Search for Ultra-High Energy photons at the Pierre Auger Observatory

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PIERRE AUGER OBSERVATORY

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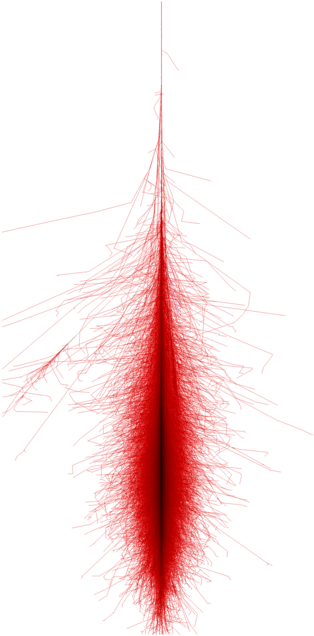
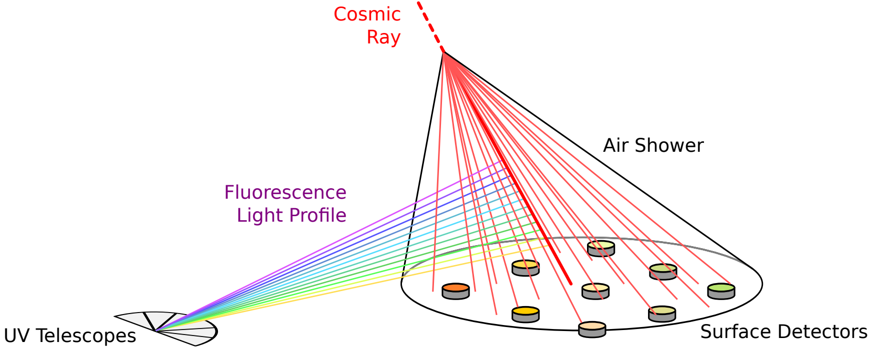


[F. Schmidt, "CORSIKA Shower Images"]

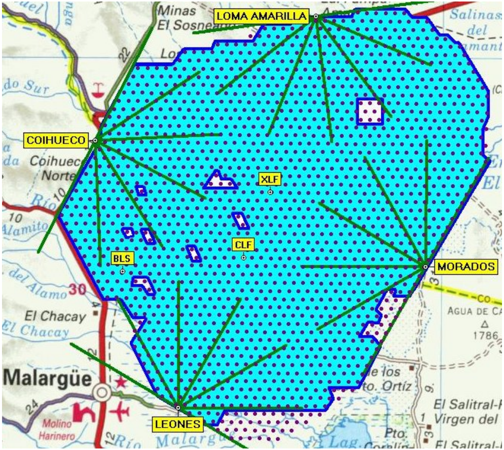
Cosmic ray induced extensive air showers (EAS)

- Earth atmosphere is constantly hit by cosmic ray particles with energies up to several 10^{20} eV (mostly nuclei, composition still unclear)
- very low flux at highest energies
  $\Rightarrow$ no direct detection possible
  $\Rightarrow$ use earth atmosphere as calorimeter with large ground based detector
- interaction of particles with air produces multiple secondary particles
  $\Rightarrow$ extensive air showers down to the ground level



The Pierre Auger Observatory

- hybrid cosmic ray detector for energies between $10^{17}\,\mathrm{eV}$ and $10^{20}\,\mathrm{eV}$
- in Argentine Pampa
- measures properties of extensive air showers



Surface Detector (SD)

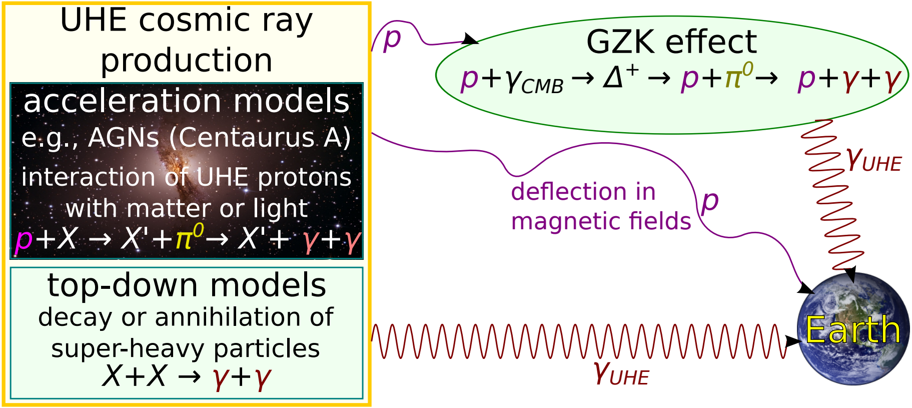
- 1660 water-Cherenkov detector stations
- $1.5\,\mathrm{km}$ tank spacing
- $3000\,\mathrm{km}^2$
- measures lateral distribution

Fluorescence Detector (FD)

- 4 fluorescence telescope sites
- 24 telescopes
- measures longitudinal shower development

Detector components of the Pierre Auger Observatory

Sources of ultra-high energy (~EeV) photons

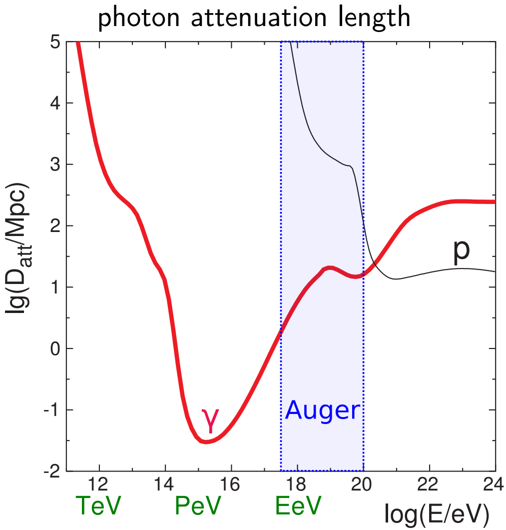


⇒ UHE photons allow to constrain theoretical models:

- UHECR production
- new physics

photons point back to their point of production
⇒ directed searches possible

UHE photon propagation



[M. Risse, P. Homola, Mod.Phys.Lett., 2007]

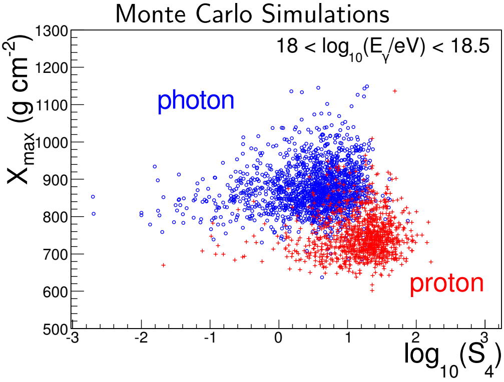
- interaction with low energy background photons:
  $\gamma + \gamma_{\text{low}} \rightarrow e^{+} + e^{-}$
- attenuation length of roughly 5 Mpc in the EeV energy range
  - $\Rightarrow$ nearest AGN (Centaurus A) included in horizon
- important to search for UHE photons, even when no photons at the PeV scale have been detected

Search for diffuse UHE photon fluxes (hybrid)

diffuse search for photons, directional information is not used

Hybrid 2011 analysis

- observables:
  - atmospheric depth of shower maximum (X_{max})
  - surface detector signal (S_4)
- statistical method to separate photons and hadrons
- energies above 10^{18} eV



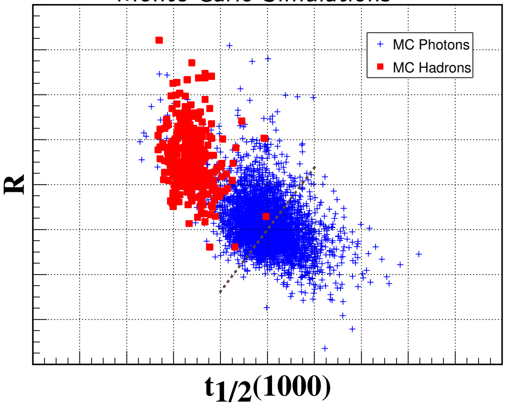
6 photon candidates above 1 EeV (compatible with expected nuclear background), no candidates above 2 EeV

More details: [M. Settimo et al., Proc. 32nd ICRC, 2011] diffuse search for photons, directional information is not used

SD 2008 analysis

- SD observables:
  - curvature of shower front (R)
  - spread of arrival times of shower particles ($t_{1/2}(1000)$)
- energies above 10^{19} eV
- no usage of FD
  ⇒higher duty cycle

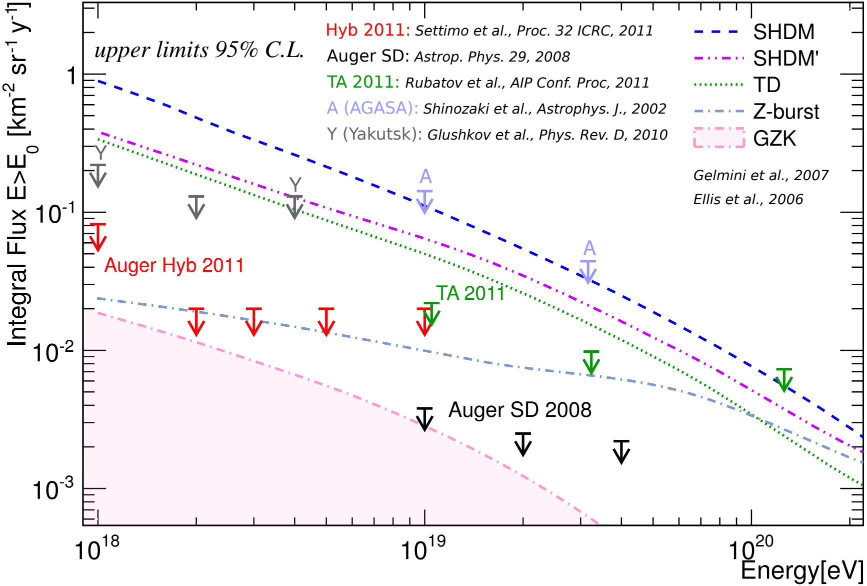
Monte Carlo Simulations



no photon candidates above 10 EeV

More details: [Pierre Auger Coll., Astropart. Phys. 29, 243-256, 2008]

Limits on diffuse UHE photon fluxes



no evidence for UHE photons found ⇒ constrains top-down models

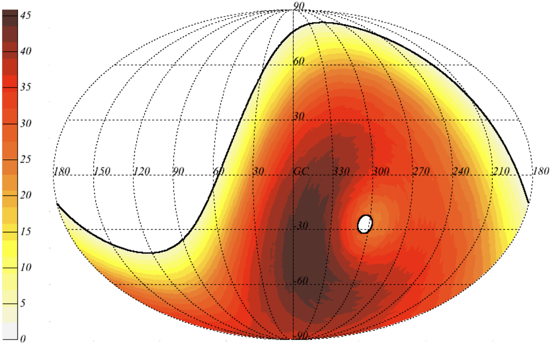
Search for UHE photon point sources

Search for photon excess from point-like sources over background

- multiple air shower observables (FD+SD)
- multivariate analysis to separate photons
- energies between $10^{17.3}$ eV and $10^{18.5}$ eV
- 0.7° angular resolution
- background estimated from data through scrambling method*

[*: G. L. Cassiday et al., Nucl. Phys. Proc. Suppl 14A, 1990]

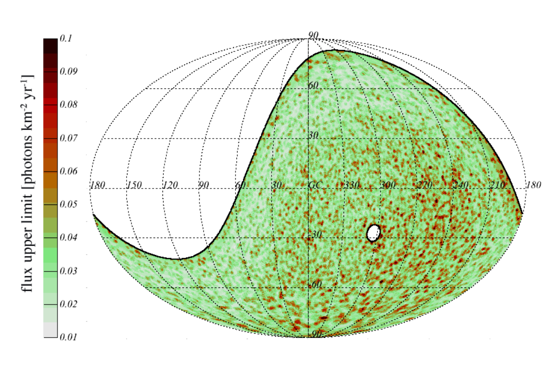
expected count of background events:



[D. Kuempel et al., 33rd ICRC, 2013]

Upper limits on flux of UHE photon point sources

no significant excess found ⇒ set limits

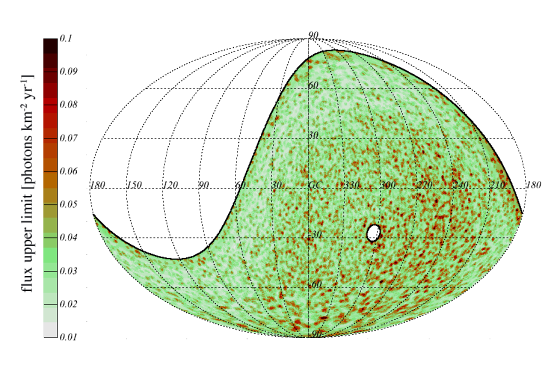


- max. upper flux limit: 0.14 photons km^{-2} yr^{-1}
- max. energy flux: 0.25 eV cm^{-2} s^{-1} (assuming spectral index $\gamma = -2$)
  less energy per decade than in the TeV range

More details: [D. Kuempel et al., 33rd ICRC, 2013]

Upper limits on flux of UHE photon point sources

no significant excess found ⇒ set limits



- Centaurus A as prominent source candidate not visible
- no strong regularly emitting non-beamed EeV γ sources in our galaxy

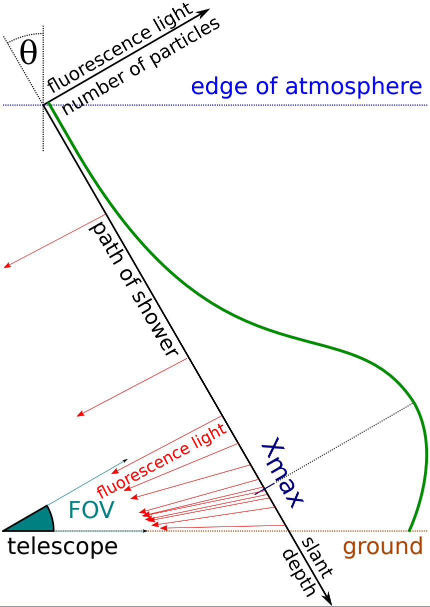
More details: [D. Kuempel et al., 33rd ICRC, 2013]

Summary

- the Pierre Auger Observatory is the biggest UHE cosmic ray experiment
- multiple searches for photons in the EeV range have been performed
- no evidence for UHE photons found until now
  - most stringent limits from the Pierre Auger Observatory
  - various top-down models of UHECR production constrained
  - observation or restriction of GZK effect within reach
- new limits on UHE photon point sources

Backup

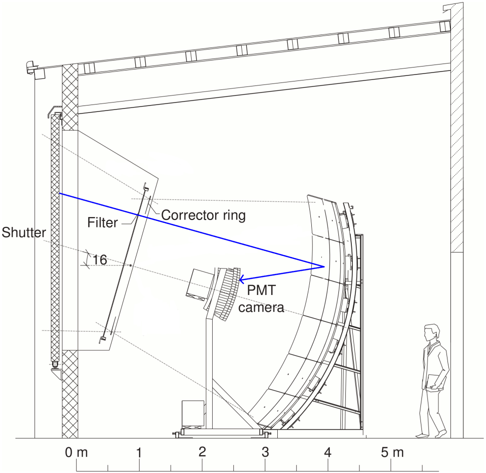
Fluorescence detection of cosmic rays



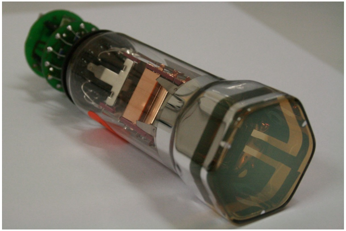
- air emits fluorescence light isotropically when excited by shower particles
- light $\propto$ number of particles $\propto$ E
- calorimetric measurement of particle energy

- measures longitudinal shower development
- shower maximum X_{max} as important shower property

Auger Fluorescence Telescopes

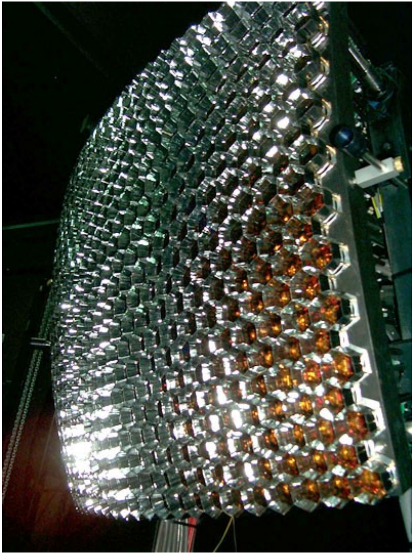


- Schmidt camera
- aperture diameter 2.2 m
- $3.8 \times 3.8\,\mathrm{m}^2$ mirror
- $30^\circ \times 30^\circ$ field of view (FOV)
- only works in moonless nights
- UV-pass filter

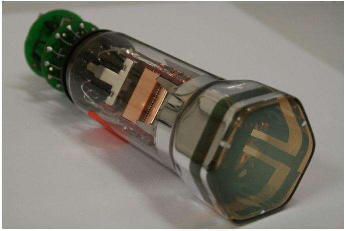


- 440 hexagonally arranged PMTs
- 1.5° FOV per pixel

Auger Fluorescence Telescopes

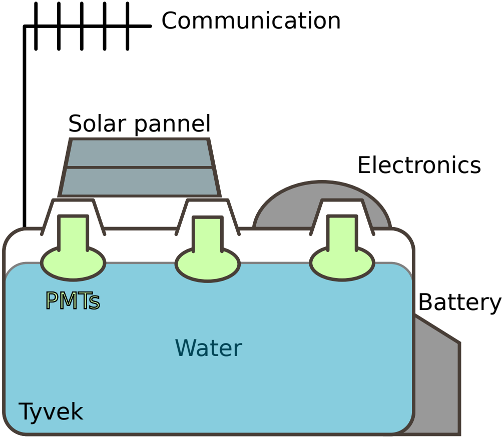


- Schmidt camera
- aperture diameter 2.2 m
- 3.8 × 3.8 m^2 mirror
- 30° × 30° field of view (FOV)
- only works in moonless nights
- UV-pass filter



- 440 hexagonally arranged PMTs
- 1.5° FOV per pixel

Auger Surface Detector station

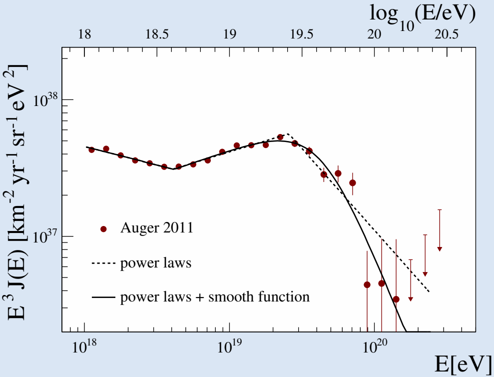


- water Cherenkov detector
- 3.6 m diameter
- 1.2 m height
- Tyvek liner to reflect light
- 3 PMTs per station
- autonomous power supply (solar pannel, battery)

- charged shower particles (μ, $e^{\pm}$) produce Cherenkov light in water
- permanently active

The Greisen–Zatsepin–Kuzmin (GZK) effect

energy spectrum of cosmic rays



[F. Salamida et. al., Proc. 32nd ICRC, 2011]

steep drop above a few 10^{19} eV

possible explanations:

- GZK effect
- source features

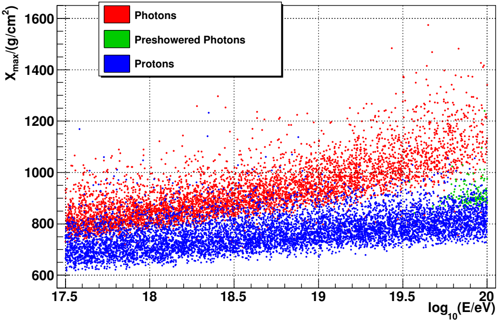
- resonant interaction of protons with cosmic microwave background (CMB) photons:
  $p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$
  $p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$
- above $\approx 6 \cdot 10^{19}$ eV
- GZK-cutoff in energy spectrum predicted
  - depends on composition (particle type) of cosmic rays
- production of UHE photons through decay of π^0

Characteristic properties of photon induced air showers

Compared to hadronic showers

- develops deeper in atmosphere
- much fewer non-EM-particles
  $\Rightarrow$ well described by electromagnetic cascade
- higher shower-to-shower fluctuations
- smaller footprint on the ground

Monte Carlo Simulations



Examples of photon sensitive FD observables

- X_{max} (depth of shower maximum):
  photon showers usually evolve deeper in the atmosphere (bigger X_{max})
- Greisen function describes a purely electromagnetic shower:
  usually fits better (χ^2) for photon showers than for hadron showers

Examples of photon sensitive SD observables

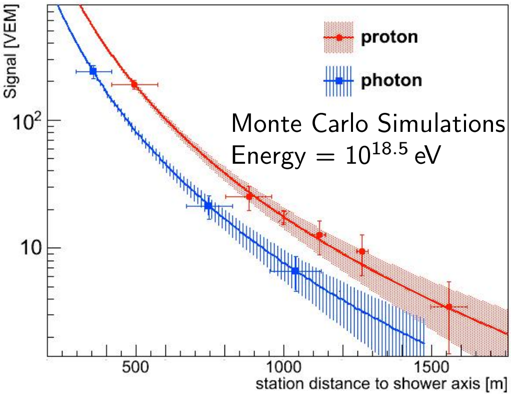
- $S_b = \sum_i S_i \left(\frac{R_i}{1000\,\mathrm{m}}\right)^b$

  $b = 2..5$

  S_i: station signal

  R_i: distance of station to shower axis

  usually smaller for photon induced showers



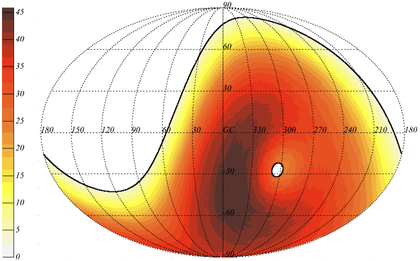
- arrival time of particles at single station: *bigger spread for photons*
- curvature of shower front (correlated with X_{max}, for SD-only analyses)
- muon content of shower particles on ground (*less for photons*)

Search for UHE photon point sources

Search for photon excess from point-like sources over background

- FD and SD observables used in multivariate analysis (MVA):
  - $X_{\max}$
  - reduced χ^2 and energy of Greisen fit
  - S_3 (lateral shower profile)
  - shape parameter (particle arrival time)
- training with CORSIKA MC simulations (30k Photons, 60k Protons, QGSJET01c)
- cut on MVA output β optimized for best expected limit (when measurement equals background expectation)

background estimated from data through scrambling method[*]:

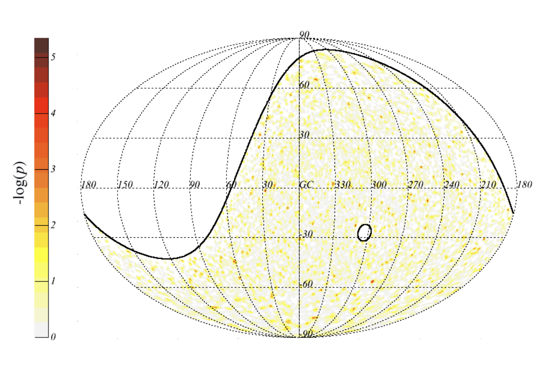


[*] G. L. Cassiday et al., Nucl. Phys. Proc. Suppl 14A, 1990

Result of search for UHE photon point sources

p-value

probability to find as much signal in an isotropic map in a given direction



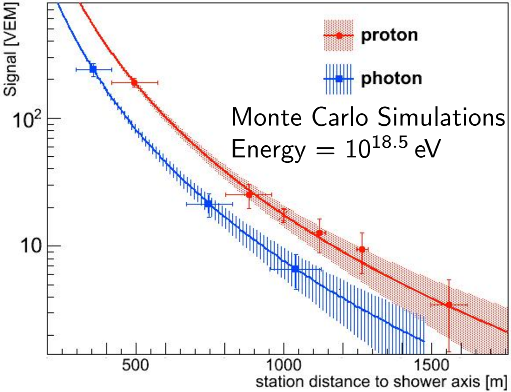
- minimum p-value: 4.5×10^{-6}
- probablity to have a lower p-value *anywhere* on an isotropic sky: $36\,\%$

More details: D. Kuempel et al., 33rd ICRC, 2013

Photon energy scale

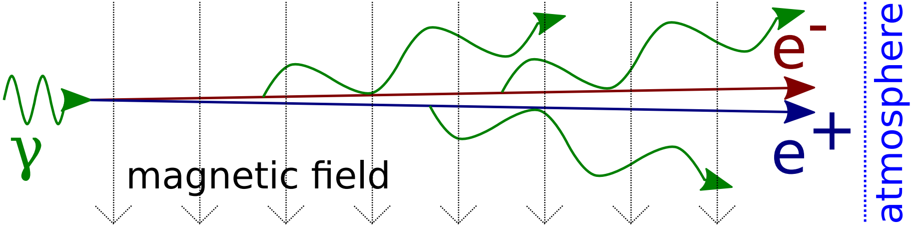
SD energy estimation

- $S(1000)$: SD signal at 1000 m distance from shower core
- $S(1000)$ used for energy estimation
- cross calibrated with FD



- $S(1000)$ lower for photon induced showers
  $\Rightarrow$ underestimation of photon energy for SD measurements ($\approx$ factor 2)
- energy estimation either correct for photon primary **or** hadron primary
  $\Rightarrow$ major uncertainty for photon fraction calculations
- only small effect for calorimetric FD energy measurement ($\approx 1\%$)

Preshower effect

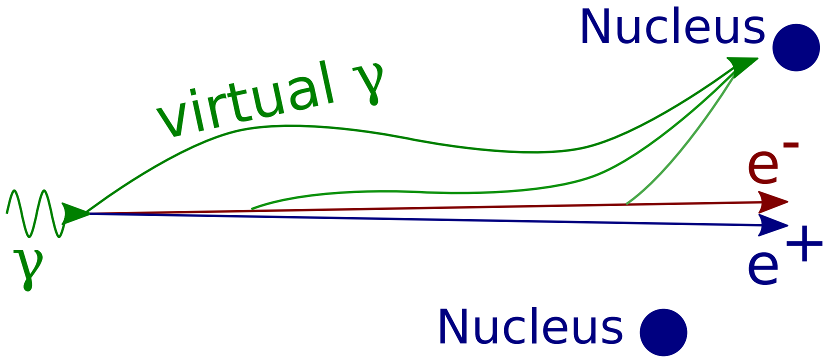


- e^+ e^- pair production in earth's magnetic field
- synchrotron radiation of electrons/ positrons
- some hundred electromagnetic particles enter the atmosphere
- probability increases with:
  - photon energy
  - transversal magnetic field ⇒ direction dependence

- probability $> 1\,\%$ at approx. 50 EeV in Argentina
- reaches approx. 40 % probability at 100 EeV (for events distributed over the whole visible sky)

Landau–Pomeranchuk–Migdal (LPM) effect

- reduces cross section for pair production (γ) and bremsstrahlung (e)
- destructive interference between interactions at multiple nuclei
- relevant at high energy (greater than 10^{18} eV) of primary particle
- in simulations mostly implemented through a *suppression factor* that statistically discards interactions



LPM effect

- affects bremsstrahlung (e) and pair production (γ)
- destructive interference between interactions at multiple nuclei
- effect increases with:
  - energy of primary particle (energies greater than 10^{18} eV)
  - particle density of the air

- reduce cross section for first interaction (pair production)
- density dependence of suppression $\Rightarrow$ depth of first interaction no longer follows exponential distribution
- favor strong asymmetries in energies of electron+positron
  $\Rightarrow$ again LPM effect for bremsstrahlung
- retards shower development
- showers with multiple maxima are possible

competes with preshower effect