The newly discovered Ω_c resonances and doubly charmed Ξ_{cc} state

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Outline

- Introduction to the standard and non-conventional hadrons
- Particle Factories: LHCb
- New Ω_c resonances: b-partners and other possible resonances
- Ξ_{cc} state: b-partners and other doubly/triply charmed-bottom baryons
- Concluding remarks

❖ Introduction to the standard and non-conventional hadrons

Dictionary:

Hadron: a Greek word (hadros) means “composite”

Meson: comes from the Greek word “mesos”, which means “intermediate”
The first discovered meson was π meson which has a mass between e and P.

Baryon: a Greek word (barys) means “heavy”.

Quark:

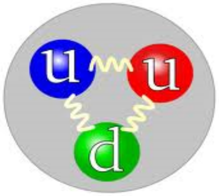
Three quarks for Muster Mark!
Sure he hasn't got much of a bark
And sure any he has it's all beside the mark.

Gluon: they "glue" quarks together

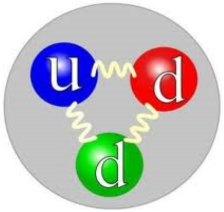
Resonances: excited states with the same spin and quark contents as the ground state

Exotics: non-conventional hadrons

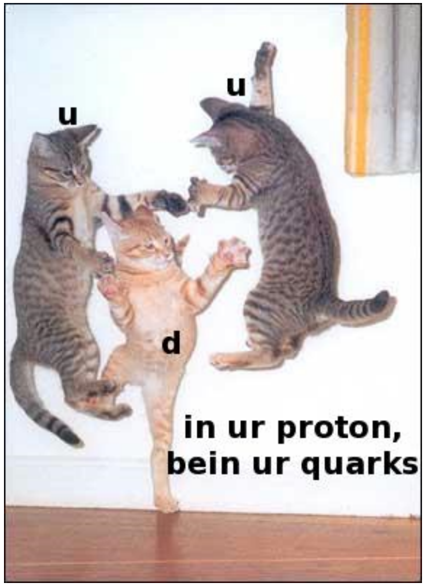
The famouse baryons

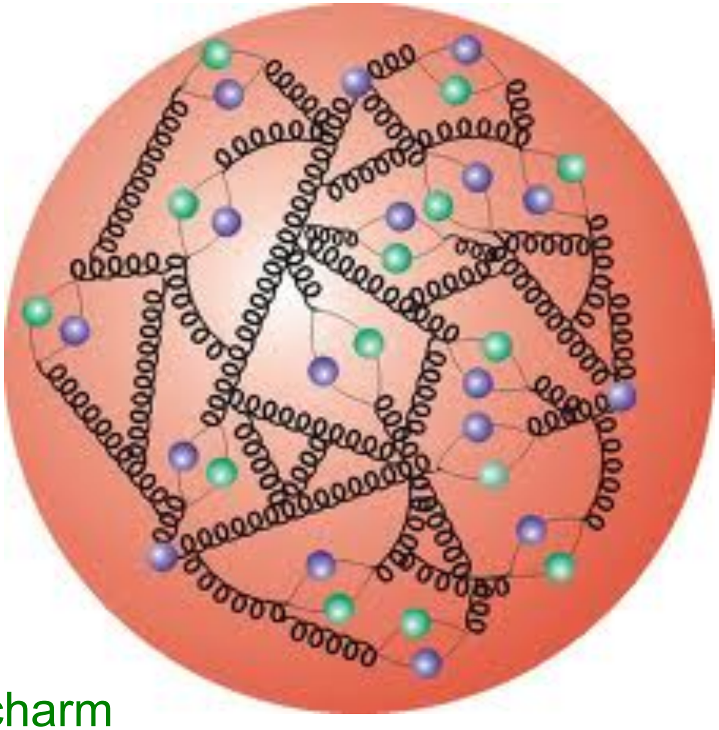


proton



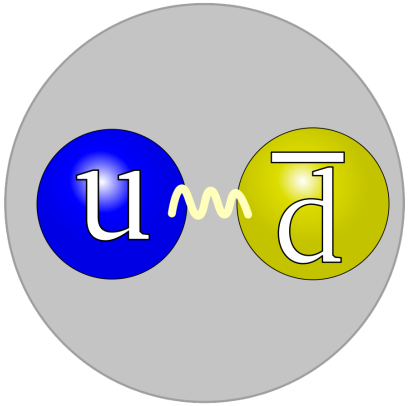
neutron



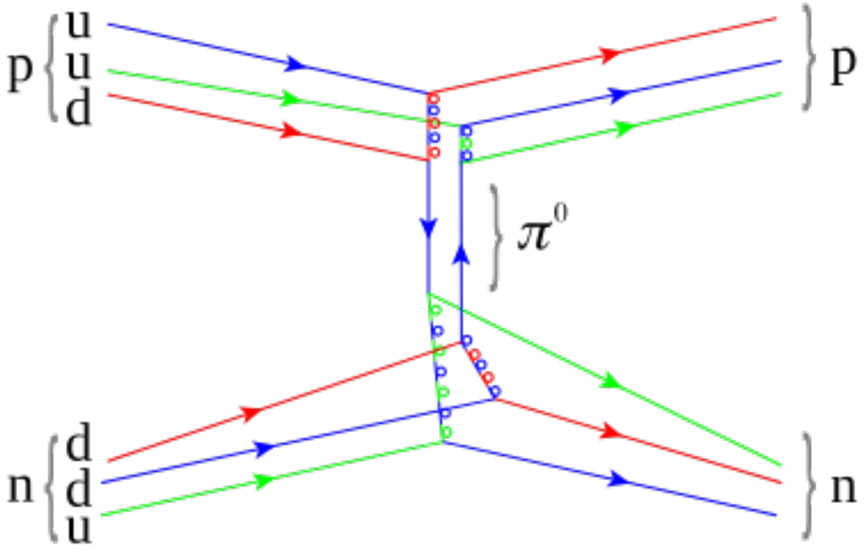


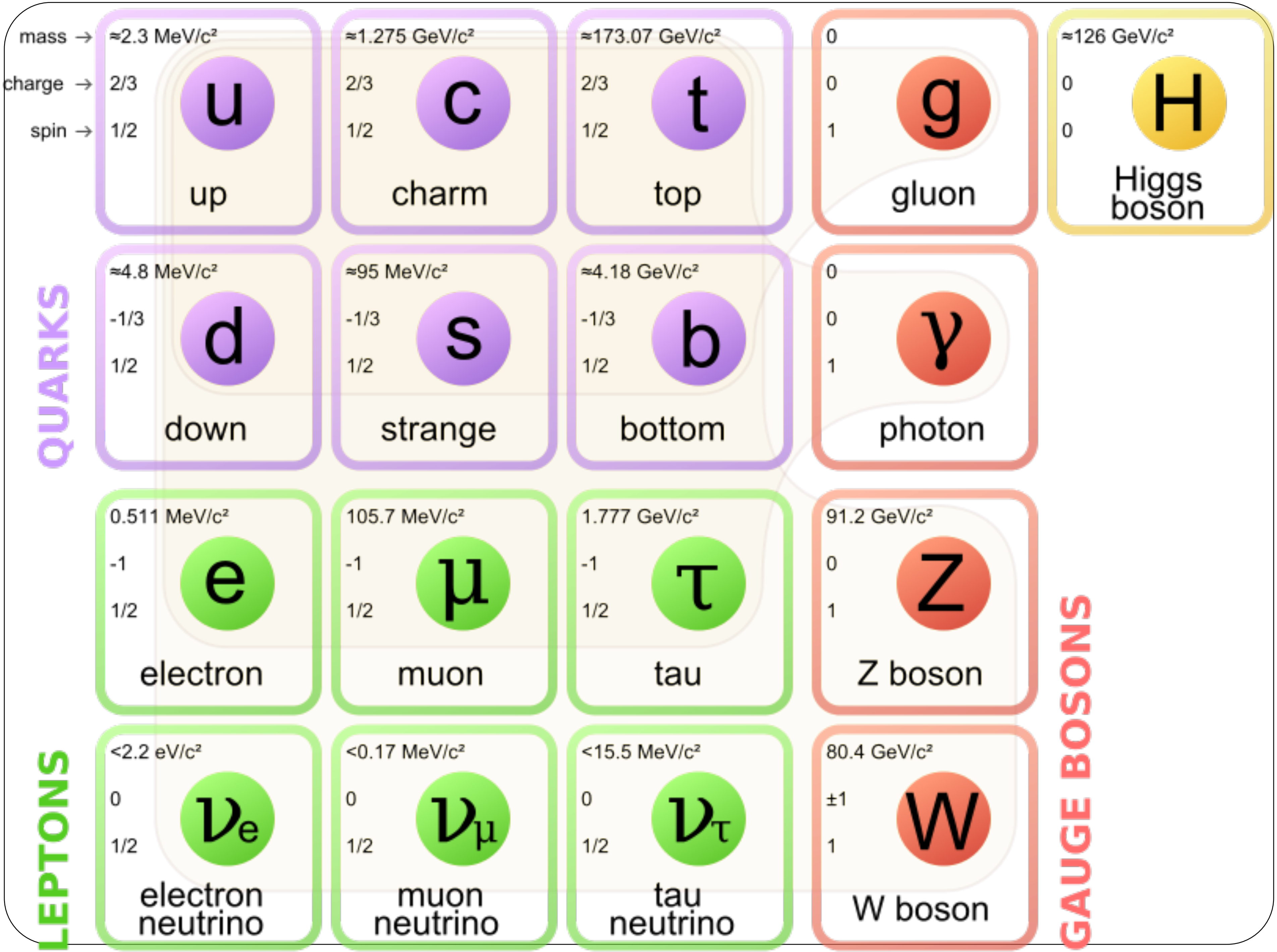
Nucleons have also strange and charm content !!!!!!!!!!!!!!!

The famouse meson: π



π+





mass →
charge →
spin →
QUARKS
LEPTONS
GAUGE BOSONS
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson

6-1=5 quarks: a lot of hadrons. Top quark does not make any bound state.

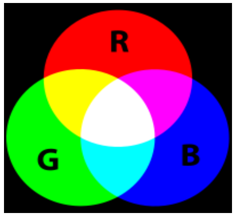
Among all hadrons only proton and neutron are stable. Neutrons have infinite life-time only inside the nuclei. A free neutron decays to proton after 880.2 +- 1.0 s via the beta decay. The rest of particles are produced at hadron colliders and live only about 10^{-18}------10^{-12} s.

Importance of other hadrons and quarks !!!!!!!!!!!!!!

❖Standard and non-conventional (exotic) particles

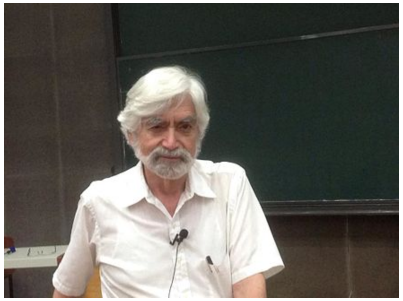
Standard hadrons

- Mesons: one quark and one anti-quark (color+anticolor=white)
- Baryons: 3 quarks (anti-quarks)



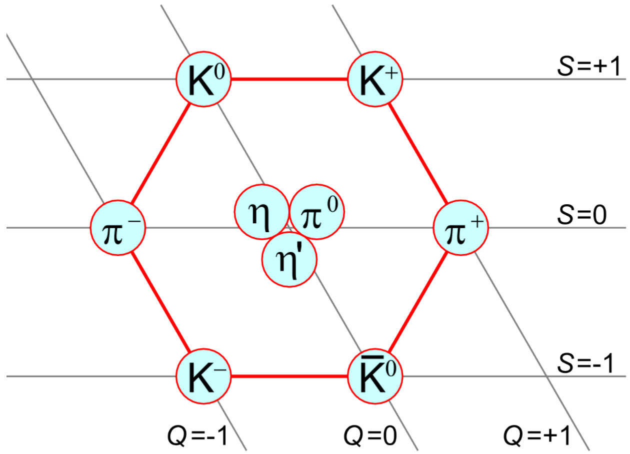
The standard hadrons are well described by the quark model (classification scheme for hadrons in terms of their valence quarks), independently proposed in 1964 by

Murray Gell-Mann

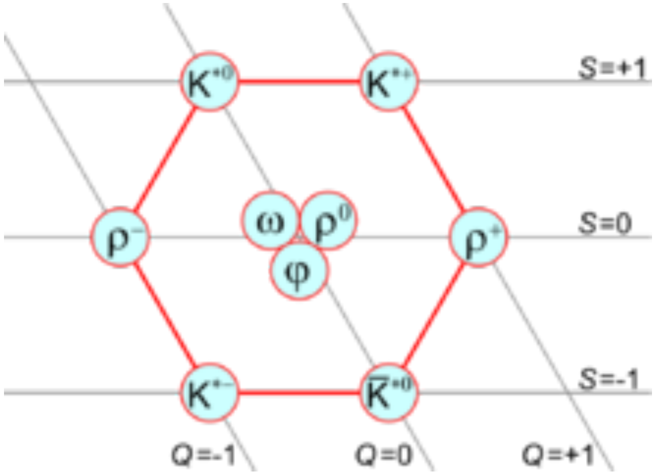


George Zweig

Meson Multiplets

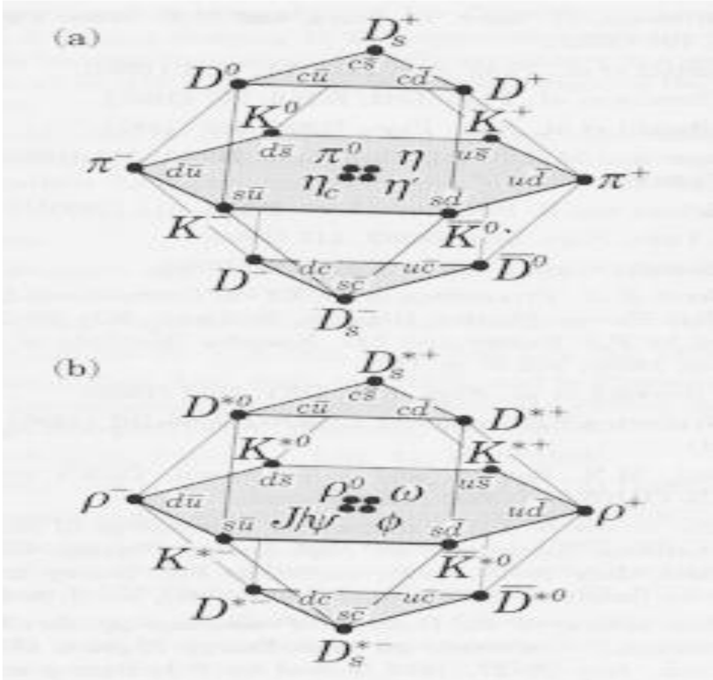


Light PS Mesons



Light Vector Mesons

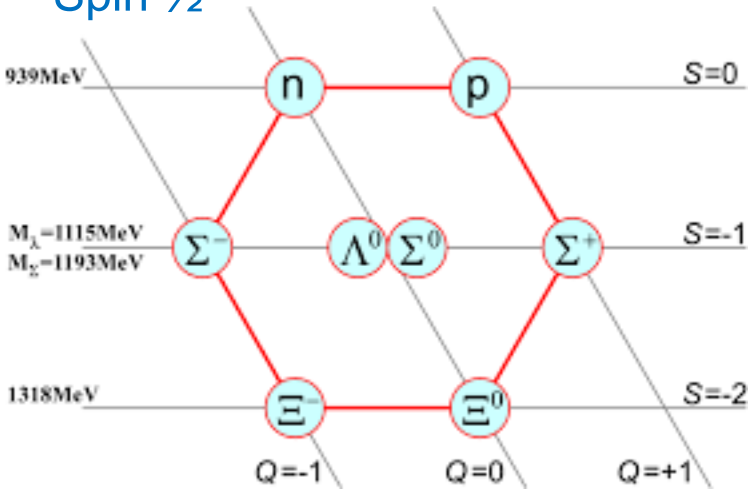
Heavy and Light Mesons:



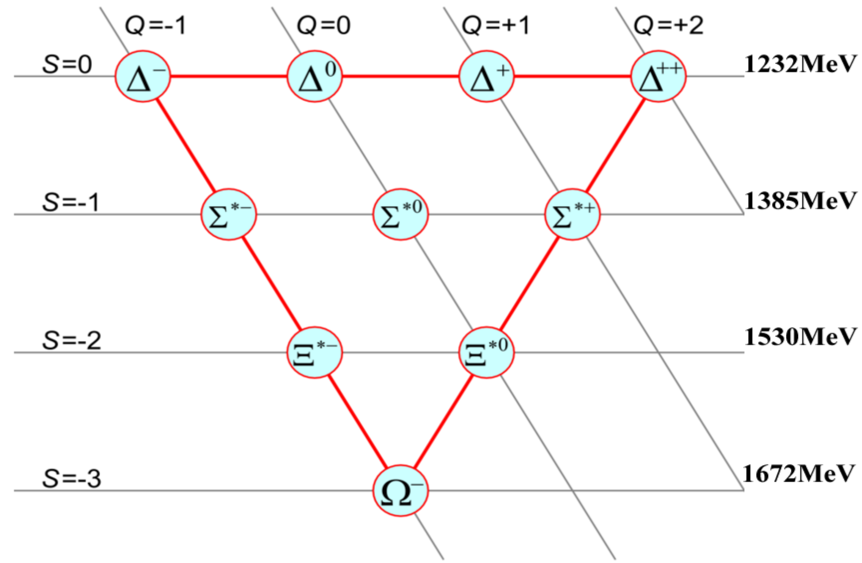
All light and heavy mesons predicted by theory have been discovered in the experiment. Even their many excited states. Theoretical works on excited mesons are welcome.

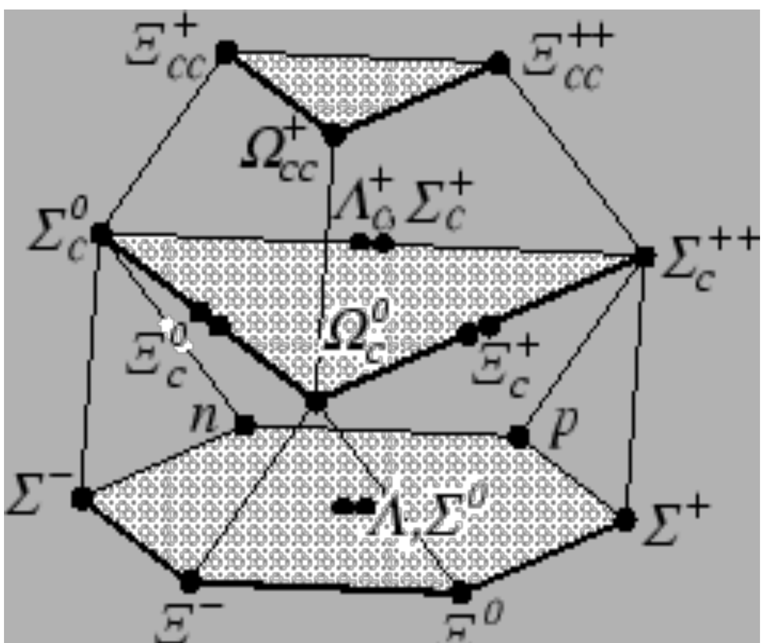
Baryon Multiplets

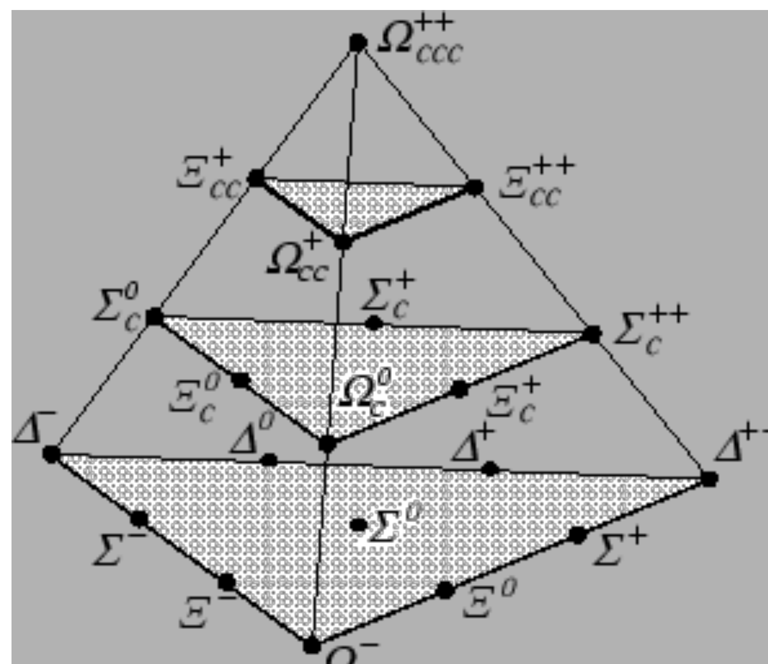
Spin ½



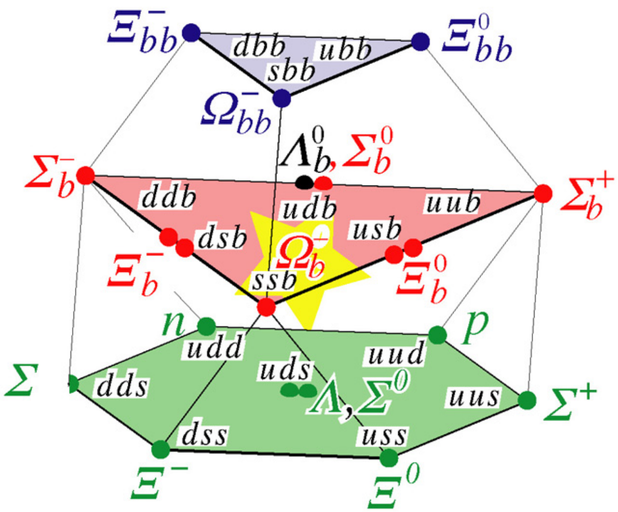
Spin 3/2

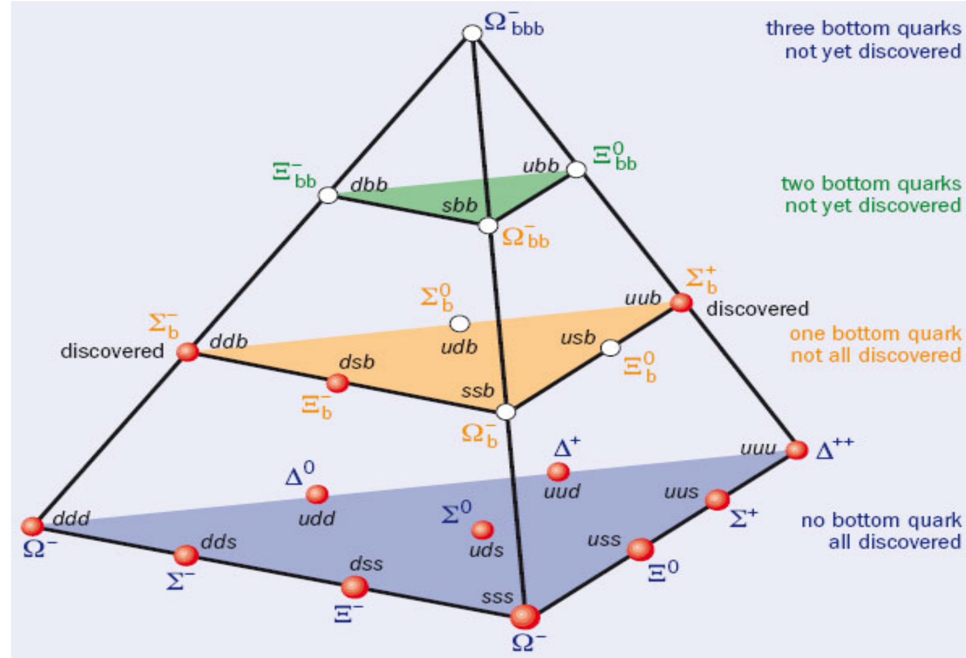






$J = 1/2$ b Baryons





Ξ_{bb}
Ω_{bb}
Ξ_{bc}
Ω_{bc}
Ξ_{cc}
Ω_{cc}
Ξ'_{bc}
Ω'_{bc}

Ξ^*_{cc}
Ω^*_{cc}
Ξ^*_{bc}
Ω^*_{bc}
Ξ^*_{bb}
Ω^*_{bb}

Baryon
Ω_{bbc}
Ω_{ccb}

Baryon
Ω^*_{bbc}
Ω^*_{ccb}
Ω^*_{bbb}
Ω^*_{ccc}

Situation in the Experiment

1- all light baryons and many of their resonances have been discovered.

2-all single-charmed baryons have been observed. Recently some Ω_c resonances have also been observed by LHCb.

3- Except spin 3/2 Ω^*_b all single b-baryons have been discovered.

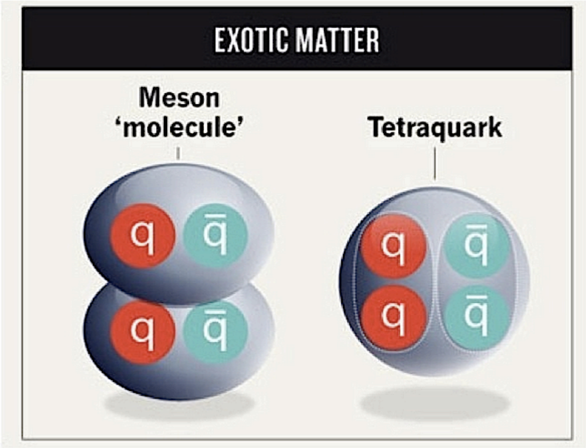
4- Only Ξ_{cc} as doubly charmed baryons has been seen.

5- No doubly-bottom as well as triply charmed/bottom baryons have been discovered yet.

Both the quark model and theory of strong interactions, QCD, do not exclude the non-conventional structures out of $q\bar{q}$ and qqq structures . For this, both experimentalists and theoreticians are searching for these structures for many decades. They have made a good progress: they have found many exotic states and could describe their physical properties.

Well-known exotic states:

Tetraquarks: diquark-antidiquark
Meson molecules: bound states of two mesons

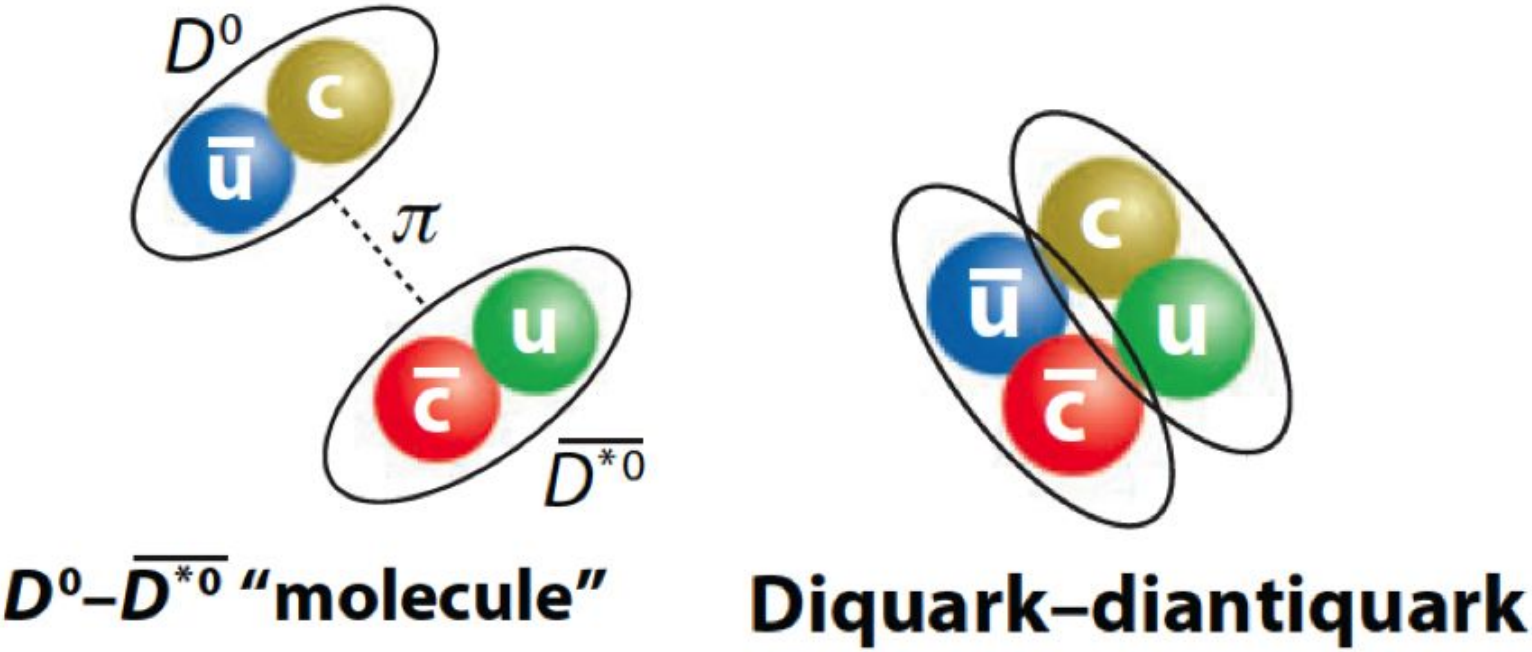


Famous Candidates:

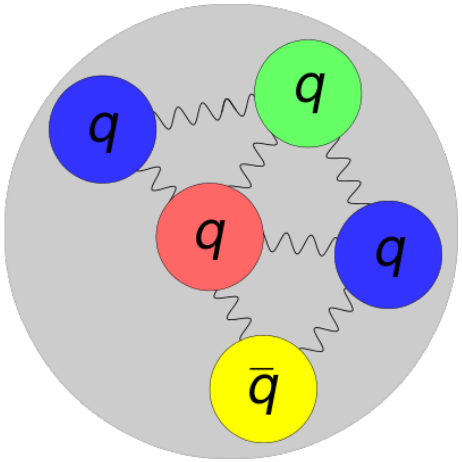
X (3872): 2003 Belle
D_{sJ}(2632): 2004 Fermilab SELEX
Z(4430): 2007 Belle
Y(4140) : 2009 Fermilab, 2012 CMS, 2013 D0,
Belle did not found, LHCb confirmed
Zc(3900): 2013 BESIII, Belle
Z(4430):2014 LHCb
X(5568): February 2016 D0, LHCb and CMS did not found.
X(4274), X(4500) and X(4700): June 2016 LHCb

For a history on theoretical studies see for instance: S. S. Agaev, K. Azizi, H. Sundu, *Phys.Rev. D93 (2016) no.7, 074002* ; *Phys.Rev. D93 (2016) no.11, 114036* .

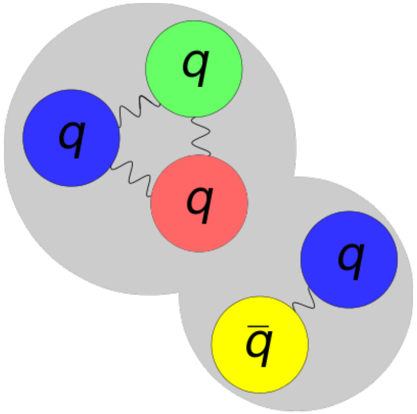
X (3872)


D^0
c
$\bar{u}$
π
u
$\bar{c}$
$\overline{D^{*0}}$
D^0–$\overline{D^{*0}}$ "molecule"
c
$\bar{u}$
u
$\bar{c}$
Diquark–diantiquark

Pentaquarks:



4 quark-1 antiquark



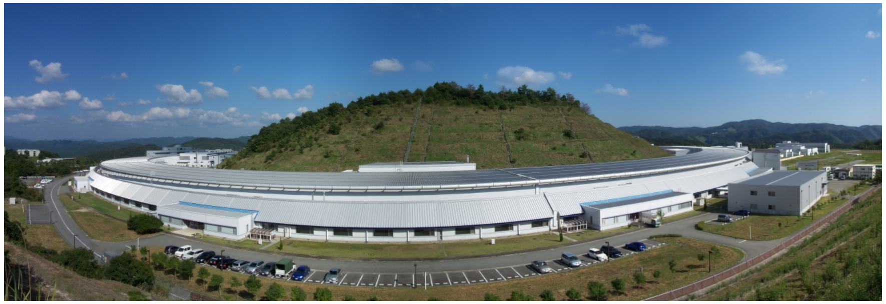
Baryon-Meson Molecule

Famous Candidates:

Pentaquarks have a long experimental history:

Θ^+: 2003, LEPS reported a resonance of 1540 MeV (uudd---anti-s).

LEPS (Laser Electron Photon Experiment) at
SPring-8 (an acronym of Super Photon Ring – 8 GeV)
Is located at hyogo Japan



The 2008 review of PDG ruled out the existence of this resonance. Despite null results from many collaborations LEPS announced a Penta state of 1524 MeV in 2009.

For a historical review see the following Ref. and references therein:

K. Azizi, Y. Sarac, H. Sundu, arXiv:1612.07479

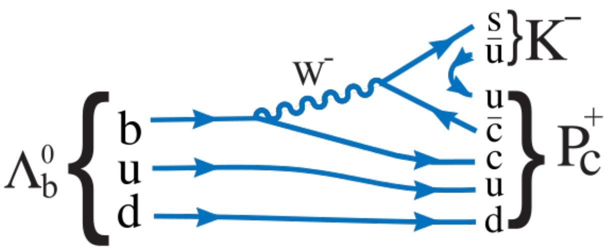
LHCb Pentaquarks, 2015:P_c (4380) and P_c(4450)

R. Aaij et al. [LHCb Collaboration], Phys. Rev. Lett.115, 072001 (2015).

The LHCb collaboration[1]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, which we refer to as charmonium-pentaquark states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis of the three-body final-state reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.



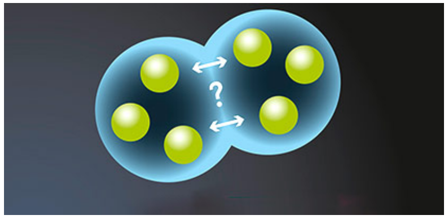
Di-baryons: six quark states, baryon molecules

2014: WASA detector@Cooler Synchrotron (COSY) Collaboration-Jülich, Germany

Evidence for a New Resonance from Polarized Neutron-Proton Scattering

Exclusive and kinematically complete high-statistics measurements of quasifree polarized $\vec{n}p$ scattering have been performed in the energy region of the narrow resonancelike structure d^* with $I(J^P) = 0(3^+)$, $M \approx 2380$ MeV, and $\Gamma \approx 70$ MeV observed recently in the double-pionic fusion channels $pn \to d\pi^0\pi^0$ and $pn \to d\pi^+\pi^-$. The experiment was carried out with the WASA detector setup at COSY having a polarized deuteron beam impinged on the hydrogen pellet target and utilizing the quasifree process $\vec{d}p \to np + p_{\text{spectator}}$. This allowed the np analyzing power, A_y, to be measured over a broad angular range. The obtained A_y angular distributions deviate systematically from the current SAID SP07 NN partial-wave solution. Incorporating the new A_y data into the SAID analysis produces a pole in the ${}^3D_3 - {}^3G_3$ waves in support of the d^* resonance hypothesis.

$NN \quad \Delta\Delta \quad \ldots\ldots$

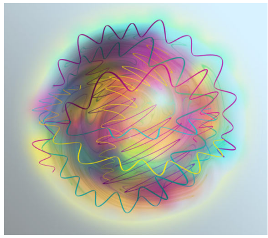


More investigations are needed.

Hybrids: quark-antiquark, Gluon

Candidates (seen by different collaborations) :

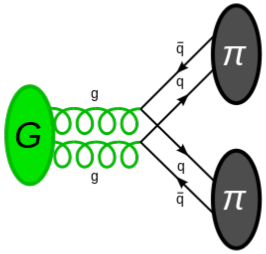
$\pi_1(1400\ ),\ \pi_1(1600),\ \pi(1800),\ \eta_2(1870)$,....



Glueballs (gluonium, gluon-ball): made of only gluons

Candidates (seen by different collaborations) :

$f_0(500)$, $f_0(980)$, $f_0(13800)$, $f_0(1500)$, $f_0(1710)$, X(3020),.....



Possible light and heavy Hybrids and Glueballs need more theoretical and Experimental investigations.

Theoretical appoaches

These objects which are formed in low energies very far from the "asymptotic freedom" and perturbative region.

To investigate their properties, we need some non-perturbative approaches.

QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \bar{\psi}_q (i \not{D} - m_q) \psi_q$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f^{abc} G^b_\mu G^c_\nu ,$$

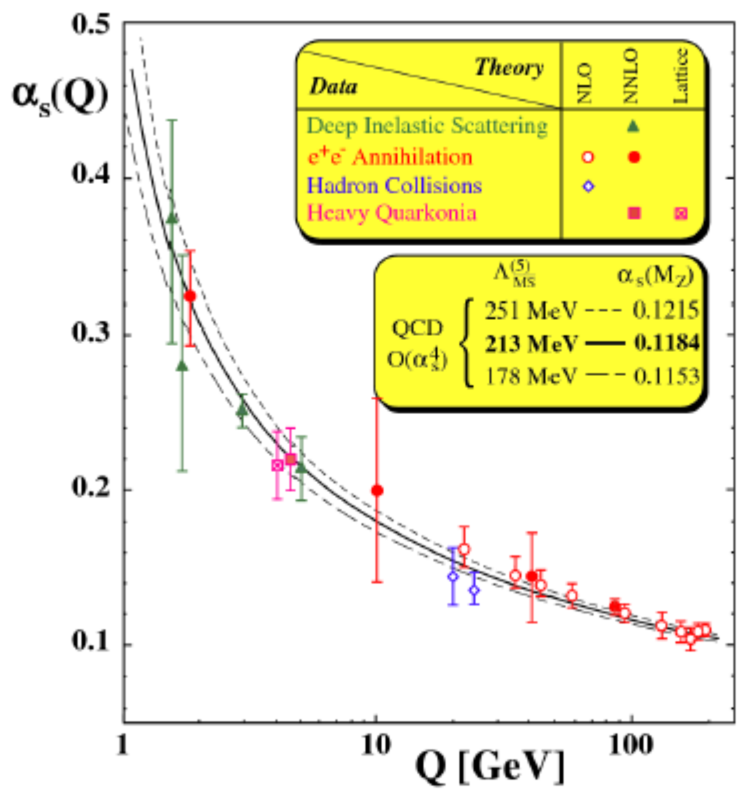
$$\not{D} = \mathcal{D}_\mu \gamma^\mu$$

$$\mathcal{D}_\mu = \partial_\mu + i \frac{g}{2} \lambda^a G^a_\mu$$

In principle, besides the dinamics of quarks and gluons, this lagrangian should be responsible for determination of hadronic properties. Unfortunately, it is valid only in a limited region.

➢In very high energies, due to “asymptotic freedom” we can use this Lagrangian and perturbation theory. However, when energy is decreased the coupling constant between quarks and gluons becomes large and perturbation theory fails.

S. Bethke, J Phys G 26, R27 (2000)

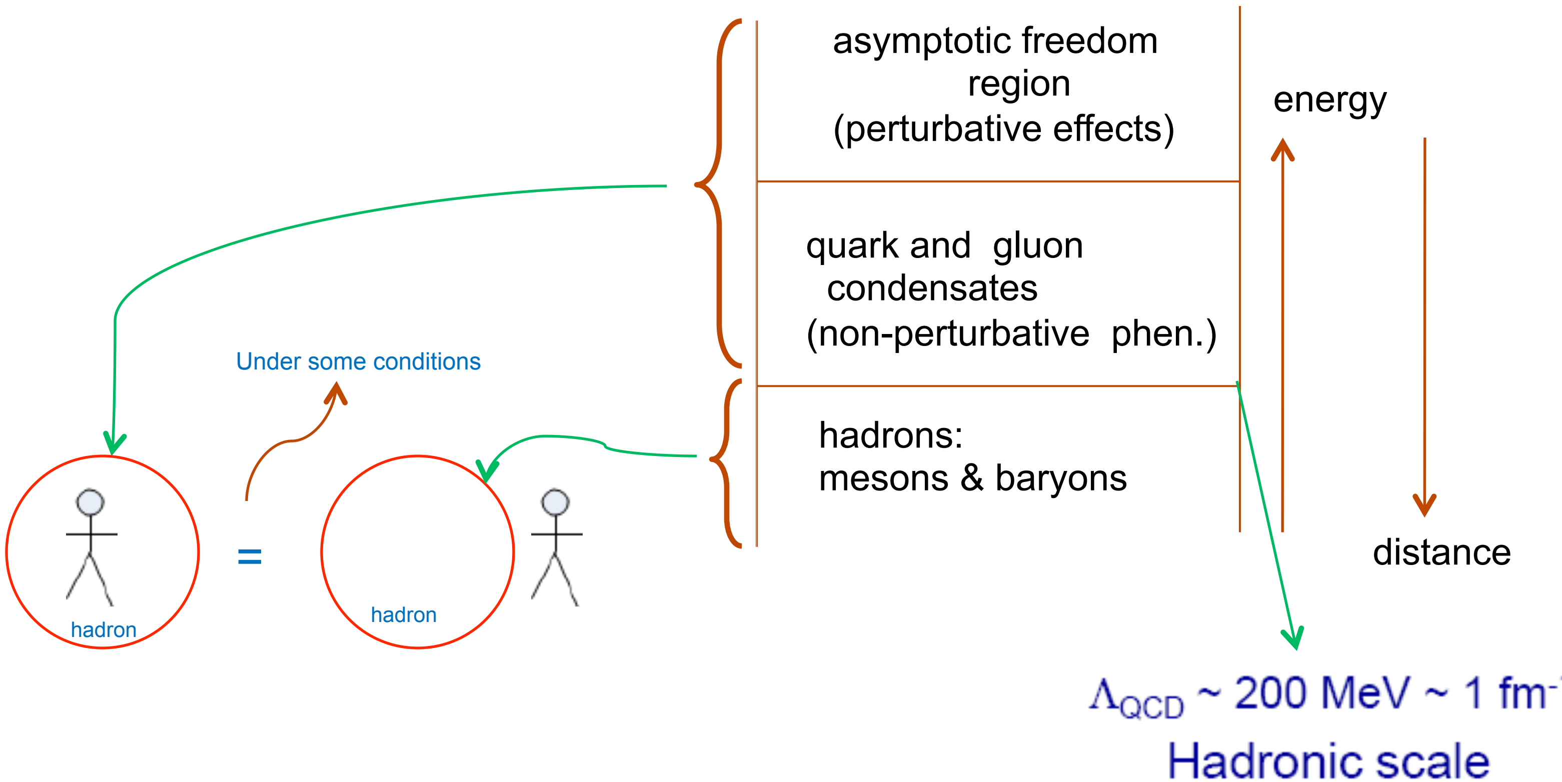


Some non-perturbative methods:

- ✓ Different "relativistic" and "non-relativistic" quark models
- ✓HQET
- ✓Nambu–Jona-Lasinio model
- ✓Lattice QCD
- ✓ ....
- ✓QCD sum rules → This is one of the most attractive and applicable non-perturbative phenomenological tools to Hadron physics.

- ○ applicable to the light and heavy systems, conventional and non-conventional states
- ○ does not include any free parameter
- ○ is based on QCD Lagrangianin
- ○ gives results in a good consistency with existing EXP. data
- ○ its results agree with Lattice predictions on light systems
- ○ can be expanded to hot and dense medium (medium in heavy ion collision experiments)

➢Formation of hadrons and QCDSR



QCD sum rules: Bosphorus Bridge Istanbul

Borel transf. to suppress the contr. of higher states and cont. with the same quantum numbers

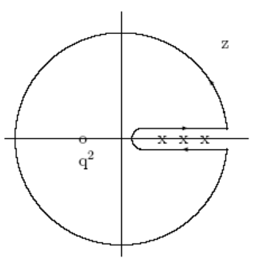
European Side

OPE Side

Asian Side

Hadronic Side

Continuum subtraction & quark hadron duality assumption



$$\mathcal{B}_{M^2} f(q^2) = lim_{\substack{Q^2, n\to\infty \\ \frac{Q^2}{n}=M^2}} \frac{(-q^2)^n}{(n-1)!}\left(\frac{d}{dq^2}\right)^{n-1} f(q^2),$$

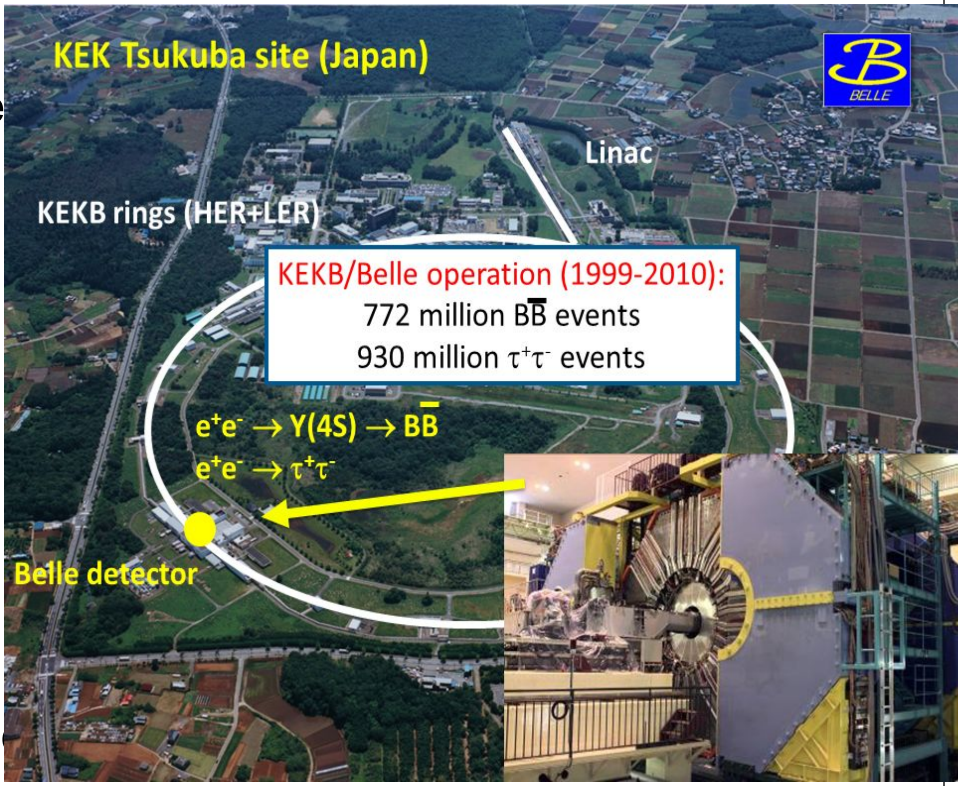
$$\int_{s_0^h}^{\infty} ds\rho^h(s)e^{-s/M^2} = \int_{s_0}^{\infty} ds\rho^{OPE}(s)e^{-s/M^2},$$

Famous Hadron Factories (vacuum):

Belle (1999-2010): at the High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan.

Belle II Experiment is an upgrade of Belle will operate in 2018.

designed to study the properties of B mesons (heavy particles containing a bottom quark)



At Belle: observation of large CP-violation in the neutral B meson system, b-->sll, Search for new physics, observation of the new particle X(3872) (the famous exotic particle), tetraquark Z(4430), $Z_b(10610)$, $Z_b(10650)$ …

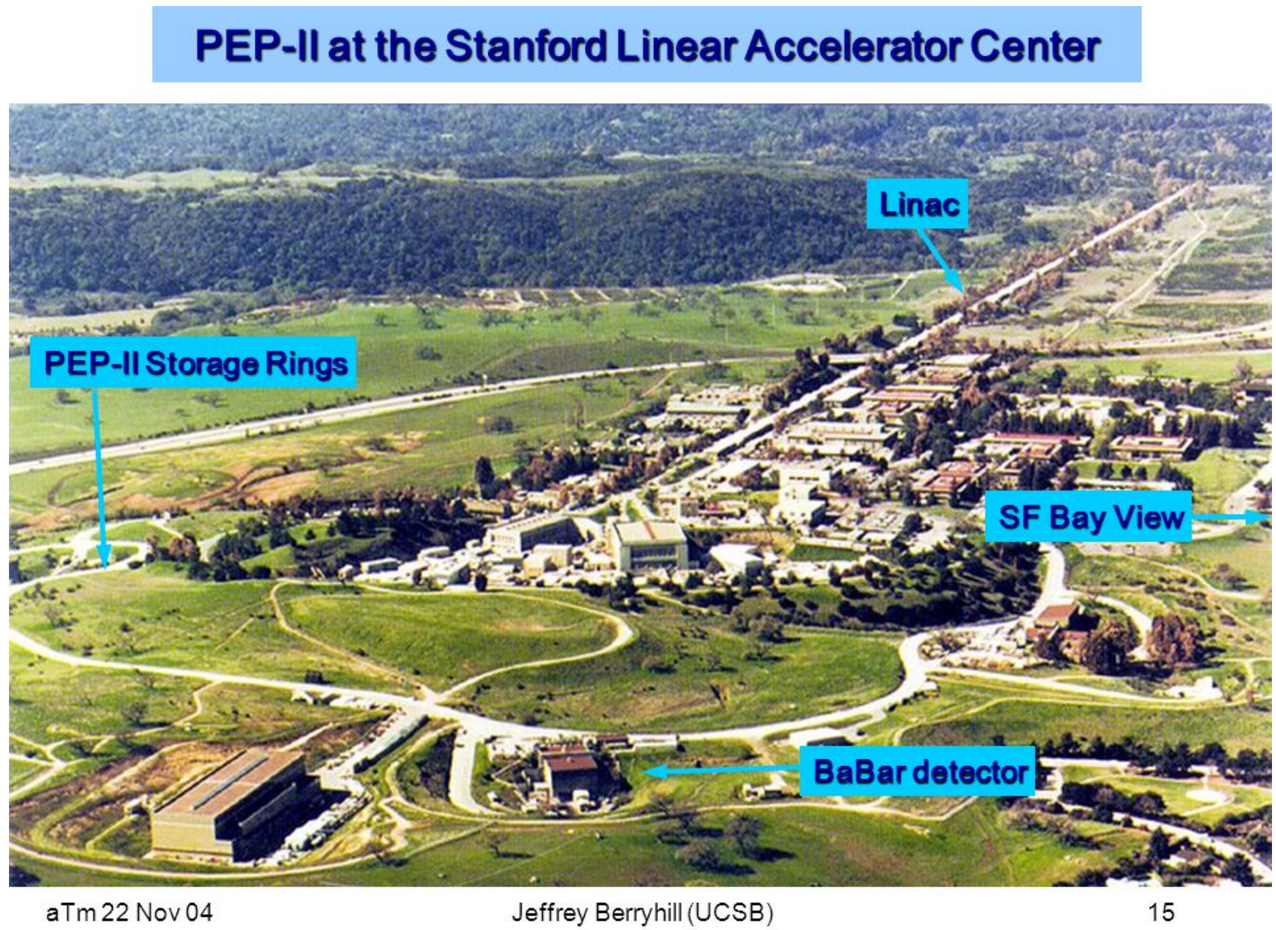
The Belle detector in Tsukuba Hall, KEK

BaBar experiment: SLAC National Accelerator Laboratory, which is operated by Stanford University for the Department of Energy in California

Discovery of lightest bottomonium η_b (2008),

2012: "B to D*-tau-nu" happens more often than the Standard Model says it should

(with $3.4\,\sigma$) < 5σ.

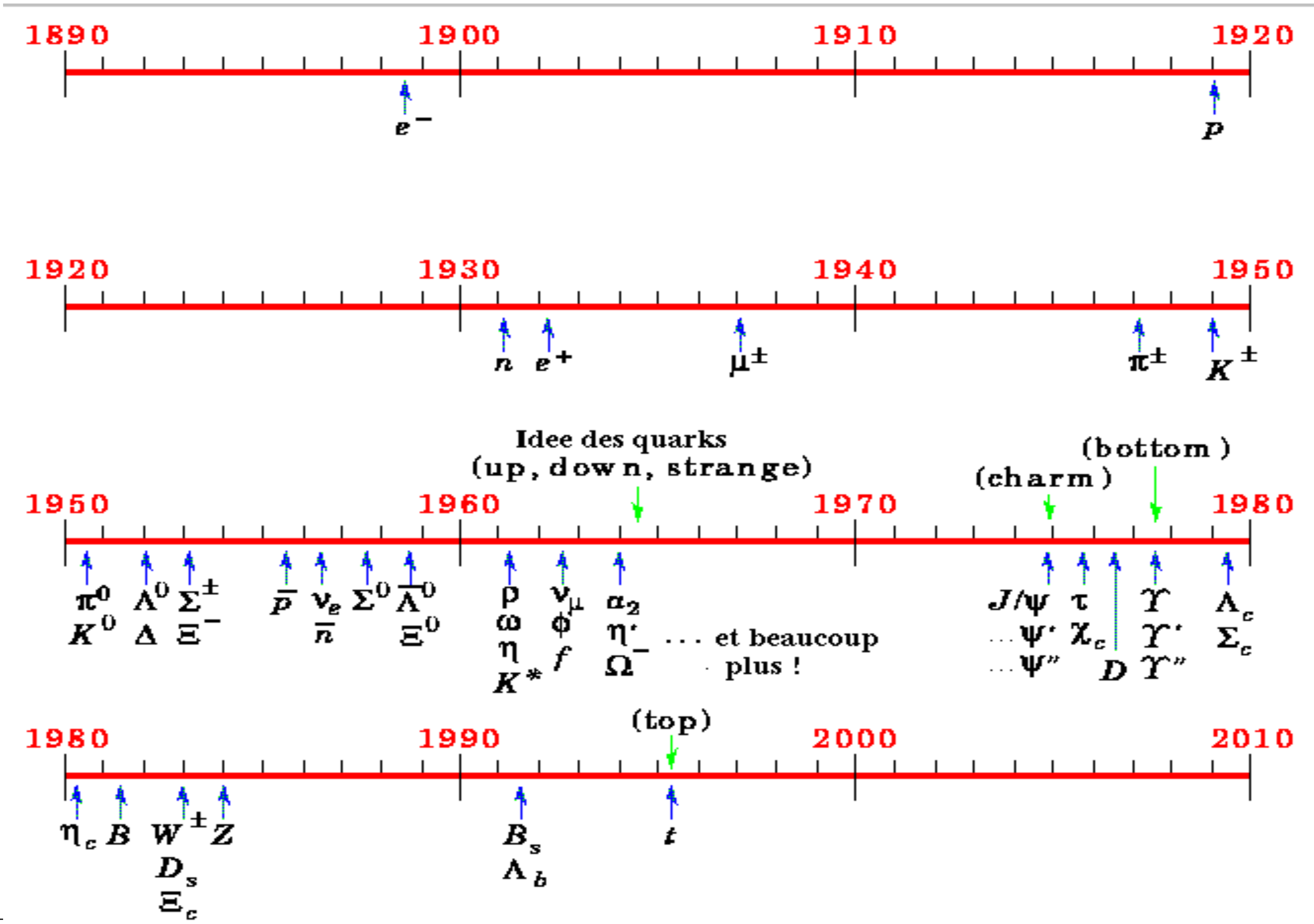


CDF experiment at FermiLab: discovery of top-quark together with D0(1995) .

D0 experiment at FermiLab: discovery of top-quark (1995), Ξ_b(2007), X(5568)!!!!.

CLEO experiment at Cornel: Y(4s), B meson, D meson,….

BES III: China: charm physics, the tetraquark Z_c(3900)



LHCb

-2015: Pentaquarks $P_c(4380)$, $P_c(4450)$, tetraquarks X(4140), X(4274), …..

-Deviations from the SM predictions on many b-hadron decays up tu 3.9 σ,
-CP violation in Λ_b decays, $\Lambda_{b^-}\rightarrow P\,\pi^-\pi^+\pi^-$: 3.3σ

-Lepton Flavor Universality violation (2.6σ):

$$R_K \equiv R_K^{\mu/e} = \frac{\mathcal{B}(\bar{B}\to\bar{K}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{K}ee)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

SM expectation: 1.0003+-0.0001

❖ New Ω_c resonances: b-partners and other possible resonances

PRL **118**, 182001 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Observation of Five New Narrow Ω_c^0 States Decaying to $\Xi_c^+ K^-$

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 14 March 2017; published 2 May 2017)

The $\Xi_c^+ K^-$ mass spectrum is studied with a sample of pp collision data corresponding to an integrated luminosity of 3.3 fb^{-1}, collected by the LHCb experiment. The Ξ_c^+ is reconstructed in the decay mode $pK^-\pi^+$. Five new, narrow excited Ω_c^0 states are observed: the $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$, $\Omega_c(3090)^0$, and $\Omega_c(3119)^0$. Measurements of their masses and widths are reported.

DOI: 10.1103/PhysRevLett.118.182001

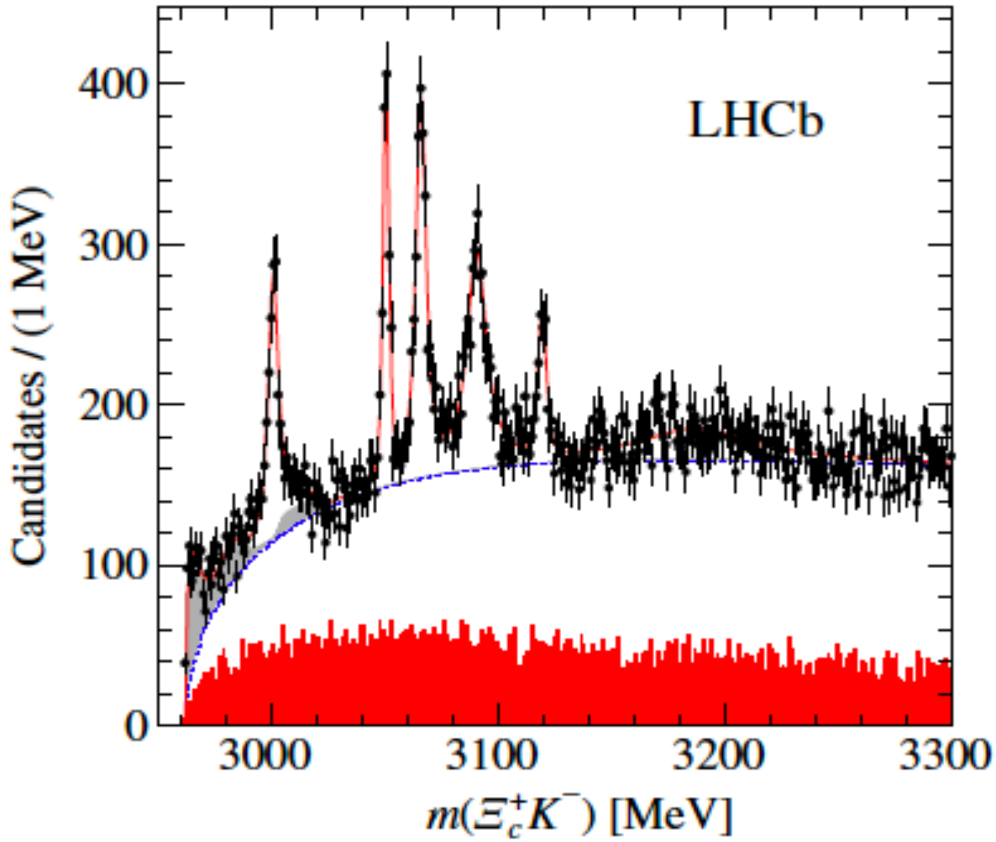


FIG. 2. Distribution of the reconstructed invariant mass $m(\Xi_c^+ K^-)$ for all candidates passing the likelihood ratio selection; the solid (red) curve shows the result of the fit, and the dashed (blue) line indicates the fitted background. The shaded (red) histogram shows the corresponding mass spectrum from the Ξ_c^+ sidebands, and the shaded (light gray) distributions indicate the feed-down from partially reconstructed $\Omega_c(X)^0$ resonances.

TABLE I. Results of the fit to $m(\Xi_c^+ K^-)$ for the mass, width, yield, and significance for each resonance. The subscript fd indicates the feed-down contributions described in the text. For each fitted parameter, the first uncertainty is statistical and the second systematic. The asymmetric uncertainty on the $\Omega_c(X)^0$ arising from the Ξ_c^+ mass is given separately. Upper limits are also given for the resonances $\Omega_c(3050)^0$ and $\Omega_c(3119)^0$ for which the width is not significant.

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		<1.2 MeV, 95% C.L.		
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		<2.6 MeV, 95% C.L.		

The LHCb could not fix their quantum numbers !!!!!!!!

After discovery: many theoretical interpretations

Before discovery: predictions before discovery

K. Azizi and H. Sundu, Eur. Phys. J. Plus **132**, 22 (2017).

$$m_{\Omega_c^\star} = 3080 \pm 120 \text{ GeV} \qquad J^P = 3/2^-$$

When working on the magnetic moment of negative parity spin-3/2 baryons (2016); published January 2017. QCD sum rules

Some of them were predicted via different quark models

D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **84**, 014025 (2011).

A. Valcarce, H. Garcilazo and J. Vijande, Eur. Phys. J. A **37**, 217 (2008).

J. Vijande, A. Valcarce, T. F. Carames and H. Garcilazo, Int. J. Mod. Phys. E **22**, 1330011 (2013).

Z. Shah, K. Thakkar, A. K. Rai and P. C. Vinodkumar, Chin. Phys. C **40**, 123102 (2016).

Or two-point sum rules

Z. G. Wang, Eur. Phys. J. C **54**, 231 (2008).
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Z. G. Wang, Phys. Lett. B **685**, 59 (2010).

After discovery:

First interpretation via only mass:

On the nature of the newly discovered Ω states

S. S. Agaev, K. Azizi and H. Sundu

EPL, **118** (2017) 61001

Table 4: The sum rule results for the parameters of $1S$, $1P$ and $2S$ spin-1/2 and -3/2 charmed baryons.

(n, J^P)	$(1S, \frac{1}{2}^+)$	$(1P, \frac{1}{2}^-)$	$(2S, \frac{1}{2}^+)$	$(1S, \frac{3}{2}^+)$	$(1P, \frac{3}{2}^-)$	$(2S, \frac{3}{2}^+)$
M^2 (GeV^2)	$3.5-5.5$	$3.5-5.5$	$3.5-5.5$	$3.5-5.5$	$3.5-5.5$	$3.5-5.5$
s_0 (GeV^2)	$3.0^2-3.2^2$	$3.3^2-3.5^2$	$3.5^2-3.7^2$	$3.1^2-3.3^2$	$3.4^2-3.6^2$	$3.6^2-3.8^2$
m_{Ω_c} (MeV)	2685 ± 123	2990 ± 129	3075 ± 142	2769 ± 89	3056 ± 103	3119 ± 108
$\lambda_{\Omega_c}\cdot10^2$ (GeV^3)	6.2 ± 1.8	11.9 ± 2.8	17.1 ± 3.4	7.1 ± 1.0	16.1 ± 1.8	25.0 ± 3.1

PDG: 2695.2 ± 1.7 MeV 2765.9 ± 2.0 MeV

Our predictions

on the masses of the charmed baryons allow us to interpret the resonances $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3066)^0$ and $\Omega_c(3119)^0$, recently discovered by the LHCb Collaboration, as the first orbitally $(1P,\ 1/2^-)$, $(1P,\ 3/2^-)$ and radially excited $(2S,\ 1/2^+)$, $(2S,\ 3/2^+)$ charmed baryons,

respectively.

$\Omega_c(3000) \longrightarrow (1P,\ 1/2^-)$

$\Omega_c(3050) \longrightarrow (1P,\ 3/2^-)$

$\Omega_c(3066) \longrightarrow (2S,\ 1/2^+)$

$\Omega_c(3119) \longrightarrow (2S,\ 3/2^+)$

Other interpretations: see our paper

Agaev S. S., Azizi K. and Sundu H., Eur. Phys. J. C, 77 (2017) 395.

The problems connected with the Ω_c^0 states have been addressed in Refs. [36–48]. The new particles have been assigned to be P-wave Ω_c baryons in Ref. [36], where the authors evaluated widths of their decay channels. Calculations there have been performed in the framework of HQET using the sum rule approach. In Refs. [37, 38] $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$ have been interpreted as P-wave excited states of the Ω_c^0 baryons with the spin-parities $1/2^-$, $1/2^-$, $3/2^-$, $3/2^-$ and $5/2^-$, respectively. In Ref. [37] an alternative set of assignments, namely $3/2^-$, $3/2^-$, $5/2^-$, $1/2^+$ and $3/2^+$ is made for these states, as well. In this case $1/2^-$ states are expected around 2904 and 2978 MeV. In both of Refs. [37, 38] the authors utilized the heavy-quark-light-diquark model for Ω_c baryons. On the basis of lattice simulations the same conclusions have been made also in

Ref. [39]. Attempts have been done to classify new states as five-quark systems or S-wave pentaquark molecules with $J^P = 1/2^-$, $3/2^-$ and $5/2^-$ [40, 41]. The possible pentaquark interpretation of the Ω_c^0 baryons on the basis of the quark-soliton model has been suggested also in Ref. [42].

The explorations carried out in the context of a constituent quark model have allowed authors of Ref. [43] to conclude, that $\Omega_c(3000)$ and $\Omega_c(3090)$ can be considered as states with $1/2^-$, $\Omega_c(3050)$ and $\Omega_c(3066)$ as the baryons with $3/2^-$ and $5/2^-$, whereas the $\Omega_c(3119)$ might correspond to one of the radial excitations $(2S, 1/2^+)$ or $(2S, 3/2^+)$. In Ref. [44] the first three states from the LHCb range of excited Ω_c baryons have been classified as P-wave states with $1/2^-$, $5/2^-$ and $3/2^-$, whereas last two particles have been assigned to be $2S$ states with spin-parities $1/2^+$ and $3/2^+$, respectively. These states have been analyzed as the P-wave excitation of the Ω_c^0 baryons with spin-parities $1/2^-$, $1/2^-$, $3/2^-$, $3/2^-$ and $5/2^-$ also in Ref. [45]. The studies have been performed using the two-point sum rule method by introducing relevant interpolating currents.

The newly discovered Ω_c^0 states, their spin-parities has been analyzed in Refs. [46–48], too. Thus, studies in Ref. [46] showed that five resonances Ω_c^0 can be grouped into the 1P states with negative parity, i.e. the resonances $\Omega_c(3000)$ and $\Omega_c(3090)$ have been considered there as $(1P, 1/2^-)$ states, $\Omega_c(3066)$ and $\Omega_c(3119)$ as resonances with $(1P, 3/2^-)$, and $\Omega_c(3050)$ as $(1P, 5/2^-)$ state. The alternative explanation has been suggested in Ref. [47], where the resonances $\Omega_c(3066)$ and $\Omega_c(3090)$ have been interpreted as $1P$-wave states with the spin-parity $J^P = 3/2^-$ or $J^P = 5/2^-$. Starting from decay features of the remaining three resonances in Ref. [47] the authors have assigned them to be $1D$-wave Ω_c^0 states. Finally, in Ref. [48] the resonances $\Omega_c(3000)$ and $\Omega_c(3066)$ have been classified as the $(1P,\ 1/2^-)$ and $(1P,\ 3/2^-)$ states, respectively.

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The only interpretation via mass and width:

Eur. Phys. J. C (2017) 77:395
DOI 10.1140/epjc/s10052-017-4953-z

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

Interpretation of the new Ω_c^0 states via their mass and width

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Table 1 The sum rule results for the masses and residues of the Ω_c^0 baryons with the spin-1/2

(n, J^P)	$(1S, \frac{1}{2}^+)$	$(1P, \frac{1}{2}^-)$	$(2S, \frac{1}{2}^+)$
M^2 (GeV^2)	3.5–5.5	3.5–5.5	3.5–5.5
s_0 (GeV^2)	3.0^2–3.2^2	3.3^2–3.5^2	3.5^2–3.7^2
m_{Ω_c} (MeV)	2685 ± 123	2990 ± 129	3075 ± 142
$\lambda_{\Omega_c} \cdot 10^2$ (GeV^3)	6.2 ± 1.8	11.9 ± 2.8	17.1 ± 3.4

Table 2 The predictions for the masses and residues of the spin 3/2 Ω_c^0 baryons

(n, J^P)	$(1S, \frac{3}{2}^+)$	$(1P, \frac{3}{2}^-)$	$(2S, \frac{3}{2}^+)$
M^2 (GeV^2)	3.5 – 5.5	3.5 – 5.5	3.5 – 5.5
s_0 (GeV^2)	$3.1^2 - 3.3^2$	$3.4^2 - 3.6^2$	$3.6^2 - 3.8^2$
m_{Ω_c} (MeV)	2769 ± 89	3056 ± 103	3119 ± 108
$\lambda_{\Omega_c} \cdot 10^2$ (GeV^3)	7.1 ± 1.0	16.1 ± 1.8	25.0 ± 3.1

Ground states

	Ω_c^0 (MeV)	$\Omega_c(2770)^0$ (MeV)	$\Omega_c(3000)^0$ (MeV)	$\Omega_c(3050)^0$ (MeV)	$\Omega_c(3066)^0$ (MeV)	$\Omega_c(3090)^0$ (MeV)	$\Omega_c(3119)^0$ (MeV)
(n, J^P)	$(1S, \frac{1}{2}^+)$	$(1S, \frac{3}{2}^+)$	$(1P, \frac{1}{2}^-)$	$(1P, \frac{3}{2}^-)$	$(2S, \frac{1}{2}^+)$	–	$(2S, \frac{3}{2}^+)$
Ref. [1]	–	–	$3000.4 \pm 0.2 \pm 0.1$	$3050.2 \pm 0.1 \pm 0.1$	$3065.6 \pm 0.1 \pm 0.3$	$3090.2 \pm 0.3 \pm 0.5$	$3119.1 \pm 0.3 \pm 0.9$
Ref. [2]	2695.2 ± 1.7	2765.9 ± 2.0	–	–	–	–	–
This w.	2685 ± 123	2769 ± 89	2990 ± 129	3056 ± 103	3075 ± 142	–	3119 ± 108

TABLE III: Our results for the masses of Ω_c^0 baryons with spins 1/2 and 3/2, and experimental data from Refs. [1, 2].

[1] LHCb
[2] PDG

Ω_c^0	$\Omega_c(3000)^0$ (MeV)	$\Omega_c(3050)^0$ (MeV)	$\Omega_c(3066)^0$ (MeV)	$\Omega_c(3090)^0$ (MeV)	$\Omega_c(3119)^0$ (MeV)
Ref. [1]	$4.5 \pm 0.6 \pm 0.3$	$0.8 \pm 0.2 \pm 0.1$	$3.5 \pm 0.4 \pm 0.2$	$8.7 \pm 1.0 \pm 0.8$	$1.1 \pm 0.8 \pm 0.4$
This work	4.7 ± 1.2	0.6 ± 0.2	6.4 ± 1.7	–	1.9 ± 0.6
Ref. [43]	4.18	1.12	2.0	4.71	0.074
Ref. [46]	–	2.7	3.3	8.8	0.7

TABLE IV: The theoretical predictions and experimental data for width of the Ω_c^0 states.

[1] LHCb

Our final interpretation via mass & width

$\Omega_c(3000)$ → $(1P, 1/2^-)$

$\Omega_c(3050)$ → $(1P, 3/2^-)$

$\Omega_c(3119)$ → $(2S, 3/2^+)$

$\Omega_c(3066)$ or $\Omega_c(3090)$ → $(2S, 1/2^+)$ Different than previous interp.

b-partners: S. S. Agaev, K. Azizi, H. Sundu, EPL 118 (2017) 61001.

Table 2: The m_{Ω_b} and λ_{Ω_b} of the ground-state and excited bottom baryons with $J = 1/2$ and $J = 3/2$.

(n, J^P)	$(1S, \frac{1}{2}^+)$	$(1P, \frac{1}{2}^-)$	$(2S, \frac{1}{2}^+)$	$(1S, \frac{3}{2}^+)$	$(1P, \frac{3}{2}^-)$	$(2S, \frac{3}{2}^+)$
M^2 (GeV^2)	$6.5 - 9.5$	$6.5 - 9.5$	$6.5 - 9.5$	$6.5 - 9.5$	$6.5 - 9.5$	$6.5 - 9.5$
s_0 (GeV^2)	$6.3^2 - 6.5^2$	$6.6^2 - 6.8^2$	$6.8^2 - 7.0^2$	$6.4^2 - 6.6^2$	$6.7^2 - 6.9^2$	$6.9^2 - 7.1^2$
m_{Ω_b} (MeV)	6024 ± 157	6336 ± 183	6487 ± 187	6084 ± 161	6301 ± 193	6422 ± 198
$\lambda_{\Omega_b} \cdot 10^2$ (GeV^3)	12.1 ± 1.2	17.5 ± 2.9	19.8 ± 4.1	9.3 ± 1.4	19.2 ± 3.1	29.1 ± 5.3

Table 3: The various theoretical predictions for masses of the spin-1/2 and -3/2 bottom baryons.

$\Omega_b(1S, \frac{1}{2}^+)$ (MeV)	$\widetilde{\Omega}_b(1P, \frac{1}{2}^-)$ (MeV)	$\Omega_b'(2S, \frac{1}{2}^+)$ (MeV)	$\Omega_b^\star(1S, \frac{3}{2}^+)$ (MeV)	$\widetilde{\Omega}_b^\star(1P, \frac{3}{2}^-)$ (MeV)	$\Omega_b^{\star\prime}(2S, \frac{3}{2}^+)$ (MeV)	
6024 ± 157	6336 ± 183	6487 ± 187	6084 ± 161	6301 ± 193	6422 ± 198	this work
6064	6330	6450	6088	6340	6461	Ref. [17]
6056	6340	6479	6079	–	6493	Ref. [19]
6081	6301	6472	6102	6304	6478	Ref. [20]
6130 ± 120	–	–	6060 ± 130	–	–	Refs. [9,10]

$m = 6071 \pm 40$ MeV.

Exp: PDG

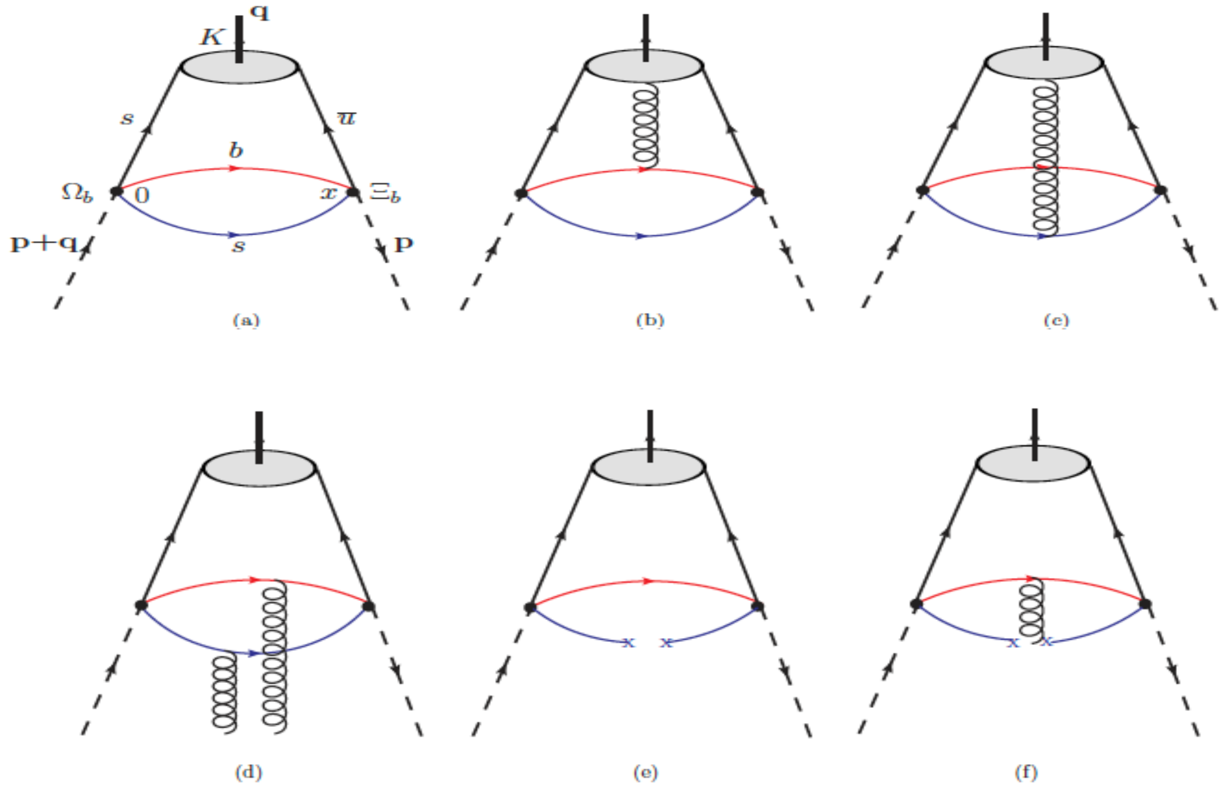
Decay widths of the excited Ω_b baryons

S. S. Agaev,[1] K. Azizi,[2,3] and H. Sundu[4]

A. $\widetilde{\Omega}_b \to \Xi_b^0 K^-$ **and** $\Omega_b' \to \Xi_b^0 K^-$ **decays**

B. **Decays** $\widetilde{\Omega}_b^{\star} \to \Xi_b^0 K^-$ **and** $\Omega_b^{\star\prime} \to \Xi_b^0 K^-$

arXiv:1708.07348 [hep-ph], submitted to Phys. Rev. D.



$$\Gamma\left(\widetilde{\Omega}_b \to \Xi_b^0 K^-\right) = 3.97 \pm 0.91 \text{ MeV},$$
$$\Gamma\left(\Omega_b' \to \Xi_b^0 K^-\right) = 5.51 \pm 1.42 \text{ MeV}.$$

$$\Gamma(\widetilde{\Omega}_b^\star \to \Xi_b^0 K^-) = 0.04 \pm 0.01 \text{ MeV},$$
$$\Gamma(\Omega_b^{\star\prime} \to \Xi_b^0 K^-) = 2.57 \pm 0.78 \text{ MeV}.$$

The obtained results may be useful for forthcoming experiments to explore bottom baryons and measure their spectroscopic and dynamical parameters.

There may be other resonances in $\Xi_{b(c)}$, $\Lambda_{b(c)}$, $\Sigma_{b(c)}$ channels that need theoretical and experimental studies.

❖Ξ_{cc} state: b-partners and other doubly/triply charmed-bottom baryons

Selected for a Viewpoint in *Physics*
PRL **119**, 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\ \text{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001

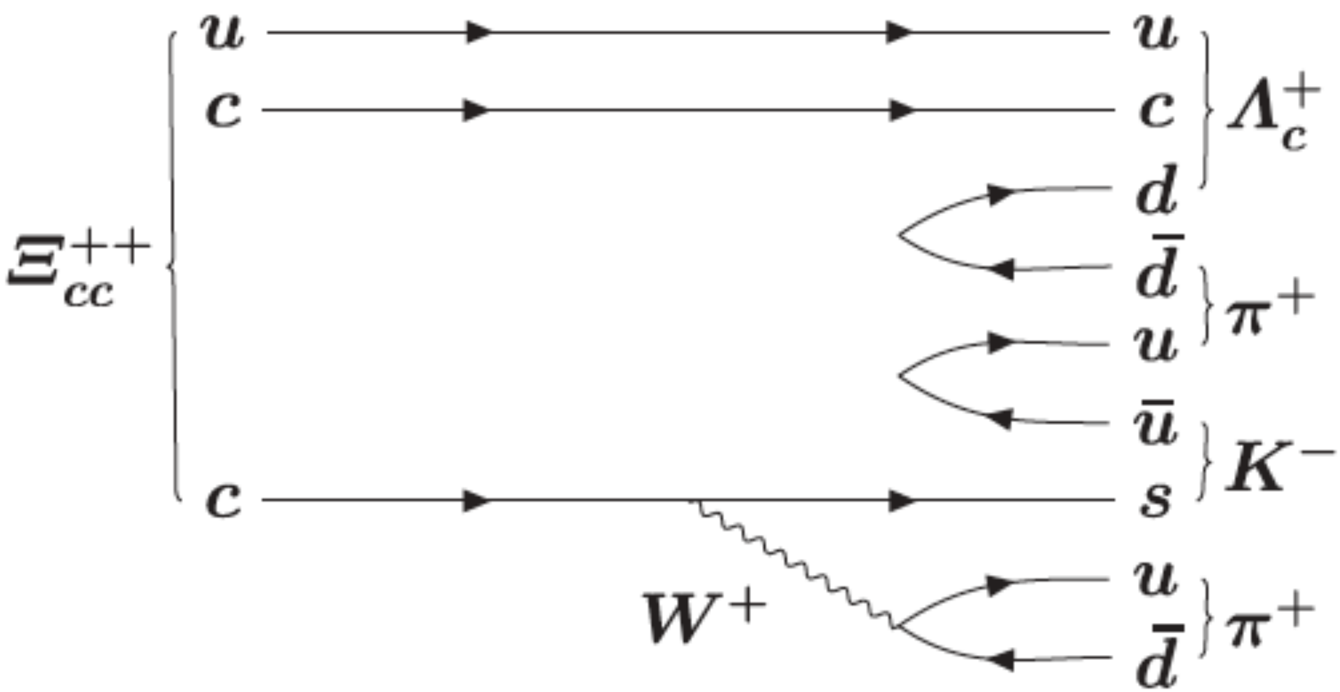


FIG. 1. Example Feynman diagram contributing to the decay $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$.

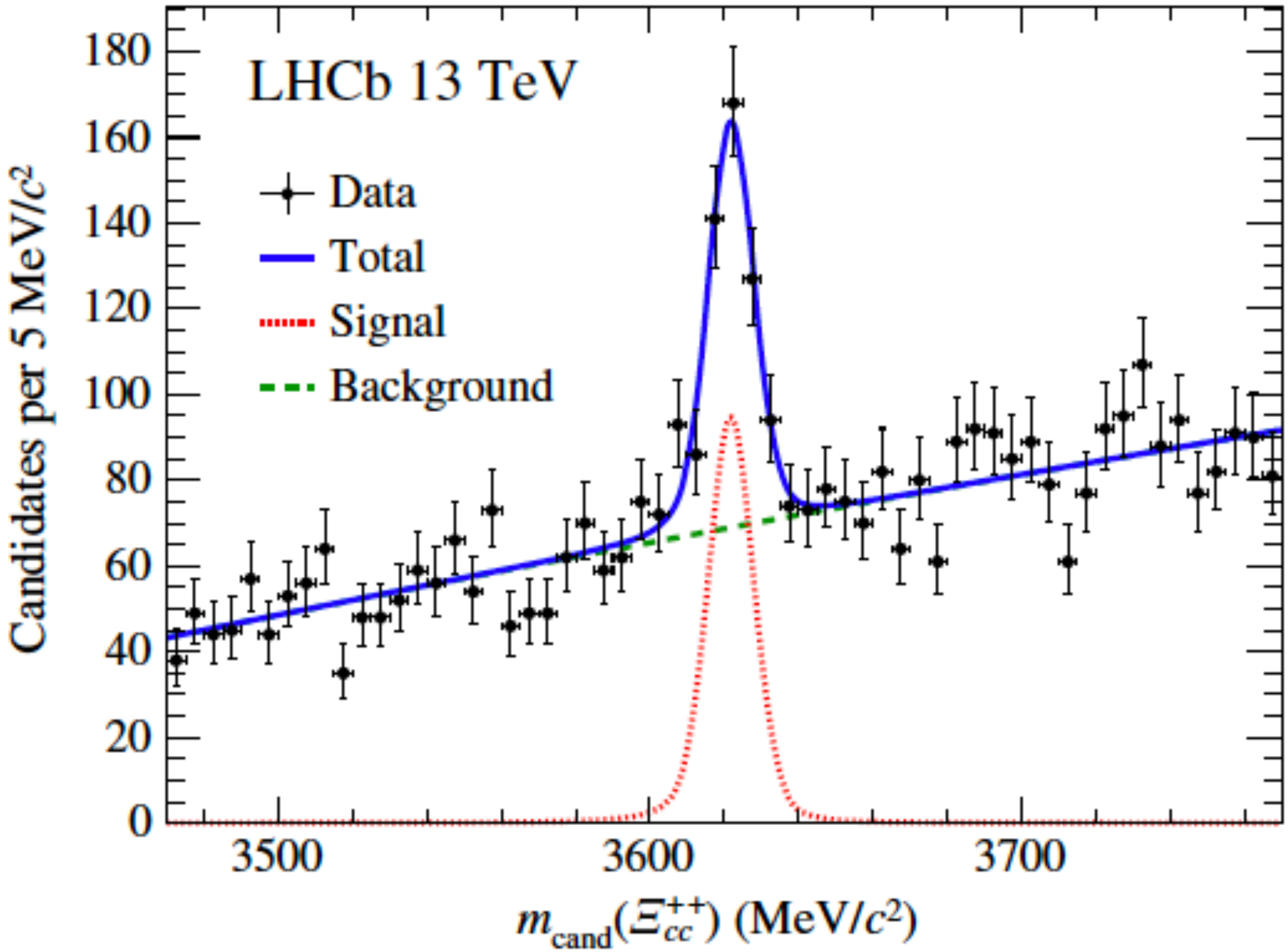


FIG. 3. Invariant mass distribution of $\Lambda_c^+ K^- \pi^+ \pi^+$ candidates with fit projections overlaid.

LHCb mass

$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

Is it a new discovery??????

2017 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

DOUBLY CHARMED BARYONS
$(C = +2)$
$\Xi_{cc}^{++} = ucc$, $\Xi_{cc}^{+} = dcc$, $\Omega_{cc}^{+} = scc$

INSPIRE search

Ξ_{cc}^{+} $\quad I(J^P) = ?(?^?)$

This would presumably be an isospin-1/2 pa . However, opposed to the evidence cited below, the BABAR experiment has found no evidence for a Ξ_{cc}^{+} in a search in $\Lambda_c^+ K^- \pi^+$ and $\Xi_c^0 \pi^+$ modes, and no evidence of a Ξ_{cc}^{++} in $\Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_c^0 \pi^+ \pi^+$ modes (AUBERT,B 2006D). Nor have the BELLE (CHISTOV 2006 , KATO 2014) or LHCb (AAIJ 2013CD) experiments found any evidence for this state.

Ξ_{cc}^{+} MASS	3518.9 ± 0.9 MeV
Ξ_{cc}^{+} MEAN LIFE	$< 33 \times 10^{-15}$ s CL=90.0%

Decay Modes

Mode		Fraction (Γ_i /Γ)	Scale Factor/ Conf. Level	P (MeV/c)
Γ_1	$\Lambda_c^+ K^- \pi^+$			867
Γ_2	$pD^+ K^-$			604

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PDG Live — 1957 2017 particle data group

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pdgLive Home > Ξ_{cc}^{+} > Ξ_{cc}^{+} **MASS**

2017 Review of Particle Physics.
C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update.

Ξ_{cc}^{+} MASS

INSIRE search

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
3518.9 ± 0.9	**OUR AVERAGE**				
3518 ±3	6	[1] OC		LX	Σ^- nucleus ≈ 600 GeV
3519 ±1	16	[2] MATTSON	2002	SELX	Σ^- nucleus ≈ 600 GeV

[1] OCHERASHVILI 2005 claims ``an excess of 5.62 events over ... 1.38 ± 0.13 events" for a significance of 4.8~σ in pD^+K^- events.

[2] MATTSON 2002 claims ``an excess of 15.9 events over an expected background of 6.1 ± 0.5 events, a statistical significance of $6.3\ \sigma$" in the $\Lambda_c^+ K^- \pi^+$ invariant-mass spectrum. The probability that the peak is a fluctuation increases from 1.0×10^{-6} to 1.1×10^{-4} when the number of bins searched is considered.

References:

OCHERASHVILI	2005	PL B628 18	Confirmation of the Doubly Charmed Baryon $\Xi_{cc}(3520)^+$ via its Decay to pD^+K^-
MATTSON	2002	PRL 89 112001	First Observation of the Doubly Charmed Baryon Ξ_{cc}^{+}

SELEX result (MeV): 3518.9 ± 0.9 OUR AVERAGE

↓

FermiLab

Theoretical predictions:

T. M. Aliev, K. Azizi, and M. Savcı, Nucl. Phys. A895, 59 (2012):

3.72 +- 0.20 GeV

Theory says: it should a bit higher than the SELEX prediction. The LHCb measures:

$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

The LHCb cites our paper !

Other predictions on the mass of doubly-charmed spin 1/2 baryons and their b-partners

T.M. Aliev, K. Azizi, M. Savci, Nucl.Phys. A895 (2012) 59

QCDSR, Ioffe — Quark model

Baryon	M^2	$\sqrt{s_0}$	This work	[11]	[12]	[13]	[6]	[19]	Exp [20]
Ξ_{bb}	11.0	10.9	9.96(0.90)	9.78(0.07)	10.17(0.14)	9.94(0.91)	10.202	–	–
Ω_{bb}	11.0	10.9	9.97(0.90)	9.85(0.07)	10.32(0.14)	9.99(0.91)	10.359	–	–
Ξ_{bc}	8.0	7.5	6.72(0.20)	6.75(0.05)	–	6.86	6.933	7.053	–
Ω_{bc}	8.0	7.5	6.75(0.30)	7.02(0.08)	–	6.864	7.088	7.148	–
Ξ_{cc}	5.0	4.6	3.72(0.20)	4.26(0.19)	3.57(0.14)	3.52(0.06)	3.620	3.676	3.5189(0.0009)
Ω_{cc}	5.0	4.6	3.73(0.20)	4.25(0.20)	3.71(0.14)	3.53(0.06)	3.778	3.787	–
Ξ'_{bc}	8.0	7.5	6.79(0.20)	6.95(0.08)	–	–	6.963	7.062	–
Ω'_{bc}	8.0	7.5	6.80(0.30)	7.02(0.08)	–	–	7.116	7.151	–

Table 1: The mass of the doubly heavy spin–1/2 baryons (in units of GeV) at $\beta = \pm 2$.

SELEX Collaboration

M. Mattson et.al, SELEX Collaboration, Phys. Rev. Lett. 89, 112001 (2002).

Baryon	Present work	[11]	[12]
Ξ_{bb}	0.44(0.08)	$0.067 \div 0.057$	0.252(0.064)
Ω_{bb}	0.45(0.08)	–	0.311(0.077)
Ξ_{bc}	0.28(0.05)	$0.046 \div 0.021$	–
Ω_{bc}	0.29(0.05)	–	–
Ξ_{cc}	0.16(0.03)	$0.042 \div 0.026$	0.115(0.027)
Ω_{cc}	0.18(0.04)	–	0.138(0.030)
Ξ'_{bc}	0.30(0.05)	–	–
Ω'_{bc}	0.31(0.06)	–	–

Table 2: The residues of the doubly heavy spin–1/2 baryons (in units of GeV^3).

[11] J. R. Zhang, M. Q. Huang, Phys. Rev. D 78, 094007 (2008).

[12] Z. G. Wang, Eur. Phys. J. A 45, 267 (2010).

QCD sum rules, Ioffe current

Doubly heavy spin--3/2 baryons :

We have no experimental data yet

	Our Work		[10] and [15]	[11]	[6]	[14]
	Structure $\not{q} g_{\mu\nu}$	Structure $g_{\mu\nu}$				
Ξ_{cc}^*	3.69±0.16	3.72±0.18	3.58±0.05	3.90±0.10	3.727	3.61±0.18
Ω_{cc}^*	3.78±0.16	3.78±0.16	3.67±0.05	3.81±0.06	3.872	3.76±0.17
Ξ_{bb}^*	10.4±1.0	10.3±0.2	10.33±1.09	10.35±0.08	10.237	10.22±0.15
Ξ_{bc}^*	7.25±0.20	7.2±0.2	—	8.00±0.26	6.98	—
Ω_{bc}^*	7.3±0.2	7.35±0.25	—	7.54±0.08	7.13	—
Ω_{bb}^*	10.5±0.2	10.4±0.2	10.38±1.10	10.28±0.05	10.389	10.38±0.14

Table 3: The mass spectra of the spin–3/2 doubly heavy baryons in units of GeV.

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[6]: Quark model
[10,11,14,15]: QCD sum rules

	Our Work		[10]	[14]
	Structure $\not{q} g_{\mu\nu}$	Structure $g_{\mu\nu}$		
Ξ^*_{cc}	0.12±0.01	0.12±0.01	0.071 ± 0.017	0.070±0.017
Ω^*_{cc}	0.14±0.02	0.13±0.01	—	0.085±0.019
Ξ^*_{bb}	0.22±0.03	0.21±0.01	0.111 ± 0.040	0.161±0.041
Ξ^*_{bc}	0.15±0.01	0.15±0.01	—	—
Ω^*_{bc}	0.18±0.02	0.17±0.01	—	—
Ω^*_{bb}	0.25±0.03	0.25±0.02	—	0.199±0.048

Table 4: The residues of the spin–3/2 doubly heavy baryons in units of GeV^3.

[10, 14]: QCD sum rules

[10] E. Bagan, M. Chabab, S. Narison, Phys. Lett. B **306**, 350 (1993).

[14] Z. G. Wang, Eur. Phys. J. C **68**, 459 (2010).

Triply heavy spin--1/2 baryons: T.M. Aliev, K. Azizi, M. Savci, **JHEP 1304 (2013) 042**

	This work ($\not{q}$)	This work (I)	[20]	[12]	[13]	[19]	[14]
Ω_{bbc}	11.73 ± 0.16	11.71 ± 0.16	11.50 ± 0.11	11.139	11.280	10.30 ± 0.10	11.535
Ω_{ccb}	8.50 ± 0.12	8.48 ± 0.12	8.23 ± 0.13	7.984	8.018	7.41 ± 0.13	8.245
$\overline{\Omega}_{bbc}$	10.59 ± 0.14	10.56 ± 0.14	10.47 ± 0.12	-	-	-	-
$\overline{\Omega}_{ccb}$	7.79 ± 0.11	7.74 ± 0.11	7.61 ± 0.13	-	-	-	-

Table 2: The masses of the triply heavy spin–1/2 baryons (in units of GeV). For the baryons with over-line, the $\overline{MS}$ values of the quark masses are used.

	This work ($\not{q}$)	This work (I)	[20]
Ω_{bbc}	0.53 ± 0.17	0.45 ± 0.15	0.68 ± 0.15
Ω_{ccb}	0.38 ± 0.13	0.30 ± 0.10	0.47 ± 0.10
$\overline{\Omega}_{bbc}$	0.85 ± 0.28	0.65 ± 0.22	0.68 ± 0.15
$\overline{\Omega}_{ccb}$	0.56 ± 0.18	0.38 ± 0.13	0.47 ± 0.10

Table 3: The residues of the triply heavy spin–1/2 baryons (in units of GeV^3). For the baryons with over-line, the $\overline{MS}$ values of the quark masses are used.

[12,13,14] QCD Bag model, relativistic three-quark model, quark model, respectively

[19,20] QCD sum rules, Ioffe current

Triply heavy spin--3/2 baryons

	$M^2(GeV^2)$	$\sqrt{s_0}(GeV)$	$m(GeV)$	$\lambda(GeV^3)$
$\Omega_{ccc}(\frac{3}{2}^+)$	$4.5-8.0$	5.6 ± 0.2	4.72 ± 0.12	0.09 ± 0.01
$\Omega_{ccc}(\frac{3}{2}^-)$	$4.5-8.0$	5.8 ± 0.2	4.9 ± 0.1	0.11 ± 0.01
$\Omega_{ccb}(\frac{3}{2}^+)$	$6.0-10.0$	8.8 ± 0.2	8.07 ± 0.10	0.06 ± 0.01
$\Omega_{ccb}(\frac{3}{2}^-)$	$6.0-10.0$	9.0 ± 0.2	8.35 ± 0.10	0.07 ± 0.01
$\Omega_{bbc}(\frac{3}{2}^+)$	$8.0-10.5$	12.0 ± 0.2	11.35 ± 0.15	0.08 ± 0.01
$\Omega_{bbc}(\frac{3}{2}^-)$	$8.0-10.5$	12.2 ± 0.2	11.5 ± 0.2	0.09 ± 0.01
$\Omega_{bbb}(\frac{3}{2}^+)$	$12.0-18.0$	15.3 ± 0.2	14.3 ± 0.2	0.14 ± 0.02
$\Omega_{bbb}(\frac{3}{2}^-)$	$12.0-18.0$	15.5 ± 0.2	14.9 ± 0.2	0.20 ± 0.02

No experimental data yet

$$\langle 0 \left| \eta_\mu \right| B_{(3/2)^+}(q) \rangle = \lambda_{(3/2)^+} u_\mu(q) \; ,$$

$$\langle 0 \left| \eta_\mu \right| B_{(3/2)^-}(q) \rangle = \lambda_{(3/2)^-} \gamma_5 u_\mu(q) \; ,$$

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Concluding remarks:

-Despite the recent experimental and theoretical progresses, more studies are needed on the identification, properties, internal quark organizations and nature of the standard and non-conventional hadrons, especially the newly discovered resonances.

-Collaboration with LHCb can be very useful.


Thank You