Production of $f_0(980)$ meson at the LHC: 
color evaporation versus color-singlet gluon-gluon fusion

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Abstract

The production of the $f_0(980)$ meson at high energies is not well understood. We investigate two different potential mechanisms for inclusive scalar meson production in the $k_t$-factorization approach: color-singlet gluon-gluon fusion and color evaporation model. The $\gamma^*\gamma^* \rightarrow f_0(980)$ form factor(s) can be constraint from the $f_0(980)$ radiative decay width. The $g^*g^* \rightarrow f_0(980)$ form factors are obtained by a replacement of $\alpha_{em}$ electromagnetic coupling constant by $\alpha_s$ strong coupling constant and appropriate color factors. The form factors for the two couplings are parametrized with a function motivated by recent results for scalar quarkonia. The differential cross sections are calculated in the $k_t$-factorization approach with modern unintegrated gluon distributions. Unlike for quarkonia it seems rather difficult to describe a preliminary ALICE data for inclusive production of $f_0(980)$ exclusively by the color singlet gluon-gluon fusion mechanism. Two different scenarios for flavour structure of $f_0(980)$ are considered in this context. We consider also mechanism of fusion of quark-antiquark associated with soft gluon emission in a phenomenological color evaporation model (CEM) used sometimes for quarkonium production. Here we use $k_t$-factorization version of CEM to include higher-order contributions. In addition, for comparison we consider also NLO collinear approach with $q\bar{q}q$ and $q\bar{q}g$ color octet partonic final states. Both approaches lead to a similar result. However, very large probabilities are required to describe the preliminary ALICE data. The pomeron-pomeron fusion mechanism is also discussed and results are quantified.

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I. INTRODUCTION

The production of light mesons in high-energy proton-proton collisions is rather poorly understood. Representative examples is production of \(f_0(500), \rho(770), f_0(980)\) or \(f_2(1270)\). Parallel we discussed inclusive production of \(f_2(1270)\) meson in proton-proton collisions [1] where it is found that the preliminary ALICE data [2] can be almost explained at higher \(f_2(1270)\) transverse momentum \(p_t > 3\, \text{GeV}\) using color-singlet gluon-gluon fusion mechanism. The \(f_2(1270)\) meson is usually considered to have a \(\frac{1}{\sqrt{2}} (u\bar{d} + d\bar{u})\) flavour structure. Here we wish to explore the situation for the production of a rather enigmatic \(f_0(980)\).

In general, light scalar mesons are poorly understood [3]. In particular, it is not clear whether they are of the \(q\bar{q}\) character or are tetraquarks [4]. Most mesons are thought to be formed from combinations of \(q\bar{q}\). In the literature, the hadronic structure of the \(f_0(980)\) meson has been discussed for decades and there are many different interpretations, from the conventional \(q\bar{q}\) picture [5, 6] to multiquark [7, 8] or \(K\bar{K}\) bound states [9–12]. Some authors introduce the concept of \(qq\bar{q}\) states [4] or even superpositions of the tetraquark state with the \(q\bar{q}\) state [13, 14]. The structure of \(f_0(980)\) can be studied also in nonsemileptonic decays of \(D, D_s\) mesons [15] or \(B, B_s\) mesons [16, 17].

Note that \(f_0(980)\) state was seen in both \(\pi\pi\) and \(K\bar{K}\) channel [18] with a considerable branching fraction. For the branching ratios see the discussion, e.g., in Refs. [14, 19].

In the present letter we investigate whether the gluon-gluon fusion or color evaporation approaches known from quarkonium production can explain the new preliminary ALICE data [2]. As this is a first analysis on the subject we shall consider a simple \(q\bar{q}\) structure of \(f_0(980)\) meson. We shall consider different flavour combinations. This has of course important consequences for \(\gamma^*\gamma^* \to f_0(980)\) coupling due to charges of quarks/antiquarks. Such couplings are important ingredients for calculating \(f_0(980)\) contribution to light-by-light component to anomalous magnetic moment of the muon [20–22]. In Ref. [23] it was argued that \(f_0(980)\) must be dominantly \(s\bar{s}\) to describe radiative decay \(\phi \to f_0(980)\gamma\). This is dictated by the fact that \(\Gamma(\phi \to f_0(980)\gamma) \gg \Gamma(\phi \to a_0(980)\gamma)\). In Ref. [24] the \(\gamma^* - f_0(980)\) transition form factor was studied assuming the simple \(s\bar{s}\) structure. Only \(F_{TT}\) transverse form factor was included in this analysis. The role of \(F_{LL}\) longitudinal form factor was not studied so far.

II. SOME DETAILS OF THE MODEL CALCULATIONS

A. The \(\gamma^*\gamma^* \to f_0(980)\) fusion process

In the formalism presented e.g. in [25] the covariant matrix element for the \(\gamma^*\gamma^* \to f_0(980)\) process is written as:

\[
\mathcal{M}^{\mu\nu} = 4\pi\alpha_{\text{em}} \frac{\nu}{m_{f_0}} \left[ -R^{\mu\nu}(q_1, q_2) F_{TT}(Q_1^2, Q_2^2) \right. \\
+ \left. \frac{\nu}{X} \left( q_1^{\mu} + \frac{Q_2^2}{\nu} q_2^{\mu} \right) \left( q_2^{\nu} + \frac{Q_1^2}{\nu} q_1^{\nu} \right) F_{LL}(Q_1^2, Q_2^2) \right],
\]

(2.1)
where \( \nu = (q_1 \cdot q_2) \), \( X = \nu^2 - q_1^2 q_2^2 \), and

\[
R^{\mu\nu}(q_1, q_2) = -g^{\mu\nu} + \frac{1}{X} \left[ \nu (q_1^\mu q_2^\nu + q_2^\mu q_1^\nu) - q_1^\mu q_2^\nu q_2^\mu q_1^\nu \right].
\] (2.2)

Here \( q_1 \) and \( q_2 \) denote the momenta of the photons, \( Q_1^2 = -q_1^2 \), \( Q_2^2 = -q_2^2 \), and \( m_{f_0} \) is mass of the \( f_0(980) \) meson. In Eq. (2.1), the scalar meson structure information in encoded in the form factors \( F_{TT} \) and \( F_{LL} \) which are functions of the virtualities of both photons. \( F_{TT} \) or \( F_{LL} \) correspond to the situation where either both photons are transverse or longitudinal, respectively. By definition the form factors are dimensionless.

For scalar quarkonium states a microscopic calculation is reliable; see [26]. For light mesons the situation is more complicated. Here we will try to rather parametrize the form factors.

The two-photon decay width of the \( f_0(980) \) meson can be calculated as:

\[
\Gamma(f_0(980) \to \gamma\gamma) = \frac{\pi a^2_{em}}{4} m_{f_0} |F_{TT}(0,0)|^2.
\] (2.3)

Only \( F_{TT} \) form factor can be constraint from (2.3). The radiative decay width is relatively well known, see [18]. Using the average decay width quoted in [18]

\[
\Gamma(f_0(980) \to \gamma\gamma) = 0.31 \text{ keV}.
\] (2.4)

and \( m_{f_0} = 980 \) MeV we obtain from (2.3) \( |F_{TT}(0,0)| = 0.087 \). Then the transverse form factor is parametrized as:

\[
\frac{F_{TT}(Q_1^2, Q_2^2)}{F_{TT}(0,0)} = \left( \frac{\Lambda_M^2}{Q_1^2 + Q_2^2 + \Lambda_M^2} \right),
\] (2.5)

\[
\frac{F_{TT}(Q_1^2, Q_2^2)}{F_{TT}(0,0)} = \left( \frac{\Lambda_D^2}{Q_1^2 + Q_2^2 + \Lambda_D^2} \right)^2,
\] (2.6)

where cut-off parameters \( \Lambda_M \) or \( \Lambda_D \) are expected to be of order of 1 GeV. Both monopole (2.5) and dipole (2.6) parametrizations of \( F_{TT} \) will be used in the following. In the calculations we take \( \Lambda_M = \Lambda_D = m_{f_0} \).

The \( F_{LL} \) form factor is rather unknown but via construction do not enter the formula for the radiative decay width (2.3) as

\[
F_{LL}(0, Q_2^2) = F_{LL}(Q_1^2, 0) = 0.
\] (2.7)

We propose to use the following parametrization for the \( F_{LL} \) form factor:

\[
F_{LL}(Q_1^2, Q_2^2) = R_{LL/TT} \frac{Q_1^2}{M_0^2 + Q_1^2} \frac{Q_2^2}{M_0^2 + Q_2^2} F_{TT}(Q_1^2, Q_2^2).
\] (2.8)

Such a form is consistent with a microscopic calculation for \( \gamma^* \gamma^* \to \chi_{c0} \) [26] using quarkonium wave functions obtained from the potential models. In our present case we expect \( R_{LL/TT} \approx \pm 0.5 \) and \( M_0 \sim m_{f_0} \).
FIG. 1. General diagram for inclusive $f_0(980)$ production via gluon-gluon fusion in proton-proton collisions.

B. Color singlet $g^*g^* \to f_0(980)$ fusion

In Fig.1 we show a generic Feynman diagram for $f_0(980)$ meson production in proton-proton collision via gluon-gluon fusion. This diagram illustrates the situation adequate for the $k_t$-factorization calculations used in the present paper.

The differential cross section for inclusive $f_0(980)$ meson production via the $g^*g^* \to f_0(980)$ fusion in the $k_t$-factorization approach can be written as:

$$\frac{d\sigma}{d\gamma d^2p} = \int \frac{d^2q_1}{\pi q_1^2} F(x_1, q_1^2) \int \frac{d^2q_2}{\pi q_2^2} F(x_2, q_2^2) \delta(2)(q_1 + q_2 - p) \frac{\pi}{(x_1x_2s)^2} |M|^2. \quad (2.9)$$

Here $q_1, q_2$ and $p$ denote the transverse momenta of the gluons and the $f_0(980)$ meson. $M_{g^*g^*\rightarrow f_0}$ is the off-shell matrix element for the hard subprocess and $F_g$ are the gluon unintegrated distribution functions (UGDFs) for both colliding protons. The UGDFs depend on gluon longitudinal momentum fractions $x_1, x_2 = m_T \exp(\pm y) / \sqrt{s}$ and $q_1^2, q_2^2$ entering the hard process. In principle, they can depend also on factorization scales $\mu_{F,i}^2, i = 1, 2$. It is reasonable to assume $\mu_{F,1}^2 = \mu_{F,2}^2 = m_T^2$. Here $m_T$ is transverse mass of the produced $f_0(980)$ meson; $m_T = \sqrt{p^2 + m_{f_0}^2}$. The $\delta(2)$ function in Eq. (2.9) can be easily eliminated by introducing $q_1 + q_2$ and $q_1 - q_2$ transverse momenta.

The off-shell matrix element can be written as (we restore the color indices $a$ and $b$)

$$M^{ab} = \frac{q_{1\mu}q_{2\nu}}{|q_1||q_2|} M_{\mu\nu}^{ab} = \frac{q_{1\mu}q_{2\nu}}{|q_1||q_2|} n^{+\mu} n^{-\nu} M_{\mu\nu}^{ab} = \frac{x_1x_2s}{2|q_1||q_2|} n^{+\mu} n^{-\nu} M_{\mu\nu}^{ab} \quad (2.10)$$

with the lightcone components of gluon momenta $q_{1+} = x_1 \sqrt{s/2}, q_{2-} = x_2 \sqrt{s/2}$.

The $g^*g^* \rightarrow f_0(980)$ coupling entering in the matrix element squared can be obtained from that for $\gamma^*\gamma^* \rightarrow f_0(980)$ coupling (see e.g. [28]) by the following replacement:

$$\alpha_{em}^2 \rightarrow \alpha_s^2 \frac{1}{4N_c(N_c^2 - 1)} \frac{1}{(<e_q^2>)^2}. \quad (2.11)$$

(<$e_q^2$>) above strongly depends on the flavour structure of the wave function. In the
following we consider a few examples of quark-flavour composition:

$$|f_0(980)⟩ = \frac{1}{\sqrt{2}} (|u\bar{u}⟩ + |d\bar{d}⟩)$$, \hspace{1cm} (2.12)

$$|f_0(980)⟩ = |s\bar{s}⟩$$, \hspace{1cm} (2.13)

$$|f_0(980)⟩ = \frac{1}{\sqrt{2}} (|[s]\bar{[u]}⟩ + |[s][d]\bar{d}⟩)$$ . \hspace{1cm} (2.14)

The first function is written in analogy to the rather well known flavour wave function of $f_2(1270)$ meson. The second function was suggested by analysis of radiative decays of φ meson as discussed in the introduction. The last function (tetraquark) is supported by spectroscopy of scalar mesons (see e.g. [4]). The scalar mesons with masses below 1 GeV can be understood to be of the tetraquark character and those above 1 GeV as of the $q\bar{q}$ or glueball character. There is, however, no general consensus and the situation is open in our opinion. To reach final picture one must include very different processes simultaneously.

In realistic calculations the running of strong coupling constants must be included. In our numerical calculations presented below, we set the factorization scale to $\mu_F^2 = m_T^2$, and the renormalization scale is taken in the form:

$$\alpha_s^2 \rightarrow \alpha_s (\max \{m_T^2, q_1^2\}) \alpha_s (\max \{m_T^2, q_2^2\})$$ . \hspace{1cm} (2.15)

C. Color evaporation model (CEM)

The general diagram representing the color evaporation model (CEM) \[29, 30\] is shown in Fig. 2. In this approach one is using the perturbative calculation of $q\bar{q}$ minijets.

![Diagram of Color Evaporation Model](image_url)

**FIG. 2.** General diagram for inclusive $f_0(980)$ production in proton-proton collisions in the color evaporation approach.

Fig. 3 represents diagram with $q\bar{q}$ production in the $k_t$-factorization approach in proton-proton collisions. Here, we calculate $u\bar{u}$ and $d\bar{d}$ production, or alternatively $s\bar{s}$ production, in a similar way as it was done for $c\bar{c}$ production \[31\]. The color of the $u\bar{u}$ or $d\bar{d}$ is typically in the octet representation. The further emissions of soft gluons are not explicit but will be contained in a multiplicative factor $P_{\text{CEM}}$ defined below.

Everything is contained in a suitable renormalization of the $q\bar{q}$-cross section when integrating over certain limits in the $q\bar{q}$ invariant mass. Having calculated differential cross
section for $q\bar{q}$-pair production one can obtain the cross section for $f_0(980)$ meson within the framework of the CEM. The $q\bar{q} \to f_0(980)$ transition can be formally written as follows:

$$
\frac{d\sigma_{f_0}(p_{f_0})}{d^3p_{f_0}} = P_{\text{CEM}} \int_{m_{f_0} - \Delta M}^{m_{f_0} + \Delta M} d^2p_{q\bar{q}} \frac{d\sigma_{q\bar{q}}(M_{q\bar{q}}, P_{q\bar{q}})}{dM_{q\bar{q}} d^3P_{q\bar{q}}} \delta^3(p_{f_0} - \frac{m_{f_0}}{M_{q\bar{q}}} P_{q\bar{q}}),
$$

(2.16)

where $P_{\text{CEM}}$ is the probability of the $q\bar{q} \to f_0(980)$ transition which is fitted to the experimental data, $M_{q\bar{q}}$ and $P_{q\bar{q}} = |\vec{P}_{q\bar{q}}|$ are the invariant mass and momentum of the $q\bar{q}$ system. Here we take $\Delta M = 100$ MeV.

![Diagram](image)

**FIG. 3.** Typical $k_t$-factorization process with the production of $u\bar{u}$ and $d\bar{d}$ pairs that are intermediate state for color evaporation.

In Fig. 4, we show an example of the diagram relevant for collinear next-to-leading order approach. A full list of processes included in the calculation will be presented in the result section. Within the collinear-factorization approach in the leading-order (LO) approximation, the transverse momentum of the $q\bar{q}$ pair is equal to zero. In fact, the NLO diagrams for the inclusive minijets, such as $gg \to gq\bar{q}$ or $q\bar{q} \to qq\bar{q}$, constitute the LO contributions for the $q\bar{q}$-pair transverse momentum. Similarly, the next-to-next-to-leading-order (NNLO) topologies for this quantity are effectively NLO. The situation is different in the $k_t$-factorization approach where nonzero $q\bar{q}$-pair transverse momentum can be obtained already at leading order within the $g^*g^* \to q\bar{q}$ and $q^*q^* \to q\bar{q}$ mechanisms.
FIG. 4. An alternative collinear approach with the production of $u\bar{u}$ and $d\bar{d}$ pairs associated with soft gluon emission that are intermediate state for color evaporation.

III. NUMERICAL RESULTS

In this section we will present results for the color-singlet gluon-gluon fusion and color evaporation model.

To convert to the number of $f_0(980)$ mesons per event, as was presented in Ref. [2], we use the following relation:

$$\frac{dN}{dp_t} = \frac{1}{\sigma_{\text{inel}}} \frac{d\sigma}{dp_t}. \quad (3.1)$$

The inelastic cross section for $\sqrt{s} = 7$ TeV was measured at the LHC and is:

$$\sigma_{\text{inel}} = 73.15 \pm 1.26 \text{ (syst.) mb}, \quad (3.2)$$
$$\sigma_{\text{inel}} = 71.34 \pm 0.36 \text{ (stat.)} \pm 0.83 \text{ (syst.) mb}, \quad (3.3)$$

as obtained by the TOTEM [32] and ATLAS [33] collaborations, respectively. In our calculations we take $\sigma_{\text{inel}} = 72.5 \text{ mb}$.

A. Gluon-gluon fusion

As discussed in the previous section the result of the colour-singlet gluon-gluon fusion strongly depends on the flavour structure of $f_0(980)$ which is related to the $\langle e_q^2 \rangle^2$ in Eq. (2.11). For example $\langle e_q^2 \rangle^2 = 25/162$ for first scenario (2.12), $\langle e_q^2 \rangle^2 = 1/81$ for the $s\bar{s}$ scenario (2.13). For the tetraquark scenario $\langle e_q^2 \rangle^2 = 1/162$ (2.14) assuming diquark as elementary object, but everything depends on details and assumptions made for diquark.

Here, we use two different UGDFs which are available from literature, e.g. from the CASCADE Monte Carlo code [34].

- We use a glue constructed according to the prescription initiated in [35] and later updated in [36, 37], which we label as “KMR UGDF”.

•
The second type of UGD which we use has been obtained by Hautmann and Jung [38] from a description of precise HERA data on deep inelastic structure function by a solution of the CCFM evolution equation [39–41]. We use “JH-2013-set2” of Ref. [38], which we label as “JH UGDF”.

In Fig. [5] we present the $f_0(980)$ meson transverse momentum distributions at $\sqrt{s} = 7$ TeV and $|y| < 0.5$. A representative results for the gluon-gluon fusion contribution for the $s\bar{s}$ scenario for two different UGDs, JH UGDF (left panel) and KMR UGDF (right panel), are shown together with the preliminary ALICE data from [2]. We show results for the monopole (2.5) and dipole (2.6) form factors with the cut-off parameter $\Lambda_M = \Lambda_D = m_{f_0}$. For the LL form factor (2.8) we take $R_{LL/TT} = \pm 0.5$. The upper solid lines are for $R_{LL/TT} = -0.5$ while the bottom lines for 0.5. The JH UGDF (see the left panel) gives slightly larger cross section than the KMR UGDF (see the right panel). The theoretical distribution for the monopole form factor with $\Lambda_M = m_{f_0}$ exceeds the ALICE data for $p_t > 2$ GeV.

The obtained results are much below the preliminary ALICE data [2] at low $f_0(980)$ transverse momenta. Does it mean that other mechanism(s) is (are) at the game?

It seems that even the $s\bar{s}$ scenario does not allow to describe the ALICE data. A big gluonic component in the $f_0(980)$ wave function could help to improve the situation. Large $K\bar{K}$ molecular component could be another solution.

In addition to the gluon-gluon fusion contribution we show the contribution of the exclusive $pp \rightarrow ppf_0(980)$ process proceeding via the pomeron-pomeron fusion mechanism. The result is represented by the red dotted line. Here the calculation was made in the tensor-pomeron approach in the Born approximation (without absorptive corrections). Absorption corrections are important only when restricting to purely exclusive processes. For details regarding this approach we refer to [42–45]. In the calculation we take the pomeron-pomeron-$f_0(980)$ (PP$f_0(980)$) coupling parameters from [45], that is, $(g', g'') = (0.53, 2.67)$; see Table II of [45]. We have checked, that with these parameters we describe, within experimental errors, the cross sections reported very recently by the CMS Collaboration [46] for the exclusive $pp \rightarrow pp(f_0(980) \rightarrow \pi^+\pi^-)$ process.

Below we shall consider also color octet contribution calculated in the color evaporation approach.

### B. Color evaporation model

In the present study the cross sections for $u\bar{u}$ and $d\bar{d}$ or alternatively $s\bar{s}$ minijet pair production are calculated in the $k_t$-factorization approach or in the collinear approach. In both cases the calculations are done with the help of the KaTie Monte Carlo code [47]. Considering production of (soft) minijets a real problem is a regularization of the cross section at small transverse momenta. Here we follow the methods adopted for collinear approach in PYTHIA and multiply the calculated cross section by a somewhat arbitrary suppression factor:

$$F_{\text{sup}}(p_t) = \frac{p_t^4}{((p_t^1)^2 + p_t^2)^2},$$

where $p_t^0$ is a free parameter of the model. In the following calculations we take different values of $p_t^0$, in order to show sensitivity of the results to the choice of this parameter.
FIG. 5. The $f_0(980)$ meson transverse momentum distributions at $\sqrt{s} = 7$ TeV and $|y| < 0.5$. The preliminary ALICE data from [2] are shown for comparison. For the $g^*g^* \to f_0(980)$ contribution two different UGDFs are used: the JH (left panel) and KMR (right panel). Here, the $s\bar{s}$ flavour wave function of $f_0(980)$ is taken into account. Shown are TT and LL components in the amplitude and their coherent sum (total) for the monopole (green solid lines) and dipole (black solid lines) form factor parametrizations. In this calculation we used $\Lambda_M = \Lambda_D = m_{f_0}$ and $R_{LL/TT} = \pm 0.5$. The upper solid lines are for $R_{LL/TT} = -0.5$ while the bottom lines for 0.5. The dotted line corresponds to the Born-level result for the $pp \to pp f_0(980)$ process via pomeron-pomeron fusion.

The parameter goes also into the argument of the strong coupling constant $\alpha_s(\mu_R^2) = \alpha_s((p_{T1}^0)^2 + p_{T2}^2)$.

C. The $k_t$-factorization approach to CEM with the KMR UPDFs

In the $k_t$-factorization approach the non-zero $q\bar{q}$ pair transverse momentum can be generated even at leading-order when only the $2 \to 2$ three-level partonic processes are taken into account. Here we include both the $gg$-fusion and $q\bar{q}$-annihilation mechanisms. By applying the KMR UPDFs one effectively includes a part of real higher order corrections. Large amount of extra hard emissions present in this model may lead to large transverse momentum of the produced system, without any additional emissions at the level of hard matrix elements.

Technically, in the numerical calculations here, the suppression factor includes the fact that the transverse momenta of outgoing minijets are not balanced and it takes the following form:

$$F_{\text{sup}}^{(2)}(p_{T1}^2, p_{T2}^2) = \frac{p_{T1}^2}{(p_{T1}^0)^2 + p_{T1}^2} \times \frac{p_{T2}^2}{(p_{T2}^0)^2 + p_{T2}^2}. \quad (3.5)$$

The $\text{KaNiTe}$ Monte Carlo generator does not have any problems with the generation of
the events in the case of the $2 \rightarrow 2$ processes, even if there is no additional cut-off on the outgoing minijets transverse momenta (thus low-$p_t$ cuts are not necessary here). The generated events for massless quarks/antiquarks are weighted by the suppression factor $(3.5)$.

In Fig. 6 we show the results for different values of $p_t^0$ in $(3.5)$, that is, $p_t^0 = 0.01, 0.5,$ and $1.0$ GeV. Large damping of the $q\bar{q}$-pair $p_t$ distributions is visible. In the following, we choose $p_t^0 = 0.01$ GeV.

![Figure 6](image.png)

**FIG. 6.** The transverse momentum distribution of $f_0(980)$ for the KMR-CT14lo UPDFs for different $p_t^0$ in $(3.5)$ for the $gg$-fusion (left) and $q\bar{q}$ (right) mechanisms. The calculations were done for $M_{q\bar{q}} \in (0.88, 1.08)$ GeV.

As can be seen from Fig. 7 we obtain a good description of the ALICE data even with the leading-order $2 \rightarrow 2$ mechanisms only. In the top panels of Fig. 7 we show results for the first $\frac{1}{\sqrt{2}}(|u\bar{u}| + |d\bar{d}|)$ scenario $(2.12)$ while in the bottom panels of Fig. 7 for the $|s\bar{s}|$ scenario $(2.13)$. We show also the dependence of the final results on the collinear parton distributions used to the calculation of the KMR UPDFs. The results in the left panels correspond to the CT14lo PDF [48] while in the right panels to the MMHT2014lo PDF [49]. The differences at so small scales between different collinear PDFs could be significant.

Since the assumption of $\frac{1}{\sqrt{2}}(|u\bar{u}| + |d\bar{d}|)$ for the flavour wave function of $f_0(980)$ may be not realistic we consider also the $s\bar{s}$ scenario as was done for color-singlet gluon-gluon fusion. It is obvious that the corresponding cross section will be smaller than that for the light $q\bar{q}$ scenario. In the right bottom panel of Fig.7 we show corresponding results for the $s\bar{s}$ scenario. It is obvious that here (KMR-MMHT2014lo UPDF) the $g^*g^* \rightarrow s\bar{s} \rightarrow f_0(980)$ is the dominant mechanism. Assuming massless $s$ and $\bar{s}$ the corresponding cross section is very similar as for $\frac{1}{\sqrt{2}}(|u\bar{u}| + |d\bar{d}|)$ scenario because for high-energy collisions the gluon-gluon fusion is the dominant contribution.

The calculations done so far were performed for massless quarks/antiquarks. How important is the quark/antiquark mass for our $k_t$-factorization results is illustrated in Fig. 8. Here we show $M_{q\bar{q}}$ invariant mass distributions for three different quark masses: $m_q = 0$ GeV (with the extra regularization procedure given by Eq. $(3.5)$, $p_t^0 = 0.01$ GeV), $m_q = 0.1$ GeV (current $s/\bar{s}$ mass), $m_q = 0.3$ GeV (constituent light quark ($u,d$) masses).
FIG. 7. The $f_0(980)$ meson transverse momentum distributions at $\sqrt{s} = 7$ TeV and $|y| < 0.5$ calculated in the color evaporation model based on the $k_t$-factorization approach using the KMR-CT14lo (left) and KMR-MMHT2014lo (right) UPDFs together with the preliminary ALICE data from [2]. The calculations were done in quark-antiquark invariant mass region $M_{q\bar{q}} \in (0.88, 1.08)$ GeV for the light $q\bar{q}$ scenario (2.12) (see the top panels) and for the $s\bar{s}$ scenario (2.13) (see the bottom panels). The results for the $gg$-fusion and $q\bar{q}$ mechanisms are shown separately. Their sum is shown by the solid line. Here we used extremely small $p_T^0 = 0.01$ GeV in (3.5).

We show also the window of $M_{q\bar{q}}$ selected for the $f_0(980)$ meson, used in the color-evaporation model calculations; see Eq. (2.16). For finite quark/antiquark masses no extra regularization is needed. There is no strong dependence on $m_q$ provided it is not too big. For instance for $m_q \approx 0.5$ GeV, the $s$ quark constituent mass, the cross section for the color evaporation model vanishes when $M_{q\bar{q}} > m_{f_0}$.

In Fig. 9 we show transverse momentum distribution for the $g^* g^* \rightarrow q\bar{q}$ and $q^* \bar{q}^* \rightarrow q\bar{q}$ mechanisms added together for different final state quark/antiquark masses: 0.1, 0.3 GeV. Technically, we use here off-shell matrix elements derived for heavy quark production including both the $gg$-fusion and light quark $q\bar{q}$-annihilation into heavy (massive) quark-antiquark pair. We conclude that the results does not depend too much on the mass of produced quark/antiquark.
FIG. 8. $M_{qq}$ invariant mass distribution for three different quark/antiquark masses specified in the figure.

FIG. 9. The transverse momentum distributions of $f_0(980)$ for the KMR UPDFs for two mass of produced quark/antiquark: $m_q = 0.1$ GeV (dotted) and $m_q = 0.3$ GeV (dashed). Calculations were done in the $qq$ invariant mass region $M_{qq} \in (0.88, 1.08)$ GeV.

D. The collinear approach to CEM with the $2 \to 3$ tree-level partonic processes

In the collinear approach the non-zero $q\bar{q}$ pair transverse momentum can be generated only beyond the leading-order approximation. In the calculations we take into account the $2 \to 3$ partonic processes at the tree-level. So here the $q\bar{q}$-pair is associated with extra gluon or quark which comes from the hard matrix elements. Here we include all the partonic subprocesses with $gg$-, $qg$- and $q\bar{q}$-types of initial states. The full list of the processes included is shown below:

- $gg$-fusion:
IV. CONCLUSIONS

In this letter we have presented a first exploratory calculation of inclusive $f_0(980)$ meson production at the LHC energies. Two different mechanisms have been considered.

• $qg$-interaction:
  
  \[ gg \rightarrow gu\bar{u}, \quad gg \rightarrow g\bar{g} \]

  \[ uu \rightarrow uu\bar{u}, \quad gd \rightarrow du\bar{u}, \quad gs \rightarrow su\bar{u}, \quad g\bar{s} \rightarrow \bar{s}u\bar{u}, \quad ug \rightarrow uu\bar{u}, \]

  \[ dg \rightarrow du\bar{u}, \quad sg \rightarrow su\bar{u}, \quad \bar{u}g \rightarrow uu\bar{u}, \quad dg \rightarrow du\bar{u}, \quad \bar{s}g \rightarrow \bar{s}u\bar{u}, \quad gu \rightarrow udd, \quad gd \rightarrow d\bar{d}, \quad gs \rightarrow s\bar{d}, \quad ug \rightarrow udd, \quad dg \rightarrow d\bar{d}, \quad \bar{s}g \rightarrow s\bar{d} \]

• $q\bar{q}$-annihilation:
  
  \[ uu \rightarrow gu\bar{u}, \quad dd \rightarrow gu\bar{d}, \quad ss \rightarrow gu\bar{u}, \quad uu \rightarrow uu\bar{u}, \quad dd \rightarrow dd\bar{d}, \quad ss \rightarrow ss\bar{s}, \quad uu \rightarrow g\bar{d}, \quad dd \rightarrow g\bar{d}, \quad uu \rightarrow u\bar{d}, \quad dd \rightarrow d\bar{d}, \quad ss \rightarrow s\bar{d} \]

In the case of the collinear calculations of the $2 \rightarrow 3$ processes the suppression factor takes the following form:

\[
F_{\text{sup}}^{(3)}(p_{T1}^2, p_{T2}^2, p_{T3}^2) = \frac{p_{T1}^2}{(p_{T1}^0)^2 + p_{T1}^2} \times \frac{p_{T2}^2}{(p_{T2}^0)^2 + p_{T2}^2} \times \frac{p_{T3}^2}{(p_{T3}^0)^2 + p_{T3}^2}.
\] (3.6)

The final results that correspond to the collinear approach are shown in Fig. 10. Again, here we need to check sensitivity of the results related to the choice of the collinear PDFs. In the left panel we show results for the CT14lo PDF while in the right panel for the MMHT2014lo PDF.

FIG. 10. The $f_0(980)$ meson transverse momentum distributions at $\sqrt{s} = 7$ TeV and $|y| < 0.5$, calculated in the color evaporation model based on the collinear approach, using the CT14lo (left) and MMHT2014lo (right) PDFs together with the preliminary ALICE data from [2]. The calculations were done in quark-antiquark invariant mass region $M_{q\bar{q}} \in (0.88, 1.08)$ GeV. Here the $gg$, $qg$ and $q\bar{q}$ induced interaction mechanisms are shown separately. Shown are results for the light $q\bar{q}$ scenario (2.12) for the flavour wave function of $f_0(980)$. In the calculations we used $p_{T1}^0 = 0.01$ GeV in (3.6).
The first mechanism is the color-singlet gluon-gluon fusion known to give a rather good description of the $\eta_c$ and $\chi_c$ production [26, 28]. The second is the color evaporation model used e.g. to describe the production of $J/\psi$ meson [31]. The results have been compared to preliminary ALICE data [2].

We have started our analysis by considering the $\gamma^*\gamma^* \to f_0(980)$ coupling. Unlike for charmonia we have taken a more phenomenological approach. The general structure of the $\gamma^*\gamma^* \to f_0$ and $g^*g^* \to f_0$ vertices were known from the literature. However, the corresponding form factors for $g^*g^* \to f_0(980)$ are rather poorly known. The $F_{TT}(0,0)$ has been fixed based on the formula for $\Gamma(f_0(980) \to \gamma\gamma)$; see Eq. (2.3). $F_{LL}(Q^2_1, Q^2_2)$ for $f_0(980)$ is rather unknown and in principle a model of the $f_0(980)$ wave function is needed. In the present analysis we have parametrized the $F_{LL}(Q^2_1, Q^2_2)$ form factor in analogy to the results obtained recently from a microscopic calculation for $\chi_c0$ [26]. The parametrizations for $F_{TT/LL}(Q^2_1, Q^2_2)$ were restricted only to some extent by the Belle data for the $e^+e^- \to e^+e^-\pi\pi$ reactions [50, 51].

Then the $g^*g^* \to f_0(980)$ coupling has been obtained by replacing electromagnetic coupling constant by strong coupling constant and by modifying relevant color factors.

The contribution of color-singlet gluon-gluon fusion strongly depends on the assumed flavour structure of the $f_0(980)$ meson. For instance result for the $s\bar{s}$ scenario (2.13) is almost an order of magnitude larger than that for the light $q\bar{q}$ scenario (2.12). Large gluonic component in the $f_0(980)$ meson would further increase the cross section for colour-flavour component.

The results for hadroproduction depend on $g^*g^* \to f_0(980)$ form factors $F_{TT}$ and $F_{LL}$ that have been parametrized in the present paper; see Eqs. (2.5–2.8). With a plausible parametrization one can almost understand transverse momentum distribution of $f_0(980)$ at $p_t > 3$ GeV in the $s\bar{s}$ scenario, but the results for the light quark/antiquark scenario is much below the data for $p_t < 2$ GeV. Clearly a different mechanism is needed to describe the region of small transverse momenta of $f_0(980)$. The light $q\bar{q}$ scenario gives result much below the ALICE data.

In the present paper we have considered also color evaporation mechanism. Also the color evaporation cross sections have been calculated in the $k_t$-factorization approach, as done recently for $J/\psi$ production. The KMR unintegrated parton distribution functions (both for gluons, quarks, and antiquarks) have been used in this context. Many different processes leading to $u\bar{u}$, $d\bar{d}$ or $s\bar{s}$ final states have been considered. We have done also similar calculations at collinear NLO tree-level partonic approach. Some regularization procedure has been used in both cases. Both the $k_t$-factorization and the collinear NLO approaches lead to rather similar results.

We conclude that the color-singlet gluon-gluon fusion is not able to describe the preliminary ALICE data [2] in the whole range of transverse momenta. The color evaporation model nicely describes the shape of transverse momentum distribution. To describe absolute normalization rather maximal probabilities ($P_{\text{CEM}} = 1$) must be used. It seems to early to draw definite conclusion. More global picture may arise by analysis of production of other isoscalar mesons (such as $\eta, \eta', f_2(1270), f_1(1285)$, etc.). This clearly goes beyond the scope of the present analysis.

We have calculated also $p\bar{p} \to f_0(980)$ fusion contribution and found nonnegligible but small contribution. This contribution is concentrated at rather small $f_0(980)$ transverse momenta ($p_t < 2$ GeV) but its role is rather marginal.
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