Estimating the mass of cosmic rays by combining radio and muon measurements

Ewa M. Holt for the Pierre Auger Collaboration

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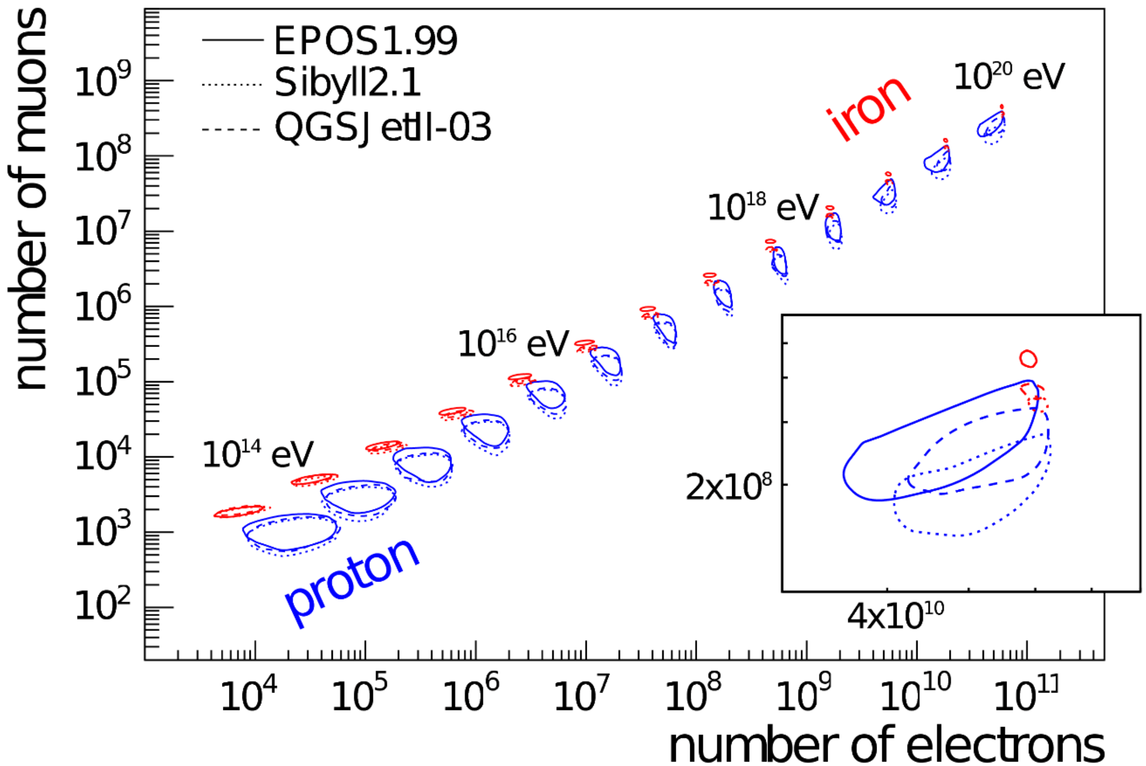
ARENA 2018
June 12, 2018

Separate measurements of muons + radio

K.H. Kampert, M. Unger, Astropart. Phys., Vol.35, Issue 10, pp. 660-678

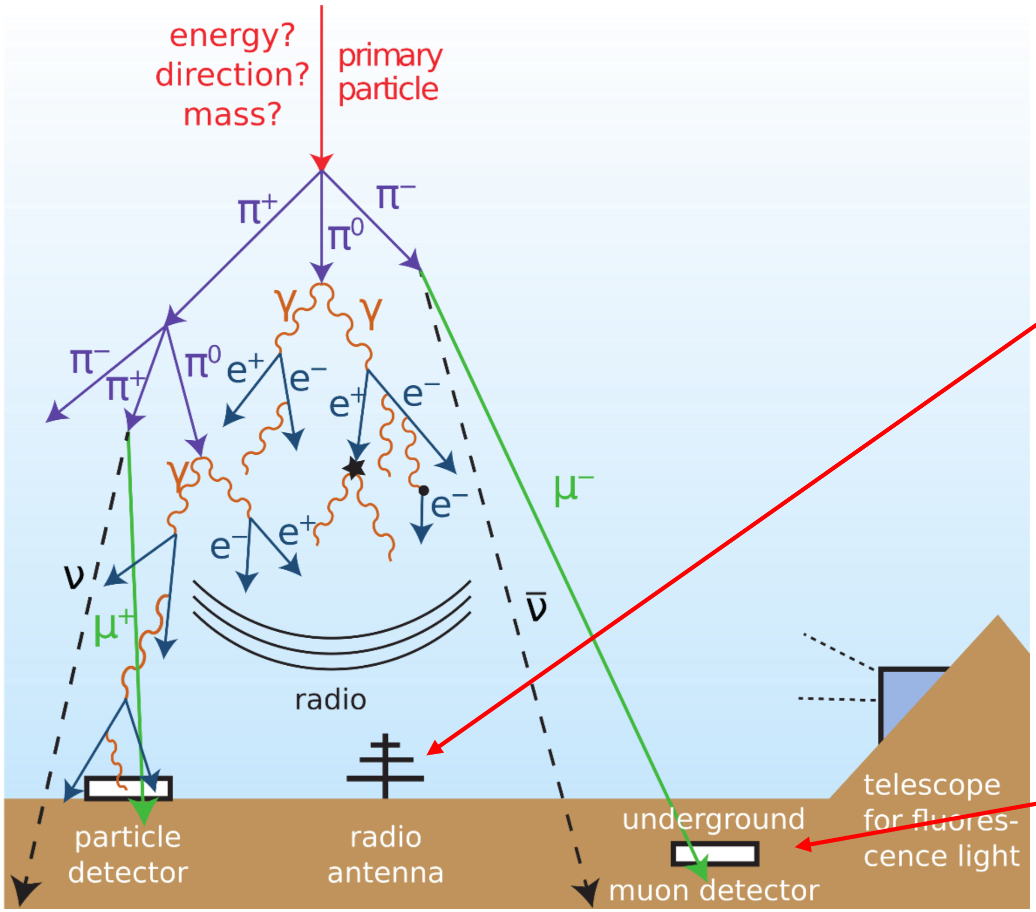
AMIGA

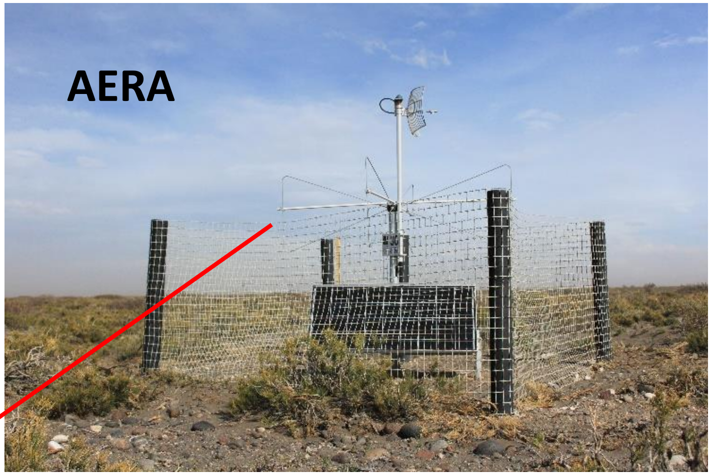


AERA

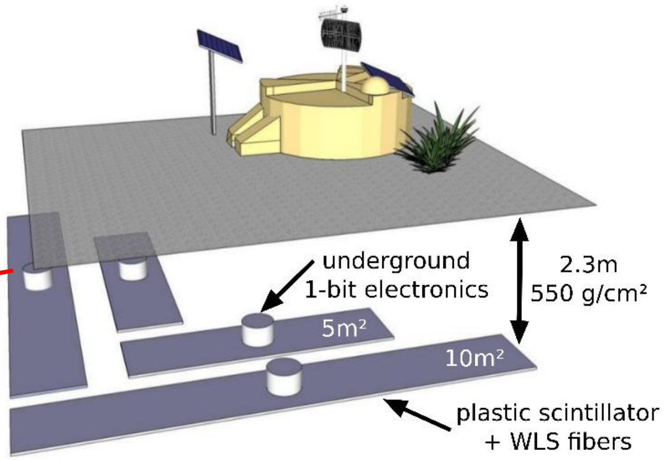
- separate measurements of components
- estimation of mass via ratio

AERA & AMIGA at the Pierre Auger Observatory



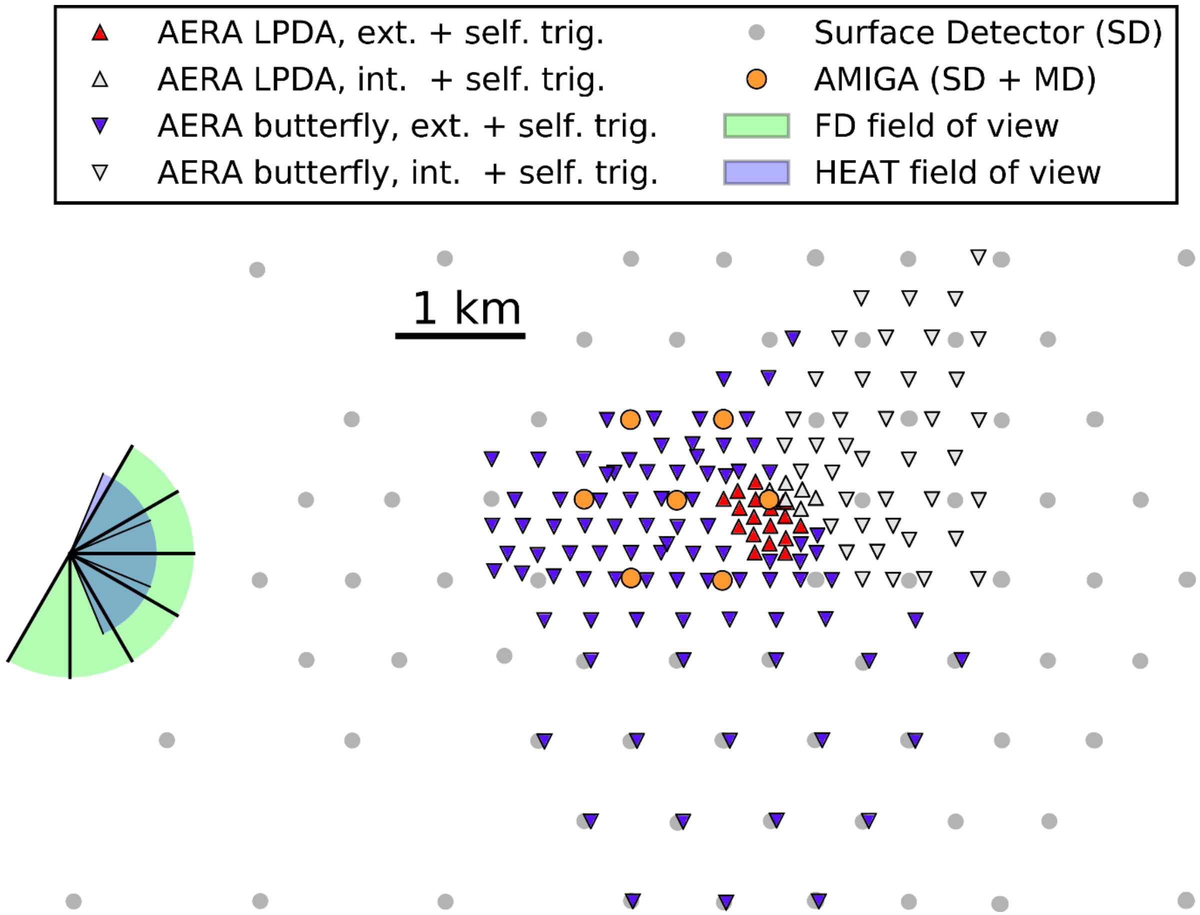


AMIGA (Auger Muons and Infill for the Ground Array)



e^+, e^- μ^+, μ^- ⇒ **separate measurements**

AERA & AMIGA detector configuration

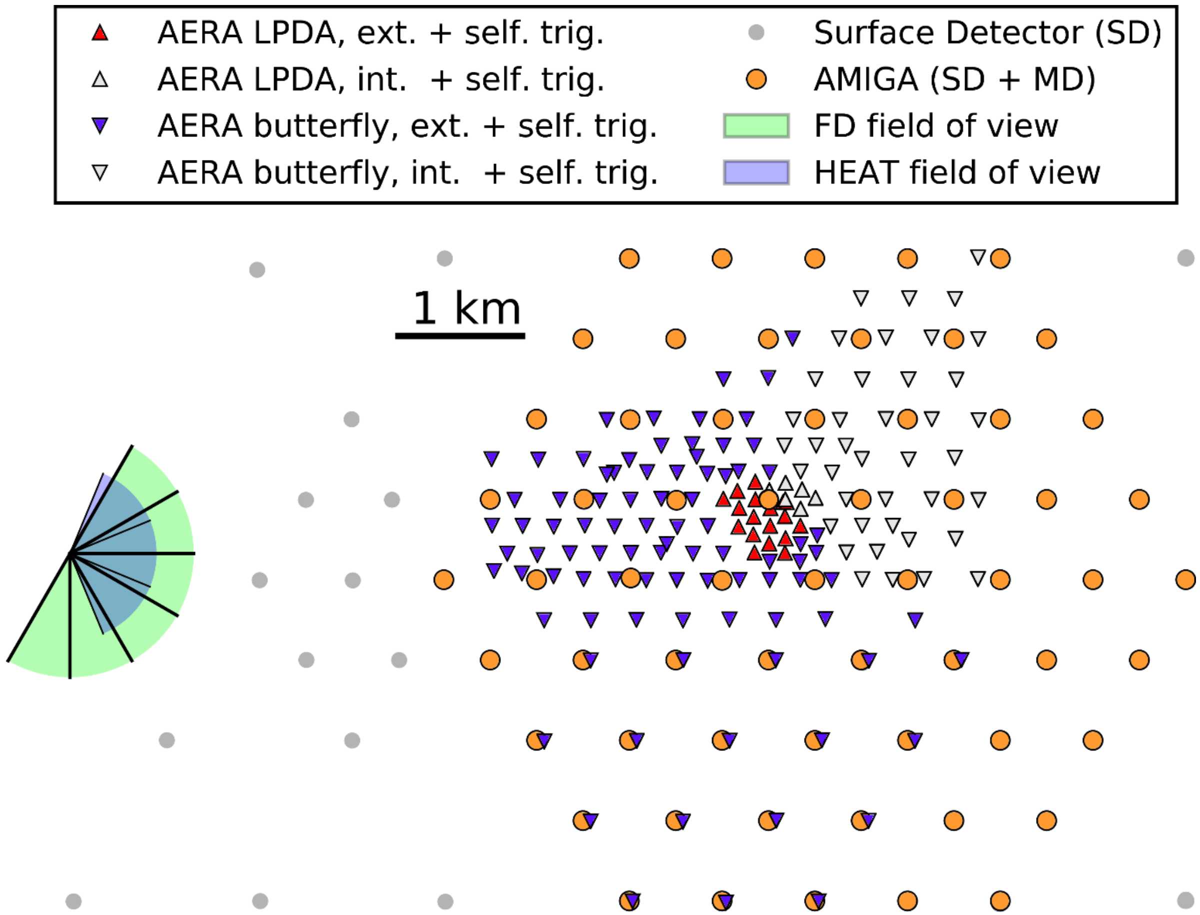


AMIGA:
750 m spacing

AERA:
125 – 750 m spacing

Low energy enhancements
E > 10^{17} eV

AERA & AMIGA detector configuration



AMIGA:
750 m spacing

AERA:
125 – 750 m spacing

Low energy enhancements
$E > 10^{17}$ eV

AugerPrime: cover full AMIGA with underground muon scintillators (MD)

Air shower simulation study

proton and iron primaries

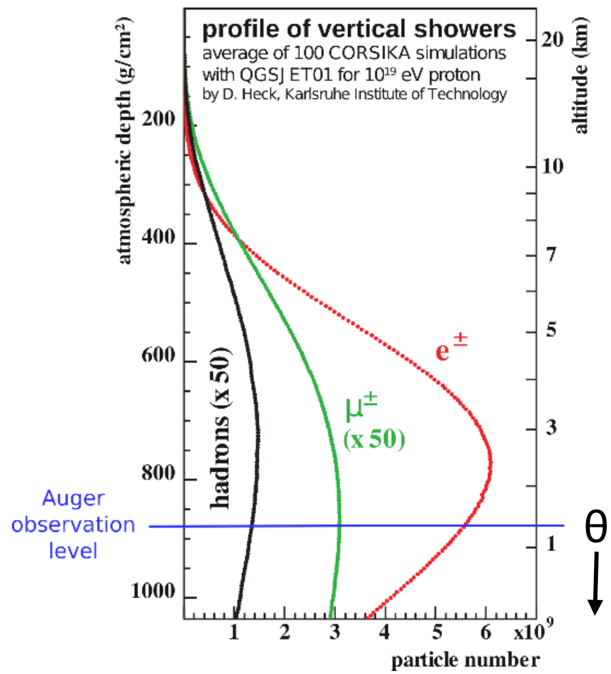
each 5302 simulations

CORSIKA, QGSJETII-04 + FLUKA

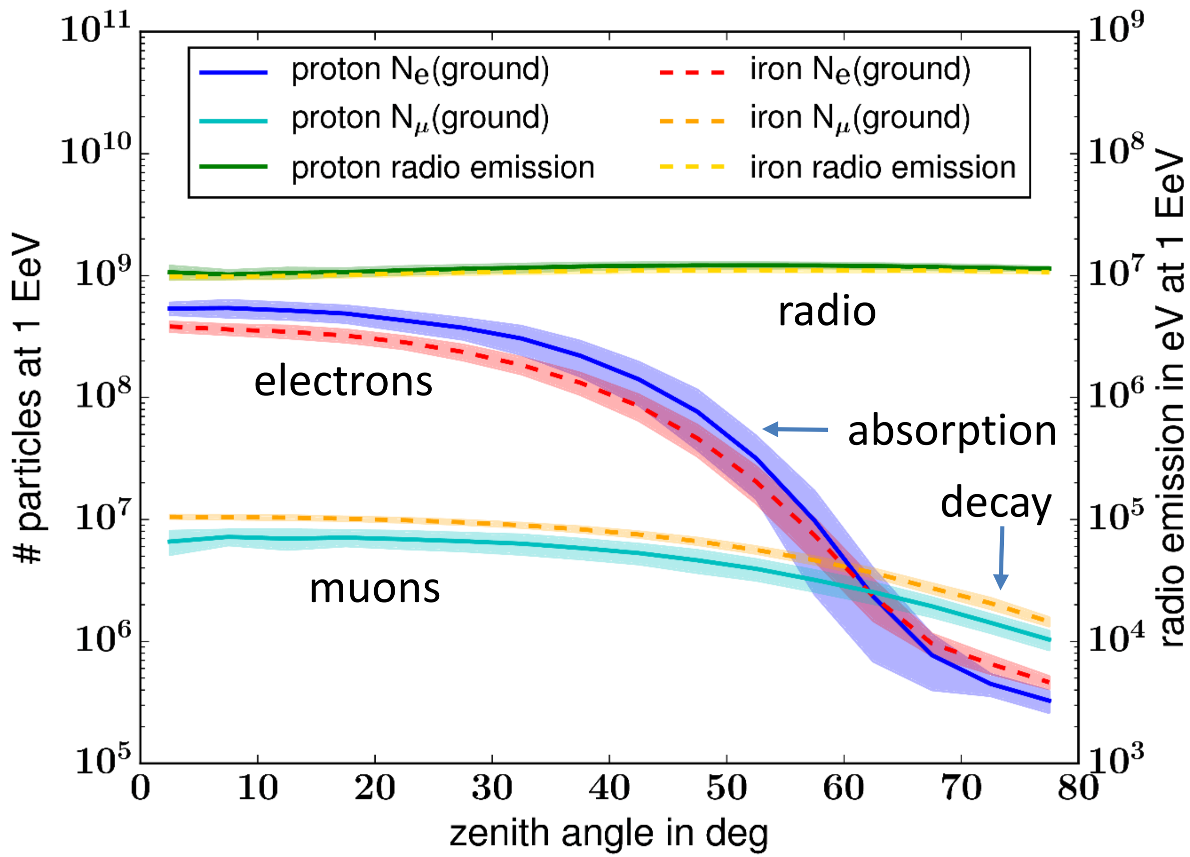
Radio emission modeled from CoREAS simulations in

[C.Glaser et al., JCAP 09 (2016) 024]

Zenith angle dependence of shower components

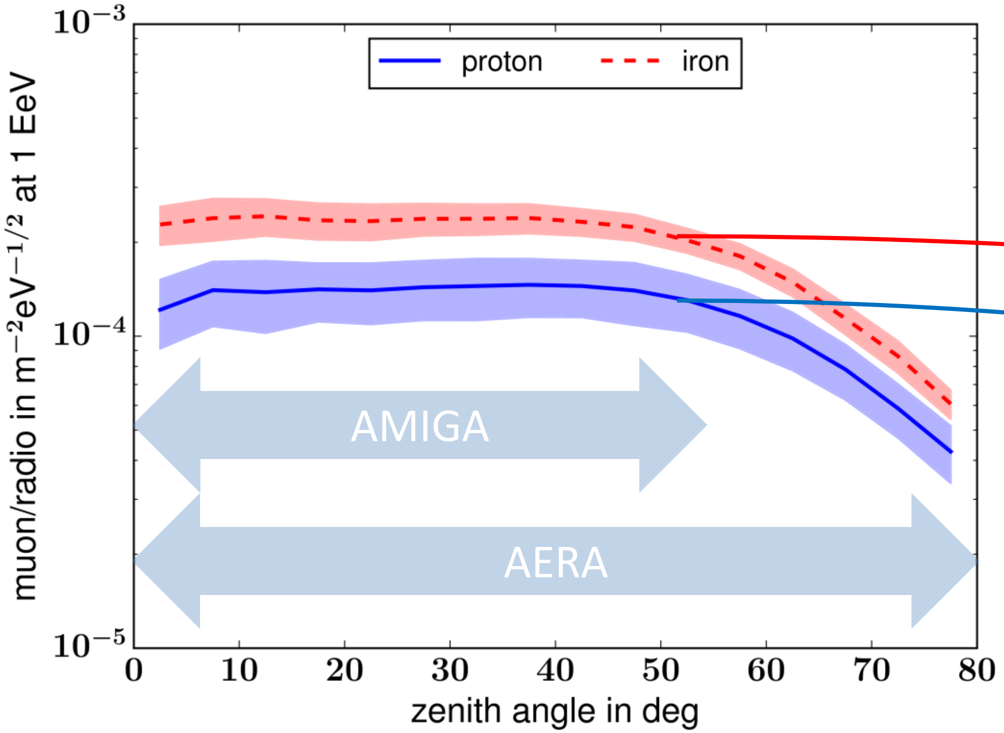


ground = Auger site 1452 m a.s.l.

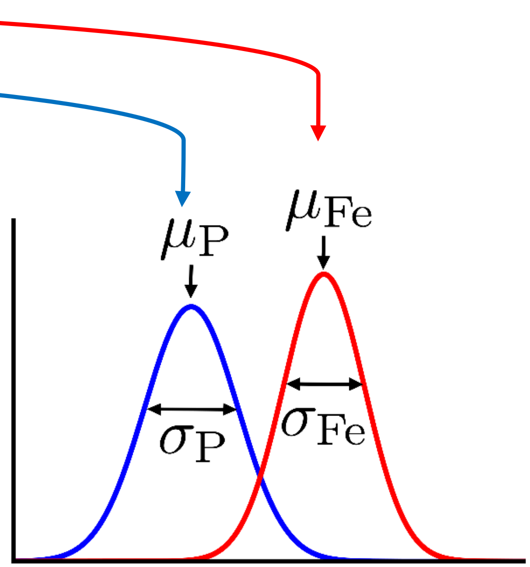


Increasing atmospheric depth to ground

Muon-radio ratio



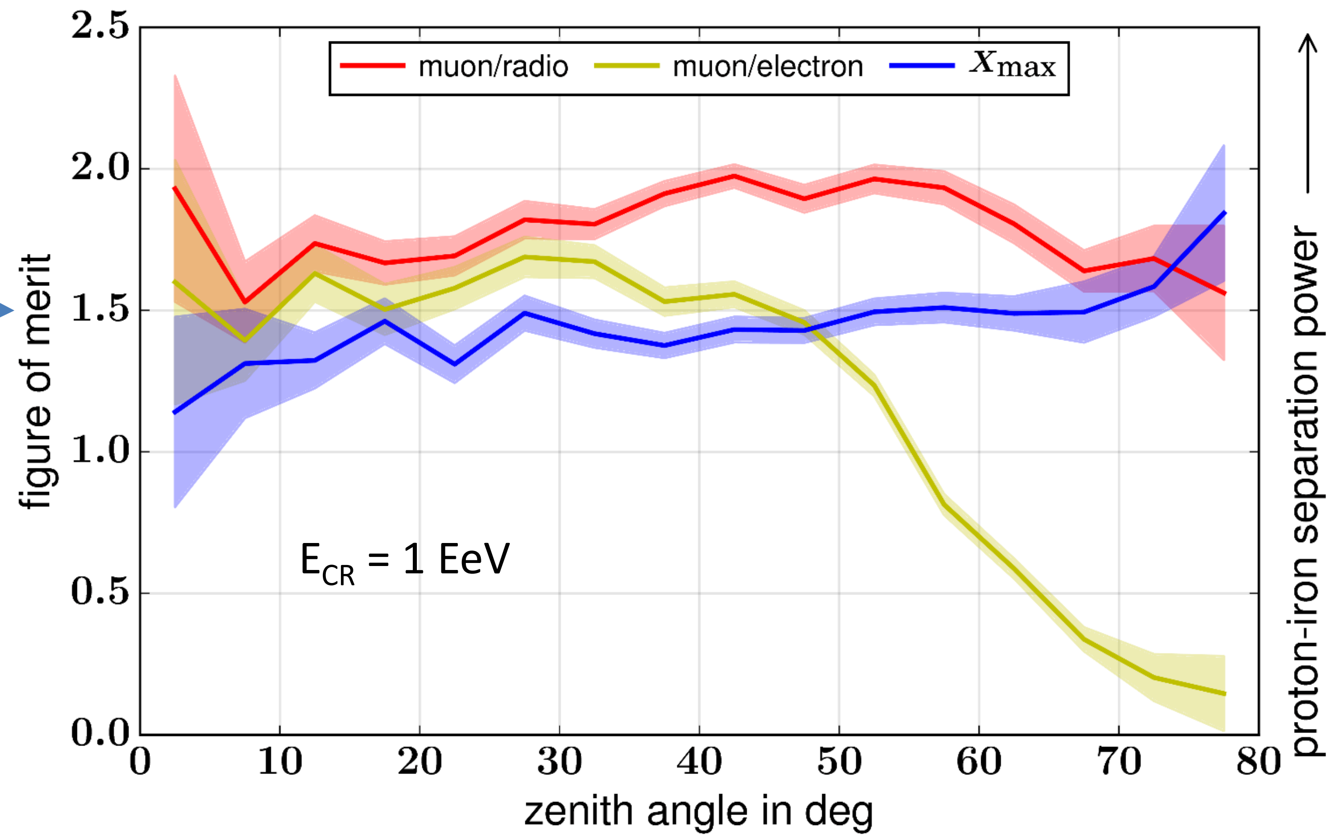
Quantify mass separation power with figure of merit



$$FOM = \frac{|\mu_{\mathrm{P}} - \mu_{\mathrm{Fe}}|}{\sqrt{\sigma_{\mathrm{P}}^2 + \sigma_{\mathrm{Fe}}^2}}$$

Mass separation power

AugerPrime design goal



New mass estimator superior for inclined showers!

Influence of detector responses

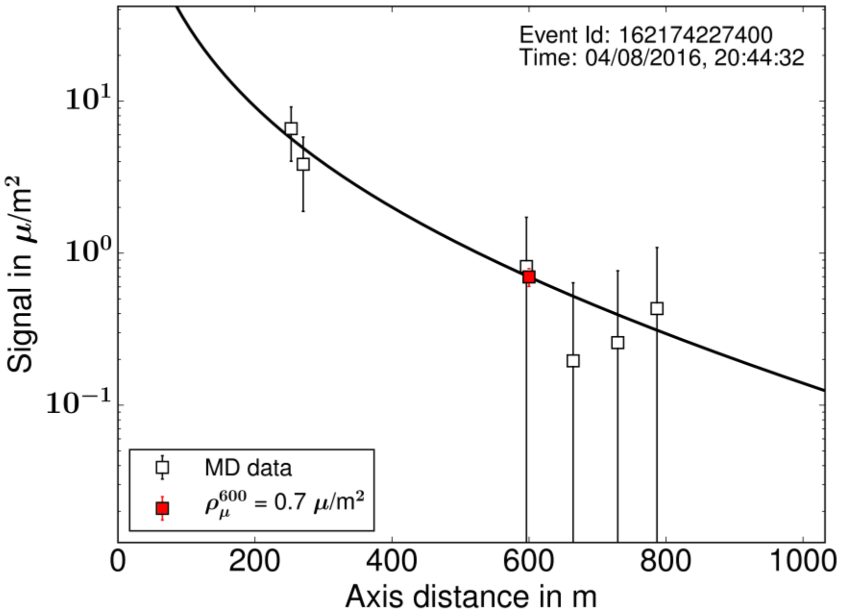
AERA and AMIGA

AMIGA: muon density ρ_μ^{600} at 600 m

Count muons in each segmented scintillator

$E_\mu > 1$ GeV

Fit lateral distribution function



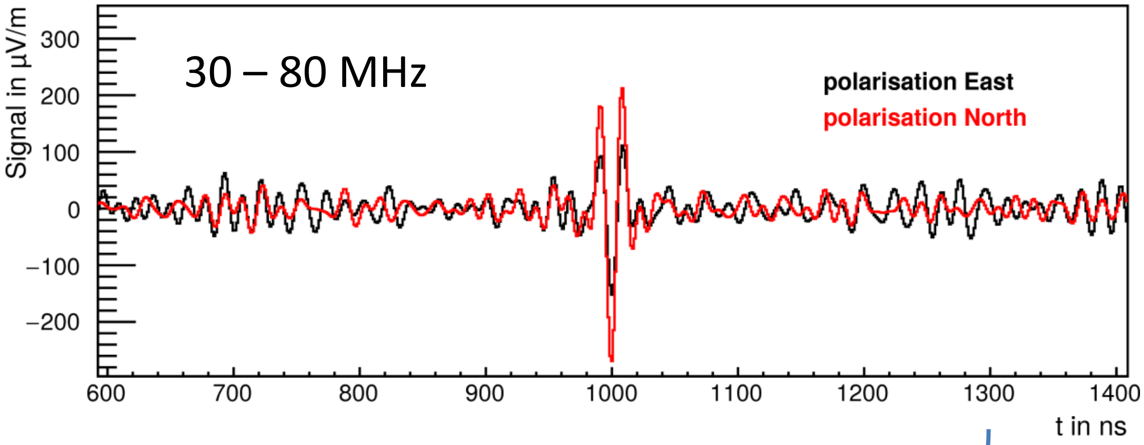
Muon density at scintillator:
$\rho_\mu = N_\mu$ / area

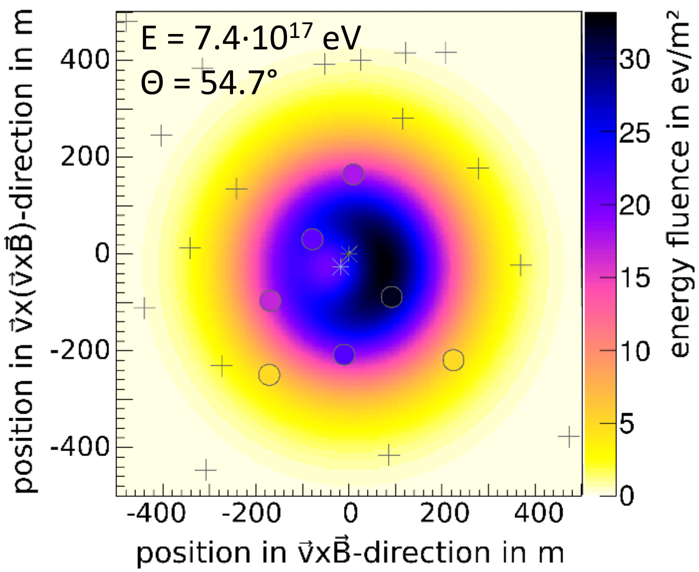
Distance with best mass separation power

$$\rho_\mu^{600}$$

AERA: radiation energy $S_{\mathrm{RD}}^{\rho\theta}$

Measure time trace in each antenna → energy fluence





Fit 2-dimensional lateral distribution

Integral over lateral distribution

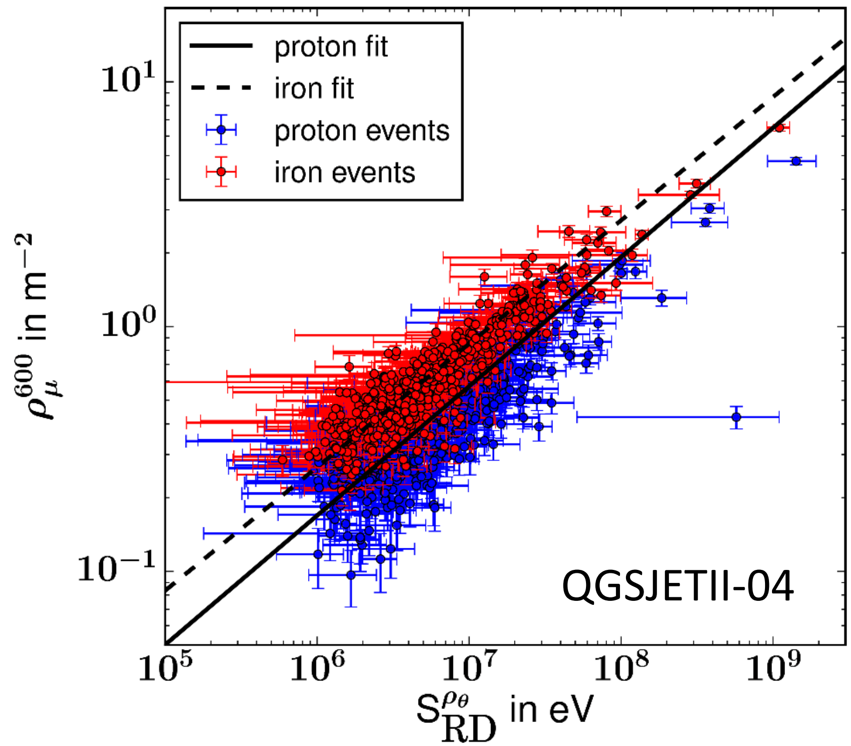
↓

energy contained in radio emission

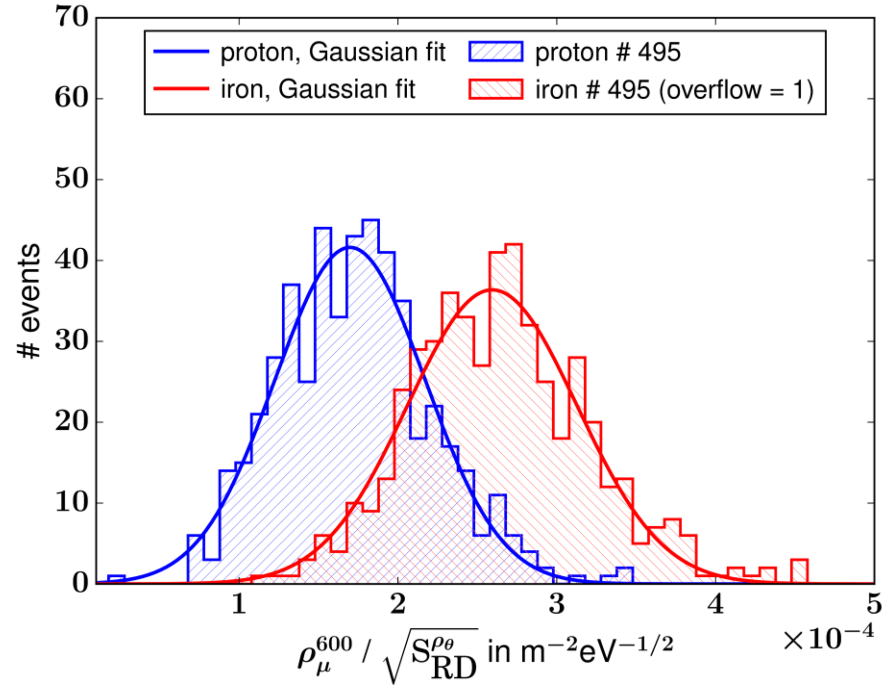
$S_{\mathrm{RD}}^{\rho\theta}$

Observables including detector responses

CORSIKA + CoREAS simulations + detector responses



ratio

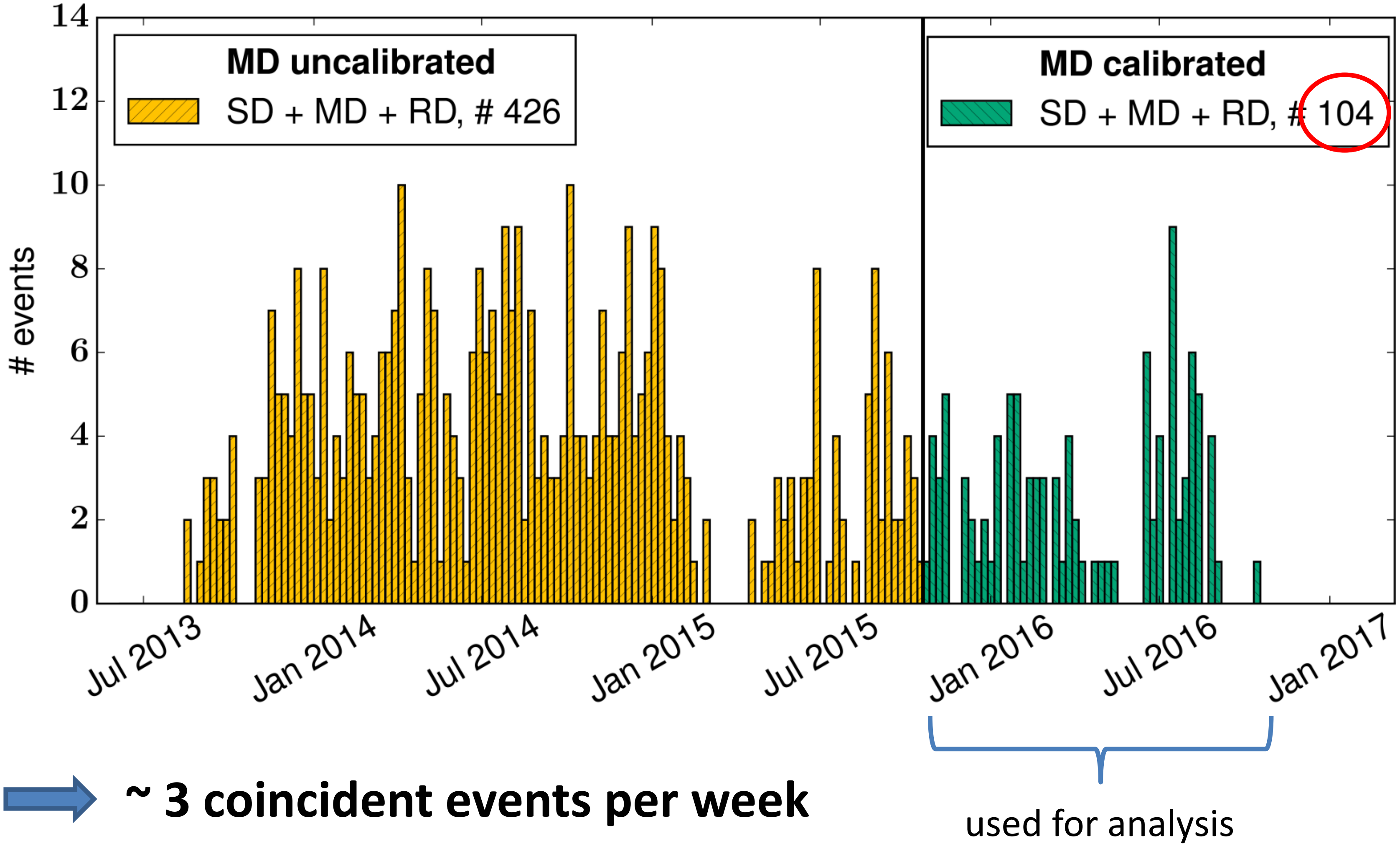


$$\rho_\mu^{600} \propto \sqrt{S_{RD}^{\rho_\theta}}$$

Application to
AERA & AMIGA data

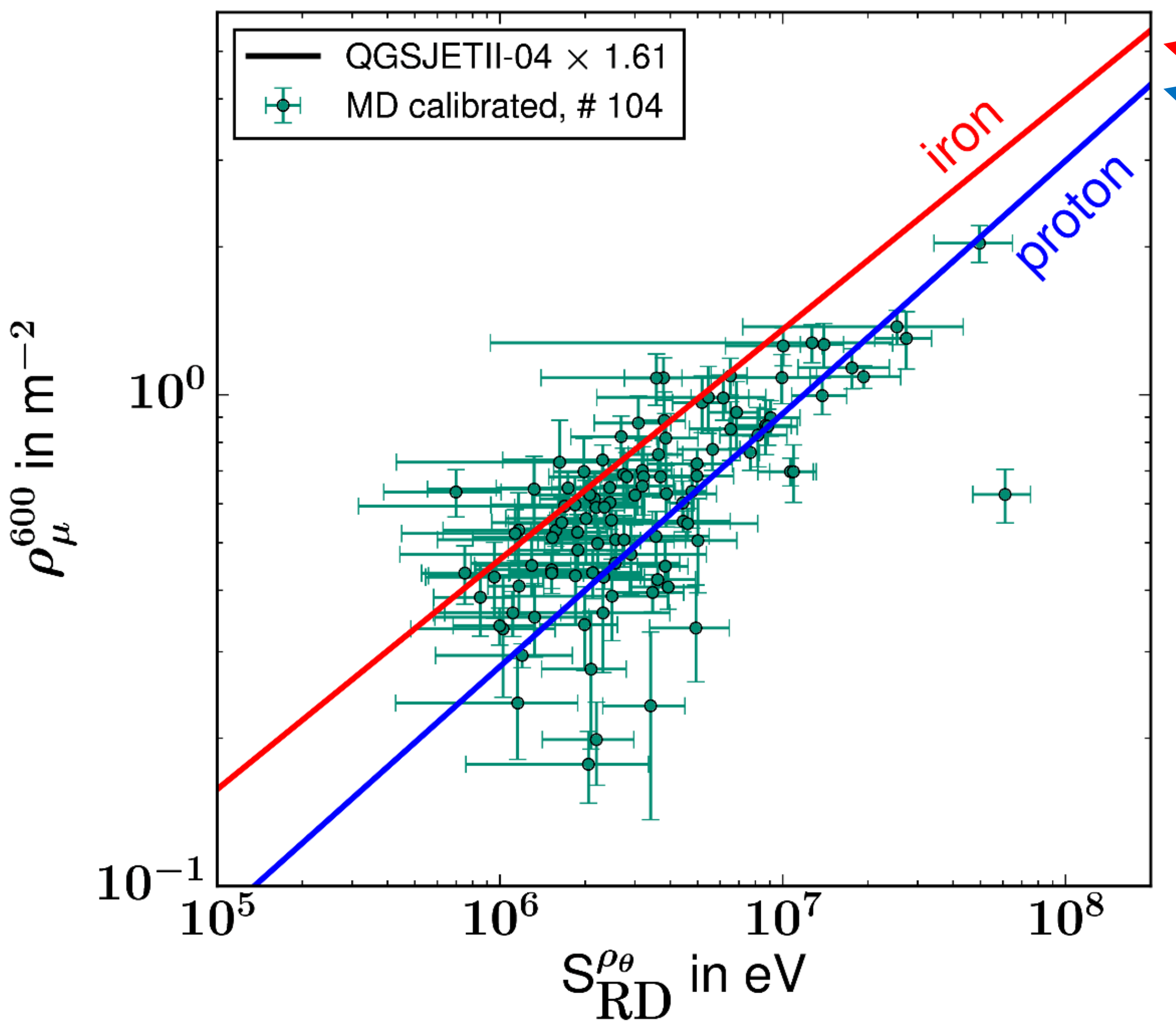
AERA & AMIGA coincident events

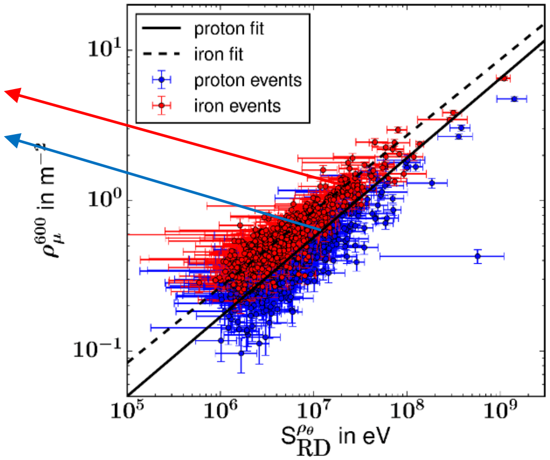
Prototype experiments: variation in calibration, electronics, antenna type, spacing, …



~ 3 coincident events per week

Muon-radio correlation





+ shift mean of predictions by known discrepancy on the muon number of 61%, measured by surface detector of Auger
[Phys. Rev. Lett. 117, 192001 (2016)]

Mean of data well in between mean of proton and iron predictions

Conclusion

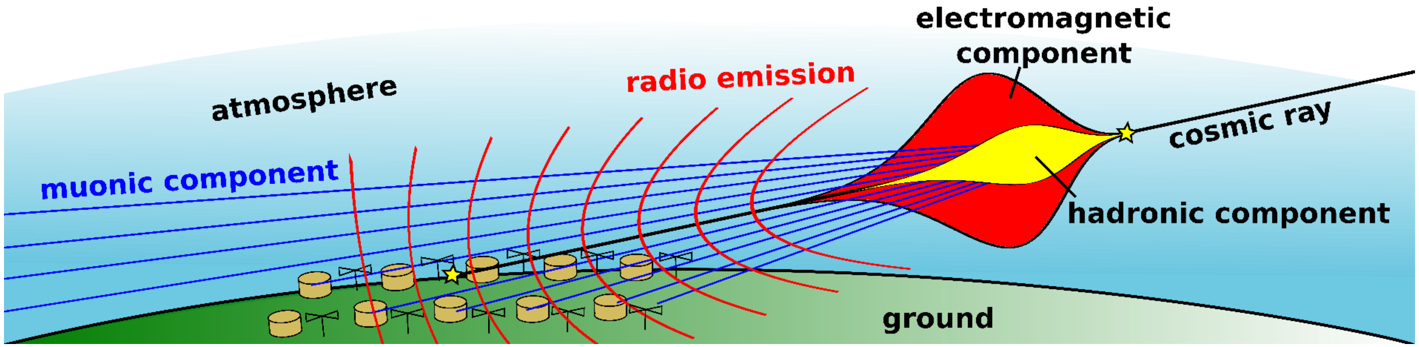
Origin of ultra high energy cosmic rays: Mass composition measurements essential

Novel technique for **mass estimation** combining **radio and muon** measurements**:** validated with simulations and data

Superior mass separation power for **inclined showers**

PhD thesis: DOI:10.5445/IR/1000083318

Future applications



Large radio array at the Pierre Auger observatory: Increase sky coverage for mass composition measurements

Talk J. Hörandel Wednesday 11:30

Other experiments: IceCube surface array, GRAND, …

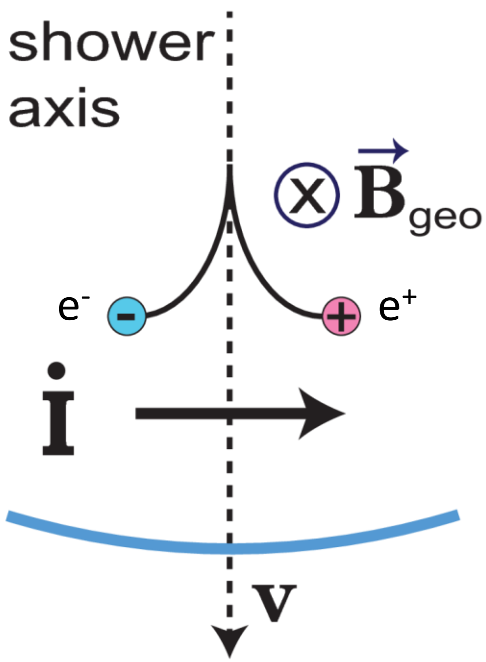
Talk F. Schröder Tuesday 17:30

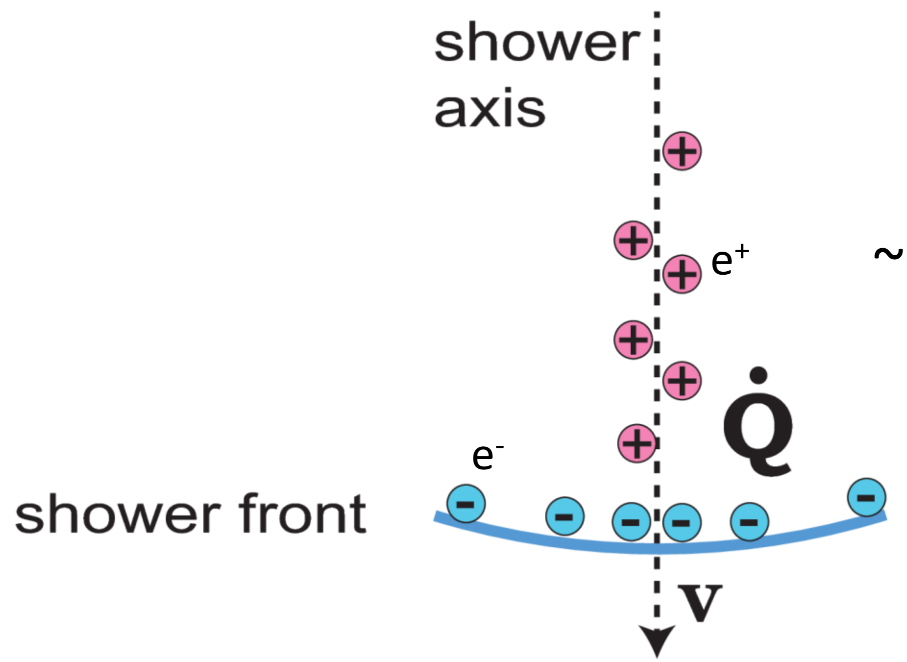
https://whatismyipaddress.com/backup-files

Radio emission of air showers

Two dominant **emission mechanisms:**

~90%





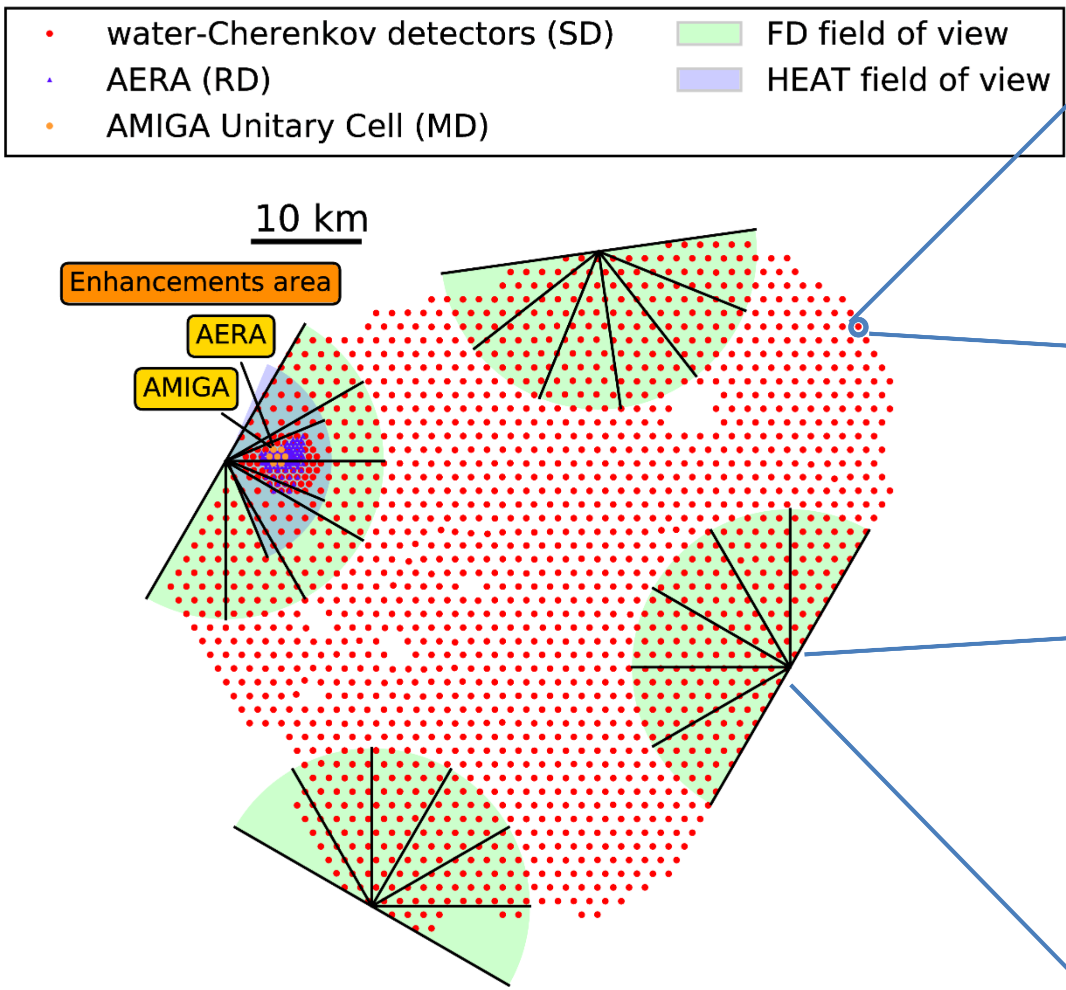
~10%

Geomagnetic effect

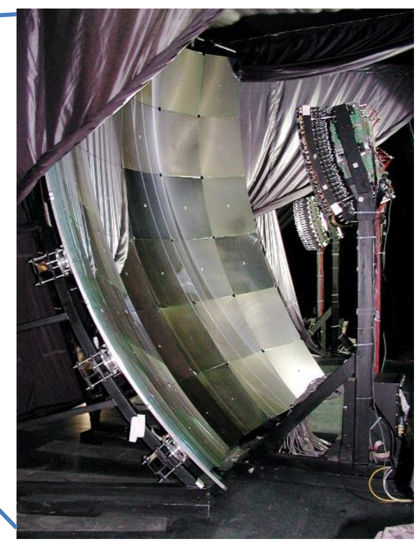
Askaryan effect

Charged electromagnetic component

Pierre Auger Observatory

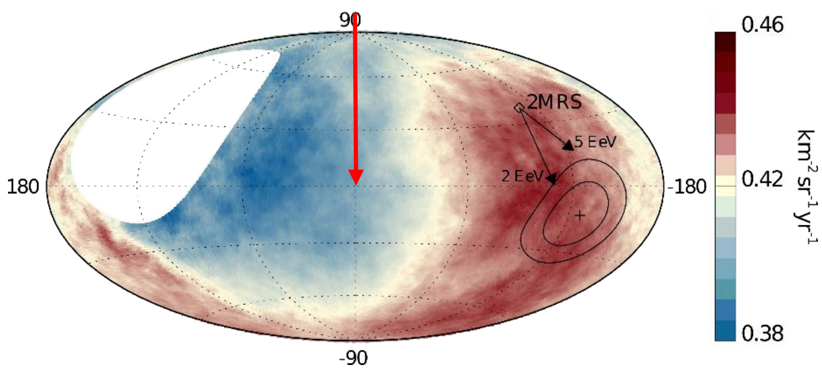


1660 particle detectors
1.5 km spacing
3000 km² covered area
27 fluorescence telescopes



World's largest observatory for ultra-high-energy cosmic rays

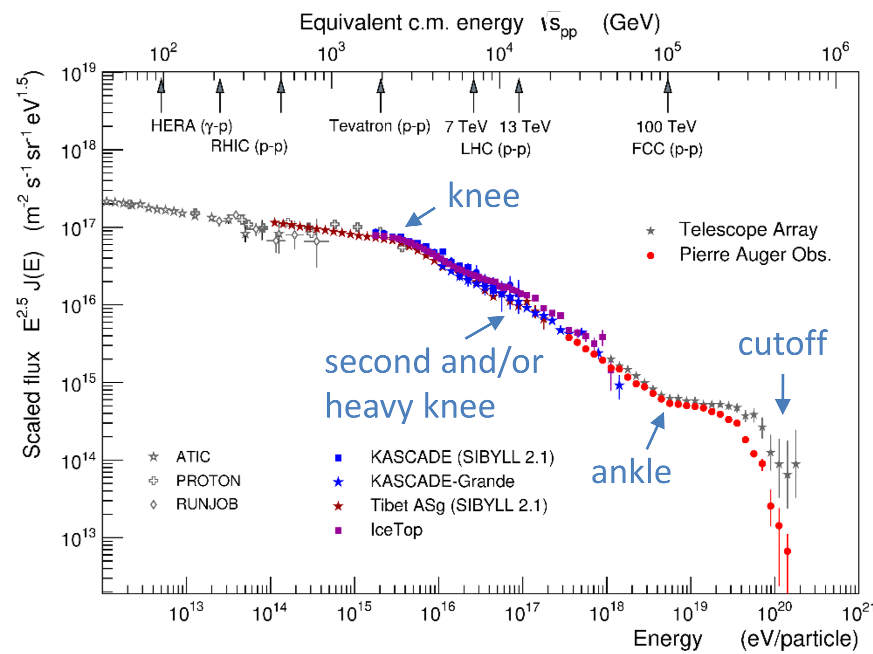
Origin of cosmic rays



Pierre Auger Collaboration, Science (2017), Vol.357

Arrival directions:
Extragalactic origin of ultra-high energy cosmic rays

Sources??



R. Engel, D. Heck, T. Pierog, Ann.Rev.Nucl.Part.Sci 61 (2011) 467-489

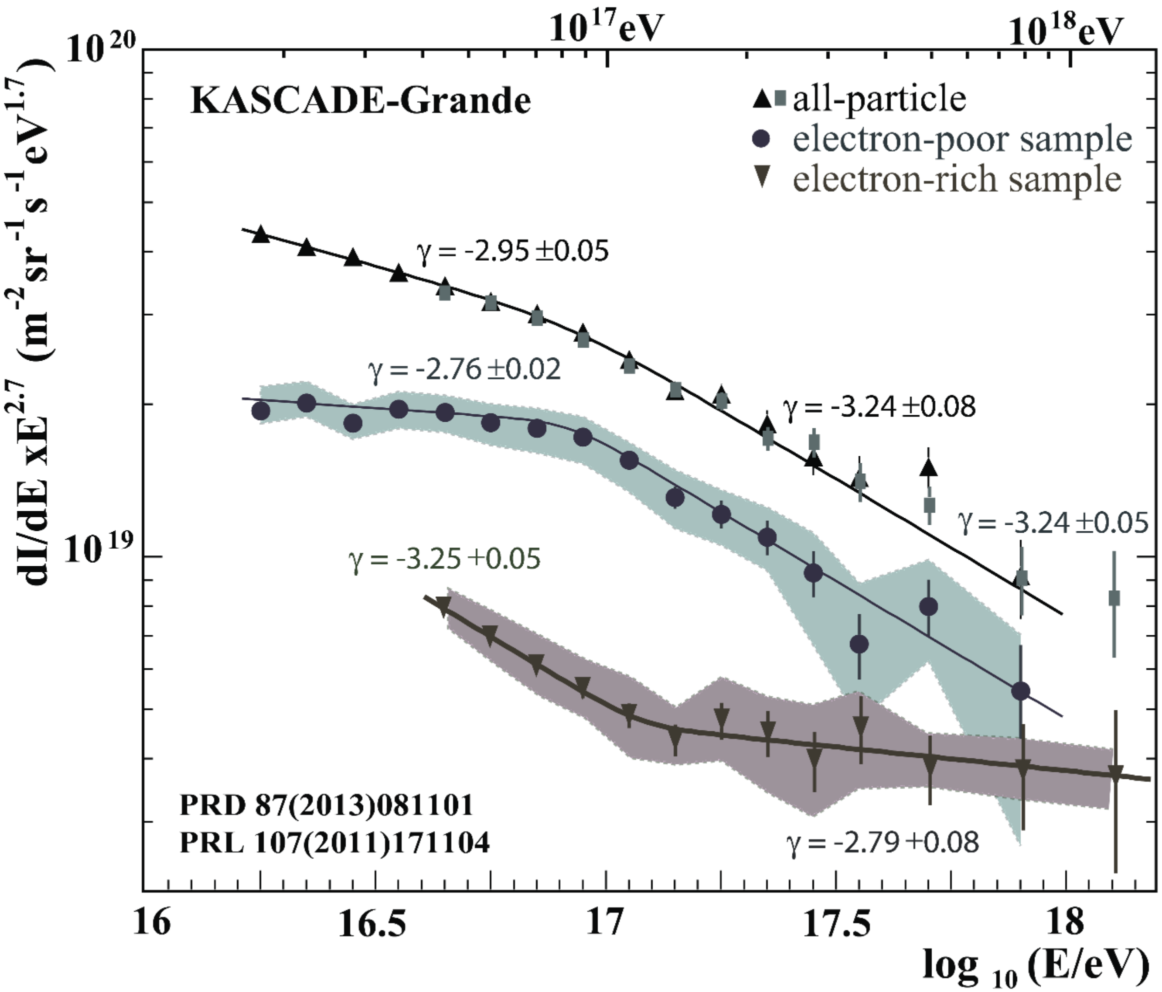
Features in energy spectrum:
information about sources and propagation

Acceleration and propagation effects proportional to Z or A??

⇓

Mass composition measurements

Light and heavy energy spectrum

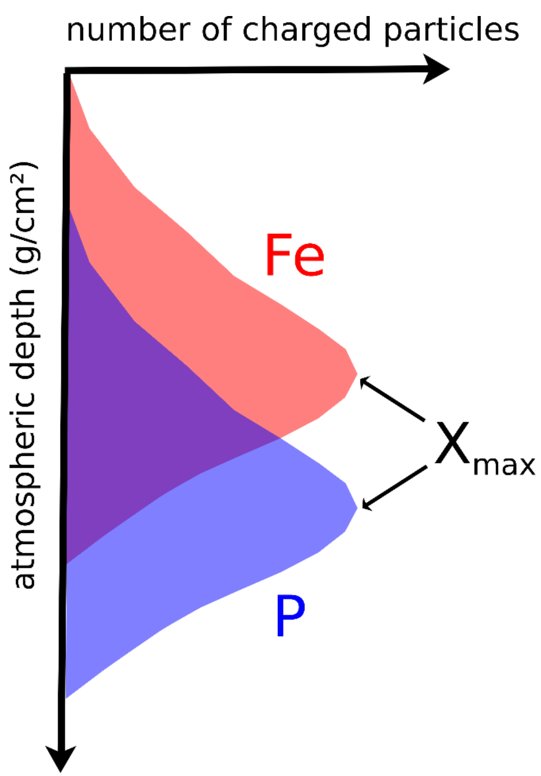


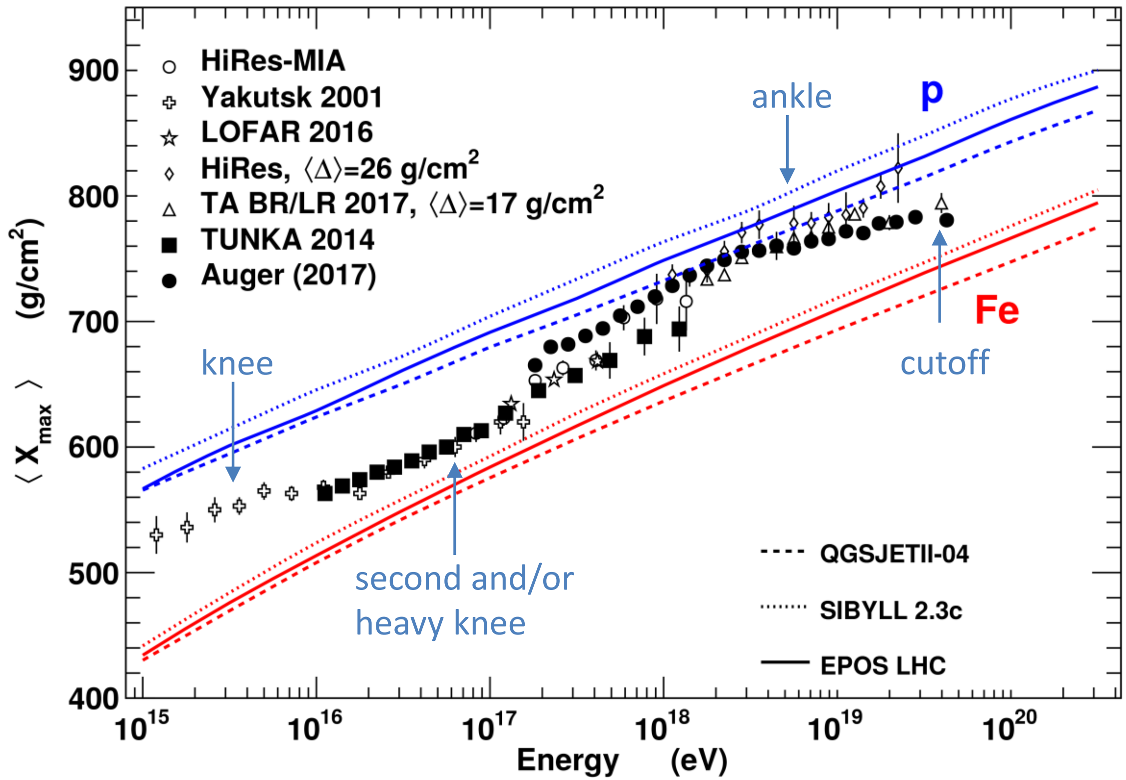
D. Kang, XXV ECRS 2016

Knee and ankle at different energies for light and heavy cosmic rays

Positions of light and heavy features agree with **rigidity dependence** of acceleration and propagation mechanisms

Mass estimation via shower maximum





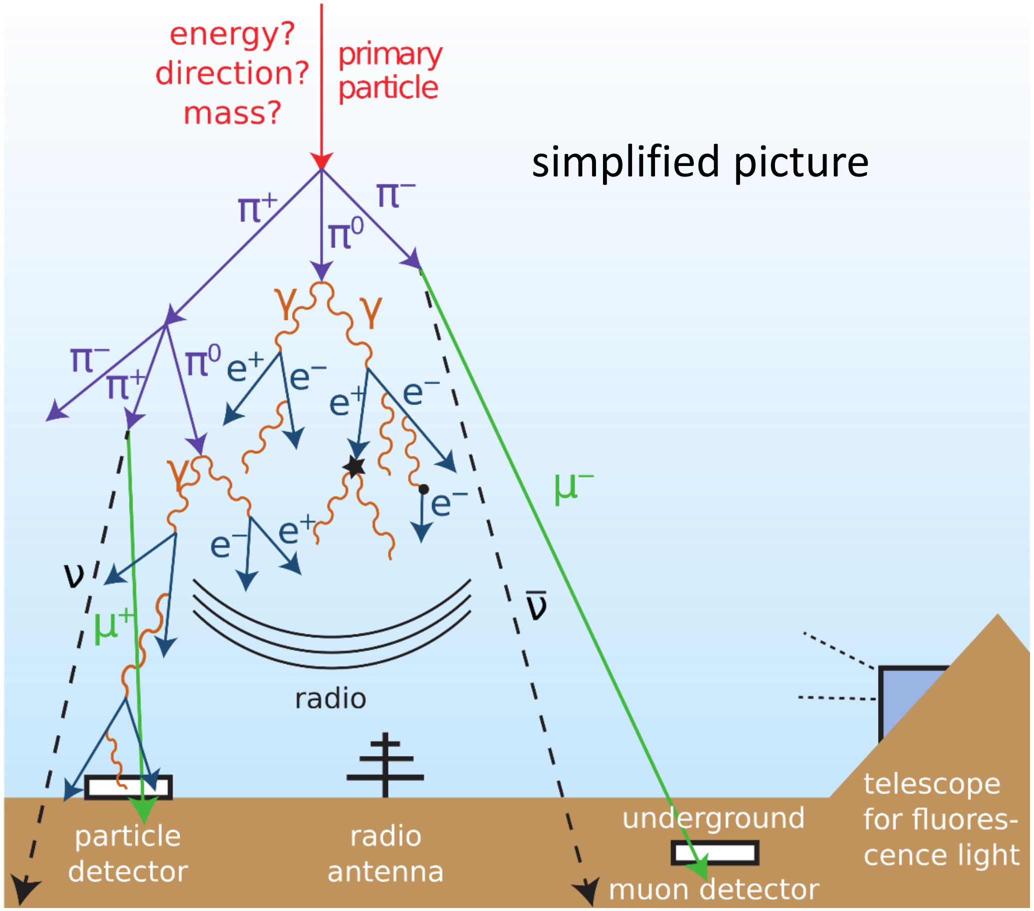
T. Pierog

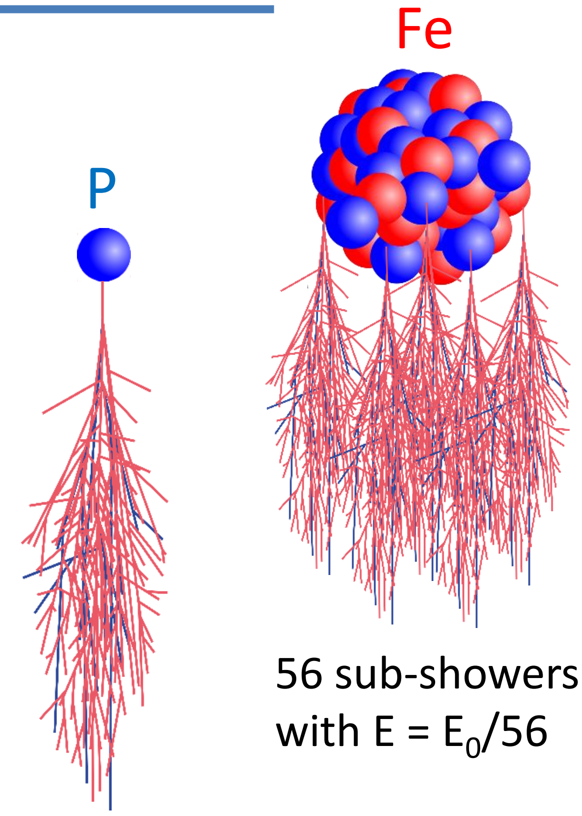
Large shower-to-shower fluctuations: measure only mean Xmax

Optical measurements limited to dark clear nights: 10 – 15 % duty cycle

Measurements at highest energies not yet conclusive

Mass estimation via particle numbers



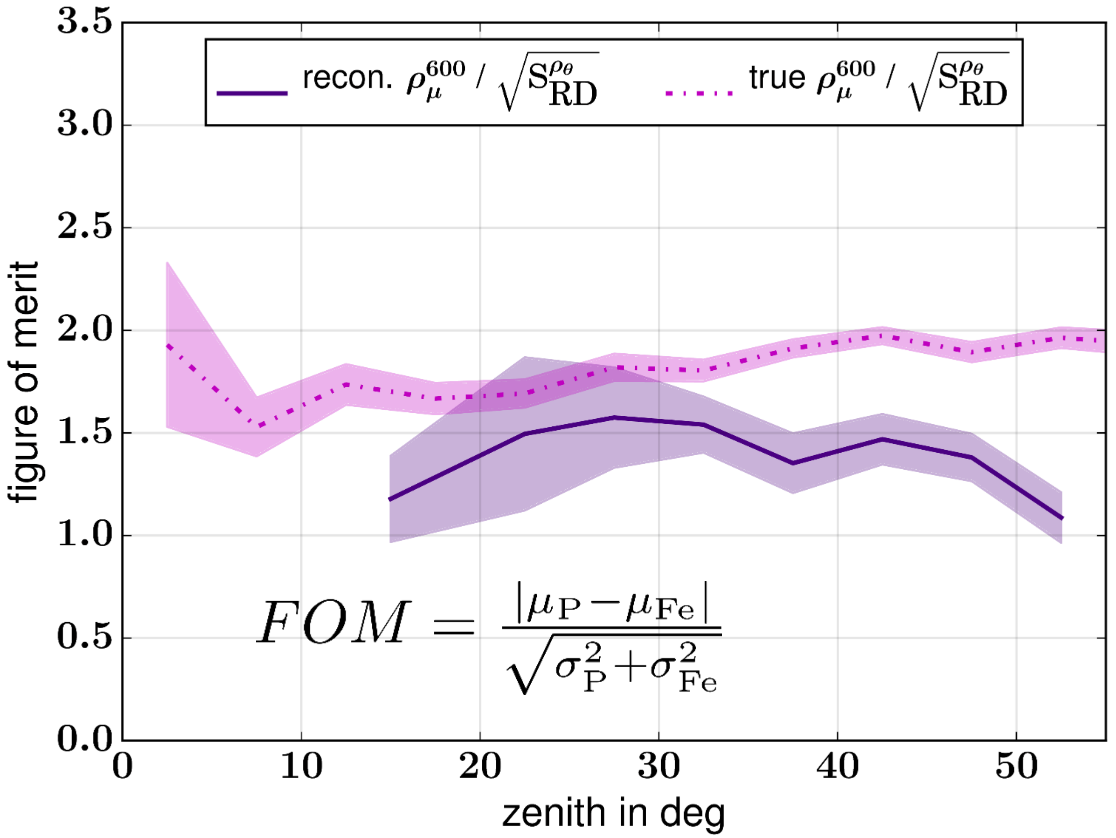


Larger hadronic component for heavier primary particles

At ground: more muons in iron showers
more electrons in proton showers

Mass separation power

Uncertainties σ_P , σ_{Fe}:
shower-to shower fluctuations
+ detection



Mass separation power only slightly decreased by measurement uncertainties

Mass sensitivity for distances to shower axis

Highest mass separation power at distances between 600 m – 800 m for zenith angle range 0° – 55°

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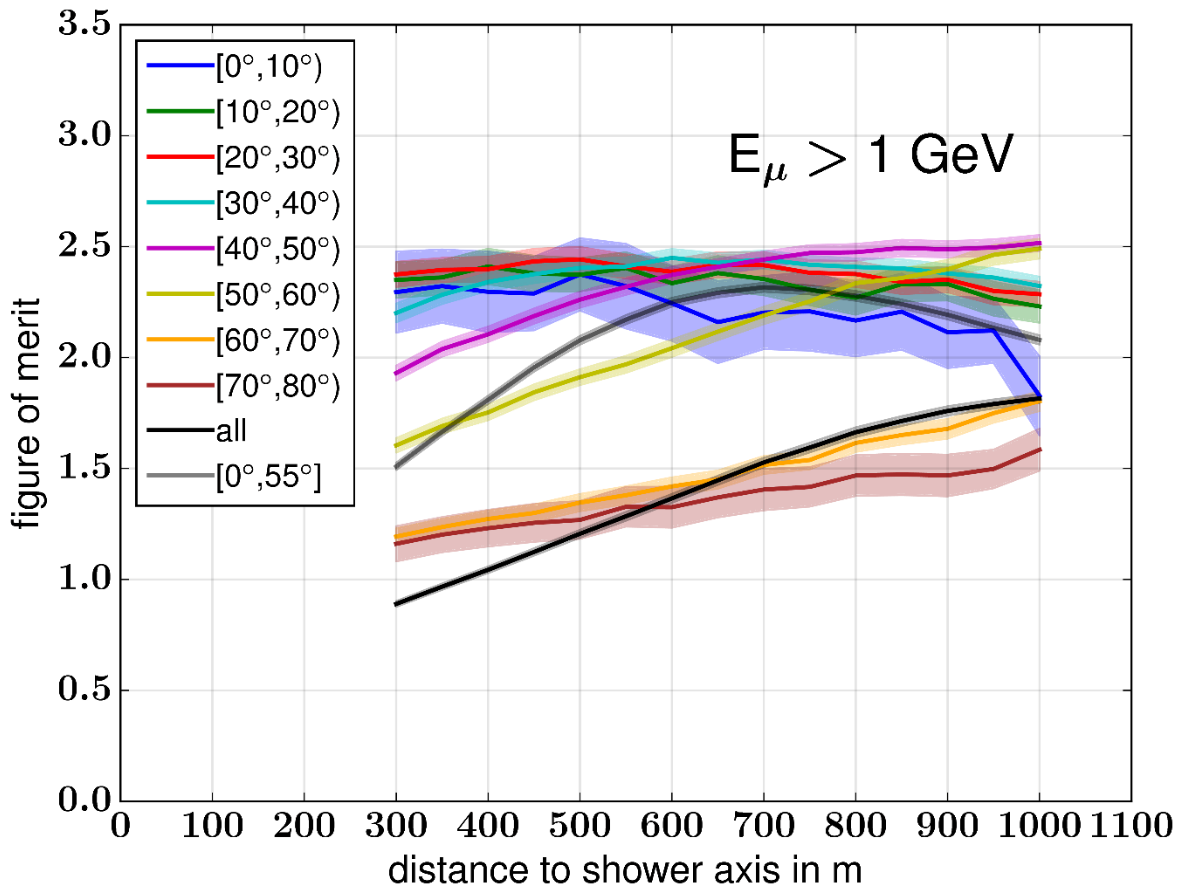
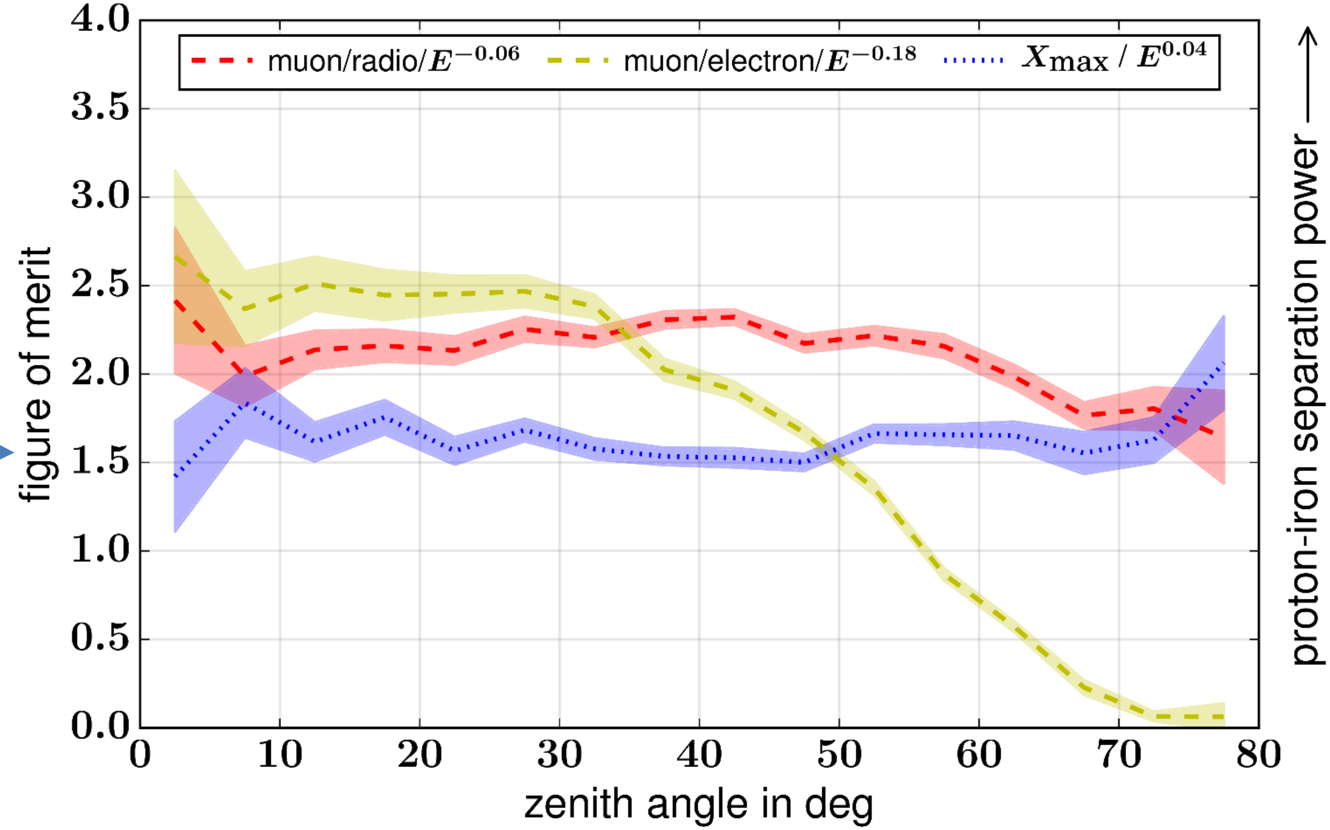
Use 600 m, lowest poisson fluctuations expected for limited detector size.



Mass separation power

AugerPrime design goal

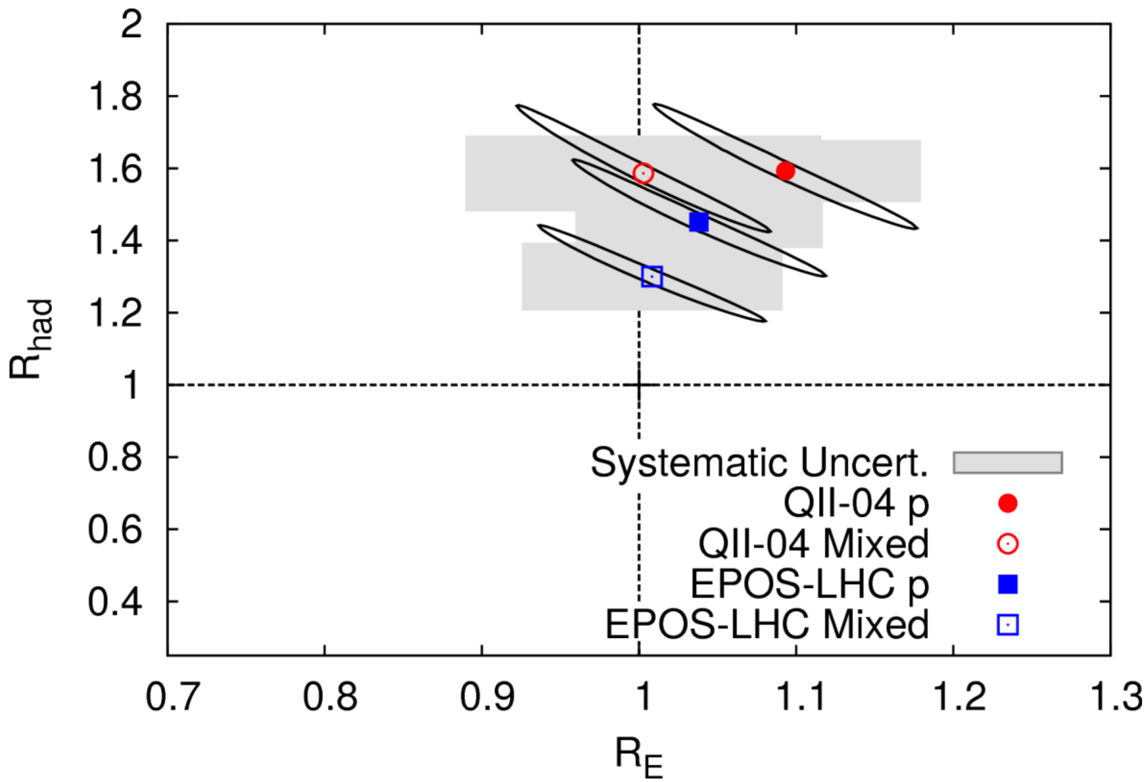


New mass estimator superior for inclined showers!

Underestimation of muons in hadronic models

Number of muons is underestimated in hadronic models compared to data

Underestimation measured by Auger SD (complementary):
(61±21)% for QGSJETII-04
[Phys. Rev. Lett. 117, 192001 (2016)]



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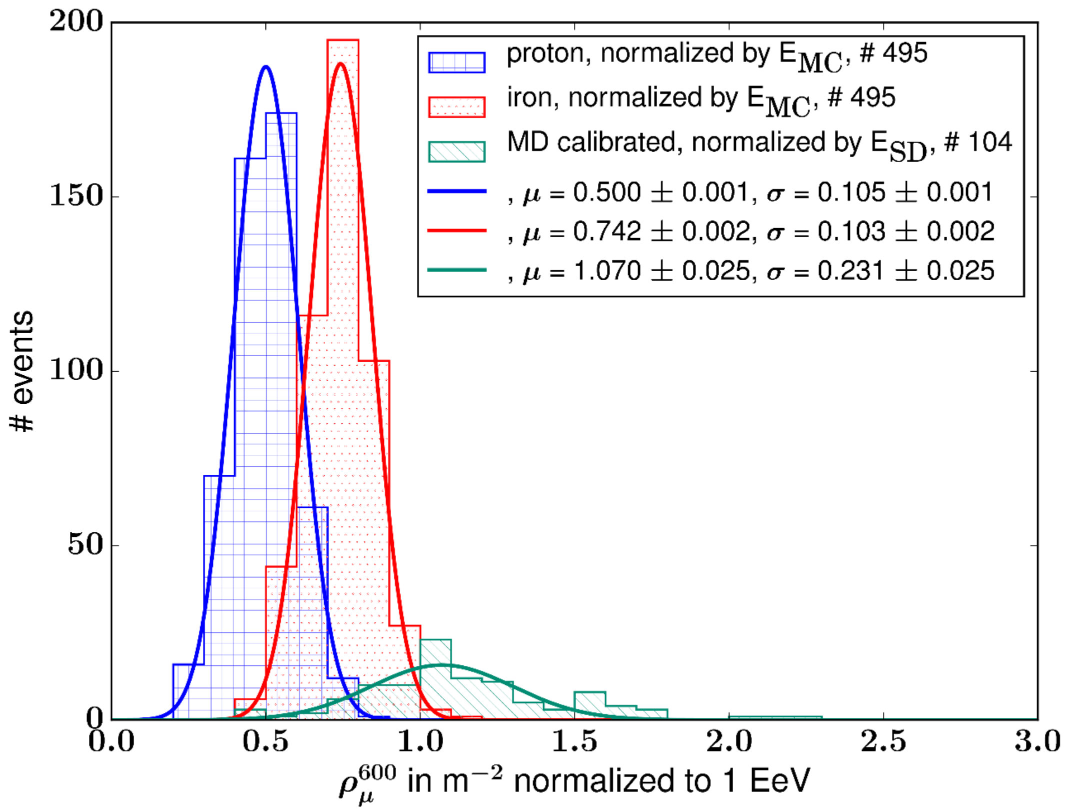
Muon density measured with AMIGA: 44 – 110 % larger in data

Shift predictions by 61% for comparison with data



Discrepancy between hadronic models and measurements confirmed