# Systematic uncertainty of first-principle calculations of the radiation energy emitted by EAS

**Marvin Gottowik, Christian Glaser, Tim Huege and Julian Rautenberg**

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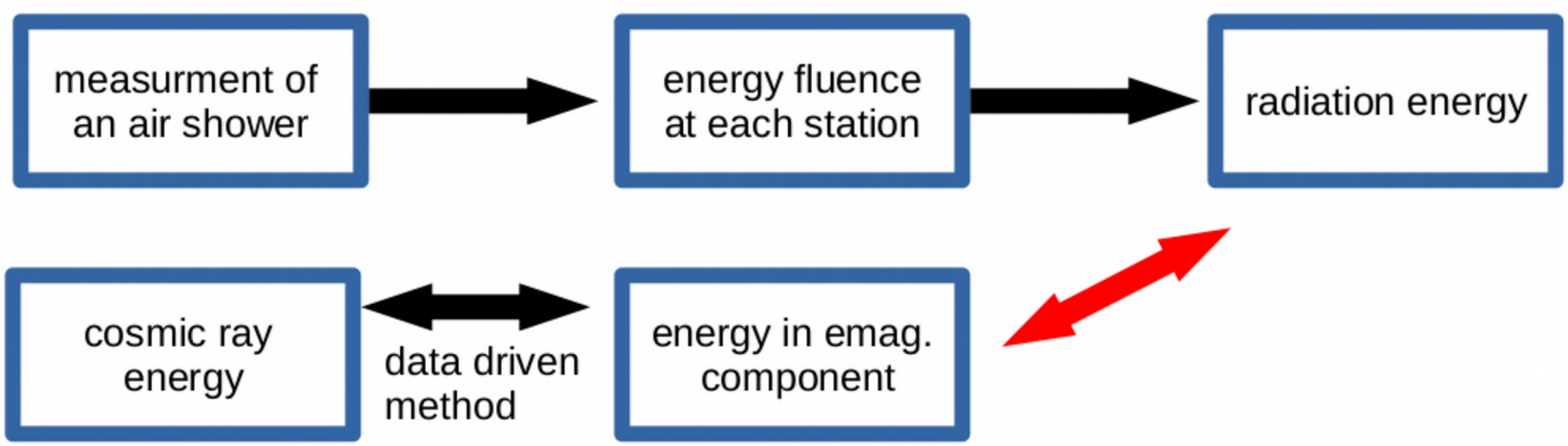
# Energy Estimation

- Estimate CR energy based on radio emission
  1) Signal at reference distance
  2) **Total emitted radio signal (radiation energy)**
- $E_{rad}$ propotional to electromagnetic energy
- Can be calculated using first principles
- Shower property, i.e. detector independent



# Energy Scale

- Determination of energy scale with radio
- „Radio yield“ given by first principle calculation
- Estimate systematic uncertainty of „radio yield“ with CoREAS and ZHAireS simulations
- @Auger: Phys. Rev. D 93, 122005 (2016)

$$E_{30-80\,\mathrm{MHz}} = (15.8 \pm 0.7(\mathrm{stat}) \pm 6.7(\mathrm{sys}))\,\mathrm{MeV} \times \left(\sin\alpha\,\frac{E_{\mathrm{CR}}}{10^{18}\,\mathrm{eV}}\,\frac{B_{\mathrm{Earth}}}{0.24\,\mathrm{G}}\right)^2,$$

- 6.7 (sys): 28% on radio, 16% on SD energy scale

# Systematics at Auger

| source of uncertainty | $\sigma_{\lvert\vec{E}\rvert}$ | $\sigma_{S_{\text{radio}}}$ |
|---|---|---|
| **event-by-event** | | |
| temperature dependence | 4% | 8% |
| angular dependence of antenna response pattern | 5% | 10% |
| reconstructed direction | negligible | negligible |
| LDF fit uncertainty | - | error propagation of fit parameters |
| **total event-by-event uncertainty** | **6.4%** | **12.8% $\oplus$ fit uncertainty** |
| **absolute scale** | | |
| absolute scale of antenna response pattern | 12.5% | 25% |
| analog signal chain | 6% | 12% |
| LDF model | <2.5% | <5% |
| **total absolute scale uncertainty** | **14%** | **28%** |

Phys. Rev. D 93, 122005 (2016)

- Antenna response reduced ~10%

  → total uncertainty ~16%

# Simulation Setup

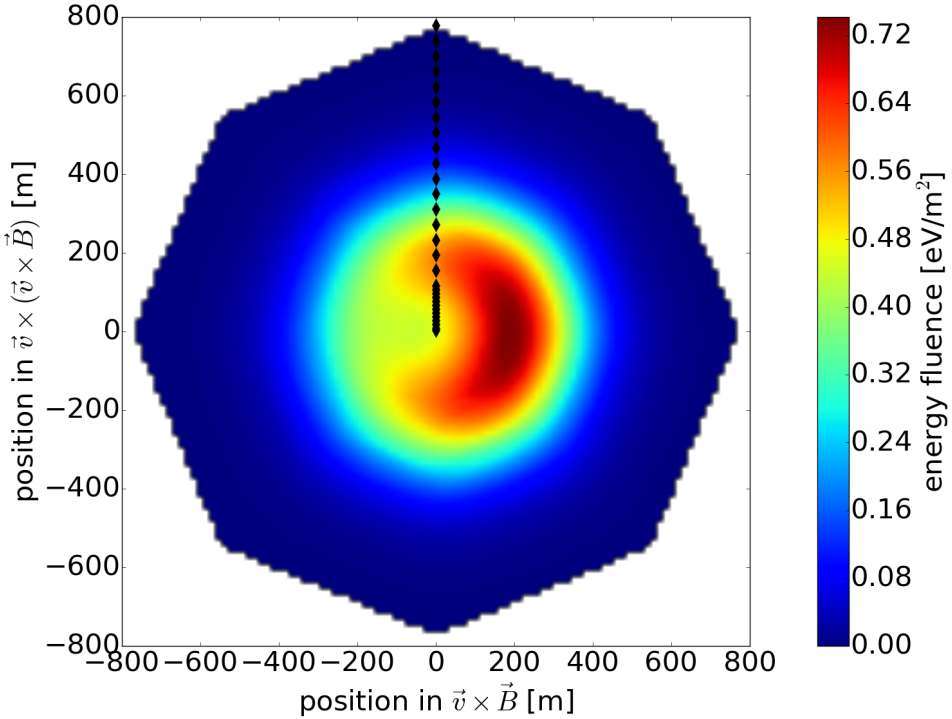
- Air Shower
  - CORSIKA 7.4100 (Oct. 12, 2015), Aires 2.8.4a (Dec. 12, 2006)
  - SIBYLL 2.1 as hadronic interation model
  - Endpoint formalism vs. ZHS algorithm
- Simulation
  - Exp. Scaling of refractive index
  - Proton and iron primary with energy in 100 PeV – 10 EeV
  - Azimuth in 0° - 360°, zenith 0° - 75°
- Technical Parameters:
  - Low E had. interaction model, thinning, trace lengths

# Radiation Energy

- Electrical field only in shower plane
- Computation of energy fluence *f* on $v \times (v \times B)$ axis
- Radiation energy

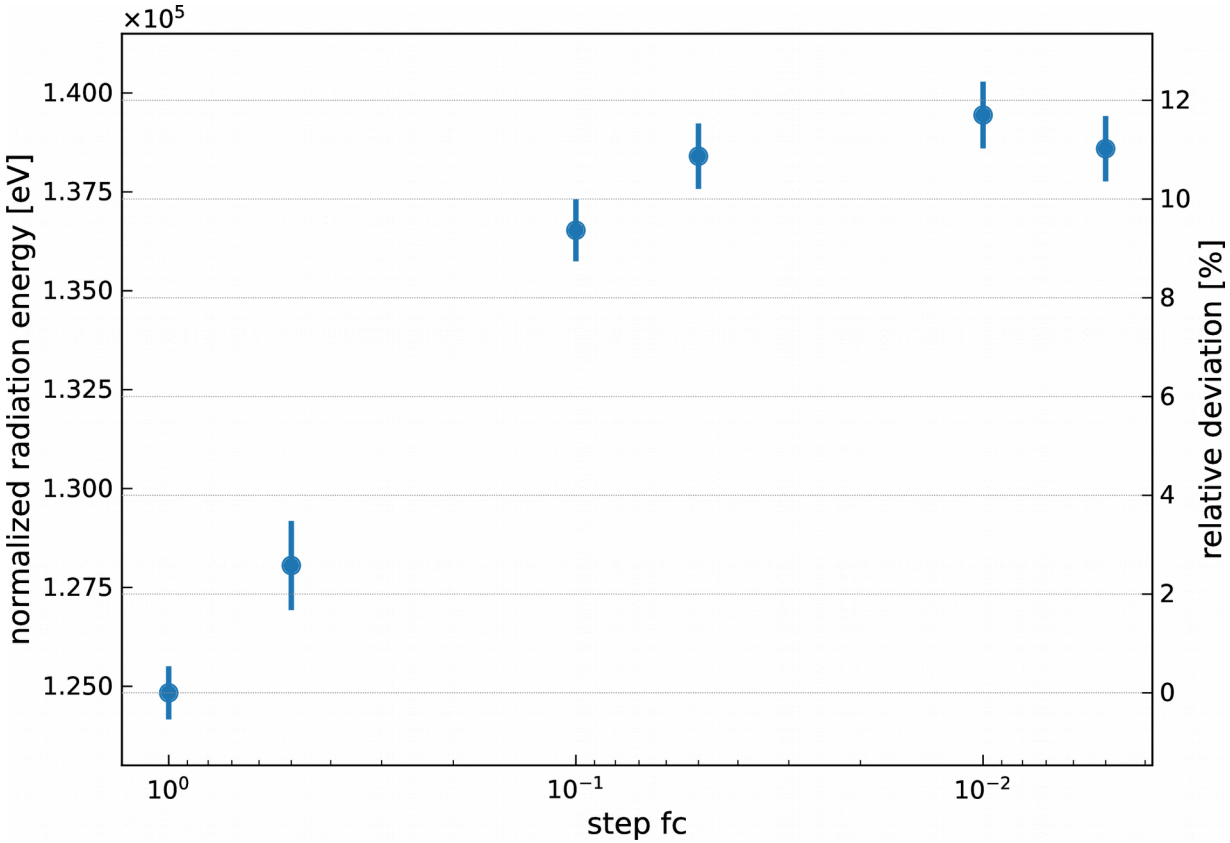
$$E_{\mathrm{rad}} = 2\pi \int dr\, r \cdot f(r, \varphi = 90°)$$

- Assumptions:
  1) ce and geo are in phase
  2) Individual LDFs are radially symmetric
- Simplification from star shape: ~1.5% overestimation



# Corsika STEPFC parameter

- STEPFC: „*Factor by which the multiple scattering length for electrons and positrons in EGS4 simulations is elongated*“
- 11 % impact on radiation energy



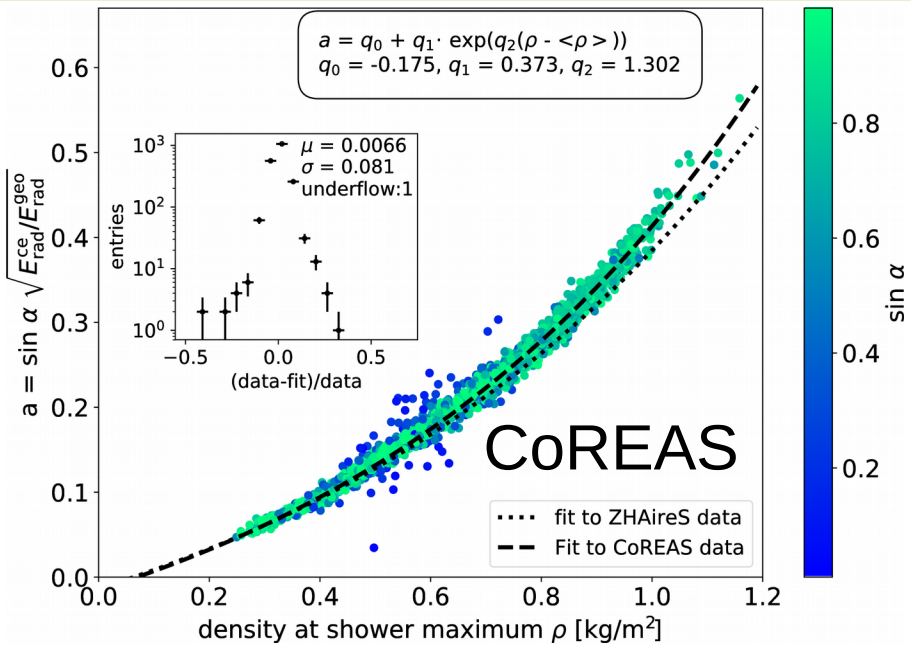

- Lower STEPFC (0.05) value needed for convergence, but increase in computing time (~ x 4)

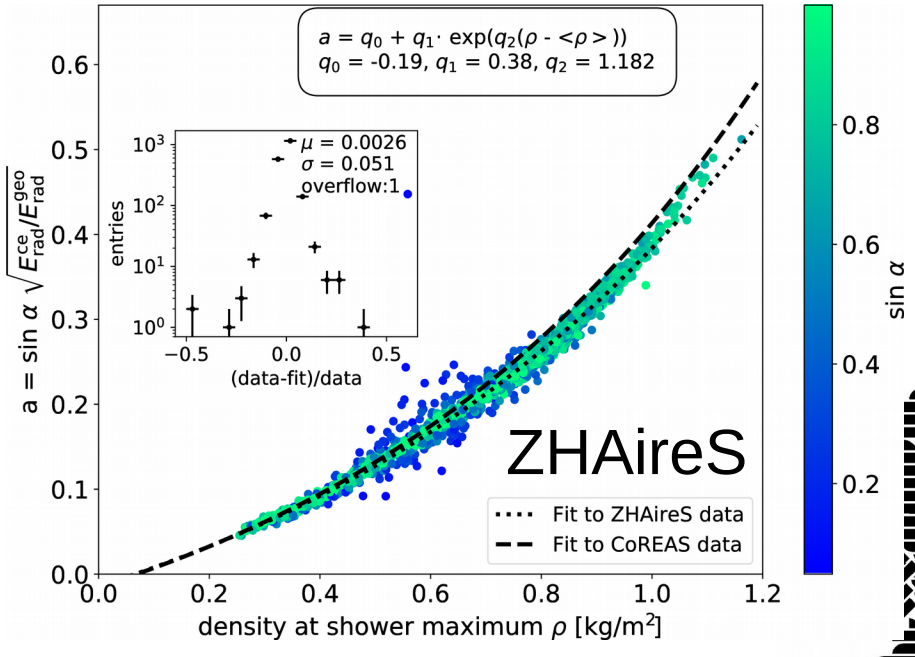
# Charge-Excess Fraction *a*

- Definition

$$a = \sin\alpha \sqrt{E_{\mathrm{rad}}^{\mathrm{ce}} / E_{\mathrm{rad}}^{\mathrm{geo}}}$$

- *a* depends on the density at shower maximum
- Differences at high densities and small sin α



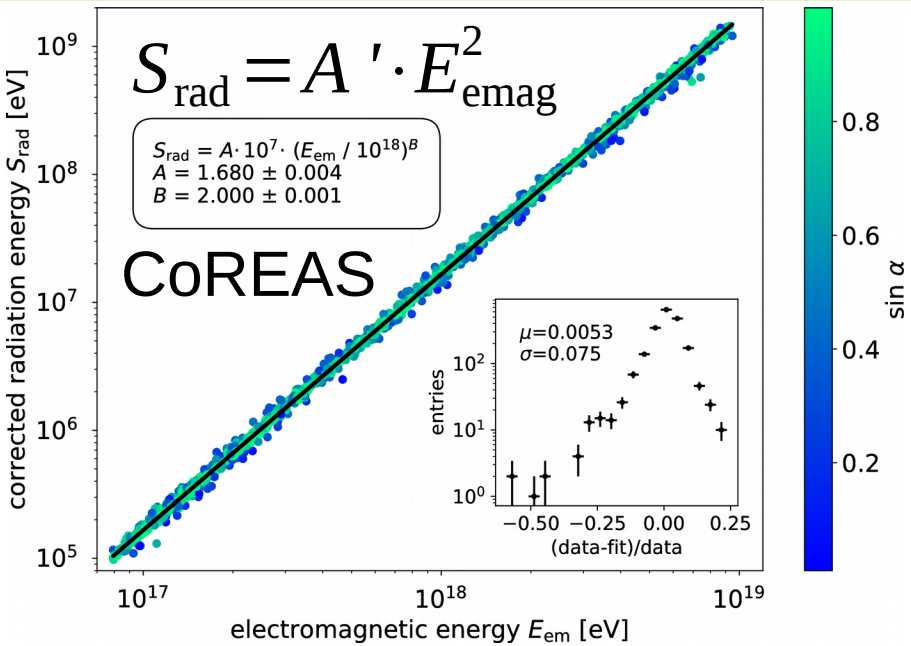



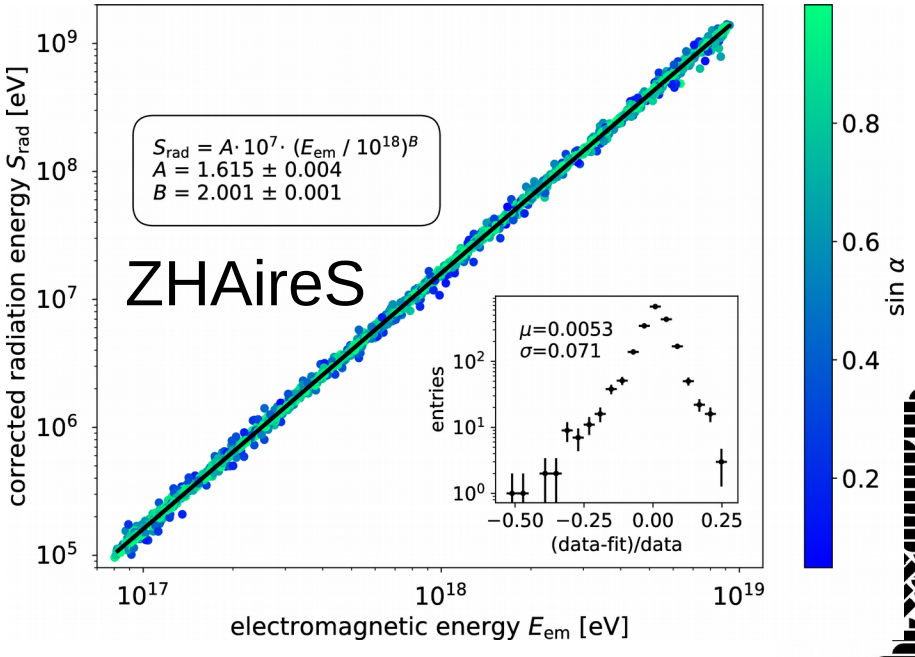
# Radiation vs. Electromagnetic Energy

- Energy estimator

$$S_{\mathrm{rad}} = \frac{E_{\mathrm{rad}}}{a(\rho(X_{\max}))^2 + (1 - a(\rho(X_{\max}))^2)\sin^2\alpha} \cdot \frac{1}{(1 - p_0 + p_0 \exp(p_1(\rho(X_{\max}) - \langle \rho(X_{\max}) \rangle)))^2}$$

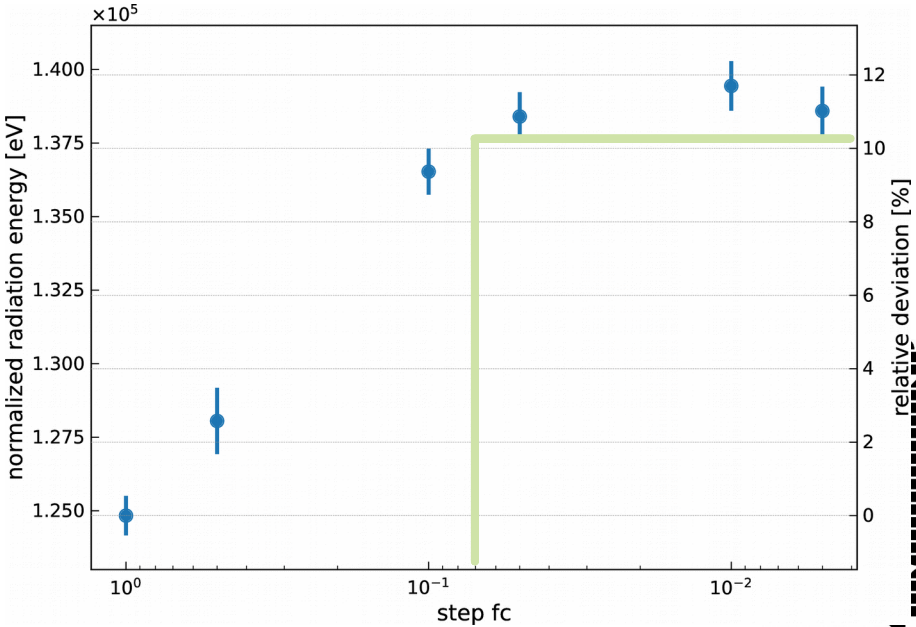
- Scatter: ~ 7 %
- $A_{\mathrm{CoREAS}} / A_{\mathrm{ZHAireS}}$ : 4 %
- On $E_{\mathrm{emag}}$ :
  - $-\sqrt{7}$ % stat.
  - – 2 % sys.



# Combined Corrections

- Fit constants $q_i$ (charge excess fraction) and $p_i$ (energy estimator) on a combined data set
- Only fit power law individually with combinded corrections
- **5.2% more radiation in CoREAS**
- Check stepsizes for atmospgeric heights
  - ZHAireS slightly larger at lower heights
  - Possible ~ 1% increase for ZHAireS with reduced stepsize based on CoREAS STEPFC study



# Other simulation uncertainties

| source of uncertainty | uncertainty of radiation energy |
|---|---|
| hadronic interaction models [12] | 0.3% |
| approximations in the air-shower simulation | |
| particle thinning [12] | $< 0.3\%$ |
| energy thresholds of shower particles [12] | $< 1\%$ |
| state of the atmosphere [12] | $< 3\%$ |
| **underlying first principle calculations (this work)** | **<5.2%** |

**Table 1**: Systematic uncertainties of the calculation of the radiation energy from the electromagnetic shower energy.

- First principle calculation biggest uncertainty
- compare 16% new systematic of Auger
- CoREAS ZHAireS differences important

# Additional Checks

- Refractivities at sea level
  - no significant differences for CoREAS and ZHAireS
- Magnetic Field Strength
  - no significant differences for CoREAS and ZHAireS
- Primary particles
  - 3% more radiation for p than Fe shower with same electromagnetic energy
  - Additional composition sensitivity of radio emission

# Summary

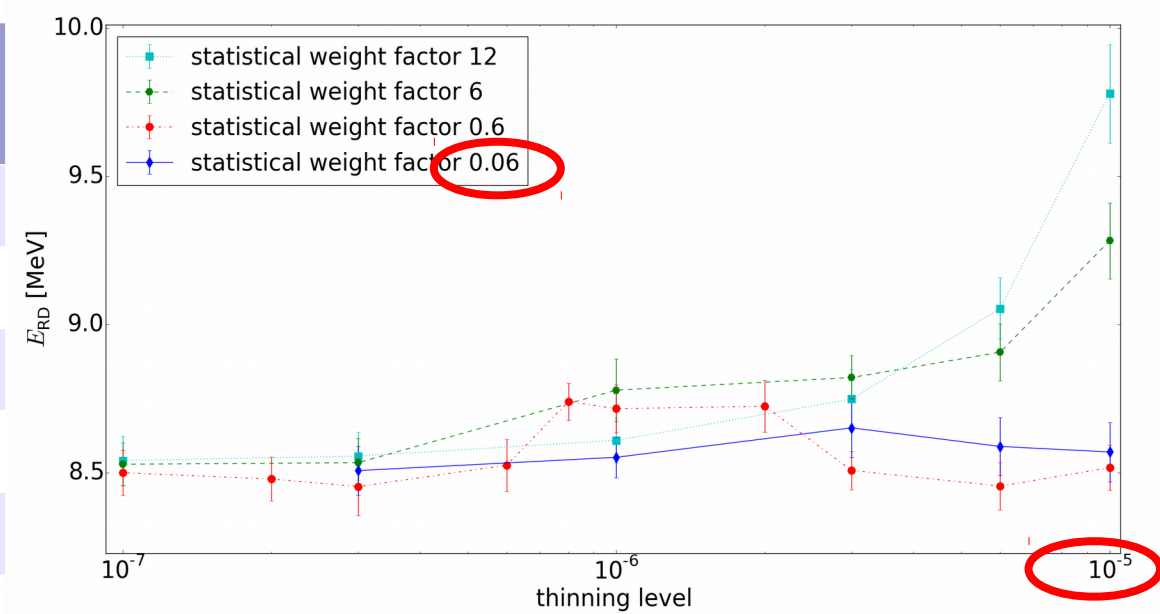
- CoREAS and ZHAireS consistent
- $S_{rad}$ well suited estimator of CR energy
- Technical and physical effects studied
- Small STEPFC value suggest for CoREAS simuations
- Final difference in radiation energy 5.2%

  → 2.6% difference on electromagnetic energy

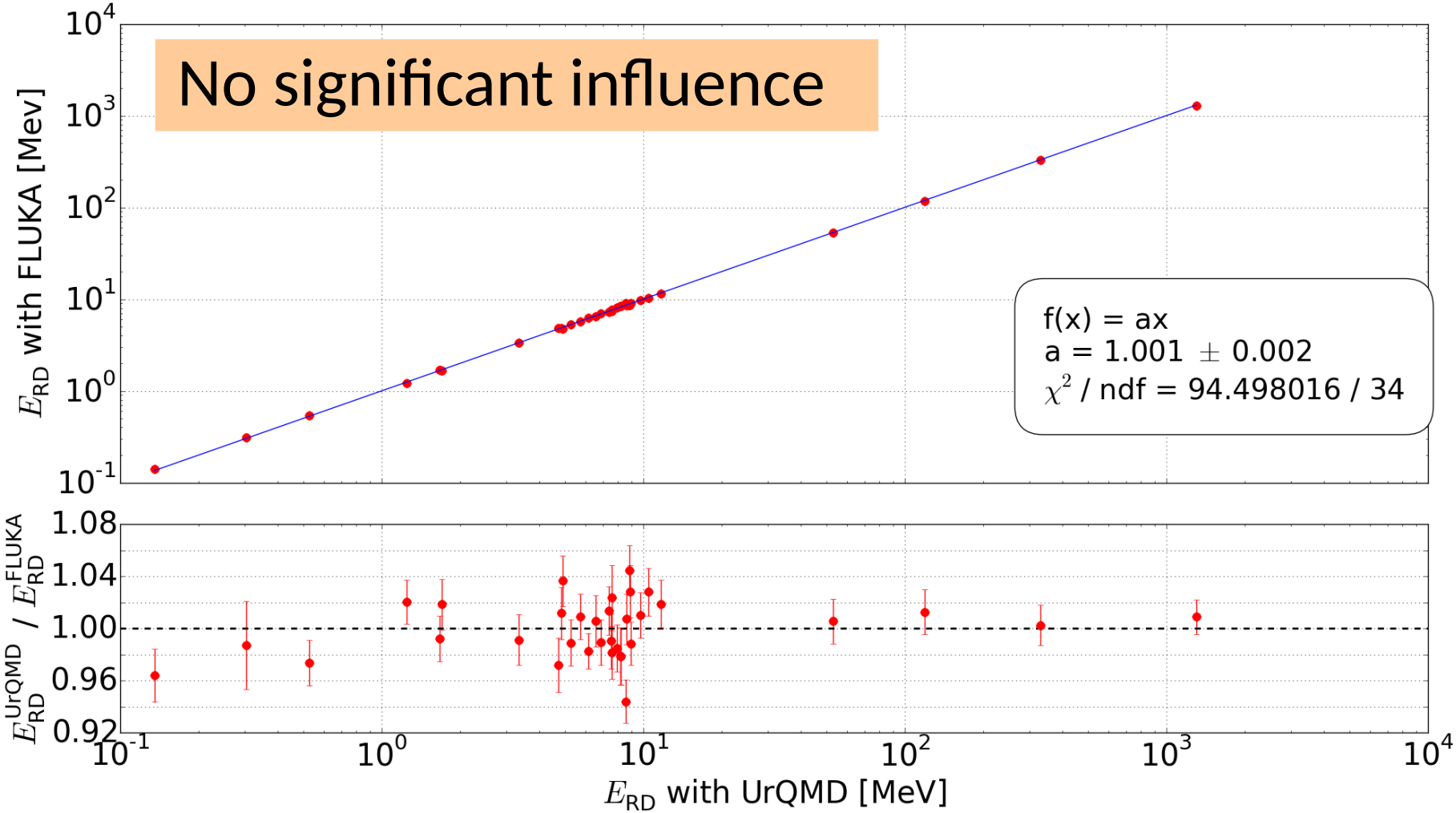
# Thinning Algorithm

- Thin shower if sum of energy of all secondary particles in an interaction below threshold
- Thinning level of $10^{-5}$ sufficient

| Thinning Level | Rad. E / MeV | #Sim |
|---|---|---|
| 1e-3 | 10.2(2) | 40 |
| 1e-4 | 8.5(1) | 40 |
| 1e-5 | 8.3(1) | 40 |
| 1e-6 | 8.3(1) | 40 |
| 1e-7 | 8.4(1) | 21 |



# Low Energy Hadronic Model



# LDF Fit

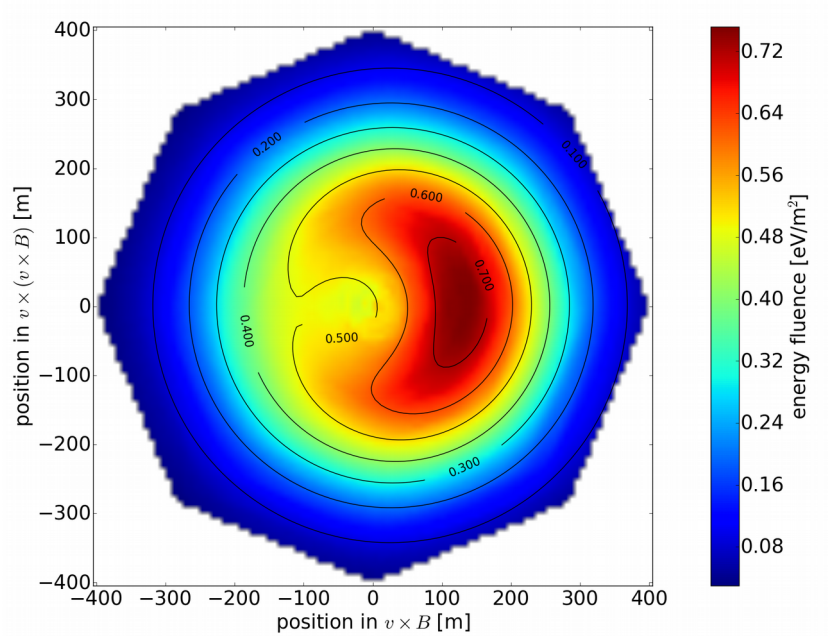
- Sum of 2 gaussians

$$f(x,y) = A_+ \exp\left(-\frac{(x-X_+)^2+(y-Y_+)^2}{\sigma_+^2}\right) - A_- \exp\left(-\frac{(x-X_-)^2+(y-Y_-)^2}{\sigma_-^2}\right)$$

- Reduced LDF

$$f(\vec{r}) = A\left(\exp\left(-\frac{\vec{r}+C_1\vec{e}_{v\times B}-\vec{r}_{\mathrm{core}}}{\sigma^2}\right) - C_0 \exp\left(-\frac{\vec{r}+C_2\vec{e}_{v\times B}-\vec{r}_{\mathrm{core}}}{(C_3\exp(C_4\cdot\sigma))^2}\right)\right)$$

- $C_i$ determined by simulations
- Limit relevance:
  - Detector dependent
  - Here: Auger vs. sea level
  - In general good agreement



# FFT & Bandpass Filtering

- Filter radio emission to 30 – 80 MHz
  - CoREAS: 28.79 – 81.57 MHz
  - ZHAireS: 30.00 – 80.17 MHz
- ZHAireS trace longer than CoREAS → finer frequency resolution
- 5 % more effective bandwith used in CoREAS
- 10 % more radiation energy