Exotic hadrons at LHCb

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2nd EMMI workshop on
anti-matter, hyper-matter and exotica production at the LHC

November 6-10, 2017 – Turin

The LHCb experiment

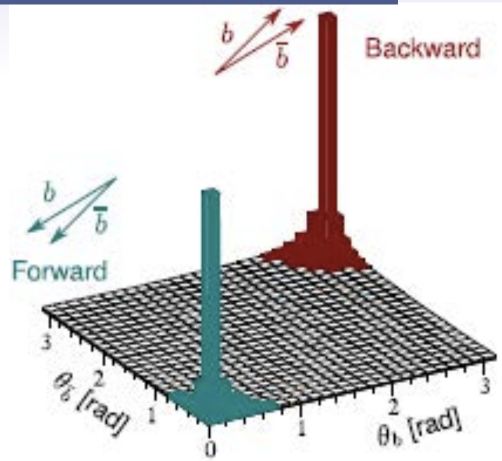
JINST 3 (2008) S08005
IJMP A30 (2015)1530022

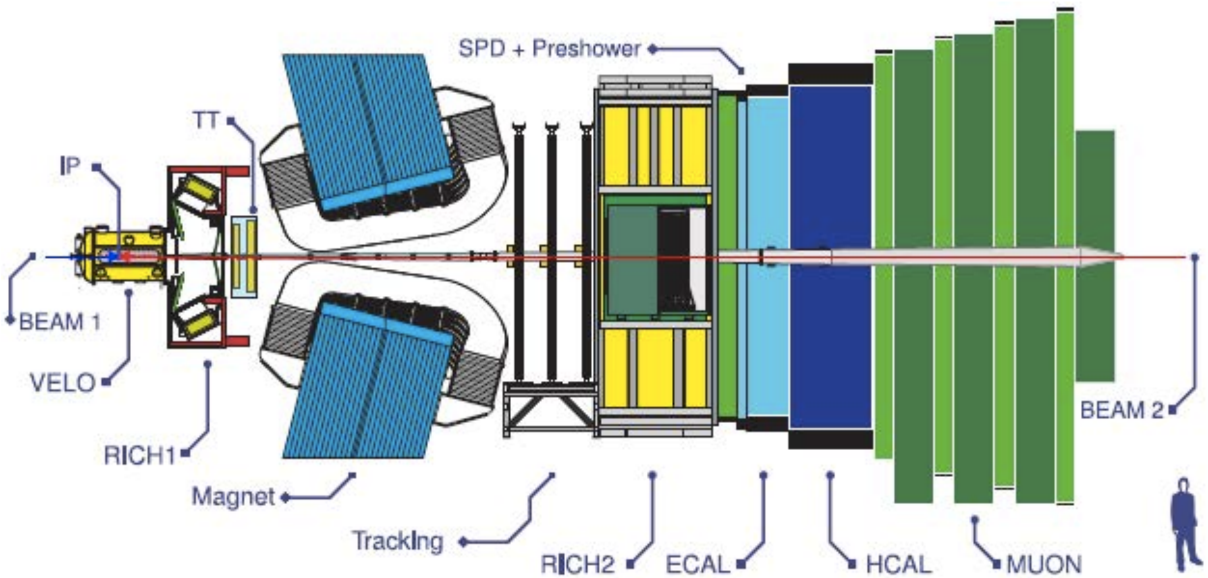
LHC has record numbers of b (and c) hadrons:

$\sigma_{b\bar{b}} \approx 250\ \mu\text{b}$ @ 7 TeV $\quad \sigma_{c\bar{c}} \approx 20 \times \sigma_{b\bar{b}}$

LHCb designed to study rare decays and CP violation in b-hadrons

single-arm spectrometer covering the forward pseudorapidity region $2 < \eta < 5$





excellent performance:

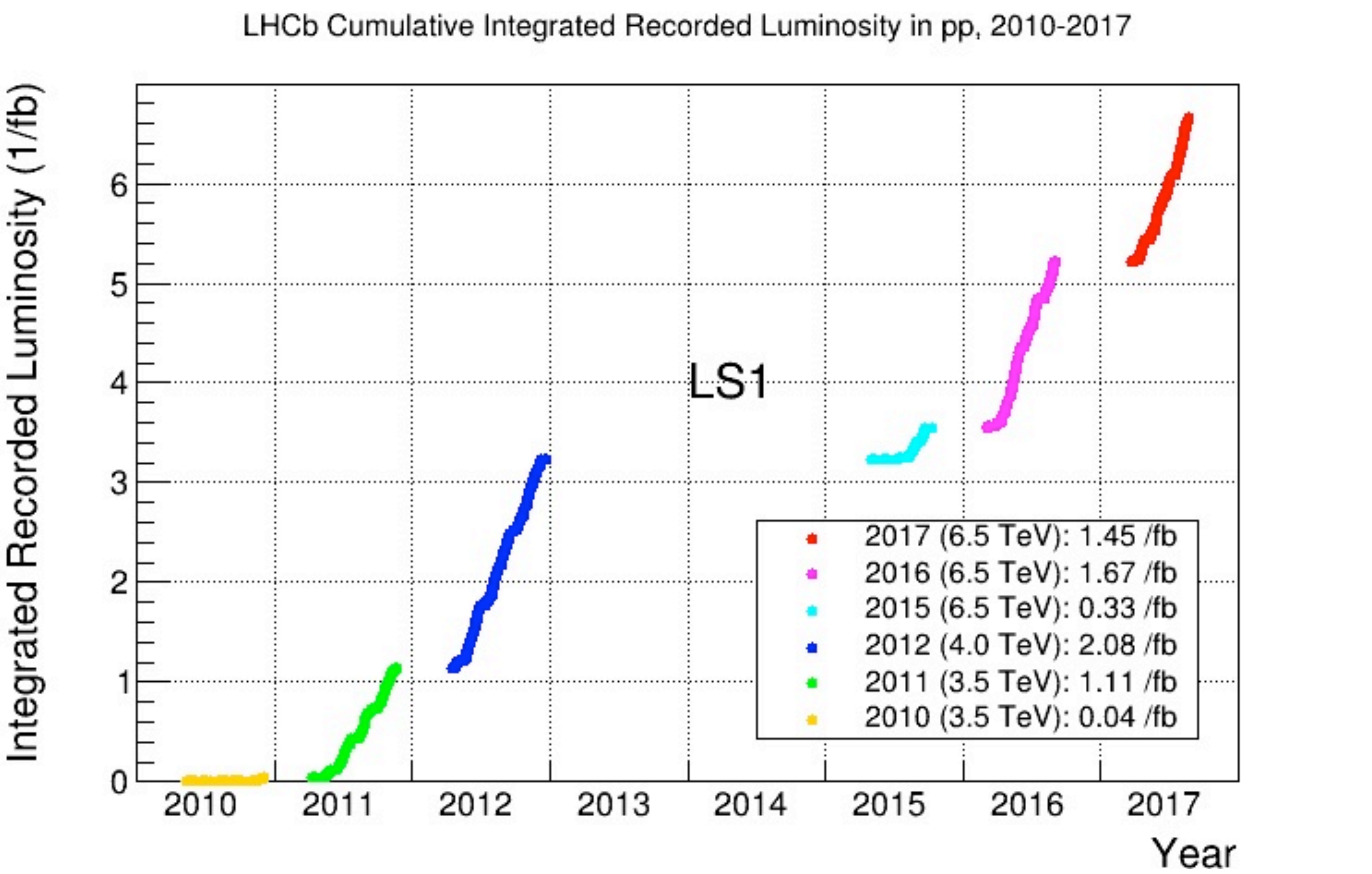
- vertexing and tracking: good time of flight and invariant mass resolution
- PID for pions, kaons, protons and muons
- calorimeter

Trigger on high-p_t lepton or hadron from displaced vertexes

c and b-hadrons

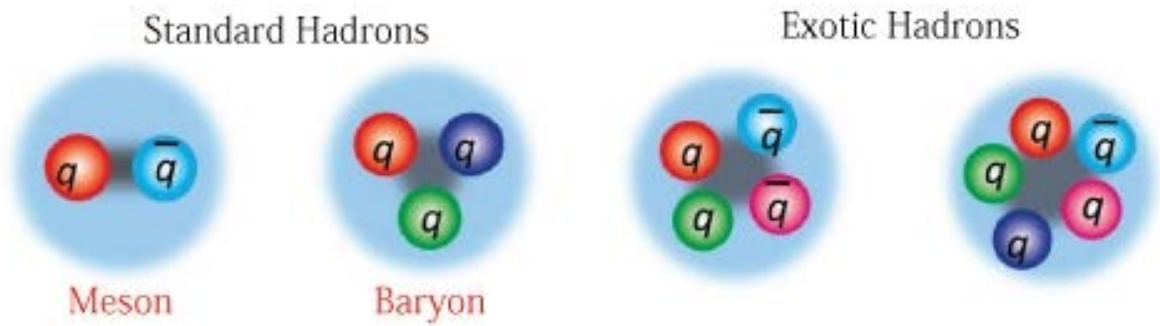
ideal place for spectroscopy!

LHCb data

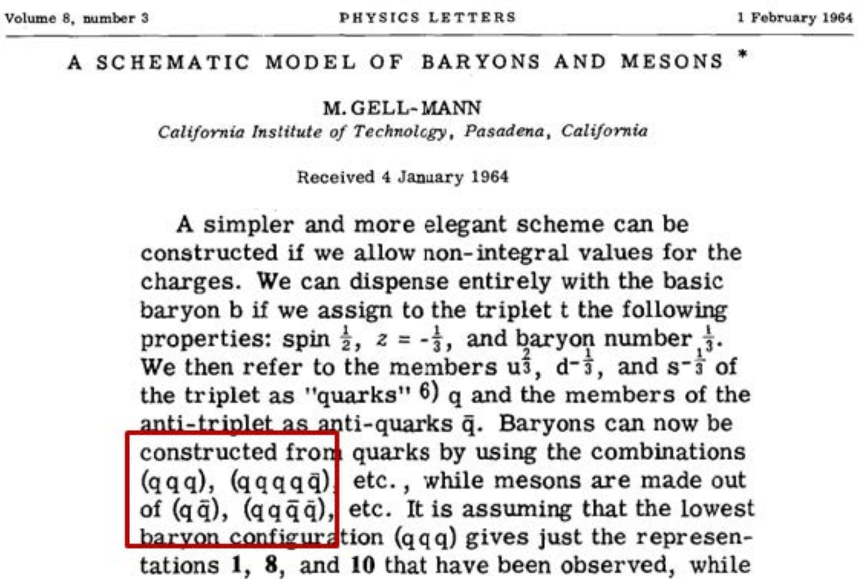

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2017
Integrated Recorded Luminosity (1/fb)
0
1
2
3
4
5
6
2010
2011
2012
2013
2014
2015
2016
2017
Year
LS1
2017 (6.5 TeV): 1.45 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb

Standard and Exotic Hadrons

Mesons and baryons with other than $q\bar{q}$ or qqq configurations are not forbidden by QCD (as long as they remain colour-less)



Their possibility admitted as early as the quark model was introduced



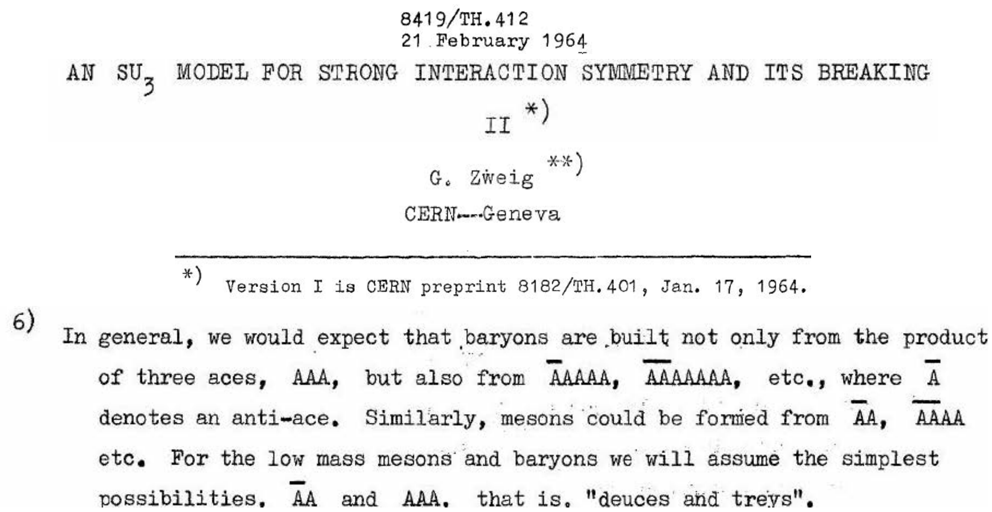
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

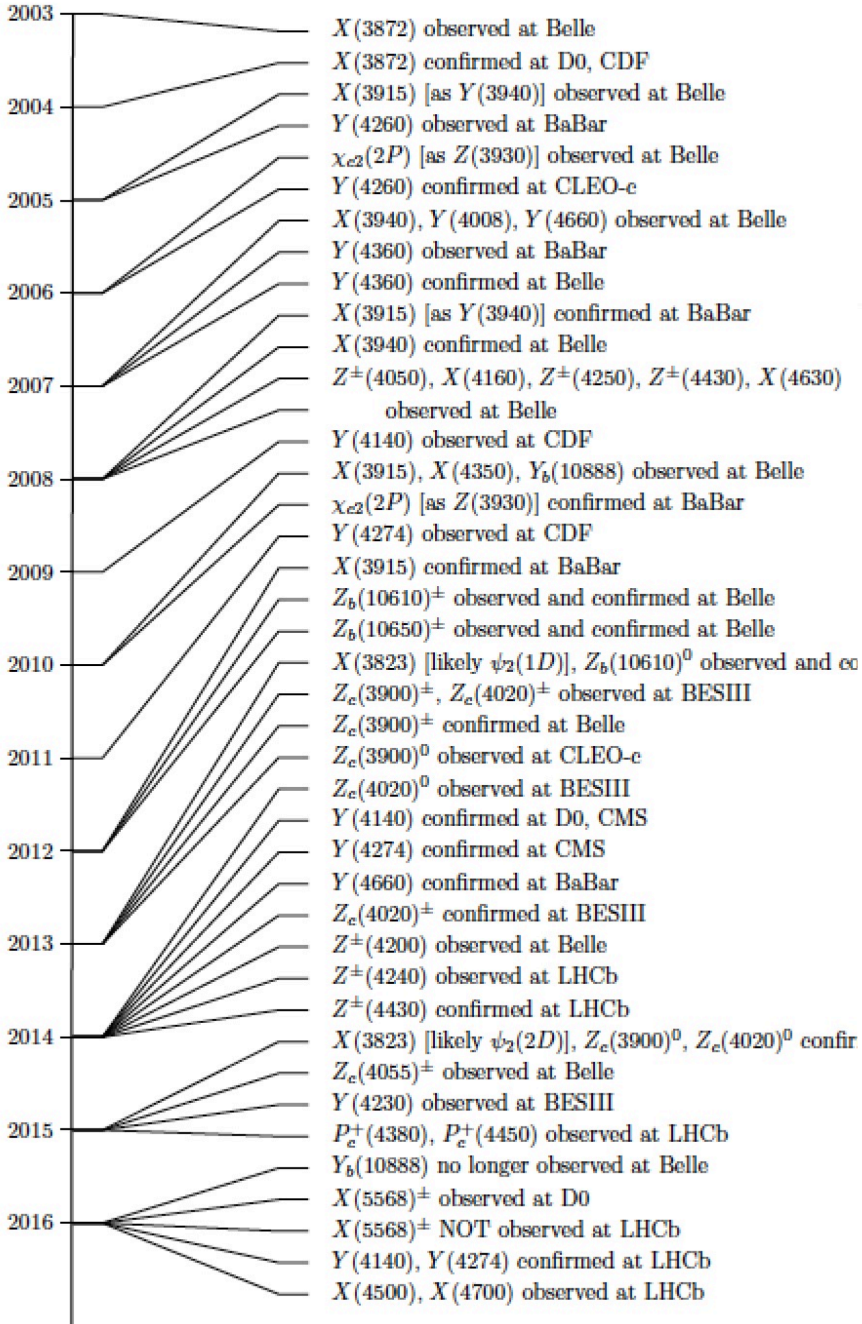
G. Zweig **)
CERN---Geneva

*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

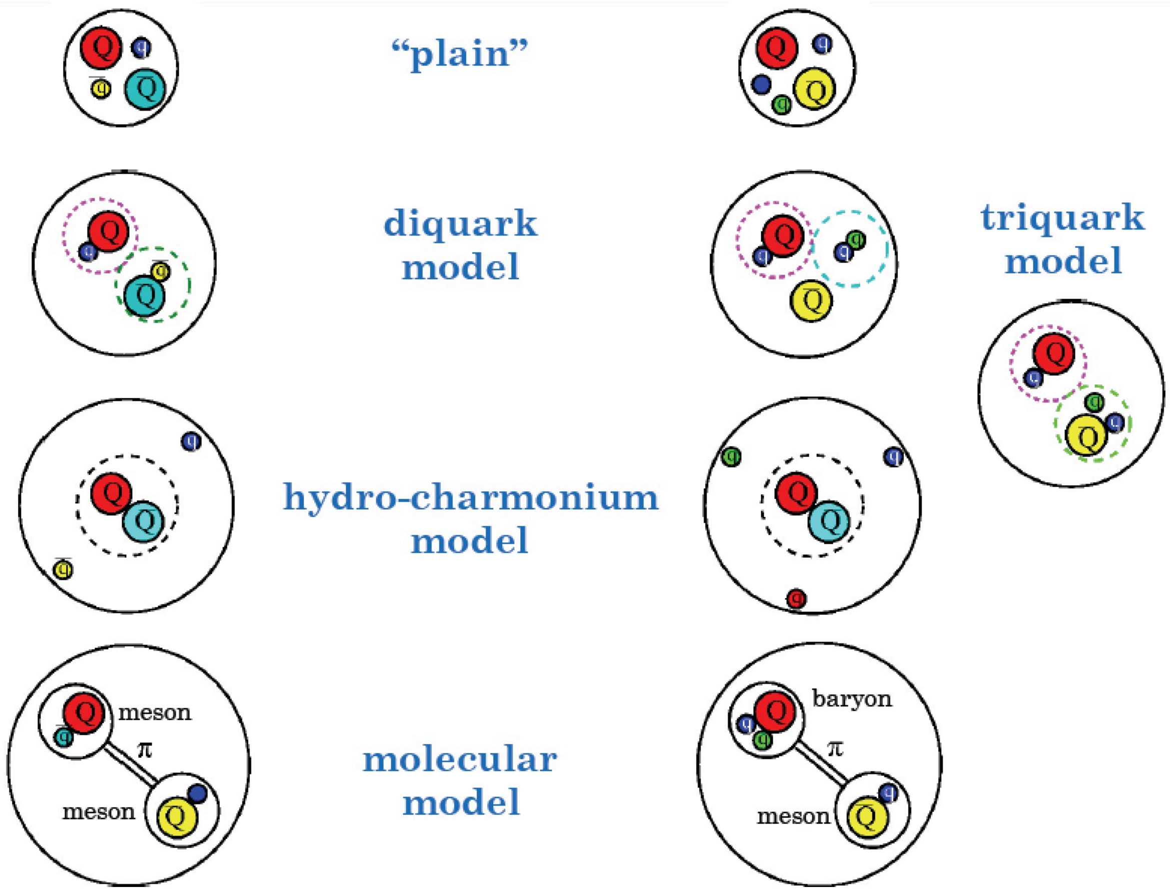
no undisputed evidence yet in light hadrons

Exotic hadrons with heavy quarks



in the past decade a pletora of new states with constituent heavy $Q\bar{Q}$

which is their structure?



B mesons – and their decay products – copiously produced at hadron machines

Exotic or not?

How can you tell if a state is exotic?

not easy and not always straightforward!

Manifestly exotic

- quantum numbers not allowed for $q\bar{q}'$ or $qq'q$"
- >3 valence quarks required

Undisputed

(but many possible exotic states would not fit)

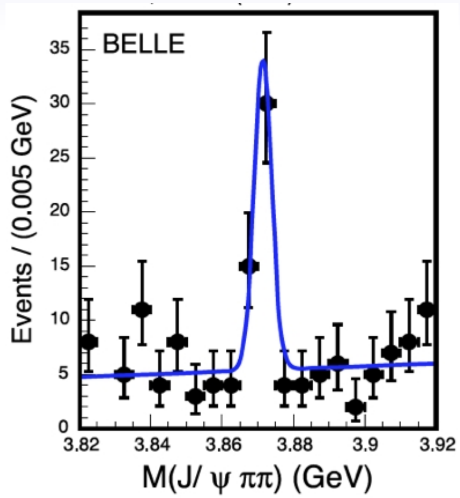
"Cryptoexotic"

- mass/width not fitting in meson or baryon spectra
- overpopulation of the spectra
- production or decay properties incompatible with standard mesons/baryons

...endless disputes..

The $X(3872)$

PRL 91 (2003) 262001



Discovered by Belle as a narrow peak in $J/\psi\pi^+\pi^-$ invariant mass in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays.

Well above open charm threshold

... yet very narrow: $\Gamma < 1.2\,\mathrm{MeV}$

– mass amazingly close to the $D^0 - D^{*0}$ threshold

loosely bound $D - D^*$ molecule?

– radiative decays to $J/\psi\,\gamma \Longrightarrow C = +$

– $J/\psi\,\pi^+\pi^-$ compatible with $J/\psi\,\rho$, yet significant $J/\psi\,\pi^+\pi^-\pi^0$ $(J/\psi\,\omega)$

I-spin violation?

– prompt production in $p\bar{p}$ and pp at similar rates as $c\bar{c}$

Extremely difficult to identify as a conventional charmonium state, but some of its properties look like charmonium

Determination of the $X(3872)$ quantum numbers

CDF PRL 98 (2007) 132002 , Belle PRD 85 (2012) 052003 , *BABAR* PRD 82 (2010) 011101

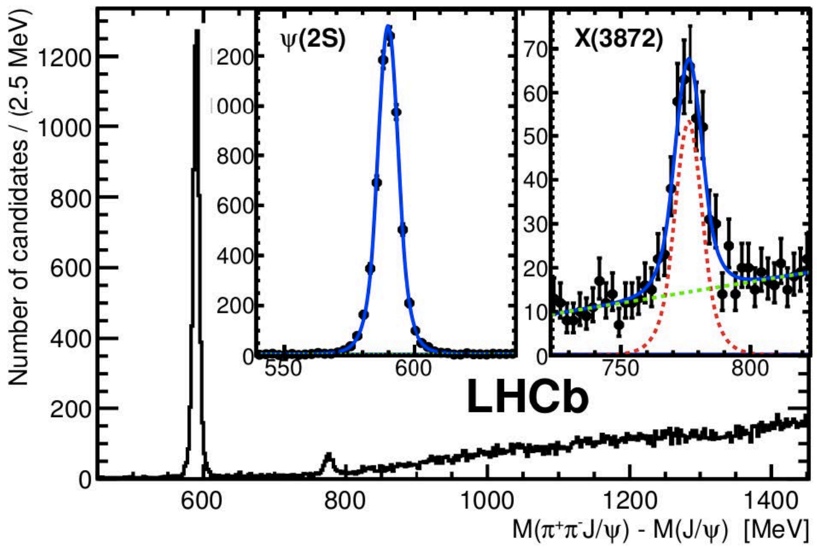
1D angular distribution – all J^{PC} assignments excluded except 1^{++} or 2^{-+}

LHCb: **PRL 110, 222001 (2013)**

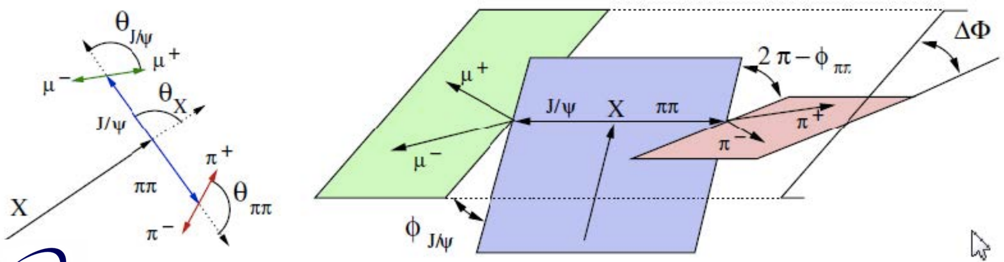
5D angular analysis of

$$B^+ \to K^+ X(3872) \to K^+ J/\psi \pi^+ \pi^-$$

Angular correlations in the B^+ decay chain carry information on the J^{PC} of the $X(3872)$



$$\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\psi}, \Delta\phi_{X,J/\psi})$$



Matrix elements in the helicity formalism

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

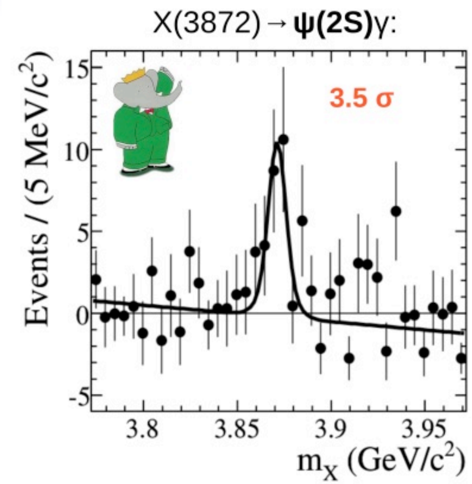
$X(3872)$ radiative decays

Predictions:

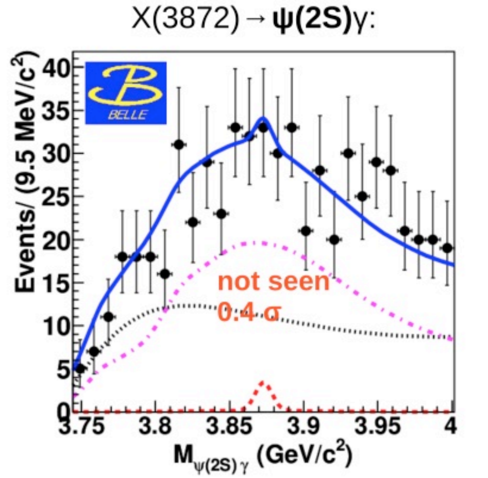
$\mathcal{B}(\psi(2S)\gamma) \approx 0$ for purely molecular state

inconclusive results from B-factories

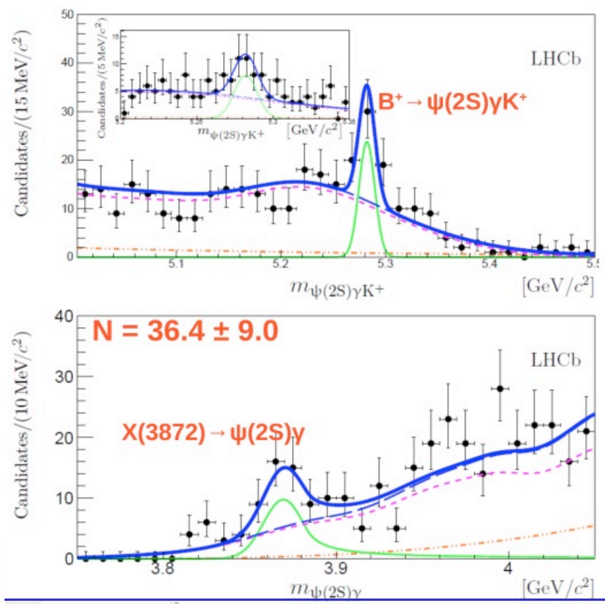
PRL 102(2009) 132001



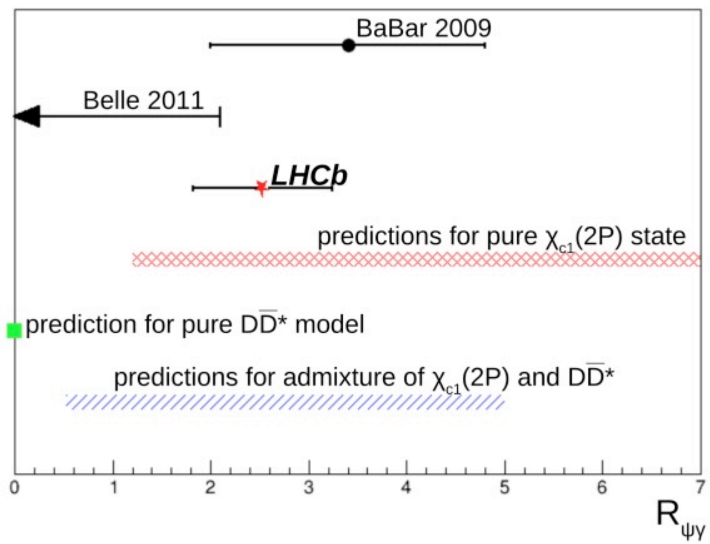
PRL 107 (2011) 091803



LHCb: **NP B886 (2014) 665**



$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64\,(\text{stat}) \pm 0.29\,(\text{syst})$$



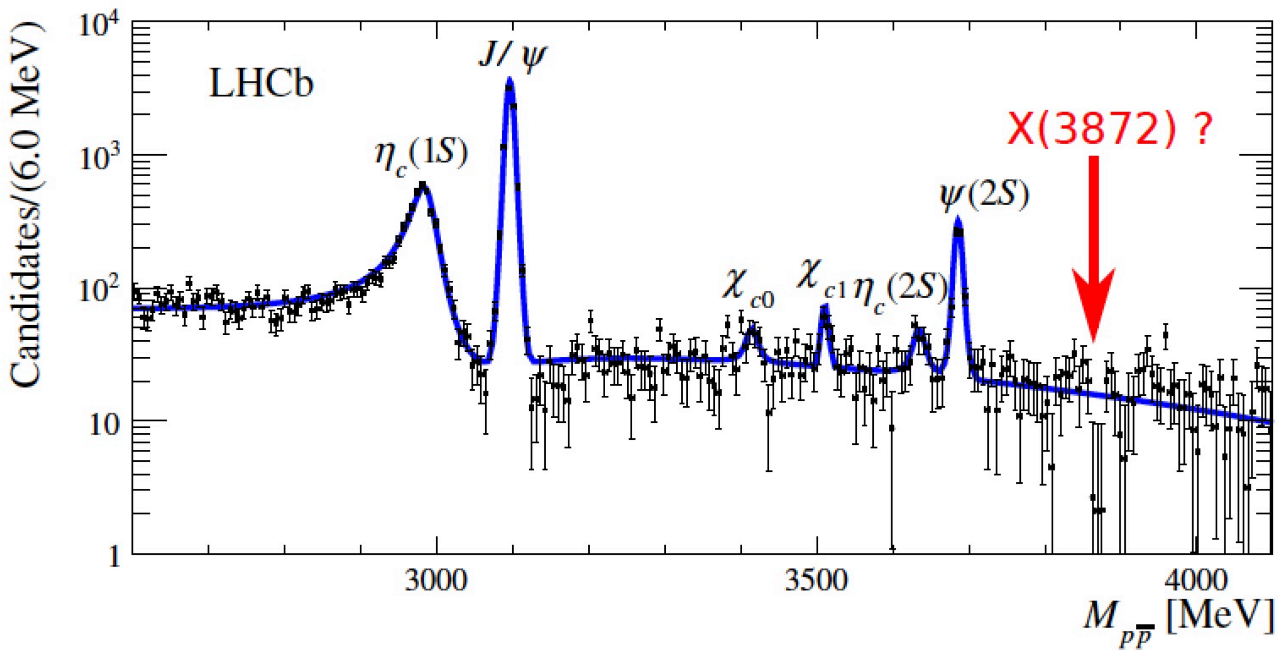
$X(3872) \to p\bar{p}$?

$\mathcal{B}(X(3872) \to p\bar{p})$: predictions for regular charmonia larger (usually) than for other interpretations

Prospects for $X(3872)$ of PANDA or other $p\bar{p}$ formation experiments depend on its value

$B^+ \to K^+ p\bar{p}$

PL B769 (2017) 305



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

also: measurements of $\eta_c(2S) \to p\bar{p}$, mass and width of $\eta_c(1S)$

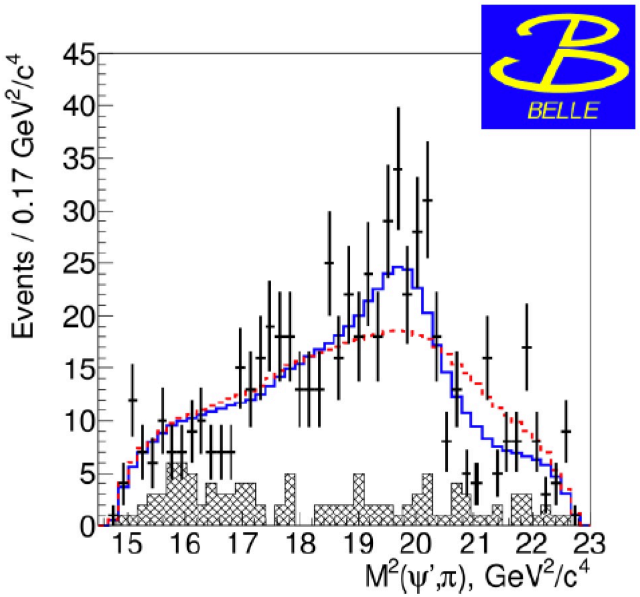
$Z(4430)^{+}$

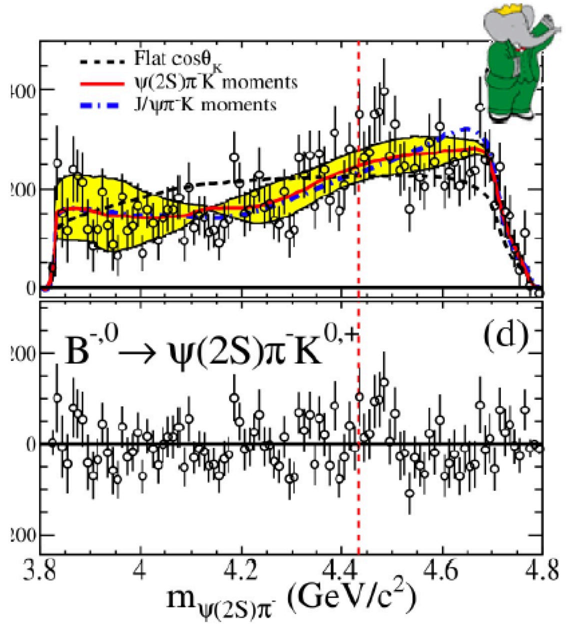
Discovered by Belle in $B^0 \to \psi(2S)\pi^- K^+$

PRL 100 (2008) 142001

PRD 80 (2009) 031104

PRD 88 (2013) 074026



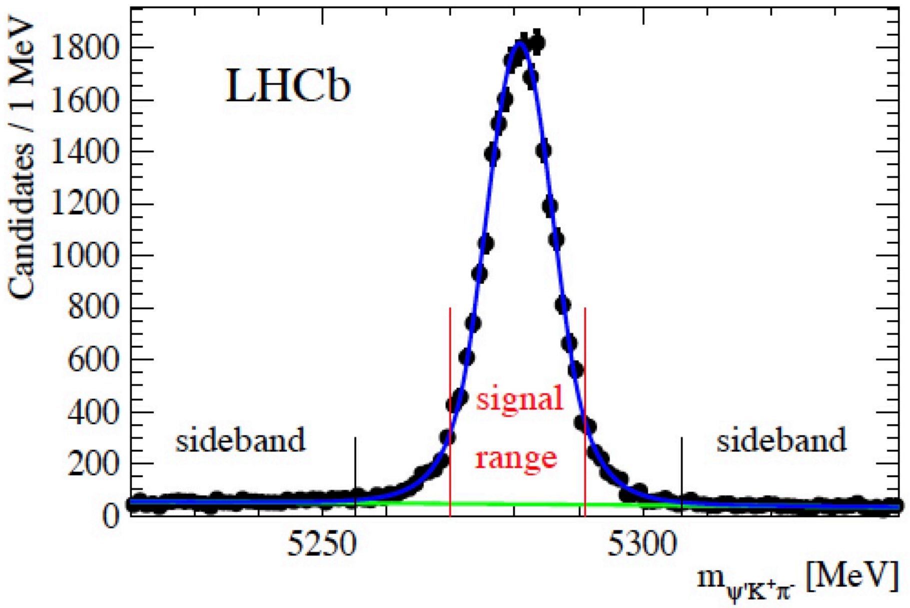


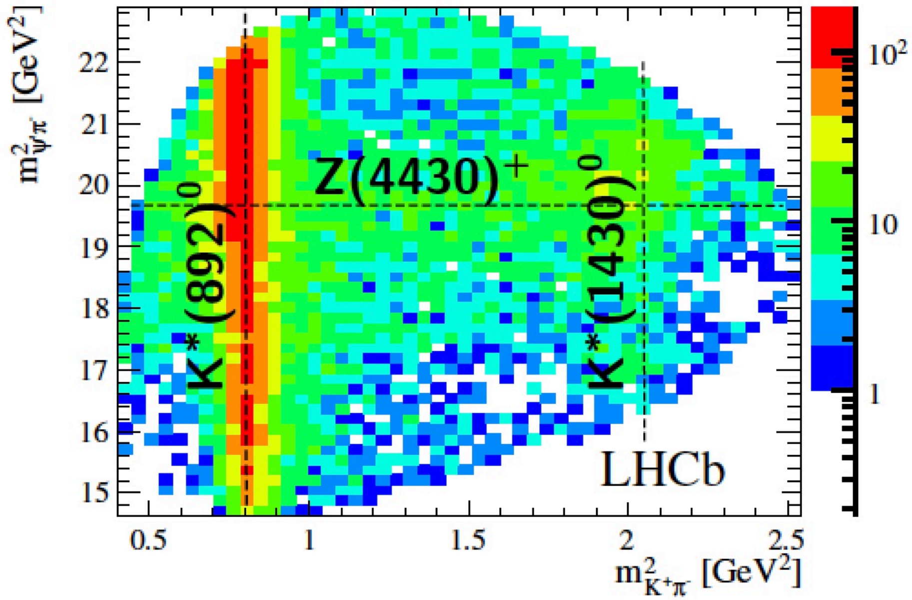
not confirmed by *BABAR* PRD79 (2009) 112001

manifestly exotic: no charged standard mesons with valence $c\bar{c}$

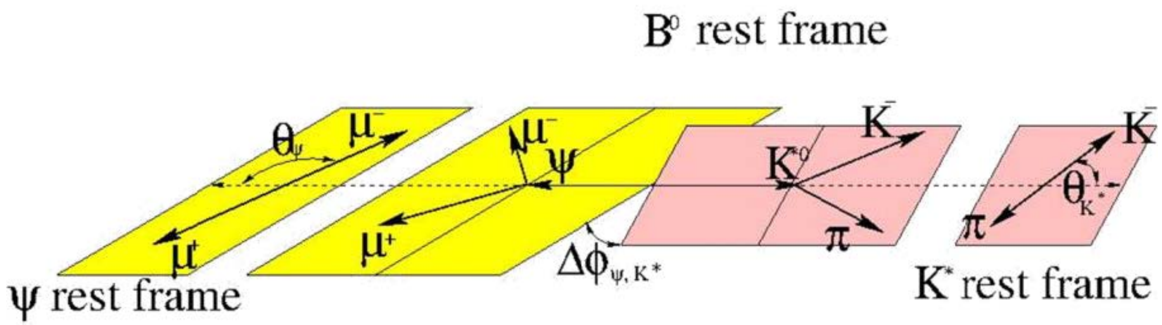
$Z(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$ at LHCb

$\approx$ 25k $B^0 \to \psi(2S)K^+\pi^-$ with $\approx$ 4% combinatorial background

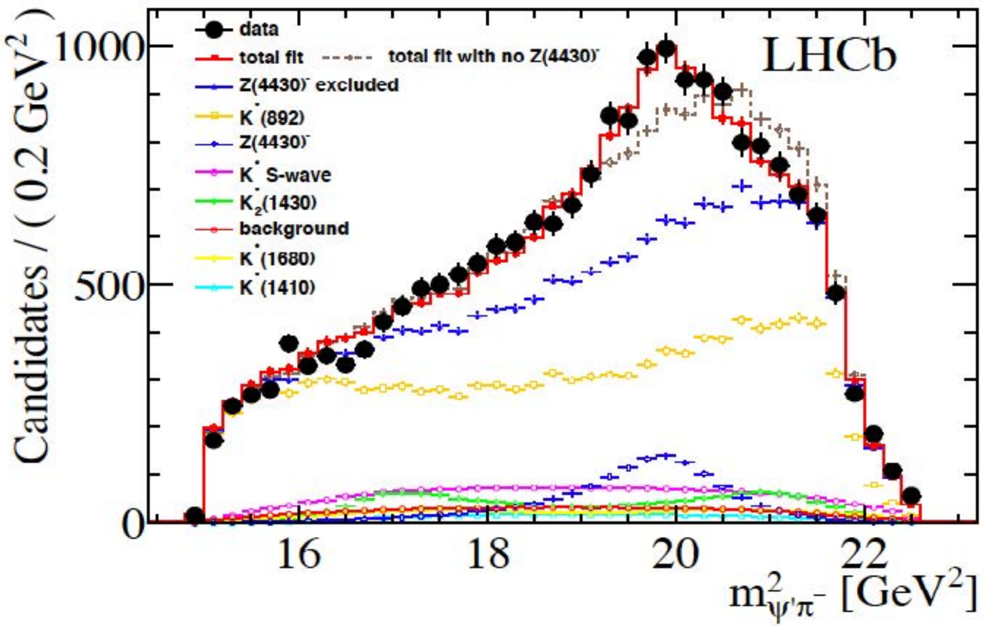


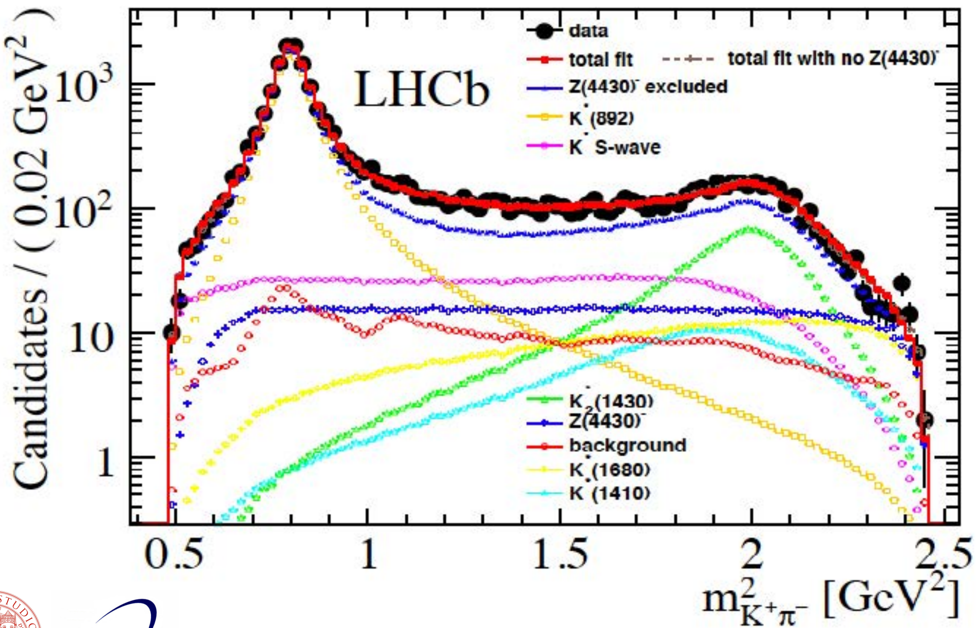


perform 4D amplitude analysis **PRL 112 (2014)222002**



$Z(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$ at LHCb



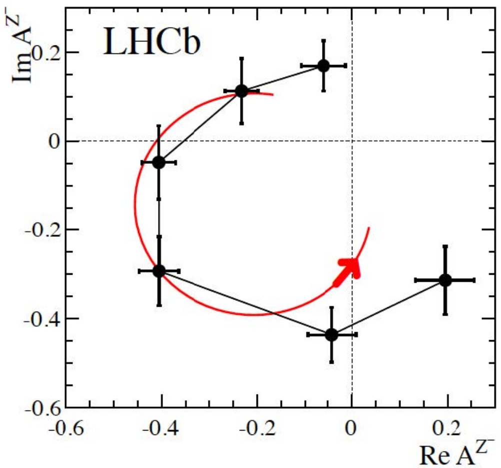


PRL 112 (2014)222002

$$M = 4475 \pm 7^{+15}_{-25} \text{ MeV}/c^2$$

$$\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}$$

- $J^P = 1^+$
- Argand plot shows resonant behaviour



Model independent confirmation of $Z(4430)^+$ in $B^0 \to \psi(2S)K^+\pi^-$

PRD 92 (2015) 112009

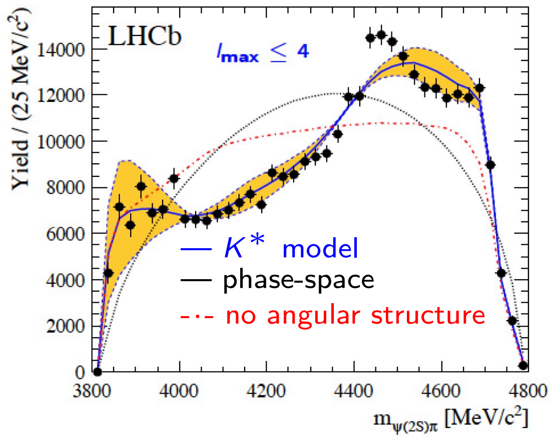
Check that $K^-\pi^+$ amplitudes only fail to describe the decay

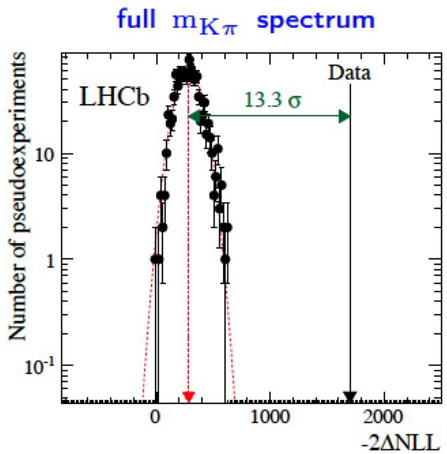
K* resonances should contribute to low angular moments, while exotic $\psi\pi$ would contribute to all moments

Allow relative angular momenta up to ℓ_{max} and compare to unreasonably large $\ell_{max} = 30$

$\ell_{max} \leq 4$

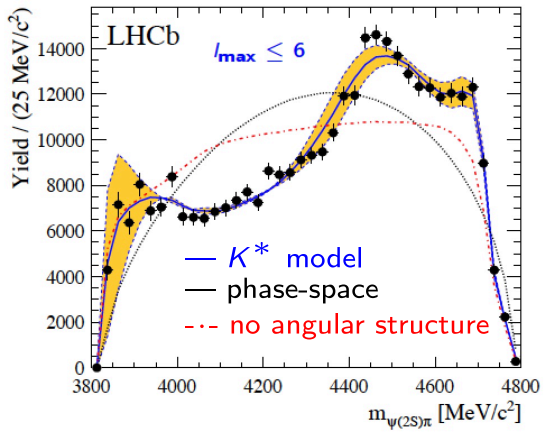
(S, P and D waves)

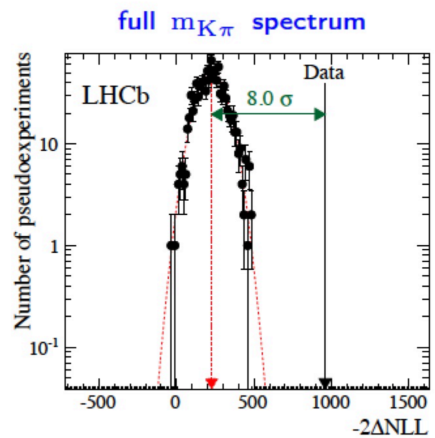




$\ell_{max} \leq 6$

(S, P, D and F waves)

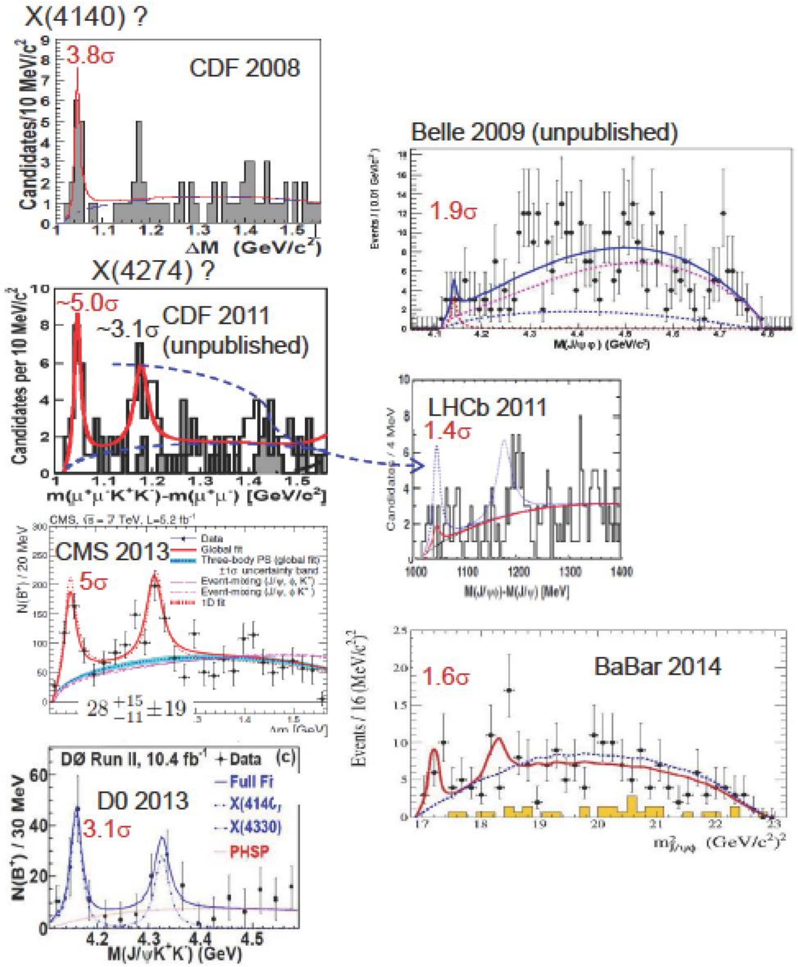


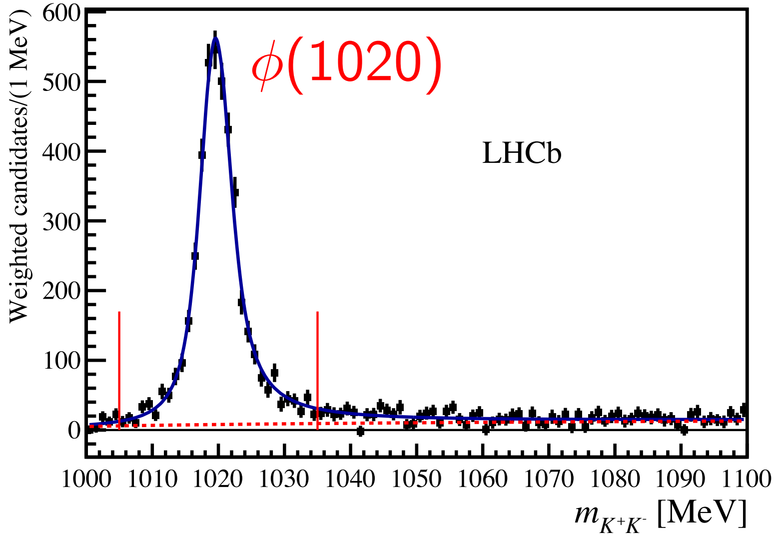


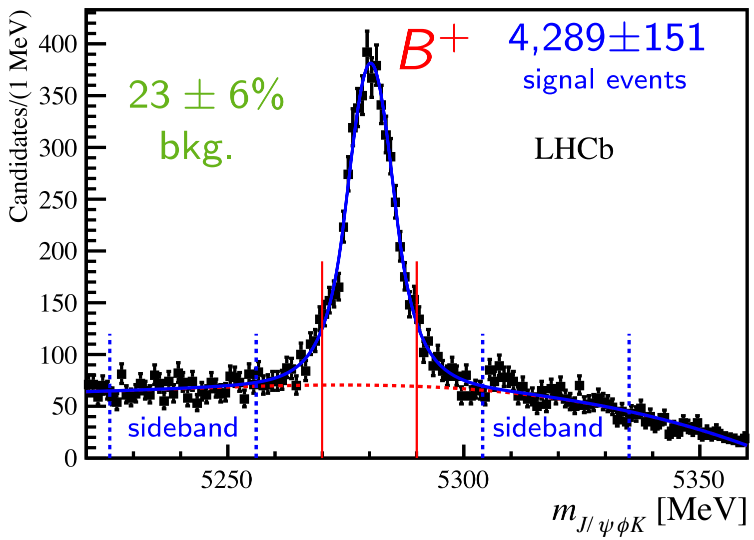
Exotic(?) states $X \to J/\psi\,\phi$?

PRL 118 (2017) 022003
PRD 95 (2017) 012002

Many experiments reported states decaying to $J/\psi\phi$:
$X(4140)$ and/or other higher mass states in B decays, but also $\gamma\gamma$, double $c\bar{c}$.



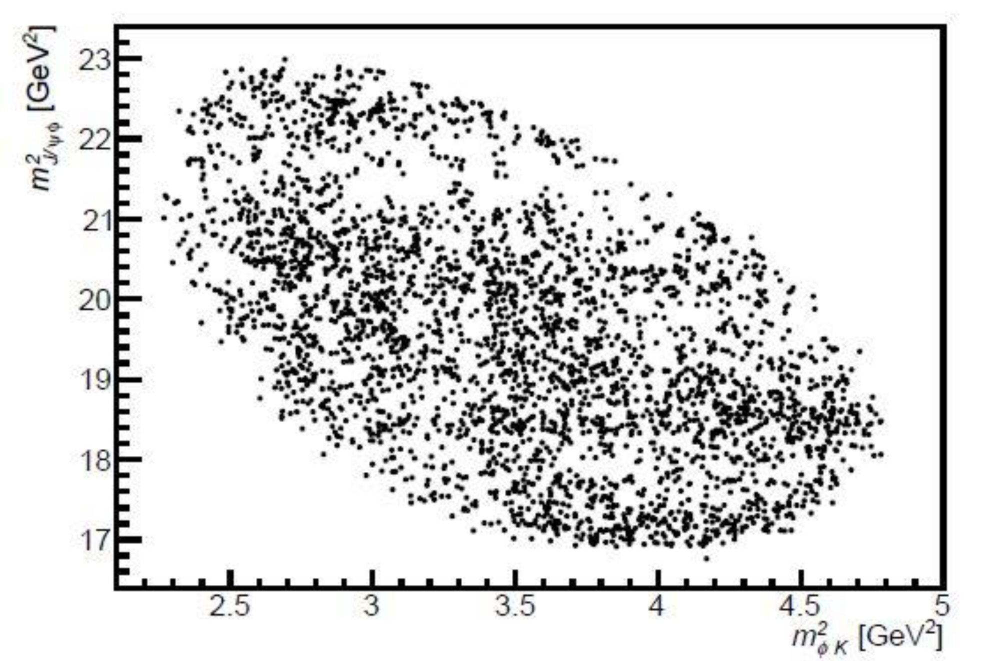


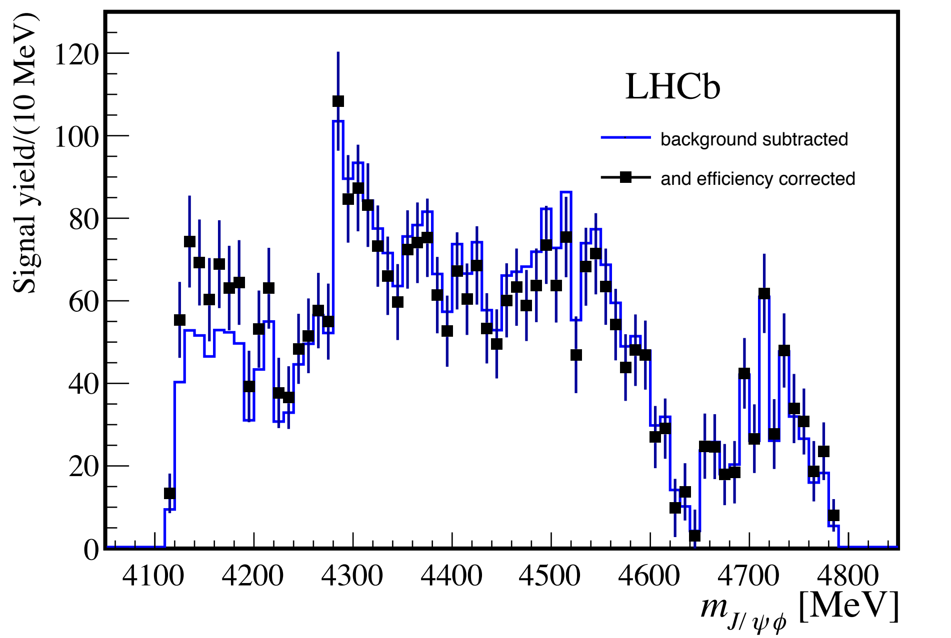


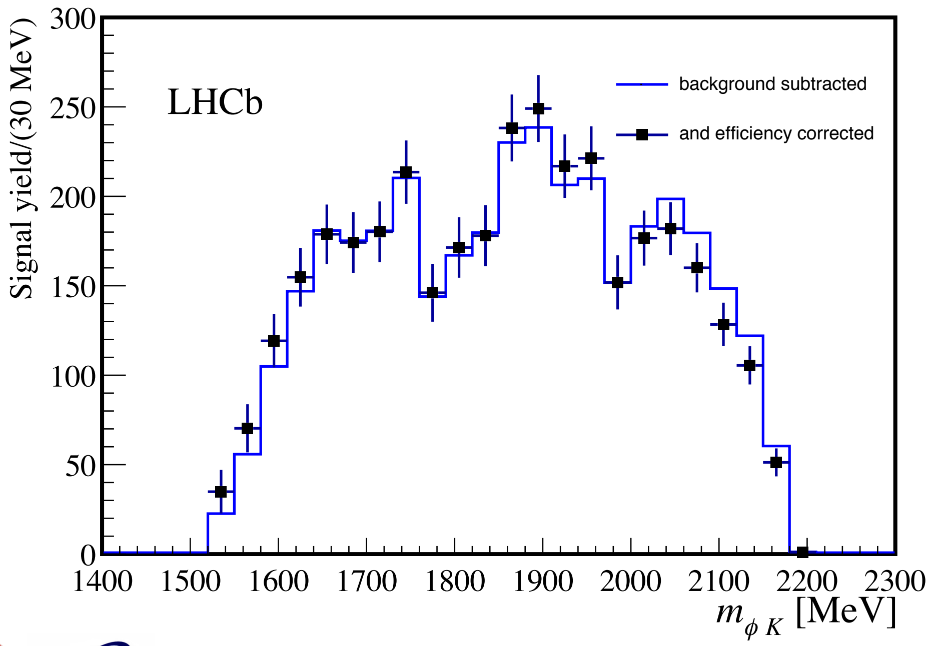
The LHCb sample of $B^+ \to J/\psi\,\phi K^+$ from Run1 is the largest analysed so far

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

PRL 118 (2017) 022003
PRD 95 (2017) 012002







All previous results based on 1D projections

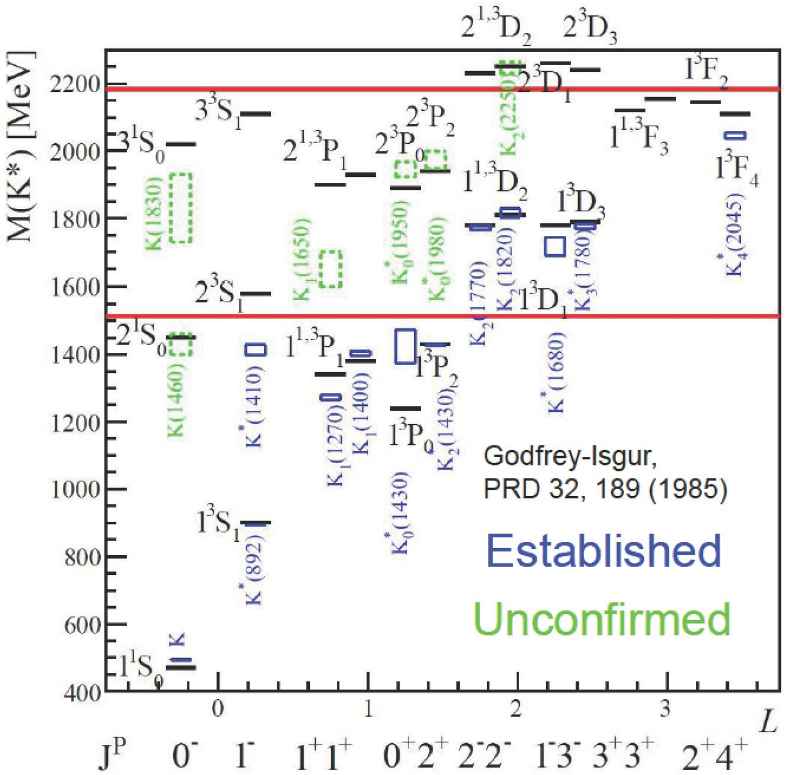
Need to understand reflections of interfering higher K^*

Amplitude fits

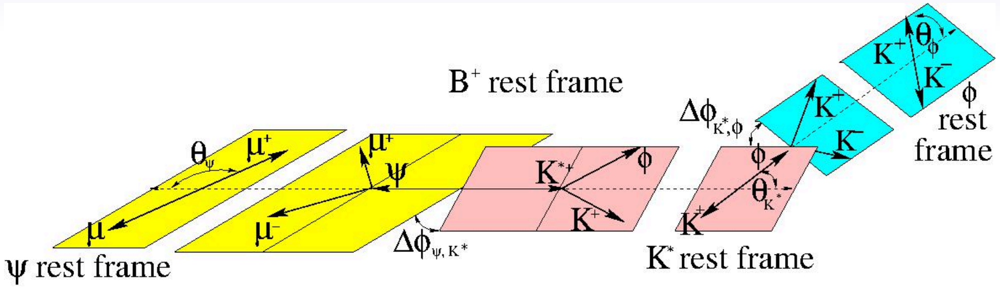
PRL 118 (2017) 022003
PRD 95 (2017) 012002

6D fit including K^* resonances + interfering NR background (0^{++} not allowed)

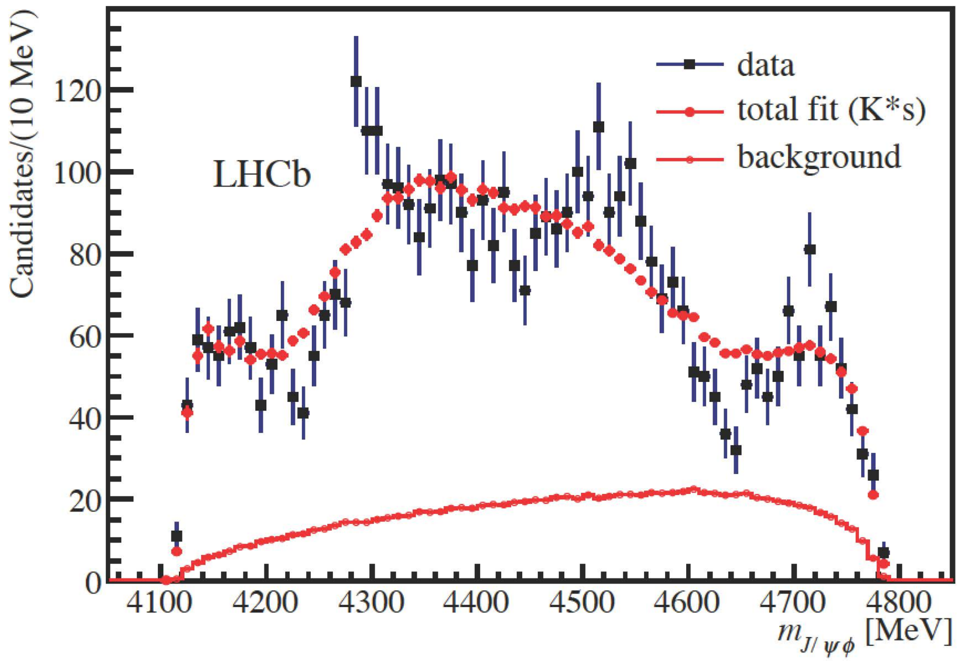
Experimental knowledge + predictions to choose the states to include in the model



masses and widths not constrained



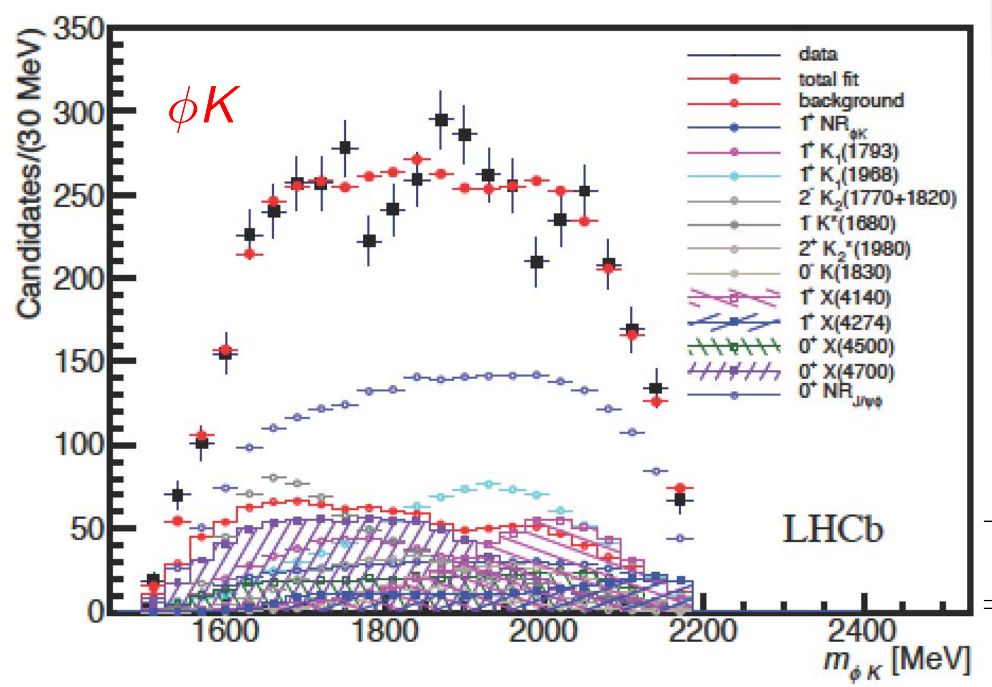
1-4 complex helicity terms per K^*

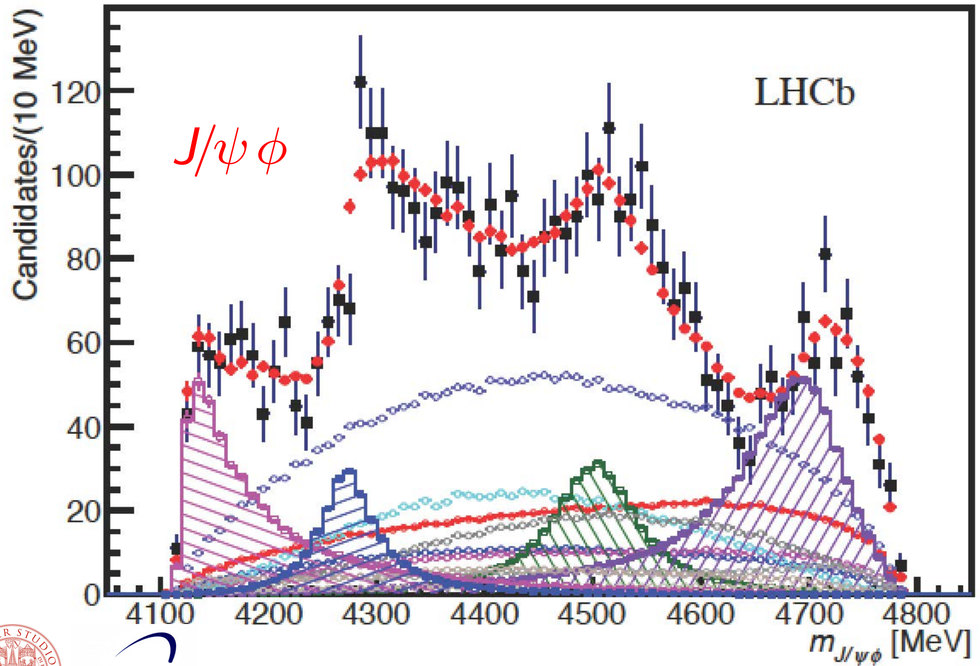


K^* resonances alone don't describe data

Fits allowing exotic components

PRL 118 (2017) 022003
PRD 95 (2017) 012002





Add X and Z^+ components with various quantum numbers

Z^+ components improve fit marginally

Two 1^{++} and two 0^{++} states with large significance

Contri-bution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\,^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13.0\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF	[26]	$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS	[23]	$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\,\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$

Significance of $J^{PC}=1^{++}$ incl. syst.:
$X(4140)$: 5.7σ $X(4274)$: 5.8σ

Significance of $J^{PC}=0^{++}$ incl. syst. :
$X(4500)$: 4.0σ $X(4700)$: 4.5σ

pentaquarks

PDG1974

S=1 I=0 EXOTIC STATES (Z_0)

$Z_0(1780)$ → 95 Z*0(1780, JP=1/2+) I=0 P_{01}

```
SEE THE MINI-REVIEW PRECEDING THIS LISTING.

WILSON 72 AND GIACOMELLI 74 FIND SOME SOLUTIONS
WITH RESONANT-LIKE BEHAVIOR IN THE P01 PARTIAL WAVE.
THE EFFECT SEEN IN THE I=0 TOTAL CROSS SECTIONS.
IF A RESONANCE, MUST HAVE SPIN=1/2, BECAUSE THE
INELASTIC CROSS SECTION IS VERY SMALL AND THE TOTAL
CROSS SECTION IS ABOUT 4*PI/K**2.

              95  Z*0(1780) MASS (MEV)

M        1780.0     10.0          COOL       70 CNTR +  K+P, D TOTAL      1/71
M   D    SEEN                     DOWELL     70 CNTR     K+P,D TOTAL      7/70
M   D    SEE ALSO DISCUSSION OF LYNCH 70                                  7/70
M   W   (1800.)                   WILSON     72 PWA     K+N P01 WAVE      3/72
M   W  ESTIMATE OF PARAMETERS FROM BW + QUADRATIC BACKGROUND FIT TO P01.  3/72
M   1   (1750.)                   CARROLL    73 CNTR    KN I=0 TCS,FIT 1  9/73
M   1   (1825.)                   CARROLL    73 CNTR    KN I=0 TCS,FIT 2  9/73
M   1  FIT 1=FIT OF SINGLE L=1 BW+BACKGROUND TO I=0 TCS FROM .4-1.1 GEV/C 9/73
M   1  FIT 2=FIT OF L=1 AND L=2 BWS TO SAME DATA.SEE Z0(1865) FOR L=2 PART 9/73
M       (1740.)                   GIACOMEL   74  PWA    .38-1.51 GEV/C   10/74*

              95  Z*0(1780) WIDTH (MEV)

W        (565.0)                  COOL       70 CNTR +  K+P, D TOTAL      1/71
W   W    (300.)                   WILSON     72 PWA     K+N P01 WAVE      3/72
W   1    (600.)                   CARROLL    73 CNTR    KN I=0 TCS,FIT 1  9/73
W   1    (845.)                   CARROLL    73 CNTR    KN I=0 TCS,FIT 2  9/73
W        (300.)                   GIACOMEL   74  PWA    .38-1.51 GEV/C   10/74*
```

Z BARYONS
($S = +1$)

PDG1992

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The ...m about baryons not made of three quarks, and the ...any experimental activity in this area, make it likely

EXOTIC BARYONS

Minimum quark content: $\Theta^+ = uudd\bar{s}$, $\Phi^{--} = ssdd\bar{u}$, $\Phi^+ = ssuu\bar{d}$.

$\Theta(1540)^+$ 　 $I(J^P) = 0(?^?)$

It is difficult to deny a place in the Summary Tables for a state that six experiments claim to have seen. Nevertheless, we believe it reasonable to have some reservations about the existence of this state on the basis of the present evidence.

PDG2004

Mass $m = 1539.2 \pm 1.6$ MeV
Full width $\Gamma = 0.90 \pm 0.30$ MeV

NK is the only strong decay mode allowed for a strangeness $S=+1$ resonance of this mass.

$\Theta(1540)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
KN	100%	270

Citation: W.-M. Yao *et al.* (Particle Data Group), J. Phys. G **33**, 1 (2006) (URL: http://pdg.lbl.gov)

$\Theta(1540)^+$ 　 $I(J^P) = 0(?^?)$ 　 Status: $*$

PDG 2006

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006 by G. Trilling (LBNL).

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997

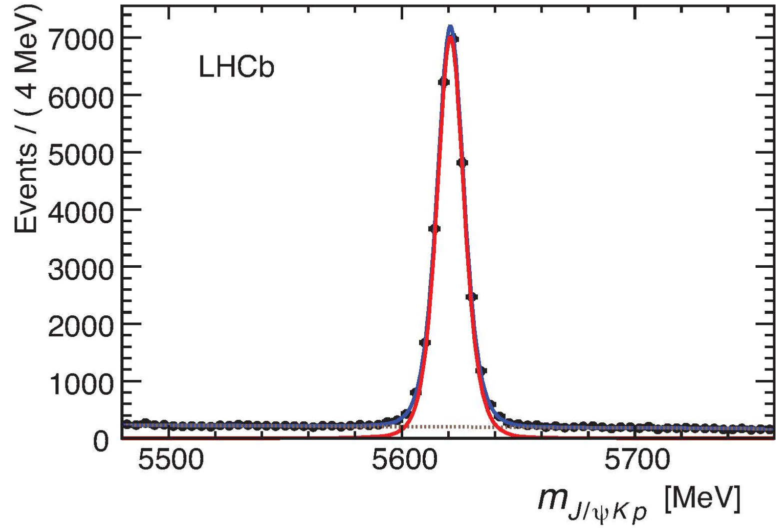
$\Lambda_b^0 \to J/\psi p K^-$

PRL 115 (2015) 072001

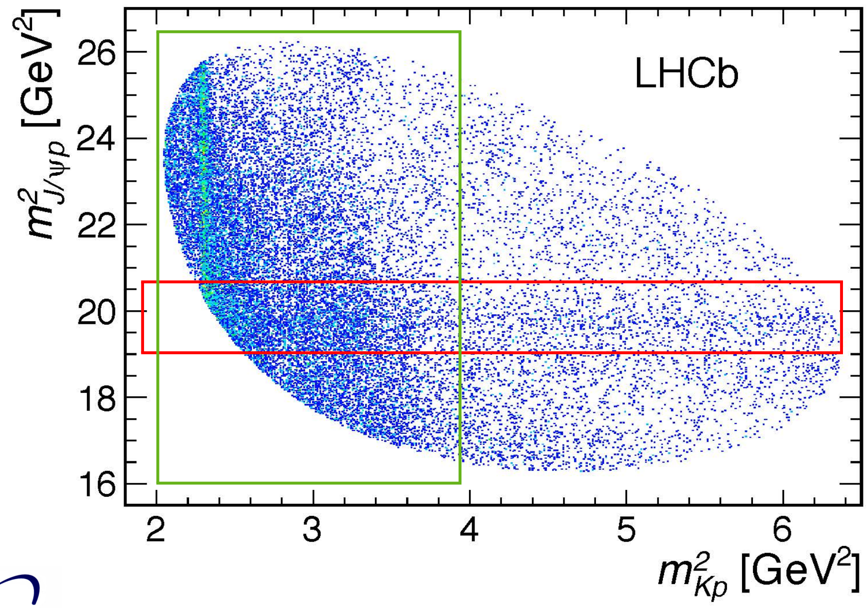
This decay mode, not observed before, found to have large rates and low background

Used to measure the Λ_b^0 lifetime with 1 fb^{-1} collected in 2011

PRL 111 (2013) 102003



Clean signal of 26,000 candidates with 5.4% background within $\pm 2\sigma$ in the whole Run 1 data sample (3 fb^{-1})



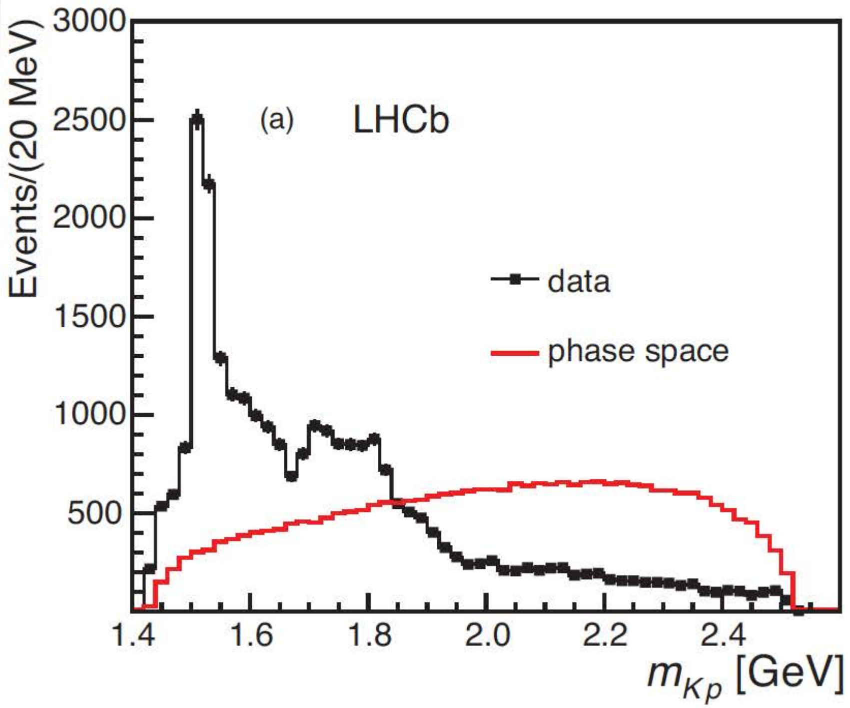
... but the Dalitz plot has unusual features:

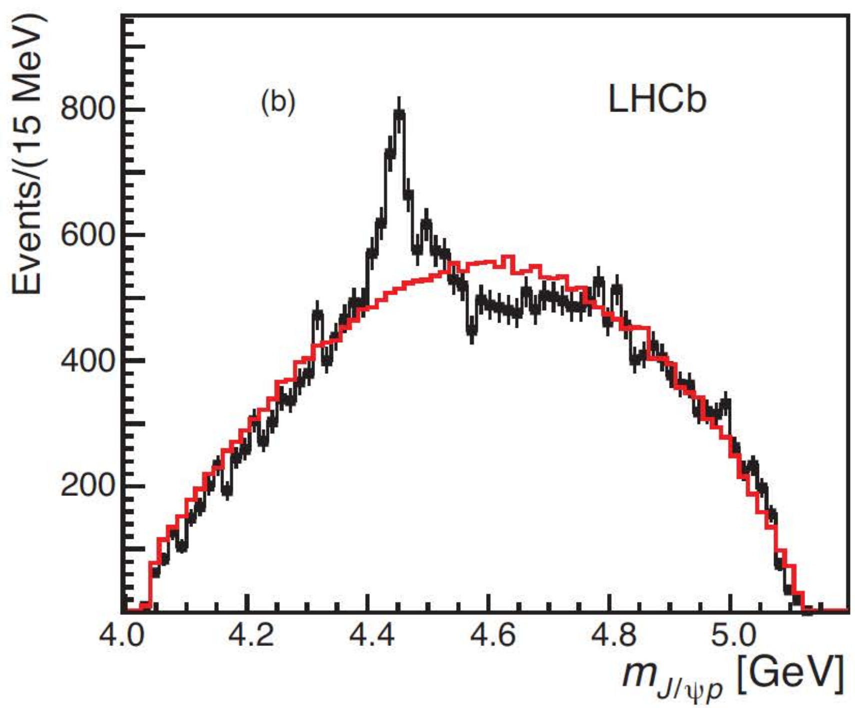
vertical bands for Λ^*'s

Horizontal band???

PRL 115 (2015) 072001

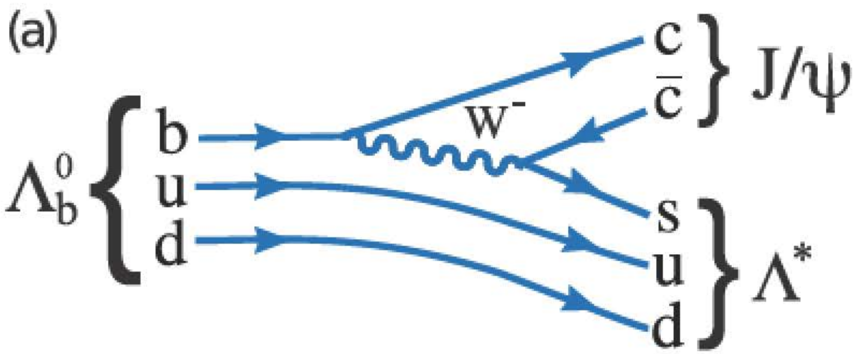
Dalitz plot projections

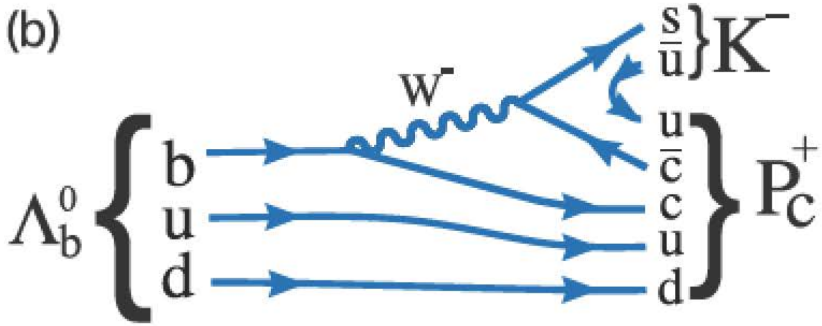




many Λ^* $\Longrightarrow$ Interference!

reflections from m(Kp)?
or exotic resonances???



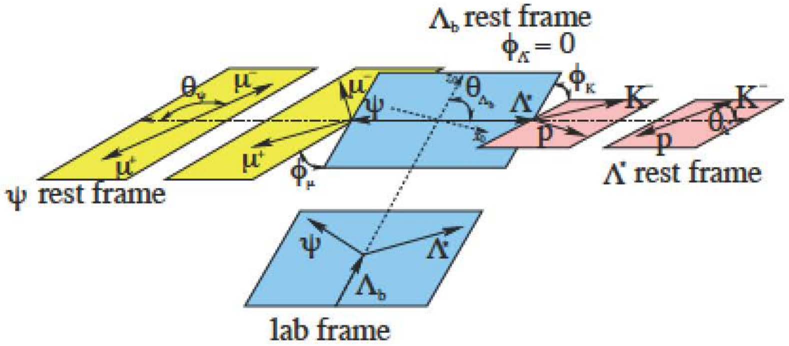


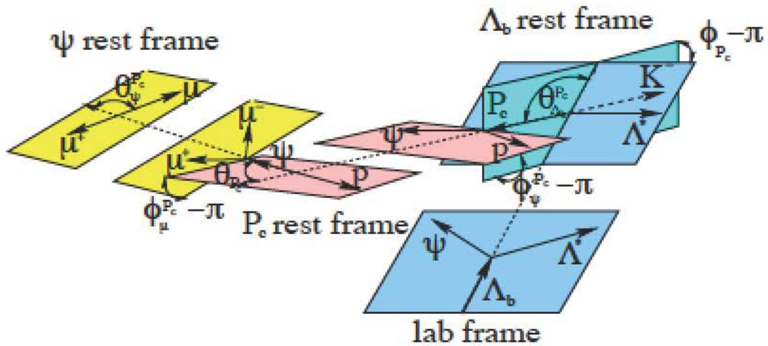
PRL 115 (2015) 072001

Amplitude Model

Six-dimensional amplitude fit: invariant mass, three helicity angles and two differences between decay planes. Allow for two interfering channels:

$\Lambda_b^0 \to J/\psi \Lambda^*$ $\Lambda_b^0 \to P_c^+ K^-$





all known Λ^* resonances (Extended)

or

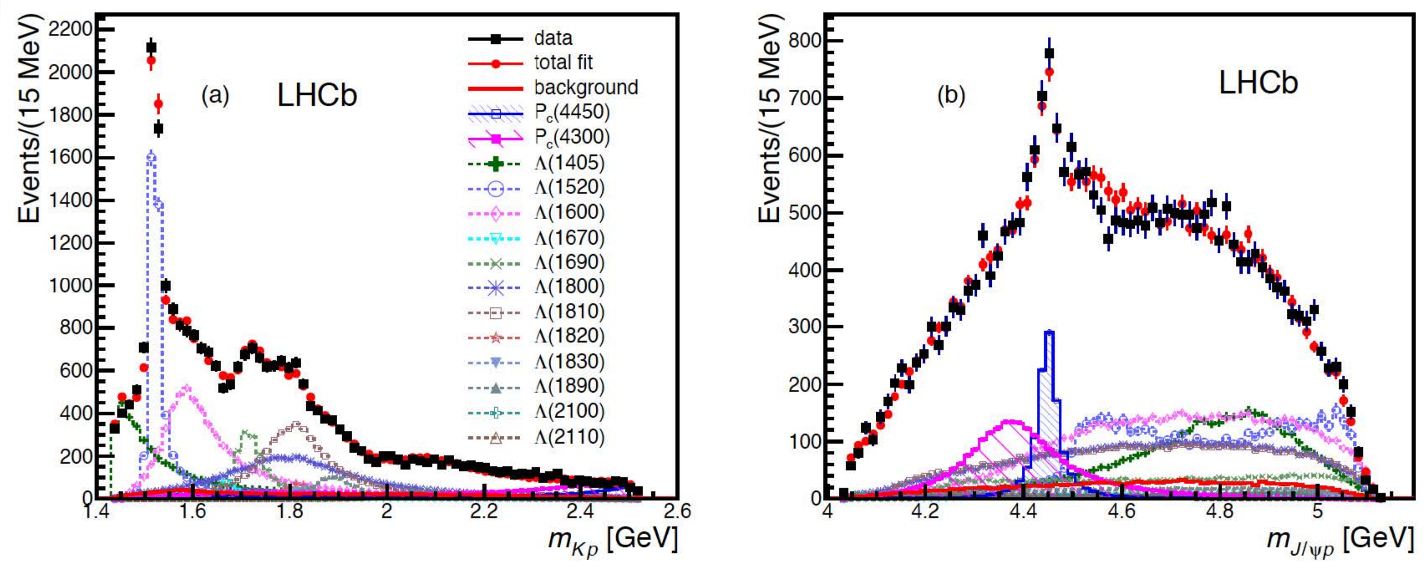
just well motivated (Reduced)

Angular distribution in helicity formalism

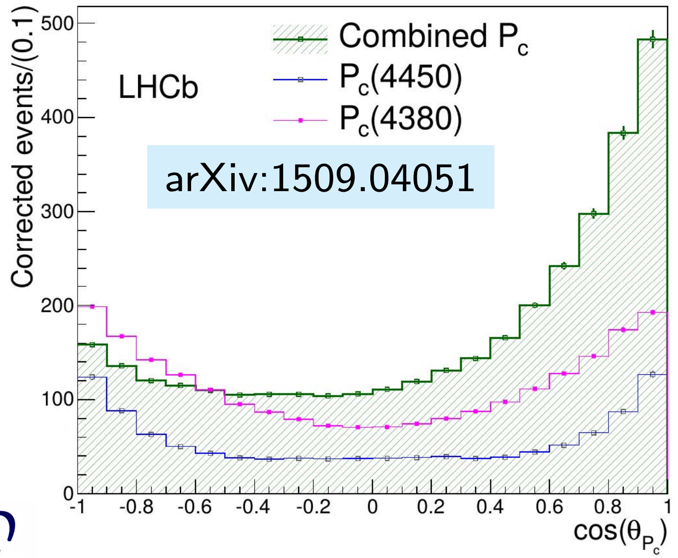
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	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

Amplitude Model: results

Two exotic states are required to obtain an adequate fit



Interference between two P_c of opposite parity required to explain the P_c decay angular distribution



The P_c parameters from the "reduced" fit are

	$P_c(4380)^+$	$P_c(4450)^+$
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/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

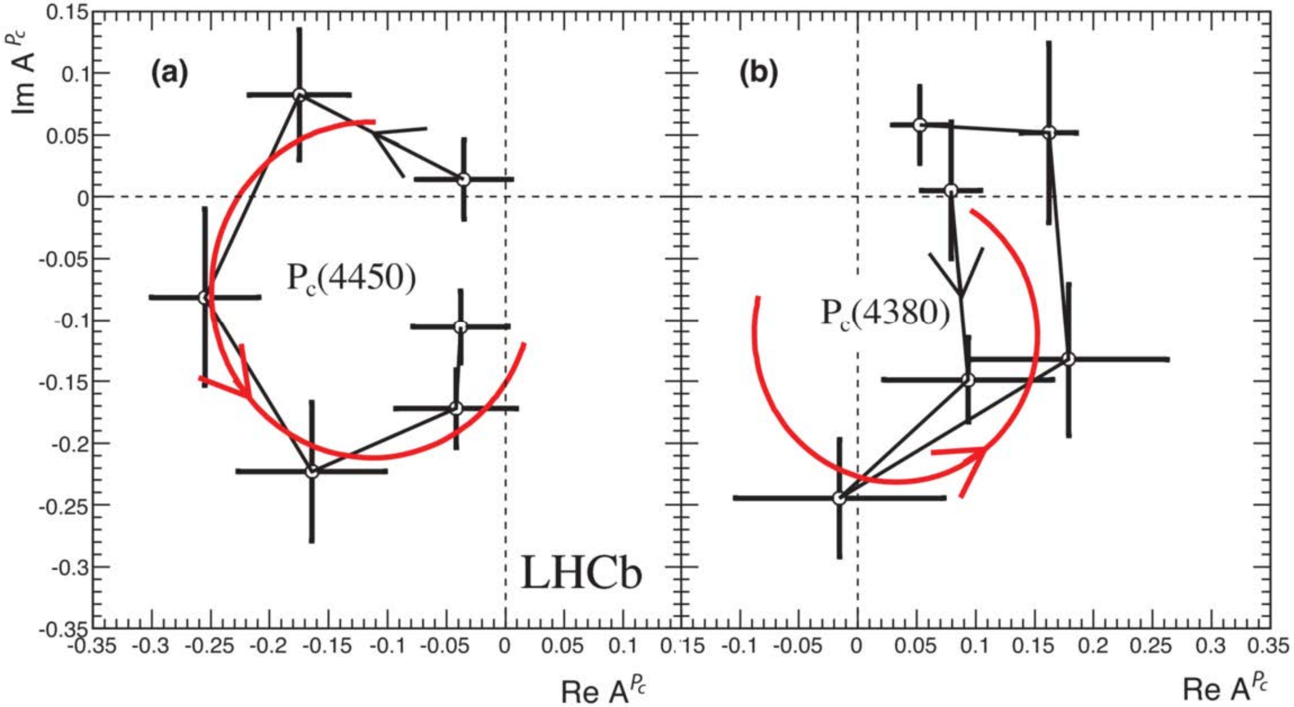
significance from pseudo-experiments (includes systematic)

The combined significance $> 15\sigma$

PRL 115 (2015) 072001

Resonance?

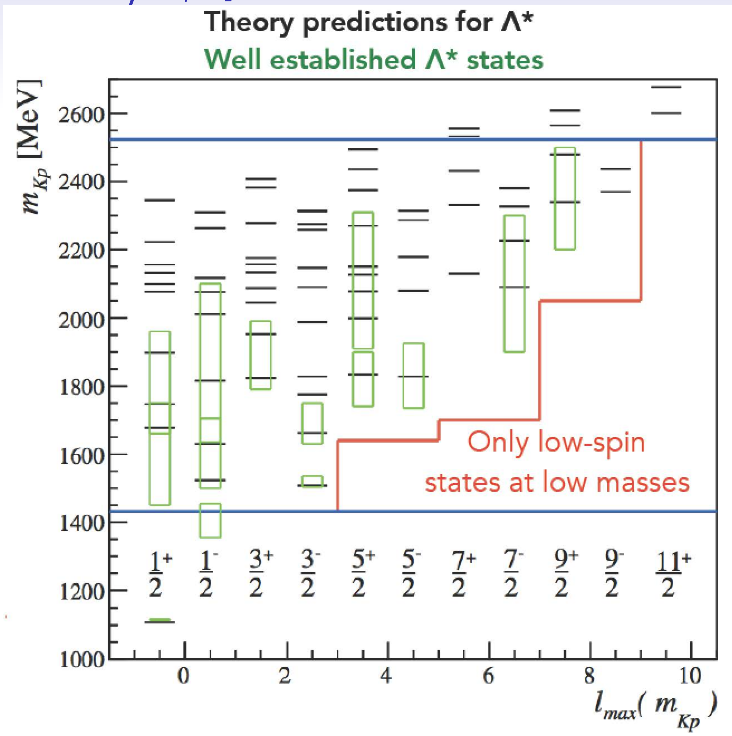
Real and immaginary part of the amplitude determined independently in 6 bins between $M - \Gamma$ and $M + \Gamma$



The $P_c(4450)$ amplitude shows a phase variation consistent with what expected for a Breit-Wigner resonance

Not conclusive for $P_c(4380)$

Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

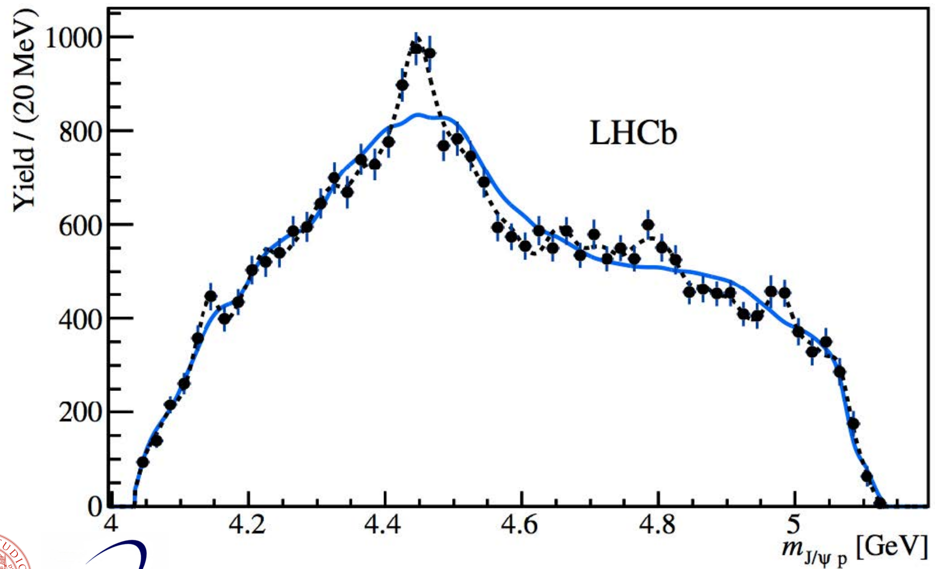


The $\Lambda*$ spectrum is the largest systematic uncertainty in the P_c observation

The NR $K^- p$ component could have non trivial mass-dependence

Model independent approach: no assumption on Λ^*, Σ or NR structure

Only restrict maximum spin of Λ^* component in each interval of Kp invariant mass



Compare $m(J/\psi p)$ in data to MC weighted as to reproduce $\Lambda^* \to Kp$ reflections based on angular moments

The hypothesis that data can be described by reflections of Kp structures is excluded at 9σ

Search for exotics in $\Lambda_b^0 \to J/\psi p \pi^-$

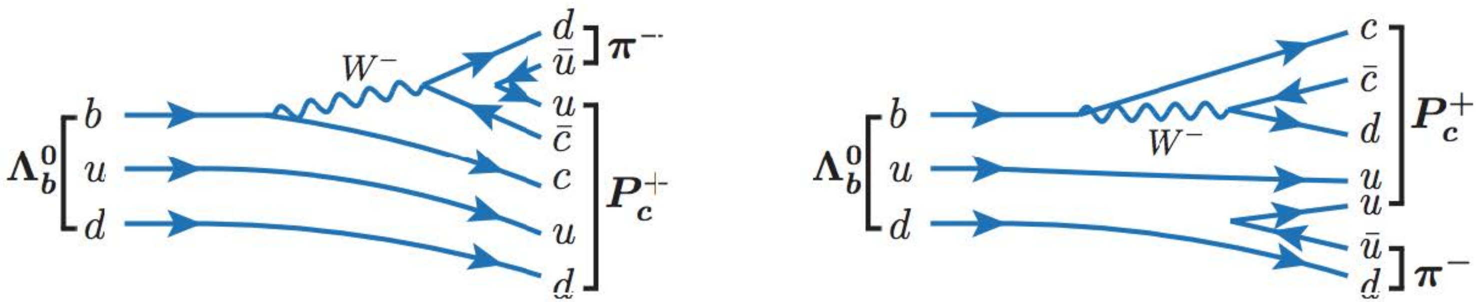
Cabibbo-suppressed – observed by LHCb **JHEP 1407 (2014) 103**

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst})$$

Observing the same P_c^+ states in a different decay mode could indicate they are really resonances and not some kinematical effects

Wang et al; PRD 93 (2016) 094001

Cabibbo-suppressed Λ_b^0 decays to baryonic exotic resonances



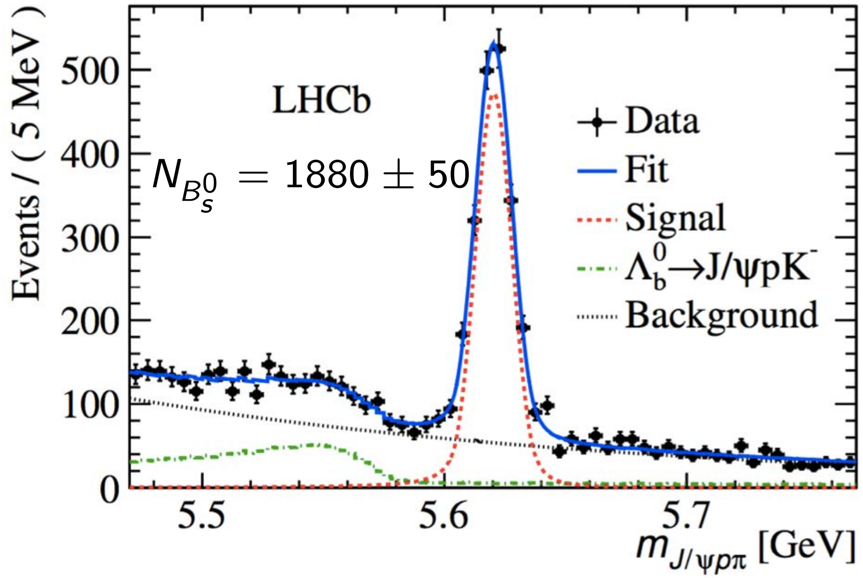
are predicted to have Cheng, Chua: PRD 92 (2015) 096009

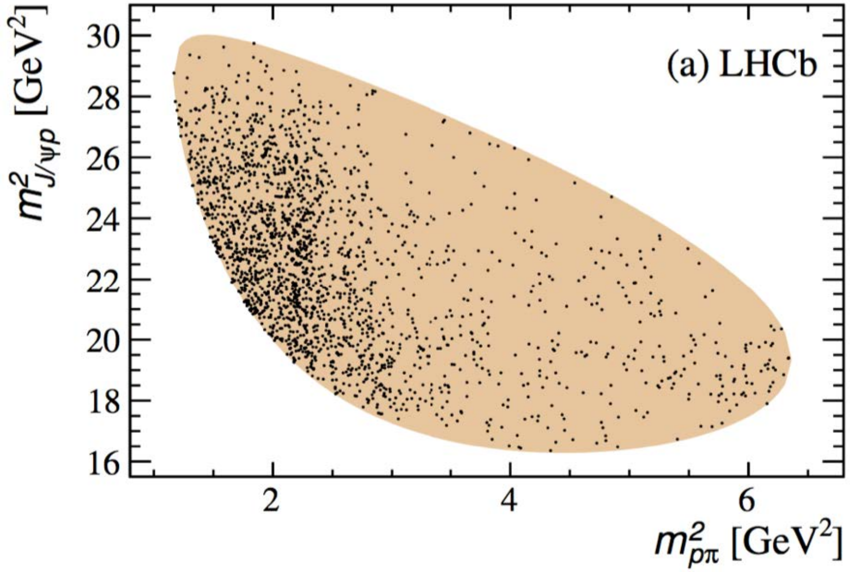
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

PRL 117 (2016) 082003

$\Lambda_b^0 \to J/\psi p \pi^-$

Similar candidates selection as for $\Lambda_b^0 \to J/\psi p K^-$, with additional vetos for specific background sources ($\bar{B}^0 \to J/\psi K^+\pi^-$, $\bar{B}_s^0 \to J/\psi K^+K^-$, $\Lambda \to K^+\pi^-$)





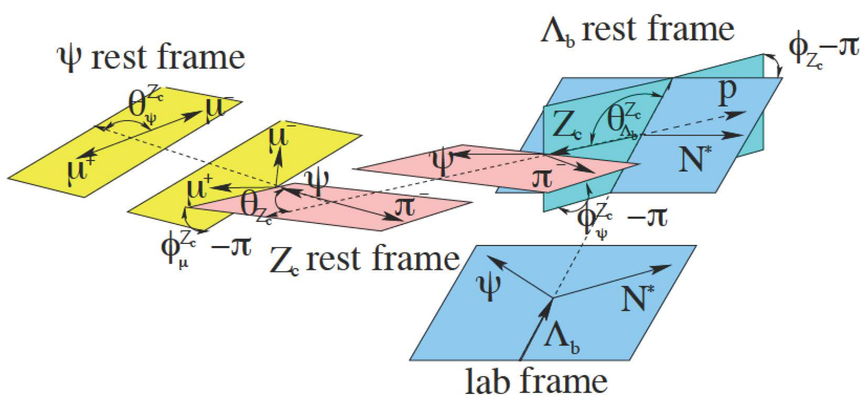
No striking features in the Dalitz plot, perform amplitude analysis

As in the CF mode, six-dimensional fit to interfering amplitudes. In this case:

- $\Lambda_b^0 \to J/\psi N^*$
- $\Lambda_b^0 \to P_c^+ \pi^-$
- $\Lambda_b^0 \to Z_c^- p$

$Z_c(4200)^- \to J/\psi \pi^-$ reported by Belle in $B^0 \to J\psi K\pi$ PRD 90 (2014) 112009

$\Lambda_b^0 \to Z_c^+ p$



PRL 117 (2016) 082003

Amplitude model fits to $\Lambda_b^0 \to J/\psi p \pi^-$

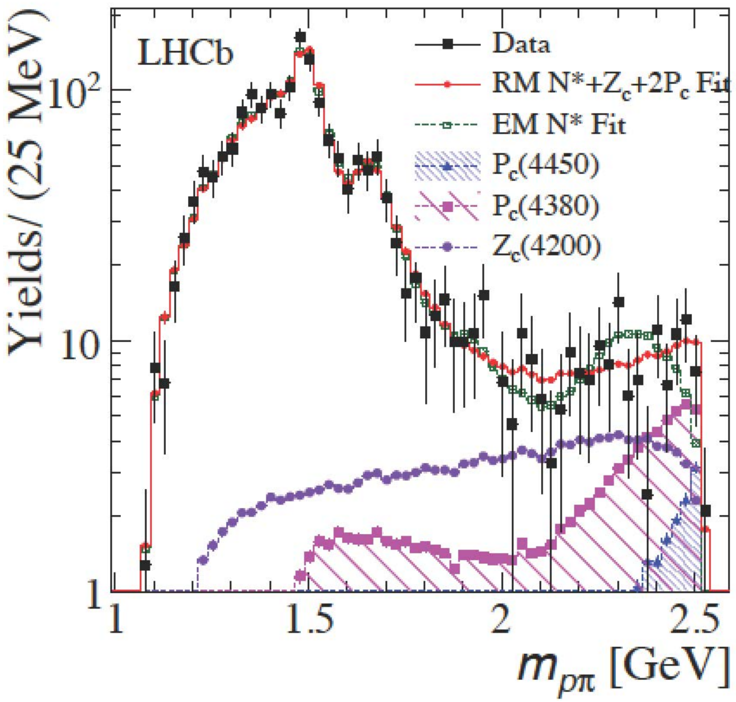
State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	0	3
$N(1700)$	$3/2^-$	1700	150	0	3
$N(1710)$	$1/2^+$	1710	100	0	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	0	3
$N(1900)$	$3/2^+$	1900	200	0	3
$N(2190)$	$7/2^-$	2190	500	0	3
$N(2220)$	$9/2^+$	2250	400	0	0
$N(2250)$	$9/2^-$	2275	500	0	0
$N(2600)$	$11/2^-$	2600	650	0	0
$N(2300)$	$1/2^+$	2300	340	0	3
$N(2570)$	$5/2^-$	2570	250	0	3
Free parameters				40	106

Include in the fit

- all known N^* (Extended)
- only well motivated (Reduced)

All L allowed

Limited sample size: fix P_c and Z_c parameters when testing if their amplitudes are required



The $m(p\pi^-)$ projection is adequately described by fits with N^* only

Exotic components seem not required

... but in a 6D fit differences may manifest only in restricted regions

Evidence for exotic components in $\Lambda_b^0 \to J/\psi p \pi^-$

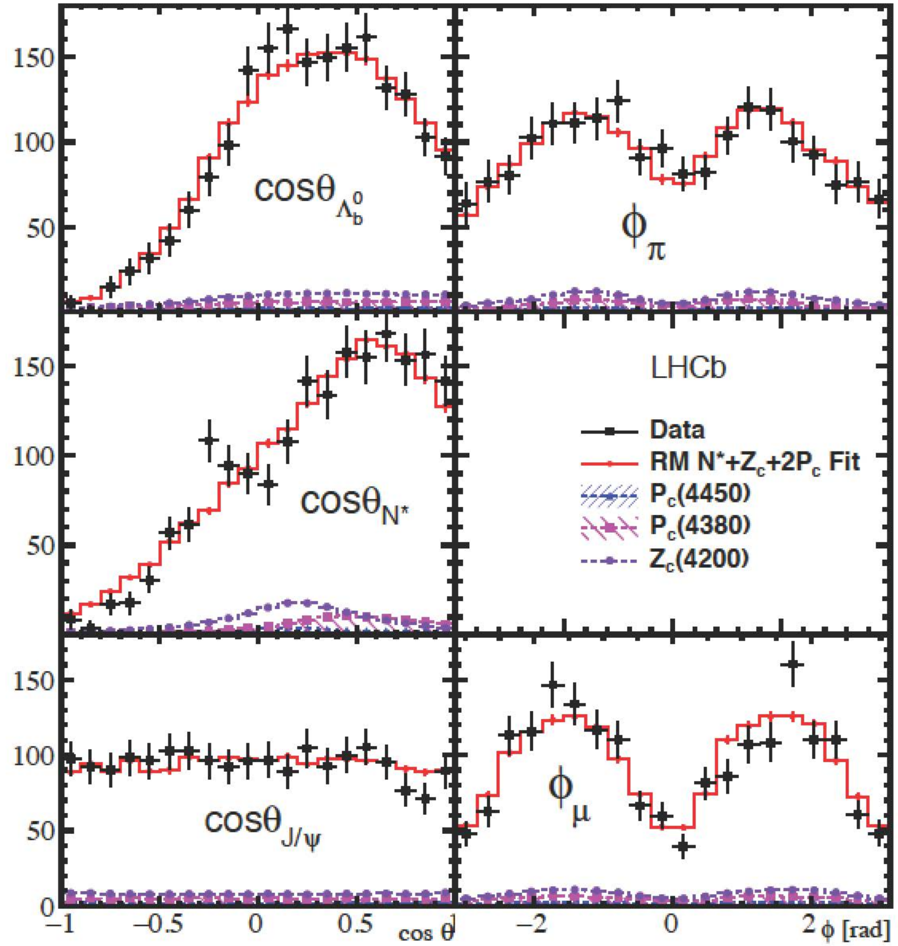
PRL 117 (2016) 082003

The N^*-only (extended) model does not describe data in all variable space

The reduced models with exotic (2 P_c or Z_c, or both) have acceptable fits in all variables

The significance (including syst) for $2P_c$ without Z_c is 3.3σ
None has individually large significance.

States	Fit fraction (%)
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$



Ratios of CS/CF for exotic components compatible with $0.07 - 0.08$ (albeit large errors!)

Cheng, Chua PRD 92 (2015) 096009

$$R_{\pi^-/K^-}(4380) = 0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$$
$$R_{\pi^-/K^-}(4450) = 0.033^{+0.016+0.011}_{-0.014-0.009} \pm 0.009$$

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)}$$

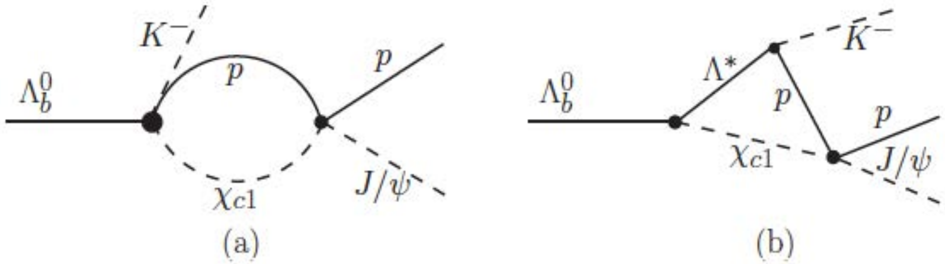
$P_c(4450)$: resonance or kinematical effect?

The $P_c(4450)^+$ lies just above the $\chi_{c_1}\,p$ threshold

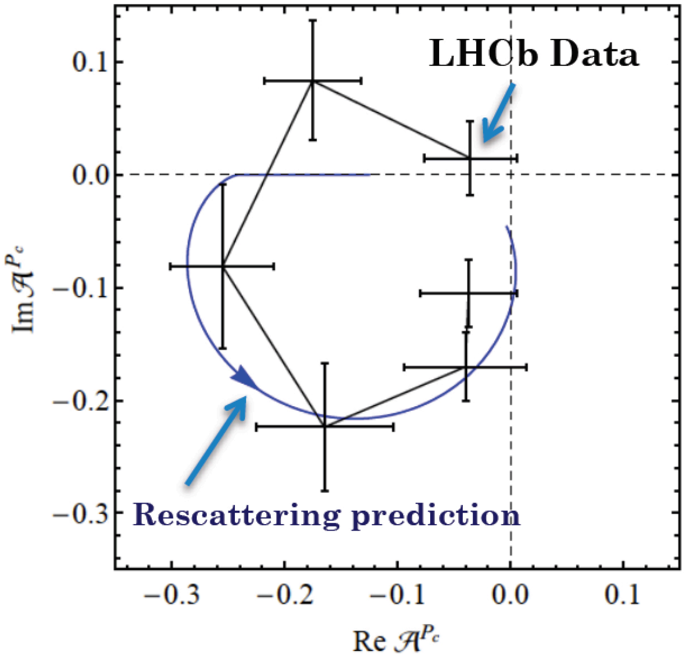
could be explained by kinematical rescattering effects

Meißner et al. PLB 751 (2015) 59

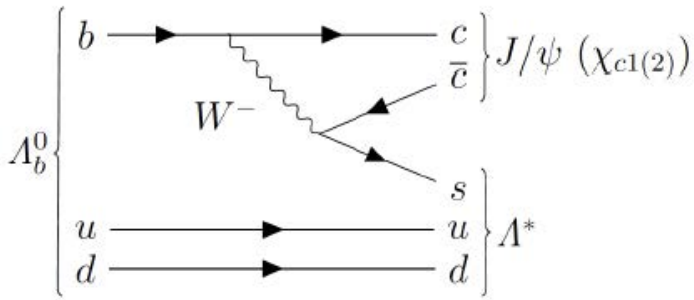
Guo et al. PRD 92 (2015) 071502



with current statistics the Argand plot cannot resolve the issue



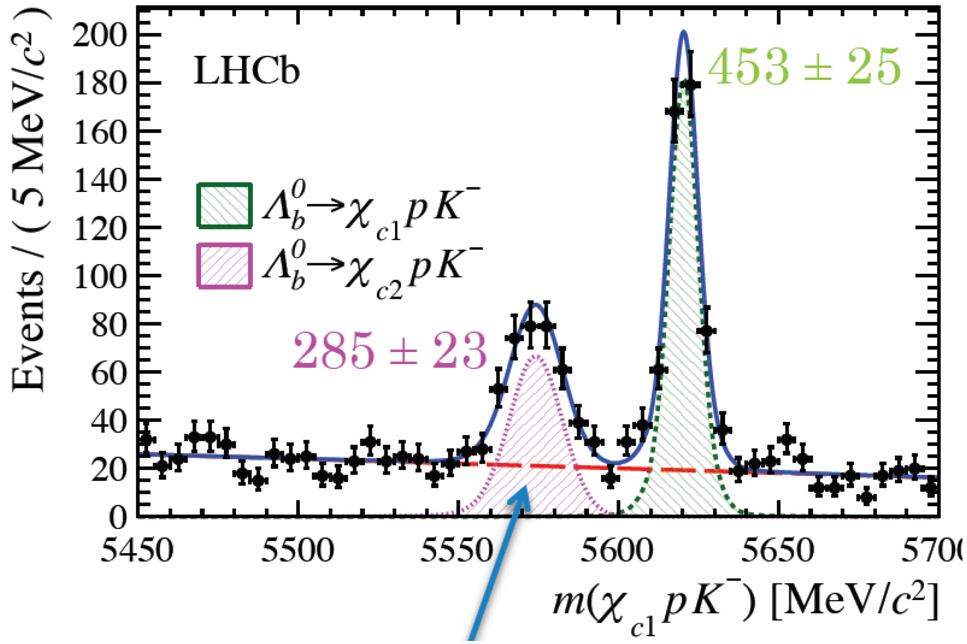
Rescattering would not explain a narrow enhancement in $\chi_{c_1}\,p$



Observation of $\Lambda_b^0 \to \chi_{c_{1,2}} pK$ decays

Reconstruct the $\chi_{c_{1,2}} pK$ final state with $\chi_{c_{1,2}} \to J/\psi\,\gamma$

- Dataset: $3\,\text{fb}^{-1}$
- invariant mass of $J/\psi\,\gamma$ constrained to χ_{c_1} mass
  - signal for $\Lambda_b^0 \to \chi_{c_2} pK$ shifted at lower mass
- large significance for both modes
  - $29\,\sigma$ for $\Lambda_b^0 \to \chi_{c_1} pK$
  - $17\,\sigma$ for $\Lambda_b^0 \to \chi_{c_2} pK$



$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

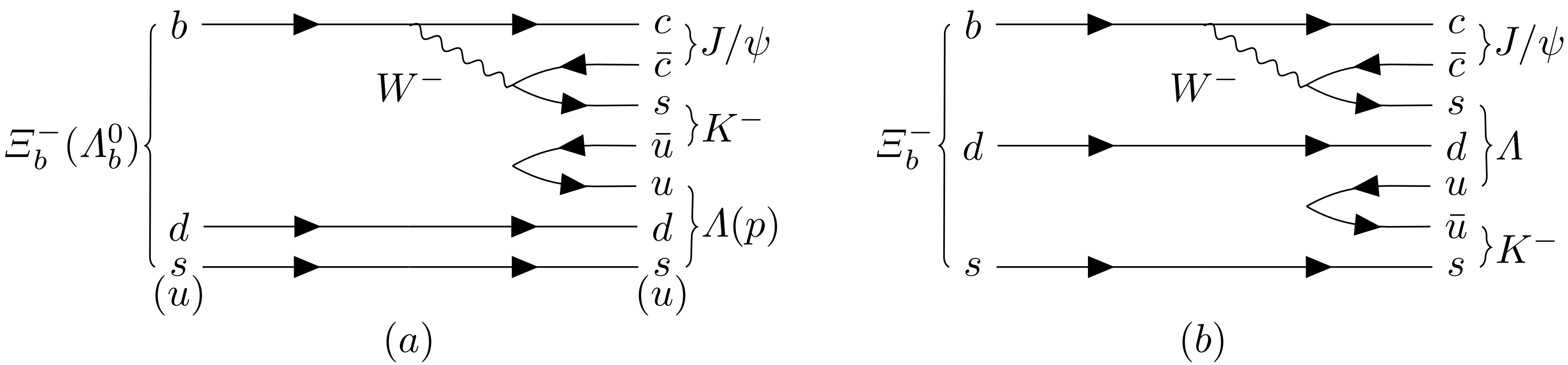
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05,$$

Pentaquark multiplets?

Narrow ($\Gamma \approx 10\ \mathrm{MeV}$) strangeness hidden charm pentaquark predicted at $4650\ \mathrm{MeV}/c^2$ Chen et al, PRC 93 (2016) 065203

expected to decay to $J/\psi\,\Lambda$

possible diagrams:



$\Xi_b^- \to J/\psi\,\Lambda K \quad \Leftrightarrow \quad \Lambda_b^0 \to J/\psi\, pK$
replacing $u \Leftrightarrow s$

contributes only to Ξ_b^- decay

PL B772 (2017) 265

Observation of $\Xi_b^- \to J/\psi\, \Lambda K$

Data sample: 3 fb^{-1}

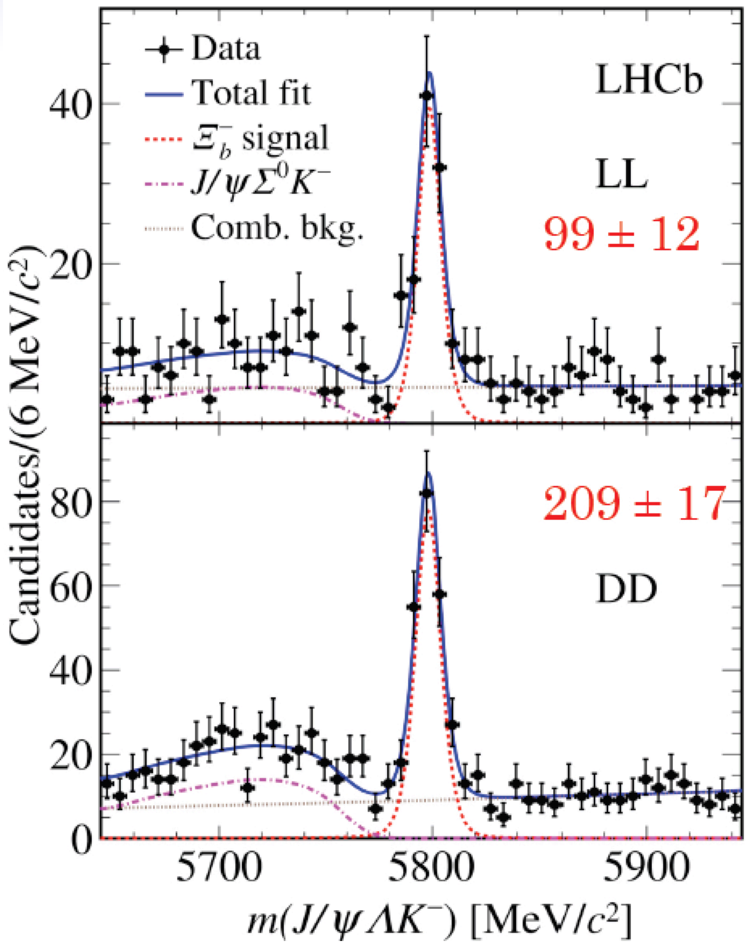
Search for $\Xi_b^- \to J/\psi\, \Lambda K$ with $\Lambda \to pK$ vertex reconstructed

(LL) within vertex detector

(DD) downstream of vertex detector

Constrain J/ψ and Λ invariant masses

Measure branching fraction relative to $\Lambda_b^0 \to J/\psi\, \Lambda$



$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29_{\rm stat} \pm 0.15_{\rm syst}) \times 10^{-2},$$

f_x: fragmentation fractions $b \to \Xi_b^-$ or Λ_b^0

Conclusions: tetraquarks (and tetraquark candidates)

- $X(3872)$: already a wealth of results
  - quantum numbers
  - Mass (and width?)
  - radiative decays
  - p_t dependence of prompt production
  - other decay modes? exclusive production in other than $B^{\pm}$?
- $Z(4430)^+$
  - confirmed with both amplitude analysis and model dependent approach
  - resonant behaviour
  - quantum numbers
- $B^+ \to J/\psi\,\phi K^+$
  - 4 $J/\psi\,\phi$ structures

Conclusions: pentaquarks

- Observation of $P_c(4450)^\pm$ and $P_c(4380)^\pm \to J/\psi\, p$ in $\Lambda_b^0 \to J/\psi\, pK^-$ from both amplitude analysis and model independent approach
  - $c\bar{c}uud \implies$ pentaquark!
  - resonant behaviour of $P_c(4450)^\pm$ amplitude
  - resonant behaviour inconclusive for $P_c(4380)^\pm$
- Evidence for exotic hadrons in $\Lambda_b^0 \to J/\psi\, p\pi^-$
  - compatible with P_c states in different decay mode
  - amplitude analysis limited by sample size
- $\Lambda_b^0 \to \chi_c pK^-$ and $\Xi_b^- \to J/\psi\, \Lambda K^-$
  - investigate new $P_c(4450)$ decay modes and search for further pentaquarks

    new decay modes observed
  - might have sufficient statistics for amplitude analysis by the end of upcoming data taking

Still a lot to understand – and a lot of data at LHC!

already on disk and more in the near future

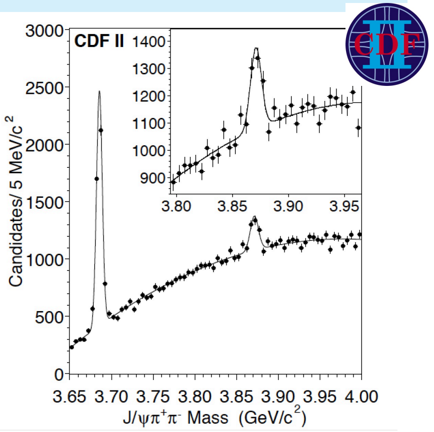
Extra Slides

$X(3872)$ production in $p\bar{p}$ and pp collisions

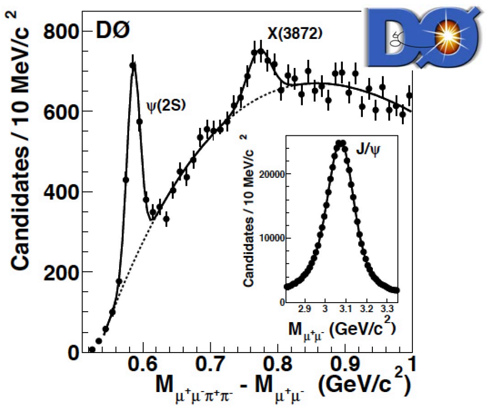
Origin from B decays or primary interaction ("prompt")? Compare to $c\bar{c}$

$p\bar{p}$ collisions (Tevatron):

PRL 93(2004)072001

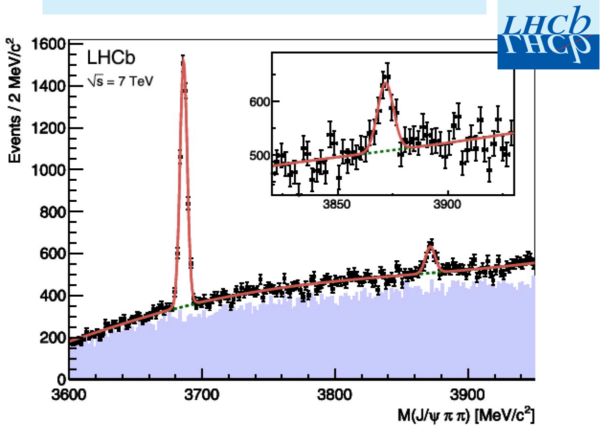


PRL 93 (2004)162002

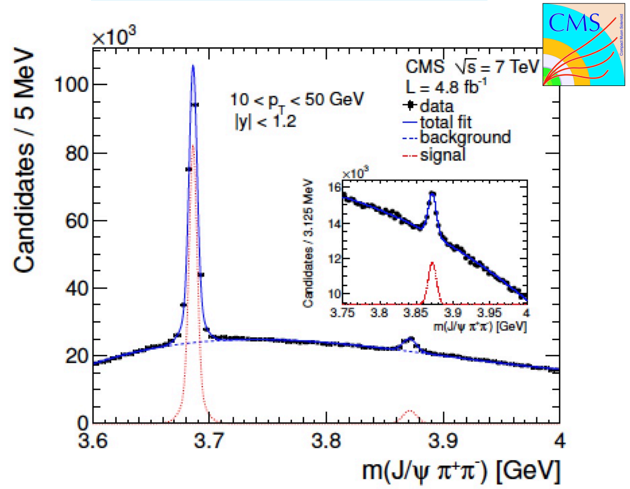


pp collisions (LHC):

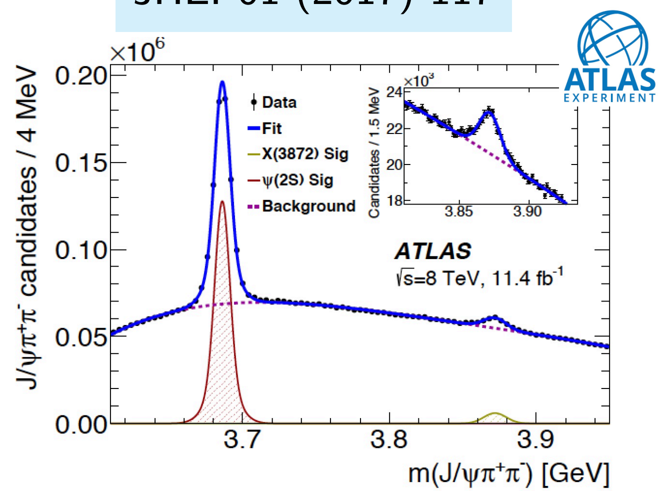
EPJ C 72 (2012) 1972



JHEP04 (2013) 154



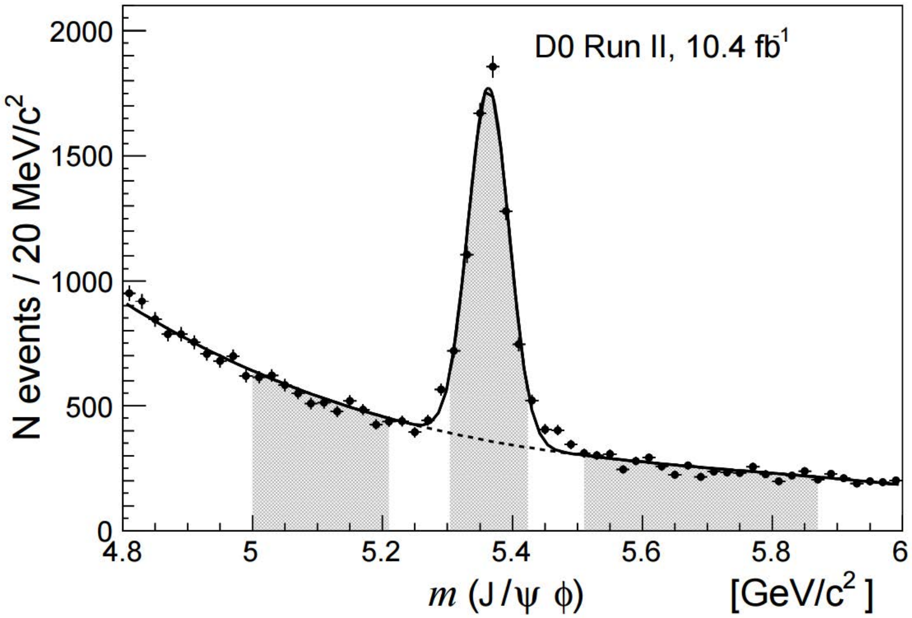
JHEP01 (2017) 117

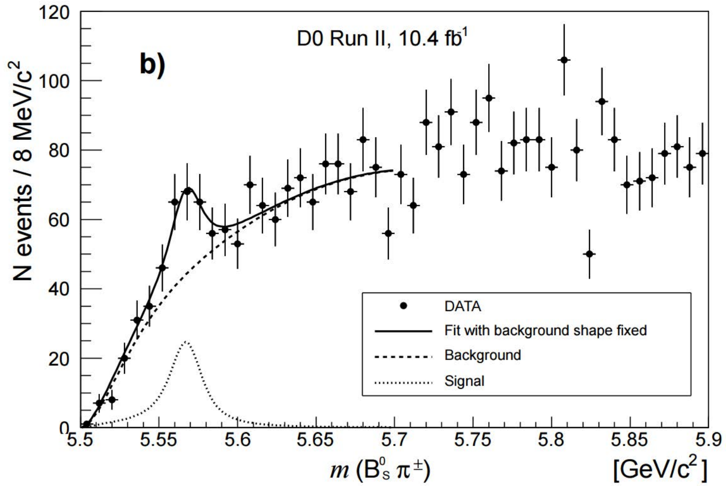


prompt production rate too large for purely molecular state

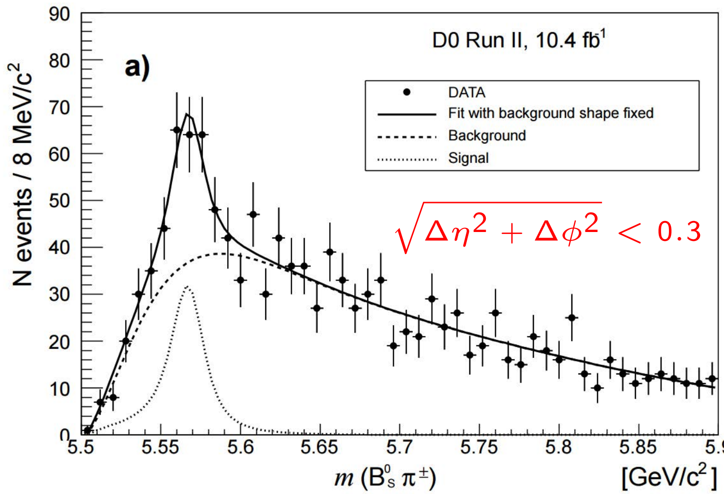
$B_s^0\pi^-$ spectroscopy

DØ reported observation (5.1σ) of a tetraquark candidate $X(5568)^+ \to B_s^0\pi^+$ with ≈ 5500 B_s^0 signal events reconstructed in $J/\psi\,\phi$ PRL 117 (2016) 022003





$N_X = 133 \pm 31$ with π^+ in a cone around B_s^0



$$m = 5567.8 \pm 2.9\,(\text{stat})\,^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\text{stat})\,^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

with a large fraction of B_s^0 from $X(5568)^+$ decays:

$$\rho_X^{\text{D0}} \equiv \left.\frac{\sigma(p\bar{p} \to X + \text{anything}) \times \mathcal{B}(X \to B_s^0\pi)}{\sigma(p\bar{p} \to B_s^0 + \text{anything})}\right|_{\text{D0Acc.}} = (8.6 \pm 1.9 \pm 1.4)\%$$

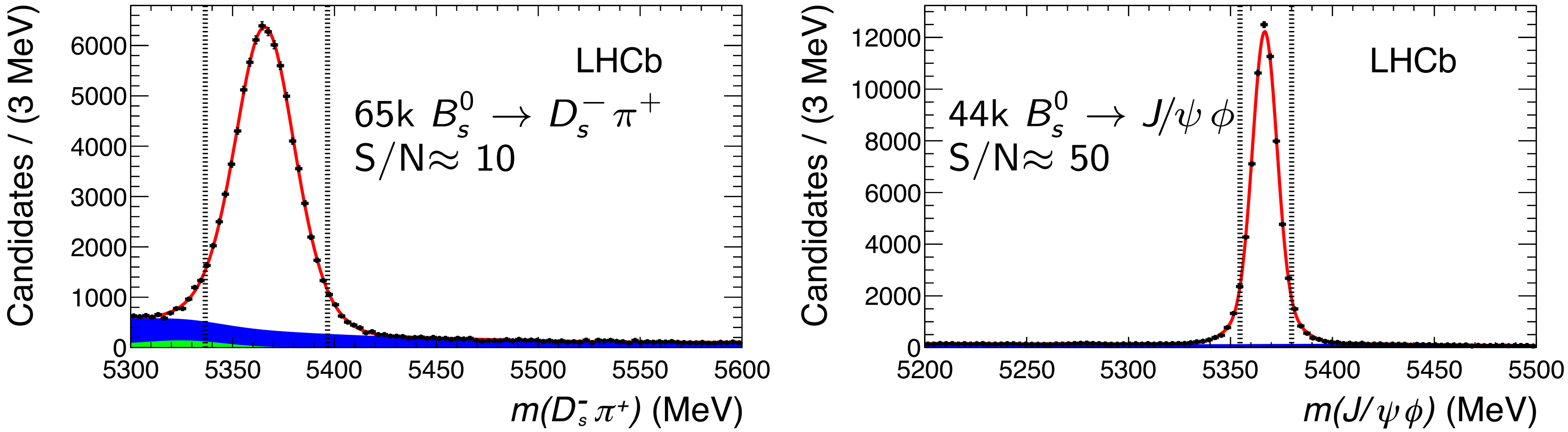
Unique state with four different quarks $\bar{b}su\bar{d}$

LHCb: $B_s^0\pi^-$ spectrum

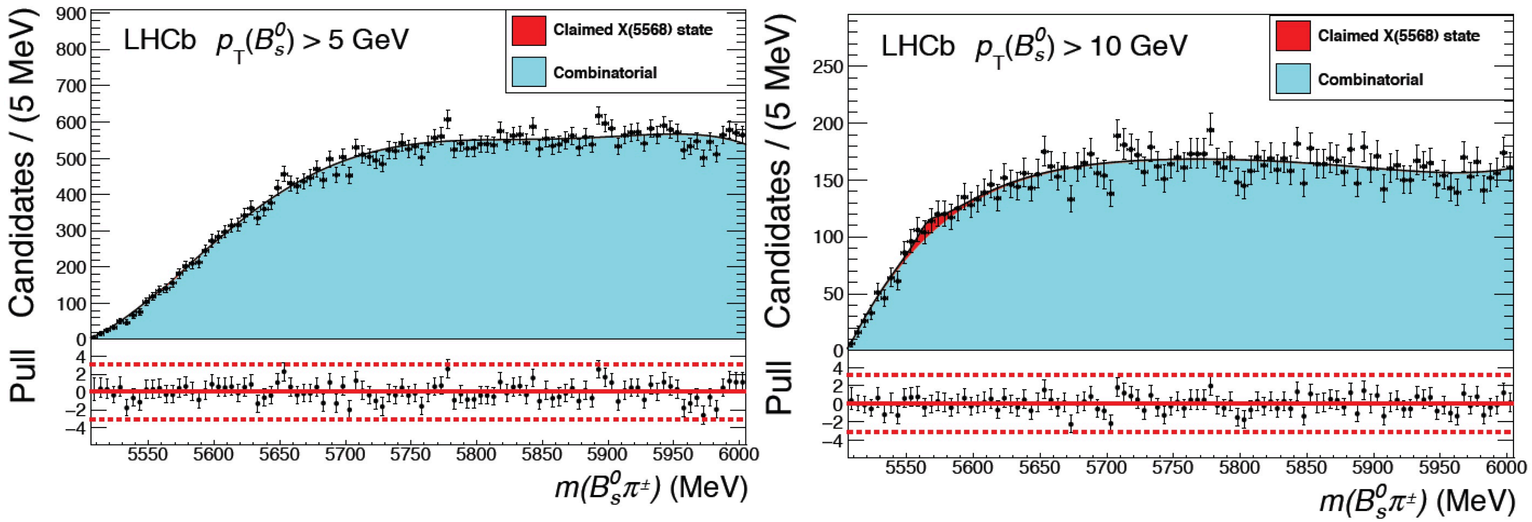
PRL 117 (2016) 152003

Large and clean B_s^0 samples reconstructed in $J/\psi\,\phi$ and $D_s^-\pi^+$

Constrain J/ψ and D_s mass to improve resolution



pair π^+ from primary vertex with a displaced B_s^0



Fit spectrum with and without a narrow resonant structure.

no signal $\Longrightarrow$ upper limit

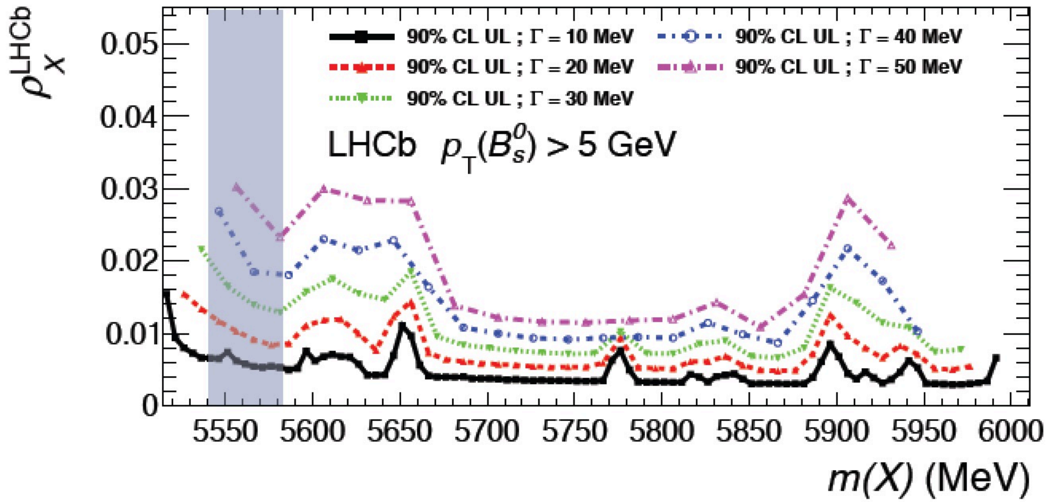
LHCb: no evidence for $X(5568) \to B_s^0\pi^+$

PRL 117 (2016) 152003

Set upper limit on the B_s^0 production ratio (including systematic)

$$\rho_X^{\rm LHCb} \equiv \frac{\sigma(pp \to X(5568) + \text{anything}) \times \mathcal{B}(X(5568) \to B_s^0\pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

Set UL as a function of M_X for different values of Γ_X and different values of the minimum transverse B_s^0 momentum



for the $X(5568)$ parameters reported by DØ and different values of the transverse B_s^0 momentum the limits are

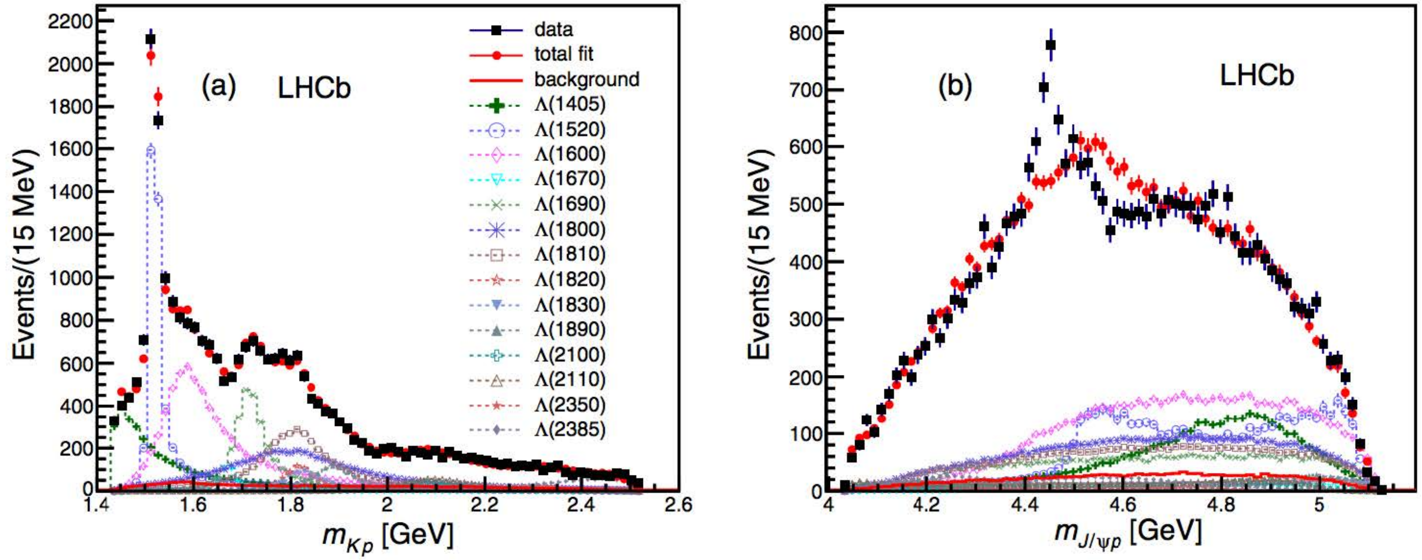
$$\rho_X^{\rm LHCb}(p_{\rm T} > 5\,{\rm GeV}/c) < 1.1\ (1.2)\% \text{ at } 90\ (95)\% \text{ CL}$$

$$\rho_X^{\rm LHCb}(p_{\rm T} > 10\,{\rm GeV}/c) < 2.1\ (2.4)\% \text{ at } 90\ (95)\% \text{ CL}$$

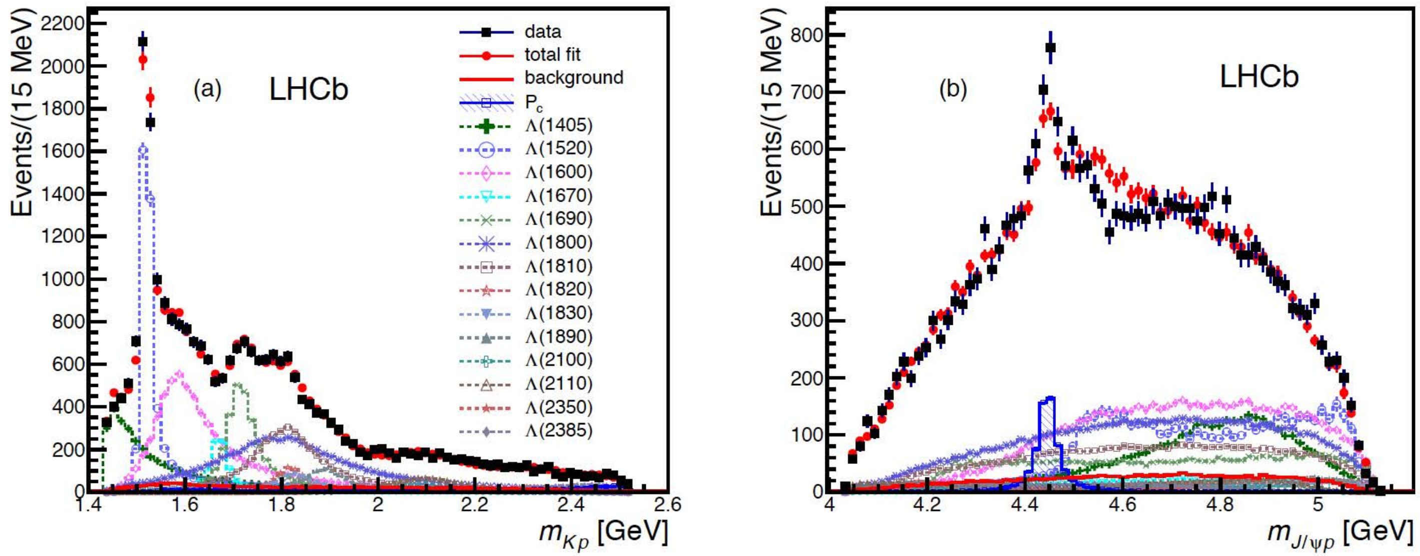
$$\rho_X^{\rm LHCb}(p_{\rm T} > 15\,{\rm GeV}/c) < 1.8\ (2.0)\% \text{ at } 90\ (95)\% \text{ CL}$$

Extended Model fits to $\Lambda_b^0 \to J/\psi p K^-$

The extended fit without additional exotic resonances describes well the $K^- p$ projection, fails to describe the $J/\psi p$ projection



adding one exotic resonance is not enough:



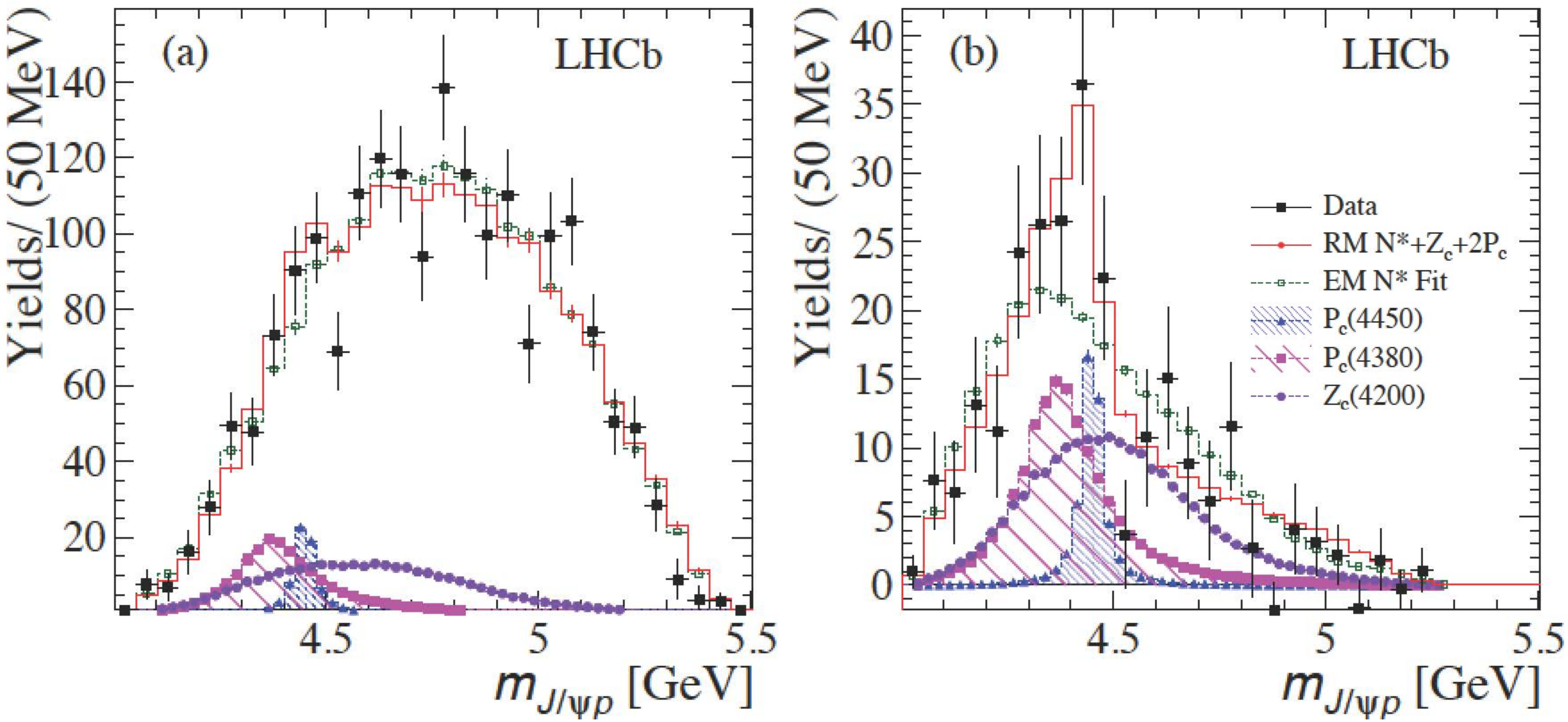
Fits with and without exotic hadrons

PRL 117 (2016) 082003

The amplitude model without P_c or Z_c amplitudes may appear adequate in the projections, but exotic components are required for an acceptable fit in all regions of variable space

All events

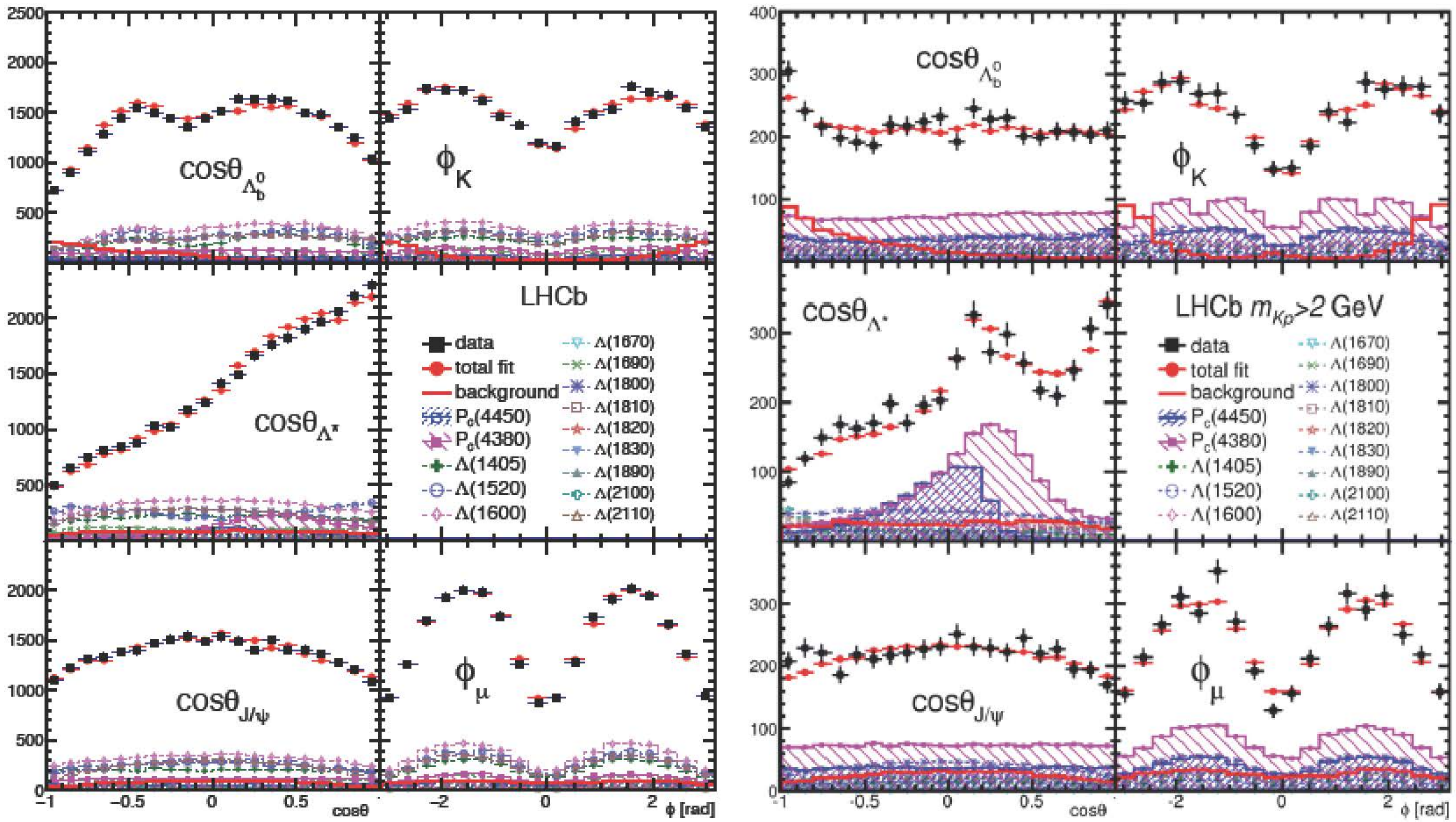
$m_{p\pi} > 1.8\,\mathrm{GeV}$



Differences in a six-dimensional fit often manifest only in restricted regions

Fit projections $\Lambda_b^0 \to J/\psi p K^-$

Reduced fit $+2$ P_c describes data well in all fit variables, also in restricted variable ranges



Efficiency and backround $\Lambda_b^0 \to J/\psi p\pi^-$

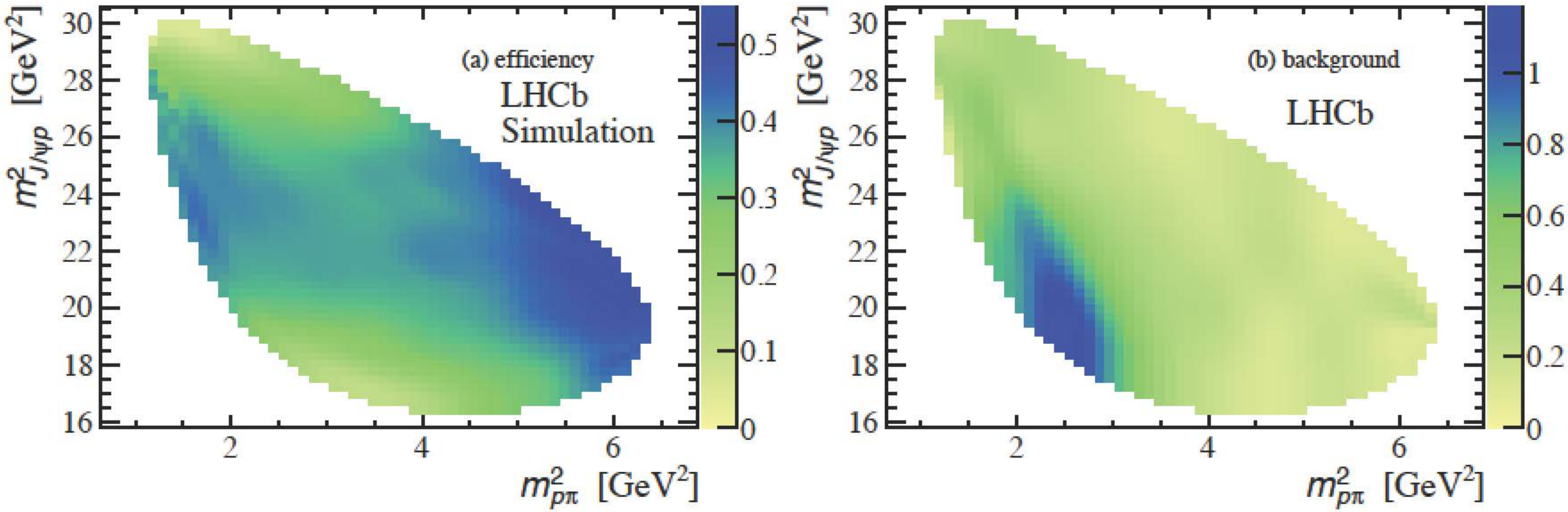
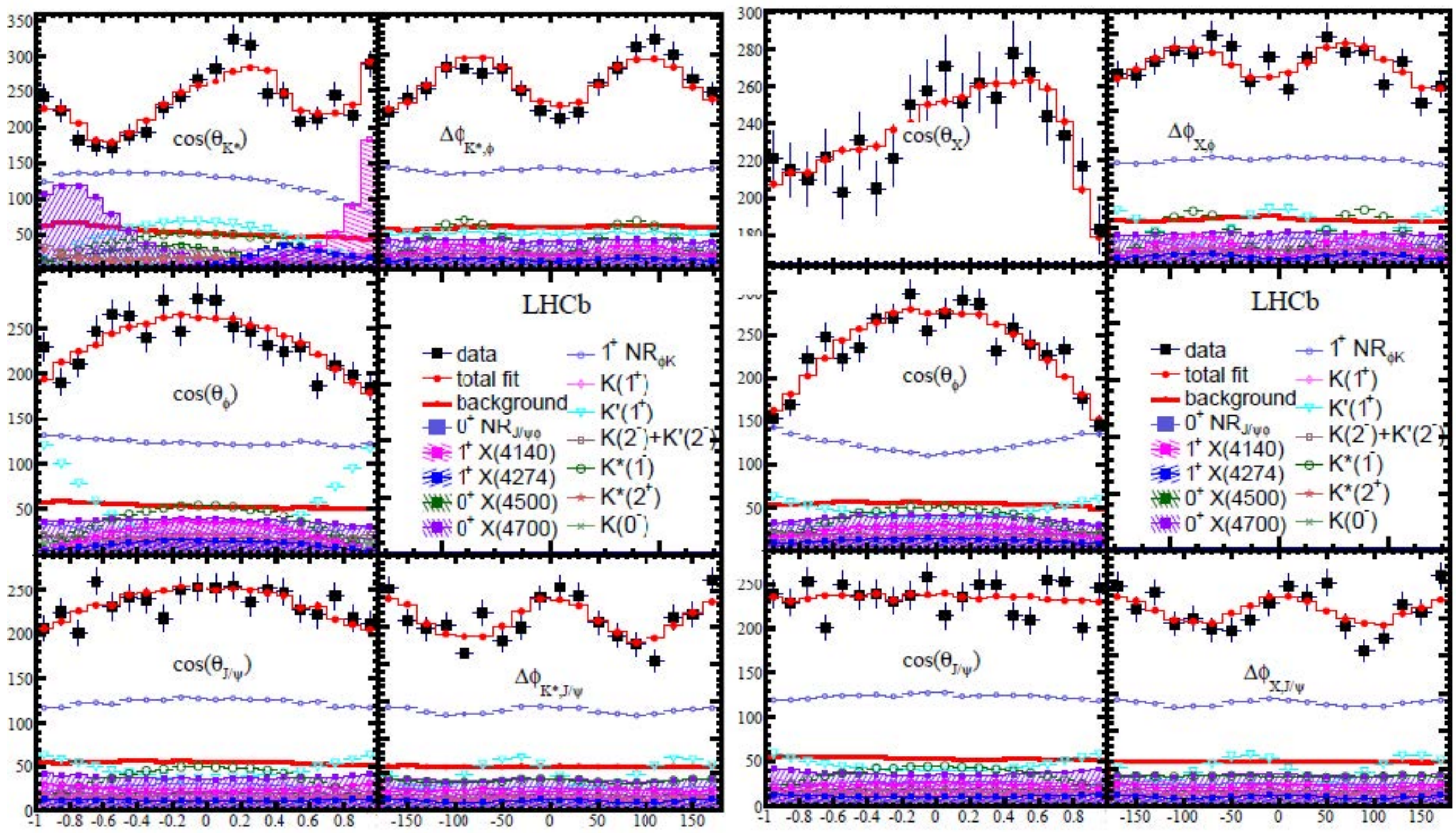


Figure 7: (a) Signal efficiency and (b) background distribution on the Dalitz plane.

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

The fit with 4 X states describes well data in all angles



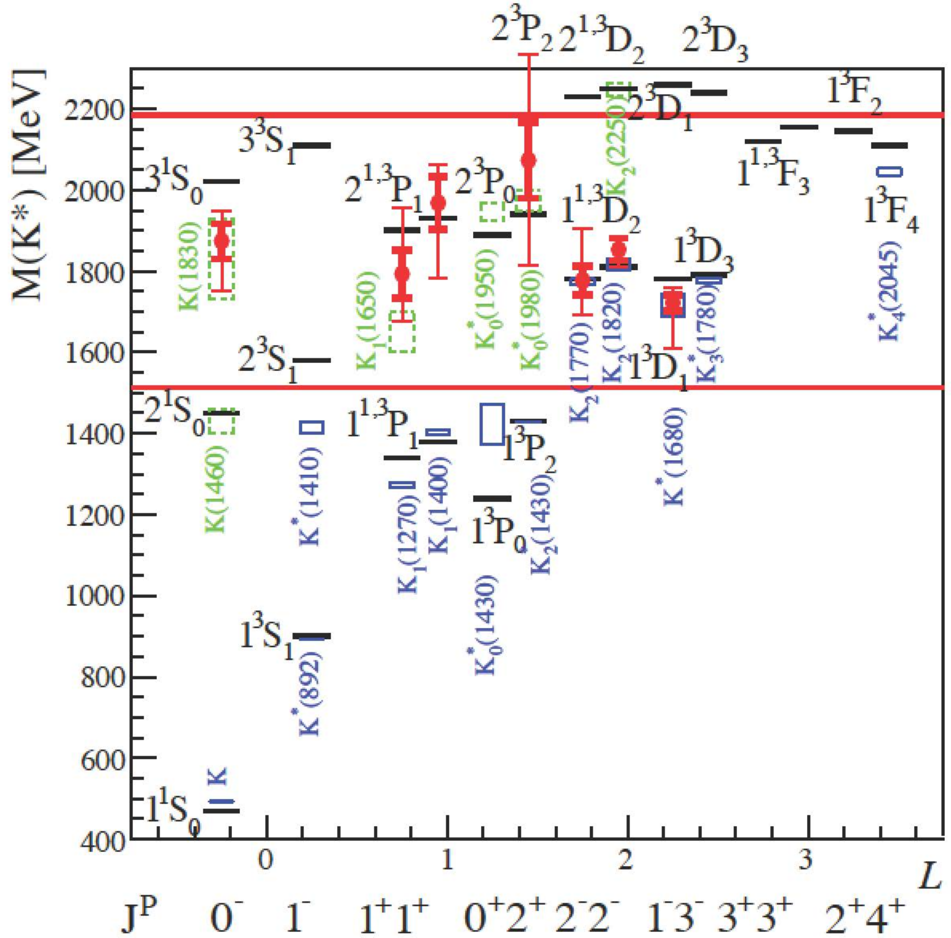
K^* spectroscopy in $B^+ \to J/\psi\,\phi K^+$

PRL 118 (2017) 022003
PRD 95 (2017) 012002

Our results for mass and widths of higher kaon excitations as red points

Excellent agreement with theory and previous experiments

$J = 3 - 4$ states not observed expected to be suppressed in B decays
(angular momentum barrier)

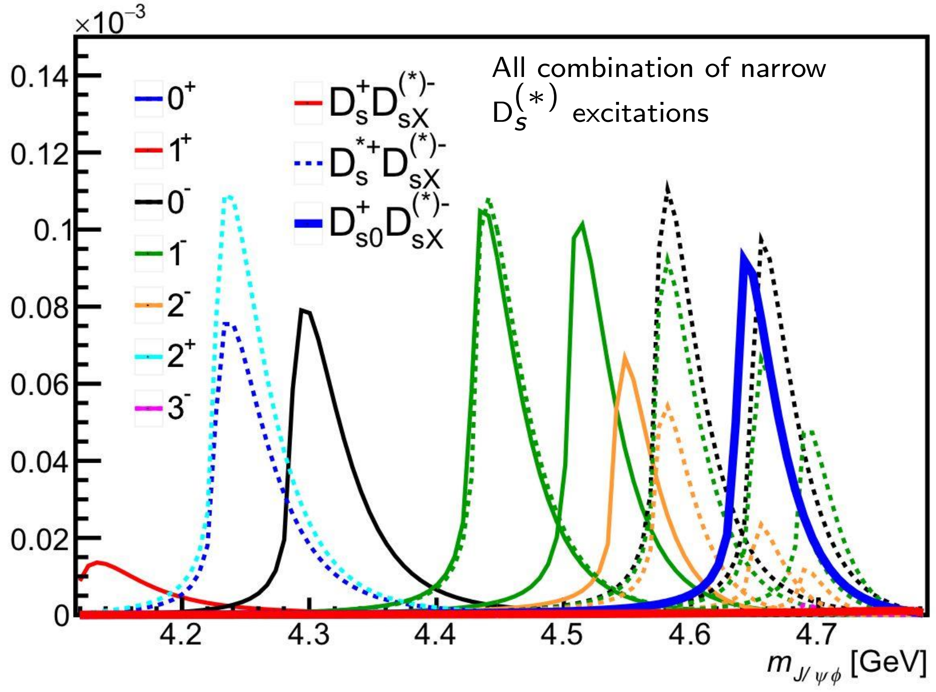


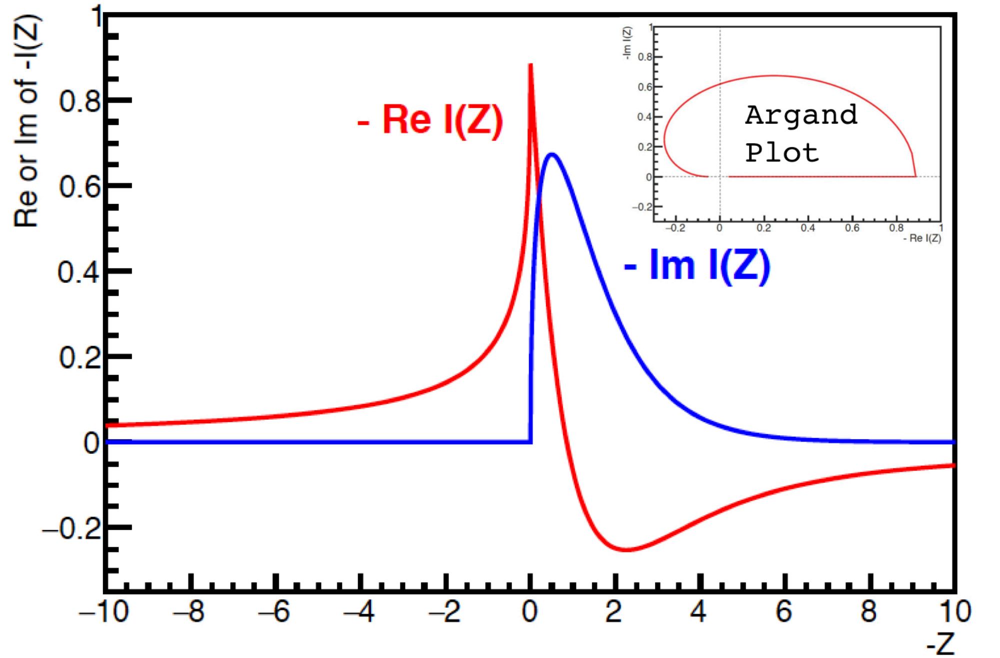
Resonances or cusps?

PRL 118 (2017) 022003
PRD 95 (2017) 012002

4 states...?? Kinematical effects?

Rescattering in S-wave. J^P is that of virtual $D_s^{(*)}$ pair. Cusp peaks at sum of $D_s^{(*)}$ masses





Test one of the cusp models which proposes to explain Z's just above $D^{(*)}\bar{D}^{(*)}$ thresholds (rescattering) Swanson, IJMP E25 (2016)1642010

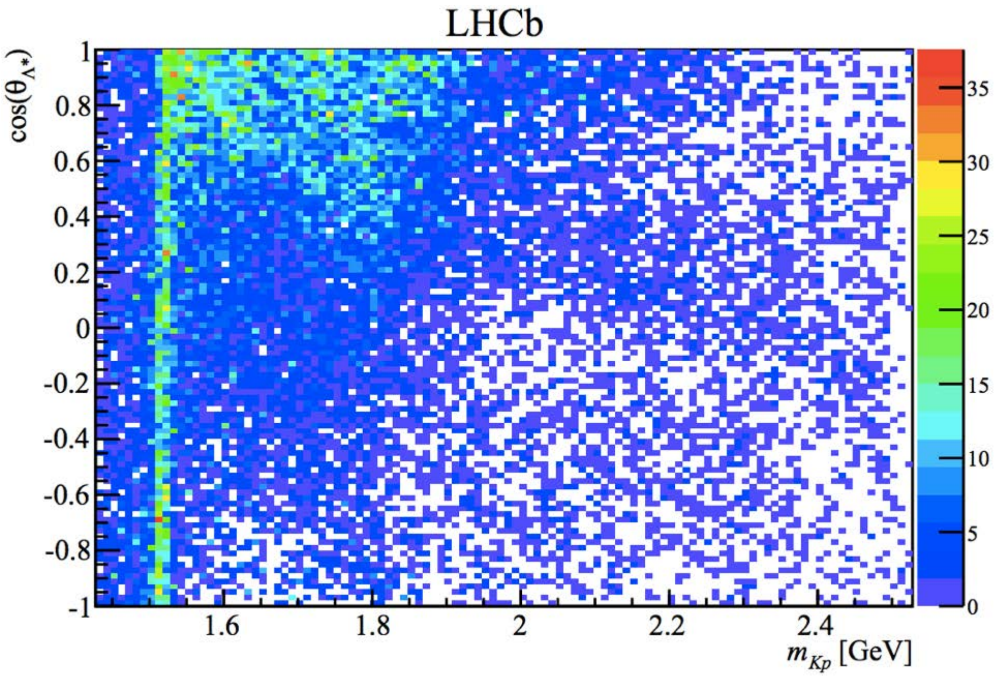
For the $X(4140)$ the cusp amplitude gives a better fit than BW (by 1.6σ)

For all other X's this cusp model has a worse fit

Model independent analysis of $\Lambda_b^0 \to J/\psi p K^-$

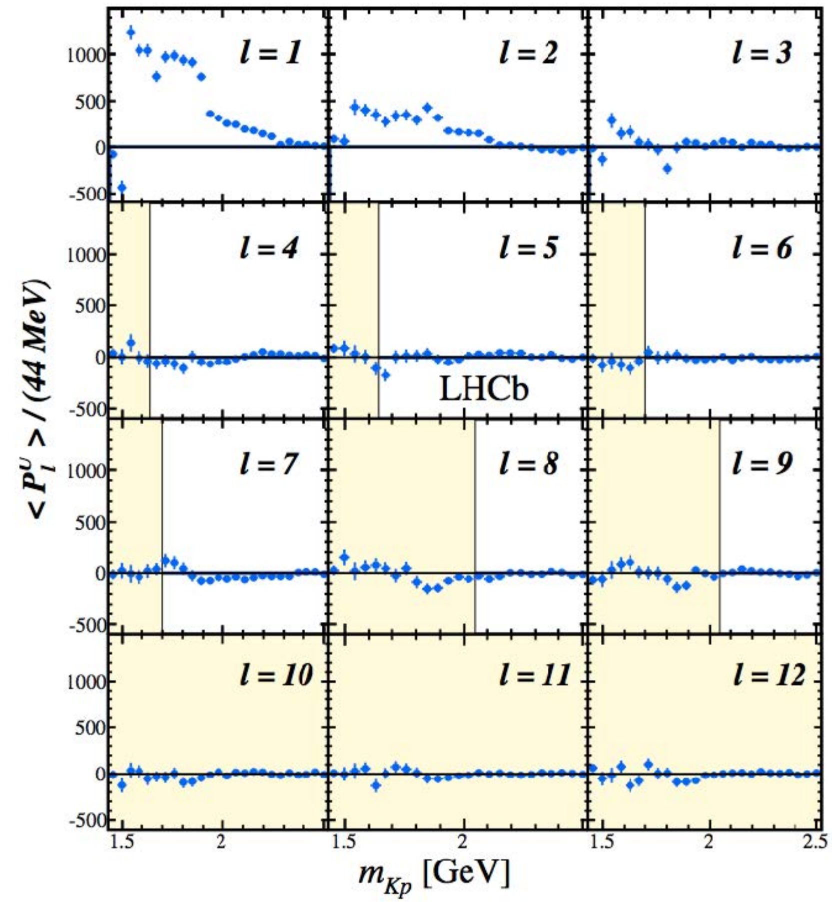
PRL 117 (2016) 0820

Hypothesis: data can be described by Kp mass and angular structures



Moments from data in bins of $m(Kp)$

$$\langle P_l^U \rangle^k = \sum_{i=1}^{n_{\text{cand}}^k} (w_i/\epsilon_i) P_l(\cos\theta^i_{\Lambda^*})$$



In each bin of $m(Kp)$, the $\cos\theta_{\Lambda *}$ distribution in terms of Legendre polynomial

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

Rank $\mathrm{l_{max}} < 2\mathrm{J_{max}}$

J_{max} : highest spin in $m(Kp)$ bin