# A strong dependence of the radio emission of air showers on $X_{max}$ and primary composition: Revisiting the Radio LDF.

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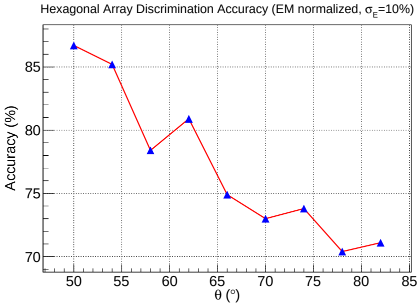
# Summary

- Motivation: ML Random Forest primary composition discrimination method (using simulated events at the GRAND prototype):
  - Analysis uncovered a strong electric field amplitude dependence on $X_{max}$ , even accounting for the EM energy of the showers.
- Objective: Explain this effect, in a semi-quantitative way, in terms of two simple competing scalings of the electric field
  - Radio emission: E-field dependence on distance and air density
  - Proposed scalings and loss of coherence
  - Predictions and comparison to full simulations
  - Conclusions
- Extra (if enough time): The spectral slope "LDF"
  - Slopes are also affected by $X_{max}$ (well known)
  - We propose the loss of coherence effect as the main physical reason

# Motivation: ML discrimination

- We developed a Machine Learning (ML) Random Forest algorithm
  - Discriminates between heavy (Fe) and light (p) primary compositions on an event-by-event basis (both at GRAND and a generic array)
  - Bypasses any $X_{max}$ reconstruction and infers composition directly
  - Very simple features: just antenna distances and field amplitudes
  - Unexpected good accuracies, even with a huge 30% energy smearing
- Analysis of the feature importances: proton showers seemed to be brighter than Fe near the core on most geometries

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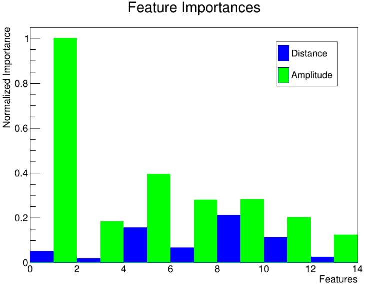
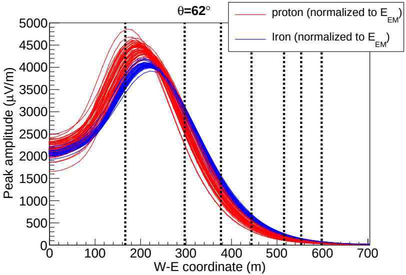
# Explaining the parameter importances: Example at $\theta = 62^\circ$

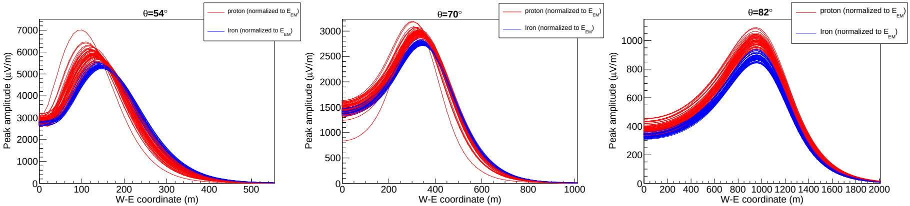
- Most important features:
  - Amplitude of the closest antenna followed by the amplitude of the third closest antenna, and then decreasing for larger distances
- Observed a strong and well behaved amplitude dependence on $X_{max}$ :
  - Effect is very large
  - Even accounting for the different EM energy of the showers
  - An $X_{max}$ dependence also equates to a composition dependence
  - This effect can fully explain the behavior of the feature importances and is what the forest uses to obtain such good accuracies



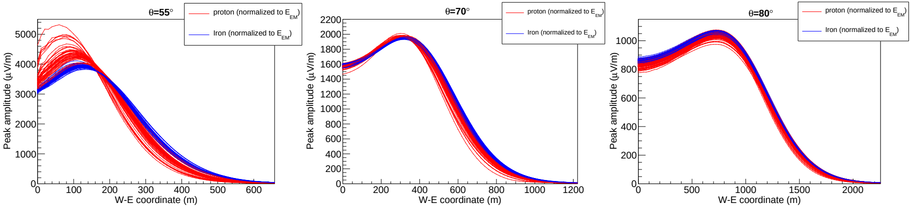



# Example LDFs: Behavior depends on zenith and site ($\vec{B}$)

## GRAND ($|\vec{B}| = 56.4\mu T$)



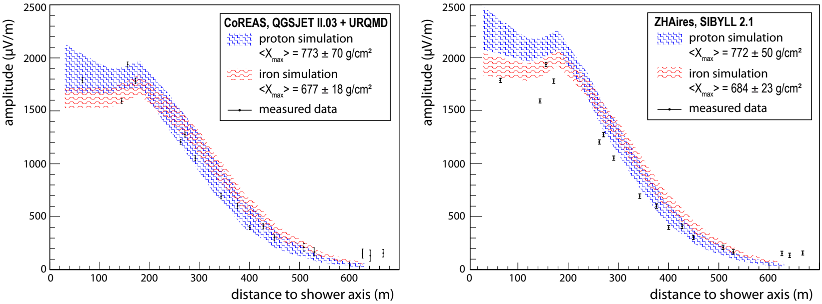

## AUGER ($|\vec{B}| = 24.0\mu T$)



# Effect was seen before, but historically disregarded

- This dependence was seen before, but was never fully pursued
- Mostly dismissed as just an EM/missing energy effect
- This effect was historically overlooked!
  - Introduction of the LOFAR $X_{max}$ reconstruction ($\chi^2$ based, "black-box")
  - People stopped looking at LDFs for multiple compositions

First comparison between CoREas, ZHAireS and AERA data (ca. 2013):




Tim Huegue, arXiv:1310.6927, Braz. J. Phys., 44, 5, 520-529, (2014)

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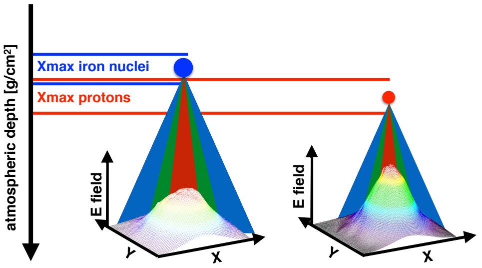
LOFAR $X_{max}$ reconstruction method ("black-box")

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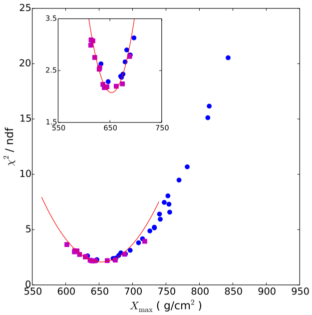
Buitink, et al., arXiv:1408.7001 (2014)




Florian Gaté, arXiv:1609.06510 (2016)

# Why does the amplitude depend on $X_{max}$ ?

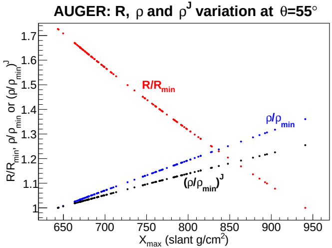
- Vector potential contribution from a single finite particle track:

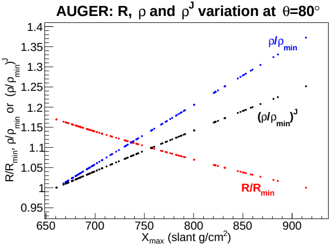
$$\vec{A}(t,\hat{u}) = \frac{\mu e}{4\pi R c^2}\,\vec{v}_\perp\,\frac{\Theta(t-t_1^{det})-\Theta(t-t_2^{det})}{1-n\vec{\beta}\cdot\hat{u}}, \qquad \vec{E} = -\frac{\partial \vec{A}}{\partial t} \qquad \text{(ZHS formalism)}$$

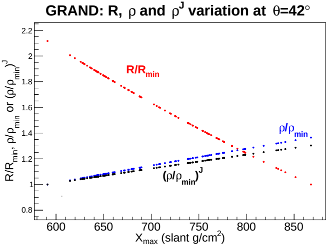
- Emission consistent with 2 main emission mechanisms:
  - Askaryan or charge excess ($R$ only) and geomagnetic ($R$ and $\vec{v}_\perp$)
- The Lorentz force constantly tries to increase $\vec{v}_\perp$, but there is a limit due to the interactions of the charged particles with the air molecules
  - Governed by the drift velocity $v_d \propto 1/\rho$, akin to a terminal velocity
  - $\vec{v}_\perp \propto v_d \propto 1/\rho \rightarrow \boxed{\vec{v}_\perp \propto 1/\rho}$
- As $X_{max}$ increases the shower develops lower in the atmosphere, so:
  - The distance $R$ from $X_{max}$ to the array decreases with $X_{max}$ :
    - **$1/R$ scaling** $\rightarrow$ ***increases*** field as $X_{max}$ increases
  - The air density $\rho$ at $X_{max}$ increases with $X_{max}$ , decreasing $v_d$ and $\vec{v}_\perp$:
    - **$1/\rho$ scaling** $\rightarrow$ ***decreases*** field as $X_{max}$ increases
  - Two **competing** effects as $X_{max}$ varies!

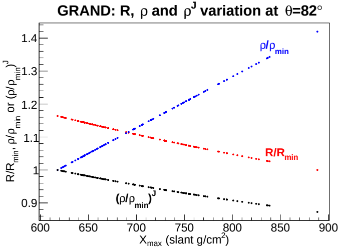
# $R$ and $\rho$ variations just due to shower geometry

- The variation of $R = R(\theta, X_{max})$ and $\rho = \rho(\theta, X_{max})$ with $X_{max}$ only depend on the shower geometry and atmospheric model (no sims)



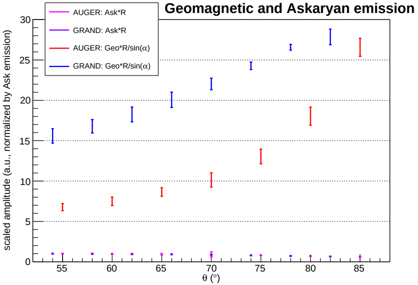



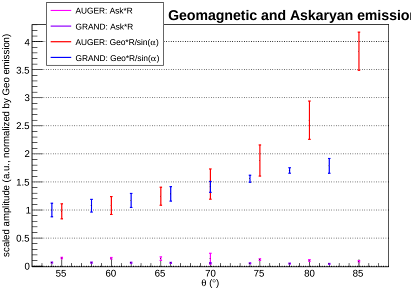
# Amplitude scaling with R: valid for the whole atmosphere

- Average peak amplitudes as a function of $\theta$, multiplied by $R$, for each emission mechanism separately (Ask and Geo)
- The Askaryan emission is almost constant for all $\theta$:
  - Amplitude scales roughly with 1/R over the whole atmosphere
- Much higher geomagnetic emission at GRAND than at AUGER
  - As expected, due to $|\vec{B}|_{Auger} = 24.0\mu T$, $|\vec{B}|_{Grand} = 56.5\mu T$
- But the geomagnetic emission increases much faster at AUGER. Why?

(Normalized by the Askaryan emission)



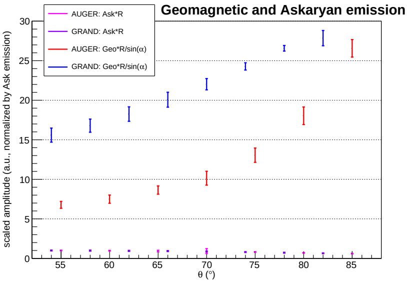

(Normalized by the Geomagnetic emission)



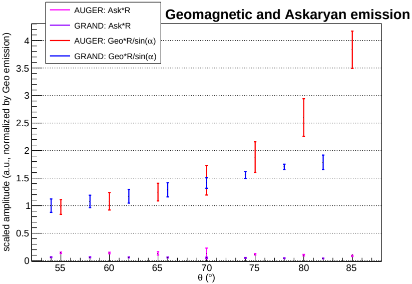
# Loss of coherence at low air densities

- At lower densities (higher $\theta$) the drift velocity $v_d \propto 1/\rho$ increases:
  - Deflections due to the Lorentz force also increases
- Bigger deflections introduce extra time delays that lower the coherence of the emission: JCAP08, 015, (2023), JCAP05, 055, (2024) and PRL132, 231001, (2024)
- This loss of coherence also increases with $|\vec{B}|$ (bigger Lorentz force):
  - At GRAND, the higher geomagnetic field increases coherence loss
  - So, the geomagnetic emission increases less with $\theta$ at GRAND

(Normalized by the Askaryan emission)

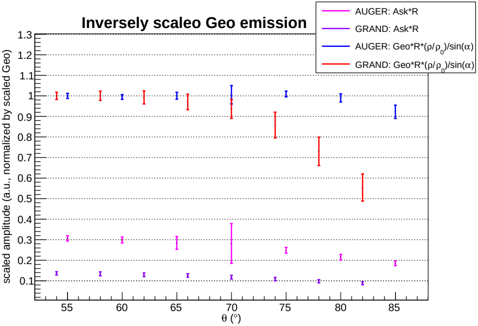



(Normalized by the Geomagnetic emission)



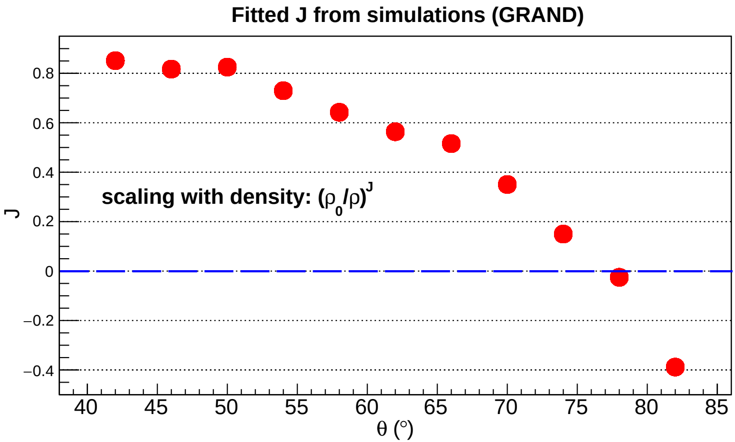
# Amplitude scaling with the density $\rho$

- The geomagnetic emission scales only very roughly with $1/\rho$
  - As $\rho$ decreases, the increase in $v_d$ and $\vec{v}_\perp$ leads to higher fields
  - But the loss of coherence diminishes the strength of this $1/\rho$ scaling
- Inversely scaled geomagnetic component: $\mathrm{Geo}R(\rho/\rho_0)/\sin(\alpha)$
  - While the $(1/\rho)$ linearity holds, this value should be constant
- Much higher $|\vec{B}|$ at GRAND increases coherence loss:
  - The $(1/\rho)$ scaling starts to loose linearity much sooner at GRAND.



# Estimating the $\rho$ scaling non linearity: Loss of coherence

- Fitted $J(\theta)$ from the simulation sets to estimate loss of coherence
- Changed density scaling: $(1/\rho) \rightarrow (1/\rho)^{J(\theta)}$
- Loss of coherence decreases the strength of the $(1/\rho)$ scaling



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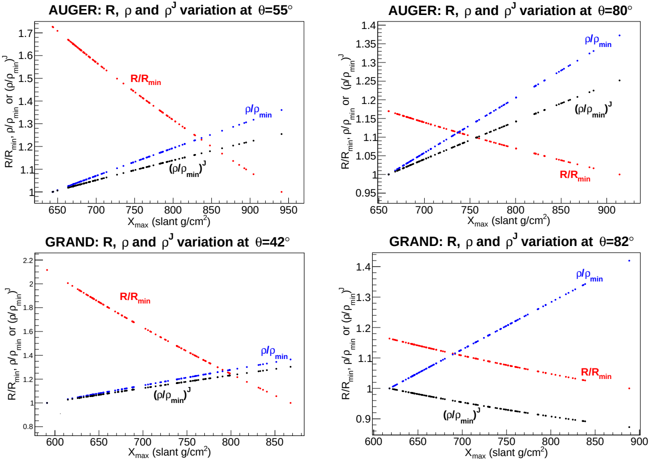
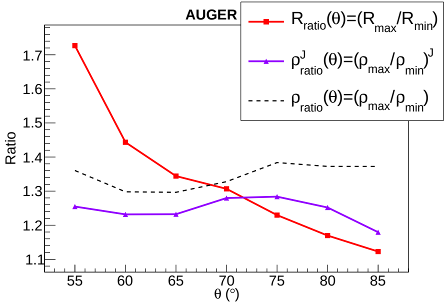
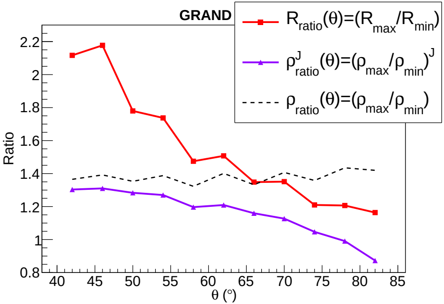


# Predictions from the $1/R$ and $(1/\rho)^{J(\theta)}$ scalings

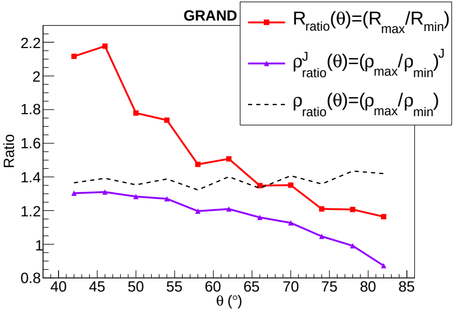
- Which effect dominates depends on the region in the atmosphere:
  - At low $\theta$ (high $\rho$) R varies more than $\rho$: R scaling always wins
  - At high zeniths $\rho$ varies more than R: the **linear** $\rho$ scaling would win
  - But the actual density scaling $(1/\rho)^{J(\theta)}$ will depend on the loss of coherence and thus on the geomagnetic field $\vec{B}$ at the site
- Expected relative strength of the $1/R$ and $(1/\rho)^{J(\theta)}$ scalings:

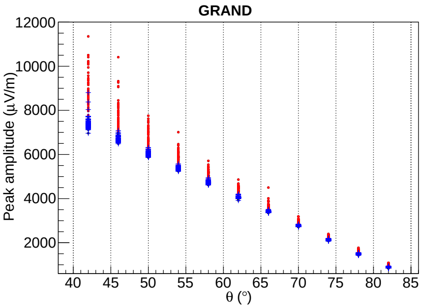


# Comparison to the full simulation results: GRAND

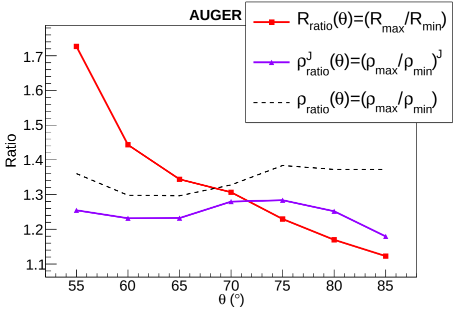
- Protons tend to have higher $X_{max}$ : lower R, but higher $\rho$ than Fe
  - The $1/R$ scaling tends to increase the field of p showers
  - While the $1/\rho$ scaling tends to increase the field of Fe showers
- At GRAND, there is a greater loss of coherence due to the higher $\vec{B}$ :
  - This denies the increase of the $(1/\rho)^{J(\theta)}$ with zenith
  - The 1/R scaling dominates everywhere
  - Protons tend to have higher fields at every zenith, as observed

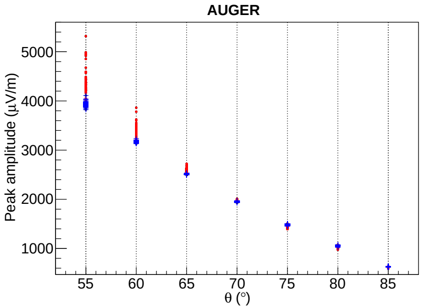


# Comparison to the full simulation results: AUGER

- At Auger, there is a lot less loss of coherence (much lower $|\vec{B}|$):
  - The non-linearity term $J(\theta)$ diminishes less with zenith
- Which scaling dominates will depend on the zenith angle
- Our prediction: the $(1/\rho)^{J(\theta)}$ scaling dominates above $\theta = 72°$, so:
  - Protons would tend to have higher fields for $\theta \lesssim 72°$
  - But Iron would tend to have the higher fields for $\theta \gtrsim 72°$
  - This perfectly matches the behavior of our full simulations



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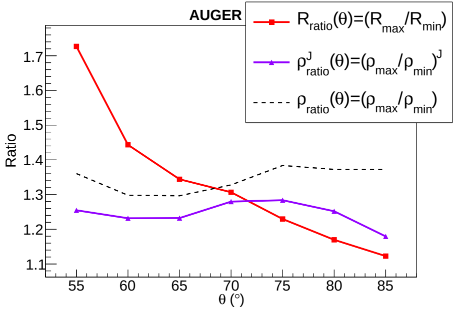
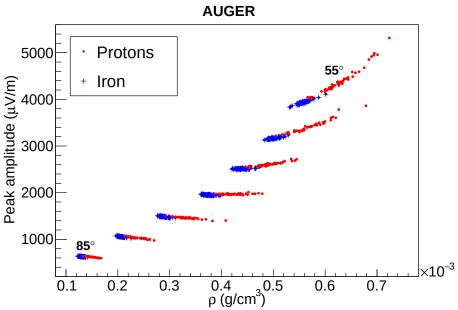
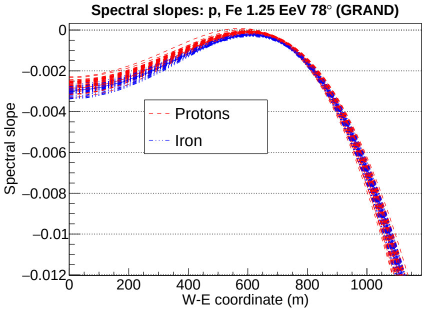


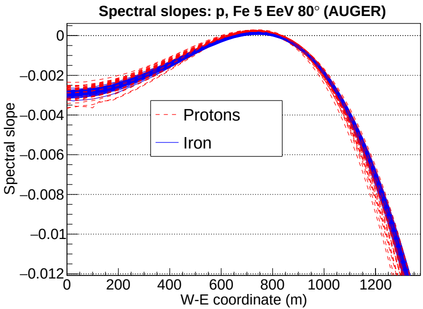
# New: slope "LDF" behaviour

- The slope "LDF" dependence on $X_{max}$ could have the same physical reasons as the amplitude dependency
- Mainly due to the loss of coherence effect at low densities and high $\vec{B}$
- The distance effect of $X_{max}$ should be very small
- At lower zeniths, the loss of coherence is small:
  - Smaller $X_{max}$ density effect
  - Similar slopes at AUGER and GRAND

High $\vec{B}$: High loss of coherence




Low $\vec{B}$: Low loss of coherence



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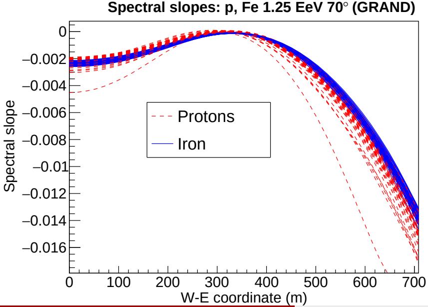
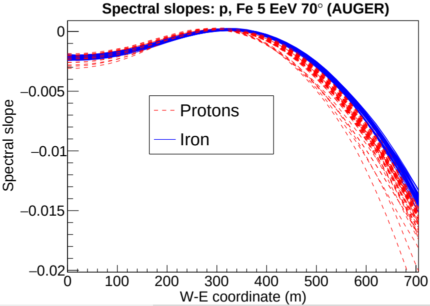
Low zenith: Low loss of coherence




Low zenith: Low loss of coherence



# Conclusions

- There is a strong dependence of the radio LDF on $X_{max}$ (composition)
- It is much bigger than any EM energy differences between p and Fe
- Can be understood in terms of two simple competing scalings:
  - A 1/R and a $(1/\rho)^{J(\theta)}$ scaling of the electric field, where $J(\theta)$ quantifies the coherence loss
  - This loss of coherence is due to the larger time delays induced by the larger deflections and heavily depends on $\vec{B}$
- At GRAND, matching our prediction, proton induced showers tend have higher measured electric fields for all $\theta$ due to the high $\vec{B}$
- The much lower $\vec{B}$ at AUGER creates a transition region at $\theta \simeq 72^\circ$
  - For $\theta \lesssim 72^\circ$, the 1/R scaling dominates and proton induced showers tend to have higher fields
  - For $\theta \gtrsim 72^\circ$, the $(1/\rho)^J$ scaling dominates and now iron induced showers tend have the higher fields

# Conclusions

- The spectral slope "LDF" seems to be sensitive to the loss of coherence effect, but not sensitive to the distance effect
- This historically overlooked dependence of the field amplitude on $X_{max}$ can also be used to create new, more refined event-by-event composition discrimination methods.
- Outlook:
  - This $X_{max}$ dependence also suggests that there could be a composition bias in the current energy reconstruction methods that use radio amplitude data.
  - The estimated EM energy resolution of these methods may be underestimated, as the quoted 5% is smaller than the amplitude differences between p and Fe.
  - These methods should be checked to look for a possible $X_{max}$ /composition bias

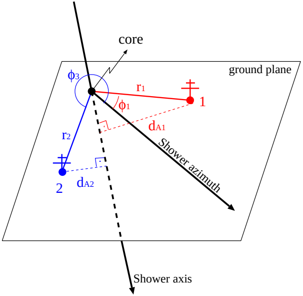
# Questions?

**Other applications of Radio...**

BACKUP

# Random Forest Features

- Triggered antennas are ordered with increasing distance to the axis
- For each antenna $i$ we used:
  - The distance $d_{Ai}$ to the shower axis and the peak amplitude $|E_i|$
  - Features: $d_{A1}, |E_1|, d_{A2}, |E_2|, ..., d_{Ai}, |E_i|$
  - The number of features is $2\times$ the number of antennas triggered by the event with the most antennas
  - For events with less antennas, missing features are substituted by zeros
  - Primary composition also saved (p or Fe)

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# Full ZHAireS simulations

- Antennas on a single line East of the core (no asymmetry!)
- 50 p and 50 Fe showers per zenith angle
- Electric fields normalized by the EM energy of each shower
  - Removes effects due to missing energy differences between p and Fe
    - At 1.25 EeV, on average, $\sim 10\%$ for p and $\sim 15\%$ for Fe
- 2 sites: GRAND and AUGER
- GRAND:
  - Ground at 1264 m, $|B| = 56.4\mu T$, 50-200 MHz
  - Showers with $E_0 = 1.25$ EeV coming from the North
  - Zeniths between 42 and 82° in steps of 4°
- AUGER (older simulation set):
  - Ground at 1400 m, $|B| = 24.0\mu T$, 30-80 MHz
  - Showers with $E_0 = 5$ EeV coming from the South
  - Zeniths between 55 and 85° in steps of 5°

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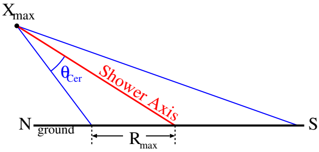
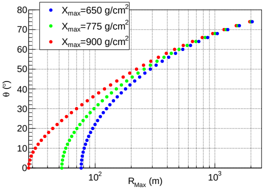
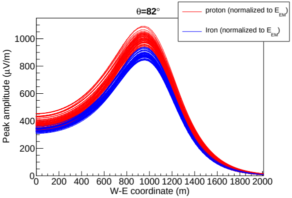
# The “Magic angle” ($\sim 84°$)

- Near the “Magic angle” $\sim 84°$:
  - The footprint size decrease due to a decreasing $\theta_{Cher}$ with altitude cancels out the size increase due to the larger distances (projection)
  - Around this angle the radio footprint shape (illuminated area, ring position) does not depend on $X_{max}$ anymore.
  - Footprint shape is the same regardless of $X_{max}$ , but the amplitude still depends on $X_{max}$ (composition)




W. Carvalho and J. ALvarez-Muñiz, arXiv:1712.03544

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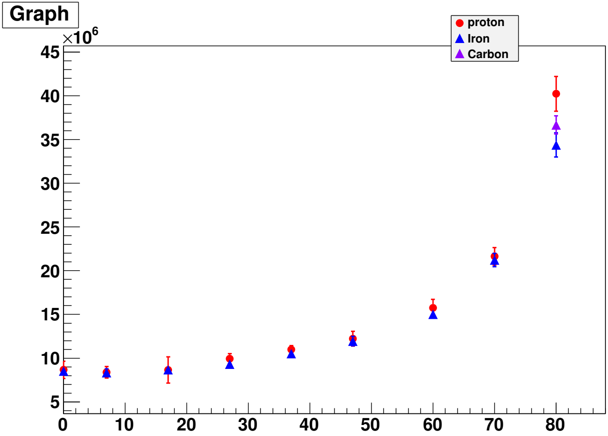
# Possible composition bias on Energy Reconstruction?

Old plots from 2016....



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