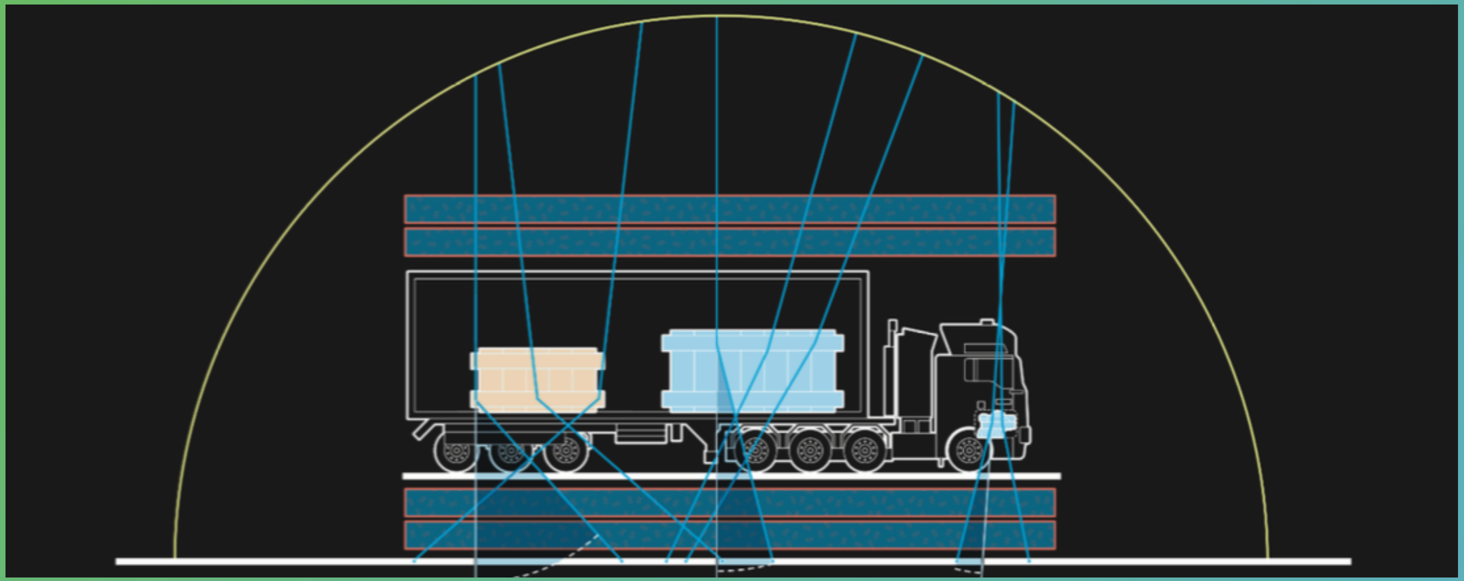
May 26-30, 2025

Palazzo Franchetti - Venezia

Muon4Future 2025



# A versatile and efficient cosmic muon generator for secondary cosmic-ray muon applications (EcoMug)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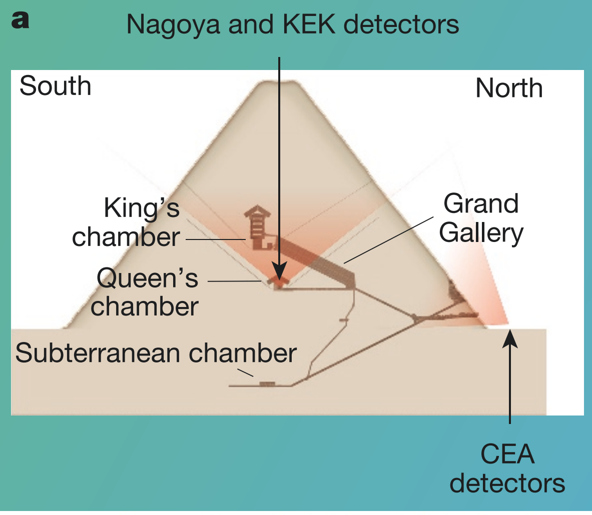
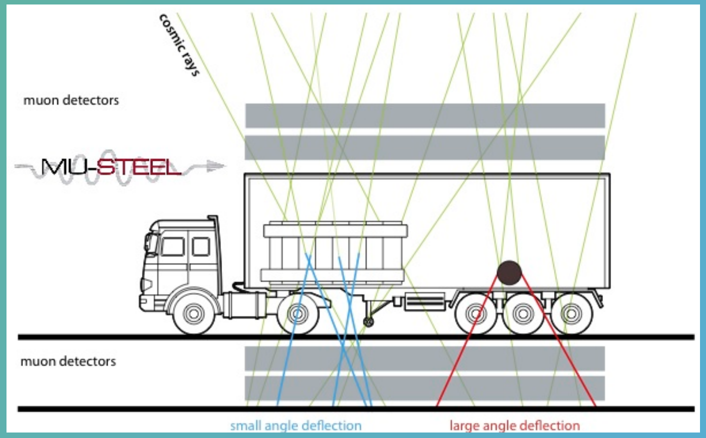
# MOTIVATION

To build and share a useful tool for simulations in:

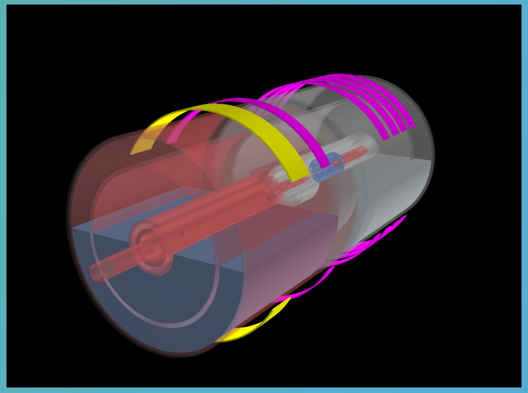
**MUON RADIOGRAPHY**




**MUON TOMOGRAPHY**



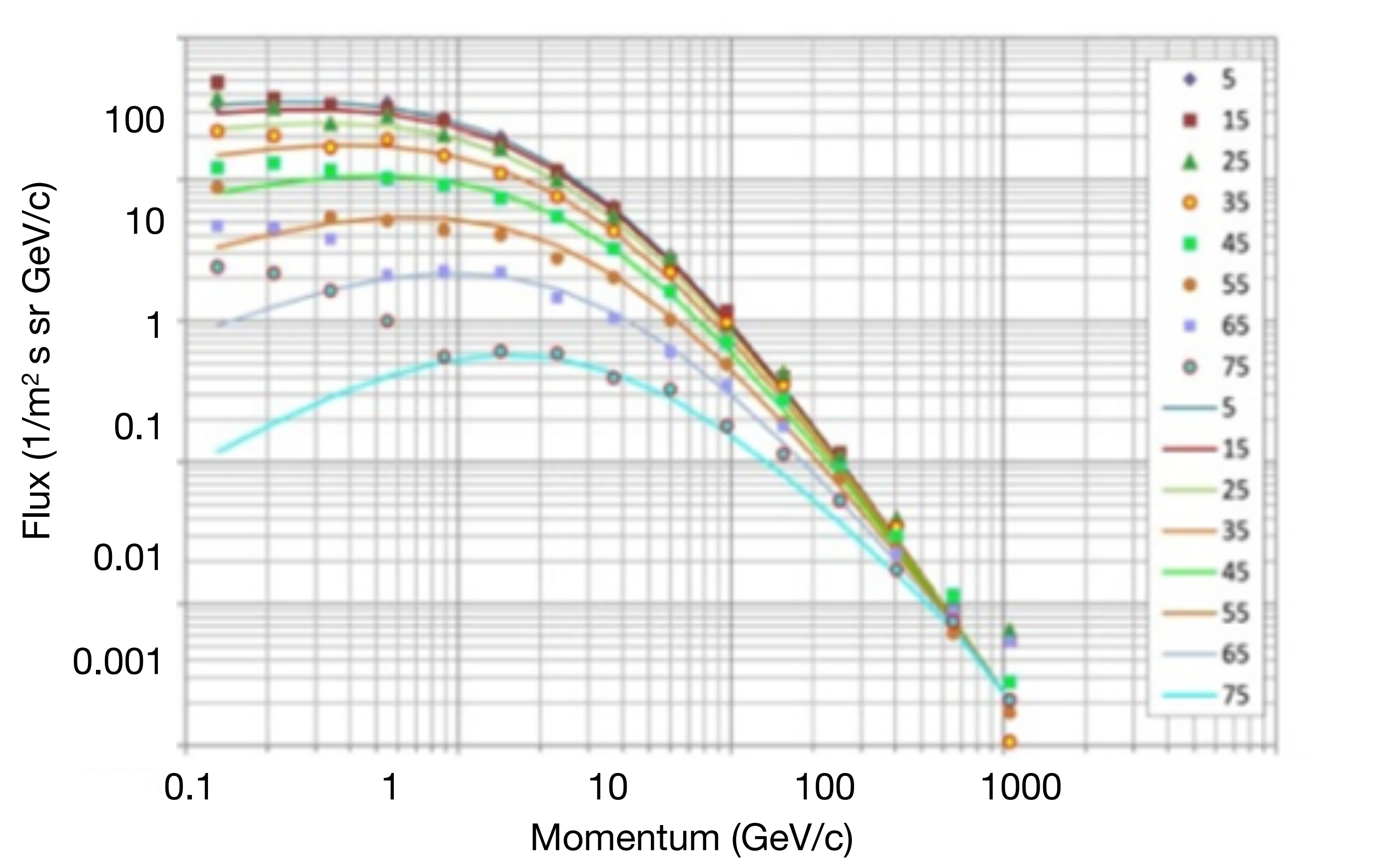

**DETECTOR CALIBRATION**



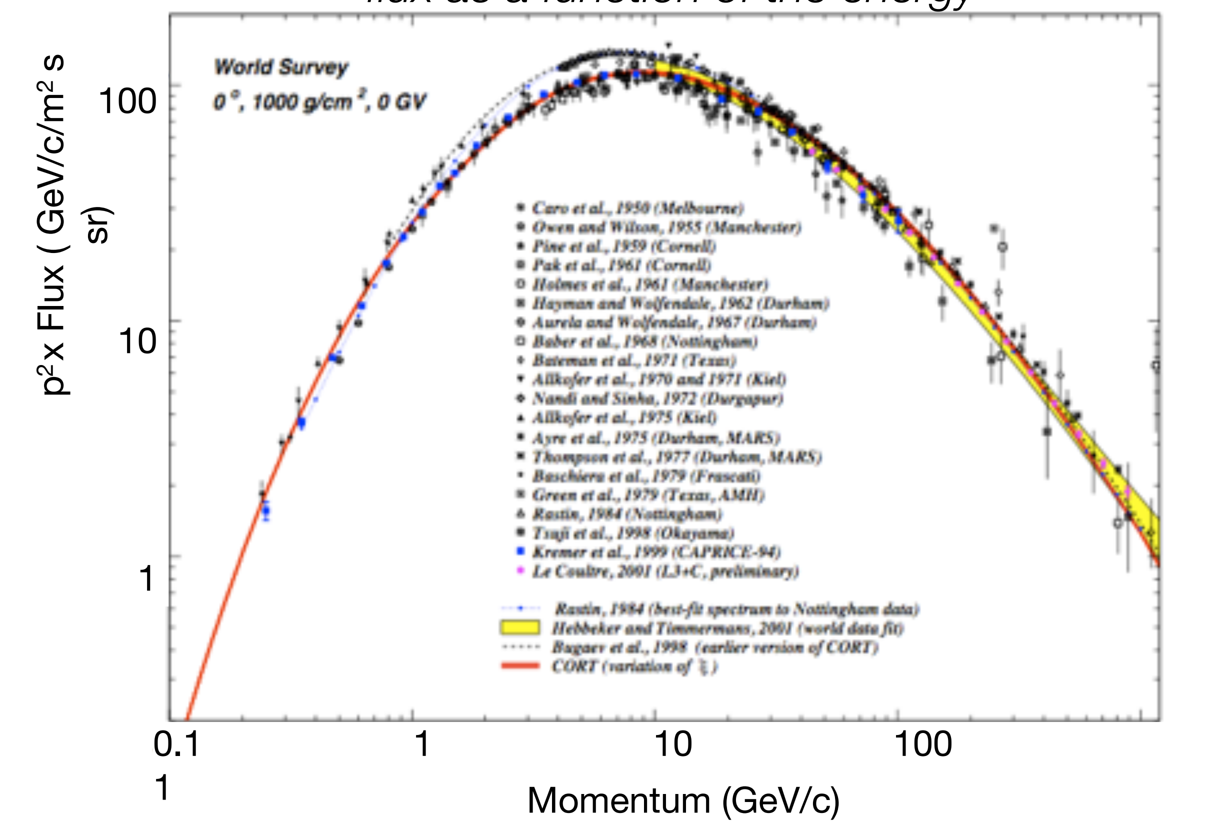
# (secondary) Muons: flux

- **10000** cosmic rays/(minute m$^2$) hit the ground (*600 of them cross our body every minute*)
- at sea level mostly are **muons**, with mean energy of 3÷4 GeV
- the flux is maximum at the zenith (**vertical**) and it scales approximately as $\cos^2(\theta)$

*Differential flux at different angles*




*flux as a function of the energy*



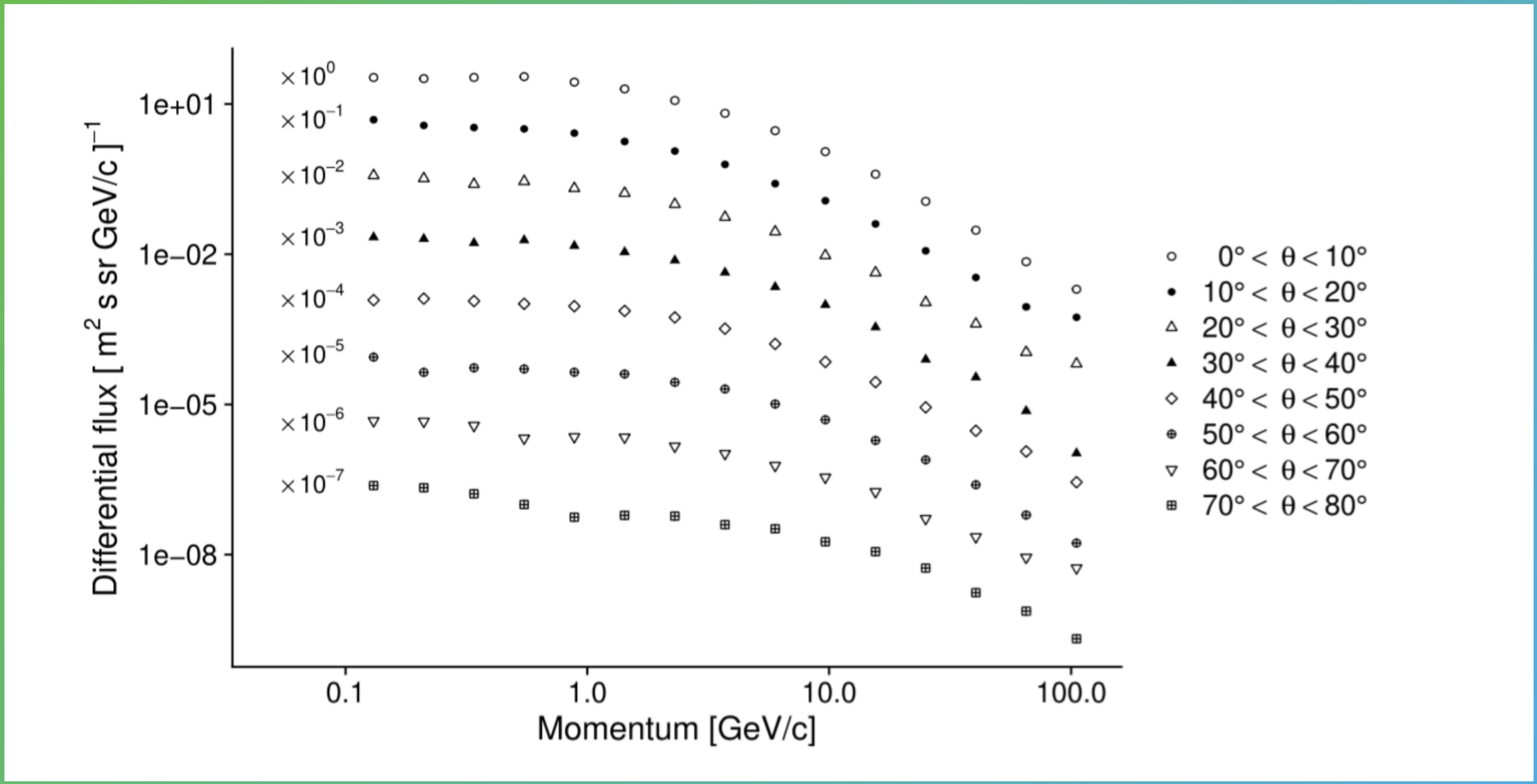
EXPERIMENTAL DATA taken as reference

Parametrisation

EcoMug Monte Carlo GENERATOR

# EXPERIMENTAL DATA

Cosmic ray flux measured by tilting the detector




[1] L. Bonechi, M. Bongi, D. Fedele, M. Grandi, S. Ricciarini, E. Vannuccini, Development of the ADAMO detector: test with cosmic rays at different zenith angles, in: 29th International Cosmic Ray Conference Vol. 9, 2005, pp. 283.

more accurate ALTERNATIVE to the more known:

[2] T.K. Gaisser, R. Engel, E. Resconi, Cosmic Rays and Particle Physics, Cambridge University Press, 2016.

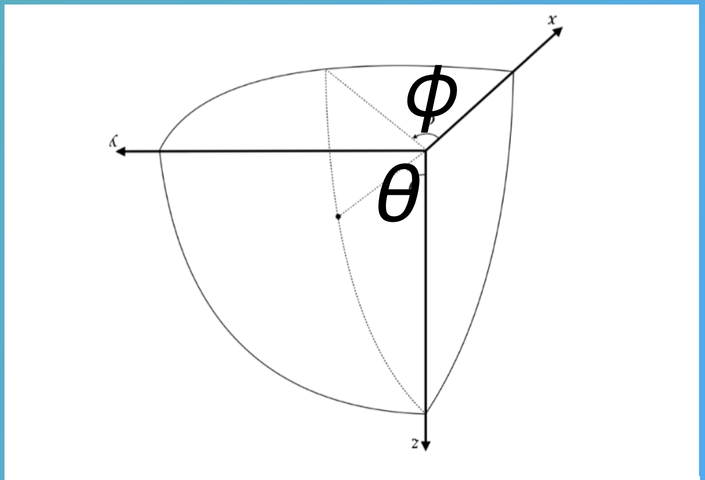
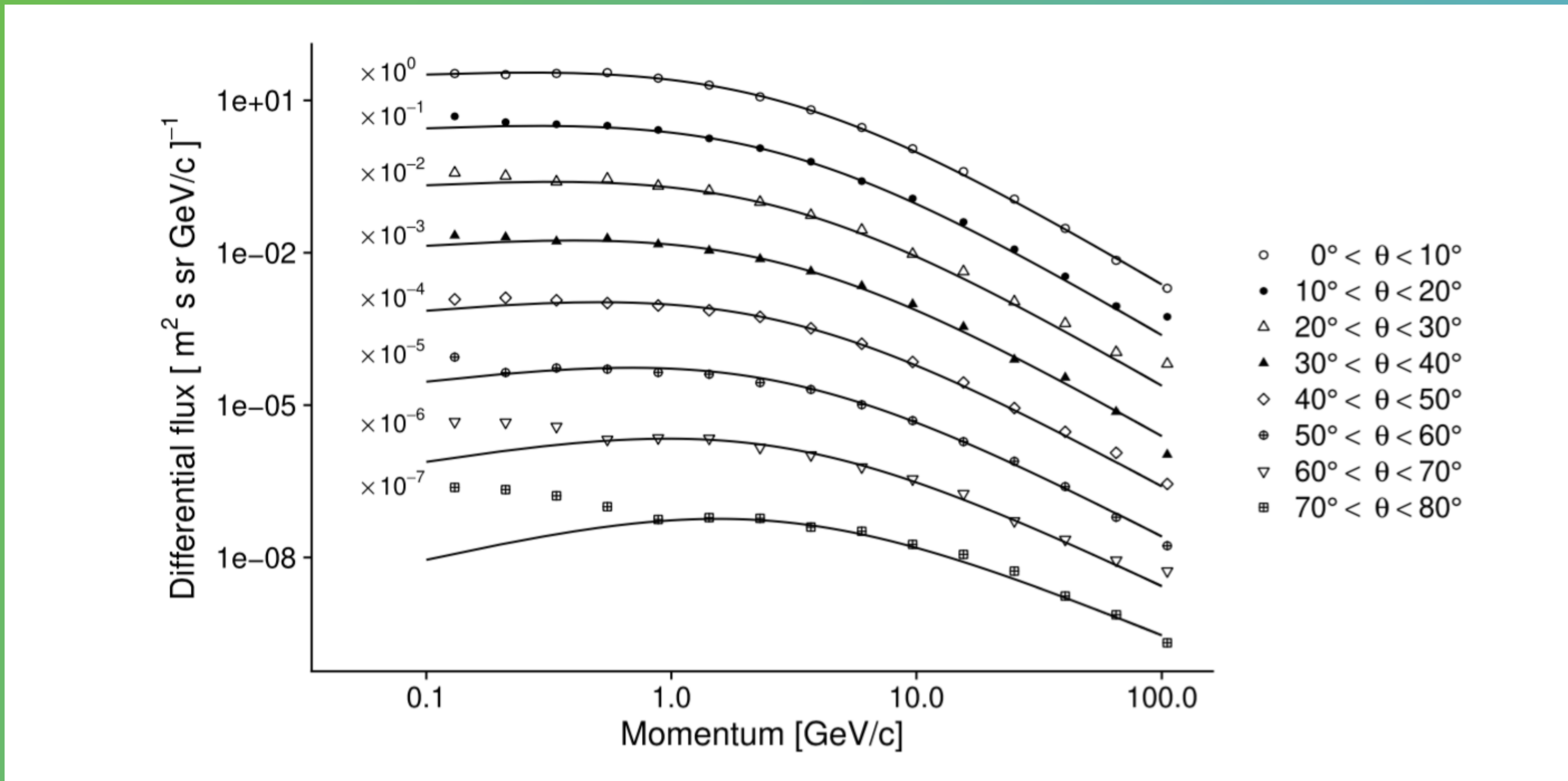



**Fig. 2.** Definition of the coordinate system used in EcoMug.

# PARAMETRIZATION

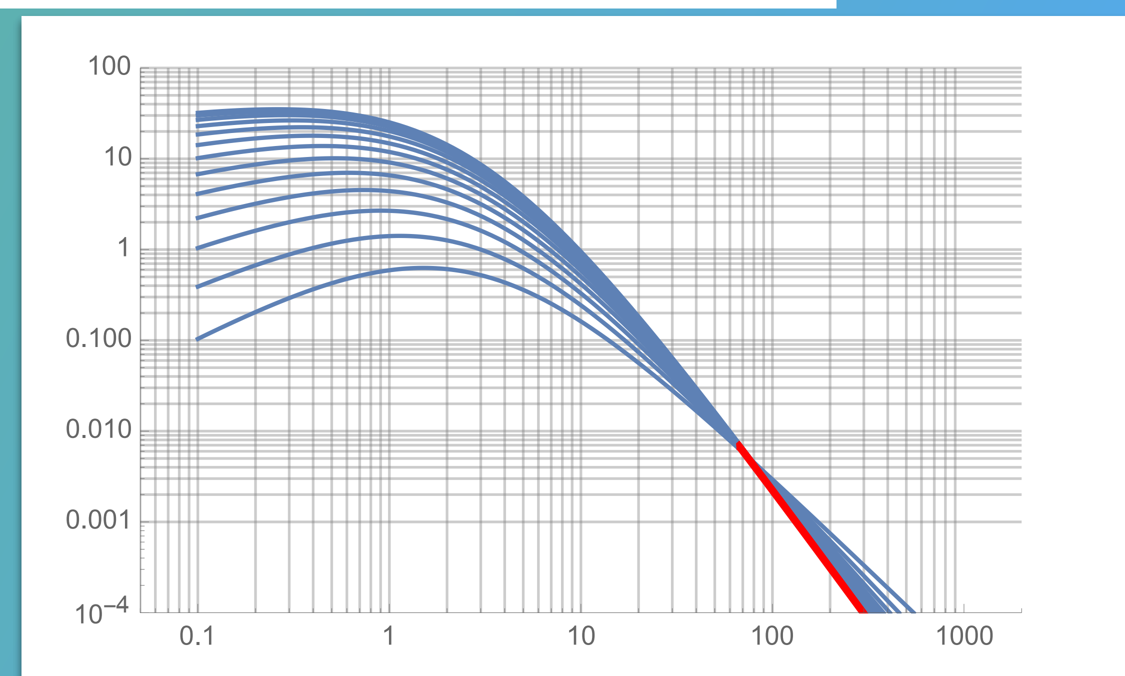



$$J = \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right] \cdot (\cos\theta)^n \cdot \frac{1}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{GeV/c}}, \quad (2)$$

where $p_0 = 1$ GeV/c and $n$ is a function of $p$ equal to

$$n(p) = \max\left[0.1,\ 2.856 - 0.655 \cdot \ln\left(\frac{p}{p_0}\right)\right],$$

with $p > 0.040$ GeV/c.



# EcoMug Monte Carlo GENERATORS

Planar, horizontal generation ("Flat Sky")
Cylindrical generation
Half-spherical generation

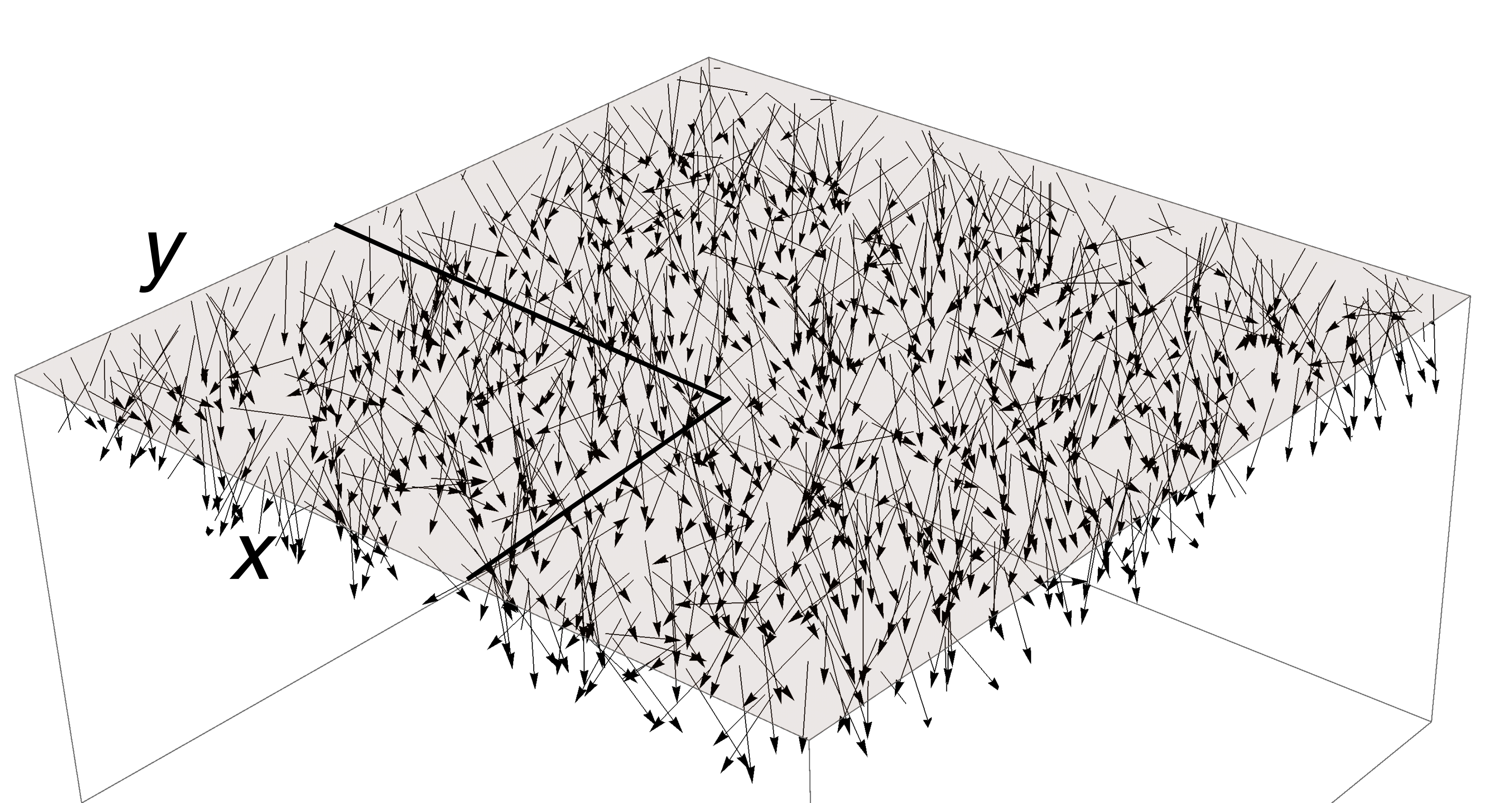
# "Flat Sky"

$$J'_z \equiv \frac{dN}{dt \cdot dp \cdot d\theta \cdot d\phi \cdot dS_z}$$
$$= \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right]$$
$$\cdot (\cos\theta)^{n+1} \cdot \sin\theta \cdot \frac{1}{\mathrm{m^2 \cdot s \cdot sr \cdot GeV/c}}.$$

Usual method, already implemented in previous generators

# “Flat Sky”

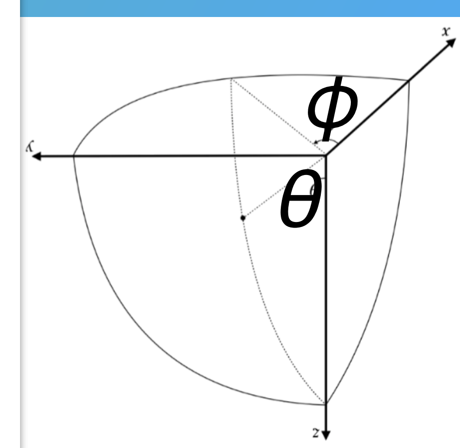
$$J'_z \equiv \frac{dN}{dt \cdot dp \cdot d\theta \cdot d\phi \cdot dS_z} = \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right] \cdot (\cos\theta)^{n+1} \cdot \sin\theta \cdot \frac{1}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{GeV/c}}.$$



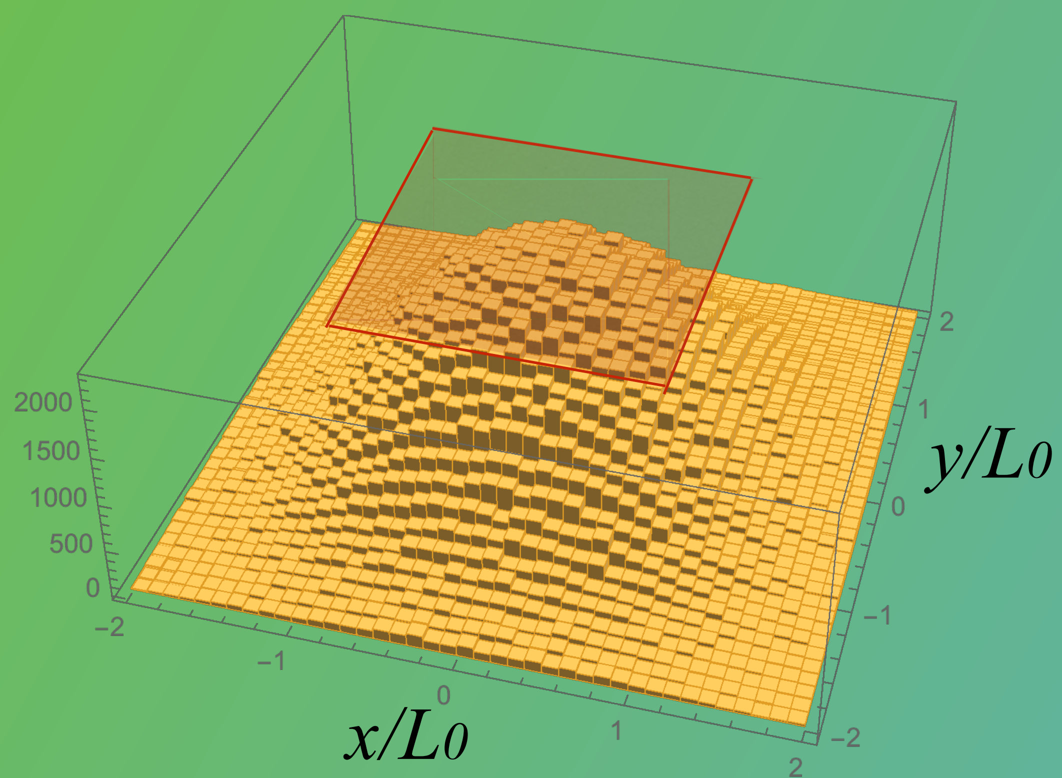

x, y and $\phi$ are uniformly generated

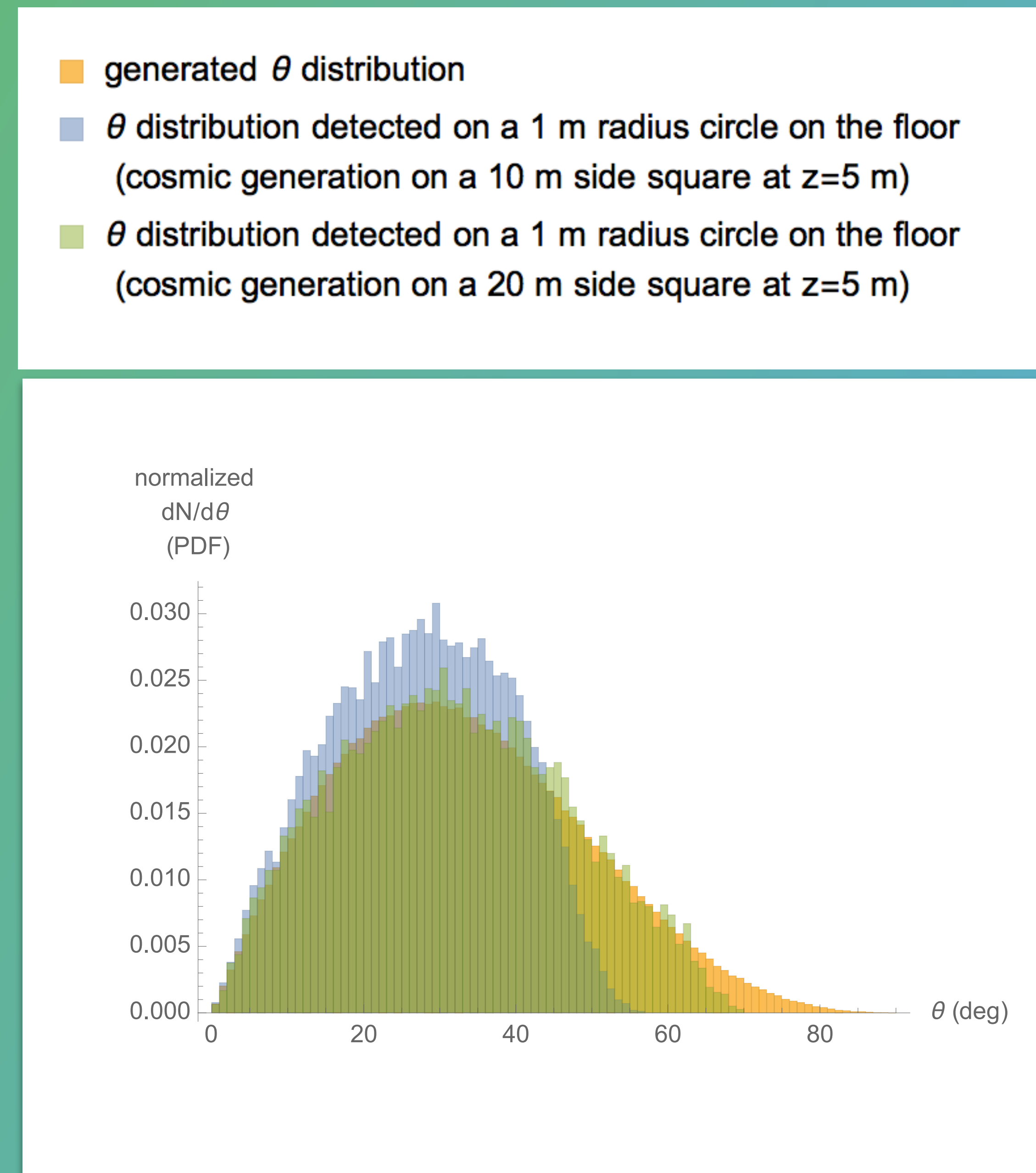
p is generated with a mix of the Inverse-Transform Method and the Acceptance–Rejection Method

$\theta$ is generated with the Acceptance–Rejection Method



distribution of the points where the muons reach the floor



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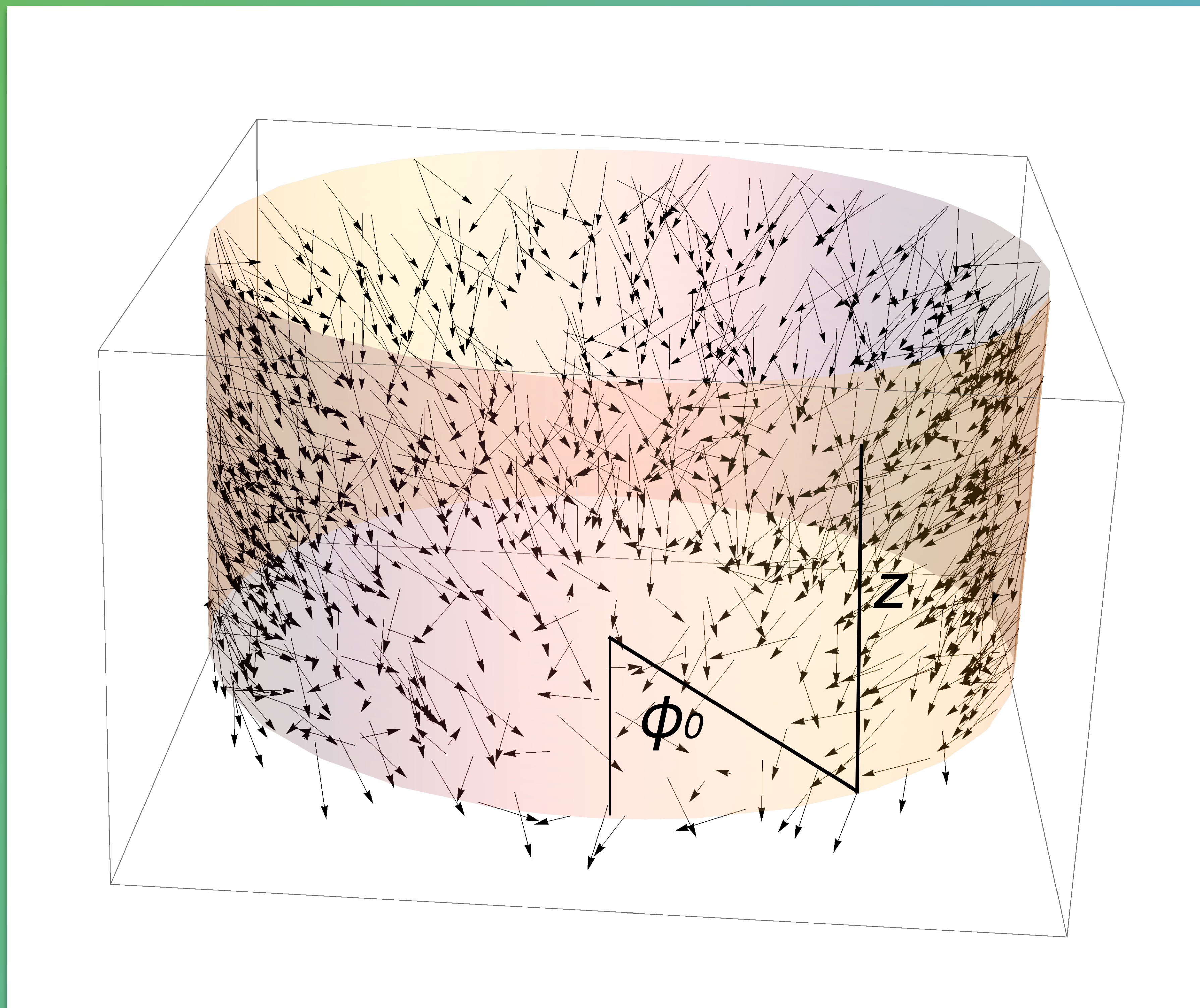
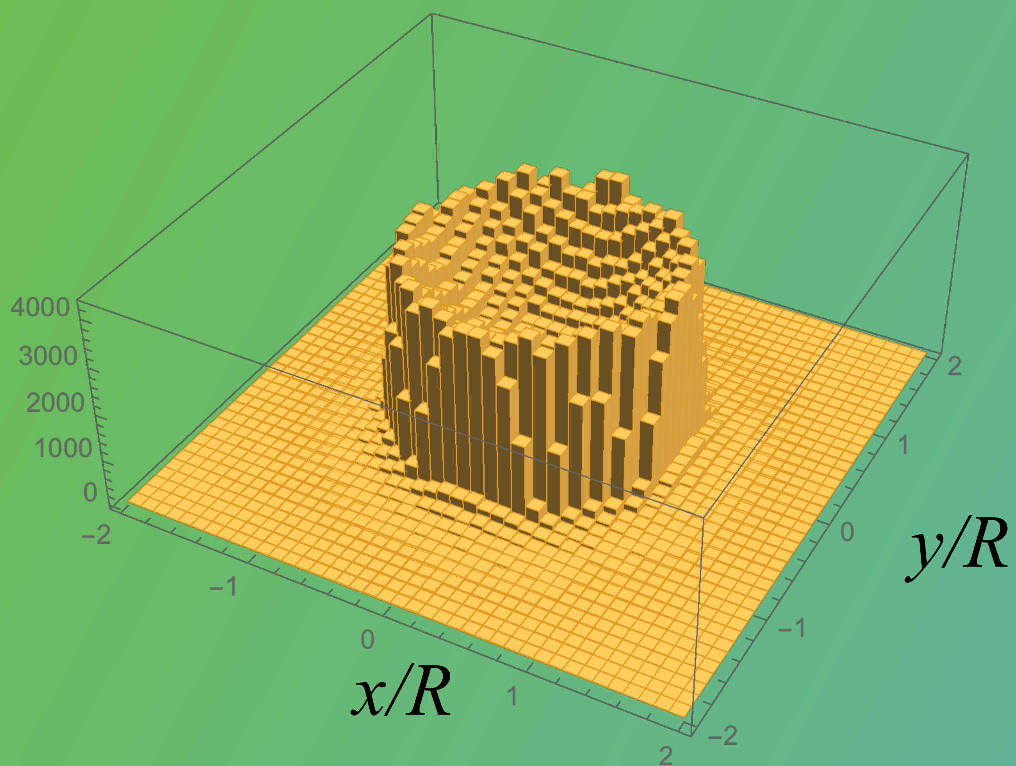
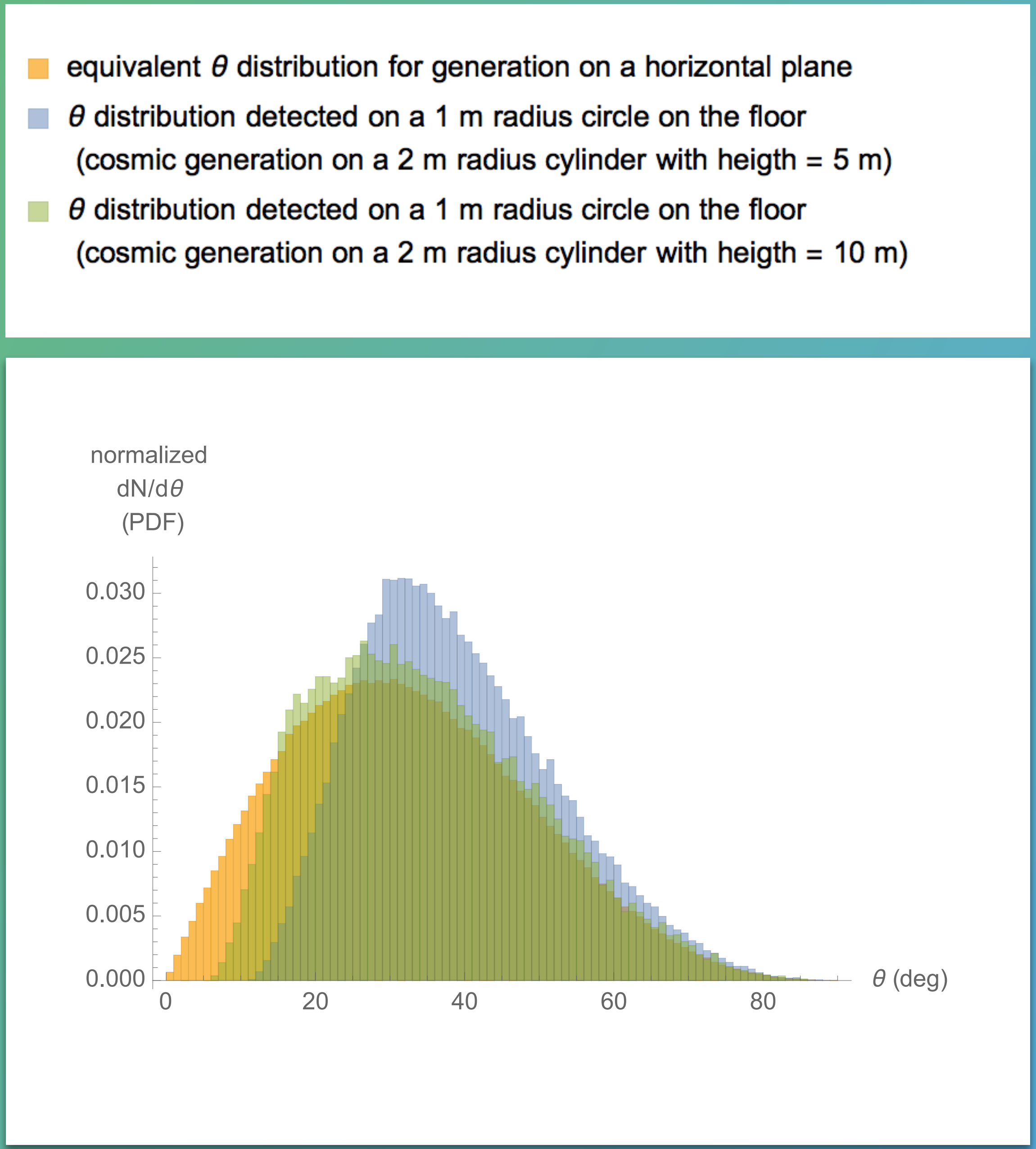
# Cylindrical generation

$$
\begin{aligned}
J'_x &\equiv \frac{dN}{dt \cdot dp \cdot d\theta \cdot d\phi \cdot dS_x} \\
&= \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right] \\
&\quad \cdot (\cos\theta)^n (\sin\theta)^2 \cos\phi \cdot \frac{1}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{GeV/c}}.
\end{aligned}
$$

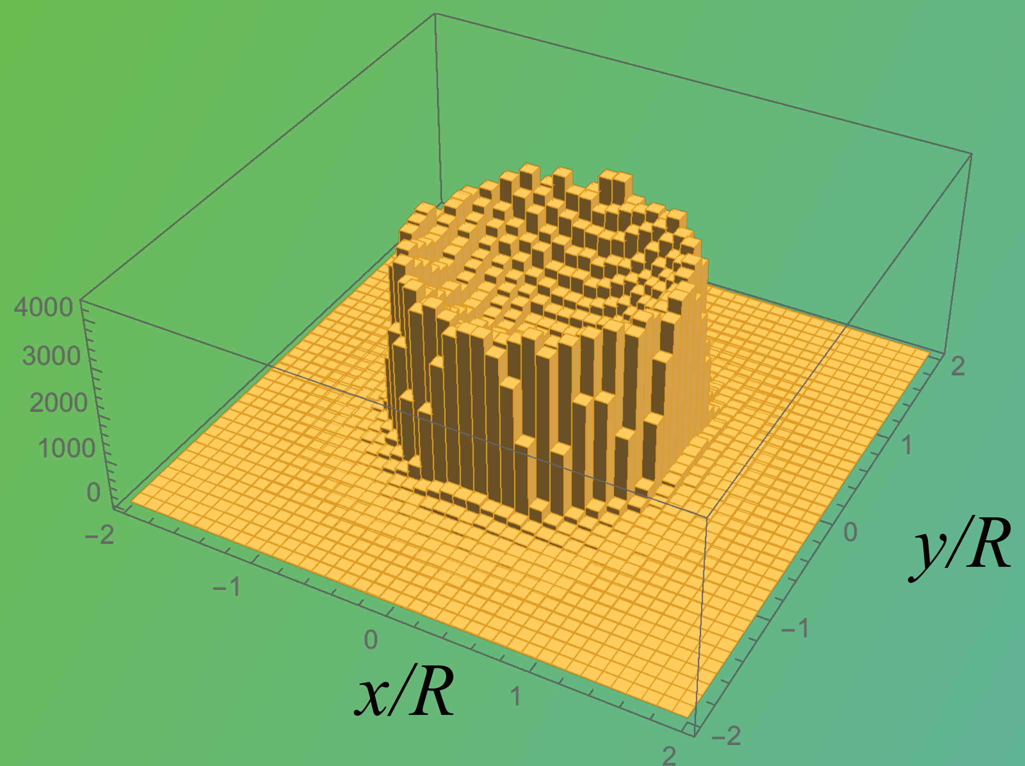


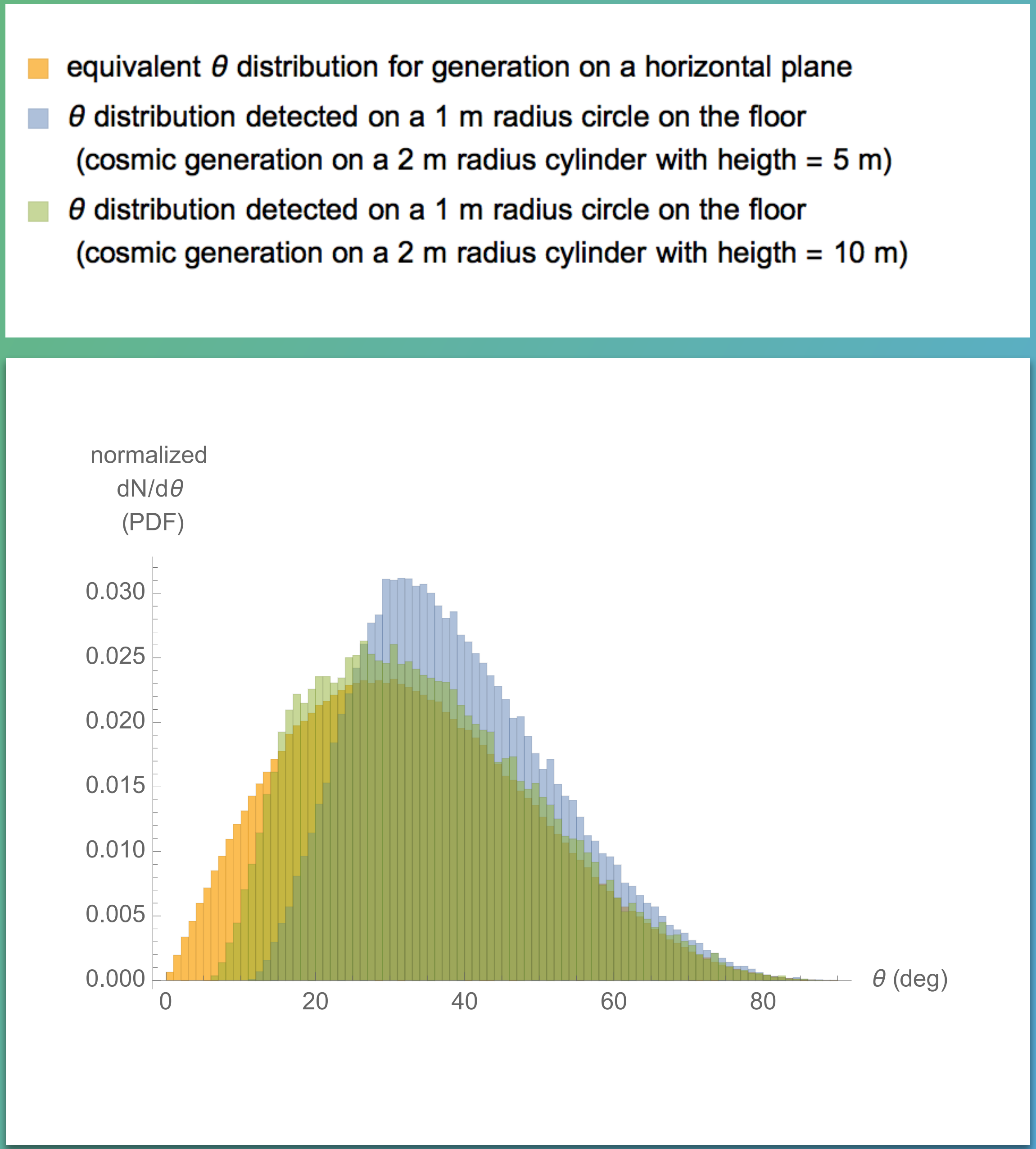
distribution of the points where the muons reach the floor

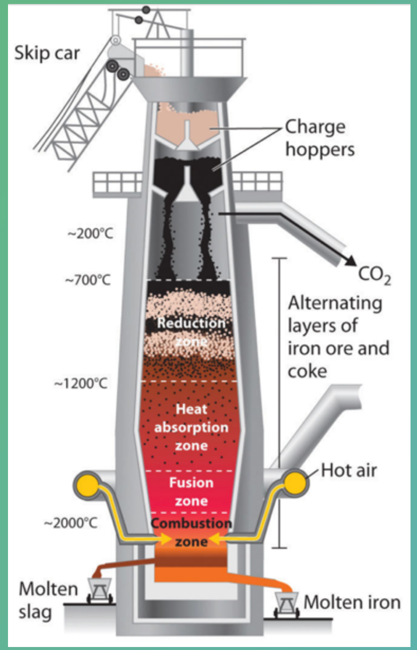


distribution of the points where the muons reach the floor




ideal for Blast furnace monitoring

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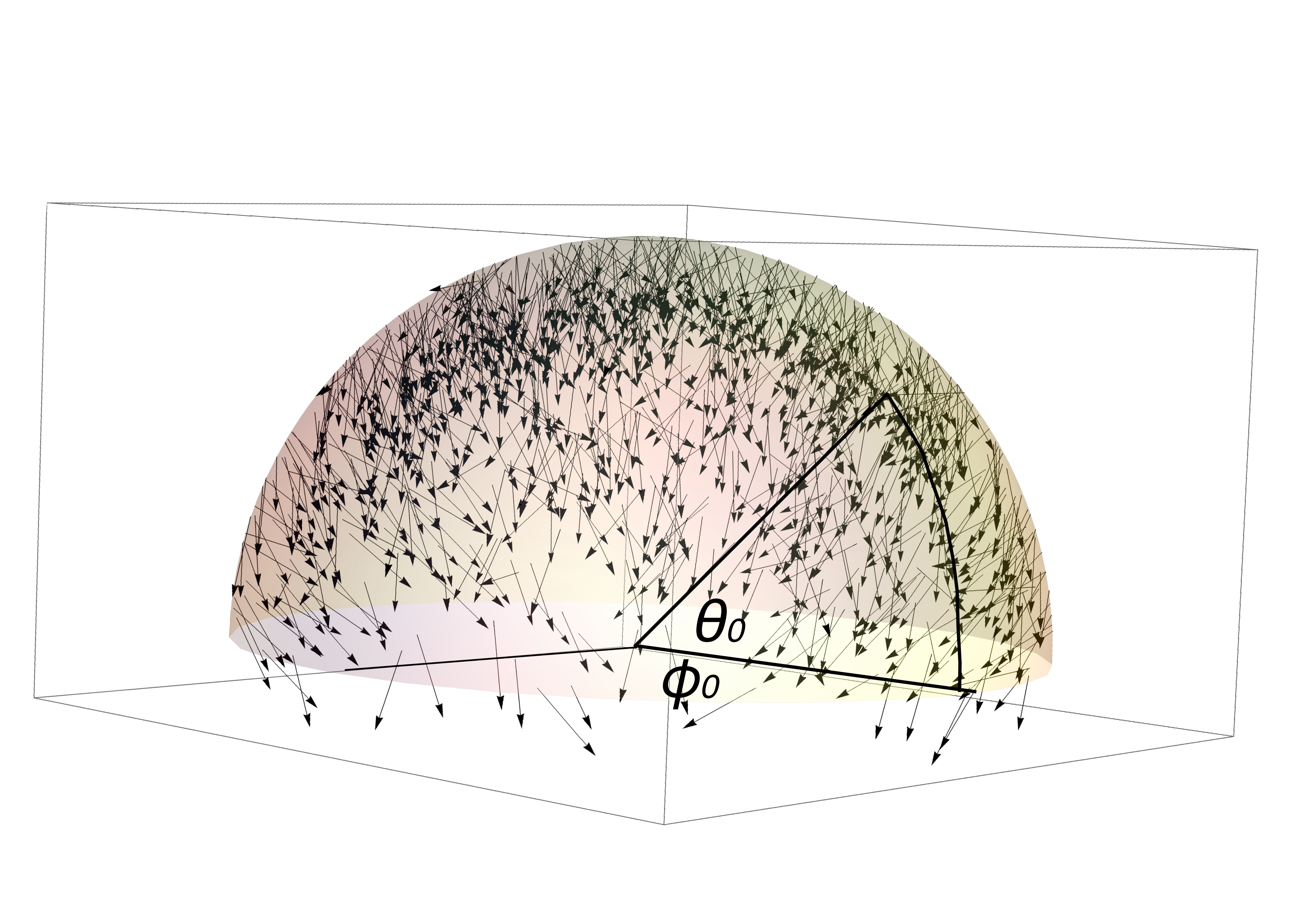
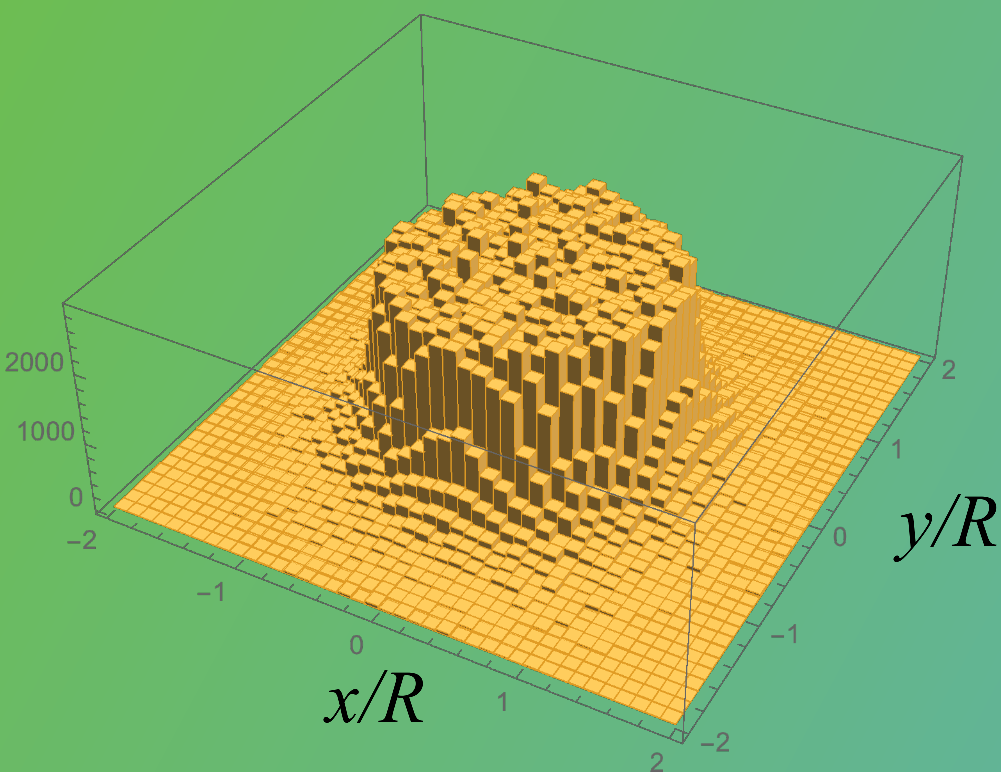
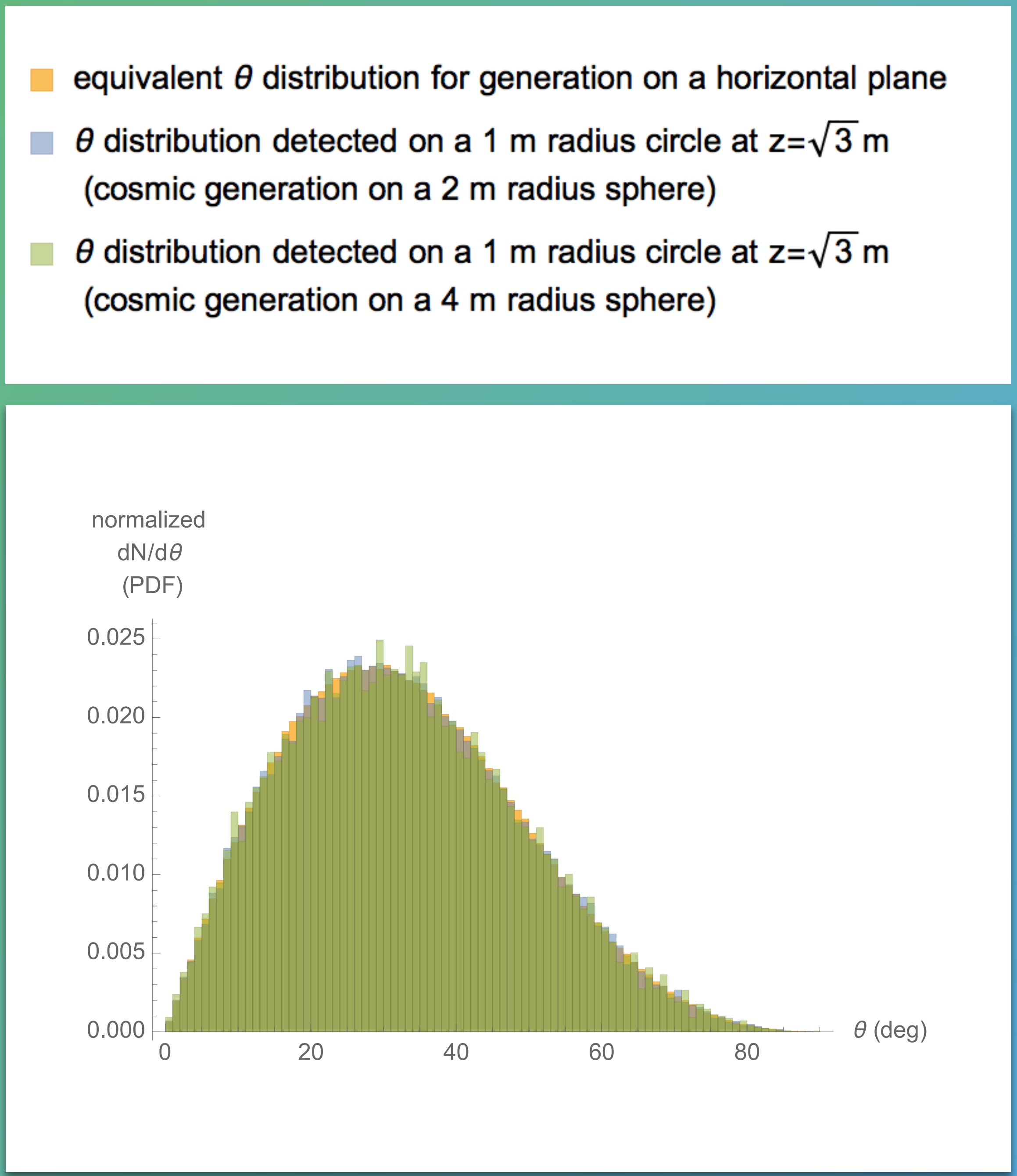
# Half-spherical generation

$$J'_t \equiv \frac{dN}{dt \cdot dp \cdot d\theta \cdot d\phi \cdot dS_t}$$
$$= \left[1600 \cdot \left(\frac{p}{p_0} + 2.68\right)^{-3.175} \cdot \left(\frac{p}{p_0}\right)^{0.279}\right]$$
$$\cdot (\cos\theta)^n \left[\sin\theta_0 (\sin\theta)^2 \cos\phi + \cos\theta_0 \cos\theta \sin\theta\right] \cdot \frac{1}{\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{sr} \cdot \mathrm{GeV/c}}.$$

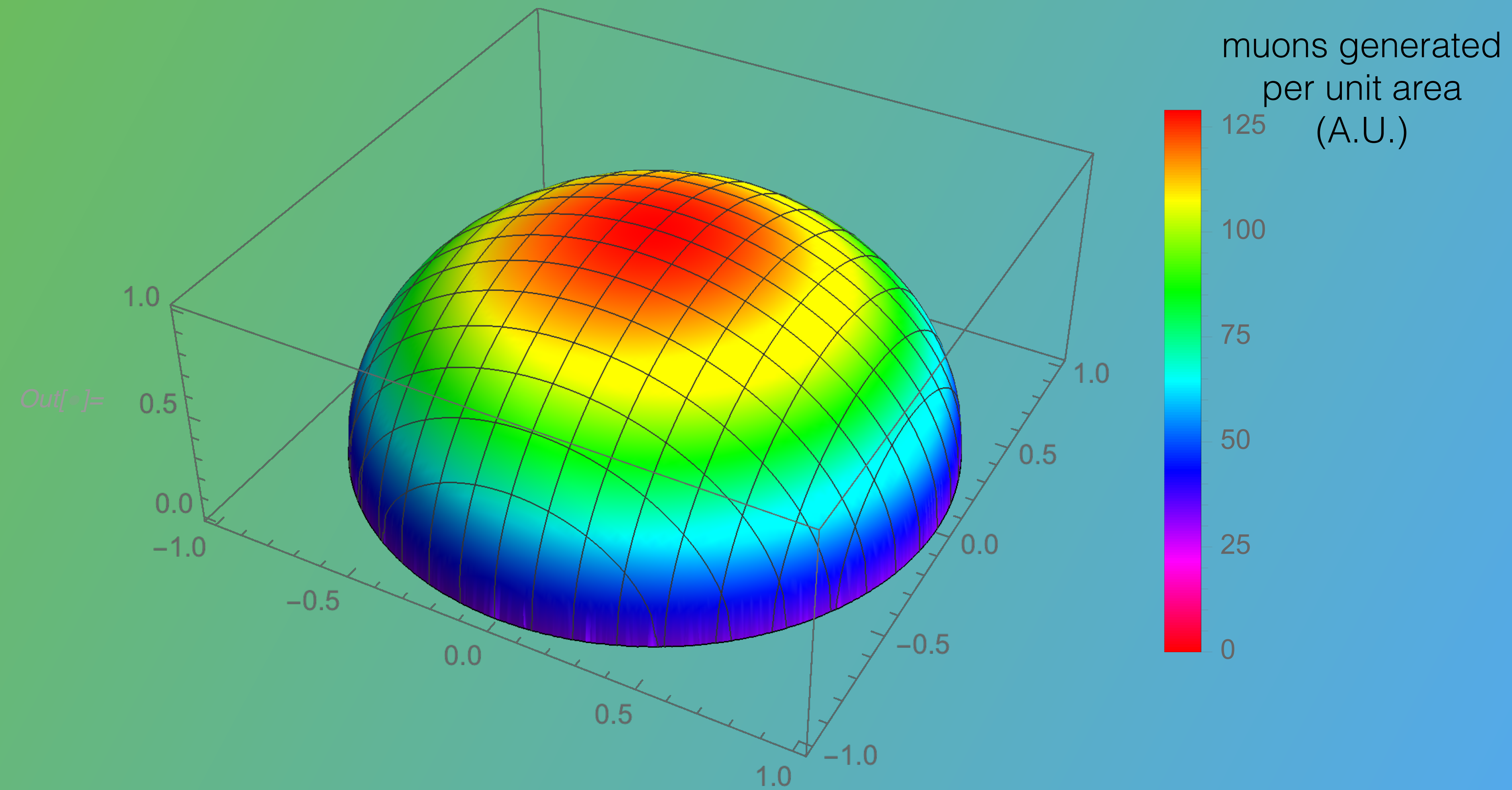


distribution of the points where the muons reach the floor



# Notice that in this case the density of "muon sources" is not uniform! (all the angles are coupled but $\phi_0$)



Computational time:
it is between $3 \cdot 10^5$ and $10^6$ muons per second
depending on the generation scheme
on a (fairly old) CPU
2,2 GHz Intel Core i7 (2015)

# Conclusions

We have briefly presented a Monte Carlo generator for secondary cosmic ray muons (EcoMug)

main EcoMug FEATURES:

- written in C++
- designed to be included as a header file
- fully integrated in Geant4
- 3 different generation surfaces (SetGenerationMethod())
- customisable parametrisation (SetDifferentialFlux())
- customisable range of the involved variables, if needed
- there is a version compiled and integrated in Mathematica

It can be downloaded at:
https://github.com/dr4kan/EcoMug
under the GPL-3.0 license

see also for documentation
https://dr4kan.github.io/EcoMug/class_eco_mug.html

# References:


- D. Pagano, G. Bonomi, A. Donzella, A. Zenoni, G. Zumerle and N. Zurlo, *EcoMug: An Efficient COsmic MUon Generator for cosmic-ray muon applications*, Nucl. Instrum. Methods Phys. Res. A, Vol. 1014, 165732 (2021).

- G.Bonomi et al., *A Monte-Carlo Muon Generator for Cosmic-Ray Muon Applications*, Journal for Advanced Instrumentation in Science, Vol. 2022, No. 1, (2022).

- N. Zurlo et al., *A new Monte Carlo muon generator for cosmic-ray muon applications*, Proceedings of Science, Volume 409, 19 (2022). DOI: https://doi.org/10.22323/1.409.0019

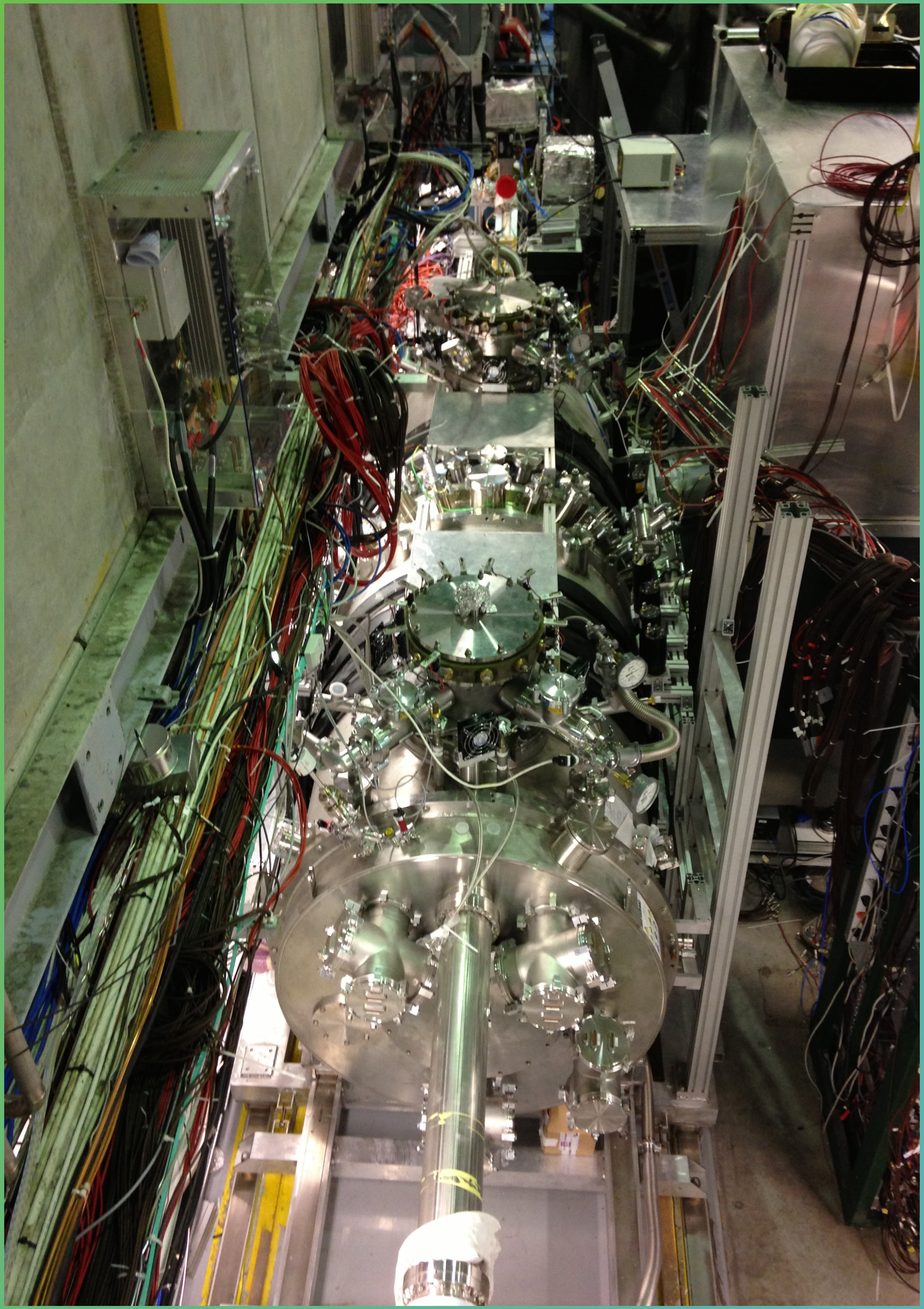
# Thank you

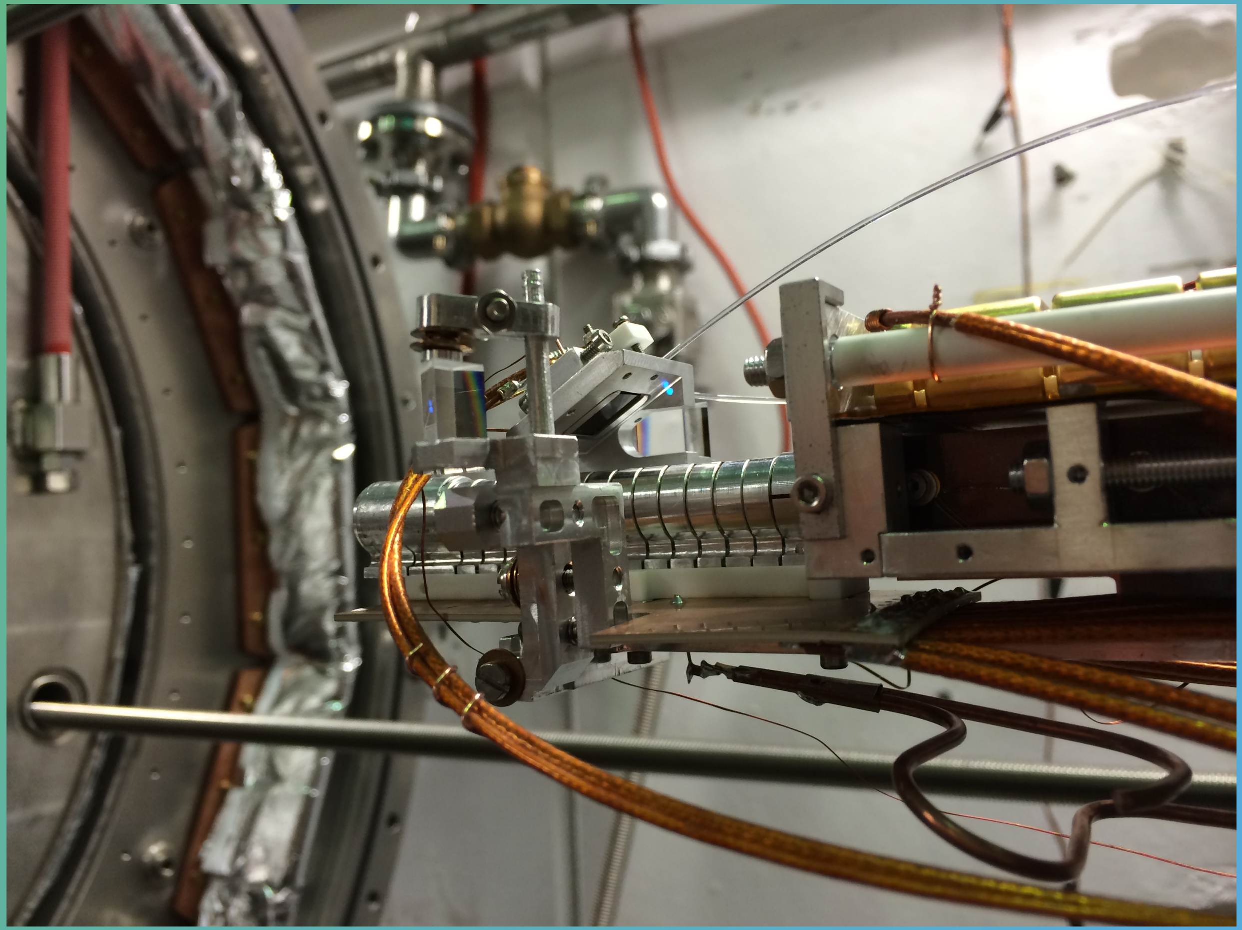
for your attention!

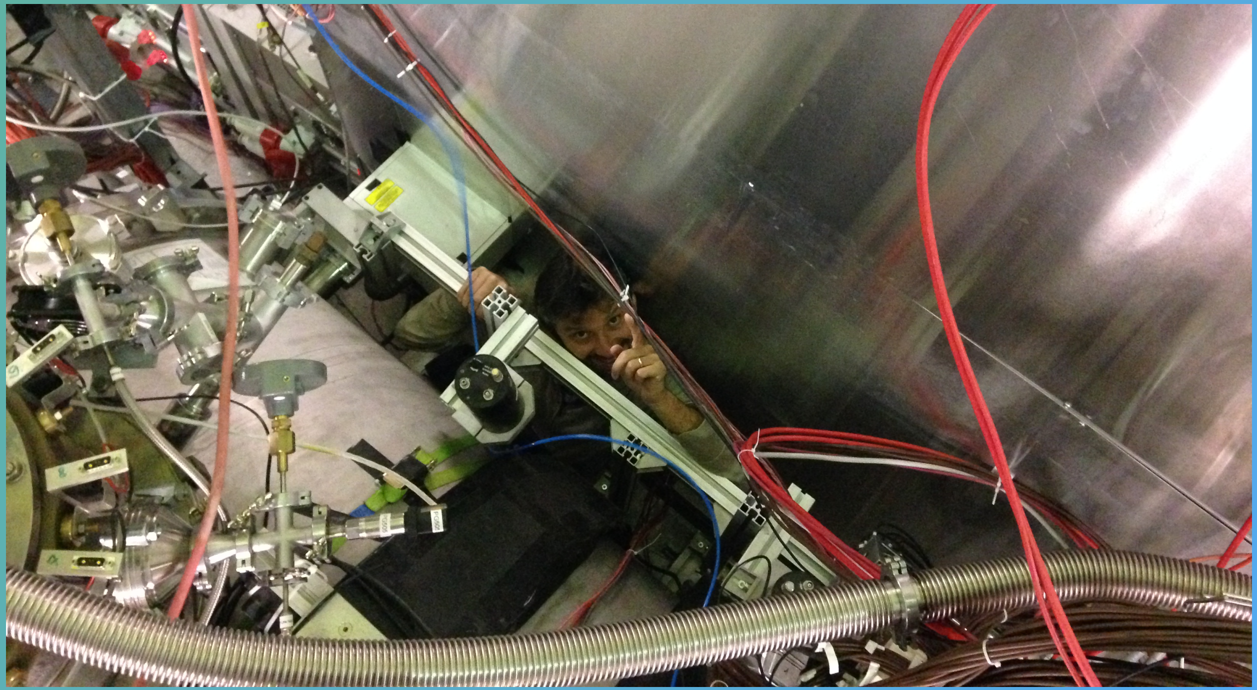
**Backup slides…**

# DETECTOR CALIBRATION

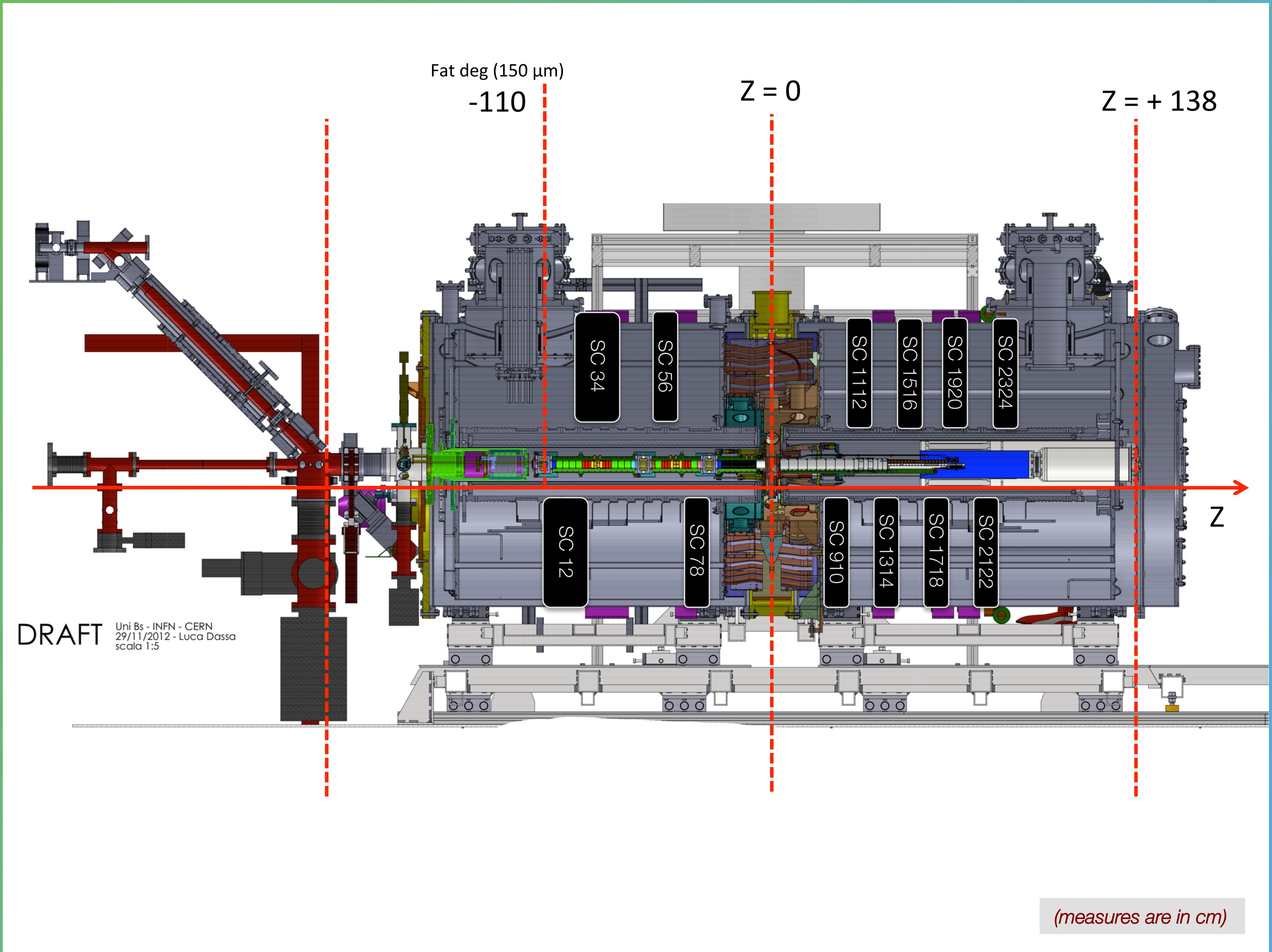
# AEgIS experiment @CERN Antiproton Decelerator



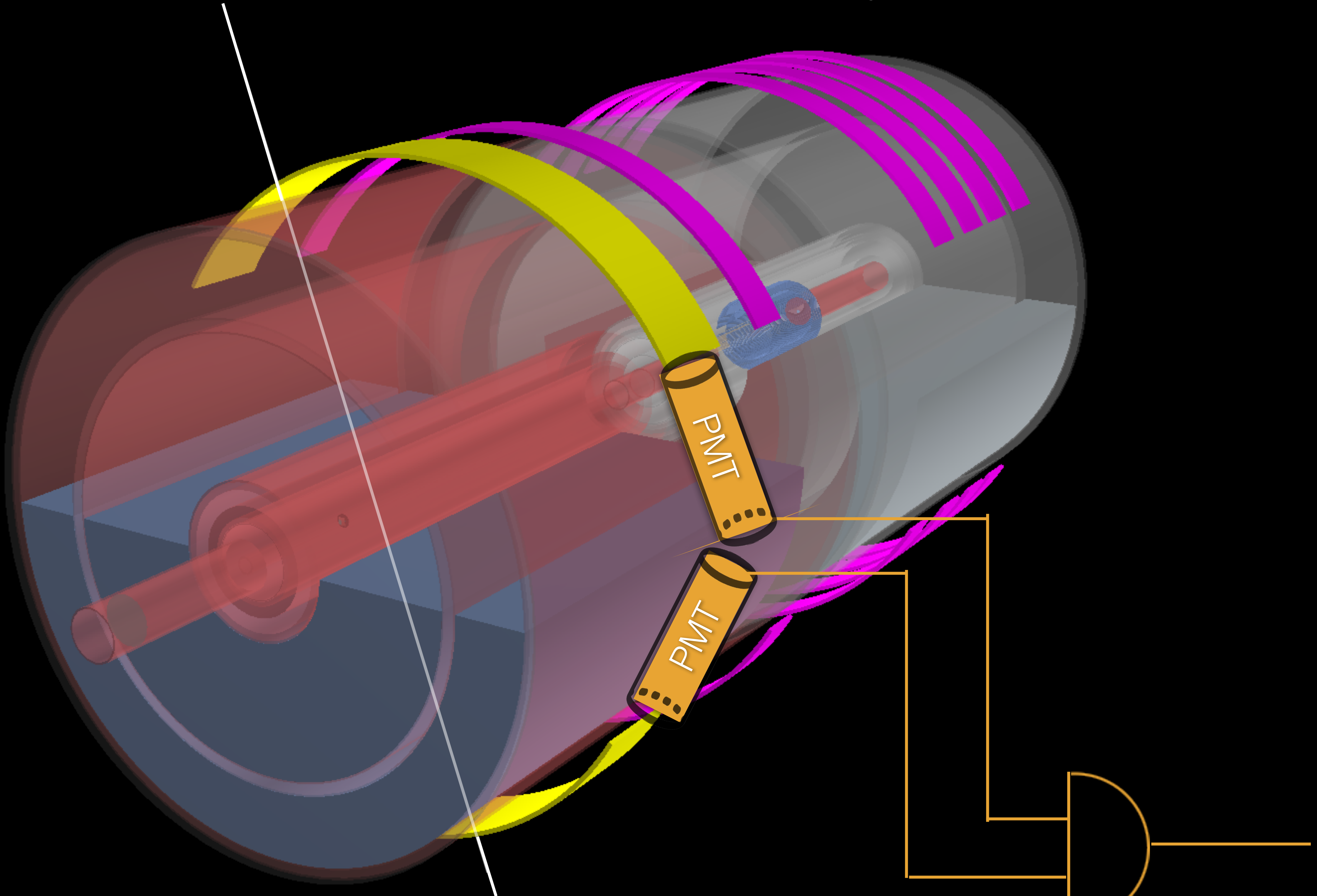




# Particle annihilation diagnostic system

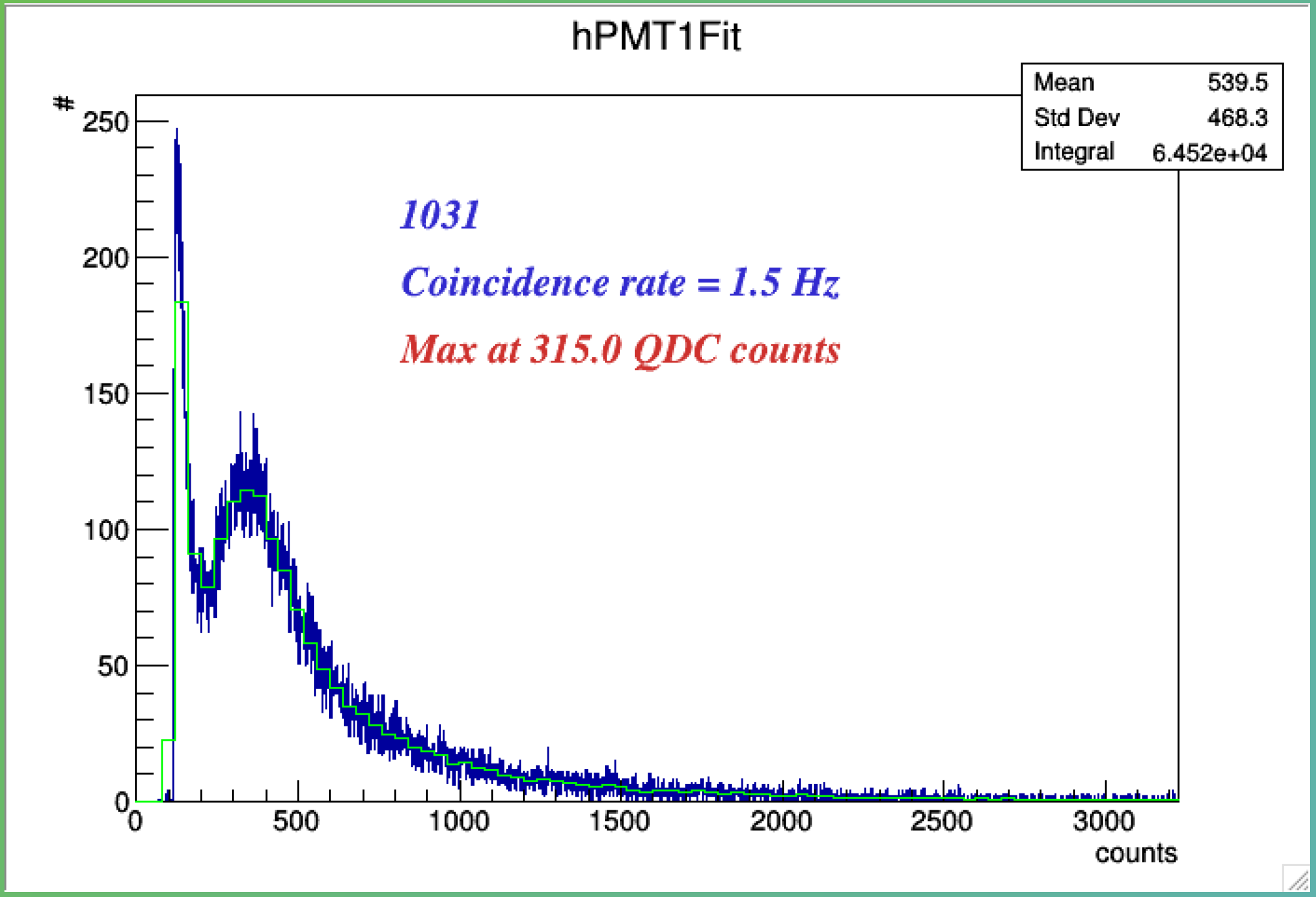


# Calibration with cosmic rays

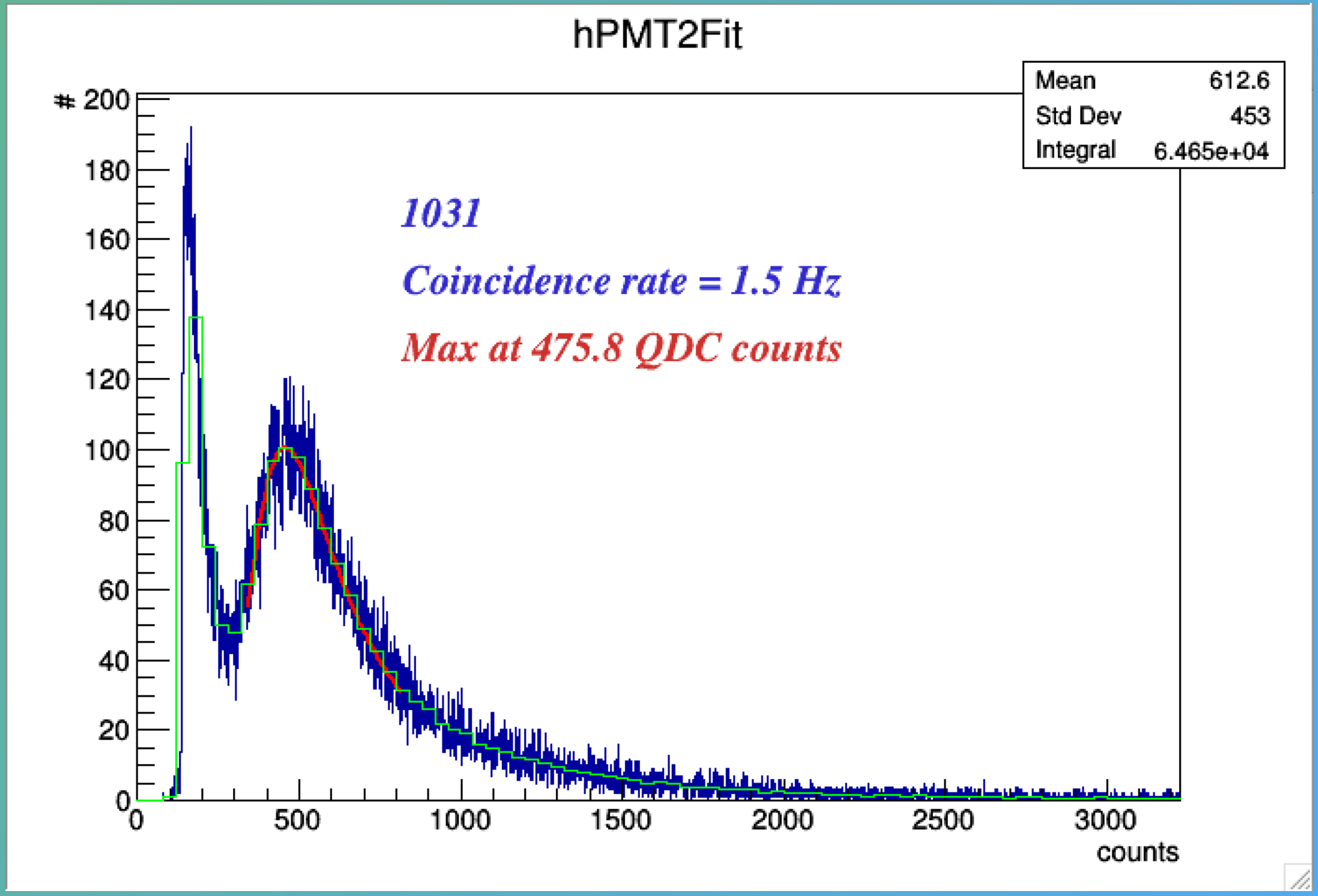


distribution of the integrated charge **in coincidence**

PMT 1

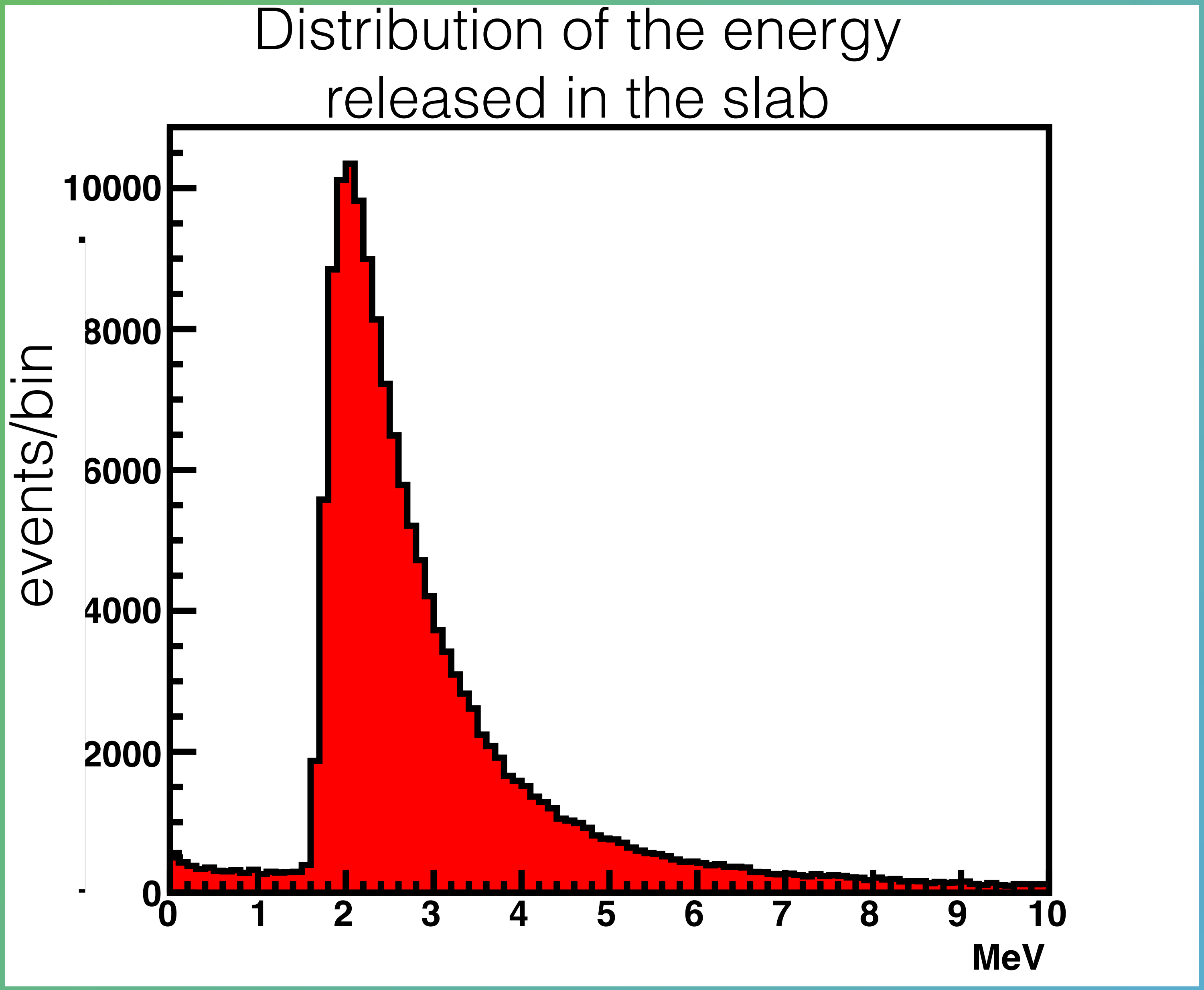



PMT 2



# Monte Carlo simulation of cosmic rays

the full apparatus has been implemented in Geant4 via Geant4VMC





[1] Zurlo, N. et al., AEgIS Collaboration. Calibration and equalisation of plastic scintillator detector for antiproton annihilation identification over positron/positronium background. Acta Phys. Pol. B 51, 213–223 (2020).

[2] Amsler, C., Antonello, M., Belov, A. et al. Pulsed production of antihydrogen. Commun Phys 4, 19 (2021). https://doi.org/10.1038/s42005-020-00494-z