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Analysis of muon production in P42 and their effect on the M2 beamline

Abstract

During the 2022 operation of the P42 beamline, high radiation levels were observed at the ramp to EHN1 and the M2 tunnel in CERN's North Area. This study employs BDSIM simulations to investigate the influence of muons originating from P42 on the M2 beamline, which are located in the North Area at CERN. The simulations reveal that muons effectively reach the CEDAR region of M2, exhibiting a uniform distribution at approximately 10^{-6} muons per dm per primary proton on T4, both in x and y. However, within a 1-meter radius of M2, this uniform distribution ceases due to the presence of magnetic fields of the M2 magnets, causing the deflection of muons away from this area. The majority of these muons possess momenta less than 20 GeV/c.

Keywords: P42, M2, muons, BDSIM, CERN North Area

Figure 1: Aerial overview of the North Area and its various beamlines and targets [1].

1 Introduction

The European Organization for Nuclear Research (CERN), is a global hub for high-energy particle physics research. While much attention is typically given to its flagship accelerator, the Large Hadron Collider (LHC), CERN also hosts a cluster of experiments and facilities in its North Area. CERN's North Area is a collection of experimental setups designed to complement and extend the reach of the research conducted at the LHC. The North Area started operation in 1978 and was conceived as a facility to provide highly flexible beamlines that can adapt to a multitude of physics experiments as well as test beam and R&D activities [2]. An aerial overview of the North Area is shown in Figure 1.

The North Area uses a 400 GeV proton beam from the Super Proton Synchrotron (SPS), which is slowly extracted through the TT20 transfer line and brought to the primary targets T2, T4 and T6. When the primary protons from the SPS hit the primary targets, secondary particles of different types, charge and energy are created. In order to select secondary beams of a specific particle type and energy, the unwanted particles (and energies) are filtered out. This is achieved by the use of magnets, collimators and momentum slits to bend unwanted particles and energies away from the beamline and absorb them in collimators.

The selected particles are picked up by the secondary beamlines H2, H4, H6, H8, P42, K12 and M2, which transfer these particles to the surface halls EHN1 and EHN2 as well as the experimental cavern ECN3. Here, various experiments are performed such as tests for detector R&D, detector validation tests, fixed target experiments (NA62 [3], AMBER [4], NA64µ [5], MUonE [6]) and other projects such as the proposed Beam Dump Facility [7] and the Neutrino Platform [8].

One particle type that is difficult to filter out is the muon. Muons have a relatively long lifetime of 2.2 µs, which allows a 1 GeV muon to travel 6 km in vacuum on average before decaying. Muons only interact through the electroweak interaction but unlike electrons, muons are not easily stopped by EM interactions when traversing material due to their high mass. This makes it challenging to absorb them effectively. Muons are also produced in a wide energy range, which makes it challenging to deflect them.

During the 2022 operation of the P42 beamline, high radiation levels were observed at the ramp to EHN1, as well as in parts of the M2 tunnel. A possible cause of these high radiation levels is the production of secondary muons by the P42 beamline. In this analysis, the effect of muons produced by P42 on the M2 beamline is investigated. These muons can contribute to background radiation in EHN2 experiments and thus their energy and spatial distributions are important parameters to investigate. Two scenarios are considered and compared, one where the P42 beamline has its collimators open and one where the P42 beamline has its collimators closed, as was the case during the 2022 operation when the high doses were observed.

2 BDSIM simulations

In this analysis, the Beam Delivery Simulation tool (BDSIM) [9] was used to simulate particle transport and interactions in the P42 and M2 beamlines. BDSIM is a C++ program that uses the Geant4 [10] toolkit to simulate the transport as well as the interactions of particles in particle accelerators. Geant4 is a Monte Carlo (MC) simulation of the passage of particles through matter. BDSIM can exploit all the physics processes that come with Geant4 and is used for the analysis and optimization of the beam delivery systems in the North Area.

Existing models of the P42 and M2 beamlines were used to perform MC simulations in BDSIM. The P42 model uses a beam distribution of protons defined by measured beam parameters as input and starts roughly a meter before the T4 target station. The TAX is located after the T4 target station, which is a series of primary beam dump-collimators. The beam will continue through various quadrupole and dipole magnets. The M2 and P42 beamlines run parallel between 100 and 520 m from the T4 target station, after which there is a bend in P42 which leads to the T10 target station. The M2 tunnel continues to go straight and eventually bends upwards, towards EHN2.

In these BDSIM models, primary protons as well as any secondary particles produced, can then be tracked through the entire 838 m long beamline. Samplers are placed in the model to store various properties of the particles such as position, momenta and track information as these particles pass through.

For efficient simulations, it is advantageous to define only the processes that are relevant as opposed to simulating all possible physics processes. These physics processes are specified in physics lists. The physics list used in this analysis is `g4FTFP_BERT`.

To investigate the effect of muons created in P42 on M2, a simulation was done where samplers were placed along P42 and used as input for M2. The P42 beamline was simulated with 10^7 primary protons. Four samplers were placed between 203 m and 503 m from T4, with 100 m in between each sampler, as shown in Figure 2. In this region, the P42 and M2 beamlines run parallel to each other. Any muons produced by P42 in this region will traverse the tunnel along the M2 beamline and could end up in EHN2. The simulation uses a muon splitting factor of 20. Every time a muon is created in the P42 simulation, this splitting factor will instead create 20 muons, all weighted by a factor of $\frac{1}{20}$. This allows for more statistics on muons and thus reduce the variance on the results, without having to simulate more primary particles. The output files from the P42 simulation were skimmed to only include events with muons present. These events are then used as input for M2.

To track the muons along M2, the samplers from P42 are shifted to their corresponding coordinates in the M2 frame and the muons registered by them are used as input and simulated along the M2 beamline. New samplers in M2 are placed in the CEDAR region of M2 to obtain spatial and momentum distributions of muons in these locations. This is done for both the open and closed collimator settings of P42. The results of these simulations are then compared.

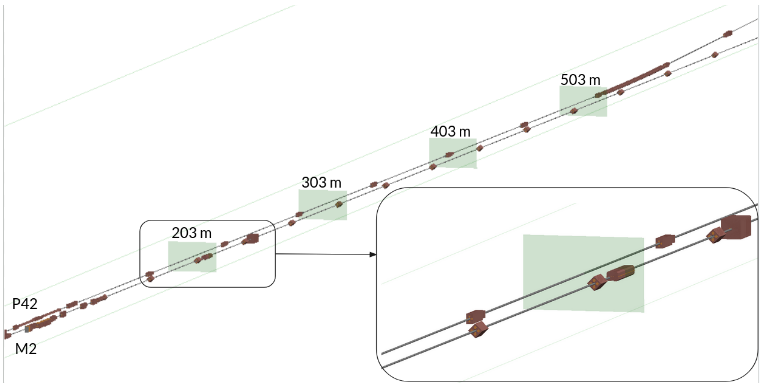

Figure 2: A visualization of the P42 and M2 beamlines side by side in BDSIM. The P42 samplers are placed on the section where P42 and M2 run parallel.

3 Results & discussion

The beam and energy losses in P42 are shown in Figure 3. Most primary protons are lost in the first 50 m of the P42 beamline, which includes the T4 target station and the TAX. Over the entire beamline 16% of primary protons are lost. Proton loss and energy deposits happen in the same regions, predominantly in the regions where beamline elements such as collimators, quadrupole and dipole magnets are located.

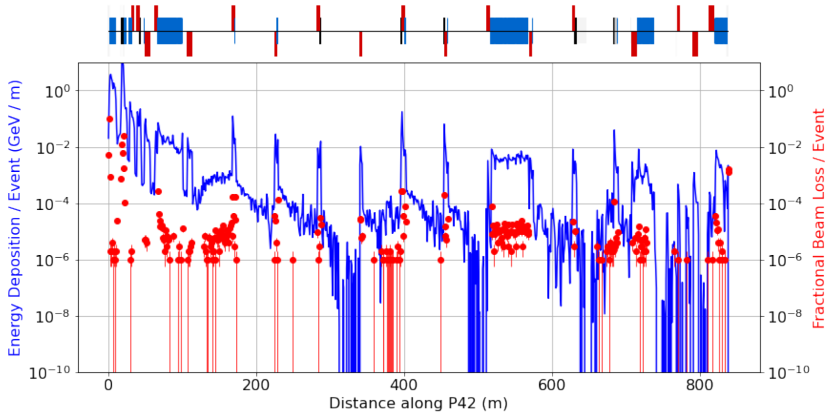

Figure 3: Energy deposition (blue) and beam loss (red) versus distance along P42, normalized per proton on T4. This simulation uses 10^6 primary protons. The machine diagram above the plot shows the various beamline elements. The dipole magnets are indicated in blue, the quadrupole magnets in red and the collimators in black.

3.1 Muon contributions from P42 entering M2

Two BDSIM simulations of P42 were performed, each with 10^7 primary protons, where one simulation uses open collimators and the other closed collimators. The aperture sizes and locations of these are summarized in Table 1. The muon distributions recorded at the samplers are shown in Figures 4, 5 & 6. These are used as input for the M2 simulations.

Collimator	Position along P42	Vertical aperture	Horizontal aperture
XCHV.043.286	286 m	12 mm	12 mm
XCHV.043.396	396 m	40 mm	30 mm
XCHV.043.454	454 m	45 mm	15 mm

Table 1: Apertures of the closed collimator configuration of P42.

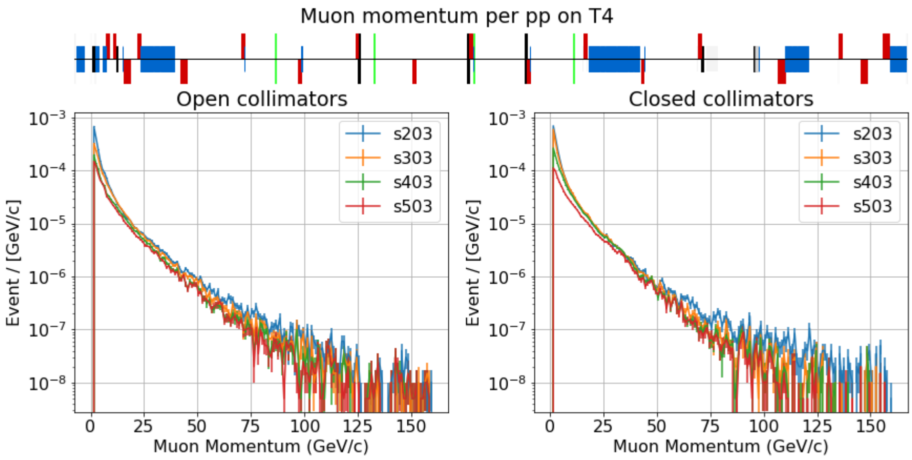

Figure 4: Momentum distributions of muons recorded by the P42 samplers. The machine diagram depicts the position of the samplers with respect to P42 in green. The plots are normalized per primary proton (pp) on the T4 target.

The momentum distributions of muons from P42 are shown in Figure 4. It can be seen that both the muon distributions of the open and closed collimator settings follow the same trend and that most muons are created towards the start of the beamline, as the earlier samplers contain more muons than the later ones. The closed collimator configuration shows more low-energy muons in s303 and s403 compared to the open collimator configuration, but this difference is less than an order of magnitude per GeV/c.

Both the closed and open collimator configurations show a somewhat uniform muon distribution in x and y, of the order 10^{-6} muons per cm per primary proton (pp) on the T4 target. The closed collimator configuration shows a higher muon distribution, however the increase compared to the open collimator configuration is of a factor less than 2. Because of the higher number of muons, the variance on the closed collimator configuration is also lower. From the closed collimator configurations it can be seen that the muon distributions of s203 and s303 are less uniform and are slightly higher towards the center of P42 and drop off exponentially away from the beamline.

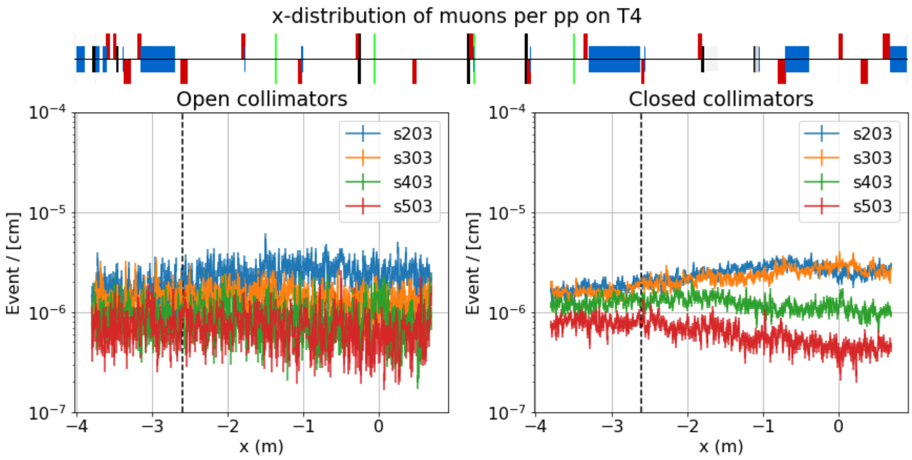

Figure 5: x versus number of muons per bin. P42 is positioned at the origin and M2 is positioned at -2.6 m, as indicated by the dotted line. The machine diagram depicts the position of the samplers with respect to P42 in green. The plot is normalized per primary proton on the T4 target.

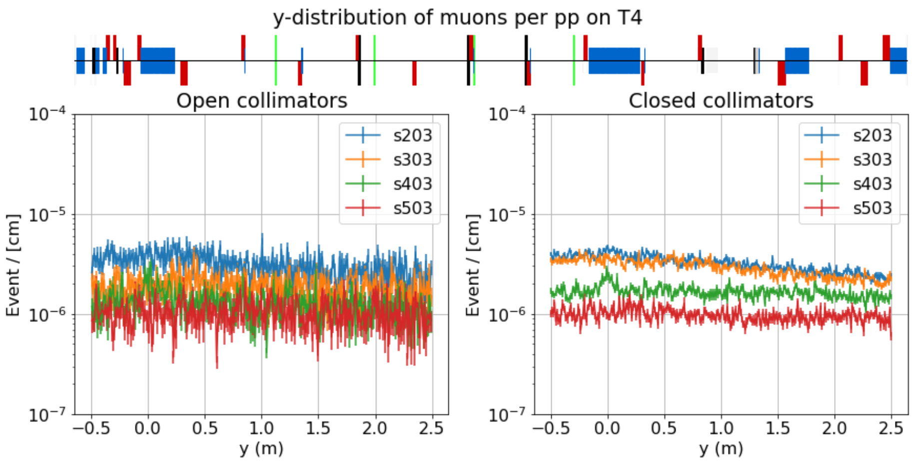

Figure 6: y versus number of muons per bin. The machine diagram depicts the position of the samplers with respect to P42 in green. The plot is normalized per primary proton on the T4 target.

3.2 Muon distributions in CEDAR region of M2

Each sampler was used separately as input for M2 and simulated along the M2 beamline. In this M2 simulation, new samplers were placed along the CEDAR region and the end of M2. The CEDAR region is around 1083 m to 1096 m along M2 and the end of M2 is around 1130 m. The distributions measured by the samplers in these locations show similar results and hence only the sampler at 1089 m is shown here, which corresponds to the middle of the CEDAR region in M2.

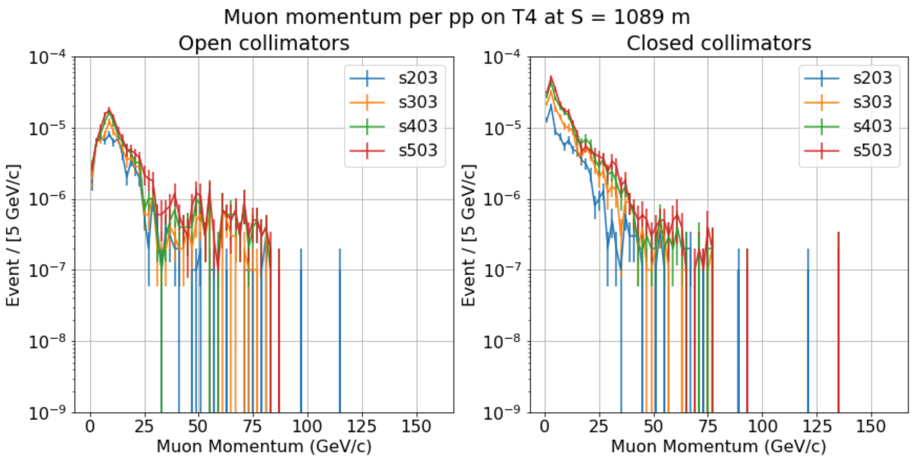

Figure 7: Momentum distributions of muons in the middle CEDAR region of M2, resulting from the P42 samplers as input. The plots are normalized per primary proton on T4.

Figure 7 shows the momentum distributions of muons at the CEDAR region of M2. The closed collimator configuration shows a higher number of muons below 10 GeV/c and has a different shape from the open collimators configuration. This is because in the open collimator case, most low-momentum (up to 20 GeV/c) muons are produced early in P42 and are then deflected by magnetic fields along their path in the tunnel. Furthermore, these muons are produced with large angular distributions and thus end up outside of the samplers further along the tunnel. In the closed collimator case, more low-momentum muons are produced where the collimators are located and these can make it further along the tunnel then the muons produces earlier in the beamline.

Overall, in both cases the majority of muons have momentum below 20 GeV/c, with contributions ranging from 10^{-6} till 10^{-4} muons per 5 GeV/c per primary proton on T4. The closing of the collimators seems to increase the number of muons arriving in the CEDAR region, but mainly in the low-momentum range. The distributions of higher energy muons seems to be statistically consistent for both collimator settings within the error bars. The muon distribution above 75 GeV/c drops to 10^{7} muons per primary proton on T4, with large error bars. Because in total 10^{7} primary protons were simulated, the statistics in this region only show events in the order of 1 muon, with a high uncertainty on the lower bound on the distribution. More primary protons and a higher muon splitting factor can result in better statistics for this high energy region.

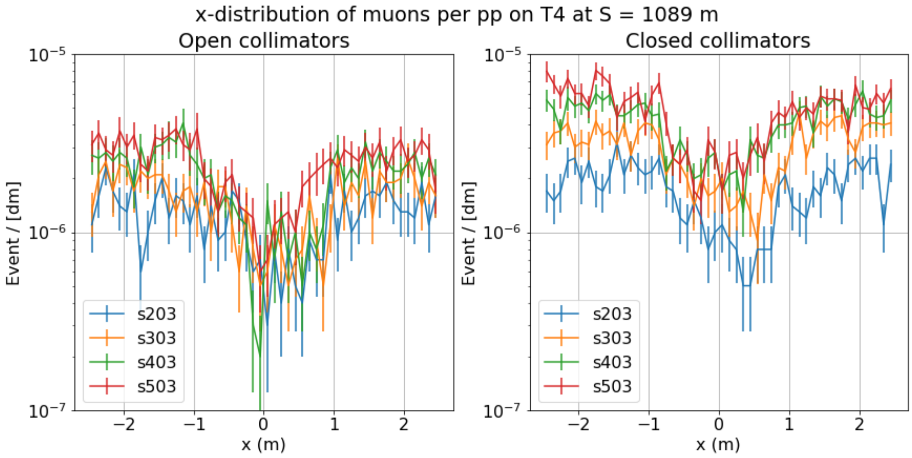

Figure 8: x versus muons per bin in the middle CEDAR region of M2, resulting from the P42 samplers as input. M2 is centered at the origin. The plots are normalized per primary proton on T4.

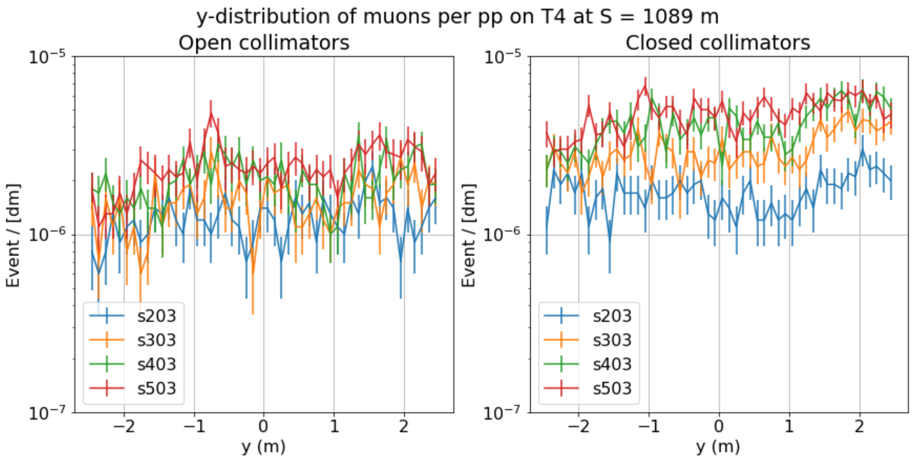

Figure 9: y versus muons per bin in the middle CEDAR region of M2, resulting from the P42 samplers as input. M2 is centered at the origin. The plots are normalized per primary proton on T4.

Figures 8 & 9 show the spatial distributions of muons from P42 around the CEDAR region of M2. Figure 10 shows a 2D histogram of these distributions. The distributions are uniform across most of the range except for the region within a radius of 1 m of the center of the M2 beamline. This is because magnets surrounding M2 deflect most muons away from the beamline. Outside this region, muons are uniformly distributed with the order of 10^{-6} muons per dm per primary proton on T4.

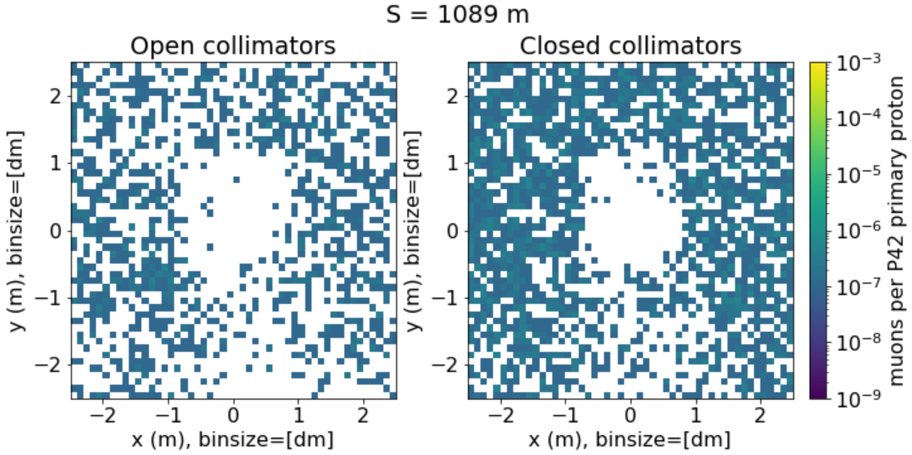

Figure 10: 2D histograms showing the muon distribution in the xy-plane in the middle CEDAR region of M2. The origin represents the center of the M2 beamline. The plots are normalized per primary proton on T4.

An improvement on the simulations would be to simulate both the P42 beamline and the M2 beamline simultaneously. In this analysis, only one beamline was simulated at a time and because of this, not all magnetic fields are taken into account at all instances. Especially the dipole magnets between 500 and 600 m along P42 could have a big impact in deflecting muons away from the M2 beamline. This and other magnets have not been taken into account and could reduce the number of muons that end up at the M2 CEDAR region.

To determine if these muons from P42 are the cause of the high radiation levels observed in the M2 tunnel, a comparison should be done between the simulation and the radiation levels measured when P42 was in operation, as well as an analysis of the muon contributions from M2 and the observed radiation levels when both beamlines are in operation.

4 Conclusions

BDSIM simulations were performed to find the effect of muons generated in P42 on the M2 beamline. According to these simulations, muons were able to make it to the CEDAR region of M2, with a uniform distribution of the order of 10^{-6} muons per dm per primary proton on T4. This distribution stopped being uniform within a radius of 1 m of M2, where almost no muons were observed because of magnetic fields surrounding M2 deflecting the muons out of this region. The vast majority of these muons have a momentum smaller than 20 GeV/c. Next steps in the analysis would be to simulate the P42 beamline and M2 beamline simultaneously, to observe the effects of all magnetic fields in the tunnel at the same time. The results from these simulations should also be compared to measurements of various radiation monitors in the tunnel, as well as a comparison to the radiation coming from M2 when it is in operation.

A Software & code versions used

All files and models used to generate the results can be found on GitLab:
https://gitlab.cern.ch/en-ea-le-groups/north-area/p42-summerproject
https://gitlab.cern.ch/en-ea-le-groups/north-area/m2/-/tree/master/bdsim/models/p42-muons-100GeV

```
Package/software       Version
---------------------- -------------
ubuntu                 22.04 LTS
python                 3.10.12
ipython                8.3.0
bdsim                  1.7.develop
gcc                    11.4.0
cmake                  3.22.1
clhep                  2.4.6.4
geant4                 11.1.2
root                   6.26.02
xerces                 3.2.4
flex                   2.6.4
bison                  3.8.2

pybdsim                3.4.0
pymadx                 2.0.1
matplotlib             3.5.1
numpy                  1.22.3
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```

Simulations ran on condor are found in the following folder:
https://gitlab.cern.ch/en-ea-le-groups/north-area/p42-summerproject/-/tree/master/farm
These runs are performed on lxplus by sourcing:

```
/cvmfs/beam-physics.cern.ch/bdsim/x86_64-centos7-gcc11-opt/bdsim-env-v1.7.3-
g4v10.7.2.3-ftfp-boost.sh
```

The root files resulting from the simulations can be found on CERNBox:
https://cernbox.cern.ch/s/VRAgNrIUNKFoCvT

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