072001](#)]
- $Z(4430)^-$  confirmation in  $B_d \rightarrow \psi(2S)K^+\pi^-$ 
  - model independent analysis [[PRD 92 \(2015\) 112009](#)]
  - amplitude analysis and resonant character [[PRL 112 \(2014\) 222002](#)]
- $X(3872)$  studies
  - quantum numbers measurement  $\Rightarrow J^{PC} = 1^{++}$  [[PRD 92 011102\(R\) \(2015\)](#)], [[PRL 110 222001 \(2013\)](#)]
  - measurement of  $\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)/\mathcal{B}(X(3872) \rightarrow J/\psi\gamma)$  [[Nucl.Phys.B 886 \(2014\) 665-680](#)]
  - mass measurement [[JHEP 06 \(2013\) 065](#)]
  - search for new decays [[EPJC \(2013\) 73:2462](#)], [[arXiv:1607.06446](#)]
  - production [[EPJC \(2012\) 72:1972](#)]

# How the X(5568) would appear if $\rho^{\text{LHCb}} = \rho^{\text{D}0}$ ?

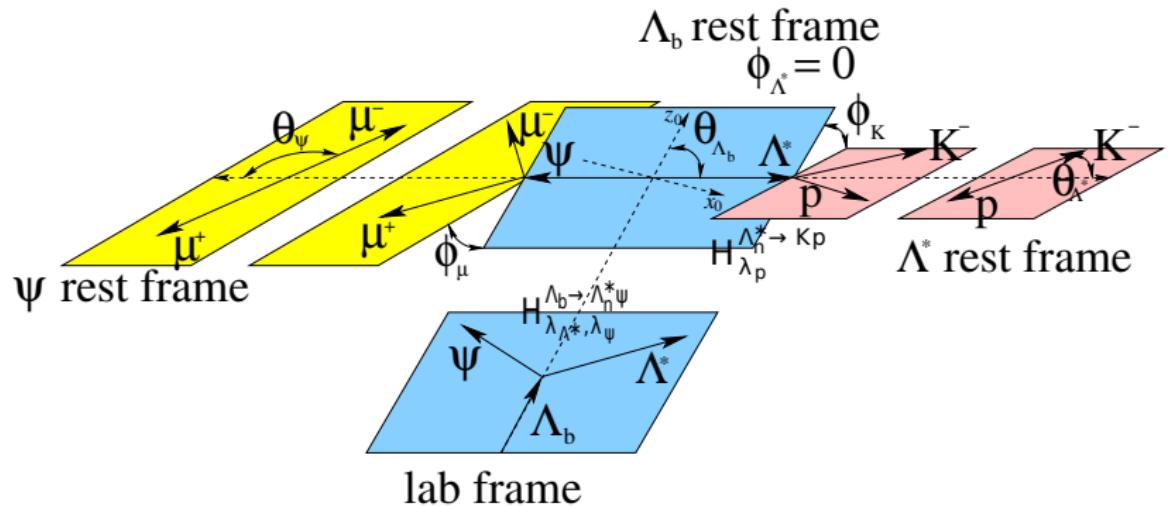


[LHCb-CONF-2016-004]

# $B_s^0\pi^-$ cross-check channels



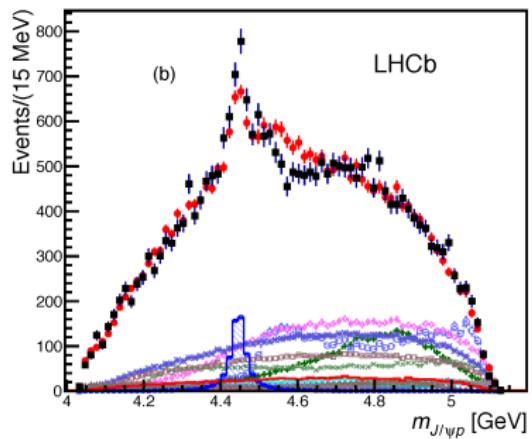
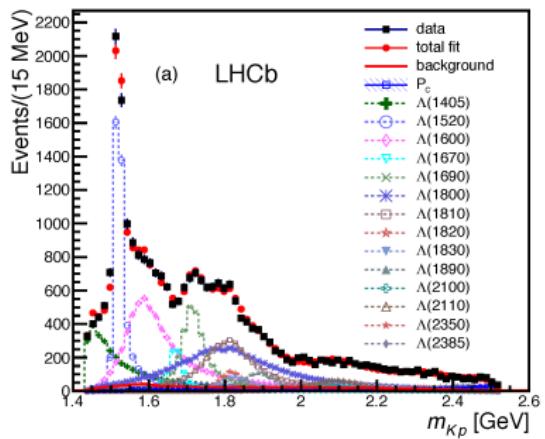
# Isobar model for $\Lambda_b^0 \rightarrow J/\psi \Lambda^*$



$$\begin{aligned} \mathcal{M}_{\lambda_{\Lambda_b}, \lambda_p, \Delta \lambda_\mu}^{\Lambda^*} &= \sum_n R_n(m_{Kp}) \mathcal{H}_{\lambda_p}^{\Lambda_n^* \rightarrow Kp} \sum_{\lambda_\psi} e^{i \lambda_\psi \phi_\mu} d_{\lambda_\psi, \Delta \lambda_\mu}^1(\theta_\psi) \\ &\quad \sum_{\lambda_{\Lambda^*}} \mathcal{H}_{\lambda_{\Lambda^*}, \lambda_\psi}^{\Lambda_b \rightarrow \Lambda_n^* \psi} e^{i \lambda_{\Lambda^*} \phi_K} d_{\lambda_{\Lambda_b}, \lambda_{\Lambda_n^*} - \lambda_\psi}^{\frac{1}{2}}(\theta_{\Lambda_b}) d_{\lambda_{\Lambda^*}, \lambda_p}^{J_{\Lambda_n^*}}(\theta_{\Lambda^*}) \end{aligned}$$

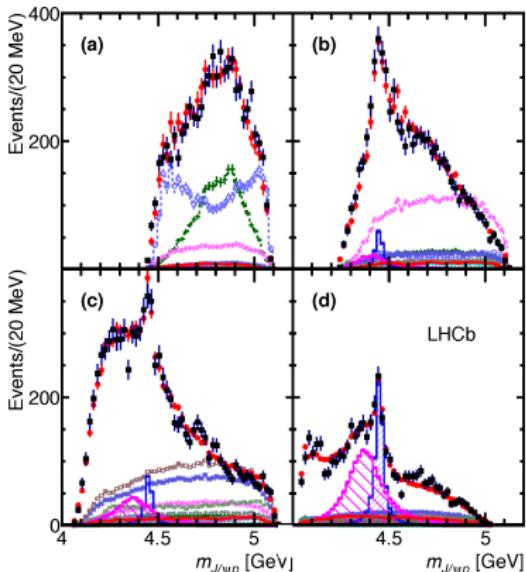
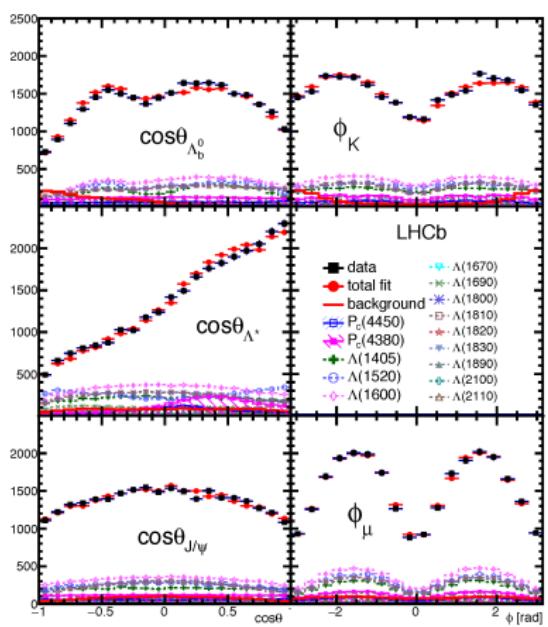
[PRL 115 (2015) 072001]

# One $P_c^+$ resonance



[PRL 115 (2015) 072001]

# $\Lambda_b^0 \rightarrow J/\psi K^- p$ fit projections

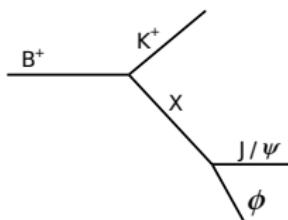


- different ranges of  $m_{Kp}$
- interference evident for  $m_{Kp} > 2 \text{ GeV}$  (d)

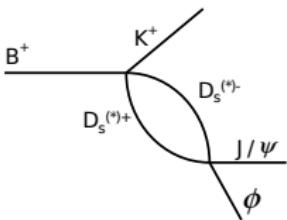
[PRL 115 (2015) 072001]

## Resonance vs cusp interpretations

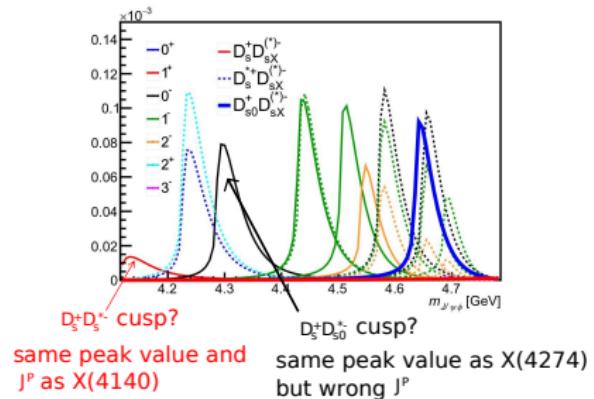
$X(4140)$  and  $X(4274)$  peaks are compatible with kinematical effects due to the S-wave rescattering of virtual  $D_{sX}^{(*)\pm}$  pairs (**cusps**) [arXiv:1504.07952]



Breit-Wigner



Cusp



- the cusp amplitude provides a better fit than BW ( $1.6 \sigma$ ) for the  $X(4140)$
- $X(4274)$  is better parametrized with a Breit-Wigner