How air shower and heavy ion physics benefit from each other

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Abstract

We discuss recent progress in air shower simulations of very high energy cosmic rays, with special emphasis on the interplay between collider results and air shower observations.

Cosmic rays at the highest possible energies are so rare that they can only be observed via the billions of secondary particles in the so-called airshowers – cascades of particles, multiplying themselves due to suc-

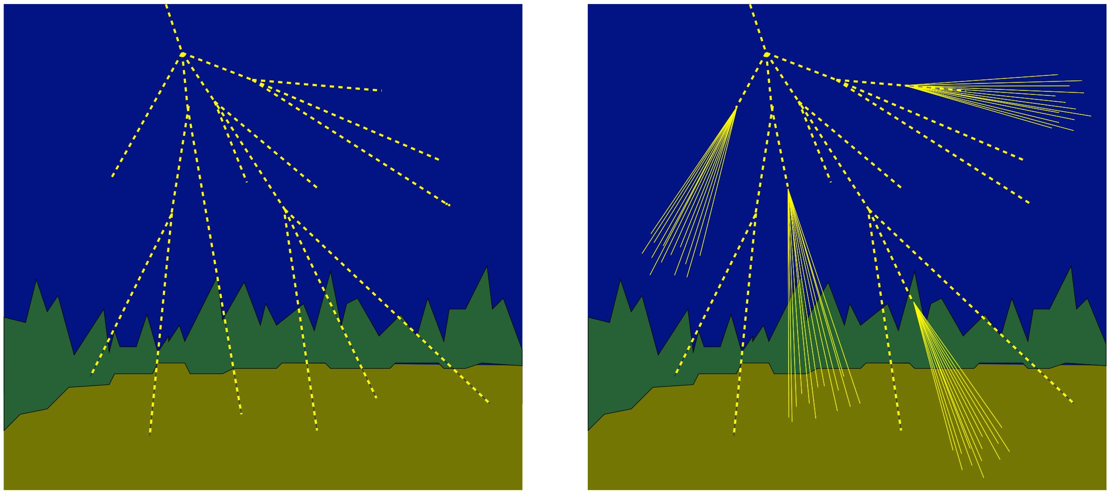

Figure 1: The hadronic cascade (left) and the complete airshower, including electromagnetic cascade (right).

cessive interactions in the atmosphere. There is first of all the hadronic cascade (see fig. 1(left)), composed of hadrons, produced in hadron + air collisions. These hadrons are mainly pions, but also kaons, and protons, where the latter ones will play an important role in the later discussions. The charged pions decay preferentially into muons and neutrinos: $\pi^- \to \mu^- \overline{\nu}_\mu$ and $\pi^+ \to \mu^+ \nu_\mu$, with a lifetime of $2.6\,10^{-8}$s. The neutral pions, however, decay almost exclusively into two two photons, with a lifetime of $0.8\,10^{-16}$s – in other words immediately, before having a chance to scatter.

The two photons of the neutral pion decay initiate a so-called electromagnetic cascade of photons and electrons, with the main processes at high energies being pair creation and Bremsstrahlung, see fig. 2.

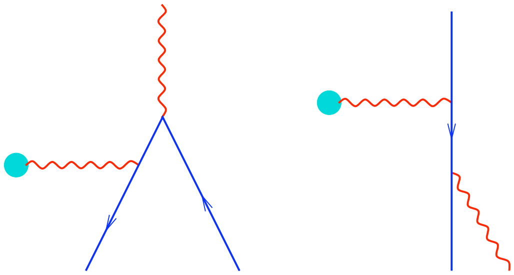

Figure 2: Pair creation and Bremsstrahlung, each one doubling the number of particles per interaction.

The main observables are the electrons (from the electromagnetic cascade), the muons (from the decays of hadrons which do NOT decay into photons), and also fluorescence light, radio signals, and so on. We will focus here on the electrons and the muons.

There has been a longstanding problem in airshower physics: the number of muons obtained from airshower simulations has always been too low compared to the measurements. Any attempt to modify the hadronic interaction models in order to get more muons created other problems. In 2006, non of the existent models (QGSJET(1), SIBYLL(2)) could consistently describe all cosmic ray airshower data.

Starting to use EPOS(3; 4; 5) as interaction model, is was found that one gets significantly more muons, without changing observables like $X_{\max}$ too much, see (6). As an example, we show in fig. 3 the muon density at a fixed distance from the core, as measured by the MIA collaboration(7), compared to simulations based on QGSJET and EPOS. Significantly more muons are produced in the EPOS simulations. Similar results have been obtained more recently from the AUGER collaboration(8).

Why are there more muons produced in EPOS ? Because EPOS produces more baryons! In fig. 4, we plot the antiproton over pion ratio in

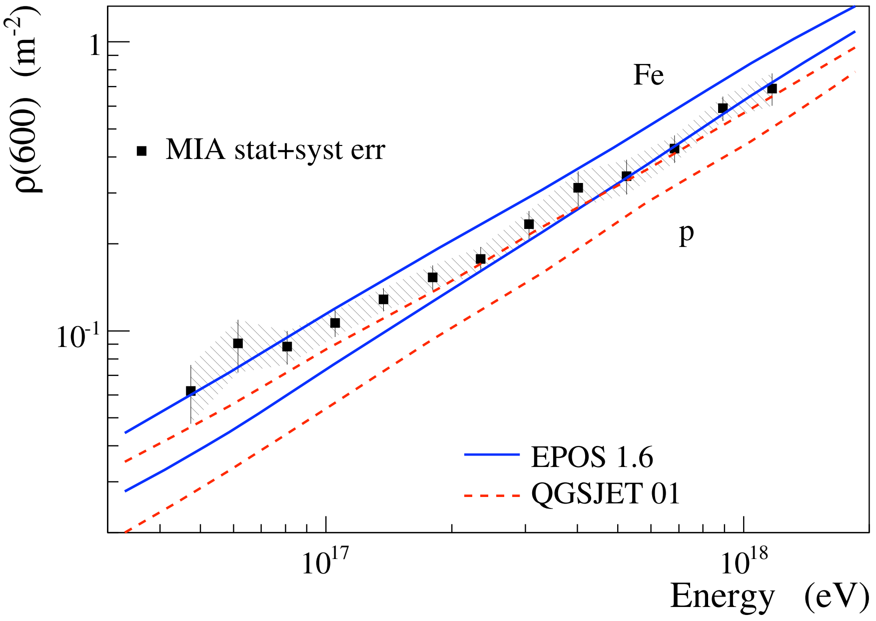

Figure 3: The muon density at a fixed distance from the core, as measured by the MIA collaboration(7), compared to simulations based on QGSJET and EPOS.

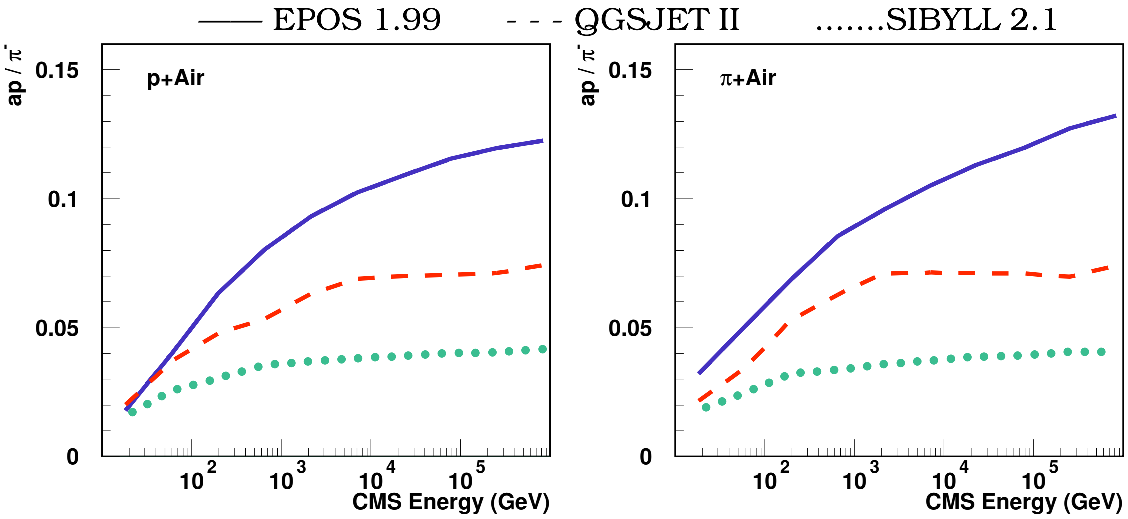

Figure 4: The antiproton over pion ratio in p+Air collisions for EPOS, QGSJET, and SIBYLL, as a function of the energy.

p+Air collisions for EPOS, QGSJET, and SIBYLL, as a function of the energy. Knowing that the pion rate in the three models is similar, we can see that the antiproton production increases much more in EPOS compared to the other models. This fact is also observed for other baryons.

The particular role of the baryons concerning muon production is easily understood. The main property of the baryon, in this context, is the fact that is not a π^0. This latter particle decays immediately into two photons, its energy is given to the corresponding electromagnetic cascade, no muons can be produced in the following. On the contrary, a baryon can still interact, producing charged pions, which then decay into muons. Also, baryons have a softer pion spectrum than pions in the next generation, leading to less energy lost in to electromagnetic channel in case of π^0 production in the next collision with air. So although baryons are not the most abundant particles in the cascade, their role is very important concerning the muon rate.

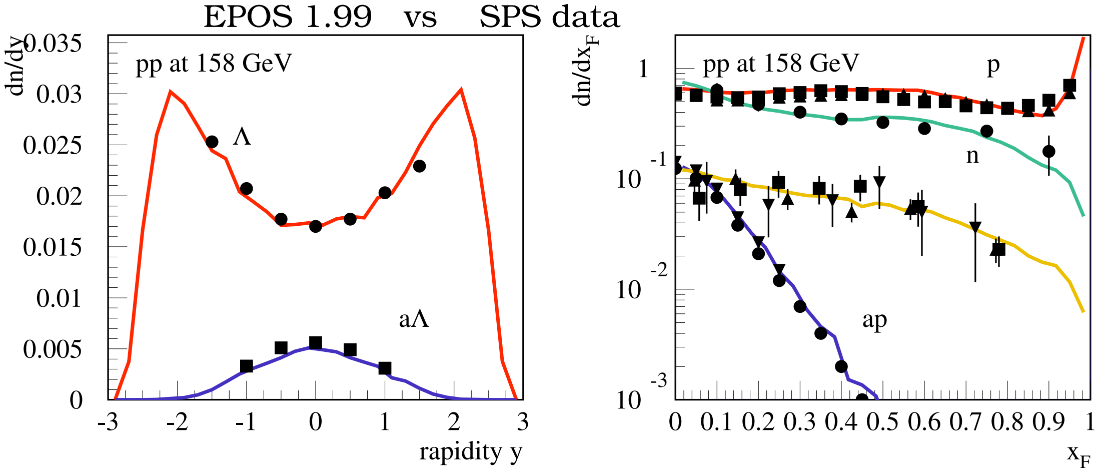

Figure 5: The yields of different kinds of baryons in proton-proton collisions at 158 GeV, compared to data from SPS/NA49(9; 10).

EPOS has been designed (and optimized) to understand ALL types of hadrons by carefully studying baryon production in accelerator experiments, without thinking about CR applications. In fig. 5, we plot the yields of different kinds of baryons in proton-proton collisions at 158 GeV, from EPOS calculations, compared to data from SPS/NA49(9; 10). An enormous amount of pp ($p\bar{p}$) data has been considered, at SPS, ISR, RHIC, TEVATRON , also πp, pA and πA collisions. As another example, we show in fig. 6 the antiproton over pion ratio in pp scattering at 1800 GeV (left), and proton production in pion carbon scattering at 100 GeV (right).

If we compare EPOS to other models, we find similar results concerning

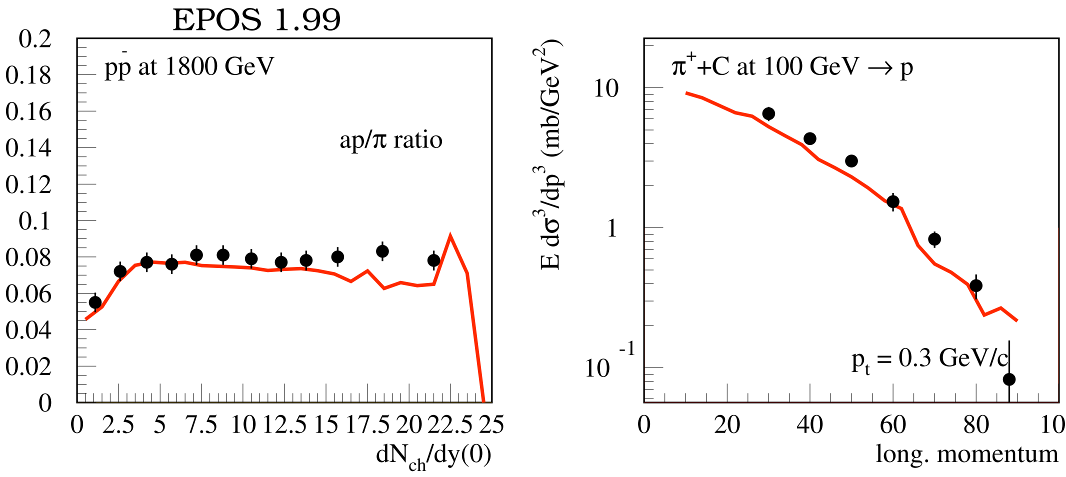

Figure 6: Antiproton over pion ratio as a function of the multiplicity density, in pp scattering at 1800 GeV (left), and proton production in pion carbon scattering at 100 GeV (right). We compare EPOS calculations with data(11; 12).

pions, but big differences concerning baryons, see fig. 7, where we show

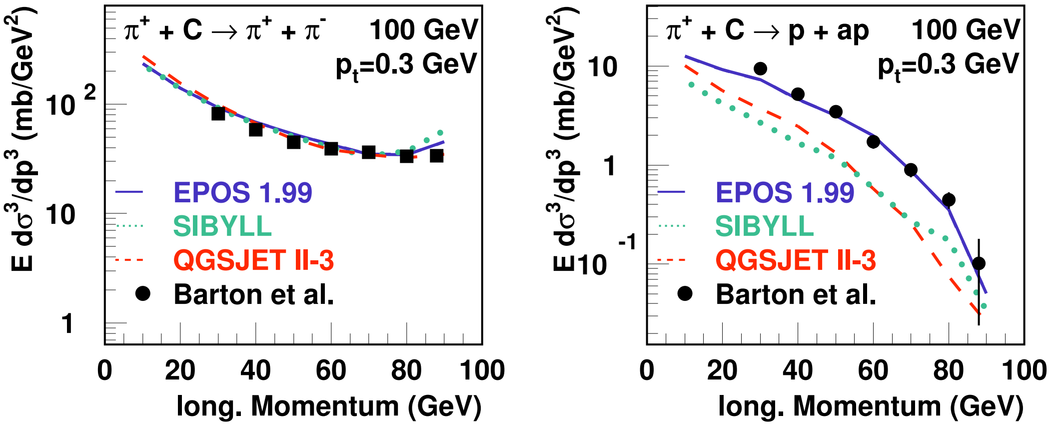

Figure 7: Pion production (left) and proton production (right) in pion carbon scattering at 100 GeV.

pion production (left) and proton production (right) in pion carbon scattering at 100 GeV. We compare calculations from different models with data(12). Clearly visible the large difference between EPOS and the other models, in case of protons. Whereas EPOS is close to the data, the other models are lower by as much as a factor of 2-3.

Having increased the muon number without affecting too much the electrons leads, however, to some contradictions. The problems comes from KASCADE data(13), where the number of muons is correlated with the number of electrons. Here, the current models seem to work, so increasing the muons and not the electrons will give a wrong electron-muon correlation. The solution is related to a completely different subject: non-linear effects (already considered for particle production) should also be taken into account for cross section calculations (which has not been done in earlier EPOS versions). Introducing non-linear effects as discussed in (1) also for cross section calculations, we obtain the results as shown in fig. 8. Both cross sections from EPOS calculations are below the results from the other models. There is also a trend in the data towards lower values, in more recent measurement compared to older data. Using our new results (with lower cross sections compared to other models), we get more electrons at ground, since the shower gets deeper into the atmosphere. We seem to be in agreement with the KASCADE muon-electron correlations, but having both more electrons and more muons compared to the other models. Studies are under way to make precise comparisons between the new EPOS and KASCADE.

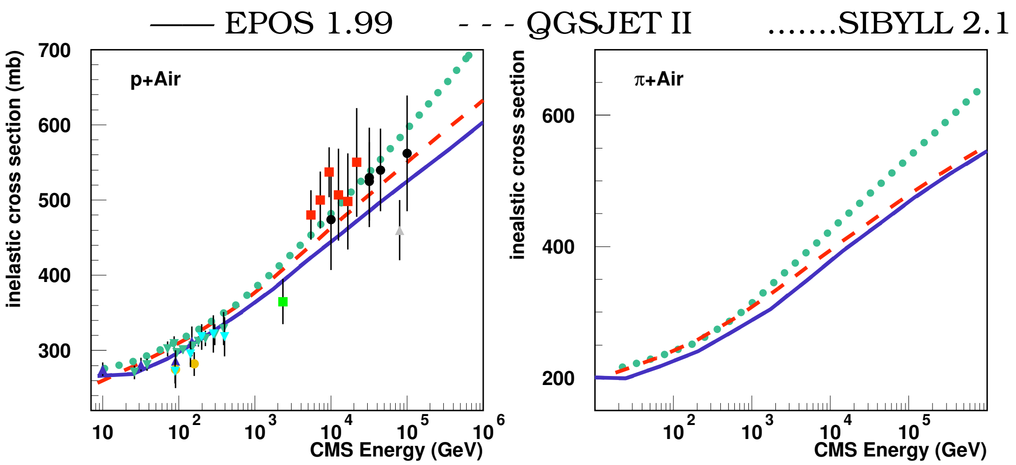

Figure 8: The inelastic cross section in p-Air and π-Air collisions, for different models.

Having a smaller inelastic cross section compared to earlier calculations (and other models) has also an impact on Xmax: it will be bigger, see fig. 9.

From the above discussion we see that the new hadronic interaction model EPOS seem to be able to solve a longstanding problem in airshower

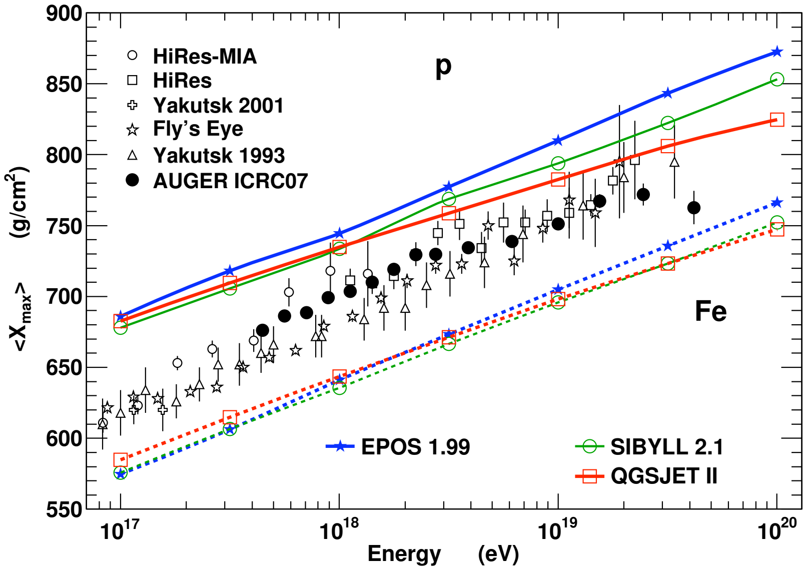

Figure 9: Xmax from different models compared to data..

physics, by providing more muons compared to simulations based on other models. EPOS is not fundamentally different compared to the other models, it is more a question how the different components are implemented and optimized. The main point is that EPOS has been designed in order to understand accelerator data, in particular particle production at RHIC and SPS. Here one tries to understand the relative production rates of different kinds of hadrons (pions, kaons, lambda, etc). Baryon production for example is of great interest.

EPOS is a multiple scattering model in the spirit of the Gribov-Regge approach. Here, one does not mean simply multiple hard scatterings, the elementary processes corresponds to complete parton ladders, which means hard scatterings plus initial state radiation. In this case, this elementary process carries an important fraction of the available energy, and therefore we treat very carefully the question of energy sharing in the multiple scattering process. Open and closed ladders have to be considered, see fig. 10, in order to have a consistent quantum mechanical treatment. The corresponding graphs are squared, and we employ cutting rule techniques and Markov chains to obtain finally partial cross sections. The cut parton ladders are identified with longitudinal color fields or flux tubes, treated via relativistic string theory. Not to forget the remnants, which are projectile and target after the interactions.

Particle production comes from remnants and flux tube (string) decay.

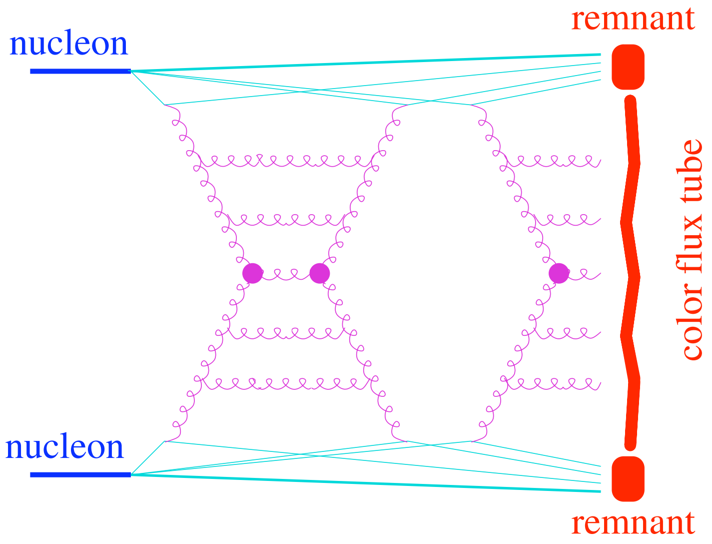

Figure 10: Multiple scattering diagram in EPOS.

This two source picture (string-remnant) seems to be unavoidable, if one wants to understand the complete set of experimental data on particle production in pp scattering from some 10 GeV up to Tevatron, in particular the large amount of detailed measurements from NA49(14). A correct description of the rapidity (or Feynman x) spectra of identifies hadrons relies heavily on this string-remnant picture, and reproducing these spectra is crucial for describing air showers correctly.

It is interesting to see that even RHIC heavy ion data can serve as a confirmation of our string-remnant approach: in these collisions one has usually high initial energy – but not everywhere. We therefore distinguish between the high density core (which then evolves hydrodynamically – and the corona (no collectivity, but nevertheless particle production). Since there is a large number of string mainly covering the central region, the strings constitute essentially the core. The remnants are more in the forward or backward regions, much less dense, they contribute mainly to the corona. It seems that this separation is measurable: only the collectively behaving core contributes to elliptical flow, not the corona. This shows up as a triangular form of the elliptical flow, see fig. 11. The theoretical curves correspond to different freeze out scenarios: the dashed curve refers to a hydrodynamical evolution till the final freeze out at 100 GeV, the dotted curves represents an early freeze out at a temperature of 169 MeV (just leaving the mixed phase), and the full lines refer to early freeze out at 169 MeV, with subsequent hadronic cascade (UrQMD(15)). Since

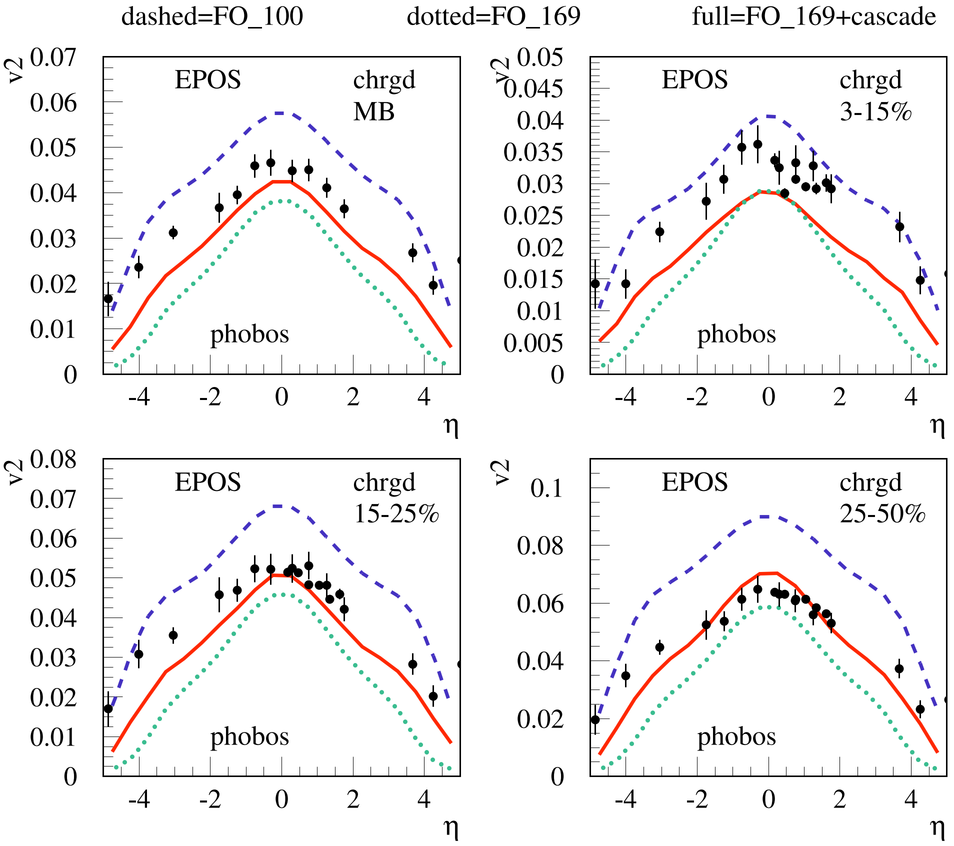

Figure 11: Elliptical flow fro a hydrodynamical calculation based on EPOS initial conditions, for different freeze our scenarios, compared to data(16).

the calculations are very preliminary and many details have still to be improved (equation-of-state, non-zero baryon chemical potentials, event-by-event treatment), we do not want to comment on differences between theory and experiment. We would like to stress that both theory and experiment show a triangular shape, and this is a robust result. There is no other model which gives such a triangular shape for all centralities. Usually hydrodynamical calculations give rather flat shapes in rapidity. The main reason for the particular EPOS result comes from the fact, that when going from central towards forward or backward rapidities, the relative contribution of corona (from remnants mainly) gets more and more important, and this contribution does contribute to particle production, but not to the elliptical flow.

To summarize: air shower simulations with EPOS provide more muons, due to more baryon production, compared to conventional models. A long-standing problem seems to be solved (without creating new ones). EPOS is a multiple scattering approach, with particle production from flux tube (string) breakup, and remnant decay. This flux tube-remnant picture applied to HI physics leads to a triangular η dependence of the elliptical flow, as suggested by PHOBOS data. Important in this context: the core-corona separation applied on our string remnant picture.

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