Estimation of the invisible energy with the data collected by the Pierre Auger Observatory

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Outline

Physics of the invisible energy

Measurement of the invisible energy with the Surface Detector(SD) of the Pierre Auger Observatory:

- **Near vertical events data sample ($\theta < 60°$)**
- **Inclined events data sample ($\theta > 60°$)** **New result!**

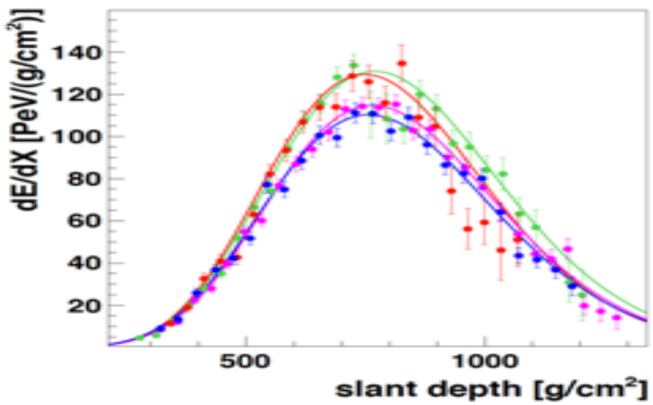
Parametrization of the average invisible energy as a function of the calorimetric energy

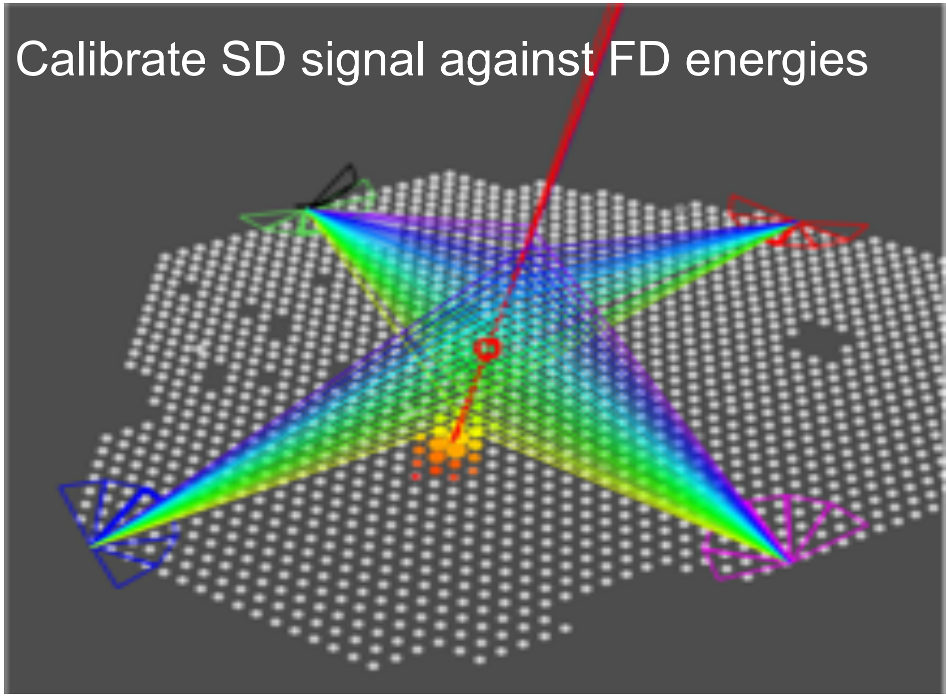
Auger hybrid detector

Fluorescence detector FD

Measures longitudinal development of the e.m component of EAS:

E_{Cal} and X_{max}





Invisible energy (E_{inv}): fraction of the primary energy carried away by neutrinos and high energy muons is a priori unknown (~ 15 % at 0.1 EeV decreasing with $\mathbf{E_0}$) .

Calorimetric energy (E_{Cal}): integral of the energy deposit profile

$$\mathbf{E_{Cal} = \int dE/dX \; dX}$$

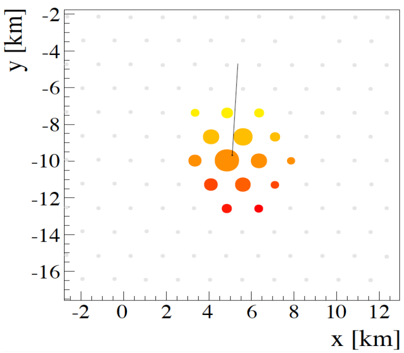
Total energy (E_0) :

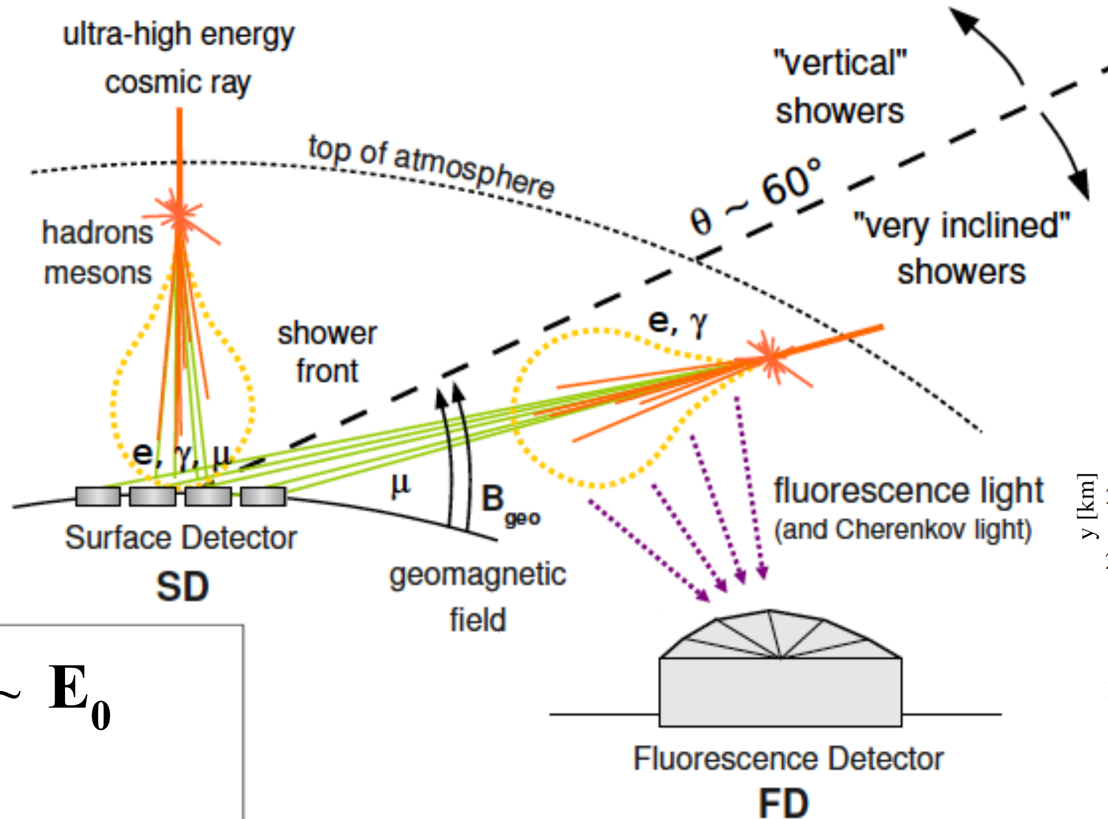
$$\mathbf{E_0 = E_{Cal} + E_{Inv}}$$

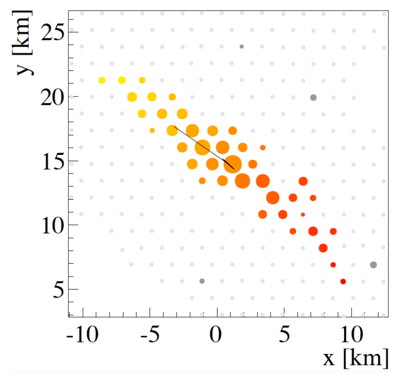
Auger hybrid detector

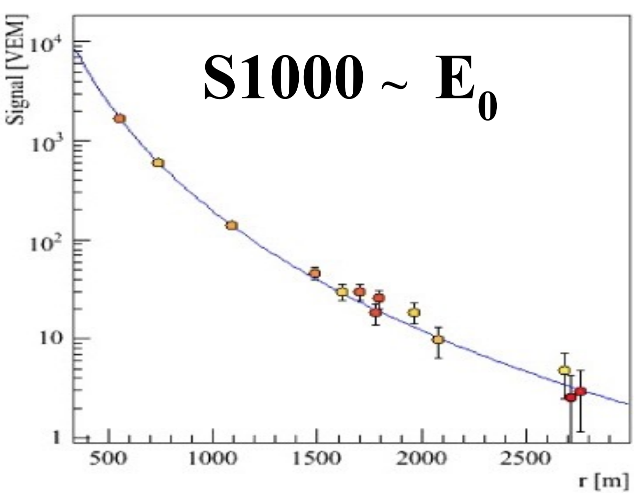
<u>Surface detector SD</u>

Water Cherenkov detectors have enhanced sensitivity to muons.







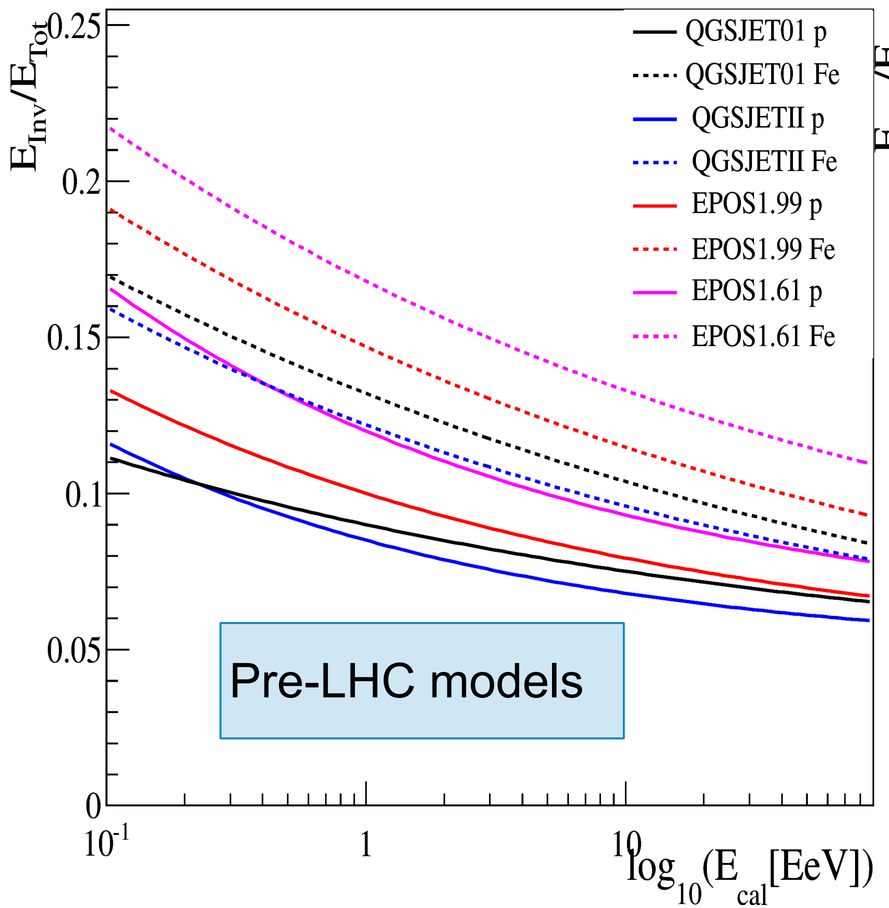


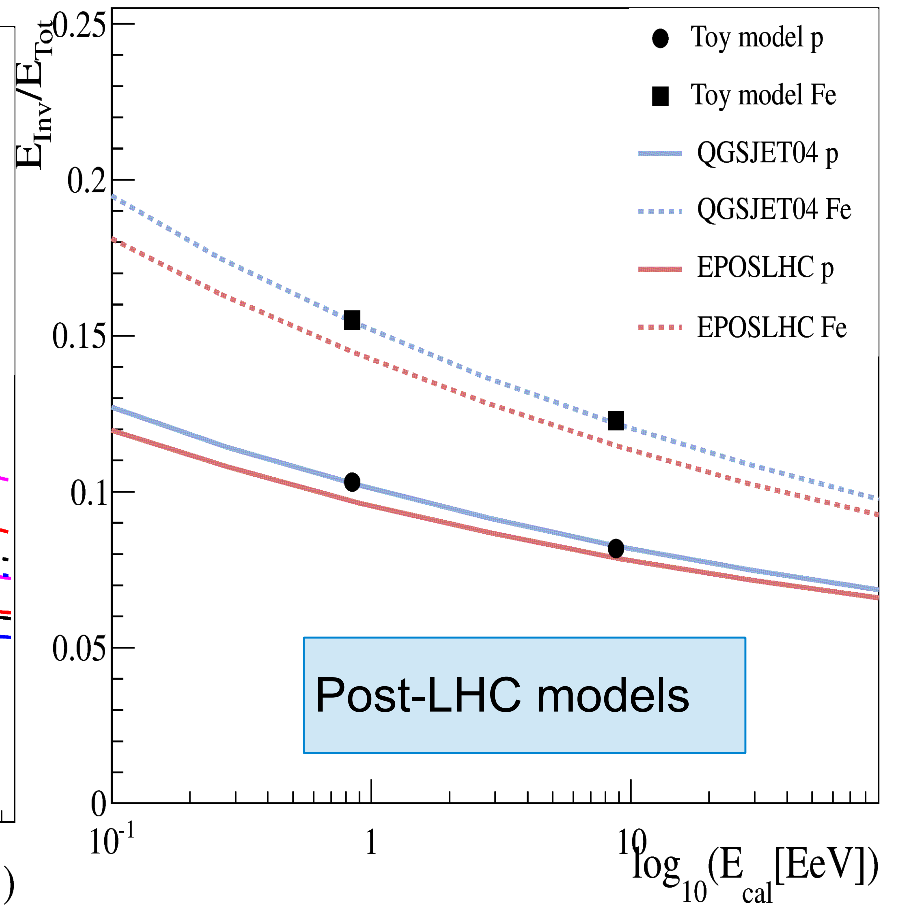
<u>Surface detector **inclined events**</u>

Muon content can be measured directly as the electromagnetic component dies out.

Invisible energy in MC simulations

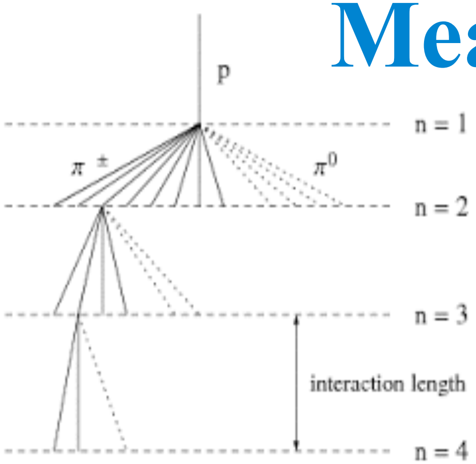
Average invisible energy as a function of E_{Cal} depends on the assumed **primary mass composition** and the **high energy hadronic interaction model** used in the simulations.

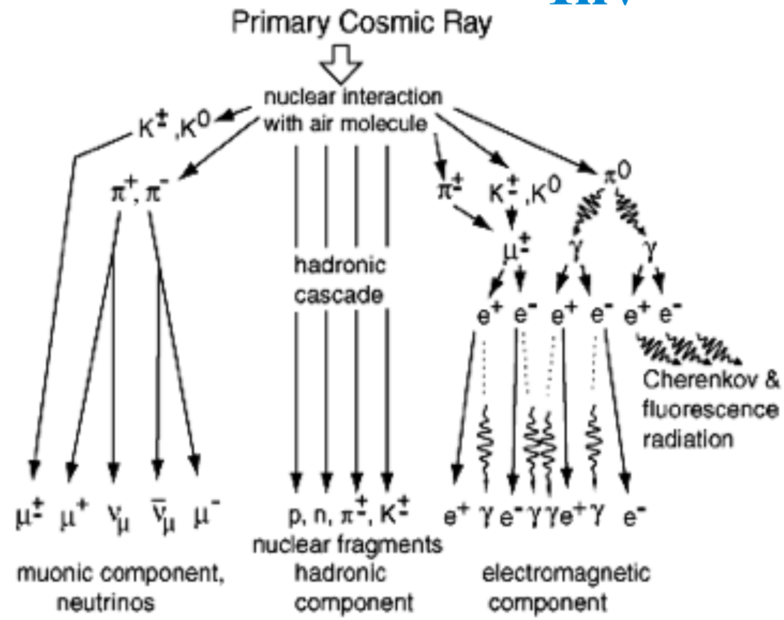


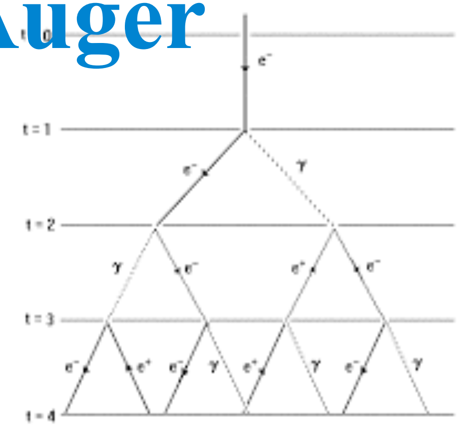


E_{Inv} calculation done as in *H. Barbosa et al., Astropart. Phys., 2004, 22:159*

Measurement of E_{Inv} at Auger







$$E_{Inv} = \xi_c^{\pi} N_\mu$$

$$E_0 = E_{Cal} + E_{Inv}$$

$$E_0 = \xi_c^{e} N_e + \xi_c^{\pi} N_\mu$$

Muon EAS content is directly correlated with the invisible energy

(confirmed using simulations by *M. Nyclicek et al., Proc. 31st ICRC, Ł´od´z, Poland, 2009)*

$$N_\mu = \beta_0 \; (E_0 / \xi_c^{\pi})^{\beta}$$

$$E_0 = \gamma_0 \; S(1000)^{\gamma}$$

Near vertical showers

E_0 from S(1000) + β_0 correction from N_{19}

Independent data sample - different SD reconstruction

$$N_\mu \sim N_{19}$$

Inclined showers

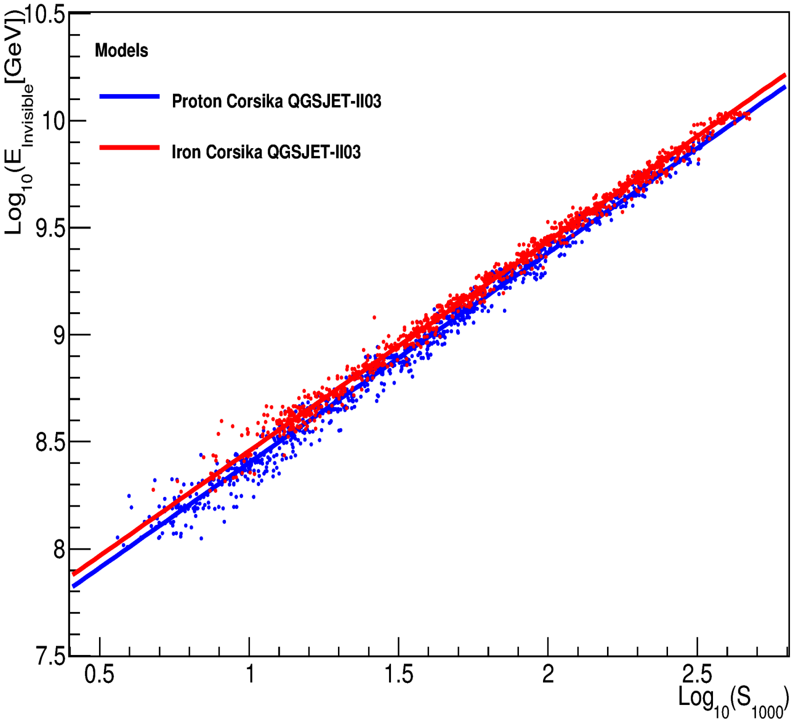
N_{19} : direct measurement of muons at ground as showers are dominated by muons

More straightforward

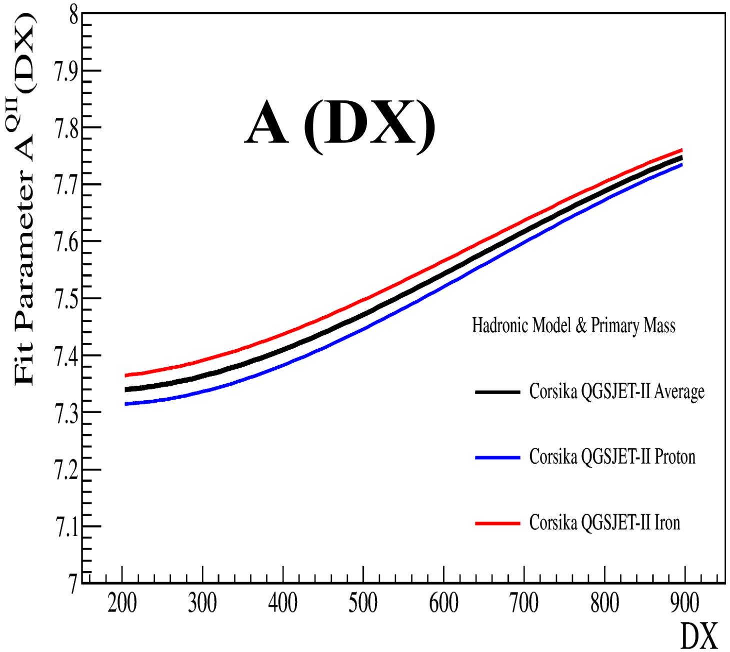
E_{Inv} (S1000)

We used QGSJet-II mixed composition sample to estimate A(DX) and B

Fit in each bin of $DX = X - X_{max}$



$$\mathrm{Log}_{10}E_{Inv} = A(DX) + B\ \mathrm{Log}_{10}S1000$$

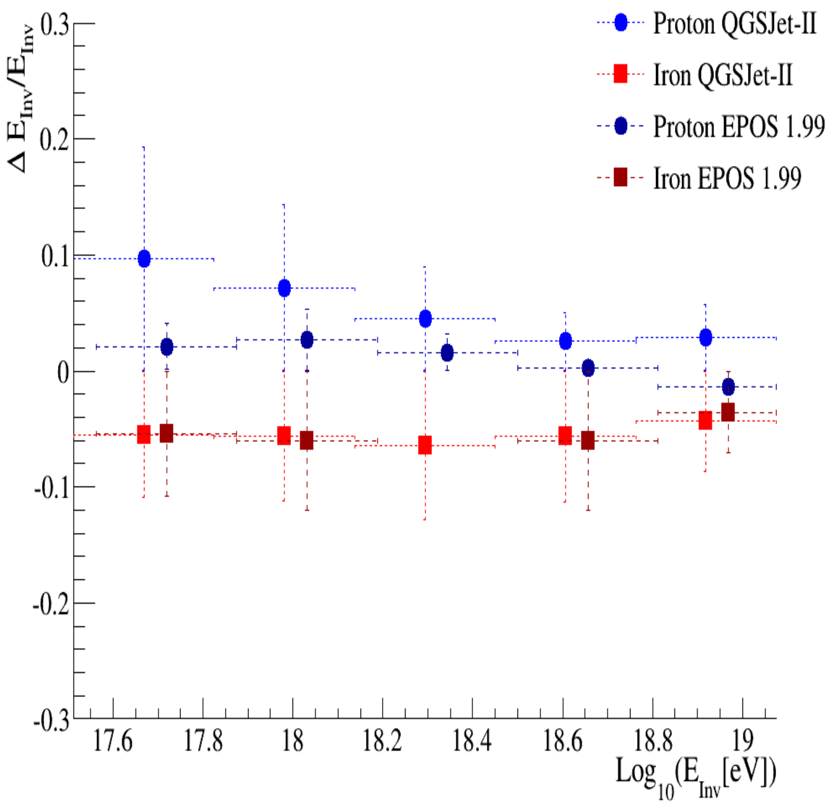


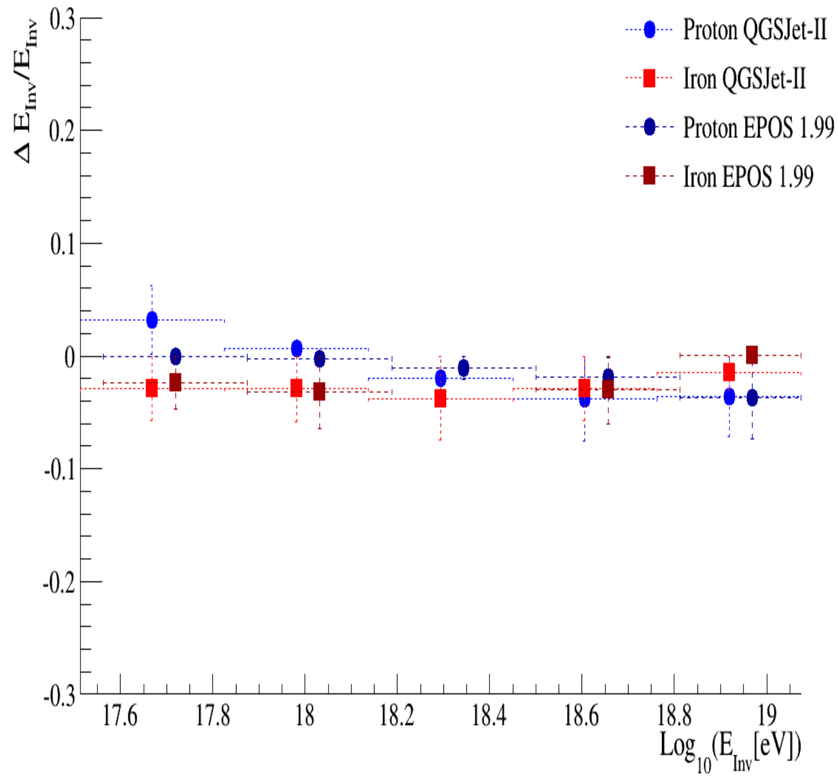
$$B = \gamma\,\beta \approx 0.98 \pm 0.04$$

Assuming no variation of mass composition with energy

M. Tueros for the Pierre Auger Collaboration ICRC 2013 arXiv:1307.5059 [astro-ph]

Invisible energy in simulations





Invisible energy deviation from true value when reconstructed using A(DX) and B obtained from a QGSJet-II mixed composition simulated sample (left) , corrected for attenuation and muon content (right)

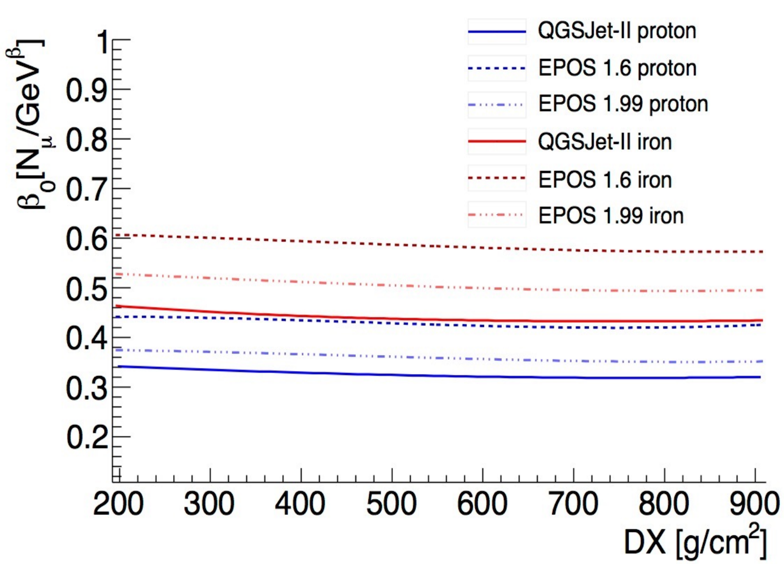
E_{Inv} (S1000)

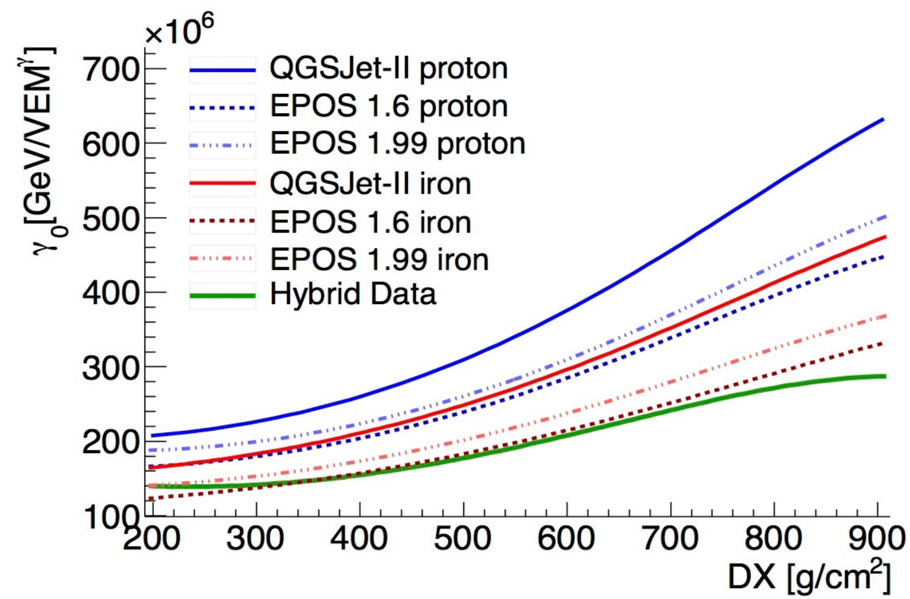
$$A^{MC}(DX) = A^{QII}(DX) + \mathrm{Log}_{10}\left(\left(\gamma_0^{MC}(DX) / \gamma_0^{QII}(DX)\right)^{\beta} \beta_0^{MC} / \beta_0^{QII} \right)$$

$$N_\mu = \beta_0 \left(E_0 / \xi_c^{\pi}\right)^{\beta}$$

<u>correction</u> to A(DX) for attenuation and muon content

$$E_0 = \gamma_0 (S1000)^{\gamma}$$

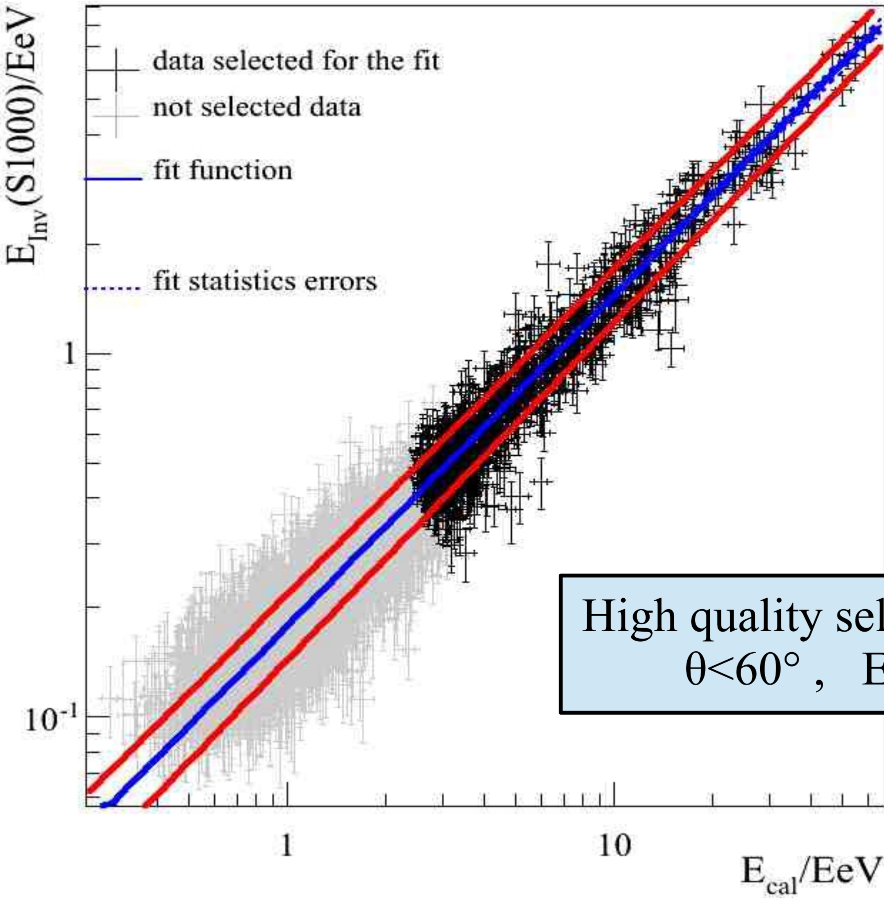


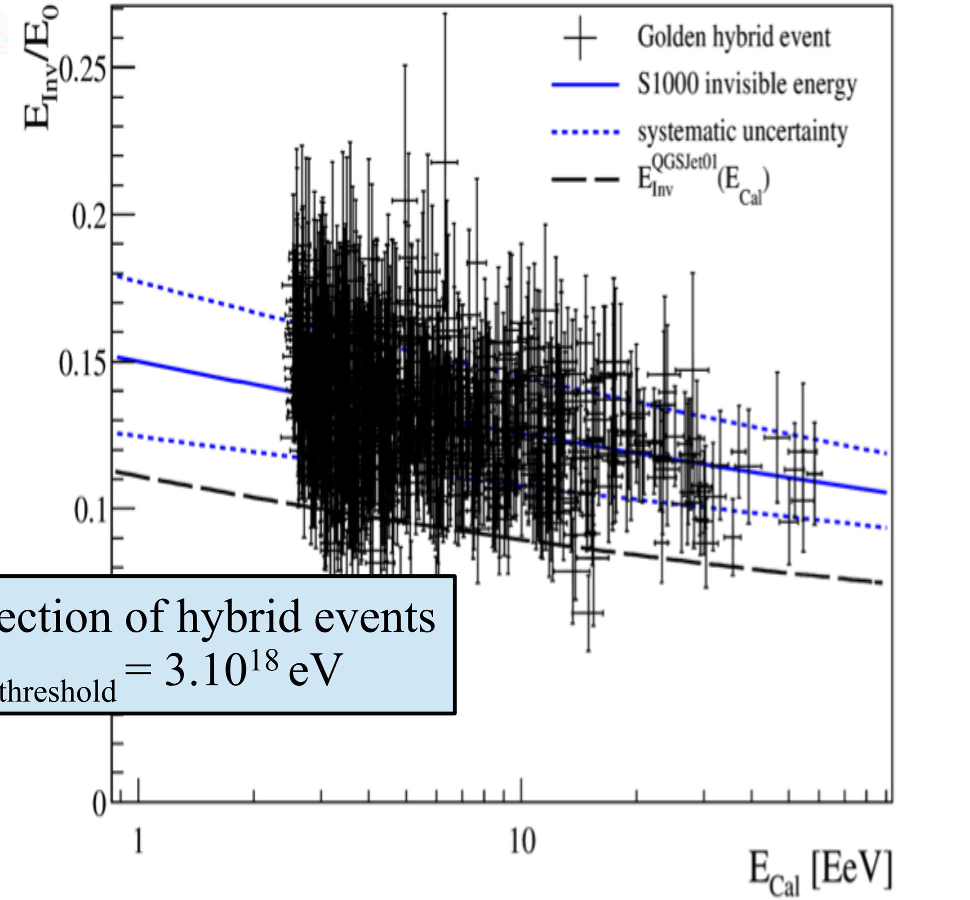


<u>application to the data</u>: correction to A for attenuation (hybrid events) and muon content at a fixed mixed mass and $E_0=10^{19}$ eV (N_{19} inclined showers)

E_{Inv}(S1000) parametrization with E_{Cal}

$$E_{Inv} = a_0 \ (E_{Cal})^{a1}$$





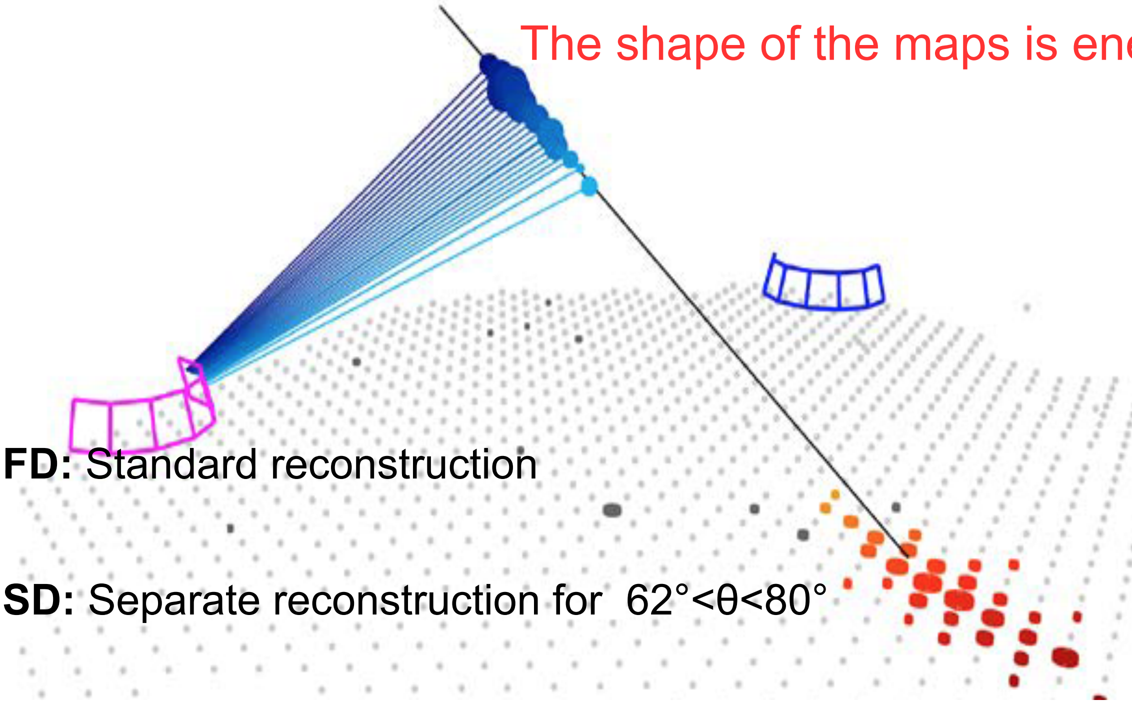
High quality selection of hybrid events
$\theta<60°$, $E_{threshold} = 3.10^{18}$ eV

$E_{inv}(E_{Cal})$ systematic uncertainty: propagated systematic uncertainty associated with the measurement of S1000 and DX + systematic uncertainty of the method (propagating the uncertainties associated with the parameters of A(DX) and B used to determine E_{Inv})

Inclined showers (62°<θ<80°)

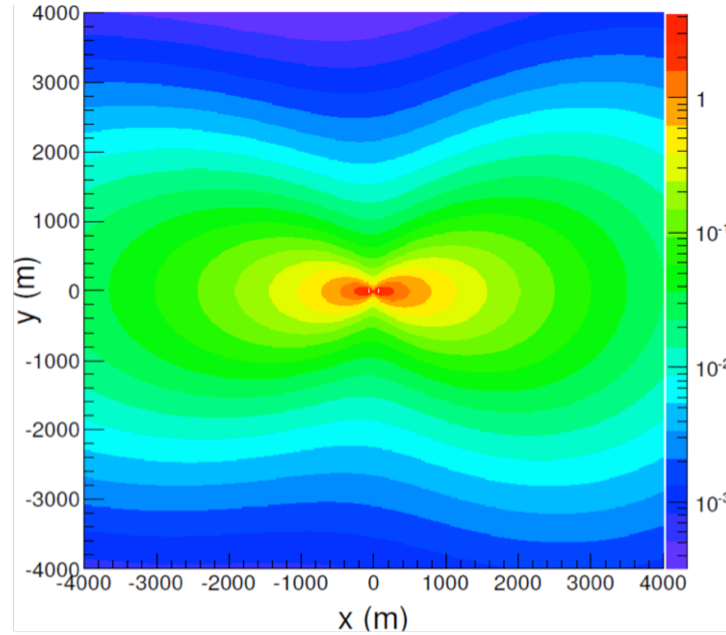
Muon dominated signals → size at ground from muon density maps

The shape of the maps is energy, mass & model independent



FD: Standard reconstruction

SD: Separate reconstruction for 62°<θ<80°

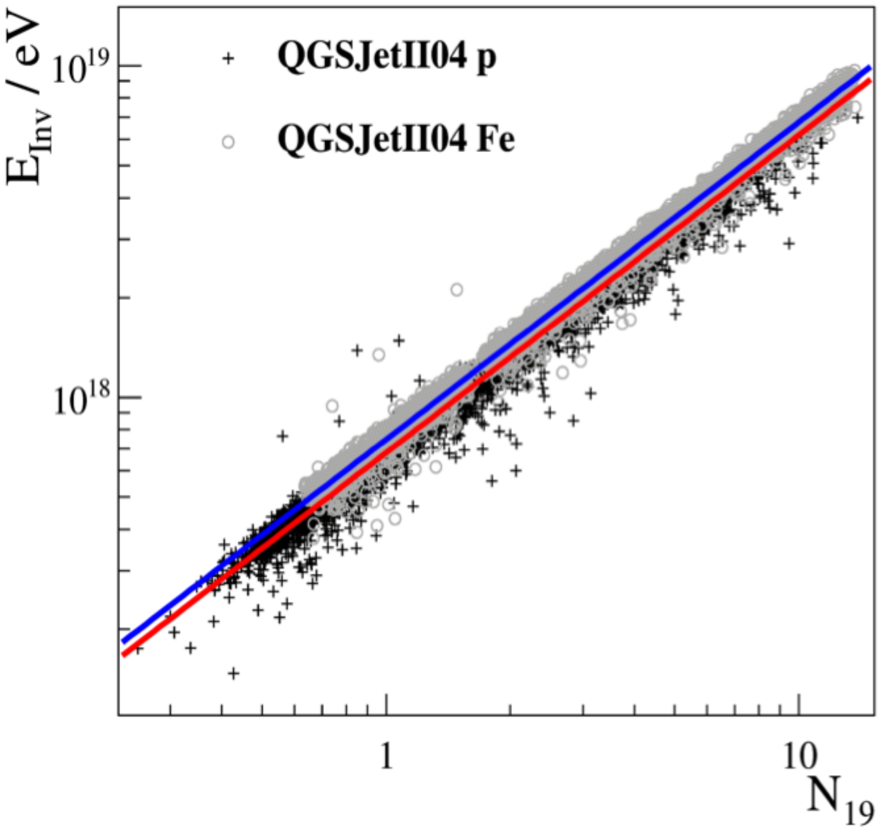


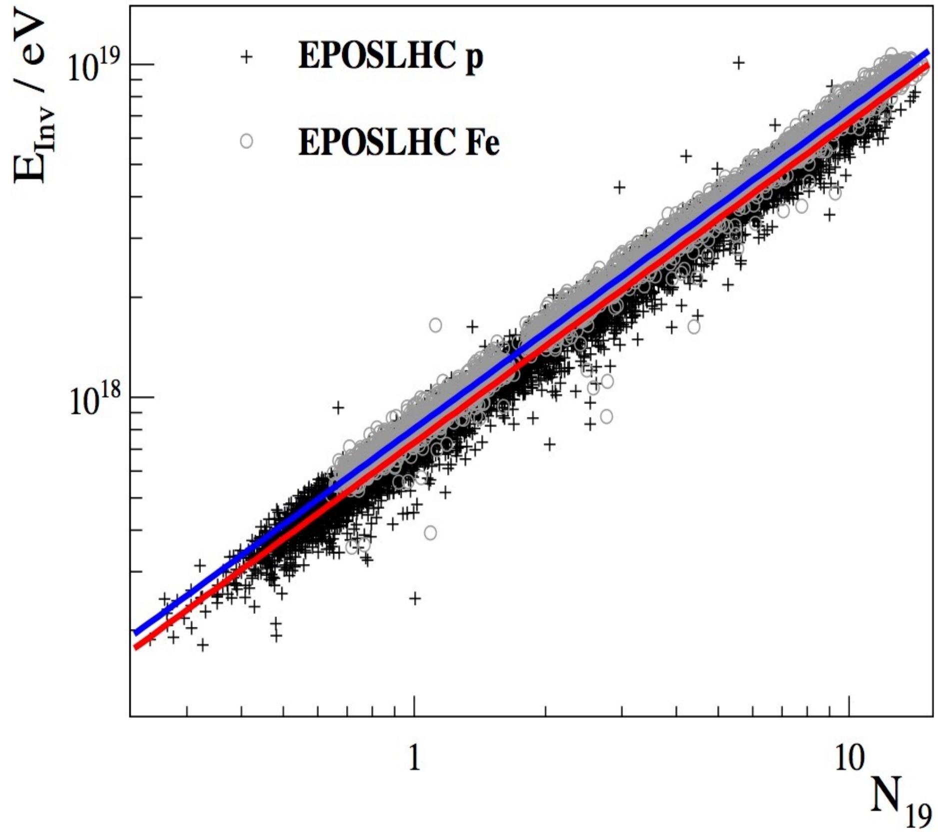
Reconstruction based on muon distribution maps at ground for 10^{19} eV protons QJSJetII03. Muon maps are fitted to observations to obtain the muon content from the normalization → N_{19} (muon scale reference value)

$$\mathbf{n_\mu = N_{19}(E_0\,,A)\ \ n_\mu(x,y,\theta,\varphi)}$$

The Pierre Auger Collaboration JCAP 08 (2014) 019

E_{Inv} (N_{19})



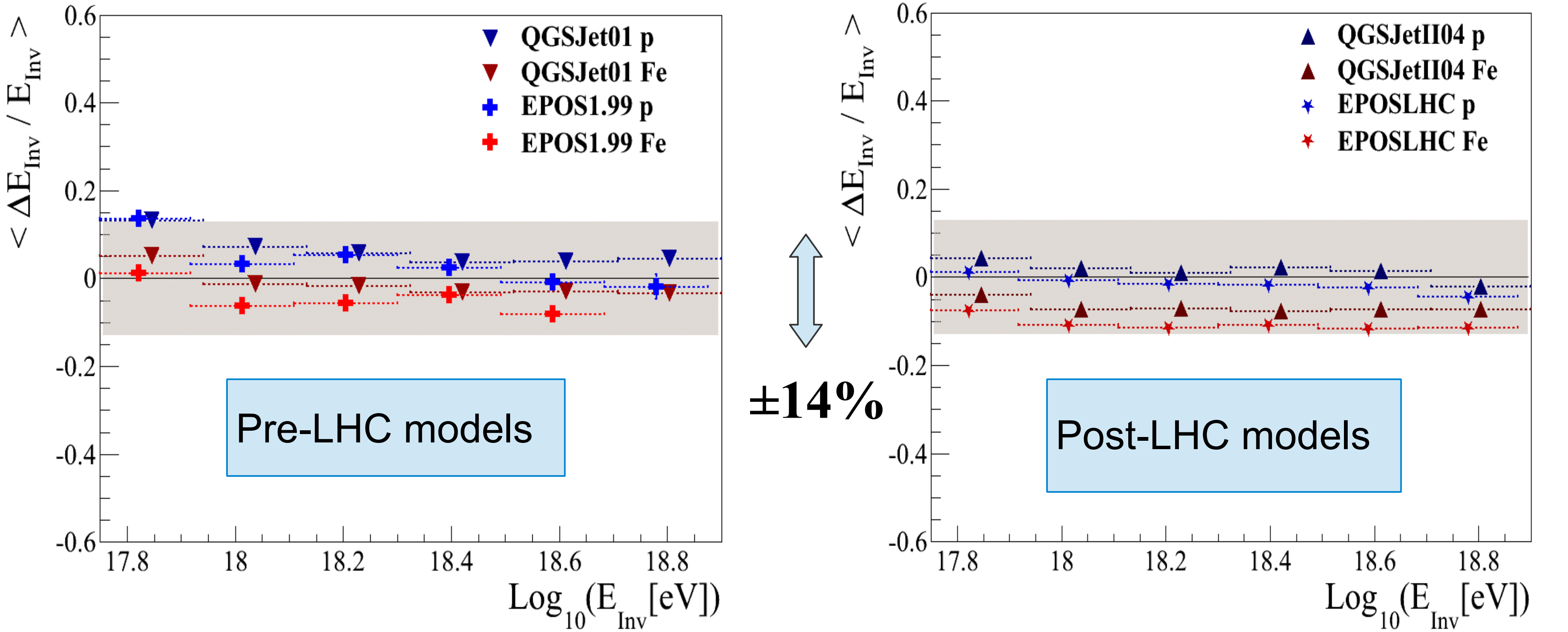


correlation is very good !

We will use from now on E_{Inv} [eV] = p0 $(N_{19})^{p1}$ with p0 and p1 obtained for QGSJetII04 mixed p-Fe composition sample.

E_{Inv} (N_{19})

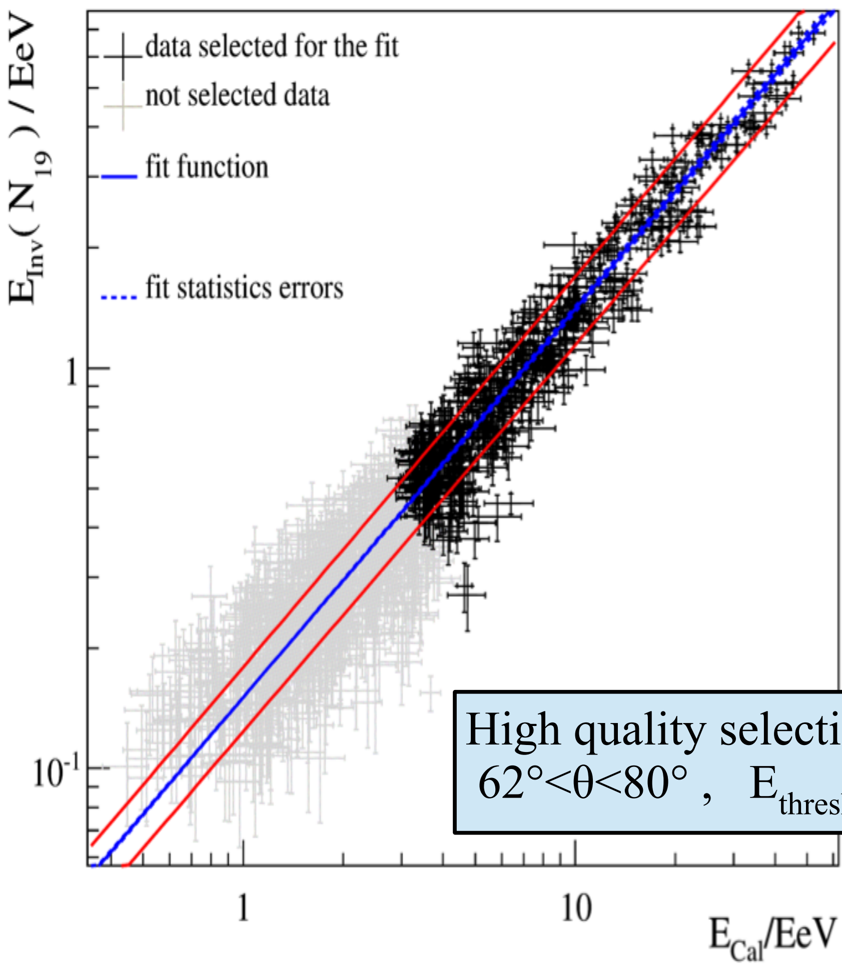
Deviation reconstructed invisible energy from inclined showers for simulated data samples with different mass and high energy hadronic interaction models

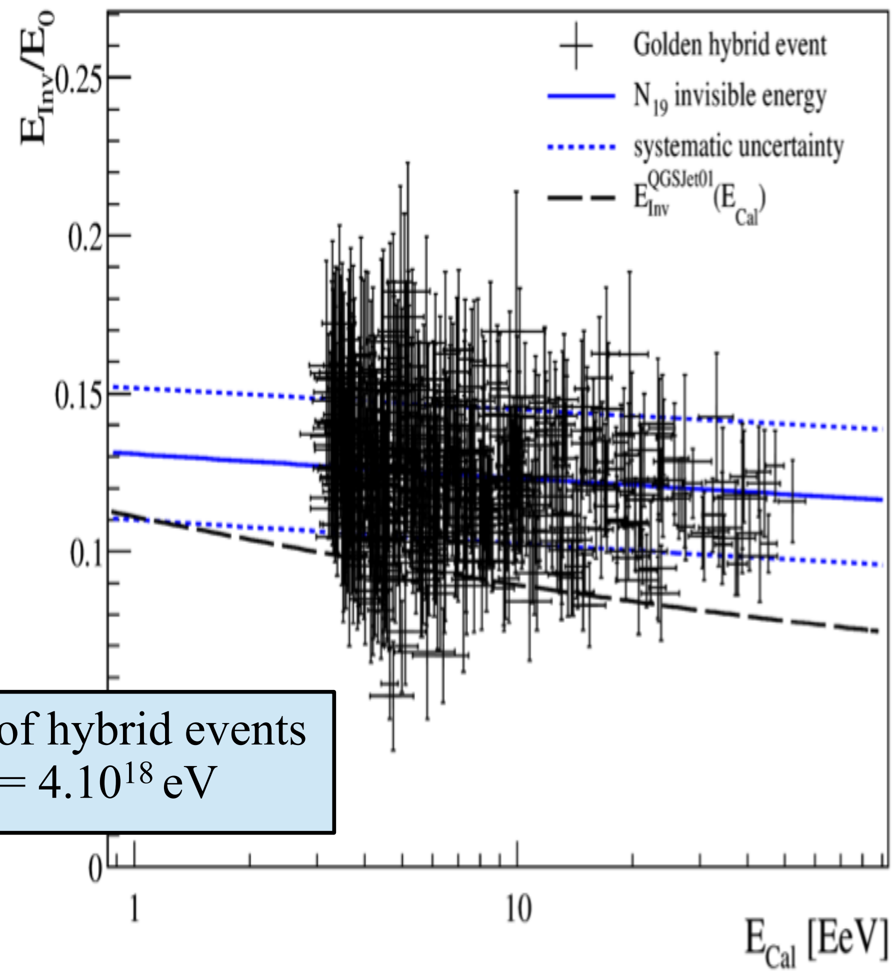


$E_{Inv} = p0\,(N_{19})^{p1}$ reconstructed using p0 and p1 obtained for QGSJetII04 mixed P-Fe composition sample.

$E_{Inv}(N_{19})$ parametrization with E_{Cal}

$$E_{Inv} = a_0 \ (E_{Cal})^{a1}$$



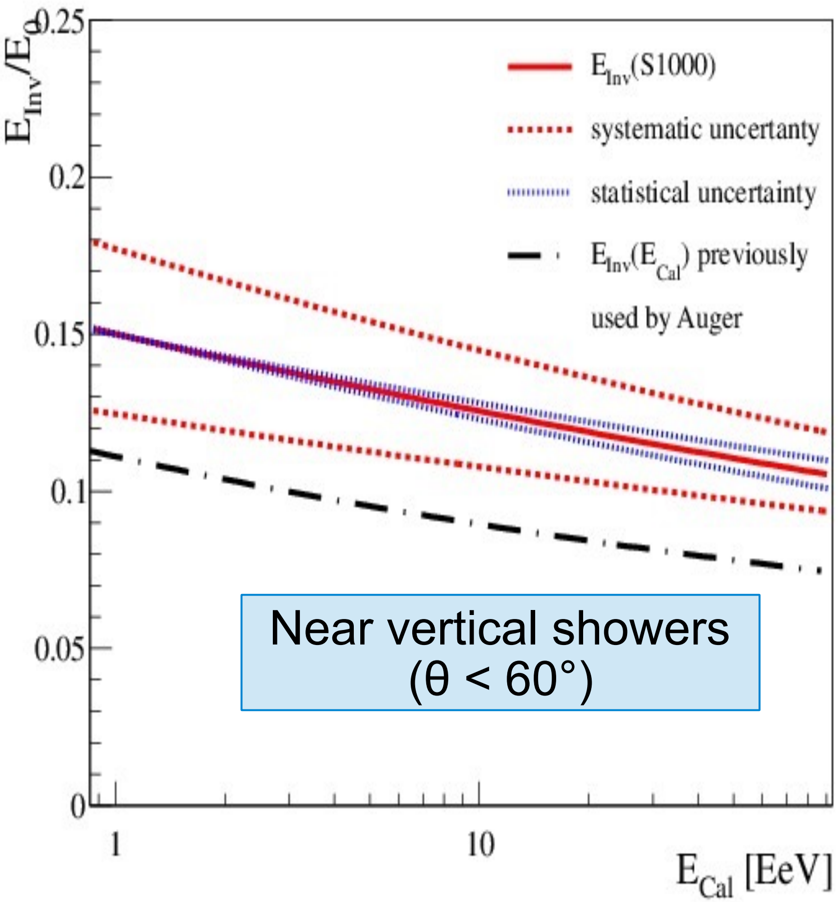


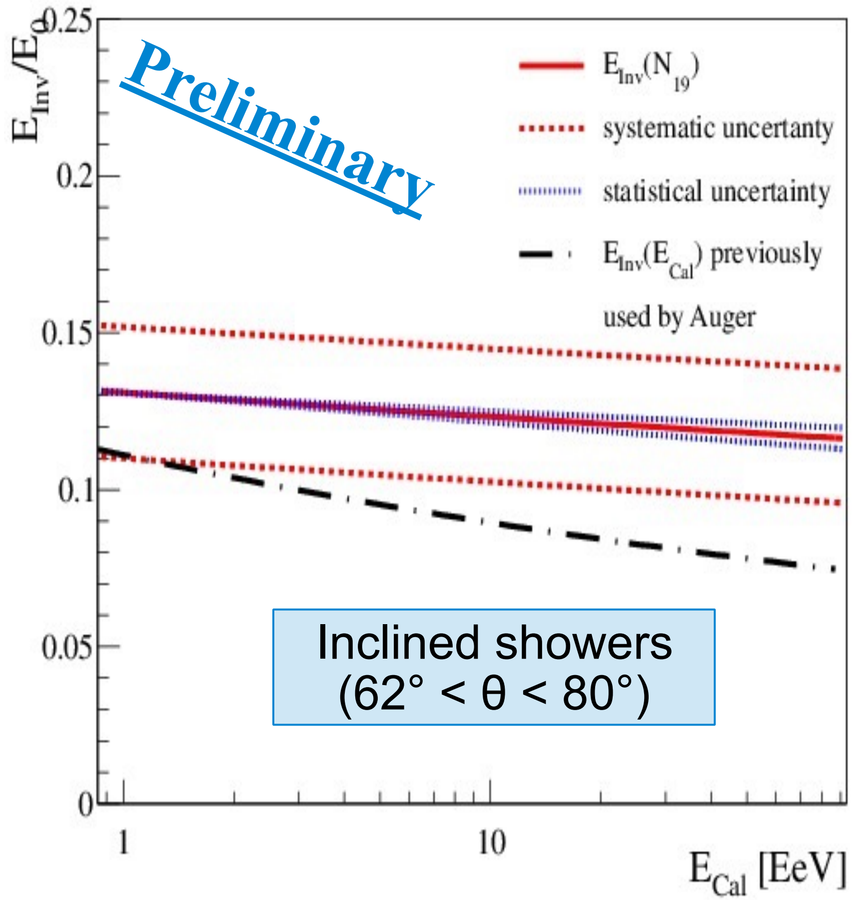
High quality selection of hybrid events
$62° < \theta < 80°$, $E_{threshold} = 4.10^{18}$ eV

$E_{inv}(E_{Cal})$ systematic uncertainty: propagated systematic uncertainty associated with the measurement of N_{19} + systematic uncertainty of the method (due variation of mass composition and high energy hadronic interaction models).

E_{Inv} parametrization with E_{Cal}

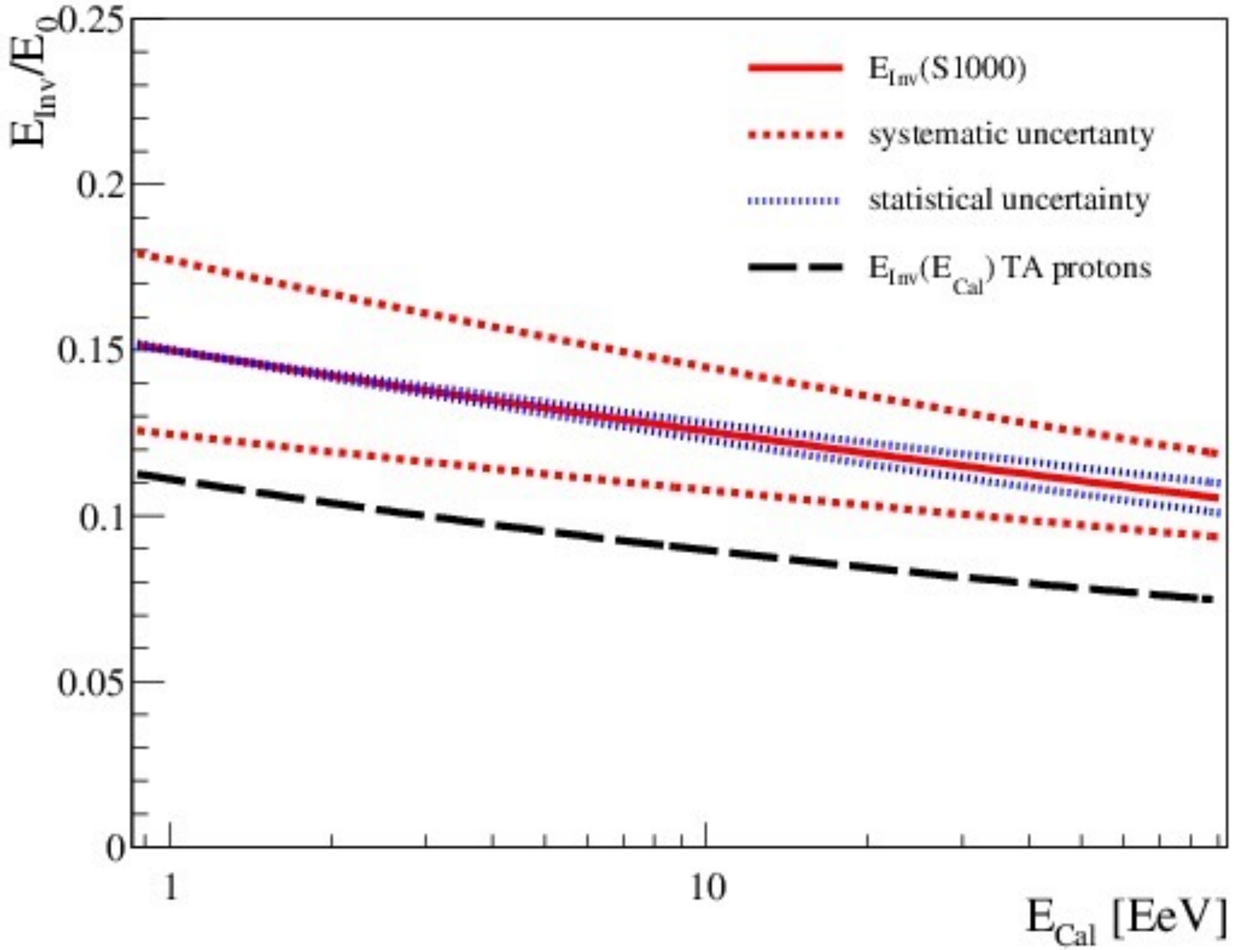
Average E_{Inv} parametrization for two independent data samples





E_{Inv} parametrization with E_{Cal}

Average E_{Inv} parameterizations used in Auger and TA



Auger E_{Inv} is larger than E_{inv} from Telescope Array [*]

[*] T.Abu-Zayyad et al., Astropart. Phys. (2014) arXiv:1305.7273

Conclusions

- The invisible energy was obtained for two independent data samples of vertical and inclined hybrid events of the Pierre Auger Observatory

- These novel estimations of E_{Inv} from data are basically independent of the high energy hadronic interaction model used in Monte Carlo simulations.

- A parametrization of the average invisible energy as a function of the calorimetric energy was given. This parametrization could also be used by other FD experiments taking into account the relative difference in the energy scale.

- Analysis of the systematic uncertainties on the invisible energy shows a correlated uncertainty in the total energy which decreases with energy from 3% to 1.5% [#].

[#] V Verzi for the Pierre Auger Collaboration, 33rd International Cosmic Ray Conference (2013) arXiv:1307.5059