Exploring the internal structure of the exotic resonances with ALICE

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On behalf of the ALICE Collaboration
Indian Institute of Technology Bombay
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Introduction - Exotic Hadrons

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 a 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

\[ n_L - n_R \]

The classification of Standard Hadrons based on the constituents of quark model - Baryons (qqq), Mesons (qq̄)
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 promising 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 of number $n_{\ell} - n_{\overline{\ell}}$ 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 $X = -1$, so that the four particles $d$, $s$, $u$, and $b$ 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 $\frac{1}{2}$, $X = -\frac{1}{2}$, and baryon number $\frac{1}{2}$. We then refer to the members $u$, $d$, and $s$ of the triplet as "quarks" $^{2}$), and the members of the anti-triplet as anti-quarks $\overline{q}$. Baryons can now be constructed from quarks by using the combinations $qqq$, $qqq\overline{q}$, etc., while mesons are made out of $qq$, $qq\overline{q}$, 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 (qq) similarly gives just 1 and 3.
Introduction - Resonances

- Hadronic resonances are short-lived particles and their lifetimes are comparable or less than that of the hadronic gas created after the collisions.

![Diagram showing the time evolution of hadronic resonances and their yield changes](image)

- **QGP** (Quark-Gluon Plasma)
- **Phase transition**
- **Chemical freeze out**
- **Kinetic freeze out**

**Hadron yields**
- **Change**
- **Momenta change**

**Most Hadron yields**
- **Fixed**
- **Momenta change**

**Hadron yields**
- **Fixed**
- **Momenta fixed**

- **(Pseudo-) Elastic Collisions**
- **Inelastic Collisions**

- **Regeneration** - (Pseudo-) elastic scatterings - Increase in resonance yield
- **Rescattering** - Rescattering of decay daughters - Reduction of the measured resonance yield

More by N.Agrawal on 5th Sept at 12:20
## Exotic Resonances

A list of (exotic) resonances in 1-2 GeV/c² mass range

Quark contents of these scalar mesons are still controversial.

<table>
<thead>
<tr>
<th>Quark Contents</th>
<th>Lifetime (fm/c)</th>
<th>Mass (MeV)</th>
<th>J/(P)</th>
<th>(Q^0)</th>
<th>K*(892)</th>
<th>f₀(980)</th>
<th>(\phi)(1020)</th>
<th>f₁(1285)</th>
<th>(f₀)(1370)</th>
<th>(\Sigma)(1385)</th>
<th>(f₀)(1500)</th>
<th>(\Lambda)(1520)</th>
<th>(\Xi)(1530)</th>
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<tr>
<td>(u\bar{u} + d\bar{d}) / 2</td>
<td>1.3</td>
<td>775</td>
<td>1-</td>
<td>(\rho^0)</td>
<td>892</td>
<td>990</td>
<td>1020</td>
<td>1280</td>
<td>1200-1500</td>
<td>1385</td>
<td>1506</td>
<td>1520</td>
<td>1530</td>
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<tr>
<td>(d\bar{s})</td>
<td>4.2</td>
<td>892</td>
<td>1-</td>
<td>1-</td>
<td>0+</td>
<td>1-</td>
<td>1+</td>
<td>0+</td>
<td>(3/2)+</td>
<td>0+</td>
<td>(3/2)-</td>
<td>(3/2)+</td>
<td></td>
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<tr>
<td>(s\bar{s})</td>
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<td>980</td>
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<td>0+</td>
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<td>0+</td>
<td>(3/2)+</td>
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<td>(3/2)-</td>
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<td>~5?</td>
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Particle Data Group

More by N.Agrawal on 5th Sept at 12:20
Structure of Exotic Resonances

- **Diquark**: Quark and antiquark
- **Meson-meson molecule**: Combination of two mesons
- **Tetraquark**: Combination of four quarks
- **Glueball**: Meson-meson molecule
- **Hybrid state**: Combination of quark and antiquark with a gluon field
Structure of Exotic Resonances

Diquark

\[ q \bar{q} \]  

Meson-meson molecule

\[ q \bar{q} q \bar{q} \]  

Tetraquark

\[ q \bar{q} q \bar{q} \]  

Glueball

Hybrid state

\[ g \bar{g} \]

\[ f_0(980) \]

- \[ n\bar{n} = (u\bar{u} + d\bar{d})/2 \] state: Phys.Rev.D 67 (2003) 094011

- Molecular state (K\bar{K}):

- Tetraquark: Phys.Rev.D 103 (2021) 1, 014010
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meson-meson molecule

Tetraquark

Glueball

Hybrid state

\[ n\bar{n} = (u\bar{u} + d\bar{d})/2 \]

- \( f_1(1285) \)
- \( n\bar{n} = (u\bar{u} + d\bar{d})/2 \) state: Phys.Rev.D 96 (2017) 5, 054012
Structure of Exotic Resonances

- **Diquark**
  - $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: Phys.Rev.D 67 (2003) 094011
  - Molecular state ($K\bar{K}$): Phys.Rev.D 101 (2020) 9, 094034
  - Tetraquark: Phys.Rev.D 103 (2021) 1, 014010

- **Meson-meson molecule**

- **Tetraquark**
  - Review of Particle Physics (PDG)

- **Glueball**

- **Hybrid state**
  - $f_1(1285)$: $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: Phys.Rev.D 96 (2017) 5, 054012

More by Satoshi Yano’s poster
Glueball hunting

- Lattice QCD predicts the possible existence of glueballs [1],[2].
- **Glueball**: A particle composed of gluons only, because gluons carry color charge and have bound states without the valence quarks.
- Expected properties: Mass range $1 \sim 2 \text{ GeV/c}^2$, and total angular momentum, charge and parity $J^{PC} = 0^{++}$ (lightest one)
- Candidates: $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ are suitable candidates for searching glueball.

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WA102 [3], ZEUS have measured the $K_S^0 K_S^0$ mass peak

Various resonances can be found in $K_S^0 K_S^0$ channel
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**Structure, quark content and nature yet not understood**

Can we see these states in pp collisions with the ALICE detector ?

WA102 [3], ZEUS have measured the $K^0_S K^0_S$ mass peak

Various resonances can be found in $K^0_S K^0_S$ channel
A multipurpose detector of LHC with excellent tracking and particle identification capability
The ALICE Detector in Run2

**Inner Tracking System (ITS)**
- $|\eta| < 0.9$
- 6 layers of silicon detectors
- Particle identification & tracking
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  - Multi-gap resistive plate chambers
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- **V0A & V0C**
  - V0A($2.8 < \eta < 5.1$), V0C($-3.7 < \eta < -1.7$)
  - Array of scintillators
  - Trigger and multiplicity estimator
The ALICE Detector in Run2 - PID
Measurement of $f_0(980)$

- Diquark: $q\bar{q}$
- Meson-meson molecule: $q\bar{q}q\bar{q}$
- Tetraquark: $q\bar{q}q\bar{q}$
- Glueball: $g\bar{g}$
- Hybrid state: $g\bar{g}$

$f_0(980)$

- $n\bar{n} = (u\bar{u} + d\bar{d})/2$ state: Phys. Rev. D 67 (2003) 094011
- Molecular state ($K\bar{K}$): Phys. Rev. D 101 (2020) 9, 094034
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Measurement of $f_0(980)$

ALICE

$pp$, $\sqrt{s} = 5.02$ TeV

Counts / (0.02 GeV/c$^2$)

$M_{\pi\pi}$ (GeV/c$^2$)

Data (stat. uncert.)
Signal + background
Total background
$f_0(980)$
$f_2(1270)$
$\rho(770)$
Residual background

$0.6 < p_T < 0.8$ (GeV/c)
Measurement of $f_0(980)$

**Signal extraction:** Invariant mass analysis via $f_0(980) \rightarrow \pi^+\pi^-$ decay channel in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV

**Contributions** from three resonances, $f_0(980)$, $\rho^0(770)$, and $f_2(1270)$: fitted with relativistic Breit-Wigner functions

**$p_T$-differential yields** are obtained with the combined fit of signal description and corrected for the detector acceptance and reconstruction efficiency
$f_0(980)$ spectra, yield and mean $p_T$

**$p_T$ Spectra**

- Spectra are measured in four multiplicity classes & inelastic/non-single diffractive collisions.
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**f_0(980) spectra, yield and mean p_T**

- **Spectra** are measured in four multiplicity classes & inelastic/non-single diffractive collisions.

- **p_T - Integrated yield and mean-p_T** increase with the multiplicity in **pp and p-Pb collisions**.
Internal quark structure of $f_0(980)$

Average pseudo-rapidity density of charged particles

$\langle dN_{ch}/d\eta \rangle$ - $\langle dN_{ch}/d\eta \rangle$ - Average pseudo-rapidity density of charged particles
Internal quark structure of $f_0(980)$

Predictions based on the $\gamma_s$-CSM are calculated by assuming two scenarios:
- $|S| = 0$ (Data differ by 1.9$\sigma$)
- $|S| = 2$ (Data differ by 4.0$\sigma$)

$f_0/\pi$ vs $\langle dN_{ch}/d\eta \rangle$: Canonical Statistical Model (arXiv:1906.03145) underestimates the ratio

$\gamma_s$-CSM predicts higher values for yield ratio when assuming net strangeness 0 ($|S| = 0$) compared to $|S| = 2$ in the low $\langle dN_{ch}/d\eta \rangle$

The two predictions match each other for $\langle dN_{ch}/d\eta \rangle \geq 100$

\[ \langle dN_{ch}/d\eta \rangle \] - Average pseudo-rapidity density of charged particles
Internal quark structure of $f_0(980)$

ALICE Preliminary

$\gamma_s$-CSM

$p$–$Pb$, $\sqrt{s_{NN}} = 5.02$ TeV

$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}^{1/3}$

$\gamma_s$-CSM

$f_0(|S|=0)$

$f_0(|S|=2)$

PRC 100, 054906 (2019)
Internal quark structure of $f_0(980)$

$\frac{f_0(980)}{K^0}$ is calculated with two assumptions i.e strange and anti-strange quark ($|S|=2$) or not?

- **Double ratio** of $f_0(980)$ to $K^*0$ yields compared with $\gamma_s$-CSM model.
  - $|S|=2$ (Increasing trend)
  - $|S|=0$ (Declining trend)

If strangeness content exists ($|S|=2$), we should observe a rising trend as $K^*$ possesses ($S=1$), and the model suggests a **mild increasing trend**

The data’s behaviour aligns qualitatively with the second scenario.
Nuclear modification factor, $Q_{pPb}$

A significant centrality dependent suppression observed for the $f_0(980)$ yield at low $p_T$: may be the presence of rescattering effects.

More suppression in central collisions.

No Cronin peak is observed in the intermediate region: may suggest an ordinary meson structure of $f_0(980)$.

$$Q_{pPb}(p_T, \text{cent}) = \frac{d^2N_{\text{cent}}^{pPb}/dydp_T}{<T_{\text{cent}}^{pPb}> \cdot d^2\sigma_{\text{inel}}^{pPb}/dydp_T}$$

$$<T_{\text{cent}}^{pPb}> = \frac{N_{\text{cent}}^{\text{coll}}}{\sigma_{\text{NN}}}$$

$$\sigma_{\text{NN}} = 70 \pm 5 \text{ mb}$$
Measurement of $f_1(1285)$

- Diquark
- Meson-meson molecule
- Tetraquark
- Glueball
- Hybrid state

$n\bar{n} = (u\bar{u} + d\bar{d})/2$ state:
- Phys.Rev.D 96 (2017) 5, 054012

Tetraquark:

Molecular state:
- Phys. Rev D42 (1990) 874

Hybrid state:
Measurement of $f_1(1285)$ in pp collisions

First measurement of $f_1(1285)$ at ALICE
Measurement of $f_1(1285)$ in pp collisions

First measurement of $f_1(1285)$ at ALICE

Signal extraction: Invariant mass analysis via $f_1(1285) \rightarrow K_SK_P$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV

Contributions from three resonances $f_1(1285)$, $f_1(1420)$, and $\eta(1475)$ are fitted with Breit-Wigner functions.
$f_1(1285)$ Spectra and yield

$\rho_T$ spectrum is obtained from 1 GeV/c to 12 GeV/c in pp collisions at $\sqrt{s} = 13$ TeV

Spectrum is fitted with Levy-Tsallis fit
**f_1(1285) Spectra and yield**

- **pp, 13 TeV**

  \[ p_T \text{ spectrum is obtained from 1 GeV/c to 12 GeV/c in pp collisions at } \sqrt{s} = 13 \text{ TeV} \]

  - Spectrum is fitted with Levy-Tsallis fit

- Thermal model predictions of particle ratios with \( f_1(1285) \) having strange quark content \(|S|=0\) are closer to the experimental measurements than \(|S|=2\)

\[ \sigma = \frac{\text{Ratio}_{\text{data}} - \text{Ratio}_{\text{model}}}{\text{Error}_{\text{data}}} \]
Glueball search

- Diquark
- meson-meson molecule
- Tetraquark
- Glueball
- Hybrid state

Glueball candidate:
Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

Signal extraction: Invariant mass distribution from $K^0_sK^0_s$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV

- Signal extraction has been performed and $f_0(1270)$, $f_2(1525)$, $f_0(1710)$ are fitted with Breit-Wigner functions.
**Glueball search: f_0(1370), f_2(1525), f_0(1710)**

**pp, 13 TeV**

- Signal extraction: Invariant mass distribution from $K_S^0 K_S^0$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV
- Signal extraction has been performed and $f_0(1270)$, $f_2(1525)$, $f_0(1710)$ are fitted with Breit-Wigner functions

**K_S^0 K_S^0** channel: 3 peaks are seen -> consistent with the observation in ep collisions at HERA[1].

**K K** channel: 2 peaks are visible.

---

Signal extraction: Invariant mass distribution from $K_S^0 K_S^0$ decay channel in $pp$ and $p-Pb$ collisions at $\sqrt{s} = 5.02$ TeV.

Signal extraction has been performed, $f_0(1370)$, $f_2(1525)$, $f_0(1710)$.

Target: $R_{pA}$ measurement of $f_0(1710)$ - enhancement expected due to large gluon density.
Glueball search: $f_0(1370)$, $f_2(1525)$, $f_0(1710)$

Signal extraction: Invariant mass distribution from $K_s^0 K_s^0$ decay channel in pp and p–Pb collisions at $\sqrt{s} = 5.02$ TeV

- Signal extraction has been performed, $f_0(1370)$, $f_2(1525)$, $f_0(1710)$
- Target: $R_{pA}$ measurement of $f_0(1710)$ - enhancement expected due to large gluon density

More by Satoshi Yano’s poster
Summary

- **Exotic resonances** like $f_0$, $f_1$ and $f_2$ have stirred debates over their quark compositions (e.g. diquarks, tetraquarks, molecules, hybrid, glueball?)

- No Cronin peak is observed in the intermediate $p_T$ region. This may suggest an ordinary meson structure of $f_0(980)$

- First measurement of $f_1$ production in pp collisions

- Comparison to CSM (canonical statistical model): close to scenario $|S|=0$. This may suggests that most likely $f_1$ resonance is made of up and down quarks only

- First measurement of $f_0$, $f_2$ production in pp and p–Pb collisions

- More results will come with Run 3 data collected by ALICE
Thank you for your kind attention!!
Canonical Statistical Model

In CSM, the multiplicity dependence of hadron production is driven by the canonical suppression, namely the exact conservation of baryon number, electric charge, and strangeness over the correlation volume.

$\gamma_s$: CSM incorporates incomplete equilibration of strangeness by introducing a strangeness saturation factor ($\gamma_s$).