RNO-G

Radio Neutrino Observatory - Greenland

CORSIKA 8 Ray Tracing

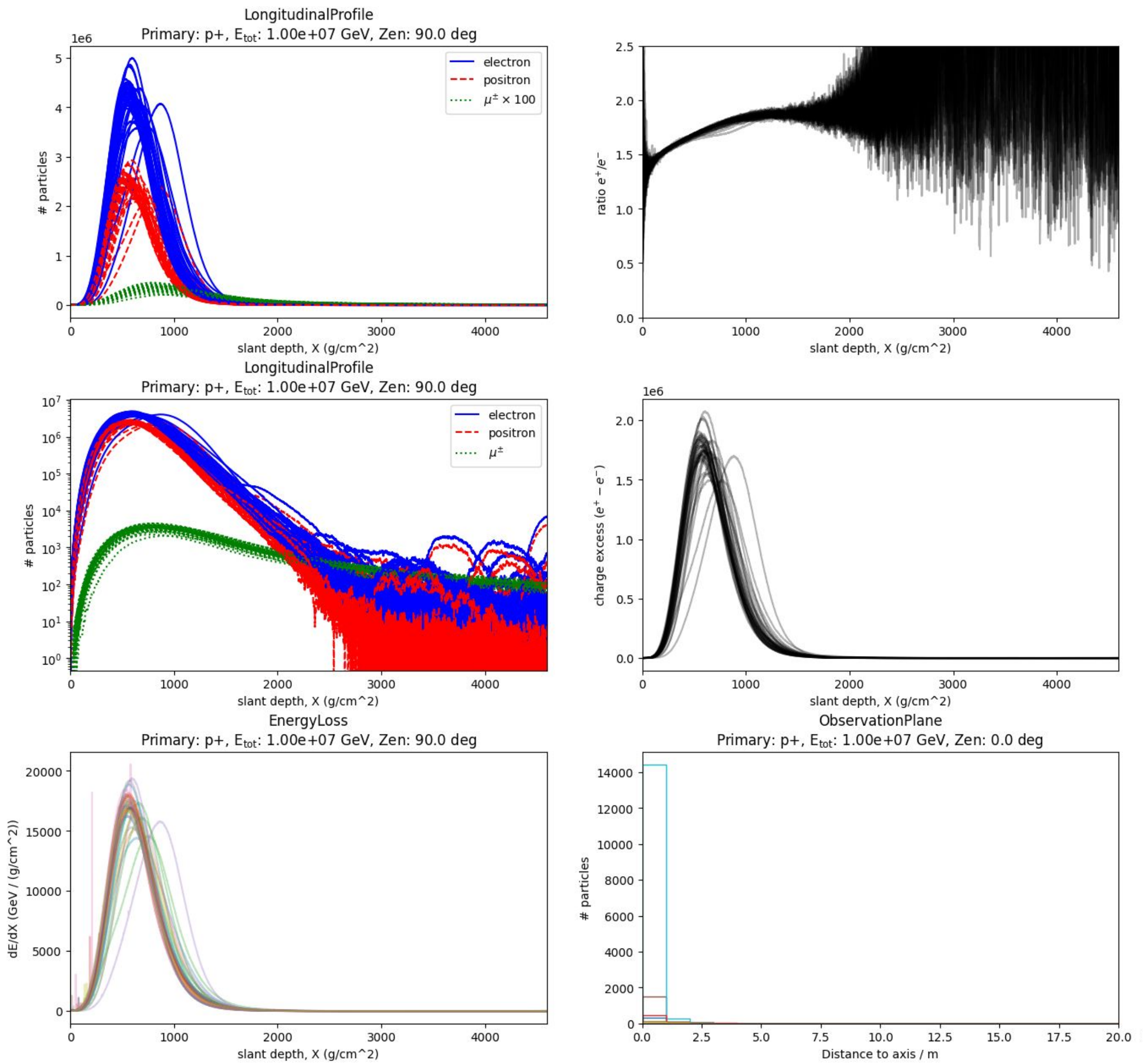
Alan Coleman

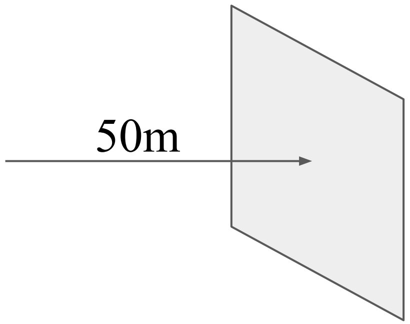
Maria Duran de las Heras

2023.02.29 (Leap Day!)

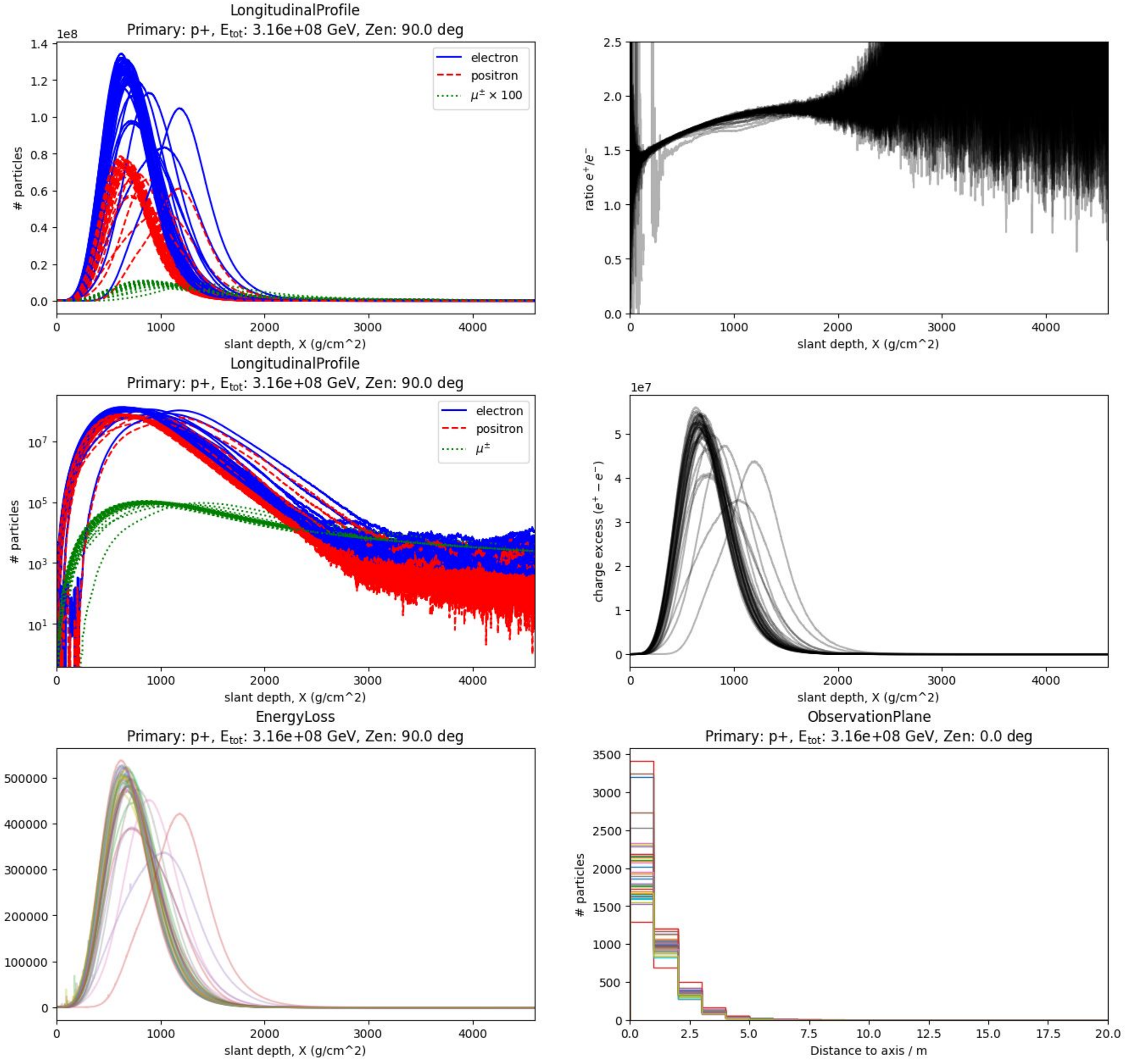
UPPSALA UNIVERSITET

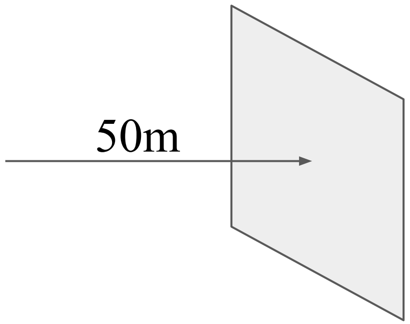
In Ice Showers





lg(E/eV) = 16.0
proton

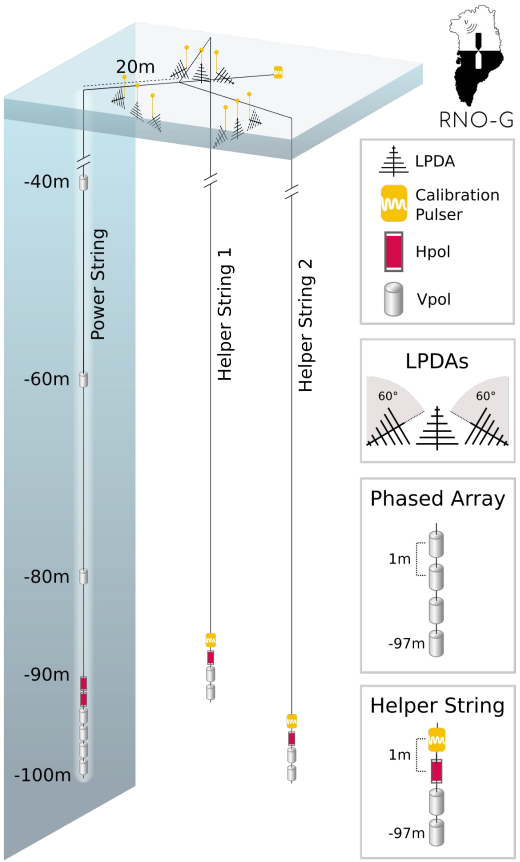


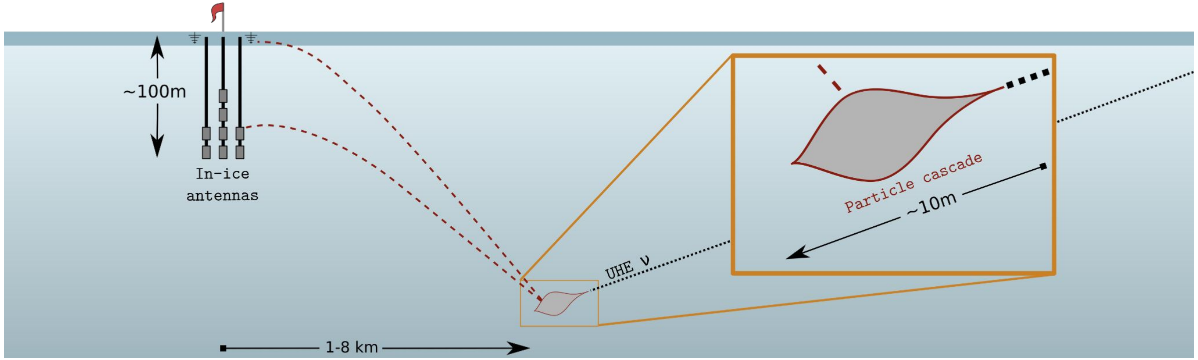


lg(E/eV) = 17.5
proton

In Ice Radio Emission

Refractive Trajectories





In CORSIKA7 (and 8, so far) assume line-of-sight

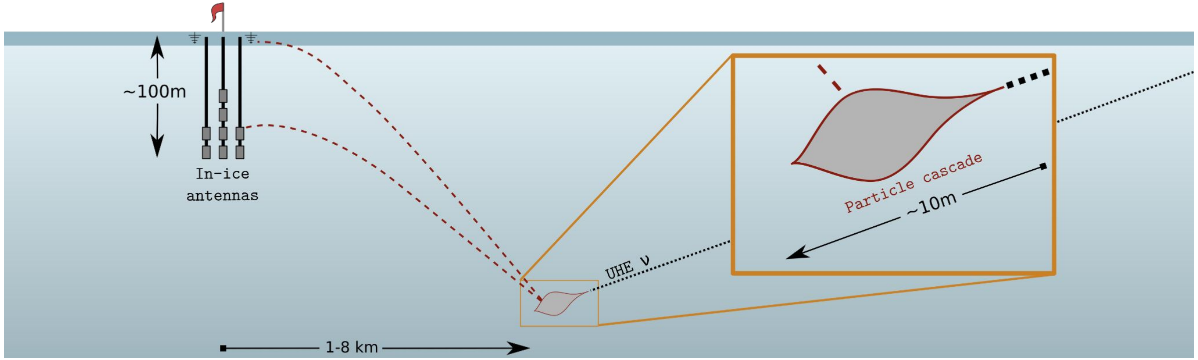
Good approximation for air showers

Bad approximation for ice showers

Technical Details

dv/dt = grad(n) / n^2

dx/dt = v / n



AKA: these are the kinematic equations

with g → g(h)

Many integrators "on the market" to solve this → Cash-Karp algorithm

Includes estimations of the uncertainty per step ⇒ allows for adaptive step size

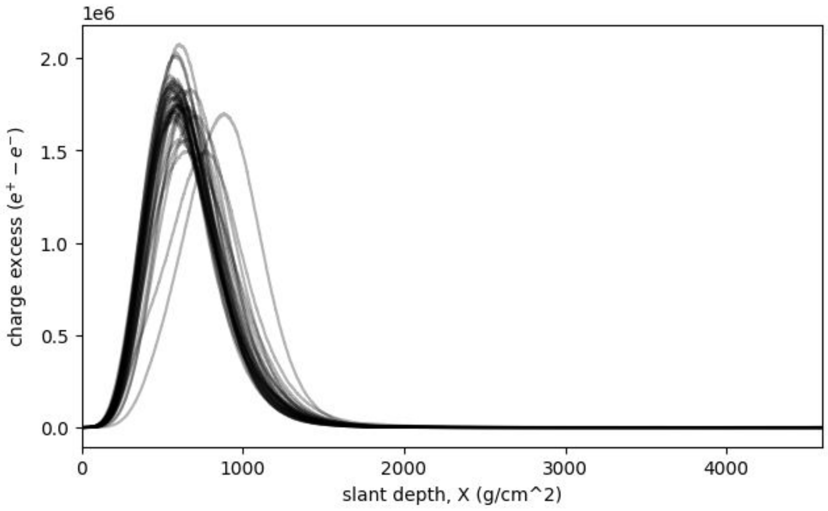
Taken from "RadioPropa" which was taken from "CRPropa"   :)

NuRadioMC Emission

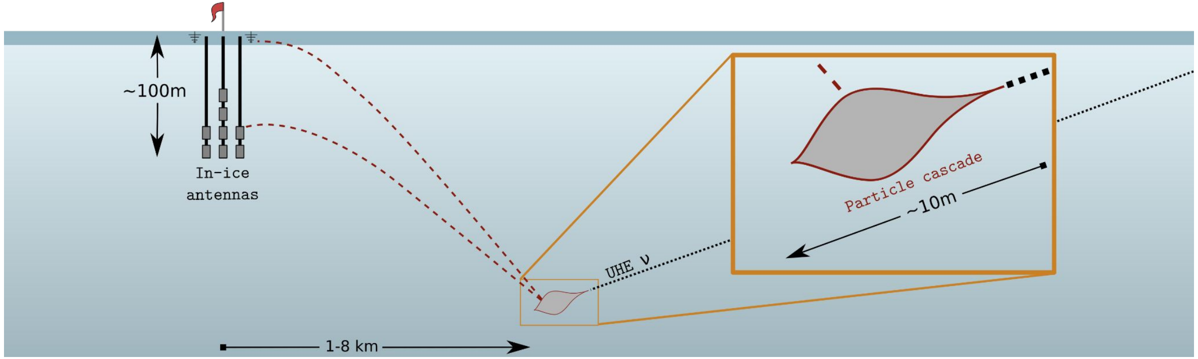
Pulses generated as a function of frequency and angle from axis is modeled ("ARZ")

10 charge excess profiles per lg(E) = 0.1 are stored as tables. Randomly choose one per simulation

Generate neutrino signal by **convolving the signal model (ARZ) with tabulated charge excess profiles**

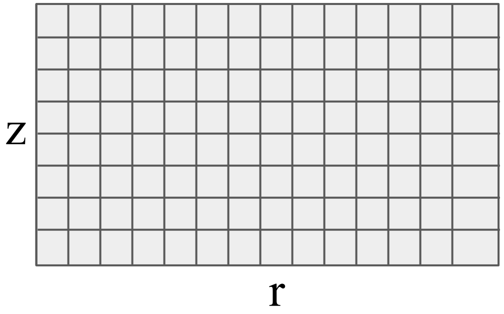


Goal



Before the shower begins
generate a table of ray solutions from each antenna to “all” points in the ice

At run-time:
For each secondary, interaction look-up/interpolate the solution from the table



For now, tackle the main use case:
translationally/cylindrically symmetric ice profiles

Ray Tracing

Ray tracing in ice models for monotonically changing index of refraction

Needed quantities:

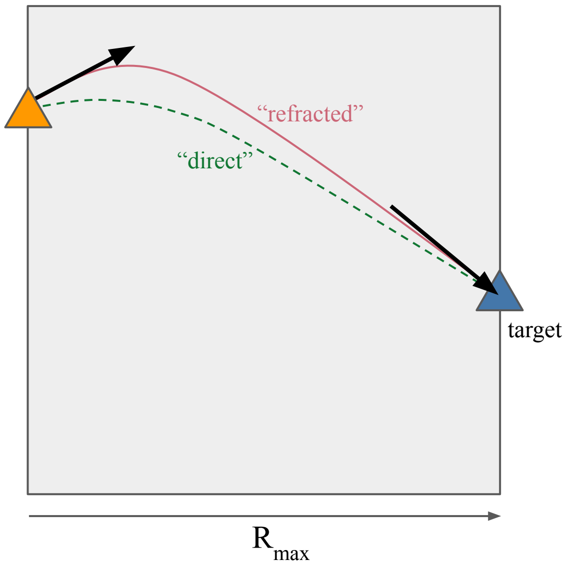
1. launch angle?
2. receiving angle → response of the antenna
3. length of path → attenuation of signal (1/r)
4. time of flight → when the signal arrives

Implemented in C8

1. ray propagator (arbitrary refraction scalar field)
2. basic reflections off of surface
3. solution finder for field which changes in 1D (along z, in this case)

To implement:

1. higher order optical effects (lensing, phase delays)

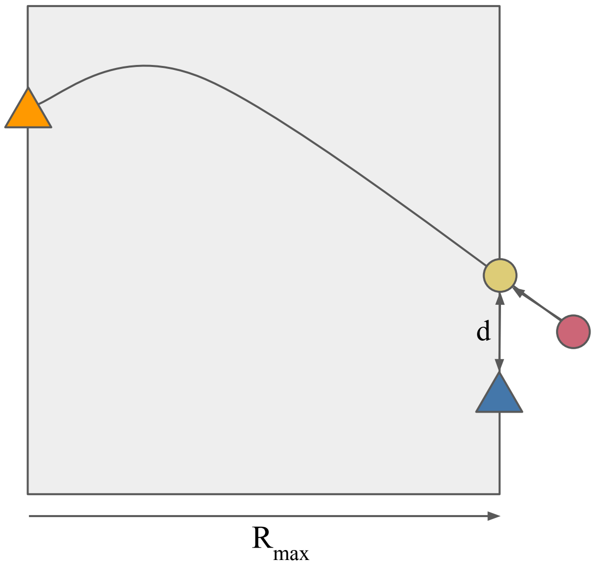


3D Propagation

Propagates in **arbitrary** medium for which n(x) and Grad n(x) are defined

Implemented solution finder assuming that ice is cylindrically symmetric

```
minimize d {
    While (r < R_max)
        propagate forwards
        perform reflections, as needed
    Find point on trajectory where r == R
    d = |r - r_target|
}
```

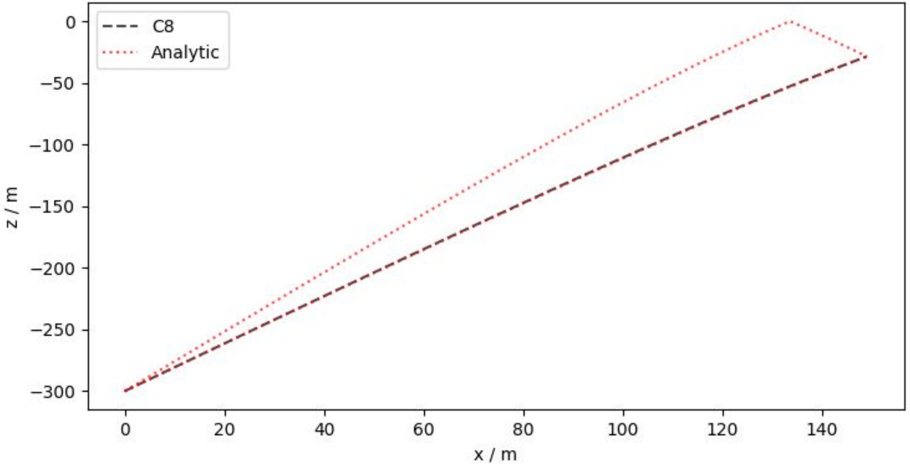


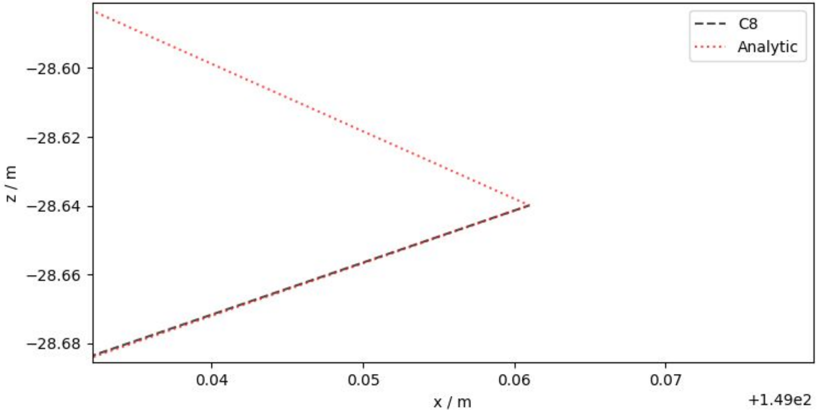
minimization performed using numerical derivative

Comparison to NuRadioMC

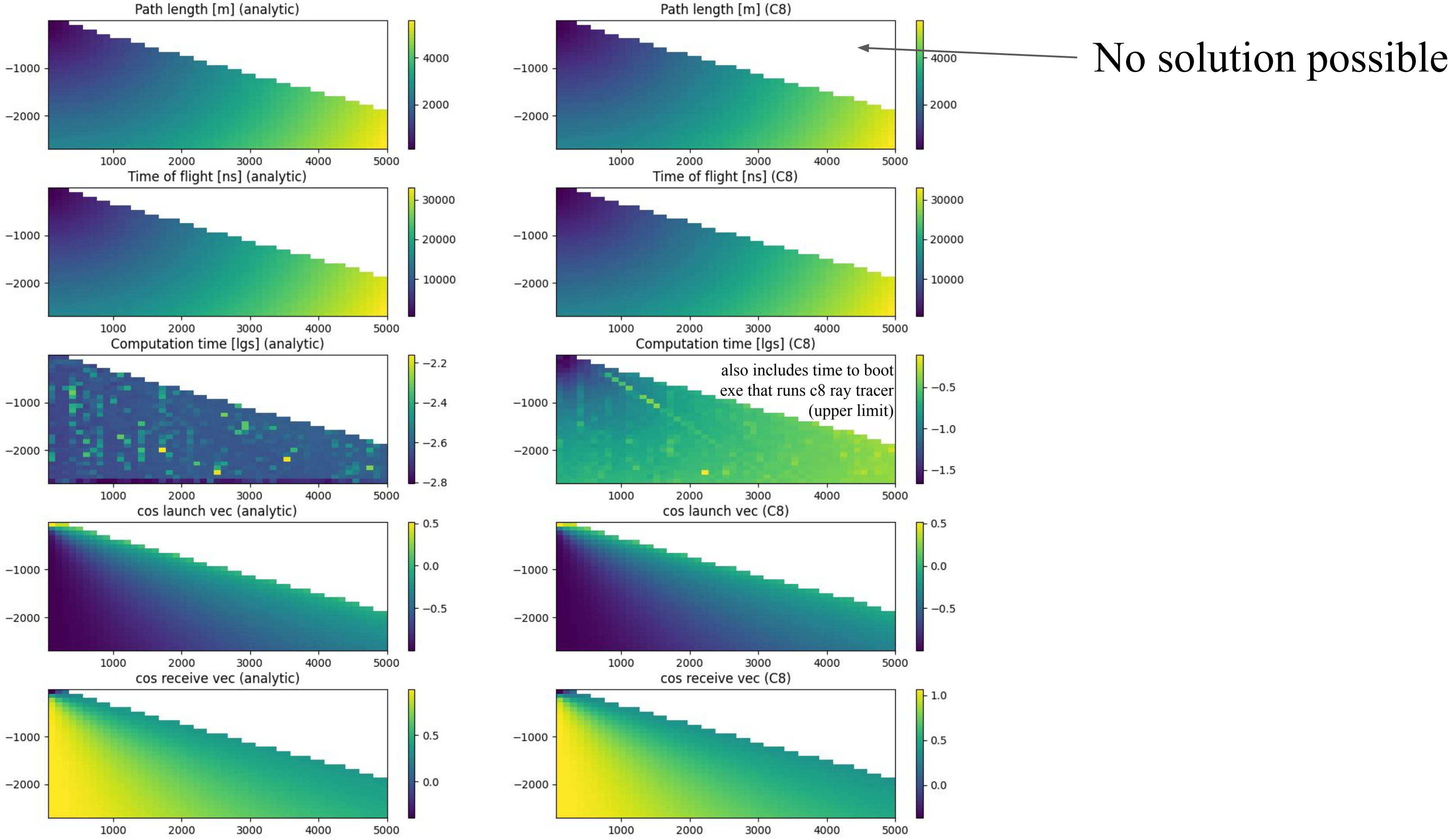
IF: the refractive index changes exponentially, can solve paths analytically

Benchmark my implementation to solutions in NuRadioMC for exponential n-profile

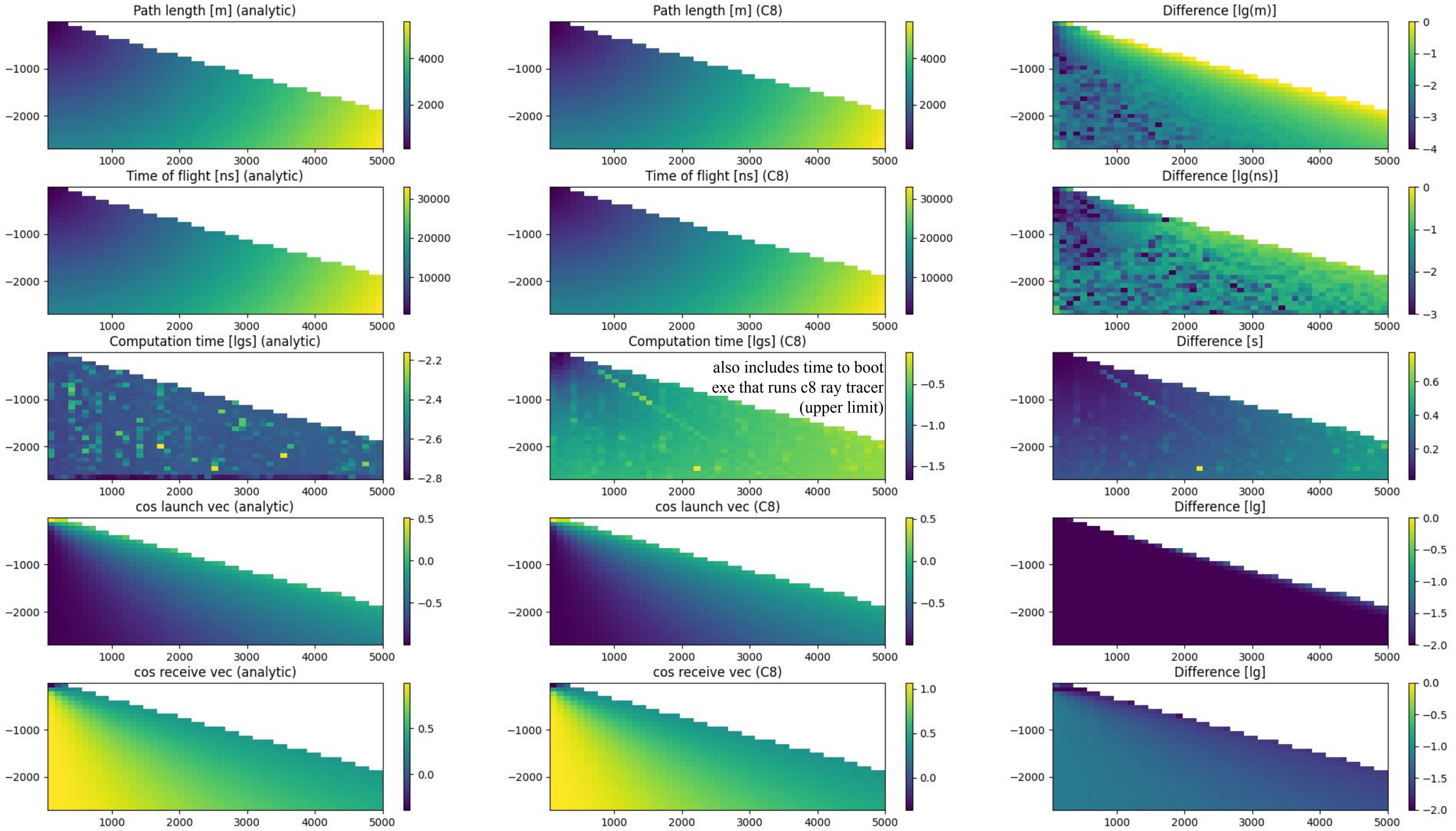




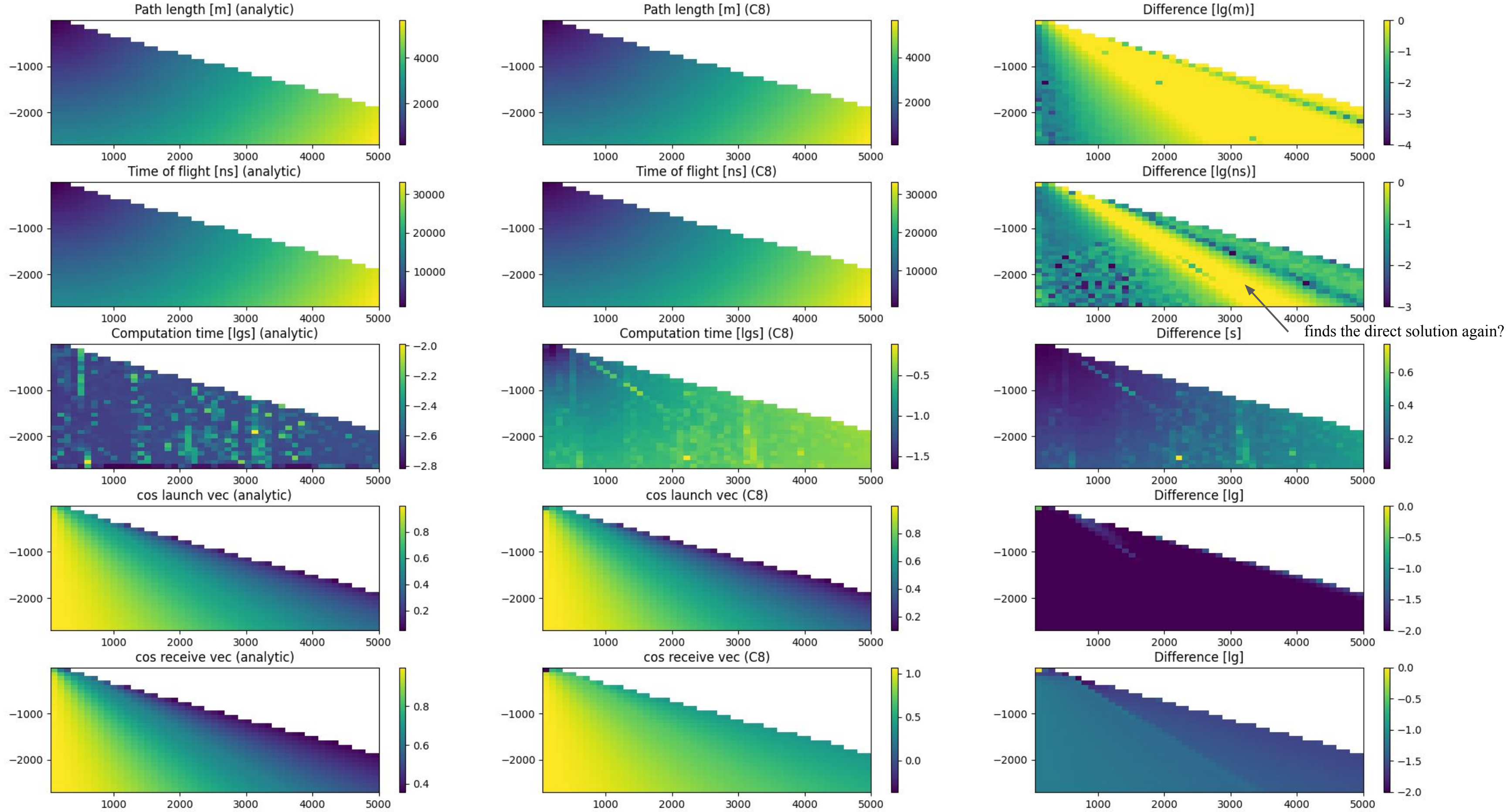
Comparison for South Pole Ice (direct)



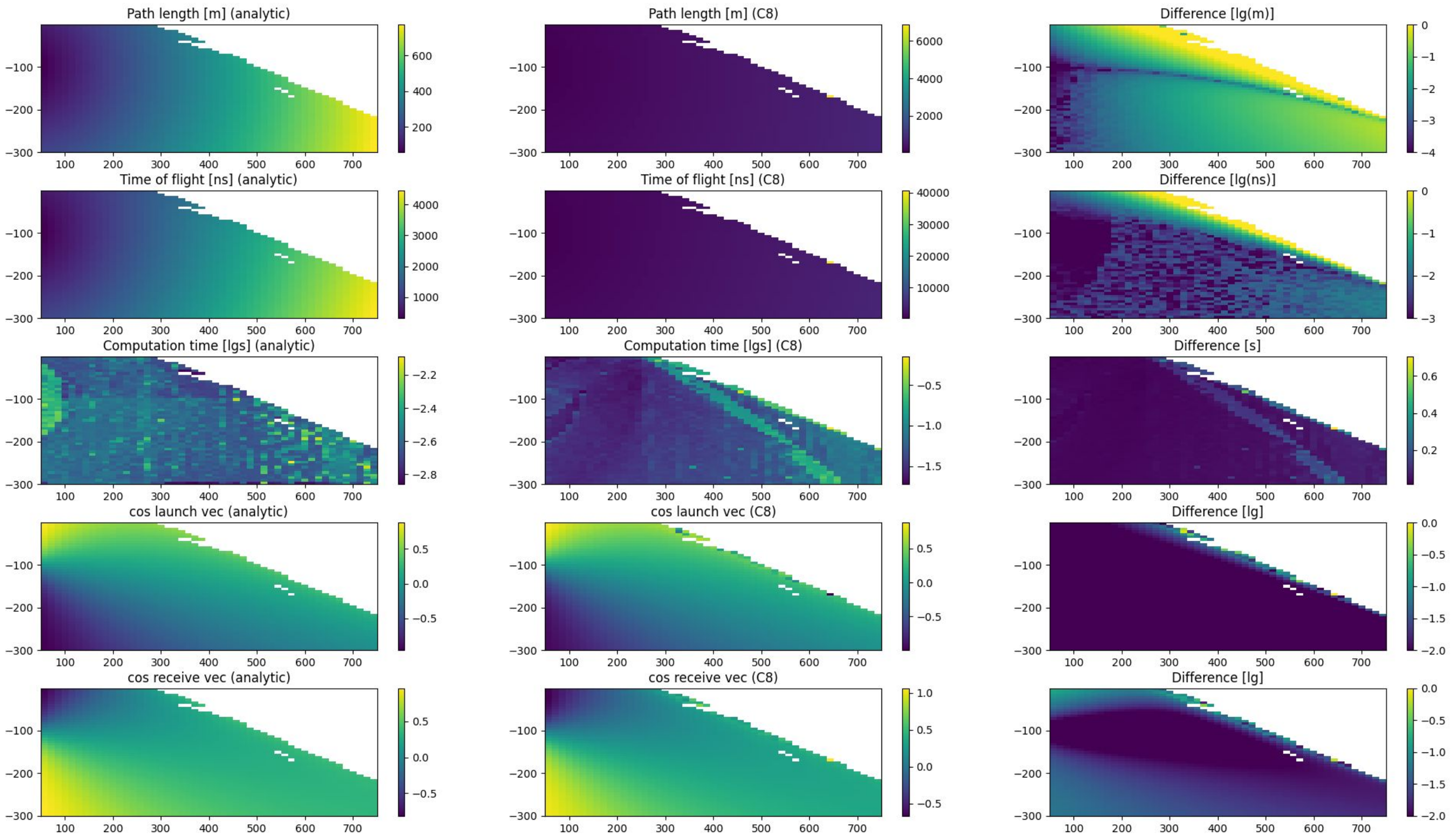
Comparison for South Pole Ice (direct)



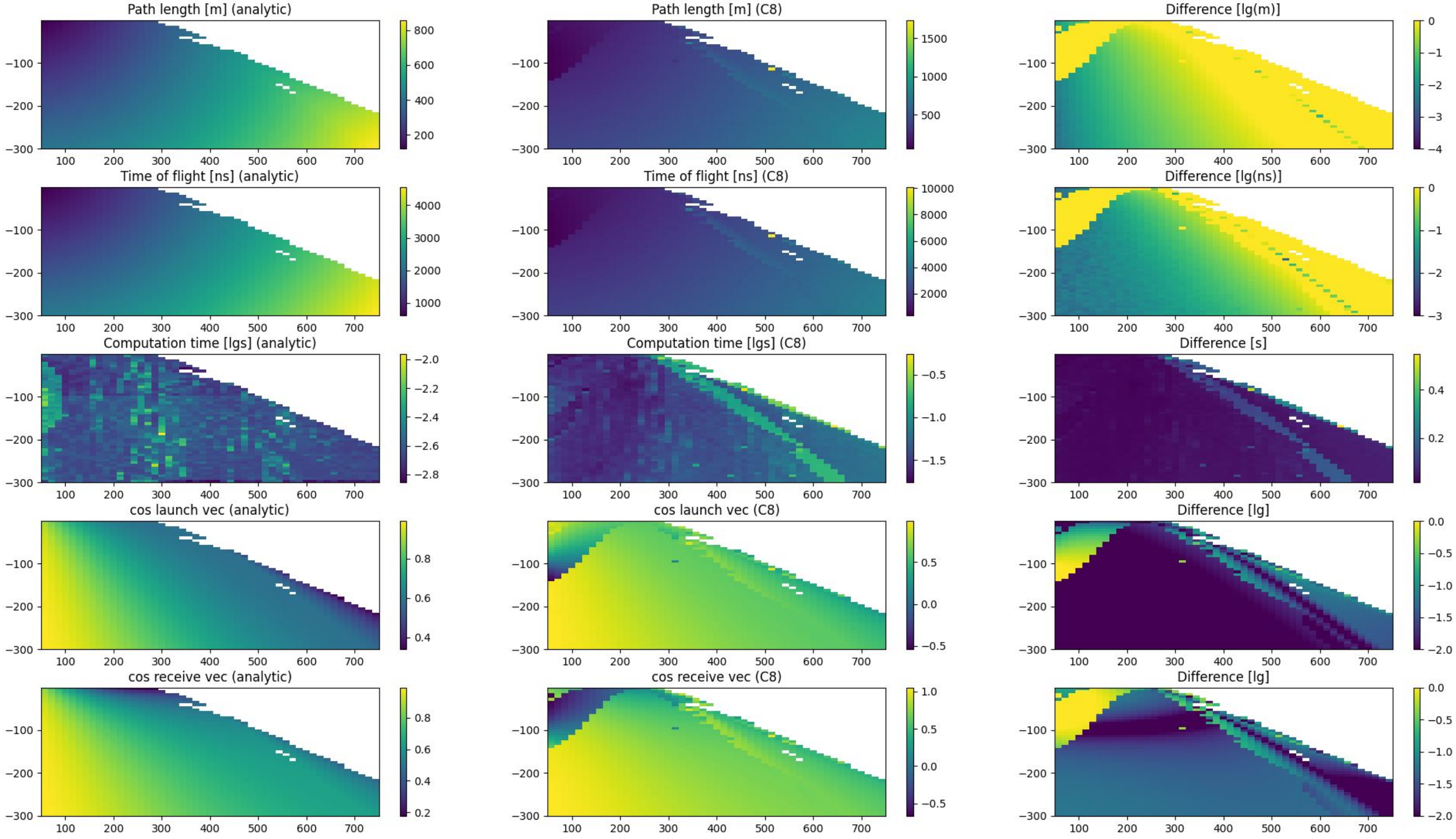
Comparison for South Pole Ice (refracted)



Comparison for South Pole Ice (direct)



Comparison for South Pole Ice (refracted)

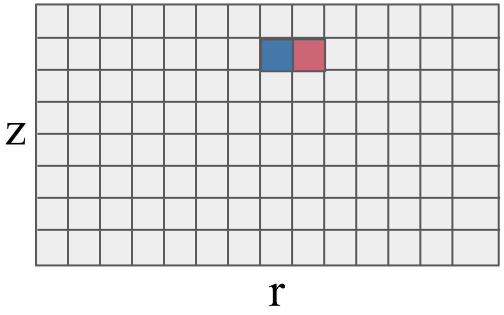


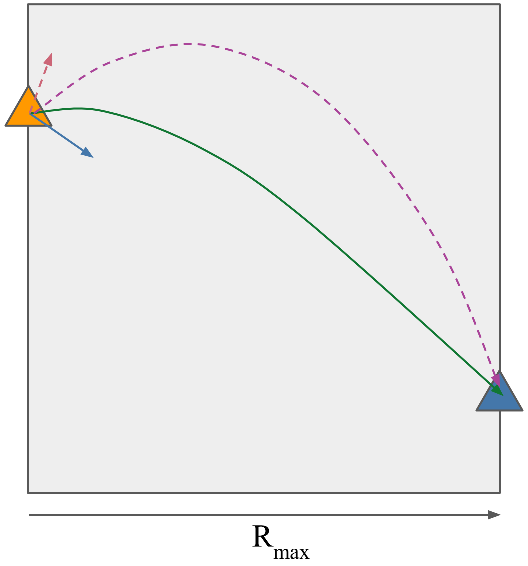
Seeding Issue

1. First seed (direct) is line-of-sight
2. Find actual (?direct?) solution
3. Seed (refracted) with $\cos(\theta_{refract}) = -\frac{1}{4}\cos(\theta_{direct}) + \frac{3}{4}$
4. Find actual (refracted) solution

The minimizer can skip over the refracted solution or is initialized in the wrong "valley"

Solution: when building the tables, use the solution of the adjacent cell as a seed, should be close to correct

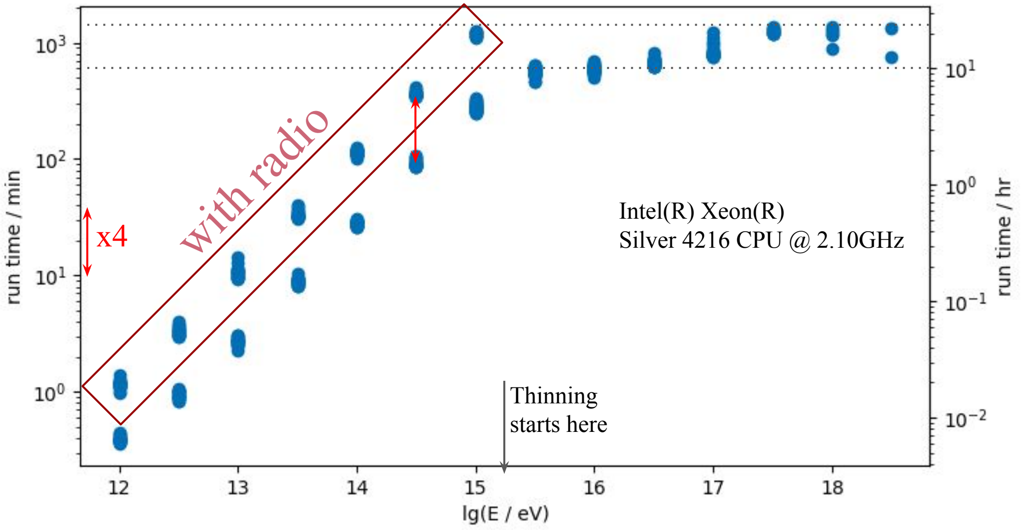


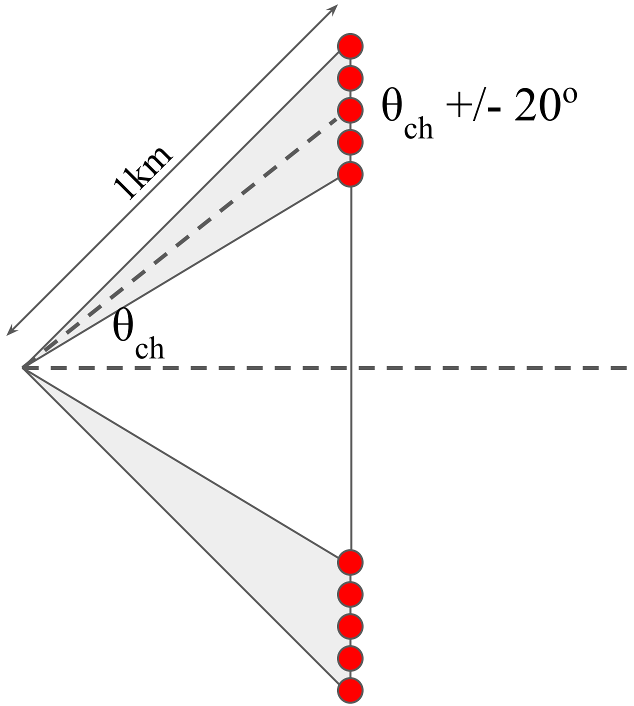


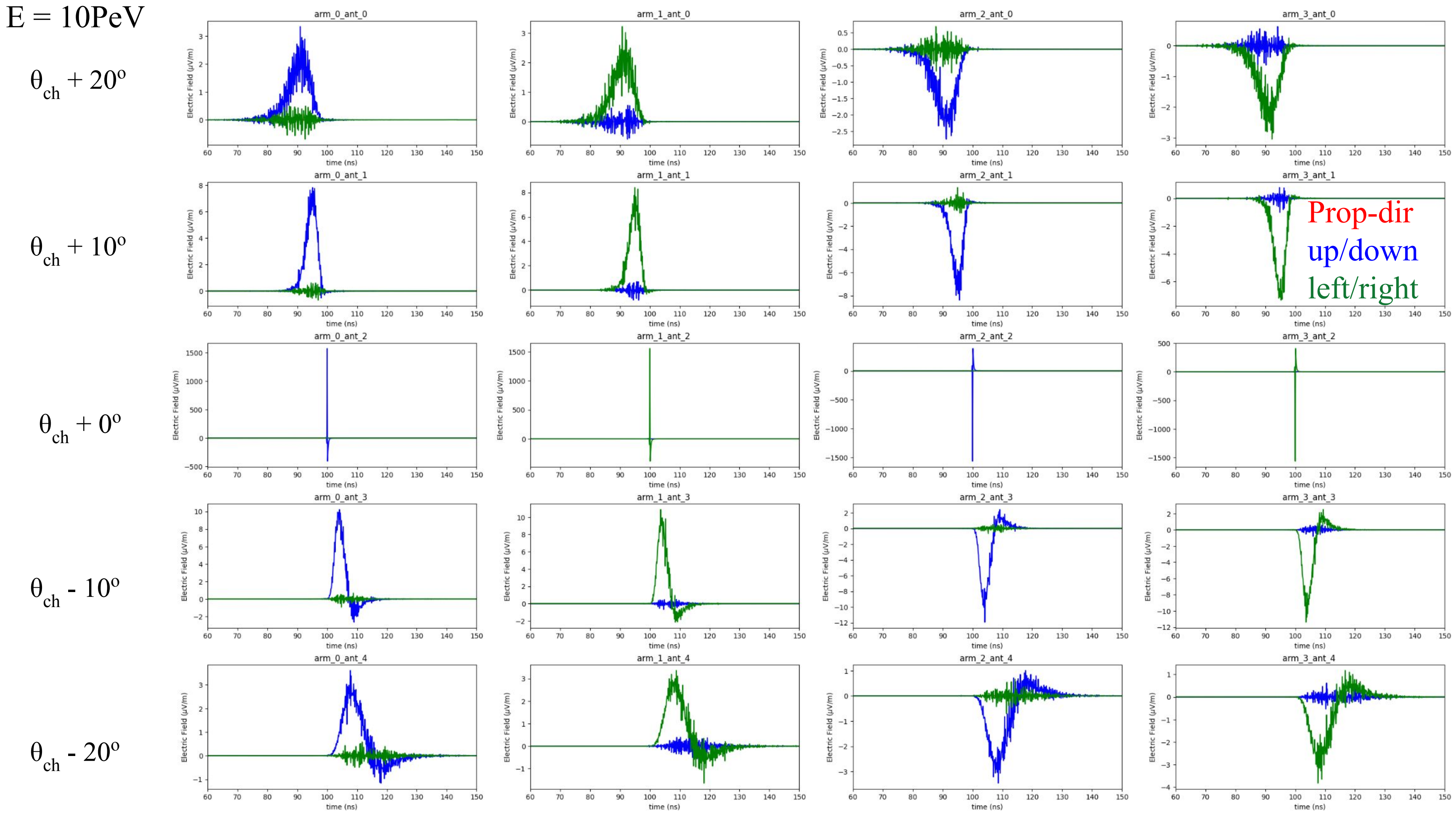
Simulations with Radio

C8 Simulations

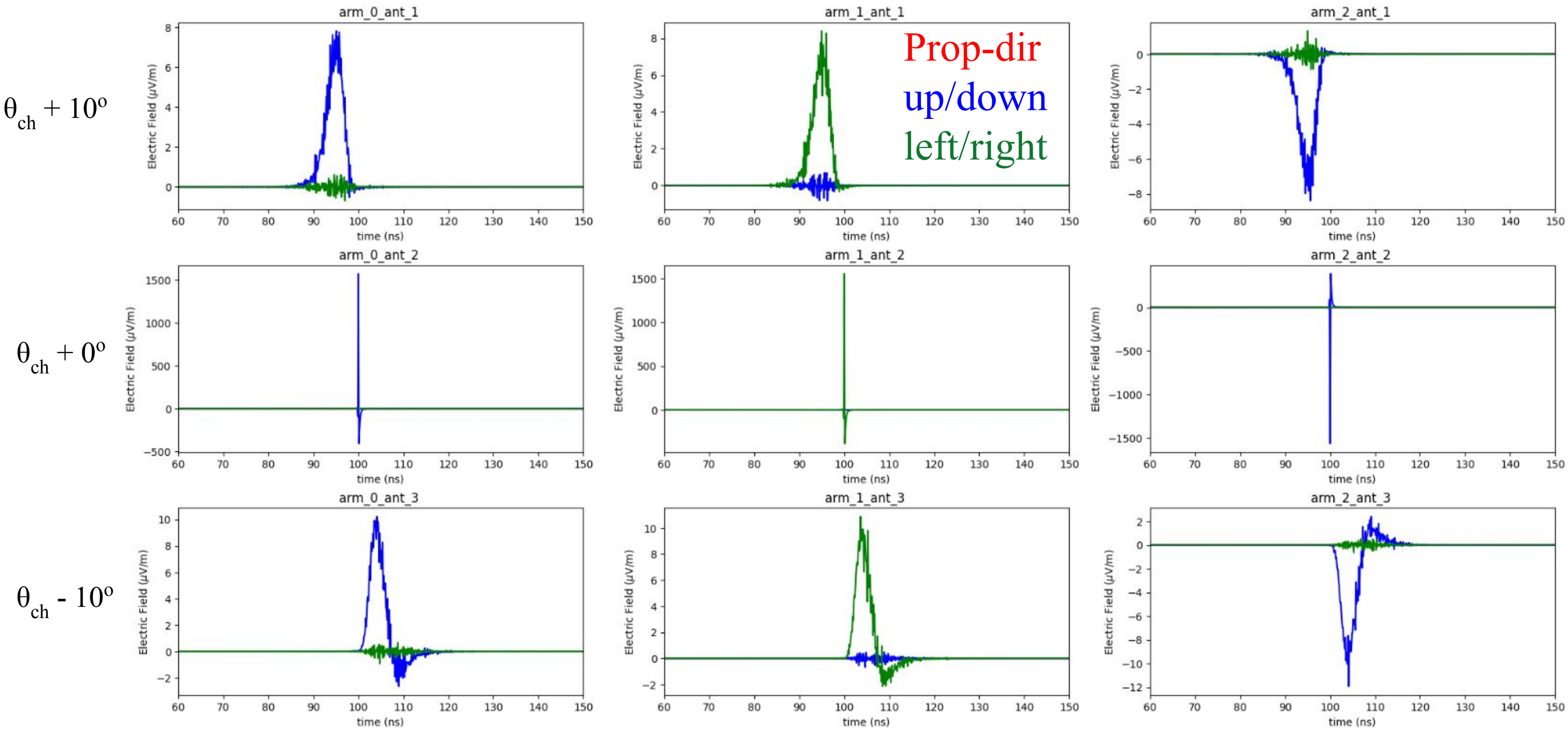
Simulations in ice
Uniform refractive index
End-point-formalism for <u>straight line propagation</u>
20 antennas spread across the Cherenkov cone






E = 10PeV
$\theta_{ch} + 20^o$
$\theta_{ch} + 10^o$
$\theta_{ch} + 0^o$
$\theta_{ch} - 10^o$
$\theta_{ch} - 20^o$
arm_0_ant_0
arm_1_ant_0
arm_2_ant_0
arm_3_ant_0
arm_0_ant_1
arm_1_ant_1
arm_2_ant_1
arm_3_ant_1
arm_0_ant_2
arm_1_ant_2
arm_2_ant_2
arm_3_ant_2
arm_0_ant_3
arm_1_ant_3
arm_2_ant_3
arm_3_ant_3
arm_0_ant_4
arm_1_ant_4
arm_2_ant_4
arm_3_ant_4
Electric Field (μV/m)
time (ns)
Prop-dir
up/down
left/right

E = 10PeV



$\theta_{ch} + 10^o$
$\theta_{ch} + 0^o$
$\theta_{ch} - 10^o$
arm_0_ant_1
arm_1_ant_1
arm_2_ant_1
arm_0_ant_2
arm_1_ant_2
arm_2_ant_2
arm_0_ant_3
arm_1_ant_3
arm_2_ant_3
Prop-dir
up/down
left/right
Electric Field (μV/m)
time (ns)

E = 10PeV

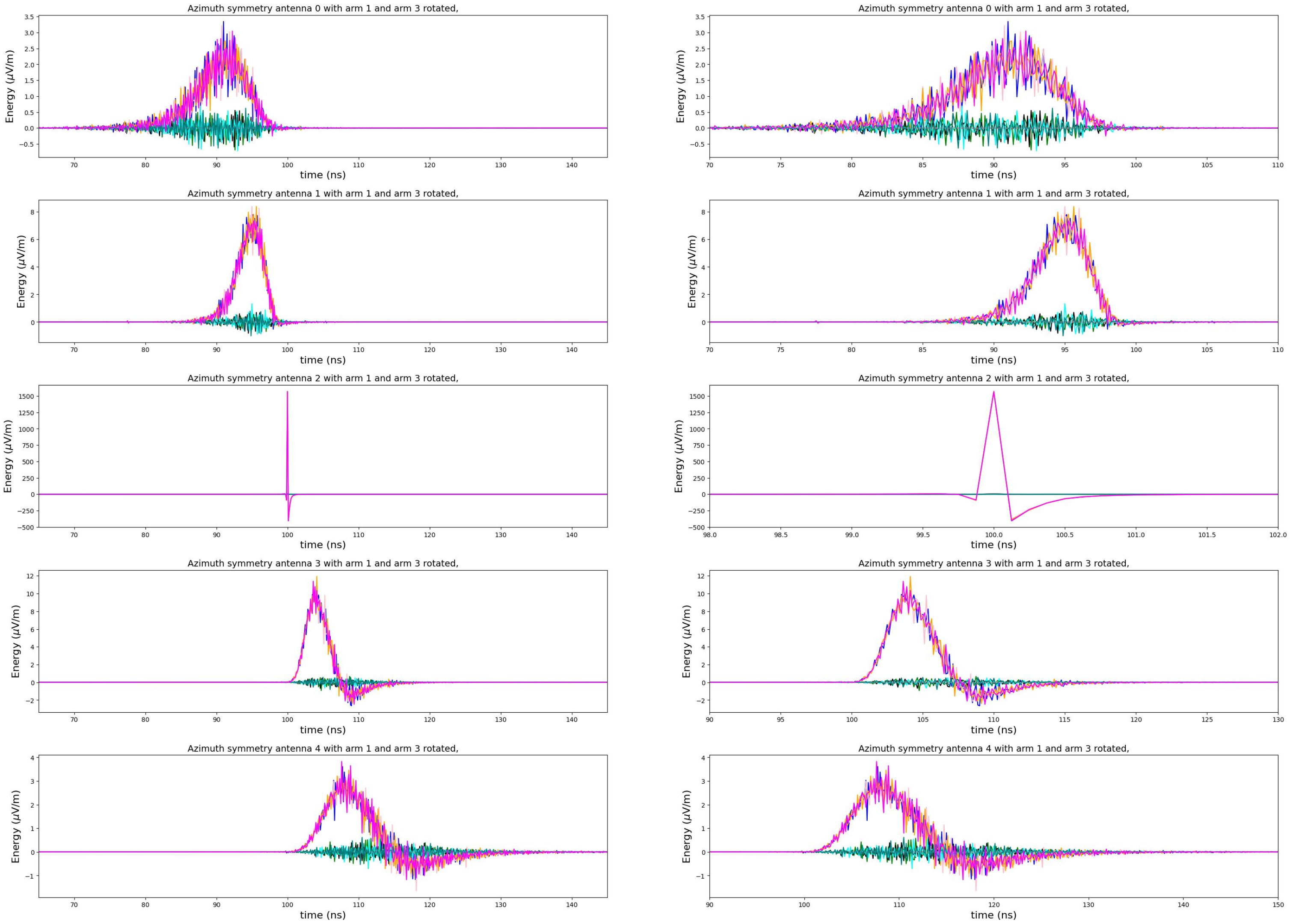
θ_{ch} + 20°

θ_{ch} + 10°

θ_{ch} + 0°

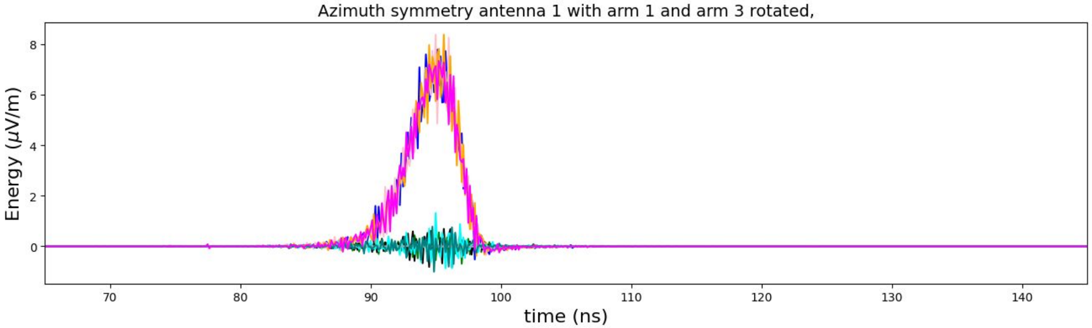
θ_{ch} - 10°

θ_{ch} - 20°

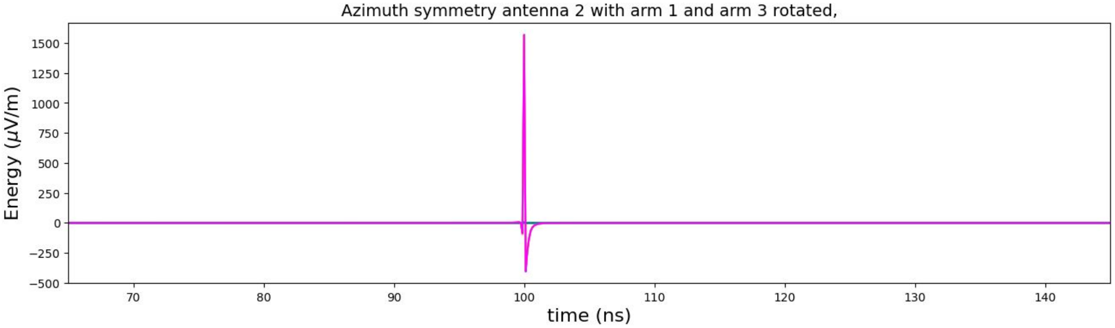


E = 10PeV

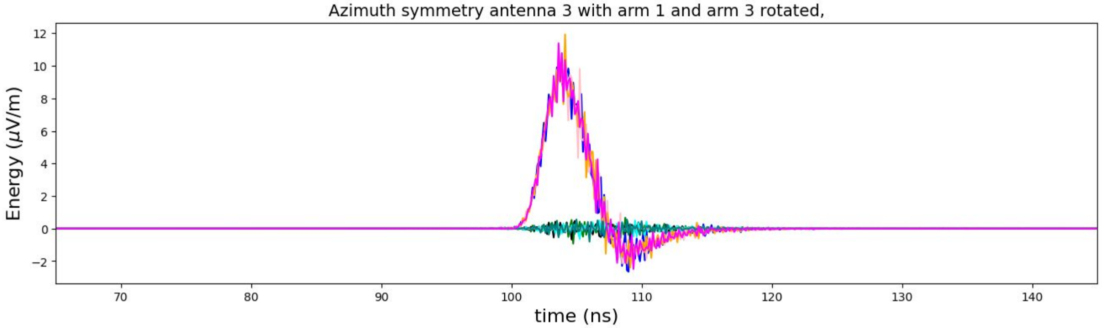
$\theta_{ch} + 10^o$



$\theta_{ch} + 0^o$



$\theta_{ch} - 10^o$

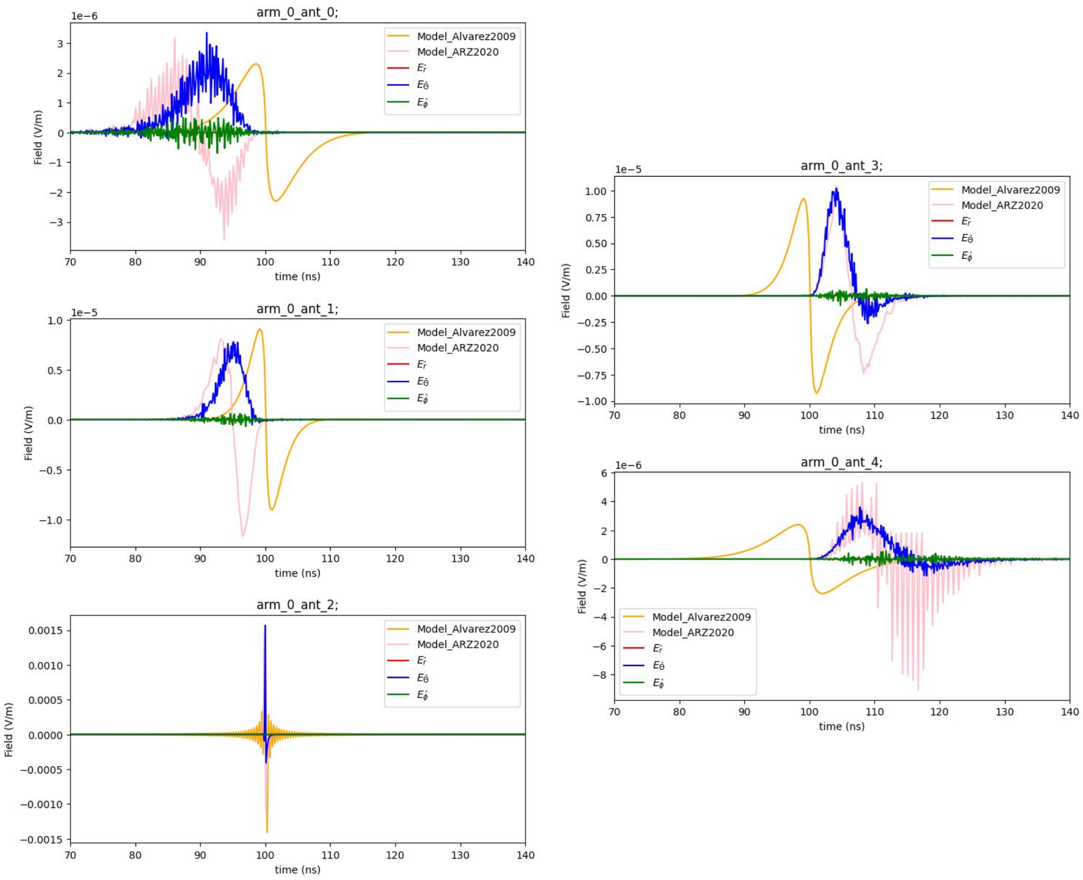


Comparison to NuRadioMC

Two models for radio emission in NuRadioMC
ARZ is more advanced

Compare for a 10^{16} eV shower
(not apples-to-apples)

These models have negative pulse, generally lacking in C8
Which is correct?



Next Steps

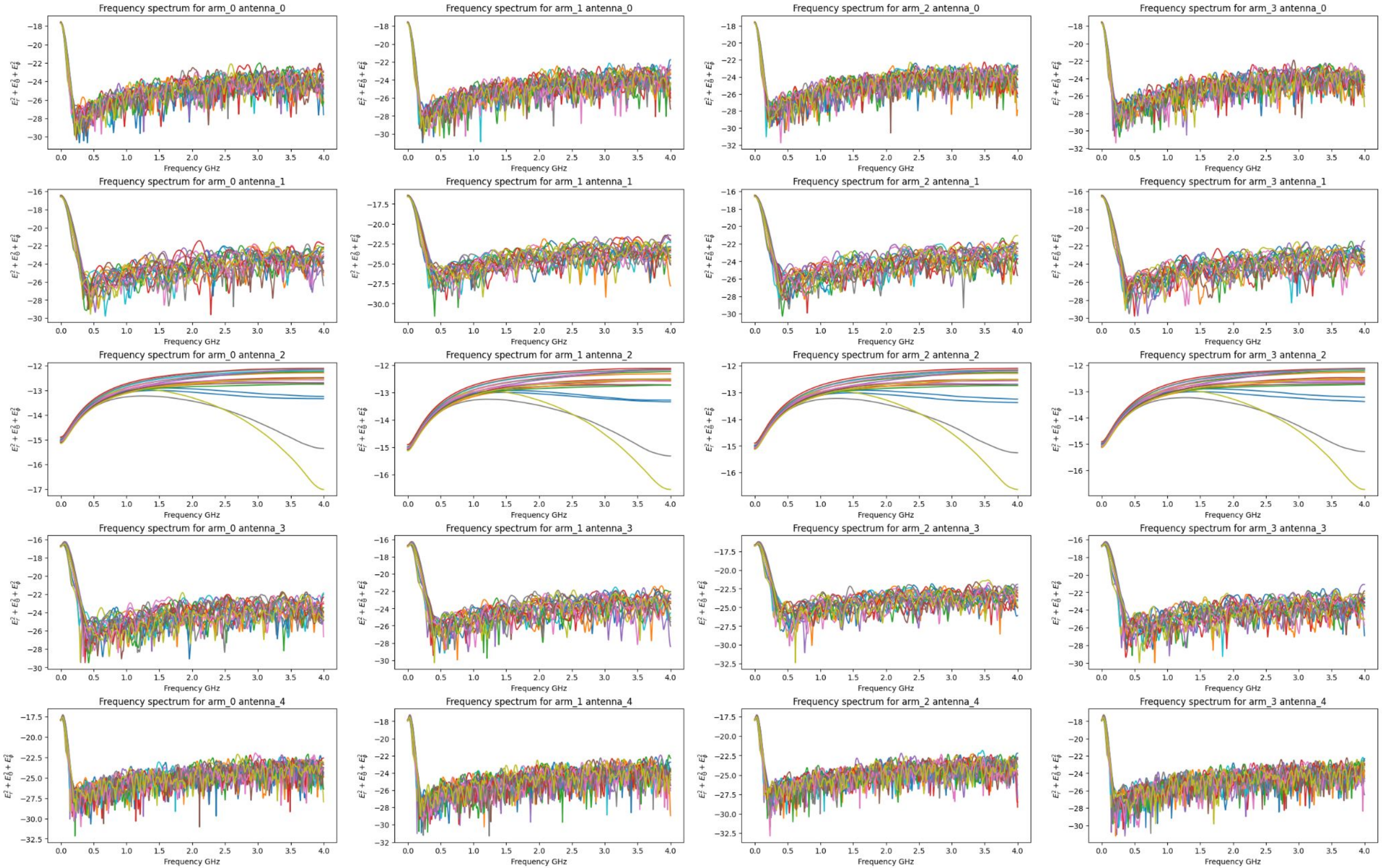
Use neutrino interactions instead of protons (thanks Felix Max!)

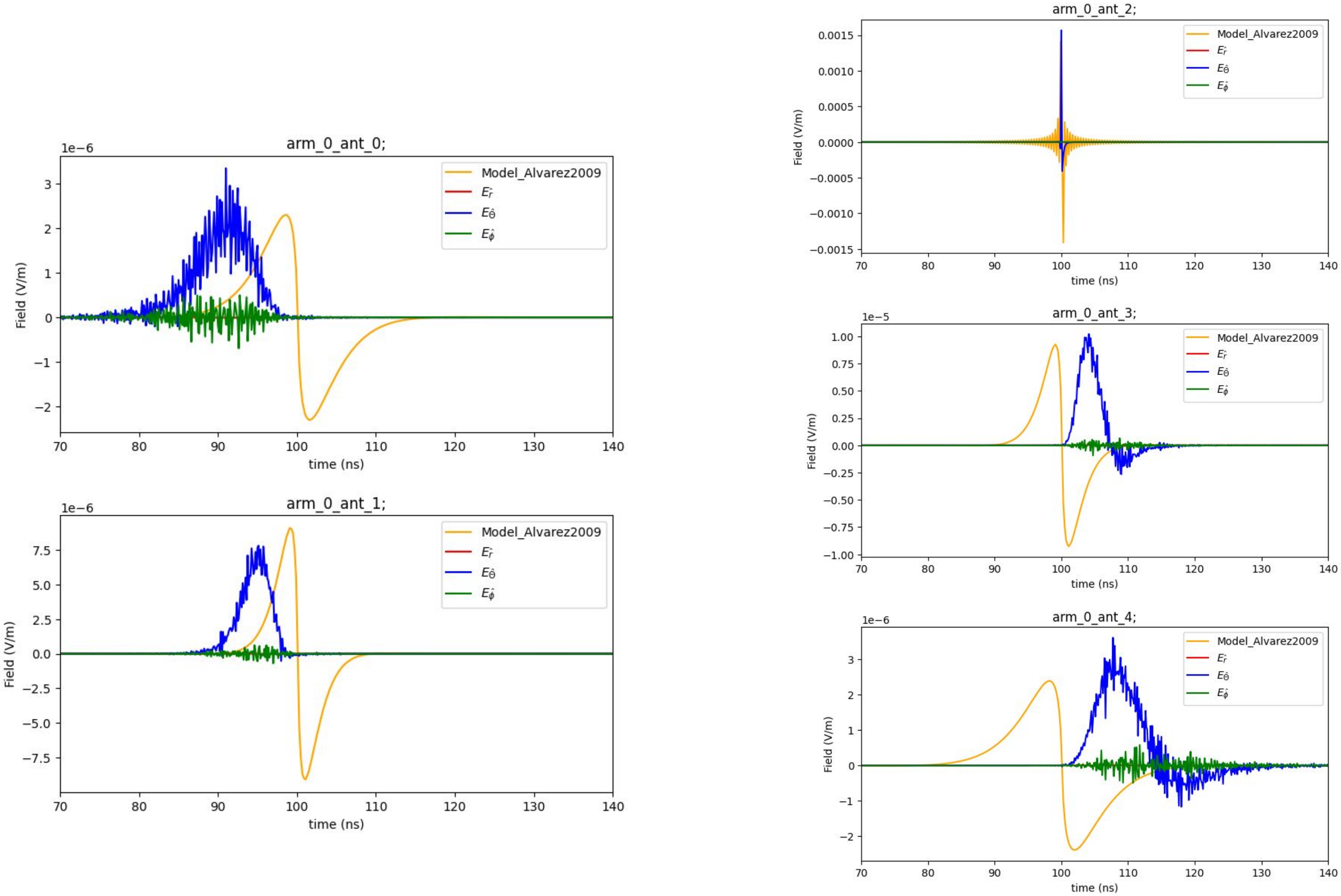
Working on robust table-generator (avoiding same-solution-twice issue)

Include higher-order optics (phase-shifts, etc.)

Feed C8 charge-excess profile to NuRadioMC and see pulses generated for various distances (NRMC may break down in the near field)

E = 10PeV


Frequency spectrum for arm_0 antenna_0
Frequency spectrum for arm_1 antenna_0
Frequency spectrum for arm_2 antenna_0
Frequency spectrum for arm_3 antenna_0
Frequency spectrum for arm_0 antenna_1
Frequency spectrum for arm_1 antenna_1
Frequency spectrum for arm_2 antenna_1
Frequency spectrum for arm_3 antenna_1
Frequency spectrum for arm_0 antenna_2
Frequency spectrum for arm_1 antenna_2
Frequency spectrum for arm_2 antenna_2
Frequency spectrum for arm_3 antenna_2
Frequency spectrum for arm_0 antenna_3
Frequency spectrum for arm_1 antenna_3
Frequency spectrum for arm_2 antenna_3
Frequency spectrum for arm_3 antenna_3
Frequency spectrum for arm_0 antenna_4
Frequency spectrum for arm_1 antenna_4
Frequency spectrum for arm_2 antenna_4
Frequency spectrum for arm_3 antenna_4
Frequency GHz
$E_r^2 + E_\theta^2 + E_\phi^2$


arm_0_ant_0;
arm_0_ant_1;
arm_0_ant_2;
arm_0_ant_3;
arm_0_ant_4;
Model_Alvarez2009
$E_{\hat{r}}$
$E_{\hat{\theta}}$
$E_{\hat{\phi}}$
Field (V/m)
time (ns)
1e−6
1e−5