Cosmic Rays and Multiparticle Production at LHC

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(Forschungszentrum Karlsruhe)
Outline

- Cosmic-ray physics
  - Flux & elemental composition
  - Measurement techniques and problems
- Simulation of air showers & multiparticle production
- What have we learned from HERA
- What do we hope to learn from LHC
Primary cosmic ray flux (1)

<table>
<thead>
<tr>
<th>Energy (eV/particle)</th>
<th>Equivalent c.m. energy $\sqrt{s}_{pp}$ (GeV)</th>
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Scaled flux $E^{2.5} J(E)$ (m$^2$ sec$^{-1}$ sr$^{-1}$ eV$^{1.5}$)

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

- 6 part./min/km$^2$/sr
- 1 part./day/km$^2$/sr
- 1 part./100yr/km$^2$/sr

Energy (eV/particle)
Primary cosmic ray flux (2)

Energy (eV/particle)

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

Ankle

Knee

Greisen-Zatsepin-Kuzmin suppression?
Knee: possible interpretations

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

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

Nothing special (fine tuning?):

- fixed target (p-A)
- HERA ($\gamma$-p)
- RHIC (p-p)
- Tevatron (p-p)
- log(Flux)
- log(E/particle)

- p
- Fe
Knee: possible interpretations

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

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- AGASA

Acceleration/propagation:

- p
- Fe

log(Flux)

factor 26

Nothing special (fine tuning?):

- p
- Fe

log(Flux)

log(E/particle)
Knee: possible interpretations

**Particle physics:**

- Logarithm of energy (eV/particle)
- Logarithm of flux
- Factor 56
- Iron (Fe)
- Proton (p)

**Acceleration/propagation:**

- Logarithm of flux
- Factor 26
- Proton (p)
- Iron (Fe)

**Nothing special (fine tuning?):**

- Tevatron (p-p)
- Logarithm of flux

**Graphs:**

- Energy (eV/particle)
- Energy (m^2 sec^-1 sr^-1 eV^1.5)
- Equivalent c.m. energy \( \sqrt{s_{pp}} \)
Air shower ground arrays

Example:
KASCADE-Grande (Karlsruhe)
Air shower ground arrays

Combined energy-composition analysis

Example:
KASCADE-Grande (Karlsruhe)
KASCADE

Karlsruhe, Germany

Area ~ 0.04 km², 252 surface detectors
Composition in Knee region (1)

Equivalent c.m. energy $\sqrt{s}_{\text{PF}}$

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

Fixed target (p-A)

HERA ($\gamma$-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)

ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
MSU
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2005

SIBYLL 2.1

KASCADE Collab.
Astropart. Phys. 24 (2005) 1

energy $E$ [GeV]

energy $E$ [GeV]
Composition in Knee region (1)

\[ \frac{dN}{dE} \cdot E^{2.5} \left[ \text{m}^{-2} \cdot \text{s}^{-1} \cdot \text{sr}^{-1} \cdot \text{GeV}^{-1.5} \right] \]

\[ \text{energy} E \ [\text{GeV}] \]

\[ 10^6 \quad 10^7 \quad 10^8 \]

\[ 10^4 \quad 10^5 \quad 10^6 \]

\[ 10^3 \]

\[ \text{QGSJet 01} \]

\[ \text{SIBYLL 2.1} \]

\[ \text{KASCADE Collab.} \]

Astropart. Phys. 24 (2005) 1
Composition in Knee region (2)

KASCADE Collab.
Int. Cosmic Ray Conf. 2005

SIBYLL 2.1

QGSJet II

1.5 GeV$^{-1}$ sr$^{-1}$ sec$^{-2}$ [m$^{2.5}$ Ed$N$/d$E$]

SIBYLL 2.1

KASCADE (QGSJET 01)
MSU
Akeno
HiRes-MIA
HiRes I
HiRes II
AGASA
Auger 2005

SIBYLL 2.1

energy E [GeV]

10^6 10^7 10^8

energy E [GeV]

10^6 10^7 10^8

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Energy (eV/particle)
Primary cosmic ray flux

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

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

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Energy (eV/particle)

10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20

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

10 10^2 10^3 10^4 10^5 10^6

Power law fit

Greisen-Zatsepin-Kuzmin suppression?

Ankle

Knee

fixed target (p-A)

HERA ($\gamma$-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
LHC (C-C)
Primary cosmic ray flux: Ankle

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

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

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Ankle

Extra-galactic cosmic rays

Galactic cosmic rays

fixed target (p-A)

HERA ($\gamma$-p)

RHIC (p-p)

Tevatron (p-p)

LHC (p-p)

LHC (C-C)
Ankle: possible interpretations

Berezinsky et al.:
- Ankle is feature due to extragalactic proton propagation
- Injection spectrum $dN/dE \sim E^{-2.7}$

Hillas:
- Ankle is transition galactic to extragalactic cosmic rays
- Injection spectrum $dN/dE \sim E^{-2.3}$

Elemental composition different
Fluorescence telescopes

Fluorescence light:
- Number of photons ~ ionization energy deposit
- Photons emitted isotropically
- Calorimetric energy measurement
- Shower profile measurement
- Monitoring of atmospheric conditions
- Aperture depends on shower energy
- Good reconstruction of shower geometry needed

Example: Auger two-mirror event
Southern Pierre Auger Observatory

Malargue, Argentina

Area ~3000 km², 1600 surface detectors, 24 telescopes
Composition analysis using shower profiles

- Energy well determined
- Primary particle type: mean and fluctuations of shower depth of maximum

Example: event measured by Auger Collab. (ICRC 2003)
HiRes prototype & MIA measurement

$\alpha = 93.0 \pm 8.5 \pm (10.5)$

Depth of shower maximum: fast transition from heavy to light composition

$\beta = 0.73 \pm 0.03 \pm (0.02)$

Muon density measurement at 600m from shower core: very heavy primary particle expected

Cosmic ray flux: first Auger data

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

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

Auger: still large sys. energy uncertainty (30% - 50%) and low statistics

Within sys. uncertainty of energy calibration

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

High-energy models:

• DPMJET II.5 and III
  (Ranft / Roesler, RE, Ranft)

• neXus 2 and 3
  (Drescher, Hladik, Ostapchenko, Pierog, Werner),

• EPOS (Pierog, Werner)

• QGSJET 01 and II
  (Kalmykov, Ostapchenko)

• SIBYLL 2.1
  (RE, Fletcher, Gaisser, Lipari, Stanev)

Low-/intermediate energy models:

• GHEISHA (GEANT3, Fesefeld)
• FLUKA (Ferrari, Ranft, Roesler, et al.)
• UrQMD (Bleicher, Stöcker, et al.)
Model assumptions

- Gribov-Regge theory (pomeron)
- Minijets (cross section, multiplicity)
- Multiple interactions
- Unitarization of Born amplitudes
- Projectile / target remnants
- Glauber approximation for nuclei
- Many phenomenological model parameters

Examples:
- pQCD pt cutoff (energy-dependence)
- Factorization scale / k-factor
- Energy sharing for hadron remnants
- Soft multiple interactions
- Diffraction dissociation

Dual Parton Model (DPM)
Quark-Gluon Strings Model (QGS)
Conceptual problem: matching soft/hard

\[ \frac{dN}{dp_t^2} \]

\[ \text{trans. region} \]

\[ \text{soft} \]

\[ k_0 \]

\[ \text{hard} \]

\[ \text{pt cutoff} \]

\[ \sigma_{\text{soft}} \sim s^{0.1} \]

\[ \sigma_{\text{hard}} \sim s^{0.3} \]

Example: two cross section fits

\begin{align*}
\log_{10} \left( \frac{E_{\text{lab}}}{\text{eV}} \right) & \quad \text{pp/pp data} \\
\sigma_{\text{tot}} & \\
\sigma_{\text{ela}} & \\
\end{align*}

\begin{align*}
\text{low } p_t \text{ cut} & \\
\text{high } p_t \text{ cut} & \\
\end{align*}
HERA: parton densities & minijet model

Minijet model unreliable:

- Steeply rising parton densities
- PQCD seems to describe even semi-hard phenomena
- Saturation phenomena?
- PQCD cutoff cannot be energy-independent (simple model)
- Inclusive pt distribution
- Cross section extrapolation
- Multiplicity (mean & distribution)

- DPMJET update (new PDFs, energy-dependent pt cutoff, string fusion)
- SIBYLL 1.7 → SIBYLL 2.1 (new PDFs, new diffraction, energy-dependent pt cutoff)
- QGSJET 01 → QGSJET II (new PDFs, resummation of enhanced pomeron graphs)
HERA: leading baryon production (1)

$\frac{1}{N} \cdot \frac{dE}{d\eta^*}$ [GeV]

- $\langle Q^2 \rangle \approx 0$ GeV$^2$
- $\langle Q^2 \rangle \approx 11$ GeV$^2$
- $\langle Q^2 \rangle \approx 38$ GeV$^2$
- $\langle Q^2 \rangle \approx 520$ GeV$^2$

Measurement: $\gamma^*-p$
Simulation: $p-p$
No model tuning

Equivalent lab. energy $\sim 2 \cdot 10^{13}$ eV
HERA: leading baryon production (2)

\[ p p \rightarrow p X, \quad \text{NAL Hydrogen Bubble Chamber} \]

\[ dN/dx_{\text{lab}} \]

\[ x_{\text{lab}} \]

\[ ZEUS, \text{high } Q^2 \]
\[ ZEUS, \text{low } Q^2 \]
\[ \text{SIBYLL 2.1} \]
\[ \text{QGSjet} \]
\[ \text{DPMJET II.5} \]

\[ E_{\text{lab}} = 405 \text{ GeV, x1000} \]
\[ E_{\text{lab}} = 303 \text{ GeV, x100} \]
\[ E_{\text{lab}} = 205 \text{ GeV, x10} \]
\[ E_{\text{lab}} = 102 \text{ GeV} \]

\[ x_F = 2 E_p / \sqrt{s} \]

Detailed comparison with proton and neutron data in preparation (T. Sloan et al.)

After tuning
Limited predictive power of models, no direct correlation between central/forward particle production: forward measurements needed
LHC: minimum bias measurements (2)

Multiplicity distributions (p-p at 14 TeV CMS)

Central detector (-3 < \( \eta \) < 3)

Forward detector (5 < \( \eta \) < 7)

Even simple distributions are very interesting
Models don’t show a simple one-to-one correspondence of central particle production in p-p and p-C collisions
LHC: light ion option (2)

Models don't show a simple one-to-one correspondence of forward particle production in p-p and p-C collisions.
Summary & conclusions

- Cosmic ray physics depends on particle physics measurements
- Precision of elemental composition analyses limited by modeling of hadronic interactions
- Indications of serious shortcomings in simulations (or new particle physics?)
- HERA has answered many questions in a way that make predictions more difficult (impossible?)
- Minimum bias and cross section measurements at LHC will reduce spread of extrapolations significantly
- Central and forward detectors are needed to exploit physics potential
- Data taking during the initial low luminosity runs of LHC will be of outstanding importance