Introduction to cross section measurements using extensive air showers

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Introduction

Air showers and their observation
- Shower development
- Fluctuations

Analysis methods
- Unaccompanied hadrons
- Frequency attenuation (ground based)
- Distribution of $X_{\text{max}}$
  - RMS
  - Tail
  - Deconvolution

Sources of systematic uncertainties
- Cosmic ray composition
- Methodical
- Air shower fluctuations
- Hadronic interaction models
Air shower development

Main shower ingredients

- Electromagnetic bulk
- Penetrating muons
- Hadronic core
- Invisible (neutrinos)
- Fluorescence/Cherenkov photons
First interaction and fluctuations in air showers

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Auger hybrid event

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Air shower profile development (extended Heitler model)

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

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

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

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

(distributions for proton interactions at 10 EeV)

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Contributions to total cross section

- Total cross section
  - Elastic cross section
    - Quasi-elastic cross section
      - Target breakup
      - Beam breakup (only nuclei)
  - Inelastic cross section
    - Production cross section
      - Non-diffractive interactions
      - Diffraction dissociation
        - Target diffraction dissociation
        - Beam diffraction dissociation
        - Double diffraction dissociation

No sensitivity
Some sensitivity
Strong sensitivity
Uncertain composition above $\sim 10^{15.5}\text{eV}$ impacts all air shower observables
Unaccompanied hadrons

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

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→ Attenuation of shower cascades in the atmosphere

constant $N\mu \Rightarrow$ equal $E_0$

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

experimental results from: Honda et al. (1993), Hara et al. (1999), Aglietta et al. (1999), ...
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experimental results from: Honda et al. (1993), Hara et al. (1999), Aglietta et al. (1999), ...
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)

→ observed attenuation is only partly due to cross section

compare for example Alvarez-Muniz et al. (2002)
$X_{\text{max}}$ 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 (Haverah Park, 1982)
- Linsley (1985)

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

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

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

method proposed by Belov et al. (HiRes)
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
Dependence on HE model parameters

\[ \frac{dN}{d\Delta X} \]

"CONEX, QGSJETII, 10 EeV"

- Similar dependence on multiplicity expected

\[ P_{\Delta X} \text{ is a function of } \sigma \text{ and other correlated HE model parameters (multiplicity, ...) } \]
Impact of helium primaries

(\(E_0 = 10\) EeV with a detector resolution of 30 gcm\(^{-2}\))

→ significant impact
Impact of gamma primaries

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

- qgsjet, protons and gammas
- qgsjetII, protons and gammas
- sibyll, protons and gammas
- epos, protons and gammas

\( E_0 = 10 \text{ EeV with a detector resolution of } 30 \text{ gcm}^{-2} \)

\[ \rightarrow \text{significant impact} \]
measuring $\sigma_{p\rightarrow \text{air}}$ 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

Future

- Better understanding of fluctuations
- Measurement of composition
- Updated analysis approach (Auger)
- New experiments (fluorescence/Cherenkov, muons, ...)

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Air shower profile fluctuations

- Electrons
- Muons
- Protons, $10^{19}$ eV

Minimum of shower fluctuations

All simulations performed with CONEX

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Auger air shower data

Event: 1364365

Los Morados

Los Leones

Ig(E/eV)~19.3
(\theta,\varphi)=(63.7, 148.3) deg

SD array: Ig(E/eV)~19.1
(\theta,\varphi)=(63.3, 148.9) deg

Ig(E/eV)~19.2
(\theta,\varphi)=(63.7, 148.4) deg
Auger triple event

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→ significant difference in multiplicity and diffraction
Changing composition - data
Equal intensity cut

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

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

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

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

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

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

\[ \theta \sec(\theta) \]

- \( 8 < \log_{10}(N_{ch}) < 8.25 \)
- \( 8.25 < \log_{10}(N_{ch}) < 8.5 \)
- \( 8.5 < \log_{10}(N_{ch}) < 8.75 \)
- \( 8.75 < \log_{10}(N_{ch}) < 9 \)

constant intensity → same primary energy (isotropic flux)

relates shower size \( N_{ch} \) at different zenith angle with primary energy
Energy reconstruction/selection accurate ($E_0 = 10\text{EeV}$), $\frac{\Delta(N_e)}{N_e} = 0.05$, $X_{\text{obs}} = 920 \text{gcm}^{-2}$
Energy reconstruction/selection accurate \( (E_0 = 10\text{EeV}) \), \( \frac{\Delta(N_e)}{N_e} = 0.05 \), \( X_{\text{obs}} = 920\text{gcm}^{-2} \)
Helium

- %
- attenuation
- gcm

- qgsjet
- qgsjetII
- sibyll
- epos

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Gamma percent gamma [%]

\[ \Lambda(\text{attenuation}) \text{ [gcm}^{-2} \text{]} \]

percent gamma [%]

- qgsjet
- qgsjetII
- sibyll
- epos
Independence of $\Delta X$-distribution from $X_1$

QGSJET01, protons $10^{18}$eV ($\sim$200,000 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 $10^{18}$eV and $10^{19}$eV)
Sensitivity of deconvolution

\[ E_0 = 10^{19} \text{eV} \]
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Final - 'progressive' picture

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

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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