On the measurement of the proton-air cross section using air shower data

**Ralf Ulrich**

J. Blümer, R. Engel, F. Schüssler, M. Unger

KIT, Forschungszentrum Karlsruhe

Aspen 2007
Introduction

Analysis methods
- Unaccompanied hadrons
- Frequency attenuation
- Distribution of $X_{\text{max}}$
  - RMS
  - tail
  - shape

Sources of systematic uncertainties
- Cosmic ray composition
- Methodical
- Air shower fluctuations
- Hadronic interaction models
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Contributions to total cross section

Total cross section

Elastic cross section

Inelastic cross section

Quasi-elastic cross section

Production cross section

Diffraction dissociation

- No sensitivity
- Some sensitivity
- Strong sensitivity

Target breakup

Beam breakup (only nuclei)

Non-diffractive interactions

Target diffraction dissociation

Beam diffraction dissociation

Double diffraction dissociation
First interaction and fluctuations in air showers

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Air shower profile fluctuations

![Graph showing the distribution of electrons and muons in air showers.](image)

- **Electrons**: $10^{19}$ eV
- **Muons**: $10^{19}$ μm

**Minimum of shower fluctuations**

All simulations performed with CONEX

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Air shower profile development (extended Heitler model)

\[
\frac{n(\text{charged})}{n(\text{neutral})} = \frac{2}{1}
\]

\[
X_{\text{max}} \propto \lambda_{\text{inel}} + \lambda_{\text{e.m.}} \cdot \ln\left(\frac{E_0}{n_{\text{mult}} E_c}\right)
\]

Oppenheimer, Heitler, Matthews (2005)
High energy hadronic interaction models

\[
\frac{dP}{dX_{\text{max}}} \sim P(n_{\text{mult}}) \otimes P(n_{\text{inel}}) \otimes P(r_{\text{e.m.}}) \otimes \ldots
\]
HE models

microscopic parameters

- diffraction
- parton distribution
- fragmentation

→ all macroscopic parameters are correlated

model

macroscopic parameters

- cross section
- multiplicity
- elasticity
- ...
Composition - impact on $X_{\text{max}}$

Uncertain composition above $\sim 10^{15.5}$eV impacts all air shower observables.
Unaccompanied hadrons

experimental results from: Nam et al. (1975), Siohan et al. (1978), Mielke et al. (1994), ...
Unaccompanied hadrons

protons

satellite

ballone

atmospheric boundary

ground level

hadron calorimeter

anti-coincidence array

experimental results from: Nam et al. (1975), Siohan et al. (1978), Mielke et al. (1994), …
Unaccompanied hadrons

experimental results from: Nam et al. (1975), Siohan et al. (1978), Mielke et al. (1994), ...
Unaccompanied hadrons - cross section

\[ \phi(X) = \frac{1}{\lambda} \cdot e^{-X/\lambda} \]

Top of atmosphere

\[ \phi_{\text{top}} = \phi(X_{\text{top}} = 0 \text{gcm}^{-2}) \text{ by satellites, or} \]
\[ \phi_{\text{top}} = \phi(X_{\text{top}} \sim 5 \text{gcm}^{-2}) \text{ ballones} \]

Bottom of atmosphere

\[ \phi_{\text{bottom}} = \phi(X_{\text{ground}}) \text{ measured by calorimeter} \]

Flux attenuation

\[ \lambda_{\text{prod}} = \frac{\Delta X}{\log(\phi_{\text{top}}/\phi_{\text{bottom}})} \text{ with } \Delta X = X_{\text{bottom}} - X_{\text{top}} \]

\[ \sigma_{\text{prod}} = \sigma_{\text{tot}} - \sigma_{\text{el}} - \sigma_{q-\text{el}} - \sigma_{\text{diffr}} \]
→ Attenuation of shower cascades in the atmosphere

constant $N_\mu \Rightarrow$ equal $E_0$

constant $N_e \Rightarrow$ same distance to $X_{\text{max}}$

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AGASA like experiment \(X_{\text{obs}}=920\,\text{gcm}^{-2}, \frac{\Delta (N_e)}{N_e} = 0.05, \frac{\Delta (N_\mu)}{N_\mu} = 0.1\)

(toy detector simulation, \(\Phi \sim E^{-2.7}, 0^\circ < \theta < 60^\circ\), protons only)

\[ \rightarrow \text{observed attenuation is only partly due to cross section} \]

compare for example Alvarez-Muniz et al. (2002)
Energy reconstruction/selection accurate ($E_0 = 10$EeV), $\frac{\Delta(N_e)}{N_e} = 0.05$, $X_{\text{obs}} = 920 g cm^{-2}$
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$X_{\text{max}}$ distribution: tail and fluctuations

\[ \lambda_{\text{int}} = k \cdot \Lambda_{\text{obs}} = \frac{\langle M \rangle}{\sigma_{\text{int}}} \]

all detector effects and fluctuations are contained in $k$

RMS
- Walker & Watson (Havera Park, 1982)
- Linsley (1985)

tail
- Baltrusaitis et al. (Fly's eye, 1984)
- Knurenko et al. (Yakutsk, 1999)
$X_{\text{max}}$-resolution is $30gcm^{-2}$. Energy reconstruction is accurate ($E_0 = 10\text{EeV}$).
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Deconvolution of $X_{\text{max}}$-distribution

\[ X_{\text{max}} = X_1 + \Delta X \]

\[ P_{X_{\text{max}}}(X_{\text{max}}) = \int_0^\infty dX_1 \ P_{X_1}(X_1) \cdot P_{\Delta X}(\Delta X|X_1; \text{HEM}) \]

method proposed by Belov et al. (HiRes)
Independence of $\Delta X$-distribution from $X_1$

QGSJET01, protons $10^{18}\text{eV}$ ($\sim200.000$ profiles):

$X_1$ and $\Delta X$ are independent parameters $P_{\Delta X}(\Delta X|X_1) = P_{\Delta X}(\Delta X)$

(confirmed for NEXUS3, SIBYLL2.1, QGSJETII.3, QGSJET01 for protons at $10^{18}\text{eV}$ and $10^{19}\text{eV}$)
Dependence on HE model

$\Delta X$ is a function of $\sigma$ and other correlated HE model parameters (multiplicity,...)

$P_{\Delta X}$ is a function of $\sigma$ and other correlated HE model parameters (multiplicity,...)

$\rightarrow$ similar dependence on multiplicity expected
Position of maximum shifts up to $\sim 60\text{gcm}^{-2}$

Exponential slope after maximum changes up to a factor of $\sim 1.36$

→ Model-dependence
Sensitivity of deconvolution

\[ \sigma_{\text{true}} \]

\[ \sigma_{\text{rec}} \]

\[ \Delta x_{\text{QGSJET}}, x_{\text{max}}^{\text{QGSJETII}} \]

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

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Sensitivity of deconvolution

\[ \sigma_{\text{rec}} - \sigma_{\text{true}} \]

\[ \frac{\Delta X(QGSJET), \ X_{\text{max}}(QGSJET)}{\Delta X(QGSJETII), \ X_{\text{max}}(QGSJETII)} \]

\[ \Delta X(QGSJET), \ X_{\text{max}}(\text{SIBYLL}) \]

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

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On the measurement of the proton-air cross section using air shower data
measuring $\sigma_{p\text{-}air}$ means measuring EAS fluctuations

assuming CR primary interaction length the only source of EAS fluctuations is not enough. At least needed:

- Additional HE interaction characteristics (multiplicity,...)
- The first few interactions at still extreme energy
- diffraction

Meaningful estimate of uncertainty needs: HE model dependence and CR composition $x$

Future

$\rightarrow$ better understanding of fluctuations
$\rightarrow$ measurement of composition
$\rightarrow$ new experiments (fluorescence/cherenkov, muons, ...)

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<table>
<thead>
<tr>
<th>method</th>
<th>HE-model</th>
<th>composition</th>
<th>fluctuations</th>
</tr>
</thead>
<tbody>
<tr>
<td>unaccompanied hadrons</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗</td>
</tr>
<tr>
<td>frequency attenuation</td>
<td>⊗</td>
<td>⊗</td>
<td>⊗ ⊗</td>
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<tr>
<td>$X_{\text{max}}$ RMS</td>
<td>⊗</td>
<td>⊗ ⊗</td>
<td>⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗</td>
</tr>
<tr>
<td>$X_{\text{max}}$ tail</td>
<td>⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗</td>
<td>⊗ (⊕) ⊗</td>
<td>⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗</td>
</tr>
<tr>
<td>$X_{\text{max}}$ deconvolution</td>
<td>⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗ ⊗</td>
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</tr>
</tbody>
</table>
Cross section (proton-air) [mb]

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

- Mielke et al. 1994
- Nam et al. 1975
- Siohan et al. 1978

Lower limits

Energy [GeV]

- Tevatron (p-p)
- LHC (p-p)
- LHC (C-C)
Final - 'progressive' picture

Cross section (proton-air) [mb]

- Mielke et al. 1994
- Baltrusaitis et al. 1984
- Nam et al. 1975
- Siohan et al. 1978

98% confidence limit

⇒ weak constraints on HE interaction models

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Equal intensity cut

constant intensity $\rightarrow$ same primary energy (isotropic flux)

relates shower size $N_{ch}$ at different zenith angle with primary energy
Equal intensity cut

constant intensity → same primary energy (isotropic flux)

relates shower size $N_{ch}$ at different zenith angle with primary energy

$8 < \log_{10}(N_{ch}) < 8.25$

$8.25 < \log_{10}(N_{ch}) < 8.5$

$8.5 < \log_{10}(N_{ch}) < 8.75$

$8.75 < \log_{10}(N_{ch}) < 9$

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