Theoretical description of hadroproduction and production on nuclear targets of $\phi$-mesons at very high energies

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Abstract. We expose the current experimental and theoretical situation of the interesting case of the production of $\phi$-mesons in up to very high energy collisions of hadrons on both nucleon and nuclear targets.

The $\phi$-meson is a system of $s\bar{s}$ quarks, and though $s$ and $\bar{s}$ quarks have non-zero masses, their masses are not large enough to make standard perturbative Quantum Chromodynamics (QCD) applicable. This makes the $\phi$-meson an interesting intermediate case between the soft (non-perturbative) and the hard (perturbative) regimes. At the same time, the $\phi$-meson is rarely produced, and it can be sensitive to the production mechanism.

Here, we update the theoretical description of the experimental data of $\phi$-mesons hadroproduction on nucleon and nucleus targets in a wide energy region already presented in [1, 2], by including more recent experimental data into the analysis. We use the Quark-Gluon String Model (QGSM) formalism [3, 4] that gives a quantitatively consistent description of the spectra of secondary $\phi$ mesons in $pp$-collisions for a large scope of the initial energy, going up to RHIC and LHC. In the case of collisions with a nuclear target, the QGSM description of the experimental initial energy dependence of the produced $\phi$-mesons is also quantitatively good.

At the same time, the QGSM provides a natural explanation for the unusually small shadow corrections experimentally observed in proton-nucleus and nucleus-nucleus collisions at very high energies for the inclusive density (saturation of the inclusive density) [5, 6] in the central rapidity region.

In Fig. 1, the rapidity dependence of the density $dn/dy$ of $\phi$-mesons produced in $pp$-collisions at 158 GeV/c [7, 8] is compared to the results of the corresponding calculation based on QGSM (solid curve). The agreement is quite reasonable. We also compare two new experimental points by the ALICE Collaboration on the density $dn/dy$ of $\phi$-mesons produced in $pp$-collisions at 2,76 [9] and 7 TeV [10], with the results of the corresponding QGSM calculations. The dashed curve represents the theoretical results for 2.76 TeV, and the dashed-dotted curve those for 7 TeV. The dotted curve shows the model prediction for 14 TeV. As it can be seen in Fig. 1,
the results of the QGSM calculations are remarkably higher than the experimental data. This

discrepancy is quite unexpected, since in general the QGSM calculations show a good agreement
with the experimental data for proton-nucleus and nucleus-nucleus collisions, both at RHIC and
LHC energies. The explanation could be connected with the extrapolation to $p_T = 0$ of the
experimental data, that were actually measured at transverse momenta $p_T \geq 0.4$ GeV/c. The
experimental data are shown in Fig. 1, as in the original papers [9, 10], after extrapolation.

In Fig. 2, the experimental data by the HERA-B Collaboration on the rapidity dependence
of the inclusive cross section for $\phi$-meson production, $d\sigma/dy$, in $pA$ collisions for different $C, Ti, \text{ and W}$ targets at $\sqrt{s} = 41.6$ GeV [11], and for rather small rapidity ranges, are given along with
the results of corresponding calculations based on the QGSM. The theoretical results reasonably
compare with these experimental data everywhere, with the exception of some differences in the
positive region of $y \geq 0$. These differences slightly increase with the atomic number $A$ of the
target, becoming more apparent for the $W$ nucleus.

In the case of the production of particles such as pions and kaons, which make a dominant
contribution to the mean multiplicity, a new shadowing effect [12] becomes significant, starting
from an energy of $\sqrt{s} = 40$ to $60$ GeV. For $\phi$-meson production this new screening effect is in
principle not noticeable, even in the region of the RHIC energies, but it clearly appears at the
LHC energies possibly due to the fact that the mass of the strange quark is not negligible.

Let us now consider the experimental data on $\phi$-meson production in heavy ion collisions at
energies from $\sqrt{s} = 17.3$ to $200$ GeV. In Table 1, the experimental values of the midrapidity
inclusive densities, $dn/dy$ ($|y| \leq 0.5$), for $\phi$-meson production in central nucleus-nucleus
collisions, obtained by the NA49 Collaboration ($\sqrt{s} = 17.3$ GeV [7, 8]), and those obtained
at RHIC (STAR and PHENIX Collaborations, $\sqrt{s} = 62.4$ GeV [13], 130 GeV [14, 15], and

Figure 1. Experimental data [7, 8] on the $y$-spectra $dn/dy$ of $\phi$-mesons produced in $pp$ collisions
at 158 GeV/c, and the results of the corresponding calculation based on the QGSM (solid line).
The dashed and dashed-dotted lines represent the results of the QGSM calculations at 2.76 and
7 TeV, and they are compared with corresponding experimental points in the central rapidity
region, $|y| \leq 0.5$ [9, 10]. The dotted line is the QGSM prediction for 14 TeV.
Figure 2. Experimental data on the $y$ dependence of the cross section for $\phi$-meson production, $d\sigma/dy$, in $pA$ collisions on different nuclei ($A = C, Ti, W$), at the energy $\sqrt{s} = 41.6$ GeV [11] (stars and triangles) and results of corresponding calculations based on QGSM (curves).

Table 1. Experimental values of $dn/dy$, $|y| \leq 0.5$, for $\phi$-meson production in central nucleus-nucleus collisions at different energies, and results of corresponding calculations based on the QGSM.

| Reaction | Centrality | Energy $\sqrt{s}, \text{GeV}$ | Experimental data on $dn/dy$ ($|y| \leq 0.5$) | QGSM |
|----------|------------|-------------------------------|---------------------------------|------|
| Pb + Pb  | 0−5%       | 17.3                         | 2.35 ± 0.15 [7, 8]              | 2.764|
| Au + Au  | 0−20%      | 62.4                         | 3.52 ± 0.08 ± 0.45 [13]        | 3.36 |
| Au + Au  | 0−11%      | 130                          | 5.73 ± 0.37, ± 0.57 [14, 15]  | 6.15 |
| Au + Au  | 0−5%       | 200                          | 7.95 ± 0.11 ± 0.73 [13]        | 8.12 |
| Au + Au  | 0−5%       | 200                          | 7.70 ± 0.30 [16]               | 8.12 |

200 GeV [13, 16]), are compared with the results of corresponding calculations based on the QGSM. The QGSM calculations show that in the case of $\phi$-meson production, the inelastic-shadowing effects are very weak even at RHIC energies, being virtually invisible against the experimental errors.

Next, we estimate the significance of the shadowing contribution for $\phi$-meson production in the LHC energy range. In ref. [12], it was explained that already at RHIC the inclusive density for the production of secondary particles exhibits significant saturation effects, both in $pPb$ and in $PbPb$ collisions, what it has since been experimentally confirmed [17, 18]. Saturation effects can be explained by inelastic-shadowing corrections connected to the multipomeron interactions [12], that are negligible at low energies due to the suppression of the longitudinal part of the nuclear form factor. In the case of interactions with nuclei, the mean number of Pomerons is large, and even at the RHIC and LHC energies their interactions become significant. Since the growth of the initial energy weakens the suppression of the longitudinal part of the nuclear factor, the inelastic-shadowing corrections become more and more significant as the initial energy increases.
The calculations of inclusive densities and multiplicities with accounting for the inelastic shadowing can be performed in the percolation approach, both for $pp$ [19] and heavy ion collisions [20]. The results of these calculations are in good agreement with the experimental data over a broad energy region. The detailed description of the application of the percolation approach to $\phi$ meson hadroproduction was published in reference [1, 2].

Now, we compare the experimental data on $\phi$-meson production in collisions on nuclear targets at LHC energies, with the results of the corresponding QGSM calculations. In Fig. 3 we present the result of the QGSM calculations for the rapidity dependence of the density $dn/dy$ of $\phi$-meson production in $PbPb$ collisions, for centrality 5% with (solid curve) and without (dashed curve) including the inelastic-shadowing effect [2]. One can see that the inelastic-shadowing contribution is sizeable in the midrapidity region, but it decreases sharply as the rapidity $y$ grows. Also in Fig. 3, the QGSM prediction [2] is compared with the experimental point on $dn/dy$ for $\phi$-meson production in central $PbPb$ collisions at $\sqrt{s} = 2.76$ TeV by the ALICE Collaboration [21].

In Table 2 we present the results of the QGSM calculations for LHC energies, obtained without using any additional parameter with respect to the calculations at lower energies, so these results can be considered as theoretical predictions. The comparison with the corresponding available experimental data is also shown. Unfortunately, only one experimental point by the ALICE Collaboration [21] is currently available on the $\phi$-meson production density $dn/dy$ ($|y| \leq 0.5$) in $PbPb$ collisions at $\sqrt{s} = 2.76$ TeV and centrality 5%, and the same occurs for $\phi$-meson production in $pPb$ collisions at $\sqrt{s} = 5.02$ TeV for non-single diffraction (NSD) events [22]. As we can see in Table 2, QGSM gives a rather good description of these ALICE Collaboration points, but, of course, new experimental data on $\phi$-meson production at LHC energies, both for $pPb$ and $PbPb$ collisions, will be crucial in order to draw final conclusions.
Table 2. Experimental point by the ALICE Collaboration [21] on $dn/dy$, $|y| \leq 0.5$, for $\phi$-meson production in $PbPb$ collisions at $\sqrt{s} = 2.76$ TeV, compared to the result of corresponding QGSM calculation. We also compare the result of the QGSM calculation with the experimental point on $pPb$ collisions at $\sqrt{s} = 5.02$ TeV, for non-single diffraction (NSD) events [22].

| Reactions | Centrality | Energy $\sqrt{s}$, TeV | Experimental data $dn/dy (|y| \leq 0.5)$ | QGSM |
|-----------|------------|----------------|---------------------------------|-------|
| Pb + Pb   | 0−5%       | 2.76          | $13.8 \pm 0.5 \pm 1.7 \pm 0.1$ [21] | 13.57 |
| p + Pb    | NSD        | 5.02          | $0.1344 \pm 0.005 \pm 0.0069 \pm 0.0081$ [22] | 0.14  |

The QGSM provides a reasonable description of the rapidity $y$ spectra of $\phi$-meson production for the interaction of different hadron beams with a nucleon target in a wide energy region, by using for the only unknown parameter in the QGSM analysis, the normalization parameter $a_\phi$, the value $a_\phi = 0.11$, determined by comparison with experimental data in the energy region up to the RHIC range, where the screening contribution is negligible for $\phi$-meson production. At LHC energies, a new parameter $n_{max}$ appears in the calculation of the inelastic nuclear shadowing contribution [2]. This parameter is connected with the number of cutted pomerons, and it has a smooth energy dependence. The QGSM results shown in Table 2 for $pPb$ collisions at $\sqrt{s} = 5.02$ TeV, and for $PbPb$ collisions $\sqrt{s} = 2.76$ TeV, were obtained by taking values $n_{max} = 32$ and 37, respectively.

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