MINT - A SIMPLE MODEL FOR LOW ENERGY HADRONIC INTERACTIONS

M. SCHMELLING

MPI for Nuclear Physics, Saupfercheckweg 1
D-69117 Heidelberg, Germany

The bulk of inelastic hadronic interactions is characterized by longitudinal phase space and exponentially damped transverse momentum spectra. A simple model with only a single adjustable parameter is presented, making it a very convenient tool for systematic studies, which gives a surprisingly good description of pA-collisions at 920 GeV beam energy.

1 Introduction

As illustrated in Fig.(1), proton-nucleus (pA) collisions can proceed with or without colour exchange. The latter case applies for example in diffractive scattering, where beam or target can emerge in a high mass excited state. Reactions with colour exchange, referred to as "normal inelastic interactions" in the following, constitute the bulk of the total cross section. Here a single high mass system is created which decays into the observable final state particles.
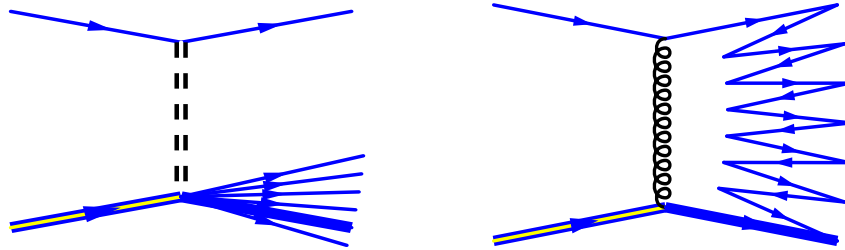

Figure 1: Examples for inelastic pA collisions showing diffractive scattering (left hand side), mediated without colour exchange by a pomeron, in comparison to a normal inelastic interaction (right) involving gluon exchange.

Interactions without colour exchange are characterized by an exponential spectrum $dn/dt \sim e^{bt}$ for the momentum transfer t and mass spectra $dn/dM \sim 1/M$ for diffractively excited states, essentially independent of the target nucleus A. This is consistent with the picture that reactions without colour exchange are peripheral, involving momentum transfer only between the beam proton and a single nucleon of the target nucleus. In contrast, normal inelastic interactions show a significant A-dependence, indicating a more central character of such collisions.

A Monte Carlo model for the generation of exclusive final states in pA collisions can be constructed in a straightforward way, using as external input the measured cross sections for the different sub-processes and a prescription for the transition of an initial high mass system into final particles. The latter is provided by MINT, based on the assumption that this transition is universal, i.e. it is the same for normal inelastic interactions or diffractive masses.

2   The MINT Model

The phenomenological basis of the MINT model is the observation that in hadronic interactions with center-of-mass energy E_{cm} large against the nucleon mass, the typical transverse momenta of final state particles are negligible compared to their longitudinal momenta. Assuming further that dynamical effects such as hard parton-parton scattering can be ignored, which is a reasonable approximation at low energies, the final state is governed by longitudinal phase space. Then, for zero transverse momentum, $p_T = 0$, the Lorentz invariant phase space element of a free particle, $d^3p/2E = dp_T^2 \, d\phi \, dy/4$, implies a uniform particle density in rapidity y. In MINT, for normal inelastic interactions the longitudinal direction in the center-of-mass system is along the axis defined by the momenta of the colliding particles. For diffractive scattering it is chosen along the direction of the outgoing systems.

To reconcile longitudinal phase space and finite transverse momenta of the final state particles, MINT employs a two step procedure. The basic idea is to start by generating primary clusters with zero transverse momentum, which then perform two-body decays into the actual final state particles. The mass spectrum of the primary clusters

$$\frac{dn}{dm} = a^2 m e^{-am} \qquad \text{easily generated by} \qquad m = -\frac{1}{a} \ln(r_1 r_2) \qquad (1)$$

from two uniform random deviates $r_1, r_2 \in [0, 1]$ and the still to be defined parameter a, thus determines the p_T-spectrum of the final state particles. The case of massless secondaries can be solved analytically to yield $dn/dp_T = 4a^2 p_T K_0(2a p_T)$ where K_0 is the modified Bessel function of order zero. For large p_T it shows an approximately exponential behaviour, in agreement with observations. The mean transverse momentum is given by $\langle p_T \rangle = \pi/4a$ which motivates to use the rescaled quantity $\alpha = 4a/\pi$ as the free parameter of the model. For decays into massive secondaries the spectrum will be slightly different, but will not change qualitatively.

Given the mass m of a cluster, its rapidity is generated uniformly over the kinematically allowed range $\pm \ln(E_{cm}/m)$. The generation of mass and rapidity is iterated until the total invariant mass M of the system exceeds E_{cm}. Then the generation stops and the primary clusters are shifted in rapidity such that the longitudinal momentum balances, using $p_L = m_T \sinh y$ and $m_T = m$ for $p_T = 0$. Finally all masses are scaled such that $M = E_{cm}$, i.e. MINT satisfies exact energy-momentum conservation. Note also that in this scheme the particle multiplicity distribution is an absolute prediction by the model.

Since flavour physics is not the objective of MINT, only decays into pions and photons are considered. Clusters with a mass $m < 2m_\pi$, where m_π is the charged-pion mass, are neutral and decay into two photons. Heavier clusters are assumed to behave like ρ-mesons. They are randomly assigned charges $Q = \{-1, 0, +1\}$ with equal probability but subject to the constraint of global charge conservation. Charged primaries decay according to $X^\pm \to \pi^\pm \pi^0 \to \pi^\pm \gamma \gamma$ and neutral ones via the mode $X^0 \to \pi^+ \pi^-$.

The above discussion defines the generation of final state particles from a single high mass system. It remains to specify how normal inelastic pA interactions shall be modeled. In MINT this is done as the incoherent sum of n subsystems. Here $1 \leq n \leq A$ is the number of participating nucleons from the target nucleus, drawn from a Poisson distribution with mean value given by the number of nucleons intercepted by the beam proton. A uniform distribution of the impact point of the beam proton on the target nucleus is assumed. Every subsystem has the same invariant mass, which is a natural assumption for the case where the beam proton hits the nucleus at rest, its charge is randomly chosen from $Q = \{0, +1\}$, with a probability Z/A for $Q = +1$. To account for the charge of the beam proton, the charge of the first subsystem is increased by one unit. A more detailed discussion of the implementation of the model can be found in a HERA-B note describing the MINT model [1].

3 Model Tuning and Comparison with Real Data

Since MINT is based on the assumption that the transition of a primary high mass system into final state particles is universal, the adjustment of the only free parameter of the model is done to the transverse momentum spectrum observed in target single diffraction processes [2]. Figure (2) shows for three values α how, as a function of the mass M_x of the diffractive system, MINT compares with data for the average p_T in the range $0.25 \text{ GeV}/c < p_T < 2 \text{ GeV}/c$. The value $\alpha = 0.28$ roughly matches the measurements and was used throughout later on. Given the relative simplicity of the model, no attempt was made to perform an actual fit to the data.
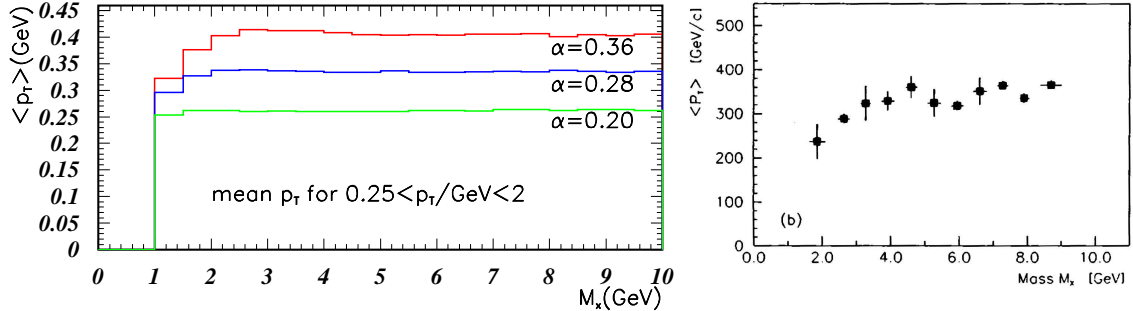

Figure 2: Average transverse momentum of secondaries from target single diffractive scattering as a function of the diffractive mass for MINT (left) and real data [2] (right – here the units of the ordinate should read MeV/c).

As a first test, in Fig.(3) the mean charged particle multiplicities for inelastic proton-proton collisions predicted by MINT as a function of the center-of-mass energy is compared to a real data. Up to the energies reached at the CERN Intersecting Storage Rings (ISR) the agreement is surprisingly good, with a discrepancy below one track per event. Approximate KNO scaling is found for charged and total multiplicities in the energy range from $E_{cm} = 10$ to 60 GeV.
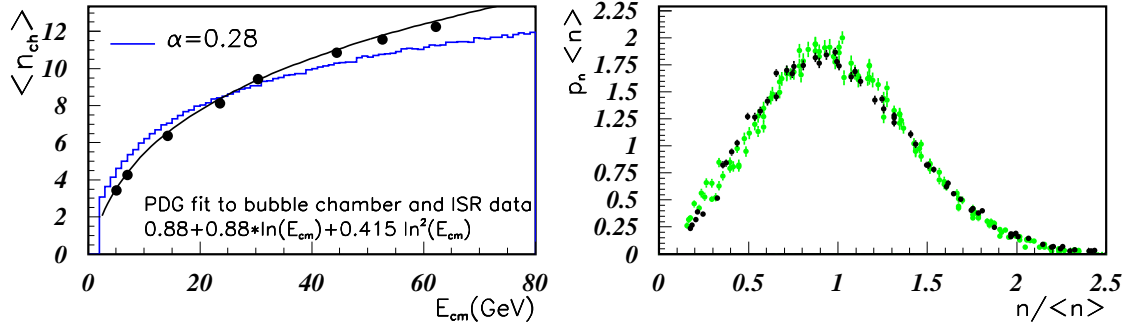

Figure 3: Multiplicities in inelastic pp-collisions. On the left the average charged multiplicities predicted by MINT (histogram) compared to a compilation of measurements (points) and a global parameterization [3] (line) by the PDG as a function of E_{cm}. The right hand side displays for E_{cm} between 10 and 60 GeV the scaled multiplicities for charged (black dots) and all particles (grey dots), showing that approximate KNO scaling holds in MINT.

In addition, a comparison was done with data from pA collisions recorded by the HERA-B [4] fixed-target experiment at the HERA storage ring of DESY/Hamburg. The nucleon-nucleon center-of-mass energy was $\sqrt{s_{NN}} = 41.5$ GeV. The detector is a forward magnetic spectrometer with an angular acceptance of $15 - 220$ mrad in the bending plane. The tracking systems consists of a vertex detector (VDS) before and Outer Tracker chambers behind the magnet; particle identification is performed by a RICH detector, an electromagnetic calorimeter (ECAL) and a muon system. Target materials used in 2002/03 were Carbon, Titanium and Tungsten.

Figure (4) shows how MINT and the FRITIOF [5] model after the full detector simulation compare to real data. The comparison covers sub-detector specific quantities, such as track

segments reconstructed in the VDS, the number of hits seen in the RICH and the number of clusters per event from the ECAL, as well as physics quantities like the number of charged tracks per event passing through the entire tracking system, the transverse momentum distribution and the pseudo-rapidity distribution of those tracks. In general, MINT describes the data as well as FRITIOF. Given the simplicity and minimal amount of tuning that went into the model, it is surprisingly accurate. Interestingly, the number of hits in the RICH and the transverse momentum spectrum with its high-p_T tail is better reproduced by MINT than by FRITIOF. The same qualitative findings apply for the lighter Carbon and the heavier Tungsten target without retuning the model.
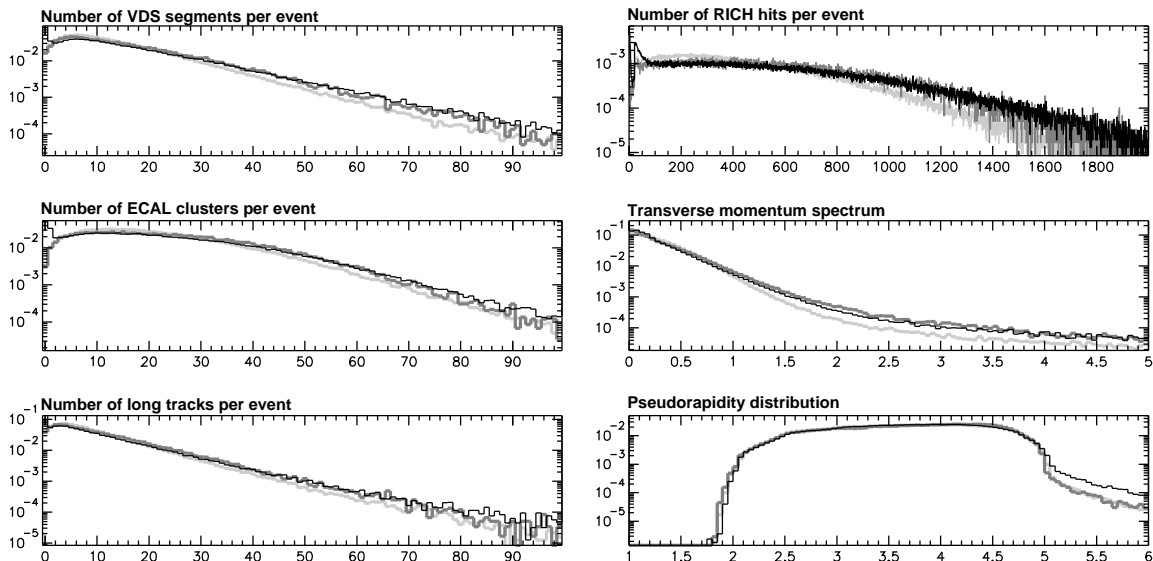

Figure 4: Comparison between HERA-B raw data and Monte-Carlo models after full detector simulation. Thin black lines are real data, the prediction by FRITIOF and MINT are shown in light and dark grey, respectively.

4   Summary

A simple and surprisingly accurate model has been presented for the description of pA-collisions with nucleon-nucleon center-of-mass energies up to $E_{cm} \sim 60$ GeV. The model has only a single adjustable parameter, which makes it very convenient for systematic studies exploring the sensitivity of a physics analysis to details of a Monte Carlo model. MINT, which incorporates also elastic and diffractive scattering in its implementation satisfies exact energy-momentum and charge conservation, but features only charged pions and photons in the final state.

Acknowledgments

References

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