Remnant break-up and muon production in cosmic ray air showers

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We discuss the relation between remnant fragmentation in inelastic high-energy hadronic interactions and muon production in extensive cosmic ray air showers. Using a newly developed tool, a simple and flexible hadronic event generator, we analyze the forward region of hadronic interactions. We show that measurements of the Feynman-x distribution in the beam fragmentation region at LHCf will be key to understanding muon production in air showers quantitatively.

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I. INTRODUCTION

Muon production in cosmic ray induced air showers has been of great interest recently. The number of muons observed by the Auger collaboration exceeds the one predicted by popular hadronic interaction models by as much as 50% [1].

A possible mechanism for more muon production in air-shower models has been proposed by the EPOS model [2], which describes successfully a large variety of Relativistic Heavy Ion Collider (RHIC) data. In that model, the production of most hadron species (in particular, of baryons) relative to neutral pions is enhanced. Thus, a larger fraction of the shower energy remains in the hadronic channel which, in turn, leads to a higher number of muons than in other hadronic air-shower models such as QGSJET-II [3] and SIBYLL [4].

In this paper we point to another mechanism that influences muon production in air showers significantly, namely, the treatment of the remnant of the projectile in a hadronic interaction. The break-up of the hadronic remnant determines the amount of energy remaining in the hadronic channel of the air shower (by producing baryons or charged mesons) relative to that "lost" to the electromagnetic part due to production of neutral pions. Remnant break-up shows up in the very forward region (large Feynman-x_F) of collider experiments and therefore measurements of the LHCf collaboration [5] will be important to understand muon production in air showers.

A generic difficulty in studying hadronic interactions for air showers is the fact that one always compares inherently different Monte Carlo event generators. As a typical result of detailed comparisons one has model A which produces e.g. more muons than model B. One can then compare generic properties of the underlying hadronic models, like multiplicity, baryon production, strangeness or charm production, and forward scattering and try to argue for an observed effect. This method remains always very qualitative, since one cannot disentangle the importance of the different contributions and one is always left with the uncertainty that other (possibly neglected) effects are actually also important.

In order to relate a specific property of air showers (e.g. muon number) unambiguously to a specific feature of a given hadronic interaction model (e.g. remnant break-up) we developed a new hadronic interaction model. The goal is to keep the model as simple and flexible as possible. We then study air-shower properties by changing only one parameter at a time. To investigate the influence of the remnant break-up on muon production we explore different treatments of the remnant but do not vary anything else. Likewise, the effects from baryon production can be studied by exclusively varying the diquark probability in the string fragmentation.

II. THE TOOL, THE PQCD EVENT GENERATOR PICCO

The new tool, pQCD Interaction Code for COsmics (PICCO), is a standard event generator. Details will be published elsewhere; here we just outline the basic features. The interaction is modeled by a superposition of a soft and a semihard Pomeron. The Pomeron parameters are fit to reproduce the total and elastic cross section for hadron-hadron scattering. Hard scattering is performed by PYTHIA [6], and the partons are mapped onto strings. Each Pomeron gives exactly 2 strings each of which connects a quark-antiquark pair scattered out of the interacting particles. The longitudinal momentum distribution of the string-ends is the same as in other models, $dx/\sqrt{x}$ for each (anti)quark. The remaining particle, the remnant, has a $x^{1.5}dx$ distribution in the case of baryons, versus $x^{-0.5}dx$ for mesons [7]. Fragmentation of the strings is done via the Lund fragmentation scheme as implemented in PYTHIA.

The treatment of the remnant is important for air-shower applications. With a given probability $p_{\rm ex}$, the remnant can be in an excited state with an invariant mass M; the distribution for M is dM^2/M^2. To model the fragmentation of such an excited remnant state, it could be viewed, for example, as a quark matter droplet or as a simple string. In our model we choose the string approach. If the remnant has a remaining light-cone momentum fraction x^+ (which is the momentum fraction of one string-end), the corresponding momentum fraction of the other string-end is given by $x^- = M^2/x^+$. Remnant strings may have different fragmentation parameters in order to enhance forward baryon or strangeness production.

The remnant treatment outlined above is not new, it has been used in many models: QGSJET-98/01 [8], QGSJET-II [3], the versions NEXUS 2 [9] and NEXUS 3 [10], and EPOS [2]. In other models, the remnant is modeled by attaching one of the strings resulting from Pomeron exchange to a diquark. While this approach has some drawbacks which will be outlined below, it is also theoretically less appealing, because one of the interactions (the one including the diquark) is preferred over the other ones. By separating the remnant, all interactions are treated on equal footing.

III. SOFT REMNANT BREAK-UP

In this section we consider soft remnant break-up, i.e. remnant excitation. We shall first discuss the relevant parameters. p_{ex} is the excitation probability. In the case of excitation, the invariant mass is determined randomly according to the distribution dM^2/M^2 in between the limits M_{min} and M_{max}. In our approach, we choose M_{min} to be the minimum mass corresponding to the flavor content of the remnant plus twice the pion mass. In the case of a proton-like remnant (quark content uud), for example, $M_{\mathrm{min}} = (0.938 + 0.28)$ GeV. M_{max} is taken to be $0.5\sqrt{s}$. Our simulations show that the mass limits are more of a technical nature; their exact value does not change the results significantly.

The excitation probability p_{ex}, however, is of utmost importance. The exact value of this parameter has been fitted to reproduce low-energy forward scattering data from Ref. [11], see Fig. 1. We find $p_{\mathrm{ex}} = 0.6$. Also shown in the same figure is the forward particle distribution for the case $p_{\mathrm{ex}} = 1$, i.e., when the remnant is excited always. Notice how this affects the forward distribution of final-state protons: a dip appears in the region $0.5 < x_F < 1$. The explanation is simple. If the remnant decays into two or more particles, the region below $x_F < 0.5$ will be populated. The region $0.5 < x_F < 1$ corresponds to a mere longitudinal momentum loss of the remnant rather than to its fragmentation. The lower panel of Fig. 1 depicts the forward particle distribution at higher energies.

PYTHIA implements a different approach. Instead of treating the remnant separately, one of the strings created in the interaction is attached to a diquark from the projectile while the other string is attached to the remaining valence quark. This topology, however, appears to have problems explaining the ratio of anti-omega to omega baryons. Sufficiently massive strings ending in a diquark tend to produce more antibaryons than baryons near that end, which is not supported by the data [12]. In Fig. 1 we see that a diquark string also fails to reproduce the forward proton production data, since, similar to a decaying remnant, the momentum of the diquark is shared among two or more particles.

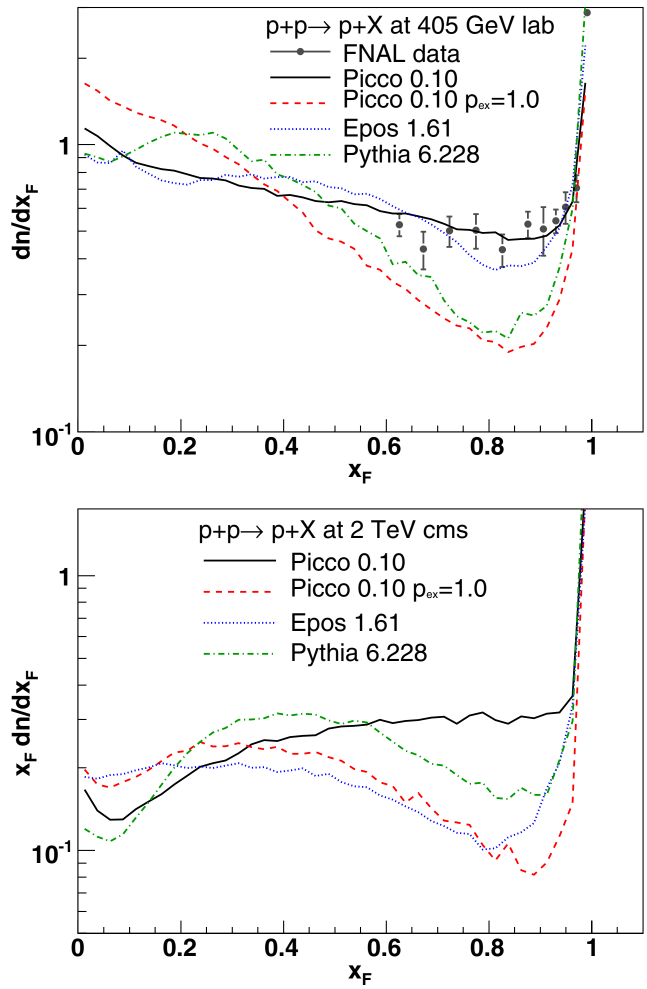

FIG. 1 (color online). Feynman-x distributions of protons for proton-proton collisions. The data is from Ref. [11]. The model featuring extreme (100%) remnant excitation probability, and the diquark approach of PYTHIA, lead to a dip in the forward spectrum.

For pion induced reactions, the situation is different, with the remnant consisting of a simple quark-antiquark pair. Again, with a probability p_{ex}, the remnant gets excited and decays by forming a string. A $\pi^+ + p$ reaction at 250 GeV has been studied by the EHS/NA22 collaboration [13]. Figure 2 shows the forward production of charged particles. In the case of PICCO, a better fit is obtained with a lower excitation probability. EPOS, which has a higher excitation probability yields an even slightly better description of the data. The forward π^0 production is shown in the lower panel of Fig. 2. Here, enhanced break-up improves the description of the differential cross section, but all models are still far from the data. In fact, no other model is able to describe this data. If one modifies parameters extremely to reproduce neutral pions, then one fails to describe the charged-pion spectra. The situation is similar with data on π^- proton scattering at 360 GeV measured by the NA27 LEBC/EHS collaboration [14]. A new measure-

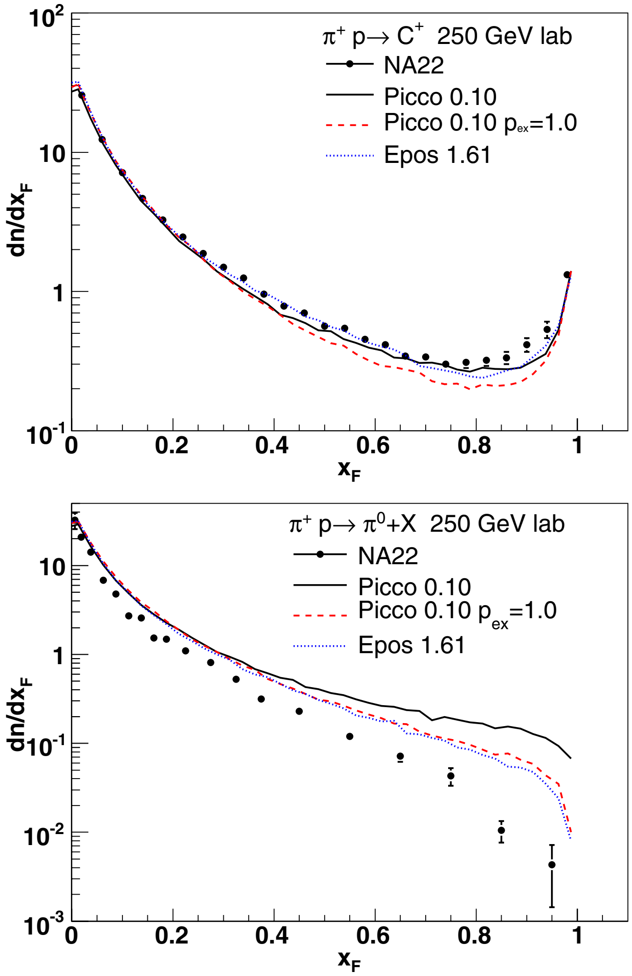

FIG. 2 (color online). Feynman-x distributions of π^0 for π^+ proton collisions. The data is from Ref. [13].

ment of π^0 production in pion induced reactions would be extremely helpful.

IV. INFLUENCE ON MUON PRODUCTION IN AIR SHOWERS

How does the remnant affect muon production in air showers? The basic reasoning is very simple: if the remnant decays into two or more particles its energy is redistributed among particles which stay in the hadronic channel and eventually produce muons (charged mesons, baryons) and particles which go into the electromagnetic channel (mainly neutral pions).

Let us first consider the break-up of baryons. The remnant of a baryon induced collision is always a baryon. The flavor content might of course change due to charge exchange (for example, a proton induced reaction might give a neutron as remnant, which nevertheless remains in the hadronic channel of the air shower). If the remnant however gets excited and breaks up, generically it produces a number of neutral pions. Therefore, baryonic remnant break-up should in fact reduce muon production.

For charged-pion induced reactions, the outcome is very different. Figure 3 shows the energy fraction of neutral pions in the remnant, for the two extreme cases without excitation ($p_{ex} = 0$) and with complete break-up ($p_{ex} = 1$). We see that remnant break-up reduces the energy in neutral pions. Because of charge exchange, the remnant can be either of the flavor of a charged pion (ignoring strangeness for the purpose of this argument) or of a neutral pion. The decay of an excited charged pion therefore reduces muon production since additional neutral pions are produced. The opposite is true for the decay of neutral pion remnants, where additional charged pions increase the energy available in the hadronic channel. In the following we give a qualitative argument why the total effect of remnant break-up reduces the π^0s. With one Pomeron exchange, the remnant is with 50% probability charged and with 50% probability neutral. This can be easily seen by inserting quark-antiquark pairs (underlined) into a $u\bar{d}$ system:

$$\text{projectile} \rightarrow \text{remnant} + \text{string-ends} \rightarrow u\bar{d} + \underline{d}\,\bar{d} \quad (1)$$

$$\rightarrow u\bar{u} + \underline{u}\,\bar{d} \quad (2)$$

$$\rightarrow \bar{d}\,\underline{u} + \bar{u}u \quad (3)$$

$$\rightarrow \bar{d}\,\underline{d} + \bar{d}u \quad (4)$$

(1) and (3) will give a charged remnant, (2) and (4) a neutral one. When the remnant decays, due to isospin symmetry one expects an equal amount for all three pions.

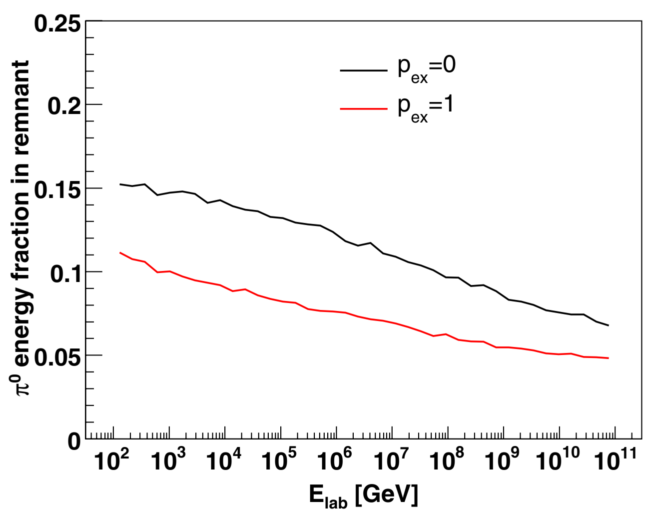

FIG. 3 (color online). Energy fraction of neutral pions in the remnant for π^+ + air collisions, for the cases with and without break-up. Remnant break-up reduces the energy fraction in π^0 and thus enhances muon production in air showers.

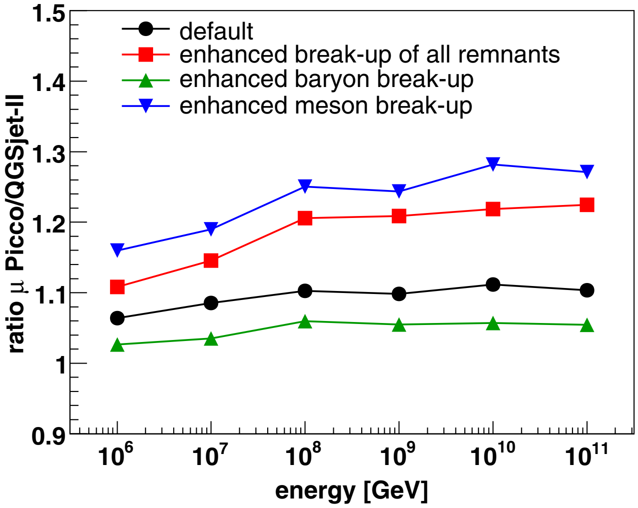

FIG. 4 (color online). The ratio of total muon numbers of vertical proton induced air showers for enhanced break-up ($p_{ex} = 1.0$ instead of $p_{ex} = 0.6$) of baryonic and mesonic remnants.

So, the fraction of π^0 is reduced from 1/2 to 1/3, which gives the ratio of 2/3 that can be seen in Fig. 3. When we consider strangeness and baryon production, additional particles are created at the expense of the number of pions, and this ratio will be even further reduced.

Next, we calculate the total muon number with a full air-shower simulation using SENECA [15]. We simulate proton induced average vertical showers, the observation altitude is 1400 m above sea level, and we normalize to the QGSJET-II model. The result is shown in Fig. 4, for the different cases of enhanced break-up ($p_{ex} = 1$) of baryonic and mesonic remnants. We observe that additional break-up of baryons reduces muon production while break-up of mesons enhances it. The net effect is an enhancement of muons, since pion induced collisions are more abundant.

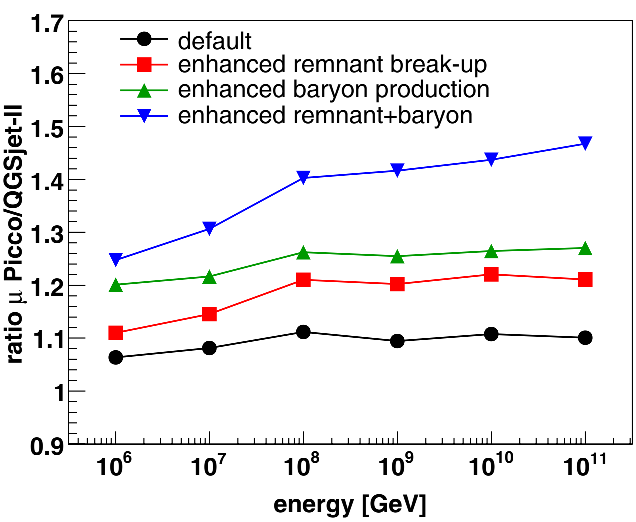

FIG. 5 (color online). The ratio of total muon numbers of vertical proton induced air showers for different remnant break-up and baryon production scenarios. Enhanced baryon production means $p_{\text{diq,str}} = 0.12$ and $p_{\text{diq,rem}} = 0.3$ instead of the default value $p_{\text{diq}} = 0.10$ from PYTHIA.

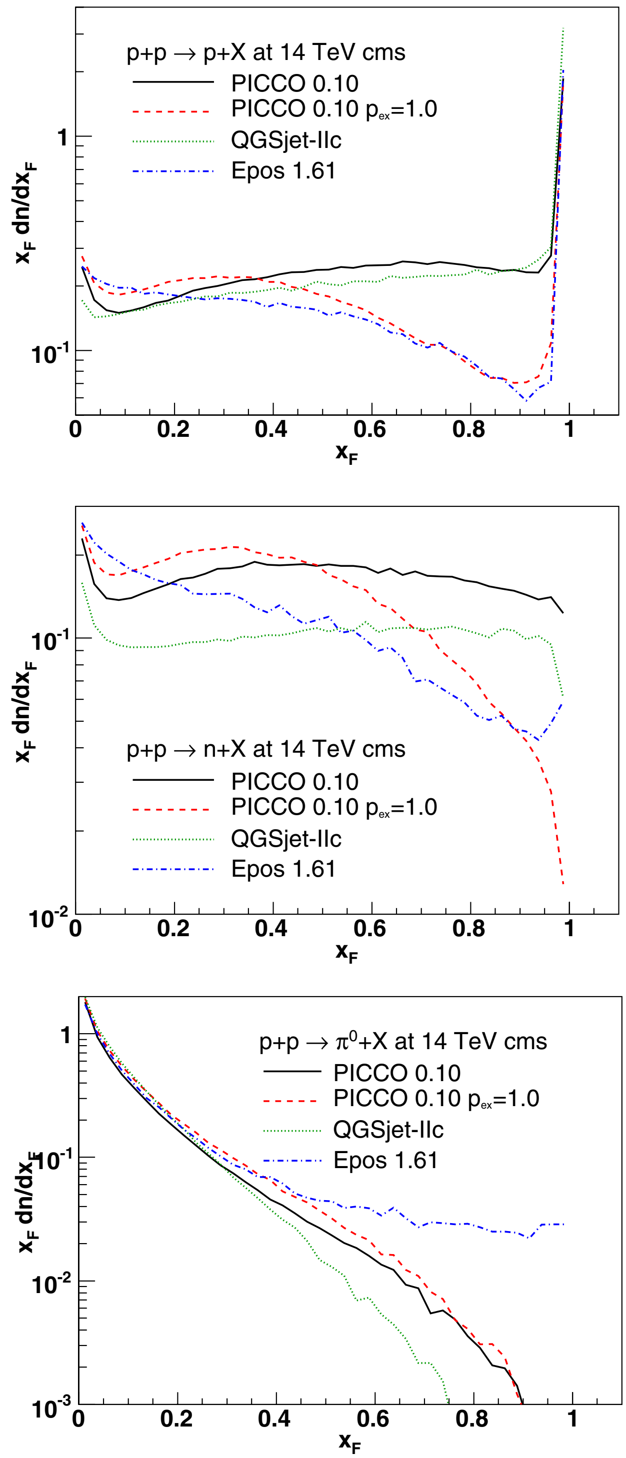

FIG. 6 (color online). Feynman-x distributions of identified particles for proton-proton collisions at 14 TeV cms energy.

We are now in a position to consider as well enhanced baryon production. The parameters for the diquark production in the string fragmentation are adjusted to give qualitatively similar results to EPOS. We choose $p_{\text{diq,str}} = 0.12$ and $p_{\text{diq,rem}} = 0.3$ as diquark-antidiquark pair production probabilities in central strings and remnant strings, respectively. The higher probability for diquark production from remnant strings is motivated by the remnant encountering a denser target and leads to more baryons in the forward region, as found to be important by the authors of EPOS. Figure 5 shows that muon production in PICCO with default parameters (i.e. $p_{\text{diq,str/rem}} = 0.1$ from PYTHIA) is within 10% similar to QGSJET-II. Enhanced baryon production gives 25% more muons. However, the combined effects of both enhanced baryon production and remnant break-up add up to 40%.

One might argue that total break-up at high energy could be excluded by constraints on the position of the shower maximum $X_{\max}$. In the case of reduced forward scattering, one expects a somewhat lower $X_{\max}$. While this is qualitatively true, the simulations show that this effect is small, the mean value of $X_{\max}$ is reduced by less than $5\text{g}/cm^2$.

At low energies, complete remnant break-up of baryons is excluded by the data (see Fig. 1) and the results shown in Fig. 5 should actually be considered as an upper limit. However, we do not know whether the relevant parameter changes at high energies. If we keep the one obtained at low energies, $p_{\text{ex}} = 0.6$, we find a rather flat distribution $x_F dn/dx_F$ of protons at 2 TeV center of mass energy, whereas one notices a dip in the forward scattering spectrum for the case of complete remnant break-up.

A motivation for an enhanced remnant break-up is the fact that at higher energies the projectile probes smaller gluon momenta in the target and therefore encounters a higher gluon density. This effect has already been investigated within the color glass condensate (CGC) framework for hadron-nucleus collisions at colliders in Ref. [16] and has been applied to air showers in Ref. [17]. The main consequence of the enhanced remnant break-up is a suppression of forward particle production; this leads to a faster absorption in air showers and hence to a lower shower maximum $X_{\max}$. Furthermore, an enhanced muon production was observed in Ref. [18] but was attributed mainly to an increased overall multiplicity. Efforts are currently ongoing to implement this particular mechanism of forward suppression into the PICCO model, which will allow us to test for its influence on the muon number. We will also investigate projectile break-up due to a dense target in proton-proton collisions at LHC energies, and apply this mechanism to air-shower simulations.

V. FORWARD SCATTERING AT LHC ENERGIES

Finally, we compare model predictions in the kinematic range relevant for the forthcoming LHCf [5] experiment. This experiment plans to measure photons, neutral pions, and neutrons in the very forward region with a small detector between the two beam pipes of the LHC collider. Except for the diffractive peak, neutrons and protons are expected to show similar distributions in this region, with neutrons being somewhat outnumbered. The results are shown in Fig. 6. The slope of the forward neutron spectrum will give insight into remnant break-up at these energies and will therefore allow one to constrain muon production in air showers. It is also interesting to examine the absolute normalization of the very forward neutron spectrum as this relates directly to the treatment of the flavor content of the remnant. QGSJET-II predicts less neutrons since it allows for only one charge exchange reaction.

As for neutral pions: here the differences due to remnant break-up are much smaller. The relatively flat forward spectrum of EPOS stems from a specific implementation of the popcorn effect [19], where the two leading particles of string fragmentation can be interchanged with some probability.

VI. SUMMARY

We have shown that remnant fragmentation in hadronic interaction models for air showers has significant influence on muon production. If the projectile remnant decays into two or more particles the energy fraction which goes into the hadronic or electromagnetic channel changes. Enhanced baryon break-up reduces and enhanced meson break-up increases muon production in air showers. At low energies, forward scattering data constrains the break-up probability of the remnant to roughly 60%. The measurements of the LHCf experiment will be extremely helpful for our understanding of remnant break-up at higher energies, and hence will provide important constraints for muon production in air showers.

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