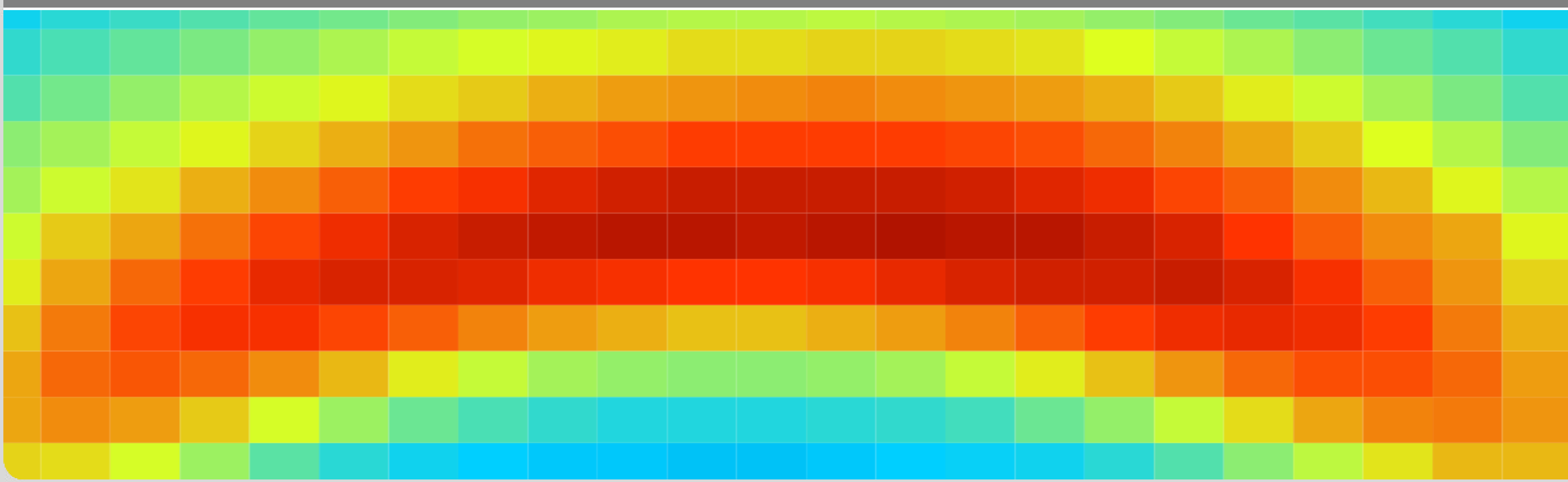
Karlsruhe Institute of Technology

Modeling of radio emission from a particle cascade in magnetic field and its experimental validation

Anne Zilles for the SLAC T-510 collaboration
ARENA 2016, Groningen, The Netherlands

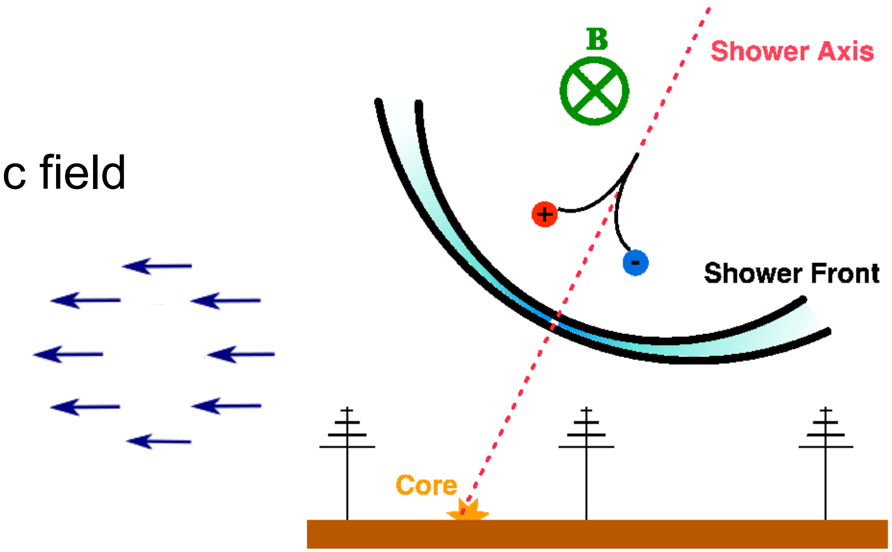
Institut für Experimentelle Kernphysik (IEKP), KIT



Emission of radio signals from air showers

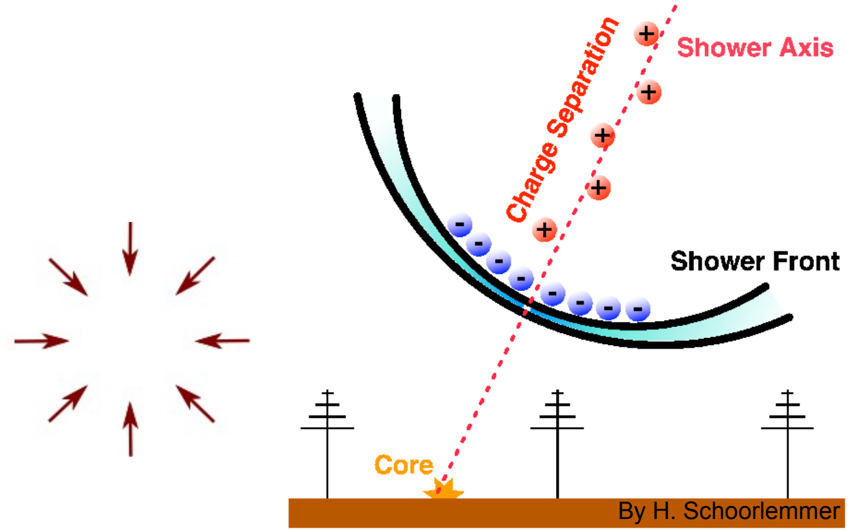
1. Geomagnetic emission

Deflection of e^- and e^+ in Earth´s magnetic field
→ **time dependent transverse current,**
linearly polarised $\vec{E} \propto \vec{v} \times \vec{B}$



2. Askaryan effect

Time variation of net charge excess
→ linearly polarised,
$\vec{E}$ radial oriented around shower axis

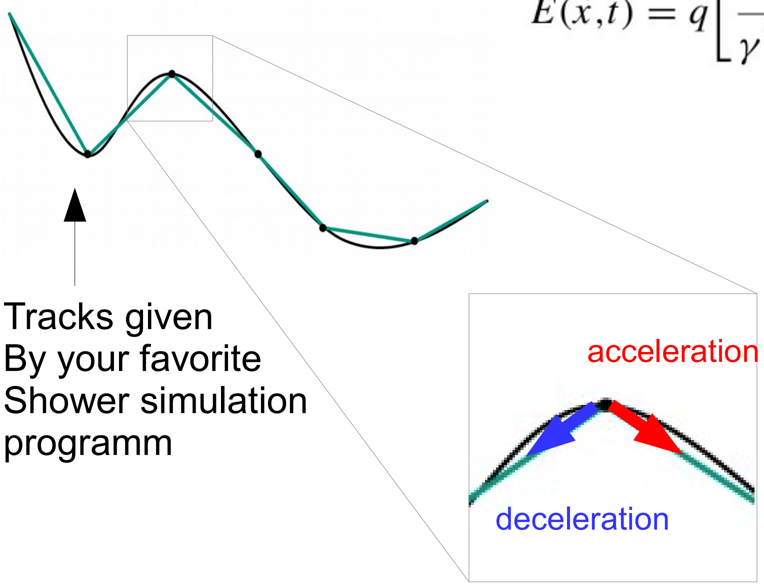


[See: arXiv:1601.07426]

Simulating radio emission: e.g. the Endpoint formalism

Karlsruhe Institute of Technology

$$\vec{E}(\vec{x},t) = q\left[\frac{\hat{r} - n\vec{\beta}}{\gamma^2(1 - n\vec{\beta}\cdot\hat{r})^3 R^2}\right]_{\text{ret}} + \frac{q}{c}\left[\frac{\hat{r}\times[(\hat{r} - n\vec{\beta})\times\dot{\vec{\beta}}]}{(1 - n\vec{\beta}\cdot\hat{r})^3 R}\right]_{\text{ret}}$$



Tracks given
By your favorite
Shower simulation
programm

continuous

↓

discrete

Instantaneous @ Endpoints:

- deceleration from β to rest
- acceleration from rest to β

(Production and annihilation taken into account)

$$\int \vec{E}dt = \frac{e}{cR_2}\left(\frac{\vec{r_2}\times(\vec{r_2}\times\vec{\beta})}{(1-n\vec{\beta}\vec{r_2})}\right) - \frac{e}{cR_1}\left(\frac{\vec{r_1}\times(\vec{r_1}\times\vec{\beta})}{(1-n\vec{\beta}\vec{r_1})}\right)$$

with $\delta t \ll \frac{1}{\nu_{\text{observed}}}$

[see: arxiv:1007.4146]

Radiation from the 'implied' acceleration
at the 'endpoints' of a track

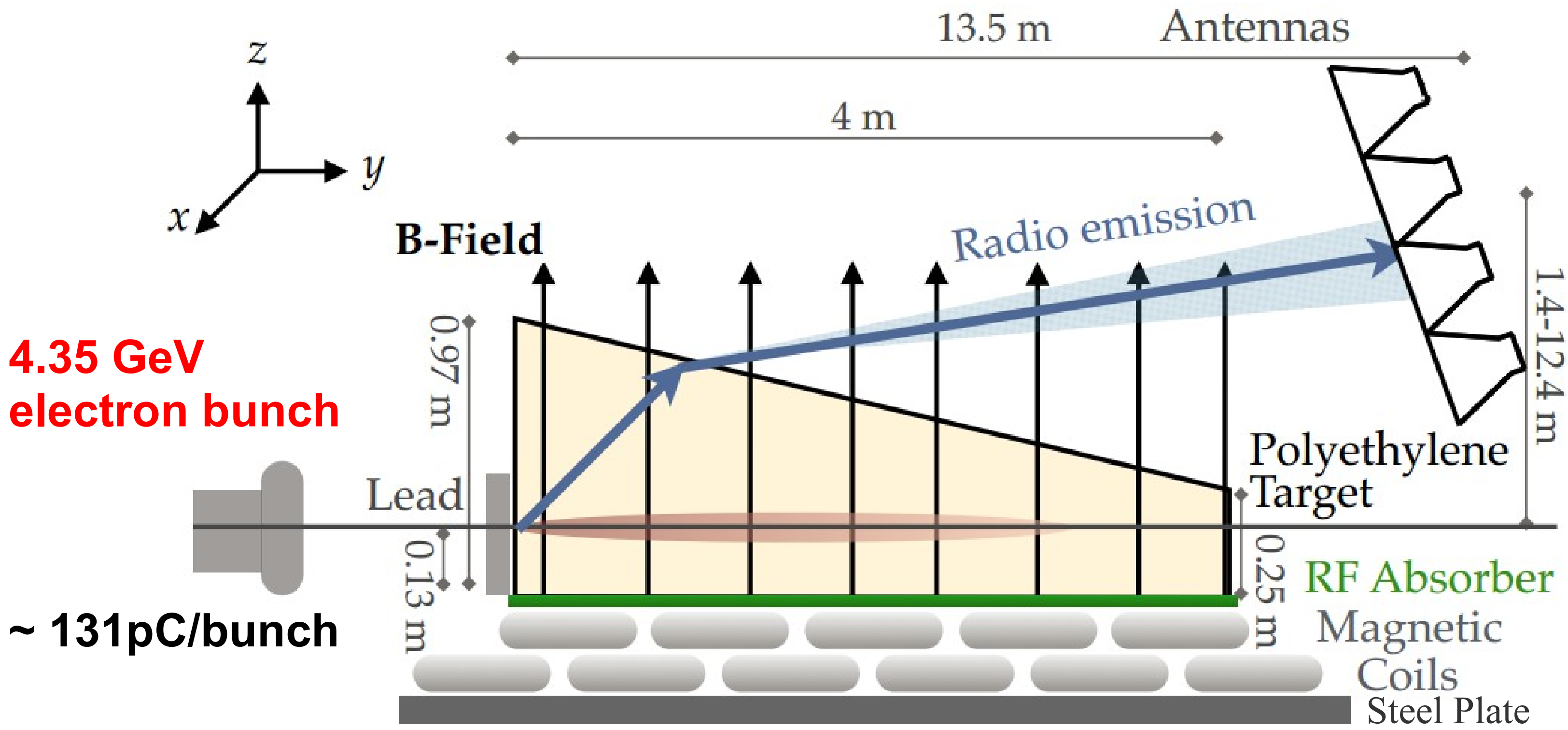
Does this formalism reproduce the correct signal strength?
→ Test formalisms under controlled lab conditions

 [See: arXiv:1007.4146v3]

Simulating T510 @ SLAC

Goal: Testing the particle-level simulations under controlled lab conditions

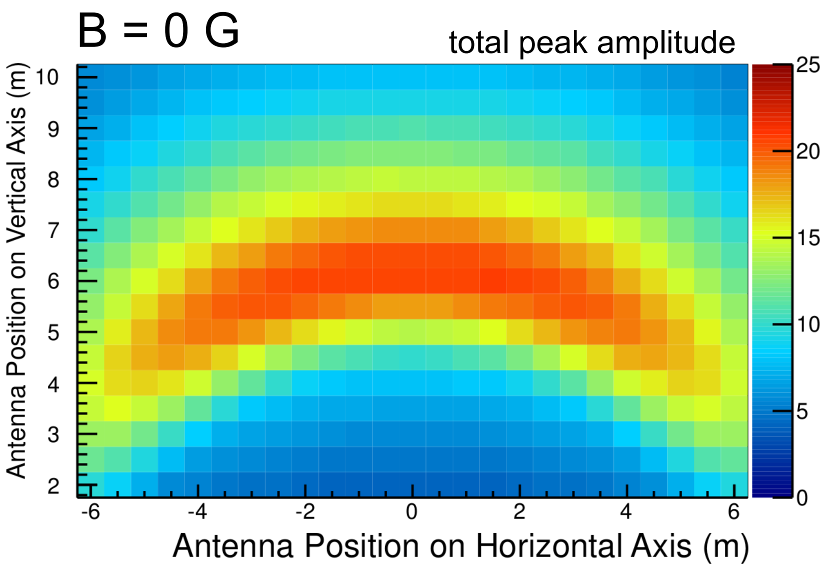
→ produce an extensive shower by a primary particle of known energy, in controllable magnetic field

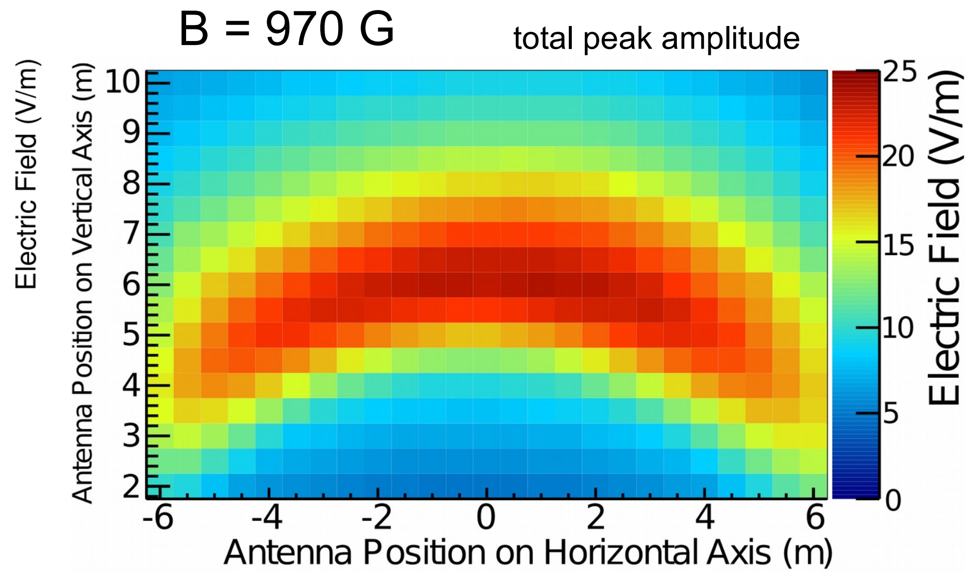


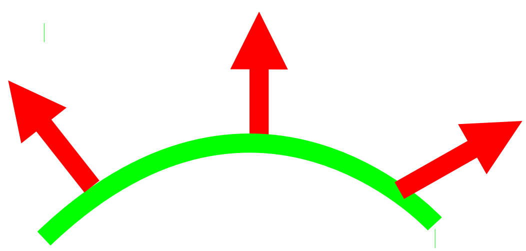
- ZHS and Endpoint formalisms parallel in Geant4
- **Refraction** and **Transmission** through slanted (upper) surface included

Superposition of emission mechanisms

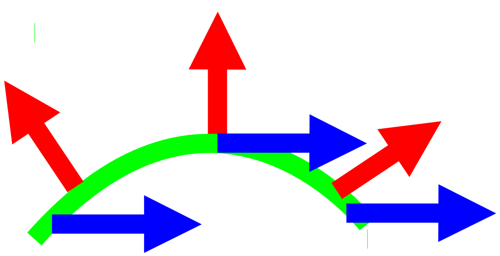
using the Endpoint formalism
5pol butterworth filter (300-1200MHz)







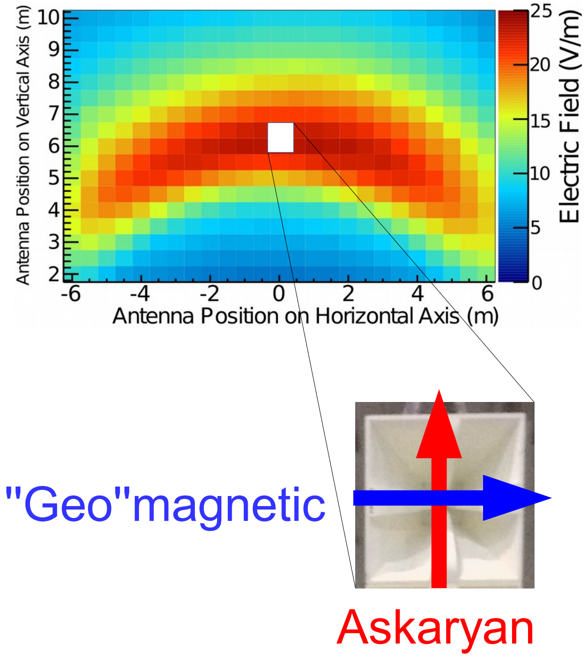
Askaryan (radial pol.)



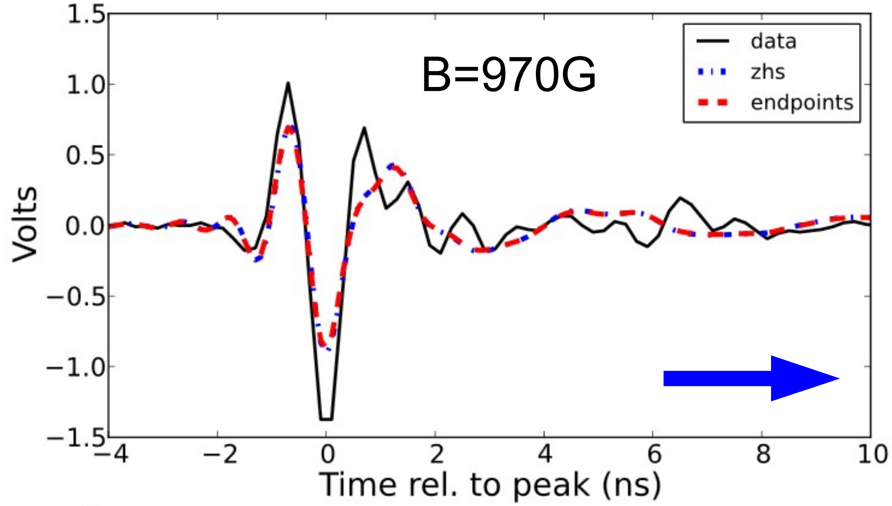
Askaryan + "Geo"Magnetic (linear pol.)

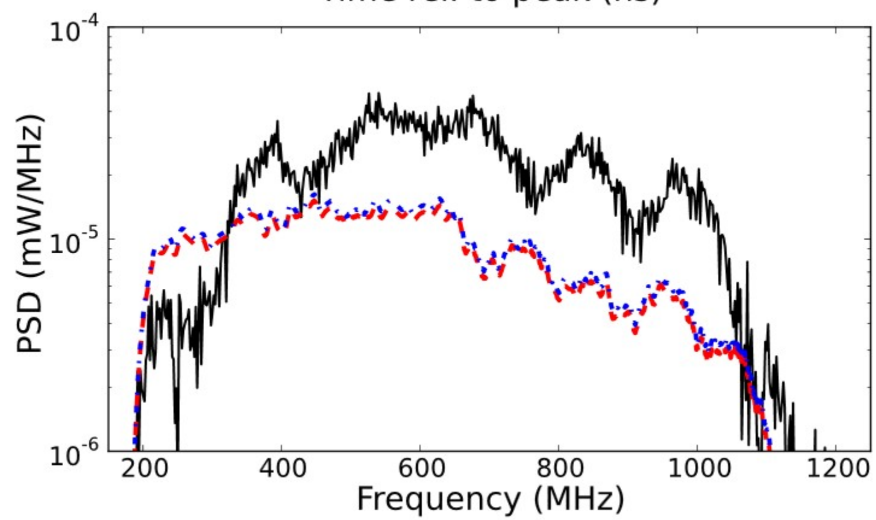
Comparison between data and simulation

Karlsruhe Institute of Technology



- Time-domain peaks of both simulations agree with 3%
- **Data time-domain peaks exceed the simulations by 35%**, commensurate with the systematic uncertainty

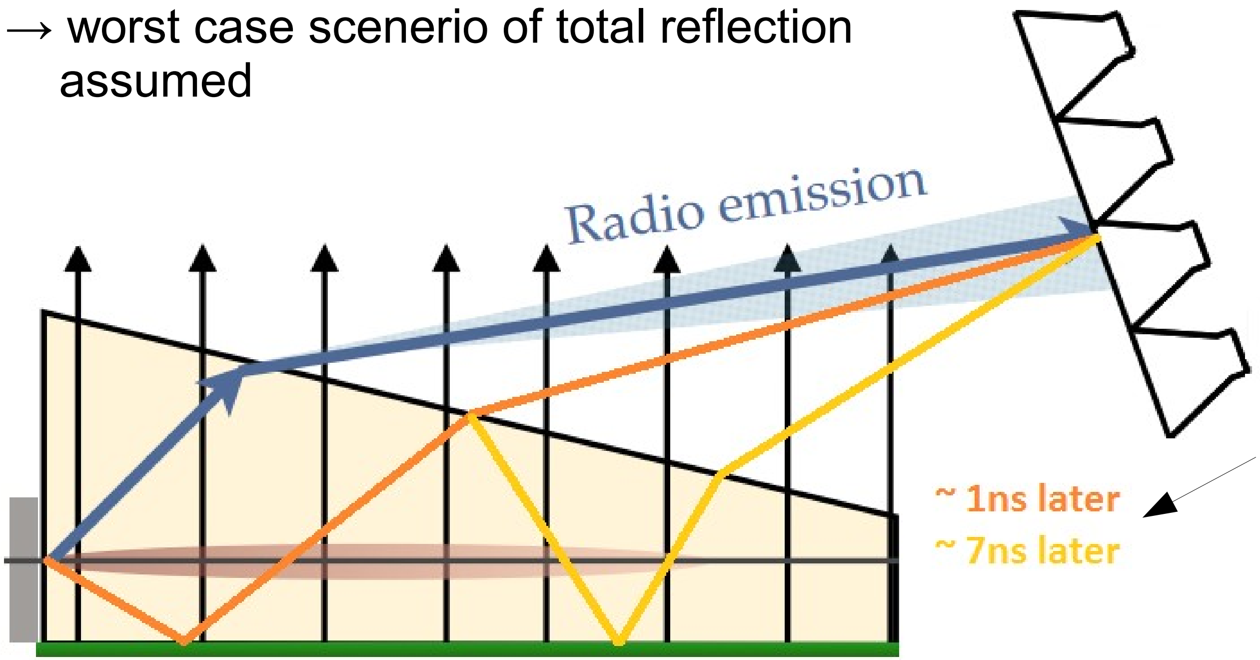




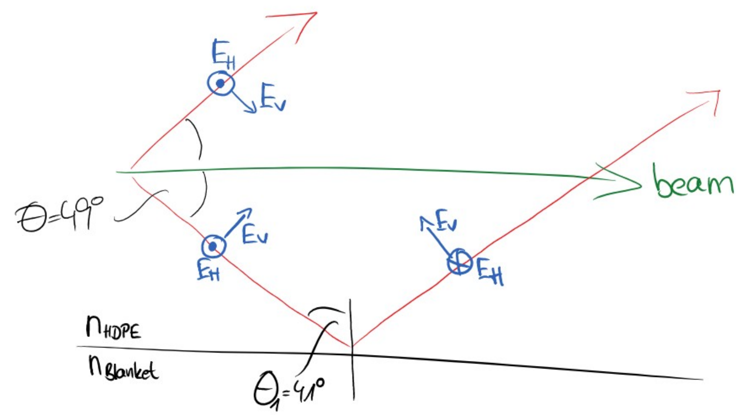
Limited by **first order reflection from the bottom surface** of the target (not included in simulations)

Internal reflection at the bottom surface

Unknown properties of the RF absorbing blanket
→ reflection can not be modeled
→ worst case scenerio of total reflection assumed

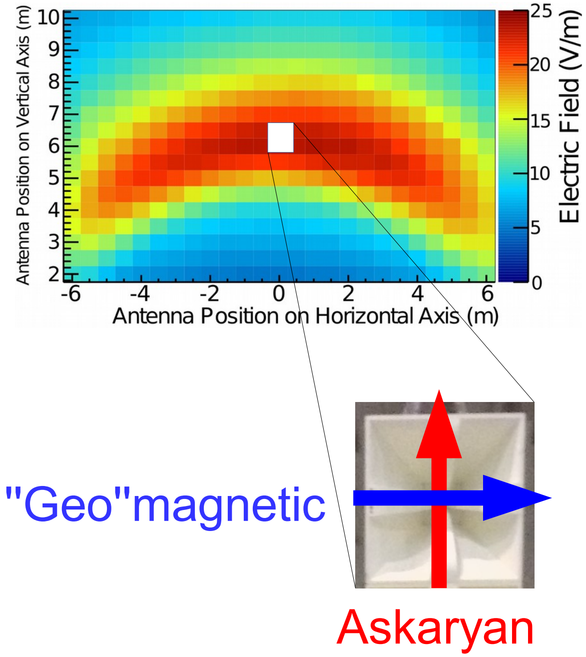


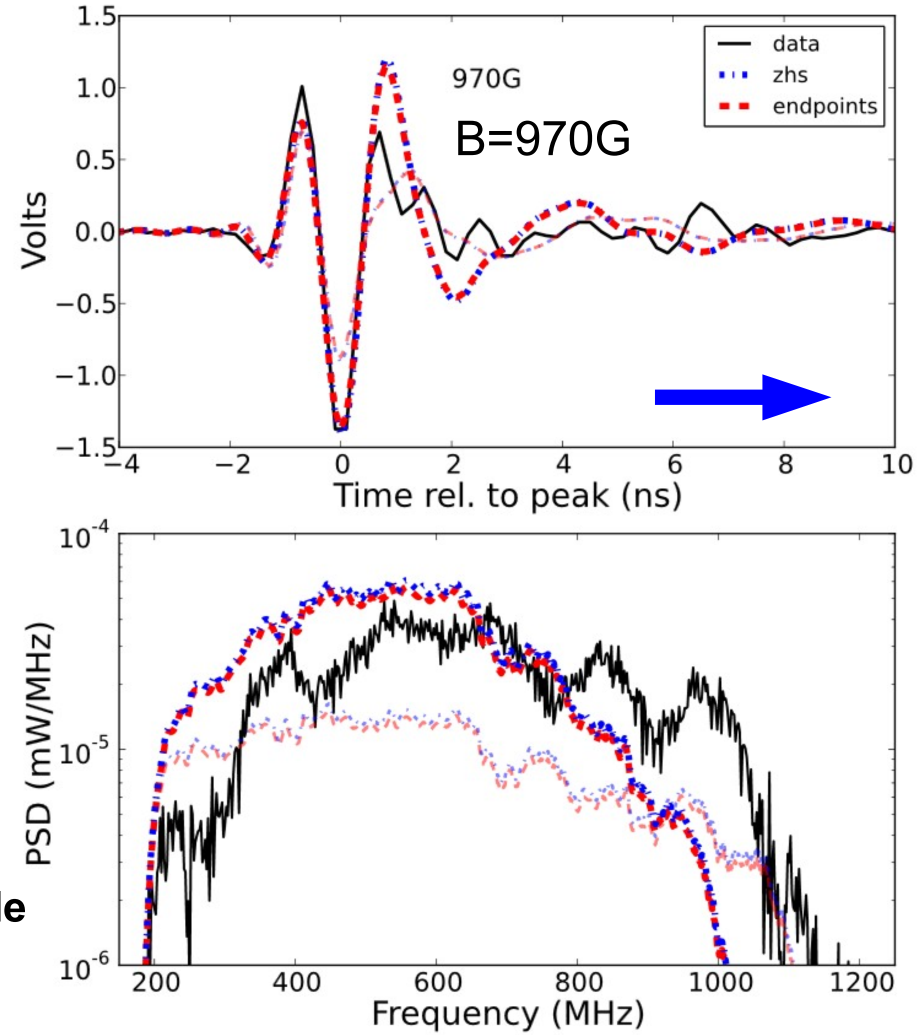
Difference in arrival time of reflected pulses to direct signal given by geometry



Assuming blanket has a higher refractive index (n_2) than HDPE (n_1)
→ reflection arrives at antenna ~1ns later after direct pulse but inverted

Comparison including first reflection





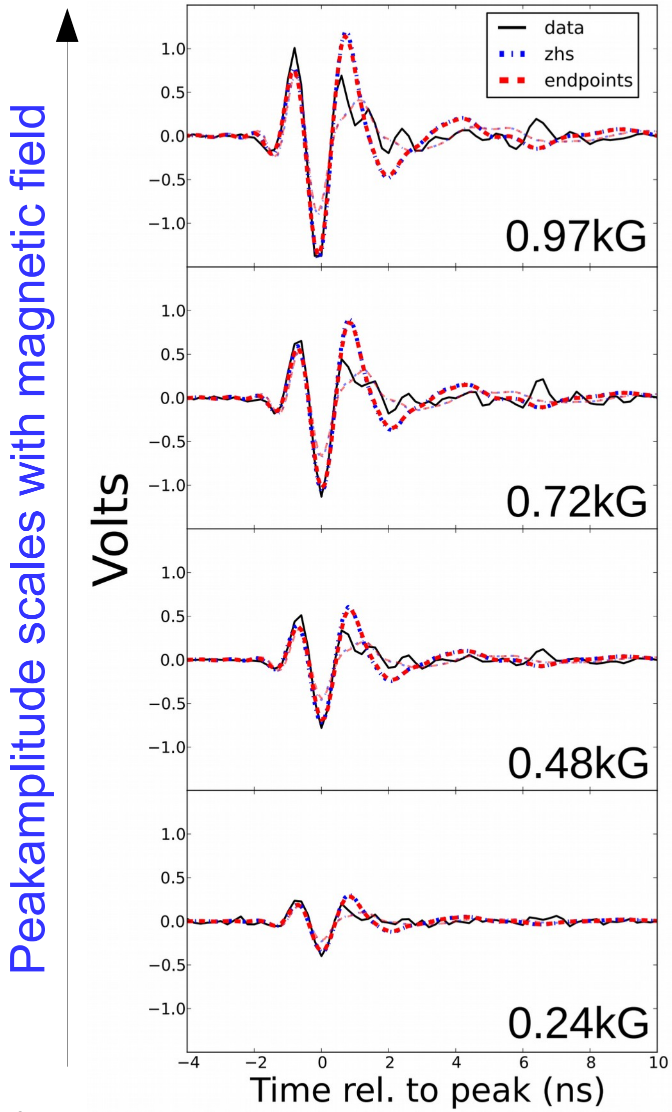
Assumptions on impact of reflection by adding a time delayed equal amplitude reflection to the direct pulse for a particular antenna

→ **gives a good description of peak amplitude**

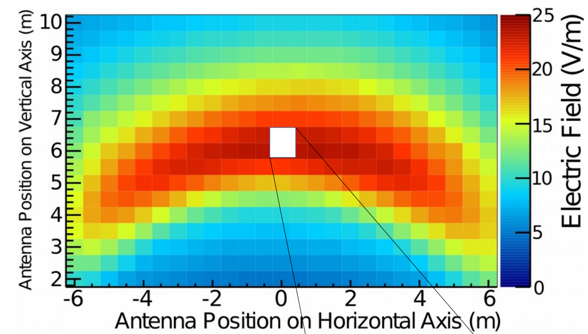
→ frequency spectrum shows:
assumption too simple

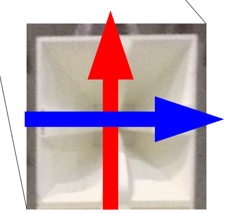
Scaling with magnetic field

Karlsruhe Institute of Technology



"Geo"magnetic component





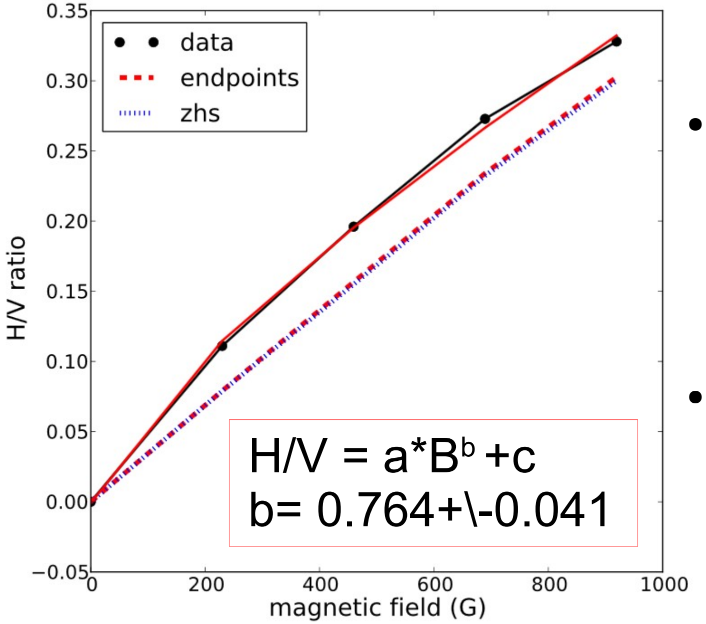
- Vertically polarised emission observed as constant
- horizontally polarised emission ("geo"magnetic effect):

  amplitude dependent on magnetic field strength

→ **transverse currents generate magnetic emission in showers**

Including modeled first reflection

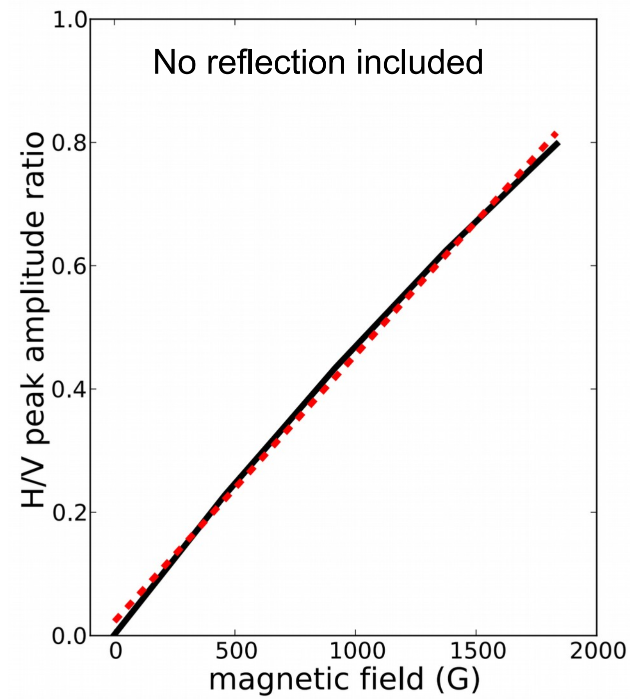
Linear scaling with magnetic field?



- Data seems to scale linear with magnetic field strength
  BUT: there is a **flattening observed**
  → **power law fit: exponent ≠ 1**

- Also in **simulations?**

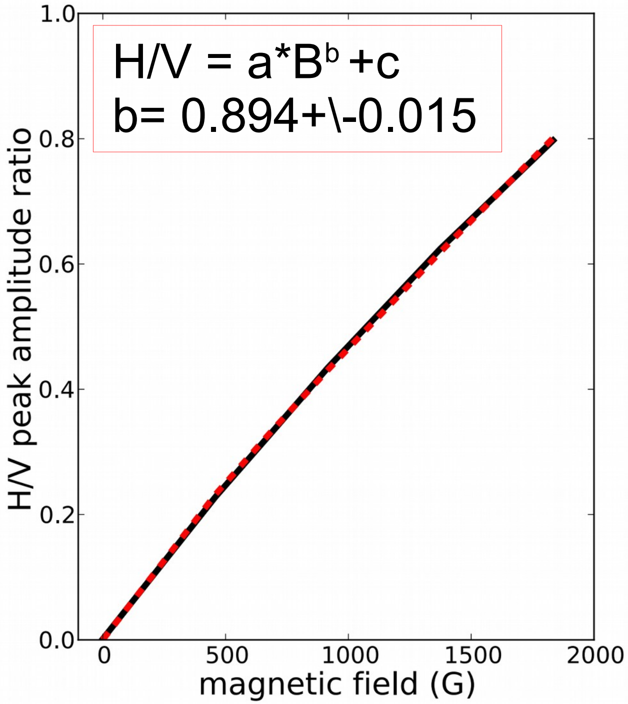
Run simulations with higher magnetic field strengths
→ flattening to higher magnetic fields observable
→ can not be described by a linear function anymore



Simulation filtered from 300-1200MHz,
not convolved with detector effects

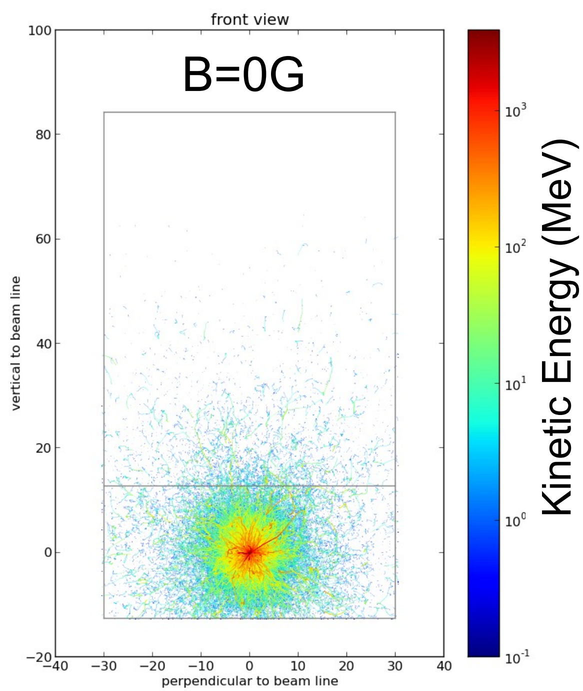
Linear scaling with magnetic field?

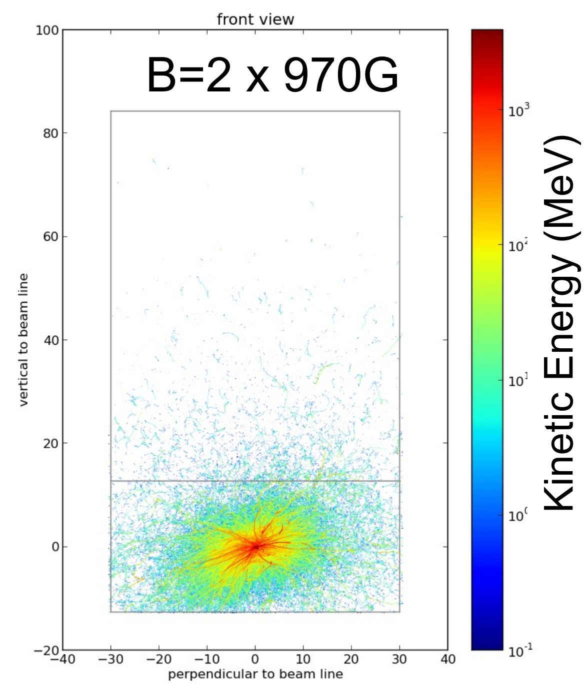
Simulation filtered from 300-1200MHz, **not convolved with detector effects**



1) new physical effect, not observed so far
(saturation of lateral drift velocity?)
2) high energy particles escaping
3) due to non-uniform magnetic field
→ rotation of the shower→ polarisation change

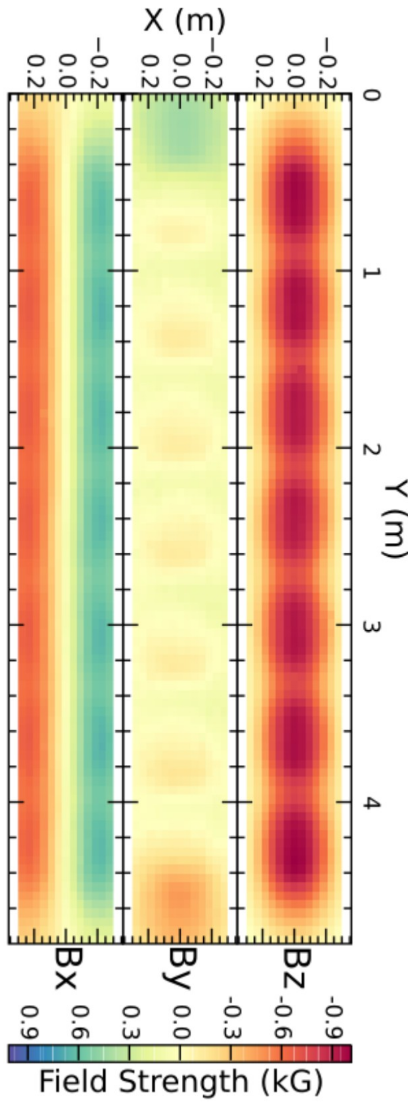
Power law fit
returns exponent ≠ 1
→ no linear scaling





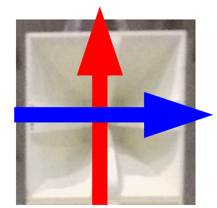
Linear scaling with magnetic field?

Simulation filtered from 300-1200MHz, **not convolved with detector effects**



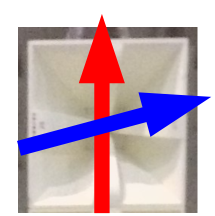
1) new physical effect, not observed so far
   (saturation of lateral drift velocity?)
2) high energy particles escaping
3) due to non-uniform magnetic field
   → rotation of the shower→ polarisation change

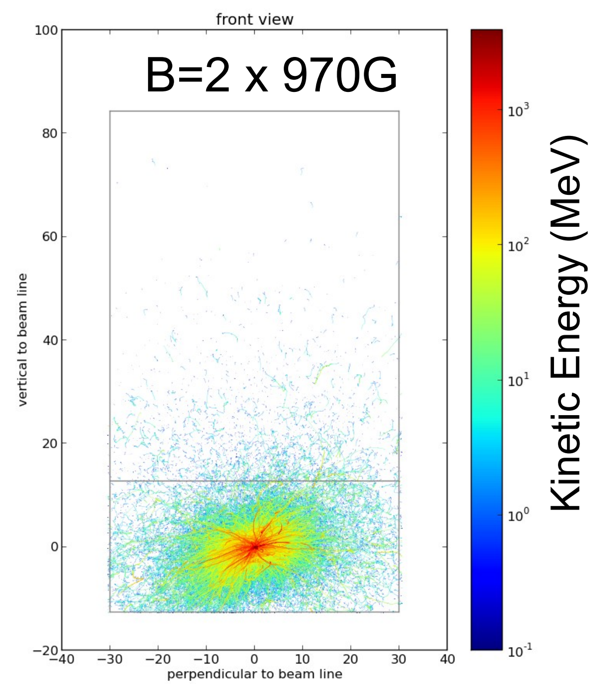
B=0G

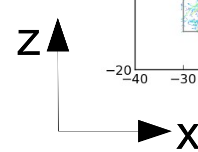


Polarisation
rotated

B≠0G



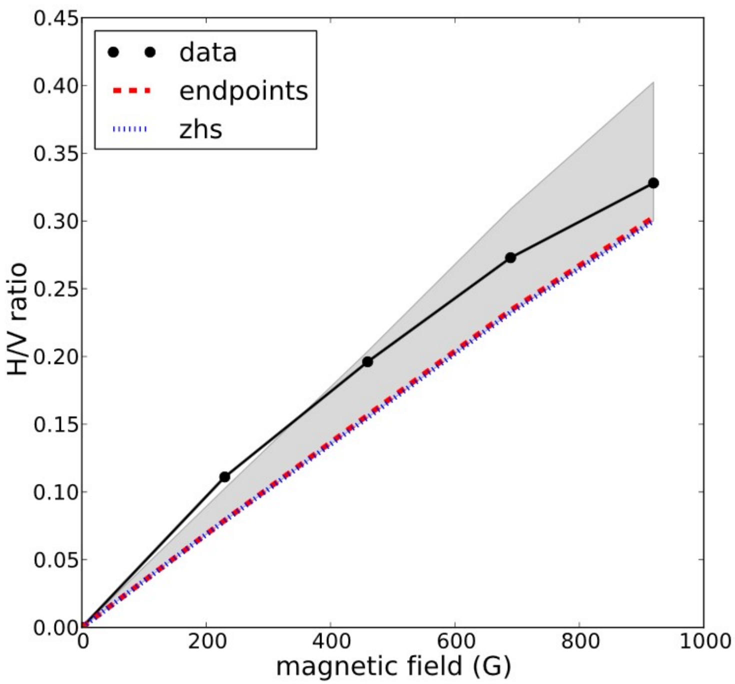




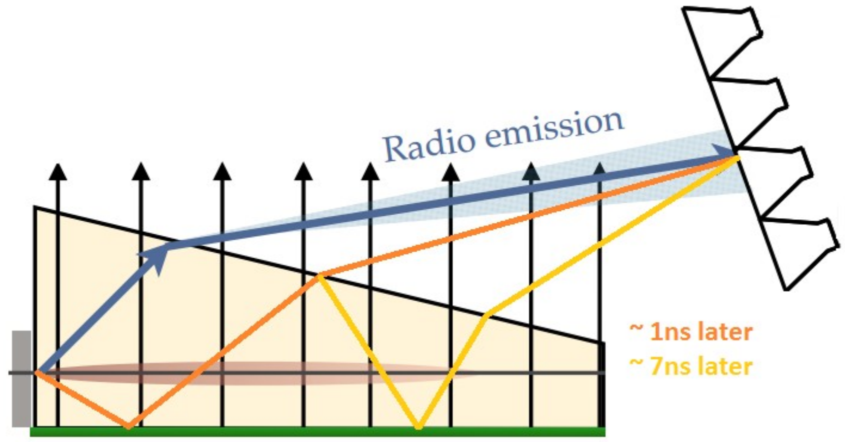
Non-linear scaling due to reflection?

Karlsruhe Institute of Technology

Simulations convolved with detector effects



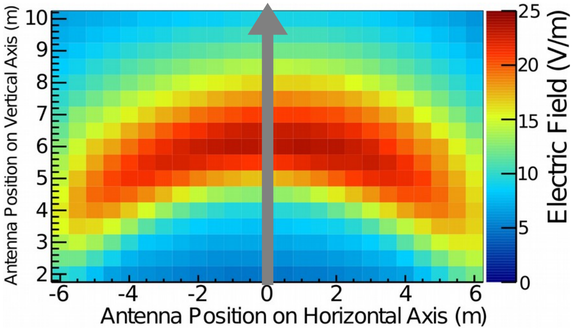
gray error band:
possible impact of reflections



Simulations including first reflection
→ leads to a higher H/V ratio
→ error band includes the data
→ BUT: reflection in H and V handled similarly
→ assumption too simple

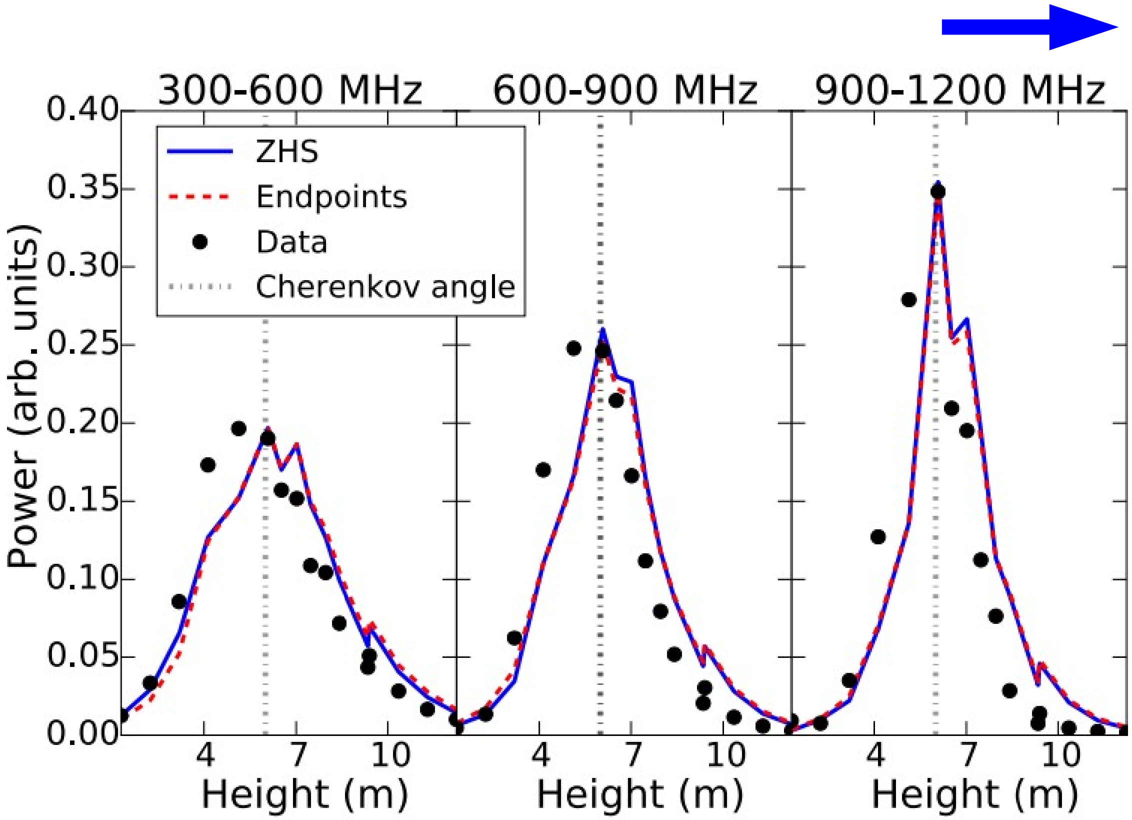
→ observed flattening in data has to be studied in more detail!

Measuring the Cherenkov cone



Measurement of the angular radiation pattern by vertical axis scan
- simulations do not include reflections

Magnetically induced emission forms a Cherenkov cone



- Observed **cone position** in agreement with expectations
  → Refractive index important for accurate modeling of electrodynamics
- **Width of cone** scales with 1/f
  → ability to simulate emission
- Accurate predictions of **absolute scale** by first-principle calculations with different systematic uncertainties than air shower experiments

[Phys. Rev. Lett. 116, 141103]

Summary

Karlsruhe Institute of Technology

first laboratory benchmark of radio-frequency radiation from electromagnetic cascades under the influence of a magnetic field

- predictions rely on electrodynamics first principles → **no free parameters**
- comparison of radio emission: data and simulation

  → simulations accurately predict the absolute scale of the radio emission to within our systematic uncertainty, but assumptions on non-frequency-depending reflections too simple

  → observed radiation grows with magnetic field and forms a cone centered around Cherenkov angle → **linear scaling?**

  → **electromagnetic simulations can be used to predict radio emission from extensive air showers**

- Results published in:

  Accelerator Measurements of Magnetically Induced Radio Emission from Particle Cascades with Applications to Cosmic-Ray Air Showers
  K. Belov, K. Mulrey, A. Romero-Wolf, S. A. Wissel, A Zilles, et al.
  (T-510 Collaboration)
  Phys. Rev. Lett. 116, 141103 2016

More about T510:

http://t-510.physics.ucla.edu/

Thank you for your attention!