# Exotic states at LHCb

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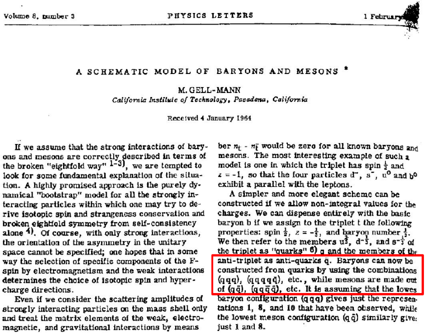
# What are exotic states?

- The quark model allows for colour-neutral states beyond the well established $q\bar{q}$ mesons and $qqq$ baryons
- States such as $qqqq\bar{q}$ (pentaquark), $qq\bar{q}\bar{q}$ (tetraquark) are postulated in Gell-Mann's and Zweig's original quark model papers (1964) *Phys.Lett. 8 (1964) 214-215, CERN-TH-412*



Volume 8, number 3 PHYSICS LETTERS 1 February

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
*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

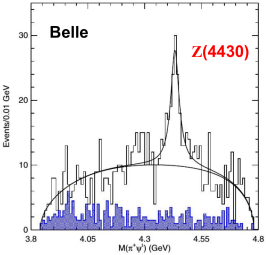
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles $d^-$, $s^-$, $u^0$ and $b^0$ exhibit a parallel with the leptons.

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 $(qqq)$, $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes baryon configuration $(qqq)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

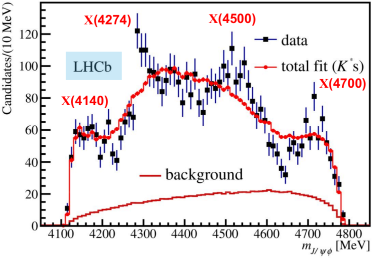
- We now refer to any hadron that does not follow $q\bar{q}/qqq$ as exotic

# What are exotic states?

We keep finding exotic candidates... especially in charm...




PRL100, 142001(2008)



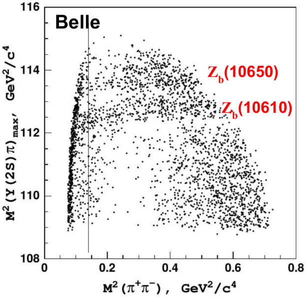

PRL118, 022003(2017)

$Z^+(4430)$ charged, $c\bar{c}u\bar{d}$, hidden charmonium tetraquark at Belle in $B^0 \to \psi(2S)\pi^+K^-$ decays

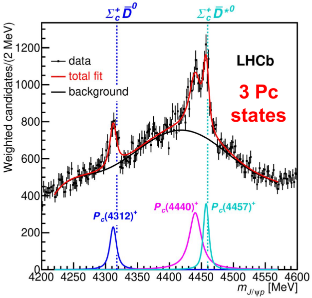
Four X state tetraquarks in $J/\psi\phi$ at LHCb - minimal quark content $cs\bar{c}\bar{s}$

# What are exotic states?

and we keep finding exotic candidates... especially in charm...




PRL108,122001(2012)




PRL122, 222001(2019)

$Z_b$ bottomonium tetraquarks with $b\bar{b}u\bar{d}$ decaying to upsilon resonances at Belle

$P_c$ state pentaquarks in $J/\psi p$ with minimal quark content $c\bar{c}uud$ at LHCb

# What are exotic states?

LHCb is in a unique position to search for exotic contributions in decays of all $b$ hadrons

- $b$ hadrons in LHCb acceptance have the ratio 4:2:1 for $B^0 : \Lambda_b^0 : B_s^0$
- LHCb is the only detector able to do the physics discussed in this talk

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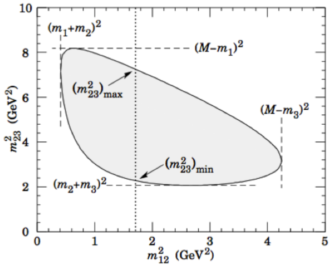
# Whats a Dalitz plot?

Consider a 3-body pseudoscalar decay $X \to 123$. It can be completely described by 2 independent variables $m_{12}$ and $m_{23}$




A 2D scatter plot of 2-body invariant masses in the decay $X \to 123$.

This is a Dalitz plot - a visual representation of the resonant substructure of (or different decay paths contributing to) a decay. From it we can determine

- Resonances present in a decay
- A resonances spin
- Interference between resonances

# Whats a Dalitz plot?

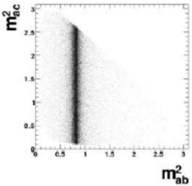
Consider a single resonance (amplitude component/decay path) contributing to a decay $X \rightarrow abc$ so $X \rightarrow (i \rightarrow ab)c$

$$A_i = |A_i| e^{i\theta_i}$$


Observable on Dalitz plot

$$|A|^2 = |A_i|^2$$

Lose all information about phase of amplitude




Single band in $m_{ab}$ at $m_i^2$

# Whats a Dalitz plot?

Consider a single resonance (amplitude component/decay path) contributing to a decay $X \to abc$ so $X \to (i \to ab)c$

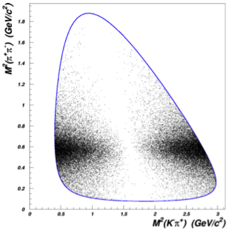
$$A_i = |A_i| e^{i\theta_i}$$

i

Initial state

Final state

If a resonance has spin $S$ it's amplitude component has $\cos^S$ dependence

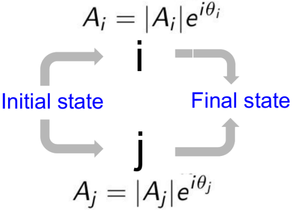


Resonance of spin 1

This can lead to reflections!(Note a resonance decaying to $bc$ would be seen on diagonal)

# Whats a Dalitz plot?

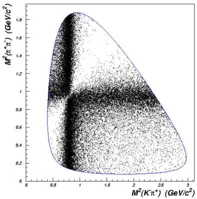
Now consider 2 resonances (amplitude components/decay paths) contributing to a decay $X \to abc$ so $X \to (i \to ab)c$ and $X \to (j \to ac)b$




Observable on Dalitz plot

$$|A|^2 = |A_i|^2 + |A_j|^2 + 2|A_i||A_j|\cos(\theta_i - \theta_j)$$

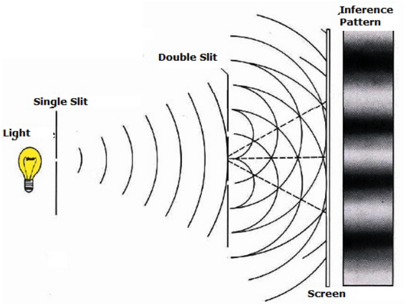
Now have access to the amplitude component phases through interference!



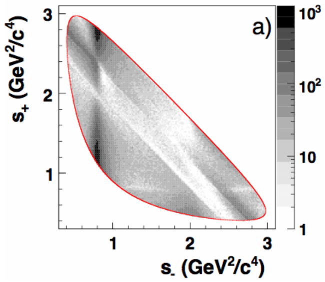

Destructive interference between two resonance bands

# Whats a Dalitz plot?

We use quantum interference effects between indistinguishable decay paths from same intitial state to same final state. Interfering decay paths create complex phasespace distribution




Interference with light

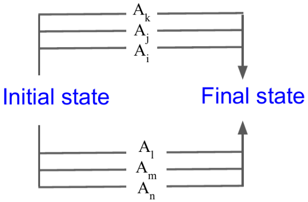



$D^0 \to K^0_S \pi^+\pi^-$ decays. Spin 1 $K^{*0}(892)$ resonance clearly visible.

An amplitude analysis fits this phasespace distribution

# Whats an amplitude analysis?

Amplitude analyses decompose a total decay amplitude into amplitude components, $A_i$, each weighted by a complex coefficient, $a_i$




$$A_{TOT} = \sum_i a_i A_i$$

Amplitude components are made up of 3 terms

$$A_i = \text{Angular term} \times \text{Form factors} \times \text{Lineshape}$$

Conserves angular momentum - involves quantum numbers $J^P$ of resonance
Accounts for spatial extent of particles
Often a Breit Wigner - appropriate if the resonance is narrow/well separated - involves mass/width of resonance

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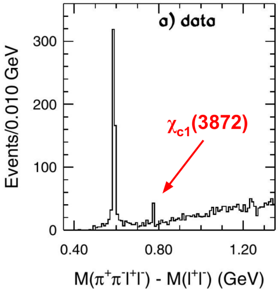
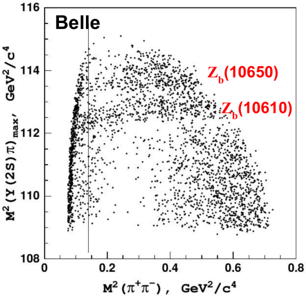
# Enhancements in mass distributions or on the Dalitz plot

Short lived exotic states appear as resonances in decays

- Exotic resonances can be seen as enhancements in mass distributions or on the Dalitz plot




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



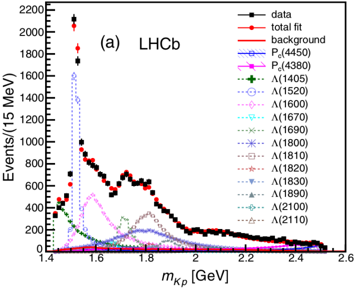

$Z_b$ states in $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$

- Pros: Easy measurement of mass/width of states - Breit Wigner model
- Cons: Interfering resonances and reflections can fake 'bumps'

# A full amplitude analysis

Exotic resonances interfere with known resonances creating complex phasespace distributions

- A full amplitude analysis is required to untangle these contributions and determine mass/width AND quantum numbers ($J^P$) of exotic states

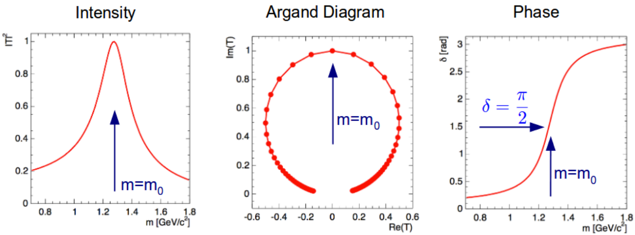



- Pros: Can determine all properties of a new state
- Cons: Model dependent (lineshape etc.) - requires the most assumptions about other states (which decay paths do we include) and is the most complex of procedures

# Model independent approaches - Argand diagrams

Argand diagrams can confirm if a bump behaves like a resonance

- The decay of an isolated resonance can be described by the Breit Wigner PDF in the complex plane (derived from the propagator of an unstable particle)
- The Breit Wigner amplitude has characteristic nature in complex plane
  - Anticlockwise circular trajectory
  - Phase change of $\pi/2$ across pole mass $m_0$

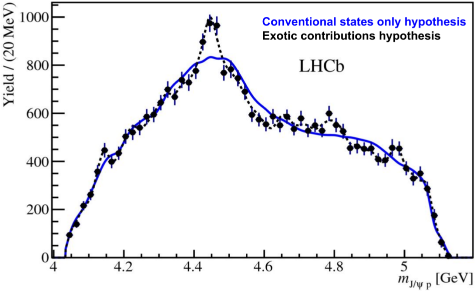



*iktp.tu-dresden.de/IKTP/Seminare/IS2012/pelizaeus.pdf*

- Pros: It is very unlikely that this signature can be 'faked'
- Cons: Only true for resonances well separated from other resonances/thresholds

# Model independent approaches - moments analysis

Model independent approaches can evaluate the null-hypothesis that only conventional states are needed to describe the data




Evidence for non-conventional states in $\Lambda_b^0 \to J/\psi p K^-$

- Pros: Model independent - only require knowledge of the spins of conventional states
- Cons: Can only tell you that 'something' beyond the simple conventional state interpretation is required. This 'something' could be including kinematic effects

# How do we know if a state is exotic?

Its exotic

- Quantum numbers are not allowed for $q\bar{q}'$ or $qq'q''$ - state must contain $>$3 quarks

n: radial quantum #
S: total spin of quarks
L: orbital ang. mom. btw quarks - S,P,D...

$$n^{(2S+1)}L_J$$

J=L+S
P=$(-1)^{L+1}$
C=$(-1)^{L+S}$

| $L$ | $S$ | $J^{PC}$ | $L$ | $S$ | $J^{PC}$ | $L$ | $S$ | $J^{PC}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 0 | $0^{-+}$ | 1 | 0 | $1^{+-}$ | 2 | 0 | $2^{-+}$ |
| 0 | 1 | $1^{--}$ | 1 | 1 | $0^{++}$ | 2 | 1 | $1^{--}$ |
| | | | 1 | 1 | $1^{++}$ | 2 | 1 | $2^{--}$ |
| | | | 1 | 1 | $2^{++}$ | 2 | 1 | $3^{--}$ |

Allowed quantum numbers for $q\bar{q}$. eg. cannot have $1^{-+}$

- Many exotic states do not fulfill this condition

It might be exotic...

- Mass/width do not fit into predicted spectra
- Production/decay incompatible with conventional hadrons

It is difficult to claim something is definitely exotic

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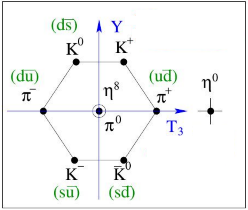
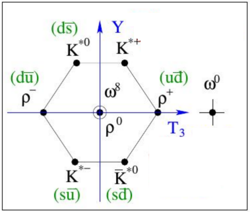
# The hadron multiplets

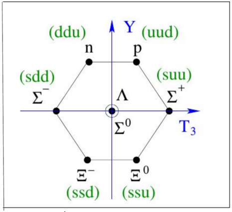
Have been able to classify light hadrons well using the multiplet system



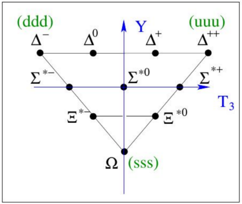

$J^P = 0^-$ pseudoscalar meson multiplet




$J^P = 1^-$ vector meson multiplet



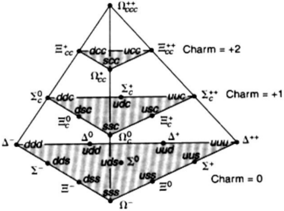

$J^P = \frac{1}{2}^+$ baryon multiplet



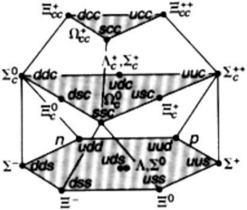

$J^P = \frac{3}{2}^+$ baryon multiplet

# The hadron multiplets

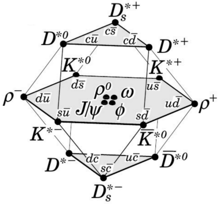
Even with the addition of Charm...



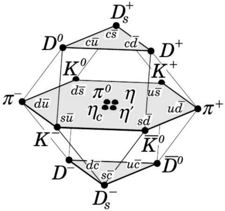

$J^P = \frac{3}{2}^+$ baryon multiplet




$J^P = \frac{1}{2}^+$ baryon multiplet



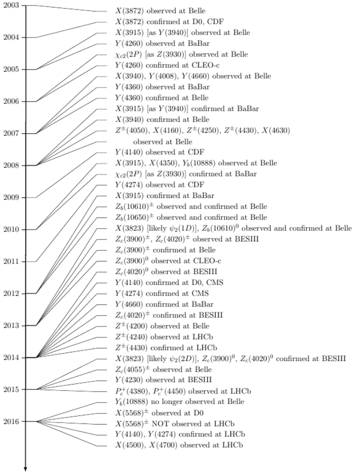

$J^P = 1^-$ vector meson multiplet




$J^P = 0^-$ pseudoscalar meson multiplet

# The situation now...

Over 20 states in charm sector alone that do not fit into conventional hadron model




Discoveries of heavy quark exotic candidates
arXiv:1610.04528

What are XYZ states?

Some are standard quarkonia... most are exotics

$X$ states:

- Neutral, positive parity

$Y$ states:

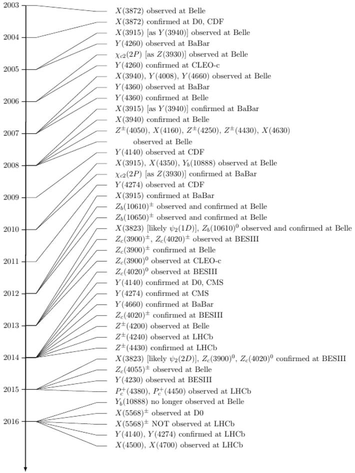
- Neutral, $J^{PC} = 1^{--}$, ISR

$Z$ states:

- Charged/neutral, typically positive parity

# The situation now...

Over 20 states in charm sector alone that do not fit into conventional hadron model




Discoveries of heavy quark exotic candidates
arXiv:1610.04528

The quark model is over 50 years old, only in 2003 was the first exotic discovered

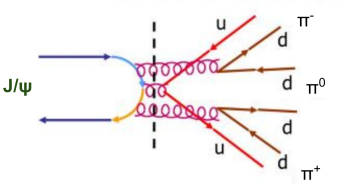
Why did it take so long to find exotic states?

- Light sector (<2.4 GeV) is crowded and states are broad
- Can only be extracted through complex partial wave analysis

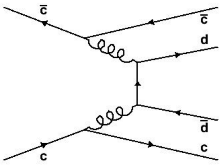
# The importance of Charmonium

Why were exotics first discovered in the charm system?

- Decays of conventional $c\bar{c}$ states with masses below open charm threshold $m_{D\bar{D}}$ are OZI suppressed - states are narrow and well separated




OZI-suppressed




OZI-allowed

- Above the open charm threshold OZI allowed processes dominate - wider resonances but still significantly narrower than light quark states

*OZI-suppressed - there is some time when all energy/momentum is carried by gluons - can cut through only gluon lines leaving initial state particles on left and final state particles on right*

# The importance of Charmonium

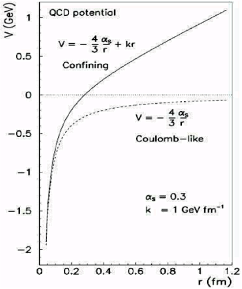
- Charm is the lightest 'heavy' quark - $m_c >> \Lambda_{QCD}$ - can determine charmonium spectrum with simple non-relativistic quantum-mechanical treatment

$$V^{c\bar{c}}(r) = -\frac{k\alpha_s}{r} + br$$

Small distance gluon exchange

Large distance confinement

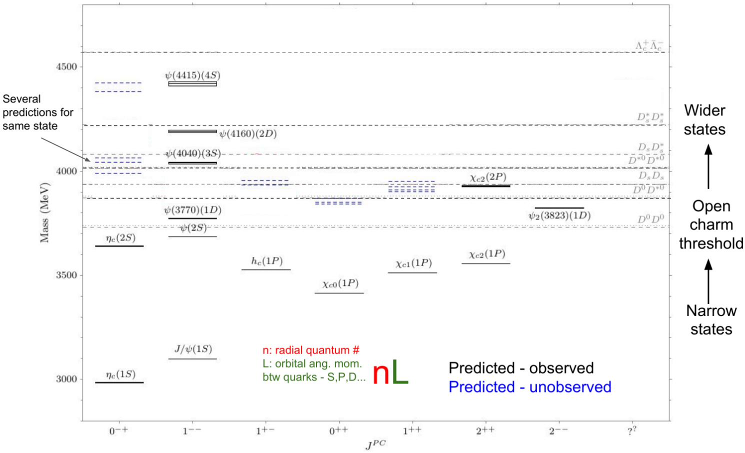
plus spin-spin and spin-orbit terms




- Using $V^{c\bar{c}}(r)$ with SE can predict entire $c\bar{c}$ spectrum below open charm threshold and some states above

# The importance of Charmonium

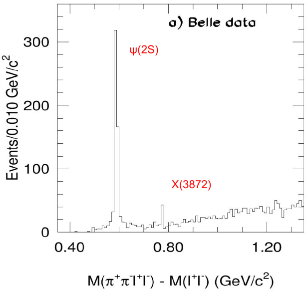
States well separated
Have reliable predictions of expected conventional states



# $X(3872)$ the first exotic

$X(3872)$ first observed in 2003 by Belle when studying $B \to K(\pi^+\pi^- J/\psi)$ decays

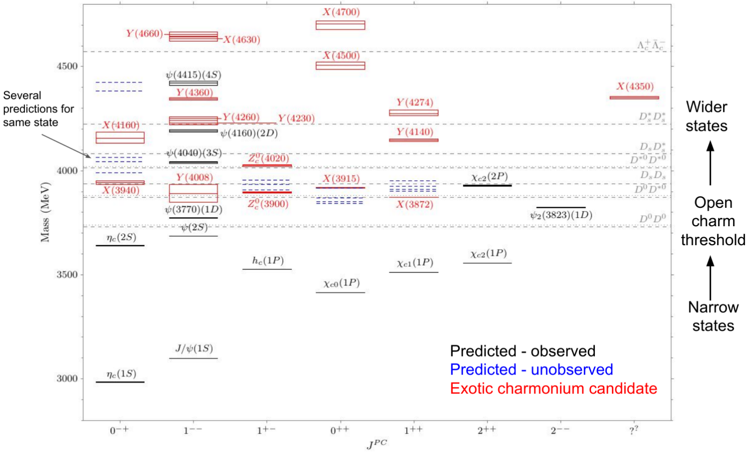
- Resonance in $J/\psi\pi\pi$ spectrum seen as enhancement in mass distribution
- Mass measured as $3871.8 \pm 0.7 \pm 0.4$ MeV
- Width measured as $\Gamma < 3.5$ MeV
- Favoured quantum numbers $J^{PC} = 1^{++}$




Phys. Rev. Lett. 91, 262001 (2003)

Could $X(3872)$ just be excited charmonium state?

# $X(3872)$ the first exotic

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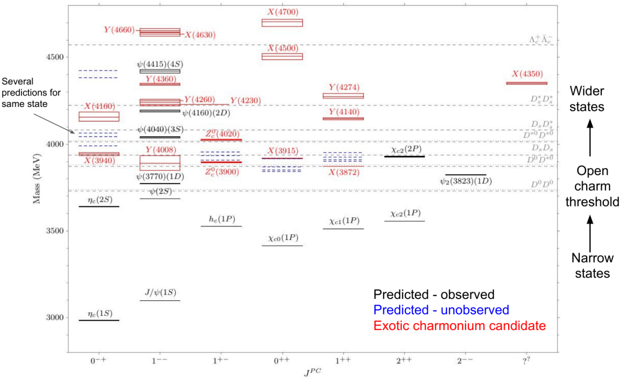
# $X(3872)$ the first exotic




- LHCb confirmed quantum numbers $J^{PC} = 1^{++}$ - nearest conventional undiscovered charmonium state is $\chi_{c1}(2P)$
- Width is very small - would expect larger widths for charmonium states above open charm threshold

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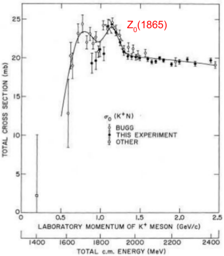
# Pentaquarks - false starts

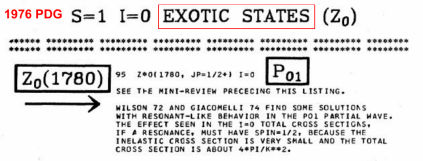
*Three quarks cannot produce $S = 1$ baryon resonances and this has probably been the the primary motivation for the great amount of experimental effort that has gone into $S = 1$ baryon physics during the last several years* (1976 PDG)

Any resonance with $S = 1$ must be mainfestly exotic, e.g a pentaquark with quark content $qqqq\bar{s}$

Claims of exotic contributions $Z_0(1780), Z_0(1865), Z_1(1900)$ in kaon-nucleon scattering experiments in 1970s but none significant




$K^+d$ scattering data from Bugg (1968), Cool(1970)



# Pentaquarks - false starts

Skepticism about results in kaon-nucleon scattering where many other broad resonances exist and no significant confirmation followed ...

**1986 PDG**

**NOTE ON THE $S$ = +1 BARYON SYSTEM**

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and more recently by Kelly[2] and by Oades.[3] Two new partial-wave analyses[4] have appeared since our 1984 edition. Both claim that the $P_{13}$ and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

# Pentaquarks - false starts

and followed...

1992 PDG

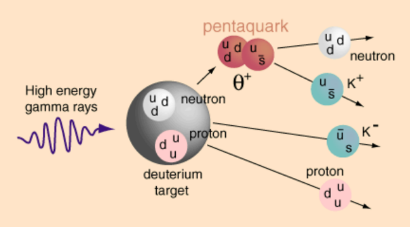
## $Z$ BARYONS
## $(S = +1)$

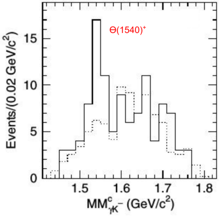
**NOTE ON THE $S = +1$ BARYON SYSTEM**

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 $Z_1(2500)$.

In 1997 the existance of a low-mass pentaquark was predicted with the quark content $uudd\bar{s}$, $m = 1.53$ GeV and $\Gamma < 15$ MeV

In 2003 a narrow peak in the $nK^+$ distribution of $\gamma n \to nK^+K^-$ data was observed at $1.54 \pm 0.01$ GeV at $4.6\sigma$




Phys.Rev.C79:025210,2009

The $\gamma n \to K^+K^-n$ reaction on $^{12}$C has been studied by measuring both $K^+$ and $K^-$ at forward angles. A sharp baryon resonance peak was observed at $1.54 \pm 0.01$ GeV/$c^2$ with a width smaller than 25 MeV/$c^2$ and a Gaussian significance of $4.6\sigma$. The strangeness quantum number ($S$) of the baryon resonance is $+1$. It can be interpreted as a molecular meson-baryon resonance or alternatively as an exotic five-quark state ($uudd\bar{s}$) that decays into a $K^+$ and a neutron. The resonance is consistent with the lowest member of an antidecuplet of baryons predicted by the chiral soliton model.

# Pentaquarks - false starts

Nine other experiments in the next year claimed to observe the $\Theta^+(1540)$ with $> 4\sigma$ significance

$\boxed{\Theta(1540)^+}$ **2004 PDG** $I(J^P) = 0(?^?)$ Status: $***$

As is done through the *Review*, papers are listed by year, with the latest year first, and within each year they are listed alphabetically. NAKANO 03 was the earliest paper.

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

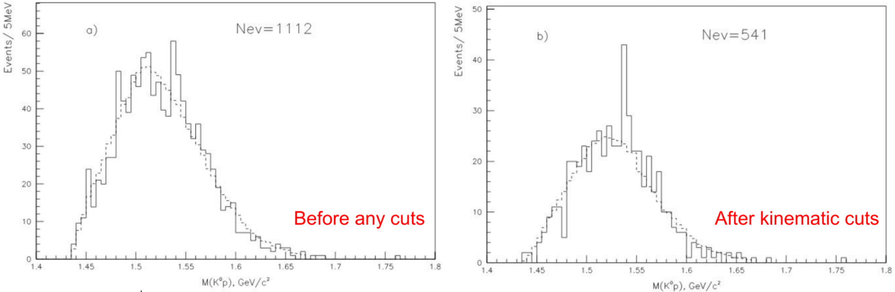
| *VALUE* (MeV) | *EVTS* | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1539.2± 1.6 OUR AVERAGE** | | | | |
| 1533 ± 5 | 27 | [1] ASRATYAN 04 | BC | $\nu, \overline{\nu}$ in $p,d$,Ne, BEBC and 15-ft |
| 1555 ±10 | 41 | [2] KUBAROVSKY 04 | CLAS | $\gamma p \to \pi^+ K^- K^+ n$ |
| 1539 ± 2 | 29 | [3] BARMIN 03 | XEBC | $K^+ \mathrm{Xe} \to K^0 p \mathrm{Xe}'$ |
| 1540 ± 4 ±2 | 63 | [4] BARTH 03 | SPHR | $\gamma p \to n K^+ K^0_S$ |
| 1540 ±10 | 19 | [5] NAKANO 03 | LEPS | $\gamma\, ^{12}\mathrm{C} \to K^+ K^- n X$ |
| 1542 ± 5 | 43 | [6] STEPANYAN 03 | CLAS | $\gamma d \to K^+ K^- p n$ |

PDG gives 3-star status to $\Theta^+(1540)$

Despite the statistical significance of the $\Theta^+(1540)$ some problems were uncovered...

# Pentaquarks - false starts

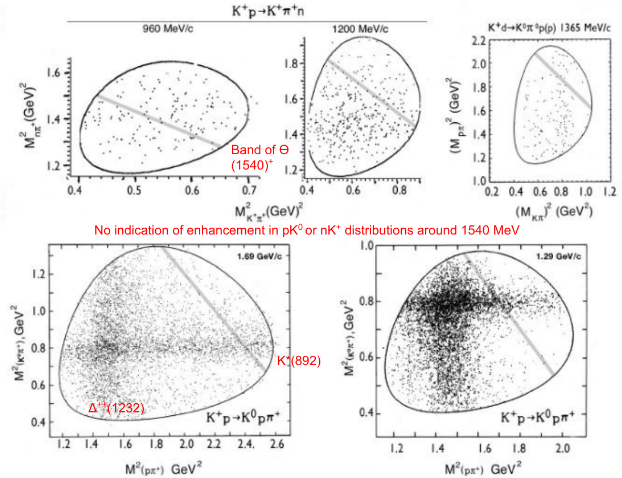
Cuts were found to inadvertantly to enhance signal




Low energy $K^+ - Xe$ collisions in Xenon bubble chamber DIANA. Phys. Atom. Nucl.66, 1715-1718 (2003)

# Pentaquarks - false starts

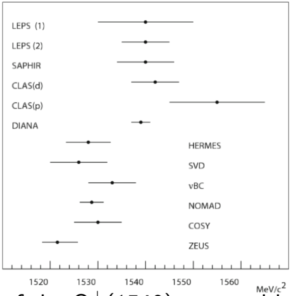
Re-analysis of 70's bubble chamber data where no cuts have been applied do not show a peak



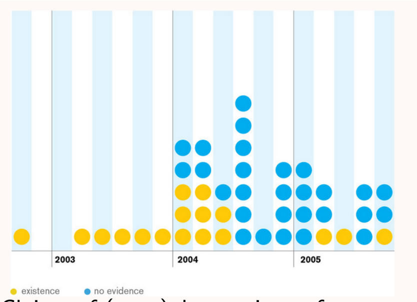

$K^+N \to KN\pi$ reactions in Hydrogen and Deuterium bubble chambers. Bland et al. (1969), Hirata et al. (1971) and Berthon et al. (1973)PDG 2005 reviews

# Pentaquarks - false starts

Mass peak positions varied between experiments far more than expected for a very narrow state and experiments with far greater statistics failed to even see the $\Theta^+(1540)$




Mass of the $\Theta^+(1540)$ reported by various experiments Eur. Phys. J. H 37, 1–31 (2012)




Claims of (non-)observations of $\Theta^+(1540)$ over time symmetrymagazine.org

# Pentaquarks - false starts

$\boxed{\Theta(1540)^+}$ **2006 PDG** $I(J^P) = 0(?^?)$ Status: $*$

OMITTED FROM SUMMARY TABLE

**PENTAQUARK UPDATE**

Written February 2006 by G. Trilling (LBNL).

paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the $\Theta^+$; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the $\Theta^+$; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the $\Theta^+$, in particular, do not exist, appears compelling.

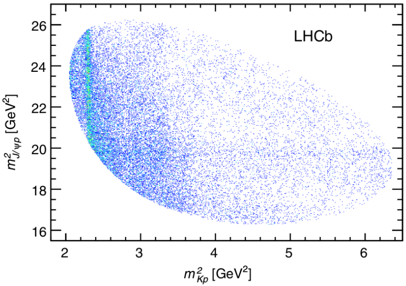
PDG rescinds $\Theta^+(1540)$ 3-star status

And this is how it remained...

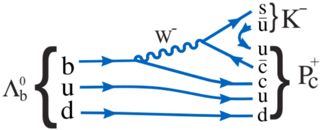
# Table of Contents

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

- LHCb first observed the $\Lambda_b^0 \to J/\psi p K^-$ decay in 2011 when performing a measurement of the $\Lambda_b^0$ lifetime
- Dalitz plot of run 1 (3 $\mathrm{fb}^{-1}$) data shows structures in
  - $m^2_{K^- p}$ due to well-known $\Lambda_b^0 \to \Lambda^*(\to K^- p) J/\psi$ resonances
  - $m^2_{J/\psi p}$ due to ???




*PRL 115, 072001 (2015)*




- Here a resonance decaying strongly to $J/\psi p$ has minimal quark content $uudc\bar{c}$

Perform full amplitude analysis to determine nature of this structure

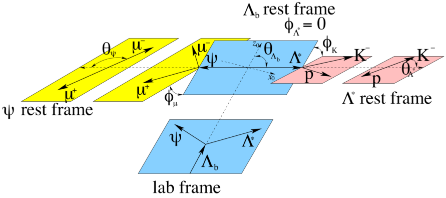
# $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

- Consider the two interfering decay channels

$$\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^- \quad \Lambda_b^0 \to P_c^+ K^-, P_c^+ \to J/\psi p$$

- Fit 6-dimensional phasespace ($m_{K^-p}$ and 5 decay angles) using helicity formalism

$$\mathcal{A}^{\Lambda^*} \equiv \sum_n \mathcal{A}^{\Lambda_b^0 \to \Lambda_n^* \psi}$$



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

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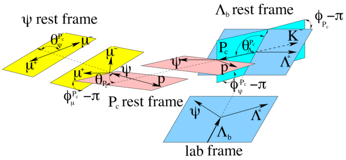
- Fit 6-dimensional phasespace ($m_{K^-p}$ and 5 decay angles) using helicity formalism

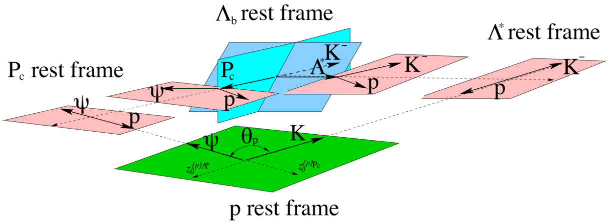
$$\mathcal{A}^{P_c} \equiv \sum_j \mathcal{A}^{\Lambda_b^0 \to P_{cj} K}$$



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

Add two decay chains coherently (at amplitude level, allowing interference)

$$|\mathcal{A}|^2 = |\mathcal{A}^{\Lambda^*} + \mathcal{A}^{P_c}|^2$$

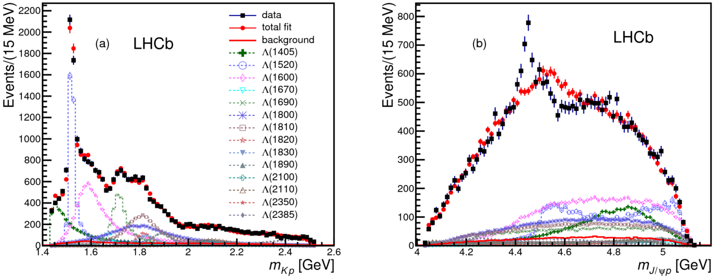


# $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

Fit using only $\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to p K^-$ decay chain

- 146 free parameters from helicity couplings alone

Cannot reproduce structure in seen in $m_{J/\psi p}$

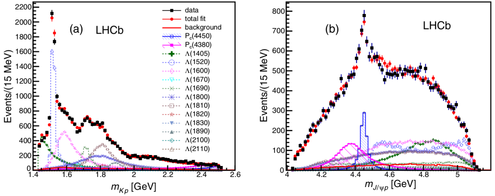


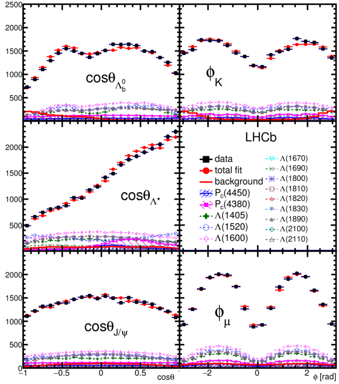
# $\Lambda_b^0 \to J/\psi p K^-$ amplitude analysis

| State | $J^P$ | $M_0$ (MeV) | $\Gamma_0$ (MeV) |
|---|---|---|---|
| $\Lambda(1405)$ | $1/2^-$ | $1405.1^{+1.3}_{-1.0}$ | $50.5 \pm 2.0$ |
| $\Lambda(1520)$ | $3/2^-$ | $1519.5 \pm 1.0$ | $15.6 \pm 1.0$ |
| $\Lambda(1600)$ | $1/2^+$ | 1600 | 150 |
| $\Lambda(1670)$ | $1/2^-$ | 1670 | 35 |
| $\Lambda(1690)$ | $3/2^-$ | 1690 | 60 |
| $\Lambda(1800)$ | $1/2^-$ | 1800 | 300 |
| $\Lambda(1810)$ | $1/2^+$ | 1810 | 150 |
| $\Lambda(1820)$ | $5/2^+$ | 1820 | 80 |
| $\Lambda(1830)$ | $5/2^-$ | 1830 | 95 |
| $\Lambda(1890)$ | $3/2^+$ | 1890 | 100 |
| $\Lambda(2100)$ | $7/2^-$ | 2100 | 200 |
| $\Lambda(2110)$ | $5/2^+$ | 2110 | 200 |
| $\Lambda(2350)$ | $9/2^+$ | 2350 | 150 |
| $\Lambda(2585)$ | ? | $\approx$2585 | 200 |

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

Add two $P_c^+$ components - $P_c$ states describe structure in $m_{J/\psi p}$




| | $P_c(4380)^+$ | $P_c(4450)^+$ |
|---|---|---|
| Mass | $4380 \pm 8 \pm 29$ | $4449.8 \pm 1.7 \pm 2.5$ |
| Width | $205 \pm 18 \pm 86$ | $39 \pm 5 \pm 19$ |
| $J^P$ | $3/2^-$ | $5/2^+$ |
| Fit fraction | $4.1 \pm 0.5 \pm 1.1$ | $8.4 \pm 0.7 \pm 4.2$ |
| Significance | 9 | 12 |

$(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$ also acceptable

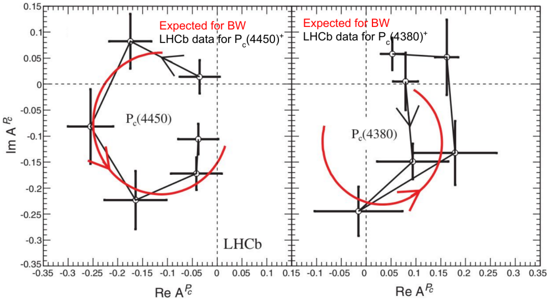
$P_c(4380)^+$ is BROAD

*PRL 115, 072001 (2015)*

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

What about the Argand plots?

- Represent $P_c$ amplitude as 6 points in complex plane with $m_{J/\psi p}$ values equally spaced between $M_{P_c} - \Gamma_{P_c} < M_{P_c} < M_{P_c} + \Gamma_{P_c}$ that are to be fit
- Interpolate between fitted points




*PRL 115, 072001 (2015)*

Despite visual agreement very large statistical errors exist - not conclusive

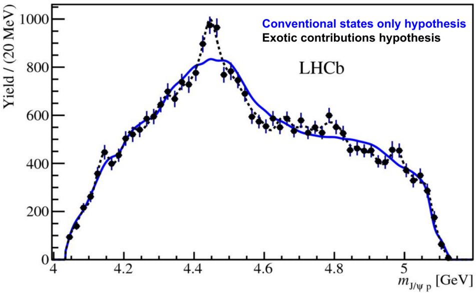
# $\Lambda_b^0 \to J/\psi p K^-$ model independent approach

In the model-dependent analysis above had to make a lot of assumptions

- $\Lambda^*$ spectroscopy is complex - many more higher mass excitations predicted that have not been found experimentally and we dont know how to properly model them
- Want a model-independent method that makes no assumptions about how many $\Lambda^*$ states exist and their parameterisation
- In a moments analysis exotic resonances contribute at orders greater than that of conventional states
- Test hypothesis that data can be described by only $\Lambda^*$ - $H_0$. Use moments with rank achievable with conventional states only

# $\Lambda_b^0 \to J/\psi p K^-$ model independent approach

- Alternative hypothesis $H_1$ where rank of moments is allowed to be large enough to reproduce possible pentaquark structures




*PRL 117, 082002 (2016)*

$H_0$ hypothesis, $H_1$ hypothesis

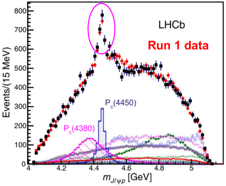
- $H_0$ rejected at more than $9\sigma$
- Cannot rule out that this is due to rescattering effects of ordinary hadrons

# $\Lambda_b^0 \to J/\psi p K^-$ - 1D analysis

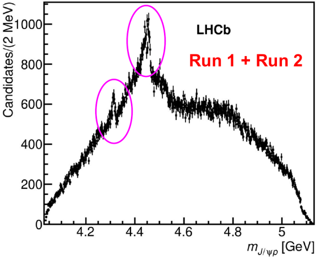
In Run 1:

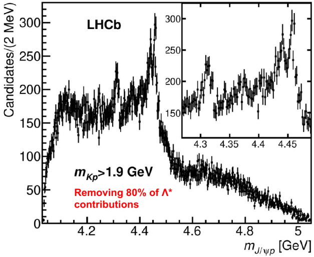
- Model dependent analysis showed exotics in $\Lambda_b^0 \to J/\psi p K^-$ decays
- Exotic contributions near 4450 MeV supported by MI analysis $> 9\sigma$

What about run 2 data...



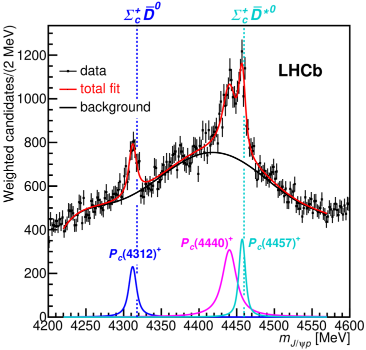

Nine-fold increase in statistics for 2019 analysis! Structure at 4312 MeV evident and $P_c(4450)^+$ resolved into 2 narrower structures



# $\Lambda_b^0 \to J/\psi pK^-$ - 1D analysis

New structures narrow enough (cannot be reflections) to use 1D mass fit with BW amplitudes to begin to analyse nature (amplitude analysis ongoing).

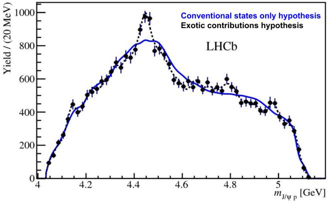



-7.3$\sigma$ for new $P_c(4312)$
-5.4$\sigma$ for 2-peak structure rather than single peak at 4450 MeV
-Fits with/without a broad $P_c$ both describe data well-full amplitude analysis required with comprehensive understanding of dominant $\Lambda^* \to pK^-$ spectrum

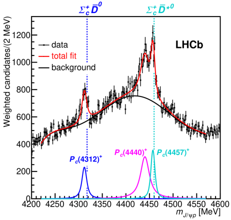
| State | $M$ [ MeV ] | $\Gamma$ [ MeV ] | (95% CL) |
|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+3.7}_{-4.5}$ | $(< 27)$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+8.7}_{-10.1}$ | $(< 49)$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+5.7}_{-1.9}$ | $(< 20)$ |

# The LHCb Pentaquarks

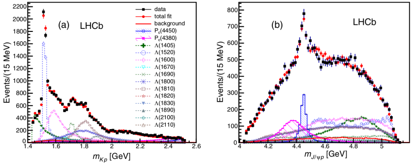
LHCb has used three methods to conclude there are exotics in $\Lambda_b^0 \to J/\psi p K^-$...




2016 model independent analysis




2019 fit to 1D invariant mass distributions

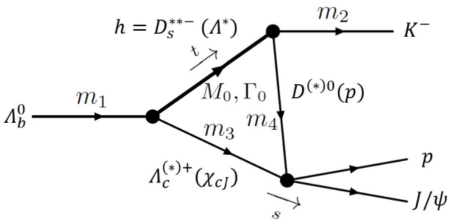



2015 full amplitude analysis

How to interpret these... some ideas...

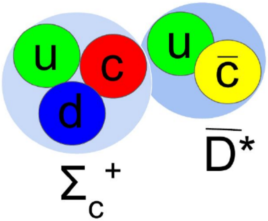
# The LHCb Pentaquarks

Re-scattering effects - triangle diagrams




- $P_c(4457)$ peaks at $\Lambda_c^+(2595)\bar{D}^0$ threshold - $D_{s1}(2860)$ excited strange hadron suitable candidate to be exchanged in triangle
- Purely kinematical effect - $P_c$ not a resonant state
- Some investigations into this in PRL122, 222001 (2019)

Molecular Model - bound state of baryon and meson



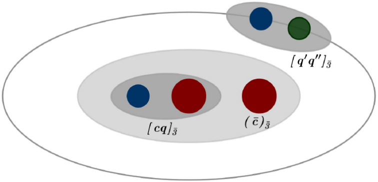

- Three $P_c$ states very close to $\Sigma_c \bar{D}$ thresholds but crucially below
- Molecular models can predict multiplet of states eg. 7 bound states, three of which correspond to the observed $P_c$ states

| $P_c(4312)$ | $P_c(4440)$ | $P_c(4457)$ |
|---|---|---|
| $\Sigma_c^+ \bar{D}^0$ $1/2^-$ | $\Sigma_c^+ \bar{D}^{*0}$ $1/2^-$ | $\Sigma_c^+ \bar{D}^{*0}$ $3/2^-$ |

Molecular + HQSS model. arxiv:1904.01296

# The LHCb Pentaquarks

Compact di-quark model




Tri-quark + light di-quark = colour singlet pentaquark

| $P_c(4312)$ | $P_c(4440)$ | $P_c(4457)$ |
|---|---|---|
| $\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 0$<br>$3/2^-$ | $\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1$<br>$3/2^+$ | $\bar{c}[cu]_{s=1}[ud]_{s=0}; L_P = 1$<br>$5/2^+$ |

arxiv:1904.00446

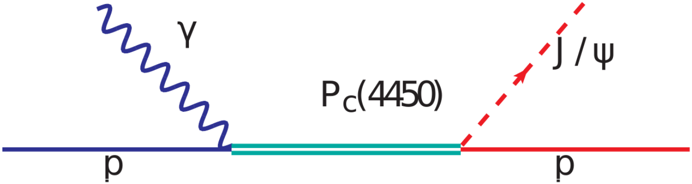
Predicted $J^P$ of $P_c(4312)$ for this model disagrees with all molecular models

# Table of Contents

# Production

Look for the $P_c$ states in other production mechanisms

- JLAB can search for $P_c$ states in $J/\psi$ photoproduction
- Observation of the $P_c$ states here would exclude the $P_c$ being a result of kinematical effects such as triangle singularities



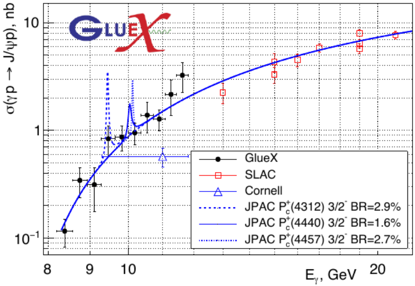

See JLAB talk for more experimental details

# Production

Presented at Hadron 2019

## J/ψ @ GlueX: Search for $P_c$ states

**PRL 123, 072001 (2019): Editor's Suggestion!**




JPAC A.N. Hiller Blin, et al., PRD 94, 034002 (2016).

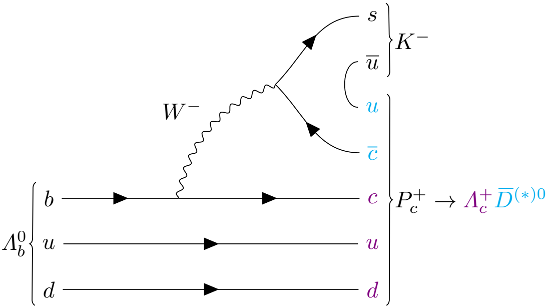
- No evidence of Pc states!
- Model-dependent upper limits at 90% CL (assuming $J^P=3/2^-$):
  - Br($P_c(4312)$ → J/ψ p) < 4.6%
  - Br($P_c(4440)$ → J/ψ p) < 2.3%
  - Br($P_c(4457)$ → J/ψ p) < 3.8%

  [ULs scale as (2J+1)]
- Disfavors hadrocharmonium and some molecular models. Pc's could preferentially couple to other channels?
  - Need consistent picture with $\Lambda_b$ decays.

# Decays to other final states

Look for the $P_c$ states in other final states

- Multitude of possible channels in which $P_c$ states could be observed with models of the $P_c$ states predicting their couplings
- Some models predict higher couplings of the $P_c$ states to $\Lambda_c^+ D^{(*)0}$ in the decay $\Lambda_b^0 \to \Lambda_c^+ D^{(*)0} K^-$ than the discovery channel
- Use these channels to discriminate between models of $P_c$



# Search for other members of the multiplet

Look for the rest of the $P_c$ multiplet

- Each model yields a different multiplet of states
- Potential neutral isospin partners ($c\bar{c}udd$) of $P_c$?
- The obvious $P_c \to J/\psi n$ channel is not reconstructible at LHCb
- Use $\Lambda_b^0 \to \Lambda_c^+ D^- \bar{K}^{*0}$ channel where $P_c \to \Lambda_c^+ D^-$ to search for neutral $P_c$ state