Detecting inclined air showers with the AugerPrime Observatory

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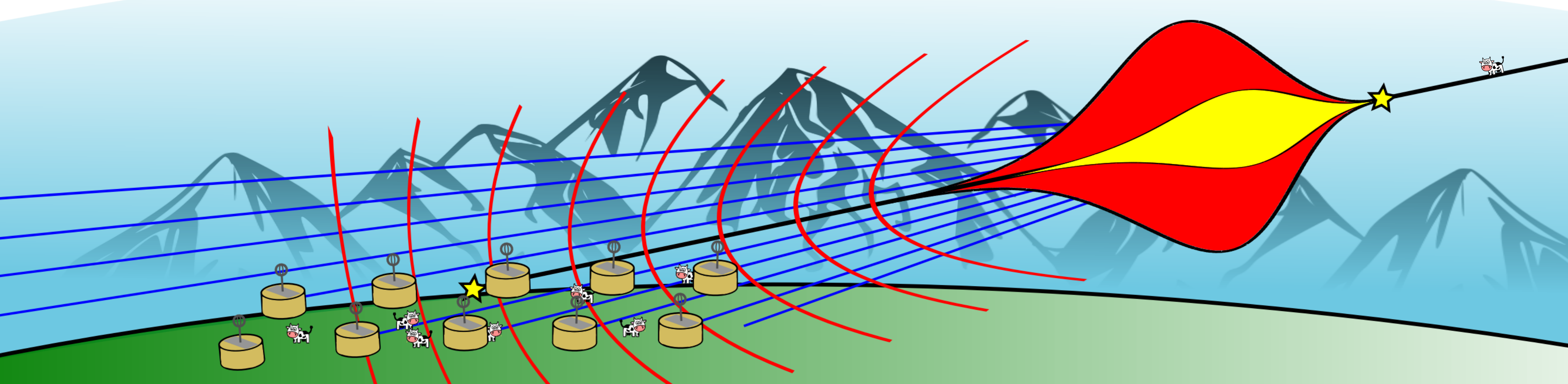
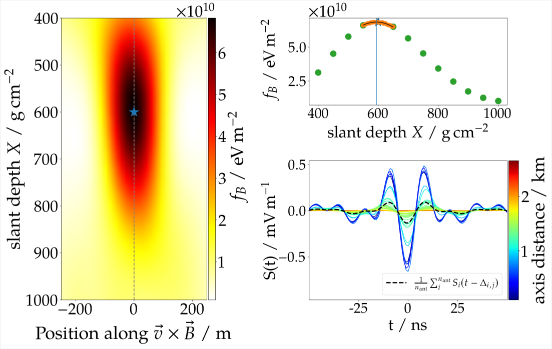


Recap, Recent Work, and Plans

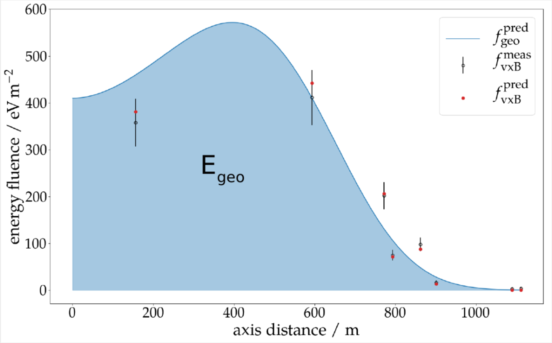
Interferometric Reconstruction



- Last HIRSAP talk
- Not applicable for Auger

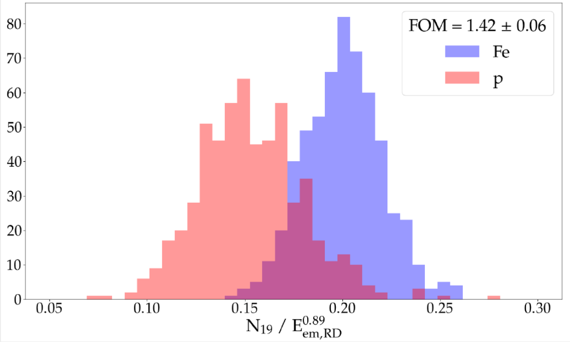
GAP 2020-54, JINST 16 P07048

Reconstruction of inclined Air Shower



- My first HIRSAP talks / POS(ICRC2021)209
- ~~Still improving;~~ SAL in prep; Talk at OCM

Performance of the Auger Radio Detector

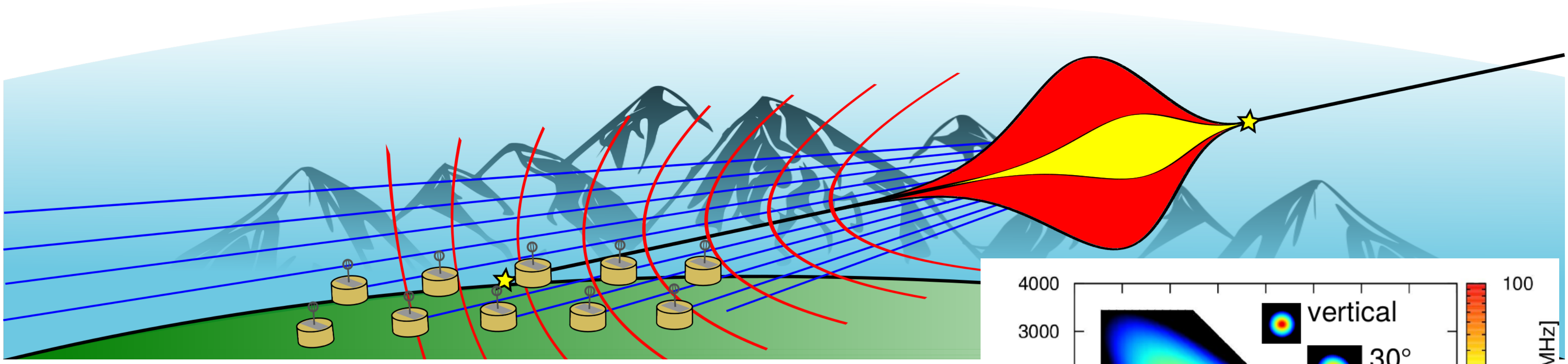


- RD Science Case Report
- PoS (ICRC21) 262
- **<u>This talk</u>**

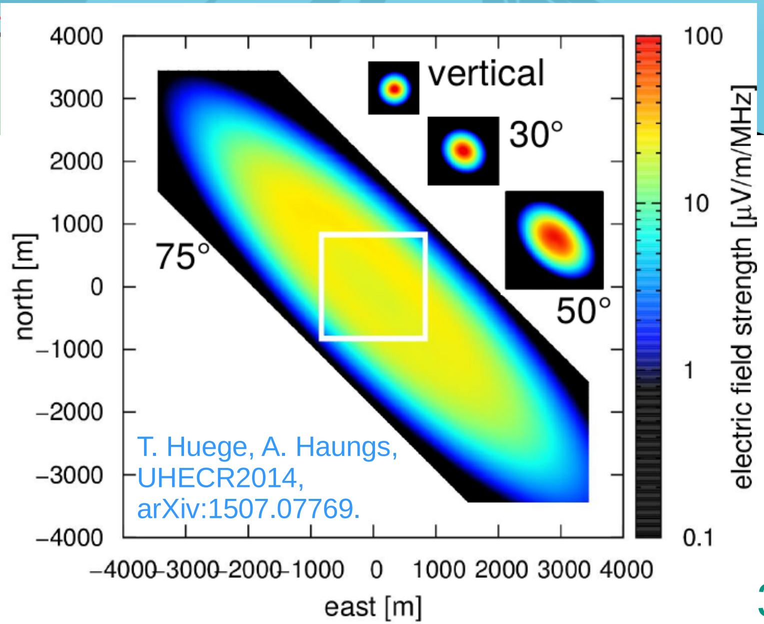
Last years:

- Refractive displacement of radio-emission footprint Eur. Phys. J. C 80, 643 (2020)
- Emission depth on the radiation; Contribution of low energetic electrons to radio signal

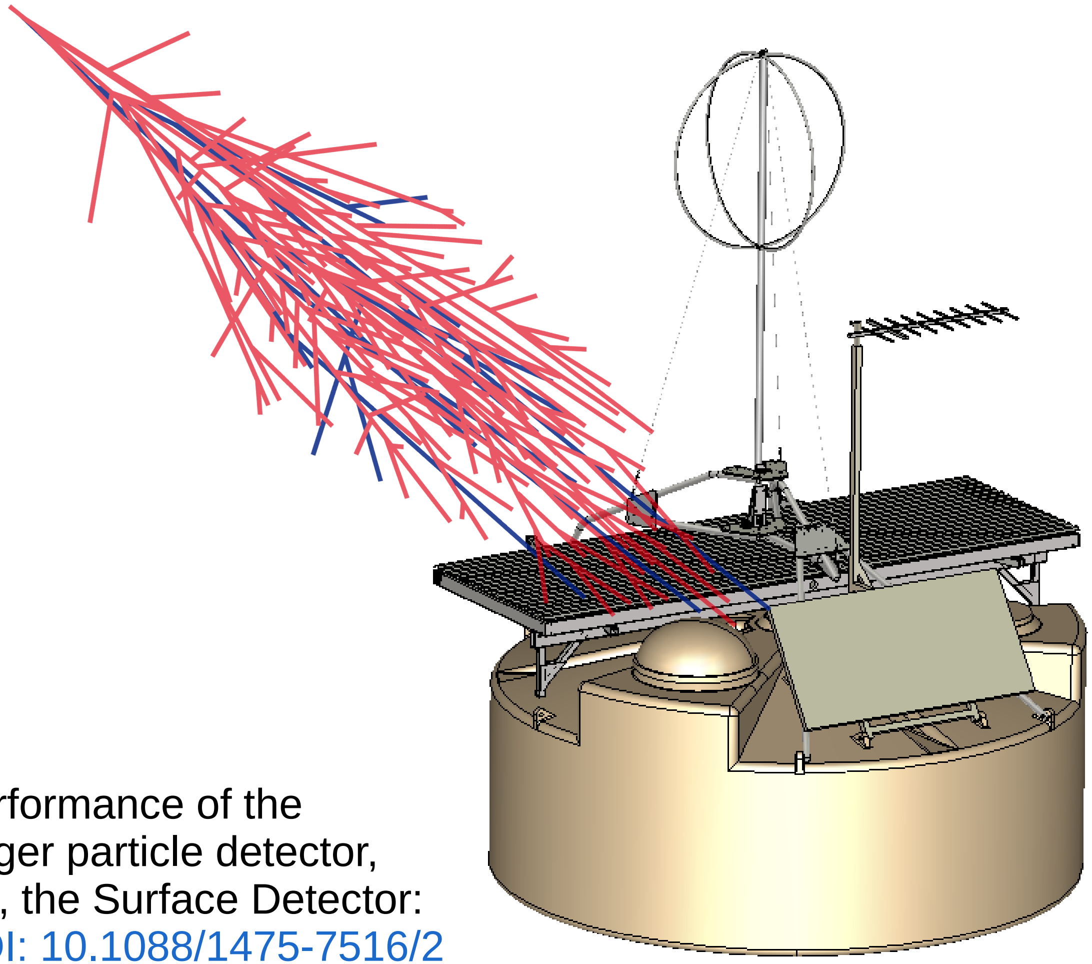
Goal: Extends sky-coverage of mass-sensitive measurements



- Radio Detector (RD) combined with Auger particle detector will provide **muon-electron separation** → mass sensitivity
- **Very inclined air showers**: $65° \lesssim \theta \lesssim 85°$
- Highest energies: $\lg(E / eV) \gtrsim 18.8$



Expected performance of the AugerPrime Radio Detector



Performance of the
Auger particle detector,
i.e., the Surface Detector:
DOI: 10.1088/1475-7516/2014/08/019

End-to-end simulation study:

Monte-Carlo air shower simulations

↓

Full detector simulation

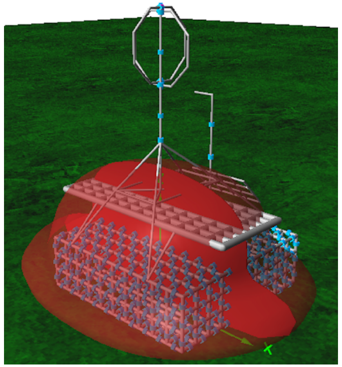
↓

Full & realistic event reconstruction

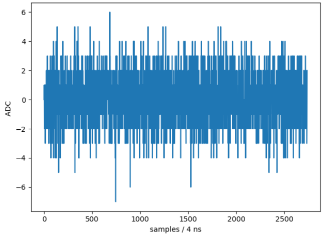
↓

Physics performance

RD detector simulation



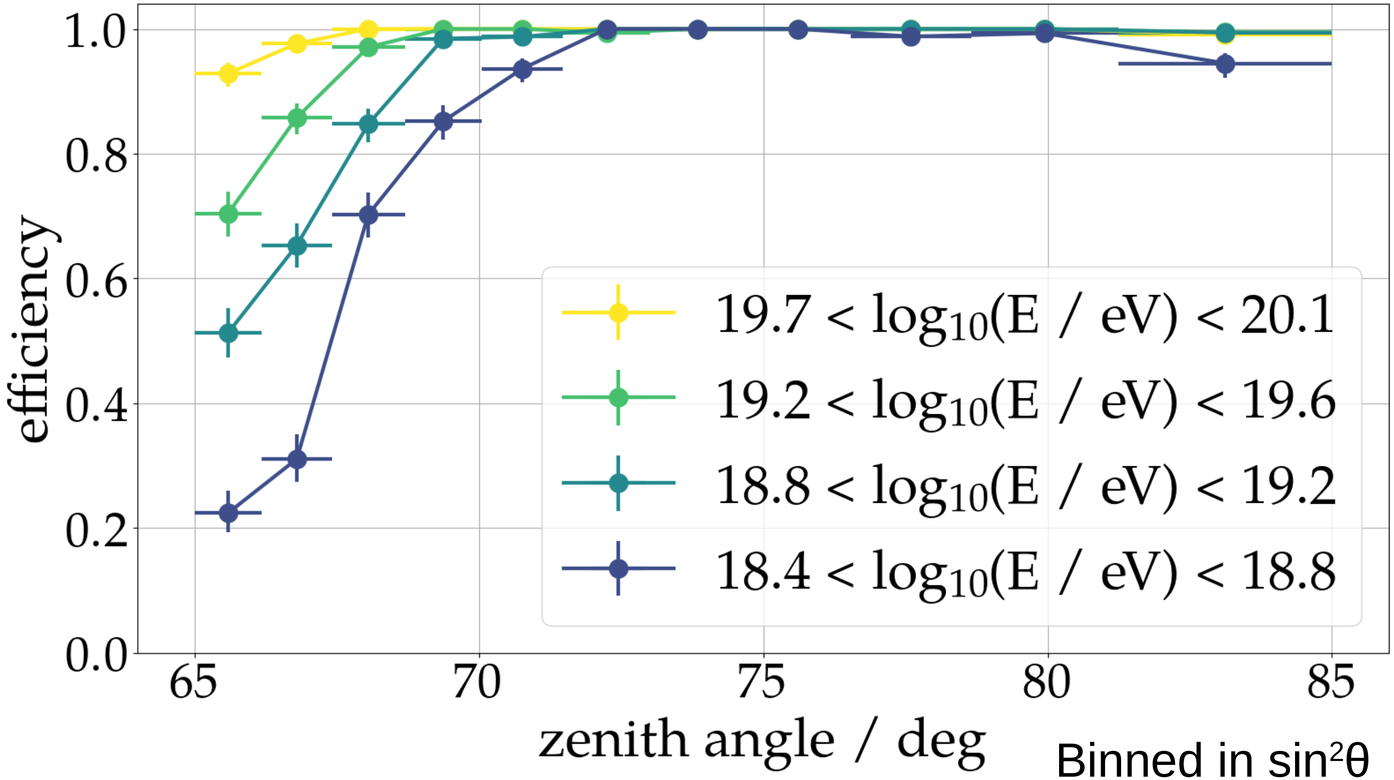
1. Apply directional sensitivity (antenna pattern)
   - Use MC axis (plane wave front)
2. Apply absolute gain (amplifier, cables, impedance matching, …)
   - Use preliminary galactic calibration
3. Apply Gaussian amplitude smearing (frequency independent)
   - Use 5% -> variation in AERA antennas when integrating over the whole sky
   - Directional dependent variation needs further investigation!
4. Resampling and clipping of traces
5. Analog to digital conversion (incl. flooring)
6. Add measured noise (one station, fairly clean!)
7. Add 6ns time jitter



Detection efficiency

- Min. 3 antennas with signal
- Strong dependence on zenith angle
  - Increasing footprint size
- Weak dependence on energy
- Nearly fully efficient for θ ≳ 70° at higher energies

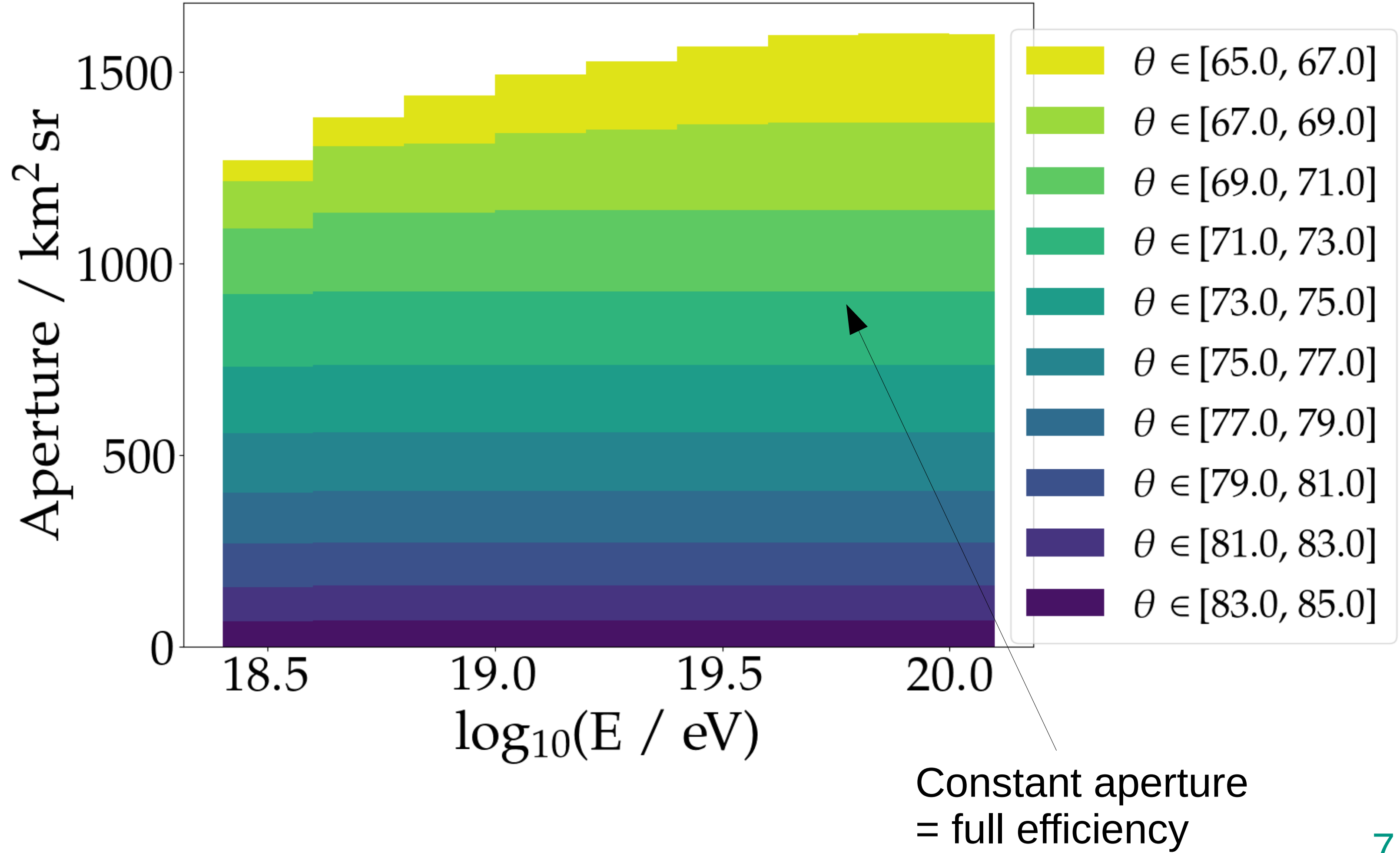
Normalized to WCD-reconstructed showers



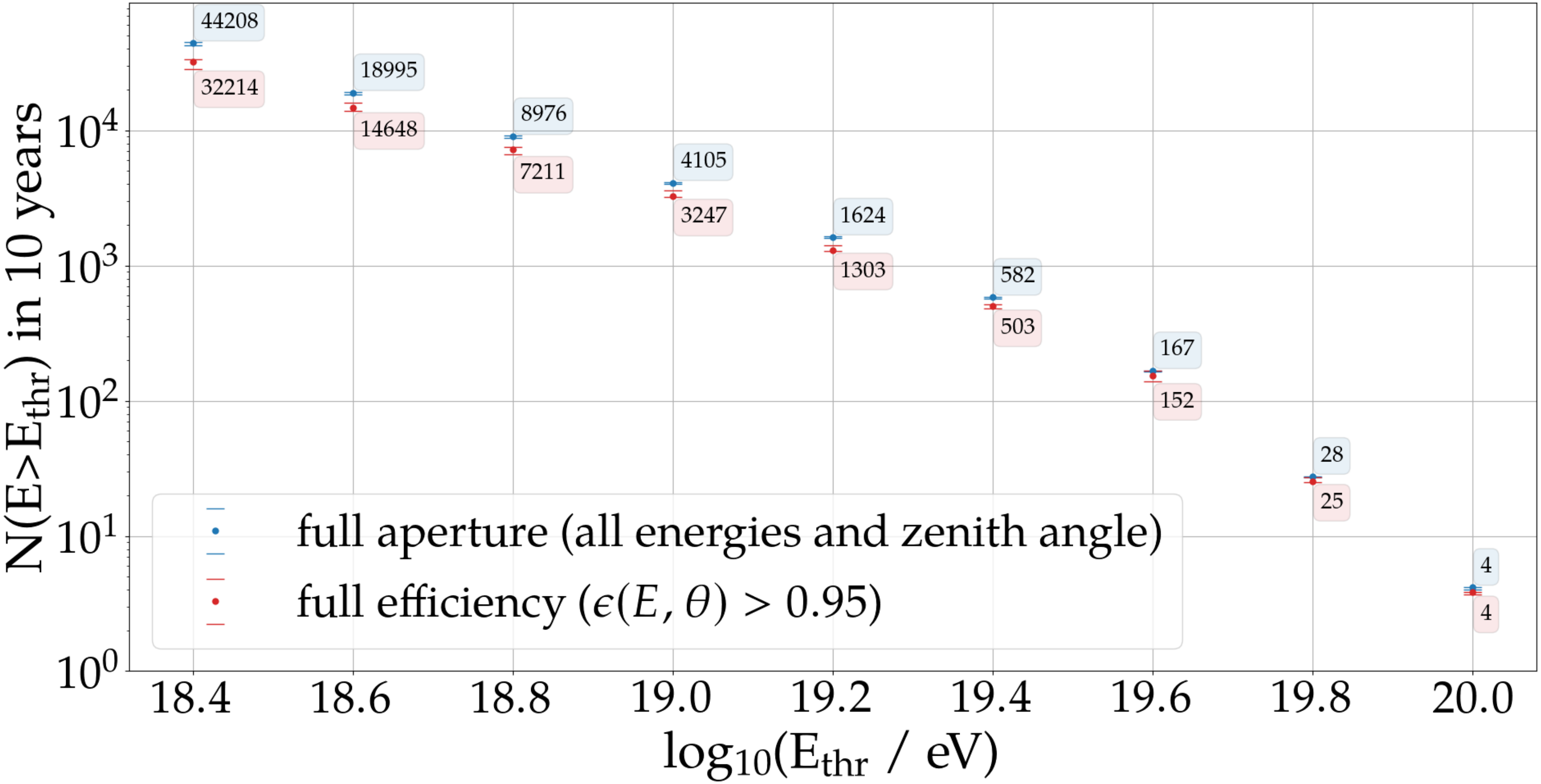
Binned in $\sin^2\theta$

Aperture for 3000 km^2 array

- For "contained events"
- Good agreement with previous study
  B. Pont, Auger POS (ICRC2019)395



10-year event statistics



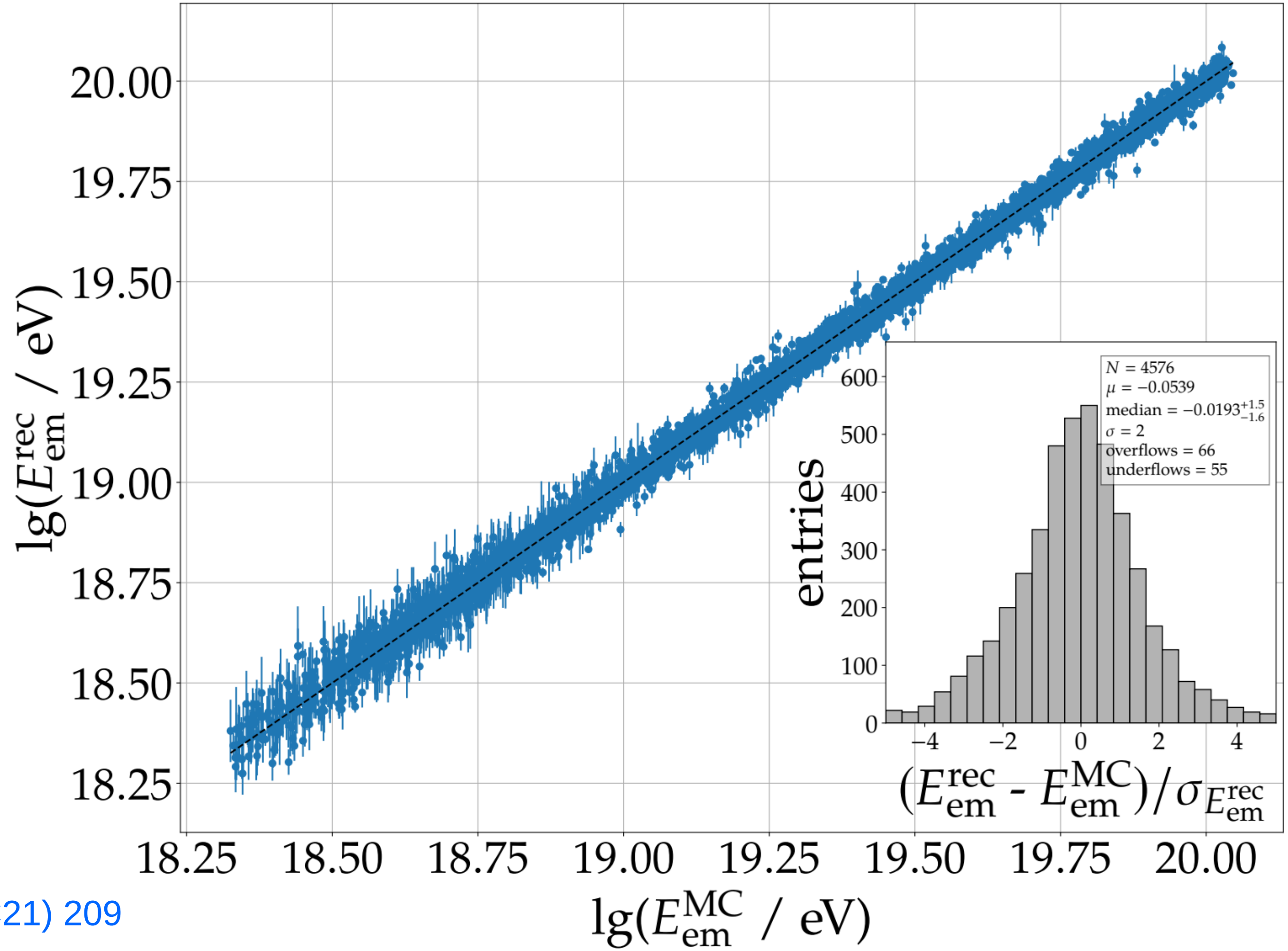
Estimated with Auger-measured flux:
Auger, PRD 102 (2020) 062005

Aperture estimated in bins of $\sin^2\theta$

→ N(E > 10 EeV) ~ 4100 N(E > 32 EeV) ~ 330

Shower reconstruction

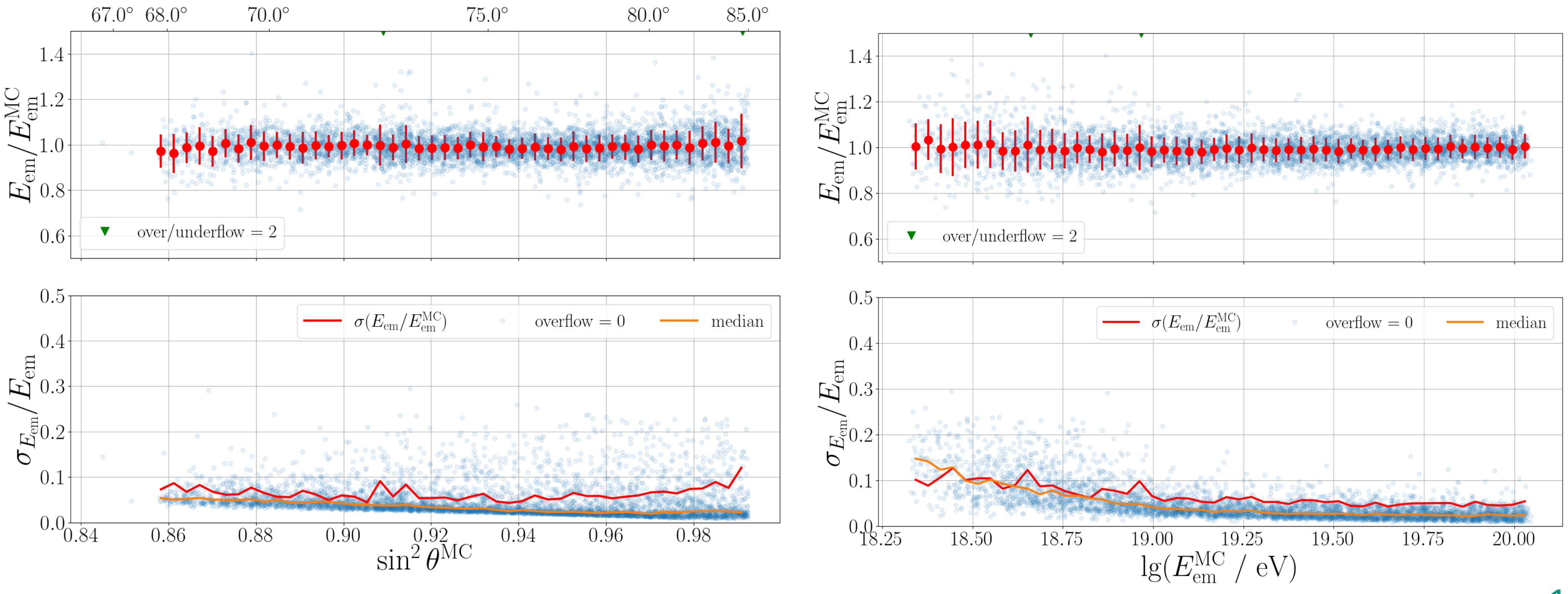
- Fit 4 parameters*
  - Electronmagnetic energy E_{em}
- Selection applied
  - Min. 5 signal stations, $\Theta_{RD} > 68°$, …
  - Not equally efficient for all primaries
- Uncertainties underestimated



*LDF model T. Huege, FS, PoS (ICRC21) 209

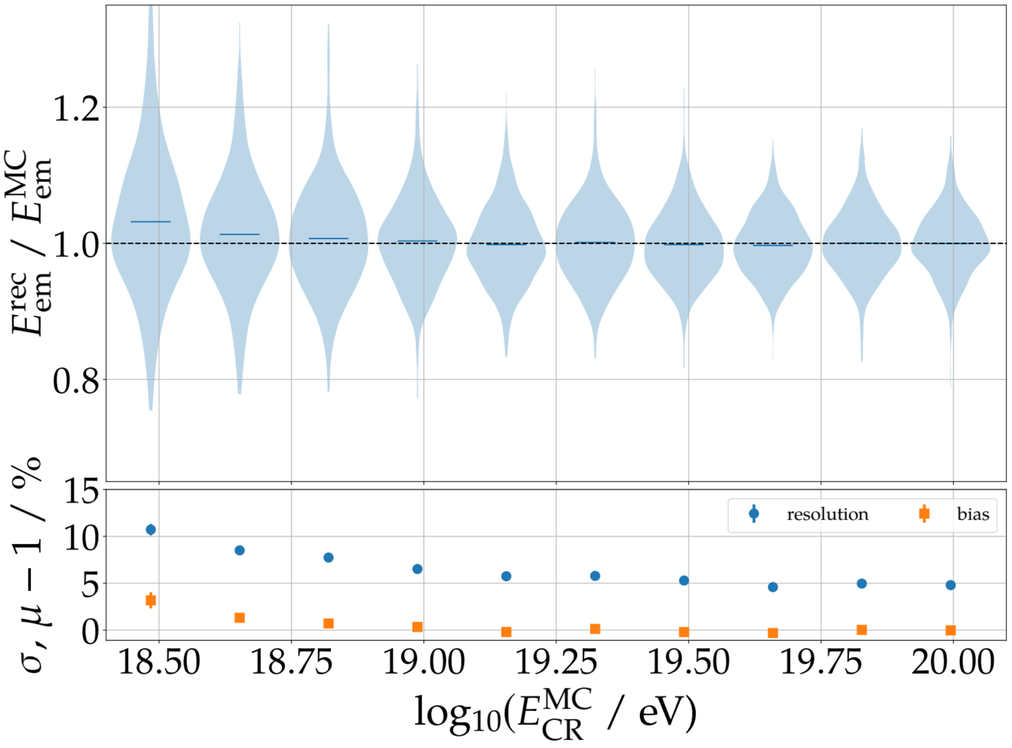
Uncertainties

- Uncertainty does not describe resolution (mismatch between red and orange lines)
- Similar picture for E_{geo} and d_{max}; Validated that the fit uncertainties are properly estimated → uncertainty model for energy fluence

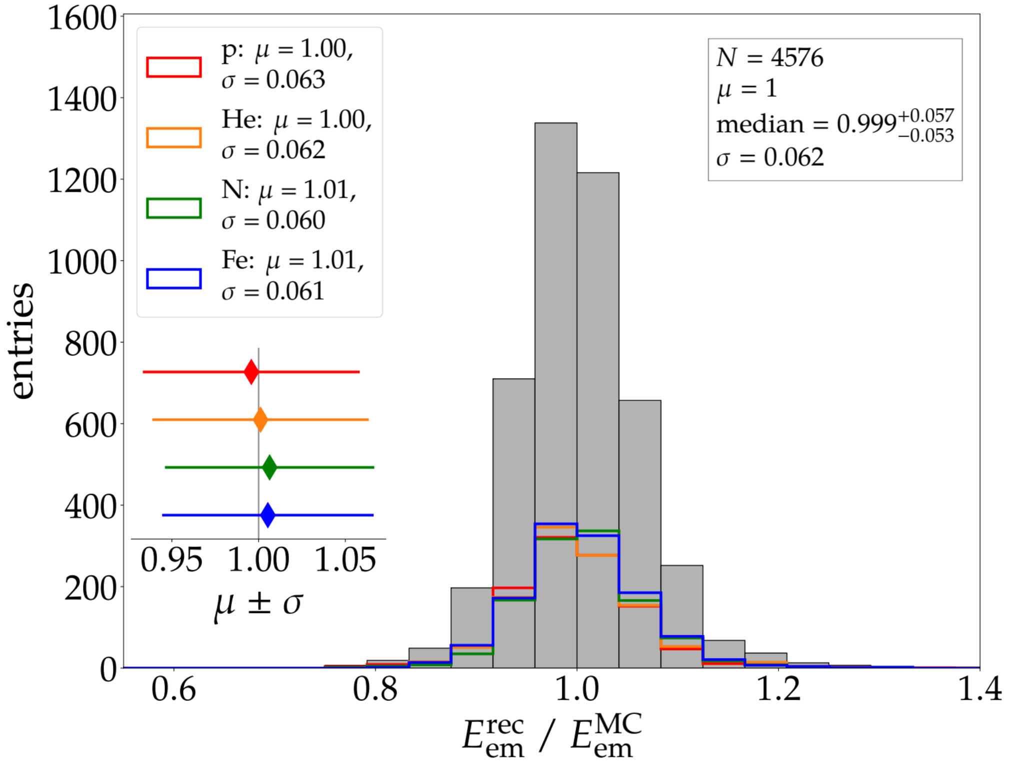


Shower reconstruction

- Resolution < 10% at higher energies
  - Improves with energy expected due to noise

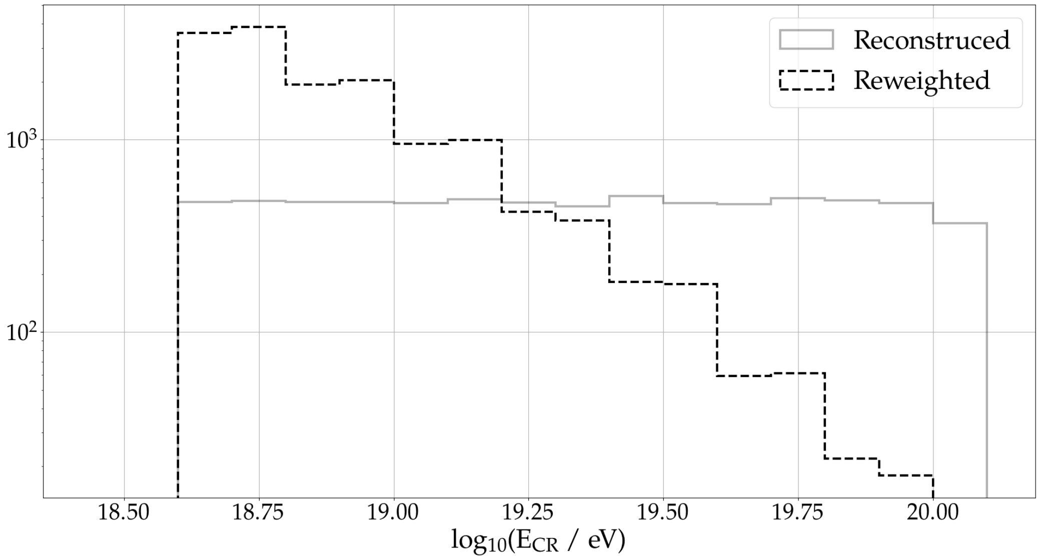


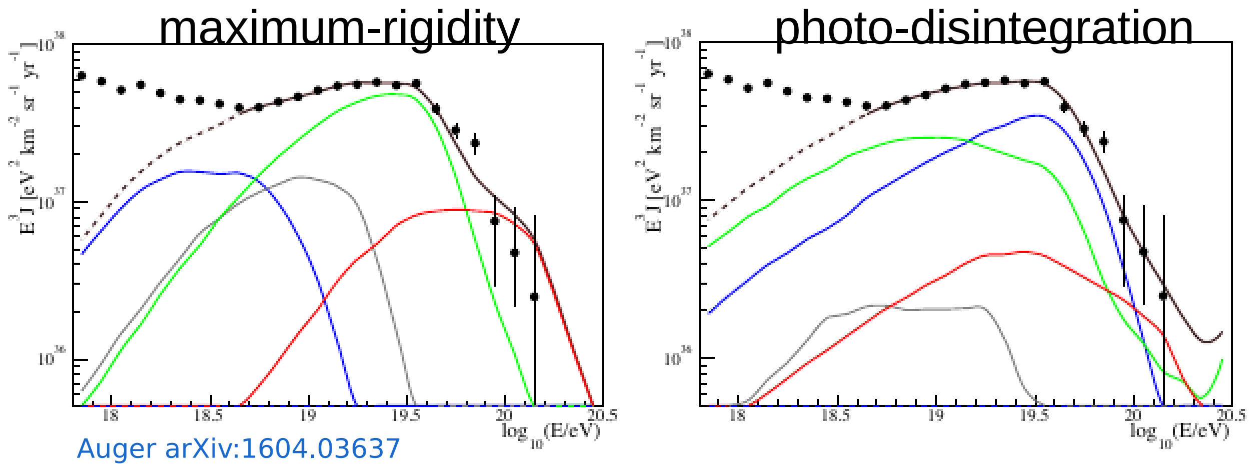
- No significant bias
- No dependency on mass



Reweighing events to Auger spectrum

- Draw events for discrete energy bins but across all allowed zenith angles
- Re-use showers lgE <~ 19.3
- Extract primary fractions: $p_i(E)$ for two benchmark scenarios



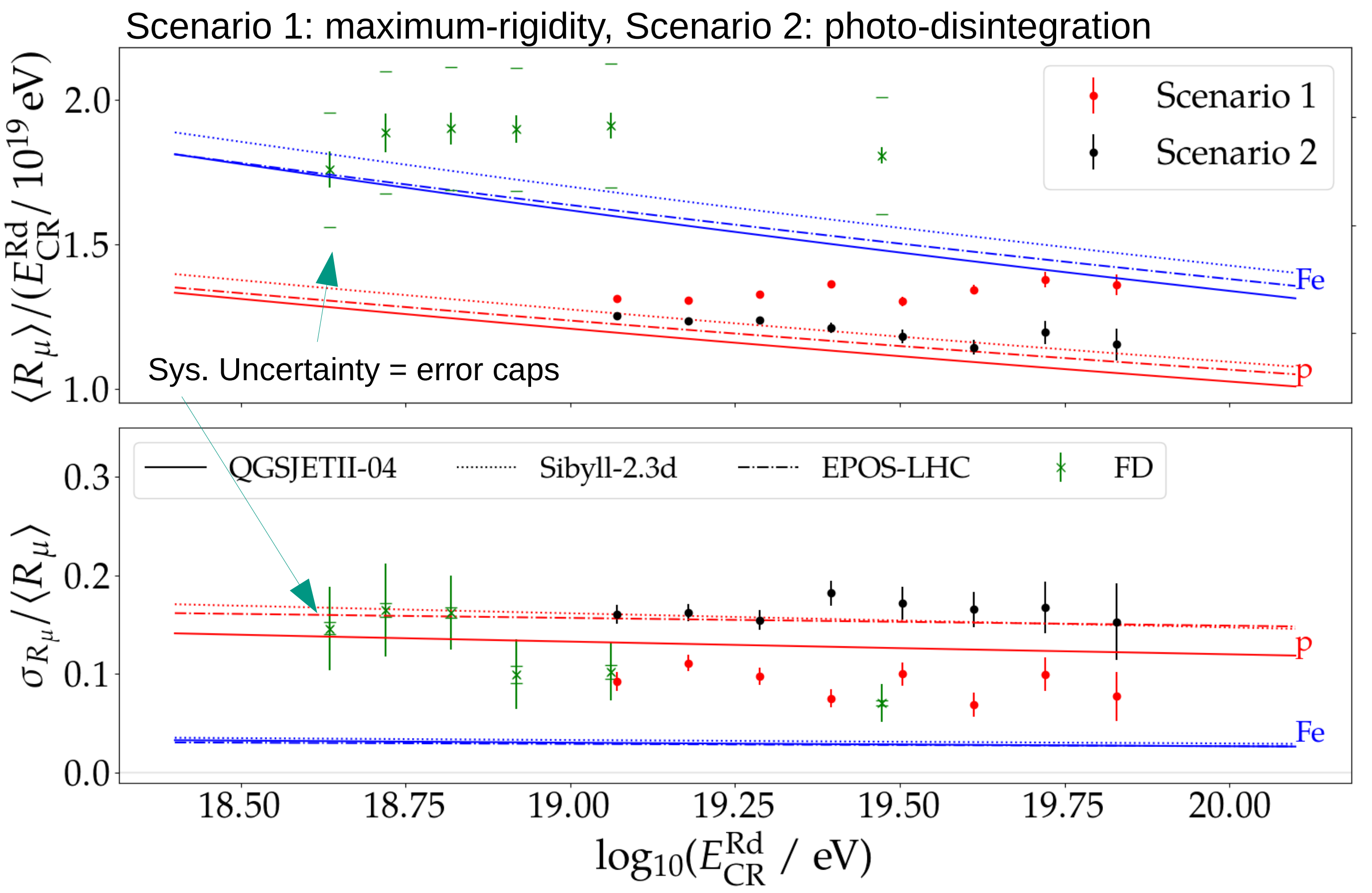


p, He, N, Fe

Auger arXiv:1604.03637

Relative number of muons

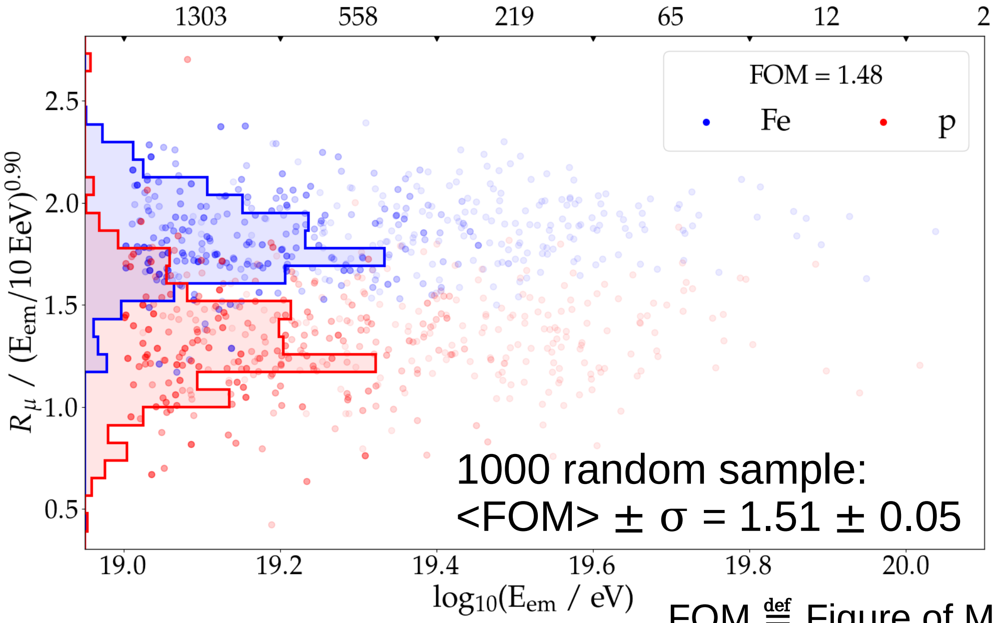
- Exp. exposure and two mass-composition scenarios*
- Use (simplified) binned analysis (no power law fit)
- **Higher statistics (w.r.t. FD)** at highest energies
- Fluctuation less affected by systematic uncertainties → **discrimination potential**

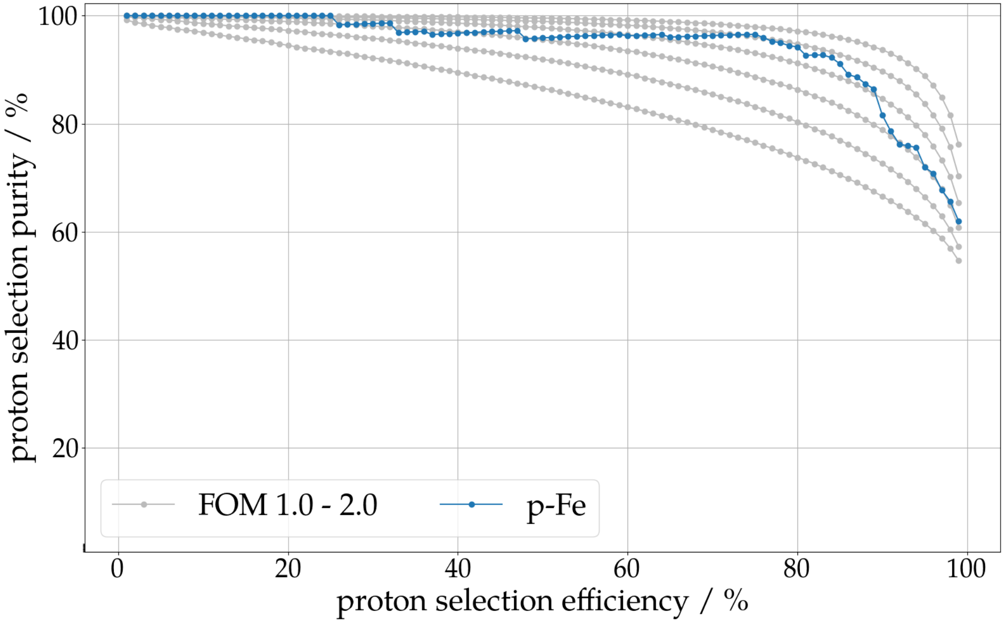


*AugerPrime Design Report arXiv:1604.03637

Event-by-event mass discrimination

- 50-50 p-Fe, with expected energy spectrum
- Simple, energy-independent discriminator $R_{\mu} / E^{0.9}_{em}$ (~ Fisher analysis)
  - Good energy resolution critical!
  - FOM of 1.5 ≅ separation with X_{max} at σ_{Xmax} = 15 g/cm²





FOM $\stackrel{def}{=}$ Figure of Merit

Summary & Conclusion

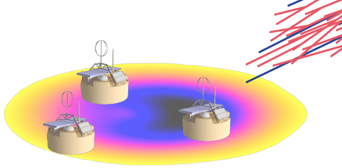
- End-to-end simulation study of the Radio Detector:
  - Monte-Carlo shower simulations, full detector simulation, measured background, realistic reconstruction
- Expected performance:
  - Event statistics: N(10y, lgE > 19) ~ 4100
  - Preliminary energy resolution: $\sigma_E < 10\%$
- Explored potential of hybrid measurements
  - Discriminate between composition scenarios
  - Discrimination between proton and iron / Contain a wealth of mass information

Outlook

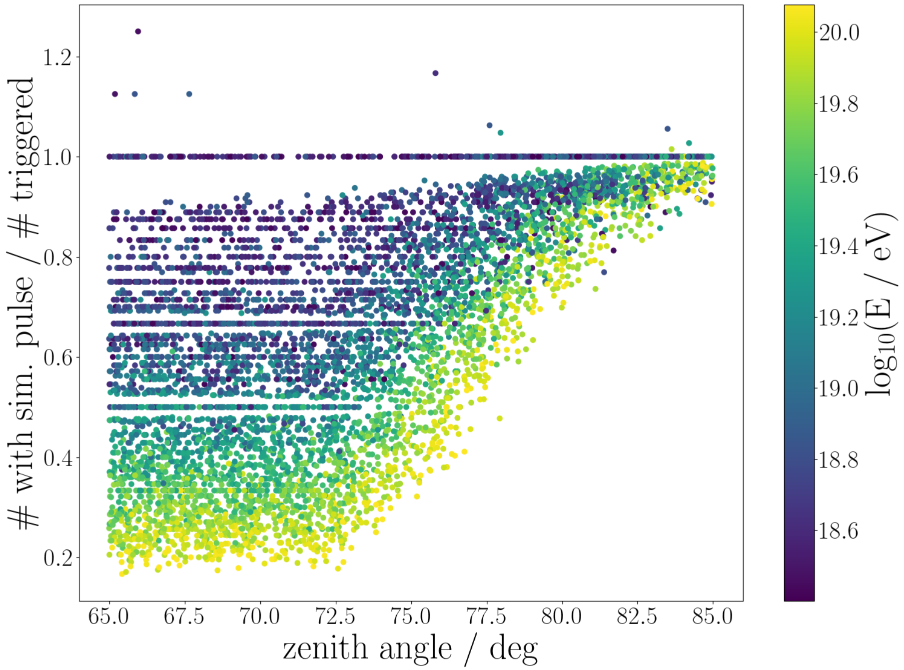
- A lot of changes pending:
  - Run with updated trigger (UUB)
  - Run with pure noise traces
  - Twisting arrival direction for antenna response
  - Run validation with individual arrival directions

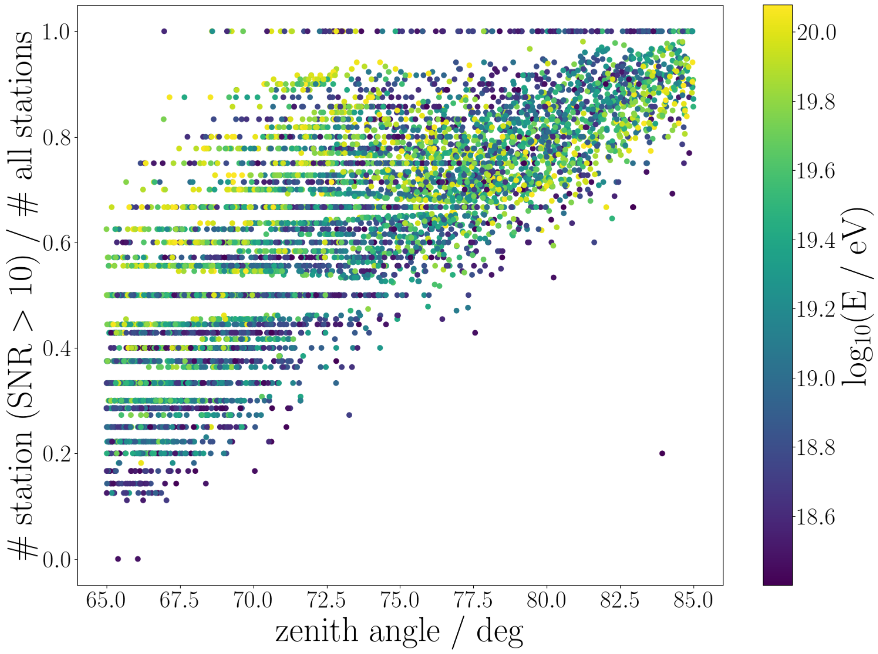
Backup

CORSIKA/CoREAS simulations



- Select station to be simulated depending only on zenith angle





More details in backup!

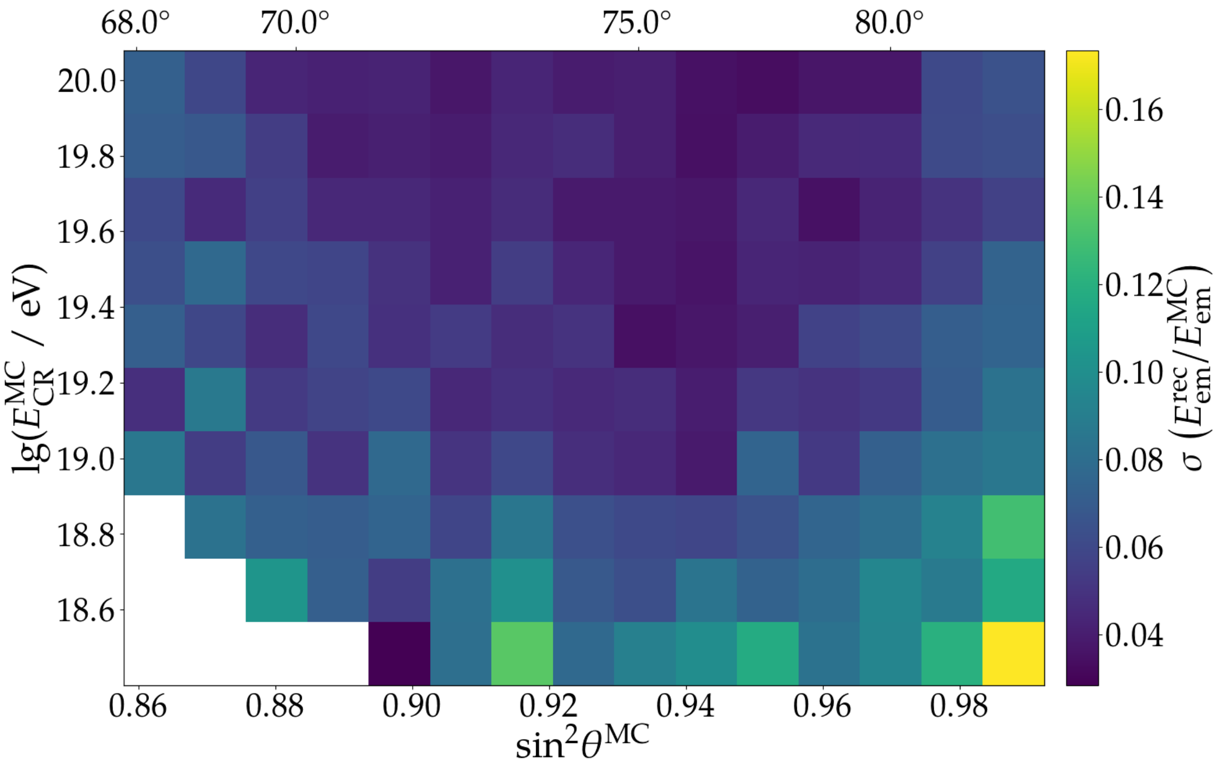
Selection for good RD energy reconstruction

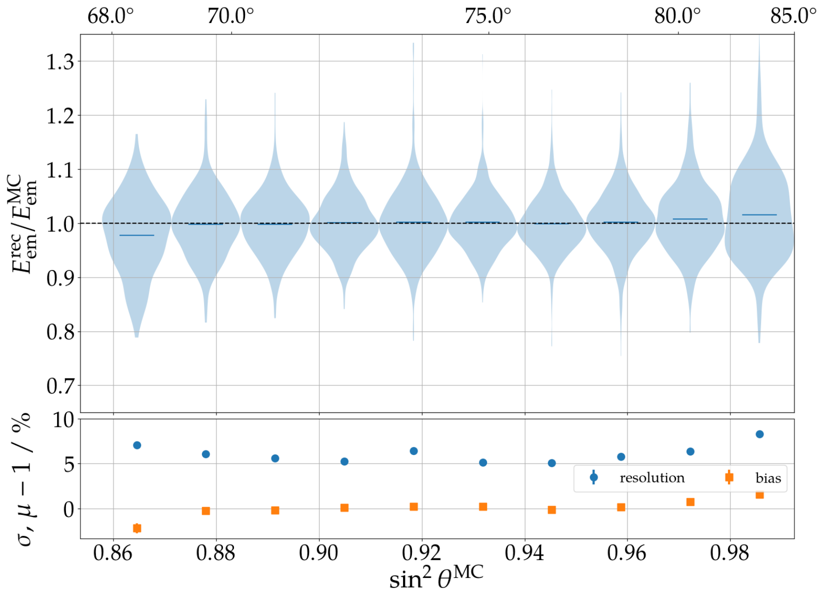
- Selection bias for different primaries

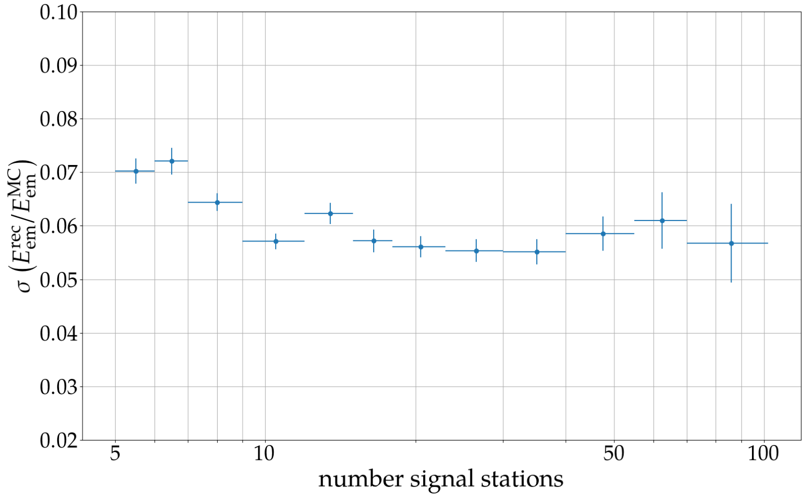
	p / 1996	Fe / 1979	All / 3975
Has SD rec. LDF	1911 (95.7%)	1954 (98.7%)	3865 (97.2%)
min. RD signal stations: 5	1305 (68.3%)	1396 (71.4%)	2701 (69.9%)
Has RD spherical fit	1288 (98.7%)	1388 (99.4%)	2676 (99.1%)
$\alpha_{RD} > 20.0°$	1268 (98.4%)	1364 (98.3%)	2632 (98.4%)
$\theta_{RD} \geq 68.0°$	1232 (97.2%)	1310 (96.0%)	2542 (96.6%)
$\sigma_{\theta_{RD}} < 0.3°$	1229 (99.8%)	1309 (99.9%)	2538 (99.8%)
Has RD rec. LDF	1229 (100%)	1309 (100%)	2538 (100%)
RD LDF with core	1229 (100%)	1309 (100%)	2538 (100%)
$n_{stat}(r < 1.5r_0) > 0$	1201 (97.7%)	1289 (98.5%)	2490 (98.1%)
$\sigma_{S_{rad}} < 60.0\%$	1145 (95.3%)	1266 (98.2%)	2411 (96.8%)
$\sigma_{d_{max}} < 30.0\%$	1141 (99.7%)	1256 (99.2%)	2397 (99.4%)
χ^2 / ndf < 5.0	1113 (97.5%)	1235 (98.3%)	2348 (98.0%)
fitted core at limit[3]	1106 (99.4%)	1233 (99.8%)	2339 (99.6%)
$\measuredangle(\hat{a}_{RD}, \hat{a}_{SD}) < 1.50°$	1098 (99.3%)	1222 (99.1%)	2320 (99.2%)

Energy reconstruction

- Θ > 68°, n_{ant} >=5, ...

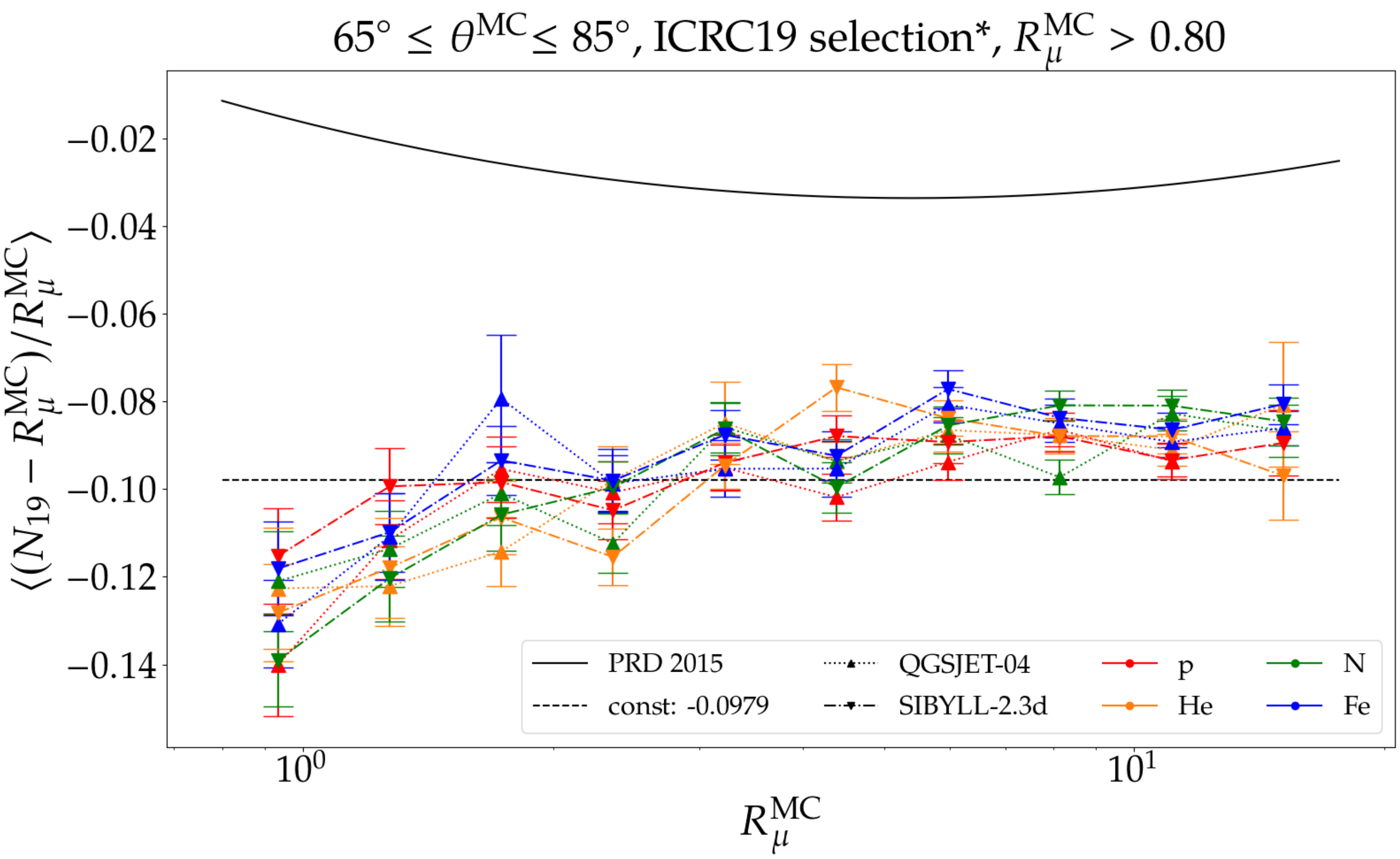




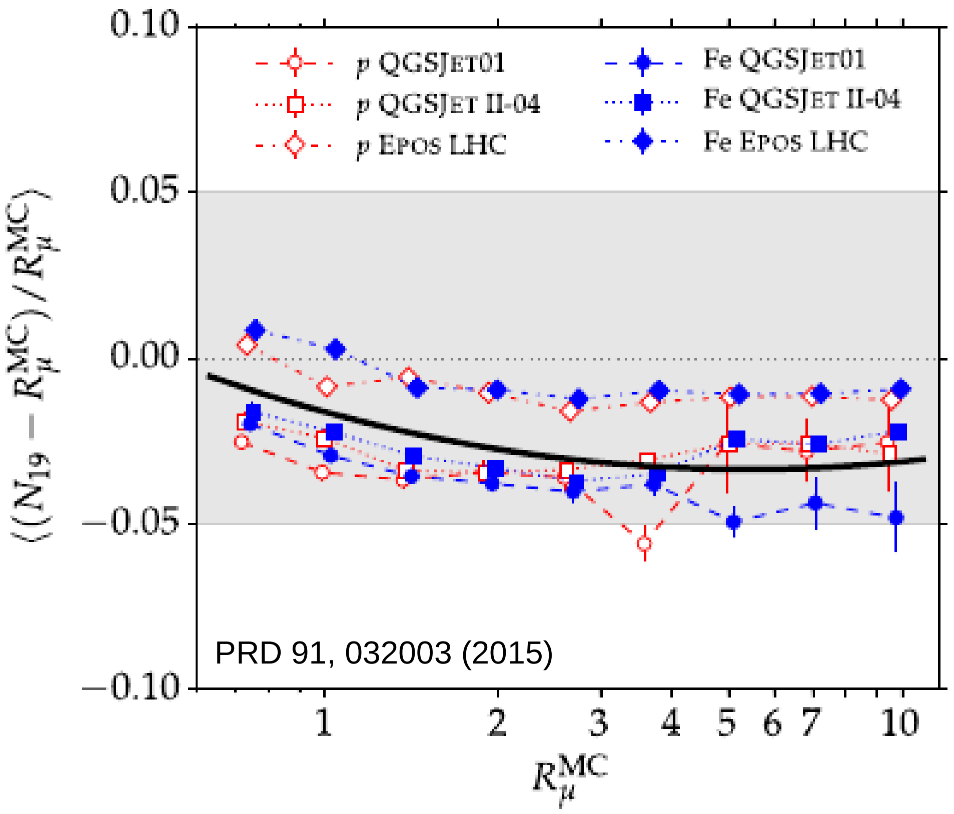


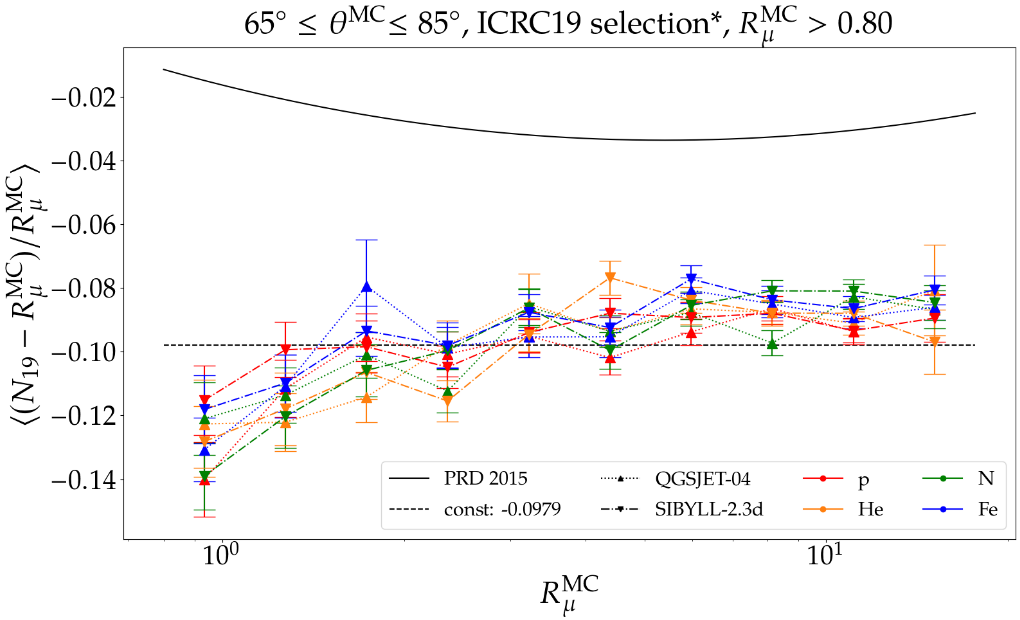
Reconstructing the Muon number

- N19: reconstructed by Offline
- R_μ^{MC} counted from simulations
- Use cut $R_\mu^{MC} > 0.8$
- Found significant larger bias (Cross-checked with F. Riehn)
- Use constant bias correction



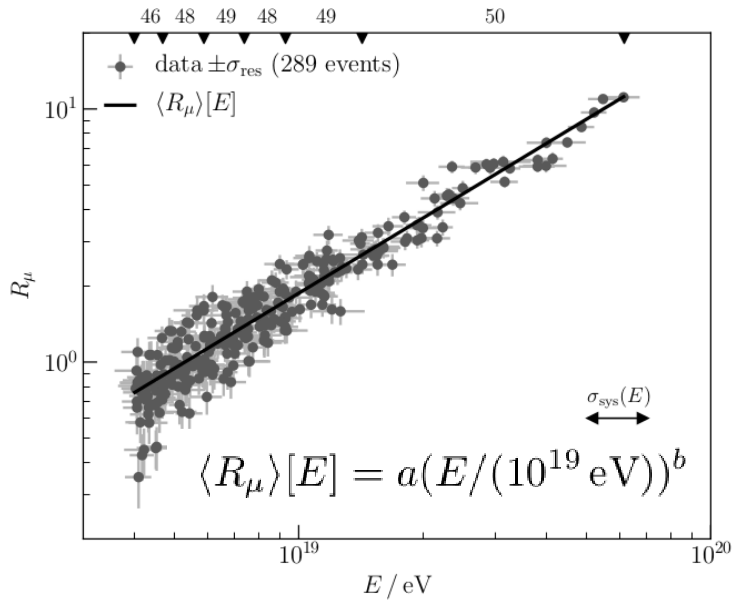
Reconstructing the Muon number

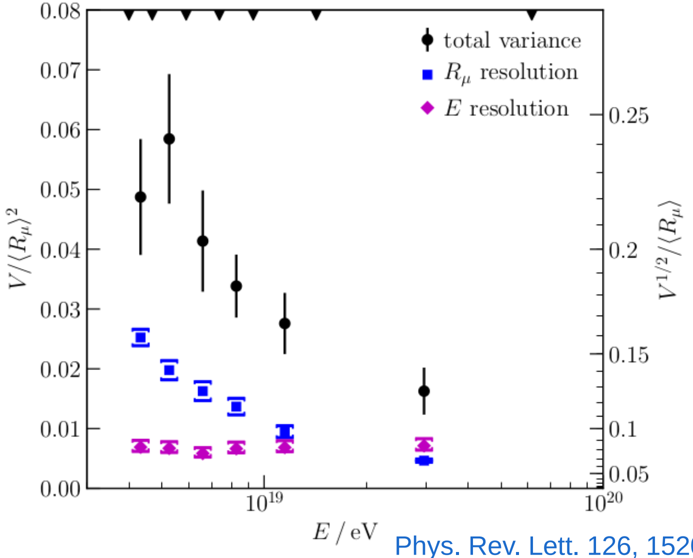




Measurement of muon number

- Not performing likelihood power-law fit, using simplified analysis instead:
  - Def. mean muon number as $\langle R_\mu\rangle[E] = \langle R_\mu / (E / 10\ \text{EeV})\rangle$
  - Fluktuation: $\sigma^2 \simeq V - s_E^2 - s_\mu^2$
  - $V = \text{Var}(R_\mu / (E / 10\ \text{EeV})) / \langle R_\mu / (E / 10\ \text{EeV})\rangle$
  - Determine uncertainty on mean & std* + Gaussian error propagation





*Relative uncertainty on std:

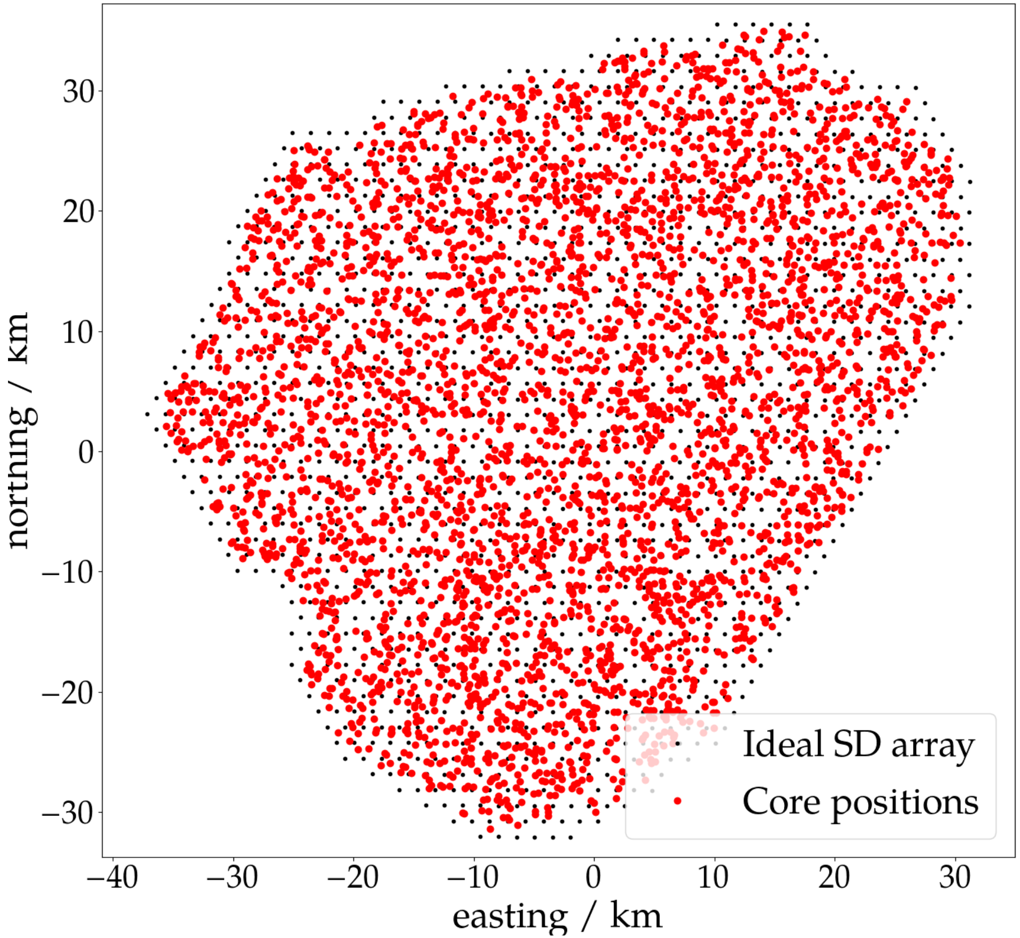
$$\sigma_{K_n S}/\sigma = \hat{\sigma}_{K_n S}/(K_n S) = \frac{K_n\sqrt{V_n}}{\sqrt{n-1}} \approx \frac{1}{\sqrt{2(n-1)}} \quad \text{for large } n.$$

Ahn, Sangtae & Fessler, Jeffrey. (2003)

Phys. Rev. Lett. 126, 152002

Simulation library

- 7972 p, He, N, Fe showers
  - p ~ sin(θ) ^ 2 from 65 - 85°
  - p_E ~ lgE from 18.4 to 20.1
- Simulated radio signals for stations within $r_{max}(\theta)$
- Malargüe October atmosphere
  - density profile & refractivity
- QGSJETII-04 / URQMD
- Also 8000 showers with Sibyll



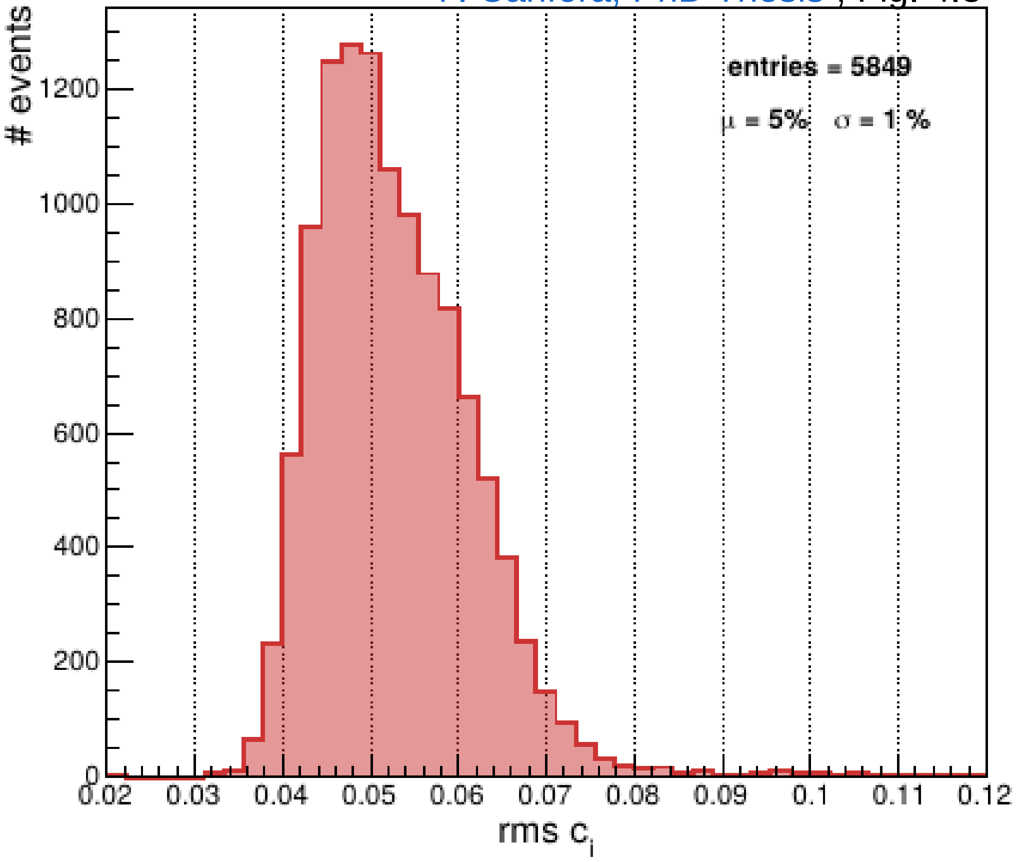
Potential effects on the energy resolution

- If antenna-to-antenna variation (on amplitude) of 5% is underestimated
  - Effects on analog gain will be easy to control and well below 5%
  - Data from AERA indicates 5% (F. Canfora, next slide)
  - Effects on directional response of antenna pattern under investigation
  - Affected by ambient conditions (due to reflection)
- If preliminary calibration is overestimating sensitivity of antennas
- If strong effects from ambient conditions which are not yet considered or monitoring, of those considered, to inaccurate
- If added noise is not representative
  - Will vary within the whole array
  - EA site (used here) is more radio quite than (loud) AERA site

Antenna-to-antenna variation for AERA Butterfly antennas

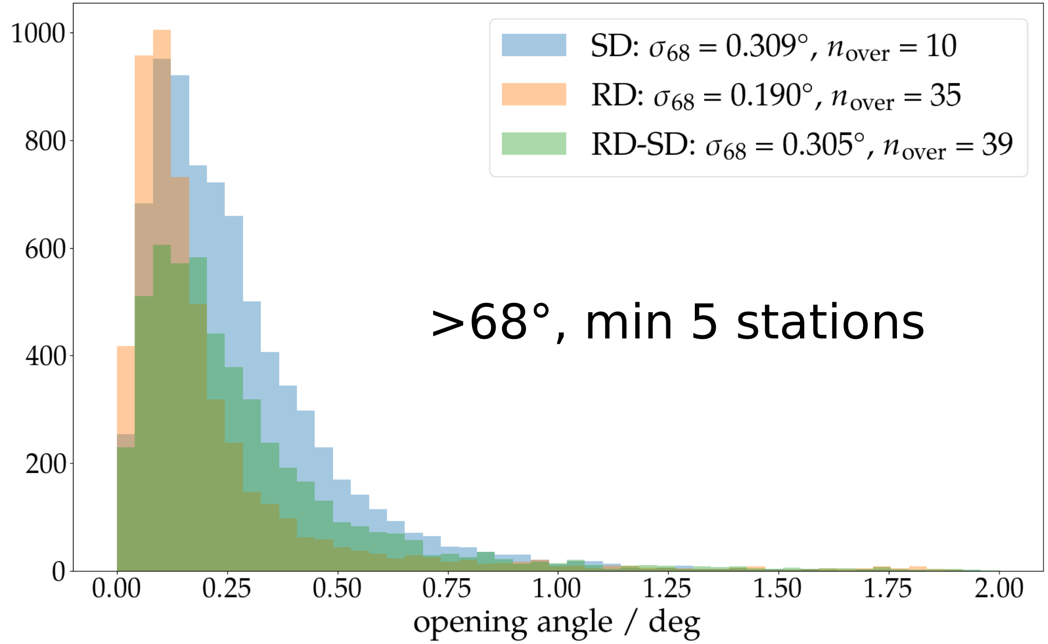
- After galactic calibration
- $$c_i = \frac{1}{n} \sum_{j=\nu_1}^{\nu_n} \frac{A(\nu_i)}{\overline{A}_{\nu_i}},$$ i: frequency bin
  - c_i: spread of amplitude(v) in single antenna over all antennas within 1 periodic trigger event
  - Average over polarization
- Calculate RMS(c_i) for each event (100s trigger)
- Use mean of RMS as error est.

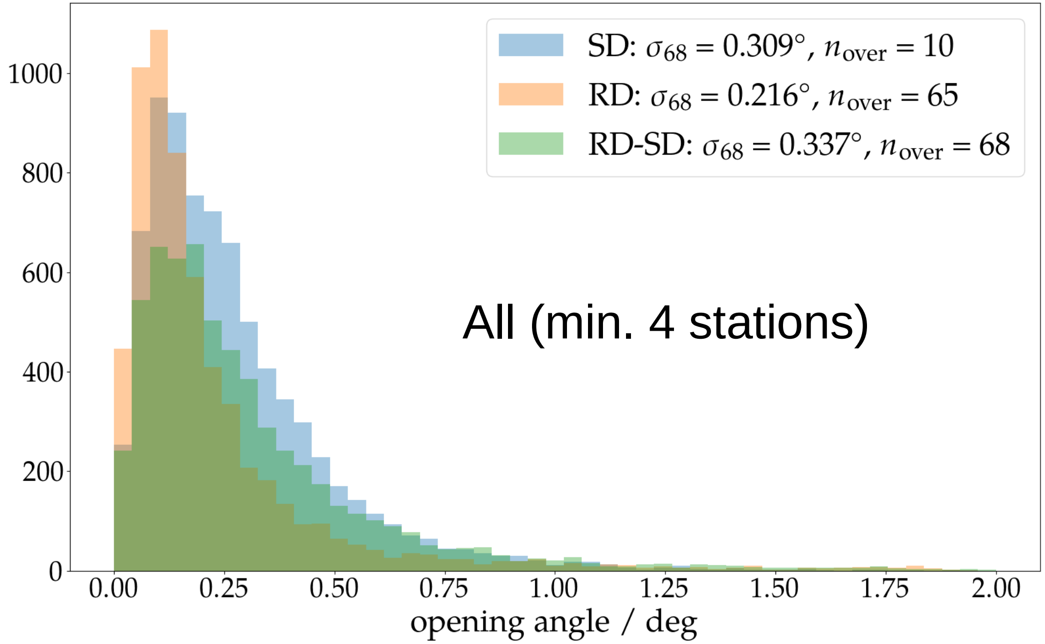
F. Canfora, PhD Thesis , Fig. 4.8



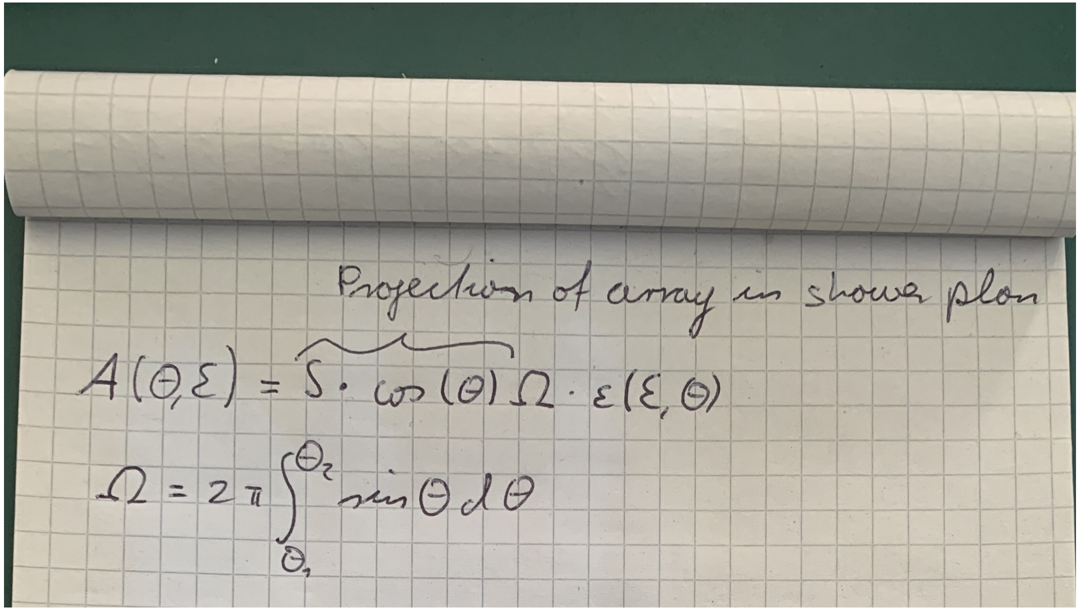
Arrival direction reconstruction

- RD: Spherical fit (point sources, spherical expansion, changing radius)





Aperture calculation



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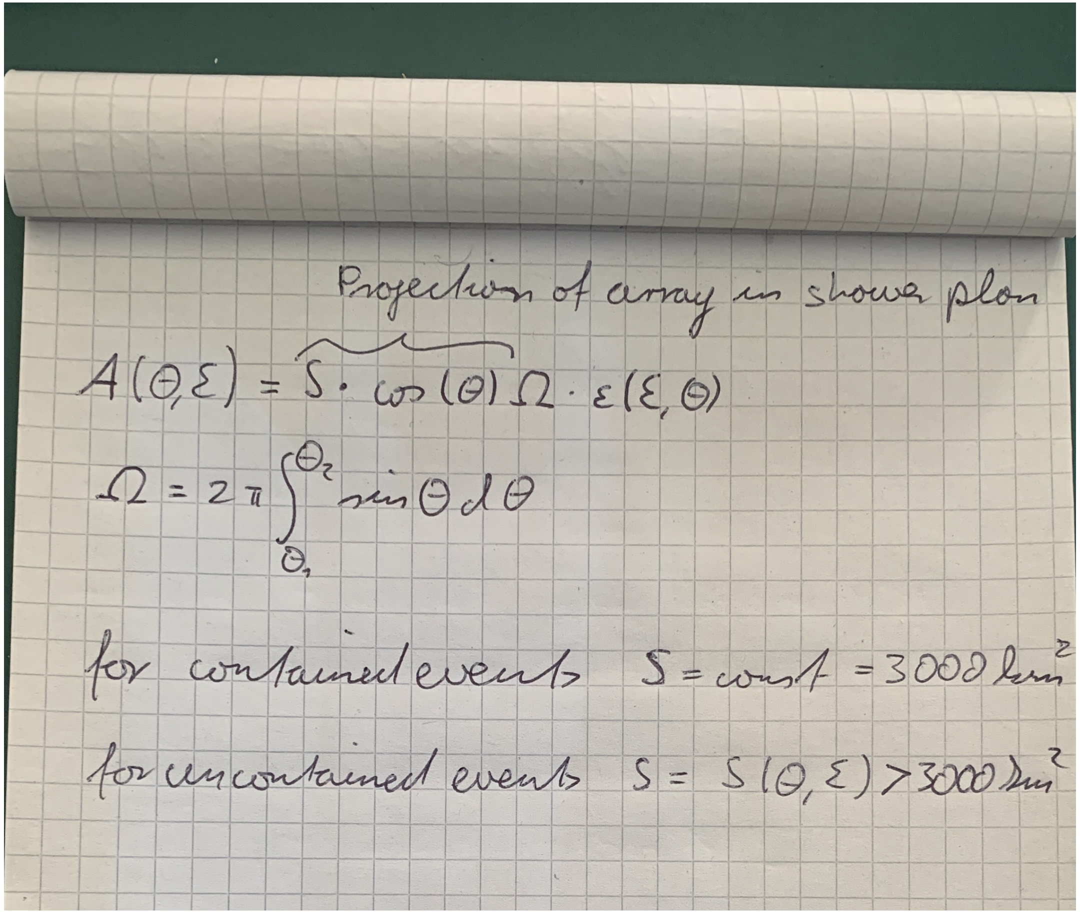
Aperture calculation



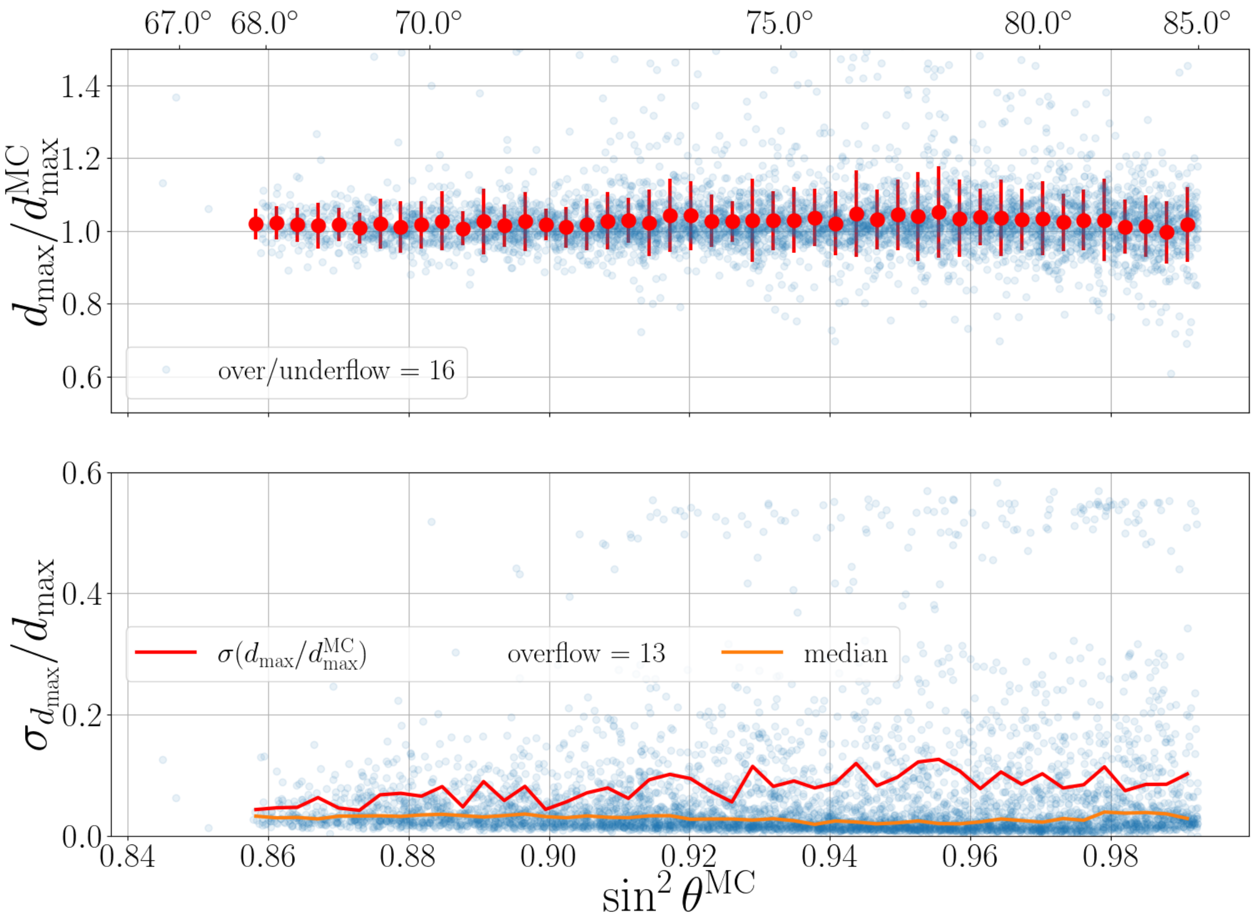
- Projection still limits aperture
- "effective" area increases
  - By how much
- Trade off between aperture and reconstruction quality

Aperture calculation

Back-of-the-envelope calculation:

- Imagine we can reconstruct a radio shower at 85 deg if core is not further away than 1 (1.8) km (in shower plane) from closest station
  ~ 11 (20) km in ground plane
  - Assuming Auger is a perfect circle: I**ncrease area from 3000 km2 to ~ 5500 (8000) km2**
- Issue: will SD trigger (and at which energies?) and how is the reconstruction quality
  - Only full MC can give us some serious answer
  - Worth it?

Uncertainties



Sources of uncertainties

- E_{geo} from fit
- $f_{corr}(\rho)$ propargated from d_{max} (from fit)
- S_{rad} also includes uncertainty in the geomagnetic angle
- Uncertainty on arrival direction is underestimated
- What might cause underestimation?
  - uncertainty model for station signal
  - error estimation from fit