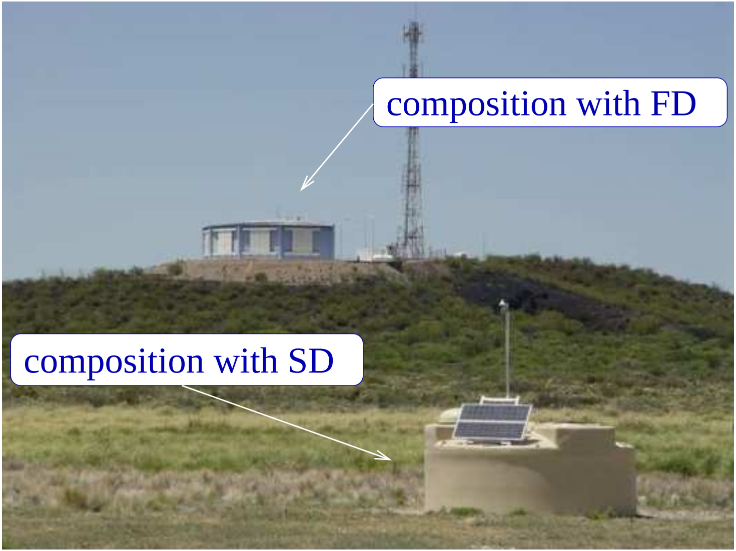
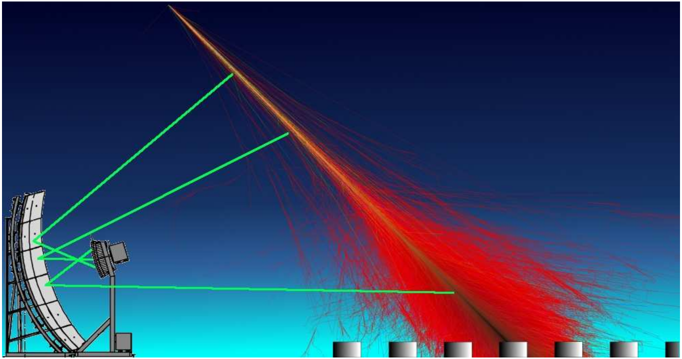
Study of the Cosmic Ray Composition with the Pierre Auger Observatory

Michael Unger for the Pierre Auger Collaboration
(Karlsruher Institut für Technologie)

Outline



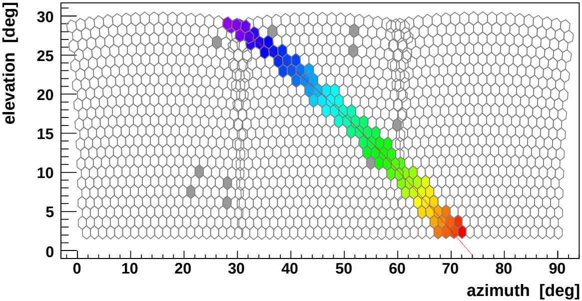
Fluorescence Detector: Longitudinal Shower Profiles



Detection of fluorescence light as a function of slant depth

Fluorescence Detector: Longitudinal Shower Profiles

event 1542115, CO



Fluorescence Detector: Longitudinal Shower Profiles

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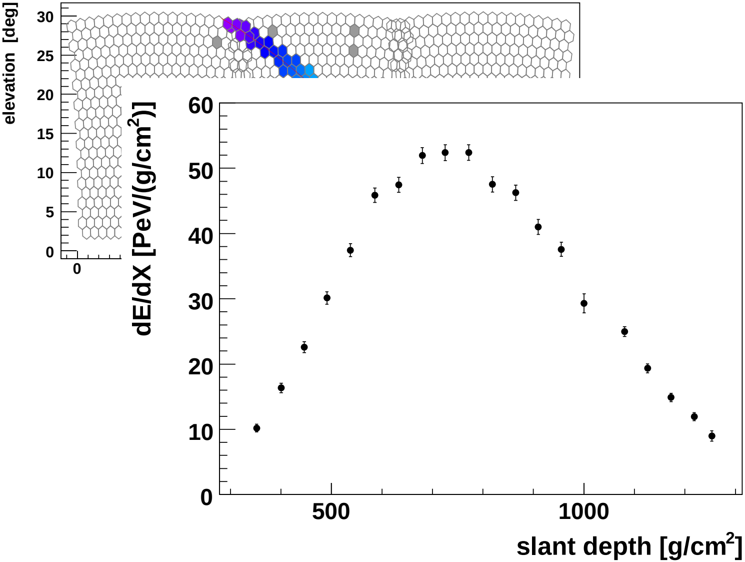
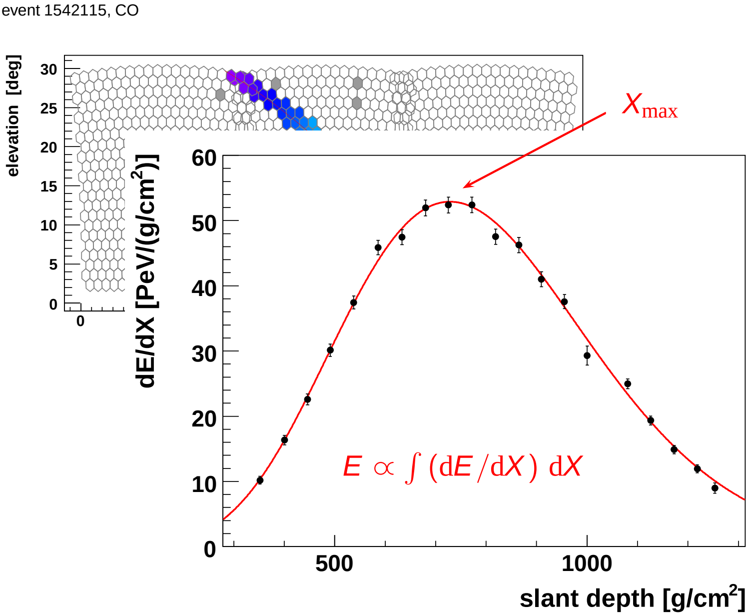


Fluorescence Detector: Longitudinal Shower Profiles



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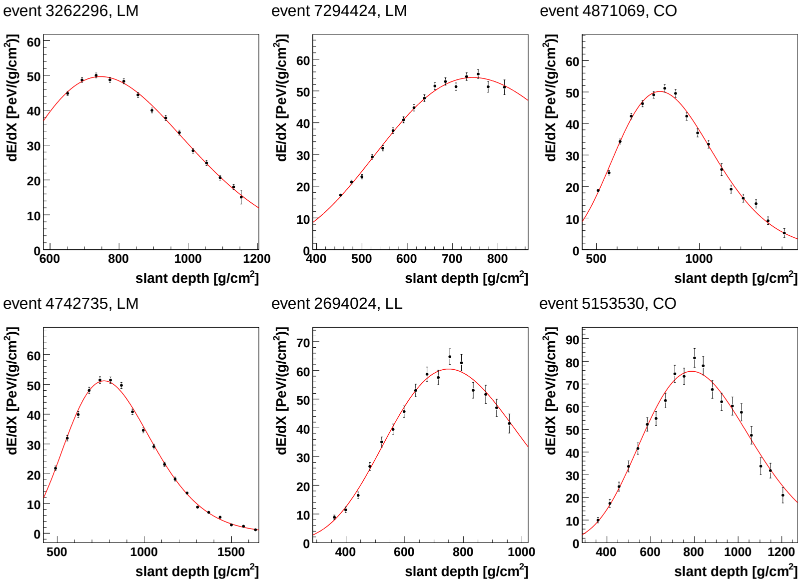


Average Shower Maximum, $\langle X_{\max} \rangle$

primary protons:

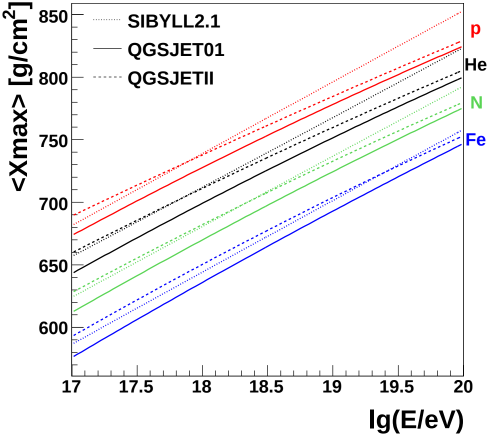
$$\langle X_{\max} \rangle = D_{10} \lg(E) + \text{const}$$

superposition model:

$$\langle X_{\max} \rangle = D_{10} \lg(E/A) + \text{const}$$

elongation rate theorem:

$$D_{10} \leq X_0 \ln(10)$$



Shower-to-Shower Fluctuations, RMS(X_{max})

primary protons

$$\mathrm{RMS}(X_{\mathrm{max}})^2 = \lambda_p^2 + V(\mathrm{Shower})$$

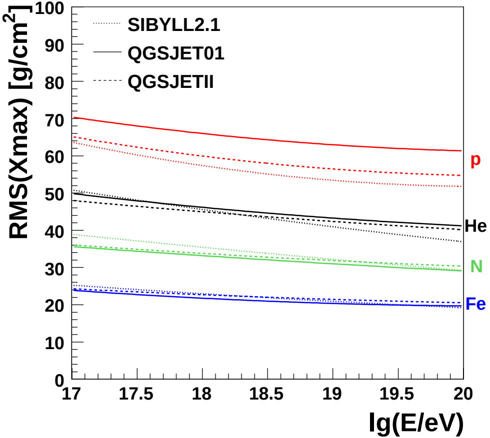
superposition model...

$$\mathrm{RMS}(A) = \mathrm{RMS}(p)/\sqrt{A}$$

...does not work here (fragmentation), but qualitatively

$$\mathrm{RMS}(A_1) < \mathrm{RMS}(A_2)$$

for $A_1 > A_2$



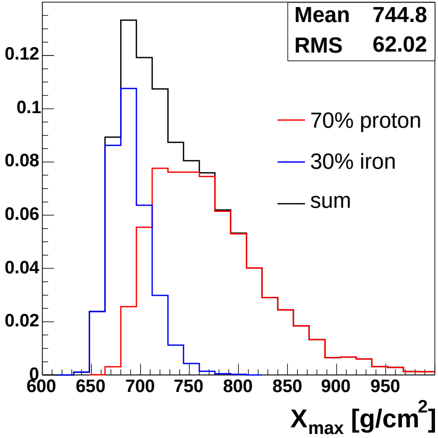
Mixed composition

- $\langle X_{\max} \rangle \propto \langle \ln A \rangle$
- difference in $\langle X_{\max} \rangle$ contributes to RMS
- e.g. p and Fe mixture, p-fraction f

  $$\langle X_{\max} \rangle = f\,\langle X_{\max} \rangle_{\mathrm{p}} + (1-f)\,\langle X_{\max} \rangle_{\mathrm{Fe}}$$

  and

  $$\mathrm{RMS}^2 = f\,\mathrm{RMS}^2_{\mathrm{p}} + (1-f)\,\mathrm{RMS}^2_{\mathrm{Fe}} + f(1-f)(\langle X_{\max} \rangle_{\mathrm{p}} - \langle X_{\max} \rangle_{\mathrm{Fe}})^2$$



Data Selection

atmosphere&calibration

- good camera calibration constants
- require measured aerosol profile
- reject 'dusty' periods (VAOD@3 km $<$0.1)
- cloud fraction $<$ 25%

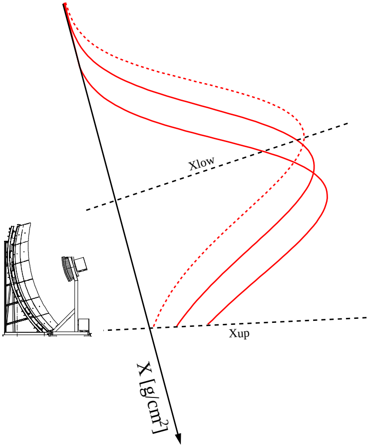
fiducial volume cuts

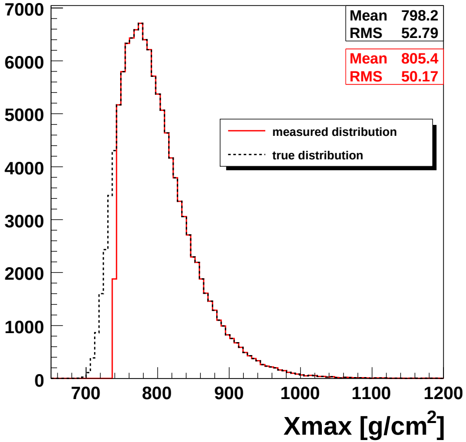
- tank distance and zenith angle
- field of view (see next slides)
- minimum viewing angle $> 20^\circ$

quality selection

- hybrid geometry reconstruction
- X_{max} observed
- expected $\sigma(X_{\mathrm{max}}) < 40$ g/cm^2
- reduced χ^2 of profile fit < 2.5

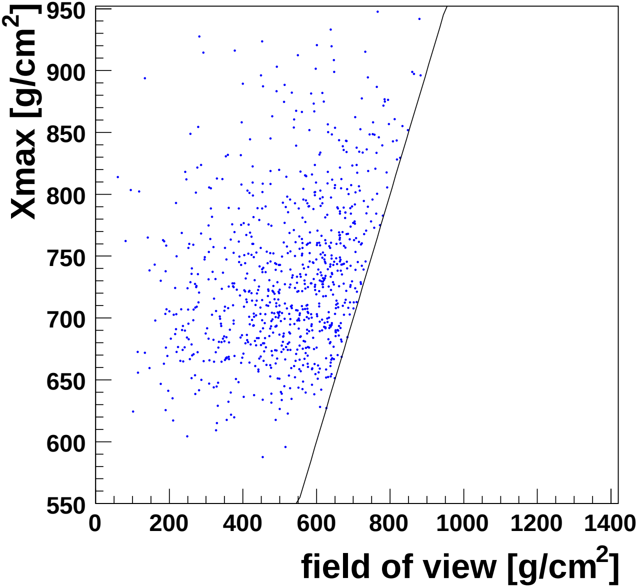
FD Field Of View (illustration)





limited FD field of view potentially biases measured X_{max} distribution

FD Field Of View (data)



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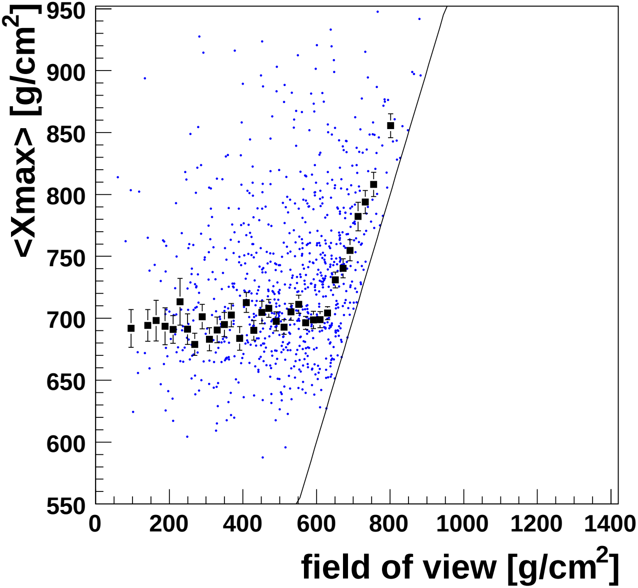
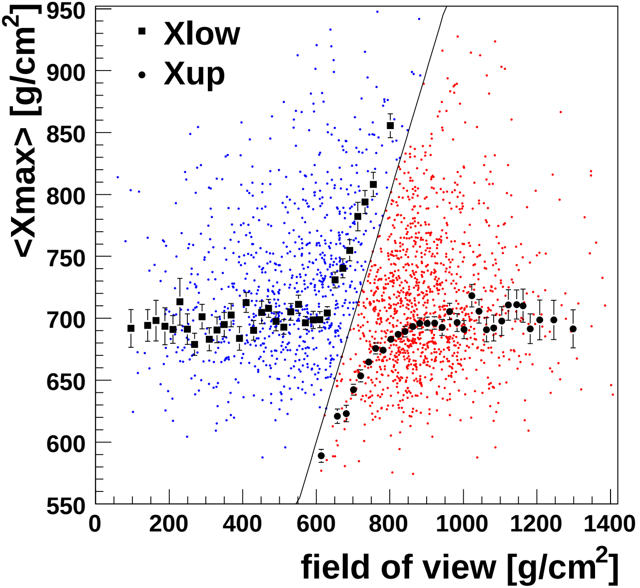


FD Field Of View (data)



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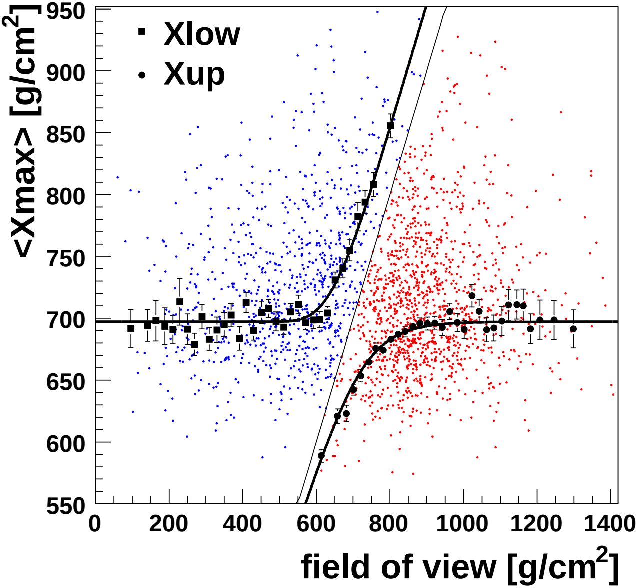

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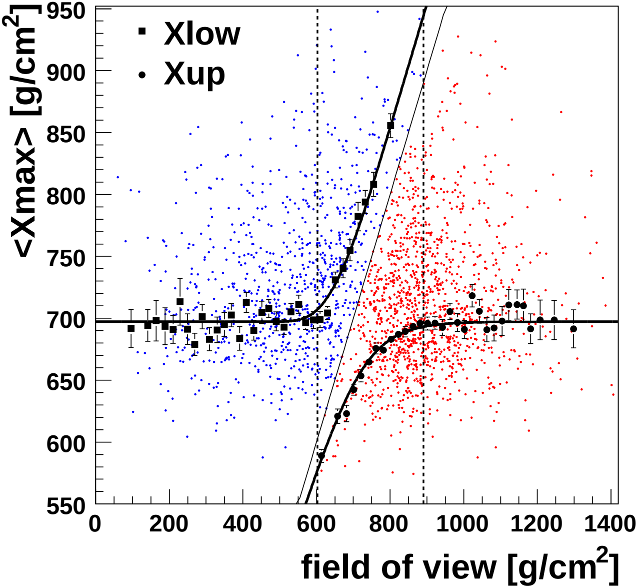
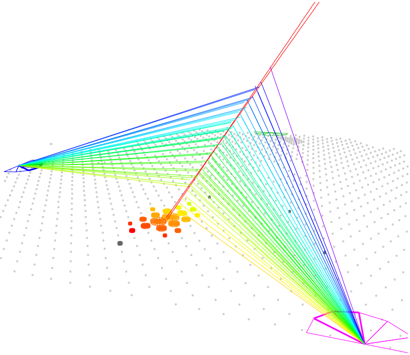
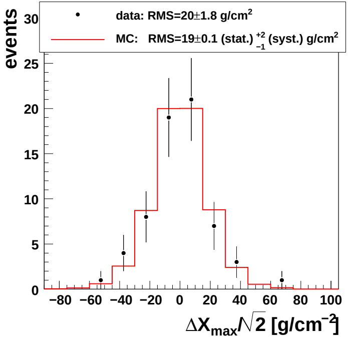
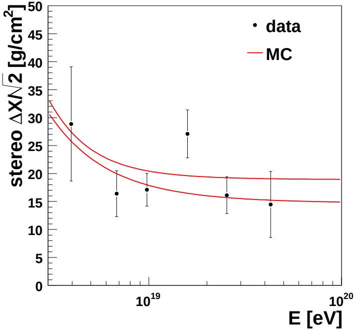


X_{max} Resolution

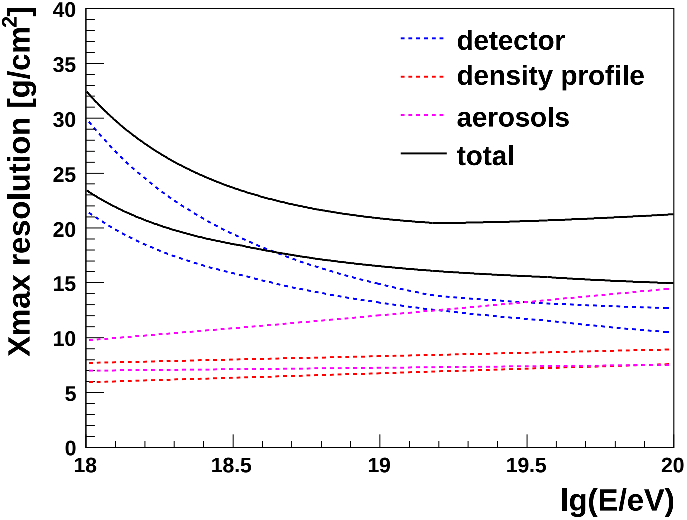
MC validation with
stereo events





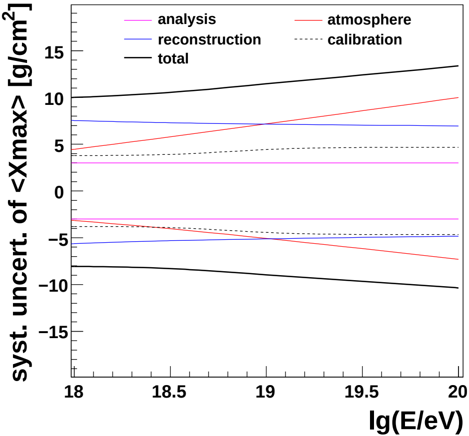


X_{max} Resolution

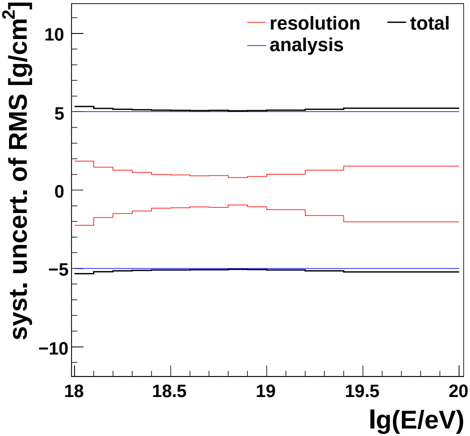


Systematic Uncertainties

$\langle X_{max} \rangle$:

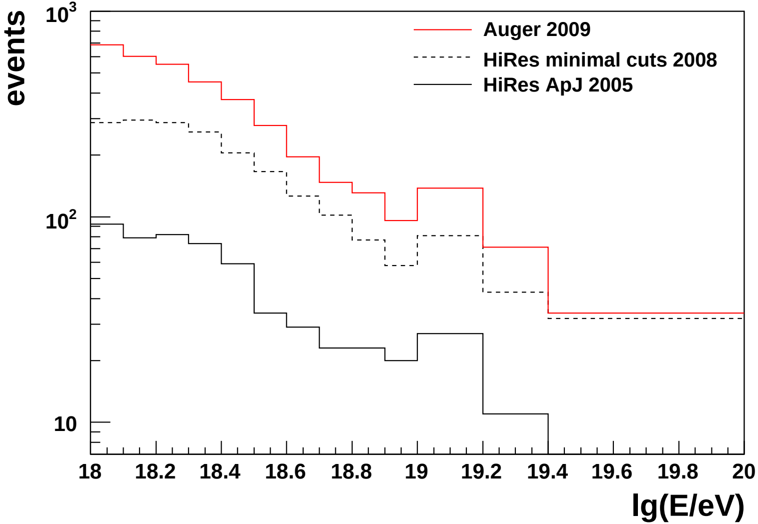


RMS(X_{max}):



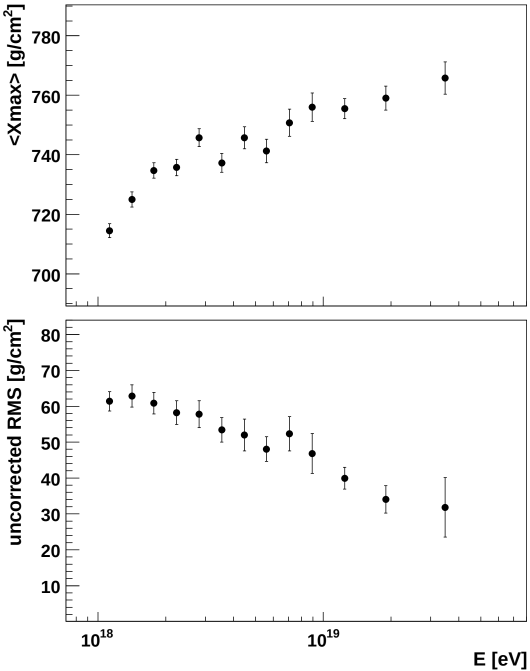
FD Results

number of events after selection:



FD Results

- $\langle X_{\max} \rangle$ and RMS vs E
- resolution correction
- broken line fit: slopes D $[\mathrm{g/cm^2}/\mathrm{decade}]$
- comparison to air shower simulations
- published HiRes data (update cf. Pierre's talk)



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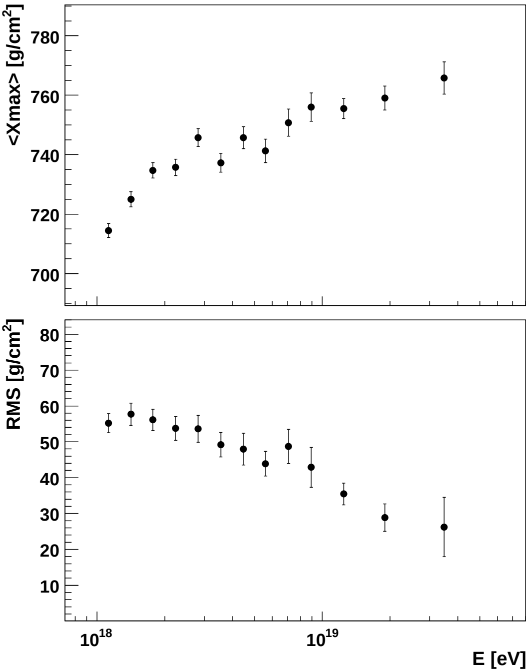

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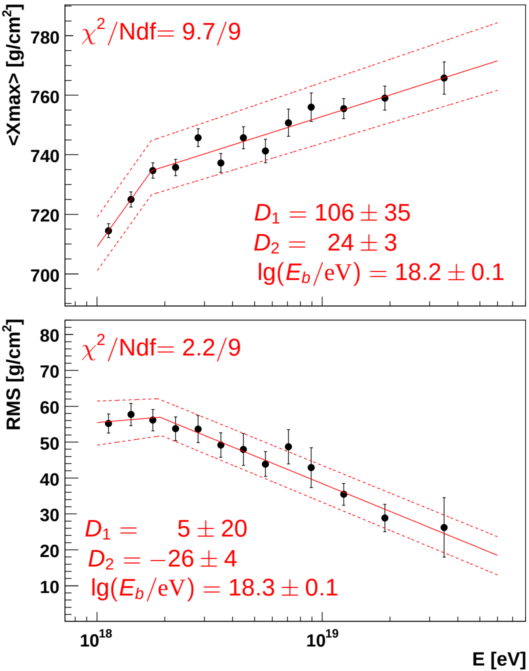

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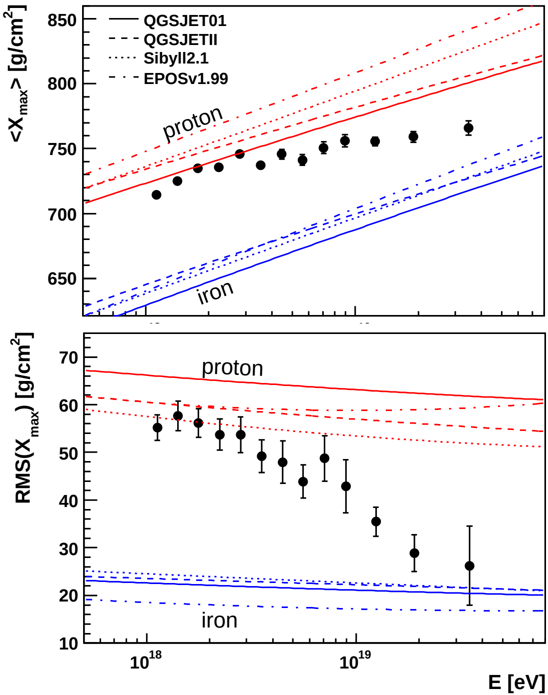

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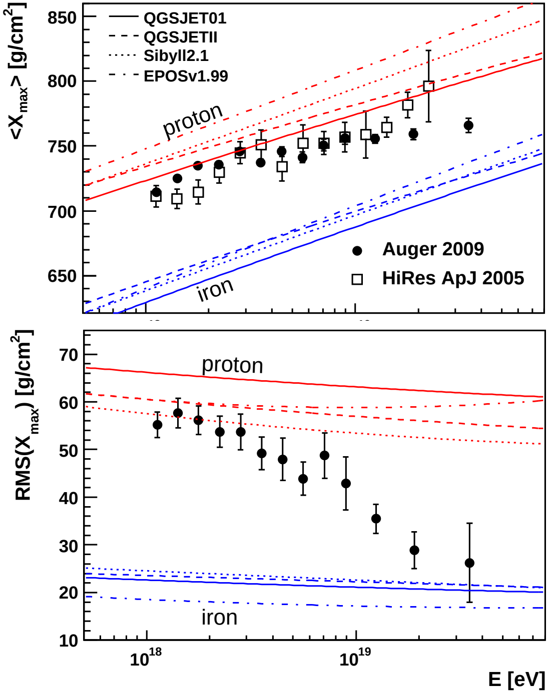
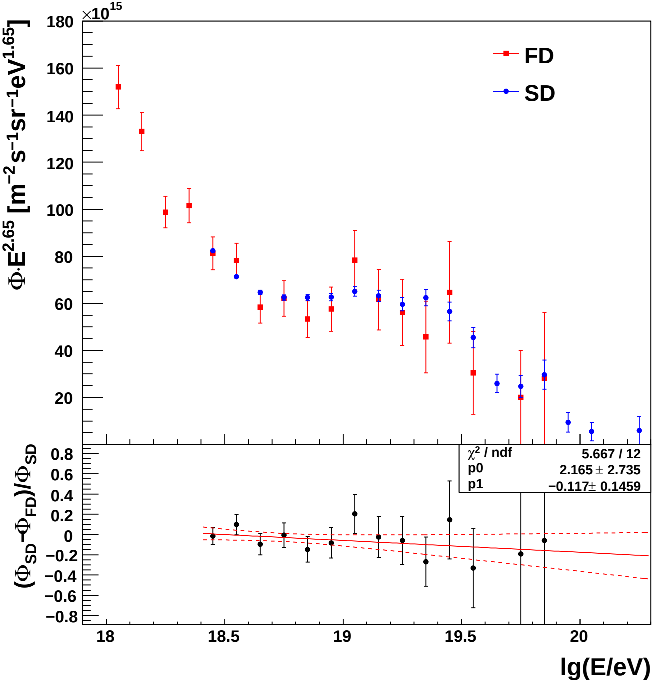


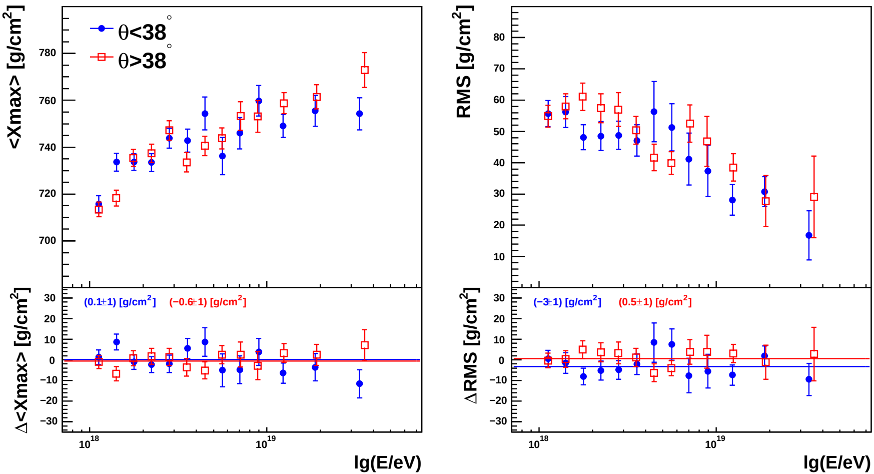
Cross Checks -

Energy Spectrum

missing events
at high energies?



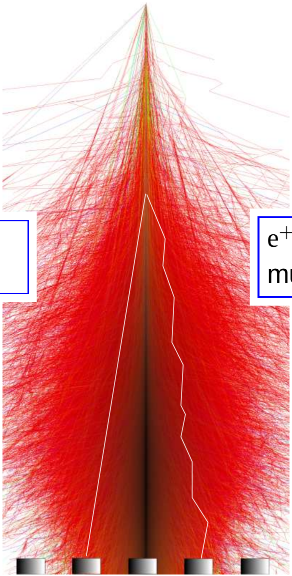
Cross Checks - inclined vs. near vertical



inclinded: large $h(X_{\mathrm{max}})$, upper FOV, small aerosol attenuation
vertical: small $h(X_{\mathrm{max}})$, lower FOV, larger aerosol attenuation

Composition with SD - a) Signal Rise Time ($t_{1/2}$)

muons:
$\approx$ straight line

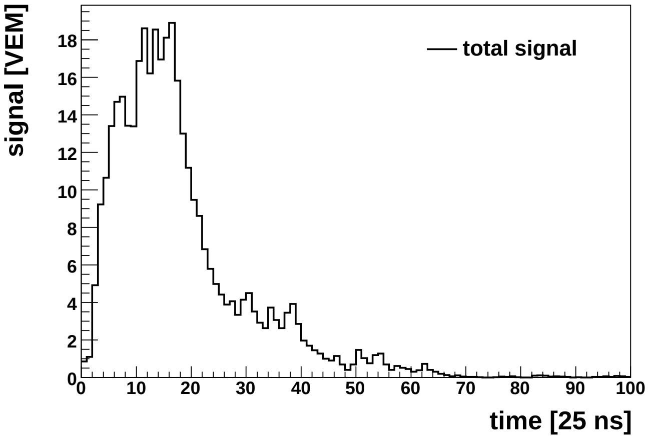


$e^{+}e^{-}$:
multiple scattering

$t_{\mu} < t_{e^{+}e^{-}}$

Signal Rise Time ($t_{1/2}$)

CORSIKA+GEANT4 of tank signal at 1000 m ($\theta = 38^\circ$)



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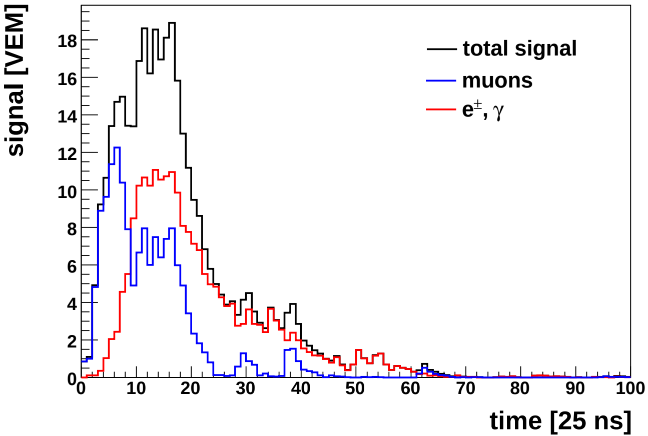

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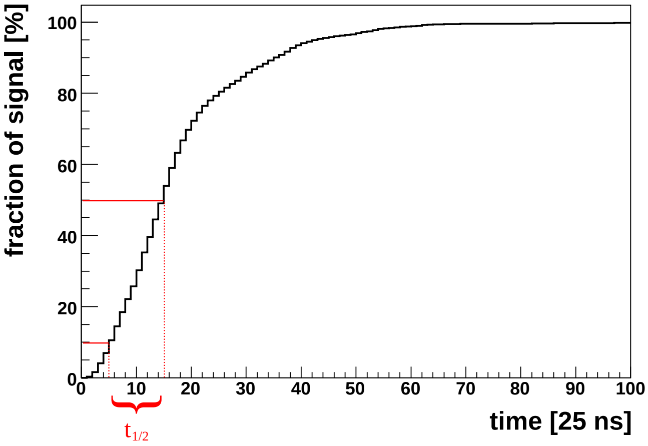
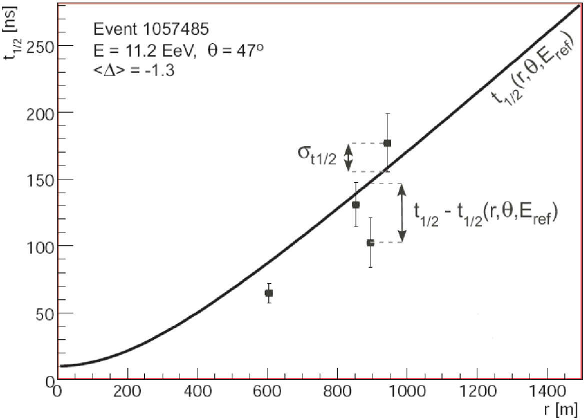


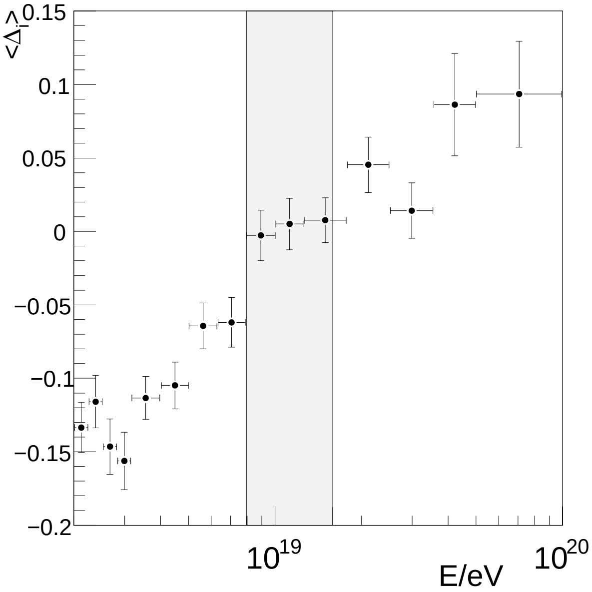
Deviation to Average Rise Time: $\langle\Delta\rangle$

$$\langle\Delta\rangle = \sum \frac{t^i_{1/2} - \langle t_{1/2}(E^\star, r, \theta)\rangle}{\sigma_i}$$

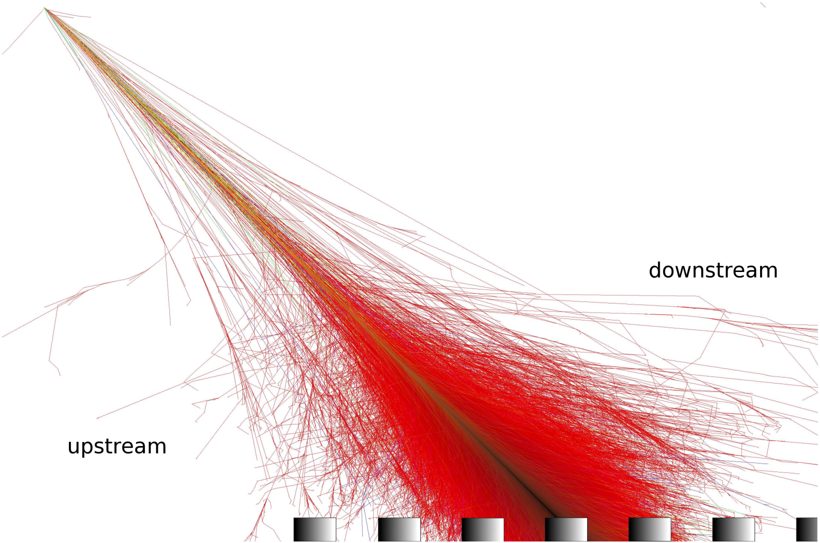
('benchmark' $\langle t_{1/2}\rangle$ at reference energy $E^\star$)



⟨Δ⟩ Elongation Rate



Composition with SD - b) Rise Time Asymmetry



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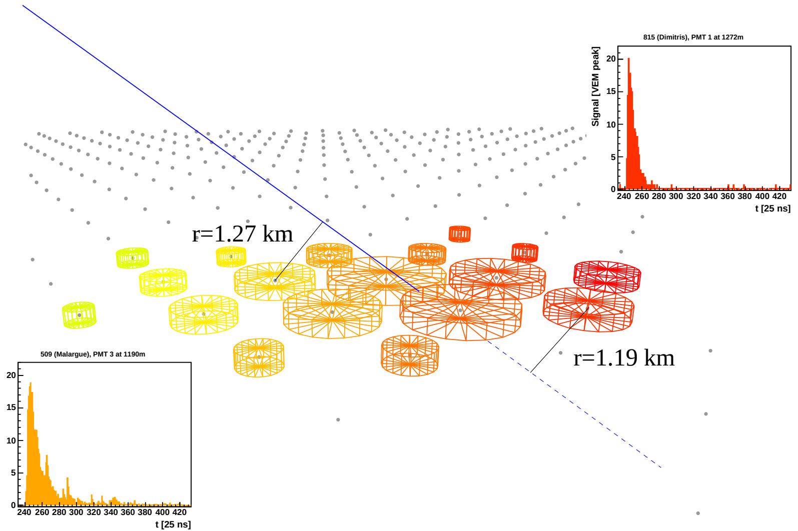
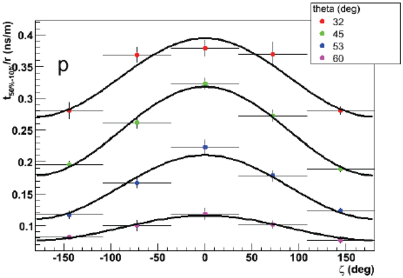
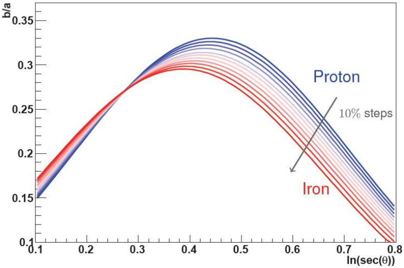


Composition with SD - b) Rise Time Asymmetry

$t_{1/2}$ vs. shower plane azimuth ξ
(upstream: $-90^\circ < \xi < 90^\circ$)



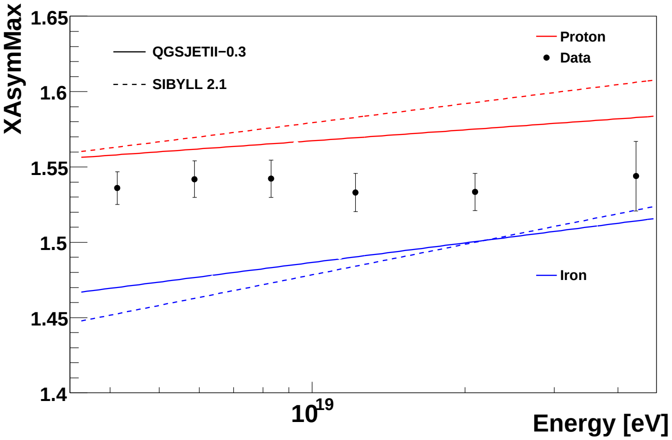
asymmetry for proton$\rightarrow$iron



$$t_{1/2}/r = a + b\cos\xi$$

$\rightarrow$ 'asymmetry' b/a

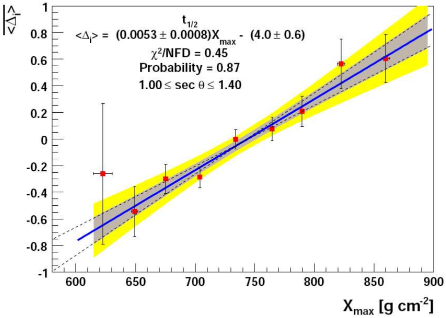
Asymmetry Elongation Rate

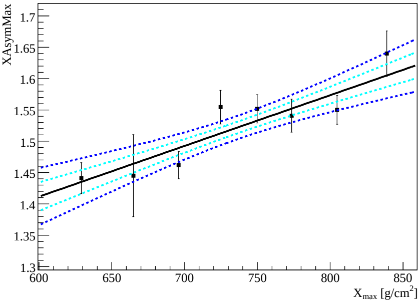


'XAsymMax': $\sec\theta$ position at which asymmetry b/a is maximal

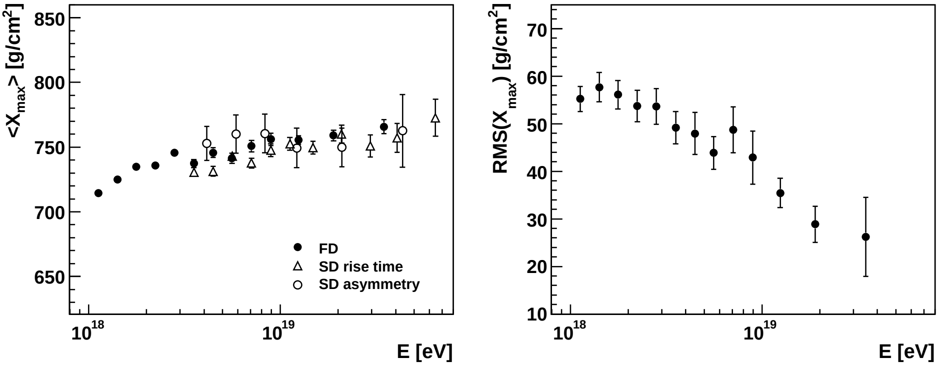
'Calibration' of SD with FD (preliminary)

measurement of correlation of $\langle\Delta\rangle$ and XAsymMax with $X_{\max}$





Summary of Auger Results (preliminary)



- elongation rate flattens at high energy
- fluctuations decrease with energy

FD paper expected to be submitted to PRL by mid-July