

RDSim: a simple and fast toymodel-based radio detection simulation

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University
Nijmegen**

Motivation

- Investigate with just a few ZHAIRES full simulations:
 - Large Area (including outside the array for inclined events)
 - Low detection probability events
 - Array layout geometrical effects
 - Aperture
- Optimize the generation of shower libraries for more detailed studies
 - Sweep the phase space: $P_{trig}(E_{sh}, A, X_{int}, \theta, \phi, x, y)$
 - Estimate the total and relative number of full simulations needed
 - Specially important for ν (τ) induced showers due to huge phase space
 - Extra variables with large impact on shower characteristics
 - Depth of interaction X_{int} (h_{int}): e.g. footprint size and field intensity
 - Type of interaction and it's fluctuations: e.g. E_{sh} and μ content

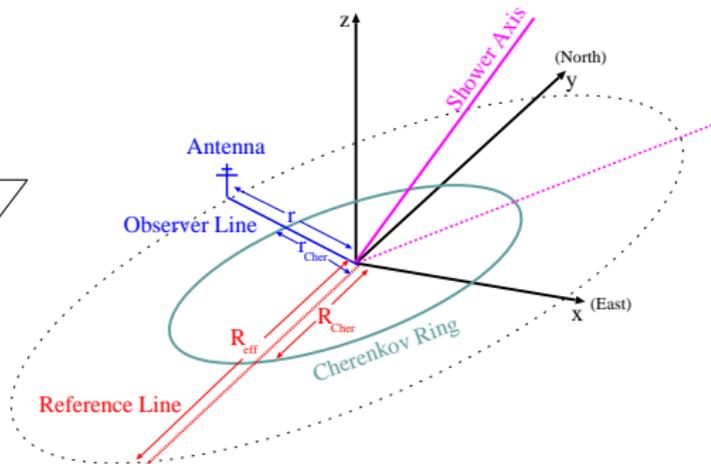
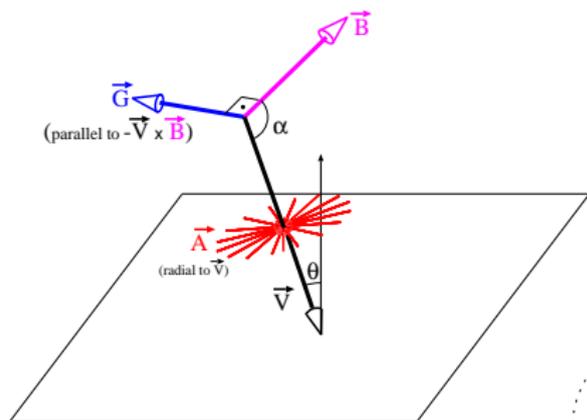
RDSim main characteristics

- Fast and comprehensive:
 - Can simulate millions of events in a very short time
 - Can handle large areas and geometries with very low trigger probability
 - Can investigate effects due to asymmetric arrays, infills and other border effects
 - Takes into account the main characteristics of the detector
 - Trigger setups, thresholds and antenna patterns
 - Simple particle trigger simulation based on muon density at ground level
- Can handle any ZHAIRES downgoing shower including:
 - Showers induced by ν CC and NC interactions (HERWIG)
 - Showers induced by τ -lepton decays (TAUOLA)
 - Can propagate τ s from creation to decay
- Uses very fast toy models:
 - Radio emission: based on full ZHAIRES simulations
 - τ propagation: parametrizations of τ propagation simulations
 - Muons at ground level: based on low thinning AIREs simulations

Radio emission: Superposition “toymodel”

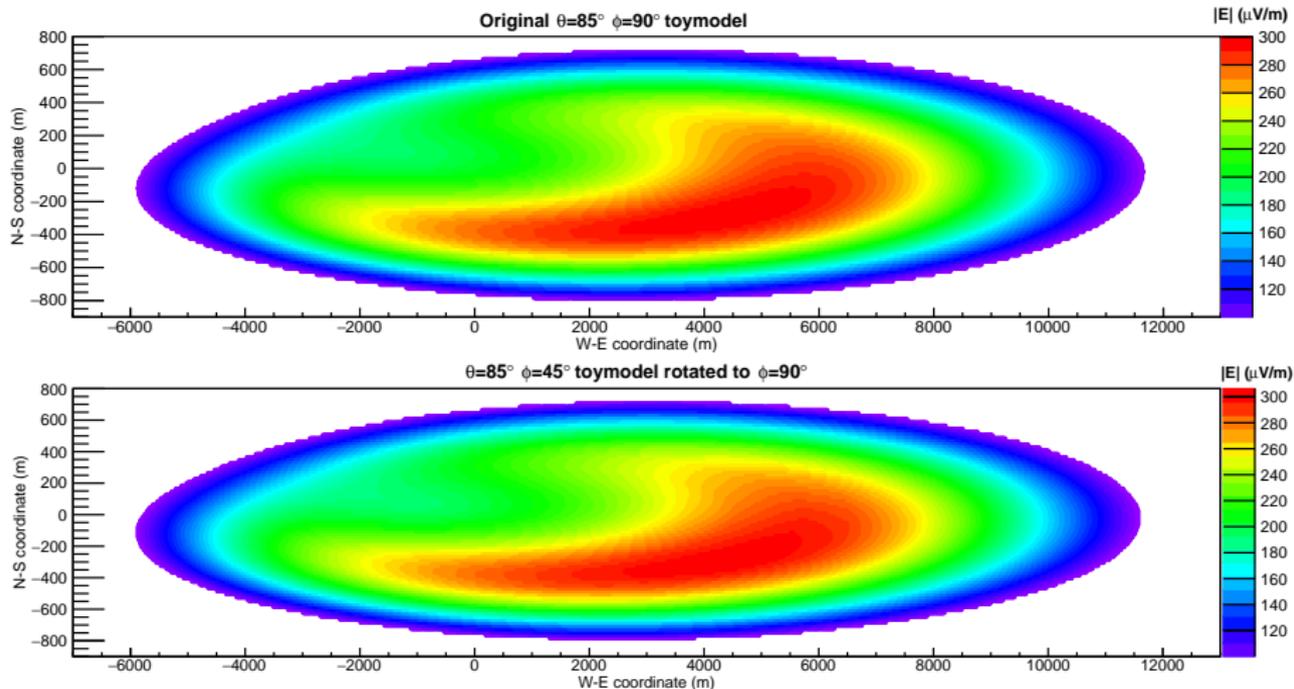
- Based on theoretical polarizations and elliptical symmetry
- Disentangles the Askaryan and geomagnetic components to estimate the electric field in any position on the ground
- Input: Full simulation with specific arrival directions and few antennas
- Extension of old toymodel in *Astropar.Phys.* **59**, 2014, 29
- Toymodel can now be rotated to use simulations of a fixed azimuth angle for multiple arrival directions (takes into account $\sin \alpha$, etc...)
- Early/Late effects and electric field linear scaling with energy included
- Can sweep the phase space with much fewer input simulations

Radio emission: Superposition “toymodel”

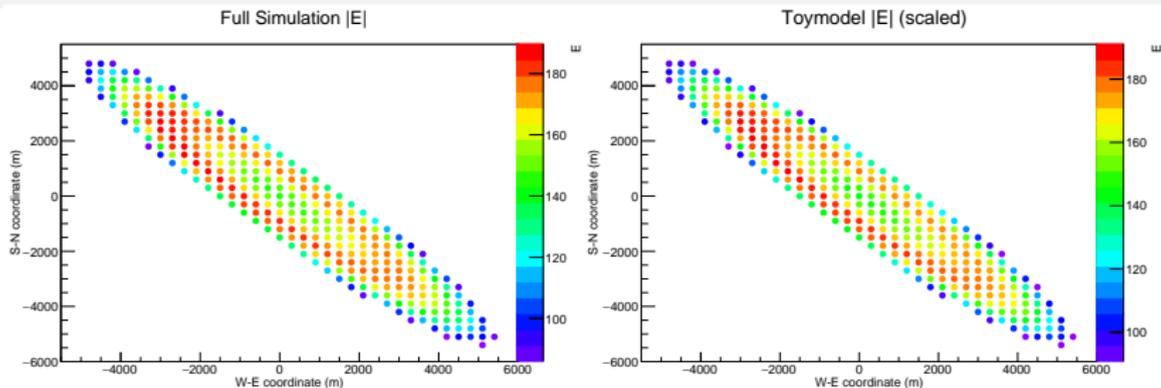


Example rotation: $\theta = 85^\circ$ from NW to W

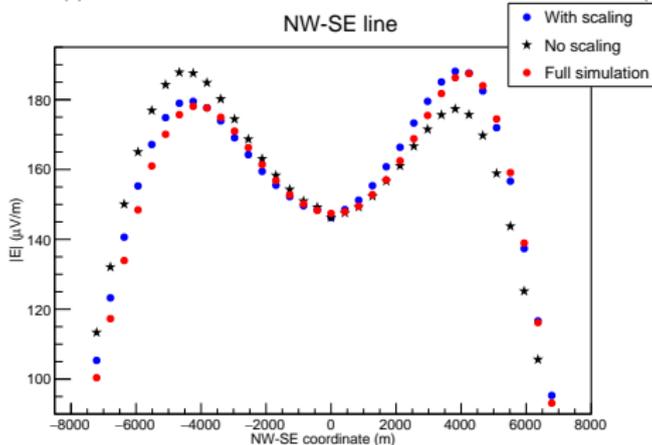
Maximum difference between rotated toy model and dedicated toy model $\sim 2\%$



Toymodel p 1EeV 80°: Comparison to full simulation



max. diff. $\sim 6\%$

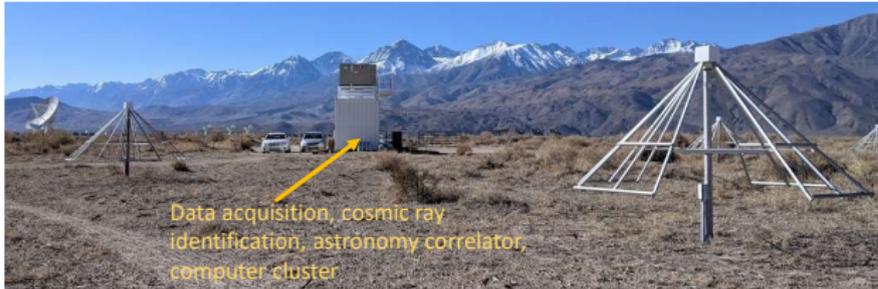


The Long Wavelength Array at the Owens Valley Radio Observatory (OVRO-LWA)



- Cosmic ray search will run full time alongside other astronomy
- Science goals relate to extrasolar space weather, cosmic rays, solar flares, hydrogen in the high-redshift universe, and more

The Long Wavelength Array at the Owens Valley Radio Observatory (OVRO-LWA)



Data acquisition, cosmic ray identification, astronomy correlator, computer cluster

- 352 dual polarization antennas within 2.4 km
- 12—85 MHz
- All antennas are continuously digitally sampled in a central location
- Cosmic ray detection and RFI rejection use only radio signal



Slide from Kathryn Plant

Summary of Radio-Only System



Detection Part 1

1. Detect impulse signal.
2. Compare nearby antennas.
3. Reject events seen by distant antennas.
4. Trigger whole array to read out buffered data.

FPGA

Detection Part 2

1. Estimate direction and core position.
2. Reject events that are badly fit by model wavefront.
3. Reject events from known key RFI directions.
4. Reject events from airplane tracks.
5. Confirm power LDF and polarization.

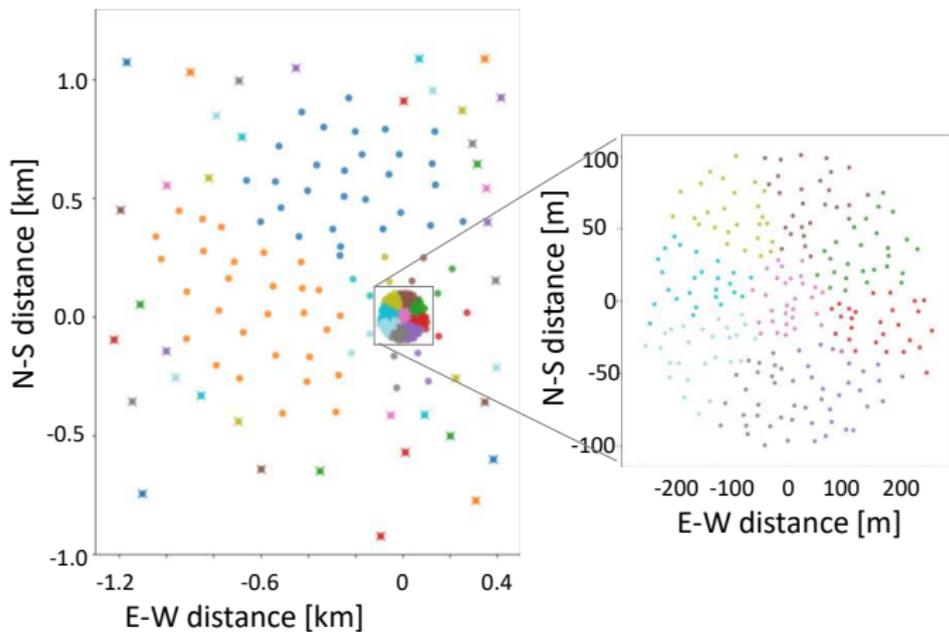
CPU

Analysis

Compare data to simulations to estimate:
-- energy
-- Xmax

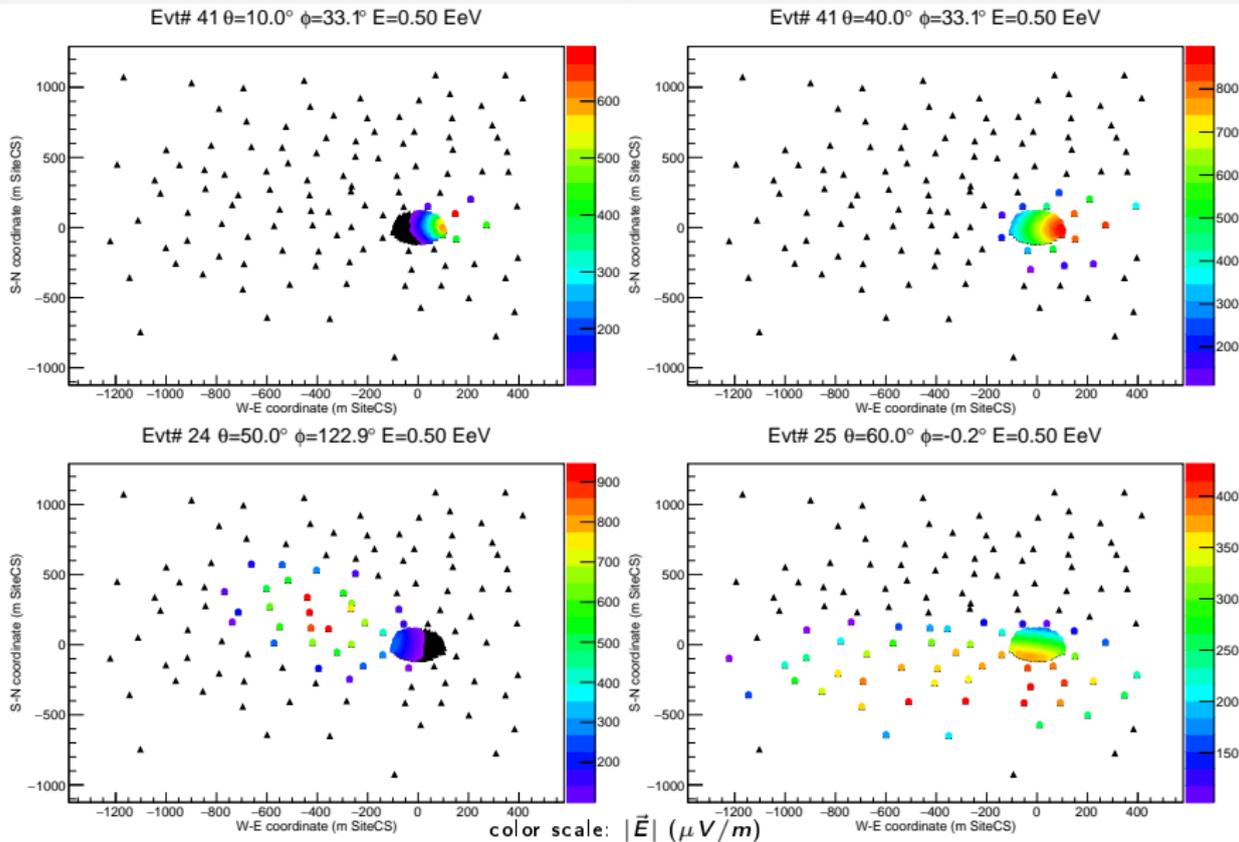
CPU

Using Distant antennas to reject RFI

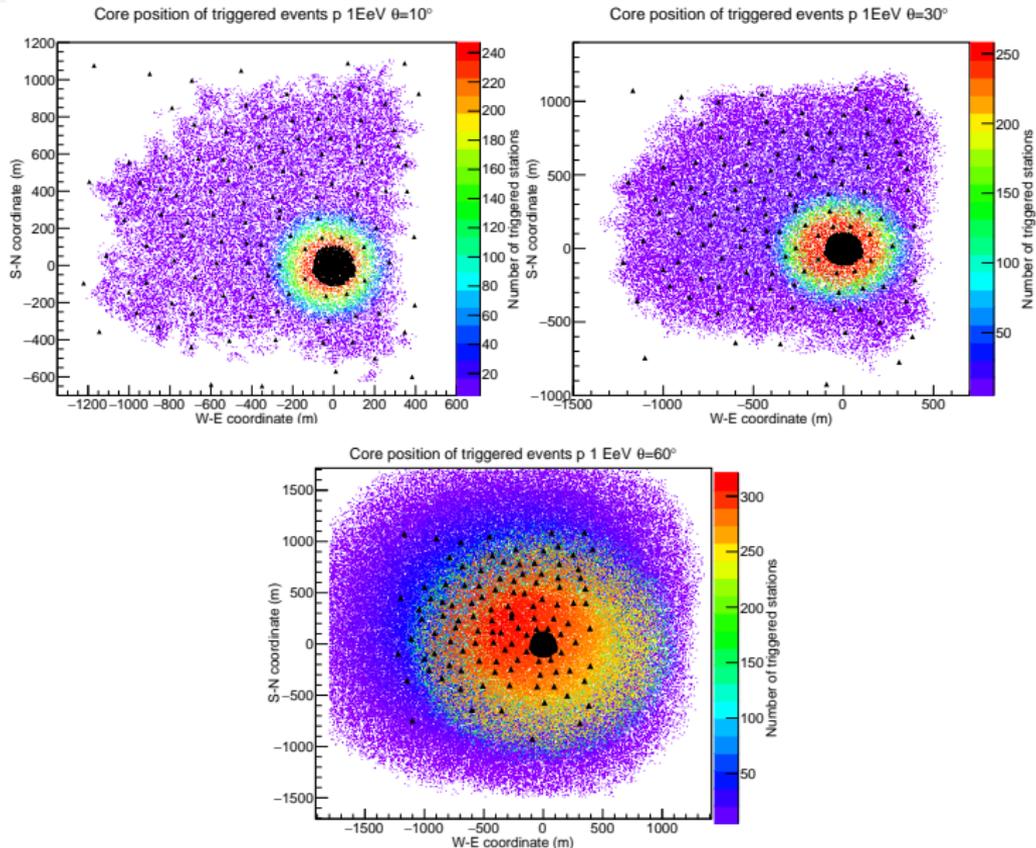


- Color indicates FPGA group
- x indicates veto

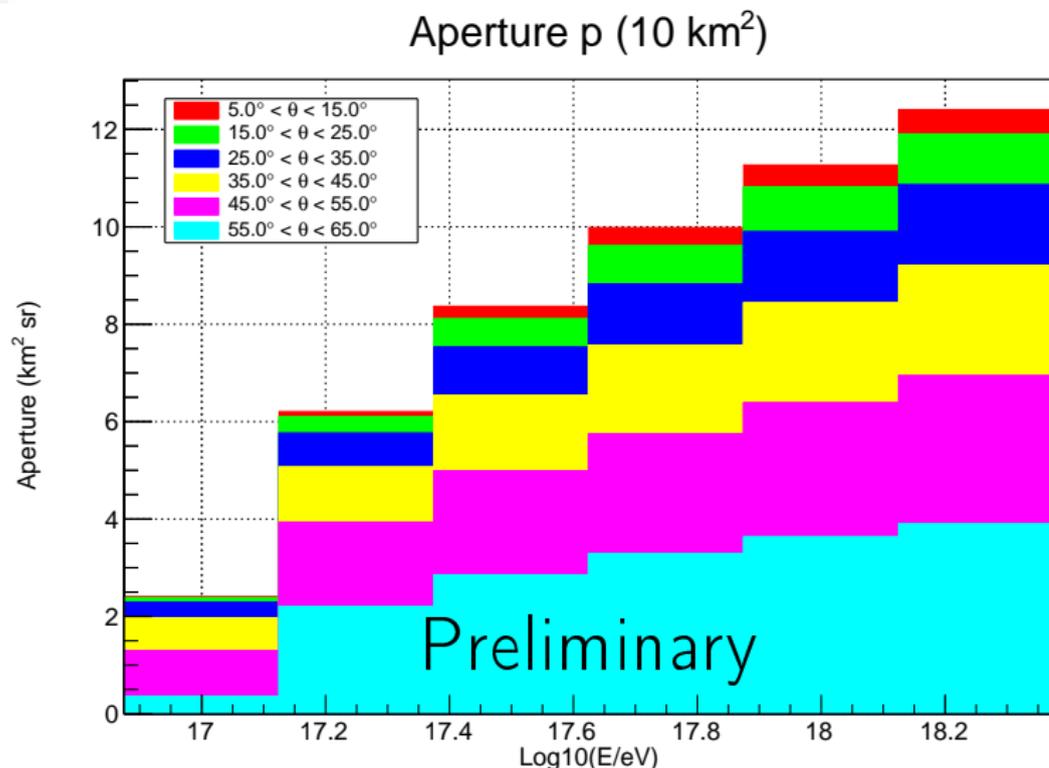
Example events at OVRO-LWA: proton $5 \cdot 10^{17}$ eV



Example 1 EeV triggered core positions at OVRO-LWA



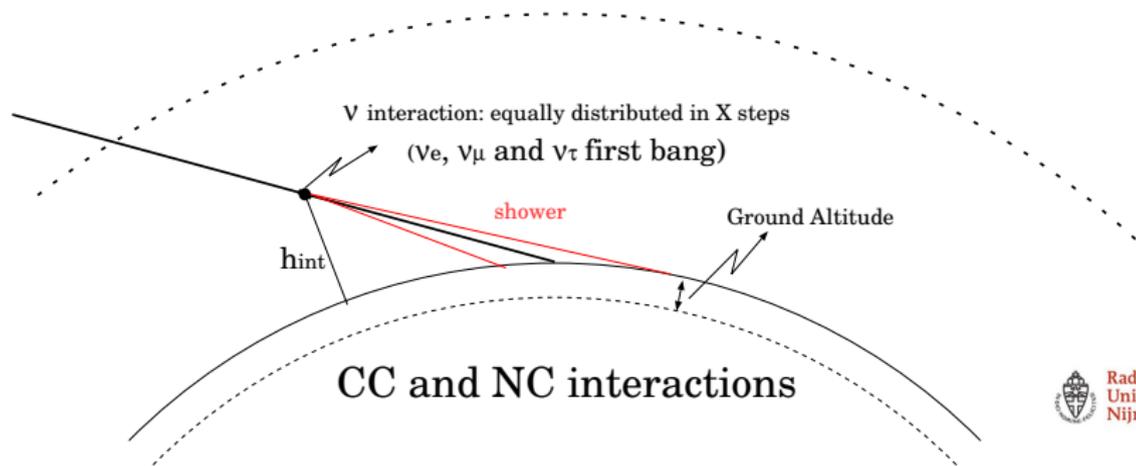
Aperture estimate for protons at OVRO-LWA



Note: Does not yet take into account veto antennas for RFI rejection (large zenith)

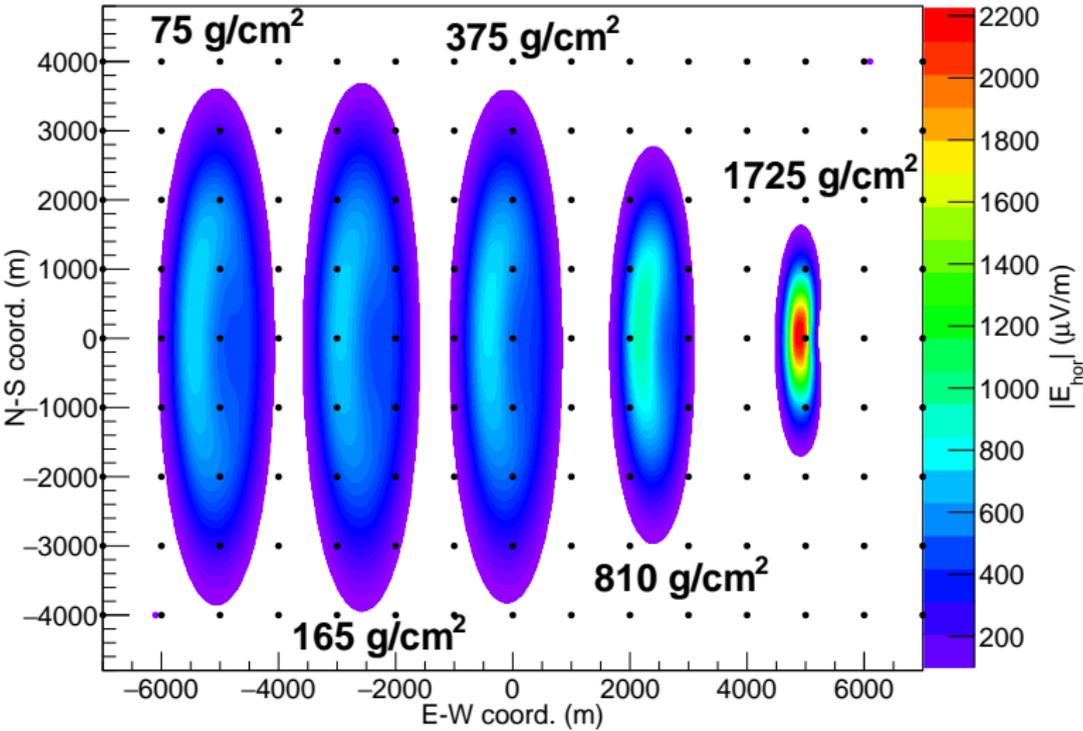
Downgoing CC and NC events

- ν cross-section very small even at highest energies
 - Approx.: ν interaction point equally distributed in X
 - Divide atmosphere in ΔX steps: Many more steps at low altitude (ρ)
- Toymodel creation at each X :
 - Products of ν interaction (Herwig) injected into ZHAireS \rightarrow Toymodel \vec{E}
- Randomly choose one step for ν interaction $\rightarrow X_{\text{int}} (h_{\text{int}})$

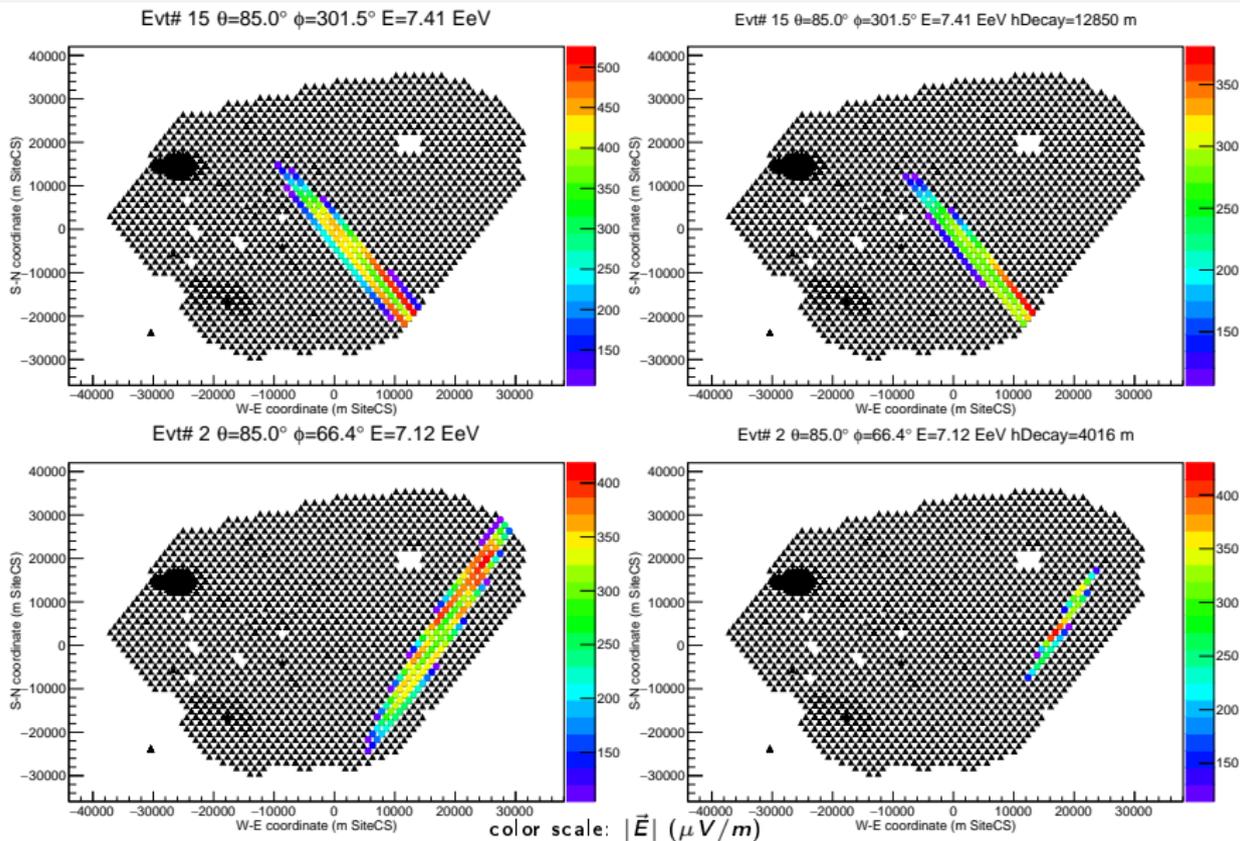


Downgoing neutrinos: Importance of X_{int} variation

Radio footprints v CC $\theta=75^\circ$

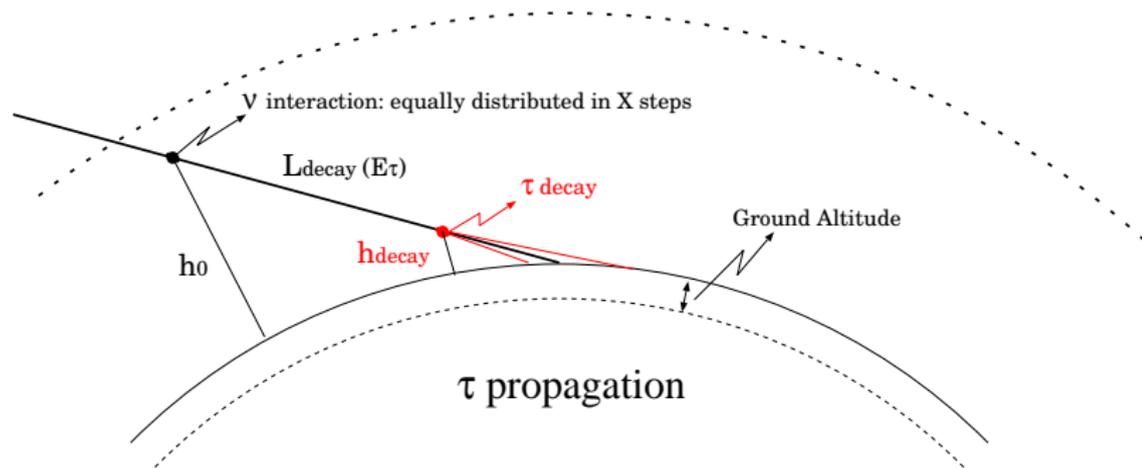


Example γ and ν_e CC events at $\theta = 85^\circ$ at Auger RD



Tau propagation

Products of τ decay (Tauola) injected into ZHAireS



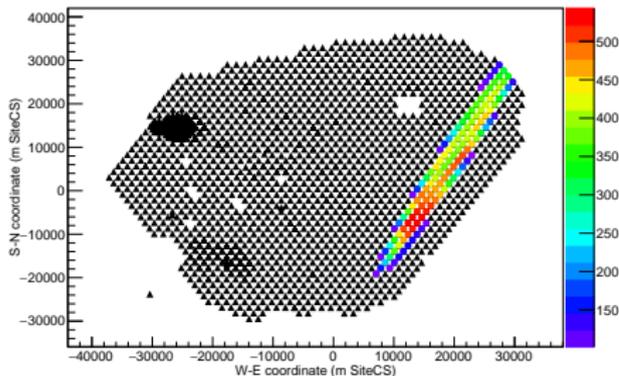
Sampling h_0 , $L_{decay}(E)$ and h_{decay}

- For speed, we use a simple external τ propagation simulation
- dP : probability of τ decay in 1 m
 - $dP(E_\tau) = \frac{m_\tau}{E_\tau \tau}$, where $\tau = 86.93 \mu m$ is the decay length
- $L_{decay}(E_\tau)$: propagation distance from interaction to decay
 - Propagate along ΔL steps based on dP
 - We disregard the τ energy losses in air
- From these external simulations we obtain:
 - Fraction of τ s that do not decay before reaching the ground
 - Parametrizations of the distribution of h_{decay} for those that decay above ground (takes into account equal h_0 sampling in X)
- Inside the main RDSim:
 - We first test if decay occurs above ground
 - If it decays above ground we sample the h_{decay} parametrization and continue the simulation.

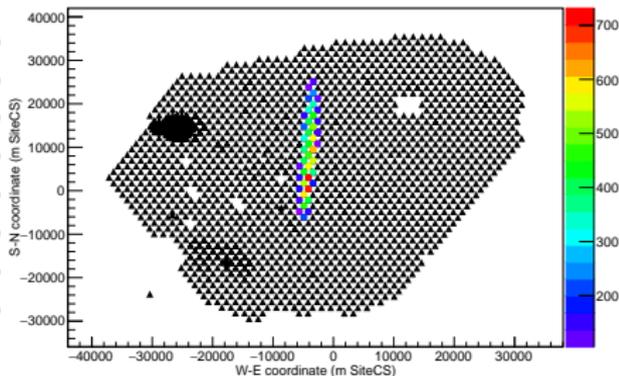
Example τ events at $\theta = 85^\circ$ at Auger RD

Even larger variation in footprint size due to τ propagation

Evt# 4 $\theta=85.0^\circ$ $\phi=245.7^\circ$ E=10.00 EeV hDecay=15456 m



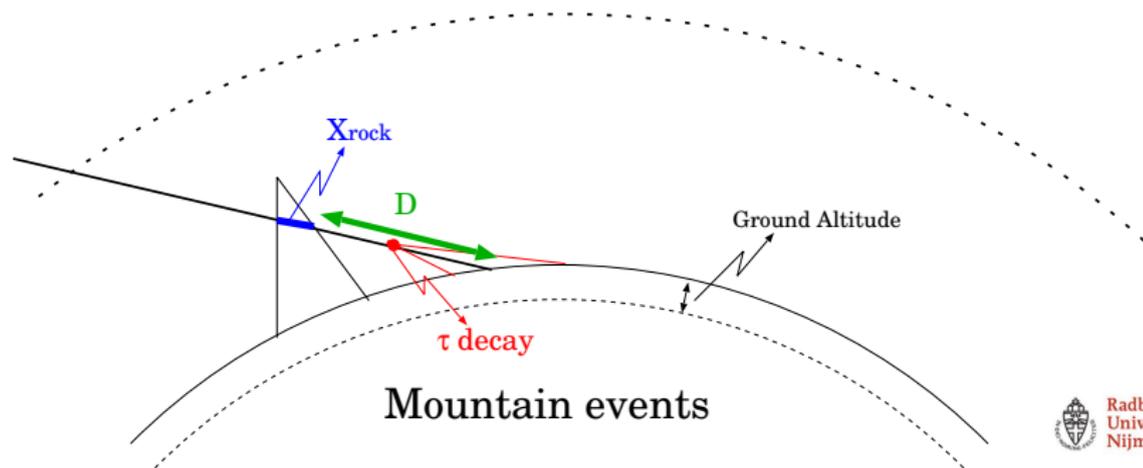
Evt# 224 $\theta=85.0^\circ$ $\phi=267.1^\circ$ E=10.00 EeV hDecay=4540 m



color scale: $|\vec{E}|$ ($\mu V/m$)

ToDO

- Mountain events:
 - Use topography maps to produce a “Rock depth” $X_{rock}(\theta, \phi, x_{core}, y_{core})$ map along with a distance $D(\theta, \phi, x_{core}, y_{core})$ to mountain face.
 - Calculate probability of tau exit $P_{\tau}(E_{\nu}, E_{\tau}, X_{rock})$ using e.g. NuTauSim
 - Apply same procedure as regular downgoing τ decay



Questions?

Other applications of Radio...



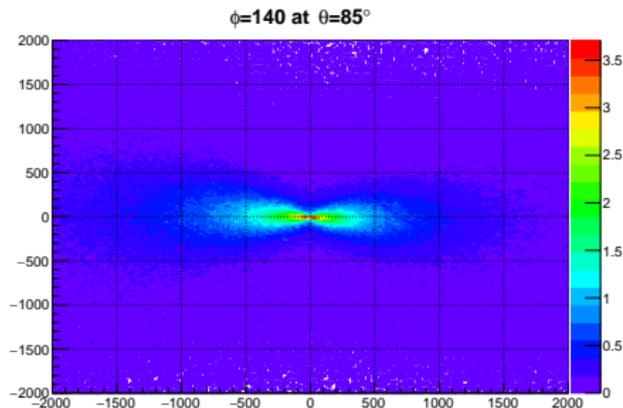
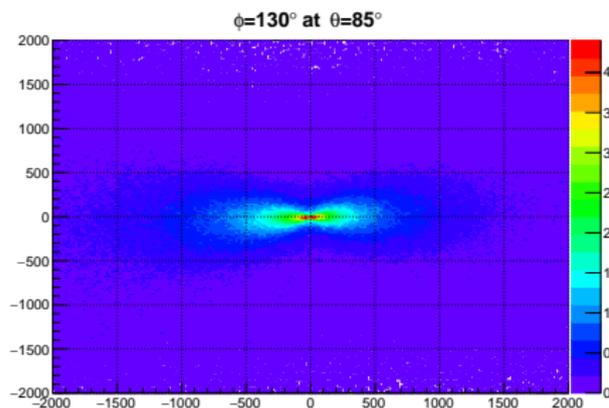
BACKUP

Simple Particle detector trigger simulation

- Relevant for detectors that trigger with particles (e.g. Auger RD)
- For now only muons (relevant for inclined showers)
- Based on μ density map toymodel
 - input: Low thinning AIREs simulations of ground muons
 - Can rotate maps: a single AIREs simulation can be used to generate μ maps for many arrival directions
- Samples number of muons crossing the particle detector
- Takes into account main characteristics of particle detector
- Effective Area: $A_{\text{eff}}(\theta)$ (shadow area for tanks)
- Simple Threshold (in number of muons crossing detector)

Estimating maps using different azimuth simulation

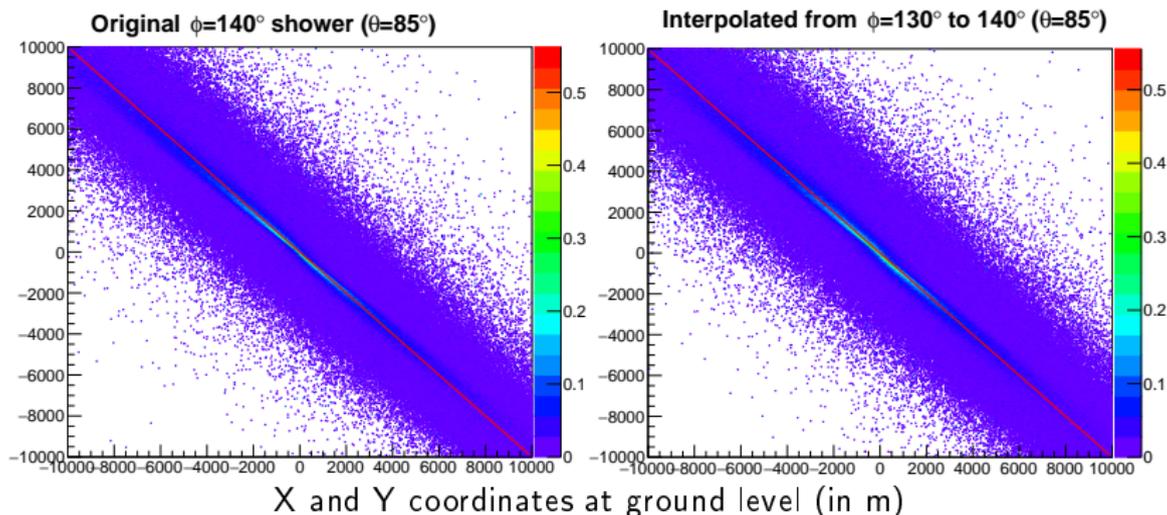
- Ground muons are projected into the perpendicular plane (θ, ϕ)
- Perpendicular plane projection taken to be valid for a different azimuth
 - Small difference in the angle α between shower axis and \vec{B}
 - Small difference in Lorentz force intensity and direction
 - Small differences in the perpendicular plane map
 - But ϕ' must be close to original ϕ (max. diff. $\sim 10^\circ$)



X and Y coordinates on the perpendicular plane (in m)

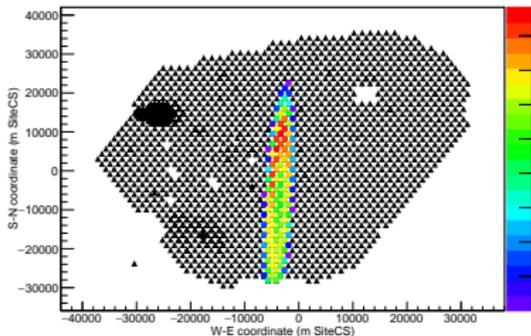
Estimating maps using different azimuth simulation

- Muons in the perpendicular plane are now projected back to the ground using the new arrival direction (θ, ϕ')
- A ground μ density map is then created
- The number of muons crossing the detector is sampled from a Poisson distribution based on the μ map

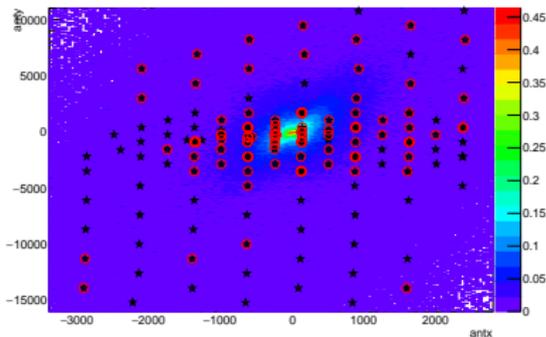
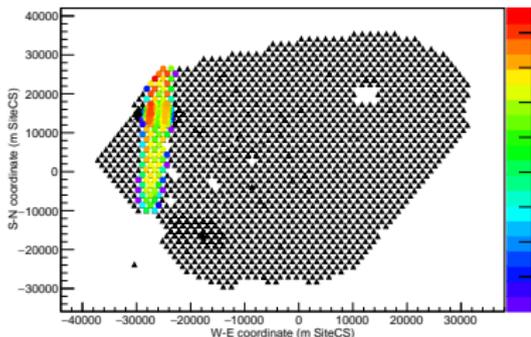
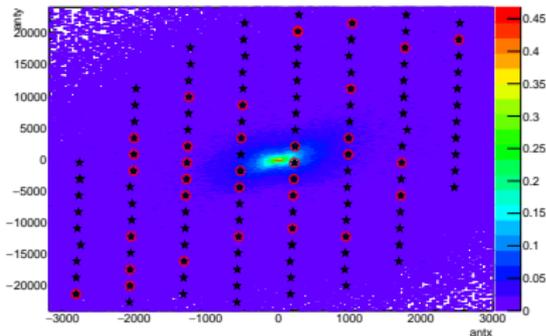


Few examples of the simple particle trigger

Event map (color is $\mu V/m$)



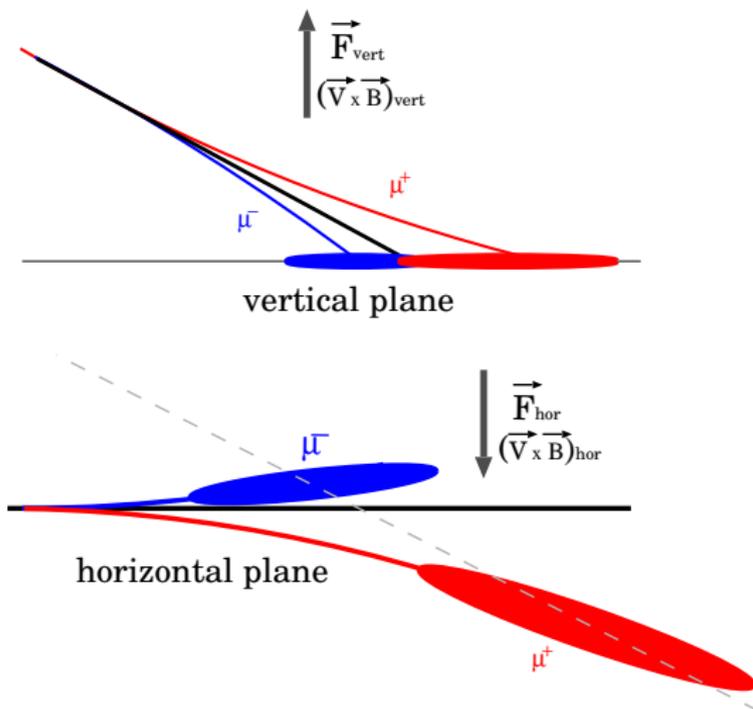
μ map and triggered stations (color is N_{μ}/m^2)



Effect of \vec{B} on muon maps: vertical component

- Vertical and horizontal components of $\vec{V} \times \vec{B}$ have different effects on muon footprint
- Vertical component pushes μ^- towards the ground diminishing their paths and pushes μ^+ up increasing their paths until they reach the ground
 - Smaller average path decreases total deflection of μ^- if compared to μ^+ .
 - μ^- are concentrated in the early part of the shower footprint and μ^+ in the late part.
 - Number density asymmetry: Higher number density in the early part of the muon footprint (μ^-) due to the smaller deflections on average. Easily visible on projected maps on the perpendicular plane.

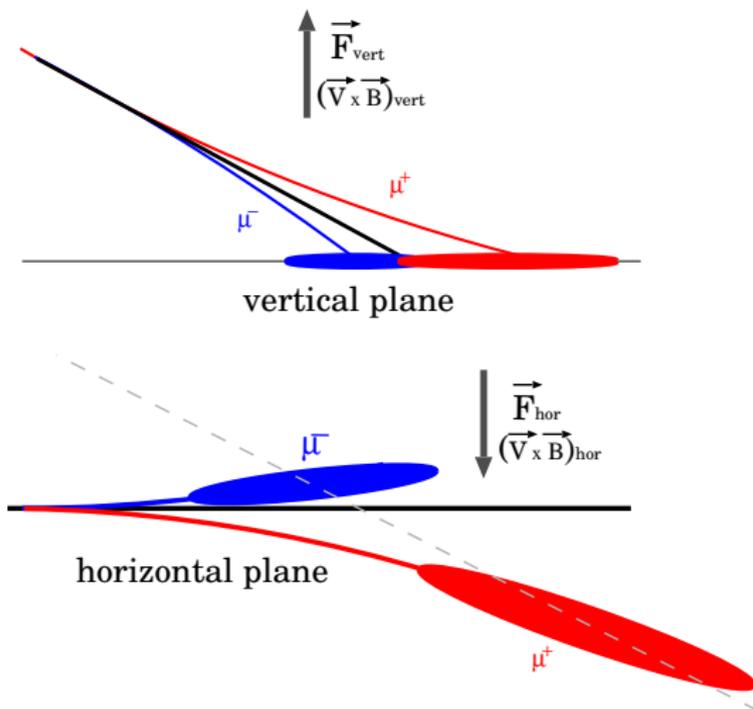
Effect of \vec{B} on muon maps: vertical component



Effect of \vec{B} on muon maps: horizontal component

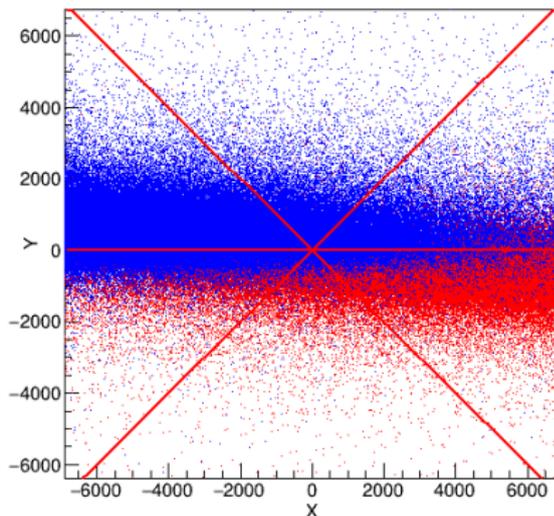
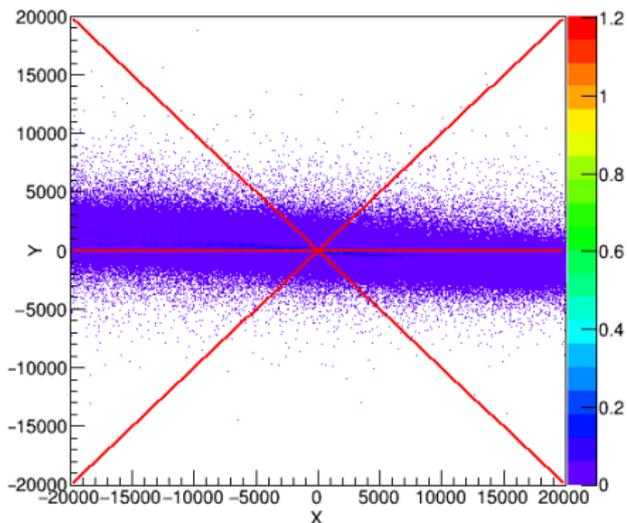
- Horizontal component separates μ^+ and μ^- perpendicularly w.r.t. the ground projection of the shower axis
 - If there is a large vertical component of the Lorentz force, the path difference between μ^+ and μ^- makes μ^+ deflect more
 - Late part of the shower is more deflected, creating a rotation on the muon map w.r.t. the shower axis: Structure of the muon map is not parallel to shower axis projection
- Large azimuth and B inclination dependence. Can cause rotations on the perpendicular plane (pattern may not align with $\vec{V} \times \vec{B}$).

Effect of \vec{B} on muon maps: horizontal component



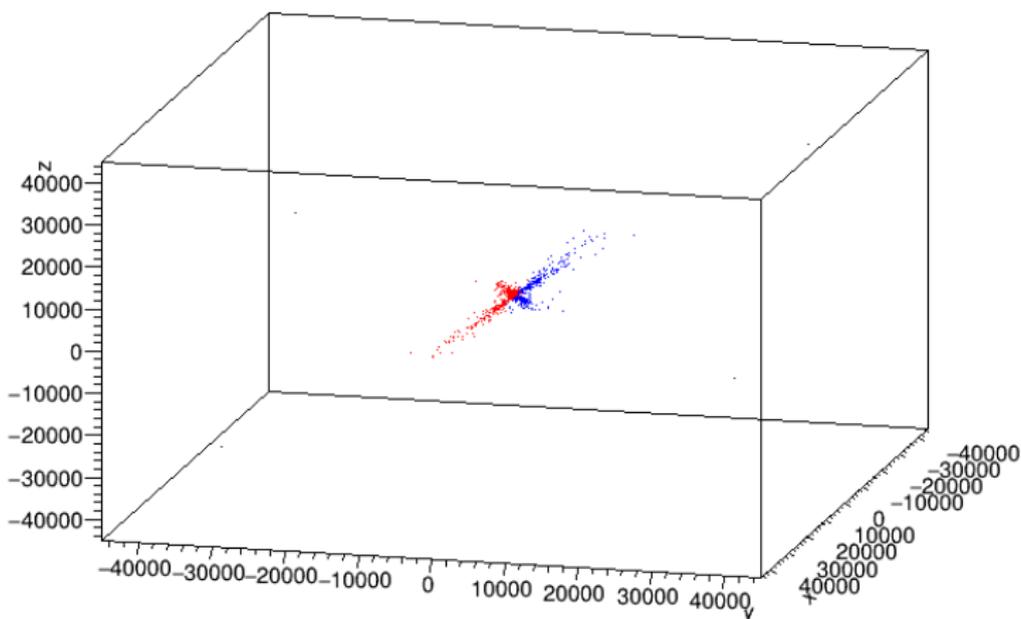
Largest effect example: Shower from W, with B incl.

- Large vertical $\vec{V} \times \vec{B}$ component
- Non-zero perpendicular component (For \vec{B} with inclination)
- Straight from the Sim, muon footprint is rotated (Not on E-W line!)



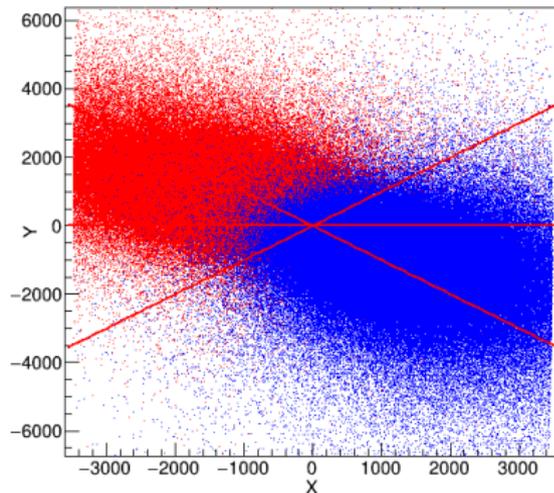
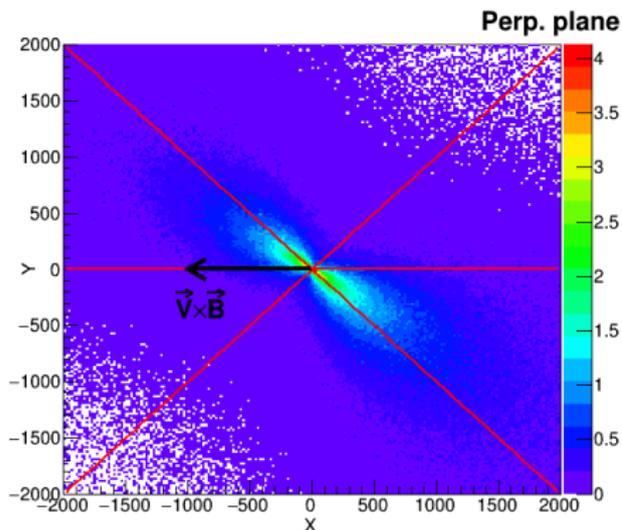
Largest effect example: Shower from W, with B incl.

- Rotation clear on shower plane (about 45° w.r.t. $\vec{V} \times \vec{B}$)
 - Due to the perpendicular horizontal deflection and projection
- Early-Late density asymmetry clearly visible



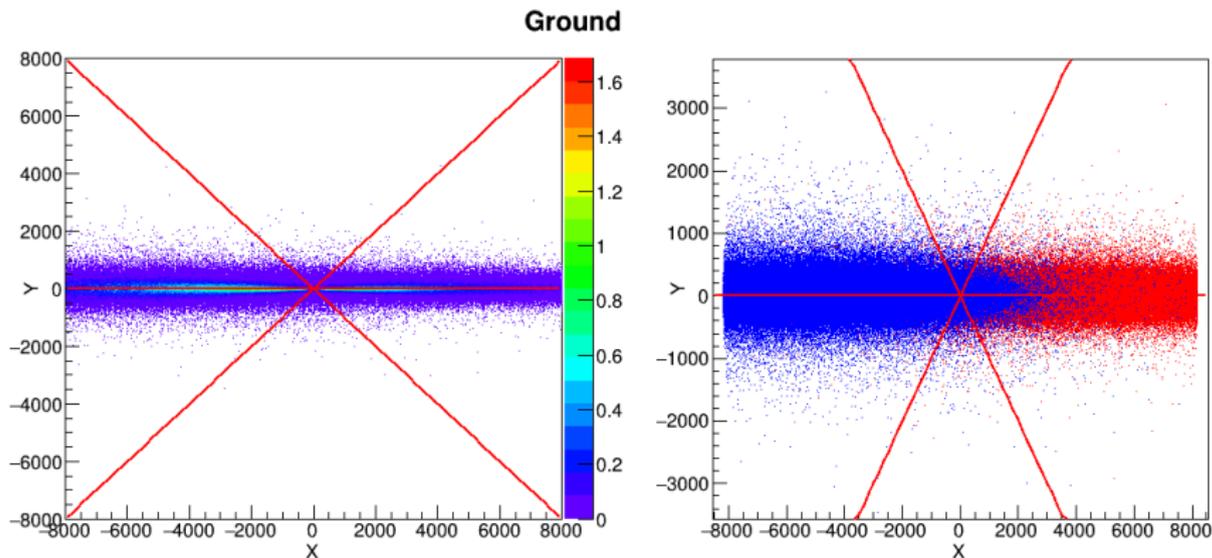
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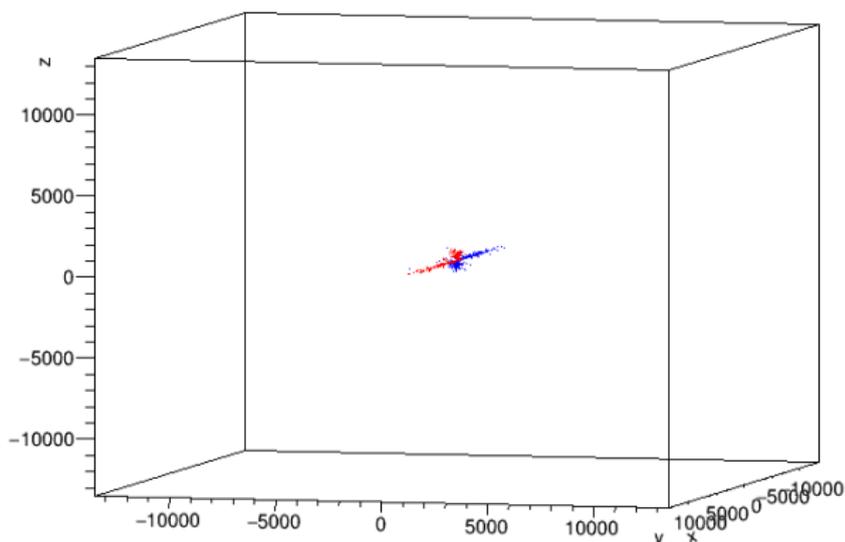
No horizontal $\vec{V} \times \vec{B}$ component: from W, no B incl.

- B horizontal $\rightarrow \vec{V} \times \vec{B}$ perfectly vertical
- No more horizontal deflection \rightarrow No more rotations
- Footprint perfectly aligned with arrival direction
- Vertical effect still present
 - Early μ^- and Late μ^+ . Footprint still asymmetric



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Perp. plane

