Hadronic Interaction Models and Accelerator Data

Ralph Engel, Dieter Heck, Sergey Ostapchenko, Tanguy Pierog, and Klaus Werner
Outline

• **Introduction:** Color flow and strings

• **String fragmentation**
  - Baryon-antibaryon production
  - Popcorn effect

• **String configurations of different models**
  - Configurations and data
  - High-density effects

• **Model predictions and comparison with data**
  - Accelerator data
  - Air shower predictions
Color flow and strings (i)

Generic scattering diagram
Color flow and strings (ii)

Generic scattering diagram

QCD color string

proton

di-quark

quark

di-quark

quark

proton

 gluon
QCD string fragmentation

Chain of hadrons:
- large long. momenta near ends
- small trans. momenta
String fragmentation: baryon pairs

leading meson

leading baryon

baryon anti-baryon pair

diquark - anti-diquark pair
String fragmentation: popcorn effect

Diquark splitting: improved description of leading meson and baryon data
SIBYLL minimum string configuration

Special fragmentation function for leading diquarks needed for description of data
QGSJET minimum string configuration

Generation of sea quark anti-quark pair and leading/excited hadron
EPOS minimum string configuration

Generation of sea quark pair for each string

Micro-canonical decay of remnants to hadrons
Two-string models:

- very successful
- long-range correlations
- charge distribution
- delayed threshold for baryon pair production

(Capella et al., Physics Reports 1994)
Examples of comparisons with data

$E_{\text{cm}} = 630$ GeV
Simulations with P238 (Harr et al.) trigger

$E_{\text{cm}} = 900$ GeV
Simulations with UA5 trigger

$p p \rightarrow p X$, NAL Hydrogen Bubble Chamber

$E_{\text{lab}} = 405$ GeV, $x_{1000}$

$E_{\text{lab}} = 303$ GeV, $x_{100}$

$E_{\text{lab}} = 205$ GeV, $x_{10}$

$E_{\text{lab}} = 102$ GeV

SIBYLL 2.1
QGSJet
DPMJET II.55
neXus 2
QGSJET01
SIBYLL 2.1
Harr et al.
UA5
**EPOS: string contributions**

Only model for description of multi-strange baryon production (next slides)
EPOS remnant model and data (i)

Since $q/H_{11002}qq$ strings and $q\bar{q}/H_{11002}q\bar{q}\bar{q}$ strings have the same probability to appear from cut Pomerons, baryons and antibaryons are produced equally. However, from remnant decay, baryon production is favored due to the initial valence quarks.

VI. RESULTS

Here we will concentrate on baryon-antibaryon production, because there we obtain strikingly different results compared to other models. However, we also carefully checked mesons—essentially pion and kaon—rapidity and transverse.

FIG. 17. Rapidity spectra of baryons and antibaryons calculated from NEXUS 3.0 projectile remnant contribution: dashed lines; target remnant contribution: dotted lines; Pomeron contribution: dashed-dotted lines; sum: solid lines. NA49 data (Liu et al., PRD 2003)

NA49 data
EPOS remnant model and data (ii)

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Two-gluon scattering: SIBYLL

Kinematics etc. given by parton densities and perturbative QCD
Two strings stretched between quark pairs from gluon fragmentation
Two-gluon scattering: QGSJET

Sea quark pairs form end of strings, generated from model distribution

\[
\frac{dP}{dx} \sim \frac{1}{\sqrt{x}}
\]
Two-gluon scattering: EPOS

Two strings with high-pt kinks

Independent sea quarks form string ends
SIBYLL: high parton density effects

\[ \pi R_0^2 \approx \frac{\alpha_s(Q_s^2)}{Q_s^2} \cdot x g(x, Q_s^2) \]

No dependence on impact parameter!

\((R.E. \ et \ al., \ ICRC \ 1999)\)
QGSJET: high parton density effects

Re-summation of enhanced pomeron graphs

Without enhanced graphs

With enhanced graphs

(Ostapchenko, PLB 2006, PRD 2006)
EPOS: high parton density effects (i)

No effective coupling

\[ A_{\text{pom}} \sim (x_1 x_2)^\beta \]

With effective coupling

\[ A_{\text{pom}} \sim x_1^{\beta - \varepsilon} x_2^{\beta - \varepsilon} \]

Parametrization

\[ \varepsilon_S = a_S \beta_S Z, \]
\[ \varepsilon_H = a_H \beta_H Z, \]

(Werner et al., PRC 2006)
EPOS: high parton density effects (ii)

![Diagram of parton ladders and screening](image)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Corresponding variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_M$</td>
<td>Minimum squared screening energy</td>
<td>$(25 \text{ GeV})^2$</td>
</tr>
<tr>
<td>$w_M$</td>
<td>Defines minimum for $z'_0$</td>
<td>6.000</td>
</tr>
<tr>
<td>$w_Z$</td>
<td>Global Z coefficient</td>
<td>0.080</td>
</tr>
<tr>
<td>$w_B$</td>
<td>Impact parameter width coefficient</td>
<td>1.160</td>
</tr>
<tr>
<td>$a_S$</td>
<td>Soft screening exponent</td>
<td>2.000</td>
</tr>
<tr>
<td>$a_H$</td>
<td>Hard screening exponent</td>
<td>1.000</td>
</tr>
<tr>
<td>$a_T$</td>
<td>Transverse momentum transport</td>
<td>0.025</td>
</tr>
<tr>
<td>$a_B$</td>
<td>Break parameter</td>
<td>0.070</td>
</tr>
<tr>
<td>$a_D$</td>
<td>Diquark break probability</td>
<td>0.110</td>
</tr>
<tr>
<td>$a_S$</td>
<td>Strange break probability</td>
<td>0.140</td>
</tr>
<tr>
<td>$a_P$</td>
<td>Average break transverse momentum</td>
<td>0.150</td>
</tr>
</tbody>
</table>

\[ Z_T(i, j) = z_0 \exp\left(-\frac{b_{ij}^2}{2b_0^2}\right) + \sum_{j' \neq j} z'_0 \exp\left(-\frac{b_{ij'}^2}{2b_0^2}\right), \]

\[ b_0 = w_B \frac{\sigma_{\text{inel}}}{\pi} \]

\[ z_0 = w_Z \log s/s_M, \]

\[ z'_0 = w_Z \sqrt{(\log s/s_M)^2 + w_M^2}, \]

(Weiner et al., PRC 2006)
Comparison with RHIC data

**Proton-proton**

$E_{cm} = 200$ GeV

**Deuteron-gold**

$E_{cm} = 200$ GeV

(Werner et al., PRC 2006)

**RHIC data:** very good agreement, (some measurements inconsistent)
Model comparison: fixed target p-p data

\[ p + p \rightarrow \pi^+ \quad P_{\text{lab}}=100 \text{ GeV} \]

\[ p_t = 0.3 \text{ GeV/c} \]

\[ E \frac{d^3 \sigma}{dp^3} \text{ (mb/GeV}^2) \]

\[ p + p \rightarrow \pi^- \quad P_{\text{lab}}=100 \text{ GeV} \]

\[ p_t = 0.3 \text{ GeV/c} \]

\[ p + p \rightarrow K^+ \quad P_{\text{lab}}=100 \text{ GeV} \]

\[ p_t = 0.3 \text{ GeV/c} \]

\[ p + p \rightarrow K^- \quad P_{\text{lab}}=100 \text{ GeV} \]

\[ p_t = 0.5 \text{ GeV/c} \]
Model comparison: fixed target $\pi$-p data

\[ \pi^+ + p \rightarrow \pi^+ \text{ P}_\text{lab}=100 \text{ GeV} \]

\[ \pi^+ + p \rightarrow \pi^- \text{ P}_\text{lab}=100 \text{ GeV} \]

\[ \pi^+ + p \rightarrow K^+ \text{ P}_\text{lab}=100 \text{ GeV} \]

\[ \pi^+ + p \rightarrow K^- \text{ P}_\text{lab}=100 \text{ GeV} \]

$p_t = 0.3 \text{ GeV/c}$

$p_t = 0.5 \text{ GeV/c}$
Model comparison: fixed target p-C data

(see also talk by E.-J. Ahn this meeting)

Note: SIBYLL plotting error, has to be scaled down by ~20%
Model comparison: fixed target $\pi$-C data

Note: SIBYLL plotting error, has to be scaled down by $\sim$30%
Model comparison: Tevatron data

$p + ap \rightarrow \text{chrg at } 1.8 \text{ TeV}$

$\frac{dN}{dy(0)}$

$|\eta| < 1$

$p + p \rightarrow \Omega$ at 1.8 TeV

$\frac{dN}{dy(0)}$

$|\eta| < 1$
Mean depth of shower maximum

\[
\langle X_{\text{max}} \rangle = \frac{1}{N} \sum_{i=1}^{N} X_{\text{max},i}
\]

\begin{align*}
\text{Energy} & \quad (\text{eV}) \\
15 & \quad 10 \\
16 & \quad 10 \\
17 & \quad 10 \\
18 & \quad 10 \\
19 & \quad 10 \\
20 & \quad 10
\end{align*}

\[X_{\text{max}} < \text{X}\]

- HiRes-MIA
- HiRes
- Yakutsk 2001
- Fly’s Eye
- Yakutsk 1993

\begin{align*}
\text{Energy} & \quad (\text{eV}) \\
10^{15} & \quad 10^{16} \\
10^{17} & \quad 10^{18} \\
10^{19} & \quad 10^{20}
\end{align*}

\begin{align*}
\langle X_{\text{max}} \rangle & \quad (\text{g/cm}^2) \\
400 & \quad 450 \\
500 & \quad 550 \\
600 & \quad 650 \\
700 & \quad 750 \\
800 & \quad 850 \\
900 & \quad \end{align*}

- p
- Fe

\begin{align*}
\text{QGSJET 01} & \quad \text{QGSJET II-3} \\
\text{SIBYLL 2.1} & \quad \text{EPOS 1.60}
\end{align*}
Mean number of muons at ground

Iron (QGSJET) = proton (EPOS)
(at $10^{18}$ eV)
Electron-muon number correlation

\[ \log_{10}(N_{\text{Fe}}) \]

\[ \log_{10}(N_{\text{p}}) \]

EPOS 1.60
QGSJETII
SIBYLL 2.1
QGSJET01

10^{18} \text{ eV}
10^{17} \text{ eV}
10^{16} \text{ eV}
10^{15} \text{ eV}
Lateral particle distribution

Note: Xmax similar for EPOS and SIBYLL 2.1

EPOS: much flatter lateral distribution for both muons and em. particles
Why is EPOS so much different?

Possible sources of differences:
- baryon antibaryon pair production rate & spectra
- leading meson production (?)

(Pierog & Werner, astro-ph/0611311)

EPOS predicts up to 5 times more baryons in hadronic shower core at high energy

Relevant effects (confirmed with modified version of SIBYLL):
- baryon quantum number conservation
- transverse momentum distribution of baryons
Fixed target data on baryon production (i)

- QGSJET II
- EPOS 1.60
- QGSJET01
- SIBYLL 2.1

Graphs showing the differential cross sections for various reactions:

- $p + C \rightarrow \pi^+ + \pi^-$
- $\pi^+ + C \rightarrow p + \pi^-$
- $p + C \rightarrow ap$
- $\pi^+ + p \rightarrow p + ap$
Fixed target data on baryon production (ii)

Data: possible misidentification of π⁺ and p ???

Need more data (MIPP, NA49)
Tevatron data on baryon production

- Multiplicity: not really conclusive, EPOS better than other models
- Transverse momentum important
Model comparison: high energy

EPOS predicts up to 5 times more baryons in hadronic shower core.
Popcorn effect: leading mesons

Tevatron measurements would be extremely helpful
Estimated signal for Auger tanks

Prediction can be tested with Auger hybrid events

![Graph showing Cherenkov density over core distance with various lines for different models: EPOS1.55 + FLUKA, QGSJET01 + FLUKA, QGSJET-II3 + FLUKA, SIBYLL21 + FLUKA.]

- **Gamma contribution**
- **Positron contribution**
- **Electron contribution**
- **Muon contribution**

Vertical proton $E_0 = 10^{19}$ eV

Prediction can be tested with Auger hybrid events.
Hybrid measurement: HiRes-MIA

Mean depth of shower maximum

\[ \alpha = 93.0 \pm 8.5 \pm (10.5) \]

Muon density at 600 m

\[ \beta = 0.73 \pm 0.03 \pm (0.02) \]

(HiRes-MIA, PRL 2000)
Simulation of HiRes-MIA data

Mean depth of shower maximum

Simulation done for QGSJET and EPOS

(Pierog & Werner, astro-ph/0611311)
Conclusions

• Different model concepts
• Models in reasonable agreement with pion production data
• Some discrepancies for K+ production
• Baryon antibaryon production underestimated

• EPOS gives very good description of data
• More fixed target measurements needed
• Tevatron and LHC measurements would help

• Cosmic ray data will help to discriminate between models
  (KASCADE: $N_e$-$N_\mu$, hadrons; Auger hybrid events; inclusive muon flux measurements)
Hybrid measurement: Pierre Auger Observatory


**First Estimate of the Primary Cosmic Ray Energy Spectrum above 3 EeV from the Pierre Auger Observatory**

The Pierre Auger Collaboration
Presenter: P. Sommers (sommers@physics.utah.edu)

Measurements of air showers are accumulating at an increasing rate while construction proceeds at the Pierre Auger Observatory. Although the southern site is only half complete, the cumulative exposure is already similar to those achieved by the largest forerunner experiments. A measurement of the cosmic ray energy spectrum in the southern sky is reported here. The methods are simple and robust, exploiting the combination of fluorescence detector (FD) and surface detector (SD). The methods do not rely on detailed numerical simulation or any assumption about the chemical composition.

Simulation: particles at ground correspond to 25% higher shower energy than measured shower profile

Caution: within current systematic uncertainty

*P. Sommers et al. astro-ph/0507150*