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MEASUREMENT OF THE MUON RATE AT THE SND EXPERIMENT WITH THE TIMEPIX3 RADIATION MONITOR

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Abstract

Using a Timepix3 Radiation Monitor, the muon rate at the Scattering and Neutrino Detector (SND) location at the Large Hadron Collider (LHC) was measured during luminosity production at the ATLAS collision point. Filters are applied on the measured data to distinguish between background radiation and the muon signal by analyzing the cluster morphology. The energy deposition E_{dep} of the muons are consistent with the FLUKA simulated muons coming from ATLAS *pp* collisions, with an energy distribution peaked at 100 GeV. The Timepix3 measured muon rate is reported here at $(4.88 \pm 0.78) \cdot 10^4$ counts/(fb^{-1} cm^{-2}), which agrees within the uncertainty with the SND reported one at $(4.16 \pm 0.19) \cdot 10^4$ counts/(fb^{-1} cm^{-2}) and the FLUKA simulated one at $4.79 \cdot 10^4$ counts/(fb^{-1} cm^{-2}). Finally, taking advantage of the Timepix3 detector time resolution of 1.5265 ns, the bunch-by-bunch spacing (25 ns) of the beam is assessed.

INTRODUCTION

A test campaign at the Scattering and Neutrino Detector (SND) [1] location in the Large Hadron Collider (LHC) [2] was performed, aiming to measure the muon rate during proton-proton *pp* luminosity production at the ATLAS Interaction Point 1 (IP1) [3]. The results are compared with both dedicated FLUKA [4–6] simulations and the SND@LHC measurements [7].

The test campaign involved the Timepix3 Radiation Monitor [8], a p-in-n Silicon detector composed of 256 × 256 pixels with a pixel pitch of $p = 55\,\mu$m, which was operated at a partial bias voltage of 50 V leading to a depletion volume thickness of $W = 250\,\mu$m. The data collection was performed during the LHC proton operation at $E_p = 6.8$ TeV in 2024 from the beginning of the operational year until Technical Stop 1 (February until June 6th). The detector was placed at the SND experiment location in the TI18 tunnel, roughly 480 m away from IP1, where the *pp* collisions are the source of neutrinos for SND [9, 10].

The measured data was filtered based on cluster morphology to isolate the muon signal from other sources of background, and then compared to the SND 2024 measurements [7]. The result is consistent with the expected energy deposition in the sensor from FLUKA simulations. The Timepix3 detector capabilities were further utilized to examine the bunch-by-bunch structure of the LHC beam, as well as to study the angular and spatial distribution of the muons flux.

MUON SELECTION: FILTERING STEPS

Filters have been applied to discriminate the muon signal from other sources of background radiation, by analyzing the cluster morphology: shape, reconstructed angle of incidence, and length.

Cluster Shape

Muons behave like Minimum Ionising Particles (MIPs) in the energy range ($\approx$ 100 GeV) they are expected to arrive at the SND location, thereby leaving straight tracks in Timepix3 detector [11, 12]. As such, only these straight tracks are retained, while all other cluster shapes (types) are filtered out.

Azimuth Angle

The azimuth angle φ describes the orientation of the particle's trajectory within the sensor's 2D plane. Since the detector has been installed such that the incoming muons are perpendicular to the x-axis of the detector, most of the straight tracks are observed around $\varphi = 90°$. Moreover, one can use the Time of Arrival (ToA) information of the detector to assign a directionality, i.e. 90°, coming from the IP, or −90°, from the LHC arc region [2].

In practice, the detector is not perfectly aligned with the Line of Sight (LoS) from IP1, hence some muons could be reconstructed having slightly different angles than 90°. An angle of acceptance (φ_{acc}) is assumed[1], representing the maximum deviation from the ideal angle. Therefore, the considered range is $\varphi \in (90 \pm 26.57)\,°$.

Muon Track Length

A cluster length filter was also applied to differentiate the muons originating from IP1 from the background sources. The detector has been oriented with an incidence (polar) angle of $\theta_0 = 39.1°$ wrt. to the incoming muons. This choice has been made because a particle that arrives at an angle of $\Theta^{max}_{monopixel}$=12° or larger must interact with at least two pixels of the detector, thereby allowing to filter the signal by the number of pixels in the particle track, while minimally compromising on the acceptance window with a $1/\cos\theta$ factor. Considering the orientation of the detector at θ_0, the maximum cluster length (L) that a muon can have is:

$$L = \frac{W}{p \cdot \cos\theta_0} \approx 6 \text{ pixels.} \tag{1}$$

Therefore, clusters with a length of $L = 3$ up to 6 were considered, and the ones outside of this range were excluded.

[1] For this, an L-shaped cluster consisting of four pixels has been taken into account, with a length of $l = 4$ pixels and a width of $w = 2$ pixels, yielding $\varphi_{\text{acc}} = \tan^{-1}(w/l) \approx 26.57°$.

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Moreover, a summary of the filtering process, including the corresponding counts and the fraction of data retained at each step, is presented in Table 1.

Table 1: Summary of the applied filtering steps on the Timepix3 Radiation Monitor measured data, in order to isolate the muon signal coming from IP1.

Step	Description	Count	%
0	Initial Data Count	1 572 946	100.00
1	Cluster Type: Straight Tracks	881 818	56.06
2	Azimuth angle $\varphi \in [90 \pm 26.57]^\circ$	499 693	31.77
3	Cluster Length: $L \in [3, 6]$	358 538	22.79

MUON ENERGY DEPOSITION DISTRIBUTION

Regarding the energy distribution, most of the muons have an energy of 100 GeV [7], corresponding to a linear energy transfer (LET) of $dE/dx|_{Si} = 6.5\,\mathrm{MeV\,cm^{-1}}$ in silicon [13]. Given an incidence angle of $\theta_0 = 39.1°$, the expected energy deposition in the detector is found to be $E_{\mathrm{dep}} \approx 209\,\mathrm{keV}$, 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:

$$ToT = (203 \pm 61)\ [25\,\mathrm{ns}] \quad E_{dep} = (182 \pm 38)\ [\mathrm{keV}], \quad (2)$$

which has been converted to energy based on the calibration from Ref. [8].

MUON FLUX SPATIAL DISTRIBUTION

From the SND data [7], there is a known spatial gradient of the muon flux in the transversal plane. Along the diagonal $L = 28.28$ cm of the SND detector plane, whose SciFi tracks have an area of $A = 1600\,\mathrm{cm}^2$, this gradient is evaluated at:

$$\left.\frac{d\Phi}{dl}\right|_{\mathrm{SND}} = 3.0 \cdot 10^2\ \mathrm{counts}/(\mathrm{fb}^{-1} \cdot \mathrm{cm}^2)/\mathrm{cm}. \quad (3)$$

Considering the small active area of the Timepix3 detector with a diagonal length of just $L_{tpx} = 2$ cm, such a gradient corresponds to an absolute difference of:

$$\Delta\Phi_\mu\Big|_{\mathrm{tpx}} = \left.\frac{d\Phi}{dl}\right|_{\mathrm{SND}} \cdot L_{tpx} = 6.0 \cdot 10^2\ \mathrm{counts}/(\mathrm{fb}^{-1} \cdot \mathrm{cm}^2), \quad (4)$$

which is lower than the measurement uncertainty of the muon flux, shown later in Eq. 5. Nevertheless, due to the mentioned spatial gradient in the muon flux, knowing the position of the Timepix3 Radiation Monitor with the Line of Sight (LoS) from IP1 and with the SND detector is essential in order to compare the measured muon fluxes. The Timepix3 detector was placed with a transversal offset wrt. the IP1 LoS, of approximately $\Delta x = (-15 \pm 1)$ cm in the horizontal axis and $\Delta y = (+40 \pm 1)$ cm in the vertical axis.

TIMEPIX3 COUNT RATE

The Timepix3 Radiation Monitor is expected to measure the muons coming from *pp* collisions at IP1. Operationally, the LHC fill stages (called modes) [2], start with injection of the proton bunches beam, accelerate the beam and collide the two beams, thereby producing the instantaneous luminosity $\mathscr{L}_{inst}$. Exemplarily, fill #9694 is displayed in Fig. 1, together with the Timepix3 Radiation Monitor pixel count rate, indicating that there is no measured count rate before collisions occur. This confirms that most of the measured particles originate from collision products from the IP, and not other sources of radiation (e.g. beam-gas collisions in the arcs).

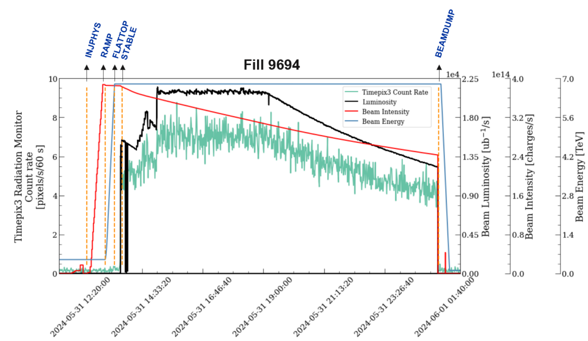

Figure 1: LHC beam cycle for fill #9694. The Timepix3 count rate (green), beam luminosity (black), and beam intensity at the interaction point (red) are shown. Dashed lines mark beam mode transitions.

Seven fills with significant luminosity production were successfully measured during the monitor's deployment. After applying the filters described above, the muon signal can be isolated. Figure 2 shows the correlation between measured Timepix3 muon rate Φ_μ and the instantaneous luminosity rate $\mathscr{L}_{inst}$, yielding a strong linear correlation as:

$$\Phi_\mu^{eff} = \frac{\Phi_\mu}{A \cdot \cos(\theta_0)} = (4.88 \pm 0.78) \cdot 10^4 \frac{\mathrm{counts}}{\mathrm{fb}^{-1}\,\mathrm{cm}^2}, \quad (5)$$

where an effective count rate is obtained by considering the orientation of the Timepix3 at θ_0, and a uniform irradiation over the detector's area $A = 2.14\,\mathrm{cm}^2$. The contributing sources of uncertainty are: the Poisson measurement statistics of the Timepix3 detector $\Delta\Phi = 14\%$, the fitting result of $\Delta_{fit} = 2\%$ and the luminosity measurement uncertainty assumed at $\Delta\mathscr{L} = 2\%$ [2].

The measured Timepix3 muon flux of Eq. 5 agrees within uncertainty with the SND muon flux measured in 2024 at $(4.16 \pm 0.19) \cdot 10^4$ counts/(fb^{-1} cm^2) [7], where the error bar is given by the quadrature sum of statistical and systematic ones, where for the latter the same $\Delta\mathscr{L} = 2\%$ uncertainty on the IP1 luminosity is assumed, and $\Delta\varepsilon_{SciFi}4\%$ SciFi tracking efficiency uncertainty. Moreover, the FLUKA simulated values is reported at $4.79 \cdot 10^4$ counts/(fb^{-1} cm^2) [14].

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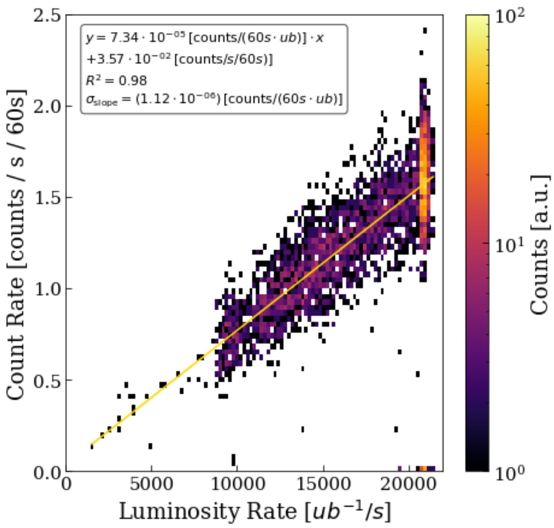

Figure 2: Timepix3 particle rate Φ_μ plotted against the instantaneous delivered luminosity $\mathscr{L}_{inst}$ at IP1, revealing a linear correlation. Most of the luminosity data points correspond to the nominal luminosity rate of $\mathscr{L}_{inst}^{nom} = 2.2 \cdot 10^5$ μb^{-1}/s.

BUNCH-BY-BUNCH RESOLUTION

The LHC beam is not continuous, but bunched with a spacing of 25 ns [2], hence primary collision products traveling at the speed of light are expected to be observed with regular patterns, while secondary products from other sources (e.g. background radiation from the LHC tunnel) should be more stochastic. The Timepix3 detector has a ToA time resolution of 25 ns, matching the LHC bunch spacing, and a fast Time-of-Arrival (fToA) clock with a refined resolution of $25/16 = 1.625$ ns, possibly allowing to probe the time structure of the beam. The fToA distribution of the filtered muon rate is shown in Fig. 3. A clear structure in the beam is observed as most of the particles arrive with low fToA values, revealing how the Timepix3 Radiation Monitor can be used to measure the bunched structure of the beam in an integrated manner (i.e. over longer periods of time); however, a bunch-by-bunch instantaneous measurement is not possible because the count rate is not high enough to yield a strong enough signal.

CONCLUSION

This work demonstrates the precision capabilities of the Timepix3 Radiation Monitor in characterizing high-energy muon fluxes originating from proton-proton collisions at the ATLAS interaction point, marking a significant step forward in compact, high-resolution particle monitoring within large-scale collider environments. The energy deposition in the detector is consistent with the expected 100 GeV muons coming from IP1. By leveraging fine-grained temporal and spatial resolution, and applying selection filters, the measured muon flux was determined to be $\Phi_\mu = (4.88 \pm 0.78) \cdot 10^4$ counts/(fb^{-1} cm^{-2}),

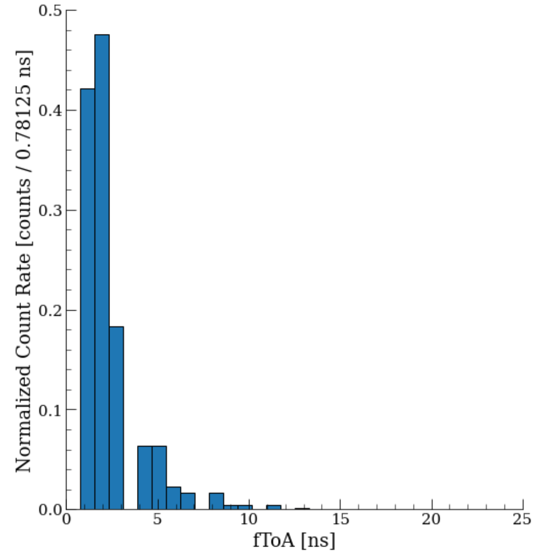

Figure 3: The fToA distribution of the filtered muon rate, as measured by the Timepix3 Radiation Monitor. One fToA unit corresponds to 1.5625 ns.

matching the SND@LHC muon flux measured in 2024, at $(4.16 \pm 0.19) \cdot 10^4$ counts/(fb^{-1} cm^{-2}) [7] and the FLUKA simulated one at $4.79 \cdot 10^4$ counts/(fb^{-1} cm^{-2}).

Beyond this validation, the analysis reveals the Timepix3's potential as a standalone instrument for real-time beam monitoring, capable of resolving the LHC's bunch structure, as a clear pattern of the beam was observed in the measured fast Time of Arrival (fToA) values, as most of the particles arrive with low or close to zero fToA values. This opens new opportunities for in-situ beam diagnostics and particle flux mapping in high-radiation environments.

Looking ahead, the deployment of such advanced pixel detectors could play a signficant role in radiation protection, beamline optimization, and precision luminosity monitoring, especially as collider facilities evolve toward higher luminosities and more complex operational modes.

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