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Analysis of light vector mesons in p–p collisions at $\sqrt{s} = 13$ TeV

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Abstract

Here goes your abstract

Contents

1 Introduction[1]

why is a1 interesting? –> short intro in QCD, chiral symmetry of QCD and chiral partners broadening and mass degeneracy in QGP, ...

1.1 The QCD Lagrangian

To understand the effects of the strong interaction we use the theory which has been proven most succesful in this matter in the end of the last century: QCD (e.g. [2]). We start from the classic Lagrangian of QCD with 3 flavours which is the unique Lagrangian which is invariant under a gauged SU(3) symmetry

$$\mathscr{L}_{QCD} = \bar{\psi}_i \left(i\gamma_\mu D^\mu - m\right)_{ij} \psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \tag{1}$$

where $\psi = (u,d,s)$ are the quark fields, $D^\mu = \partial^\mu - igA^\mu$ is the covariant derivative in the fundamental representation and $G^a_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + g f^{abc} A^b_\mu A^c_\nu$ is the field strength of the gluon fields A^a_μ with the structure constants f^{abc} of SU(3). Following the usual procedure of perturbative renormalization we can calculate the β-function in QCD. At 1-loop order it is given by

$$\beta(\alpha_S) = \mu_R^2 \frac{d\alpha_S}{d\mu_R^2} = -\left(11 - \frac{2}{3} n_f\right) \frac{\alpha_S^2}{2\pi} + O(\alpha_S^3) \equiv -\beta_0 \frac{\alpha_S^2}{2\pi} + O(\alpha_S^3) \tag{2}$$

where n_f is the number of flavours and β_0 the 1-loop β-function coefficient. Solving the differential equation in eqn. 2 in terms of the renormalized scale μ_R^2 we get an expression for the running coupling in QCD. Using the 1-loop expression we get

$$\alpha_S(\mu) = \frac{4\pi}{\beta_0 \log \frac{\mu^2}{\Lambda^2}} \tag{3}$$

where Λ is the QCD scale and we fixed $\alpha(\mu) \xrightarrow{\mu\to\Lambda} \infty$. A plot of the running coupling along with the newest measurements can be seen in fig. 1.

[1]The introduction is mostly based on [1] with other references used where cited.

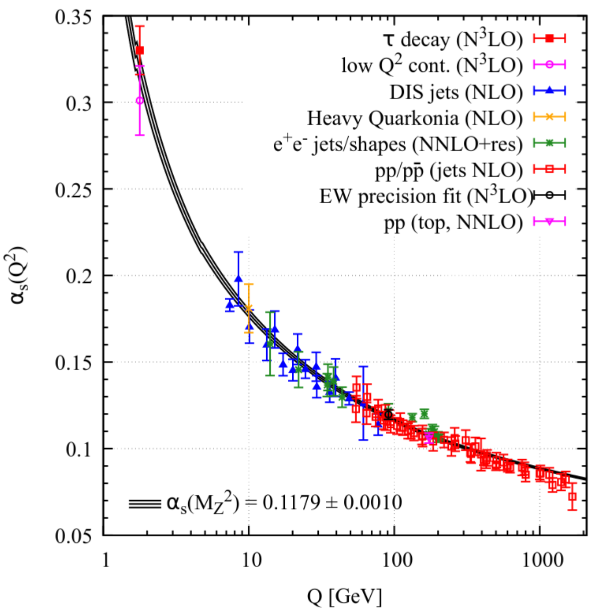

Fig. 1: The running coupling of QCD [3]. Summary of measurements of α_S as a function of the scale Q. The order in QCD perturbation theory which was used in the calculation is indicated in brackets.

From eqn. ?? it is obvious that perturbation theory is not applicable at energy scales close to the fundamental scale of our theory. Unfortunately this is the regime we are interested in, so we have to think of another way to approach scales $\mu < \Lambda_{QCD}$.

1.2 Chiral Symmetry of QCD

One of the ways to approach regimes where $\mu < \Lambda_{QCD}$ is to build an effective Lagrangian based on the symmetries of the fundamental Lagrangian of QCD. In this section we investigate this approach and see which implications it has for the particle spectrum of the theory.
We start from the Lagrangian of QCD in eqn. 1. Of particular interest to us for the chiral symmetry is the quark term in the Lagrangian which can be split into two parts

$$\mathscr{L}_{\text{quarks}} = \bar{\psi} i \gamma_\mu D^\mu \psi - m\bar{\psi}\psi \equiv \mathscr{L} + \delta\mathscr{L} \tag{4}$$

The suggestive names will make sense in a second. Since the doublet of quark fields in $\mathscr{L}$ are contracted in an inner product the Lagrangian is invariant under an inner symmetry. In our case this is a U(2) symmetry for both chiralities, so U(2)$_L$× U(2)$_R$ in total. We can also think of the symmetries in terms of axial and vector currents instead of left and right handed currents which is more useful in this analysis, so the symmetry group is U(2)$_V$× U(2)$_A$. We only consider the SU(2) part of both subgroups, since U(1)$_V$ can be identified with baryon number conservation and U(1)$_A$ is anomalous because th, so it is not a real symmetry of our theory. Let us consider the following SU(2) transformations

$$U_V = \exp\left(-i\alpha^i \frac{\sigma^i}{2}\right) \approx 1 - i\alpha^i \frac{\sigma^i}{2} \in SU(2)_V \tag{5}$$

$$U_A = \exp\left(-i\gamma_5\alpha^i \frac{\sigma^i}{2}\right) \approx 1 - i\gamma_5\alpha^i \frac{\sigma^i}{2} \in SU(2)_A \tag{6}$$

of the quark fields and their action on $\mathscr{L}$

$$\mathscr{L} = i\psi^\dagger\gamma_0\gamma^\mu D_\mu\psi \xrightarrow{U_V} i\left(U_V\psi\right)^\dagger\gamma_0\gamma^\mu D_\mu U_V\psi = i\psi^\dagger e^{+i\alpha^i\frac{\sigma^i}{2}}\gamma_0\gamma^\mu D_\mu e^{-i\alpha^i\frac{\sigma^i}{2}}\psi = i\bar{\psi}\not{D}\psi \tag{7}$$

and

$$\mathscr{L} = i\psi^\dagger\gamma_0\gamma^\mu D_\mu\psi \xrightarrow{U_A} i\left(U_A\psi\right)^\dagger\gamma_0\gamma^\mu D_\mu U_A\psi = i\psi^\dagger e^{+i\alpha^i\gamma_5\frac{\sigma^i}{2}}\gamma_0\gamma^\mu D_\mu e^{-i\gamma_5\alpha^i\frac{\sigma^i}{2}}\psi = i\bar{\psi}\not{D}\psi \tag{8}$$

where we used $\{\gamma^\mu, \gamma_5\} = 0 = [D^\mu, \gamma_5]$ and $\gamma_5^\dagger = \gamma_5$. So $\mathscr{L}$ is invariant under both U_V and U_A. The corresponding currents are

$$j^i_\mu = \bar{\psi}\gamma_\mu\frac{\sigma^i}{2}\psi \tag{9}$$

$$j^i_{5\mu} = \bar{\psi}\gamma_\mu\gamma_5\frac{\sigma^i}{2}\psi \tag{10}$$

Now we can check the effect of the transformations on $\delta\mathscr{L}$

$$\delta\mathscr{L} = -m\psi^\dagger\gamma^0\psi \xrightarrow{U_V} -m\left(U_V\psi\right)^\dagger\gamma^0 U_V\psi = -m\psi^\dagger e^{+i\alpha^i\frac{\sigma^i}{2}}\gamma^0 e^{-i\alpha^i\frac{\sigma^i}{2}}\psi = -m\bar{\psi}\psi \tag{11}$$

and

$$\delta\mathscr{L} = -m\psi^\dagger\gamma^0\psi \xrightarrow{U_A} -m\left(U_A\psi\right)^\dagger\gamma^0 U_A\psi = -m\psi^\dagger e^{+i\gamma_5\alpha^i\frac{\sigma^i}{2}}\gamma^0 e^{-i\gamma_5\alpha^i\frac{\sigma^i}{2}}\psi = -me^{2i\gamma_5\alpha^i\frac{\sigma^i}{2}}\bar{\psi}\psi \neq \delta\mathscr{L} \tag{12}$$

where we used the same identities as above. We see that the mass term is not invariant under axial transformations while it is left invariant by vector transformations. The axial symmetry is therefore explicitly broken by the quark mass term. But as long as the quark masses are smaller than the scale our theory we can still use the theory as an approximate symmetry. This is indeed the case, since $m_u, m_d \sim O(5\text{ MeV}) \ll \Lambda_{QCD} \simeq 200$ MeV.

1.3 Mesons and Their Transformation Properties Under Chiral Transformations

With our 2 quark fields we can now build bosonic fields that have the quantum numbers of the mesons in nature. We find

$$\begin{aligned} &\text{pion}-\text{like state}: \vec{\pi} \equiv i\bar{\psi}\vec{\sigma}\gamma_5\psi; \qquad &&\text{sigma}-\text{like state}: \sigma \equiv \bar{\psi}\psi \\ &\text{rho}-\text{like state}: \vec{\rho}_\mu \equiv \bar{\psi}\vec{\sigma}\gamma_\mu\psi; \qquad &&a_1-\text{like state}: \vec{a}_{1\mu} \equiv \bar{\psi}\vec{\sigma}\gamma_\mu\gamma_5\psi \end{aligned}$$

Of particular interest to us will be the ρ and the a_1 states because they correspond to the conserved currents from eqn. ?? and ??. Let us see now how these particles transform under the chiral transformations in infinitesimal form, so we can understand the symmetry better. Starting with the π state and with the vector transformation from eqn. ?? we get

$$\begin{aligned} i\bar{\psi}\sigma^i\gamma_5\psi \xrightarrow{U_V} i\left(U_V\psi\right)^\dagger\gamma^0\sigma^i\gamma_5 U_V\psi = i\bar{\psi}\sigma^i\gamma_5\psi + \alpha^j\left(\bar{\psi}\sigma^i\frac{\sigma^j}{2}\gamma_5\psi - \bar{\psi}\frac{\sigma^j}{2}\sigma^i\gamma_5\psi\right) + O(\alpha^2) = \\ = i\bar{\psi}\sigma^i\gamma_5\psi + i\alpha^j\varepsilon^{ijk}\bar{\psi}\sigma^k\gamma_5\psi \end{aligned} \tag{13}$$

where we have used the $SU(2)$ algebra $\left[\sigma^i,\sigma^j\right] = 2i\varepsilon^{ijk}\sigma^k$. We can do similar calculations for all of the other states as well and get for the vector transformations

$$\vec{\pi} \xrightarrow{U_V} \vec{\pi} + \vec{\alpha}\times\vec{\pi} \tag{14}$$

$$\sigma \xrightarrow{U_V} \sigma \tag{15}$$

$$\vec{\rho}_\mu \xrightarrow{U_V} \vec{\rho}_\mu + \vec{\alpha}\times\vec{\rho}_\mu \tag{16}$$

$$\vec{a}_{1\mu} \xrightarrow{U_V} \vec{a}_{1\mu} + \vec{\alpha}\times\vec{a}_{1\mu} \tag{17}$$

Which is also what we expect when we identify $SU(2)_V$ with isospin. $\vec{\pi}$, $\vec{\rho}_\mu$ and $\vec{a}_{1\mu}$ are all in the fundamental of isospin and are therefore affected by the isospin symmetry. Whereas, σ is a scalar under isospin and is therefore not affected.
However, for the axial transformations the particles mix as follows

$$\vec{\pi} \xrightarrow{U_A} \vec{\pi} + \vec{\alpha}\sigma \tag{18}$$

$$\sigma \xrightarrow{U_A} \sigma - \vec{\alpha}\cdot\vec{\pi} \tag{19}$$

$$\vec{\rho}_\mu \xrightarrow{U_A} \vec{\rho}_\mu + \vec{\alpha}\times\vec{a}_{1\mu} \tag{20}$$

$$\vec{a}_{1\mu} \xrightarrow{U_A} \vec{a}_{1\mu} - \vec{\alpha}\times\vec{\rho}_\mu \tag{21}$$

Since 2 pairs of particles are rotated into each other by axial rotations, this suggests that these particles have the same mass or after the explicit breaking of $SU(2)_A$ by the quark mass term at least a similar mass. But this does not seem to be the case in nature, since e.g. the a_1 has a mass of $m_{a_1} \simeq 1260$ MeV which is almost double the mass of the ρ meson with a mass of $m_\rho \simeq 770$ MeV. So, clearly $m_{a_1} \not\simeq m_\rho$ and $SU(2)_A$ can not be a symmetry of the vacuum and must therefore be spontaneously broken: $SU(2)_V \times SU(2)_A \to SU(2)_V$. We can now interpret the three spin-0 particles $\vec{\pi}$ from above as the Goldstone bosons of the spontaneously broken $SU(2)_A$. If $U(1)_A$ wasn't anomalous, we could identify the σ as its Goldstone boson, which in the case of three flavours can be identified with the η'.
We could now turn on the usual machinery for spontaneously broken symmetries and construct the effective Lagrangian of the pions. But since we don't do any original calculations in this paper, let us skip that and look at some implications of the spontaneous symmetry breaking and the possible return of the symmetry. Especially in the for the vector mesons whose field configurations correspond to the conserved currents.

1.4 Effects of Spontaneous Chiral Symmetry Breaking

We also see that [4] correlations function change but might be restored in medium and/or high temperatures. Also from axial trafo of mesons which can be identified with currents

$$j_V \xrightarrow{U_A} j_V + \alpha j_A \tag{22}$$

2 Data Analysis

2.1 MC production

3 Results

References

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