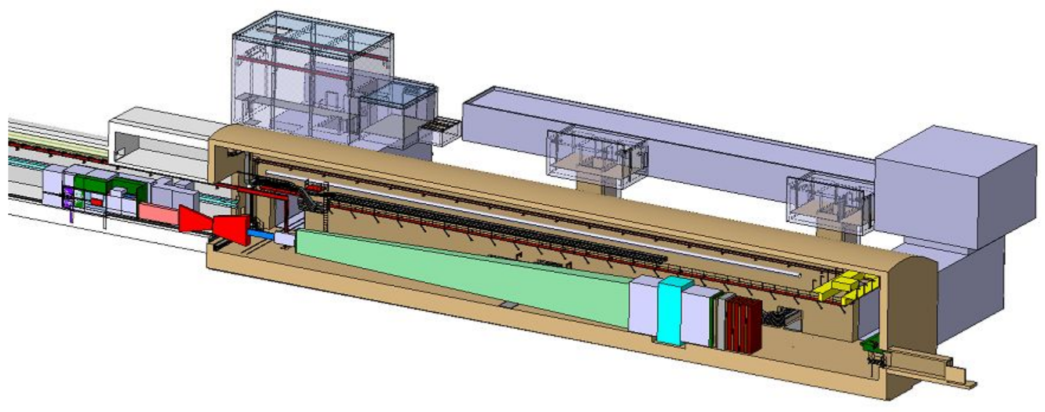
Multi-parameter detector optimization: SHiP case

Evgeny Kurbatov[1,2], Fedor Ratnikov[1,2], Eduard Ursov[3,4]

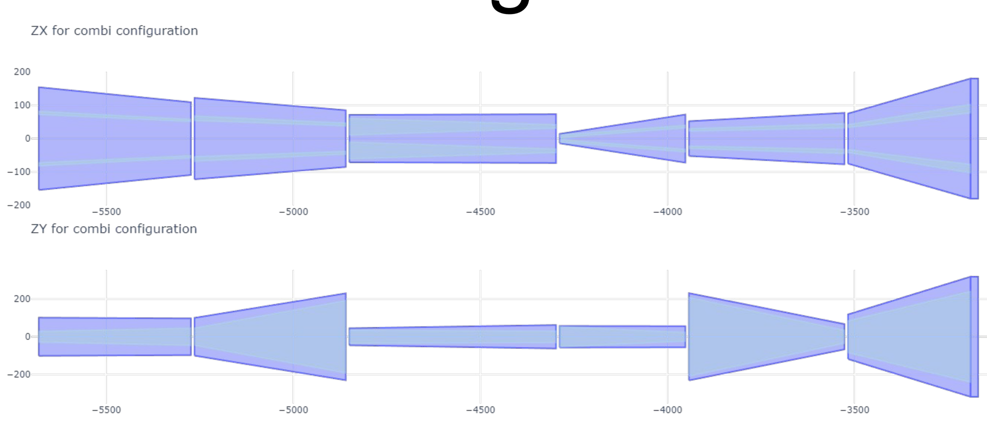
[1]HSE University,
[2]Yandex School of Data Analysis,
[3]SINP MSU,
[4]NUST MISIS

SHiP Experiment:

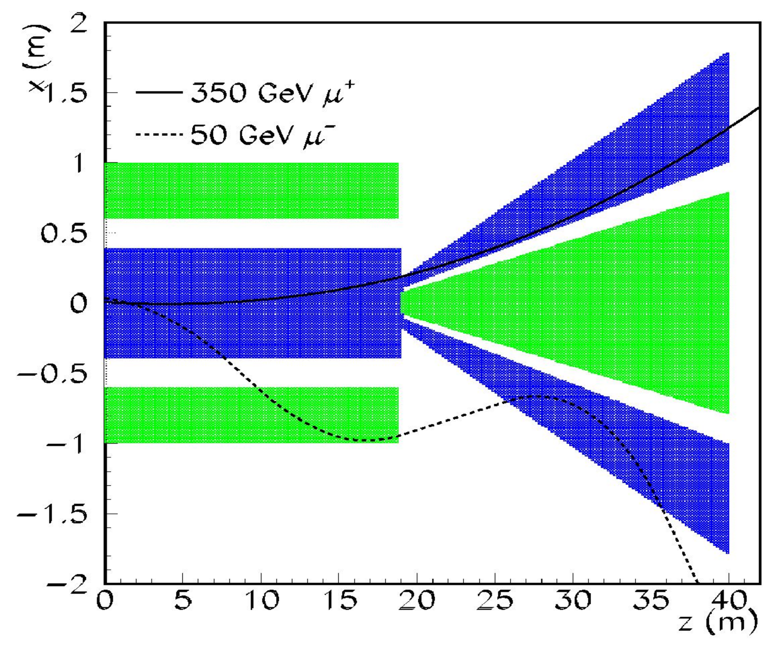


SHiP and the associated SPS Beam Dump Facility is a new general-purpose experiment proposed at the SPS to search for "hidden" particles as predicted by a very large number of recently elaborated models of Hidden Sectors which are capable of accommodating dark matter, neutrino oscillations, and the origin of the full baryon asymmetry in the Universe.The detector incorporates two complementary apparatuses which are capable of searching for hidden particles through both visible decays and through scattering signatures from recoil of electrons or nuclei. Moreover, the facility is ideally suited to study the interactions of tau neutrinos.

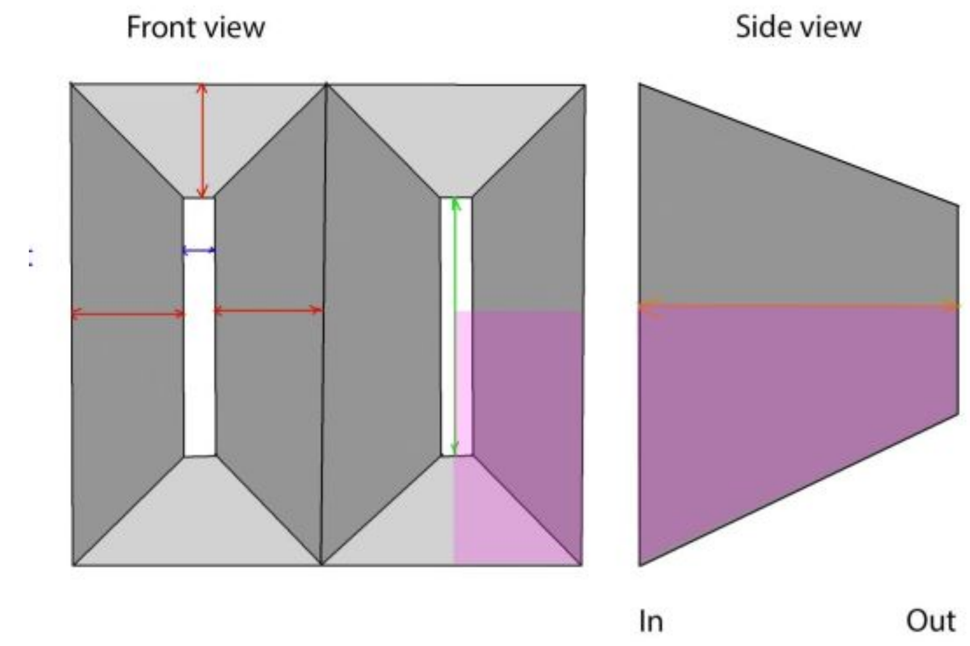
Muon Shield & muon background



SHiP is declared as an experiment with zero background. The Muon Shield is the key element to do this. So on the one hand it have to provide a good background suppression, on the other hand not to bee too heavy or expensive.



Shield magnets shape and parametrization



42 parameters in total to describe the Muon Shield shape:
- 6 magnets:
  - 7 parameters for 1 magnet:
    - 3 parameters ms for IN plane
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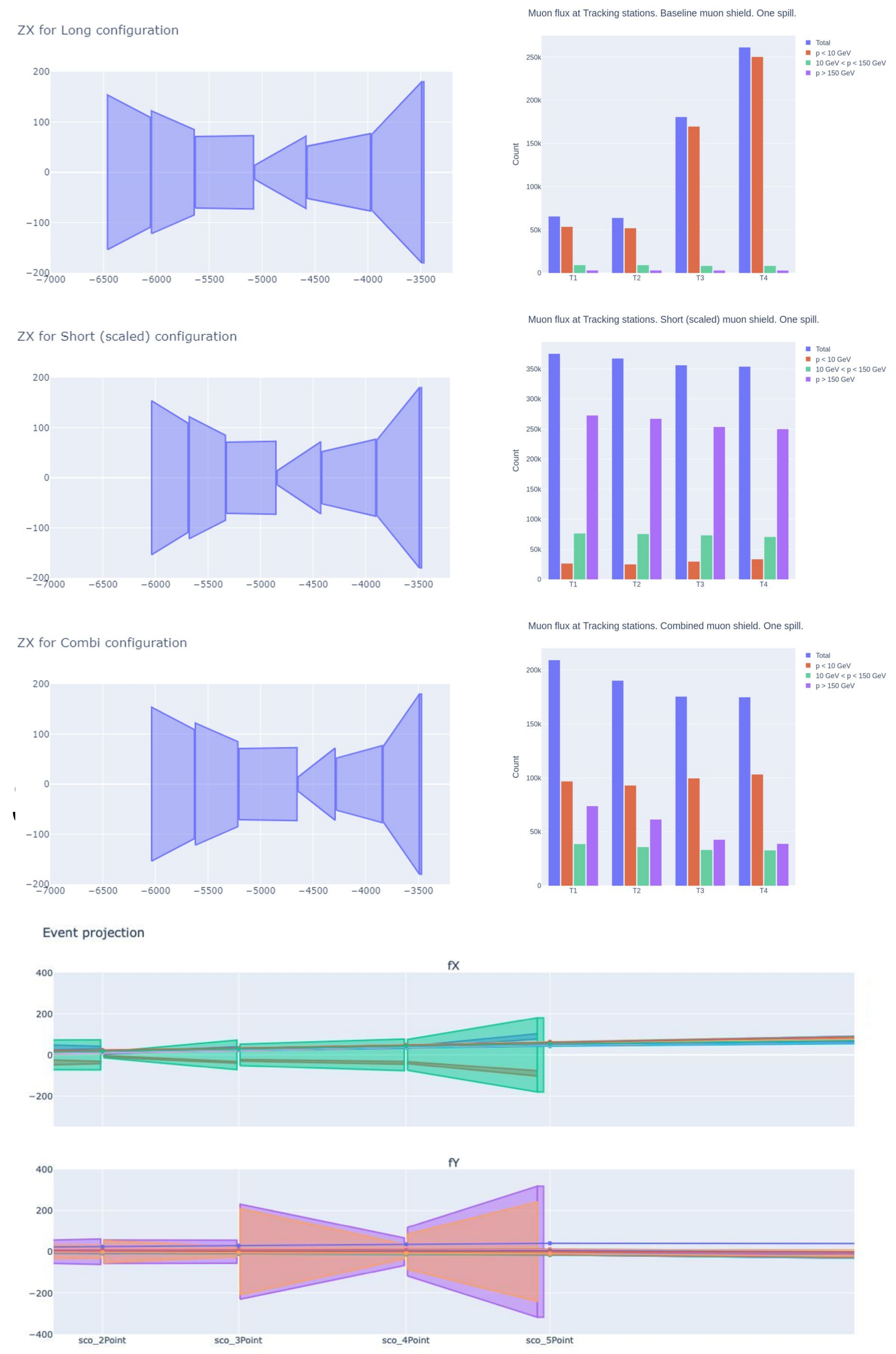
    - Length of the magnet

Ongoing changes:

During the last year the SHiP experiment has undergone a number changes. One of them is the Muon Shield length reduction from 35m down to 30m. The previously used configuration was obtained during the optimization cycle and have been fine tuned to work on the peak performance. Two direct "brute-force" manual scaling (scaling of 6 magnets – "**Scaled**", and scaling 3 last magnets only – "**Combi**").



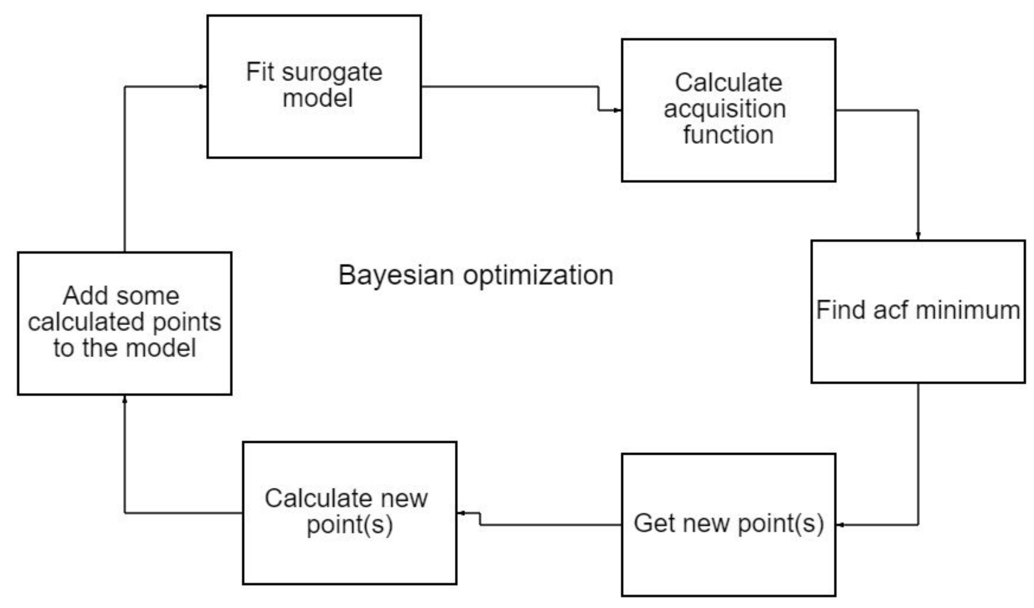
The new Muon Shield optimization cycle has been done to obtain some new shield configuration to match the new size limits and demonstrate the steady background suppression.

Simulation software:

A special software stack is used for reproducible simulation of the detector.
Environment is controlled by Alibuild system from the Alice experiment software stack. The core physic tracking is done with geant4 library, while the overall control is provided by FairRoot library. This allows to isolate all the geometry and output related parts to the python code.

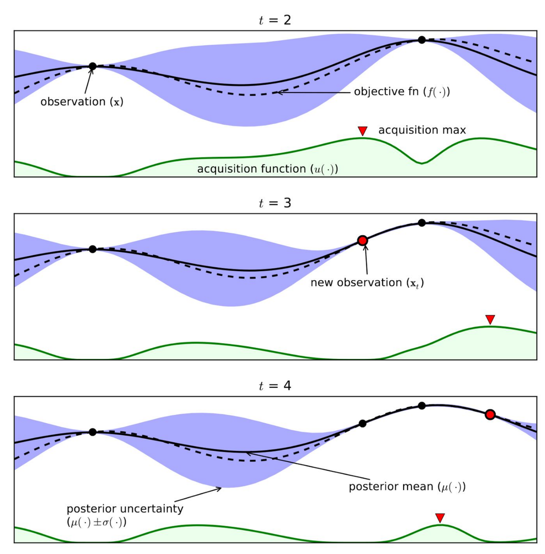
Optimization details:

Bayesian optimization with Gaussian processes is used to obtain the good shield configuration.

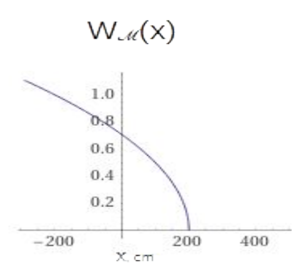


Optimization penalty function:

$$(1 + e^{\frac{10 \cdot (M - M^*)}{M^*}}) * (1 + \Sigma W_\mu)$$



where M is the shield mass, M* - some constant, W_μ is a non-linear function of the muon hits X coordinates.



The penalty function has 2 parts:
- The first one increases when the mass of the shield increases. This part allow to control the price of the Shield while the cost is mostly defined by the amount of material.
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Ax ↔ BoTorch ↔ GPyTorch

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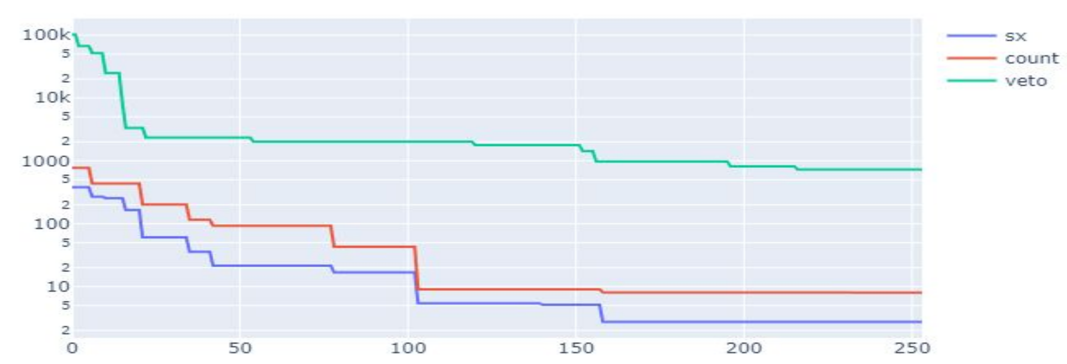
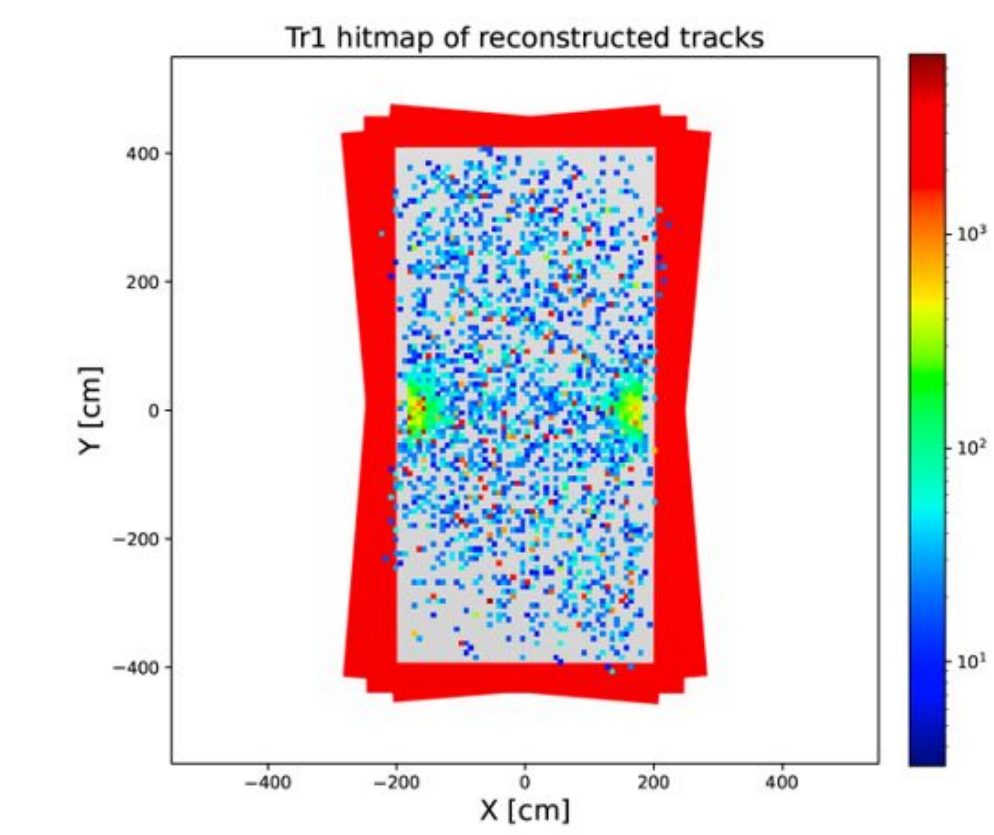


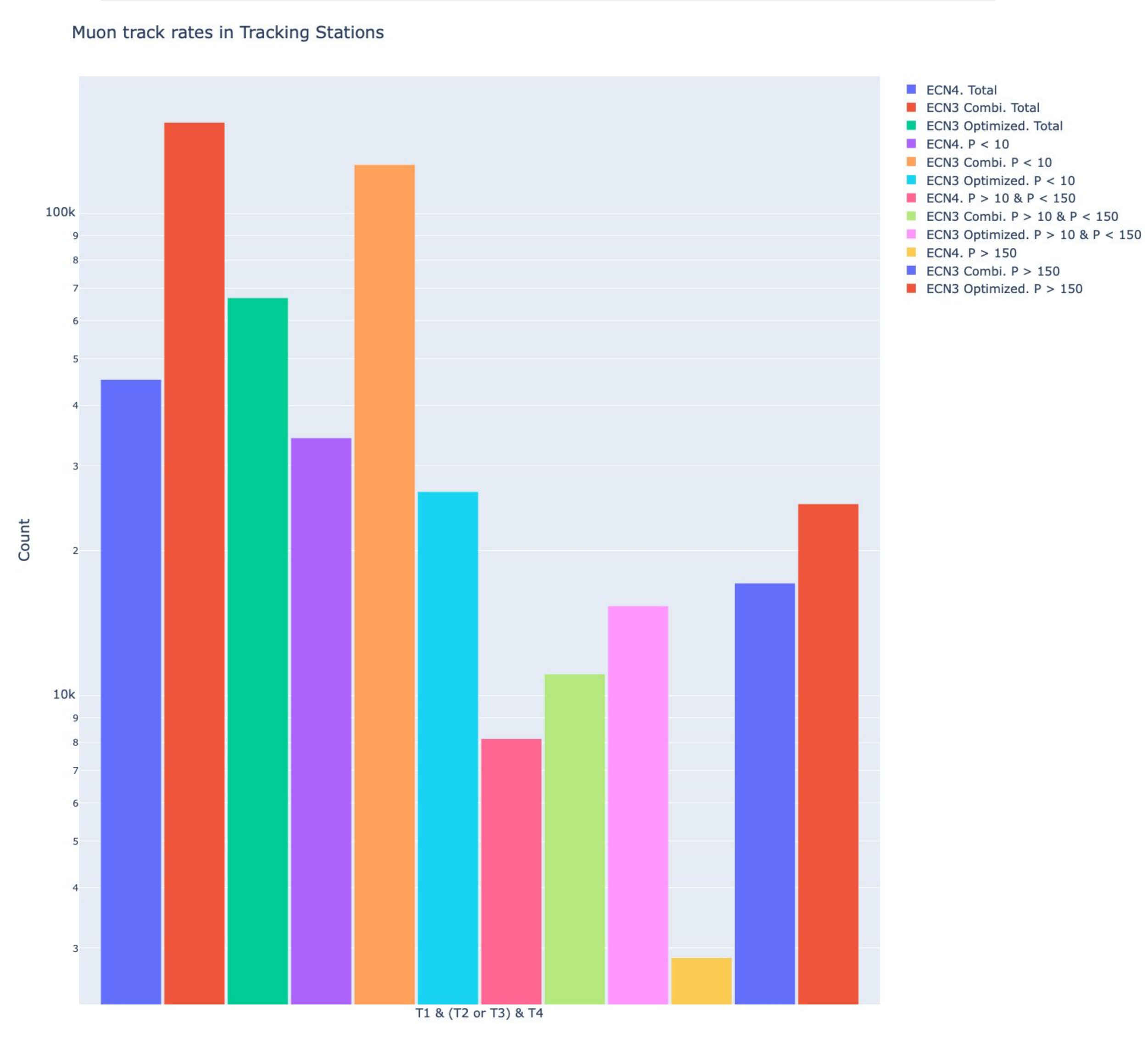
Results:

To avoid overfitting in high-dimensional space Sparse Axis-Aligned Subspace Bayesian Optimization (SAASBO) is used.

Bayesian optimization significantly outperform the manual shield modifications. Muon shield optimization at ECN3 succeeded in decrease the total muon rate by 2.5 times in comparison with the combi configuration (~160 kHz vs. 65 kHz). The most significant decrease was reached in soft momenta P < 10 GeV.

The muon rate achieved during the optimization are within the allowed physical limits.





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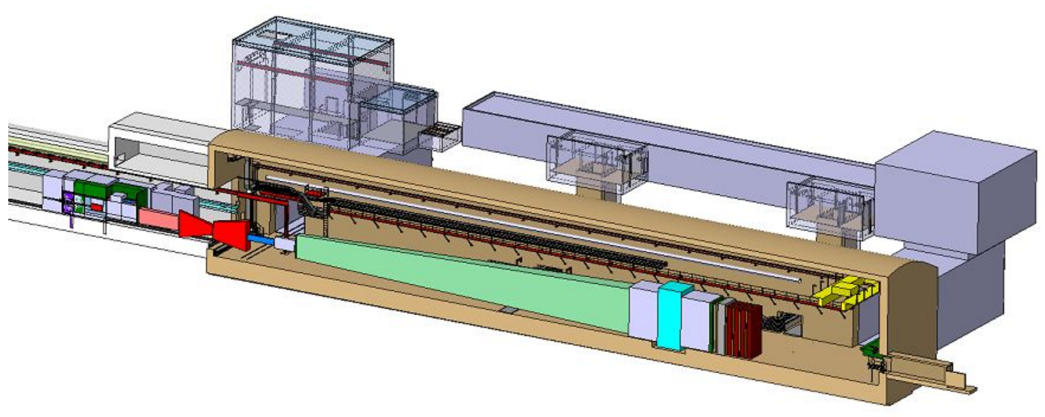

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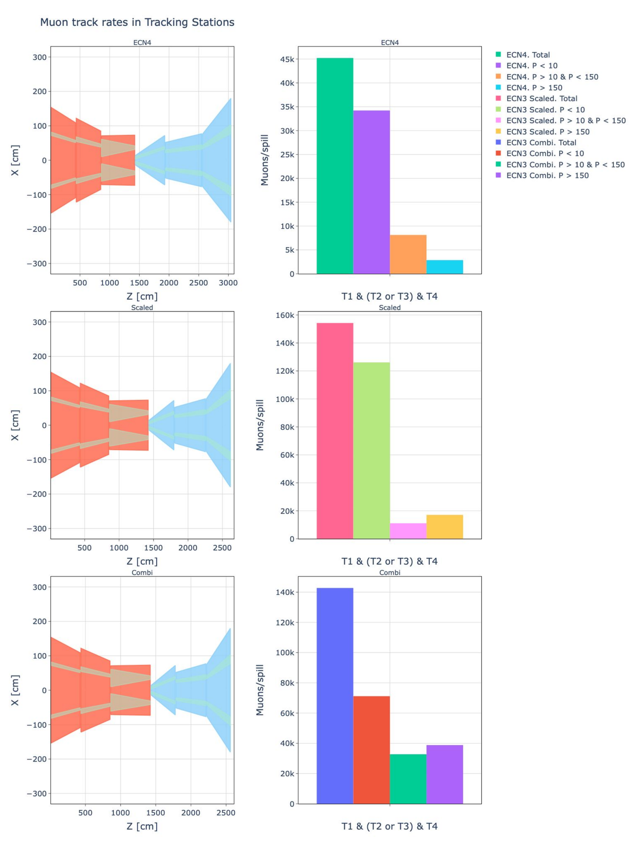

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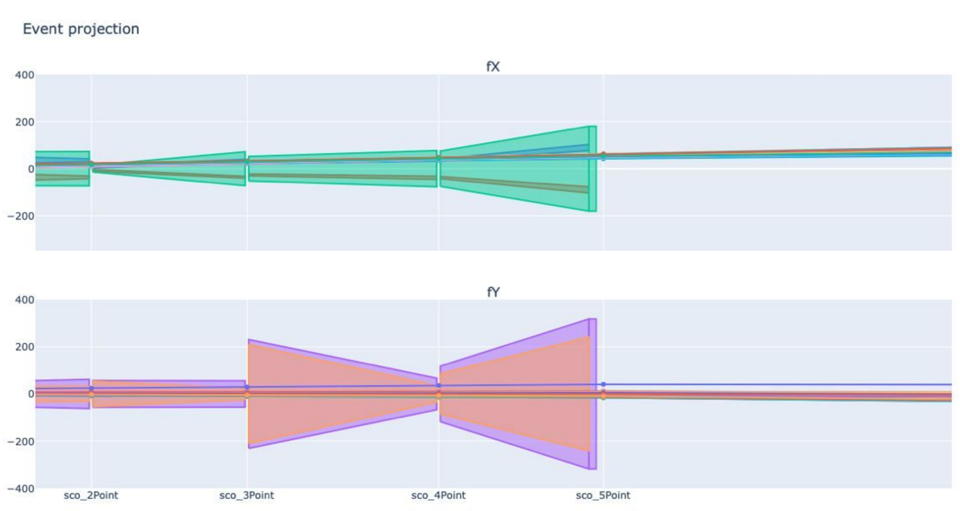

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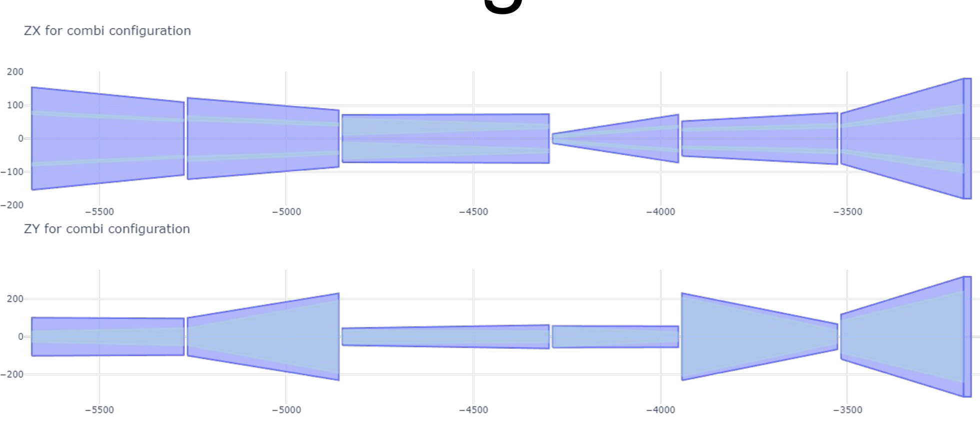

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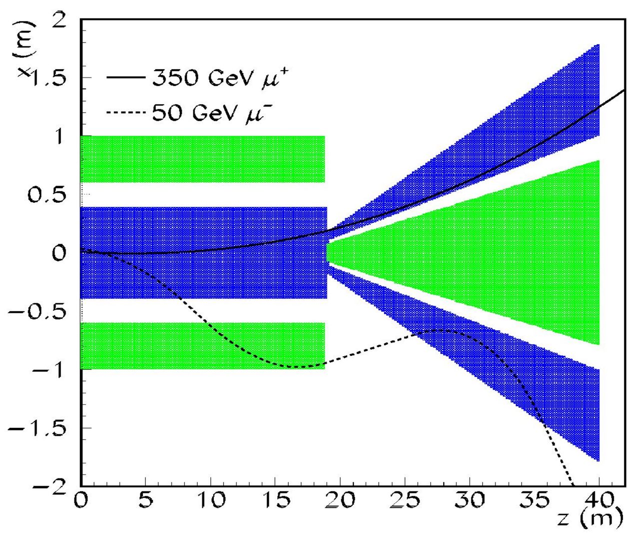

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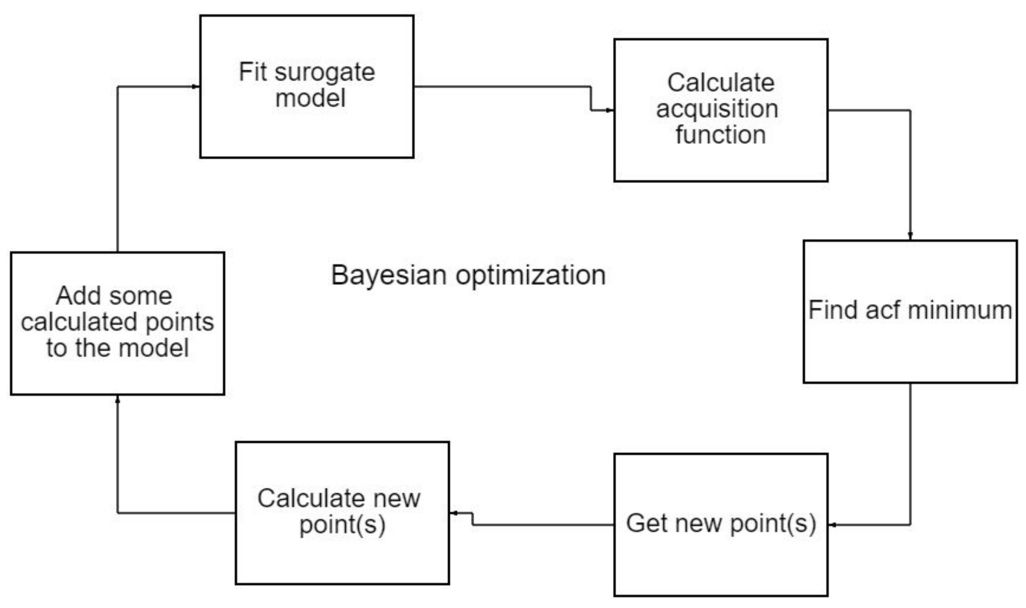

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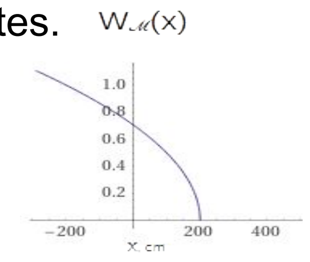

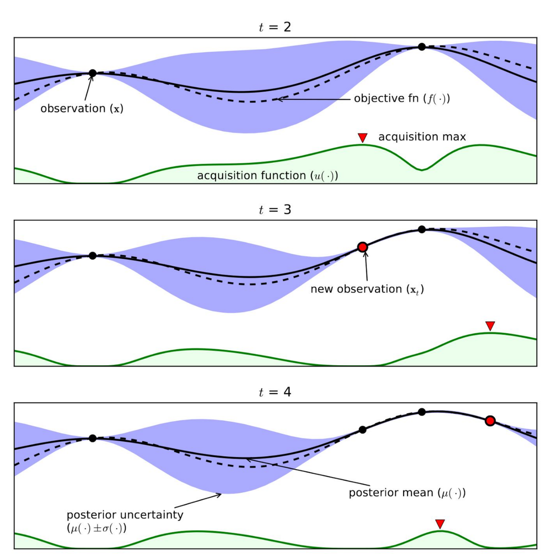

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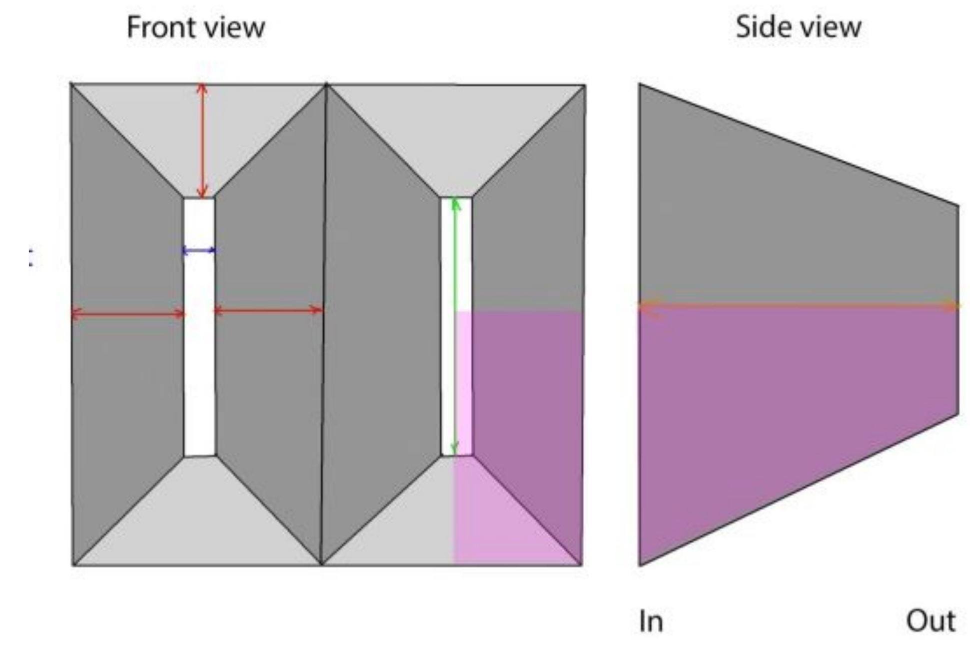

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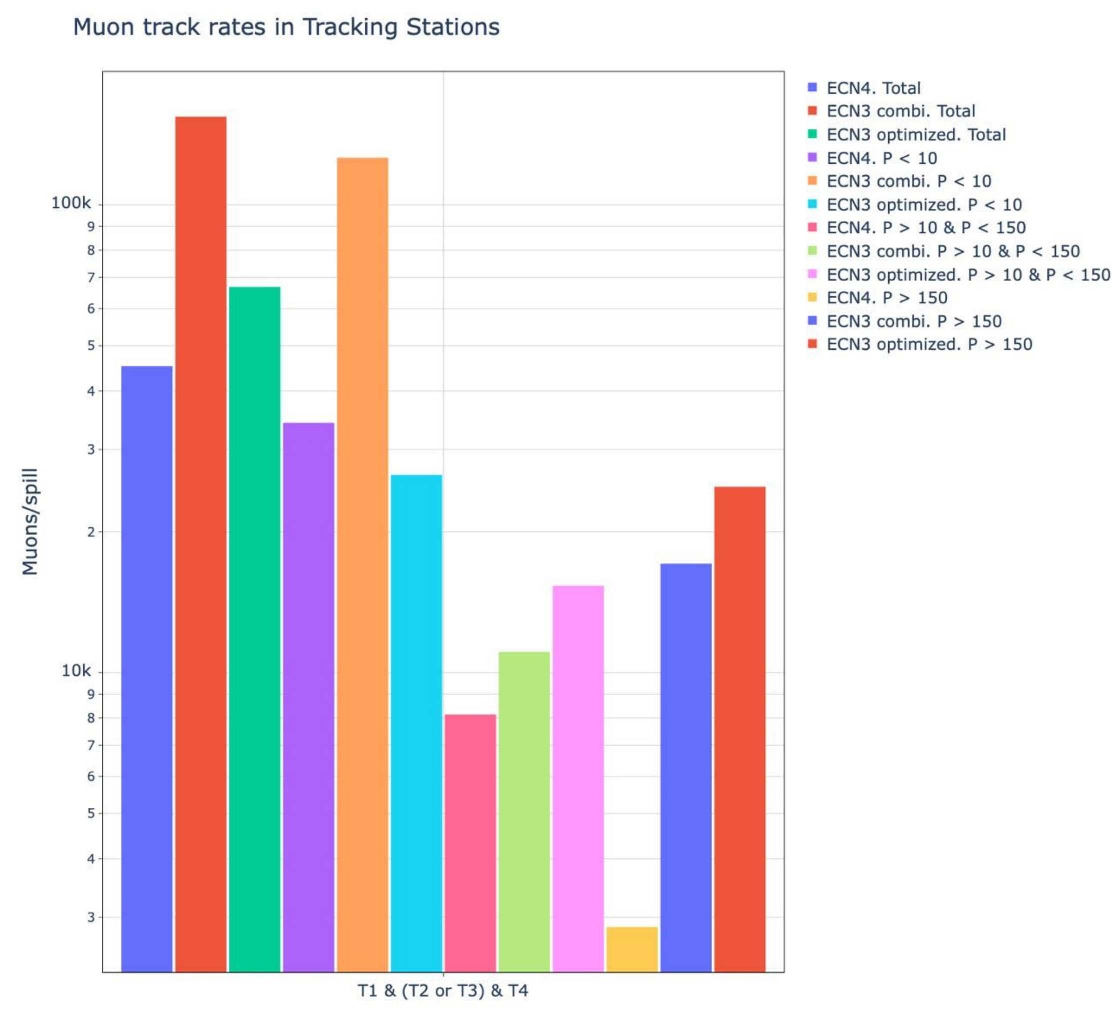

Conclusions:

- The overall muon rate was reduced by 2.5 times while keeping weight (and the price) of the Muon Shield nearly the same
- The muon rates achieved by the optimization are within the allowed physical limits
- The "curse of dimensionality" has been solved by using special surrogates in the optimization