Karlsruhe Institute of Technology

A detailed comparison of REAS3 and MGMR radio emission simulations
(and the history of how we got there …)

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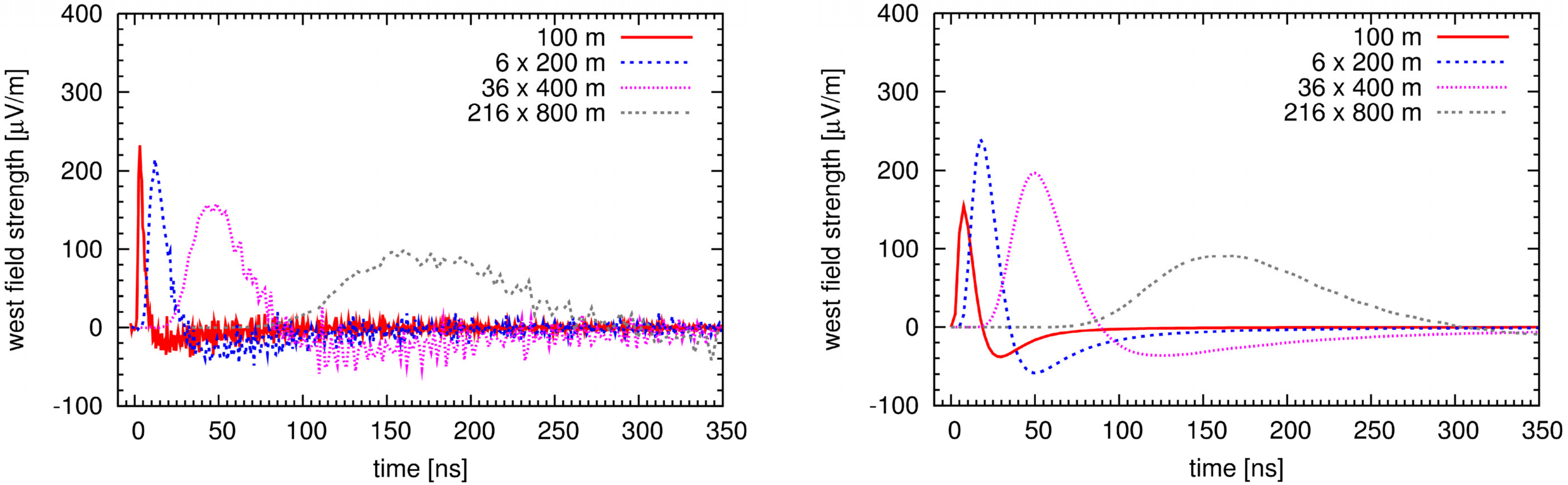


Radio emission from EAS – historical models

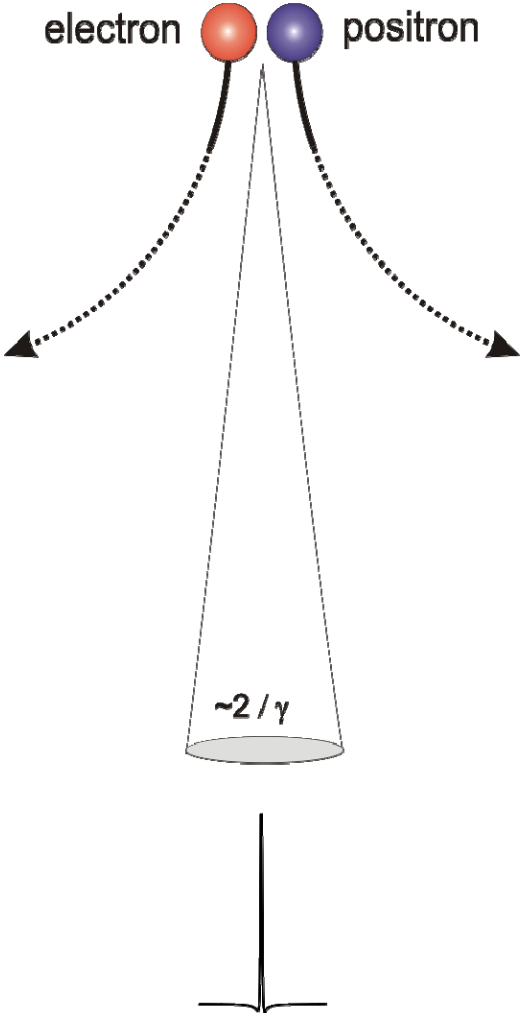
Year	Authors	Type	Regime	Comment
1961/65	Askaryan	Cherenkov	frequency	charge excess
1966	Kahn & Lerche	Cherenkov & geomagnetic	frequency	transverse currents, dipole
1967	Colgate	geomagnetic	both	electromagnetic pulse
1967	Allan	geomagnetic	*time*	Feynman approach
1969	Fuji & Nishimura	Cherenkov & geomagnetic	frequency	combine approaches with *cascade theory*
1969	Castagnoli et al.	Cherenkov & geomagnetic	frequency	combine approaches with *Monte Carlo*
…	…	…	…	…

Usability of historical works

- investigated the primary physics mechanisms
- demonstrated dominance of geomagnetic mechanism
- very simplified air shower descriptions
    - point sources
    - rings of charges
    - other simplifications
- more sophisticated modelling efforts (e.g., Monte Carlo codes) were not sufficiently documented in the literature
- all in all not detailed enough for comparison with concrete modern measurements
- *today's researchers had to start their own modelling efforts*

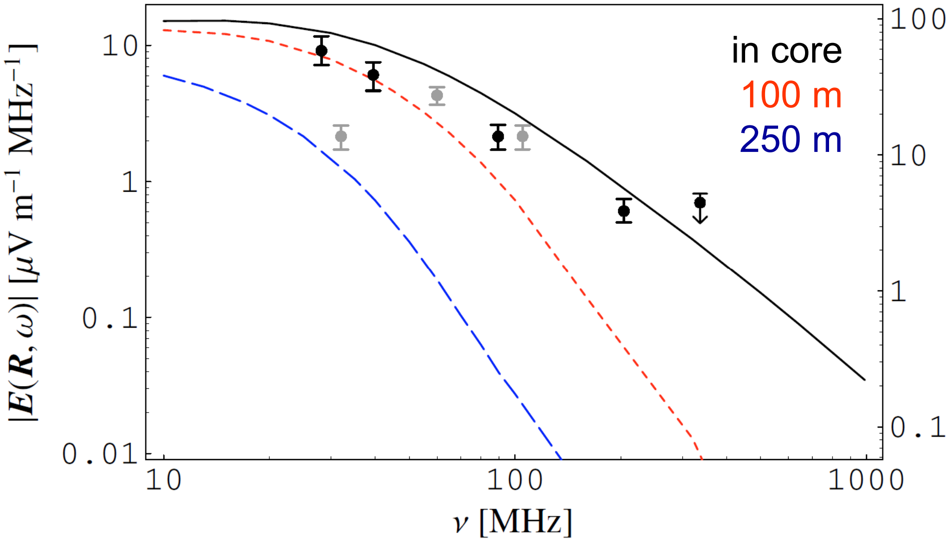
Analytical geosynchrotron model

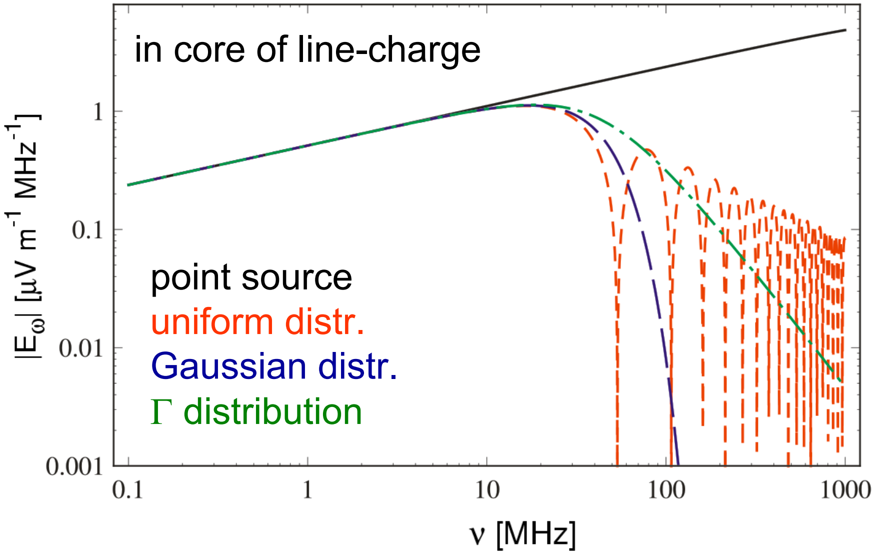
- basis: analytical synchrotron frequency spectrum radiated by an electron-positron pair
- analytical parametrisations
  - air shower evolution
  - spatial particle distributions
  - particle energy distributions
  - particle momentum angle distributions
- integrate over all shower electron-positron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



Huege & Falcke, Astronomy & Astrophysics (2003)

Results of analytical geosynchrotron model

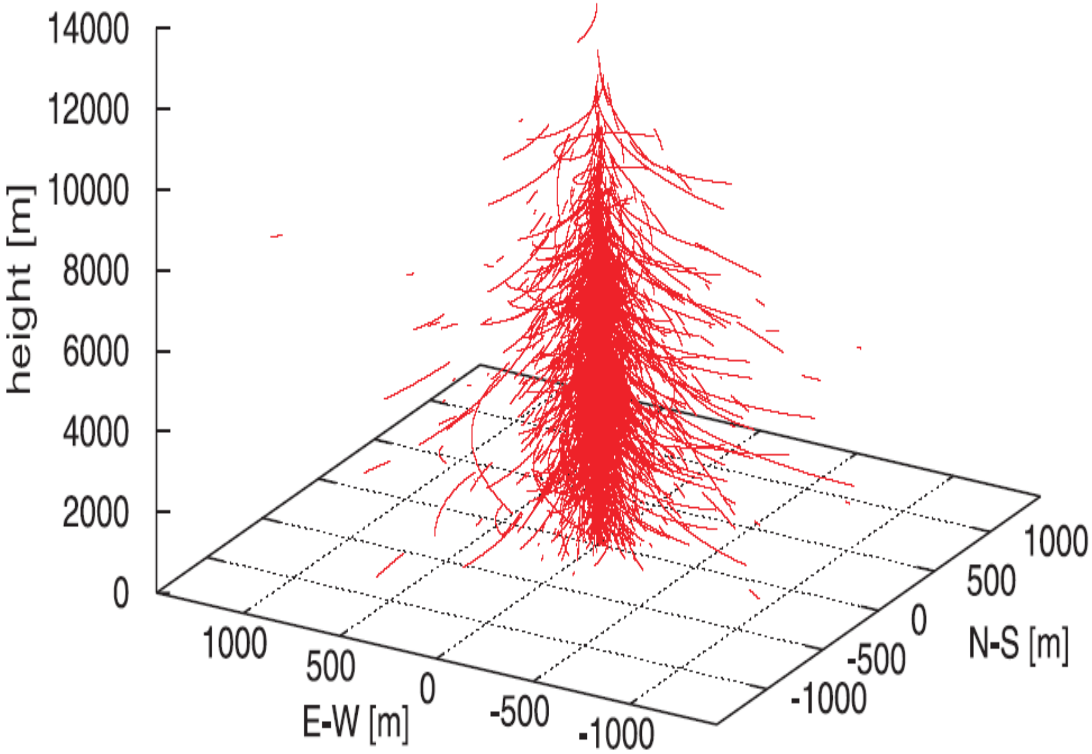




- comparisons with historical data were encouraging
  - naturally, focused on observing frequencies above ~10 MHz
- synchrotron spectra fall off to zero at frequency zero!
- next step: cross-check and increase complexity with a Monte Carlo

Huege & Falcke, Astronomy & Astrophysics (2003)

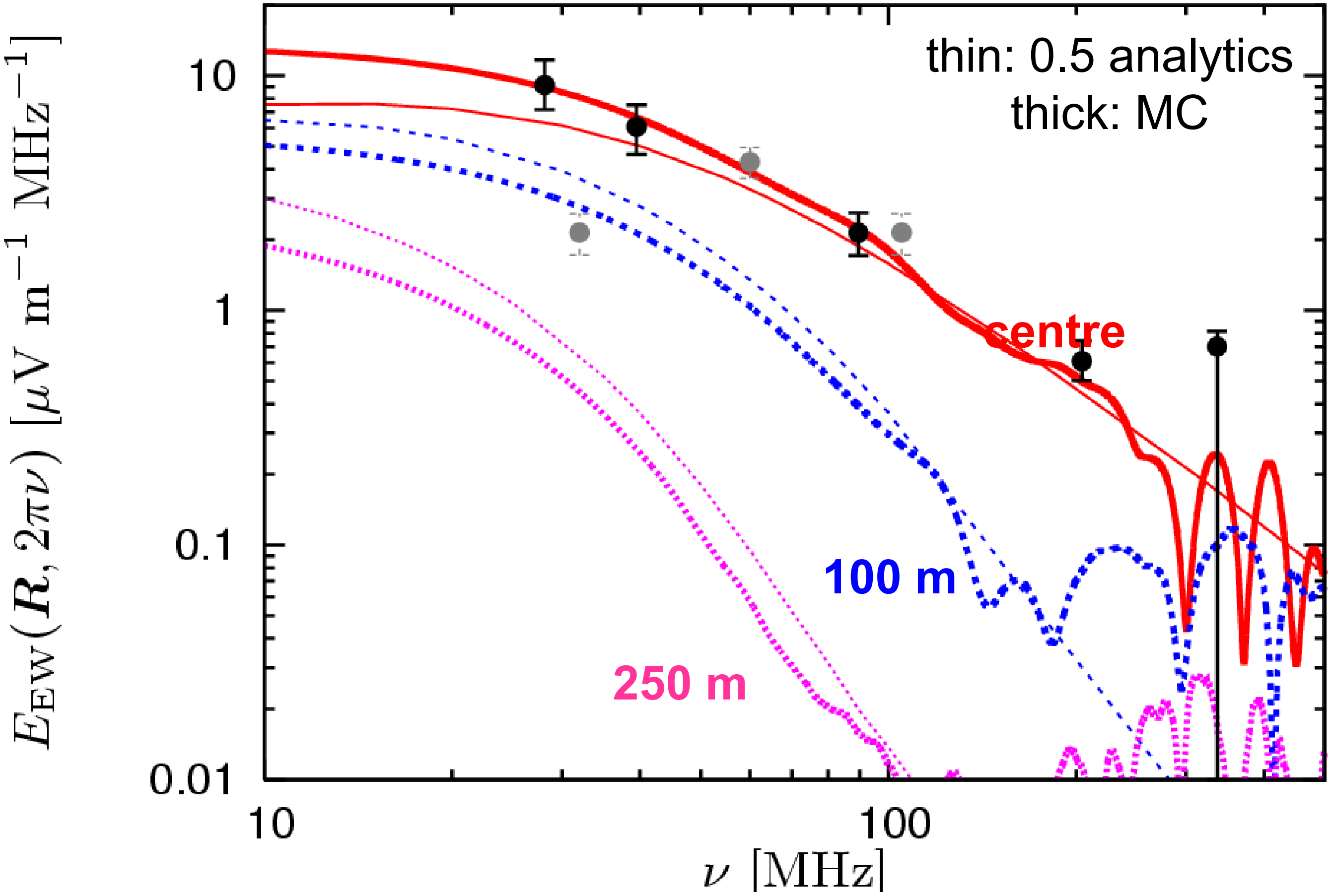
REAS1 simulations



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

Huege & Falcke, Astroparticle Physics (2005)

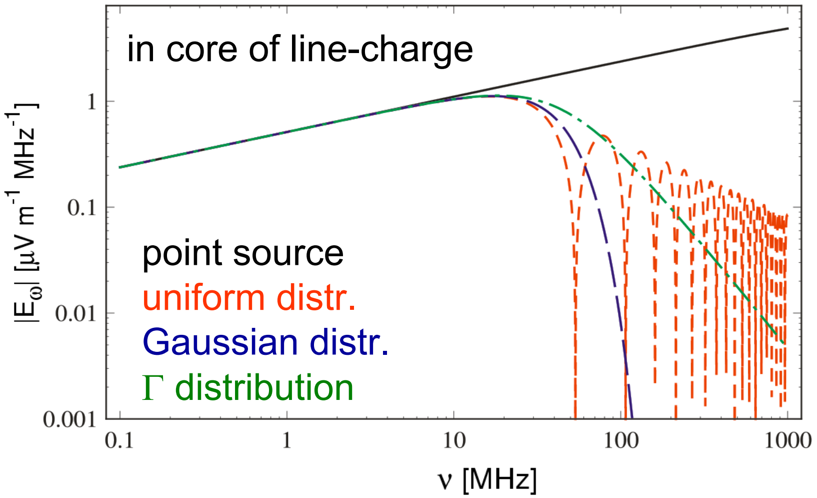
Analytics, REAS1 and data

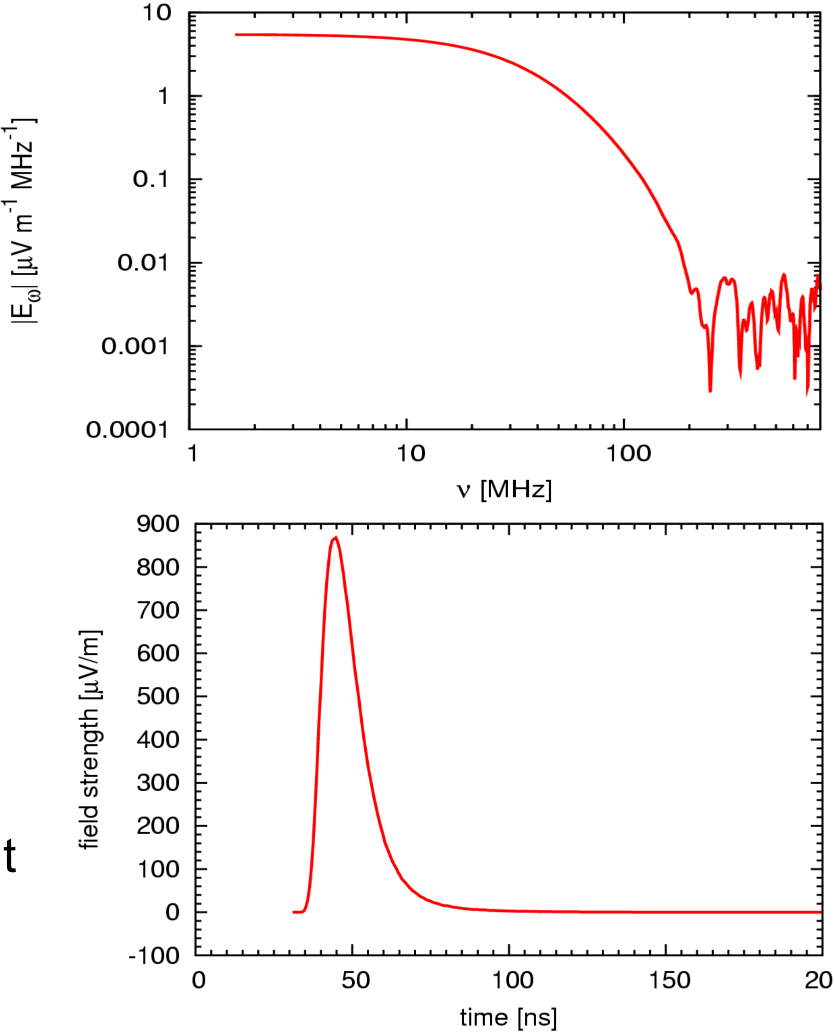


- two very different approaches yield good agreement above ~10 MHz

Huege & Falcke, Astroparticle Physics (2005)

On closer look: changes at low frequencies

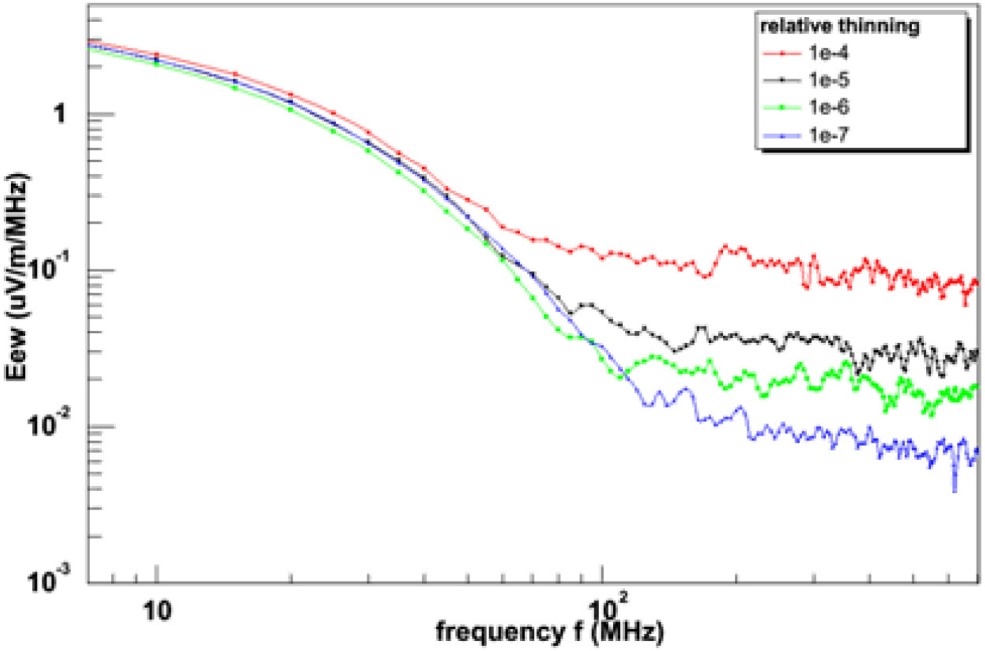

analytical


REAS1

- analytical model had spectrum falling to zero at frequency zero
- REAS1 spectrum levels off at small frequencies
  - unipolar pulses with DC component
- not deemed important at the time

The ReAires code

- identical modelling approach as in REAS1
- implemented in AIRES air shower Monte Carlo
- results are qualitatively similar to REAS1
  - circularity of the footprint, energy-dependence
- but: factor of 10-20 higher amplitudes than REAS1
  - too high also in comparison with data

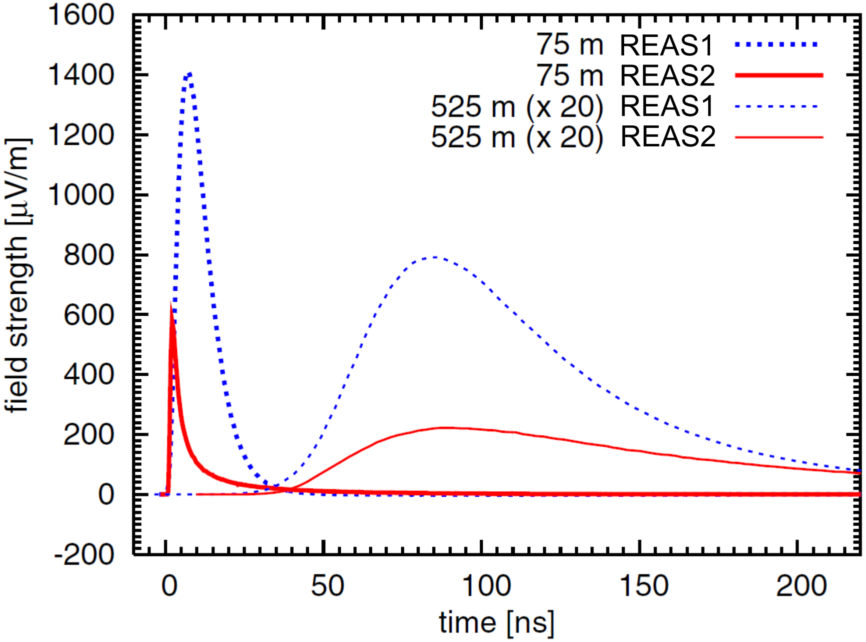


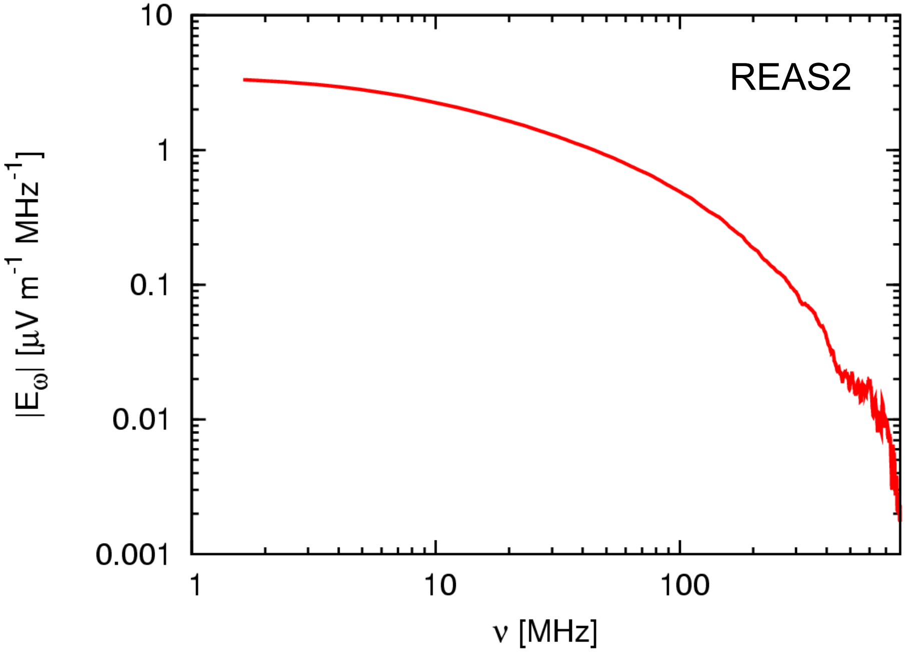
- like REAS1, ReAIRES predicts unipolar pulses and spectra levelling off at low frequencies!

DuVernois et al., ICRC 2005

Transition from REAS1 to REAS2

- keep radio emission physics from REAS1
- replace parameterized air shower with detailed CORSIKA simulations



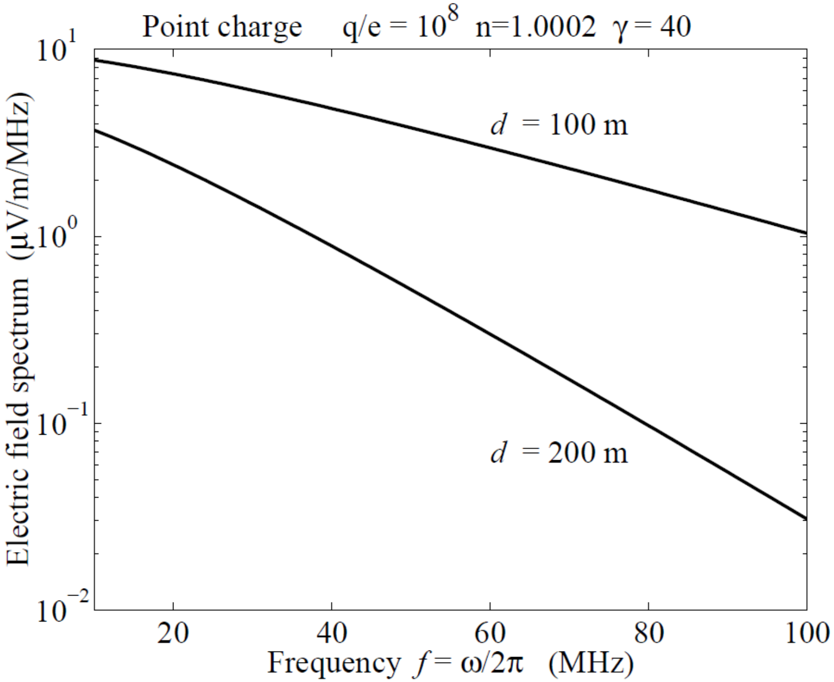


- significant changes to the pulse heights, LDFs, …
- unipolar pulses as in REAS1, spectra still level off at low frequencies

Huege, Ulrich, Engel, Astropart. Phys. (2007)

Meyer-Vernet et al.

- analytical frequency-domain calculation of
  - boosted Coulomb field (low-energy particles)
  - Cherenkov field (high-energy particles)
- somewhat simplified air shower geometry
- parameterized shower evolution with charge variation



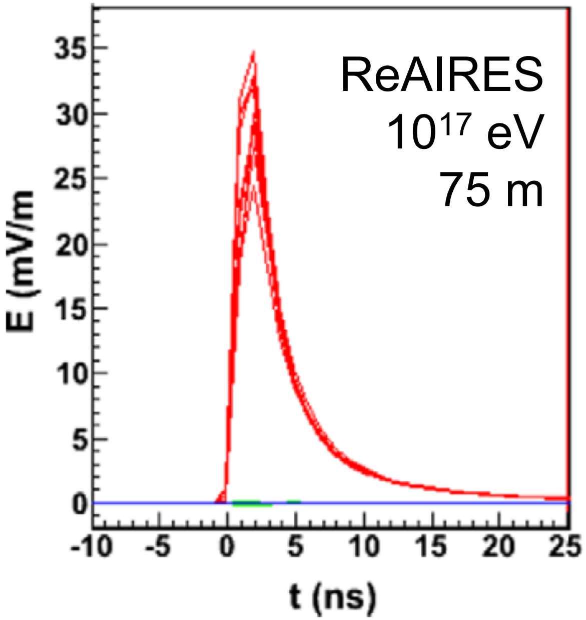
$$\frac{\omega d}{\gamma' v} \ll 1 \quad E(\mathbf{r},\omega) \simeq \frac{q e^{i\omega z/v}}{2\pi\epsilon_0 n^2 v d}$$

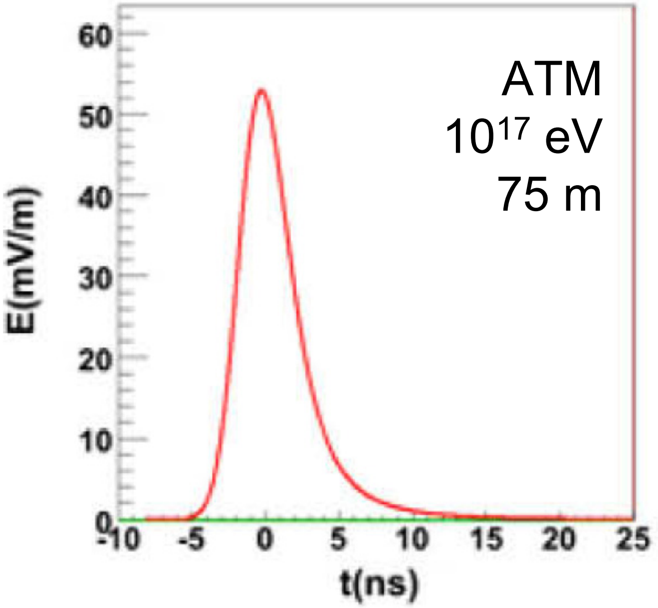
- predicts spectra levelling off at a constant value at low frequencies

Meyer-Vernet, Lecacheux, Ardouin, A&A (2008)

Chauvin et al. „analytic toy model“

- analytical time-domain model for a point source
- intended for quick estimations rather than full-fledged simulation
- predictions are very similar to ReAIRES calculations
  - unipolar pulses, spectra level off at low frequencies



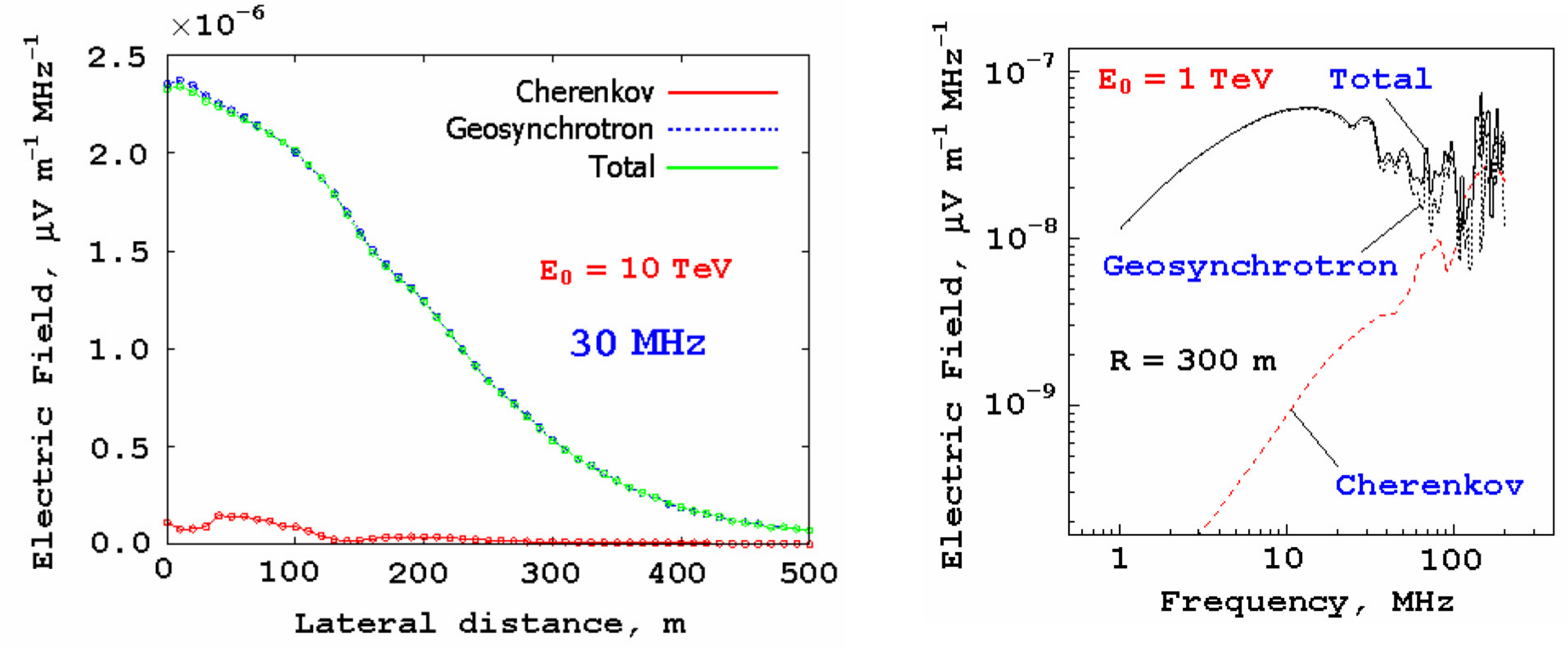


- both therefore qualitatively similar to REAS2, both factor ~10-20 higher!?

Chauvin, Rivière, Montanet et al., Astrop. Phys. (2010)

Konstantinov et al. code

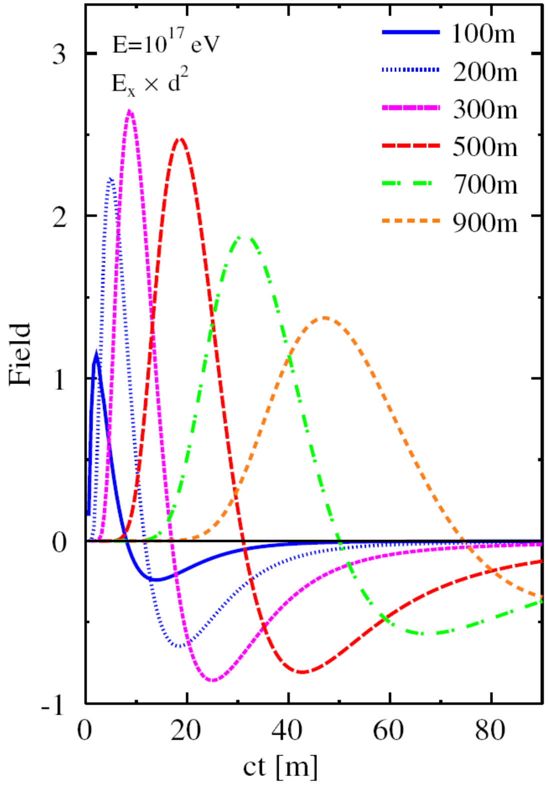
- frequency-domain calculation with EGSnrc Monte Carlo
  - limited reach in energy, very slow at >10^{15} eV (by now with thinning)
- includes Cherenkov effects (refractive index of atmosphere)
- confirms dominance of geomagnetic contributions
- spectra fall off to zero at zero frequency!

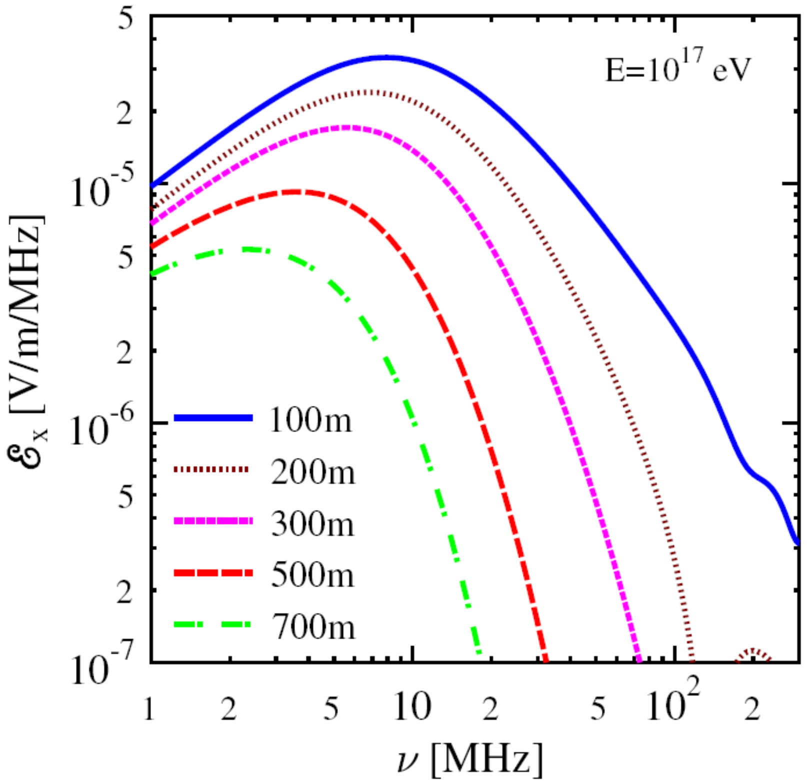


Engel, Kalmykov, Konstantinov, ICRC 2005

The MGMR model

- Kahn & Lerche type approach, parameterized air shower model
- macroscopic description in the time-domain (see talk Krijn de Vries)
    - relates pulse features to longitudinal shower evolution
    - time-derivative of air shower evolution directly yields bipolar pulses

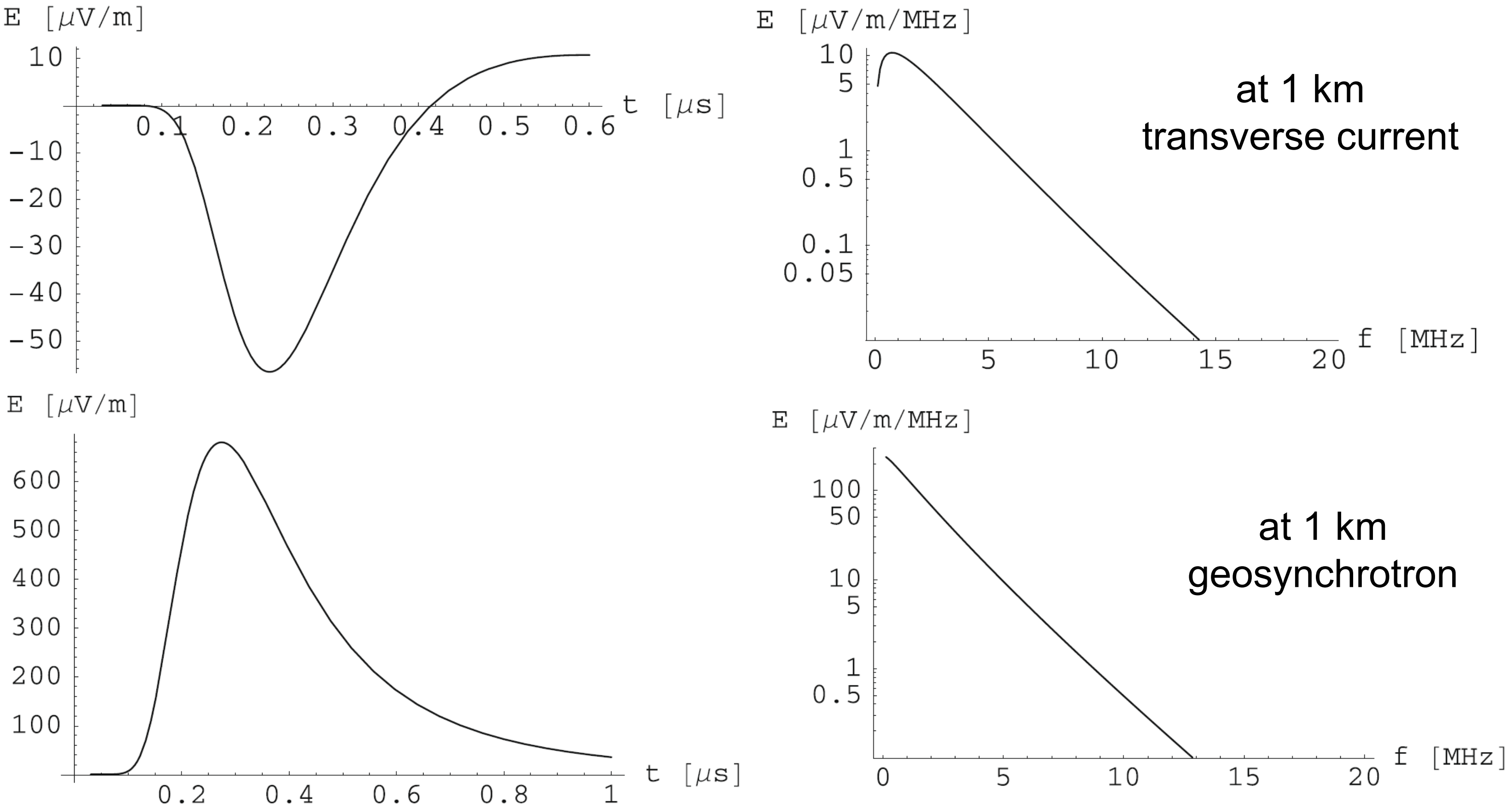




Scholten, Werner, Rusydi, A.Ph. (2008)

Large impact parameter model Gousset et al.

- analytic approximation for large impact parameters
- calculation in the time-domain
- explicit comparison of „transverse current“ and „geosynchrotron“ emission



at 1 km
transverse current

at 1 km
geosynchrotron

Gousset, Lamblin, Valcares, Astrop. Phys. (2008)

Summary of the situation

- models with unipolar pulses, spectra leveling off at zero
  - REAS1
  - ReAIRES
  - REAS2
  - Meyer-Vernet et al.
  - Chauvin et al.
  - …
- models with bipolar pulses, spectra with zero at zero freq.
  - analytical geosynchrotron
  - Konstantinov et al.
  - MGMR
  - REAS3 (talk M. Ludwig)

Gousset et al.

blue: time-domain
black: frequency-domain

- what is the reason for the discrepancy?
  - the models with unipolar pulses neglect an important radiation component, **the radio emission from charge variation** (not the variation itself, but the emission caused by it)

Illustration of the problem

- here for the example of an analytic calculation (Chauvin et al.)
- starting point: Liénard-Wiechert fields for single moving particle

$$\vec{E}_{EM} = \vec{E}_C + \vec{E}_R = \frac{1}{4\pi\epsilon_0}\left[\frac{e\left(\vec{n}-\vec{\beta}\right)}{\gamma^2 R^2 \left(1-\vec{\beta}\vec{n}\right)^3}\right]_{ret} + \frac{1}{4\pi\epsilon_0 c}\left[\frac{e\vec{n}\times\left(\left(\vec{n}-\vec{\beta}\right)\times\dot{\vec{\beta}}\right)}{R\left(1-\vec{\beta}\vec{n}\right)^3}\right]_{ret},$$

additional terms

time-variability of charge must be included here

time derivative

$$\Phi(\mathbf{r},t) = \frac{1}{4\pi\epsilon_0 n^2}\left[\frac{q}{\mid 1-n\boldsymbol{\beta}\cdot\mathbf{n}\mid R}\right]_{ret}$$

$$\mathbf{A}(\mathbf{r},t) = n^2\boldsymbol{\beta}\Phi(\mathbf{r},t)/c$$

- then fold in particle motion and calculate total shower electric field as

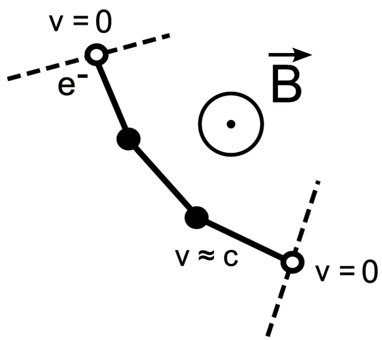
$$\vec{E}(t_r) = N(x_e)(\eta\vec{E}_C(t_r) + \vec{E}_R(t_r))$$

num particles as f(shower evolution)

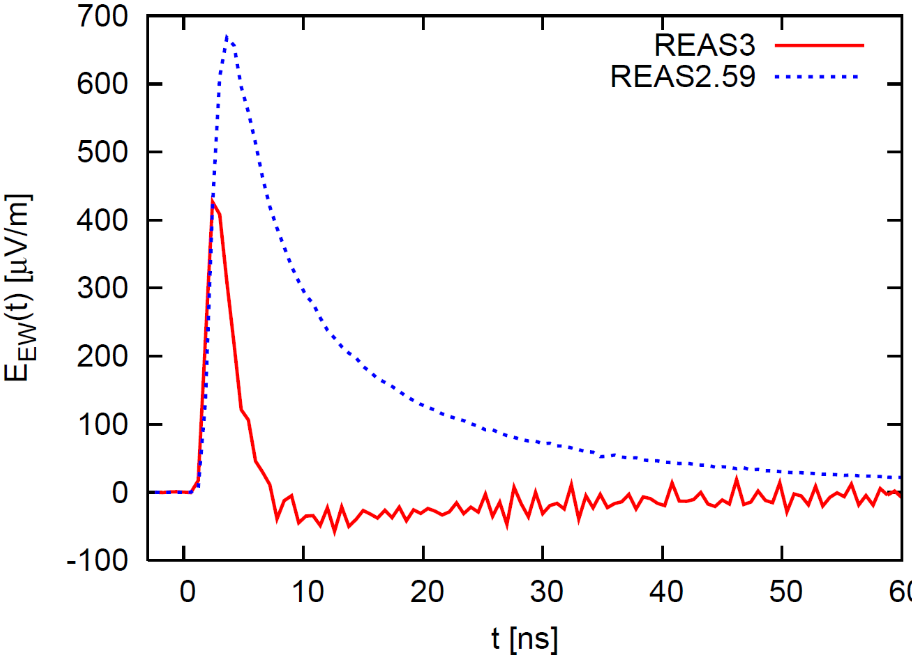
charge excess (22%)

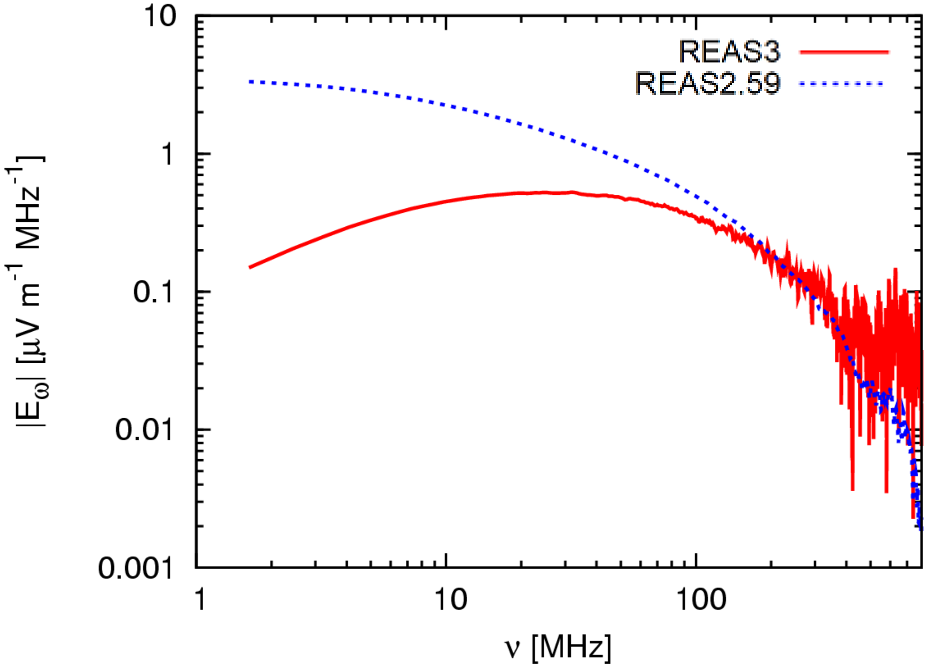
- this includes the variation of the total charge – but not the radiation caused by it!

REAS3



- how to include radiation in Monte Carlo simulation?
  - using „endpoints“ (see talk Marianne Ludwig)
- in REAS3, pulses become bipolar and spectra fall to zero at frequency zero
- increased numerical noise, but mostly at high frequencies and for near-vertical showers

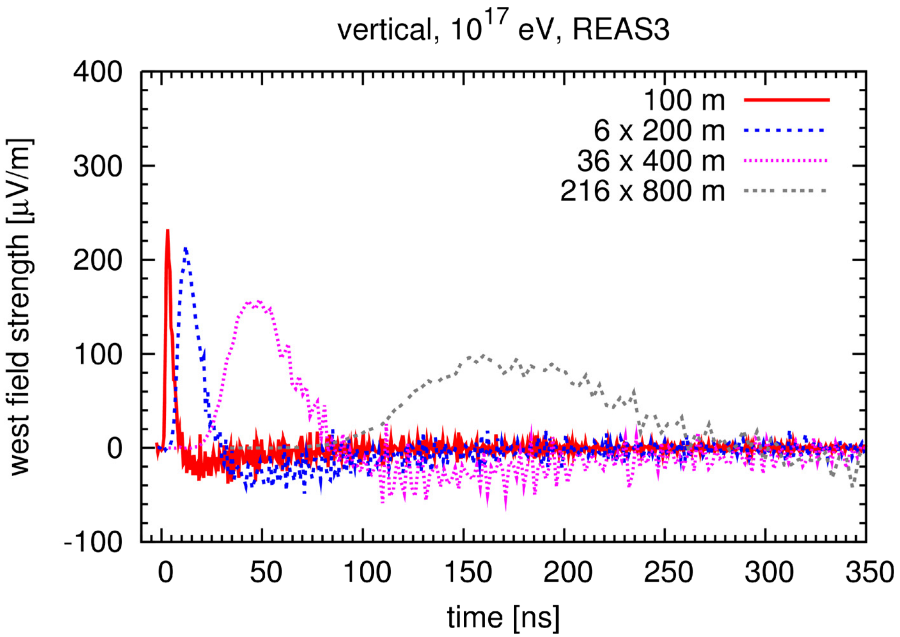




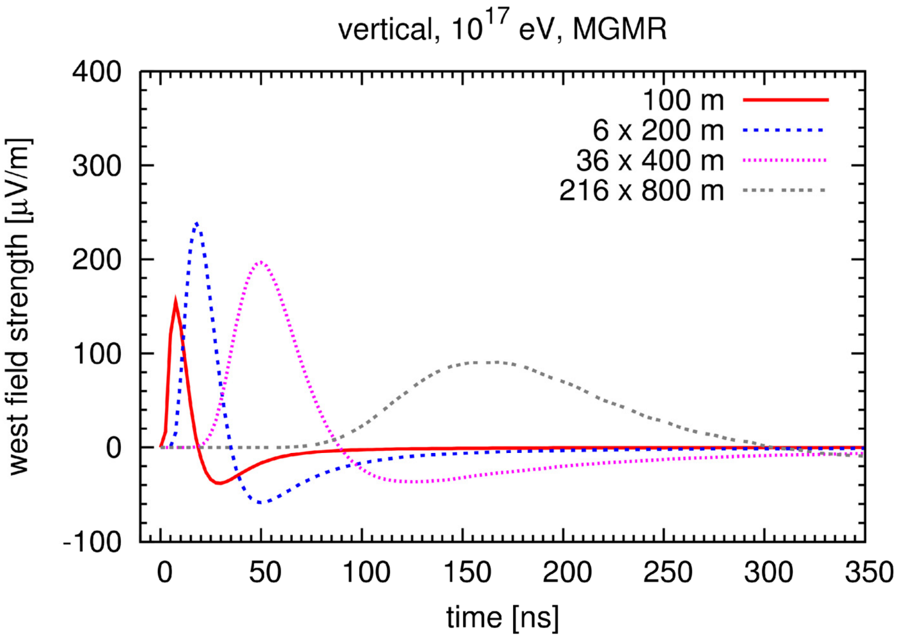
A detailed comparison of MGMR and REAS3

- once REAS3 was ready, we decided to to a detailed comparison with the MGMR model
- in both models, we simulated the same proton-induced air showers
  - vertical 10^{17} eV, 10^{18} eV, 10^{19} eV with Argentinean B-field
  - vertical 10^{17} eV with horizontal, vertical and no B-field
  - 50° zenith angle 10^{17} eV with Argentinean B-field
- shower-to-shower fluctuations were excluded by using the CORSIKA longitudinal file of the REAS3 simulation in the MGMR simulation

Pulses for a vertical 10^{17} eV shower



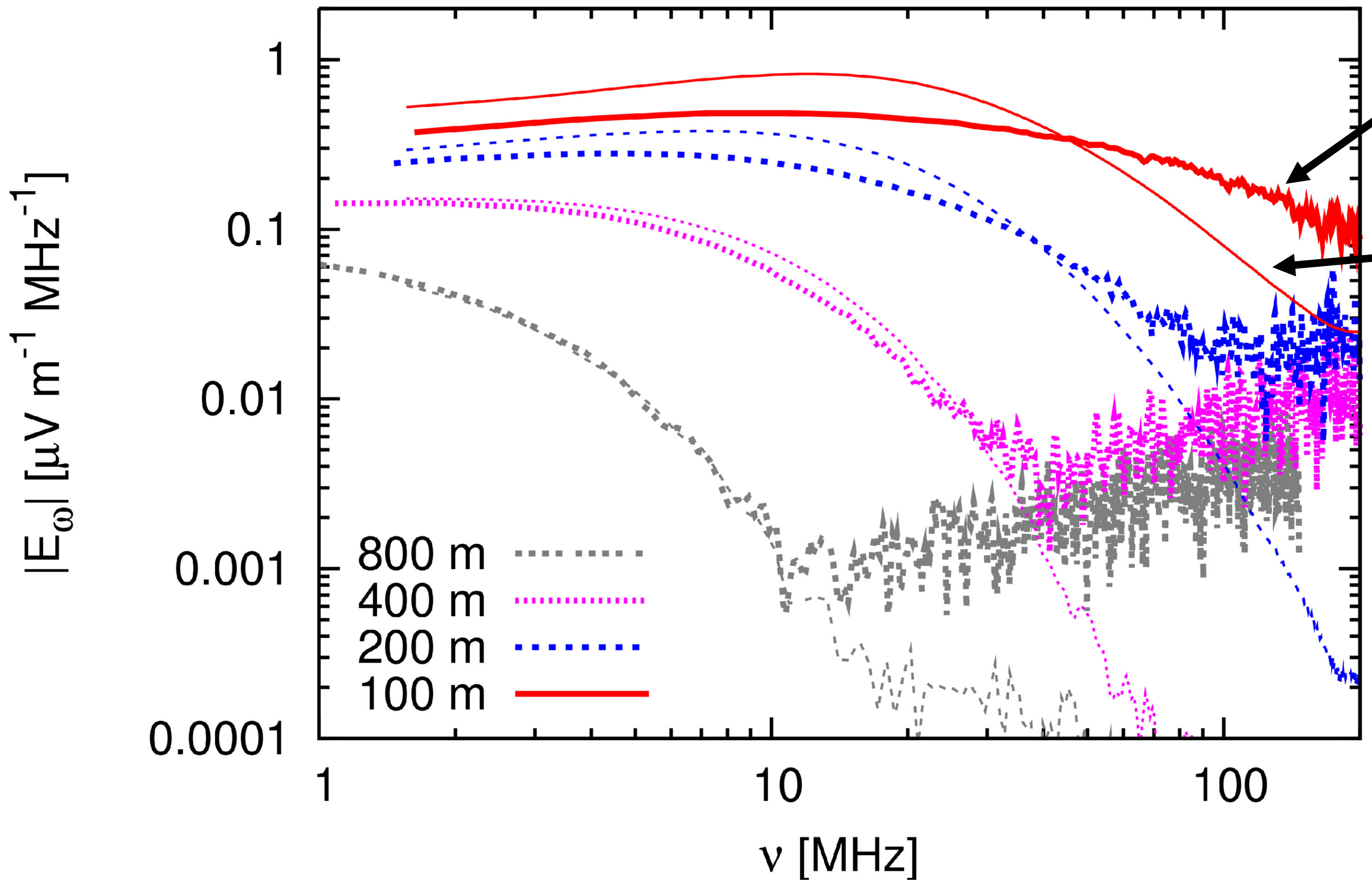
vertical, 10^{17} eV, REAS3



vertical, 10^{17} eV, MGMR

- both models predict bipolar pulses
- field strengths match to better than a factor of 2!
- lateral distribution seems different, MGMR weaker near shower axis

Spectra for a vertical 10^{17} eV shower

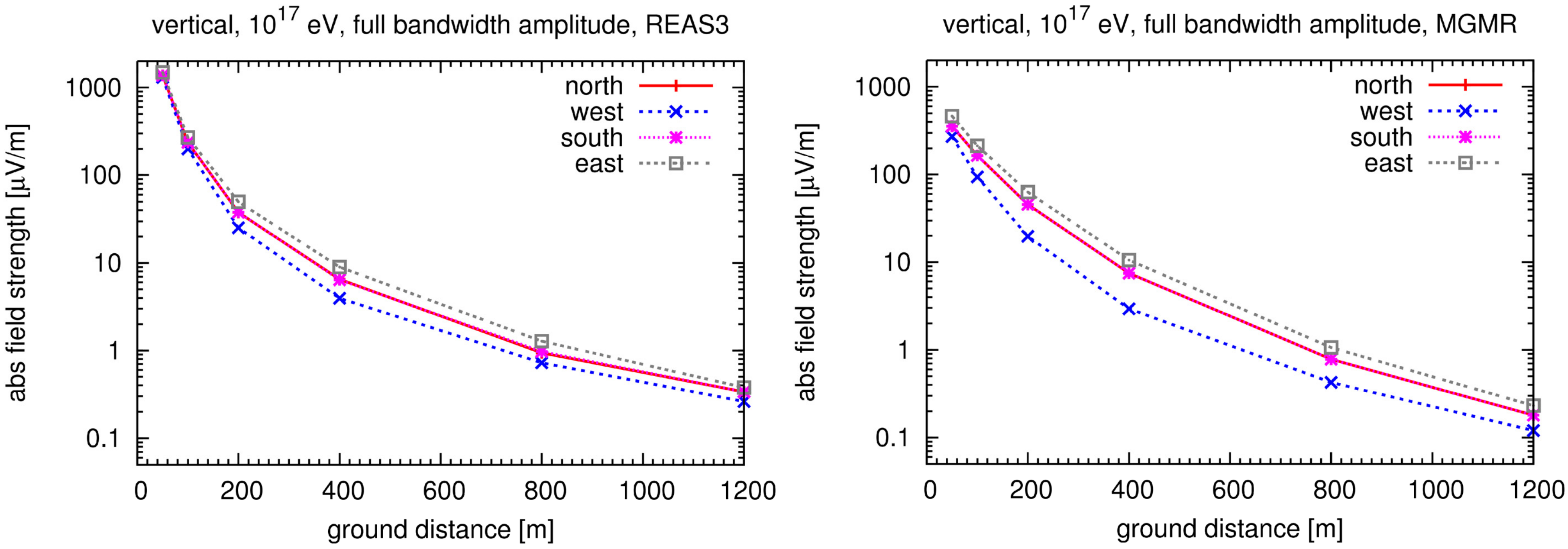


thick:
REAS3

thin:
MGMR

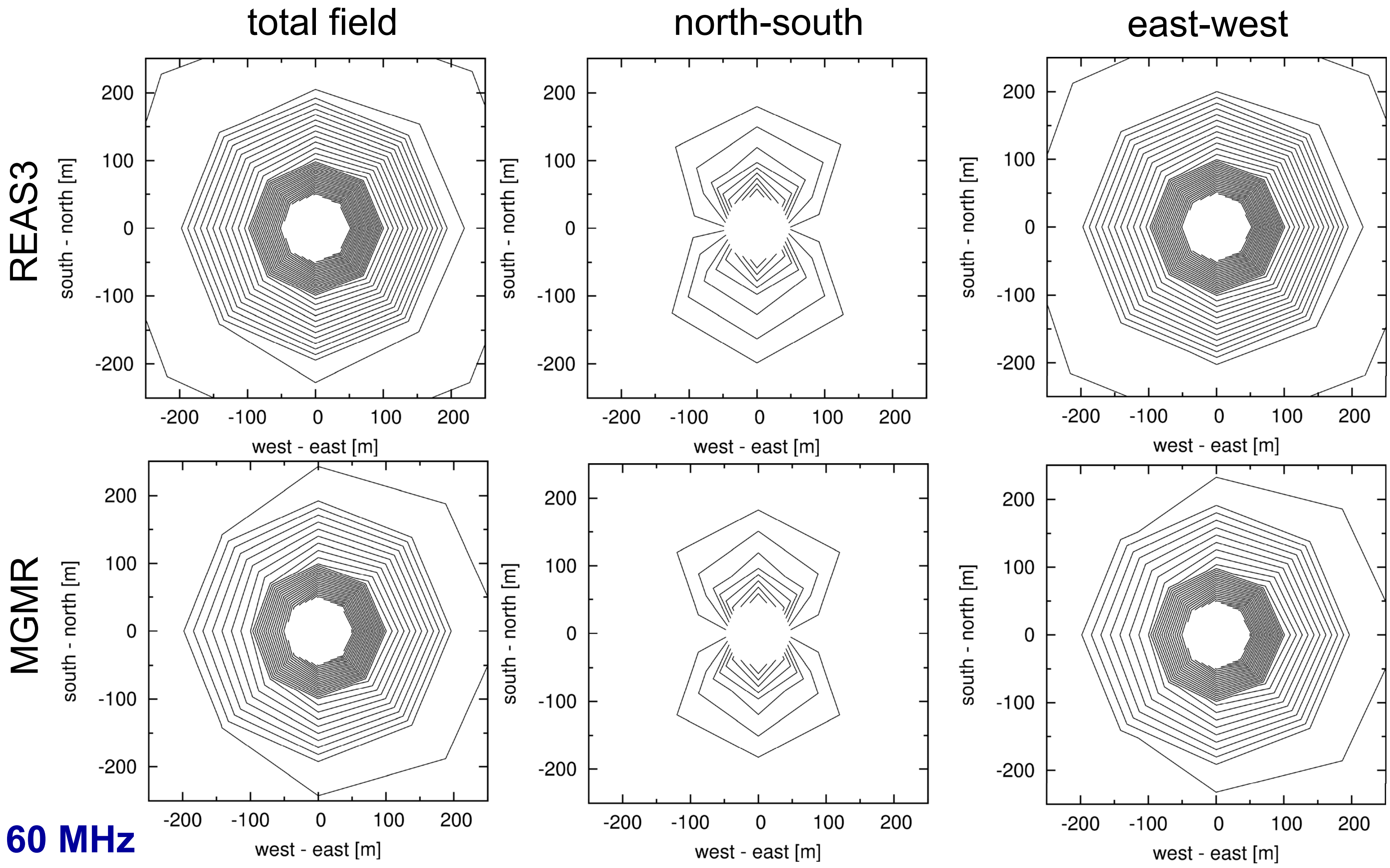
- spectra look similar, differences near the shower axis

Lateral dependence of a vertical 10^{17} ev shower



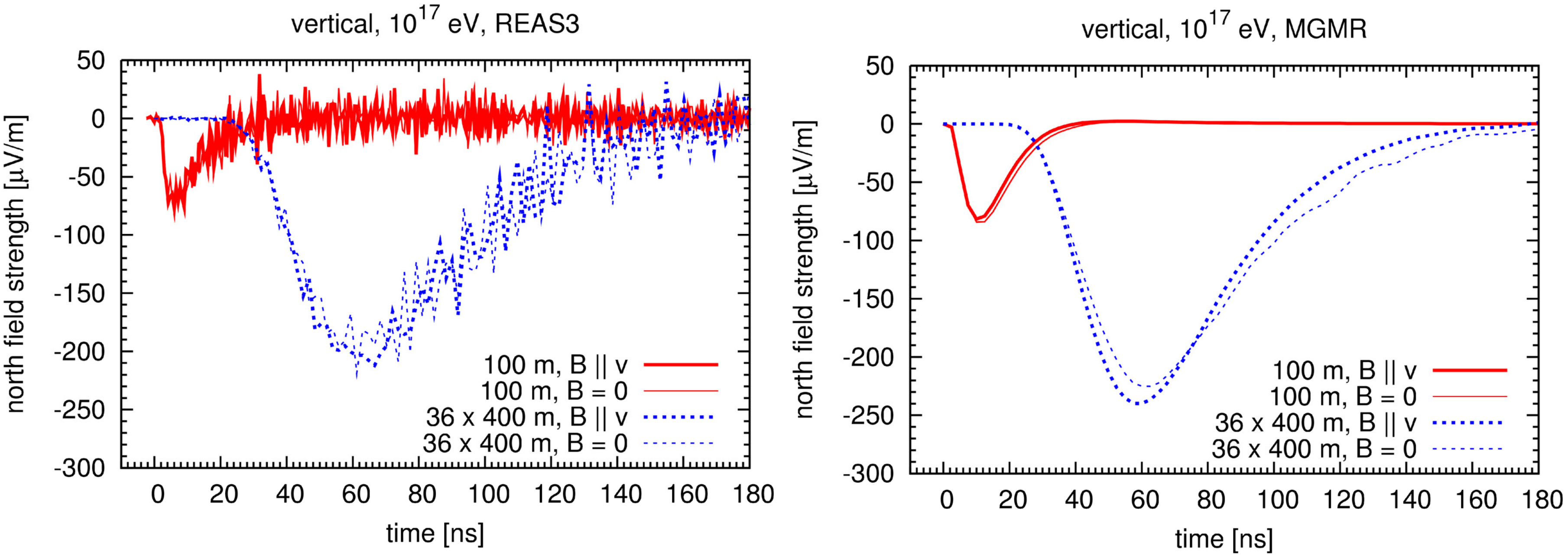
- full bandwidth amplitudes: not an exponential LDF
- east-west asymmetry in both models
  - slightly stronger in MGMR model
- REAS3 predicts higher field strengths close to the shower axis

Polarisation for a vertical 10^{17} eV shower



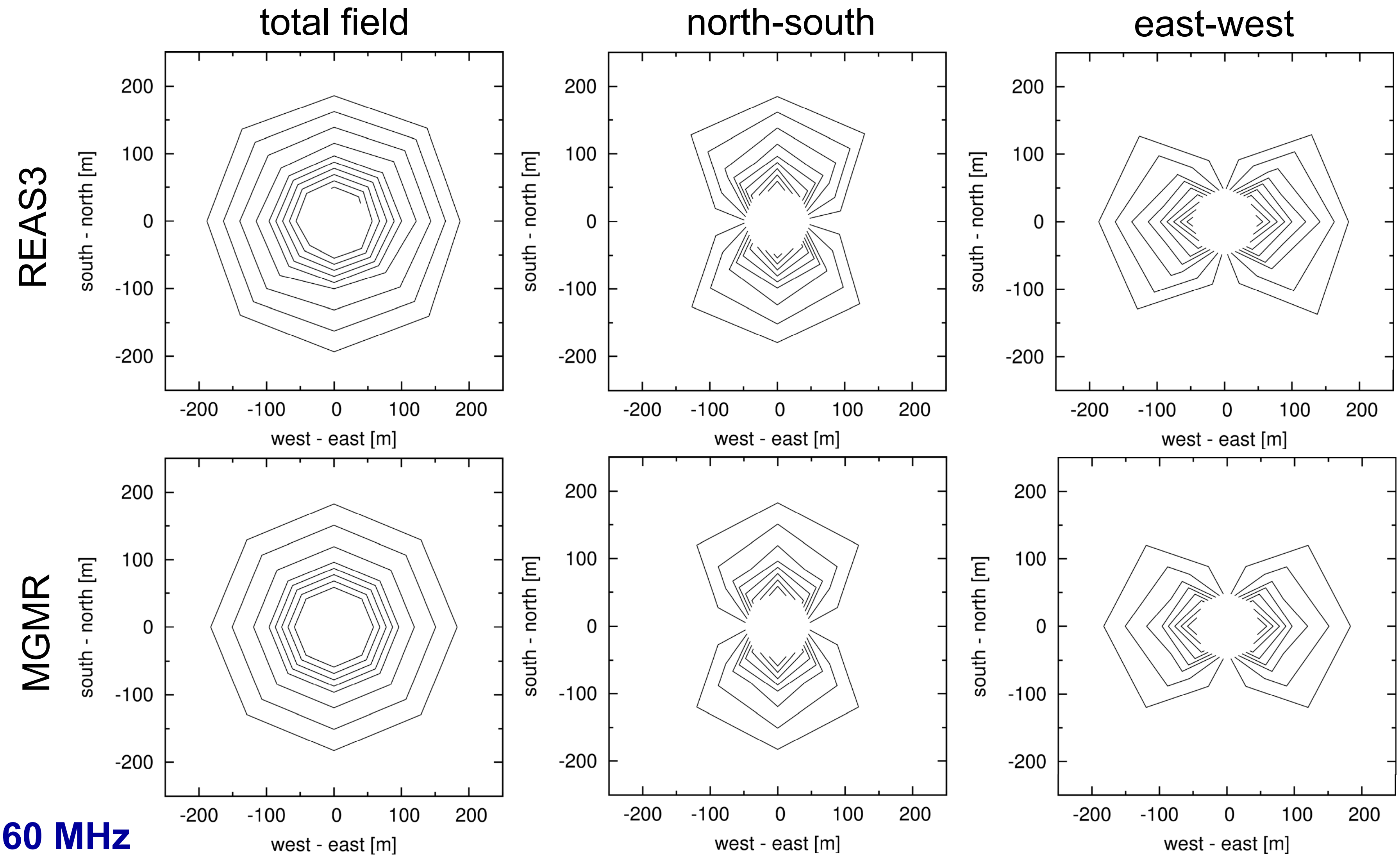
60 MHz

Test cases: B = 0 and B along shower axis



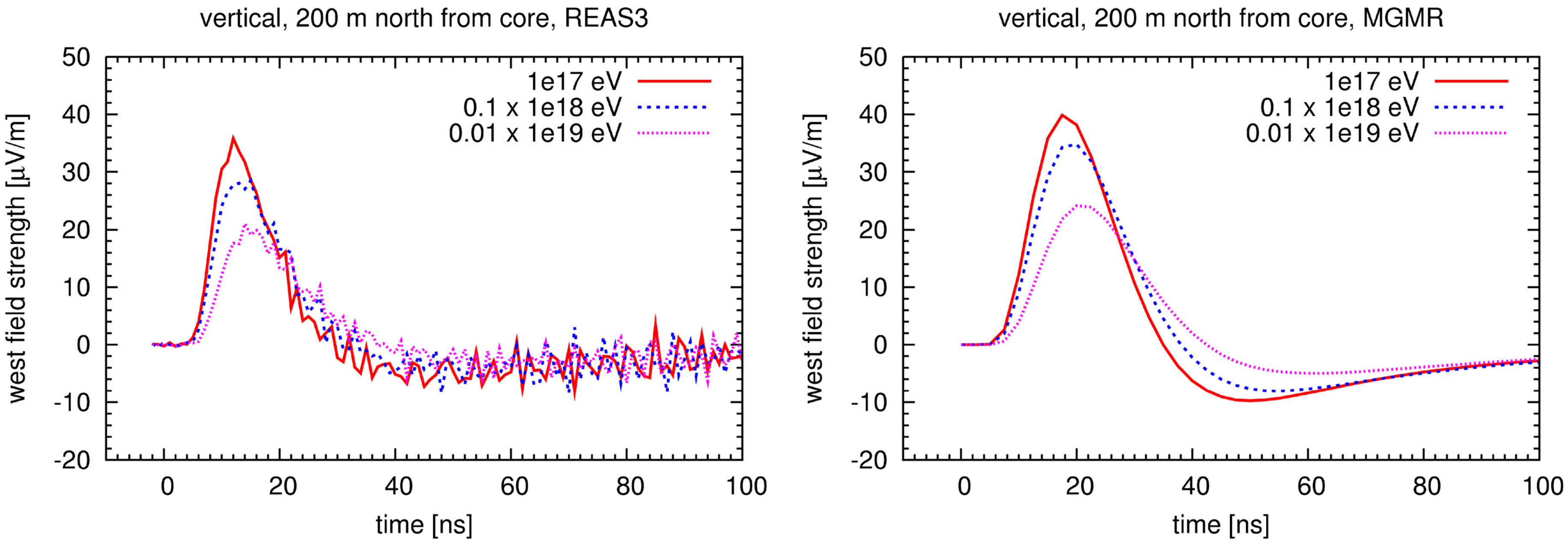
- in both models, pure charge excess (no B-field) produces radiation
  - extremely similar results, a very good cross-check
- vertical B-field almost same result as no B-field
  - in both models vertical B-field gives slightly smaller pulses
- as a consequence: emission is not purely geomagnetic, not ***v*** x ***B***
  - see talk Harm Schoorlemmer

Radial polarisation in case of no B-field



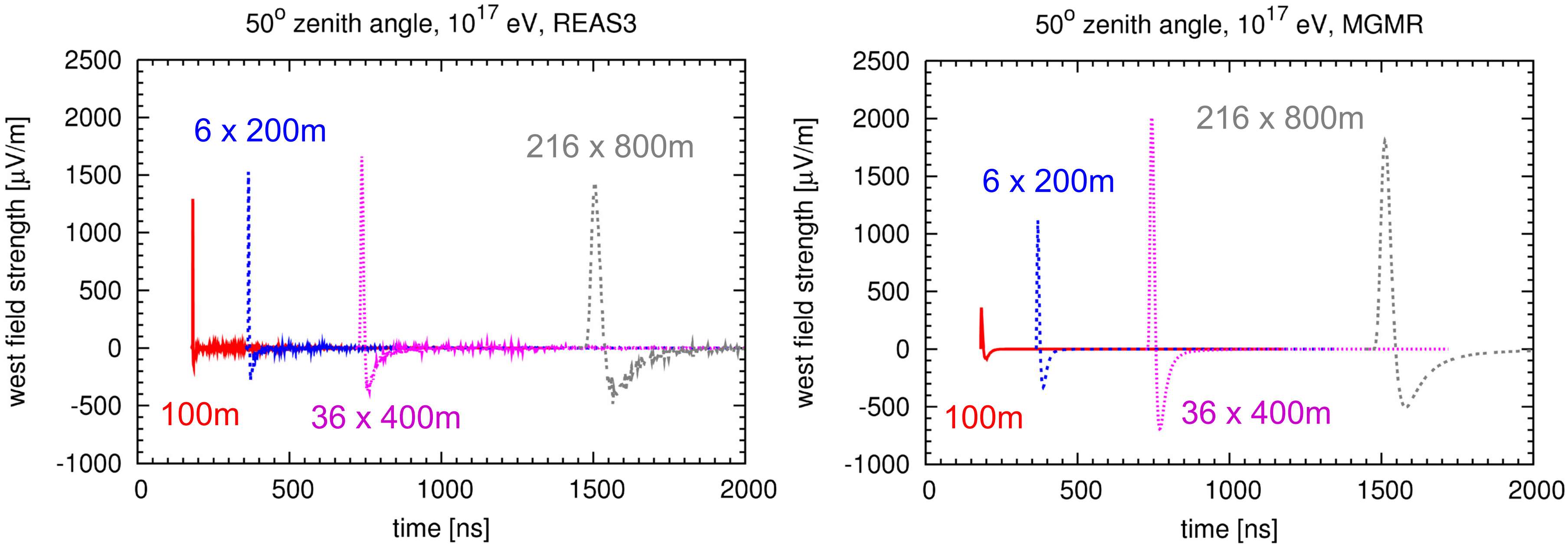
60 MHz

Energy scaling from 10^{17} to 10^{19} eV



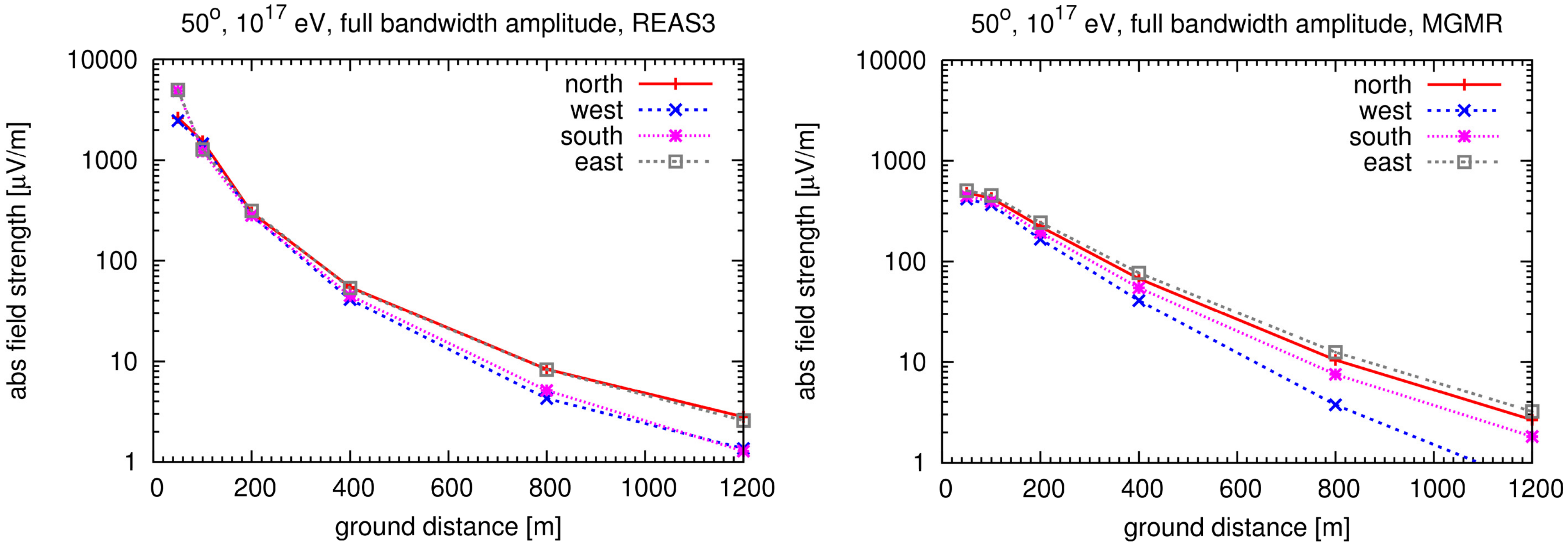
- both models scale very similarly with energy
  - not a simple factor of 10 increase per decade, due to air shower physics
  - pulse width changes, too! probably geometric effect due to Xmax increase

Pulses for a 50° inclined 10^{17} eV shower



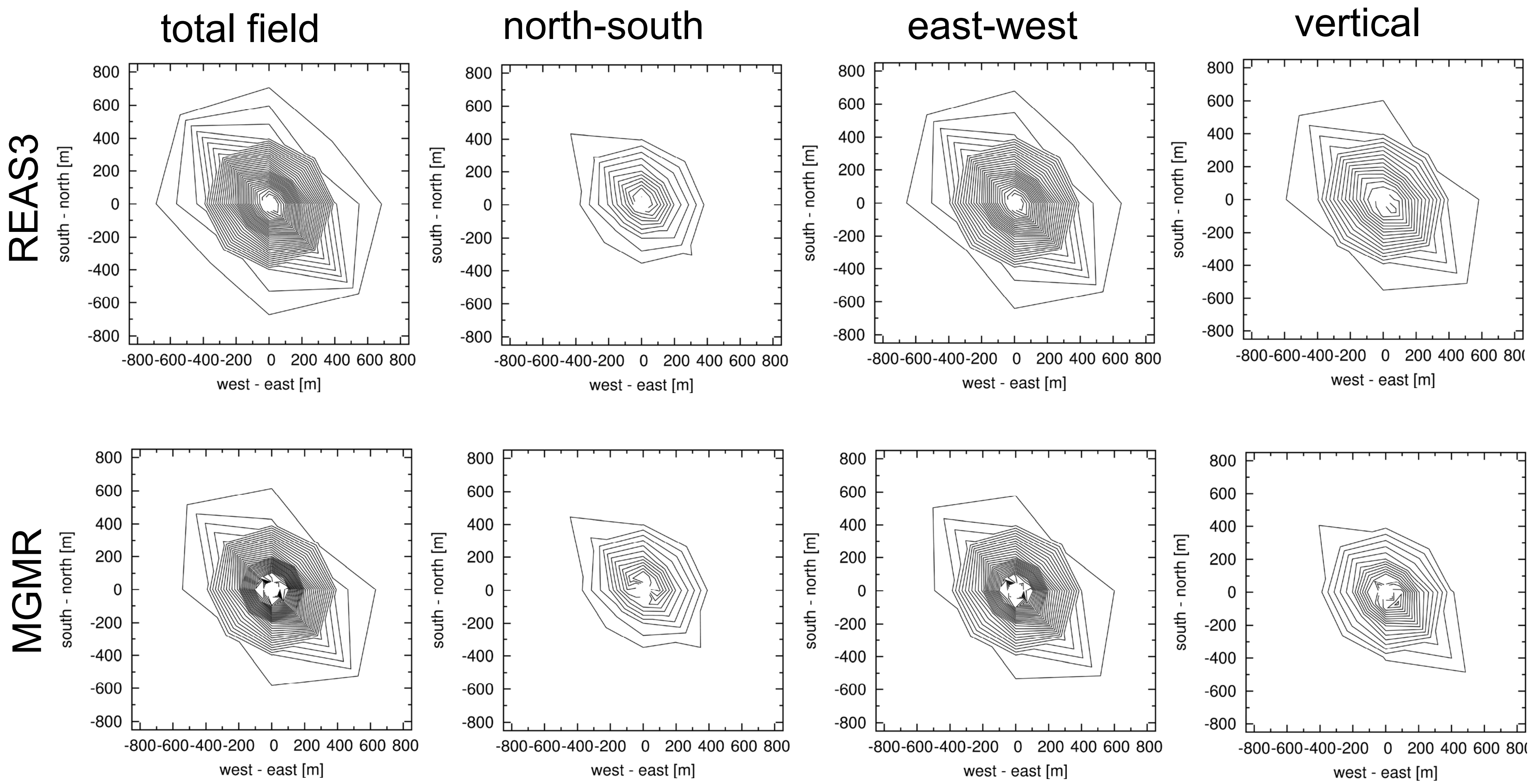
- REAS3 predict stronger pulses near the shower axis
- for inclined showers, given axis distances correspond to larger ground distances, so the region where differences appear grows

Lateral dependence for 50° inclined, 10^{17} eV



- significantly stronger pulses in REAS3 at ground distances <200 m
- west-south asymmetry in MGMR simulation

Contour plots for 50° inclined, 10^{17} eV



60 MHz

Conclusions

- so far, most (time-domain) models miss radiation from charge variation
- REAS3 includes this emission via a universl „endpoint“ treatment
- for the first time, two very different models, MGMR and REAS3, give similar results
    - huge success and progress regarding radio emission physics!
- some relevant differences remain
    - MGMR predicts smaller pulses than REAS3 close to the shower axis
    - for inclined showers the differences can be large (up to ~200 m obs. dist.)
- differences can probably be explained by different air shower models
    - REAS3 uses (almost) complete information from CORSIKA
    - MGMR model is somewhat simplified (no lateral distribution, …)
    - this should mostly affect the signal predictions close to the shower axis (which is indeed where the differences are strongest)