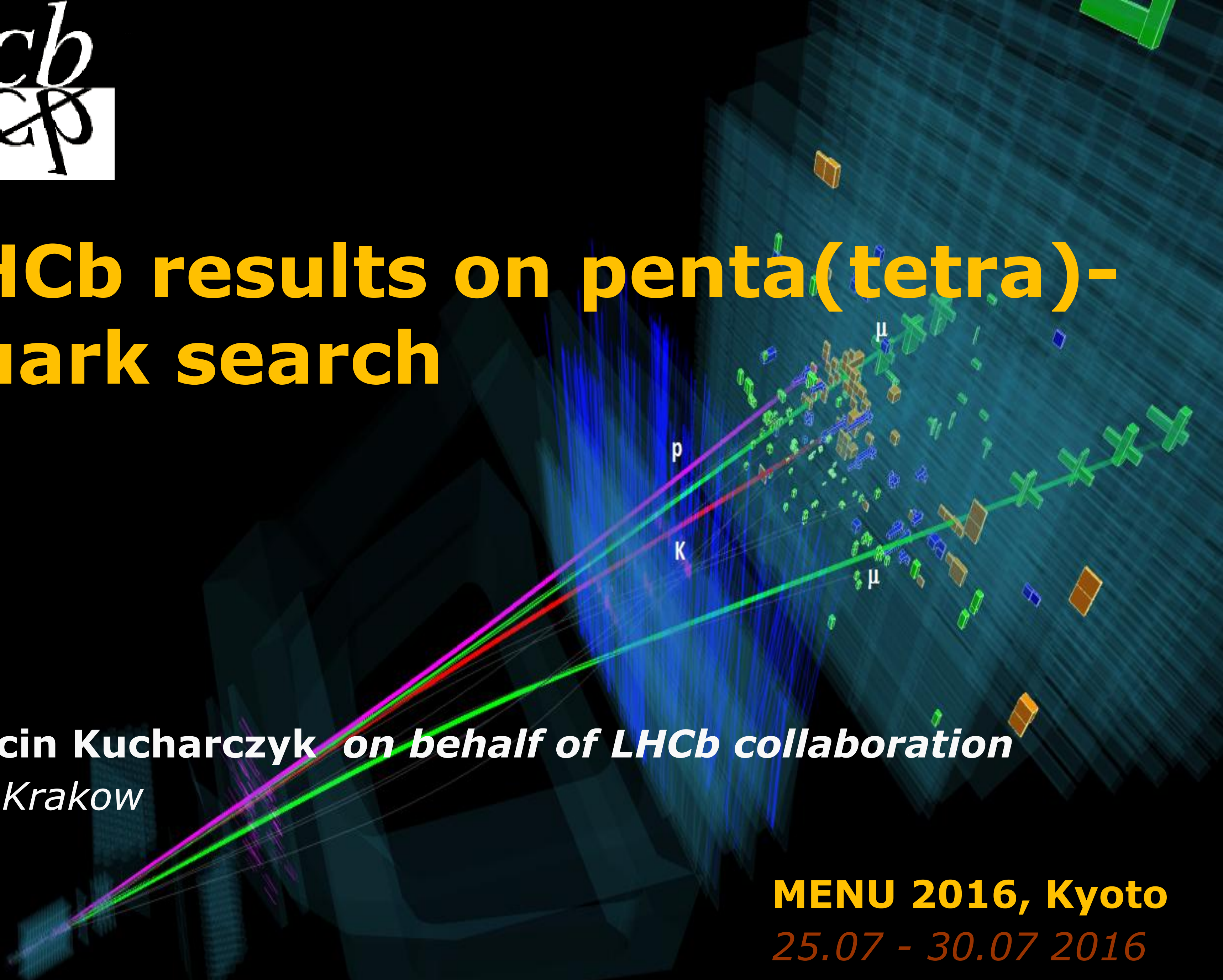
LHCb results on penta(tetra)-quark search



Marcin Kucharczyk ***on behalf of LHCb collaboration***
HNI Krakow

MENU 2016, Kyoto
25.07 - 30.07 2016

Outline

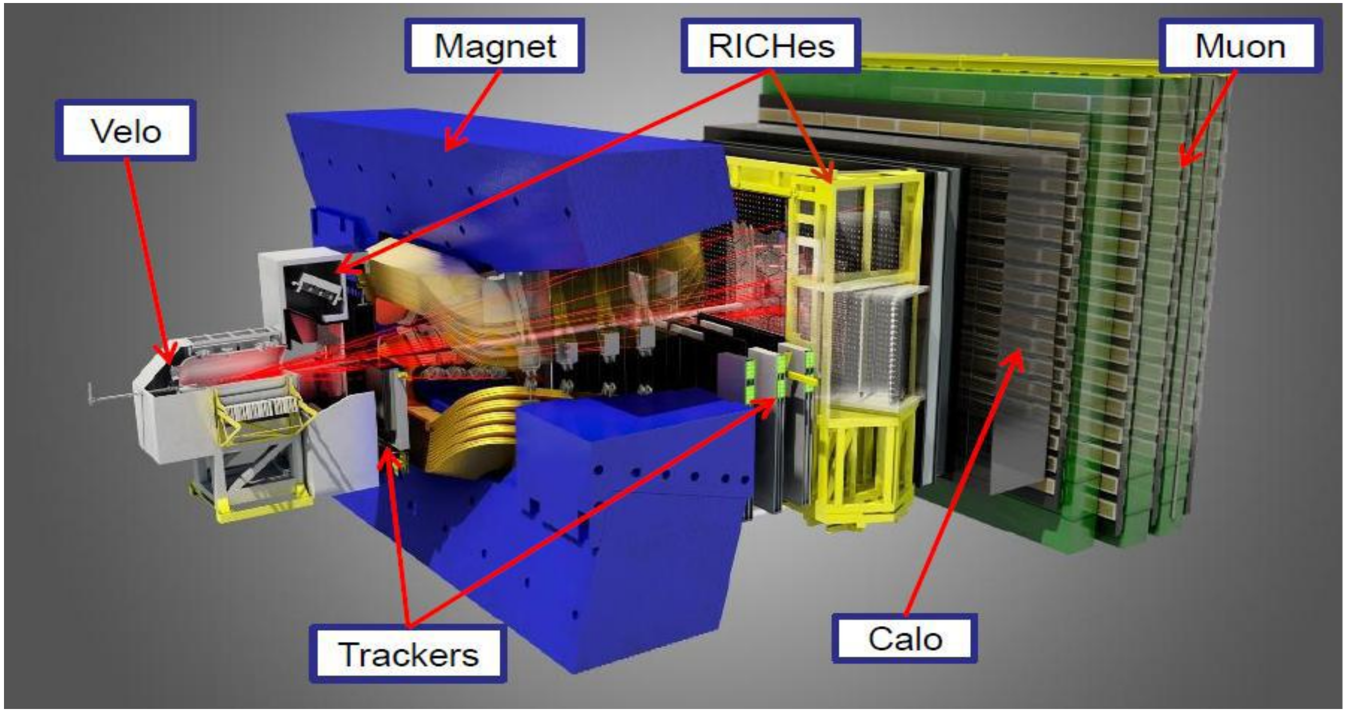
- **Pentaquark discovery in $\Lambda_b \to J/\psi\ p\ K$**
  - $\to$ full amplitude analysis [PRL 115 (2015) 072001]
  - $\to$ model independent analysis [LHCb-PAPER-2016-009]
- Exotic baryonic resonances in $\Lambda_b \to J/\psi\ p\ \pi$ [LHCb-PAPER-2016-015]
- Confirmation of resonant nature of $Z(4430)^-$
  - $\to$ 4D amplitude analysis [PRL 112 (2014) 222002]
  - $\to$ moment analysis [PRD 92 (2015) 112009]
- Probing *X(3872)* composition
  - $\to$ quantum number confirmed 1^{++} [PRD 92 (2015) 011102]
- Tetraquark searches in $B_s\ \pi$
  - $\to$ preliminary results [LHCb-CONF-2016-004]

LHCb detector

- forward spectrometer at LHC pp collider

[Int. J. Mod. Phys. A30 (2015) 1530022]

- designed for CP violation & rare decays of heavy mesons



- precision coverage unique for LHCb $2 < \eta < 5$ *(~40% of bb in forward region)*
- excellent tracking and vertexing *(σ(IP) ~ 20* μm *for high-p_T tracks)*
- good PID separation up to 100 GeV
- efficient trigger with *μ's*

Dataset: 1 + 2 fb^{-1} in 2011 + 2012

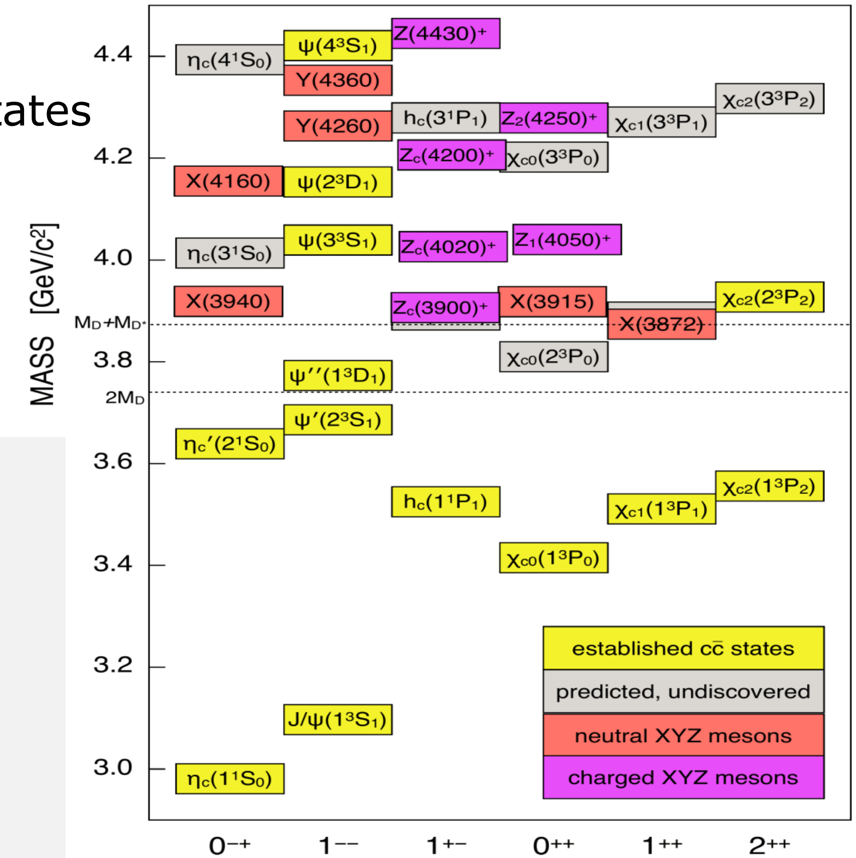
XYZ states

[Olsen arXiv:1403.1254]

Bound states of quarks were first proposed in 1964 by Gell-Mann and Zweig

- many different exotic charmonium-like states has been seen so far
- CDF/D0, Belle/BaBar, LHC, BESIII
- properties do not fit very well to the quarkonia picture

charmonium & charmonium-like mesons



+2 P_c's +4 new $J/\psi\varphi$

Many theoretical interpretations discussed

→ conventional quarkonia

→ multiquark states

→ meson molecules

→ hybrid mesons

→ threshold effects

No clear picture

→ *need experimental & theoretical effort to understand strong interaction dynamics that can cause their production and structure*

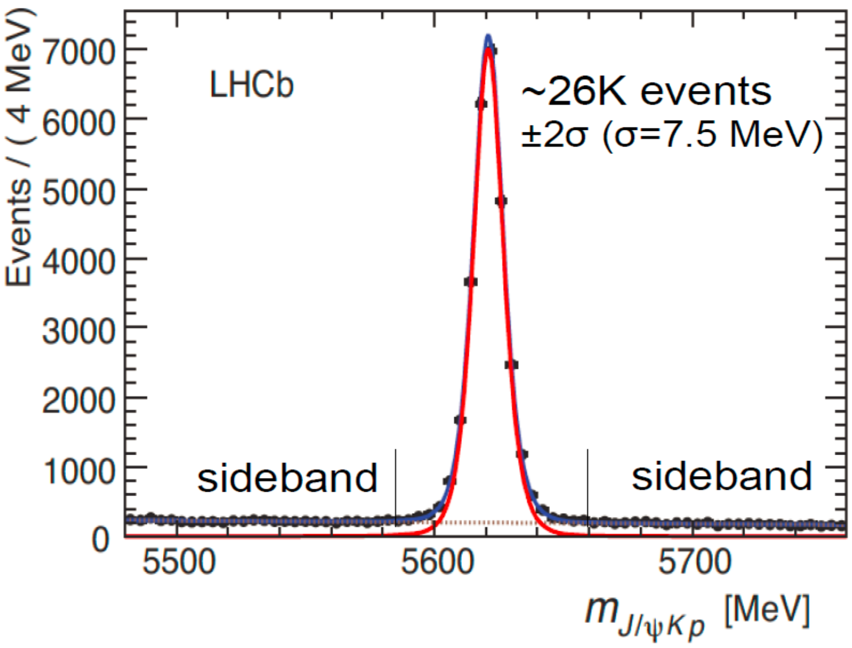
Pentaquarks

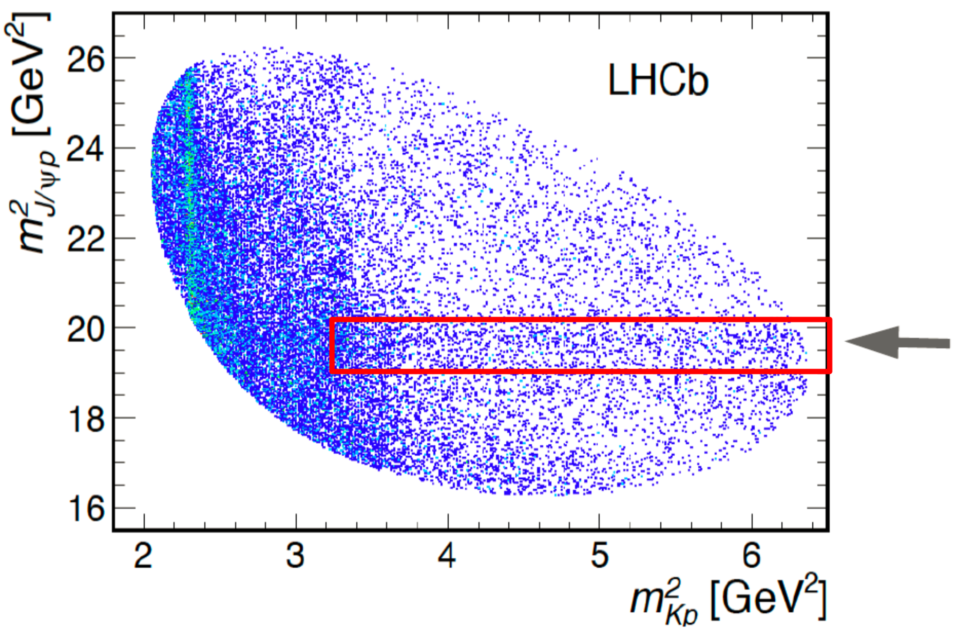
P_c: $\Lambda_b \rightarrow J/\psi\ p\ K$ production

PRL 115 (2015) 072001

Use large production of b-baryons at LHCb

- sample with > 26K signal candidates
- background from sidebands
- 5.4% of combinatorial background in the signal region





→ peak in m_{Kp} due to excited resonances

→ unusual feature in $m_{J/\psi p}$

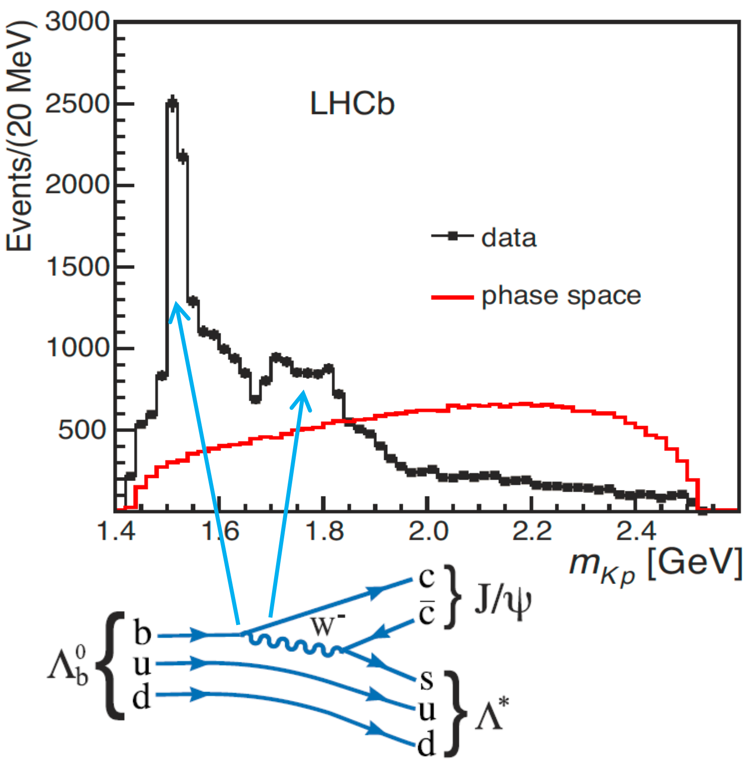
P_c: *unexpected structure*

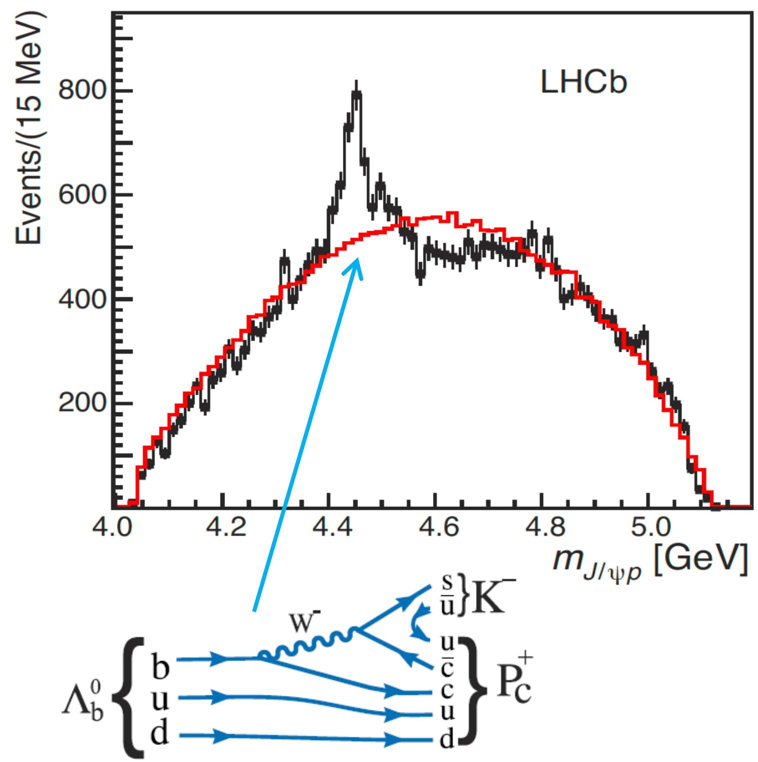
Mass projections of $\Lambda_b \rightarrow J/\psi\ p\ K$

PRL 115 (2015) 072001

- expect Λ^* resonances to dominate
- $J/\Psi p$ resonance must have $c\bar{c}uud$

unexpected peaking structure observed in $J/\psi p$ system





Alternative explanations:

- *specific veto for $B_s \rightarrow J/\psi KK$ and $B_0 \rightarrow J/\psi K\pi$*
- *ghost- and clone-tracks are removed*
- ***is this a Λ^* reflection?***

P_c: *amplitude analysis*

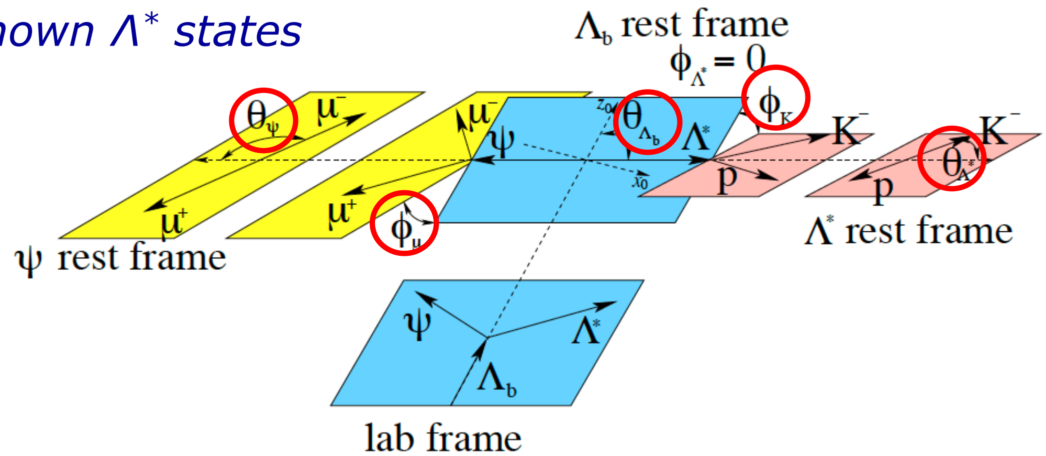
PRL 115 (2015) 072001

Six-dimensional amplitude fit

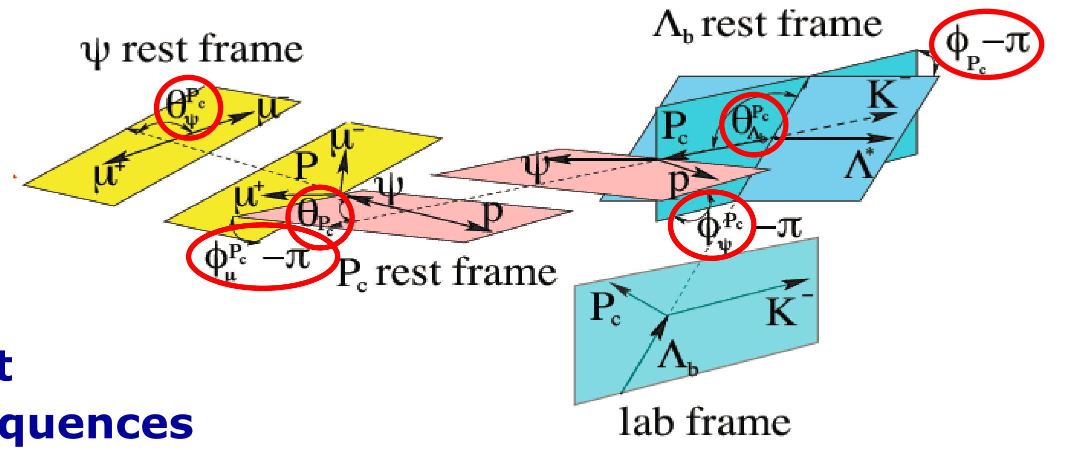
- resonance inv. mass, 3 helicity angles, 2 differences between decay planes
- resonances described by Breit-Wigner or Flatté
- *amplitude model includes all known Λ^* states*

Two interfering channels:

$\Lambda_b^0 \to J/\psi \Lambda^*, \ \Lambda^* \to pK^-$



$\Lambda_b^0 \to P_c^+ K^-, \ P_c^+ \to J/\psi p$



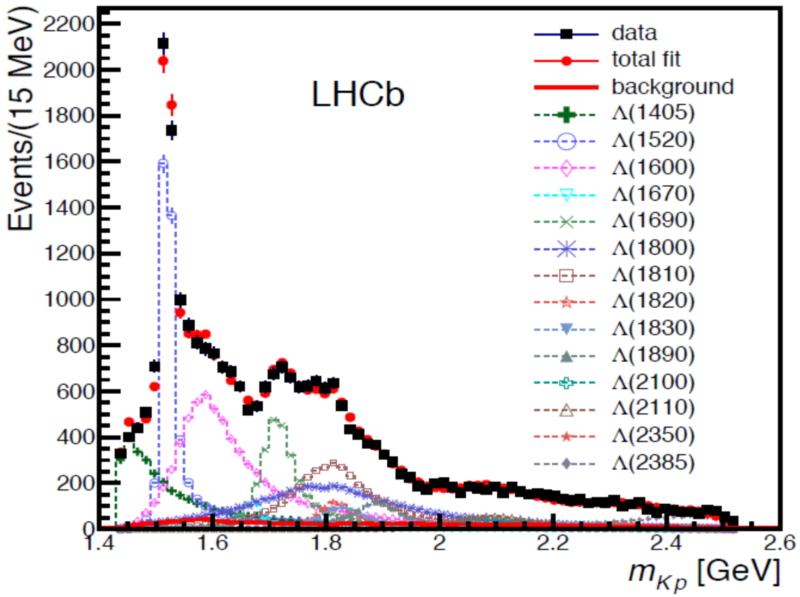
Full amplitude analysis that incorporates both decay sequences

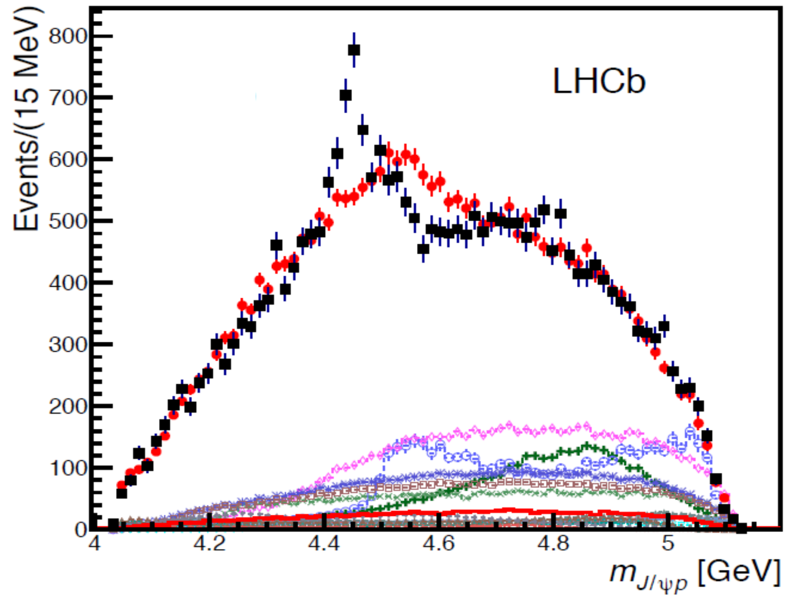
P_c: *results without P_c states*

PRL 115 (2015) 072001

Extended model with all possible known Λ^* amplitudes

- $m(pK)$ looks good but not $m(J/\psi p)$





Other possibilities checked:

- isospin violating decays of Σ^{*0}
- adding two new Λ^* states with free mass & width
- additional non-resonant Λ^*'s

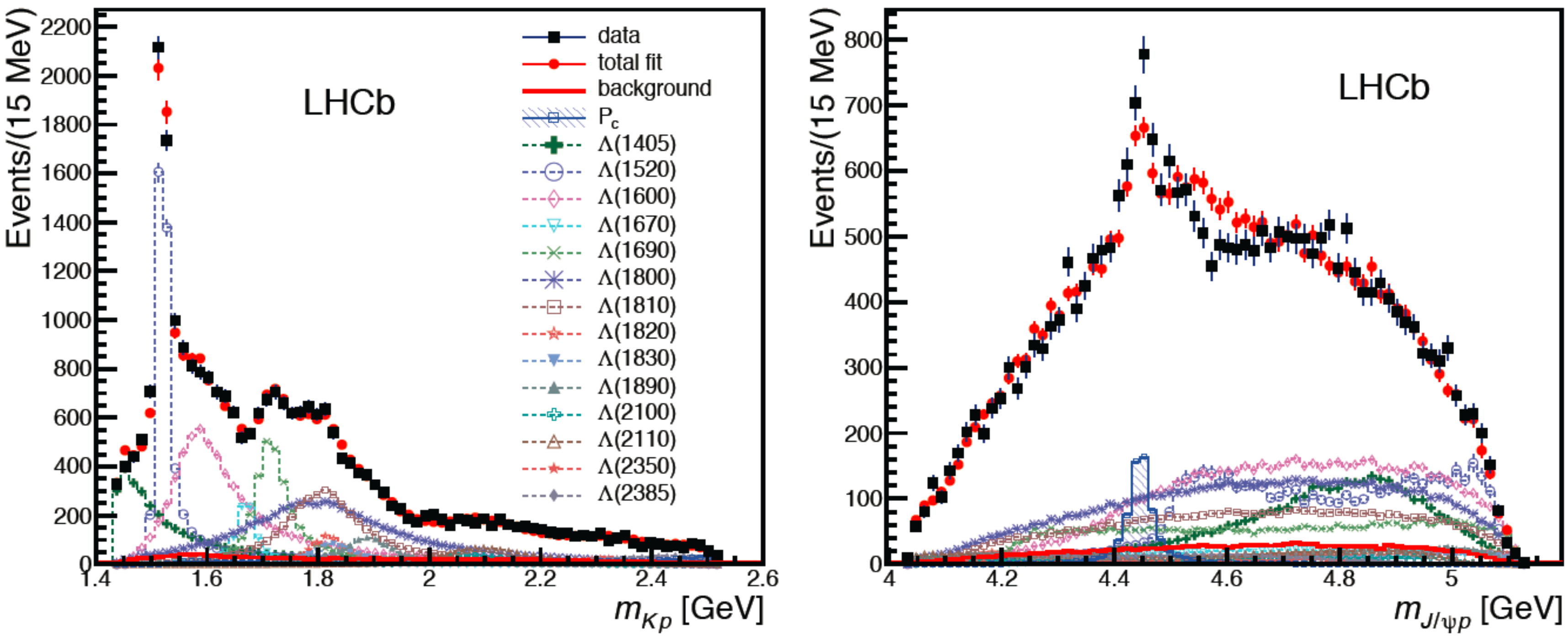
Still fail to describe the data!

P_c: *extended model with one P_c*

PRL 115 (2015) 072001

Try all Λ*'s with J^P up to 7/2±

- improvement with adding a $J^P = 5/2^+$ pentaquark
- still not a good fit to m($J/\psi p$)

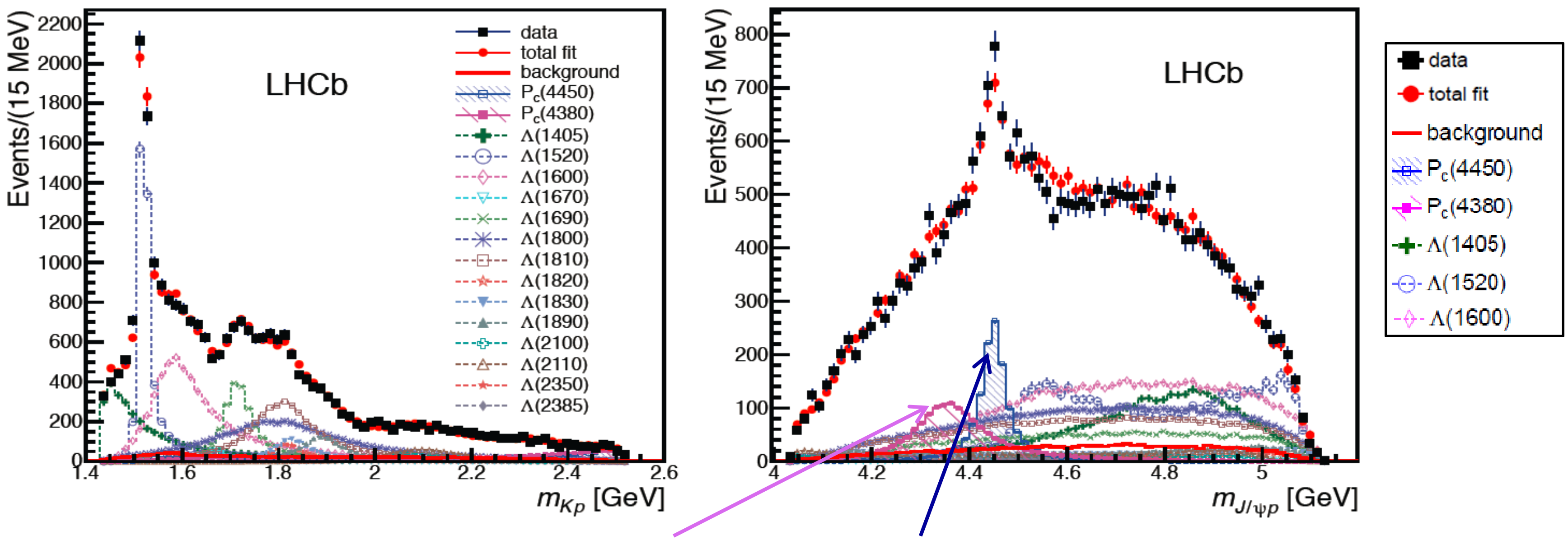


P_c: *reduced model with two P_c's*

PRL 115 (2015) 072001

Two peaking components in m($J/\psi p$) with opposite parities required to fit data

- best fit has J^P = 3/2$^-$ *(lower mass)* and 5/2$^+$ *(higher mass)*
- (5/2$^+$,3/2$^-$) also give good fits



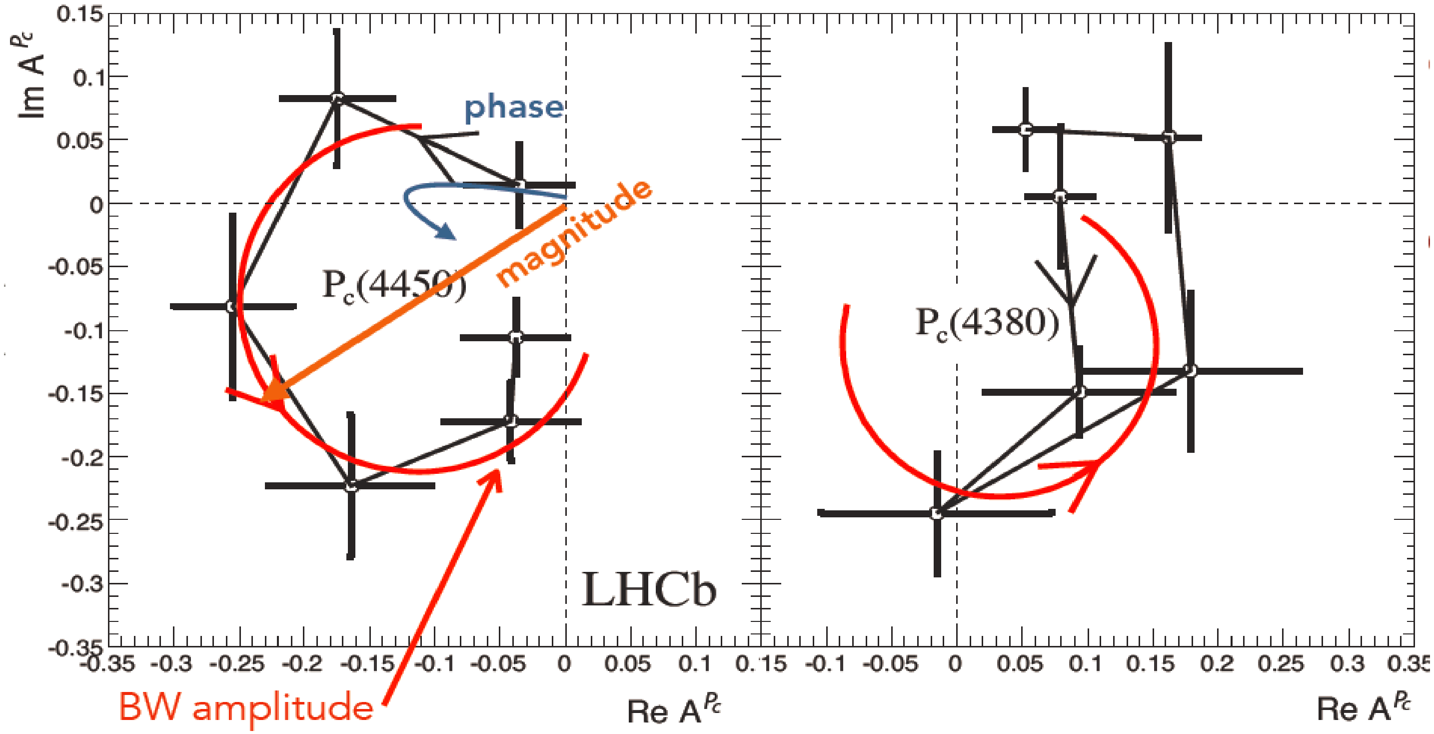
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

P_c: *resonant behaviour*

PRL 115 (2015) 072001

Argand diagrams show the typical phase motion of a resonance

- amplitudes for 6 bins between $+\Gamma$ and $-\Gamma$
- fast change of phase crossing maximum of magnitude
- clear resonant-like behavior of the $P_c(4450)^+$
- for the $P_c(4380)^+$ it is not obvious → *one point is off by 2σ*

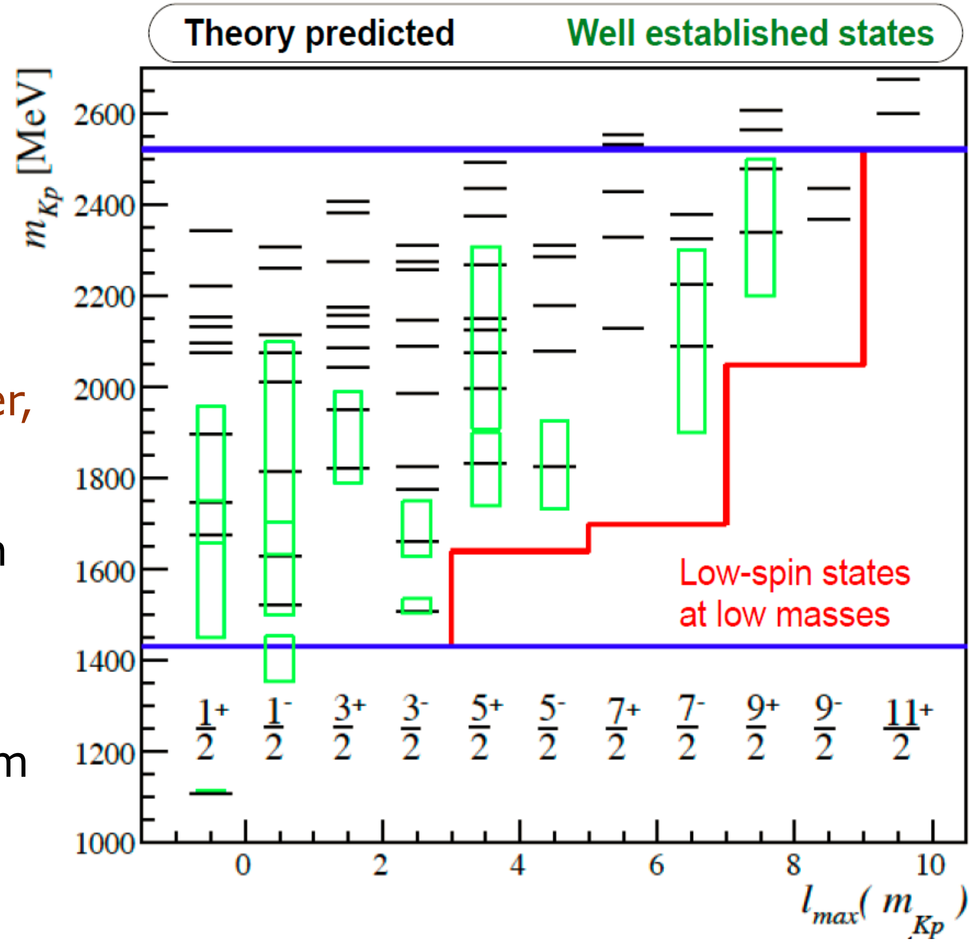


P_c: *model independent*

LHCb-PAPER-2016-009

Study $\Lambda_b \rightarrow J/\psi pK$ decay with a model independent approach wrt *Kp* contributions

- confirm that conventional *Kp* contributions cannot describe data
- no assumptions about their number, masses, widths and interference
- allow maximum orbital momentum depending on *Kp* mass
- analysis based on the Legendre polynomial moments extracted from the *Kp* system



H_0: hypothesis that the data are described by $\Lambda_b \rightarrow J/\psi\ \Lambda^*\ (\Lambda^* \rightarrow pK)$

P_c: *model independent*

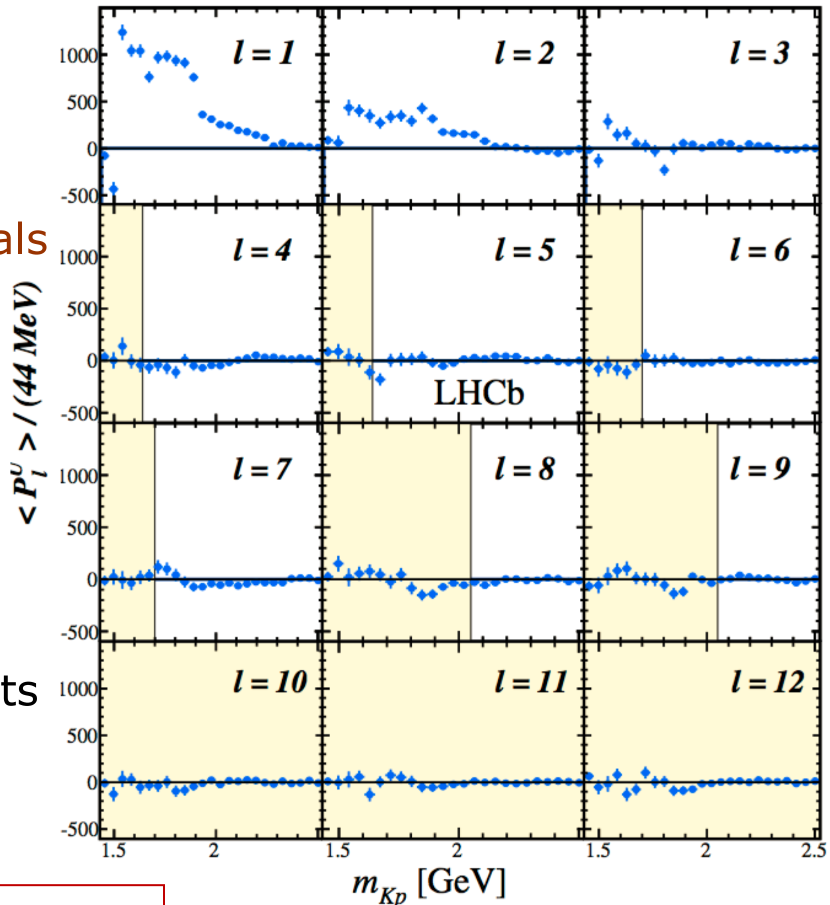
LHCb-PAPER-2016-009

Method introduced by Babar [PRD 79 (2009) 112001], improved by LHCb in Z(4430) analysis

- 2D Dalitz analysis
- same data as in amplitude analysis
- describing $\cos(\theta_{\Lambda^*})$ with Legendre polynomials

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

- l_{max} cannot be higher than 2 J_{max} *(J_{max} - twice the highest Kp spin)*
- other narrow resonances would add moments of higher rank



Construct hypothesis from measured moments
- H_0 : $\Lambda^* \to pK$ only, $l \leq l_{\max}$
- H_1 : allow contributions from high order moments

Filter out maximum spin for each m(*Kp*)

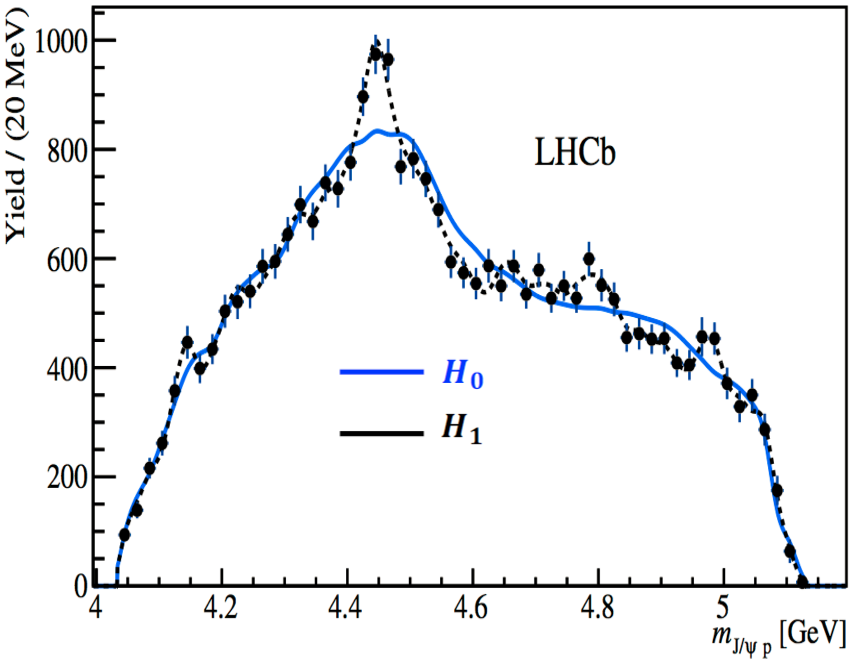
P_c: *model independent*

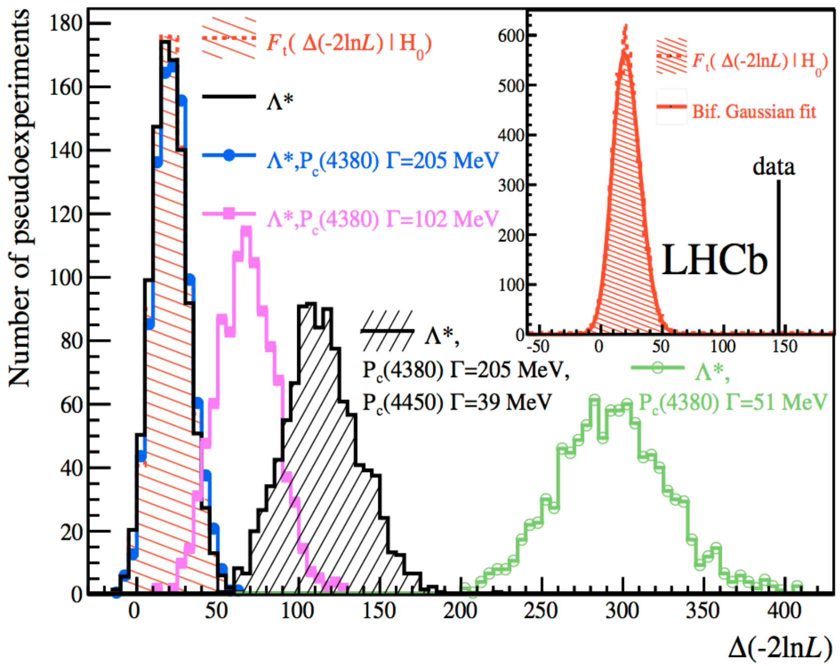
LHCb-PAPER-2016-009

Use theoretical predictions and experimental results to set $l_{max}(m_{Kp})$ for all masses within the kinematically allowed range

- weight according to m_{Kp} and the moments *(filter out l_{max} according to m_{Kp})*
- look at reflections of the *Kp* system into the *J/ψp* system

likelihood ratio to test various hypotheses





null hypothesis gives poor description of $m_{J\psi p}$

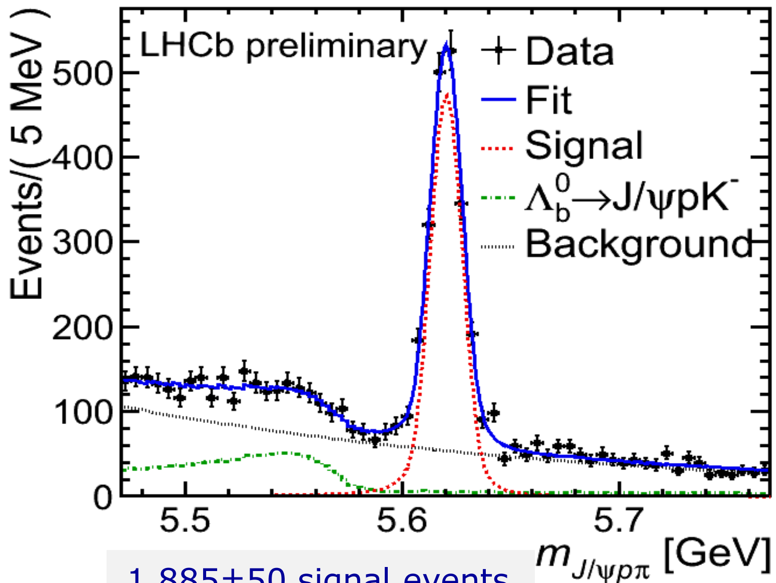
H_0 hypothesis rejected at > 9σ

P_c: *Cabibbo suppressed $\Lambda_b \to J/\Psi\ p\ \pi$*

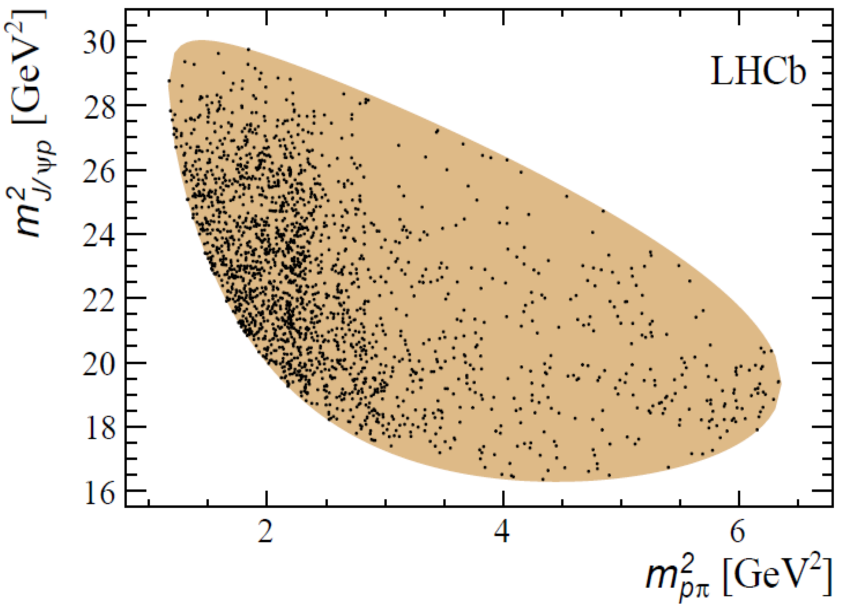
LHCb-PAPER-2016-015

Confirm that P_c states are really resonances

- Cabibbo suppressed signal > 10 times lower wrt $\Lambda_b \to J/\Psi\ p\ K$
- background > 3 times higher



1,885±50 signal events
~18% background



No obvious structure on Dalitz plot → amplitude analysis

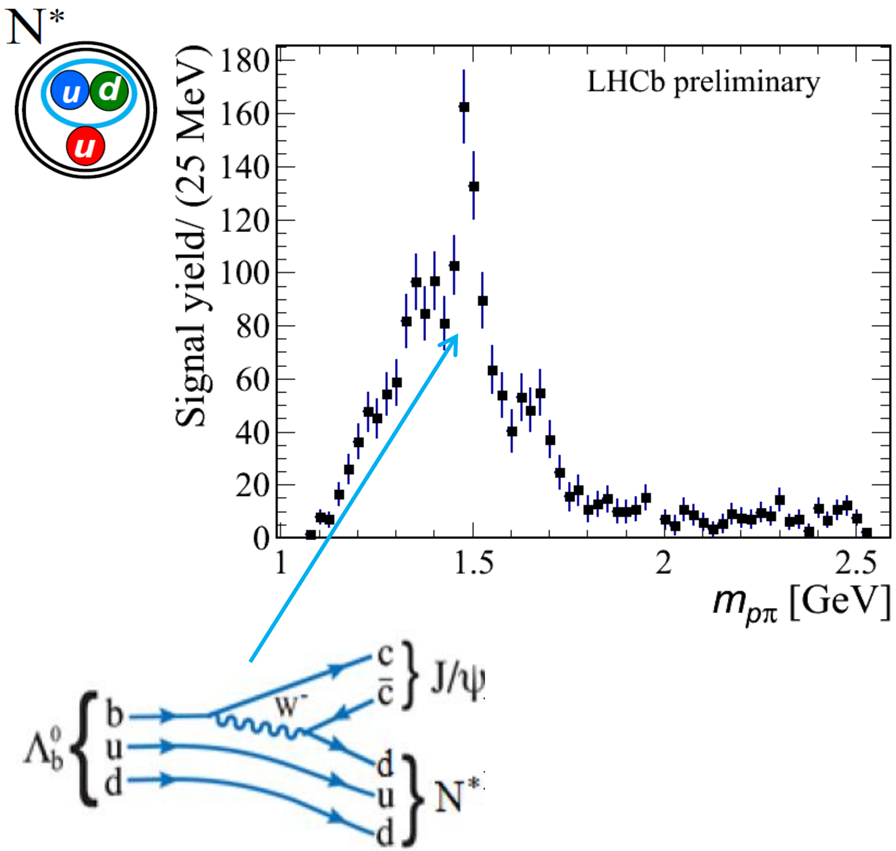
- consistency check with Cabibbo favored $\Lambda_b \to J/\Psi\ p\ K$
- 6D fit to interfering amplitudes: $\Lambda_b \to J/\Psi\ N^*$, $\Lambda_b \to P_c^+ \pi^-$, $\Lambda_b \to Z_c\ p$ [PRD 90 (2014) 112009]
- limited statistics → *some parameters fixed*

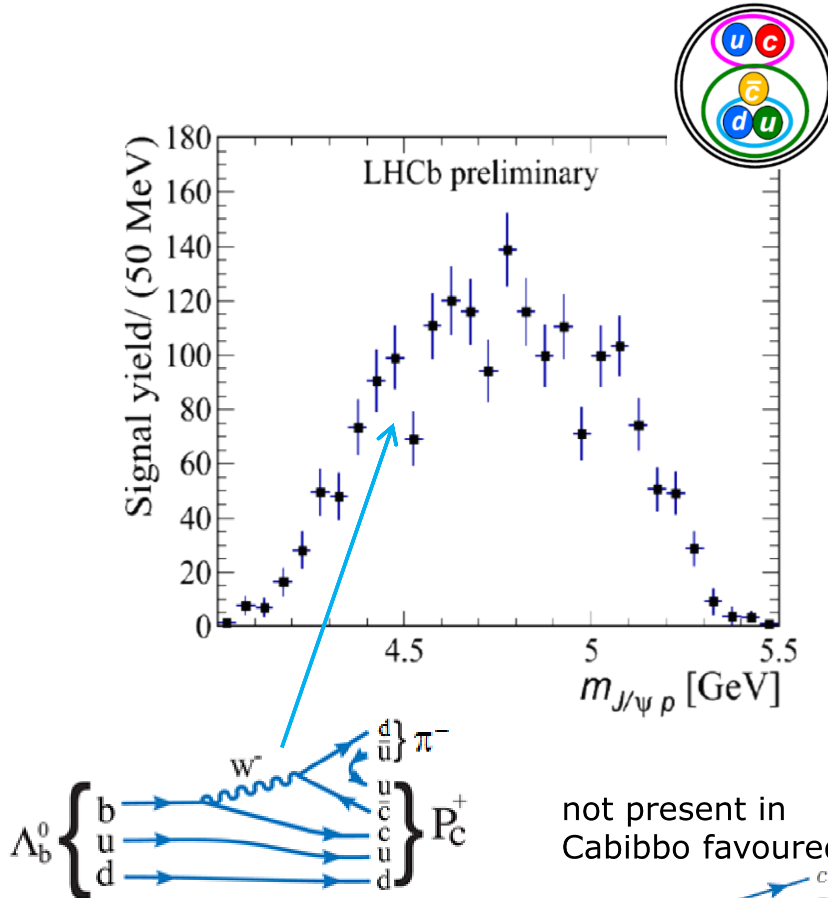
P_c: *Pentaquarks in $\Lambda_b \rightarrow J/\Psi\ p\ \pi$*

LHCb-PAPER-2016-015

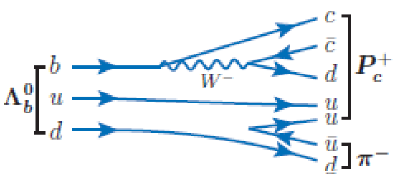
Mass projections of $\Lambda_b \rightarrow J/\psi\ p\ \pi$

- nucleon excitations $\rightarrow m_{p\pi}$
- exotic pentaquark $\rightarrow m_{J/\psi p}$





not present in
Cabibbo favoured



No obvious structure in $m_{J/\psi p}$

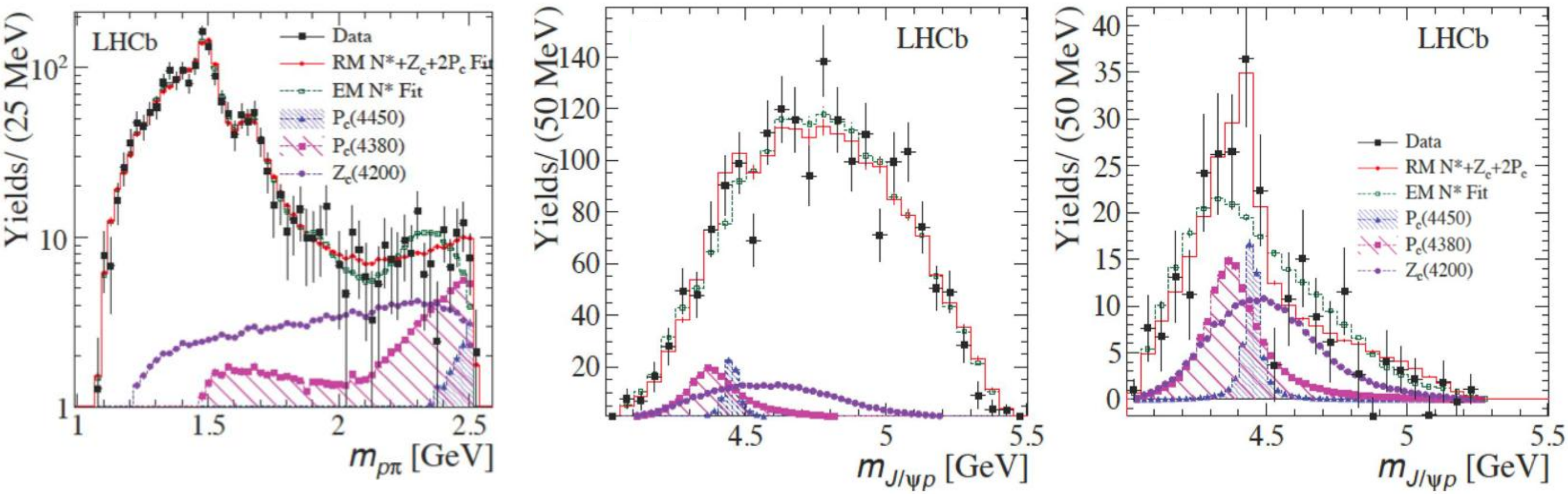
P_c: *Amplitude analysis of $\Lambda_b \to J/\Psi\ p\ \pi$*

LHCb-PAPER-2016-015

Not enough statistics for open-ended search of exotic hadrons in $\Lambda_b \to J/\Psi\ p\ \pi$

- test the data for presence of previously observed states:
  - → $P_c(4380)^+$, $P_c(4450)^+$ (LHCb)
  - → $Z_c(4200)^-$ (Belle, [PRD, 90, 112009 (2014)])

$m_{p\pi} > 1.8$ GeV



Exotic components required for acceptable fit in all regions of phase-space

- combined significance of 3 states together > 3σ evidence for exotic hadrons
- individual exotic hadron contributions are not significant

P_c: *interpretations*

PRL 115 (2015) 072001

Data preference for 2 states

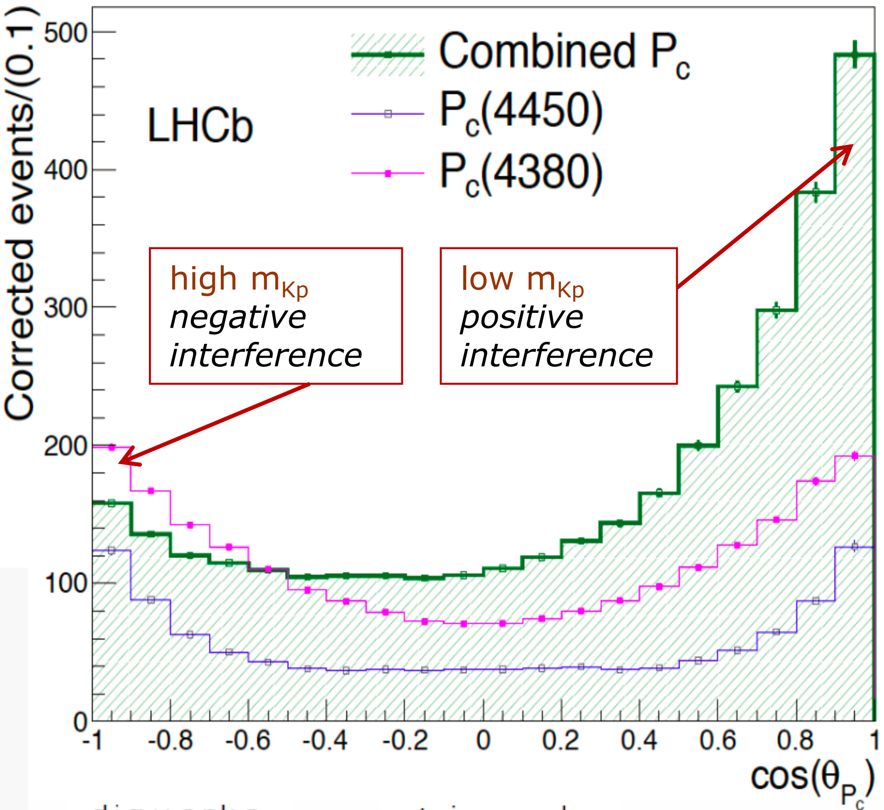
- interference pattern only for states with opposite parity
- needed to explain P_c decay anglular distributions

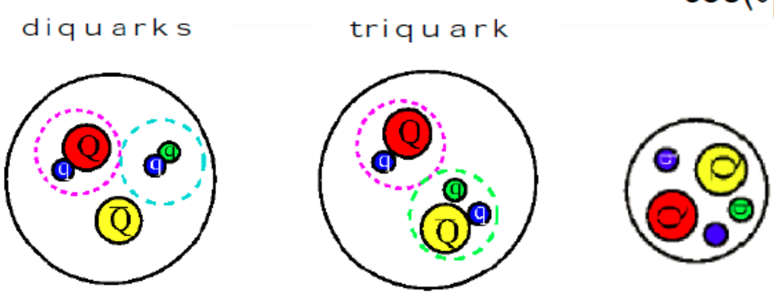
Models have to explain two P_c states + their properties

Pentaquark models

- two colored diquarks + anti-quark [Maiani et al arXiv:1507.04980]
- colored diquark + colored triquark [Lebed arXiv:1507.05867]
- tightly bound quarks [Nucl. Phys. B123 (1977) 507]

(see previous theory talks)

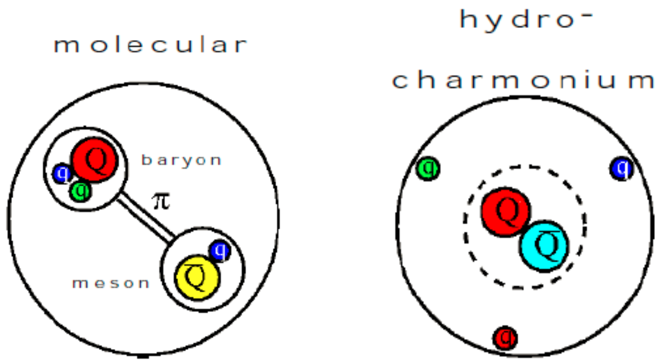




P_c: *interpretations*

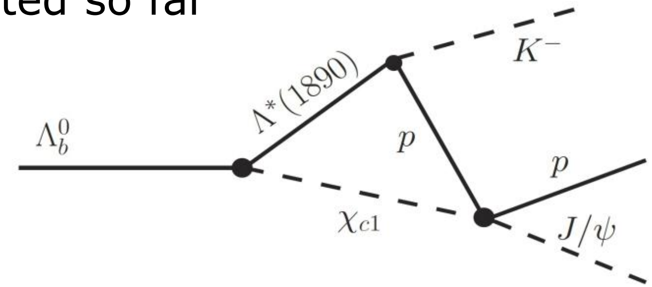
Molecular models

- meson exchange for binding
  [Z. Phys. C61 (1994) 525]
- baryo(hydro)charmonium
  $\rightarrow$ molecular-like state of $J/\psi\ N$
  [arXiv:1508.00888]



Kinematic effects in non-perturbative rescattering processes

- size of rescattering amplitude not predicted so far
- difficult to predict two states
  [Phys.Rev. D92 (2015) 071502]
  [Phys.Lett. B751 (2015) 59-62]



Experimental programme

- new decay modes and production mechanisms *(e.g. $\Lambda^0_b \rightarrow P^0_c K^0 \rightarrow J/\Psi n K^0$)*
- look for isospin, strangeness, bottom partners *(e.g. $\Lambda^0_b \rightarrow P^0_{cs} \varphi \rightarrow J/\Psi \Lambda \varphi$)*
- open-charm and charmless decays *(e.g. $\Lambda^0_b \rightarrow \Sigma^+_c D^-$, $\Lambda^0_b \rightarrow \Lambda^+_c D^{*0}$*

Summary on pentaquarks

LHCb has observed two resonant states in $\Lambda_b \to J/\psi\, p\, K$ consistent with pentaquarks

- **$P_c(4380)^+$** observed with 9.0σ in multidimensional amplitude fit
- **$P_c(4450)^+$** observed with 12.0σ in multidimensional amplitude fit
- Minimal quark content of these two states is $c\bar{c}uud$

  → *called pentaquark-charmonium states*
- Relative rates within expectations
- Evidence of resonant behaviour

Evidence for exotic hadrons in $\Lambda_b \to J/\psi\, p\, \pi$

- discriminate between resonance and kinematic effects
- amplitude analysis limited by sample size

More data needed to confirm quantum numbers and disprove scattering

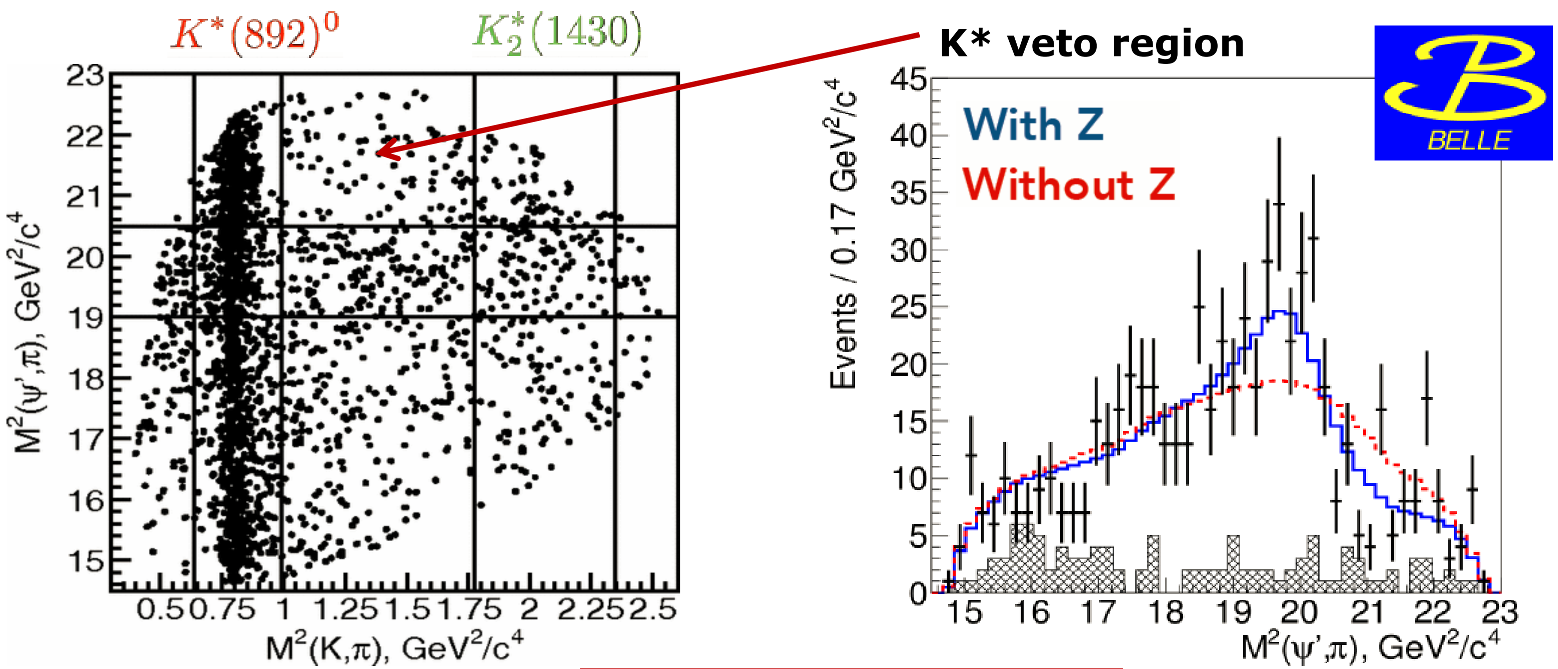
Tetraquark candidates

Z(4430)$^{\pm}$

[PRD 88 (2013) 074026]

Charged charmonium-like state in $B^0 \to \psi(2S)\pi K$

- originally found by Belle in ***B→K(Z→ψ(2S)π-)*** and ***B→K(Z→J/ψπ-)***
  [PRL 100(2008) 142001, PR D80(2009) 031104, PR D88(2013) 074026]
- not confirmed by BaBar [PR D79 (2009) 112001]



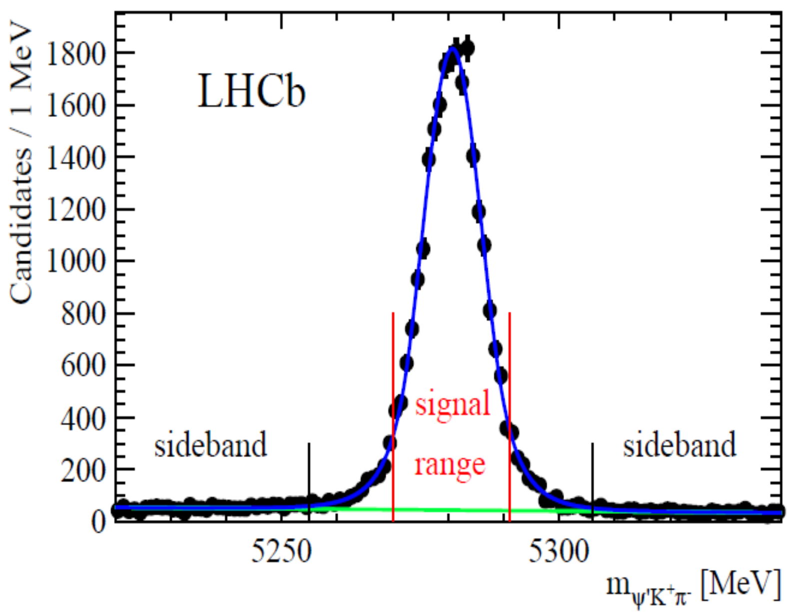
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV}/c^2$$

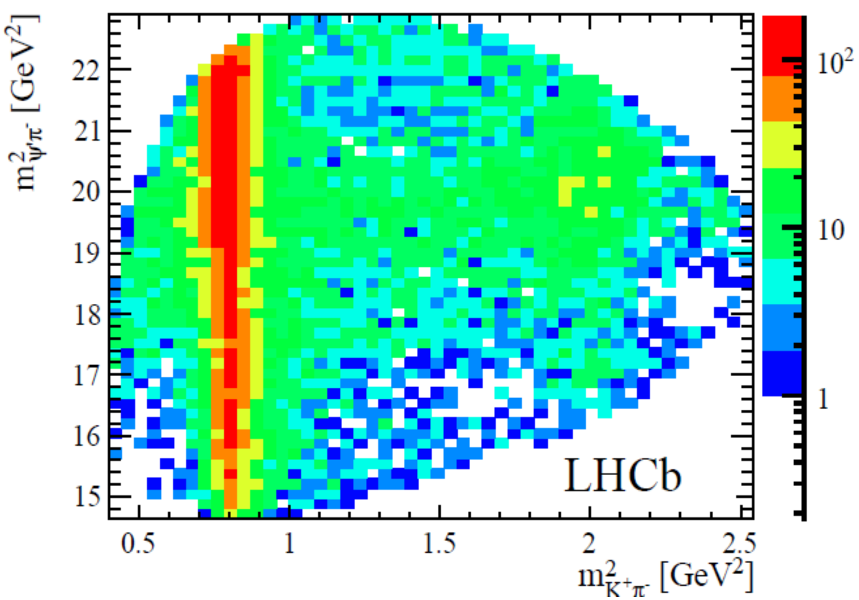
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}/c^2$$

Z(4430)±: *LHCb confirmation*

LHCb full amplitude analysis using 3 fb^{-1} [PRL 112 (2014) 222002]

- ~25K $B^0 \to K^+ \psi(2S) \pi^-$ candidates (x10 Belle/BaBar)
- two different analysis approaches
  - → 4D amplitude analysis *(invariant masses, helicity and decay planes angles)* to measure resonance parameters and J^P
  - → model independent analysis based on the Legendre polynomial moments extracted from the *Kπ* system *(similar to what was done for pentaquark)*

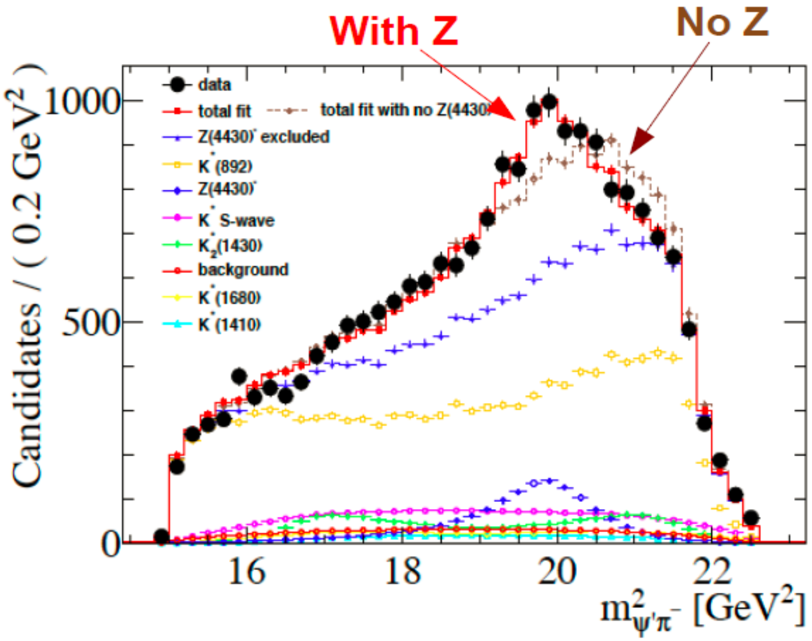


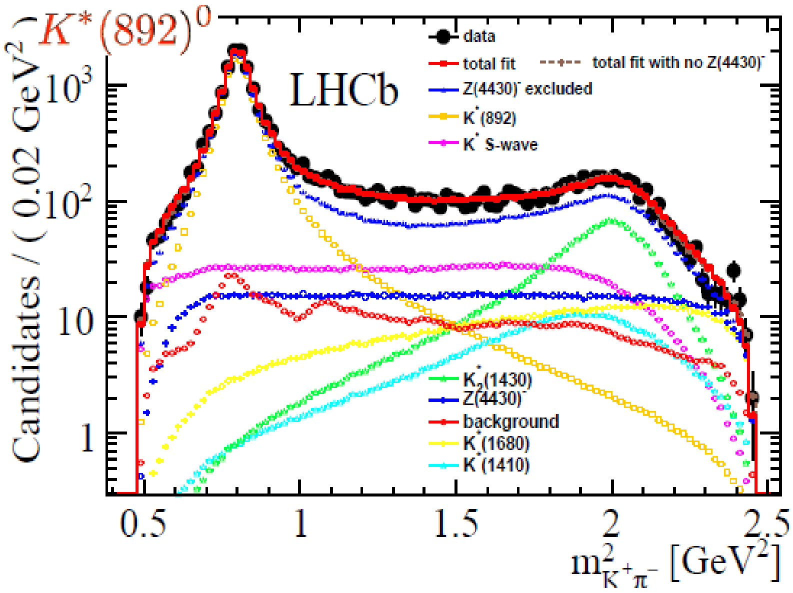


Background from sidebands (4% of combinatorial background in the signal region)

$Z(4430)^{\pm}$: *amplitude fit*

[PRL 112 (2014) 222002]





4D amplitude analysis fit

- $J^P = 1^+$ confirmed
- others assignment excluded with large significance
- mass close to $D^*D_1(2420)$ threshold
- excellent agreement between LHCb & Belle

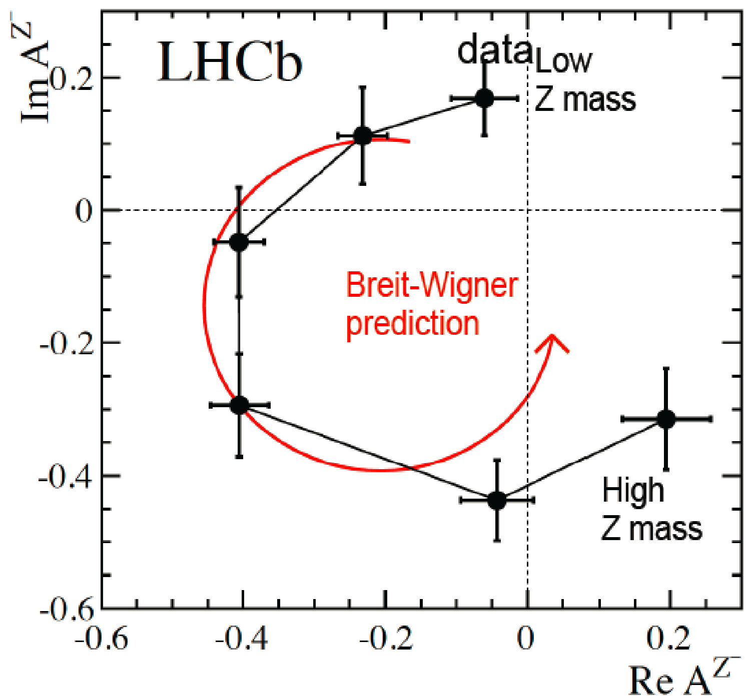
	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+

$Z(4430)^{\pm}$: *resonant nature*

[PRL 112 (2014) 222002]

Argand plot shows a clear resonant behaviour

- additional fit: *Z amplitude with complex parameters in 6 $m_{\psi'\pi^-}$ bins*
- phase rotation as expected for Breit-Wigner resonance



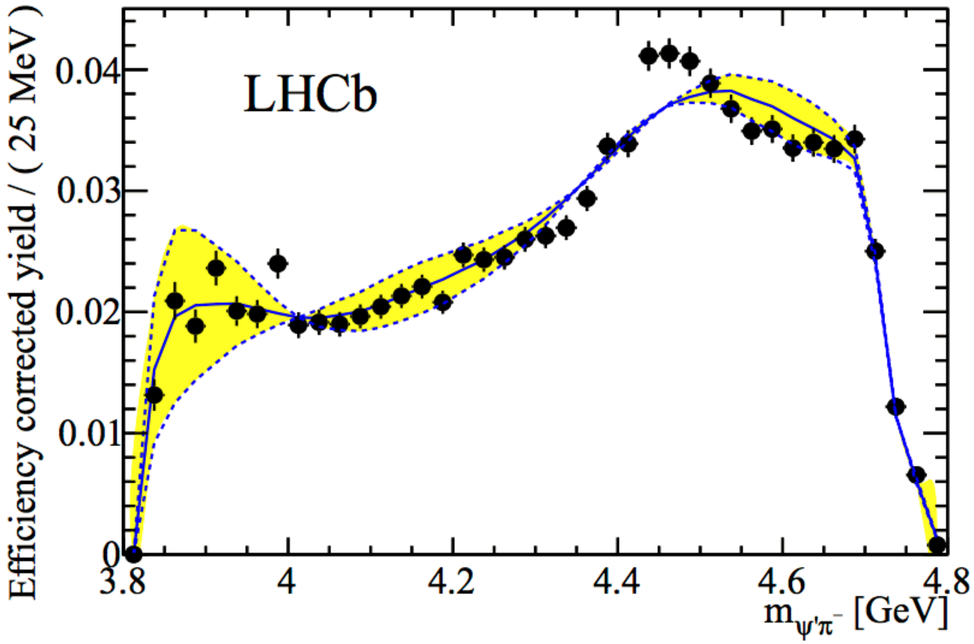
Results confirm Z(4430) with $J^P=1^+$ and its resonant behaviour

Z(4430)$^{\pm}$: *model independent*

[PRD 92 (2015) 112009]

Can the Z(4430) be explained by K^* reflections?

- sideband subtract and efficiency correct $B^0 \to K^+\psi(2S)\pi^-$ sample
- no assumptions on the K^* resonances: *only its maximum J is limited*
- angular structure of the $K\pi$ system extracted with Legendre polynomial moments



K^* reflections cannot describe properly the Z(4430) region

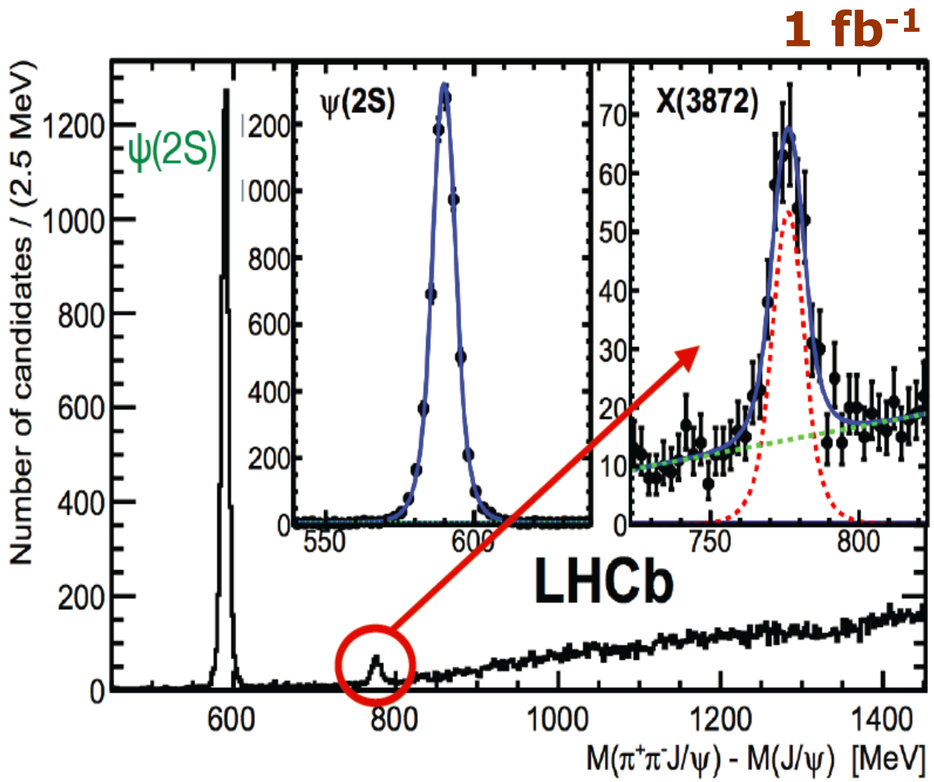
Among all tetraquark candidates the Z(4430)$^-$ is special

$\rightarrow$ *being charged it cannot be a c anti-c state*

X(3872): *1 fb^{-1}*

$B^+ \to X(3872)K^+$, $X(3872) \to J/\psi\rho^0$, $J/\psi \to \mu^+\mu^-$, $\rho^0 \to \pi^+\pi^-$ [PRL 110, 222001 (2013)]

- observed by Belle in 2003 [PRL 91 (2003) 262001]
  - → revolution in exotic meson/baryon
  - → seen now at 7 experiments
  - → mass close to DD^* threshold
- conventional charmonium?
  - → $X \to J/\psi\ \rho/\omega$ violate isospin
  - → $c\bar{c}$ not expected to have large BF to $(J/\psi\ \rho)$



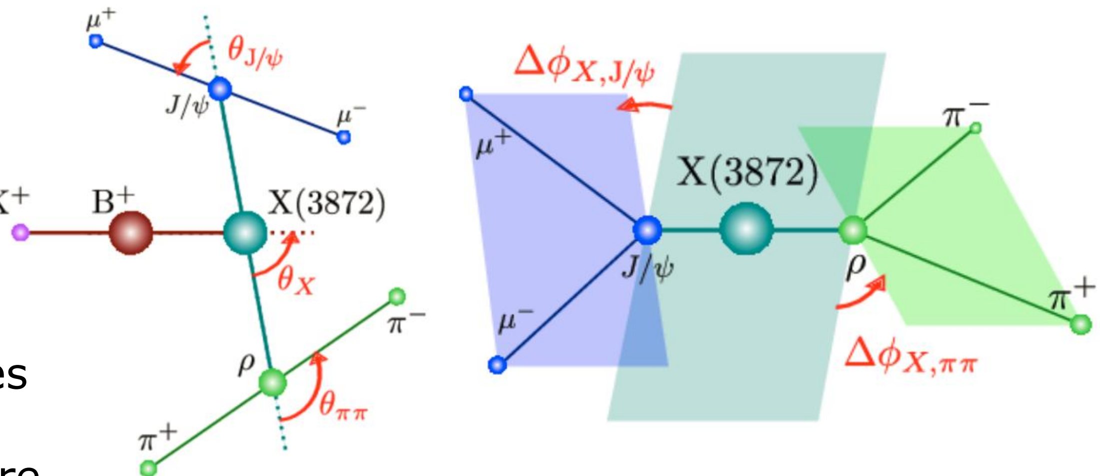
- **exotic interpretation**
  - → $D^0D^{*0} = (c\bar{u})(\bar{c}u)$ molecular state, $c\bar{c}u\bar{u}$ tetraquark, $c\bar{c}g$ hybrid, glueball,...
- **crucial: unambiguous quantum number *J^PC***

$$M_{X(3872)} = 3871.69 \pm 0.17\ \mathrm{MeV}/c^2$$
$$\Gamma_{X(3872)} < 1.2\ \mathrm{MeV}/c^2$$

X(3872): *angular analysis with 3 fb^{-1}*

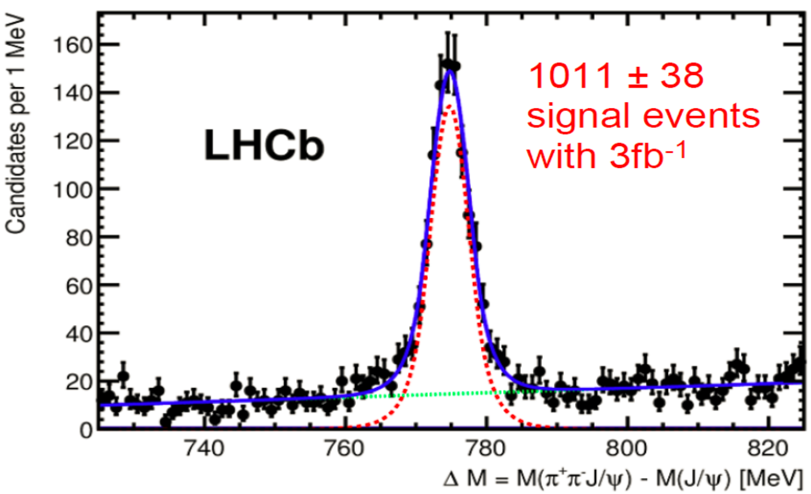
[PRD 92 (2015) 011102]

5 independent angles describing the decay



Full angular 5D analysis of $B^+ \to K^+(X(3872) \to \rho\, J/\psi)$

- ~1000 candidates at **3 fb^{-1}**
- helicity formalism
  → decay described by 5 angles
- likelihood ratio test to compare J^{PC} hypotheses
- **fit with no assumptions on orbital angular momentum!**



CDF determined quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+} [PRL 98 (2007) 132002]

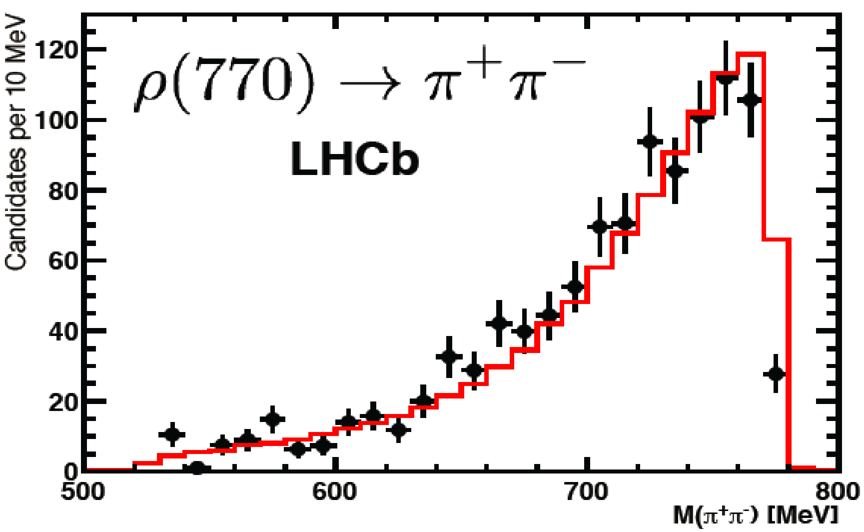
X(3872): *quantum numbers*

[PRD 92 (2015) 011102]

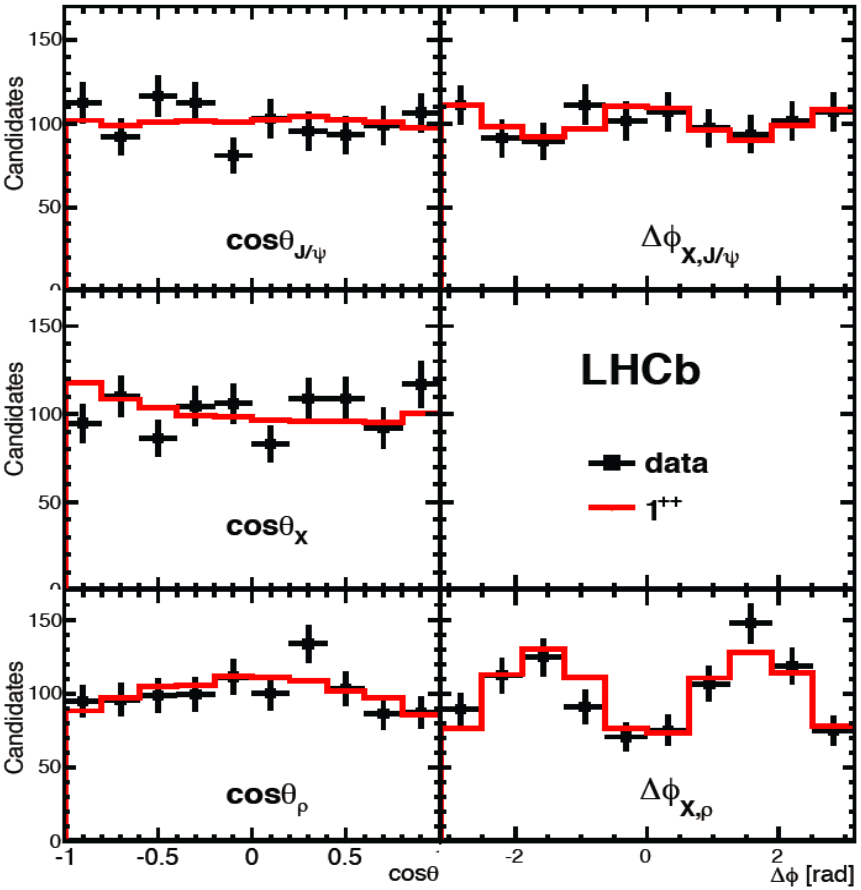
$J^{PC} = 1^{++}$ confirmed!

- 3x larger sample than previous result
- decay mainly through S-wave
  (suggests compact state)
- D-wave negligible *(< 4% @ 95% CL)*
- *ρ(770)* → *ππ* dominates

  → decay violates isospin
  (unlikely to be ordinary ccbar)



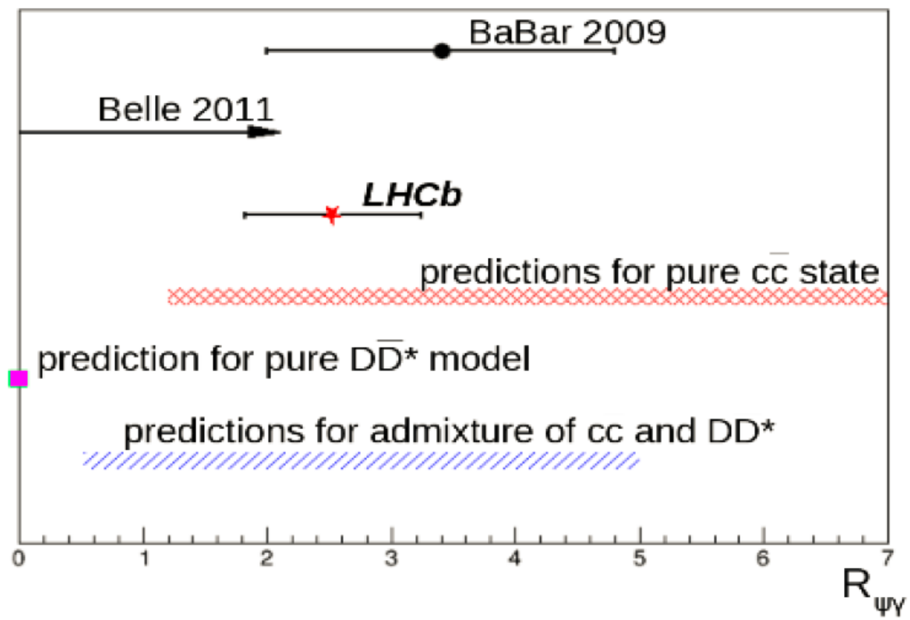
Best fit to data with 1^{++} hypothesis



X(3872): *radiative decays*

- *X(3872) → J/Ψγ, Ψ(2S)γ* disfavors pure DD^* molecule by 4.4σ *(C = +1)*
  [LHCb, NP B886 (2014) 665]

- consistent with cc(bar) state where the presence of the threshold lowers the mass and width



[PRL 102 (2009) 132001]
[PRL 107 (2011) 091803]
[NP B886, (2014) 665]

$$R_{\psi\gamma} = \frac{N_{\psi(2S)}}{N_{J/\psi}} \times \frac{\varepsilon_{J/\psi}}{\varepsilon_{\psi(2S)}} \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)},$$

Charged partners of X(3872) predicted by some tetraquark models

- next step at LHCb

  → precision mass measurement $m_{X(3872)}$ - $m_{\Psi(2S)}$

Exotics in $B_s\pi$

X(5568)?

[PRL 117 (2016) 022003]

$X(5568)^{\pm} \rightarrow B^0_s\, \pi^{\pm}$ decay reported by D0 with significance of 5.1σ

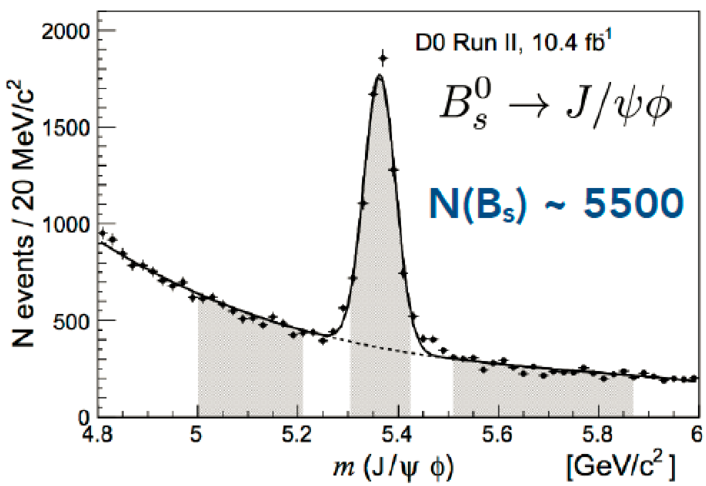
[arXiv:1602.07588]

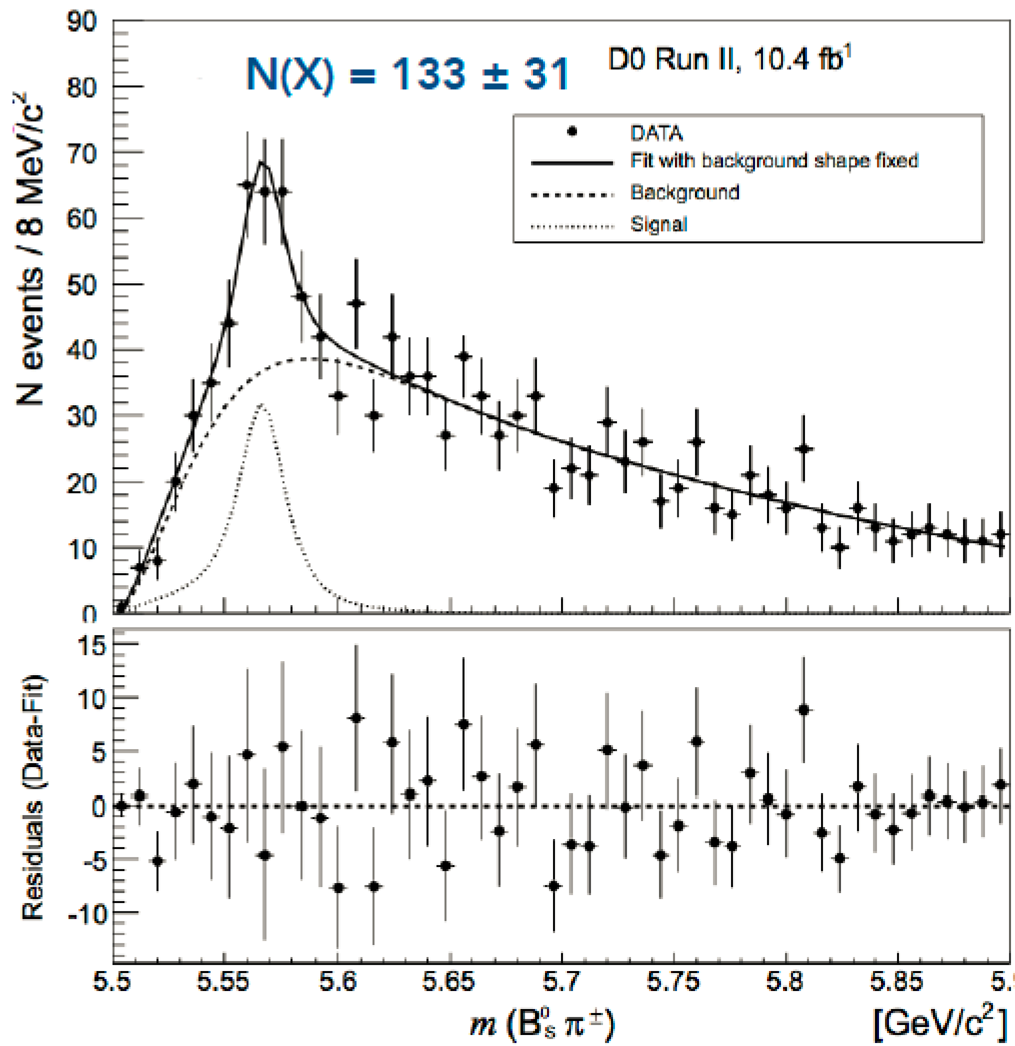
- large B_s production rate:

  ρ^{D0}_X = (8.6 ± 1.9 ± 1.4)%

- minimal quark content $\bar{b}su\bar{d}$

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\mathrm{MeV}/c^2$$



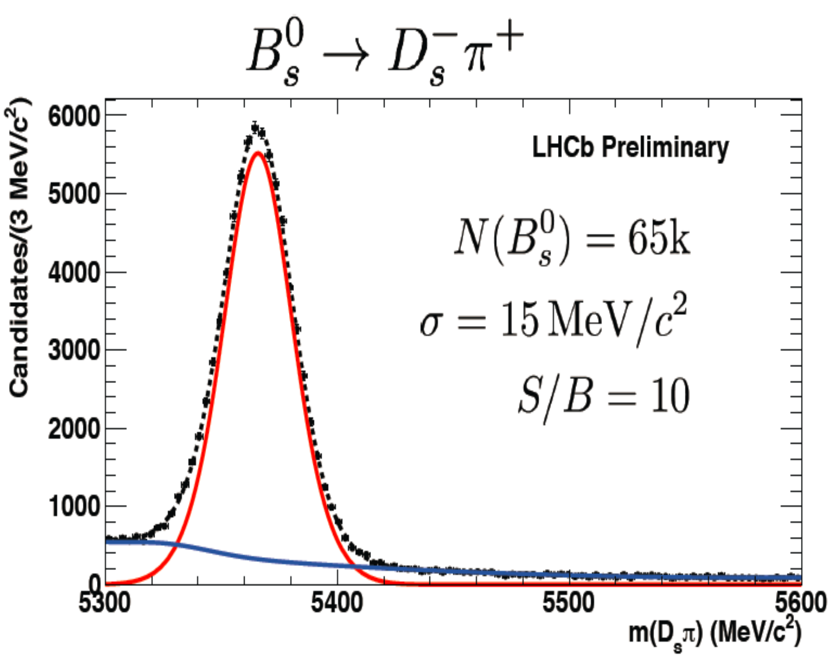


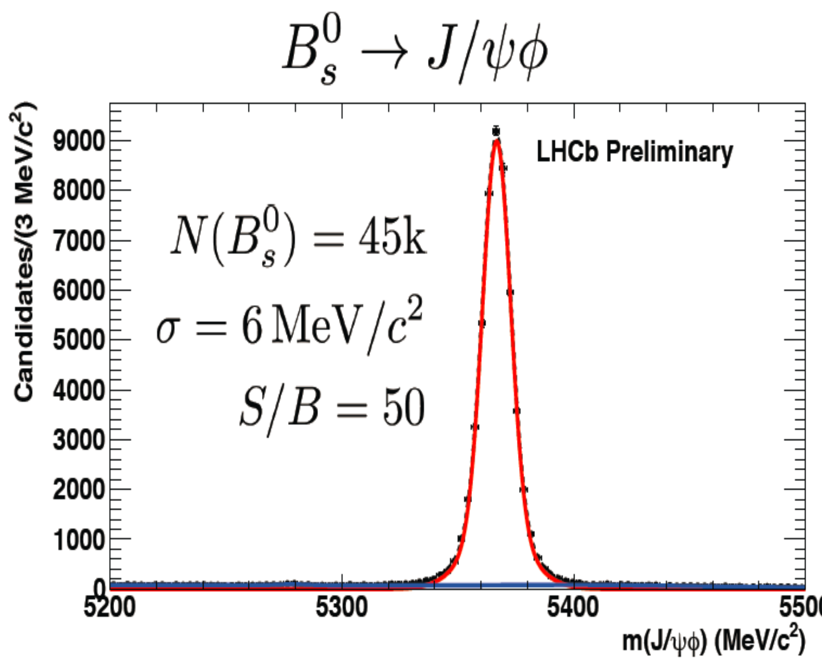
LHCb data sample of B_s

[LHCb-CONF-2016-004]

Very large and clean B_s sample at LHCb

- 20 times the D0 sample
- cut-based selection to clean B_s sample
- mass constraints on J/ψ and D_s to improve mass resolution





$B_s\pi$ mass spectrum

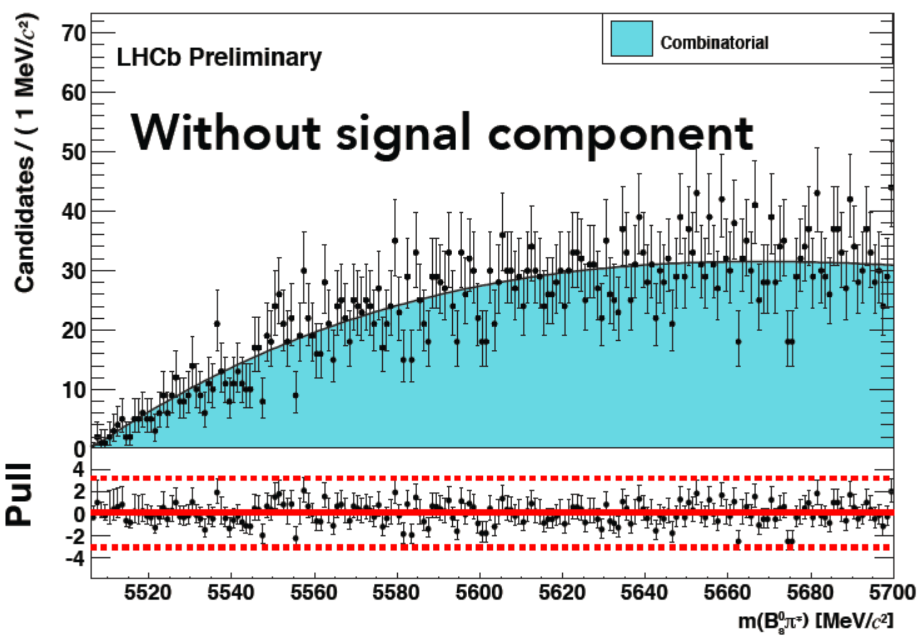
[LHCb-CONF-2016-004]

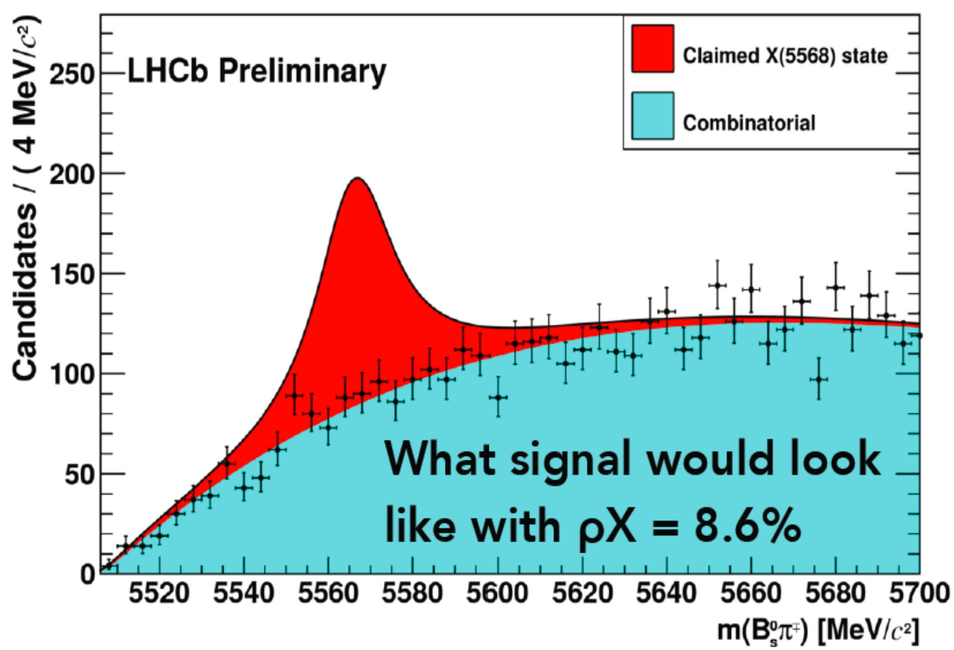
- B_s and π required to come from same PV
- signal shape is S-wave Breit-Wigner with parameters from D0
- polynomial for background

LHCb sees nothing!

→ upper limit by integrating likelihood in physical *(non-negative ρ)* region

$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 5\,{\rm GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ {\rm CL}$$
$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 10\,{\rm GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ {\rm CL}$$





Summary on tetraquark candidates

- Z(4430)$^+$ in $B^0 \to \Psi(2S)\, K^- \pi^+$ is now well established tetraquark
  - → *existence confirmed with > 13 σ in multidimensional amplitude fit*
    with > 8 σ in model independent analysis
  - → *quantum numbers determined $J^P = 1^+$*
  - → *resonant behavior observed in Argand diagram*
- 1^{++} confirmed for X(3872)
- D0 claims a $\bar{b}su\bar{d}$ state, but we do not!
- Recent LHCb results on 4 new *J/ψφ* states [LHCb-PAPER-2016-019]
  - → X(4140), 1^+, 8.4σ
  - → X(4274), 1^+, 6.0σ
  - → X(4500), 0^+, 6.1σ
  - → X(4700), 0^+, 5.6σ *(see backup)*
- Other tetraquark candidates *(no amplitude analysis so far)*
  - → *Y(3940), Y(4260), Y(4350), Y(4660),… (Belle, BaBar, BES)*

Conclusions

- LHCb has made great progress in exotic spectroscopy
- Many new states discovered since the first observation of the X(3872)
- Discovery of two pentaquark states $P_c(4450)^+$ and $P_c(4380)^+$
- Other exotic containing cc (or bb) quarks e.g. $Z(4430)^+$

  → *good candidate for tetraquark with $J^P=1^+$*

  → *plus four new states seen in $J/\psi\varphi$*
- Amplitude analysis crucial to interpret data

  → *establish quantum numbers*

  → *exclude some production mechanisms, e.g. threshold, rescattering,…*
- Data sample tripled in RUN II

Extensive experimental program

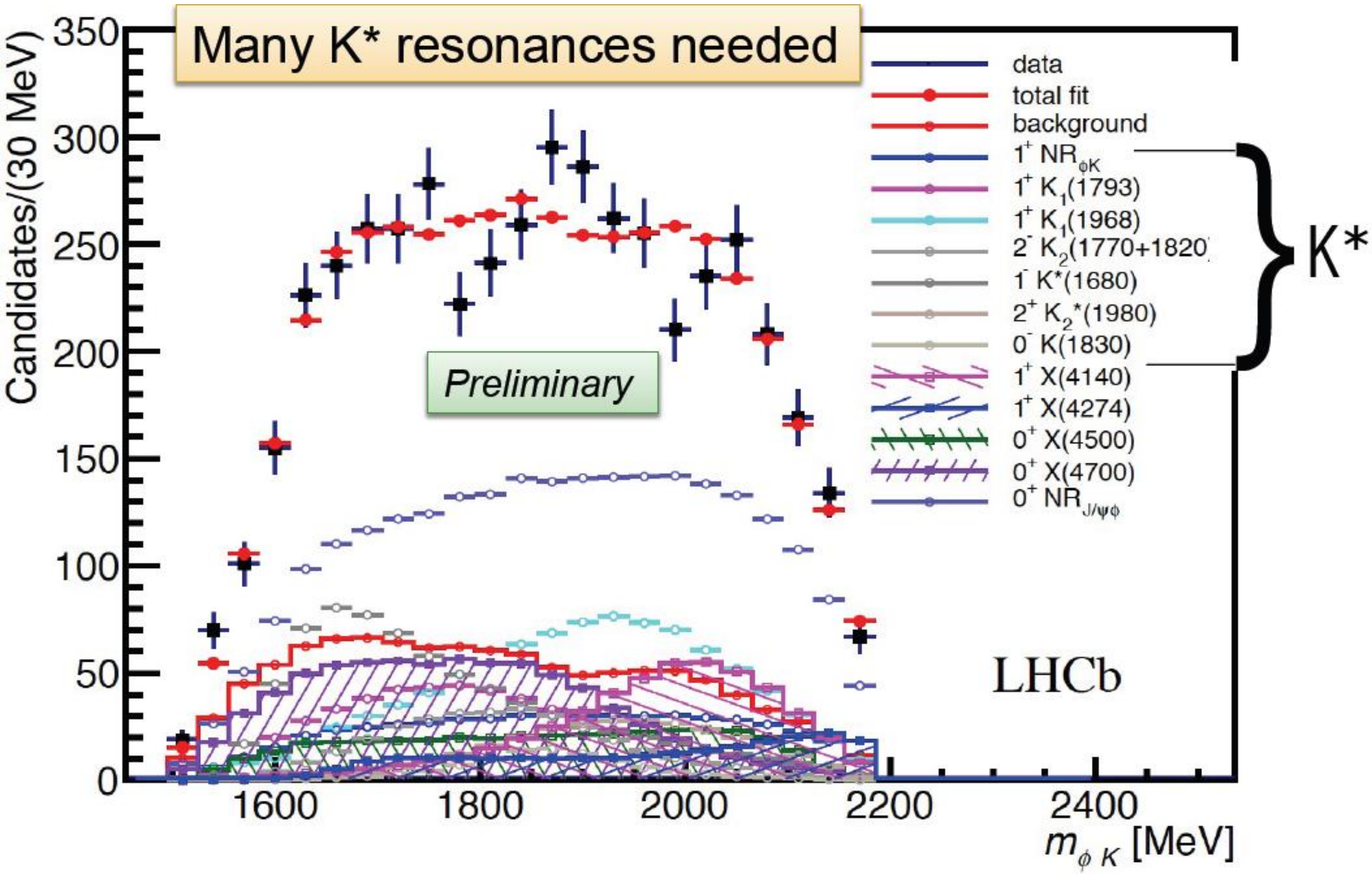
LHCb, CMS, ATLAS, BaBar, Belle, Belle-II, BES-III, COMPASS

Backup

J/ψφ states

[LHCb-PAPER-2016-019]

Full amplitude fit including interferences between
B→J/ψK, K*→φK* and *B→X⁰K, X⁰→J/ψφ*



J/ψφ states

[LHCb-PAPER-2016-019]

4 structures visible: fit with BW amplitudes