Remnant fragmentation and muon production in Cosmic Ray Air Showers

INT Seattle Feb, 2008

Hans-Joachim Drescher
Frankfurt Institute for Advanced Studies
Johann Wolfgang Goethe-Universität

• Leading particle production in Monte Carlo models
• Influence on muon production
• Map hadronic event generator properties to air shower properties
Muon production in air showers

Muons are produced by decay of pions and kaons

What properties of hadronic event generators influence muon number?

- Multiplicity
  more pions produce more muons
- Vary amount of energy in hadronic or electromagnetic part of the cascade (via production of $\pi^0, \gamma$) via:
  - baryon production
    larger fraction of energy stays in the hadronic channel of the cascade
  - Charge exchange reaction for $\pi^\pm$ induced reactions
    $\pi^\pm + \text{Air} \rightarrow \pi^0 + X$
Muon production in air showers

Epos: large Muons numbers due to enhanced baryon production in forward region

New facts about muon production in Extended Air Shower simulations.
T. Pierog  Klaus Werner, Nov 2006.
e-Print: astro-ph/0611311

From: Pierog Werner, AIP
A new flexible and modular event generator as a tool to study influence of hadronic models on air showers:

**Picco** (pQCS Interaction Code for Cosmics) (hadron-Nucleus)

\[ \chi(s,b) = \gamma \frac{s^{\alpha(0)-1}}{\lambda(s)} \exp \left( \frac{-b^2}{4 \lambda(s,b)} \right) \quad \lambda(s) = R_0^2 + \alpha'(0) \ln s \]

\[ \sigma_{inel}(s) = \int d^2b \left[ 1 - e^{-2\chi(s,b)} \right] \]

Two Pomerons (eikonals): soft and semi-hard, parameters fitted to cross section of pp,πp,Kp data each cut pomeron gives 2 strings:

Hard scattering (hard partons) and string fragmentation via Pythia/Lund model

Remnant energy fraction:

\[
\begin{align*}
\frac{1}{\sqrt{x}} & \quad \text{baryon} \\
\frac{3}{2} x & \quad \text{meson}
\end{align*}
\]
Remnant treatment in air shower models

Usual approach: diquark string end (Pythia)

diquark gives leading baryon:
- treats first interaction different from the others

Other Problem:
- diquark string predicts anti-$\Omega/\Omega > 1$

\[
\begin{align*}
\text{anti-} & \quad \bar{s} & \quad s & \quad ss & \quad s\bar{s} & \quad \bar{d} & \quad d & \quad ud \\
\text{u} & \quad \bar{s} & \quad s & \quad ss & \quad s\bar{s} & \quad \bar{d} & \quad d & \quad ud \\
\end{align*}
\]

Consistent remnant treatment
each elementary interaction (soft or hard)
pulls a quark-antiquark pair from the nucleon
(QGSjet,Nexus,Epos,Picco)

Consistent remnant treatment
each elementary interaction (soft or hard)
pulls a quark-antiquark pair from the nucleon
(QGSjet,Nexus,Epos,Picco)

Epos: picks up any sea quark/antiquark   ---> remnant as quark bags
Picco: picks up valence quark/anti sea quark    ---> remnant always 3 quarks
QGSjet-II: one charge exchange reaction only  ---> remnant always 3 quarks

After dealing with flavor content of remnant: excitation
\[ f(M) \sim M^\alpha \quad \alpha \sim -2 \quad \text{with excitation probability } P_{ex} \quad \text{with } M_{\text{min}} \text{ and } M_{\text{max}} \]
remnant then forms diquark-quark string or proton/neutron/Lambda
Picco represents a conservative extrapolation to high energies
so far no nuclear screening/high density effects
simple construction permits parameter studies of models (incl. all Pythia parameters)
Fix excitation probability in forward pp scattering

Fitting data yields $P_{ex} \sim 0.5$ for Picco

$P_{ex}$ determines dip or flat forward spectrum
Forward pion-proton scattering

Data from NA22/EHS (1992)
Situation less clear:
Are all models wrong or has the data some problems?

Forward charged

Forward pi0
A closer look on $\pi^0$ production

Final data

$\pi^+ + p \rightarrow \pi^0 + X$ at 250 GeV

- Picco $p_{ex} = 0.6$
- Sibyll
- Q
- Q-II
- Epos
- Picco $p_{ex} = 1$

EHS/NA22
Z.Phys.C 54 (1992) 247

preliminary data

- Picco $p_{ex} = 0.6$
- Sibyll
- Q
- Q-II
- Epos
- Picco $p_{ex} = 1$

NA22 preliminary
Charged and $\pi^-$ production

$\pi^+ + p \rightarrow C^+ + X$ at 250 GeV

$\pi^+ + p \rightarrow \pi^- + X$ at 250 GeV

data: NA22
preliminary
Predictions for LHCf

measures $\pi^0$ and neutrons in forward region

enhanced break-up at high energy??
how much charge exchange ??
how much forward $\pi^0$ ??
Work in progress: black disk limit for pA and pp scattering at LHC and GZK energies

Gluon densities are comparable to heavy ion collision

Valence quarks: high $x_F$

Small $x$ probed in target

$$x_T = \frac{Q^2}{x_P s} \approx \frac{2}{0.1 \cdot 14000^2} \approx 10^{-7}$$

See M. Strikman today
Remnant break-up influences muon production in air showers

Baryon remnant break-up increases $\pi^0$ fraction and decreases muons

\[ p \rightarrow b + f \pi^0 + X \]

Pion remnant break-up decreases $\pi^0$ and increases muons

\[ \pi^+ \rightarrow \frac{1}{3} \pi^0 + \frac{2}{3} \pi^\pm \]
\[ \pi^0 \rightarrow \frac{1}{3} \pi^0 + \frac{2}{3} \pi^\pm \]

If $\pi^+$ and $\pi^0$ before break-up is similar then the $\pi^0$ fraction is reduced from $\frac{1}{2}$ to $\frac{1}{3}$

\[ \rightarrow \text{ratio} \frac{2}{3} \]

Baryon break-up decreases muons

Meson break-up increases muons
Influence on muon production

proton induced vertical shower at 1400m altitude (Auger)

Total muon numbers on the ground are plotted normalized to QGSjet-II.
Check influence of baryon production as well

Test adjusted diquark parameters which enhance baryon production similar to Epos:

- Default: \( p_{\text{diq}} = 0.1 \)
- Enhanced: \( p_{\text{diq, str}} = 0.12 \), \( p_{\text{diq, rem}} = 0.3 \)
Let's look at other event generator properties and influence on Xmax

Multiplicity
baryon production
strangeness production
elasticity
cross section
......

No data comparison here, see many papers which do that
Most models reproduce the same low energy data ....

one can learn about consistency just by qualitative comparison of models.
Multiplicity of Models

Scaled by $E^{0.25}$
Proton/antiproton to $\pi^+$ ratios as a function of energy

#### Proton air

- $p/\pi^-$ ratios
- $pbar/\pi^-$ ratios

#### Pion air

- $p/\pi^+$ ratios
- $pbar/\pi^+$ ratios

**Graphs:**
- Plots show the ratios as functions of energy $E_{lab}$ in GeV.
- Different models are represented with distinct line colors.

**Legend:**
- Picco 0.1
- Sibyll 2.1
- QGSjet01
- QGSjet-II
- Epos 1.61
Strangeness: $K_+, K^0_S$ to $\pi$ ratio

Proton air

Pion air

$K^+/\pi^+$ ratio

$K^0_S/\pi^+$ ratio
Energy fraction in $\pi^0/\gamma$

$p^0$ energy fraction  $\pi^+$ induced

$\pi$ Air

$\pi$ Air

$p$ Air

$p$ induced

kaon induced

kaon Air
Inelastic cross section and elasticity (mean $x_F$ of fastest particle)
Elasticity for Models
proton-Air
pion-Air
kaon-Air

Elasticity

proton air
pion air
kaon air

$E_{\text{lab}}$ [GeV]
Some other elasticity:
fraction of energy in forward region $0.01 < x_F < 1$

$$L_{0.01} = \int_{0.01}^{1} x_F \frac{dn}{dx_F} \, dx_F$$

$L = \langle x_F \rangle$ of fastest
Xmax of models

- Auger
- Hires
- Picco 0.1
- Sibyll 2.1
- QGSjet01
- QGSjet-II
- Epos 1.61

Y-axis: Xmax
X-axis: E [GeV]

Graph showing the relationship between Xmax and energy (E) for different models.
Uncertainties due to models:

use $\sigma_{\text{inel}}$ of QGSjet01 and Sibyll (as lower and higher bound) for each of the models

- width of band represents uncertainty due to unknown $\sigma_{\text{inel}}$
- spread of models shows uncertainty due to forward scattering
Conclusions

- Forward hadron production quite unclear in models
- Flat $dn/dx_F$ spectrum at low energies for baryons, meson induced data unclear
- LHCf to measure forward neutrons/π0
- Forward scattering influences muon production in air showers and position of maximum: Break up of leading particle increases muons