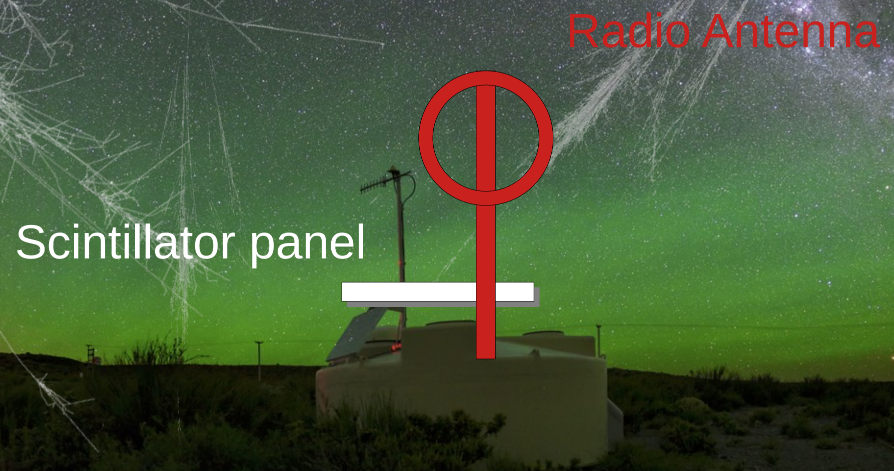
Performance of the AugerPrime Radio Detector

Felix Schlüter

Goal:
Mass sensitivity at highest energies!

Solution:
Electron / muon separation with Surface Detector



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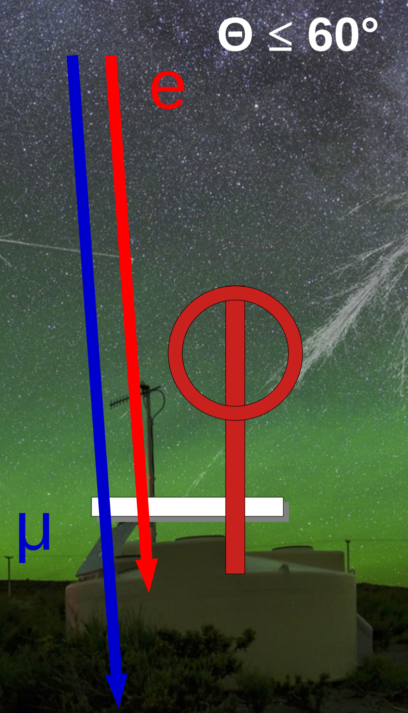


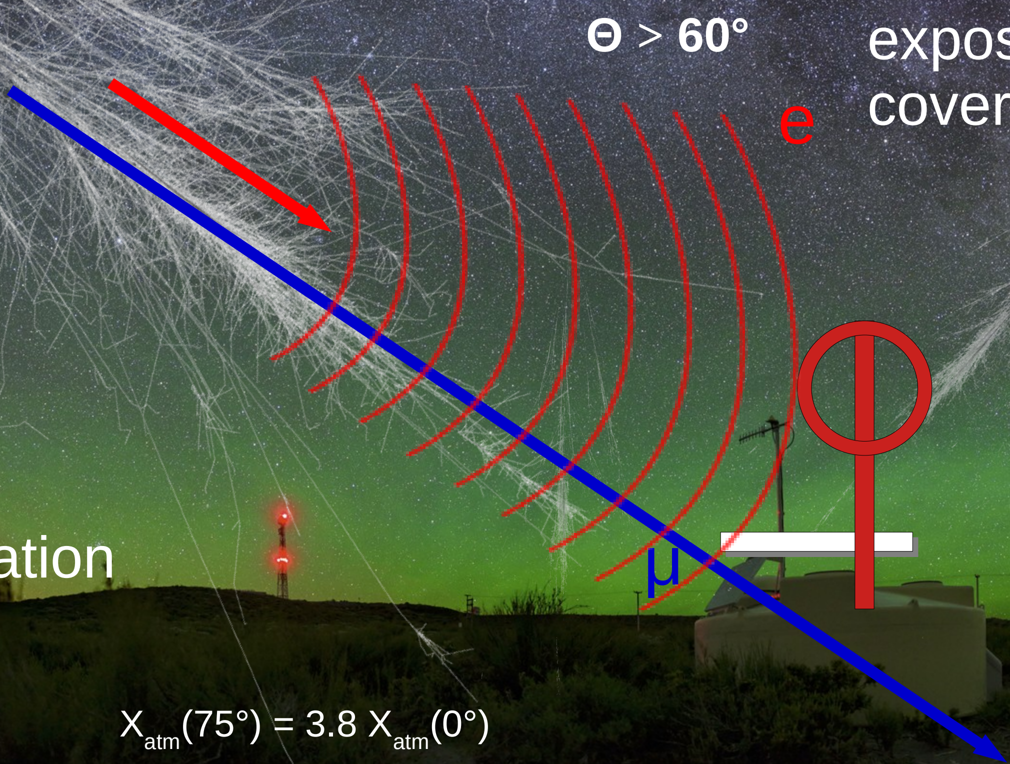
Performance of the AugerPrime Radio Detector

Felix Schlüter

Radio Detector:
Increase mass-sensitive exposure + extends sky coverage

Goal:
Mass sensitivity at highest energies!

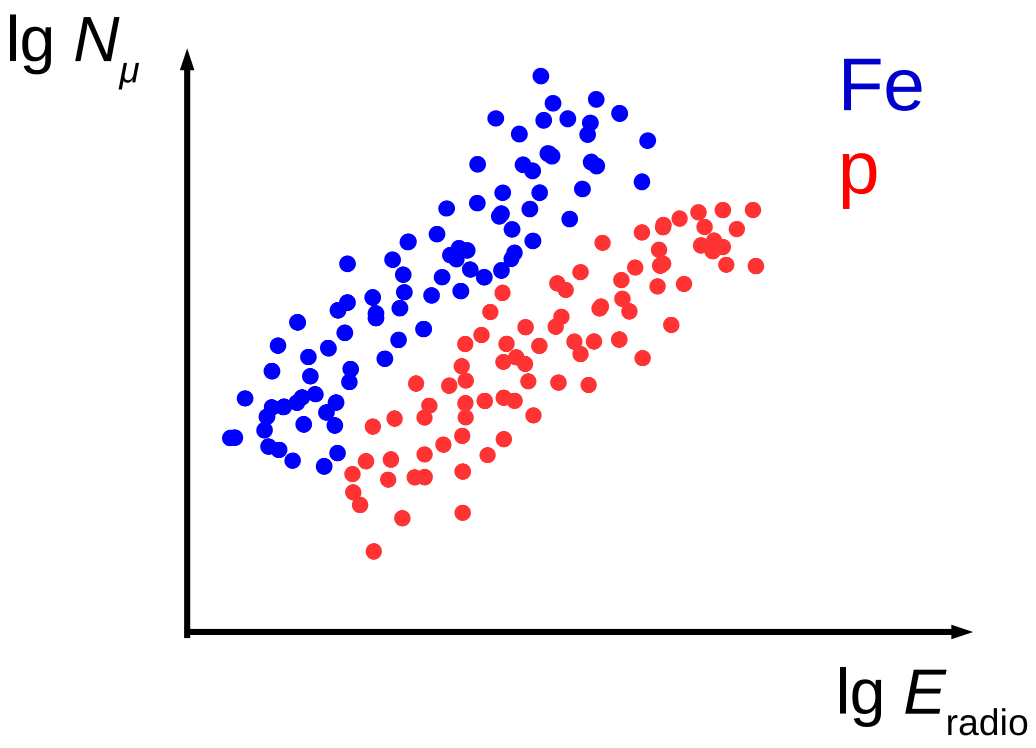
Solution:
Electron / muon separation with Surface Detector



Mass sensitivity from μ – e separation

A: mass number

WCD:



Heitler-Matthews model:

1) $N_{\mu,A} \approx A^{0.1} N_{\mu,p}$

2) $N_\mu \sim E^{0.9}$

3) $E_{radio} \sim N_{e,A} \approx N_{e,p}$

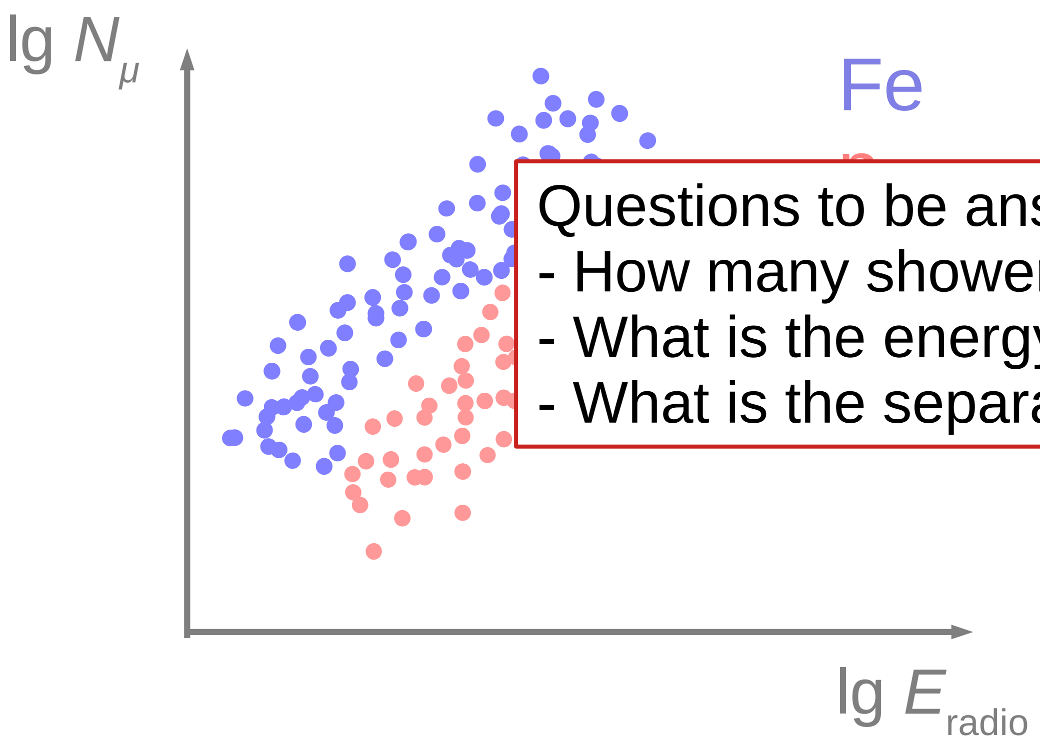
- Independent and unbiased energy
- Good energy resolution

Concept already tested with WCD + FD (low statistics!)

Mass sensitivity from μ – e separation

A: mass number

WCD:



Questions to be answered:
- How many showers will we detect?
- What is the energy resolution?
- What is the separation power?

Heitler-Matthews model:

$A^{0.1}\,N_{\mu,p}$

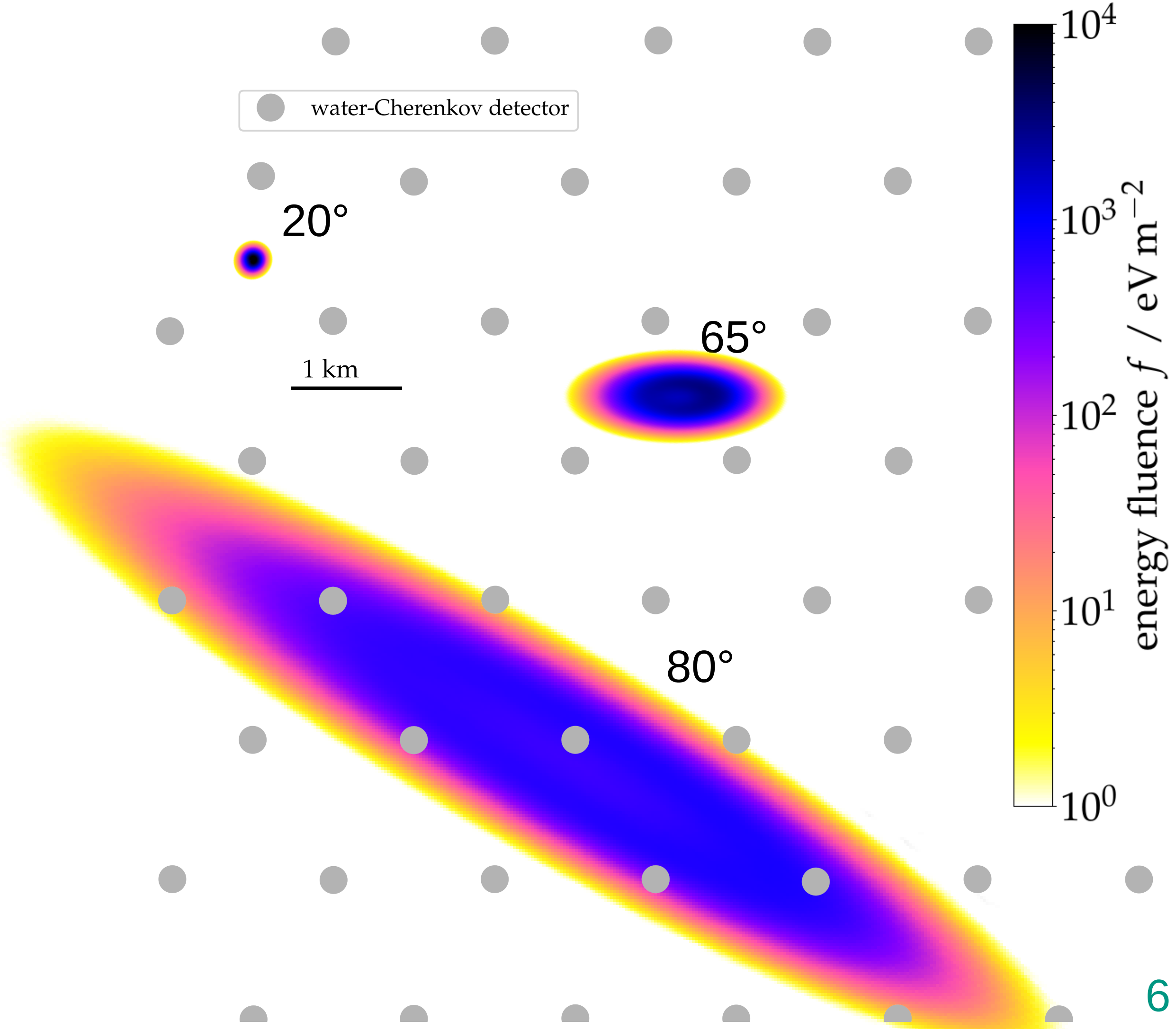
$N_{e,A} \approx N_{e,p}$

- Independent and unbiased energy
- Good energy resolution

Concept already tested with WCD + FD (low statistics!)

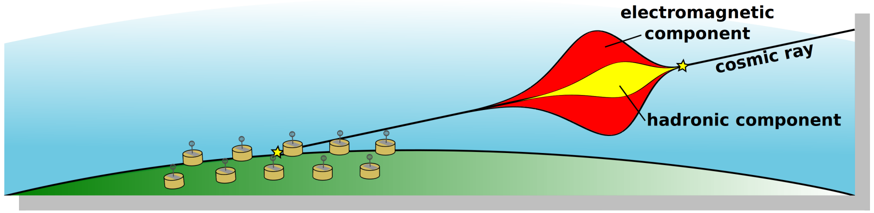
Inclined radio showers

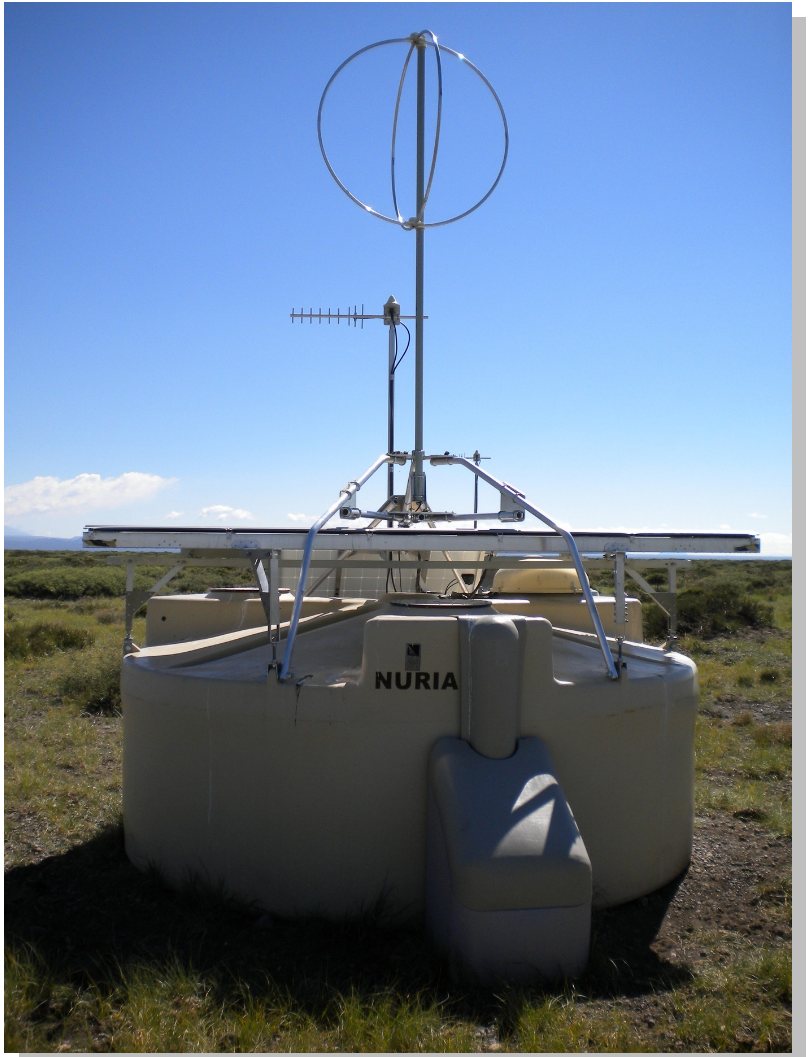
- Detectable with sparse arrays
  - Open window to highest energies
- Gained a lot of attention the last few years



AugerPrime Radio Detector

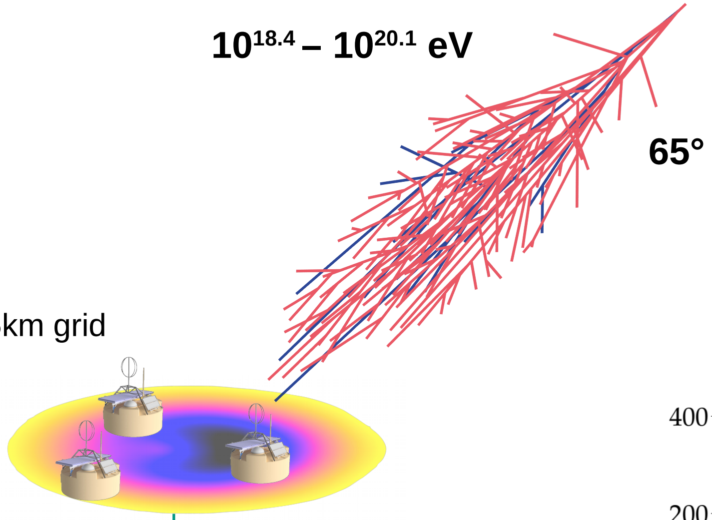
- Sensitive to radio emission in 30 – 80 MHz
- Fully integrated in SD ➞ triggered by WCD
- Engineering array with 10 antennas since November ‘21
  - Record first air shower signals and ambient background
  - Currently in mass production





End-to-end simulation

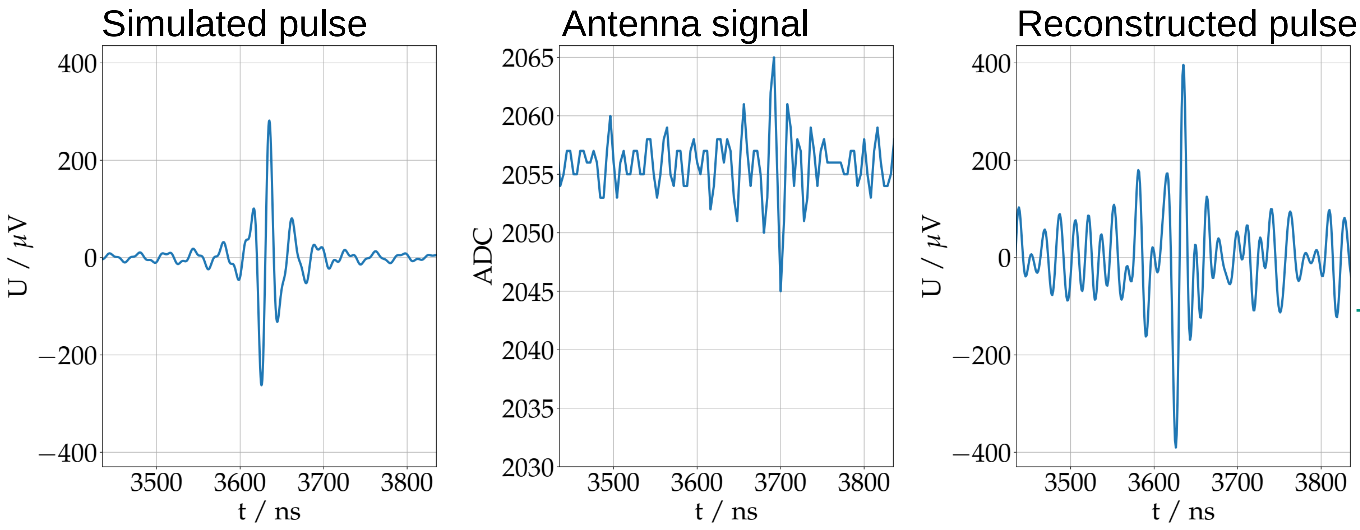
8000 CoREAS showers



Simulate instrumental response

(directional response, analog gain, digitization, …..)

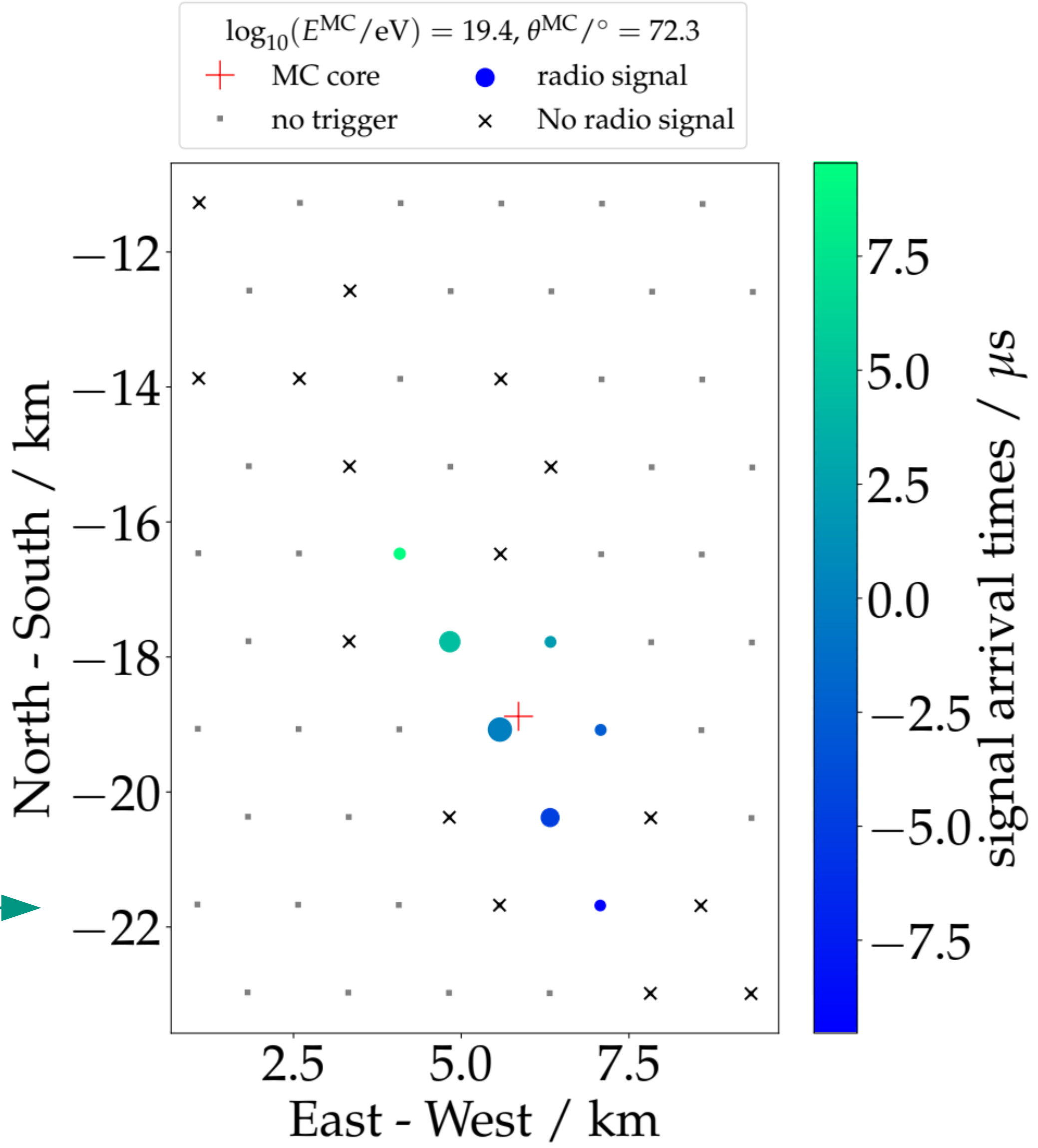
- Including uncertainties (σ_A = 5%)
- Measured noise



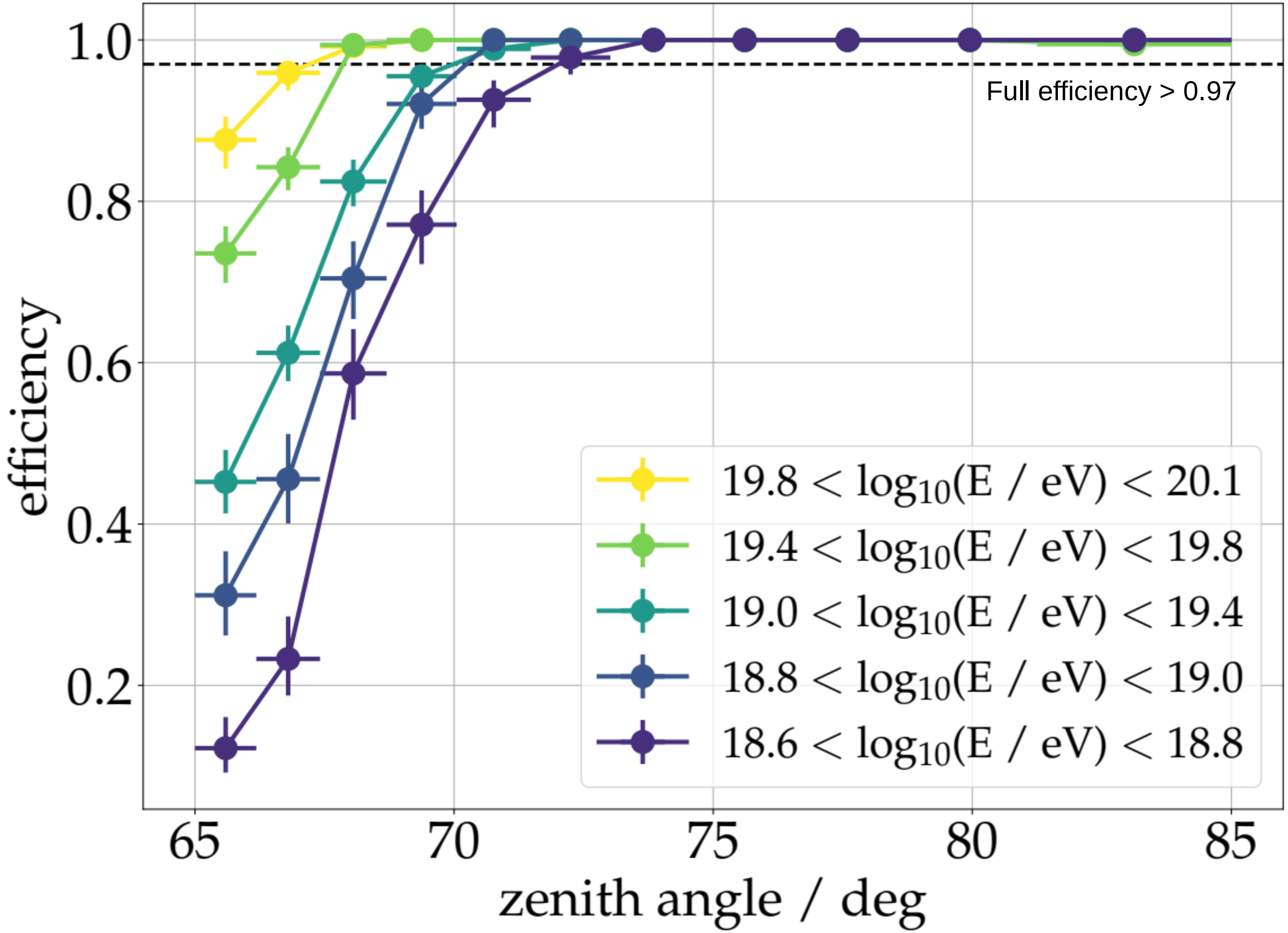
Full event reconstruction

For each station determine:

- Signal-to-noise ratio SNR
- Signal arrival time
  - Arrival direction
- Signal energy fluence (power)
  - Shower energy
- Etc.



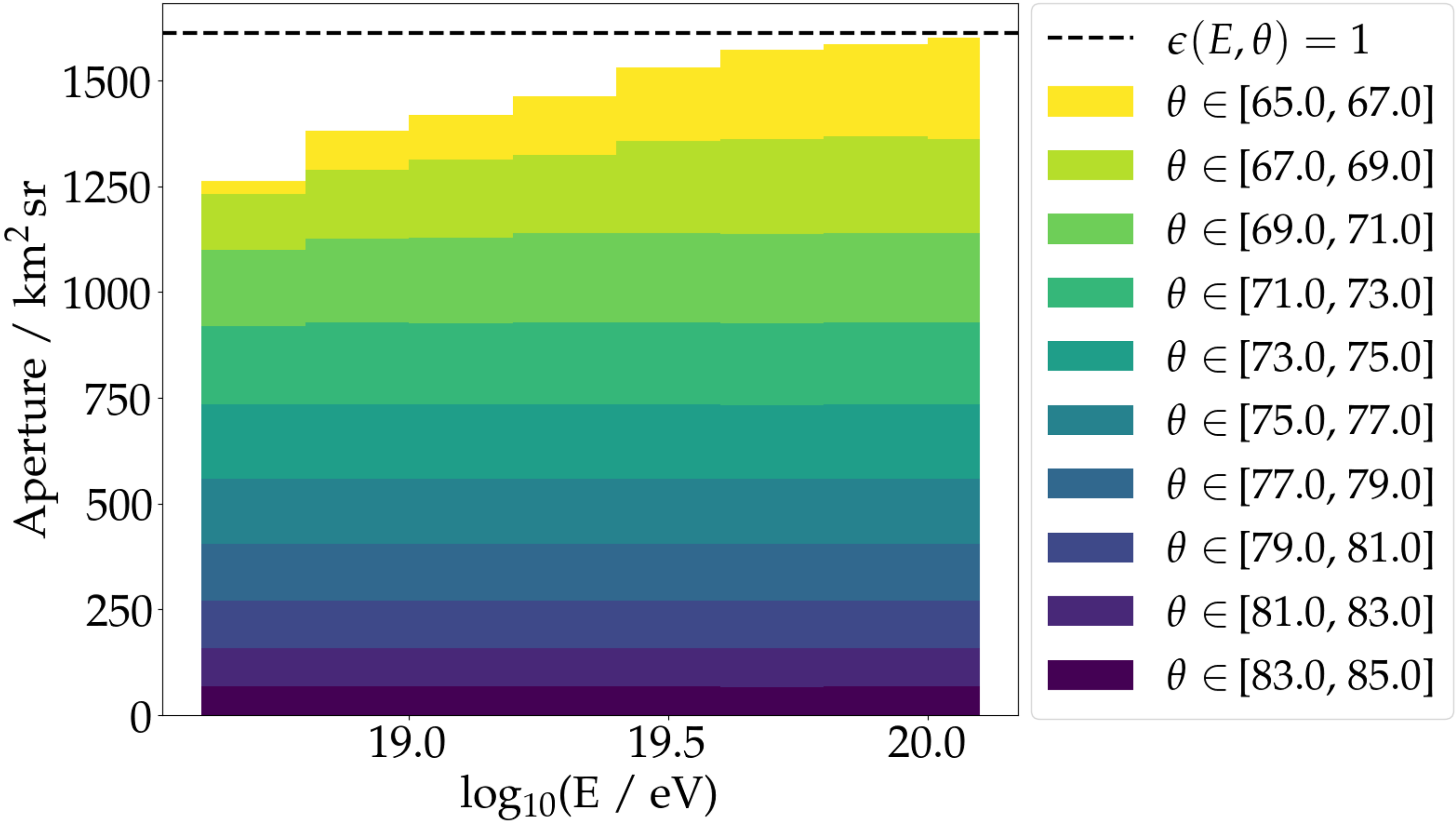
Detection efficiency



Detection condition:
min. 3 signal stations

➔ Full efficiency:
$\theta \gtrsim 70°$ &
$\lg(E\ /\ \mathrm{eV}) > 18.8$

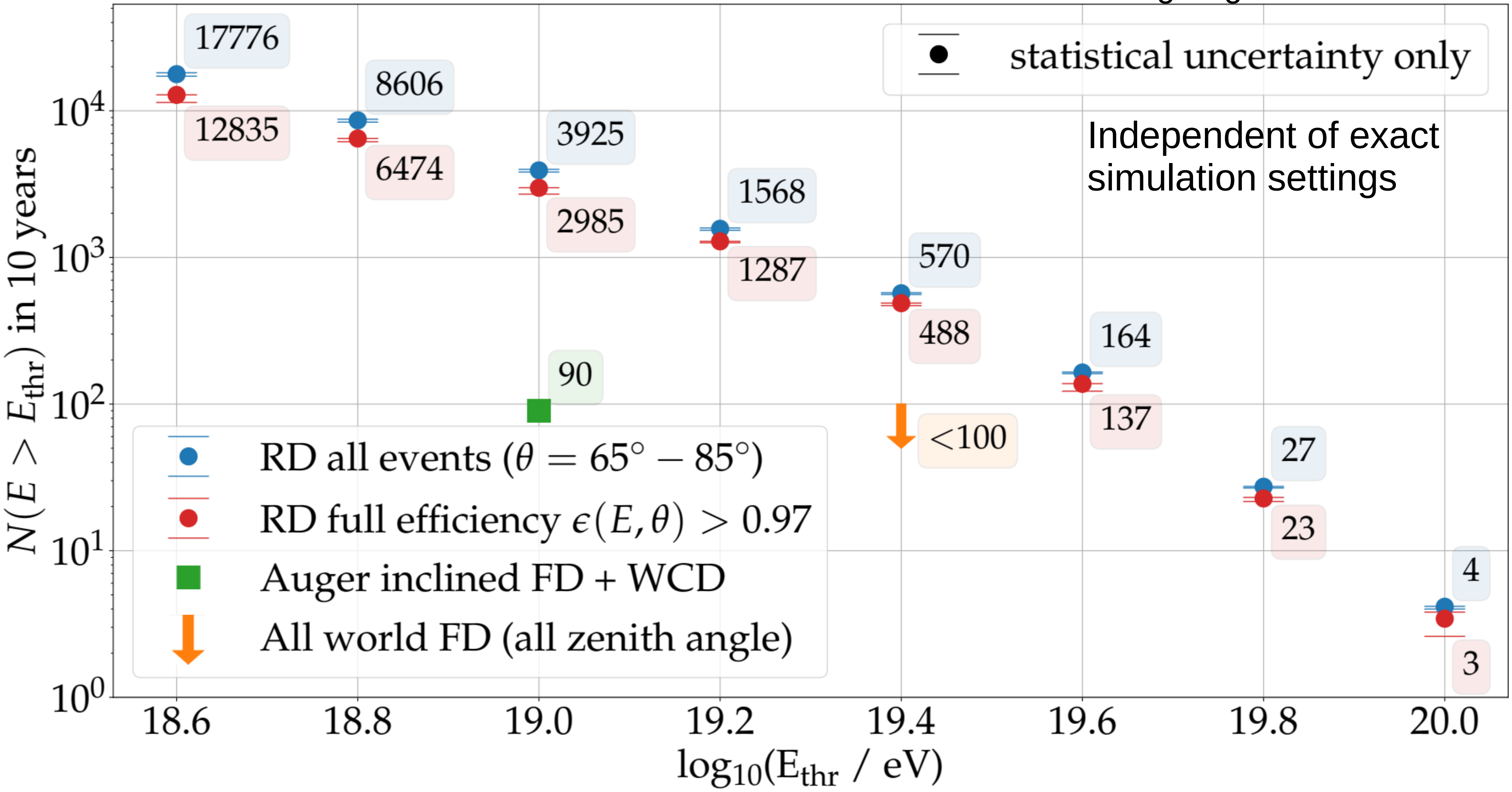
Aperture for 3000 km^2 array



- Decreases with θ
- At highest energies approaches ideal aperture
- ~25% of aperture with vertical air showers (0 – 60°)

Event statistics for 10-year exposure

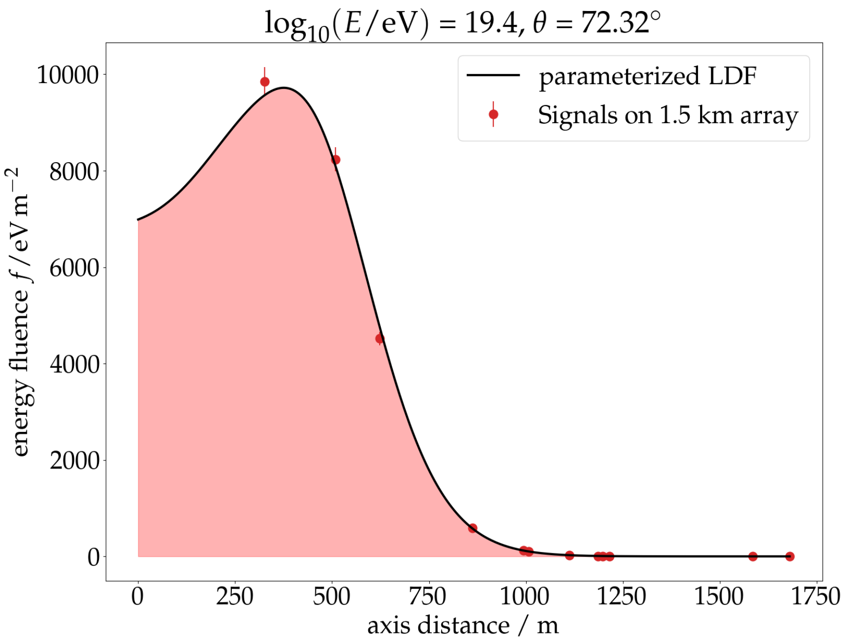
Using Auger-measured flux

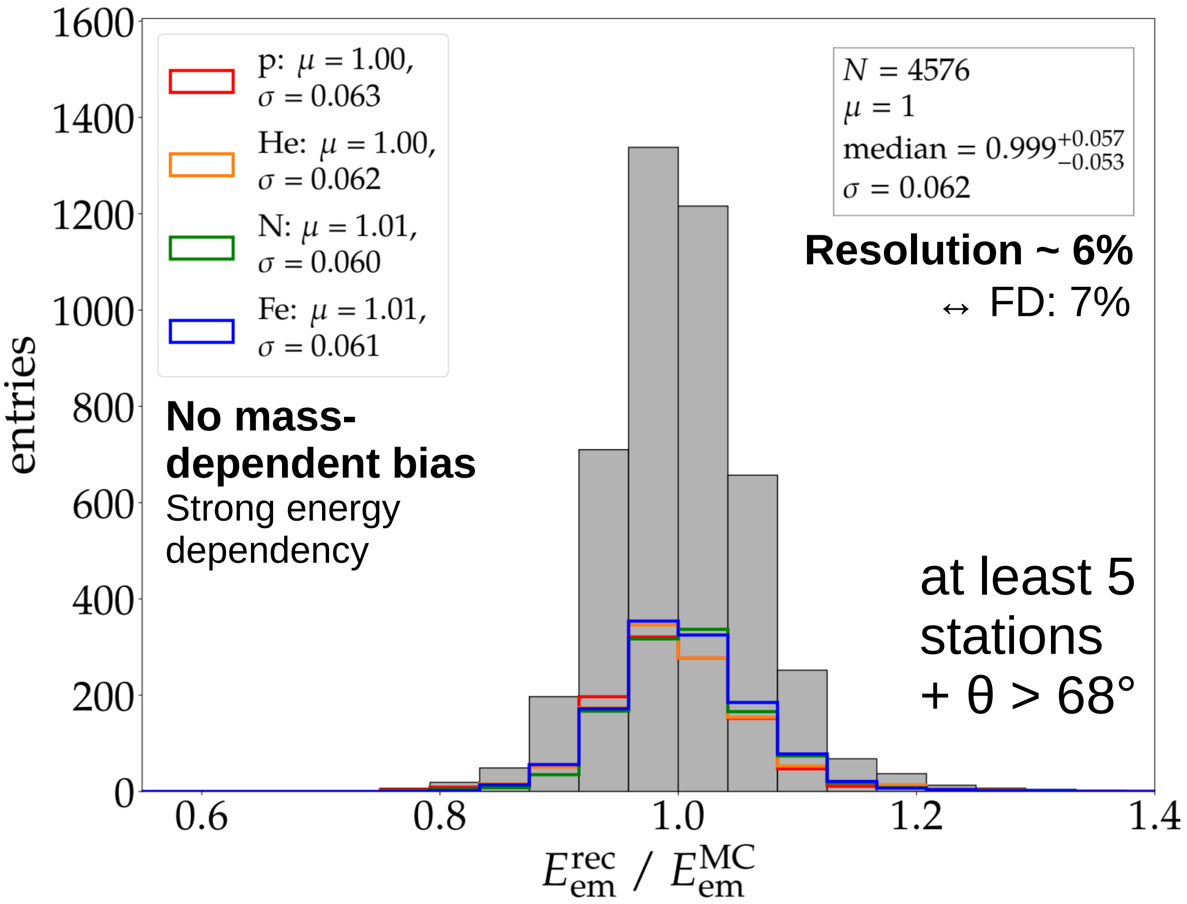


Independent of exact simulation settings

Shower reconstruction

Developed dedicated signal model!





No mass-dependent bias
Strong energy dependency

Resolution ~ 6%
↔ FD: 7%

at least 5 stations + θ > 68°

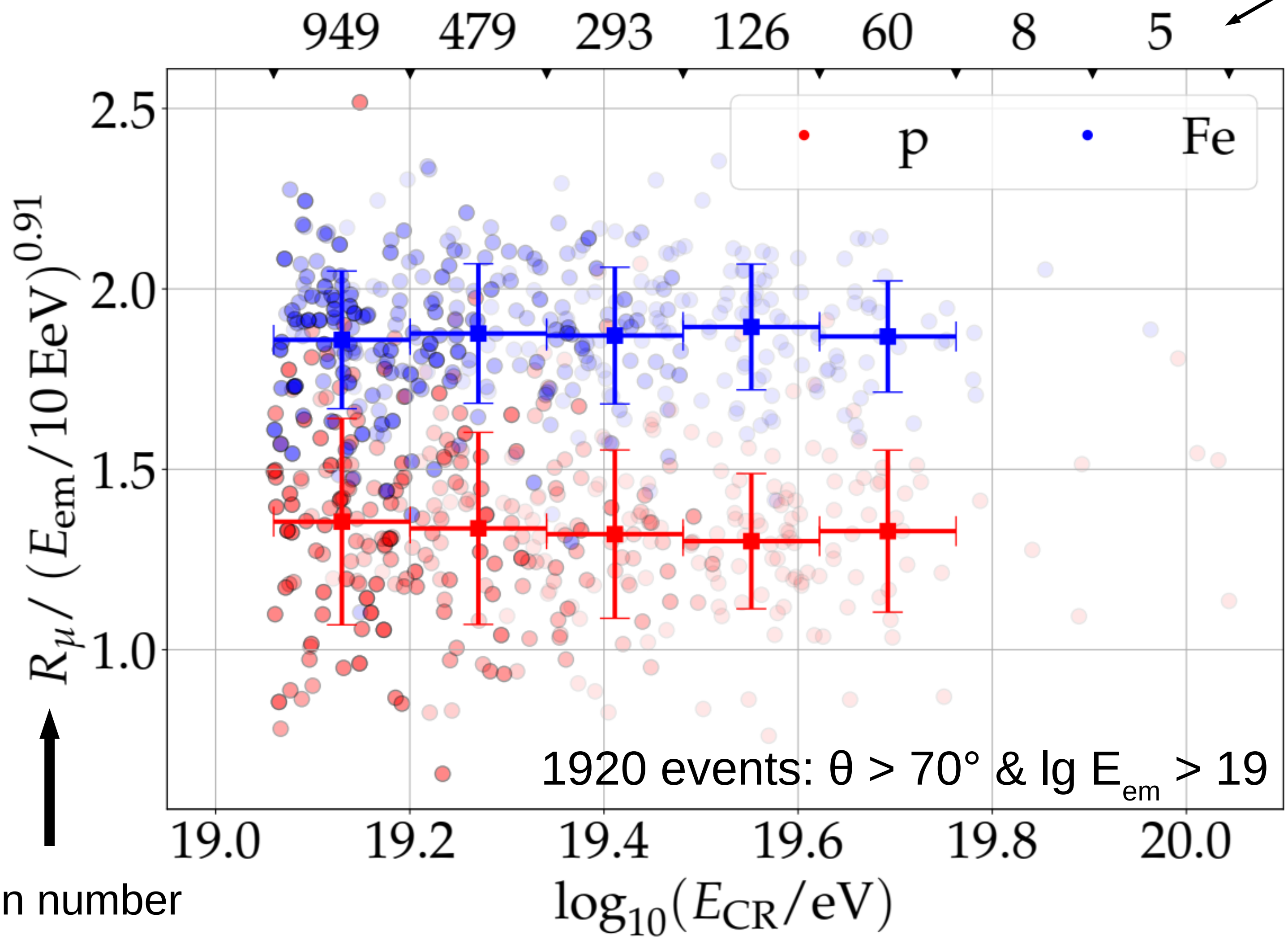
Prepared for submission to JCAP

Signal model and event reconstruction for the radio detection of inclined air showers

F. Schlüter[a,b,1] and T. Huege[a,c]

Event-by-event mass discrimination

50/50 p-Fe composition
with 10-year RD spectrum



Muon number

Figure of Merit:

$$\mathrm{FOM} = \frac{|\langle r_p \rangle - \langle r_{Fe} \rangle|}{\sqrt{\sigma_{r_p}^2 + \sigma_{r_{Fe}}^2}}$$

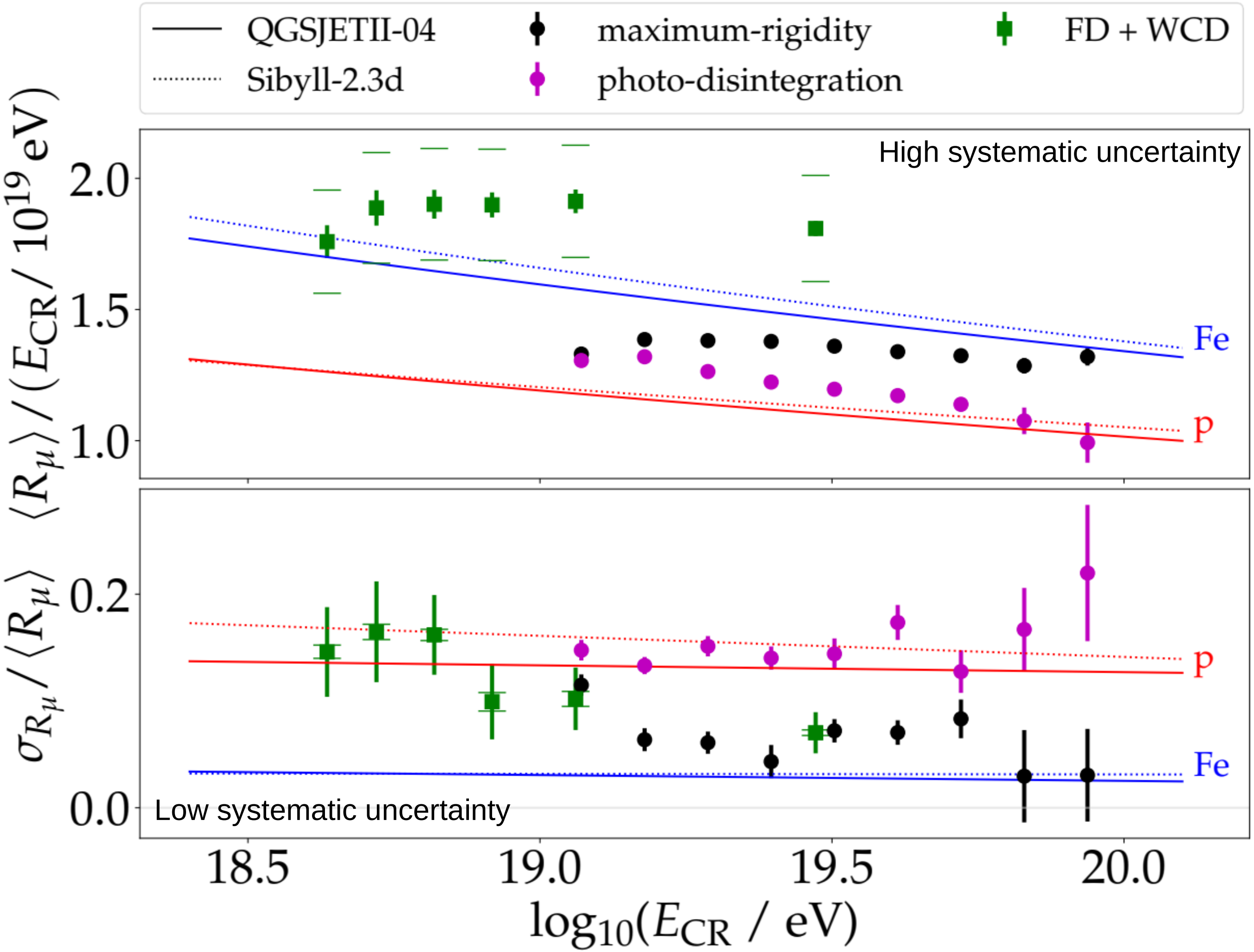
FOM = 1.61 ± 0.04

Equal to X_{max} with perfect resolution!

Goal for the Upgrade: 1.5

Muons in inclined air showers

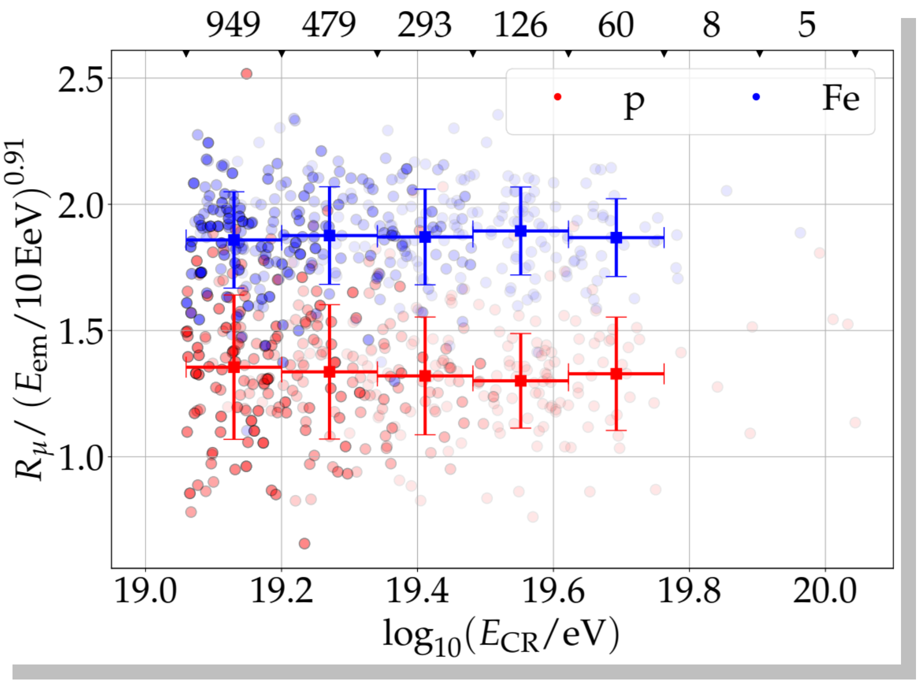
- Higher energies and larger statistics
- Muon deficit
- Discrimination potential with fluctuation



Summary & Conclusion

RD measures cosmic ray at ultra-high energies and high inclinations with excellent mass sensitivity

- Improve statistics by more than factor 10
- Energy resolution ~ 6%
- Proton-iron discrimination FOM = 1.6
- Measurement of mass composition

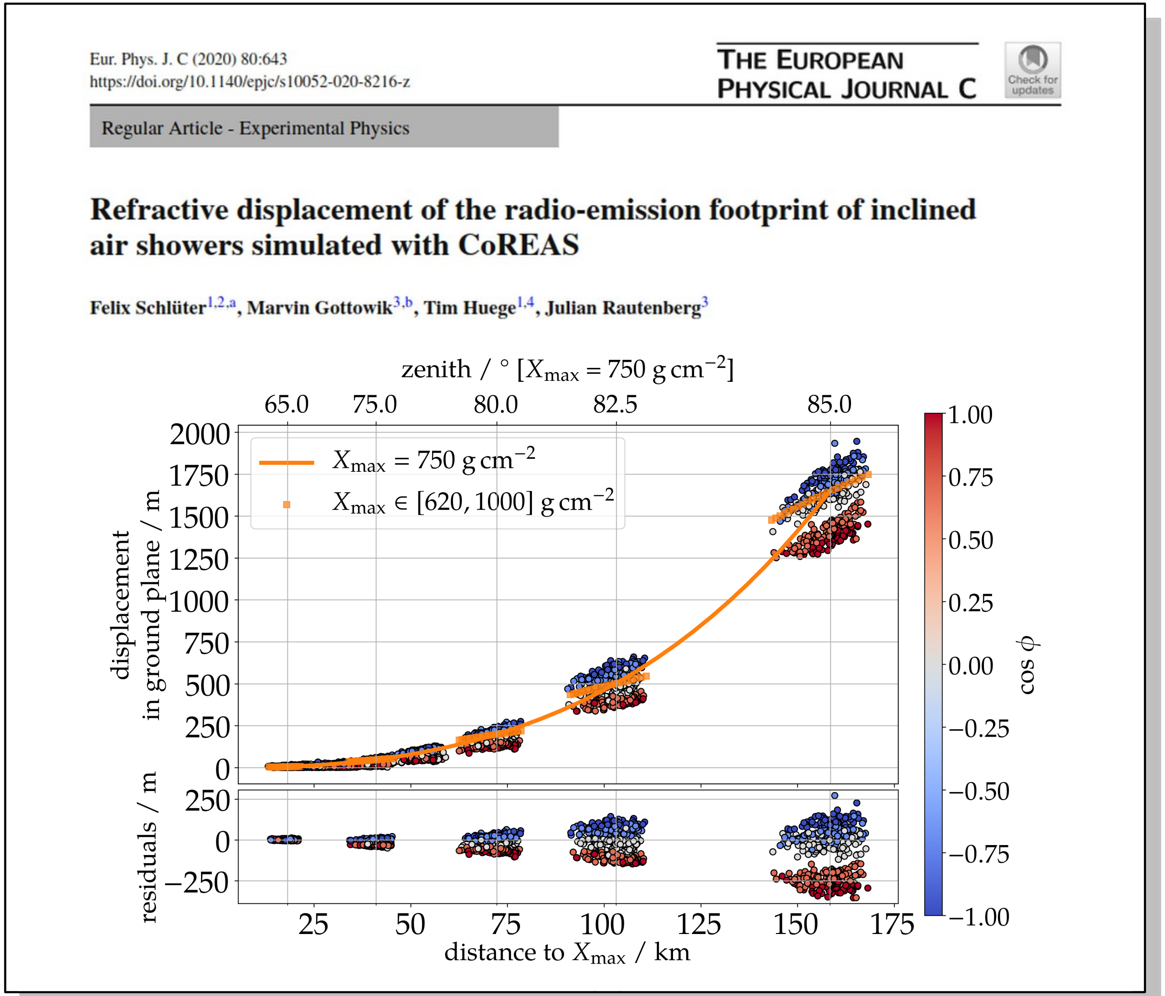


We are ready for data!

Backup

- Geometry
- Fudge factor
- Systematics

Refractive displacement of the radio emission



Eur. Phys. J. C (2020) 80:643
https://doi.org/10.1140/epjc/s10052-020-8216-z

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

Refractive displacement of the radio-emission footprint of inclined air showers simulated with CoREAS

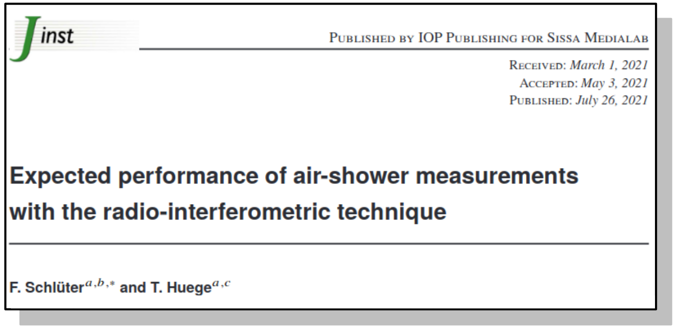
Felix Schlüter[1,2,a], Marvin Gottowik[3,b], Tim Huege[1,4], Julian Rautenberg[3]

Crucial for:

- Development of precise signal modeling
- Interpretation of hybrid data

Details in Backup!

Outlook

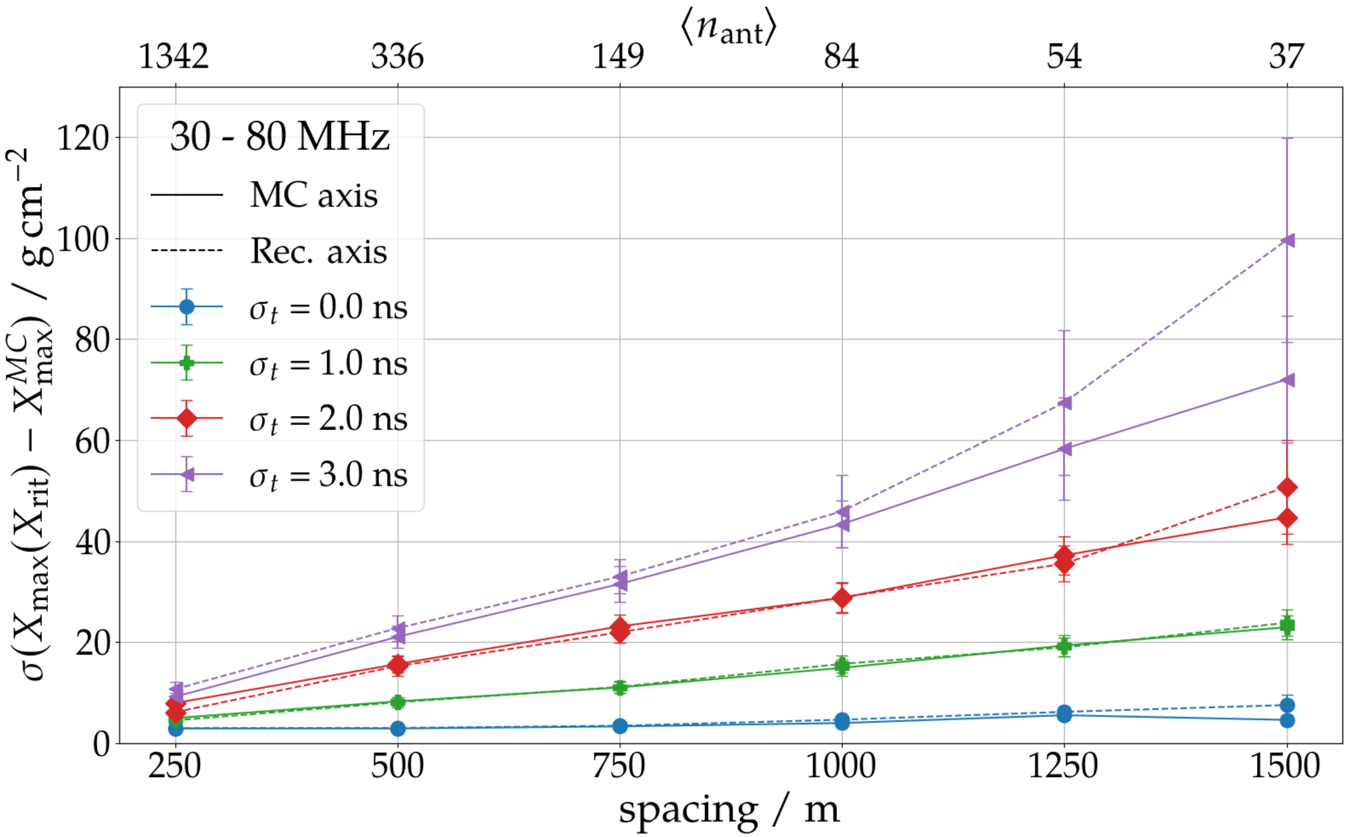

JINST
Published by IOP Publishing for Sissa Medialab
Received: March 1, 2021
Accepted: May 3, 2021
Published: July 26, 2021

Expected performance of air-shower measurements with the radio-interferometric technique

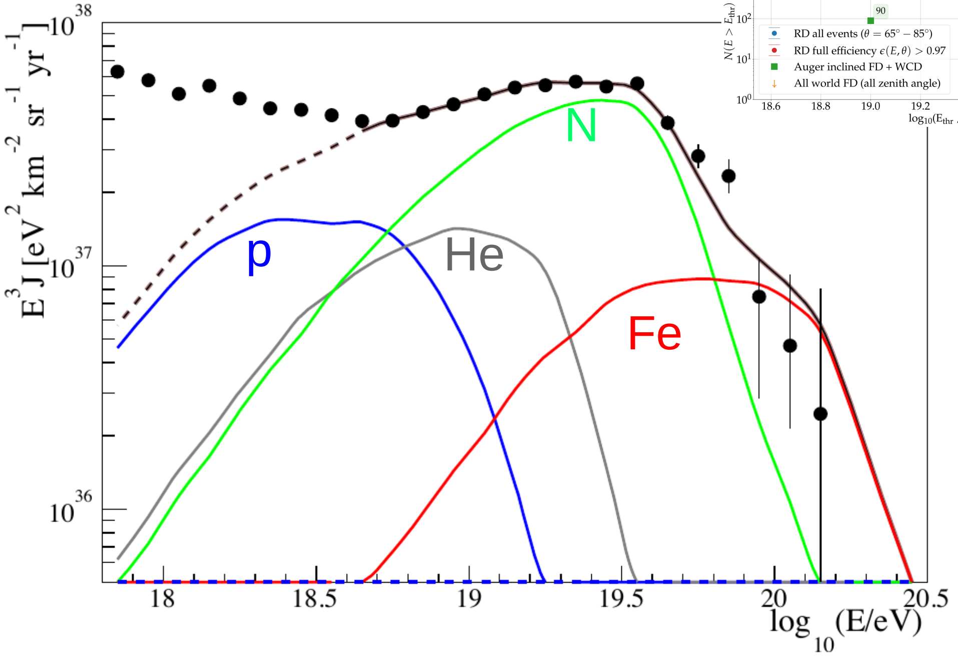
F. Schlüter[a,b,*] and T. Huege[a,c]

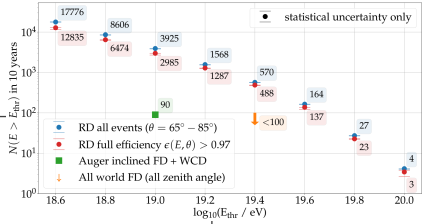
- Time resolution of Auger insufficient with current setup
- Huge potential:
  - in combination with muon detector
  - radio standalone

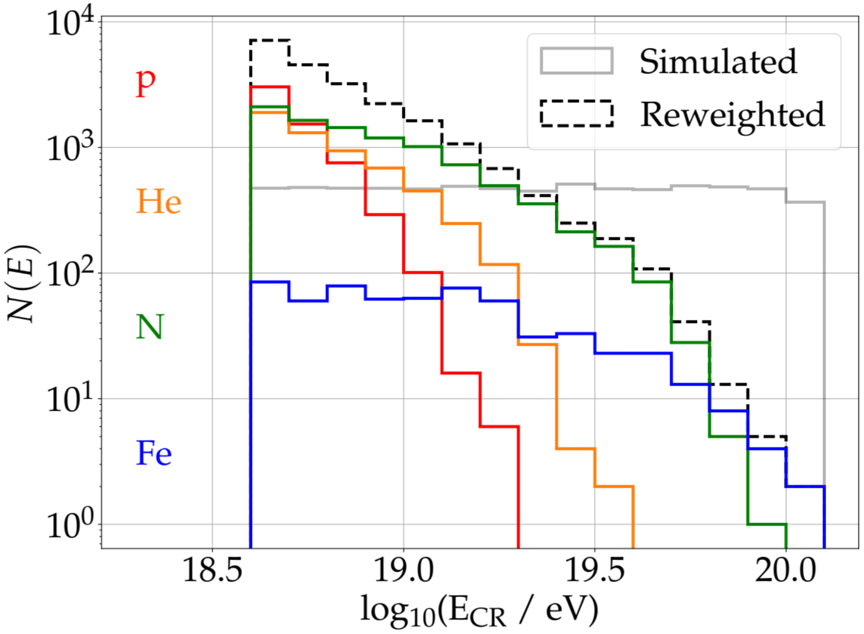
Interferometric reconstruction of the depth of the shower maximum



Re-sampling simulations



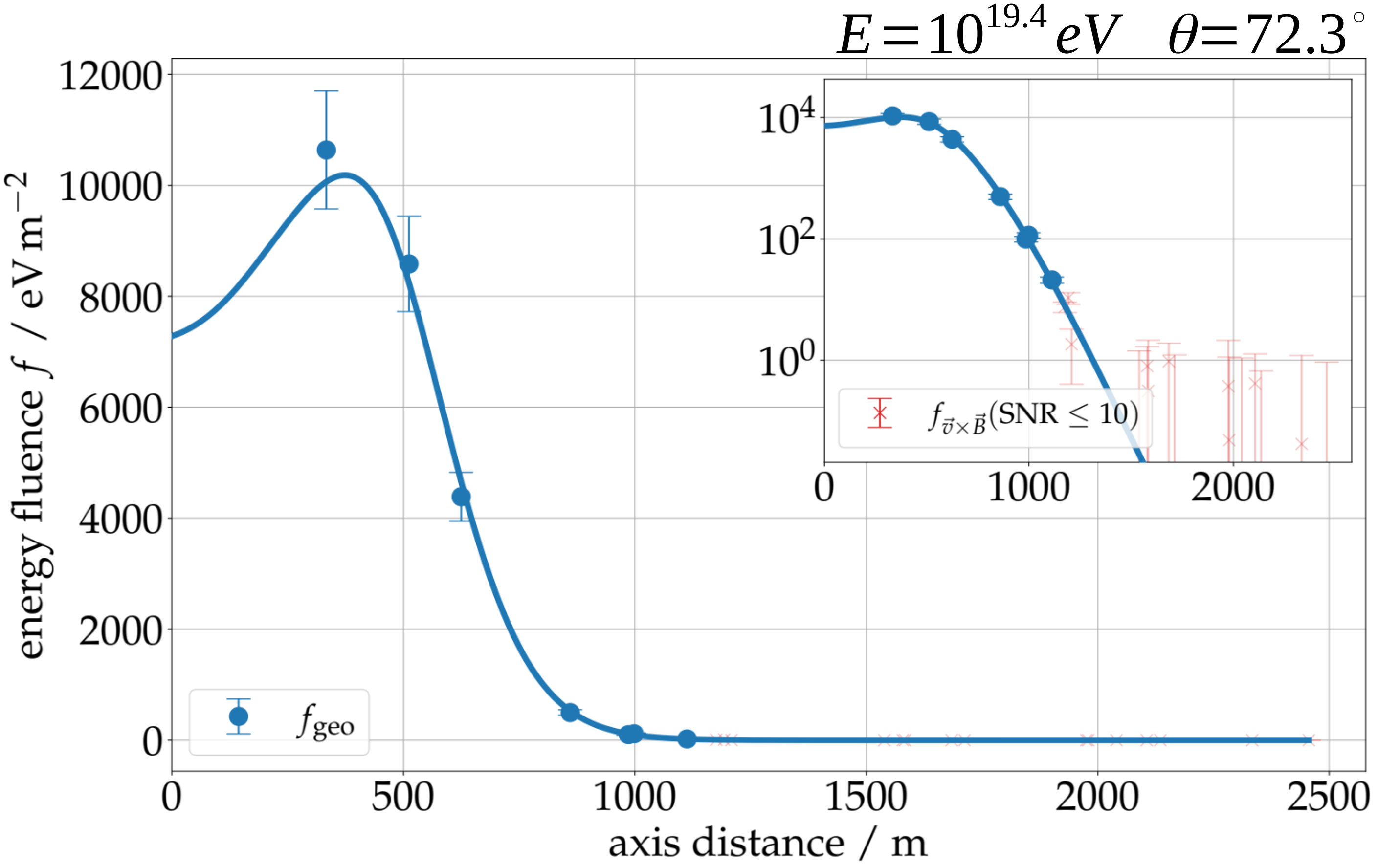




Lateral signal distribution

Newly developed LDF model*

- 2 parameter + core coordinates
- Derive start values from WCD
  (use radio rec. arrival direction)
- Integral yields energy estimator



*

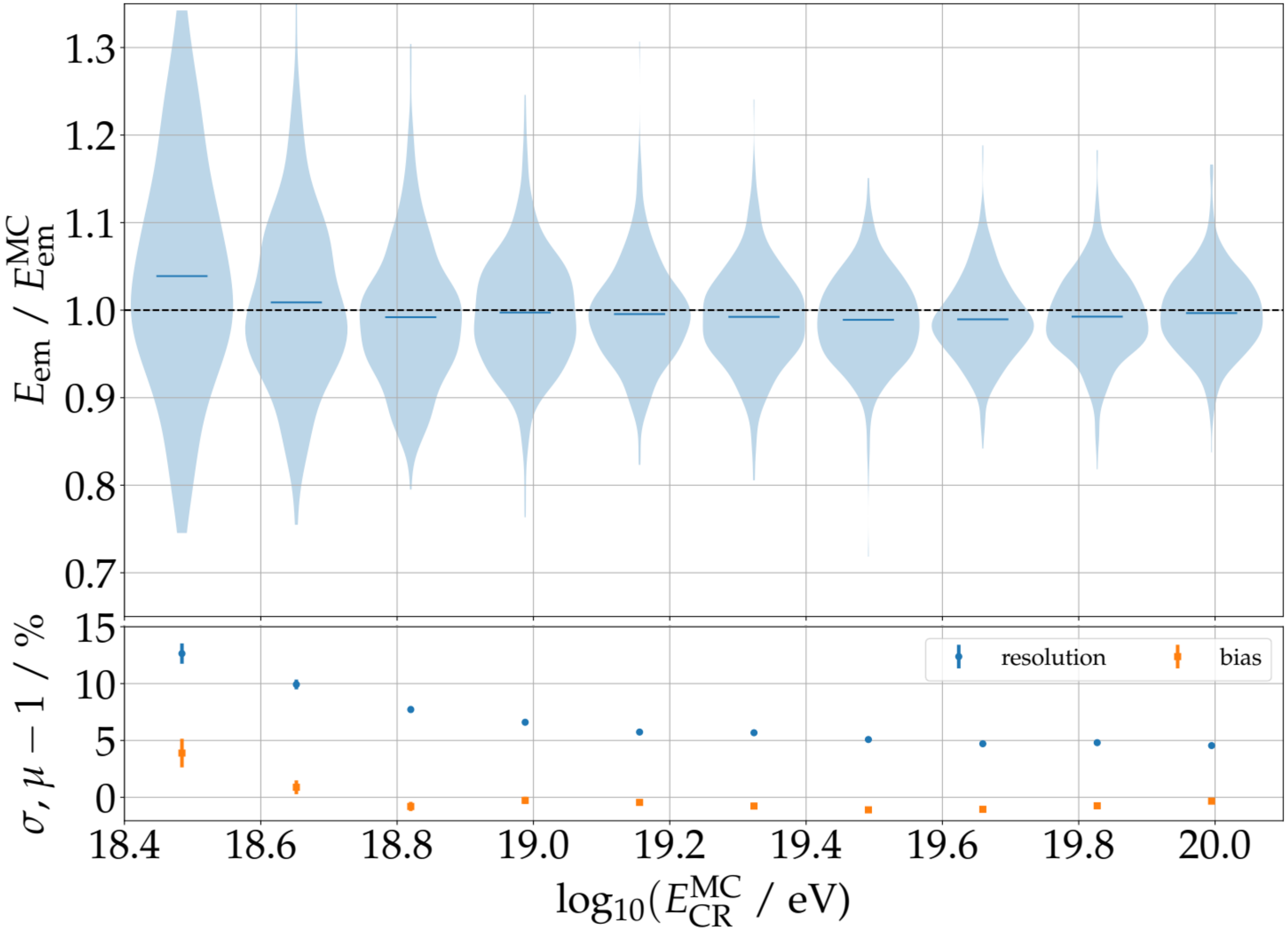
Signal model and event reconstruction for the radio detection of inclined air showers using sparse antenna arrays
Felix Schlüter
3:25 PM - 3:45 PM

Shower reconstruction

Showers with at least 5 signal stations and θ > 68°

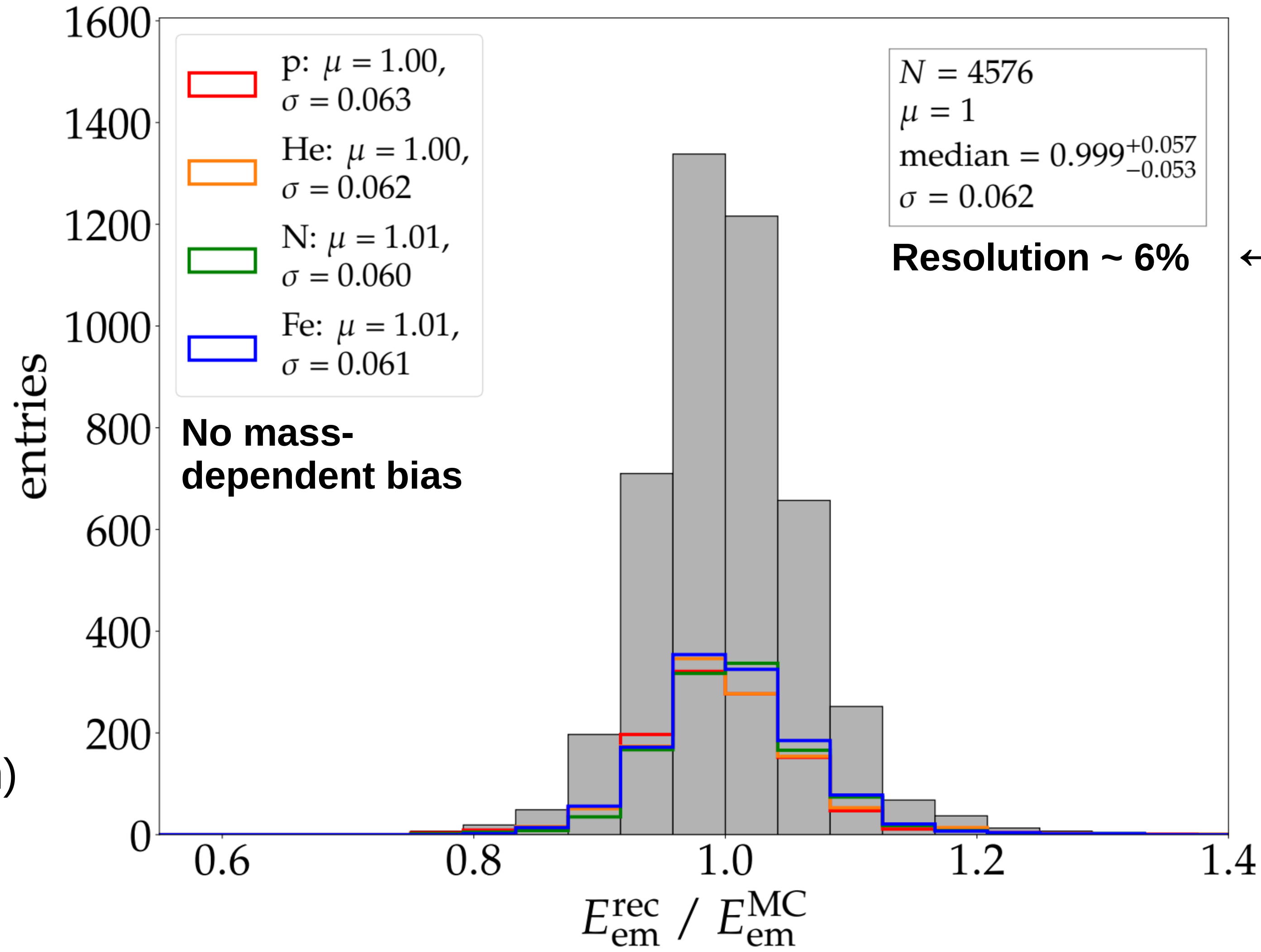
quality cuts: ~95% efficiency

Resolution improves with energy



Shower reconstruction

Resolution increases to 9% with 10% amplitude uncertainty

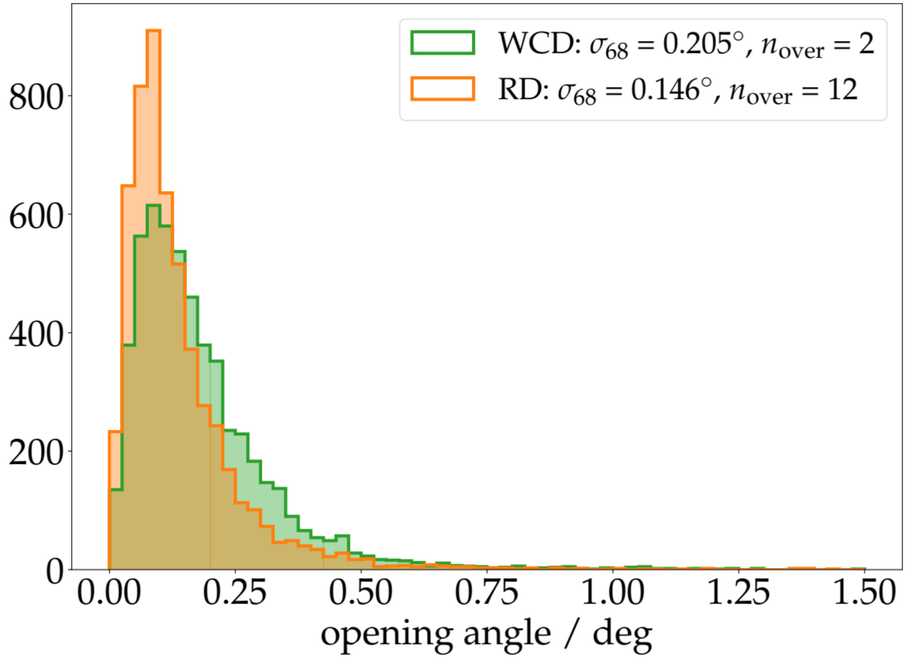


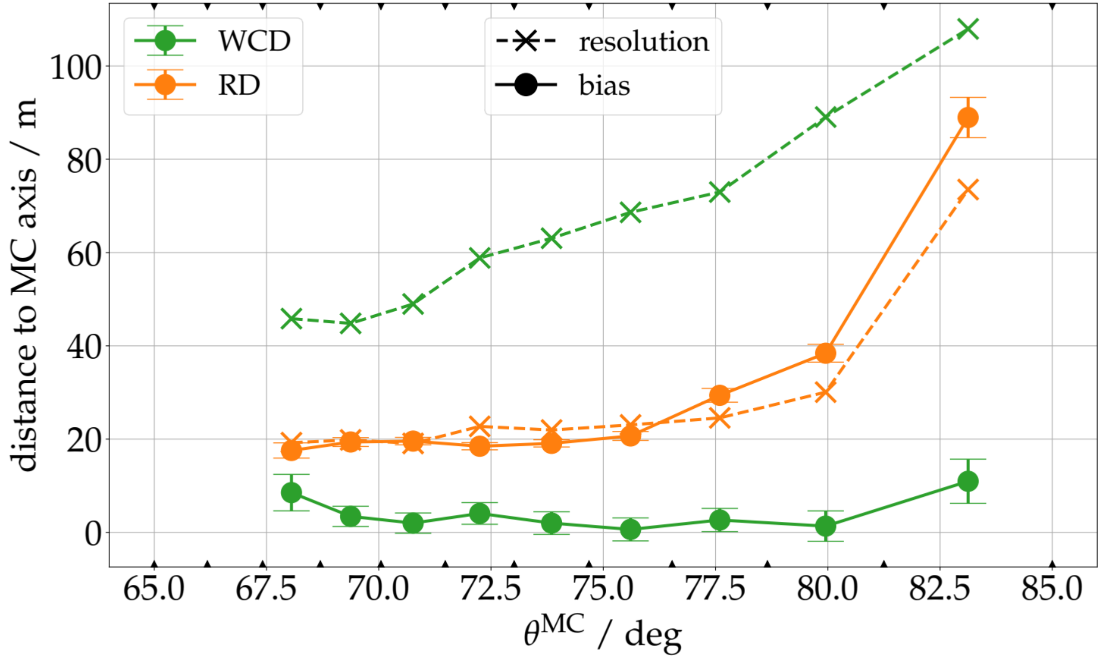
No mass-dependent bias

Resolution ~ 6% ↔ FD: 7%

Issue with the estimated resolution (use parameterization)

Geometry



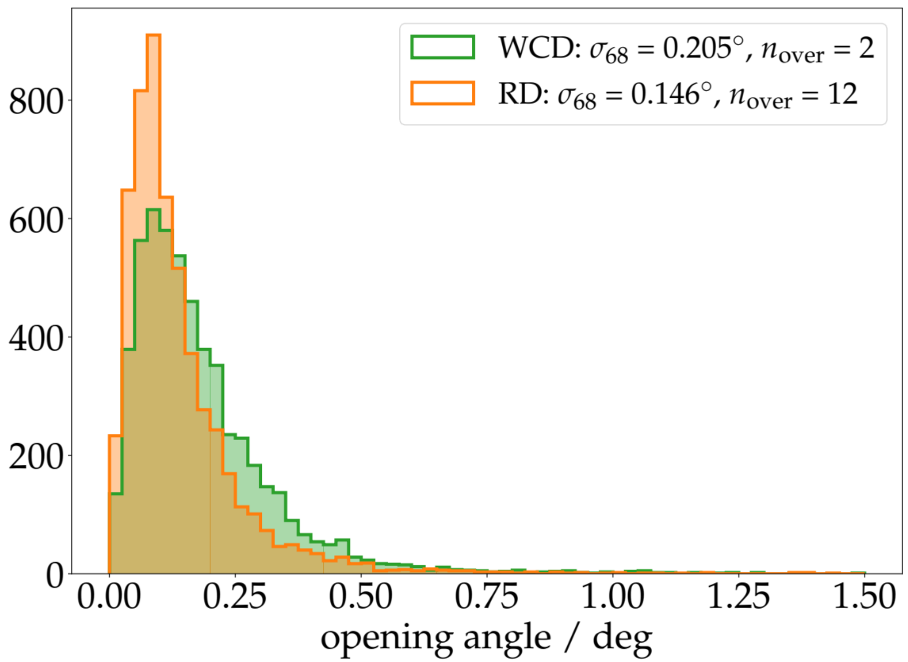


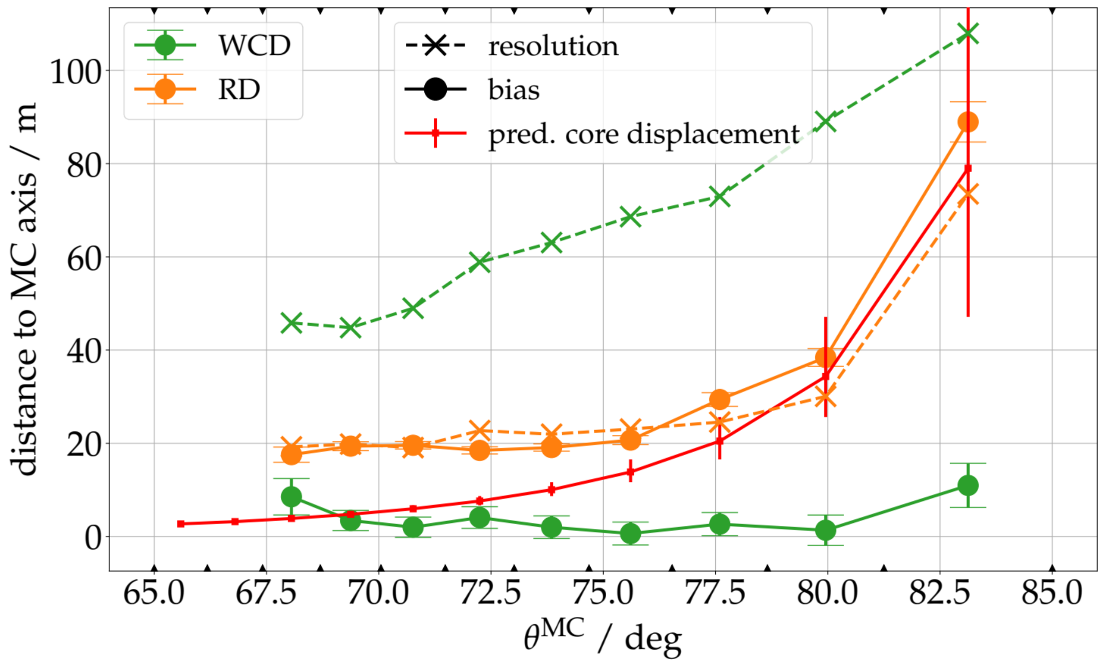
Spherical wavefront fit
4 signal stations

Fitted with LDF model
5 signal stations and θ > 68°

Geometry

FS et al., EPJC 80 (2020) 7, 643



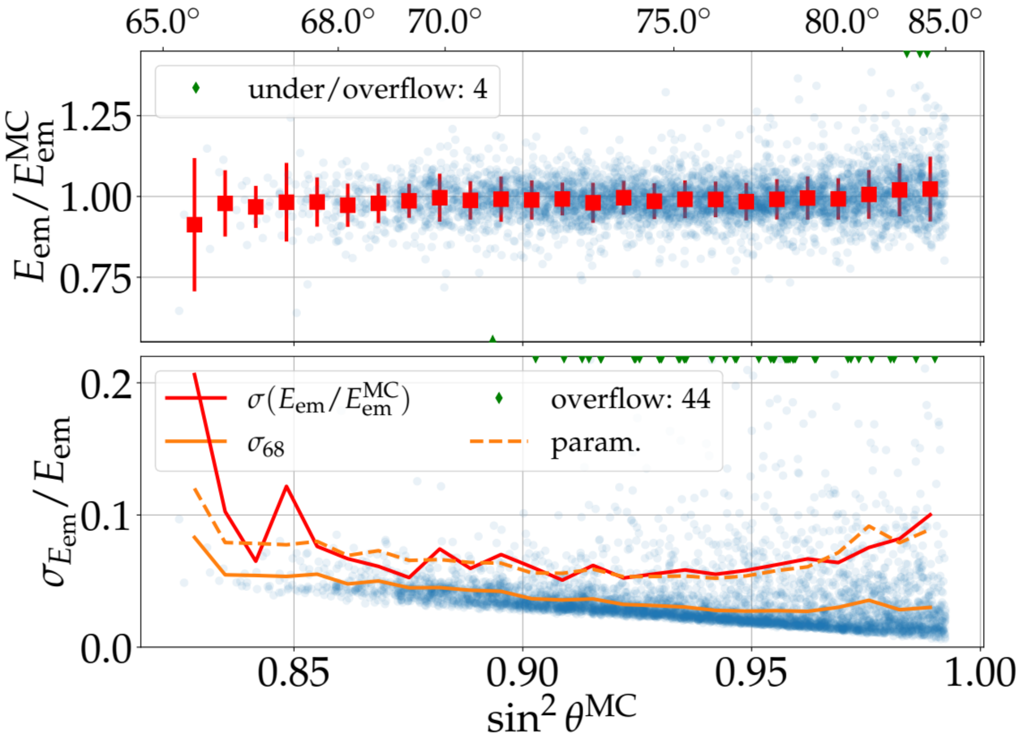


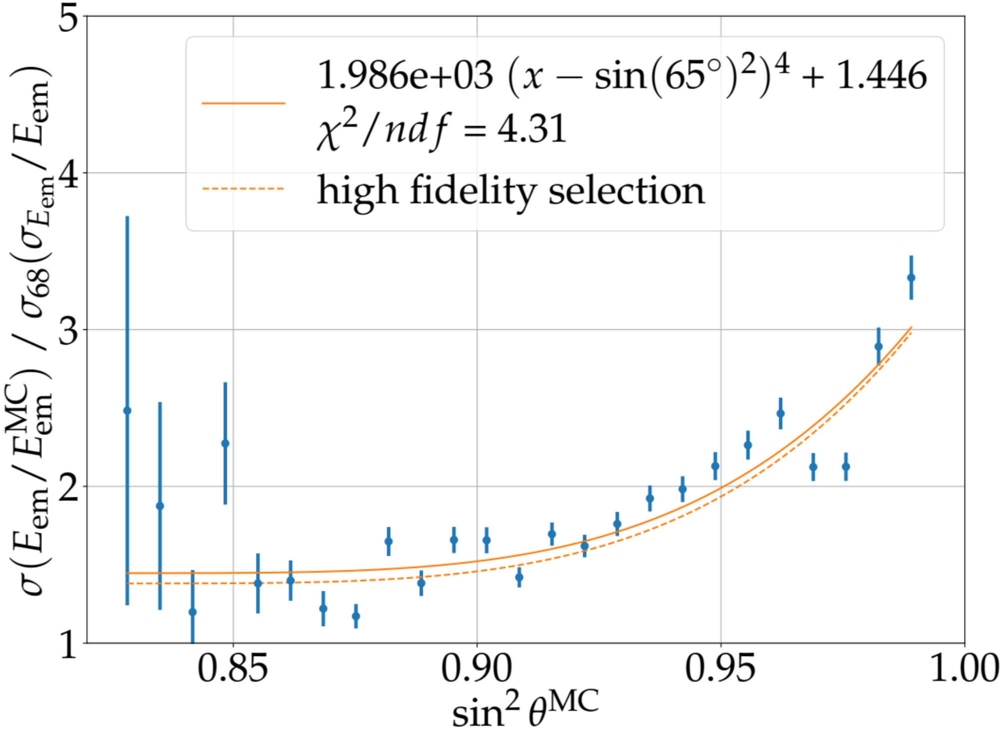
Spherical wavefront fit
4 signal stations

Fitted with LDF model
5 signal stations and θ > 68°

Uncertainty estimation

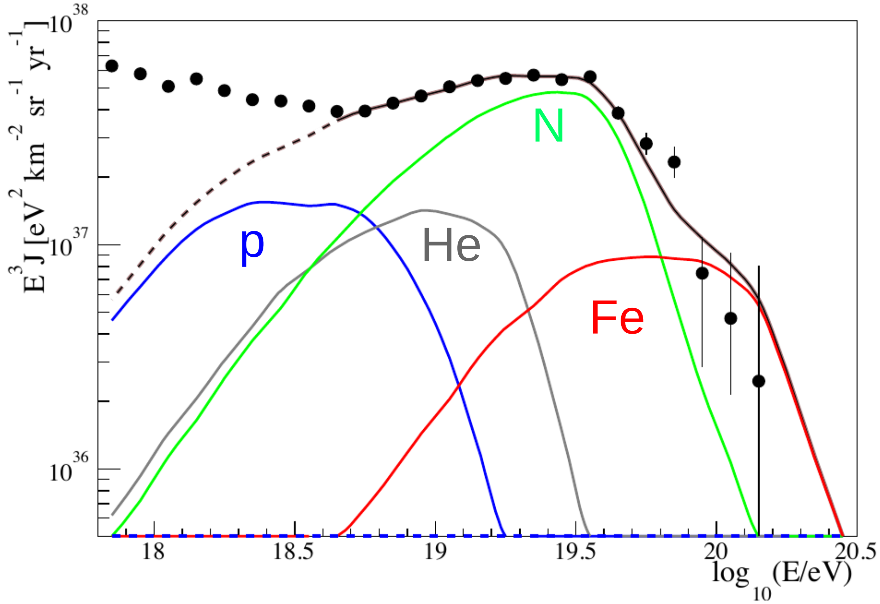
- Disagreement in resolution between MC-derivation and fit-derivation (uncertainty)





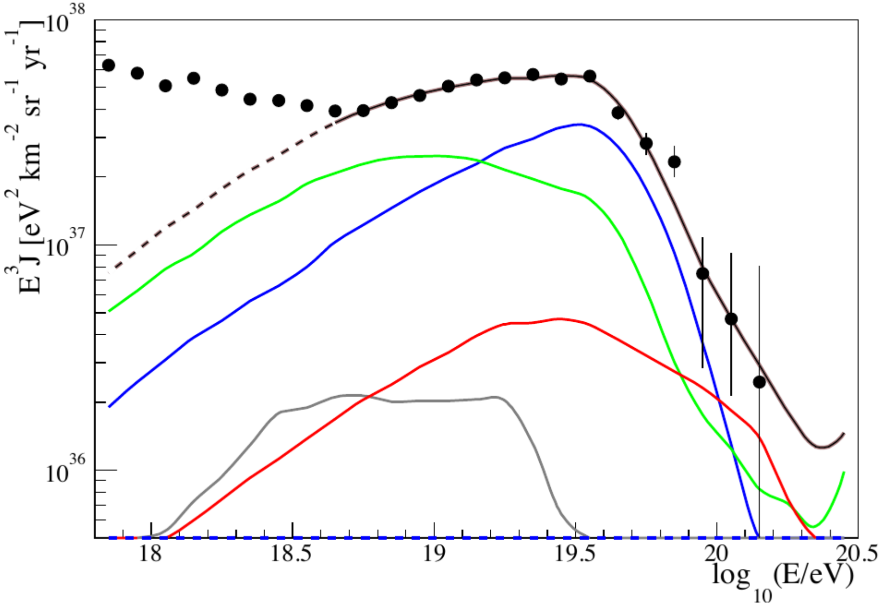
Mass composition scenarios

Maximum-rigidity scenario → trend to heavier composition



Rigidity dependent accelerator run out of power

Photo-disintegration scenario → light composition



Composition at Earth is dominated by photo-disintegration products

+ Fit to X_{max} data

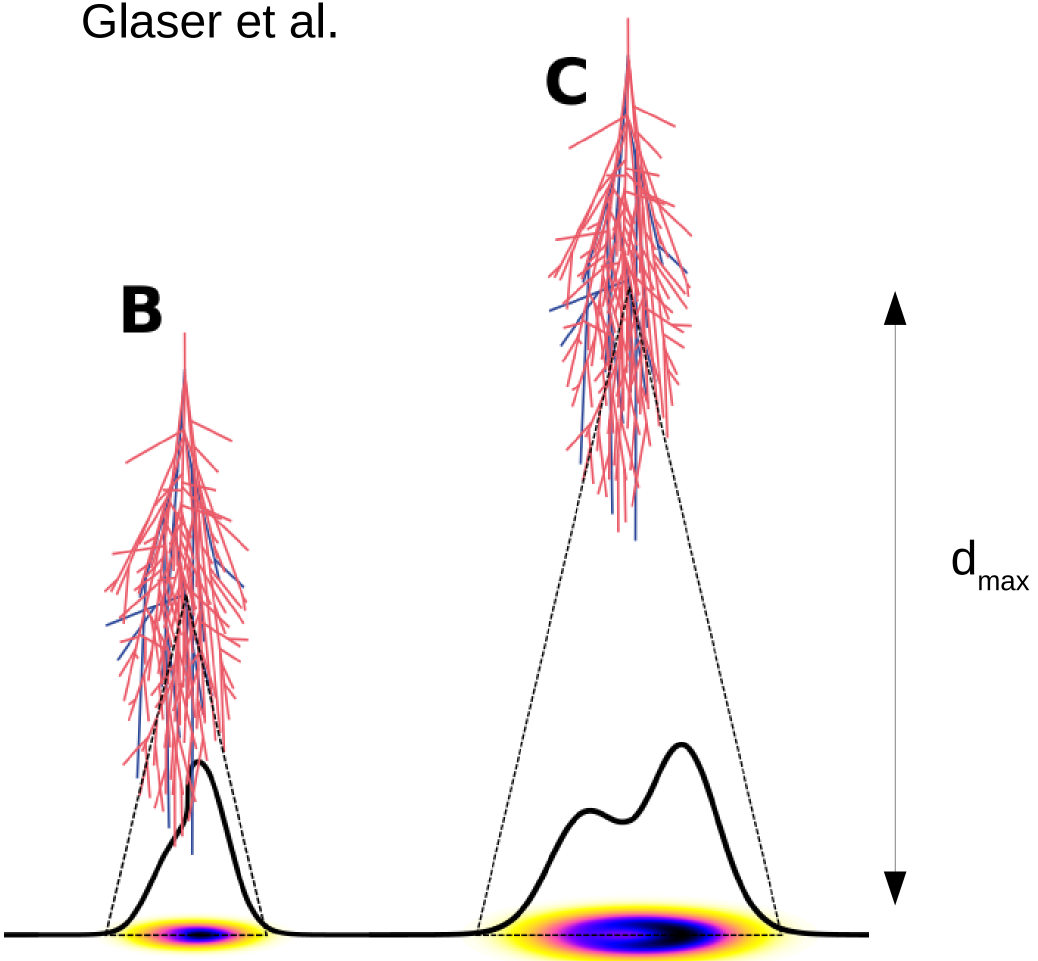
Reflects knowledge of ~2015

AugerPrime Design Report arXiv:1604.03637

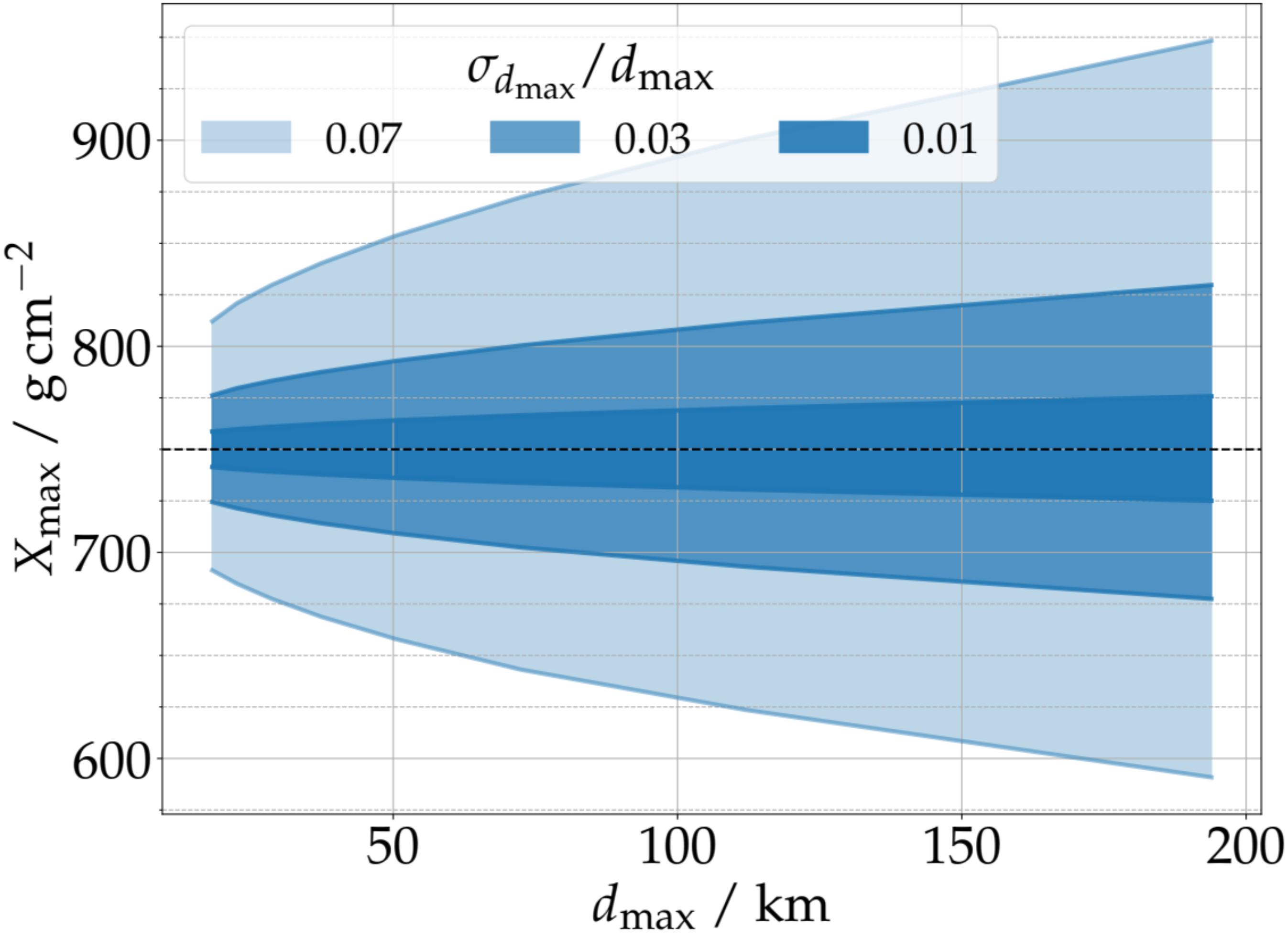
Forward beamed radio emission

- Radio sensitive to distance to Xmax

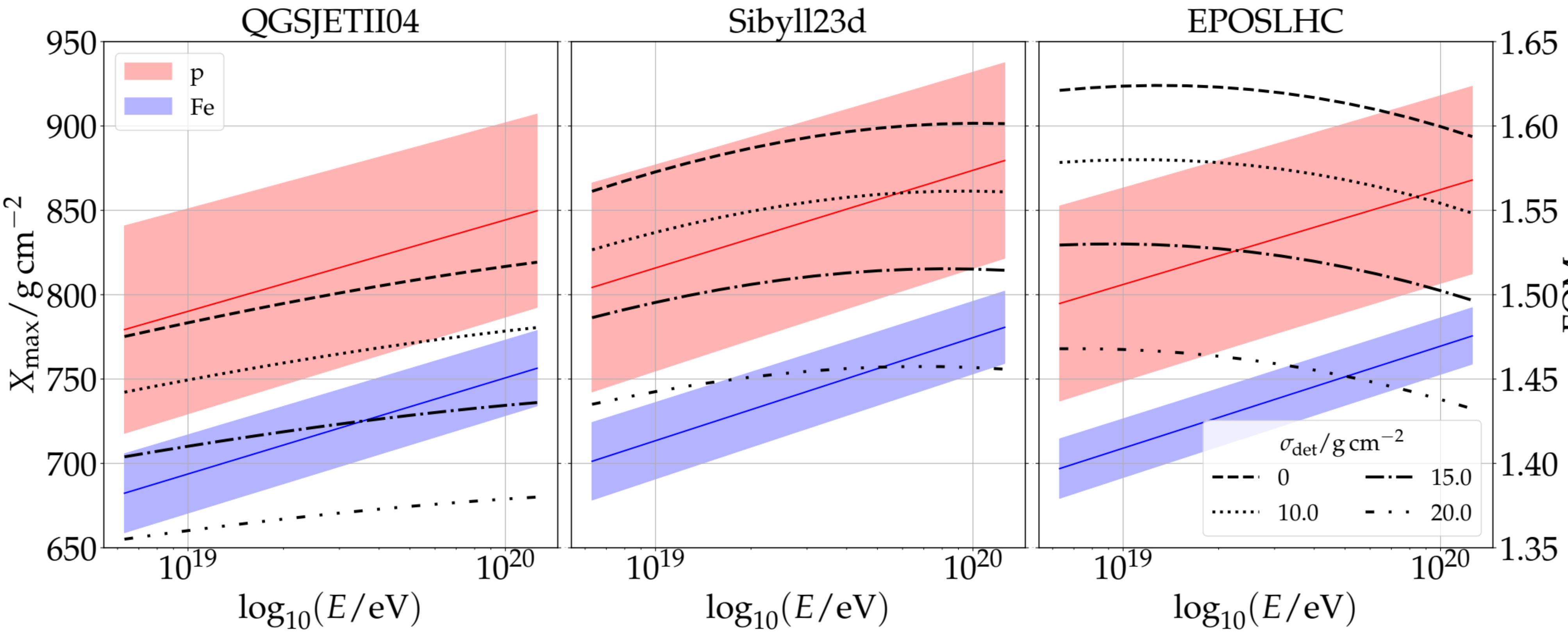
Glaser et al.



X_{max} reconstruction for inclined air showers



- Traditional approach: LDF sensitivity
- Intrinsic resolution 3%
- Realistic resolution 7%

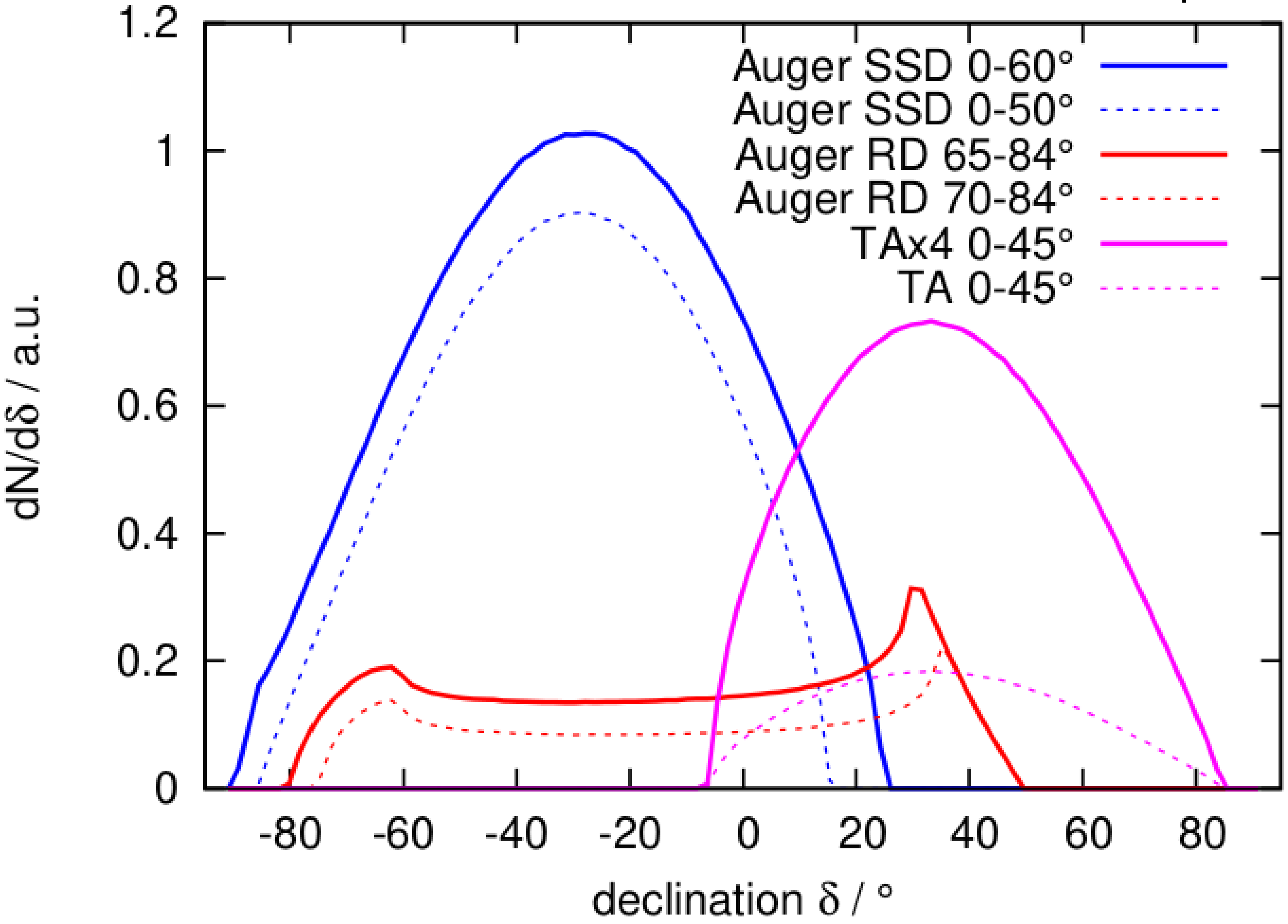


QGSJETII04
Sibyll23d
EPOSLHC
p
Fe
$X_{max}/g\,cm^{-2}$
FOM
$\log_{10}(E/eV)$
$\sigma_{det}/g\,cm^{-2}$
0
10.0
15.0
20.0
950
900
850
800
750
700
650
1.65
1.60
1.55
1.50
1.45
1.40
1.35
10^{19}
10^{20}

Aperture

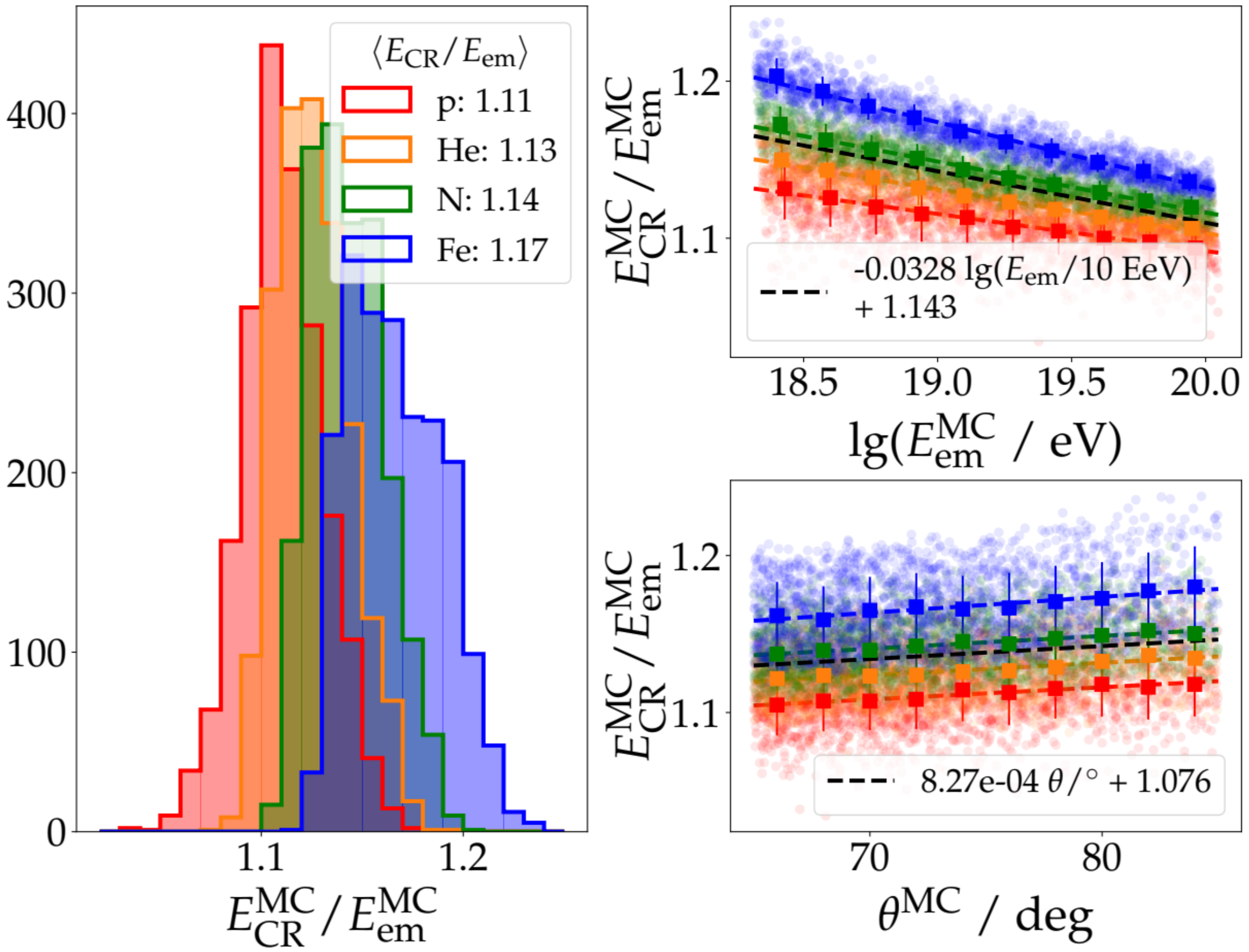
- Increase sky coverage
  - Overlap with TA
- Increases overall aperture
  - ~23%

Internal RD sciences case report



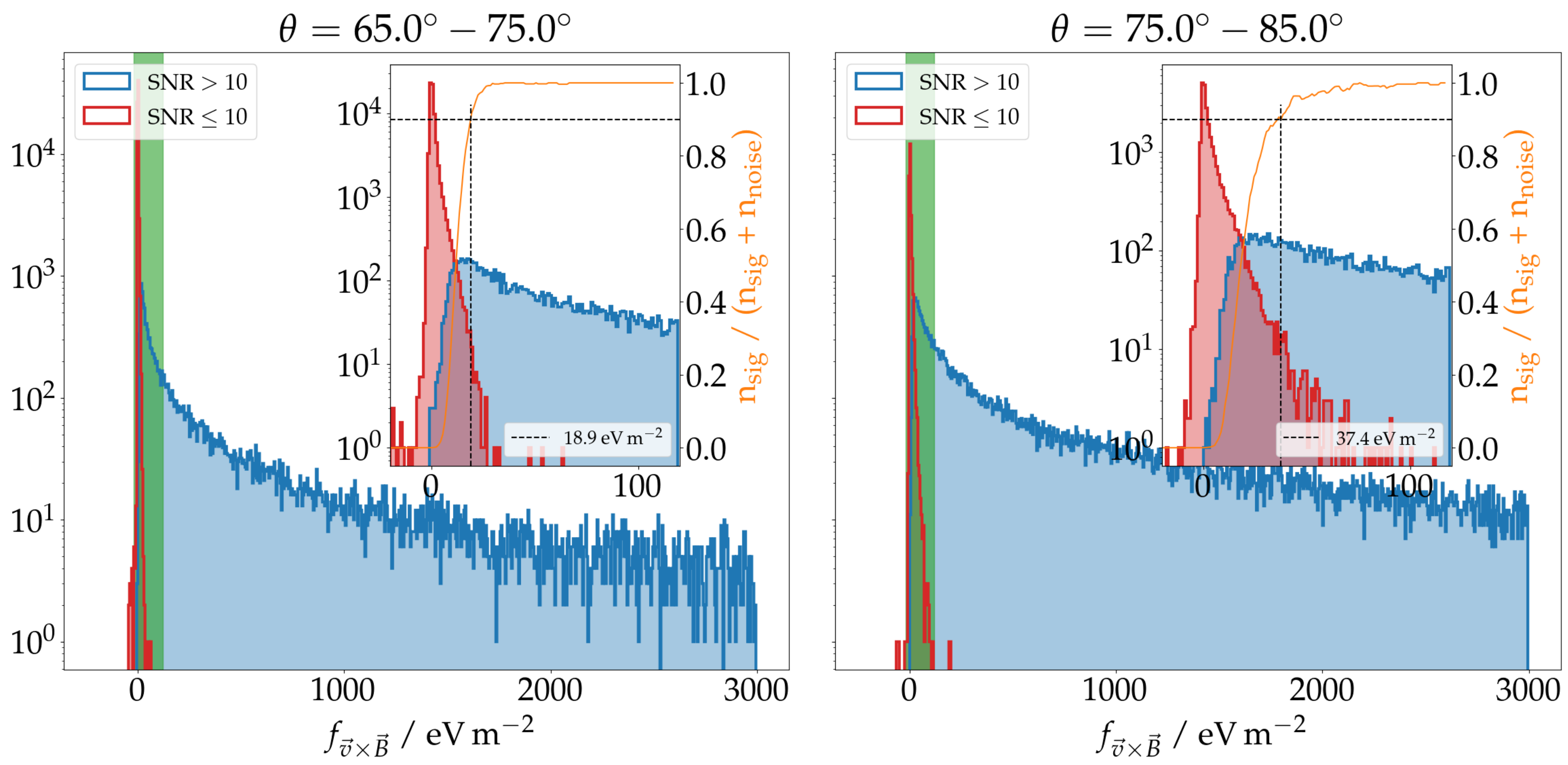
Energy calibration

- Independent of hadronic interaction model

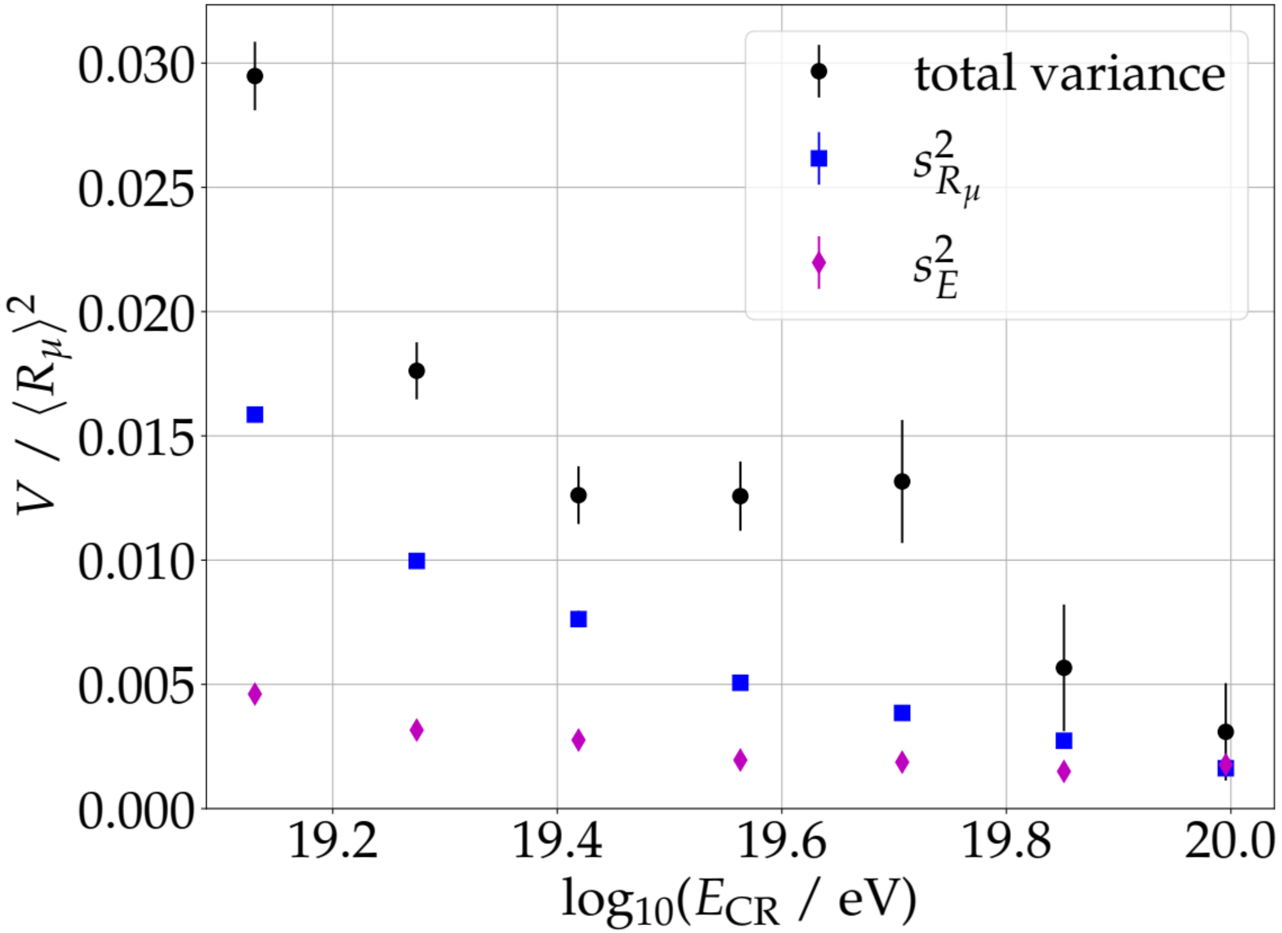


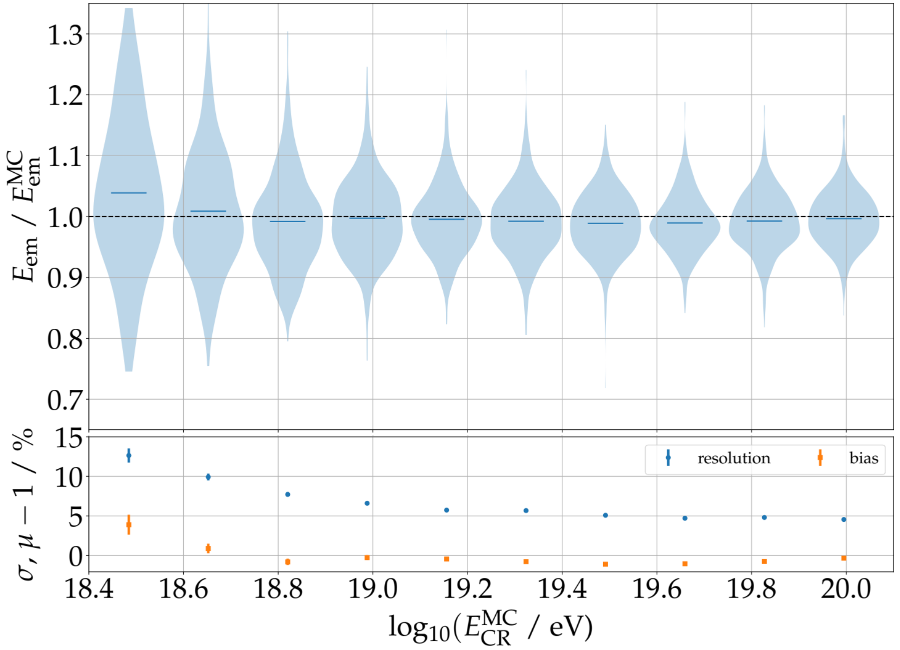
Felix Schlüter - felix.schlueter@kit.edu

Detection threshold

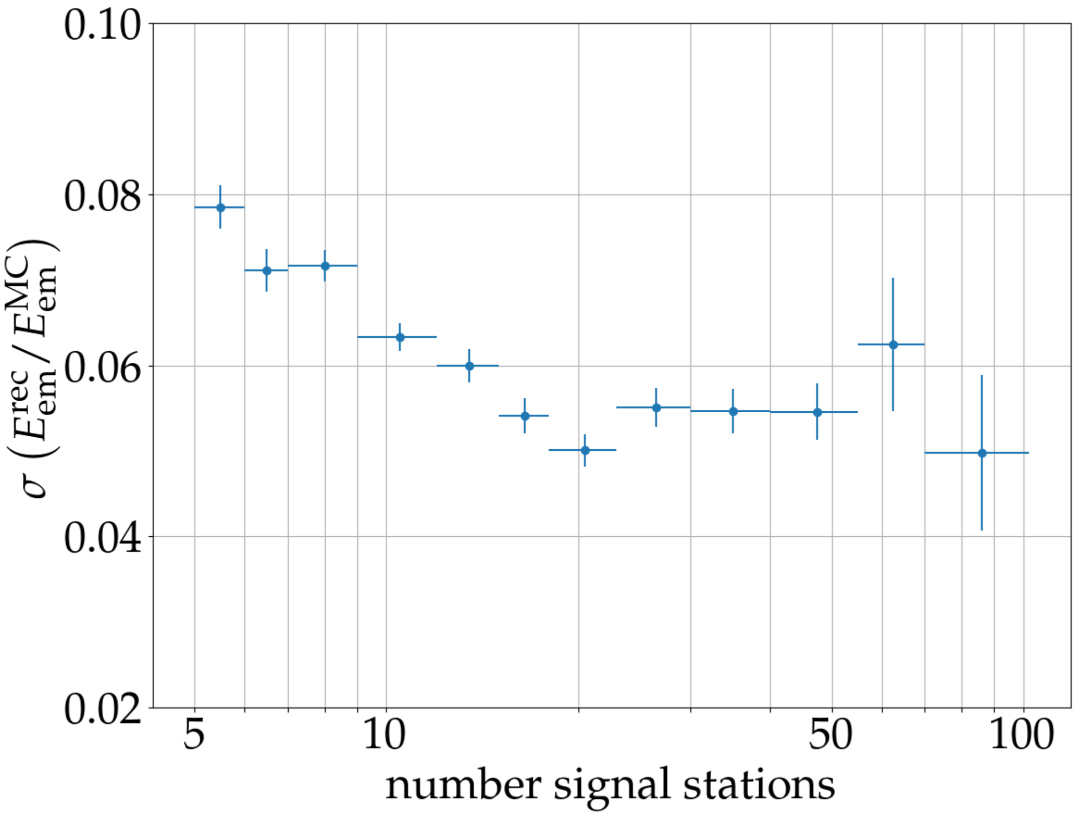


Variance reconstructed muon number





E_{em} / E_{em}^{MC}
$\sigma, \mu - 1$ / %
resolution
bias
$\log_{10}(E_{CR}^{MC}$ / eV)

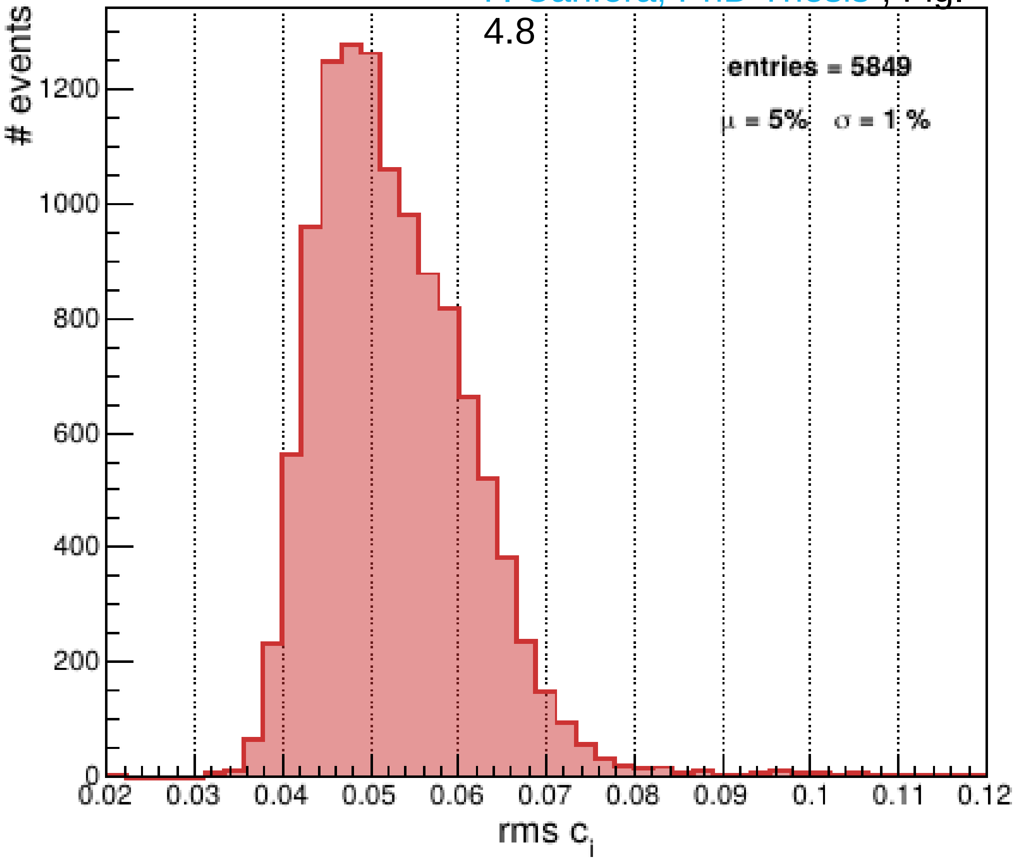


$\sigma\left(E_{em}^{rec} / E_{em}^{MC}\right)$
number signal stations

Antenna-to-antenna variation for AERA Butterfly antennas

- After galactic calibration
- $$c_i = \frac{1}{n}\sum_{j=\nu_1}^{\nu_n} \frac{A(\nu_i)}{\overline{A}_{\nu_i}},$$
  - spread of the amplitudes in single antennas over all antennas for 1 periodic trigger event
- Average over polarization
- Average of RMS is 5%

F. Canfora, PhD Thesis , Fig. 4.8



Backup

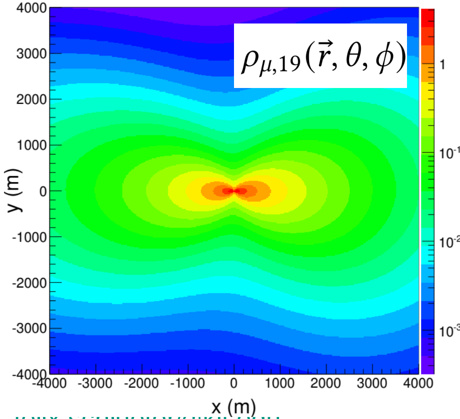
Muon reconstruction

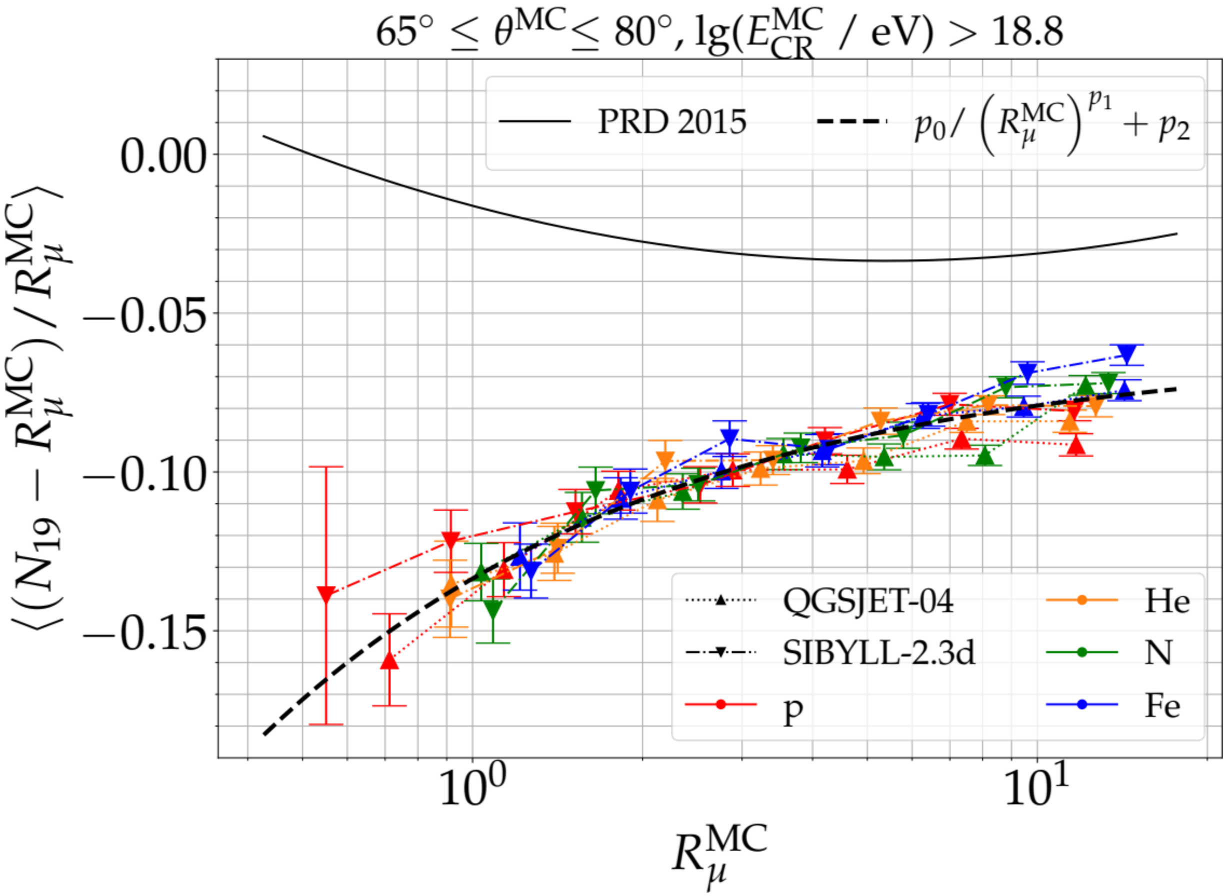
2d simulated density map

- $$\rho_\mu^{\text{pred}}(\vec{r}) = N_{19}\, \rho_{\mu,19}(\vec{r}, \theta, \phi)$$

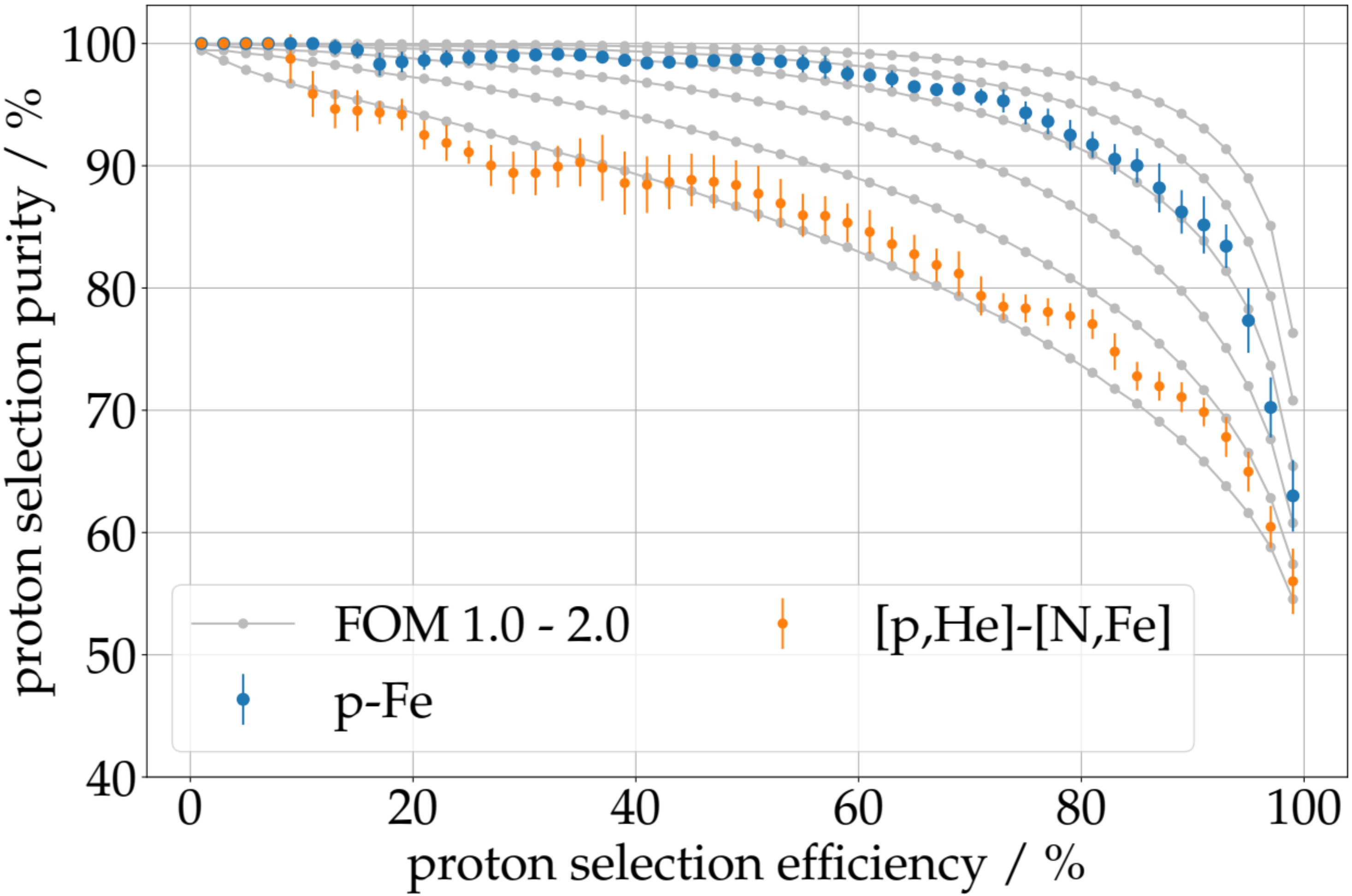
Scaling parameter

- Muon reconstruction bias
  - Zenith angle dependency!





Proton selection efficiency



Simulated RD event