INFN
Istituto Nazionale di Fisica Nucleare

Investigating the hadron nature of high energy photons with PeVatrons

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Why this talk

In the last years shower arrays located at extreme altitude (LHAASO but also HAWC and Tibet ASγ) are detecting a number of photons above 100 TeV in a background-free regime.

Therefore, ***for the first time we have a pure sample of showers produced by high energy photons***

LHAASO in particolar is observing about 4000 photons per year above 100 TeV and about 20 above 1 PeV

These observations offer for the first time the possibility to study the characteristics of photon induced showers and to compare with MonteCarlo simulations.

In particular this allow to measure for the first time the ***pion photo-production cross section even at energies marginally or not investigated yet at accelerators***.

These studies are very important to clarify some issues in the photon-hadron interactions.

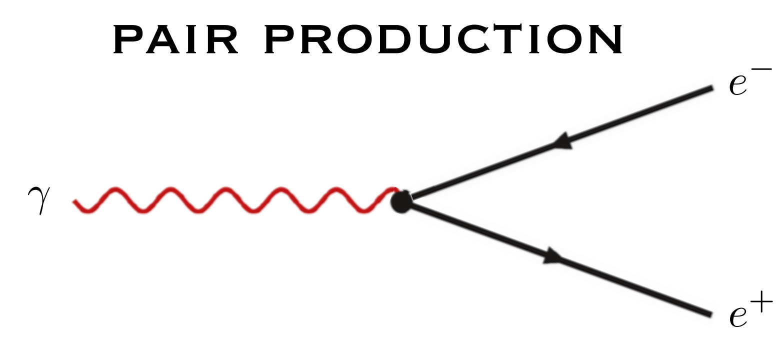
In the near future, the ***SWGO*** (and also ***ALPACA***) experiment in the Southern hemisphere is expected to detect a larger sample of PeVatrons thus extending this study at higher energies.

Why is the study of photon-hadron interactions interesting?

The photon: gauge boson of QED

The photon is the gauge boson of quantum electrodynamics and is regarded as ***point-like*** and ***structureless.***

With increasing energy, after an interaction with a Coulomb field, the photons could materialize as pairs of electrons through the process $\gamma \rightarrow e^+e^-$ if the energy available is sufficiently high, $> 2m_e c^2$



→ it is possible to interpret the pair production as arising through the scattering of ***photon constituents*** by the Coulomb potential.

This illustrates the point that at different energy scales, different aspects of the underlying dynamics become visible

In high energy ***photo-production***, in many aspects, the photon exhibits an ***internal structure which is very similar to that of hadrons***, with a small relative probability of order $\alpha \approx 1/137$.

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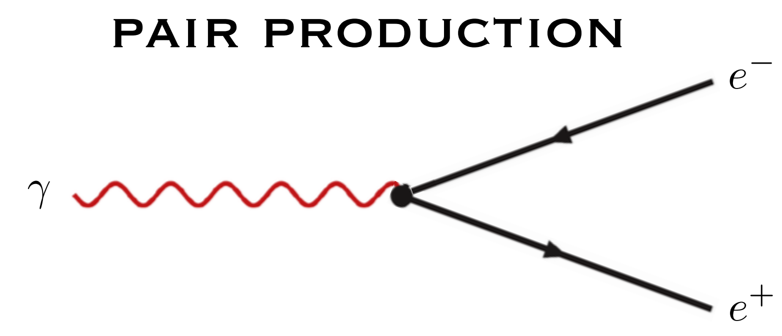

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On general grounds, ***photo-production*** is a process where something is produced by the interaction of a high energy photon. Something like $\gamma + N \rightarrow \pi + N, \quad \pi \rightarrow \mu$

Pion photo-production is the main process to produce muons in $\gamma-$induced showers

Gamma-Ray Astronomy with EAS arrays

Any γ-ray signal is completely overwhelmed by air showers produced by ordinary charged CRs (mainly protons) spread evenly over the sky.

$\Phi_{CRAB}(>1\ TeV) \sim 2 \cdot 10^{-11}\ ph/cm^2 \cdot s$

$\Phi_{bkg}(>1\ TeV) \cdot \Delta\Omega(=1\ msr) \sim 1.5 \cdot 10^{-8}\ nuclei/cm^2 \cdot s$

$$\Phi_{signal} \approx 10^{-3} \cdot \Phi_{bkg}$$

For energies >1 TeV, inside a solid angle of 1 msr around a point source with a Crab-like energy spectrum, the signal due to photons is only $\approx 10^{-3}$ the background of CRs.

No possible veto with an anti-coincidence shield as in satellite experiments. In addition…

Cosmic Ray showers ≈ γ-ray showers !

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In 1960 Maze and Zawadzki suggested that CRs can be identified and rejected by identifying EAS with an ***abnormally small number of muons N_μ :*** the so-called ***'muon poor' technique.***

IL
NUOVO CIMENTO
ORGANO DELLA SOCIETÀ ITALIANA DI FISICA
SOTTO GLI AUSPICI DEL CONSIGLIO NAZIONALE DELLE RICERCHE

Vol. XVII, N. 5 — Serie decima — 1° Settembre 1960

On an Attempt of Detection of Primary Cosmic Photons of Very High Energy.

R. Maze

Cosmic Ray Laboratory, Ecole Normale Supérieure - Paris

A. Zawadzki

Nuclear Research Institute of the Polish Academy of Sciences Cosmic Ray Laboratory - Lodz

(ricevuto il 29 Febbraio 1960)

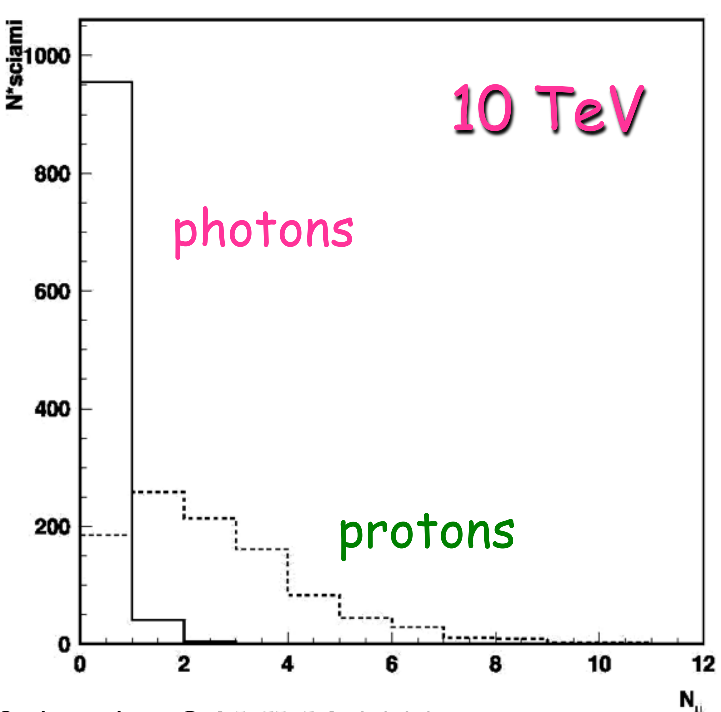
Summary. — In relation to the primary proton flux of very high energy ($(10^{15}\div10^{16})$ eV), the possible photon flux of equal energy created by the p-p collisions of protons with the diffused matter of the Universe, is evaluated taking into account the multiple production of the π^0-mesons and their decay. If a trace of very high energy photons exists among the primary flux, two types of EAS must be produced in the air: 1) ordinary EAS; 2) pure photon-electron cascades. Taking advantage of the difference between the number of electrons produced at sea level by a protonic and by a photonic EAS of equal energy (therefore resulting in an amplification factor of the observable effect by at least ten times) it is shown that it is possible to separate these two types by studying the penetrating component with the help of a large detection area and to disclose a real limit rate as small as 10^{-4}. Considering current cosmological estimates, it gives some possibility of observing a significant rate. This method therefore may give new experimental information on the origin of cosmic rays and on individual interaction at very high energy.

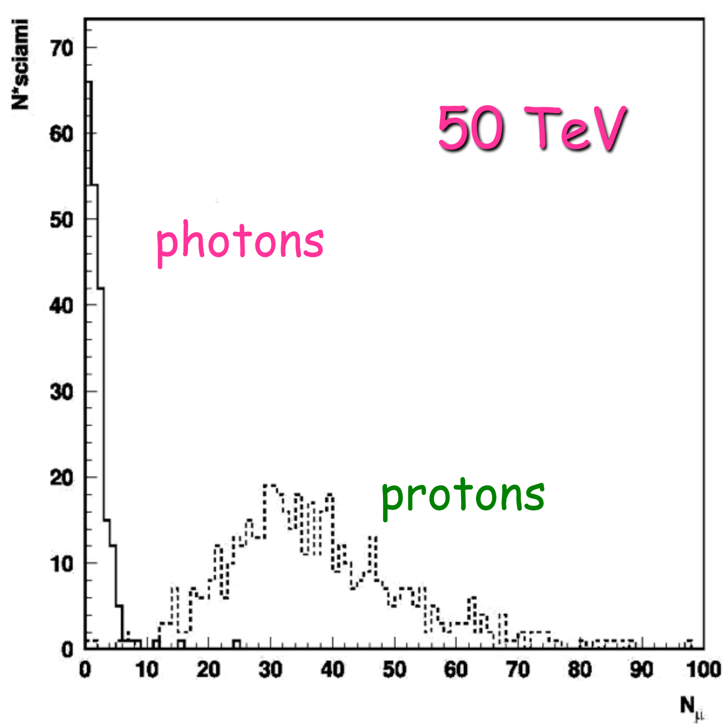
Background rejection with EAS arrays

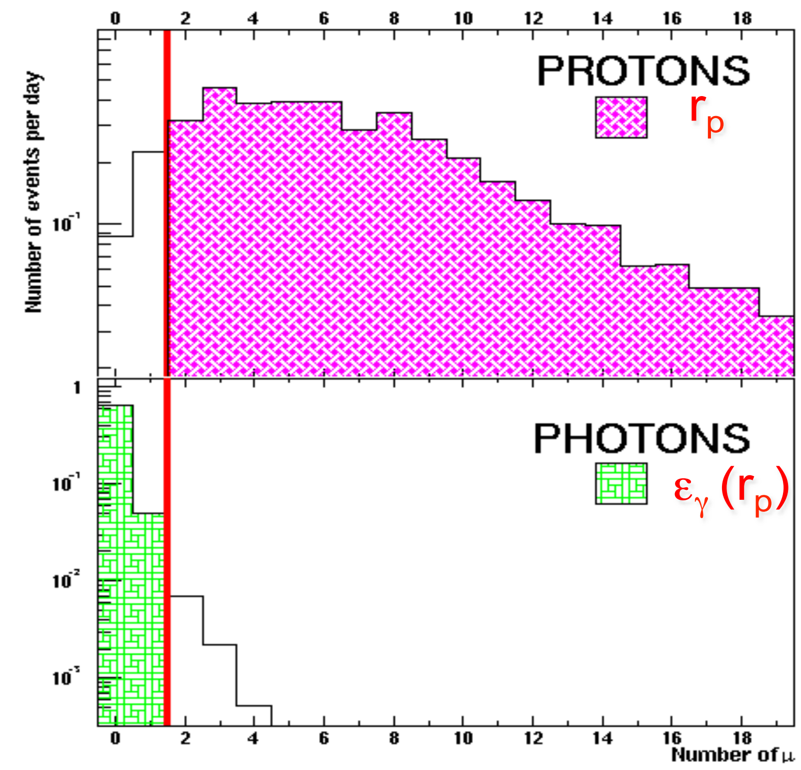
The standard technique is to look for ***"muon-poor"*** showers.

The ratio between the cross sections of photo-production and nucleus-nucleus interaction processes is $\sim 10^{-3}$ resulting in $< N_{\gamma\to\mu} > / < N_{p\to\mu} > \approx 2 \cdot 10^{-2}$

The main limitation of this technique is due to the extent of ***fluctuations*** in hadron-initiated showers and to the ***small number of muons.***







Di Sciascio, GAMMA 2000

The discrimination capability increases with the energy and the μ–detector area.

➡ *large muon detector !*

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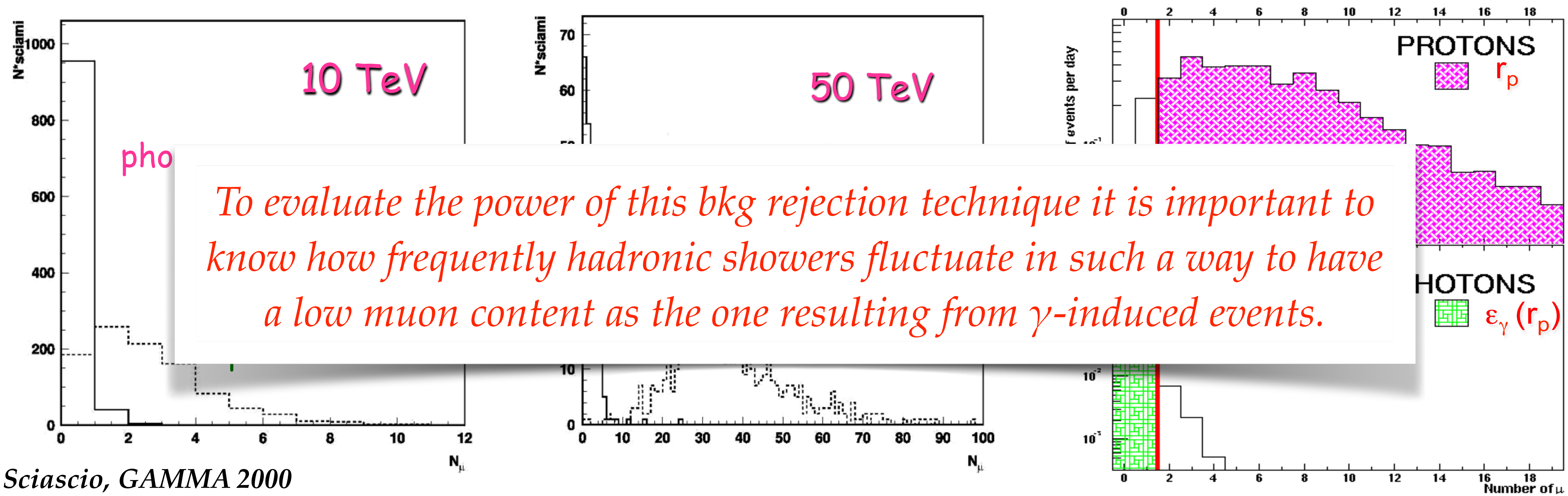

Di Sciascio, GAMMA 2000

To evaluate the power of this bkg rejection technique it is important to know how frequently hadronic showers fluctuate in such a way to have a low muon content as the one resulting from γ-induced events.

The discrimination capability increases with the energy and the μ–detector area.

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Muon Astronomy?

"Ironically, early indications [in first experiments exploiting the 'muon poor' technique] ***are that the signal seems to have the same muon content as the background"*** *(TK Gaisser)*

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One striking feature of ***the Cyg X-3 signal was that the showers were not "muon poor" as expected for e.m. showers***.
In addiction, 2 underground detectors reported excesses of TeV muons pointing to the direction of Cyg X-3: Sudan 1 and NUSEX → ***Muon Astronomy?***

Volume 155B, number 5,6 PHYSICS LETTERS 6 June 1985

OBSERVATION OF A TIME MODULATED MUON FLUX IN THE DIRECTION OF CYGNUS X-3

G. BATTISTONI [a], E. BELLOTTI [b], C. BLOISE [a], G. BOLOGNA [c], P. CAMPANA [a], C. CASTAGNOLI [c], A. CASTELLINA [c], V. CHIARELLA [a], A. CIOCIO [a], D. CUNDY [d], B. D'ETTORRE-PIAZZOLI [c], E. FIORINI [b], P. GALEOTTI [c], E. IAROCCI [a], C. LIGUORI [b], G. MANNOCCHI [c], G. MURTAS [a], P. NEGRI [b], G. NICOLETTI [a], P. PICCHI [c], M. PRICE [d], A. PULLIA [b], S. RAGAZZI [b], M. ROLLIER [b], O. SAAVEDRA [c], L. SATTA [a], P. SERRI [b], S. VERNETTO [c] and L. ZANOTTI [b]
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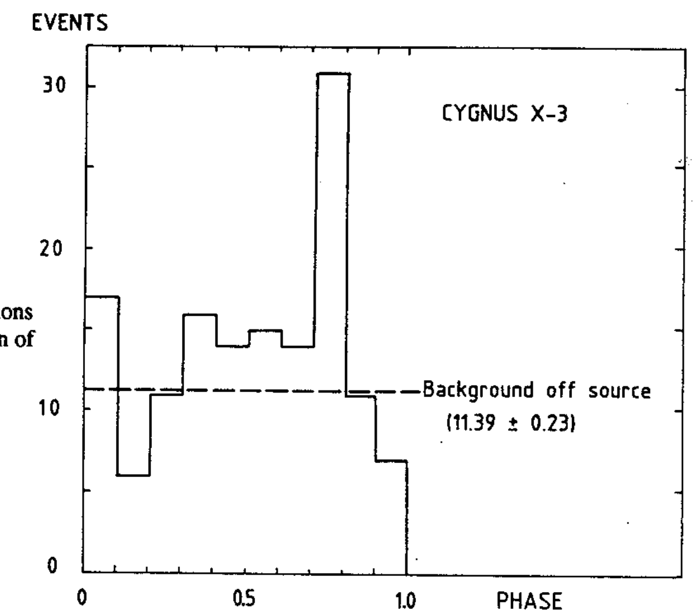

FIG. 1 - Phase distribution for muons arriving within 4.5° off the direction of Cygnus X-3 (June '82-January '85).

The most compelling evidence for the association of the muons with Cyg X-3 was the modulation of te muon arrival time with the 4.8 hr orbital period of the source

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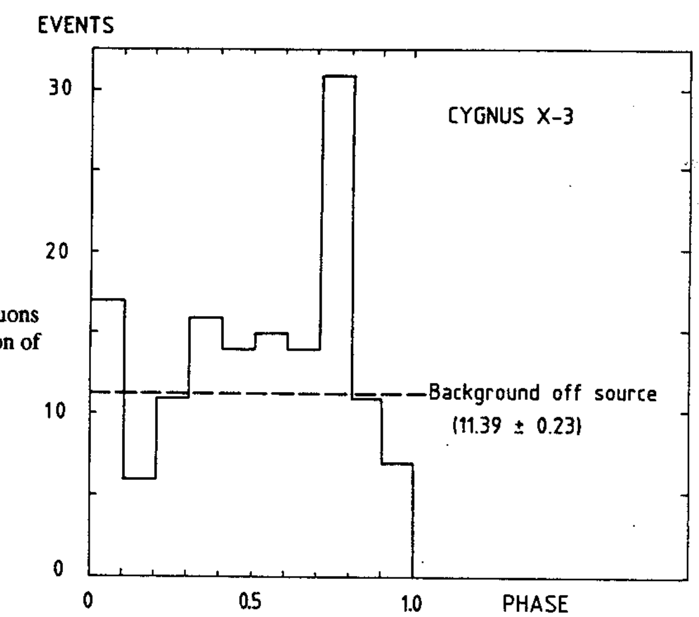

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The interest in the detection of muons from cosmic sources come from the fact that there is not simple explanation in the framework of the standard model of particle physics (new particles, some high energy resonance in the γp cross section, …) .

→ the search for muon emission from cosmic sources is a search for exotic physics!

J. Phys. G: Nucl. Part. Phys. **18** (1992) 1269–1279. Printed in the UK

Neutral particles of extremely high energies: a clue to the enigma of Cyg X-3?

F A Aharonian and A M Atoyan
Yerevan Physics Institute, 375036 Yerevan, Alikchanian Brothers Street 2, Armenia

Received 29 April 1991, in final form 4 October 1991

Abstract. A hypothesis is suggested such that the anomalous TeV muon and hadron events detected from the direction of Cyg X-3 are initiated by extremely high-energy primaries (gamma-rays and/or neutrons). This hypothesis requires the existence of massive particles with $M_X \sim 1$ TeV and lifetime $\tau_X \sim 10^{-6}$ s, which are created at interactions of primaries in the atmosphere, then effectively cascade and decay, producing high-energy muons and hadrons at large angles.

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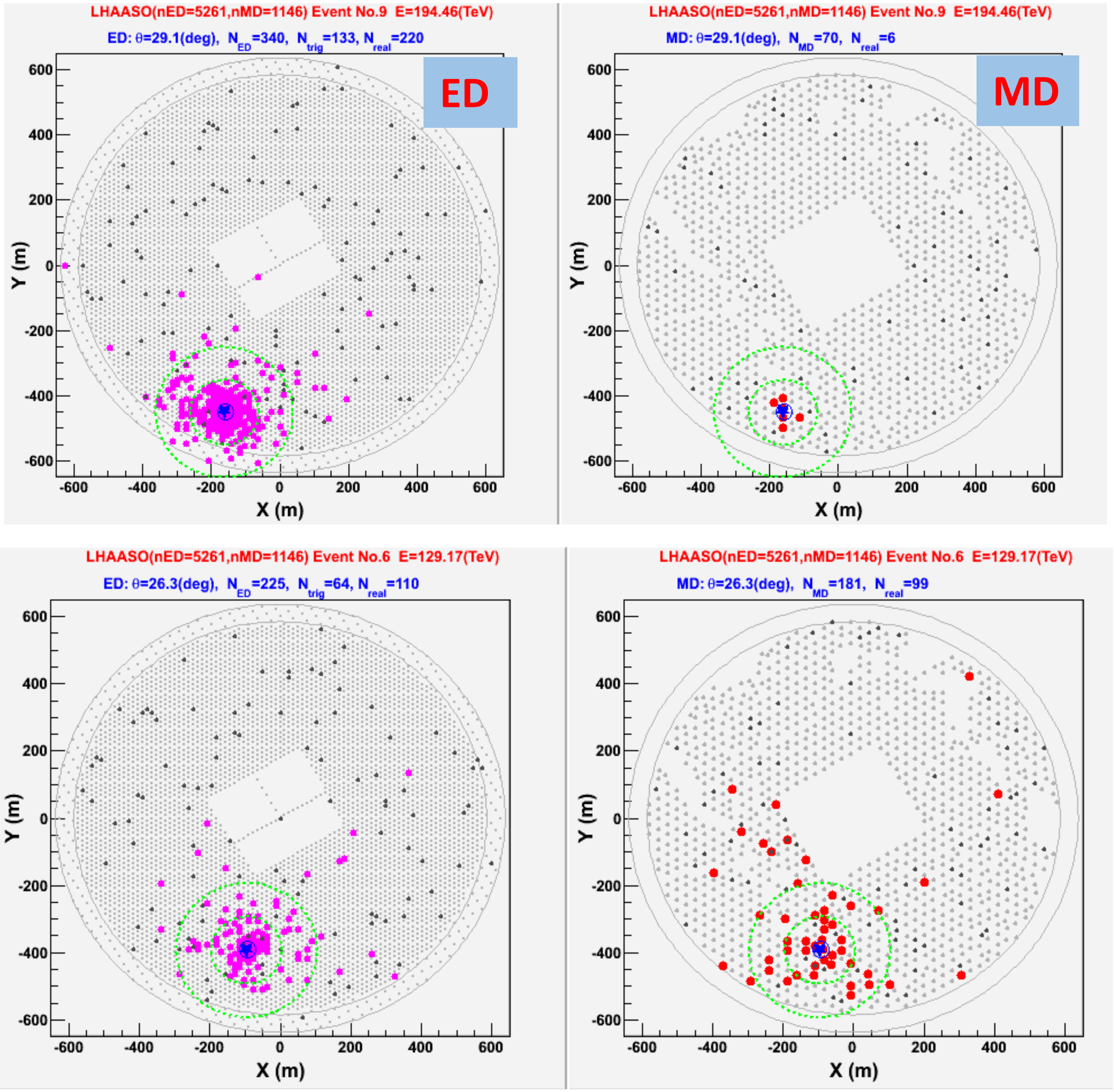
It is intriguing that LHAASO recently confirmed emission from the Cygnus region up to the PeV range!

The importance of measuring the photo-production cross section above 100 TeV, studying the characteristics of the showers produced by VHE photons, therefore has more than just historical interest.

Muon-poor technique with LHAASO

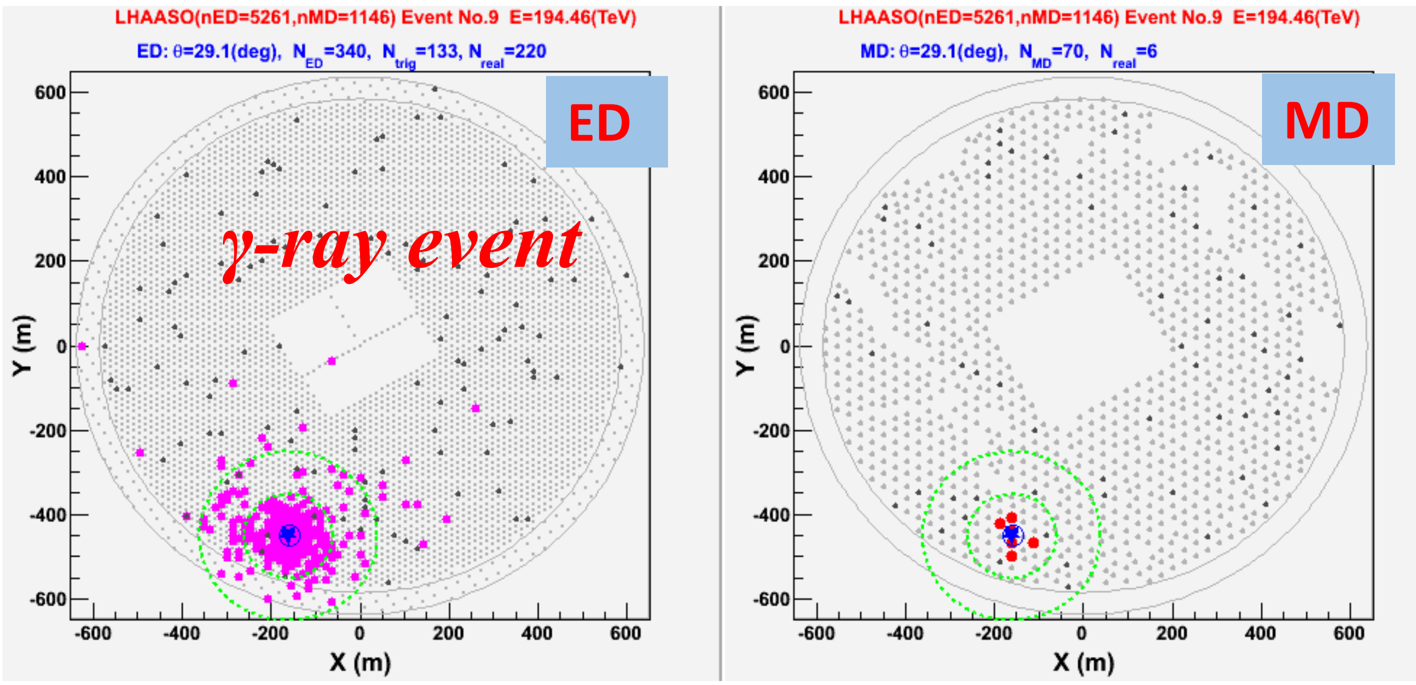


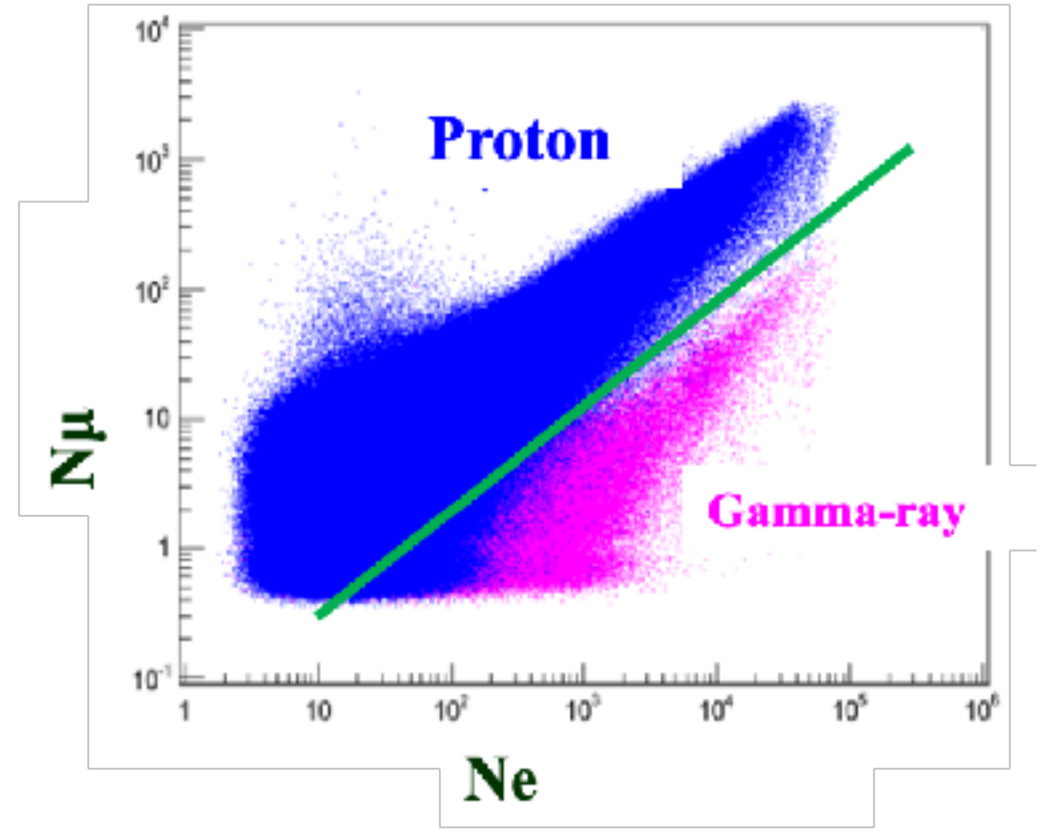
Gamma-ray
E=194 TeV

Proton
E=129 TeV

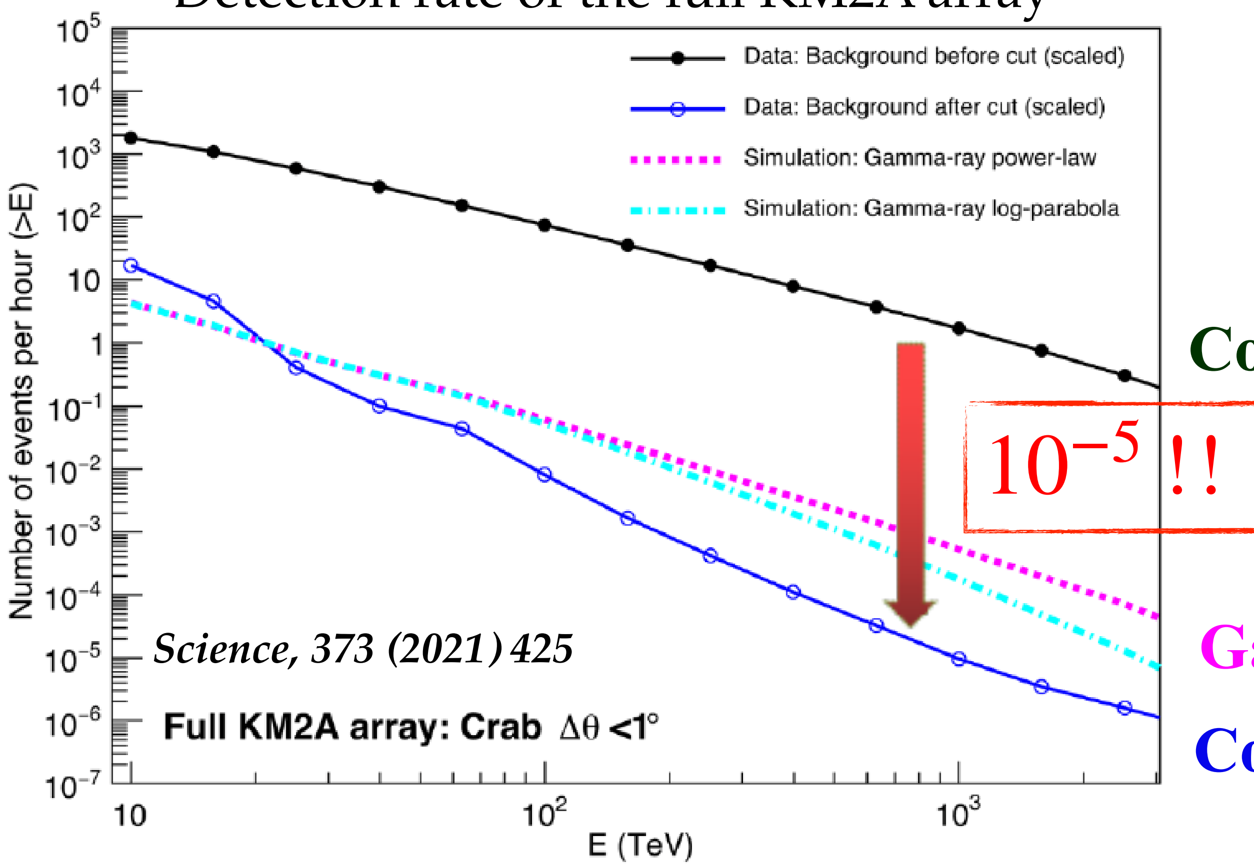
S.Z. Chen, WASDHA 2018

Muon-poor technique at high energy





Detection rate of the full KM2A array



Impressive background rejection capability with more than 40,000 m² of μ−detector

Cosmic ray rate before cut

Gamma-ray rate

Cosmic ray rate after cut

The Photon as Hadron

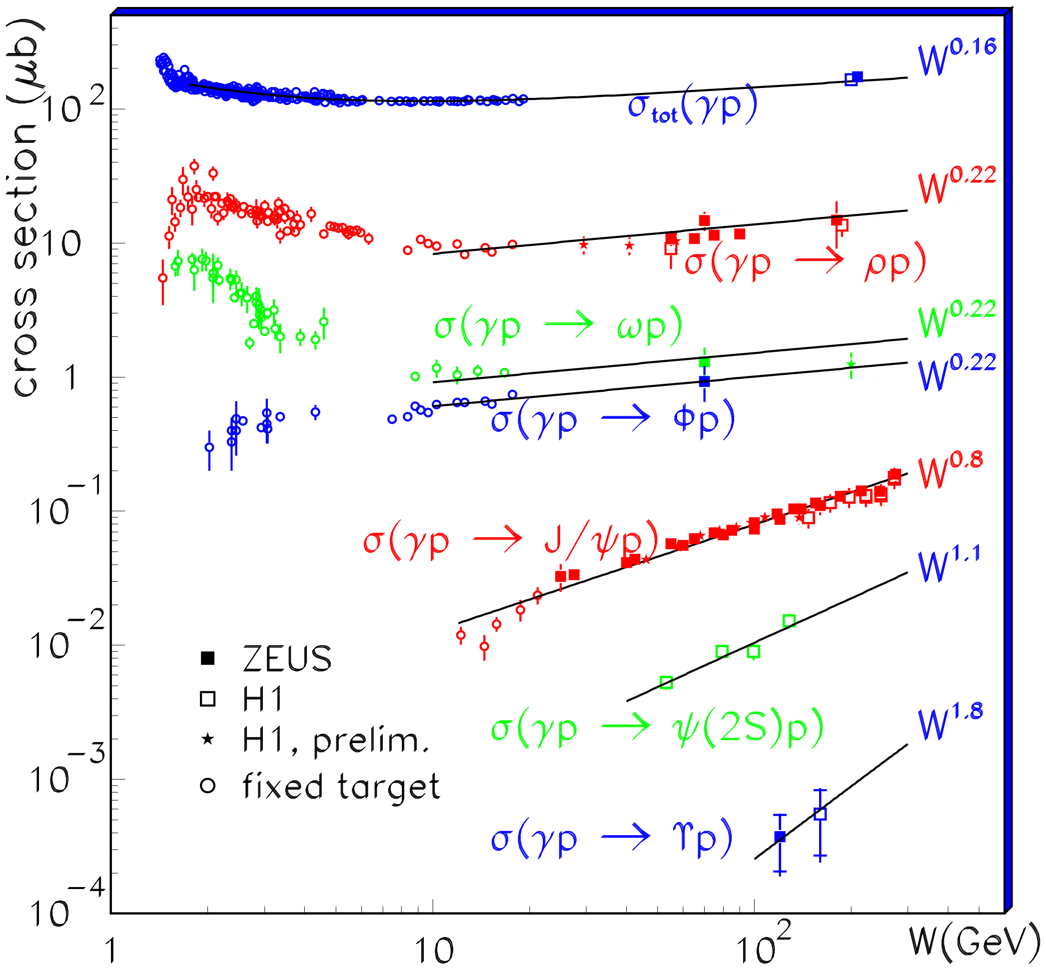
Photons of very high energy behave as hadrons when interacting with other hadrons

In many aspects, the photon appears very much like a hadron and a photon-hadron interactions can be understood if the ***physical photon*** is viewed as a ***superposition of a bare photon and an accompanying small hadronic component*** which feels conventional hadronic interactions.

That is, its interaction cross-sections behave (apart from a normalization factor) very much like hadronic cross-sections, and at the highest energies ***the photon even appears to 'contain' quarks and gluons***, just as the proton or, more specifically, a vector meson does.

The simplest model for describing the hadron nature of the photon is the ***Vector Meson Dominance (VMD) model***.

The complex hadronic structure of the photon is far less well understood.



The total $\gamma p \to Vp$ cross-section compared with the cross-sections for exclusive vector meson production, as a function of the γp center of mass energy W.

The Vector Meson Dominance Model

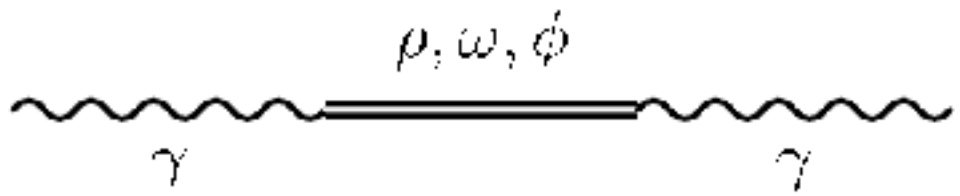
Photon–proton cross-sections at $\sqrt{s} > GeV$ can be related to hadron–hadron cross-sections using the ***Vector Meson Dominance Model*** (VMD) proposed by ***Sakurai*** in 1960 before the introduction of QCD.

ANNALS OF PHYSICS: **11**, 1–48 (1960)

Theory of Strong Interactions*

J. J. SAKURAI

The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois



Hadronic contribution to the photon propagator in the VMD model

Therefore, ***interactions between photons and hadronic matter occur by the exchange of a hadron between the dressed photon and the hadronic target.***

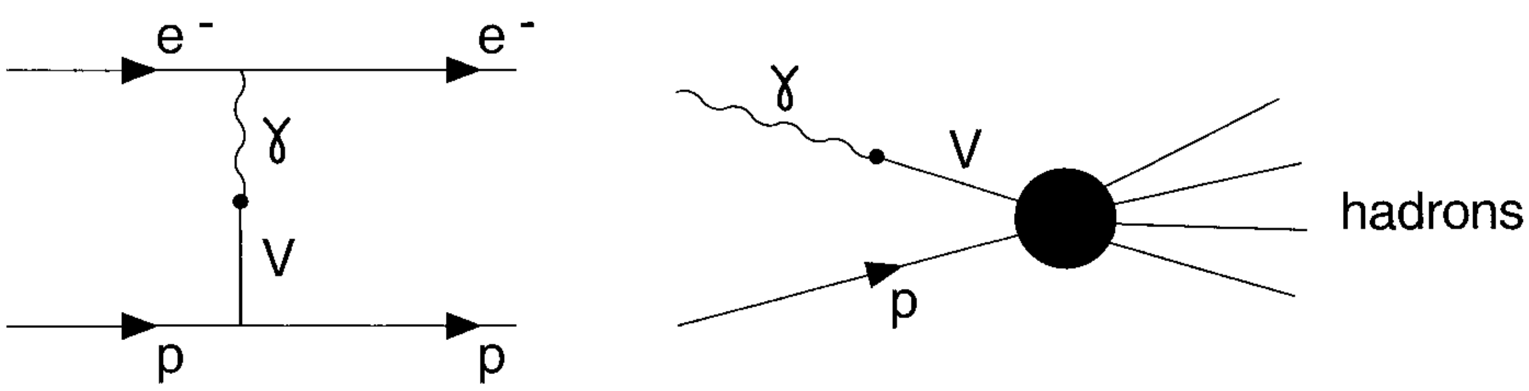
In this model, the photon is assumed to transform, before an interaction, to a ***neutral vector meson*** V, $\gamma \to V$, (such as the ρ^0, ω, ϕ) while the interaction of the bare photon with hadrons becomes negligible at high energies.

The quark model predicts that the photon should behave as if it were ***75% ρ, 8% ω and 17% φ.***

This really means, of course, that in a large sample of interactions the photon will behave as a rho in 75% of the interactions, as an omega in 8%, and as a phi in 17%.

The Vector Meson Dominance Model

The high energy photon-hadron interaction may then be thought of as occurring in two steps: ***first, the photon materializes into a vector meson*** in the vicinity of the interacting hadron, and ***second, this vector meson interacts strongly with the hadron.***



(a) (b)

Two situations where a photon interaction proceeds through an intermediate vector meson.

(a) Elastic electron scattering with a ***virtual photon***. Here the vector meson is usually regarded as yielding a modification of the target charge distribution.

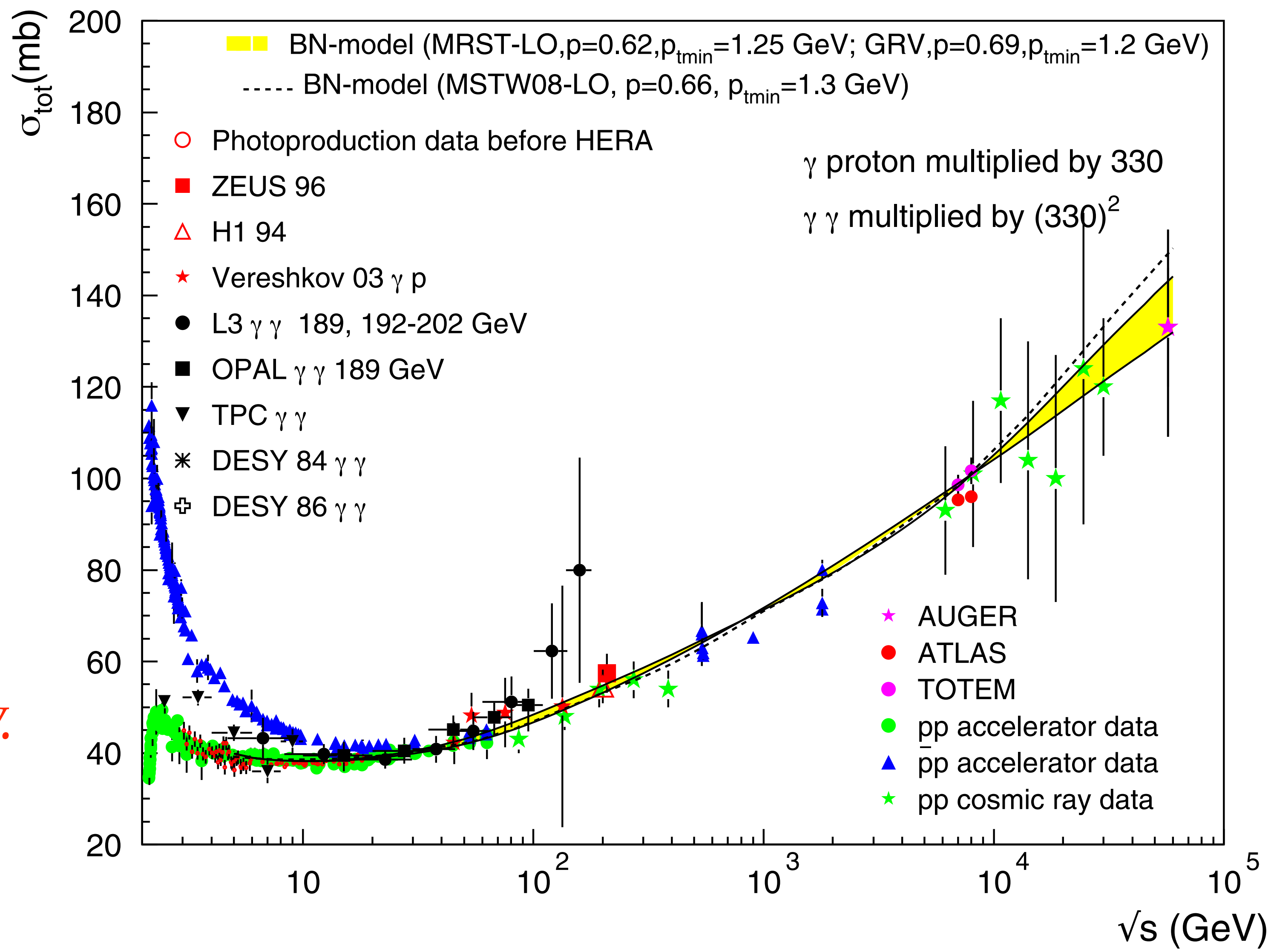
(b) High-energy interaction of a ***real photon***. The conversion takes place well outside the target and the vector meson V is considered part of the photon's hadronic structure.

The total hadronic cross sections

The ***pion photo-production*** $\gamma N \to \pi N$ is the only (main) process able to produce ***muons*** in photon-induced Extensive Air Showers (EAS).

The knowledge of the photo-production cross section is therefore crucial to evaluate the expected number of muons in γ-showers and to set a correct threshold to discriminate, in high energy **γ-ray astronomy**, the showers induced by the photons from the background due to charged CRs.

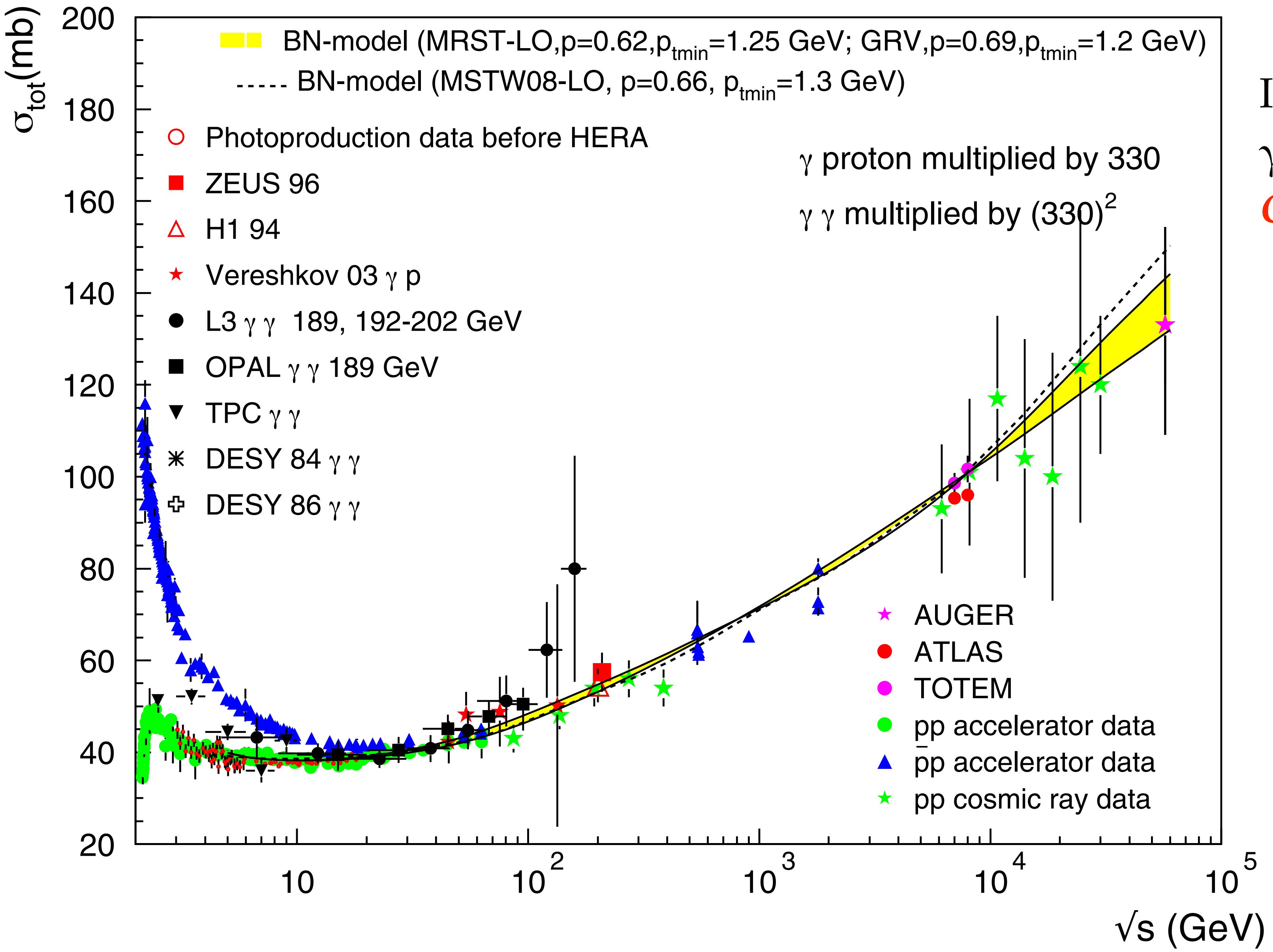
Total pp and $p\bar{p}$ total cross sections, together with normalised γp and $\gamma\gamma$ data



Measurements of the hadronic cross sections are made with different techniques due to the different projectiles and targets used.

The study of the interactions of primary CR with the atmosphere allowed to measure the p-air and pp cross sections up to $\sqrt{s} = 57$ *TeV.*

Photo-production cross section



Information on photo-production γp and $\gamma\gamma$ cross-sections are limited to $\sqrt{s} \leq 200$ ***GeV*** from data collected at HERA.

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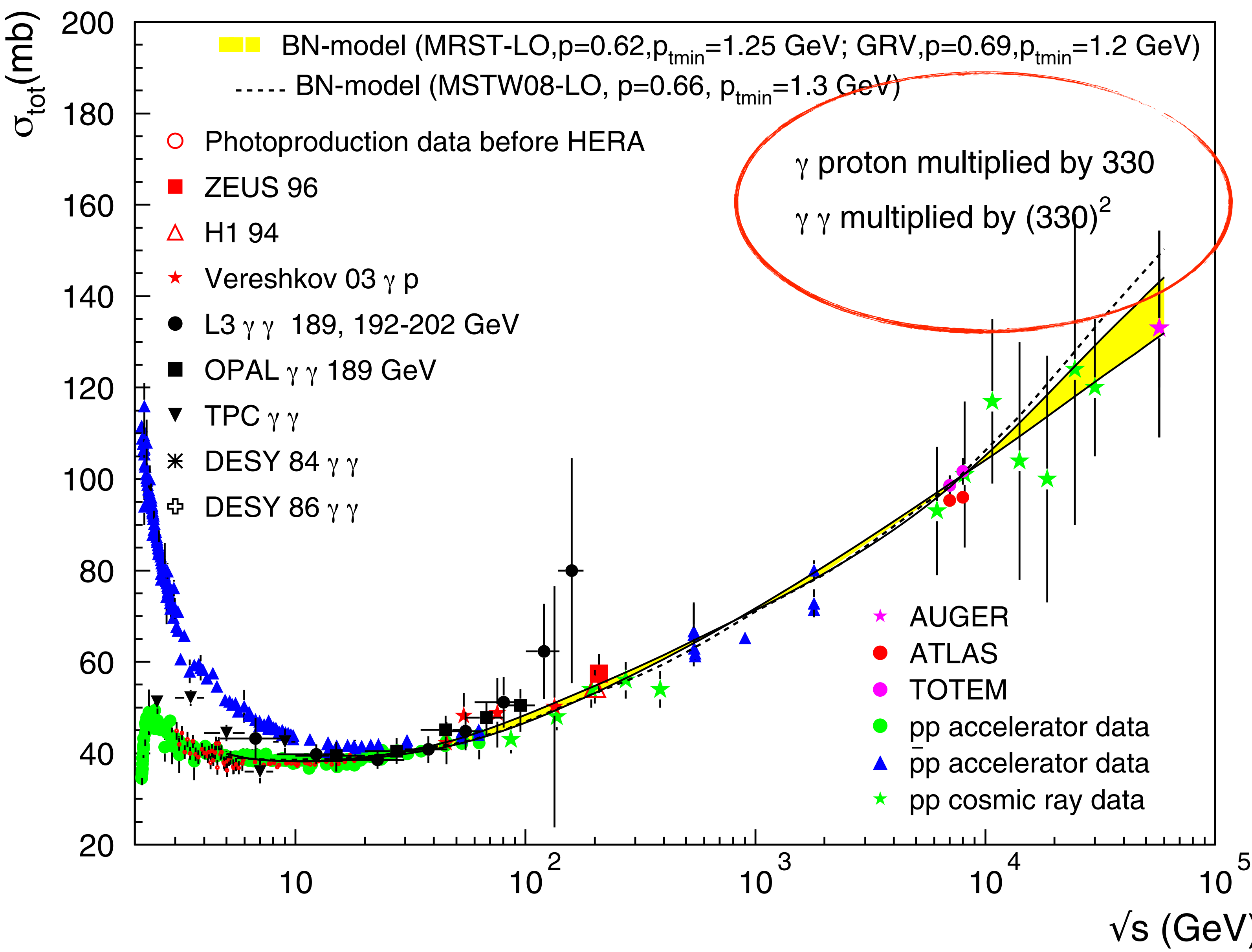

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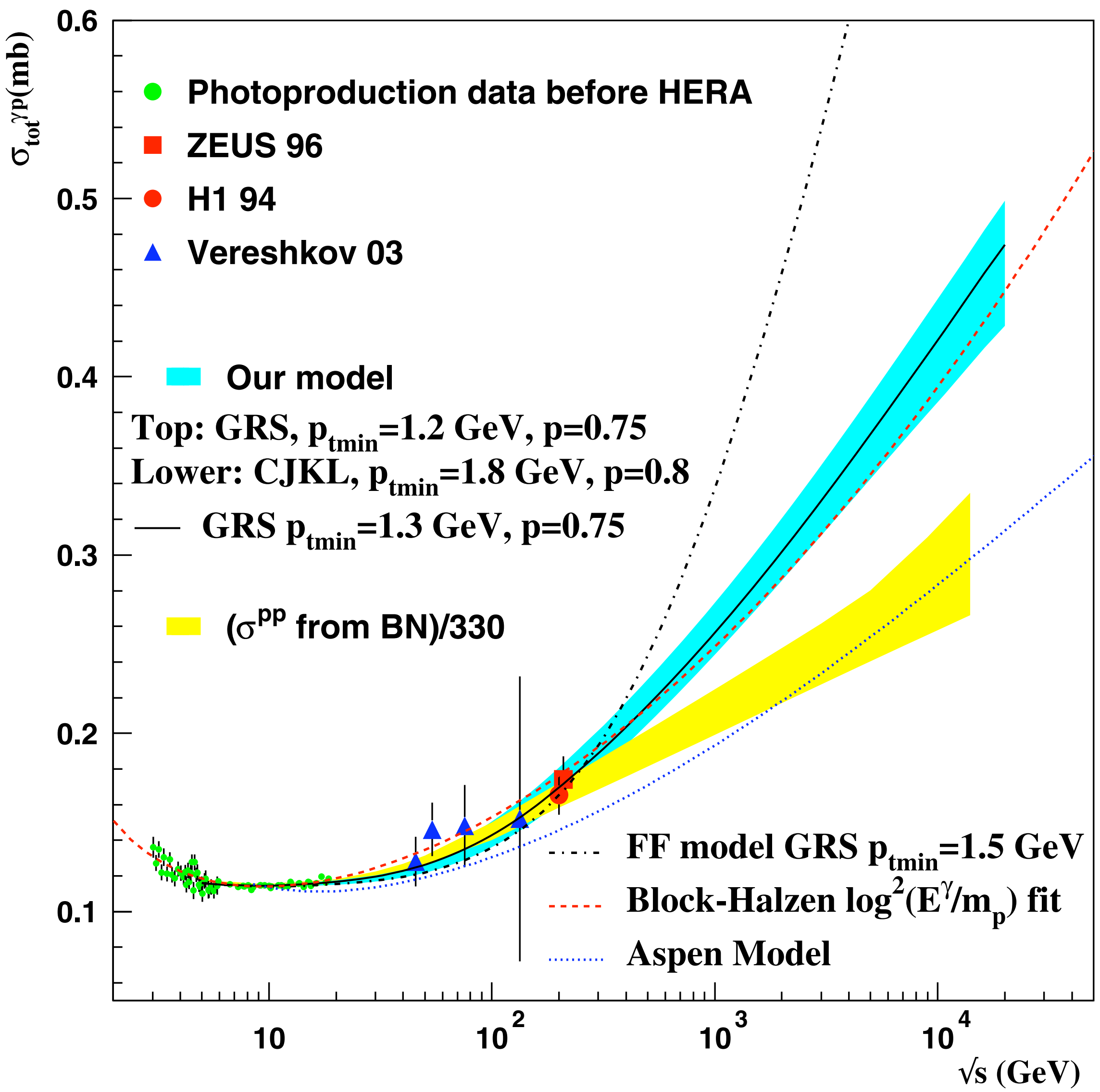
The photo-production γp and $\gamma\gamma$ cross-sections above $\sqrt{s} \leq 200$ *GeV* are typically extrapolated from the pp cross section with factorisation models and used in MonteCarlo simulations up to the highest energies.

Total γp cross-section



Total photon-proton cross sections measured in different experiments compared with expectations from different models

To calculate the γp cross-section up to the highest CR energies, several models have been developed. They include

- *factorisation models*, in which by means of a simple multiplicative factor the photon processes are compared with each other and with the pure proton ones
- *microscopic models*, such as Block-Nordsiek models, with quarks and gluons.

All factorisation models imply that there is a universal behaviour of the energy dependence

For a comprensive review of cross section measurements and calculations:
Pancheri&Srivastava, Eur. Phys. J. C (2017) 77:150

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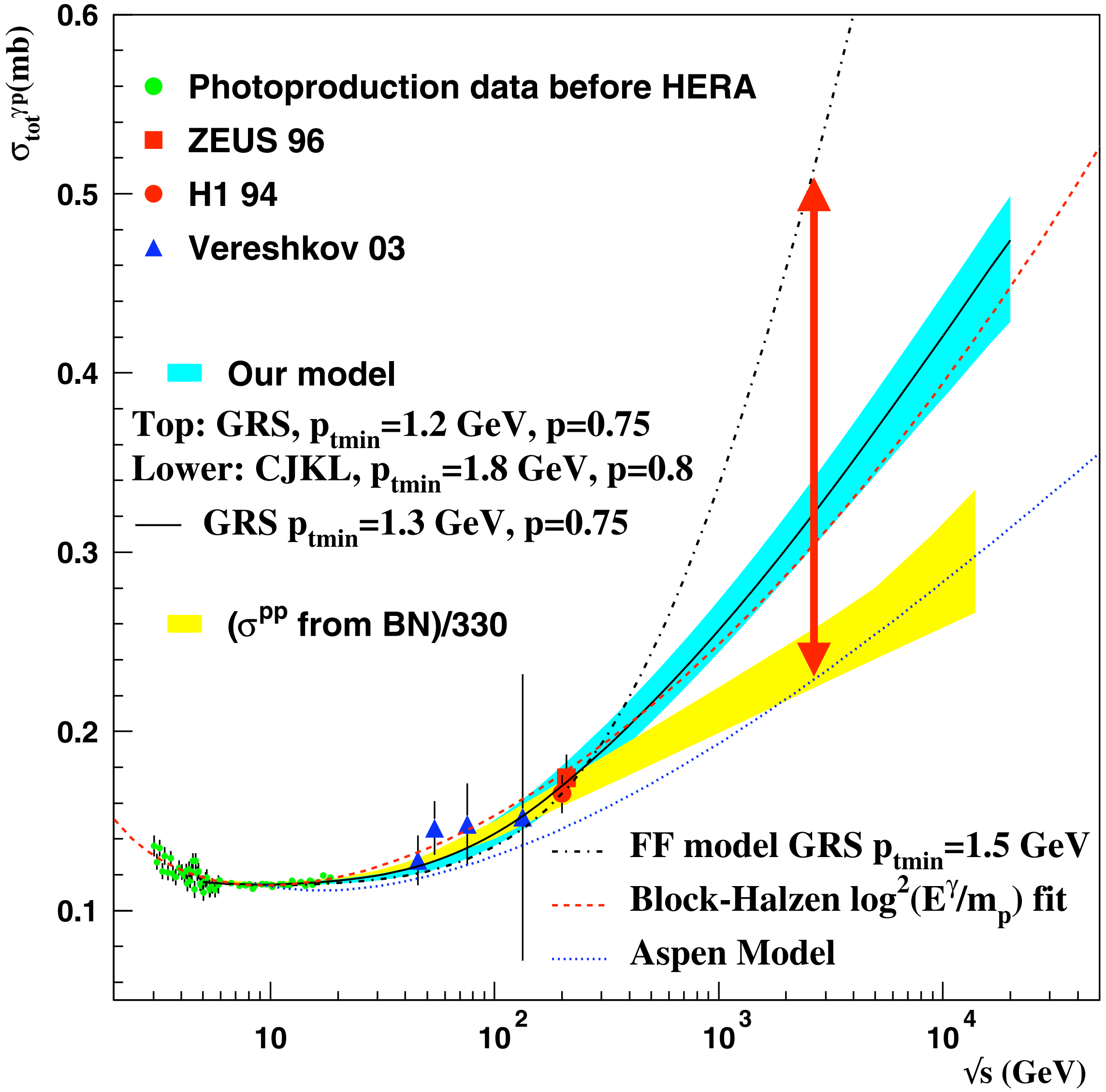

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While at moderate, HERA-like energies, all the models, factorizations and microscopic, give good fits to the data, ***a remarkable difference*** between their high energy extrapolations can be appreciated ***starting from*** $\sqrt{s} \sim 200$ ***GeV.***

→ ***Different muon content expected!***

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The factorisation model

In the factorization models a brute force factorization is applied to models describing the proton-proton interaction to obtain the $p\gamma$ cross sections.

The photon is considered (always) hadron-like and $\sigma_{tot}^{\gamma p} = R_\gamma \cdot \sigma_{tot}^{pp}$, where R_γ is the probability that the photon makes occasional transitions to a hadronic state.

The VMD model allows to estimate the factor R_γ at $\sqrt{s} = 10 - 20\ GeV$ before the beginning of the high-energy rise of cross sections. With the $\rho-$meson data $R_\gamma \approx 1/360$ is obtained

The crucial question of factorization to be addressed is following, ***is a photon like a proton just multiplied by a constant factor?***

We can explore the effects of the hadronic structure of the photon through the analysis of the total cross sections involving photons.

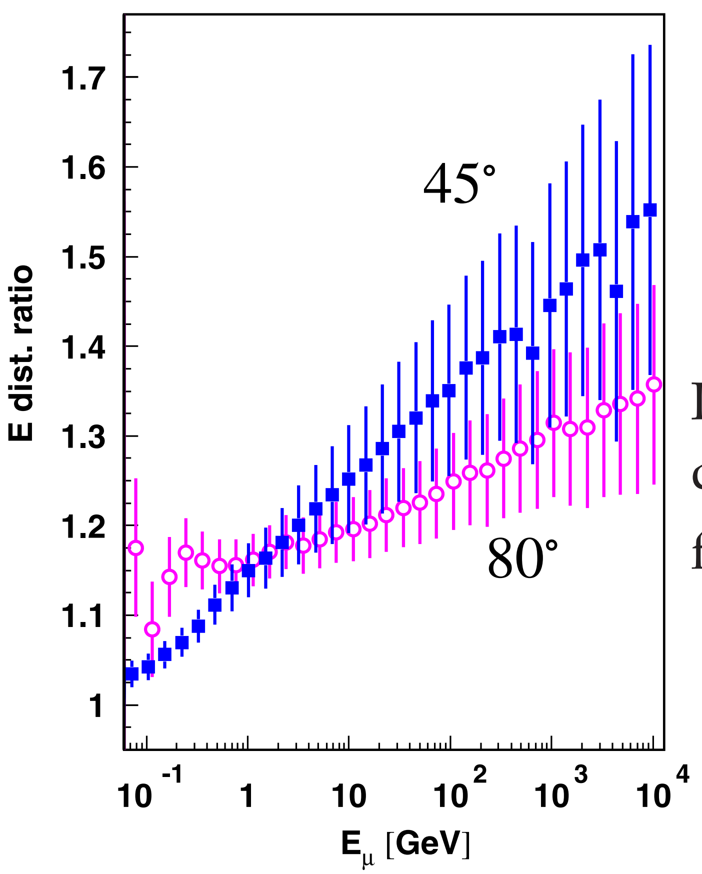
The measurement of the γp cross section above $\sqrt{s} \sim 200$ GeV is crucial to disentangle between different models and this goal can be reached only with ***gamma-ray astronomy above 100 TeV***.

Photo-production and shower development

The large difference between models may impact strongly on high-energy CR physics and in particular on the evaluation of the photon content in the primary flux up to the energies investigated by the AUGER experiment

Uncertainties in the photo-production cross section may affect the muon content in γ-showers and the background selection in gamma-ray astronomy.

Measurements of PeVatrons energy spectra and cutoffs may be affected by different selection cuts.



Ratio between ground muon energy distributions obtained with two models, for 10^{19} eV photon showers.

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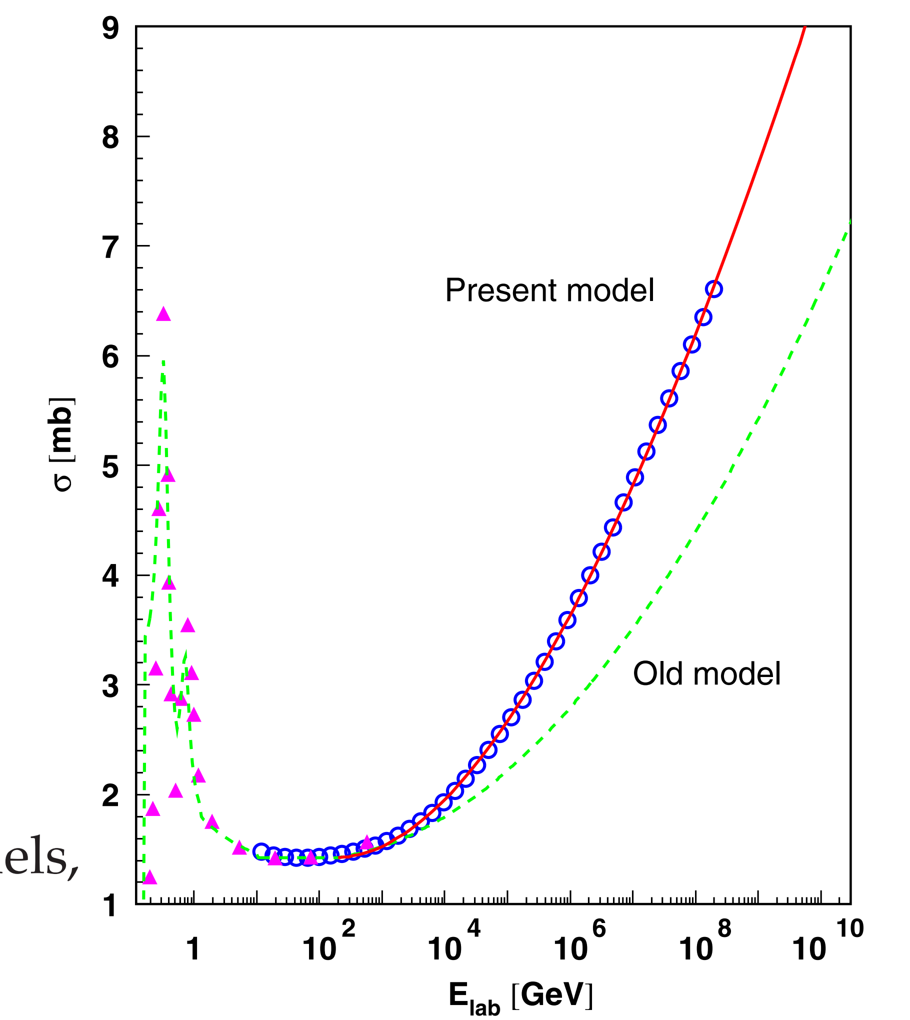


Photon-air nucleus cross sections versus the photon lab energy.

Muons in Air Showers

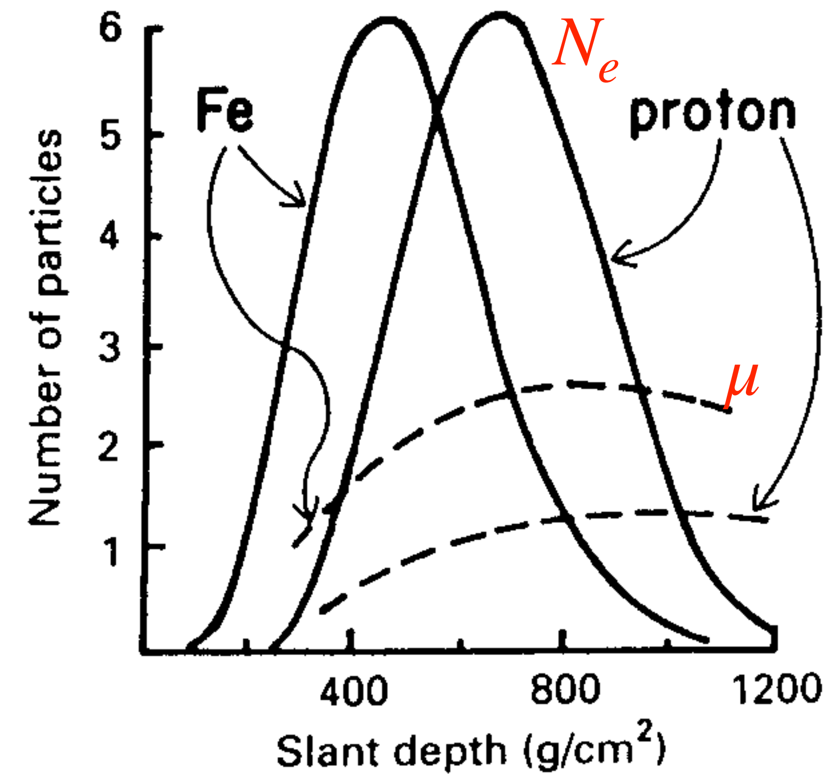
The total number of ***normal muons*** $(N_\mu)_{norm}$ is related to the elemental composition of the primary nucleus and the characteristics of hadronic interactions.

It increases with primary energy as $(N_\mu)_{norm} \sim E_p^\alpha$, $\alpha < 1$.

The number of ***photo-produced muons*** $(N_\mu)_{\gamma\to\mu}$ reflects the number of photons in air showers and is nearly proportional to the shower size at max, $(N_\mu)_{\gamma\to\mu} \sim (N_e)_{max} \sim E_p$.

Therefore, the fraction of photo-produced muons to normal muons increases with E_p:

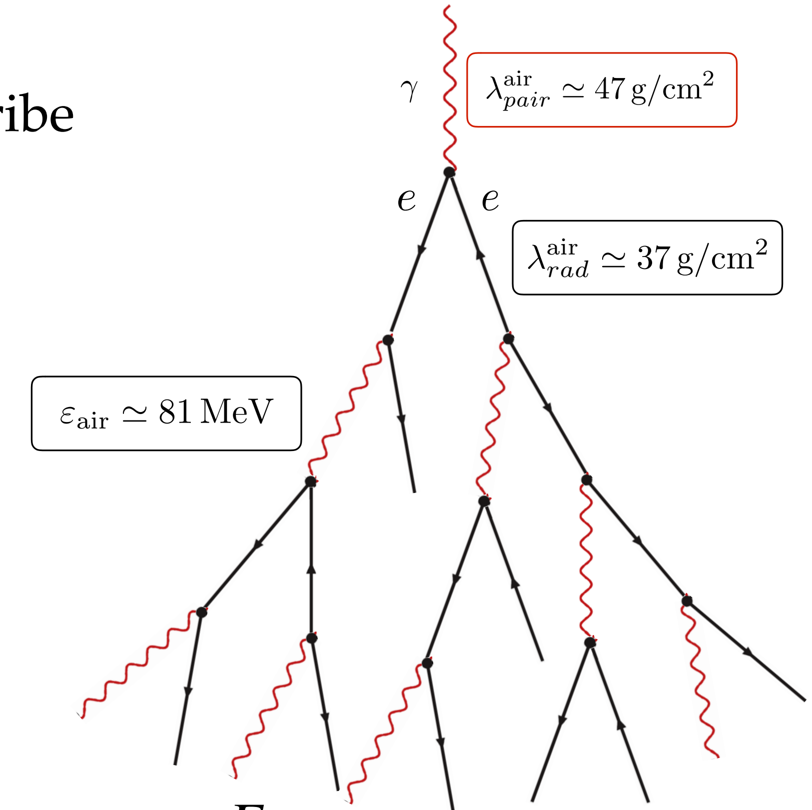
$$\frac{(N_\mu)_{\gamma\to\mu}}{(N_\mu)_{norm}} \sim E_p^{1-\alpha}$$



The number of photo produced muons depends only on the number of photons at the shower max both for $\gamma-$ray and hadronic showers.

The bulk of the hadronic cascades in $\gamma-$showers are produced deep in the atmosphere by low-energy photo-production processes.

Pion photo-production in EAS



Extending the simple Heitler toy model we can include muons and describe the main characteristics of pion photo-production in air showers

After n radiation lengths, we obtain a particle cascade which has evolved into $N = 2^n$ particles of equal energy $E_n = \dfrac{E_0}{2^n}$, of which 1/3 are photons.

Then, we have

$$N_\gamma = \frac{1}{3}N \qquad N_e = \frac{2}{3}N$$

If the number of splittings to have an average particle energy equal to E_c is $n_{Max} \sim \ln\left(\dfrac{E_0}{E_c}\right)$,

therefore, ***the number of splittings to have and energy of order GeV is*** $n \sim \ln\left(\dfrac{E_0}{1\ GeV}\right) \sim 15$

for showers with a size $N_e \sim 10^6$.

$$N_{\gamma\rightarrow\mu} = N_\gamma \cdot R_\gamma$$

$$R_\gamma = \frac{\sigma_{\gamma\rightarrow\pi\rightarrow\mu}}{\sigma_{\gamma\rightarrow e^+e^-}} \approx 3 \cdot 10^{-3}$$

The small ratio of the cross sections is the reason $\gamma-$showers are muon-poor

Number of muons in $\gamma -$showers

In air shower experiments the energy of detected muons is about 1 GeV.

For arrays located at high altitude ($\sim$ 4000 m asl) ***the max number of splittings is*** $n_{max} = 600/37 \sim 16$

As an example, we can consider a cascade initiated by a ***E_0 = 100 TeV photon.***

Layer $n = 13$ has about $N = 2^{13} \sim 8200$ particles of which $1/3$ are photons of average energy

$$< E > \sim \frac{10^{14} eV}{8200} \sim 12 \;\; GeV.$$

Since $E_{\gamma \to \mu} \sim 0.6 \cdot E_{\gamma}$ this is the last layer where one can produce muons of a few GeV energy relevant to air shower experiments

The ***number of GeV muons in a 100 TeV $\gamma -$shower*** is

$$N_{\gamma \to \mu} = N_{\gamma} \cdot R_{\gamma} \sim \frac{1}{3} \cdot 8200 \cdot 3 \cdot 10^{-3} \cdot 2 \approx 20$$

Factor 2 takes into account the fact that all previous layers contain about the same number of photons of the last layer (Halzen, Zas 1990)

Muons in a 1 PeV γ−shower

For a $E_0 = 1$ *PeV photon* we have

Layer $n = 16$ has about $N = 2^{16} \sim 66000$ particles of which 1/3 are photons of average energy

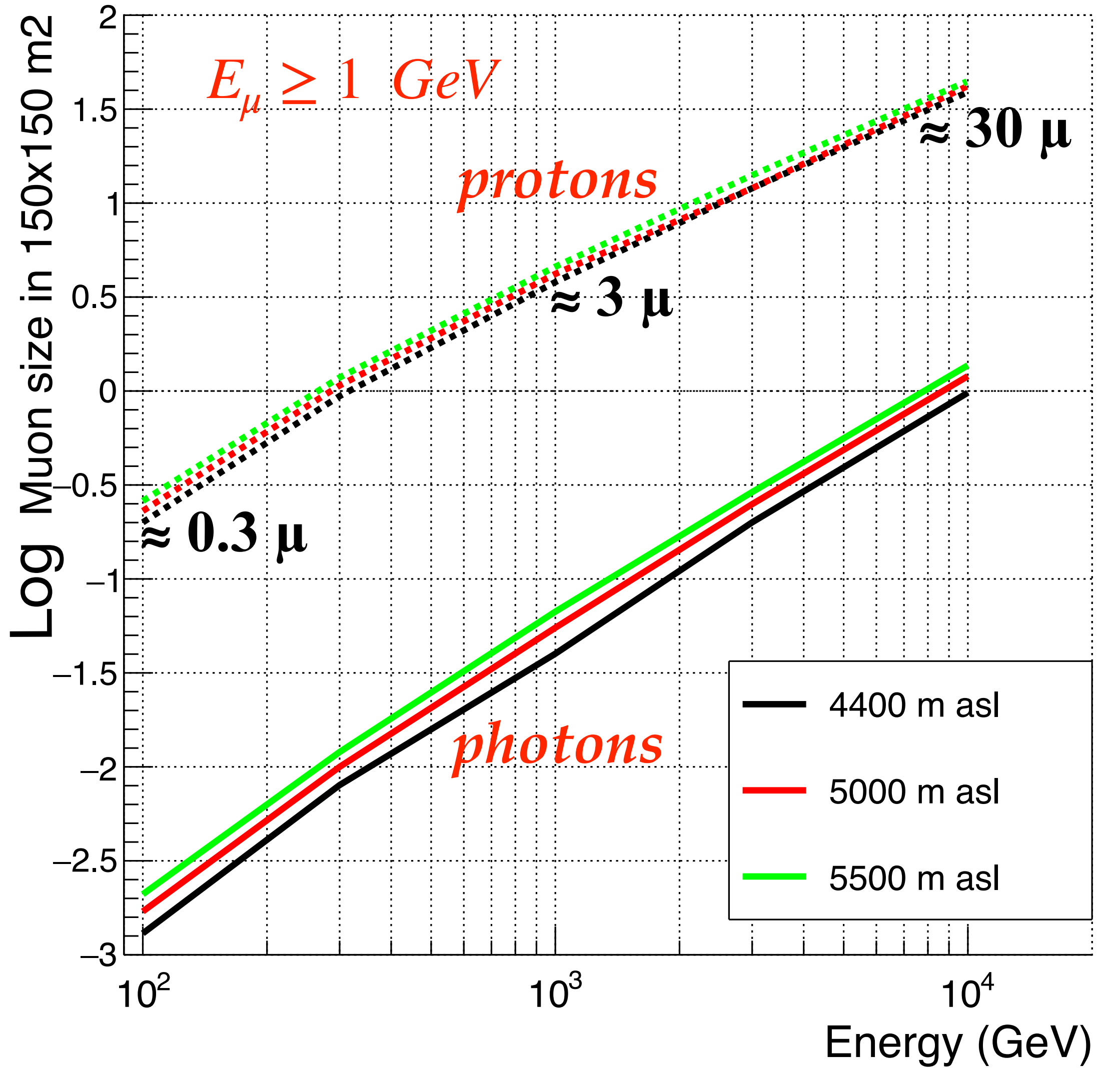
$$< E > \sim \frac{10^{15} eV}{66000} \sim 15 \;\; GeV.$$

The ***number of GeV muons in a 1 PeV γ−shower*** is

$$N_{\gamma \to \mu} = N_\gamma \cdot R_\gamma \sim \frac{1}{3} \cdot 66000 \cdot 3 \cdot 10^{-3} \cdot 2 \approx 130$$

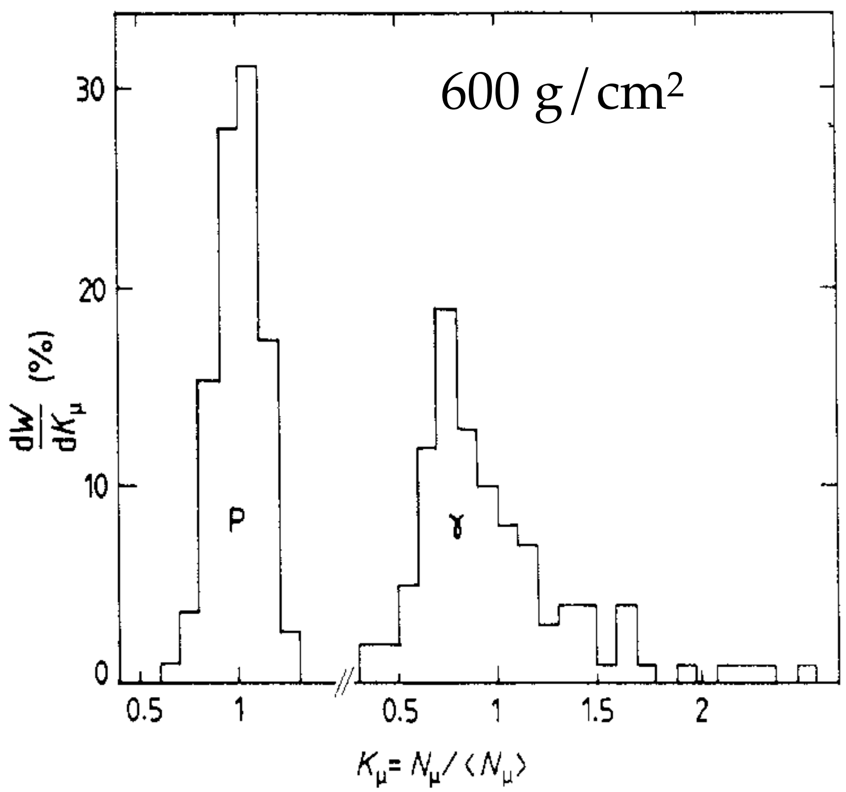
$$N_{p \to \mu} \approx 10^4$$

Consistent with MonteCarlo simulations



Fluctuations

The fluctuations $W(K_\mu)$, $K_\mu = \frac{N_\mu}{< N_\mu >}$ of the muon sizes in showers initiated by primary photons with N_e = constant, are essentially larger $(\sigma(N_{\gamma\to\mu})/ < N_{\gamma\to\mu} > = 0.42)$ than in the proton-showers $(\sigma(N_{p\to\mu})/ < N_{p\to\mu} > = 0.12)$ for the same size and observation level.



The fluctuation is very large because of the competition at each stage of the shower development between the photo-production and pair production cross sections.

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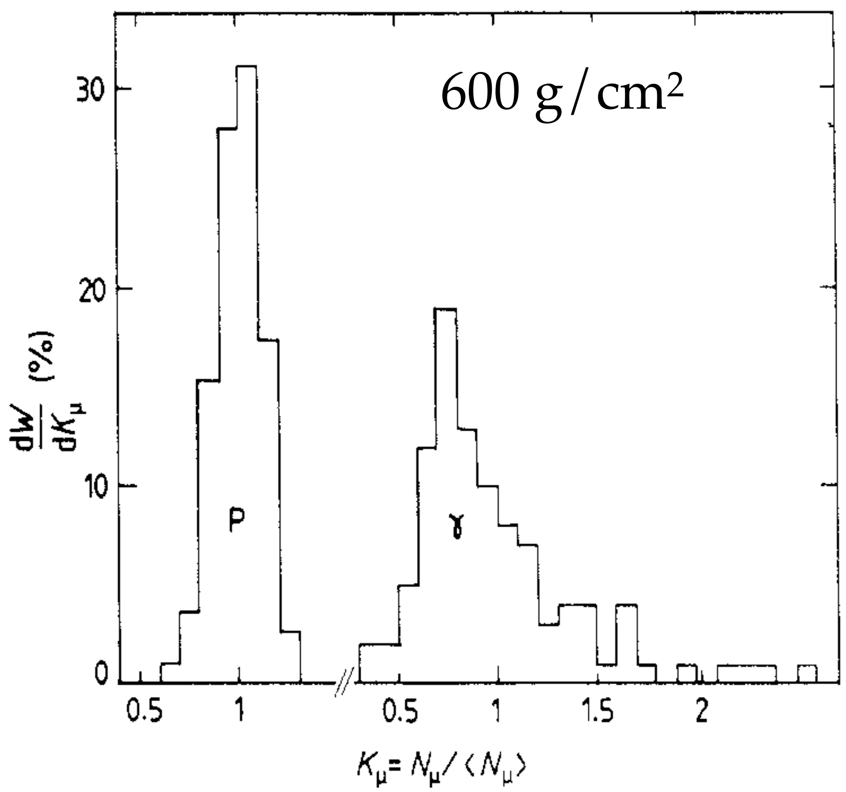
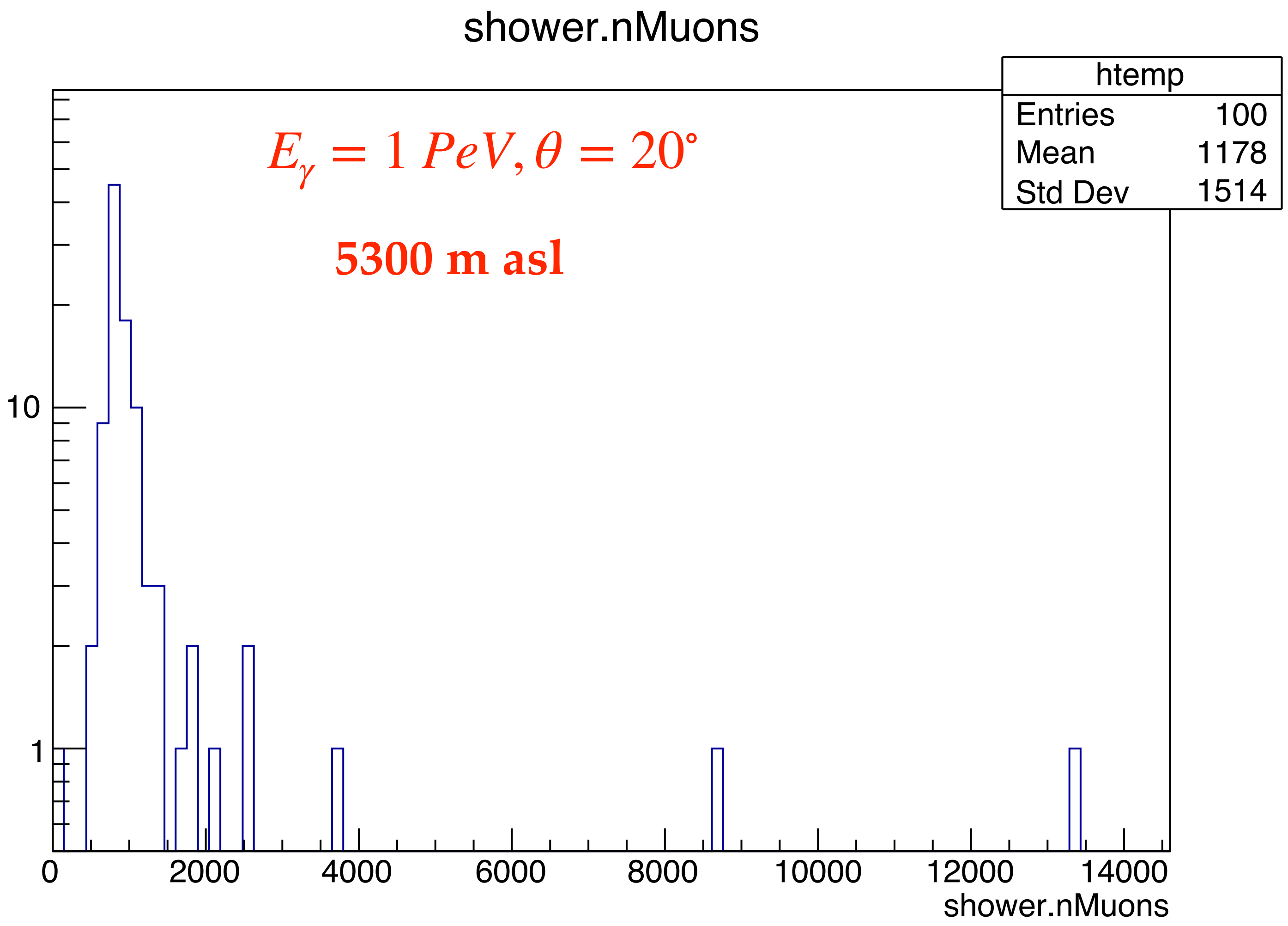


The fluctuation is very large because of the competition at each stage of the shower development between the photo-production and pair production cross sections.
Roughly a fraction R_γ of the showers photo-produce in the early stage of the cascade and hence develop a hadron shower.

The study of fluctuations is crucial in $\gamma-$ray astronomy to evaluate the power of the bkg rejection via "muon poor" technique.

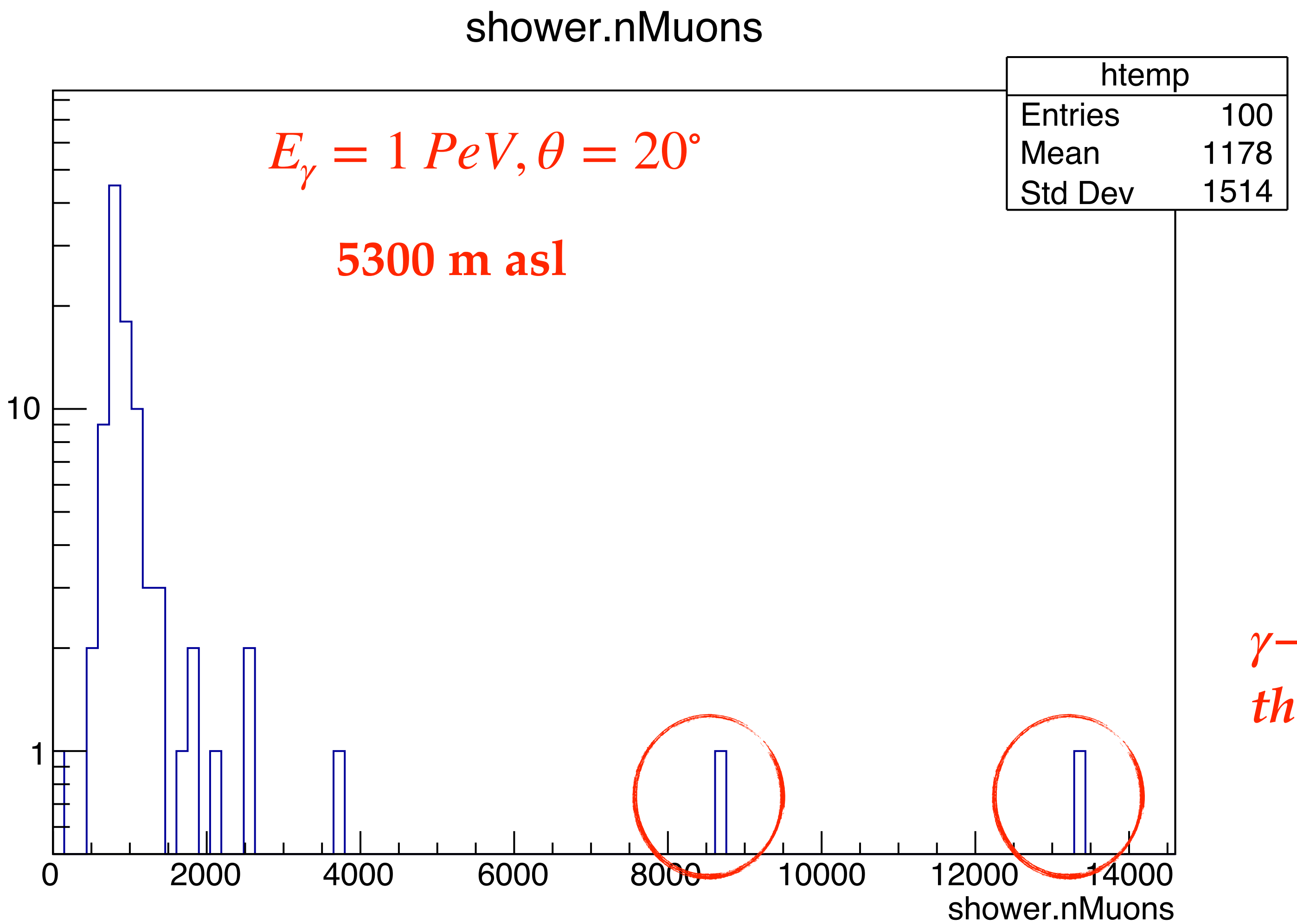
In this technique it is important to know how frequently hadronic showers fluctuate in such a way to have a low muon content as the one resulting from γ-induced events.

Fluctuations and high energy photo-production



Fluctuations in the number of muons in photon-induced events are different from showers induced by charged cosmic rays

Fluctuations and high energy photo-production



Fluctuations in the number of muons in photon-induced events are different from showers induced by charged cosmic rays

$\gamma-$showers photo-produced in the early stage of the cascade and hence developed a hadron shower.

$$N_{p\rightarrow\mu}(1\ PeV) \sim 10^4$$

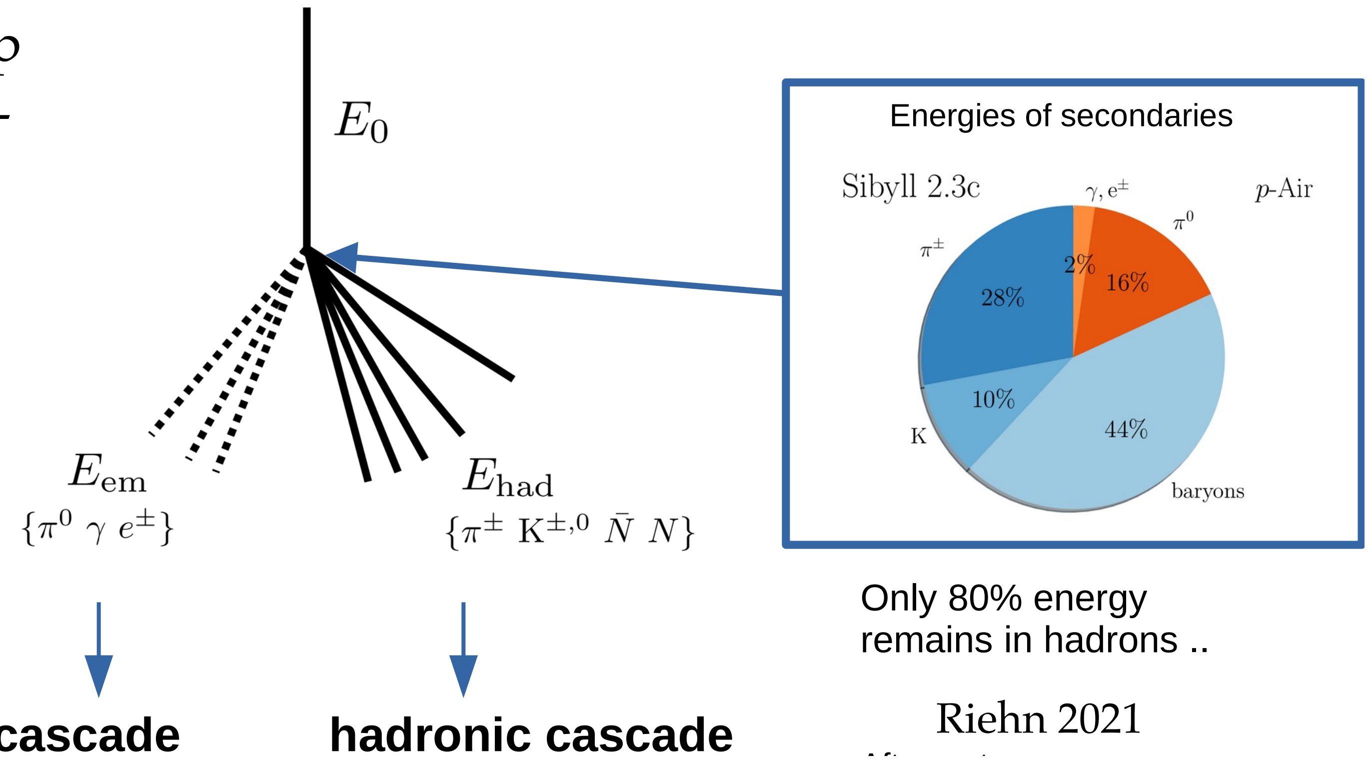
If the first interaction of the primary photon is hadronic (probability $\approx \alpha = 1/137 \sim 10^{-3}$) the shower is ***indistinguishable for a normal proton-induced shower***

These events limit the sensitivity of the 'muon poor' technique
But are important to study characteristics of photo-nuclear interactions at high energy.

High energy photo-production

According to our simulations, at high altitude deep first interactions are the dominant source of muon-poor hadron showers.
At lower altitudes fluctuations towards π^0-rich showers are the main responsible.

The detection of $\gamma-$induced events with large muon content is crucial to study the pion photo-production due to high energy photons.



But *these events are typically rejected by selection cuts based on the muon number* and must be carefully evaluated.

Different criteria are under study to identify and study these showers: muon lateral distribution, muon time profile, etc.

On general grounds, the lateral distribution of photo-produced muons is expected flatter than that of normal muons because they originate mainly from low-energy photons in e.m. cascades, whereas normal muons originate in nuclear cascades.

The energy of secondary photon can be reconstructed by the photo-produced muon number

Measurement of cross sections

Table 1. Overview of the air shower based analyses of the proton-air cross section. The energy range of the analysis is quoted, as well as the number of events used for the analysis N_{evt}, the experimental resolution of X_{max}, the observed exponential attenuation of air showers in the atmosphere, and the derived proton-air cross section with statistical uncertainties.

Experiment	lg E/eV	N_{evt}	$\sigma_{res}(X_{max})$/gcm^{-2}	Λ_{obs}/gcm^{-2}	σ(p − air)/mb
Fly's Eye	17.7	≈500	70	73. ± 9	530 ± 66
AGASA	16.2-17.6	553065	n/a	n/a	480–550
HiRes	18.5	1348	≈ 27	63.2 ± 4.7	460 ± 49
EAS-TOP	15.3	O(10^7)	n/a	n/a	338 ± 41
ARGO-YBJ	12.6-13.9	O(10^8)	n/a	n/a	272–318
Yakutsk*	16.5-18.5	1783	80-90	n/a	470–550
Auger	18.24	3082	< 25	55.8 ± 2.8	505 ± 23

Ulrich, ISVHECRi 2012

LHAASO after 3 years of data taking detected about 10^4 photons above 100 TeV → a measurement of photo-production cross section is possible to setting up the method and to cross check the background selection in gamma-ray astronomy.

Conclusions

In the last years shower arrays located at extreme altitude (LHAASO but also HAWC and Tibet ASγ) are detecting a number of photons above 100 TeV in a background-free regime.

Therefore, ***for the first time we have a pure sample of showers produced by high energy photons***

LHAASO in particolar is observing about 4000 photons per year above 100 TeV and about 20 above 1 PeV

This fact offer for the first time the possibility to study the characteristics of photon induced showers and to compare with MonteCarlo simulations.

In particular this allow to measure for the first time the ***pion photo-production cross section even at energies marginally or not investigated yet at accelerators***.

These studies are very important to clarify some issues in the photon-hadron interactions.

In the near future, the ***SWGO*** (and also ***ALPACA***) experiment in the Southern hemisphere is expected to detect a larger sample of PeVatrons thus extending this study at higher energies.

Studies are under way to improve the selection of photons and to investigate the sensitivity of present and future shower arrays.