Gluino production in ultrarelativistic heavy ion collisions and nuclear shadowing

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In this article we investigate the influence of nuclear effects in the production of gluinos in nuclear collisions at the LHC, and estimate the transverse momentum dependence of the nuclear ratios $R_{pA} = \frac{d\sigma}{dyd^{2}p_{T}} / A$ and $R_{AA} = \frac{d\sigma}{dyd^{2}p_{T}} / A^{2}$. We demonstrate that depending on the magnitude of the nuclear effects, the production of gluinos could be enhanced, compared to proton-proton collisions. The study of these observables can be useful to determine the magnitude of the shadowing and antishadowing effects in the nuclear gluon distribution. Moreover, we test different SPS scenarios, corresponding to different soft SUSY breaking mechanisms, and find that the nuclear ratios are strongly dependent on that choice.

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The main aim of the Large Hadron Collider (LHC), which is already running and soon will be in complete operation with 14 TeV, is to find the Higgs particle. That discovery may either confirm the Standard Model (SM) or open new windows towards new physics. Although the SM explain all experimental data except neutrino masses, there are many reasons to go beyond it. Some theoretical problems in the SM are: hierarchy problem, electroweak symmetry breaking, gauge coupling unification, etc \cite{1}. The Minimal Supersymmetric Standard Model (MSSM) is the simplest supersymmetric extension of the SM, being a good candidate to Physics Beyond Standard Model \cite{1,2}. In the MSSM, for each usual particle, one assigns a superpartner with opposite statistics: it means that for each boson there is a fermionic superpartner, and the reverse in the case of fermions. In the strong sector, one has the so called supersymmetric QCD (sQCD), where besides the gluon (boson) and quarks (fermions), there are the corresponding superpartners: gluinos (fermions) and squarks (bosons). On this model, the gluinos are the superpartners of gluons, they are color octet fermions and therefore they can not mix with other particles, as a result its mass is a parameter of soft SUSY breaking terms. Gluinos are Majorana fermions, expected to be one of the most massive MSSM sparticles, and therefore, their production is only feasible at very energetic machines such as the LHC. The gluino and squark masses are still unknown parameters, but they cannot be smaller than around a half TeV, as predicted by several models for SUSY breaking. The “Snowmass Points and Slopes” (SPS) \cite{3} are a set of benchmark points and parameter lines in the MSSM parameter space corresponding to different scenarios in the search for supersymmetry at present and future experiments (See \cite{3} for a very nice review). The aim of this convention is reconstructing the fundamental supersymmetric theory, and its breaking mechanism, from the experimental data. The different scenarios correspond to three different kinds of models. The points SPS 1-6 are Minimal Supergravity (mSUGRA) model, SPS 7-8 are gauge-mediated symmetry breaking (GMSB) model, and SPS 9 are anomaly-mediated symmetry breaking (mAMSB) model \cite{3,4}. Each set of parameters leads to different masses of the gluinos and squarks, which are the only relevant SUSY parameters in our study, and we shown their values in Tab.(I). It will be shown below that the choice of SPS scenario affects the results for gluino production.

Another aim of the LHC is to study the possible creation and characterization of the so called quark gluon plasma (QGP), which is one of the predictions of the

| Scenario | $m_{\tilde{g}}$ (GeV) | $m_{\tilde{q}}$ (GeV) |
|----------|------------------|------------------|
| SPS1a    | 595.2            | 539.9            |
| SPS1b    | 916.1            | 836.2            |
| SPS2     | 784.4            | 1533.6           |
| SPS3     | 914.3            | 818.3            |
| SPS4     | 721.0            | 732.2            |
| SPS5     | 710.3            | 643.9            |
| SPS6     | 708.5            | 641.3            |
| SPS7     | 926.0            | 861.3            |
| SPS8     | 820.5            | 1081.6           |
| SPS9     | 1275.2           | 1219.2           |

TABLE I: The values of the masses of gluinos and squarks in the SPS scenarios.
Quantum Chromodynamics (QCD) (see e.g. [6]). The heavy ion program at RHIC have brought many interesting results about the evidences of the QGP formation, which is in fact consistent with an almost perfect liquid [7]. Apart from the QGP, cold matter effects play also a very important role, changing the amount of interacting quarks and gluons in a given kinematic region.

If the gluinos are found in proton-proton (pp) collisions ($\sqrt{s} = 14\,\text{TeV}$) at the LHC and if their masses are not much larger than 1 TeV, they might also be produced in collisions involving nuclei - pA (proton-nucleus, $\sqrt{s} = 8.8\,\text{TeV}$) and AA (nucleus-nucleus, $\sqrt{s} = 5.5\,\text{TeV}$) LHC modes. In this case, nuclear effects have to be considered in the searches for this supersymmetric particles. One important initial state effect is the so called shadowing effect, which makes the parton distribution functions of the bound proton in a nucleus $A$ (nPDFs) to be different from the usual PDFs in the free proton, $f_i^A(x, Q_0^2) = R_i^A(x, Q_0^2) f_i^p(x, Q_0^2)$, where $R_i^A$ are the nuclear modification ratios which parametrize the nuclear effects. There are several parametrizations of nuclear PDFs, based on different assumptions and techniques to perform a global fit of different sets of nuclear experimental data using the DGLAP evolution equations: EKS98 [8], DS [9], HKN [10], EPS08 [11] and EPS09 [12], where the two later include different RHIC data for the first time. Also, EPS09 includes an uncertainty band around the central values. The typical $x$ behavior of the nuclear modification ratios is the following: a supression for $x \lesssim 10^{-2}$ (shadowing), followed by an increasement around $10^{-1}$ (antishadowing), again a supression for $x \gtrsim 0.3$ (EMC effect), and a bigger increasement when $x$ approaches 1 (Fermi motion). The whole effect is usually called shadowing.

To illustrate how shadowing can influence the amount of partons in the nuclear medium, we show in Fig. 1 the results for a few nuclear modification ratios for the gluons ($R_g$), valence ($u_v, d_v$) and sea ($u_s, d_s, s$) quarks. Results for charm and bottom are not shown, since they are not
In the case of gluino production, because of the large gluino masses, the values of x probed tend to be quite high (from $x \gtrsim 10^{-2}$ to almost 1), and then the antishadowing, EMC effect and even Fermi motion may be important (depending on the kinematic region and nuclear PDF), which may enhance the gluino production rate compared to that obtained from single nucleon collisions at the same energy. Therefore, whereas the smaller center of mass energy (5.5 TeV (AA) and 8.8 TeV (pA)) will reduce the gluino production rates (compared to 14 TeV (pp)), there may be an enhancement due to the amount of quarks and gluons on the nuclear medium compared with the nucleon parton distributions on a single proton, due to high density nuclear effects. In this work we investigate whether this enhancement/suppression is present or not.

This article is organized as follows. The basic formulae to calculate gluino production are presented in section I. Our results for gluino produced in nuclear collisions at the LHC are presented in section II followed by the conclusions.
can be written as \[ 22 \]

\[
E \frac{d\sigma}{d^3p} = \sum_{ij} \int_{x_{\text{min}}}^{1} dx_a x_b f_i(x_a, \mu) f_j(x_b, \mu) \frac{x_a x_b}{x_a - x_\perp} \left( \frac{\zeta + \cos \theta}{2 \sin \theta} \right) \frac{d\sigma}{dt}(ij \rightarrow \tilde{g}d),
\]

(1)

where \( f_{ij} \) are the parton distributions of the incoming protons and \( \frac{d\sigma}{dt} \) is the LO partonic cross section \[ 22 \] for the subprocesses involved. The identified gluino is produced at center-of-mass angle \( \theta \) and transverse momentum \( p_T \), and \( x_\perp = \frac{2 \sin \theta}{\sqrt{s}} \). The Mandelstam variables of the partonic reactions \( ij \rightarrow \tilde{g}, \tilde{g} \) are then

\[
\hat{s} = x_a x_b s,
\]

\[
\hat{t} = m_g^2 - x_a x_\perp s \left( \frac{\zeta - \cos \theta}{2 \sin \theta} \right),
\]

\[
\hat{u} = m_g^2 - x_b x_\perp s \left( \frac{\zeta + \cos \theta}{2 \sin \theta} \right).
\]

(2)

Here

\[
x_b = \frac{2 v + x_a x_\perp s \left( \frac{\zeta - \cos \theta}{2 \sin \theta} \right)}{2 x_a s - x_\perp s \left( \frac{\zeta + \cos \theta}{2 \sin \theta} \right)},
\]

\[
x_{\text{min}} = \frac{2 v + x_a x_\perp s \left( \frac{\zeta + \cos \theta}{2 \sin \theta} \right)}{2 s - x_\perp s \left( \frac{\zeta - \cos \theta}{2 \sin \theta} \right)},
\]

\[
\zeta = \left( 1 + \frac{4 m_g^2 \sin^2 \theta}{x_a x_\perp} \right)^{1/2},
\]

\[
v = m_g^2 - m_d^2.
\]

(3)

where \( m_g \) and \( m_d \) are the masses of the final-state partons produced. The center-of-mass angle \( \theta \) and the differential cross section above can be easily written in terms of the pseudorapidity variable \( \eta = -\ln \tan(\theta/2) \), which is one of the experimental observables.

Predictions for gluino production in \( pp \) collisions at the LHC (\( \sqrt{s} = 14 \text{ TeV} \)), in all SPS scenarios, are shown in a former work \[ 26 \], where there is a huge difference in the magnitude of \( p_T \) distributions for different SPS points, making it possible to distinguish between some different SUSY breaking scenarios. We can ask if the same occurs in nuclear processes, and answering this question is also a goal on this article.

II. GLUINO PRODUCTION IN NUCLEAR COLLISIONS

Let us now focus on gluino production in nuclear collisions. The calculation is done as explained in the previous section, replacing the parton distributions in the free nucleon \( f_i^p \) in Eq. (1) by the corresponding nuclear parton distributions \( f_i^A \) (for the proton PDF we use the CTEQ6L1 \[ 27 \]). The nuclear effects are then studied by comparing the different nPDF’s (for consistency, we use the LO version of all nPDF’s). To be sure that the nPDF’s are within the regions of validity, we have used \( Q = m_g \) as the hard scale (as done in \[ 2 \]). Another possible choice, a \( p_T \) running \( Q = m_g + p_T \) scale, would push some of the nPDF’s outside the region of validity (EPS08 and EPS09 are frozen in \( Q = 1000 \text{ GeV} \) for values above that scale, whereas DS is not valid in that region). For this reason, the DS could not be considered in the SPS9 scenario (see Table I), with extra large gluino masses. To start with, we consider the SPS1a scenario as the first (most optimistic) choice of gluino and squark masses.

In Fig. 3 we show our results for the transverse momentum dependence of the nuclear modification factor \( R_{pA} \) for inclusive gluino production in \( pA \) collisions at the LHC (\( \sqrt{s} = 8.8 \text{ TeV} \), \( |\eta| \leq 2.5 \)) for distinct nPDF’s.

![Graph showing transverse momentum dependence of the nuclear modification factor](image)

FIG. 3: (Color online) Transverse momentum dependence of the nuclear modification factor \( R_{pA} \) for inclusive gluino production in \( pA \) collisions at the LHC (\( \sqrt{s} = 8.8 \text{ TeV} \), \( |\eta| \leq 2.5 \)) for distinct nPDF’s.
for gluino production in nucleus-nucleus collisions at the LHC ($\sqrt{s} = 5.5$ TeV). In this case, the nuclear effects are amplified because of the presence of two nuclei. Besides, the probed values of $x$ are pushed into very high-$x$ due to the smaller center of mass energy. Indeed, the EPS suppression increases with $p_T$ in a stronger way than in the pA case (around 15% for higher $p_T$). The DS nPDF has an enhancement pattern, increasing with $p_T$, which shows that this distribution has reached the Fermi motion effect in the very right side of Fig. 1. The enhancement is also larger for the HKN, above 20% with a very tiny increment with $p_T$. It seems that, if the latest EPS09 nPDF is the more correct distribution, the gluino production will be slightly suppressed compared with $pp$ collisions at the same energy, whereas the DS and HKN suggests that there will be some enhanced production of gluinos in nuclear collisions.

The possible increase of the gluino production rate in nuclear collisions (compared with $pp$ collisions at same energy) shown above is in fact too low to really improve the small feasibility of detecting the gluinos when going from $pp$ to pA and AA. In fact, the higher hadronic activity in nuclear collisions make the detection of gluinos more difficult, and the smaller CM energy available produces a smaller number of gluinos compared to 14 TeV $pp$ collisions. The expected luminosity to be reached in the AA collisions ($L_{NN} \approx 10^{27} A^2 \text{cm}^{-2}\text{s}^{-1}$) is seven orders of magnitude smaller than in the $pp$ mode ($L_{pp} \approx 10^{34} \text{cm}^{-2}\text{s}^{-1}$), and this is the main limitation to detecting nuclear gluinos (they will be produced but will hardly be seen). In the pA mode, one expects a luminosity of $L_{pA} \approx 7.4 \times 10^{29} \text{cm}^{-2}\text{s}^{-1}$, which becomes $7.4 \text{ pb}^{-1}$ assuming a full LHC year $10^8 \text{s}$ (one usually considers a month ion running time $10^6 \text{s}$) in the ion mode. With only our LO estimation, and considering the more suppressed EPS09, one would than obtain around 31 gluinos produced in the pA mode for the $p_T$ integrated region, so statistics is really limited. It has been suggested that the pA luminosity could eventually be upgraded to $L_{pA} \approx 10^{31} \text{cm}^{-2}\text{s}^{-1}$, in this case our estimate would increase to 430 gluinos in one year run. For more realistic estimates, the NLO correction would still increase the cross-sections for the various production processes by up to a factor of less than two.

Not only the nuclear shadowing but also the SUSY breaking parameters affect the nuclear ratios. This dependence is indirect, since the gluino and squark masses ($m_\tilde{g}$, $m_\tilde{q}$), are the only parameters that really affect the results, but these masses are consequences of the different SUSY breaking parameters in the different SPS scenarios. This is shown in Fig. 5 where different SPS scenarios give different absolute values for the $R_{AA}$ nuclear ratios (this can be seen by comparing for example the starting point of each curve). The $p_T$ growth for the DS nPDF is even more steeper for the higher mass SPS scenarios (higher $x$). For the SPS09 scenario, the results should not be trusted, since most parametrizations are not valid in that region: the HKN predicts an enhancement essentially constant with $p_T$, and the frozen EPS's suppression decreases with $p_T$. Because of the odd interplay of nuclear effects and SUSY breaking scenarios, one needs to put better constraints on the nuclear PDF's before describing precisely gluino production in nuclear collisions. Conversely, the discovery and measurement of the gluino and squark masses will be important in the searches for sparticles produced in nuclear collisions, taking into account the correct nuclear effects which also depend on the those masses.

III. CONCLUSIONS

To conclude, in this work we studied the nuclear effects in pA and AA gluino production at the LHC. We have shown different results of enhancement or suppression depending on the nuclear PDF, the effects being smaller in pA interactions and larger in nuclei collisions. Gluinos will probably be copiously produced in the $pp$ channel. Once the details of gluino production are known in $pp$ interactions, studying this final state in pA and AA collisions could give unprecedented constraints on the nPDFs in a heretofore unexplored region of $Q^2$. One could use the higher energy to get a good measurement of gluino production and search for deviations from that in the measurable $p_T$ range for pA and AA to measure quark and gluon shadowing at very high scales where nothing at all is known about it. Uncertainties on the nPDF’s (and cold matter effects in general), and on the SUSY breaking scenarios (which give different masses for the gluinos and squarks) has to be disentangled in the future searches. For heavy nuclei collisions, where its expected the formation of the quark gluon plasma, it may appear other channels where gluino is produced. Here we only investigated cold matter effects, namely the shadowing of the nuclear distributions. If gluinos are discovered in
FIG. 5: (Color online) Transverse momentum dependence of the ratio $R_{AA}$ in single gluino production at the LHC ($\sqrt{s} = 5.5 \text{ TeV}$), for different choices of nuclear parton distributions: DS [9], HKN [10], EPS08 [11] and EPS09 [12], in different SPS scenarios.

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