Karlsruher Institut für Technologie

Radio universality and template-based pulse synthesis

by David Butler, Tim Huege, Olaf Scholten

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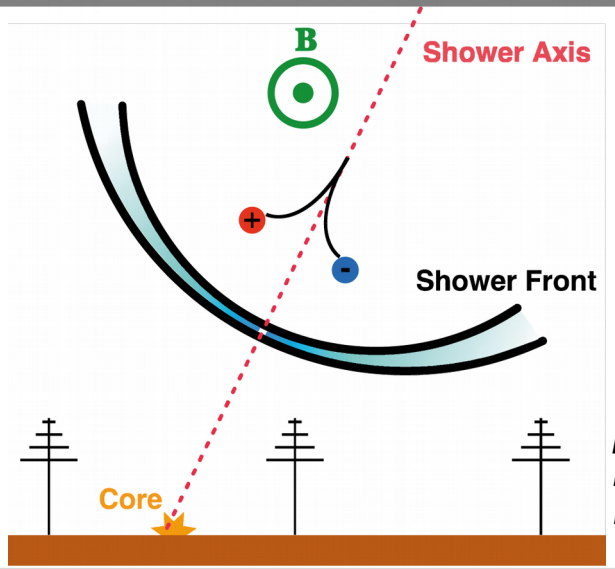
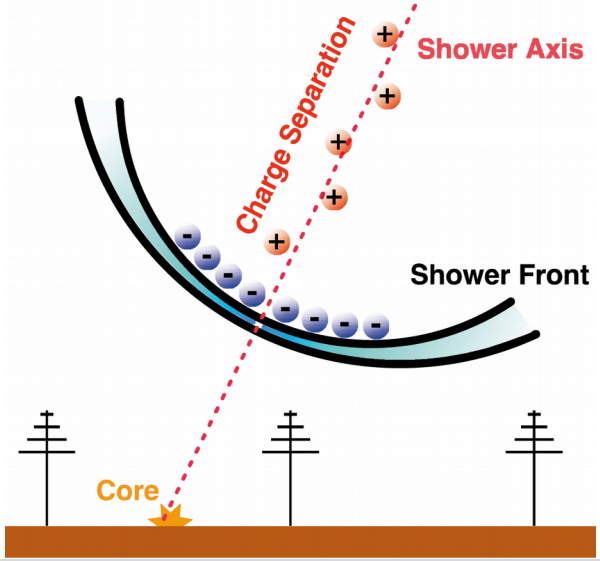
Institut für Kernphysik (IKP)



[H. Schoorlemmer, Tuning in on cosmic rays, Ph.D. thesis, Radboud Universiteit Nijmegen, 2012.]



Forward Model

- Large computation cost of full particle physics simulation

  ⇒ Accurate simulation-based reconstructions very expensive
- Poor control over indirect inputs (X_{max})
- No analytical understanding
- Fully macroscopic models not accurate enough

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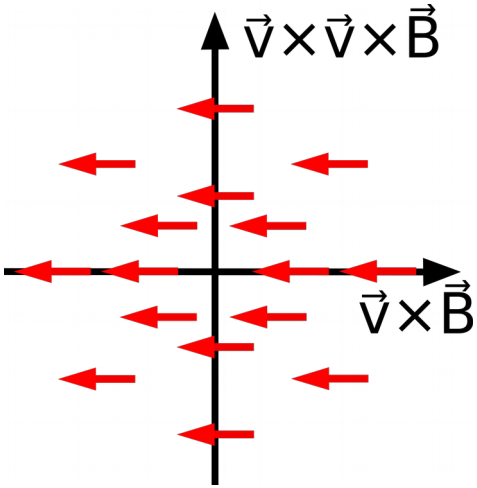
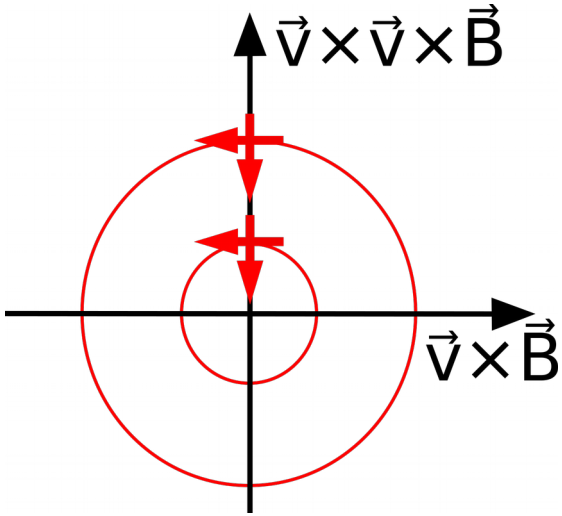
- Build templates from CoREAS output
- Use macroscopic theory to modify templates
- For now: focus on 10^{17}eV vertical proton showers

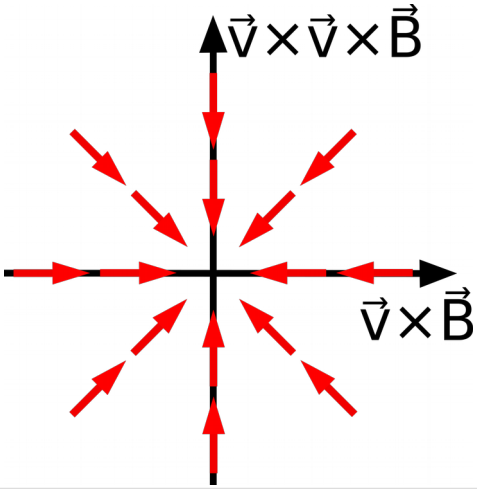
Radio Emission – Shower Plane



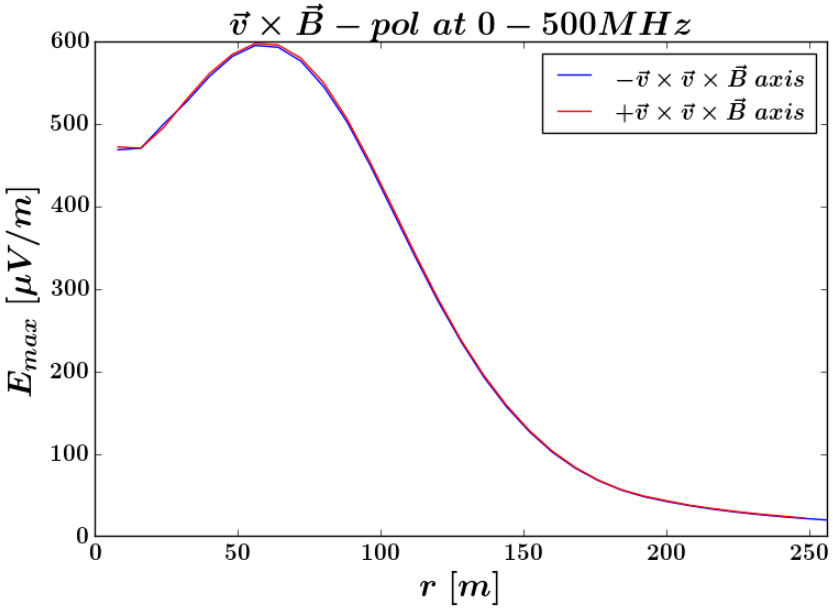
Geomagnetic



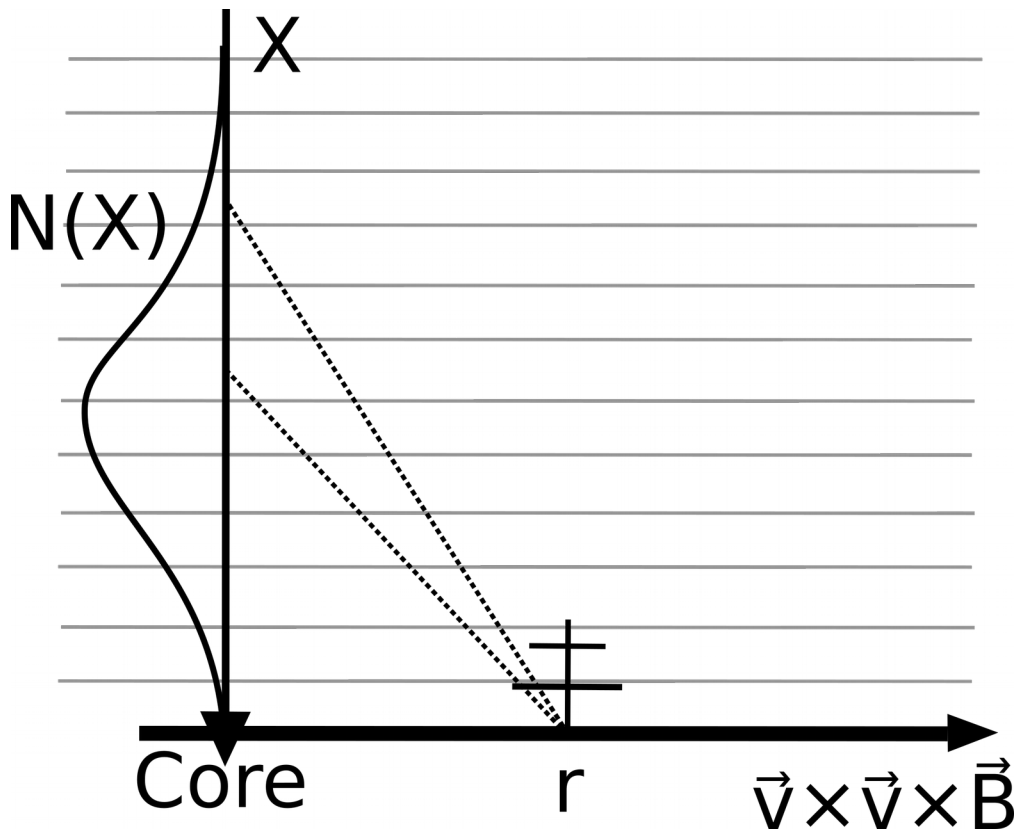
$$\vec{E} = E_G \cdot \hat{v}\times\hat{B} + E_A \cdot \hat{e}_r$$



Askaryan



Longitudinal – Slicing

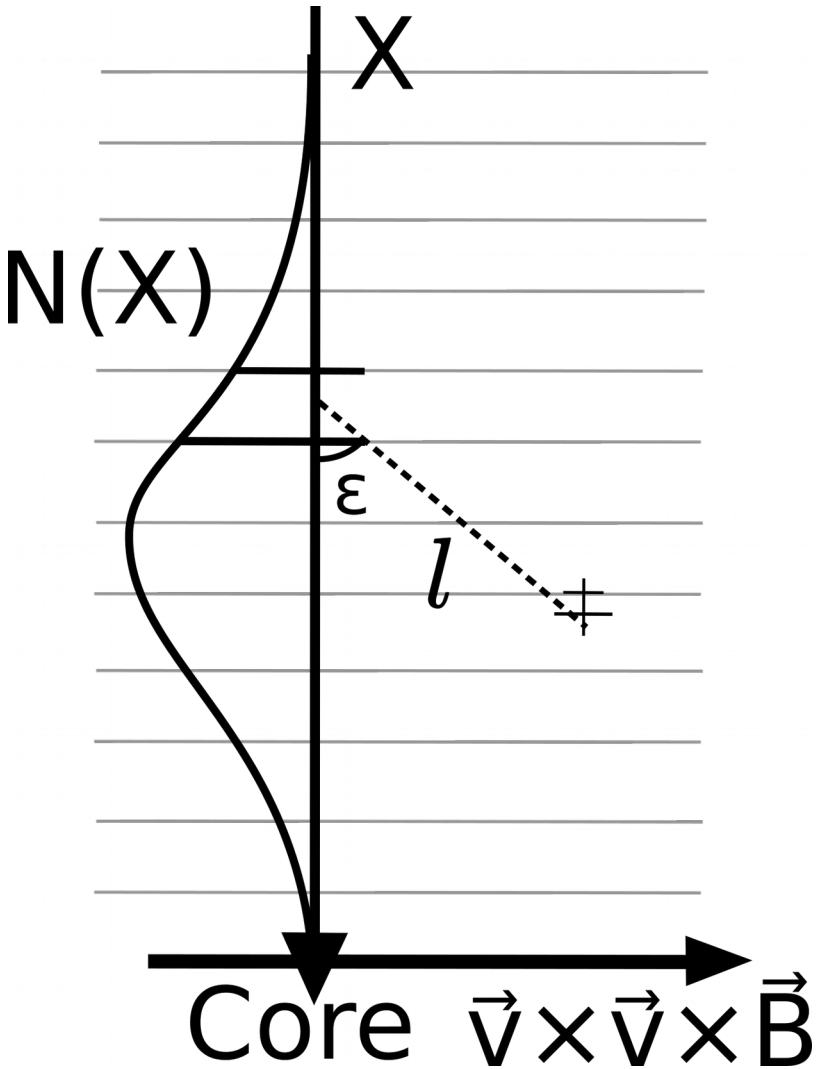


$$\vec{E}(t,r)=\sum_{X}\vec{E}(t,r,X)$$

- Radio emission sliced by atmospheric depth of origin
- Sum of all slices reproduces measurable signal
- Slices much larger than radio wavelengths, but smaller than longitudinal coherence length

Longitudinal – Parametrisation

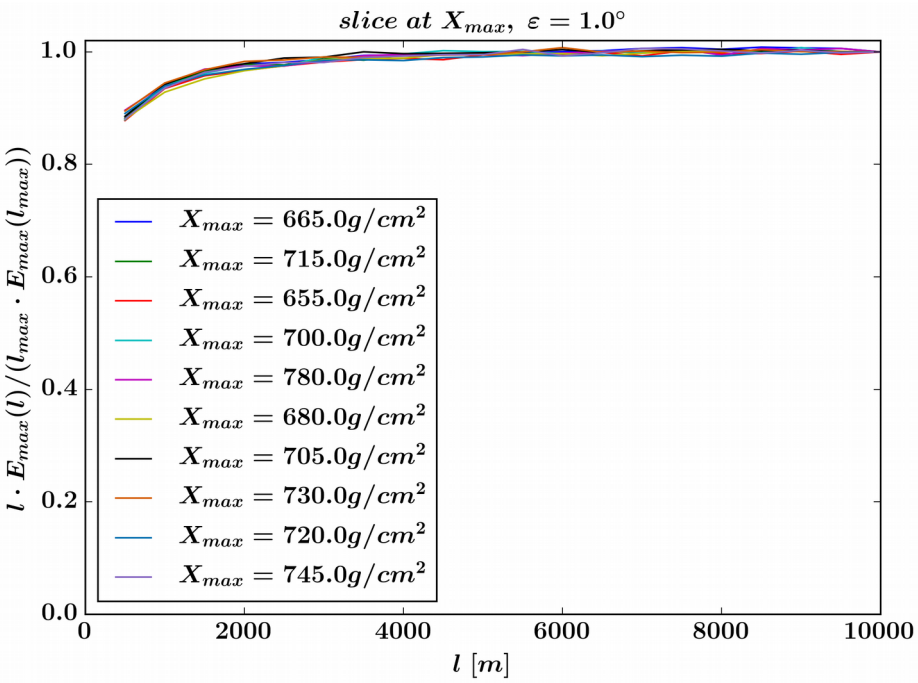
- Key assumption: slice acts as discrete source
  - Point source amplitude scales as 1/l
  - Radiation propagates in straight line with speed c/n_{eff}
  - Internal structure reducible to a few key parameters

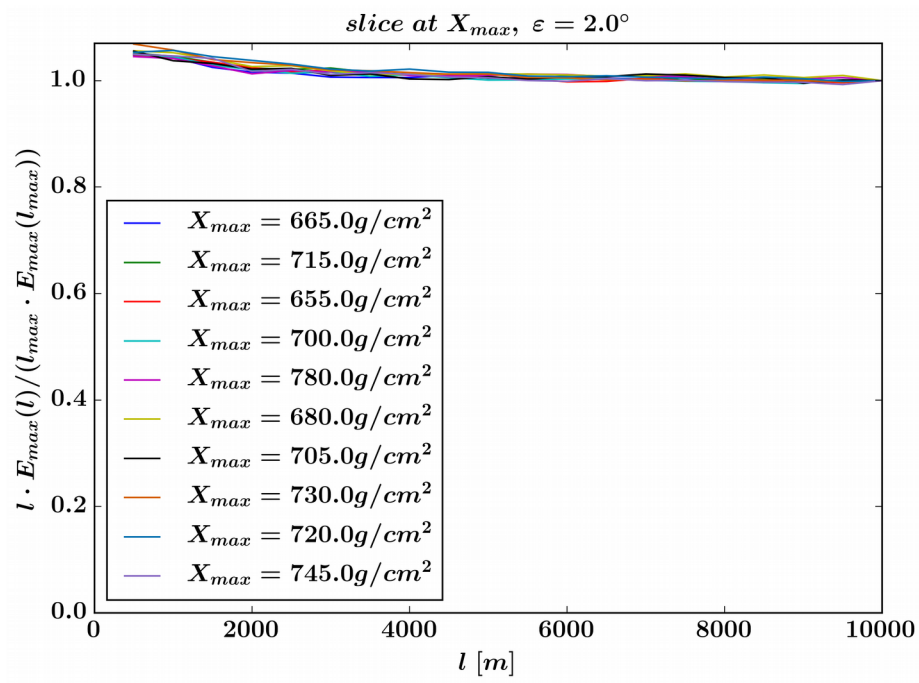


Line-of-sight scaling

- Radio wavelengths >0.5m, slices >50m ⇒ expect near-field effects
- Scaling appears to be universal
- Convergence for l>4km corresponding to vertical X<600g/cm^2

  ⇒ <u>10% systematic deviation</u> for late stage of vertical showers

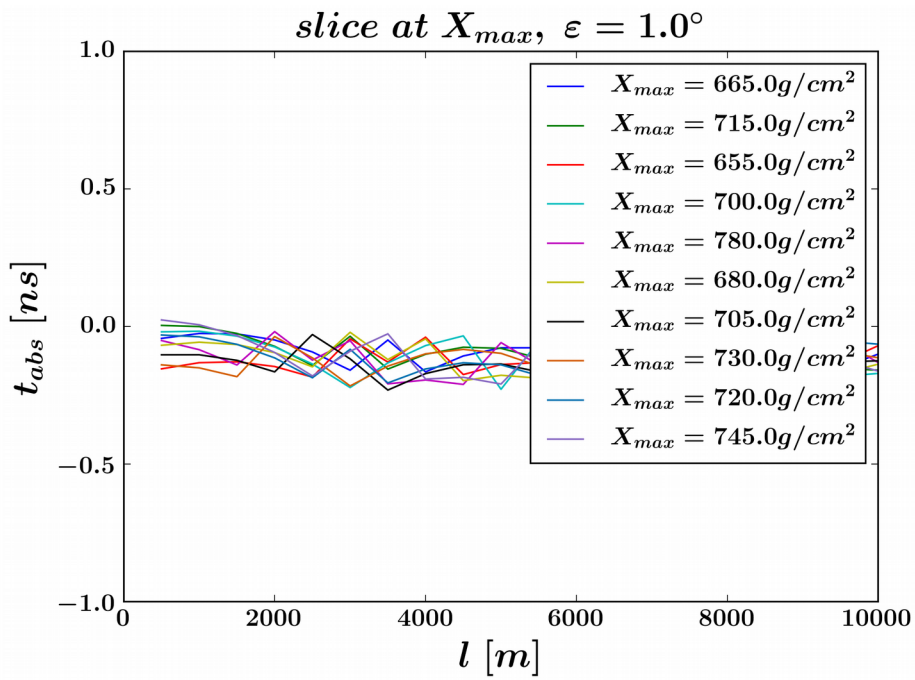


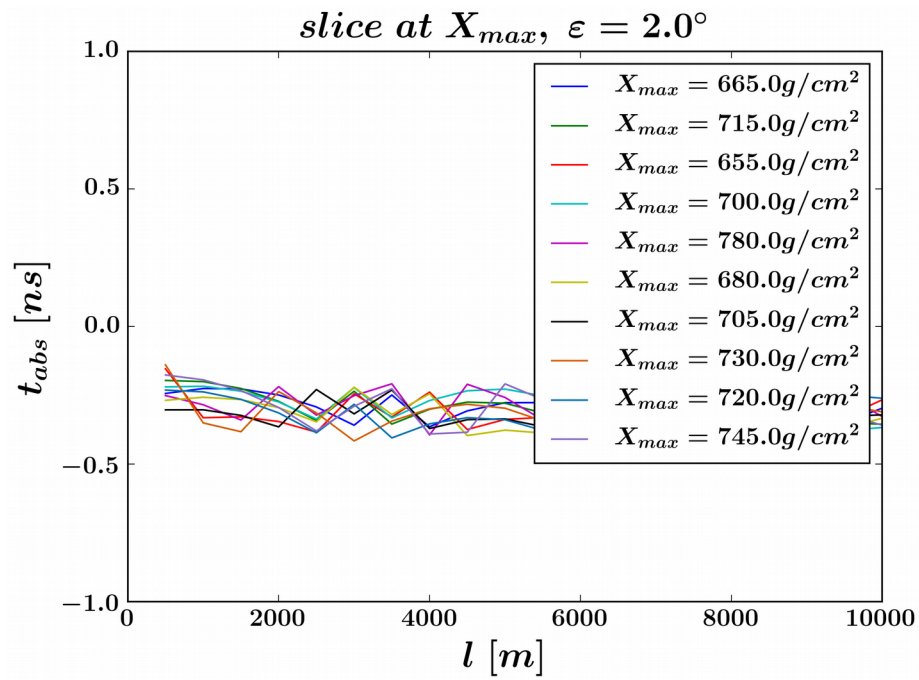


Pulse timing

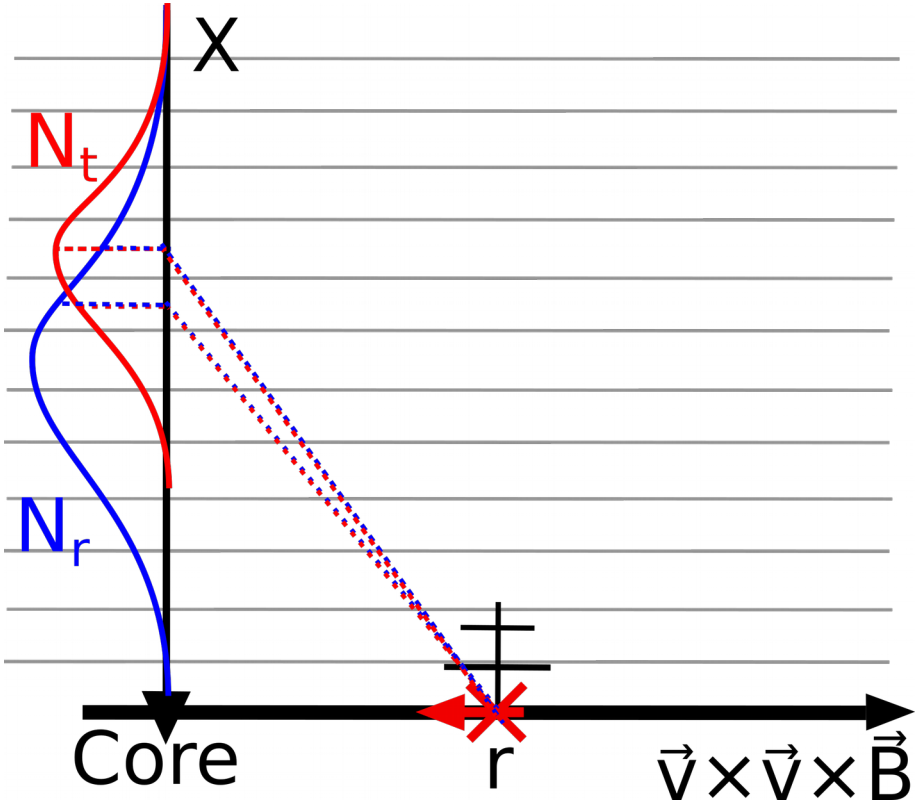
- Peak position propagated by $\Delta t = n_{eff}(l) \cdot l / c$
- Shower front calculated with flat atmosphere
- CoREAS time precision dt = 0.2ns

  ⇒ Classical ray timing <u>consistent within numerical limits</u>





Longitudinal – Template Synthesis

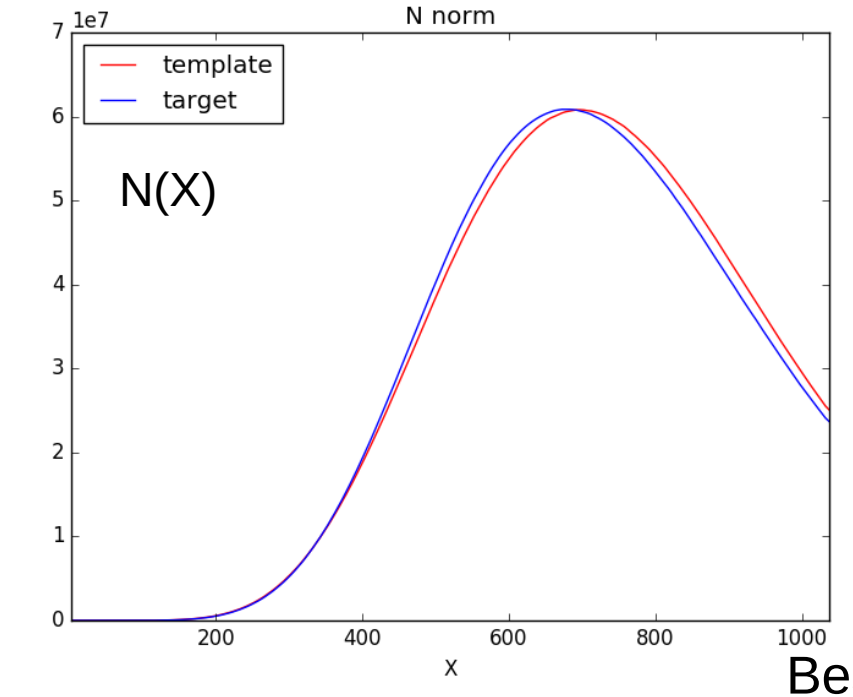


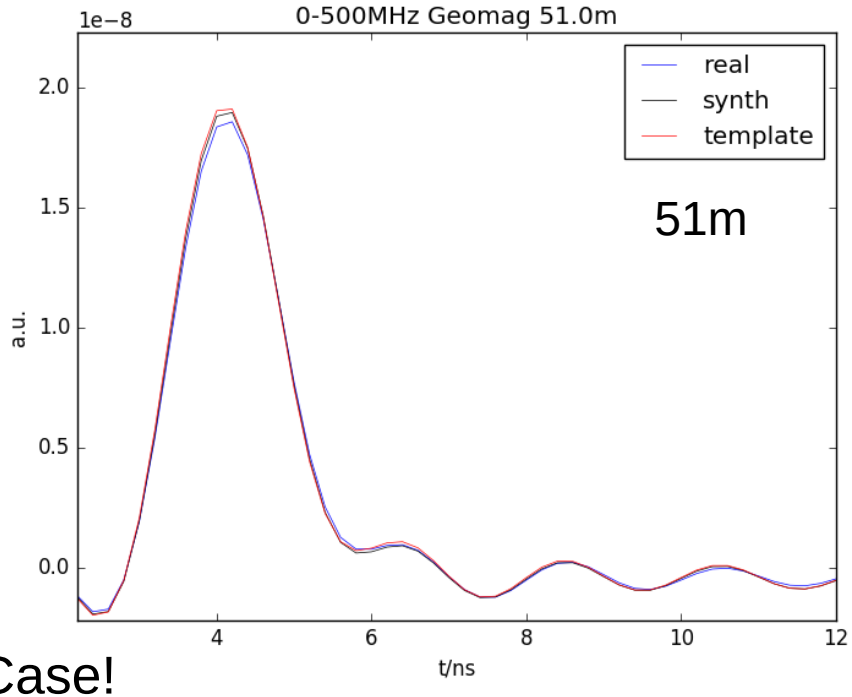
$$\vec{E}_s = \sum_X \frac{N_r(X)}{N_t(X)} \vec{E}_t(X)$$

- Synthesis requires normalisation function N(X)
- Start with linear rescaling by electron+positron count (almost identical to standard longitudinal profile)
- True universality if valid for individual slices, sum on ground sufficient for synthesis
- Alternatively consider

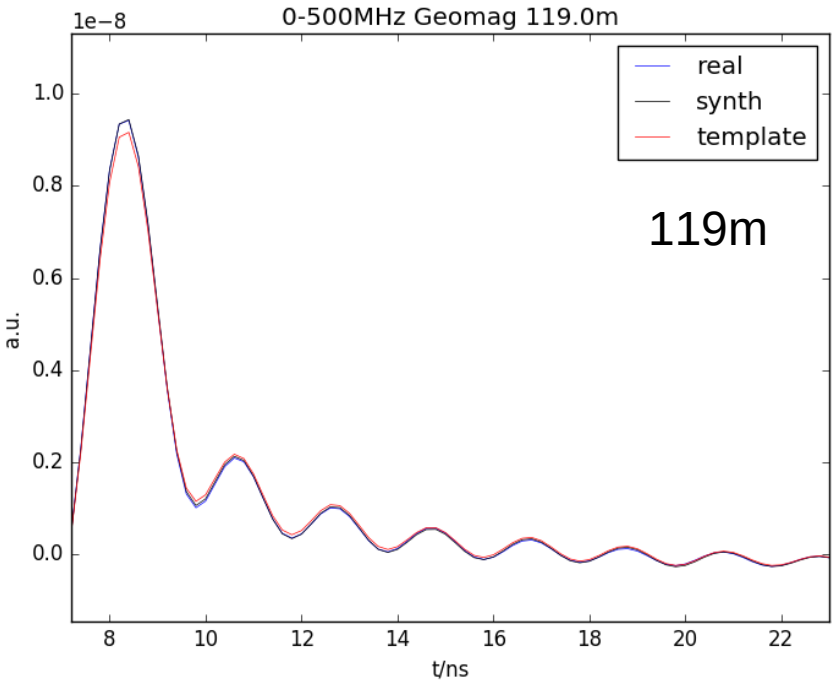
$$\Delta X = X - X_{max}$$

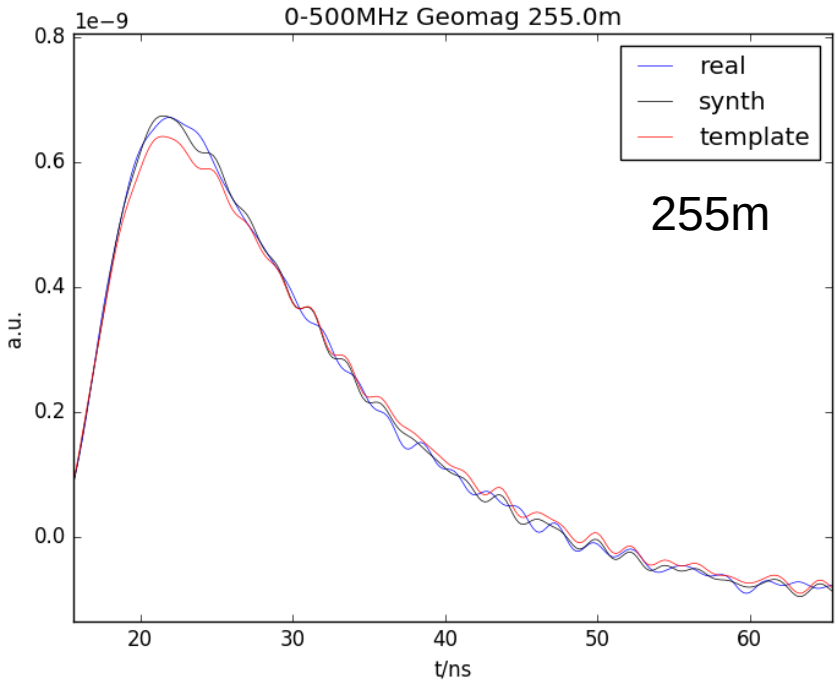
and compensate geometry

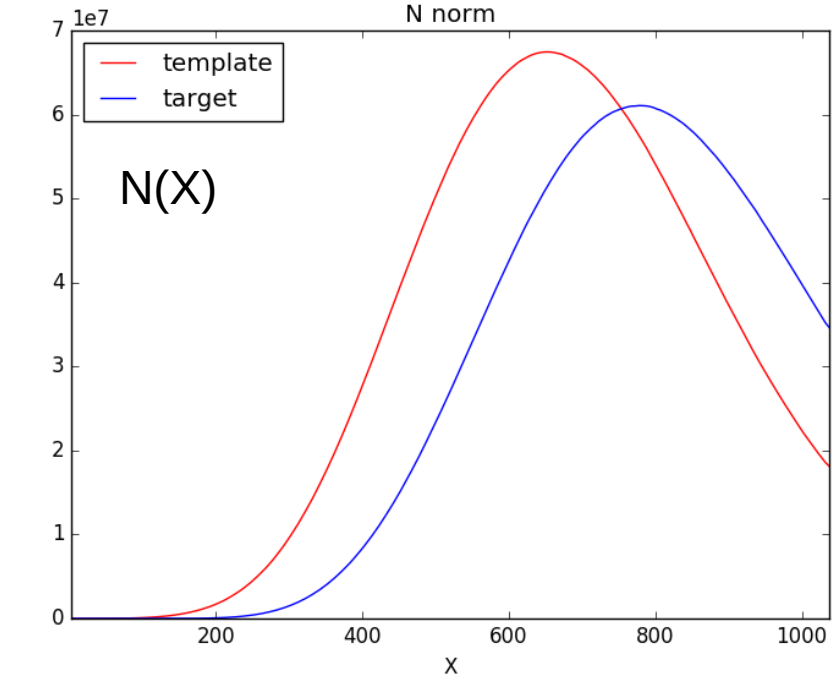

N norm
1e7
template
target
N(X)
X

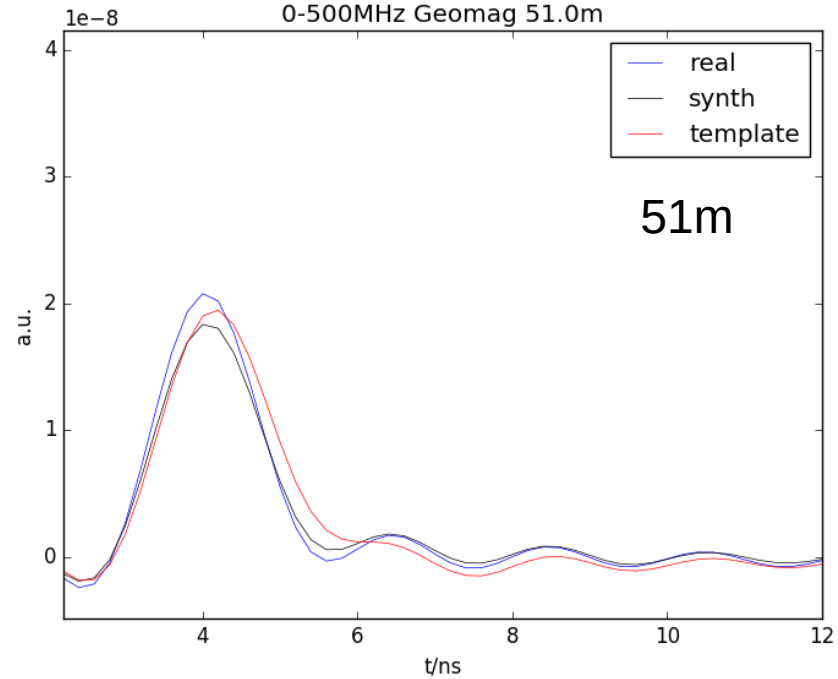

0-500MHz Geomag 51.0m
1e−8
real
synth
template
51m
a.u.
t/ns

Best Case!


0-500MHz Geomag 119.0m
1e−8
real
synth
template
119m
a.u.
t/ns


0-500MHz Geomag 255.0m
1e−9
real
synth
template
255m
a.u.
t/ns


N norm
1e7
template
target
N(X)
X


0-500MHz Geomag 51.0m
1e−8
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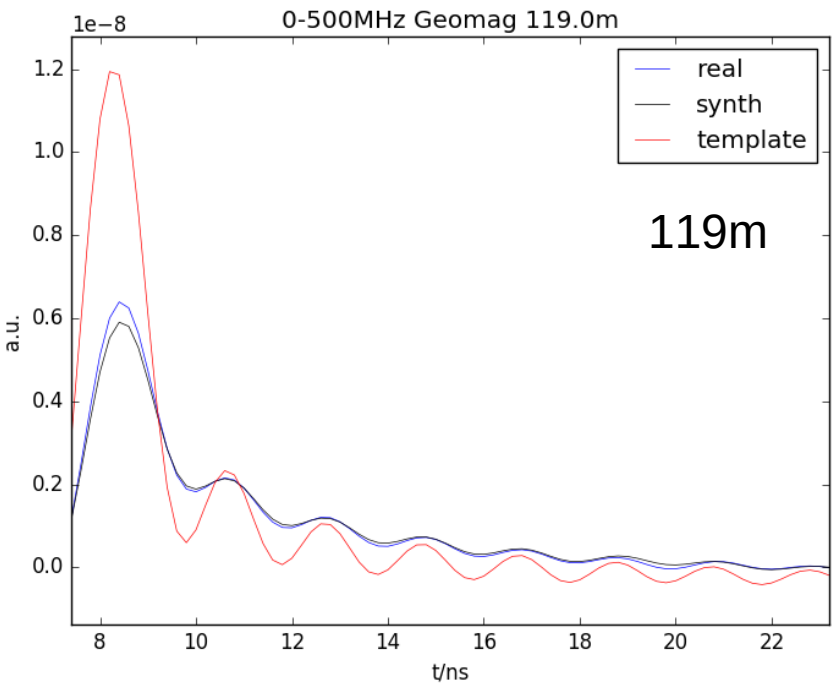
t/ns


0-500MHz Geomag 119.0m
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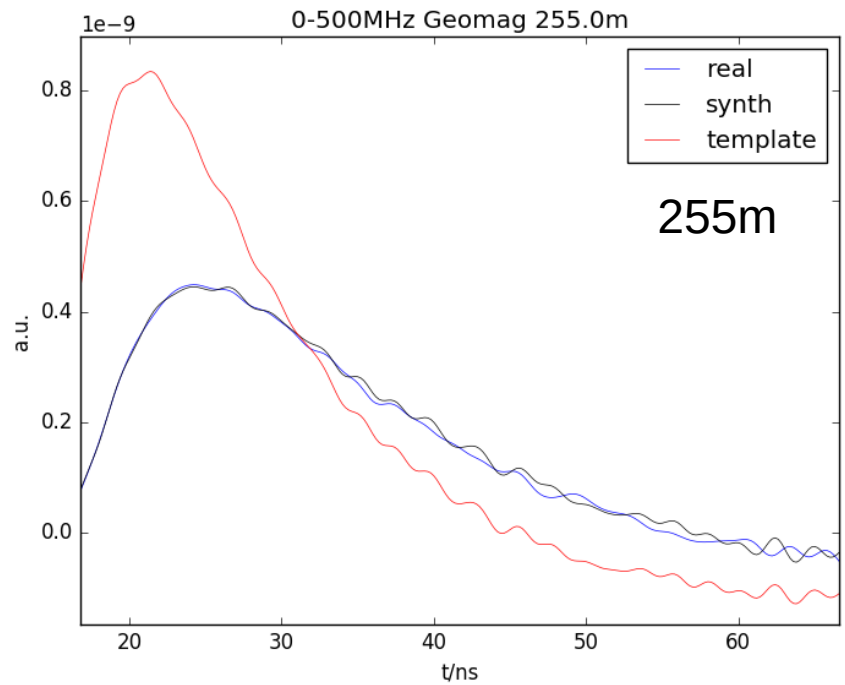
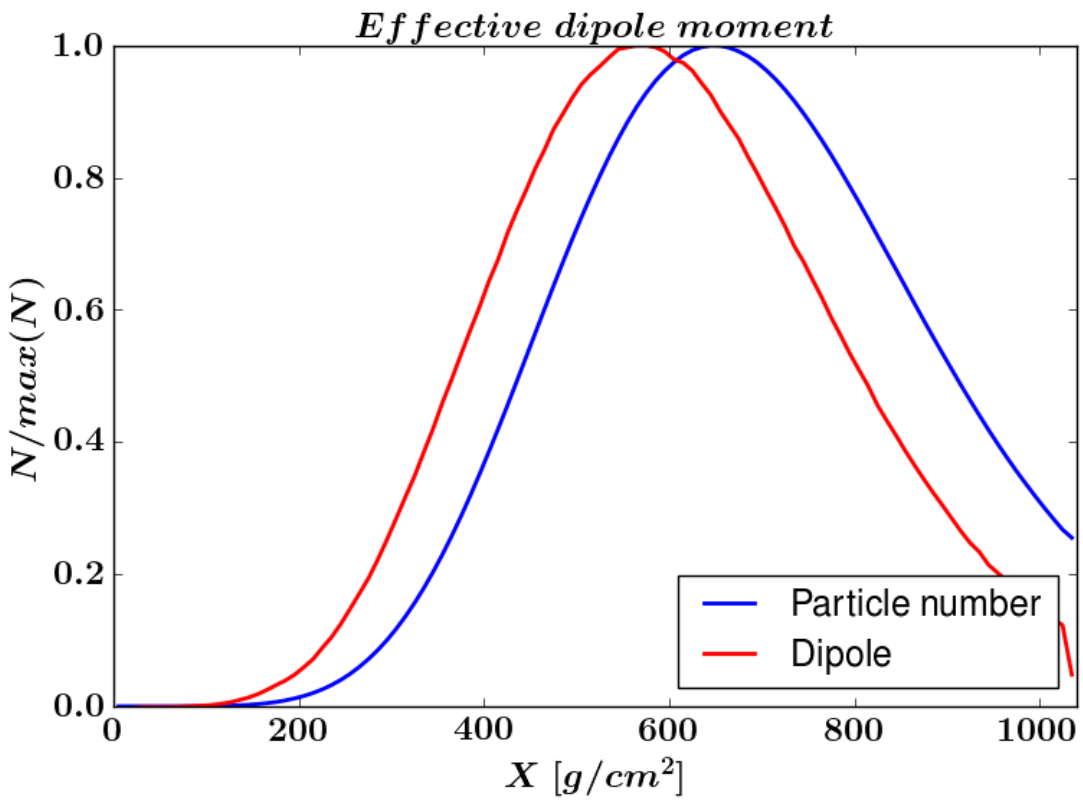

0-500MHz Geomag 255.0m
1e−9
real
synth
template
255m
a.u.
t/ns

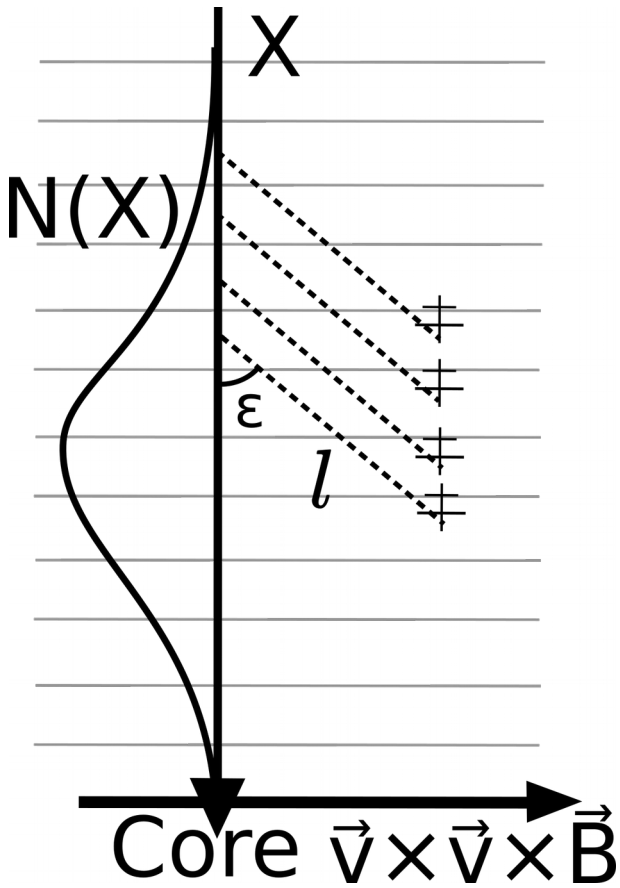
Longitudinal – Effective Dipole

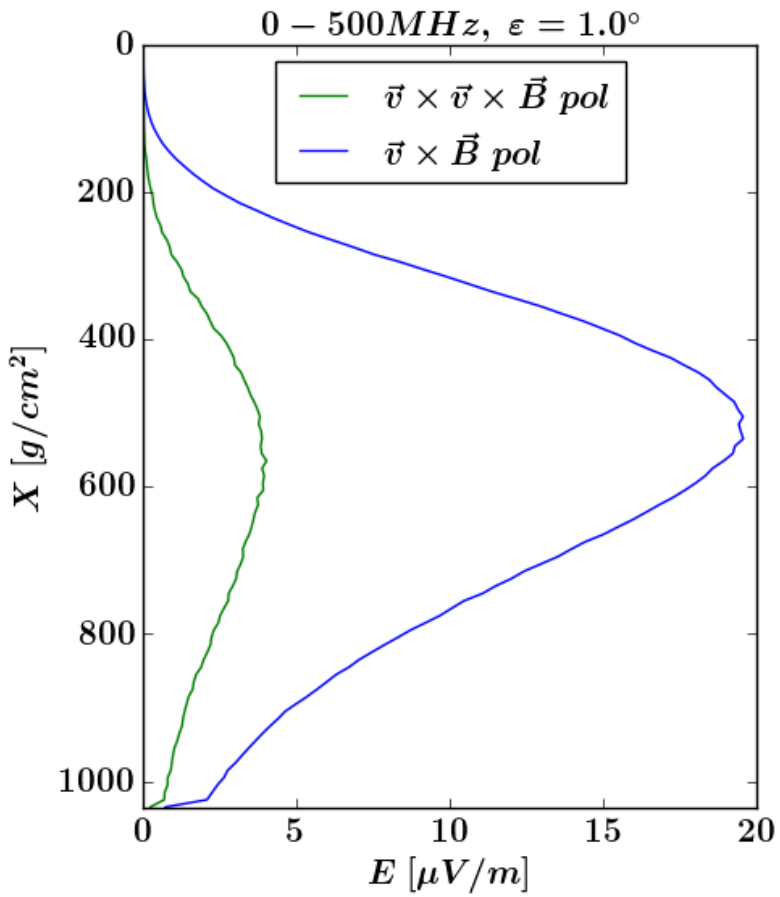
$$\vec{D}(X) = \sum_{slice} q \cdot (\vec{r}_{end} - \vec{r}_{start}) \sim n(X)/\rho(X)$$

- Refine particle count by considering distance traveled
- Quantity reflects an effective dipole moment across the slice
- Proportional to particle density and mean free path length in the slice



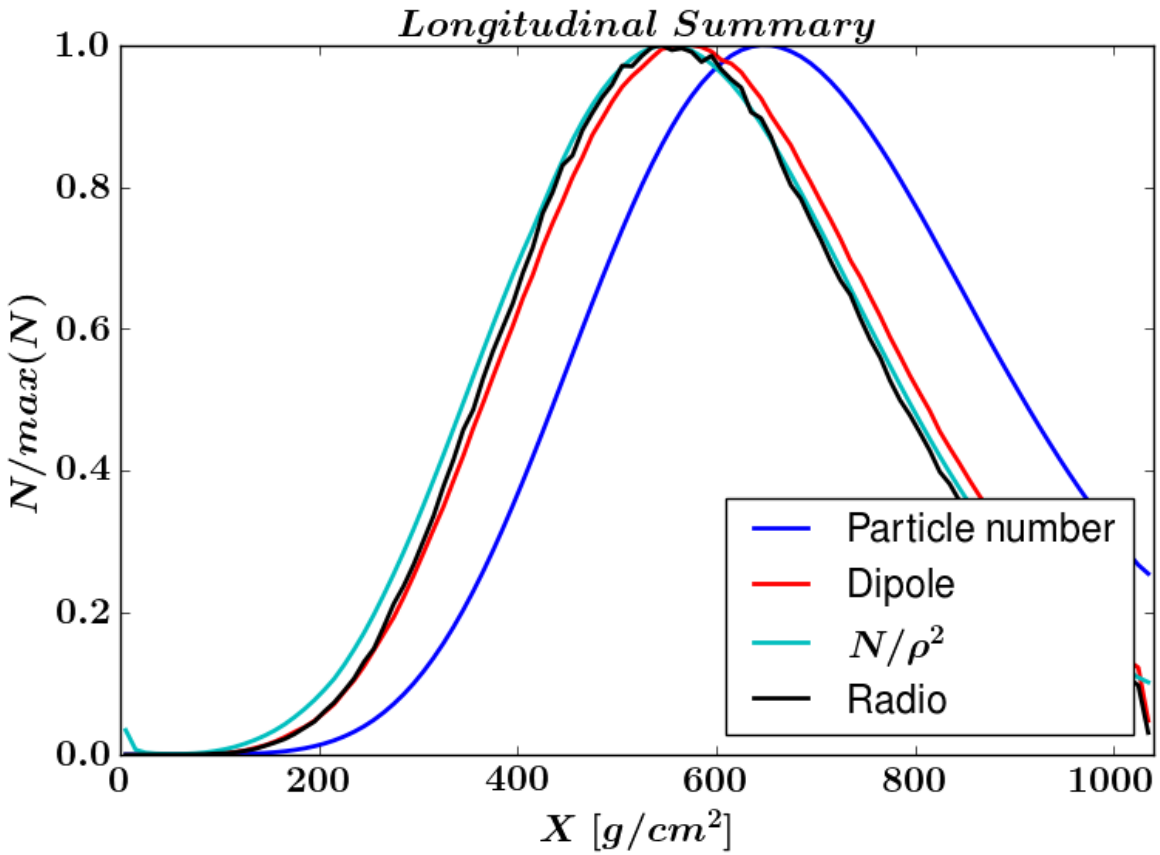
Longitudinal – Radio Emission





- Equal transmission geometry ⇒ closest equivalent to particle profile
- Not observable

Longitudinal – Summary



- No perfect match
- Radio emission has small-scale fluctuations
- Further study underway

Forward Model – Next Steps

- Find valid longitudinal description
- Quantify residuals and fluctuations
- Fill in lateral plane

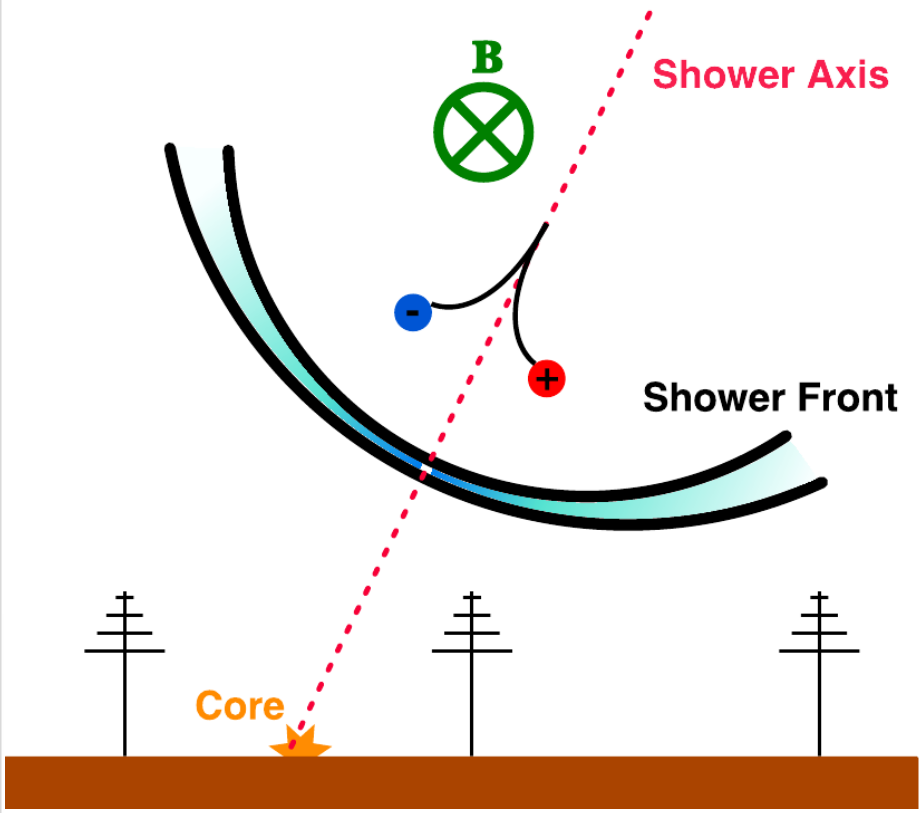
- Generalise to other arrival geometries,
- Primary energies,
- Atmospheres etc.

Thank you!

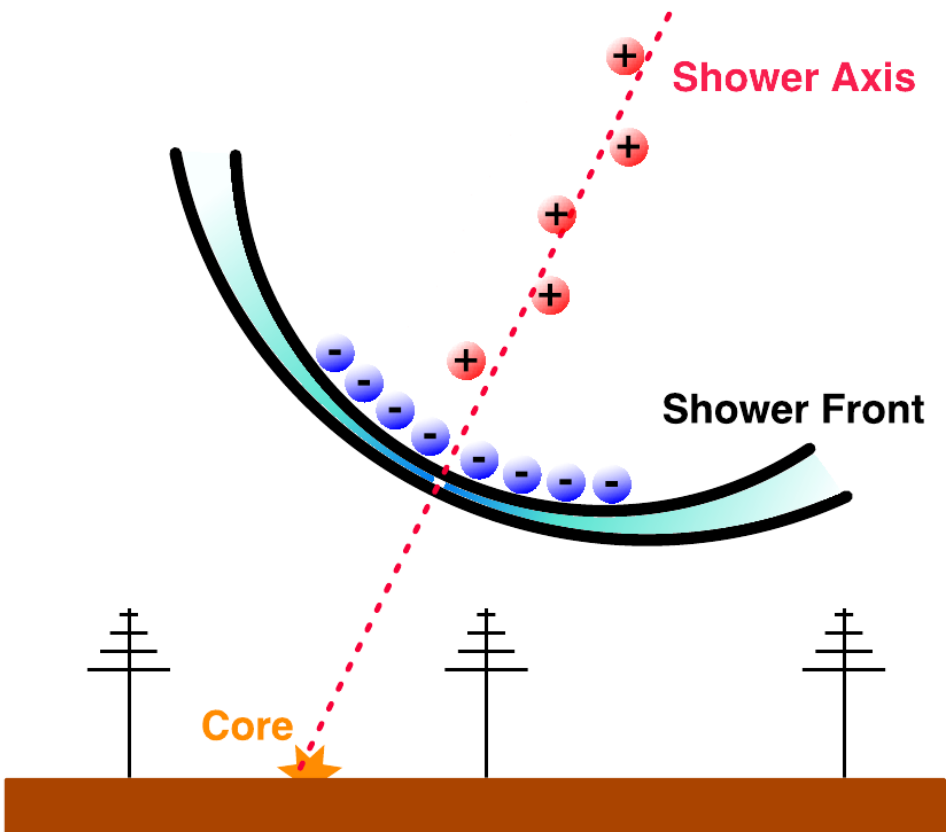
Questions?

Backup

Radio emission



Geomagnetic



Askaryan

[H. Schoorlemmer, Tuning in on cosmic rays, Ph.D. thesis, Radboud Universiteit Nijmegen, 2012.]

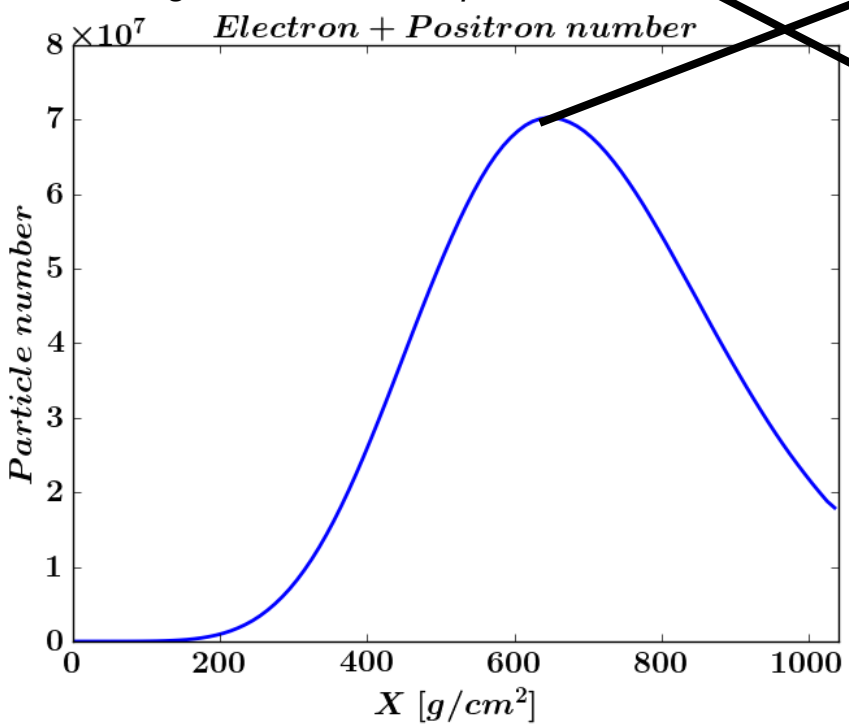
Primary particle → air shower → radio pulse front

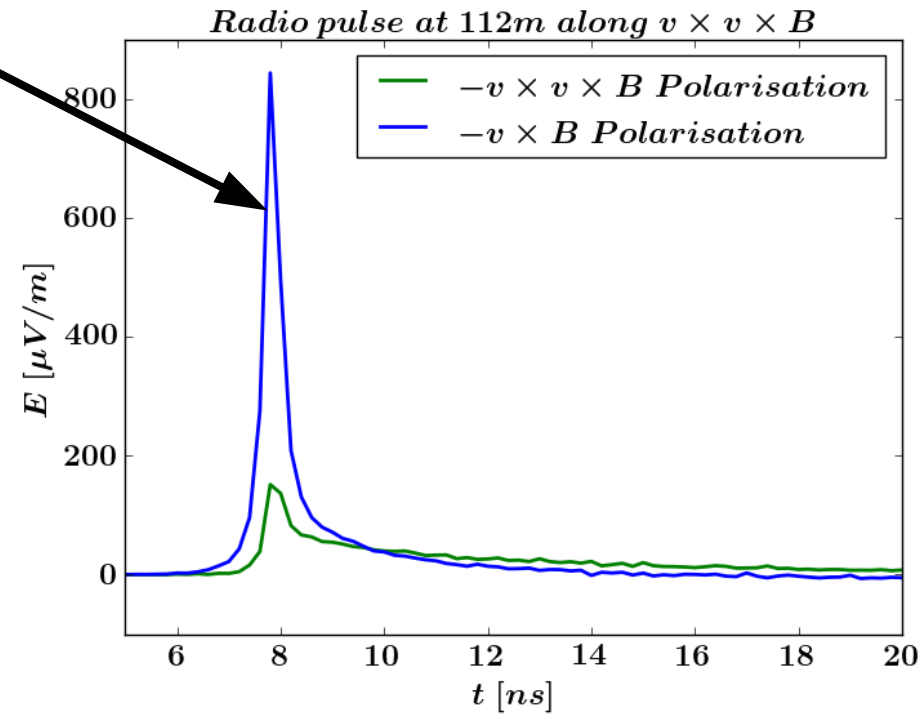
Radio analysis

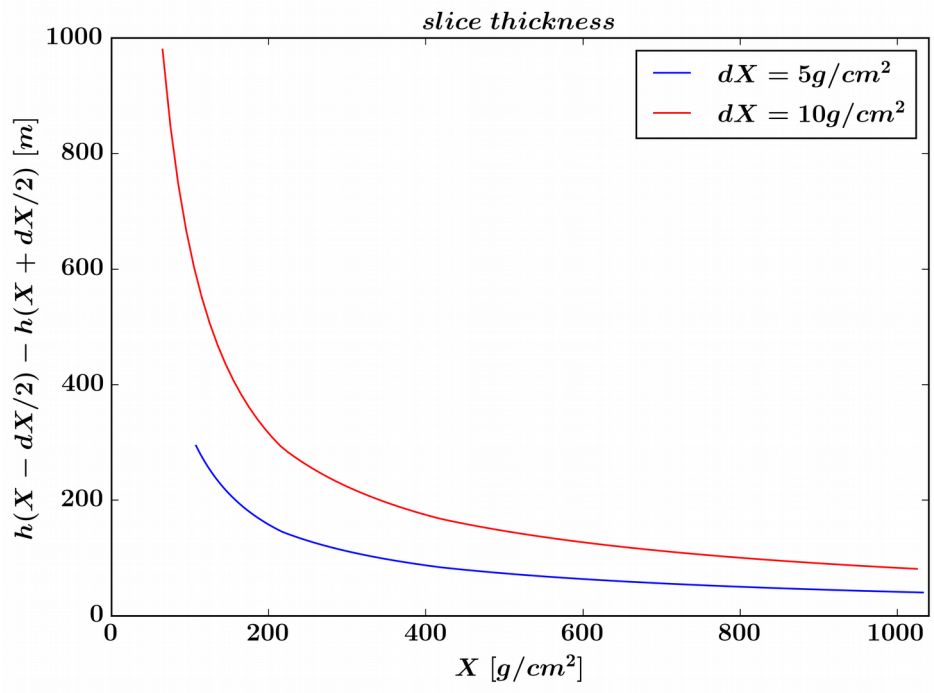
- Current radio analysis: MCMC simulation:

$$\vec{E}(t) = CoREAS(E_0, X_{max})$$

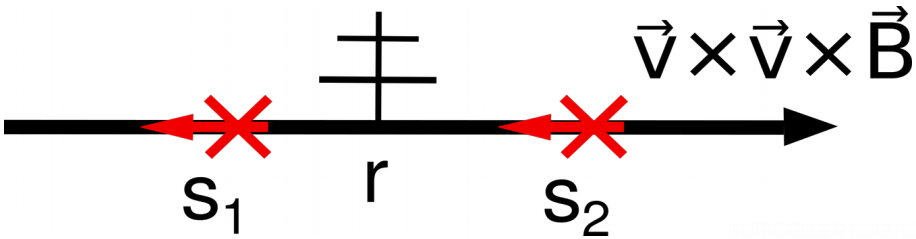
In following: vertical 10^{17}eV proton





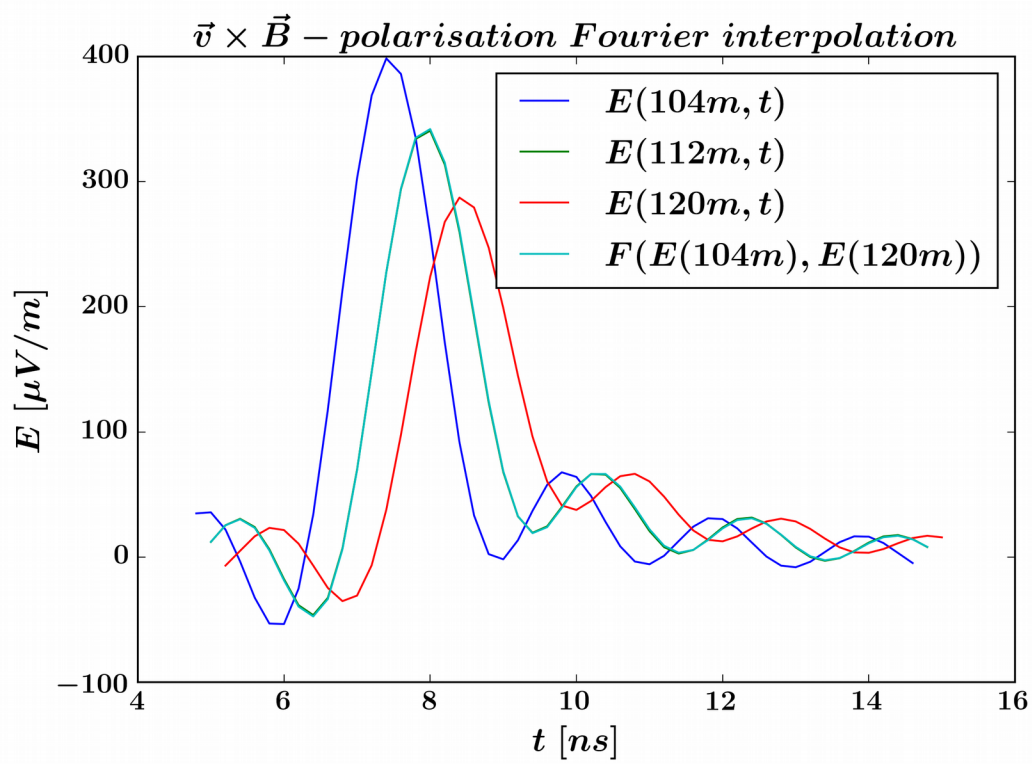

slice thickness
$dX = 5g/cm^2$
$dX = 10g/cm^2$
$h(X - dX/2) - h(X + dX/2)\ [m]$
$X\ [g/cm^2]$
0
200
400
600
800
1000

Radio Emission – Lateral Distribution



$$\vec{E}=F\left(\vec{E}(s_1),\vec{E}(s_2)\right)$$

- Here: linear interpolation of Fourier amplitudes and phases



Radio EAS Arrays