Theory and Phenomenology of Extensive Air Showers

Ralph Engel

Forschungszentrum Karlsruhe, Germany
Outline

Basics of extensive air showers (EAS)

Electromagnetic EAS
  - Heitler's model, cascade theory
  - Landau-Pomeranchuk-Migdal effect
  - Magnetic bremsstrahlung and pair-production

Hadron-induced EAS
  - Extension of Heitler's model, superposition model
  - Hadronic interaction models
  - Predictions and model dependence

Summary & outlook
Cosmic ray interactions

low- and medium energy:
inclusive flux of secondary particles

high energy:
extensive air shower

Typical energies in atmosphere:
- ch. π's: ~150 GeV
- kaons: ~600 GeV
- neu. π's: ~10^9 GeV
Cosmic ray flux and energy scales

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5}J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- MSU
- Akeno
- HiRes-MIA
- HiRes I
- HiRes II
- AGASA

Energy (eV/particle)
Measurement techniques

Example: Pierre Auger Observatory

E \sim 10^{20} \text{ eV}
Characterization of extensive air showers

Shower particles: mainly $e^\pm, \gamma$

80 – 95% of primary energy converted to ionization energy

Up to $10^{11}$ charged particles

Atmospheric depth:

$$\int_{h}^{\infty} \rho(l) \, dl = X(h)$$
Electromagnetic showers
Heitler's model of em. showers

Primary particle: photon

Assumption: shower maximum reached if $E(X) = E_c$

$$n = \frac{X}{\lambda}$$

$$N(X) = 2^n = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{2^{X/\lambda}}$$

$$N_{max} = \frac{E_0}{E_c} \quad X_{max} \sim \lambda \ln\left(\frac{E_0}{E_c}\right)$$
Quantitative treatment: cascade Eqs.

Energy loss of electron:
\[ \frac{dE}{dX} = -\alpha - \frac{E}{X_0} \]

Critical energy:
\[ E_c = \alpha X_0 \approx 80 \text{ MeV} \]

Cascade equations (Rossi & Greisen Rev.Mod.Phys. 13, 1940)

\[ \frac{d\phi_e(E)}{dX} = -\sigma_e \phi_e(E) + \int_E^{E_0} \sigma_e \phi_e(\tilde{E}) \ P_{e\rightarrow e}(\tilde{E}, E) \ d\tilde{E} \]
\[ + \int_E^{E_0} \sigma_\gamma \phi_\gamma(\tilde{E}) \ P_{\gamma\rightarrow e}(\tilde{E}, E) \ d\tilde{E} - \alpha \frac{\partial \phi_e(E)}{\partial E} \]

\[
X_{\text{max}} \approx X_0 \ln\left(\frac{E_0}{E_c}\right) \quad N_{\text{max}} \approx \frac{0.31}{\sqrt{\ln\left(\frac{E_0}{E_c}\right)} - 0.33} \frac{E_0}{E_c}
\]
Photon shower: long. shower profile

- **Cascade Eqs.:** CONEX (mean shower profile)
  - Photons: pair production, Compton scattering
  - Electrons: bremsstrahlung, Moller scattering
  - Positrons: bremsstrahlung, Bhabha scattering

- **Monte Carlo:** CORSIKA (average over many showers)
  - EGS4 adapted to air with variable density

(Pierog et al., astro-ph/0411260)
Photon shower: energy distribution

Photons:
- Number infinite
- Carry finite fraction of total energy

Electrons & positions:
- Number finite
- Excess: ~20-30% more electrons than positons
Landau-Pomeranchuk-Migdal effect

Pair production (sea level, $E_{LPM} \sim 10^{17}$ eV)

$$E \sim \frac{1}{y(1-y)E}$$

Example: photon $3 \times 10^{20}$ eV
Pre-showering in geomag. field

Interaction probability (strong field)

Unique signature of photons

(E homola et al. astro-ph/0311442)
Highest energy Fly's Eye event

Energy: \(~3.2 \times 10^{20}\) eV

Chance probability: 
\(~13\% (1.5 \sigma)\)

(Risse et al., Astropart Phys 21, 2004)
Hadron-induced showers
Muon production in had. showers

Primary particle: proton

$\pi^0$ decay immediately

Only charged pions initiate new hadronic cascades

Cascade ends with decay at energy $E_{\text{dec}}$

$$E(X) = \frac{E_0}{(n_{\text{tot}})^n} = E_{\text{dec}}$$

$$N_\mu = (n_{\text{ch}})^n$$

$$N_\mu = \left( \frac{E_0}{E_{\text{dec}}} \right)^\alpha, \quad \alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82 ... 0.95$$
Application: superposition model

Proton shower characteristics:

\[ N_{\text{max}} = E_0 / E_c \]
\[ \lambda_e \ln (E_0) \]

Assumption:

nucleus of mass \( A \) and energy \( E_0 \) acts like \( A \) independent nucleons with energy \( E_n = E_0 / A \)
Toy model parameters

Hadronic interaction model
- interaction cross section
- multiplicity of secondary particles
- ratio of neutral to charged pion multiplicity

Atmosphere as target and calorimeter
- critical energy
- typical pion decay energy

Number of shower particles proportional to energy
Comparison of energies

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

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- **PROTON**
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fixed target (p-A)

HERA ($\gamma$-p)

RHIC (p-p)

Tevatron (p-p)

LHC (p-p)

LHC (C-C)
Hadronic interaction models

Requirements:

- simulation of $\pi$, K, p, n, ...., Fe collisions with air nuclei (C,N,O, Ar)
- coverage of full energy range from production threshold to $\sqrt{s} \sim 400,000$ GeV
- minimum bias event simulation
  - central and peripheral collisions
  - diffractive and non-diffractive interactions
- optimal description of high-energy secondary particles

- tuned to existing fixed-target and collider data
- variable projectile/target combinations
- variable collision energy
- fast simulation
Cosmic ray hadronic interaction models

**High energy models:**

- DPMJET II.5 and III (Ranft / Roesler, RE & Ranft)
- neXus 2.0 and 3.0 (Drescher, Hladik, Ostapchenko, Pierog & Werner)
- QGSJET 98 and 01 (Kalmykov & Ostapchenko)
- SIBYLL 1.7 and 2.1 (Engel / RE, Fletcher, Gaisser, Lipari & Stanev)

**Low/intermediate energy models:**

- GHEISHA (Fesefeldt)
- Hillas' splitting algorithm (Hillas)
- FLUKA (Fasso, Ferrari, Ranft & Sala)
- UrQMD (Bass, Bleicher et al.)
- TARGET (RE, Gaisser, Protheroe & Stanev)
- HADRIN/NUCRIN (Hänßgen & Ranft)
- SOPHIA (Mücke, RE, Rachen, Protheroe, Stanev)

- Gribov-Regge type models, minijets
- Parametrizations of data
Tuning to accelerator data (i)

Proton-antiproton at CERN SPS

\[ \eta = -\ln \tan(\theta/2) \]
Tuning to accelerator data (ii)

Mean charged particle multiplicity

Mean transverse momentum

Proton-antiproton at CERN SPS & Tevatron
Hadronic interaction model predictions

Wide range of predictions:
- Air showers rather insensitive
- Correlation of cross section and multiplicity: partial compensation

Production cross section p-air

Secondary particle multiplicity (charged)

(Heck, 2003)
Extrapolation of leading particle production

Distribution of momentum fraction of leading baryon

$p\text{-}\text{air} \rightarrow p/n \ X$

Extremely inelastic events

Nearly elastic events
Air shower predictions
Energy/composition: $N_e - N_\mu$ correlation

Model dependence increasing with energy

$$N^A_\mu = A^{1-\alpha} \left( \frac{E_0}{E_{dec}} \right)^\alpha$$

Standard method for surface detector arrays (from lateral distribution)
Energy/composition: shower profile

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET

\[
N^A_{\text{max}} = N_{\text{max}}, \quad X^A_{\text{max}} \sim \lambda_e \ln \left( \frac{E_0}{A} \right)
\]
Mean depth of shower maximum

\[ X_{\text{max}}^A \sim \lambda_e \ln \left( \frac{E_0}{A} \right) \]

Superposition model:

MC simulation (CORSIKA):
predictions depend on had. interaction model used for simulation

Ralph Engel, 13 March 2005
Fluctuations of depth of maximum

(Qierog et al., astro-ph/0411260)

\[ E = 10^{18} \text{eV} \]

- proton QGSJet
- iron QGSJet
- proton Nexus
- iron Nexus

QGSJET vs. NEXUS:

- Mean \( X_{\text{max}} \) very different
- Fluctuations show similar structure

Fluctuations almost model-independent and related to mass

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Energy reconstruction: fluorescence technique

The higher the energy of the primary particle the smaller the fraction of unseen energy

Fraction of “unseen” energy $E_u$

$$E = E_{cal} + E_u$$

Discrimination potential of LHC

- p-p collisions at LHC at $\sqrt{s} = 14$ TeV
- major experiments consider to do CR relevant measurements (for example, CMS / CASTOR / TOTEM)
Constraints from cosmic ray data

Difficulties with cosmic ray beams:

- no direct measurement of interaction
- primary energy, particle unknown

Possible methods of constraining models:

- comparison of measurements to simulated showers assuming a primary energy spectrum and composition
- consistency checks within limits given by expected primary composition
- multiparameter measurements: check of parameter correlations

Model-independent limits on interaction characteristics impossible
Cross section measurement

Correlation between first interaction point and depth of shower maximum

Slope in $X_{\text{max}}$ distribution related to interaction length
- selection of proton showers
- selection by energy

(Belov, HiRes 2004)
HiRes cross section measurement

HiRes result on p-air production cross section

\[ \sigma_{p-Air} = 456 \pm 17 \text{(stat)} + 39 \text{(sys)} - 11 \text{(sys)} \text{ mb} \]

possible influence of heavier primaries and gamma-rays
Summary & outlook

- Electromagnetic showers reasonably well understood

- Uncertainties due to hadronic interaction models limit energy and composition measurements

- Some observables less model dependent
  - high statistics needed
  - multi-observable / hybrid measurements

- Importance of measurements from accelerator experiments (fixed target and collider)

- New hadronic interaction models in preparation (QGSJET II, EPOS, ...)

- Studies of systematic uncertainty of CR measurements due to models needed