Determination of cosmic-ray primary mass on an event-by-event basis using radio detection

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Overview and motivation

- Traditionally, X_{max} is used as a surrogate for composition
- Large overlap in X_{max} distributions for different compositions
  - Even a very accurate estimate of X_{max} cannot lead to an event-by-event composition analysis
- X_{max} radio reconstructions have large uncertainties for inclined events
  - Radio experiments are using less dense but larger arrays, e.g. AERA
  - Larger arrays lead to better UHECR statistics
  - But sparser arrays can only properly sample footprints of inclined events
  - An alternative is needed for composition analysis
- We propose a new method that bypasses X_{max} reconstructions and infers primary composition directly
  - Based on comparisons between event and simulations of various primary compositions
  - Large event-by-event composition discrimination efficiency, even when taking into account some characteristic detection uncertainties

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X_{max} radio reconstruction

- First X_{max} radio reconstruction technique developed by LOFAR
  - Based on comparisons between the measured electric fields and scintillator data with simulations of proton and iron initiated showers
- Variants of this method currently used by multiple radio experiments
  - Some use only radio data
  - Comparable uncertainties to FD for less inclined showers ($\sim 20\text{g/cm}^2$)
- We developed a simplified variant of the LOFAR method
  - Investigate how the uncertainty in X_{max} varies with zenithal angle
  - Used ZHAIRES simulations along with the "two component" model

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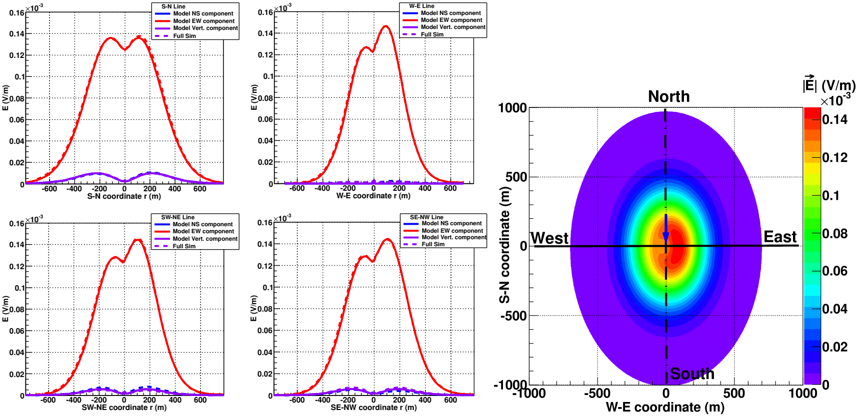
ZHAireS and the two component approach

- Superposition model used in lieu of “interpolation”
- Superposition of Askaryan and Geomagnetic components
- Obtain field at any position from simulations at only a few positions along a single direction w.r.t. the core: Very Fast!

Astropar. Phys. **59**, 29, 2014



Simplified Radio X_{max} reconstruction

- Σ_s used to quantify the difference between event and simulation

$$\Sigma_s(f_s, \vec{r}_{core}) = \sum_{all\ antennas} \left[|\vec{E}_{ant}| - f_s \cdot |\vec{E}|(x_{ant} - x_{core}, y_{ant} - y_{core}) \right]^2$$

- $|\vec{E}_{ant}|$: amplitude of measured peak electric field
- $|\vec{E}|(x, y)$: amplitude of simulated peak electric field at position (x, y)
- f_s: Energy/amplitude scaling factor (Energy uncertainty)
- (x_{ant}, y_{ant}): Antenna position
- (x_{core}, y_{core}): Core position (core position uncertainty)
- No SD particle data is used in the reconstruction
- For each simulation one can vary the core position and f_s.
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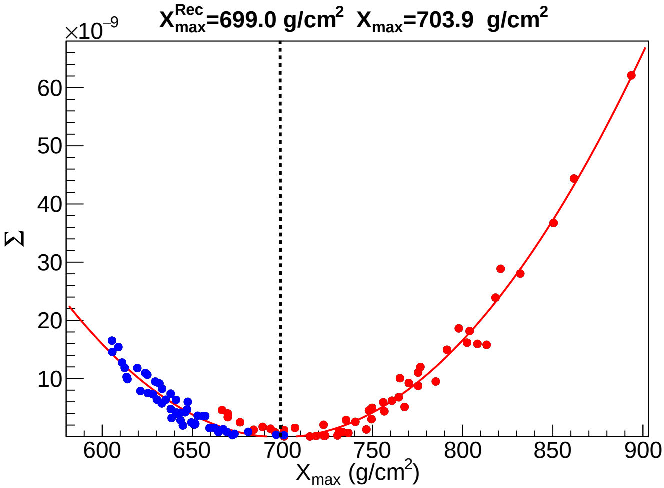
X_{max} reconstruction: Σ vs X_{max}

30°, ideal square array with D=500 m.



Dependance of $\sigma_{X_{max}}$ on zenithal angle

- Obtain lower limit for uncertainty in X_{max} (intrinsic to the method)
- No detection uncertainties folded into simulated events
- Ideal square array with D=500 m
- Large increase in $\sigma_{X_{max}}$ for $\theta > 60^\circ$
- 50 reconstructions per zenith angle

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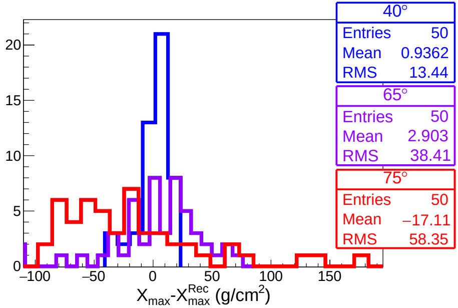

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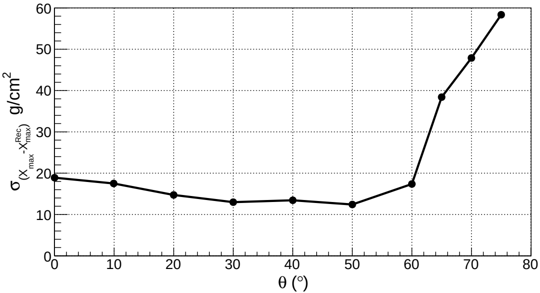

Increase in $\sigma_{X_{max}}$ for large θ

- Increase in $\sigma_{X_{max}}$ due to intrinsic characteristics of the radio footprint
- Radio footprint becomes less sensitive to X_{max} at large θ
- Reconstruction becomes more difficult
- Less variation on the position of the Cherenkov ring (R_{max}) with X_{max}
- Large $\theta \rightarrow$ low $\rho_{air} \rightarrow$ larger Geo/Ask ratio $\rightarrow$ more symmetric

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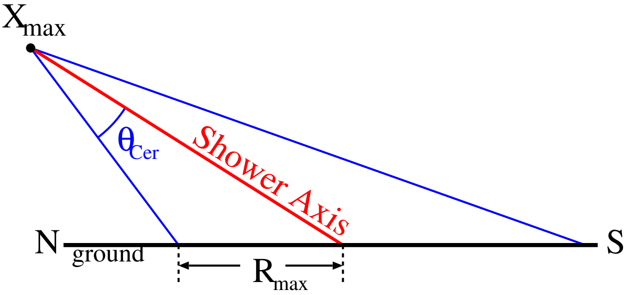

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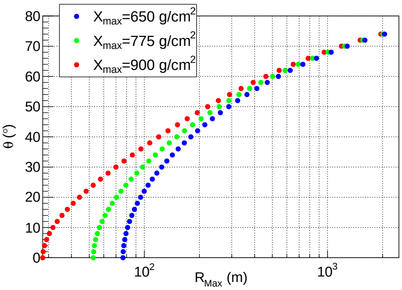

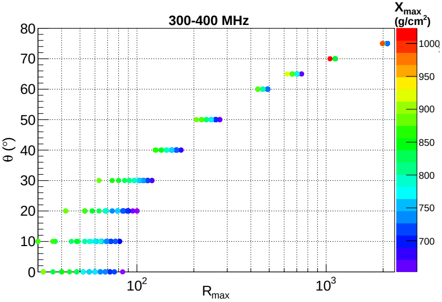

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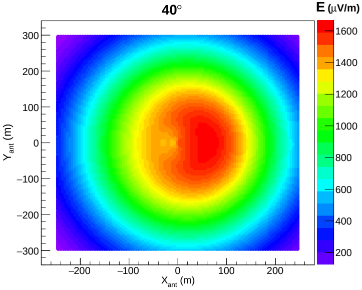

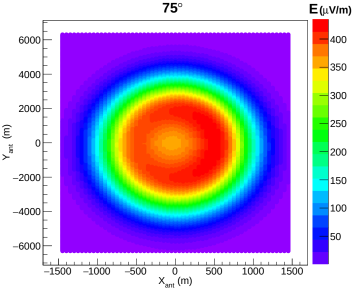

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- Sum over each component $i = x, y, z$ of the peak electric field

$$\Delta_s^2(f_s, \vec{r}_{core}) = \sum_i \sum_{antennas} \left[E_{i_{ant}} - f_s \cdot E_i(x_{ant} - x_{core}, y_{ant} - y_{core})\right]^2$$

- $E_{i_{ant}}$: amplitude of ith component of the measured peak electric field
- $E_i(x, y)$: amplitude of ith component of the simulated peak electric field at position (x, y)
- f_s: Energy/amplitude scaling factor (Energy uncertainty)
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- For each simulation one can vary the core position and f_s.
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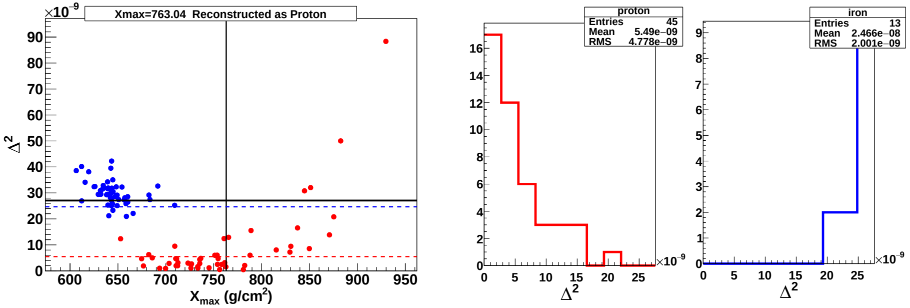
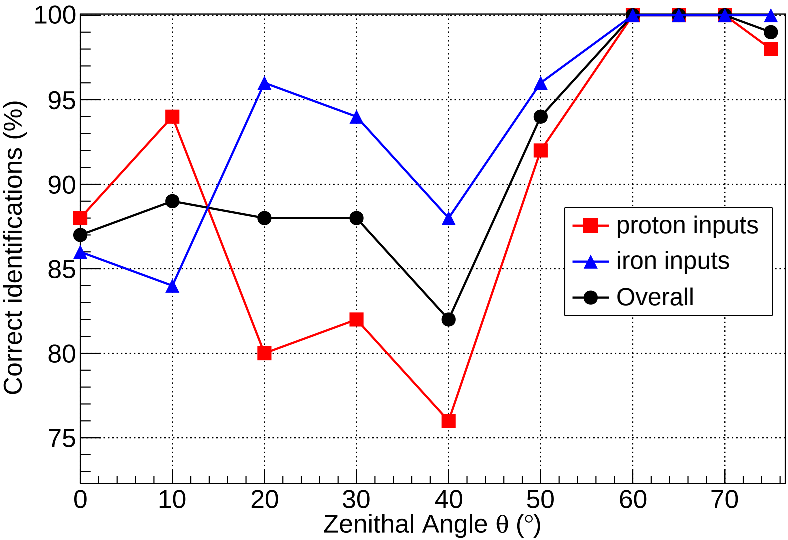
Example composition Reconstruction: Ideal array

- Input event: proton, $\theta = 65^\circ$
- Simulations: 50 p and 50 Fe, same energy and direction as input event
- Ideal square array with $D = 500$ m
- Different Δ^2 for different compositions, even with similar X_{max}



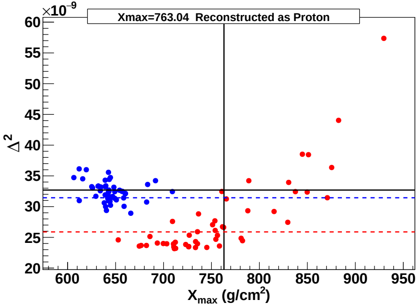
Results: Ideal array

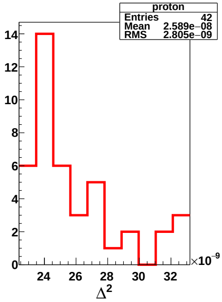


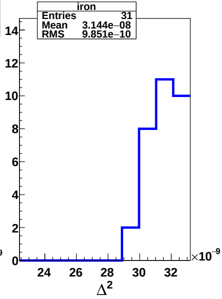
Detection uncertainties

- Effect of noise and background folded in the peak amplitudes of the input event
- Gaussian Noise: $\sigma_{noise} = 30\mu V/m$ per component of the electric field
- Background: Fixed at $3\mu V/m$, single isotropic direction per event
- Core position error $(r_{core}, \varphi_{core})$:
  - Gaussian r_{core} with $\sigma_{core} = 50$ m, equally distributed φ_{det}
  - Antenna coordinates of the input event are shifted by $(r_{core}, \varphi_{core})$ before reconstruction
- Increased distance between antennas in array to $D = 750$ m
- No energy and arrival direction uncertainties were included ($f_s = 1$)

Example Reconstruction: with detection uncertainties







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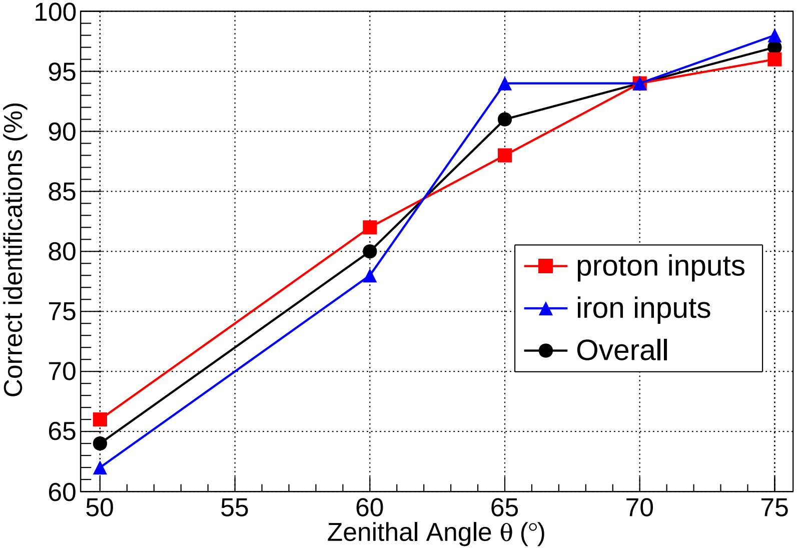
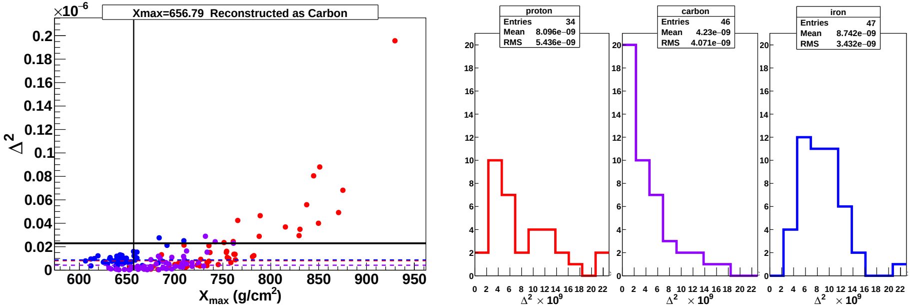


Including a semi-heavy composition

Example Carbon input event, 65°, ideal array with $D = 500$ m
No detection uncertainties



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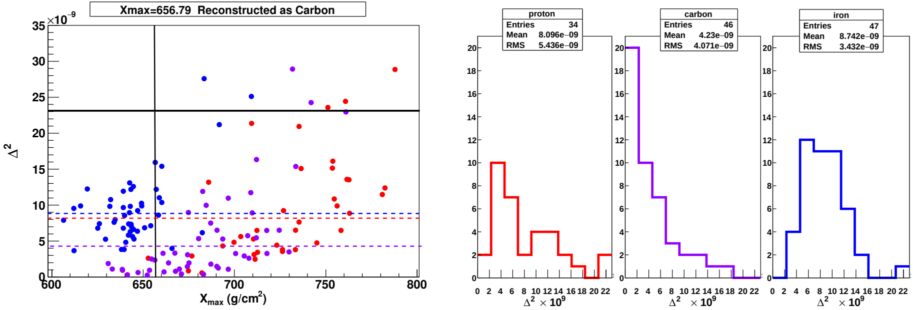
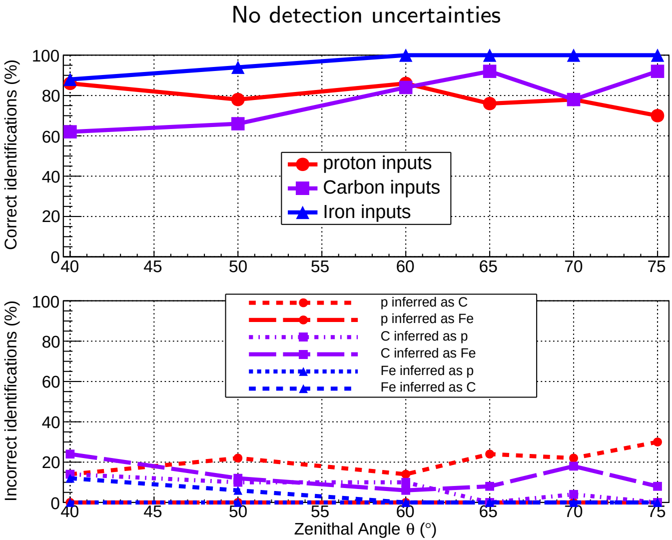
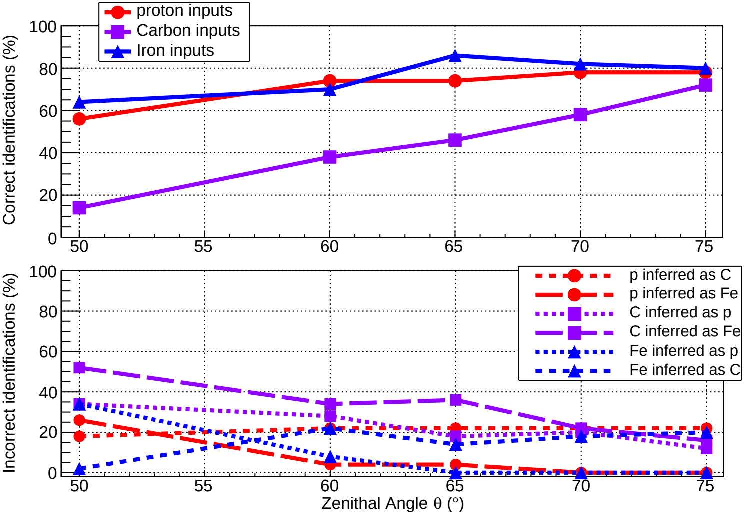


Results including C: No detection uncertainties



Results including C: With detection uncertainties

With detection uncertainties: Not good enough for event-by-event analysis



Conclusions

- Large increase in the intrinsic X_{max} uncertainty for inclined events
- $\sigma_{X_{max}} \gtrsim 40$ g/cm^2 for $\theta > 60°$: unsuitable for composition analysis
- An alternative is needed for composition analysis of inclined events
- Do we really need X_{max} for composition analyses using radio?
- New method: Bypasses X_{max} and infers composition directly
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  - Could be feasible by improving the method further
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  - Maximum-likelyhood or Bayesan analysis
  - Use shape of Δ^2 distributions
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Questions?

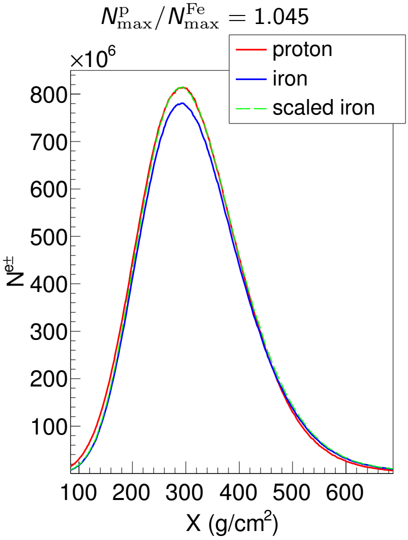
Other applications of Radio...

BACKUP SLIDES

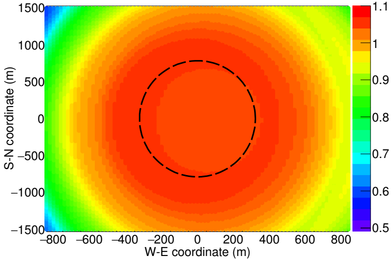
Pair of events: Similar X_{max} with different compositions

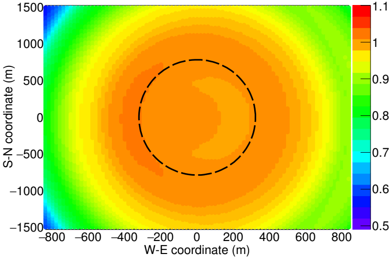
- Pair of events: one p and one Fe with similar X_{max}
- Average number of pairs for $\Delta X_{max} < 3$ g/cm^2: 14
- Average number of pairs for $\Delta X_{max} < 20$ g/cm^2: 101
- Investigate the fraction of correctly identified pairs (both p and Fe)
  - Without detection uncertainties:
    - $\sim$ 0% for $\theta < 50^\circ$
    - $\sim$ 65% for $\theta = 50^\circ$
    - 100% for $\theta > 60^\circ$
  - With detection uncertainties:
    - $\sim$ 20% for $\theta = 50^\circ$
    - $\sim$ 95% for $\theta > 70^\circ$
- X_{max} dominates the variation in the radio footprint at lower θ
  - Either p or Fe of the pair is incorrectly discriminated
- As θ increases X_{max} becomes less important
  - Δ^2 becomes sensitive to other degrees of freedom
  - It becomes possible to correctly discriminate both p and Fe of the pair

Main sources of the differences in the footprint



Ratio $|E_p|/|E_{Fe}|$





Energy uncertainty

- If f_s used as a free parameter for each simulation
  - Inherent differences in the amplitude of the longitudinal profiles are masked
  - Artificially decreases the differences between proton and iron showers
- Included energy uncertainties on our set of events at 65°
  - f_s allowed to vary freely between 0.8 and 1.2 in the minimization
  - Minimized f_s for proton (iron) was 0.95 (1.00)
  - Matches the average difference of $\sim 5\%$ in $N_{\max}$ between p and Fe
  - Only small decrease in the overall (p and Fe) discrimination efficiency
  - From 91% (fixed f_s) to 83% (f_s as a free parameter)
- Effect can be mitigated further by enhancing energy estimate
  - e.g. using AERA energy reconstruction
- Impact at other geometries still needs to be investigated