PENTAQUARKS

in a Bethe-Salpeter approach

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Introduction

- **1964:** Quark model by Gell-Mann and Zweig. Difference between conventional and exotic states
  - $J^{PC} = 0^{--}$, $P = (-1)^{L+1}$, $C = (-1)^{L+S} \in \{0^{+-}, 1^{-+}, \cdots\}$.
  - Electric charge content.
  - Same J^{PC} and approximately mass but decays in unexpected channels.

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 lowest 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**.

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

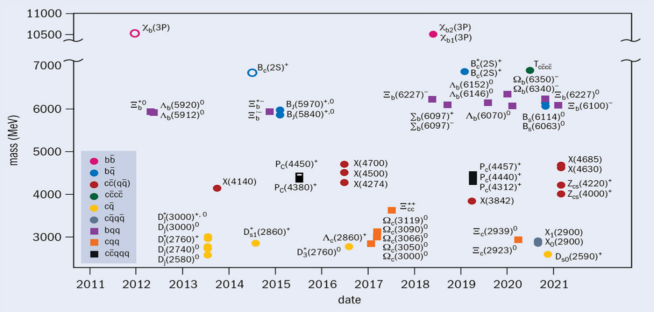
II *)

G. Zweig **)
CERN---Geneva

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

Introduction

- **1964:** Quark model by Gell-Mann and Zweig.
- **2003:** Exotic state $X(3872)$ in 2003 in Belle [Col03].
- **2011-2021:** New hadrons measured in LHC [EPP17].



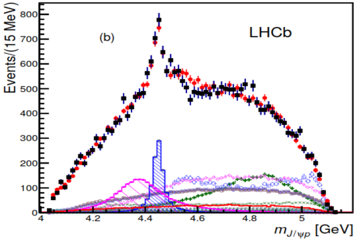
[*Col*03] Belle Collaboration. Observation of a narrow charmoniumlike state in exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}j/\psi$ decays.
Phys. Rev. Lett., 91:262001, Dec 2003

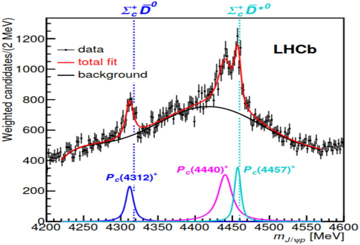
[*EPP*17] A. Esposito, A. Pilloni, and A.D. Polosa. Multiquark resonances.

Physics Reports, jan 2017

Overview

- LHCb measurements in 2015 & 2019. [Col15, Col19]





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Phys. Rev. Lett., 122:222001, Jun 2019

Overview

- LHCb measurements in 2015 & 2019.
- Different approaches
  - Reviews: [EPP17, CCLZ16, LMS17, OSZ18, GHM+18, ALS17]
  - One-gluon exchange: [DRGG75, CIK79, GI85, CI86]
  - Goldstone-boson exchange: [SPG98, WGPV00, MPS08]
  - Lattice [ABC+17, SP19]

[CI86] Maurizio Alberti, Gunnar S. Bali, Sara Collins, Francesco Knechtli, Graham Moir, and Wolfgang Söldner. Hadroquarkonium from lattice qcd.
Phys. Rev. D, 95:074501, Apr 2017

[WGPV00] R.F. Wagenbrunn, L.Ya. Glozman, W. Plessas, and K. Varga. Extension of the gbe chiral constituent quark model.
Nuclear Physics A, 666-667:29–32, 2000.

The Structure of the Nucleon

- Bethe-Salpeter approach
  - Baryons Review:[ESAW+16]
  - Tetraquarks: [EFH+20]

[ESAW+16] Gernot Eichmann, Christian S. Fischer, Walter Heupel, Nico Santowsky, and Paul C. Wallbott. Four-quark states from functional methods.
Few-Body Systems, 61(4), oct 2020

Our goal

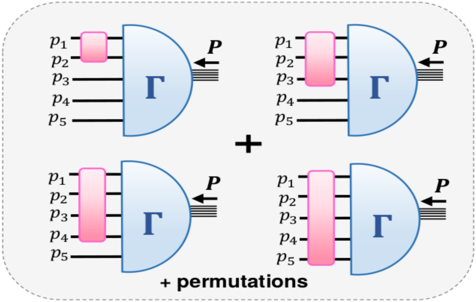
- Calculate the properties of Pentaquarks using nonperturbative functional methods, combination of Dyson-Schwinger equations and Bethe-Salpeter equations. [ESAW+16], [EFH+20]

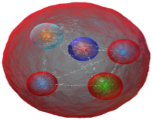
$$K\psi_i = \lambda_i\psi_i$$

	dim K	*memory*
Mesons	10^3	$20\,Mb$
Baryons	10^8	$10^7\,Gb$
Tetraquarks	10^{13}	$10^{18}\,Gb$

Our goal

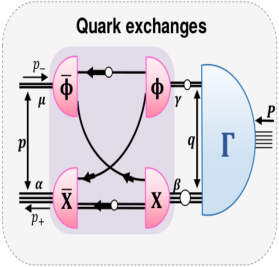
- Calculate the properties of Pentaquarks using nonperturbative functional methods, combination of Dyson-Schwinger equations and Bethe-Salpeter equations.
- Solve the 5-body equation.

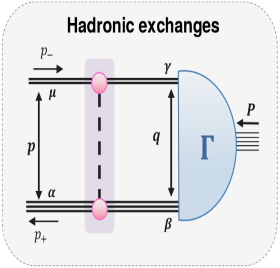


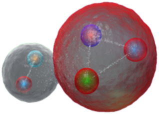


Our goal

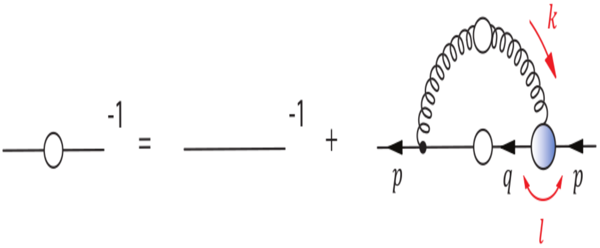
- Calculate the properties of Pentaquarks using nonperturbative functional methods, combination of Dyson-Schwinger equations and Bethe-Salpeter equations.
- Solve the 5-body equation.
- Solve and compare with 2-body system.







Dyson-Schwinger Equation for Quark Propagator

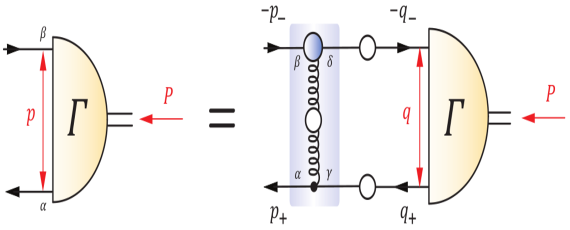


$$S(p)^{-1} = Z_2(i\not{p} + m_0) + \Sigma(p), \quad D^{\mu\nu} = \frac{Z(k^2)}{k^2} T_k^{\mu\nu}$$

$$\Sigma(p) = -\frac{4g^2}{3} Z_\Gamma \int_q i\gamma^\mu S(q) D^{\mu\nu}(k) \Gamma^\nu(l,k)$$

- **Rainbow-Ladder Truncation**
- **Effective interaction**

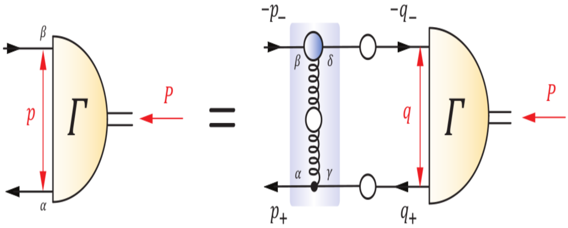
Bethe-Salpeter equation for Mesons



- The quark-antiquark bound state amplitude $\Gamma(p, P)$

$$\Gamma_{\alpha\beta}(p, P) = \int_q^{\Lambda} K_{\alpha\gamma,\delta\beta}(p, q, P) \left\{ S(q_+)\Gamma(q, P)S(-q_-) \right\}_{\gamma\delta}$$

Bethe-Salpeter equation for Mesons



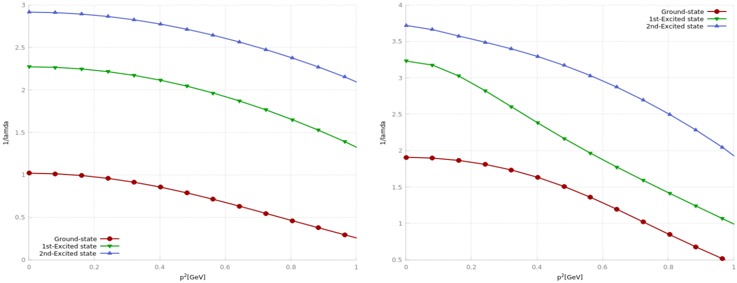
- The quark-antiquark bound state amplitude $\Gamma(p, P)$
- Pseudo-scalar and vector meson amplitudes

$$\Gamma(p, P) = \sum_{k=1}^{4} f_k^{ps}(q^2, z, P^2)\left\{i\gamma^5 \tau_k(q, P)\right\} \otimes \frac{\delta_{AB}}{\sqrt{3}} \otimes \mathbf{r}_{ab}^{e},$$

$$\Gamma^{\mu}(q, P) = \sum_{k=1}^{12} f_k^{vc}(q^2, z, P^2)\left\{i\tau_k^{\mu}(q, P)\right\}_{\alpha\beta} \otimes \frac{\delta_{AB}}{\sqrt{3}} \otimes \mathbf{r}_{ab}^{e}$$

Bethe-Salpeter equation: examples

- Eigenvalue spectrum for Pion (0^{-+}) and Rho (1^{--})



1. Motivation
2. Pentaquarks
3. Ingredients
4. Conclusion & Outlook

Conclusion & Outlook

- We studied the quark propagator with different methods in the complex plane.
- We calculated the BSE for mesons/diquarks in different basis.
- Work the tensor basis for a Pentaquark in the 5-body BSE and for a molecule picture.
- Calculate structure observables of pentaquarks such as their electromagnetic form factors, which could be measured in future experiments (LHCb, Amber).

Thanks!

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