High-energy particle interaction phenomenology and implications for air shower experiments

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Workshop on UHE cosmic rays, neutrinos and photons
Penn State University, May 16-17 2007

- the challenge
- model phenomenology
- models vs lab data
- models vs shower data
- the future
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- the challenge
- model phenomenology
- models vs lab data
- models vs shower data
- the future

observer's view, not theorist's!

Thanks to Ralph Engel, Sergey Ostapchenko
The challenge

**Air showers**: extreme energy, forward directions
OK: QED, decays; but: *hadronic interactions* ...
The challenge

Air showers: extreme energy, forward directions
OK: QED, decays; but: hadronic interactions ...

Theory

• small momentum transfer
  → pertubative QCD not applicable

Experiment

• mostly at large momentum transfer
  → most particles
  → easier to measure
  → more attractive to measure
  what can be predicted ...

→ Models, based on phenomenology and guided by data
Basic picture: protons scatter by gluon exchange

... which means color flow ...
Basic picture: color flow

Generic scattering diagram

... within color-neutral objects: strings ...

from [1]
Basic picture: string production

Generic scattering diagram

... tension increases: fragmentation..

from [1]
Basic picture: string fragmentation via quark–antiquark pairs

\[ q + (q \text{ anti-}q) \rightarrow \text{meson} + q \]

\[ qq + (q \text{ anti-}q) \rightarrow \text{baryon} + \text{anti-}q \]

Chain of hadrons:
- large long. momenta near ends
- small trans. momenta

from [1]
Basic picture: string fragmentation via Di-(quark–antiquark pairs)

(EPOS model: keep energy in baryons -> less quickly in EM -> more muons)

from [1]
String fragmentation: popcorn effect

(Diquark splitting: improved description of leading meson and baryon data)

(EPOS model: larger fluctuations possible. Could be tested at colliders)
Models and minimum string configurations

**SIBYLL** (Engel et al. 1999)

![Diagram of SIBYLL model]

Special fragmentation function for leading diquarks needed for description of data

**QGSJET** (Ostapchenko et al. 2001)

![Diagram of QGSJET model]

Generation of sea quark anti-quark pair and leading/excited hadron

**EPOS** (Pierog & Werner 2006)

![Diagram of EPOS model]

Generation of sea quark pair for each string

Micro-canonical decay of remnants to hadrons

**model differences**

in realisation of strings and in fragmentation (hadronisation);

*also in* 2-gluon scattering and treatment of high-density effects

*=>* different predictions

from [1]
The fundament: models vs lab data

• tuning of model parameters
  
  - note: sometimes systematics in data ...
  
  e.g. $\sigma_{\text{tot}}(p\text{-ap})@1.8\ \text{TeV}: 72-80\ \text{mb}$
Models vs lab data: examples

CERN SPS

~OK

fixed target

from [1]
Models vs lab data: carbon

EPOS: good description of data, particularly antibaryons
EPOS: excellent in lambda – \( p_t \), possible undershoot in multiplicity

from [1]
The fundament: models vs lab data

- two-string models: usually ~reasonable agreement
  - note: more free parameters to fit the data => less predictive power
Models vs shower data

Primary parameters to be determined from shower data: model dependence?

☑ arrival time, impact point: ~no (but: boring so far)

☑ arrival direction: ~no (possibly our highway to UHE sources)
Models vs shower data

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✔ energy:

  ➔ fluorescence telescopes: minor (rather atmospherics)

  ➔ ground array: sizeable (20-30%, or more? unless hybrid)
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✔ composition: large (for individual event)
  ➔ use characteristics of event sample, e.g. elongation rate or fluctuations
  ➔ exception: primary photons!
Models vs shower data

a model dependence of an observable is

- annoying if you aim at astrophysics
- an opportunity for particle physics

useful: sensitivity studies

- find robust observables
- check which particle physics
KASCADE calorimeter: distances between $>100$ GeV hadrons

$320 \text{ m}^2$

1. $\leq E_0 \leq 3.2$ PeV

- KASCADE
- $p$
- Fe

$N/d_{4 \text{ max}} = f(p_t)$ (KASCADE Collab., PRD 2005)

- Data bracketed by $p$ & Fe
  (problem a large distance?)

- Fe more developed
  $\Rightarrow$ larger distances

$\Rightarrow$ test: $d_{4 \text{ max}} = f(p_t)$
Simulation: increase $p_t$ of secondaries by factor 2

- distributions broader
- events with small $d_4^{\text{max}}$ not reproduced (even for pure p)!
- scenario of doubled $p_t$ in high-energy hadron interactions disfavoured by data

(KASCADE Collab., PRD 2005)
Simulation: reduce $p_t$ of secondaries by factor 2

- distributions narrower
- events with large $d_4^{\text{max}}$ not reproduced (even for pure Fe)!
- scenario of half $p_t$ in high-energy hadron interactions disfavoured by data

standard $p_t$ does not seem grossly wrong!

(KASCADE Collab., PRD 2005)
Models vs shower data: cross-section

indicates 10% difference

(Ulrich, Aspen 2007)
Models vs shower data: $X_{\text{max}}$

- Indicates 30 g cm$^{-2}$ difference

from [1]
EPOS and number of muons

surprise!
EPOS: + ~30%

EPOS: more baryon-antibaryon production; more re-interaction -> more muons. Confirmed by artificial increase of b-ab production in SIBYLL.
KASCADE: mass group spectra from muons & electrons

- reconstruction model dependent ... lighter composition with QGSJET
  - neither QGSJET not SIBYLL could fit data well
- EPOS -> ?? (even lighter?)
HiRes-MIA and EPOS

- QGSJET @ $10^{18}$ eV: $X_{\text{max}} \rightarrow p$, muon $\rightarrow$ Fe ?? (@ $10^{17}$ eV even $>\text{Fe}$)

- EPOS: p shifts towards muon data

(from [1]

(Pierog & Werner, astro-ph/0611311)
Auger Observatory and muons

- determine energy with fluorescence telescopes
- compare signal measured by ground array with predictions

from [1]
The future

**Fixed target** (π-C, p-C):
- HARP (<12 GeV), analysis on-going; no big surprises
- MIPP (~150 GeV), Tevatron
- NA49 -> NA61 (~400 GeV), beam time ~Sept.

**LHC:**
- TOTEM, elastic protons extremely close to beam; cross-section
- LHCf, forward production of neutral particles (n, π^0) (e.g. popcorn effect)
Conclusions

- **Models reflect our ignorance**
  - remain skeptical
  - sensitivity studies can give good analysis hints both for astrophysics and particle physics

- **Future**
  - experiment: more & useful input to come
  - theory: no quantum leap expected
  - phenomenology: further surprises possible
What are models?

V.F. Weisskopf (1908-2002):

Models are like Austrian train schedules. Austrian trains are always delayed. Once a Prussian visitor asked an Austrian conductor why they worried so much about printing schedules at all. The conductor answered:
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Models are like Austrian train schedules. Austrian trains are always delayed. Once a Prussian visitor asked an Austrian conductor why they worried so much about printing schedules at all. The conductor answered: How else would we know how late the trains are?
Two-gluon scattering

SIBYLL

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

QGSJET

Sea quark pairs form end of strings, generated from model distribution
\[ \frac{dP}{dx} \sim \frac{1}{\sqrt{x}} \]
Two strings with high-pt kinks

EPOS

Two strings with high-pt kinks

Independent sea quarks form string ends
High parton density effects

**SIBYLL**

SIBYLL: simple geometric criterion

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

**QGSJET**

Re-summation of enhanced pomeron graphs

**EPOS**

No effective coupling

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

With effective coupling

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

Parametrization

\[ \varepsilon_S = a_S \beta S Z, \]

\[ \varepsilon_H = a_H \beta_H Z, \]

(Werner et al., PRC 2006)

from [1]
Plots
KASCADE: all-particle flux

- models ~agree
- ~40% flux systematics of data (~15% in energy)
The future

- anti-baryons at high energy

EPOS predicts up to 5 times more baryons in hadronic shower core
KASCADE: mass group spectra from muons & electrons

“calibration“ is model dependent. Note large shift for EPOS from [1]
Sensitivity study: which cross-section?

- sensitivity to non-diffractive (ND) part of inelastic cross-section
  - see also KASCADE Collab. 2001: trigger vs hadron rates

\[ \text{default} \]
\[ \text{diffraction switched off} \]
\[ \text{all interactions ND} \]
\[ \text{only ND with ND-cross-section} \]
\[ \text{only ND with total cross-section} \]

\[ \leftrightarrow k_{\text{inel}} < 0.1 \]
Help from direct measurements? -> proton spectrum

not conclusive ...

systematics (of shower data) of similar size as statistics uncertainty (of direct data)
\[ X_{\text{max}} \text{ and fluctuations} \]

- width of \( X_{\text{max}} \) distribution is
  - good indicator of composition
  - less model dependent!

from [2]