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

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# 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: $P_{trig}(E_{\text{sh}}, A, X_{\text{int}}, \theta, \phi, x, y)$
  - Estimate the total and relative number of full simulations needed
  - Specially important for $\nu$ ($\tau$) induced showers due to huge phase space
    - Extra variables with large impact on shower characteristics
    - Depth of interaction $X_{int}$ ($h_{\text{int}}$): e.g. footprint size and field intensity
    - Type of interaction and it's fluctuations: e.g. $E_{\text{sh}}$ and $\mu$ content

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# 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 $\nu$ CC and NC interactions (HERWIG)
  - Showers induced by $\tau$-lepton decays (TAUOLA)
  - Can propagate $\tau$s from creation to decay
- Uses very fast toymodels:
  - Radio emission: based on full ZHAIRES simulations
  - $\tau$ propagation: parametrizations of $\tau$ propagation simulations
  - Muons at ground level: based on low thinning AIRES simulations

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# 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

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# Radio emission: Superposition "toymodel"

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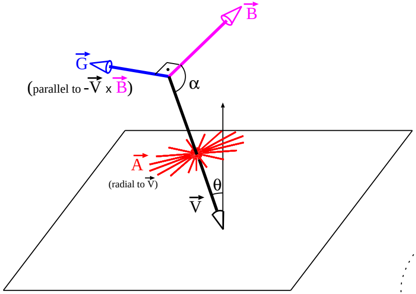
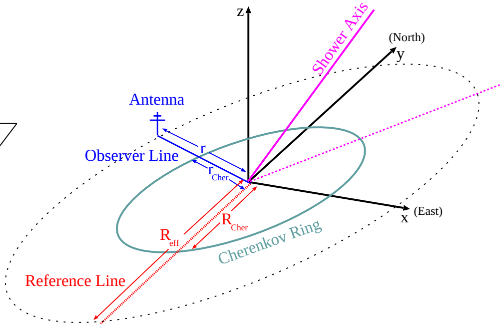
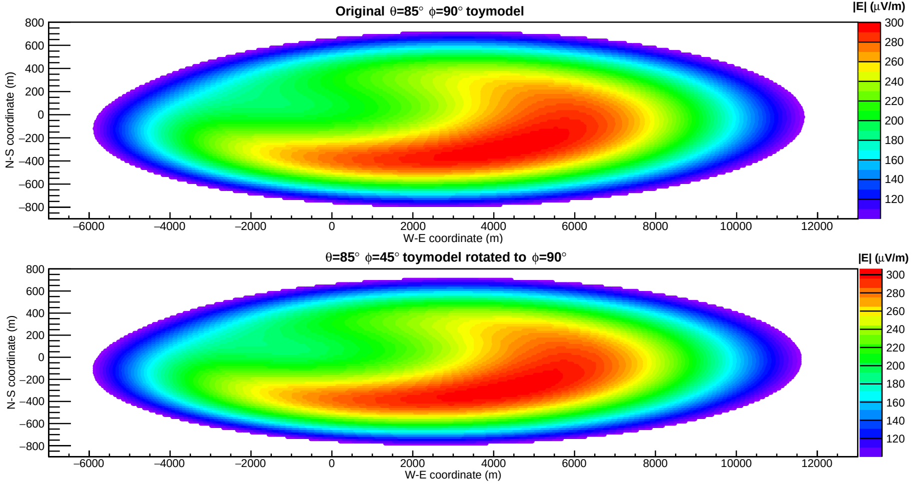


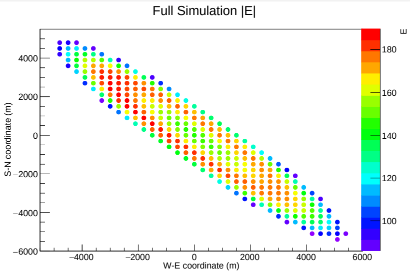



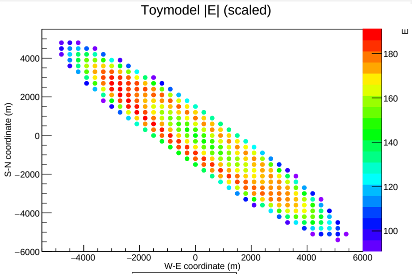
# Example rotation: $\theta = 85^\circ$ from NW to W

Maximum difference between rotated toymodel and dedicated toymodel $\sim 2\%$

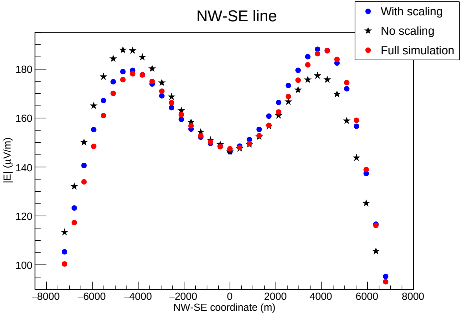


# Toymodel p 1EeV 80°: Comparison to full simulation

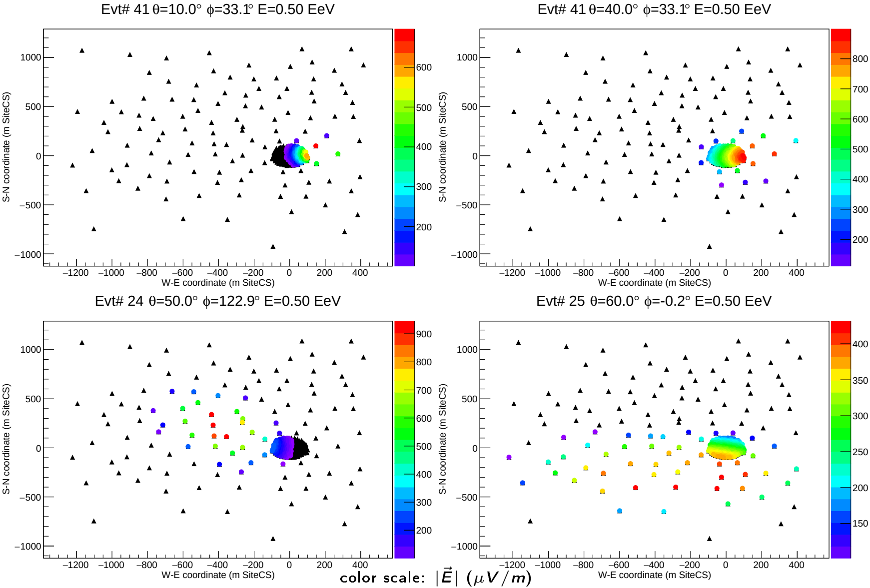



max. diff. $\sim 6\%$

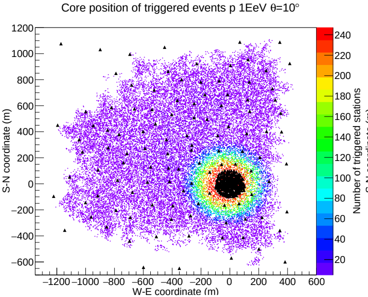


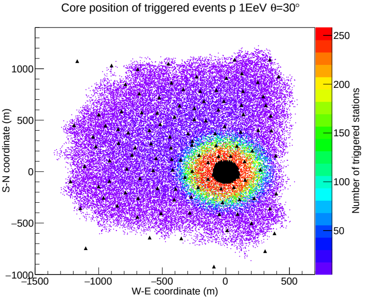
# Example events at OVRO-LWA: proton $5 \cdot 10^{17}$ eV

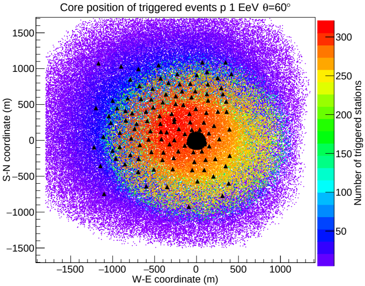



color scale: $|\vec{E}|$ $(\mu V/m)$

# Example 1 EeV triggered core positions at OVRO-LWA

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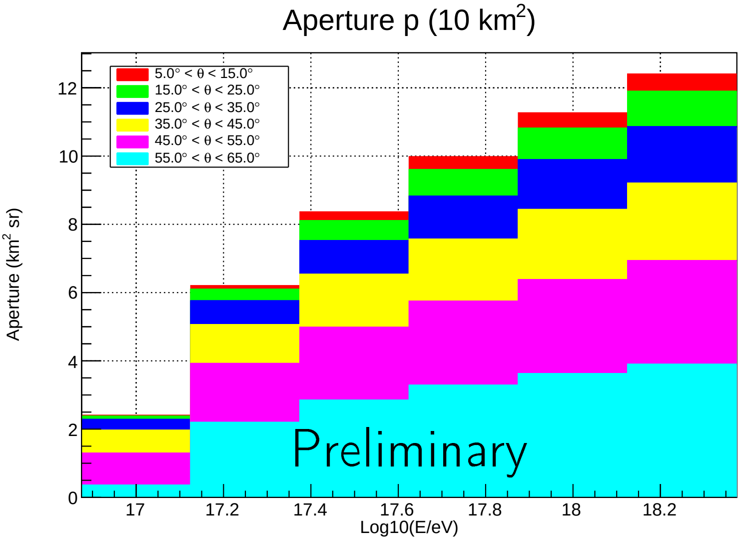
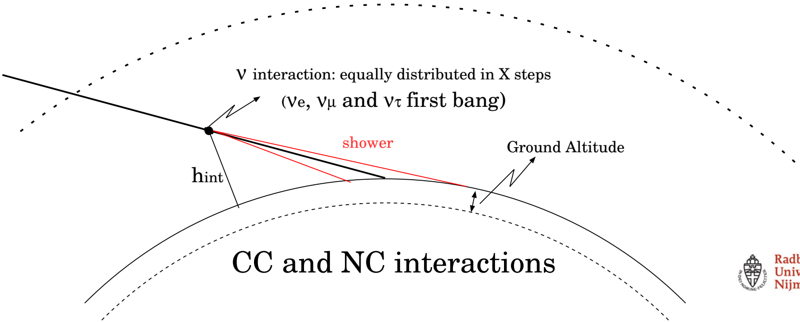
# Aperture estimate for protons at OVRO-LWA



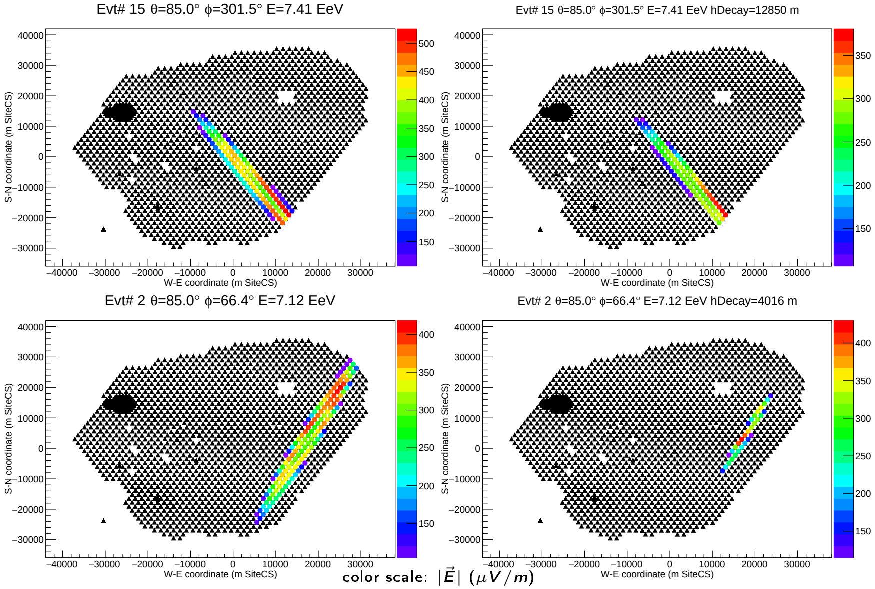

Note: Does not yet take into account veto antennas for RFI rejection (large zenith)

# Downgoing CC and NC events

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



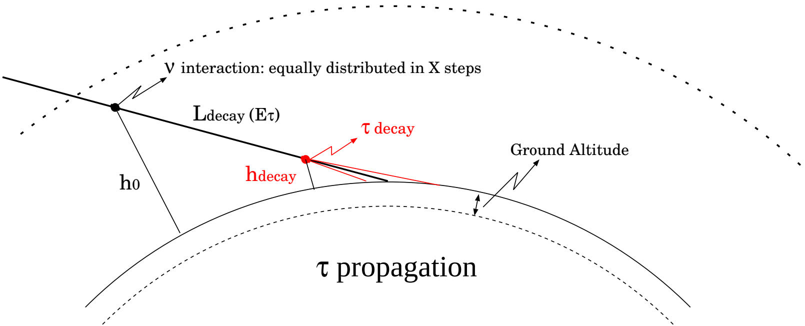
# Example $\gamma$ and $\nu_e$ CC events at $\theta = 85^\circ$ at Auger RD




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

# Tau propagation

Products of $\tau$ decay (Tauola) injected into ZHAireS

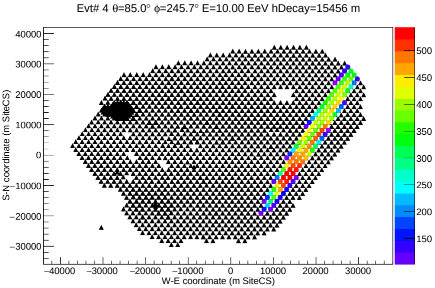


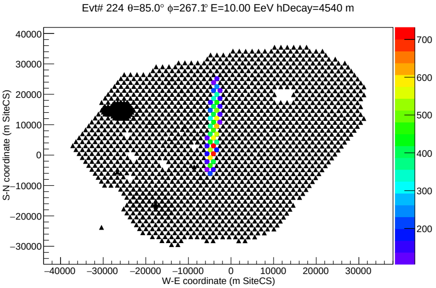
# Sampling $h_0$, $L_{decay}(E)$ and $h_{decay}$

- For speed, we use a simple external $\tau$ propagation simulation
- $dP$: probability of $\tau$ 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 $\Delta L$ steps based on $dP$
  - We disregard the $\tau$ energy losses in air
- From these external simulations we obtain:
  - Fraction of $\tau$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 equl $h_0$ 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 $\tau$ events at $\theta = 85^\circ$ at Auger RD

## Even larger variation in footprint size due to $\tau$ propagation




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

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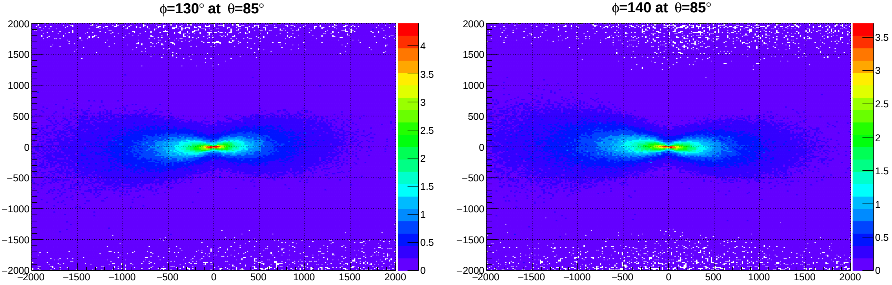
# Simple Particle detector trigger simulation

- Relevant for detectors that trigger with particles (e.g. Auger RD)
- For now only muons (relevant for inclined showers)
- Based on $\mu$ density map toymodel
  - input: Low thinning AIRES simulations of ground muons
  - Can rotate maps: a single AIRES simulation can be used to generate $\mu$ 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

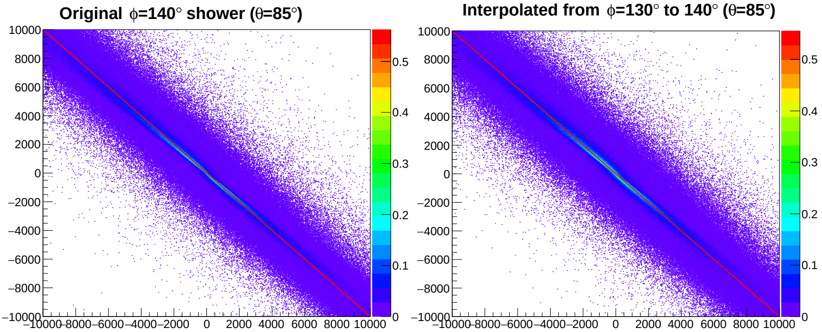
- Ground muons are projected into the perpendicular plane $(\theta, \phi)$
- Perpendicular plane projection taken to be valid for a different azimuth
  - Small difference in the angle $\alpha$ between shower axis and $\vec{B}$
  - Small difference in Lorentz force intensity and direction
  - Small differences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




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 $(\theta, \phi')$
- A ground $\mu$ density map is then created
- The number of muons crossing the detector is sampled from a Poisson distribution based on the $\mu$ map

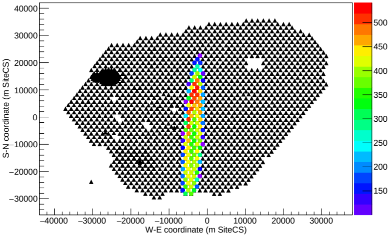


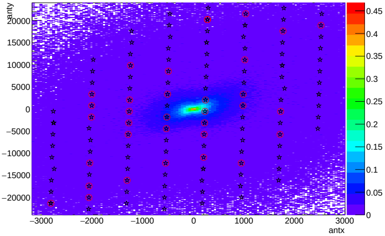

X and Y coordinates at ground level (in m)

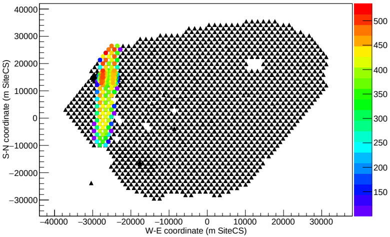
# Few examples of the simple particle trigger

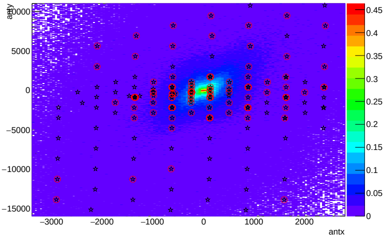
Event map (color is $\mu V/m$)

$\mu$ map and triggered stations (color is $N_\mu/m^2$)



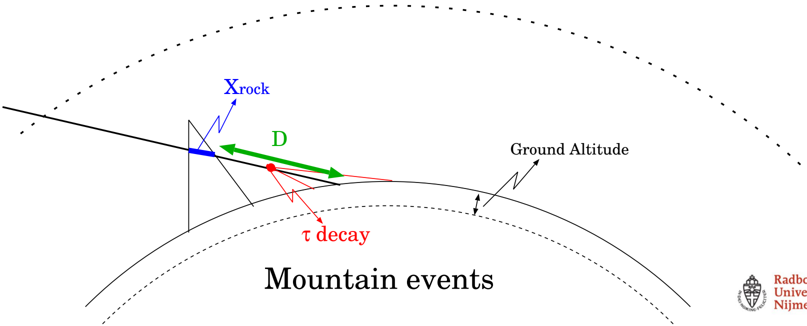



# ToDO

- 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 probablity of tau exit $P_\tau(E_\nu, E_\tau, X_{rock})$ using e.g. NuTauSim
  - Apply same procudure as regular downgoing $\tau$ decay



# Questions?

**Other applications of Radio...**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# BACKUP

# 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 $\mu^-$ towards the ground diminishing their paths and pushes $\mu^+$ up increasing their paths until they reach the ground
  - Smaller average path decreases total deflection of $\mu^-$ if compared to $\mu^+$.
  - $\mu^-$ are concentrated in the early part of the shower footprint and $\mu^+$ in the late part.
  - Number density asymmetry: Higher number density in the early part of the muon footprint ($\mu^-$) due to the smaller deflections on average. Easily visible on projected maps on the perpendicular plane.

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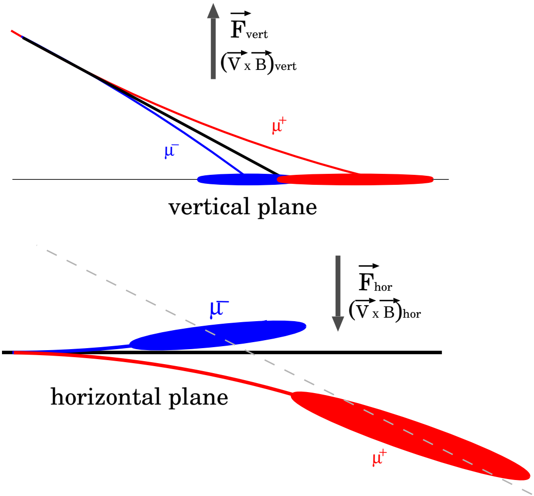
# Effect of $\vec{B}$ on muon maps: vertical component



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

- Horizontal component separates $\mu^+$ and $\mu^-$ 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 $\mu^+$ and $\mu^-$ makes $\mu^+$ 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 paralell to shower axis projection
- Large azimuth and B inclination depence. Can cause rotations on the perpendicular plane (pattern may not align with $\vec{V} \times \vec{B}$).

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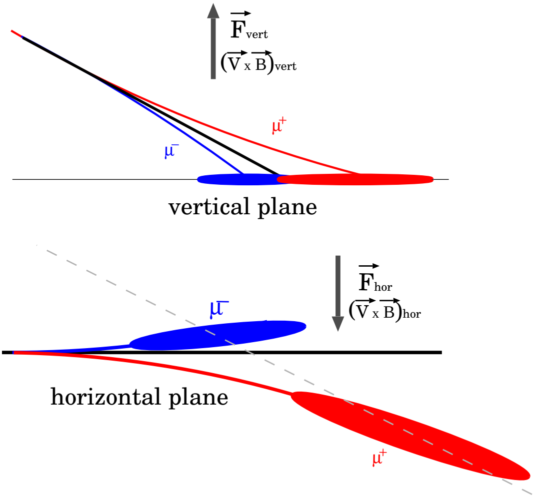
# Effect of $\vec{B}$ on muon maps: horizontal component

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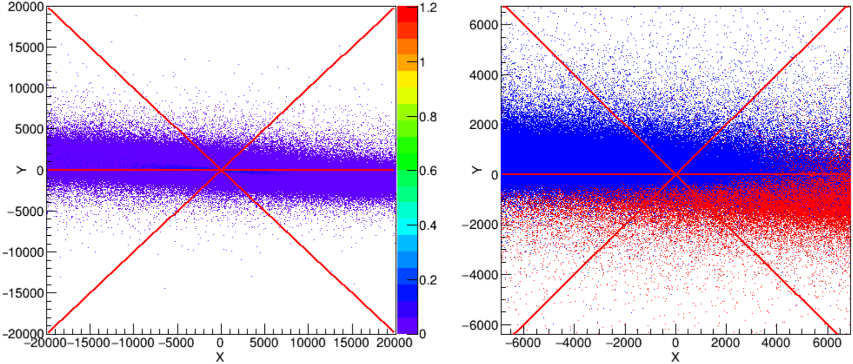
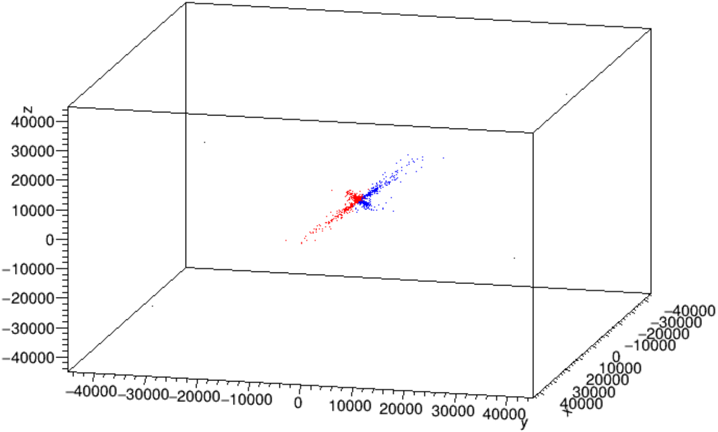
# Largest effect example: Shower from W, with B incl.

- 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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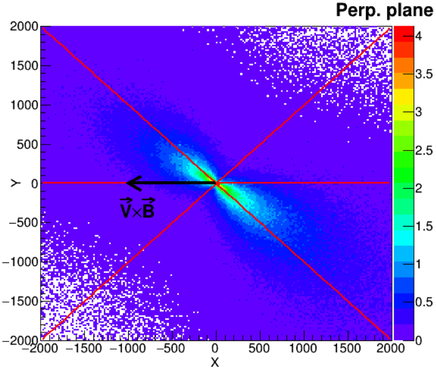
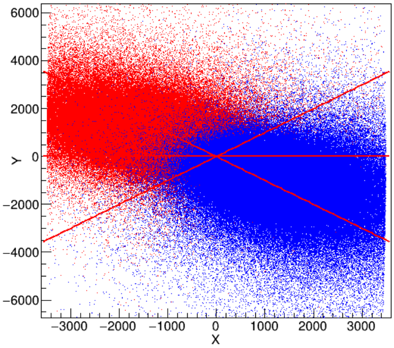
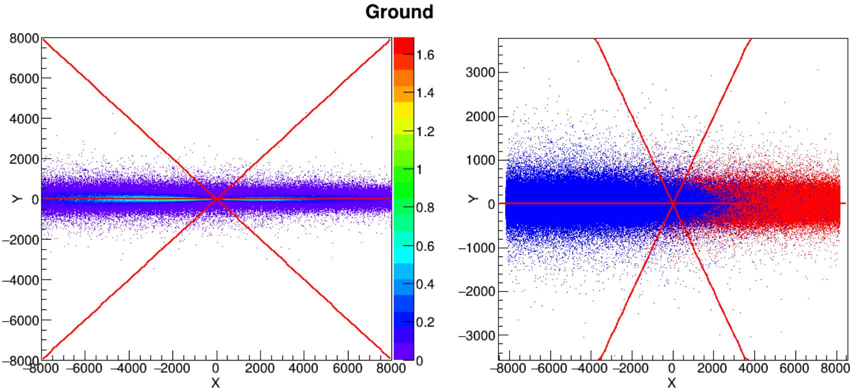


# No horizontal $\vec{V} \times \vec{B}$ component: from W, no B incl.

- 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 $\mu^-$ and Late $\mu^+$. Footprint still asymmetric



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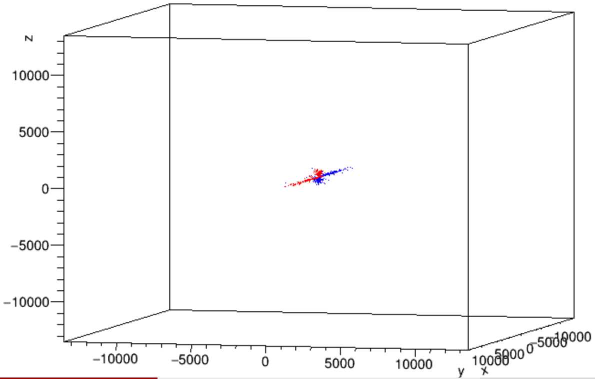


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