Analysis of Air Showers with respect to Primary Composition of Cosmic Rays

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http://www-hep2.fzu.cz/~vicha/Dissertation/Dizertace.pdf

Seminar of Division of Elementary Particle Physics, 22. 9. 2016

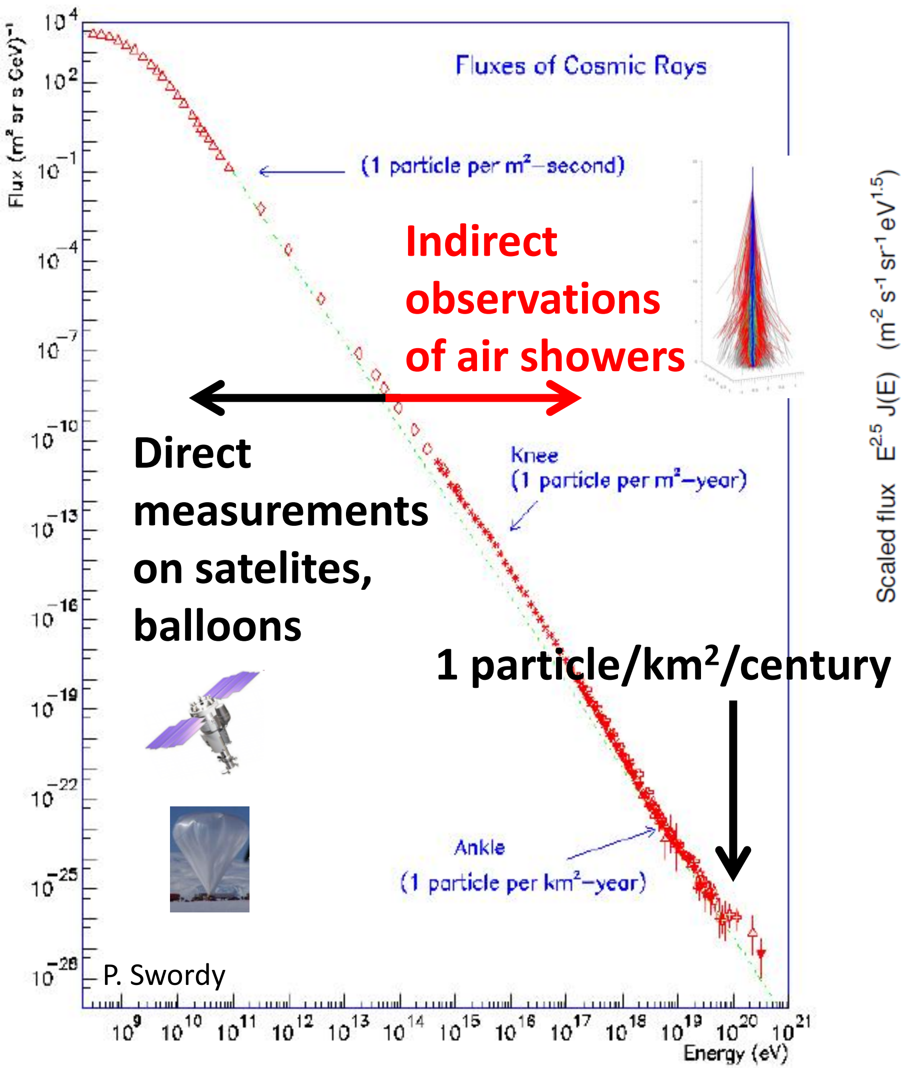
Outline

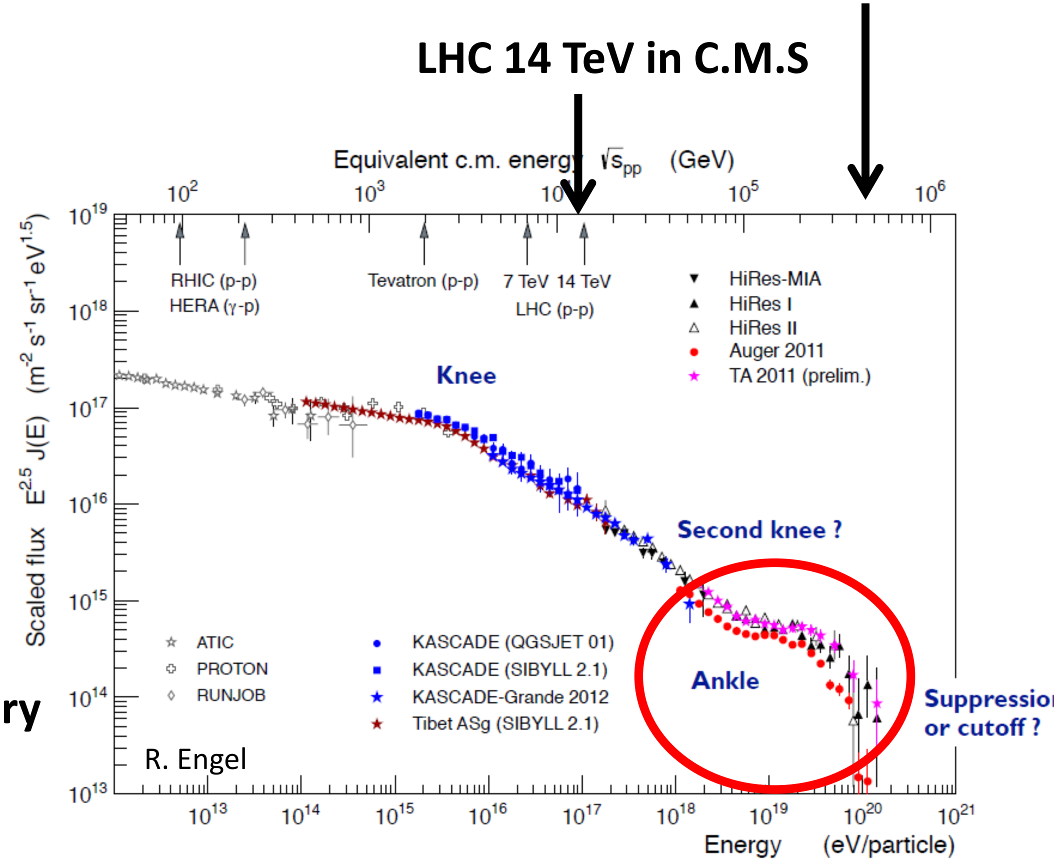
- **Motivation** to study mass composition of cosmic rays of ultra-high energies (above ~10^{18} eV, UHECR)
- **Mass composition** of UHECR – current state of knowledge
- Sensitivity of Attenuated Signals in Surface Detectors to Primary Masses
  - **MC study of current and future observatories**
- Combined Analysis of Ground Signal and Depth of Shower Maximum
  - **applied to the data measured at the Pierre Auger Observatory**
- Number of Muons with Resistive Plate Chambers
  - **potential of possible upgrade of the Pierre Auger Observatory**

Spectrum of cosmic rays $\approx E^{-2.7}$

500 TeV in C.M.S.

LHC 14 TeV in C.M.S





UHECR observed by giant observatories like the Pierre Auger Observatory or Telescope Array

What is the origin of flux suppression?

Propagation effect or acceleration limit?

Greisen-Zatsepin-Kuzmin effect (1966)

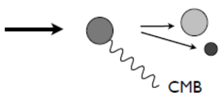


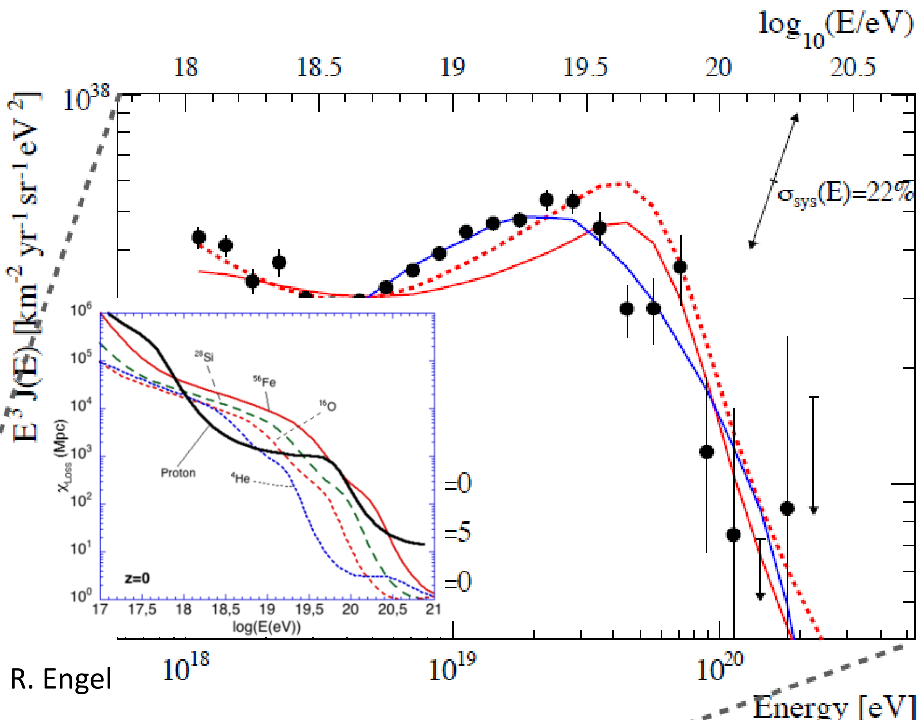
Photo-pion production

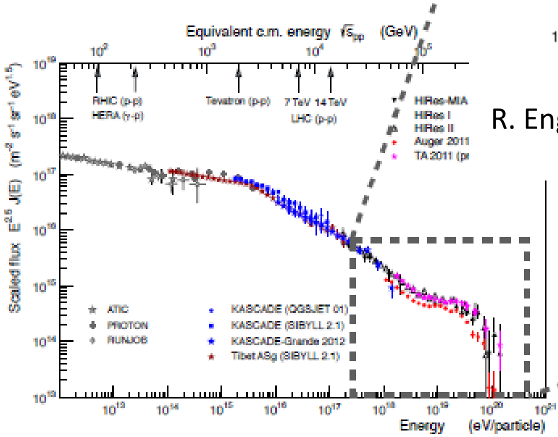
Proton dominated flux

Ankle: e^+e^- pair production

Suppression: delta resonance

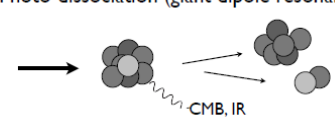
(Dip model of Berezinsky et al.)





R. Engel

Photo-dissociation (giant dipole resonance)



Iron dominated flux

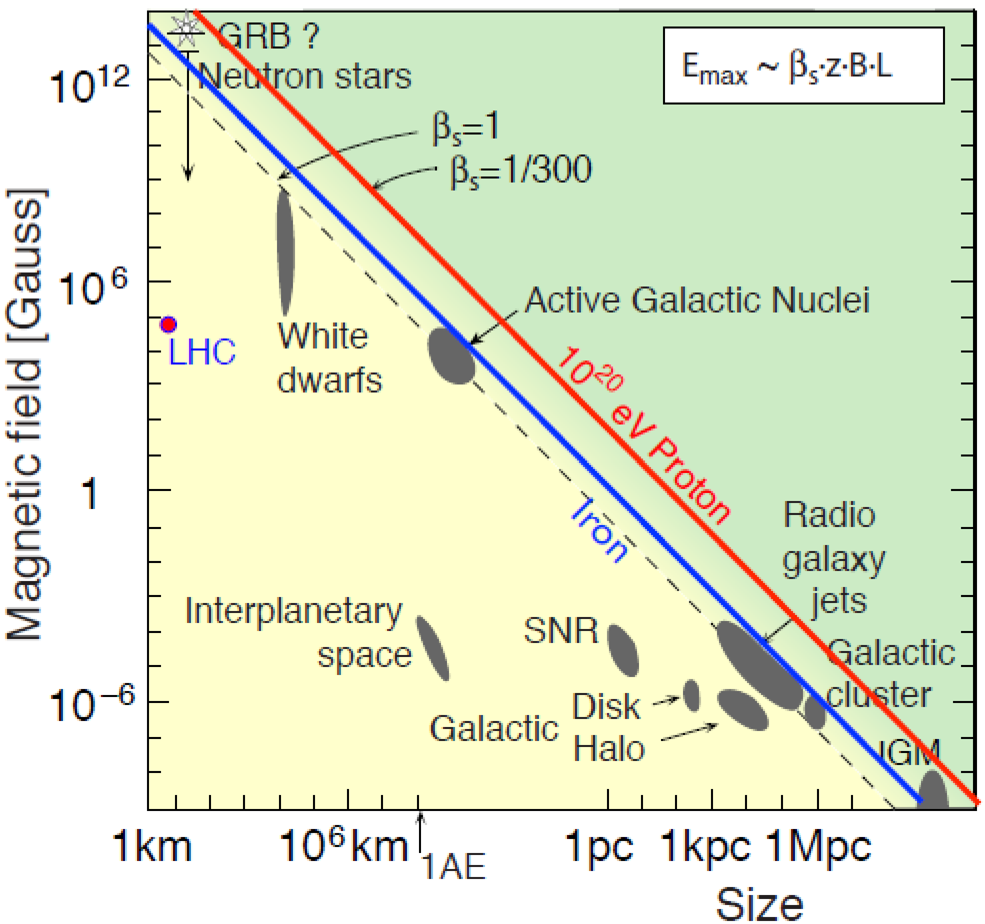
Ankle: transition to galactic sources

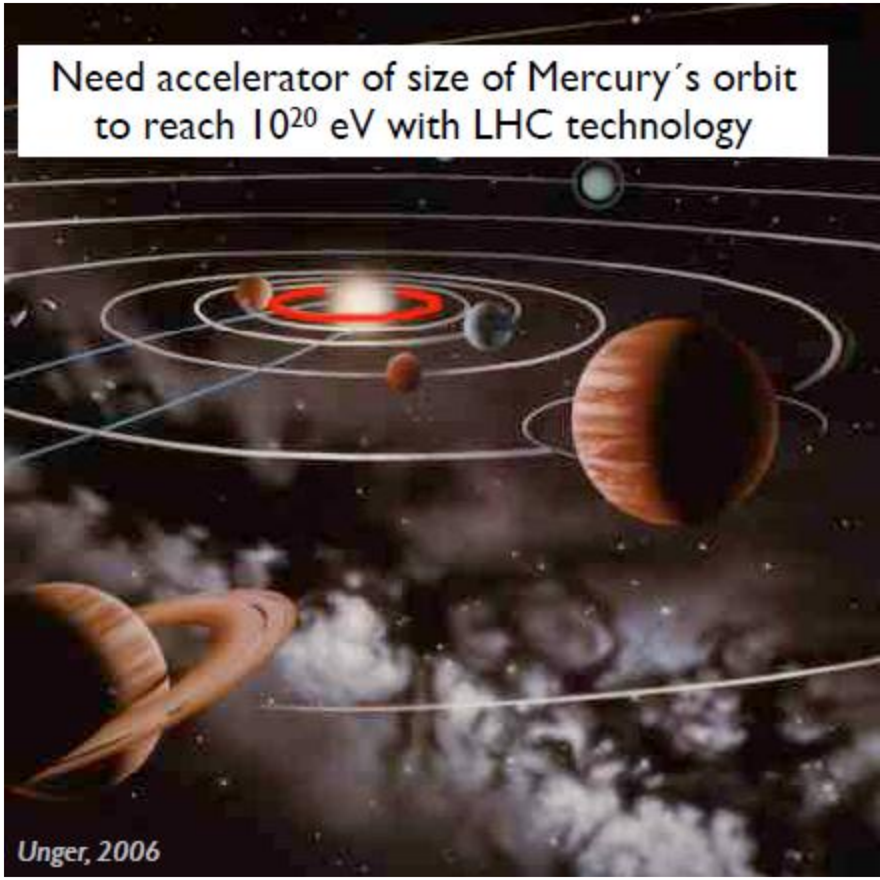
Suppression: giant dipole resonance

Or rigidity-dependent flux ?

The mysterious 10^{20} eV particles

Hillas plot (1984)





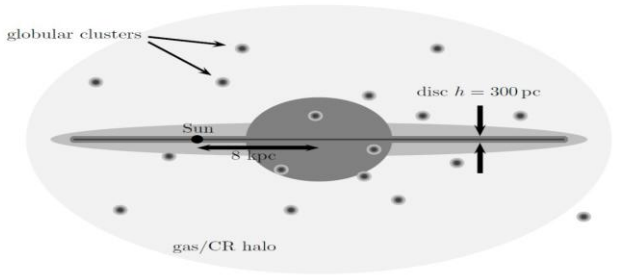
Distortions in magnetic fields

$$r_l[kpc] = \frac{E[10^{18}eV]}{Z \cdot B[\mu G]}$$

Galactic field

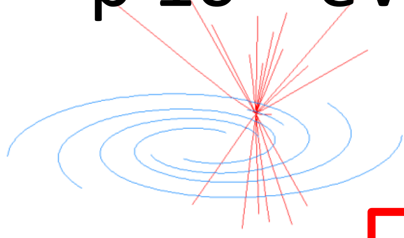
- $B_G \sim 3\mu G$
- Proton with E ~ 10^{18} eV

  => r_l = 0.3 kpc (disc thickness)



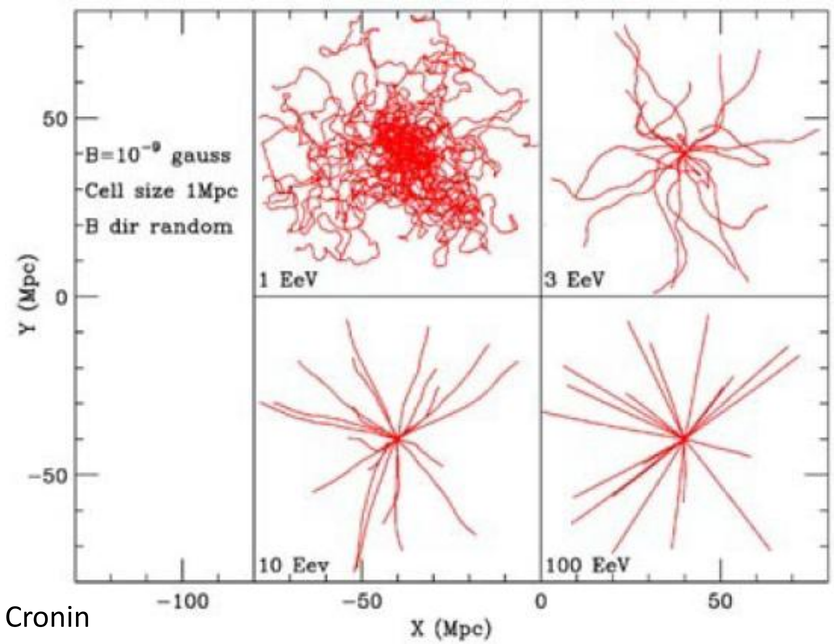
p 10^{18} eV

p 10^{20} eV



Extragalactic field

- Extragalactic field $B_{EG} \leq$ nG
- The closest AGN is Centaurus A (~ 4 Mpc)



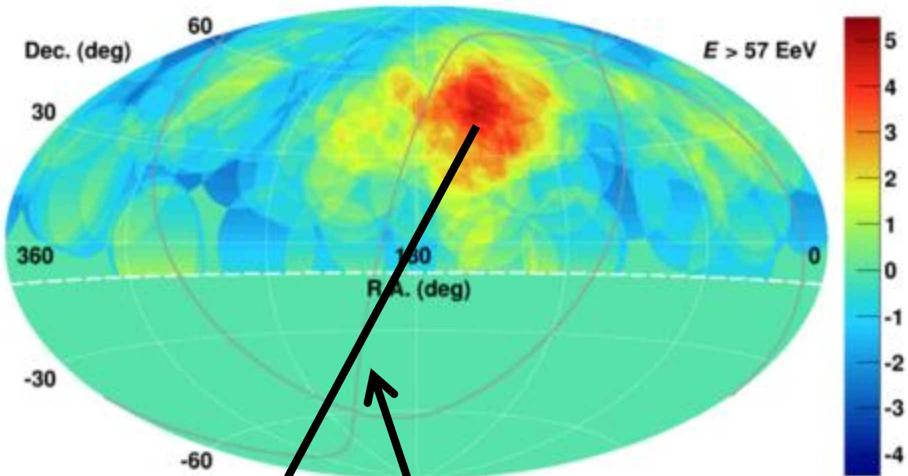
J. Cronin

~ few deg expected for 50 EeV protons

Anisotropies at the highest energies

Telescope Array (eq. coord.)

[R. Abbasi et al., ApJ 790 (2014) L21]

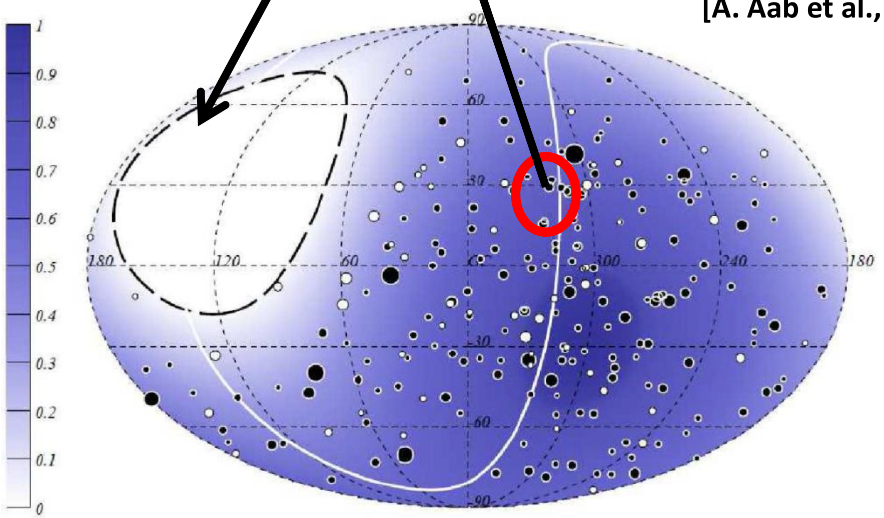


~ 5 σ local significance
(no obvious source nearby)

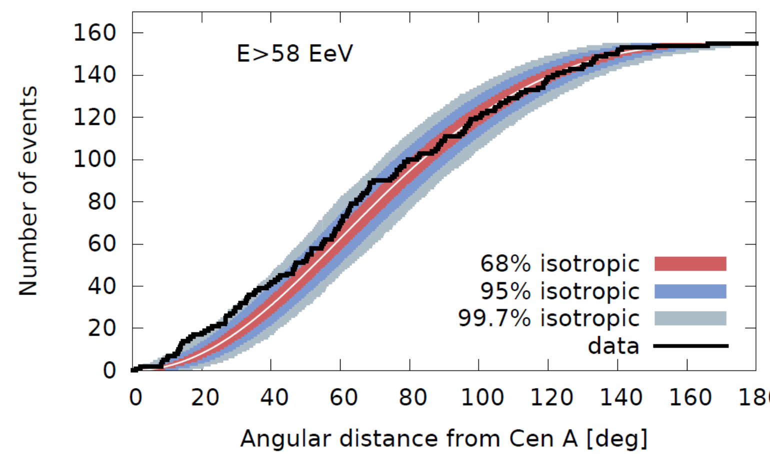
20 deg hot spots!

Pierre Auger Observatory (gal. coord.)

[A. Aab et al., ApJ 804 (2015) 15]



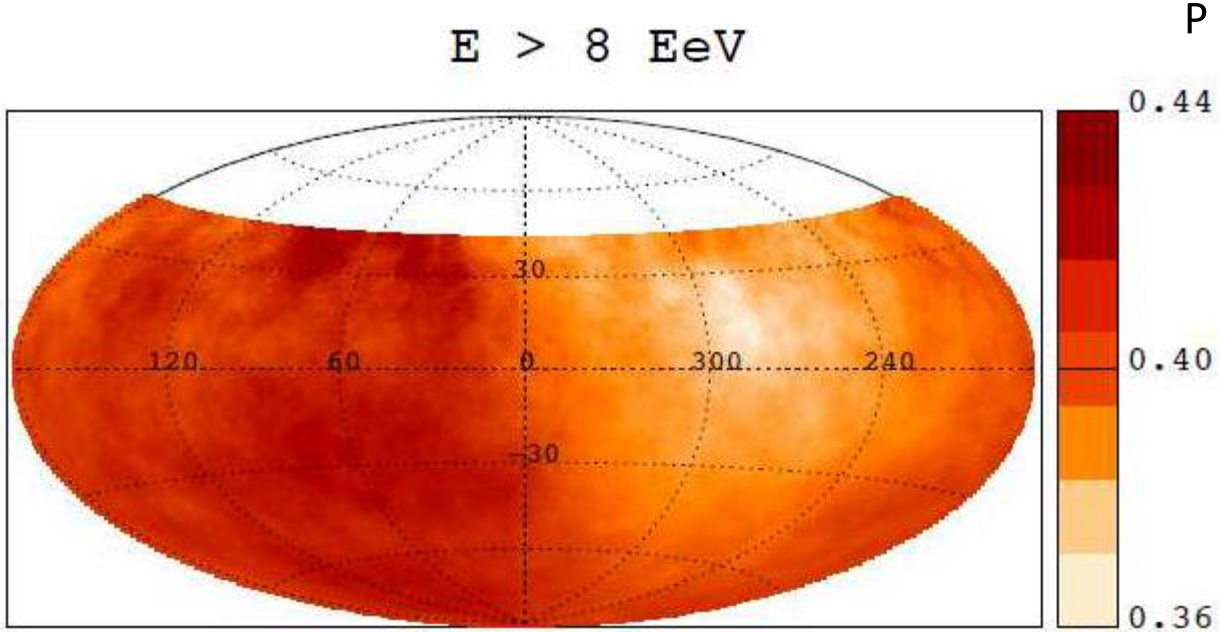
~ 3 σ local significance
(around Cen A – AGN 4 Mpc)



Weak dipole ~ 4% observed

[A. Aab et al., Phys. Rev. D 90, 012012 (2014)]

P = 6.4 · 10^{-5}

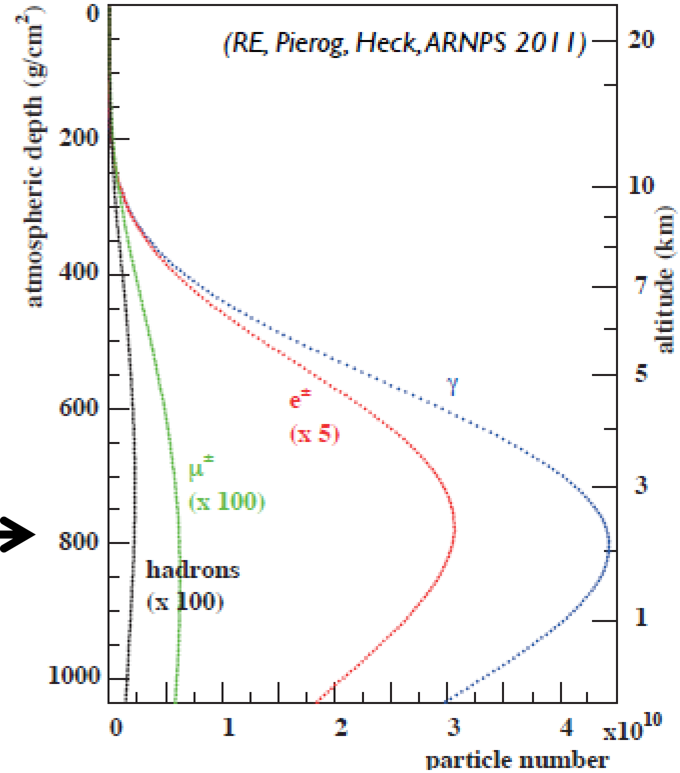


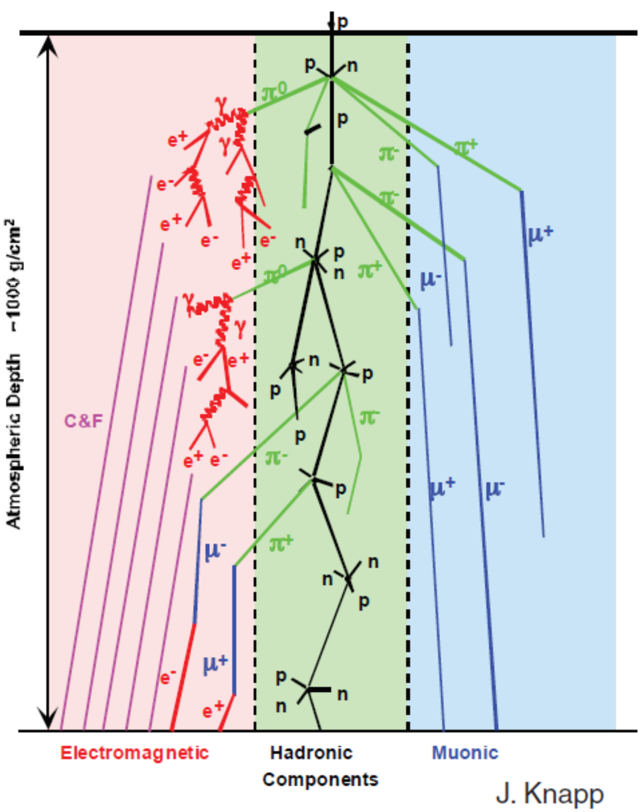
Pierre Auger Observatory (eq. coord.)

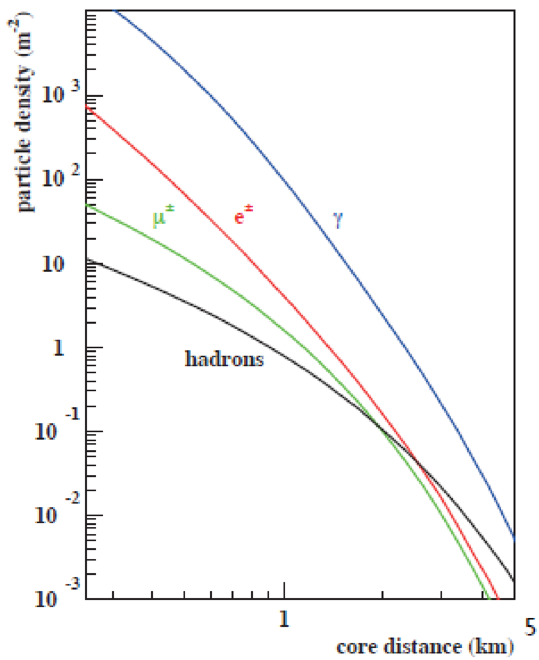
Smaller than expected => Stronger extragalactic fields?
UHECR of higher charge?
Inhomogeneous distribution of sources in the sky?

Extensive Air Showers

X_{max} →







Longitudinal profile: **fluorescence and Cherenkov light collected by optical telescopes (13% duty cycle)** (*bulk of particles measured*)

Lateral profile: **particle densities measured on ground (100% duty cycle)** (*very small fraction of particles sampled*)

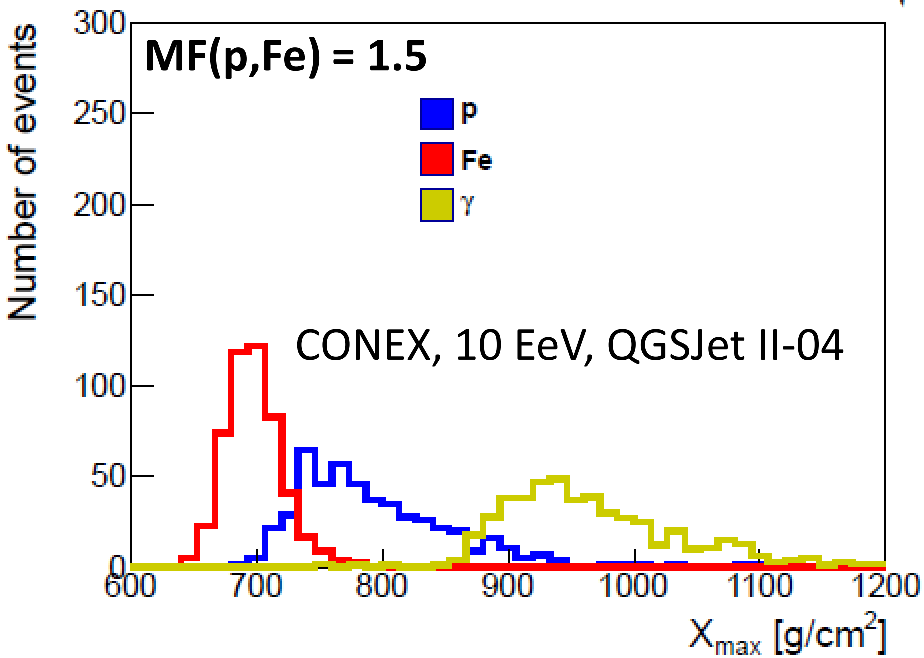
Shower parameters sensitive to the mass composition of primary particles

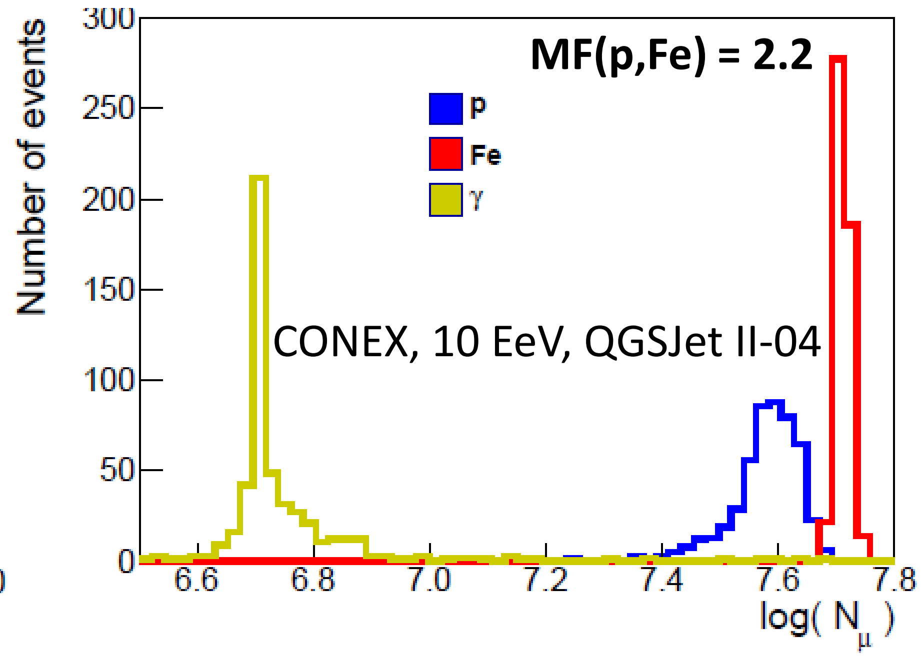
Depth of shower maximum | **Number of muons on ground**

X_{max}

$$MF(\mathrm{i,j}) = \frac{|\langle H_\mathrm{i}\rangle - \langle H_\mathrm{j}\rangle|}{\sqrt{\sigma^2(H_\mathrm{i}) + \sigma^2(H_\mathrm{j})}}$$

N_μ

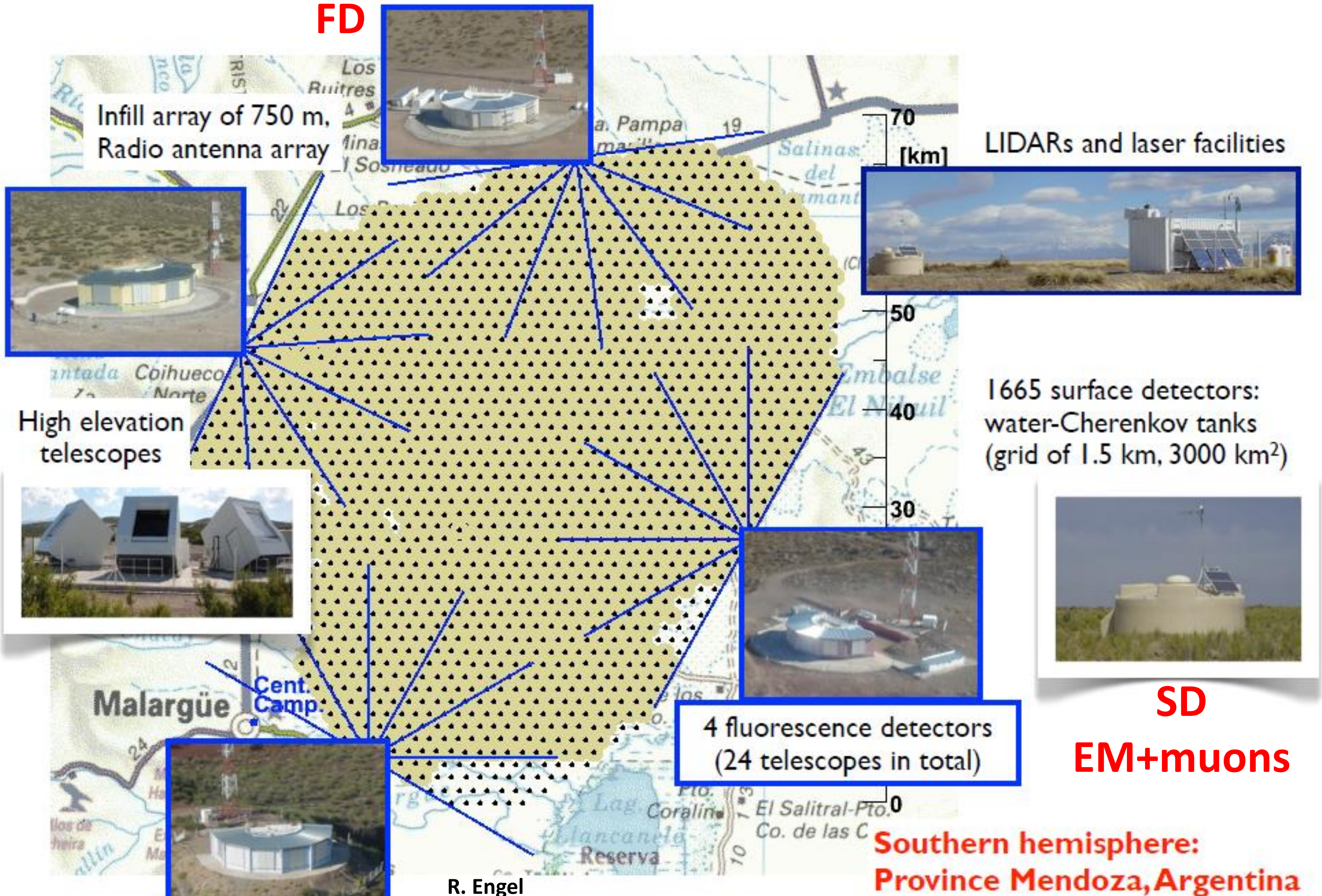




Additional detector smearing typically 15-20 g/cm²

Additional detector smearing typically 10-20 %

Pierre Auger Observatory



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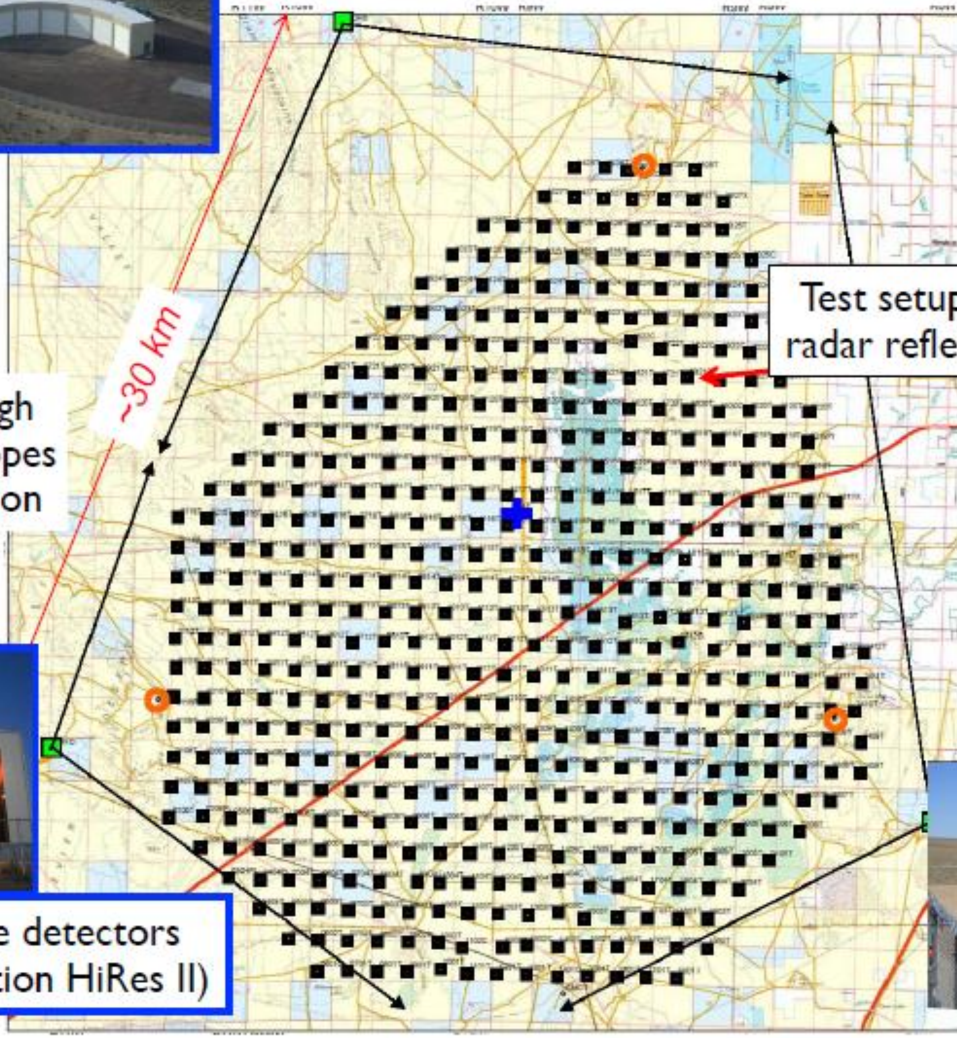
Telescope Array

FD

Middle Drum: based on HiRes II

LIDAR
Laser facility

Infill array and high elevation telescopes under construction

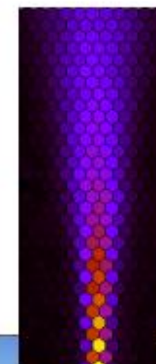


3 fluorescence detectors
(2 new, one station HiRes II)

507 surface detectors:
double-layer scintillators
(grid of 1.2 km, 680 km^2)

SD

EM only



Electron light source
(ELS): ~40 MeV

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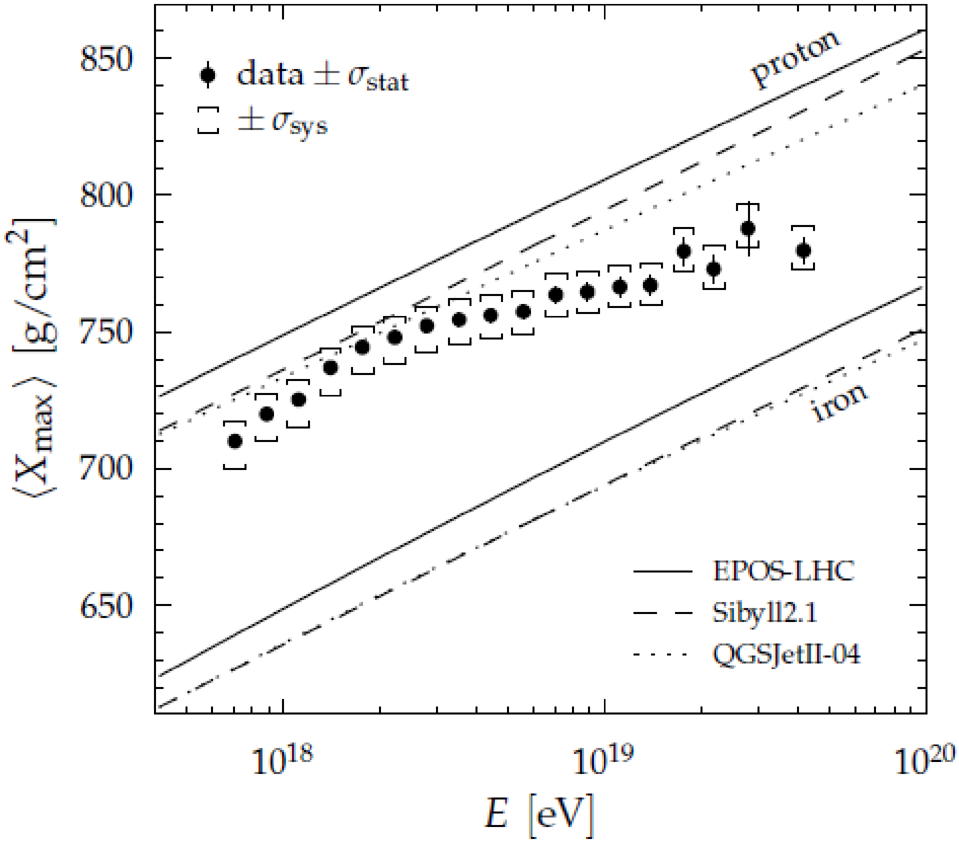
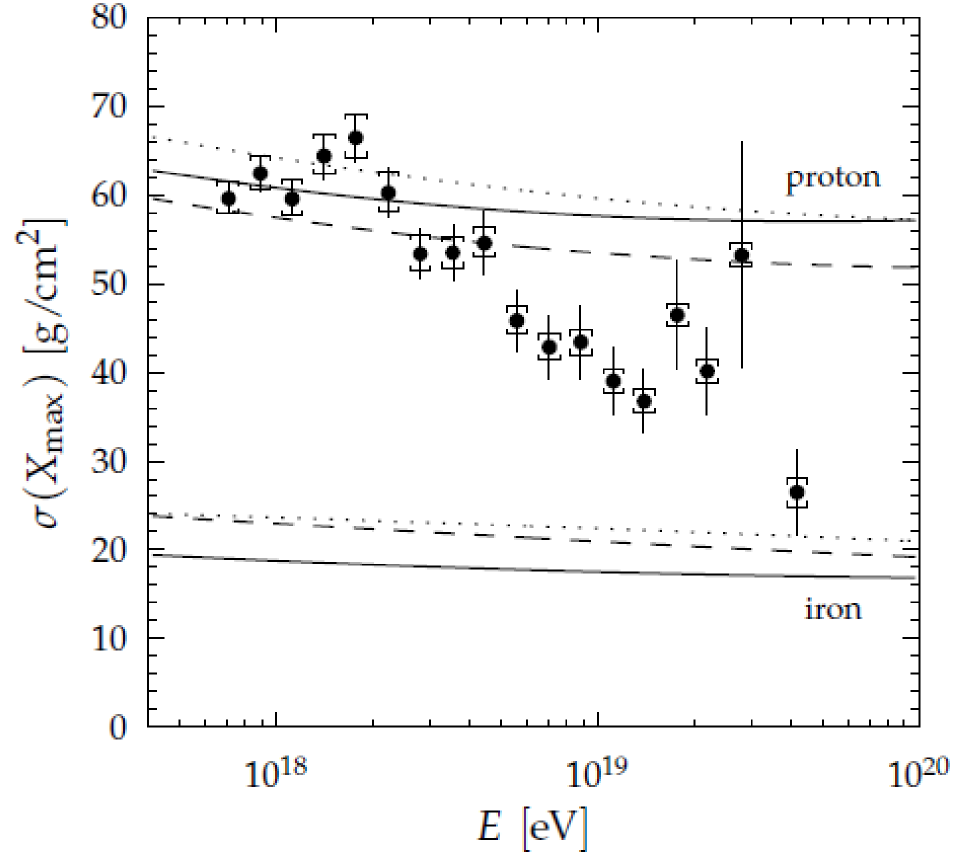
Northern hemisphere: Utah, USA

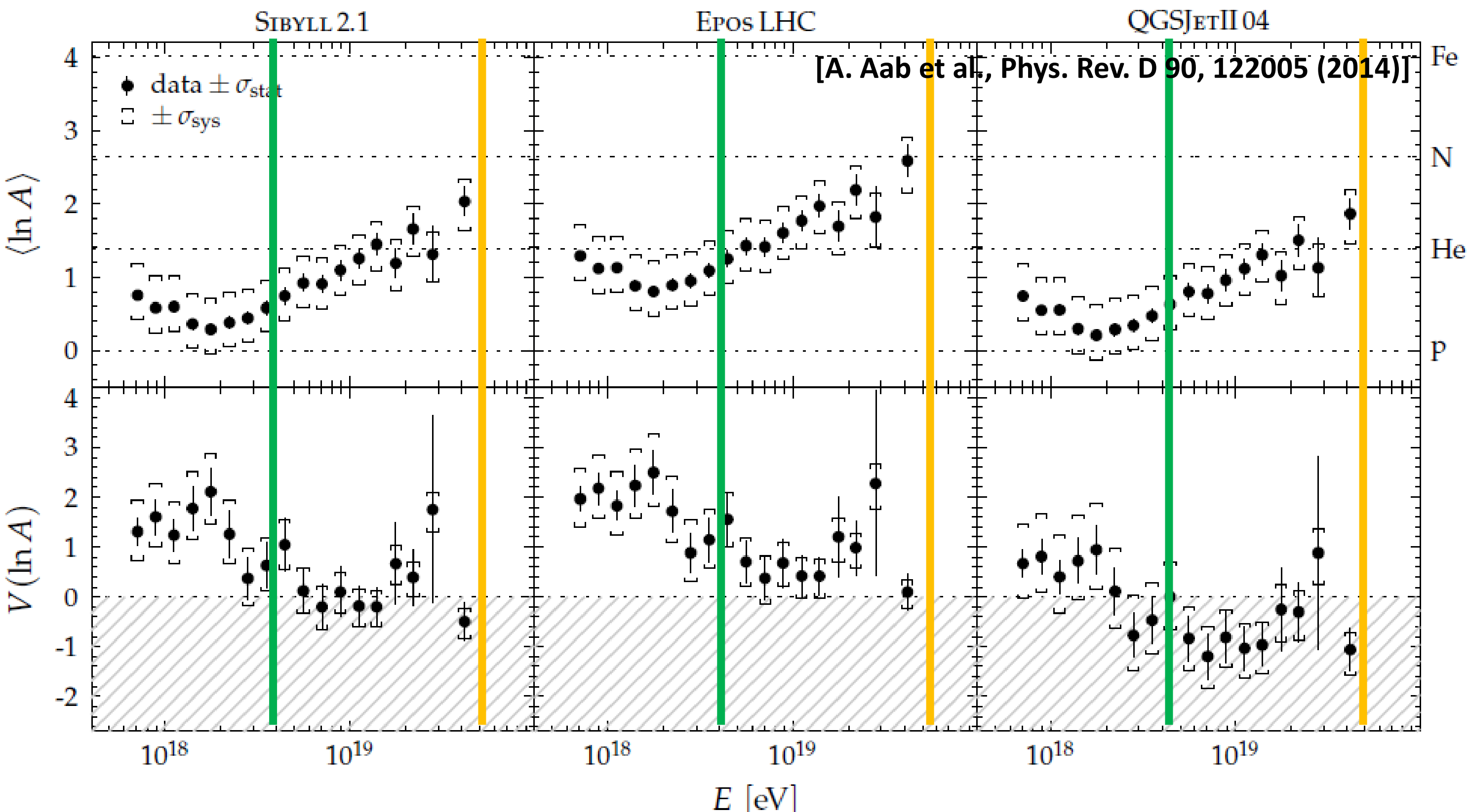
Mass composition – X_{max} moments at the Pierre Auger Observatory

[A. Aab et al., Phys. Rev. D 90, 122005 (2014)]





Mass composition – X_{max} moments interpreted with ln A moments



Ankle

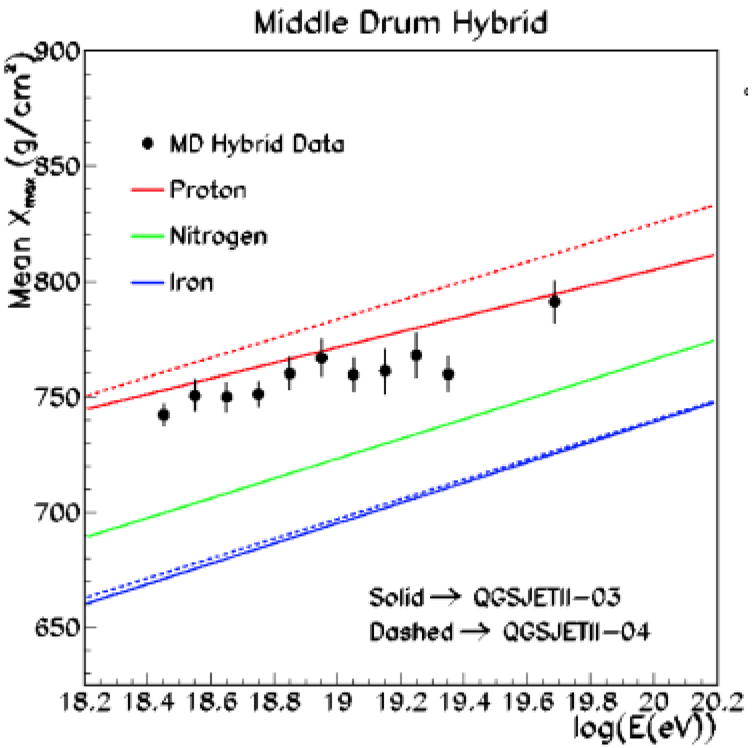
Beginning of Suppression

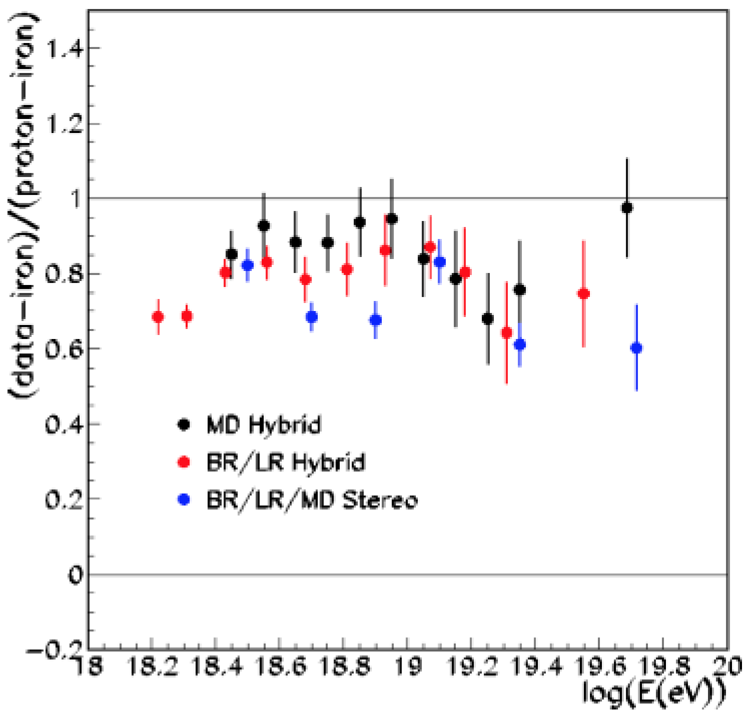
$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{\rm sh}(\langle \ln A \rangle)}{b\ \sigma^2_p + f_E^2}$$

Mass composition – Mean X_{max} at the Telescope Array

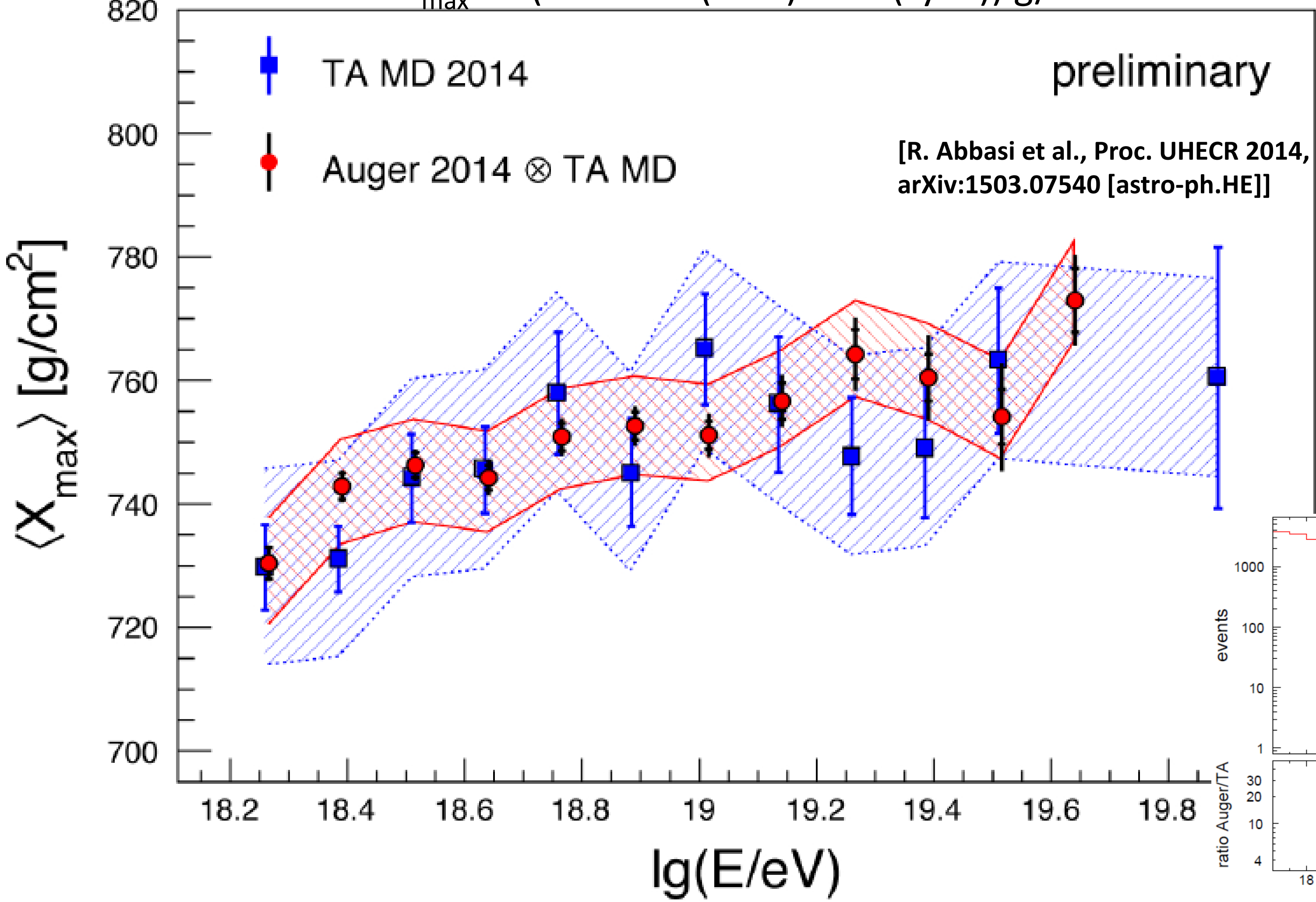
[J. Belz et al., PoS (ICRC2015) 351]

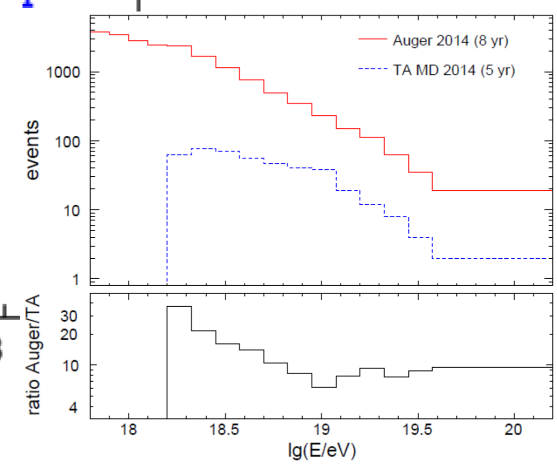




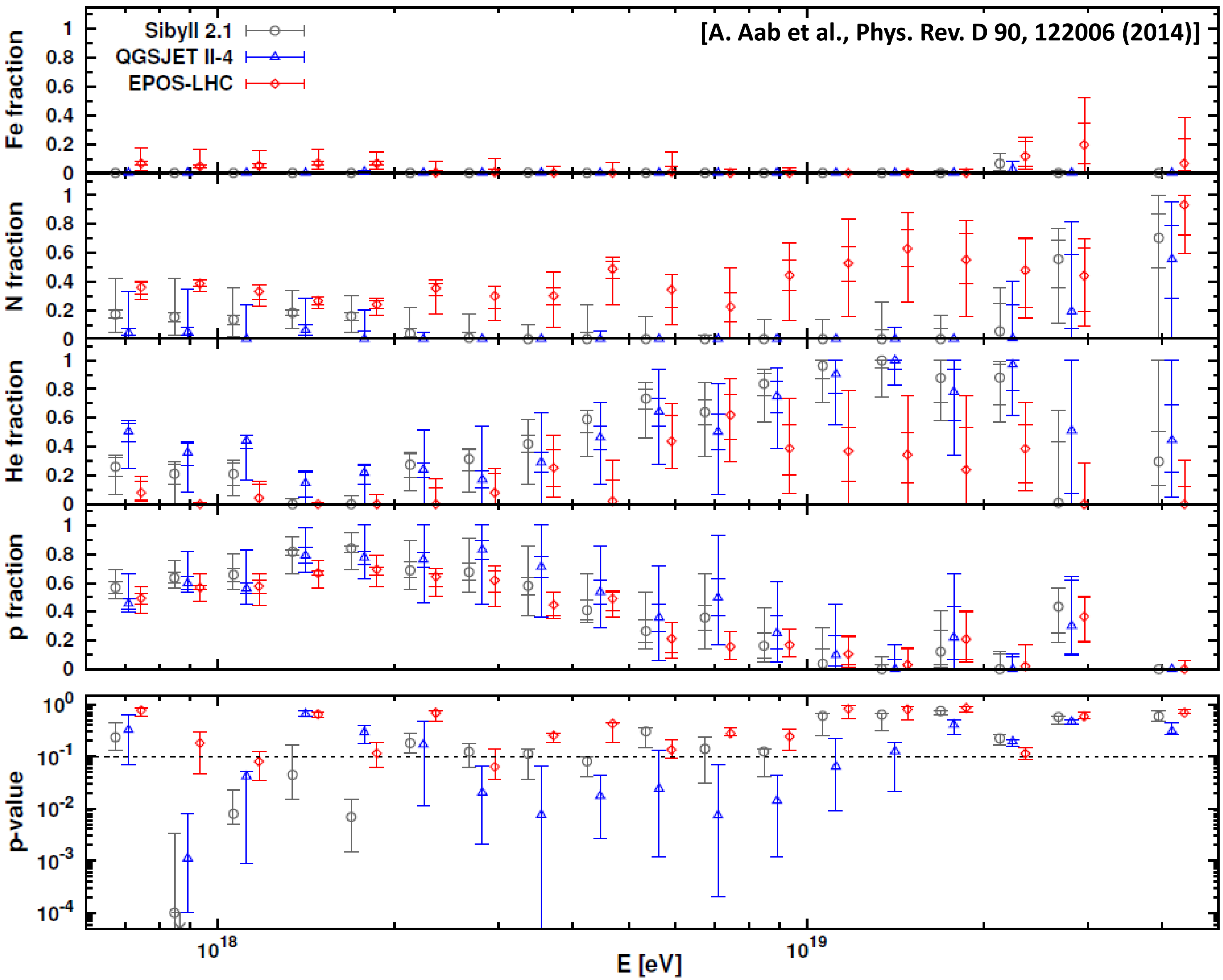
$<X_{max}>$ measurements of the Pierre Auger Observatory and Telescope Array are in good agreement !

$\Delta<X_{max}> = (2.9 \pm 2.7 \text{ (stat.)} \pm 18 \text{ (syst.)})$ g/cm2



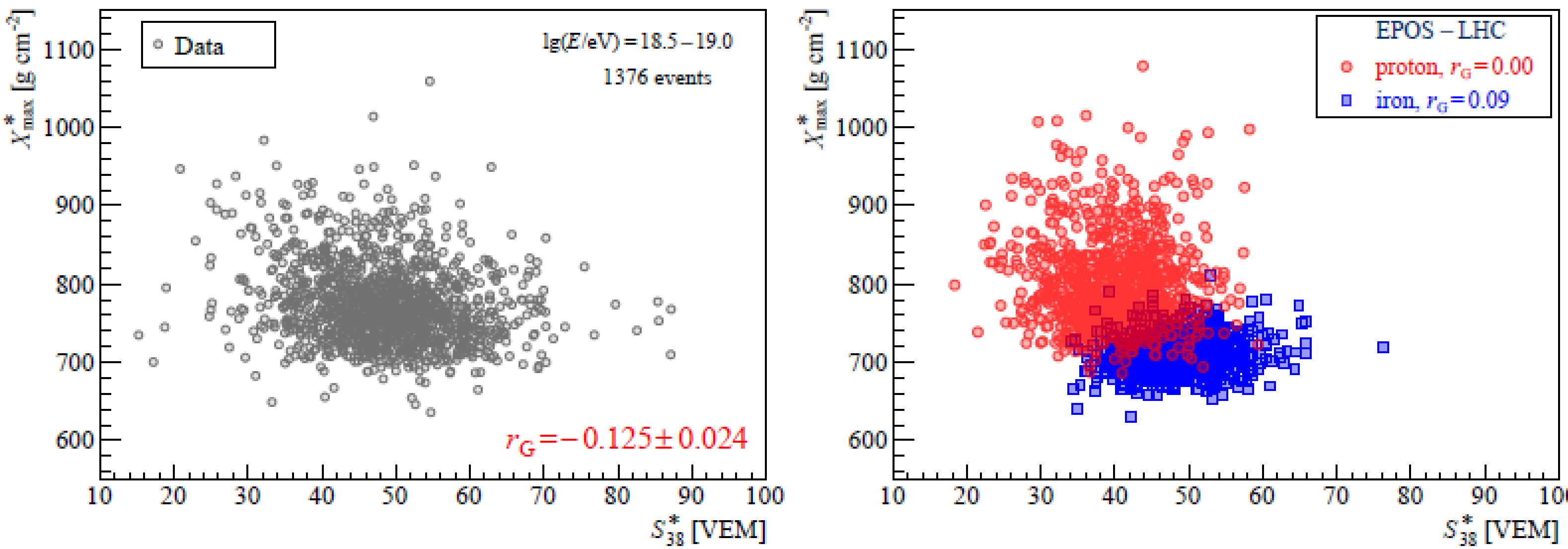


Fitting the X_{max} distributions Pierre Auger Observatory data

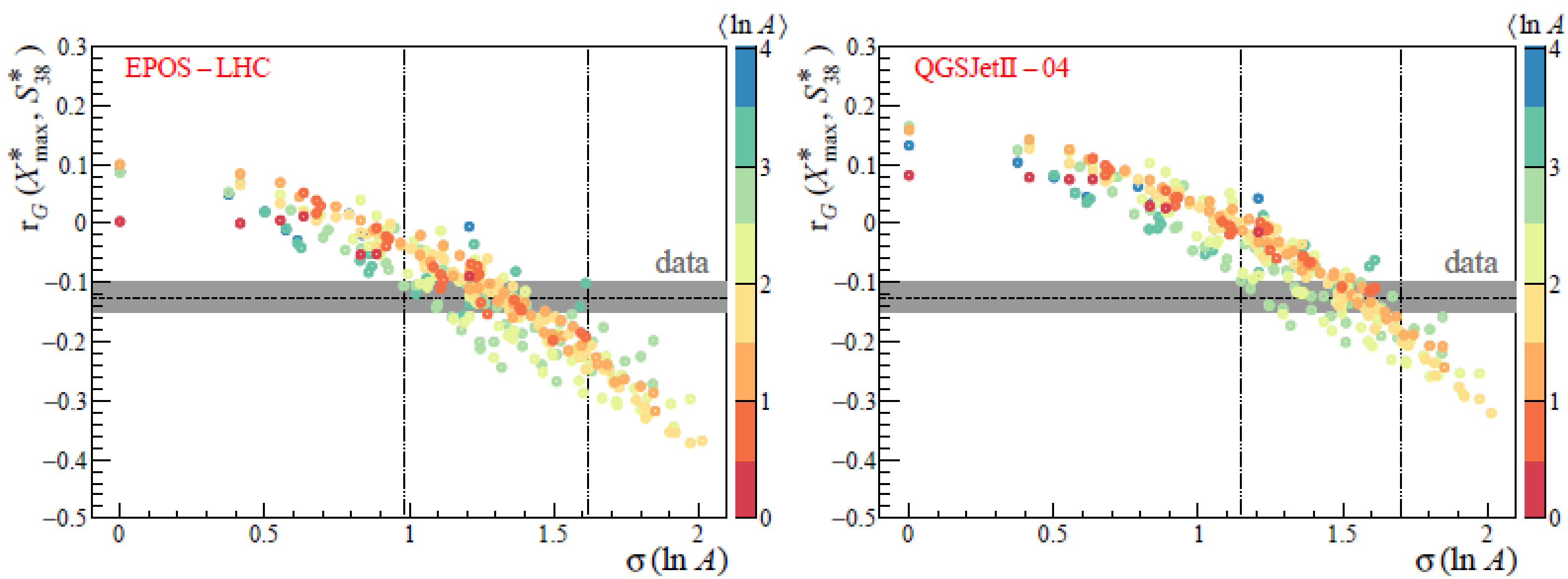


Correlation between Ground signal and X_{max}

[A. Aab et al., accepted in Phys. Lett. B (2016)]

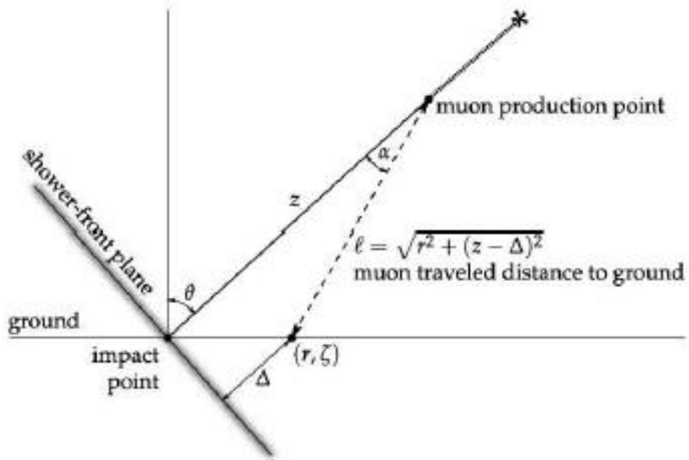


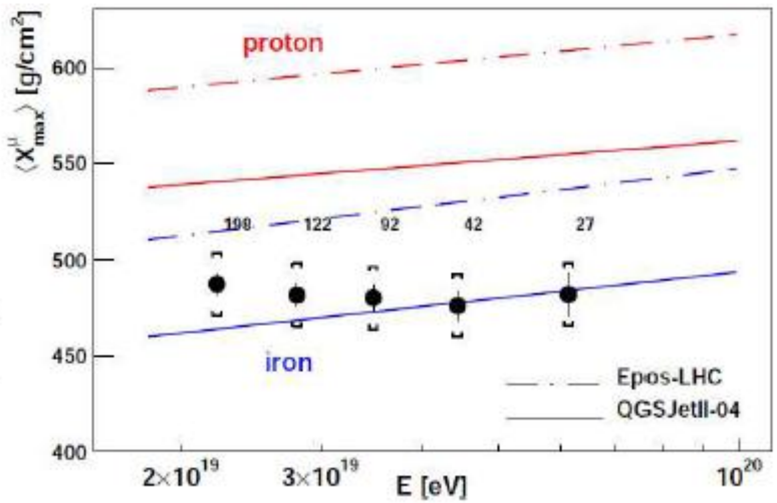
Cosmic rays are of mixed composition in log(E/eV) = 18.5-19.0

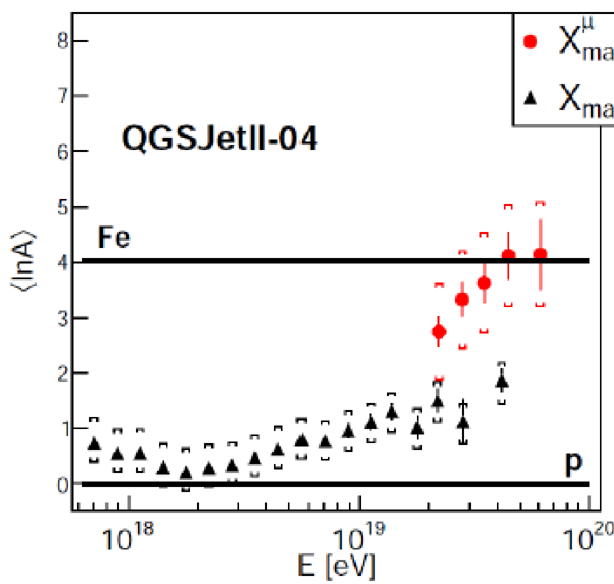


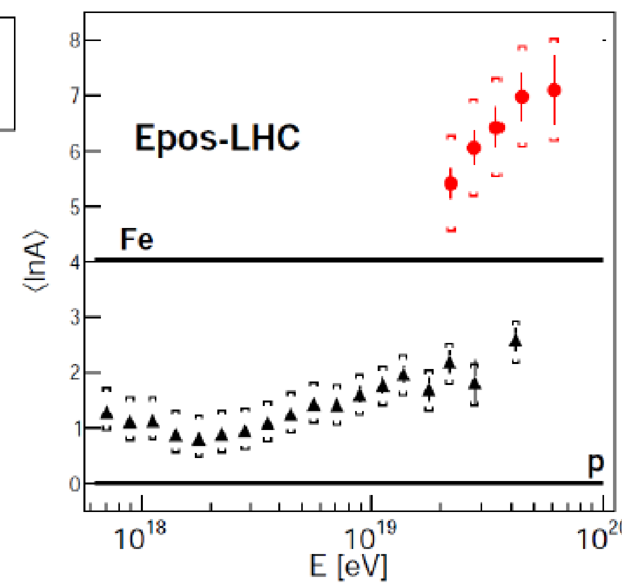
Measurement of the Muon Production Depth at the Pierre Auger Observatory

[A. Aab et al., Phys. Rev. D 90, 012012 (2014)]





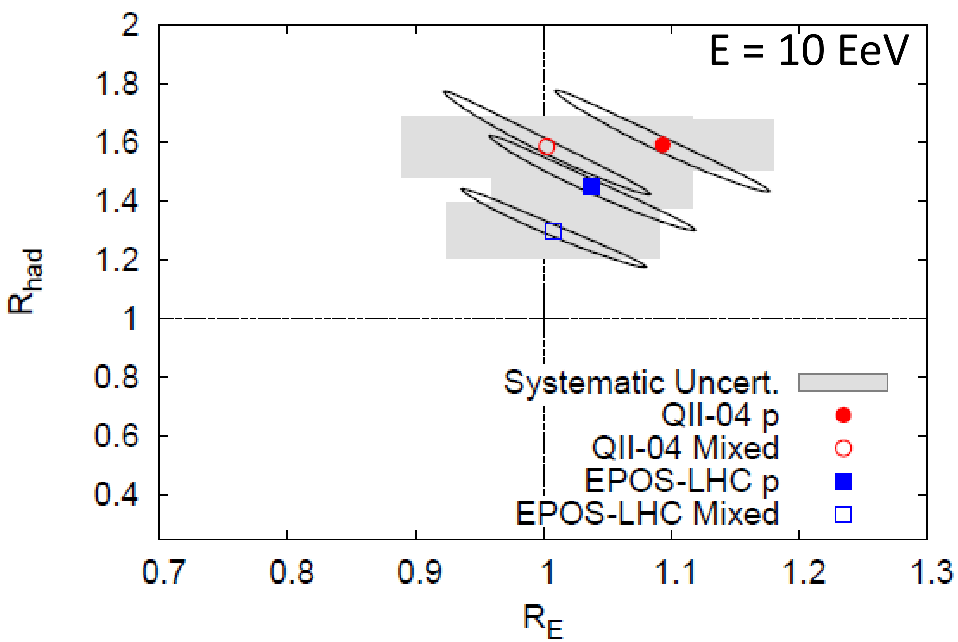




Excess of muons in measured data wrt. MC
Pierre Auger Observatory

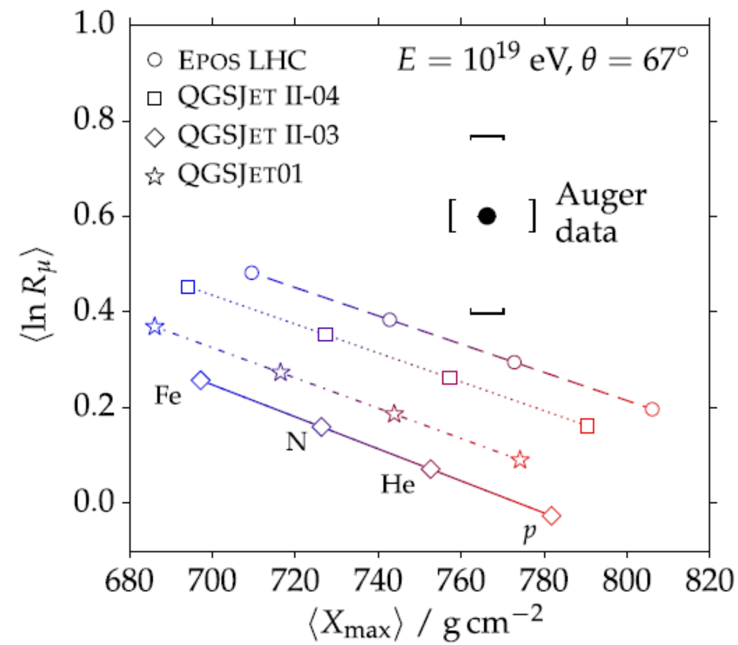
Zenith (0-60)deg

[Accepted for publication in PRL (2016)]



Zenith (62-80)deg

[A. Aab et al., Phys. Rev. D 91 (2015) 032003]



EPOS-LHC needs 10-50% more muons

QGSJet II-04 needs 30-80% more muons

Mass composition of UHECR is important for:

- Anisotropy searches at the highest energies (we need to select protons)
- Estimation of Gal. & EGal magnetic fields
- Explanation of the spectral features
- Theoretical origin of the most energetic particles
- Tests of consistency between MC and data

But it is uncertain due to different predictions of models of hadronic interactions and it is even unknown at the highest energies ...

Correction for attenuation of ground signal

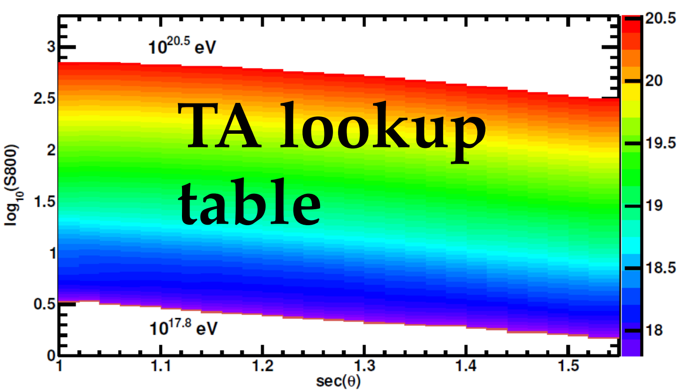
MC-based approach

- MC predictions for primary protons simulated with one model of hadronic interactions
- **Used at Telescope Aray**
- Energetic dependence

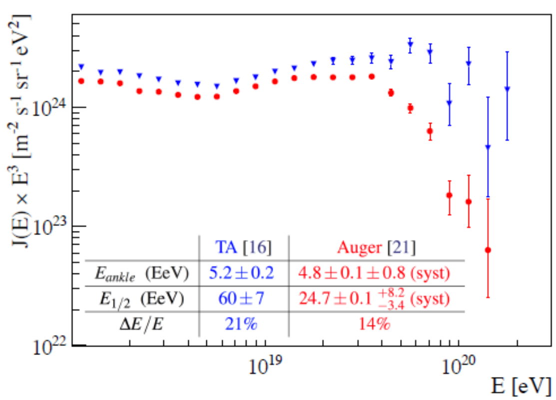
CIC method

- Measured data used
- Selection of Nth largest signal S in bins of $\cos^2(\Theta)$ of measured data (isotropy assumption)
- Cut N ~ flux @ certain energy
- **Used at the Pierre Auger Observatory**
- Energy independence assumed

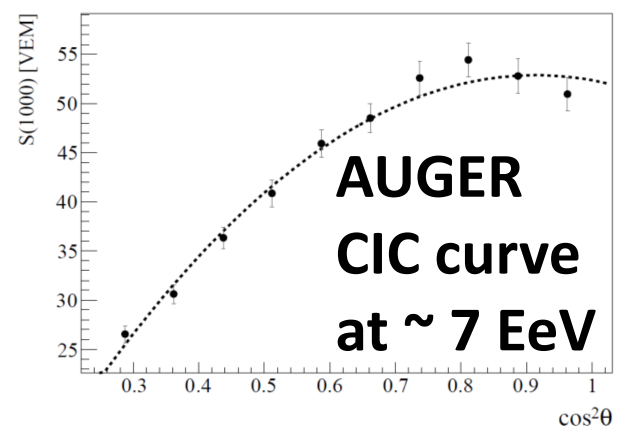
[D. Bergman et al., *Proc. UHECR Physics 2012*]



[V. Verzi, PoS(ICRC2015)015]



[R. Pesce et al., *Proc. of ICRC 2011*]

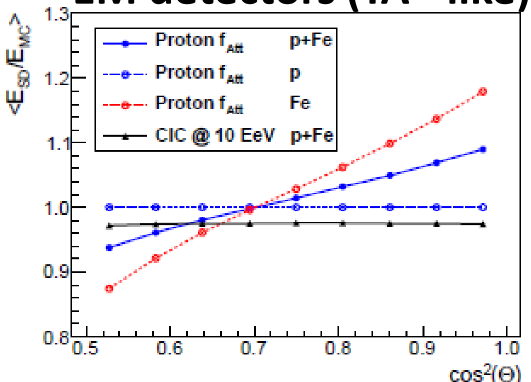


Toy MC (wide energy range) was used in combination with outputs of shower simulations produced by CORSIKA (detector response) at energy 10^{19} eV

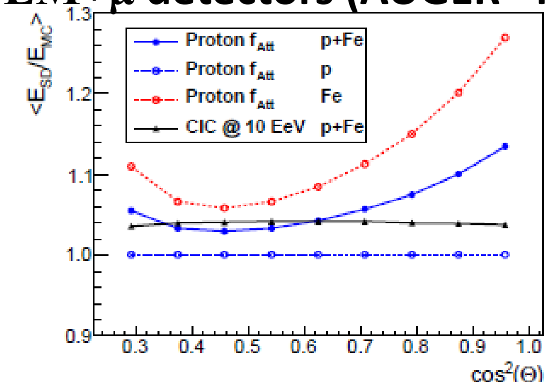
Advantages and proof of stability of CIC method

[J. Vícha et al., Proc. of the 33rd ICRC 2013, ISBN: 978-85-89064-29-3, arXiv:1310.0330 [astro-ph.HE]]

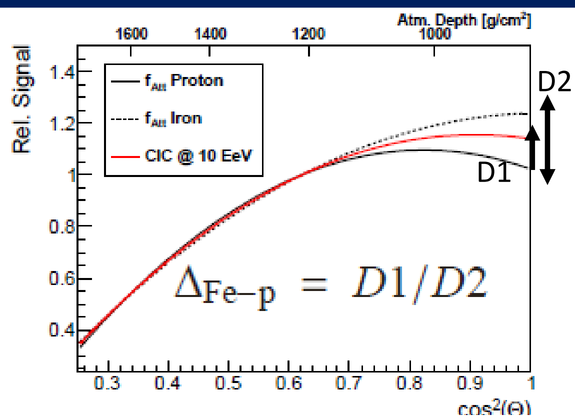
EM detectors (TA - like)

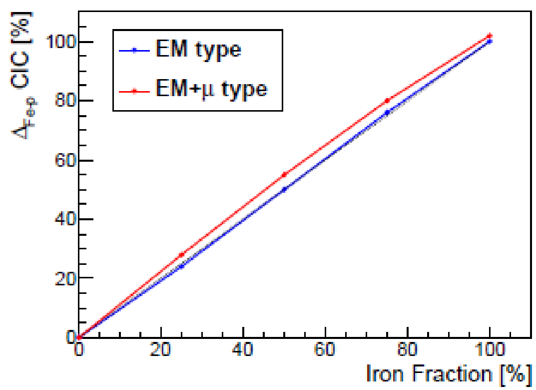


EM+μ detectors (AUGER - like)

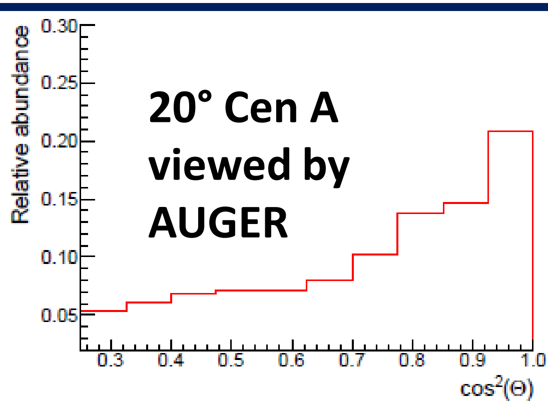


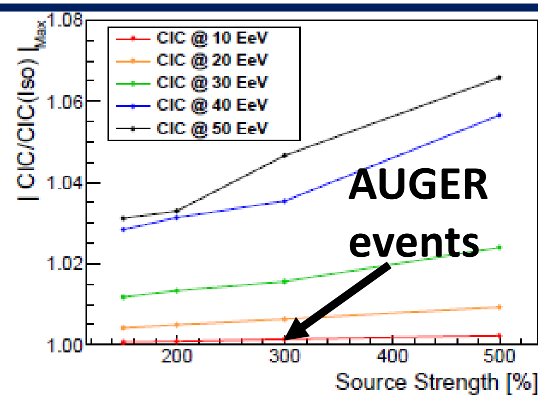
- Zenith angle bias in MC-based approach in case of mixed composition





- Shape of CIC curve can be used as parameter sensitive to the primary mass

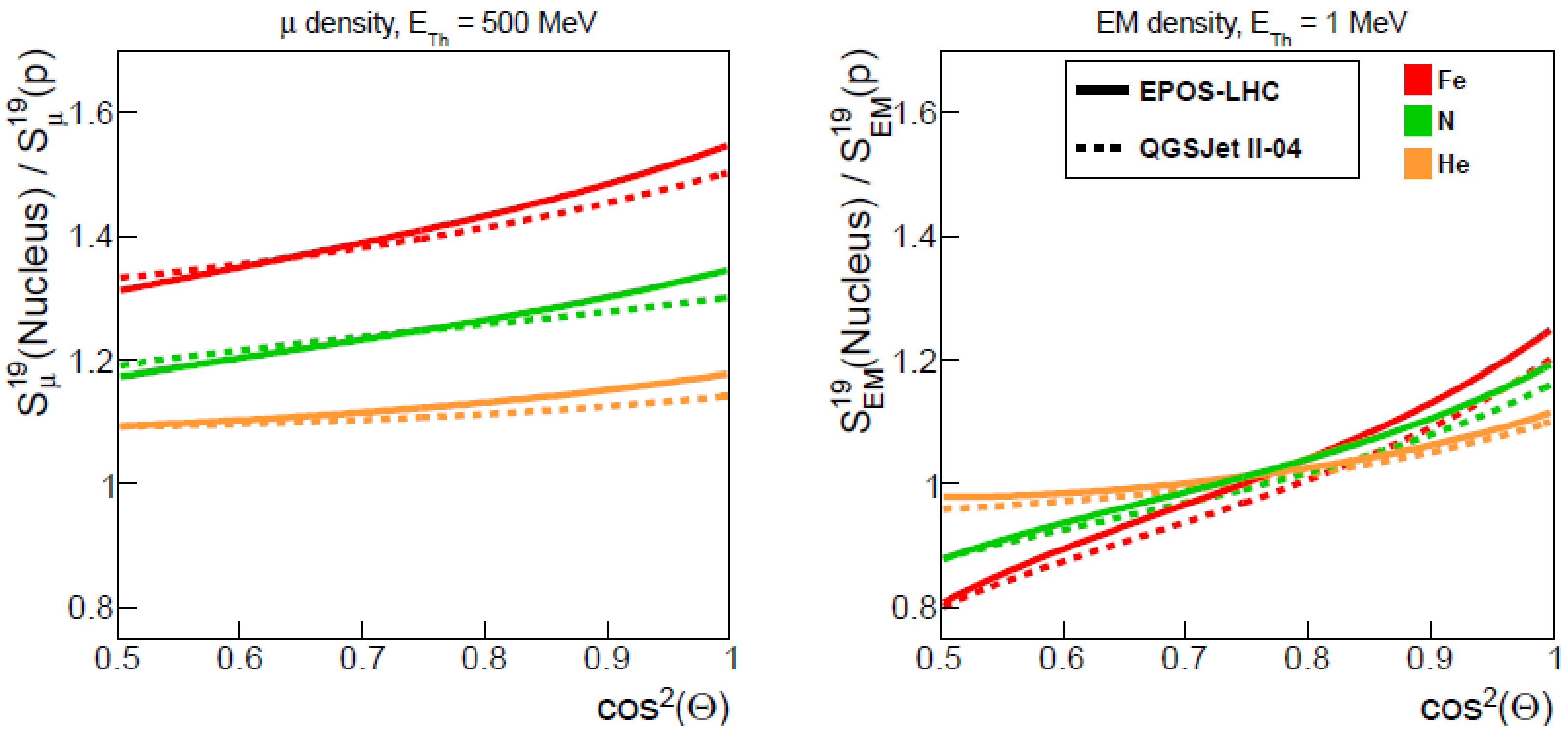




- Presence of a strong source has only negligible effect on CIC curve

Different zenith angle dependence of EM and μ components

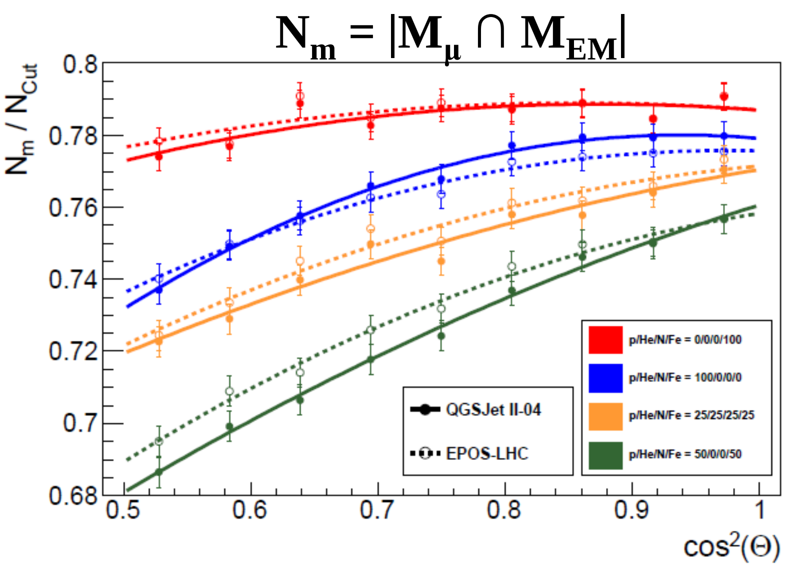
[J. Vícha et al., Astropart. Phys. 69 (2015) 11]



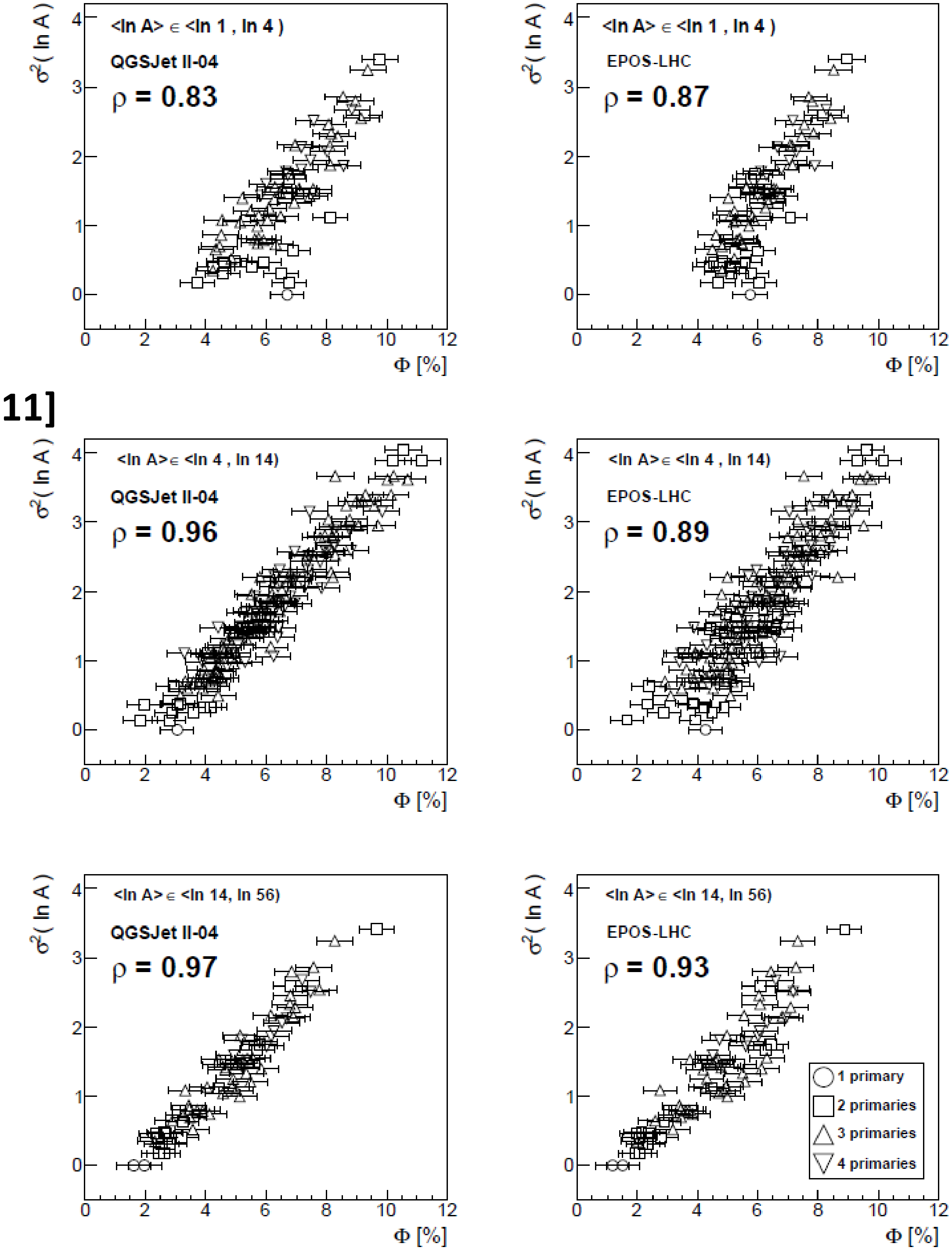
- **Hypothetical observatory with EM and muon detectors considered**
- **CIC approach applied to introduce parameter sensitive to the spread of primary masses**

Sensitivity to the spread of primary masses

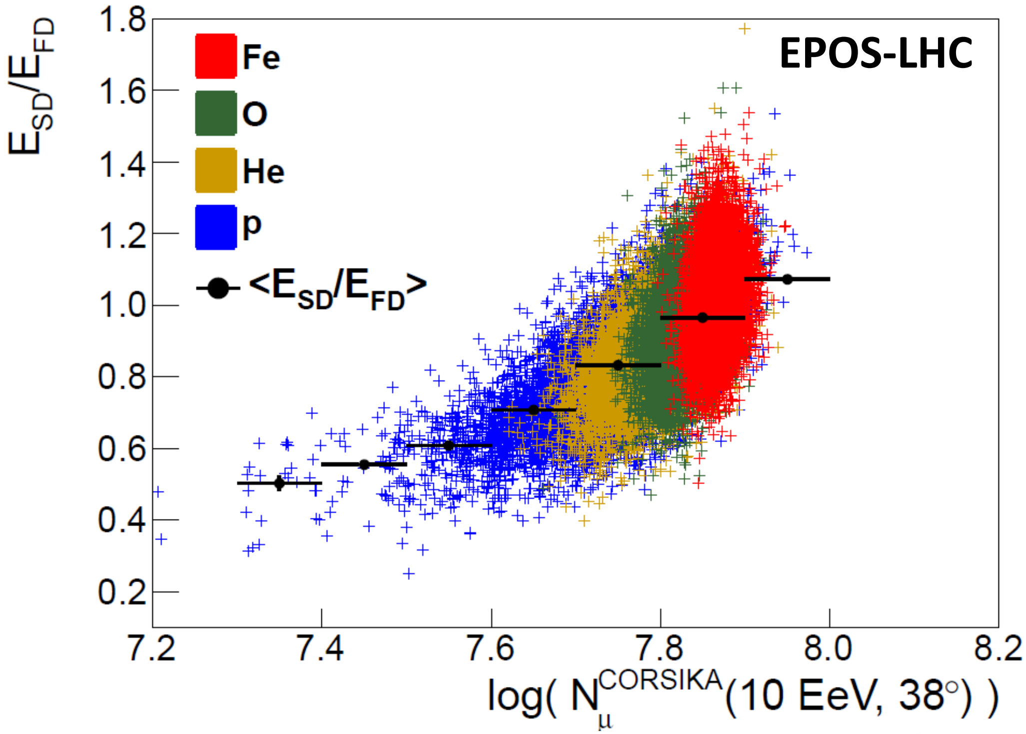
[J. Vícha et al., Astropart. Phys. 69 (2015) 11]



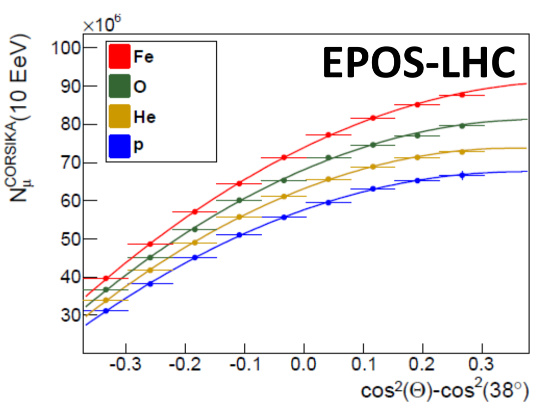
$$\Phi = 1 - \frac{N_m(\Theta = 45^\circ)}{N_m(\Theta = 0^\circ)}$$

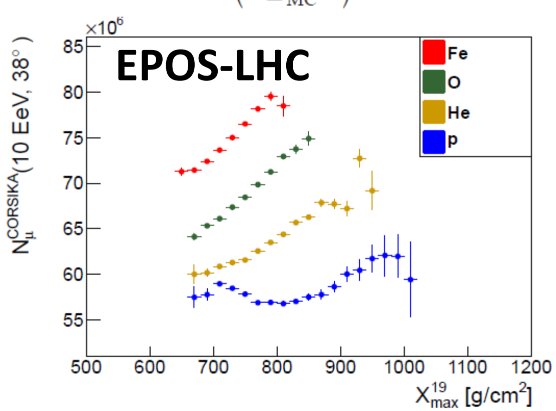


Observables: $E_{SD}/E_{FD} \sim N_\mu$, X^{19}_{max}



$$N_\mu^{\text{CORSIKA}}(10\text{ EeV}, \Theta) = N_\mu^{\text{CORSIKA}}(E_{\text{MC}}, \Theta) \cdot \left(\frac{10^{19}\text{ eV}}{E_{\text{MC}}}\right)^\beta$$





- E_{SD}/E_{FD} is sensitive to N_μ (see e.g. GAP-2011-042)
- In fact the same as S_{38}* from "Correlation paper"

$$X^{19}_{\max} = X_{\max} + D \cdot \left(19 - \log\left(E_{\text{FD}}[\text{eV}]\right)\right)$$

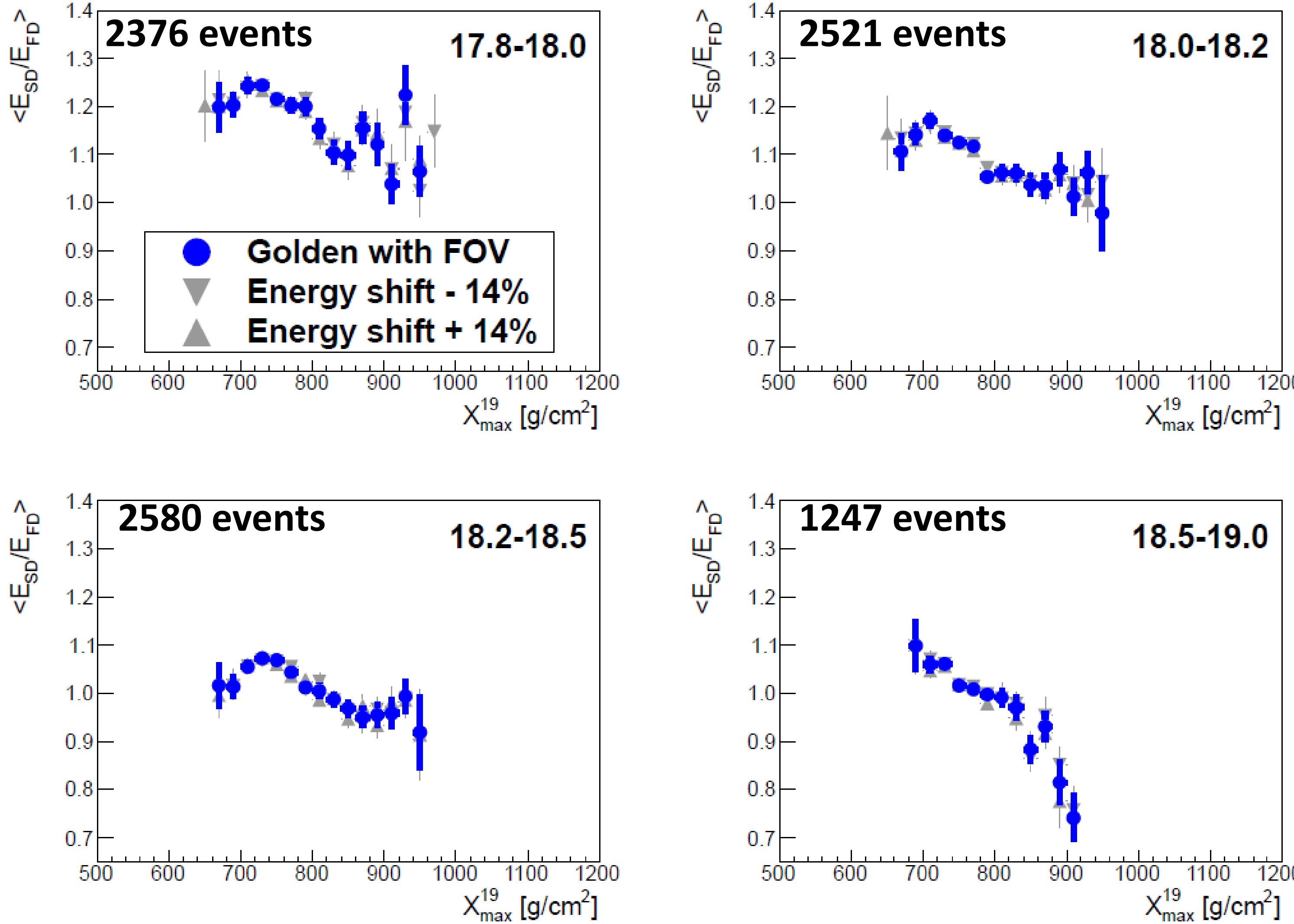
using D = 56 g/cm² per log E_{FD}

D ∈ <54, 58> g/cm² [GAP-2014-083]

E_{SD}/E_{FD} and X^{19}_{max} are energy and zenith independent

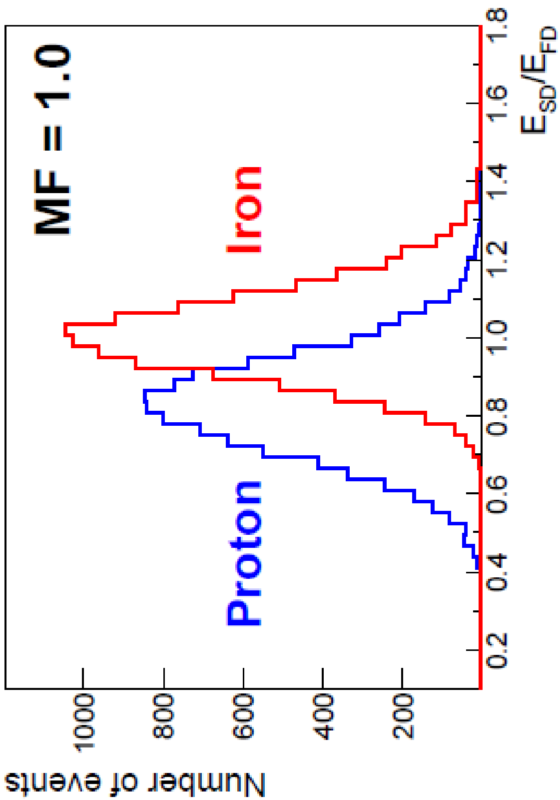
Note that the sensitivity to the energy scale is only in X^{19}_{max}

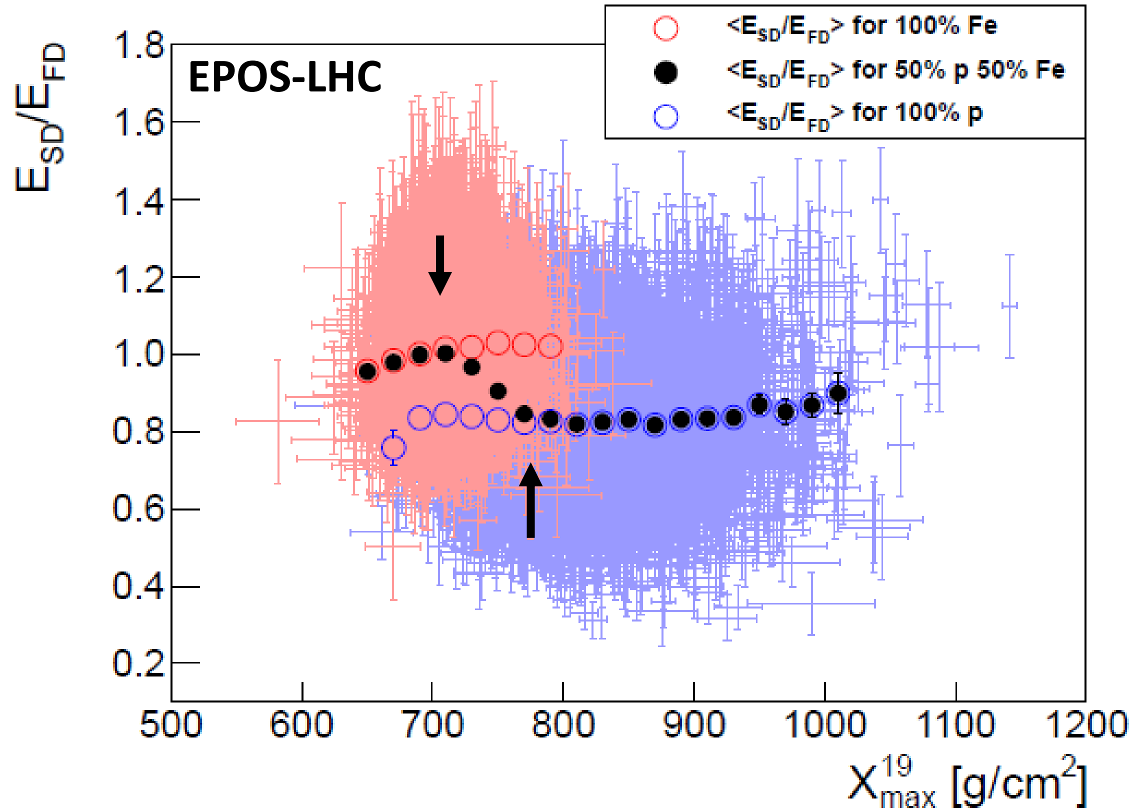
Measured Golden data (SD+FD)



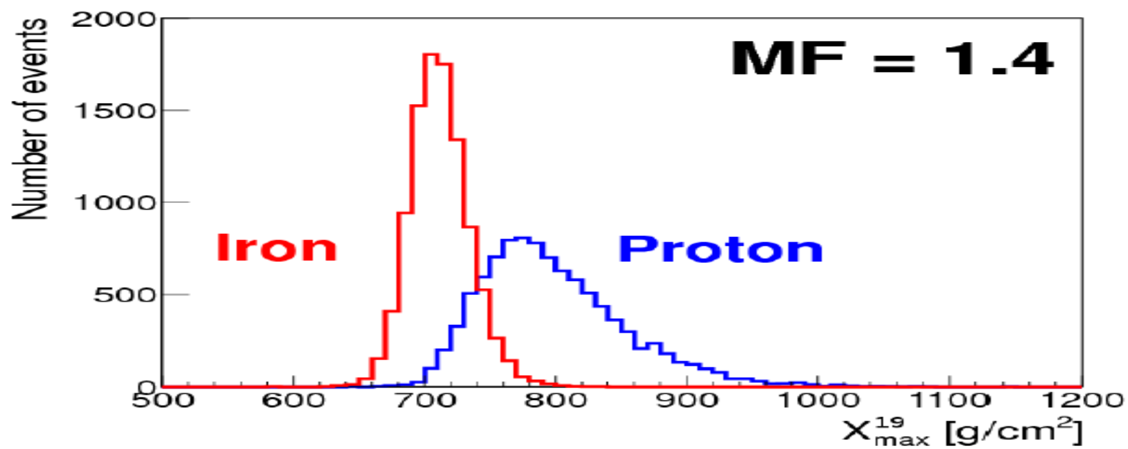
No reconstruction issue found => Mass composition bias in E_{SD}

Origin of the “two-break“ structure ...





... is in mixed composition



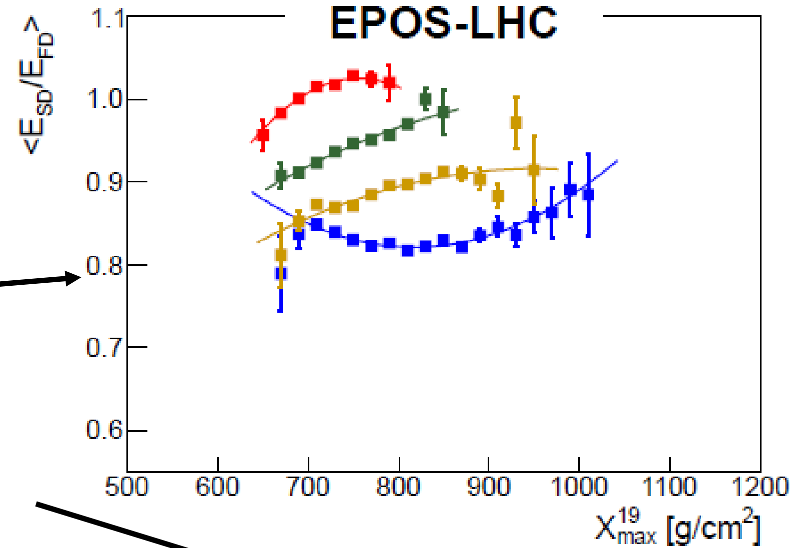
Method

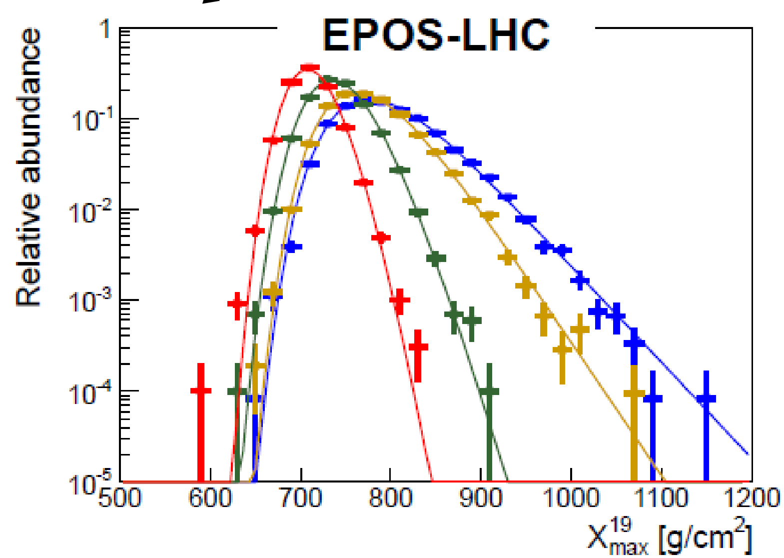
i = p, He, O, Fe

- $\langle E_{SD}/E_{FD}\rangle_i(X^{19}_{max})$ parametrized with quadratic functions for 4 primaries
- Normalized X^{19}_{max} distributions parametrized with **Gumbel functions** $g_i(X^{19}_{max})$ for 4 primaries
- f_{SD} is rescaling factor of $\langle E_{SD}/E_{FD}\rangle_i$ ~ f_μ
- Combination of 4 primaries with **fractions** f_i then gives

$$\langle E_{SD}/E_{FD}\rangle = \sum_{i=1}^{4}\left(w_i \cdot \langle E_{SD}/E_{FD}\rangle_i \cdot f_{SD}\right)$$

$$w_i = \frac{f_i \cdot g_i}{\sum_{i=1}^{4} f_i \cdot g_i}, \qquad \sum_{i=1}^{4} f_i = 1$$



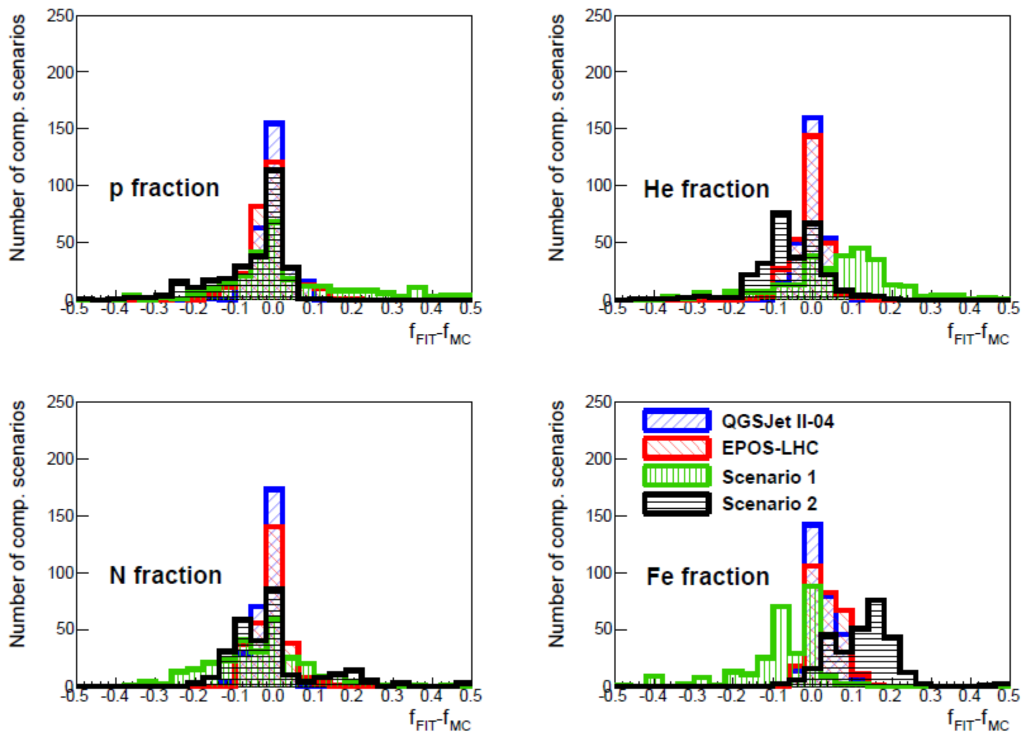


4-parameter (f_1, f_2, f_3 and f_{SD}) fit

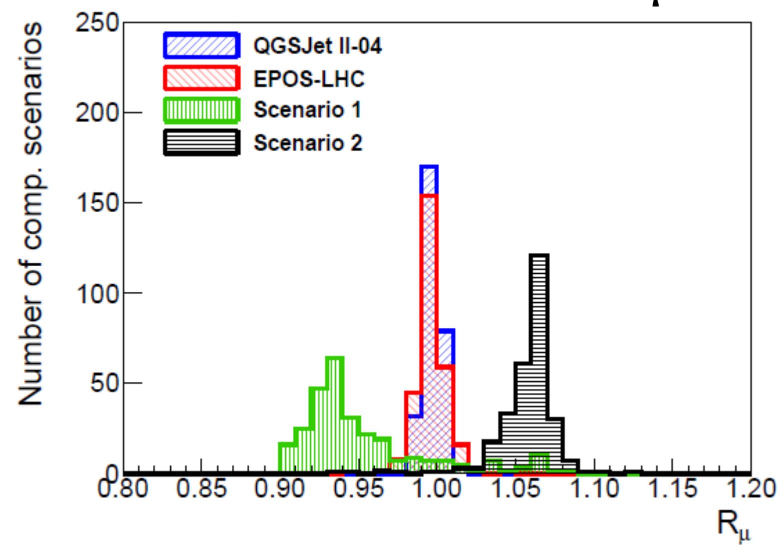
Tests of method with CONEX simulations

[J. Vícha et al., Proc. of the 34th ICRC 2015, PoS(ICRC2015)433]

Primary fractions

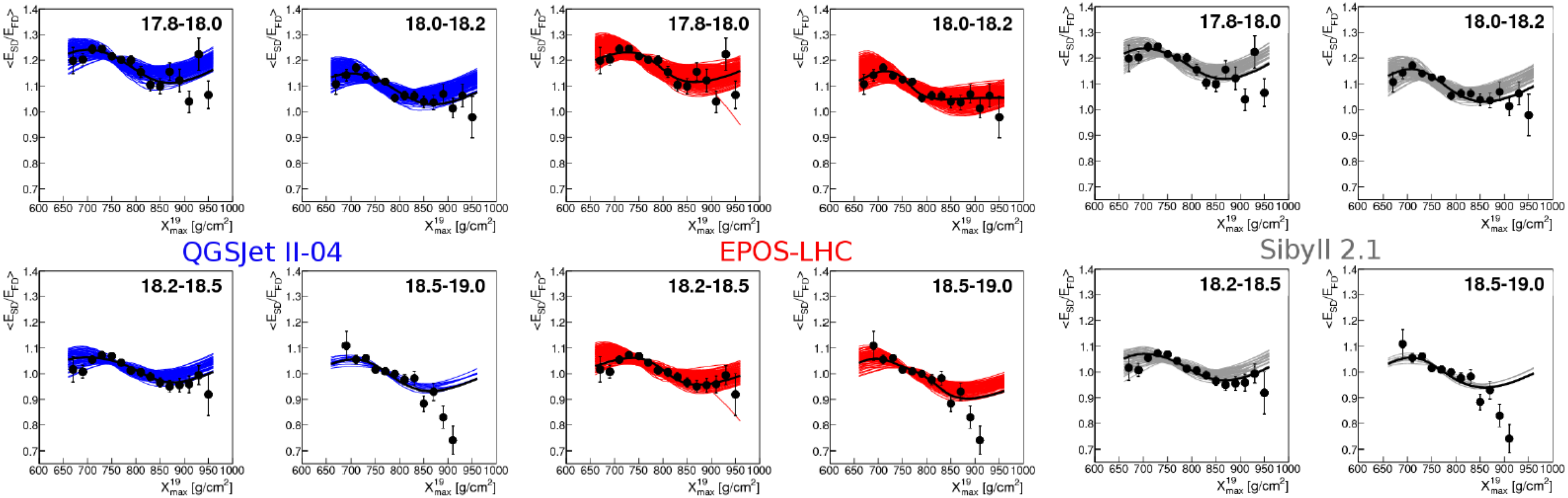


Rescaling of N_μ



- **When hadronic interactions are known, the method returns precise values around few %**
- **When hadronic interactions are different, the method returns still precise value of R_μ, but much worse primary fractions**

Trend of data can be described by MC



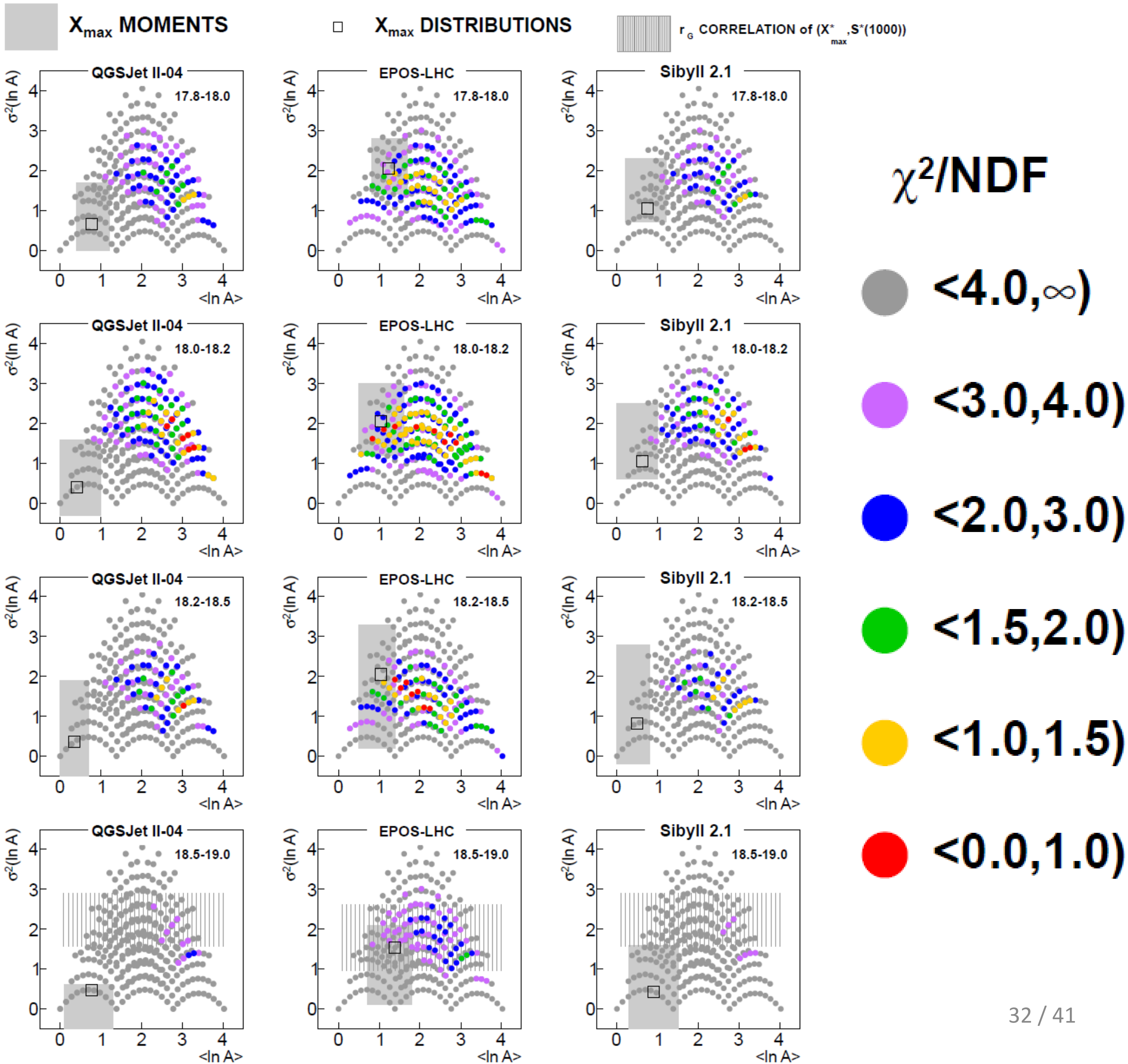
Only the solutions with $\chi^2/\mathbf{NDF} < \mathbf{4}$ are depicted

log E_{FD} in <17.8,18.0>

log E_{FD} in <18.0,18.2>

log E_{FD} in <18.2,18.5>

log E_{FD} in <18.5,19.0>

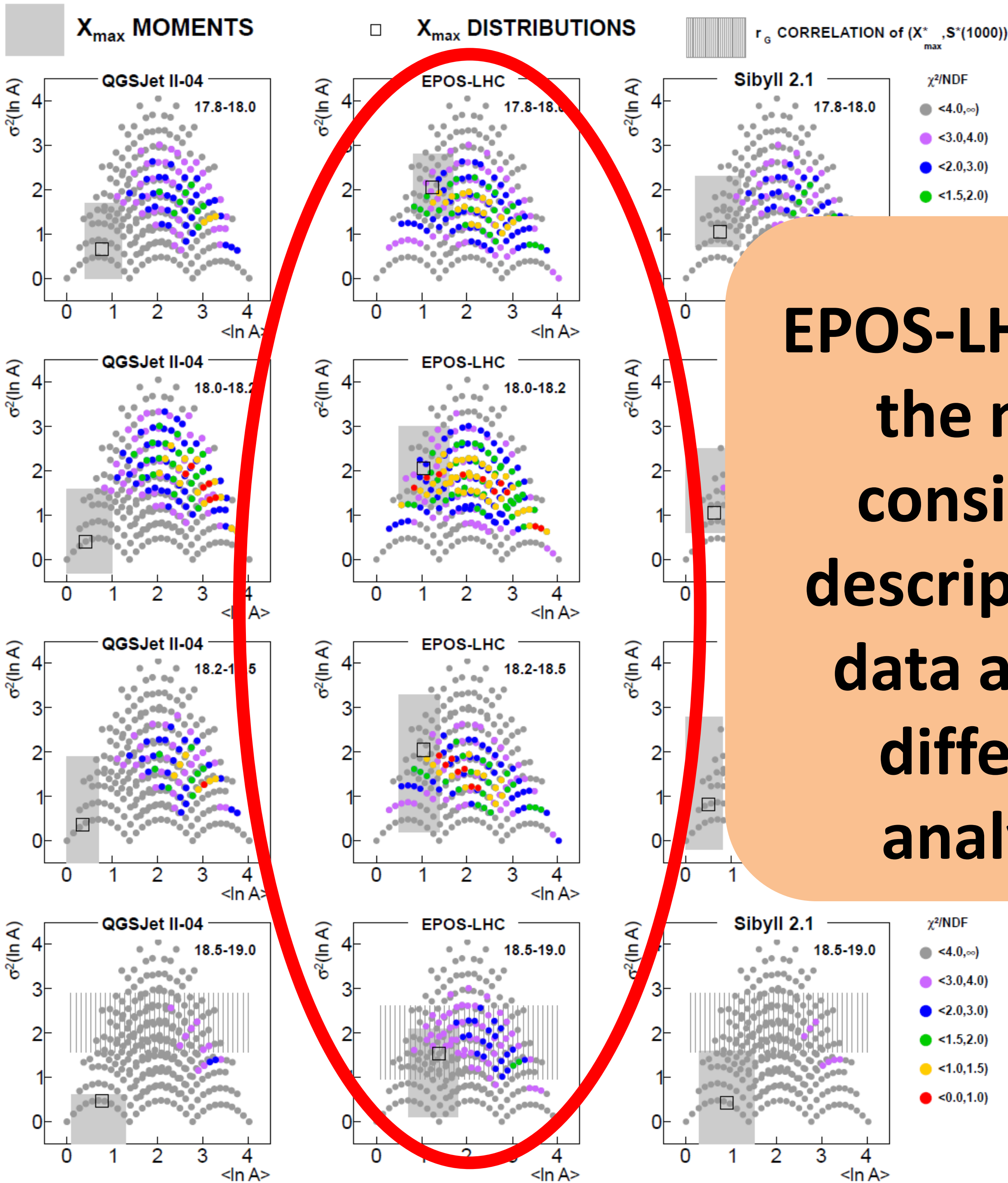


log E_{FD} in <17.8,18.0>

log E_{FD} in <18.0,18.2>

log E_{FD} in <18.2,18.5>

log E_{FD} in <18.5,19.0>



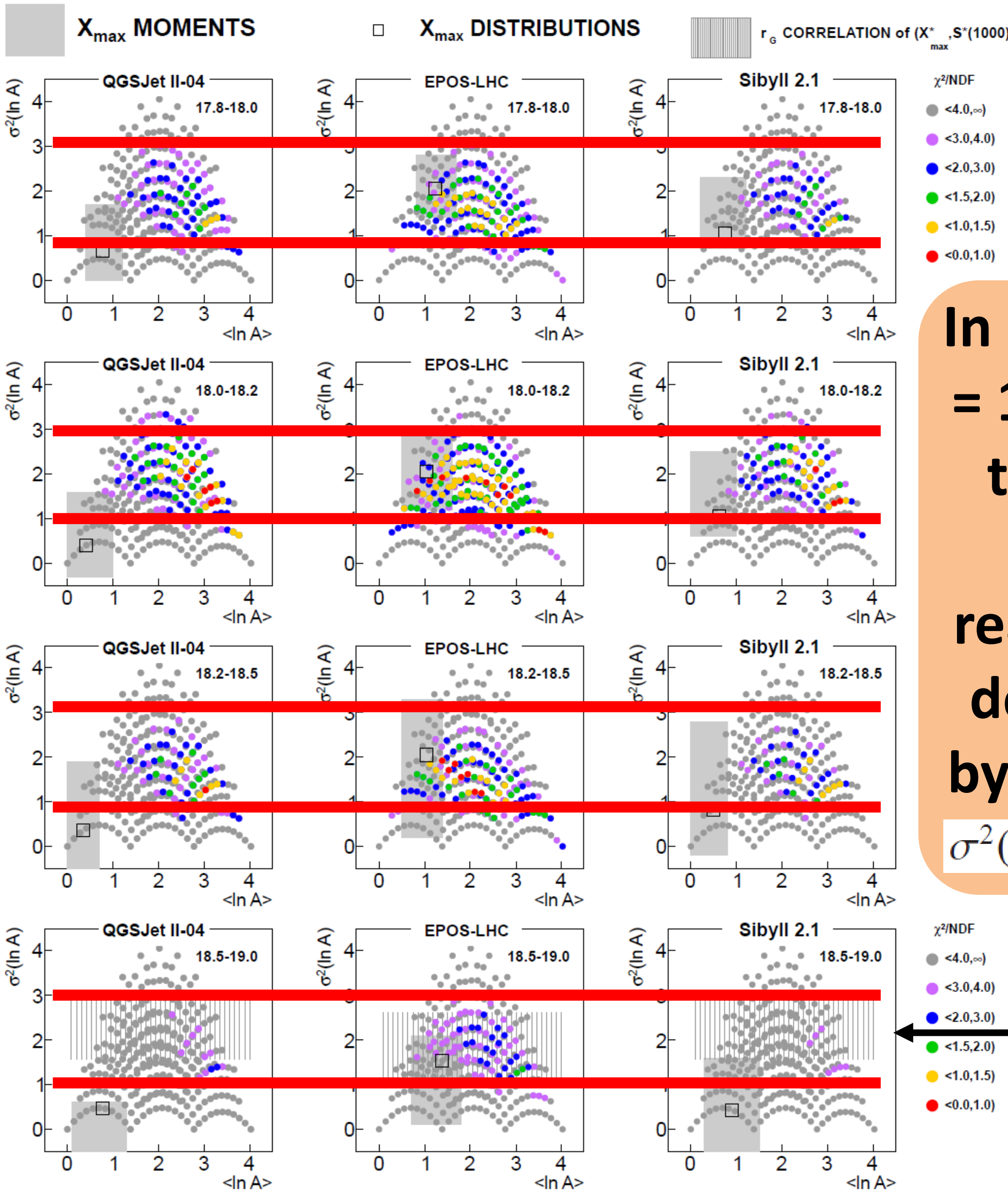
EPOS-LHC gives the most consistent description of data among different analyses

log E_{FD} in <17.8,18.0>

log E_{FD} in <18.0,18.2>

log E_{FD} in <18.2,18.5>

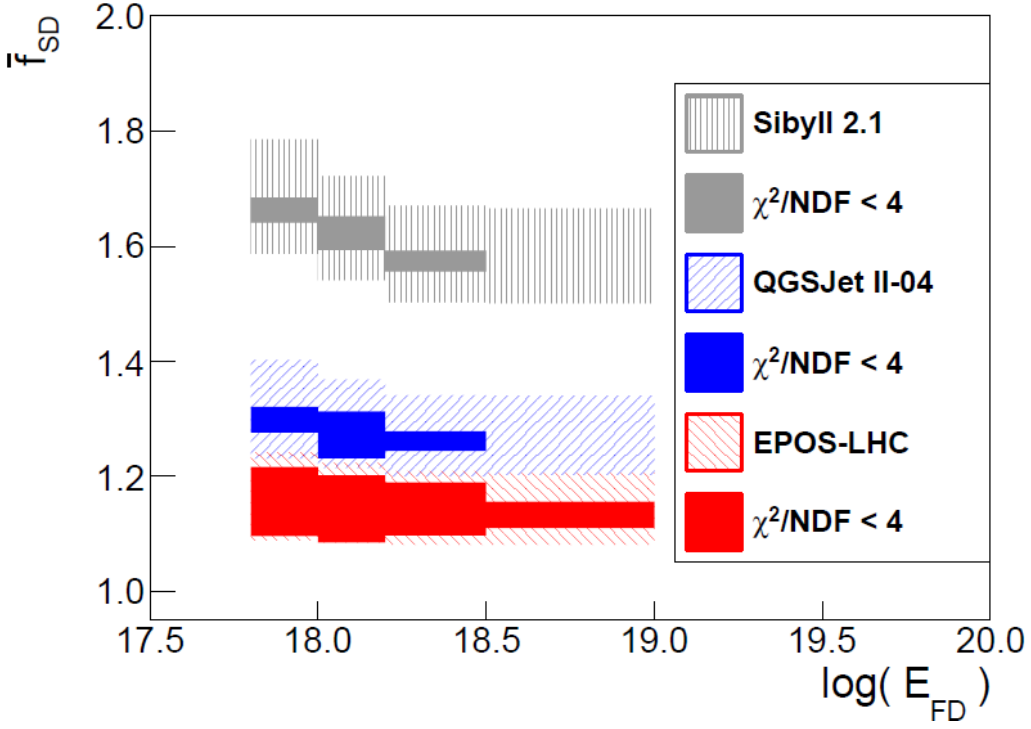
log E_{FD} in <18.5,19.0>

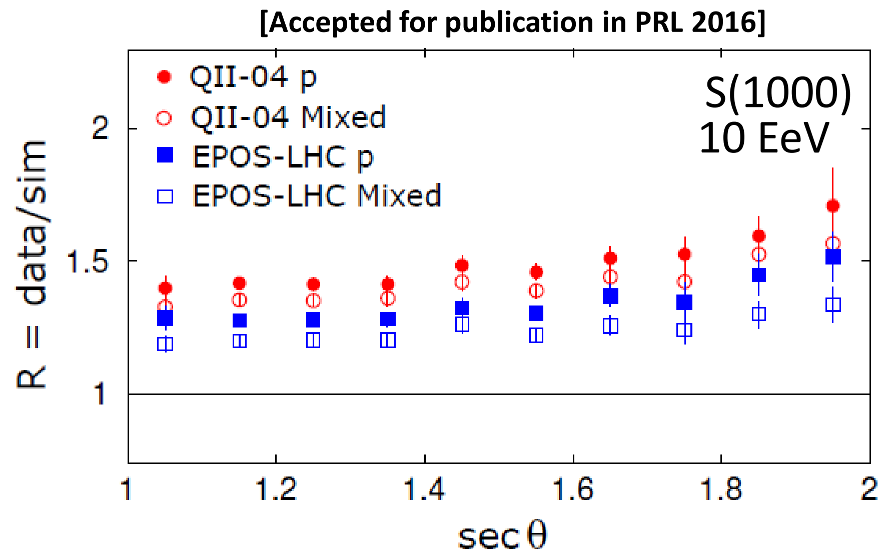


In log(E/eV) = 17.8-19.0 the data can be reasonably described by MC with $\sigma^2(\ln A) \in \langle 1,3 \rangle$

Consistent with r_G of (X^*_{max},$S^*(1000)$)

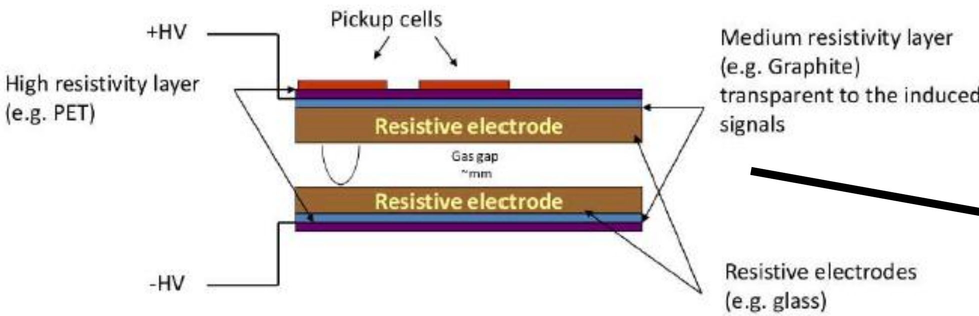
$\bar{f}_{SD}$ values for f_p+f_{He} >= 0.5

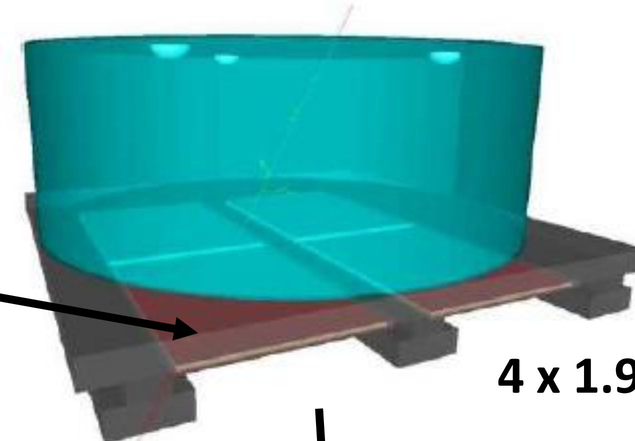




EPOS-LHC		**10-20%**	
QGSJet II-04	**needs by**	**25-35%**	**higher SD signal to match**
Sibyll 2.1		**55-70%**	**the measured data**

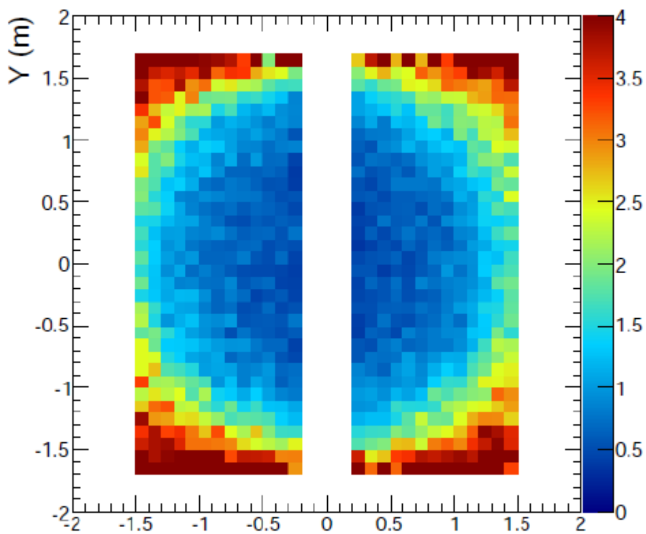
Muon Auger RPC Tank Array (MARTA)



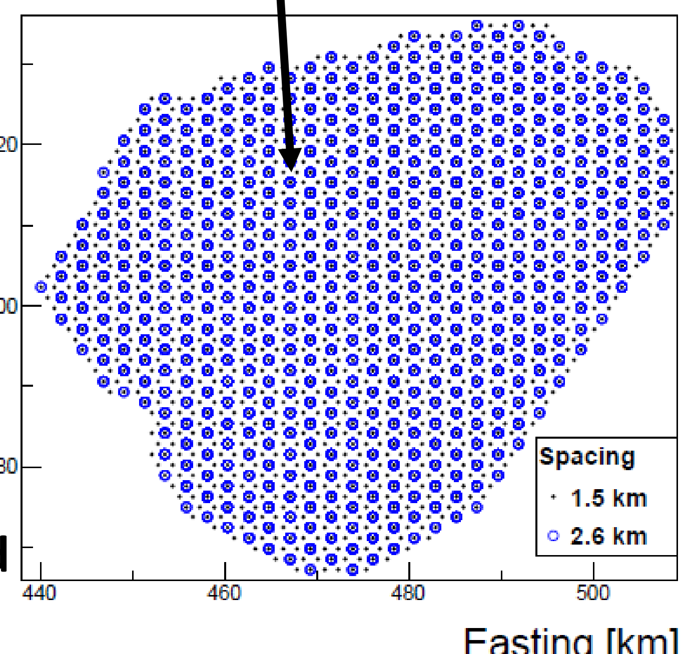


4 x 1.92 m²

Average EM contamination



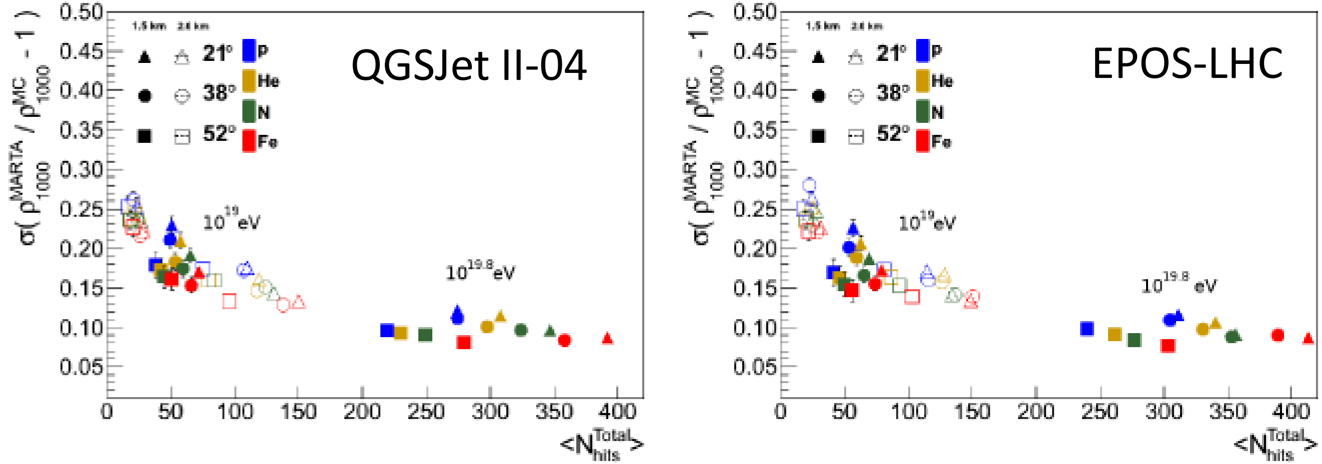
2 MARTA spacings considered



Evaluation of MARTA potential

- **Detailed MC simulations used (Simulation challenge for 5 upgrade proposals)**

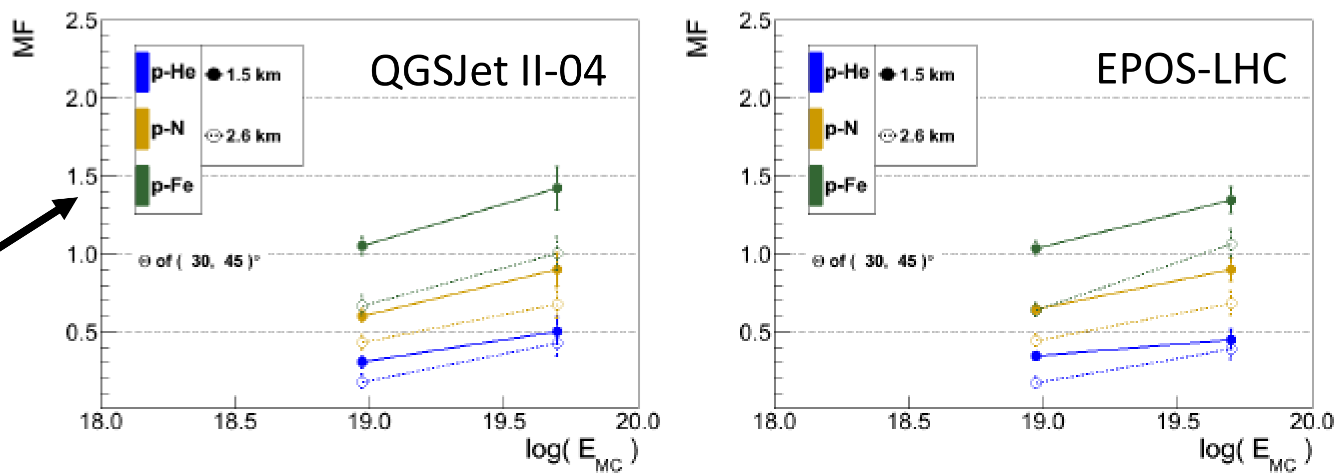
Resolution



Merit Factor

$$MF(\mathrm{i},\mathrm{j}) = \frac{|\langle H_\mathrm{i}\rangle - \langle H_\mathrm{j}\rangle|}{\sqrt{\sigma^2(H_\mathrm{i}) + \sigma^2(H_\mathrm{j})}}$$

X_{max} MF(p,Fe)



Conclusions on Topic 1

CIC method found stable, most appropriate and moreover sensitive to primary masses

- CIC method provides unbiased E_{SD} wrt. zenith angle in case of mixed composition
- Observation of varying dependence of $\langle E_{SD}/E_{FD} \rangle$ on $\cos^2\theta$ with Telescope Array data -> mixed composition or wrong attenuation correction
- CIC method is negligibly influenced even in case of strong anisotropic sources
- Shape of CIC curve is sensitive to the mass composition of primary particles
- Applying CIC method to a surface array of independent muon and EM detectors the **spread of primary masses** can be inferred with the introduced method

Conclusions on Topic 2

Another method combining X_{max} and N_{μ} measurements investigated in detail and applied to Pierre Auger Observatory data

- Original method how to infer primary masses and simultaneously the rescaling of the number of muons was introduced and tested with MC
- Preliminary application of the method to the data of the Pierre Auger Observatory:
  - **EPOS-LHC gives consistent results** among different analyses, QGSJet II-04 and Sibyll 2.1 do not
  - Combination of SD and FD measurement indicates a mixed composition of primaries with $\boldsymbol{\sigma^2(\ln A) \in < 1, 3 >}$ in energy range $\mathbf{10^{17.8\text{-}19.0}}$ **eV**
  - Results were an **important cross-check of a paper** prepared by the Pierre Auger Collaboration
  - **SD signal in MC needs to be increased** by 10-20%, 25-35% and 55-70% for EPOS-LHC, QGSJet II-04 and Sibyll 2.1, respectively, to fit the measured data

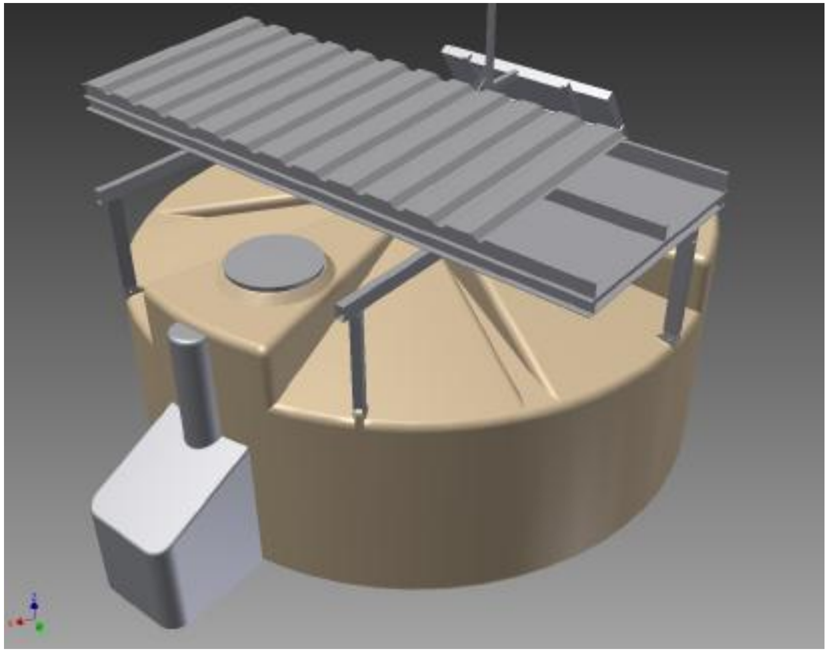
Conclusions on Topic 3

Potential of RPC array at the Pierre Auger Observatory quantified, input for the Upgrade committee

- RPC in combination with water-Cherenkov tanks is a promising novel detection technique suitable for measurement of the muonic component
- For the detector spacing (1.5km) of the Pierre Auger Observatory at the highest energies a separability of primaries comparable with X_{max} measurement can be achieved selecting almost all events with a resolution $\delta(N_\mu)/N_\mu$=10%
- However the EM bias was found too large (up to 25%)
- Upgrade Committee selected for upgrade scintillators placed above the water-Cherenkov tanks

Thank you for your attention!

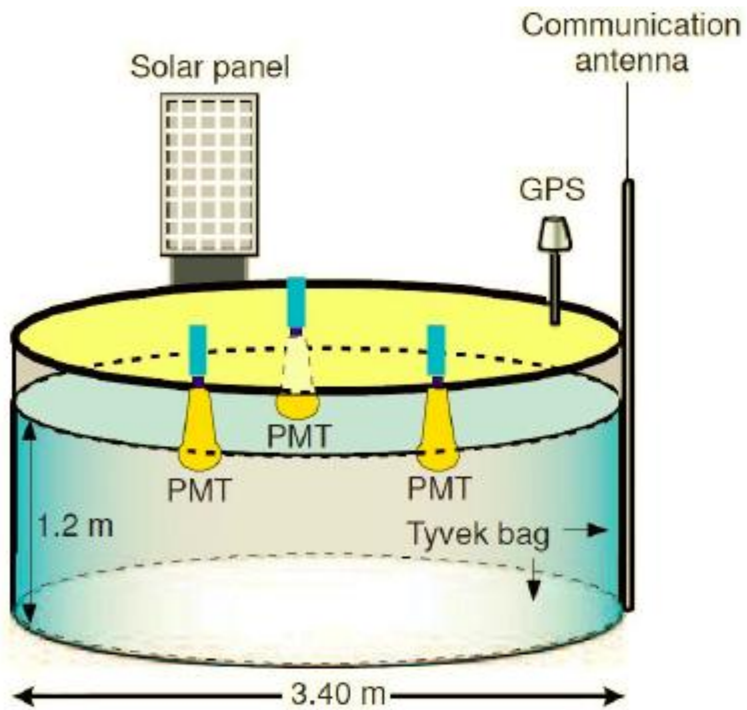
AugerPrime

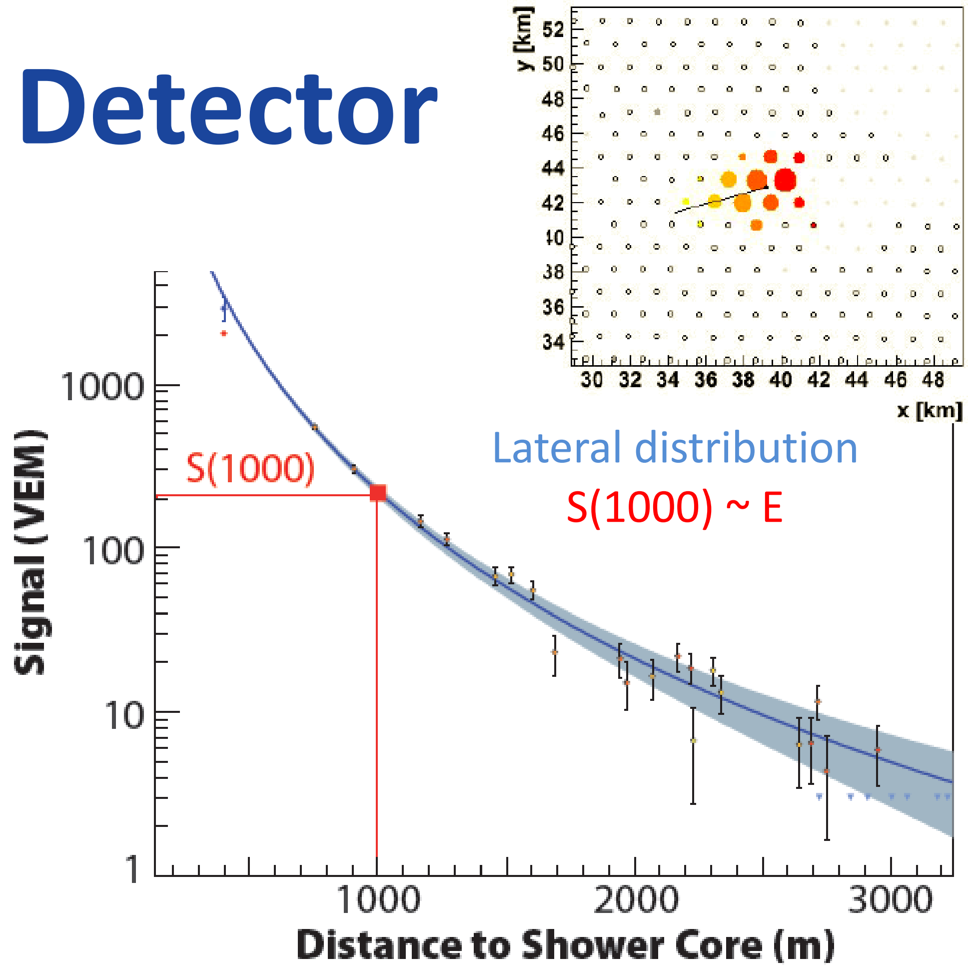


The story continues ...

Back-up slides

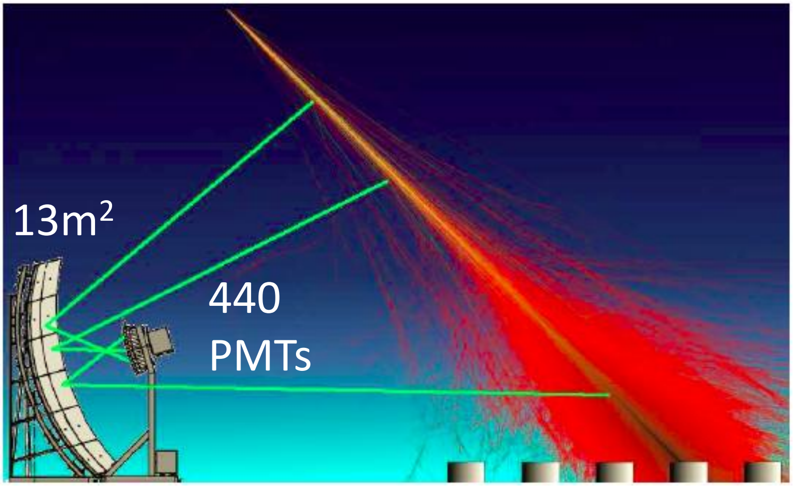
Surface Detector



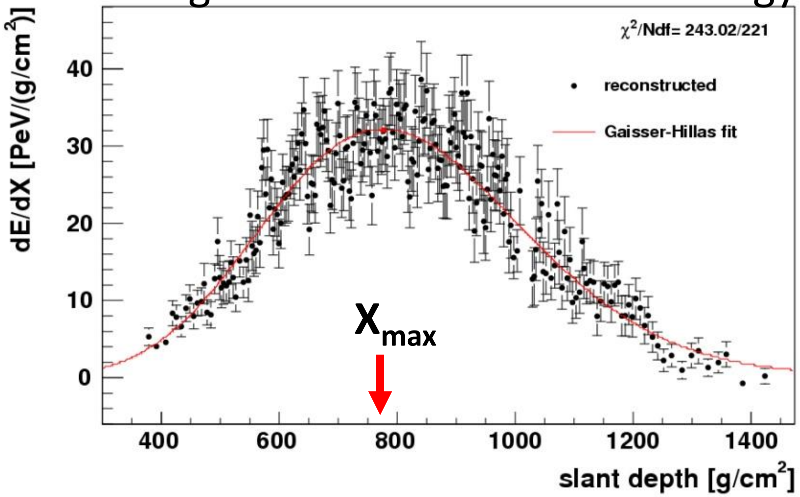


- Water Cherenkov tanks sensitive to **muons and EM** component
- **100% duty cycle**
- Signal attenuation corrected by the CIC method
- Energy calibration using FD, resolution **17-12 %**, angular < 1° above 10 EeV
- For zenith angles **> 60°** SD signal from **muon** component

Fluorescence Detector

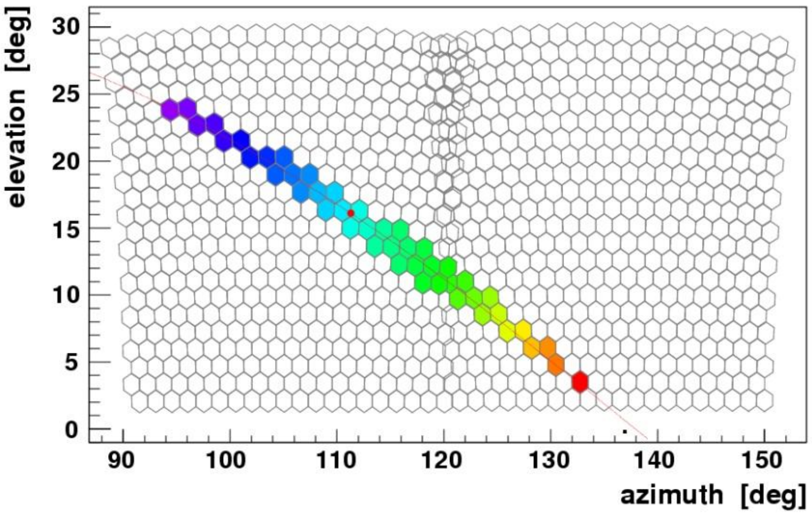


Integration of G.H. fit -> cal. energy



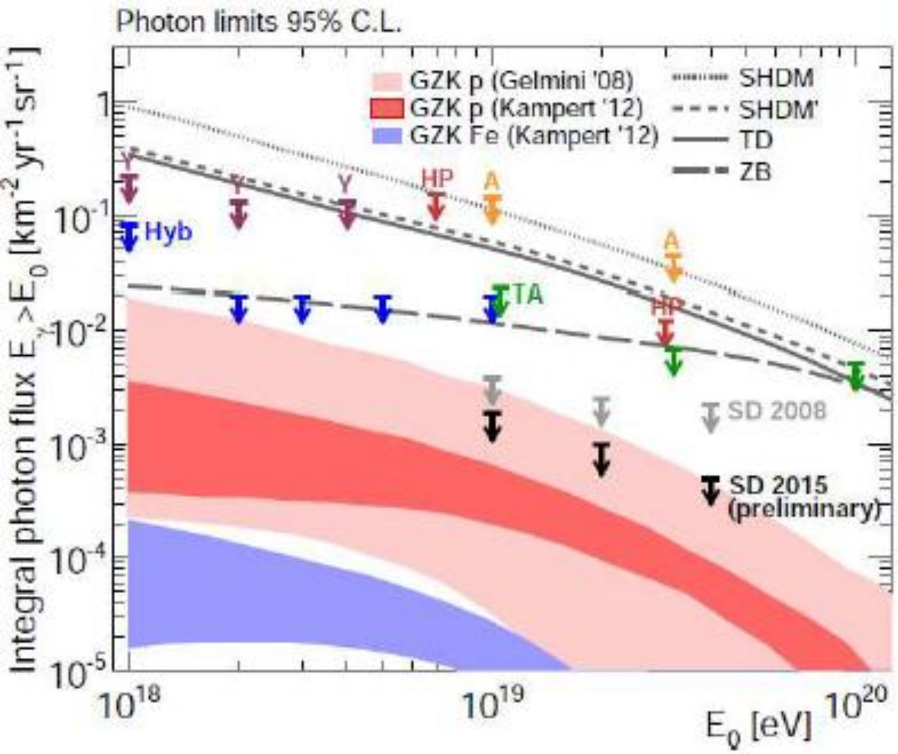
- **Calorimetric** measurement

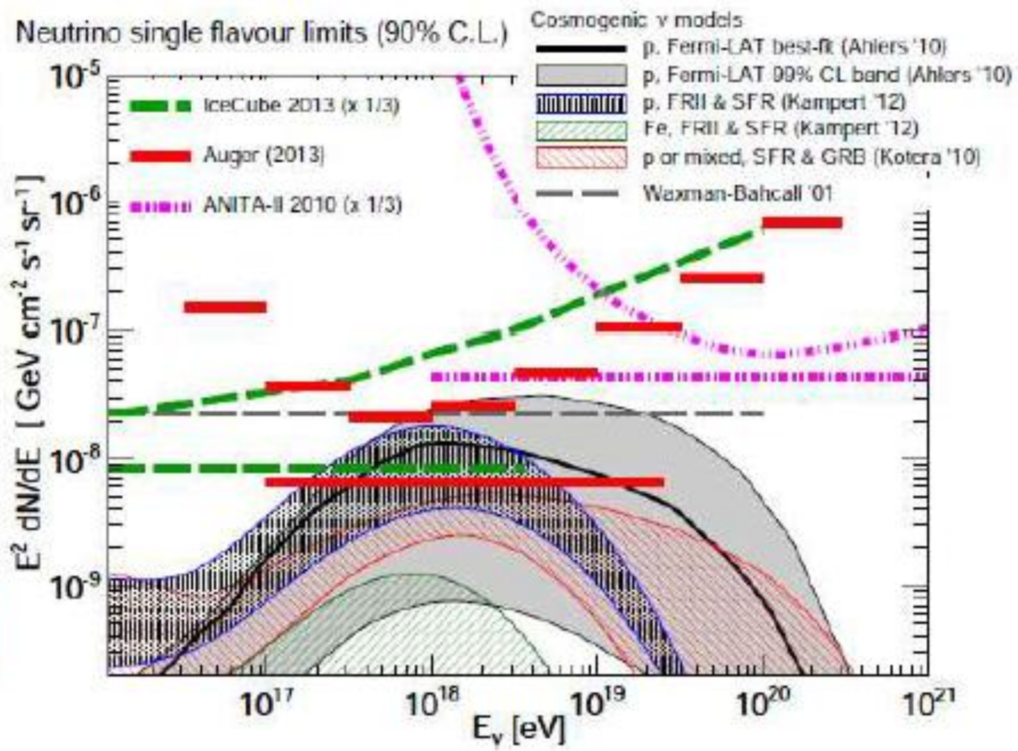
  (+ correction for invisible energy)
- **13%** duty cycle
- Hybrid detection improves the precision of shower reconstruction



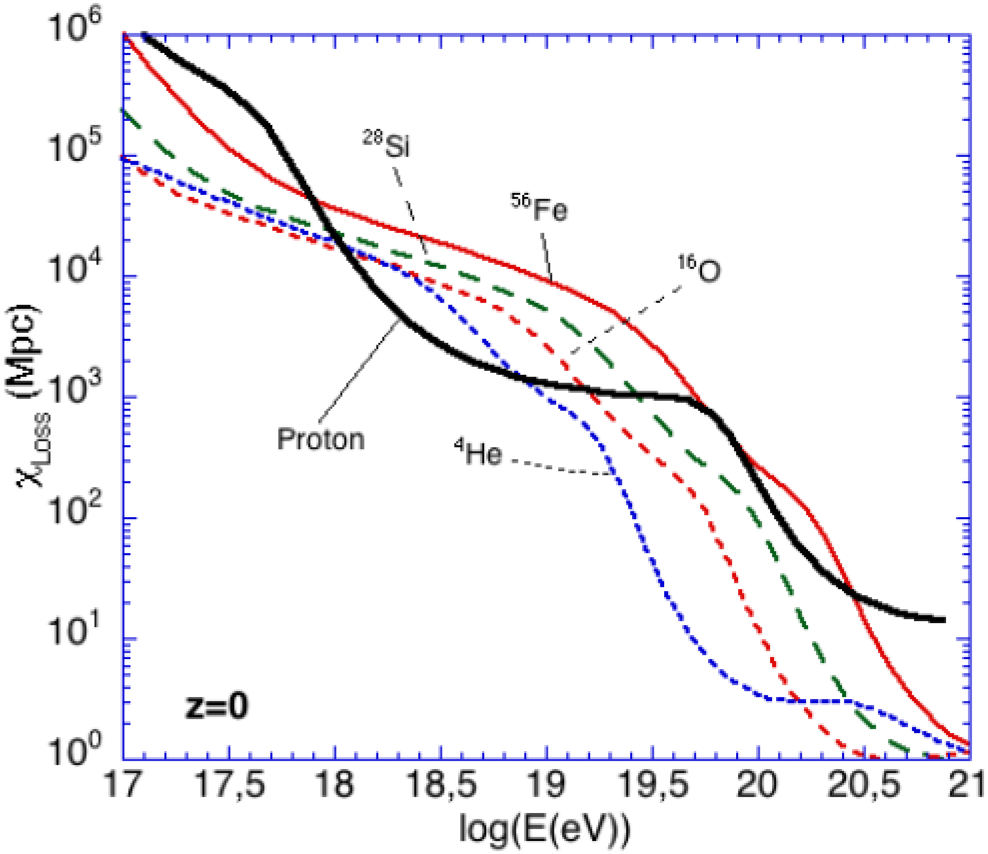
- Observation of X_{max} in FOV
- Energy resolution **7-8%**
- Systematic uncertainty decreased to **14%**

Photon and neutrino limits

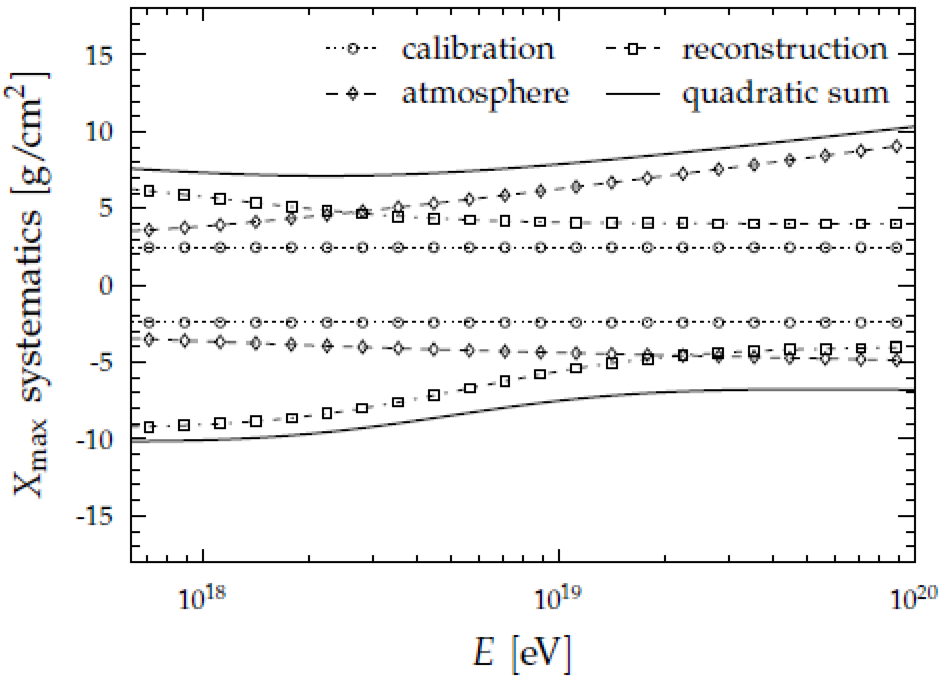


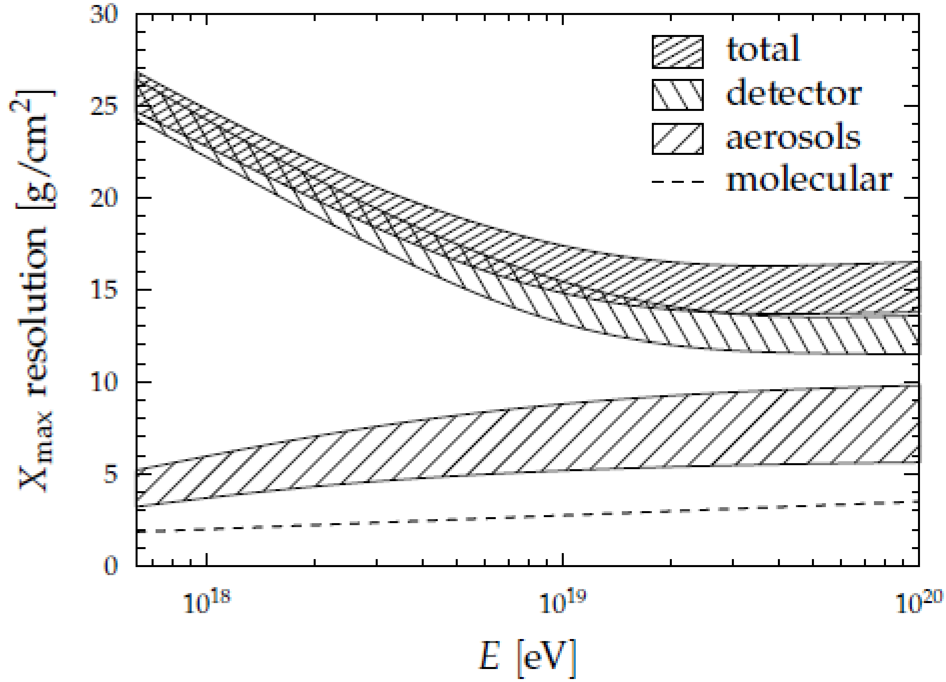


Attenuation length



X_{max} systematics and resolution at the Pierre Auger Observatory





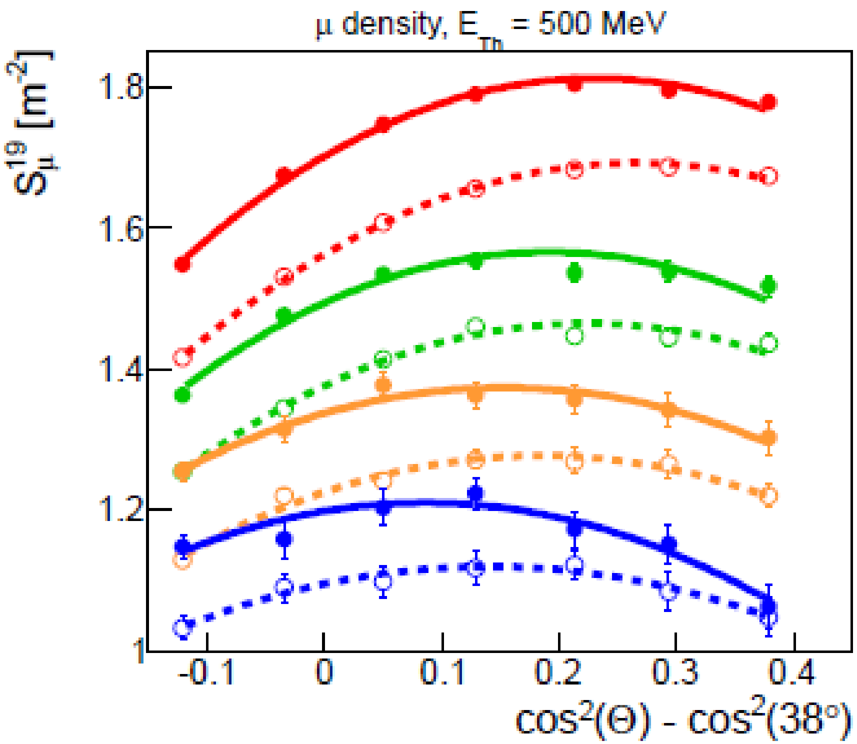
Modelled description of shower development (Heitler-Matthews)

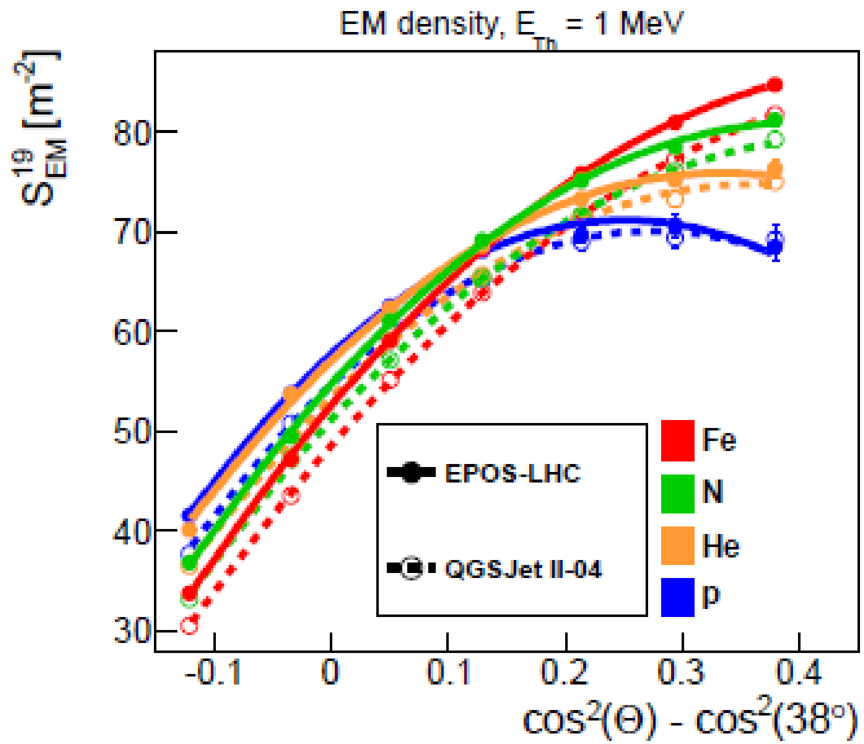
$$X_{\max}^{\mathrm{A}} = X_{\max}^{\mathrm{p}} - X_0 \cdot \ln(A),$$

$$N_{\mu}^{\mathrm{A}} = N_{\mu}^{\mathrm{p}} \cdot A^{1-\beta},$$

$$X_{\max}^{\mathrm{p}} = X_1 + X_0 \cdot \ln\left(\frac{E_0}{3 \cdot N_{\mathrm{ch}} \cdot \xi_{\mathrm{c}}^{\mathrm{e}}}\right) \qquad N_{\mu}^{\mathrm{p}} = N_{\max}^{\pi} = (N_{\mathrm{ch}})^{n_{\mathrm{c}}} = \left(\frac{E_0}{\xi_{\mathrm{c}}^{\pi}}\right)^{\beta}$$

Reference signals from CORSIKA as input to Toy MC





$$J(E_{\mathrm{MC}}) = \frac{\mathrm{d}N}{\mathrm{d}E_{\mathrm{MC}}} = E_{\mathrm{MC}}^{-\gamma} \frac{1}{1 + \mathrm{e}^{\frac{\log(E_{\mathrm{MC}}) - \log(E_{1/2})}{\log(W_{\mathrm{E}})}}}$$

$$E_{\mathrm{MC}} = a \cdot S_{38}^{b}$$

E_{SD}/E_{FD} ~ muon signal

- <$E_{SD}/E_{FD}(X_{max})$> is sensitive to the muon content
  - **GAP-2011-042**, talk @ Compostela 2011
- E_{SD}/E_{FD} is **similar as S19** (Jeff @ Malargue, Mar 2011)
  - talk @ Malargue, Nov 2011
- E_{SD}/E_{FD} is very **similar** to **S^*(1000)** used in GAP-2014-006

$$S^*(1000) = S_{38} \cdot \left(\frac{10^{19}\,\text{eV}}{E_{\text{FD}}} \right)^{1/B}$$

$$E_{\text{SD}} = A \cdot S_{38}^{B}$$

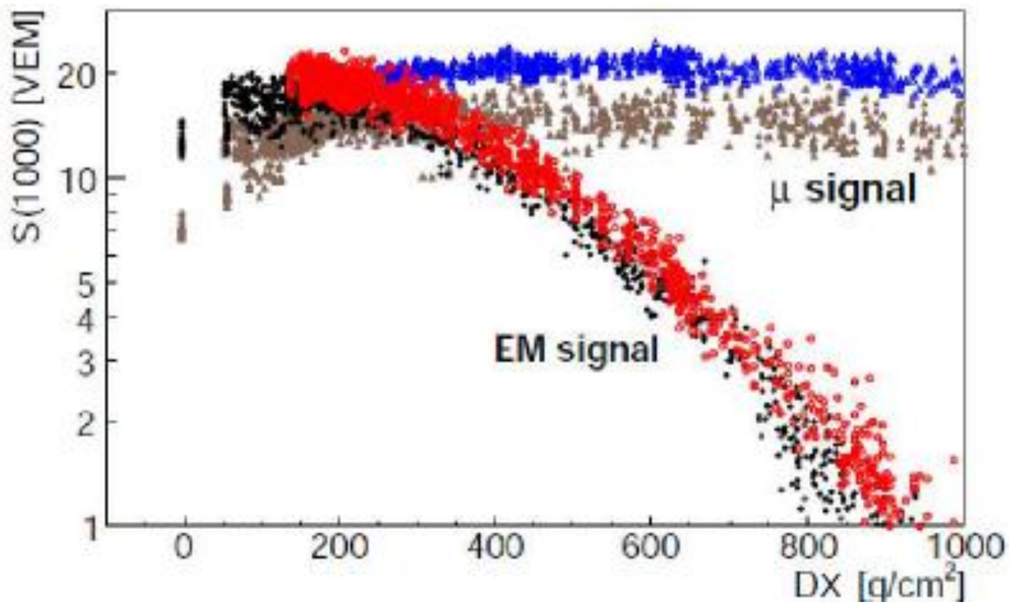
A = 0.19 EeV,
B = 1.025 [ICRC 2013]

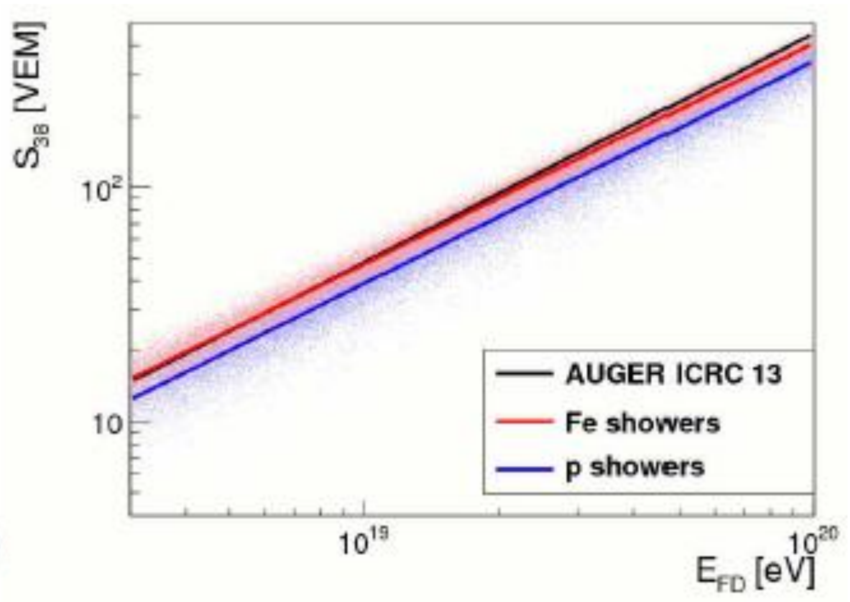
$$S^*(1000) = \left(E_{\text{SD}} / E_{\text{FD}}\right)^{1/B} \cdot \left(\frac{10^{19}\,\text{eV}}{A} \right)^{1/B}$$

see GAP-2016-001

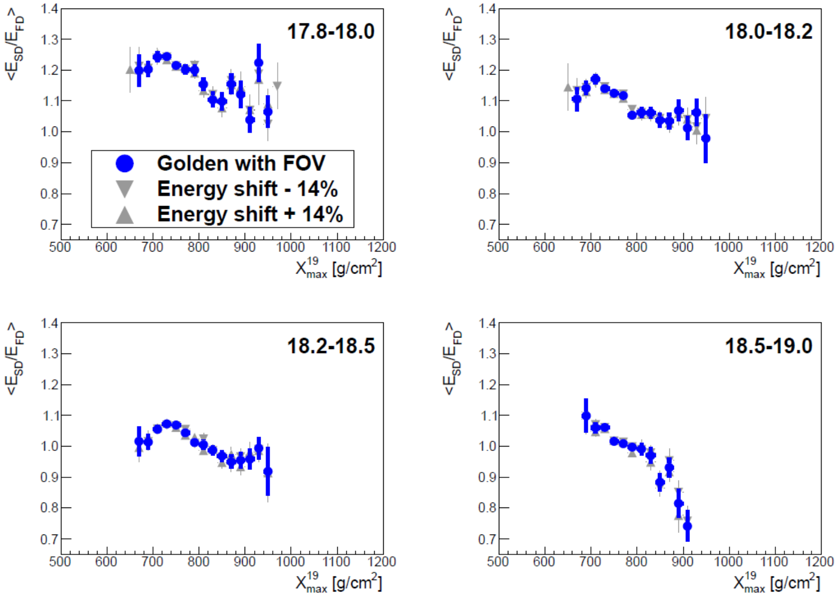
$$S^*(1000) \cong \left(E_{\text{SD}} / E_{\text{FD}}\right) \cdot 47.8\ \text{VEM}$$

Mass composition bias in E_{SD}





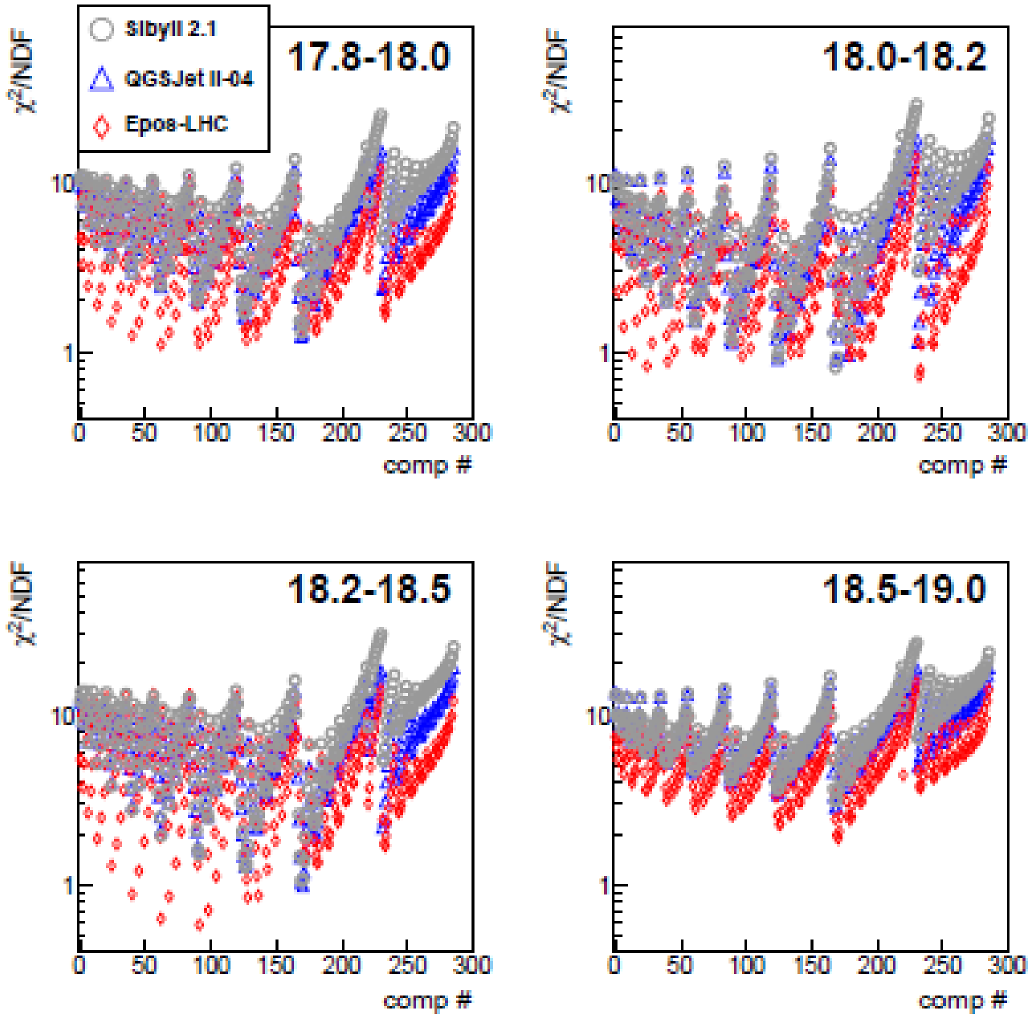
Dependencies checked for:

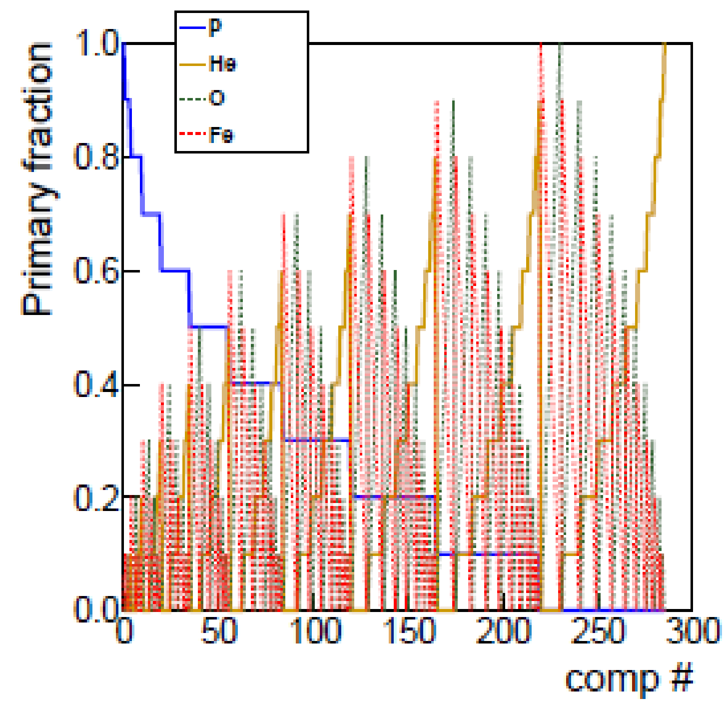


- Time evolution
- Energy scale
- FOV cuts (limited aperture effect)
- Attenuation curve
- Elongation rate
- Different stage of evolution
- Zenith angle

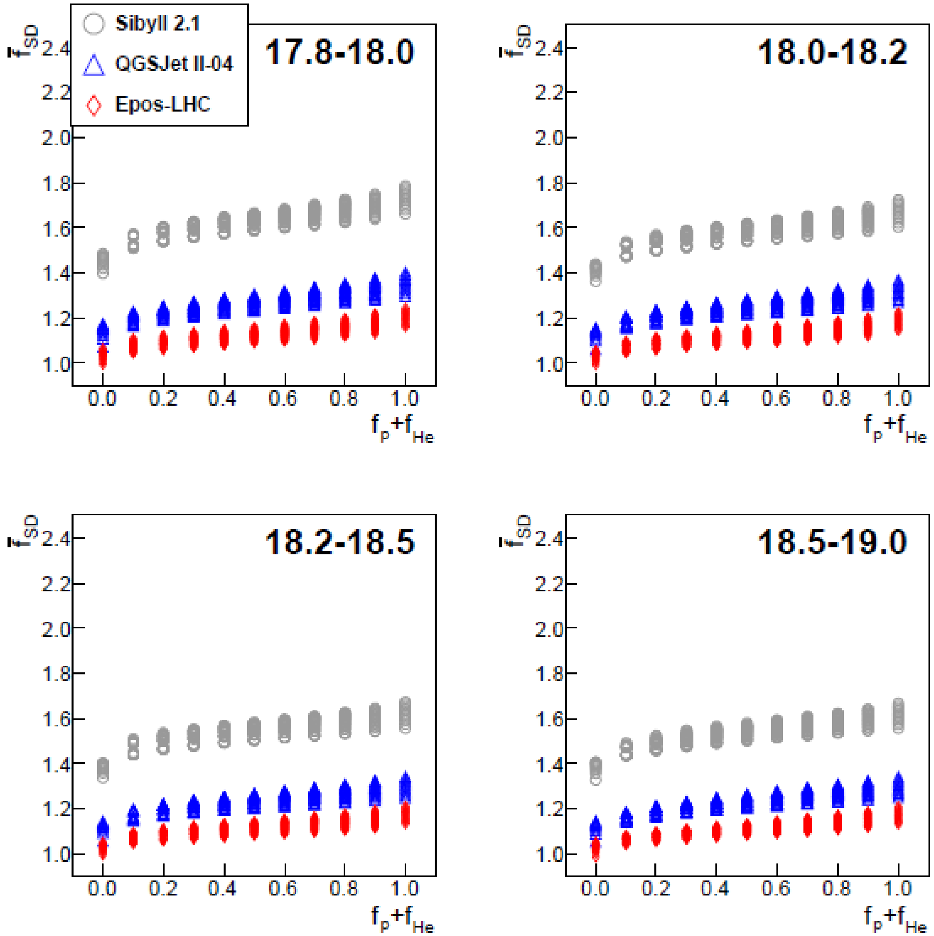
=> manifestation of mass composition bias in E_{SD}

No distinct minima found

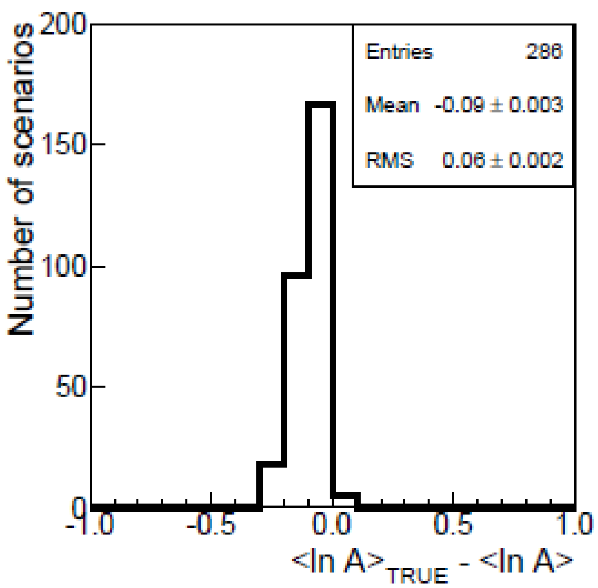


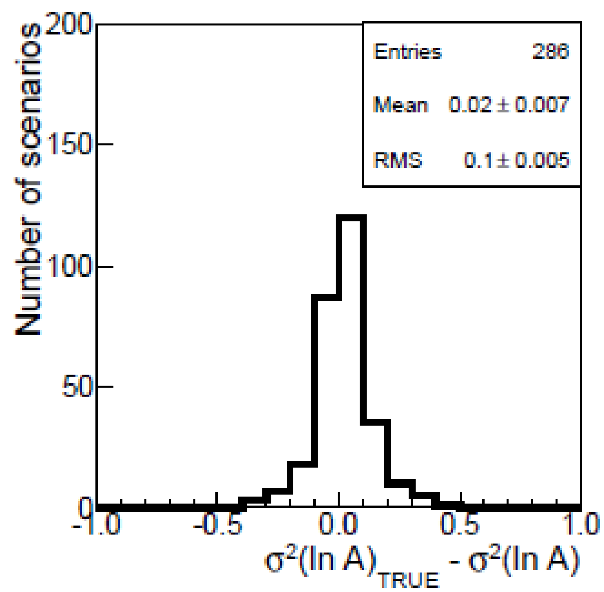


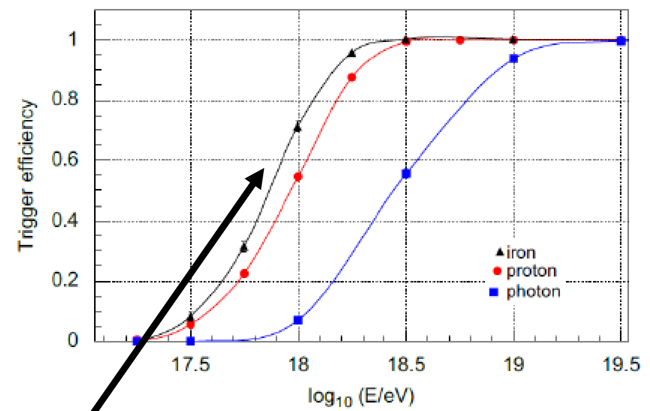
Rescaling of ground signal for all combinations of primaries



Maximal effect of SD trigger on lnA moments







Considering trigger efficiency for p: 55%, He: 60%, O:65%, Fe: 70%

Further RPC plots

$$\langle \rho(r) \rangle = \rho_{1000} \left(\frac{r}{1000} \right)^{\beta} \left(\frac{r + 700}{1000 + 700} \right)^{\beta + \gamma}$$