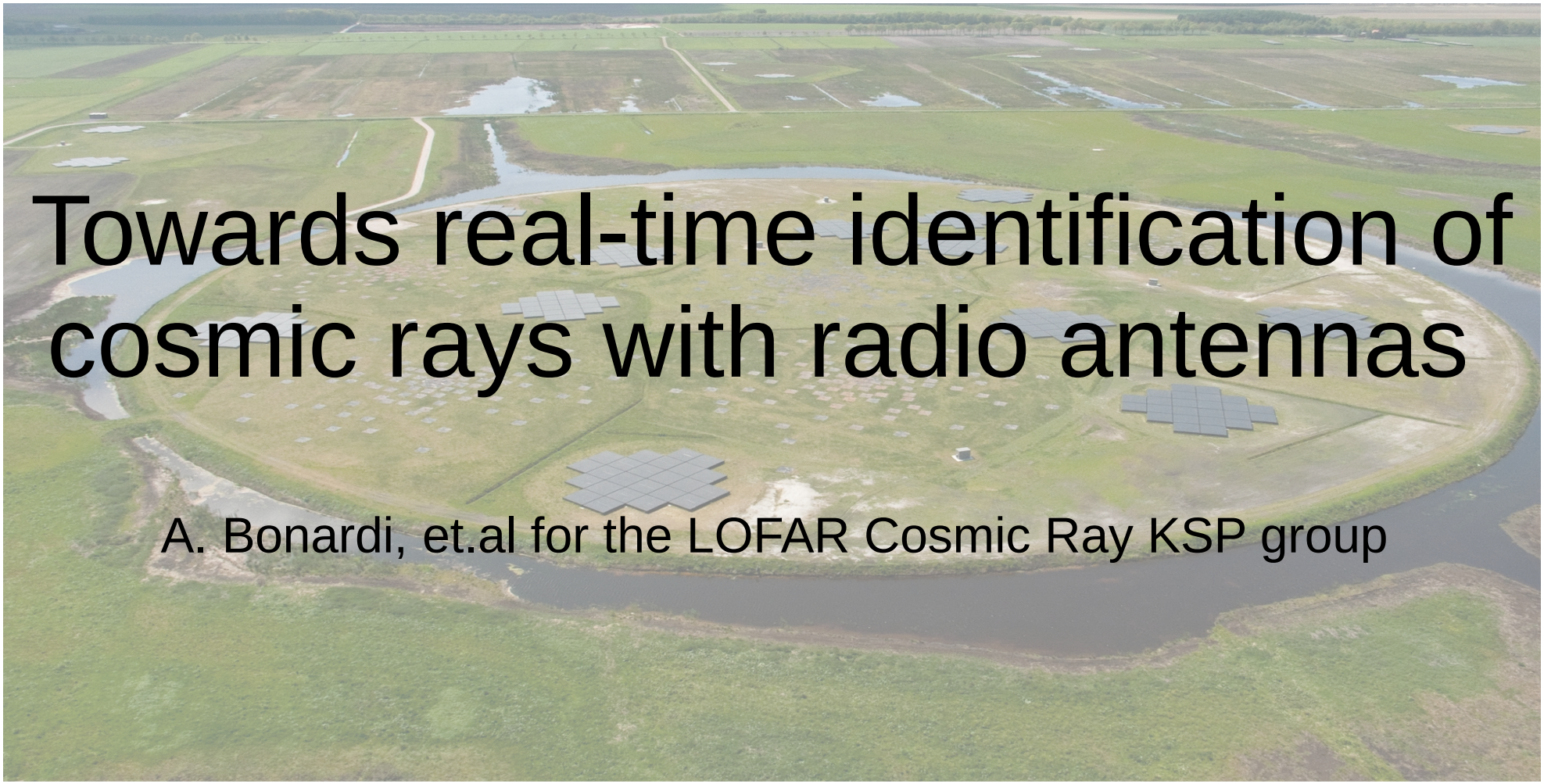
Radboud University

LOFAR



Towards real-time identification of cosmic rays with radio antennas

A. Bonardi, et.al for the LOFAR Cosmic Ray KSP group

The LOw Frequency ARray

50 stations in Northern Europe

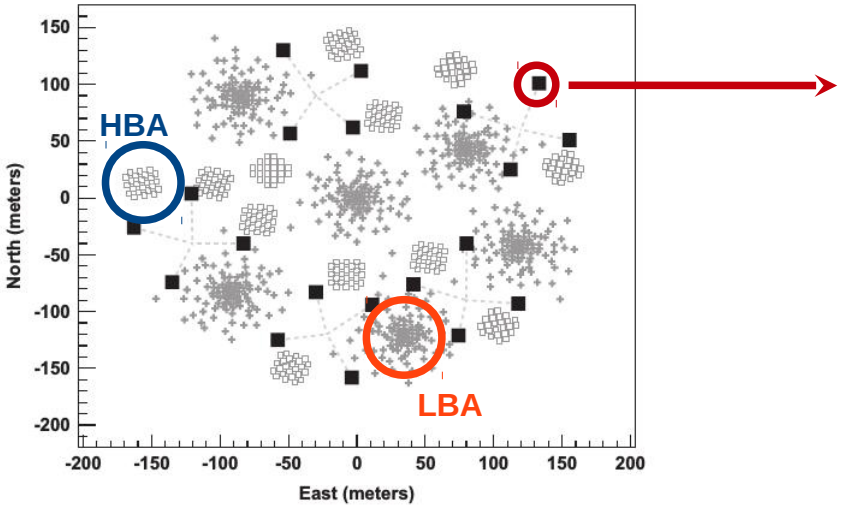
6 stations in the SuperTerp, the densest region

For each station 96 LBA (10-90 MHz) and 96(48) HBA (110-240 MHz)

Observations are driven by astronomical targets (ToOs)

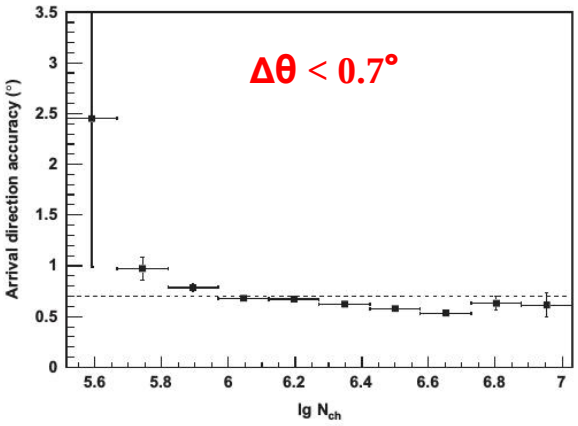
When a CR trigger occurs, the time buffer of all the 24 closest stations is downloaded for the off-line analysis

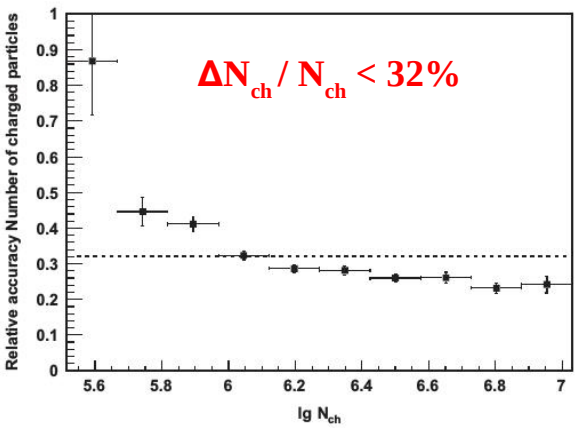
The LOfar Radboud Air Shower Array

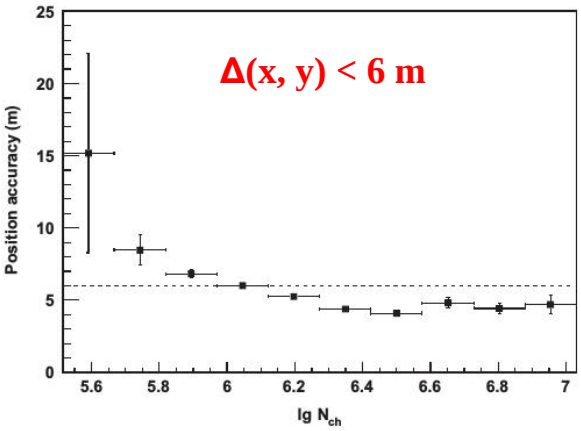


20 scintillator detectors (~ 1 m^2 each) located in the SuperTerp:

- main trigger for LOFAR CR detection
- arrival direction measurement
- energy measurement between 10^{16} – 10^{19} eV







S. Thoudam et al., Nucl. Inst. Meth. A 767, 339, 2014

Requirements for LOFAR self-triggering

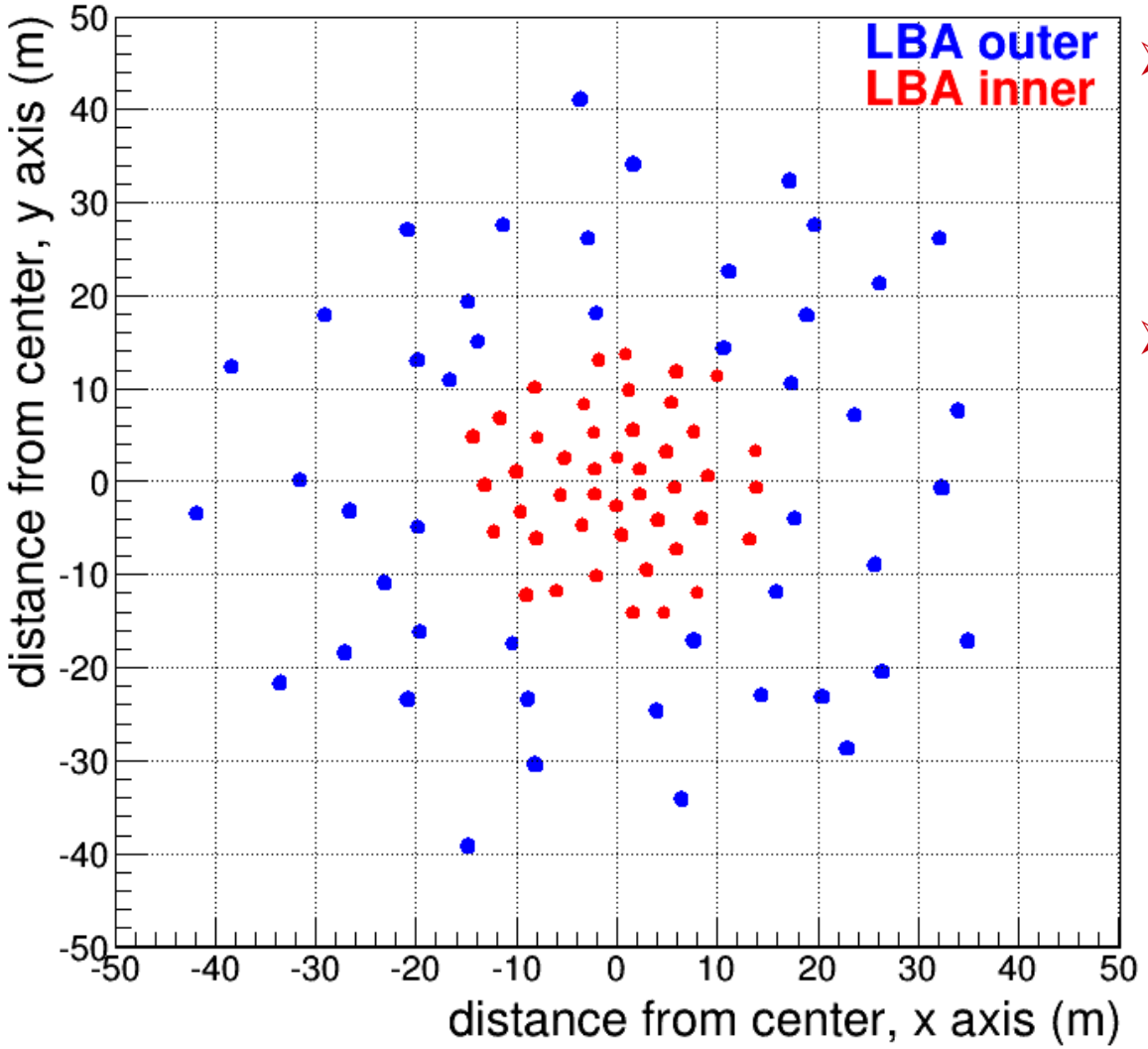
Facts

- CR signal is very short (10-100 ns) and very rare
  by assuming an average event rate of ~1 event per hour at E > 10^{16} eV, the time window ratio is about 10^^{11}
- RFI can easily mimic CR radio signals
  strong 43 MHz FM band, electric sparks from close-by electric fences
- LOFAR capability of downloading the time buffers is limited by the data transmission bandwidth

Therefore

1) RFI suppression to less than 1 fake trigger per hour is crucial
2) High CR selection efficiency is advisable, but not crucial
3) Trigger algorithm has to be as simple as possible

LBA inner & LBA outer



- Accordingly to the astronomical ToO, only LBA outer or only LBA inner antennas are ON
- When a CR trigger occurs, the time buffer of all the closest stations is frozen, downloaded, and off-line analyzed

Trigger algorithm must be studied for both cases independently

LBA outer self-trigger algorithm

Trigger criterion:

1) for each antenna the two polarizations are evaluated independently

2) Majority of 23 antennas along one polarization over a given threshold, on coincidence time window of 30 ns on each dipole

RFI rejection:

1) signal time length must be shorter than 300 ns

2) the ratio of I(30 MHz < F < 45 MHz) and I(45 MHz < F < 70 MHz) must be encompassed between 1 and 2

3) if two consecutive pulses are identified within 5 μs, both pulses are rejected

Self-trigger with LOFAR LBA outer

events considered: 4081
Energy: E > 3 · 10^15 eV
Total independent real time: 8.9 s
Total real time: 118.7 s

THR = 3 RMS
total number of stations triggered by CR signal = **1536**

THR = 4 RMS
total number of stations triggered by CR signal = **899**

THR = 5 RMS
total number of stations triggered by CR signal = **598**

THR = 10 RMS
total number of stations triggered by CR signal = **196**

Self-trigger with LOFAR LBA outer

events considered: 4081
Energy: E > 3 · 10^15 eV
Total independent real time: 8.9 s
Total real time: 118.7 s

THR = 3 RMS
total number of stations triggered by CR signal = 1536
fraction of stations triggered by CR signal and vetoed = 387 / 1536 = **25%**

THR = 4 RMS
total number of stations triggered by CR signal = 899
fraction of stations triggered by CR signal and vetoed = 185 / 899 = **21%**

THR = 5 RMS
total number of stations triggered by CR signal = 598
fraction of stations triggered by CR signal and vetoed = 132 / 598 = **22%**

THR = 10 RMS
total number of stations triggered by CR signal = 196
fraction of stations triggered by CR signal and vetoed = 48 / 196 = **24%**

Self-trigger with LOFAR LBA outer

events considered: 4081
Energy: E > 3 · 10^15 eV
Total independent real time: 8.9 s
Total real time: 118.7 s

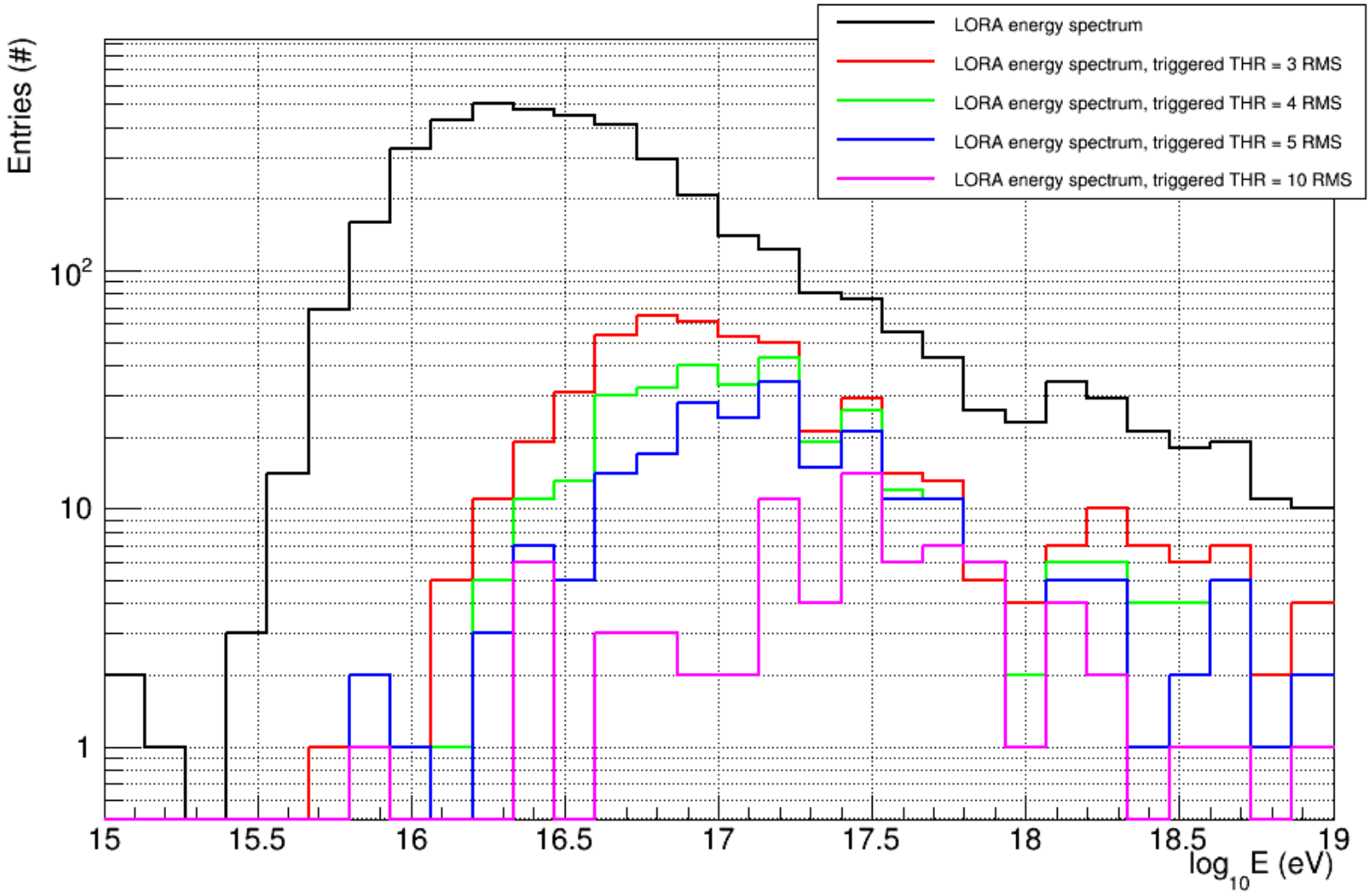
THR = 3 RMS
total number of stations triggered by CR signal = 1536
fraction of stations triggered by CR signal and vetoed = 387 / 1536 = 25%
Events with at least one RFI signal triggered after RFI rejection= **4**

THR = 4 RMS
total number of stations triggered by CR signal = 899
fraction of stations triggered by CR signal and vetoed = 185 / 899 = 21%
Events with at least one RFI signal triggered after RFI rejection= **2**

THR = 5 RMS
total number of stations triggered by CR signal = 598
fraction of stations triggered by CR signal and vetoed = 132 / 598 = 22%
Events with at least one RFI signal triggered after RFI rejection= **2**

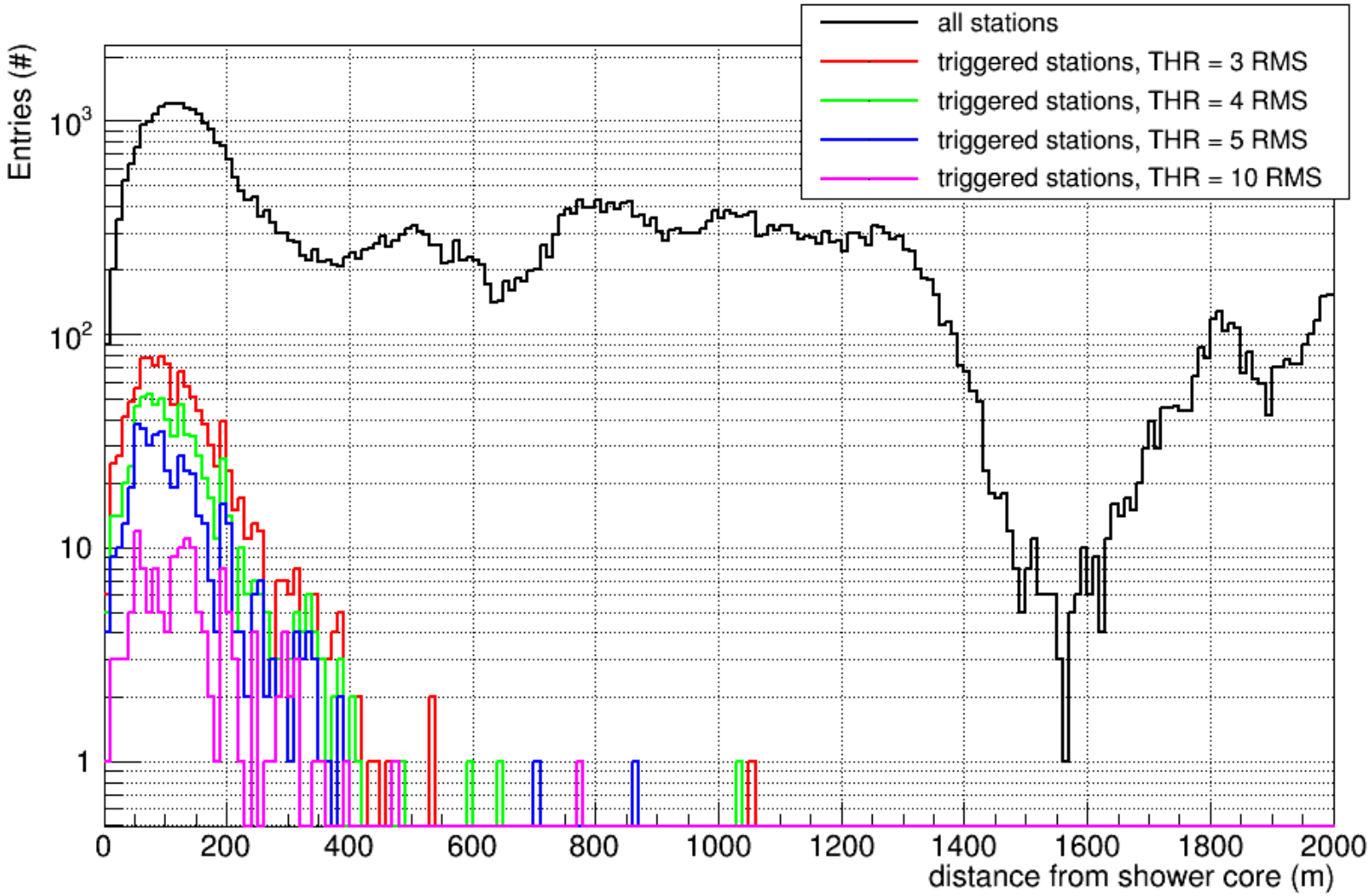
THR = 10 RMS
total number of stations triggered by CR signal = 196
fraction of stations triggered by CR signal and vetoed = 48 / 196 = 24%
Events with at least one RFI signal triggered after RFI rejection= **0**

LBA outer – Energy distribution



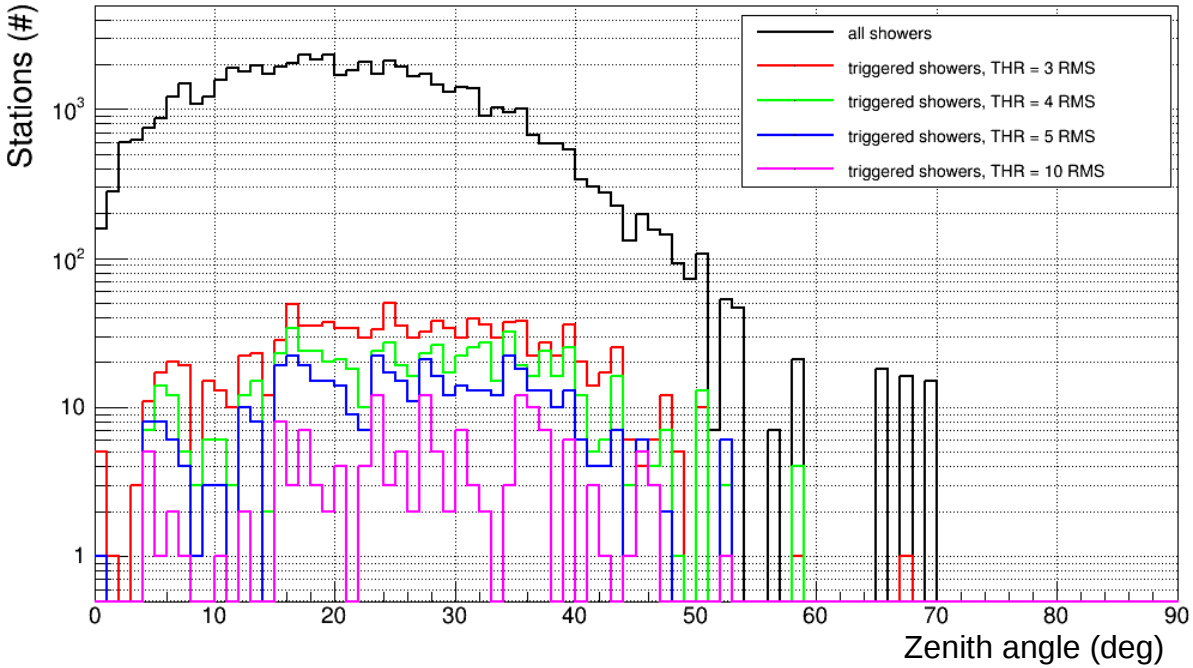
- Energy threshold varies accordingly to the single antenna trigger threshold
- Different threshold levels drive to different CR detection sensitivity due to the different effective collecting area

LBA outer – Station distance distribution



- Energy threshold affects the maximum distance of a detectable CR shower
- In the 0-400 m region, the triggered station distribution follows the distribution of available stations

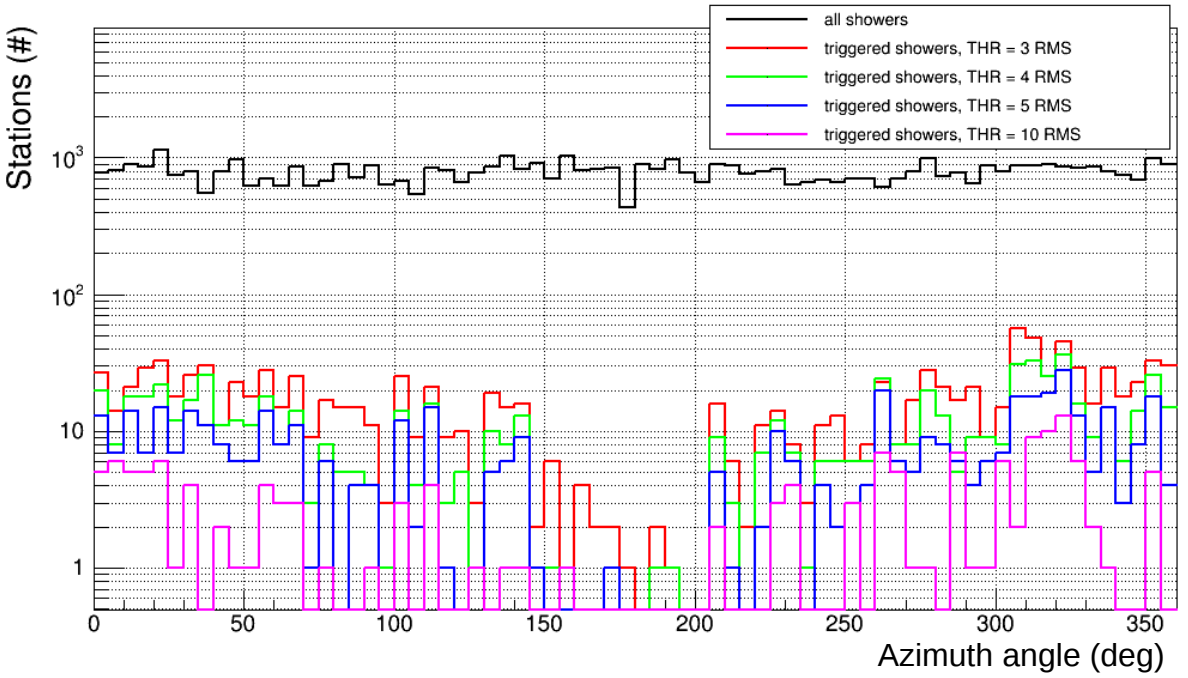
LBA outer – Angular distribution



Inclined showers (θ>40°) are favored compared to lower zenith ones

Detection of showers with azimuth angle between 150° and 200° is suppressed

Both angular dependencies are coherent with a radio emission dominated by the geomagnetic synchrotron emission



LBA inner self-trigger algorithm

Trigger criterion:

1) for each antenna the two polarizations are evaluated independently

2) Majority of 23 antennas along one polarization over a given threshold, on coincidence time window of **20** ns on each dipole

RFI rejection:

1) signal time length must be shorter than **75** ns

2) the ratio of I(30 MHz < F < 45 MHz) and I(45 MHz < F < 70 MHz) must be encompassed between 1 and 2

3) if two consecutive pulses are identified within 5 μs, both pulses are rejected

4) elevation angle of the signal must be $\theta > 30°$

Self-trigger with LOFAR LBA inner

events considered: 634
Energy: E > 3 · 10^15 eV
Total independent real time: 1.7 s
Total real time: 21.6 s

THR = 3 RMS
total number of stations triggered by CR signal = **395**

THR = 4 RMS
total number of stations triggered by CR signal = **246**

THR = 5 RMS
total number of stations triggered by CR signal = **168**

THR = 10 RMS
total number of stations triggered by CR signal = **51**

Self-trigger with LOFAR LBA inner

events considered: 715, reduced to 634 after quality selection
Energy: E > 3 · 10^15 eV
Total independent real time: 1.7 s
Total real time: 21.6 s

THR = 3 RMS
total number of stations triggered by CR signal = 395
fraction of stations triggered by CR signal and vetoed = 257 / 395 = **65%**

THR = 4 RMS
total number of stations triggered by CR signal = 246
fraction of stations triggered by CR signal and vetoed = 88 / 246 = **36%**

THR = 5 RMS
total number of stations triggered by CR signal = 168
fraction of stations triggered by CR signal and vetoed = 46 / 168 = **27%**

THR = 10 RMS
total number of stations triggered by CR signal = 51
fraction of stations triggered by CR signal and vetoed = 18 / 51 = **35%**

Self-trigger with LOFAR LBA inner

events considered: 715, reduced to 634 after quality selection
Energy: E > 3 · 10^15 eV
Total independent real time: 1.7 s
Total real time: 21.6 s

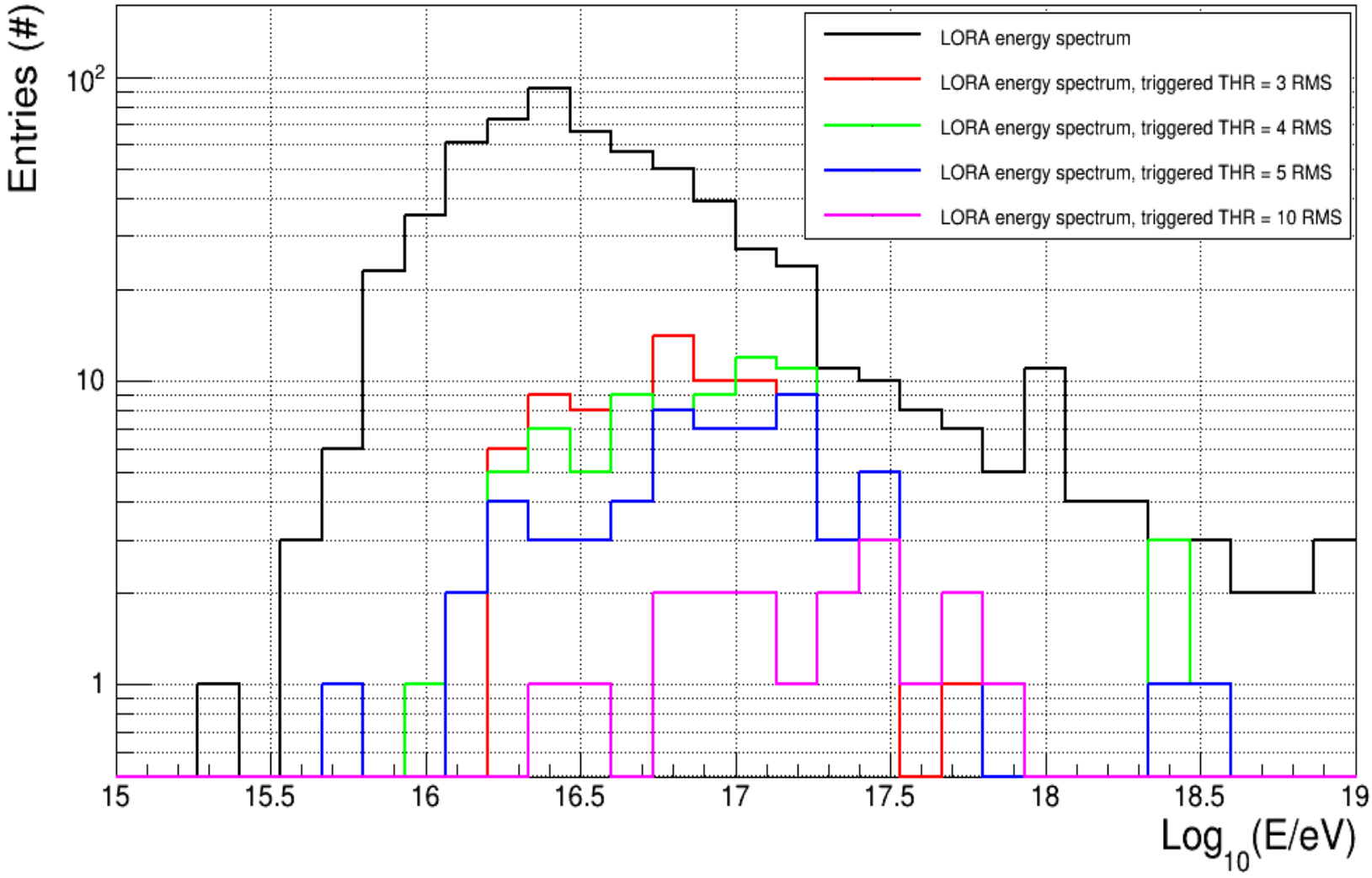
THR = 3 RMS
total number of stations triggered by CR signal = 395
fraction of stations triggered by CR signal and vetoed = 257 / 395 = 65%
Events with at least one RFI signal triggered after RFI rejection= **0**

THR = 4 RMS
total number of stations triggered by CR signal = 246
fraction of stations triggered by CR signal and vetoed = 88 / 246 = 36%
Events with at least one RFI signal triggered after RFI rejection= **0**

THR = 5 RMS
total number of stations triggered by CR signal = 168
fraction of stations triggered by CR signal and vetoed = 46 / 168 = 27%
Events with at least one RFI signal triggered after RFI rejection= **0**

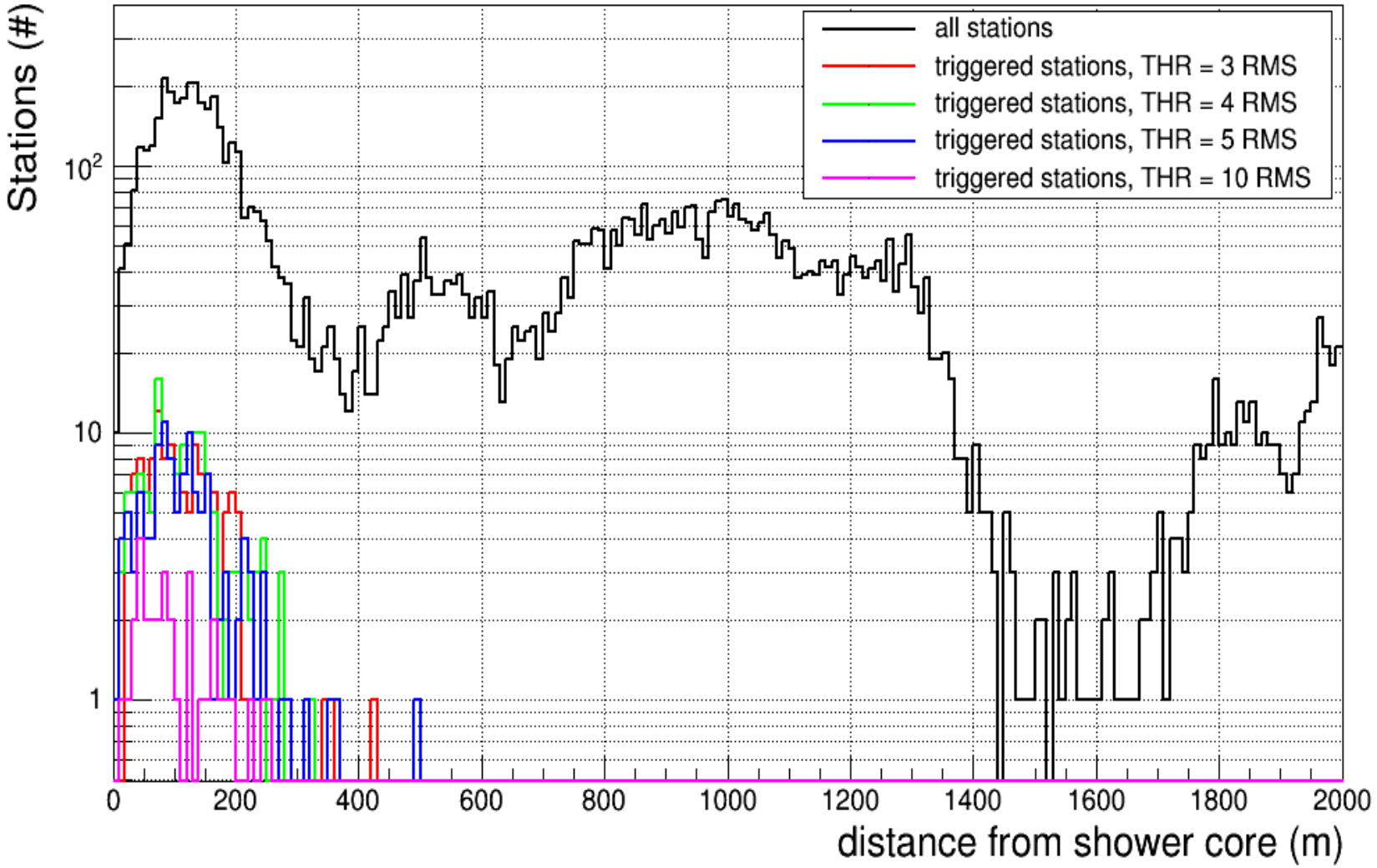
THR = 10 RMS
total number of stations triggered by CR signal = 51
fraction of stations triggered by CR signal and vetoed = 18 / 51 = 35%
Events with at least one RFI signal triggered after RFI rejection= **0**

LBA inner – Energy distribution



- Energy threshold varies accordingly to the single antenna trigger threshold
- Different threshold levels drive to different CR detection sensitivity due to the different effective collecting area

LBA inner – Station distance distribution



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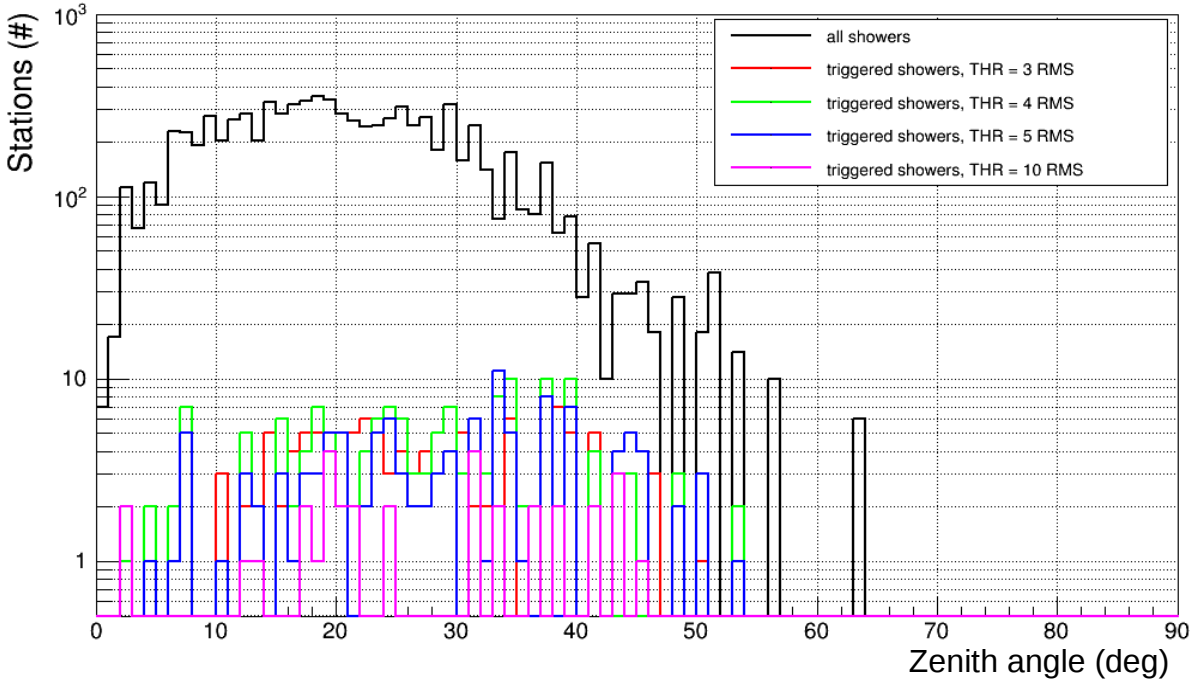
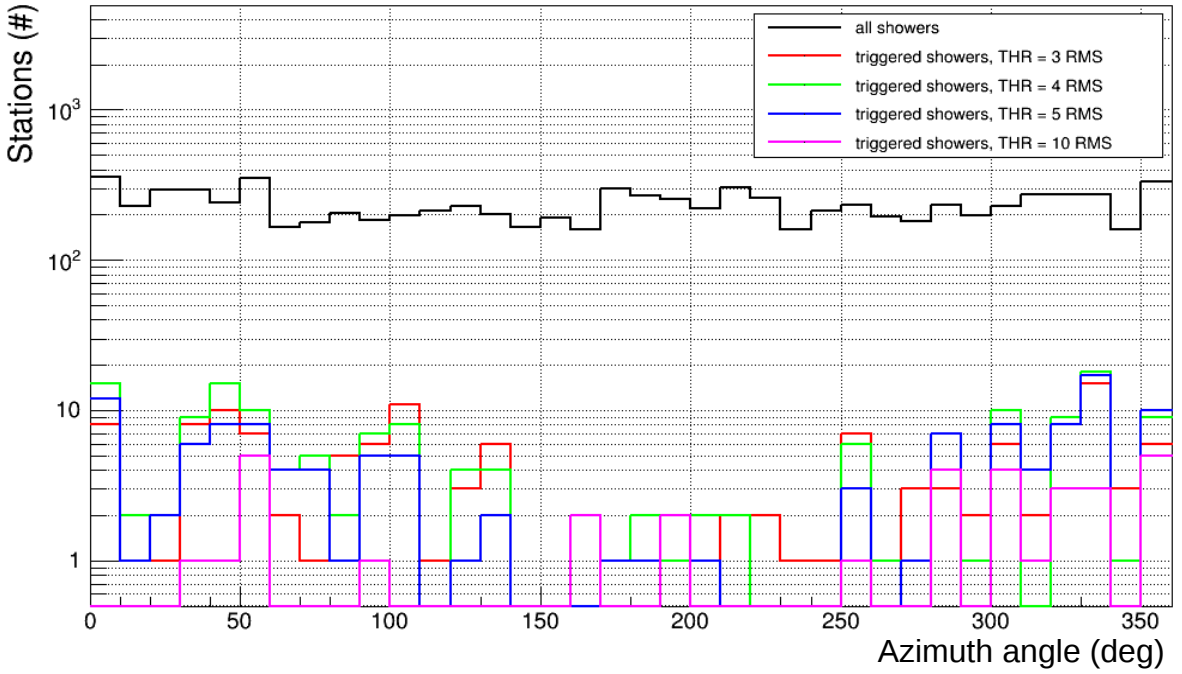
LBA inner – Angular distribution



Inclined showers (θ>40°) are favored, showers with θ<20° are suppressed

Detection of showers with azimuth angle between ~150° and ~250° is suppressed

Both angular dependencies are coherent with a radio emission dominated by the geomagnetic synchrotron emission



Self-trigger - Conclusions

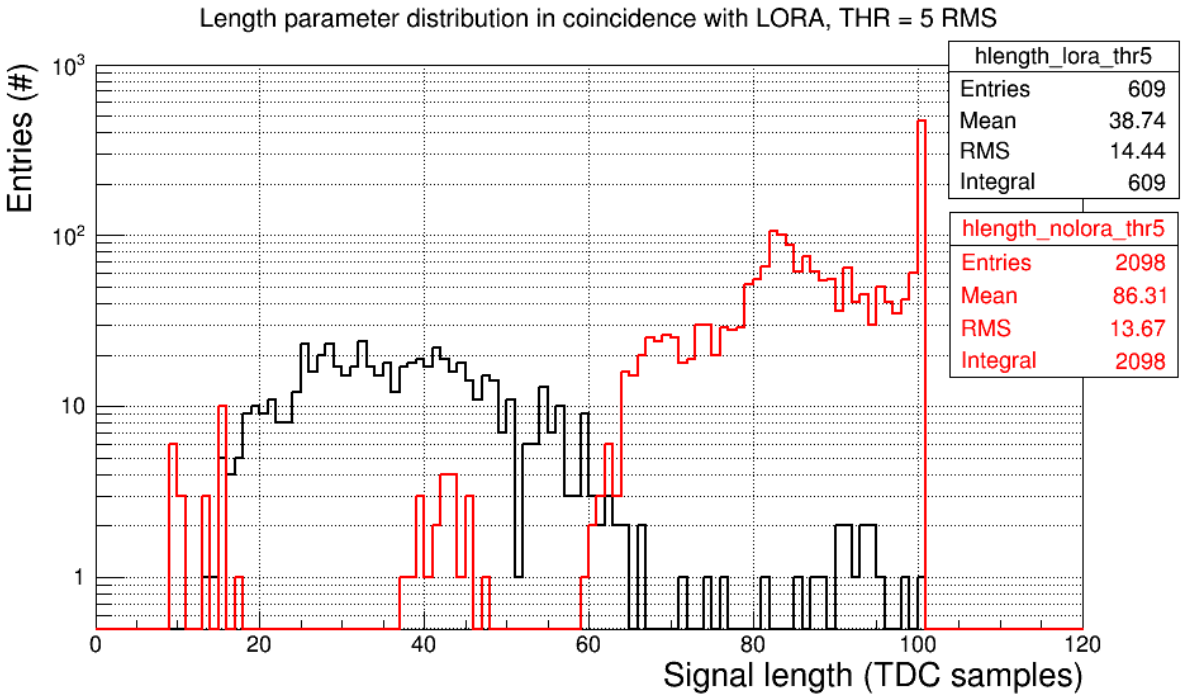
- Raw data acquired between 2012 and 2015 have been used for developing a trigger algorithm to be implemented to LOFAR stations for detecting CRs
- The algorithm is based on the single antenna detection and on the signal morphology (frequency spectrum and duration)
- The algorithm shows good acceptance efficiency both for LBA inner and LBA outer and very good RFI rejection
- Estimation of RFI rejection efficiency is limited by the available statistics

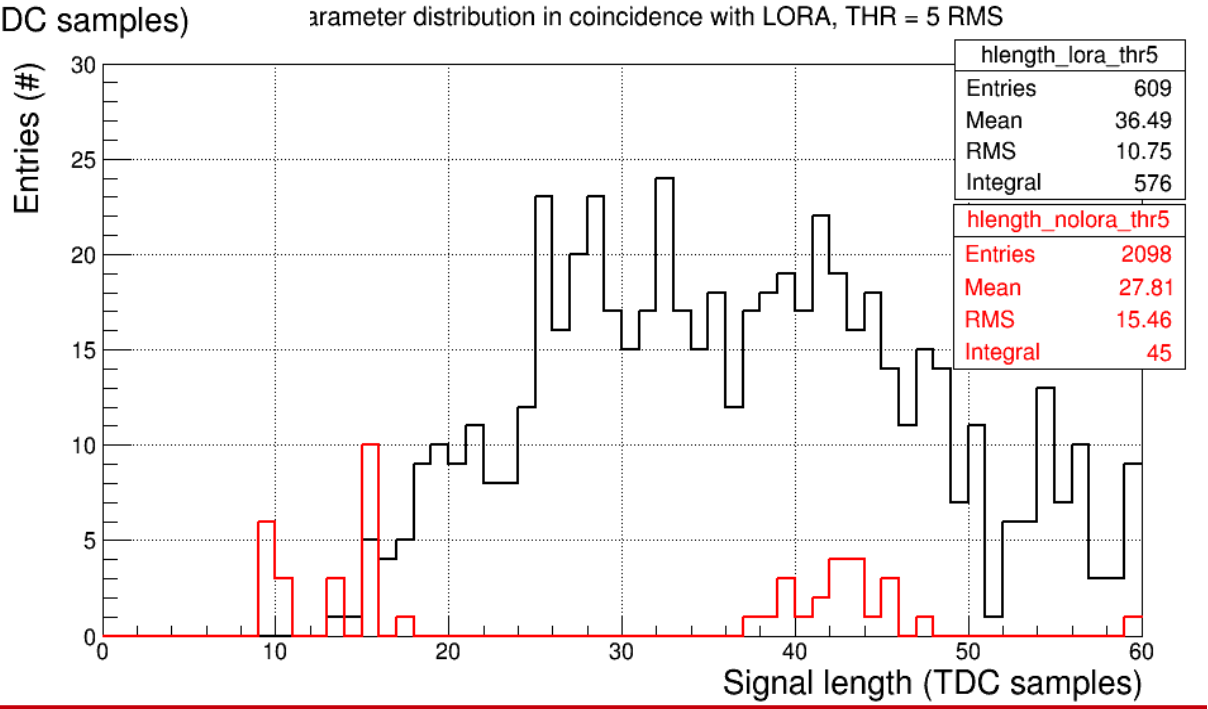
Future plans

- ➔ Low threshold acquisitions are planned to be performed on one LOFAR test station to perform a better estimation of RFI rejection efficiency
- ➔ Implement the self-trigger algorithm to the Dutch and to the International stations so to boost up the CR collecting area

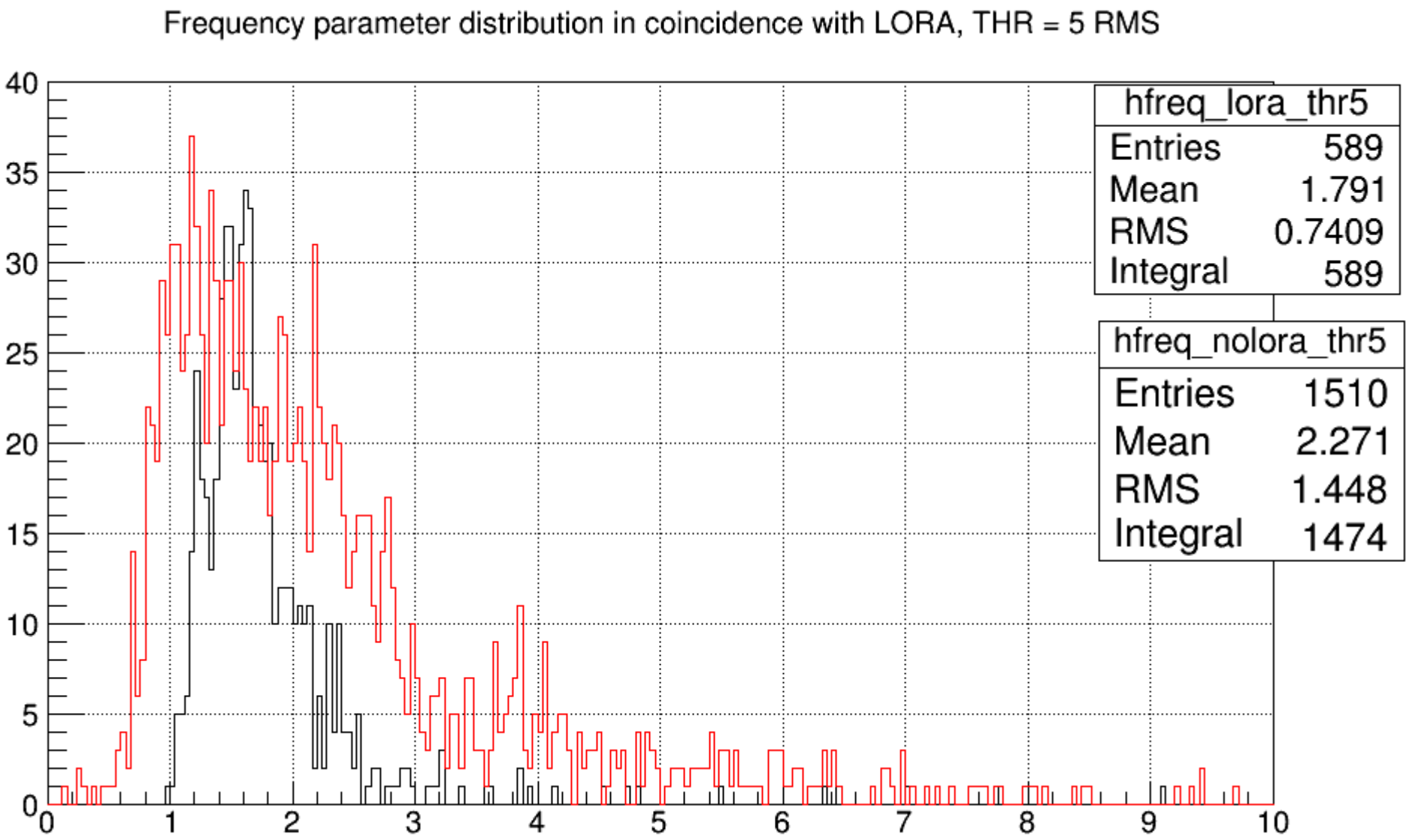
Spare Slides

LBA outer – Rejection parameters





LBA outer – Rejection parameters



LBA inner – Rejection parameters