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

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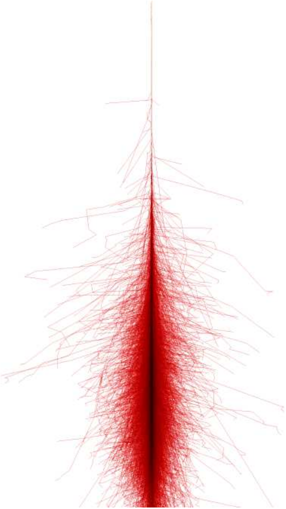
Introduction



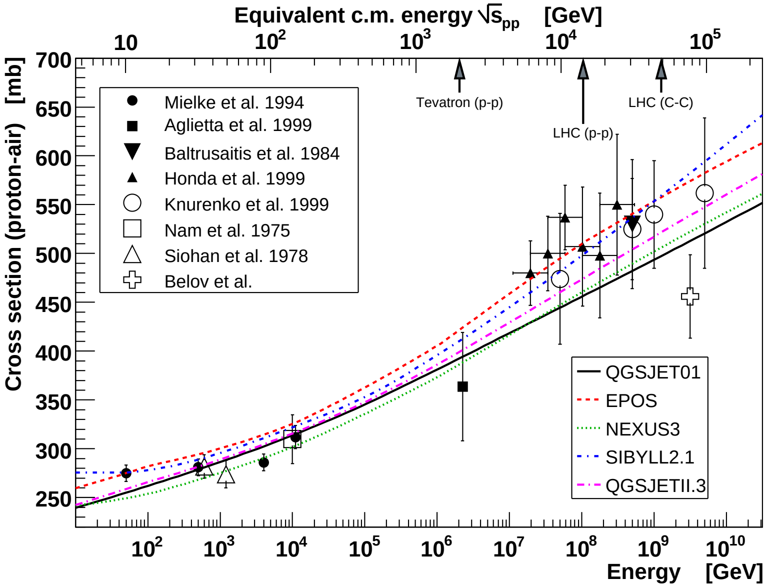
Analysis methods

- Unaccompanied hadrons
- Frequency attenuation
- Distribution of X_{max}
  - RMS
  - tail
  - shape

Sources of systematic uncertainties

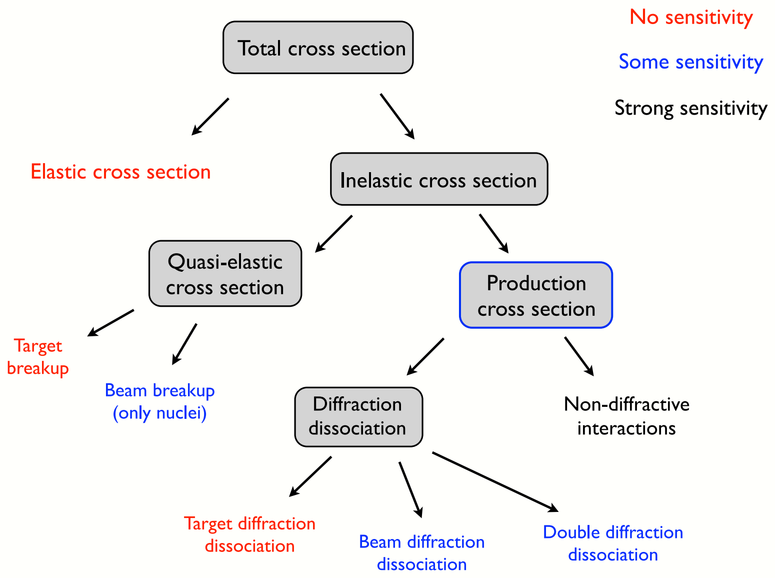
- Cosmic ray composition
- Methodical
- Air shower fluctuations
- Hadronic interaction models

Overview

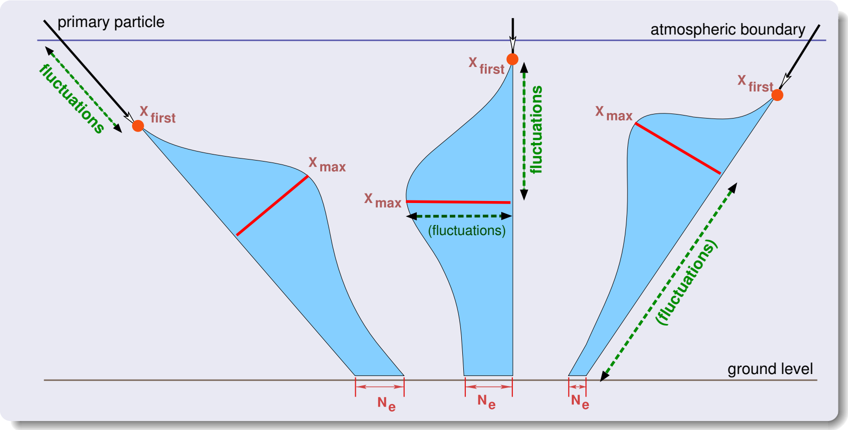


Equivalent c.m. energy √s_pp [GeV]
10
10^2
10^3
10^4
10^5
Tevatron (p-p)
LHC (p-p)
LHC (C-C)
Mielke et al. 1994
Aglietta et al. 1999
Baltrusaitis et al. 1984
Honda et al. 1999
Knurenko et al. 1999
Nam et al. 1975
Siohan et al. 1978
Belov et al.
QGSJET01
EPOS
NEXUS3
SIBYLL2.1
QGSJETII.3
Cross section (proton-air) [mb]
700
650
600
550
500
450
400
350
300
250
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
Energy [GeV]

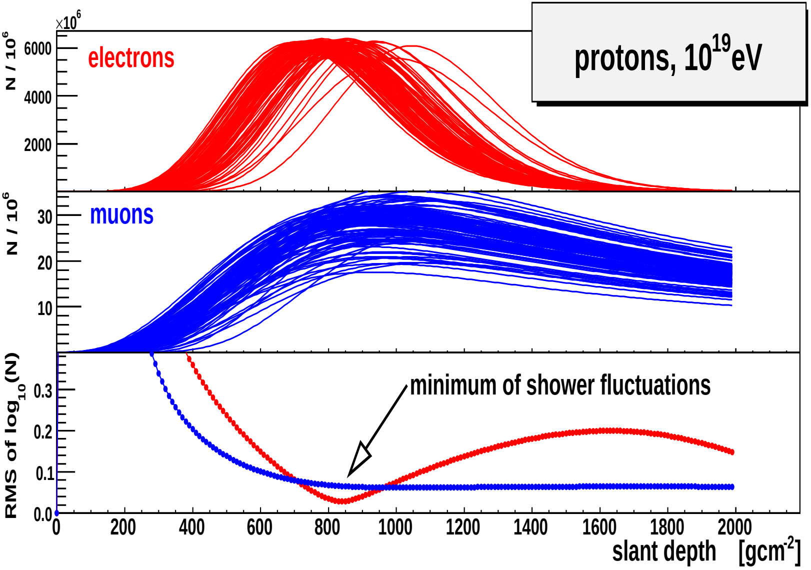
Contributions to total cross section



First interaction and fluctuations in air showers

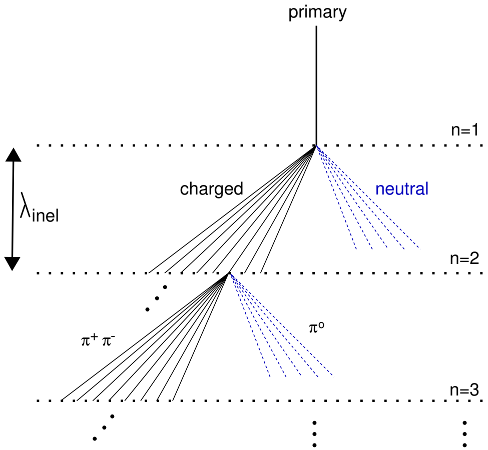


Air shower profile fluctuations



all simulations performed with CONEX

Air shower profile development (extended Heitler model)

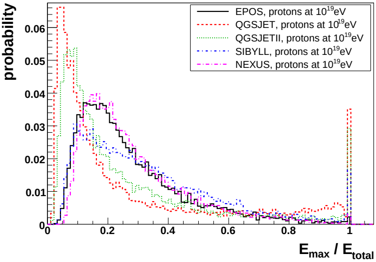


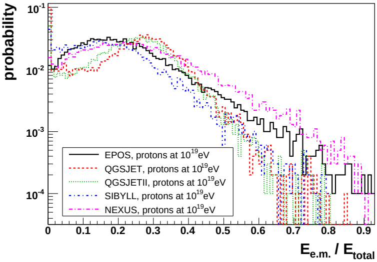
$$\frac{n(\text{charged})}{n(\text{neutral})} = \frac{2}{1}$$

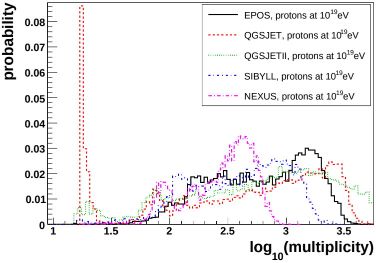
$$X_{\max} \propto \lambda_{\text{inel}} + \lambda_{\text{e.m.}} \cdot \ln\left(\frac{E_0}{n_{\text{mult}} \ E_c}\right)$$

Oppenheimer, Heitler, Matthews (2005)

High energy hadronic interaction models

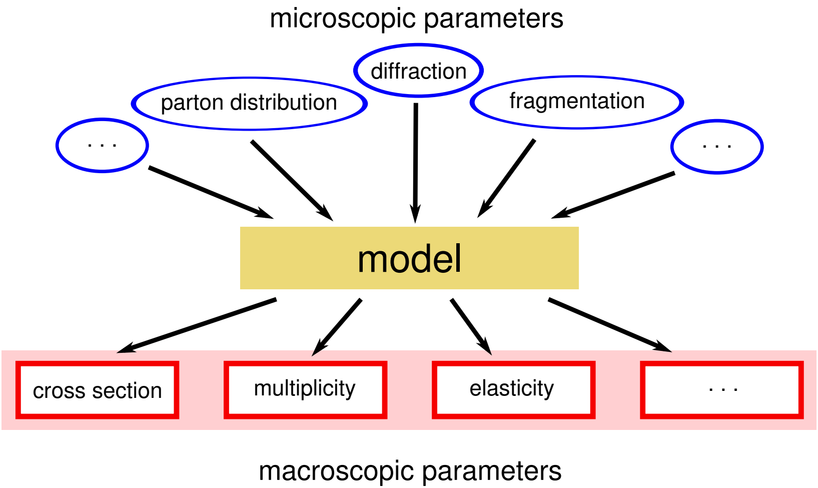






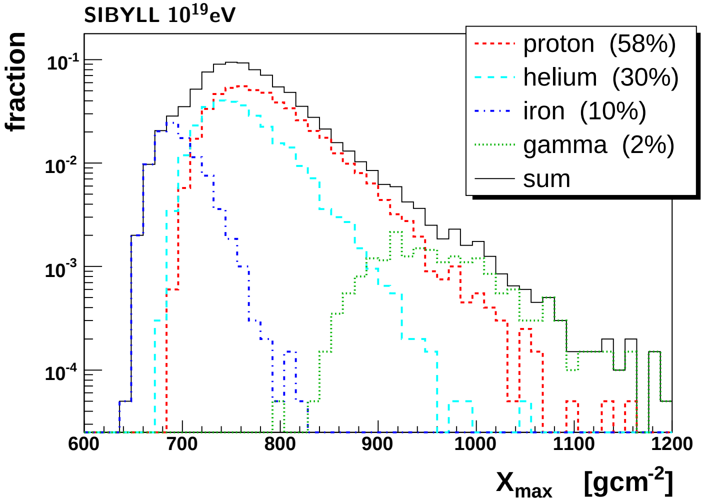
$$\frac{dP}{dX_{\rm max}} \sim P(n_{\rm mult}) \otimes P(n_{\rm inel}) \otimes P(r_{e.m.}) \otimes \ldots$$

HE models



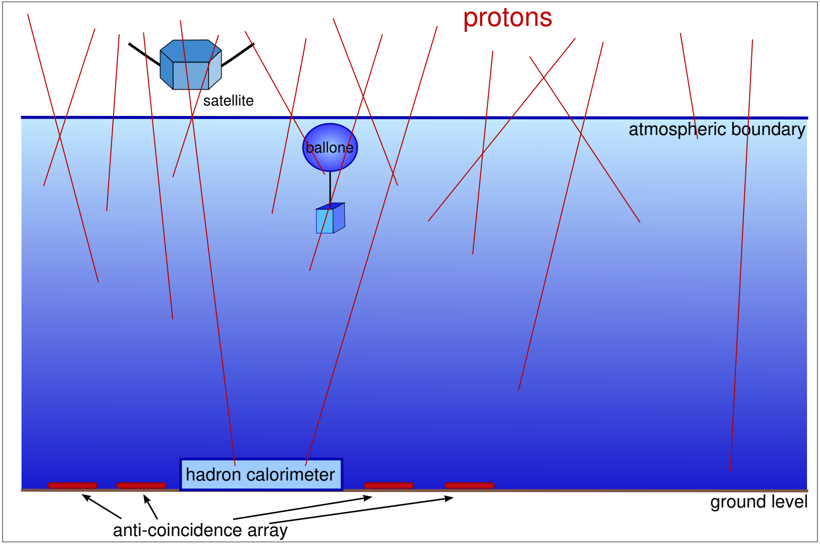
→ all macroscopic parameters are correlated

Composition - impact on X_{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), ...

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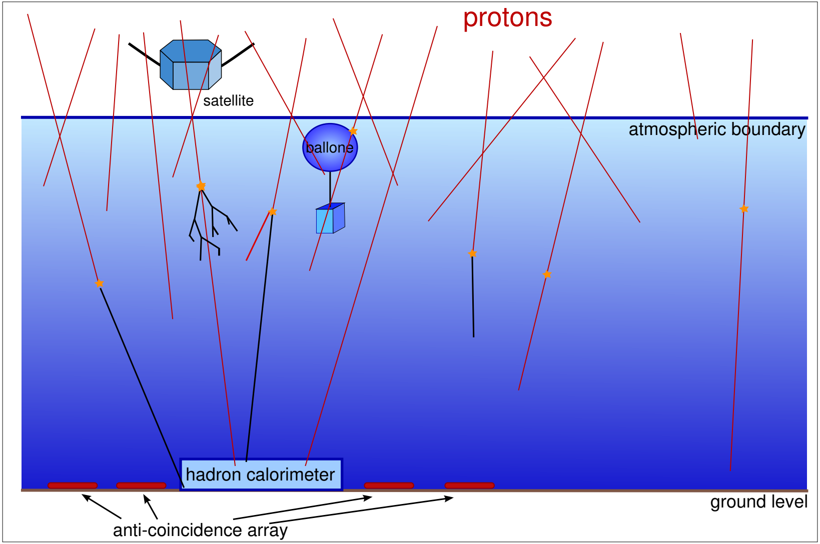

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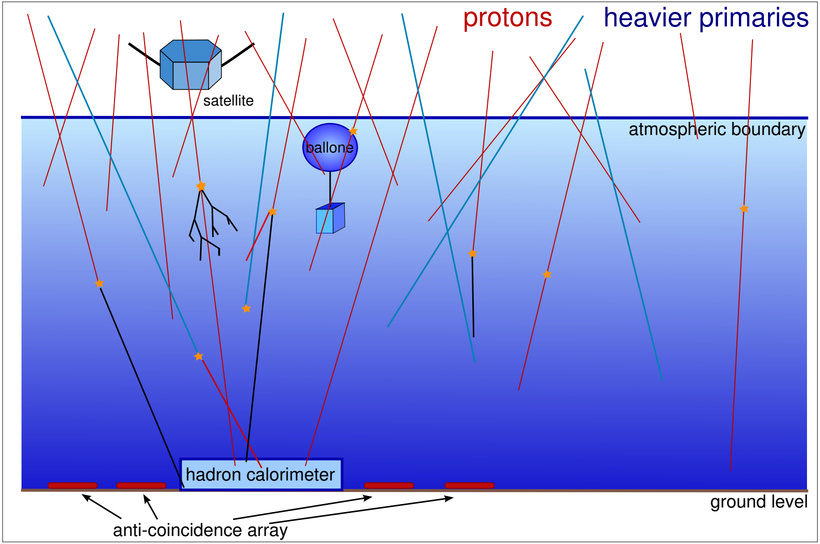

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Unaccompanied hadrons - cross section

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

Top of atmosphere

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

Bottom of atmosphere

$\phi_{\rm bottom} = \phi(X_{\rm ground})$ measured by calorimeter

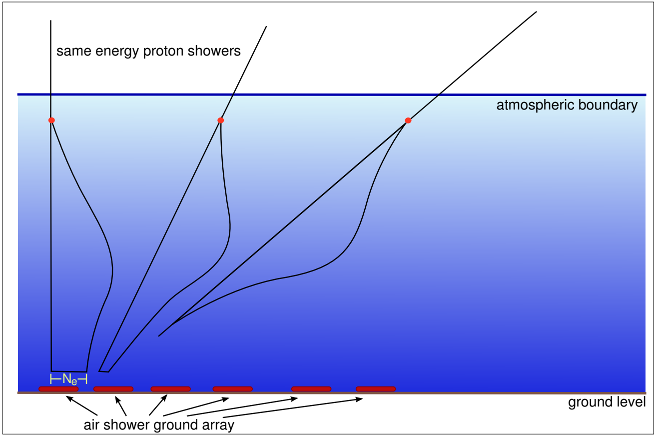
Flux attenuation

$\lambda_{\rm prod} = \Delta X / \log(\phi_{\rm top}/\phi_{\rm bottom})$ with $\Delta X = X_{\rm bottom} - X_{\rm top}$

$$\sigma_{\rm prod} = \sigma_{\rm tot} - \sigma_{\rm el} - \sigma_{\rm q-el} - \sigma_{\rm diffr}$$

Frequency attenuation

→ Attenuation of shower cascades in the atmosphere



constant $N_\mu \Rightarrow$ equal E_0

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

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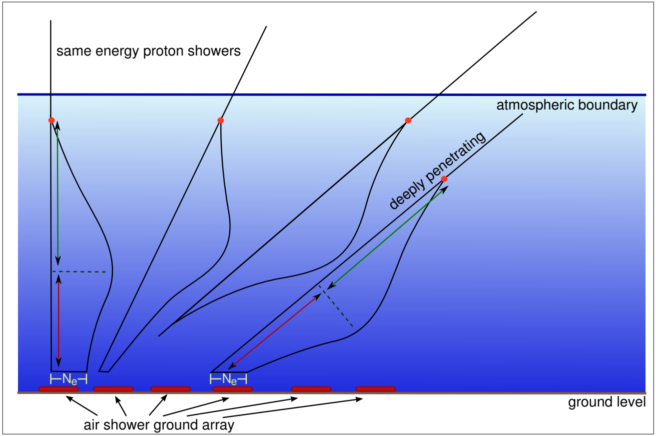

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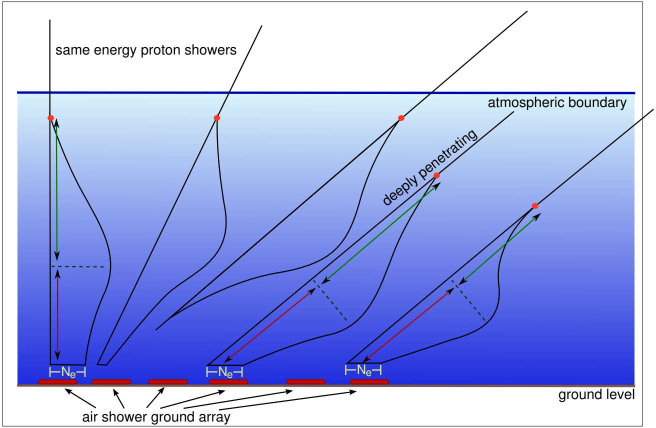

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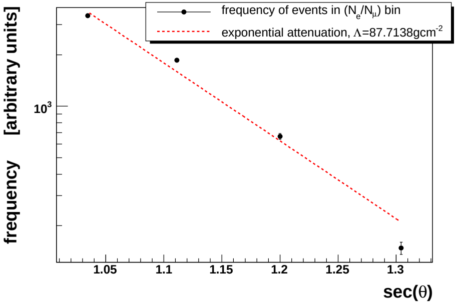
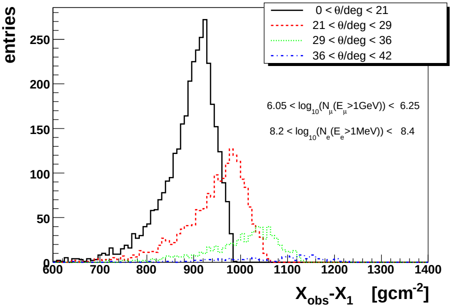
Frequency attenuation - examples

AGASA like experiment ($X_{\rm obs}$=920gcm^{-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)

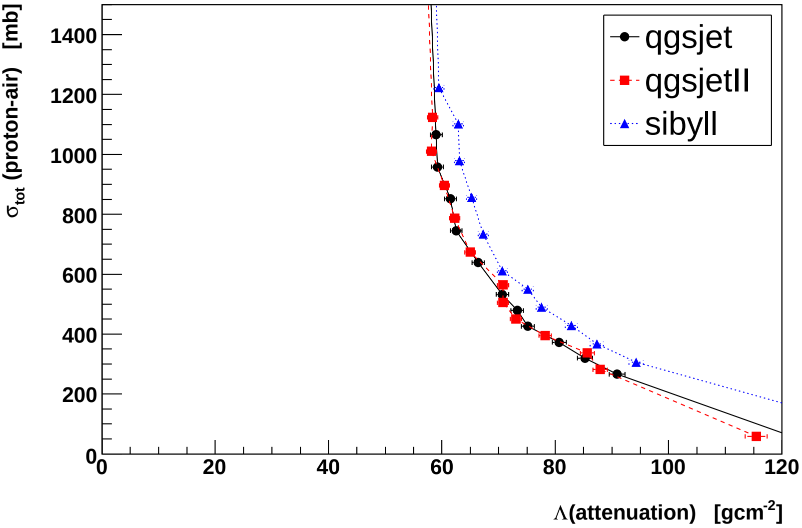




→ observed attenuation is only partly due to cross section

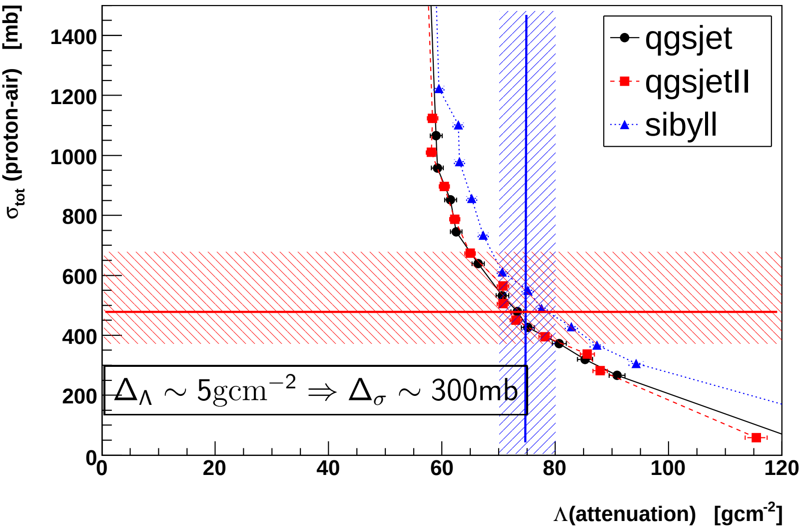
compare for example Alvarez-Muniz et al. (2002)

N_e sensitivity



Energy reconstruction/selection accurate ($E_0 = 10$EeV), $\frac{\Delta(N_e)}{N_e} = 0.05$, $X_{\rm obs}$=920gcm^{-2}

N_e sensitivity



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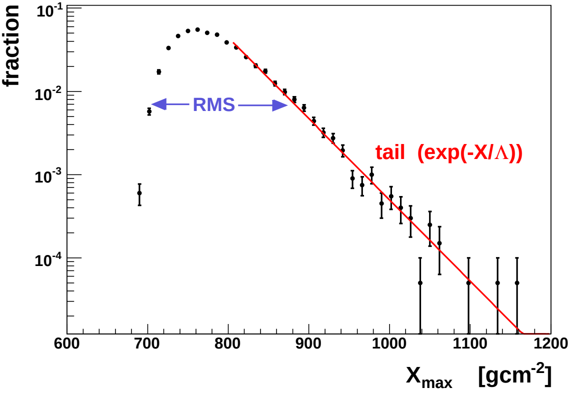
X_{max} distribution: tail and fluctuations



$$\lambda_{int} = k \cdot \Lambda_{obs} = \frac{<M>}{\sigma_{int}}$$

all detector effects and fluctuations are contained in k

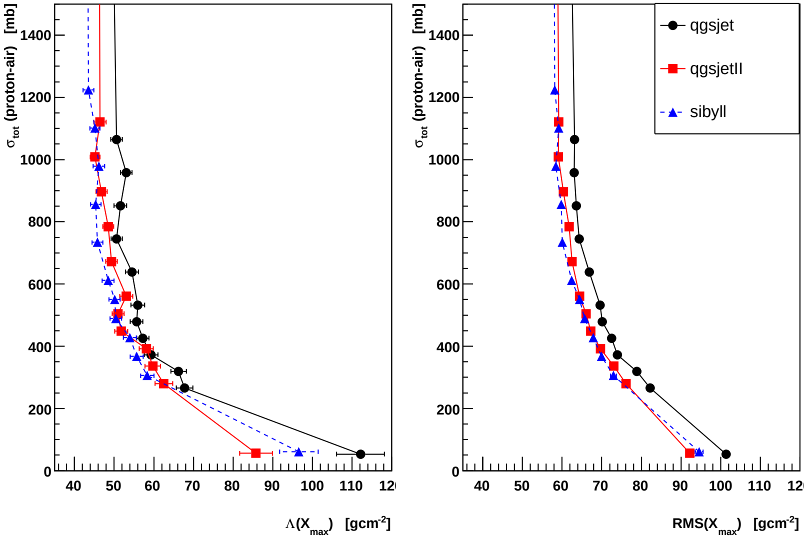
RMS

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

tail

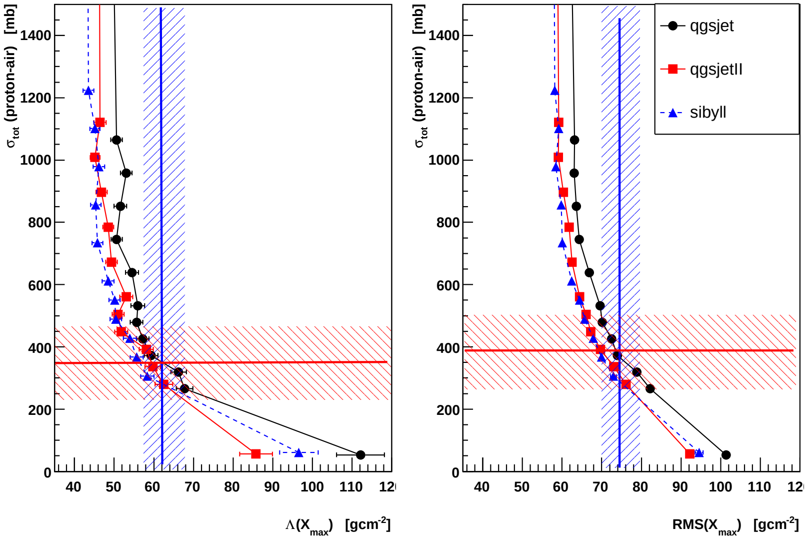
Baltrusaitis et al. (Fly's eye, 1984)
Knurenko et al. (Yakutsk, 1999)

$X_{\max}$ sensitivity



$X_{\max}$-resolution is $30gcm^{-2}$. Energy reconstruction is accurate ($E_0 = 10$EeV).

X_{max} sensitivity



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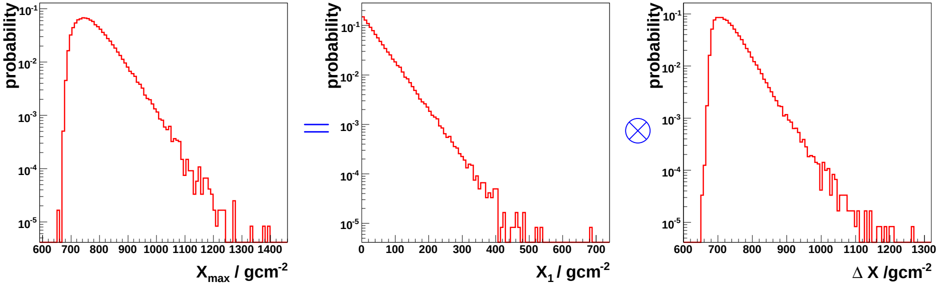
Deconvolution of $X_{\max}$-distribution

$$\boxed{X_{\max} = X_1 + \Delta X}$$

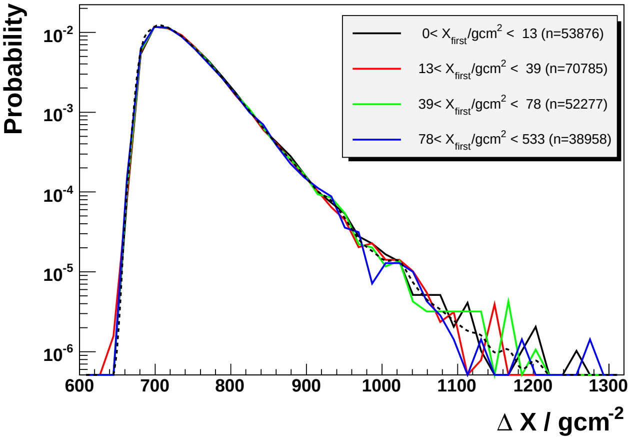


$$P_{X_{\max}}(X_{\max}) = \int_0^{\infty} dX_1 \; P_{X_1}(X_1) \cdot P_{\Delta X}(\Delta X | X_1; HEM)$$

method proposed by Belov et al. (HiRes)

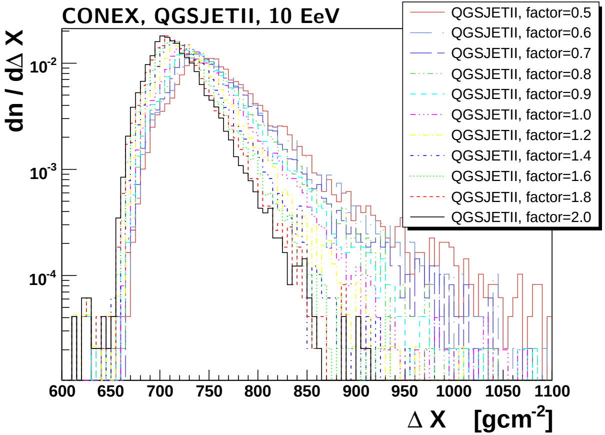
Independence of ΔX-distribution from X_1

QGSJET01, protons 10^{18}eV ($\sim$200.000 profiles):



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

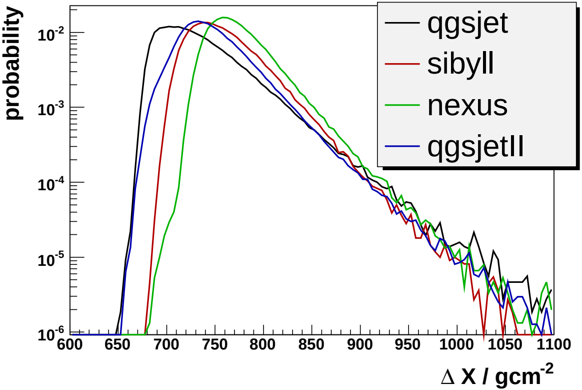
(confirmed for NEXUS3, SIBYLL2.1, QGSJETII.3, QGSJET01 for protons at 10^{18}eV and 10^{19}eV)



→ similar dependence on multiplicity expected

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

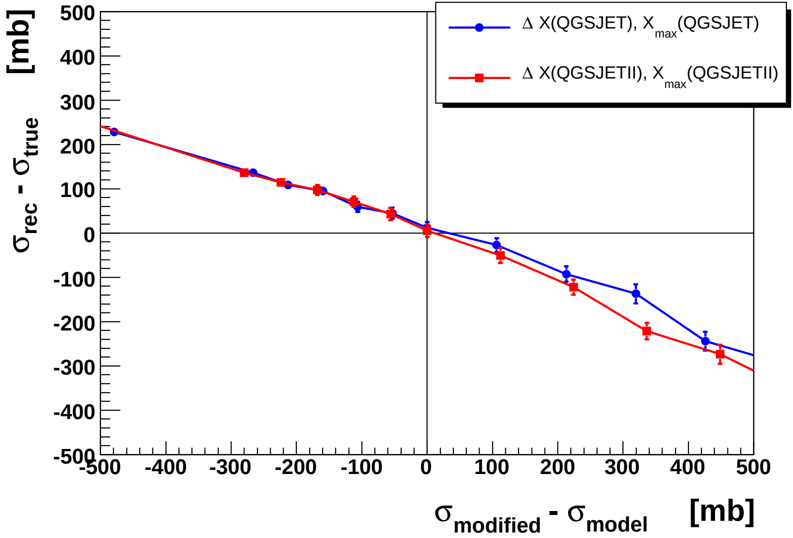
ΔX-distribution for different HE-models



- Position of maximum shifts up to $\sim 60\text{gcm}^{-2}$
- Exponential slope after maximum changes up to a factor of ~ 1.36

→ Model-dependence

Sensitivity of deconvolution



$E_0 = 10^{19} eV$

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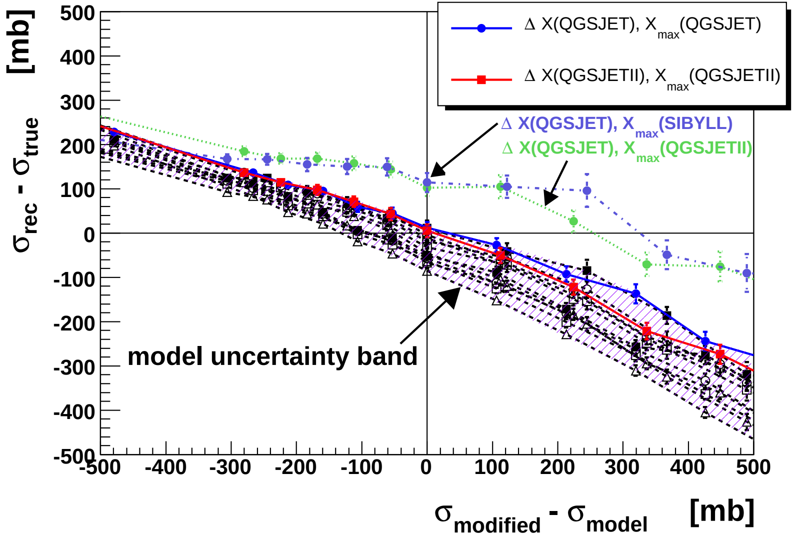

$E_0 = 10^{19} eV$

measuring σ_{p-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

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

Summary

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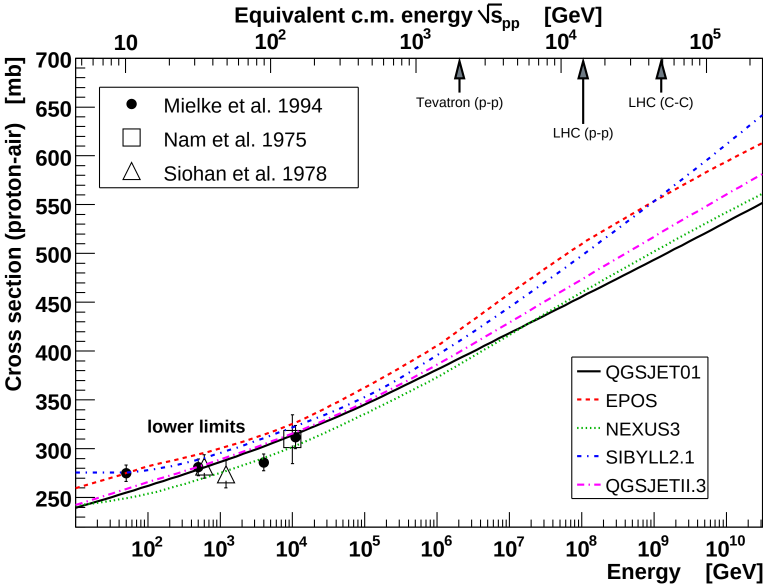
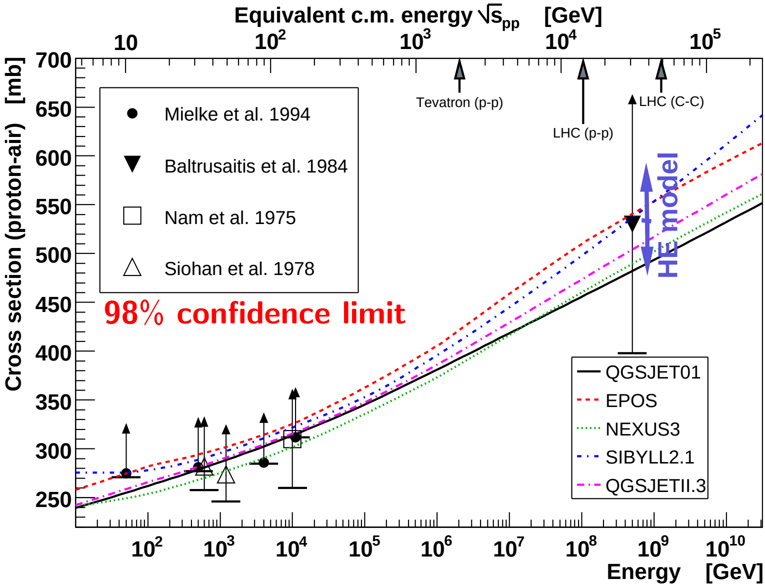
Final rating

method	HE-model	composition	fluctuations
unaccompanied hadrons	$\odot$	$\odot$	$\oplus$
frequency attenuation	$\ominus$	$\ominus$	$\ominus\ominus$
X_{max} RMS	$\ominus$	$\ominus\ominus$	$\ominus$
X_{max} tail	$\ominus$	$\odot$ ($\oplus$)	$\ominus$
X_{max} deconvolution	$\ominus\ominus$	$\ominus$	$\odot$

Final - 'conservative' picture

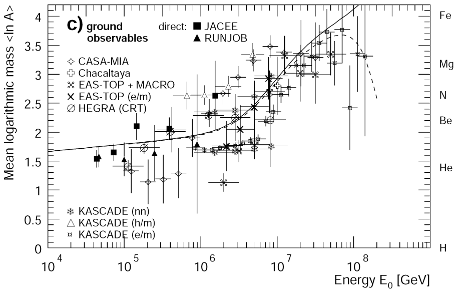


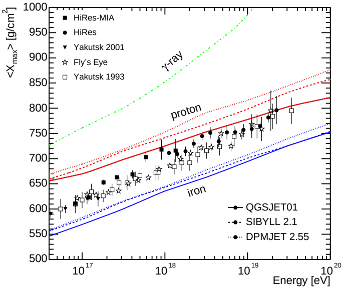
Final - 'progressive' picture



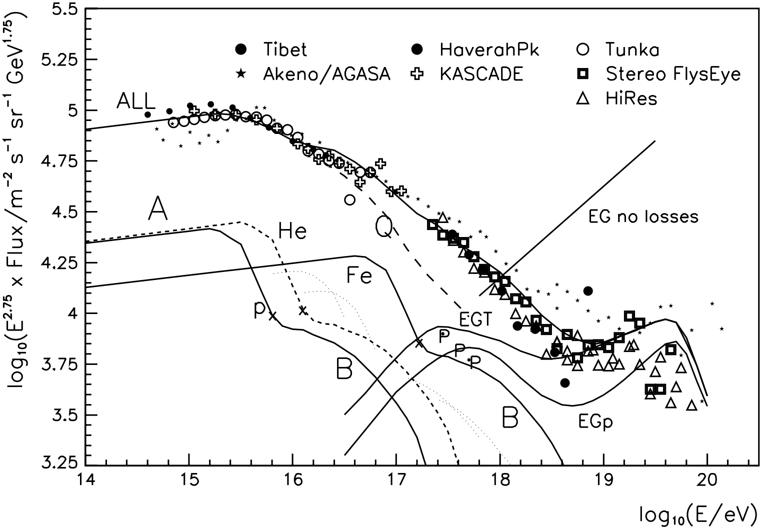
$\Rightarrow$ **weak constraints on HE interaction models**

Changing composition - data

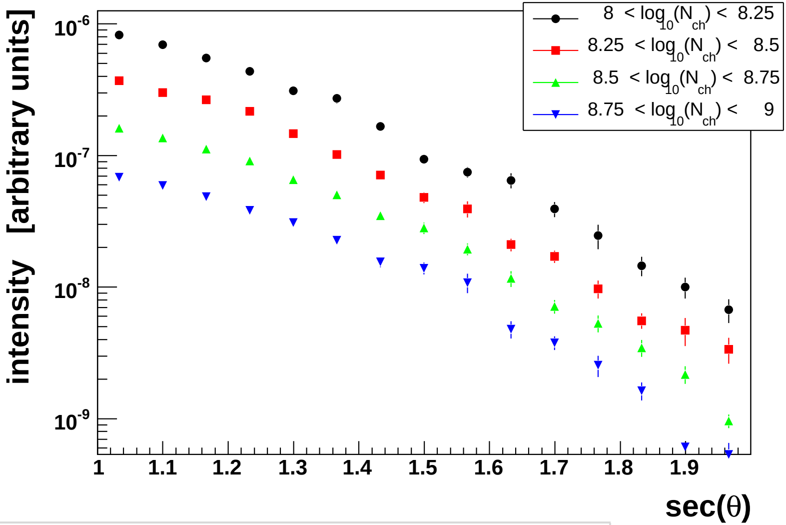




Composition - model by Hillas



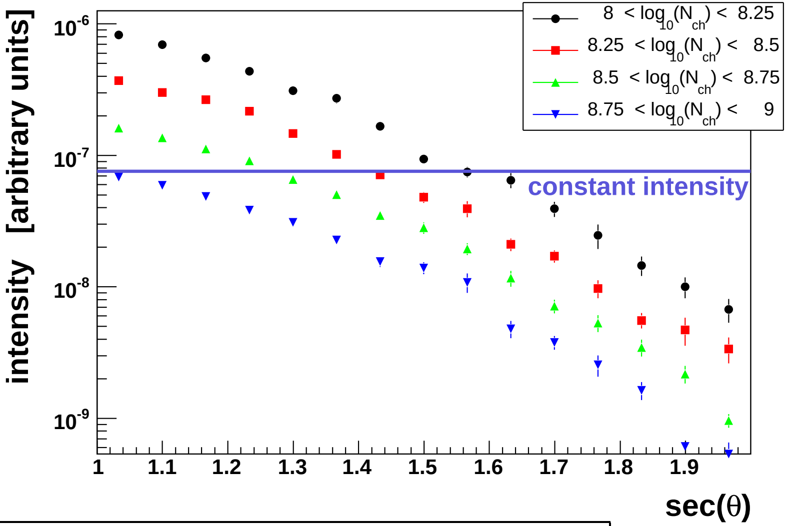
Equal intensity cut



constant intensity → same primary energy (isotropic flux)

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

Equal intensity cut



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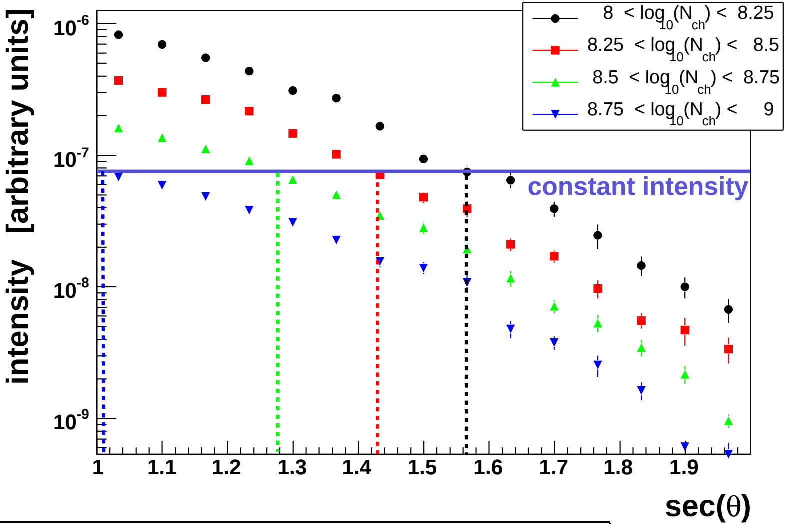

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