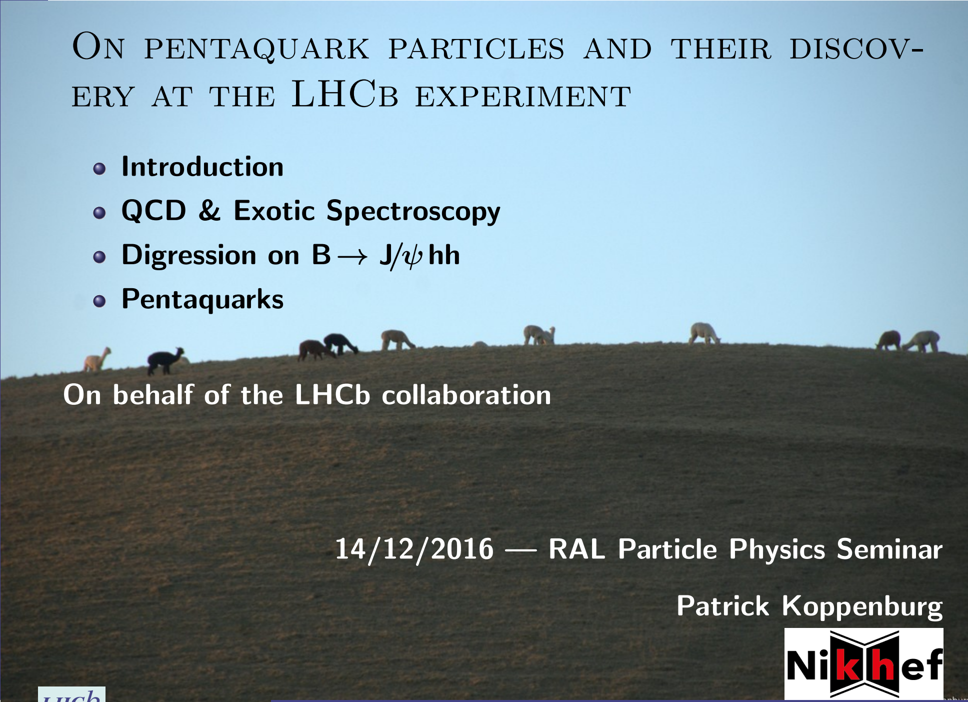
ON PENTAQUARK PARTICLES AND THEIR DISCOVERY AT THE LHCB EXPERIMENT



- **Introduction**
- **QCD & Exotic Spectroscopy**
- **Digression on B $\to$ J/ψ hh**
- **Pentaquarks**

On behalf of the LHCb collaboration

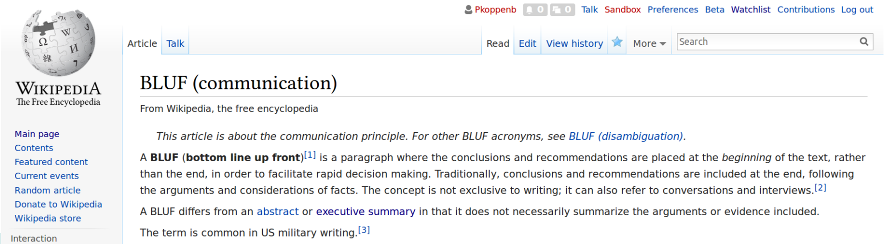
14/12/2016 — RAL Particle Physics Seminar

Patrick Koppenburg

[Bottom Line Up Front]

BLUF

- QCD is hard but necessary
  - ➜ We need to test it
  - . . . which is now often called “determining backgrounds”
- Charmonia spectroscopy is a good test-ground
- Pentaquarks have appeared and disappeared in the past
- To understand the data, a full angular fit is needed
- We see two states in $\Lambda_b^0 \to J/\psi\, pK$ involving five quarks. Their nature is yet unclear.



BLUF (communication)

From Wikipedia, the free encyclopedia

This article is about the communication principle. For other BLUF acronyms, see BLUF (disambiguation).

A **BLUF** (**bottom line up front**)[1] is a paragraph where the conclusions and recommendations are placed at the *beginning* of the text, rather than the end, in order to facilitate rapid decision making. Traditionally, conclusions and recommendations are included at the end, following the arguments and considerations of facts. The concept is not exclusive to writing; it can also refer to conversations and interviews.[2]

A BLUF differs from an abstract or executive summary in that it does not necessarily summarize the arguments or evidence included.

The term is common in US military writing.[3]

THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
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τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.

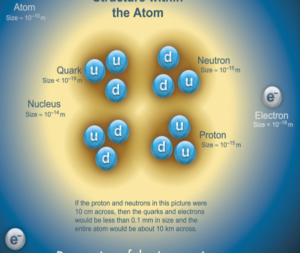
Neutrinos

Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at **ParticleAdventure.org**

Properties of the Interactions

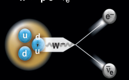
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property		Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:		All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at	10^{-18} m	10^{-41}	0.8	1	25
	3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

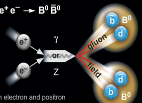
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$e^+ e^- \rightarrow B^0 \bar{B}^0$

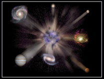


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

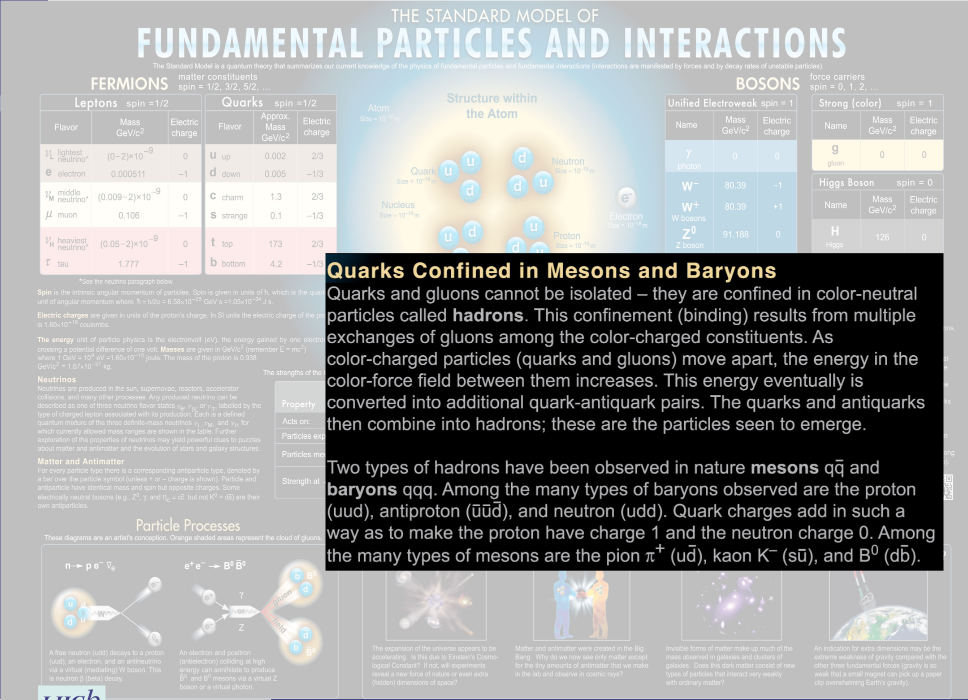
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

What is Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).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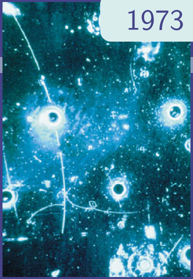
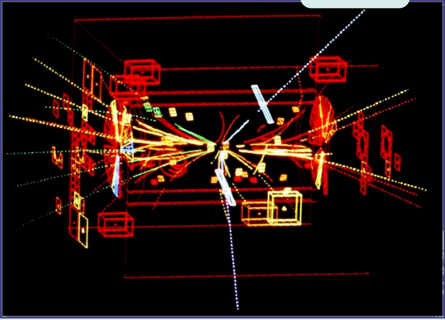
PRECISION MEASUREMENTS

Sensitive to "New" Physics effects off-shell

- When was the Z discovered?
  - 1973 from $\nu N \to \nu N$
  - 1983 at SpS collider?
- c quark needed to explain $K^0_{\mathrm{L}} \to \mu^+\mu^-$ (GIM)
- Third family (b,t) to explain CP violation (Kobayashi & Maskawa)


1973

1983


Generic New Physics Amplitude:

$$\mathcal{A} = \mathcal{A}_0 \left(\frac{C_{\mathrm{SM}}}{M_W^2} + \frac{C_{\mathrm{NP}}}{\Lambda^2} \right)$$

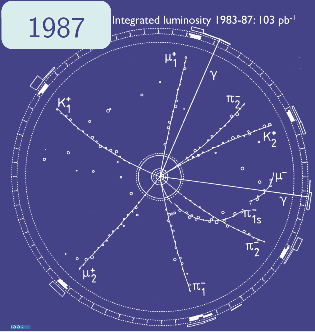
➜ Sensitive to very high NP scales Λ

PRECISION MEASUREMENTS


1973

Sensitive to “New” Physics effects off-shell

- When was the Z discovered?
  - 1973 from $\nu N \rightarrow \nu N$
  - 1983 at SpS collider?
- c quark needed to explain $K^0_\mathrm{L} \rightarrow \mu^+\mu^-$ (GIM)
- Third family (b,t) to explain CP violation (Kobayashi & Maskawa)
- ✔ Estimate masses
  - t quark from $B\overline{B}$ mixing
  - ✔ Much larger mass coverage than $\sqrt{s}$
- ✔ Get phases of couplings
  - Half of new parameters
  - Needed for a full understanding
- Look in lepton and **flavour** sectors
  - ➜ CP asymmetry in the Universe


1987

PRECISION MEASUREMENTS

Where to look?

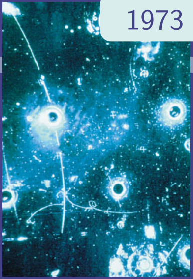
Need three ingredients:

1. **Precise SM prediction**
2. **(desirable) Precise beyond-SM predictions**
3. **Good experimental precision**

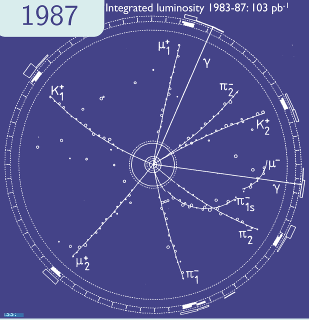
Generic New Physics Amplitude:

$$\mathcal{A} = \mathcal{A}_0 \left(\frac{C_{\mathrm{SM}}}{M_W^2} + \frac{C_{\mathrm{NP}}}{\Lambda^2} \right)$$

Check out my Scholarpedia article on Rare Decays. [Scholarpedia 32643]

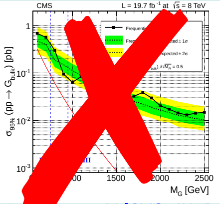


1973

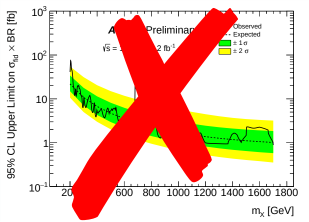


1987

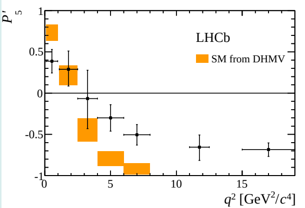
Are we already seeing New Physics?



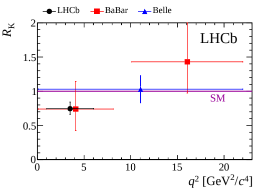
Ex at 2 TeV [CMS, JHEP 08 (2014) 174]



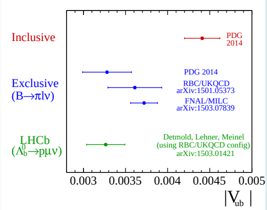
Excess at 750 GeV [ATLAS-CONF-2015-081]



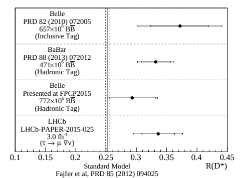
P'_5 in $B \to K^* \mu^+ \mu^-$ [JHEP 02 (2016) 104]



Lepton universality [PRL 113 (2014) 151601]

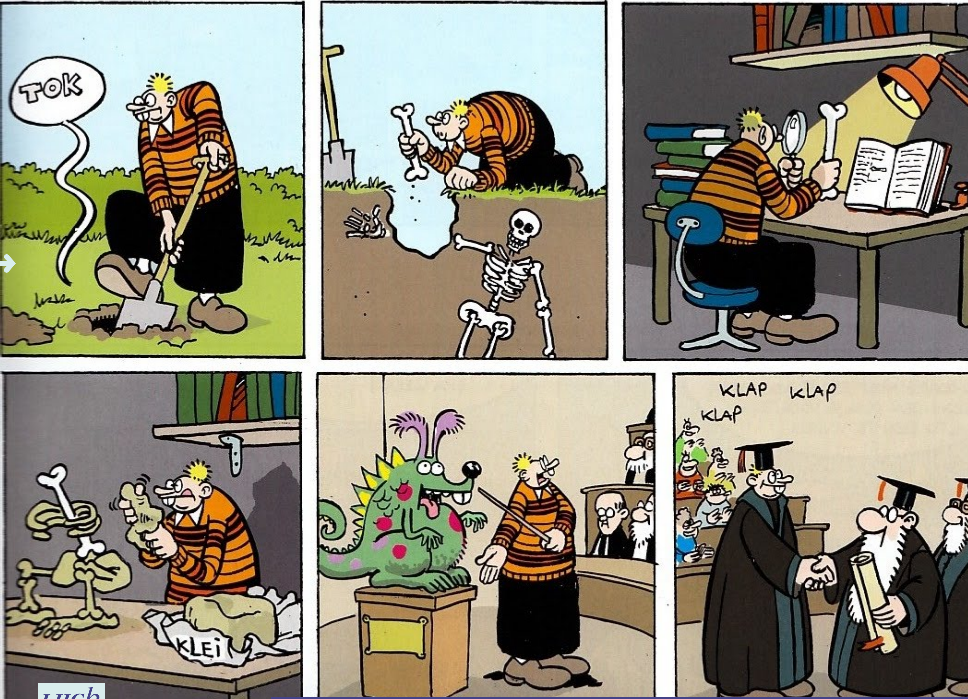


V_{ub} puzzle [Nature Physics 11 (2015) 743]



$B \to D^* \tau \nu$ [PRD 92 (2015) 011102(R)]

There's a handful of intriguing 3–4σ anomalies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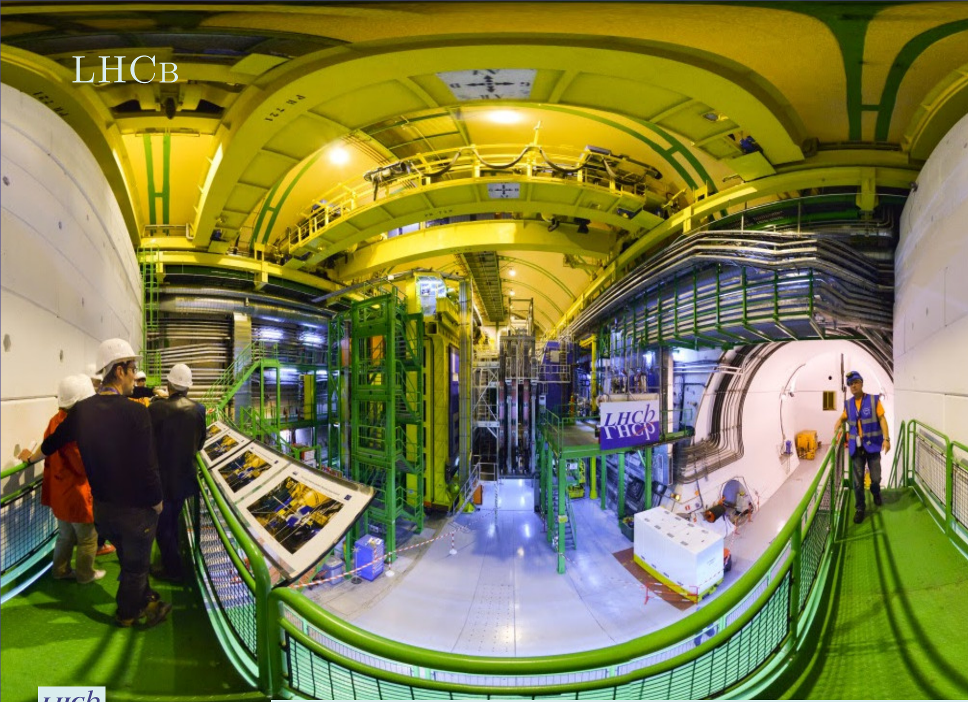
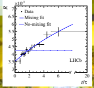
KLAP
KLAP

LHCb

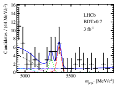


LHCb Physics Programme

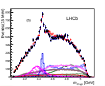
CKM and *CP* violation with *b* and *c* hadrons

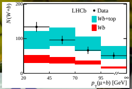


Rare decays of *b* hadrons and *c* hadrons

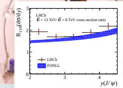


Spectroscopy in *pp* interactions and *B* decays

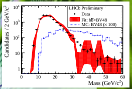




Electroweak and QCD measurements in the forward acceptance



Heavy quark production

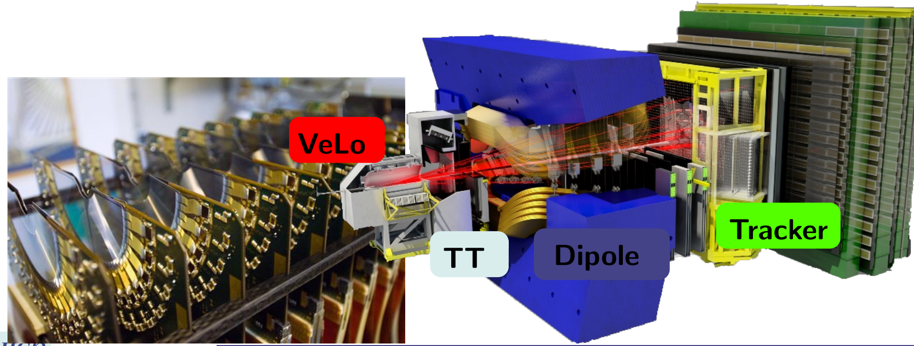


Exotica searches

LHCb DETECTOR

Forward detector (many b hadrons produced forward at LHC, $(164.6 \pm 2.3 \pm 14.6)\ \mu\mathrm{b}$ in acceptance at 13TeV [LHCb, LHCb-PAPER-2016-031, in preparation])

- Warm dipole magnet. Polarity can be reversed
- ✔ Good momentum and position resolution
  - Vertex detector gets 8mm to the beam



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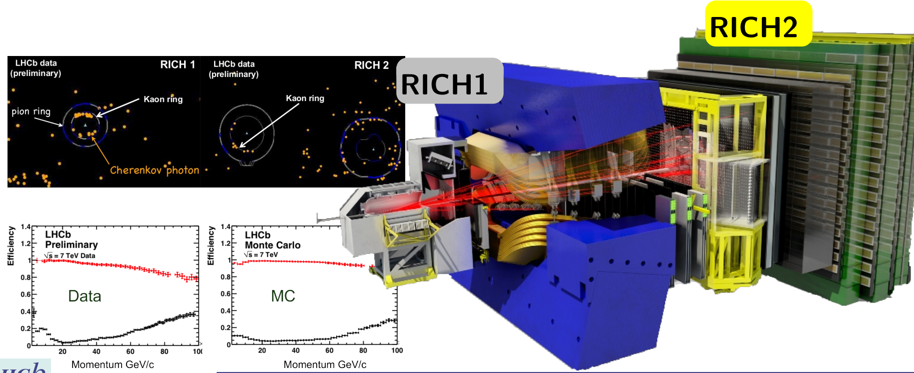
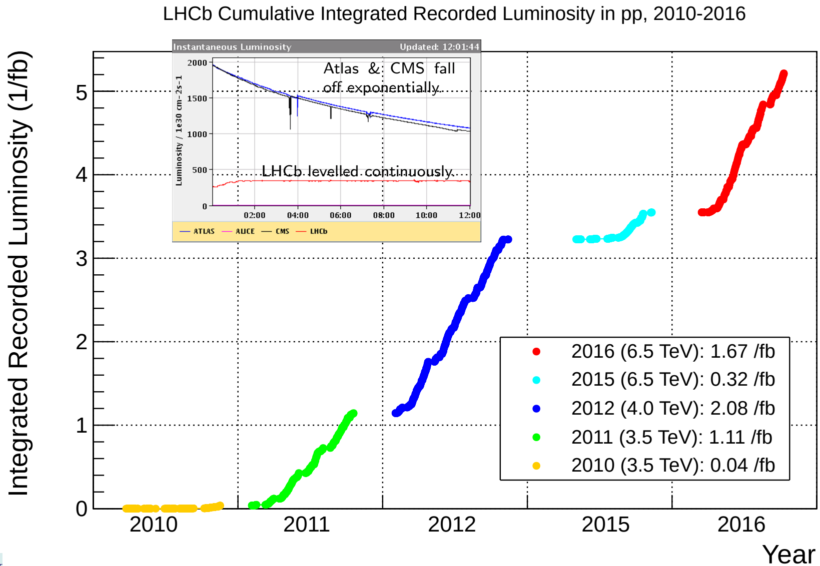
✔ Good momentum and position resolution, high efficiency

✔ Excellent Particle ID



INTEGRATED LUMINOSITY



Atlas & CMS fall off exponentially

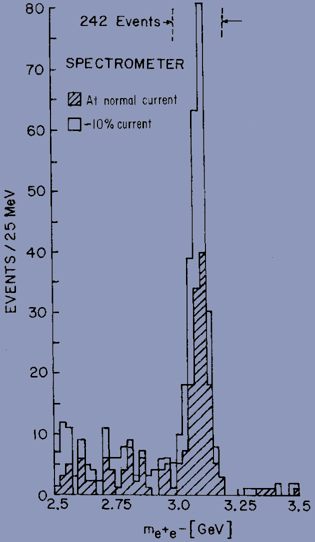
LHCb levelled continuously

Quantum Chromodynamics

QUARKONIA SPECTROSCOPY

The strongly interacting particles in the SM are quarks and gluons.
The strongly interacting particles in Nature are mesons and baryons.

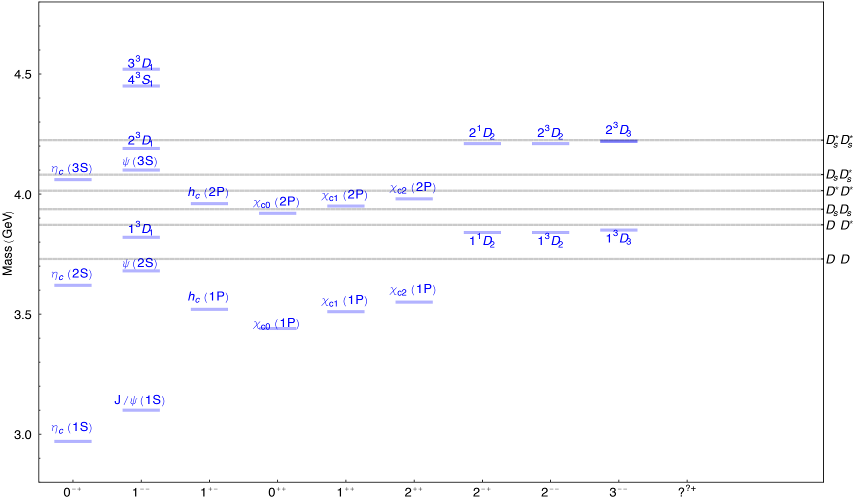
- Related to each other by long-distance QCD, which is poorly understood
  - ➜ Need QCD models, and those need testing
- Quarkonia spectroscopy is an area where these tests can be performed



[Phys. Rev. Lett. 33 (1974) 1404]

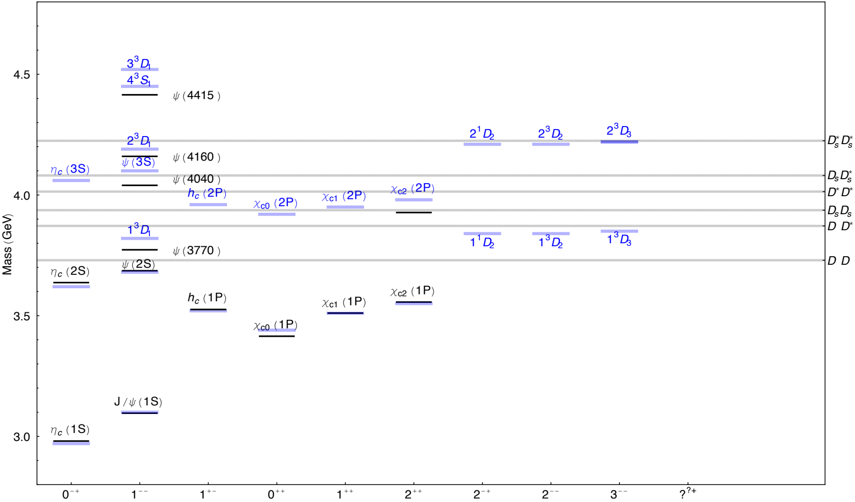
Courtesy of Antonio Polosa

Charmonium Predictions

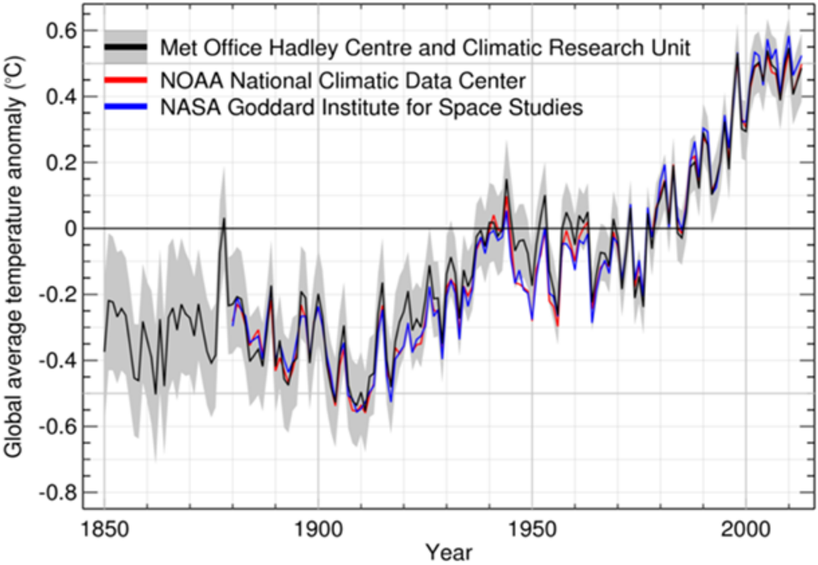


Courtesy of Antonio Polosa

Charmonium Levels

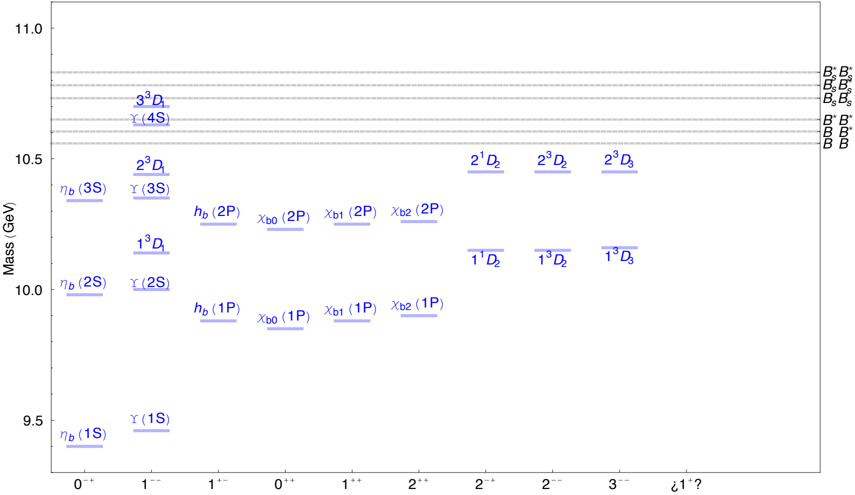


SOME DISAGREEMENT



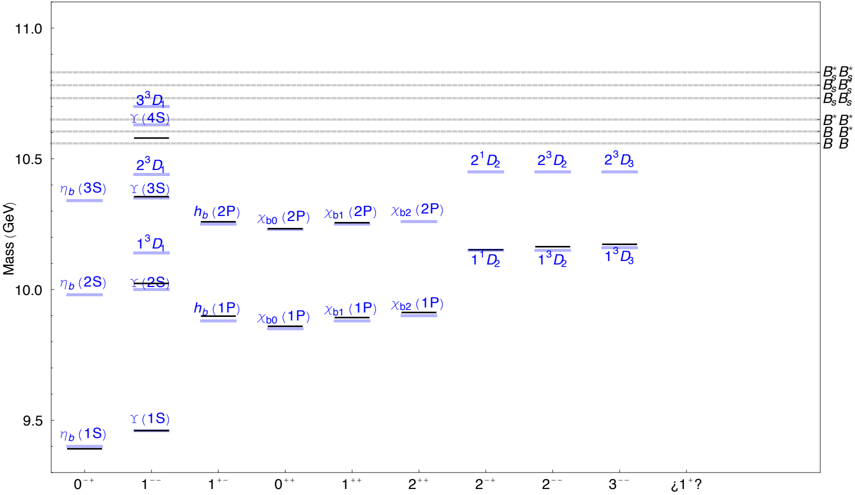
Courtesy of Antonio Polosa

Bottomonium Predictions



Courtesy of Antonio Polosa

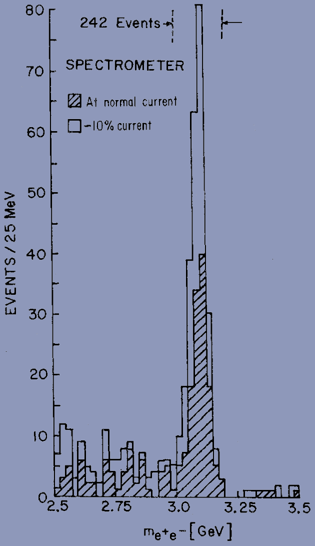
Bottomonium Levels



QUARKONIA SPECTROSCOPY

The strongly interacting particles in the SM are quarks and gluons.
The strongly interacting particles in Nature are mesons and baryons.

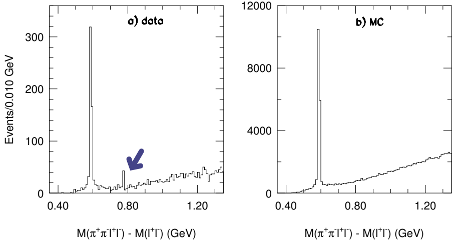
- Related to each other by long-distance QCD, which is poorly understood
  - ➜ Need QCD models, and those need testing
- Quarkonia spectroscopy is an area where these tests can be performed
  - ✔ The picture seems very successful



[Phys. Rev. Lett. 33 (1974) 1404]

[Belle, PRL 91, 262001 (2003), arXiv:hep-ex/0309032]

OBSERVATION OF THE $X(3872)$ RESONANCE

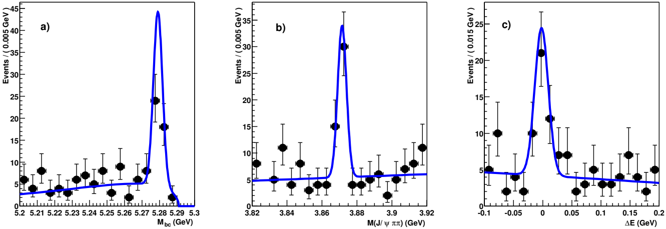


Belle reported a clear peak in the $J/\psi\pi^+\pi^-$ mass spectrum above the $\psi(2S)$ in $B^+ \to J/\psi\pi^+\pi^- K^+$ decays (36 ± 7 events)

$$M_X = 3872.0 \pm 0.6 \pm 0.5\ \mathrm{MeV}/c^2$$

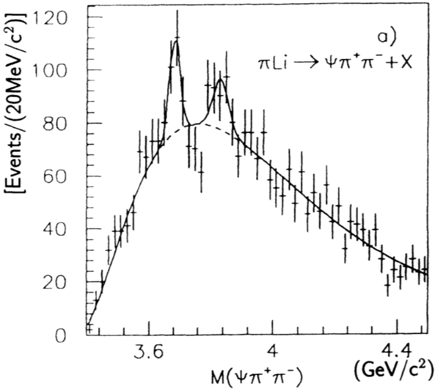
$$\Gamma < 2.3\ \mathrm{MeV}$$

close to the $D^0 D^{*0}$ threshold

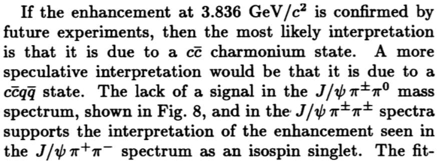


[E705, PRD 50 4258 (1994)]

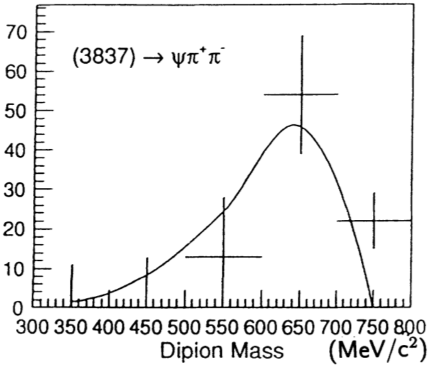
HIDDEN CHARM STATES DECAYING TO $J/\psi\,\pi^+\pi^-$



$J/\psi\,\pi^+\pi^-$ in 10 GeV/c $\pi^\pm$Li interactions



If the enhancement at 3.836 GeV/c^2 is confirmed by future experiments, then the most likely interpretation is that it is due to a $c\bar{c}$ charmonium state. A more speculative interpretation would be that it is due to a $c\bar{c}q\bar{q}$ state. The lack of a signal in the $J/\psi\,\pi^\pm\pi^0$ mass spectrum, shown in Fig. 8, and in the $J/\psi\,\pi^\pm\pi^\pm$ spectra supports the interpretation of the enhancement seen in the $J/\psi\,\pi^+\pi^-$ spectrum as an isospin singlet. The fit-



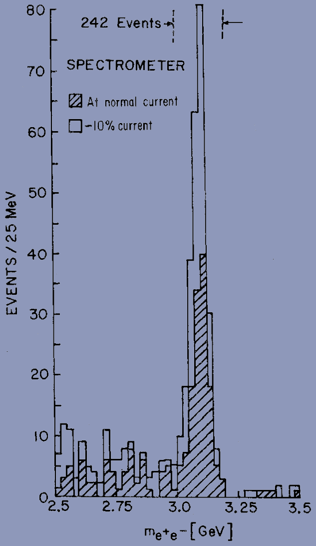
Was the X(3872) seen in 1993 at FermiLab?

Quarkonia spectroscopy

The strongly interacting particles in the SM are quarks and gluons.

The strongly interacting particles in Nature are mesons and baryons.

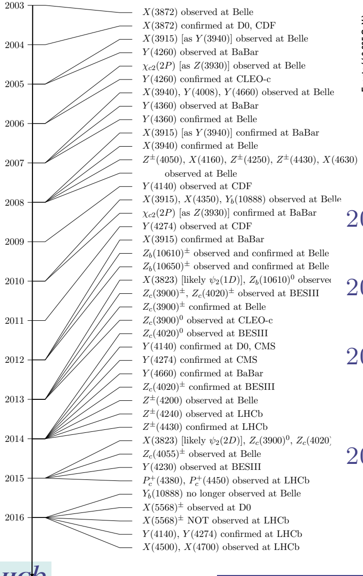
- Related to each other by long-distance QCD, which is poorly understood
  - ➜ Need QCD models, and those need testing
- Quarkonia spectroscopy is an area where these tests can be performed
- ✗ But then came the $X(3872)$ with isospin-violating decays
  - The first of a long series



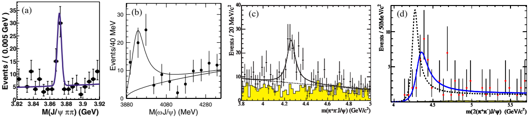
[Phys. Rev. Lett. 33 (1974) 1404]

[Lebed, Mitchell, Swanson, arXiv:1610.04528]

EXOTICA TIMELINE



$X(3872)$ observed at Belle
$X(3872)$ confirmed at D0, CDF
$X(3915)$ [as $Y(3940)$] observed at Belle
$Y(4260)$ observed at BaBar
$\chi_{c2}(2P)$ [as $Z(3930)$] observed at Belle
$Y(4260)$ confirmed at CLEO-c
$X(3940)$, $Y(4008)$, $Y(4660)$ observed at Belle
$Y(4360)$ observed at BaBar
$Y(4360)$ confirmed at Belle
$X(3915)$ [as $Y(3940)$] confirmed at BaBar
$X(3940)$ confirmed at Belle
$Z^{\pm}(4050)$, $X(4160)$, $Z^{\pm}(4250)$, $Z^{\pm}(4430)$, $X(4630)$ observed at Belle
$Y(4140)$ observed at CDF
$X(3915)$, $X(4350)$, $Y_b(10888)$ observed at Belle
$\chi_{c2}(2P)$ [as $Z(3930)$] confirmed at BaBar
$Y(4274)$ observed at CDF
$X(3915)$ confirmed at BaBar
$Z_b(10610)^{\pm}$ observed and confirmed at Belle
$Z_b(10650)^{\pm}$ observed and confirmed at Belle
$X(3823)$ [likely $\psi_2(1D)$], $Z_b(10610)^0$ observe
$Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$ observed at BESIII
$Z_c(3900)^{\pm}$ confirmed at Belle
$Z_c(3900)^0$ observed at CLEO-c
$Z_c(4020)^0$ observed at BESIII
$Y(4140)$ confirmed at D0, CMS
$Y(4274)$ confirmed at CMS
$Y(4660)$ confirmed at BaBar
$Z_c(4020)^{\pm}$ confirmed at BESIII
$Z^{\pm}(4200)$ observed at Belle
$Z^{\pm}(4240)$ observed at LHCb
$Z^{\pm}(4430)$ confirmed at LHCb
$X(3823)$ [likely $\psi_2(2D)$], $Z_c(3900)^0$, $Z_c(4020)$
$Z_c(4055)^{\pm}$ observed at Belle
$Y(4230)$ observed at BESIII
$P_c^+(4380)$, $P_c^+(4450)$ observed at LHCb
$Y_b(10888)$ no longer observed at Belle
$X(5568)^{\pm}$ observed at D0
$X(5568)^{\pm}$ NOT observed at LHCb
$Y(4140)$, $Y(4274)$ confirmed at LHCb
$X(4500)$, $X(4700)$ observed at LHCb



First observations of $X(3872)$ [Belle, PRL 91 262001 (2003)], $Y(3940)$ [Belle, PRL 94 182002 (2005)], $Y(4260)$ [BABAR, PRL 95 142001 (2005)], $Y(4360)$ [BABAR, PRL 98 212001 (2007)]

2003 Belle sees $X(3872)$ by accident in $B^+ \to J/\psi K^+\pi^+\pi^-$ [Belle, PRL 91 262001 (2003)]

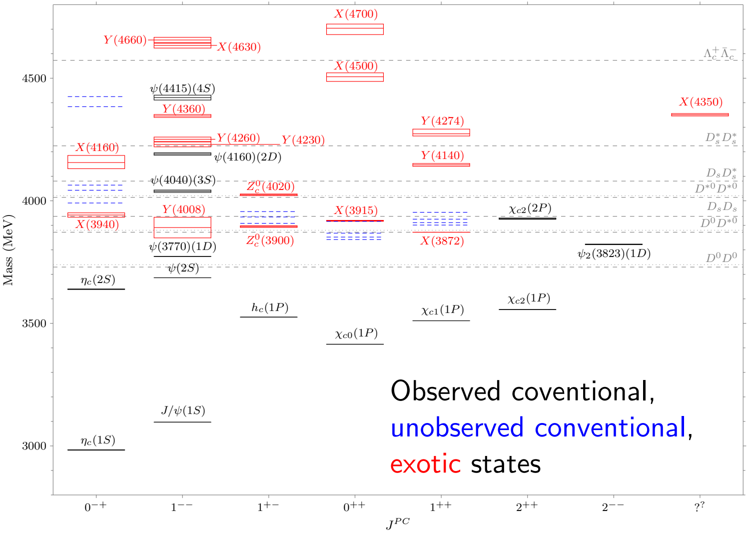
2005 Belle then searched for it in $B^+ \to J/\psi K^+\omega$ but found the $Y(3940)$ [Belle, PRL 94 182002 (2005)]

2005 BaBar searched for it in $e^+e^- \to X(3872)$ with ISR but did not find it. They found the $Y(4260)$ instead. [BABAR, PRL 95 142001 (2005)]

2006 BaBar then looked whether the $Y(4260)$ decayed to $\psi(2S)\pi^+\pi^-$ with ISR. Instead they found the $Y(4360)$. [BABAR, PRL 98 212001 (2007)]

[Lebed, Mitchell, Swanson, arXiv:1610.04528]

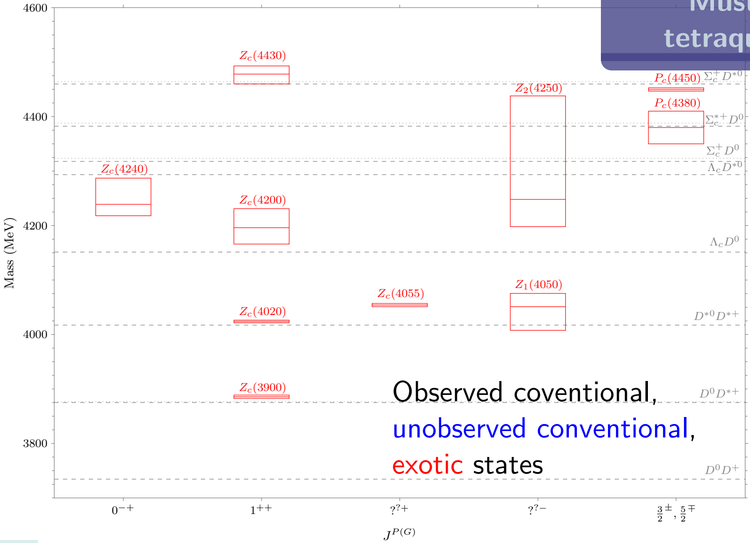
ENERGY LEVELS: NEUTRAL CHARMONIUM STATES



Observed coventional,
unobserved conventional,
exotic states

[Lebed, Mitchell, Swanson, arXiv:1610.04528]

ENERGY LEVELS: CHARGED CHARMONIUM STATES

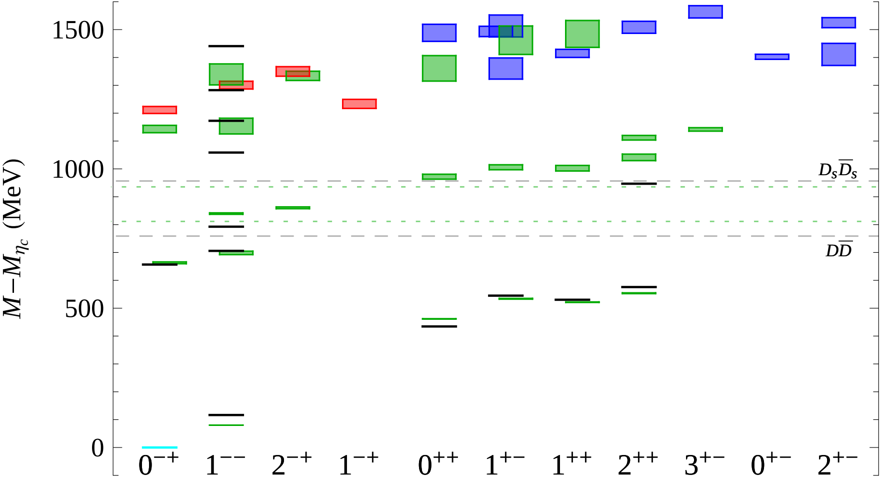


Must be tetraquarks!

Observed coventional,
unobserved conventional,
exotic states

[Liu et al., JHEP 07 (2012) 126, arXiv:1204.5425]

Energy Levels: Lattice calculations

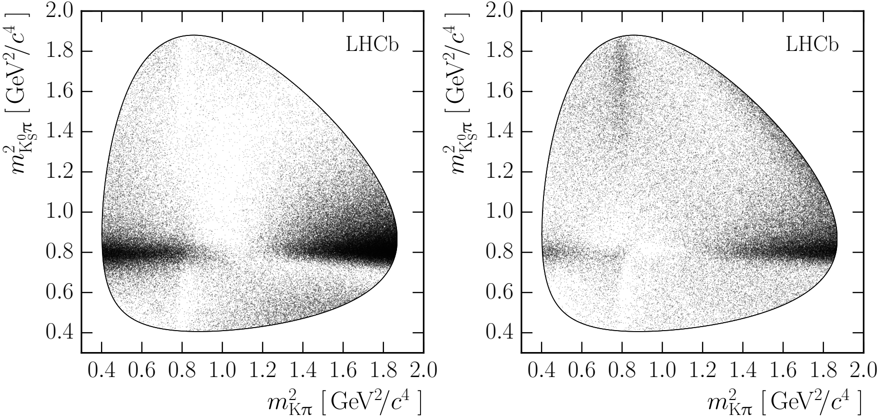


Experimental data, conventional, hybrid, excited hybrid

Digression on Dalitz Plots

[LHCb, Phys. Rev. D93 (2016) 052018, arXiv:1509.06628]

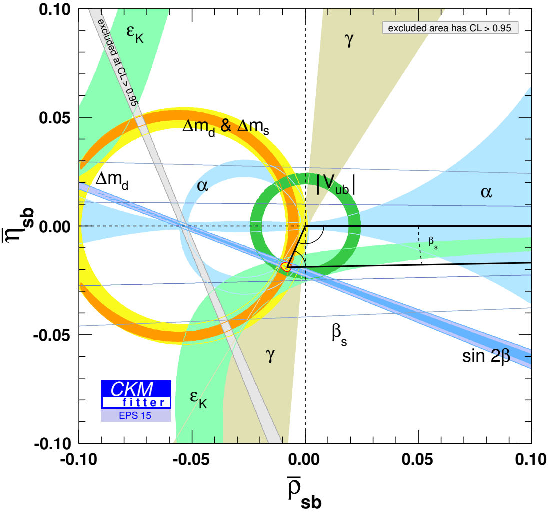
DALITZ PLOTS



$D^0 \to K^0_S K^- \pi^+$

$D^0 \to K^0_S K^+ \pi^-$

B_s^0 UNITARITY TRIANGLE



This is another CKM UT triangle, where the phase of B_s^0 mixing ϕ_s, appears.

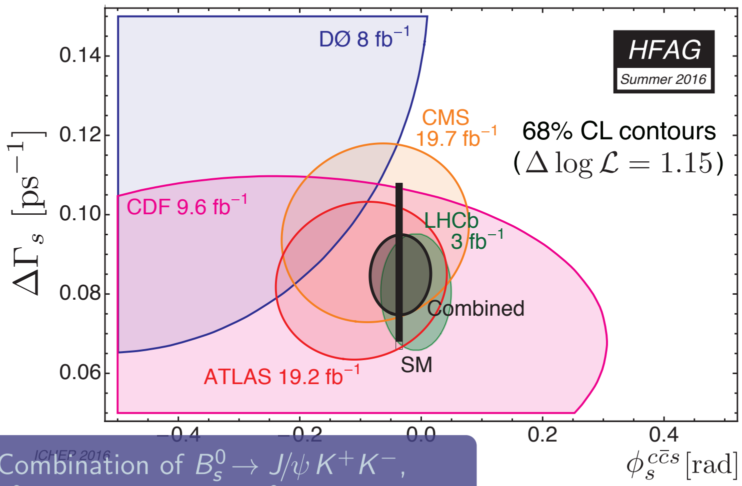
External constraints fix it very precisely to $\varphi_s = -2\arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -0.0363\,^{+\,0.0014}_{-\,0.0012}$

- ✔ Good potential for NP searches

[CKMfitter 07/15]

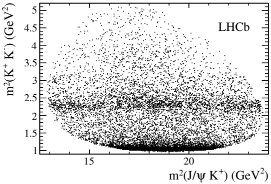
[HFAG]

$\Delta\Gamma_s$ VERSUS φ_s IN SUMMER 2016



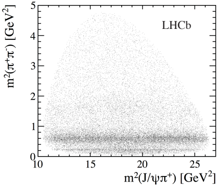
Combination of $B_s^0 \to J/\psi K^+ K^-$, $B_s^0 \to J/\psi \pi^+\pi^-$ and $B_s^0 \to D_s^+ D_s^-$: $\varphi_s = -0.034 \pm 0.033\,\mathrm{rad}$

Amplitude analyses — some examples



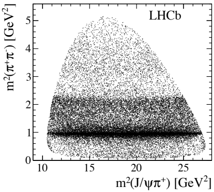
$B_s^0 \to J/\psi\, K^+ K^-$

[PRD 87 (2013) 072004]



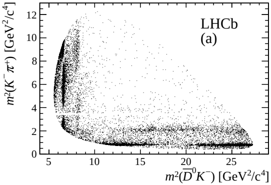
$B^0 \to J/\psi\, \pi^+ \pi^-$

[PRD 90 (2014) 012003]



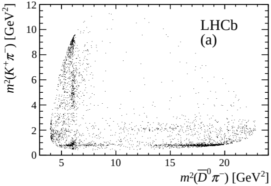
$B_s^0 \to J/\psi\, \pi^+ \pi^-$

[PRD 89 (2014) 092006]



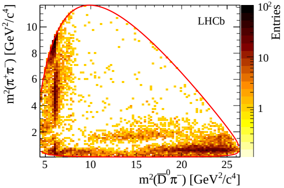
$B_s^0 \to \overline{D}{}^0 K^- \pi^+$

[PRL 113 (2014) 162001]



$B^0 \to \overline{D}{}^0 K^+ \pi^-$

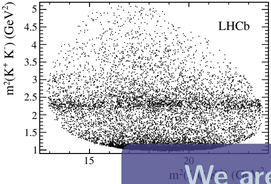
[PRD 92 (2015) 012012]



$B^0 \to \overline{D}{}^0 \pi^+ \pi^-$

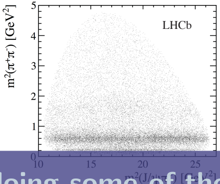
[PRD 92 (2015) 032002]

Amplitude analyses — some examples



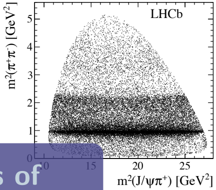
$B_s^0 \to J/\psi\, K^+K^-$

[PRD 87 (2013) 072004]



$B^0 \to J/\psi\, \pi^+\pi^-$

[PRD 90 (2014) 012003]

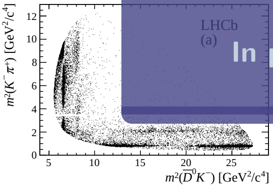


$B_s^0 \to J/\psi\, \pi^+\pi^-$

[PRD 89 (2014) 092006]

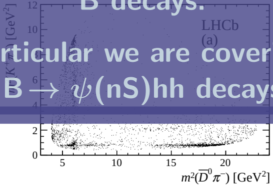
We are redoing some of the physics of the sixties and seventies, but with a well-defined and clean environment: B decays.

In particular we are covering all $B \to \psi(nS)hh$ decays



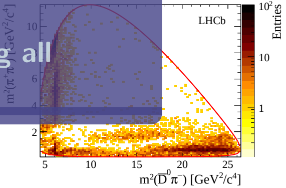
$B_s^0 \to \overline{D}^0 K^-\pi^+$

[PRL 113 (2014) 162001]



$B^0 \to \overline{D}^0 K^+\pi^-$

[PRD 92 (2015) 012012]

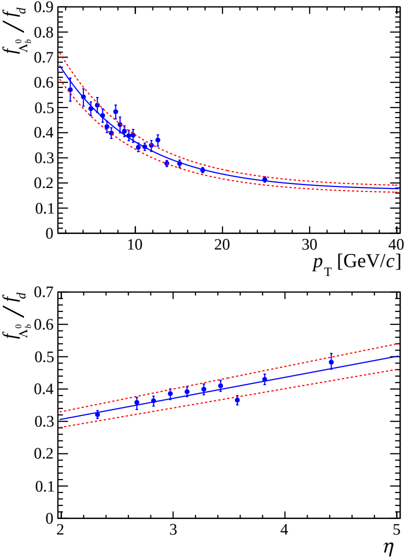


$B^0 \to \overline{D}^0 \pi^+\pi^-$

[PRD 92 (2015) 032002]

The Λ_b^0 baryon

$p_{\rm T}$ DEPENDENCE OF $f_{\Lambda_b^0}/f_d$

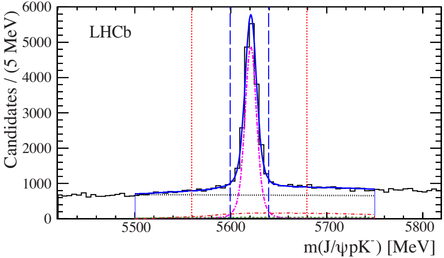


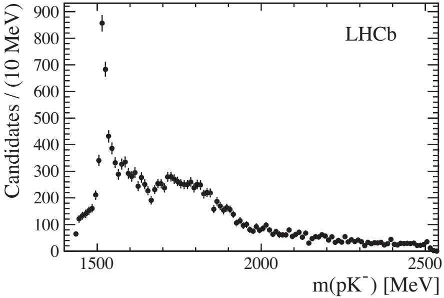
- Determine the $p_{\rm T}$ and η dependence of $f_{\Lambda_b^0}/f_d$ using $\Lambda_b^0 \to \Lambda_c^+\pi^-$ and $\overline{B}^0 \to D^+\pi^-$
  - Very similar decays
  - Absolute scale normalised using semileptonc decays [Phys. Rev. D 85, 032008 (2012), arXiv:1111.2357]
- Clear increase of Λ_b^0 at low $p_{\rm T}$ and large η
  - ➜ Many more Λ_b^0 in LHCb than central detectors

The LHC is a Λ_b^0 factory: 4:2:1 B^0:Λ_b^0:B_s^0 in LHCb acceptance

[LHCb, Phys. Rev. Lett. 111 (2013) 102003, arXiv:1307.2476]

MEASUREMENT OF THE Λ_b^0/B^0 LIFETIME

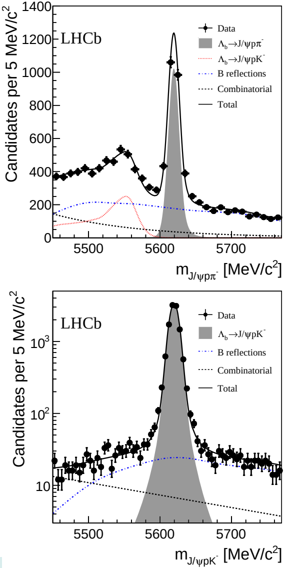




- First observation of the decay $\Lambda_b^0 \to J/\psi\, pK^-$ with 1 fb^{-1}
- Unexpected large yield, interesting structure in pK mass
- Used to measure Λ_b^0 lifetime
  - ➜ Result superseded by [LHCb, Phys. Lett. B734 (2014) 122, arXiv:1402.6242]

We did not show the $J/\psi\, p$ mass distribution

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



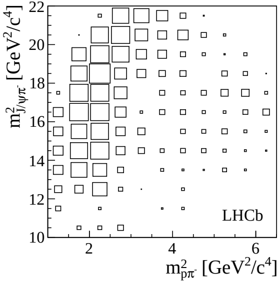
- Look for $\Lambda_b^0 \to J/\psi\, p\pi^-$ and $\Lambda_b^0 \to J/\psi\, pK^-$
  - ➜ 2102 ± 61 $\Lambda_b^0 \to J/\psi\, p\pi^-$ decays

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

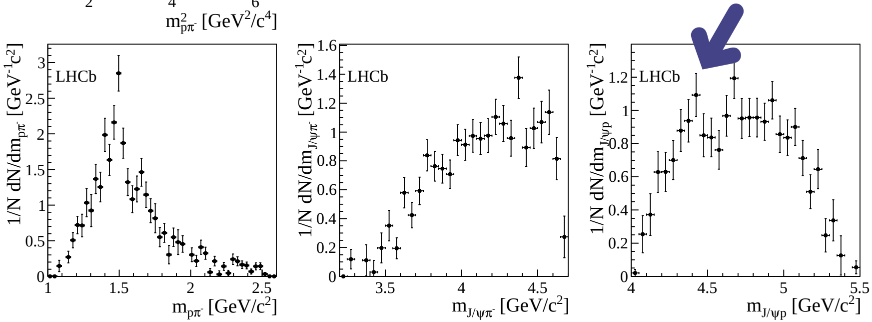
  - ✔ Consistent with CKM and phase-space, and with $\Lambda_b^0 \to \Lambda_c^+ D^-$ to $\Lambda_b^0 \to \Lambda_c^+ D_s^+$ [Phys. Rev. Lett. 112, 202001 (2014), arXiv:1403.3606]

[LHCb, JHEP 07 (2014) 103, arXiv:1406.0755]

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



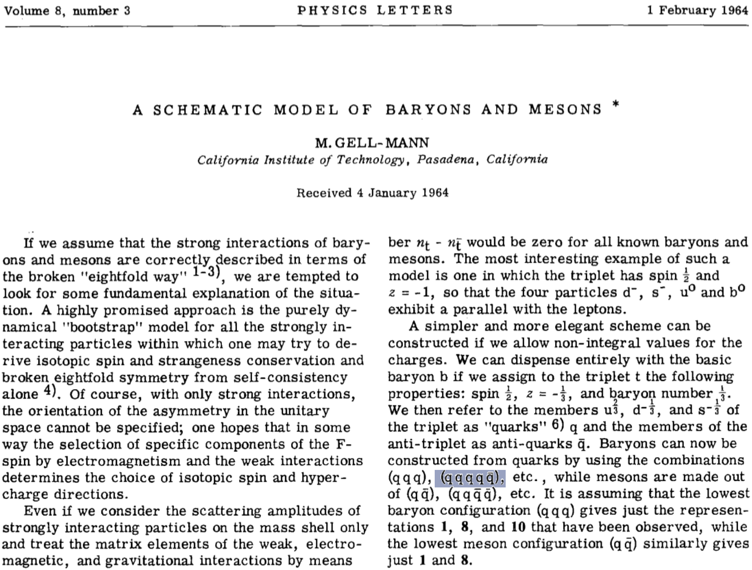
- Rich resonant structure in $p\pi$ spectrum.
  - ✗ No obvious exotics.
  - Well, now we know where the $P_c(4380)^+$ and $P_c(4450)^+$ are [LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]



The P_c^+ exotic baryon

[Phys.Lett. 8 (1964) 214-215]

GELL-MANN



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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California Institute of Technology, Pasadena, California

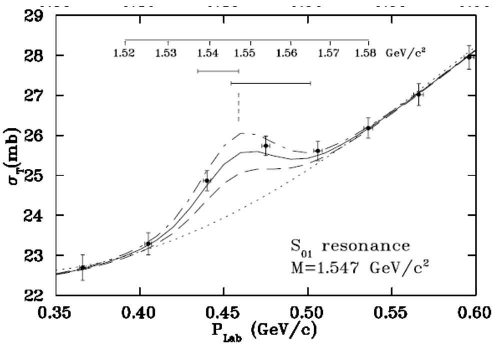
Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" $^{1-3)}$, we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone $^{4)}$. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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 the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

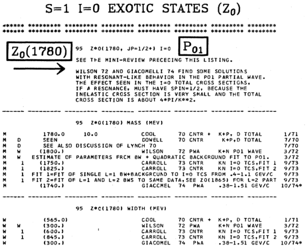
FIRST PENTAQUARK CLAIMS (1970–90)



KN cross-section data from 1970 [Bowen et al., Phys.Rev. D2 (1970) 2599] re-analysed in 2003

[Gibbs, Phys.Rev.C70 045208 (2004)]

PDG1974



S=1 I=0 EXOTIC STATES (Z_0)

$Z_0(1780)$ P_{01}

```
****** ********* ********* ********* ********* ********* ********* ********
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            95  Z*0(1780, JP=1/2+) I=0
            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*
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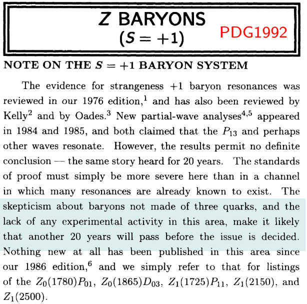


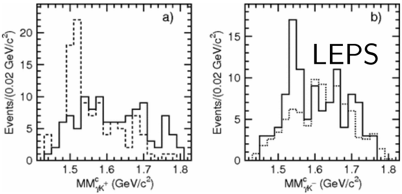
Z BARYONS
($S = +1$)

PDG1992

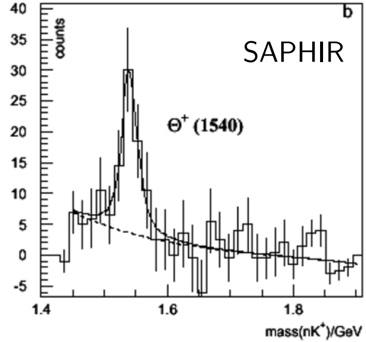
NOTE ON THE $S = +1$ BARYON SYSTEM

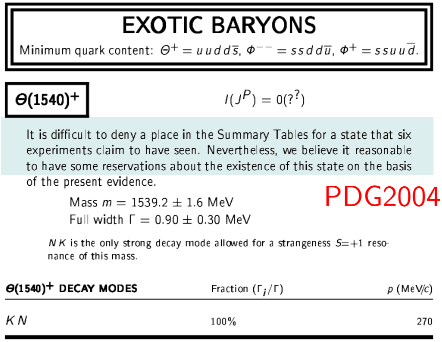
The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite 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 skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

THE $\Theta(1540)^+$ PENTAQUARK



In 2003 a $uudd\bar{s}$ was allegedly found in data from LEPS [Nakano et al.,Phys. Rev. Lett. 91, 012002], DIANA [Phys.Atom.Nucl.66:1715 (2003)], CLAS [Phys.Rev.Lett.91:252001 (2003)], SAPHIR [Phys.Lett.B572:127 (2003)].





EXOTIC BARYONS

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

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

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.

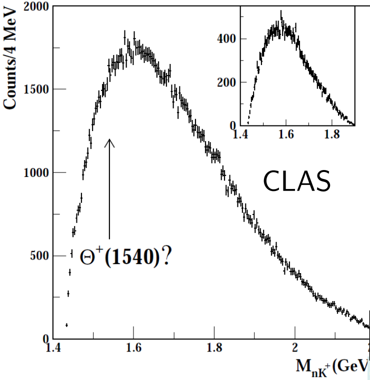
Mass $m = 1539.2 \pm 1.6$ MeV
Full width $\Gamma = 0.90 \pm 0.30$ MeV

PDG2004

$N K$ 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)
$K N$	100%	270

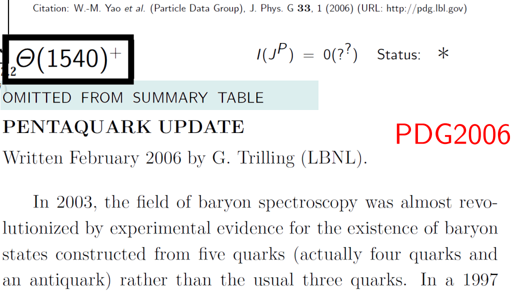
THE $\Theta(1540)^+$ PENTAQUARK



In 2003 a $uudd\bar{s}$ was allegedly found

In 2006 CLAS reported from a large-yield dedicated run and failed to find the particle [Phys.Rev.Lett.96:042001 (2006)]

Read *On the conundrum of the pentaquark* by Hicks [EPJH 37 1 (2012)]



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: ∗

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006 by G. Trilling (LBNL).

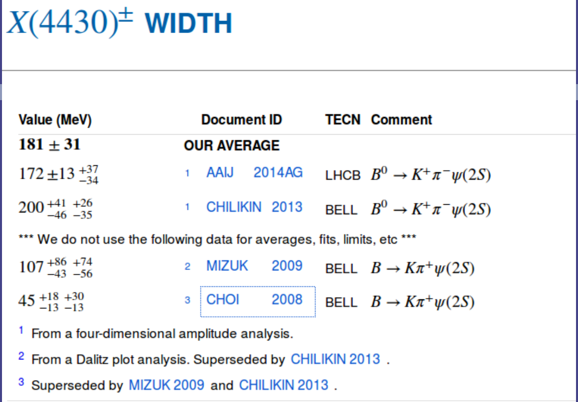
In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997

PDG2006

LESSONS

1. Pentaquark is a loaded word with a long history
2. Bumps can come and go (also at 750 GeV/c^2)
3. Pentaquarks have done so twice already

LESSONS



$X(4430)^{\pm}$ WIDTH

Value (MeV)	Document ID	TECN	Comment
181 ± 31	**OUR AVERAGE**		
$172 \pm 13\,^{+37}_{-34}$	[1] AAIJ 2014AG	LHCB	$B^0 \to K^+\pi^-\psi(2S)$
$200\,^{+41}_{-46}\,^{+26}_{-35}$	[1] CHILIKIN 2013	BELL	$B^0 \to K^+\pi^-\psi(2S)$
*** We do not use the following data for averages, fits, limits, etc ***			
$107\,^{+86}_{-43}\,^{+74}_{-56}$	[2] MIZUK 2009	BELL	$B \to K\pi^+\psi(2S)$
$45\,^{+18}_{-13}\,^{+30}_{-13}$	[3] CHOI 2008	BELL	$B \to K\pi^+\psi(2S)$

[1] From a four-dimensional amplitude analysis.

[2] From a Dalitz plot analysis. Superseded by CHILIKIN 2013 .

[3] Superseded by MIZUK 2009 and CHILIKIN 2013 .

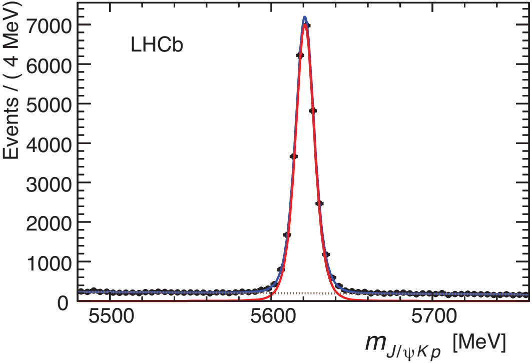
1. Pentaquark is a loaded word with a long history
2. Bumps can come and go (also at 750 GeV/c^2)
3. Pentaquarks have done so twice already
4. Breit-Wigner fits will (likely) return the wrong width

THE DECAY $\Lambda_b^0 \to J/\psi\, pK^-$

We knew there was something strange in $\Lambda_b^0 \to J/\psi\, pK^-$ [JHEP 07 (2014) 103] [PLB 734 (2014) 122] [PRL 111 (2013) 102003]

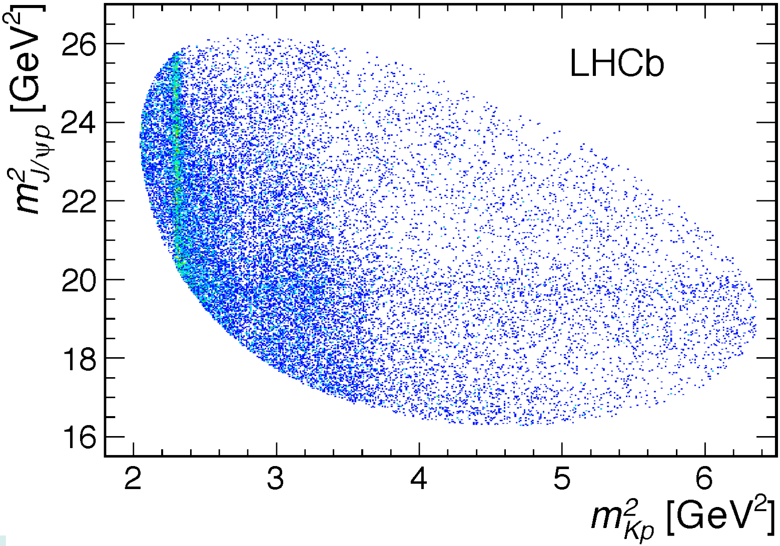
➜ Revisit this channel with a clean selection: 26000 ± 170 decays

- Reflections from B^0 and B_s^0 vetoed
- Re-optimised boosted decision tree trained on simulated signal and data background.



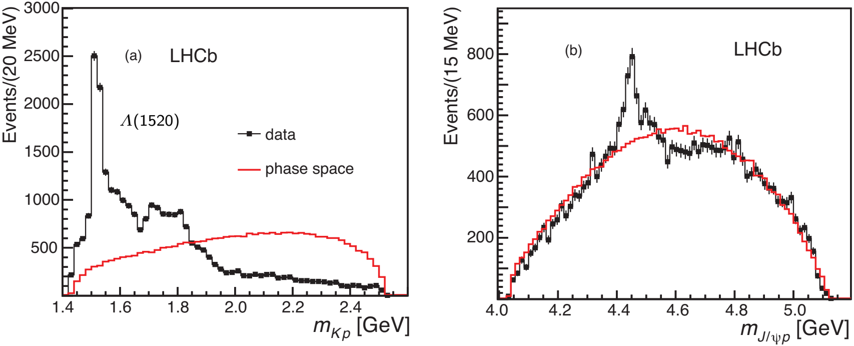
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

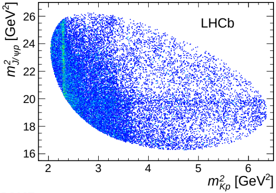
THE DECAY $\Lambda_b^0 \to J/\psi\, pK^-$



[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

The Decay $\Lambda_b^0 \to J/\psi\, pK^-$

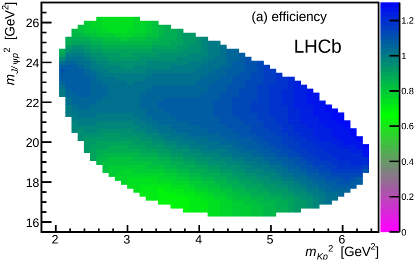


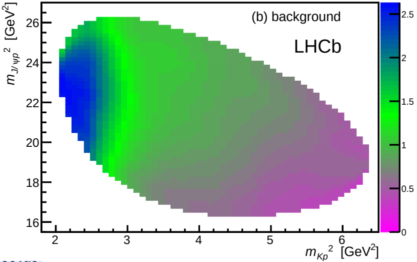


Clear difference with respect to phase-space (uniform in Dalitz plane)

- In m_{K^-p} it is due to excited Λ resonances
- In $m_{J/\psi\, p}$ it is very puzzling

CAN IT BE ARTEFACTS?





EFFICIENCIES? Can it be sculpted by efficiencies?

- Efficiencies vary smoothly by a factor two over Dalitz
- Modelled using phase-space Simulation. Our detector response is well validated in many similar analyses.

BACKGROUND? We look in the sidebands and find nothing peaking.

- Peaking B^0 and B_s^0 are vetoed.
- Reconstruction artefacts are investigated.

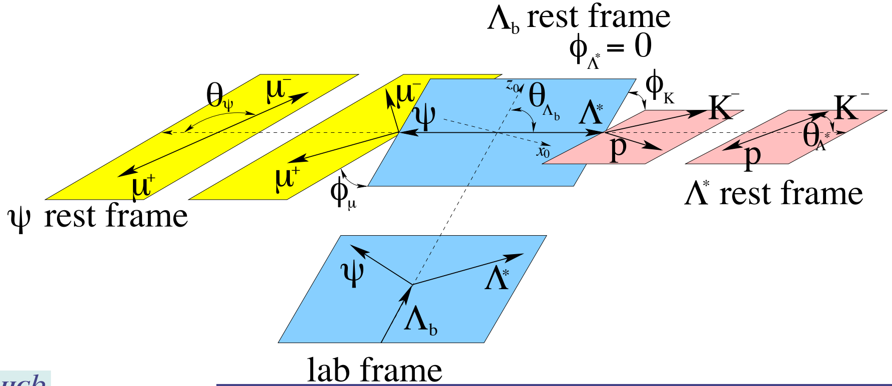
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

$\Lambda_b^0 \to J/\psi\, pK^-$ Amp. Analysis with Λ^*

If it is not an artefact, it must be physics.

- ➜ Can it be a conspiracy of interfering Λ resonances? See also [PRL 117 (2016) 082002].

Perform 6D amplitude analysis in $\theta_{\Lambda_b^0}$, θ_{Λ^*}, θ_ψ, ϕ_K, ϕ_μ, and m_{Kp}.

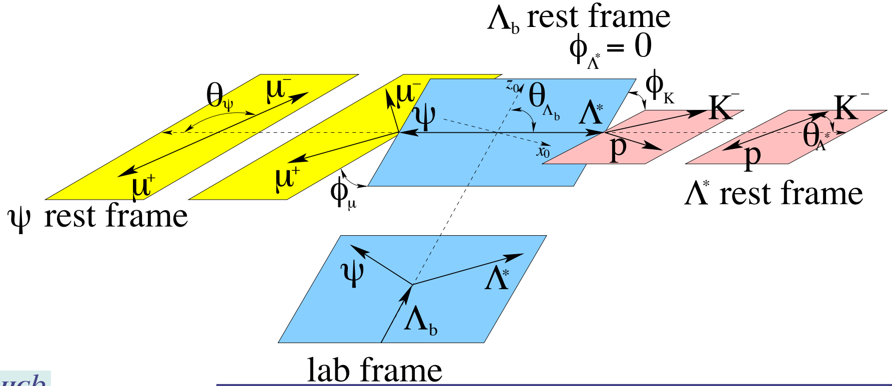


[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

$\Lambda_b^0 \to J/\psi\, pK^-$ Amp. Analysis with Λ^*

Matrix Elements with only Λ^* resonances:

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b^0},\,\lambda_p,\,\Delta\lambda_\mu} \equiv \sum_n \sum_{\lambda_{\Lambda^*}} \sum_{\lambda_\psi} \mathcal{H}^{\Lambda_b^0\to\Lambda_n^*\psi}_{\lambda_{\Lambda^*},\,\lambda_\psi} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\,\lambda_{\Lambda^*}-\lambda_\psi}(0,\theta_{\Lambda_b^0},0)^* \\ \mathcal{H}^{\Lambda_n^*\to Kp}_{\lambda_p,\,0} D^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*},\,\lambda_p}(\phi_K,\theta_{\Lambda^*},0)^* R_{\Lambda_n^*}(m_{Kp})\; D^{1}_{\lambda_\psi,\,\Delta\lambda_\mu}(\phi_\mu,\theta_\psi,0)^*,$$



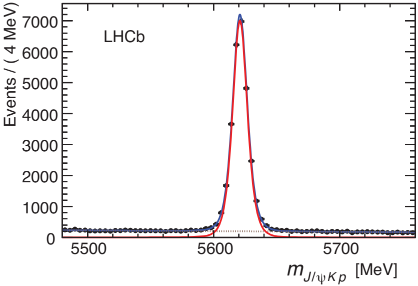
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

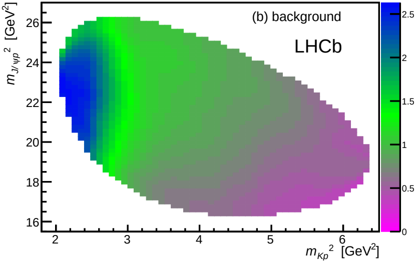
$\Lambda_b^0 \to J/\psi\, pK^-$ Amp. Analysis with Λ^*

Two different implementations of the fitter, done by two groups on two continents. They differ by the background treatment

- cFit: Sideband data are used to construct 6D model of background shape.
- sFit: Background is statistically subtracted using *sPlot* weights from mass fit [Le Diberder, Pivk, NIM A 555 356 (2005)].

It is common practice in LHCb to have these two approaches.





[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

$\Lambda_b^0 \to J/\psi\, pK^-$ Amp. Analysis with Λ^*

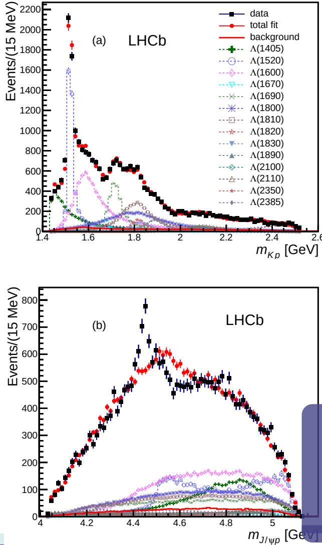
State	J^P	M_0 (MeV)	Γ_0 (MeV)	Red.	Ext.
Λ(1405)	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
Λ(1520)	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
Λ(1600)	$1/2^+$	1600	150	3	4
Λ(1670)	$1/2^-$	1670	35	3	4
Λ(1690)	$3/2^-$	1690	60	5	6
Λ(1800)	$1/2^-$	1800	300	4	4
Λ(1810)	$1/2^+$	1810	150	3	4
Λ(1820)	$5/2^+$	1820	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		6
Λ(2585)	?	≈2585	200		6
				64	146

Last columns show number of parameters are left free. Masses and Width are fixed.
Red.: Reduced model (fast). Ext.: Allows for more helicity (*LS*) couplings.

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

$\Lambda_b^0 \to J/\psi\, pK^-$ Amp. Analysis with Λ^*

Extended Model — ■ data — ● fit



All known Λ^* resonances get the pK$^-$ mass right, but not the J/ψ p mass.

- We use the extended model in this fit
    - ➜ Adding more Λ resonances does not help [PRL 117 (2016) 082002]
- Letting the width and masses float does not help
- Adding $\Delta I = \frac{1}{2}$-suppressed Σ^{*0} ($I = \frac{3}{2}$) resonances does also not help

When you have eliminated the impossible, whatever remains, however improbable, must be the truth

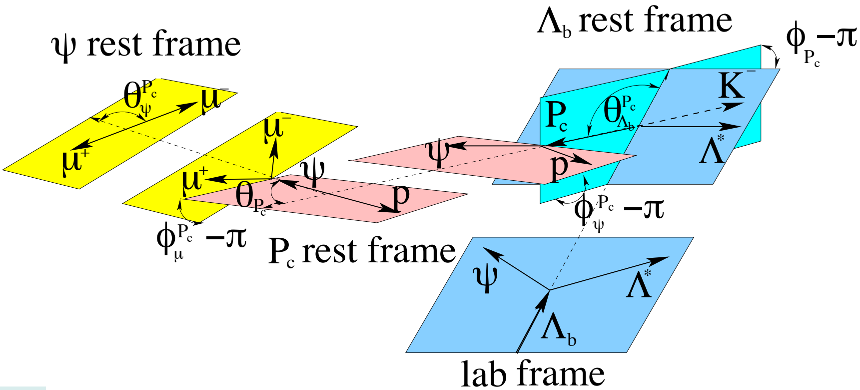
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

ADDING A PENTAQUARK

Matrix Elements with a Pentaquark:

$$\mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu^{P_c}} \equiv \sum_j \sum_{\lambda_{P_c}} \sum_{\lambda_\psi^{P_c}} \mathcal{H}^{\Lambda_b^0\to P_{cj}K}_{\lambda_{P_c},0} D^{\frac{1}{2}}_{\lambda_{\Lambda_b^0},\lambda_{P_c}}(\phi_{P_c},\theta^{P_c}_{\Lambda_b^0},0)^*$$

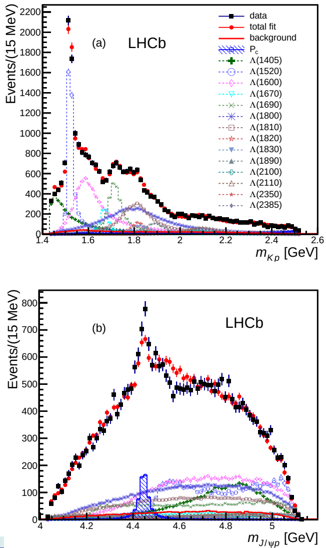
$$\mathcal{H}^{P_{cj}\to\psi p}_{\lambda_\psi^{P_c},\lambda_p^{P_c}} D^{J_{P_{cj}}}_{\lambda_{P_c},\lambda_\psi^{P_c}-\lambda_p^{P_c}}(\phi_\psi,\theta_{P_c},0)^* R_{P_{cj}}(m_{\psi p})\ \ D^{1}_{\lambda_\psi^{P_c},\Delta\lambda_\mu^{P_c}}(\phi_\mu^{P_c},\theta_\psi^{P_c},0)^*,$$



[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

Adding a Pentaquark

Reduced Model — ■ data — ● fit

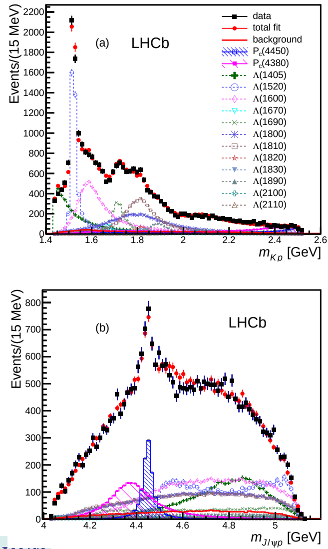


- There is an obvious peak at $m_{J/\psi\, p} = 4.45\ \mathrm{GeV}/c^2$: Add one P_c^+ state with free J^P.
  - ✗ Unsatisfactory fit. $J^P = \frac{5}{2}^+$.

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

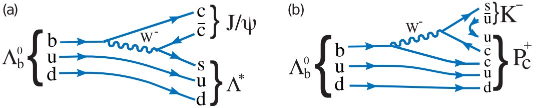
ADDING TWO PENTAQUARKS

Reduced Model — ■ data — ● fit



- There is an obvious peak at $m_{J/\psi\, p} = 4.45\ \mathrm{GeV}/c^2$: Add one P_c^+ state with free J^P.
  - ✗ Unsatisfactory fit. $J^P = \frac{5}{2}^+$.
- Add another P_c^+
  - ✓ Good fit

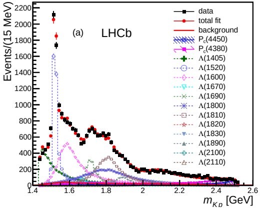
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

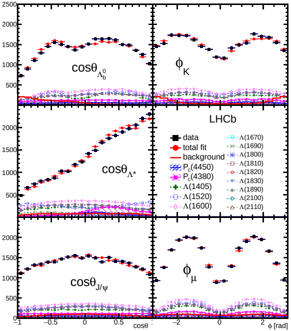


[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

ADDING TWO PENTAQUARKS

Reduced Model — ■ data — ● fit





- There is an obvious peak at $m_{J/\psi\, p} = 4.45\ \mathrm{GeV}/c^2$: Add one P_c^+ state with free J^P.
    - ✗ Unsatisfactory fit. $J^P = \frac{5}{2}^+$.
- Add another P_c^+
    - ✔ Good fit

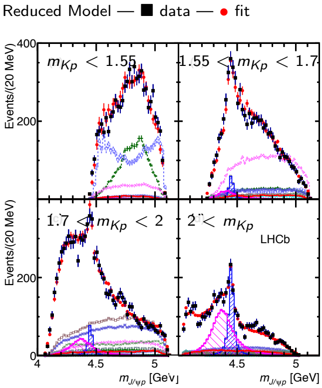
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ

✔ The angular distributions are well reproduced

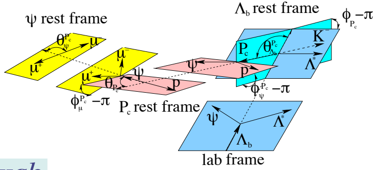
- Also OK: $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$
    - ➜ In any case opposite parities
- **Mininal quark content: $c\bar{c}uud$**

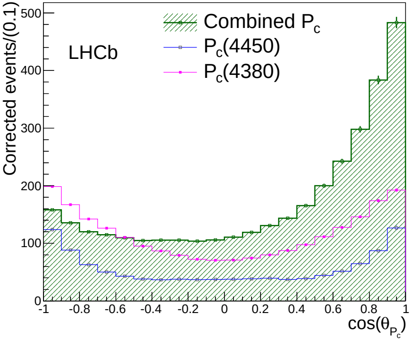
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

Opposite Parities



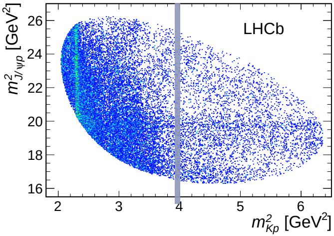
- The interference pattern confirms the opposite parities:
  - At $\cos\theta_{P_c^+} \sim -1$, low m_{Kp}: negative interference.
  - At $\cos\theta_{P_c^+} \sim +1$, high m_{Kp}: positive interference.





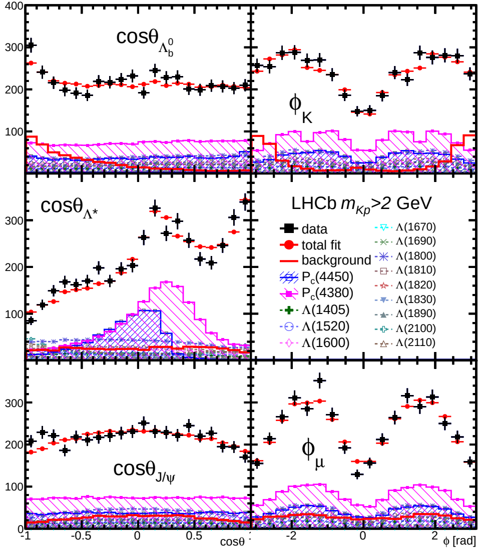
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

Better View



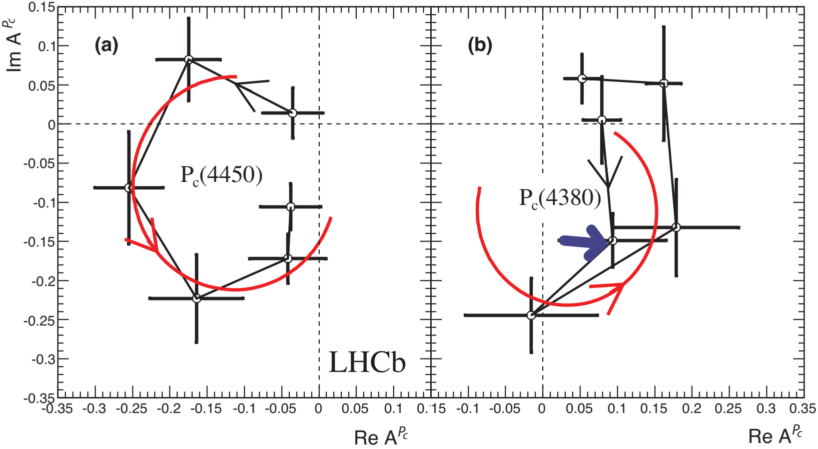
- Cutting at $m_{Kp} > 2\ \mathrm{GeV}/c^2$ enhances P_c^+ fraction

→ Should be visible in other LHC experiments



[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

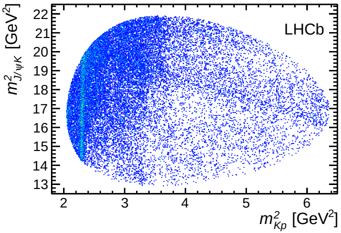
ARE THEY RESONANCES?



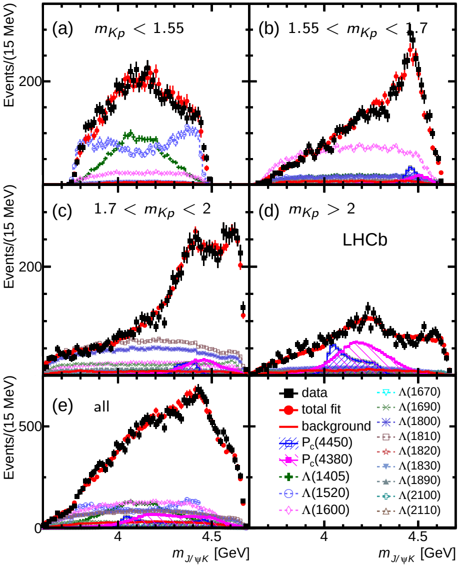
The Argand diagram shows the typical phase motion of a resonance for the $P_c(4450)^+$. For the $P_c(4380)^+$, one point is off by 2σ.

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

NEED FOR $J/\psi\,K$ RESONANCES?



- There's no need to add $J/\psi\,K^+$ tetraquarks



[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

SYSTEMATIC UNCERTAINTIES

Source	M_0 (MeV)		Γ_0 (MeV)		Fit fractions (%)			
	low	high	low	high	low	high	$\Lambda(1405)$	$\Lambda(1520)$
Extended vs. reduced	**21**	0.2	**54**	**10**	**3.14**	0.32	1.37	0.15
Λ^* masses & widths	7	0.7	20	4	0.58	0.37	2.49	**2.45**
Proton ID	2	0.3	1	2	0.27	0.14	0.20	0.05
$10 < p_p < 100$ GeV	0	**1.2**	1	1	0.09	0.03	0.31	0.01
Non-resonant	3	0.3	34	2	2.35	0.13	**3.28**	0.39
Separate sidebands	0	0	5	0	0.24	0.14	0.02	0.03
J^P $(3/2^+, 5/2^-)$ or $(5/2^+, 3/2^-)$	10	**1.2**	34	**10**	0.76	0.44		
$d = 1.5 - 4.5$ GeV^{-1}	9	0.6	19	3	0.29	0.42	0.36	1.91
$L^{P_c}_{\Lambda_b^0}$ $\Lambda_b^0 \to P_c^+$ (low/high)K^-	6	0.7	4	8	0.37	0.16		
L_{P_c} P_c^+ (low/high) $\to J/\psi\, p$	4	0.4	31	7	0.63	0.37		
$L^{\Lambda_n^*}_{\Lambda_b^0}$ $\Lambda_b^0 \to J/\psi\, \Lambda^*$	11	0.3	20	2	0.81	**0.53**	3.34	2.31
Efficiencies	1	0.4	4	0	0.13	0.02	0.26	0.23
Change $\Lambda(1405)$ coupling	0	0	0	0	0	0	1.90	0
Overall	29	2.5	86	19	4.21	1.05	5.82	3.89
sFit/cFit cross check	5	1.0	11	3	0.46	0.01	0.45	0.13

Uncertainties added in quadrature. "low": $P_c(4380)^+$, "high": $P_c(4450)^+$

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

RESULTS

State	J^P	Mass $[\mathrm{MeV}/c^2]$	Width $[\mathrm{MeV}]$	Fit Fraction [%]
$P_c(4380)^+$	$\frac{3}{2}^-$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$\frac{5}{2}^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$				$15 \pm 1 \pm 6$
$\Lambda(1520)$				$19 \pm 1 \pm 4$

These fit fractions are converted into branching fractions

[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

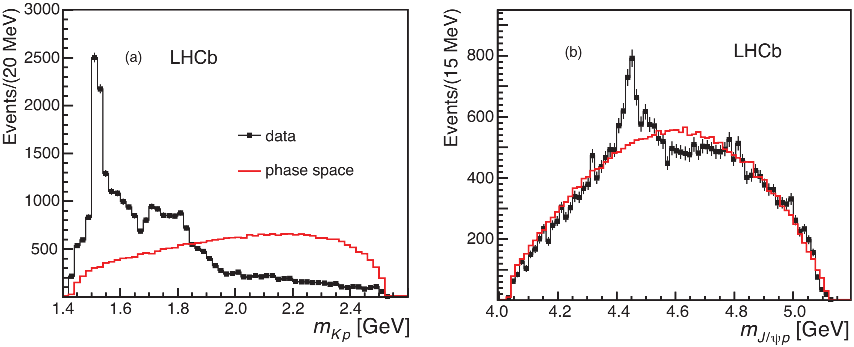
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-) \times \mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\, {}^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-) \times \mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\, {}^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

	$\Delta(-2\ln\mathcal{L})$	Significance
$0 \to 1P_c^+$	14.7^2	12σ
$1 \to 2P_c^+$	11.6^2	9σ
$0 \to 2P_c^+$	18.7^2	15σ

The significances are determined using the extended model.

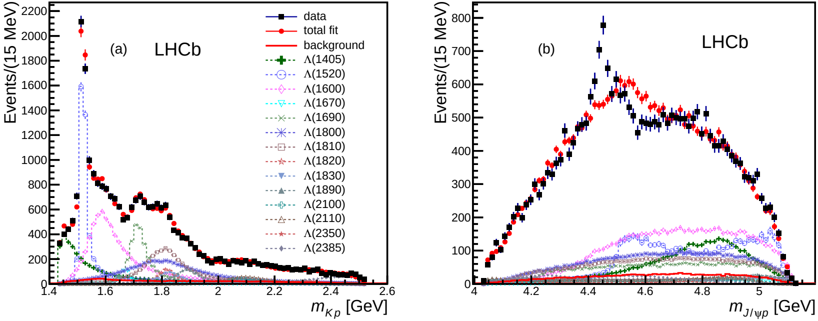
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

MASS PLOTS



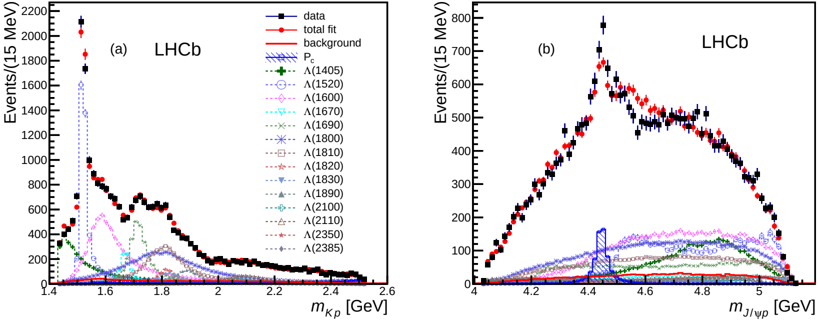
Data with phase space simulation.

MASS PLOTS



Extended Λ^* model with no P_c^+. The error bars on the points showing the fit results are due to simulation statistics.

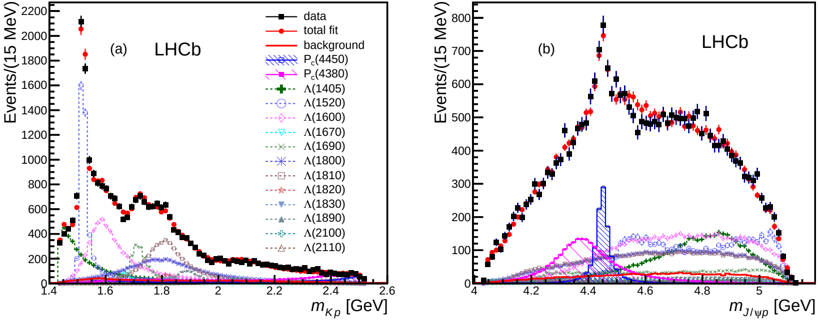
MASS PLOTS



Reduced fit with one P_c^+ added ($J^P = 5/2^+$). The error bars on the points showing the fit results are due to simulation statistics.

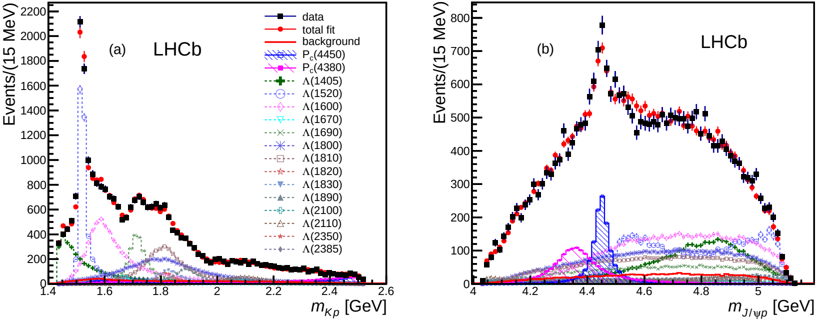
[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

MASS PLOTS

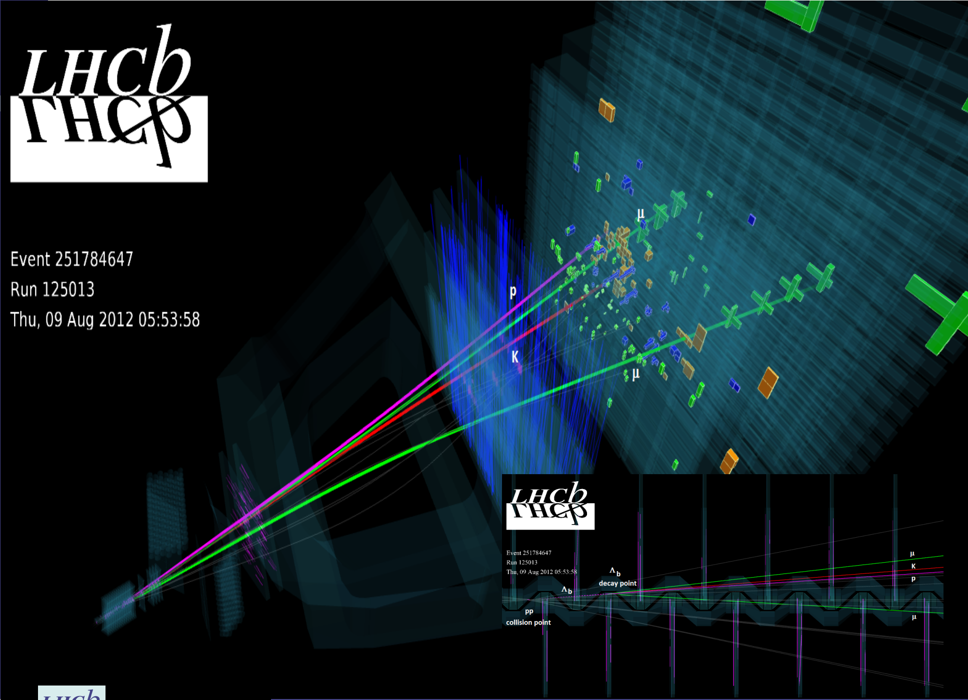


Reduced fit with two P_c^+ added. The error bars on the points showing the fit results are due to simulation statistics.

MASS PLOTS



Extended Λ^* model with two P_c^+ added. The error bars on the points showing the fit results are due to simulation statistics.


LHCb
Event 251784647
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Thu, 09 Aug 2012 05:53:58
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LHCb
Event 251784647
Run 125013
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Λ_b
decay point
Λ_b
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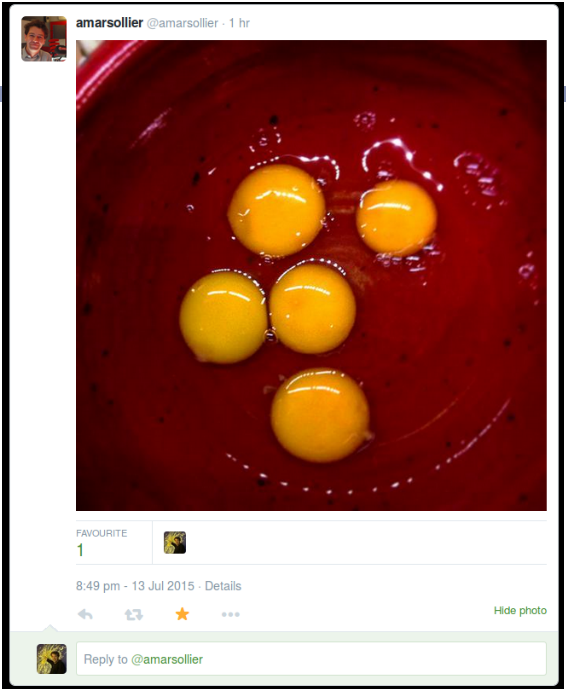
collision point
μ
K
p
μ

#PENTAQUARK

The #pentaquark tag is trending on twitter since @LHCbPhysics announced the paper.

The CERN press team sent out a teaser the night before.

CERN issued a press release (same day as Pluto fly-by)



amarsollier @amarsollier · 1 hr

FAVOURITE
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8:49 pm - 13 Jul 2015 · Details

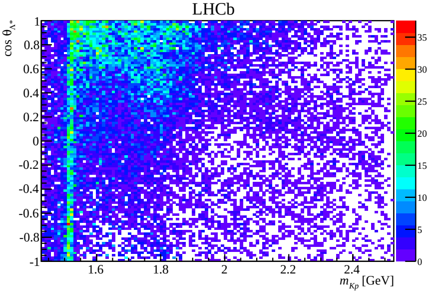
Hide photo

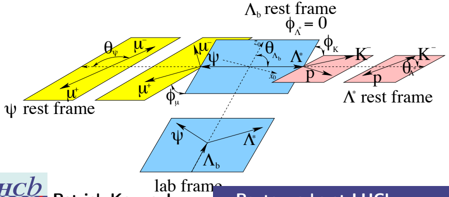
Reply to @amarsollier

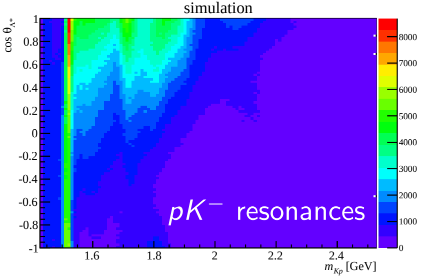
[LHCb, Phys. Rev. Lett. 117 (2016) 082002, arXiv:1604.05708]

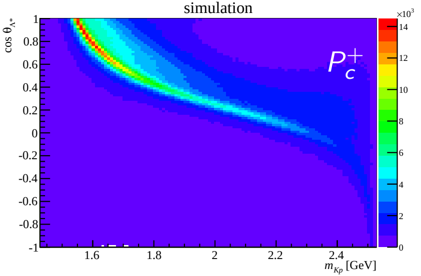
MODEL-INDEPENDENT $\Lambda_b^0 \to J/\psi\, pK^-$

Can the data be fully described by a sum of pK^- resonances?







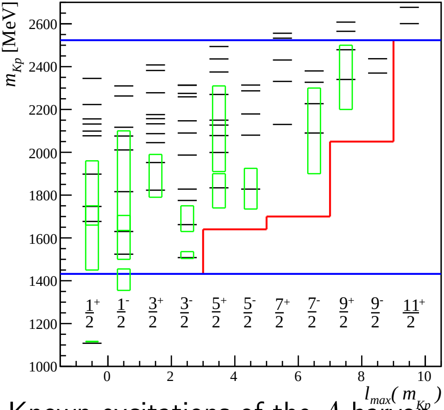


[LHCb, Phys. Rev. Lett. 117 (2016) 082002, arXiv:1604.05708]

MODEL-INDEPENDENT $\Lambda_b^0 \to J/\psi\, pK^-$

Model-independent re-analysis:

- ✔ Do not assume Λ and Δ resonances from PDG
- An infinite sum of resonances of any (large) spin can emulate any shape
- ➜ Allow maximum spin depending on pK^- mass
  - Following [BaBar PRD79 (2009) 112001, arXiv:0811.0564] and LHCb [PRD 92 (2015) 112009]
- Describe $\cos\theta_{\Lambda^*}$ with Legendre polynomials
- Test H_0 hypothesis: only pK^- resonances



Known excitations of the Λ baryon. The horizontal lines show the allowed kinematic range.

[LHCb, Phys. Rev. Lett. 117 (2016) 082002, arXiv:1604.05708]

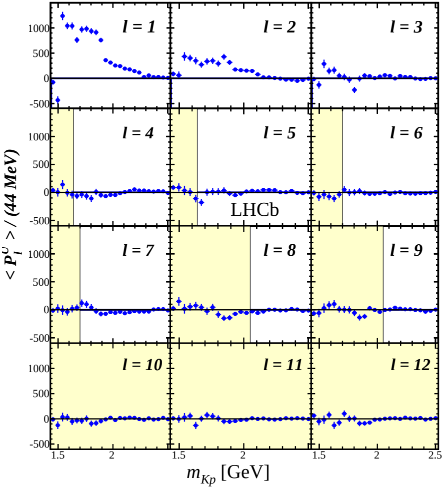
MODEL-INDEPENDENT $\Lambda_b^0 \to J/\psi\, pK^-$

Describing $\cos\theta_{\Lambda^*}$ with Legendre polynomials

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

$$\left\langle P_l^U \right\rangle = \int_{-1}^{+1} d\cos\theta_{\Lambda^*}\, P_l(\cos\theta_{\Lambda^*}) \frac{dN}{d\cos\theta_{\Lambda^*}}$$

- pK^- resonances can add moments of rank up to $2J_{\max}$
- Narrow other resonances would add moments of higher rank

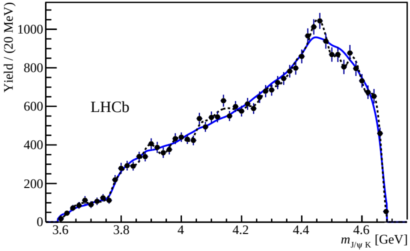


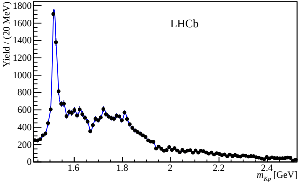
Legendre moments of $\cos\theta_{\Lambda^*}$

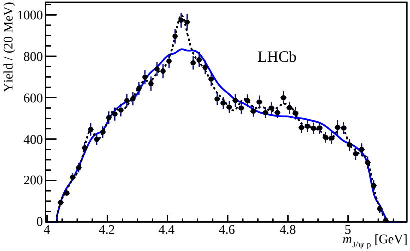
MODEL-INDEPENDENT $\Lambda_b^0 \to J/\psi\, pK^-$

- ✔ m_{pK^-} is described correctly
- ✗ $m_{J/\psi\, p}$ is not
  - ➜ A contribution is missing around 4.5 GeV/c^2
    - $> 9\sigma$ deviation
- ✗ $m_{J/\psi\, K^-}$ is also not described
  - Unclear if due to reflection of P_c^+ or also tetraquarks

The data cannot be described by pK⁻ resonances alone



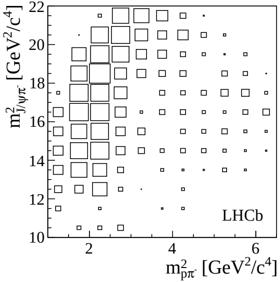




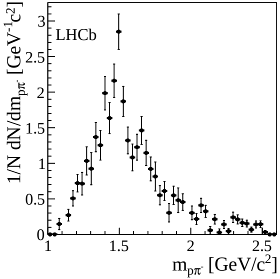
[LHCb, JHEP 07 (2014) 103, arXiv:1406.0755]

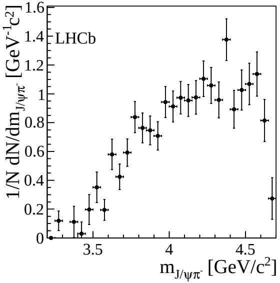
Reminder

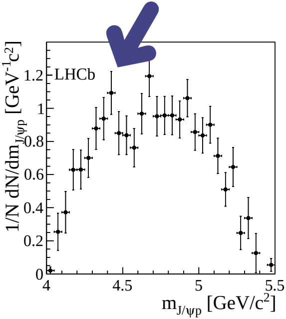
OBSERVATION OF $\Lambda_b^0 \to J/\psi\, p\pi^-$



- Rich resonant structure in $p\pi$ spectrum.
  - ✗ No obvious exotics.
  - Well, now we know where the $P_c(4380)^+$ and $P_c(4450)^+$ are [LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]







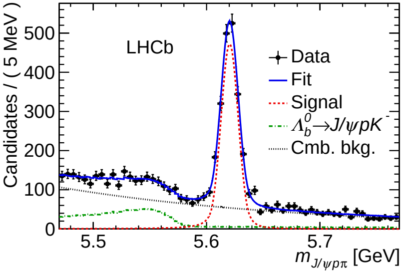
[LHCb, Phys. Rev. Lett. 117 (2016) 082003, arXiv:1606.06999]

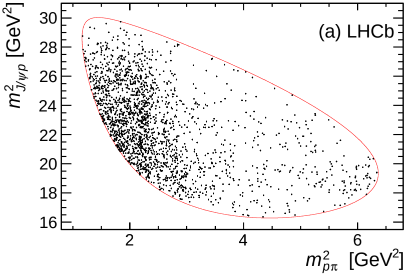
EXOTICS IN $\Lambda_b^0 \to J/\psi\, p\pi^-$

$\Lambda_b^0 \to J/\psi\, p\pi^-$ re-analysed after 2014 observation [JHEP 07 (2014) 103] with full angular fit, as in [PRL 115 (2015) 072001].

Need to describe all N resonances (Δ negligible)

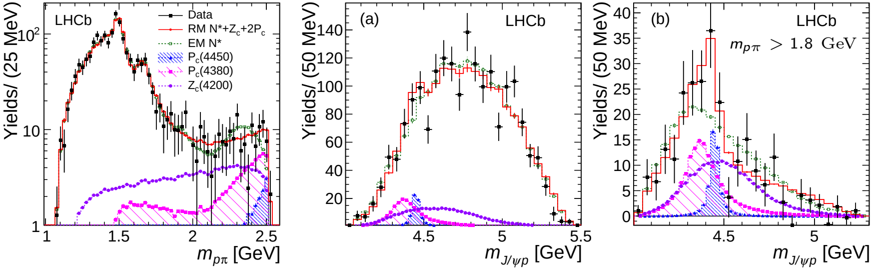
State	J^P	Mass (MeV)	Width (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	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





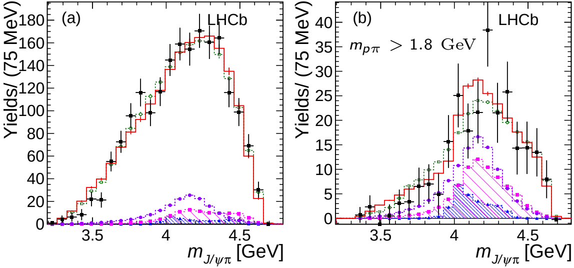
[LHCb, Phys. Rev. Lett. 117 (2016) 082003, arXiv:1606.06999]

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



Two fits:

- Only N states
- Add P_c^+ and $Z_c(4200)^- \to J/\psi\,\pi^-$



[LHCb, Phys. Rev. Lett. 117 (2016) 082003, arXiv:1606.06999]

EXOTICS IN $\Lambda_b^0 \rightarrow J/\psi\, p\pi^-$

The fit fractions are

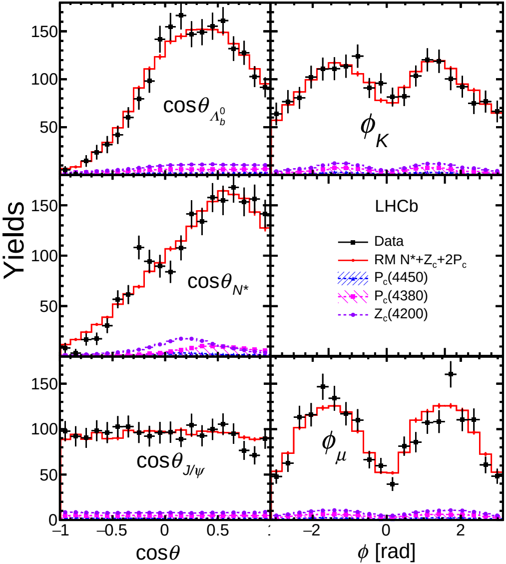
$$P_c(4380) : 5.1 \pm 1.5\, {}^{+2.1}_{-1.6}\ \%$$

$$P_c(4450) : 1.6\, {}^{+0.8}_{-0.6}\, {}^{+0.6}_{-0.5}\ \%$$

$$Z_c(4200) : 7.7 \pm 2.8\, {}^{+3.4}_{-4.0}\ \%$$

There is a 3.3σ significance for the presence of exotic states. The fit does not allow to say which.

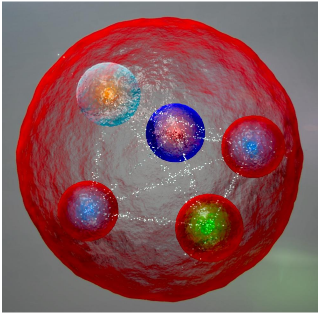
No P_c^+ would require $(17.2 \pm 3.5)\%$ $Z_c(4200)$, which is much more than in $B^0 \rightarrow J/\psi\, K^+\pi^-$ [Belle, PRD 90 (2014) 112009]

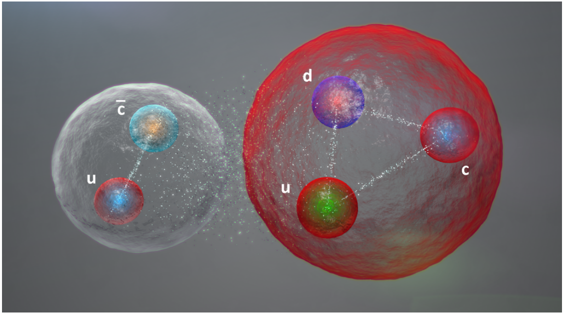


What's a pentaquark?

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

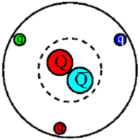
WHAT IS A PENTAQUARK?



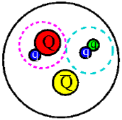


“plain”

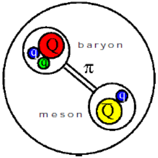
hydro-charmonium



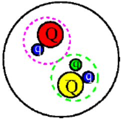
diquarks



molecular



triquark



>200 papers citing the result, with many possible interpretations.

[T. J. Burns, arXiv:1509.02460]

PHENOMENOLOGY OF $P_c(4380)^+$, $P_c(4550)^+$

	$P_c(4450)^+$				$P_c(4380)^+$	
	$\chi_{c1}p$	$\Sigma_c\bar{D}^*$	$\Lambda_c^*\bar{D}$	$J/\psi N^*$	$\Sigma_c^*\bar{D}$	$J/\psi N^*$
$\mathbf{J/\psi N}$	✓	✓	✓	✓	✓	✓
$\eta_c N$	×	×	✓	×	×	×
$J/\psi\Delta$	×	✓	×	×	✓	×
$\eta_c\Delta$	×	✓	×	×	✓	×
$\Lambda_c\bar{D}$	✓	[×]	[✓]	×	[×]	×
$\Lambda_c\bar{D}^*$	✓	✓	[✓]	✓	✓	✓
$\Sigma_c\bar{D}$	✓	[×]	✓	×	[×]	×
$\Sigma_c^*\bar{D}$	✓	✓	[×]	✓		
$J/\psi N\pi$	×	✓	×	✓	✓	✓
$\Lambda_c\bar{D}\pi$	×	×	×	×	✓	×
$\Lambda_c\bar{D}^*\pi$	×	✓	×	×		
$\Sigma_c^+\bar{D}^0\pi^0$	×	✓	✓	×		

OTHER P_c^+ CHANNELS

✔ $\Lambda_b^0 \to J/\psi\, p\pi^-$: Cabibbo-suppressed [PRL 117 (2016) 082003].

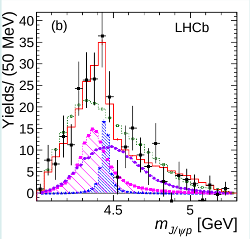
HADRONIC: $\Lambda_b^0 \to \Lambda_c^+ D^0 K^-$ is hard as we need to reconstruct both charmed hadrons

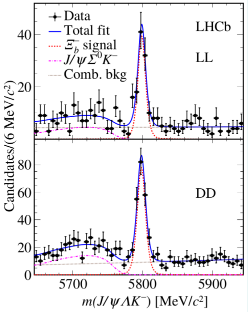
Ξ_b? The P_c^+ could also show up in Ξ_b decays [LHCb-PAPER-2016-053]

DIRECT PRODUCTION: Background is high at low p_T. Maybe our friends around the ring can do it at high p_T?

ISOSPIN PARTNERS: There may be other similar particles with different light quark content, or open strangeness.

$s\bar{s}$ PARTNER: And what about $P_s^+ \to \phi p$? [Lebed, arXiv:1510.06648] or a pD_s^+ resonance [Karliner, Lipkin, PLB 575 249 (2003)]





Still Time?

Yes

Just a bit

No

[D0, arXiv:1602.07588]

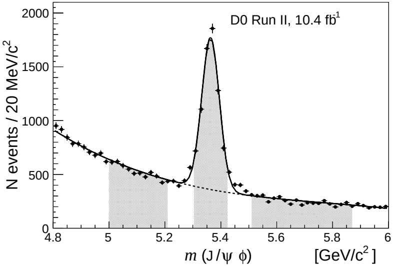
EVIDENCE FOR A NEW $B_s^0\pi^\pm$ STATE

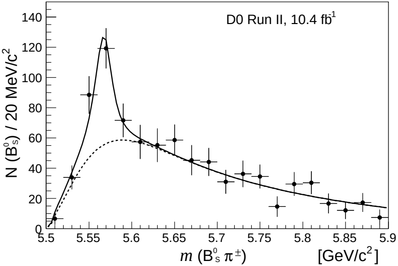
D0 see a peak in the $B_s^0\pi^+$ mass distribution, in 10.4 fb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV

- Use $B_s^0 \to J/\psi\,\phi$ ➜ cannot distinguish B_s^0 and $\overline{B}_s^0$
- $m = 5567 \pm 2.9\,^{+0.9}_{-1.9}\,\text{MeV}/c^2$ and $\Gamma = 21.9 \pm 6.4\,^{+5.0}_{-2.5}\,\text{MeV}$

✔ Checked reflections from kaons and pions

- $(8.6 \pm 1.9 \pm 1.4)\%$ B_s^0 come from that state ➜ Huge!
- The minimum quark content is $\overline{b}s\overline{d}u$ or $b\overline{s}\overline{d}u$, a 4-flavour tetraquark

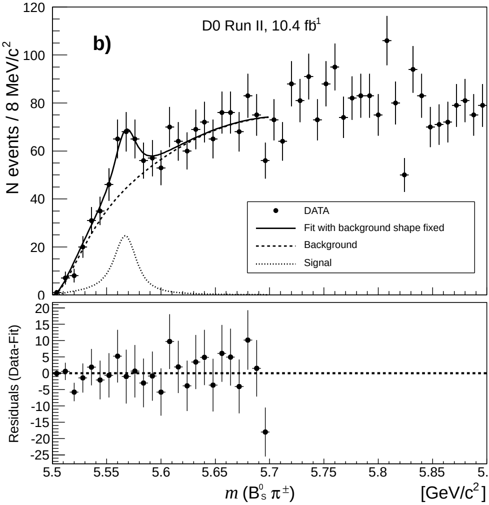




EVIDENCE FOR A NEW $B_s^0\pi^\pm$ STATE

Small peak-like structure in data

Local significance 4.8σ, global 3.9σ.



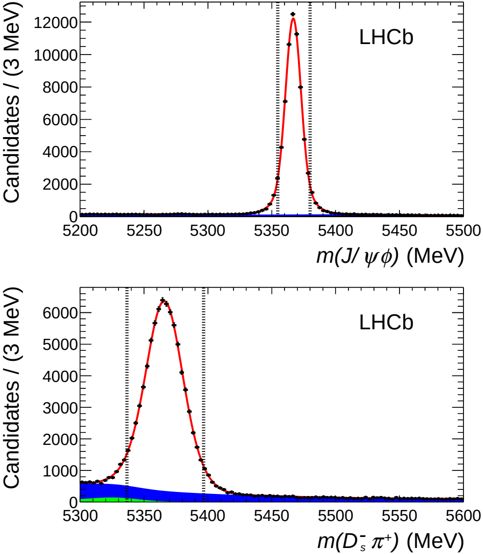
Without cone cut

[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$

LHCb looked using 46 000 $B_s^0 \to J/\psi\,\phi$ and 66 000 $B_s^0 \to D_s^-\pi^+$ decays in 3 fb^{-1} at 7–8 TeV

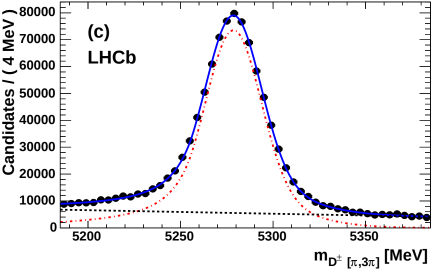
- ✔ 20 times more than D0
- ✔ $D_s^-\pi^+$ is flavour-specific, so we could investigate the quark content of the $X(5568)$

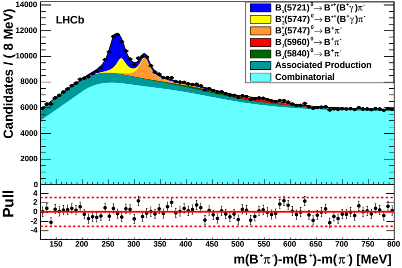


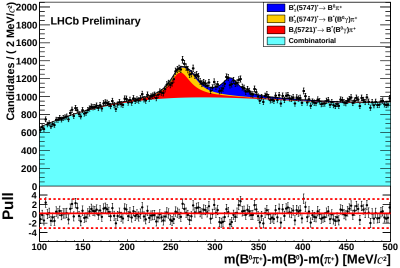
[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$

✔ Check with $B^0 \to D^-\pi^+$ that we get the $B_s^0\pi^+$ structures right. [LHCb-CONF-2016-004] [JHEP 04 (2015) 024] (p_T range is different)







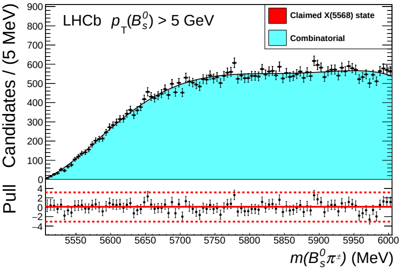
[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

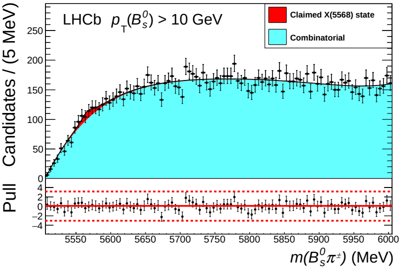
SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$

Use 112 000 B_s^0 mesons and combine with $\pi^\pm$

- ✔ 20 times more B_s^0 than D0
  - Loose PID cuts on $\pi^\pm$
  - Take all combinations
  - Not too big PV (90% efficient)
- ✗ No signal seen

		$B_s^0 \to D_s^- \pi^+$	$B_s^0 \to J/\psi\,\phi$	Sum
$N(B_s^0)/10^3$	$p_\mathrm{T}(B_s^0) > 5\,\mathrm{GeV}$	62.2 ± 0.3	43.6 ± 0.2	105.8 ± 0.4
	$p_\mathrm{T}(B_s^0) > 10\,\mathrm{GeV}$	28.4 ± 0.2	13.2 ± 0.1	41.6 ± 0.2
	$p_\mathrm{T}(B_s^0) > 15\,\mathrm{GeV}$	8.8 ± 0.1	3.7 ± 0.1	12.5 ± 0.1
$N(X)$	$p_\mathrm{T}(B_s^0) > 5\,\mathrm{GeV}$	3 ± 64	-33 ± 43	-30 ± 77
	$p_\mathrm{T}(B_s^0) > 10\,\mathrm{GeV}$	75 ± 52	12 ± 33	87 ± 62
	$p_\mathrm{T}(B_s^0) > 15\,\mathrm{GeV}$	14 ± 31	-10 ± 17	4 ± 35
$\epsilon^\mathrm{rel}(X)$	$p_\mathrm{T}(B_s^0) > 5\,\mathrm{GeV}$	0.127 ± 0.002	0.093 ± 0.001	—
	$p_\mathrm{T}(B_s^0) > 10\,\mathrm{GeV}$	0.213 ± 0.003	0.206 ± 0.002	—
	$p_\mathrm{T}(B_s^0) > 15\,\mathrm{GeV}$	0.289 ± 0.005	0.290 ± 0.004	—



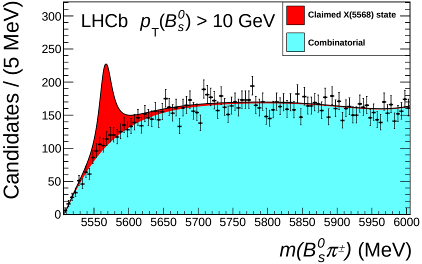


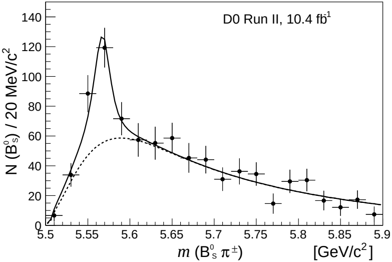
[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$

D0 reports the fraction of B_s^0 from X to be $\rho_X^{D0} = (8.6 \pm 1.9 \pm 1.4)\%$

If this value was universal, this is the signal we would expect.





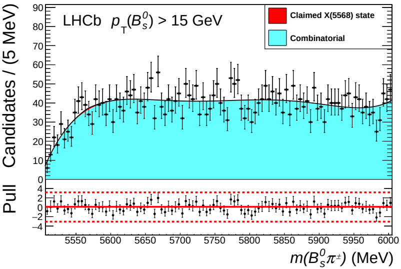
[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$

D0 reports the fraction of B_s^0 from X to be $\rho_X^{D0} = (8.6 \pm 1.9 \pm 1.4)\%$

We do not see anything, so we set limits.

- We also check there is no signal in selected rapidity bins.

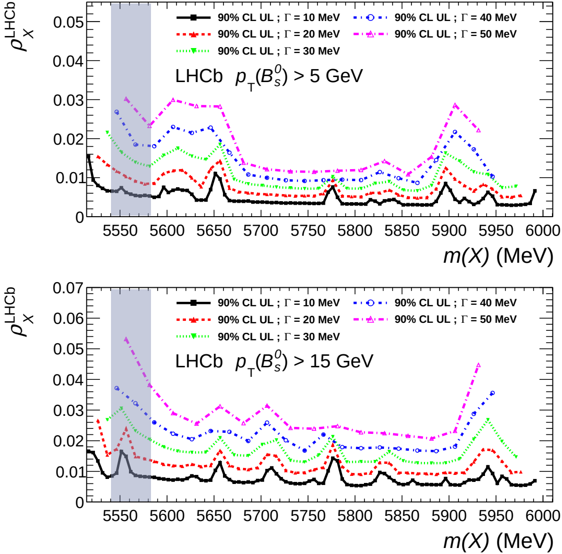


For the D0 state we measure (stat (dominating) and syst combined):

$$\rho_X^{\text{LHCb}}(p_{\mathrm{T}} > 5\,\mathrm{GeV}/c) < 1.1\,(1.2)\% \text{ at } 90\,(95)\% \text{ CL}$$
$$\rho_X^{\text{LHCb}}(p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) < 2.1\,(2.4)\% \text{ at } 90\,(95)\% \text{ CL}$$
$$\rho_X^{\text{LHCb}}(p_{\mathrm{T}} > 15\,\mathrm{GeV}/c) < 1.8\,(2.0)\% \text{ at } 90\,(95)\% \text{ CL}$$

[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

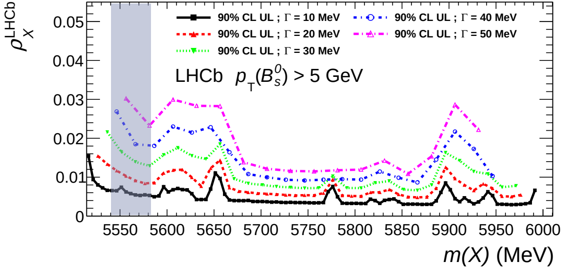
SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$



As no signal is seen anywhere, we set limtis as function of mass and width.

[LHCb, Phys. Rev. Lett. 117 (2016) 152003, arXiv:1608.00435]

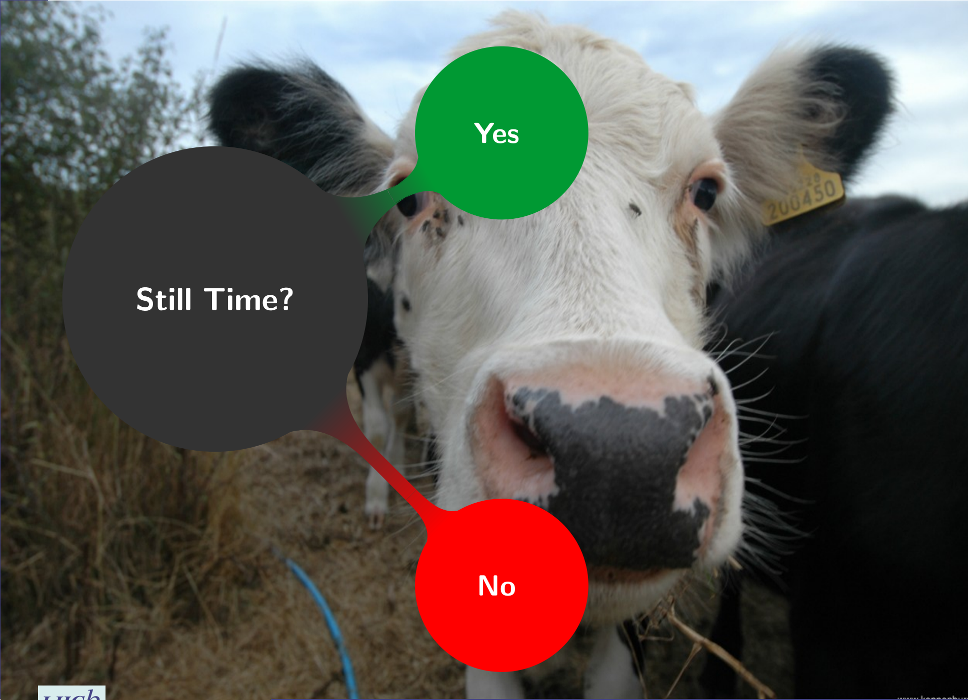
SEARCH FOR RESONANCES IN $B_s^0\pi^\pm$



As no signal is seen anywhere, we set limtis as function of mass and width.

For the D0 state we measure (stat (dominating) and syst combined):

$$\rho_X^{\rm LHCb}(p_{\rm T} > 5\,{\rm GeV}/c) < 1.1\,(1.2)\%\ \text{at}\ 90\,(95)\%\ \text{CL}$$
$$\rho_X^{\rm LHCb}(p_{\rm T} > 10\,{\rm GeV}/c) < 2.1\,(2.4)\%\ \text{at}\ 90\,(95)\%\ \text{CL}$$
$$\rho_X^{\rm LHCb}(p_{\rm T} > 15\,{\rm GeV}/c) < 1.8\,(2.0)\%\ \text{at}\ 90\,(95)\%\ \text{CL}$$



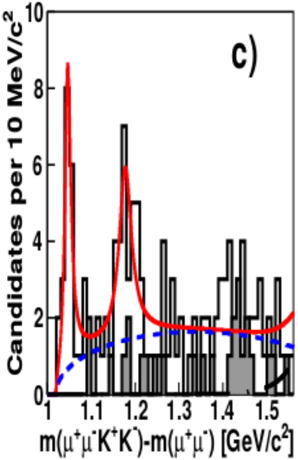
Still Time?

Yes

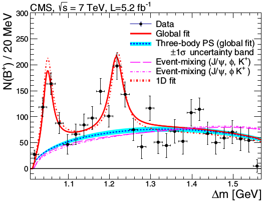
No

AMPLITUDE ANALYSIS OF $B^+ \to J/\psi\, \phi K^+$

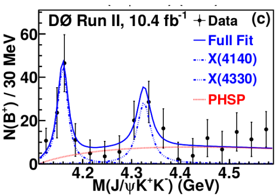
Exp.	N_B	Mass [MeV]	Width [MeV]	σ	Frac. [%]
CDF [PRL]	58	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8	
Belle [PROC]	*325*	*4143.0 fixed*	*11.7 fixed*	*1.9*	
CDF [arxiv]	*115*	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	*5.0*	$15 \pm 4 \pm 2$
LHCb [PRD]	346	4143.4 fixed	15.3 fixed	1.4	< 7
CMS [PLB]	2480	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0	10 ± 3
D0 [PRL]	215	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.1	$21 \pm 8 \pm 4$
BaBar [PRD]	189	4143.4 fixed	15.3 fixed	1.6	< 13
D0 [PRL]	–	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7–5.7	–
Average		4143.4 ± 1.9	15.7 ± 6.3		



[CDF unpublished, arXiv:1101.6058]



[CMS, Phys. Lett. B 734 (2014) 261, arXiv:1309.6920]



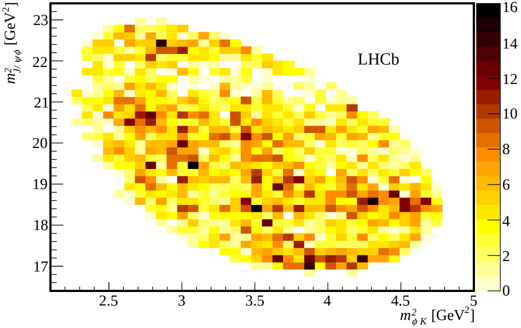
[D0, Phys. Rev. D 89 (2014) 012004, arXiv:1309.6580]

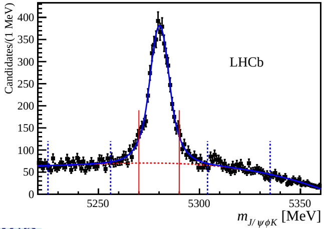
[LHCb, submitted to Phys. Rev. Lett., arXiv:1606.07895] [LHCb, submitted to PRD, arXiv:1606.07898]

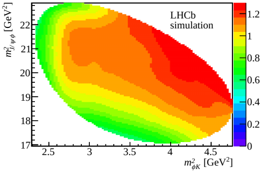
AMPLITUDE ANALYSIS OF $B^+ \to J/\psi\,\phi K^+$

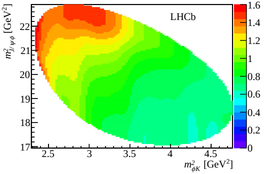
Full amplitude analysis of $3\,\text{fb}^{-1}$ data.

- 4290 ± 150 signal B^+
- Well-understood background and efficiency





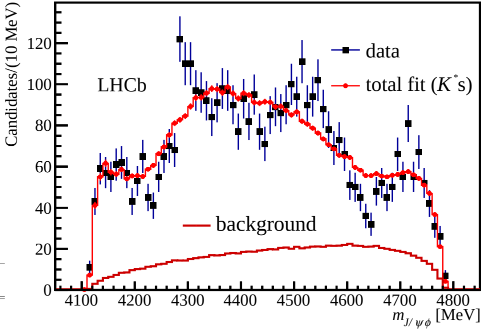




AMPLITUDE ANALYSIS OF $B^+ \to J/\psi\,\phi K^+$

Full amplitude analysis of $3\,\mathrm{fb}^{-1}$ data.

- 4290 ± 150 signal B^+
- Well-understood background and efficiency



Contribution	Sign. or Ref.	Fit results		
		M_0 [MeV]	Γ_0 [MeV]	FF %
All $K(1^+)$	8.0σ			$42\pm\ 8\,^{+\ 5}_{-\ 9}$
$\mathrm{NR}_{\phi K}$				$16\pm13\,^{+35}_{-\ 6}$
$K(1^+)\,2^1\mathrm{P}_1$	7.6σ	$1793\pm59\,^{+153}_{-101}$	$365\pm157\,^{+138}_{-215}$	$12\pm10\,^{+17}_{-\ 6}$
$K_1(1650)$	[31]	1650 ± 50	$150\pm\ 50$	
$K'(1^+)\,2^3\mathrm{P}_1$	1.9σ	$1968\pm65\,^{+\ 70}_{-172}$	$396\pm170\,^{+174}_{-178}$	$23\pm20\,^{+31}_{-29}$
All $K(2^-)$	5.6σ			$11\pm\ 3\,^{+\ 2}_{-\ 5}$
$K(2^-)\,1^1\mathrm{D}_2$	5.0σ	$1777\pm35\,^{+122}_{-\ 77}$	$217\pm116\,^{+221}_{-154}$	
$K_2(1770)$	[31]	$1773\pm\ 8$	$188\pm\ 14$	
$K'(2^-)\,1^3\mathrm{D}_2$	3.0σ	$1853\pm27\,^{+\ 18}_{-\ 35}$	$167\pm\ 58\,^{+\ 82}_{-\ 72}$	
$K_2(1820)$	[31]	1816 ± 13	$276\pm\ 35$	
$K^*(1^-)\,1^3\mathrm{D}_1$	8.5σ	$1722\pm20\,^{+\ 33}_{-109}$	$354\pm\ 75\,^{+140}_{-181}$	$6.7\pm1.9\,^{+3.2}_{-3.9}$
$K^*(1680)$	[31]	1717 ± 27	322 ± 110	
$K^*(2^+)\,2^3\mathrm{P}_2$	5.4σ	$2073\pm94\,^{+245}_{-240}$	$678\pm311\,^{+1153}_{-\ 559}$	$2.9\pm0.8\,^{+1.7}_{-0.7}$
$K_2^*(1980)$	[31]	1973 ± 26	$373\pm\ 69$	
$K(0^-)\,3^1\mathrm{S}_0$	3.5σ	$1874\pm43\,^{+\ 59}_{-115}$	$168\pm\ 90\,^{+280}_{-104}$	$2.6\pm1.1\,^{+2.3}_{-1.8}$
$K(1830)$	[31]	~ 1830	~ 250	

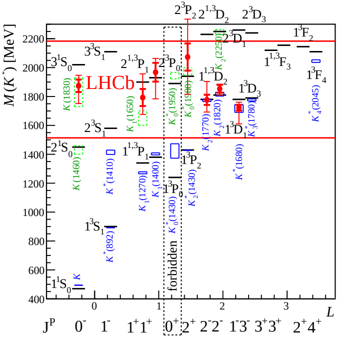
Fit with only K resonances decaying to ϕK^+

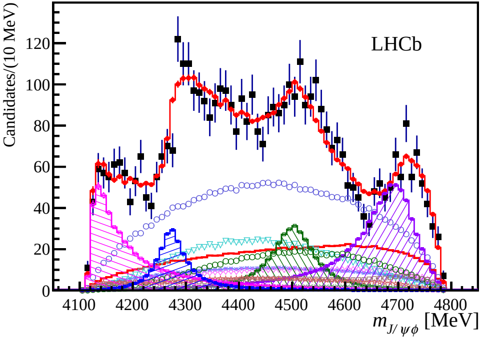
Binned $\chi^2 = 145/69$, $p < 10^{-7}$. Not good.

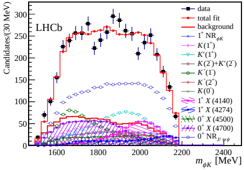
AMPLITUDE ANALYSIS OF $B^+ \to J/\psi\,\phi K^+$

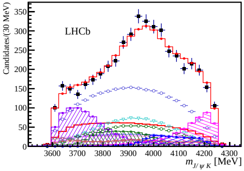
When including $J/\psi\,\phi$ resonances the fit is good : $\chi^2 = 71.5/68$ ➜ $p = 22\%$.

X(4140), X(4274), X(4500), X(4700) above 5σ









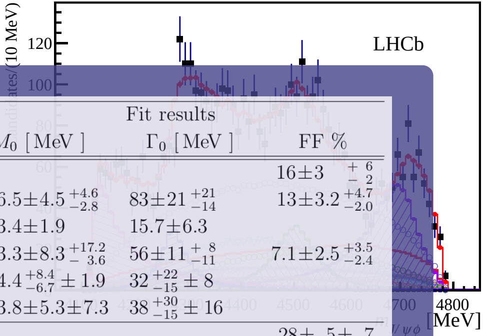
[LHCb, submitted to Phys. Rev. Lett., arXiv:1606.07895] [LHCb, submitted to PRD, arXiv:1606.07898]

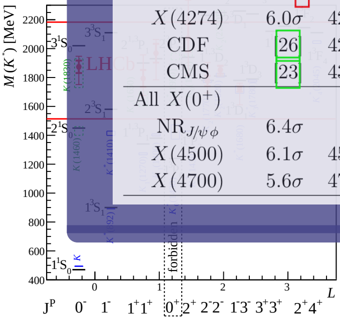
AMPLITUDE ANALYSIS OF $B^+ \to J/\psi\,\phi K^+$

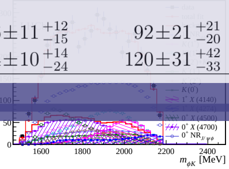
When including $J/\psi\,\phi$ resonances the fit is good : $\chi^2 = 71.5/68 \Rightarrow p = 22\%$.

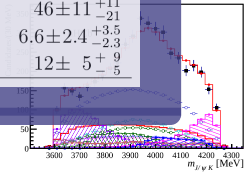
X(4140), X(4274), X(4500), X(4700) above 5σ

Contribution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\,^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.7}_{-2.0}$
ave.	Table 1	4143.4 ± 1.9	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 $X(0^+)$				$28\pm\ 5\pm\ 7$
$\mathrm{NR}_{J/\psi\,\phi}$	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	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$









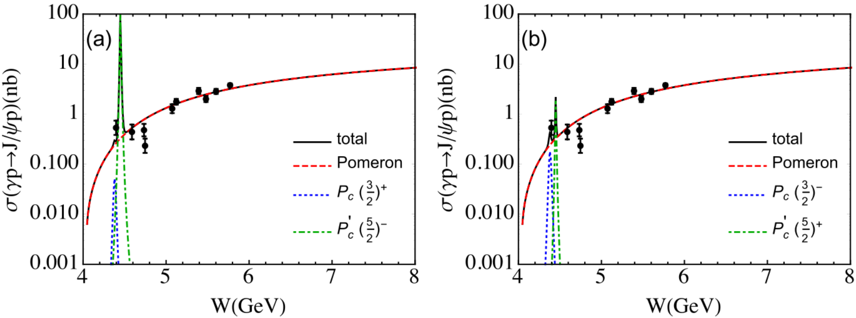
Conclusion

- **LHCb have a rich programme in exotic spectroscopy**
- **Pentaquarks were not part of it . . . until recently**
    - ➜ **We see two states consistent with being $c\bar{c}uud$ pentaquarks in $\Lambda_b^0 \to J/\psi\, pK^-$ decays**
    - **To understand the data, a full angular fit is needed**
- **This morning we reported two new $c\bar{c}s\bar{s}$ tetraquark states**
- **D0 claim a $b\bar{s}u\bar{d}$ state**
    - ✗ **We do not**
- LHCb **had a very good start in Run 2**
    - ➜ **We are commissioning the trigger and processing of the future**
    - ✓ **First J/ψ, $c\bar{c}$ and $b\bar{b}$ cross-sections**
    - **Much more to come**

Backup

[Wang et al., Phys. Rev. D 92, 034022 (2015)]

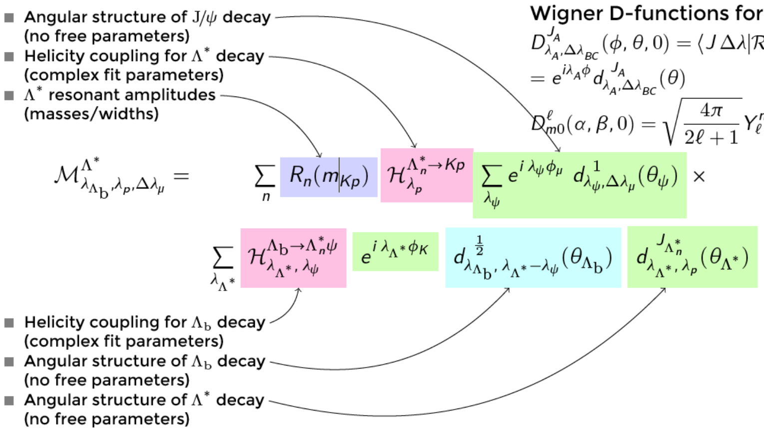
P_c^+ PHOTOPRODUCTION



s-channel production via $\gamma p \to P_c^+ \to J/\psi\, p$ and comparison with existing data. Assumes $\mathcal{B}(P_c^+ \to J/\psi\, p) = 5\%$. Could be done at JLAB.

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

FORMALISM



- Angular structure of J/ψ decay (no free parameters)
- Helicity coupling for Λ^* decay (complex fit parameters)
- Λ^* resonant amplitudes (masses/widths)

Wigner D-functions for $A \to BC$:

$$D^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\phi,\theta,0) = \langle J\,\Delta\lambda|\mathcal{R}(\phi,\theta,0)|J\lambda\rangle$$
$$= e^{i\lambda_A\phi} d^{J_A}_{\lambda_A,\Delta\lambda_{BC}}(\theta)$$

$$D^{\ell}_{m0}(\alpha,\beta,0) = \sqrt{\frac{4\pi}{2\ell+1}}\,Y^{m*}_{\ell}(\alpha,\beta)$$

$$\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b},\lambda_p,\Delta\lambda_\mu} = \sum_n R_n(m_{Kp})\,\mathcal{H}^{\Lambda^*_n\to Kp}_{\lambda_p}\,\sum_{\lambda_\psi} e^{i\lambda_\psi\phi_\mu}\,d^{1}_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)\;\times$$
$$\sum_{\lambda_{\Lambda^*}} \mathcal{H}^{\Lambda_b\to\Lambda^*_n\psi}_{\lambda_{\Lambda^*},\lambda_\psi}\; e^{i\lambda_{\Lambda^*}\phi_K}\; d^{\frac{1}{2}}_{\lambda_{\Lambda_b},\lambda_{\Lambda^*}-\lambda_\psi}(\theta_{\Lambda_b})\; d^{J_{\Lambda^*_n}}_{\lambda_{\Lambda^*},\lambda_p}(\theta_{\Lambda^*})$$

- Helicity coupling for Λ_b decay (complex fit parameters)
- Angular structure of Λ_b decay (no free parameters)
- Angular structure of Λ^* decay (no free parameters)

[LHCb, Phys. Rev. Lett. 115 (2015) 072001, arXiv:1507.03414]

Formalism

Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda^*_n},\Gamma_0^{\Lambda^*_n})$
- special case $\Lambda(1405)$ is subthreshold: Flatté ($\mathrm{K\ p}$ and $\Sigma\ \pi$ channels)
- Blatt-Weiskopf barrier factors $B'_\ell(p,p_0,d)$

$$R_n(M_{Kp}) = B'_{\ell_{\Lambda_b}^{\Lambda^*_n}}(p,p_0,d)\left(\frac{p}{M_{\Lambda_b}}\right)^{\ell_{\Lambda_b}^{\Lambda^*_n}} \times BW(M_{Kp}|M_0^{\Lambda^*_n},\Gamma_0^{\Lambda^*_n}) \times B'_{\ell_{\Lambda^*_n}}(q,q_0,d)\left(\frac{q}{M_0^{\Lambda^*_n}}\right)^{\ell_{\Lambda^*_n}}.$$

$$BW(M|M_0,\Gamma_0) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)},$$

where

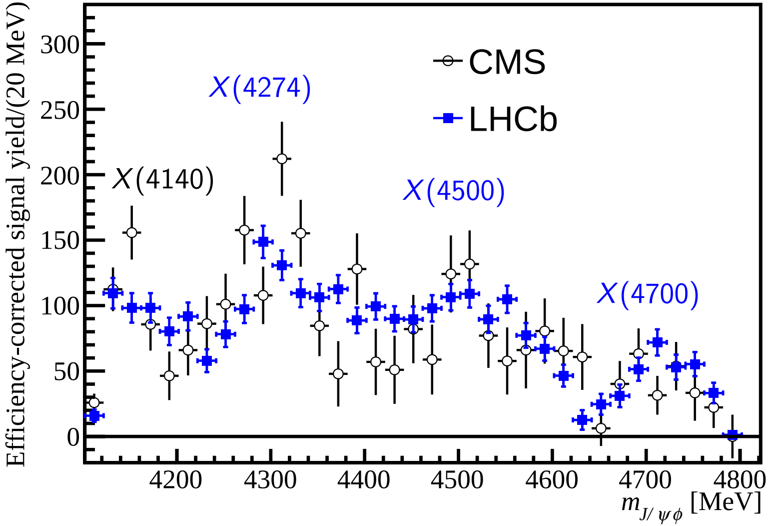
$$\Gamma(M) = \Gamma_0\left(\frac{q}{q_0}\right)^{2\,\ell_{\Lambda^*}+1}\frac{M_0}{M}B'_{\ell_{\Lambda^*}}(q,q_0,d)^2\,.$$

$p(q)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0(q_0)$ calculated on the nominal resonance mass

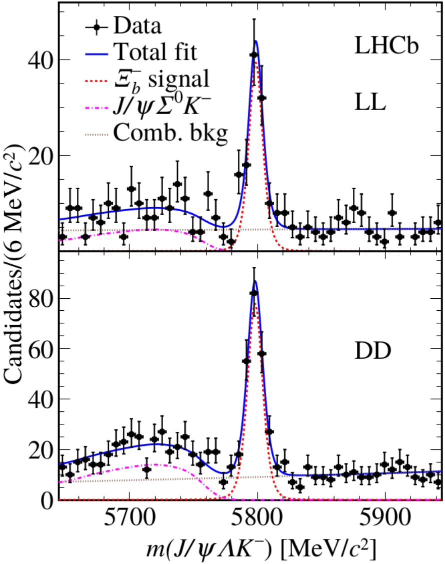
[LHCb, submitted to Phys. Rev. Lett., arXiv:1606.07895] [CMS, Phys. Lett. B 734 (2014) 261]

Comparison with CMS



OBSERVATION OF THE $\Xi_b^- \to J/\psi \Lambda K^-$ DECAY

- Placeholder



[Babar, Phys.Rev. D82 (2010) 011101, arXiv:1005.5190] [Belle, Phys. Rev. D84 052004, arXiv:1107.0163]

$X(3872)$ STATUS IN 2011

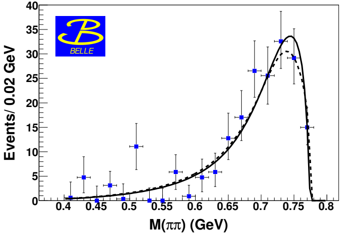
- With their full dataset, Belle confirm that the decay $X(3872) \to J/\psi\,\pi^+\pi^-$ proceeds via a ρ^0 resonance
  - ➜ Isospin 1
  - Favour $J^P = 1^+$ over 2^-

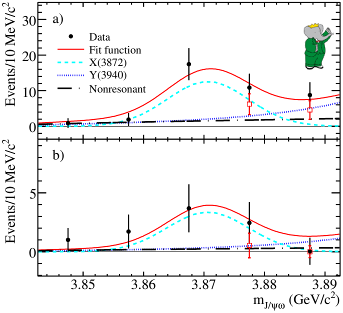
[Belle, Phys. Rev. D84 052004, arXiv:1107.0163]

- BaBar find evidence of $X(3872) \to J/\psi\,\pi^+\pi^-\pi^0$ consistent with a ω contribution below threshold.
  - ➜ Isospin 0
  - Favour $J^P = 2^-$ over 1^+

[Babar, Phys.Rev. D82 (2010) 011101, arXiv:1005.5190]

➜ The $X(3872)$ has isospin-violating decays and its quantum numbers are unclear



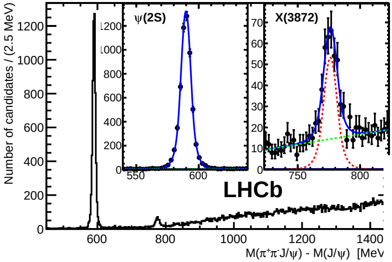


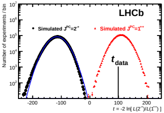
[LHCb, Phys. Rev. Lett. 110 (2013) 222001, arXiv:1302.6269]

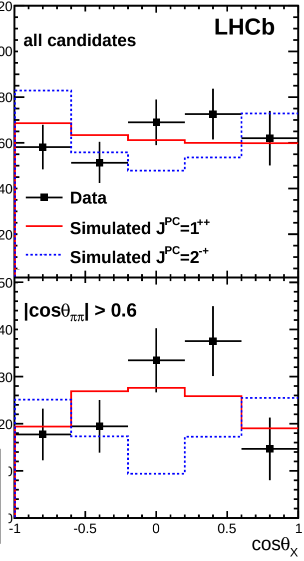
$X(3872)$ QUANTUM NUMBERS

- Five-dimensional angular analysis of $B^+ \to X(3872)K^+$ with $X(3872) \to J/\psi\,\pi^+\pi^-$ using 2011 data
  - ➜ 313 ± 26 decays in 38 000 $B^+ \to J/\psi\,\pi^+\pi^- K^+$ candidates

✔ Unambiguous assignment $J^{PC} = 1^{++}$ at 8σ. This rules out the η_{c2} (1^1D_2) hypothesis.



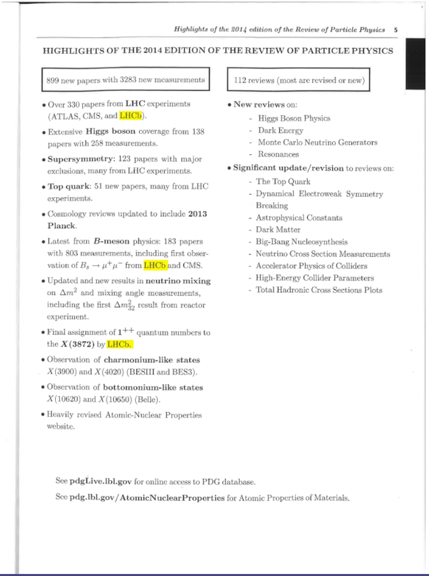




[LHCb, Phys. Rev. D92 (2015) 011102(R), arXiv:1504.06339]

$X(3872)$ QN with $X(3872) \to \rho^0 J/\psi$

- The $X(3872)$ state was observed by Belle [PRL 91 (2013) 26001] in $B \to XK$ and $X \to \pi^+\pi^- J/\psi$. Its nature is unknown.
- CDF determined the quantum numbers to be $J^{PC} = 1^{++}$ or 2^{-+} [PRL 98 (2007) 132002]
- LHCb determined $J^{PC} = 1^{++}$ [PRL 110 (2013) 222001] ($1\ \text{fb}^{-1}$)
  - ➜ One of the PDG highlights of the 2014 edition
- ✗ Both assumed the decay to be dominated by the lowest angular momentum L_{min}.



Highlights of the 2014 edition of the Review of Particle Physics 5

HIGHLIGHTS OF THE 2014 EDITION OF THE REVIEW OF PARTICLE PHYSICS

899 new papers with 3283 new measurements

- Over 330 papers from **LHC** experiments (ATLAS, CMS, and LHCb).
- Extensive **Higgs boson** coverage from 138 papers with 258 measurements.
- **Supersymmetry:** 123 papers with major exclusions, many from LHC experiments.
- **Top quark:** 51 new papers, many from LHC experiments.
- Cosmology reviews updated to include **2013 Planck**.
- Latest from ***B*-meson** physics: 183 papers with 803 measurements, including first observation of $B_s \to \mu^+\mu^-$ from LHCb and CMS.
- Updated and new results in **neutrino mixing** on Δm^2 and mixing angle measurements, including the first Δm^2_{32} result from reactor experiment.
- Final assignment of $\mathbf{1^{++}}$ quantum numbers to the $\boldsymbol{X(3872)}$ by LHCb.
- Observation of **charmonium-like states** $X(3900)$ and $X(4020)$ (BESIII and BES3).
- Observation of **bottomonium-like states** $X(10620)$ and $X(10650)$ (Belle).
- Heavily revised Atomic-Nuclear Properties website.

112 reviews (most are revised or new)

- **New reviews** on:
  - Higgs Boson Physics
  - Dark Energy
  - Monte Carlo Neutrino Generators
  - Resonances
- **Significant update/revision** to reviews on:
  - The Top Quark
  - Dynamical Electroweak Symmetry Breaking
  - Astrophysical Constants
  - Dark Matter
  - Big-Bang Nucleosynthesis
  - Neutrino Cross Section Measurements
  - Accelerator Physics of Colliders
  - High-Energy Collider Parameters
  - Total Hadronic Cross Sections Plots

See **pdgLive.lbl.gov** for online access to PDG database.

See **pdg.lbl.gov/AtomicNuclearProperties** for Atomic Properties of Materials.

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- ✗ Both assumed the decay to be dominated by the lowest angular momentum L_{min}.
- Here we present a re-analysis using 3 fb^{-1} without this assumption.

	B_{LS}	
J^{PC}	Any L value	Minimal L value
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

Parity-allowed LS couplings in $X \to \rho^0 J/\psi$

[LHCb, Phys. Rev. D92 (2015) 011102(R), arXiv:1504.06339]

$X(3872)$ QN with $X(3872)\to\rho^0 J/\psi$

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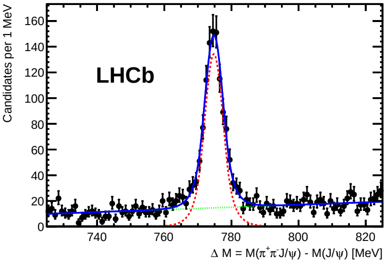
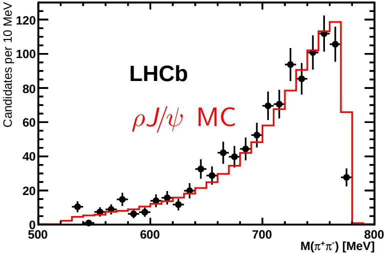
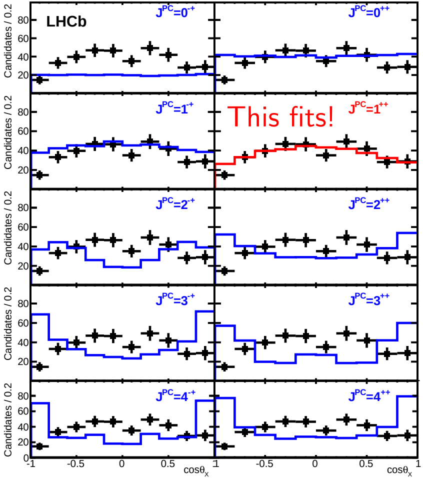
- Use 1011 ± 38 $B^+ \to X K^+$, $X \to \rho^0 J/\psi$ decays
- The phase space is limited





$X(3872)$ QN WITH $X(3872)\to\rho^0 J/\psi$

- Here we present a re-analysis using 3 fb^{-1} without this assumption.
- Use 1011 ± 38 $B^+\to XK^+$, $X\to\rho^0 J/\psi$ decays
- The phase space is limited
- Use helicity formalism to fit 5-dimensional angular distributions
- Only $J^{PC}=1^{++}$ fits and the fraction of D-wave is found to be less than 4%

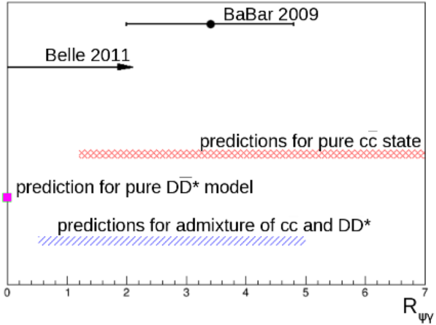


This fits!

➜ Compatible with tetraquark, molecule or $\chi_{c1}(2^3P_1)$ hypotheses (possibly mixed). It excludes any other charmonium state.

EVIDENCE FOR $X(3872) \rightarrow \psi(2S)\gamma$

- The nature of the $X(3872)$ is not clear. The ratio $R_{\psi\gamma}$ of decay widths to $\psi(2S)\gamma$ and $J/\psi\gamma$ is expected to be very different for a $c\bar{c}$ state or a pure DD^* molecule
- BaBar and Belle results were not conclusive



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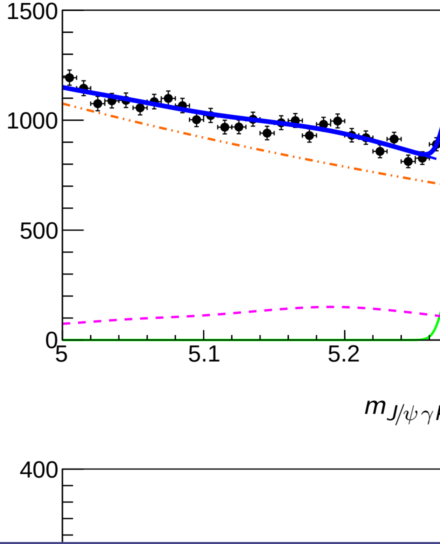
- We reconstruct $B^+ \to J/\psi\,\gamma K^+$ and fit for the X



[LHCb, Nucl. Phys. B886 (2014) 665, arXiv:1404.0275]

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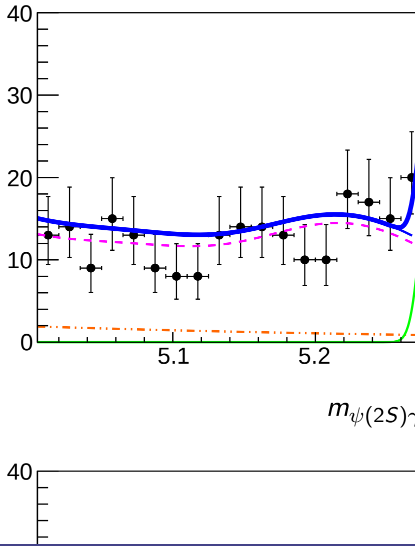
- We reconstruct $B^+ \to J/\psi\,\gamma K^+$ and fit for the X
- Same for $B^+ \to \psi(2S)\gamma K^+$: 4.4σ evidence



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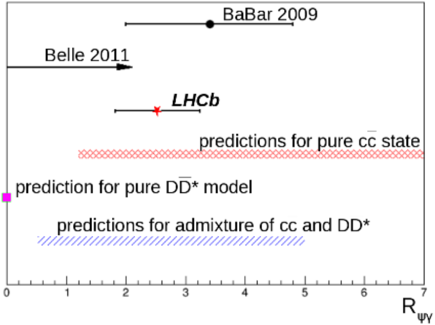
- We reconstruct $B^+ \to J/\psi\gamma K^+$ and fit for the X
- The ratio is measured to be



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

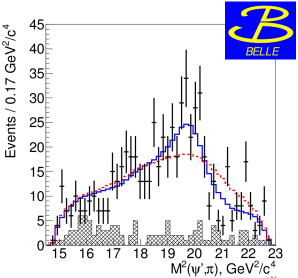
This disfavours the DD^* molecule at 4.4σ

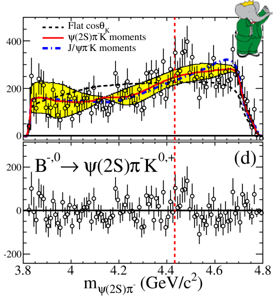
We know more and more about the X(3872), but still not what it is

[LHCb, Phys. Rev. D92 (2015) 112009, arXiv:1510.01951]

RESONANT CHARACTER OF THE $Z(4430)^-$

- Among all tetraquark candidates the $Z(4430)^-$ is special. Being charged it cannot be a $c\overline{c}$ state
- Belle first claimed it in $B^0 \rightarrow \psi(2S)K^+\pi^-$ and have evidence for its J^P to be 1^+ [Phys.Rev. D88 (2013) 074026, arXiv:1306.4894]
- Using a moments analysis, Babar claim they do not need a new resonance in their data [Phys.Rev. D79 (2009) 112001, arXiv:0811.0564]
  - Model-independent approach that assumes only $K^+\pi^-$ resonances contribute to the decay and only depends on the maximum orbital momentum of the $K^+\pi^-$ system.





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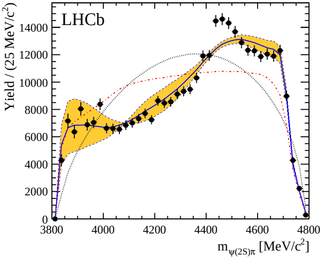
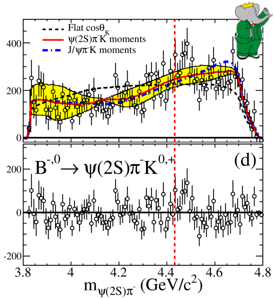
- Using $3\,\text{fb}^{-1}$ LHCb redo the moments analysis à la Babar, and clearly need something more to describe $\psi(2S)\pi^-$





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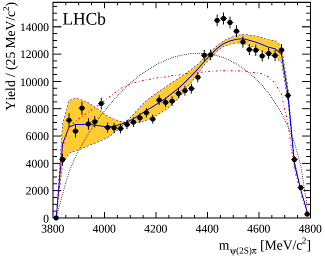
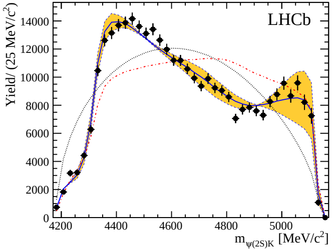


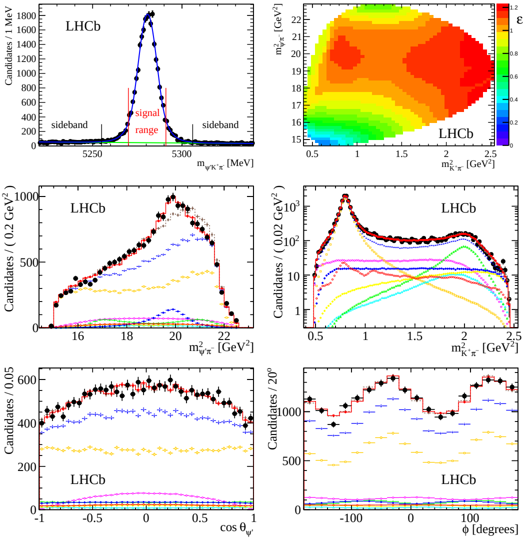


[LHCb, Phys. Rev. Lett. 112 (2014) 222002, arXiv:1404.1903]

RESONANT CHARACTER OF THE $Z(4430)^-$

Unbinned amplitude analysis with $K_0^*(800)$, $K_0^*(1430)$, $K^*(892)$, $K^*(1410)$, $K^*(1680)$, $K_2^*(1430)$, $K_3^*(1780)$ and a Z^-.

- The (binned) χ^2 probability is 2×10^{-6} without the Z, 14% with it.



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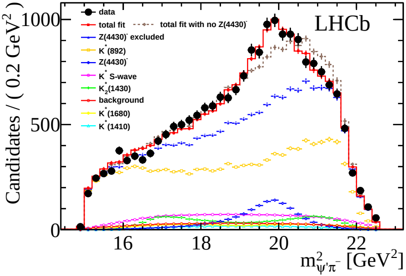
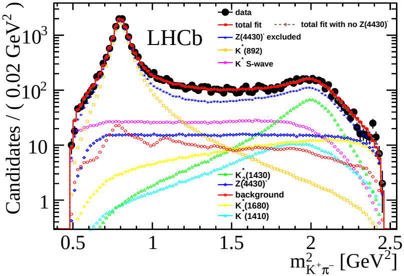
RESONANT CHARACTER OF THE $Z(4430)^-$

Unbinned amplitude analysis

- We measure $m = 4475 \pm 7\,^{+15}_{-25}\ \mathrm{MeV}/c^2$ and $\Gamma = 172 \pm 13\,^{+37}_{-34}\ \mathrm{MeV}/c^2$.

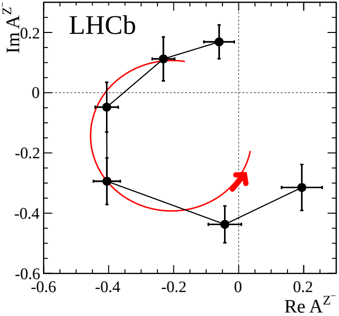


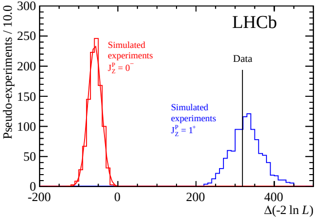


RESONANT CHARACTER OF THE $Z(4430)^-$

Unbinned amplitude analysis

- We measure $m = 4475 \pm 7 \,{}^{+15}_{-25}\ \mathrm{MeV}/c^2$ and $\Gamma = 172 \pm 13 \,{}^{+37}_{-34}\ \mathrm{MeV}/c^2$.
- The spin is confirmed to be 1^+ with overwhelming significance and the Argand plot shows the typical pattern for a resonance
  - ➜ Bin the data in mass of $J/\psi\,\pi^-$ and let the real and imaginary part of the Z float in the fit.



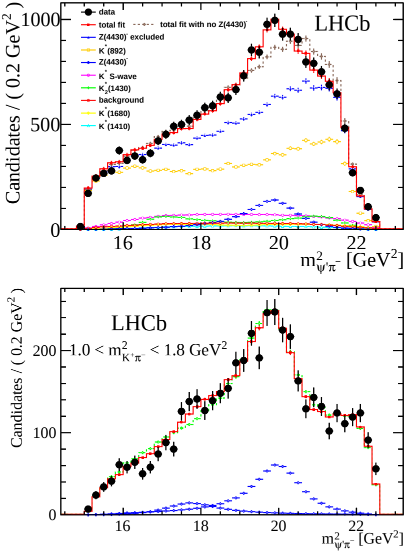


[LHCb, Phys. Rev. Lett. 112 (2014) 222002, arXiv:1404.1903]

RESONANT CHARACTER OF THE $Z(4430)^{-}$

Unbinned amplitude analysis

- We measure $m = 4475 \pm 7\,^{+15}_{-25}$ MeV$/c^2$ and $\Gamma = 172 \pm 13\,^{+37}_{-34}$ MeV$/c^2$.
- The spin is confirmed to be 1^{+} with overwhelming significance and the Argand plot shows the typical pattern for a resonance
- Adding a second Z with $J^P = 0^{-}$ the χ^2 probability improves to 26%. $m = 4239 \pm 18\,^{+45}_{-15}$ MeV$/c^2$ and $\Gamma = 220 \pm 47\,^{+108}_{-74}$ MeV$/c^2$.



[LHCb, Phys. Rev. Lett. 112 (2014) 222002, arXiv:1404.1903]

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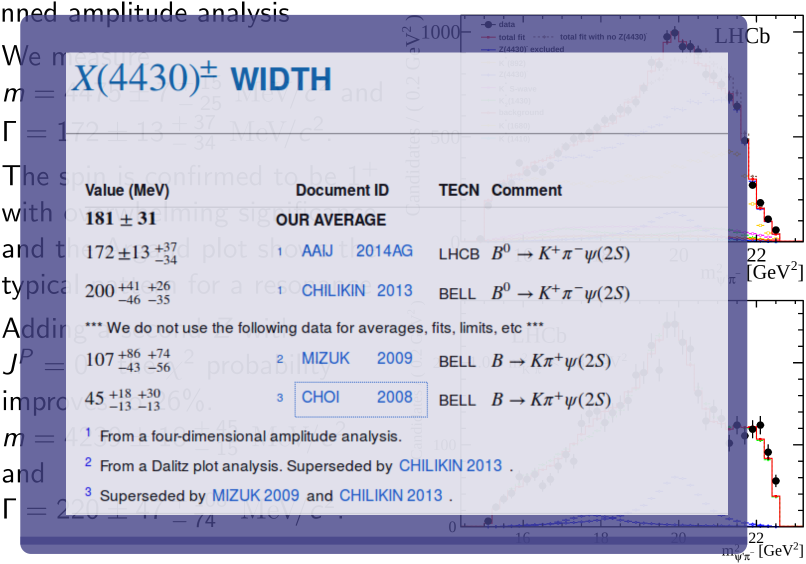
- Adding a second Z with $J^P = 0$ the χ^2 probability improves to 26%. $m = 4239 \pm 18 {}^{+45}_{-15}$ MeV/c^2 and $\Gamma = 220 \pm 47 {}^{+108}_{-74}$ MeV/c^2.



$X(4430)^{\pm}$ WIDTH

Value (MeV)		Document ID		TECN	Comment
181 ± 31		**OUR AVERAGE**			
$172 \pm 13 {}^{+37}_{-34}$	1	AAIJ	2014AG	LHCB	$B^0 \to K^+ \pi^- \psi(2S)$
$200 {}^{+41}_{-46} {}^{+26}_{-35}$	1	CHILIKIN	2013	BELL	$B^0 \to K^+ \pi^- \psi(2S)$
*** We do not use the following data for averages, fits, limits, etc ***					
$107 {}^{+86}_{-43} {}^{+74}_{-56}$	2	MIZUK	2009	BELL	$B \to K \pi^+ \psi(2S)$
$45 {}^{+18}_{-13} {}^{+30}_{-13}$	3	CHOI	2008	BELL	$B \to K \pi^+ \psi(2S)$

[1] From a four-dimensional amplitude analysis.

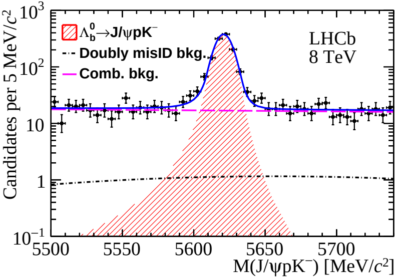
[2] From a Dalitz plot analysis. Superseded by CHILIKIN 2013 .

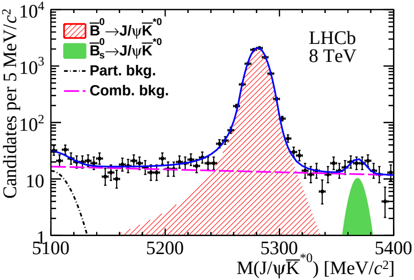
[3] Superseded by MIZUK 2009 and CHILIKIN 2013 .

[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

Λ_b^0 PRODUCTION AT THE LHC

- Study of Λ_b^0 and B^0 production in forward acceptance using $\Lambda_b^0 \to J/\psi\, pK^-$ and $B^0 \to J/\psi\, K^{*0}$

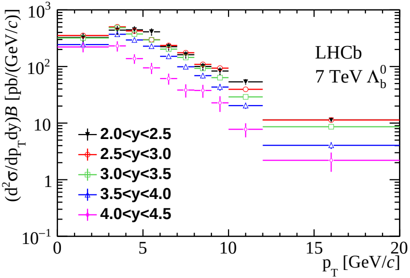


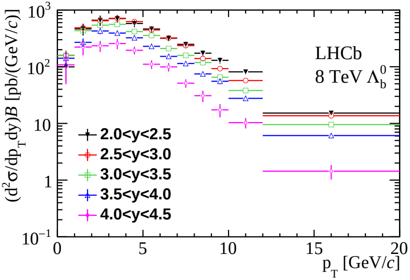


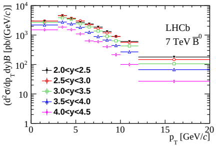
[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

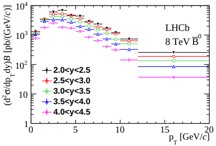
Λ_b^0 PRODUCTION AT THE LHC

- Study of Λ_b^0 and B^0 production in forward acceptance using $\Lambda_b^0 \to J/\psi\, pK^-$ and $B^0 \to J/\psi\, K^{*0}$
- Double differential cross-sections are determined







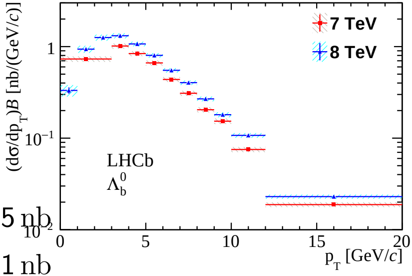


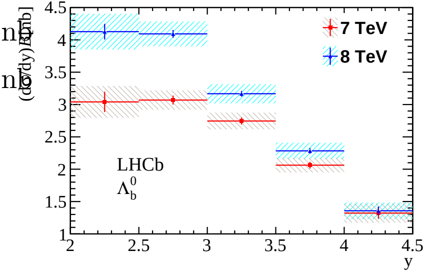
[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

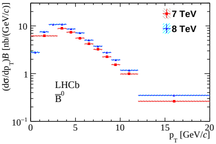
Λ_b^0 PRODUCTION AT THE LHC

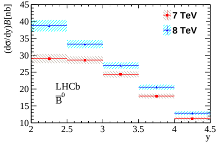
- Study of Λ_b^0 and B^0 production in forward acceptance
- Double differential cross-sections are determined
- Differential versus p_T and y

$$\sigma(\Lambda_b^0,7)\mathcal{B}(\Lambda_b^0) = 6.12 \pm 0.10 \pm 0.25\,\mathrm{nb}$$
$$\sigma(\Lambda_b^0,8)\mathcal{B}(\Lambda_b^0) = 7.51 \pm 0.08 \pm 0.31\,\mathrm{nb}$$
$$\sigma(B^0,7)\mathcal{B}(B^0) = 55.6 \pm 0.3 \pm 2.1\,\mathrm{nb}$$
$$\sigma(B^0,8)\mathcal{B}(B^0) = 66.2 \pm 0.3 \pm 2.3\,\mathrm{nb}$$







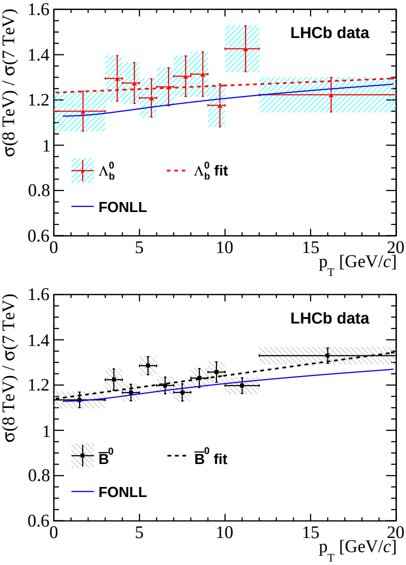


[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

Λ_b^0 PRODUCTION AT THE LHC

- Study of Λ_b^0 and B^0 production in forward acceptance
- Double differential cross-sections are determined
- Differential versus p_T and y
- Ratios of 7 to 8 TeV increase versus p_T

$$\frac{\sigma(8\text{ TeV})}{\sigma(7\text{ TeV})} = \begin{cases} 1.23 \pm 0.02 \pm 0.04 & \text{for } \Lambda_b^0 \\ 1.19 \pm 0.01 \pm 0.02 & \text{for } B^0 \end{cases}$$



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Λ_b^0 PRODUCTION AT THE LHC

- Study of Λ_b^0 and B^0 production in forward acceptance
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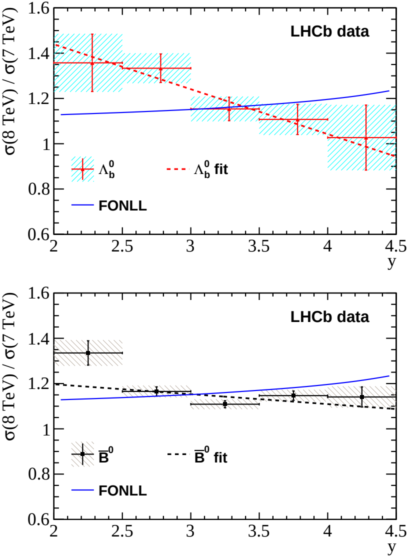
- Ratios of 7 to 8 TeV increase versus p_{T}, but decrease versus y

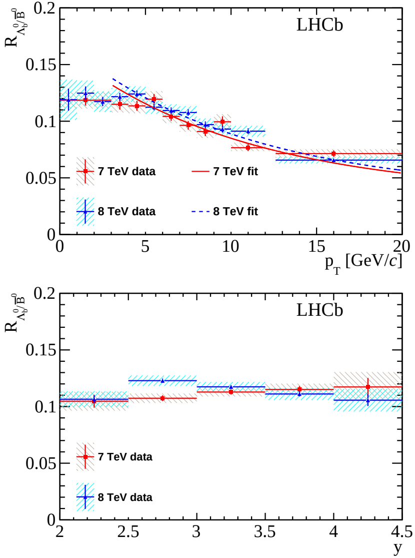
$$\frac{\sigma(8\text{ TeV})}{\sigma(7\text{ TeV})} = \begin{cases} 1.23 \pm 0.02 \pm 0.04 & \text{for } \Lambda_b^0 \\ 1.19 \pm 0.01 \pm 0.02 & \text{for } B^0 \end{cases}$$



[LHCb, Chin. Phys. C 40 (2016) 011001, arXiv:1509.00292]

$\mathit{\Lambda}_b^0$ PRODUCTION AT THE LHC

- Study of $\mathit{\Lambda}_b^0$ and B^0 production in forward acceptance
- Double differential cross-sections are determined
- Differential versus p_T and y
- Ratios of 7 to 8 TeV increase versus p_T, but decrease versus y
- Ratios of $\mathit{\Lambda}_b^0$ to B^0



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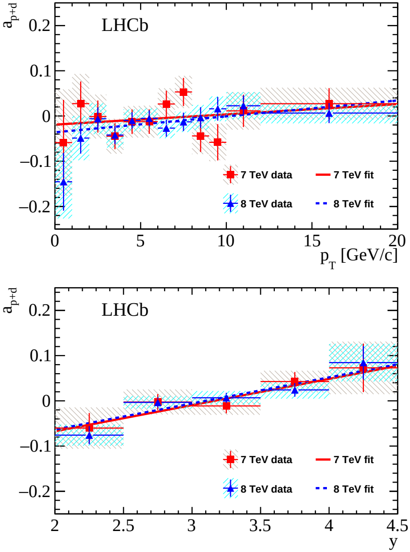
Λ_b^0 PRODUCTION AT THE LHC

- Study of Λ_b^0 and B^0 production in forward acceptance
- Double differential cross-sections are determined
- Differential versus p_{T} and y
- Ratios of 7 to 8 TeV increase versus p_{T}, but decrease versus y
- Ratios of Λ_b^0 to B^0
- Λ_b^0 production asymmetries

$$a_{\mathrm{p+d}}(y) = -(0.001 \pm 0.007) + (0.058 \pm 0.014)(y - 3.1)$$



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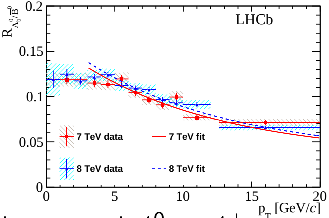
Λ_b^0 PRODUCTION AT THE LHC



The ratio of Λ_b^0 to B^0 is

$$R(p_{\mathrm{T}}) = \frac{f_{\Lambda_b^0}}{f_d}(p_{\mathrm{T}})\frac{\mathcal{B}(\Lambda_b^0)}{\mathcal{B}(B^0)}$$

We measured $f_{\Lambda_b^0}/f_d(p_{\mathrm{T}})$ using semileptonic decays and $\Lambda_b^0 \to \Lambda_c^+\pi^-$ [PRD 85 (2012) 032008] [JHEP 08 (2014) 143]. We determine the ratio of BFs and thus

$$\mathcal{B}(\Lambda_b^0 \to J/\psi\, pK^-) = \left(3.04 \pm 0.04 \pm 0.06 \pm 0.33(\mathcal{B})\, {}^{+\,0.43}_{-\,0.27}(\frac{f_{\Lambda_b^0}}{f_d})\right) \times 10^{-4}$$

from which we get [JHEP 07 (2014) 103]

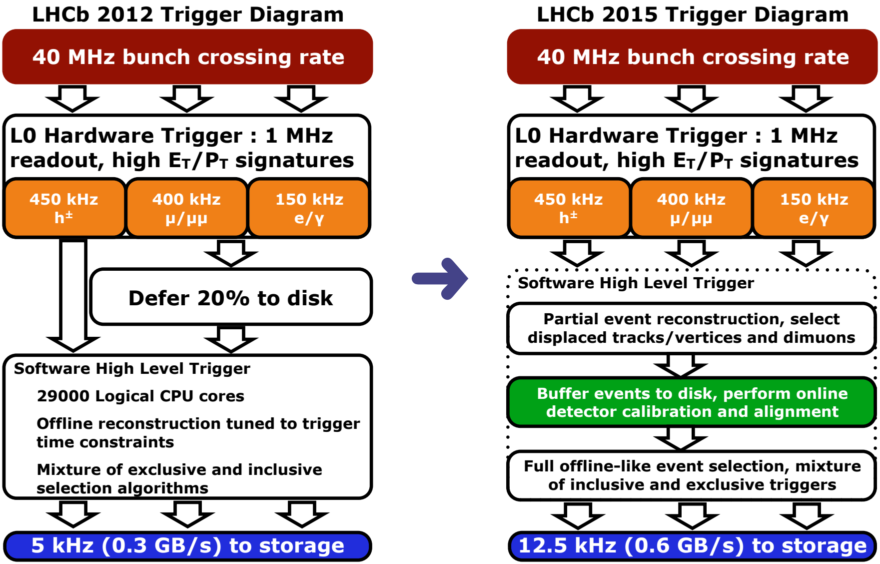
$$\mathcal{B}(\Lambda_b^0 \to J/\psi\, p\pi^-) = \left(2.51 \pm 0.04 \pm 0.08 \pm 0.13\, {}^{+\,0.45}_{-\,0.35}\right) \times 10^{-5}$$

and [PRL 115 (2015) 072001]

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\, {}^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\, {}^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

➜ LHCb can do absolute Λ_b^0 BF and A_{CP} measurements!

LHCb Trigger in Run 2



LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

→

LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

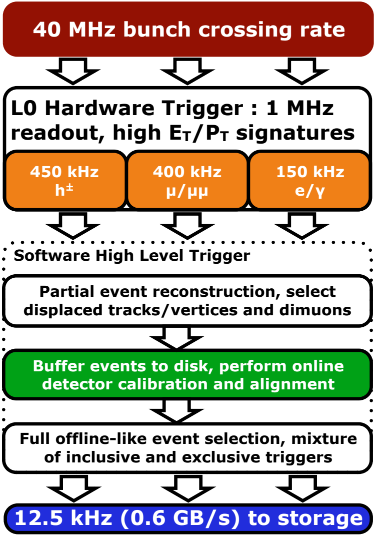
12.5 kHz (0.6 GB/s) to storage

LHCb Trigger in Run 2

New in 2015: Introducing the TURBO stream

- 5 kHz of 12 kHz go to TURBO:
- Only trigger information is saved: tracks and vertices that caused the event to trigger
  - ➜ No raw event — no offline reconstruction
- ✔ Smaller events, faster analysis
- Used for high yield exclusive trigger lines : J/ψ , D^0, D^+ …

LHCb 2015 Trigger Diagram



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