Cherenkov Signals from Neutrinos

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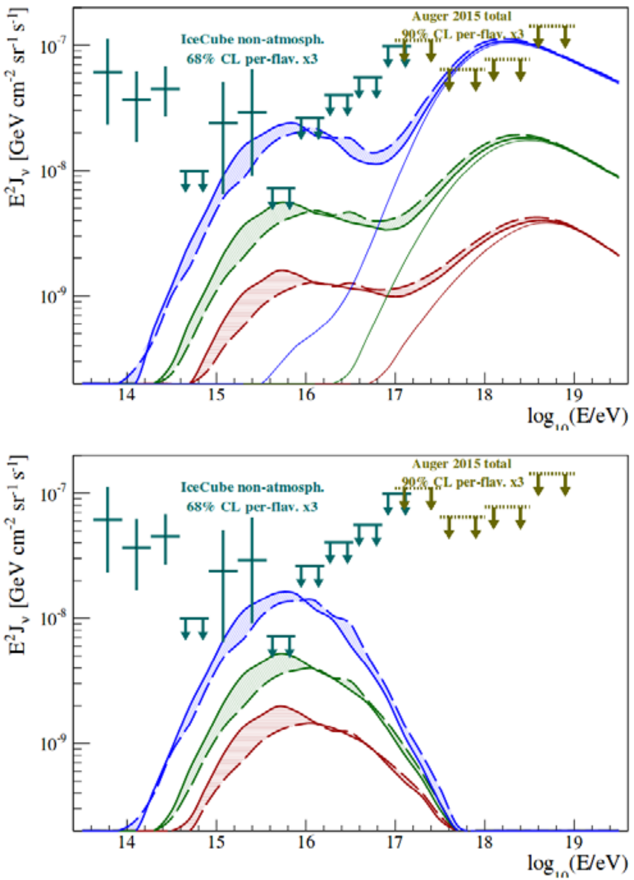
Summary of Work and Entrance to Third Year

Motivation of Work

- IceCube has confirmed the existence of high energy astrophysical neutrinos
- Estimate for highest energy neutrino observed: ~7.5PeV
- Even with the IceCube Gen-II upgrade, we are nearly blind in the energy range above 10PeV
- Opening a new window on the neutrino flux could expose us to:
  - The extension of the astrophysical flux as measured by IceCube
  - The cosmogenic flux
  - Exotic flux models



Cosmogenic neutrino fluxes for pure proton model (top) and mixed composition (bottom)

Models given by Aloisio , Boncioli, di Matteo, Grillo, Petrera, Salamida

Air Showers From Earth-Skimming Neutrinos

- High energy cosmic neutrinos experience flavor oscillation during propagation
  - Expect ~1:1:1 flavor ratio at Earth
- Neutrinos undergo charged current interactions in the Earth, which produces leptons, which may experience energy losses/decay/regeneration
  - μ, τ have high chance of Earth emergence
- Leptons may initiate upward going air showers
  - Detectable in all the normal routes: particle counters, radio, Cherenkov emission
- Increase target volume orders of magnitude

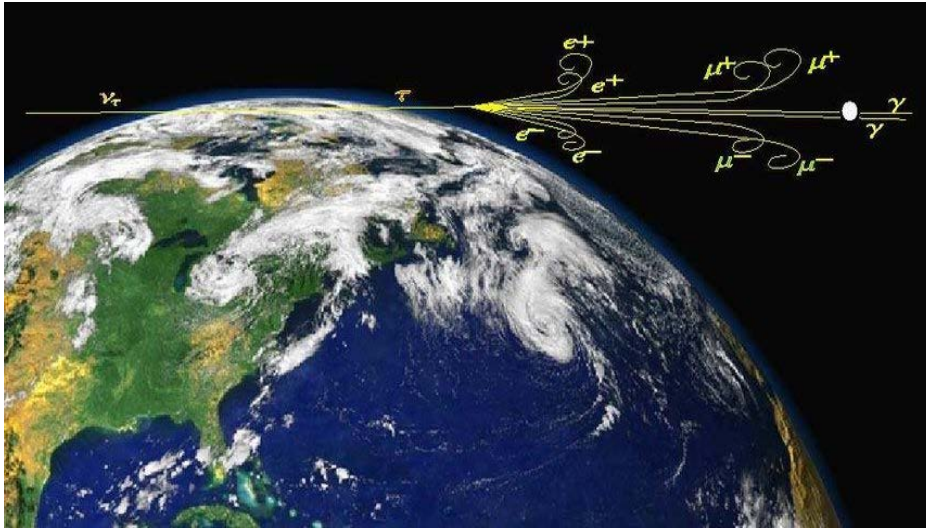


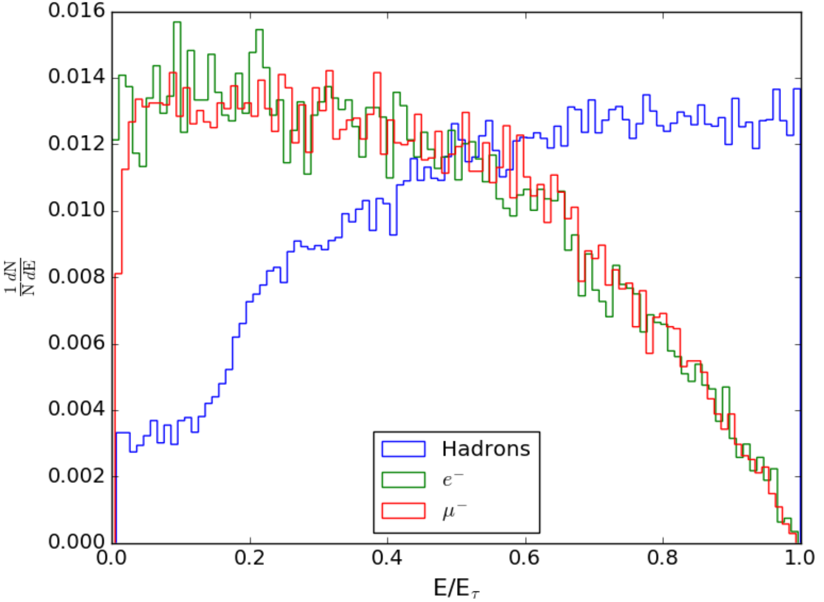
Diagram of a tau neutrino induced air shower

Tau Leptons

- Decay via hadrons 64% of the time
  - Average energy fraction: ~0.6
- Via electrons and muons 18% of the time
  - Average energy fraction: ~0.4
- Hadron/Electron induced showers well approximated by proton shower parameterizations
- Decay length: ~50km (E/1EeV)
- N

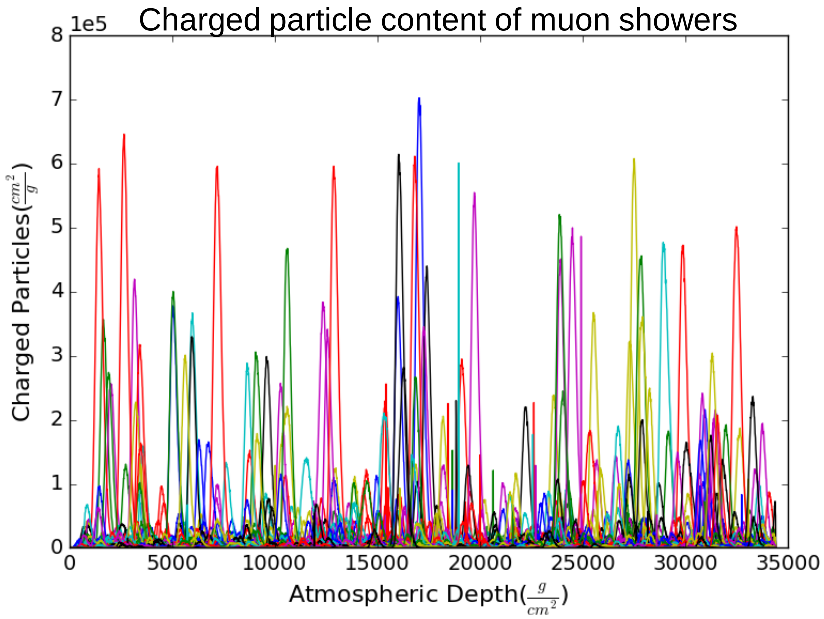
$\pi^- + \pi^0 + \nu_\tau \approx 25.49\%$
$e^- + \bar{\nu_e} + \nu_\tau \approx 17.82\%$
$\mu^- + \bar{\nu_\mu} + \nu_\tau \approx 17.39\%$
$\pi^- + \nu_\tau \approx 10.82\%$
$\pi^- + 2\pi^0 + \nu_\tau \approx 9.26\%$
$2\pi^- + \pi^+ + \nu_\tau \approx 8.99\%$
$2\pi^- + \pi^+ + \pi^0 + \nu_\tau \approx 2.74\%$
$3\pi^0 + \pi^- + \nu_\tau \approx 1.04\%$

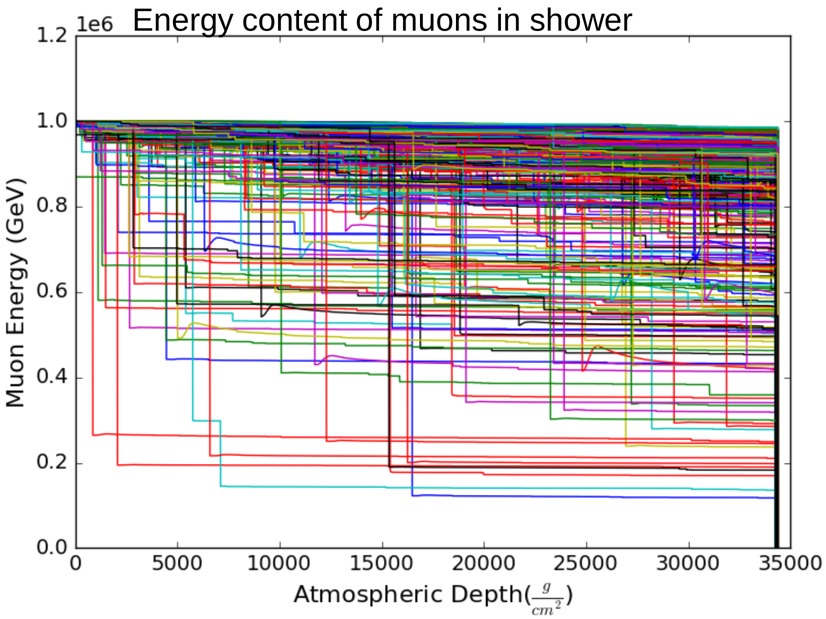
Fractional energy distributions of decay products from a relativistic tau lepton



Muon Induced Showers

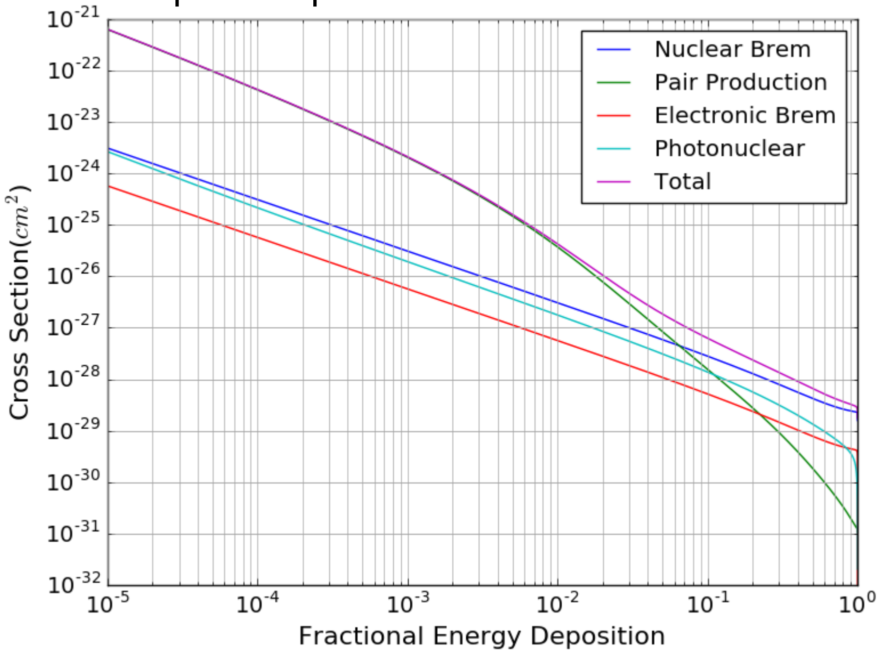
- 1000 PeV muon showers with 0° Earth emergence angle (horizontal)
- Non-negligible fraction of events initiate electromagnetic cascade
- Showers can begin very deep in the atmosphere



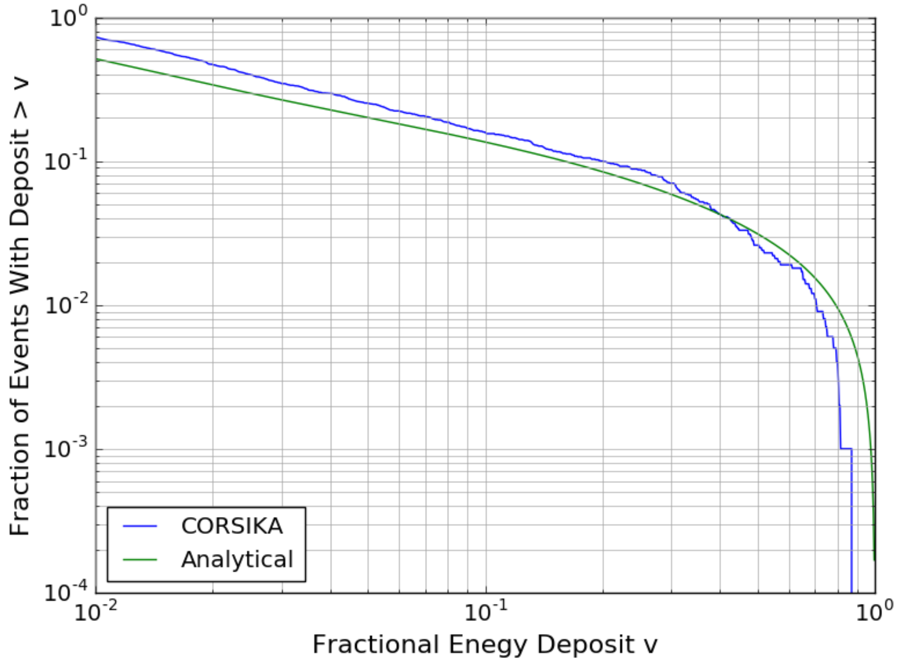


Muon Interaction Probabilities

Muon cross sections for high energy deposition processes



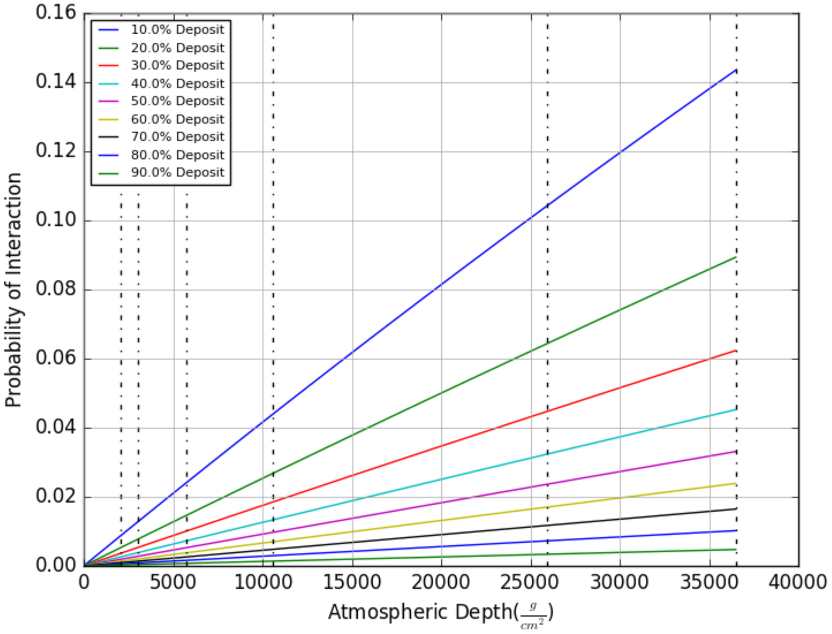
$$P_{\text{int}}(X) = 1 - e^{-X\sigma N} \quad \text{where} \quad \sigma = \int_v^1 \frac{d\sigma}{dv} dv$$



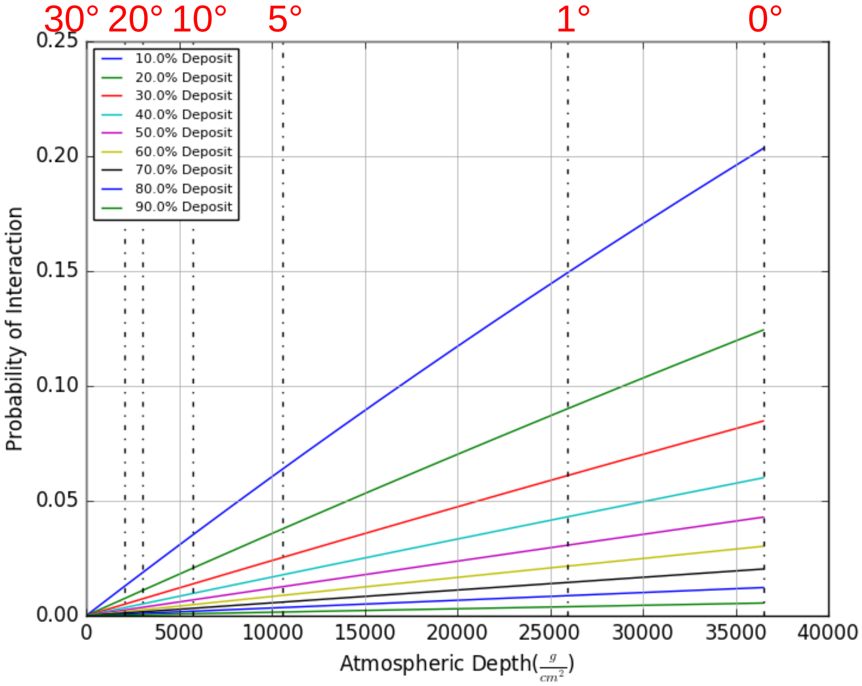
Muon Interaction Probabilities

*Dashed lines correspond to the full thickness of the atmosphere for the listed Earth emergence angles

1PeV Muon



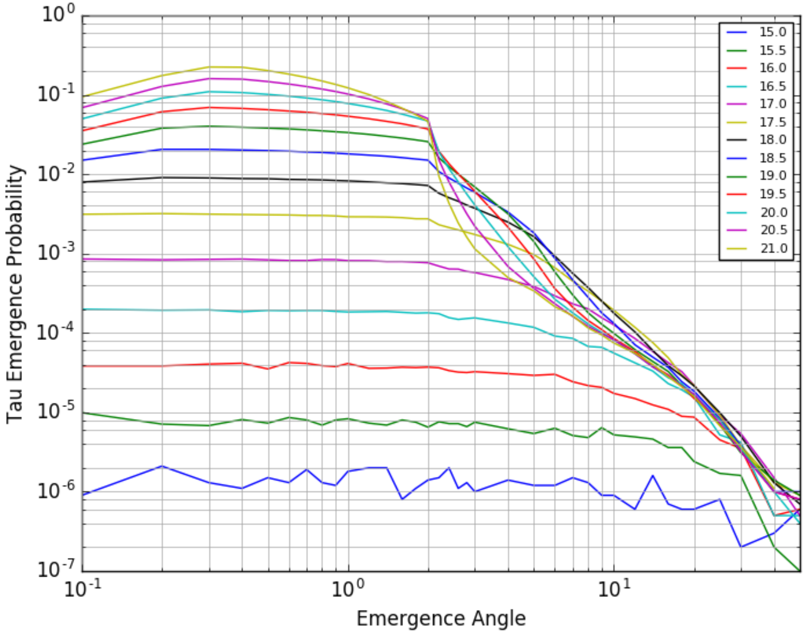
10EeV Muon



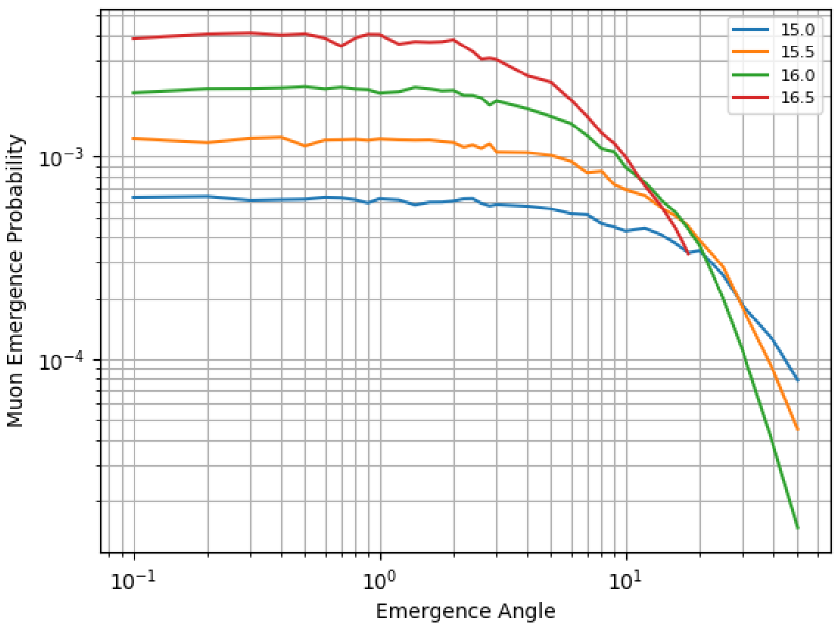
Muon Emergence Probability

- Emergence probability defined as the probability that a lepton emerges from the Earth from an input neutrino, regardless of lepton energy

Tau Emergence Probability



Muon Emergence Probability

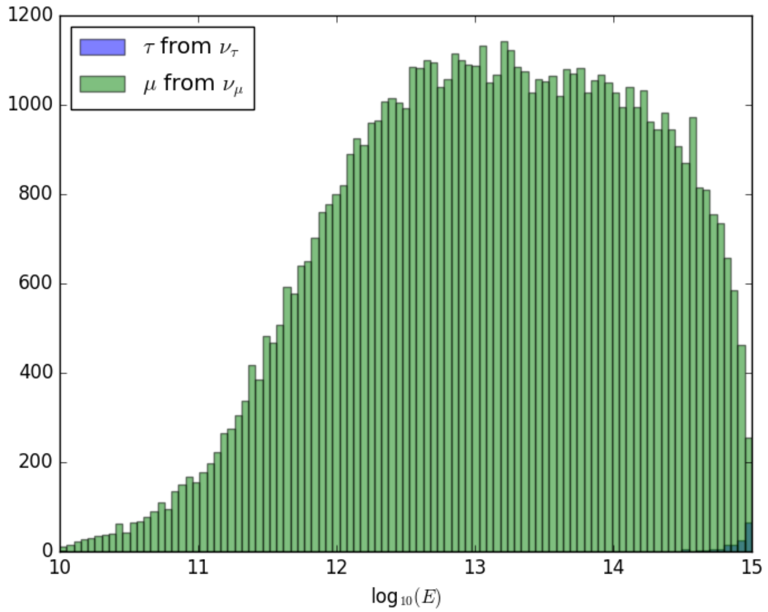


Emerging Leptons

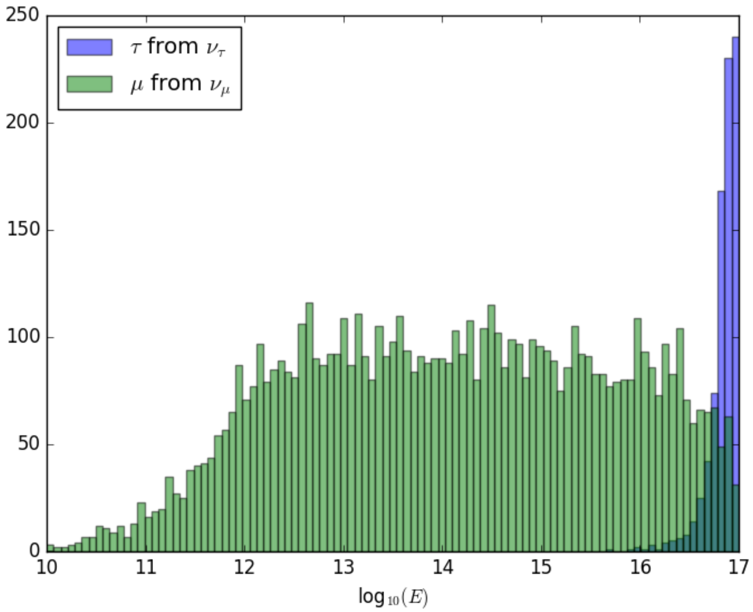
Larger muon energy losses are compensated by longer decay length. At low energies, muons have much larger Earth emergence probability.

Both at , 1° Earth Emergence Angle

10^8 1PeV Neutrinos



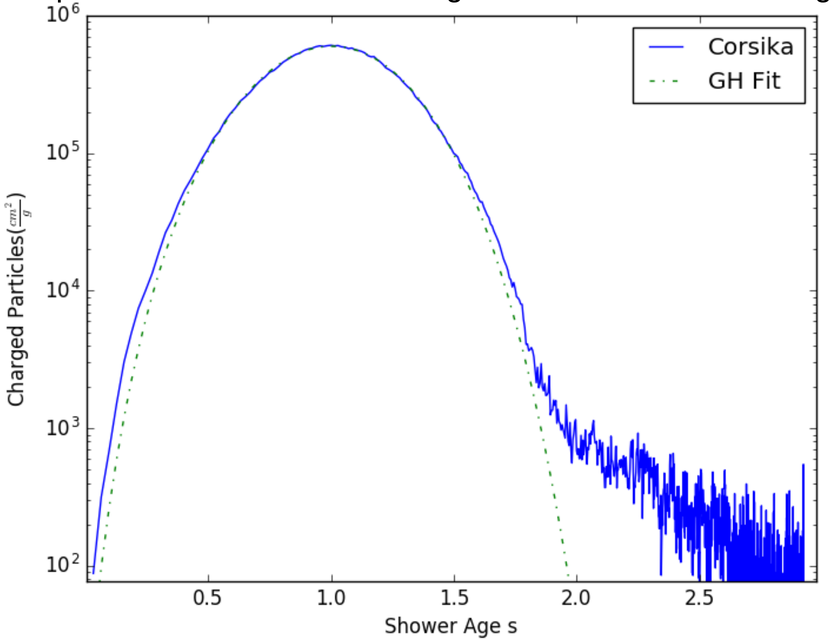
10^6 100 PeV Neutrinos



Charged Particle Profiles

- Profiles simulated, rather than parameterized
  - Doesn't underestimate particle content
  - Muon showers not well parameterized
- Particle energy content also captured
- Profiles simulated in modified CORSIKA-75600
  - Initiated at ground level
  - Perfectly horizontal
  - Taus decayed immediately and later shifted by decay distance sampled from exponential
- Primaries simulated:
  - Taus
  - Protons+Gammas for comparison with tau
  - Muons

100PeV proton shower charged particle profile as simulated in CORSIKA, with corresponding Gaisser-Hillas parameterization. Note disagreement at late shower ages

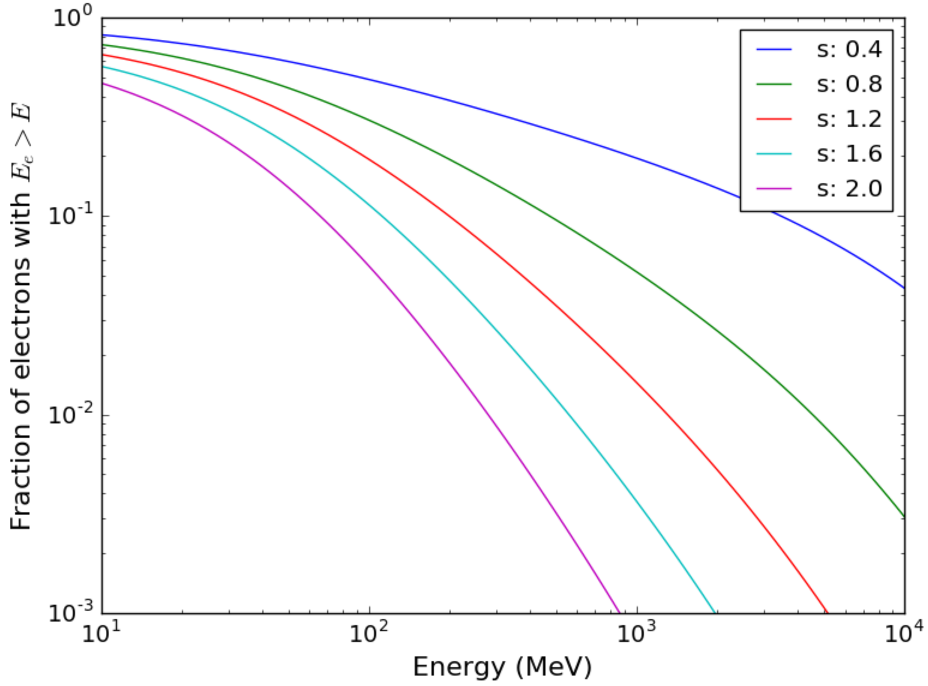


*Shower age s defined as
s = 3/[1+2(Xmax/X)]
s=0 Start of shower
s=1 Shower Maximum
s=3 End of Shower

Total Cherenkov Light Generation

- Total Cherenkov light dependent on:
  - Wavelength (brighter for smaller lambda)
  - Index of refraction (altitude)
  - Number of charged particles
  - The fraction T(E) electrons above the Cherenkov threshold, which is a function of shower age
  - Photons emitted in ring with angle cosθ = 1/nβ

$$\frac{dN_\gamma}{dX\,d\lambda} = \frac{N_{e+/-}T(E_{thr})}{\rho}\left[2\pi\alpha\frac{1}{\lambda^2}\left(1-\frac{1}{(\beta n)^2}\right)\right]$$



T(E) for different shower ages. For reference, at ground, Ethr = 20MeV at z=0km and 37MeV at z=10km

Electron Angular Distribution

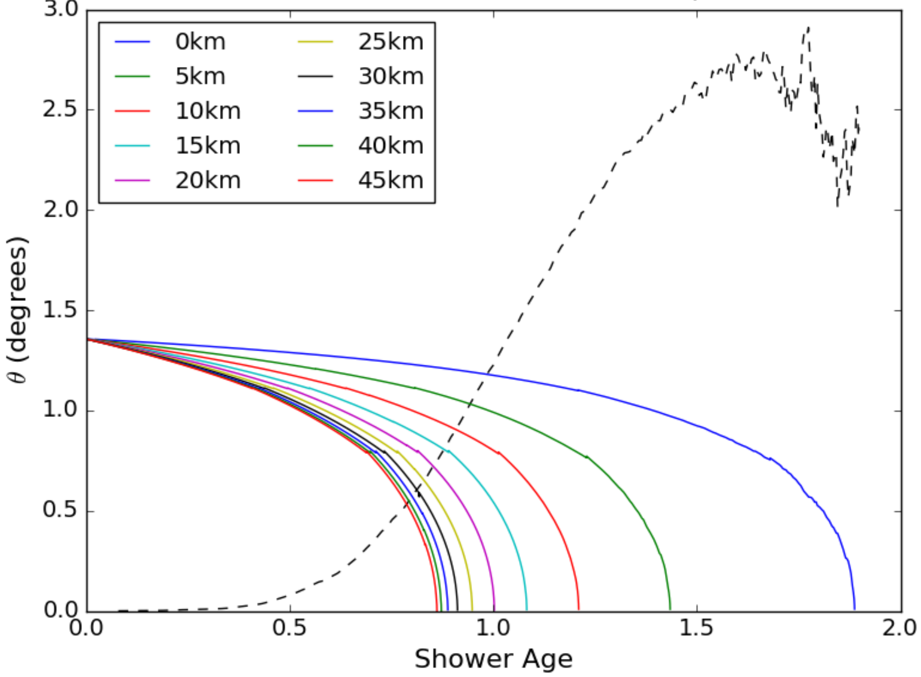
- Electron angular distribution depends only on electron energy
- To speed up calculations, we use the average energy content of electrons in a given step
- Electron scale angle greater than Cherenkov angle for certain shower configurations

Full distribution has complicated form, but can be understood as:

$$\frac{dn}{d\Omega} \propto \frac{dn}{du} \propto e(-\theta/\theta_s)$$

That is, electrons are distributed off the shower axis exponentially

Electron scale angle as a function of shower age for a 100PeV proton shower with 5° Earth emergence angle. Local Cherenkov angle also plotted for different initiated distances in the atmosphere



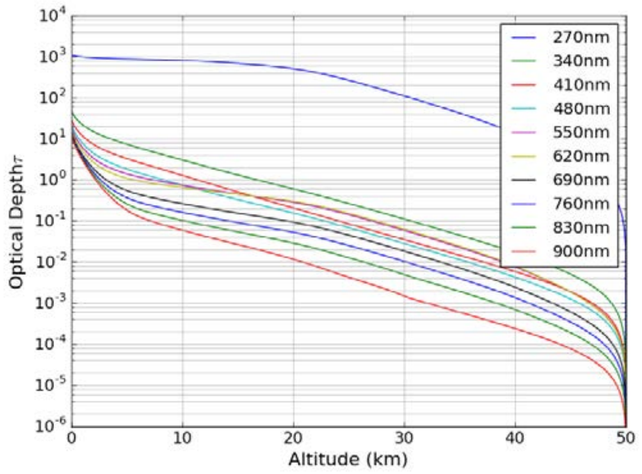
Cherenkov Light Attenuation

- Cherenkov light scattered on the way to the detector
- Components considered:
  - Rayleigh (Molecular)
  - Aerosol
  - Ozone
- Scattering much stronger for smaller wavelengths
- Number at instrument given by:

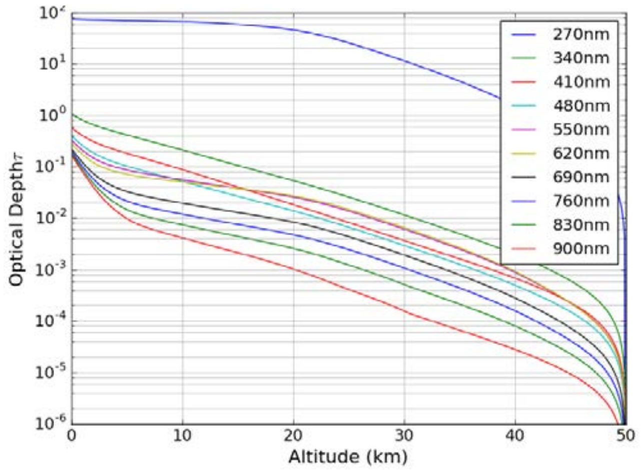
$$N = N_\gamma e^{-\tau}, \quad \tau = \int_z \alpha(\lambda, z) dl$$

$$\alpha(\lambda, z) = \sigma(\lambda) N(z)$$

Horizontal Atmosphere



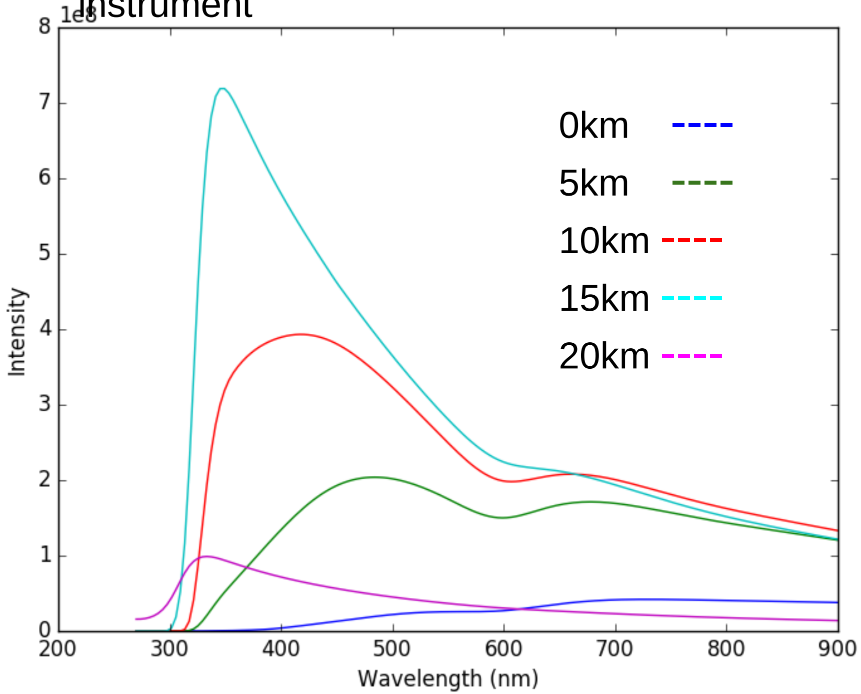
Vertical Atmosphere



Cherenkov Spectra

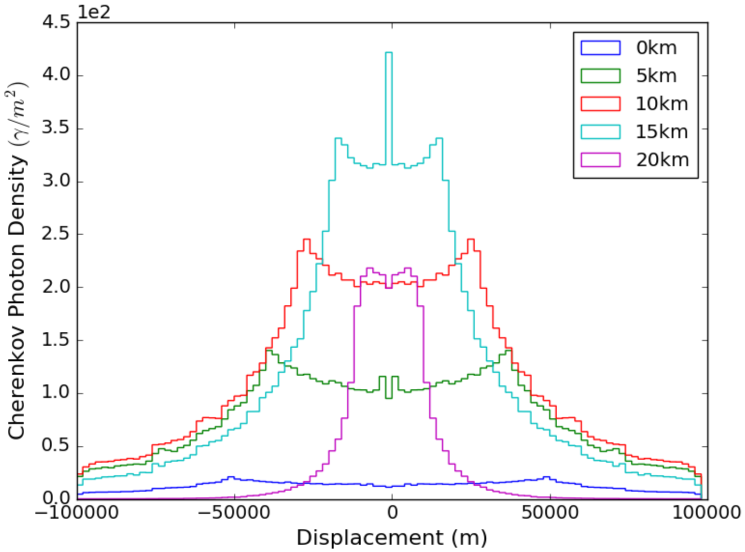
- Cherenkov emission larger for smaller wavelengths (proportional to 1/λ^2)
- Atmospheric extinction strong in visible range
  - Strongest at small wavelengths
- With increasing decay distance
  - Less atmospheric attenuation
  - Less Cherenkov generation
  - Peak wavelength shifts to lower altitude

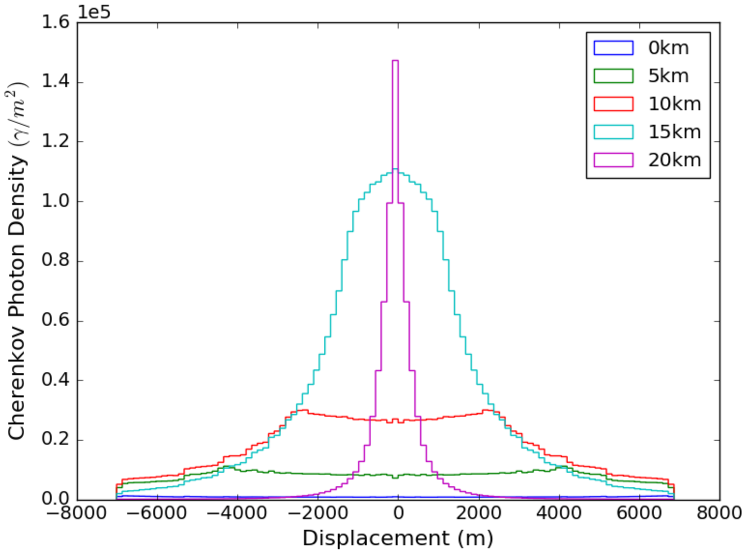
100 PeV proton shower with 5° Earth Emergence Angle initiated at different altitudes as seen by a space based instrument



Cherenkov Spatial Distribution

- Factor 100-1000 difference in intensity for space and balloon based instruments depending on geometry
- Cherenkov pool radius ~50km for space-based, ~5km for balloon-based
- A balloon based instrument can be inside shower development
- For high altitude showers, the Cherenkov distribution follows the electron distribution





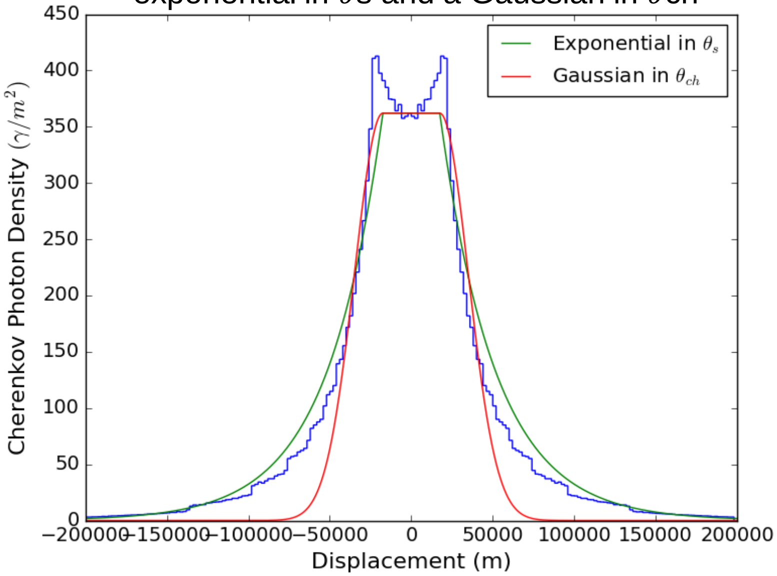
One Dimensional Modelling of Distribution

- Cherenkov light distribution can be modelled quite well as:

$$\frac{dn}{d\Omega} = \begin{cases} A & \theta < \theta_{ch} \\ Ae^{-(\theta-\theta_{ch})/\theta_s} & \theta \geq \theta_{ch} \end{cases}$$

- A corresponds to the Cherenkov photon density on shower axis
- A is calculated for every shower and θch θs at the brightest point in the shower are recorded

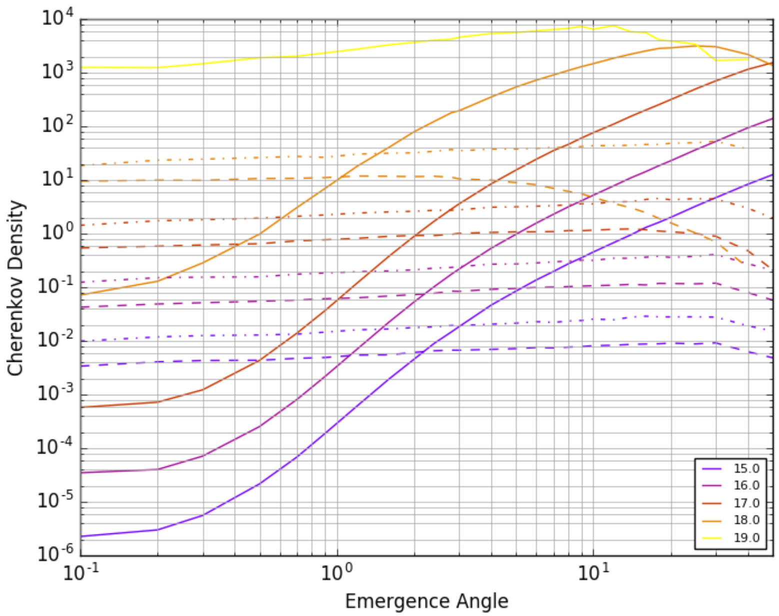
Cherenkov Distribution of a 100PeV shower with 5° Earth emergence angle initiated at z=10km, fit with an exponential in θs and a Gaussian in θch



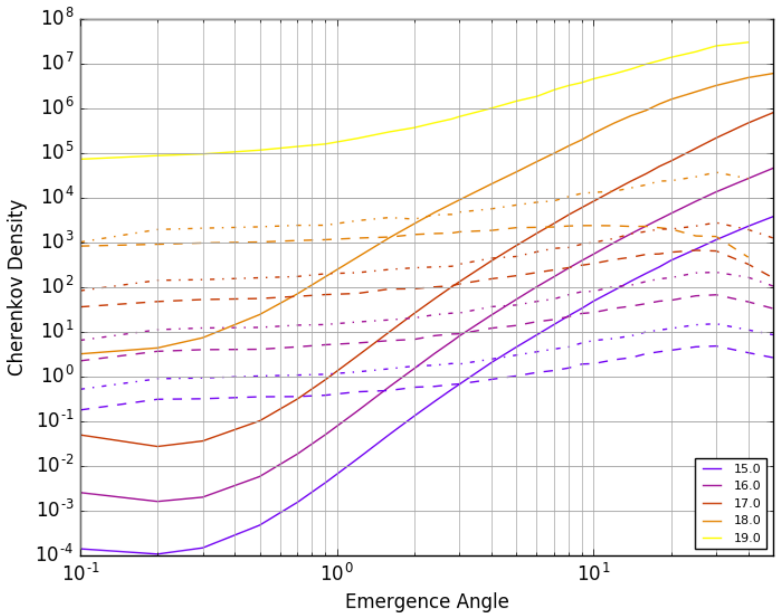
Cherenkov Intensity

Solid lines represent the hadronic and electronic decay branches of the tau shower. Dashed lines correspond to muons from tau decay. Dashed-dotted correspond to primary muons

POEMMA Median



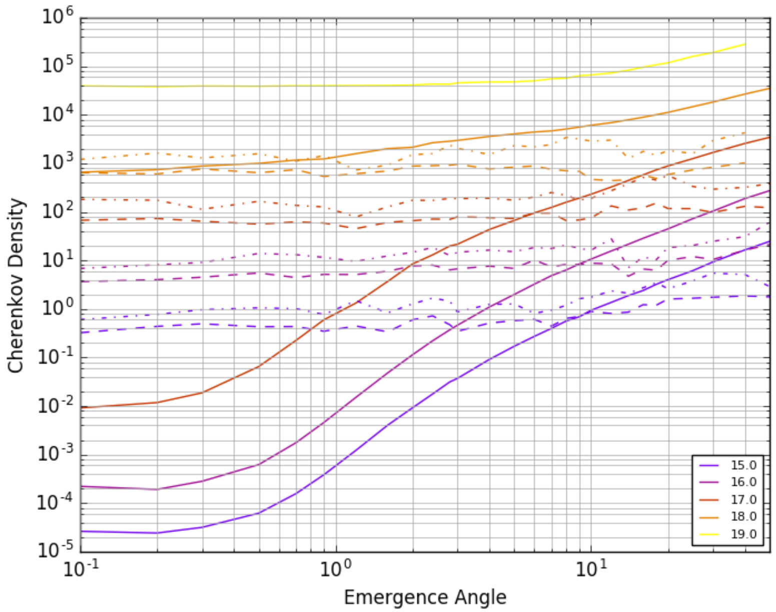
SPB2 Median



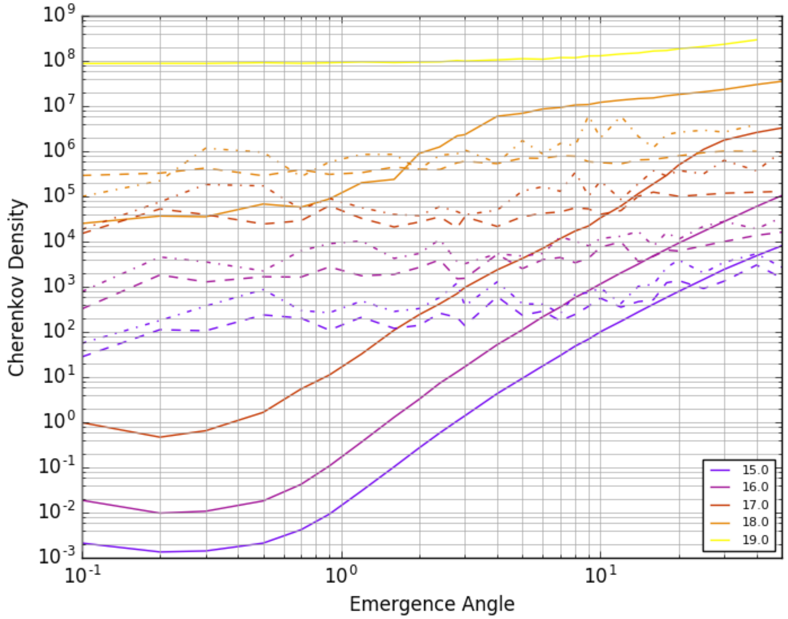
Cherenkov Intensity

Solid lines represent the hadronic and electronic decay branches of the tau shower. Dashed lines correspond to muons from tau decay. Dashed-dotted correspond to primary muons

POEMMA +3σ



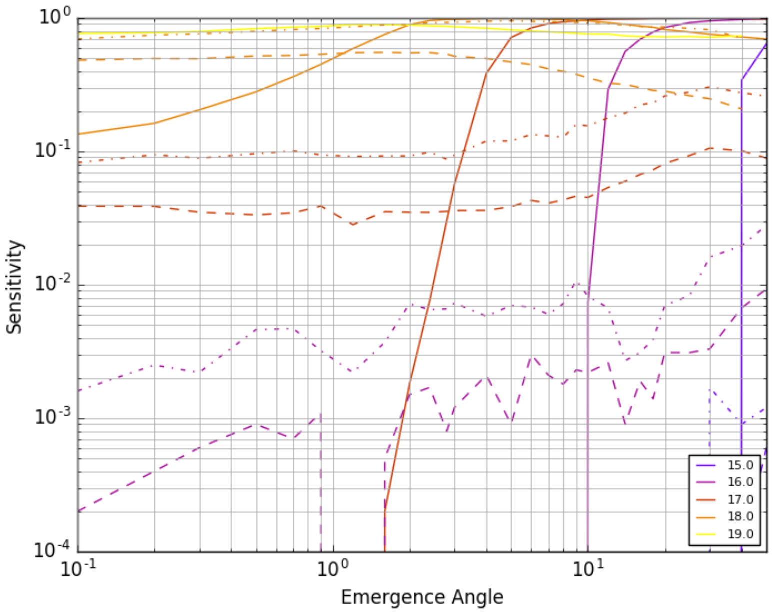
SPB2 +3σ



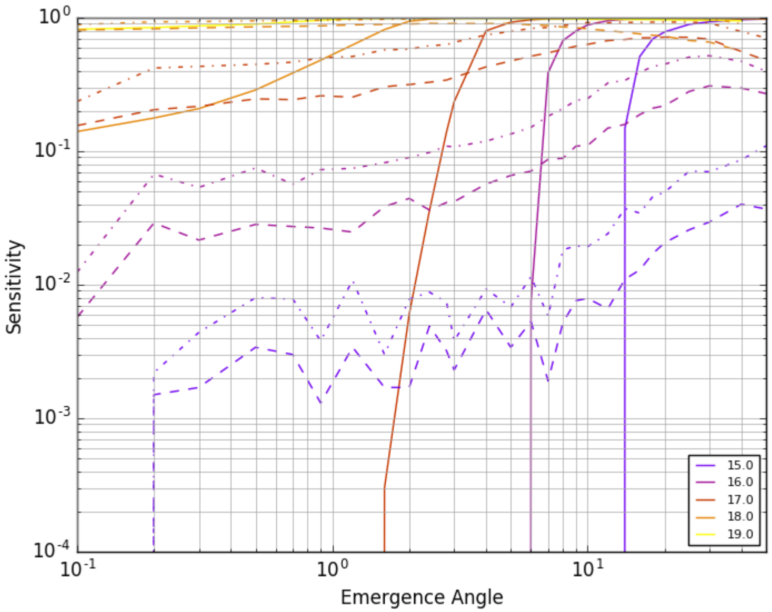
Sensitivity Estimates

Solid lines represent the hadronic and electronic decay branches of the tau shower. Dashed lines correspond to muons from tau decay. Dashed-dotted correspond to primary muons

Space Based Sensitivity (threshold 20 γ/m^2)



Balloon Based Sensitivity (threshold 200 γ/m^2)



Conclusions

- Muons (whether from tau decay or primary muon neutrinos) are brighter than hadronic and electronic showers until around 10° Earth emergence
    - This effect diminishes with increasing energy
- Muon neutrinos have a high probability of Earth emergence
    - Stronger effect at lower energies
- Space based and balloon based instruments are sensitive to these signals
    - Partially sensitive to muons
    - “Turn on” emergence angle where quickly become 100% sensitive to conventional hadronic/electronic showers
    - Balloon based instruments more sensitive to lower energies, but also have reduce coverage compared to space based instruments

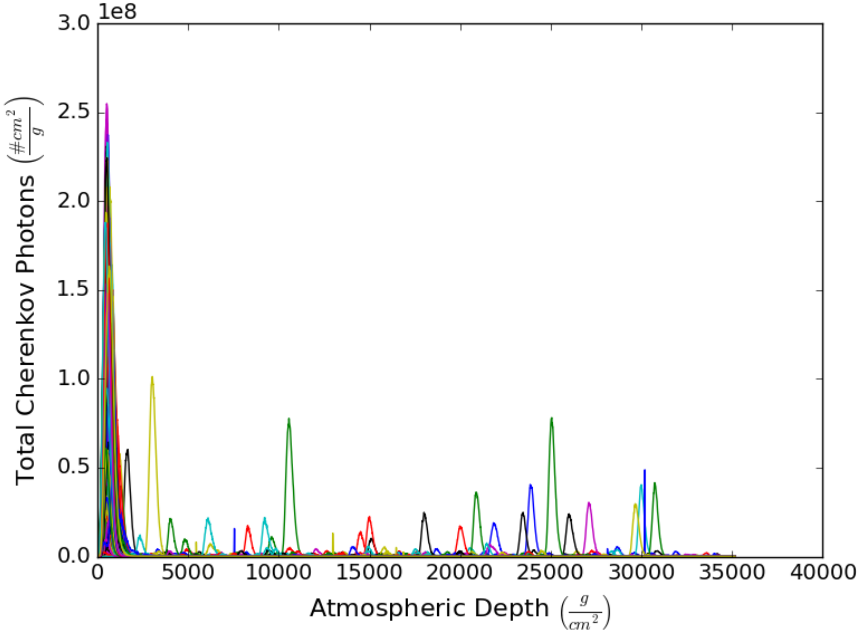
Upcoming Work

- Combine all elements listed here (emergence probabilities, sensitivities, spatial extent) to estimate exposure to different neutrino fluxes
- Estimate Cherenkov background due to cosmic rays from above Earth’s horizon

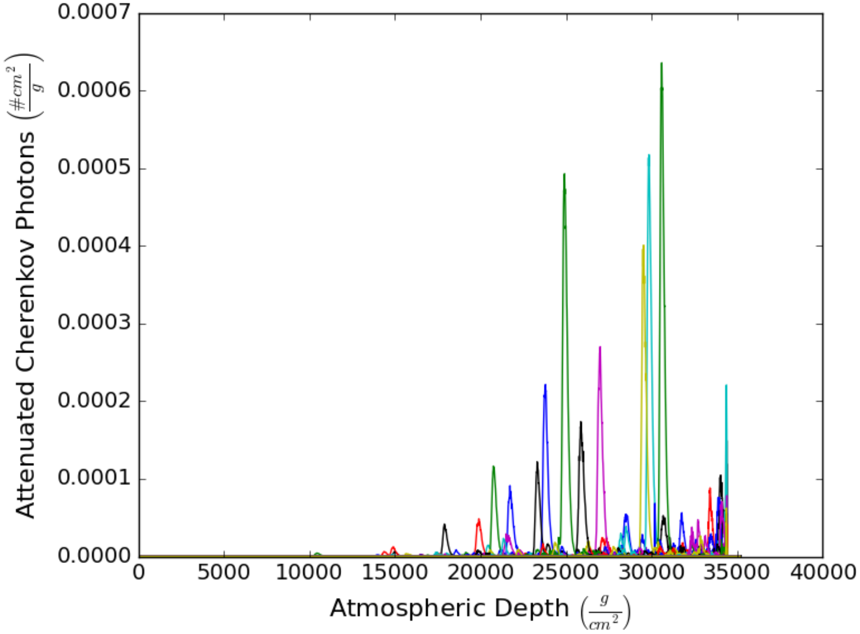
Muons from Tau Decay

1000 1PeV tau lepton showers with 0° Earth emergence angle

Cherenkov Emission

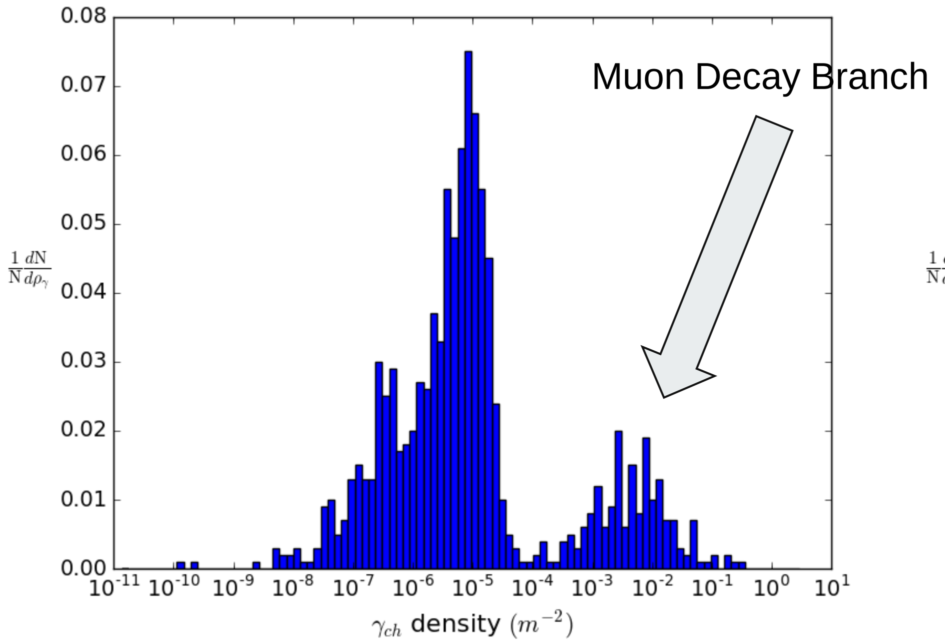


Cherenkov Emission weighted by geometric and atmospheric corrections



Muons from Tau Decay

POEMMA (horizontal)



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