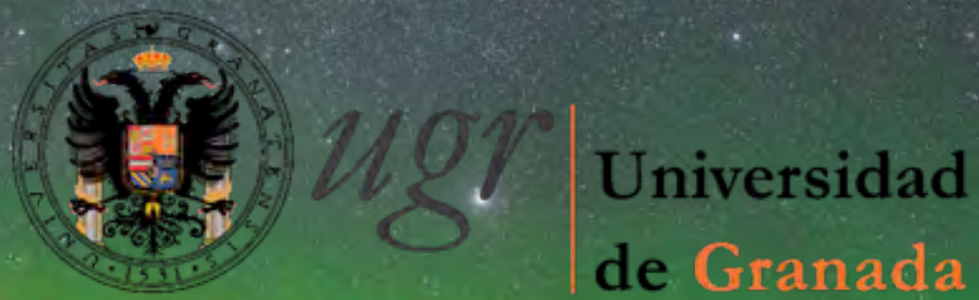
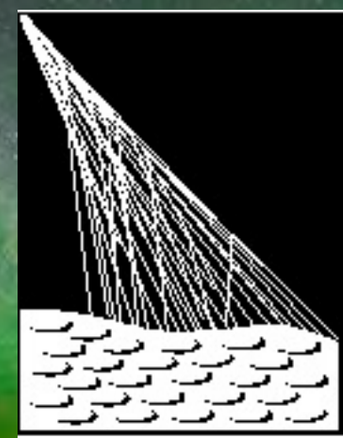
# Mass measurements with the Pierre Auger Observatory

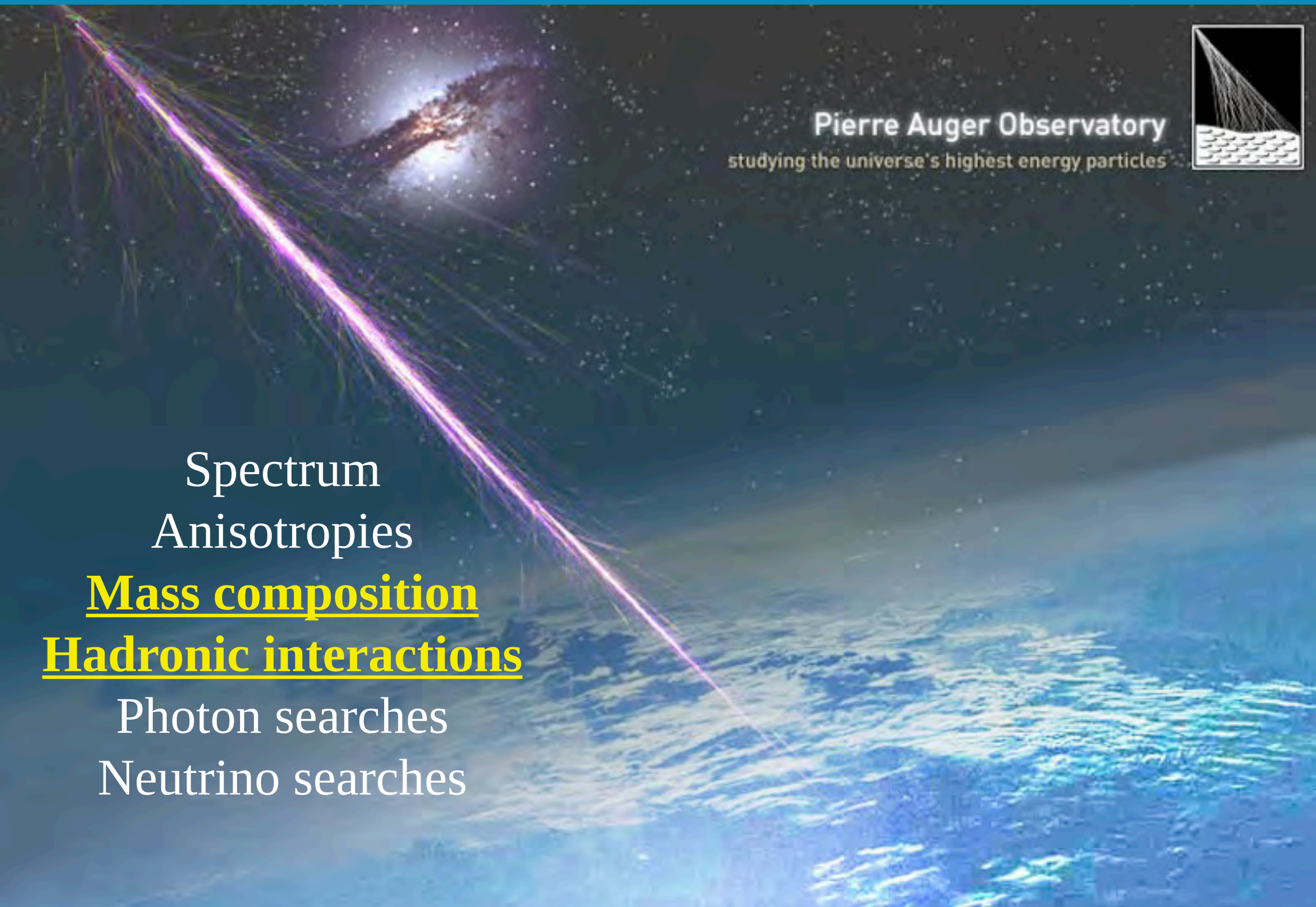
**L. Molina Bueno** for the Pierre Auger Collaboration

**STARS2015 - 3rd Caribbean Symposium on Cosmology, Gravitation, Nuclear and Astroparticle Physics**



# Physics at the Pierre Auger Observatory




Spectrum

Anisotropies

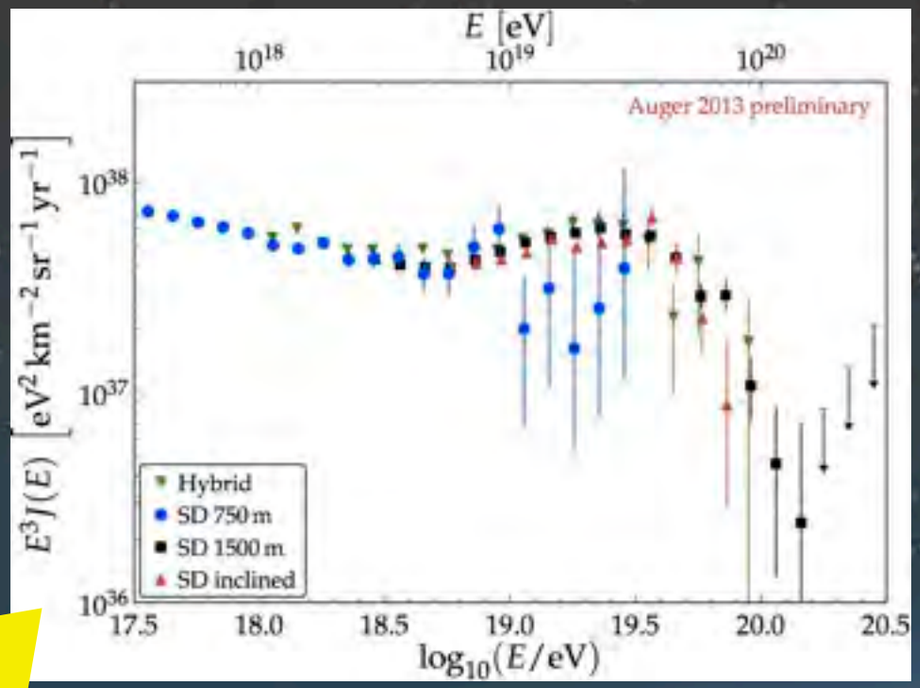
**Mass composition**

**Hadronic interactions**

Photon searches

Neutrino searches

# Physics at the Pierre Auger Observatory

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**Mass composition**

**Hadronic interactions**

Photon searches

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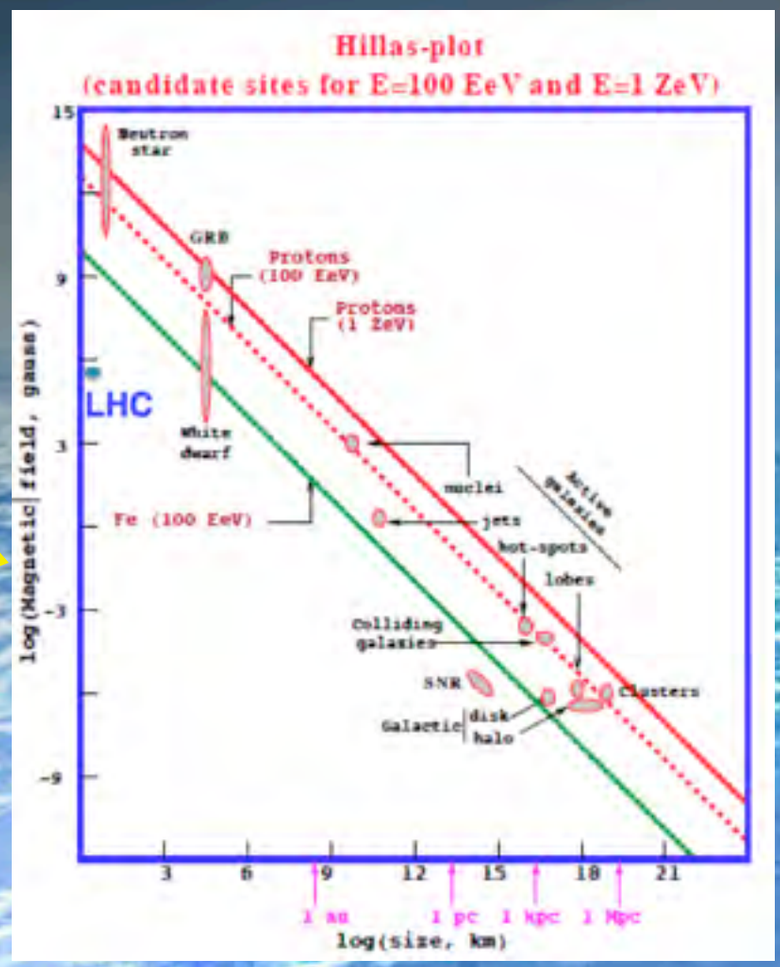


# Mass composition observables

**Fluorescence detector**

EM Longitudinal profile

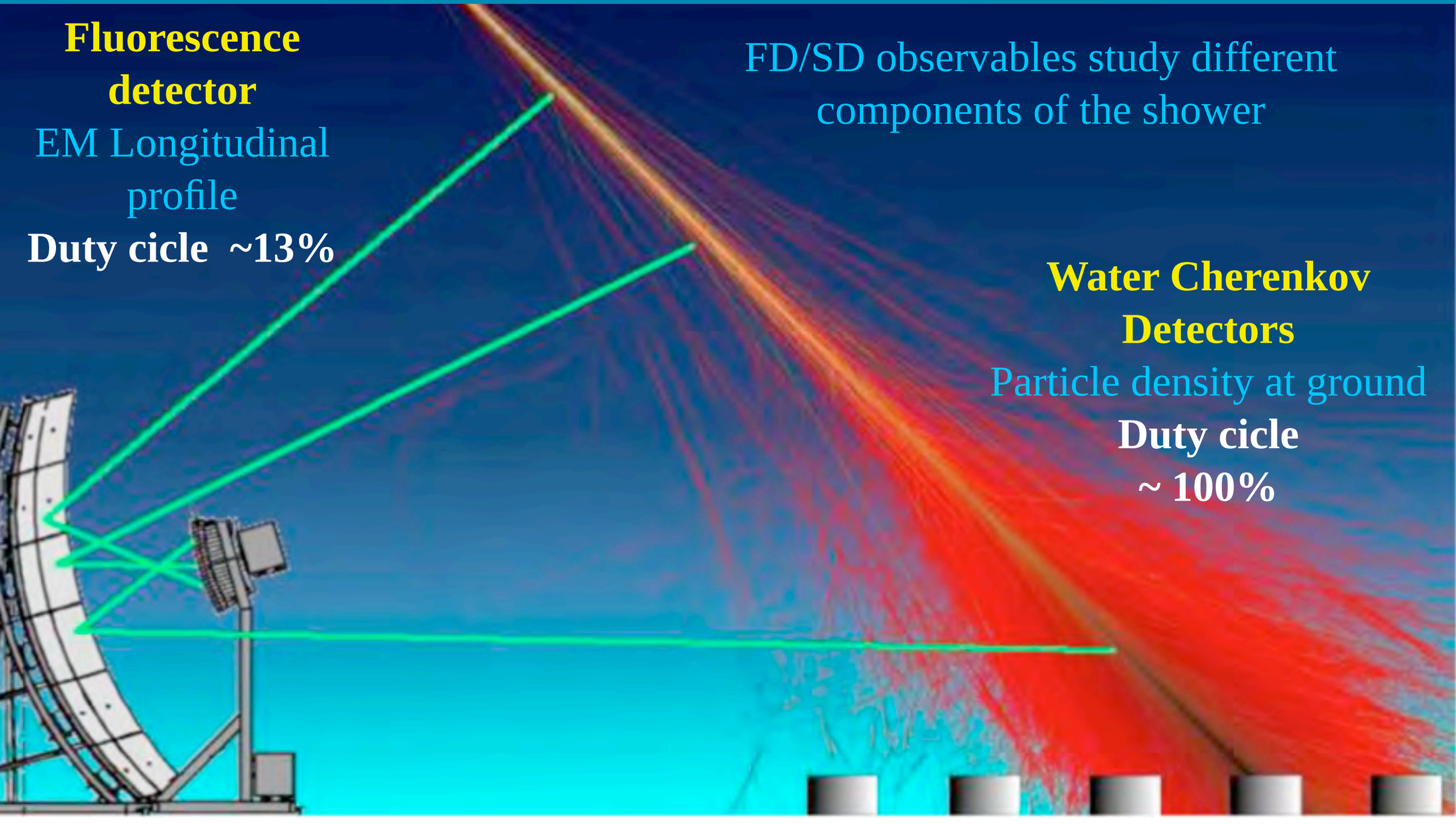
**Duty cicle ~13%**

FD/SD observables study different components of the shower

**Water Cherenkov Detectors**

Particle density at ground

**Duty cicle ~ 100%**



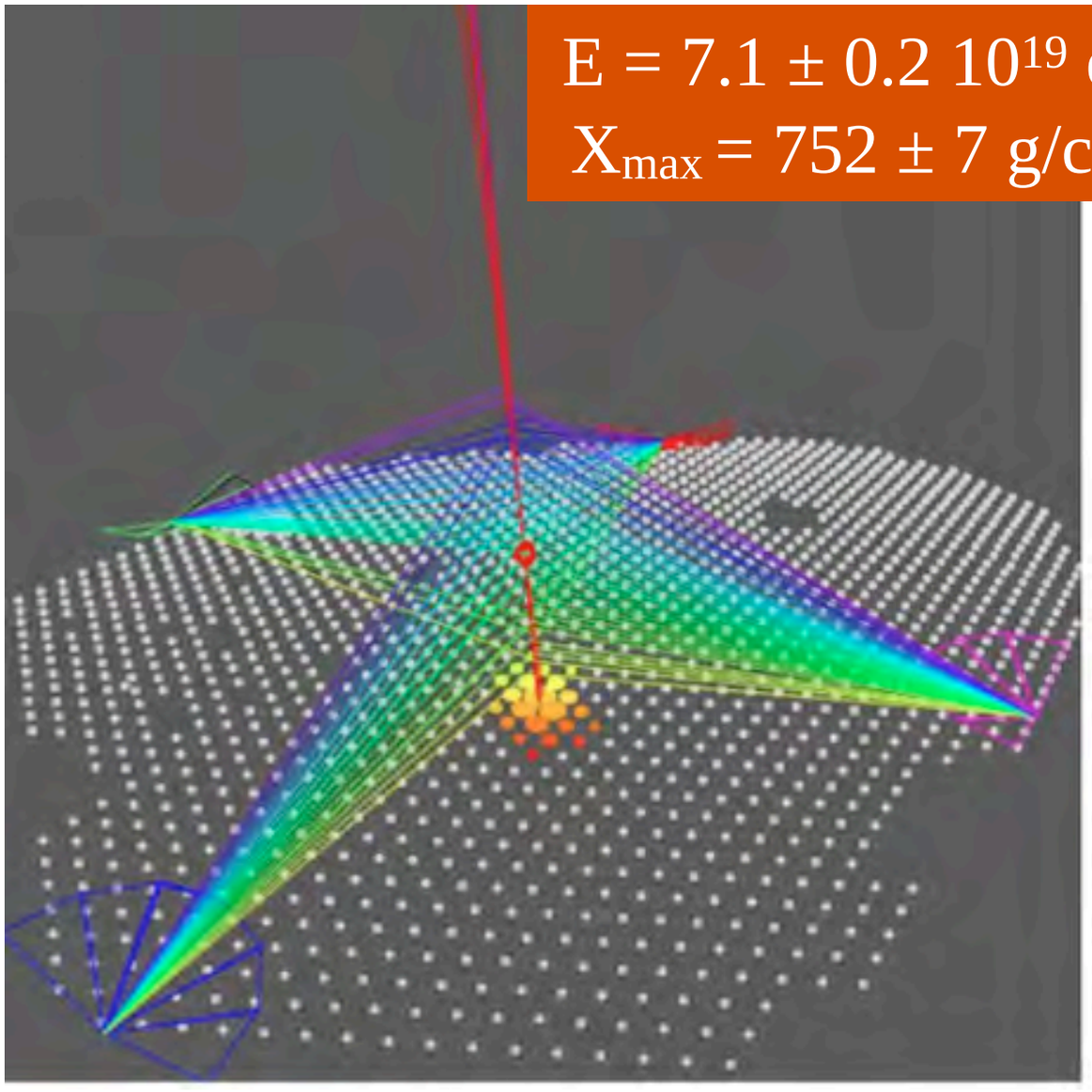
**Hybrid**

$X_{max}$ ≡ Depth at which the energy deposit reaches its maximum

**SD**

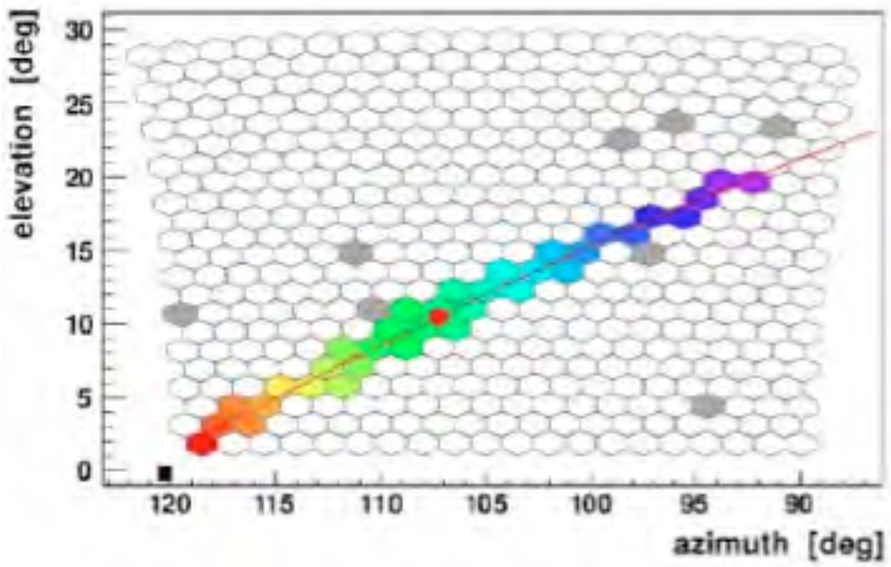
$X\mu_{max}$ ≡ Depth at which the production of muons is maximum

# $X_{max}$

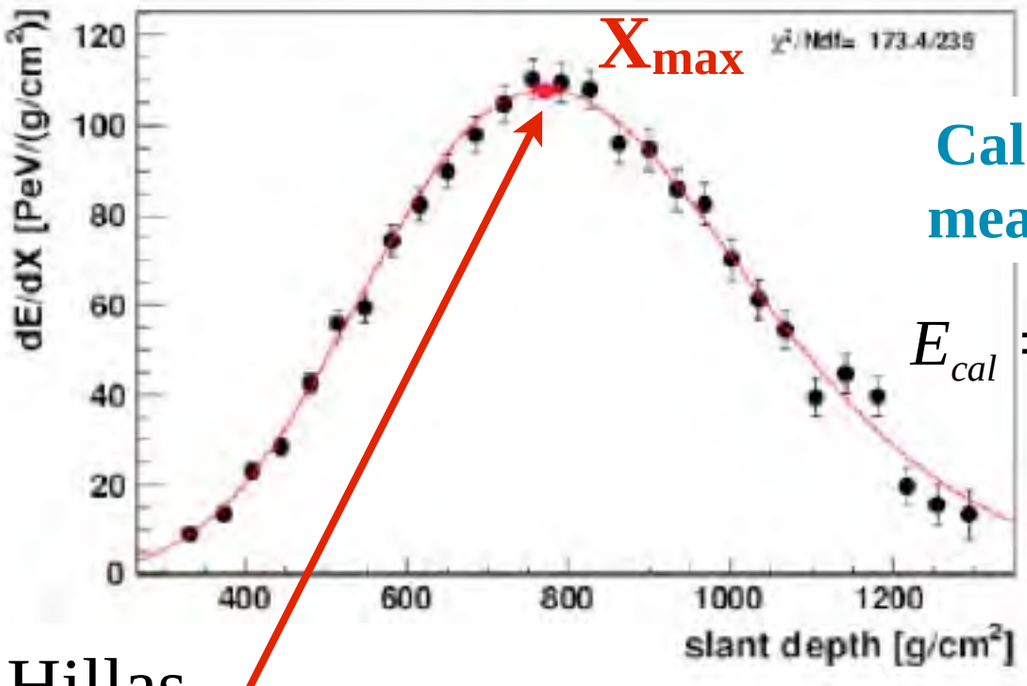


$E = 7.1 \pm 0.2\ 10^{19}$ eV

$X_{max} = 752 \pm 7$ g/cm$^2$

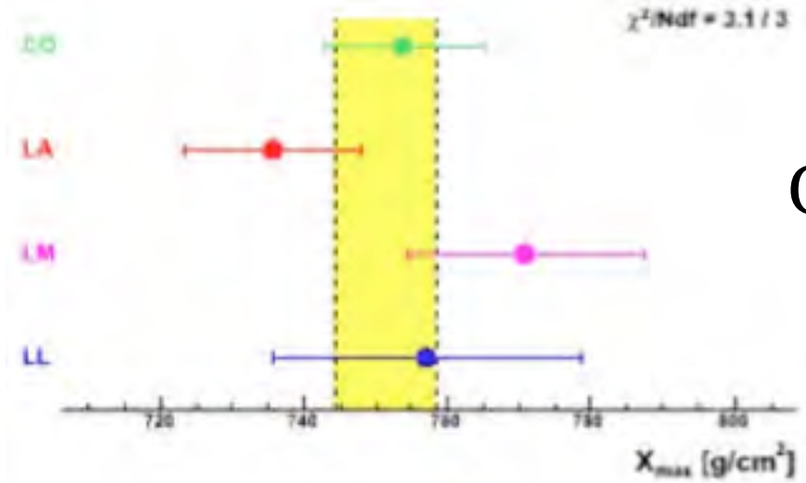



Longitudinal profile




**Calorimetric measurement**

$$E_{cal} = \int dX \frac{dE}{dX}$$




Gaisser-Hillas

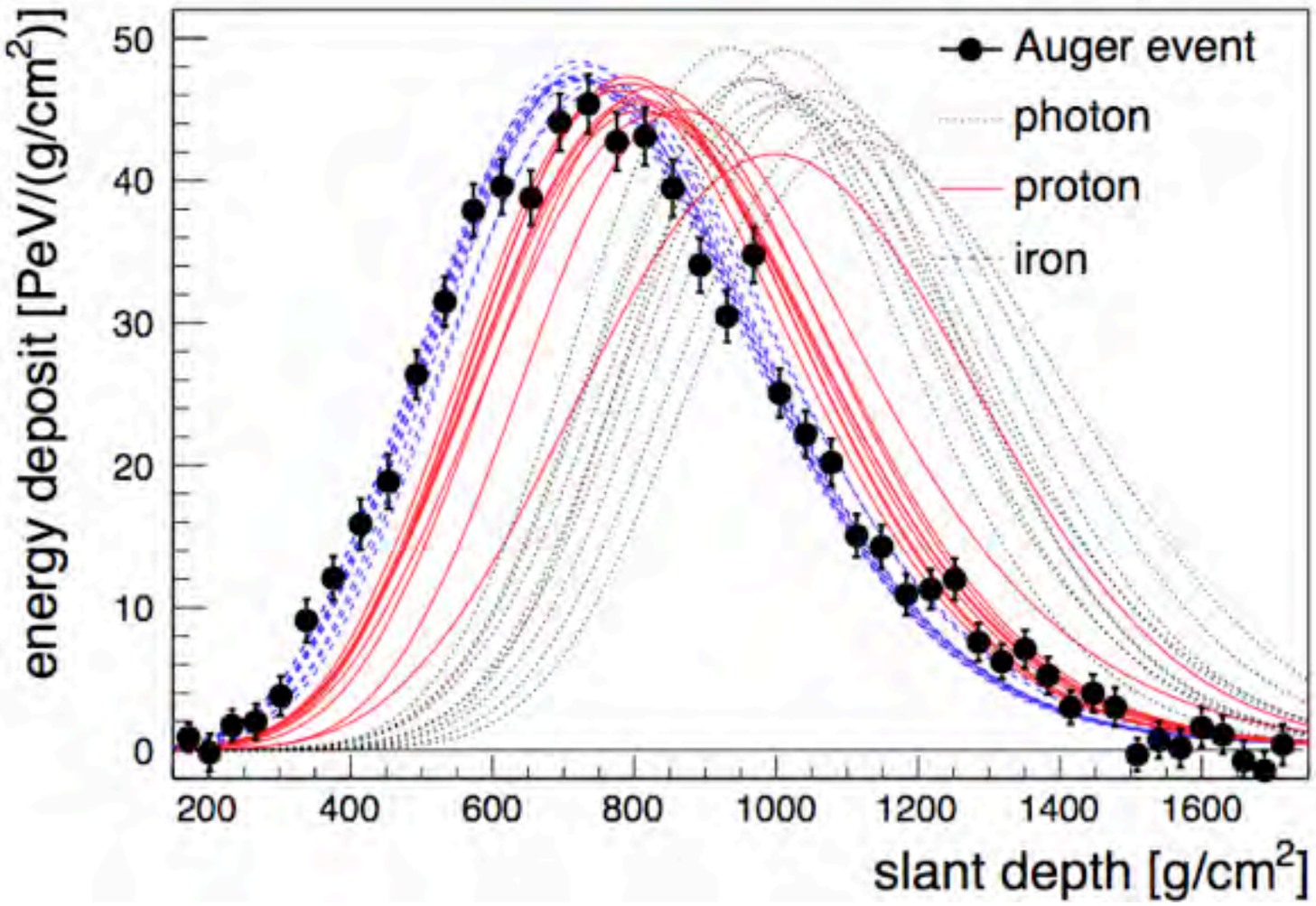
$$N(X) = N_{max}\left(\frac{X - X_0}{X_{max} - X_0}\right)^{\frac{X_{max} - X_0}{\Lambda}} \exp\left(\frac{X_{max} - X}{\Lambda}\right)$$

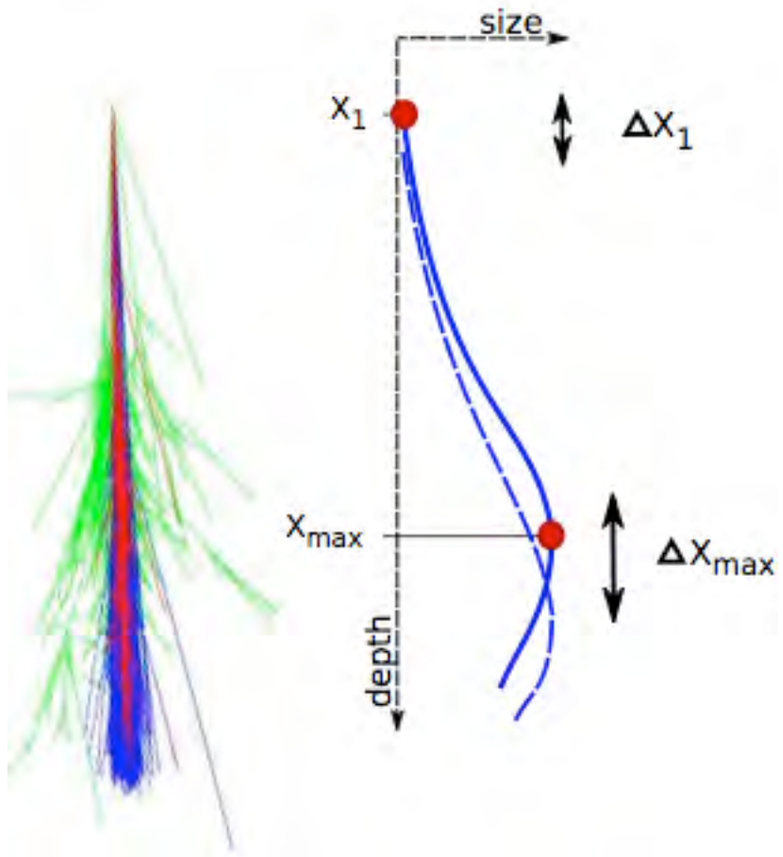
# $X_{max}$: Is sensitive to mass composition?

All mass composition observables based on the same idea → **Superposition model**

Showers from **heavy nuclei** will develop **higher, faster** and with **less shower to shower fluctuations** than **lighter** showers.

$$\left\langle X^{A}_{\max}(E_0)\right\rangle = \left\langle X^{p}_{\max}(E_0/A)\right\rangle = \left\langle X^{p}_{\max}\right\rangle - X_0 \ln A$$




Maximum distribution

Fluctuations shower to shower →

$$f(X_{\max}) = \sum_i p_i f_i(X_{\max})$$

Fraction of primary particle of type i

# Event selection

PRD 90 1220005 2014

Data from:**1/12/2004-31/12/2012**

## Pre-selection

Good data taking conditions

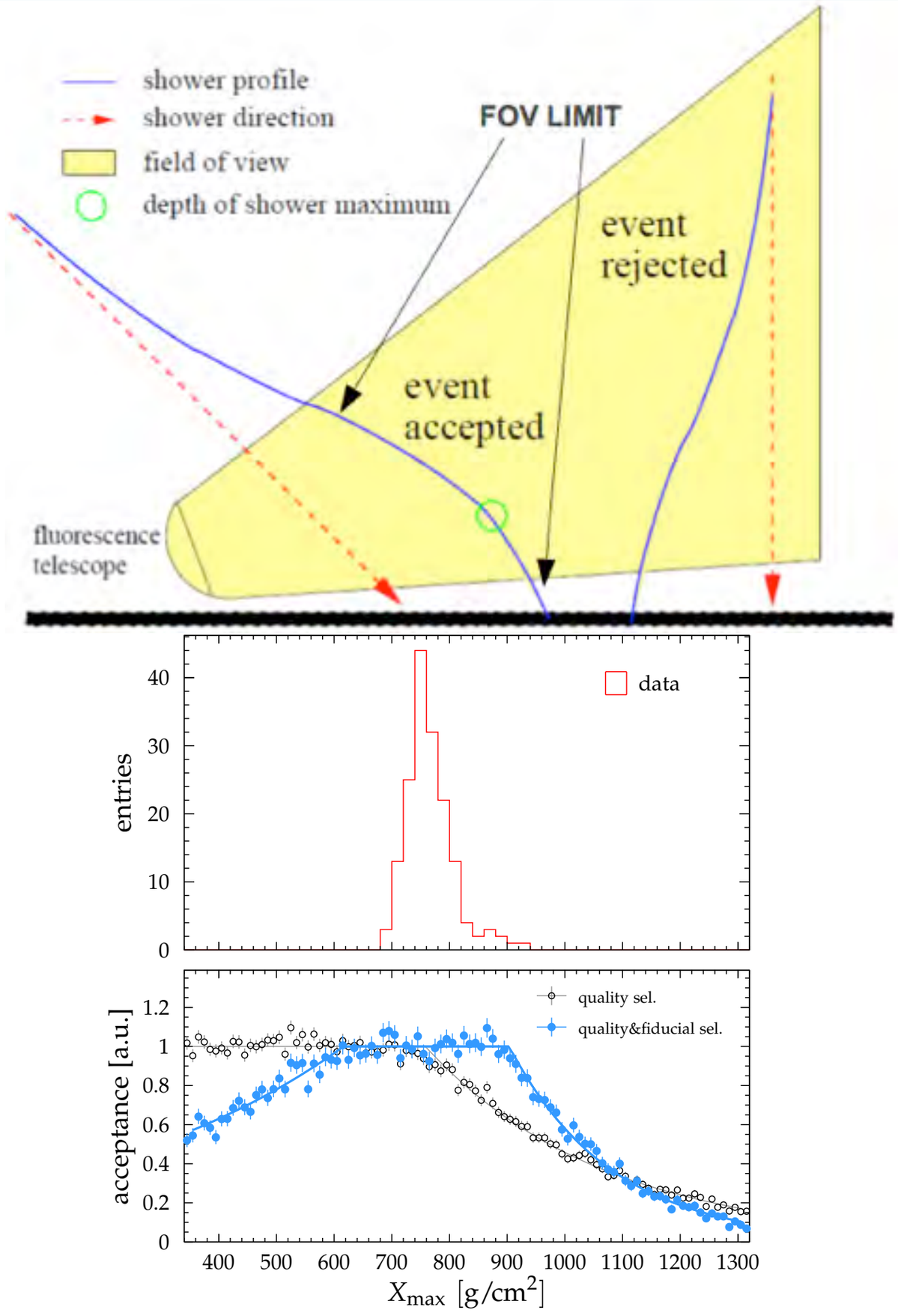
## Quality cuts

To avoid distortions in $X_{max}$ distributions.

## Fiducial cuts

Minimize the distortions due to the FOV of the telescopes.

Uniform acceptance for all $X_{max}$.



# $X_{max}$ distributions

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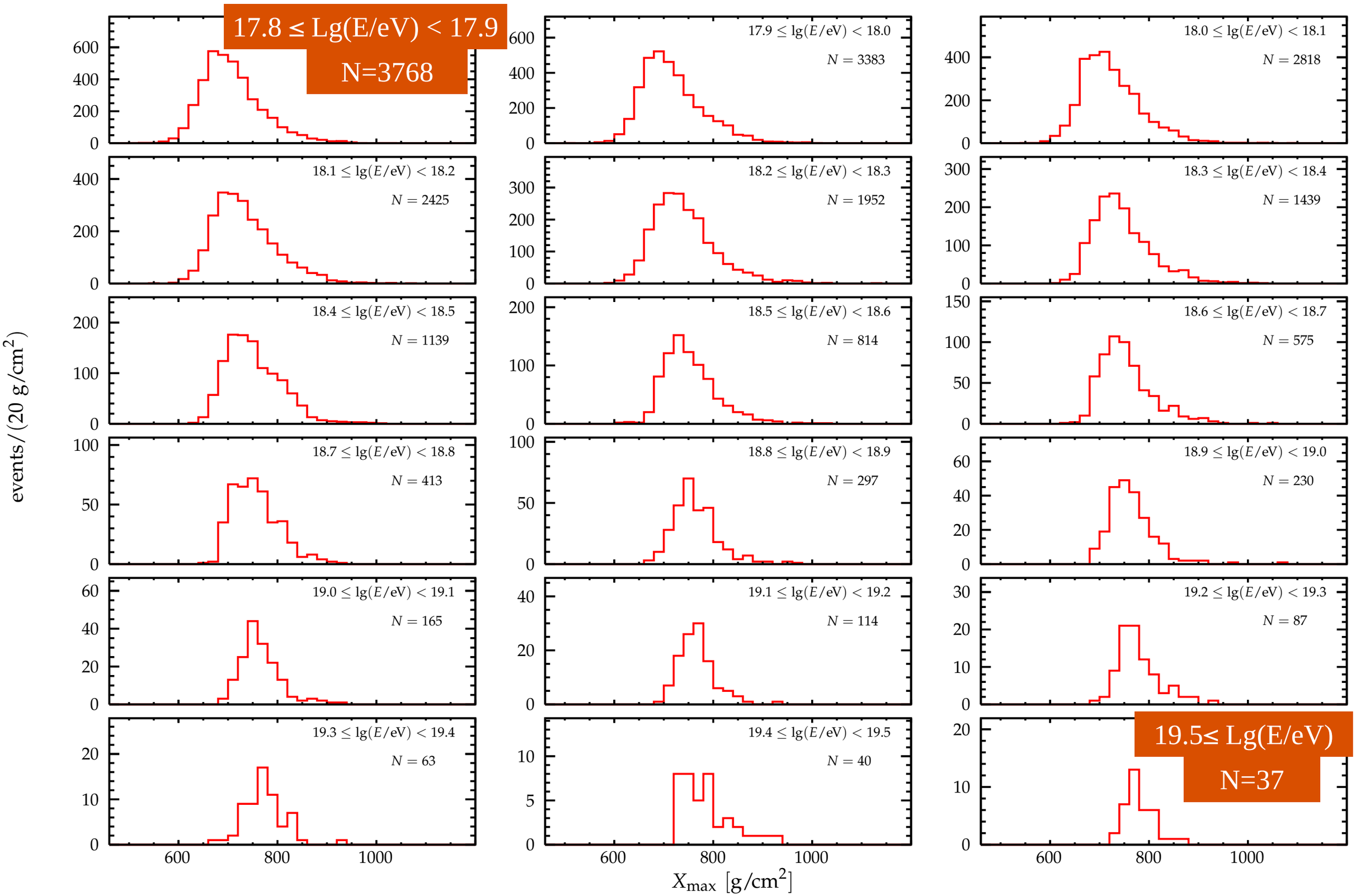

# $X_{max}$ moments

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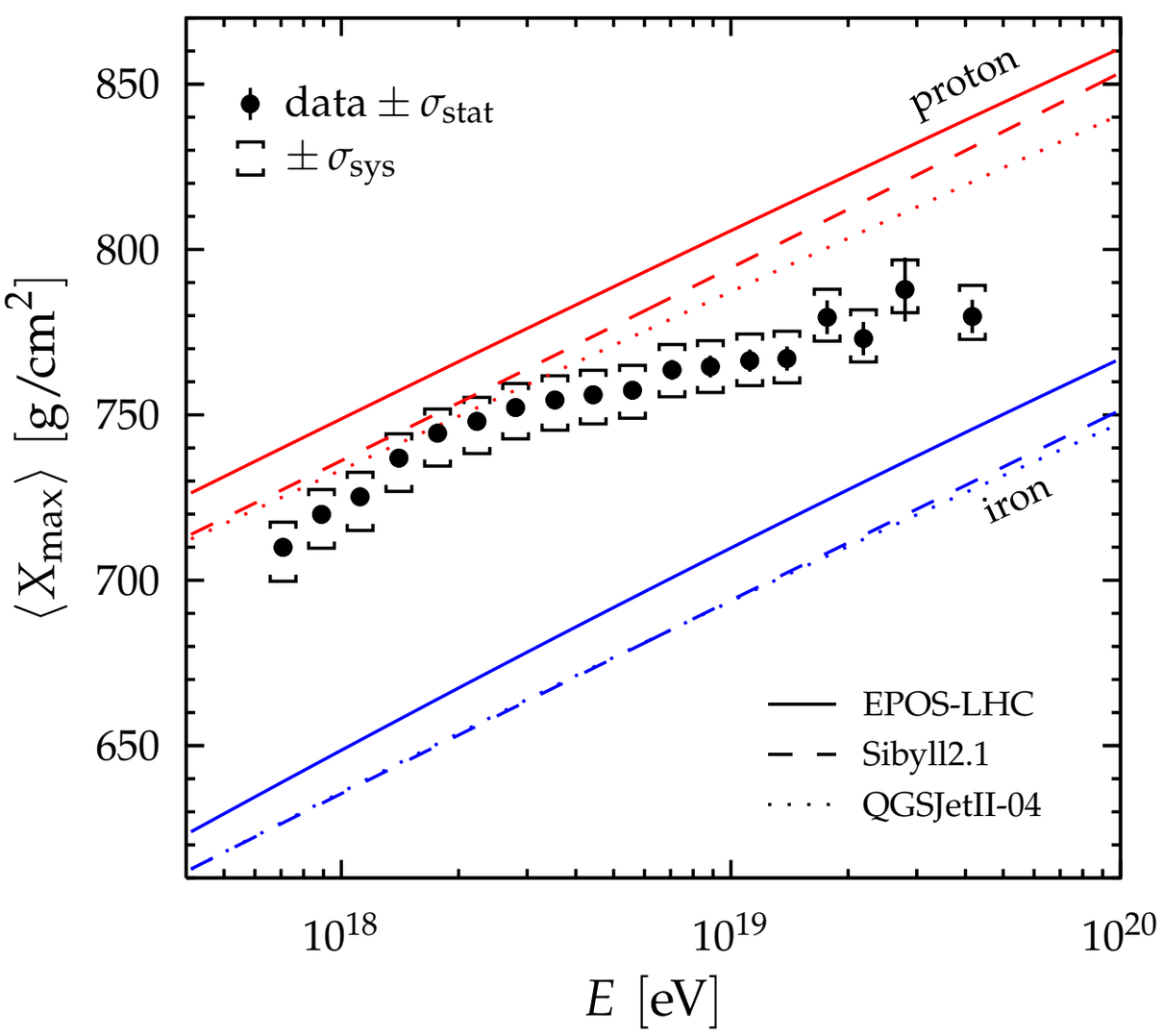
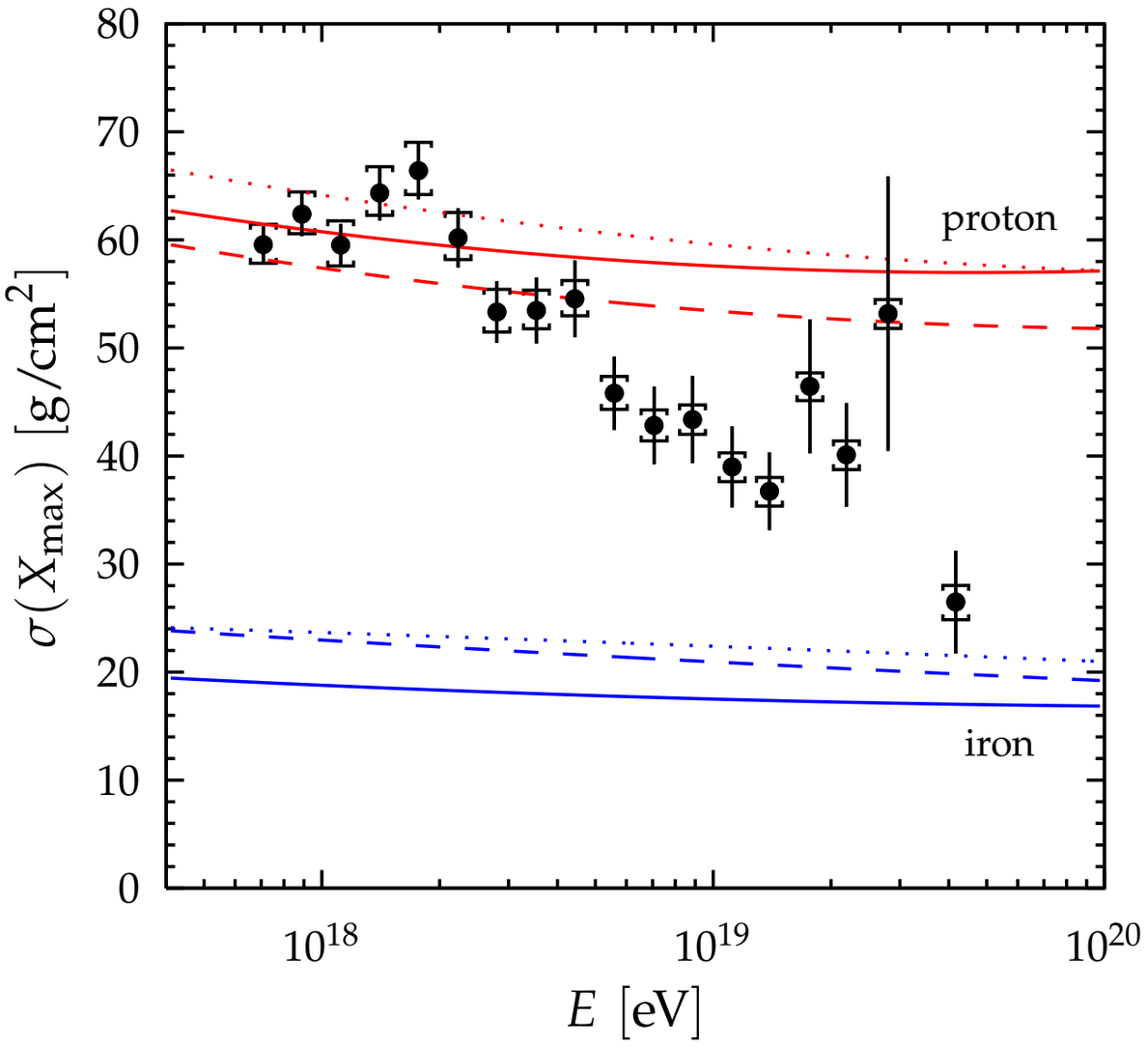
Resolution better than 20 g/cm² Syst.uncertainty below 15 g/cm²




Data better described with a break line than with a linear fit.

**Low energy**

$$D_{10} = 86.4 \pm 5.0(stat.)^{+3.8}_{-3.2}(sys.) g/cm^2/decade$$

**Energy break**

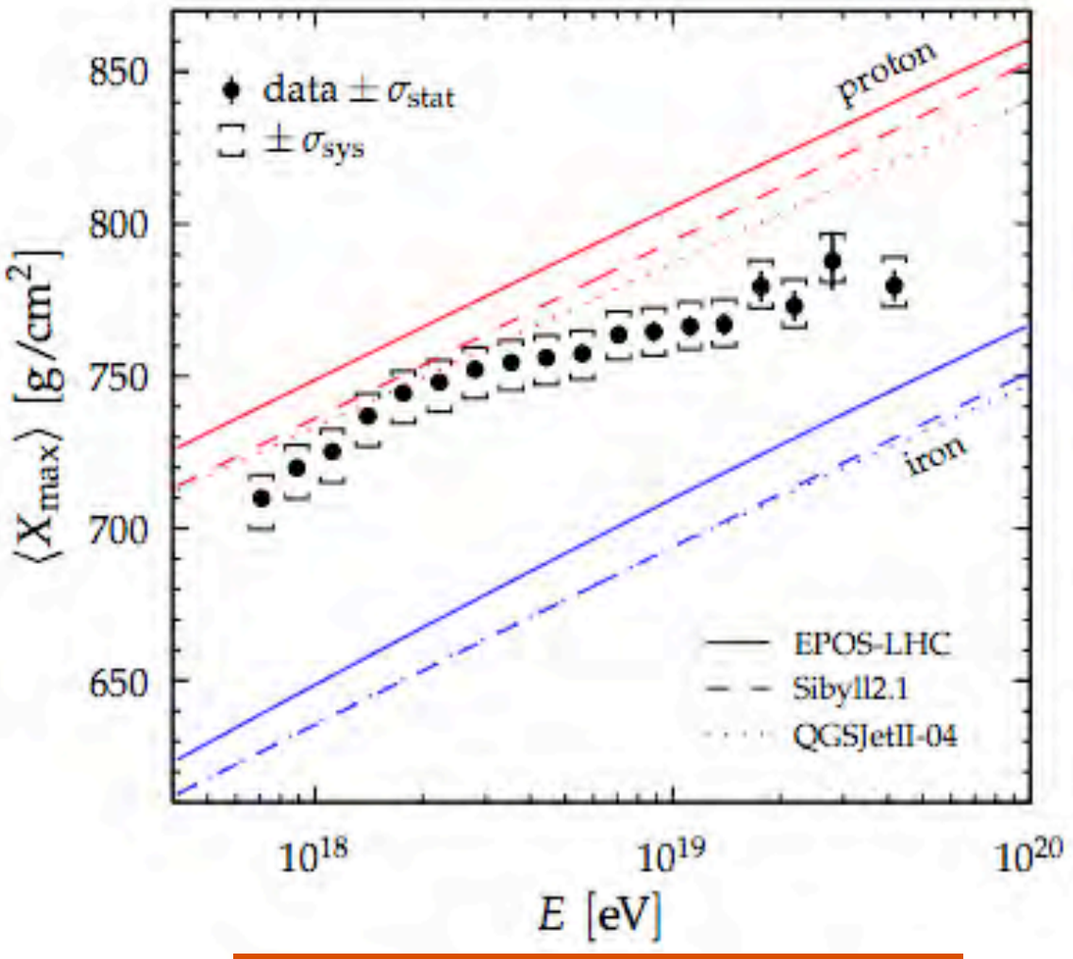
$$\lg(E_0/eV) = 18.27 \pm 0.04(stat.)^{+0.06}_{-0.07}(sys.)$$

**High energy**

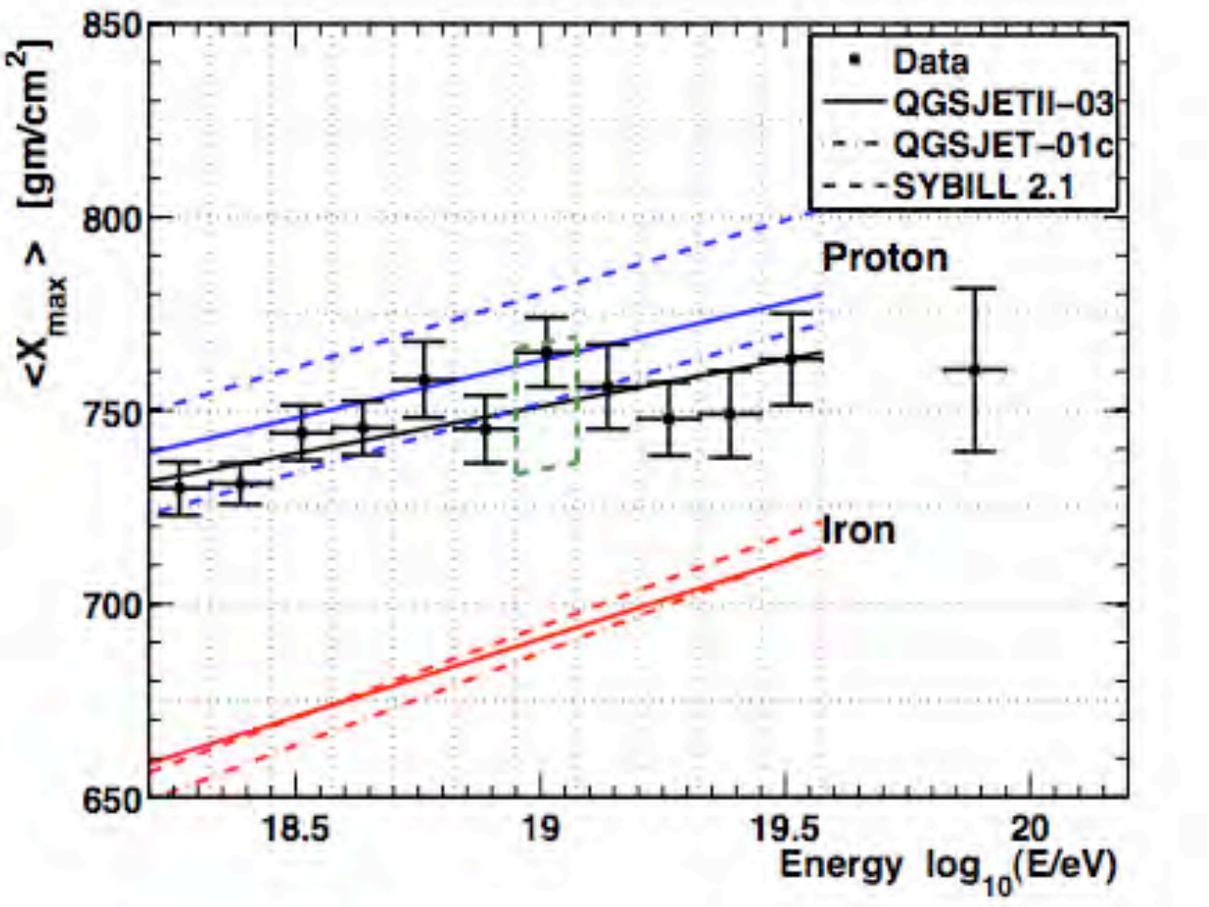
$$D_{10} = 26.4 \pm 2.5(stat.)^{+7.0}_{-1.9}(sys.) g/cm^2/decade$$

# Auger/Telescope Array data

## Report of Joint Analysis Working Group
## arXiv 1503.07540




Auger 19759 events
Surface~3000km$^2$



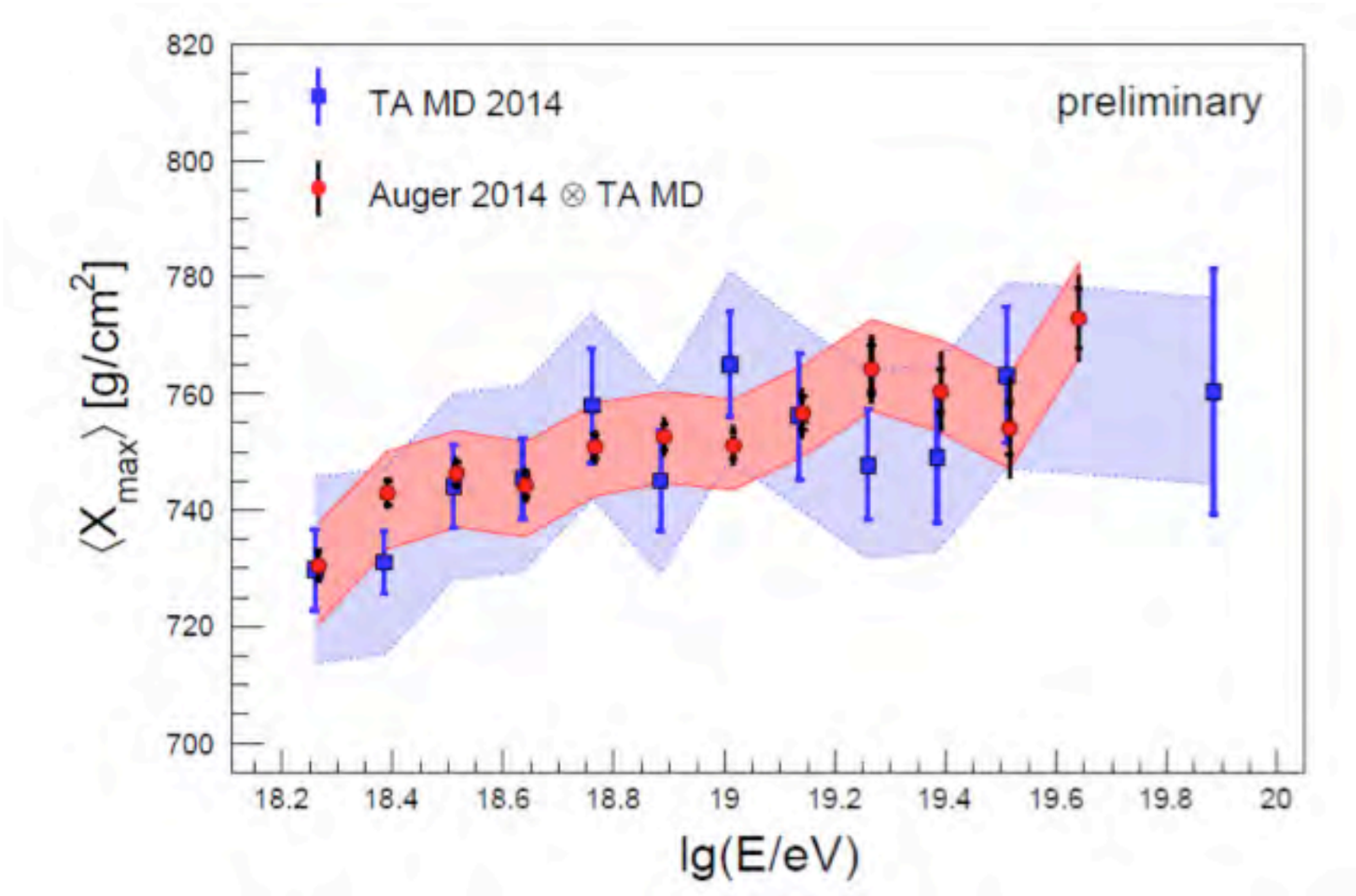

Telescope array 822 events
Surface~762km$^2$

**Direct comparison is not possible because different approaches to analysis.**

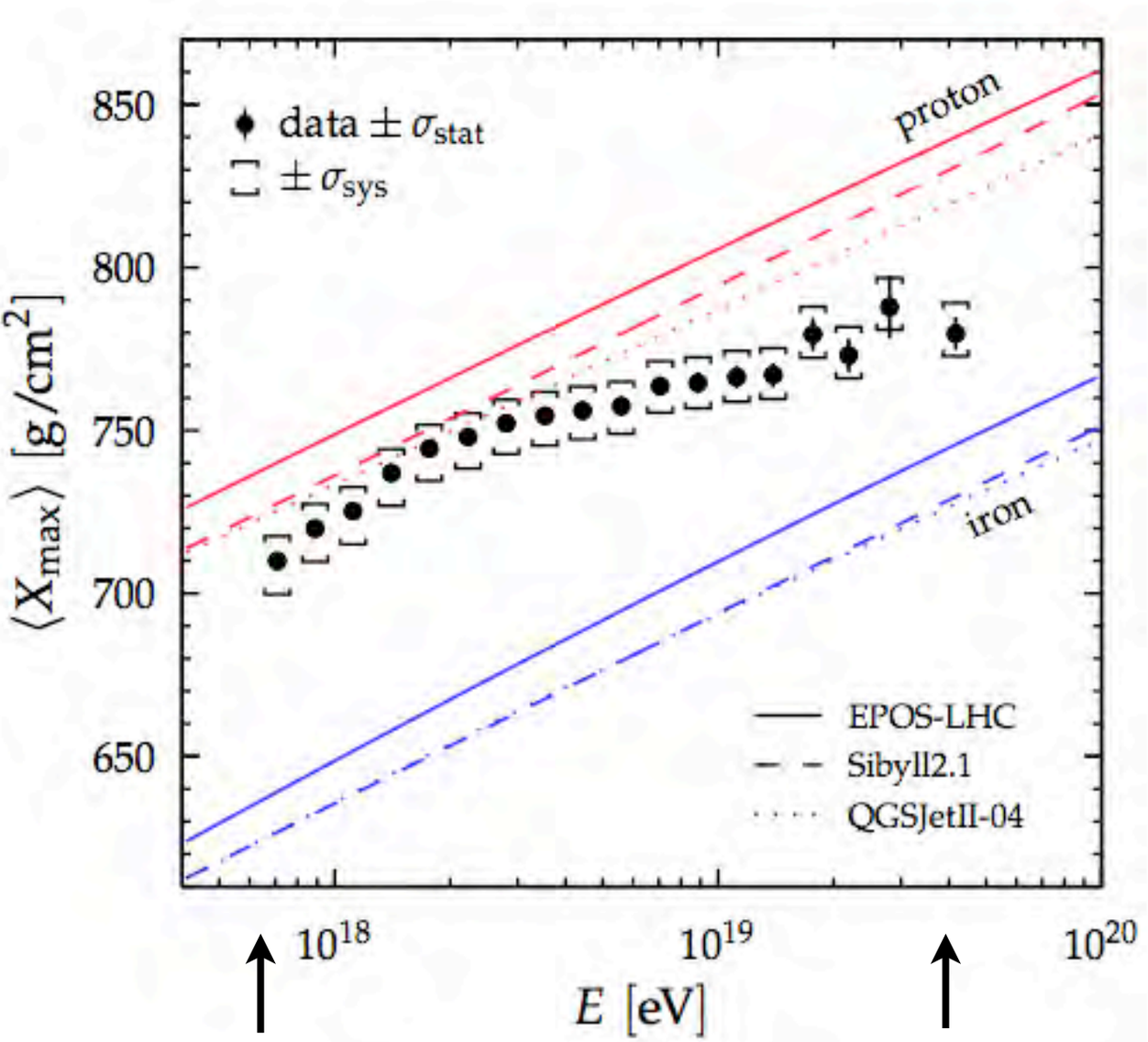
# Auger/Telescope Array data

Measured distributions by Auger described in terms of p,N,He and Fe fractions.
These fractions fully simulated and analyzed by TA using the same procedure applied to their data.

$$\Delta X_{\max} = 2.9 \pm 2.7(statistical) \pm 18(syst) g/cm^2$$



# $X_{max}$ interpretation




Energy in C.M.
4×LHC ($\sqrt{s}$ = 8TeV)

Energy in C.M.
40×LHC

Hadronic interaction models at those energies are extrapolations of measurements at LHC energies.

**Model predictions have to be carefully treated**

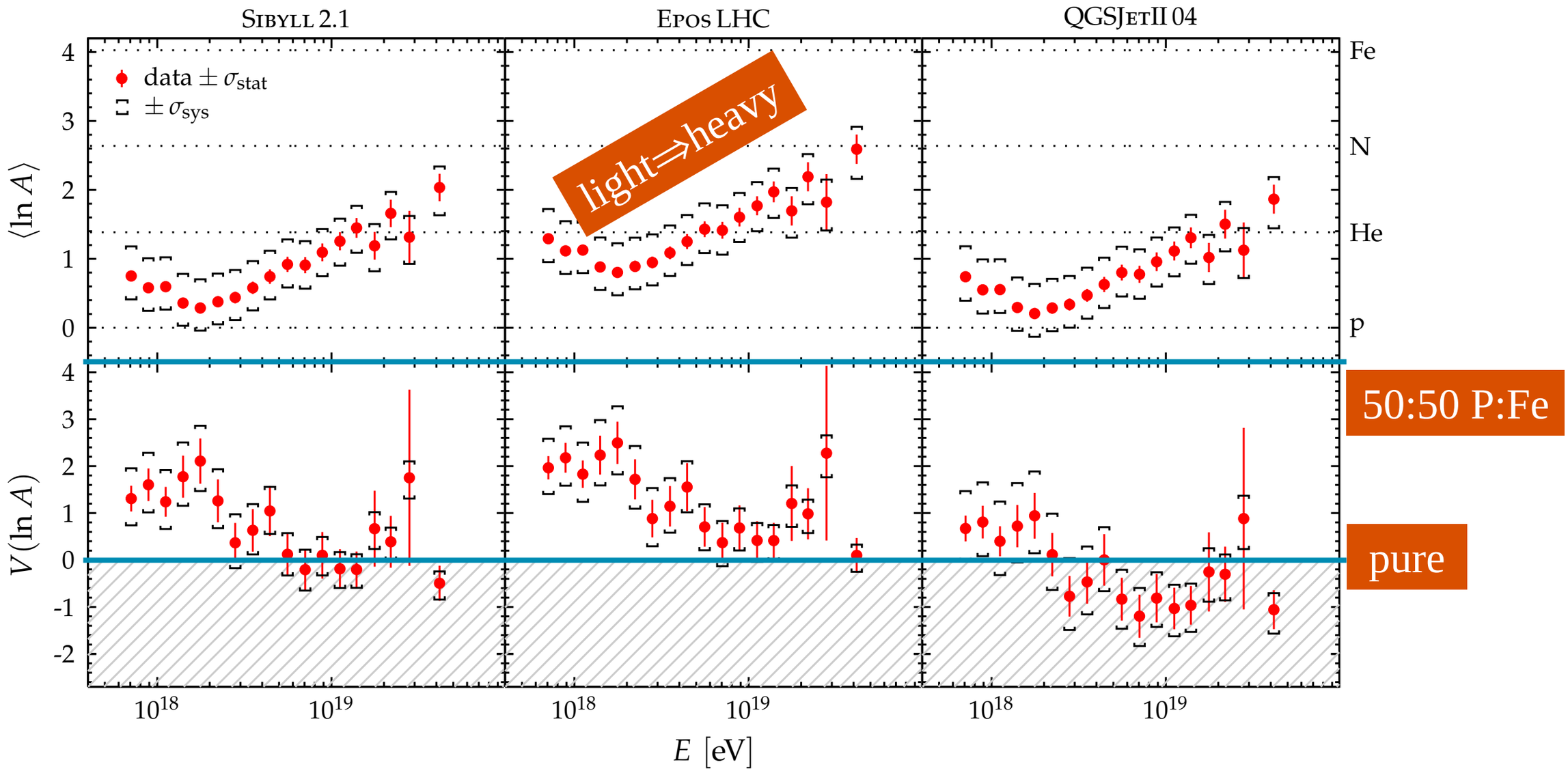
# $X_{max}$ interpretation

PRD 90 1220005 2014

## Superposition model

$$\langle X_{max} \rangle \approx \langle X^{p}_{max} \rangle - D_p \langle \ln(A) \rangle$$
$$\sigma^2[X_{max}] \approx \langle \sigma_i^2 \rangle + D_p^2 \sigma^2[\ln(A)]$$

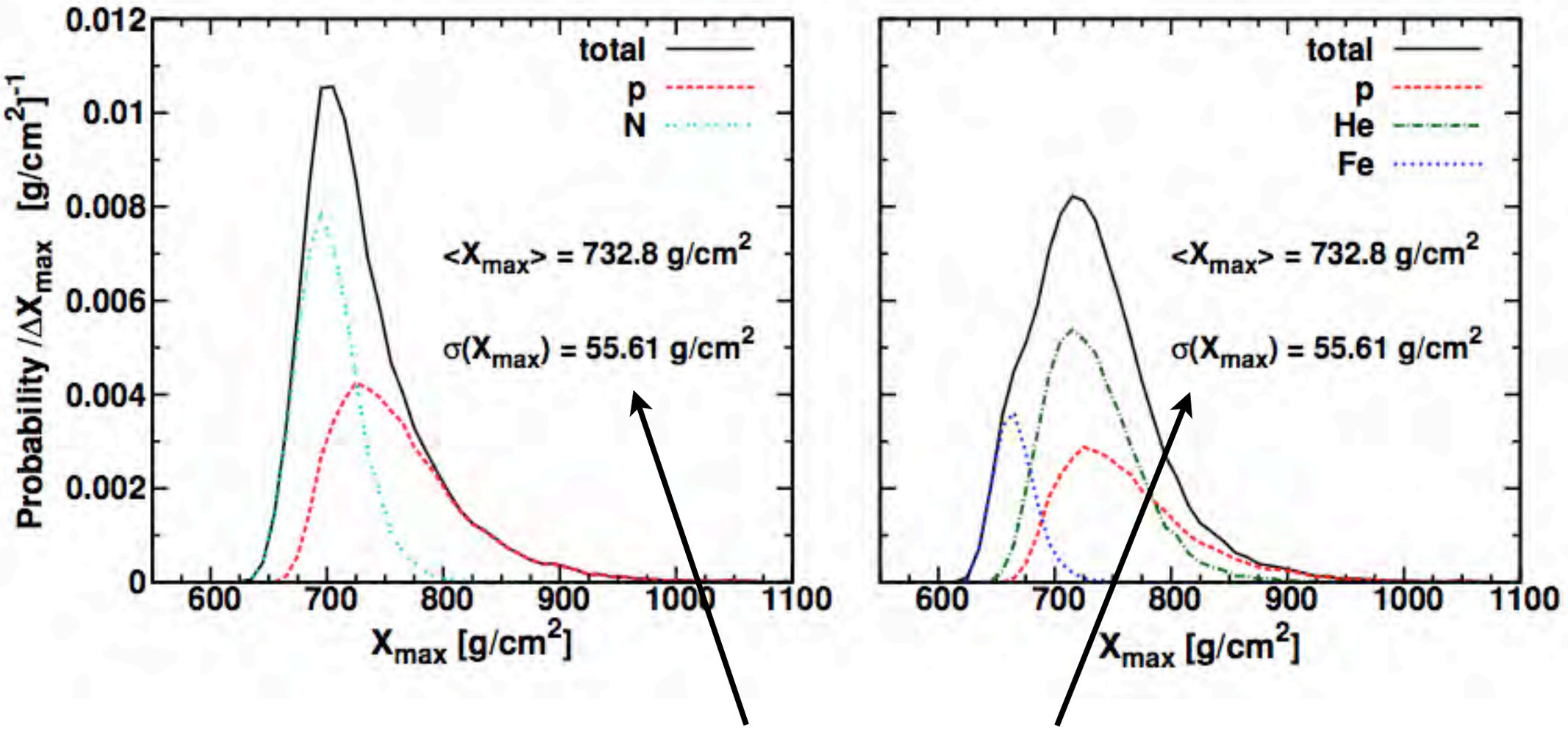
$$D_p = \frac{d < X^{p}_{\max} >}{d \ln E}$$




**V(lnA) measures the purity of the sample**

# $X_{max}$ interpretation

PRD 90 1222006 2014

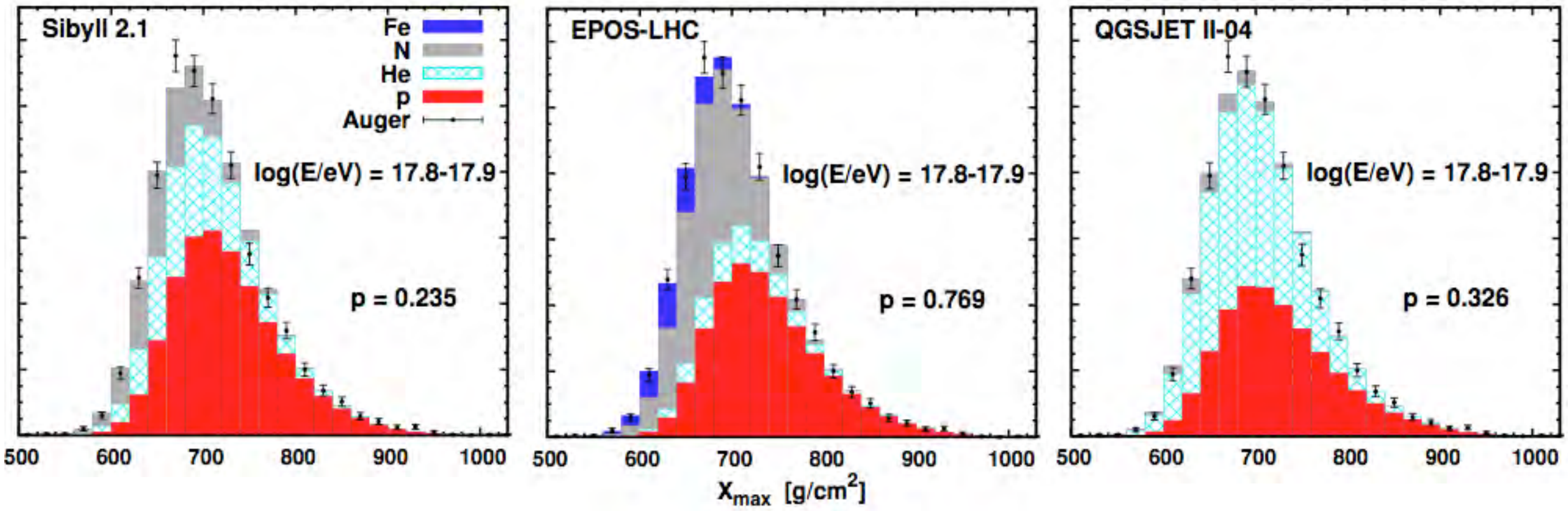



Different mixes of composition and identical moments

The $X_{max}$ distribution is compared to MC predictions formed varying nuclear fractions.
A binned maximum-likelihood discriminator is used to choose the best fit fractions.

# Pr +He + N + Fe

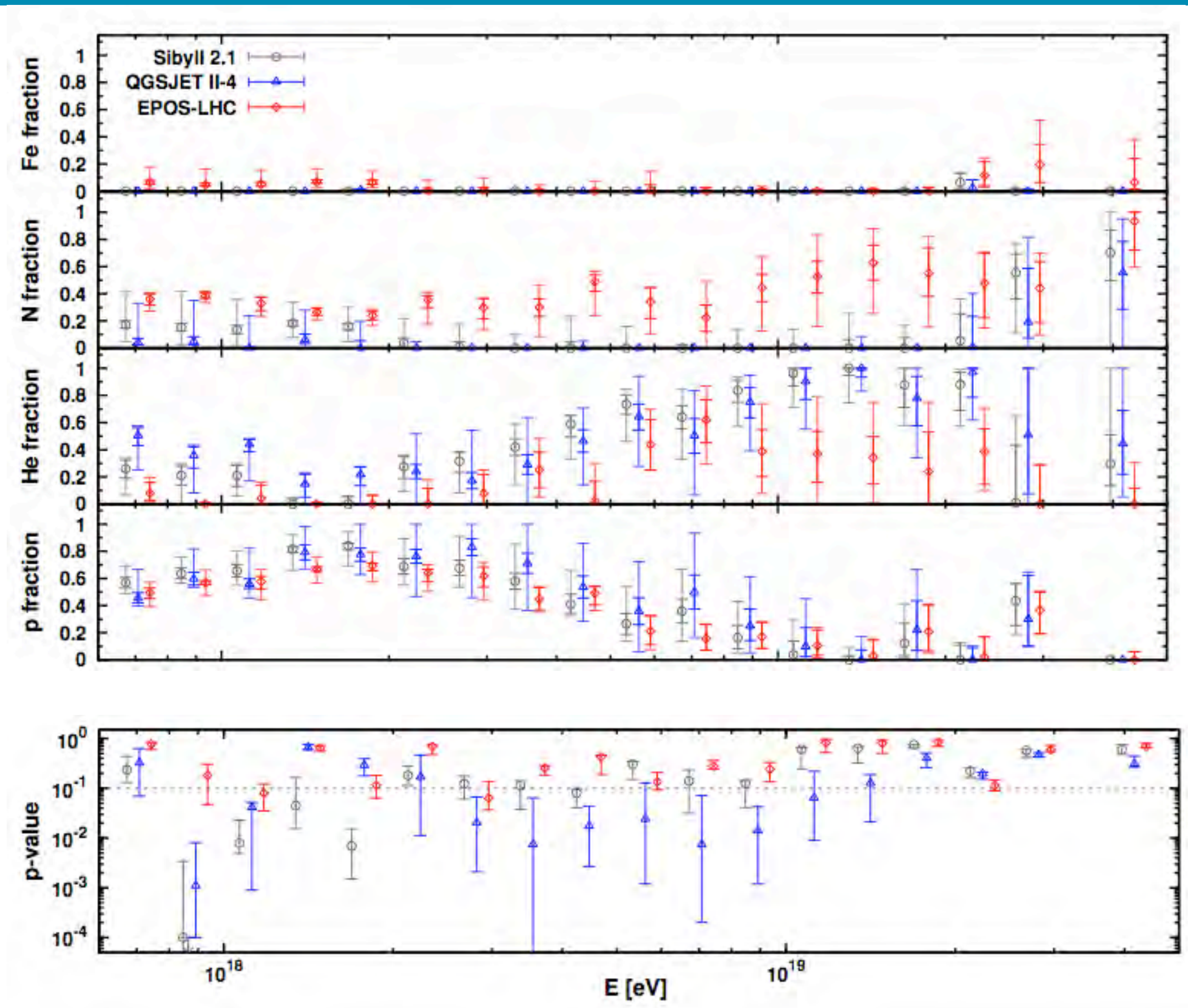
PRD 90 1222006 2014




Reasonable agreement with data.
EPOS-LHC describes better the data
Composition with Pr:Fe and Pr:Fe:N does not reproduce data

# Pr +He + N + Fe

PRD 90 1222006 2014



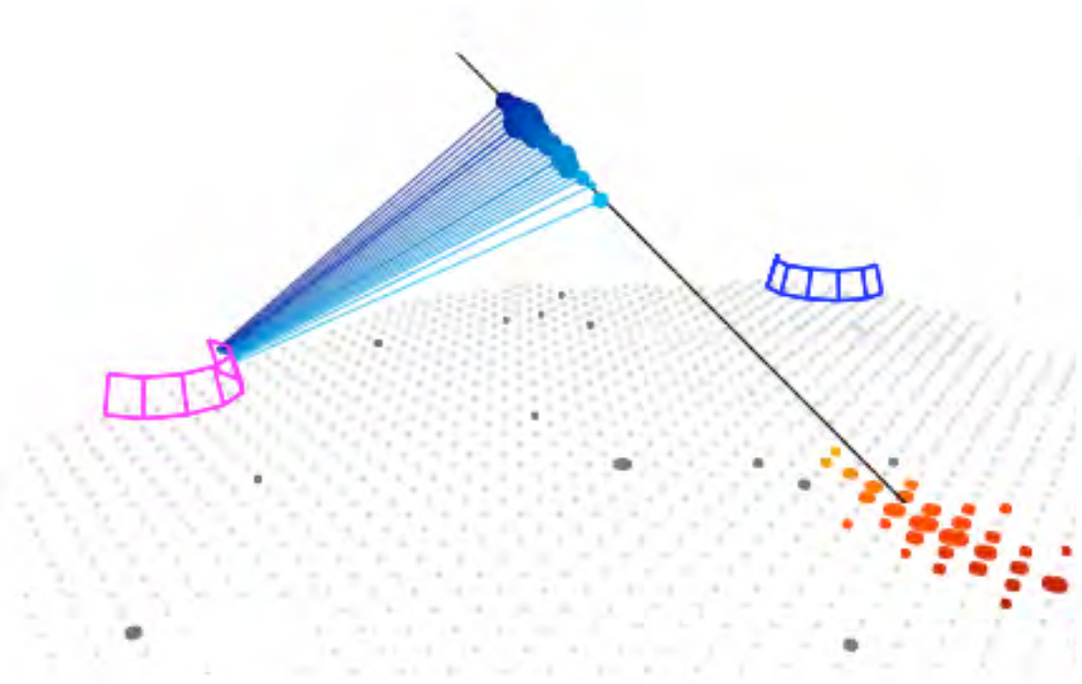
# Muon counting

PRD 91 032003 2015

**Inclined hybrid events (62º < θ < 80º and 4 < E[EeV] < 50)**

EM component very suppressed at these angles.

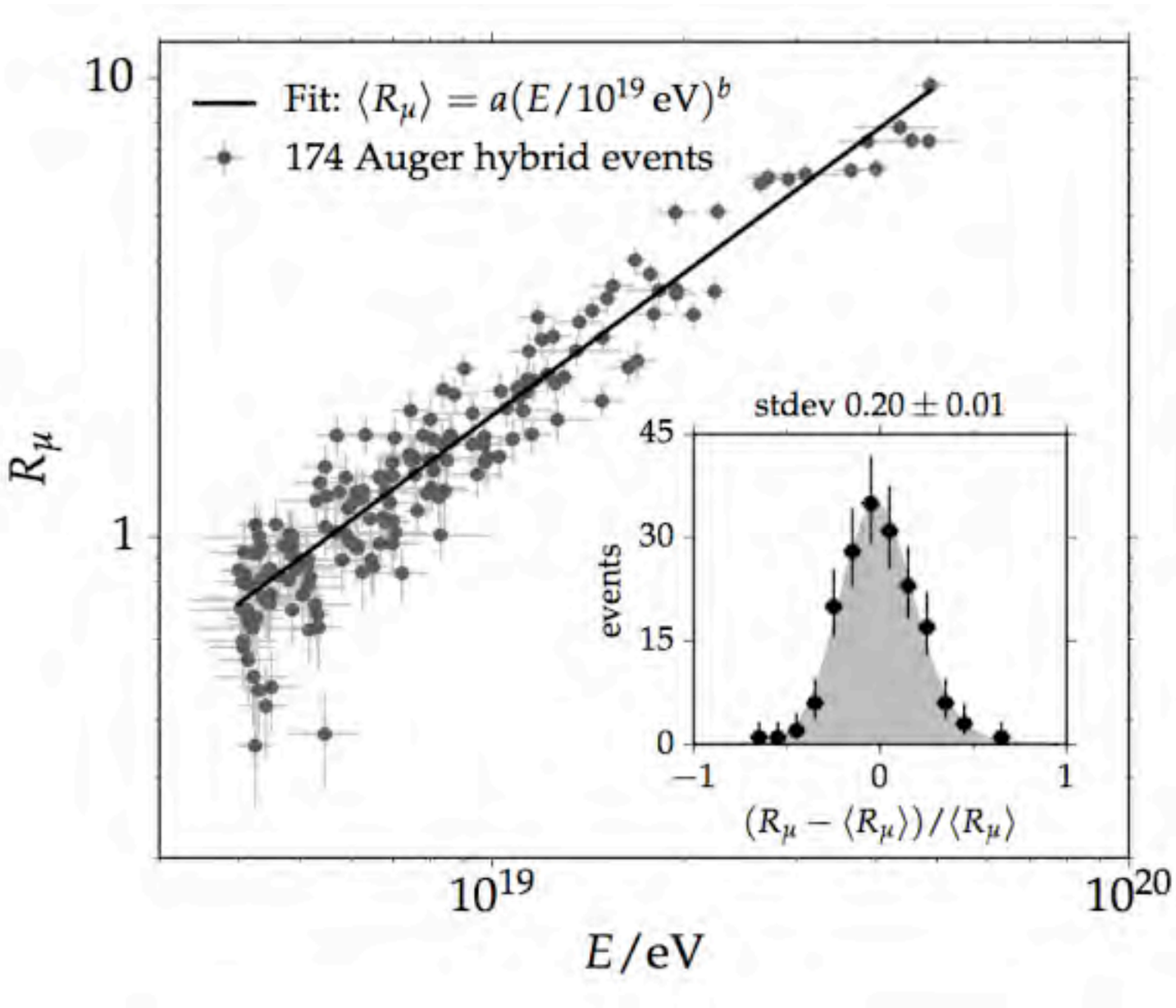
SD signals mainly due to muons.



event 201114505353, $\theta = 75.6°$, $E = 15.5$ EeV

$$R_\mu = N_\mu / N_{\mu,19}$$

Rμ is the average number of muons.



# Muon counting

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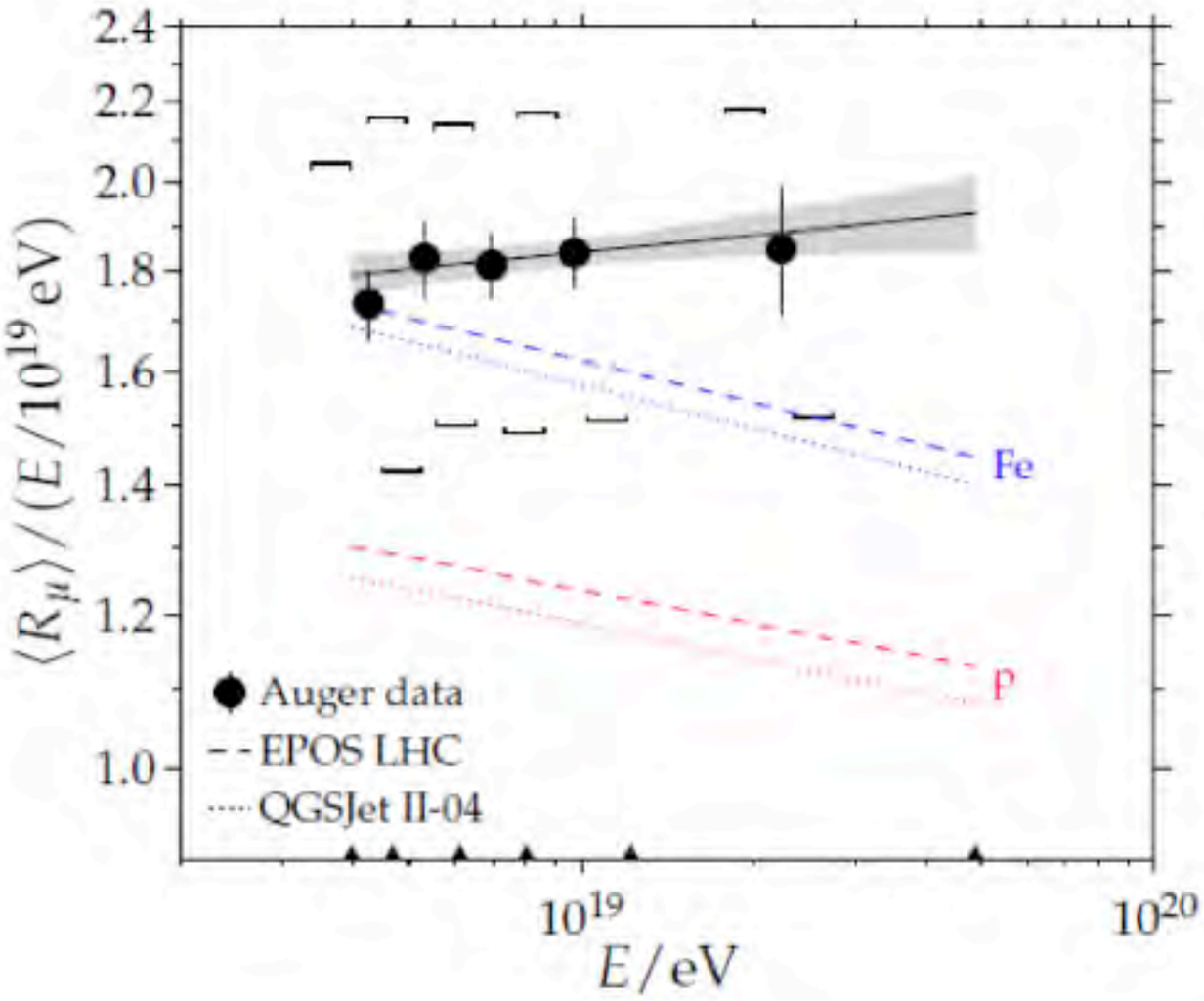
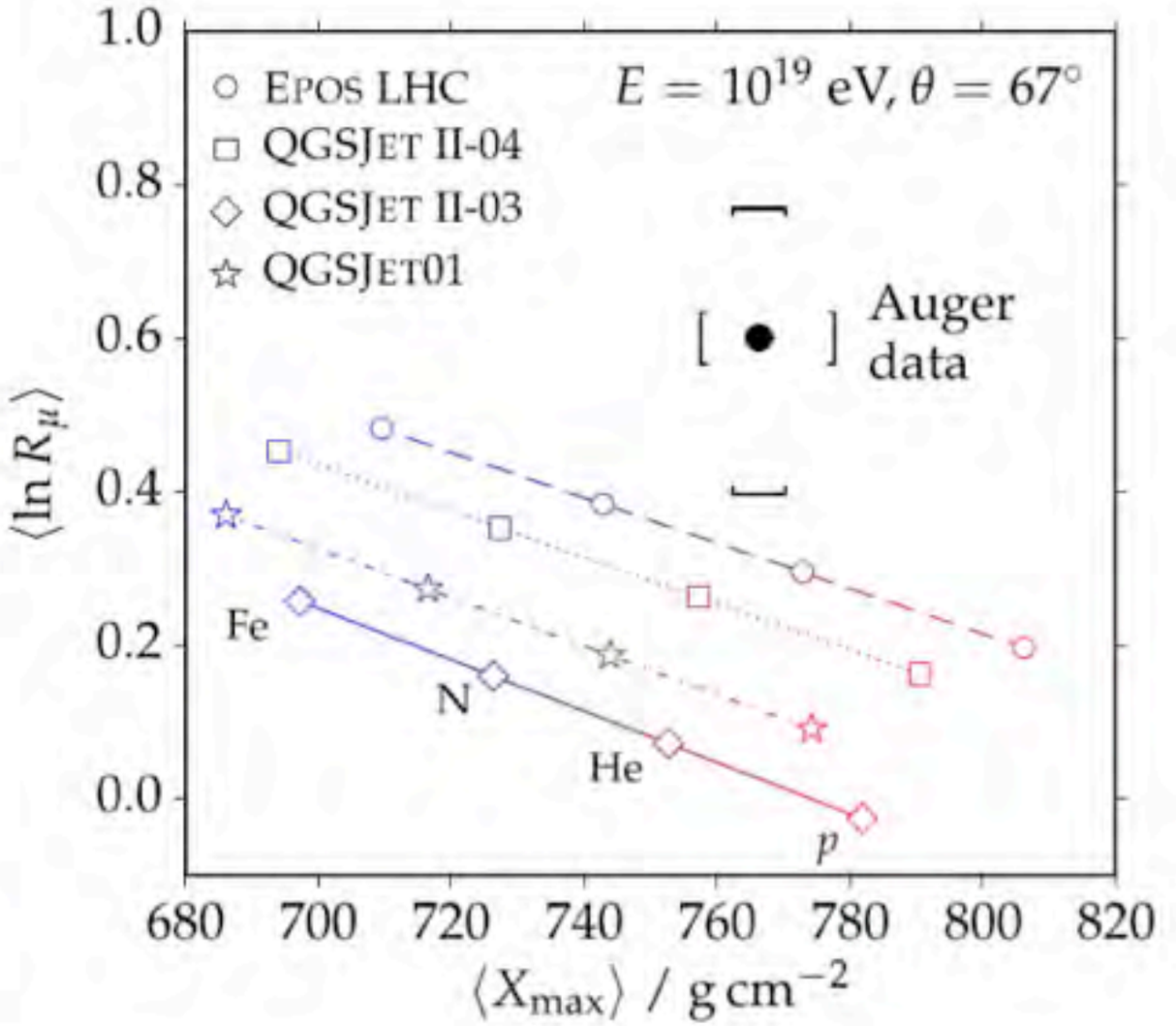



More muons in data than in simulations.




Strong interaction test at energy scales larger than LHC.

# MPD distributions

PRD 90 012012 2014

## Muons at ground carry information about their production point

2 assumptions about muons:

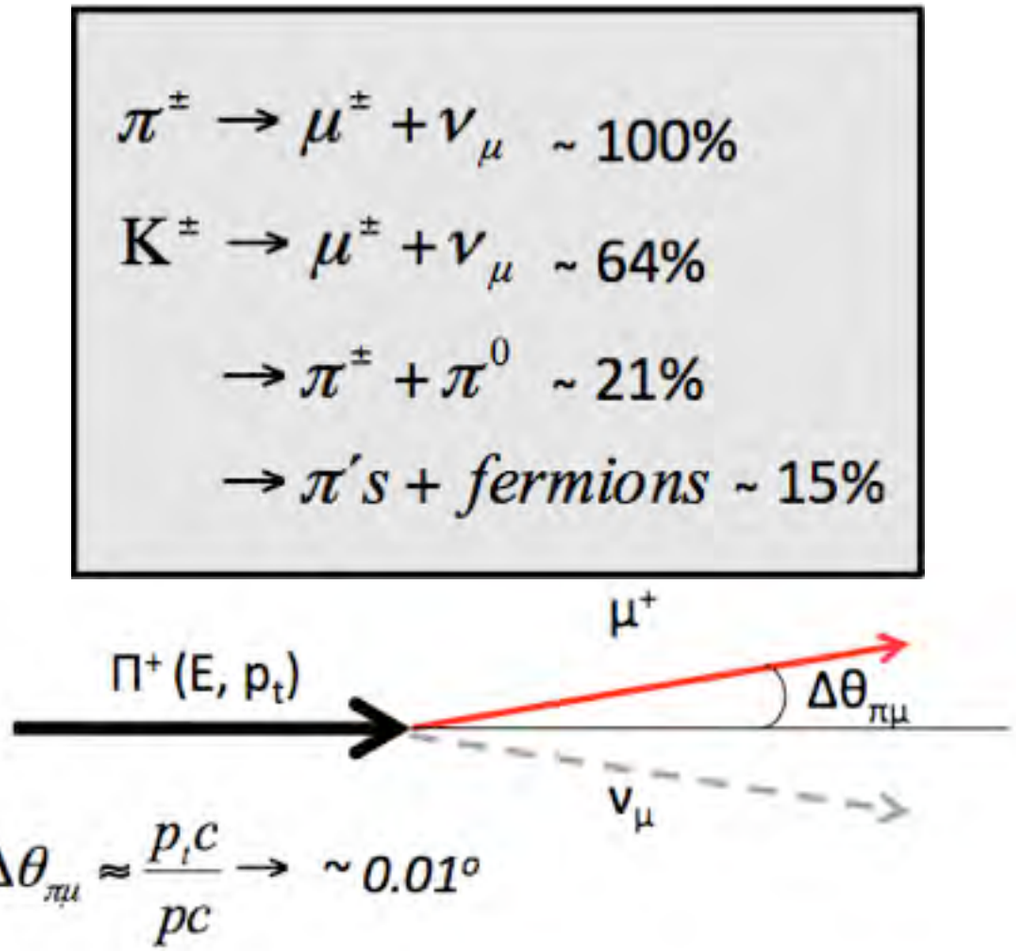
**Produced in the shower axis + Travel following straight lines at c**

$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ ~ 100%

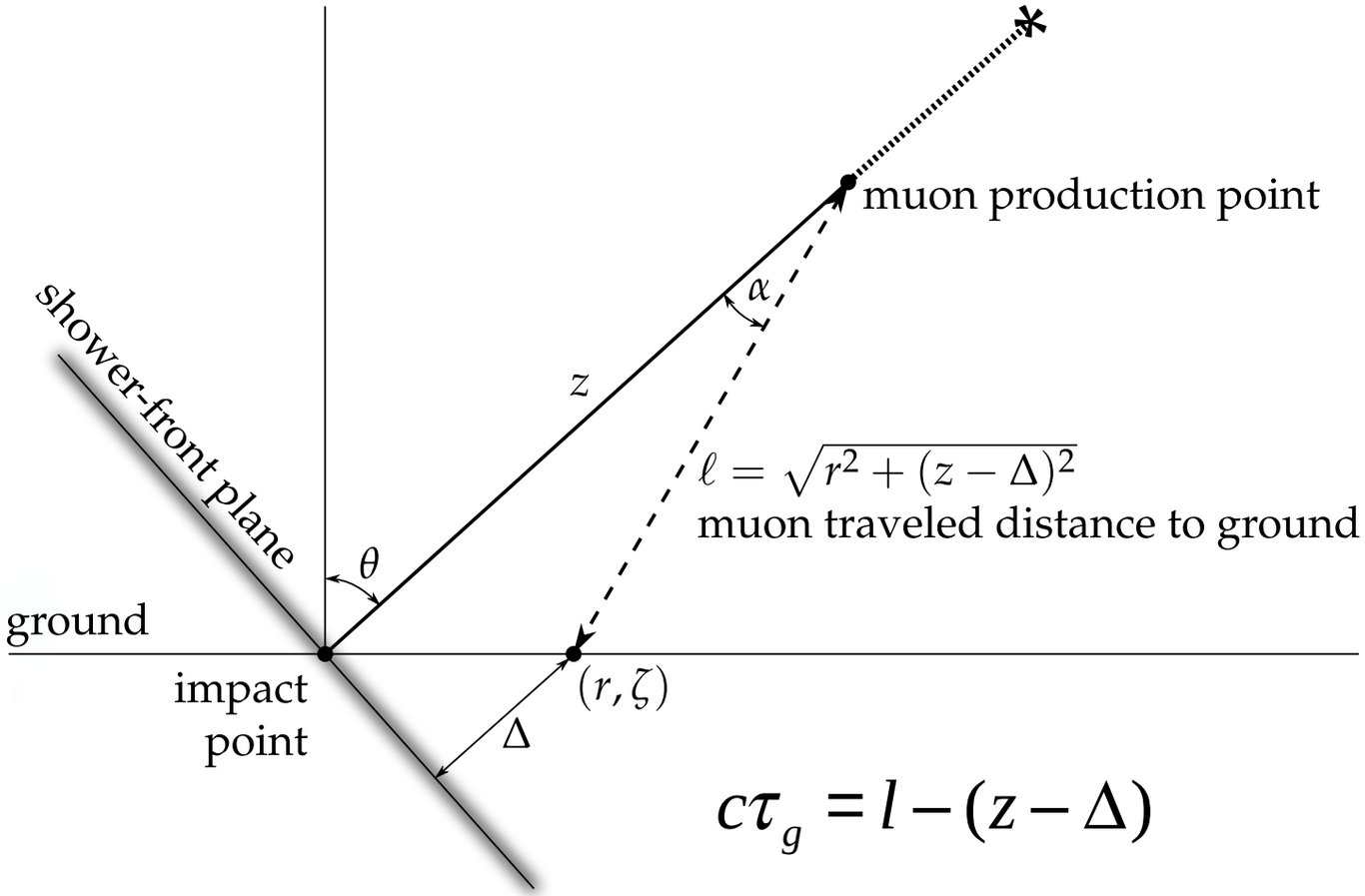
$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ ~ 64%

$\rightarrow \pi^{\pm} + \pi^{0}$ ~ 21%

$\rightarrow \pi's + fermions$ ~ 15%




$$\Delta\theta_{\pi\mu} \approx \frac{p_t c}{pc} \rightarrow \sim 0.01^{o}$$




$$c\tau_g = l - (z - \Delta)$$

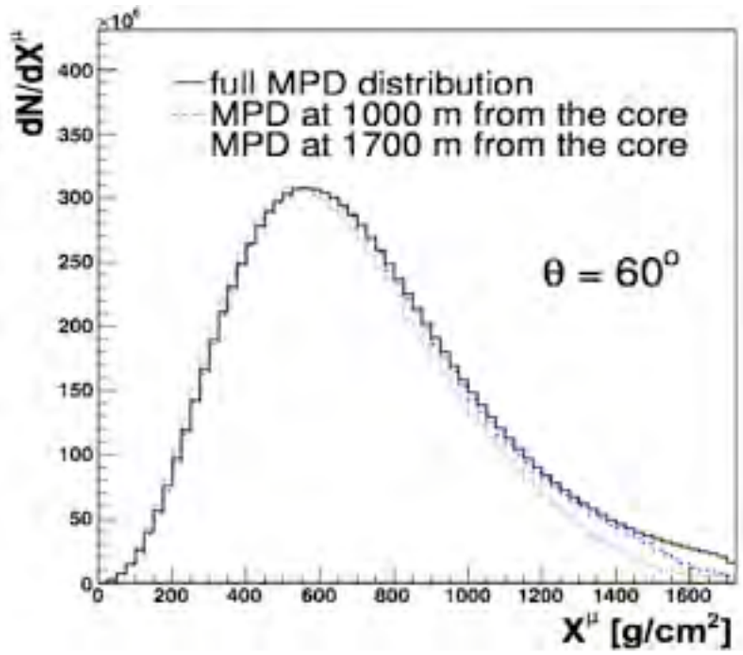
**Total delay measured in the WCDs** → τ [ns] → z[m] → $X_{\mu}$ [g/cm²]

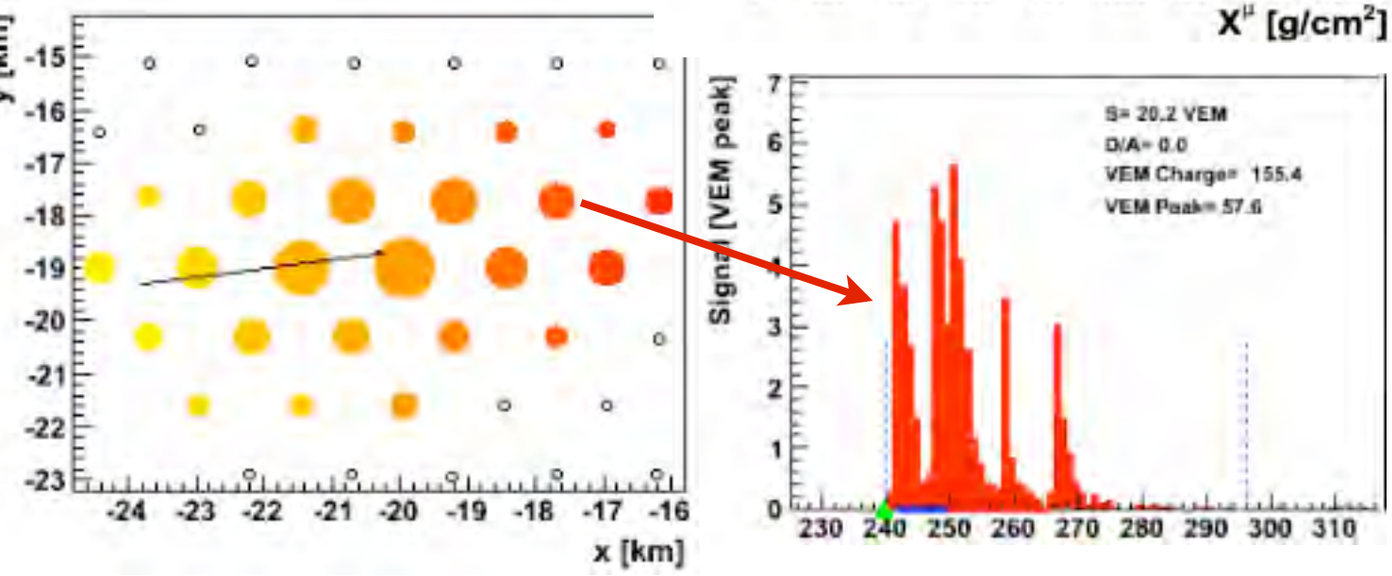
**kinematics** $\tau_g \approx \tau - \tau_{kin}$ **Atmosphere** $X^{\mu} = \int_z^{\infty} \rho(z')dz'$

# MPD building

PRD 90 012012 2014

Fixed zenith angle [55º,65º]




$$\delta X^{\mu} \propto \frac{\delta t}{r^2 \cos\theta}$$

Only WCDs at r > 1700 m

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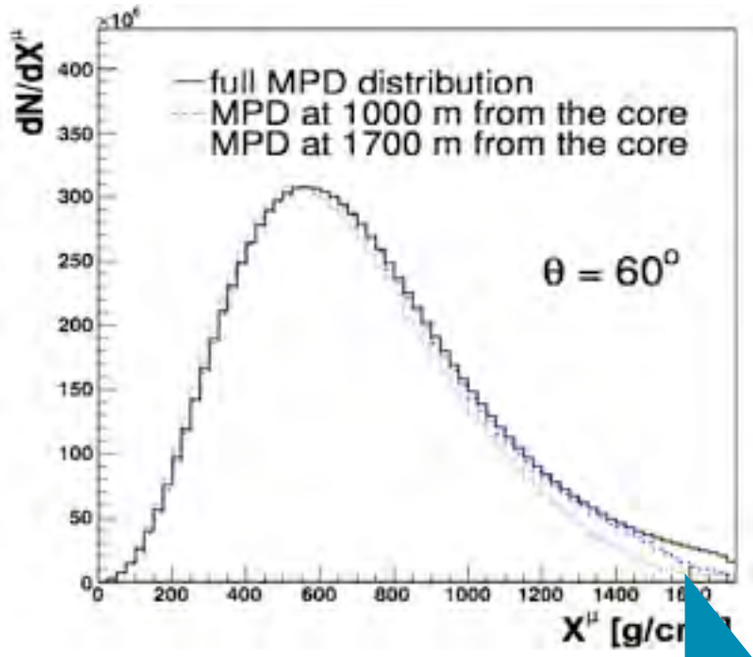


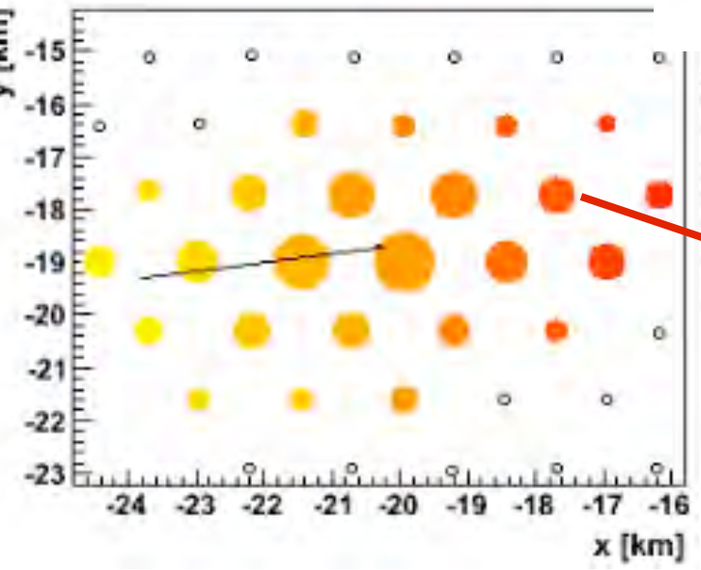


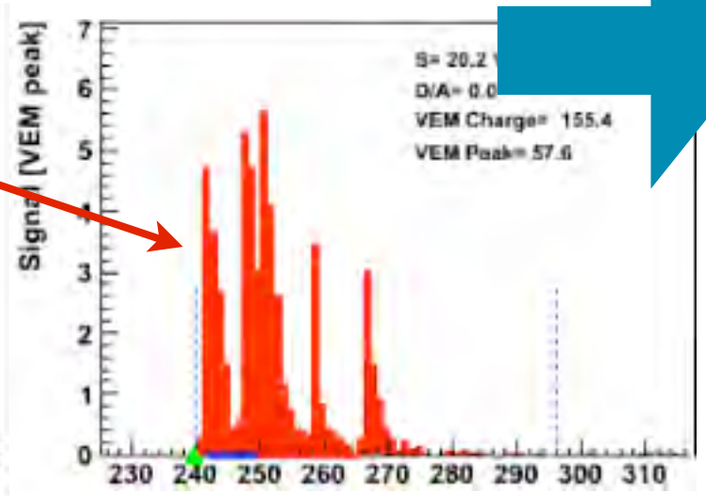


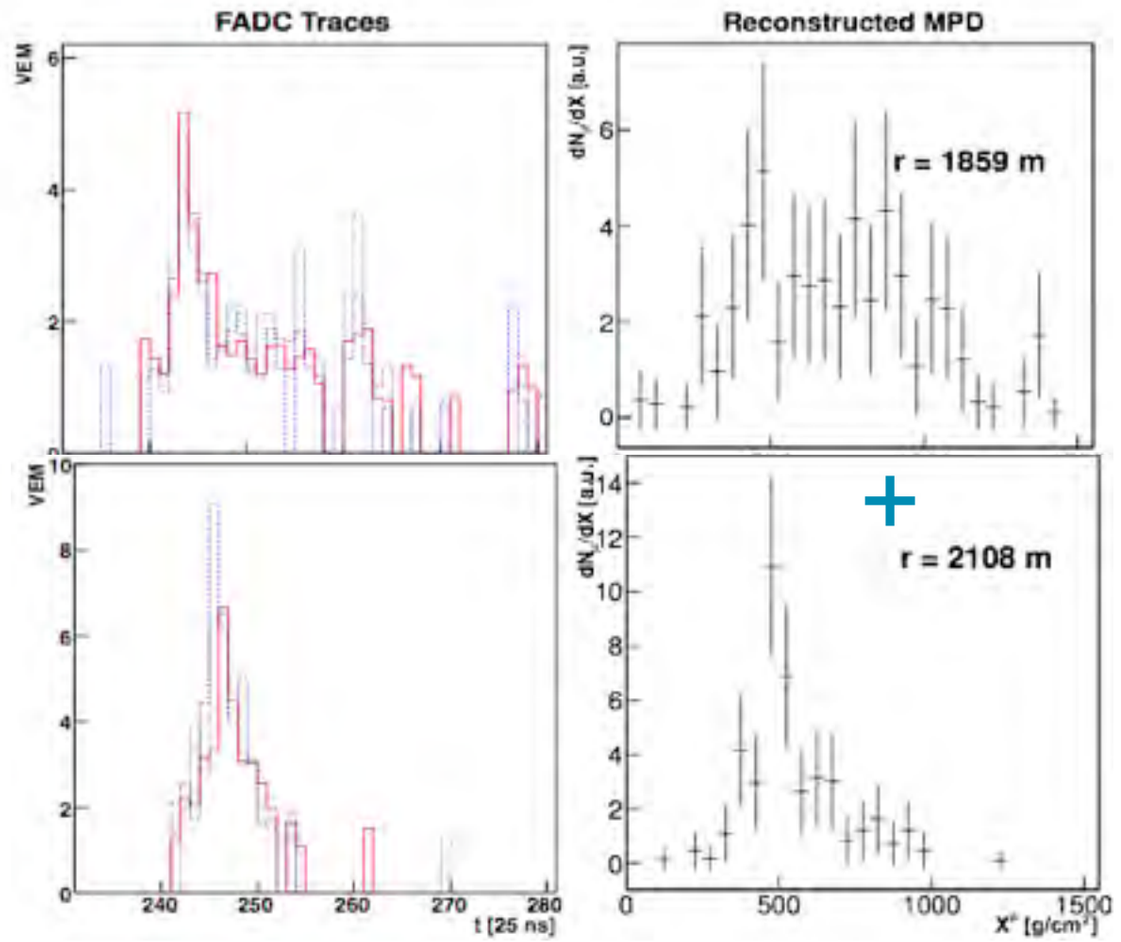


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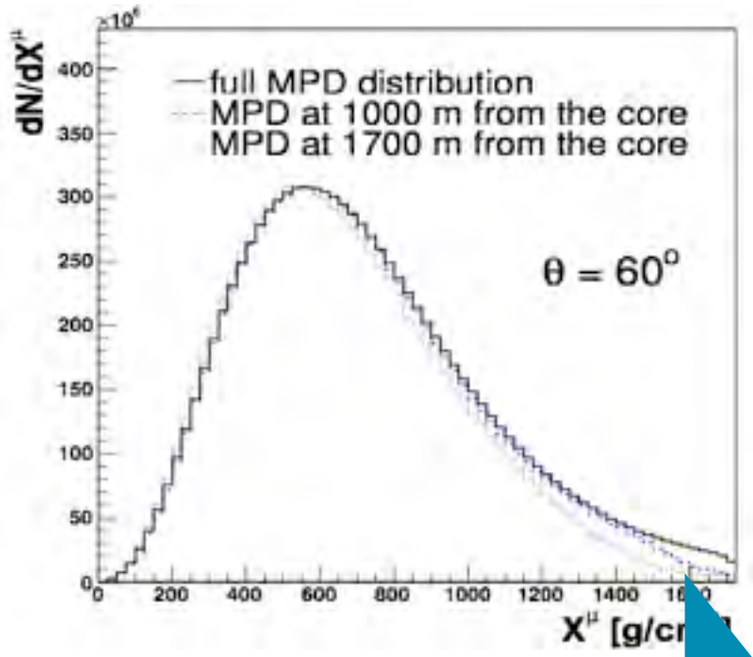


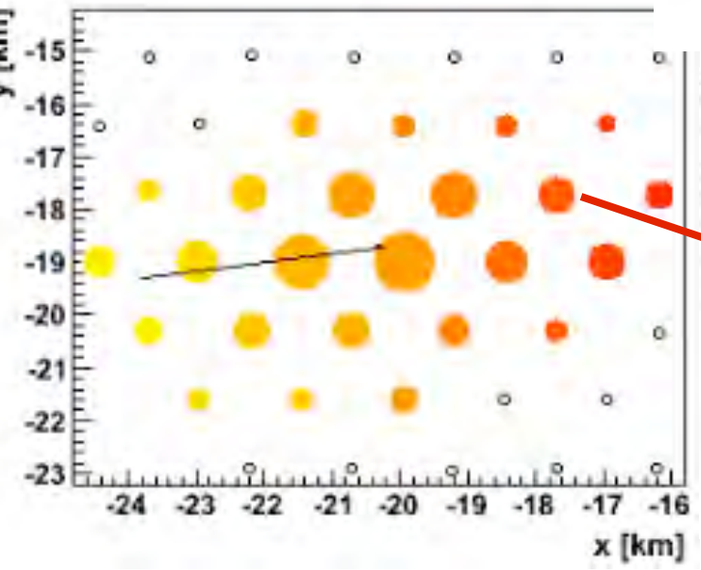


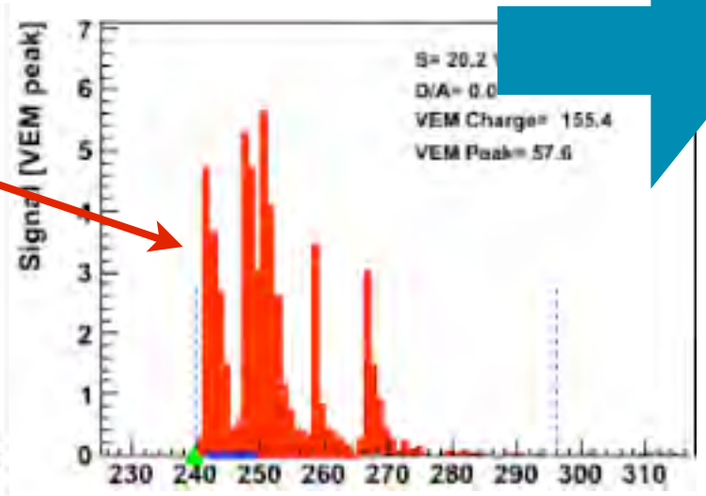


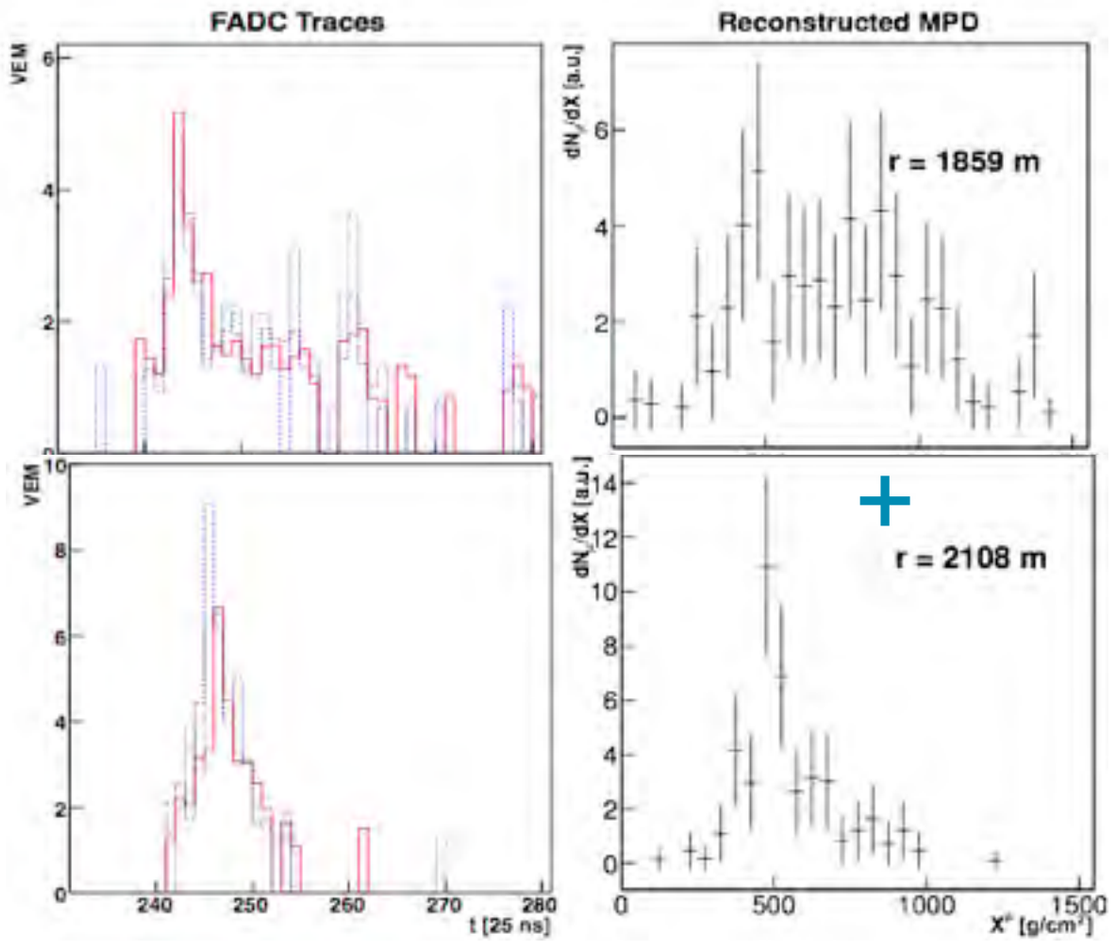


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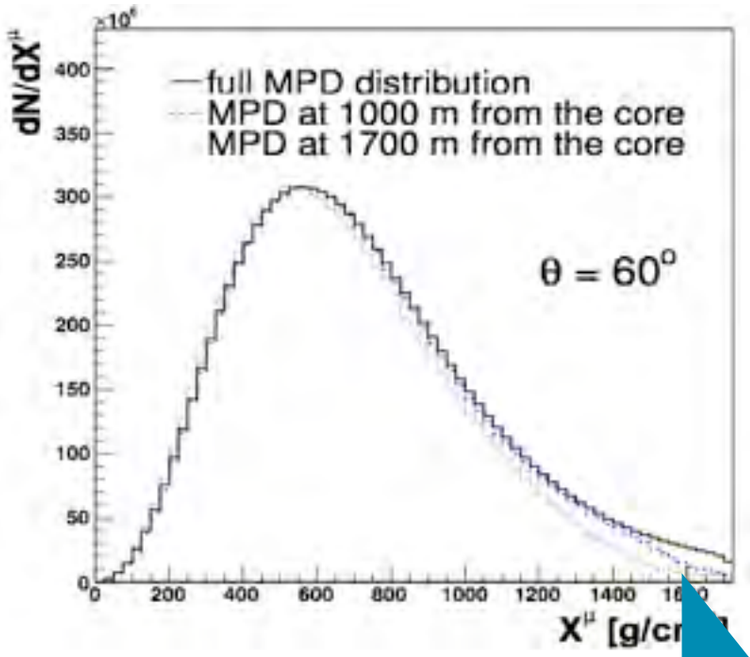


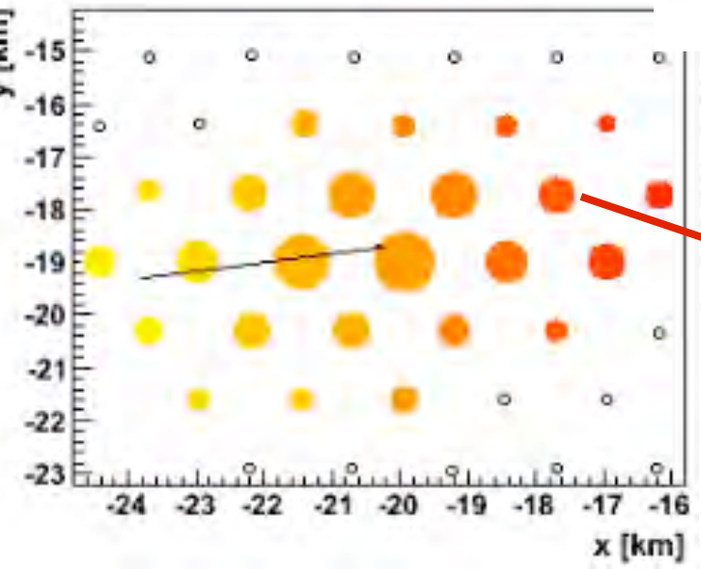


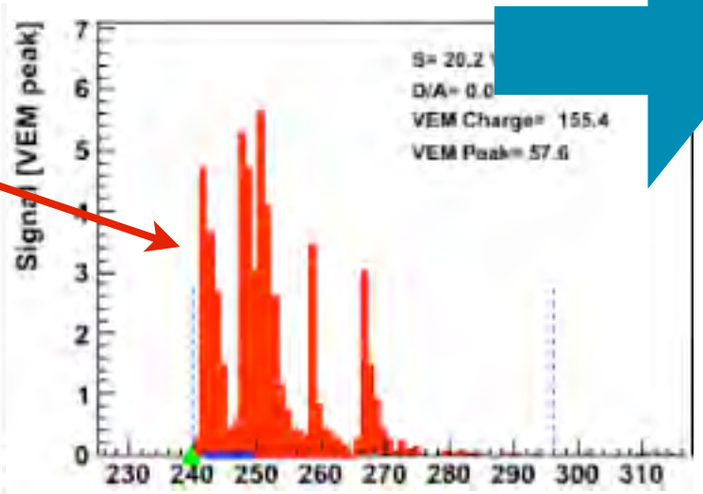


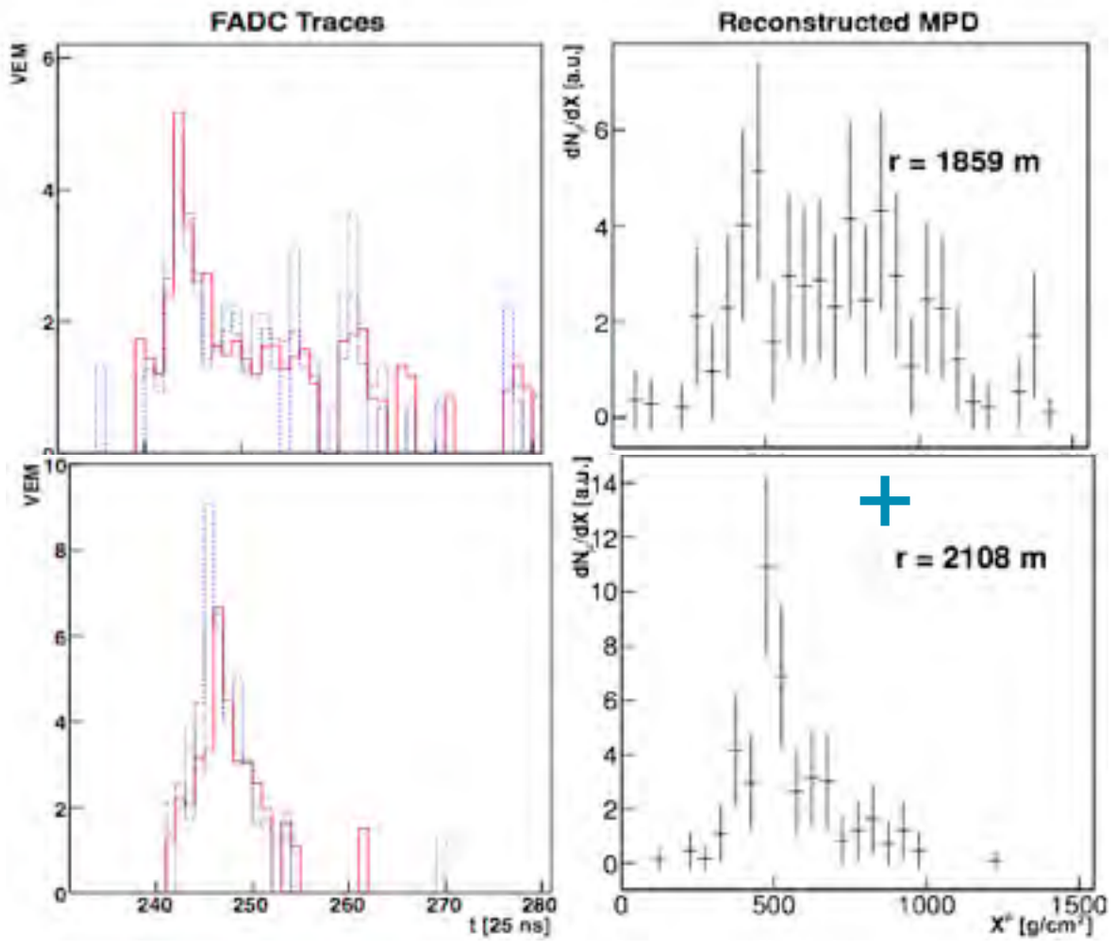


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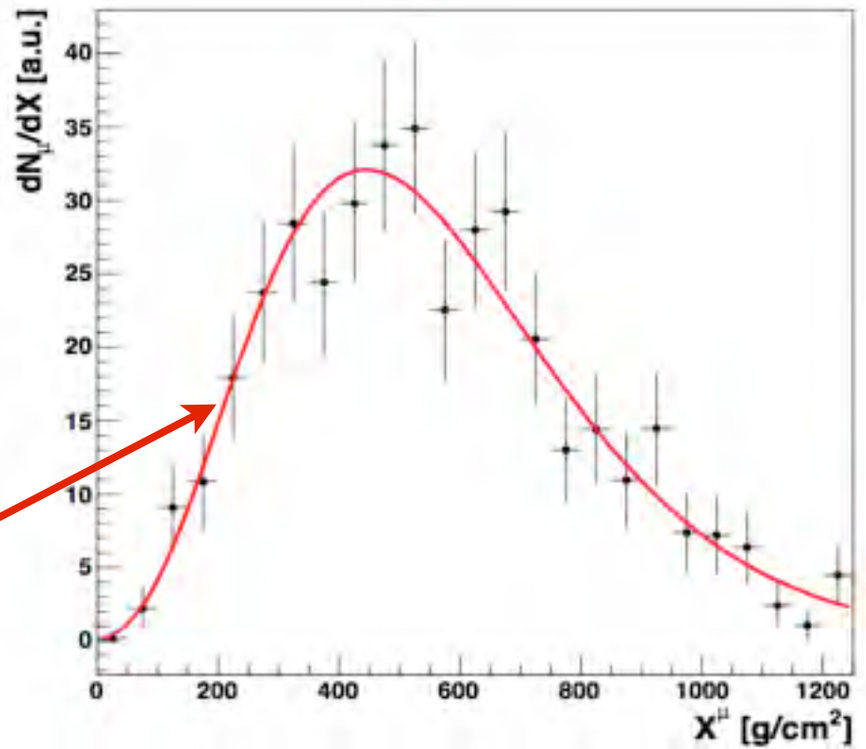


Gaisser-Hillas Fit

# MPD building

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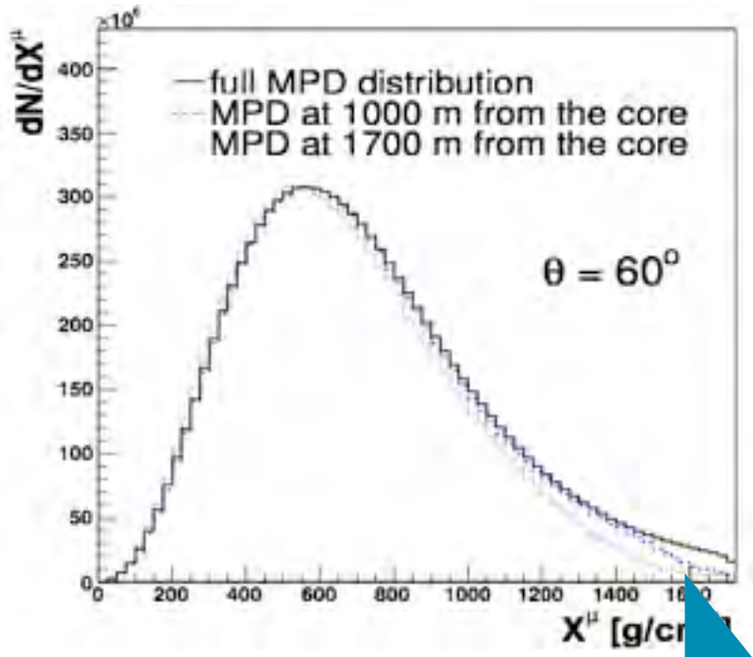
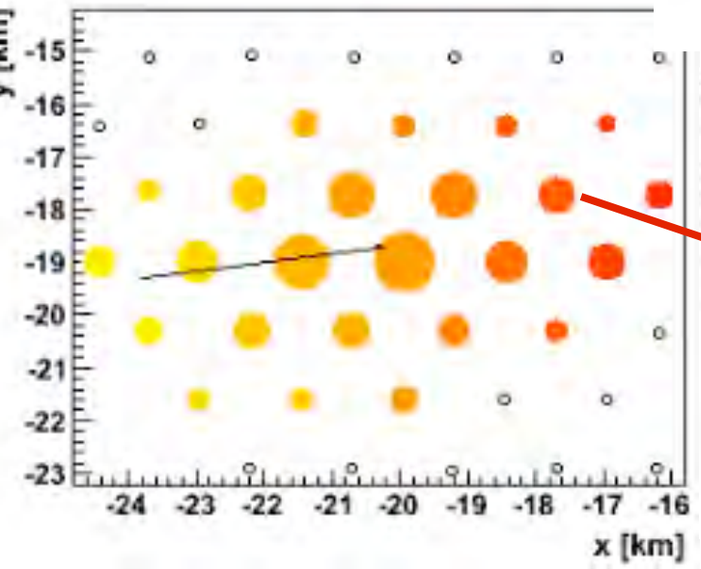
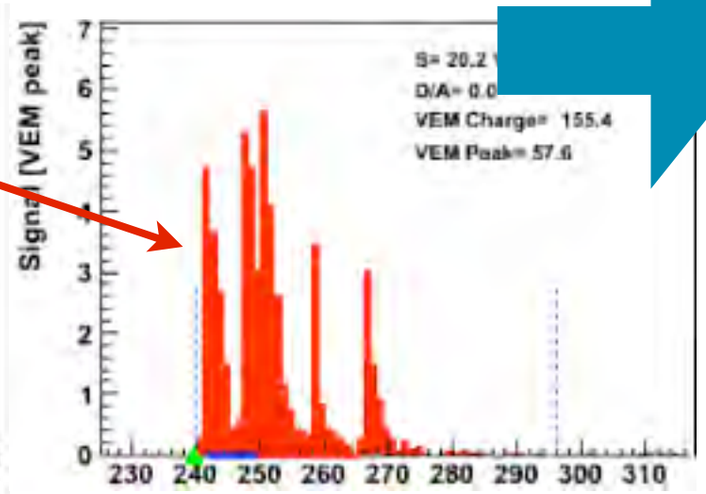
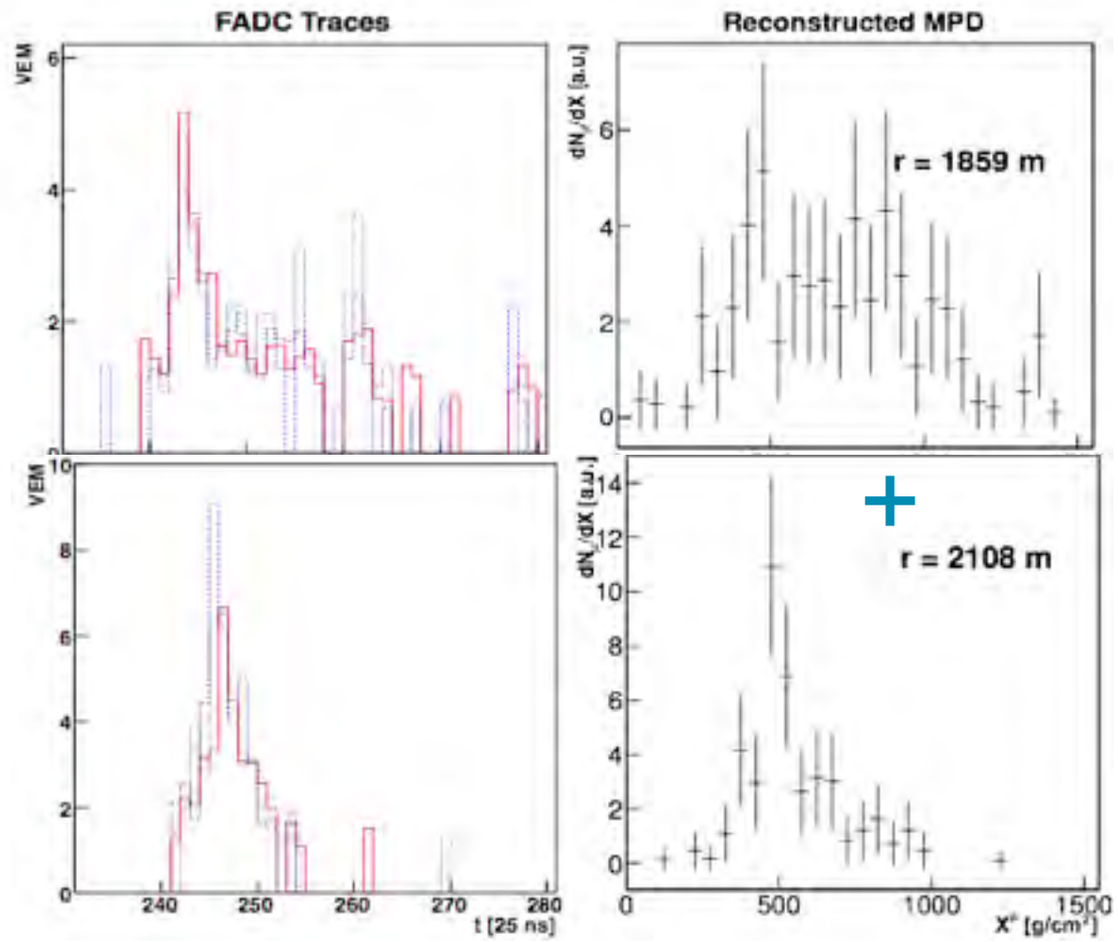


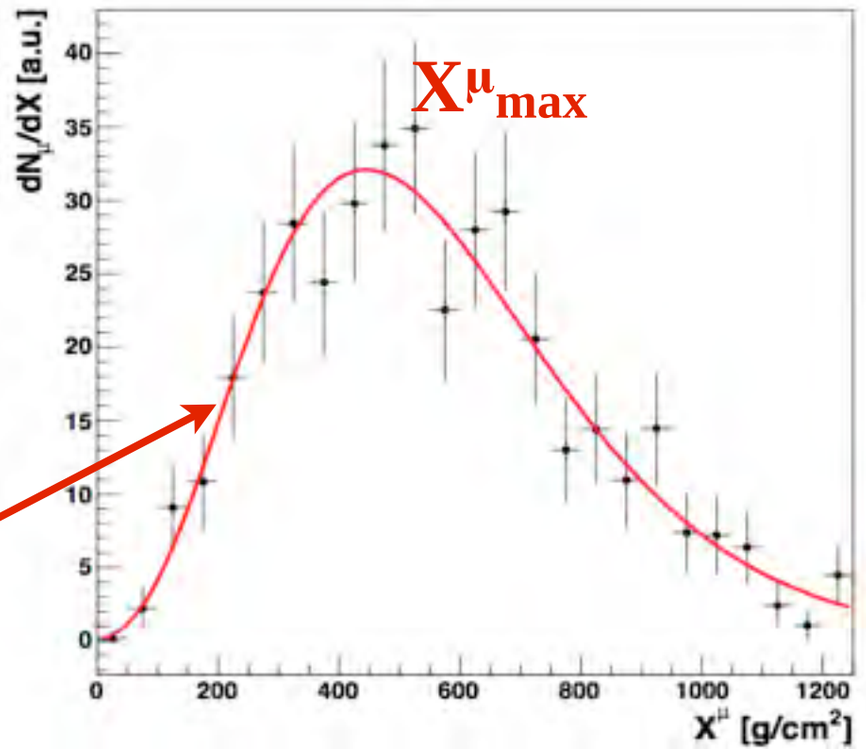




$$\delta X^{\mu} \propto \frac{\delta t}{r^2 \cos\theta}$$

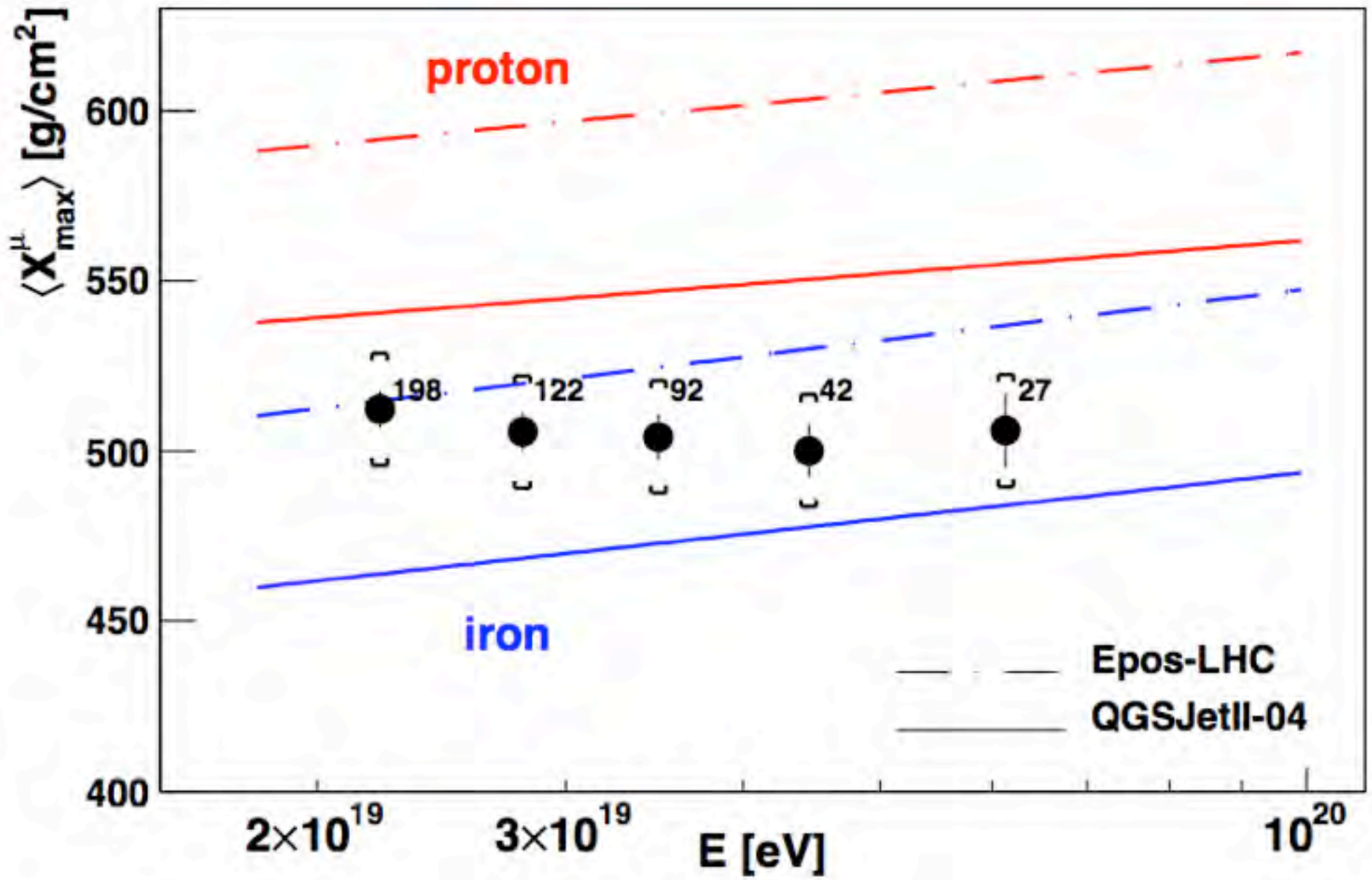
Only WCDs at r > 1700 m




Gaisser-Hillas Fit

# MPD distributions

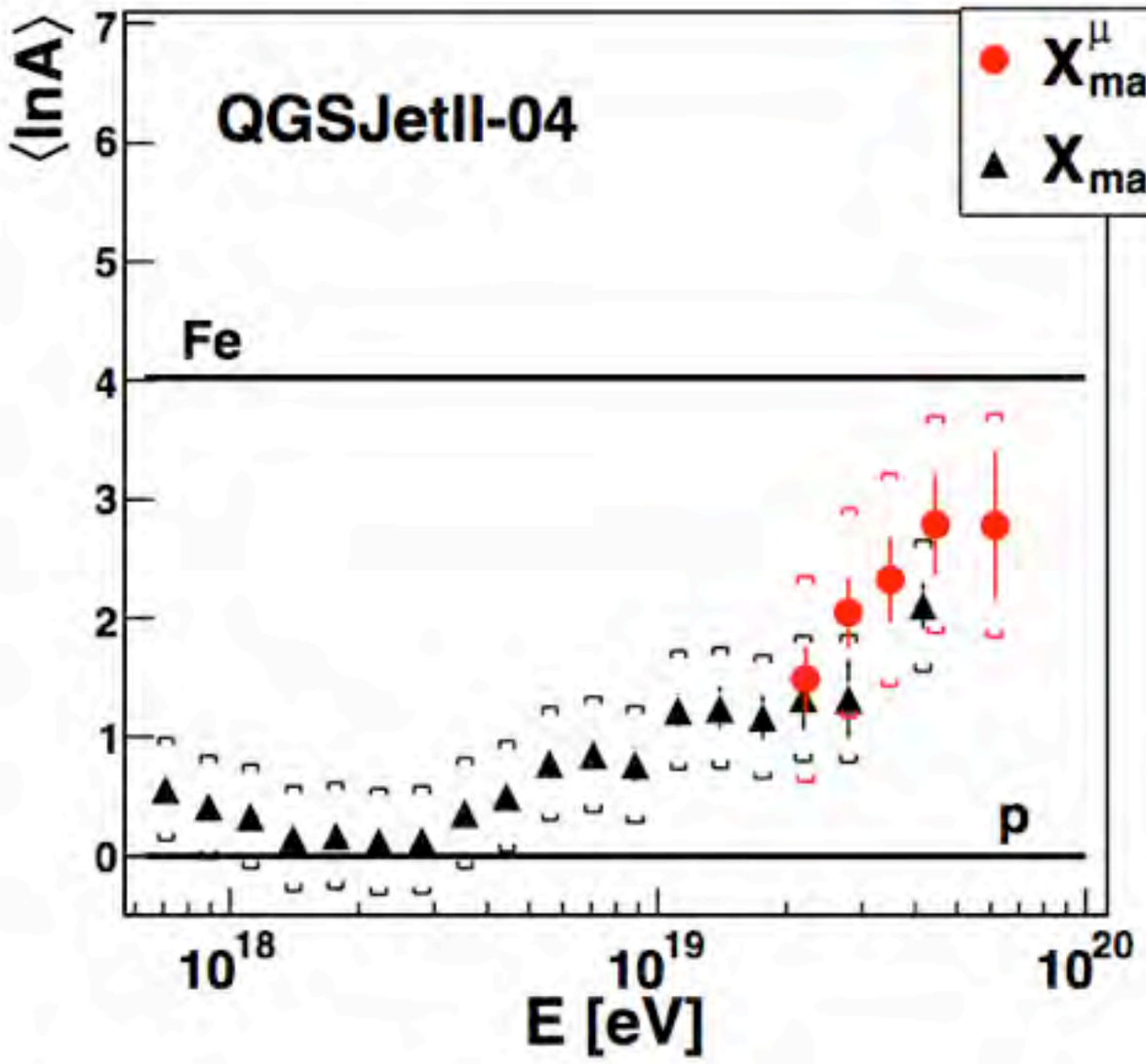
PRD 90 012012 2014

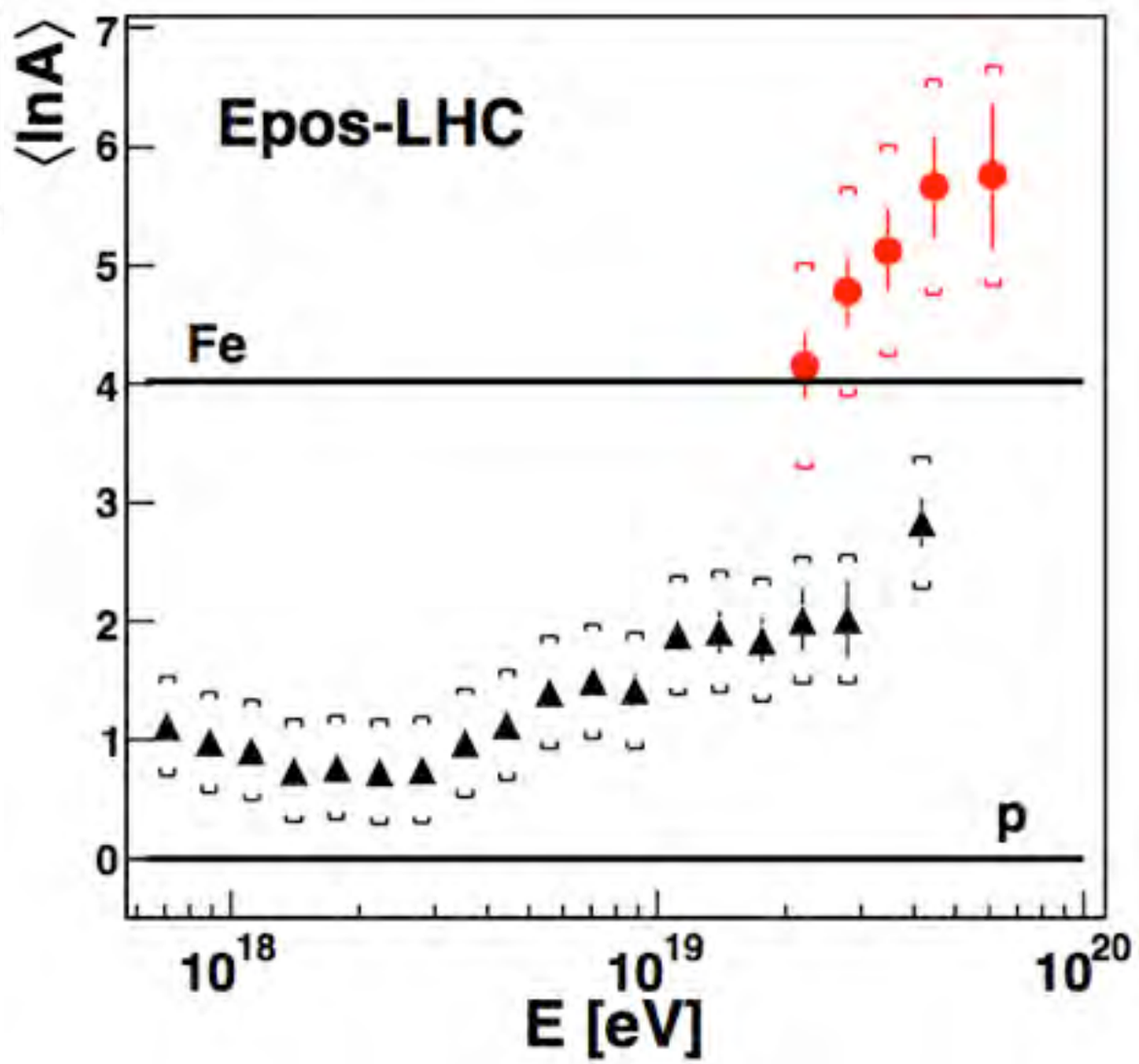



Resolution between 100-50 g/cm$^2$ due to low number of muons contributing to each MPD distribution.
Systematic uncertainty 17 g/cm$^2$.

# MPD distributions

PRD 90 012012 2014




It can be used to constrain hadronic interaction models.

# Summary

<$X_{max}$> elongation rate shows a change in the slope. If we trust hadronic interaction models it suggests a transition from light to heavy composition.

$X_{max}$ measured by TA is consistent with that found using Auger mass distributions.

Muon measurements (number of muons and depth production at maximum) are inconsistent with hadronic interaction model predictions.