Exotic forms of matter: Multiquark systems

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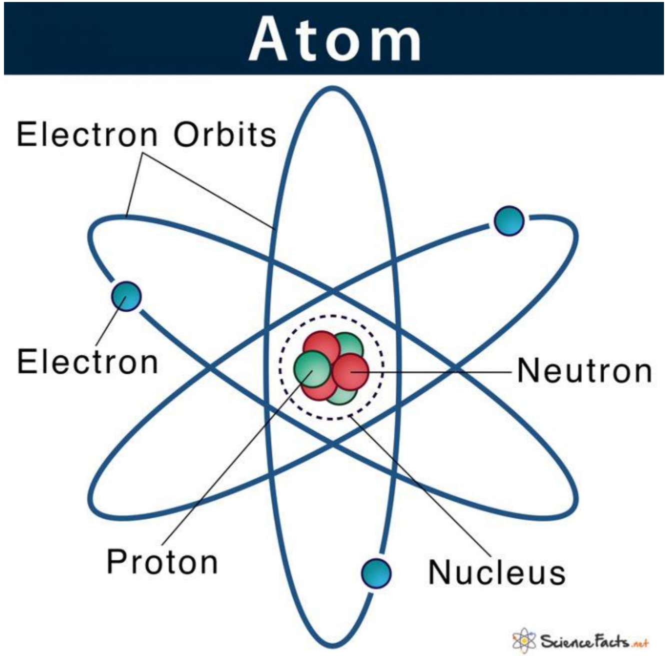
Topics

- Structure of matter: Atoms and nuclei, partons
- History of the quark-parton-model
- Multiquark systems: Tetra- and pentaquarks
- Experiments at the Large Hadron Collider (LHC) in Geneva
- Comparison of **models and theory**

Structure of matter



^{6}Lithium

- Atoms are made of electrons, protons and neutrons
- Protons and neutrons are not elementary, but consist of so-called quarks which are bound by gluons, the carrier particles of the strong force
- There exist 6 different types („flavors") of quarks (and their antiparticles). Proton and neutron contain 3 quarks of 2 different flavors

p=(up, up, down)
n=(up, down, down)

- Elementary particles carry a "color charge": blue, red, green. Composite particles are "colorless" (color confinement)

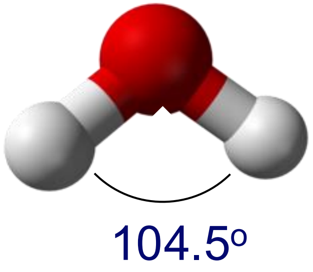
Molecules

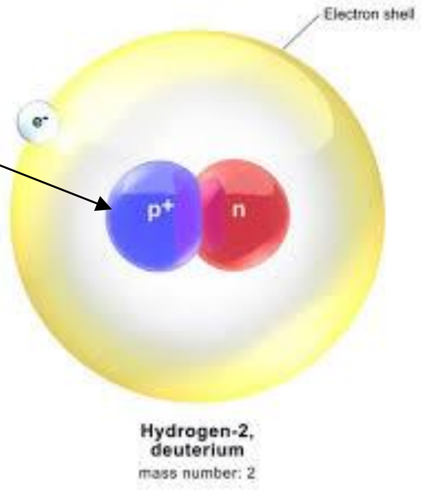
- A **molecule** is a group of two or more atoms that are held together by attractive forces known as chemical bonds
- A simple example is the water molecule of oxygen and hydrogen

- Two nuclei can also form a compound, such as a proton and a neutron forming a deuteron
- The corresponding atom is called deuterium

- In the parton picture, a deuteron is a six-quark system ("hexaquark"), but the quarks are confined in two separate hadrons:
  The deuteron is a "hadronic molecule"

H_2O

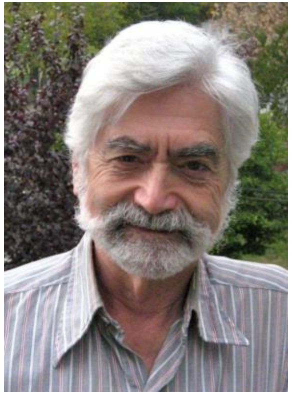




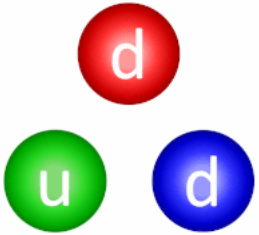
Are there multiquark systems such as tetraquarks or pentaquarks in nature, or can they be produced as short-lived entities ("resonances")?

History of the quark-parton-model

“Aces”



George Zweig, *1937



“Quarks”

Murray Gell-Mann, 1929-2019

1964: Multiquark systems are possible, theoretically

CERN-TH-401
An SU_3 model for strong interaction symmetry and its breaking
Zweig, G.
17 Jan 1964

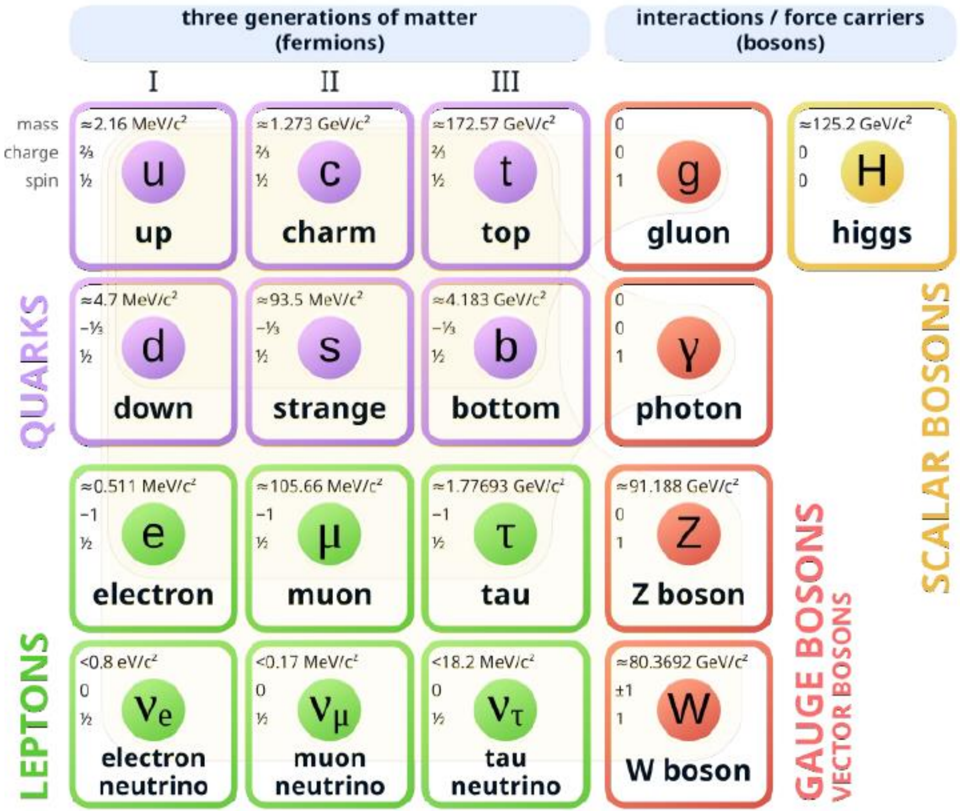
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

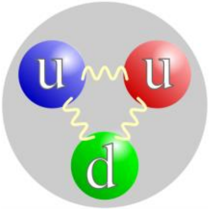
Received 4 January 1964

Standard model of elementary particles

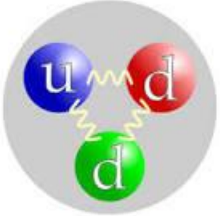


Baryons

Proton



Neutron

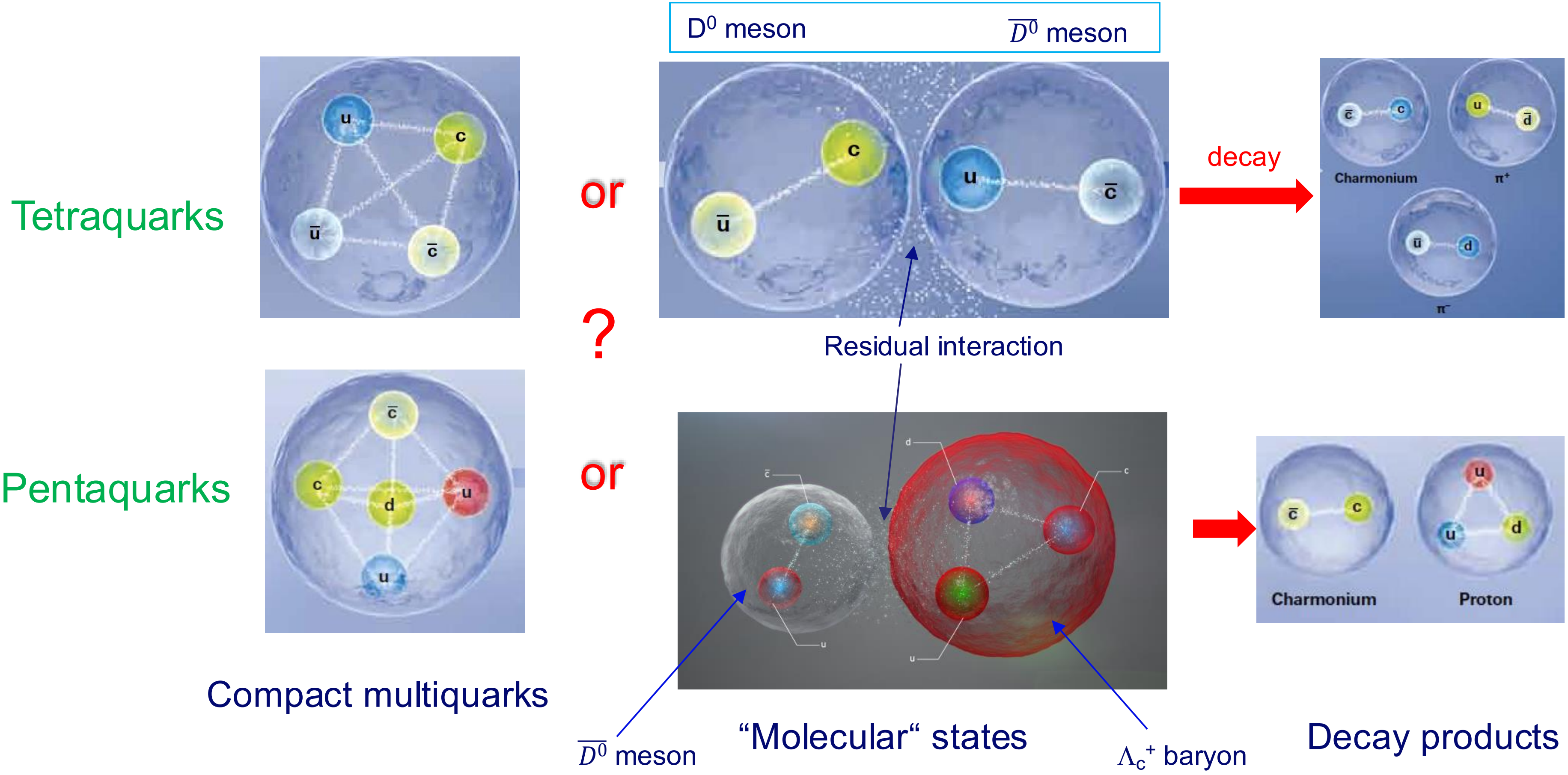


Mesons

π^+, pion

Composite particles are “colorless”

Multiquark systems



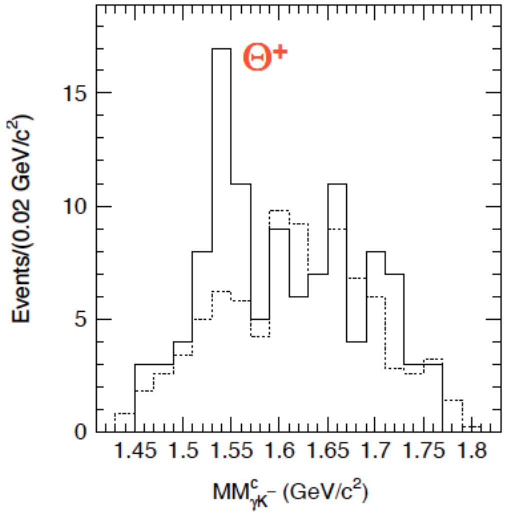
Early searches for strange pentaquarks

- Pentaquarks are made of 4 quarks and an antiquark
- No convincing experimental evidence for many years following the 1964 predictions
- In 2002/3, a Japanese group (LEPS) at the synchrotron SPring-8 published evidence for the Θ^+, a pentaquark consisting of a strange antiquark and 4 quarks, $uudd\bar{s}$ - followed by ~ a dozen supporting experiments worldwide. However, when repeated with better statistics, the evidence vanished.
- "Today, there is little belief that the Θ^+ is real, and it remains a mystery how so many experiments could have claimed statistically-significant evidence for the pentaquark", K.H. Hicks, Eur. Phys. J. H 37, 1–31 (2012).

- But: In 2025, new experiments are planned with an upgraded LEPS2 facility, $\gamma n \rightarrow K^- \Theta^+$ https://arxiv.org/abs/2503.02528

Phys.Rev.Lett. 91 (2003) 012002

hep-ex/0301020



T. Nakano et al., LEPS collaboration (Laser Electron Photon Experiment at SPring-8)

Lifetime $\tau \approx 10^{-23}$ s

Recent searches for charmed tetra- and pentaquarks

- Multiquarks could be discovered more easily when they contain the much heavier charm quarks ($m \approx 1.27$ GeV) rather than strange quarks ($m \approx 93.5$ MeV): Although the strong interaction is "flavor-blind" according to quantum chromodynamics (QCD), the quark mass influences the dynamics indirectly because the binding strength is proportional to the mass (for heavier quarks like charm quarks, the intrinsic Higgs-generated mass dominates).

- The expected charmed multiquarks have higher masses than strange multiquarks.

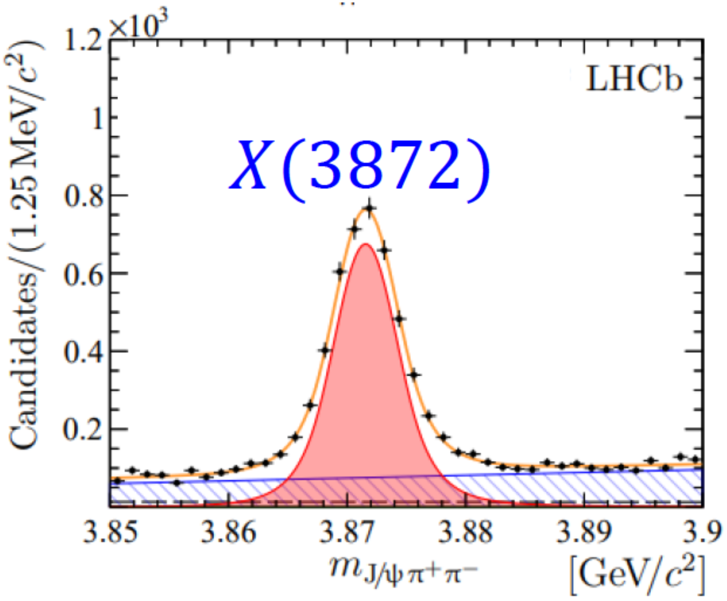
- An early success was the discovery of a tetraquark candidate, X(3872) in e^+-e^- collisions in 2003 by the BELLE collaboration at KEK Tsukuba.

- In p-p collisions at the Large Hadron Collider in Geneva, the LHCb collaboration has successfully searched for such short-living states tetraquark and pentaquark states.

A promising candidate for a charmed tetraquark

- The **X(3872)** is an exotic meson with a mass of 3871.68 MeV/c^2. It was first discovered in 2003 by the Belle experiment in Japan and later confirmed by other experimental collaborations. Several theories have been proposed for its nature, such as a mesonic molecule of D-mesons,or a compact tetraquark ($u\bar{u}c\bar{c}$).

- The quantum numbers of X(3872) have been determined by the LHCb experiment at CERN's Large Hadron Collider in March 2013. The values for J^{PC} are 1^{++}. The first evidence of X(3872) production in the quark–gluon plasma have been reported by the CMS experiment at CERN in January 2022.



The charmed X(3872)

The **Belle experiment** was a particle physics experiment conducted by the **Belle Collaboration**, an international collaboration of more than 400 physicists and engineers, at the High Energy Accelerator Research Organisation (KEK) in Tsukuba, Ibaraki Prefecture, Japan. The experiment ran from 1999 to 2010.

The **X(3872)** was first discovered in 2003 by the Belle experiment

Belle detector

Large Hadron Collider (LHC) / CERN

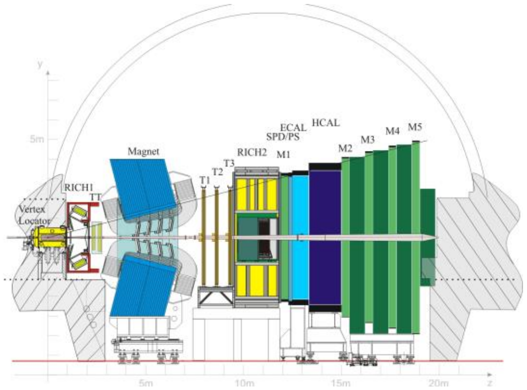
SPS

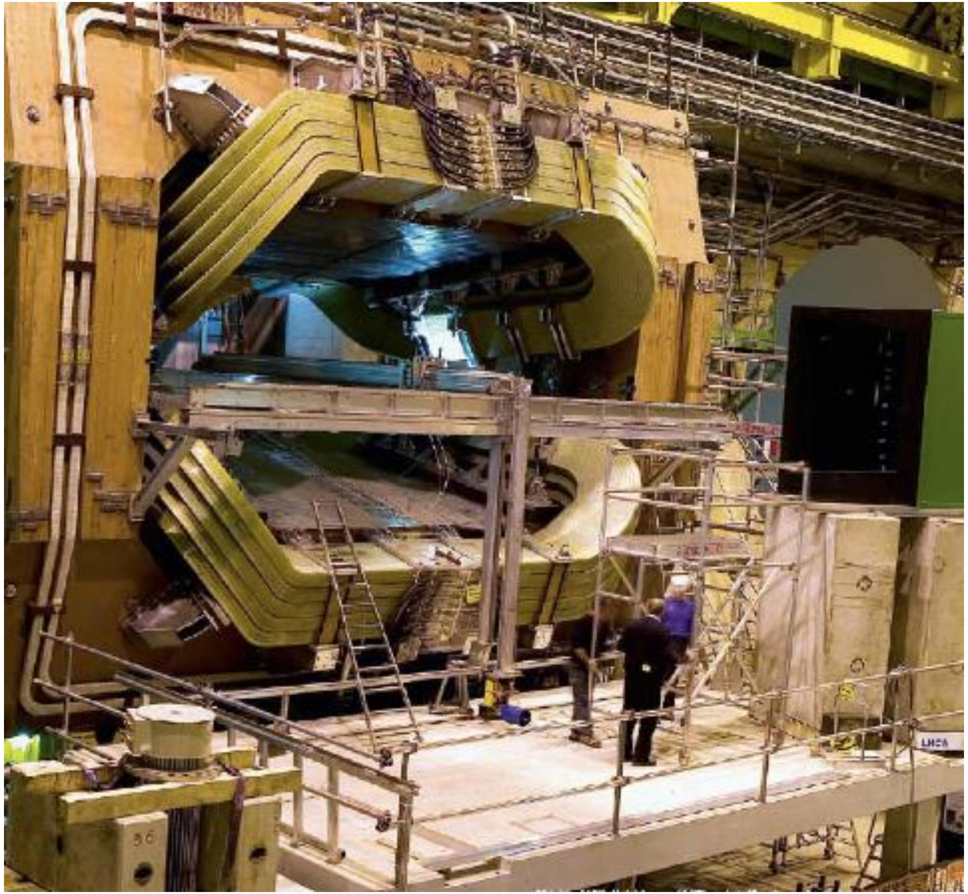
p-p @ 7,8,13,13.6 TeV: Higgs physics, Multiquark systems

In addition, **p-Pb** and **Pb-Pb** heavy-ion collisions are being investigated

The LHCb detector @ CERN

The 5600-tonne LHCb detector is made up of a forward spectrometer and planar detectors. It is 21 metres long, 10 metres high and 13 metres wide, and sits 100 metres below ground near the town of Ferney-Voltaire, France. About 1565 scientists, engineers and technicians from 20 countries make up the LHCb collaboration.





Pentaquark candidates: Mass spectrum of Λ_b^0 decay

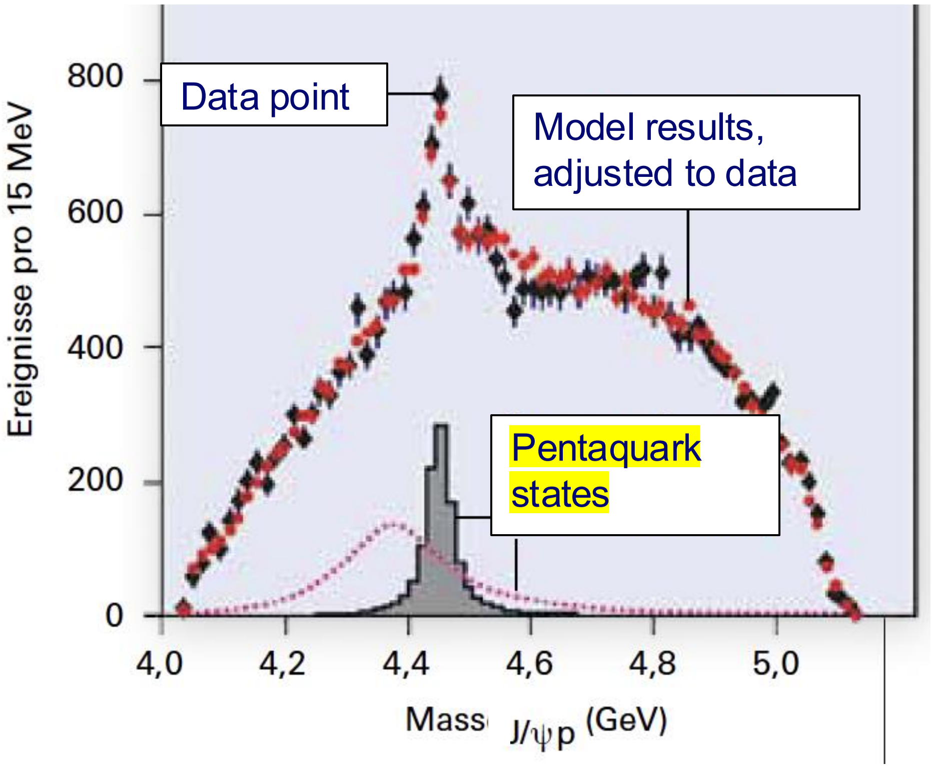
LHCb collab., PRL **115**, 072001 (2015):
Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_0^b \rightarrow J/\psi K^- p$ decays

Observed in 7 and 8 TeV p-p collisions

1) mass of 4380 MeV,
   width of 205 MeV

2) mass of 4449.8 MeV,
   width of 39 MeV.

Quark content: P ($uudc\bar{c}$); K^- = ($\bar{u}s$); p=(uud)
J/ψ=($c\,\bar{c}$); Λ_b^0=(udb)

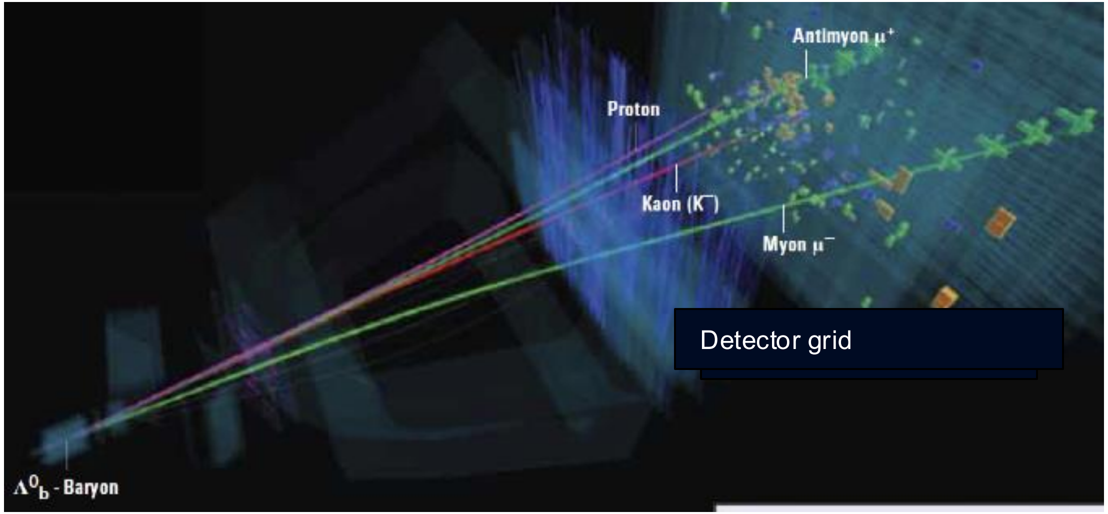


Compact pentaquark or molecular states?

Lifetime ≈ $1.7 \cdot 10^{-23}$ s

Detection of the $\Lambda_b{}^0$ decay fragments

How does the decay look like in the LHCb detector?



$$\Lambda_0{}^b \longrightarrow J/\psi K^- p$$

↓

$$\mu^+\mu$$

A new sharp pentaquark resonance: Mass spectrum of B⁻ decay

$B^- \rightarrow J/\psi\ \Lambda\ \bar{p}$

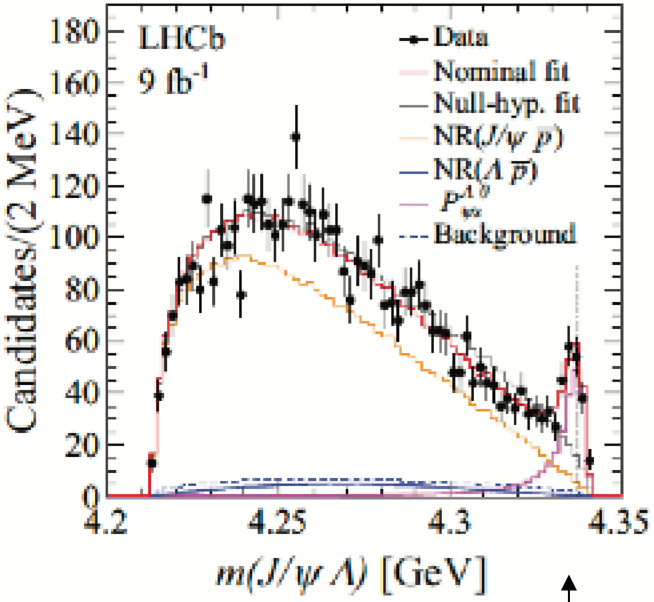
$(ub) \rightarrow (c\bar{c})(uds)(\bar{u}\bar{u}\bar{d})$

Pentaquark resonant state

$$P^0_{c\bar{c}s} = (c\bar{c}sud)^0, J^P = 1/2^-$$

at 4338.2 MeV, ΓH 7 MeV width,

Lifetime $\tau \approx 10^{-22}$ s, high statistical significance ≈ 14σ



$P^0_{c\bar{c}s} = (c\bar{c}sud)^0$

Compact multiquark or hadronic molecule?

R. Aaij *et al.* (LHCb Collaboration), Observation of a $J/\psi\Lambda$ resonance consistent with a strange pentaquark candidate in $B^- \rightarrow J/\psi\Lambda\bar{p}$, Phys. Rev. Lett. **131**, 031901 (2023).

Comparison of models and theories

- Experimental results must be compared with model predictions to decide whether the exotic short-lived multiquark systems are compact or molecular states.

- Compact tetra-/pentaquark states are expected to correspond to solutions of the four-/ five-body Schrödinger equation

$$(H - E)\Psi_{JM} = 0$$

with the Hamiltonian in a nonrelativistic quark model

$$H = \sum_i \left(m_i + \frac{\mathbf{p}_i^2}{2m_i} \right) - T_{cm}$$

$$- \frac{3}{16} \sum_{i<j=1}^{5} \sum_{a}^{8} \lambda_i^a \lambda_j^a V_{ij}(\mathbf{r}_{ij})$$

- For results, see the forthcoming work with Emiko Hiyama, Atsushi Hosaka and Makoto Oka at RIKEN: Is there a resonance indicating a compact pentaquark? Today, most theories favor the molecular interpretation for charmed pentaquarks

Conclusion

- The possible existence of short-lived multiparton states – in particular, tetraquarks and pentaquarks –, has been predicted by Zweig and Gell-Mann in 1964
- Early attempts to detect strange pentaquarks starting with the LEPS experiment at SPring-8 in 2002 remain inconclusive, but will be revived in the future
- Likely candidates for tetraquarks have been found since the discovery of the X(3872) resonance by Belle in 2003
- LHCb has since 2015 discovered charmed pentaquarks, with a new, statistically very significant result for ($c\bar{c}sud$) in 2023
- Definite results (compact or molecular?) about tetra- and pentaquarks are required for firm conclusions about the nature of the strong interaction, and for a better understanding of quantum chromodynamics

Thank you for your attention !