Karlsruhe Institute of Technology

Modern theory of radio emission from EAS

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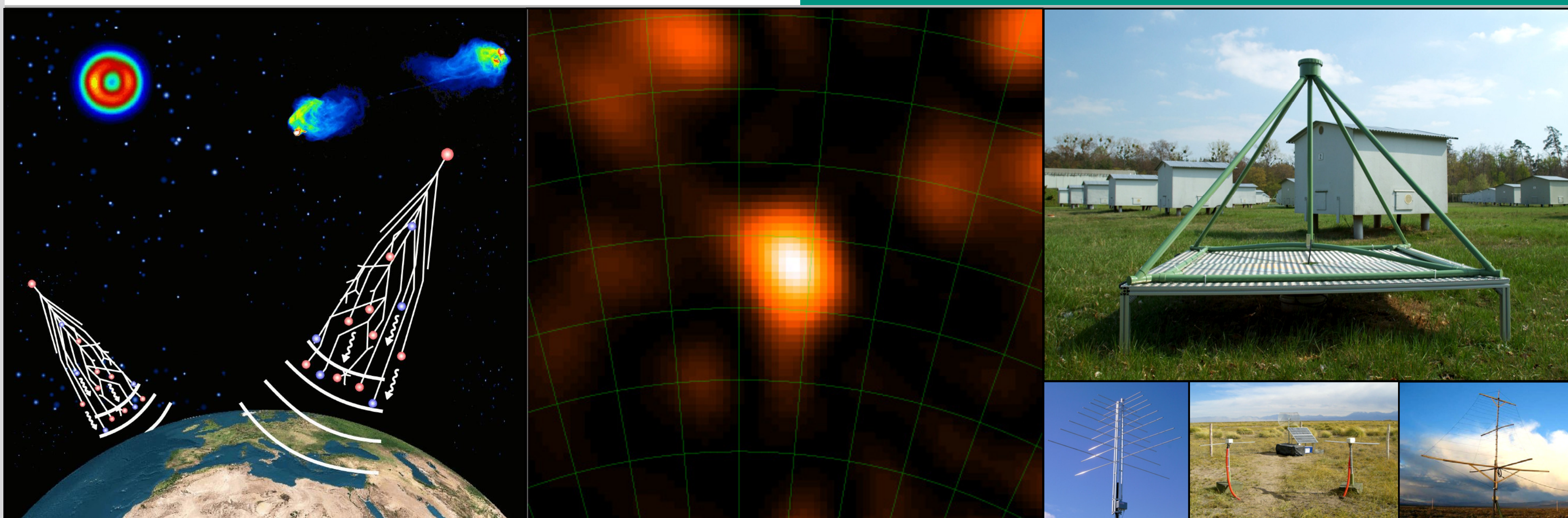
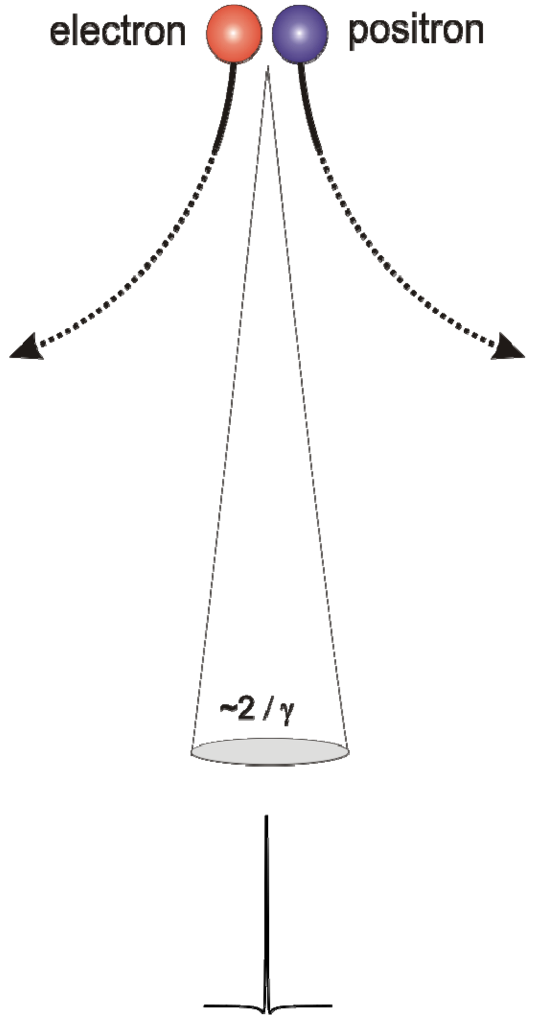
Universität Karlsruhe (TH) Research University · founded 1825



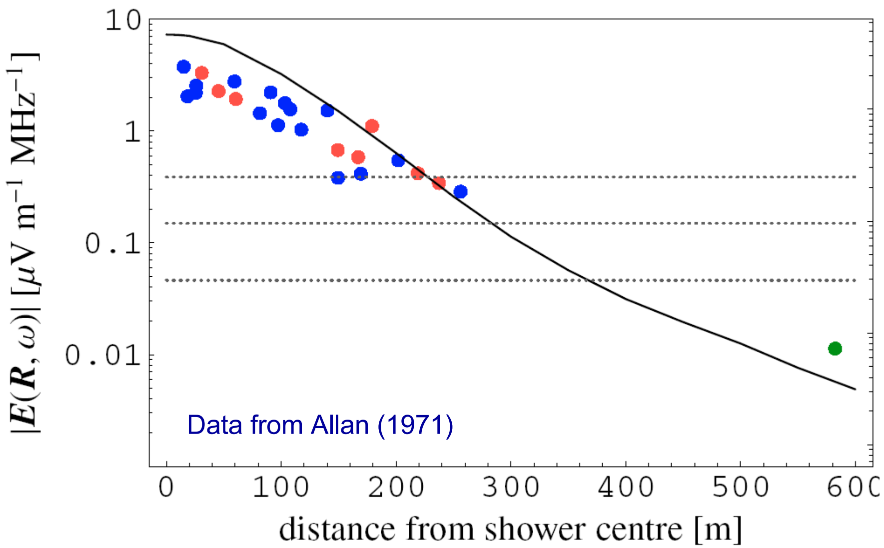
Analytical geosynchrotron model

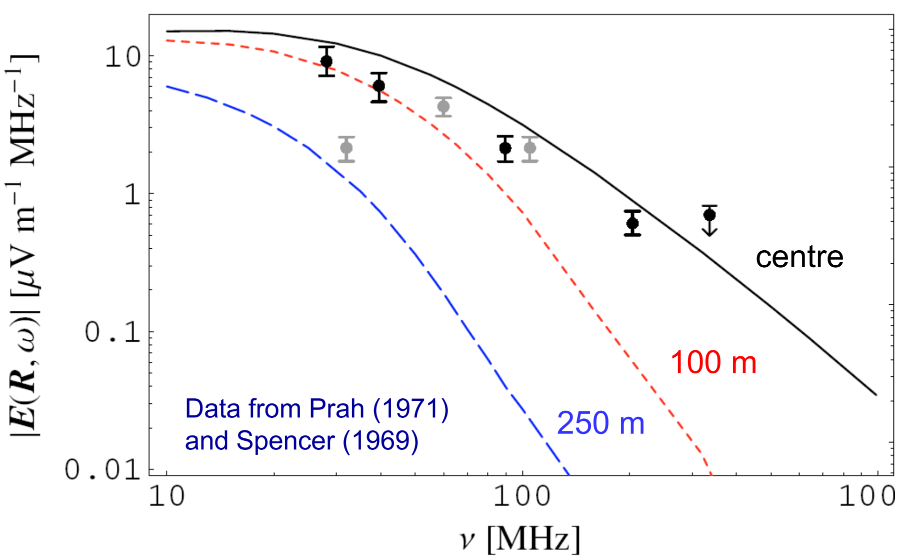
- basis: analytical synchrotron frequency spectrum radiated by an electron-positron pair
- use analytical parametrisations to describe the properties of an air shower
  - air shower evolution
  - spatial particle distributions
  - particle energy distributions
  - particle momentum angle distributions
- integrate over all electron-positron pairs in the air shower to calculate the shower radio emission
- analytical approach in frequency domain helped to understand systematics of coherence effects occurring during the integration, but is limited



Analytical geosynchrotron results

- discussion of coherence effects
- prediction of lateral dependence for vertical showers
  - absolute values and comparison with historical data
- prediction of frequency spectra for vertical showers
  - absolute values and comparison with historical data

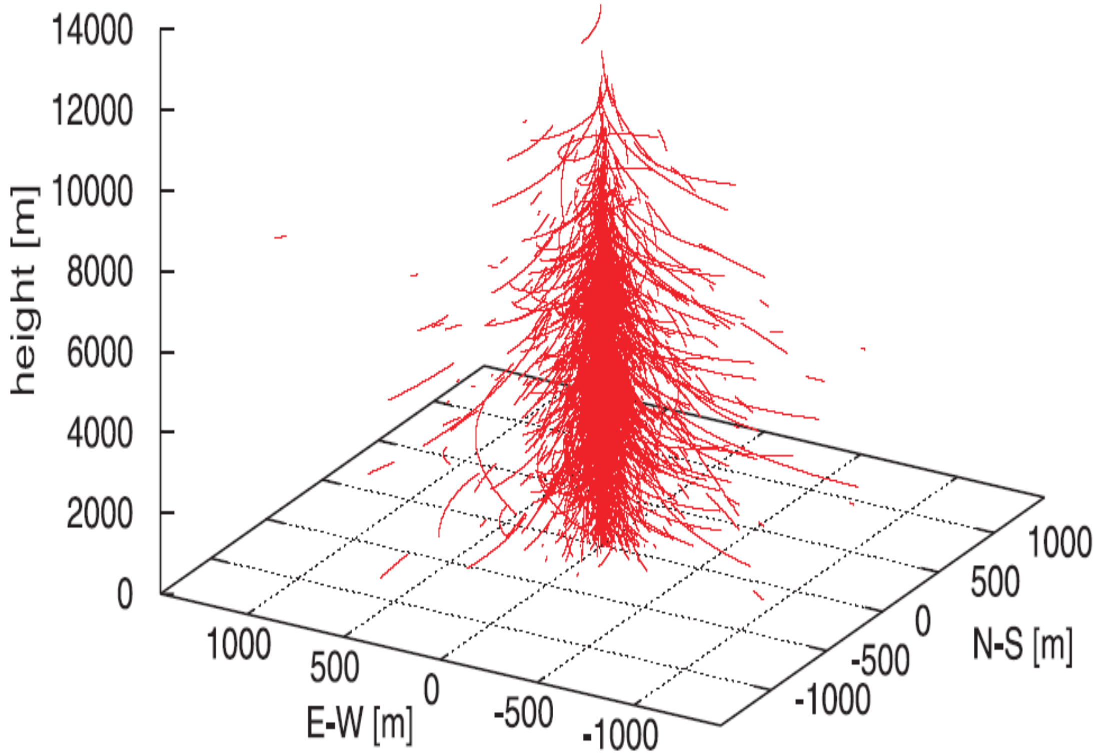




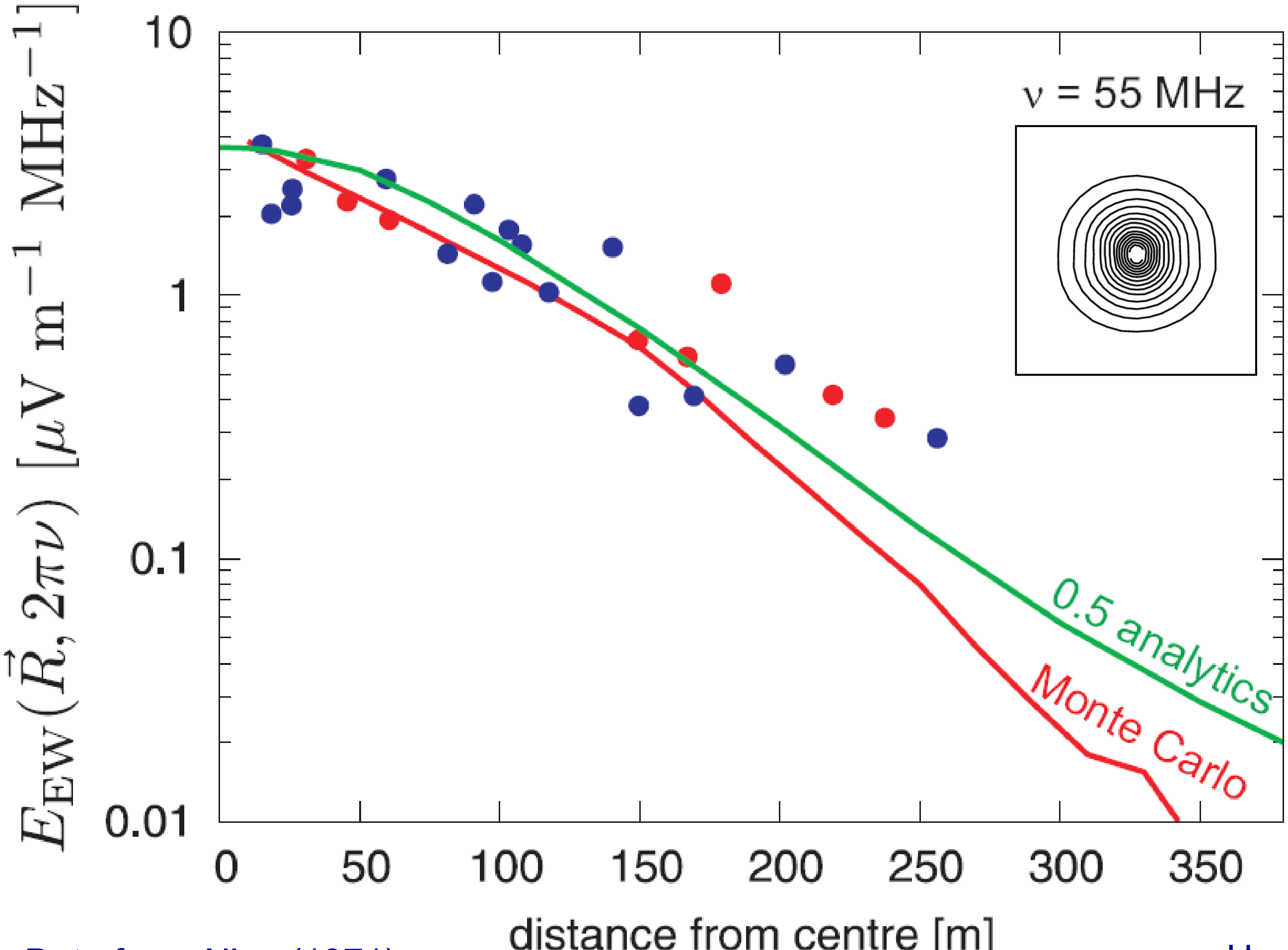
Huege & Falcke, A&A (2003)

REAS1 simulations

- time-domain Monte Carlo
- no far-field approximations
- full polarisation information
- thoroughly tested code
- uses same shower para-meterisations as earlier analytical calculations
  - allows direct comparison with analytics



Analytics, REAS1 and data

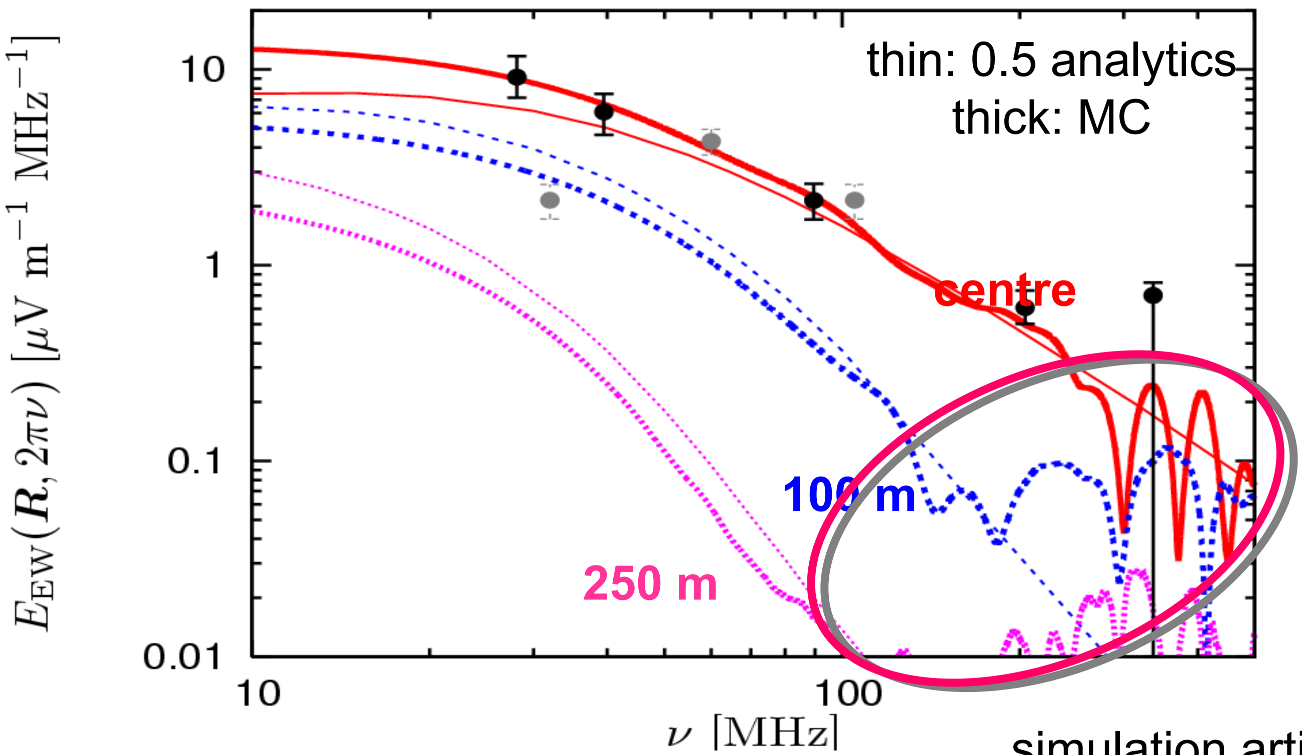


- vertical 10^{17} eV shower
- good agreement in spite of very different methods

Data from Allan (1971)

Huege & Falcke, A&A (2005)

Analytics, REAS1 and data



Data from Prah (1971) and Spencer (1969)

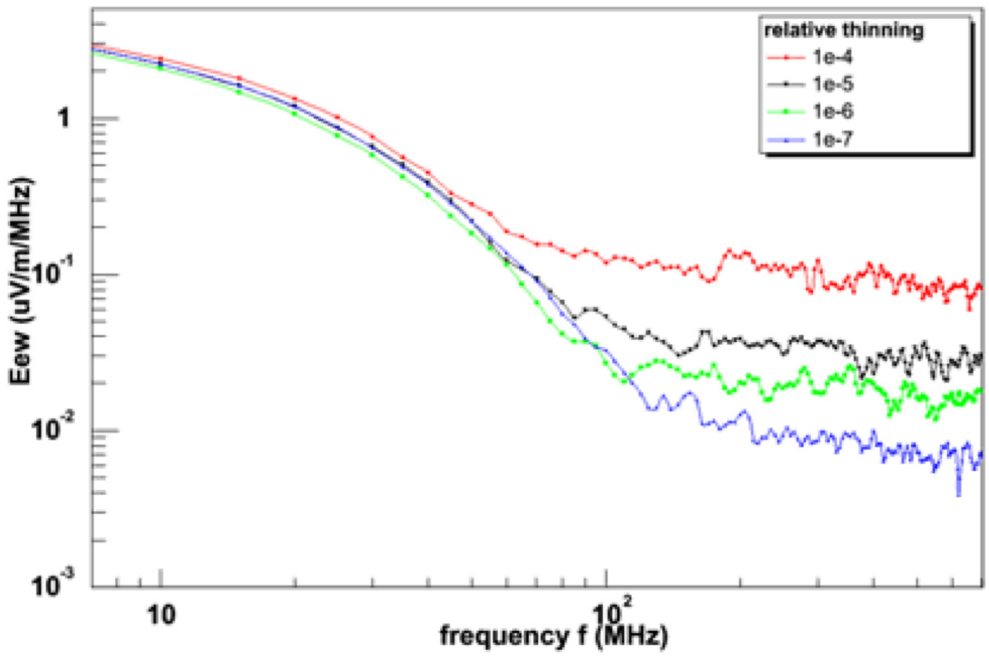
- very good agreement
- spectra steeper at higher distances
- low frequencies better for large grid spacings

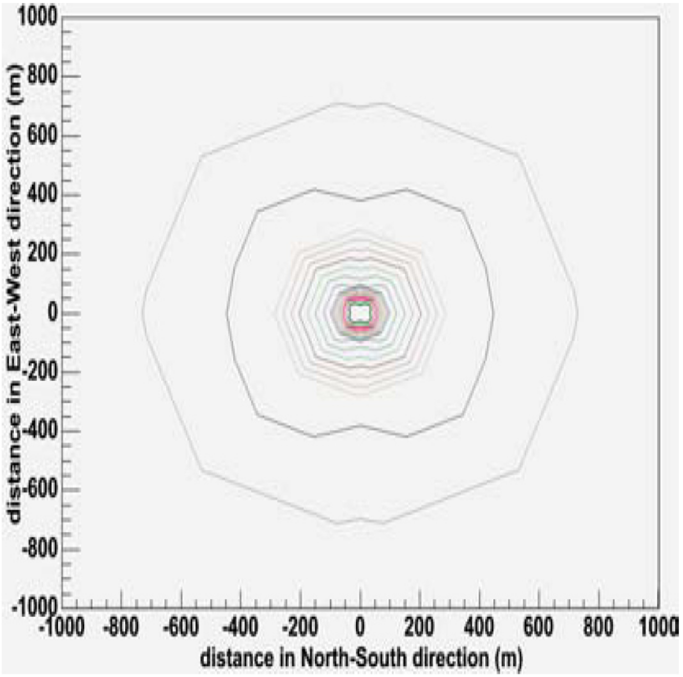
simulation artifacts (homogeneous shower) and numerical noise

Huege & Falcke, A&A (2005)

ReAIRES

- identical modelling approach as in REAS1
- implemented in AIRES air shower Monte Carlo
- results qualitatively similar to REAS1
  - spectra, circularity of the footprint, energy-dependence
- but: factor of 10 higher amplitudes than REAS1
  - too high also in comparison with data





DuVernois et al., ICRC 2005

REAS2: CORSIKA-based

- essentially keep established radio code (REAS1)
- replace parametrised air shower description with CORSIKA simulated air showers
    - histogrammed in 50 slices over shower evolution
    - separate information for electrons and positrons
    - 3d-histogram
        1. longitudinal position
        2. lateral position
        3. particle energy
    - 3d-histogram
        1. momentum angle to shower axis
        2. momentum angle to outward dir.
        3. particle energy
    - additional detailed shower evolution profile
- much more realistic model, but still allows detailed comparisons between REAS1 and REAS2

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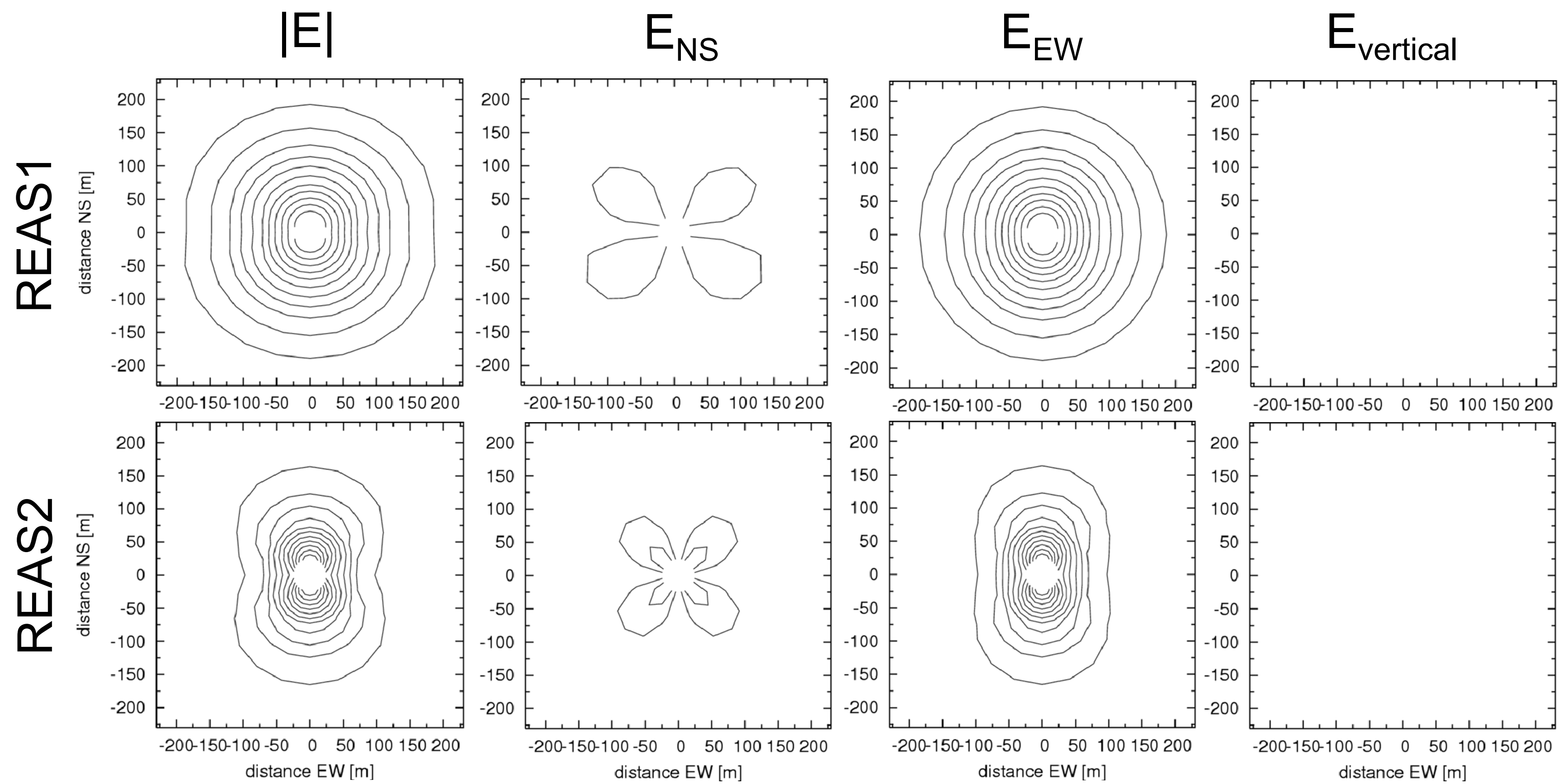
Transition from REAS1 to REAS2

vertical 10^{17} eV p-induced shower, 60 MHz

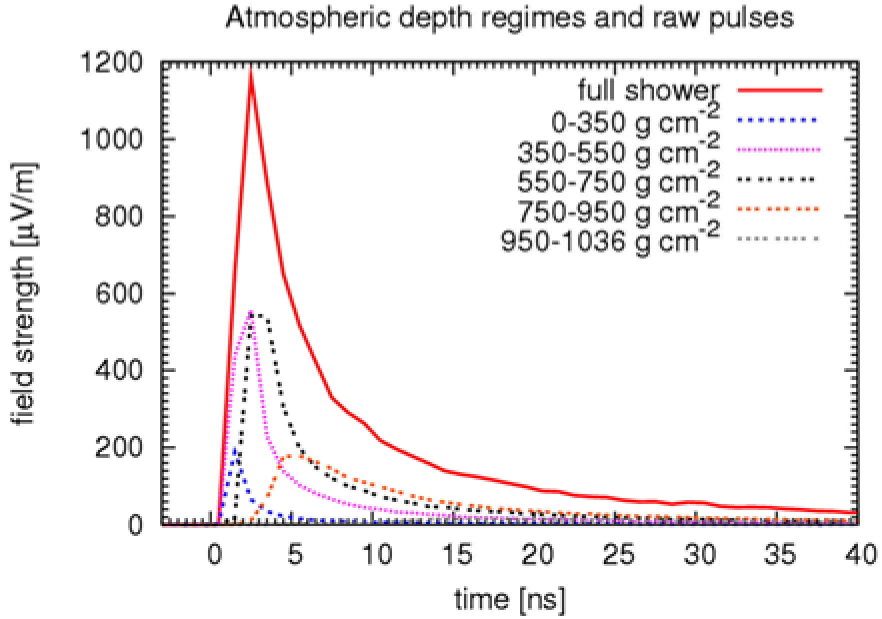


- **more asymmetric**
- **same polarisation**

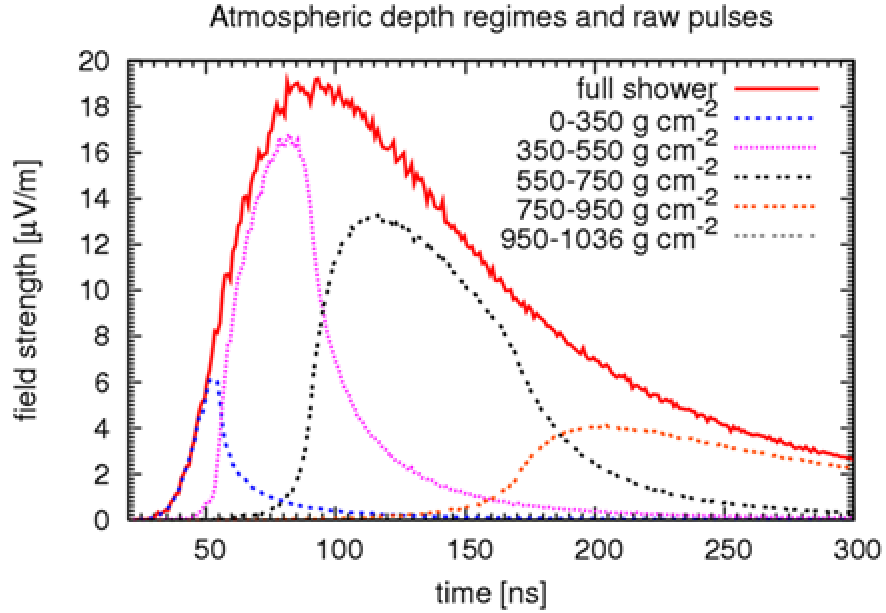
Huege, Ulrich, Engel, A. Ph. (2007)

Application: air shower phases

75 m north from core



525 m north from core

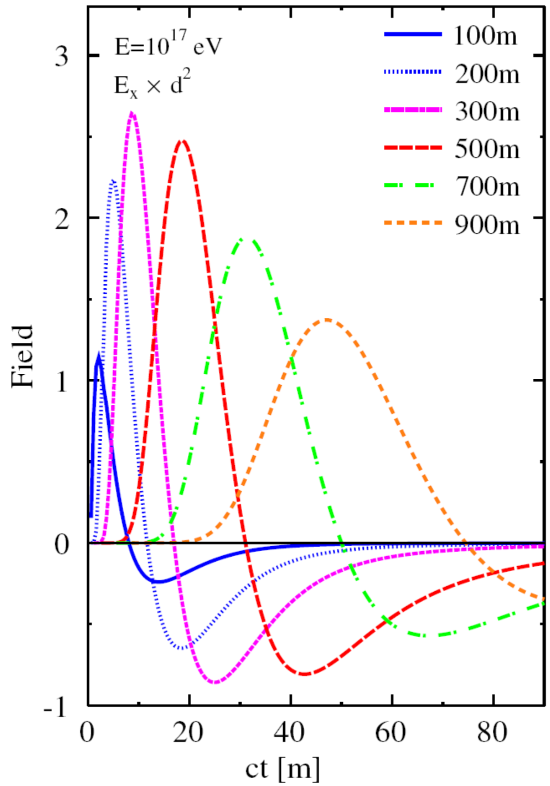


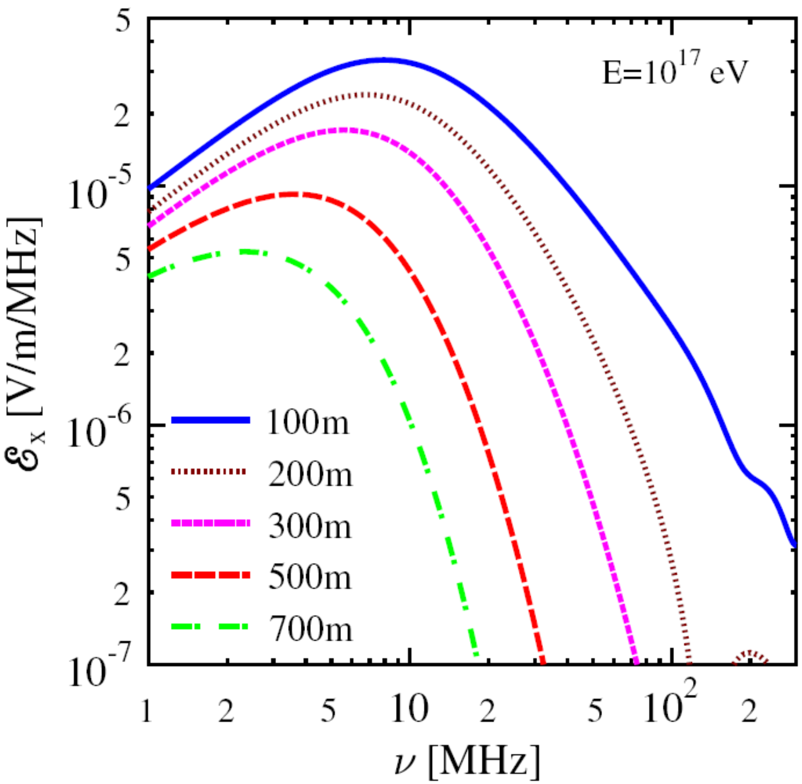
- **EAS phases contribute to different parts of overall pulse**
  - **evolving arrival time distribution**
  - **geometric delays distant from the shower core**
- **in principle, information on the air shower evolution is encoded in the pulse shape**

Huege, Ulrich, Engel, A. Ph. (2007)

The MGRM transverse currents model

- Kahn & Lerche type approach, simplified air shower model
- macroscopic description in the time-domain
  - relates pulse features to longitudinal shower evolution
- characteristic bipolar pulses from charge variation





Scholten, Werner, Rusydi, A.Ph. (2008)

REAS3

LOPES Meeting 2010

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28.01.2010

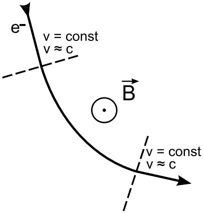
Motivation

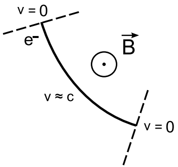
- two geomagnetic models (geosynchrotron and transverse currents) existing
- both models make different predictions for pulse shape of radio emission
- in REAS2 emission caused by variation in number of moving charges is missing

$\Longrightarrow$ complement microscopic geosynchrotron model with endpoint contributions

Geosynchrotron model

- so far radiation at "creation" and "stopping" of particles not included, i.e. particle arrives with v≈c and flies away with v≈c
- include variation in number of moving charges with "endpoint contributions"
- net contribution, if $\frac{dN}{dx} \neq 0$, i.e. if $N_{creation}(x) \neq N_{stopping}(x)$
- note: tracks of the program are not the real tracks of particles (long tracks are described with multiple shorter tracks)





Addition of charge variation: approach

- $\delta t \ll \frac{1}{\nu_{observing}}$ (instantaneous process of injection/removal)

$\Rightarrow$ consider time-averaged process

- with integrated field strength we get endpoint contributions:

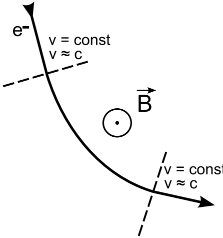
$$\int \vec{E}(\vec{x},t)dt = \int_{\delta t} \frac{e}{c} \left| \frac{\vec{n} \times [(\vec{n}-\vec{\beta}) \times \dot{\vec{\beta}}]}{(1-\vec{\beta}\cdot\vec{n})^3 R} \right|_{ret} dt = \pm \frac{e}{cR} \left(\frac{\vec{n} \times (\vec{n} \times \vec{\beta})}{(1-\vec{\beta}\vec{n})} \right)$$

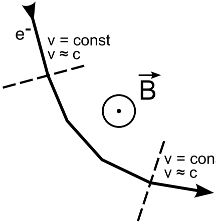
$+$ startpoints
$-$ endpoints
e - particles charge
$\vec{\beta} = \vec{v}/c$ - given by particle velocity
$R = |\vec{R}|$; $|\vec{R}|$ - vector between particle and observer position

$\vec{n} = \vec{R}/R$ - line-of-sight direction between particle and observer

Problem: combining continuous and discrete description

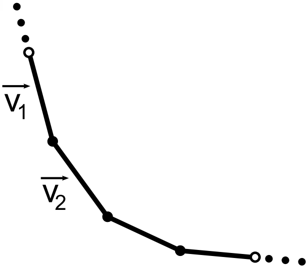
- potential problems (double counting,...) when adding discrete endpoints to continuous tracks?
- we need consistent description
- study analogy between smooth track and track with kinks





- study analogy first without endpoints

Discrete calculations



- track is splitt in straight parts with "kinks"
- change of velocity in kinks $\rightarrow$ radiation
- $\vec{v}(t_1) = \vec{v}_1 \quad \vec{v}(t_2) = \vec{v}_2$

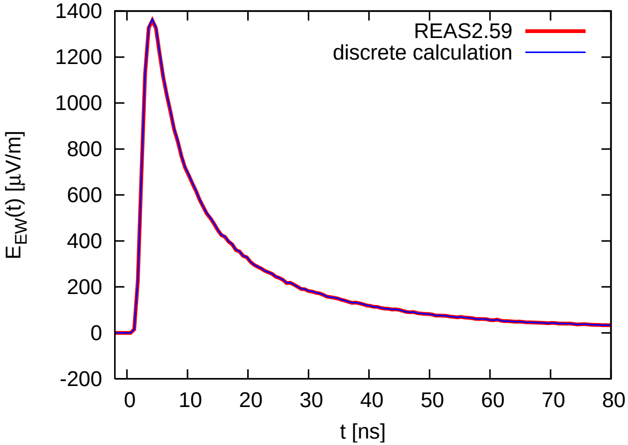
- radiation at a kink for segments of track:

$$\int \vec{E}(\vec{x},t)dt = \int_{t_1}^{t_2} \frac{e}{c} \left| \frac{\vec{n} \times [(\vec{n} - \vec{\beta}) \times \dot{\vec{\beta}}]}{(1 - \vec{\beta} \cdot \vec{n})^3 R} \right|_{ret} dt = \vec{F}(t_2) - \vec{F}(t_1)$$

$$= \frac{e}{cR} \left(\frac{\vec{n} \times (\vec{n} \times \vec{\beta}_2)}{(1 - \vec{\beta}_2 \vec{n})} \right) - \frac{e}{cR} \left(\frac{\vec{n} \times (\vec{n} \times \vec{\beta}_1)}{(1 - \vec{\beta}_1 \vec{n})} \right)$$

Continuous vs discrete calculation

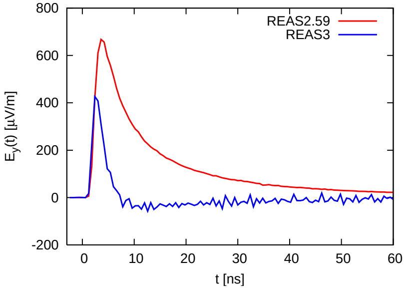
- compare output with REAS2 output

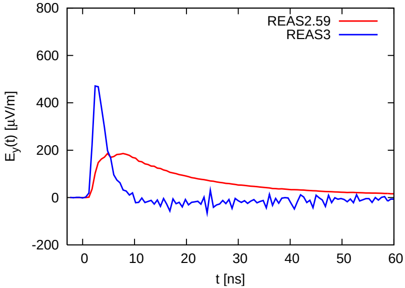


- both pulses match
- discrete description is equivalent to continuous
- in discrete picture endpoints are just kinks with $\vec{v}_i = 0 \neq \vec{v}_j$

Comparison of REAS2 and REAS3

- compare observer in north (left) and east direction at 100m for vertical shower with $E_p = 10^{17}$eV and horizontal magnetic field

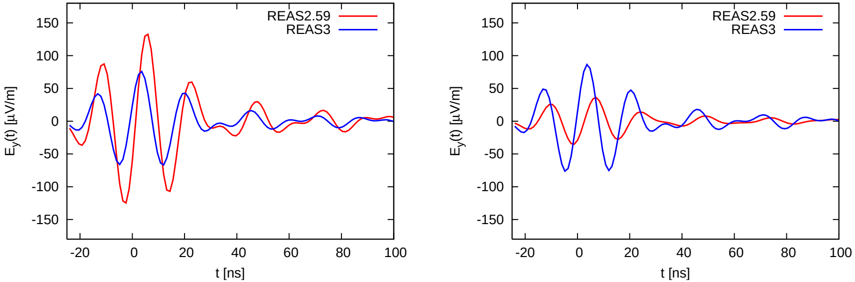




- now bipolar pulses
- geosynchrotron contributions are asymmetric, with endpoints nearly symmetric
- height of amplitude changed

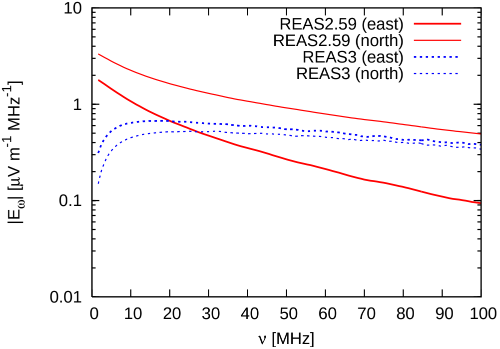
Comparison of REAS2 and REAS3

- output with frequency filter of 44MHz to 76MHz for observer 100m north (left) and east from shower core



Comparison of REAS2 and REAS3

- frequency spectra for observer 100m north (thin line) and east (thick line) for REAS2 (red) and REAS3 (blue)

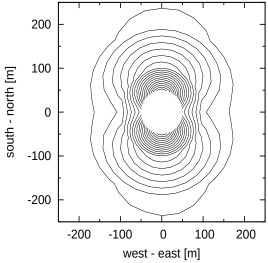


- E $\rightarrow$ 0 for frequency $\rightarrow$ 0 (bipolar pulses)
- REAS3 more symmetric

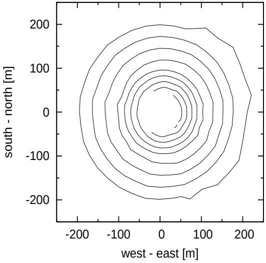
Comparison of REAS2 and REAS3

- contour plots of the 60MHz field strength, $E_p = 10^{17}$eV, vertical shower, horizontal B-Field

REAS2



REAS3

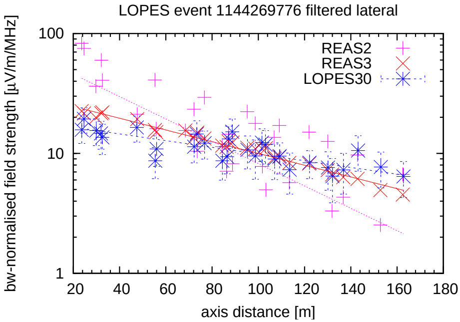


- REAS3 more symmetric
- EW-asymmetry due to electron excess

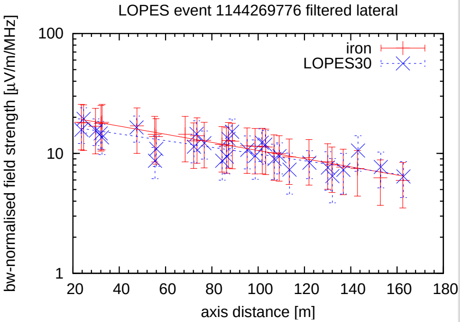
Comparison with LOPES data

- E = $2.75 \cdot 10^{17}$eV, 24° zenith angle

proton shower



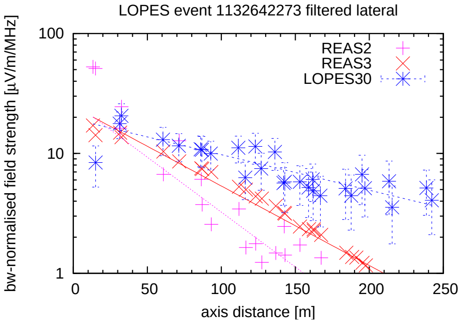
iron shower



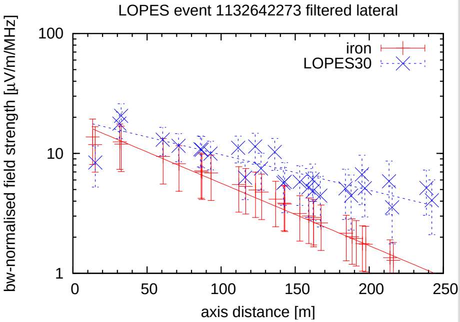
Comparison with LOPES data

- E = $3.13 \cdot 10^{17}$eV, 12° zenith angle

proton shower



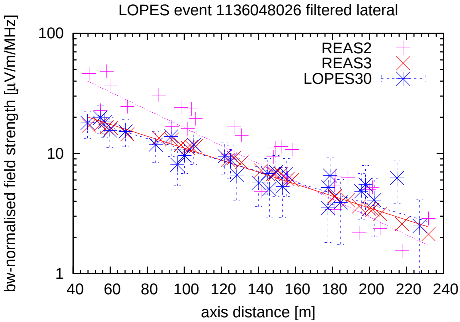
iron shower



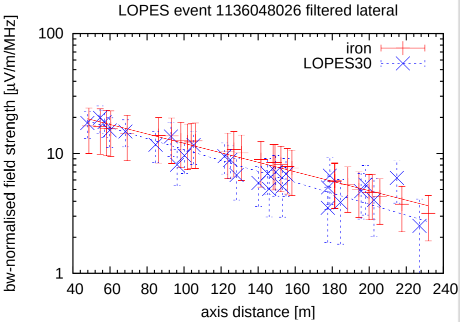
Comparison with LOPES data

- $E = 2.92 \cdot 10^{17}$eV, 31° zenith angle

proton shower



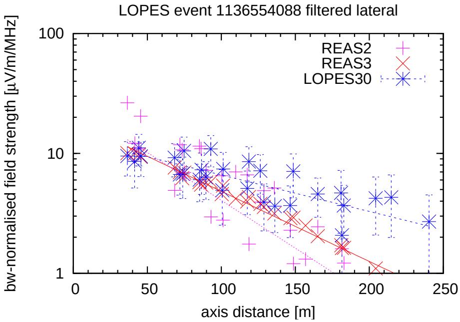
iron shower



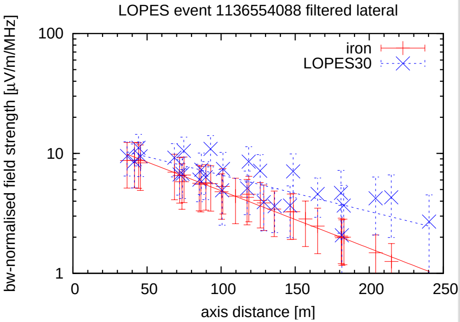
Comparison with LOPES data

- $E = 1.65 \cdot 10^{17}$eV, 14° zenith angle

proton shower



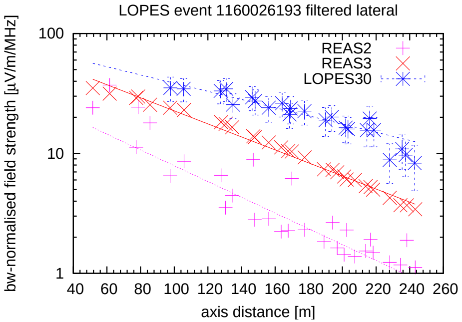
iron shower



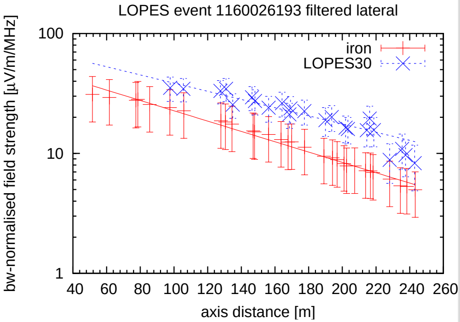
Comparison with LOPES data

- E $= 9.65 \cdot 10^{17}$eV, 29° zenith angle

proton shower



iron shower

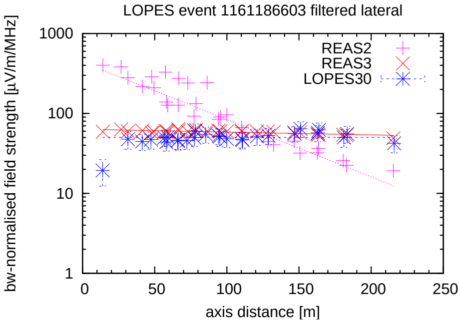


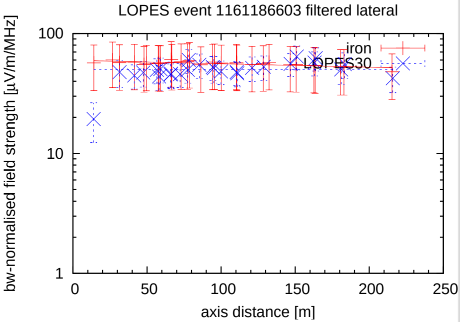
Comparison with LOPES data

- E = $2.88 \cdot 10^{18}$eV, 58° zenith angle

proton shower

iron shower





Conclusion

- geosynchrotron model is complemented with emission due to variation of number of moving charges
- use discrete calculation for consistent description
- REAS3 is more symmetric than REAS2
- first comparison with data shows good agreement
- **Outlook:**
  - comparison between microscopic and macroscopic model
  - comparison between data and simulation
  - include radio direct into CORSIKA
  - paper in preparation
  - optimize REAS3