Strongly Interacting Massive Particles at LHC

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Abstract

The search for strongly interacting massive particles (SIMP) is one of the most promising ways to observe new physics phenomena at the LHC. This paper describes the propagation in matter of stable new hadrons containing a heavy exotic quark with new quantum number. The accuracy of any exclusion limit or cross-section measurement from a search depends on the degree to which the interactions of SIMPs with detector material can be quantified with phenomenological models of strong interactions. This paper outlines a model for scattering of heavy hadrons that is based on Regge phenomenology and the Quark Gluon String Model (QGSM). We discuss also some astrophysical constraints on the possibility of H-hadrons to be next to lightest supersymmetry particle (NLSP) that makes more interesting their discovery at the LHC.

1 Introduction

First it should be mentioned that new massive particles may explain the dark matter (DM) content of the Universe. Supersymmetry is the most elaborated theory that provides us with such particles, and according to it the dark matter may consist of the lightest supersymmetry partner of the known elementary particles (LSP). As long as the dark matter candidates must be neutral and stable, from the experimental point of view the discovery of next-to-lightest supersymmetry particles (NLSP) in new physics hierachy seems to be more promising at LHC searches. These particles from beyond the Standard Model are expected to be of relatively low masses and quasistable on distances of detectors.

Looking for such particles in various versions of SUSY we see that Minimal SUSY model expects neutralinos as LSP, while Supergravity theory predicts gravitino as DM candidate. In the latter type of models it is easy to presume quasistable NLSP since it decays into gravitino with very small cross section of gravitation interaction. On the other hand, supersymmetry models should have more sophisticated constructions in order to obtain light NLSP particles. An example of how this can be obtained in found Compressed SUSY model [2] where relatively light gluino and squarks allow to slot the dark matter cosmological parameter, Ω_{DM}, into the range of known observations with the help of neutralino pair annihilation to top quark-antiquark pair via stop quark exchange. The Split SUSY model [3] has been constructed to provide the possibility of light gluino NLSP. This idea has already been discussed in [1]. The model of Warped Extra Dimensions [4] gives weakly interacting massive particles (WIMP) as a candidate for dark matter.

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As one can see there exist good reasons to explore the possibility of discovery of some strongly interacting long living NLSP at LHC energies. Here we would like to consider the stop quarks as an example of strongly interacting massive particle (SIMP) [5]. ATLAS and CMS experiments have already developed search strategies for SIMPs, which usually assume that these particles are included into heavy exotic H-hadrons that behave in muon chamber like a slow-moving muons. The QGSM [8] is then used to construct a description of the collisions of those particles with the matter and to estimate average energy losses in such collisions. Finally, we discuss the impact of some astrophysical constrains on the prospects for detecting exotic hadrons at the LHC.

Considering the interactions with matter, it is important to know the mass hierarchy of exotic hadrons. This determines the states to which a heavy exotic hadron, produced either in the primary interaction or after scattering with matter, would rapidly decay. The lowest lying neutral and charged mesonic states should be stable since the mass difference between them is expected to be far smaller than the pion mass and the meson mass $m_{u'\bar{q}}$ is given by $m_{u'\bar{q}} \approx m_{u'} + m_q$, where m_q and $m_{u'}$ the constituent masses of the SM quark and exotic quark, respectively. This statement contradicts to the suggestion adduced in [6] that only neutral heavy hadrons survive in the first moments after hadronization of SIMP and rapid decays of charged H-hadrons. Another idea we should disprove here was figured out in [9]. Authors have suggested that SIMPs deposit smaller energy in the matter than muons. Although the energy losses of SIMP in matter are to be smaller than the losses of ordinary hadrons, their energy deposit in matter are still of the order of hadronic losses, so they have to be bigger than the losses of muons. In folowing sections we describe the basic formulas of the propagation of H-hadrons in matter, but will not have a room to show the results of experimental simulations. The recent complete publication [7] contains all necessary diagrams and resulting plots.

2 Interactions of Heavy Hadrons in Matter

Interactions of H-hadrons with protons of ordinary matter are rather specific. The heavy squark will be always a spectator due to the absence of antisquarks in the detector matter to annihilate with. Thus there is only the low energy light ordinary quark in the hadron that can interact. At the LHC, the light quark's kinetic energy will typically be around several GeV and the Regge phenomenology approach [8] can be employed to describe exotic hadron interactions with matter.

In our approach one can distinguish two classes of scattering processes: reactions mediated by (a) reggeon and corresponding to planar QCD diagrams and (b) pomeron exchange related to the cylinder-type diagrams in elastic scattering. Exotic hadrons containing a light constituent anti-quark interact via pomeron and reggeon exchanges, the latter processes are due to the annihilation of light antiquarks with the quarks of detector matter. Conversely, hadrons containing a light constituent quark can only interact via pomeron exchange. Let us consider the process of interaction of a heavy H-hadron with a nucleon of the target in the target rest frame. In this frame the light antiquark of H-hadron carries only a small fraction of the total energy E

$$E_q \approx \frac{Em_{q\perp}}{M_H} = \gamma m_{q\perp}$$

where $\gamma = E/M_H$ and $m_{q\perp}$ is the transverse mass of the light antiquark. It was shown in the framework of QGSM [8], that the planar diagram contribution to the total cross section $\sigma_R(s)$ is universal for the same energy of the annihilating antiquark. This means that the contribution to the total cross section of reggeons can be written as:

$$\sigma_R(E) = K\sigma_{pl}(E = \gamma m_{q\perp}) = K g_R (2\gamma m_{q\perp}/E_0)^{\alpha_R(0)-1}, \tag{1}$$

where K is the number of possible planar diagrams, $E_0 = 1$ GeV. The vertex parameter g_R can be evaluated from the data on cross sections of hadronic interactions and the intercept of the exchange degenerate regge tragectories $\alpha_R(0)$ is equal to 0.5.

The pomeron contribution to the total cross section (σ_P) can be estimated as

$$\sigma_P \sim (2\gamma m_{q\perp}/E_0)^{\alpha_P(0)-1} \tag{2}$$

The reggeon contribution to the cross section for a H-meson and a nucleon within a nucleus, which consists of equal amounts of protons and neutrons, can be derived as the difference between the reggeon contributions to $\sigma(\pi^- p)$ and $\sigma(\pi^+ p)$ data multiplied by a factor 1.5.

3 Differential Cross Sections of H-hadron scattering

In determining the kinematics of the scattering process, we consider the inclusive process $H + N \to H' + X$, where H, H', N and X are the incoming exotic hadron, the outgoing exotic hadron, the target nucleon, and whatever else is produced in the interaction, respectively. The kinematics of such an interaction can be specified by three independent kinematic variables. Commonly used variables are t, the usual four-momentum transfer between the incoming and outgoing exotic hadrons, s, the center-of-mass energy squared of the interaction, and M_X, the mass of the final state X.

The final H'-hadron carries a fraction of energy x_F close to unity and only a small fraction of energy $1 - x_F \sim m_{q\perp}/M_H \ll 1$ is transferred to production of hadrons. This justifies the application of the triple-regge formulae to provide a description of inclusive cross sections. Strictly speaking the triple-regge description is valid for $m_X^2 \gg 1 GeV^2$ and the rapidity difference between H' and rest hadrons $\Delta y > 1$. This is equivalent to the condition $2\gamma m_{q\perp} m_N/M_X^2 \gg 1$. In hadronic interactions, the triple-regge description works usually up to $\Delta y \sim 1$ and we will assume in the following that the same is true for interaction of H-hadrons. Expressions for the contributions of different triple-regge terms iik to inclusive cross sections is straightforward to obtain noting, that for reggeons i corresponds to the factor $\exp(2(\alpha_i(t) - 1)\Delta y)$, while an exchange by the reggeon k leads to the factor $\exp((\alpha_k(0) - 1)y_q)$. Here, $y_q = \ln(M_X^2/(m_{q\perp} m_N)$ is the rapidity interval covered by produced hadrons (the total rapidity $Y = \ln(2E/M_H) = \ln(2\gamma) = \Delta y + y_q$). As for the total cross section we consider here the pomeron P and secondary reggeons R as exchanged reggeons i, k. Thus we have the following triple-regge contributions: RRR,RRP,PPR and PPP.

Using the rules described above we can write inclusive cross sections for the corresponding triple-regge terms in the following forms:

$$\frac{d^2\sigma_{RRR}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_R^2(\gamma) C_{RRR} \exp[(2B_{RH} + B_{RRR} + 2\alpha_R' \ln(\frac{2\gamma M_0^2}{M_X^2}))t]$$

$$\times \left(\frac{M_0^2}{M_X^2}\right)^{\Delta_R} \tag{3}$$

$$\frac{d^2\sigma_{RRP}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_R^2(\gamma)C_{RRP}\exp[(2B_{RH}+B_{RRP}+2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t] \times \left(\frac{M_0^2}{M_X^2}\right)^{2\Delta_R-\Delta_P} \tag{4}$$

$$\frac{d^2\sigma_{PPR}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_P^2(\gamma)C_{PPR}\exp[(2B_{PH}+B_{PPR}+2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t] \times \left(\frac{M_0^2}{M_X^2}\right)^{2\Delta_P-\Delta_R} \tag{5}$$

$$\frac{d^2\sigma_{PPP}}{dtdM_X^2}(\gamma, M_X^2) = \frac{1}{M_X^2}\sigma_P^2(\gamma)C_{PPP}\exp[(2B_{PH}+B_{PPP}+2\alpha'_P\ln(\frac{2\gamma M_0^2}{M_X^2}))t] \times \left(\frac{M_0^2}{M_X^2}\right)^{\Delta_P} \tag{6}$$

where $\Delta_R = \alpha_R(0) - 1$= -0.5, $\Delta_P = \alpha_P(0) - 1$= 0.12, $\alpha'_R = 0.9\ GeV^{-2}$, $\alpha'_P = 0.25\ GeV^{-2}$ [8] and $M_0^2 = m_N m_{q\perp} = 0.5\ GeV^2$.

The parameters, C_{iij}, and B_{iij} can be determined using Regge factorization from the triple-regge description of inclusive spectra in high-energy hadronic interactions. Let us emphasise that the RRR-term corresponds to the cutting of planar diagram or R-exchange, while the RRP-term corresponds to the cutting of the cylinder-type diagram. Due to conservation of H-hadrons integrals over M_X^2 and t give σ_R and σ_P contributions to the total cross section correspondingly.

The PPR and PPP-terms describe the diffractive dissociation of a nucleon and their cross sections can be calculated, using factorization from the corresponding cross sections extracted from pp-interactions

$$\sigma_{Hp}^{PPi} = \frac{\sigma_P(Hp)^2}{\sigma_P(pp)^2}\sigma_{pp}^{PPi} \tag{7}$$

Here, we neglected the small difference in t-dependence for Hp and PP vertices. Taking into account that $\frac{\sigma_P(Hp)}{\sigma_P(pp)} \approx 1/4$ and that the sum of PPR and PPP-contributions for pp-collisions in the relevant energy domain does not exceed 2mb, we obtain very small cross sections for diffraction dissociation of a nucleon in Hp-interactions: 0.12 mb. Thus these cross sections constitute only about 1% of the total cross section and can be safely neglected.

For parameters characterising the t-dependence of RRR and RRP-terms we take the same values as those which have been extracted from the analysis of pp-interactions: $2B_{RH}+B_{RRR} = 2B_{RH}+B_{RRP} = 4\ GeV^{-2}$.

4 The possible impact of SIMP discovery on astrophysical models

There are two astrophysical facts which resist to the hypothesis of new heavy quarks being NLSP: a) the success of big bang nucleosynthesis (BBN) model and b) the observation of perfect blackbody characteristics of cosmic microwave background (CMB). Both precise astrophysical calculations can dismiss SIMP-as-NLSP idea because the decays of new heavy quarks lead to hadronic showers that certainly destroy BBN scenario [10]. On the other hand, if the exotic quarks are living long enough, then the effect of their decay should produce a visible structure of CMB which gets in conflict with the above mentioned observations. All arguments show that detection of exotic quarks occurs intertwined between high energy particle physics and astrophysics and it may require more precise balance of observations and up-to-date physical models.

5 Conclusions

Strongly interacting massive particles are predicted by the number of scenarios of physics beyond the SM. This article presents a model for description of the interactions of exotic H-hadrons containing new heavy quarks with the matter of detector. QGSM formulas for energy dependence of cross sections and differential distributions of scattered H-hadrons were shown. Two statements follows from our recently developed approach: 1) the conversion of H-baryon into H-meson and back can be neglected in calculations due to the very small probability of nucleon trajectory exchange; 2) the processes with double charge exchange like a transition of H^{+}-mesons into H^{-} ones are also impossible. These admissions make significantly clearer the calculation of H-hadron propagation in the matter. The discovery of such strongly interacting new particles would have an important impact on modern astrophysical schemes.

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