The Tunka Radio Extension: two years of air-shower measurements

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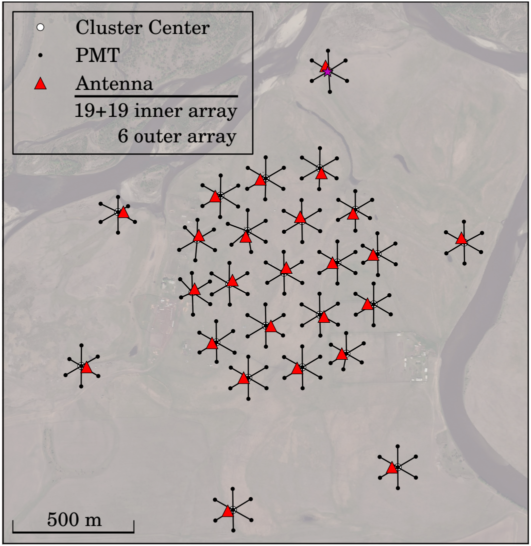
Helmholtz Russian Joint Research Group 303

INSTITUT FÜR KERNPHYSIK

Tunka-133 → TAIGA

Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy



Cosmic ray detectors

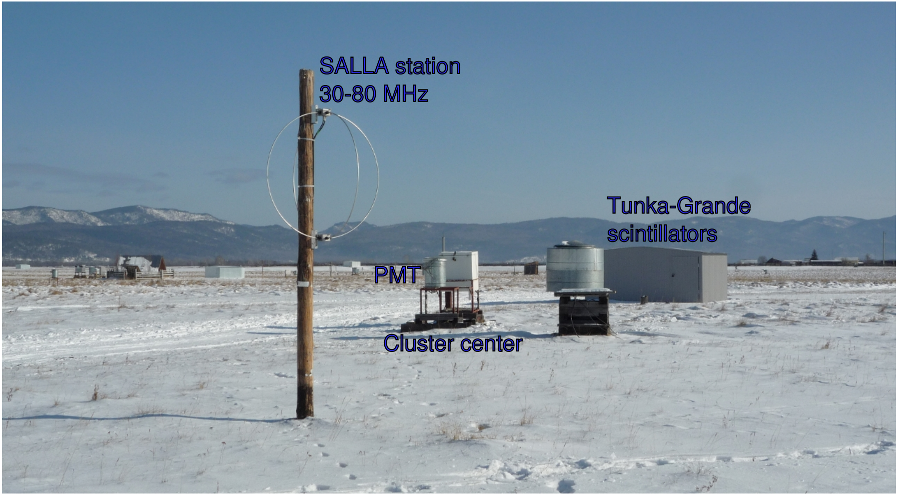
- Tunka-133 air-Cherenkov
- **Tunka Radio Extension** (Tunka-Rex)
- Tunka-Grande scintillators

Gamma ray detectors

- HiSCORE
- IACTs

see contibution PoS 1012 by L. Kuzmichev

Tunka facility



Tunka-Rex detector

- Radio quiet rural location
- Strong geomagnetic field ($\approx 60~\mu$T)
- Absolute amplitude calibration (see contribution PoS 573 by R.Hiller)

- Joint operation of radio and air-Cherenkov detectors
- Goal: precision of radio reconstruction for shower parameters (energy and shower maximum)
- Super-hybrid measurements soon: radio + air-Č + e/μ

Events aquisition and reconstruction

Effective time of measurements: 280 hours
Event rate: $\approx$ 1 candidate per hour

- Searching of the signal in power trace
  - Digital filtering
  - SNR$\geq$10
  - $N_{\mathrm{ant}} \geq$3

  $\Rightarrow$ **244 events found**

- Rejecting false positive events
  - Rejecting outliers from the LDF (using Tunka-133 core coordinates)
  - Reconstruction of arrival direction with plane fit
  - Comparison with Cherenkov reconstruction ($\Delta\Omega < 5^\circ$)

  $\Rightarrow$ **88 events remain**

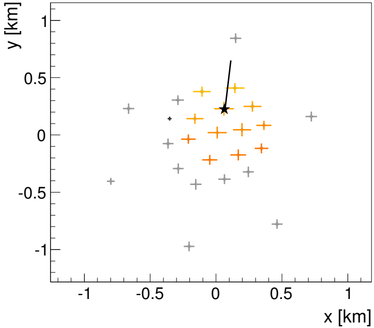
For analysis we use the radio part of the Auger Offline software
Pierre Auger Collaboration, NIM A 635 (2011) 92

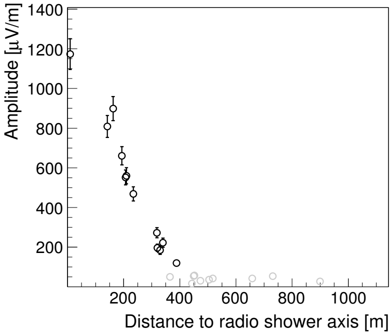
Events aquisition and reconstruction

- Quality cuts (for X_{max} reconstruction)
  - at least one antenna at $d_{\mathrm{axis}} > 200\,\mathrm{m}$

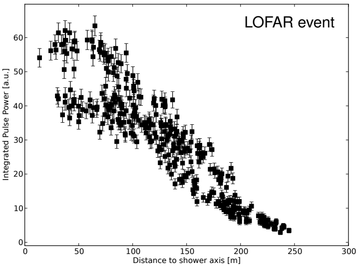
  $\Rightarrow$ **64 events remain**
  - fit uncertainty $\sigma(X_{\mathrm{max}}) < 50\,\mathrm{g/cm^2}$

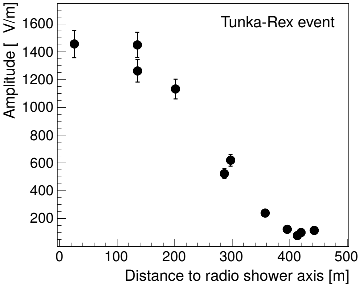
  $\Rightarrow$ **25 events remain**





Lateral distribution asymmetry





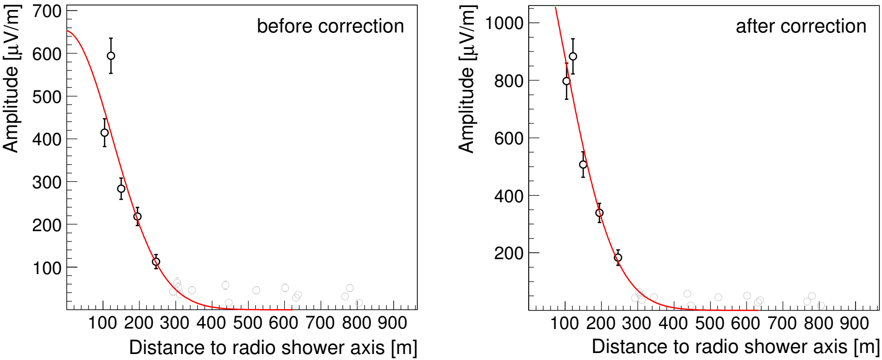
Nelles et. al.[1]	Kostunin et. al.[2]
2D asymmetric LDF	1D symmetric LDF
asymmetry included in fit	asymmetry is parametrized + corrected
large number of free parameters	small number of free parameters
works for dense arrays	works for sparse arrays

Both methods describe the same physics and should converge.

[1] published in JCAP 1505 (2015) 05, 018
[2] [arXiv:1504.05083], submitted to Astropart. Phys.

Asymmetry correction

Correction operator $\hat{K} = \left(\varepsilon^2 + 2\varepsilon \cos\phi_g \sin\alpha_g + \sin^2\alpha_g\right)^{-\frac{1}{2}}$
α_g is geomagnetic angle, $\varepsilon = 0.085$ is asymmetry, ϕ_g is azimuth of antenna



Slope (η) sensitivity to shower maximum $\delta\eta \Leftrightarrow \delta X_{\max} \lesssim 70$ g/cm^2
Energy estimator works for all $\alpha_g > 0$ (cf. Glaser et. al., PoS 364)

Air-shower reconstruction

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

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

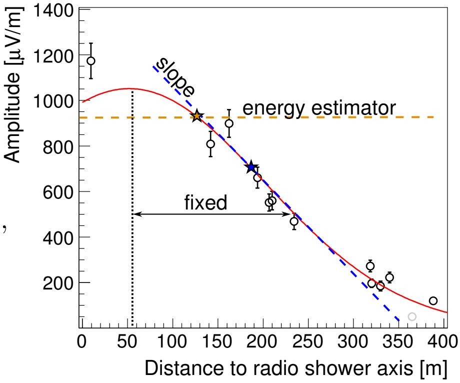
LDF slope

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

Air-shower parameters

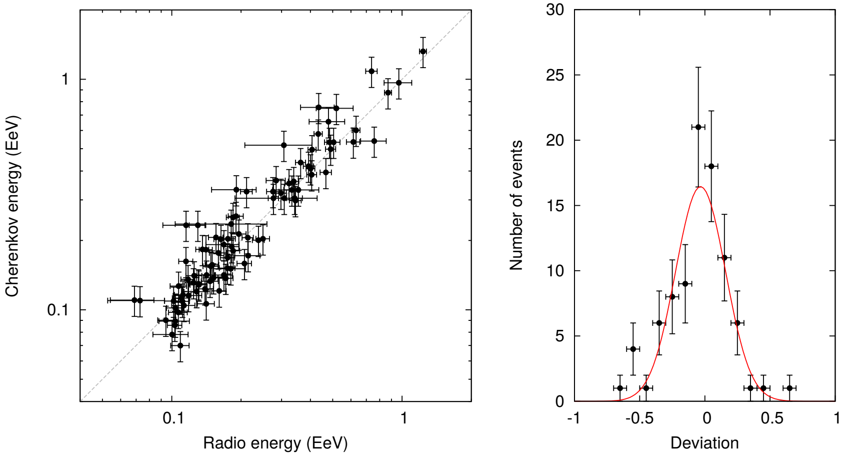
$$E_{\mathrm{pr}} = \kappa_L \mathcal{E}(r_{\mathrm{e}})$$

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



Model parameters from CoREAS simulations

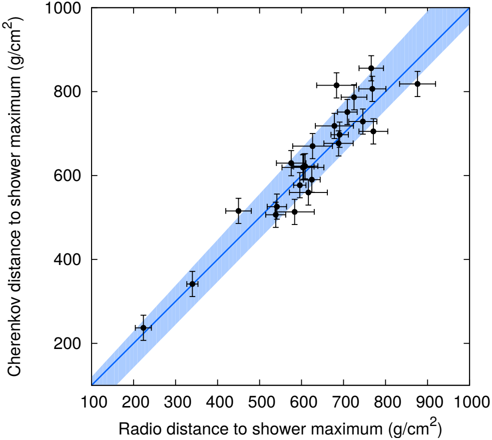
Energy correlation

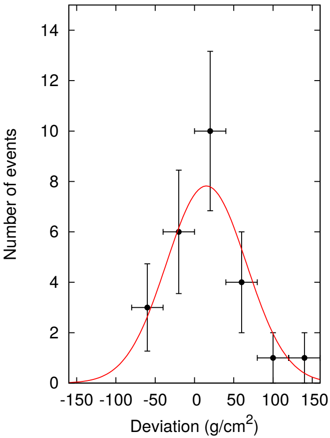


Combined resolution: $\sigma \approx 20\%$ for 91 measured events

Radio simulations (noise included): $\sigma_{\text{proton}} = 12\%$, $\sigma_{\text{iron}} = 15\%$

Shower maximum correlation



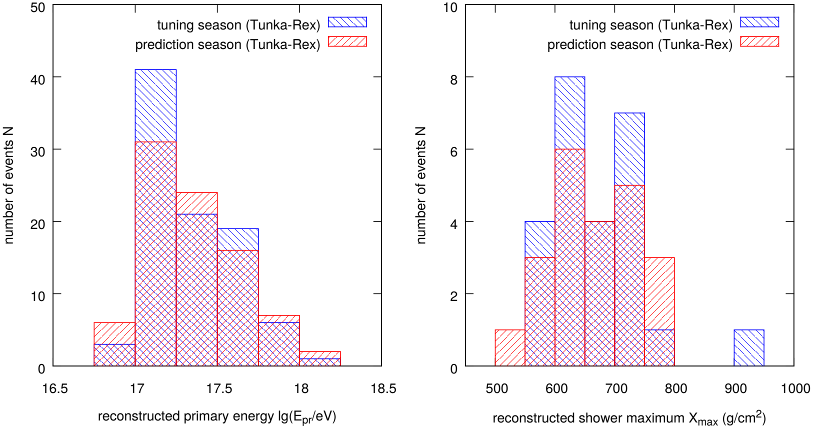


Combined resolution: $\sigma \approx 50$ g/cm^2 for 25 measured events

Radio simulations (noise included): $\sigma_{\text{proton}} = 25$ g/cm^2, $\sigma_{\text{iron}} = 40$ g/cm^2

Tuning and Prediction seasons

Effective time: 280 h / 260 h   Total N of events: 91 / 87   HQ events: 25 / 22



The encrypted file with reconstruction of blinded data can be found on

`http://reco.tunkarex.info`

Conclusion

- Tunka-Rex successfully operates since 2012.
- The combined resolution of E_{pr} and X_{max} after cross-calibration is comparable with non-imaging techniques.
- Tunka-Rex has proven that sparse low-cost radio arrays are feasible for the ultra-high energy cosmic rays detection.

Outlook

- Tunka-Grande will be calibrated using hybrid measurements with Tunka-Rex.
- After the starting hybrid measurements with doubled core shower maximum resolution should be improved to 40 g/cm^2.

BACKUP

Tunka-Rex Collaboration

P.A. Bezyazeekov[1], N.M. Budnev[1], O.A. Gress[1], A. Haungs[2], R. Hiller[2], T. Huege[2], Y. Kazarina[1], M. Kleifges[3], E.N. Konstantinov[1], E.E. Korosteleva[4], D. Kostunin[2], O. Krömer[3], L.A. Kuzmichev[4], R.R. Mirgazov[1], L. Pankov[1], V.V. Prosin[4], G.I. Rubtsov[5], C. Rühle[3], F.G. Schröder[2], R. Wischnewski[6], A. Zagorodnikov[1]

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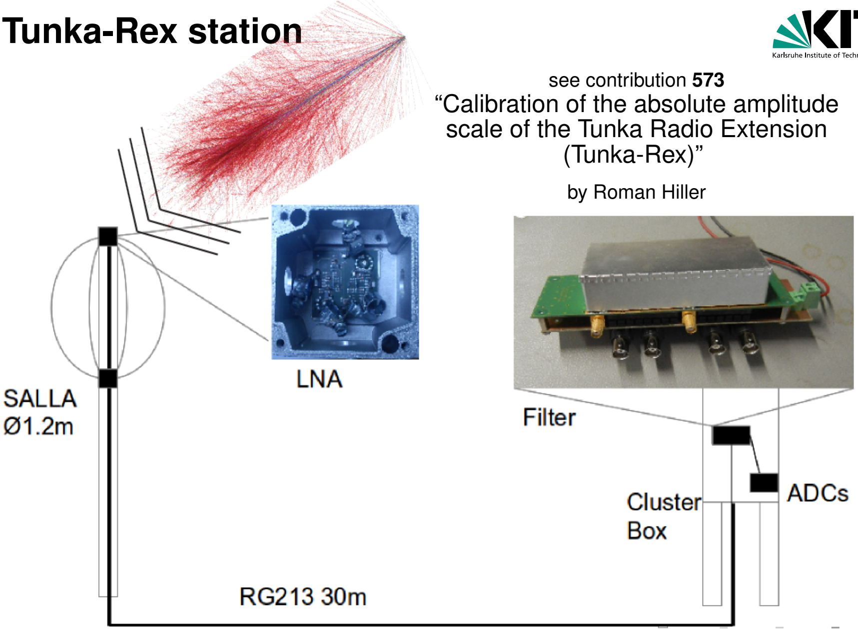
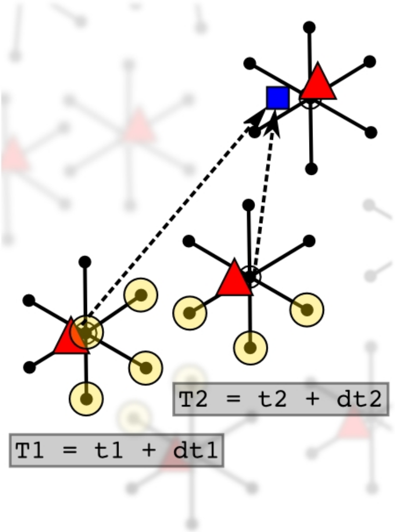
Tunka-Rex station

see contribution **573**
"Calibration of the absolute amplitude scale of the Tunka Radio Extension (Tunka-Rex)"

by Roman Hiller

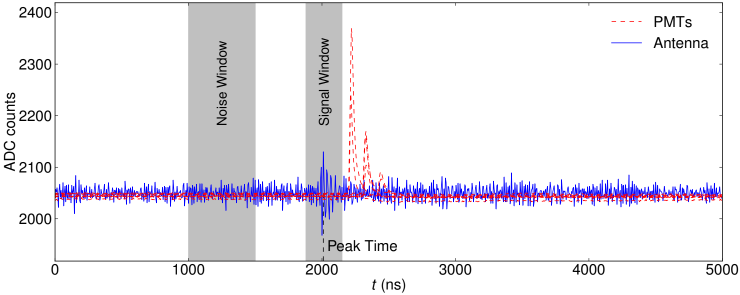


Data acquisition and event merging

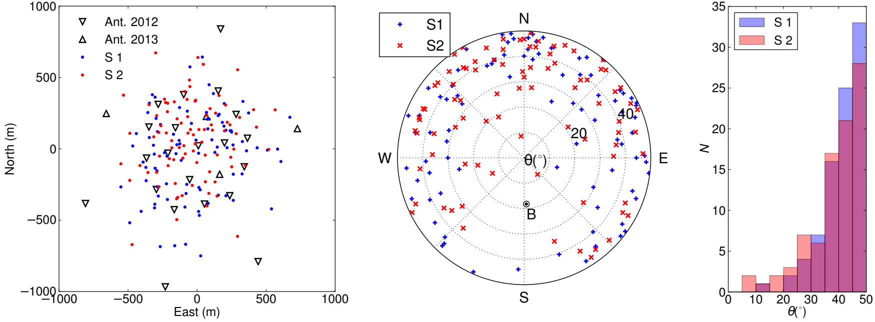


- Every run local clocks set to zero
- Cluster centers have independent triggers (more than 2 simultaneous signals from PMT consider as event)
- Delays in optical fibers are taken into account. Event time is $T =$ local time $+$ fiber delay
- We merge separate events with $\Delta T \leqslant 7000$ ns into one
- UTC time sets for each event in DAQ center and then data reader choses one for merged event.

Sample signal trace



Event distribution



Convergence of energy estimator

$$\mathcal{E}(r_\mathrm{e}) = \kappa E_\mathrm{pr} \sqrt{\varepsilon^2 + 2\varepsilon \cos\phi_\mathrm{g} \sin\alpha_\mathrm{g} + \sin^2\alpha_\mathrm{g}}$$

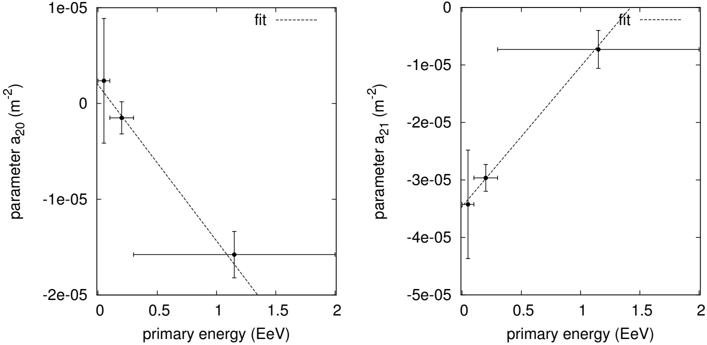
Taylor series

$$\begin{aligned}\mathcal{E}(r_\mathrm{e}, \phi_\mathrm{g} = \pi/2) &= \kappa E_\mathrm{pr} \sin\alpha_\mathrm{g} \sqrt{1 + \frac{\varepsilon^2}{\sin\alpha_\mathrm{g}^2}} \\ &= \kappa E_\mathrm{pr} \sin\alpha_\mathrm{g} \left(1 + \frac{1}{2}\frac{\varepsilon^2}{\sin\alpha_\mathrm{g}^2} + \mathcal{O}\left(\frac{1}{\sin\alpha_\mathrm{g}^4}\right)\right)\end{aligned}$$

Formula $E_\mathrm{pr} = \dfrac{\mathcal{E}(r_\mathrm{e})}{\sin\alpha_\mathrm{g}}$ works while $\sin\alpha_\mathrm{g} \gg \dfrac{\varepsilon}{\sqrt{2}}$

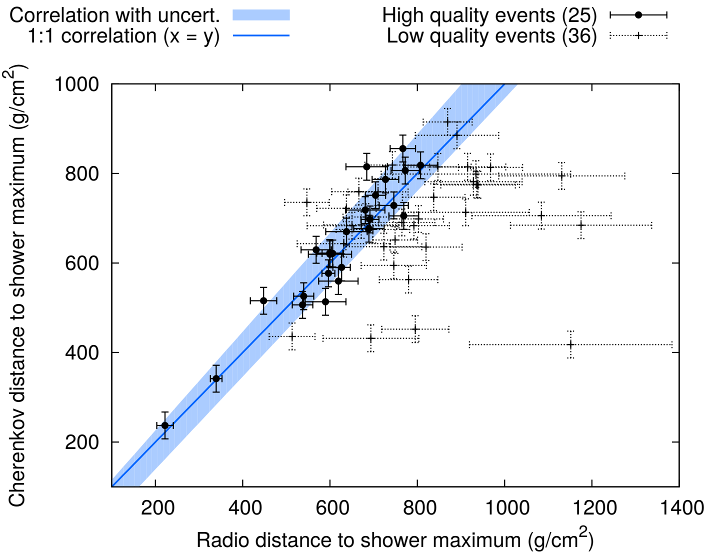
For $\varepsilon \approx 15\%$: $\alpha_\mathrm{g}^\mathrm{lim} \approx$ 0.1 (6°)

Parametrization $a_2(E_{\mathrm{pr}}, \theta)$

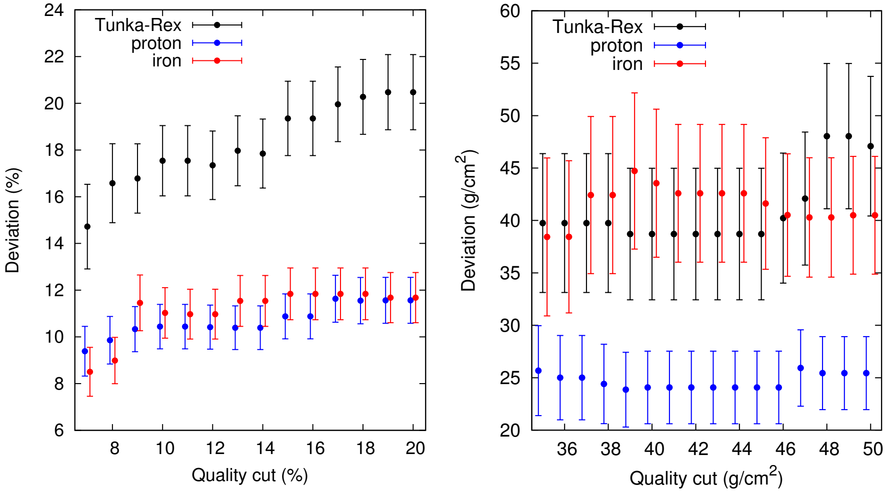


Parameter	Value
a_{200}	$1.94 \cdot 10^{-6}$ m^{-2}
a_{201}	$-0.16 \cdot 10^{-6}$ m^{-2}/EeV
a_{210}	$-0.35 \cdot 10^{-6}$ m^{-2}
a_{211}	$0.24 \cdot 10^{-6}$ m^{-2}/EeV

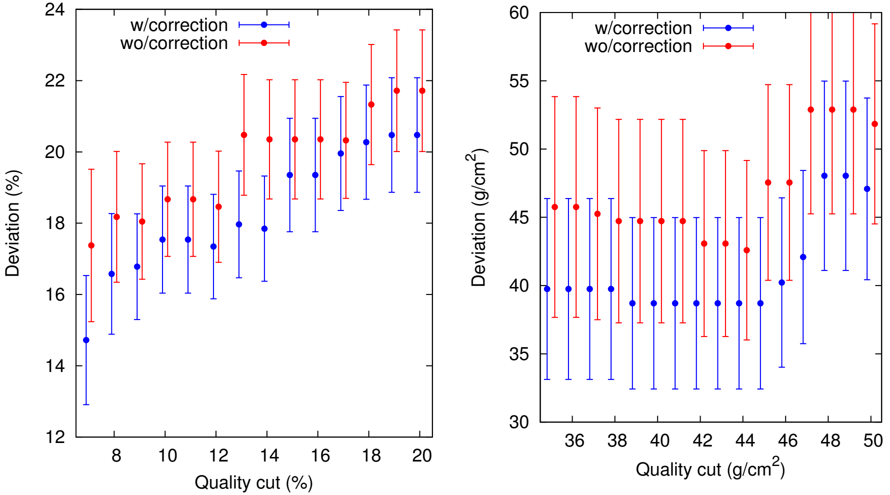
Shower maximum correlation



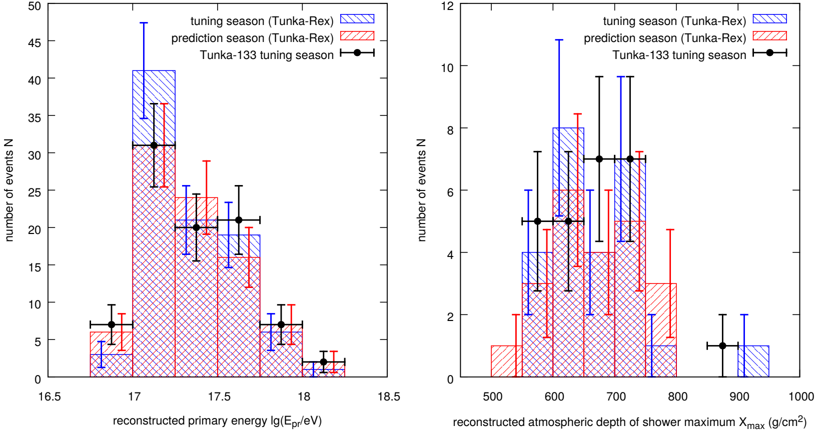
Theoretical and experimental resolution



Correction influence on resolution



Reconstructed spectra



Distribution of simulated $X_{\max}$