GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
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INFN LNGS

Numerical Simulations of X-ray Synchrotron Emission from EAS

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Astroparticle PhD Passage of Year
L'Aquila, Italy, Oct. 20, 2025

Outline

The observation of **PeV Cosmic Rays** is key to understanding: sources, acceleration mechanisms, galactic–extragalactic transition…

- Currently, CRs above ~1 PeV detected only via **Extensive Air Showers (EAS)** with ground-based methods.
- Composition still uncertain (model dependencies, systematic errors).

New direction: High-altitude detection (~30 km)

- Advantages: larger acceptance, less absorption, higher efficiency.

Focus of this work:

- **Synchrotron X-ray emission from EAS** from e^-/e^+ secondaries in the geomagnetic field.
- Unique probe of **early EAS stages** (HE electrons, >100 GeV).

Goals:

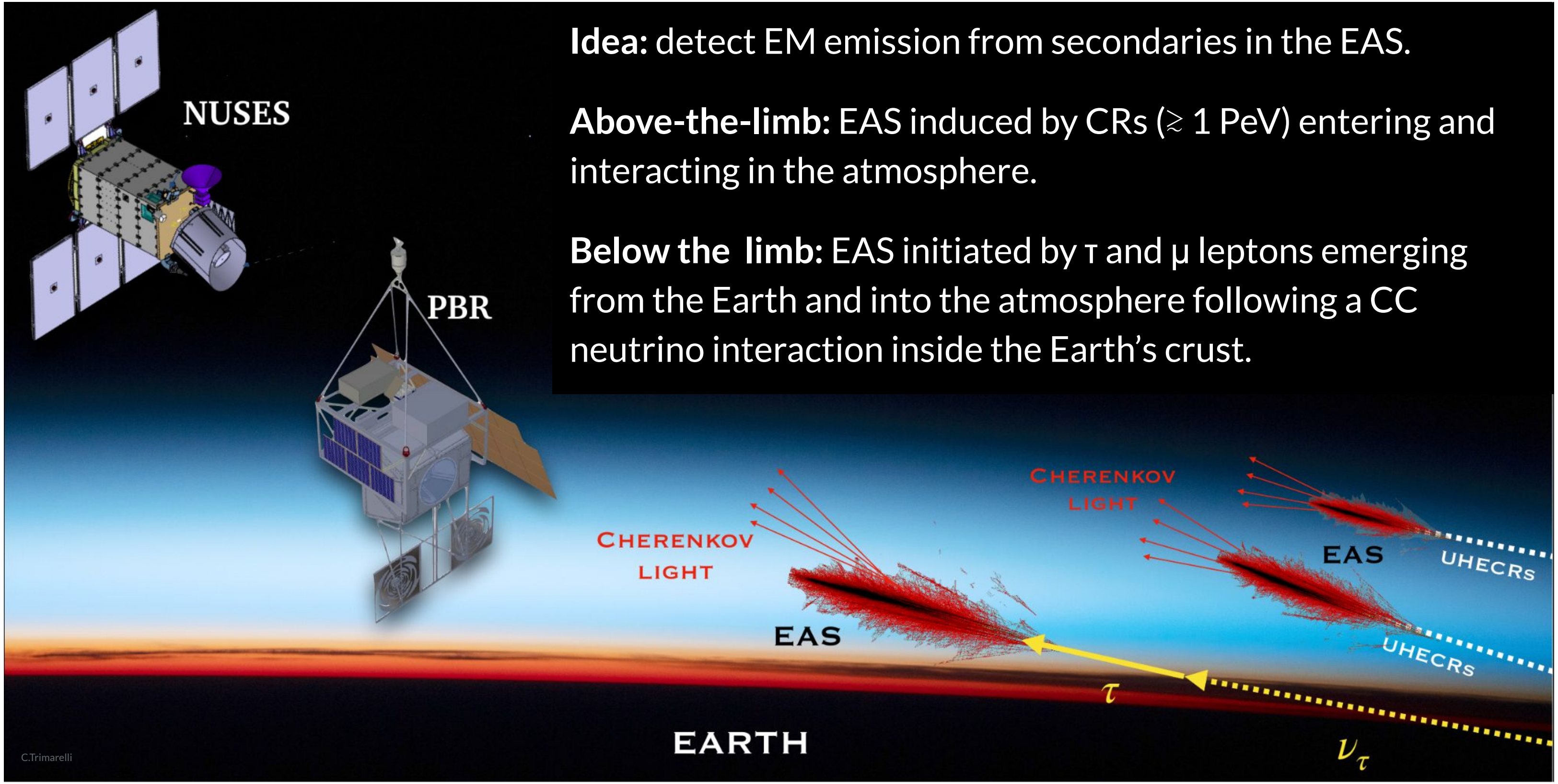
- Model the X-ray emission.
- Estimate photon fluxes at the detection plane.
- Estimate event rates.

Outline: EAS (as seen from high-up in the sky)

Idea: detect EM emission from secondaries in the EAS.

Above-the-limb: EAS induced by CRs ($\gtrsim$ 1 PeV) entering and interacting in the atmosphere.

Below the limb: EAS initiated by τ and μ leptons emerging from the Earth and into the atmosphere following a CC neutrino interaction inside the Earth's crust.



Outline: The Master Formula

For an ensemble of particles in the incoherent radiation regime, the number of photons emitted by an EAS is given by:

- the convolution of the single-particle spectrum with the electron energy distribution,
- integrated over the entire shower development.

$$\frac{dN_\gamma}{dE_\gamma}^{(EAS)} = \int_{X_{min}}^{X_{max}} \frac{dX}{\rho(X)\,c}\, Tr(E_\gamma, \Delta X)\, N(X) \int_{E_{min}}^{E_{max}} dE_e\, \frac{dn_e}{dE_e}(E_e, s(X))\, \frac{dN_\gamma}{dt\, dE_\gamma}^{(1)}(E_e, E_\gamma)$$

Number of Photons

Geometry

Absorption

Longitudinal Development

Electron Energy Distribution

Single Particle Emission

Earth's Atmosphere

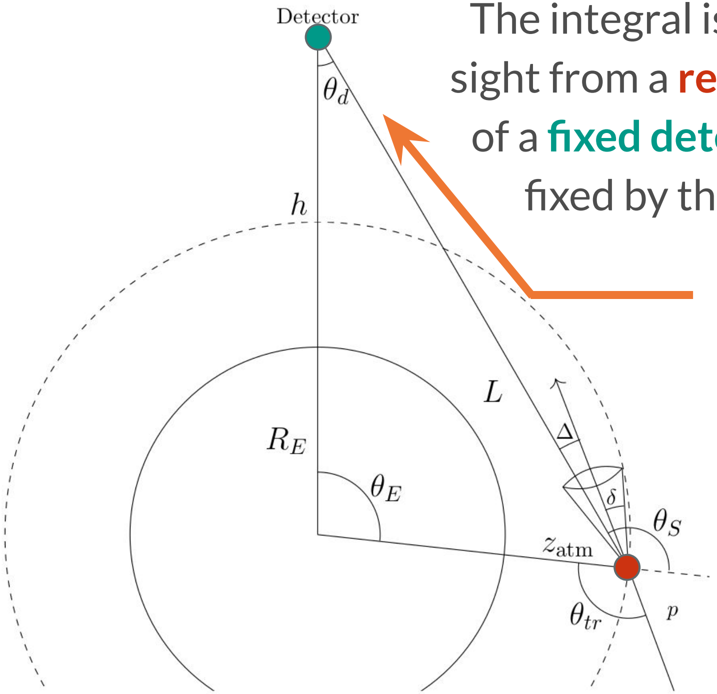
EAS Physics

Geomagnetic Synchrotron

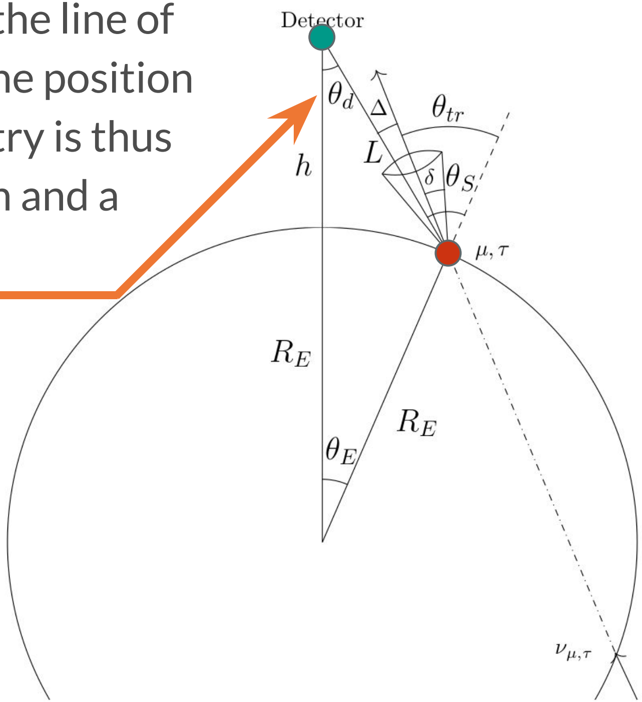
Outline: Geometry

The integral is computed along the line of sight from a **reference point** to the position of a **fixed detector**. The geometry is thus fixed by the detector position and a

viewing angle



Above-the-limb events



Below-the-limb events

Single particle emission

$$\frac{dN_\gamma^{(EAS)}}{d\epsilon} = \int_{X_{min}}^{X_{max}} \frac{dX}{\rho(X)\,c}\, Tr(\epsilon, \Delta X)\, N(X) \int_{E_{min}}^{E_{max}} dE\, \frac{dn_e}{dE}(E, s(X)) \boxed{\frac{dN_\gamma^{(1)}}{d\epsilon}(E, \epsilon)}$$

Single Particle Emission

- The power spectrum is proportional to the synchrotron function, **F(x)**, which depends only on $\mathbf{x = \omega / \omega_c}$
- $\boldsymbol{\omega_c}$ depends linearly on the Larmor frequency, $\boldsymbol{\omega_L}$, which is itself linearly proportional to the magnetic field, **B**.
- The **number of photons** emitted per unit time and frequency is just the **power spectrum divided by the photon energy**.

$$\frac{P^{(1)}}{d\epsilon}(E) = \frac{\sqrt{3}\alpha}{2\pi}\omega_L F\left(x(E)\right)$$

$$\frac{dN_\gamma^{(1)}}{dt d\epsilon}(E) = \frac{\sqrt{3}\alpha}{2\pi}\frac{\omega_L}{\epsilon}F\left(x(E)\right)$$

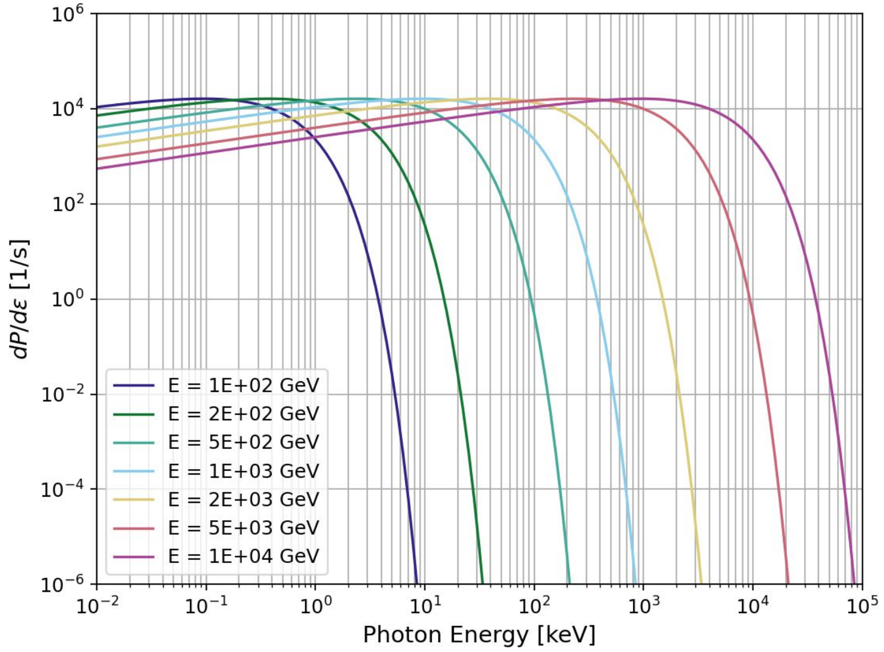
with:

$$\omega_L = \frac{q_e||\vec{B}||}{m_e c} \qquad \omega_c = \frac{3}{2}\gamma^2\omega_L \sin\alpha_p$$

Single Particle Emission: Power Spectrum

$$F(x) = x \int_x^\infty K_{5/3}(\xi) d\xi$$

- Most of the power is emitted close to the critical synchrotron frequency, ω_c
- For $\omega < \omega_c$, the power grows as a power law up to the critical frequency
- For $\omega > \omega_c$, the power falls off as an exponential (approximately)



Electron Energy Distribution

$$\frac{dN_\gamma^{(EAS)}}{d\epsilon} = \int_{X_{min}}^{X_{max}} \frac{dX}{\rho(X)\, c}\, Tr(\epsilon, \Delta X)\, N(X) \int_{E_{min}}^{E_{max}} dE \boxed{\frac{dn_e}{dE}(E, s(X))} \frac{dN_\gamma^{(1)}}{d\epsilon}(E, \epsilon)$$

Electron Energy Distribution

Hillas

Older model (1982)

- Is an empirical fit to data obtained through dedicated MC simulations in bins of shower age down to s = 0.1

Limitations:

- Only photon primary showers were simulated with energies up to 1 TeV.

Nerling

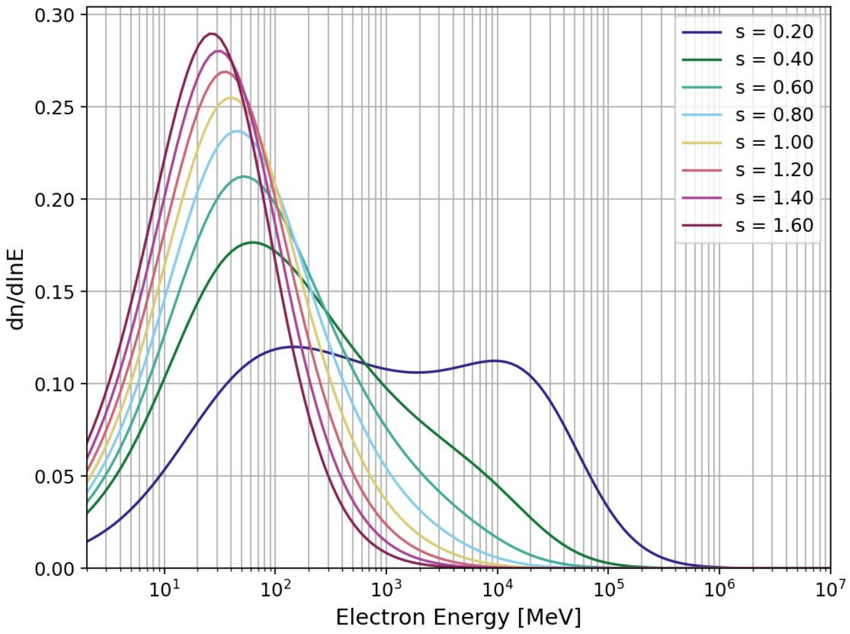
Newer Model (2006)

- Is in better agreement with CORSIKA simulations data near the shower maximum ($0.8 \leq s \leq 1.2$) .

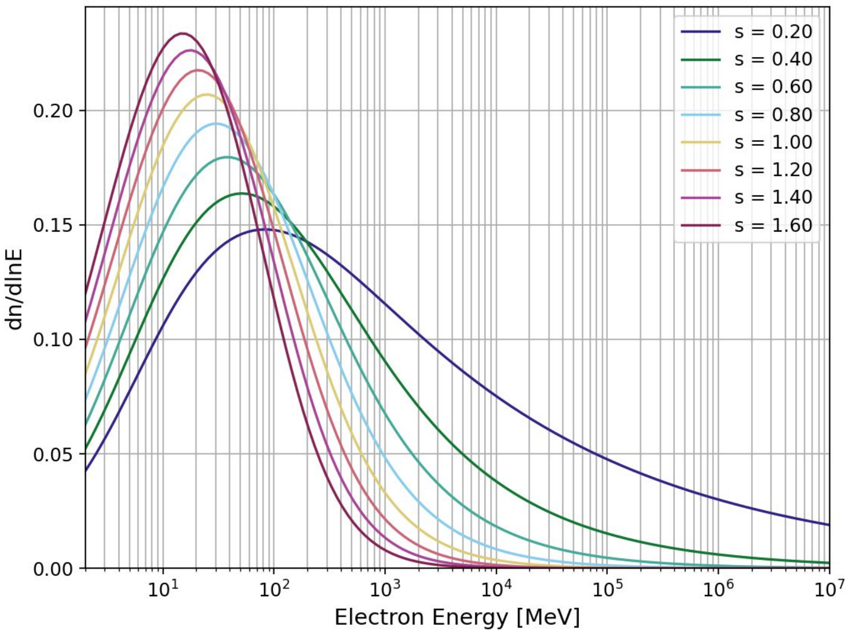
Limitations:

- Has not been validated for young showers ($s < 0.8$).

Electron Energy Distribution: Comparison



Hillas



Nerling

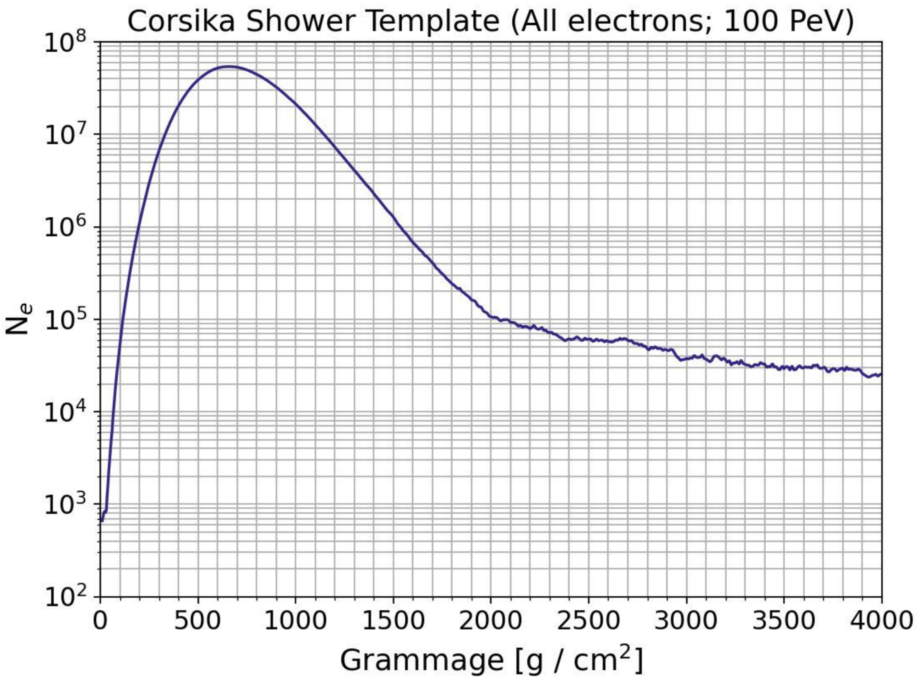
Longitudinal Template

$$\frac{dN_\gamma^{(EAS)}}{d\epsilon} = \int_{X_{min}}^{X_{max}} \frac{dX}{\rho(X)\,c}\, Tr(\epsilon, \Delta X)\, \boxed{N(X)} \int_{E_{min}}^{E_{max}} dE\, \frac{dn_e}{dE}(E, s(X))\, \frac{dN_\gamma^{(1)}}{d\epsilon}(E, \epsilon)$$

Longitudinal template

The shower size as a function of grammage was obtained by averaging a total of 1000 simulated CORSIKA showers with:

- a 100 PeV proton primary,
- QGSJETII-04 hadronic interaction model for high-energies,
- GHEISHA 2002d hadronic model for low-energies,
- slant depth, curved atmosphere, and upward geometry options enabled.



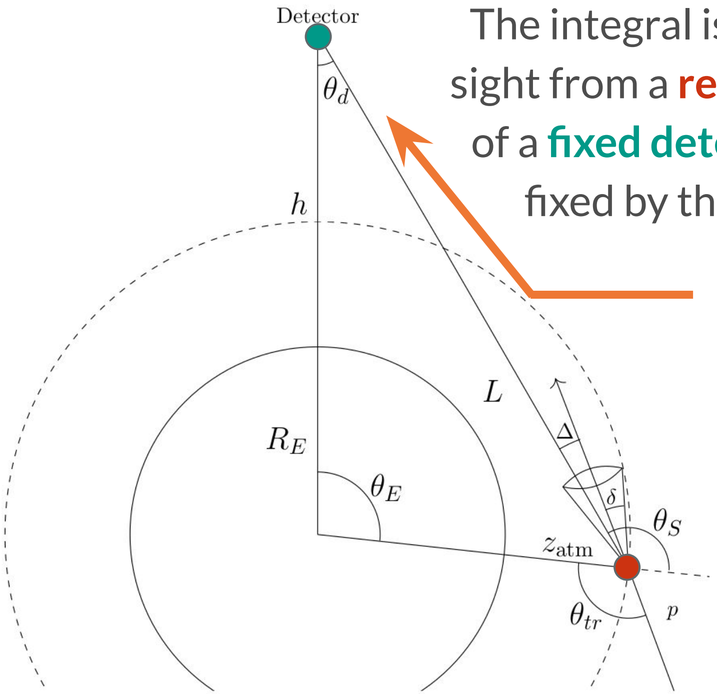
Atmosphere & Geometry

$$\frac{dN_\gamma^{(EAS)}}{d\epsilon} = \int_{X_{min}}^{X_{max}} \boxed{\frac{dX}{\rho(X)\,c} Tr(\epsilon, \Delta X)} N(X) \int_{E_{min}}^{E_{max}} dE \, \frac{dn_e}{dE}(E, s(X)) \, \frac{dN_\gamma^{(1)}}{d\epsilon}(E, \epsilon)$$

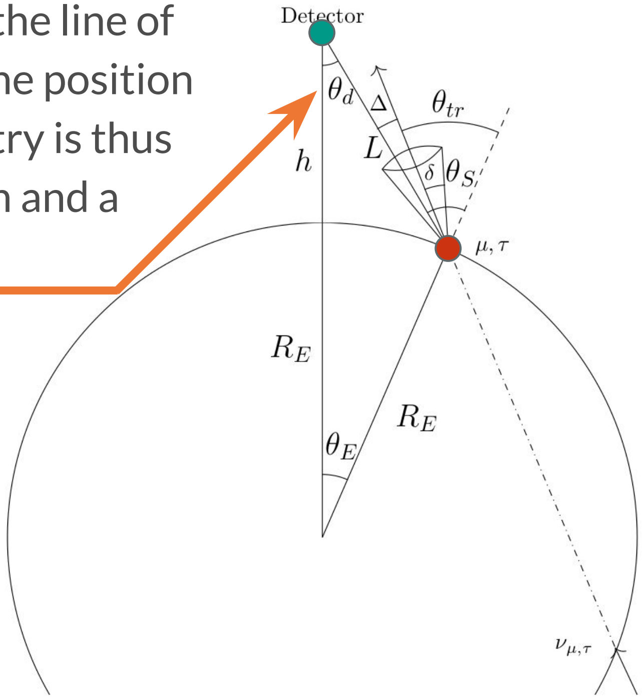
Atmosphere: Line of Sights

The integral is computed along the line of sight from a **reference point** to the position of a **fixed detector**. The geometry is thus fixed by the detector position and a

viewing angle



Above-the-limb events

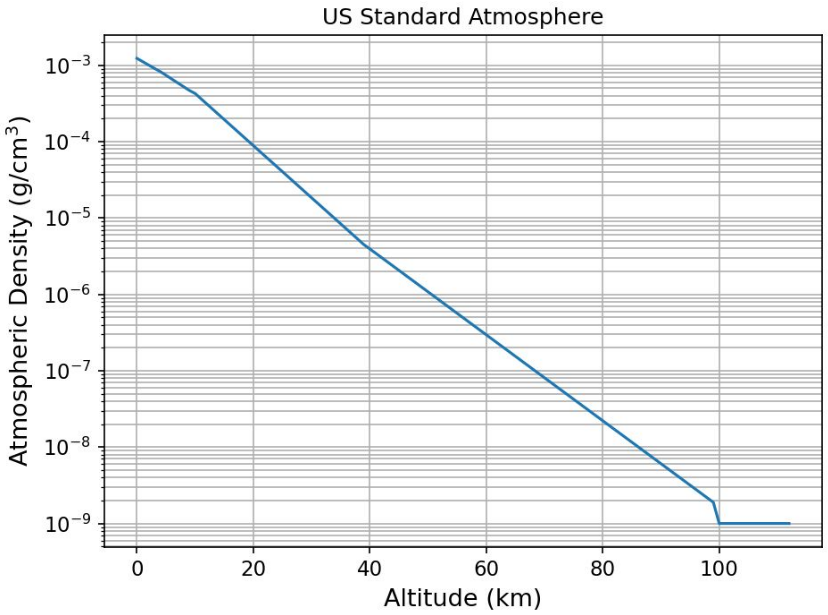


Below-the-limb events

Atmosphere: Density

$$\rho(z) = \begin{cases} \frac{b}{c} e^{-z/c} & \text{if } z \leq 100 \text{ km} \\ \frac{b}{c} & \text{if } z > 100 \text{ km} \end{cases}$$

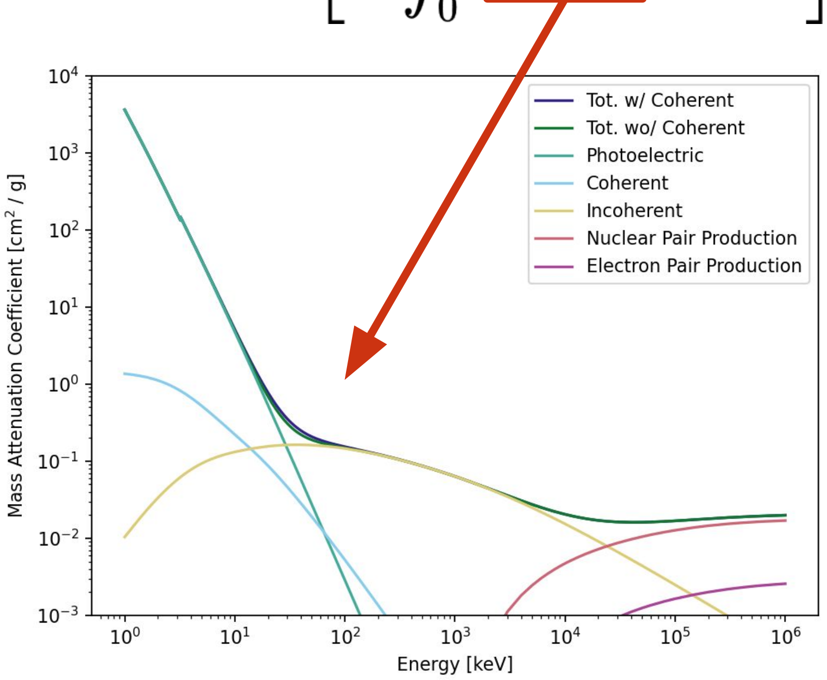
- The atmospheric density profile is based on the 1976 US Standard Atmosphere.
- Is a multi-layer exponential model with parameters depending on the atmosphere layer.
- Consistent with the models used both by CORSIKA to generate the shower size template, and by EASCherSim.



Atmospheric Attenuation

$$\mathrm{Tr}(\epsilon) = \exp\left[-\int_0^L \mu_a(\epsilon)\,\rho(l)\,dl\right]$$

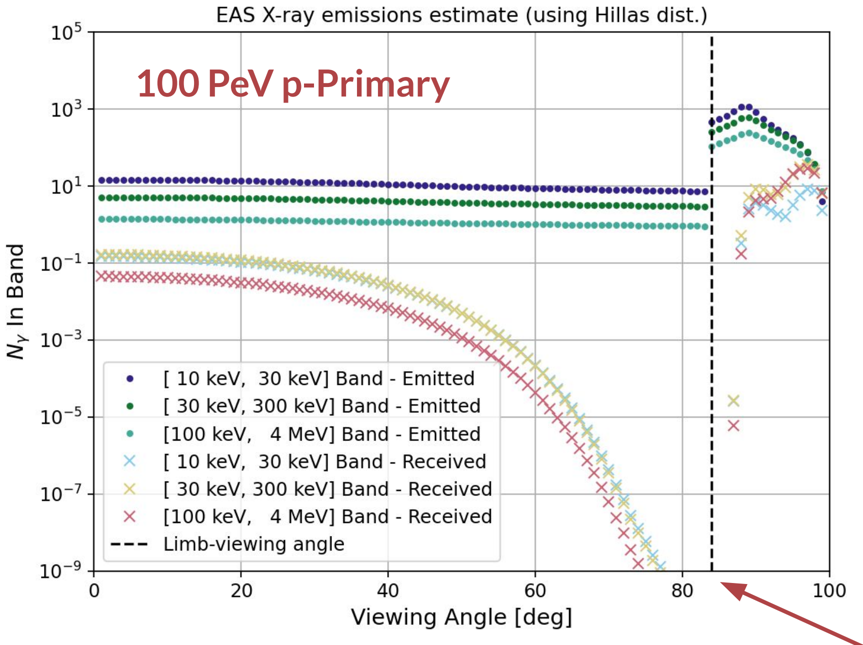
- Photons interact with the atmosphere along their path to the detector.
- The transmission factor depends on LoS integral of an attenuation coefficient.
- For a single element, this attenuation coefficient is inversely proportional to the interaction cross-section
- The NIST XCOM database was queried to obtain the attenuation coefficients.

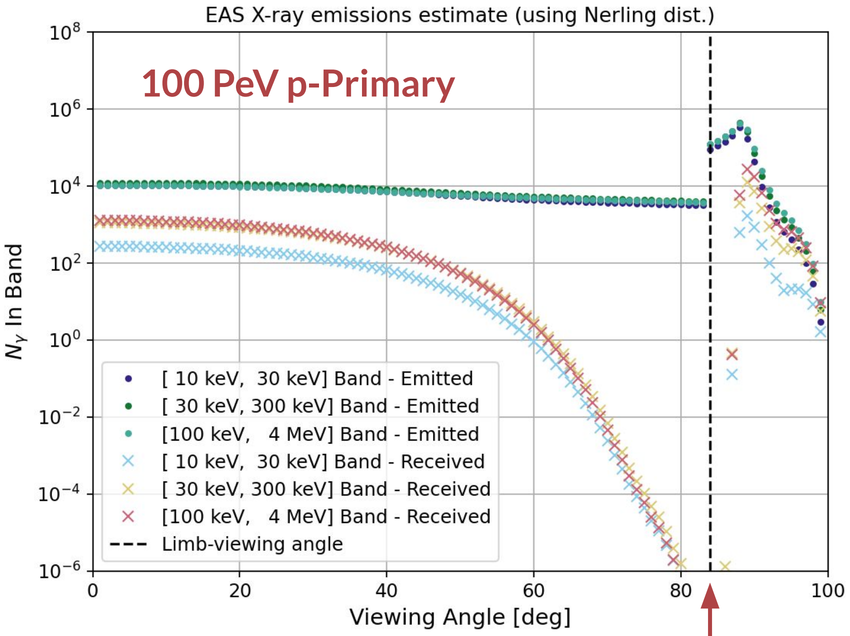


Number of Detected Photons

$$\boxed{\frac{dN_\gamma^{(EAS)}}{d\epsilon}} = \int_{X_{min}}^{X_{max}} \frac{dX}{\rho(X)\,c}\, Tr(\epsilon, \Delta X)\, N(X) \int_{E_{min}}^{E_{max}} dE\, \frac{dn_e}{dE}(E, s(X))\, \frac{dN_\gamma^{(1)}}{d\epsilon}(E, \epsilon)$$

Number of Detected Photons



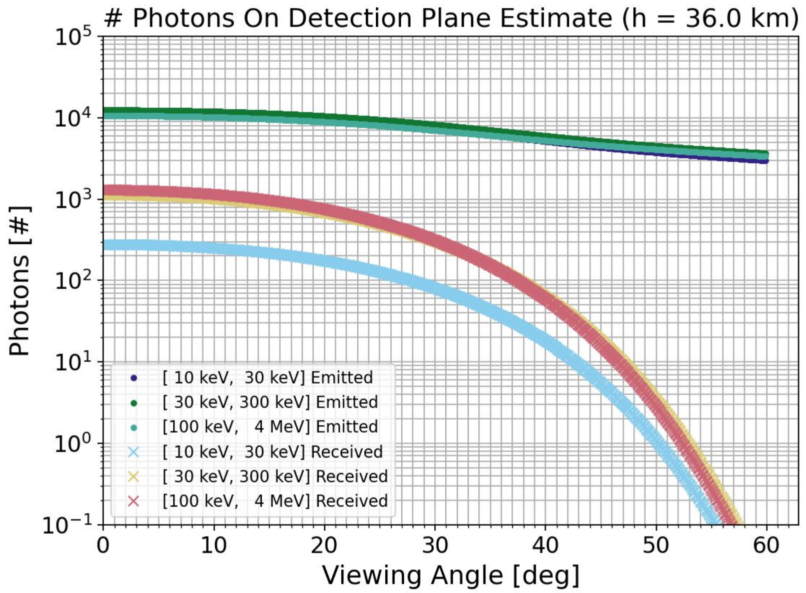


With Hillas Dist.

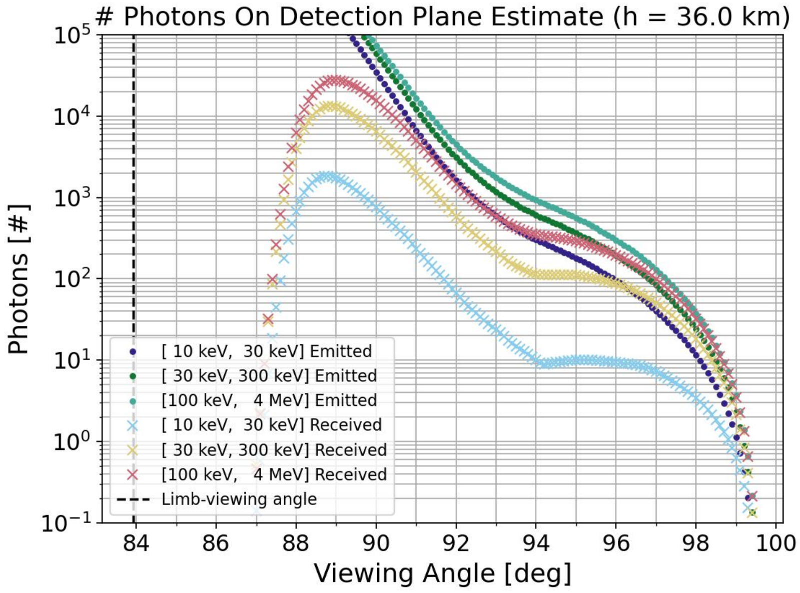
Limb-viewing angle at 36 km

With Nerling Dist.

Number of Detected Photons



Below-the-limb Events



Above-the-limb Events

Emission Footprint & Fluxes

Emission Footprint

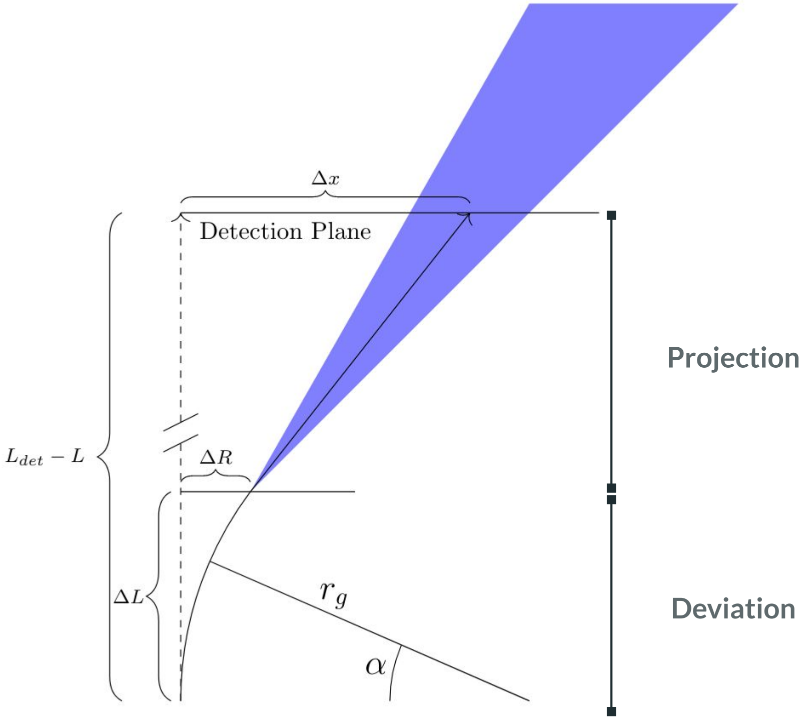
The spatial distribution of arriving photons determines the flux. Influencing factors are:

- e^- lateral deviations from the shower core,
- e^- angular distribution relative to shower axis,
- photon emission cone with aperture $\propto 1/\gamma$

Geomagnetic field effects:

- HE e^- have Larmor radii ~10^4 km in Earth's B
- High-altitude showers develop over ~10^3 km

Plus, propagation and projection effects alter footprint between emission and detection.



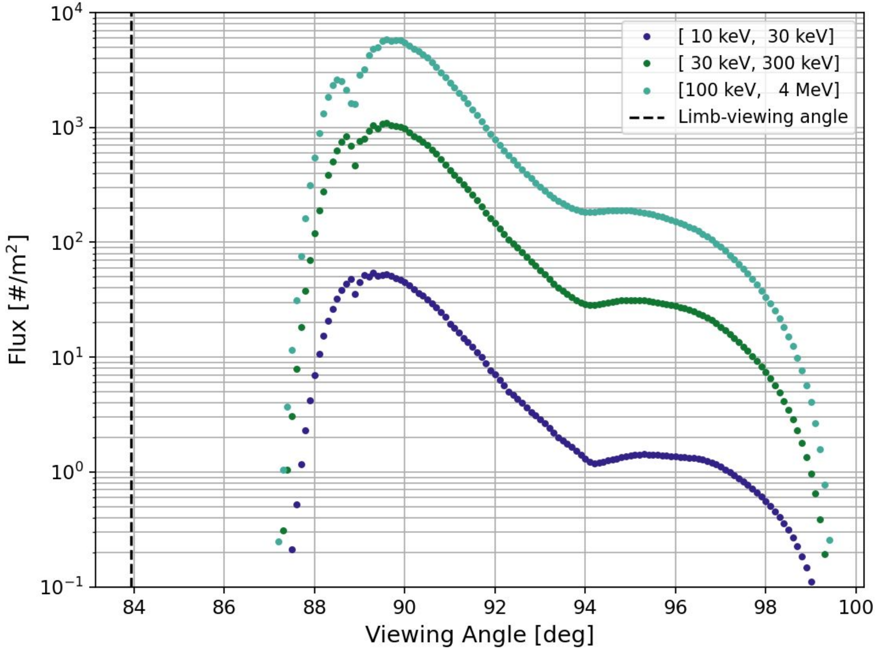
Fluxes: Procedure

For every bin in grammage:

- **Compute** the **expected angular deviations** (angular RMS) from the Bergman distribution.
- Use this angular RMS in Hillas' formula for the **expected lateral deviation** as a function of s.
- Compute the **magnetic deviation** and add it to the normal lateral and angular deviations.

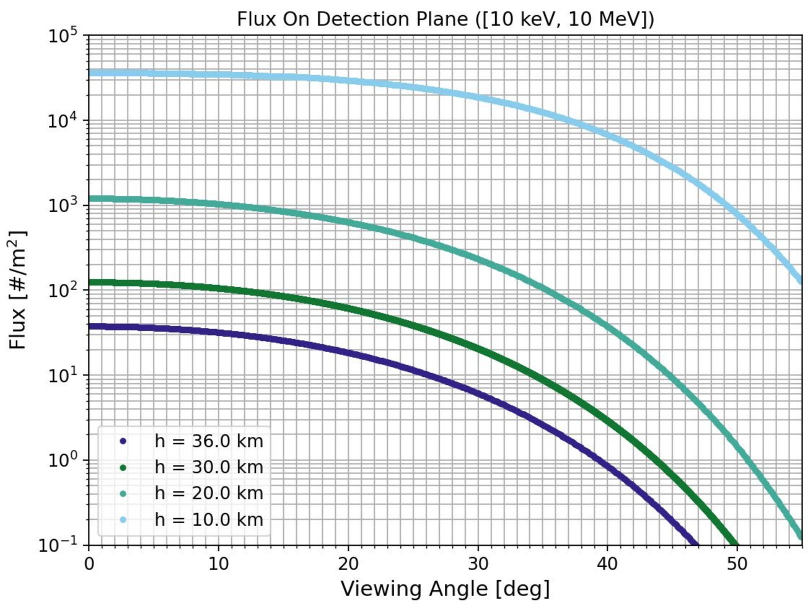
Then, perform:

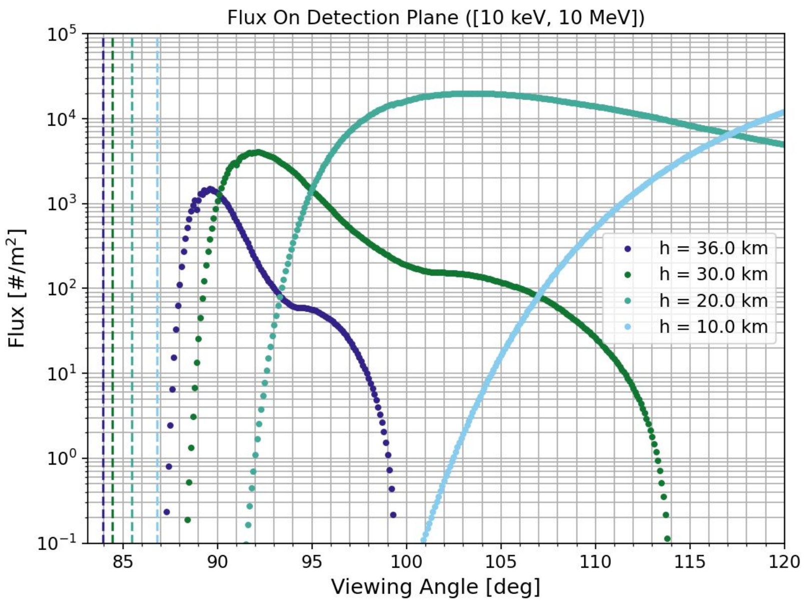
- A **weighted average of the areas using the electron energy distribution** as a weighing function.
- A second **weighted average of the areas over shower age,** using the number of transmitted photons as a weighing factor.



z = 36 km, E = 100 PeV

Fluxes: Different Altitudes





Below-the-limb Events

100 PeV p-Primary

Above-the-limb Events

Event Rate & Acceptances

Full MC Approach

The standard MC procedure calls for shooting candidates from a generation area, sampling their origin position uniformly (over the area) and their direction isotropically (over the space of all directions). Tallying the number of generated candidates that survived, the acceptance is:

$$G(E) = A_{\text{geo}}\, \Omega_{\text{geo}} \times \frac{N_{\text{det}}}{N_{\text{gen}}}$$

This procedure is justified insofar as the definition the acceptance is the factor of proportionality between the incident flux and the observed counting rate[1].

The geometric area and solid angle terms in the acceptance equation are:

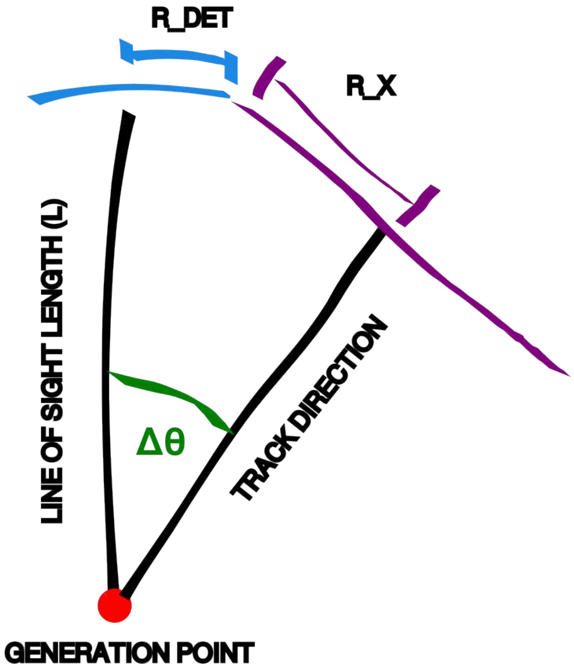
- a band on a sphere of radius equal to the radius of the earth, R_E, plus a height equals to 112.79 km which is the height after which we consider the atmospheric density to be negligible
- the solid angle spanned by the generation area at the position of the detector

However, the photon footprint area is small (<100 m^2), generating candidates with isotropic directions would be extremely inefficient.

[1] J. Sullivan, Nuclear Instruments and methods **95**, 5 (1971).

Event Rate: Effective Area

- The size of the photon footprint area directly correlates to the maximum angular deviation away from the line of sight before the projected area no longer intersects the detector area.
- A geometric estimate places the value on the order of 10^{-6} radians.
- We cannot simply shoot particles to identify track candidates: MC efficiency would be very small.
- An MC generator has been developed to scan the entire sky to find these $\Delta\theta$ factors.

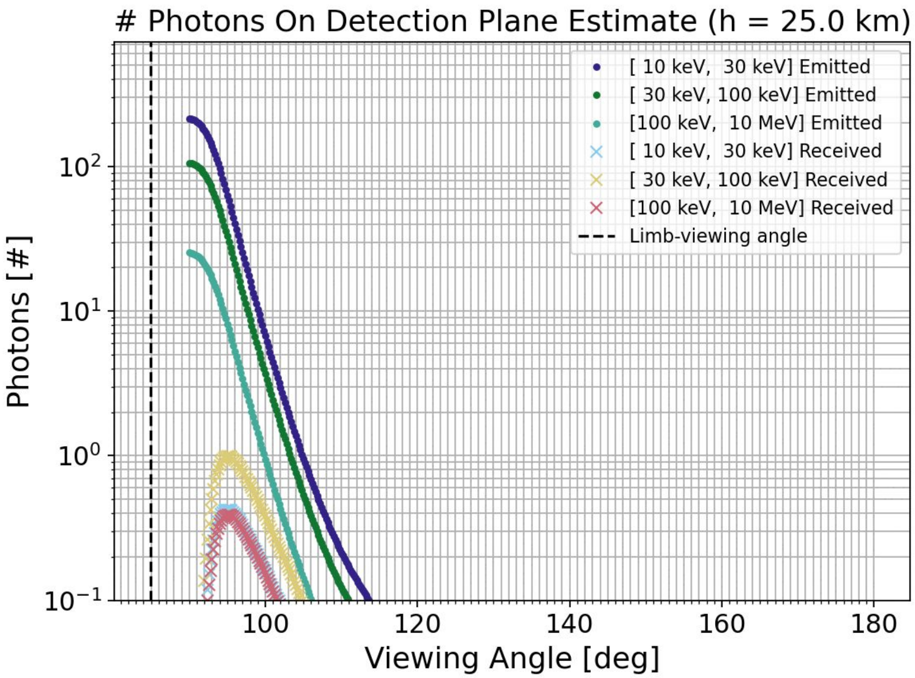


Bootstrap MC Approach: Flux Scan

For a given detector altitude, perform a scan over primary energies and viewing angles to precompute the following quantities:

- the number of photons arriving on the detection plane
- the footprint of these photons on the detection plane

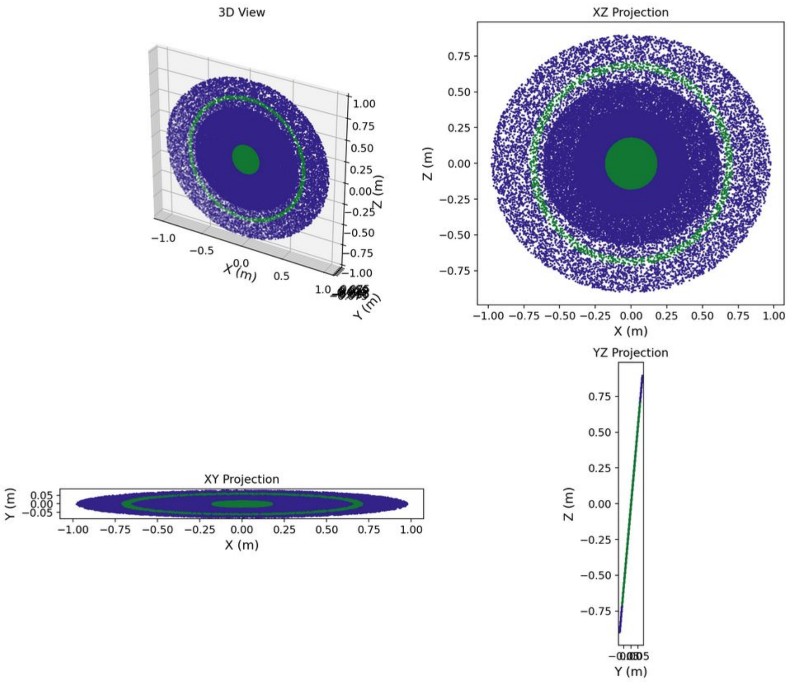
These quantities are computed for a single direction: the line that joins the point on the sky where the primary is generated to the center of our detector at a fixed altitude.



Bootstrap MC Approach: Sky Scan

For every point on our generation area:

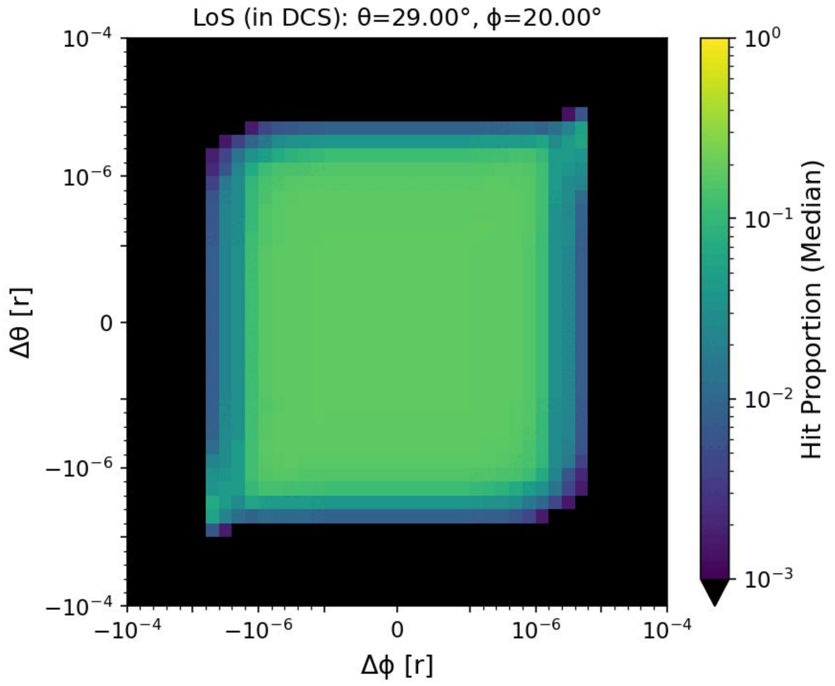
- **draw a line connecting this point to the detector** (center)
- **define a grid of directions about this point** in terms of small angular deviations, Δθ’ and Δφ’, relative to the reference direction above,
- **generate a set of positions** on the shower plane,
- **project** said positions onto the plane of the detector,
- **compute the hit proportion as** the number of positions that are inside our detector geometry (**green**) **divided by** the number that are outside the geometry (**blue**),
- **built the distribution of this hit proportion** by "bootstrapping" it, i.e., by re-sampling the same points projected on the plane with substitution,
- **extract the median value** as well as a confidence interval with 95 % coverage.



Bootstrap MC Approach: Sky Scan (Cont.)

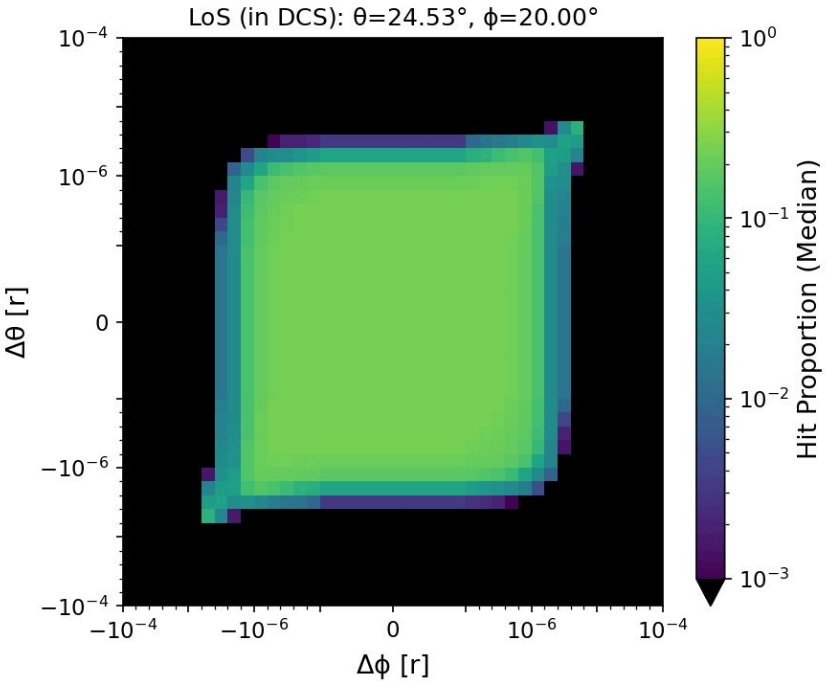
- Repeat the bootstrap procedure for the set of all directions on the grid of $\Delta\theta'$ and $\Delta\varphi'$ angular deviations with respect to the reference direction.
- Repeat this procedure for all points on our generation area, and store the results.

After this procedure, for each point on the sky, we have a map of single hit probabilities, $p_{m,n}$, for all isotropic directions from that point in the sky.

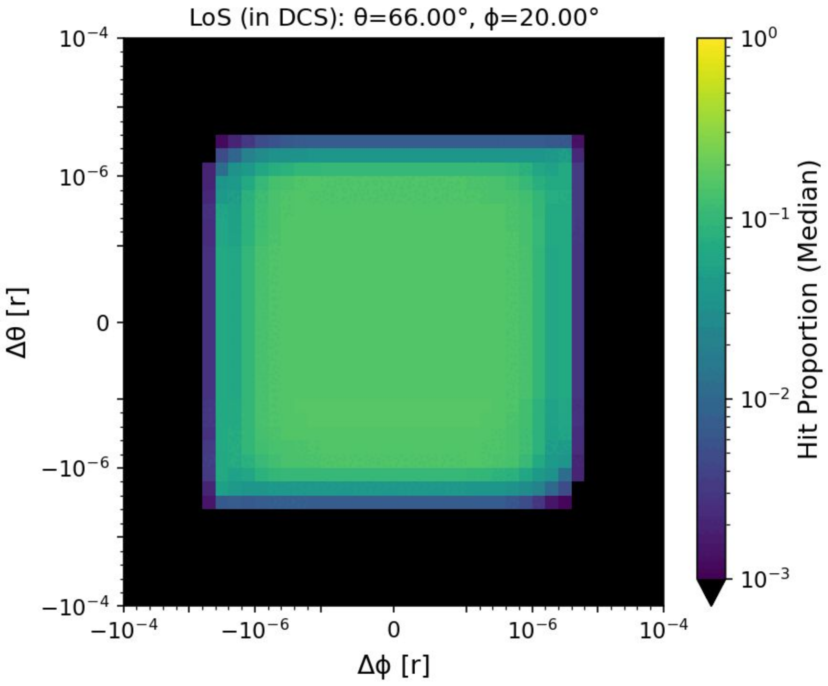


25 km

Bootstrap MC Approach: Sky Scan (Cont.)



20 km



30 km

Acceptances at Different Altitudes

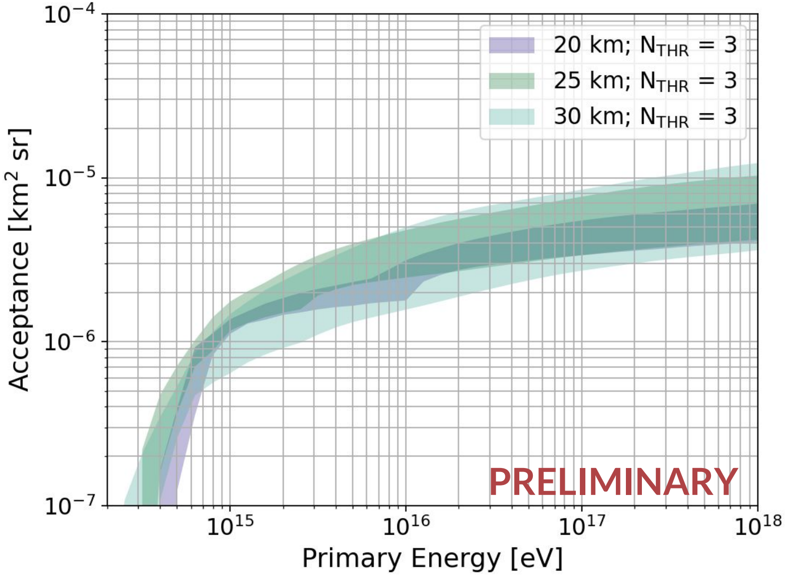
From the single hit probabilities, we compute an efficiency factor for every position in the sky as:

$$\xi_{\mathrm{i}}(E) = \sum_{\mathrm{m,n}} P(N_{\mathrm{hit}} \geq N_{\mathrm{threshold}}; N_{\gamma,i}(E), p_{\mathrm{m,n}}) \times \left(\frac{\Delta\theta'_m \Delta\phi'_n}{4\pi}\right)$$

And we compute the acceptance as:

$$G(E) = (A_{\mathrm{geo}}\, \Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{gen}}} \sum_i \frac{N_{\mathrm{gen}}}{N_{\mathrm{cells}}}\, \xi_i(E)$$
$$= (A_{\mathrm{geo}}\, \Omega_{\mathrm{geo}}) \times \frac{1}{N_{\mathrm{cells}}} \sum_i \xi_i(E)$$

Valid so long as our generation area is subdivided into equal-area cells.



Circular Detector. Looking at limb.
FoV = 70°. R = 1 m.

Acceptances at Different Altitudes

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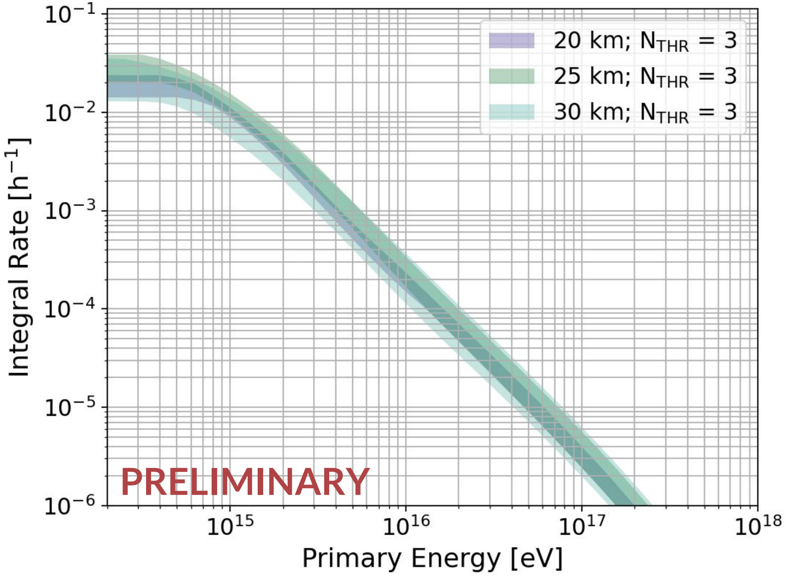


Circular Detector. Looking at limb.
FoV = 70°. R = 1 m.

Conclusions

The **results**:

- for below-the-limb trajectories, fewer photons arrive to the detection plane since the shower develops in a denser layer of the atmosphere. Further, the flux is only appreciable at angles for which the emergence probability is too small.
- for above-the-limb trajectories, the number of photons is significantly larger, and the footprint is such that the signal could be detected by a sub-orbital experiment.
- a balloon mission flying at an altitude of 20 - 30 km with a detector with an area of few m^2 could observe this signal.

Ongoing work:

- MC machinery for detailed study of the emission footprint at the detector position.
- Study of optimal detector geometries for detection.

Publications:

Proceedings:

- **R. A. Torres Saavedra** and R. Aloisio, PoS ICRC 2025, 417 (2025)
- C. Trimarelli on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 418 (2025)
- T. Montaruli on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 337 (2025)
- R. Sarkar on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 963 (2025)
- S. Davarpanah on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 235 (2025)
- R. Nicolaidis on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 1346 (2025)
- A. Liguori on behalf of the **NUSES Collaboration**, PoS ICRC 2025, 071 (2025)

Papers:

- R. A. Torres Saavedra et al., “Modelling of X-ray Synchrotron Emission from Extended Air Showers”, **under preparation**.

Conferences/Meetings/etc.:

Abroad Stays:

- Département de physique nucléaire et corpusculaire, Université de Genève, October 27- December 5 2024.

Collaboration Meetings:

- L'Aquila, Italy, December 16-18 2024, NUSES Collaboration Meeting, attended.
- Paris, France, June 2-6 2025, 37th JEM-EUSO Collaboration Meeting, invited talk.

Conferences:

- Girona, Spain, May 12-16 2025, ASAPP 2025, contributed talk.
- Geneva, Switzerland, July 14-24 2025, ICRC 2025, poster.
- L'Aquila, Italy, September 30 - October 3 2025, 14th YRM, contributed talk.

Schools and Workshops:

- Perugia, Italy, October 27-29 2025, Advanced course to FPGA programming, will attend.

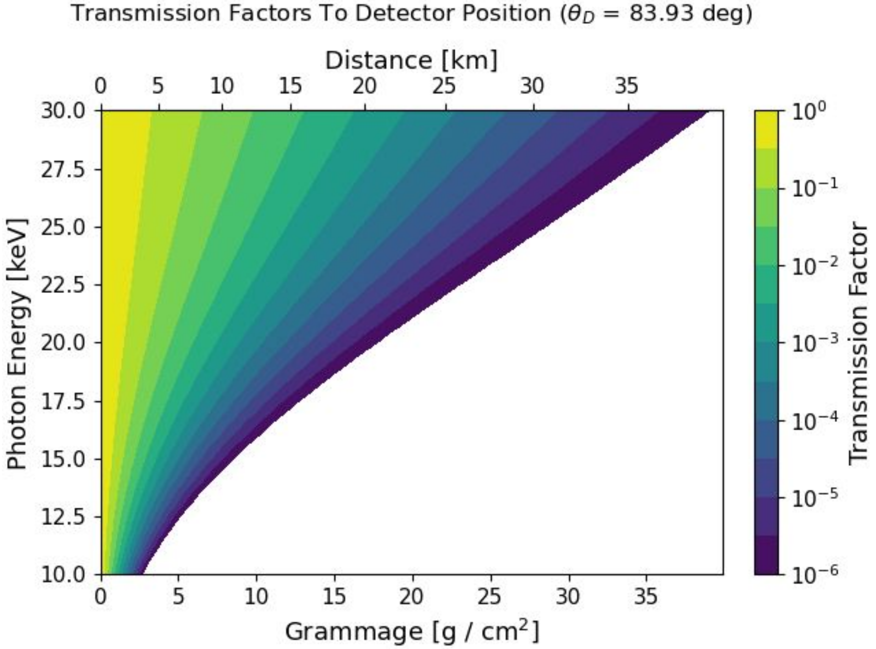
Outreach:

- Sharper, European Research Night, September 26 2025, L'Aquila.

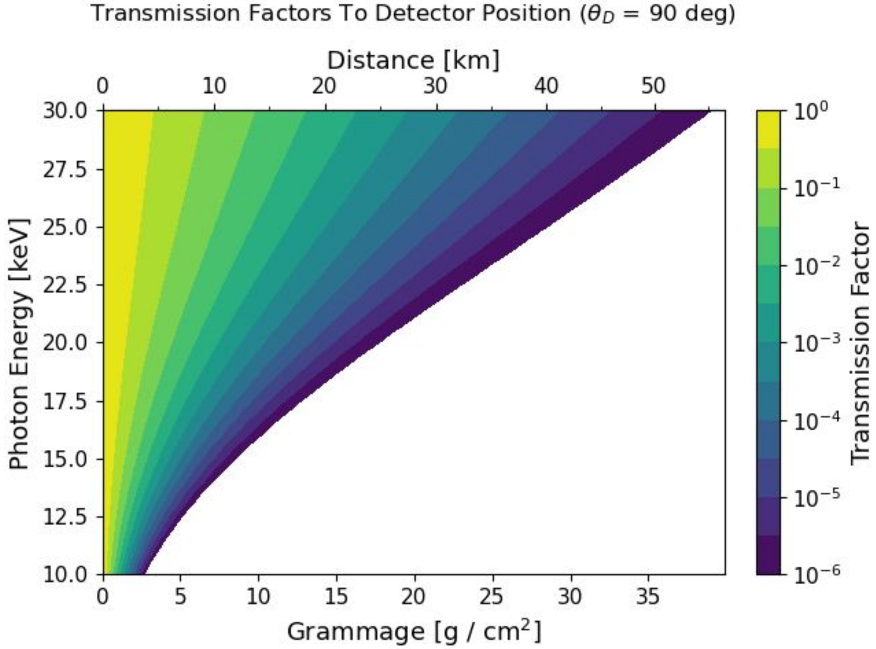
Backup

Transmission Factors

Transmission Factors ([10 keV, 30 keV] band)

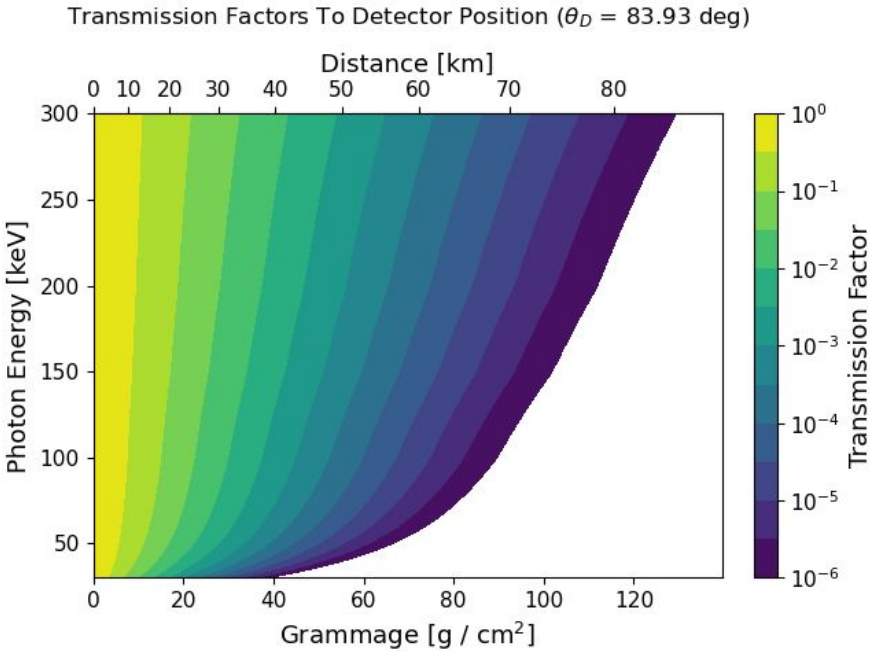


Limb-viewing

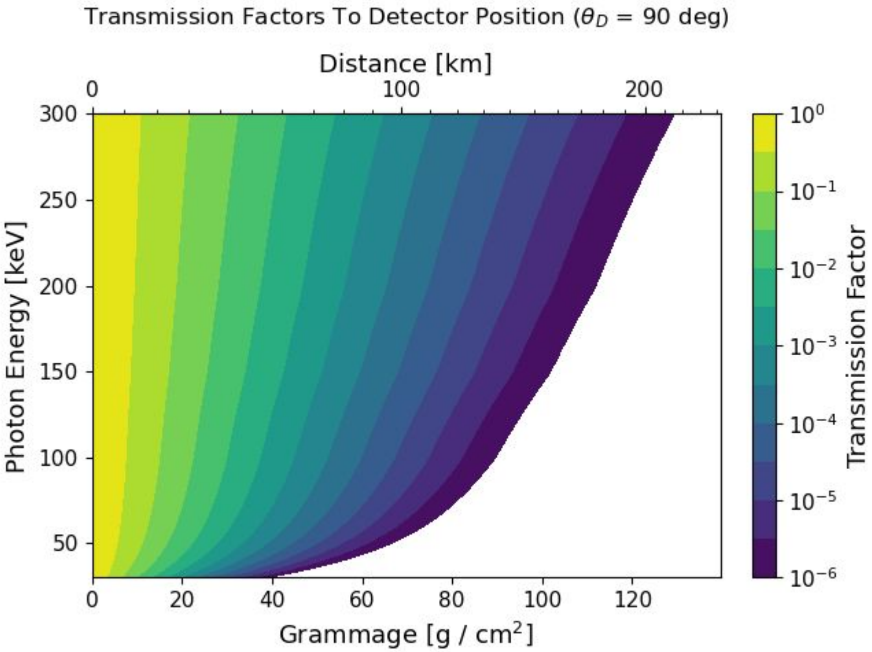


Horizontal-viewing

Transmission Factors ([30 keV, 300 keV] band)

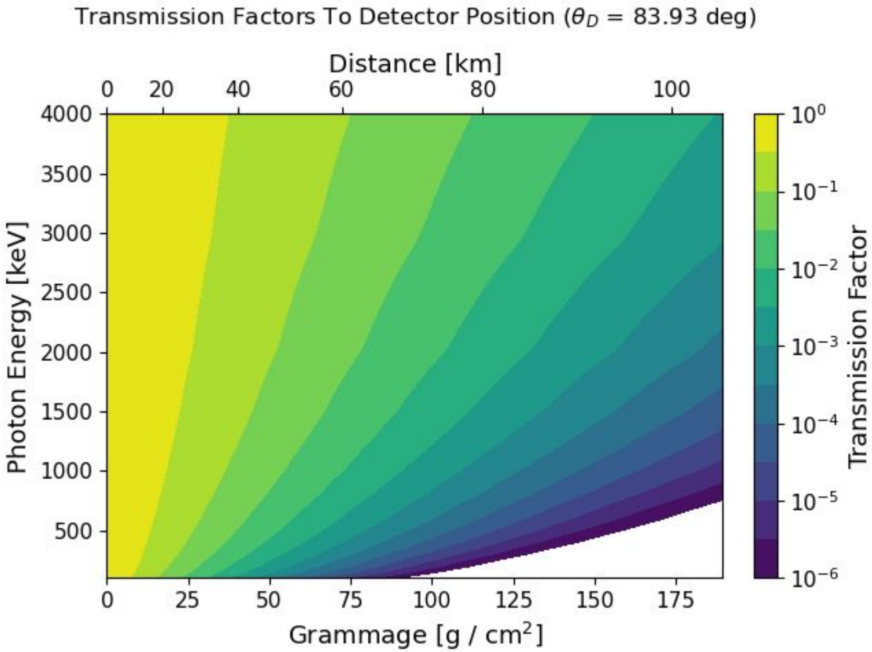


Limb-viewing

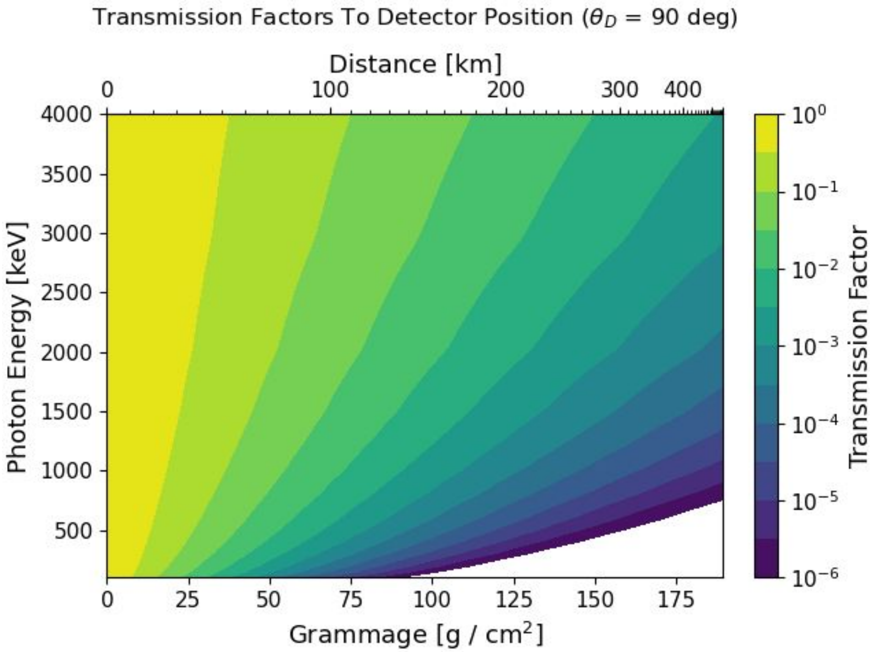


Horizontal-viewing

Transmission Factors ([100 keV, 4 MeV] band)



Limb-viewing

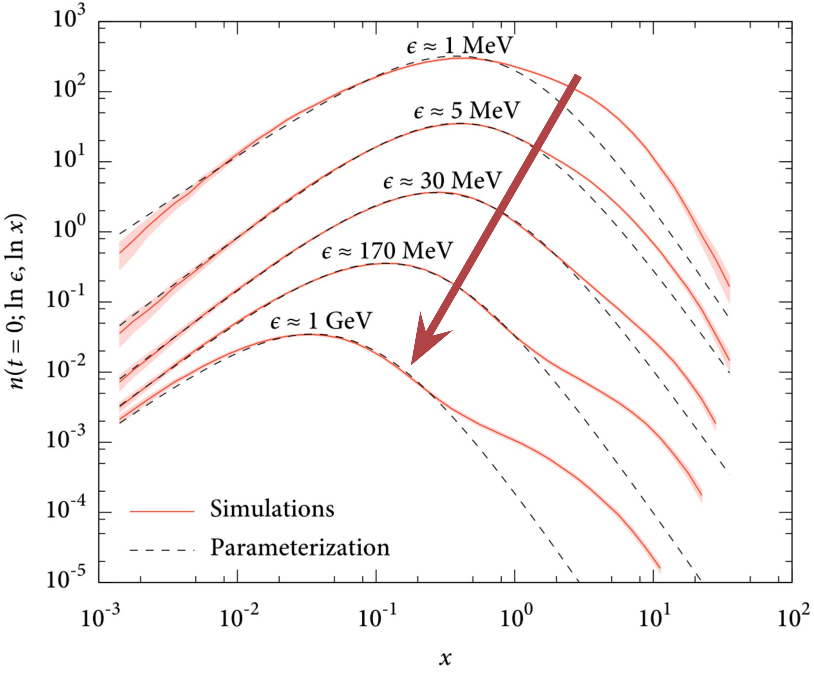


Horizontal-viewing

Emission Footprint & Fluxes (Details)

Lateral Deviations: Lafebre's Distribution

- Lateral distribution is bivariate in shower age and e^- energy.
- The model (and simulations) suggest that the scale of lateral deviations depend on e^- energy.
- Reasonable to expect higher energy $e^{-/+}$ closer to the core.
- No distribution has been explicitly verified for young showers and HE e^-.



Lafebre et al. (2009)

Lateral Deviations: Hillas' formula

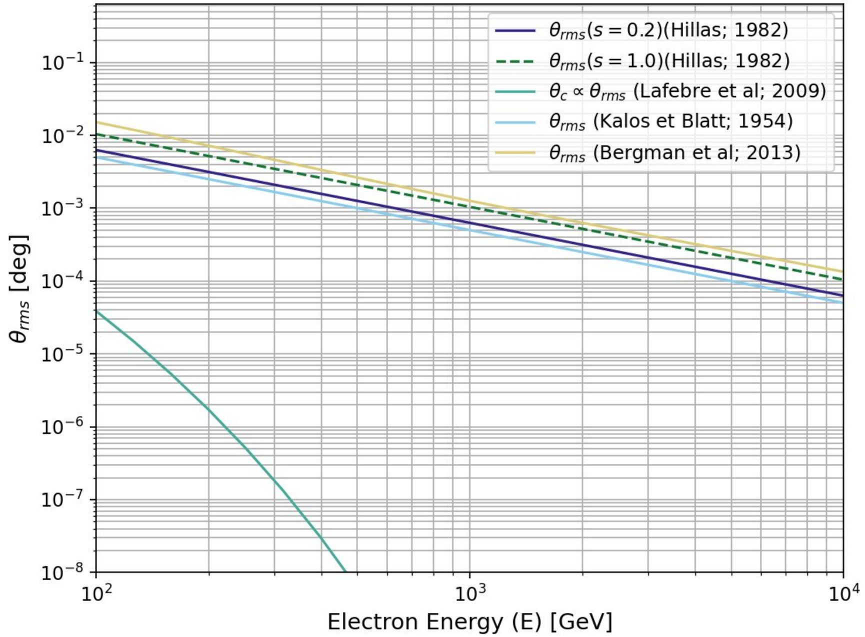
$$\langle x \rangle = (2.06 + 2.56s^2)\left(\frac{E}{MeV} - 7\right)^{\frac{1}{4}} w^{\frac{1}{2}} \left(\frac{21MeV}{E}\right)$$

- In his paper, Hillas provides a formula for the mean displacement from the core as a function of the e^- energy, ***E***, and scaled angular variable, ***w***, which is itself a function of the e^- polar angle with respect to the shower axis.
- Hillas also provides a formula for the expected value of ***w***, but since his MC simulations were of E.M showers with low primary energies, we seek a better description of the electron's angular distribution.

Angular Deviations: Distribution Comparisons

Several parameterizations were studied:

- **Hillas**: fit to low energy EM showers. Explicit dependence on s.
- **Kalos et Blatt**: approximation to the solution of a diffusion equation.
- **Lafebre et al.**: fit to CORSIKA showers, focusing on the low electron energy range (1 MeV to 1 GeV).
- **Bergman et al.**: fit to CORSIKA showers, focusing on the high electron energy range (1 GeV to 1 TeV).

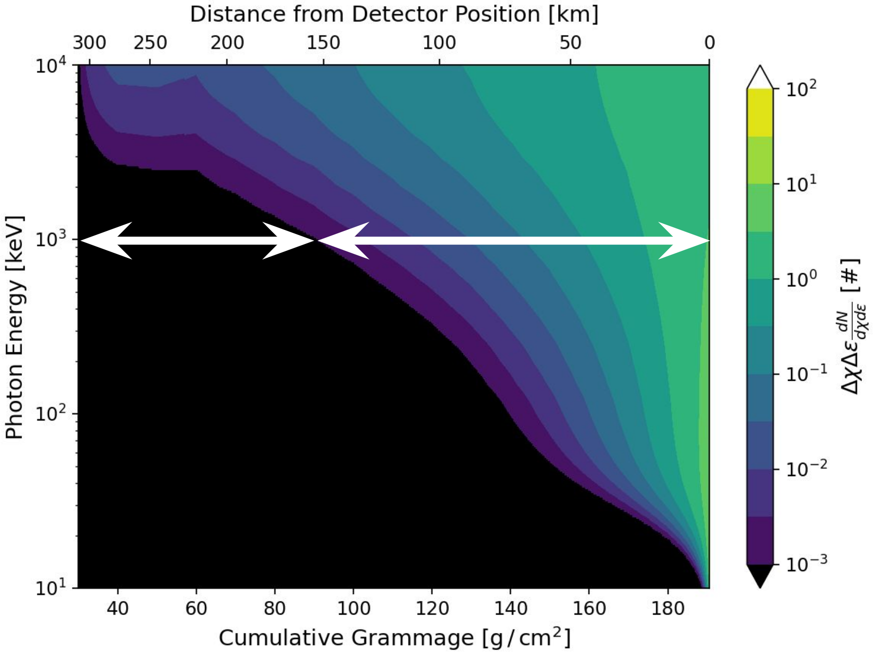


Magnetic Field: Concentric Circles Structure

Electrons will stray away from the shower core due to the effect of the magnetic field.

On the detection plane, **higher** energy X-ray photons, come from electrons that:

- come from positions early in the shower development,
- are far off from the detector,
- have suffered fewer deviations, and are thus closer to the core



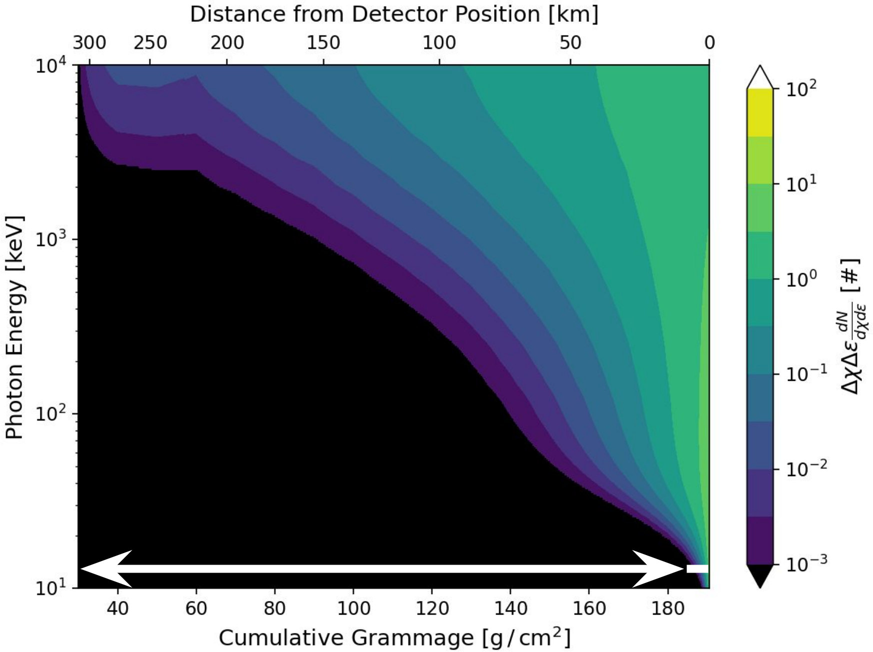
90° viewing (Nadir) angle
Transmitted

Magnetic Field: Concentric Circles Structure

Electrons will stray away from the shower core due to the effect of the magnetic field.

On the detection plane, **lower** energy X-ray photons, come from electrons that:

- come from positions later in the shower development,
- are closer to the detector
- have suffered more deviations, and are thus farther from the core



90° viewing (Nadir) angle
Transmitted

Magnetic Field: Hillas' Parameterization

- Hillas proposed the quantity, x_m, as a measure of the deflections induced by the magnetic field.
- x_m may be regarded as the effective path integral over which the magnetic field has acted on an electron of energy E, given its whole particle history.
- For high electron energies, this is on the order of a radiation length.

$$x_m = E \int \pm \frac{dx}{U(x)}$$

$$\langle x_m \rangle = \frac{30 w^{0.2}}{1 + 36/E} (\mathrm{gcm}^{-2})$$