



# An overview of the Phase I SD-433+UMD photon search

#### N. González on behalf of the Editorial Board++

Università degli studi di Torino (UniTo) Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino ITeDA (CNEA-CONICET-UNSAM)

> Neutral Particles session Auger Italy Coll. Meeting, Torino, 3-5 February 2025

#### Photon search at tens PeV with Phase I data

- ► 10-PeV diffuse photons from:
  - hadronic interactions in hot gas at the Galactic halo
  - super-heavy dark matter decay at the Galactic center
  - propagation of UHE cosmic rays

► Highest-energy photons measured by LHAASO at ~ 1 PeV. Upper limits on the diffuse photon flux between 1-150 PeV were set only from the Northern Hemisphere

► The result: the most stringent upper limits to the photon flux between 50 PeV and 150 PeV having a priviledged exposure to the Galactic center





### **Photon energy reconstruction**

- $\blacktriangleright$  NKG with one slope parameter ( $\beta$ ) used to reconstruct the LDF
- Gaisser-Hillas attenuation function  $g(\theta)$
- ► Energy calibration with E<sub>MC</sub>



#### **Proton energy reconstruction**

- ► LDF model developed with Phase I data
- Attenuation function  $g'(\theta)$  resembling CIC
- ► Direct energy calibration: unbinned likelihood to estimate the five free parameters

$$\frac{S(250)}{g'(\theta)} = \left(\frac{E_{\rm MC}}{10^{17} \,{\rm eV}}\right)^{\underline{\alpha'}}$$
$$g'(\theta) = \underline{a'} \times \left(1 + \underline{b'} \times x + \underline{c'} \times x^2 + \underline{d'} \times x^3\right)$$
$$x = \cos^2\theta - \cos^2 30^\circ$$



► <2% bias, 18% to 13% resolution

### Photon-equivalent energy scale

► A unified energy scale is essential for accurately comparing events initiated by different primary species



► If reconstructed with the photon scale, proton events have a 15% bias (due to muonic component in hadronic showers)

 $\blacktriangleright$  Noticeable angular dependence  $\rightarrow$  photon and proton showers attenuate differently in the atmosphere

 $\rightarrow$  idea: let's combine the photon and proton energy calibrations!





Proton

#### **Photon-equivalent energy scale**

► A unified energy scale is essential for accurately comparing events initiated by different primary species



- ► **Protons** reconstructed with photon-equivalent scale are assigned energies **between 5% and 10% higher than E**<sub>MC</sub>
- ► Photons reconstructed with photon-equivalent scale are assigned energies between 10% and 15% lower than E<sub>MC</sub>
- ► In a given  $E_{\gamma,eq}$  bin, protons with lower true energy with photons with higher true energy  $\rightarrow$  a conservative scenario for separation

#### M<sub>1</sub>: the discrimination observable

- $\blacktriangleright$  Discrimination based on the muon density ( $\rho_i$ ) measured by the UMD stations
- The normalization factor  $\rho_{pr}$  is the expected muon density for proton events at  $r_{pr}$  = 200 m

$$M_1 = \lg\left(\sum_i \frac{\rho_i}{\rho_{\rm pr}} \times \left(\frac{r_i}{r_{\rm pr}}\right)\right)$$



► Two metrics characterize the discrimination performance:

bkg. contamination = 
$$\int_{-\infty}^{x} f_{pr}(M_1) dM_1$$
  
sig. efficiency =  $\int_{-\infty}^{x} f_{\gamma}(M_1) dM_1$ 

## **M<sub>1</sub>: the discrimination observable**

 $\blacktriangleright$  Discrimination based on the muon density ( $\rho_i)$  measured by the UMD stations



- ► Contamination decreases with increasing primary energy due to the larger air-shower muon content
- ► Larger signal efficiency at the expense of larger contamination

Two metrics characterize the discrimination performance:

bkg. contamination = 
$$\int_{-\infty}^{x} f_{pr}(M_1) dM_1$$
  
sig. efficiency =  $\int_{-\infty}^{x} f_{\gamma}(M_1) dM_1$ 

#### **Data classification**

- ▶ M<sub>1</sub> calculated with the UMD stations of the hottest hexagon
- ▶ Since M<sub>1</sub> scales with the number of muon density measurements, any missing UMD station would bias M<sub>1</sub>
  - → event classification in six "categories" based on number and placement of available UMD stations



- Contamination increases for decreasing number of UMD stations
- ► Very low contamination!

For instance, 1 bkg event misidentified as a photon every 106 years in Cat I (NW hexagon)

#### Unblinding

• Events for each of the six categories. Lines correspond to the  $M_1$  values at which 50% signal efficiency is attained (the "photon candidate cuts")



#### Summary

► First search for a diffuse flux of primary photons above between 50 and 200 PeV from the Southern Hemisphere

► Opportunity to constrain the mass-lifetime phase-space for specific super-heavy dark matter models and to explore the photon flux from proton-proton interactions in the Galactic halo

► Groundwork for a nearly real-time search for primary photons in the tens of PeV domain





#### Outlook

► Nearly three more years of data have been acquired after the unblinded data (Dic 2020 – March 2022)

► Full deployment of UMD stations in the SD-433 array in 2022-2023 enables the use of all seven hexagons in the array for photon searches

- ► Started working on the Phase II analysis:
- Phase II SD rec (Malargue Nov '24)
- Phase II SD and UMD selection (ICRC25 Task Force, Jan '25)
- ► First UHE photons @ ICRC'27 Buenos Aires?

### Backup

#### **Paper status**

- ▶ EB: Corinne, Bruce (sci coord), NG, Ioana, Marcus (task leader) and Federico
- Official readers: Piera and Diego
- ► Six meetings between February and May 2024. Last one in October after 1<sup>st</sup> Coll. Review
- ▶ 2<sup>nd</sup> Coll. Review in November with many useful suggestions by the ORs
- Latest draft approved by the EB on 24th Jan. (with minor comments)

- ► Slides, recordings and minutes for each EB meeting
- Supporting material (gaps, talks, icrc, etc)
- Link to the latest version of the paper



/AugerWiki/PhotonsSdUmd433

Search for a diffuse flux of photons with energies above tens of PeV at the Pierre Auger Observatory

#### The Pierre Auger Collaboration E-mail: auger spokespersons@fnal.gov

Abstract. Diffuse photons of energy above 0.1 PeV, produced through the interactions between cosmic rays and either interstellar matter or background tradiation fields, are powerful tracers of the distribution of cosmic rays in the Galaxy. Furthermore, the measurement of a diffuse photon flux would be an important probe to test models of super-heavy dark matter decaying into gamma-rays. In this work, we search for a diffuse photon flux in the energy range between 50 PeV and 200 PeV using data from the Pierre Auger Observatory. For the first time, we combine the air-shower measurements from a  $2\,\mathrm{km}^2$  surface array consisting of 10 water-Cherenkov surface detectors, spaced at  $433\,\mathrm{m}$ , with the muon measurements from an array of buried scintillators placed in the same area. Using 15 months of data, collected while the array was still under construction, we derive upper limits to the integral photon flux ranging from  $13.3\,\mathrm{to}\,13.8\,\mathrm{km}^{-2}\,\mathrm{sm}^{-1}\,\mathrm{yr}^{-1}$  above tens of PeV. We extend the Pierre Auger Observatory photon searcher program towards lower energies, covering more than three decades of cosmic-ray energy. This work lays the foundation for future diffuse photon searchers: with the data from the next 10 years of operation of the Observatory, this limit is expected to improve by a factor of  $\sim 20$ .

#### Contents

1	Introduction	1
2	Detection systems and data	3
3	Energy assignment of photon and proton events 3.1 Trigger efficiency of photon and proton primaries	55
	3.2 Photon-initiated events	6
	3.3 Proton-initiated events	8
	3.4 The photon-equivalent energy scale	9
4	Discrimination between photon and proton events	10
	4.1 Muon content estimator, M <sub>b</sub>	10
	4.2 Optimization of $M_b$	11
5	Selection of photon candidates in data	13
6	Results of the photon search	16
	6.1 Upper limits calculation	16
	6.2 Systematic uncertainties on the upper limits	19
7	Conclusions and outlook	21
A	Lateral distribution function for photon events	26
в	Parametrization of the background contamination and photon candidate	
	cuts	28