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Tunka-Rex

Towards a cosmic-ray mass-composition study at Tunka Radio Extension

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INSTITUT FÜR KERNPHYSIK

Motivation

Lateral distribution description

- Gaussian with restored symmetry $\mathcal{E}(\mathcal{E}_0, a_1, a_2, \varepsilon)$ – Tunka-Rex
- Two-gaussian $\mathcal{E}(A, \sigma, C_0, C_1, C_2, C_3, C_4)$ – LOFAR, AERA
- Straight-forward $\mathcal{E}(\mathbb{E})$, $\mathbb{E} = \{\mathcal{E}_i(x_i, y_i)\}$ – LOFAR

Askaryan contribution

- Polarization angle
- Asymmetry of LDF

$X_{\max}$ resolution: ≈ 20 g/cm^2 (theory), ≈ 40 g/cm^2 (direct cross-check)

New approaches in mass composition study using radio technique?

One-dimensional slope method

Lateral distribution function (LDF)

$$\mathcal{E}(r) = \mathcal{E}_{r_0}\exp(a_1(r-r_0)+a_2(r-r_0)^2)\,,$$

Fixing quadratic term

$$a_2(\theta, E_{\mathrm{pr}}^{\mathrm{est}}) = a_{20}(E_{\mathrm{pr}}^{\mathrm{est}})+a_{21}(E_{\mathrm{pr}}^{\mathrm{est}})\cos\theta\,,$$

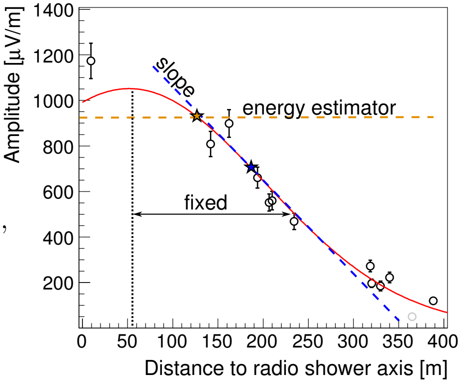
LDF slope

$$\eta = \frac{\mathcal{E}'}{\mathcal{E}}$$

Air-shower parameters

$$E_{\mathrm{pr}} = \kappa_L \mathcal{E}(r_{\mathrm{e}})$$

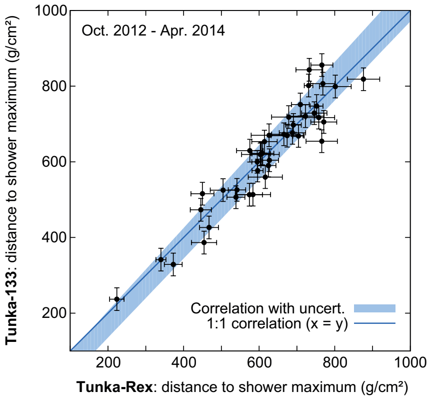
$$X_{\max} = X_0/\cos\theta - (A + B\log(\eta(r_{\mathrm{x}})+\bar{b}))$$

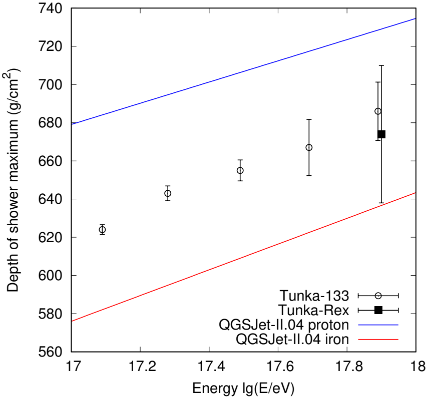


Model parameters from CoREAS simulations

doi:10.1016/j.astropartphys.2015.10.004

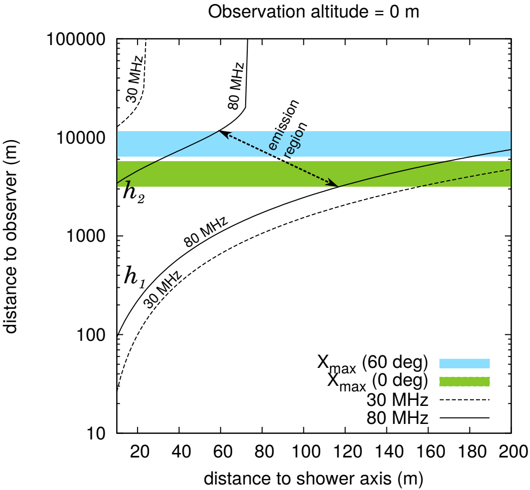
Mean depth of shower maximum





$\langle X_{\rm max}\rangle = 674 \pm 36$ g/cm^2 for $\lg(E_{\rm pr}/\text{eV}) = 17.9 \pm 0.1$ (for 8 events)

Coherence regions



$$\mathcal{E}_\nu(r) = \kappa \int_{h_1^\nu(r,n_r)}^{h_2^\nu(r,n_r)} \frac{N(h)}{h} \mathrm{d}h \propto$$

$$\propto \exp\left(-\frac{(r/r_0)^\alpha}{h_{\max}} f_{\mathrm{int}}(h_{\max}, \ldots)\right)$$

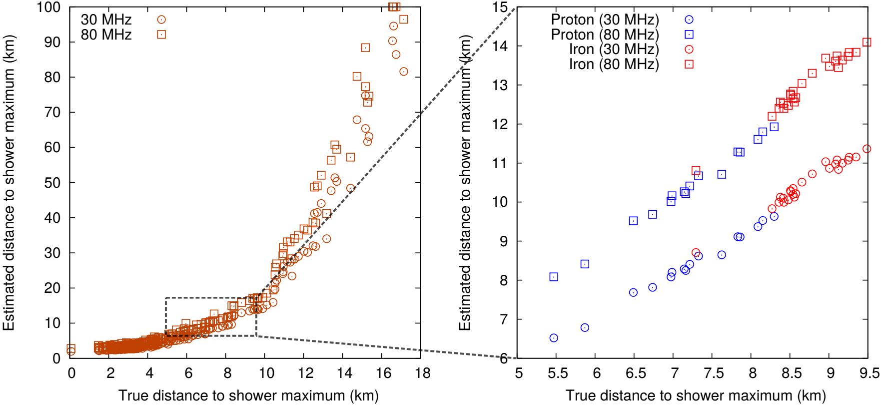
Using atmosphere n_r as input

$$h_1^\nu(r, n_r) = \left(\frac{r}{r_0(\nu)}\right)^{\alpha(\nu)}$$

$$h_2^\nu(r, n_r) \to \infty$$

Estimation of the shower maximum

Assuming $f_{\text{int}}(h_{\max}, ...) = 1$ and using $n_r(h)$ as input



$f_{\text{int}}(h_{\max}, ...)$ can be estimated using Gaisser-Hillas parametrization with parameters from hadronic models

Comparison of hadronic models

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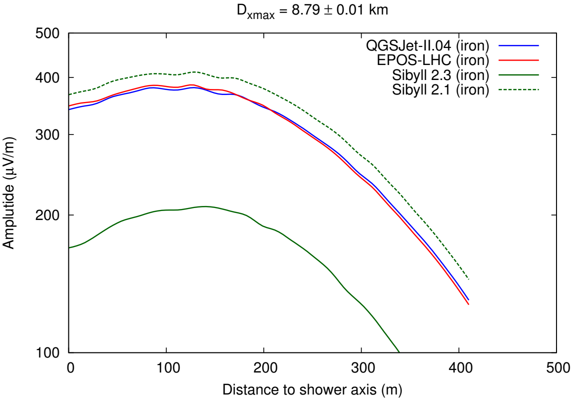
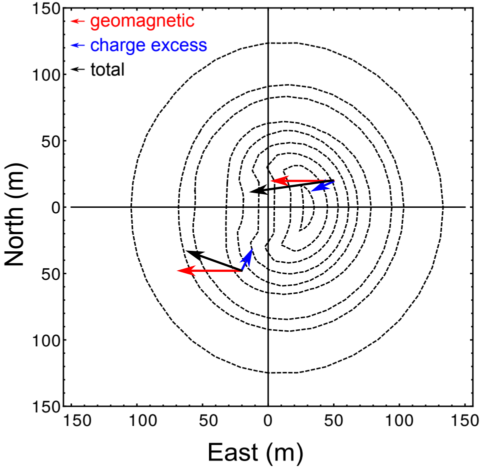


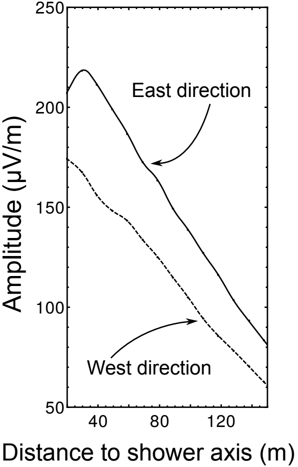
Example shower-to-shower fluctuations ($E_{\mathrm{pr}} = 0.3$ EeV and $\theta = 45^\circ$)

Model	$\mathcal{E}_{120}^{\mathrm{p}}$	$\mathcal{E}_{120}^{\mathrm{Fe}}$	Δ_{E}	$\langle D_{\mathrm{max}}^{\mathrm{p}} \rangle$	$\langle D_{\mathrm{max}}^{\mathrm{Fe}} \rangle$	$\sigma D_{\mathrm{max}}^{\mathrm{p}}$	$\sigma D_{\mathrm{max}}^{\mathrm{Fe}}$
QGSJet-II.04	5%	1.3%	12%	7.20 km	8.72 km	1.04 km	0.46 km
EPOS-LHC	5%	1.3%	12%	7.18 km	8.67 km	0.84 km	0.36 km

Charge-excess asymmetry

Simulated radio footprint





Polarization asymmetry

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Geomagnetic coordinate system

$$\hat{\mathrm{e}}_x = \hat{\mathbf{V}} \times \hat{\mathbf{B}} \qquad \alpha_{\mathrm{g}} = \angle(\mathbf{V}, \mathbf{B})$$
$$\hat{\mathrm{e}}_y = \hat{\mathbf{V}} \times (\hat{\mathbf{V}} \times \hat{\mathbf{B}}) \qquad \phi_{\mathrm{g}} = \angle(\hat{\mathbf{e}}_x, \hat{\mathbf{e}}_y)$$
$$\hat{\mathrm{e}}_z = \hat{\mathbf{V}}$$

The signal components

$$\boldsymbol{\mathcal{E}}_{\mathrm{g}} = (\mathcal{E}_{\mathrm{g}},\, 0,\, 0) = (\mathcal{E}_0 \sin\alpha_{\mathrm{g}},\, 0\,, 0)$$
$$\boldsymbol{\mathcal{E}}_{\mathrm{ce}} = (\mathcal{E}_{\mathrm{ce}} \cos\phi_{\mathrm{g}},\, \mathcal{E}_{\mathrm{ce}} \sin\phi_{\mathrm{g}},\, 0)$$

Asymmetry takes the form

$$\varepsilon = \frac{\mathcal{E}_{\mathrm{ce}}}{\mathcal{E}_0} = \frac{\mathcal{E}_y / \sin\phi_{\mathrm{g}}}{\mathcal{E}_x - \mathcal{E}_y \cot\phi_{\mathrm{g}}} \sin\alpha_{\mathrm{g}}$$

Lateral distribution asymmetry

AERA parametrization

$$\mathcal{E}_{2\mathrm{G}}(\boldsymbol{r}) = A\left[\exp\left(\frac{-(\boldsymbol{r} + C_1\,\hat{\mathbf{e}}_x)^2}{\sigma^2}\right) - C_0\,\exp\left(\frac{-(\boldsymbol{r} + C_2\,\hat{\mathbf{e}}_x)^2}{(C_3 e^{C_4\,\sigma})^2}\right)\right]$$

Tunka-Rex parametrization

$$\mathcal{E}_\phi(r, \phi_g) = \mathcal{E}_0(r)\sqrt{\sin^2\alpha_g + \varepsilon^2(r) + 2\varepsilon(r)\cos\phi_g}$$

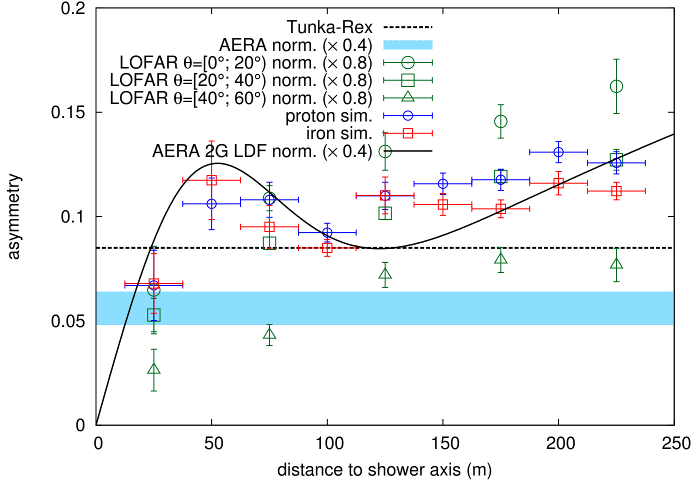
$$\boldsymbol{r} = (r\cos\phi_g, r\sin\phi_g)$$

Asymmetry as a function of two-gaussian lateral distribution

$$\varepsilon(r) = \sin\alpha_g \frac{\mathcal{E}_{2\mathrm{G}}(r) - \tilde{\mathcal{E}}_{2\mathrm{G}}(r)}{\mathcal{E}_{2\mathrm{G}}(r) + \tilde{\mathcal{E}}_{2\mathrm{G}}(r)}\,, \quad \begin{cases} \mathcal{E}_{2\mathrm{G}}(r) = \mathcal{E}_{2\mathrm{G}}(\boldsymbol{r}) : \boldsymbol{r} = (r, 0) \\ \tilde{\mathcal{E}}_{2\mathrm{G}}(r) = \mathcal{E}_{2\mathrm{G}}(\boldsymbol{r}) : \boldsymbol{r} = (-r, 0) \end{cases}$$

Asymmetry reconstruction comparison

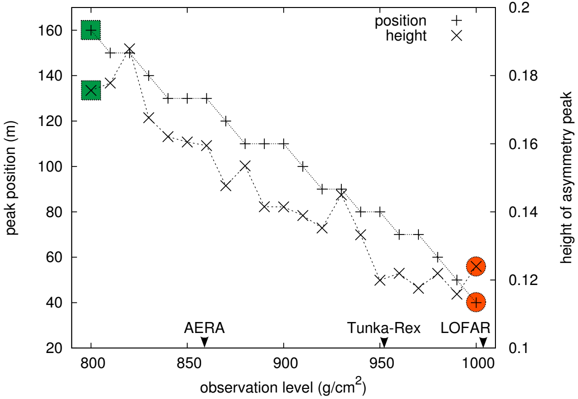
C_0, C_1, C_2, C_3, C_4 from `arxiv:1508.04267`, $\sigma(\langle X_{\max} \rangle)$ and $\alpha_g = 45°$



Q: How does AERA average over azimuth angles?

Behavior of asymmetry peak

The position and height of the peak correlates to the shower maximum



$$\frac{\tilde{\mathcal{E}}'_{2\mathrm{G}}(r_\mathrm{p})}{\tilde{\mathcal{E}}_{2\mathrm{G}}(r_\mathrm{p})} = \frac{\mathcal{E}'_{2\mathrm{G}}(r_\mathrm{p})}{\mathcal{E}_{2\mathrm{G}}(r_\mathrm{p})} \Rightarrow \varepsilon_\mathrm{p}(r_\mathrm{p}) = \sin\alpha_g \frac{\mathcal{E}'_{2\mathrm{G}}(r_\mathrm{p}) - \tilde{\mathcal{E}}'_{2\mathrm{G}}(r_\mathrm{p})}{\tilde{\mathcal{E}}'_{2\mathrm{G}}(r_\mathrm{p}) + \mathcal{E}'_{2\mathrm{G}}(r_\mathrm{p})}$$

$$X_\mathrm{max}(r_\mathrm{p}, \varepsilon_\mathrm{p}) \Leftrightarrow X_\mathrm{max}(a_1, \sigma)$$

Summary

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- Model-independent geometrical considerations indicate that slope of the lateral distribution depends on the shower maximum
- Radio signal of EPOS-LHC and QGSJet-II.04 is in agreement, Sibyll 2.3 is under investigation
- Systematic uncertainty of unknown primary particle dominates over shower-to-shower fluctuations (for energy)
- Features of charge-excess asymmetry contain information related to cascade development

BACKUP

Geometry considerations

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$$\mathcal{E}_\nu(r) = \kappa \int\limits_{h_1^\nu(r,n_r)}^{h_2^\nu(r,n_r)} \frac{N(h)}{h} \mathrm{d}h \,,$$

For $r > r_{\mathrm{ch}}$: $h_1^\nu(r, n_r) = (r/r_0(\nu))^{\alpha(\nu)}, \; h_2^\nu(r, n_r) > h_{\mathrm{top}}$

$$\mathcal{E}_\nu(r, n_r) \propto \int\limits_{(r/r_0)^\alpha}^{\infty} \exp\left(f_{\mathrm{prop}}(h, h_{\mathrm{max}}) f_{\mathrm{int}}(h_{\mathrm{max}}, ...)\right) \mathrm{d}h$$

$$\mathcal{E}_\nu(r, n_r) \propto \int\limits_{(r/r_0)^\alpha}^{\infty} \exp\left(-\frac{h}{h_{\mathrm{max}}} f_{\mathrm{int}}(h_{\mathrm{max}}, ...)\right) \mathrm{d}h$$

$$\propto \exp\left(-\frac{(r/r_0)^\alpha}{h_{\mathrm{max}}} f_{\mathrm{int}}(h_{\mathrm{max}}, ...)\right)$$

Asymmetry expression

Amplitudes with negative interference: $\mathcal{E}_-(r)$ and $\mathcal{E}_\phi(r,\pi)$
Amplitudes with positive interference: $\mathcal{E}_+(r)$ and $\mathcal{E}_\phi(r,0)$

$$\frac{\mathcal{E}_\phi(r,\pi)}{\mathcal{E}_\phi(r,0)} = \frac{\mathcal{E}_-(r)}{\mathcal{E}_+(r)}$$

$$\frac{\sin\alpha_g - \varepsilon}{\sin\alpha_g + \varepsilon} = \frac{\mathcal{E}_-(r)}{\mathcal{E}_+(r)}$$

$$\varepsilon(r) = \sin\alpha_g \frac{\mathcal{E}_+(r) - \mathcal{E}_-(r)}{\mathcal{E}_+(r) + \mathcal{E}_-(r)}$$

Shower maximum reconstruction

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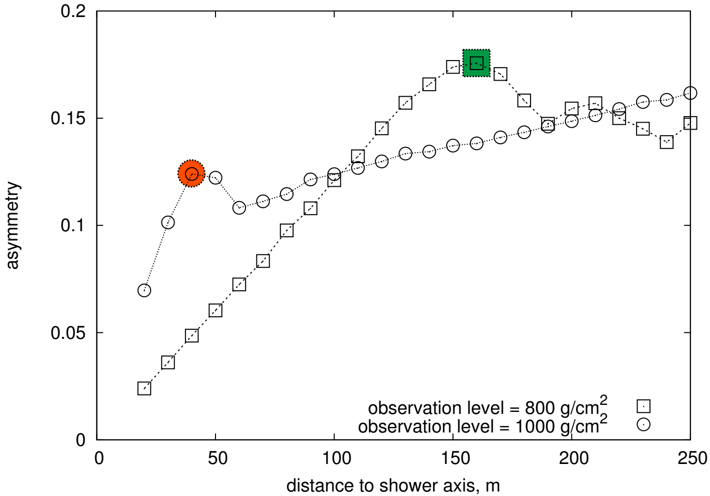
As it was shown, r_0 and $\varepsilon(r_0)$ correlate with distance to shower maximum

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(\sin\alpha_g \frac{\mathcal{E}_+(r) - \mathcal{E}_-(r)}{\mathcal{E}_+(r) + \mathcal{E}_-(r)}\right) = 0$$

$$\frac{\mathcal{E}'_-(r)}{\mathcal{E}_-(r)} = \frac{\mathcal{E}'_+(r)}{\mathcal{E}_+(r)}$$

$$\eta_-(r) = \eta_+(r)\,,\ r_0 = r\Big|_{\eta_-(r)=\eta_+(r)}$$

$$\varepsilon(r_0) = \sin\alpha_g \frac{\mathcal{E}'_+(r_0) - \mathcal{E}'_-(r_0)}{\mathcal{E}'_-(r_0) + \mathcal{E}'_+(r_0)}$$


0.2
0.15
0.1
0.05
0
asymmetry
0
50
100
150
200
250
distance to shower axis, m
observation level = 800 g/cm^2
observation level = 1000 g/cm^2