Relation between high energy particle and cosmic ray physics

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Cosmic ray flux and interaction energies

Center-of-mass energy

Laboratory energy

Equivalent c.m. energy $E_{pp}$ (GeV)

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

Energy (eV/particle)

Tevatron (p-p) 7 TeV 14 TeV LHC (p-p)

HERA (r-p) RHIC (p-p)

HiRes-MIA HiRes II

HiRes I

Auger ICRC 2013 TA SD 2013

ATIC PROTON RUNJOB

KASCADE (SIBYLL 2.1) KASCADE-Grande 2012

Tibet ASg (SIBYLL 2.1)

IceTop ICRC 2013

p → air → p
Example: cosmic-ray data at the highest energies
The Pierre Auger Observatory

1665 surface detectors: water-Cherenkov tanks (grid of 1.5 km, 3000 km²)

High elevation telescopes

Infill array of 750 m, Radio antenna array

4 fluorescence detectors (24 telescopes in total)

LIDARs and laser facilities

Southern hemisphere: Province Mendoza, Argentina
Telescope Array (TA)

Northern hemisphere: Utah, USA

507 surface detectors: double-layer scintillators (grid of 1.2 km, 680 km²)

Middle Drum: based on HiRes II

- LIDAR Laser facility
- Infill array and high elevation telescopes
- 3 fluorescence detectors (2 new, one station HiRes II)
- Electron light source (ELS): ~40 MeV

Test setup for radar reflection

Beam Shot into the Sky: Sep. 3rd, 2010

Event Display of ELS Shower

Data: Sep. 5th, 2010

- Energy: 41.1 MeV
- Charge: 50 pC/pulse

Beam Operation: Sep. 2nd-4th

# of Shot into the Sky: 1800 pulses

Output power = 41.4 MeV

40 pC/pulse

0.5 Hz
Precision measurement of shower observables

The energy spectrum from surface detector data (I)

\[
\text{slant depth (g/cm}^2\text{)}
\]

\[
1000 \\
500 \\
40 \\
30 \\
20 \\
10 \\
4 \times 10^2 \\
3 \times 10^2 \\
2 \times 10^2 \\
1 \times 10^2 \\
1 \times 10^1 \\
1 \times 10^0 \\
1 \times 10^{-1} \\
1 \times 10^{-2}
\]

\[
dE/dX [\text{PeV/(g/cm}^2]\text{)}
\]

\[
20 \\
10 \\
5 \\
2 \\
1 \\
4 \times 10^{-1} \\
3 \times 10^{-1} \\
2 \times 10^{-1} \\
1 \times 10^{-1} \\
1 \times 10^{-2} \\
1 \times 10^{-3}
\]

\[
r [\text{m}]
\]

\[
500 \\
1000 \\
1500 \\
2000 \\
2500
\]

\[
\text{Signal (VEM)}
\]

\[
1 \\
10 \\
100 \\
1000 \\
10000
\]

\[
\lg(E/VEM)
\]

\[
18.5 \\
19 \\
19.5 \\
20 \\
20.5
\]

\[
\lg(S)
\]

\[
1 \\
1.5 \\
2 \\
2.5 \\
3 \\
3.5
\]

795 events

\[
E_{\text{max}} = 6 \times 10^{19} \text{eV}
\]

C. DiGiulio (0142), this conf.

Example: event observed with Auger Observatory
Air showers: electromagnetic and hadronic components

Hadronic energy

\[ \frac{2}{3}E_0 \]

\[ \frac{2}{3} \left( \frac{2}{3}E_0 \right) \]

Electromagnetic energy

\[ \frac{1}{3}E_0 \]

\[ \frac{1}{3}E_0 + \frac{1}{3} \left( \frac{2}{3}E_0 \right) \]

After n generations ...

\[ E_{\text{had}} = \left( \frac{2}{3} \right)^n E_0 \]

\[ n = 5, \ E_{\text{had}} \sim 12\% \]

\[ n = 6, \ E_{\text{had}} \sim 8\% \]

\[ E_{\text{em}} = \left[ 1 - \left( \frac{2}{3} \right)^n \right] E_0 \]

Very efficient transfer of hadronic energy to em. component

High-energy interactions most important

(Matthews, APP22, 2005)
All-particle energy spectrum: model independent (almost)

Proton dominated flux
Suppression: delta resonance
Ankle: e⁺e⁻ pair production

(Dip model of Berezinsky et al.)

Iron dominated flux
Suppression: giant dipole resonance
Ankle: transition to galactic sources

Photo-dissociation (giant dipole resonance)
Composition from longitudinal shower profile

Example: event measured by Auger Collab.

(Auger PRD90, 2014)
Composition: model dependent interpretation

Sources in galactic plane

Proton fraction, anisotropy?

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{composition.png}
\end{figure}
Consistency constraint on interaction models

\[ \langle X_{\text{max}} \rangle \approx \langle X_{\text{max}}^p \rangle - D_p \langle \ln A \rangle \]

\[ \sigma(X_{\text{max}})^2 \approx \langle \sigma_i^2 \rangle + D_p^2 \sigma(\ln A)^2 \]

(Auger, JCAP 02 (2013) 026; update: PRD 90 (2014) 122005)

QGSJet II.04 disfavored?
Measurement of proton-air cross section

Number of charged particles

\[ \frac{dP}{dX_1} = \frac{1}{\lambda_{\text{int}}} e^{-X_1/\lambda_{\text{int}}} \]

\[ \sigma_{p-\text{air}} = \frac{\langle m_{\text{air}} \rangle}{\lambda_{\text{int}}} \]

Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)

Depth \( X \) (g/cm\(^2\))

Point of first interaction

\[ \Delta X_1 \]

\[ \Delta X_{\text{max}} \]

(Auger PRL 109, 2012; Telescope Array 1505.01860)
How reliable are the predictions of the interaction models?
Challenge of limited phase space coverage

More than 50% of shower from $\eta > 8$

(Salek et al., 2014)
Charged particle distribution in pseudorapidity

Protons: $E_{lab} = 3 \times 10^{16} \text{ eV}$

Detailed LHC comparison
(D'Enterria et al., APP 35, 2011)

Models for air showers typically better in agreement with LHC data

(data from all LHC experiments, CMS shown as example)
Cross section measurements at LHC

(Cafagna, ICRC 2015)
LHCf: very forward photon production at 7 TeV

**Figure 5.** Comparison of the single photon energy spectra between the experimental data and the MC predictions. Top panels show the spectra and the bottom panels show the ratios of MC results to experimental data. Left (right) panel shows the results for the large (small) rapidity range. Different colors show the results of the other models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

*The collision products and beam halo particles can hit the beam pipe and produce particles that enter the LHCf detectors. However, beam-gas events do not have any significant impact on the beam-beam event spectrum. The energy spectrum of beam-gas events is similar to that of beam events, so beam-gas events do not have any significant impact on the beam-beam event spectrum. In the top panels of Fig. 5, the geometrical construction of events we used the beam-center deflection of charged particles by the D1 beam separation dipole, generated and the secondary particles transported in the beam pipe. The collision products and beam halo particles can hit the beam pipe and produce particles that enter the LHCf detectors. However, beam-gas events do not have any significant impact on the beam-beam event spectrum. The energy spectrum of beam-gas events is similar to that of beam events, so beam-gas events do not have any significant impact on the beam-beam event spectrum.*

*The MC simulations using different models, QGSJET II-03 (blue), DPMJET 3.04 (red), SIBYLL 2.1 (green), EPOS 1.99 (magenta), and PYTHIA 8.145 (yellow) are called as ‘crossing bunches.’ The events associated with the crossing bunches are mixture of beam-gas events between the beam and the beam-gas background in the fills 1089–1134, we found a maximum contamination from the beam-gas background in the crossing bunch data by scaling the non-crossing bunch events. We assigned as a part of systematic uncertainty in the final energy spectrum is only 5–20% depending on the energy and the rapidity range. This is discussed in Section 6.2.*

*In the MC simulations, 1 cm shifting the beam-center by 1 mm. The spectra are modified by the effect of the beam-center on the detectors within 1 mm accuracy. In the MC simulations using different models, QGSJET II-03 (blue), DPMJET 3.04 (red), SIBYLL 2.1 (green), EPOS 1.99 (magenta), and PYTHIA 8.145 (yellow) are called as ‘crossing bunches.’ The events associated with the crossing bunches are mixture of beam-gas events between the beam and the beam-gas background in the fills 1089–1134, we found a maximum contamination from the beam-gas background in the crossing bunch data by scaling the non-crossing bunch events. We assigned as a part of systematic uncertainty in the final energy spectrum is only 5–20% depending on the energy and the rapidity range. This is discussed in Section 6.2.*

*The absolute energy scale and beam center uncertainty are quadratically added in each energy bin and shown as gray shaded areas in the MC simulations. The uncertainty on the luminosity determination (LHCf Collab., Phys. Lett. B 703, 2011) is around 6% for η > 10.15 (LHCf Collab., Phys. Lett. B 703, 2011) and do not affect the analysis presented in this Letter.*

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Examples of tuning interaction models to LHC data

(Pierog 2013, 2014)
Predictions for depth of shower maximum

New models favour interpretation as heavier composition than before

(Pierog 2013, 2014)
Combined CMS and TOTEM measurements

Figure 6: Charged-particle pseudorapidity distributions from an inclusive sample (top left), a NSD-enhanced sample (top right), and a SD-enhanced sample (bottom). The error bars represent the statistical + uncorrelated systematics between neighbouring bins and the bands show the combined systematic and statistical uncertainties. The measurements are compared to results from PYTHIA6, tune Z2*, PYTHIA8, tune 4C, HERWIG++, tune UE-EE-3 with CTEQ6L1 PDFs, EPOS, tune LHC, and QGSJETII-04.

Nominal vertex

Shifted vertex
Multitude of new LHC measurements

(CMS, JHEP04, 2013)

(LHCf, ICRC 2015)

Increasing number of articles with direct comparison with cosmic ray models
First LHC data at 13 TeV c.m. energy

Good agreement with data!

(ATLAS, EPS Geneva 2015)
Indications for shortcomings of our current understanding
Muon number in inclined showers

Number of muons in showers with $\theta>60^\circ$

Combination of information on mean depth of shower maximum and muon number at ground

(Auger, PRD91, 2015)

Several measurements: indications for muon discrepancy
Difference in fluorescence and simulated array signal

Auger: rescaling of 24% needed relative to 50/50 mix of p and Fe

TA: rescaling of 27% needed relative to protons (QGSJET II.03)
Muon production at large lateral distance

\[ E_{\pi^\pm, \text{dec}} \sim 30 \text{GeV} \]

Typically 8-10 interactions

Muons in UHE Air Showers

air shower cascade:

\[ \mu^- + \nu \rightarrow \pi^-/K^- + X \]

\[ E_0 = 10^{19} \text{ eV} \]

Energy distribution of last interaction that produced a detected muon

\[ E_{\text{dN/d(ln E)}} \]

(Maris et al. ICRC 2009)
Importance of hadronic interactions

Shower particles produced in 100 interactions of highest energy

Electrons/photons: high-energy interactions

Muons/hadrons: low-energy interactions

Muons: majority produced in ~30 GeV interactions

Global shower properties and the shower maximum are sensitive to the highest energy interactions. Muons in air showers are sensitive to the hadronic cascade over all energies → Large problem in predicting the overall muon number is small problem on the level of individual interactions.

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Change of energy transferred to electromagnetic component

1 Baryon-Antibaryon pair production  
(Pierog, Werner)
- Baryon number conservation
- Low-energy particles: large angle to shower axis
- Transverse momentum of baryons higher
- Enhancement of mainly low-energy muons
  
  (Grieder ICRC 1973; Pierog, Werner PRL 101, 2008)

2 Leading particle effect for pions  
(Drescher 2007, Ostapchenko )
- Leading particle for a \( \pi \) could be \( \rho^0 \) and not \( \pi^0 \)
- Decay of \( \rho^0 \) to 100% into two charged pions

3 New hadronic physics at high energy  
(Farrar, Allen 2012)
- Inhibition of \( \pi^0 \) decay (Lorentz invariance violation etc.)
- Chiral symmetry restauration

30% chance to have \( \pi^0 \) as leading particle

Decay of leading particle
Predictions for muon number at ground

New models favour interpretation as lighter composition than before

(Pierog 2013, 2014)
Tuning of baryon-antibaryon production

Figure 8: Multiplicity distribution of charged particles with different models.

Figure 9: Ratio of anti-proton and proton yield to charged pions.

Pierog 2013
Riehn 2015
How important is forward $\pi^0$ and $\rho^0$ production?

$\pi^+ p \to \pi^0 \to 2\gamma$
$\pi^+ p \to \rho^0 \to \pi^+ \pi^-$

$E_{\text{lab}} = 250\text{GeV}$

$Sibyll\ 2.3$ (release candidate)
$Sibyll\ 2.3$ (mod. $\pi^0$)

$\left(x_F = \frac{p_\parallel}{p_{\text{max}}}, \right.$

(Riehn 2015)
How important is forward $\pi^0$ and $\rho^0$ production?

Note: change in $X_{\text{max}}$ due to enhanced $\rho^0$ production very small (negligible) (Riehn 2015)
Compatible with data at lower energy – IceTop?

Sibyll 2.1 predictions for p and Fe bracket data

Consistency with lower energy showers essential for confirmation
Compatible with data at lower energy – KASCADE-Grande?

SIBYLL 2.1 predictions for Fe+Si/H+He are smaller than the measured data at HE for inclined EAS

(Arteaga, KASCADE-Grande, ICRC 2015)
Dedicated cosmic ray runs (π-C at 158 and 350 GeV)

(NA61, Herve ICRC 2015)
New results from NA61: $\rho^0$ production

$E_{\text{lab}} = 158\text{ GeV}$

$\pi^- C \rightarrow \rho^0 \rightarrow \pi^+ \pi^-$

Invariant mass of two charged tracks

(NA61, Herve, ICRC 2015)

(Riehn 2015)
Atmospheric neutrinos
Atmospheric neutrinos as background to astrophysical signal

IceCube preliminary

IceCube Analysis, $\nu$--induced muons, TU Dortmund (Florian Scheriau, Martin Schmitz, Tim Ruhe, Wolfgang Rhode++), see their presentation @ Neutrino 2014
Atmospheric neutrinos: conventional & prompt components

\[ \frac{dN_p}{dE_p} = A \times E_p^{-\gamma} = \Phi_p(E_p) \]

\[ \frac{dN_\nu}{dE_\nu} \sim \Phi_p(E_\nu) \int_0^1 x^{\gamma-1} \frac{dN_{p\rightarrow\pi^\pm}}{dx} \, dx \]

\[ (x = E_{\pi^\pm}/E_p) \]

\[ dN_p = A \times E_p^{-\gamma} = \Phi_p(E_p) \]

\[ \frac{dN_e}{dE_e} \sim \Phi_p(E_e) \int_0^1 x^{\gamma-1} \frac{dN_{p\rightarrow\pi^\pm}}{dx} \, dx \]

\[ (x = E_{\pi^\pm}/E_p) \]
Energies of importance for lepton fluxes

A measurement of absolute normalization contains information non-perturbative effects intrinsic charm inclusive charm cross-section partonic saturation


(Fedynitch 2015)
Additional complication: dependence on primary flux

Inclusive nucleon flux important for lepton flux


Summary

• Composition interpretation essential for understanding astrophysics
• LHC data of central importance for more reliable composition interpretation
• Very good collaboration between members of CR community and LHC/HEP
• Feedback from air shower observations, CR int. models very successful at LHC
• Cosmic ray data at $10^{19.5}$ eV most likely not protons (except exotic physics)
• Pion interactions as major uncertainty for muon discrepancy identified

  Need measurement of energy dependence of $\rho^0$ production
  Consistent description at lower energy, transition to direct measurements

• Forward charm production (theory and experiment) of increasing interest
• Primary flux composition also directly linked to inclusive lepton fluxes
Outlook: how to obtain data at higher energy?

Measurement of pion exchange at LHC

\[
\frac{d\sigma(\gamma p \to Xn)}{dx_L \, dt} = S^2 \frac{G_{\pi^+pn}^2}{16\pi^2} \frac{(-t)}{(t - m_{\pi}^2)^2} F^2(t) \times (1 - x_L)^{1-2\alpha_\pi(t)} \sigma_{\gamma\pi}^{\text{tot}}(M^2)
\]

Fixed-target experiment at LHC

Deflection of protons of beam halo by crystal

(Ulrich ICRC 2015)
Outlook: further improvement due to p-O collisions at LHC

![Graphs showing p-p and p-O interactions at different energies.](image)

Currently predicted uncertainty in most optimistic case

p-O technically feasible (O used as ion for Pb)
I. Nahodka, USSR; 1980
II. LaPaz, Bolivia & Rio de Janeiro, Brazil; 1982
III. Tokyo, Japan; 1984
IV. Beijing, China; 1986
V. Lodz, Poland; 1988
VI. Tarbes, France; 1990
VII. Ann Arbor, U.S.; 1992
VIII. Tokyo, Japan; 1994
IX. Karlsruhe, Germany; 1996
X. Assergi (Gran Sasso), Italy; 1998
XI. Campinas, Brazil & LaPaz, Bolivia; 2000
XII. Geneva (CERN), Switzerland; 2002
XIII. Pylos (NESTOR), Greece; 2004
XIV. Weihai, China; 2006
XV. Paris, France; 2008
XVI. Batavia (FNAL), USA; 2010
XVII. Berlin (DESY), Germany; 2012
XVIII. Geneva (CERN), Switzerland; 2014
XIX. Moscow (MEPhI/LPI), Russia; 2016
Backup slides
Longitudinal shower profile

\[ N_{\text{max}} = \frac{E_0}{E_c} \]
\[ X_{\text{max}} \sim D_e \ln \left( \frac{E_0}{E_c} \right) \]

Superposition model:
\[ X_{\text{max}}^A \sim D_e \ln \left( \frac{E_0}{A E_c} \right) \]
TA event simulation for surface array

CORSIKA + full detector simulation (proton primaries)

Very good agreement
Auger event simulation for surface array

CORSIKA + full detector simulation (50% p + 50% Fe)

Very good agreement
Composition and model sensitivity?

Most observables not very sensitive to details of shower simulation.
Initial and final state radiation does not really change topology.

\[ f_{\text{nuc}}^{\text{SIB}}(x) \sim (x_q^2 + \mu^2/s)^{-1/4}(1 - x_q)^3 \]
Other predicted color flow configurations

At very high energy (multi-gluon exchange):
Almost 50% of all events are elastic/diffractive scattering
Multiple soft and hard interactions

$$\sigma_{n_s, n_h} = \int d^2 b \frac{[n_{\text{soft}}(b, s)]^{n_s}}{n_s!} \frac{[n_{\text{hard}}(b, s)]^{n_h}}{n_h!} e^{-n_{\text{hard}}(b, s) - n_{\text{soft}}(b, s)}$$
Rise of pseudorapidity plateau

(Riehn et al. 2014)

Feynman scaling

\[ x_F = \frac{p_\parallel}{p_{\text{max}}} \approx \frac{2p_\parallel}{\sqrt{s}} \]

\[ 2E \frac{dN}{d^3p} = \frac{dN}{dy d^2p_\perp} \rightarrow f(x_F, p_\perp) \]

With Feynman scaling: distribution independent of energy

\[ \frac{dN}{dx} \approx \tilde{f}(x) \quad x = E/E_{\text{prim}} \]