SWGO
The Southern Wide-field Gamma-ray Observatory

# The $LCm$ variable

## Gamma/hadron discrimination and more in ground-based gamma-ray observatories


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Fourth Joint Workshop IGFAE / LIP - April $13^{th}$-$14^{th}$, 2023

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

LIP

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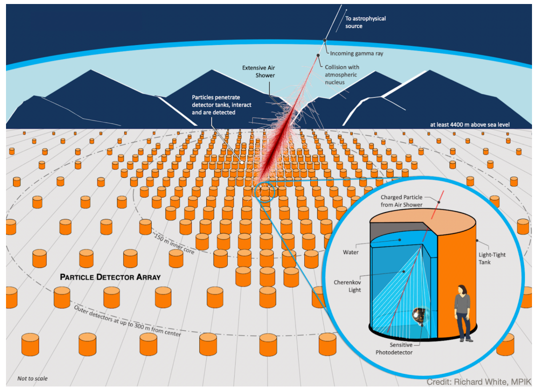
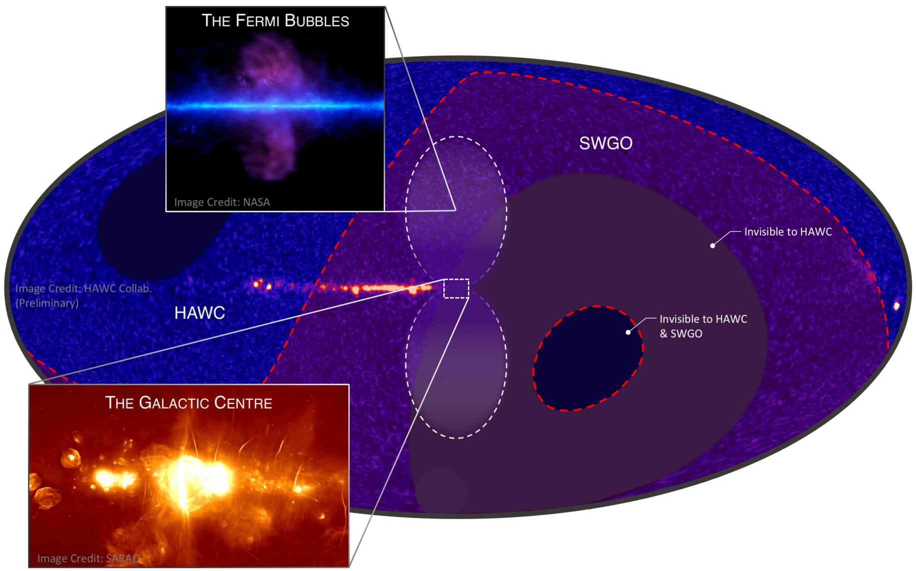
IDPASC

# The Southern Wide-field Gamma-ray Observatory




- 14-countries collaboration.
- Next generation gamma-ray observatory currently in R&D phase.
- To be built at high altitude in the southern hemisphere (→ Andes).
- Large ground-array (likely) based on Water Cherenkov Detectors.
- Able to observe the galactic center.




**But huge background to be dealt with!**

- Gamma rays buried in hadronic background.
- Excellent gamma/hadron discrimination capabilities needed.
- Muon counting → commonly used strategy, but expensive and with high environmental impact.
- Alternative: studying the fluctuations in the shower footprints.

# *LCm*-related papers

LIP's group heavily invested in *LCm*'s many aspects:

- Definition
- Gamma/hadron discrimination capabilities
- Applicability to realistic scenarios
- Dependence on hadronic models in MC simulations
- Muon content reconstruction
- Mass composition
- ...

Journal of Cosmology and Astroparticle Physics

PAPER

Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground

R. Conceição[1,2], L. Gibilisco[1,2], M. Pimenta[1,2] and B. Tomé[1,2]

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Journal of Cosmology and Astroparticle Physics, Volume 2022, October 2022
Citation R. Conceição *et al* JCAP10(2022)086
DOI 10.1088/1475-7516/2022/10/086

**Gamma/hadron discrimination in arrays of WCDs with different number of PMTs and in arrays of Scintillators**

R. Conceição [a,b], P. Costa [a,b], L. Gibilisco [a,b], M. Pimenta [a,b], B. Tomé [a,b]
[a] LIP, Portugal
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Dependence of *LCm* on hadronic models for primary energies around 100 TeV

R. Conceição[1,2], A. Diz Penas[1], L. Gibilisco[1,2], M. Pimenta[1,2], B. Tomé[1,2]
[1] LIP, Lisbon, Portugal
[2] IST,Ulisboa, Lisbon, Portugal

**Azimuthal fluctuations and number of muons at the ground in muon-depleted proton air showers at PeV energies**

A. Bakalová,[1] R. Conceição,[2,3] L. Gibilisco,[2,3] V. Novotný,[1,4] M. Pimenta,[2,3] B. Tomé,[2,3] and J. Vícha[1]
[1] *Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
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[3] *Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*
[4] *Charles University, Faculty of Mathematics and Physics, Institute of Particle and Nuclear Physics, Prague, Czech Republic*

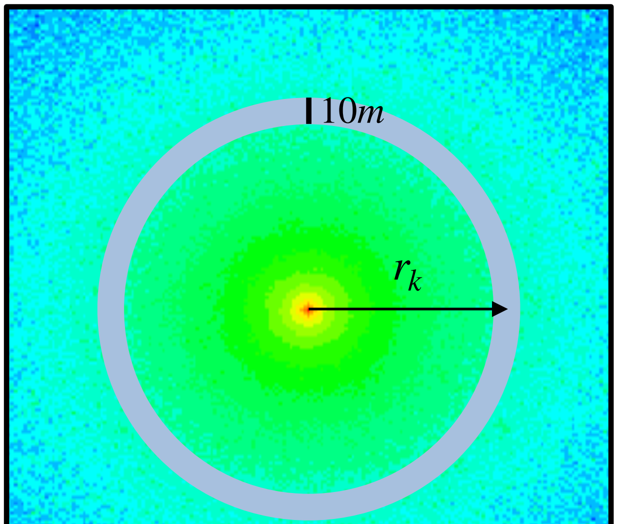
(Dated: April 7, 2023)

- Three SWGO internal notes
- Three articles (one published on JCAP, two submitted to EPJC and PRL)
- More yet to come

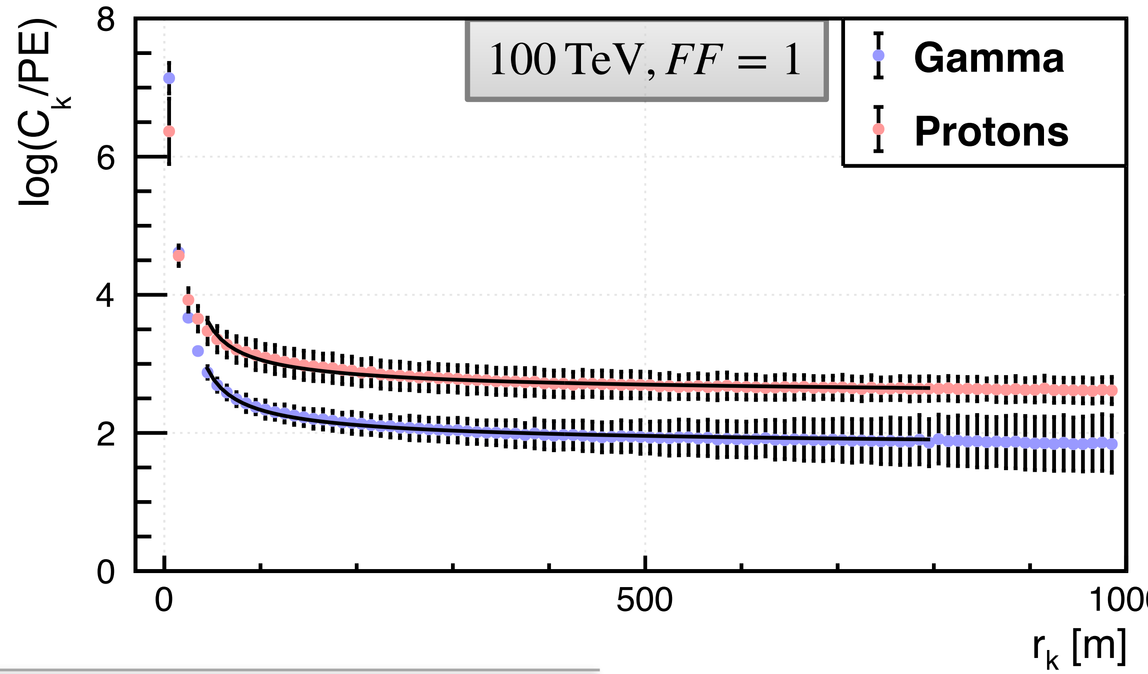
# The $C_k$ variable

$$C_k = \frac{2}{n_k(n_k-1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=i+1}^{n_k} (S_{ik} - S_{jk})^2$$

- $C_k$ is sensitive to the azimuthal fluctuations of the shower footprint at the ground!




Ring with $n_k$ stations and mean signal $\langle S_k \rangle$





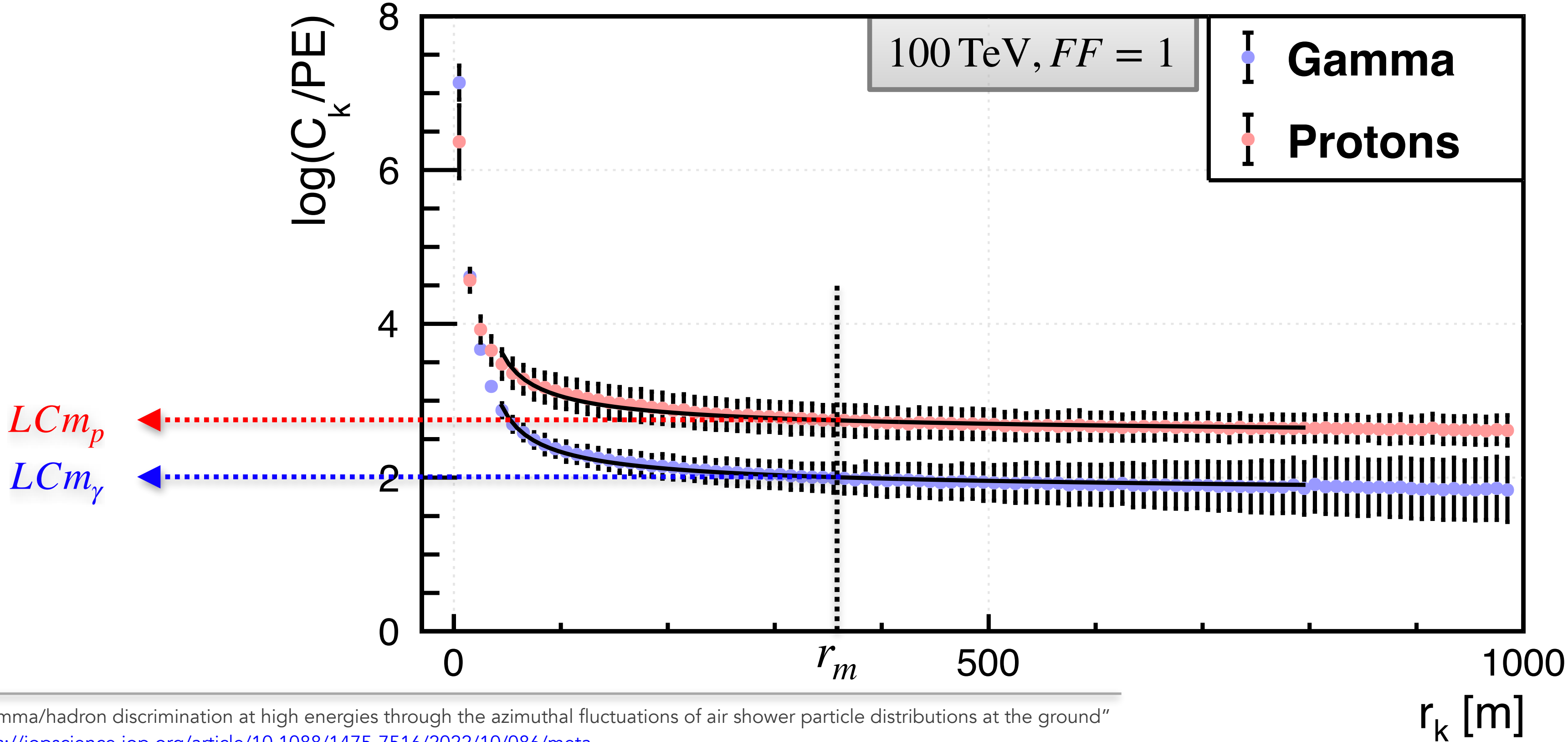
"Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground"
https://iopscience.iop.org/article/10.1088/1475-7516/2022/10/086/meta

# The $LCm$ variable

$$\log(C_k) = a + \frac{b}{\log\left(\frac{r_k}{40\,\mathrm{m}}\right) + 1}$$

$$LCm \equiv \log\left(C_k\right)\Big|_{r_k = r_m}$$

$$r_m = 360m$$

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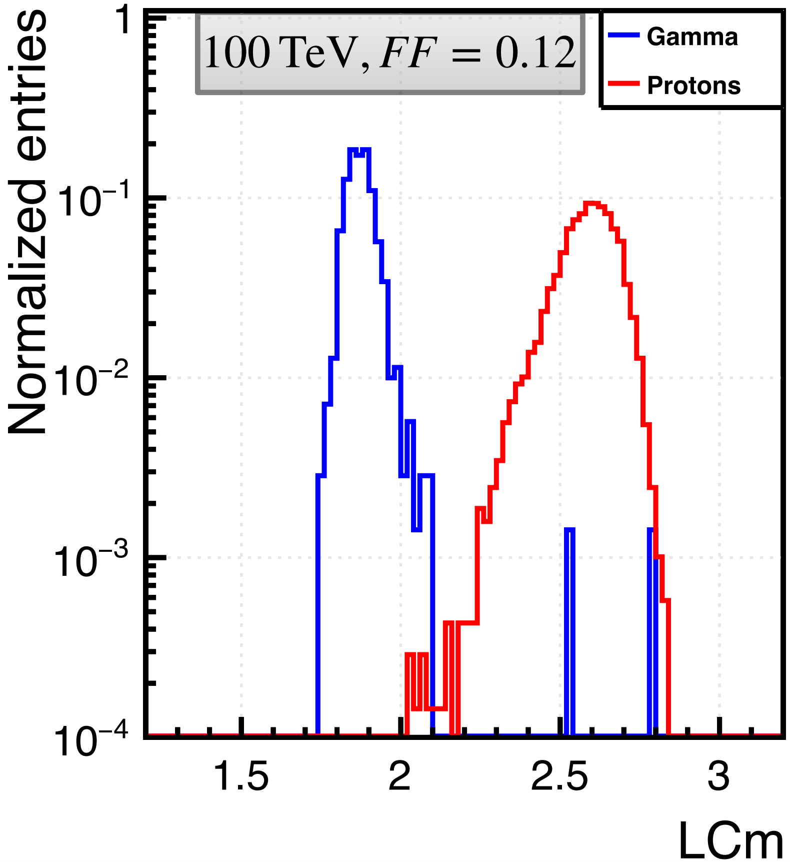
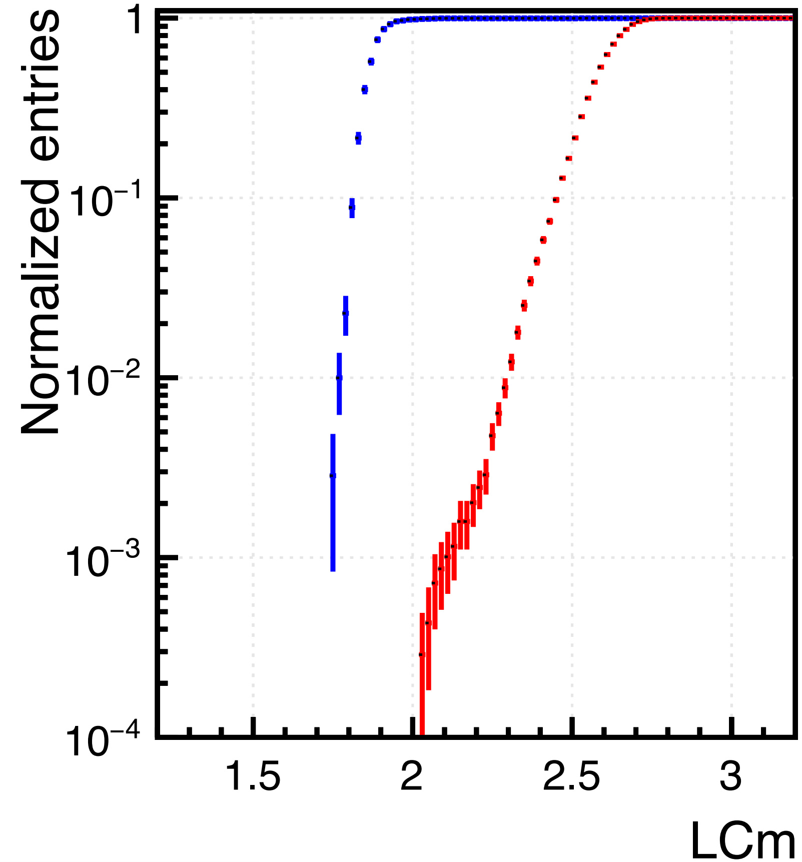
# The $LCm$ variable




"Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground"
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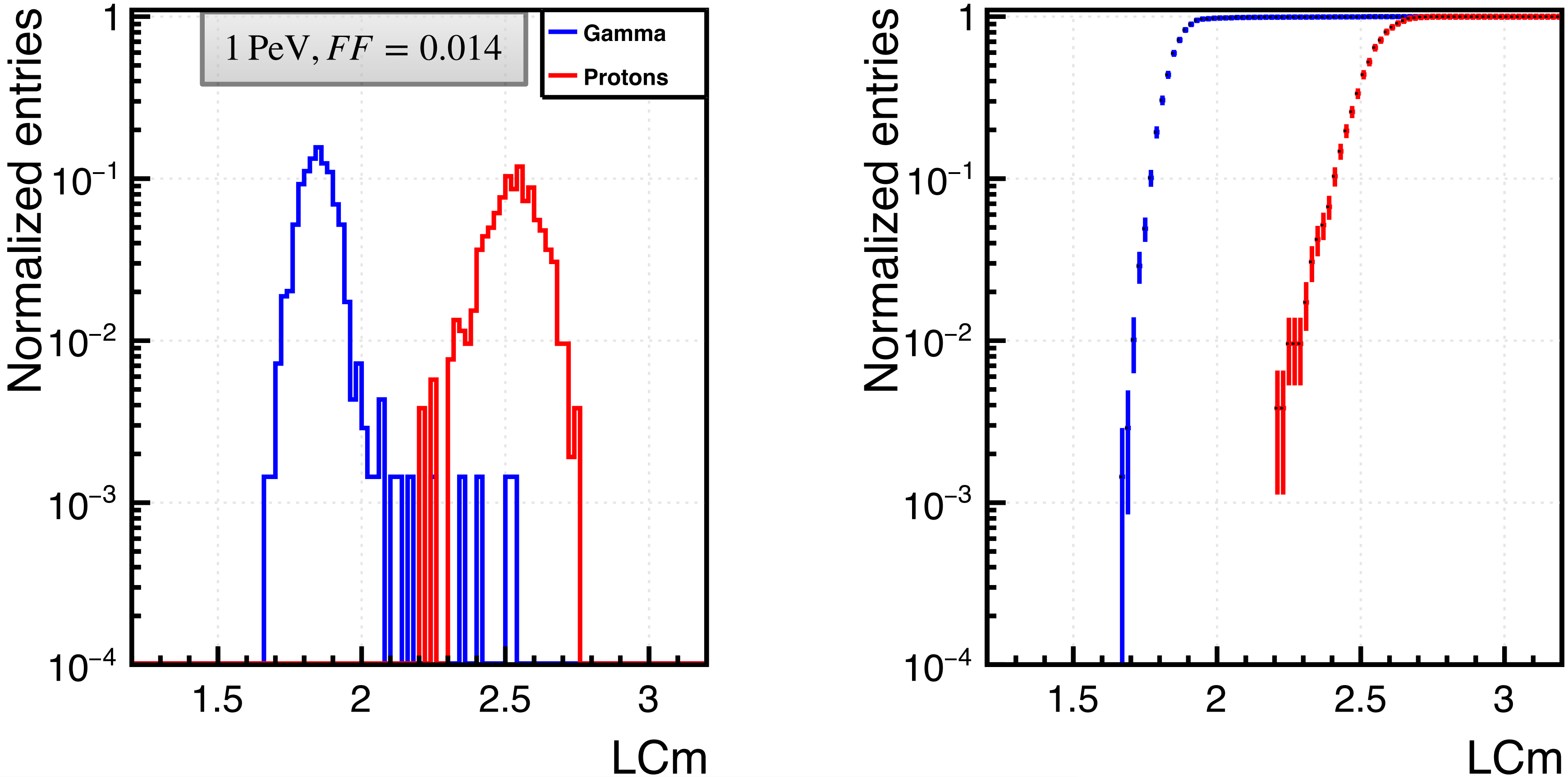
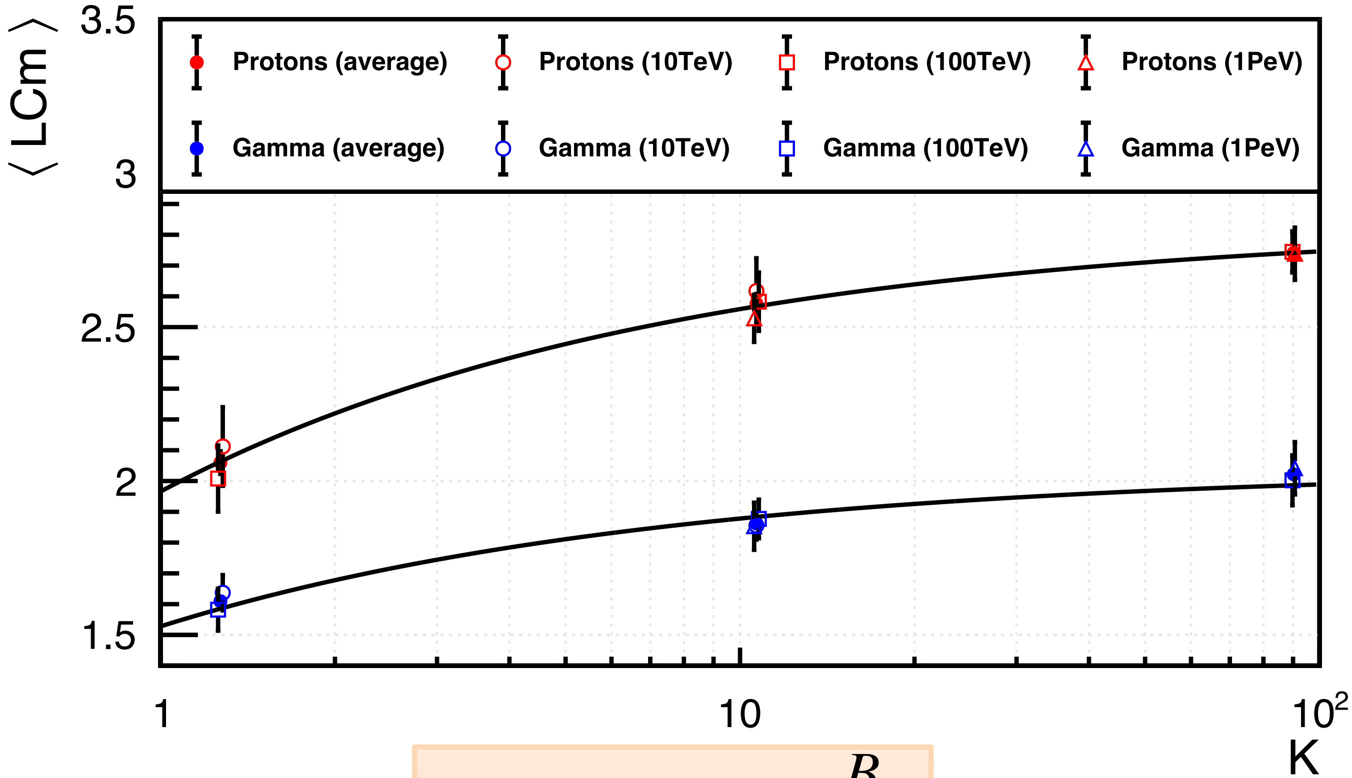
# The *LCm* variable




"Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground"
https://iopscience.iop.org/article/10.1088/1475-7516/2022/10/086/meta

# *LCm* scaling with the *K* factor




$$K = E^{\beta} \times FF$$

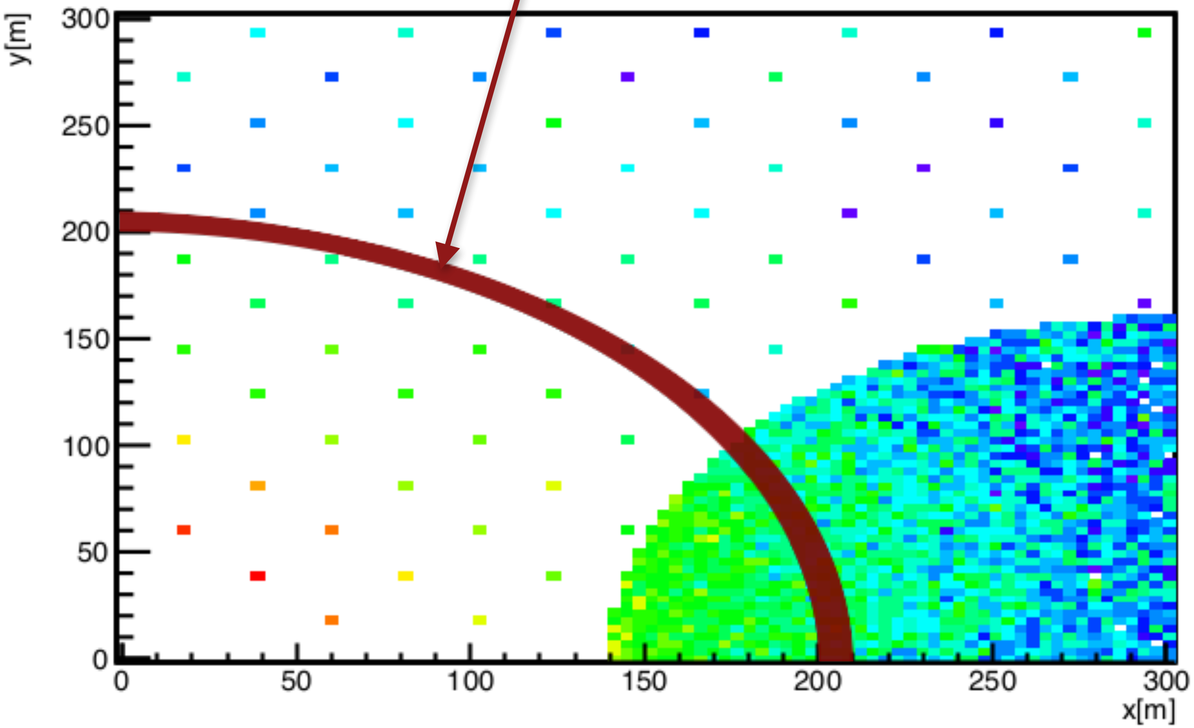
- $E$: simulated energy of the gamma showers [TeV].
- $\beta = 0.925$ - index of power dependence of mean number of muons at the ground from $E$.
- $FF$: fill factor $\in ]0,1]$.

$$LCm_i(K) \sim A_i + \frac{B_i}{\sqrt{K}}$$

"Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground"
https://iopscience.iop.org/article/10.1088/1475-7516/2022/10/086/meta

# Multi-fill-factor arrays

$$C_k = \frac{2}{n_k(n_k-1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=i+1}^{n_k} (S_{ik} - S_{jk})^2$$

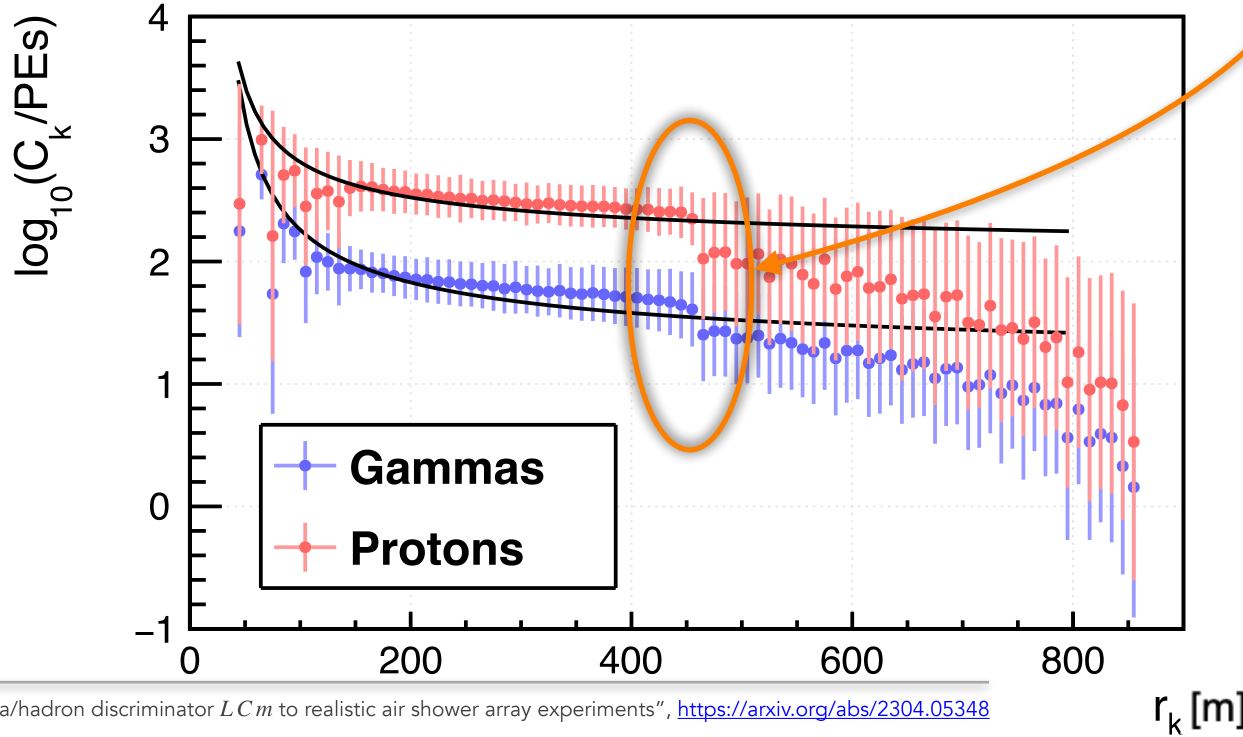



- $FF$ = fraction of instrumented area
- Ground arrays usually have regions with different fill factors
- Denser regions → low energies
- Sparser regions → high energies

# Multi-fill-factor arrays

- 1 PeV showers
- Array centered in $(300, 0)\,\mathrm{m}$
- Central compact array with $160\,\mathrm{m}$ radius and $FF = 1$
- Sparse array with $560\,\mathrm{m}$ radius and $FF = 0.014$

Corrections needed!

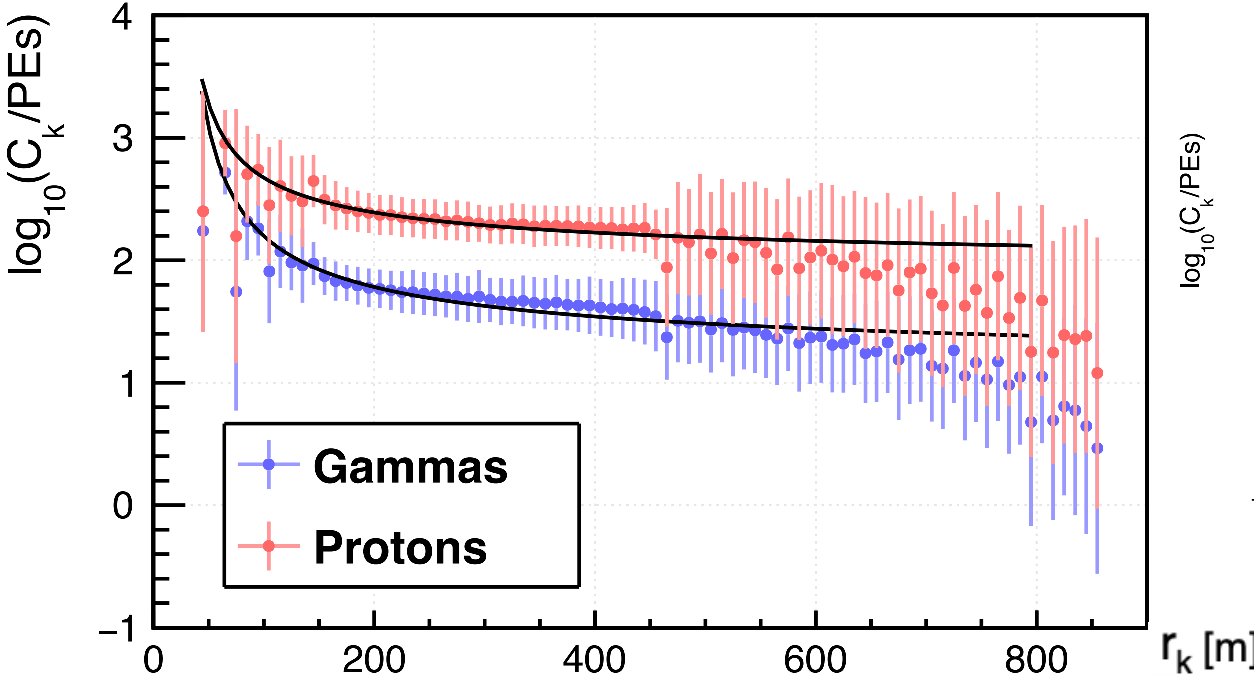



"Applications of the gamma/hadron discriminator $LCm$ to realistic air shower array experiments", https://arxiv.org/abs/2304.05348

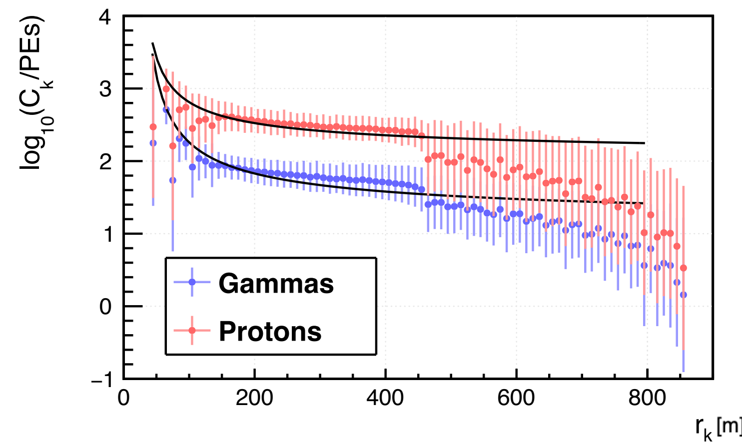
# Multi-fill factor arrays

- Each ring has its own effective fill factor $\rightarrow FF_k = \frac{n_k}{n_{k_1}}$
- $LCm$ scales with the $K$ factor as: $LCm(K) \equiv f(K) \sim A + \frac{B}{\sqrt{K}}$
- Now the $K$ factor is: $K_k = E^{\beta} \times FF_k$

$$C_{k_{cor}} = C_k \cdot 10^{(f_p(K_{ref}) - f_p(K_k))}$$



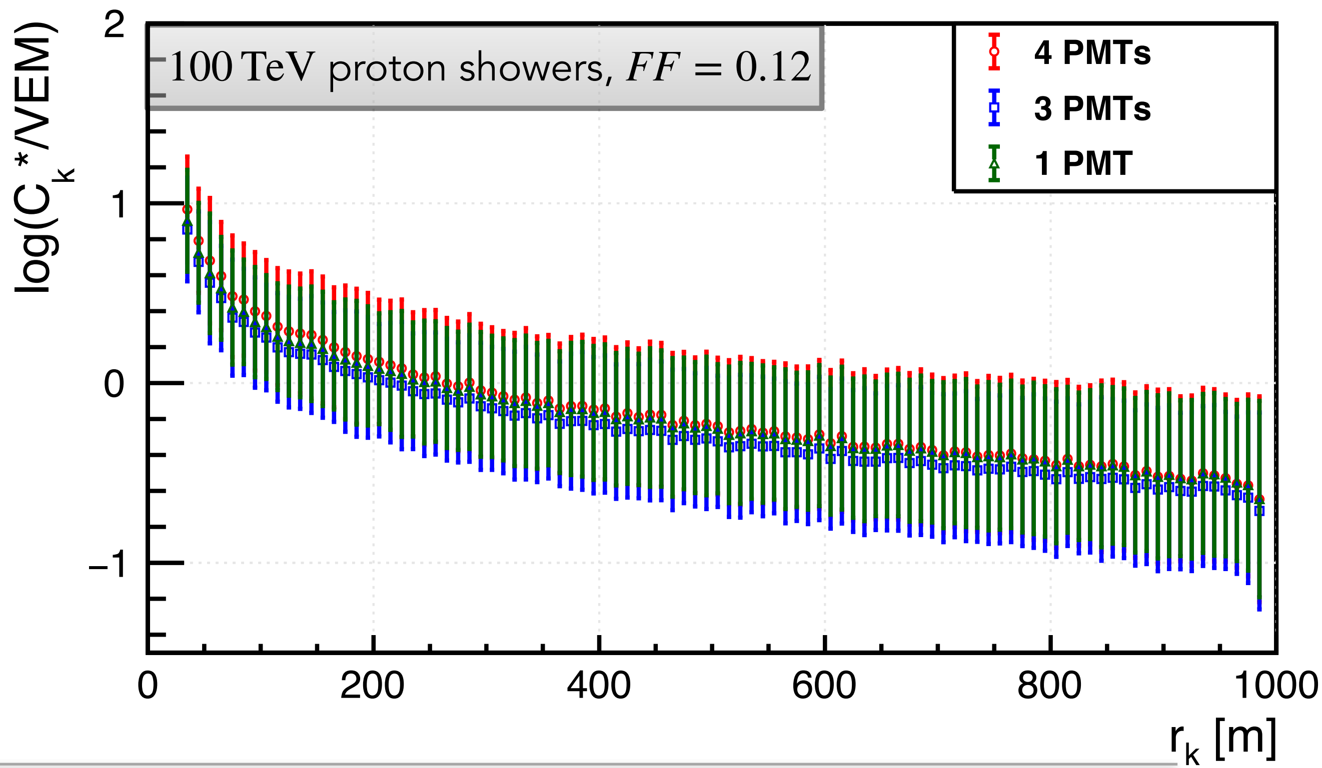

Without correction




"Applications of the gamma/hadron discriminator $LCm$ to realistic air shower array experiments", https://arxiv.org/abs/2304.05348

# $C_k$ in WCDs with different numbers of PMTs

$$C_k^* = \frac{C_k}{Q_{VEM}} \rightarrow LCm^* = \frac{LCm}{Q_{VEM}}$$

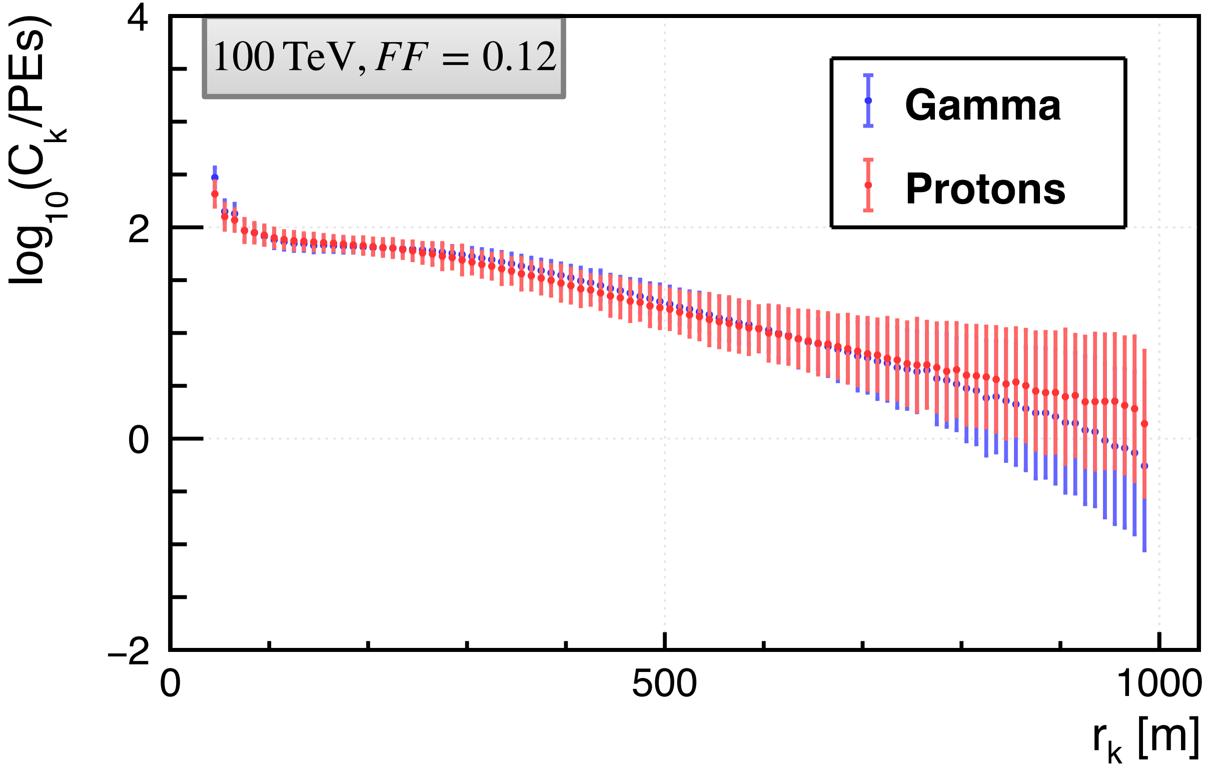



- $C_k^*$ is insensitive to the number of PMTs in a WCD!

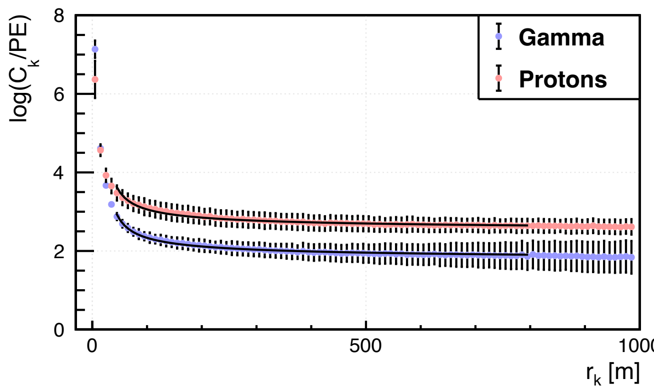
"Applications of the gamma/hadron discriminator $LCm$ to realistic air shower array experiments", https://arxiv.org/abs/2304.05348

# $LCm$ in scintillator arrays

Auger-like Scintillator Surface Detector



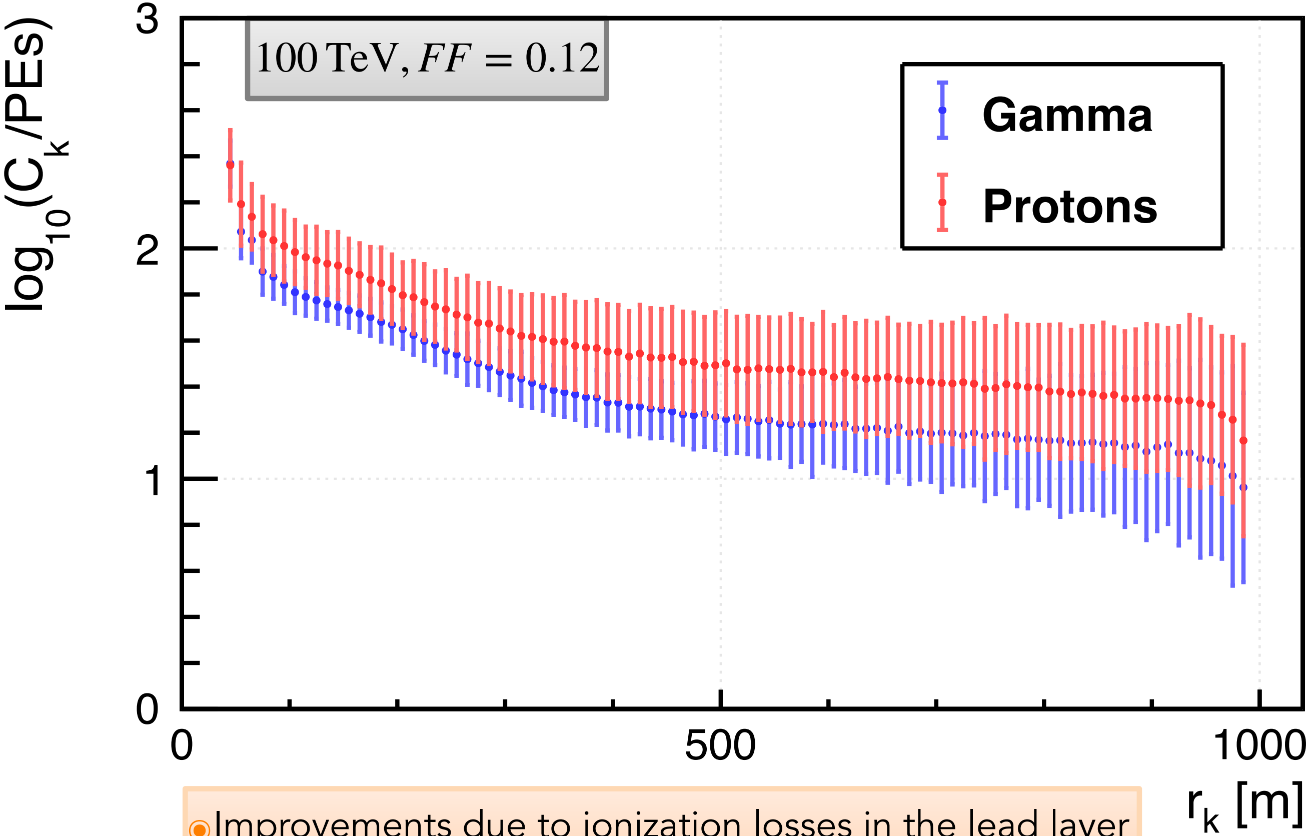

Mercedes WCD



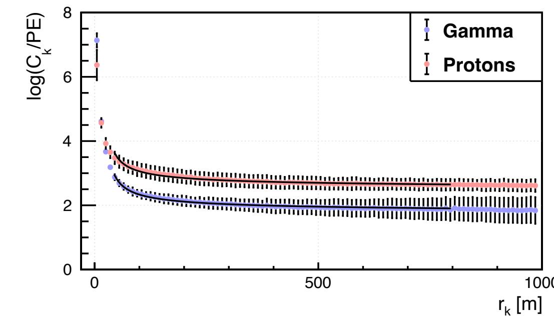

- Scintillators are insensitive to the shower's calorimetry → not good for g/h discrimination with $LCm$!

# $LCm$ in scintillator arrays

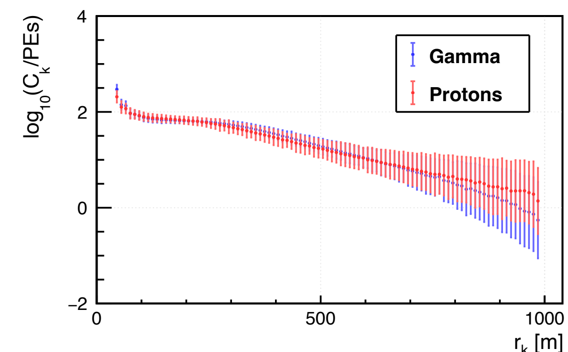
Scintillators shielded with $1X_0$-thick lead layer




Mercedes WCD



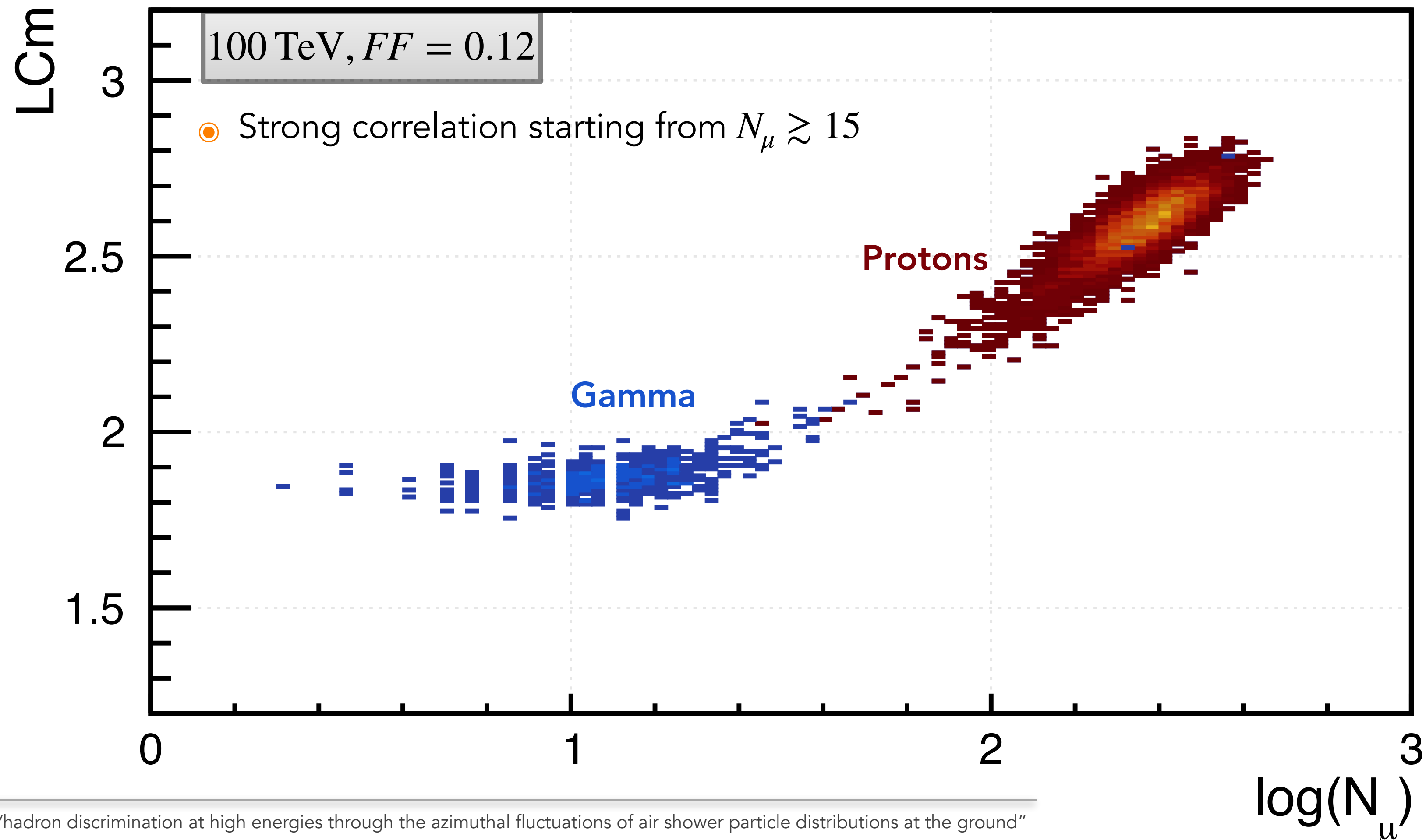

Unshielded scintillators




- Improvements due to ionization losses in the lead layer

"Applications of the gamma/hadron discriminator $LCm$ to realistic air shower array experiments", arXiv link

# $LCm$ vs $N_\mu$




“Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground”
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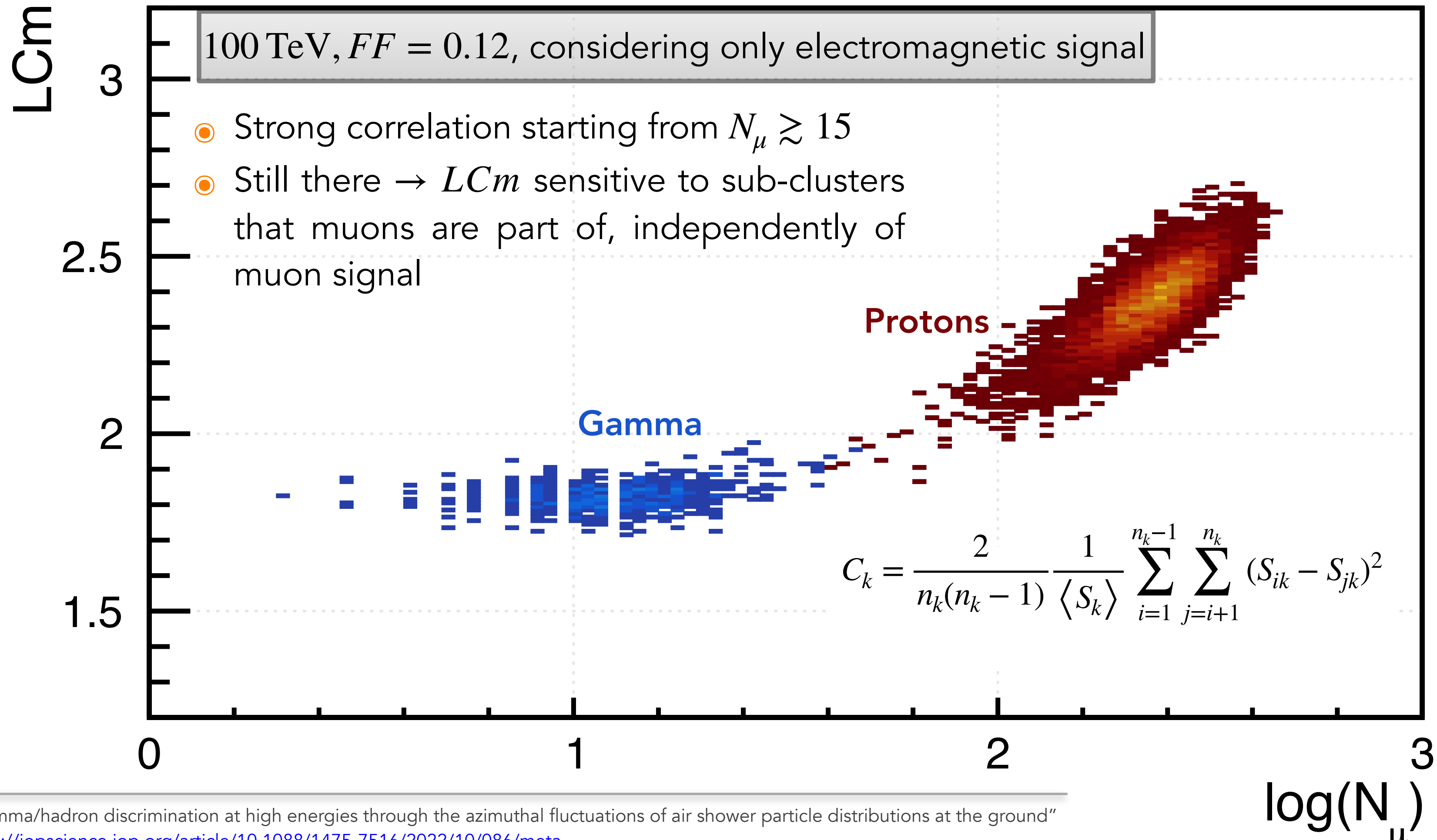
# $LCm$ vs $N_\mu$ - E.M. signal only



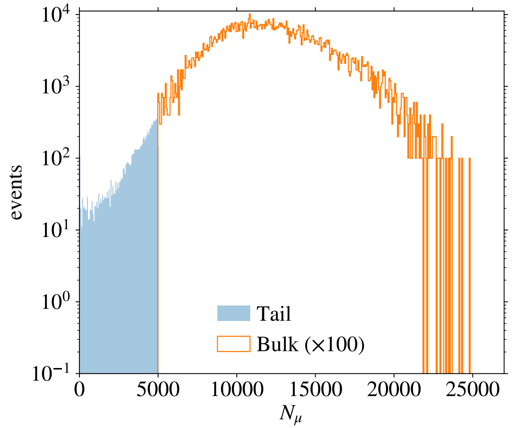

- Strong correlation starting from $N_\mu \gtrsim 15$
- Still there → $LCm$ sensitive to sub-clusters that muons are part of, independently of muon signal

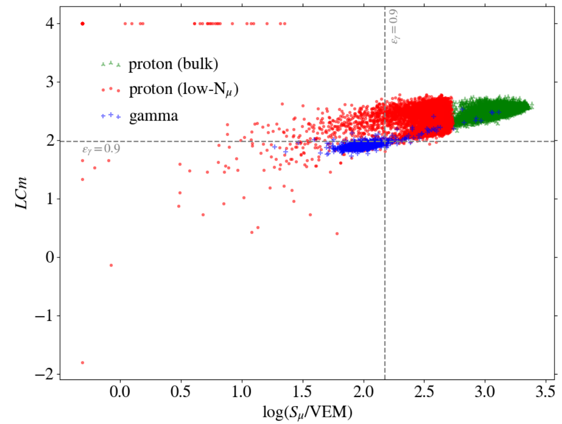
$$C_k = \frac{2}{n_k(n_k-1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=i+1}^{n_k} (S_{ik} - S_{jk})^2$$

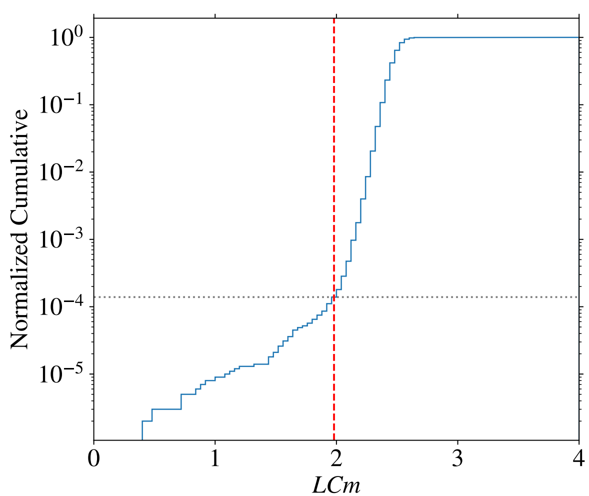
"Gamma/hadron discrimination at high energies through the azimuthal fluctuations of air shower particle distributions at the ground"
https://iopscience.iop.org/article/10.1088/1475-7516/2022/10/086/meta

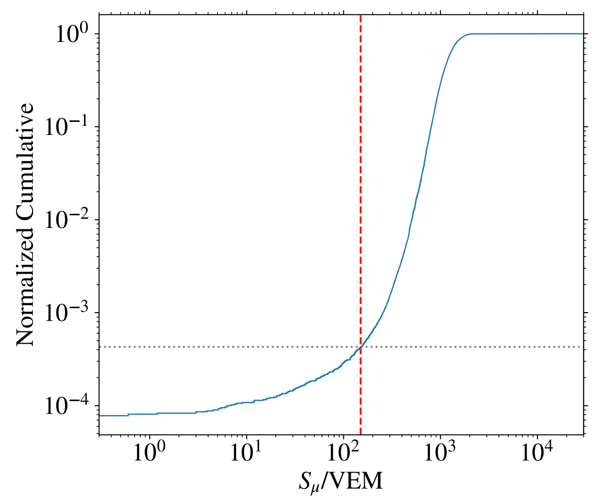
# Gamma/hadron separation in muon-depleted showers

with A. Bakalová, V. Novotny and J. Vícha




- $10^6$ 1 PeV - 2 PeV proton showers
- Analysis of bottom 1 % showers in $N_\mu$ (muon-depleted showers), compared with small gamma sample (1.6 PeV)
- Lines defined for $\epsilon_\gamma = 0.9$
- For $FF \simeq 12\,\%$, $LCm$ performs a factor of 3 better than $N_\mu$, for $FF \simeq 3\,\%$, 50 % better

"Azimuthal fluctuations and number of muons at the ground in muon-depleted proton air showers at PeV energies", https://arxiv.org/abs/2304.02988

# Conclusions

Introduced $C_k$ and $LCm$ discriminators sensitive to the azimuthal fluctuations of the shower footprints at the ground.

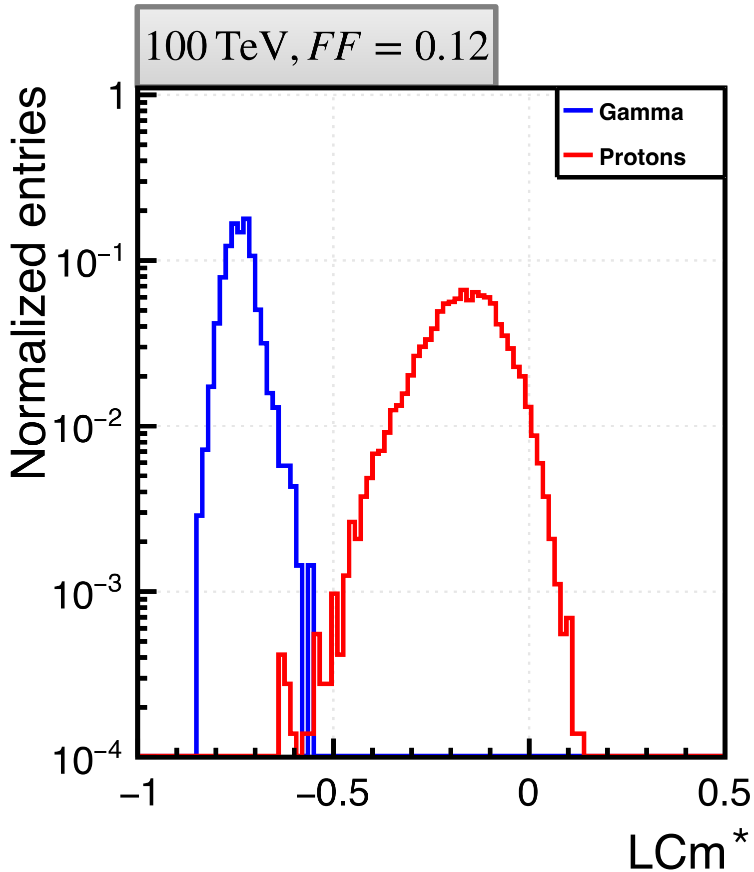
Can be generalized to deal with realistic array configurations (variable $FF$, different detectors…).

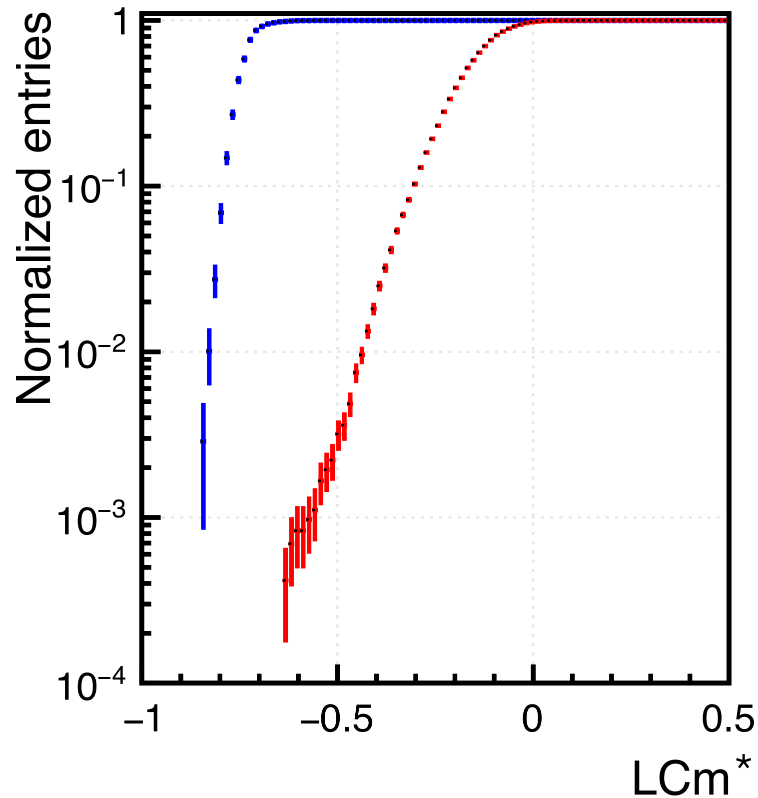
Rejection power of $10^{-4}$ at $\mathrm{PeV}$ energies → better discrimination than $N_\mu$!

More work to come: $N_\mu$ reconstruction, mass composition…

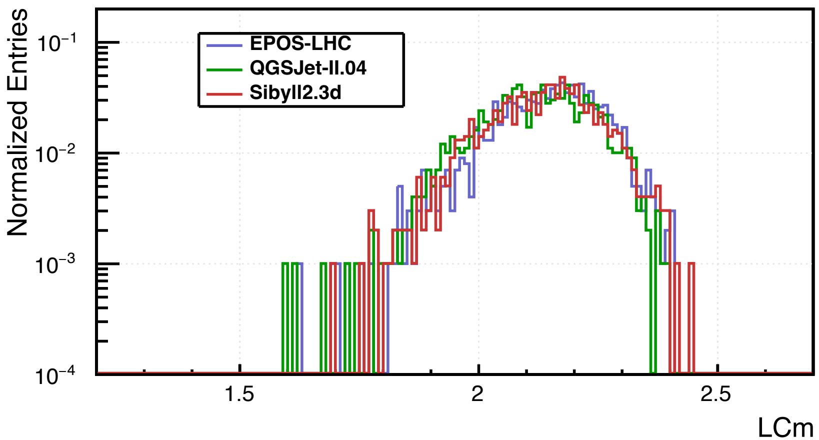
# Backup

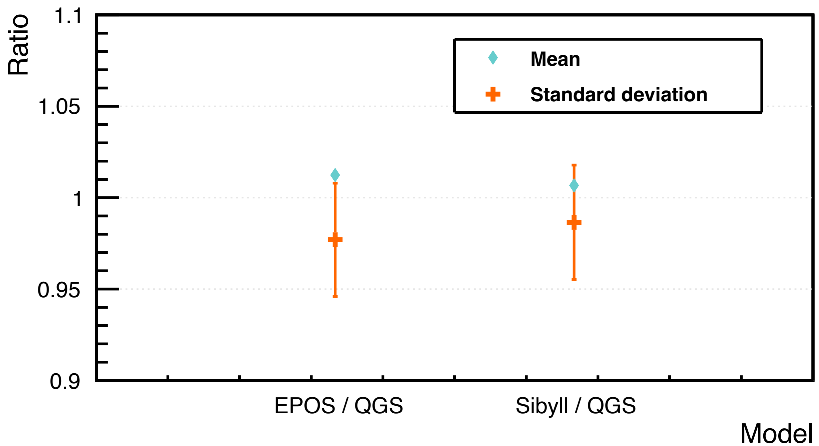
# $LCm$ for 1 PMT stations



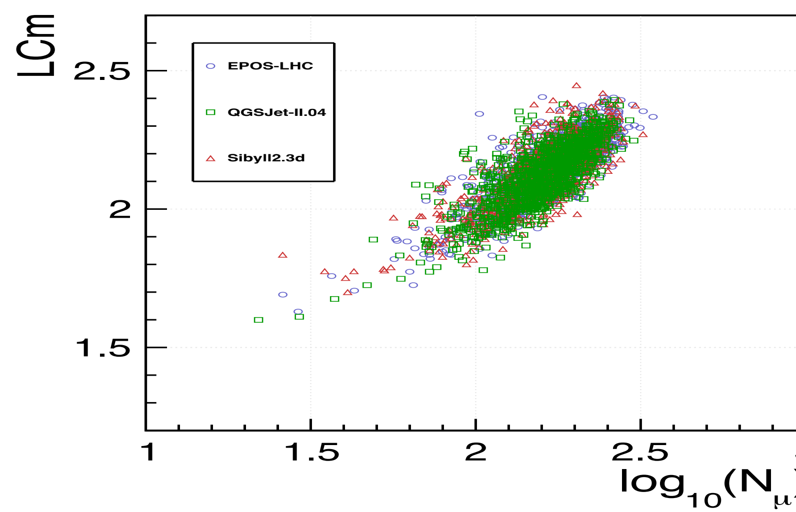



# $LCm$ and hadronic interaction models



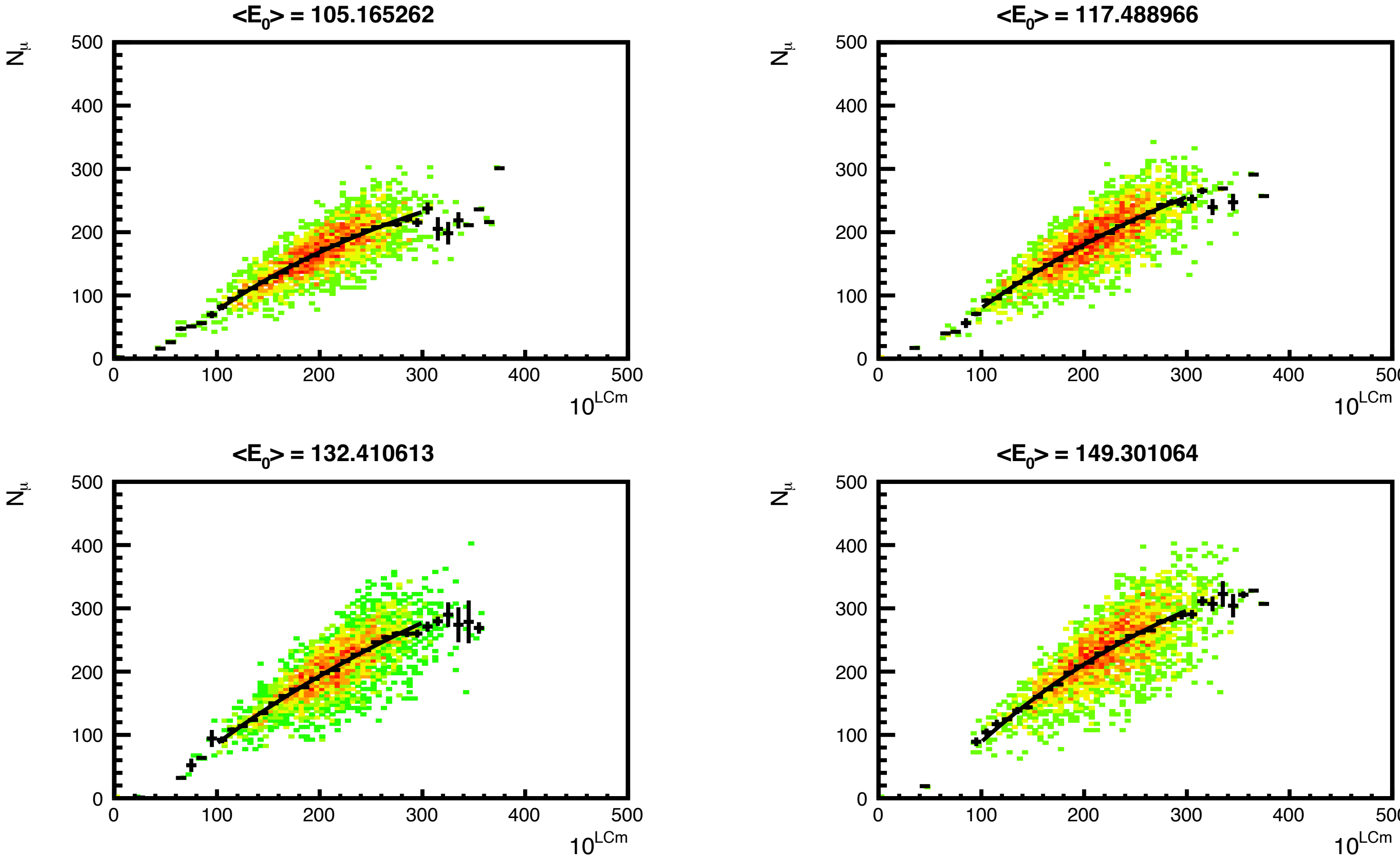




- $LCm$ computation performed on Monte Carlo data obtained with different high-energy hadronic interaction models
- Tested models: EPOS-LHC, QGSJet-II.04 and Sibyll2.3d
- $LCm$ distributions essentially identical for all the models

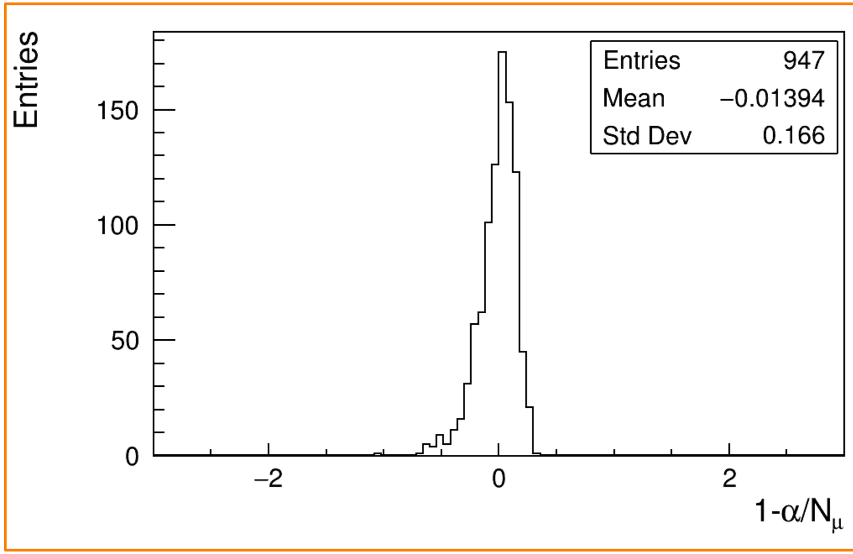


# Reconstruction of $N_\mu$ with $LCm$

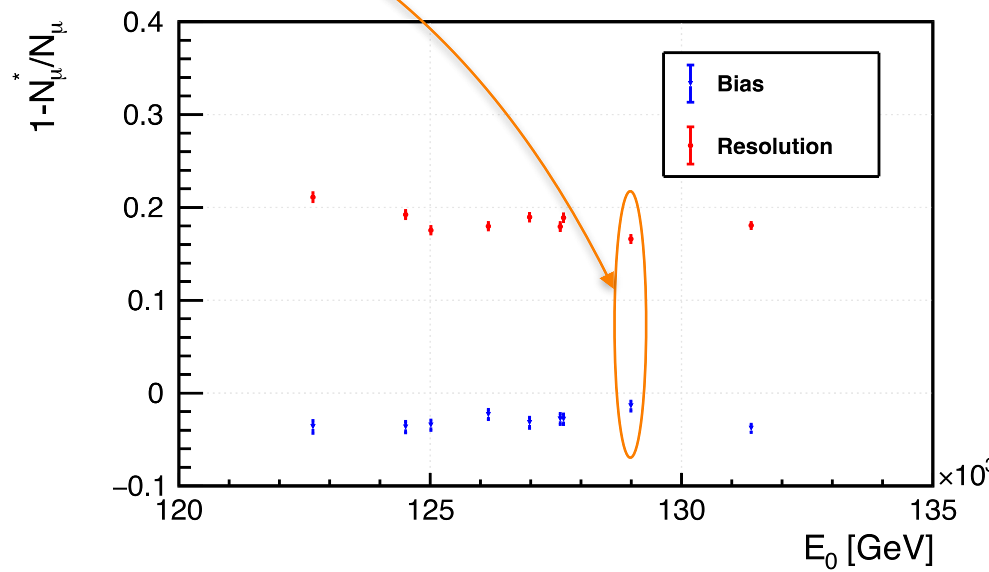
$$N_\mu = a + b\left(1 - e^{-c10^{LCm}}\right)$$



# Bias and resolution

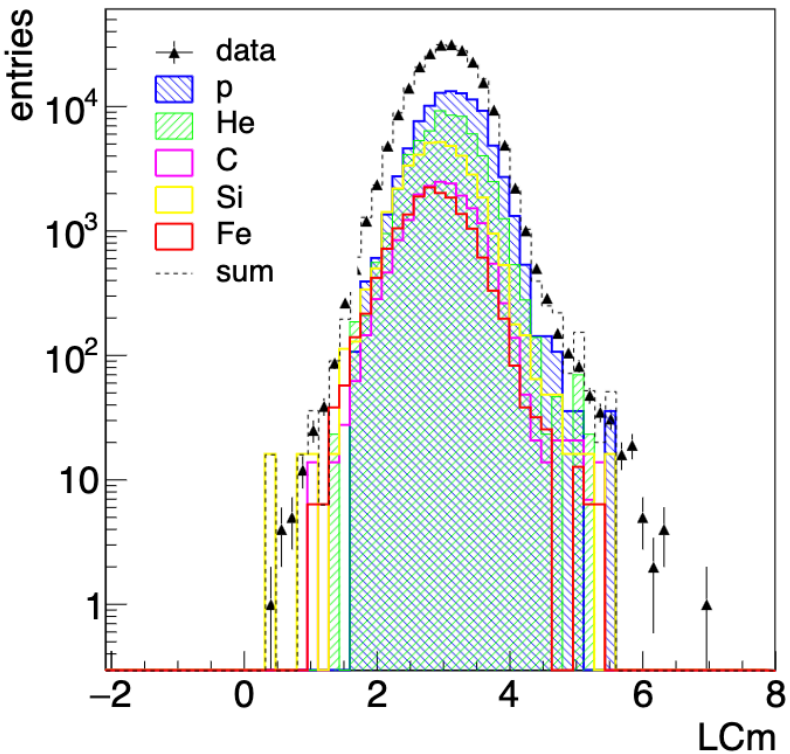


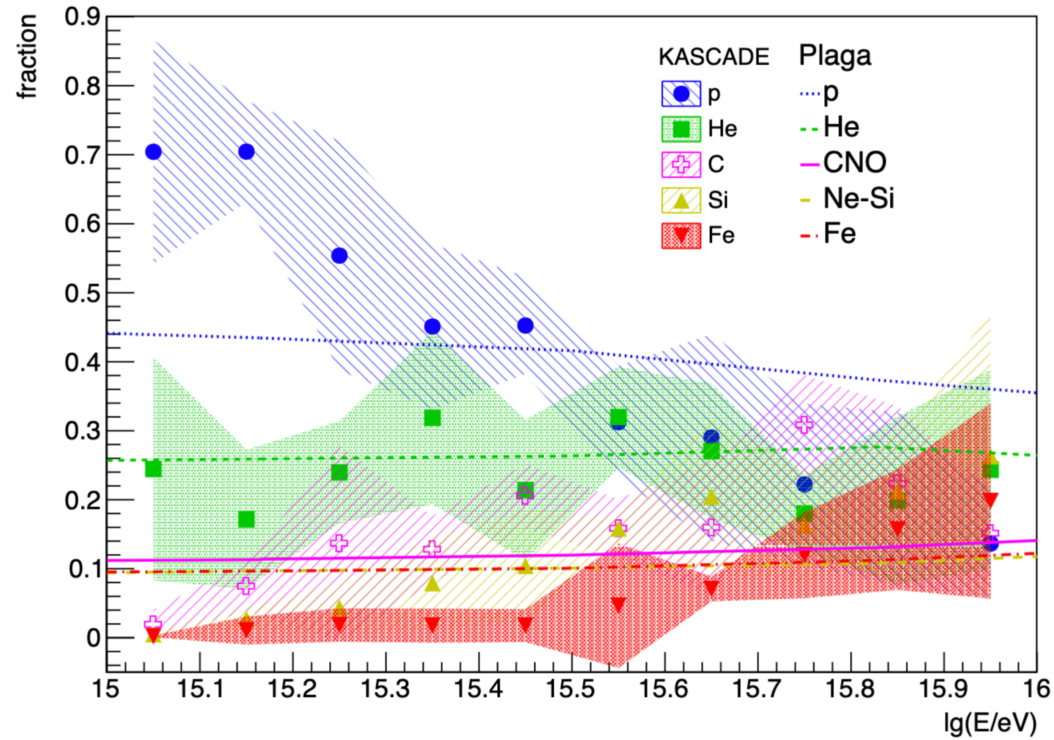

- 100 TeV, $FF = 0.12$
- Mercedes stations
- $N_\mu$ = number of detected muons from 40m to 1000m from the shower core




- Small bias ( $< 5\,\%$ ), constant in $E_0$
- Resolution within $15\,\%$ and $20\,\%$
- Method working from $\sim 10$s of TeV
- To be complemented with NN-based analysis for lower energies ( $\sim 100$s of GeV to $\sim 10$s of TeV)

# Mass composition




N. Arsene, "Cosmic ray mass composition at the *knee* using azimuthal fluctuations of air shower particles detected at ground by the KASCADE experiment"