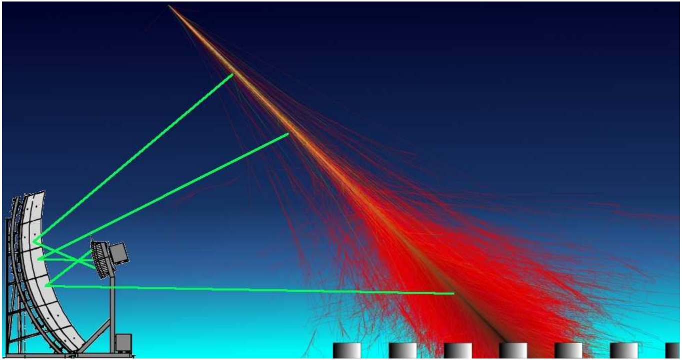
# Composition Studies with Auger

Michael Unger
(Karlsruher Institut für Technologie)

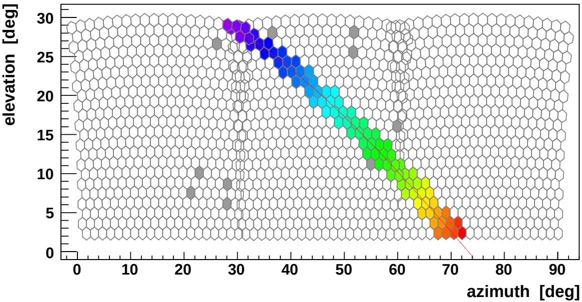
# Fluorescence Detector: Longitudinal Shower Profiles



Detection of fluorescence light as a function of slant depth

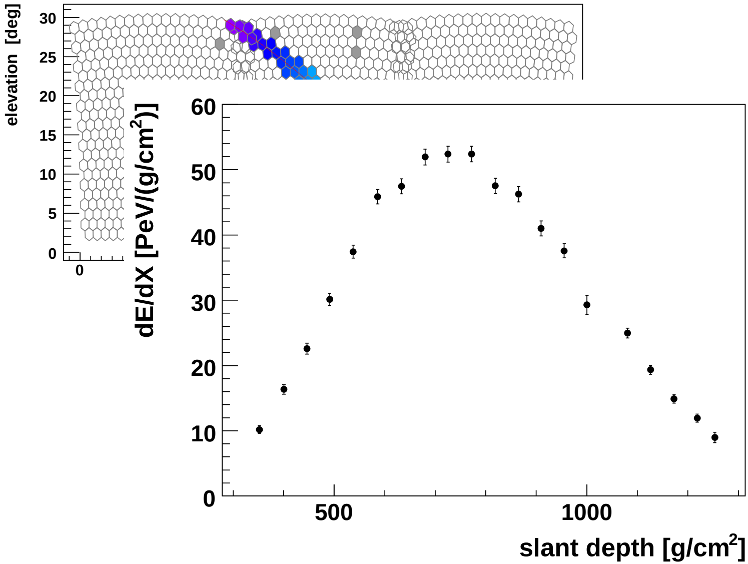
# Fluorescence Detector: Longitudinal Shower Profiles

event 1542115, CO



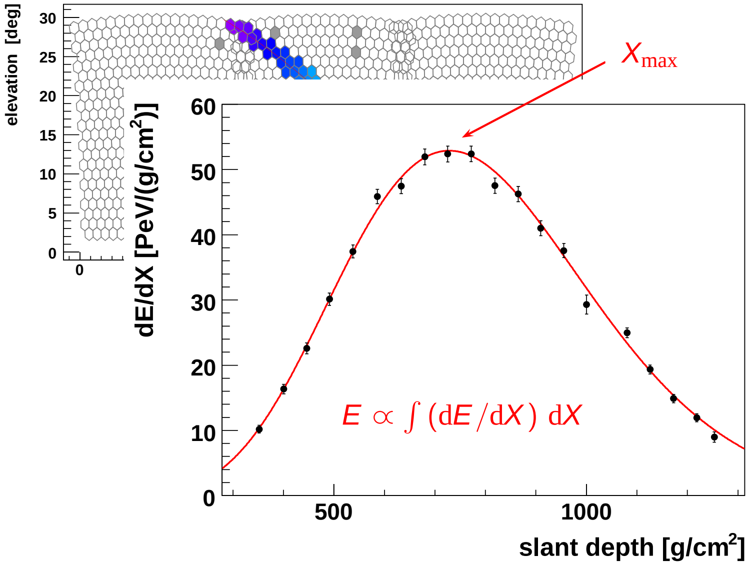
# Fluorescence Detector: Longitudinal Shower Profiles

event 1542115, CO



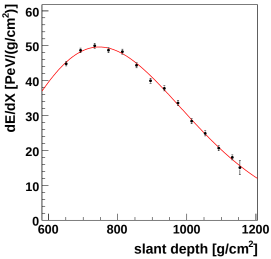
# Fluorescence Detector: Longitudinal Shower Profiles

event 1542115, CO

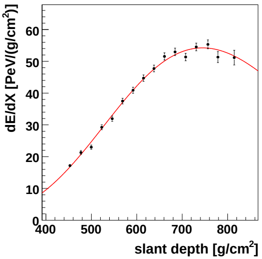


# Fluorescence Detector: Longitudinal Shower Profiles

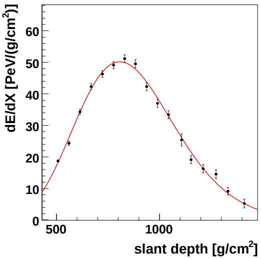
event 3262296, LM



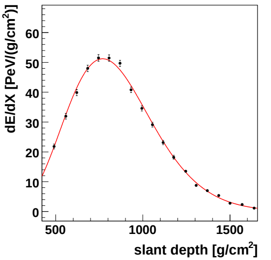

event 7294424, LM



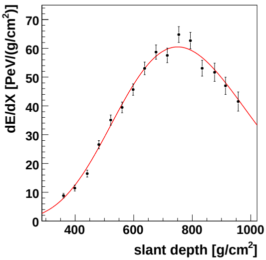

event 4871069, CO



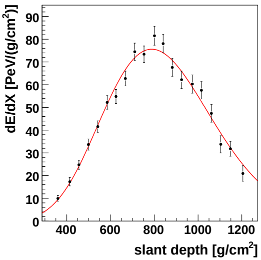

event 4742735, LM




event 2694024, LL




event 5153530, CO



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

primary protons:

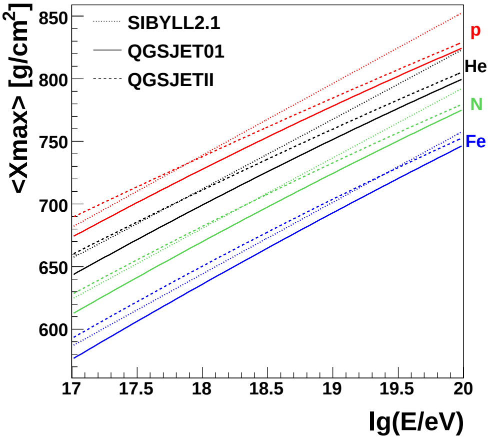
$$\langle X_{\max} \rangle = D_{10} \lg(E) + \text{const}$$

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($X_{\text{max}}$)

primary protons

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

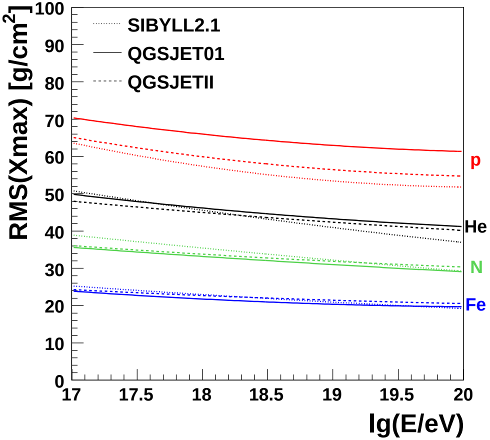
superposition model...

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

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

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

for $A_1 > A_2$



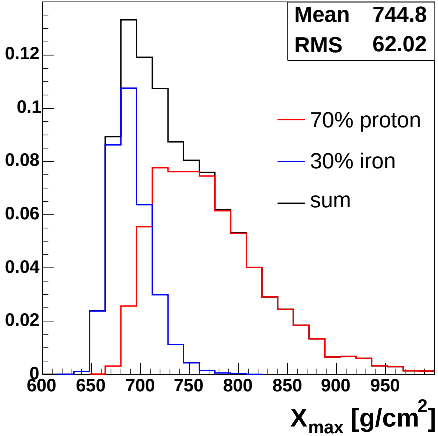
# Mixed composition

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

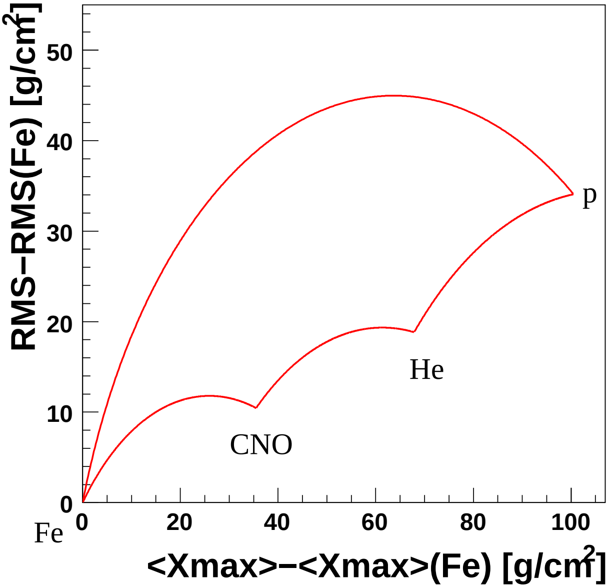
  $\langle X_{\rm max}\rangle = f\,\langle X_{\rm max}\rangle_{\rm p} + (1-f)\,\langle X_{\rm max}\rangle_{\rm Fe}$

  and

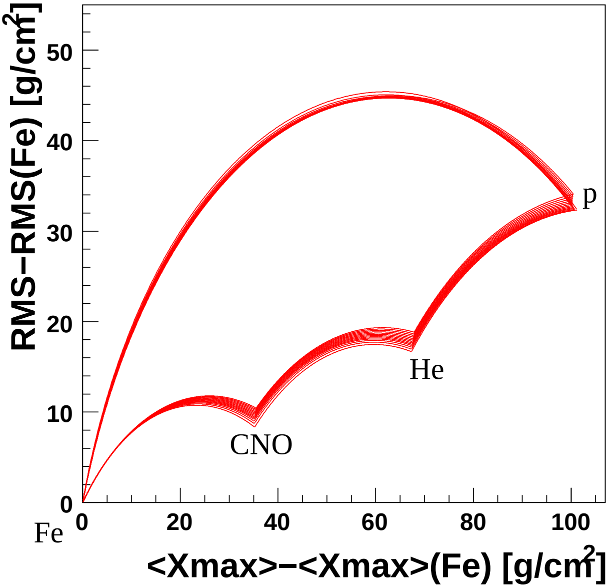
  $$\mathrm{RMS}^2 = f\,\mathrm{RMS}^2_{\rm p} + (1-f)\,\mathrm{RMS}^2_{\rm Fe} + f(1-f)(\langle X_{\rm max}\rangle_{\rm p} - \langle X_{\rm max}\rangle_{\rm Fe})^2$$



# RMS vs. $X_{max}$, SIBYLL2.1, $10^{18}$ eV



# RMS vs. $X_{max}$, SIBYLL2.1, $10^{18}$-$10^{20}$ eV



# Data Selection

**atmosphere&calibration**

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

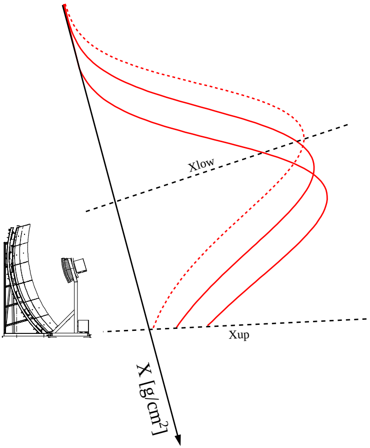
**fiducial volume cuts**

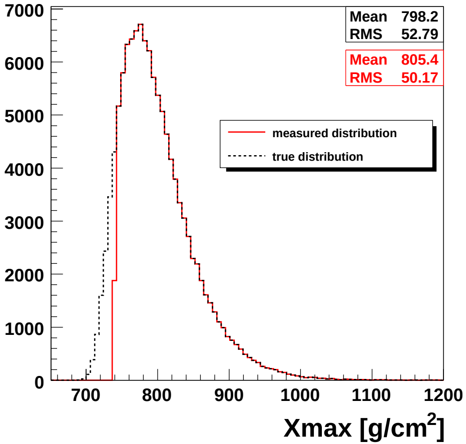
- tank distance and zenith angle
- field of view (see next slides)
- minimum viewing angle $>$ 20$^\circ$

**quality selection**

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

# FD Field Of View (illustration)

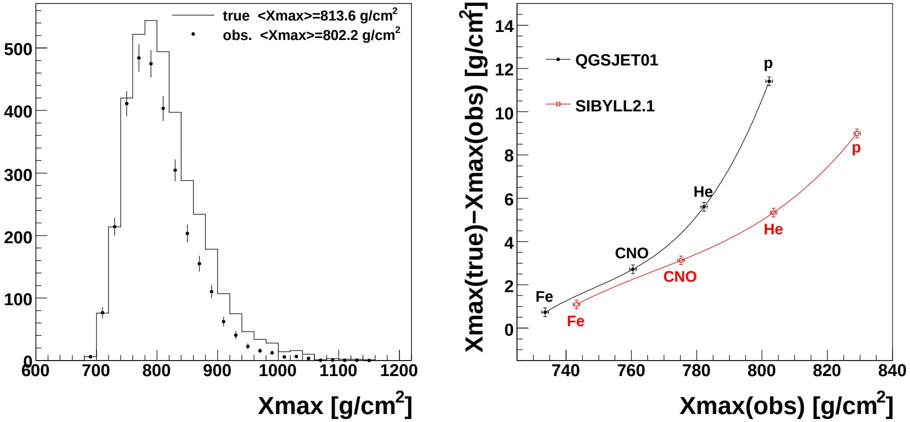



limited FD field of view potentially biases measured $X_{\mathrm{max}}$ distribution

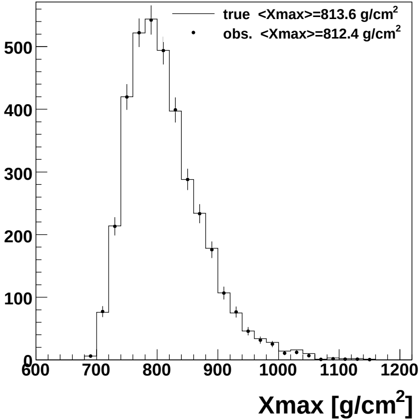
# Field of view bias - Illustration with CONEX Simulations

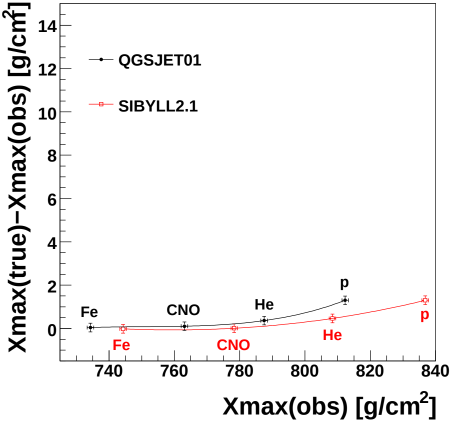
$dN/d\cos\theta \propto \cos\theta$, $R_{max}$=30 km



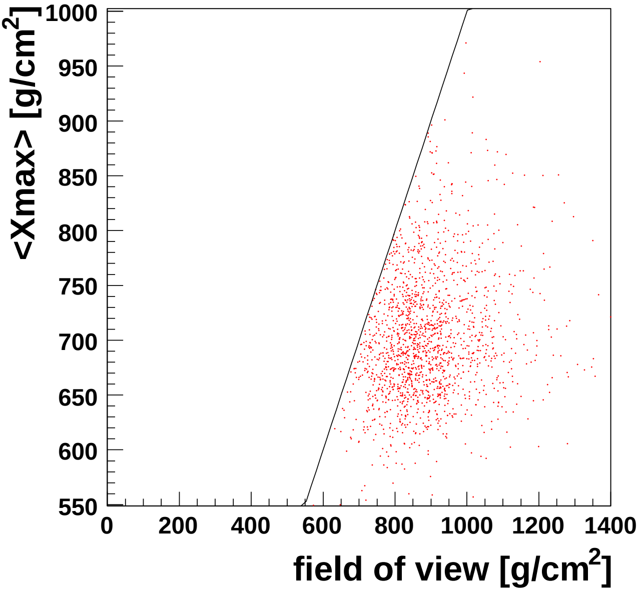
# Field of view bias - Illustration with CONEX Simulations

$dN/d\cos\theta \propto \cos\theta$, $R_{max}$=30 km, max. viewable depth>950 g/cm$^2$

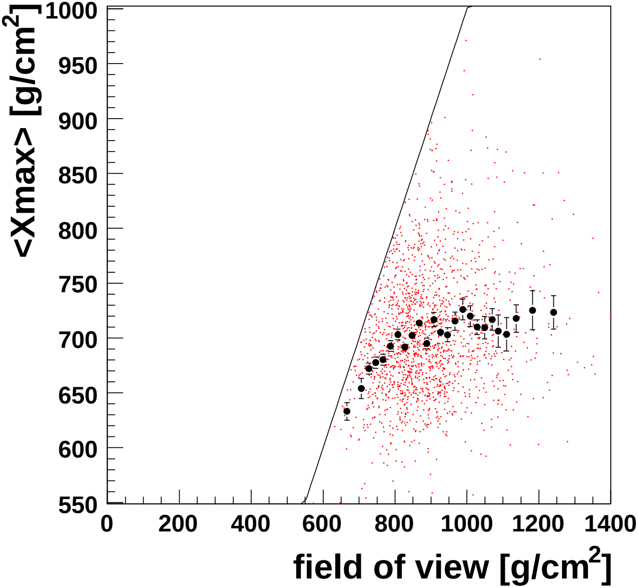


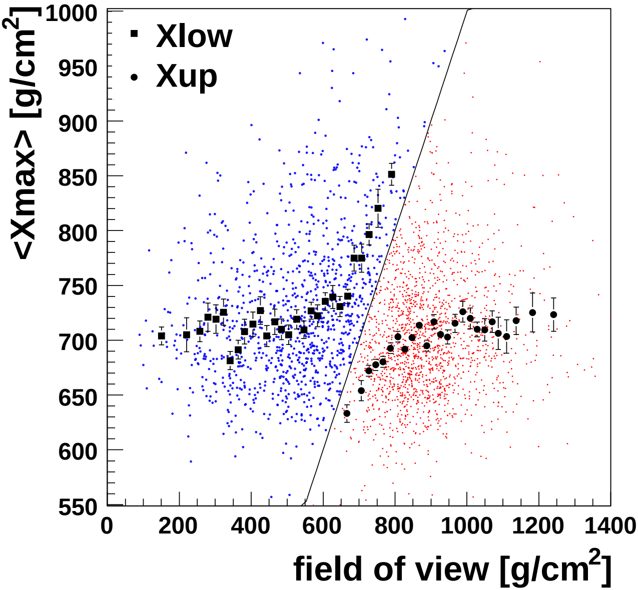
# FD Field Of View (data, $10^{18.0} - 10^{18.1}$ eV)



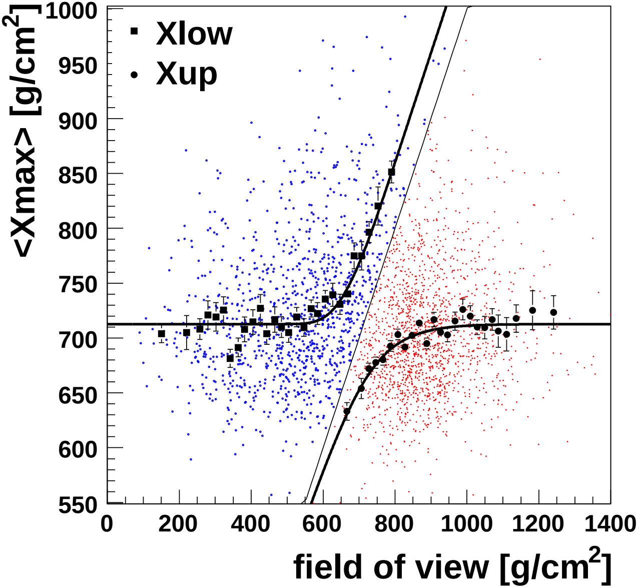
# FD Field Of View (data, $10^{18.0} - 10^{18.1}$ eV)



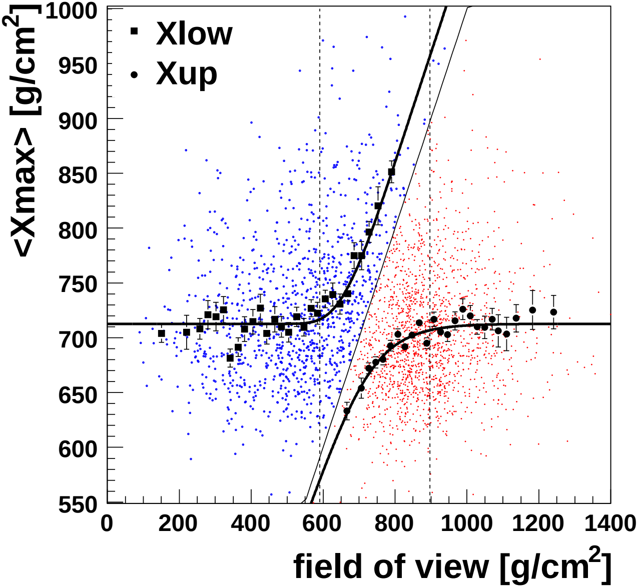
# FD Field Of View (data, $10^{18.0} - 10^{18.1}$ eV)



# FD Field Of View (data, $10^{18.0} - 10^{18.1}$ eV)

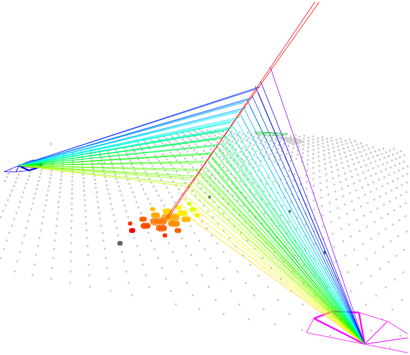


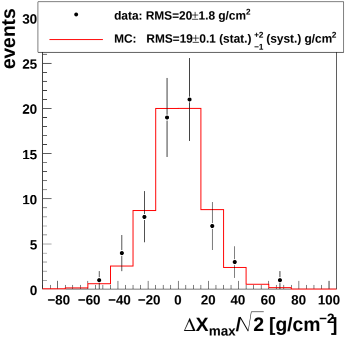
# FD Field Of View (data, $10^{18.0} - 10^{18.1}$ eV)

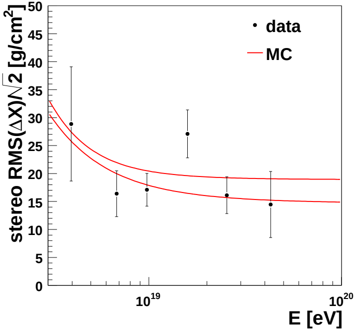


# $X_{max}$ Resolution

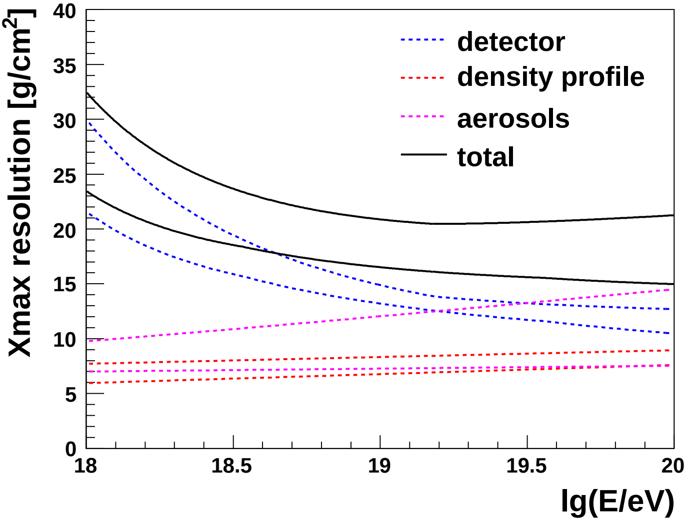
MC validation with stereo events





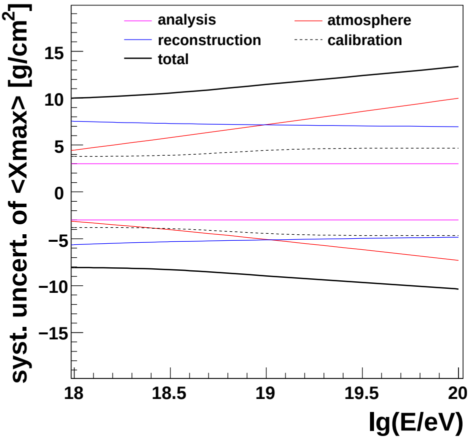



# $X_{max}$ Resolution

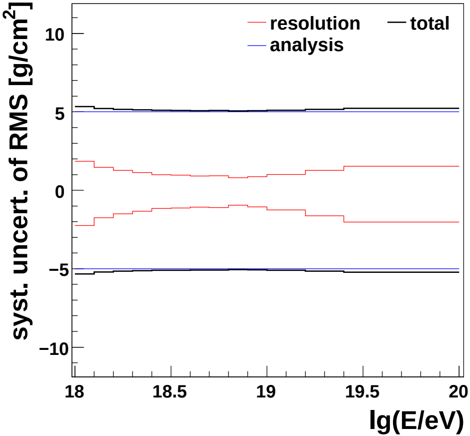


# Systematic Uncertainties

$\langle X_{\max} \rangle$:

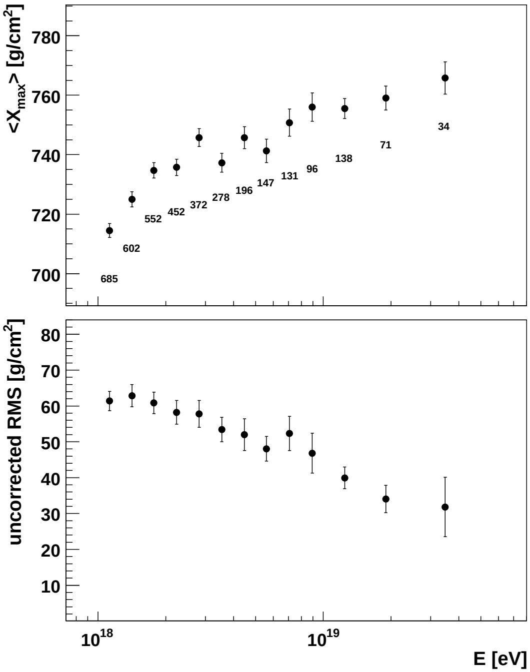



RMS($X_{\max}$):



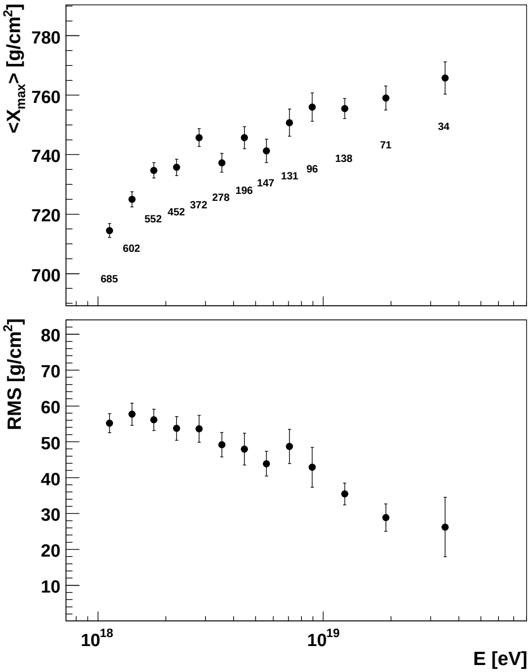
# FD Results

- $N_{sel} = 3754$
- $\langle X_{max} \rangle$ and RMS vs $E$
- resolution correction
- linear fit
  slopes $D$ [g/cm$^2$/decade]
- broken line fit



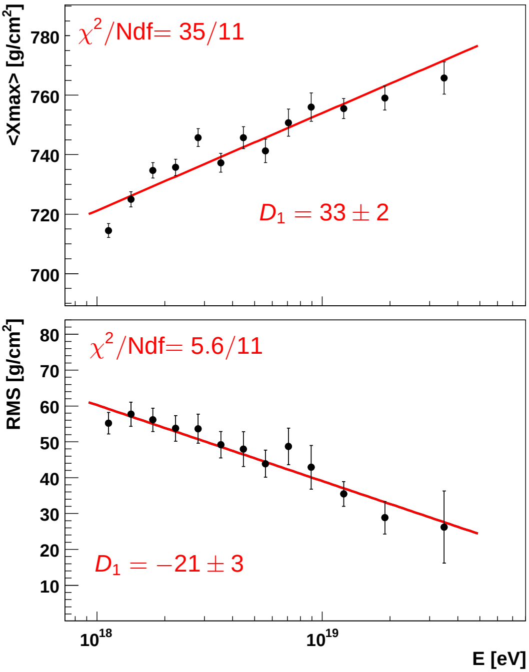
# FD Results

- $N_{\mathrm{sel}} = 3754$
- $\langle X_{\max} \rangle$ and RMS vs $E$
- resolution correction
- linear fit
  slopes $D$ $[\mathrm{g/cm^2/decade}]$
- broken line fit



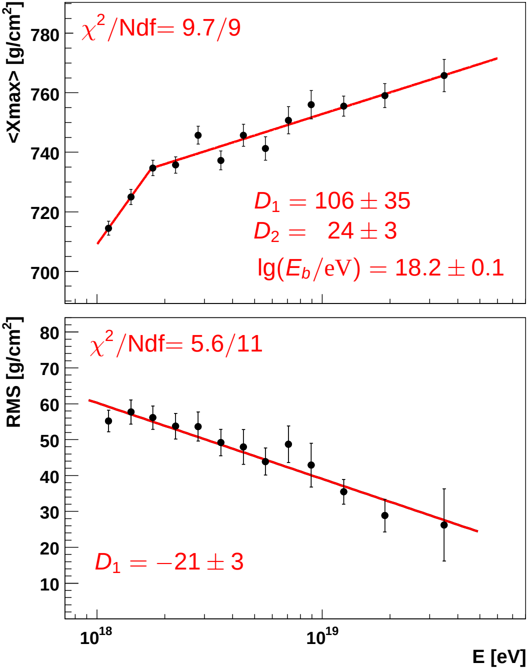
# FD Results

- $N_{\rm sel}$ =3754
- $\langle X_{\rm max}\rangle$ and RMS vs $E$
- resolution correction
- linear fit
  slopes $D$ [g/cm$^2$/decade]
- broken line fit

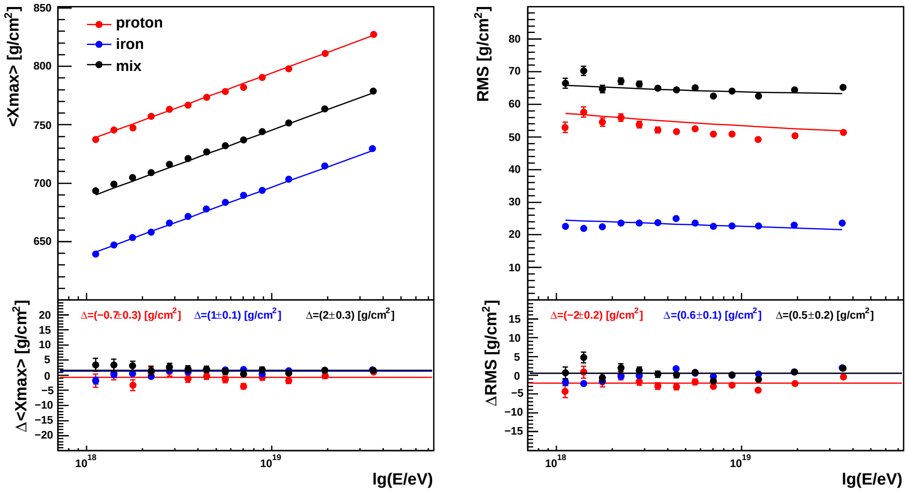


# FD Results

- $N_{\mathrm{sel}} = 3754$
- $\langle X_{\mathrm{max}} \rangle$ and RMS vs $E$
- resolution correction
- linear fit
  slopes $D$ $[\mathrm{g/cm^2}$/decade]
- broken line fit



# Cross Checks - Analysis of simulated data

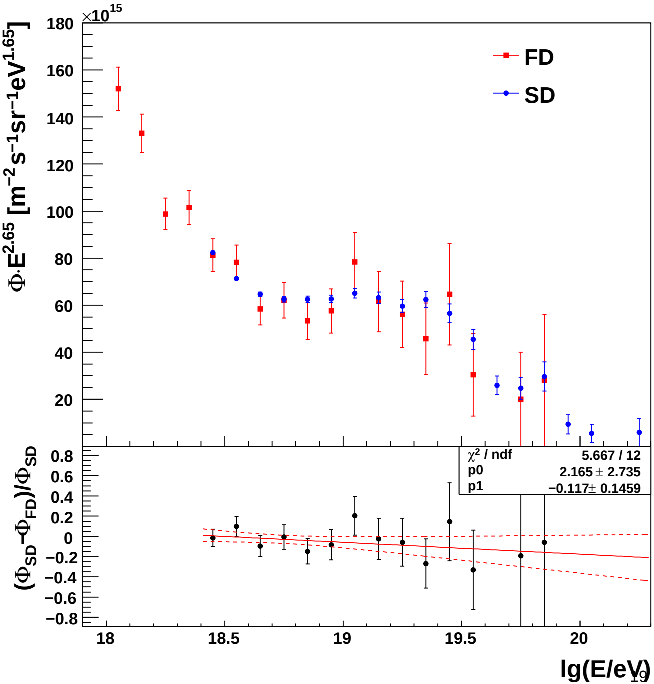



lines: generated MC, dots: reconstructed & analyzed MC (SIBYLL2.1)

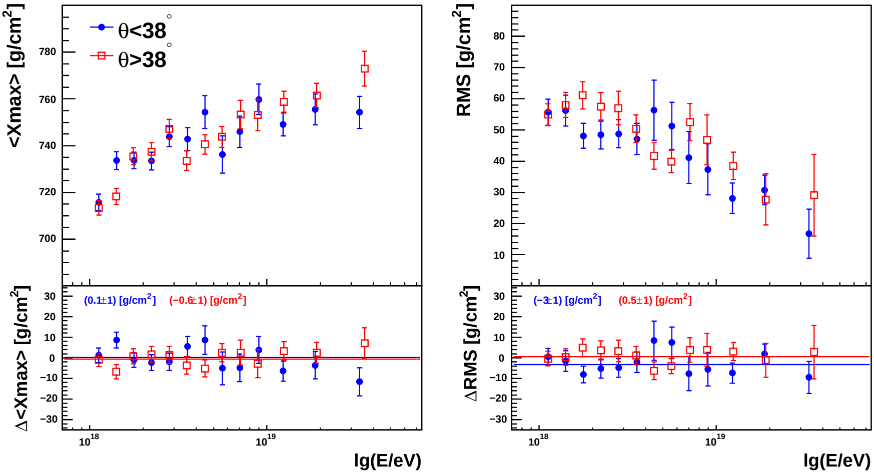
# Cross Checks -

## Energy Spectrum

missing events
at high energies?

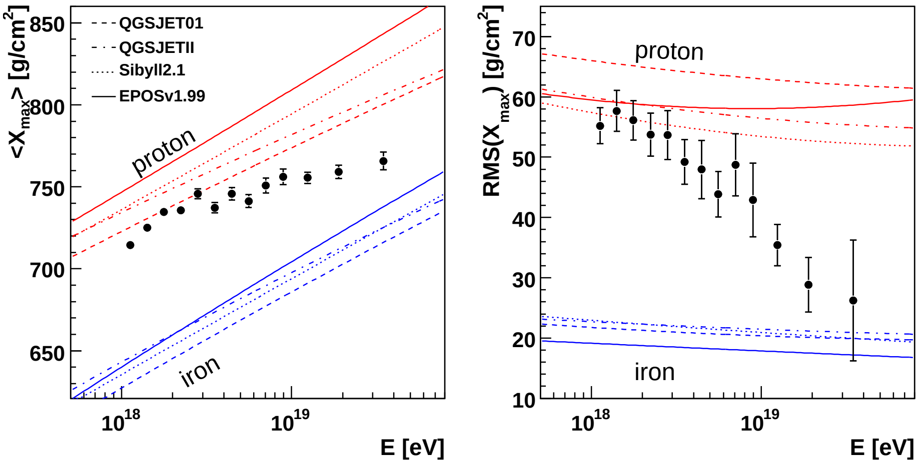


# Cross Checks - inclined vs. near vertical

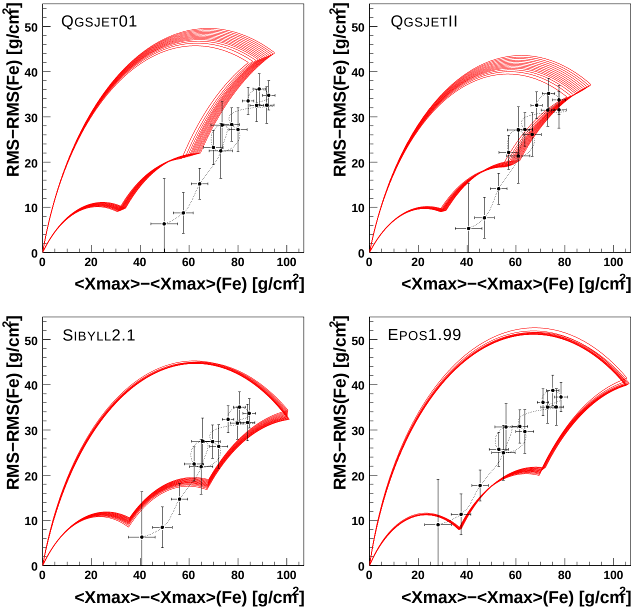



**inclined:** large $h(X_{\mathrm{max}})$, upper FOV, small aerosol attenuation
**vertical:** small $h(X_{\mathrm{max}})$, lower FOV, larger aerosol attenuation

# Comparison to Air Shower Simulations

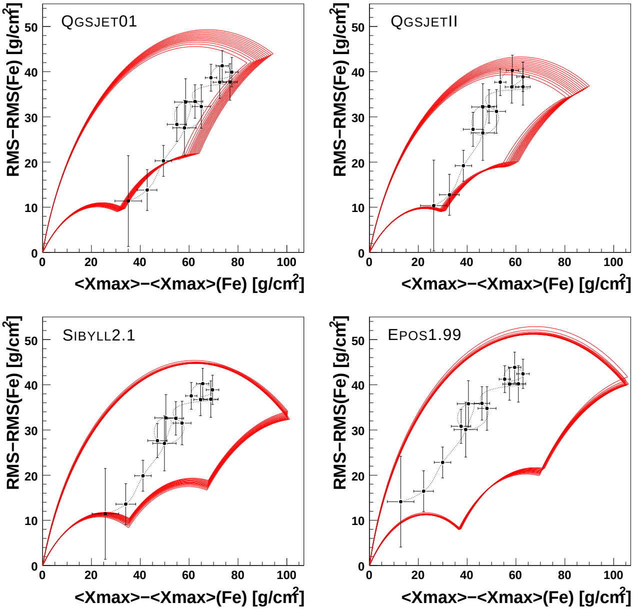


# RMS vs. $X_{max}$



QGSJET01
QGSJETII
SIBYLL2.1
EPOS1.99
RMS−RMS(Fe) [g/cm2]
<Xmax>−<Xmax>(Fe) [g/cm2]

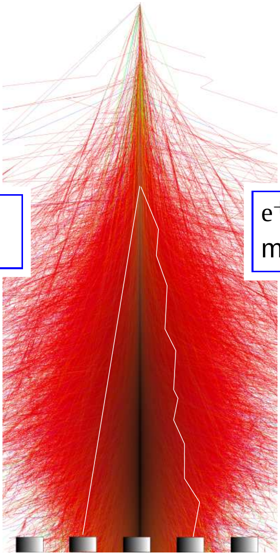
# RMS vs. $X_{max}$ - data shifted by syst. uncert.



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

muons:

$\approx$ straight line



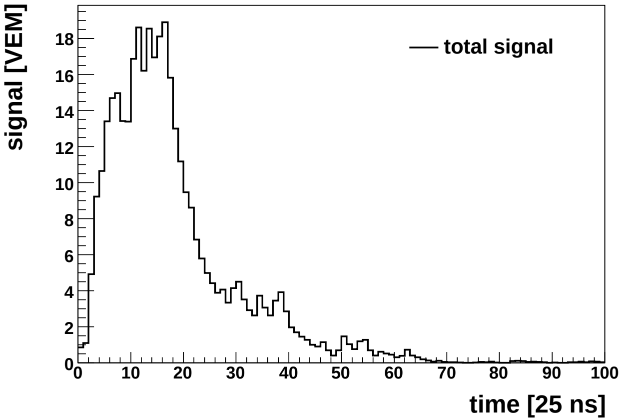
$e^+e^-$:

multiple scattering

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

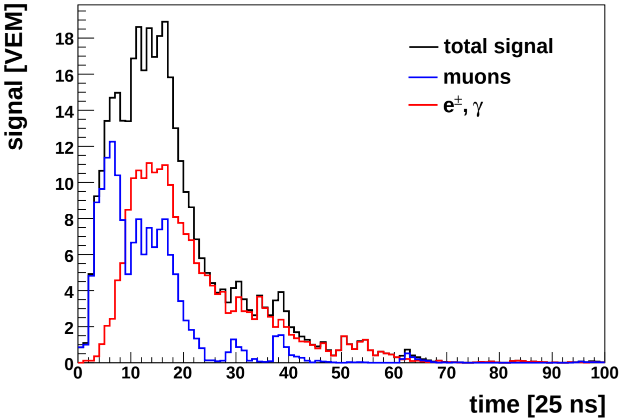
# Signal Rise Time ($t_{1/2}$)

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



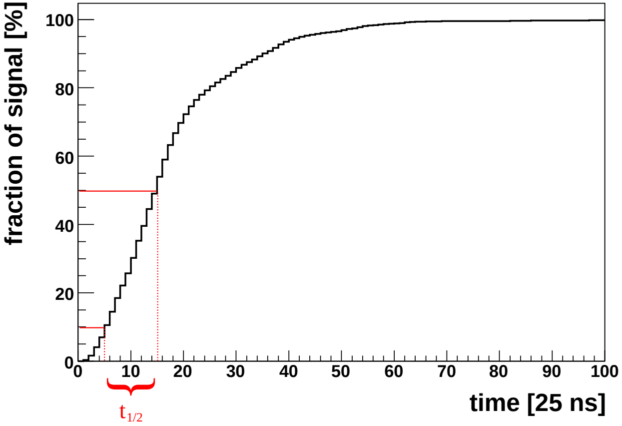
# Signal Rise Time ($t_{1/2}$)

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



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

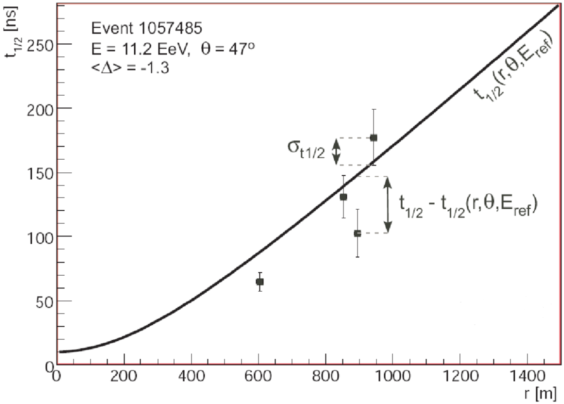
CORSIKA+GEANT4 of tank signal at 1000 m ($\theta = 38^\circ$)



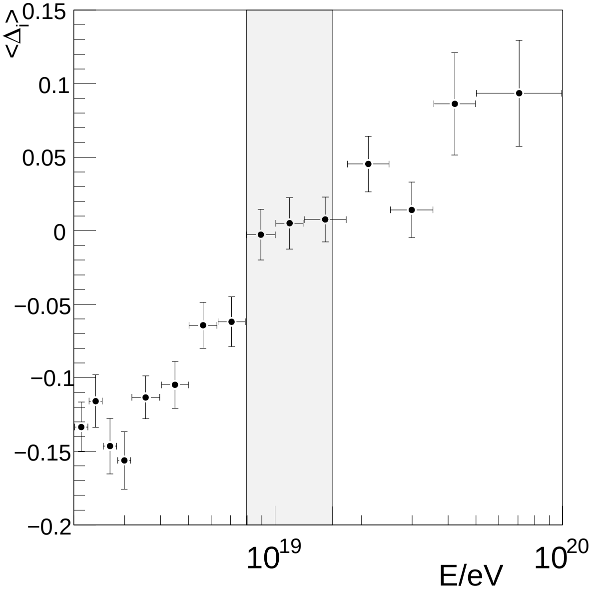
# Deviation to Average Rise Time: $\langle\Delta\rangle$

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

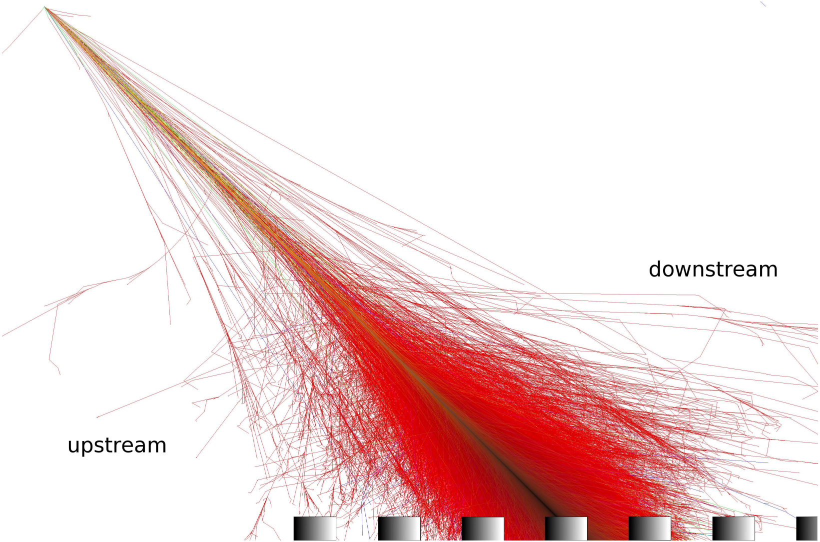
('benchmark' $\langle t_{1/2}\rangle$ at reference energy $E^\star$)



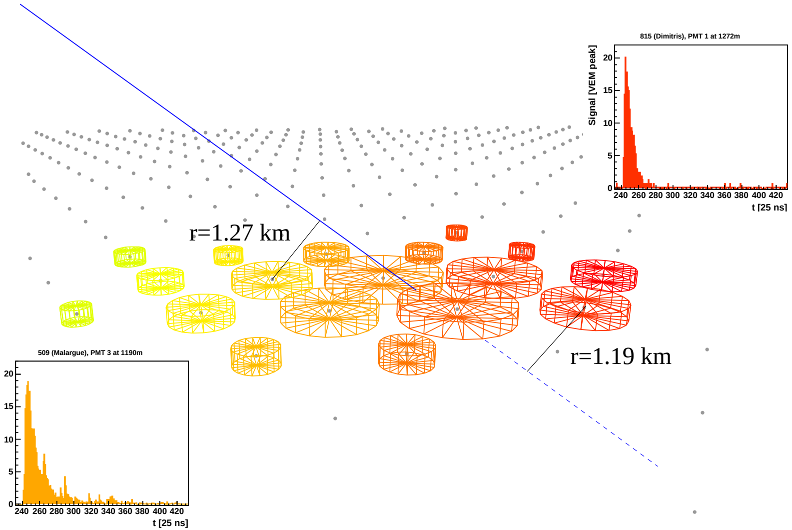
# ⟨Δ⟩ Elongation Rate



# Composition with SD - b) Rise Time Asymmetry

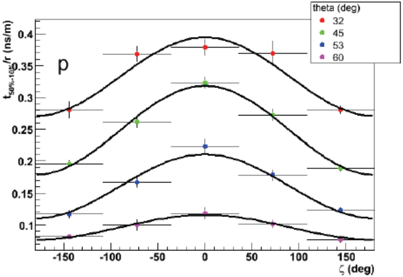


# Composition with SD - b) Rise Time Asymmetry

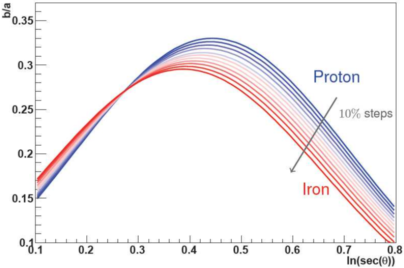


# Composition with SD - b) Rise Time Asymmetry

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



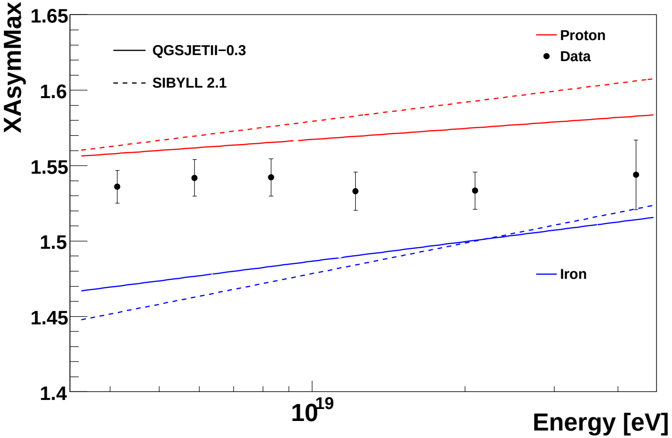

asymmetry for proton→iron




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

→ 'asymmetry' b/a

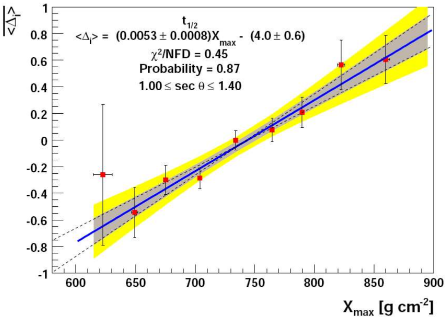
# Asymmetry Elongation Rate

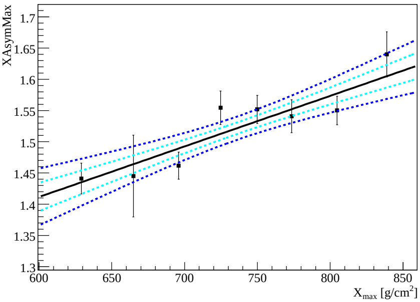



'XAsymMax': $\sec\theta$ position at which asymmetry $b/a$ is maximal

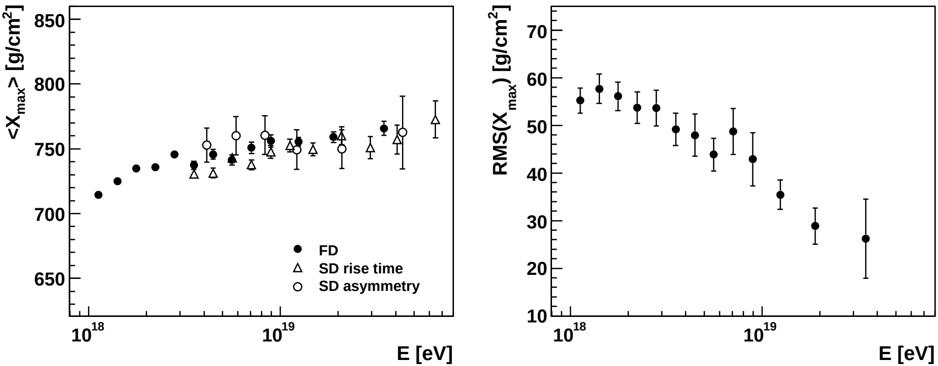
# 'Calibration' of SD with FD (preliminary)

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



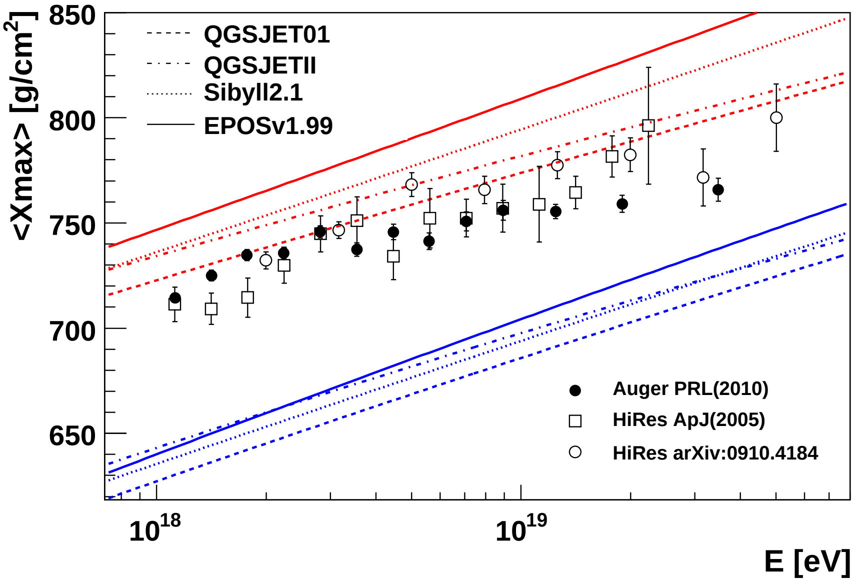
# Summary of Auger Results



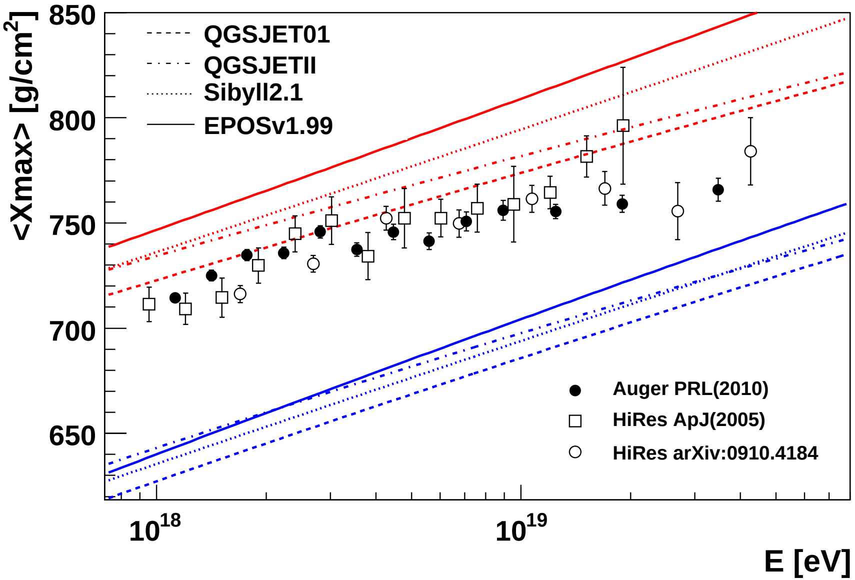

- elongation rate flattens at high energy
- fluctuations decrease with energy

FD paper accepted by PRL, SD paper in preparation

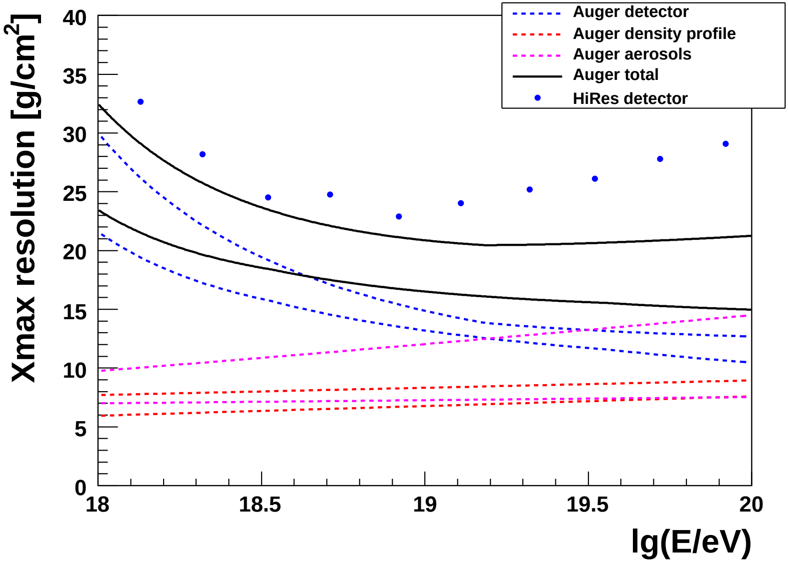
# Comparison of HiRes and Auger $\langle X_{\max} \rangle$



# HiRes energy ×0.85, no proton acceptance corr.

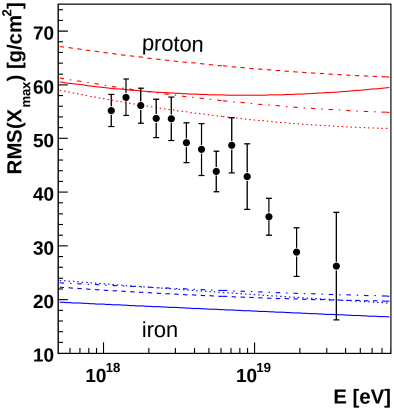


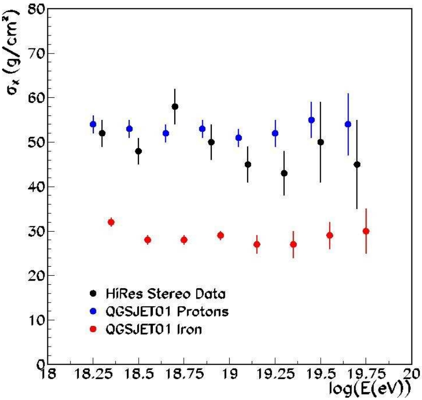
# Comparison of HiRes and Auger $X_{max}$ Resolution




(HiRes points from Nucl.Phys. B **190** (2009) 5)

# Comparison of HiRes and Auger $X_{max}$ Fluctuations




**Auger:** RMS(Xmax), corrected for resolution

**HiRes:** $\sigma_X$ =Gaussian-fit-truncated-at-two-times-RMS
not corrected for resolution