Connecting the LHC to ultra-high energy cosmic rays: from 10 to 100 TeV CMS

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Outline

Cosmic rays and air showers

First LHC data and the knee

Cross section measurements using air showers

Muons in air showers at $10^{19}$ eV

Astrophysical constraints at the highest energies
Cosmic rays

Relative abundance of elements (Si=100)

Nuclear charge number $Z$

Flux $(m^2 \text{ sr s GeV}^{-1})$

(1 particle per $m^2$–second)

(Hörandel, 2005)

Knee
(1 particle per $m^2$–year)

Ankle
(1 particle per $km^2$–year)

Simpson

ARIEL 6

Fowler

HEAO 3

Tueller + Israel

UHCRE

SKYLAB

TIGER

Trek MIR

Iron/nickel nuclei

Protons

Iron/nickel nuclei

(Swordy – U. Chicago)
Ultra-high energy: $10^{20}$ eV

Need accelerator of size of Mercury´s orbit to reach $10^{20}$ eV with current technology

Large Hadron Collider (LHC), 27 km circumference, superconducting magnets

Acceleration time for LHC: 815 years

(M. Unger, 2006)
Energy spectrum and collider energies

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

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

<table>
<thead>
<tr>
<th>Energy (eV/particle)</th>
<th>1.5 eV$^{-1}$ sr$^{-1}$ s$^{-2}$</th>
<th>J(E) (m$^2$ s$^{-1}$ sr$^{-1}$ eV$^{1.5}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10$^2$</td>
<td></td>
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<tr>
<td>100</td>
<td>10$^3$</td>
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<tr>
<td>1000</td>
<td>10$^4$</td>
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<tr>
<td>10000</td>
<td>10$^5$</td>
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</tr>
<tr>
<td>100000</td>
<td>10$^6$</td>
<td></td>
</tr>
</tbody>
</table>

Energy spectrum and collider energies

- RHIC (p-p)
- HERA (γ-p)
- Tevatron (p-p)
- LHC (p-p)
- 7 TeV
- 14 TeV

Knee

Ankle

Toes

- HiRes-MIA
- HiRes I
- HiRes II
- Auger 2009

ATIC
- PROTON
- RUNJOB

KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande 2009
- Tibet ASg (SIBYLL 2.1)
Extensive air showers

Proton-induced shower of $10^{19}$ eV

Longitudinal profile:
Cherenkov light
Fluorescence light of $N_2$

Lateral profiles:
particle detectors at ground

(RE, Pierog, Heck, ARNPS 2011)
Energy and composition measurement (Ne-Nμ)

Example: KASCADE-Grande (Karlsruhe)
Energy and composition measurement: shower profiles

Example: event measured by Auger Collab. (ICRC 2003)

- Energy well determined
- Primary particle type: mean and fluctuations of shower depth of maximum
Mean depth of shower maximum (composition?)

![Graph showing the mean depth of shower maximum vs. energy lab (eV)]

- EPOS 1.99
- QGSJET 01
- QGSJET II-3
- SIBYLL 2.1

Key data points:
- EPOS 1.99
- QGSJET 01
- QGSJET II-3
- SIBYLL 2.1

Comparison with experimental data from:
- Yakutsk 2010
- Auger 2010
- HiRes 2004
- TUNKA 2002
- Yakutsk 2001
- HiRes-MIA 2000
- Fly’s Eye 1993
First LHC data and the interpretation of the knee energy range
Exotic models for the knee

New physics: scaling with nucleon-nucleon cms energy

Cosmic ray \( E_0 \) \(
\)

Atmosphere

\( E_X \sim 100 \text{ TeV} \)

Knee due to wrong energy reconstruction of showers?

Threshold scales with \( E/A \)

Petrukhin, NPB 151 (2006) 57
Barcelo at al. JACP 06 (2009) 027
Dixit et al. EPJC 68 (2010) 573
Petrukhin NPB 212 (2011) 235
LHC data probe the region beyond the knee

~20% of energy needs to be transferred to invisible channel
LHC: distribution of charged secondary particles

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

![Graph showing distribution of charged secondary particles](image)

**Detailed LHC comparison**

D’Enterria et al. (astro-ph/1101.5596)

**Significant improvement of models expected**

$$\eta = -\ln \tan \frac{\theta}{2}$$

**LHC: Exotic scenarios for knee very unlikely, model predictions bracket LHC data on secondary particle multiplicity**
Composition in knee region (i)

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

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

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

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

ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande (prel.)
Tibet ASg (SIBYLL 2.1)

proton
helium
carbon
silicon
iron
Composition in knee region (ii)

D\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]

\begin{align*}
\text{energy } E \ [\text{GeV}] & = 10^6, 10^7, 10^8 \\
\text{dN/dE} \cdot E^{2.5} & = 10^1, 10^2, 10^3, 10^4, 10^5
\end{align*}

- **QGSJet 01**
  - proton
  - helium
  - carbon

- **SIBYLL 2.1**
  - proton
  - helium
  - carbon

\text{KASCADE (QGSJet 01)}
\text{KASCADE (SIBYLL 2.1)}
\text{KASCADE-Grande (prel.)}
\text{Tibet ASg (SIBYLL 2.1)}

\text{KASCADE Collab.}
\text{Astropart. Phys. 24 (2005) 1}

\text{Si, Fe}

\text{evatron (p-p)}
\text{LHC (p-p)}

\begin{align*}
\text{energy } E \ [\text{GeV}] & = 10^6, 10^7, 10^8 \\
\text{dN/dE} \cdot E^{2.5} & = 10^1, 10^2, 10^3, 10^4, 10^5
\end{align*}
First LHC data and the extrapolation of interaction models

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

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

Extrapolation to higher energy
Measurement of pp cross section at LHC

\[ \frac{\Delta p}{p} = \xi > 5 \times 10^{-6} \]

\[ \sigma_{\text{ATLAS}} = 60.3 \pm 0.05 \pm 0.5 \pm 2.1 \text{mb} \]

\[ \sigma_{\text{CMS}} = 59.7 \pm 0.1 \pm 1.1 \pm 2.4 \text{mb} \]

Direct comparison with model predictions (no extrapolation), extrapolation strongly model-dependent
Importance of LHC cross section measurement (i)

LHC: ATLAS \[ \sigma_{\text{ine}} = (69.4 \pm 2.4 \pm 6.9) \text{ mb} \]
CMS \[ \sigma_{\text{ine}} = (70.8 \pm 3.9) \text{ mb} \]

(extrapolated cross sections compatible)

Cross section discrepancy resolved in favour of lower measurements

TOTEM: total cross section measurement with much higher precision
Importance of LHC cross section measurement (ii)

Extrapolation with low cross section

SIBYLL 2.1 (high cross section)

SIBYLL: interpretation would change to heavier elements

QGSJET: same trend, but smaller overall effect

Study only for changed cross section, global tuning to LHC data will be needed
Extending the cross section measurements to higher energy

Maximum statistics for fluorescence observations and indications of mixed/light composition
Cross section measurement with air showers

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

\[ \text{RMS}(X_1) = \lambda_{\text{int}} \]

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

Difficulties

- mass composition
- fluctuations in shower development (model needed for correction)
  \[ \text{RMS}(X_1) \sim \text{RMS}(X_{\text{max}} - X_1) \]
- experimental resolution \( \sim 20 \text{ g/cm}^2 \)

R. Ulrich et al. NJP 11 (2009) 065018
Proton-air cross section for particle production

**Equation:**

\[ \text{Cross section (proton-air)} \quad [\text{mb}] \]

**Graph:**

- **Axes:**
  - **X-axis:** Energy [eV]
  - **Y-axis:** Cross section (proton-air) [mb]

- **Data Points:**
  - Nam et al. 1975
  - Siohan et al. 1978
  - Baltrusaitis et al. 1984
  - Mielke et al. 1994
  - Honda et al. 1999
  - Knurenko et al. 1999
  - ICRC07 HiRes
  - Aglietta et al. 2009
  - Aielli et al. 2009
  - Auger Collab. 2011

- **Models:**
  - QGSJet01c
  - QGSJetII.3
  - Sibyll 2.1
  - Epos 1.99

**Measurement:**

- **LHC Expectation**
- **Direct Comparison**
- **Possible**

**References:**


(Compilation: Pierre Auger Collab. 1107.4804)
Cross section measurement: composition

Simulation for proton showers with different cross sections:
very good sensitivity of tail of distribution

Example of distribution of $X_{\text{max}}$ for mixed composition

Only deep showers are used in analysis to enhance proton fraction in data sample.
Cross section measurement: self-consistency

\[ \Lambda_{\eta} = 55.8 \pm 2.3 \text{ g/cm}^2 \]

Depth range of analysis

Cross section accepted if simulated slope fits measured slope of \( X_{\text{max}} \) distribution

\[ \sigma_{p-\text{air}} = \left( 505 \pm 22_{\text{stat}} ^{+26}_{-34} \right)_{\text{sys}} \text{ mb} \]

Simulation of data sample with different cross sections, interpolation to measured low-energy values

E\(_0\) = 10\(^{18.24}\) eV

(Pierre Auger Collab. 1107.4804)
Conversion to proton-proton cross section

Standard Glauber calculation with harmonic oscillator potential for light nuclei, no inelastic states included

Result on p-air cross section to a good approximation model-independent, p-p cross section model-dependent

Muon production in air showers at $\sim 10^{19}$ eV

Do shower simulations reproduce the observed shower characteristics?
Hybrid detection

Lateral distribution

Auger: water-Cherenkov detectors
Telescope Array: Scintillation detectors

Shower longitudinal profile
Auger Observatory: Study of individual hybrid events

Procedure

- Selection of high-quality showers of $\sim 10^{19}$ eV
- Simulation of 400 showers for each event with reconstructed geometry
- Proton or iron primaries
- Surface detector simulation for best longitudinal profiles

Results

- Signal deficit found for both proton and iron like showers
- Showers with same $X_{\text{max}}$ show only 10-15% variation
- Discrepancy larger than 22% energy calibration uncertainty

(Pierre Auger Collab. 1107.4804)
Angular dependence of discrepancy: Muon component?

Muon contribution to detected signal increases with increasing zenith angle (em. component absorbed in atmosphere)

Very inclined showers $\Theta > 60^\circ$:

$$S_{\text{data}} / S_{\text{MC}} = 2.13 \pm 0.04(\text{stat}) \pm 0.11(\text{sys})$$

All results given relative to proton-induced showers simulated with QGSJET II.03
Do we have a muon problem?

Muon discrepancy confirmed by independent muon counting methods

Similar, but smaller discrepancy found by Telescope Array (renormalization of ~27% needed)

- muon signal less important in scintillators
- showers of zenith angle < 45°
- energy scale of TA 20% higher than Auger Observatory

Possible solution: enhanced baryon-antibaryon pair production in nuclear interactions?

(Pierog & Werner, PRL 101 (2008) 17110)
The upper end of the energy spectrum

Very limited statistics, strong flux suppression

Composition from correlations and deflection in galactic magnetic field?

Composition information from flux suppression?
Highest energies and GZK energy loss effect

CMB: Penzias & Wilson (1965)

\[ \langle E_\gamma \rangle \sim 6.3 \times 10^{-4} \text{ eV} \]

400 ph/cm\(^3\)

Greisen, Zatsepin & Kuzmin (1966)

**GZK effect**

\begin{align*}
p \gamma & \rightarrow p \pi^0 \\
p \gamma & \rightarrow n \pi^+ \\
A \gamma & \rightarrow (A - 1) n \\
A \gamma & \rightarrow (A - 2) (pn)
\end{align*}

Universe opaque for p/A with E > 10\(^{20}\) eV
GZK effect as composition selection mechanism

Protons and iron suffer smallest (and almost equal) energy loss
Distribution of Galaxies

E > 3 \times 10^{19} \text{ eV}
Distribution of Galaxies

E > $6 \times 10^{19}$ eV
Anisotropy at the highest energies

Auger Observatory: discovery of anisotropy: 70% correlation (Science 318, 2007)

(Piera Ghia, Auger Collab., parallel session)

(Auger, Astropart. Phys. 2010)

Correlation: \(38\pm0.07-0.06\%\)

Isotropy: 21%

\(E > 5.5 \times 10^{19} \text{ eV}\)

Active Galactic Nucleus (AGN) smeared by 3.1°

Note:
- anisotropy only for source distances up to GZK sphere (as one would expect)
- small deflection angle indicates presence of light elements (protons?)
**Auger Observatory: Composition data**

Change of cosmic ray composition from mixed or light to heavy?

Sys. uncertainty: 13 g/cm² (mean)
6 g/cm² (RMS)

Independent confirmation from other composition indicators

(Piera Ghia, Auger Collab., parallel session)
Anisotropy:

- no correlation found in HiRes data (smaller statistics than Auger, northern hemisphere)
- current TA data still inconclusive (limited statistics and sky coverage)
Summary

First LHC data and the knee:
exotic models disfavoured

Cross section measurements:
LHC data for extrapolation,
air shower data at higher energy

Muons in air showers at $10^{19}$ eV:
still a serious problem

Astrophysical constraints
at the highest energies:
very helpful and expected,
but situation unclear right now
Problem 1: Sources must be extreme objects

Hillas 1984:

\[ E_{\text{max}} \approx 10^{18} \text{eV} \ Z \ \beta \left( \frac{R}{\text{kpc}} \right) \left( \frac{B}{\mu \text{G}} \right) \]

\[ \text{shock velocity} \]

\[ \text{size of acc. region} \]

\[ \text{mag. field strength} \]

\[ E_{\text{max}} \sim \beta_s z B L \]

Black hole of \( \sim 10^9 \) solar masses
Problem 3: Deflection in magnetic fields

**Typical field strengths:**
- proton deflection angle ~few degrees
- iron deflection angle large
- proton astronomy?

Galactic magnetic fields

Extragalactic magnetic fields

\[ \delta \approx 3'' \frac{B}{3 \mu G \text{kpc}} \frac{L}{6 \times 10^{19} \text{eV}} \]
Magnetic fields: Confinement in the Galaxy (i)

Observed spectrum softer than injection spectrum
Magnetic fields: Confinement in the Galaxy (ii)

Diffusion: same behaviour for different elements at same rigidity $p/Z \sim E/Z$
Magnetic fields: Confinement in sources

SN remnant 1006
Distance ~ 2.2 kpc

Distance ~ 2.2 kpc

Acceleration: same behaviour for different elements at same rigidity $p/Z \sim E/Z$
Origin and physics of the knee

Energy (eV/particle)

1.5 eV \cdot 1 \text{ sr}^{-1} \text{ sec}^{-2} \text{ J(E)} (m^2 \text{ sec}^{-1} \text{ sr}^{-1} \text{ eV}^{1.5})

Scaled flux \ E

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

Accelerations/propagation:

Particle physics:

Factor 26

Factor 56

p

Fe

RHIC (p-p)

HERA (p-p)

Tevatron (p-p)

LHC (p-p)

ATIC

PROTON

RUNJOB

KASCADE (QGSJET 01)

KASCADE (SIBYLL 2.1)

KASCADE-Grande (prel.)

Tibet ASg (SIBYLL 2.1)

HiRes-MIA

HiRes I

HiRes II

Auger SD 2008
Heitler model of em. shower

Number of charged particles

Depth X \ (g/cm^2)

Shower maximum:

\[ E = E_c \]

\[ N_{\text{max}} = \frac{E_0}{E_c} \]

\[ X_{\text{max}} \sim \lambda_{\text{em}} \ln \left( \frac{E_0}{E_c} \right) \]
Muon production in hadronic showers

\[ E_0 \]

\[ \frac{E_0}{n_{\text{tot}}} \]

\[ \frac{E_0}{(n_{\text{tot}})^2} \]

\[ \frac{E_0}{(n_{\text{tot}})^n} \]

\[ n_{\text{tot}} = n_{\text{ch}} + n_{\text{neut}} \]

Primary particle proton

\[ \pi^0 \] decay immediately

\[ \pi^\pm \] initiate new cascades

Assumptions:
- cascade stops at \( E_{\text{part}} = E_{\text{dec}} \)
- each hadron produces one muon

\[ N_\mu = \left( \frac{E_0}{E_{\text{dec}}} \right)^\alpha \]

\[ \alpha = \frac{\ln n_{\text{ch}}}{\ln n_{\text{tot}}} \approx 0.82 \ldots 0.95 \]

(Matthews, Astropart.Phys. 22, 2005)
Superposition model

Proton-induced shower

\[ N_{\text{max}} = \frac{E_0}{E_c} \]

\[ X_{\text{max}} \sim \lambda_{\text{eff}} \ln(E_0) \]

\[ N_\mu = \left( \frac{E_0}{E_{\text{dec}}} \right)^\alpha \quad \alpha \approx 0.9 \]

**Assumption:** nucleus of mass \( A \) and energy \( E_0 \) corresponds to \( A \) nucleons (protons) of energy \( E_n = E_0/A \)

\[ N^A_{\text{max}} = A \left( \frac{E_0}{AE_c} \right) = N_{\text{max}} \]

\[ X^A_{\text{max}} \sim \lambda_{\text{eff}} \ln(E_0/A) \]

\[ N^A_\mu = A \left( \frac{E_0}{AE_{\text{dec}}} \right)^\alpha = A^{1-\alpha} N_\mu \]