

# A Novel Mechanism of $H^0$ Di-baryon Production in Proton-Proton Interactions from Parton Based Gribov-Regge Theory

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A novel mechanism of  $H^0$  and strangelet production in hadronic interactions within the Gribov-Regge approach is presented. In contrast to traditional distillation approaches, here the production of multiple (strange) quark bags does not require large baryon densities or a QGP. The production cross section increases with center of mass energy. Rapidity and transverse momentum distributions of the  $H^0$  are predicted for pp collisions at  $E_{\text{lab}} = 160$  AGeV and  $\sqrt{s} = 200$  GeV. The predicted total  $H^0$  multiplicities are of order of the  $\Omega^-$  yield and can be accessed by the NA49 and the STAR experiments.

The existence or non-existence of multi-quark bags, e.g. strangelets and (strange) di-baryons is one of the great open problems of intermediate and high energy physics. Early theoretical models based on SU(3) and SU(6) symmetries [1,2] and on Regge theory [3,4] suggest that di-baryons should exist. More recently, QCD-inspired models predict di-baryons with strangeness  $S = 0, -1, \text{ and } -2$ . The invariant masses range between 2000 and 3000 MeV [5–12]. Unfortunately, masses and widths of the expected 6-quark states differ considerably for these models. However, most QCD-inspired models predict di-baryons and none seems to forbid them.

Especially the search for a stable  $H$ -particle is closely related to the study of  $\Xi$  and  $\Lambda\Lambda$  hypernuclei (for very recent data on double  $\Lambda$  hypernuclei see [13,14]). From observations on double  $\Lambda$  hypernuclei, a mass of  $m_H > 2m_{\Lambda\Lambda} - 28$  MeV is expected, while Jaffe estimated a binding energy of  $\approx -80$  MeV. The  $H$  is a six quark state (uuddss) coupled to an SU(3) singlet in color and flavor. Since its mass is smaller than  $2m_\Lambda$  it is stable against strong decays. However, this object with baryon number two is not an ordinary nuclear state: the multi-quark cluster contained in the  $H$  is deconfined. Thus, the  $H$  is the smallest strangelet or might even be seen as a small droplet of Quark-Gluon-Plasma. While on the hadronic side, hypernuclei are known to exist already for a long time, e.g. double  $\Lambda$  hypernuclear events have been reported [13–15], no stringent observation of the  $H$ -particle exists. Even today, decades after the first prediction of

the  $S = -2$   $H$ -di-baryon by Jaffe [5] the question of its existence is still open.

A major uncertainty for the detection of such speculative states is their (meta)stability. Metastable exotic multihypernuclear objects (MEMOs), for example, consists of nucleons,  $\Lambda$ 's, and  $\Xi$  and are stabilized due to Pauli's principle, blocking the decay of the hyperons into nucleons. Only few investigations about the weak decay of di-baryons exist so far (see [12] for a full discussion and new estimates for the weak nonleptonic decays of strange di-baryons): In [16], the  $H$ -di-baryon was found to decay dominantly by  $H \rightarrow \Sigma^- + p$  for moderate binding energies. While the  $(\Lambda\Lambda)$  bound state, which has exactly the same quantum numbers as the  $H$ -di-baryon, was studied in [17]. Here, the main non-mesonic channel was found to be  $(\Lambda\Lambda) \rightarrow \Lambda + n$ . If the life time of the  $(\Lambda\Lambda)$  correlation or  $H^0$  particle is not too long, the specific decay channels might be used to distinguish between both states.

There are several searches in heavy-ion collisions for the  $H$ -di-baryon [18,19] and for long-lived strangelets [20,21] with high sensitivities. Hypernuclei have been detected most recently in heavy-ion reactions at the AGS by the E864 collaboration [22].

In this letter we study the formation of the  $H^0$ -di-baryon within a new approach called parton-based Gribov-Regge theory. It is realized in the Monte Carlo program NEXUS 3 [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 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 "semi-hard 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

$q\bar{q}$ ,  $q\text{-}qq$  or  $\bar{q}\text{-}\bar{q}\bar{q}$ . The probability of  $q\text{-}qq$  and  $\bar{q}\text{-}\bar{q}\bar{q}$  is controlled by the parameter  $P_{qq}$  and is uniquely fixed by the experimental yields on (multi-)strange baryons [24].

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 flavor, whenever a quark or an antiquark is taken as a string end, a corresponding anti-particle 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 [24], 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<sup>1</sup>. Only the remnants change the balance of particles and antiparticles, due to the valence quarks inside. Resulting in the possibility to solve the anti-omega puzzle [25] at the SPS.

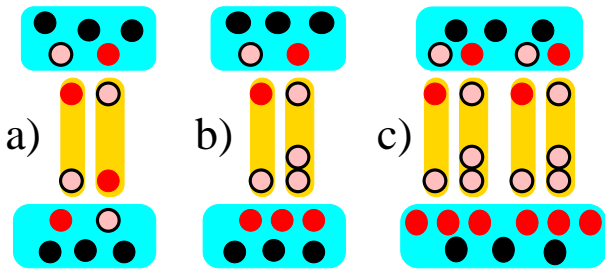


FIG. 1. (a) The typical collision configuration has two remnants and one cut Pomeron represented by two  $q - \bar{q}$  strings. (b) One of the  $q$  string-ends is replaced by a  $\bar{q}\bar{q}$  triplet state. To compensate the flavor, one of the remnants now has six quarks. In the case of a  $uuddss$  flavor content a  $H^0$  di-baryon can form. (c) Multiple Pomeron exchanges may lead to further accumulation of quarks in the remnant bag.

This prescription is able to accumulate quarks and di-quarks 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 di-quark and a quark and is transformed into a six quark bag as discussed in the following.

<sup>1</sup>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 valence 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.

The typical collision configuration has two remnants and one cut Pomeron represented by two  $q - \bar{q}$  strings, see Fig. 1(a).

However, one or more of the  $q$  string-ends can be replaced by a  $\bar{q}\bar{q}$  triplet state. To compensate the flavor, one of the remnants now has six quarks, cf. Fig.1(b). This possibility occurs with a probability  $P_{qq}$ . These six quarks are the three valence quarks  $u, u, d$  plus three sea quarks, where each of them may have the flavor  $u, d$ , or  $s$ , with relative weights  $1 : 1 : f_s$ . Both parameters,  $P_{qq}$  and  $f_s$ , are uniquely determined by multi-strange baryon data in proton-proton scatterings at 160 GeV to be  $P_{qq} = 0.02$  and  $f_s = 0.3$  [24]. Thus, there is a small but nonzero probability to have a  $uuddss$  flavor in a remnant, such that a  $H^0$  di-baryon may be formed.

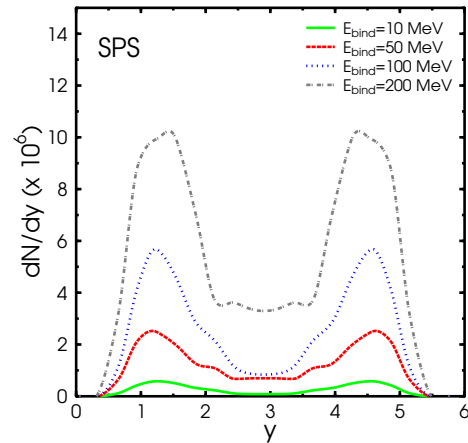


FIG. 2. Rapidity distributions of  $H^0$ 's in pp interactions at  $E_{\text{lab}} = 160$  GeV. The different lines correspond to different binding energies:  $e_{\text{binding}} = 10, 50, 100, 200$  MeV.

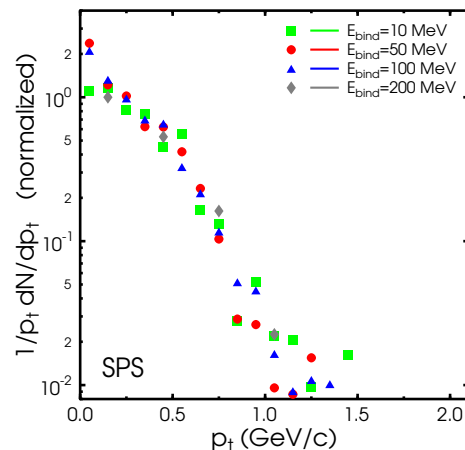


FIG. 3. Transverse momentum distributions of  $H^0$ 's in pp interactions at  $E_{\text{lab}} = 160$  GeV. The different symbols correspond to different binding energies:  $e_{\text{binding}} = 10, 50, 100, 200$  MeV.

The remnants have mass distribution  $P(m^2) \propto (m^2)^{-\alpha}$ ,  $m^2 \in (m_{\min}^2, x^+s)$ , here  $s$  is the squared CMS energy. With,  $m_{\min}$  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 1.5 and  $m_{\min} = 2m_\Lambda - e_{\text{binding}}$ . Remnants with masses  $m$  between  $2m_\Lambda - e_{\text{binding}}$  and  $2m_\Lambda$  are considered to be  $H^0$  bound states. Projection on a specific spin state is omitted.

Contrary to the mechanism of [26], which needs high baryon densities to distill strangeness in heavy ion collisions, the present approach works differently: It is independent of the baryon density and temperature. The presence of baryons enters only due to multiple scatterings. In addition, with increasing center-of-mass energy, multiple Pomeron exchanges gain importance. This results in an increased possibility to produce heavy quark bags around the target and projectile region of the collision as shown in Fig. 1(c)

Let us now study the multiplicities and momentum spectra of the calculated  $H^0$ 's. Fig. 2 depicts the rapidity distribution of the predicted  $H^0$ 's at the top SPS energy for a variety of possible binding energies. One observes a strong forward-backward peak in the  $H^0$  cross section indicating the production process from the remnants.

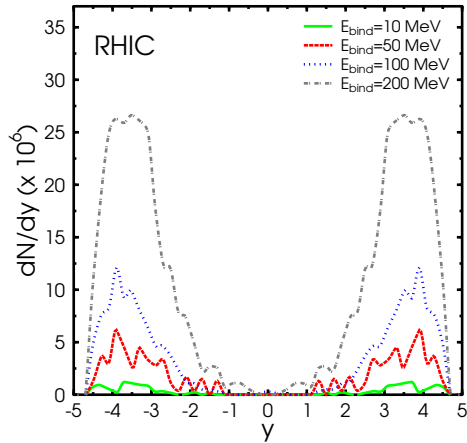


FIG. 4. Rapidity distributions of  $H^0$ 's in pp interactions at  $\sqrt{s} = 200$  GeV. The different lines correspond to different binding energies:  $e_{\text{binding}} = 10, 50, 100, 200$  MeV.

$e_{\text{binding}}$ (MeV)	Yield (SPS) ( $\times 10^5$ )	Yield (RHIC) ( $\times 10^5$ )
10	0.141	0.313
50	0.656	1.660
100	1.351	3.424
200	2.980	10.32

TABLE I. Predictions of the  $H^0$  abundances in  $4\pi$  for the different binding energies in pp collisions at 160 GeV (SPS) and  $\sqrt{s} = 200$  GeV (RHIC).

Fig. 3 depicts the transverse momentum spectra of the  $H^0$ 's for the same set of binding energies.

In Figs. 4 and 5 we show the rapidity and transverse momentum spectra at  $\sqrt{s} = 200$  GeV, again for the different binding energies. Especially at RHIC energies one clearly observes the pile-up of di-baryons in the forward and backward hemisphere. In the midrapidity region the di-baryon yield vanishes.

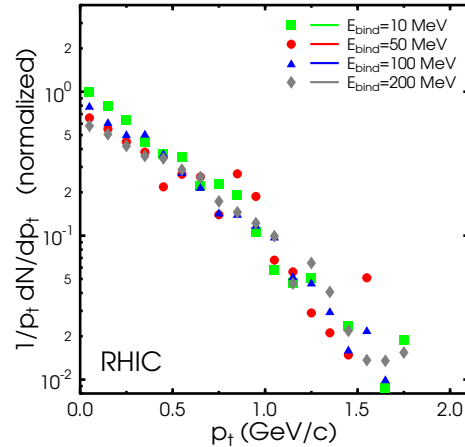


FIG. 5. Transverse momentum distributions of  $H^0$ 's in pp interactions at  $\sqrt{s} = 200$  GeV. The different symbols correspond to different binding energies:  $e_{\text{binding}} = 10, 50, 100, 200$  MeV.

We finally calculate the integrated abundances of  $H^0$  as a function of the binding energy for SPS and RHIC energies, as shown in Fig. 6. Since the total yields are given by

$$\begin{aligned} \text{yield} &\propto \int_{m_{\min}^2}^{m_{\max}^2} P(m^2) dm^2 = \frac{m_{\max}^{2-2\alpha} - m_{\min}^{2-2\alpha}}{1-\alpha} \\ &= \frac{1}{m_\Lambda} \left[ \frac{e_{\text{binding}}}{2m_\Lambda} + \left( \frac{e_{\text{binding}}}{2m_\Lambda} \right)^2 + \left( \frac{e_{\text{binding}}}{2m_\Lambda} \right)^3 + \dots \right] \\ &\cong \frac{1}{m_\Lambda} \left[ \frac{e_{\text{binding}}}{2m_\Lambda} + \left( \frac{e_{\text{binding}}}{2m_\Lambda} \right)^2 \right] \end{aligned}$$

where  $m_{\max} = 2m_\Lambda$ ,  $m_{\min} = 2m_\Lambda - e_{\text{binding}}$ , and  $\alpha = 1.5$ . Thus, one finally expects a scaling of the multiplicities with

$$\text{yield} \propto e_{\text{binding}} + \frac{e_{\text{binding}}^2}{2m_\Lambda}.$$

Fig. 6 depicts a fit with  $\gamma \times (e_{\text{binding}} + e_{\text{binding}}^2/2m_\Lambda)$  and  $\gamma = 1.35 \times 10^{-7} \text{ MeV}^{-1}$  (SPS, dashed line) and  $\gamma = 4.41 \times 10^{-7} \text{ MeV}^{-1}$  (RHIC, dotted line), respectively.

The total abundances at both investigated collision energies and the set of binding energies are summarized in Table I: For optimistic values of  $e_{\text{binding}}$ , one expects

100  $H^0$  to be observable by NA49 in the next pp run [27]. Compared to the predictions of [11] for nucleus-nucleus collisions at RHIC, the present study suggests additional di-baryon production in the forward and backward hemisphere in addition to the midrapidity region.

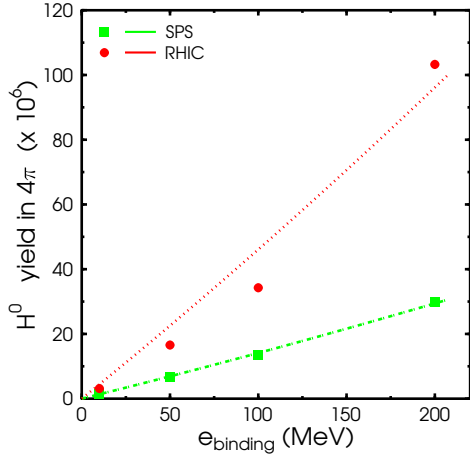


FIG. 6. Integrated amounts of  $H^0$  as a function of the binding energy for SPS (squares) and RHIC (circles) energies. The lines denote fits (see text).

In conclusion, we have presented a novel production channel of  $H^0$  di-baryons in pp collisions from parton-based Gribov-Regge theory. All model parameters are fixed by multi-strange baryon data at 160 GeV. In contrast to previous works, this mechanism does not require the production of a deconfined state, neither does it need high baryon densities. In fact, one expects an increase in di-baryon production with energy strongly peaked in beam direction. Note, that the suggested formation scenario of the  $H^0$  (i.e. the lightest strangelet state), also invalidates strangelets as a smoking gun signature of a QGP state. Multiplicities, rapidity and transverse momentum spectra are predicted for pp interaction at  $E_{\text{lab}} = 160$  GeV and  $\sqrt{s} = 200$  GeV. At SPS, the cross section for  $H^0$  production in the present study is found to be similar to the  $\Omega$  production cross section. Our predictions are accessible in the  $\Sigma^- p$  channel by the NA49 experiment at CERN and the STAR experiment at RHIC.

### Error estimates

Table II shows the size of the analyzed samples for the different settings. From this we obtain statistical errors on the multiplicities  $3\% < \Delta N/N < 9\%$ .

$e_{\text{binding}}$ (MeV)	Events (SPS)	Events (RHIC)
10	100 Mio.	50 Mio.
50	50 Mio.	20 Mio.
100	50 Mio.	50 Mio.
200	10 Mio.	12 Mio.

TABLE II. Analyzed events.

### Acknowledgments

The authors want to thank Jürgen Schaffner-Bielich for fruitful discussions on the physics of strangelets and hyper matter. M.B. acknowledges support from the region Pays de la Loire. S.O. acknowledges support by the German Ministry for Research and Education (BMBF). H.J.D. kindly acknowledges support from NASA grant NAG-9246.

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