Status of $\sqrt{s} = 3\ TeV$ MDI studies

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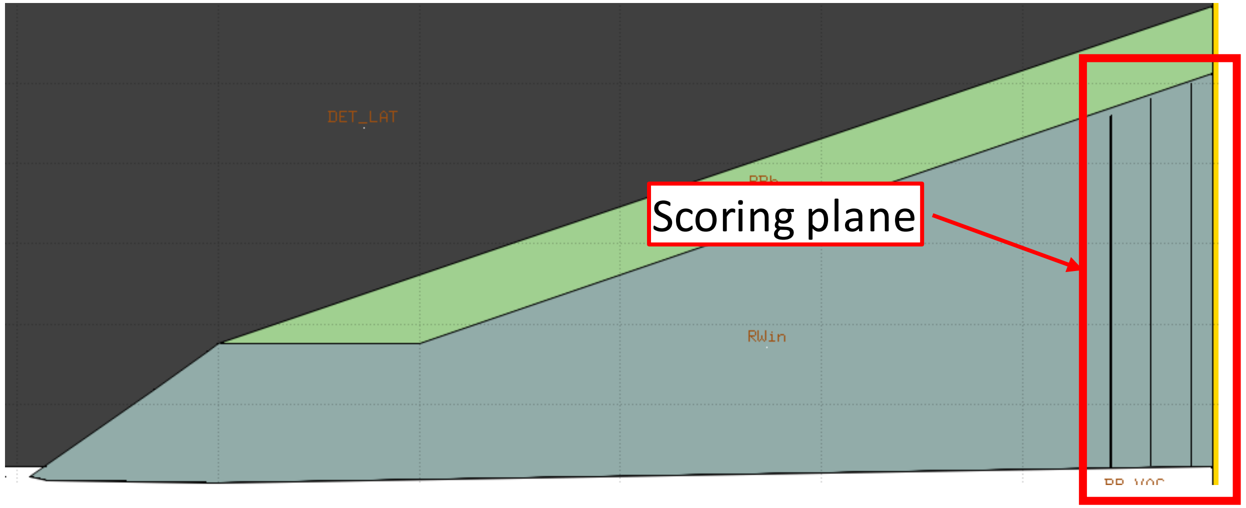
Detecting Forward Muons

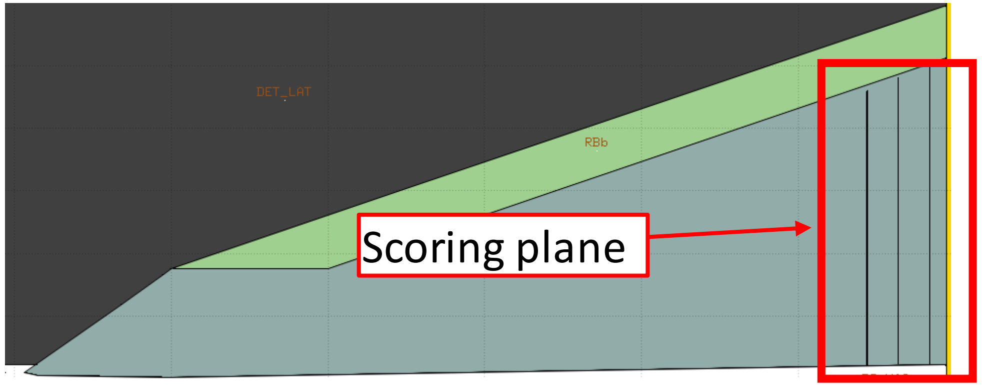
- **Instrumenting the nozzle**:
  - Small detector
  - High dose from BIB
- **Analysis** approach:
  - Three scoring layers implemented in FLUKA
  - Simulation of Forward Muons and BIB
  - Identification of Forward Muons candidate



- The goal is to **evaluate**:
  - % forward muon tagged
  - # fake forward muon from BIB

Detecting Forward Muons

- Instrumenting Nozzles
- $\mu^+\mu^- \to ZZ + \boldsymbol{\mu^+\mu^-} \to \mathrm{H} + \boldsymbol{\mu^+\mu^-} \to W^+W^- + \boldsymbol{\mu^+\mu^-}$
- Readout window $\pm 100\ ps$ w.r.t. bunch crossing
- Rough tracking of muons in layers (100% efficiency)

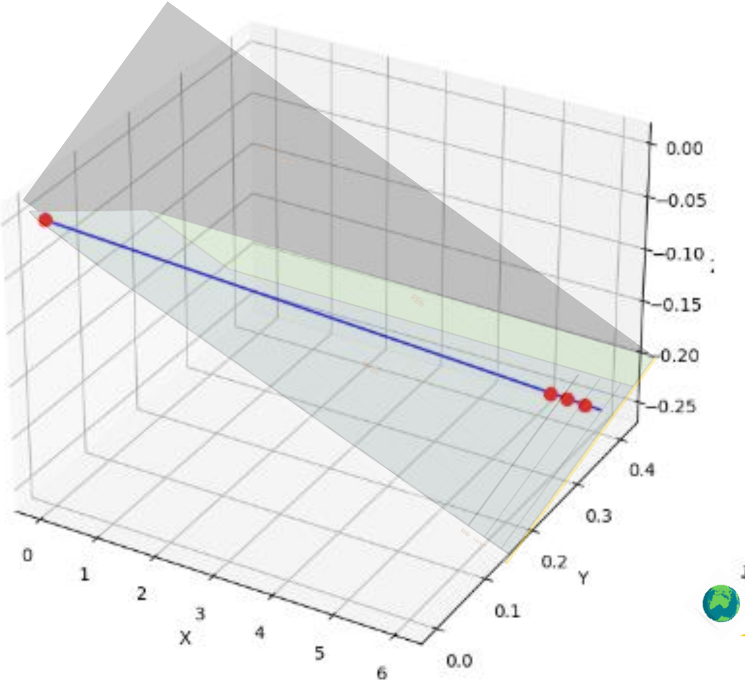


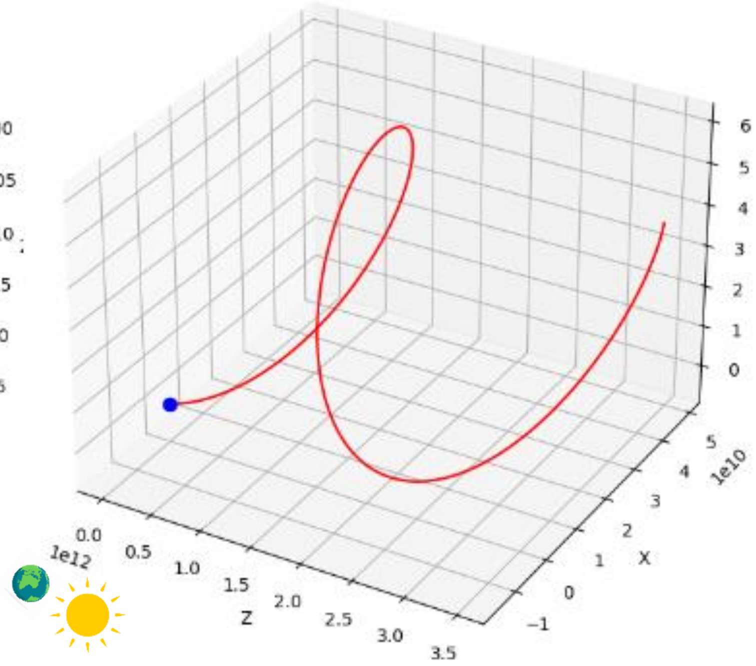
Location	Fraction
Detector	*25.0%*
All layers	*49.5%*
$1 \leq layer \leq 2$	*0.8%*
Beam Pipe	*24.7%*

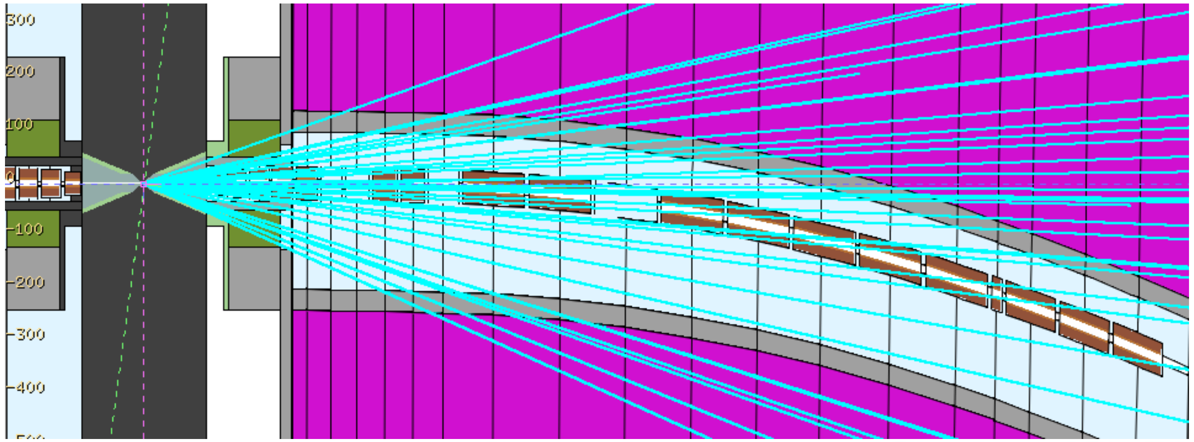
74.5% tagged

Measuring Forward Muons Energy

- Not feasible with track-like detector
- Energy deposit detector in the cavern only way

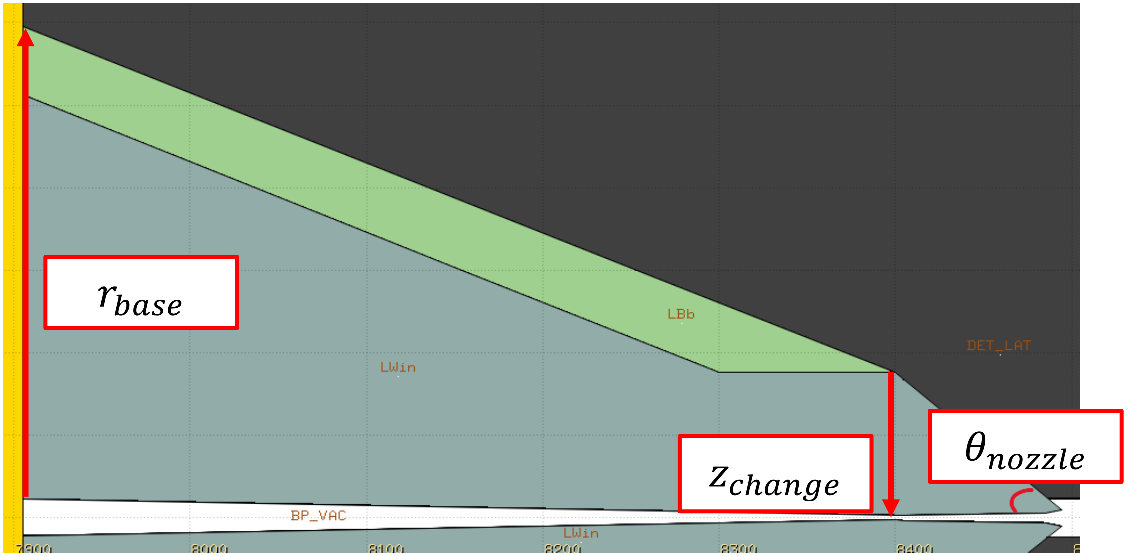






Nozzle Geometry Optimization

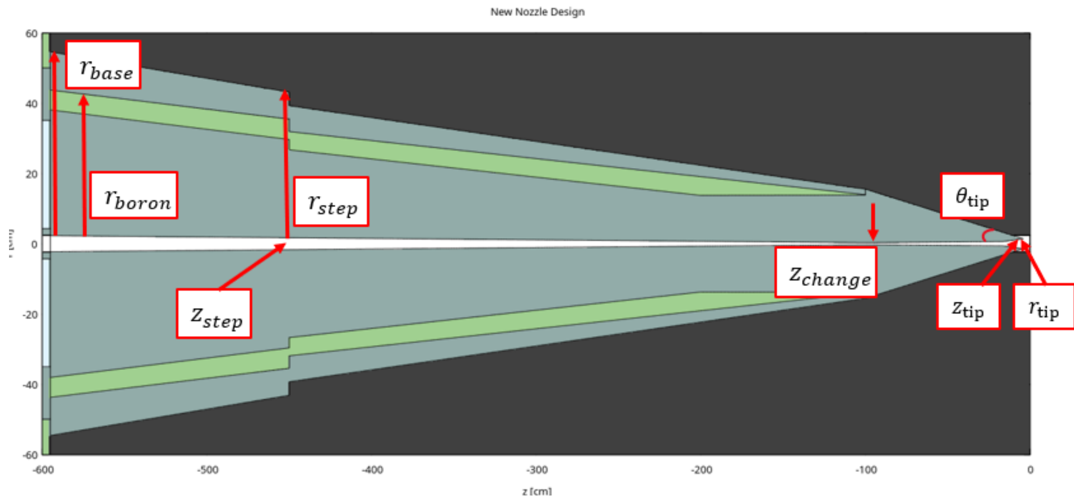
- **Goal:**
  - Reduced the BIB flux entering the detector area
  - Maximizing the detector acceptance
- **Approaches:**
  - Manual tuning with **high statistics** simulation
  - Many **low statistics** simulation to train Machine Learning algorithms
  - Bayesian optimization iterating ***medium* statistics** simulation

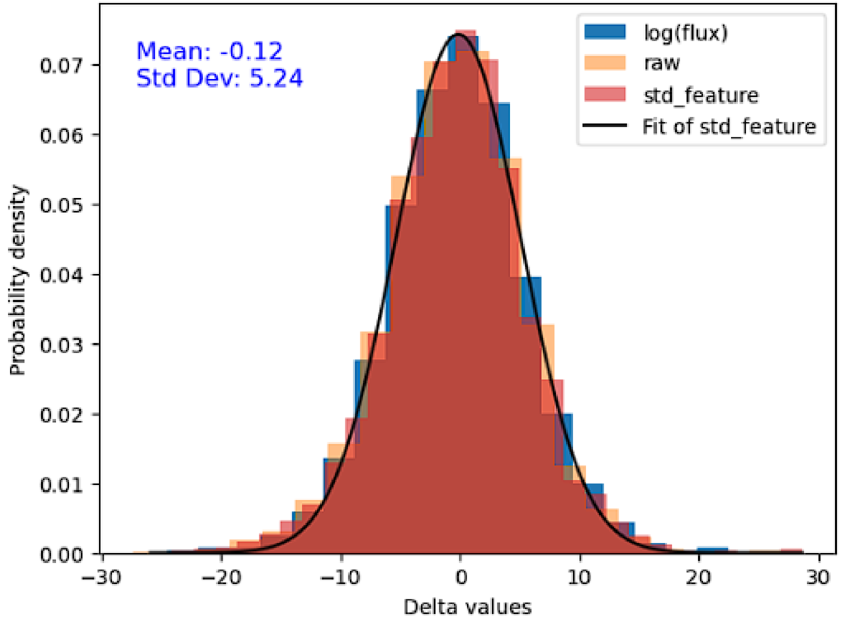


- **Figures of merit:**
  - Occupancy on the tracking system
  - Integrated flux of particles entering the Detector area

Machine Learning results

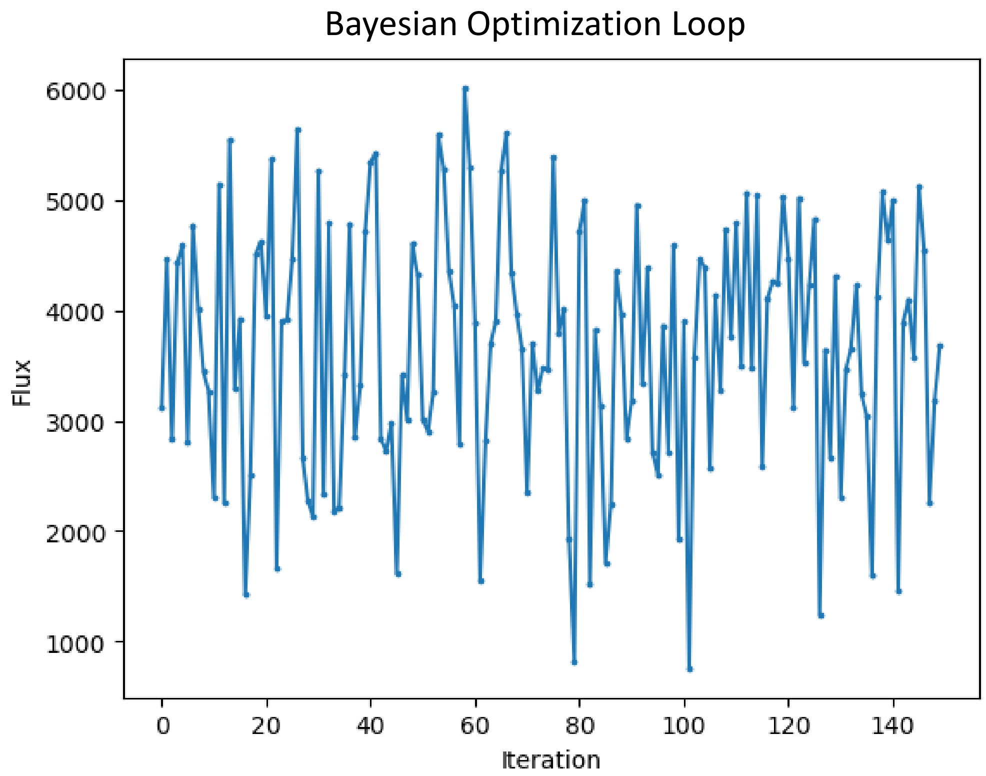
- **Method:**
  - Nozzle geometry described by 8 parameters
  - $\sim$13000 FLUKA simulation performed considering 0.02% of a bunch crossing varying the parameters
  - Several ML model trained and data transformation techniques applied
  - Models evaluated according to $\Delta[\%] = \frac{Flux_{true} - Flux_{predicted}}{Flux_{true}} * 100$
- **Goal:**
  - Using a ML model to perform large amount of pseudo-simulation
- **Results:**
  - XGBoost regressor + Standard Scaling is the best model
  - Gaussian fit of Δ distribution results in: $\overline{\Delta} = -0.12\%, \sigma = 5.24\%$





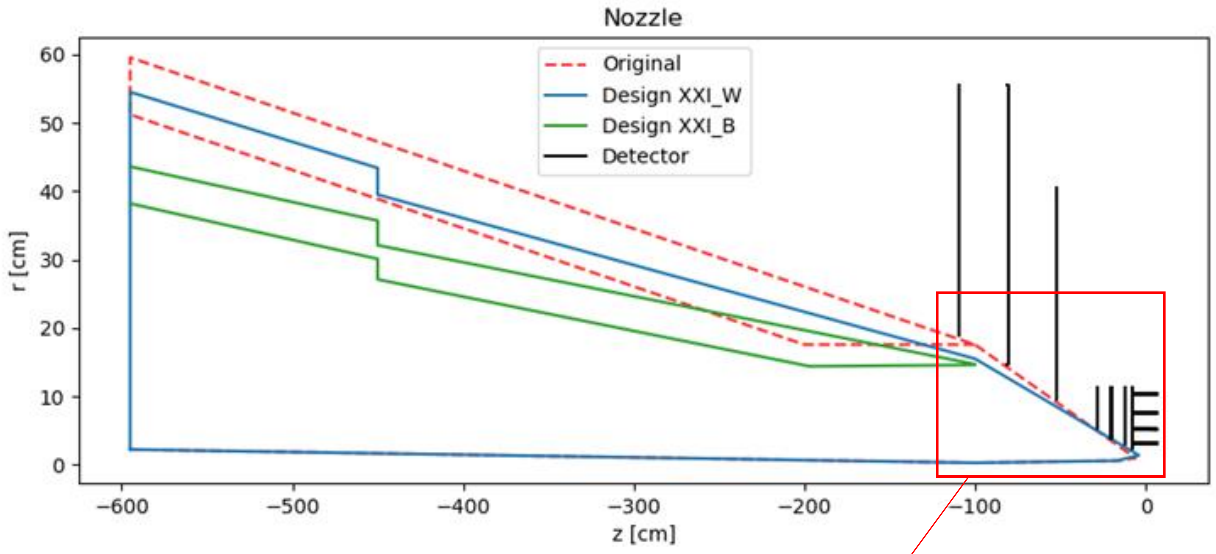
Bayesian Optimization Results

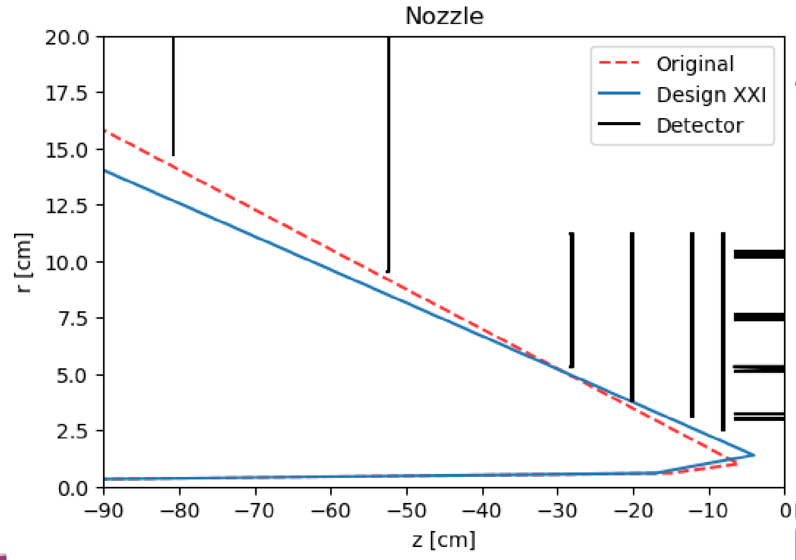
- **Bayesian Optimization Loop:**
  - Loop that builds a probabilistic model based on past evaluation during each iteration
  - Model makes an educated guess on where the best solution is in the parameters phase-space
- **Application to Nozzle optimization:**
  - Loop with 126 iteration, simulating with FLUKA 0.06% of a bunch crossing, varying 8 geometrical parameters
  - Flux of particles entering in the detector area used as metric
- **The algorithm did not converge to an optimal solution**
  - Low statistics could be the cause



Optimized Geometry

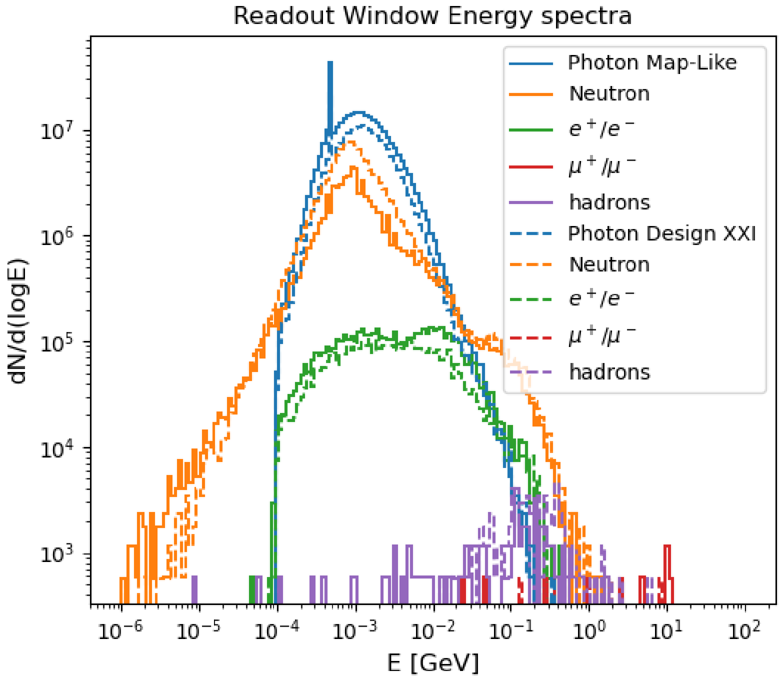
- Considering both Manual Tuning and Machine Learning studies a new design has been achieved
- **Main features:**
  - Base radius reduced
  - Nozzle body further reduced starting at 450 cm from the IP
  - Borated polyethylene coat moved under a layer of tungsten
  - Tip moved few millimeters further from the IP

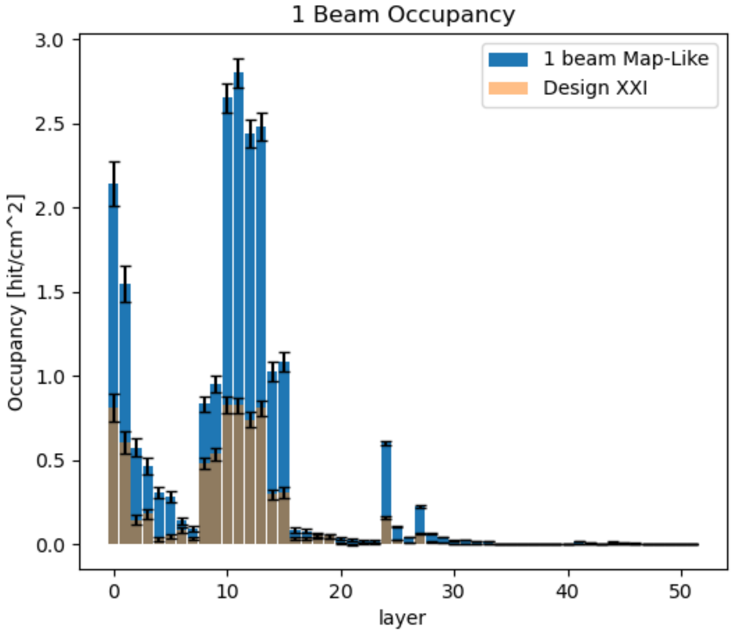




Optimized Geometry

- **Beam-Induced Background:**
  - Reduced photon and e^+/e^- flux
  - Reduced occupancy in the tracking system
  - Increased neutron flux
- **Overall consideration:**
  - Easier to sustain
  - Less material needed
  - Increased detector acceptance
  - BIB impact on tracking system and ECAL reduced
  - BIB impact on HCAL increased





Complex observable

$$flux \rightarrow a \cdot \frac{\Delta flux_{\gamma}}{flux_{ref_{\gamma}}} + b \cdot \frac{\Delta flux_{n}}{flux_{ref_{n}}} + c \cdot \frac{\Delta flux_{e}}{flux_{ref_{e}}} + d \cdot \frac{\Delta V}{V_{ref}}$$

- **Method:**
  - $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$: Plot sub-detector specific metric as function of BIB flux (Energy resolution in CALs, occupancy in vertex)
  - $\boldsymbol{d}$: Takes into account costs and acceptance gain. No idea on how quantify in relation to the other parameters **yet**.

International MUON Collider Collaboration

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Thank you for the attention

References

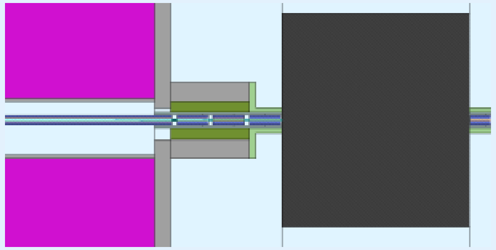
- [1] Y. Alexahin, E. Gianfelice-Wendt, A 3-TeV MUON COLLIDER LATTICE DESIGN, Insiperhep.net
- [2] P. Li, Z. Liu, K. Lyu, HIGGS WIDTH AND COUPLINGS AT HIGH ENERGY MUON COLLIDERS WITH FORWARD MUON DETECTION, arxiv.org
- [3] M. Ruhdorfer, E. Salvioni, A. Wulzer, INVISIBLE HIGGS FROM FORWARD MUONS AT A MUON COLLIDER, arxiv.org
- [4] MODE Collaboration, mode.github
- [5] A. Baranov et al., OPTIMIZING THE ACTIVE MUON SHIELD FOR THE SHIP EXPERIMENT AT CERN, SHIP optimization
- [6] Z. Liu, HIGGS WIDTH AND COUPLINGS AT HIGH ENERGY MUON COLLIDERS WITH FORWARD MUON DETECTION, indico.cern

BACKUP

BIB simulation with FLUKA

1. From muon decay to nozzle area

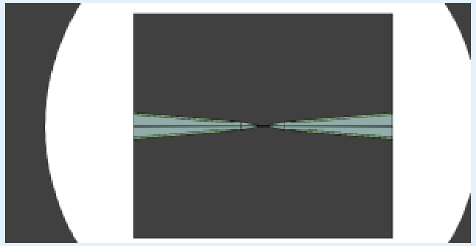
Machine dependent



- Generated one beam of μ^+ decays within $\mathbf{55\ m}$ from the Interaction Point
- **Energy threshold** for particles production fixed at $\mathbf{100\ keV}$
- Particles which arrives to the nozzles are scored

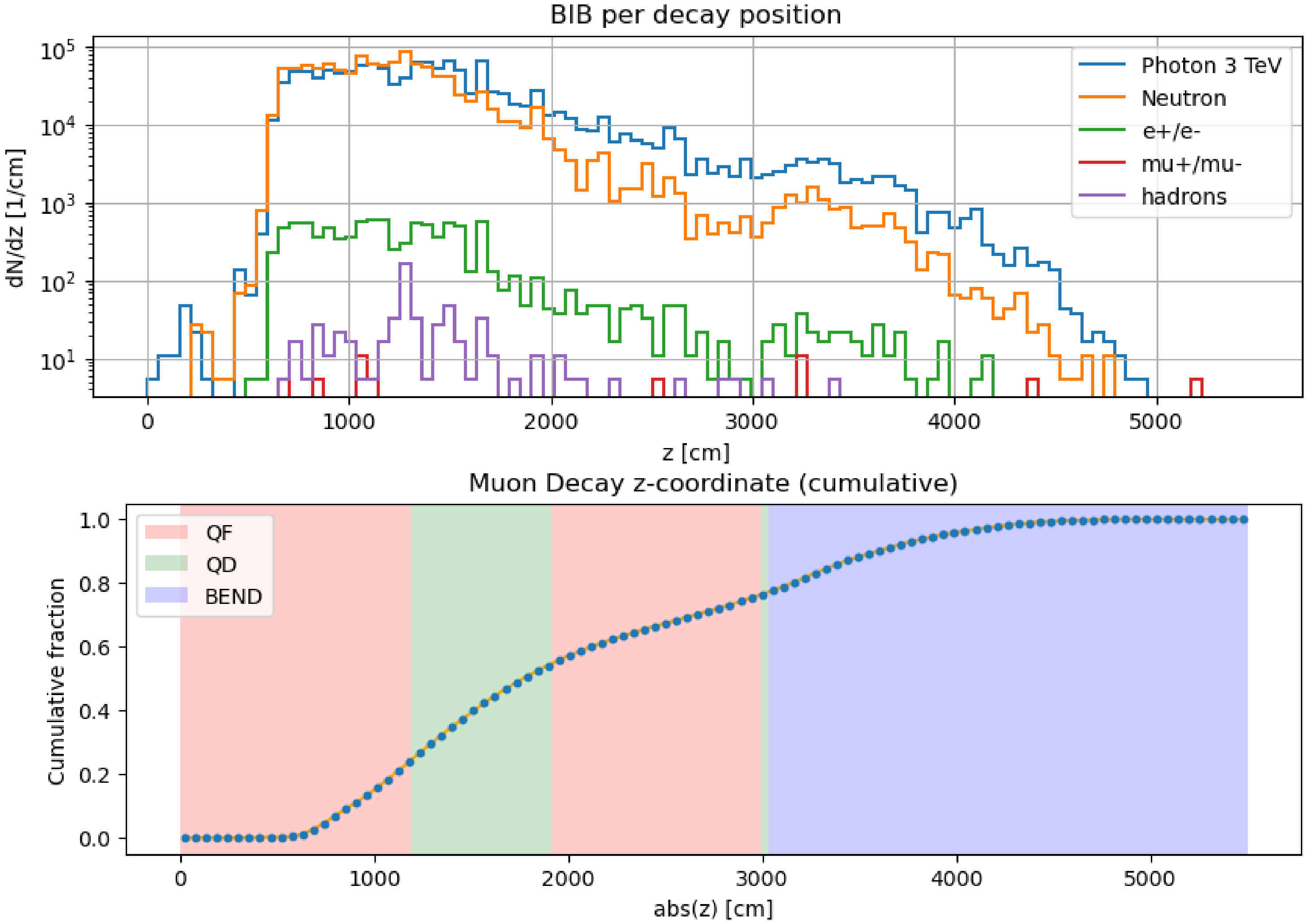
2. Nozzle area to detectors

Nozzle dependend

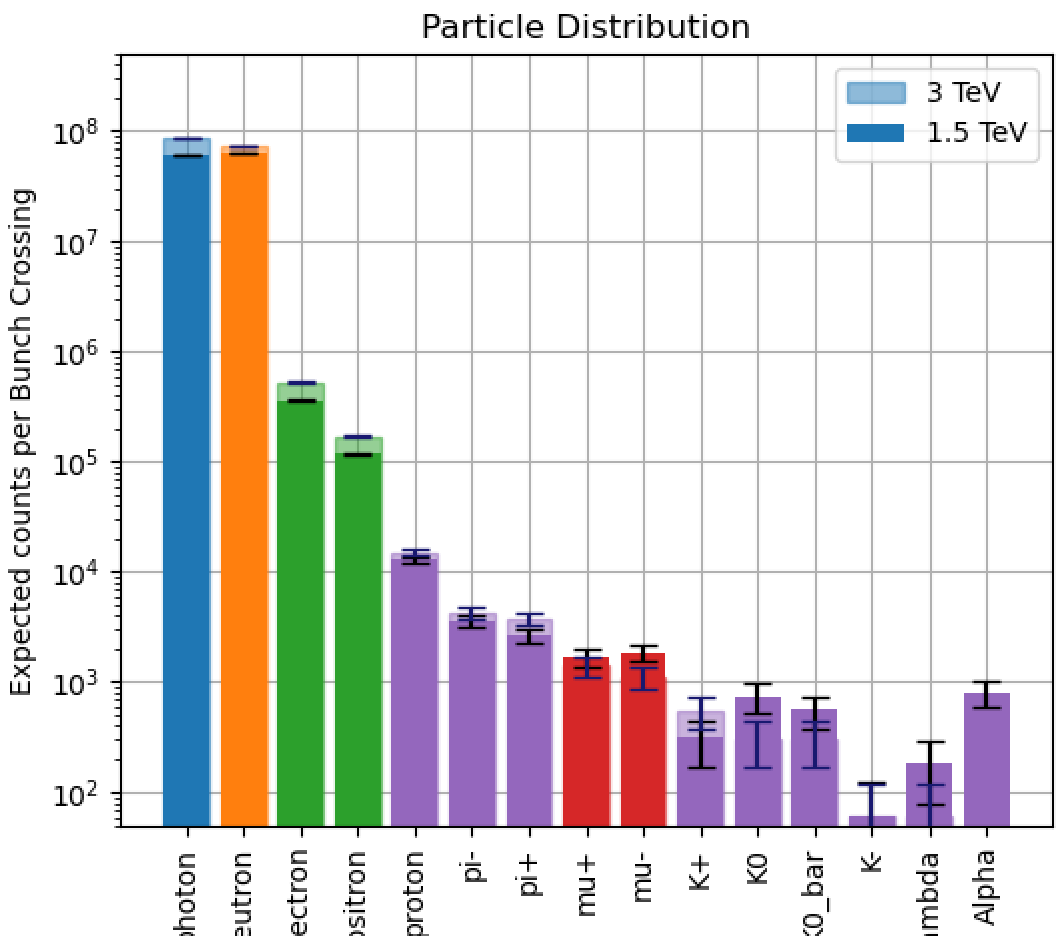


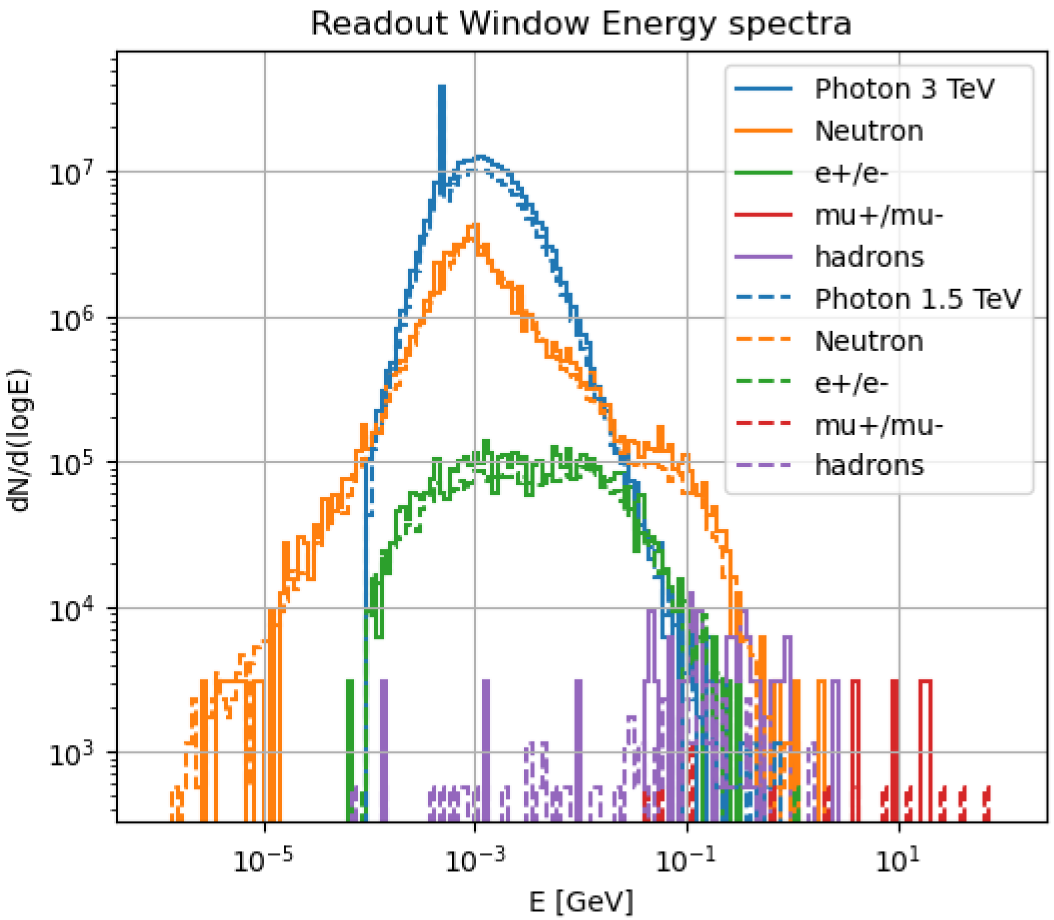
- Propagation through the Nozzles
- Particles who exit the nozzle and enters the detector area are scored
- $\sim$1.6% of one BIB event (i.e. bunch crossing) considering only 1 beam → $\boldsymbol{4\ days}$ **per simulation**

Muon decay position



BIB simulation with FLUKA





International MUON Collider Collaboration

Detector

hadronic calorimeter

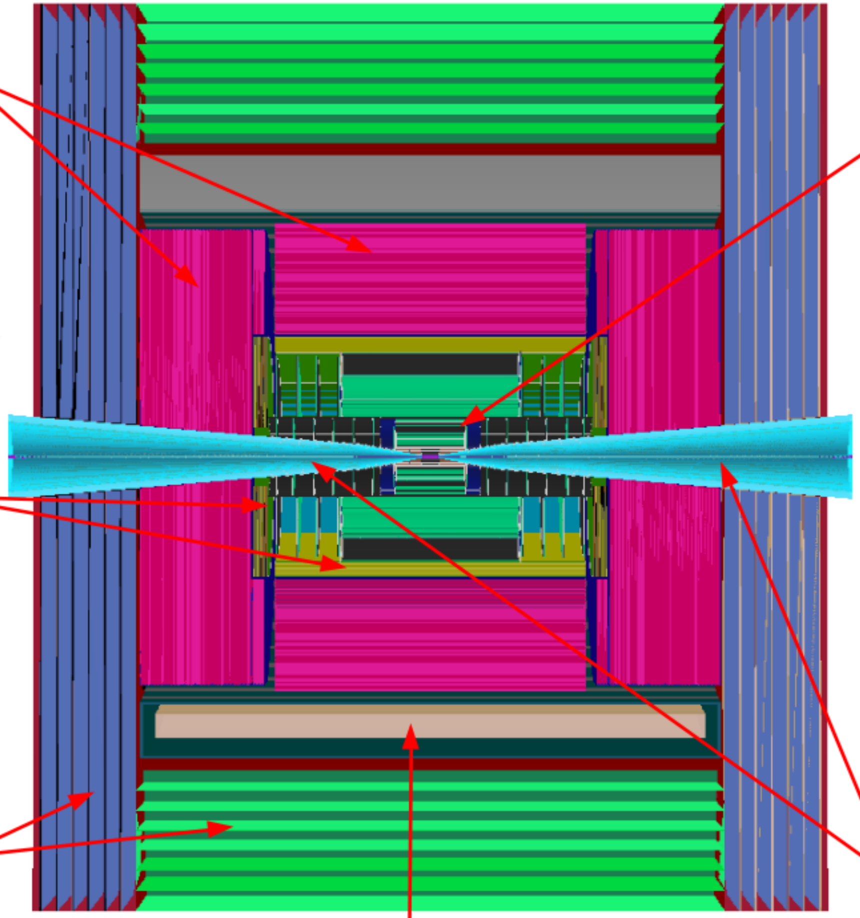
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

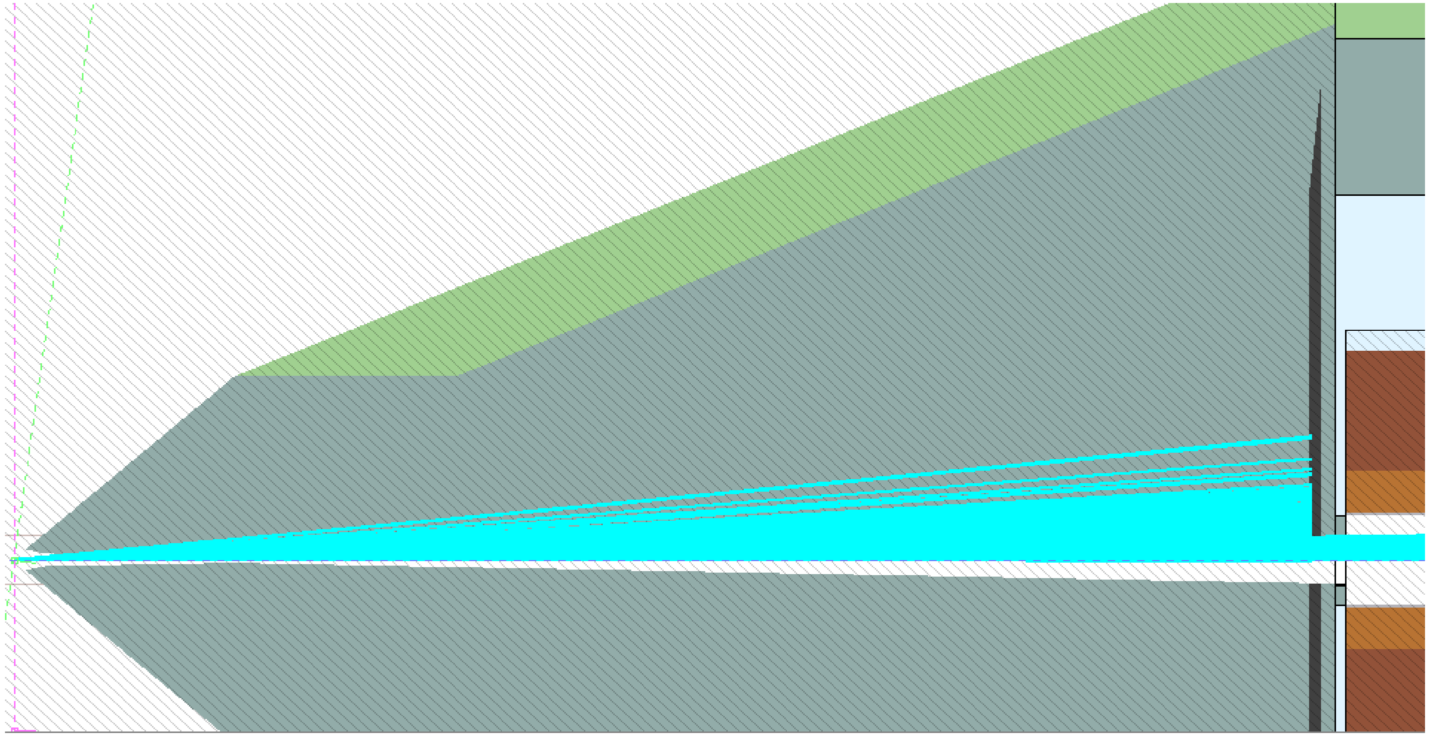
tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip Si sensors.

shielding nozzles

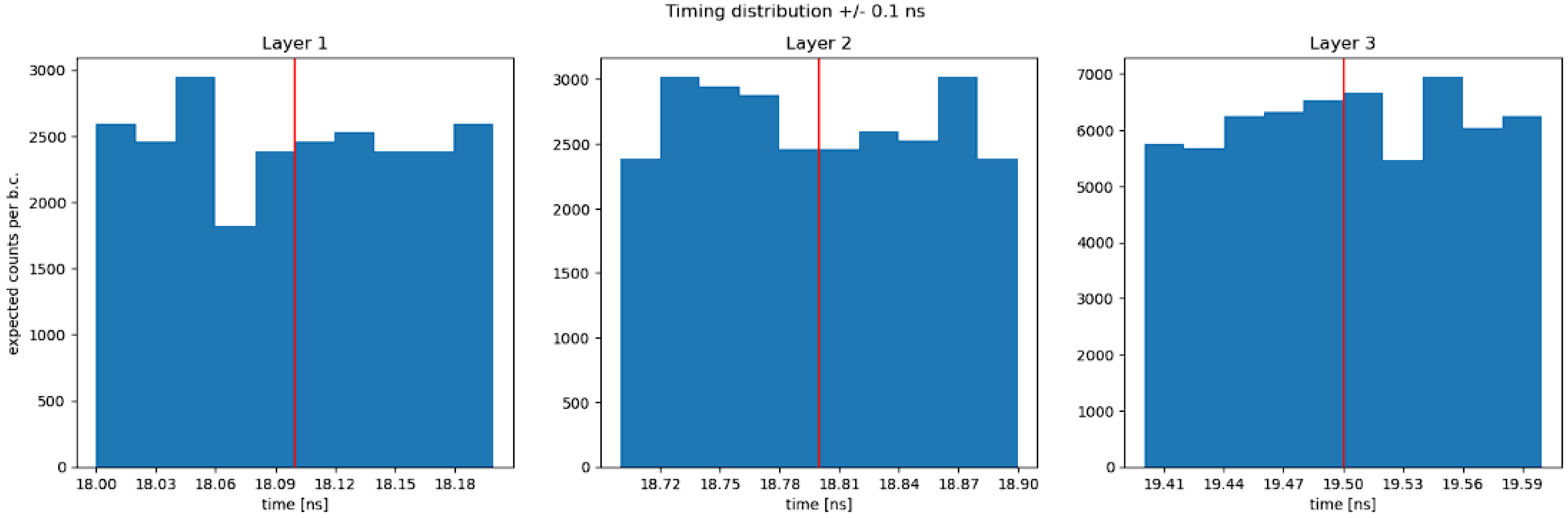
- Tungsten cones + borated polyethylene cladding.

Forward Muon in Nozzle



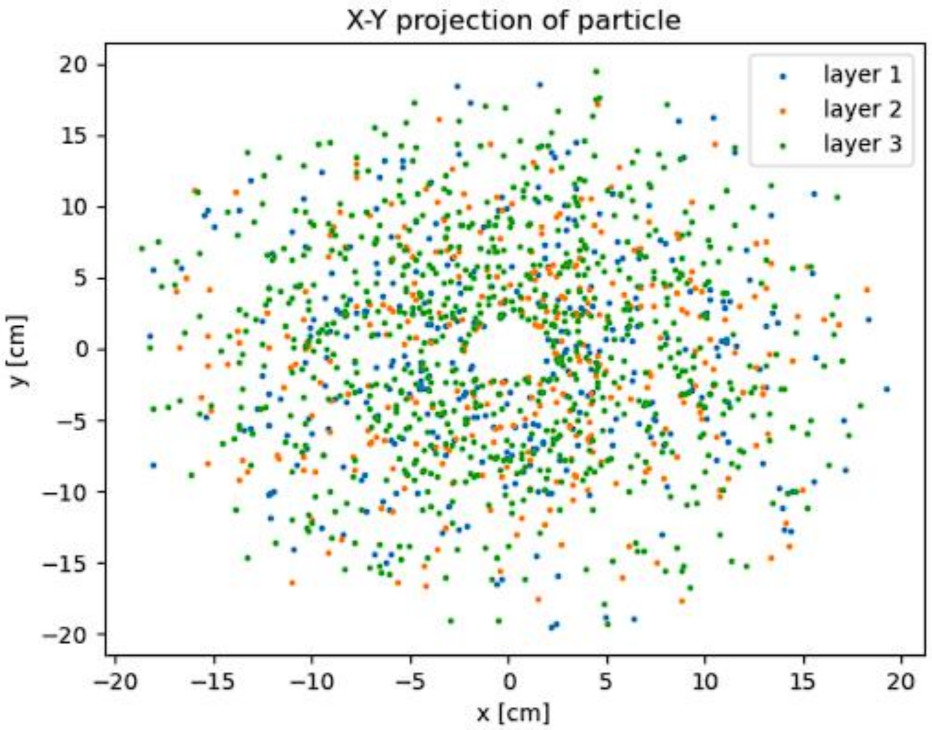
BIB characteristics

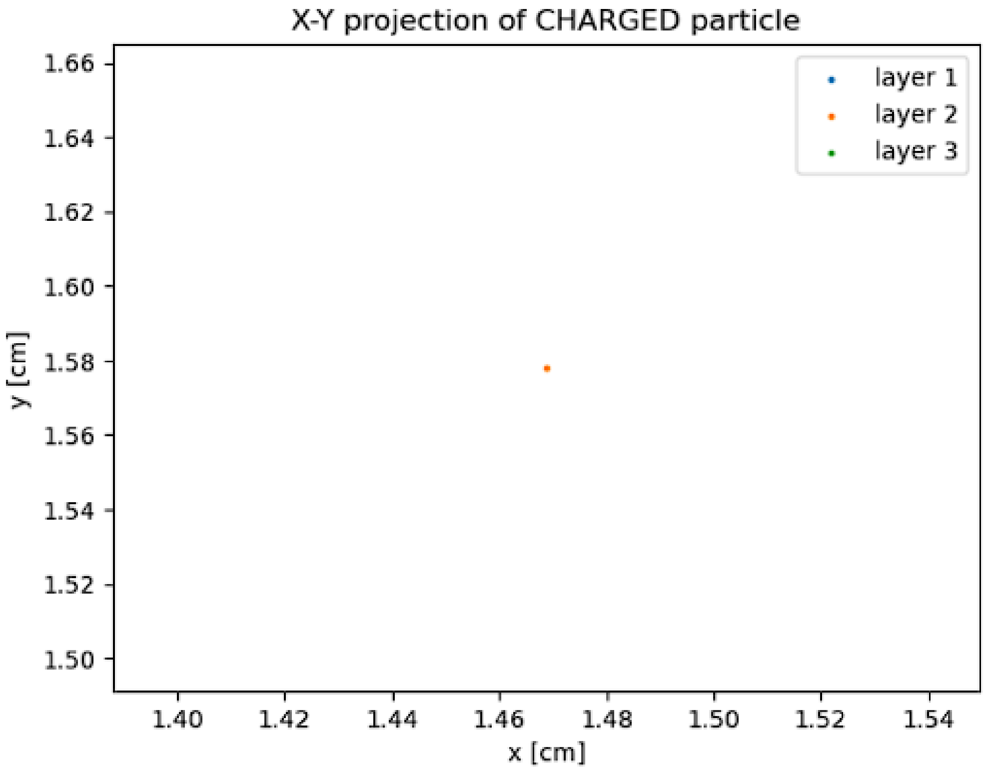
- By requiring a window of $\pm 100\ ps$ with respect to the expected time of arrival in the layers BIB reduced by 5 order of magnitudes



BIB characteristics

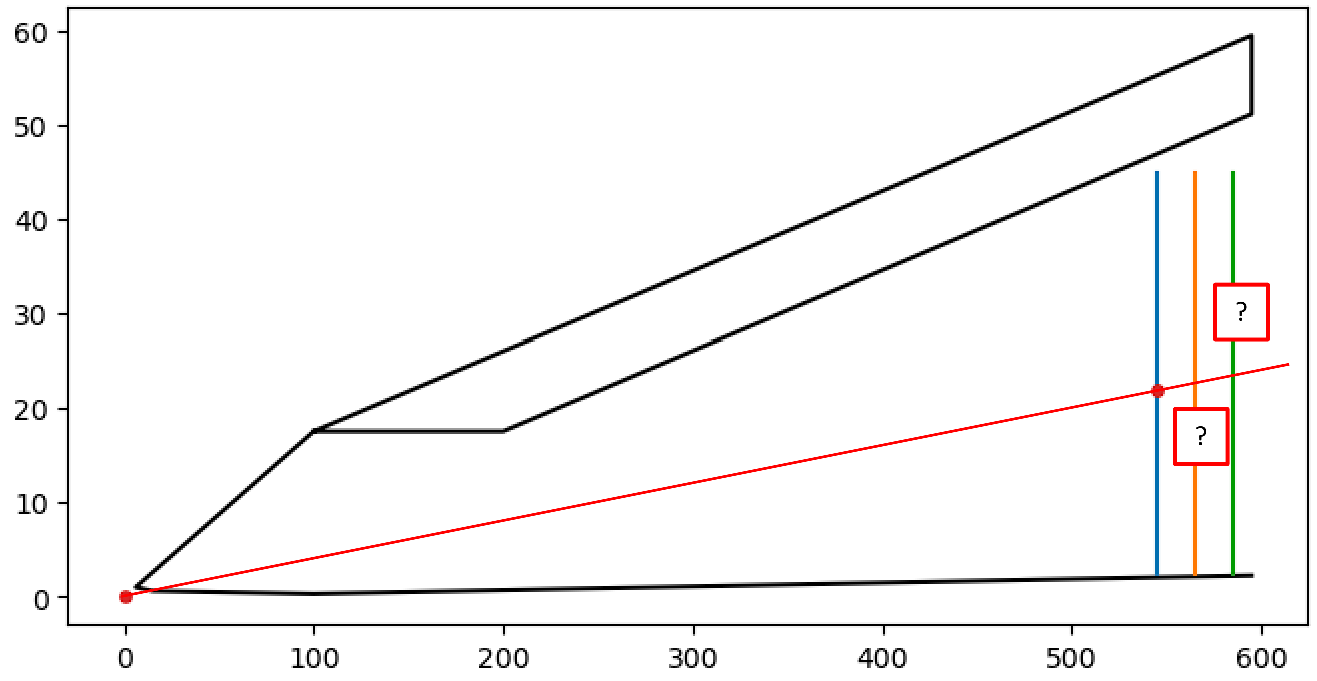
- BIB particles passing through the layers within the time window (1.4% of b.c)





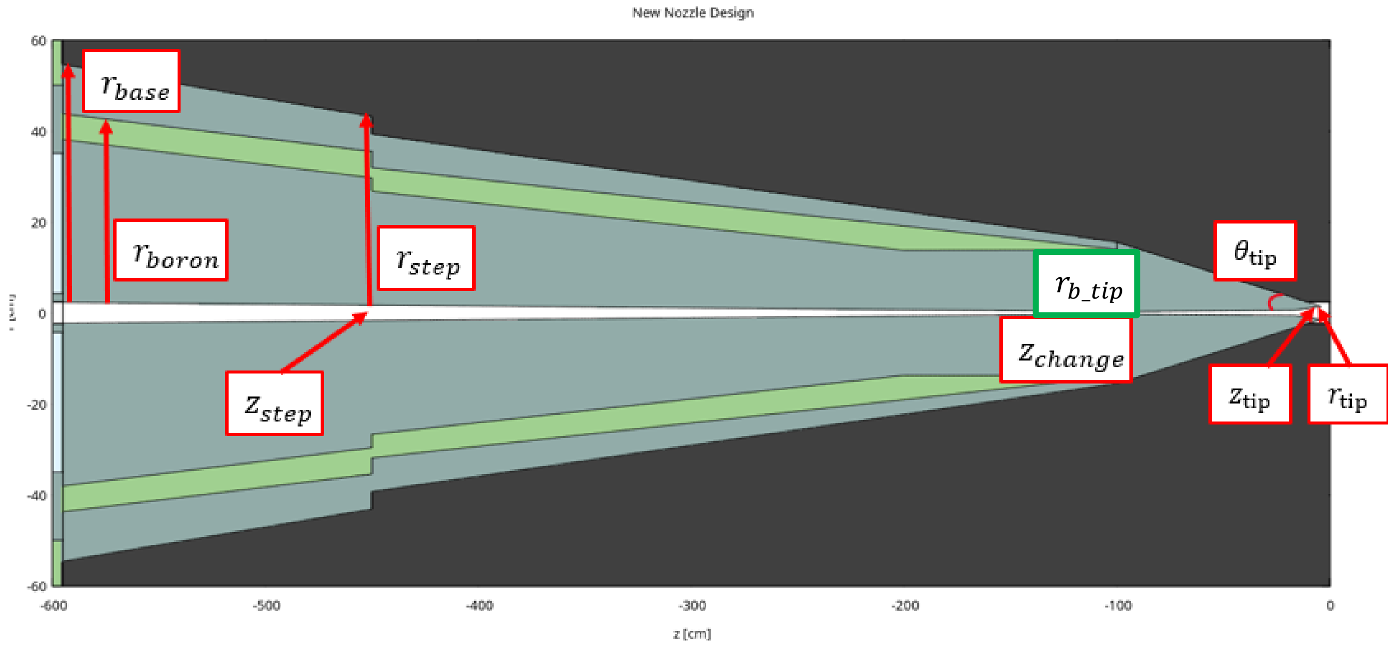
(a rough) Tracking

- Assuming that forward muons are produced at the IP, a straight line is the defined for each point in layer 1
- The line is propagated to layer 2 and 3. If at least 1 particle is present in the expected position $\pm 1\ cm$, the particle is tagged as a forward muon



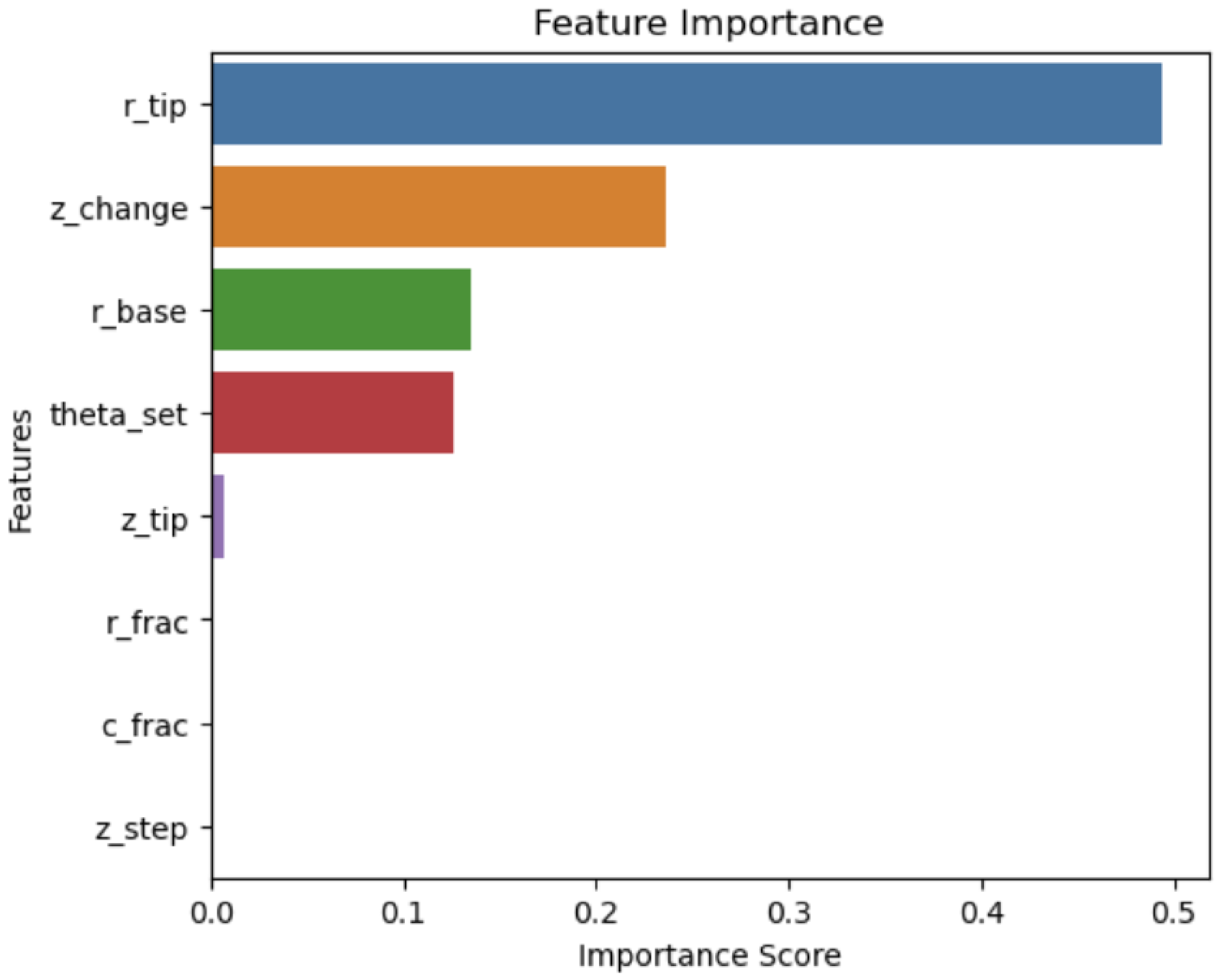
Machine Learning results

- **Limits:**
  - Fixed value of parameters
  - Each sample is a different combination on fixed parameters
- **Next Steps:**
  - 9th parameters considered
  - All independent values in a defined range
  - 20000 simulation



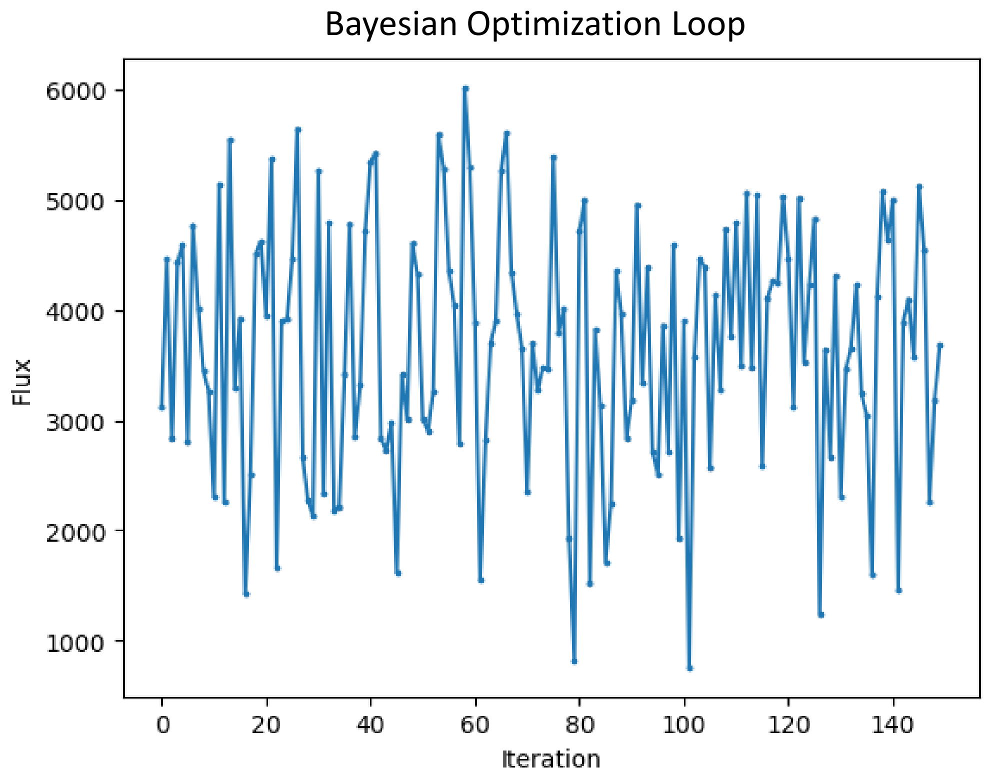
Hard ML results

- Feature Importance with XGBoost regressor



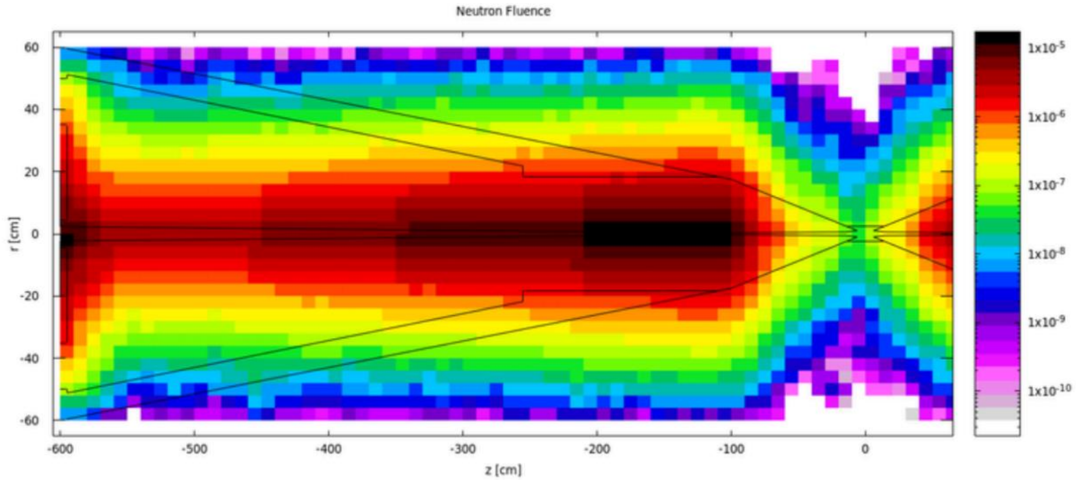
Bayesian Optimization Results

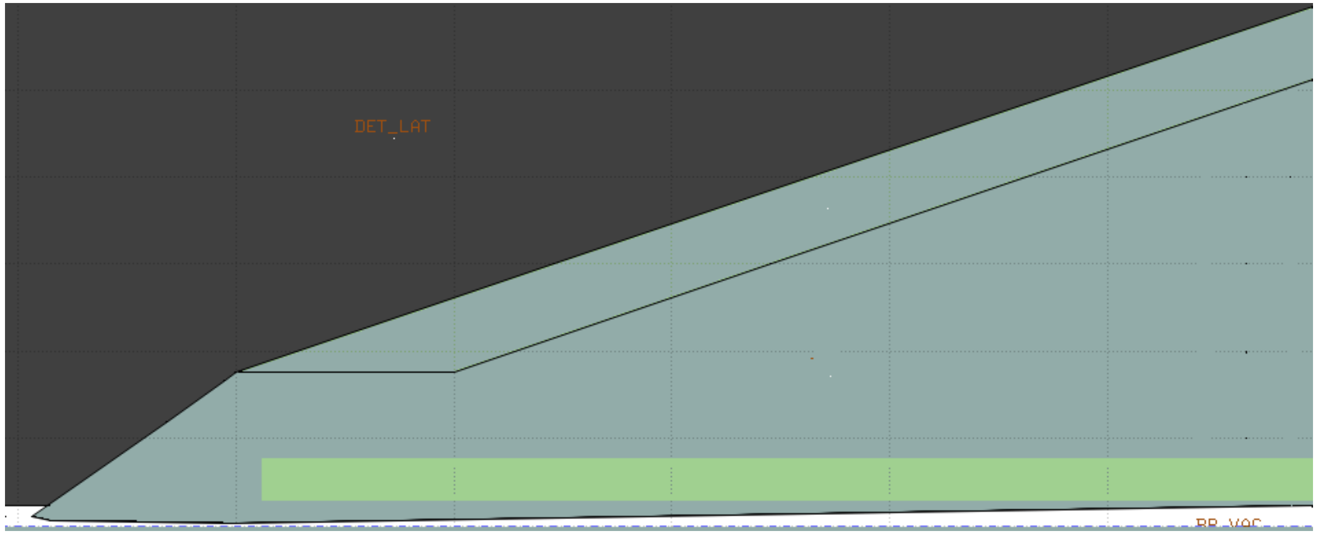
- **Next steps:**
  - 9 parameter simulation
  - High statistics used (1.6 % of bunch crossing)
  - It will take about 2 month

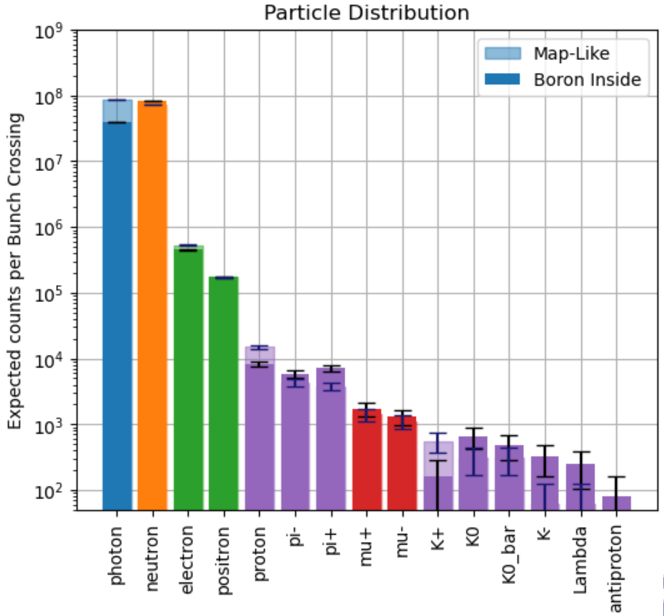


High Statistics Approach

- Lessons learned:
  - The Beam Pipe cannot be touched
  - Is Boreth layer really effective?
    - Tried to put the Boreth inside the nozzle

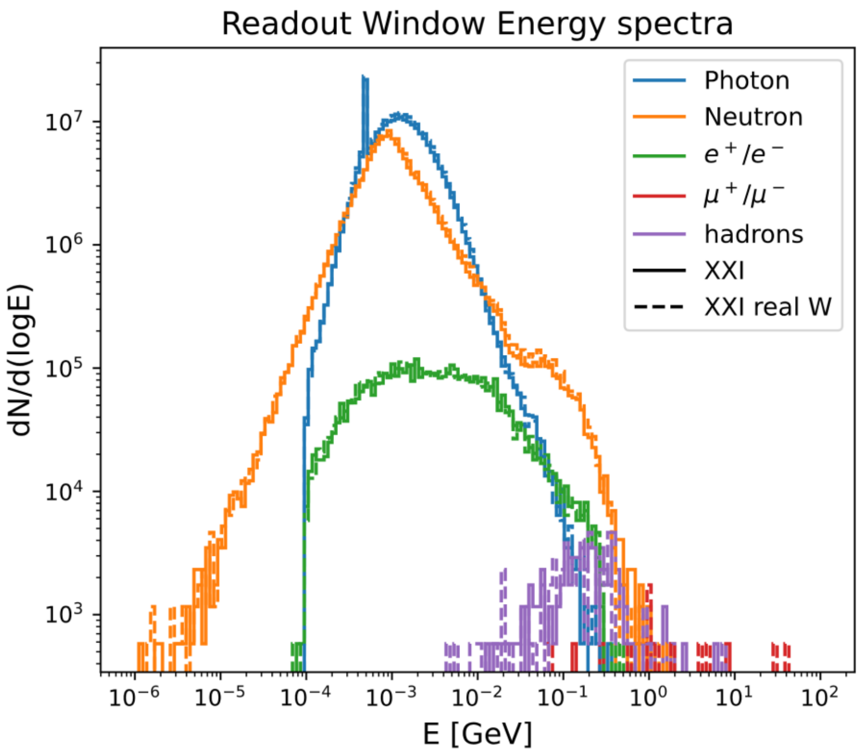


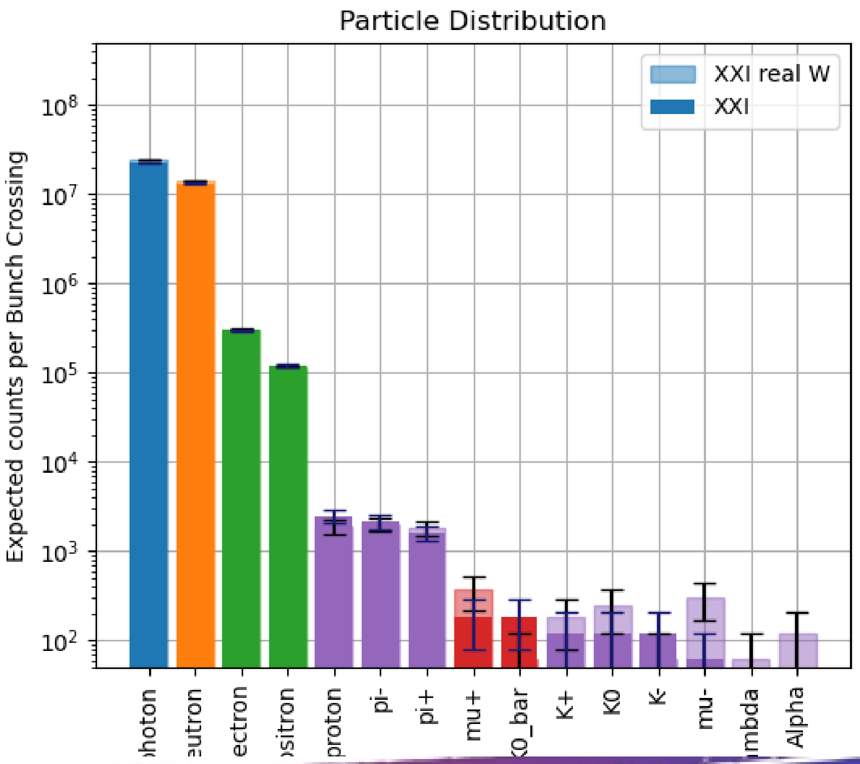




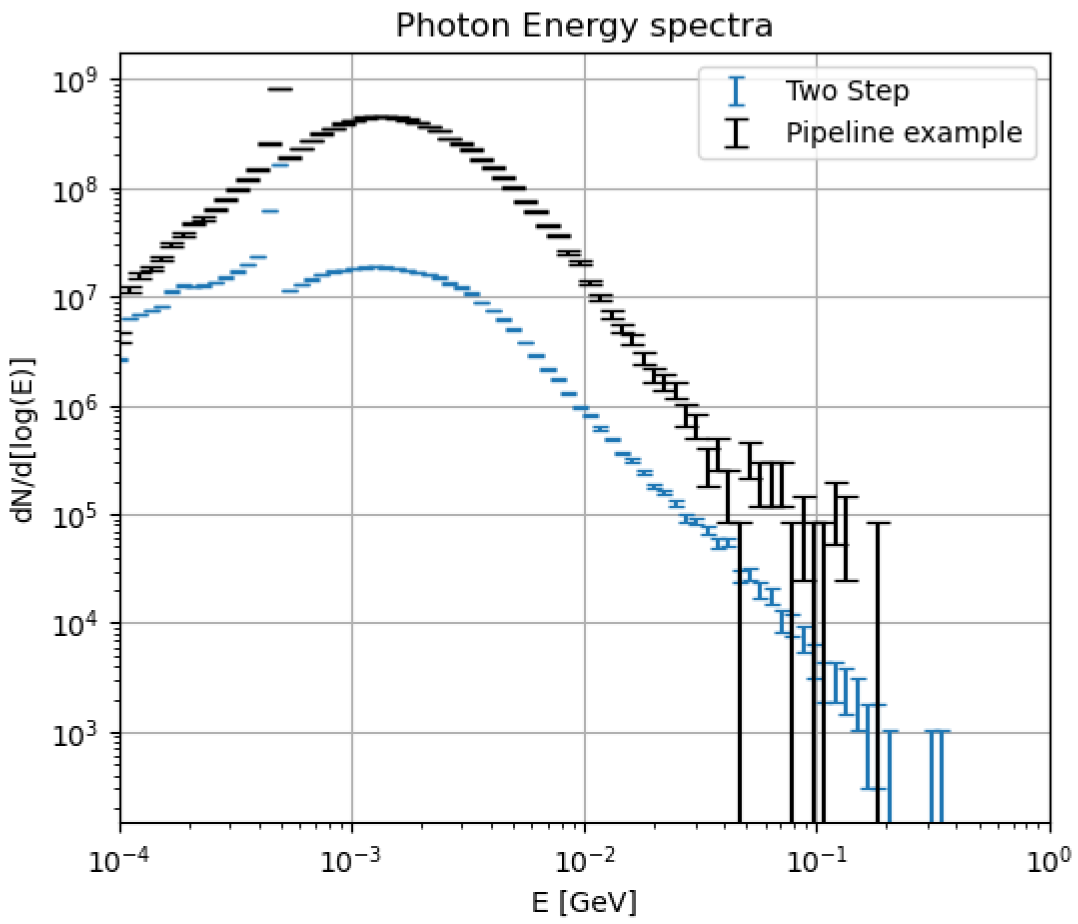
Optimized Geometry

- **Real tungsten alloy simulated:**
  - Same spectra
  - 9% more particles





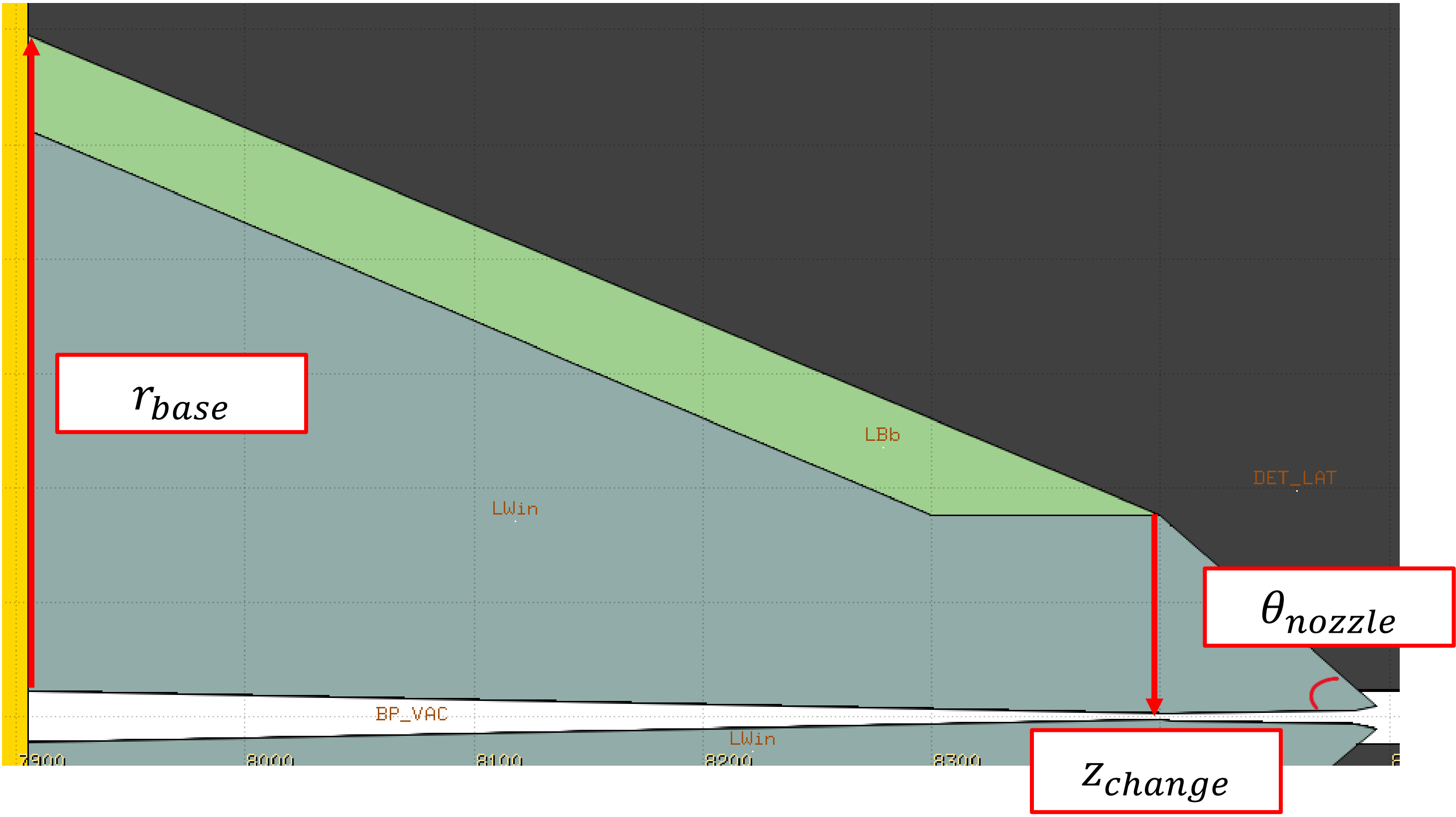
Low Statistic simulation



- Two step: 2% of one beam, one bunch crossing
- Pipeline: 0.025% of one beam, one bunch crossing
- **Pipeline nozzles smaller** than original (aperture = 20 cm)
- $\sigma = \sqrt{\#particles}$

ML Studies

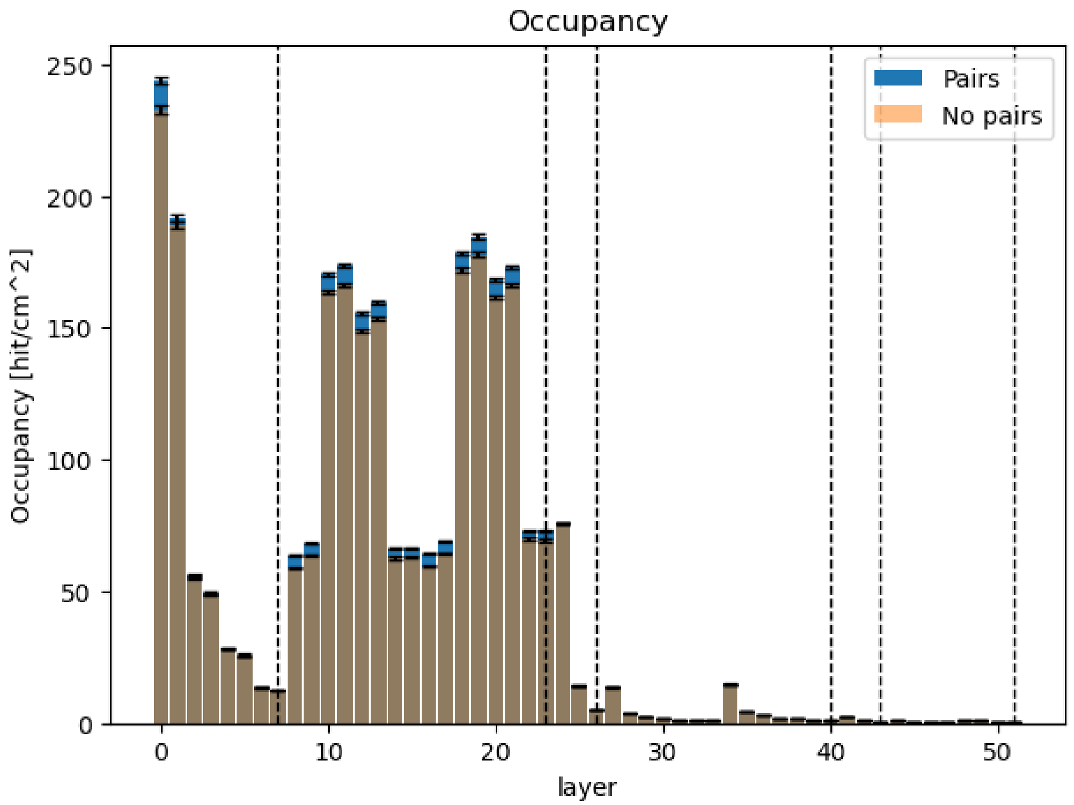
- 2*1200 simulation performed with minimum beampipe radius 0.3 (original) and 0.35
- 3 geometrical parameters:
  - $\theta_{tip} \in [3.8; 10]° \rightarrow$ 10 values
  - $|z_{change}| \in [50; 200]$ cm $\rightarrow$ 15 values
  - $r_{base} \in [20; 60]$ cm $\rightarrow$ 8 values
- 0.02% of 1 bunch crossing simulated
- Due to input settings, the real nozzle aperture is →



- $\theta_{nozzle} = tan^{-1}\left[\frac{(94 \cdot \tan\theta_{tip}) \cdot r_{base}/60}{|z_{change}| - 2}\right] \in [0.7; 18]°$

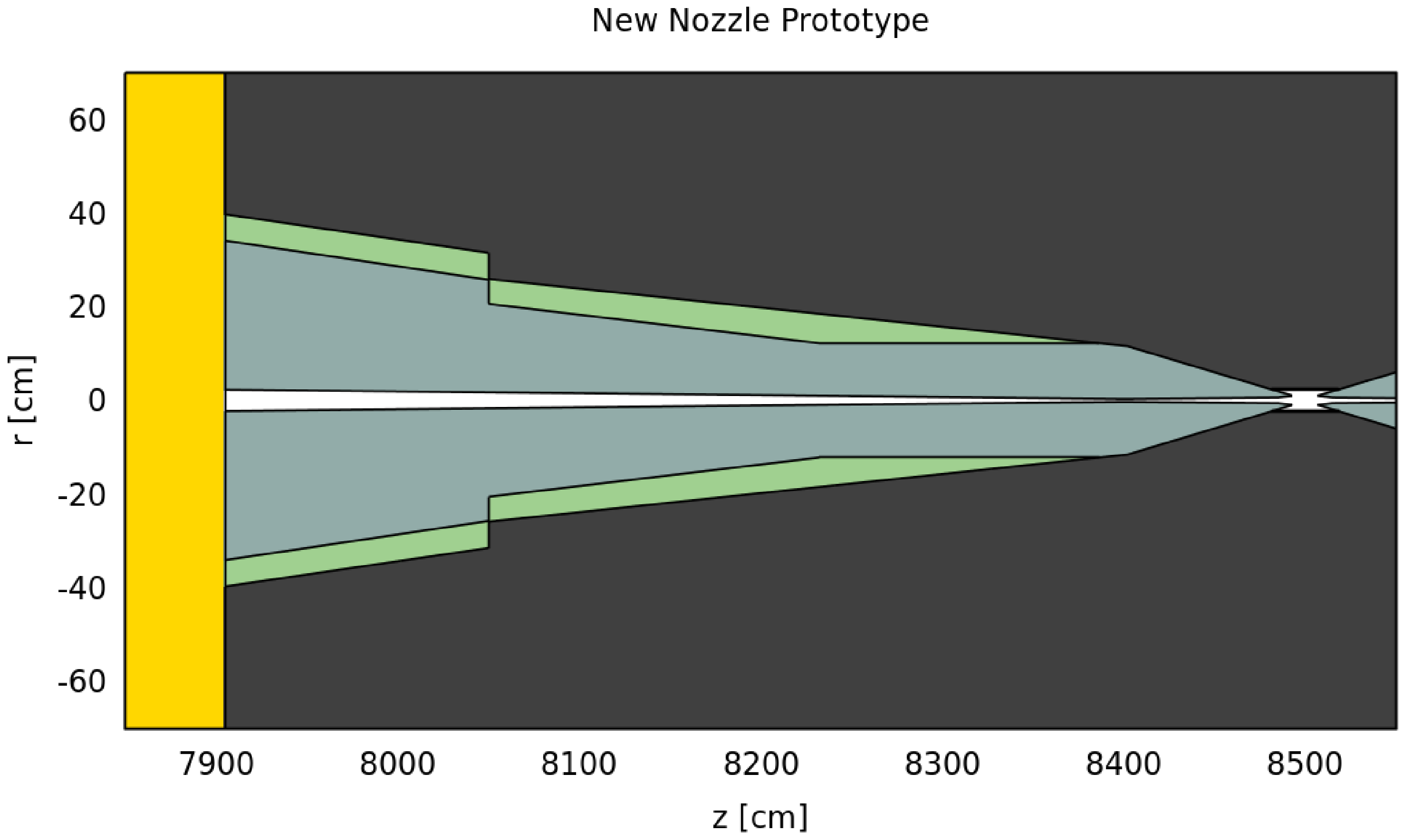
Incoherent Pair Production

- Another source of background due to beam-beam interaction
- Produced the $e^{\pm}$ pairs with GUINEAPIG
- Products propagated in FLUKA as for two Step Simulation
- Reconstruction in the tracking system
- Slightly increase in occupancy (about 5%)



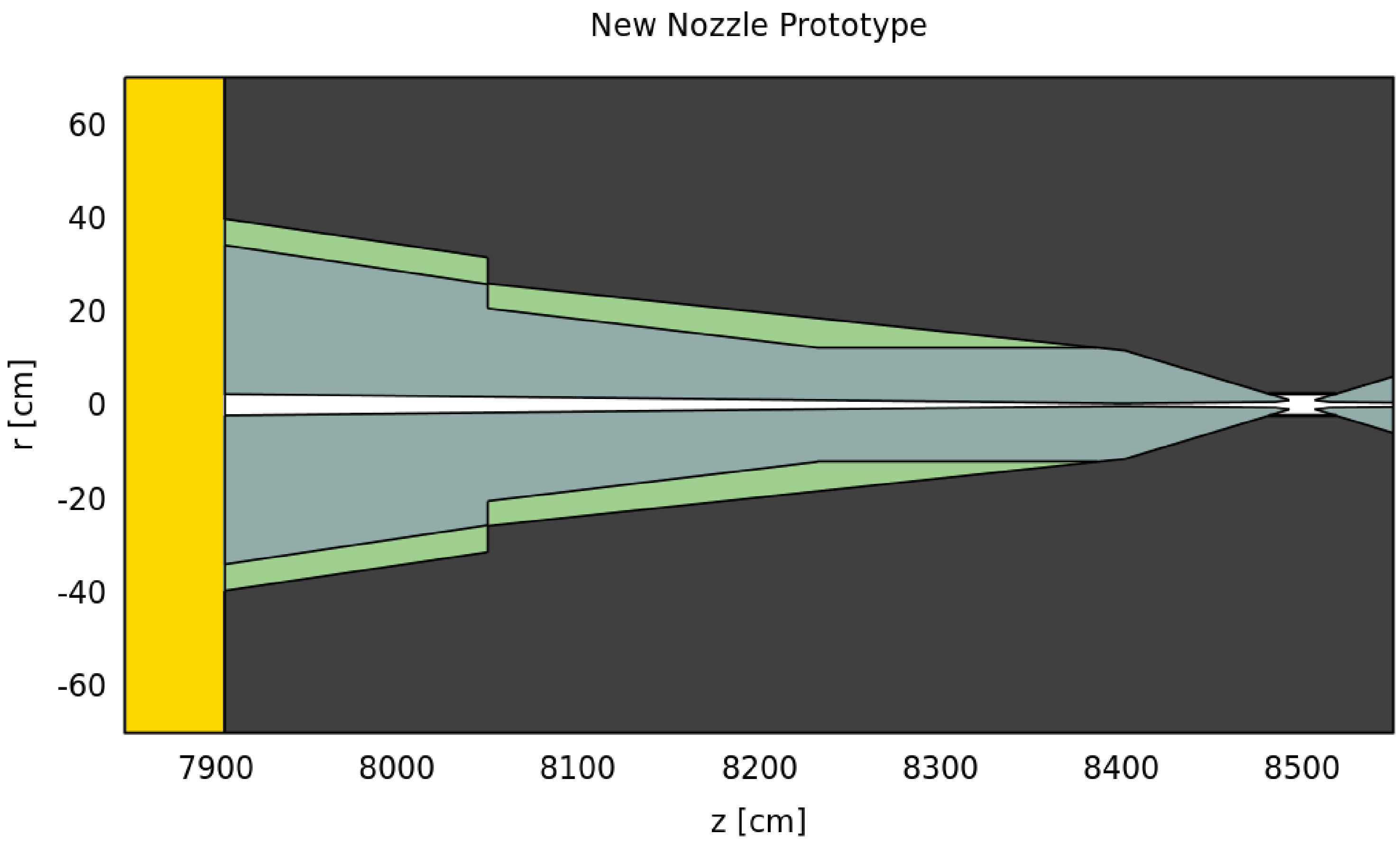
Improving the ML

- Two new parameters:
  - $z_{step} \in [-450; -200]\ cm$
  - $r_{step} \in [0.75; 0.95] * r_{base}$
- 3125 samples (5 values per each parameter)



Improving the ML - 2

- Two new parameters:
  - $z_{tip} \in [-8; -4]\ cm$
  - $r_{tip} \in [0.6; 1.4]\ cm$
- 2187 samples (3 values per each parameter)



Nozzle Design XVI