Radio emission modelizations

Interpretations

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Introduction

- Context:
  - Various experiments, in the 60's / 70's and more recent
  - Various theoretical works
- But no clear picture. Geomagnetic effect present, but a simple description?
  ➔ Try to give a simple view of radio emission:
  - main characteristics
  - dependencies over various parameters
  - make some predictions
- I will present 2 different approaches based on synchrotron radiation (not very original…)
  - analytical model, extremely simplified shower to understand what happens
  - ReAIRES (full Monte Carlo) to check what is conserved and what changes with a realistic shower
- Try to extract useful, simple, understandable results. Goal: Interpret experimental measurements. Suggest new ways to look at data.

One formula, two complementary approaches

Field created by accelerated relativistic charge:

$$\mathbf{E} = \underbrace{\frac{q}{4\pi\varepsilon_0}\left[\frac{\mathbf{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R^2}\right]_{ret}}_{\text{Coulomb}} + \underbrace{\frac{q}{4\pi\varepsilon_0 c}\left[\frac{\mathbf{n}\times\{(\mathbf{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\}}{(1-\boldsymbol{\beta}\cdot\mathbf{n})^3 R}\right]_{ret}}_{\text{Radiative}}$$

q	particle charge
$\boldsymbol{\beta} = \mathbf{v}/c$	speed
$\mathbf{n} = n.\mathbf{u}$	direction of observer
R	distance to observer
$[\ ]_{ret}$	$t_r = t_e + R(t_e)/c$ retarded time

Plus $n = 1$ (no Cherenkov) and $\dot{\vec{\beta}} = \frac{e}{\gamma m}\vec{\beta}\times\vec{B}$ (synchrotron acceleration)

- **Simplified analytical model**
  - point like shower (implicit coherence)
  - gaussian longitudinal profile
  - Coulomb and radiative terms computed
  - Field decomposed in elementary functions
- Suitable tool for understanding
- [Chauvin *et al.*, Astropart. Phys. 33 (2010)]

- **Full Monte Carlo ReAIRES**
  - realistic shower
  - Coulomb and radiative terms computed
- Expected more realistic
- Black box, parametrizations may help to interpret
- [Rivière *et al.*, ICRC09]

⇖ Interactions ⇗

⇩

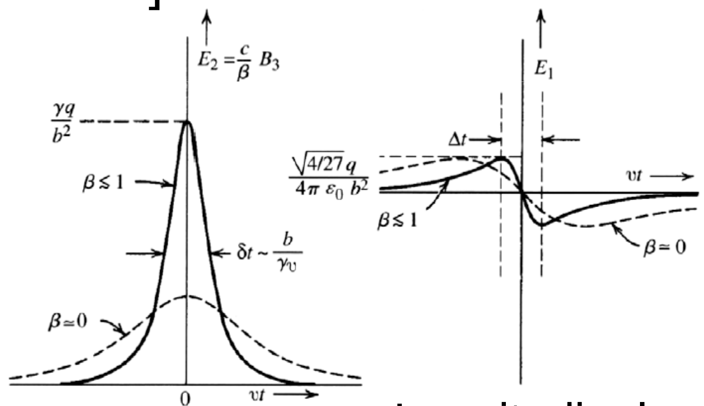
Experiments

Simplified analytical model -- Principle

- Express electric field in adapted frame, for a single charge. Find elementary longitudinal and transverse functions:
  - classic derivation of the coulomb term [Jackson]

$$\vec{E}_C = \frac{1}{4\pi\epsilon_0}\left[\frac{q\left(\vec{n}-\vec{\beta}\right)}{\gamma^2 R^2\left(1-\vec{\beta}\vec{n}\right)^3}\right]_{ret} = \frac{1}{4\pi\epsilon_0}\frac{q}{\left[(\gamma\beta c t_r)^2+b^2\right]^{\frac{3}{2}}}\begin{bmatrix}-\gamma\beta c t_r\\ \gamma b\\ 0\end{bmatrix}$$

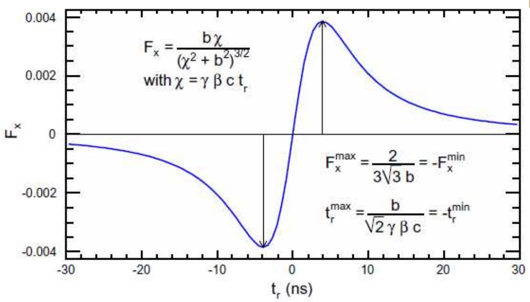
b : impact parameter



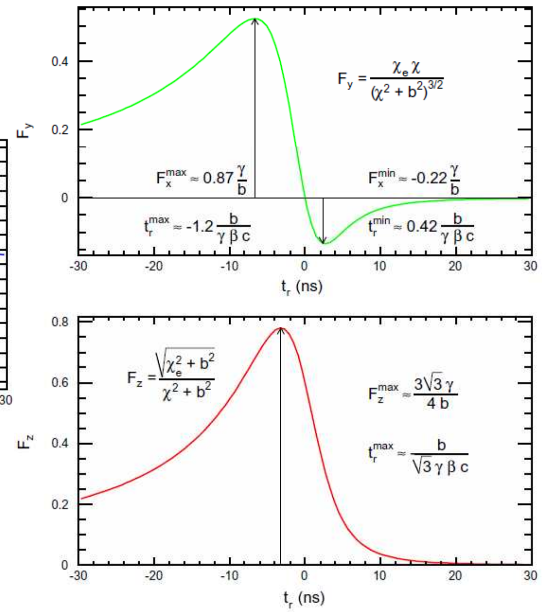
Transverse Longitudinal

- similar derivation of the synchrotron term

$$\vec{E}_R = \frac{q\omega\gamma^2\beta}{4\pi\epsilon_0 c}\begin{bmatrix}u_{Bz}F_x(t_r)\\ u_{Bz}F_y(t_r)\\ -u_{By}F_z(t_r)\end{bmatrix},\qquad F_x = \frac{b\chi}{\left(\chi^2+b^2\right)^{3/2}},\quad F_y = \frac{x_e\chi}{\left(\chi^2+b^2\right)^{3/2}},\quad F_z = \frac{\sqrt{x_e^2+b^2}}{\left(\chi^2+b^2\right)},\qquad \chi = \gamma\beta c t_r.$$



Longitudinal

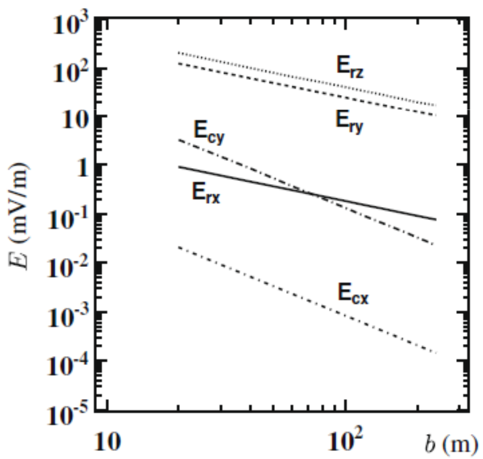


Transverse

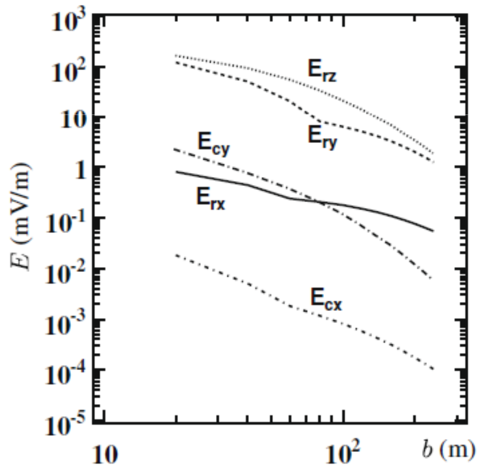
Simplified analytical model -- Results I

Shower = convolution of these functions with longitudinal profile

- Lateral distribution of the fields (vertical shower, NW direction)



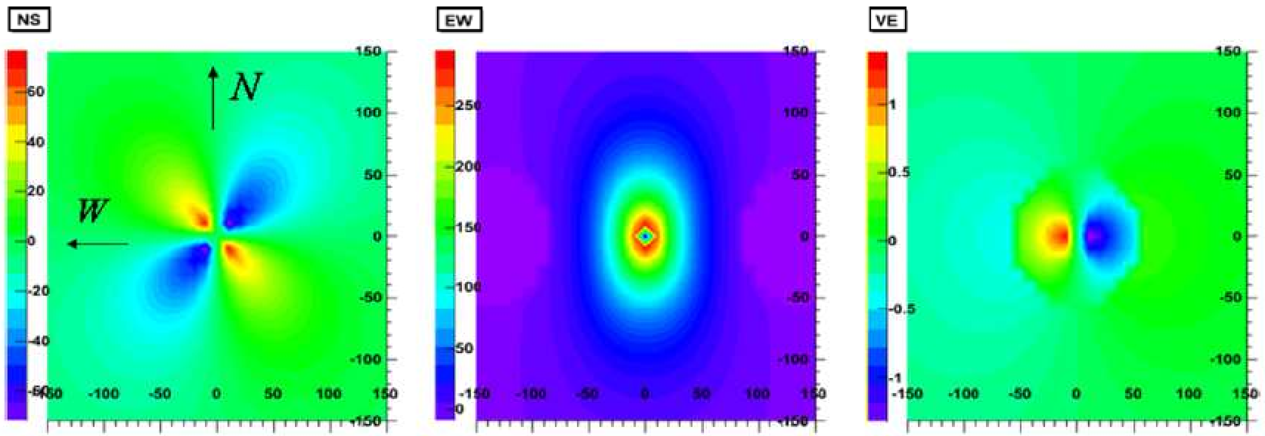
Constant longitudinal profile



Gaussian longitudinal profile

- Coulomb term negligible
- Weakness of longitudinal field
- Transverse components of the synchrotron term dominant

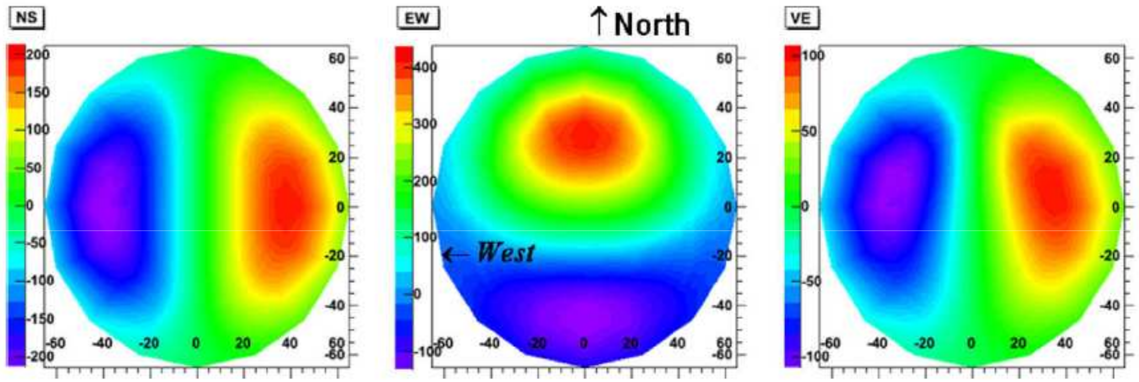
- Footprint (vertical shower)



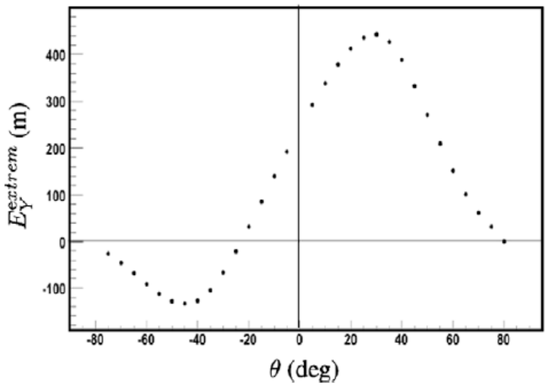
- Some patterns, but dominant component (EW) almost symmetric
- For ordinary direction, transverse field distributed over all 3 components, less pattern

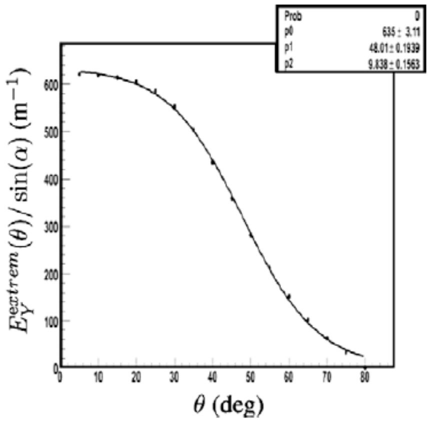
Simplified analytical model -- Results II

Let us consider one single observation point, 20 m North of the shower



- On particular for showers coming from the NS plane:





$$E_{EW} = \kappa \sin(\alpha_B \pm \theta) F_z(t_r, b_\theta) N(t_r, \theta)$$

$$(\text{here } E_{NS} = E_{Vt} = 0)$$

- One can show that if:
  - longitudinal term F_x negligible
  - two transverse terms F_y, F_z similar (true for fast signals, ie. close to shower axis)

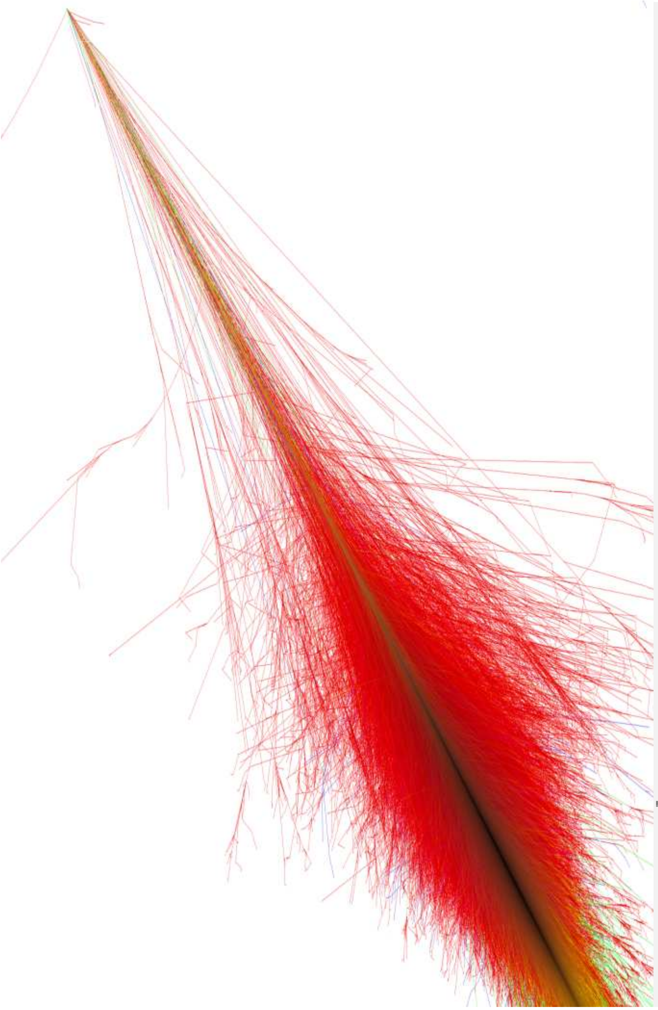
then $\mathbf{E} \propto -\mathbf{v} \times \mathbf{B}$

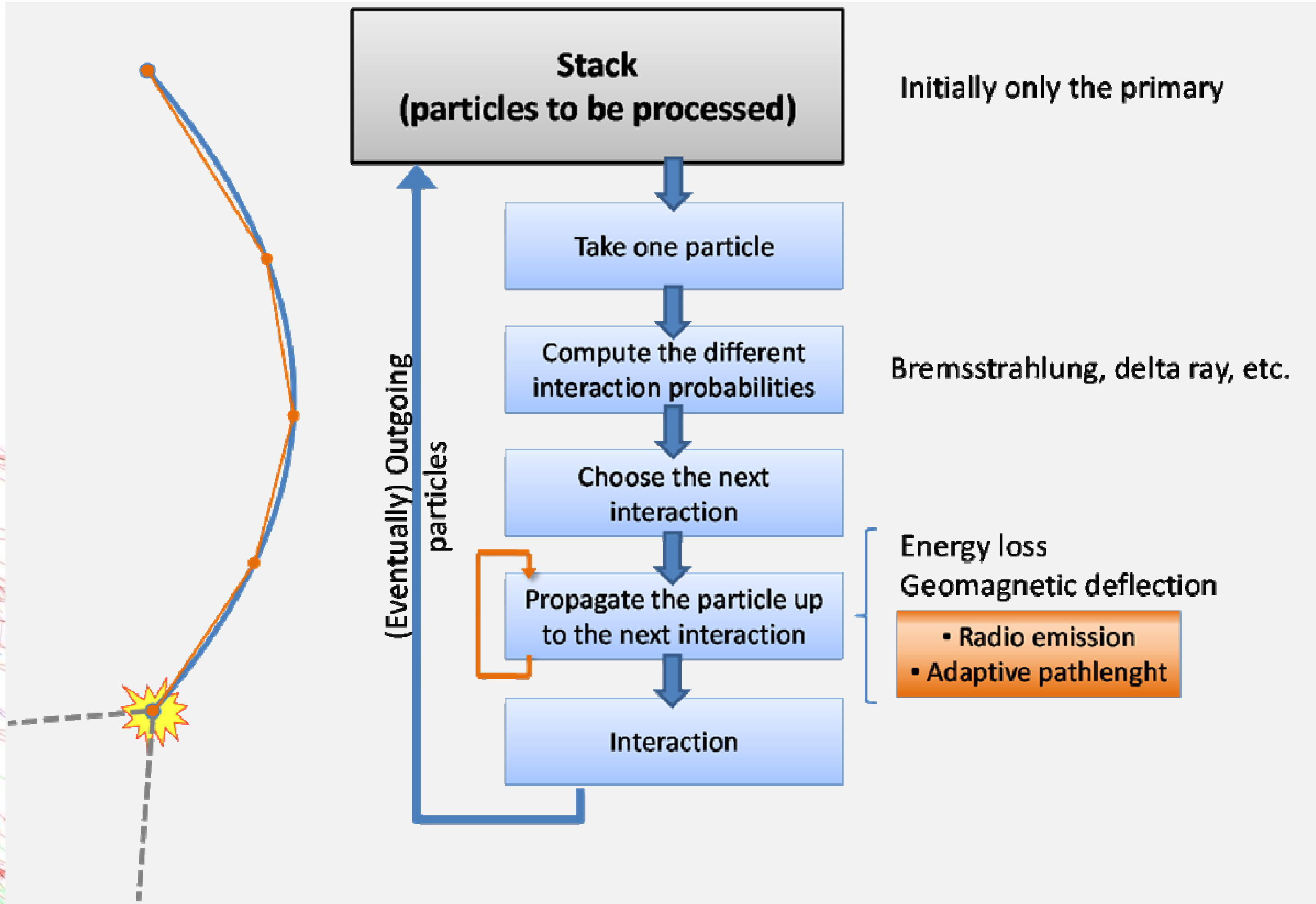
Simplified analytical model -- Summary

- Decomposition of Coulomb term **and** synchrotron term in elementary functions
- used for basic shower simulation.
- Some characteristics stressed, other and details in [Chauvin *et al.*, Astropart. Phys. 33 (2010)]

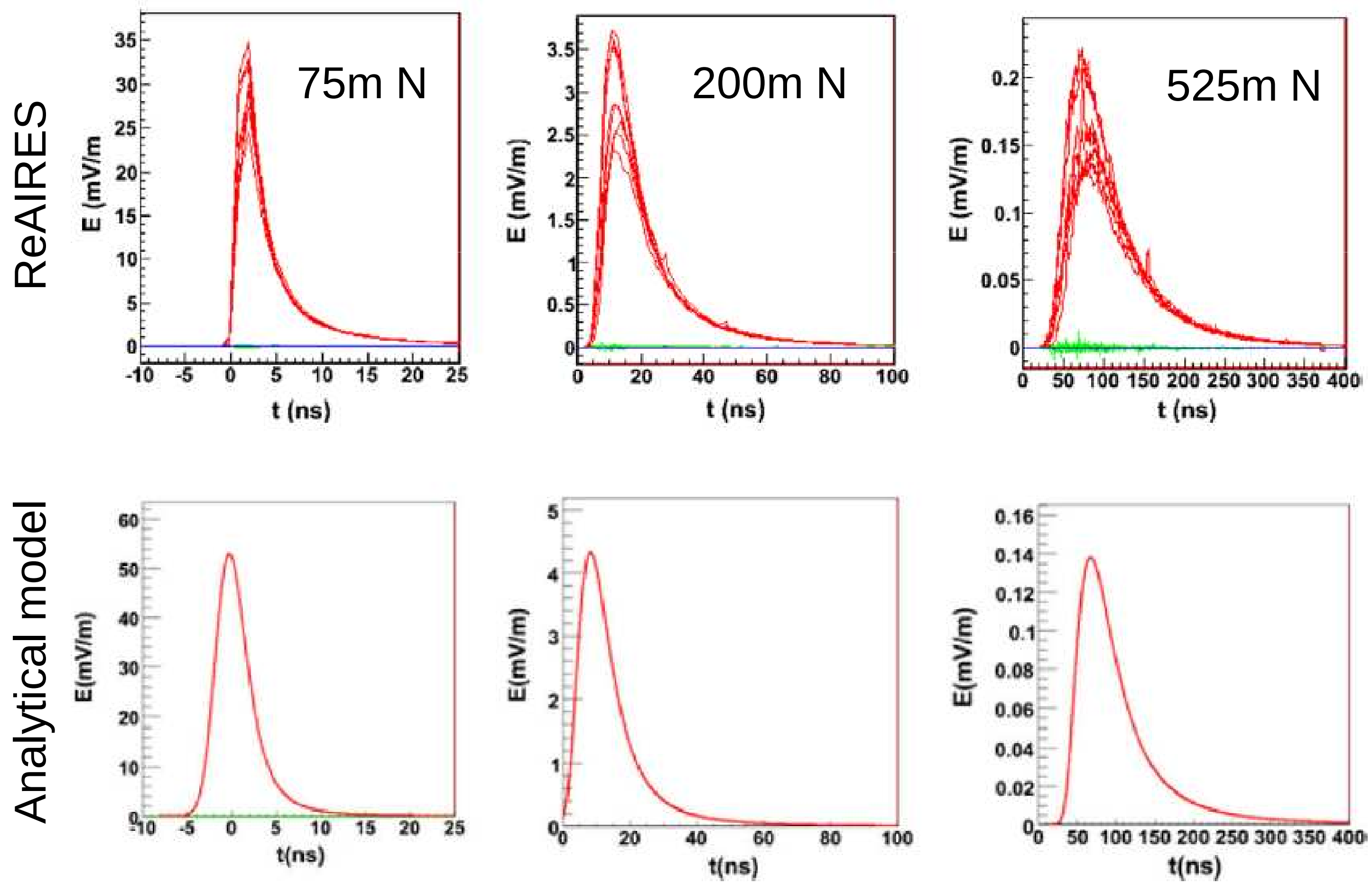
ReAIRES -- Principle

- Based on AIRES [Sciutto, http://www.fisica.unlp.edu.ar/auger/aires/]
- + radio emission computed for each elementary step, for each observation point [DuVernois *et al.*, ICRC05]





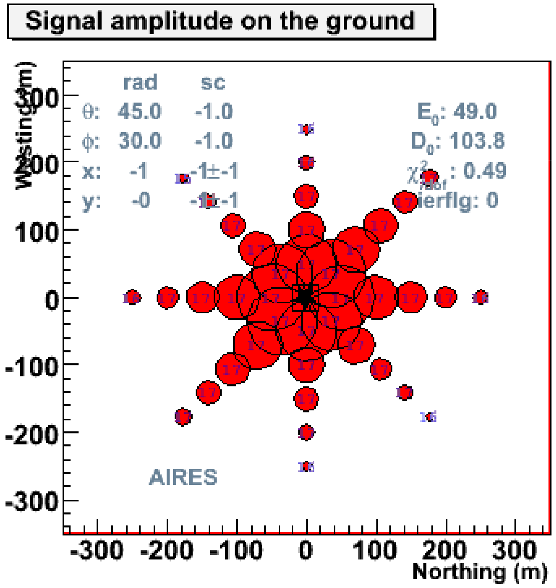
ReAIRES vs. analytical model crosscheck



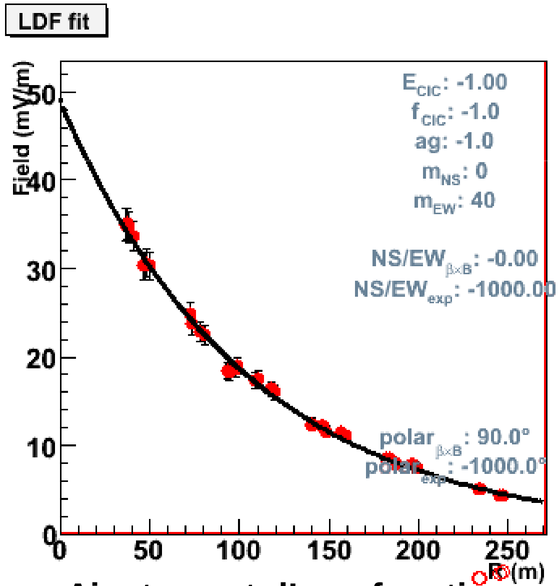
Extremely close results in this case (vertical shower, antenna to the North)

ReAIRES – Extracting parameters

- Simulation on arrays of 40 antennas.



Empreinte au sol



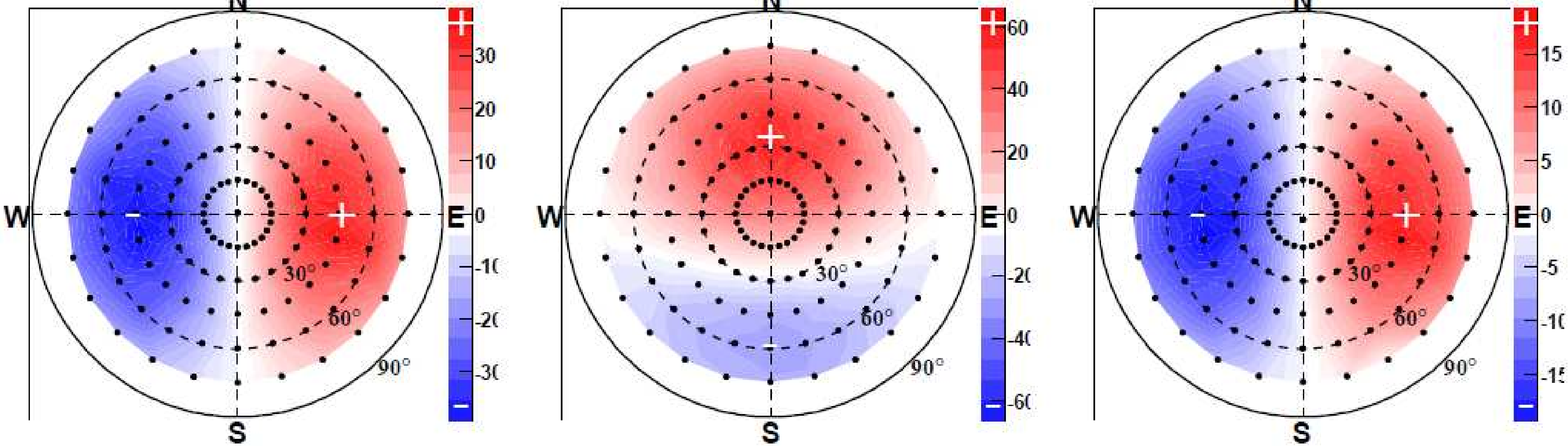
Ajustement d'une fonction de distribution latérale dans le plan de gerbe

- Topology *generally* exponential
- Extract E_0^{NS}, E_0^{EO}, E_0^{Vt}, D_0 ($=D_0^{NS}=D_0^{EO}=D_0^{Vt}$)

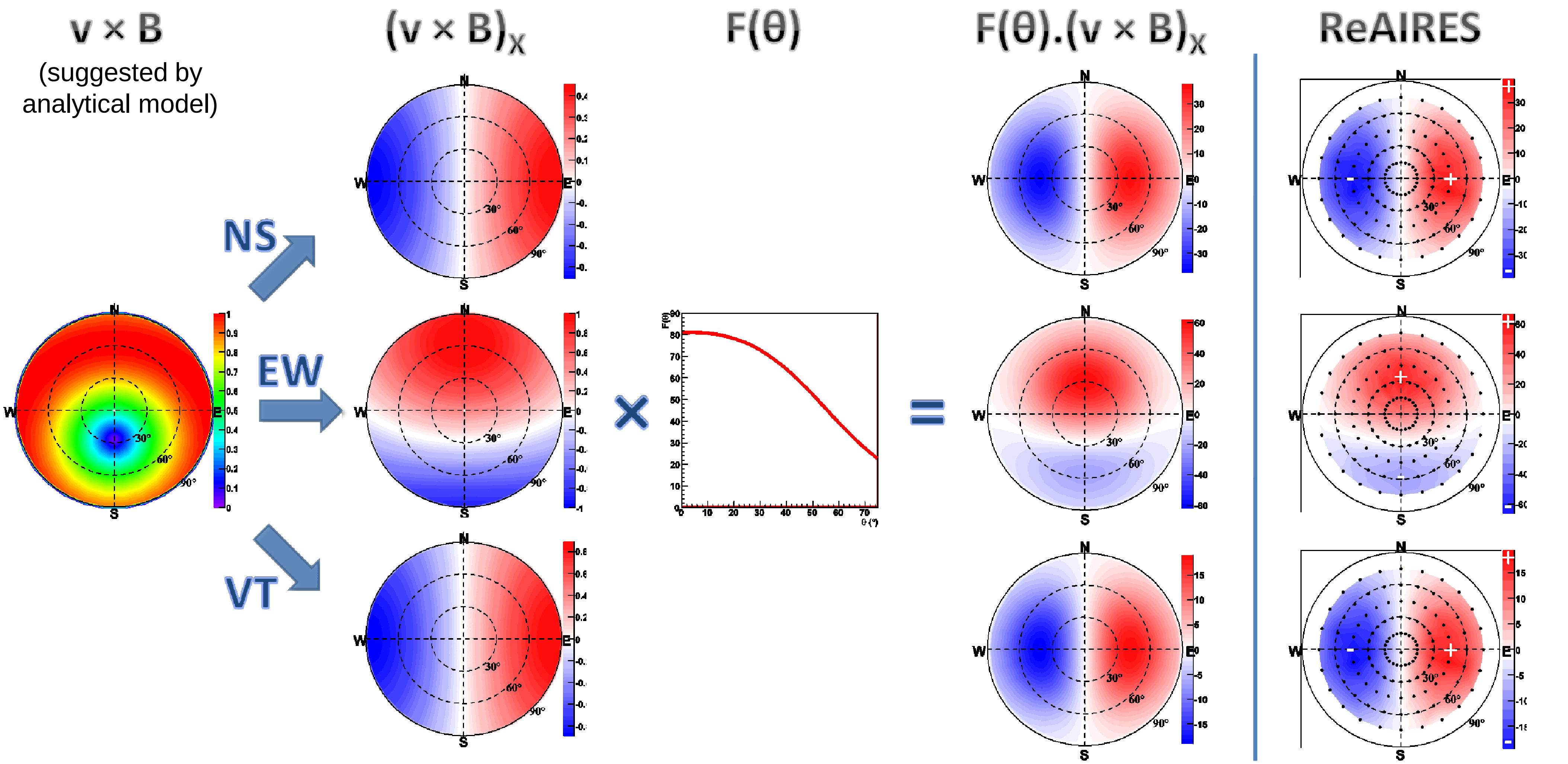
ReAIRES – Arrival direction

- Field on axis (E_0^{NS}, E_0^{EW}, E_0^{Vt}) reconstructed for 121 incoming shower directions. Primaries: 10^{17} eV protons.

E_0^{NS} (θ,φ) **E_0^{EW} (θ,φ)** **E_0^{Vt} (θ,φ)**

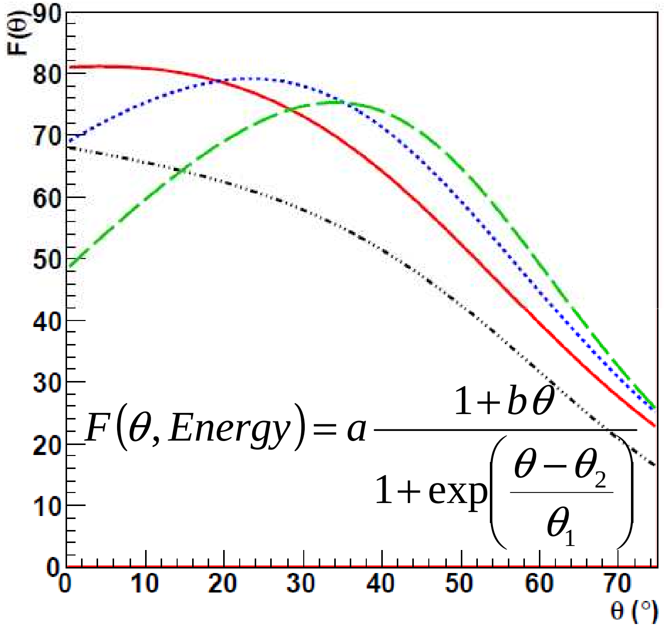


ReAIRES -- Parametrization



- ➔ Essentially vector cross product – $\mathbf{v}\times\mathbf{B}$ times a function of the zenith angle.
- ➔ Very simple first order representation

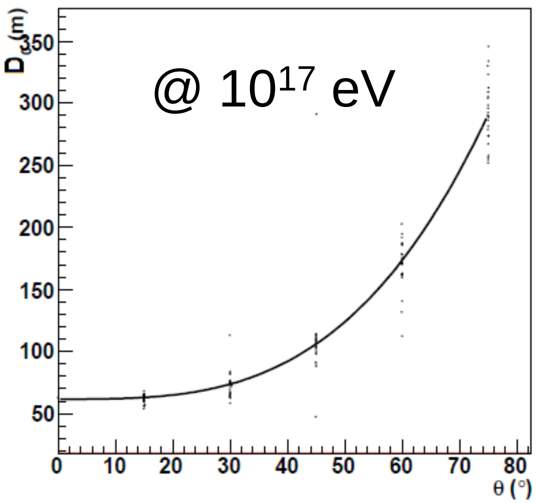
ReAIRES – Zenith function(s)



----- 10^{15} eV * 100
----- 10^{17} eV
----- 10^{19} eV * 0.01
----- 10^{21} eV * 0.0001

- F ~α Energy
- F ↘ when Θ ↗: solid angle effect
- high energy showers not developed enough at low zenith

While $-\mathbf{v}\times\mathbf{B}$ represents the emission mechanism, F contains all the information about the shower (size, development, distance, etc.)



- D0 ↗ when Θ ↗: same solid angle effect
- Similar variations expected with energy

ReAIRES – A bit further

- Overall parameterization

$$\mathbf{E}_{\nu} = 1.3 \frac{B}{47\ \mu\mathrm{T}} \frac{Energy}{10^{17}\ \mathrm{eV}} f_{17}(\theta)(-\mathbf{v}\times\mathbf{B})\, e^{-\frac{d}{D_0(\theta)}} \quad [\mathrm{mV/m/MHz}]$$

$$f_{17}(\theta) = 1.05\left(1+3.72\times10^{-3}\theta\right) / \left(1+e^{\frac{\theta-51.2}{17.5}}\right)$$

$$D_0(\theta) = 61.7\left(1+3.34\times10^{-6}\theta^{3.22}\right) \quad [\mathrm{m}]$$

- Known problem with amplitude (e.g. vs. REAS, data)
- but still guideline to interpretations: can still use some of the dependencies
- and still fields to explore (amplitude, variations with X_{Max}, curve radius, primary identification, etc.)

- Other info on [Rivière *et al.*, ICRC09]

Personal views on modelization

- Need to understand radio emission
  - Simple analytical models ➔ ideas
  - Full MC ➔ Realistic cases, but black boxes
- Need to **extract** knowledge, simple dependencies; then understand **consequences** of this model, predict results. **Check** it experimentally, look for discrepancies. Eventually **refine** the model, go to the next order description
- This work supports a $-\mathbf{v}\times\mathbf{B}$ dependency. Well, nothing really new here (already in Allan's review), but still guided Codalema's analysis [Ardouin *et al.*, Astropart. Phys. 31 (2009)]. Now various analysis uses this simple dependency, as it explains by itself most observations.
- However, it is just a first order description (even of ReAIRES), maybe crude approximation. Many room for refinement, lets use data to discriminate models (use footprint pattern, polarization measurement, …?)

Neutrino behind mountain?

- Which antenna polarization to choose, and on which side of the mountain to put the detector?
- Electromagnetic background mainly vertically ➔ measure horizontal field
- $-\mathbf{v}\times\mathbf{B}$ Horizontal shower x horizontal B component ➔ vertical radio electric field: horizontal B useless
- ➔ Need to maximize vertical B! Argentina is bad, Hawaii too, Alps, US and Tibet are good
- Then the direction of observation does not matter, one just need to put antenna direction perpendicular to the observation direction.