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# Production of $\Theta^+(1540)$ and $\Xi$ pentaquark states in proton–proton interactions

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## Abstract

The production of strange pentaquark states (e.g., Theta baryons and $\Xi^{--}$ states) in hadronic interactions within a Gribov–Regge approach is explored. In this approach the $\Theta^+(1540)$ and the $\Xi$ are produced by disintegration of remnants formed by the exchange of pomerons between the two protons. We predict the rapidity and transverse momentum distributions as well as the $4\pi$ multiplicity of the $\Theta^+$, $\Xi^{--}$, $\Xi^-$, $\Xi^0$ and $\Xi^+$ for $\sqrt{s} = 17$ GeV (SPS) and 200 GeV (RHIC). For both energies more than $10^{-3}$ $\Theta^+$ and more than $10^{-5}$ $\Xi$ per pp event should be observed by the present experiments.

Very recently in photon–nucleus [1,2] and kaon–nucleus experiments [3] a new baryon, consisting of five quarks, uudd$\bar{s}$, has been identified in the $K^+n$ or $K^0p$ invariant mass spectrum. It has been named $\Theta^+$ particle and has spin 1/2, isospin 0 and strangeness +1. Its mass is about 1.54 GeV and its width is less than 25 MeV. Such a state has been predicted by Diakonov [4] in the framework of a chiral soliton model.

This finding has renewed the experimental and theoretical interest for novel baryon states. Major progress has been reported on a possible extension of the original model [5,6], within the Skyrme model [7–9], and within the constituent quark model [10,11]. Also (lattice) QCD studies of the $\Theta^+$ (see, e.g., [12–14]) have been performed and first explorations of the $\Theta^+$ multiplicity at SPS and RHIC energies are available [15–17]. Thus, the existence of this novel state has many perspectives for pp as well as for nucleus–nucleus collisions.

In this Letter, we present predictions for the $\Theta^+$ in pp collisions from a newly developed approach for hadronic interactions. It has recently been shown [18] that the standard string fragmentation models

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which described spectra and multiplicities of many hadrons rather well need to be revised: due to their diquark–quark topology these models produce more $\bar{\Omega}$ than $\Omega$ in medium and low energetic pp interactions, in contradistinction to experiments. Therefore a key issue is presently to gain information on the details of hadron production. Especially more exotic states like the $\Lambda(1405)$ which may be a udsu$\bar{\text{u}}$ state or the $\Theta^+$ carry important information to tackle this question. If their multiplicity can be related to that of other particles one can hope to get experimentally a handle on the hadronization process.

In heavy ion collisions the multiplicity of the most abundant particles can be well described in a statistical model assuming a temperature close to that where the chiral/confinement phase transition is expected and a moderate chemical potential. Unstable particles can test how the expanding system interacts afterwards because if the decay products have still an interaction in the invariant mass spectra the resonance cannot be identified anymore. Especially long living states are very useful in this respect.

Until this year, the search for multi-quark bags focused mainly on the $H$-particle [19], because it is closely related to the study of $\Xi$ and $\Lambda\Lambda$ hypernuclei (see, e.g., [20,21]). The $H$ is a six quark state (uuddss) coupled to an SU(3) singlet in color and flavour. Unfortunately no stringent observation of the $H$-particle exists. Even today, decades after the first prediction of the $H$-dibaryon by Jaffe [19] the question of its existence is still open.

In contrast to the $H$ particle, the situation for the $\Theta^+$ baryon is very promising. Thus, in this Letter we explore the formation of the $\Theta^+$-baryon within a new approach called parton-based Gribov–Regge theory. It is realized in the Monte Carlo program NEXUS 3.97 [22,23]. In this model high energy hadronic and nuclear collisions are treated within a self-consistent quantum mechanical multiple scattering formalism. Elementary interactions, happening in parallel, correspond to underlying microscopic (predominantly soft) parton cascades and are described effectively as phenomenological soft pomeron exchanges. A pomeron can be seen as layers of a (soft) parton ladder, which is attached to projectile and target nucleons via leg partons. At high energies one accounts also for the contribution of perturbative (high $p_t$) partons described by a so-called “semihard pomeron”—a piece of the QCD parton ladder sandwiched between two soft pomerons which are connected to the projectile and to the target in the usual way. The spectator partons of both projectile and target nucleons, left after pomeron emissions, form nucleon remnants. The legs of the pomerons form color singlets, such as q–$\bar{\text{q}}$, q–qq or $\bar{\text{q}}$–$\bar{\text{q}}\bar{\text{q}}$. The probability of q–qq and $\bar{\text{q}}$–$\bar{\text{q}}\bar{\text{q}}$ is controlled by the parameter $P_{\text{qq}}$ and is fixed by the experimental yields on (multi-)strange baryons [23].

Particles are then produced from cutting the pomerons and the decay of the remnants. As an intuitive way to understand particle production, each cut pomeron is regarded as two strings, i.e., two layers of a parton ladder. Each string has two ends which are quark(s) or antiquark(s) from the two pomeron legs, respectively. To compensate the flavour, whenever a quark or an antiquark is taken as a string end, a corresponding antiparticle is put in the remnant nearby.

Since an arbitrary number of pomerons may be involved, it is natural to take quarks and antiquarks from the sea as the string ends. In order to describe the experimental yields on (multi-)strange baryons [23], all the valence quarks stay in the remnants, whereas the string ends are represented by sea quarks. Thus, pomerons are vacuum excitations and produce particles and antiparticles equally. Note that in addition to these singlet type processes, valence quark hard interactions are treated differently in the present model. To give a proper description of deep inelastic scattering data, a certain fraction of the pomerons is connected to the valance quarks of the hadron, not leading to a quark feeding of the remnant. This kind of hard processes will not be discussed here, but is included in the simulation. Only the remnants change the balance of particles and anti-particles, due to the valence quarks inside resulting in the possibility to solve the antiomega puzzle [18] at the SPS.

This prescription is able to accumulate multiple quarks and antiquarks in the remnants depending on the number of exchanged pomerons. In the most simple case of a single pomeron exchange, the remnant may gain an additional antiquark and a quark and is transformed into a pentaquark bag as discussed in the following.

The typical collision configuration has two remnants and one cut pomeron represented by two q–$\bar{\text{q}}$ strings, see Fig. 1. Four quarks and one antiquark are now in the remnant: the three valence quarks u, u, d

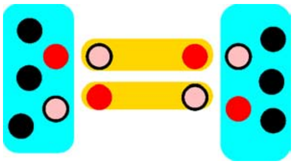

Fig. 1. The typical collision configuration has two remnants and one cut pomeron represented by two q–q̄ strings. In the case of a uudds̄ flavour content a $\Theta^+$ baryon can form.

plus a $q_i\bar{q}_j$ sea quark pair. Each of the $q_i$ may have the flavour u, d, or s, with relative weights $1:1:f_s$. The parameter $f_s$, is fixed by strange hadron data in proton–proton scatterings at 160 GeV to be $f_s = 0.26$. Thus, there is a small but nonzero probability to have a uudds̄ flavour in a remnant, such that a $\Theta^+$ pentaquark may be formed.

The remnants have mass distribution $P(m^2) \propto (m^2)^{-\alpha}$, $m^2 \in (m^2_{\mathrm{min}}, x^+ s)$, here $s$ is the squared CMS energy. With, $m_{\mathrm{min}}$ being the minimal hadron mass compatible with the remnant's quark content, and $x^+$ is the light-cone momentum fraction of the remnant which is determined in the collision configuration. In the present study, the parameter $\alpha$ is 2.25 for nondiffractive interactions and 1 for diffractive events [24]. This remnant disintegrates into hadrons according to (microcanonical) phase space [25]. This approach describes quite well multiplicity,[2] transverse momenta and rapidity of all the observed hadrons [24] in pp collisions at energies between 40 and 160 GeV.

For the present study we have embedded the $\Theta^+$ in the microcanonical approach to describe the disintegration of the remnant. It is therefore treated the same way as all the other hadrons. A similar approach was recently introduced to study $H^0$ production in pp interactions [26].

As discussed above, a pp collision in the present model involves two sources of particles production:

(1) Fragmentation of strings (from exchanged pomerons).
(2) Decay of the projectile/target remnant. The decay of the remnant can happen in two distinct ways:
    (2a) by string fragmentation, or
    (2b) by micro-canonical phase space.

Presently, pentaquarks can only be produced from the micro-canonical remnant decay. A fragmentation of strings into pentaquarks is not included.

This is in contrast to other hadrons, e.g., Lambdas that can be produced from all mentioned sources.

There is no difference in the general input parameters for calculations for $\Lambda$'s and pentaquarks. The main parameter is the probability for having a (anti)-strange quark at the pomeron leg. This parameter controls strangess (e.g., Lambda and kaon multiplicities) and pentaquark production directly.

The additional inputs for the study of pentaquark states are their masses, quark contents and spin, which have ultimately to be determined by the experimental results. Presently, we use the values from Refs. [4–6].

Contrary to grand canonical thermal model estimates [15,17], which implicitly assume chemical and thermal equilibrium, the present approach works differently: in the present approach, initial and final state dynamics of the pp interaction are fully taken into account, thus allowing to predict transverse and longitudinal momentum distributions all produced hadrons, including the $\Theta^+$. Furthermore, a micro-canonical model is employed for the remnant decay which counts exactly the phase space states for a given energy and volume of the system. Only in the limit of large volumes and many particles it agrees the grand canonical approaches.

Let us now study the multiplicities and momentum spectra of the calculated $\Theta^+$'s. Fig. 2 depicts the rapidity distribution of the predicted $\Theta^+$'s at the top SPS energy. One observes a slight dip around central rapidities due to the fact that the particles originate from remnants. The total $\Theta^+$ multiplicity per inelastic event is 0.0035. Table 1 gives also the predicted yields of the other species of pentaquarks. It is interesting to note that the $\Xi$ pentaquark is suppressed by two orders of magnitude compared to the Theta particle. This is due to the double strange quark component of the $\Xi$ pentaquark that is suppressed at pomeron legs. However, it is interesting to note that for the double-strange $\bar{\Xi}$ pentaquark has been well observed at this energy by the NA49 Collaboration. Thus, with the presently accumulated statistics of the NA49 Collaboration, the $\Theta^+$ should be easily visible in

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[2] A variation of the model parameters by 20% results in variation of the model results by roughly 10% both for the pentaquarks and the well-known hadrons. A larger variation of the parameters destroys the agreement with the NA49 pp data at 160 GeV.

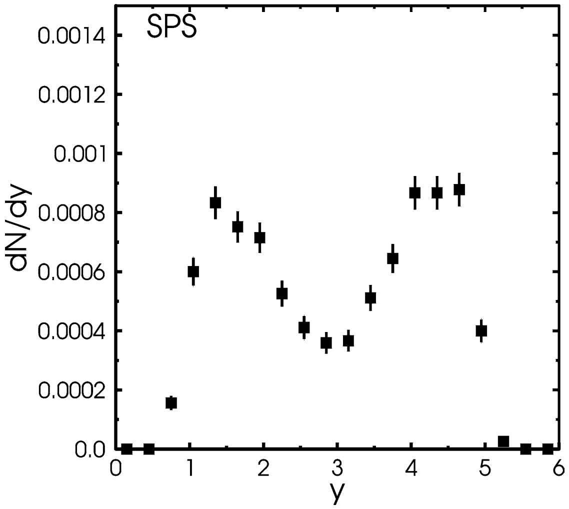

Fig. 2. Rapidity distributions of $\Theta^+$'s in pp interactions at $E_{\mathrm{lab}} = 160$ GeV.

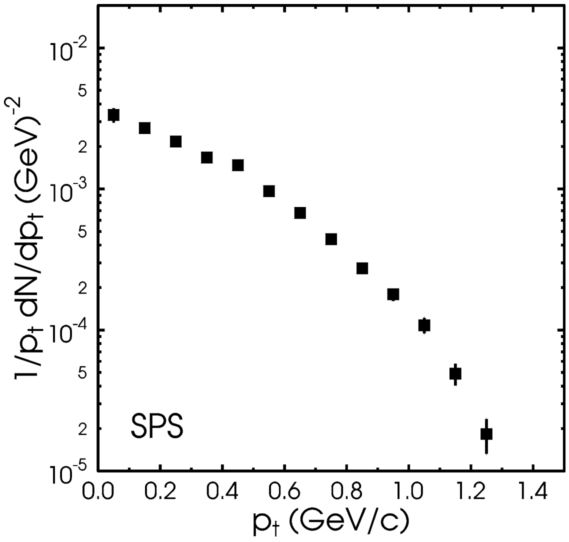

Fig. 3. Transverse momentum distributions of $\Theta^+$'s in pp interactions at $E_{\mathrm{lab}} = 160$ GeV.

Table 1
Predictions of the various pentaquark abundances in $4\pi$ for inelastic pp collisions at $E_{\mathrm{lab}} = 160$ GeV (SPS) and $\sqrt{s} = 200$ GeV (RHIC)

| Particle | Quark content | Yield (SPS) | Yield (RHIC) |
|---|---|---|---|
| $\Theta^+$ | $(uudd\bar{s})$ | $3.5 \times 10^{-3}$ | $5.2 \times 10^{-3}$ |
| $\Xi^+$ | $(ssuu\bar{d})$ | $4.8 \times 10^{-5}$ | $11.9 \times 10^{-5}$ |
| $\Xi^0$ | $(ssud\bar{d})$ | $4.7 \times 10^{-5}$ | $9.2 \times 10^{-5}$ |
| $\Xi^-$ | $(ssud\bar{u})$ | $3.0 \times 10^{-5}$ | $6.3 \times 10^{-5}$ |
| $\Xi^{--}$ | $(ssdd\bar{u})$ | $1.8 \times 10^{-5}$ | $4.5 \times 10^{-5}$ |

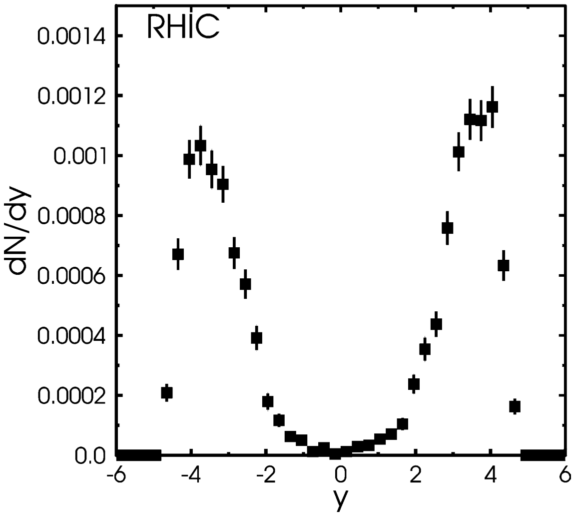

Fig. 4. Rapidity distributions of $\Theta^+$'s in pp interactions at $\sqrt{s} = 200$ GeV.

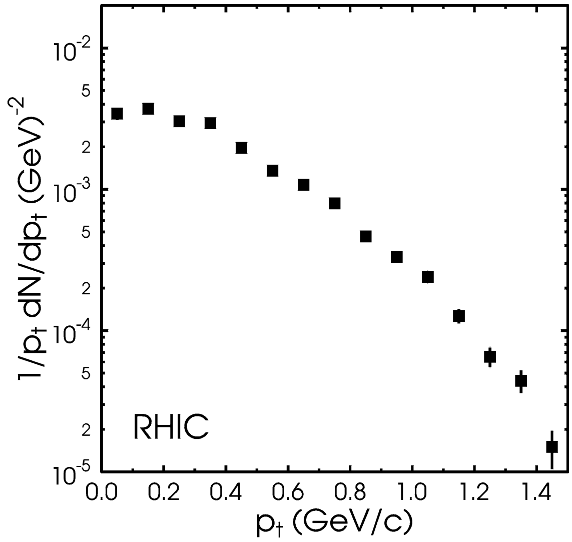

Fig. 5. Transverse momentum distributions of $\Theta^+$'s in pp interactions at $\sqrt{s} = 200$ GeV.

the data. Fig. 3 depicts the transverse momentum spectra of the $\Theta^+$'s. In Figs. 4 and 5 we show the rapidity and transverse momentum spectra at $\sqrt{s} = 200$ GeV. Especially at RHIC energies one clearly observes the pile-up of $\Theta^+$ baryons in the forward and backward hemisphere. In the midrapidity region the pentaquark yield vanishes. It should be noted that the vanishing yield at central rapidities might be filled up, if also the (yet unknown) fragmentation function into pentaquarks in a string break up is included.

In conclusion, we have studied the production of pentaquark baryons in pp collisions from parton-based Gribov–Regge theory. Multiplicities, rapidity and transverse momentum spectra for the $\Theta^+$ and $\Xi$ pentaquarks are predicted for pp interaction at $E_{\mathrm{lab}} = 160$ GeV and $\sqrt{s} = 200$ GeV. We predict a total yield of 3–5 $\times 10^{-3}$ $\Theta^+$ per inelastic pp event at SPS and RHIC. The $\Xi$ pentaquark states are suppressed by two orders of magnitude compared to the $\Theta^+$. Thus, our predictions are accessible by the NA49 experiment at CERN and the STAR experiment at RHIC.

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