CERN-SHiP-ANA-2019-005
December 19, 2019

FLUKA-Geant4 comparison for the muon flux experiment in the H4 beamline

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Abstract

The FLUKA - Geant4 comparison for the the muon flux experiment is reported. The experiment was performed in 2018 on the H4 400 GeV/c proton beamline to measure the muon flux emanating from a SHiP replica target. Good agreement between the two Monte Carlo simulations was found, in the low momentum and low p_T range the agreement is at the level of 20%, while in the tails the disagreement is at maximum of a factor ∼3. These results suggest to reduce the safety factor for future BDF/SHiP facility radiation calculations from 5 (old recommended value) to 3 (new value).

[1] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*

VERSION	DATE	COMMENTS
01	22.11.2019	First version

Contents

1 Motivation and experimental setup

In 2018 the SHiP Collaboration proposed a measurement of the muon flux from a reduced scale replica of the final SHiP target [1] to reduce the uncertainty on the expected muon background for the SHiP experiment [2]. This experiment was located on the H4 beamline and received primary proton beam from the SPS with a beam momentum of 400 GeV/c. It collected over 4 weeks $(3.27 \pm 0.07) \times 10^{11}$ protons on target (POT).

The muon flux spectrometer, as implemented in the SHiP software framework based on Geant4, is shown in Figure 1.

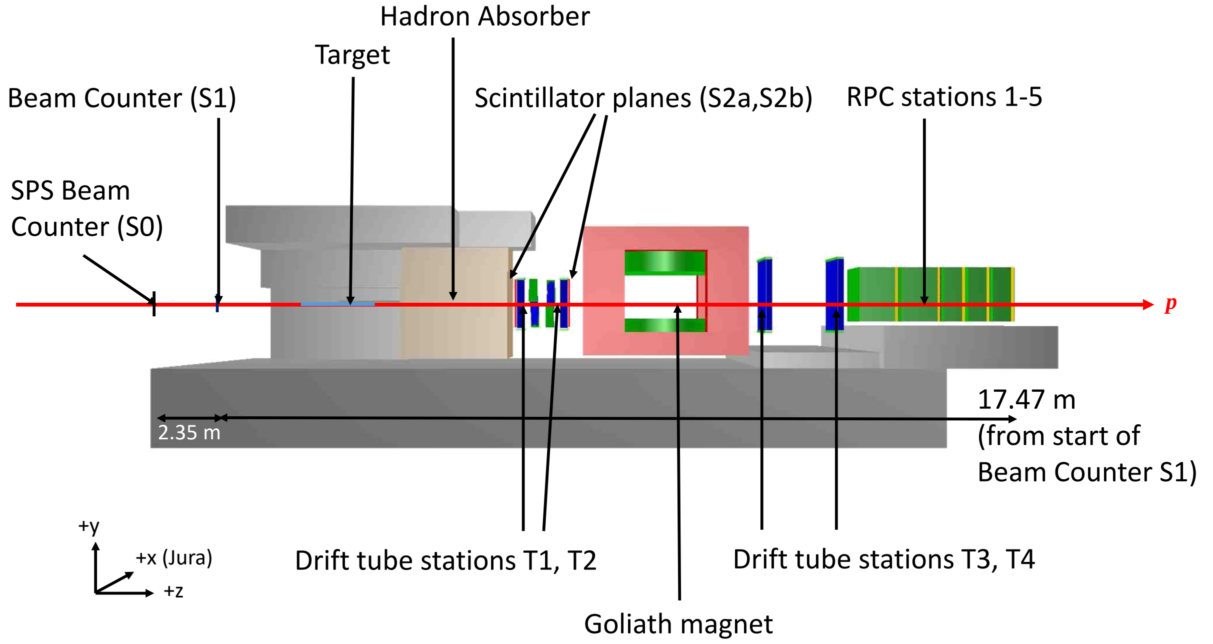


Figure 1: Layout of the spectrometer to measure the μ-flux. The FairShip coordinate system is also shown.

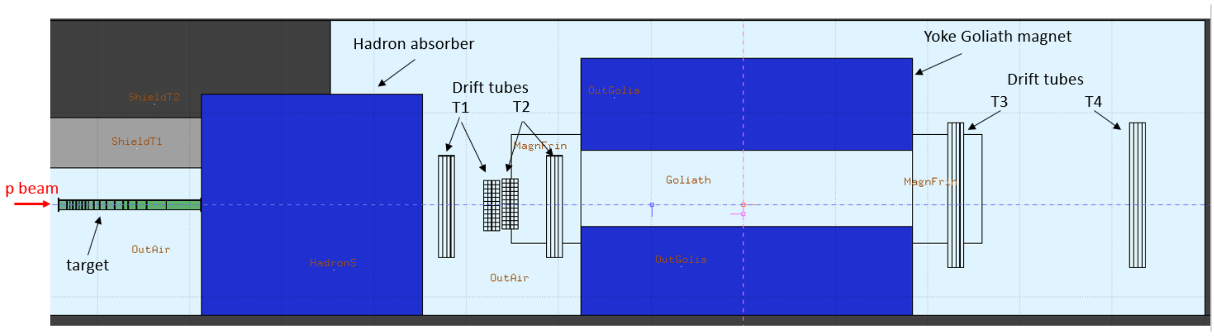
The target (154.3 cm long with a diameter of 10 cm), composed of a mixture of TZM (Titanium-Zirconium doped Molybdenum) and tungsten, was followed by a hadron absorber made of iron blocks ($240 \times 240 \times 240$ cm^3) and surrounded by iron and concrete shielding blocks. Downstream of the hadron absorber there were four drift tube tracking stations (T1-T4), two placed upstream of the Goliath magnet and two downstream. The results of the measurement are detailed in [3].

FLUKA [4, 5] simulations are used to perform the radiological assessment of the future BDF/SHiP facility [7]. Taking advantage from this measurement, a FLUKA-Geant4 comparison was performed in order to estimate a more realistic and adequate safety factor to be used in SHiP simulations of the radiation coming from muons.

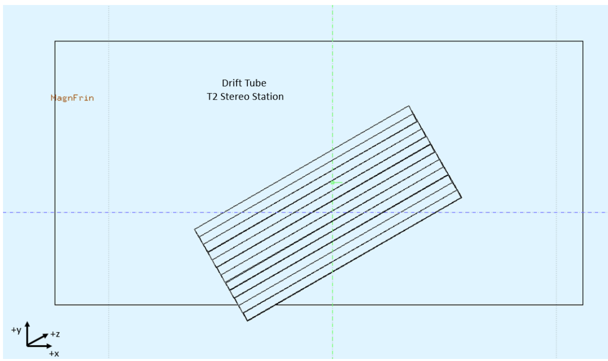
2 FLUKA simulation

2.1 Geometry and materials

The geometry of the muon flux spectrometer was reproduced in FLUKA as shown in Figure 2. The stereo drift tube stations were implemented to achieve the same geometrical acceptance.



(a)



(b)

Figure 2: Geometry of the Muon Flux setup as implemented in FLUKA. Top (a) shows the entire setup, bottom (b) shows the T2 stereo drift tube station.

The results of the CERN survey team for the alignment [6] were used to build the experimental setup in FLUKA. The parts and the dimensions of the entire setup were respected and only the following approximations were done:

- The coil of the Goliath magnet was not implemented (only yoke).
- The drift tubes were approximated with parallelepipeds instead of cylinders (cylinders inscribed into the parallelepipeds). The aluminum thickness of each tube ($\approx$ 420 μm) was respected. The tubes were filled with air.

The chemical composition of the materials used in the FLUKA simulation is reported in Table 1.

The samples were generated with "Nominal" configuration of the Goliath magnet [12].

Table 1: Chemical composition and density of the materials as used in the FLUKA studies.

Material	Density (g/cm^3)	Element	Weight percentage (%)
Molybdenum	10.16	Mo	100
W	18.85	W	100
Plastic	1.28	O	50.75
		C	42.86
		H	6.39
SS316LN	7.8	Fe	67.145
		Cr	18.5
		Ni	11.25
		Mn	2.0
		Si	1.0
		P	0.045
		S	0.03
		C	0.03
Iron	7.2	Fe	92.3
		C	3.85
		Mn	0.3
		Si	3.4
		P	0.08
		S	0.02
		Co	0.05

2.2 Physics settings

In the FLUKA simulation the nuclear interaction model used is PEANUT [8, 9] and can be schematically described as a sequence of the following steps:

- Glauber-Gribov cascade and high energy collisions.
- (Generalized)-IntraNuclear cascade.
- Preequilibrium emission.
- Evaporation/Fragmentation/Fission and final de-excitation.

Hadron-nucleon inelastic collisions are described in terms of resonance production and decay up to a few GeV. At higher energies, a model [10] based on the Dual Parton Model [11] (DPM) takes over. The Dual Parton Model is a quark/parton string model, and provides reliable results up to several tens of TeV. In DPM, hadron-hadron interactions result in the creation of two or more QCD color strings, from which hadrons have to be generated.

Further settings related to muons were employed:

- Full simulation of muon nuclear interactions and production of secondary hadrons.
- Delta ray production from muons (>10 MeV).
- Pair production and bremsstrahlung by high-energy muons.
- Full transport and decay of charmed hadrons and tau leptons.
- Decays of pions, kaons and muons with maximum accuracy and polarisation.

2.3 Monte Carlo Generation

Three samples with different momentum thresholds (set for all particles) were generated in order to speed up calculation at high momentum and therefore increase the statistics in the corresponding momentum bin. The corresponding number of POT is shown in Table 2:

Table 2: FLUKA samples produced for Muon Flux comparison with Geant4.

momentum threshold for transport of all particles	POT	Muon momentum range
5 GeV/c	1.37×10^8	$5 < p < 30$ GeV/c
27 GeV/c	5.43×10^8	$30 < p < 100$ GeV/c
97 GeV/c	5.03×10^8	$p > 100$ GeV/c

The comparison is limited to $p > 5$ GeV/c due to the generation settings used for the Geant4 simulation prepared by SHiP.

3 FLUKA - Geant4 comparison

Muons are reconstructed if passing through the T1, T2, T3 and T4 stations. The distributions are taken at the T1 station and normalized to the number of POT (see Section 2).

In this section we compare the reconstructed momentum distributions, p and p_T, between FLUKA and Geant4.

The comparison is restricted to 5 GeV/c $< p <$ 300 GeV/c and $p_T <$ 4 GeV/c. The lower limit of 5 GeV/c is an artefact of the Geant4 MC simulation procedure.

As shown in Figure 3 FLUKA predicts a lower rate compared to Geant4 and in the muon momentum range 5 GeV/c $< p <$ 200 GeV/c the agreement between the two Monte Carlo simulations is at the level of $\sim$ 20%, above 200 GeV/c the disagreement increases up to a factor $\sim$3.

As shown Figure 4 FLUKA predicts a lower rate compared to Geant4 and in the muon transverse momentum range $0 < p_T < 1$ GeV/c the level of the agreement between the two Monte Carlo simulations is at the level of $\sim 20\%$, while above 1 GeV/c a slope in the shape can be noticed reaching discrepancies up to a factor ~ 3.

In Tables 3 and 4 the rates predicted by FLUKA and Geant4 are reported in several bins of muon momentum and transverse momentum respectively.

Table 3: Bin content of momentum plot.

p bin [GeV/c]	FLUKA	Geant4	$\frac{FLUKA}{Geant4}$
5-10	$5.28 \pm 0.03 \times 10^{-5}$	$6.240 \pm 0.008 \times 10^{-5}$	0.846 ± 0.004
10-15	$3.51 \pm 0.02 \times 10^{-5}$	$3.714 \pm 0.006 \times 10^{-5}$	0.945 ± 0.006
15-20	$1.87 \pm 0.02 \times 10^{-5}$	$2.009 \pm 0.004 \times 10^{-5}$	0.930 ± 0.008
20-15	$1.11 \pm 0.01 \times 10^{-5}$	$1.2263 \pm 0.0006 \times 10^{-5}$	0.90 ± 0.01
25-30	$6.8 \pm 0.1 \times 10^{-6}$	$7.980 \pm 0.004 \times 10^{-6}$	0.85 ± 0.01
30-35	$4.43 \pm 0.04 \times 10^{-6}$	$5.427 \pm 0.004 \times 10^{-6}$	0.816 ± 0.007
35-40	$3.11 \pm 0.03 \times 10^{-6}$	$3.836 \pm 0.003 \times 10^{-6}$	0.809 ± 0.009
40-45	$2.27 \pm 0.03 \times 10^{-6}$	$2.776 \pm 0.003 \times 10^{-6}$	0.82 ± 0.01
45-50	$1.67 \pm 0.02 \times 10^{-6}$	$2.062 \pm 0.002 \times 10^{-6}$	0.81 ± 0.01
50-75	$7.75 \pm 0.07 \times 10^{-7}$	$1.0069 \pm 0.0007 \times 10^{-6}$	0.769 ± 0.007
75-100	$2.66 \pm 0.04 \times 10^{-7}$	$3.350 \pm 0.004 \times 10^{-7}$	0.79 ± 0.01
100-150	$9.2 \pm 0.2 \times 10^{-8}$	$9.92 \pm 0.02 \times 10^{-8}$	0.93 ± 0.02
150-200	$2.01 \pm 0.09 \times 10^{-8}$	$2.339 \pm 0.008 \times 10^{-8}$	0.86 ± 0.04
200-250	$3.61 \pm 0.4 \times 10^{-9}$	$6.36 \pm 0.04 \times 10^{-9}$	0.57 ± 0.06
250-300	$4.8 \pm 1.4 \times 10^{-10}$	$1.59 \pm 0.02 \times 10^{-9}$	0.30 ± 0.09

Table 4: Bin content of transverse momentum plot.

p_T bin [GeV/c]	FLUKA	Geant4	$\frac{FLUKA}{Geant4}$
0-0.2	$8.74 \pm 0.05 \times 10^{-4}$	$9.00 \pm 0.01 \times 10^{-4}$	0.972 ± 0.006
0.2-0.4	$1.371 \pm 0.007 \times 10^{-3}$	$1.584 \pm 0.002 \times 10^{-3}$	0.865 ± 0.004
0.4-0.6	$8.00 \pm 0.05 \times 10^{-4}$	$9.53 \pm 0.01 \times 10^{-4}$	0.839 ± 0.005
0.6-0.8	$3.32 \pm 0.03 \times 10^{-4}$	$3.851 \pm 0.007 \times 10^{-4}$	0.861 ± 0.008
0.8-1.0	$1.16 \pm 0.02 \times 10^{-4}$	$1.377 \pm 0.003 \times 10^{-4}$	0.85 ± 0.01
1.0-1.2	$4.08 \pm 0.09 \times 10^{-5}$	$5.05 \pm 0.01 \times 10^{-5}$	0.81 ± 0.02
1.2-1.4	$1.38 \pm 0.05 \times 10^{-5}$	$2.088 \pm 0.004 \times 10^{-5}$	0.66 ± 0.02
1.4-1.6	$5.2 \pm 0.3 \times 10^{-6}$	$9.17 \pm 0.02 \times 10^{-6}$	0.57 ± 0.03
1.6-1.8	$2.1 \pm 0.2 \times 10^{-6}$	$4.31 \pm 0.01 \times 10^{-6}$	0.48 ± 0.04
1.8-2.0	$9.2 \pm 1.1 \times 10^{-7}$	$2.14 \pm 0.01 \times 10^{-6}$	0.43 ± 0.05
2.0-2.2	$3.6 \pm 0.7 \times 10^{-7}$	$1.119 \pm 0.008 \times 10^{-6}$	0.32 ± 0.06
2.2-2.4	$2.3 \pm 0.5 \times 10^{-7}$	$5.97 \pm 0.06 \times 10^{-7}$	0.39 ± 0.08
2.4-3.0	$7.7 \pm 1.5 \times 10^{-8}$	$1.91 \pm 0.02 \times 10^{-7}$	0.40 ± 0.08
3.0-4.0	$2.1 \pm 0.6 \times 10^{-8}$	$2.00 \pm 0.05 \times 10^{-8}$	1.0 ± 0.3

4 Conclusions

The agreement between the two Monte Carlo predictions is at level of 20% in the bulk of the distributions and in the tails differences up to a factor ~ 3 are observed. The results are really good given the complexity of the processes underlying the production of muons and the approximations included in the geometry implementations. A safety factor of 3 will cover FLUKA-Geant4 differences as well as differences with data[1] over the full muon momentum and transverse momentum spectra. Such safety factor is recommended for future radiological estimates related to muons at the BDF/SHiP facility.

Acknowledgement

The authors would like to thank C. Theis for the fruitful discussions and ideas to implement an event number in FLUKA.

[1]The comparison of FLUKA with data was not straightforward due to the muon reconstruction algorithm and the detector efficiencies.

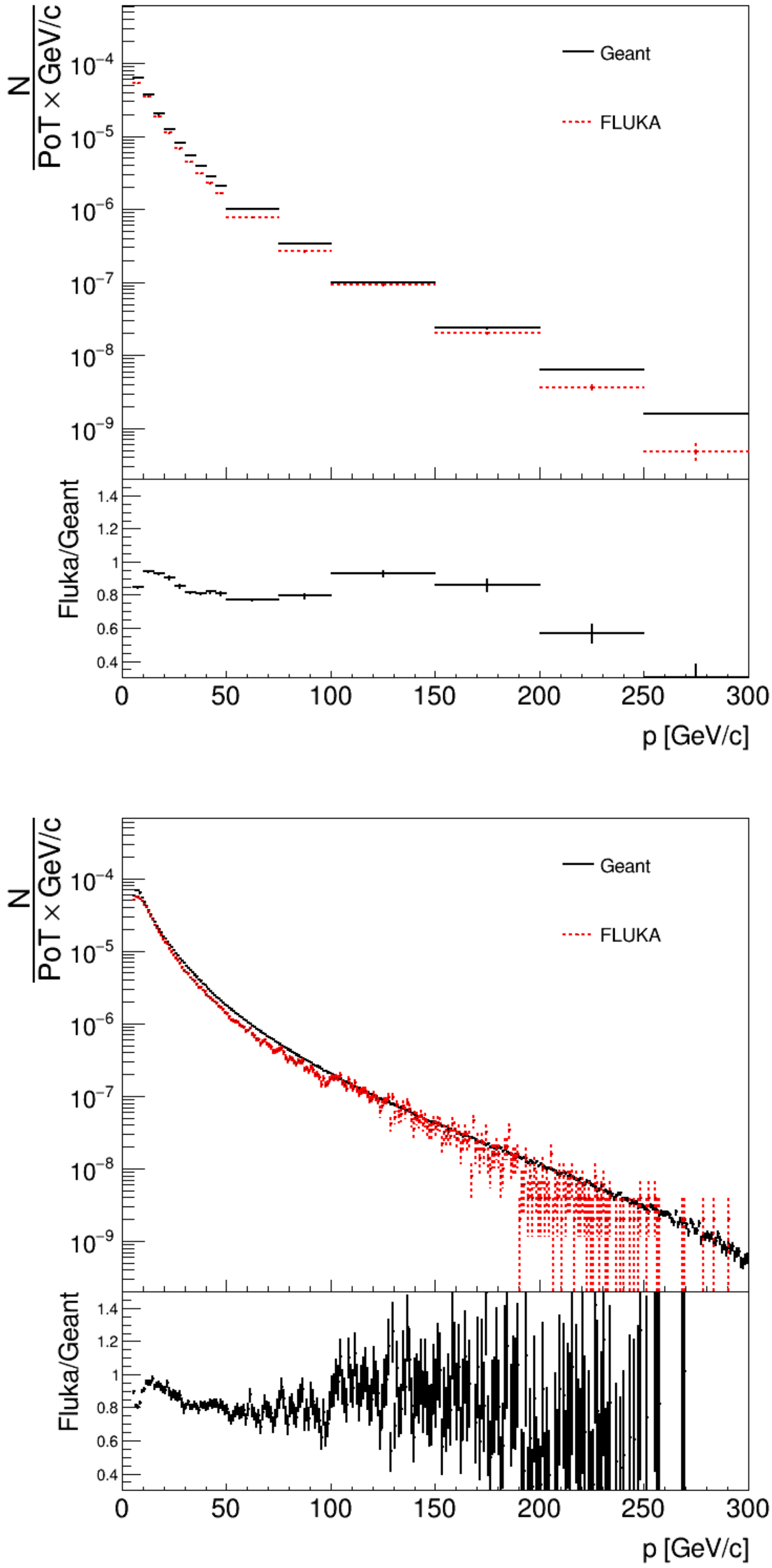


Figure 3: Momentum distributions from FLUKA and Geant4, top full range with wider binning, bottom full range with finer binning. The distributions are normalized to the number of POT.

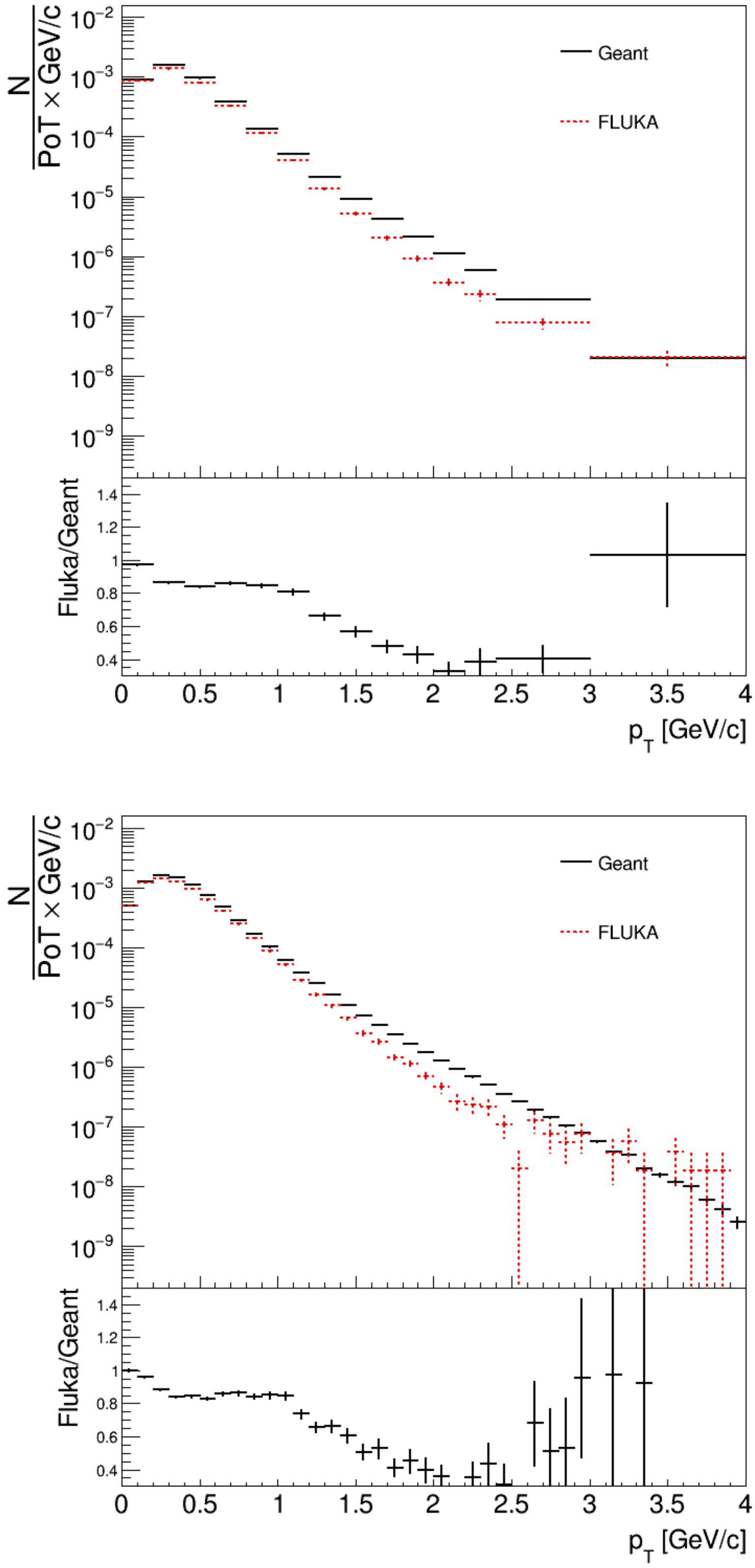


Figure 4: Transverse momentum distributions from FLUKA and Geant4, top full range with wider binning, bottom full range with finer binning. The distributions are normalized to the number of POT.

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