LHCb results on Exotics and Pentaquark States

Marco Pappagallo
University of Bari & INFN

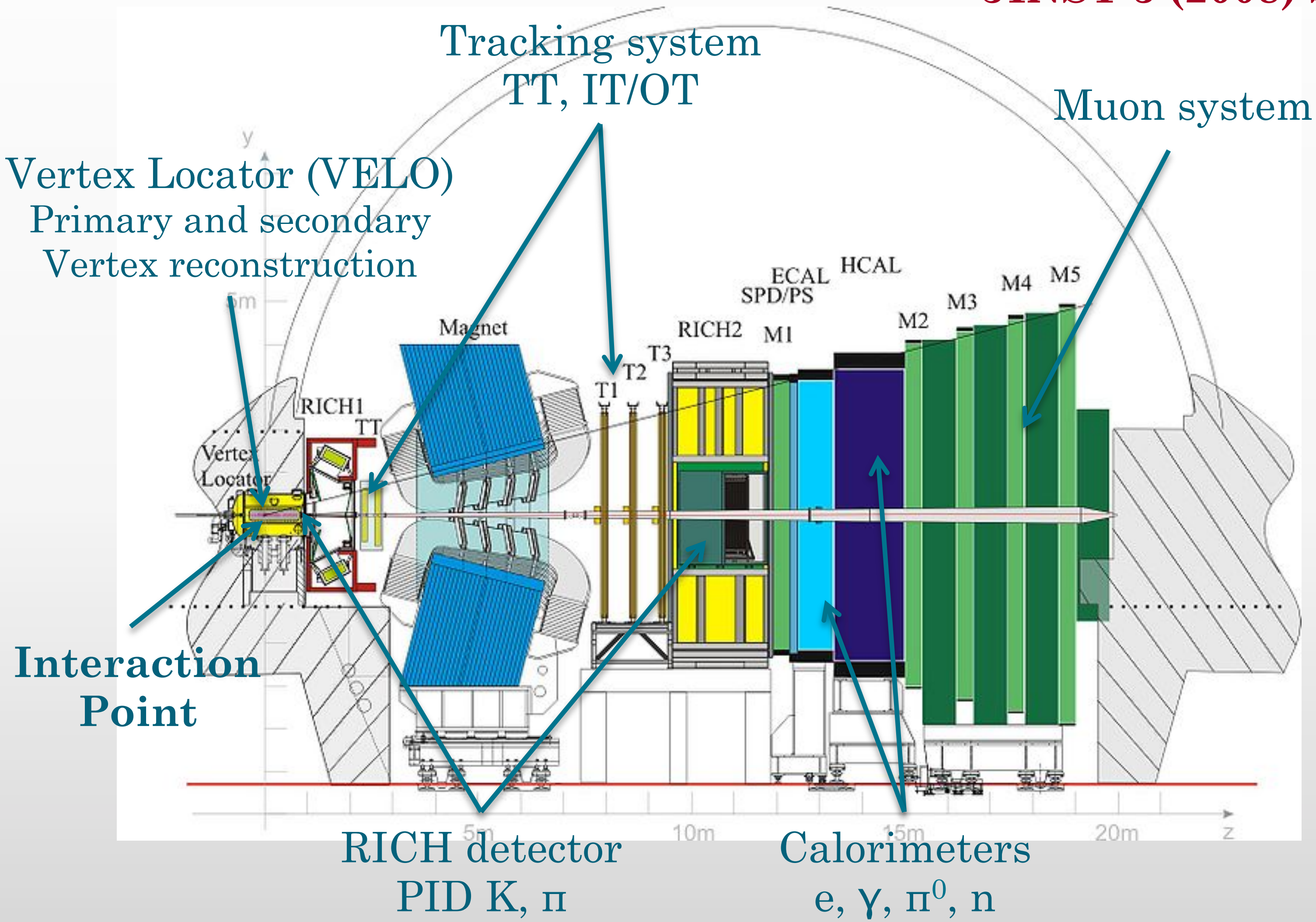
Exotic Hadron Spectroscopy
26-27 September 2016, Edinburgh, Scotland, UK

Outline

- LHCb Experiment
- Search for $X(3872) \rightarrow p\bar{p}$
- Confirmation of $Z_c(4430)^+$
- 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
- Prospects

THE LHCb DETECTOR

JINST 3 (2008) S08005

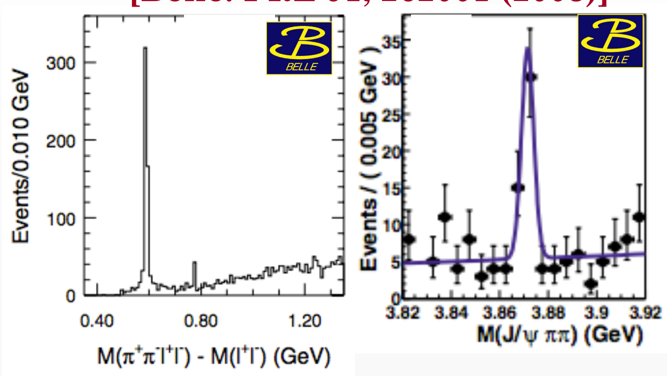


The X(3872) State

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

- 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 ($J^{PC} = 1^{++}$) ; D-wave component $f_D < 4\%$ @ 95% C.L. **[PRL 110, 222001 (2013)][PRD92, 011102 (2015)]**
- Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0 \bar{D}^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV/c^2}$$ ➡ *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)]**
- Measurement of $B(X(3872) \to \psi(2S)\gamma)/B(X(3872) \to J/\psi\gamma)$ **[Nucl.Phys.B886 (2014) 665]**

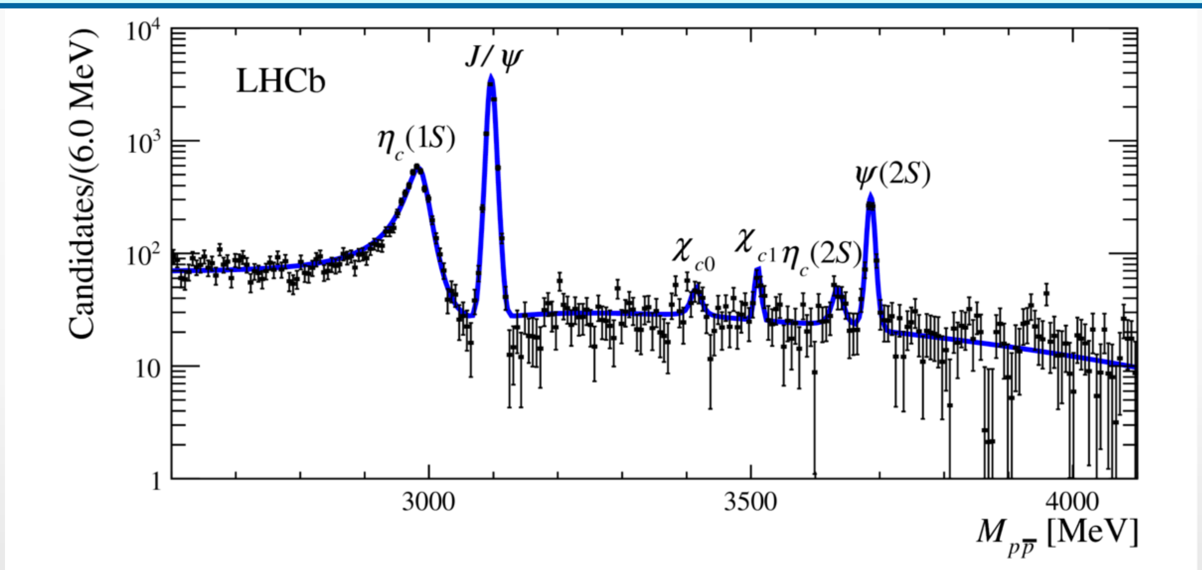
$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

Search for X(3872) → $p\bar{p}$

LHCb: arXiv: 1607.06446 submitted to PLB

Study of charmonium states decaying to $p\bar{p}$ in $B^+ \to p\bar{p}K^+$ decays

- First observation of $\eta_c(2S) \to p\bar{p}$
- Precise measurements of mass and width of $\eta_c(1S)$



No evidence of X(3872). Upper limit set:

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2} \text{ @ } 95\% \text{ CL}$$

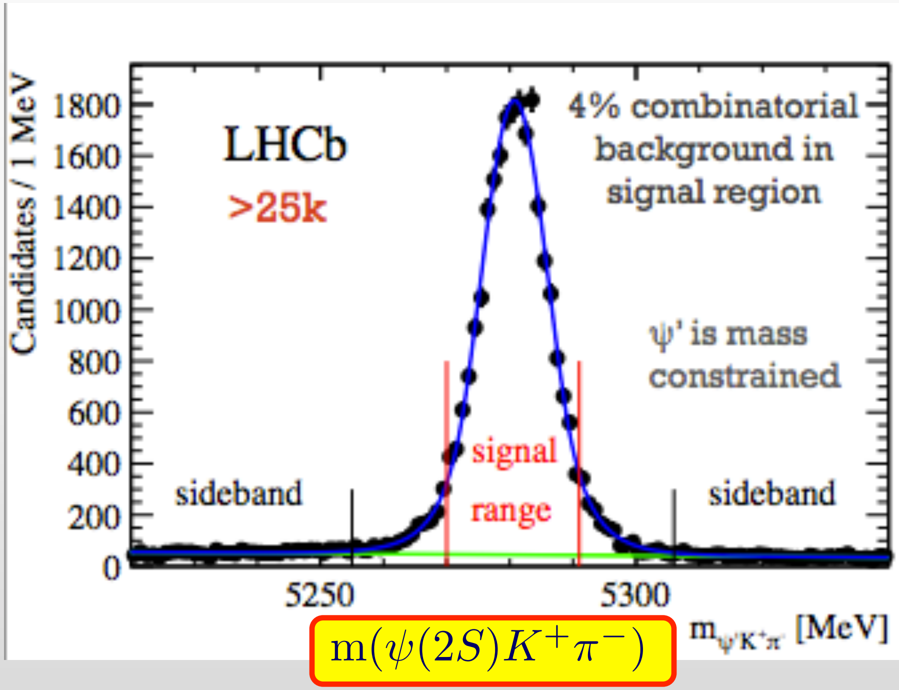
$\Gamma(X \to p\bar{p}) \propto E_b^{1/2}$. Important measurement for other experiments (e.g. Panda)

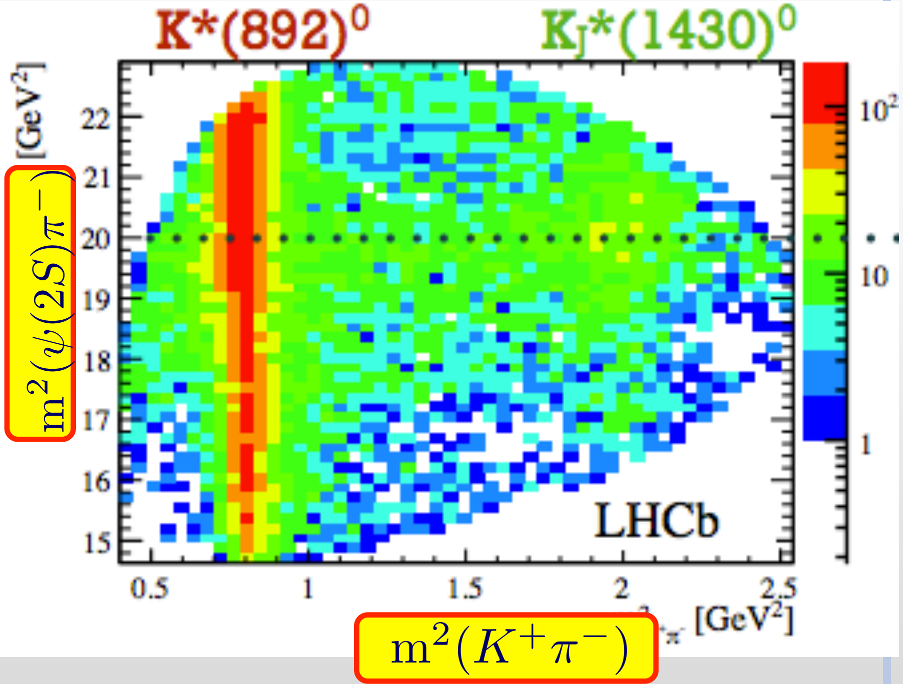
Confirmation of the $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ state (Amplitude analysis of $B^0 \rightarrow \psi(2S)\, K^- \pi^+$)

SEARCH FOR Z(4430)$^+$ AT LHCb

[LHCb: PRL 112, 222002 (2014)]

- 25k $B^0 \rightarrow \psi(2S)K^+\pi^-$ candidates in 3.0 fb^{-1} (10x Belle/BaBar)
- Small combinatorial background
- Sidebands used to build 4D model of the combinatorial background





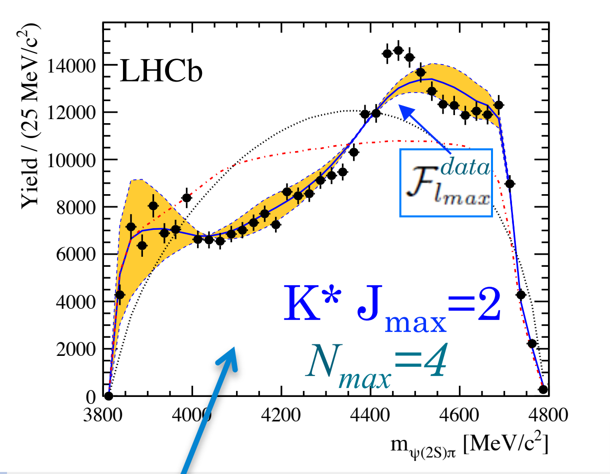
Results of the Model Independent Analysis

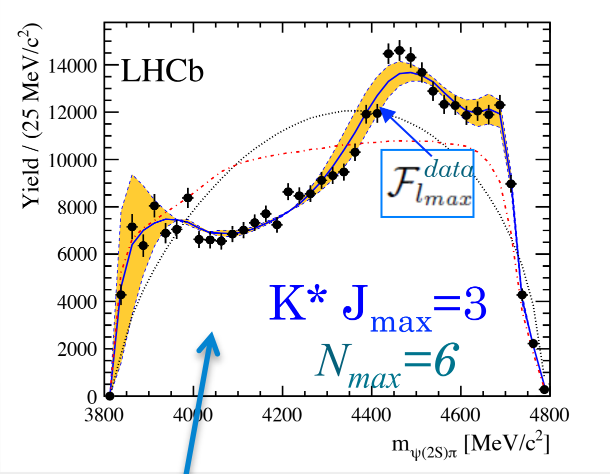
[LHCb: Phys. Rev. D 92, 112009]

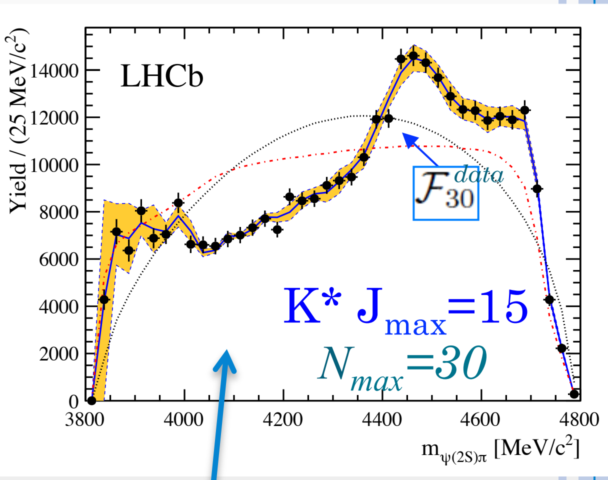
Allows for K* states up to $K^*_2(1430)$

Allows for a tail of $K^*_3(1780)$

Allows implausible K* contributions







Clear discrepancy at ~4430 MeV

It may look OK but…

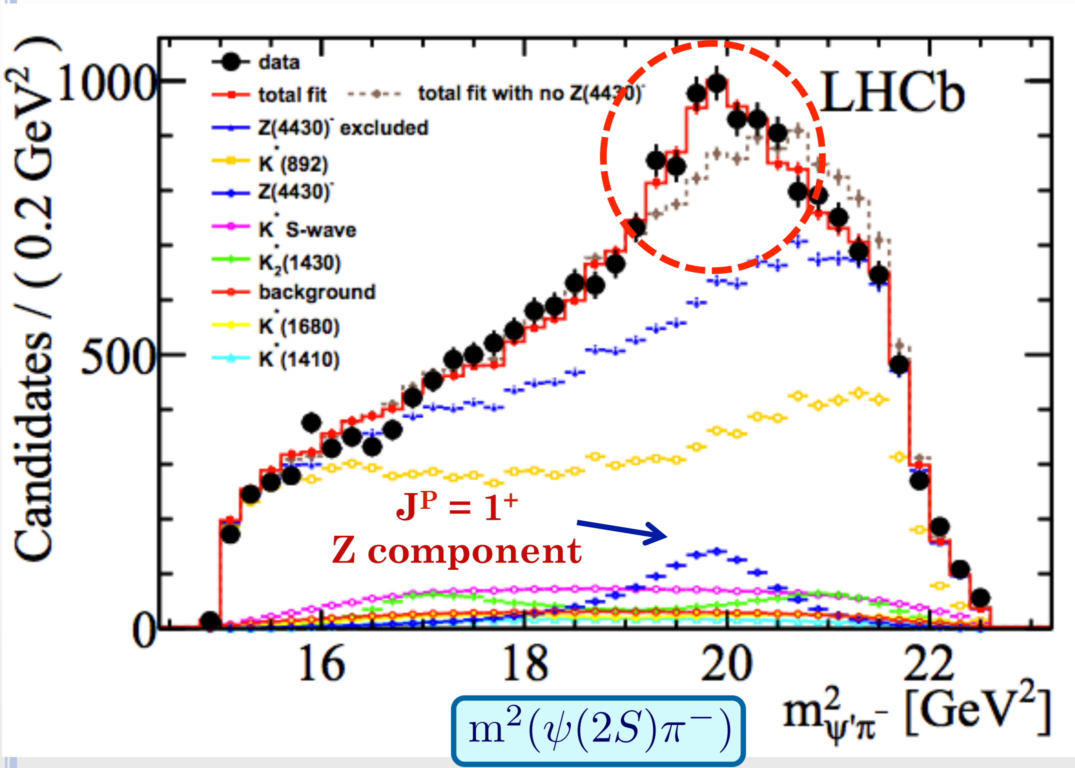
No discrepancy as expected

The yellow bands related to the uncertainty on normalized moments (due to the statistical uncertainty from the data)

Discrepancy at 8σ level

4D Amplitude Fit and confirmation of Z(4430)$^+$

[LHCb: PRL 112, 222002 (2014)]



	Rejection level relative to 1^+	
Disfavored J^P	LHCb	Belle
0-	9.7σ	3.4σ
1-	15.8σ	3.7σ
2+	16.1σ	5.1σ
2-	14.6σ	4.7σ

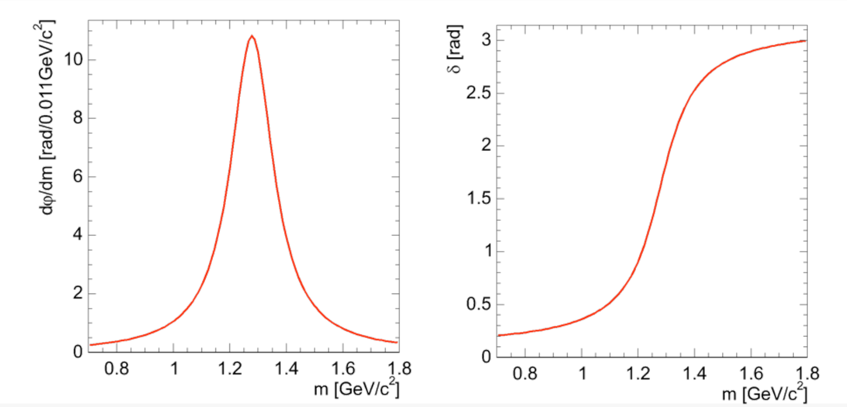
	LHCb	Belle
Mass (MeV)	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
Width (MeV)	$172 \pm 13^{+37}_{-34}$	$200\ ^{+41}_{-46}{}^{+26}_{-35}$

- Large interference between Z(4430) and K* resonances
- Very good agreement between LHCb/Belle results

Probing the Resonant Character of Z(4430)$^+$

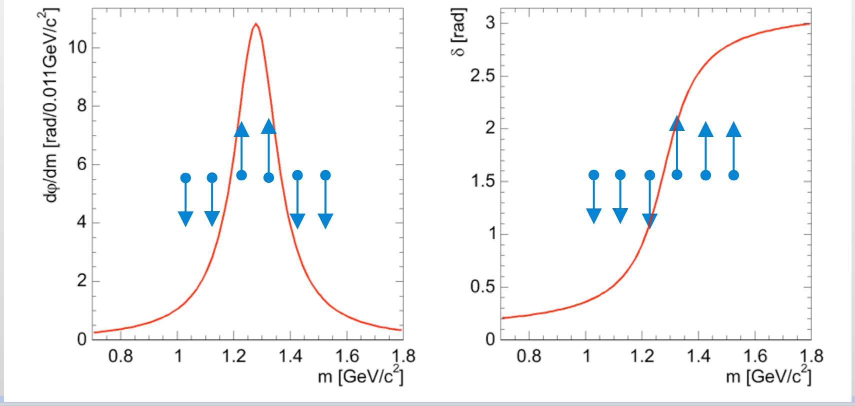
[LHCb: PRL 112, 222002 (2014)]

Nominal fit



4 free parameters:
m_0, Γ_0 + complex constant

Alternative fit
Replace BW amplitude with 6 independent complex numbers in 6 bins of m(ψ(2S)π) in region $m_0 \pm \Gamma_0$, where m_0 is the mass of Z(4430)

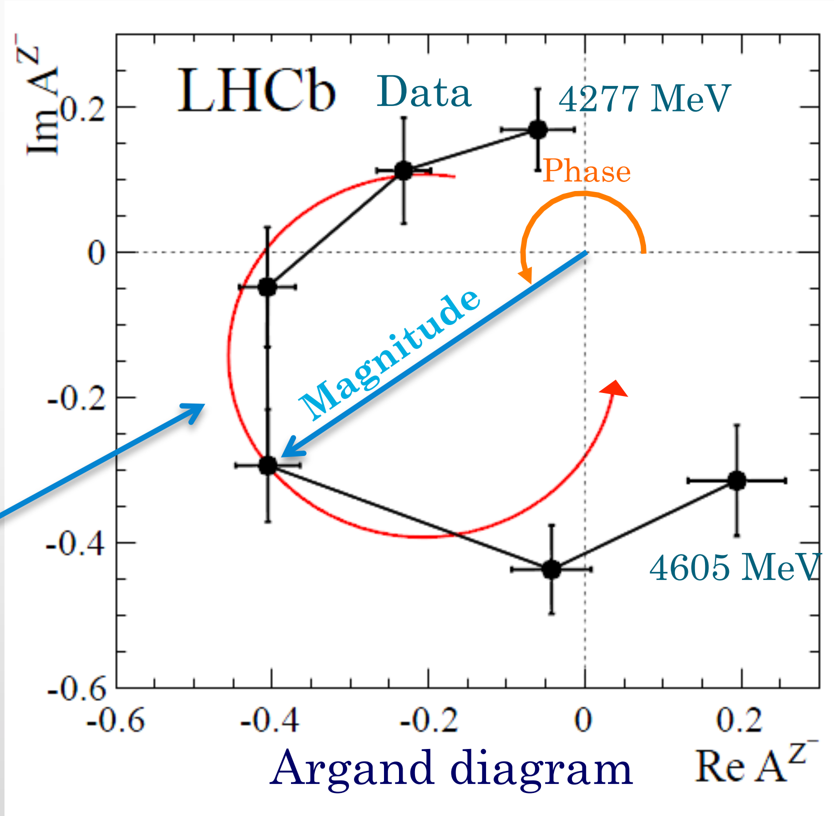


12 free parameters

Resonant Behavior of Z(4430)$^+$

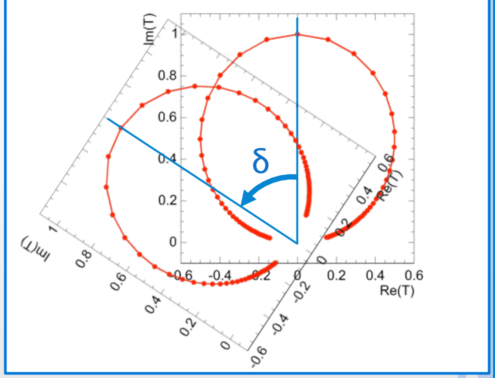
[LHCb: PRL 112, 222002 (2014)]

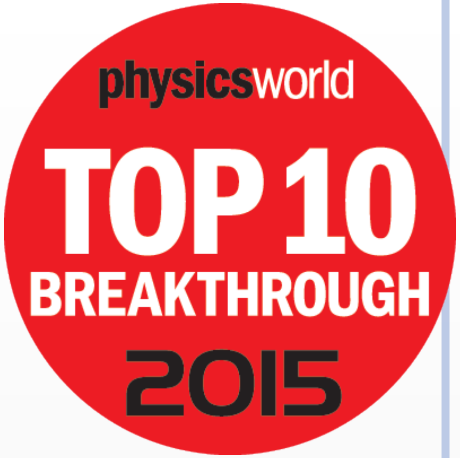
Observation of a rapid change of phase near maximum of magnitude ⇒ resonance!



BW amplitude with Z(4430) parameters from nominal fit

Tilted by an arbitrary phase δ characteristic of Dalitz analysis





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

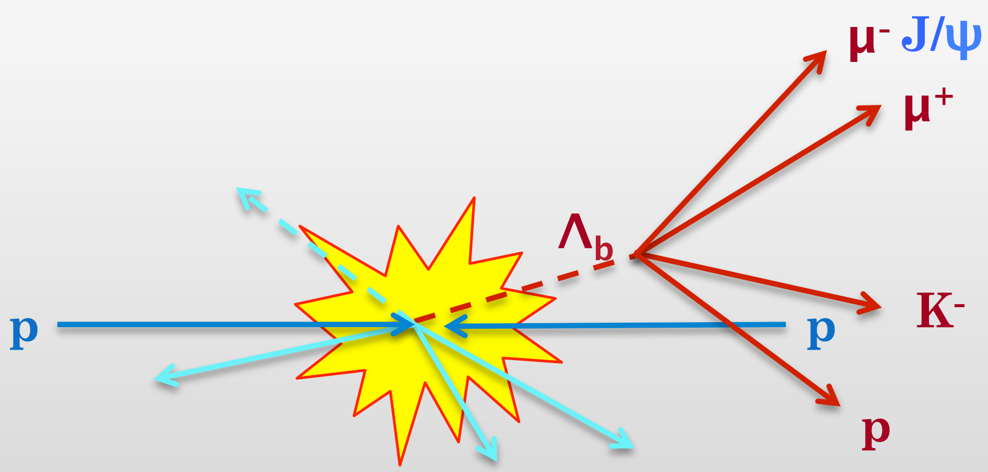
[LHCb: PRL 111 (2013) 102003]

First Observation of $\Lambda_b \rightarrow J/\psi\ K^- p$

[LHCb: PRL 111 (2013) 102003]

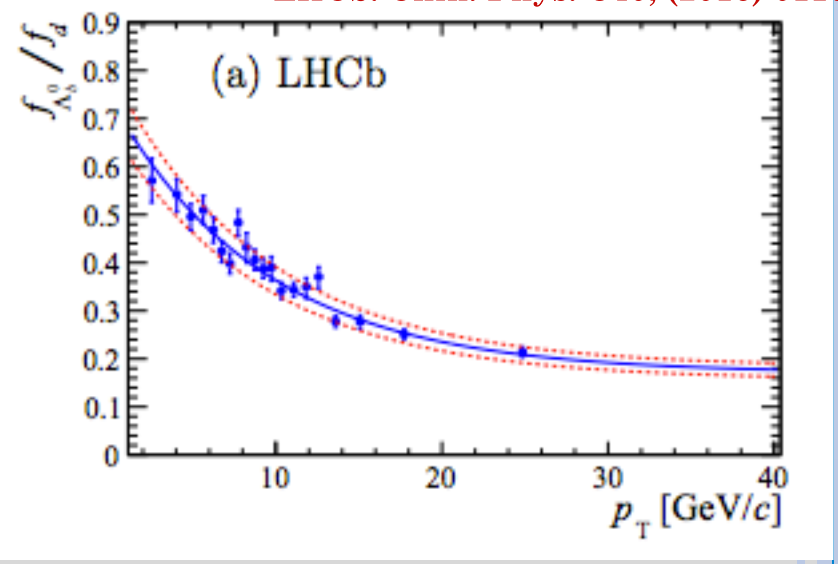
Why did LHCb arrive first? The decay was not observed before!

- ✓ J/ψ → Large trigger efficiency
- ✓ 4 Tracks → Large detection efficiency
- ✓ Large Λ_b production



LHCb: JHEP 08(2014)143

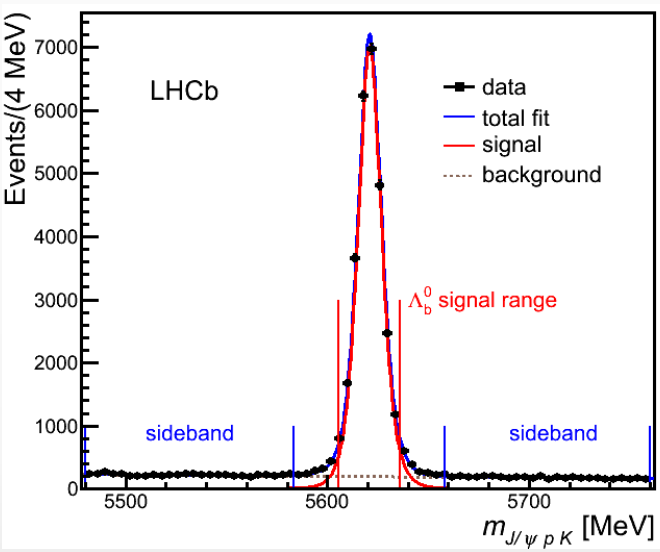
LHCb: Chin. Phys. C40, (2016) 011001

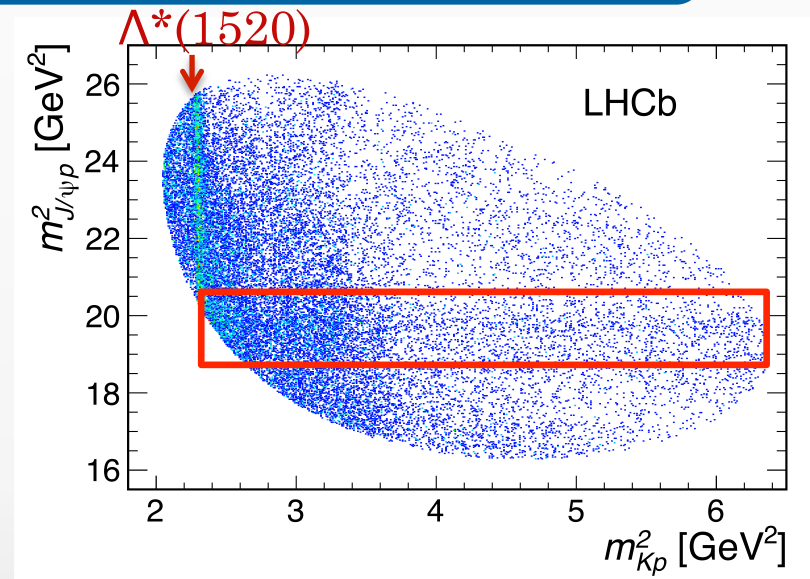


Observation of a Narrow Band in the Λ_b Dalitz plane

[LHCb: PRL 115, 07201 (2015)]

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

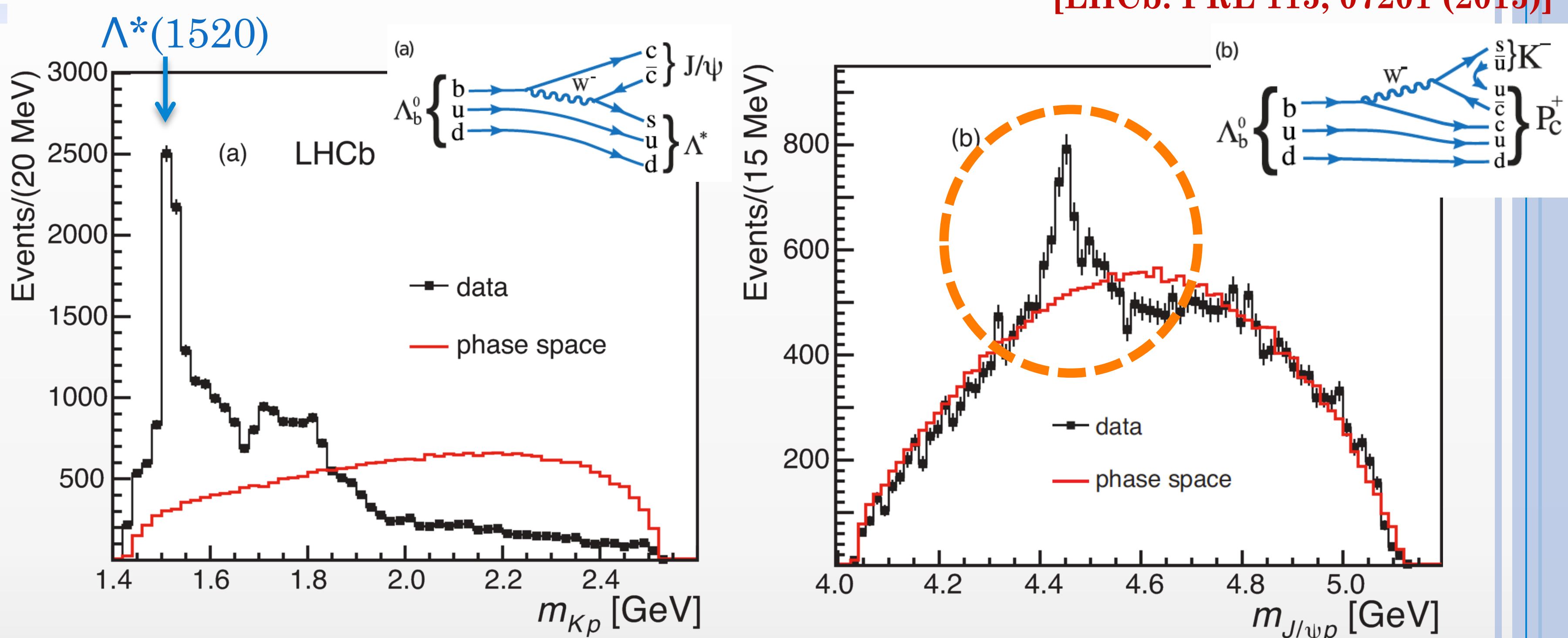




- Efficiency flat over the "Dalitz" plot
- Cross checks:
  - ✓ Veto $B_s \rightarrow J/\psi KK$ & $B^0 \rightarrow J/\psi K\pi$ after swapping the mass hypothesis of the Λ_b daughters: p ←→K or p ←→ π
  - ✓ Clone and ghost tracks carefully removed
  - ✓ Not a partially reconstructed Ξ_b decay

Unexpected Narrow Peak in m(J/ψ p)

[LHCb: PRL 115, 07201 (2015)]



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

6D Amplitude analysis

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*

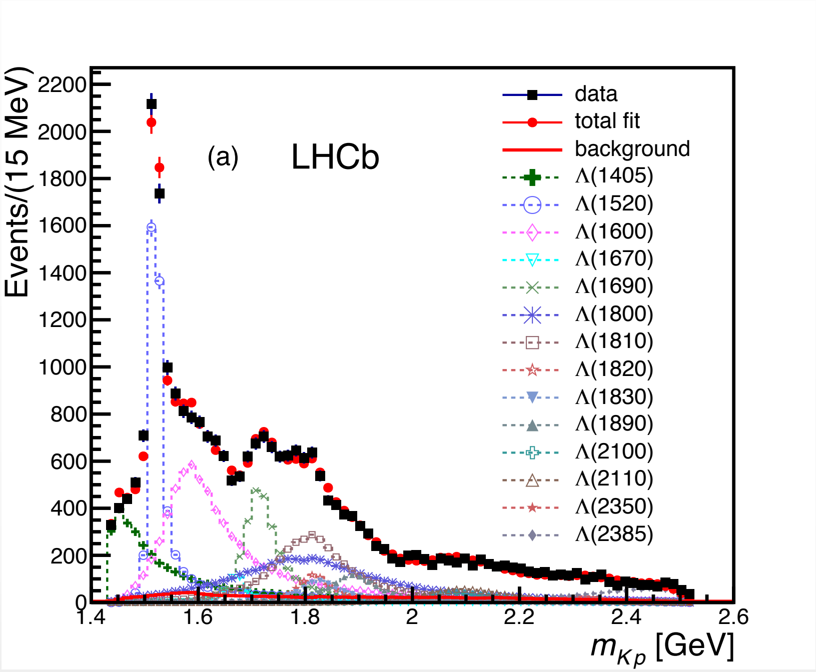
All states, all *L*

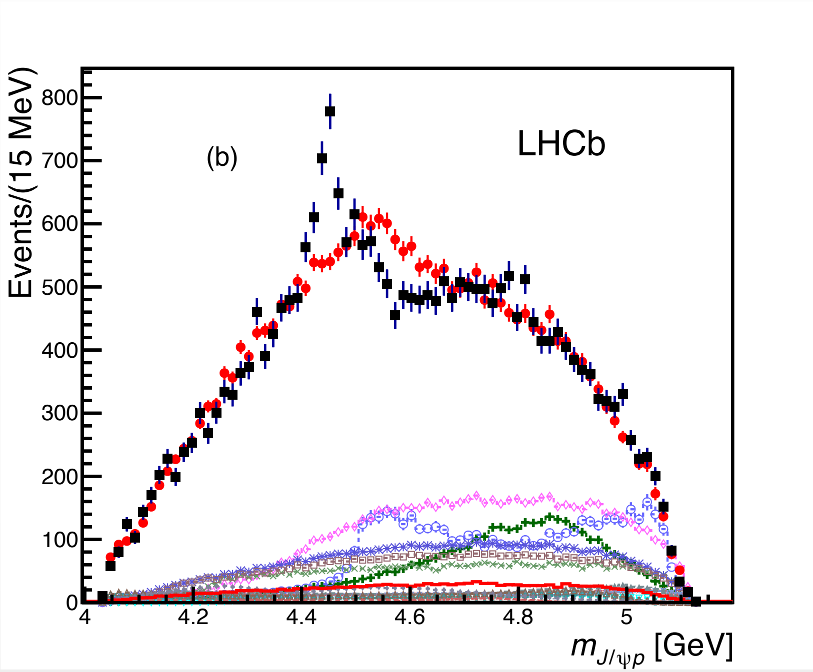
All known Λ* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
Λ(1405)	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
Λ(1520)	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
Λ(1600)	$1/2^+$	1600	150	3	4
Λ(1670)	$1/2^-$	1670	35	3	4
Λ(1690)	$3/2^-$	1690	60	5	6
Λ(1800)	$1/2^-$	1800	300	4	4
Λ(1810)	$1/2^+$	1810	150	3	4
Λ(1820)	$5/2^+$	1820	80	1	6
Λ(1830)	$5/2^-$	1830	95	1	6
Λ(1890)	$3/2^+$	1890	100	3	6
Λ(2100)	$7/2^-$	2100	200	1	6
Λ(2110)	$5/2^+$	2110	200	1	6
Λ(2350)	$9/2^+$	2350	150	0	6
Λ(2585)	?	≈2585	200	0	6
# of fit parameters:				64	146

Fit with Λ*→pK States only

[LHCb: PRL 115, 07201 (2015)]





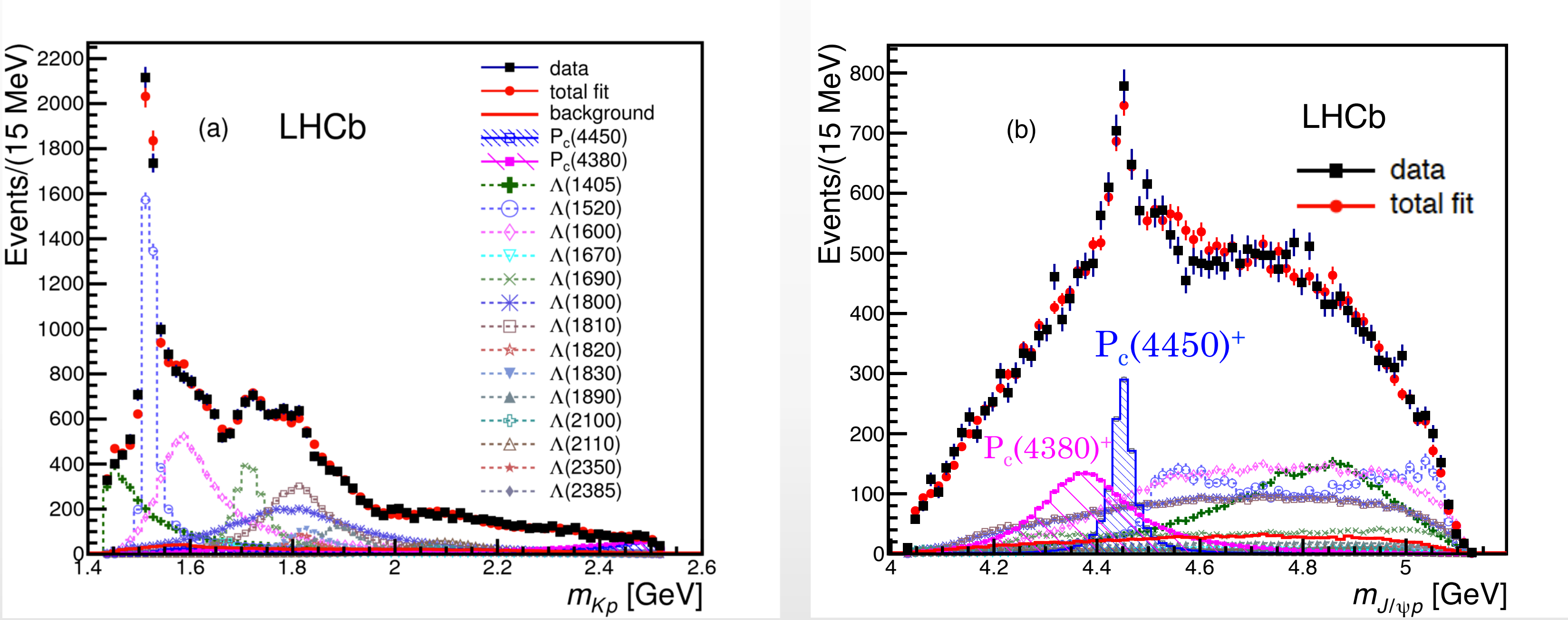
Use of extended model, so all possible known Λ* amplitudes: m_{Kp} projection looks fine, but the fit projection can't reproduce the peaking structure in J/ψ p

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

[LHCb: PRL 115, 07201 (2015)]

Reduced Λ* model + 2 states decaying to J/ψ p

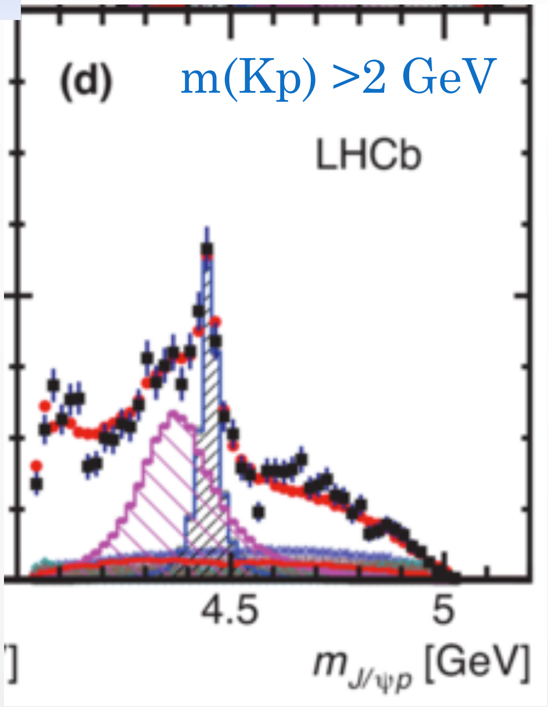
Best fit has $J^P=(3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred



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

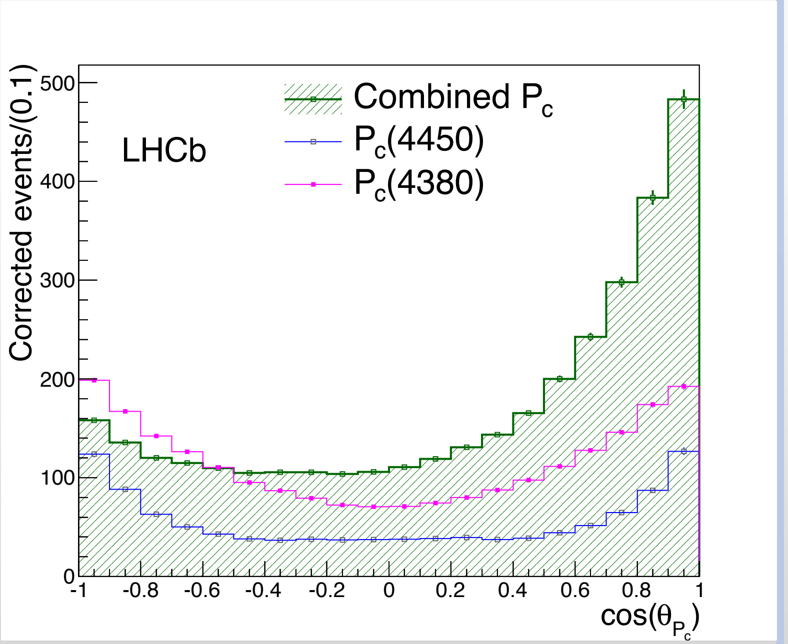
Do We really Need 2 P_c^+'s? YES

[LHCb: PRL 115, 07201 (2015)]



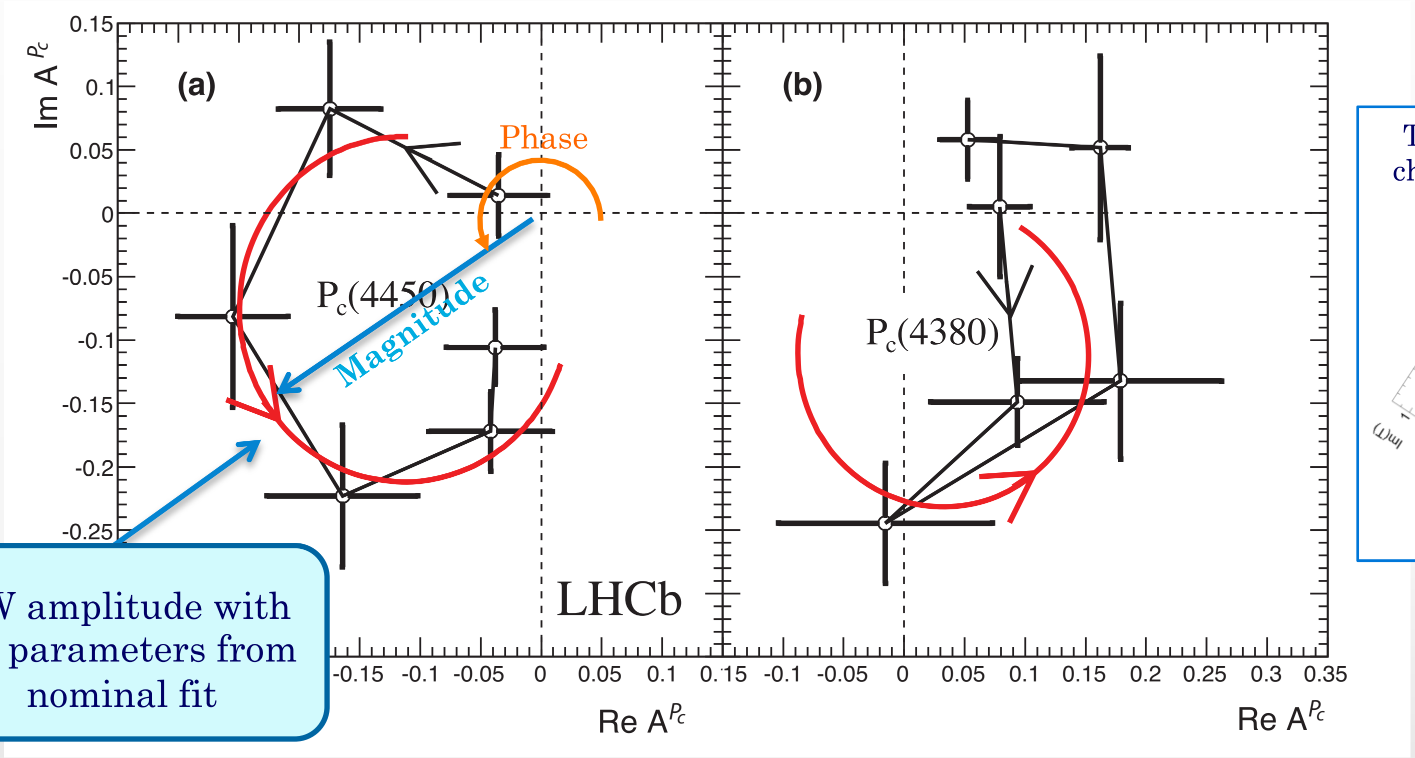
Clear need for the 2nd broad P_c^+ where the $\Lambda^* \rightarrow pK^-$ contribution is the smallest

Evidence of an interference pattern in the angular distribution



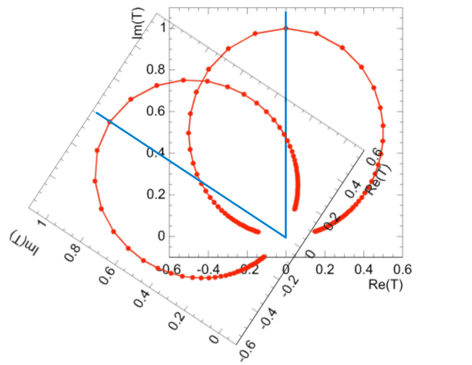
Argard Diagrams

[LHCb: PRL 115, 07201 (2015)]



BW amplitude with P_c^+ parameters from nominal fit

Tilted by an arbitrary phase δ characteristic of Dalitz analysis



- ➢ 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: Phys. Rev. Lett. 117, 082002]

Model Independent Analysis

[LHCb: PRL 117, 082002]

- 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?

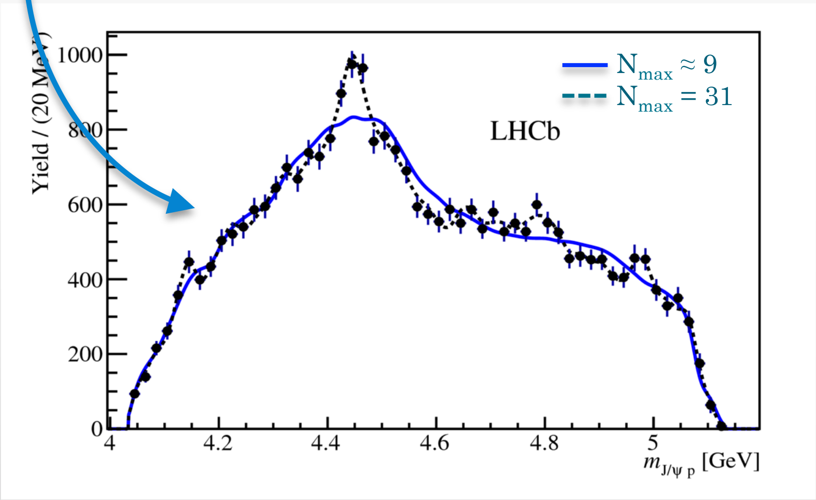
Can the reflections of the structures in $m(pK)$ and $\cos\vartheta_{\Lambda^*}$ reproduce the $m(J/\psi p)$ distribution?

Results from Model Independent Approach

[LHCb: PRL 117, 082002]

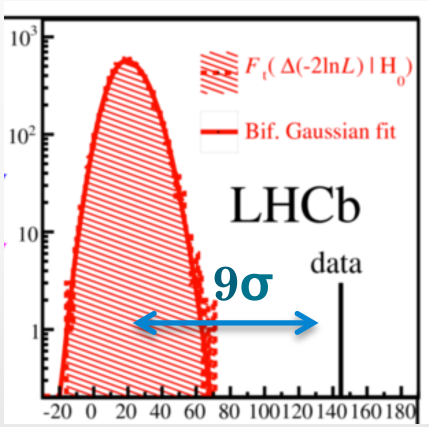
Decompose angular distribution into Legendre moments

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:

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



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

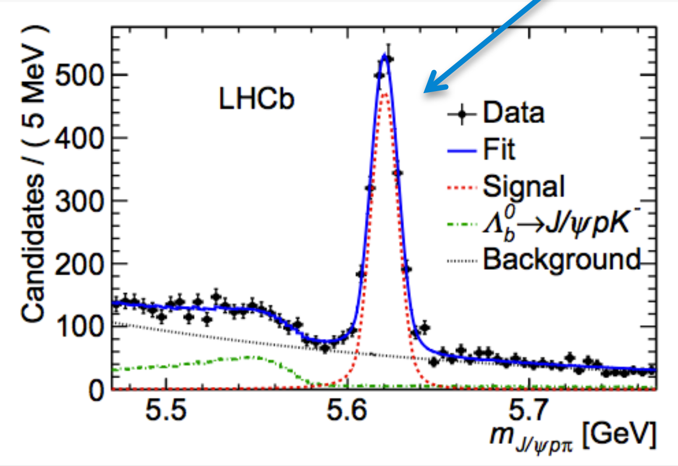
[LHCb: Phys. Rev. Lett. 117, 082003]

How to Investigate the P_c^+ States Further?

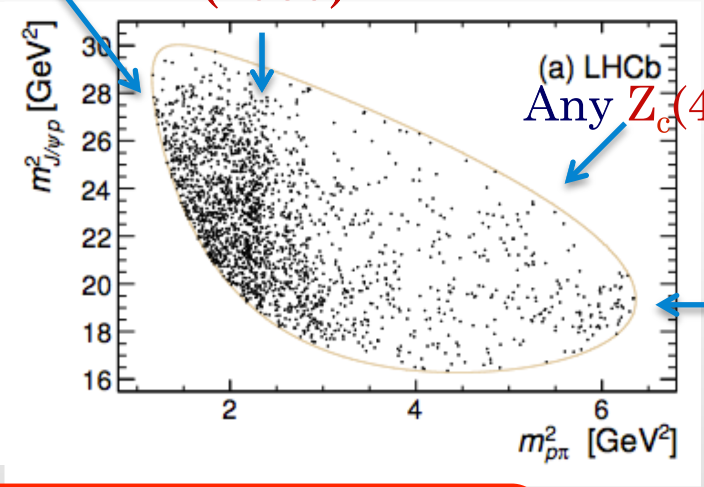
[LHCb: PRL 117, 082003]

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 → low efficiency, small BR's)
- Observation in a different environment:
  - Prompt production pp → P_c^+ + X (large track multiplicity at LHC)
  - $\Lambda_b \rightarrow J/\psi\ p\ \pi^-$: Cabibbo suppressed but feasible



N(1535)



Any $Z_c(4200)^+$?

Any P_c^+ ?

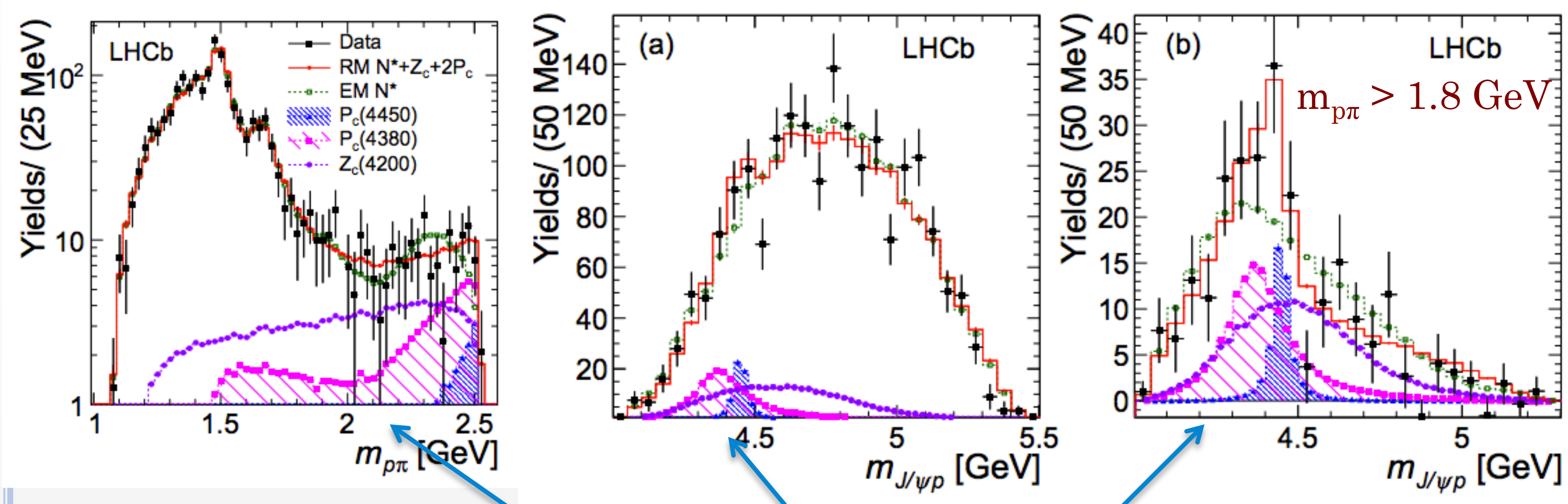
Dataset: 3 fb^{-1}

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

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

Amplitude Analysis of $\Lambda_B \rightarrow J/\psi\, p\, \pi^-$ Decay
Fit Results

[LHCb: PRL 117, 082003]



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

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1σ (including systematic uncertainty) → 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: arXiv:1608.00435 accepted by PRL (Editors' Suggestion)

A New $B^0_s\pi^\pm$ State Claimed by DØ

[DØ: PRL 117, 022003]

Claimed observation/evidence of an exotic state

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

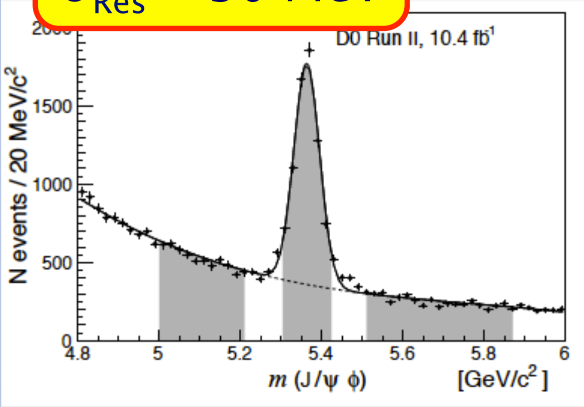
$$\mathrm{M} = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2$$

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

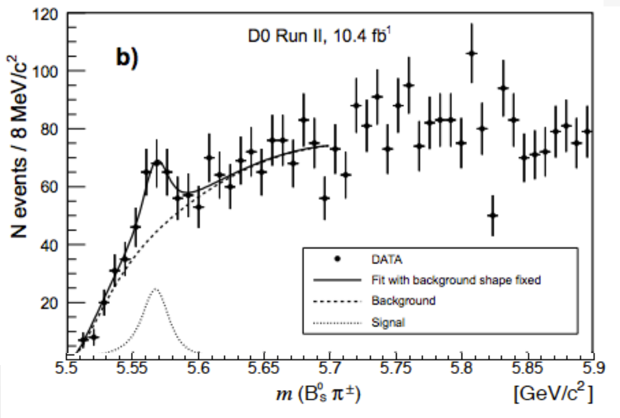
✓ Fraction of B_s^0 from $X^\pm$ decay: $\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)\ \%$

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

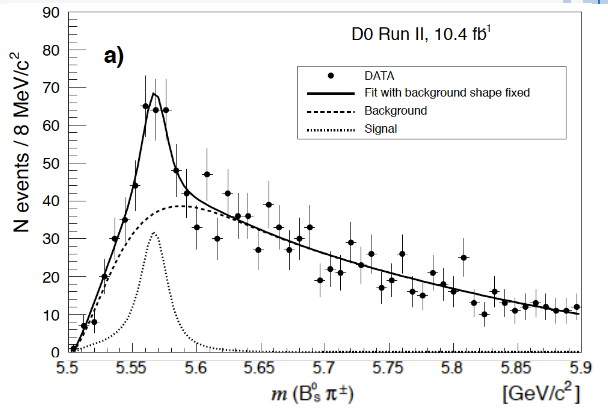
N(B_s) ~ 5500
σ_{Res} ~ 30 MeV



N(X) = 106 ± 23



N(X) = 133 ± 31



$3.9\,\sigma$ $5.1\,\sigma$

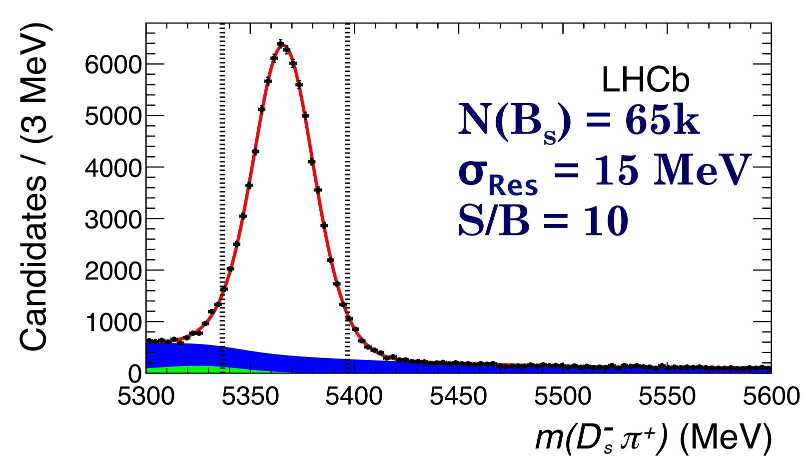
Signal significance

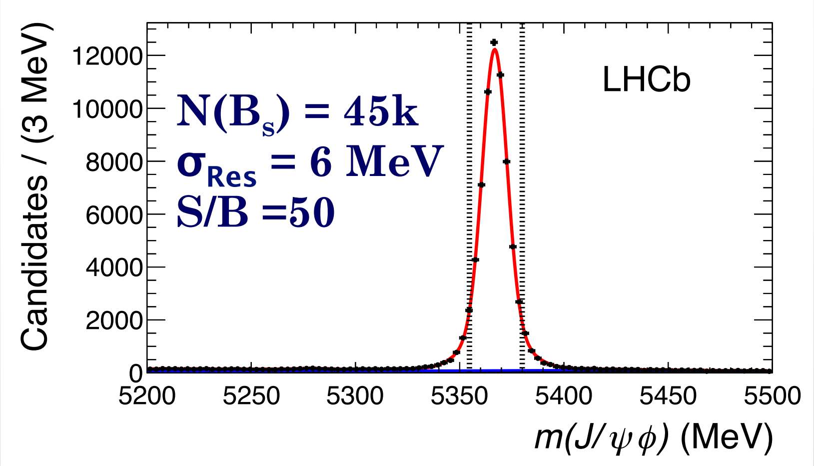
B_s Selection

LHCb: arXiv:1608.00435 accepted by PRL

- RUN I data (3 fb^{-1})
- Cut-based selections aiming to very clean B_s^0 samples
  - ✓ Both $B_s^0 \to D_s^- \pi^+$ and $J/\psi\ \phi$ (Mass constraints on the D_s and J/ψ)
  - ✓ Stick closely to tried and trusted analysis methods:

    $B^{**} \to B\pi$ and $B_s^{**} \to BK$
  - ✓ $p_T(\pi) > 500$ MeV/c
  - ✓ Baseline: $p_T(B_s^0) > 5$ GeV/c; Tight: $p_T(B_s^0) > 10$ GeV/c to match the DØ selection



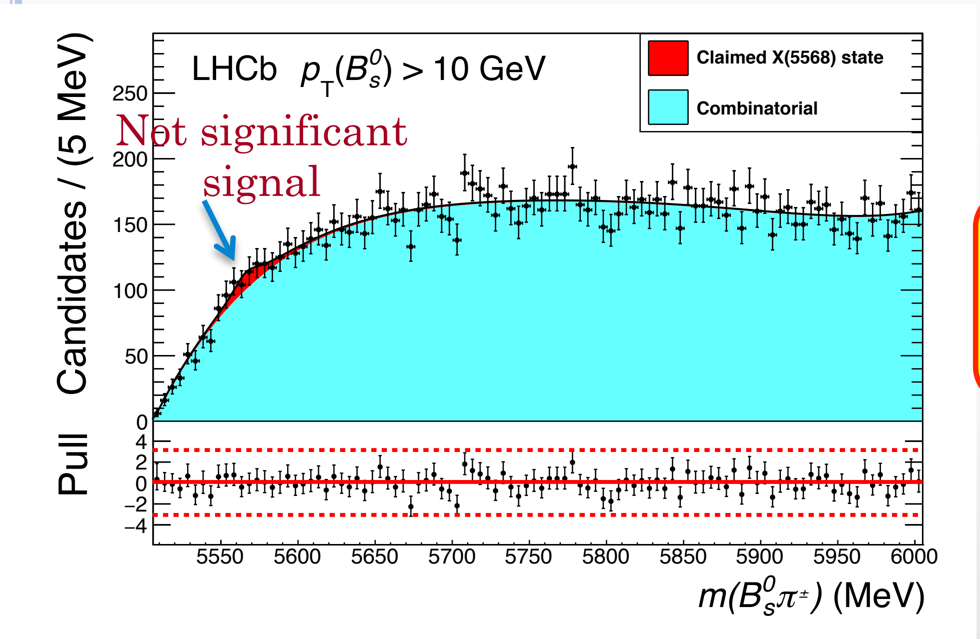


B_s sample 20x larger and much cleaner than DØ

Fit Result

LHCb: arXiv:1608.00435 accepted by PRL

Both modes combined (no "Cone" cut applied): $p_T(B_s) > 10$ GeV/c



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

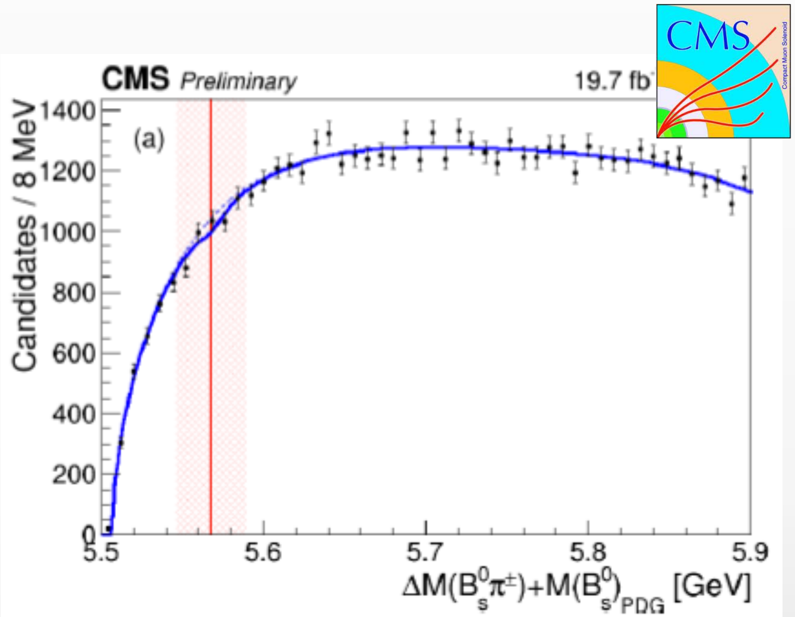
Limits are also set as function of mass (up to 6 GeV) and width (up to 50 MeV)

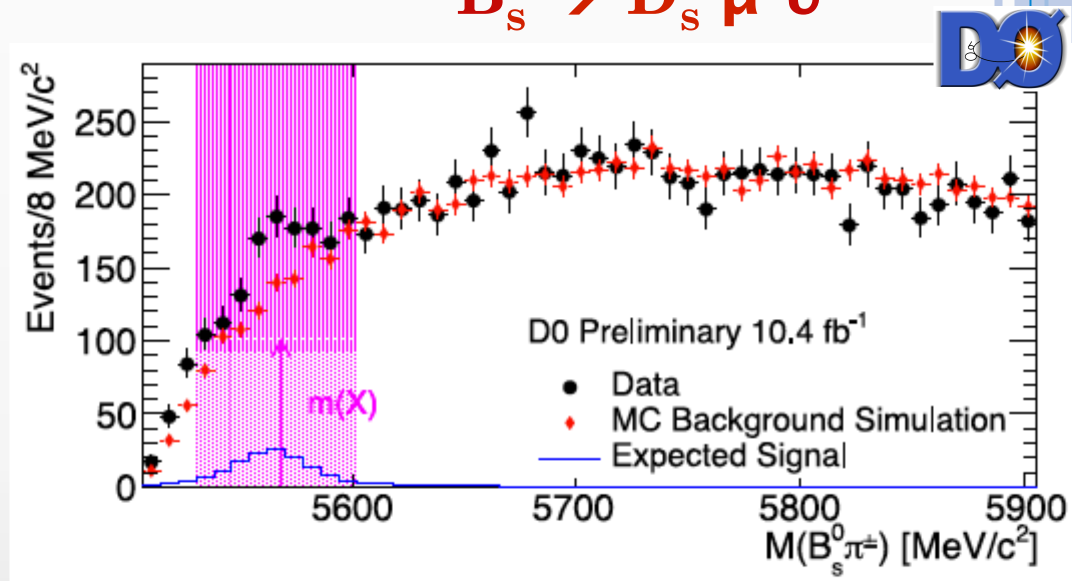
New Results @ ICHEP

CMS-PAS-BPH-16-002

DØ Note 6488-CONF

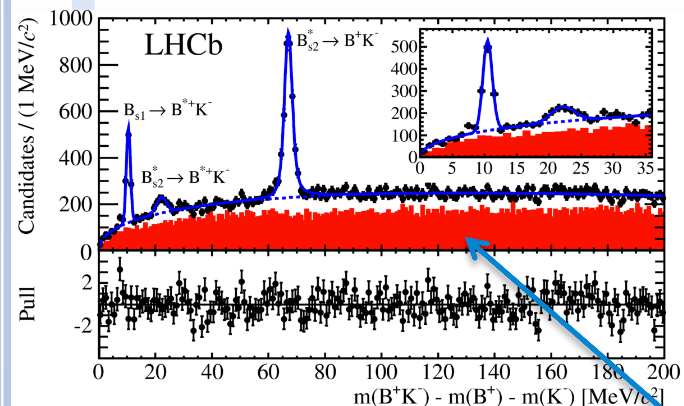
$B_s \rightarrow D_s\, \mu\, \upsilon$





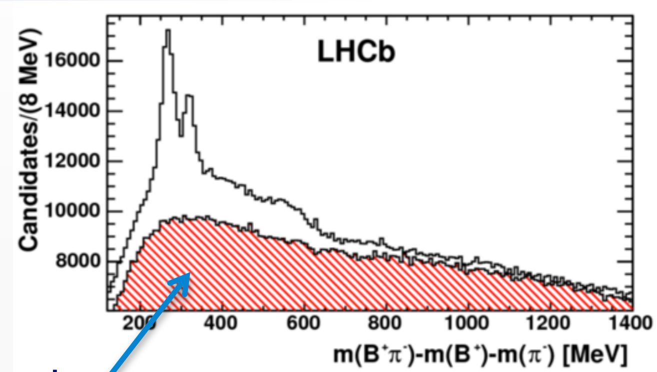
$\rho_X < 3.9\%\ @95\%\ C.L.$

Other "Implicit" Searches



PRL 110 (2013) 151803

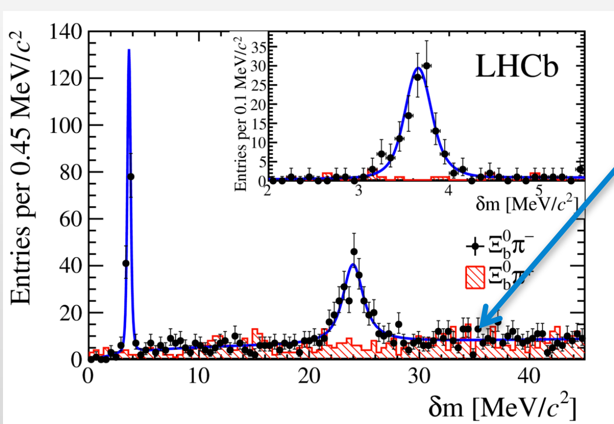
B^+K^+



$B^+\pi^+$

JHEP 1504 (2015) 024

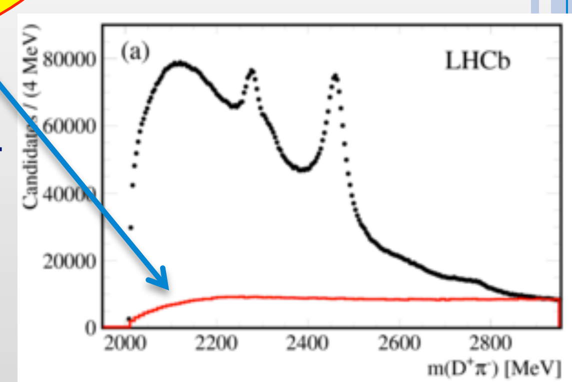
The red histograms, referred as Wrong Sign plots, are implicitly searches for tetra/pentaquark



$\Xi_b^0\pi^+$

PRL 114 (2015) 062004

$D^+\pi^+$



JHEP 09 (2013) 145

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

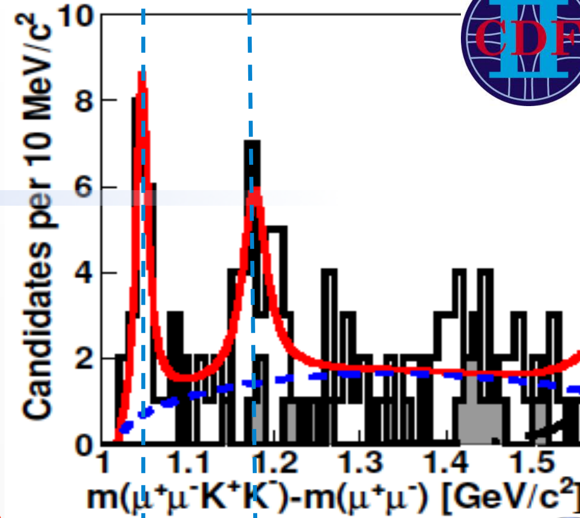
[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

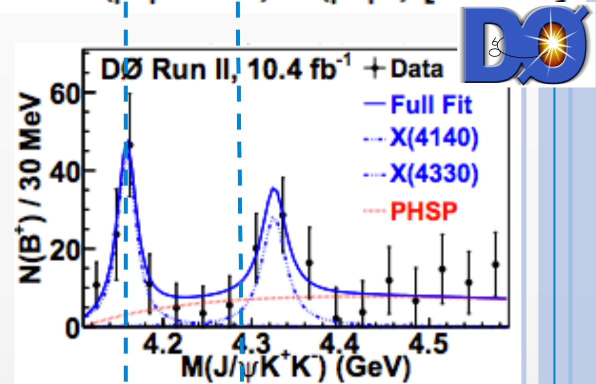
X(4140): A BIT OF HISTORY

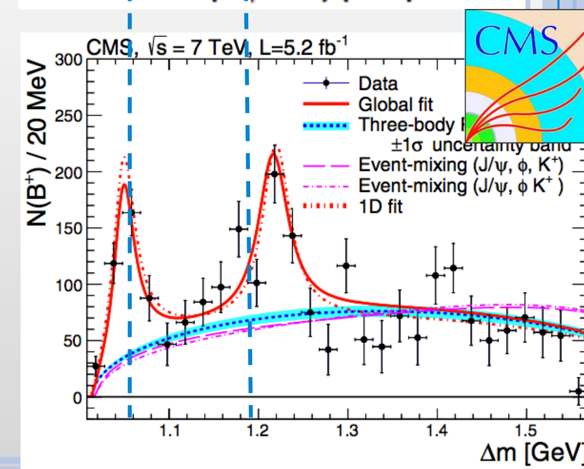
CDF: Evidence/“Observation” in $B^+ \rightarrow J/\psi\ \phi\ K^+$
[PRL 102, 242002 (2009), arXiv: 1101.6058]

X(4140)	**X(4274)**
$m = 4143.0^{+2.9}_{-3.0} \pm 0.6$ MeV $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$ MeV	$m = 4274.4^{+8.4}_{-6.7} \pm 1.9$ MeV $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$ 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)]**



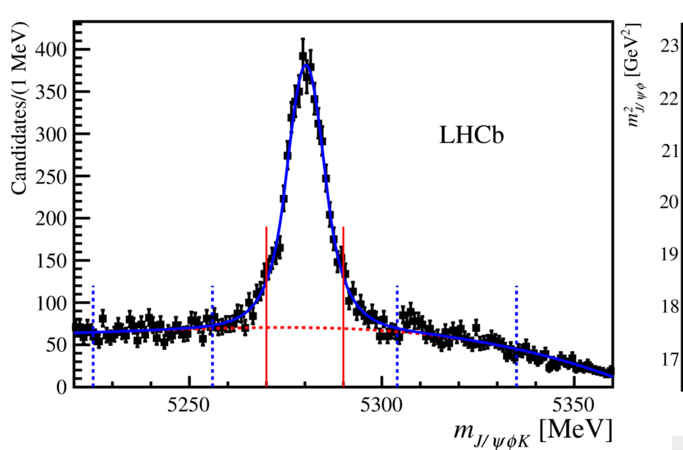


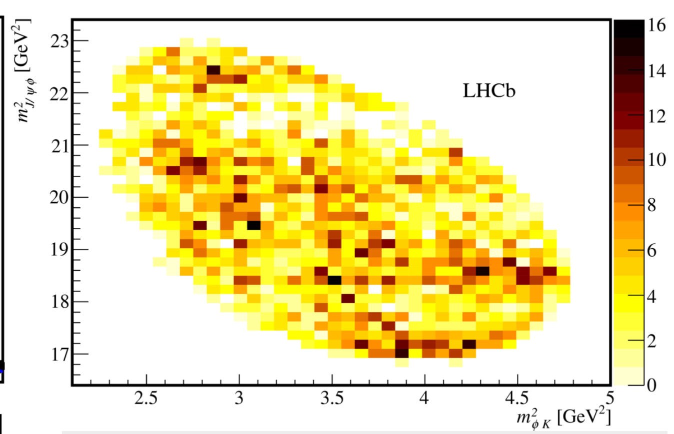


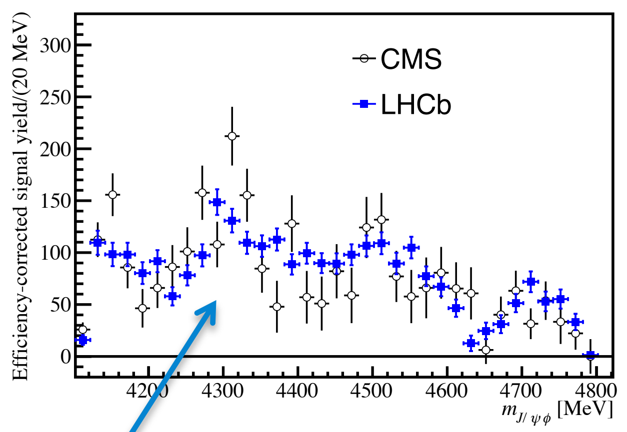
The $B^+ \rightarrow J/\psi\,\phi\,K^+$ Sample

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

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







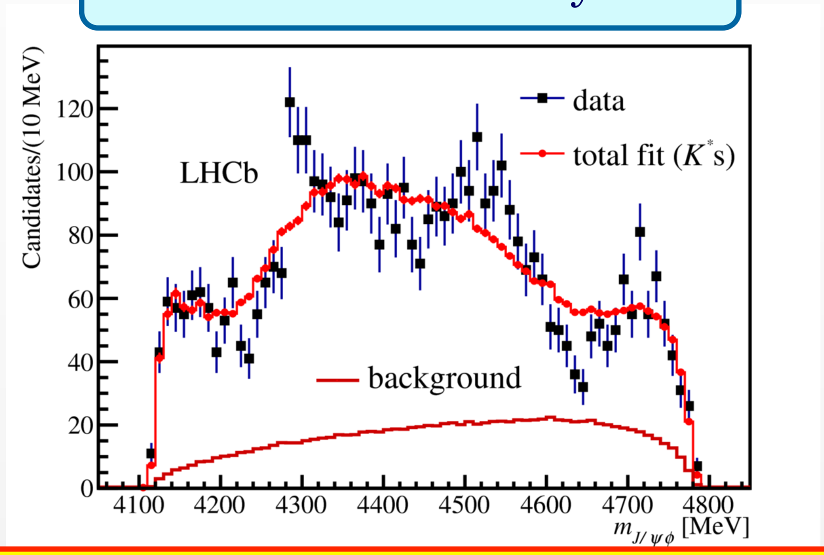
Qualitative agreement over the full mass range

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

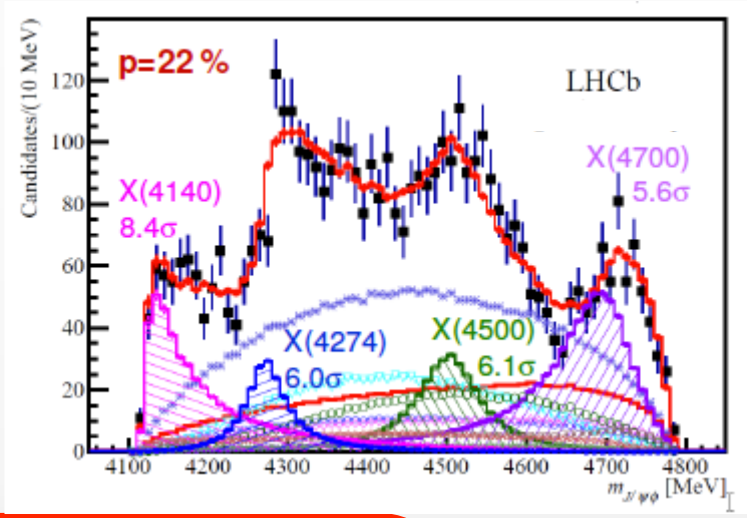
Fit Results

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

Fit with K* only



Fit with K* + 4 X's!



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

- Mass consistent with the previous measurements but <u>the width substantially larger</u>

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

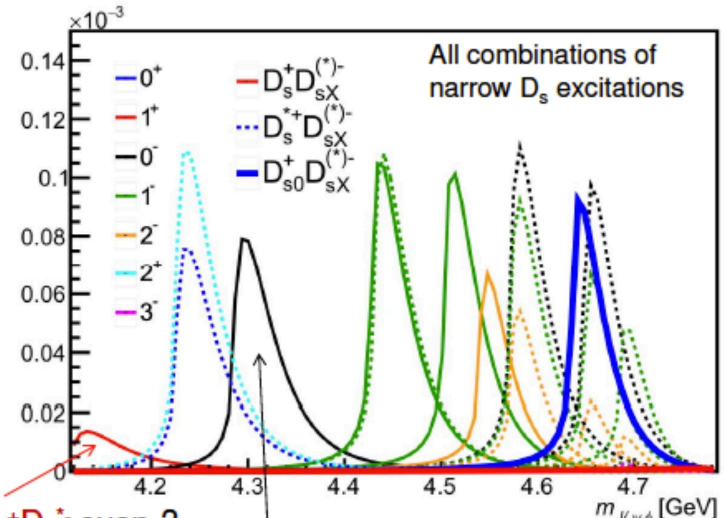
- Consistent with the unpublished CDF results.

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

Is the X(4140) a $D_s D_s^*$ cusp?

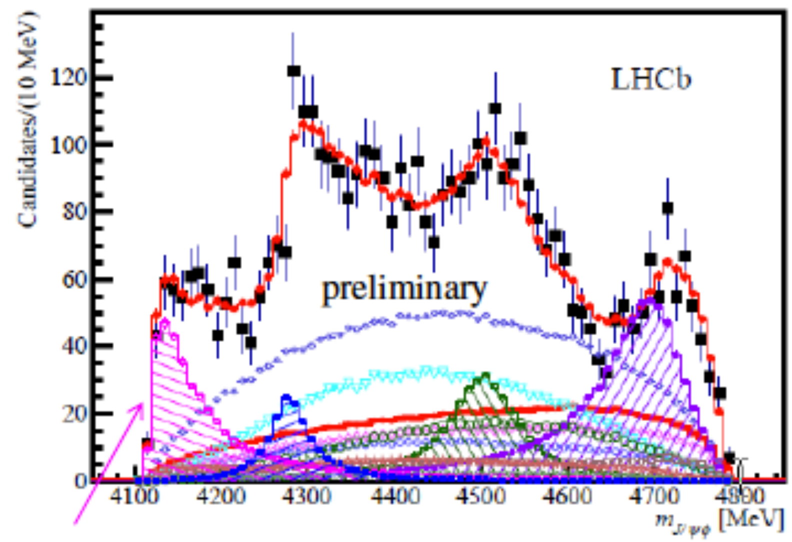
Results of alternate fit where the X(4140) parameterized by a $D_sD_s^*$ cusp

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 $J^P=0^-$



$D_s^+D_s^{*-}$ cusp

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

Amplitude Analyses are the way

Why amplitude analysis are strongly recommended?

Natural width of Z(4430) (MeV)

State	1D	2D	4D
Belle	$45\ ^{+18}_{-13}\ ^{+30}_{-13}$	$107^{+86}_{-43}\ ^{+74}_{-56}$	$200\ ^{+41}_{-46}\ ^{+26}_{-35}$
LHCb			$172 \pm 13\ ^{+37}_{-34}$

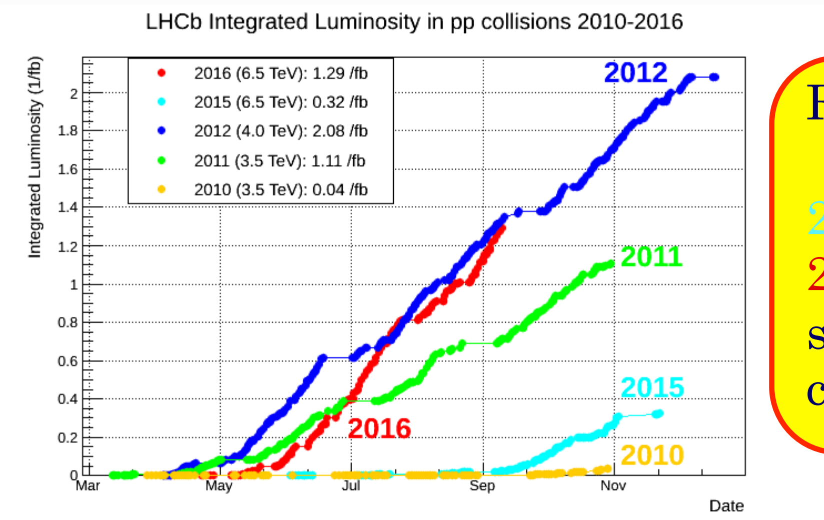
Natural width of X(4140) (MeV)

State	1D	6D
CDF	$15.3\ ^{+10.4}_{-6.1} \pm 2.5$	
LHCb		$83 \pm 21\ ^{+21}_{-14}$

- Broad structures may look narrow(er) in 1D mass projections.
- Amplitude analysis is a powerful tool to probe the quantum numbers and resonant character of the intermediate states.
- Limitation: poor knowledge of the light spectroscopy!

RUN II and Beyond

2016 Data Taking and future Plans



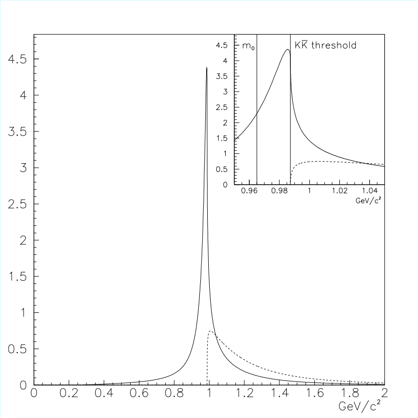
RUN II

2015: 0.3 fb^{-1}
2016: 1.3 fb^{-1} (corresponding to a larger *b-bbar* sample than collected in 2012, given larger collision energy/cross-sections)

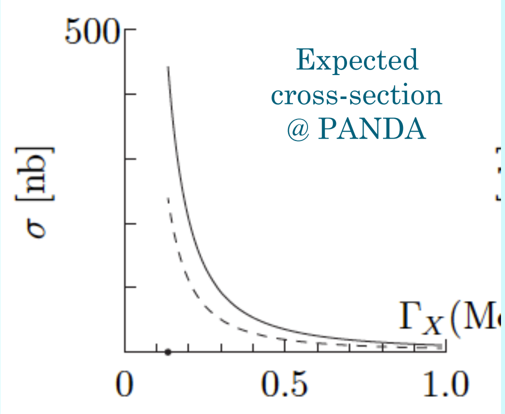
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1}
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

PROSPECTS I: X(3872)

- X(3872)
  - Precise mass measurements. Why so close to D^0D^{*0} threshold? Are we measuring the pole or the top of a Flatte function?



  - Precise measurement of the natural width for interpretation and more

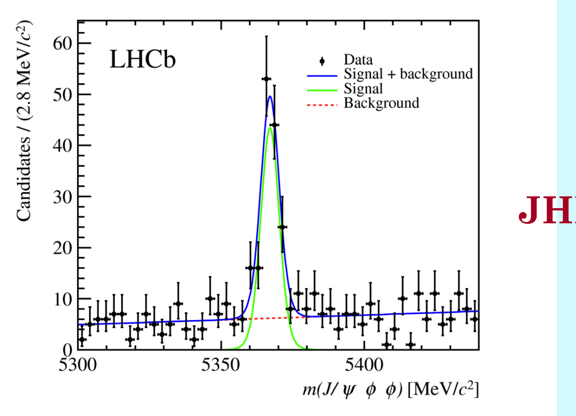


G.Y. Chen, J.P. Ma
PRD 77 , 097501, 2008

  - Search for new decay modes: (e.g.) $\chi_{c1}\,\pi\,\pi$
  - Confirmation of $J/\psi\ \omega$

Prospects II: Quarkonia-like states

- Charmonium-like states
  - Search for X(4140) → $J/\psi\ \phi$ in B_s → $J/\psi\ \phi\phi$ decays



JHEP 03 (2016) 040

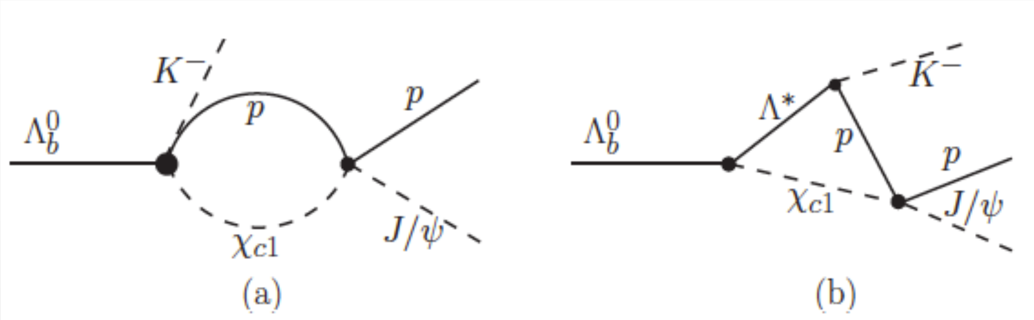
  - Search for the missing $\chi_{c0}(2P)$ and $\chi_{c1}(2P)$
  - Exploration of $D_{(s)}\overline{D^{(*)}}_{(s)}$ mass spectra from B decays
  - Central Exclusive Production (See Paolo's talk)
- Search for X_b →Y(1S) ω

Prospect III: Tetra/Pentaquarks

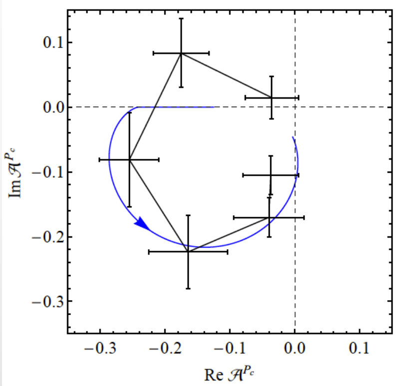
- Search for Z_c+
  - Study of B → η_c K π
  - Study of B → ψ(2S) π π
  - Study of B_c → DDD
- Pentaquarks
  - RUN II data will fix the spin-parity of the two P_c^+'s
  - The hunt to the next pentaquark is open!
    - χ_{c1} p
    - Y(1S) → J/ψ p $\bar{p}$
    - D Σ_c
    - Triple charged pentaquarks

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
  - Is the X(4140) as a cusp? Why we don't observe them at every threshold?
  - Cusps can also mimic the circle in the Argard diagram



PRD 92 (2015) 7, 071502

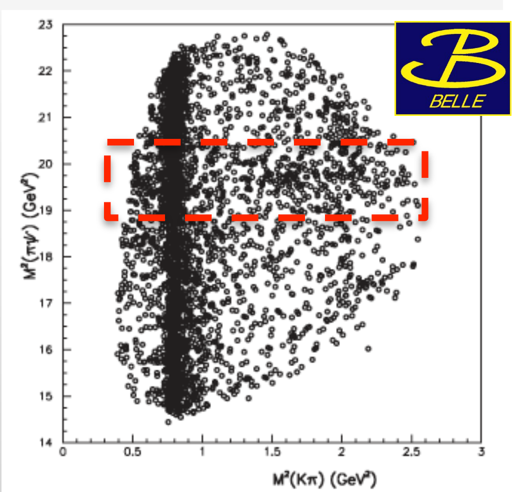


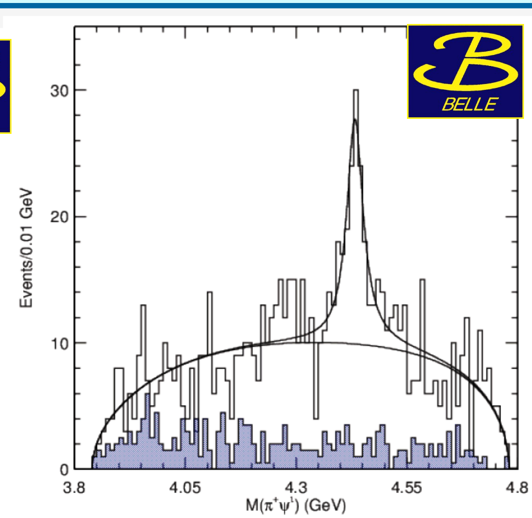
Joint efforts required from experimentalists and theorists to understand the nature of such states. LHCb will play a fundamental role. Stay tuned!

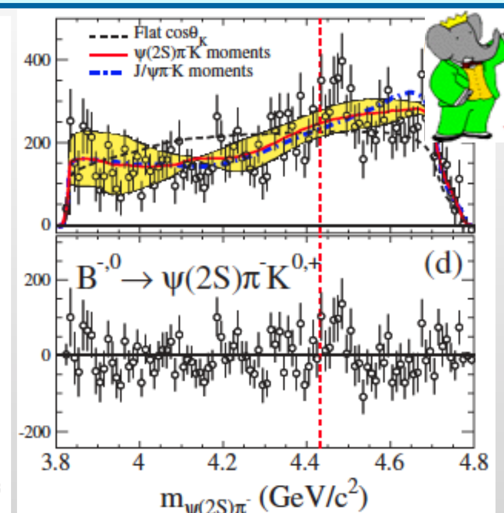
Back-up slides

A bit of History: $Z(4430)^+$

- Observed in the $\psi(2S)\pi^+$ in $B^{0(+)} \to \psi(2S)\pi^+K^{-(0)}$ decays by Belle
  [Belle, PRL100, 142001 (2008)]
- Clear signature of exotic:
  - Decay to charmonium $\to c\bar{c}$ pair content
  - Electric charged $\to$ at least 2 more light quarks $N_{quarks} >= 4$!
  - Tetraquark, D^*D_1 molecule?
- $Z(4430)^+$ not confirmed (nor excluded) by BaBar **[BaBar, PRD 79, 112001 (2009)]**
- Later 2D "Dalitz" technique: $M^2(\psi(2S)\pi^+)$ vs $M^2(K^-\pi^+)$ **[Belle, PRD 80, 031104 (R) (2009)]**
- Belle: full 4D amplitude analysis. $J^P = 1^+$ favoured but $J^P = 0^-$ not excluded
  [Belle, PRD 88 (2013) 074026]

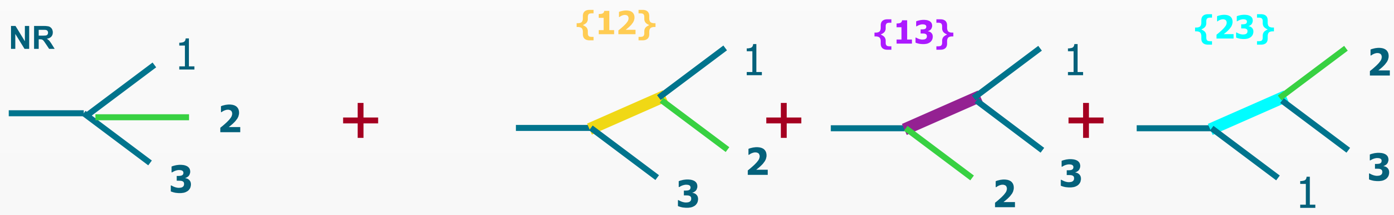






The Isobar Model

Isobar model: total decay amplitude as a coherent sum of processes where one daughter is spectator



Three-body amplitude for $B^0 \to \psi(2S)\, K\, \pi$

Sum over all K* resonances

Z(4430) component

$$|\mathcal{M}(\Phi)|^2 = \sum_{\Delta\lambda_\mu = 1,-1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_{K^*} A^{K^*}_{\lambda_\psi \Delta\lambda_\mu}(m_{K\pi}, \Omega) + \sum_{\lambda^Z_\psi=-1,0,1} A^{Z}_{\lambda^Z_\psi \Delta\lambda_\mu}(m_{\psi\pi}, \Omega^Z) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

Defined unless a phase and a constant

Rotation by α due to different helicity frame

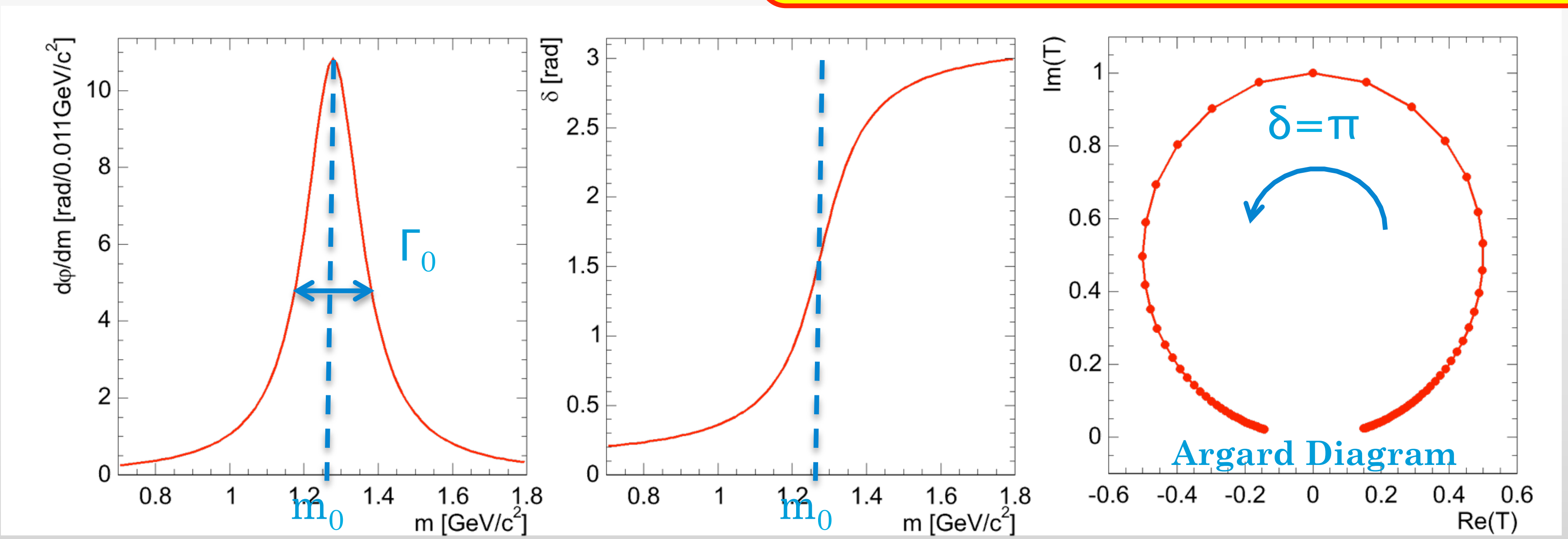
How to model a single term

$$A^{K^*}_{\lambda_\psi,\Delta\lambda_\mu}(m_{K\pi},\Omega) = H^{K^*}_{\lambda_\psi} A^{K^*}(m_{K\pi}) d^{J(K^*)}_{\lambda_\psi,0}(\theta_{K^*}) \times e^{i\lambda_\psi \phi} d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$

Free parameters
+
m_0, Γ_0 (in case of a new state)

Relativistic Breit-Wigner

$$A^{K^*}(m_{K\pi}) = \frac{1}{m_0^2 - m_{K\pi}^2 - i m_o \Gamma_0}$$



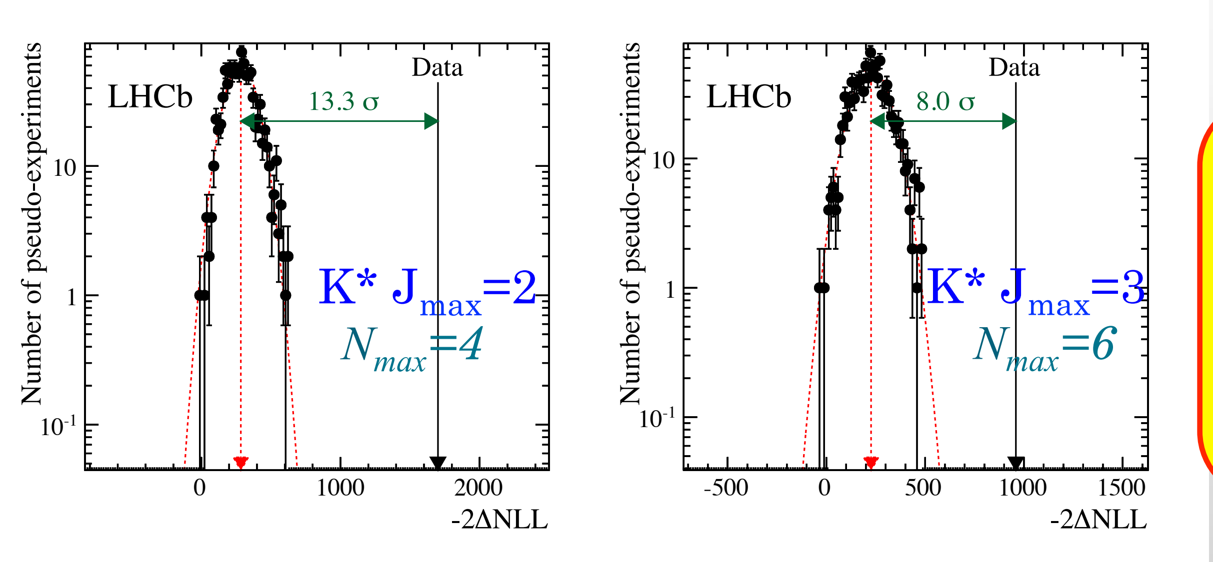
Quantitative Results from Model Independent Approach

LHCb: arXiv: 1510.01951

Test significance of implausible $N_{max} < N < 30$ moments using the log-likelihood ratio:

$$\Delta(-2\mathrm{NLL}) = -2\log\frac{\mathcal{L}_{N_{max}}}{\mathcal{L}_{30}} = -2\log\frac{\prod_i \mathcal{F}_{N_{max}}(m^i_{\psi'\pi})}{\prod_i \mathcal{F}_{30}(m^i_{\psi'\pi})}$$

Statistical simulations of pseudo-experiments generated from the $N < N_{max}$ hypotheses



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

MODEL INDEPENDENT APPROACH (*i.e.* A LA BABAR)

LHCb: arXiv: 1510.01951

(e.g.) If only K* resonances up to J = 2

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \ldots$$

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

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

Should it not happen →

There are K* resonances with J > 2
or
There are exotic(s) which make the high order terms non-zero!

Model Independent Approach (*i.e.* a la BaBar)

LHCb: arXiv: 1510.01951

Can the reflections of the structures in m(Kπ) and cos ϑ_{K^*} reproduce the m(ψ'π) distribution?

If no exotics in ψK and ψπ → Partial wave expansion in a given bin of m^2(Kπ)

Legendre Polynomials

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \ldots$$

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

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

Model Independent Approach

[LHCb: arXiv:1604.05708]

H1: If no exotics in J/ψ K and J/ψ 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

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

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

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

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

Sum of the terms up to $P_{N\text{max}}$, where N_{max} = 2*J(Λ*), 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

[LHCb-PAPER-2016-015]

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…

LHCb-CONF-2016-004

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

(Both modes combined: $p_T(B_s) > 10$ GeV/c)