A REVIEW OF UHE NEUTRINO DETECTION USING THE ASKARYAN EFFECT

J. C. Hanson - CCAPP @ The Ohio State University

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Very High Energy Particle Astrophysics Workshop, 2016. University of Hawai'i, Honolulu, Hawai'i

I. The Continuing Story of GZK neutrinos and Radio

II. *Regathering* our knowledge of the Askaryan effect - ZHS (1991)

   A. The basic effect, some definitions
   B. Energy, coherence, and viewing angle
   C. Several coherences zones, and other useful approximations
   D. Form Factors, and Landau-Pomeranchuk-Migdal effect

III. RB (2001), ARVZ (2010-11): Towards analytic expressions

   A. Our implementation of RB, agreement with others
   B. Accounting for the LPM effect

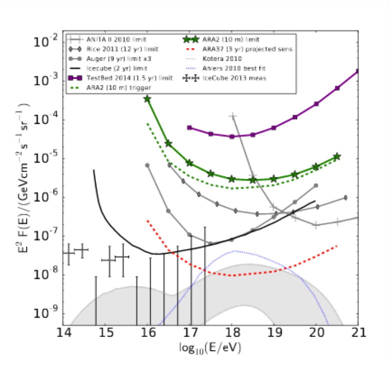
IV. Numerical Work, and The Ohio Supercomputing Cluster

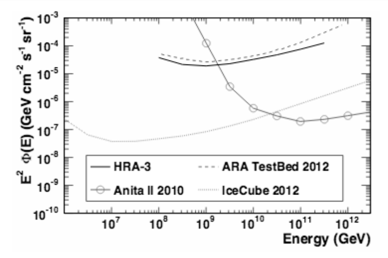
   A. Constructing the entire shower, given constraints
   B. Investigating the shower form factor - analytic expressions

V. Results, with the LPM effect and Form Factor

THE STORY CONTINUES...

The radio groups march towards the *standard* GZK flux predictions.





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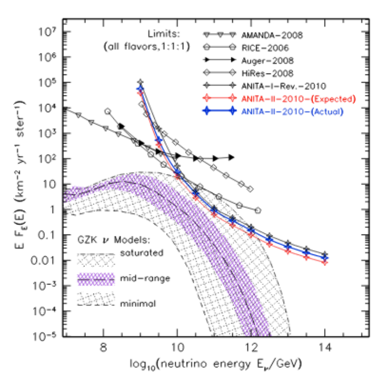


I. ARA is expanding from 3 to 5 stations, and has new data in the pipeline.

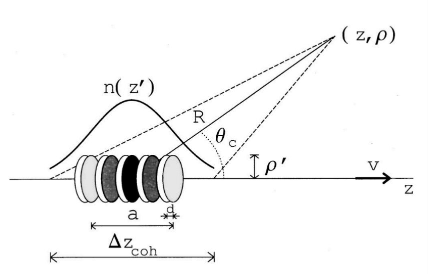
II. ARIANNA HRA complete, 8 stations, with more data in the pipeline.

III. ANITA has completed 3 flights, ANITA III data is being analyzed, ANITA IV is funded.

IV. Balloon-borne sensitivity improvements from EVA, (area and flight time).

REGATHERING OUR KNOWLEDGE OF THE ASKARYAN EFFECT

The basic effect:



$$\Delta z_{coh} < \sqrt{R/(k\sin^2(\theta))} \qquad (1)$$

$$\eta = (a/\Delta z_{coh})^2 \qquad (2)$$

Consider ”Feynman’s formula”: radiation in terms of apparent angular acceleration.

$R = \rho^2 + z^2$, (z', ρ') for charge, R(t) accel.

Fraunhofer regime: $E(\omega)$ has spherical symmetry ($\propto 1/R$)

Fresnel regime: $E(\omega)$ cylindrical symmetry ($\propto 1/\sqrt{\rho}$)

Some definitions, with shower system in cylindrical coordinates.

Longitudinal: refers to the z' coordinate, or shower axis.

Lateral: refers to the ρ' coordinate ($z^2 + \rho^2 = R^2$, $\rho/R = \sin\theta$).

θ, the viewing angle

Papers: **ZHS** - Zas, Halzen, Stanev (1991), RB - Ralston and Buniy (2001) ARZ - Alvarez-Muniz, Romero-Wolfe, Zas (2010-11)

Greisen parameterization (Prog. in Cosmic Ray Physics, 1956, ch. 1) E&M shower model. Leads to Rossi B appoximation etc.

Shower width: **a (m)** $\propto \sqrt{3/2ln(E)}$

Excess charged particles: n_{max}: $\propto E/\sqrt{ln(E)}$

Energy-scaling: Product of $n_{max}a \propto E$ (area under Gaussian to first order)

$$\vec{J} = \vec{v} n(z') f(z' - ct', \vec{\rho}') \tag{3}$$

The main result from RB:

$$R\vec{E}(\omega) = 2.52 \times 10^{-7} \frac{a}{m} \frac{n_{max}}{1000} \frac{\nu}{GHz} F(\vec{q}) \psi \vec{\mathcal{E}}(\theta, \eta) \tag{4}$$

$$\psi = -i \exp(ikR) \sin\theta \tag{5}$$

$$\vec{\mathcal{E}}(\theta = \theta_C, \eta) = \vec{e_\theta}(1 - i\eta)^{-1/2} \tag{6}$$

$$\vec{q} = (\omega/c, k\vec{\rho}/R) \tag{7}$$

Rossi showed that the Greissen solution for $n(z')$ with depth a can be approximated as a gaussian with width a

The linear ω dependence comes from acceleration factor in Lienard-Wiechert fields.

Coherence zones, and other useful approximations. The Fraunhofer approximation leads to an insight:

$$R = |\mathbf{x} - \mathbf{x}'| \gg \rho \tag{8}$$

$$R = |\mathbf{x} - \mathbf{x}'| \gg \lambda \tag{9}$$

$$i|\mathbf{k}||\mathbf{x} - \mathbf{x}'| \approx i\mathbf{k}\mathbf{R} - i\mathbf{k} \cdot \rho(\tau) \tag{10}$$

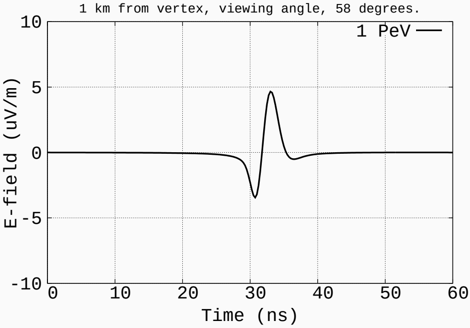
Beginning with the Lienard-Wiechert retarded potentials for decelerating charge, and focusing only on the radiation term, one can show ($y = \pi\nu\delta t(1 - n\beta\cos\theta)$):

$$\mathbf{E}(\omega, \mathbf{x}) \propto i\omega \frac{e^{ikR}}{R} \frac{\sin y}{y} \tag{11}$$

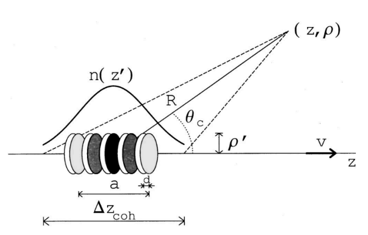
Similar to a diffraction pattern of length $\approx a$, but *requires Fraunhofer approximation*.

EQ. 24 OF ZHS (DISCUSSED YESTERDAY)

Using $v_{rms} = \sqrt{4kBTR}$, with $k = 1.4e - 23$ J/K, B = 10^9 Hz, T = 300 K, and R = 50Ω (usual RF resistance), $v_{rms} \approx 20\mu V$.



A more subtle approximation, keeping another order...



$$|\mathrm{x} - \mathrm{x}'| = \sqrt{(z - z')^2 + (\rho - \rho')^2} \quad (12)$$

$$|\mathrm{x} - \mathrm{x}'| \approx R(z') - \frac{\rho \cdot \rho'}{R} + \left(\frac{\rho'^2}{R}\right) \quad (13)$$

$$R(z') = \sqrt{(z - z')^2 + \rho^2} \quad (14)$$

Scale of the instantaneous charge excess is small compared to the longitudinal shower development. Keep the first two terms, drop the third. Integrals decouple into the **form factor,** and the **Fresnel-Fraunhofer** integrals.

The 3D Fourier transform of the charge distribution, f, the normalized charge excess distribution. (Dropping bold font for vectors).

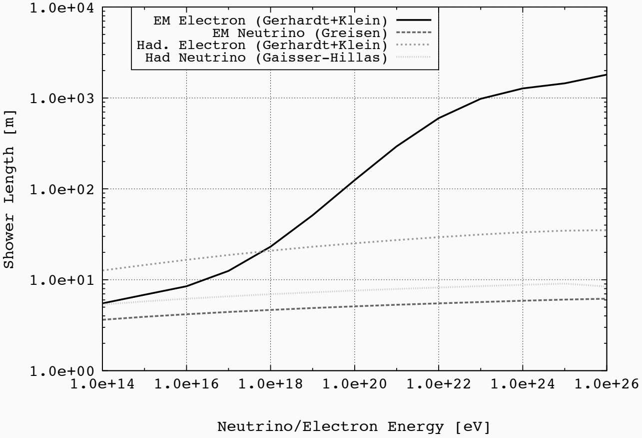
$$\int d^3x' f(x') = 1 \tag{15}$$

$$F(q) = \int d^3x' \exp\left(-iq \cdot x'\right) f(x') \tag{16}$$

$$q = \left(\frac{\omega}{c}, \frac{k}{R}\rho'\right) \tag{17}$$

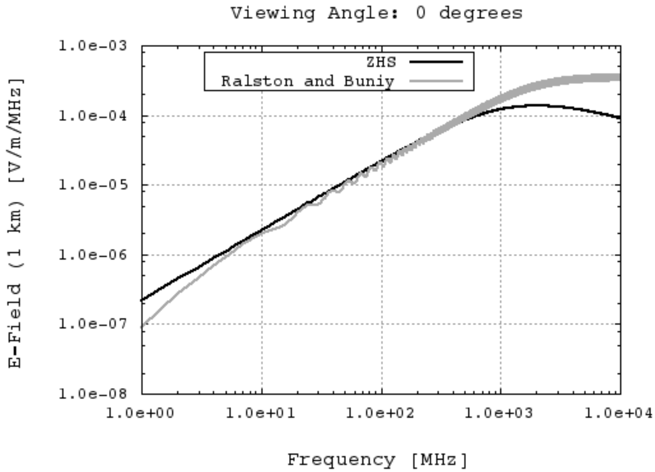
The structure of the Askaryan electric field is derived in RB, parameterized in ZHS, and fit in the time domain by ARVZ. In addition to the LPM effect, **the main thrust of this work is to analytically derive $F(q)$, and match to Monte Carlo simulations from Geant4**.

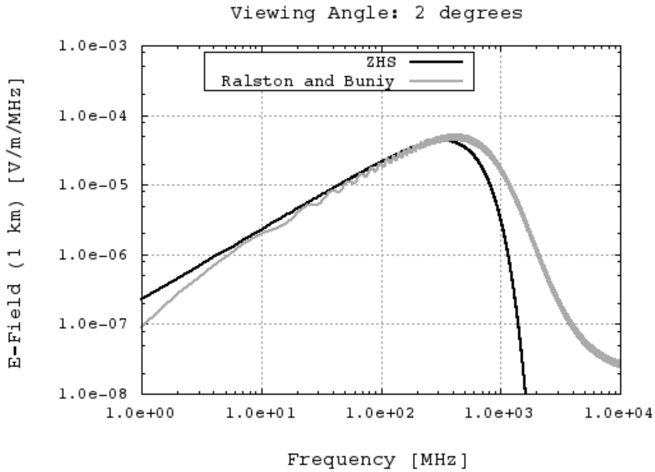
Simple incorporation: draw the a-parameter from the EM curve below, rather than Greisen.

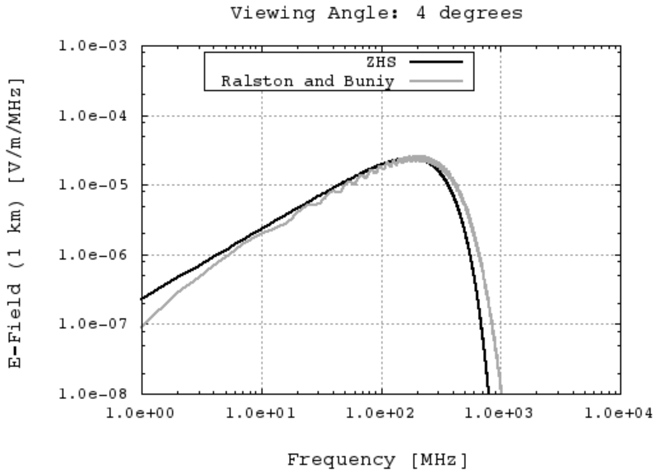


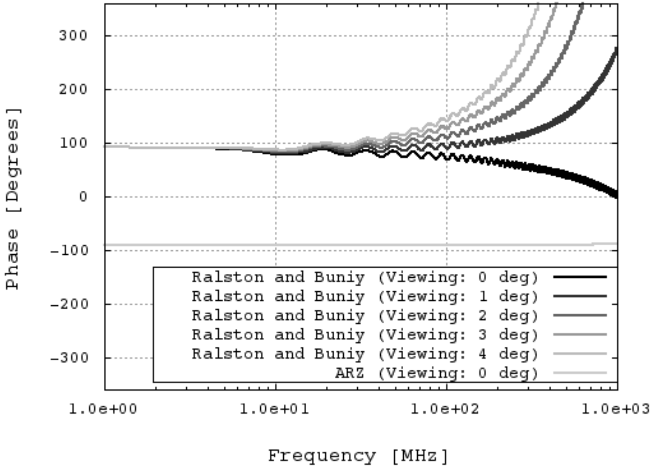
ANALYTIC FORMS OF ASKARYAN FIELDS

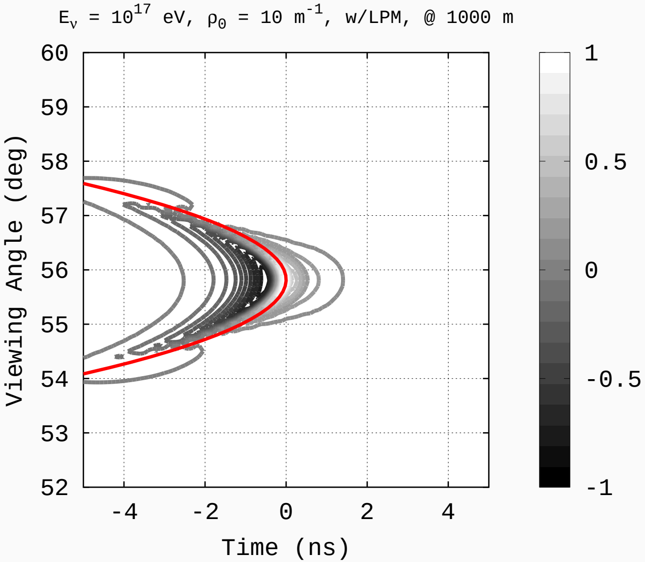
$$\vec{\mathcal{E}}=\left[-\frac{\cos\theta-\cos\theta_c}{\sin\theta}\vec{e}_R+\left(1-i\eta\frac{\cos\theta_c}{\sin^2\theta}\frac{\cos\theta-\cos\theta_c}{1-i\eta}\right)\vec{e}_\theta\right]$$
$$\times\left[1-i\eta\left(1-3i\eta\frac{\cos\theta}{\sin^2\theta}\frac{\cos\theta-\cos\theta_c}{1-i\eta}\right)\right]^{-1/2}$$
$$\times\exp\left[-\frac{1}{2}(ka)^2\frac{(\cos\theta-\cos\theta_c)^2}{1-i\eta}\right]. \qquad (19)$$


Viewing Angle: 0 degrees
ZHS
Ralston and Buniy
E-Field (1 km) [V/m/MHz]
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]

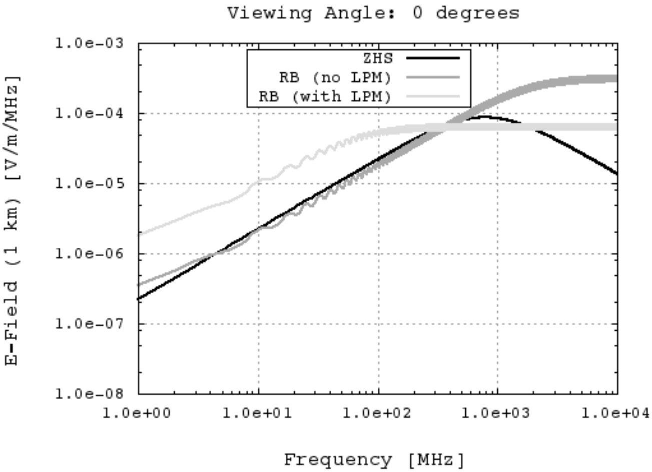

Viewing Angle: 2 degrees
ZHS
Ralston and Buniy
E-Field (1 km) [V/m/MHz]
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]

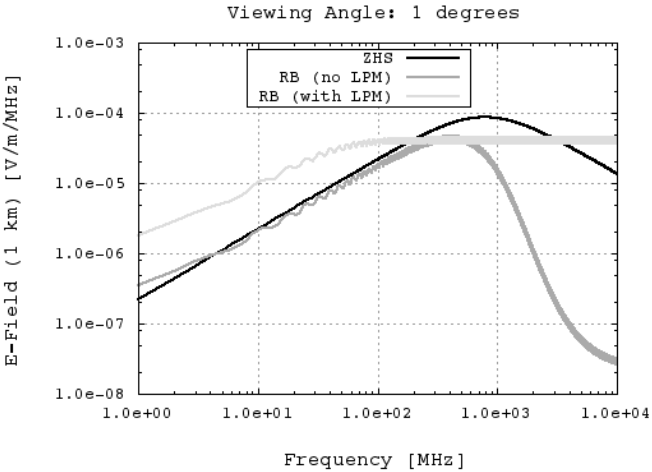

Viewing Angle: 4 degrees
ZHS
Ralston and Buniy
E-Field (1 km) [V/m/MHz]
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]

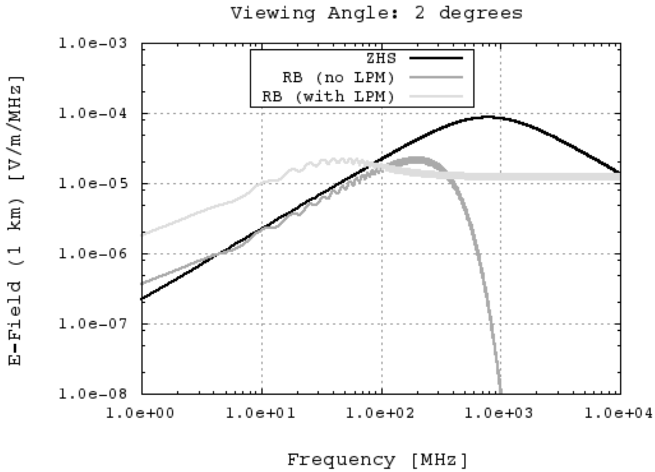

300
200
100
0
−100
−200
−300
Phase [Degrees]
1.0e+00
1.0e+01
1.0e+02
1.0e+03
Frequency [MHz]
Ralston and Buniy (Viewing: 0 deg)
Ralston and Buniy (Viewing: 1 deg)
Ralston and Buniy (Viewing: 2 deg)
Ralston and Buniy (Viewing: 3 deg)
Ralston and Buniy (Viewing: 4 deg)
ARZ (Viewing: 0 deg)


E_ν = 10^{17} eV, ρ_0 = 10 m^{-1}, w/LPM, @ 1000 m
60
59
58
57
56
55
54
53
52
Viewing Angle (deg)
-4
-2
0
2
4
Time (ns)
1
0.5
0
-0.5
-1

ACCOUNTING FOR THE LPM EFFECT - SCALING




Viewing Angle: 1 degrees
ZHS
RB (no LPM)
RB (with LPM)
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
E-Field (1 km) [V/m/MHz]
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]


Viewing Angle: 2 degrees
ZHS
RB (no LPM)
RB (with LPM)
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
E-Field (1 km) [V/m/MHz]
Frequency [MHz]

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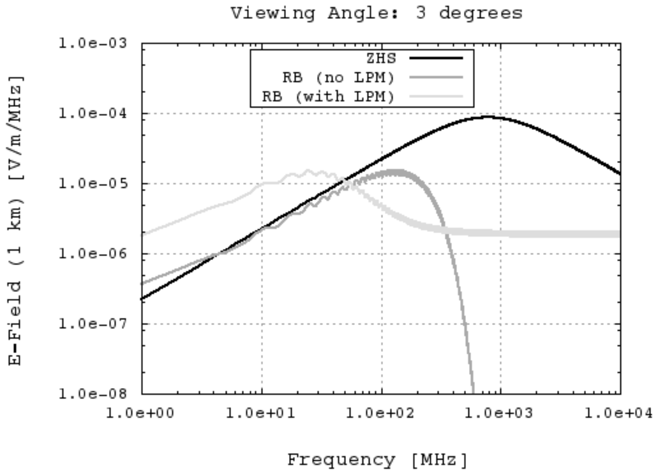
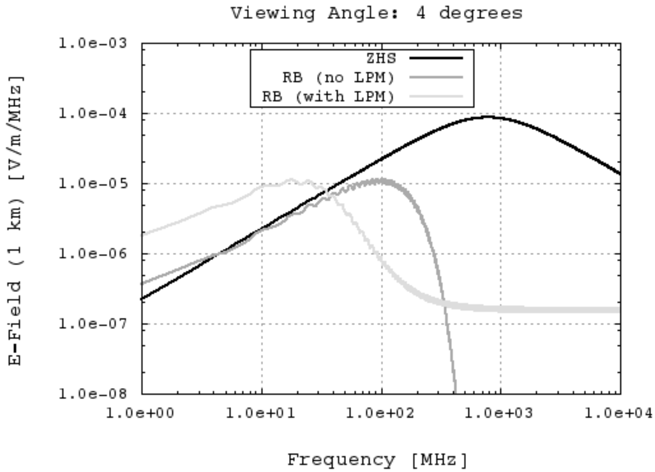
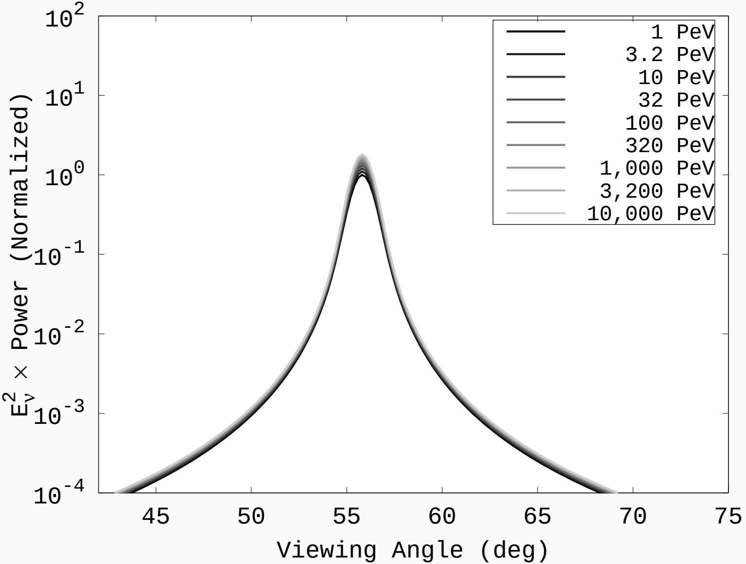
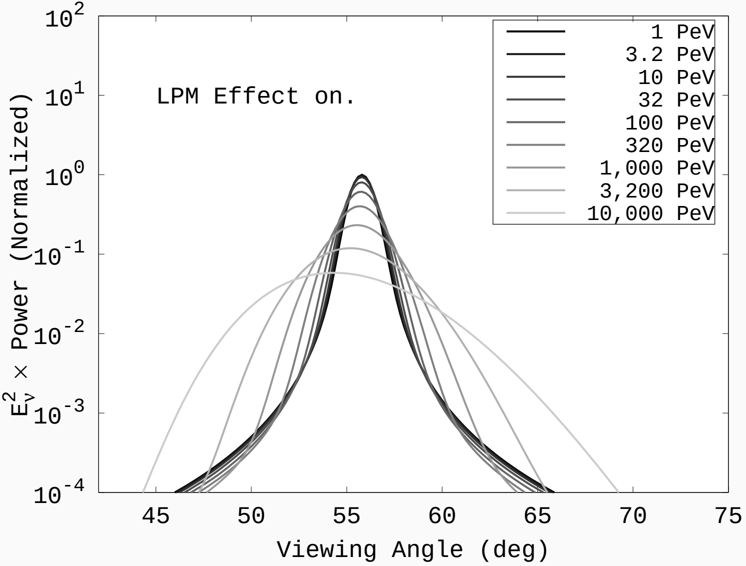


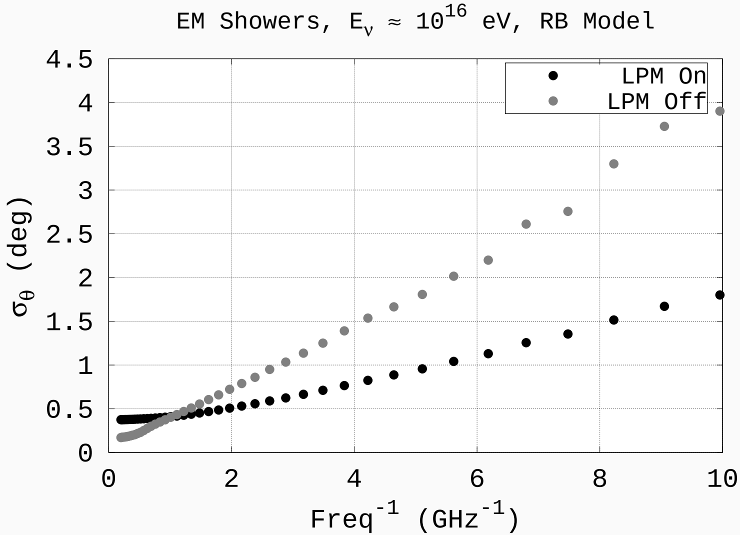

Viewing Angle: 4 degrees
ZHS
RB (no LPM)
RB (with LPM)
E-Field (1 km) [V/m/MHz]
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]

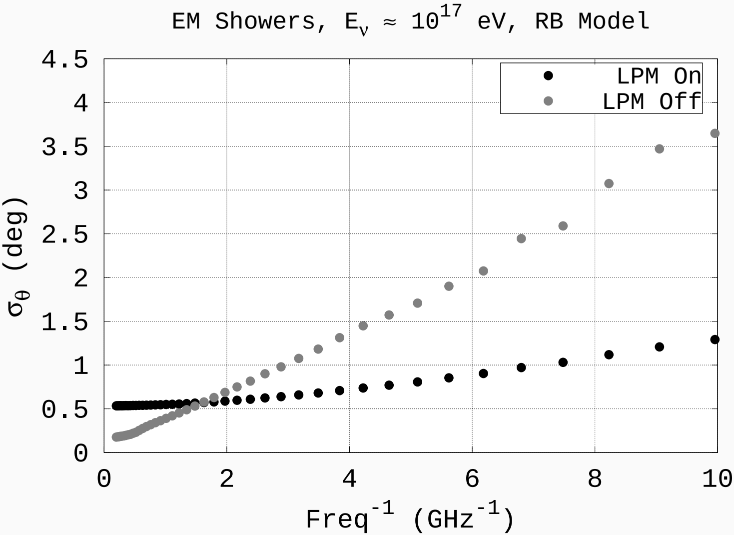
ACCOUNTING FOR THE LPM EFFECT - VIEWING ANGLE

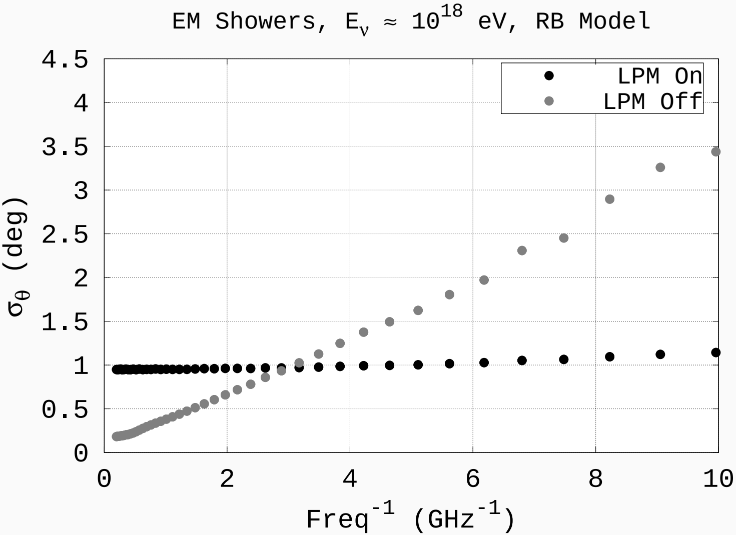


ACCOUNTING FOR THE LPM EFFECT - VIEWING ANGLE

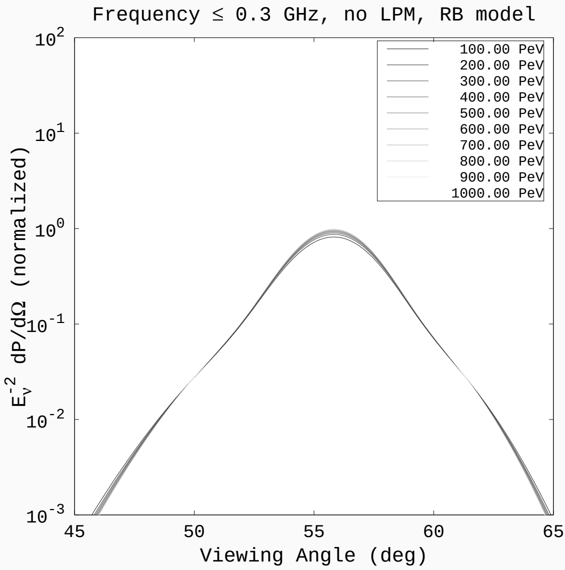



EM Showers, $E_\nu \approx 10^{16}$ eV, RB Model
LPM On
LPM Off
σ_θ (deg)
Freq^{-1} (GHz^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
2
4
6
8
10

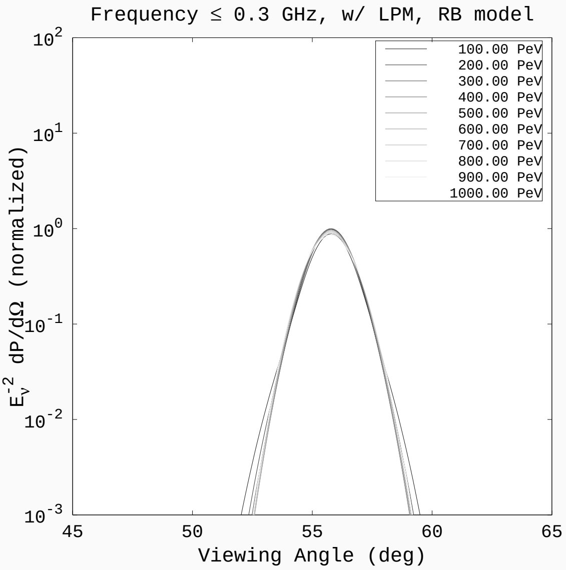

EM Showers, $E_\nu \approx 10^{17}$ eV, RB Model
LPM On
LPM Off
σ_θ (deg)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
Freq^{-1} (GHz^{-1})


EM Showers, $E_\nu \approx 10^{18}$ eV, RB Model
LPM On
LPM Off
σ_θ (deg)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
Freq^{-1} (GHz^{-1})

ACCOUNTING FOR THE LPM EFFECT - VIEWING ANGLE



ACCOUNTING FOR THE LPM EFFECT - VIEWING ANGLE



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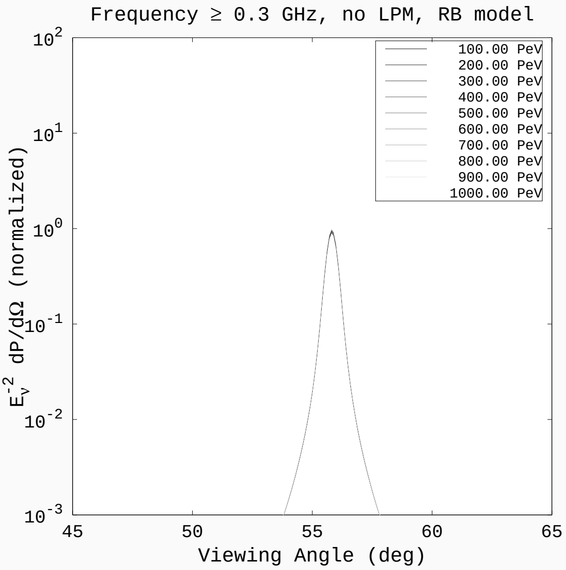
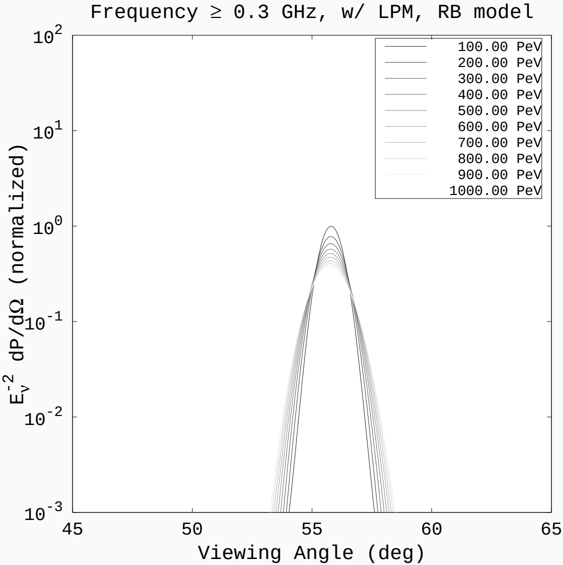
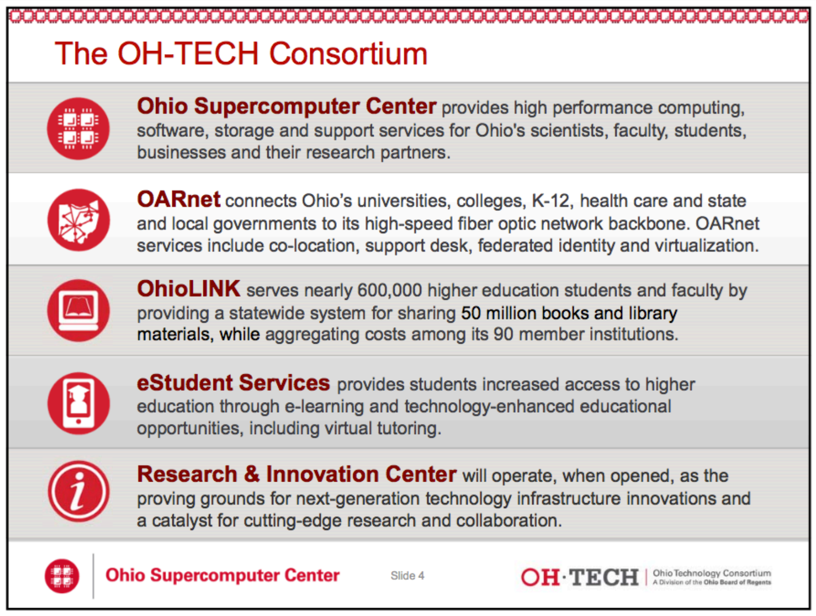


ACCOUNTING FOR THE LPM EFFECT - VIEWING ANGLE

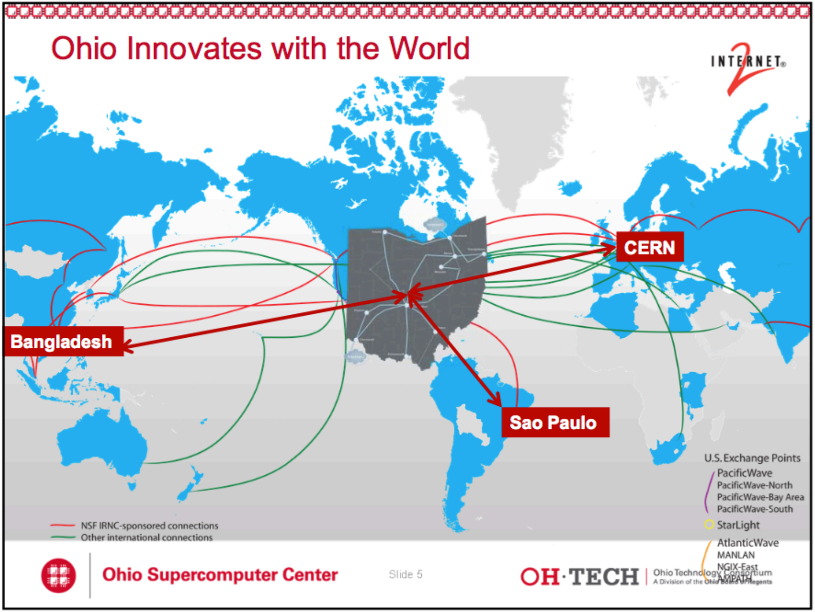


ASIDE: SUPERCOMPUTING AT OHIO STATE, AND THE STATE OF OHIO

SUPERCOMPUTING AT OHIO STATE, AND THE STATE OF OHIO



SUPERCOMPUTING AT OHIO STATE, AND THE STATE OF OHIO



SUPERCOMPUTING AT OHIO STATE, AND THE STATE OF OHIO

Supercomputers at OSC

- Ruby cluster (small cluster, limited access)
  - Online March 2015
  - Named for Ruby Dee, actress, poet, playwright, screenwriter, journalist and activist. She was born in Cleveland.
  - HP system, Intel Xeon processors, 4800 cores
- Oakley cluster
  - Online March 2012
  - Named for Annie Oakley, famous Ohio sharpshooter
  - HP system, Intel Xeon processors, 8280 cores
- Glenn cluster
  - "Glenn phase II" online July 2009
  - Named for John Glenn, Ohio astronaut and senator
  - IBM 1350, AMD Opteron processors, 3500 cores

Ohio Supercomputer Center   Slide 18   OH·TECH | Ohio Technology Consortium, A Division of the Ohio Board of Regents

Compute Nodes – Oakley

- 684 standard nodes
  - 12 cores per node
  - 48 GB memory (4GB/core)
  - 812 GB local disk space
- 8 large memory nodes
  - 12 cores per node
  - 192 GB memory (16GB/core)
  - 812 GB local disk space
- Network
  - Nodes connected by 40Gbit/sec Infiniband network (QDR)

NUMERICAL WORK

Limitations:

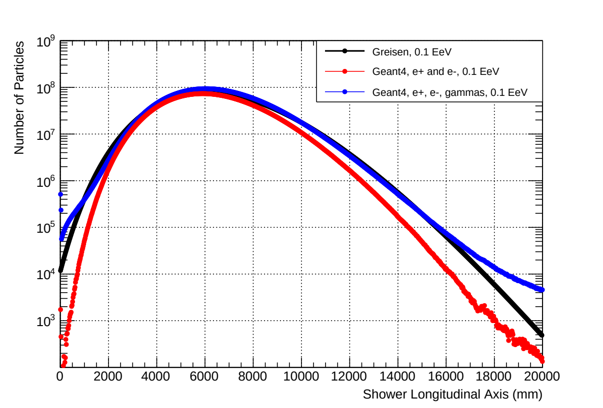
- We may only submit a few hundred jobs at once.
- Charged RUs from finite account, 1 RU = 10 CPU-hours
- Memory use < 8 GB, 16 GB special nodes (Monte Carlo thresholds)

Strategy: Implement pre-shower sub-shower strategy, with Geant4.

- Utilizes **back-fill** (each sub-shower is 10 cpu-minutes).
- Memory is less than 16 GB, typically less than 10 GB per sub-shower
- All of this work: a few hundred RUs, courtesy of Dr. Amy Connolly, @ OSU

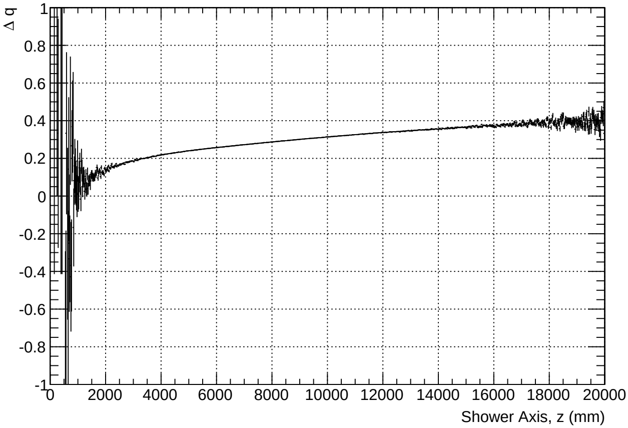
Goal: F(q) using Geant4 pre-showers and sub-showers.

GEANT4 SIMULATIONS

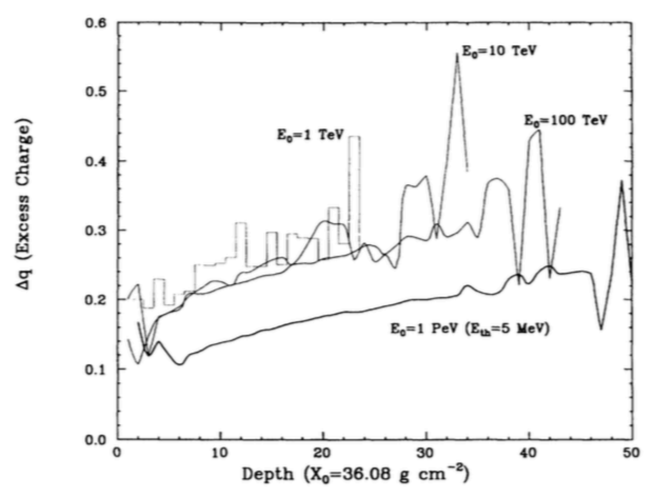


Definition: a *track* is a particle in Geant4 alive during a given step in the calculations.

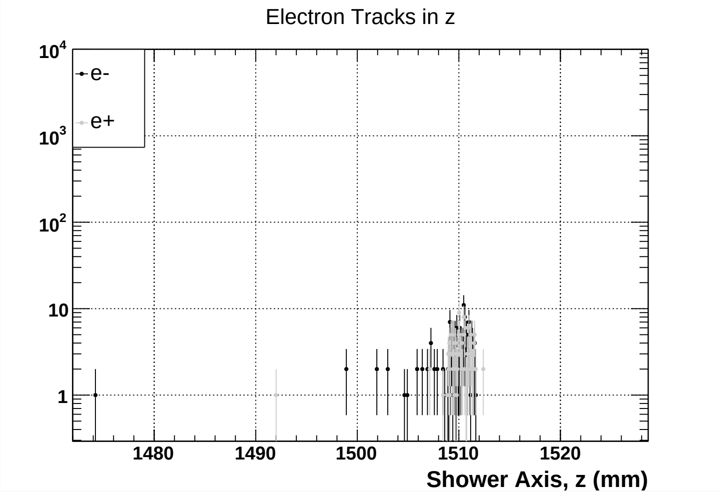
Fractional negative charge excess, Δq. A value of 1.0 means pure $e-$, -1.0 means pure $e+$.



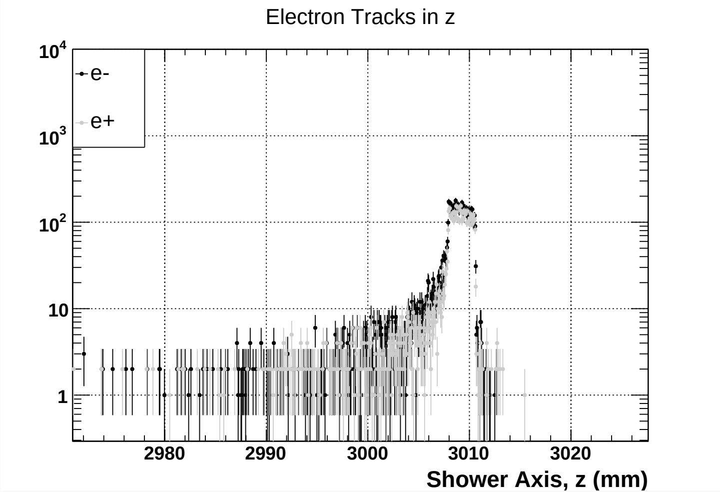
(Results from ZHS, for comparison)



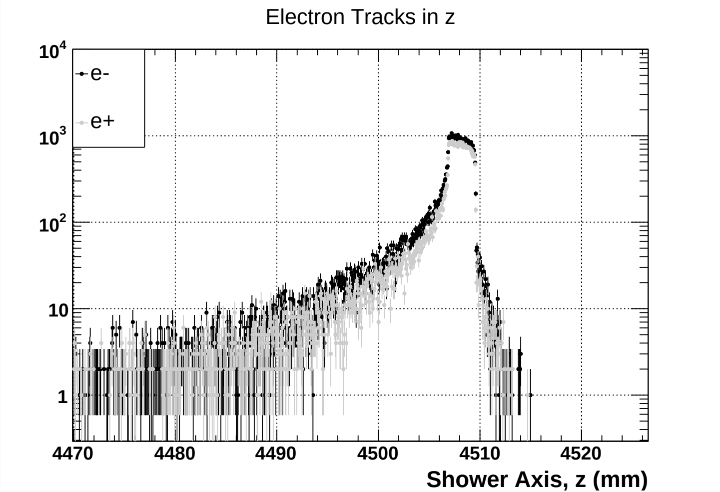
All tracks in 10 ps window @ 5 ns after primary interaction:



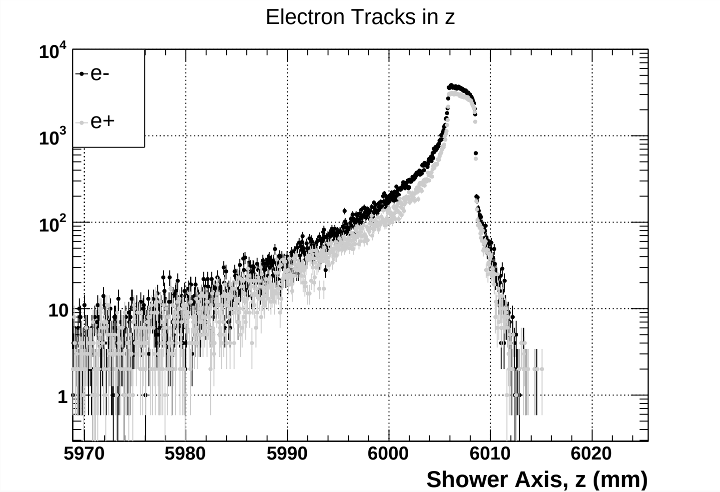
All tracks in 10 ps window @ 10 ns after primary interaction:



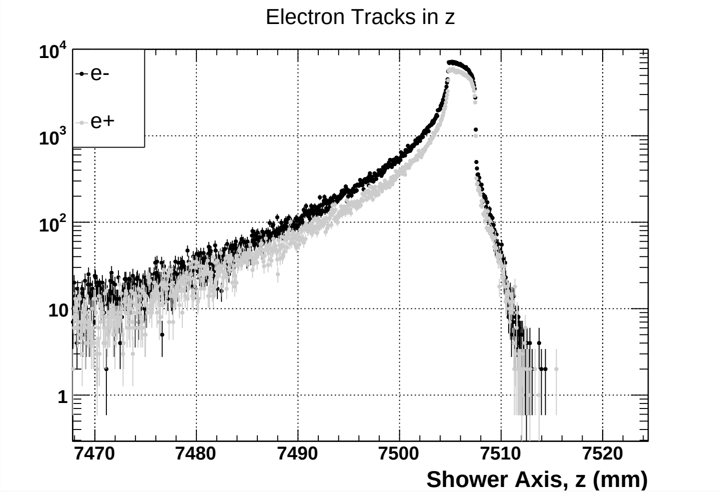
All tracks in 10 ps window @ 15 ns after primary interaction:



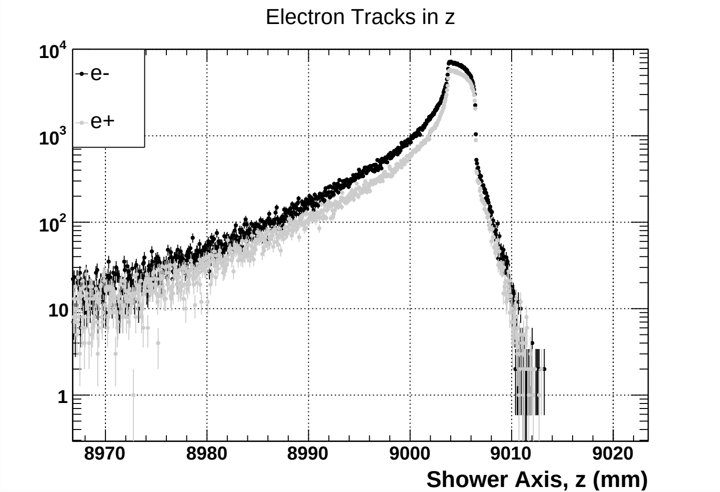
All tracks in 10 ps window @ 20 ns after primary interaction:



All tracks in 10 ps window @ 25 ns after primary interaction:



All tracks in 10 ps window @ 30 ns after primary interaction:



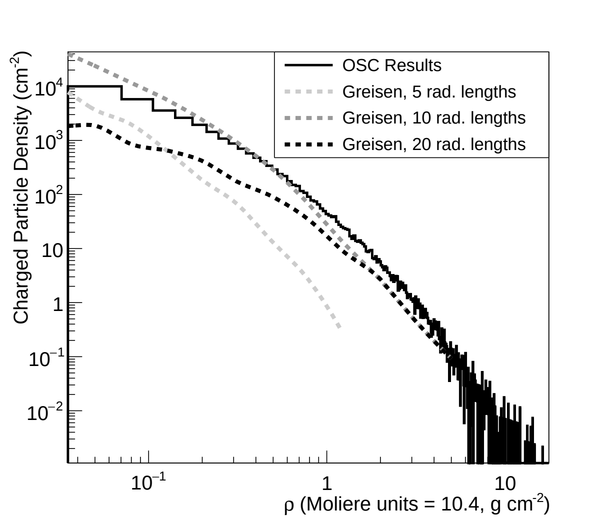
The ”instantaneous” form factor in z’ is so small, it doesn’t limit the Askaryan radiation…

Unless the time-scale that matters is actually the Nyquist frequency of the RF detectors (1 GHz or 1 ns).

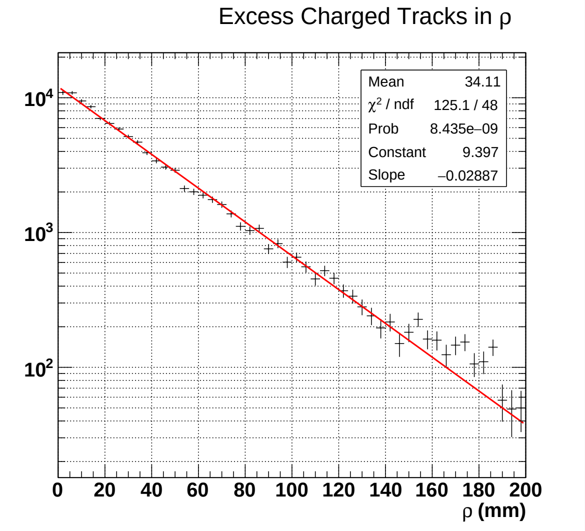
If that were true, then the z-shape could matter (long tail, flat top is limited by time-window).

One can show that the phase shift due to any z-dependence in form factors goes like

$$\phi/\Delta\theta \approx 2\pi n \left\{ \frac{\nu \Delta t}{\Delta\theta} - \frac{R}{\lambda} \sin\theta_C \right\} \tag{18}$$


OSC Results
Greisen, 5 rad. lengths
Greisen, 10 rad. lengths
Greisen, 20 rad. lengths
Charged Particle Density (cm^{-2})
ρ (Moliere units = 10.4, g cm^{-2})
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-1}
1
10

GEANT4 SIMULATIONS - ρ'-FORM FACTOR DEPENDENCE



Necessary to explain why deccelerating charge doesn't radiate up to optical frequencies: $E(k) \approx k$.

$$\boxed{F_{ZHS}(k) = \frac{1}{1 + \left(\frac{k}{k_0}\right)^2} = \frac{k_0^2}{k_0^2 + k^2}} \tag{19}$$

What does the corresponding charge distribution (inverse Fourier transform) resemble? Must treat the poles carefully.

$$f(z') = \frac{k_0^2}{2\pi} \int_{-\infty}^{\infty} \frac{e^{ikz'}}{(k + ik_0)(k - ik_0)} dk, k \in \mathbb{C} \tag{20}$$

$$f(z')/k_0^2 = \frac{1}{2\pi i} \oint \frac{ie^{ikz'}(k + ik_0)^{-1}}{(k - ik_0)} \tag{21}$$

$$f(z')/k_0^2 = \frac{1}{2\pi i} \oint \frac{ie^{ikz'}(k+ik_0)^{-1}}{(k-ik_0)} \tag{22}$$

$$f(z') = k_0^2 \left(ie^{ikz'}(k+ik_0)^{-1} \right)_{k=ik_0} \tag{23}$$

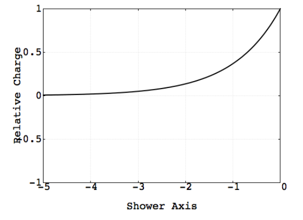
$$f(z') = \frac{k_0}{2} e^{-k_0 z'} \tag{24}$$

Exponential (interesting), normalized to $\frac{1}{2}$. Using the oppositely oriented contour, we get a different distribution:

$$f(z') = -k_0^2 \left(ie^{ikz'}(k-ik_0)^{-1} \right)_{k=-ik_0} = \frac{k_0}{2} e^{k_0 z'} \tag{25}$$

So poles in upper and lower planes lead to different effects (don't agree? - check this with Cauchy's theorem). $F_{ZHS}(k) \propto \nu^{-2}$, so it just cuts off the spectrum of $|E(\nu)|$, which is the purpose.

Poles in the upper and lower complex plane create causality violation, different charge distributions, etc. Exponential is useful:



$$f(z') = k_0 \exp(k_0 z'), z < 0 \tag{26}$$

$$f(z') = 0, z > 0 \tag{27}$$

Charge can't travel faster than c, normalized to 1, and charge doesn't fall infinitely behind the shower front.

Fourier transform gives the form factor:

$$\boxed{F_{JCH}(k) = \int_{-\infty}^{\infty} dz' e^{-ikz'} k_0 e^{k_0 z'} = \frac{k_0}{k_0 - ik}} \tag{28}$$

Only one pole, at $k = -ik_0$.

The Cauchy integral theorem states:

$$f(z_0) = \frac{1}{2\pi i} \oint \frac{f(z)dz}{z - z_0} \tag{29}$$

Taking the inverse Fourier transform of F_{JCH} requires Cauchy integral formula.

Taking the inverse Fourier transform of F_{JCH} requires closing the contour around the one pole, and using Cauchy's formula.

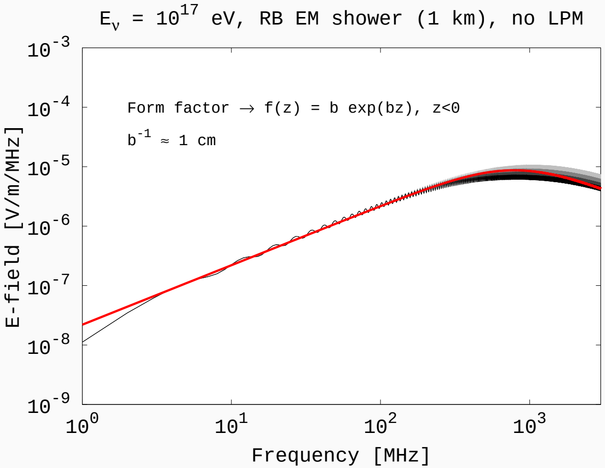
$$f(z')/k_0 = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{e^{ikz'}}{k_0 - ik} dk \tag{30}$$

$$f(z')/k_0 = \frac{1}{2\pi i}\oint \frac{ie^{ikz'}}{k_0 - ik} dk = \frac{1}{2\pi i}\oint \frac{e^{ikz'}}{k - ik_0} dk \tag{31}$$

$$f(z') = k_0 e^{k_0 z'} \tag{32}$$

Notice that $\Re(F_{JCH}) = F_{ZHS}$, and $|F_{JCH}| = \sqrt{F_{ZHS}}$ (for same k_0). This means that my form factor also cuts off the spectrum at high frequencies, and reduces to ZHS if we ignore imaginary E before taking the magnitude. Interesting that $\arg(F_{JCH}) \approx k/k_0$, so k_0 should be large, to avoid adding extraneous phases.

RESULT



E$_\nu$ = 10^{17} eV, RB EM shower (1 km), no LPM
Form factor → f(z) = b exp(bz), z<0
b^{-1} ≈ 1 cm
E-field [V/m/MHz]
Frequency [MHz]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{0}
10^{1}
10^{2}
10^{3}

ρ'-form factor dependence

I propose a normalized charge excess for ρ' as follows:

$$f(x') = f_0 \delta(z') \exp(-\sqrt{2\pi}\rho_0 \rho') \tag{33}$$

$$\int dz' d^2\rho' f(x') = 1, \quad f_0 = \rho_0^2 \tag{34}$$

$$F(q) = \int_{-\pi}^{\pi} \int_0^{\infty} \int_{\infty}^{\infty} dz' \rho' d\rho' d\phi' e^{-iq\cdot x'} f(x') \tag{35}$$

$$\gamma = k \sin\theta \quad (m^{-1}) \tag{36}$$

$$\sigma = \frac{\gamma}{\sqrt{2\pi}\rho_0} \tag{37}$$

$$\tag{38}$$

Perform z'-integration and substitute:

$$F(q) = \rho_0^2 \int_0^{\infty} \rho' d\rho' \int_{-\pi}^{\pi} d\phi' \exp\{-(i\gamma\cos\phi + \gamma/\sigma)\rho'\} \tag{39}$$

Shift $\phi \to \phi - \pi/2$ (cylindrical symmetry), and perform ϕ-integration:

$$F(q) = \rho_0^2 \int_0^\infty \rho' d\rho' \int_{-\pi}^{\pi} d\phi' \exp\{-(i\gamma \cos\phi + \gamma/\sigma)\rho'\} \tag{40}$$

$$F(q) = \rho_0^2 \int_0^\infty \rho' d\rho' \exp\left\{-\frac{\gamma}{\sigma}\rho'\right\} \int_{-\pi}^{\pi} d\phi' \exp\{-i\gamma\rho' \sin\phi\} \tag{41}$$

$$F(q) = 2\pi\rho_0^2 \int_0^\infty d\rho' \rho' \exp\left\{-\frac{\gamma}{\sigma}\rho'\right\} J_0(\gamma\rho') \tag{42}$$

$$F(q) = \sigma^{-2} \int_0^\infty du' u' \exp\{-u'/\sigma\} J_0(u') \tag{43}$$

Table of integrals...and finally:

$$\boxed{F(k,\theta) = \frac{1}{(1+\sigma^2)^{3/2}} = \left(1 + \left(\frac{k}{\rho_0}\right)^2 \left(\frac{\sin\theta}{2\pi}\right)^2\right)^{-3/2}} \tag{44}$$

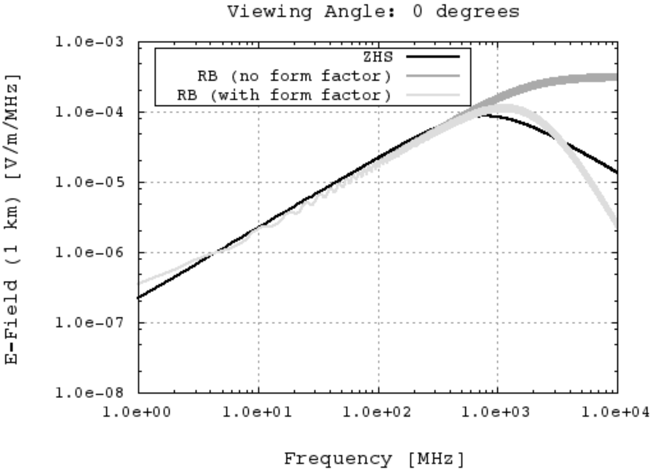
COMBINED RESULTS

ρ'-form factor dependence - Monte Carlo fit parameters

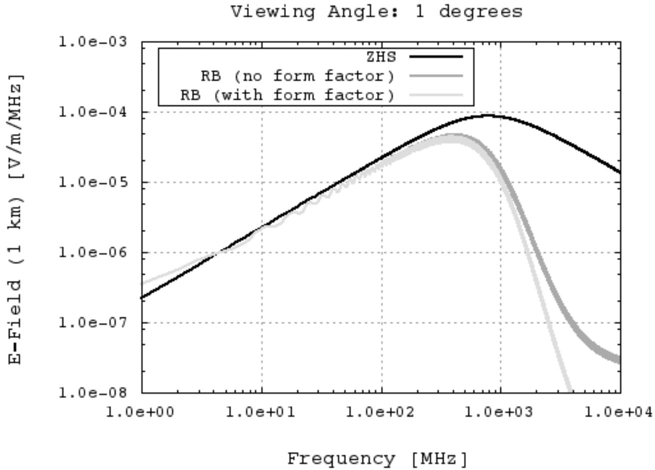
Fits are for E&M HEP option 1, in the Geant4 framework. All parameters are negative

Time (ns)	Event (#)	Fit parameter (mm^-1)	Fit parameter (m^-1)	Rho_0 (m^-1)
5	1	1.99e-1	199	79.4
5	2	2.24e-2	22.4	8.94
5	3	1.09e-1	109	43.5
5	4	4.60e-1	460	184
5	5	9.94e-2	99.4	39.7
10	1	5.41e-2	54.1	21.6
10	2	5.16e-2	51.6	20.6
10	3	5.02e-2	50.2	20.0
10	4	1.42e-2	14.2 **	5.67
10	5	4.67e-2	46.7	18.6
15	1	1.51e-2	15.1	6.03
15	2	1.07e-2	10.7	4.27
15	3	3.85e-2	38.5	15.4
15	4	1.60e-2	16.0	6.38
15	5	2.92e-2	29.2	11.7
20	1	2.81e-2	28.1	11.2
20	2	7.12e-3	7.12 **	2.84 **
20	3	8.87e-3	8.87	3.54
20	4	2.73e-2	27.2	10.9
20	5	2.02e-2	20.2	8.06
25	1	2.29e-2	22.9	9.14
25	2	2.75e-2	27.5	11.0
25	3	2.29e-2	22.9	9.14
25	4	2.14e-2	21.4	8.54
25	5	1.51e-2	15.1	6.03
30	1	1.82e-2	18.1	7.22

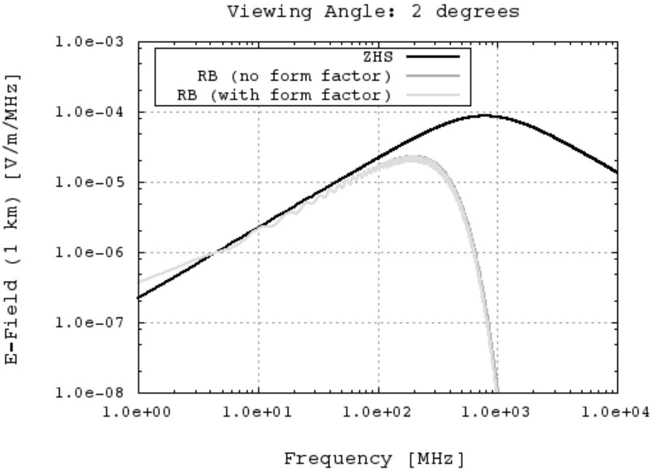
SPECTRA - ρ'-FORM FACTOR DEPENDENCE

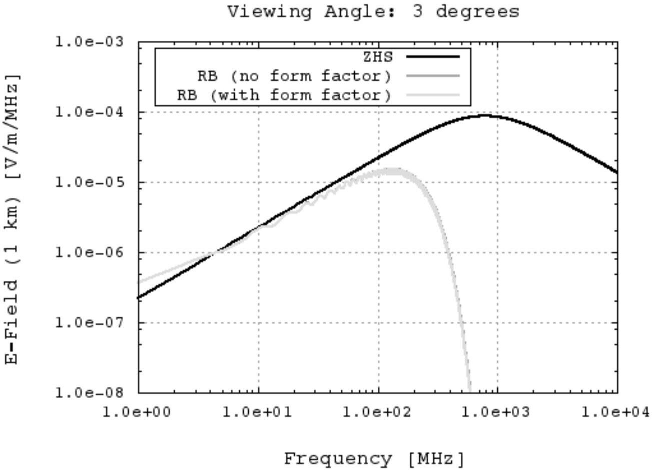


SPECTRA - ρ'-FORM FACTOR DEPENDENCE

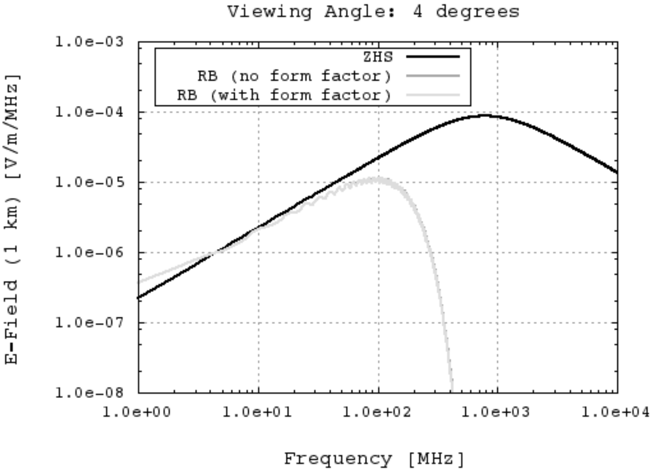


SPECTRA - ρ'-FORM FACTOR DEPENDENCE

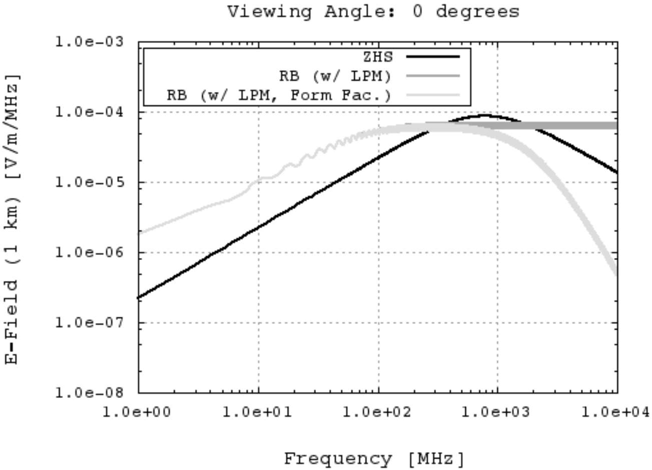



Viewing Angle: 3 degrees
ZHS
RB (no form factor)
RB (with form factor)
E-Field (1 km) [V/m/MHz]
1.0e-03
1.0e-04
1.0e-05
1.0e-06
1.0e-07
1.0e-08
1.0e+00
1.0e+01
1.0e+02
1.0e+03
1.0e+04
Frequency [MHz]

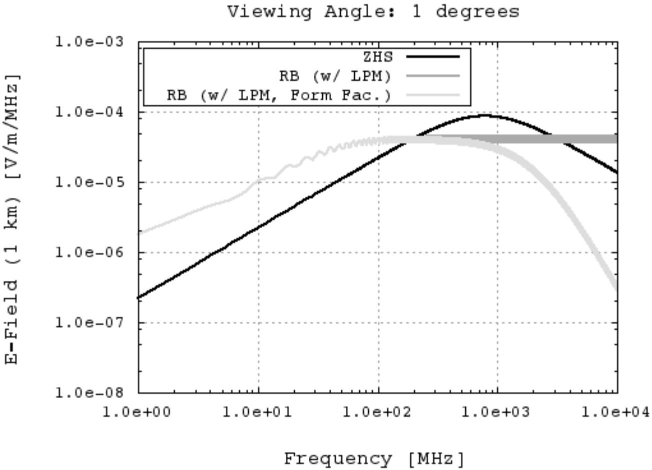
SPECTRA - ρ'-FORM FACTOR DEPENDENCE



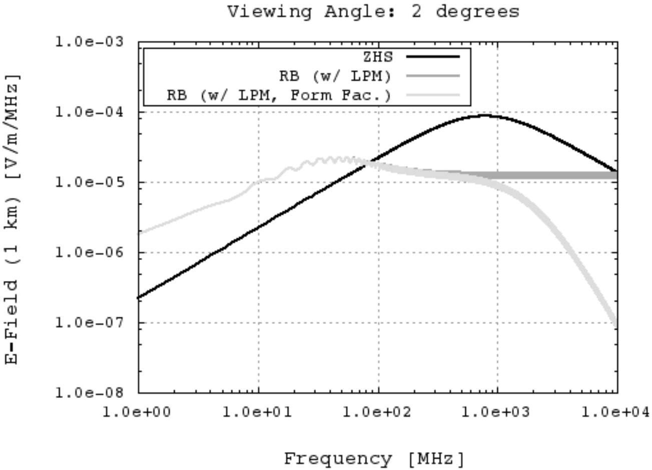
SPECTRA - ρ'-FORM FACTOR DEPENDENCE, W/ LPM SUPPRESSION



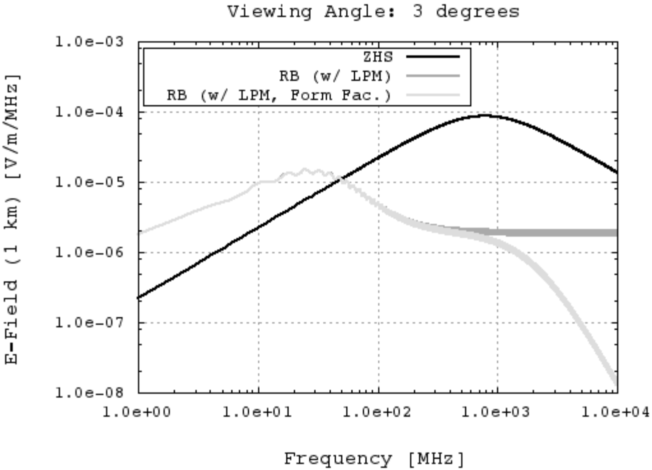
SPECTRA - ρ'-FORM FACTOR DEPENDENCE, W/ LPM SUPPRESSION



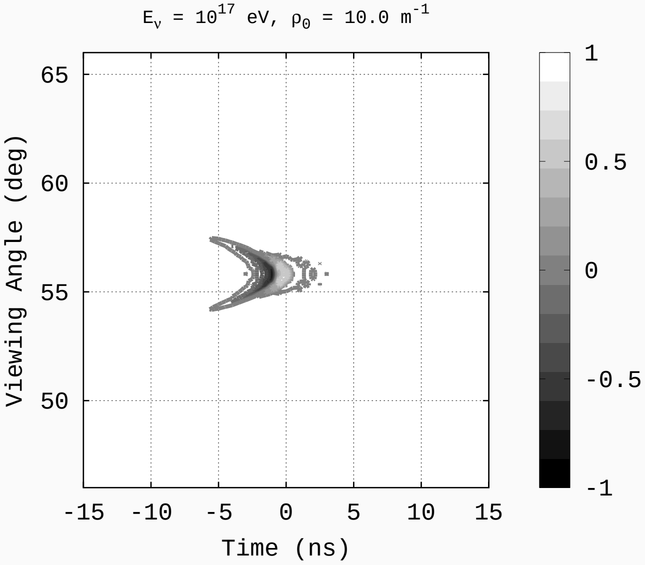
SPECTRA - ρ'-FORM FACTOR DEPENDENCE, W/ LPM SUPPRESSION

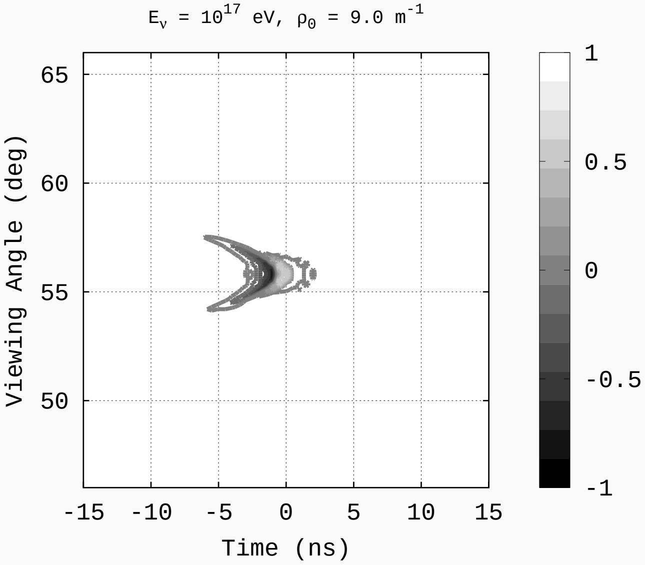


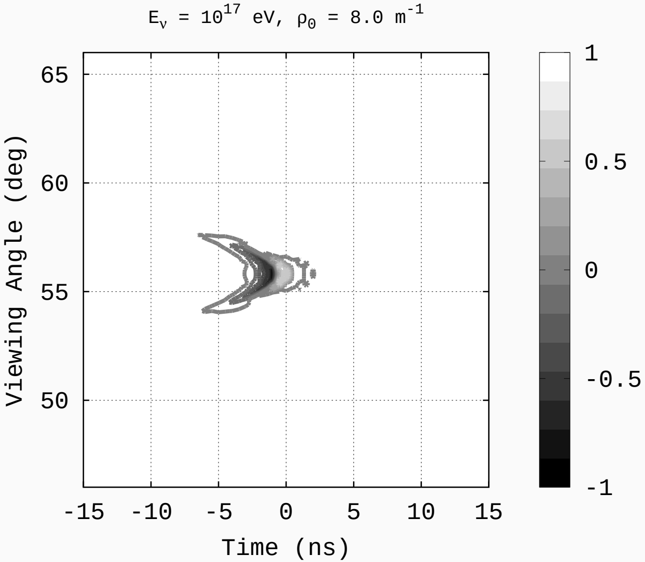
SPECTRA - ρ'-FORM FACTOR DEPENDENCE, W/ LPM SUPPRESSION

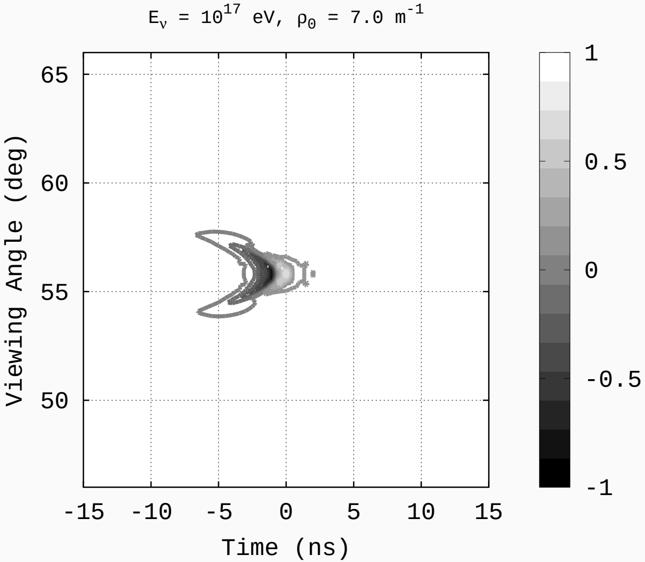


THE COMPLETE E-FIELD

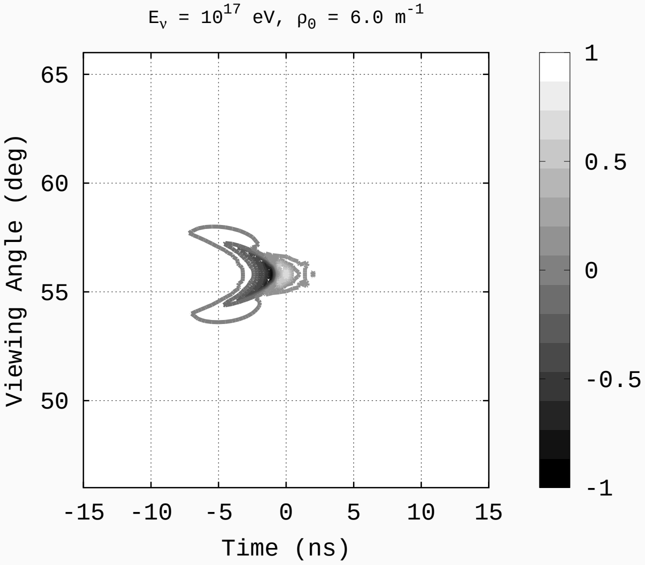



$E_\nu = 10^{17}$ eV, $\rho_0 = 9.0$ m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1

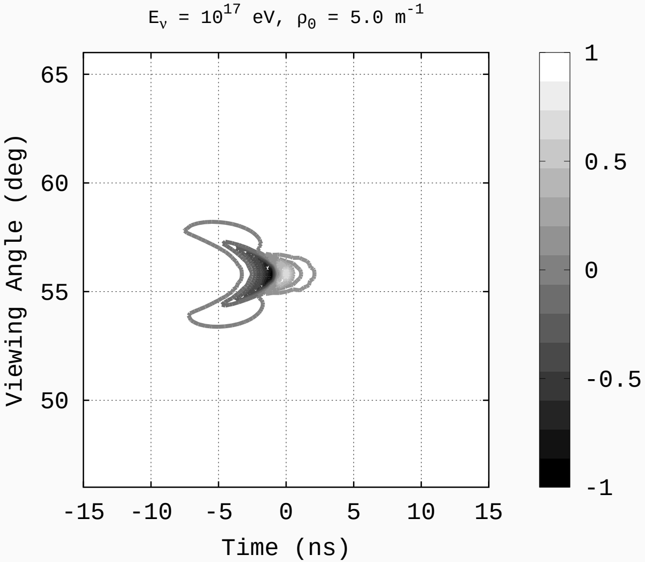

E_ν = 10^{17} eV, ρ_0 = 8.0 m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1

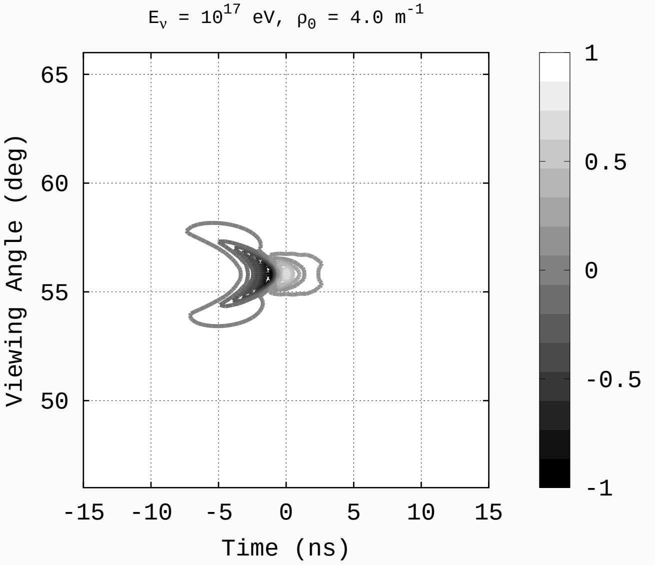


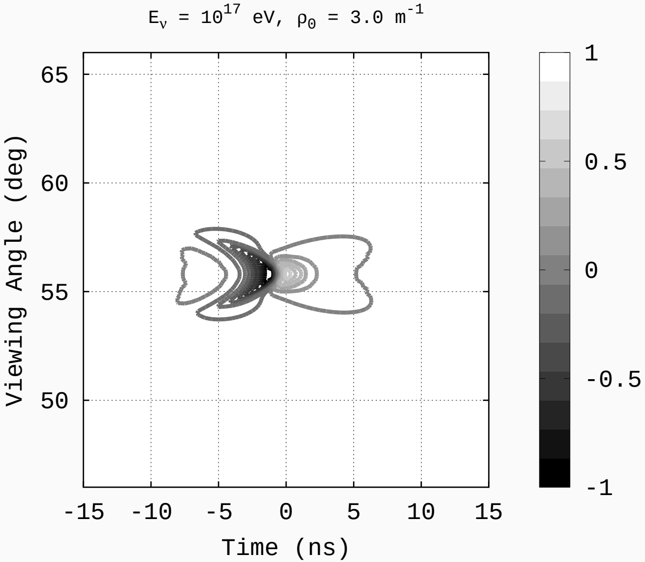
$E_\nu = 10^{17}$ eV, $\rho_0 = 7.0$ m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1

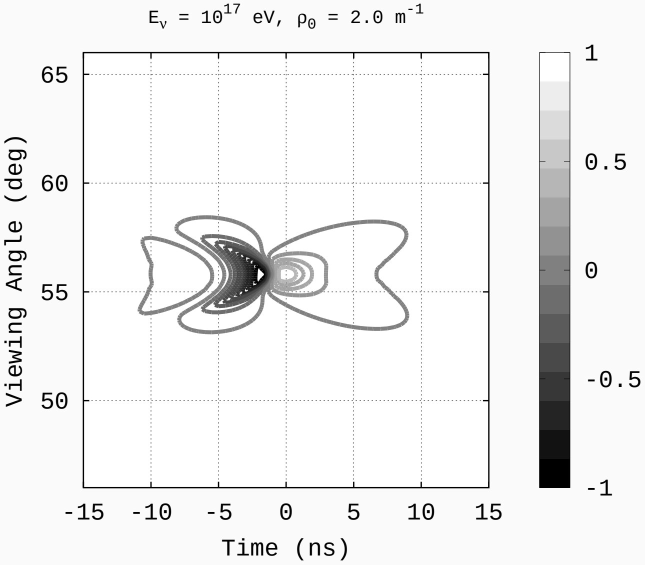

E_ν = 10^{17} eV, ρ_0 = 6.0 m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1

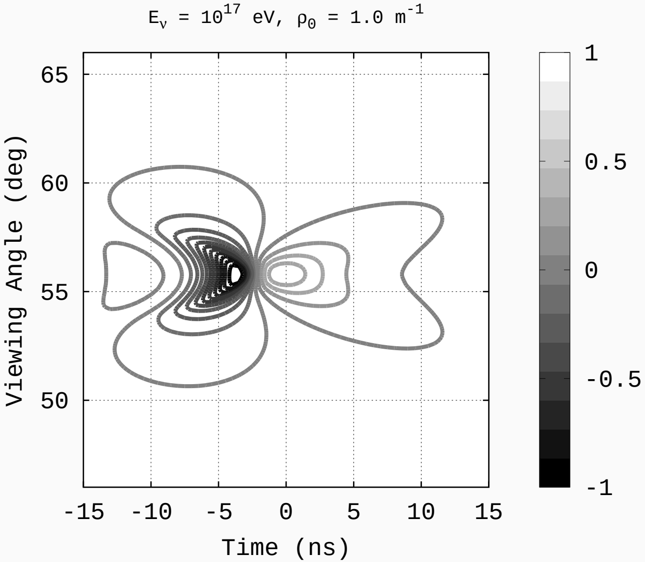
THE COMPLETE E-FIELD




E_ν = 10^17 eV, ρ_0 = 4.0 m^-1
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1


E_ν = 10^{17} eV, ρ_0 = 3.0 m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1


$E_\nu = 10^{17}$ eV, $\rho_0 = 2.0$ m^{-1}
Viewing Angle (deg)
65
60
55
50
-15
-10
-5
0
5
10
15
Time (ns)
1
0.5
0
-0.5
-1

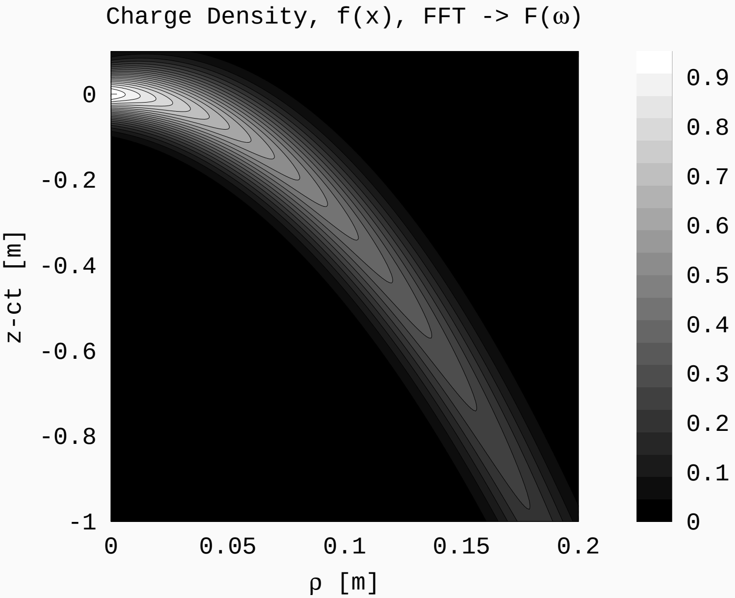

E$_\nu$ = 10^{17} eV, ρ$_0$ = 1.0 m^{-1}
Viewing Angle (deg)
Time (ns)
65
60
55
50
-15
-10
-5
0
5
10
15
1
0.5
0
-0.5
-1

CONCLUSIONS

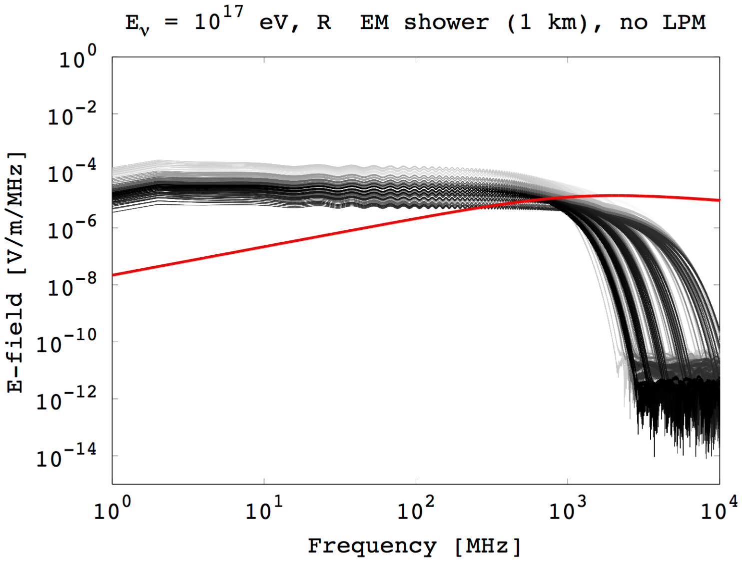
I. The Continuing Story of GZK neutrinos and Radio - ARIANNA and ARA continue to acquire data
II. *Regathering* our knowledge of the Askaryan effect - ZHS (1991)
III. RB (2001), ARVZ (2010-11): Towards analytic expressions
    A. We are making the code available on Github: **https://github.com/918particle/AraSim2**
    B. A few hundred lines, and decreasing
IV. Numerical Work, and The Ohio Supercomputing Cluster (OSC)
    A. UHE EM showers in minutes
    B. Fits for the lateral charge distribution
V. Results, with the LPM effect and Form Factor
VI. Future Work
    A. Varying the primary particle from e, to μ and τ, flavor investigations
    B. Numerical LPM, shower fluctuations

UHECR-LIKE SPECTRA

UHECR-LIKE SHOWER FRONTS - IDEA FROM STEVE BARWICK (UCI)



UHECR-LIKE SHOWER FRONTS



UHECR-LIKE SHOWER FRONTS (1-POLE HIGH-PASS FILTER ADDED)