UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

CTAO CONSORTIUM

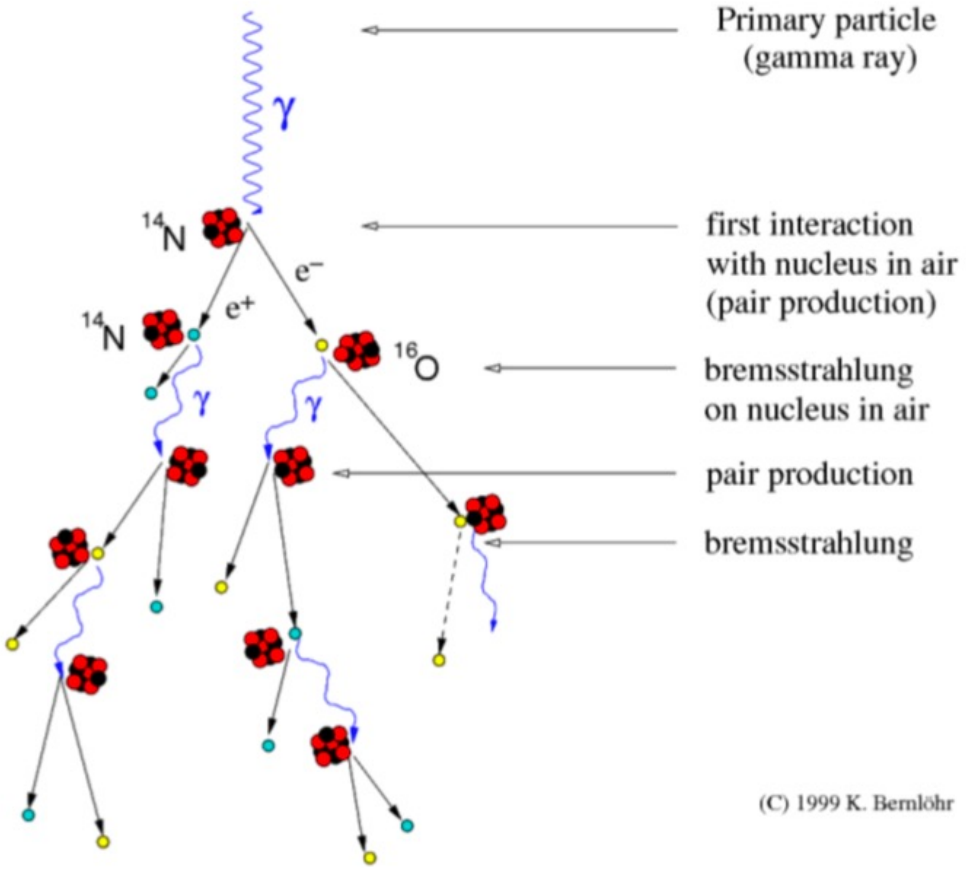
A comprehensive study of the muons detected by the Large-Sized Telescope during its commission phase

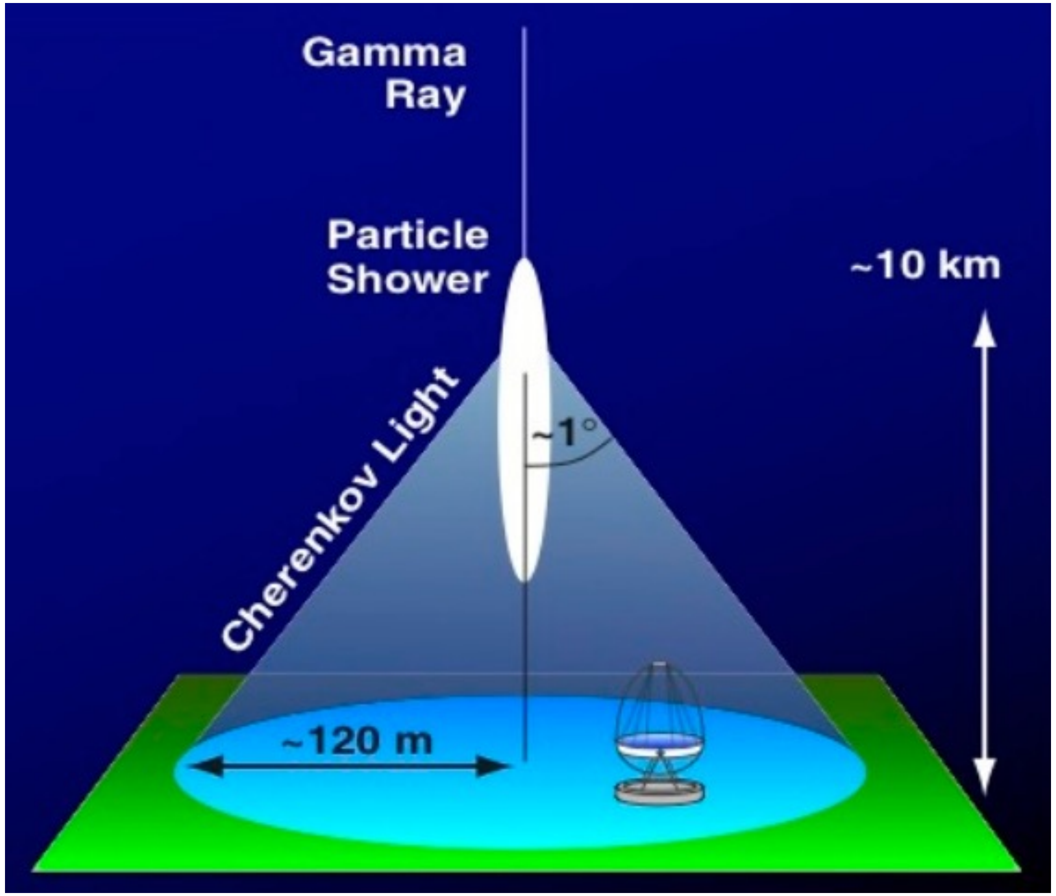
Vadym Voitsekhovskyi,

Annual Meeting of the Swiss Physical Society 2024, Zurich

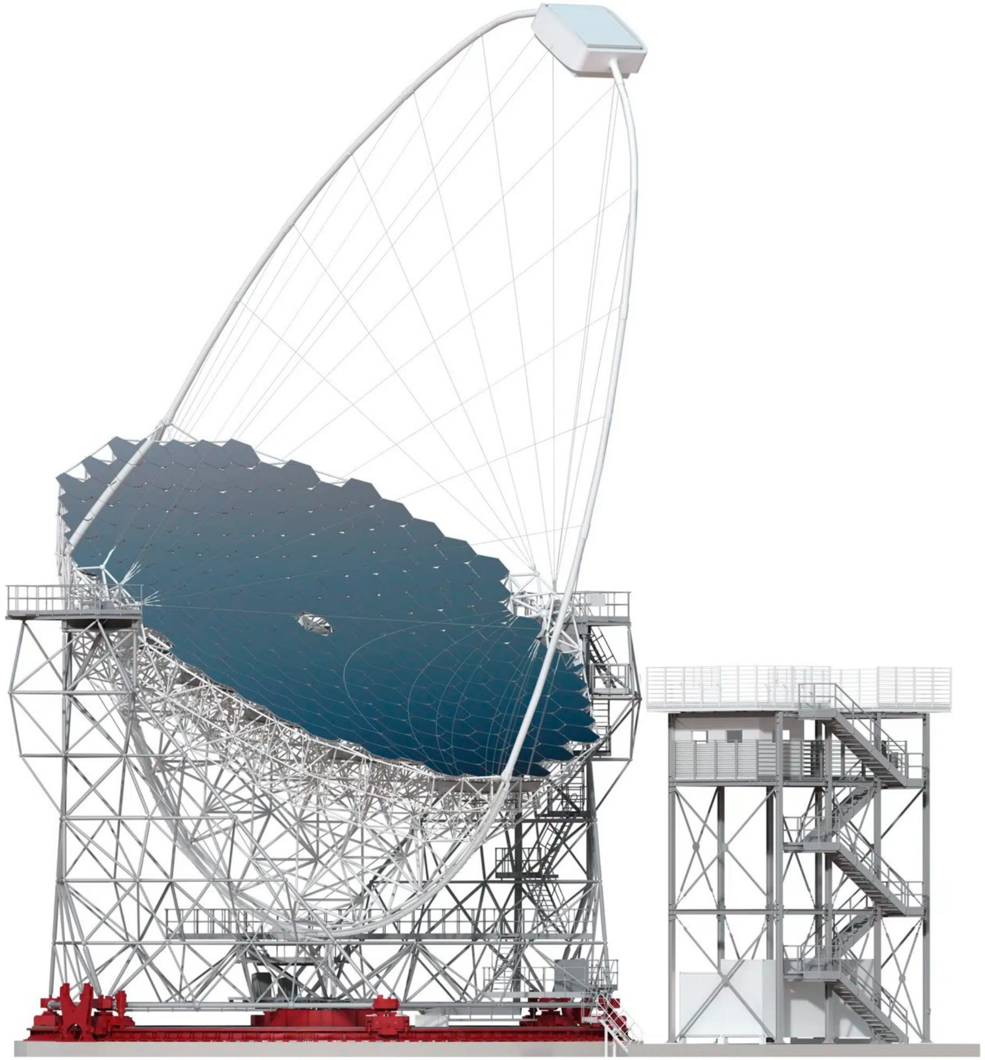
Ground based gamma-ray astronomy

The phenomenon of extensive air showers can be used to detect gamma rays from the Earth ground – Imaging Atmospheric Cherenkov Technique





Large-Sized Telescope of the Cherenkov Telescope Array Observatory



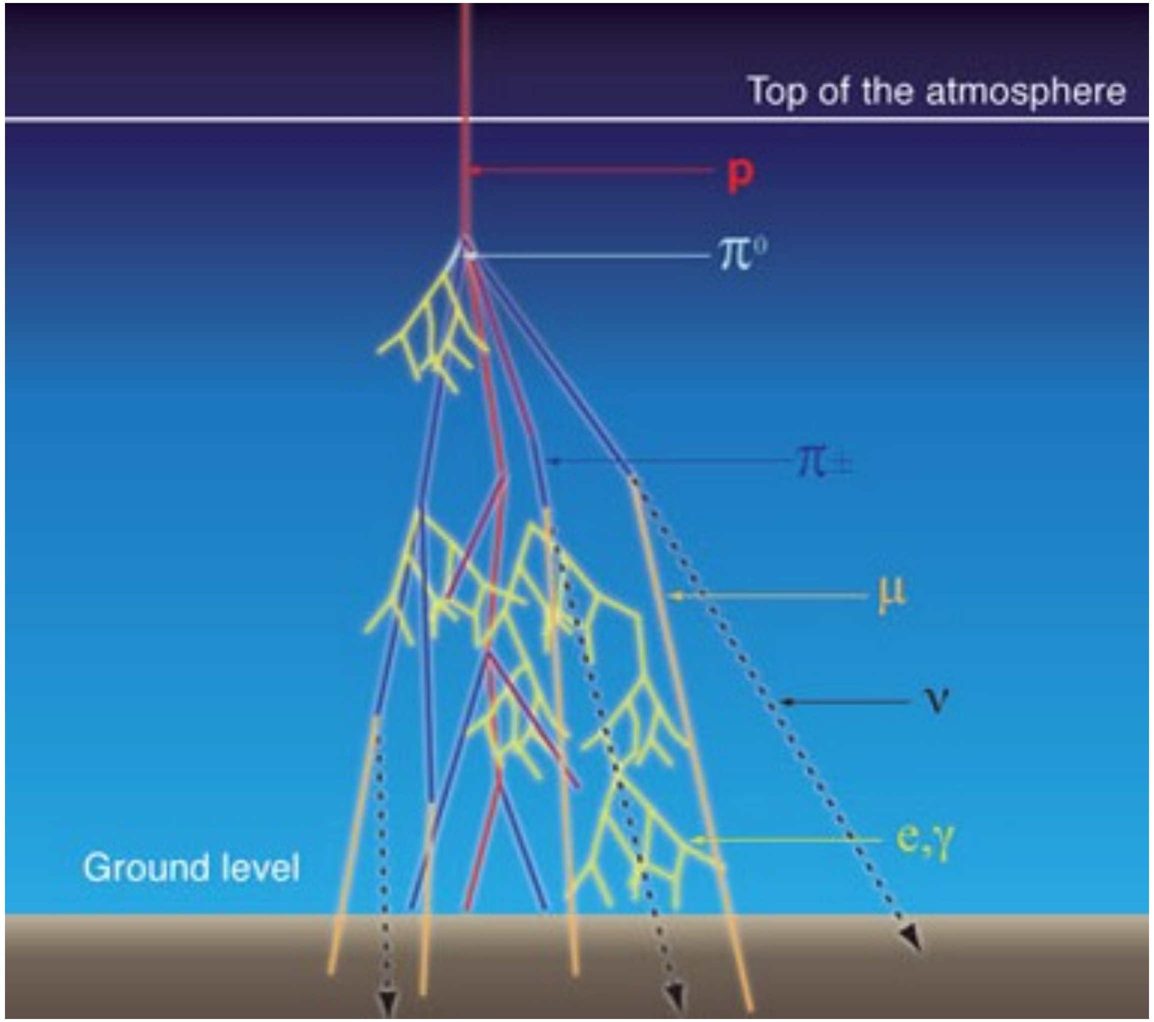
- Cherenkov Telescope Array Observatory is the future of IACT.
- LST is the largest among CTAO's telescopes.
- It is operating since November 2019 year.

North site (Canary Islands, Spain)

Muons are produced in the proton induced showers

Visualisation of the extensive air shower in the atmosphere

Schematic representation of EAS development initiated by proton



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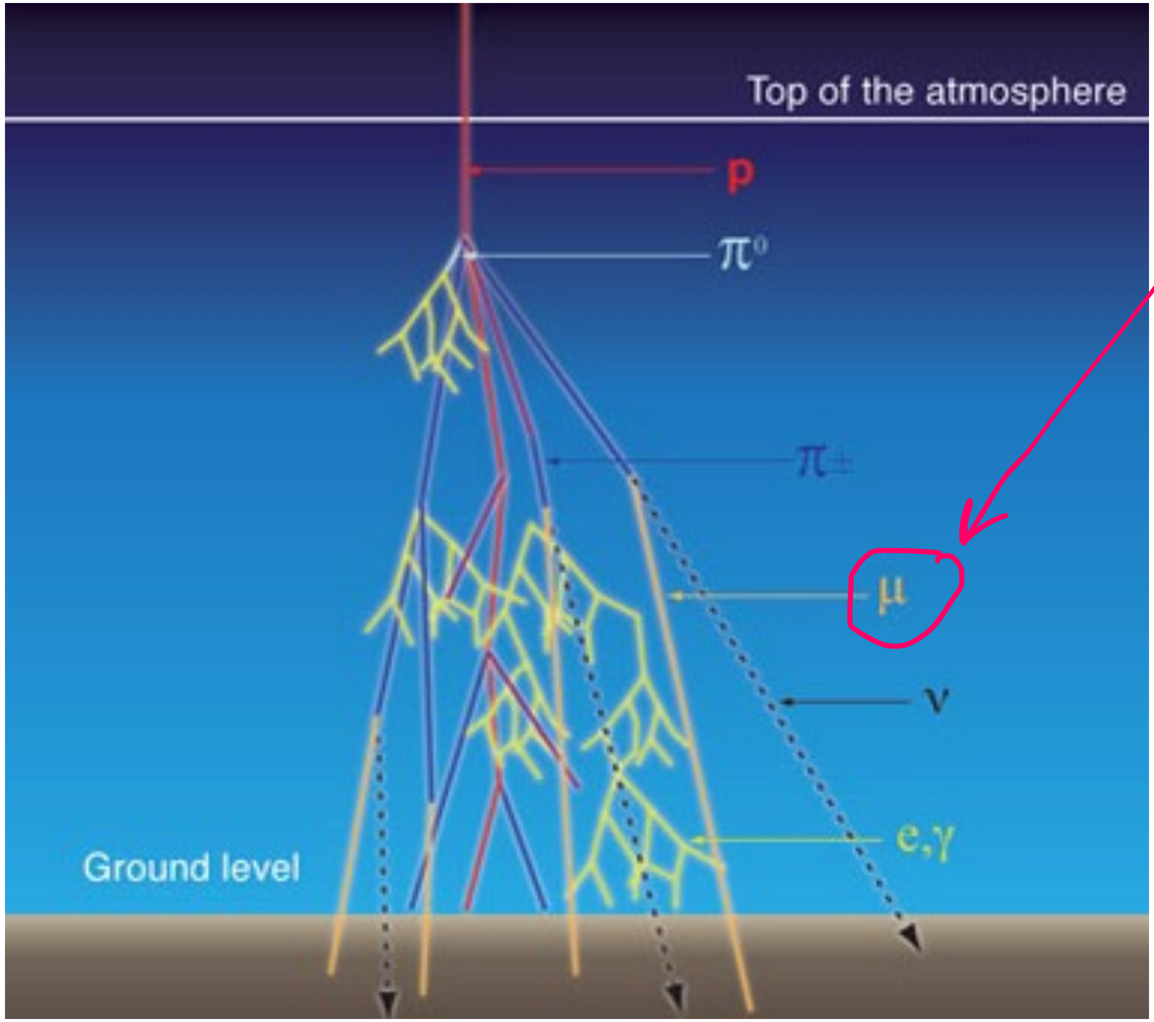
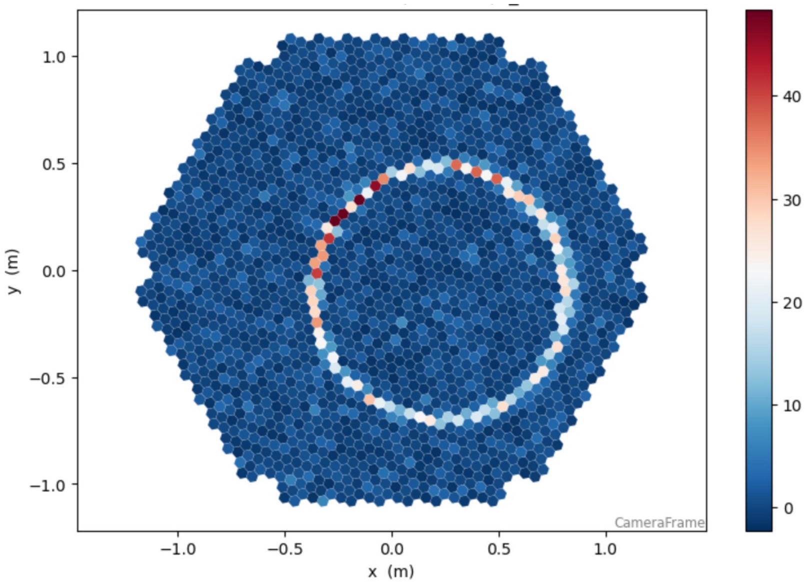


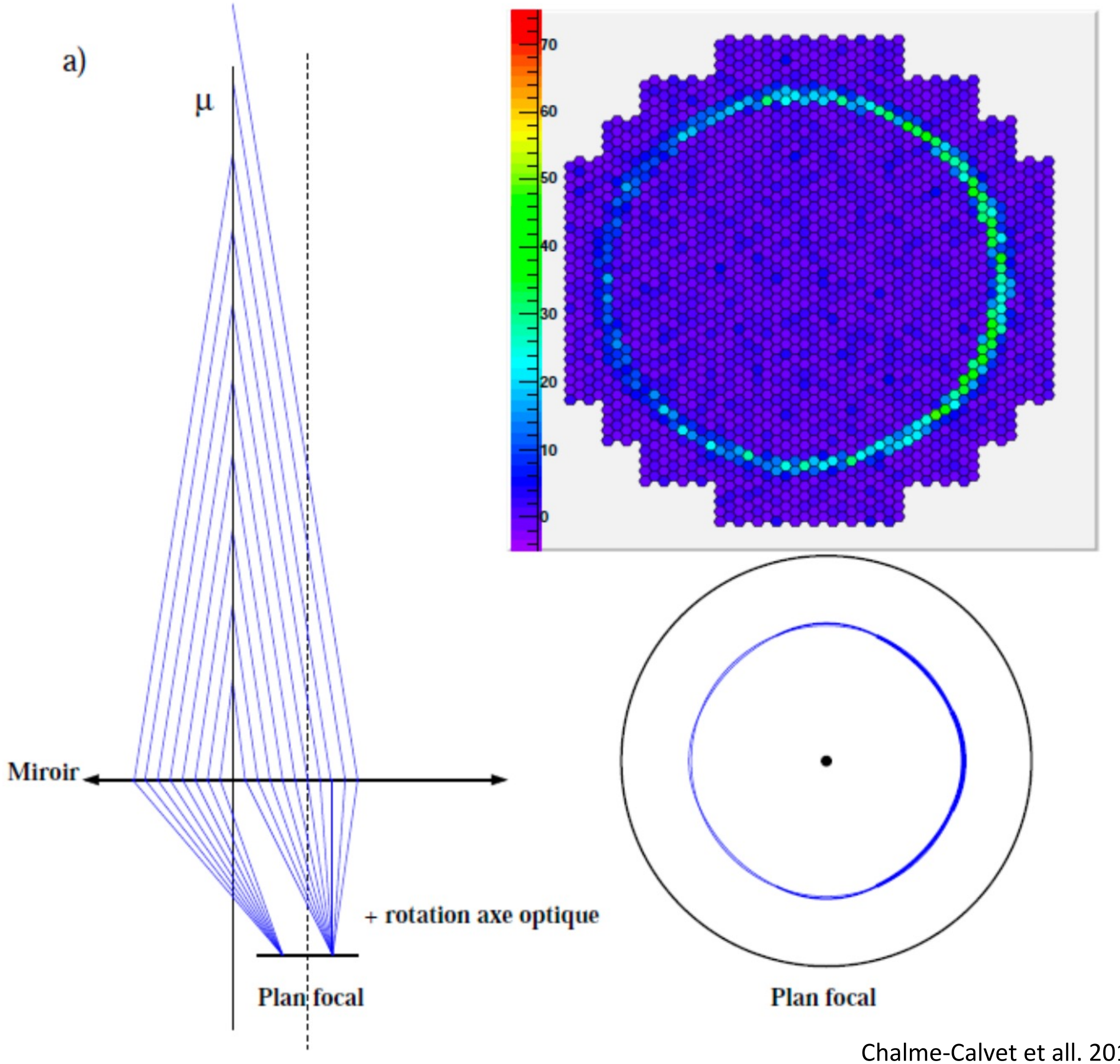
muons

Detection of the muons

- Muons passing through atmosphere emit Cherenkov light in the cone.
- Light reflected from the mirror is observed as a ring on the focal plane of the camera
- Light emitted by muons can serve as a continuously available calibration light source



Muon ring as detected by LST-1

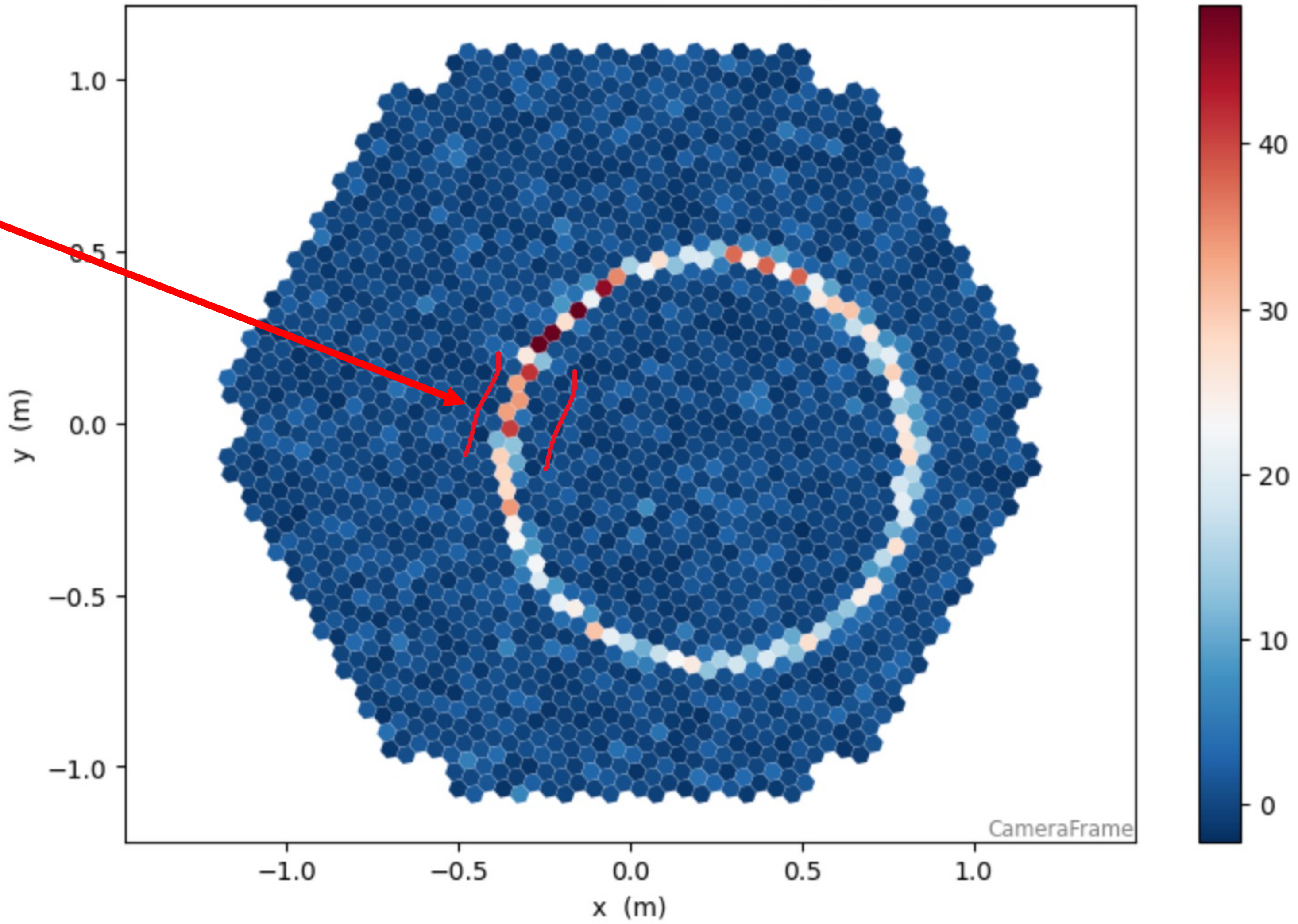


Chalme-Calvet et all. 2014

Muon ring parameters explained - width

- Width:
  - Gaussian width of muon ring in degrees
- Radius
- Size

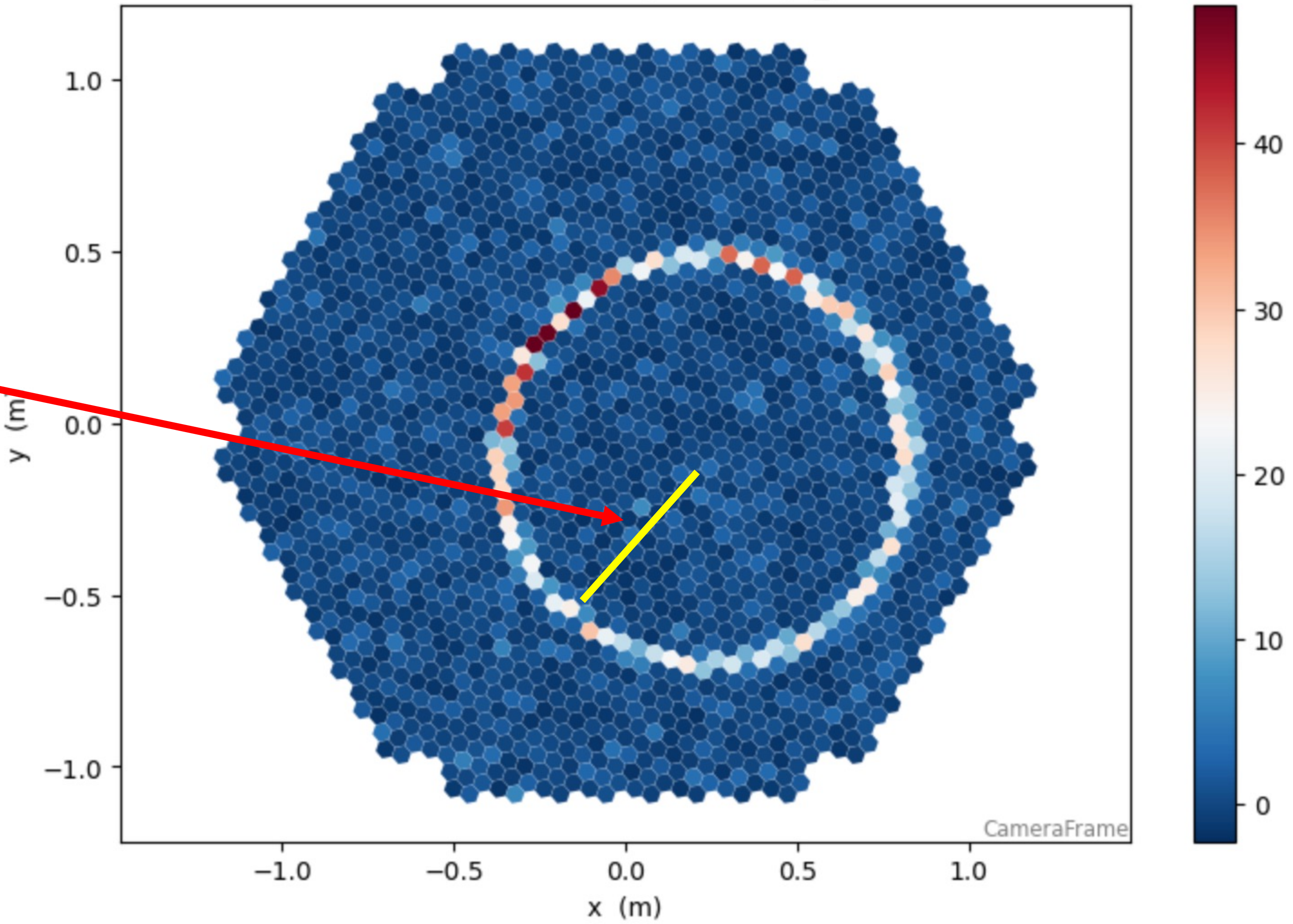
Image of muon ring as seen by LST-1



Muon ring parameters explained - radius

- Width:
  - Gaussian width of muon ring in degrees
- Radius
  - Radius of muon ring in degrees (Cherenkov angle of the muon)
- Size

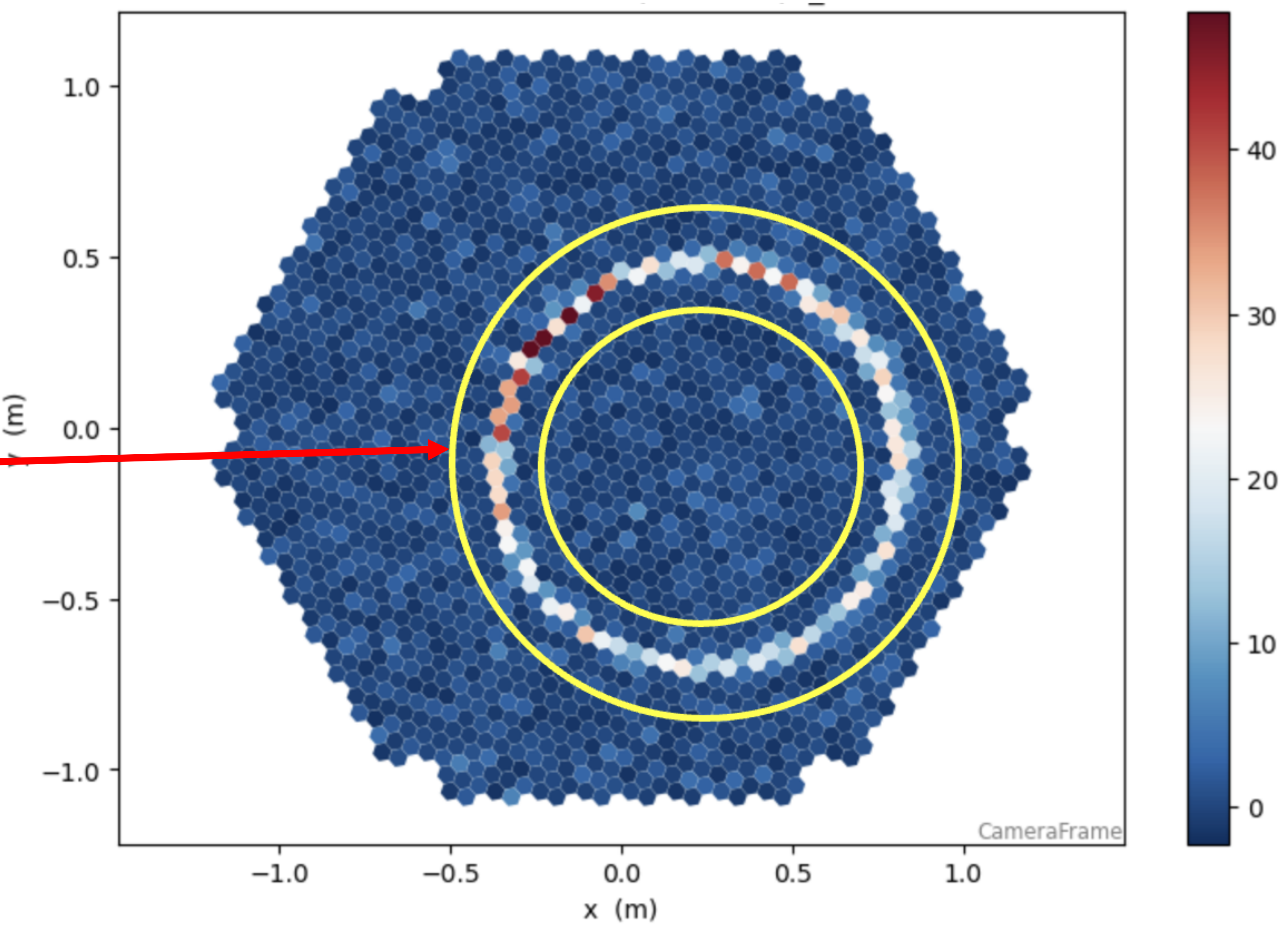
Image of muon ring as seen by LST-1



Muon ring parameters explained - size

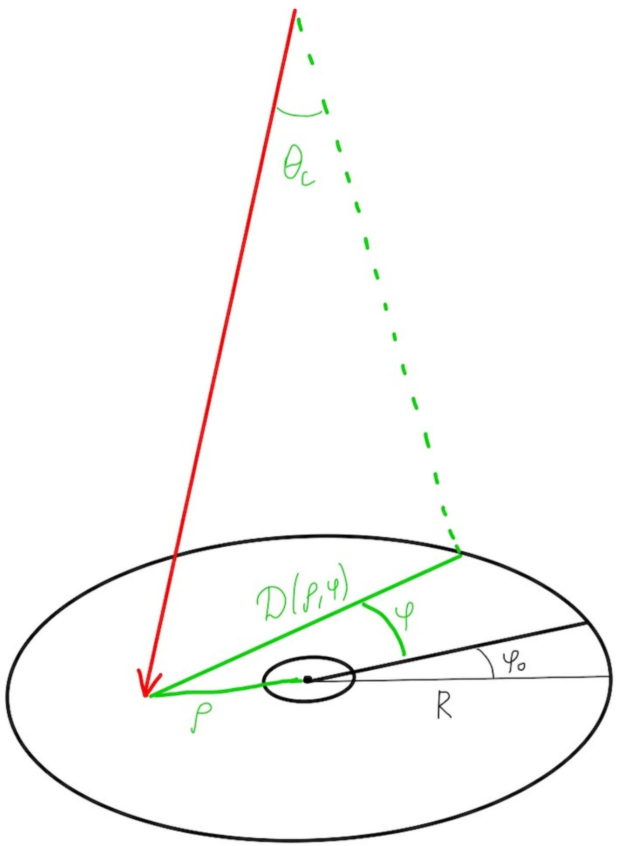
- Width:
  - Gaussian width of muon ring in degrees
- Radius
  - Radius of muon ring in degrees (Cherenkov angle of the muon)
- Size
  - Sum of the photoelectrons in the region R $\pm 0.25R$

Image of muon ring as seen by LST-1



What do we do with muons when they are detected

1. We reconstruct the ring geometry by simple analytical fit, to found out:
   - Ring center
   - Radius
2. Performed Minuit-based max log-likelihood fit between analytical model and observation to obtain next parameters:
   - Impact point of the muon on the mirror
   - Ring width
   - Optical efficiency



Analytical model for the light distribution along the muon ring:

$$\frac{d^3N}{d\phi d\lambda d\theta} = \frac{\alpha}{2} \cdot \sin 2\theta_c \cdot D(\phi) \cdot \frac{1}{\lambda^2} \cdot F(\theta; \theta_c, \sigma) \cdot \frac{\pi}{4} \cdot \Psi$$

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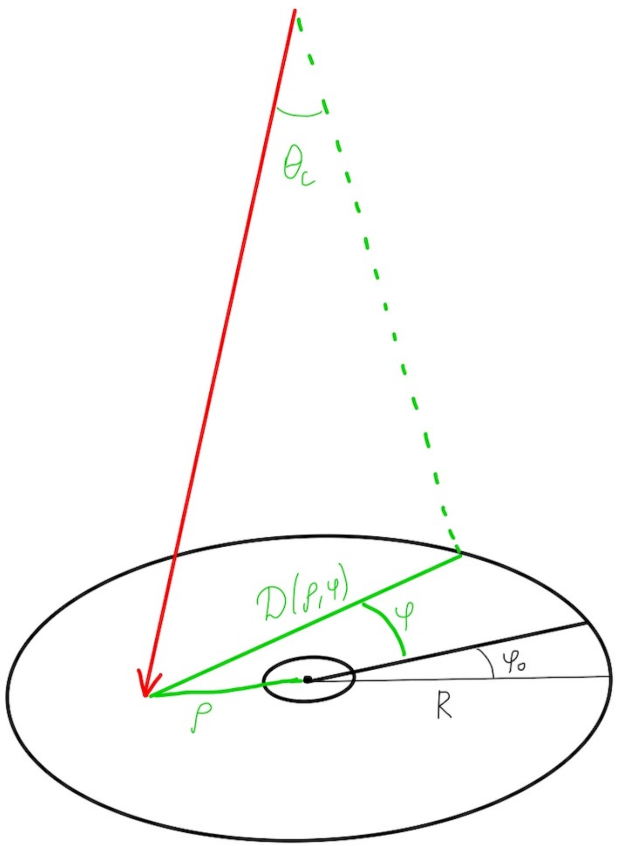

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optical efficiency

Optical efficiency of the telescope

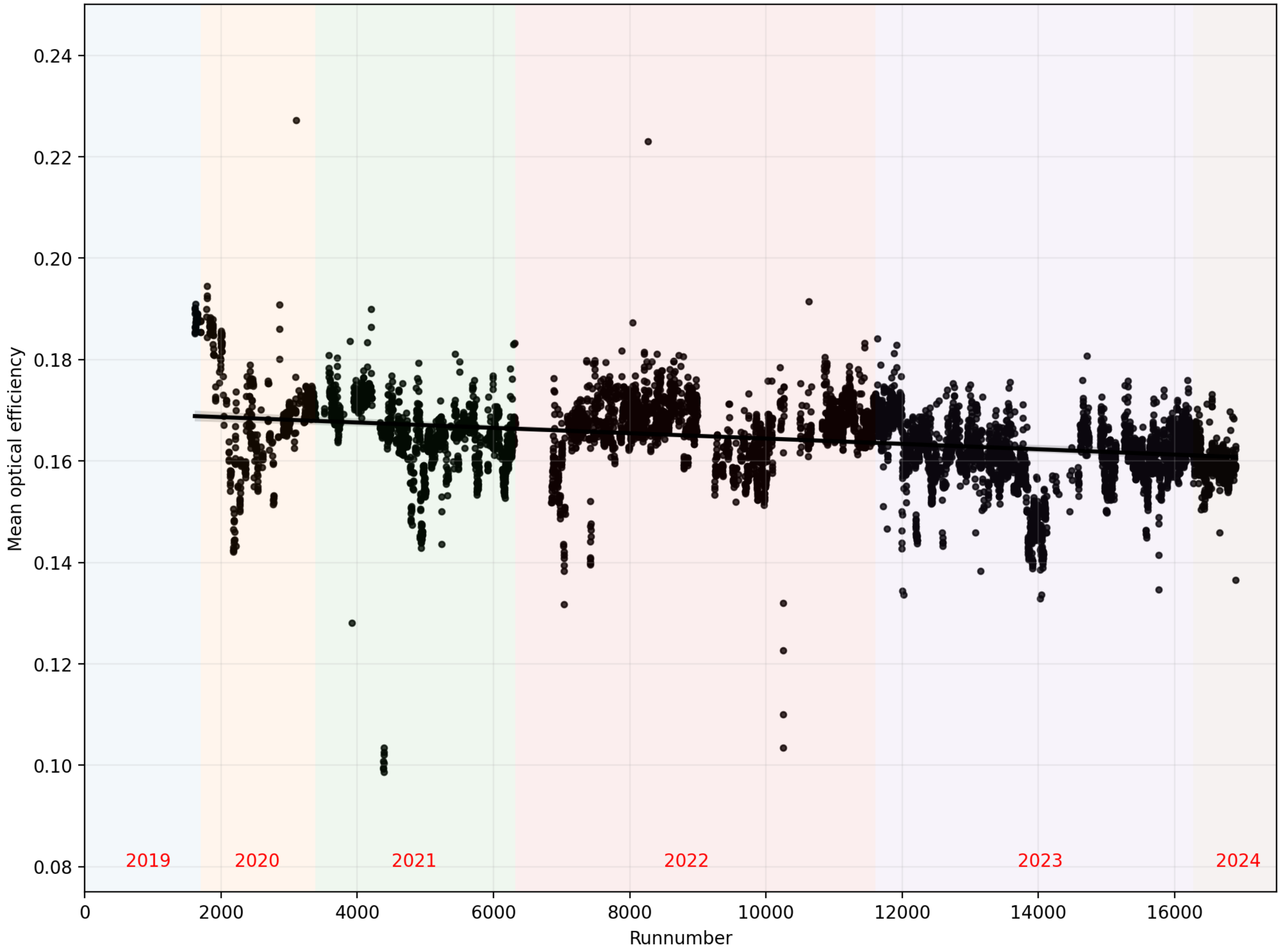
- The optical efficiency of a telescope is the parameter quantifying the capability of the optical elements of a telescope in reflecting and processing light.

- Optical efficiency degrade with time due to
  - Degradation of mirror reflectivity
  - Degradation of the photomultipliers

- Data for Jan 2020 - July 2024

Year	Optical efficiency value
2020	0.1699
2021	0.1648
2022	0.1663
2023	0.1610
2024 (Jan-July)	0.1601

optical efficiency vs time (runnumber)

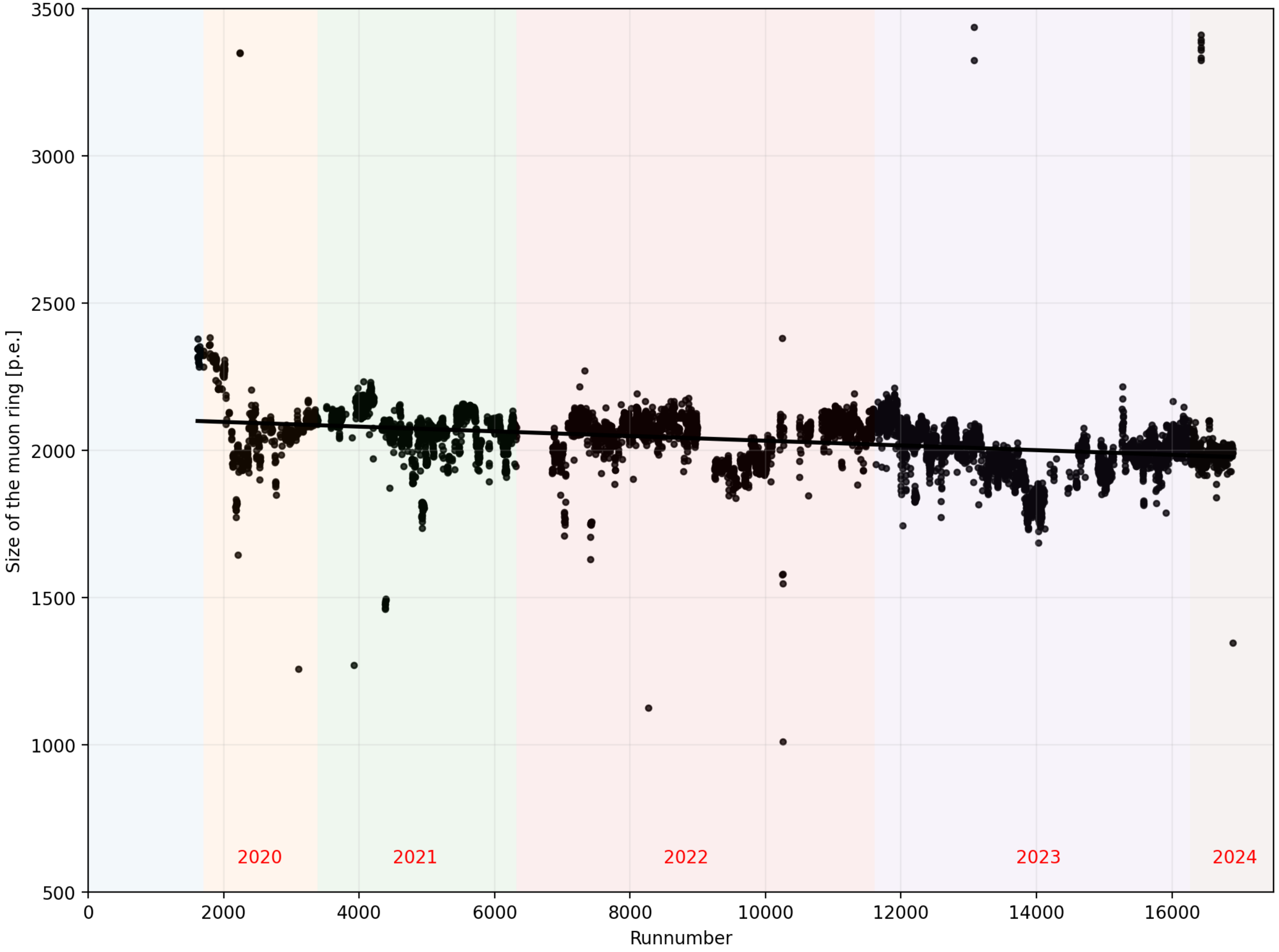


Evolution of ring size with time

- Ring size is proportional to the optical efficiency of the telescope.
- Ring size calculation doesn't depends on the additional fitting procedure of model to observations.
- Change in mean ring size from 2020 to 2024 year is around 5%

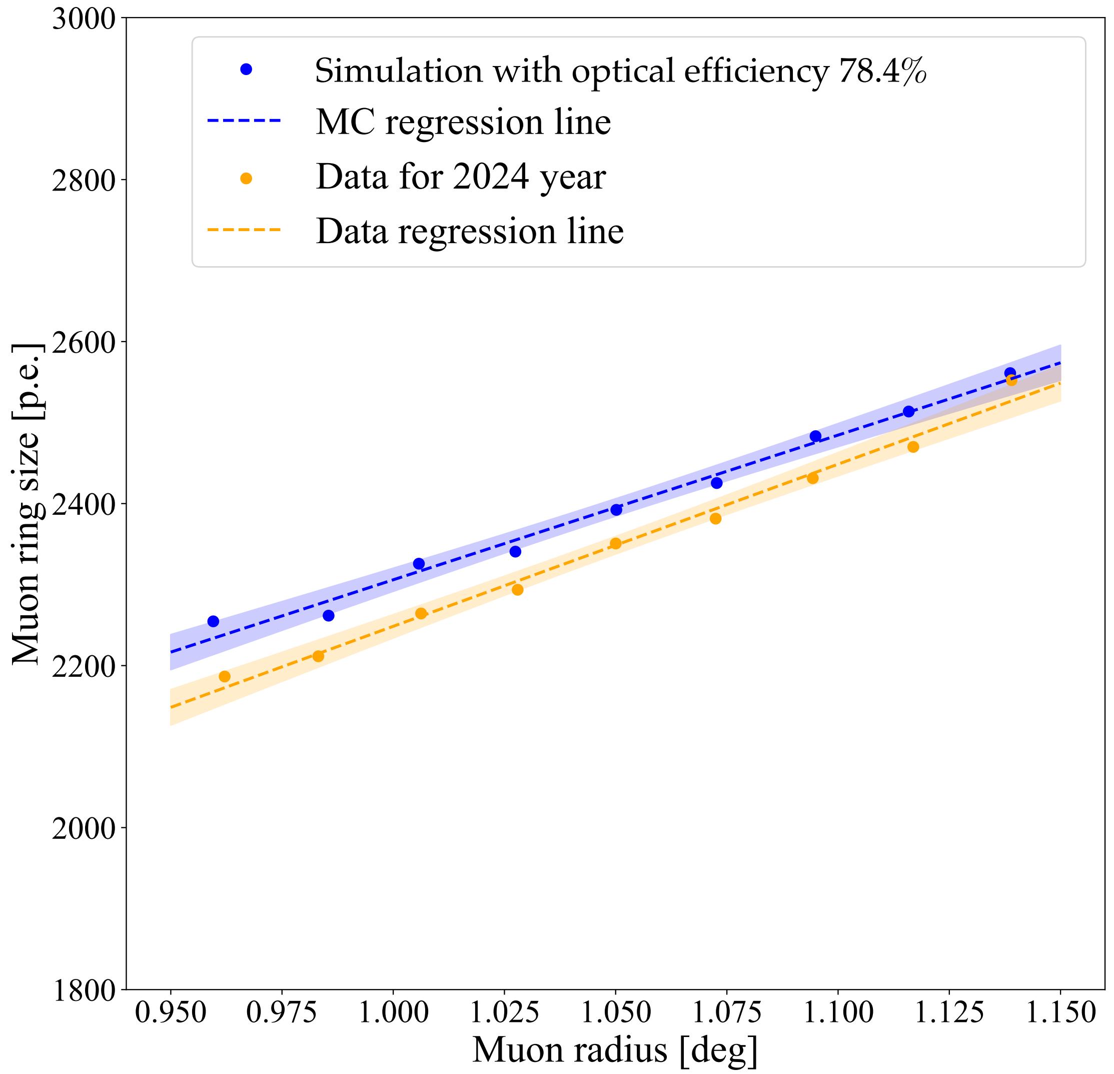
Year	Mean ring size (p.e.)
2020	2080
2021	2064
2022	2050
2023	1993
2024 (Jan-July)	1986

ring size vs time (runnumber)



Comparison of ring size between observations and simulations

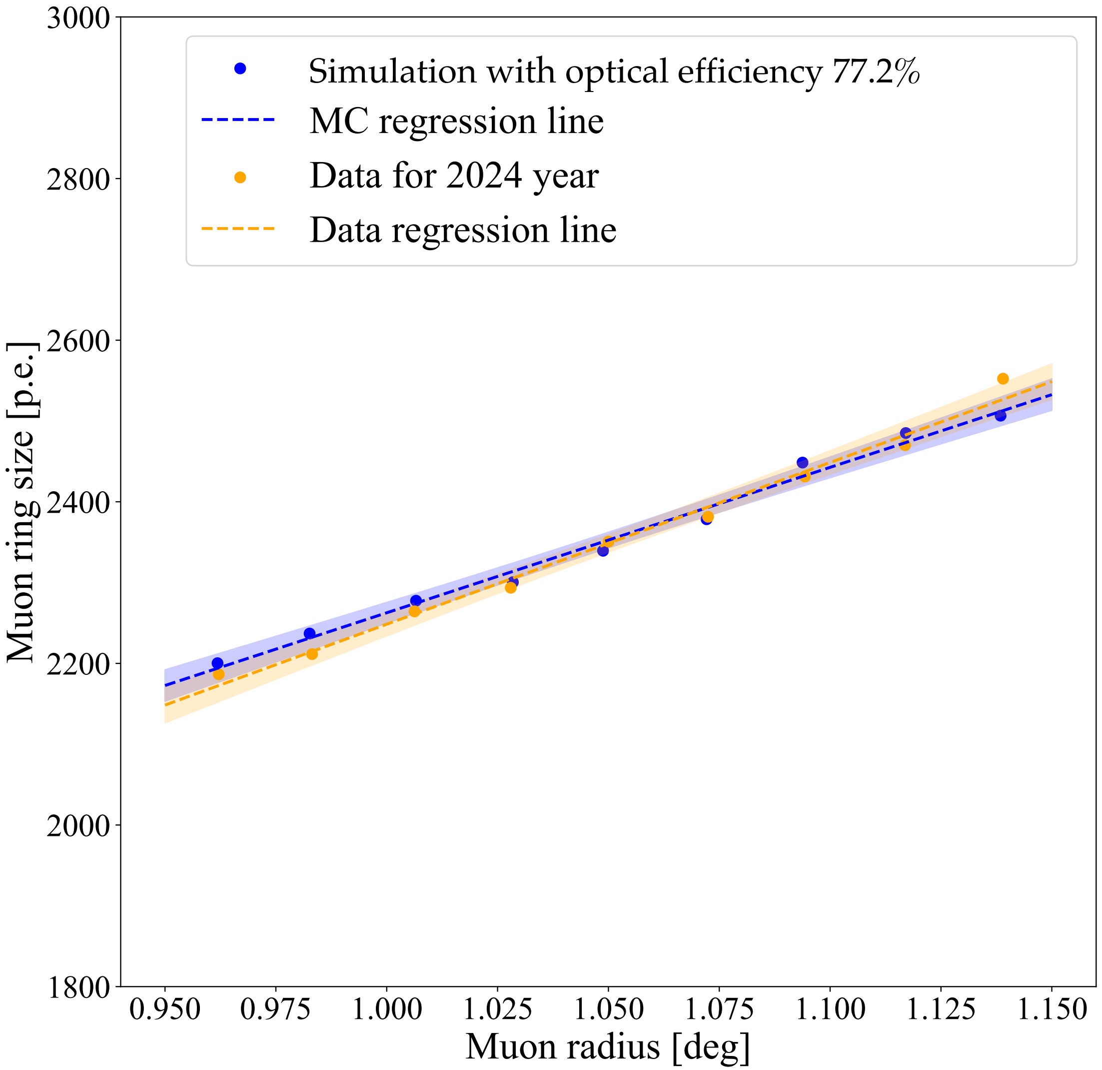
- Dependence of the ring size on the radius can be used to trace the changes in optical efficiency of the telescope
- Optical efficiency of the telescope can be set as a flat configurational parameter in the simulations.
- We can manually tune the optical efficiency parameter in simulations to coincide with the observational data and in that way estimate its real absolute value.



Comparison of ring size between observations and simulations

- By aligning the simulated curve with observable one we can find out the absolute value for the optical efficiency
- Precision of the proposed method lies in the range of 5%.
- We can see the good agreement with other methods – the decrease in absolute optical efficiency value is the same 5 %

Year	Absolute optical efficiency
2020	82.3%
2021	79%
2022	78.4%
2023	77.6%
2024 (Jan-July)	77.2%



To take home

- Muons proved themselves as a reliable source of calibration for the Imaging Atmospheric Cherenkov Telescopes

- Changes in optical efficiency after 4 years of LST-1 operation is around 5%

- By comparison of muon ring size vs muon ring radius distribution, we can estimate absolute optical efficiency value of the telescope, with accurasy and precision of 5%

Thanks for the attention

Here is the new image of a cool muon in Zurich, relaxing at an outdoor café with a scenic view of the city and the Alps. Let me know if it captures the vibe you were looking for!

Back up

Comparison between the observations and simulations

To simulations and observations were applied same post-processing quality cuts:

lstchain standard muon cuts +

Parameter name	Cut value
Muon efficiency	< 1
Size outside the ring	< 500 p.e.
Ring completeness	$> 90\%$
Ring containment	$> 90\%$

Simulation ***corsika+simtel*** configuration:

Parameter name	Value
Zenith	0 deg
Viewcone	4.8 deg
Impact parameter	15m
Energy	6 GeV – 10 TeV

+ latest standard lst-simtel config from GitHub

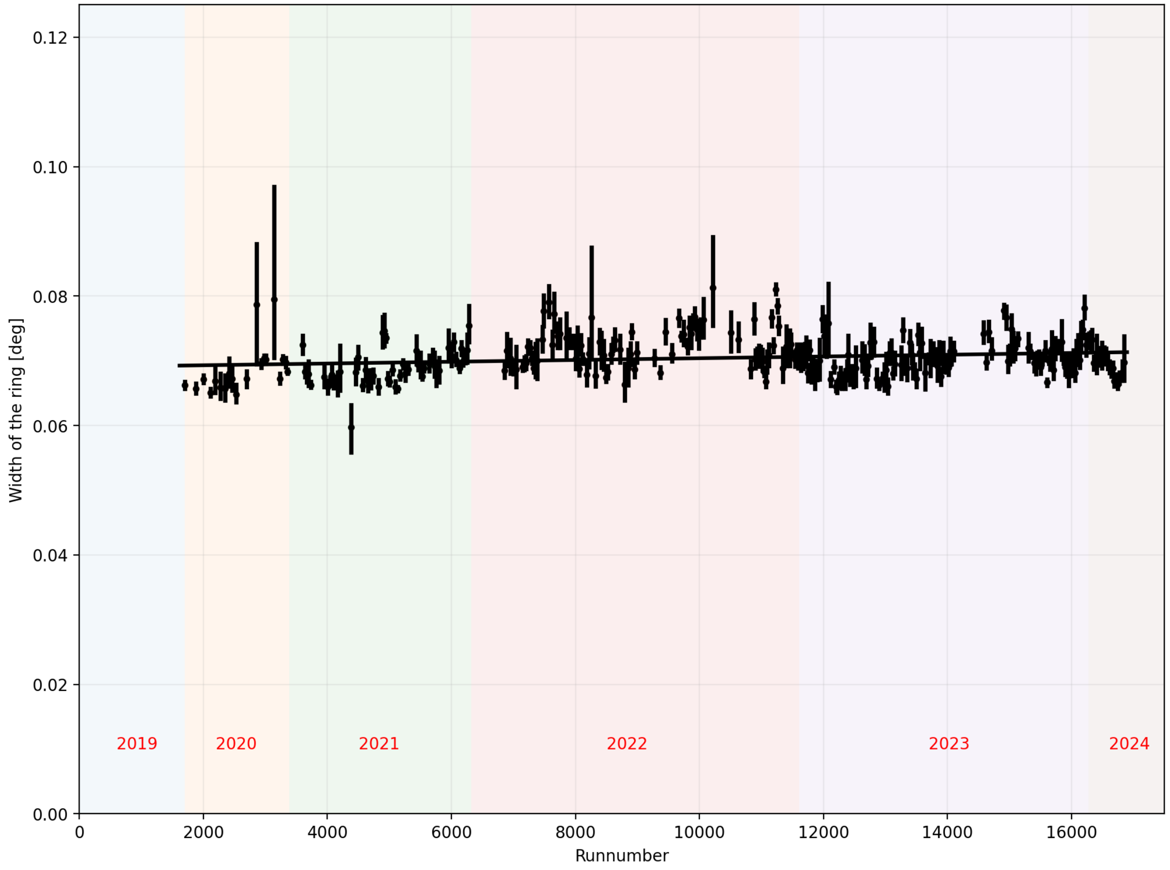
with:

mirror reflectivity = 78.4%

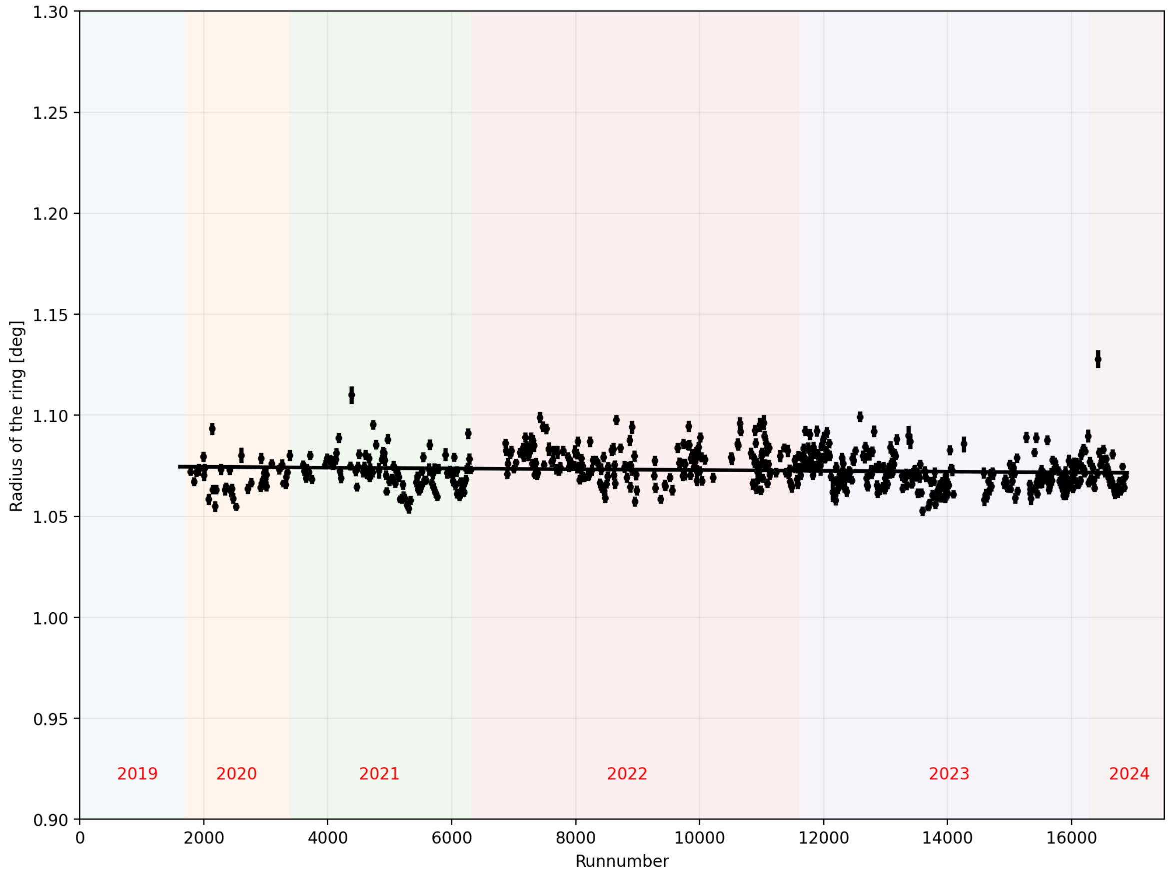
night sky background = 0.24GHz

Evolution of ring width and radius with time

ring width vs time (runnumber)



ring radius vs time (runnumber)



There is **3.2% raise in mean ring width** value from 2020 to 2024 year

Expression regarding muon reconstruction

$$D(\phi) = \begin{cases} 2R\sqrt{1-(\rho/R)^2\sin^2\phi} & \text{if } \rho > \mathrm{R} \\ R\left(\sqrt{1-(\rho/R)^2\sin\phi^2} \right. \\ \qquad \left. + (\rho/R)\cos\phi\right) & \text{if } \rho \leq \mathrm{R} \end{cases}$$

$$(1 + \mathrm{erf}(\frac{\theta - \theta_c}{\sqrt{2}\sigma}))$$

$$\cos\theta_c(x, \epsilon) = \frac{1}{\beta_\mu(x) \cdot n(\epsilon, x)}.$$

$$\theta_c \simeq \theta_\infty \cdot \sqrt{1 - (E_t/E_\mu)^2},$$

$$\Theta(\rho, v, \phi) \approx \Theta(\rho_R, \phi) = 1 - \frac{r}{R} \cdot \frac{D(\rho_R \cdot \frac{R}{r}, \phi)}{D(\rho_R, \phi)}.$$

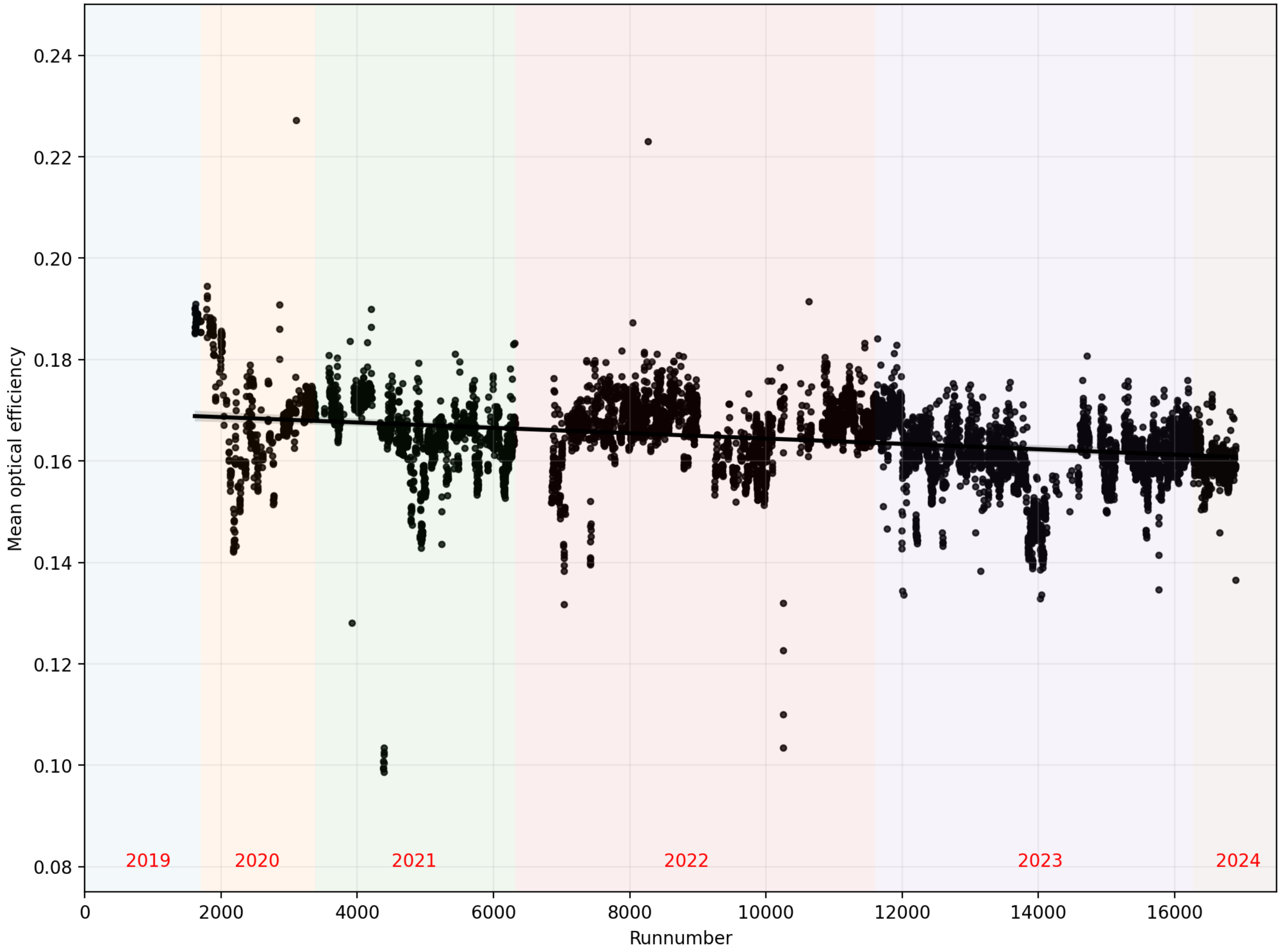
$$E_t(x, \epsilon) = \frac{m_\mu \cdot c^2}{\sqrt{1 - 1/n(\epsilon, x)^2}},$$

Evolution of optical efficiency with time

- November 2019 - February 2024
- 7153 low NSB runs
- Low NSB – runs with < 2.3 std dev of charge pedestals, which roughly corresponds to selecting moon-less data
- Change in mean optical efficiency from 2020 to 2024 year is around 5%

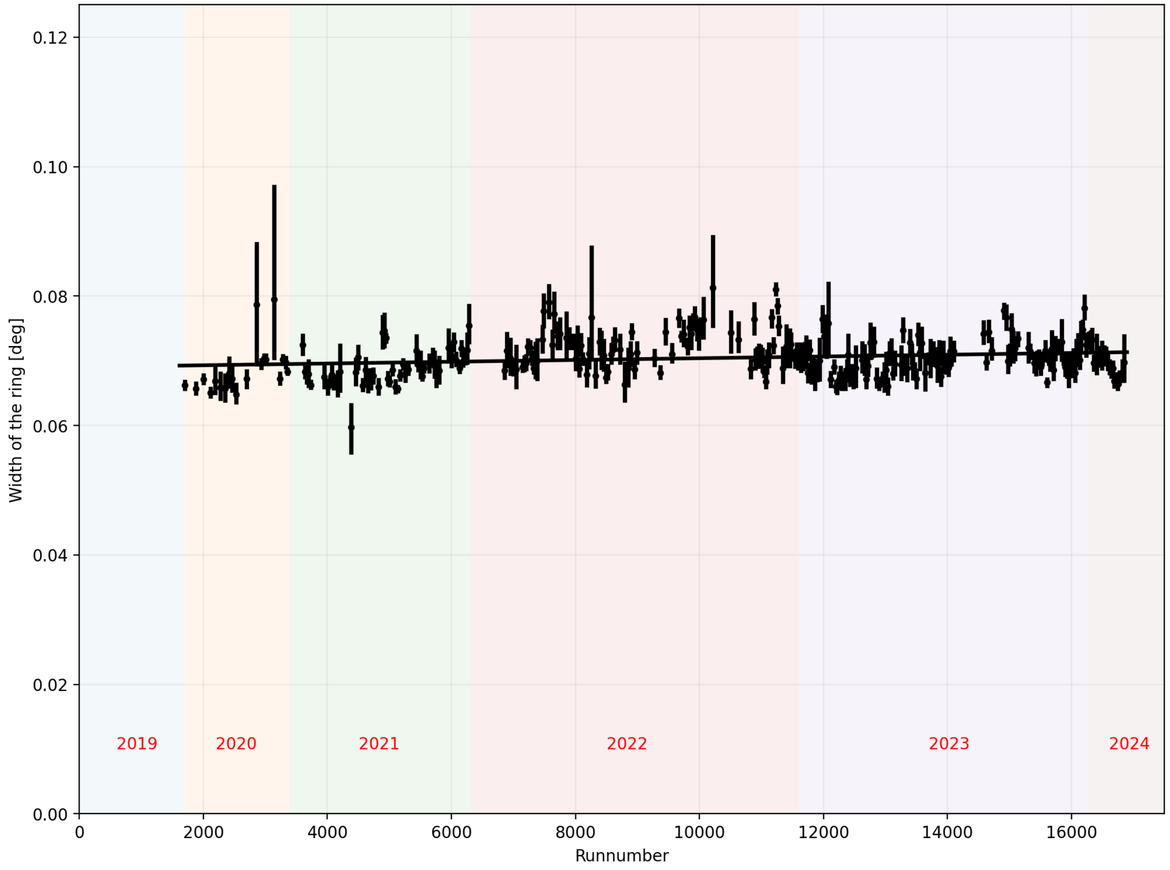
Year	Optical efficiency value
2019	0.1877
2020	0.1699
2021	0.1648
2022	0.1663
2023	0.1610
2024 (Jan-Feb)	0.1656

muon efficiency vs time (runnumber)

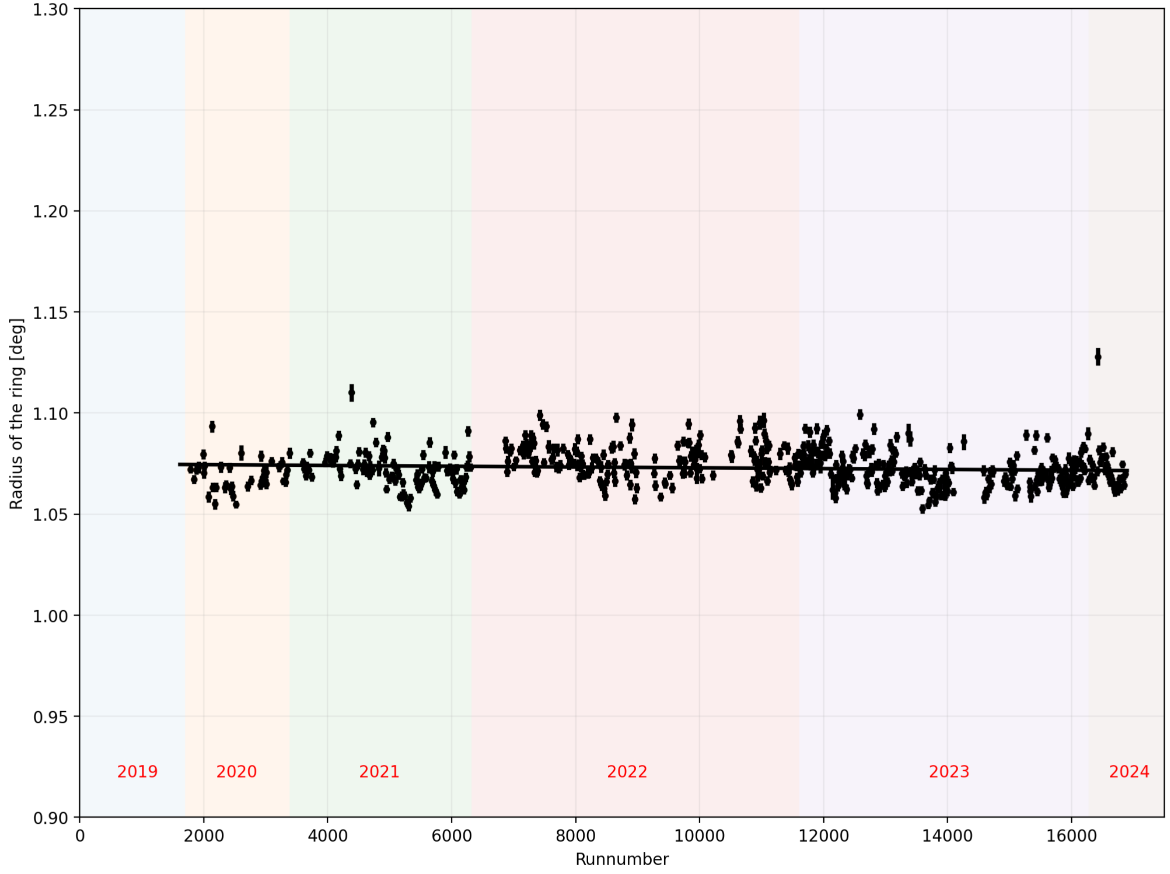


Evolution of ring width and radius with time

ring width vs time (runnumber)



ring radius vs time (runnumber)



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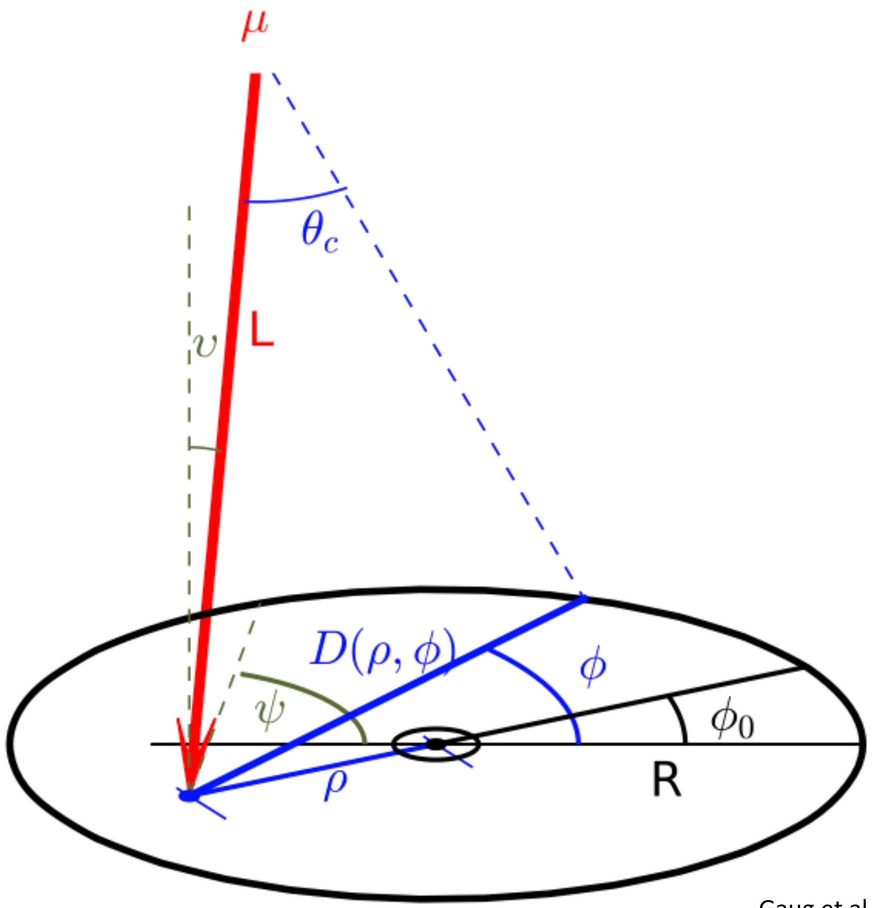

Gaug et al 19

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Chalme-Calvet et all. 2014