Simulation of Radiation Energy Release in Air Showers

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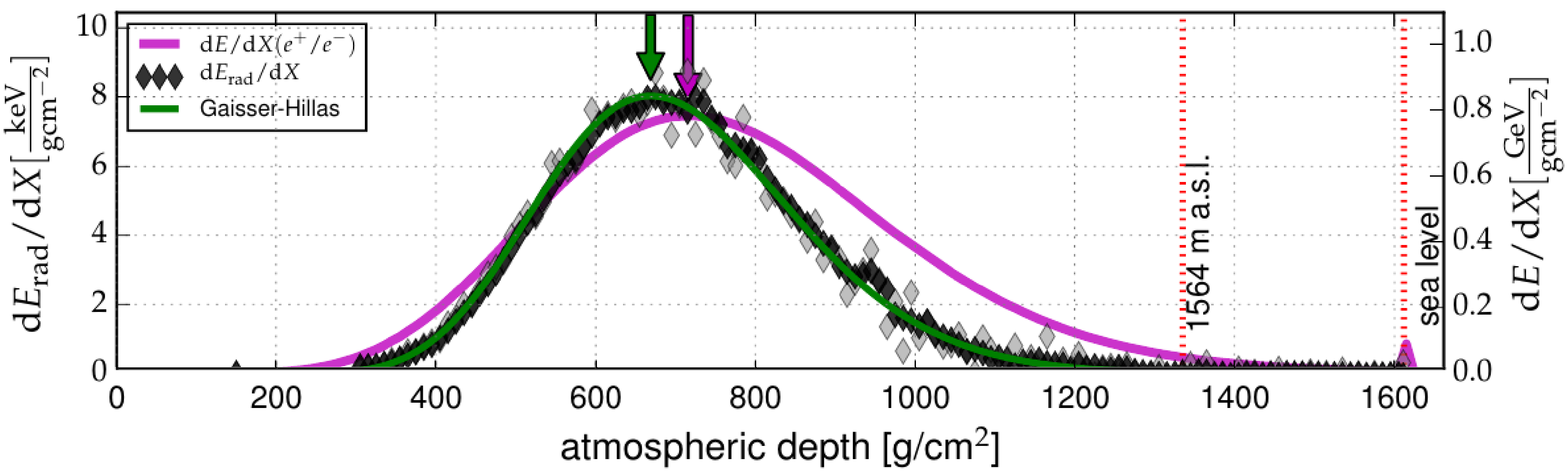
Tim Huege, Johannes Schulz



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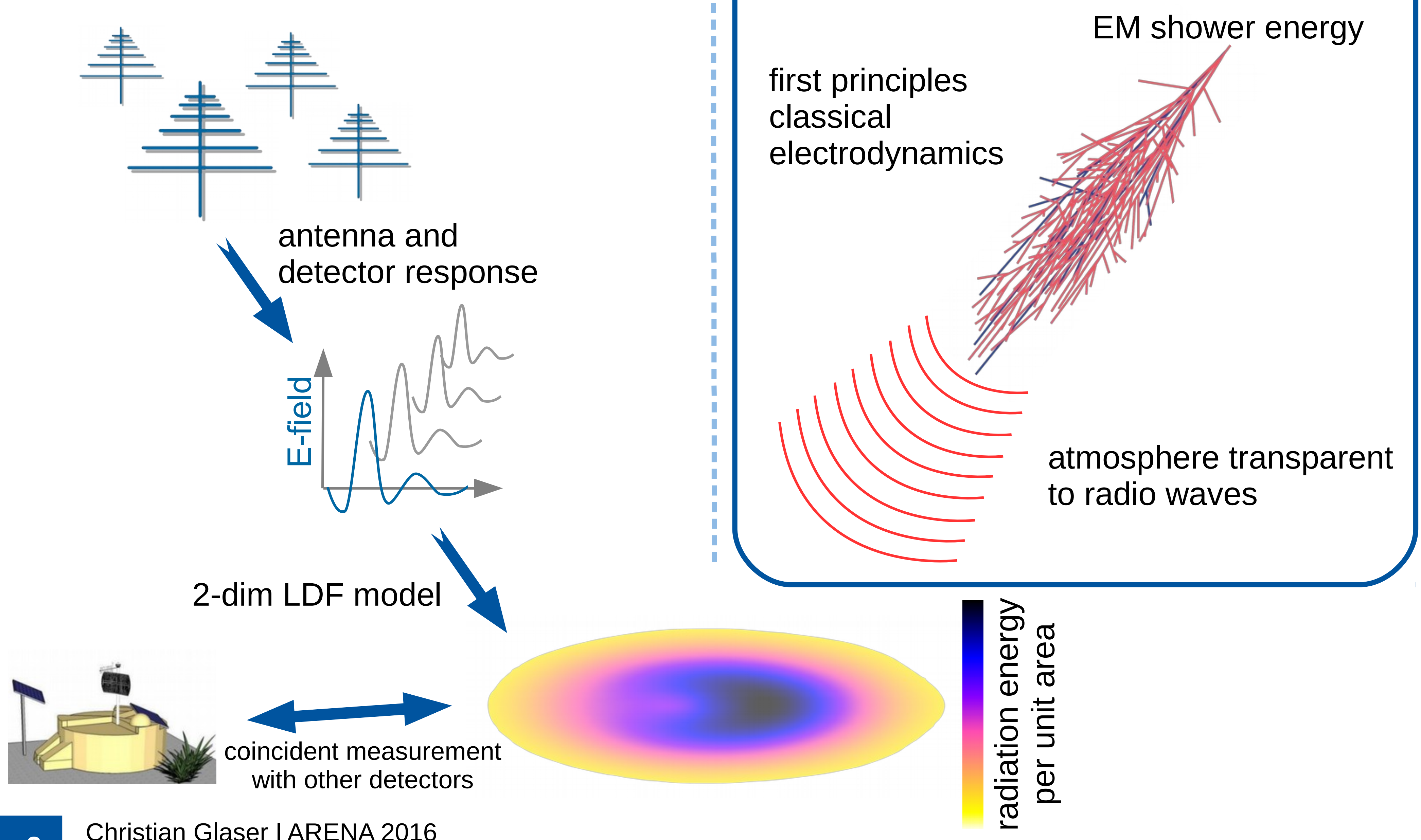
Independent Determination of Cosmic-Ray Energy Scale

Measurement

Theoretical calculation



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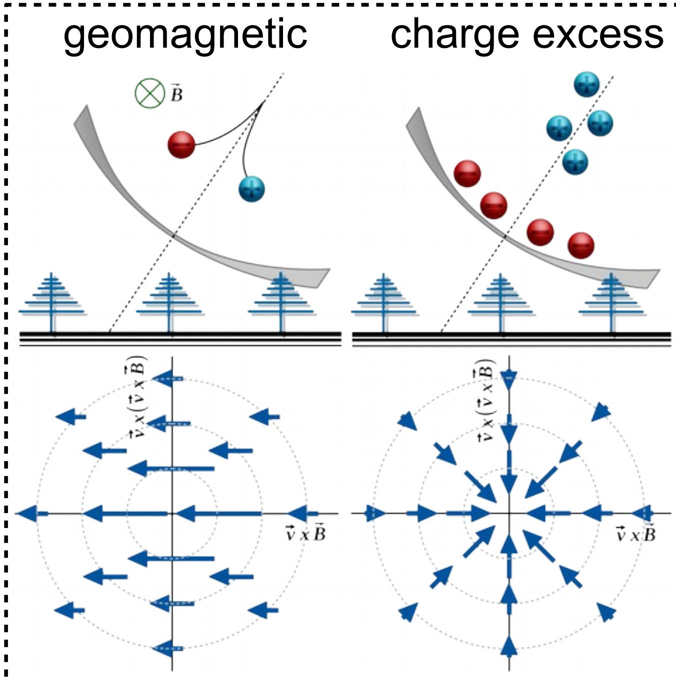
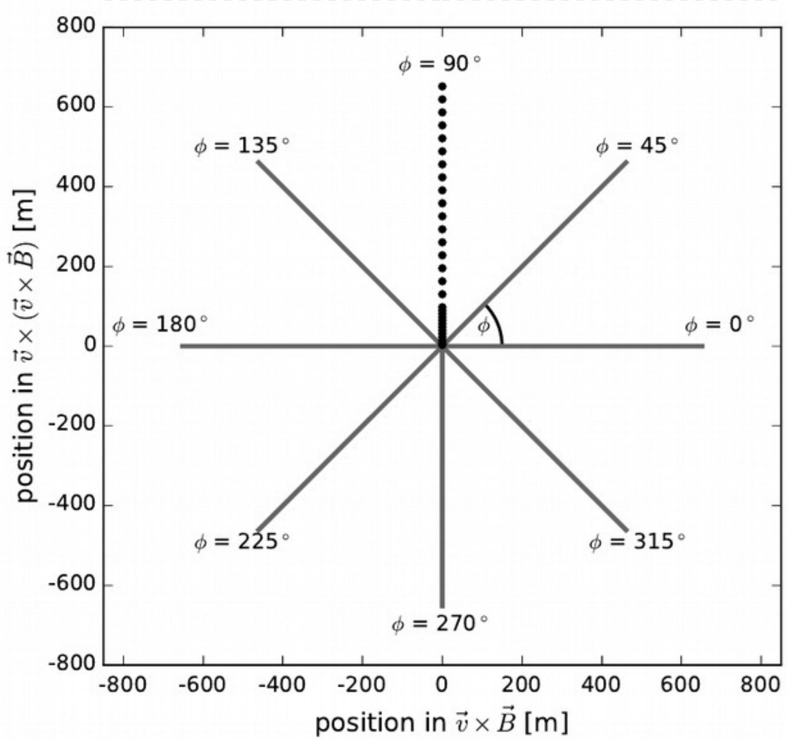
Simulation Study

- CoREAS (CORSIKA) with QGSJetII-04
- > 500 air showers
  - Energy uniform in log10 (1e17 – 1e19 eV)
  - Zenith angles up to 80°
  - Proton and iron primaries
- Efficient method to extract radiation energy
  - Uses radial symmetry of geomagnetic and charge-excess component
- $$E_{\mathrm{rad}} = 2\pi \int_0^\infty \mathrm{d}r\, r\, \left(f_{\mathrm{geo}}(r) + f_{\mathrm{ce}}(r)\right)$$
  $$= 2\pi \int_0^\infty \mathrm{d}r\, r\, \left(f_{\vec{v}\times\vec{B}}(r, \phi = 90°) + f_{\vec{v}\times(\vec{v}\times\vec{B})}(r, \phi = 90°)\right)$$
  - “Fast” simulation of radio footprint

→ detectors at different heights to determine longitudinal profile of radiation energy



- Polarized into direction of Lorentz force
- Radially polarized towards shower axis



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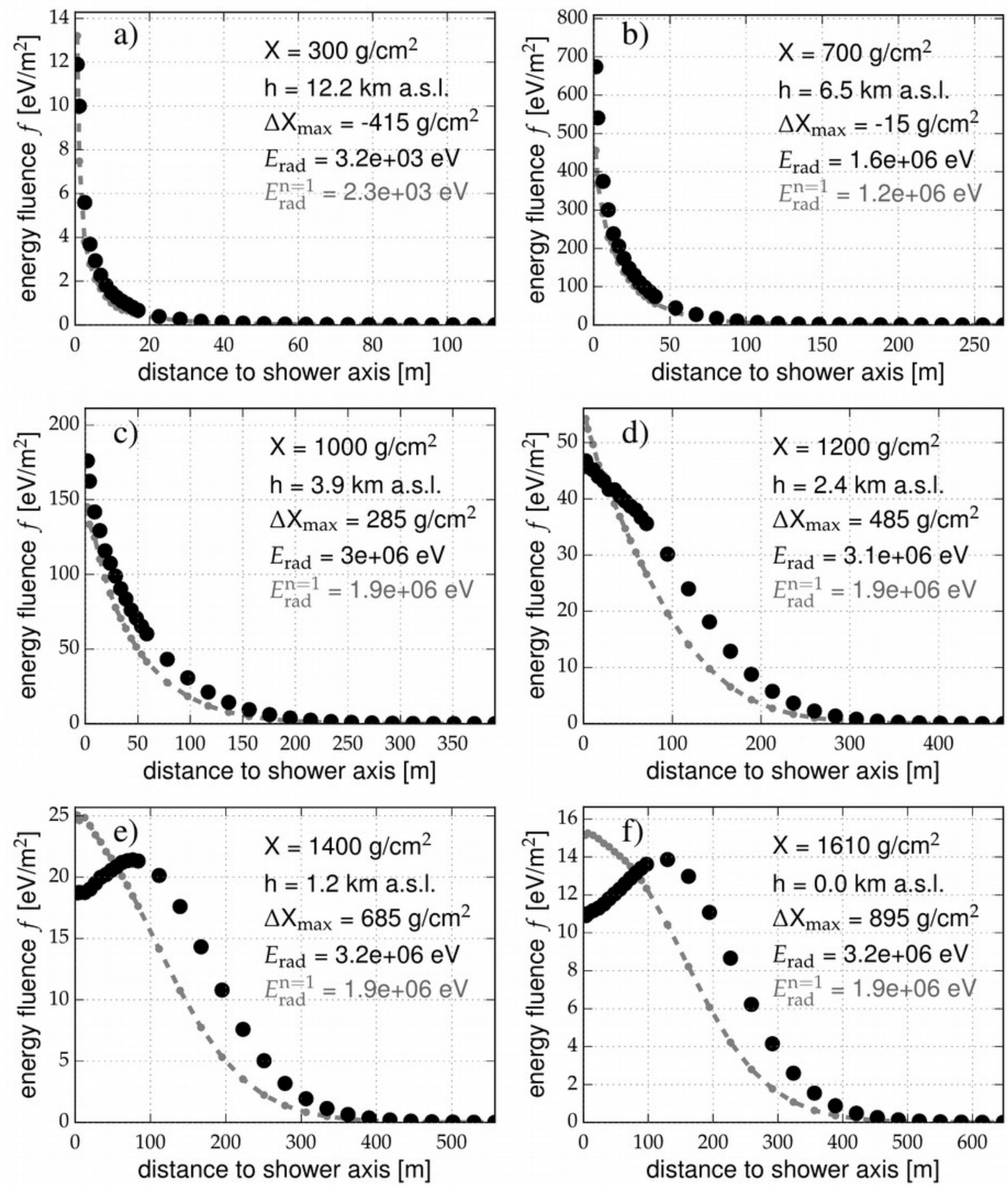
Lateral Signal Distribution at Different Heights

- LDF shape changes drastically with observation height
- Radiation energy via numerical integration



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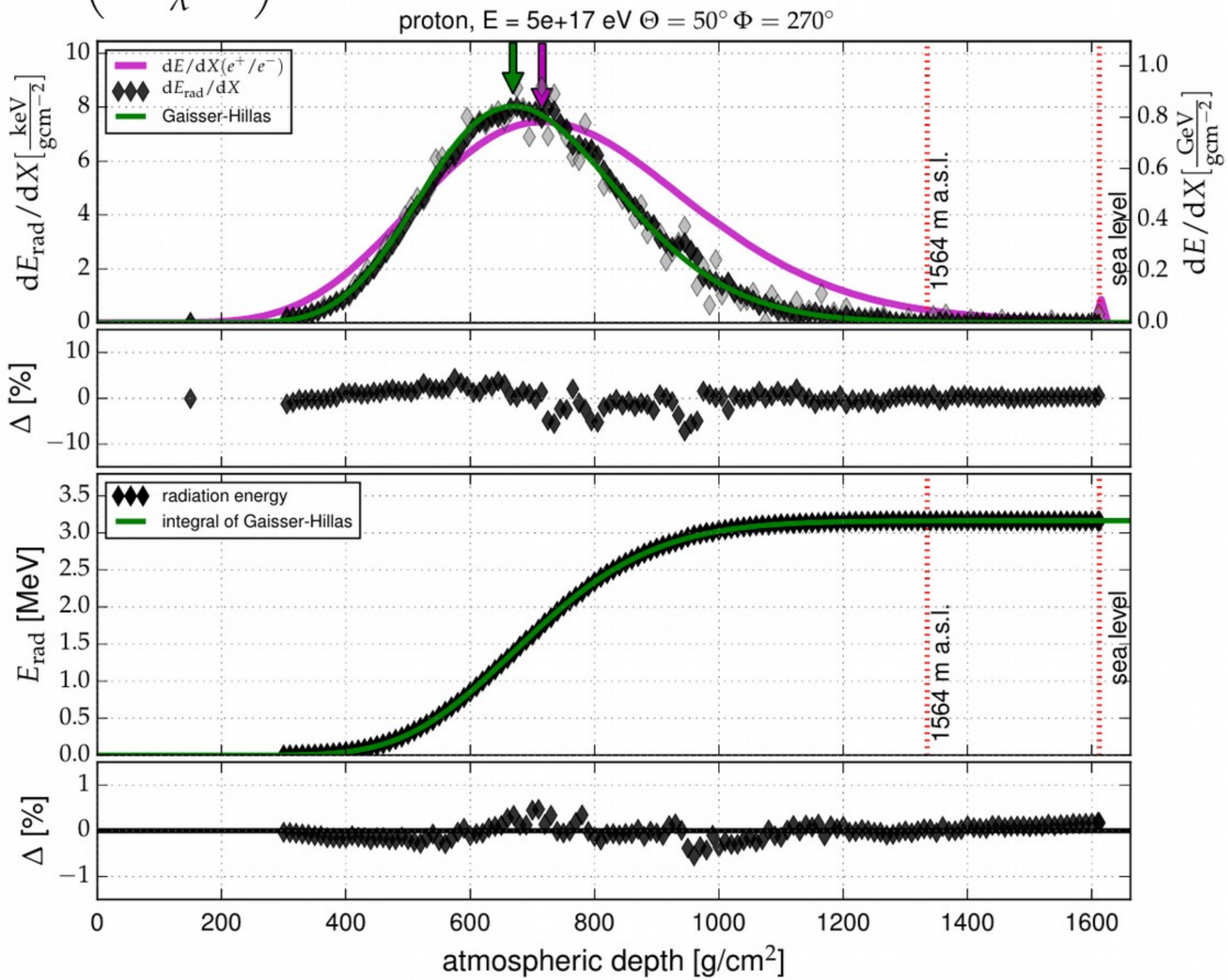
Longitudinal Profile of Radiation Energy Release

- $X_{\max}^{\text{rad}}$ before $X_{\max}$ of particle energy deposit dE/dX (~45 g/cm²)
- Profile described by Gaisser-Hillas function (3 parameters)
- $\frac{\mathrm{d}E_{\text{rad}}}{\mathrm{d}X}(X) = A \left(\frac{X}{X_{\max}^{\text{rad}}} \right)^{\frac{X_{\max}^{\text{rad}}}{\lambda}} \exp\left(\frac{X_{\max}^{\text{rad}} - X}{\lambda} \right)$



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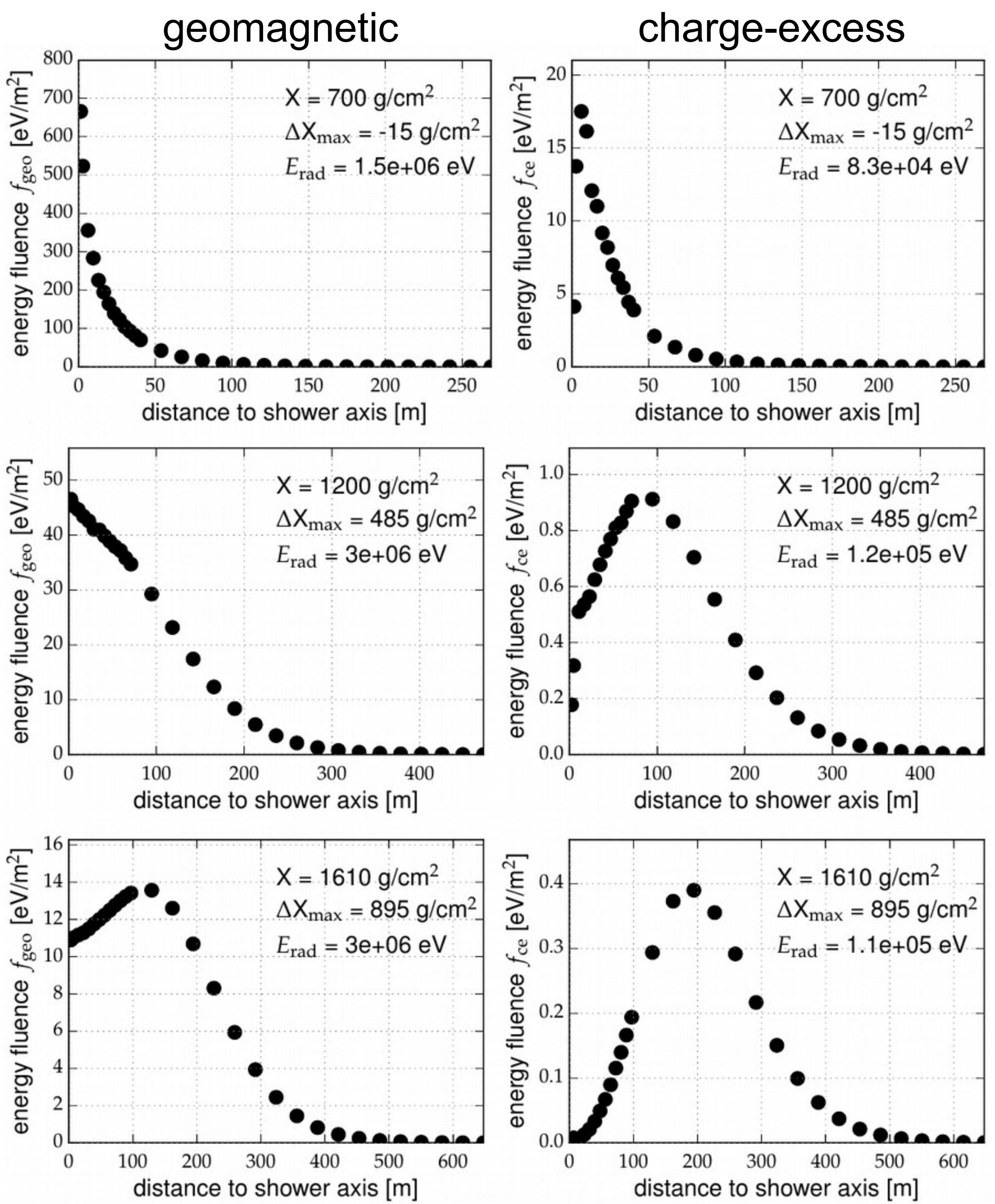
Decomposition into Radiation Processes

- Geomagnetic and charge-excess LDFs are different
- Charge-excess
  - Zero at shower axis



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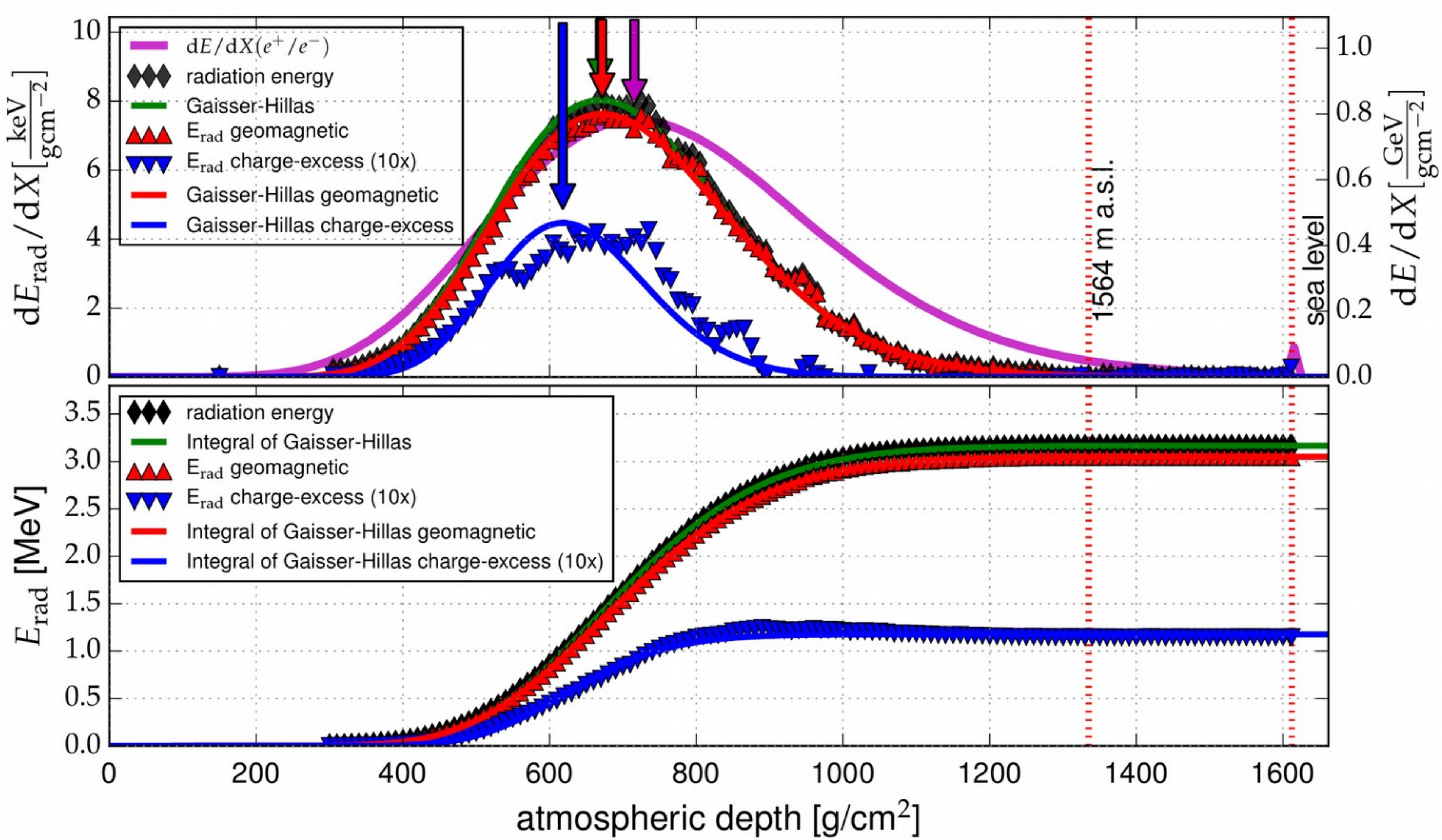
Longitudinal Profile of Radiation Energy Release

- Charge-excess develops earlier in the atmosphere (~85 g/cm²)



→ determine dependence of charge-excess fraction

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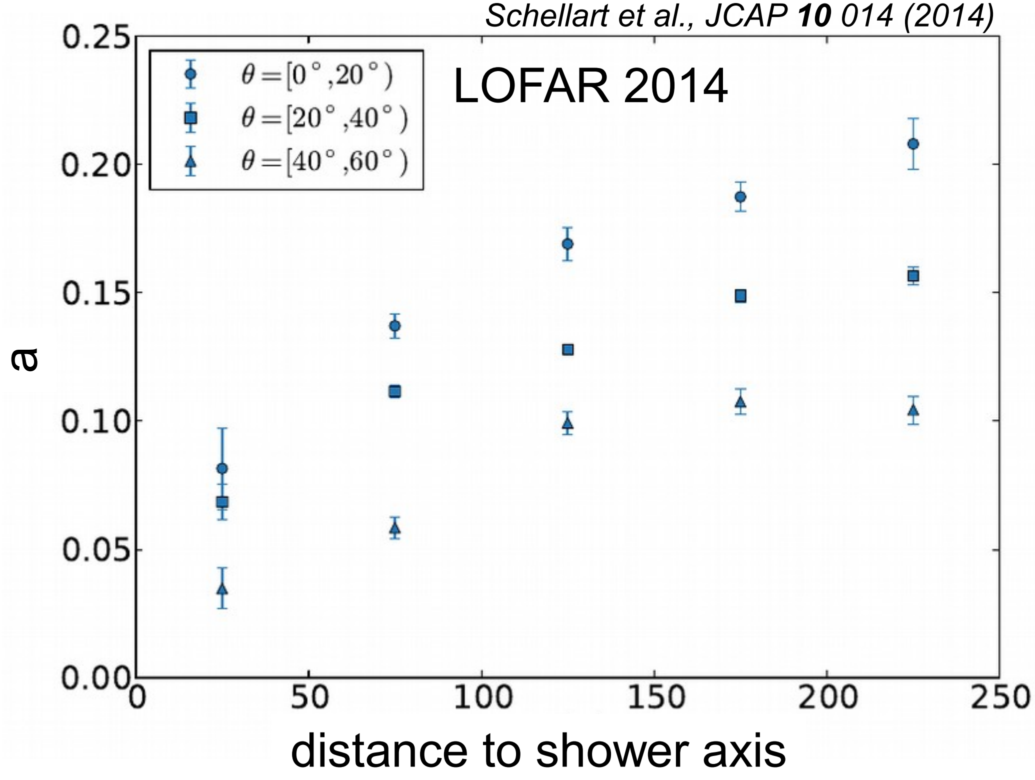
Charge-Excess Fraction

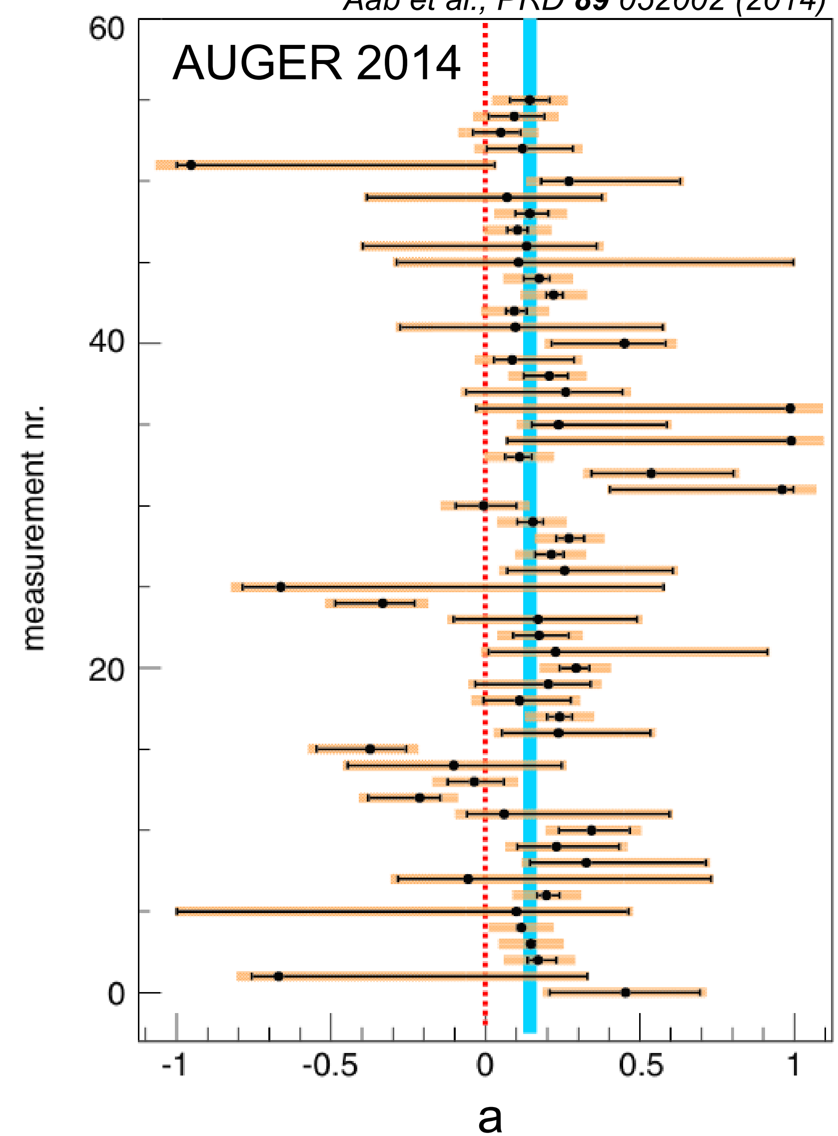
- *a* is ratio of electric field amplitudes
- *a* depends on distance to shower axis
  - encoded in different LDF shapes
- *a* depends on zenith angle

$$a = \sin\alpha \frac{|\vec{E}_{\mathrm{ce}}|}{|\vec{E}_{\mathrm{geo}}|}$$

Schellart et al., JCAP ***10*** *014 (2014)*



Aab et al., PRD ***89*** *052002 (2014)*



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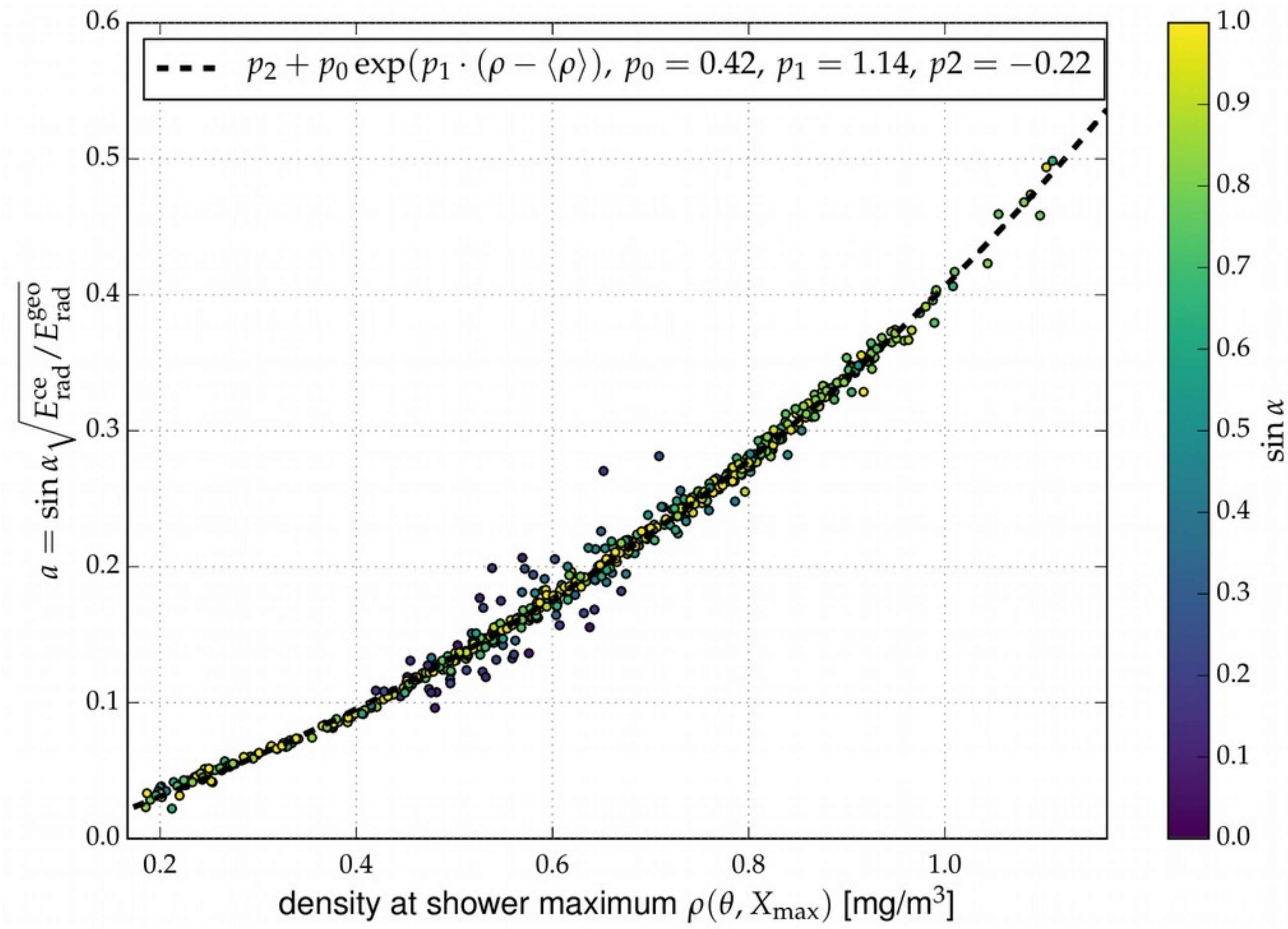
Charge-Excess Fraction

- Generalize definition of *a*: $$a = \sin\alpha \sqrt{\frac{E_{\mathrm{rad}}^{\mathrm{ce}}}{E_{\mathrm{rad}}^{\mathrm{geo}}}}$$
  - Distance dependence integrated out in determination of radiation energy
- *a* depends on zenith angle
  - True dependency: *a* depends on atmospheric density



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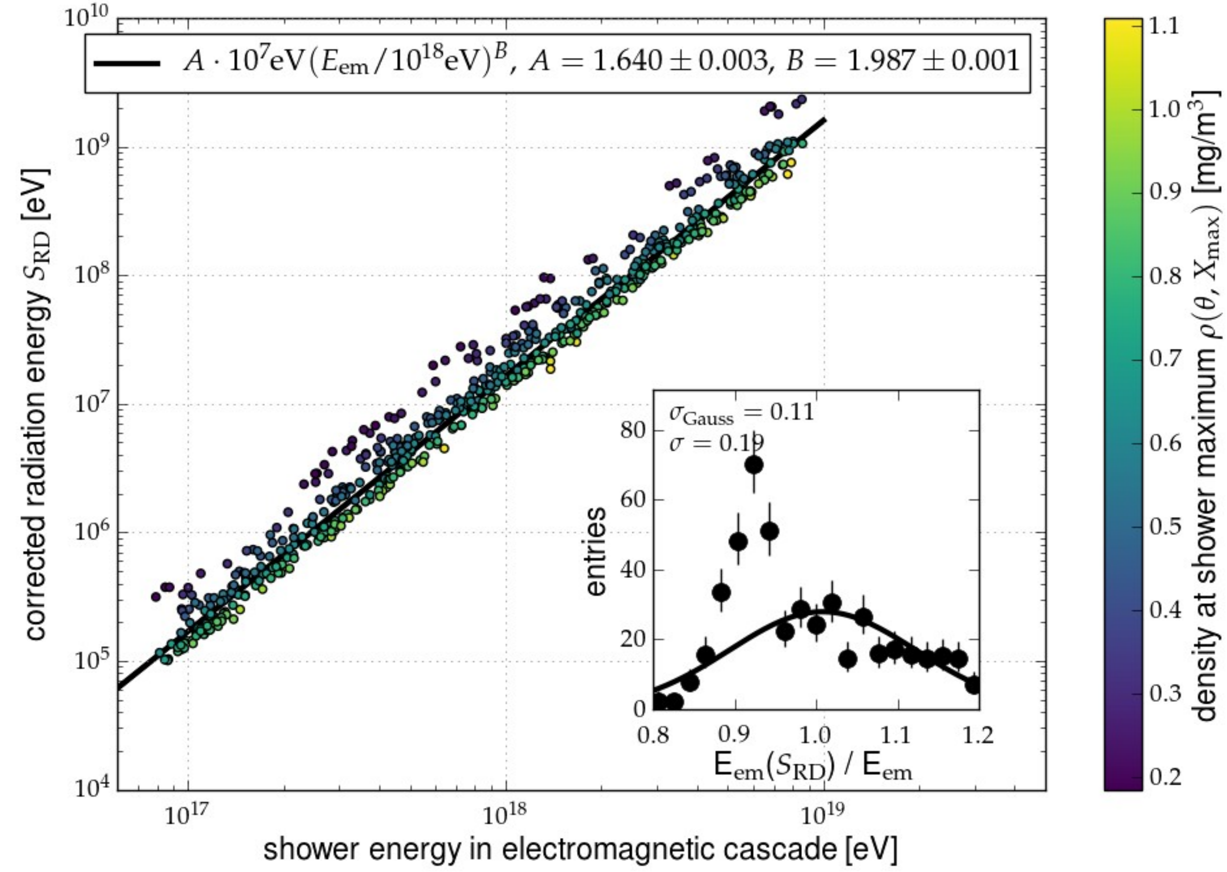
Correlation with EM Shower Energy

- Radiation energy is sum of geomagnetic and charge-excess radiation energies
- Correct only geomagnetic radiation energy with sin α
  - $$S_{\mathrm{RD}} = \frac{E_{\mathrm{rad}}}{a(\rho_{X_{\max}})^2 + (1 - a(\rho_{X_{\max}})^2)\sin^2\alpha}$$



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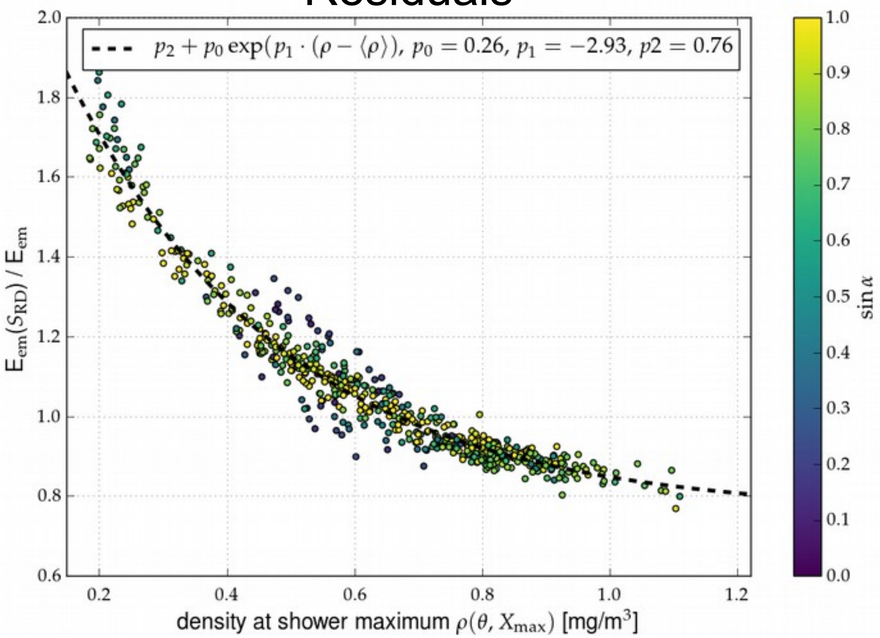
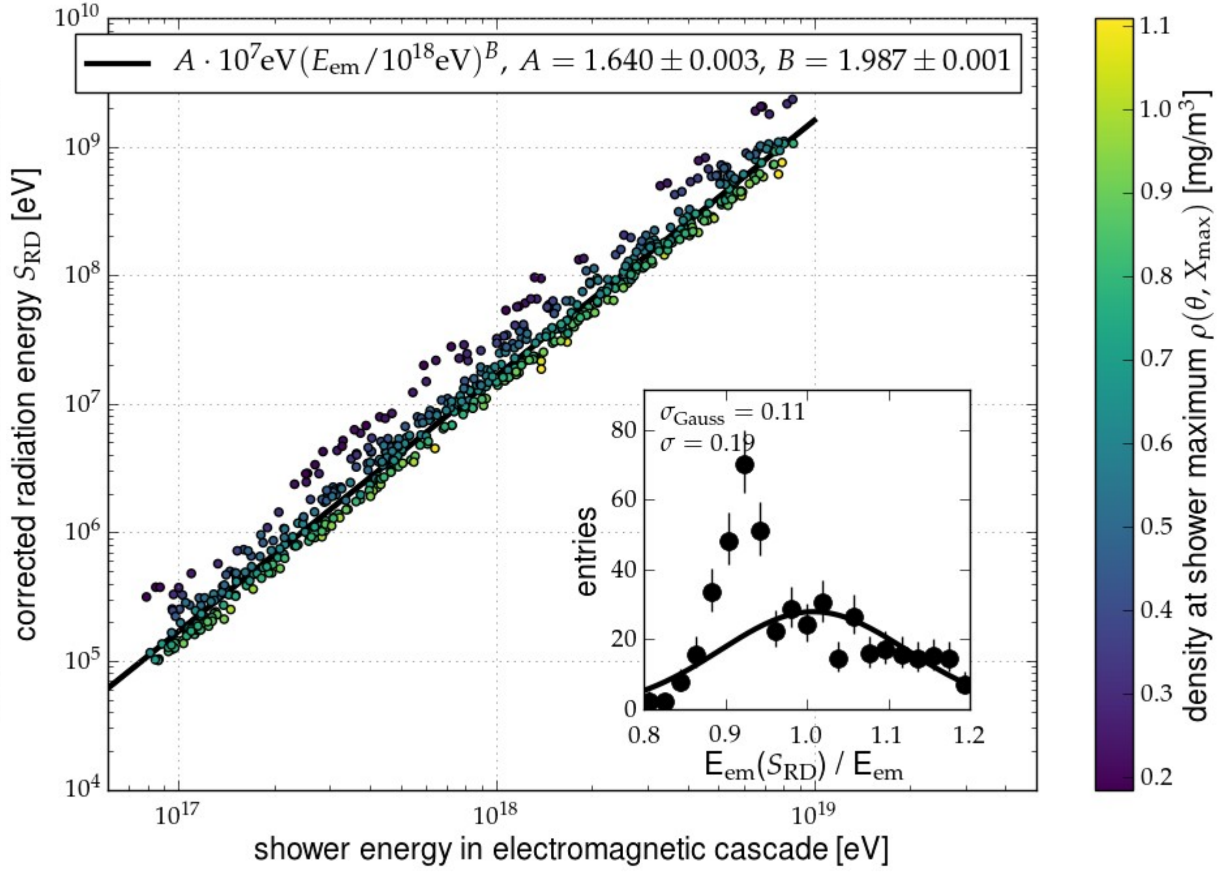
- Correct only geomagnetic radiation energy with sin α
  - ➔ $S_{RD} = \frac{E_{rad}}{a(\rho_{X_{max}})^2 + (1 - a(\rho_{X_{max}})^2)\sin^2\alpha}$

Residuals





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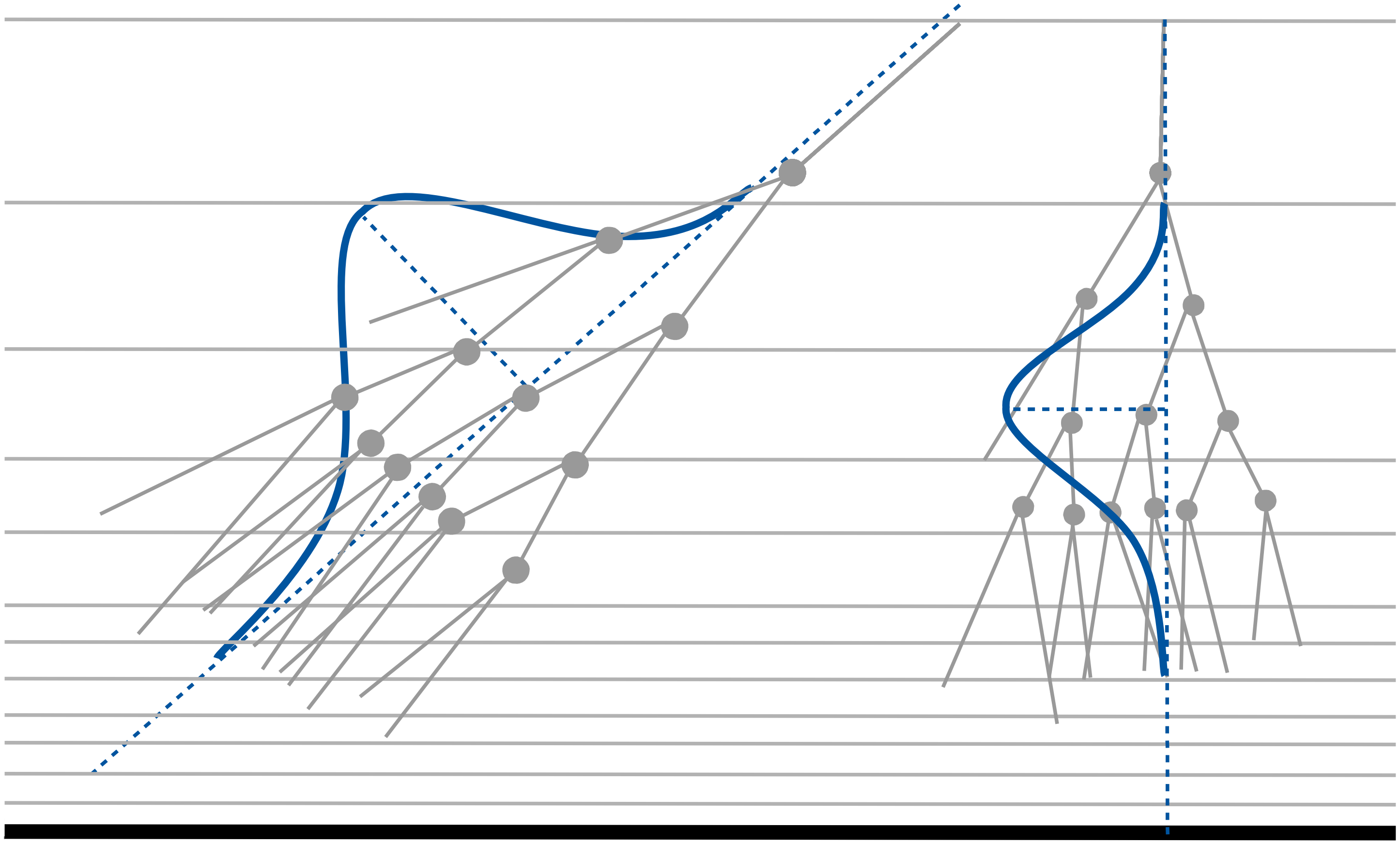
2^{nd} Order Dependencies

- Shower development ~ slant depth
- Radiation ~ geometric path length
  - more radiation energy for showers that develop early in the atmosphere
- Parametrized via atm. density at shower maximum
  - 1^{st} order: zenith angle
  - 2^{nd} order: X_{max}



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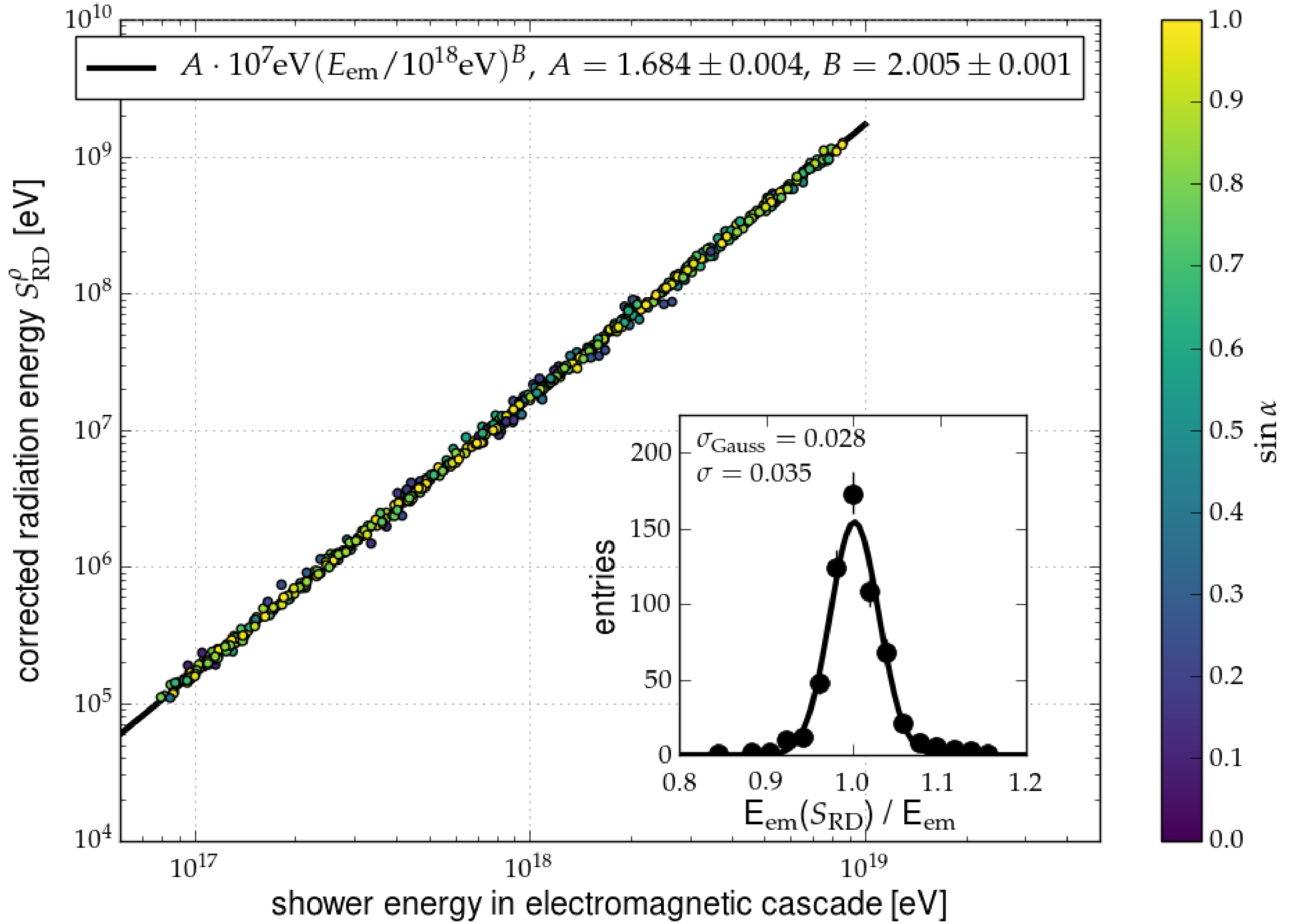
Correlation with EM Shower Energy

- Improved energy estimator
  - ➔ $$S_{RD}^{\rho} = \frac{E_{rad}}{a(\rho_{X_{max}})^2 + (1 - a(\rho_{X_{max}})^2)\sin^2\alpha} \frac{1}{(1 - p_0 + p_0 \exp[p_1(\rho_{X_{max}} - \langle\rho\rangle)])^2}$$
- Energy resolution ~3%
- All parameters determined in combined χ² fit

A	1.684 ± 0.004
B	2.005 ± 0.001
p_0	0.260 ± 0.007
p_1	-2.81 ± 0.06 mg^{-1} m^3



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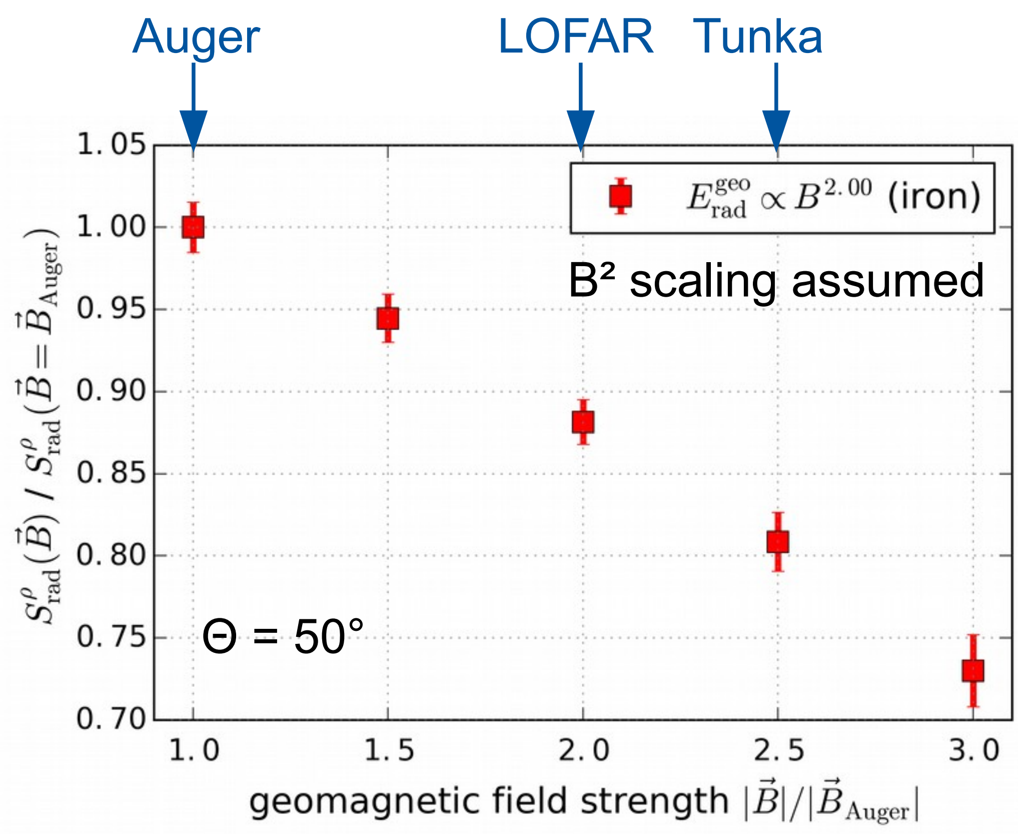
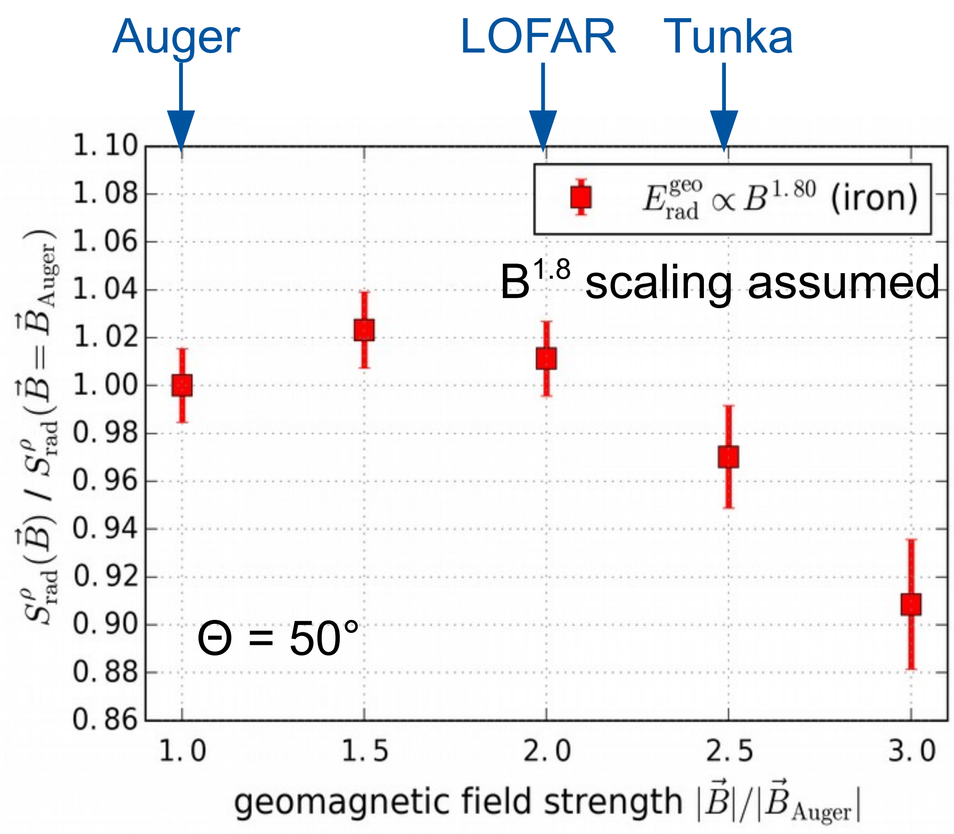
Scaling with Geomagnetic Field

- Add geomagnetic field correction
  - $$S^{\rho}_{\mathrm{RD}} = \frac{E_{\mathrm{rad}}}{a(\rho_{X_{\max}})^2 + (1 - a(\rho_{X_{\max}})^2)\sin^2\alpha \left(\frac{B_{\mathrm{Earth}}}{0.243\,\mathrm{G}}\right)^{1.8}} \frac{1}{(1 - p_0 + p_0 \exp[p_1(\rho_{X_{\max}} - \langle\rho\rangle)])^2}$$
- Significant deviation from quadratic scaling
  - Effective scaling ~$B^{1.8}$
- Additional dependence on zenith angle

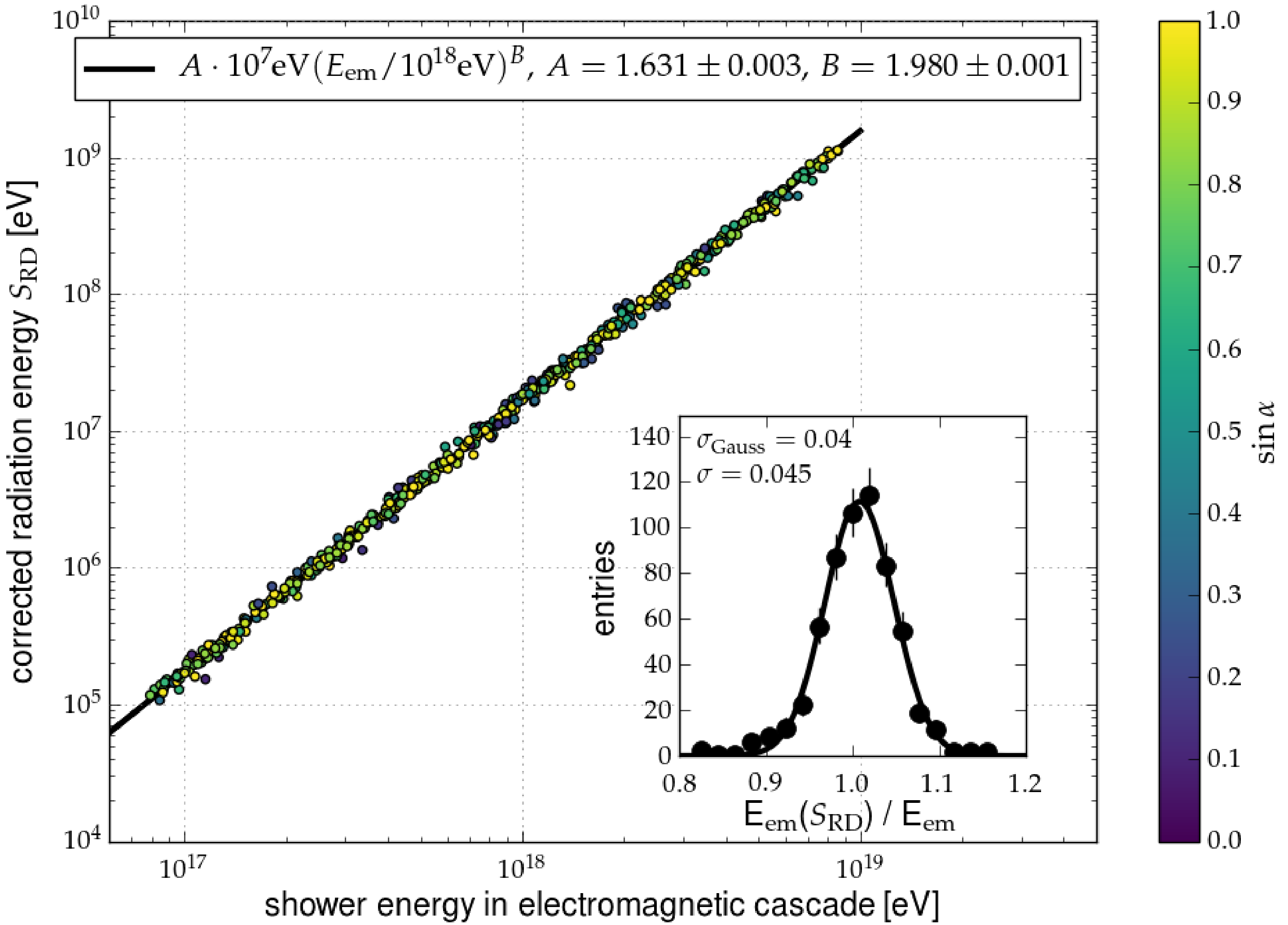




Suitable Energy Estimator for a Measurement

- Energy estimator without usage of X_{max}
  - ➔ $$S_{\mathrm{RD}}^{\rho_\theta} = \frac{E_{\mathrm{rad}}}{a(\rho_\theta)^2 + (1 - a(\rho_\theta)^2)\sin^2\alpha \left(\frac{B_{\mathrm{Earth}}}{0.243\,\mathrm{G}}\right)^{1.8}} \frac{1}{(1 - p_0 + p_0 \exp[p_1(\rho_\theta - \langle\rho\rangle)])^2}$$
- Energy resolution ~4%
- All parameters determined in combined χ² fit

A	1.631 ± 0.003
B	1.980 ± 0.001
p_0	0.252 ± 0.008
p_1	$-2.94 \pm 0.07\ \mathrm{mg}^{-1}\ \mathrm{m}^3$



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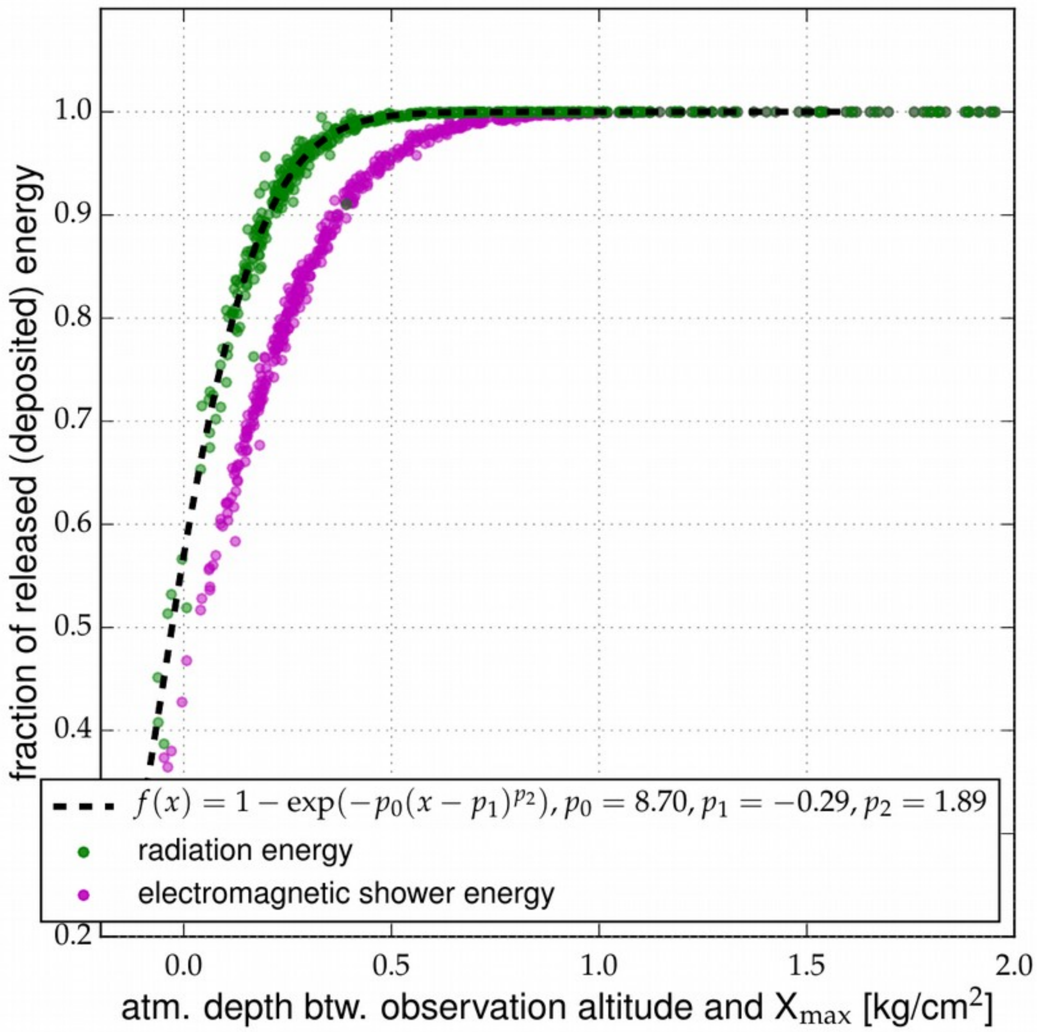
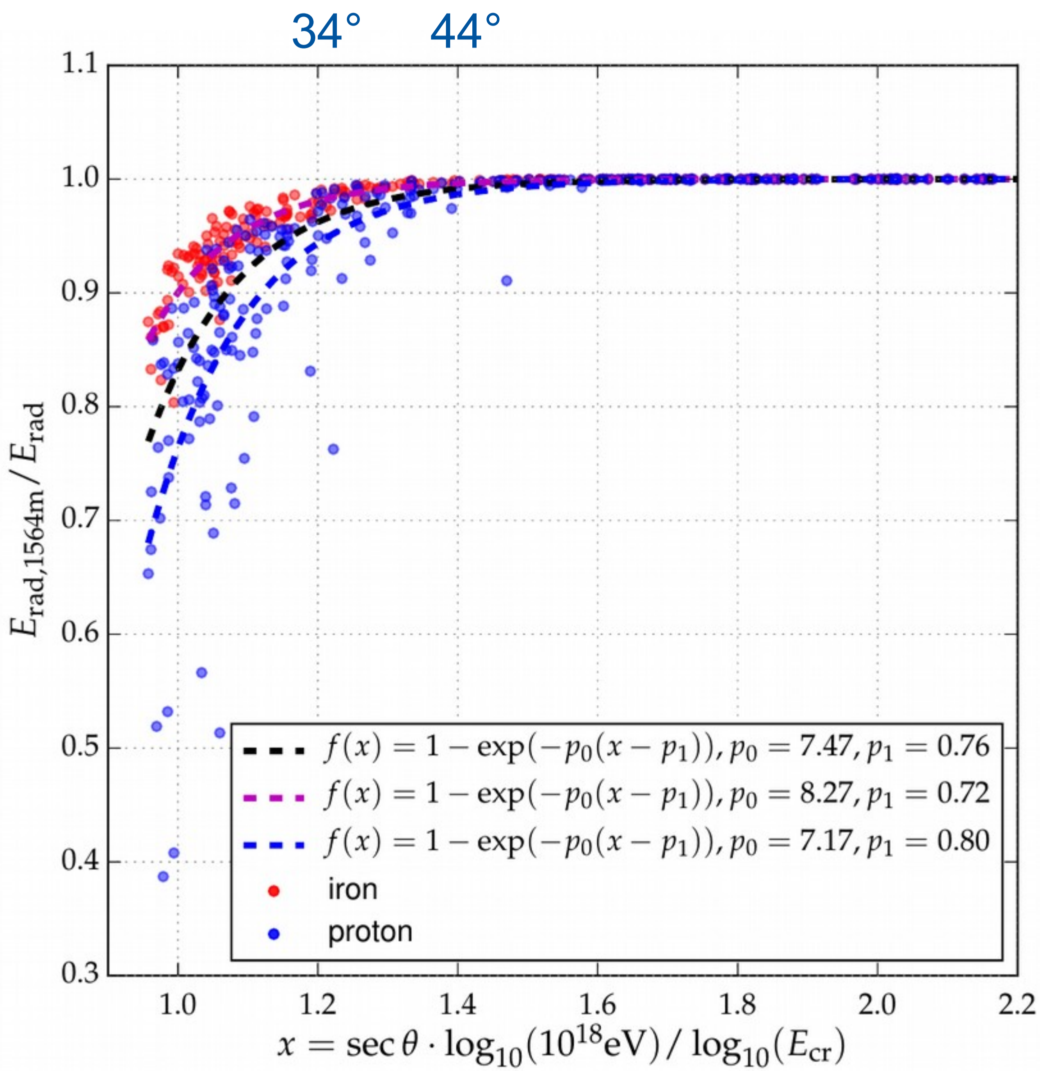
Clipping

- Air shower may hit ground before radiating all radiation energy
  - ➔ Less clipping than electromagnetic shower





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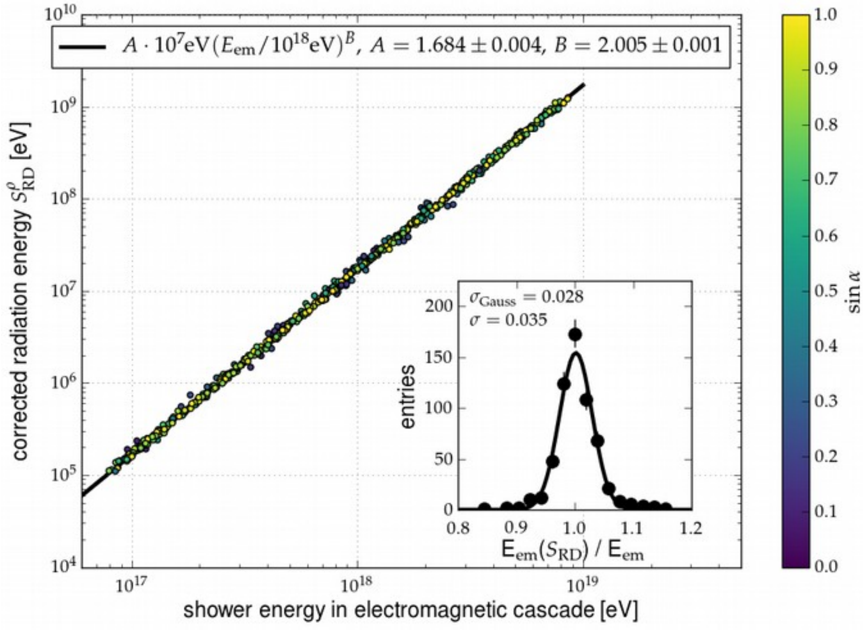
Summary

- Efficient method to obtain radiation energy from simulations
- Longitudinal profile of radiation energy release
  - LDF shape changes strongly with atmospheric depth
  - Radiation $X_{\mathrm{max}}^{\mathrm{rad}}$ ~45 g/cm² smaller than particle X_{max} (dE/dX)
- Charge-excess fraction depends on atm. density
- Radiation energy scales
  - 1^{st} order: EM shower energy
  - 2^{nd} order: Density at X_{max}
  - Energy resolution 3%
- Geomagnetic field dependence ~$B^{1.8}$
- Outlook
  - Determination of absolute energy scale
- More information: arXiv:1606.01641



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Backup

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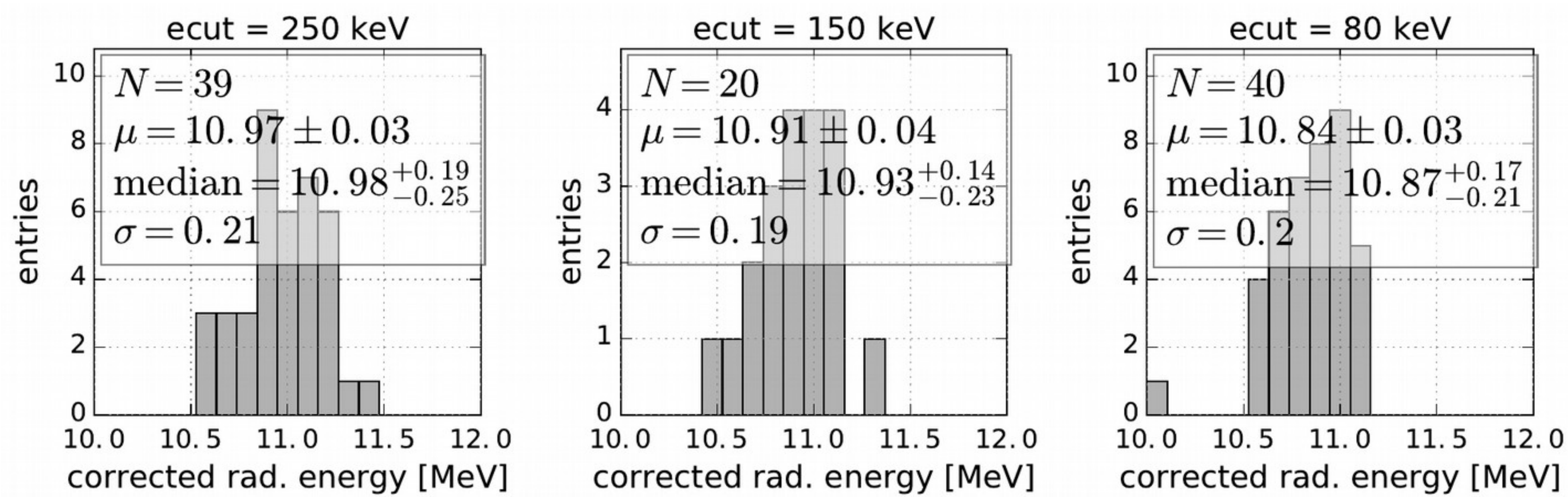
Influence of Settings of the Air-Shower Simulation

- Small dependence on air refractivity
  - ± 5% in refractivity results in ± 1.5% in radiation energy
- Choice of hadronic interaction model irrelevant
  - EPOS-LHC and QGSJetII-04 give same result
  - FLUKA and UrQMD give same result
- Thinning level of at least 10^{-5} is sufficient
- Small dependence on energy threshold of electromagnetic shower particles



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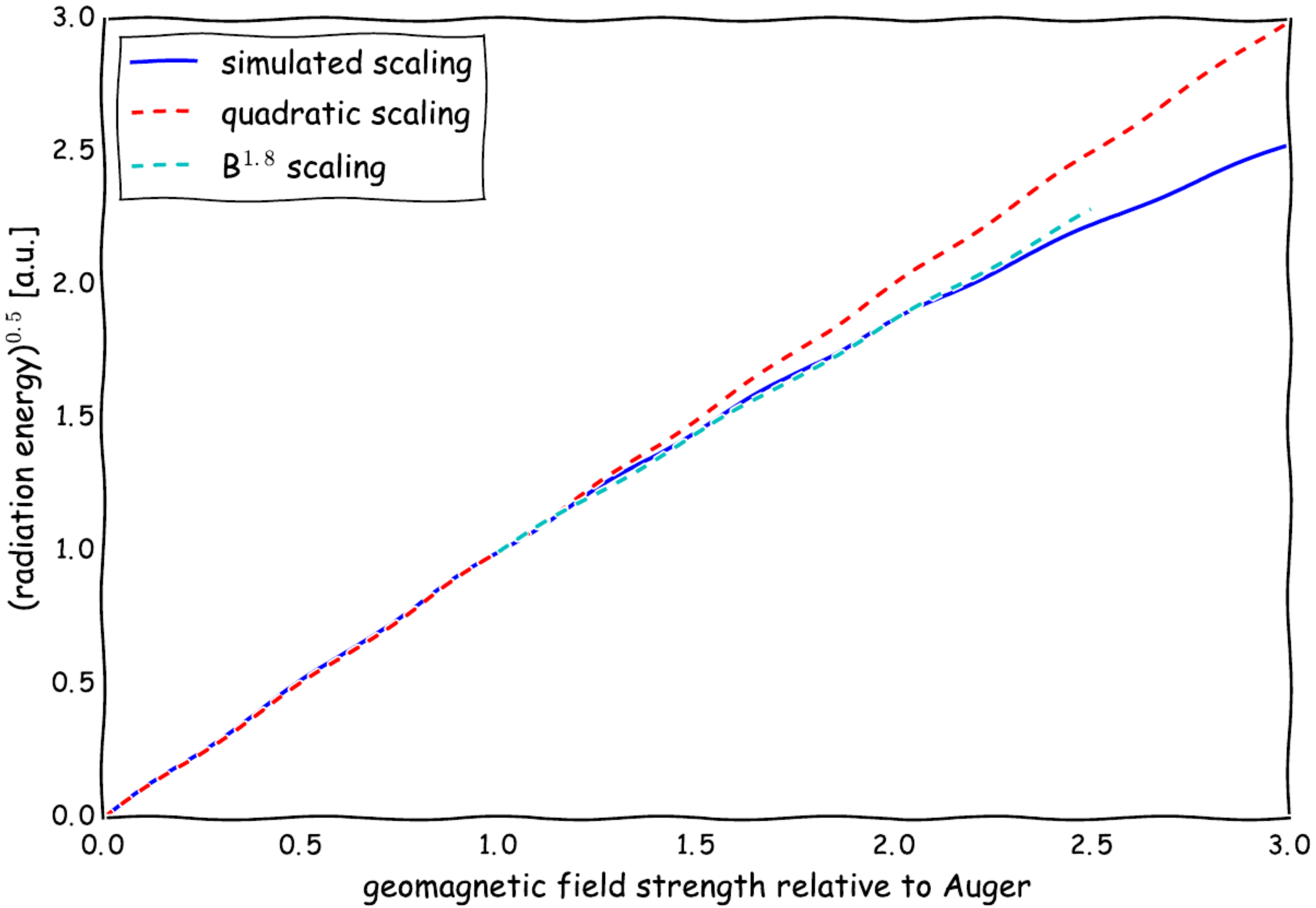
Scaling with the Geomagnetic Field



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