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Measurement of the Muon Rate at the SND Experiment with the Timepix3 Radiation Monitor

Emanuela Revani[1,2], Daniel Prelipcean[1,], Giuseppe Lerner[1], James Storey[1], Simona Ilieva Ilieva[1]*

[1]CERN (CH-1211 Geneva), [2]Constructor University (28759 Bremen), [*]Corresponding author: daniel.prelipcean@cern.ch

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1. Introduction

Using the Timepix3 Radiation Monitor [1], a test campaign at the Scattering and Neutrino Detector (SND) [2] location in the Large Hadron Collider (LHC) was performed, aiming to measure the muon rate during proton-proton (*pp*) luminosity production at the ATLAS Interaction Point 1 (IP1).

The results are compared with both dedicated simulations performed with the FLUKA.CERN [3–5] simulation code and the SND@LHC measurements [6].

2. Muon Filtering Steps

1. Muons behave like Minimum Ionizing Particles (MIPs) in the energy range of≈ 100 GeV, thereby leaving straight tracks in Timepix3 detector [7,8]. As such, only these straight tracks are retained.
2. Due to the detector orientation, the straight tracks are expected around an azimuth angle of **φ=(90 ± 26.57)°**, but considering as well possible misalignments with the Line of Sight (LOS) from IP1.
3. Considering the orientation of the detector at **Θ_0 = 39.1°** the maximum cluster length (L) that a muon can have is 6 pixels. Therefore, clusters with a length of **L = 3 up to 6** were considered.

3. Muon Energy Deposition Distribution

Most of the muons have an energy of 100 GeV [2], corresponding to a linear energy transfer (LET) of $dE/dx|_{Si}$ = 6.5 MeV/cm in Silicon [9]. Given the incidence angle **Θ_0**, the expected energy deposition in the detector is found to be E_{dep} ≈ 209 keV, assuming a muon passing, through 6 pixels. The Timepix3 Radiation Monitor measures a Time-over- Threshold (TOT) distribution for the muon beam, with a Gaussian peak of:

$$ToT = (203 \pm 61)\ [25\ ns] \qquad E_{dep} = (182 \pm 38)\ [keV]$$

4. Bunch-by-bunch resolution

The Timepix3 detector has a ToA time resolution of 25 ns, matching the LHC bunch spacing [10], and a fast Time-of-Arrival (fToA) clock with a refined resolution of 1.625 ns.

A clear structure in the beam is observed as most of the particles arrive with low fToA values, showing that the Timepix3 Radiation Monitor can measure the bunched beam over longer periods of time; however, a bunch-by-bunch instantaneous measurement is not possible as the count rate is not high enough to yield a strong enough signal.

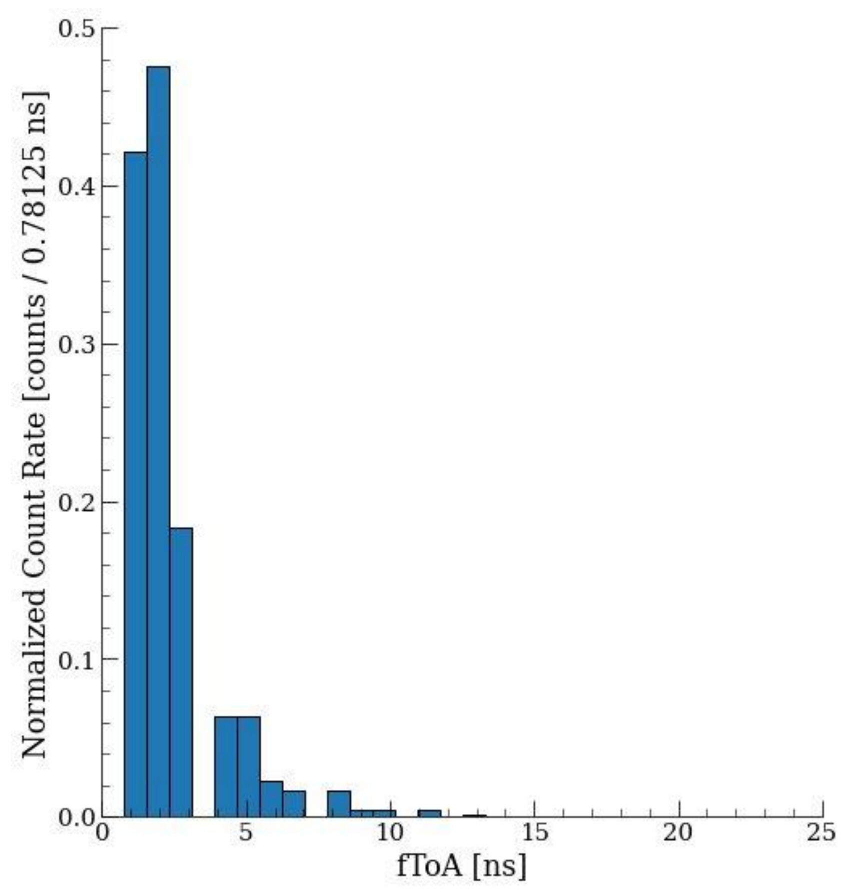

Fig. 2: The fToA distribution of the filtered muon rate, as measured by the Timepix3 Radiation Monitor. One fToA unit corresponds to 1.5625 ns.

5. Timepix3 Count rate

Operationally, the LHC fill stages [10], start with injection of the proton bunches, accelerating and then colliding the two beams, thereby producing the instantaneous luminosity L_{inst}. Seven fills were successfully measured, and after isolating the muon signal, the measured Timepix3 muon rate ϕ_μ is:

$$\phi_\mu^{Timepix3} = (4.88 \pm 0.78) \cdot 10^4\ \text{counts}/(\text{fb}^{-1}\cdot\text{cm}^2)$$

where an effective count rate is obtained by considering the orientation of the Timepix, and a uniform irradiation over the detector's area A=2.14 cm^2.

The contributing sources of uncertainty are: the Poisson measurement statistics of the Timepix3 detector ΔΦ = 14%, the fitting result of Δ_{fit} = 2% and the luminosity measurement uncertainty assumed at ΔL = 2% [10].

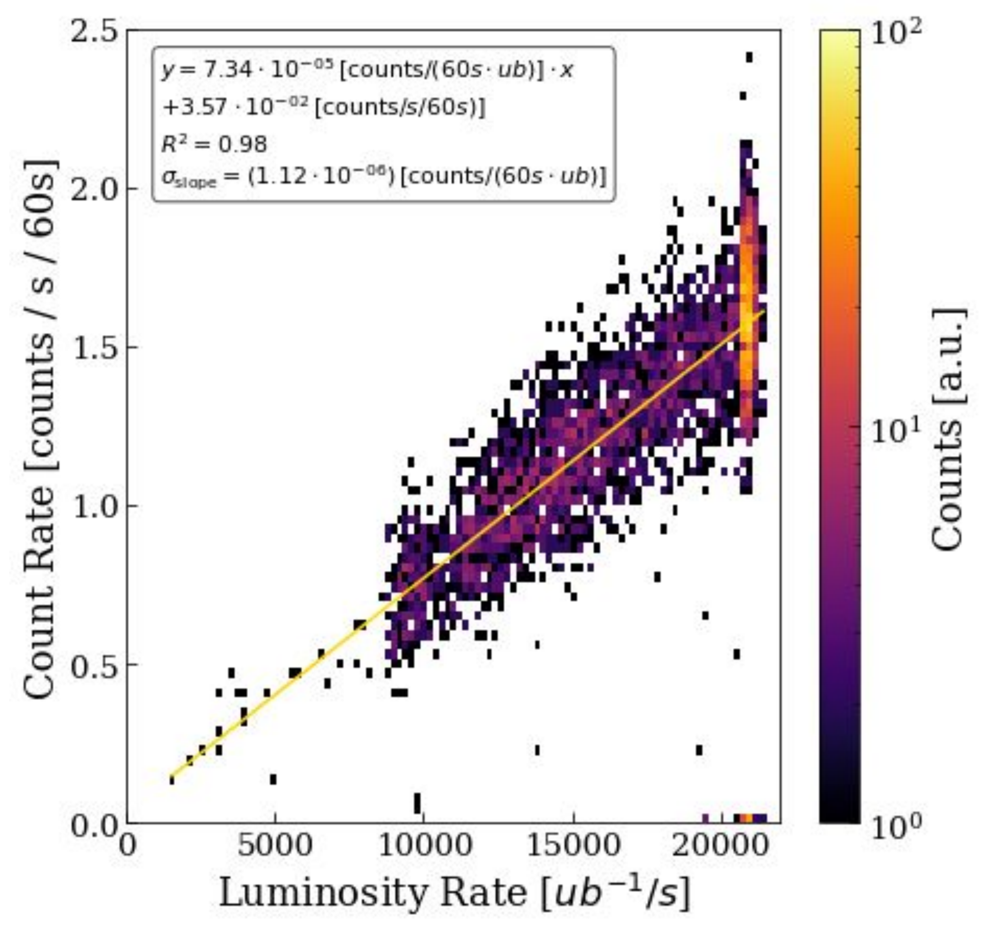

Fig. 1: Timepix3 particle rate ϕ_μ plotted against the instantaneous delivered luminosity L_{inst} at IP1, revealing a linear correlation.

The measured Timepix3 muon flux agrees within uncertainty with the SND muon flux measured in 2024 at:

$$\phi_\mu^{SND@LHC} = (4.16 \pm 0.19) \cdot 10^4\ \text{counts}/(\text{fb}^{-1}\cdot\text{cm}^2)$$

where the error bar is given by the quadrature sum of statistical and systematic ones, where for the latter the ΔL = 2% uncertainty on the IP1 luminosity is assumed, and $\Delta\varepsilon_{SciFi}$=4% SciFi tracking efficiency uncertainty. Moreover, the FLUKA simulated values is reported [11] at:

$$\phi_\mu^{FLUKA} = 4.79 \cdot 10^4\ \text{counts}/(\text{fb}^{-1}\cdot\text{cm}^2)$$

5. Conclusions

The Timepix3 Radiation Monitor detector successfully measured the muon rate at the SND experiment, located around IP1 of the LHC.

- After applying selection filters, the measured muon flux was determined, matching the SND@LHC muon flux measured in 2024, and the FLUKA simulated one.
- The energy deposition is consistent with the expected 100 GeV muons coming from IP1.
- Considering the bunch-by-bunch resolution analysis, a clear structure of the beam was observed in the measured fToA values, as most of the particles arrive with low or close to zero fToA values.

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