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

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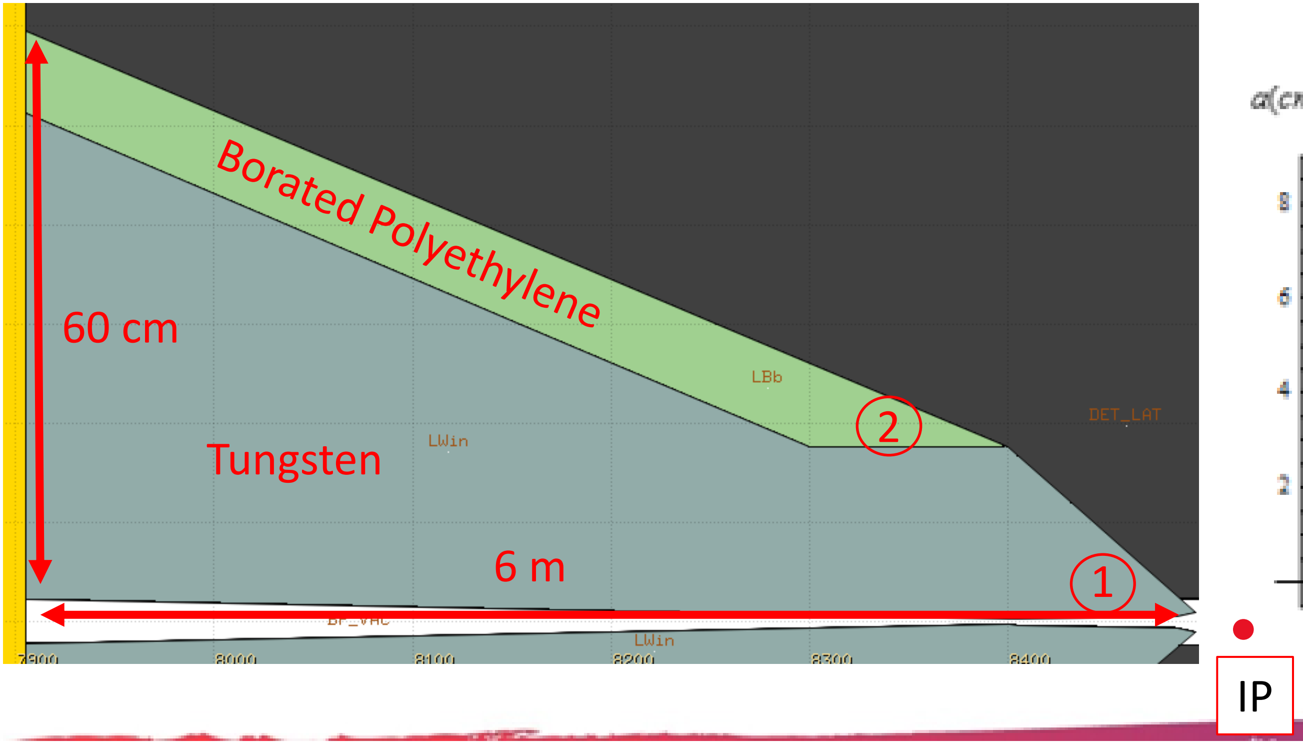
Outline

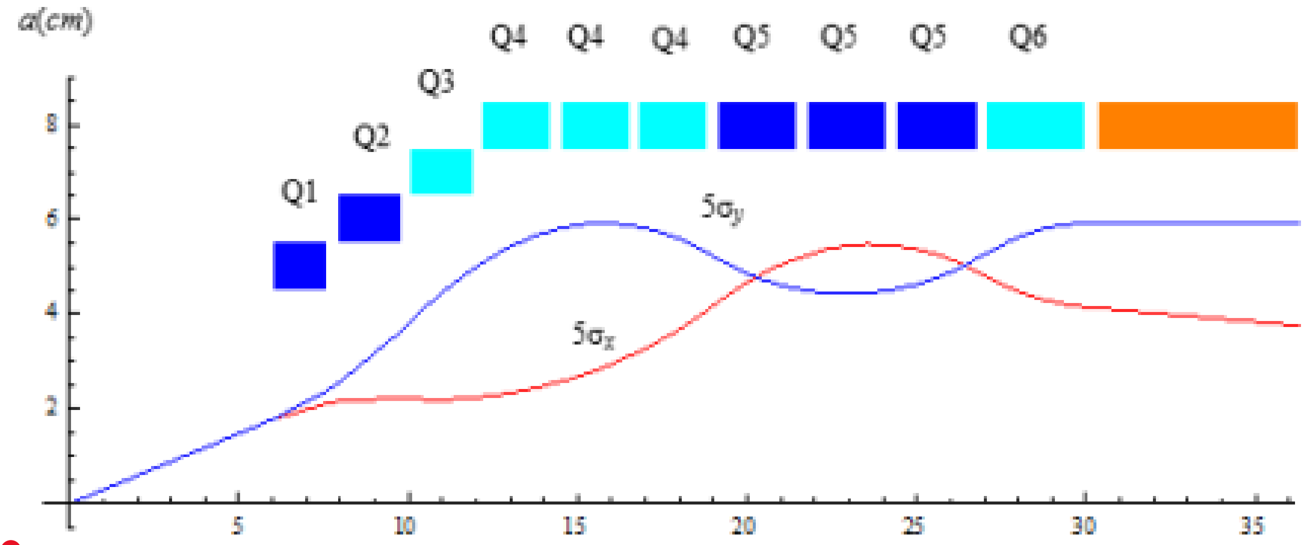
- **3 TeV MDI**
  - MAP design
  - FLUKA simulation
- **Forward Muon Study**
  - Goals
  - Simulation and results
- **Nozzle Design**
  - Long simulation approach
  - Machine Learning approach
- **Pair production**

3 TeV MDI

- MAP nozzle design:
  1) 10° closest to the IP
  2) 5° starting from $z = 100\ cm$

- MAP design[1] with mixed function FF quadrupoles (Cyan)

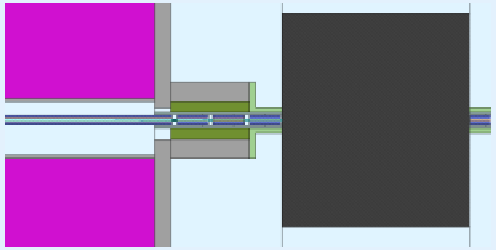




BIB simulation with FLUKA

1. From muon decay to nozzle area

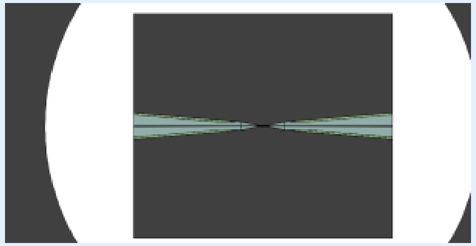
Machine dependent



- 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

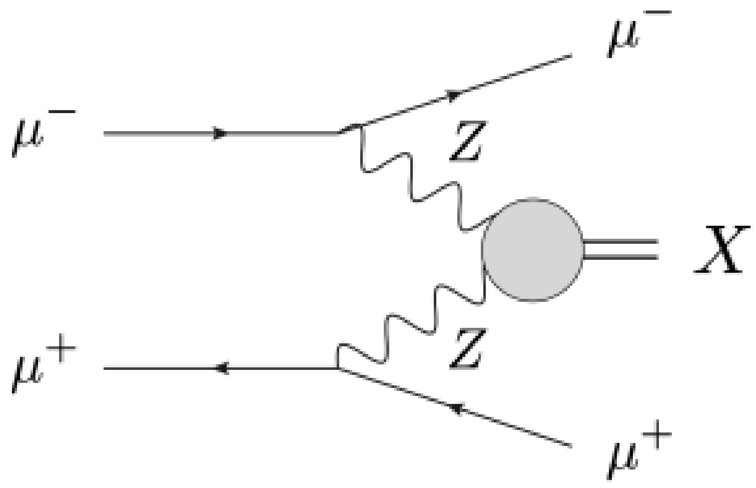


- Propagation through the Nozzles
- Particles who exit the nozzle and enters the detector area are scored
- $\sim$1.6% of one BIB event (i.e. bunch crossing) considering only 1 beam $\rightarrow$ $\mathbf{4\ days}$ **per simulation**

Pictures from D. Calzolari

Forward Muons

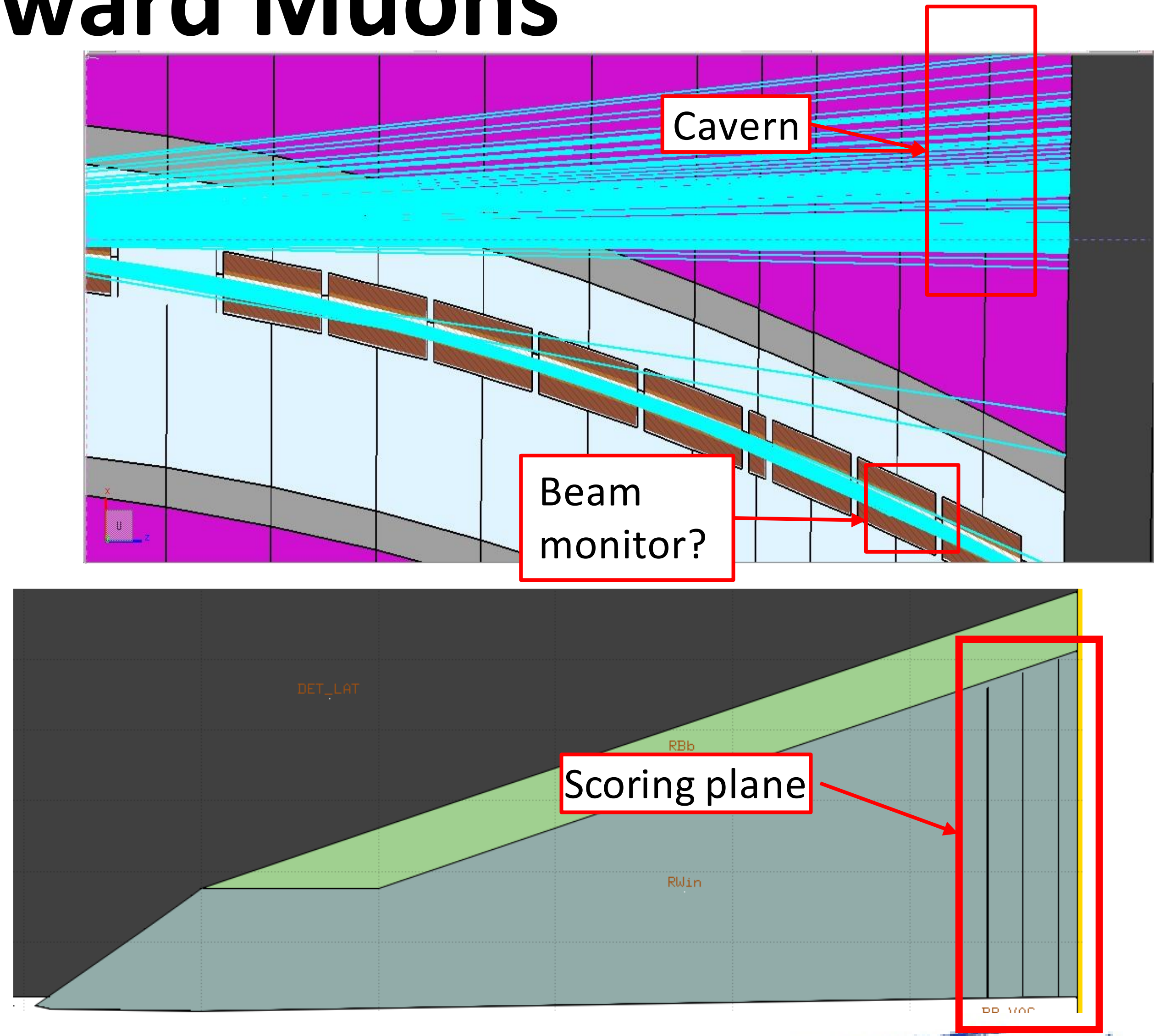
- **Why are we interested in forward muons**?
  - Allows to distinguish process from Z/W boson fusion
  - Allows precise measure of Higgs boson Width [2, 6]
  - New physics might have forward muons in the final state [3]



Z Boson fusion with forward muon production[3]

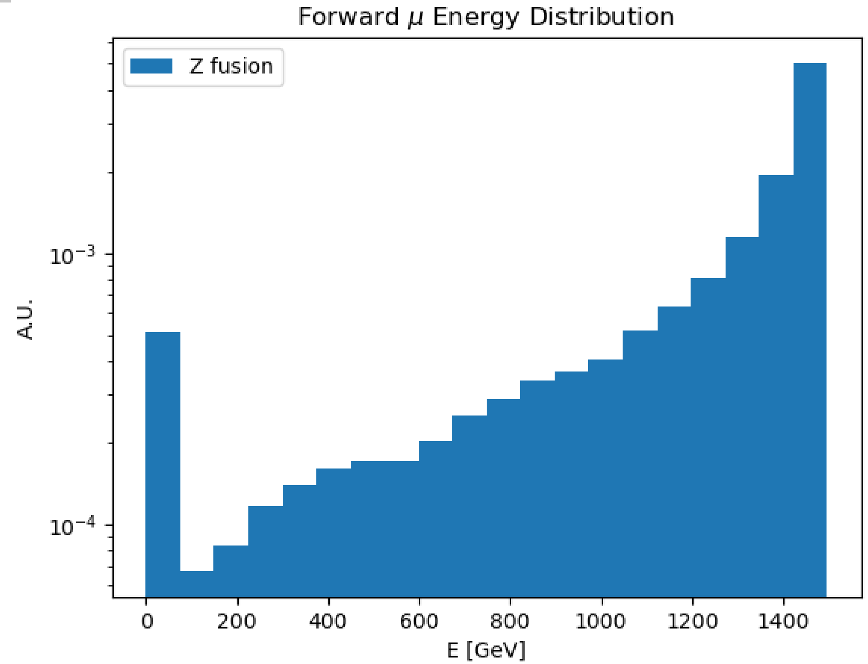
Detecting Forward Muons

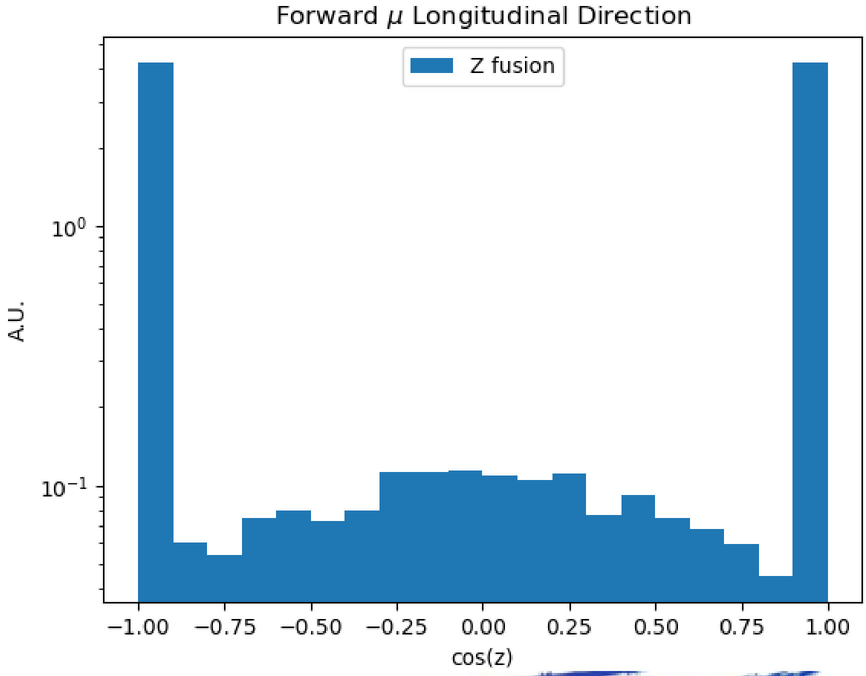
- Two main candidates:
  - Nozzle: Small detector, high dose for BIB
  - Cavern: Large detector, clean environment
- This presentation focuses on Nozzle detectors
- Three silicon layers put close to ring in FLUKA simulation as scoring planes



Simulated samples

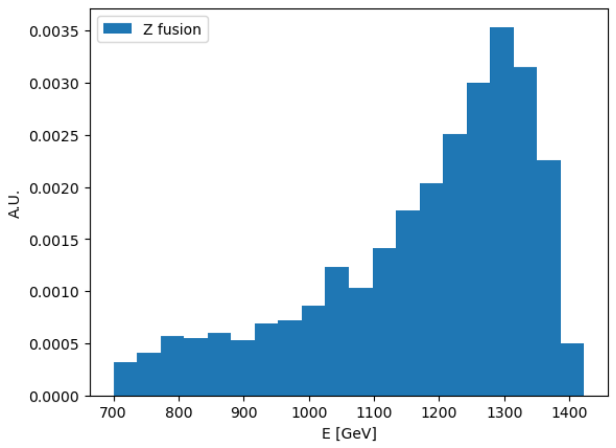
- Forward muons from:
  $\mu^+\mu^- \to ZZ + \boldsymbol{\mu^+\mu^-} \to \mathrm{H} + \boldsymbol{\mu^+\mu^-} \to W^+W^- + \boldsymbol{\mu^+\mu^-}$
  - $2 \cdot 6.15 \cdot 10^3$ Montecarlo muons from WHIZARD output
- Beam Induced Background:
  - 1.4 % of bunch crossing simulated (two step simulation)
  - Particles crossing the silicon layers are scored
  - Silicon layers **do not reproduce a detector behavior**

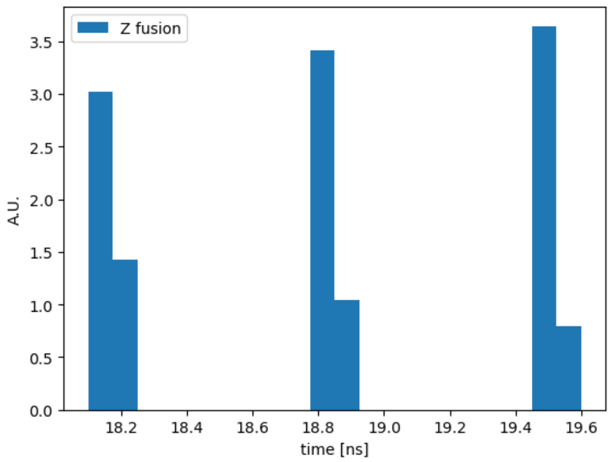


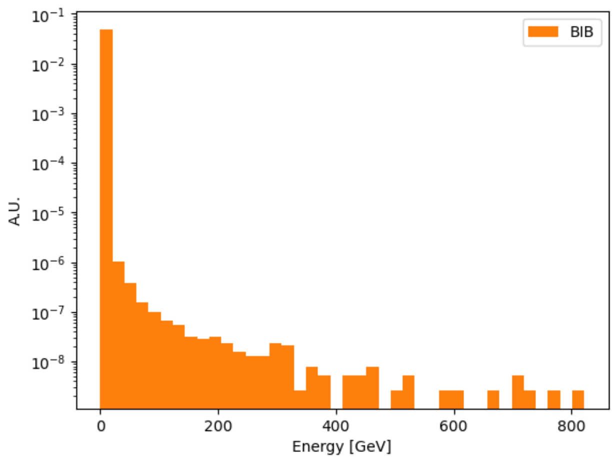


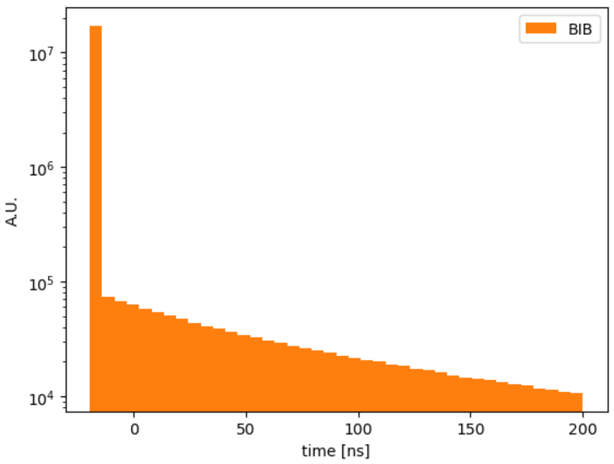
Simulation Outputs

- **Forward Muons:**
  - Fixed time of arrival in the layers
  - Coming from IP
  - High energy $\Rightarrow [0.7, 1.4]\ TeV$
- **Beam Induced Background:**
  - Most particles arrive earlier then bunch crossing
  - Time cuts discard great majority of BIB









Performance

- Total counts within $\pm 100\ ps$ time window with respect to muons arrival time on layers:

Event	Layer 1	Layer 2	Layer 3
BIB^{*}	$2.5 \cdot 10^4$	$2.7 \cdot 10^4$	$3.0 \cdot 10^4$
$Z\ fusion^{**}$	*3228/6150*	*3232/6150*	*3225/6150*

- A rough tracking is performed to discard particles that are not coming from IP:

Event	Global Efficiency [%]	Tracking Efficiency [%]
$BIB^{\#}$	< 0.28	
$Z\ fusion^{\#\#}$	52.5	99.2

*Normalized to the bunch crossing
** 6150 events simulated

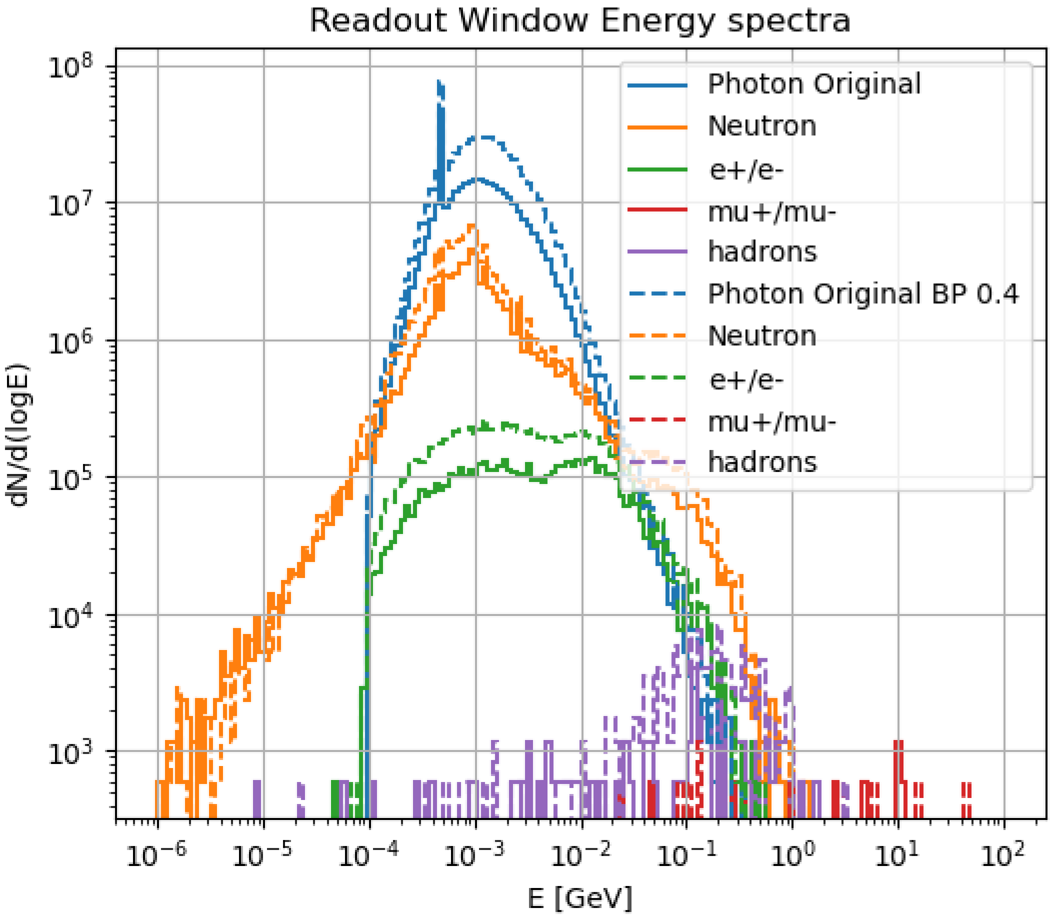
0 particles tracked, estimation on the total bunch crossing computed according to [1]
Efficiency computed on the total muon generated, i.e. 6150, not on only the ones who pass through the nozzle and the layers

Nozzle Design

- High statistics approach:
  - 1.6 % of bunch crossing per simulation
  - Focused on understand the relations between shape and BIB flux
  - Goal is to improve the detector acceptance and keep the BIB manageable
- Machine Learning approach:
  - Hundreds of low statistics simulation with several parameters considered
  - Trained a XGBoost model to predict a configuration that minimize the flux
  - Testing the configuration with the high statistics simulation
  - Interacting with MODE collaboration

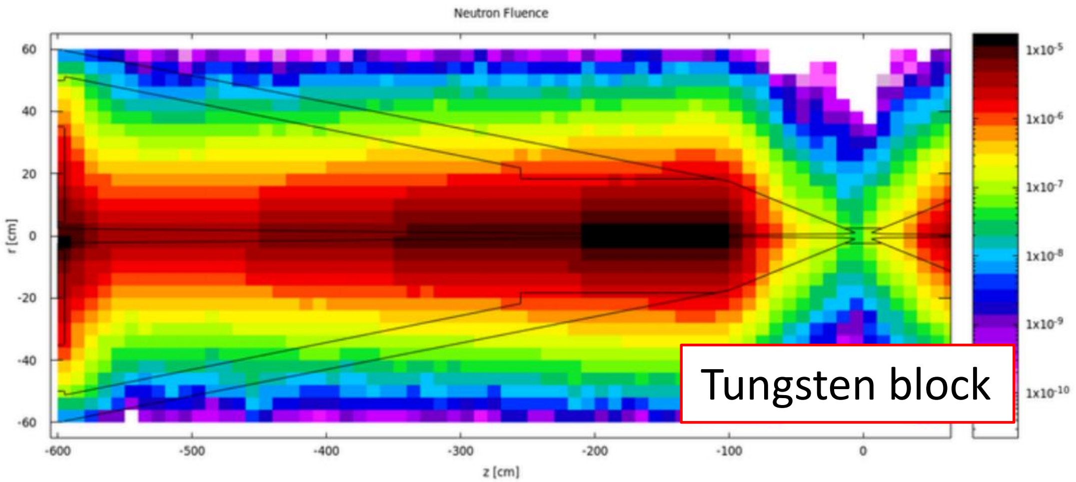
High Statistics Approach

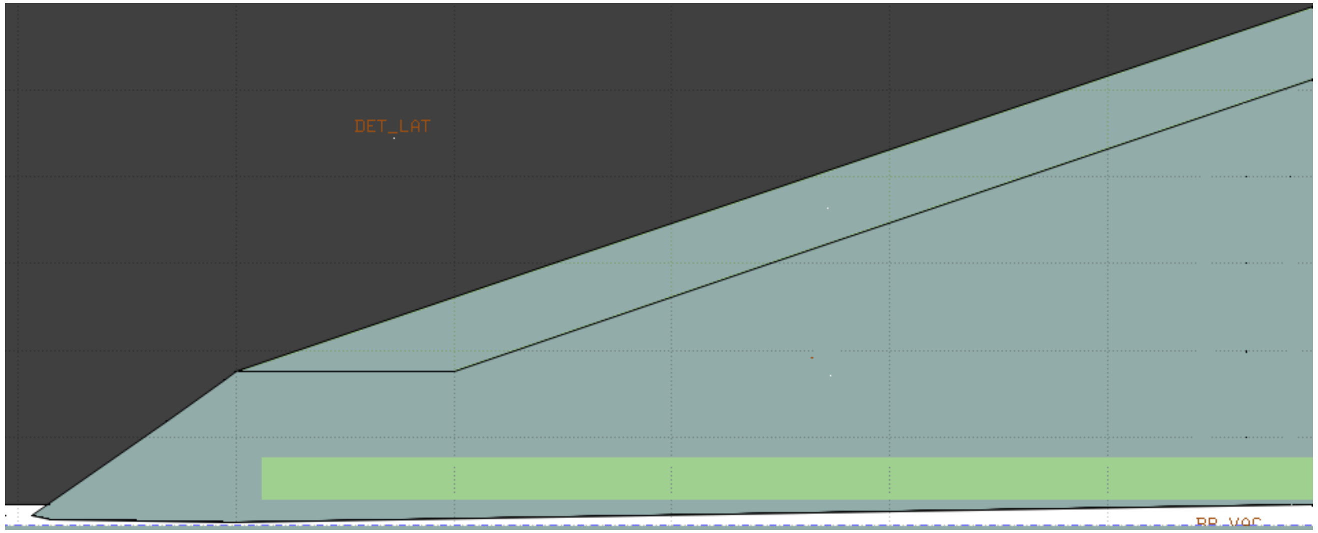
- Lessons learned:
  - The Beam Pipe cannot be touched, by increasing the minimum nozzle internal radius from $0.3 \rightarrow 0.4\ cm$, BIB increase by a factor 2

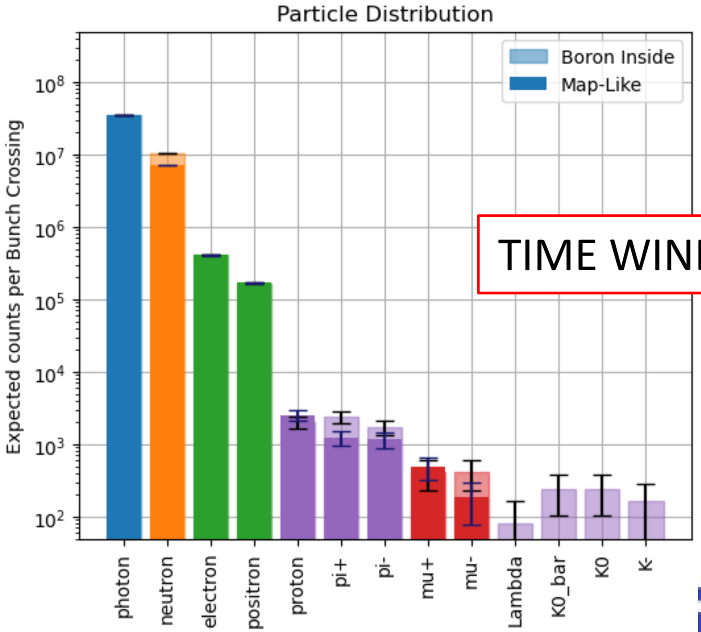


High Statistics Approach

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



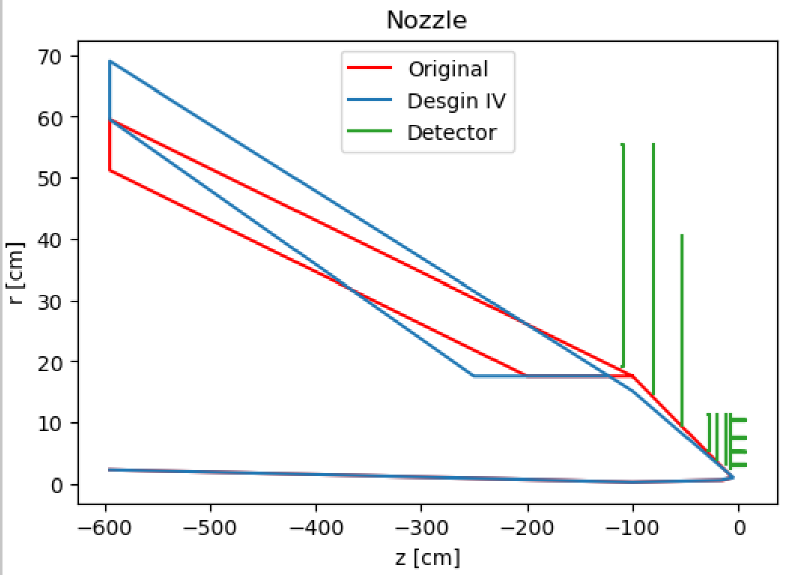


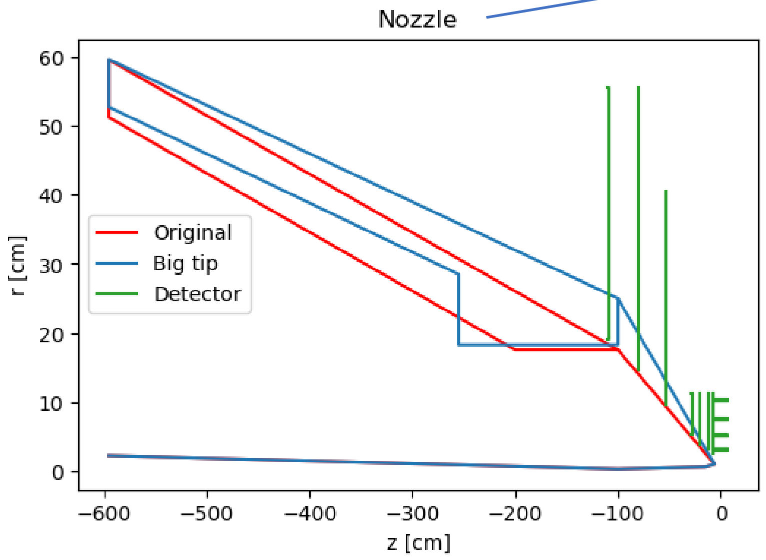


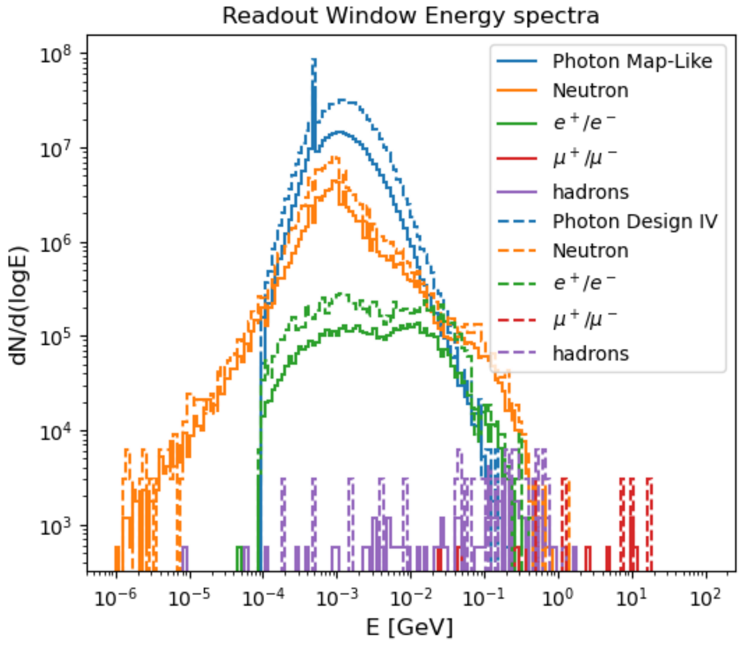
TIME WINDOW APPLIED

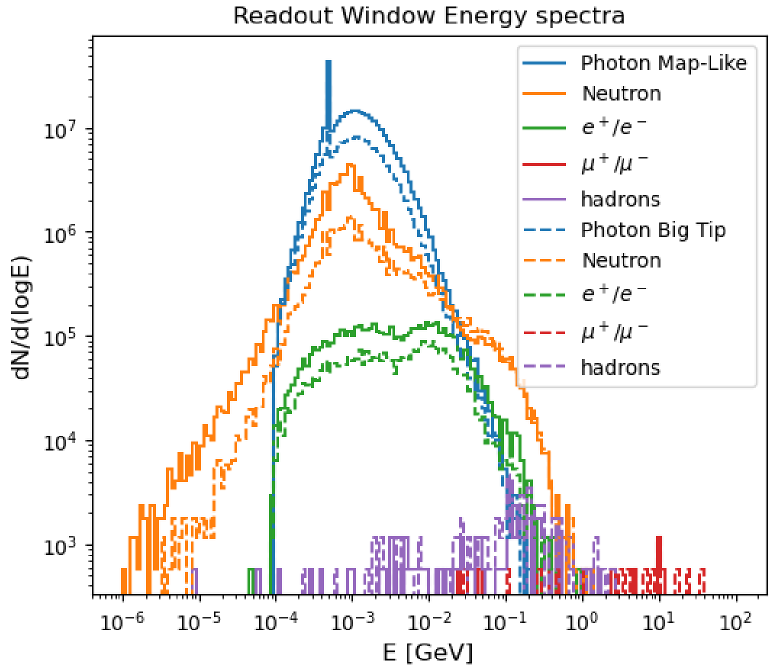
High Statistics Approach

- Lessons learned:
  - The Beam Pipe cannot be touched
  - Is Boreth layer really effective?
  - Nozzle tip is the critical part $z \in [0, 1]\ m$



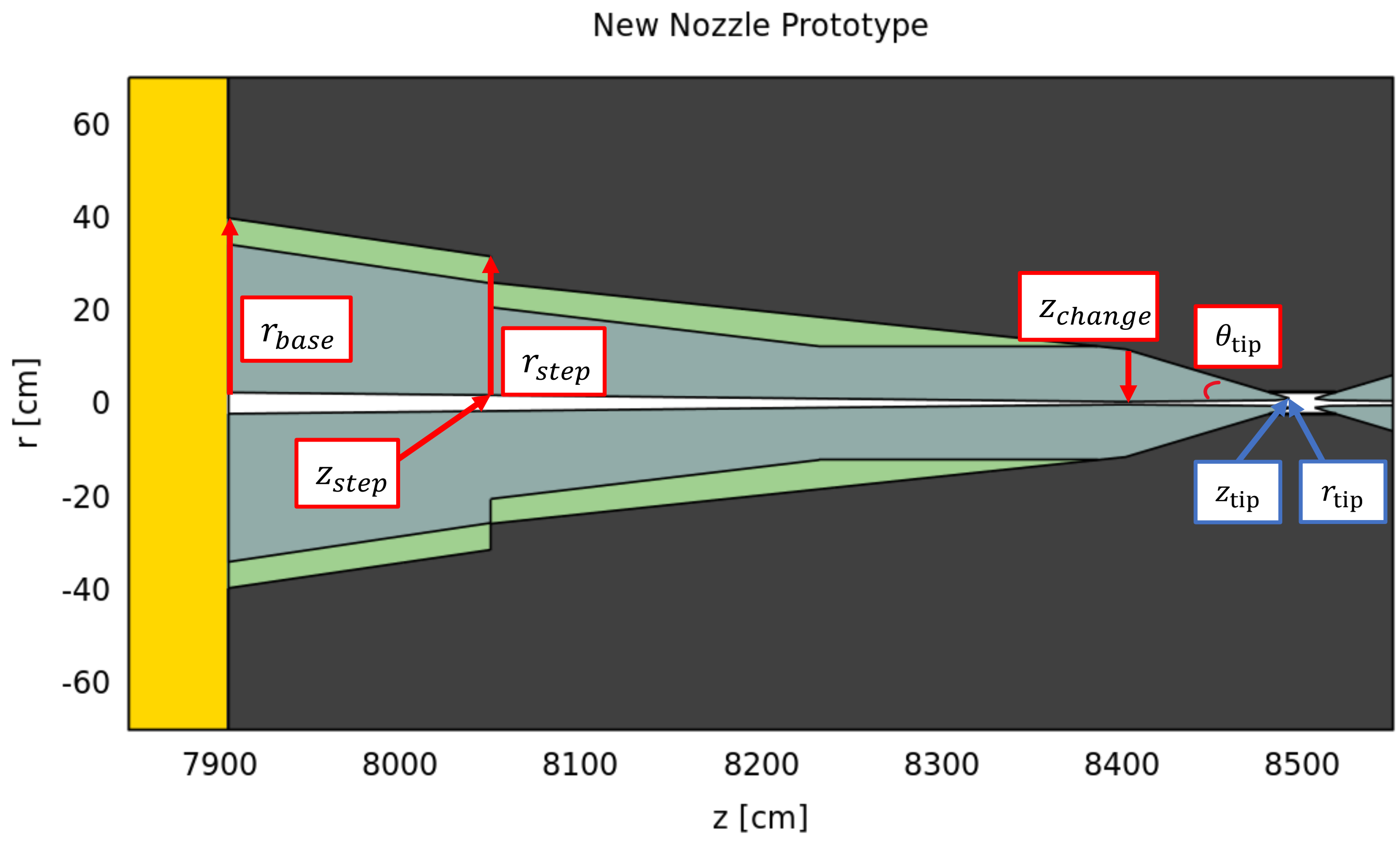






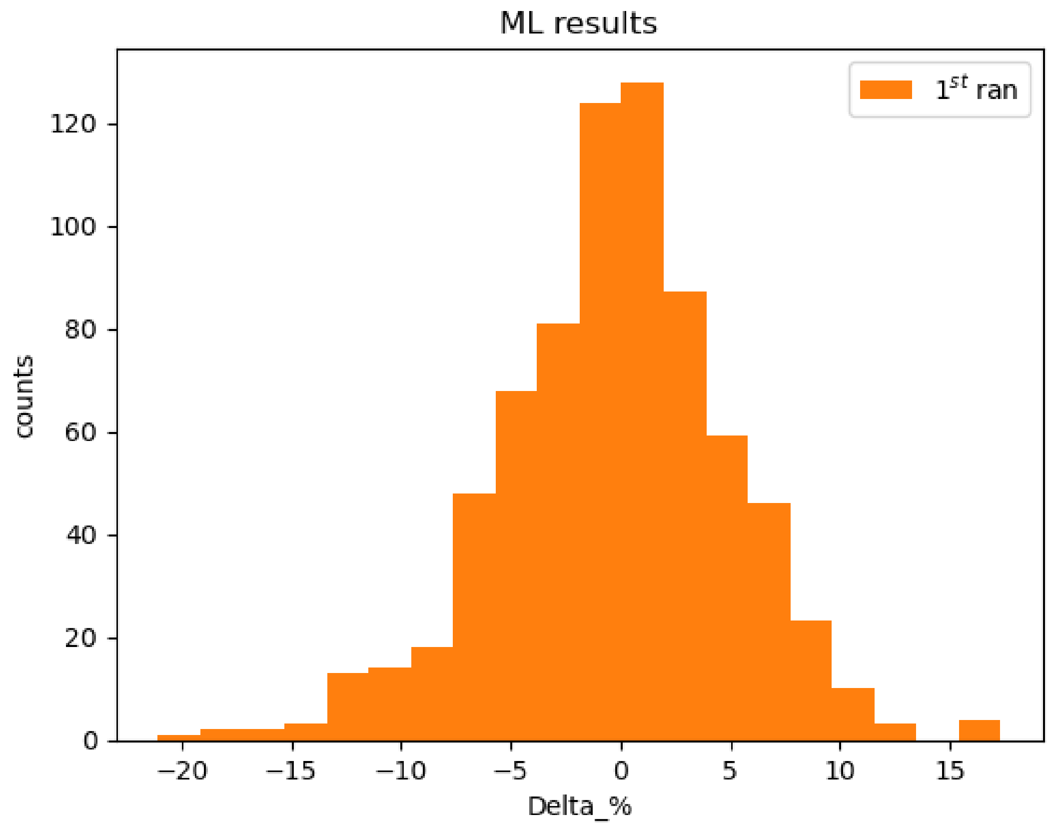
Machine Learning Approach

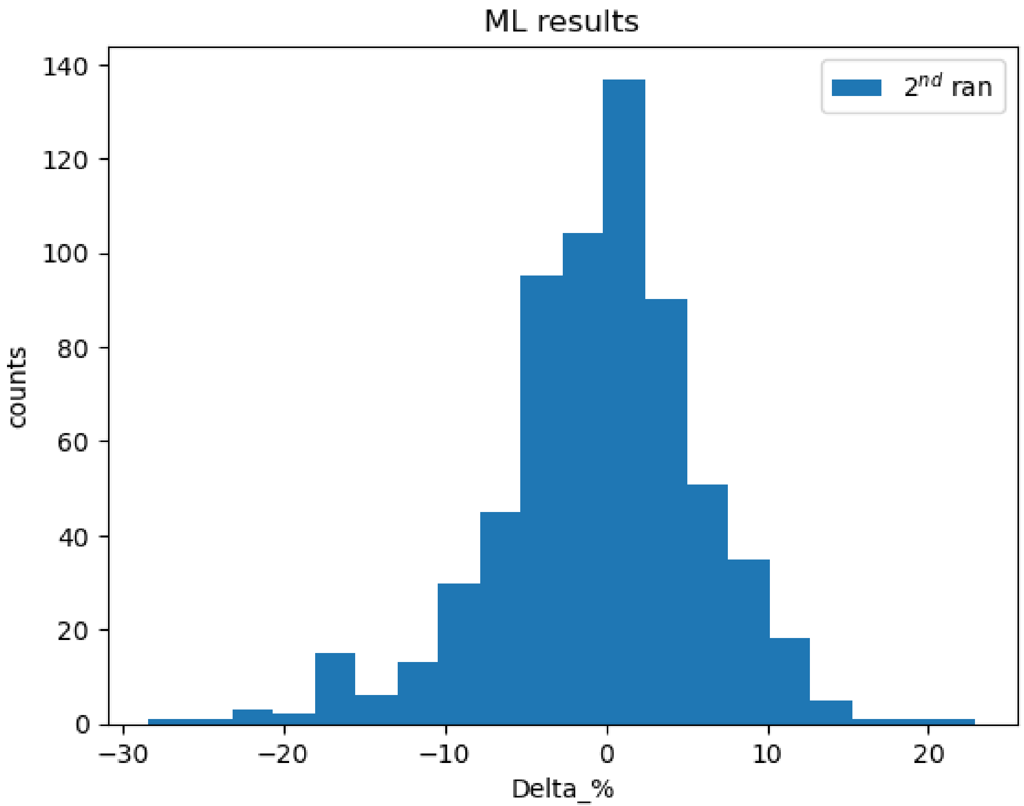
- 1^{st} ran → 5 parameters, 3125 simulations
- 2^{nd} ran →7 parameters, 2187 simulations



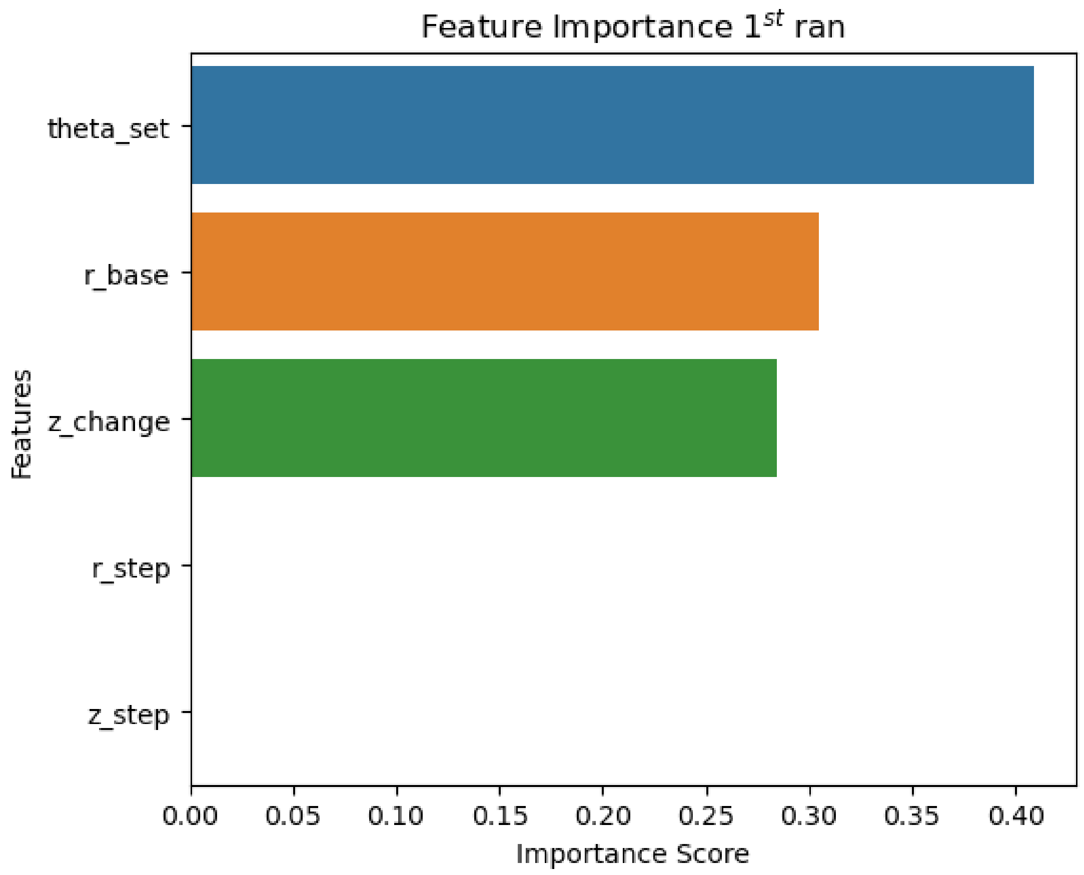
XGBoost performance

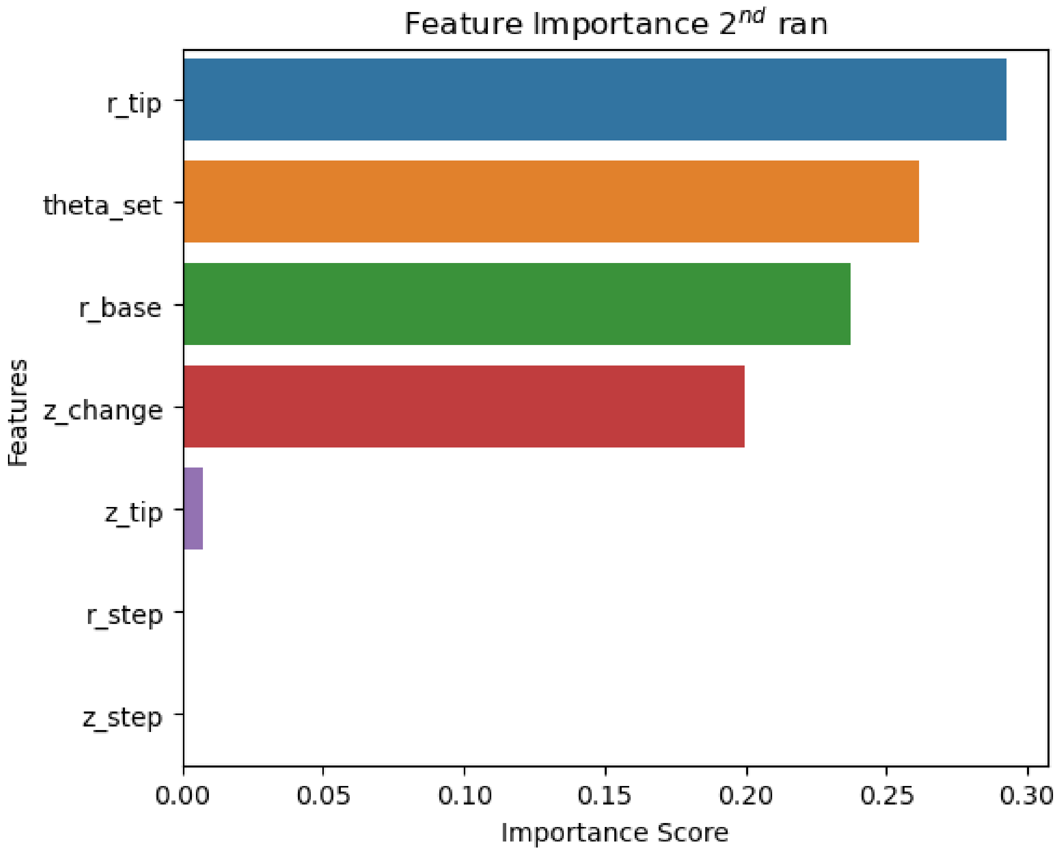
$$\Delta = \frac{Flux_{true} - Flux_{predicted}}{Flux_{true}} * 100$$





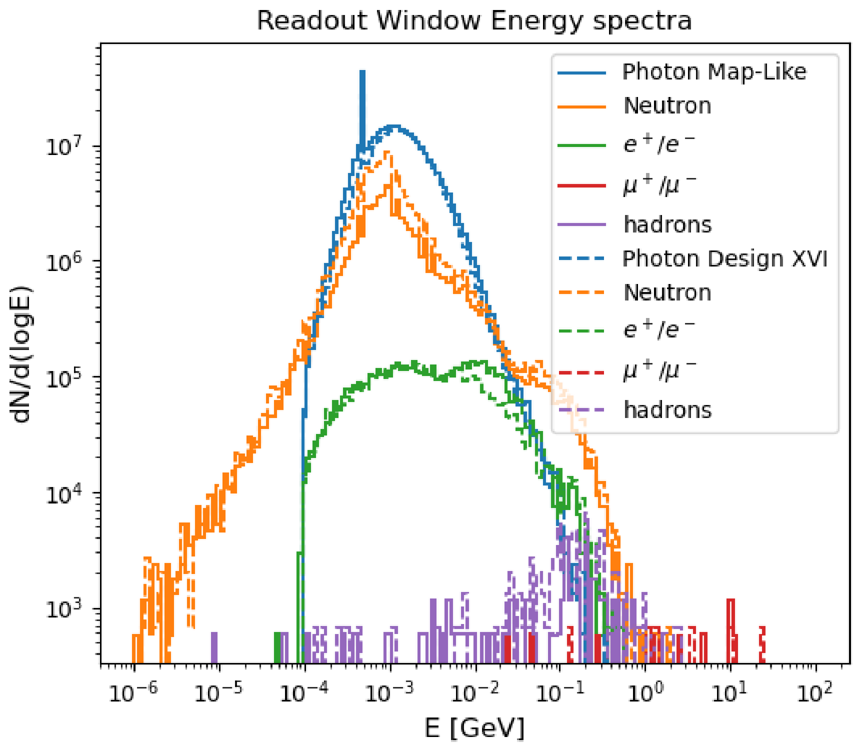
XGBoost performance

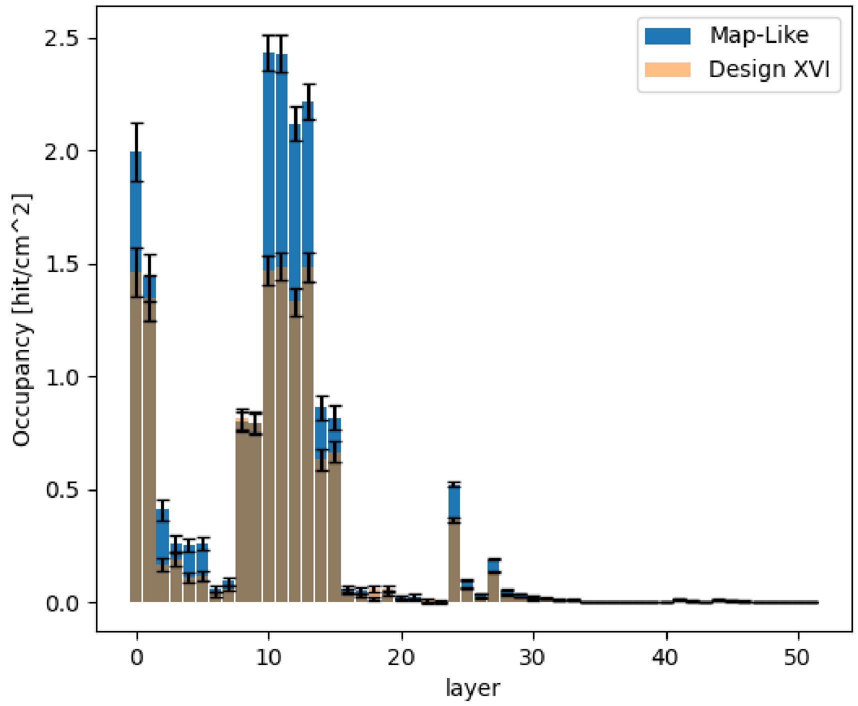




Nozzle Design XVI

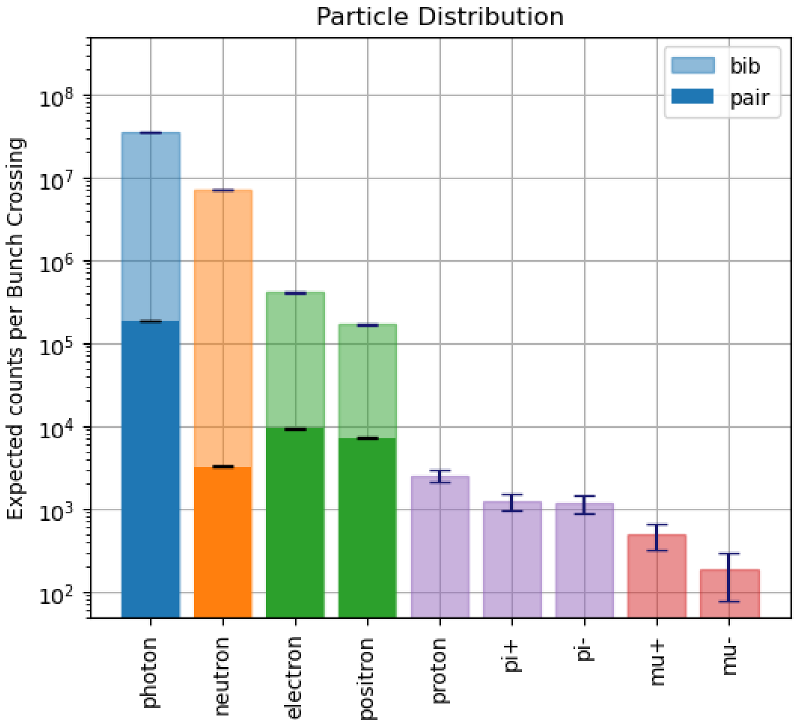
- Minimum flux according to the last ML studies
- Shape very similar to the original, but the Nozzle tip is shifted: $(-6, 1) \rightarrow (-4, 1.4)$
- Less γ and $e^{\pm}$ but more neutron

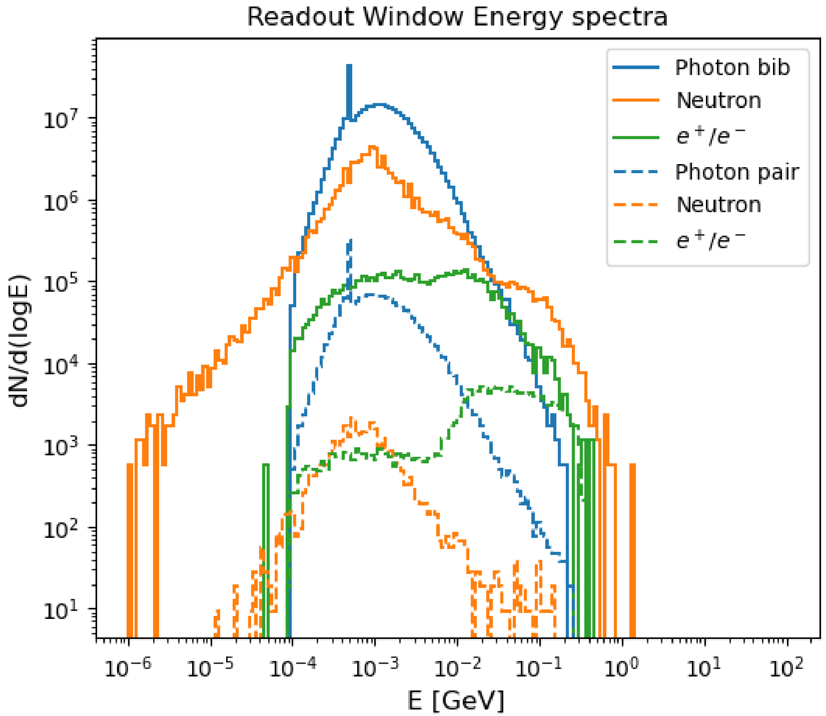




Incoherent Pair Production

- Produced the $e^{\pm}$ pairs with GUINEAPIG
- Products propagated in FLUKA as for two Step Simulation
- Done but not yet analyzed, occupancy in the detector





Conclusions

- **Forward Muons:**
  - About of 50 % of forward muons can be detected
  - Next step: measure muons momentum, study the dose on the possible detectors
- **Nozzle design:**
  - Small changes in the geometry leads to significant variation in flux and occupancy
  - Worth investigate more the impact of the tip on the BIB, not much can be done concerning the overall shape, nevertheless, I hope the collaboration with MODE will produce interesting results
- **Incoherent pair production:**
  - The contribution to the overall BIB flux is two-to-three order of magnitude less then standard BIB
  - Impact on detector must be checked

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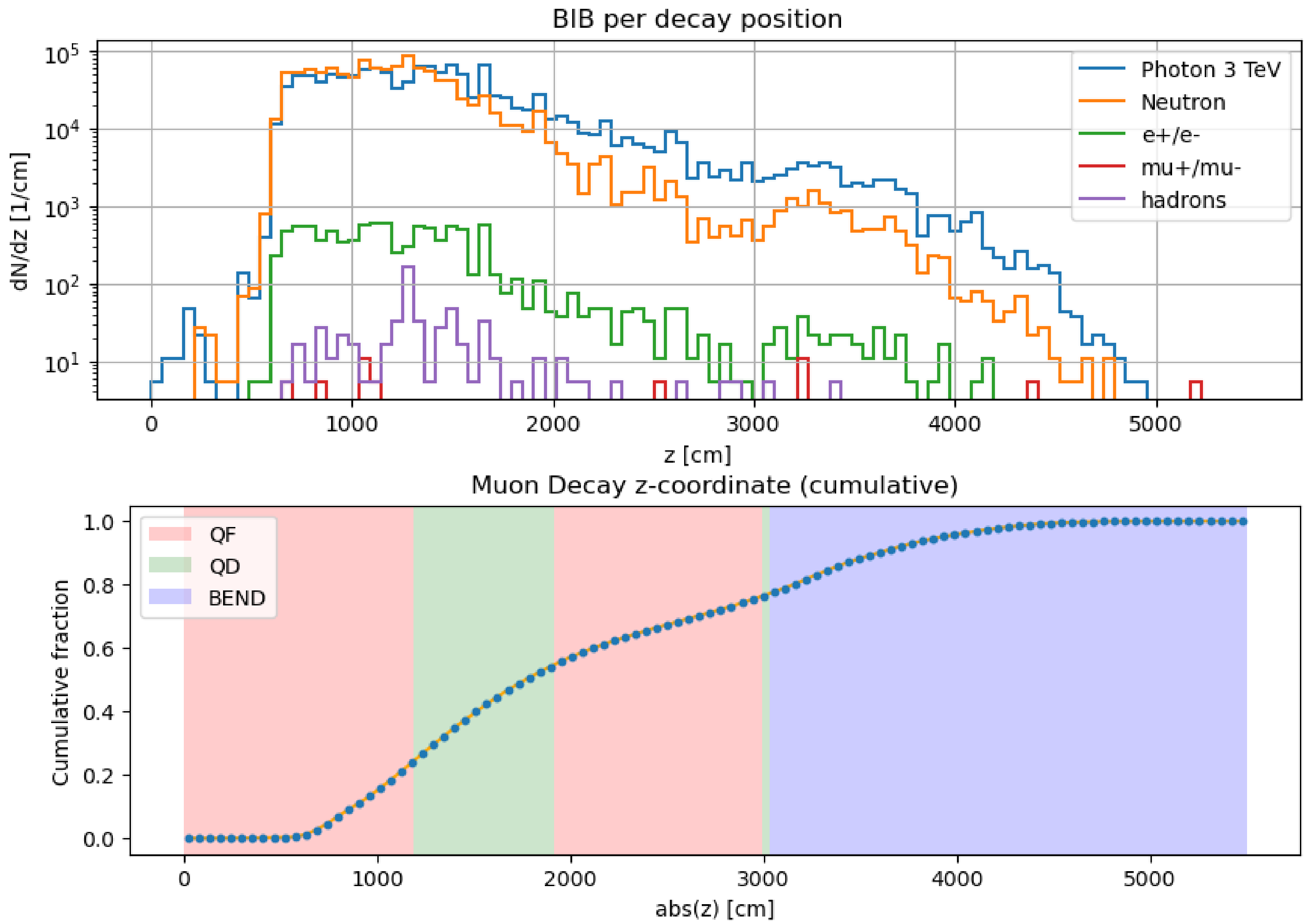
Thank you for the attention

References

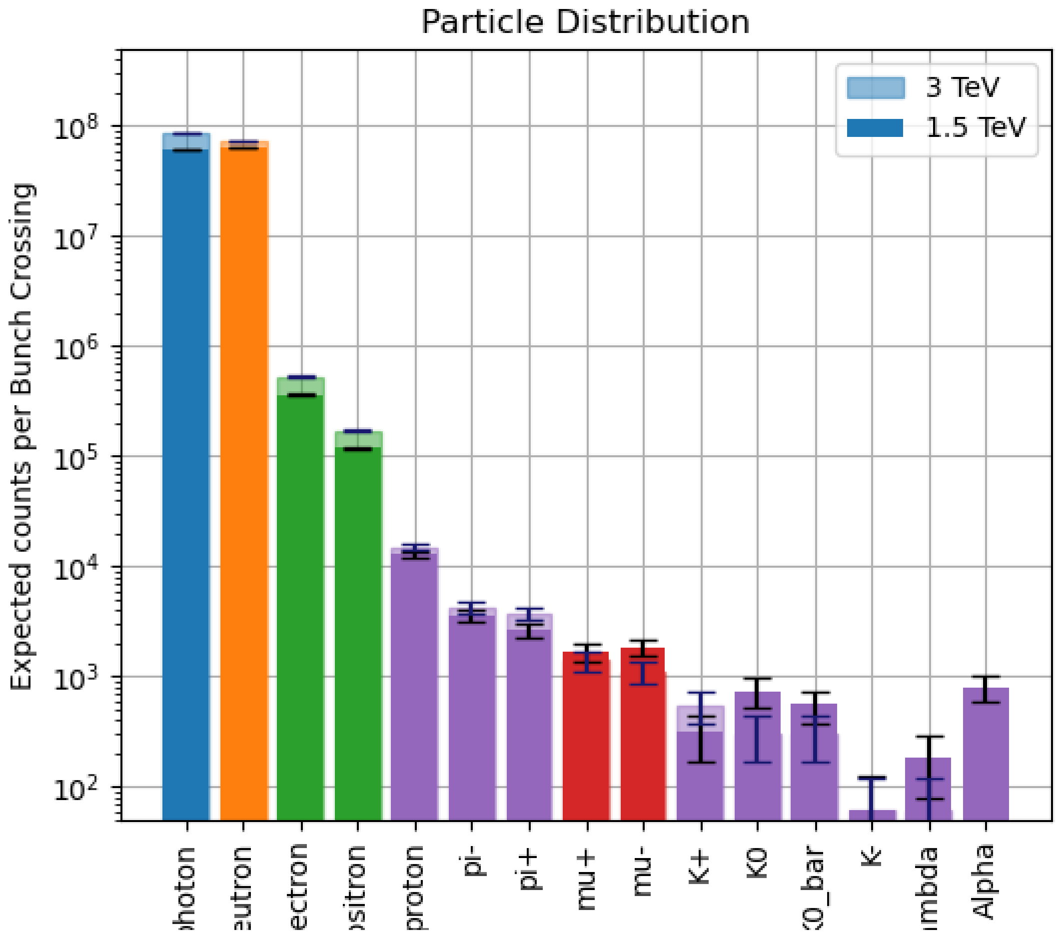
- [1] Y. Alexahin, E. Gianfelice-Wendt, A 3-TeV MUON COLLIDER LATTICE DESIGN, Insiperhep.net
- [2] P. Li, Z. Liu, K. Lyu, HIGGS WIDTH AND COUPLINGS AT HIGH ENERGY MUON COLLIDERS WITH FORWARD MUON DETECTION, arxiv.org
- [3] M. Ruhdorfer, E. Salvioni, A. Wulzer, INVISIBLE HIGGS FROM FORWARD MUONS AT A 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

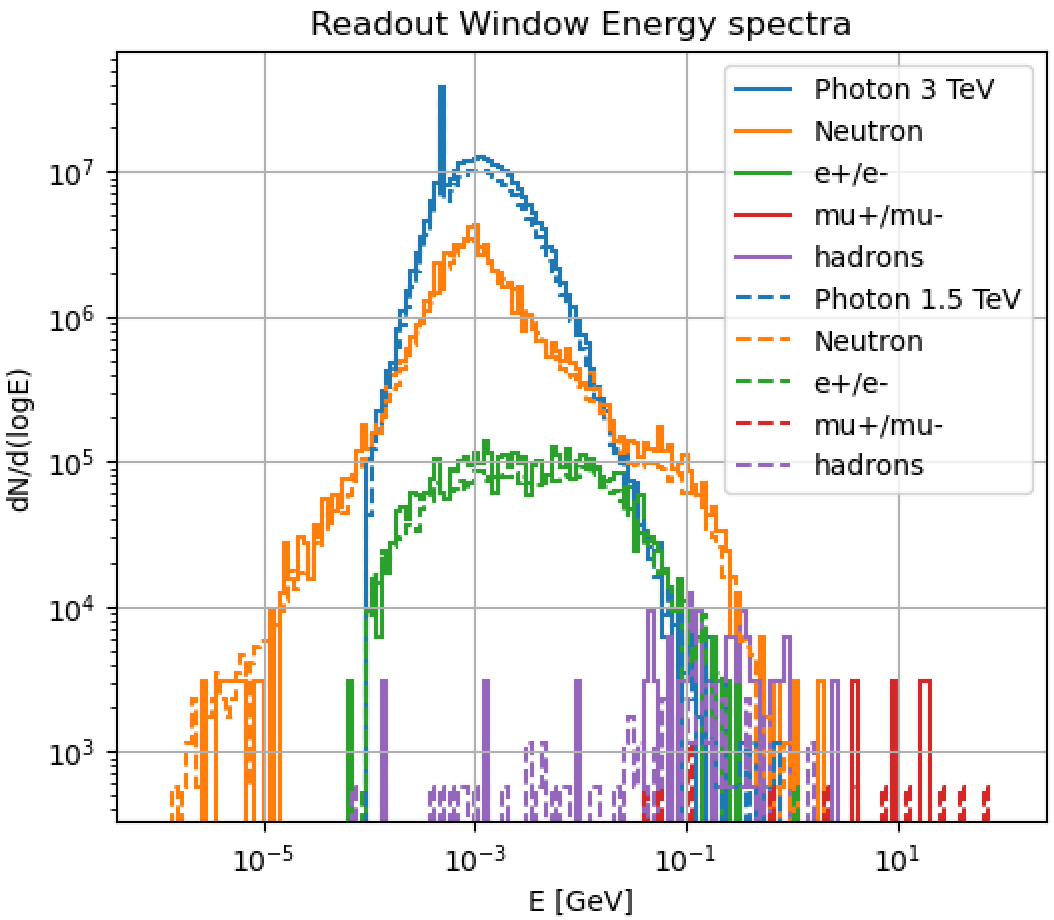
BACKUP

Muon decay position



BIB simulation with FLUKA





Detector

hadronic calorimeter

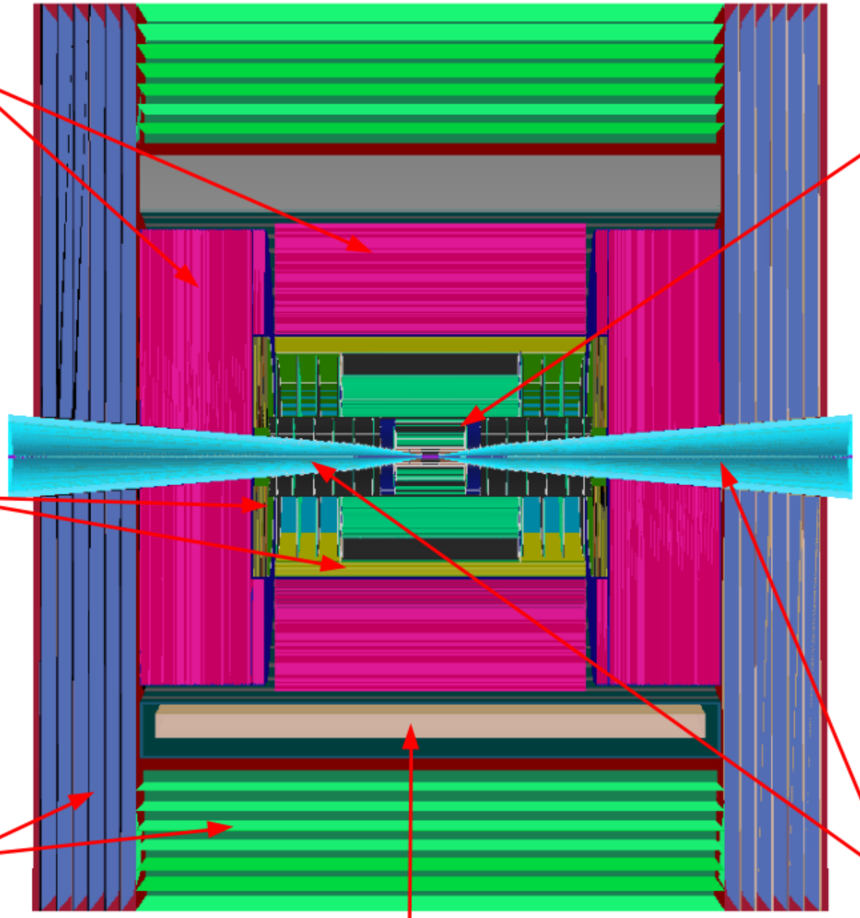
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

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)

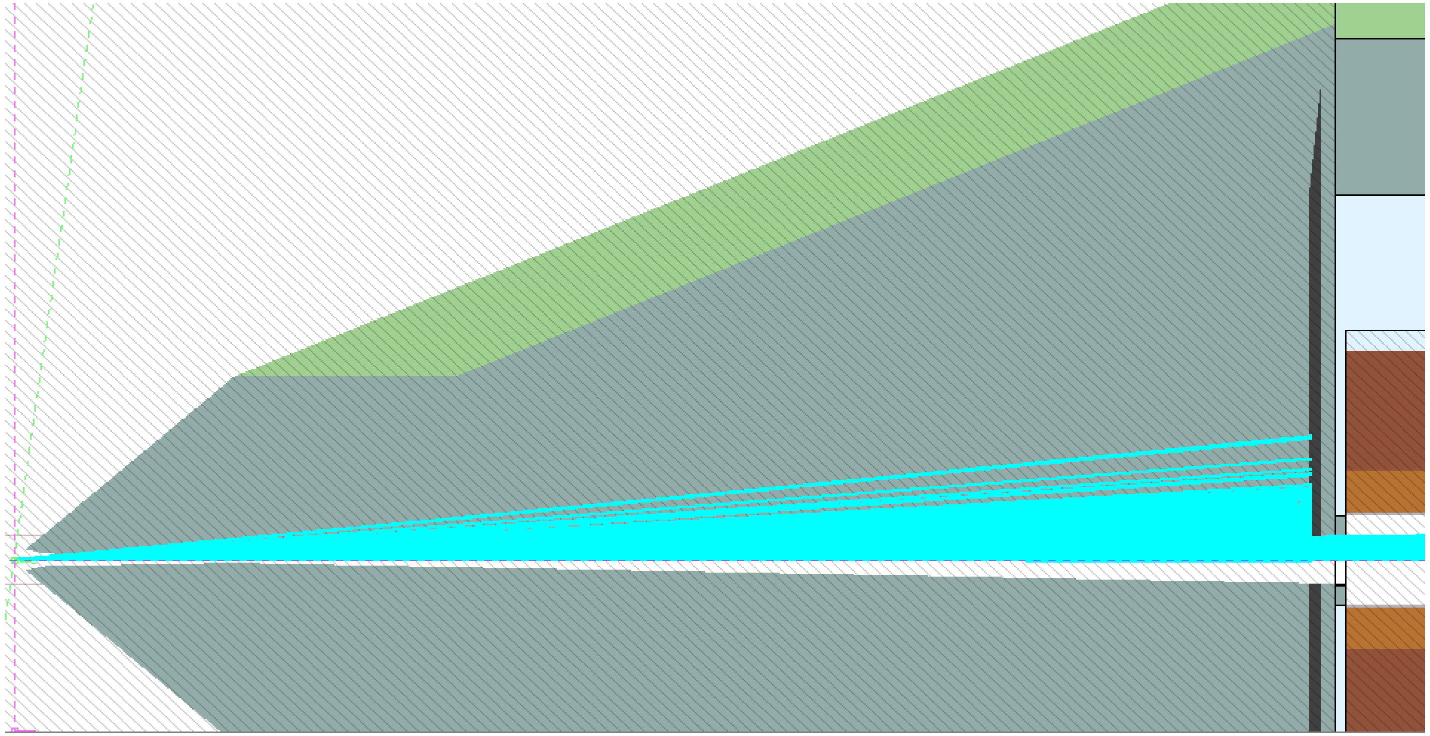
tracking system

- 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

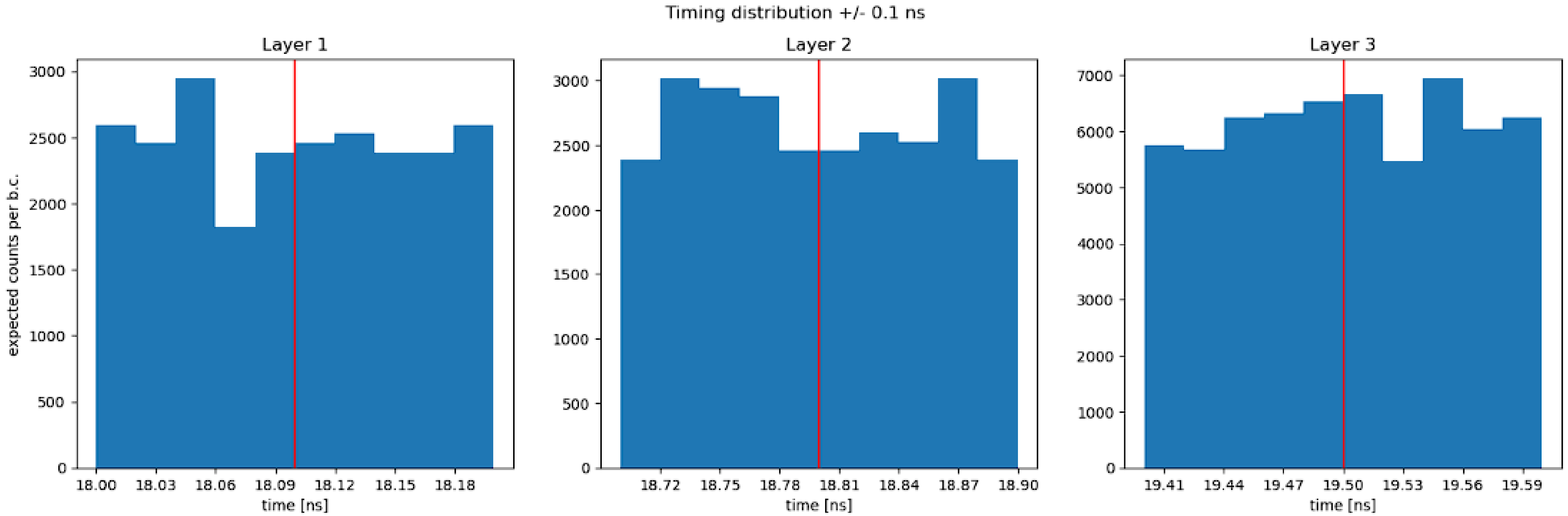
- Tungsten cones + borated polyethylene cladding.

Forward Muon in Nozzle



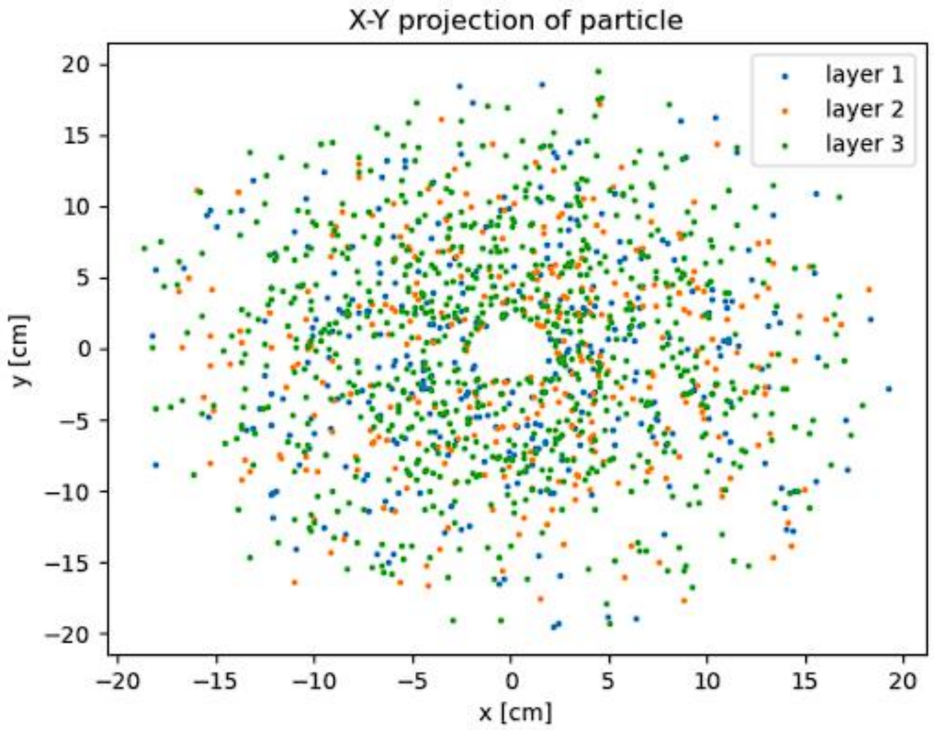
BIB characteristics

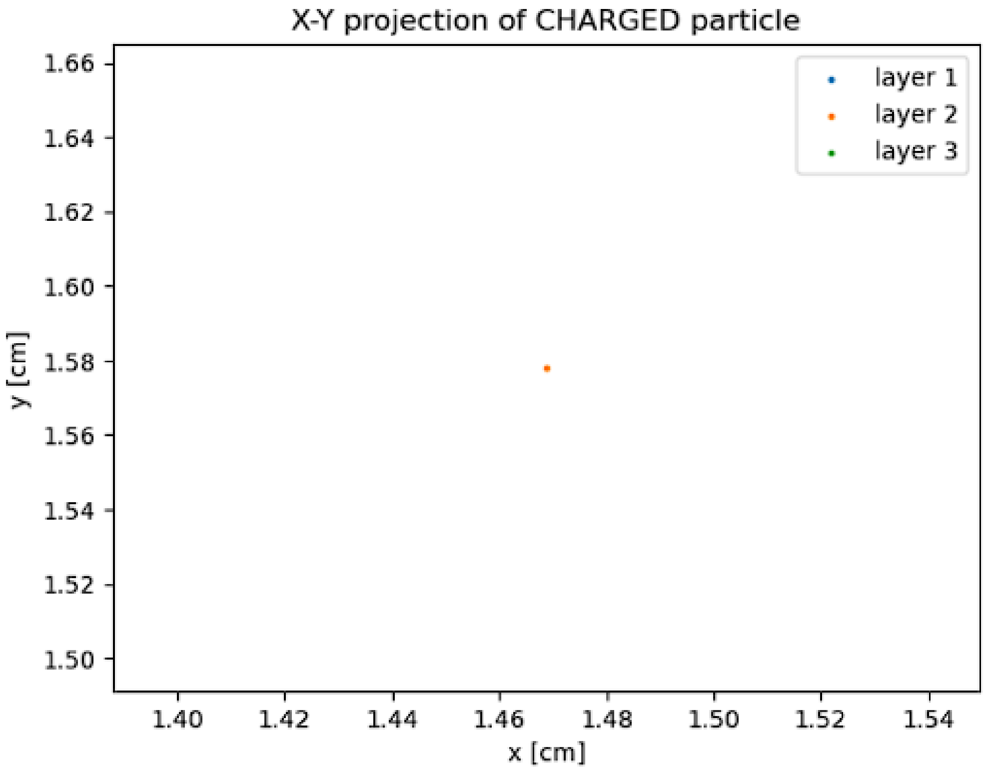
- By requiring a window of $\pm 100\ ps$ with respect to the expected time of arrival in the layers BIB reduced by 5 order of magnitudes



BIB characteristics

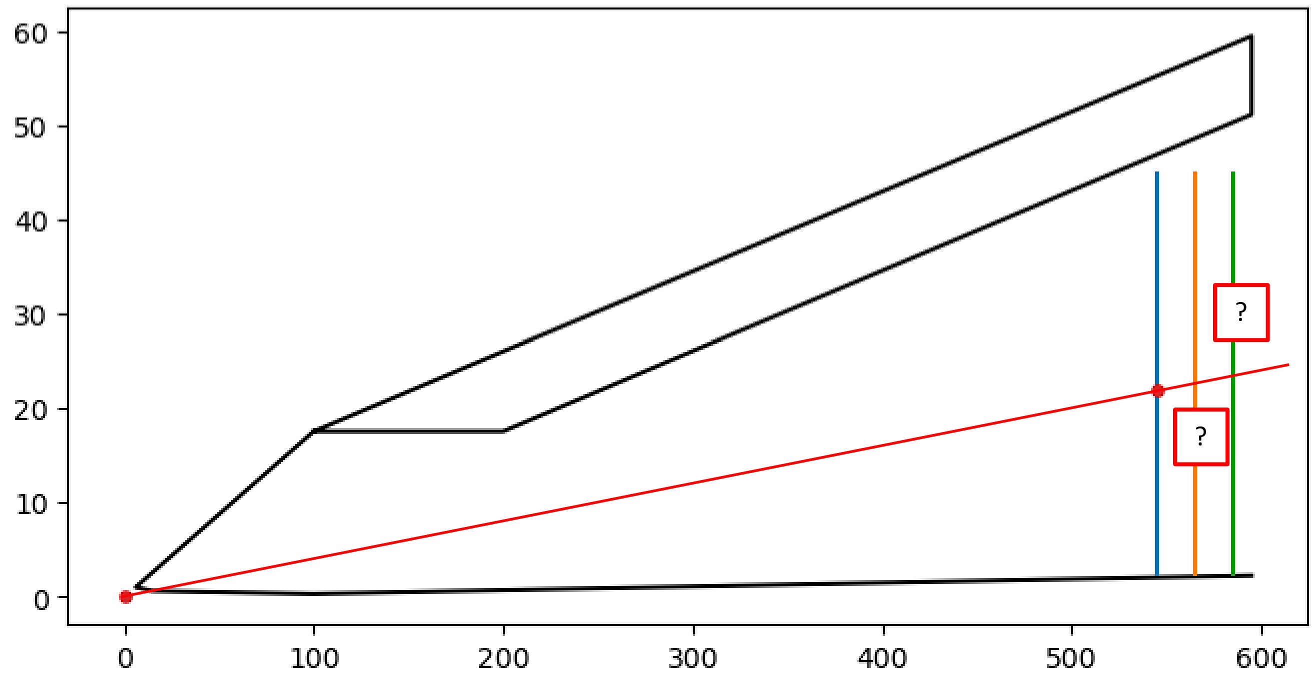
- BIB particles passing through the layers within the time window (1.4% of b.c)





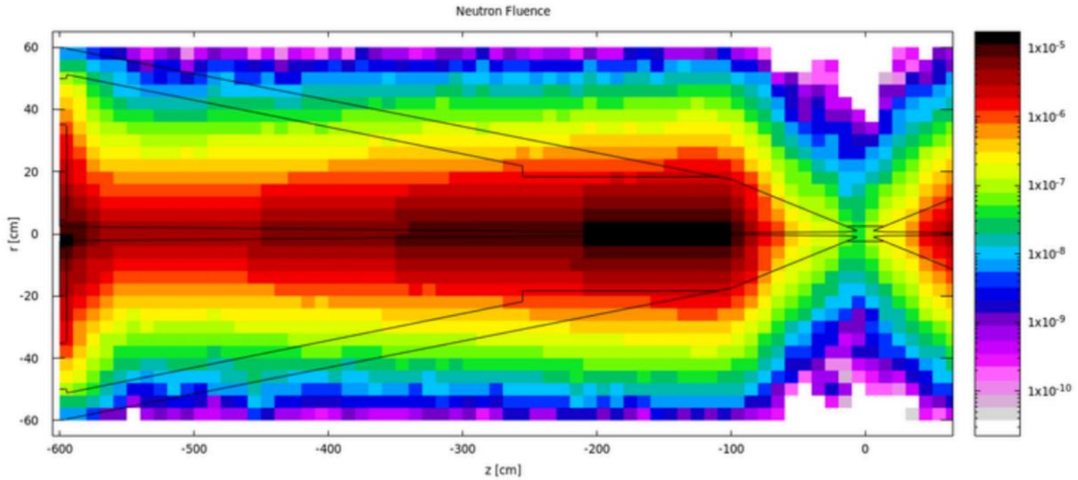
(a rough) Tracking

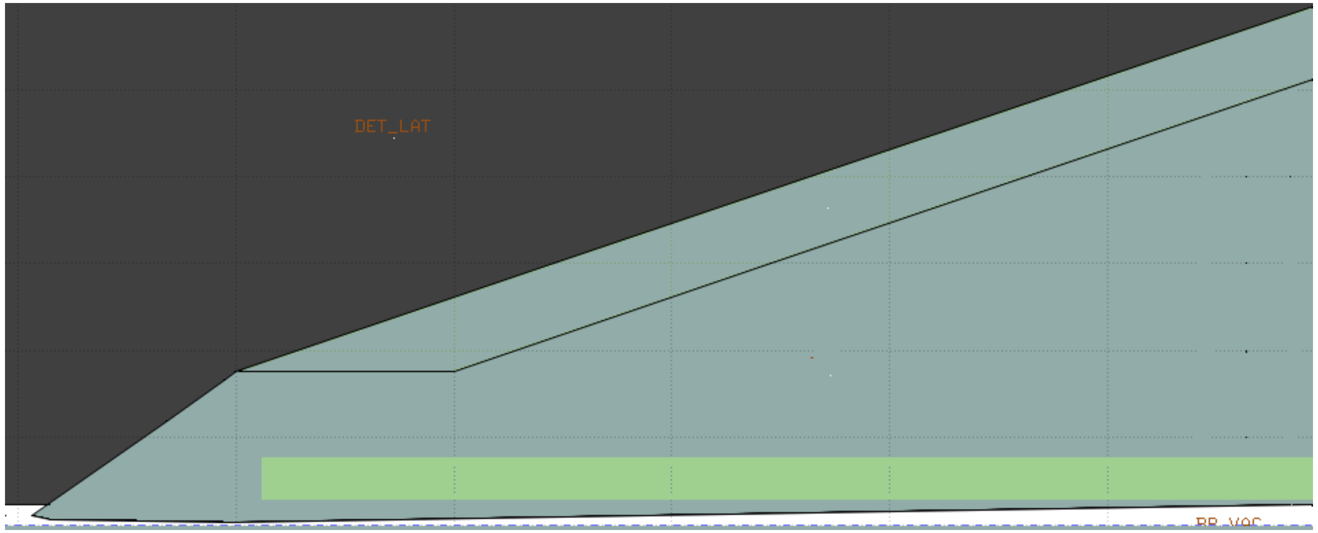
- Assuming that forward muons are produced at the IP, a straight line is the defined for each point in layer 1
- The line is propagated to layer 2 and 3. If at least 1 particle is present in the expected position $\pm 1\ cm$, the particle is tagged as a forward muon

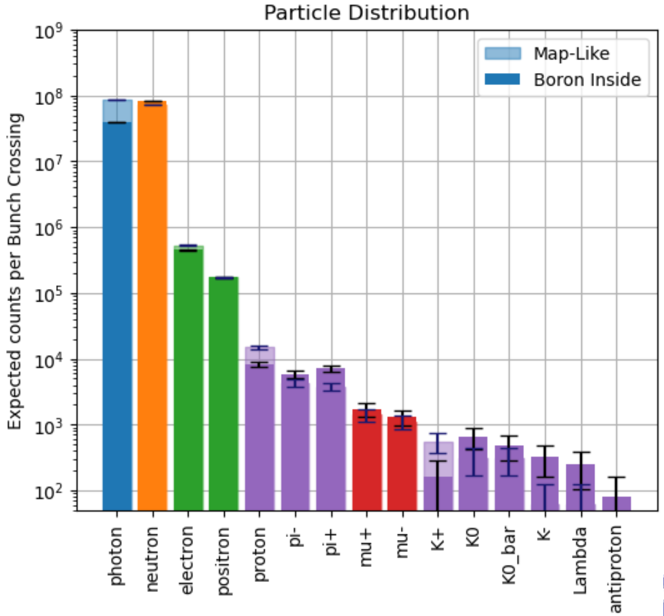


High Statistics Approach

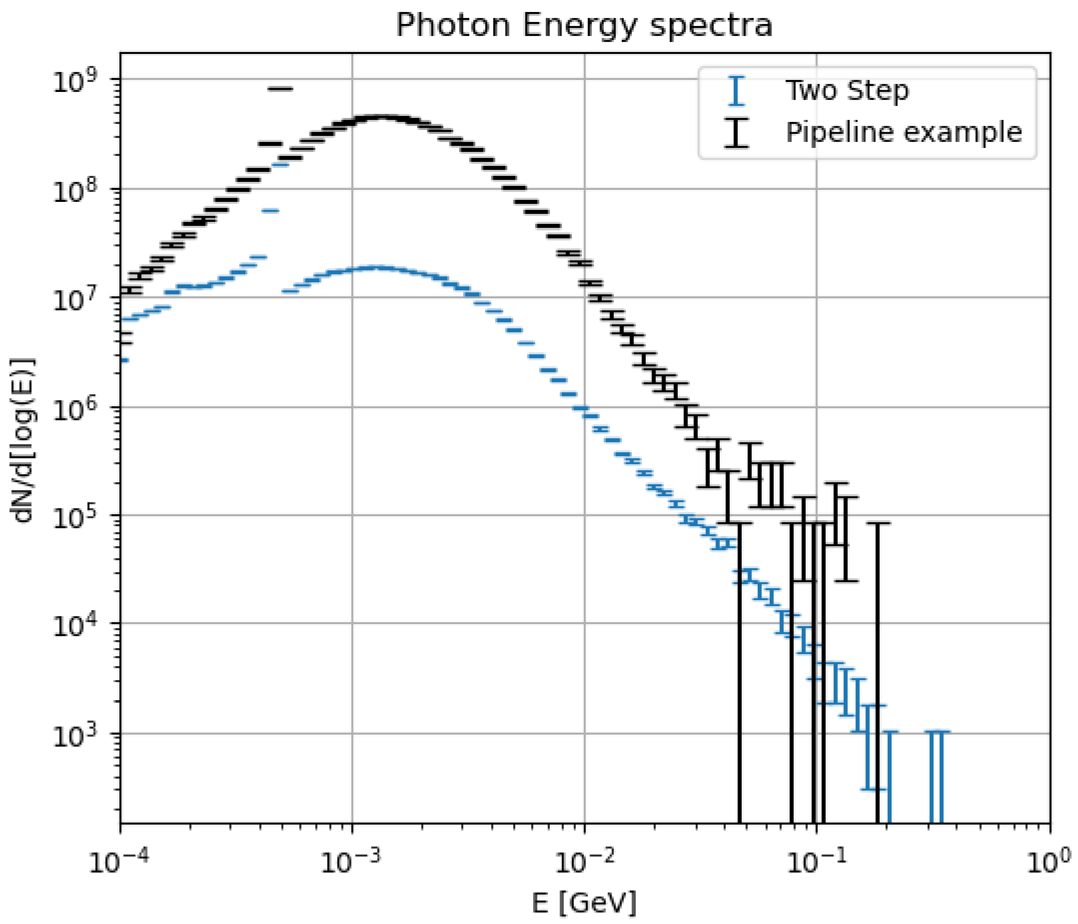
- Lessons learned:
  - The Beam Pipe cannot be touched
  - Is Boreth layer really effective?
    - Tried to put the Boreth inside the nozzle







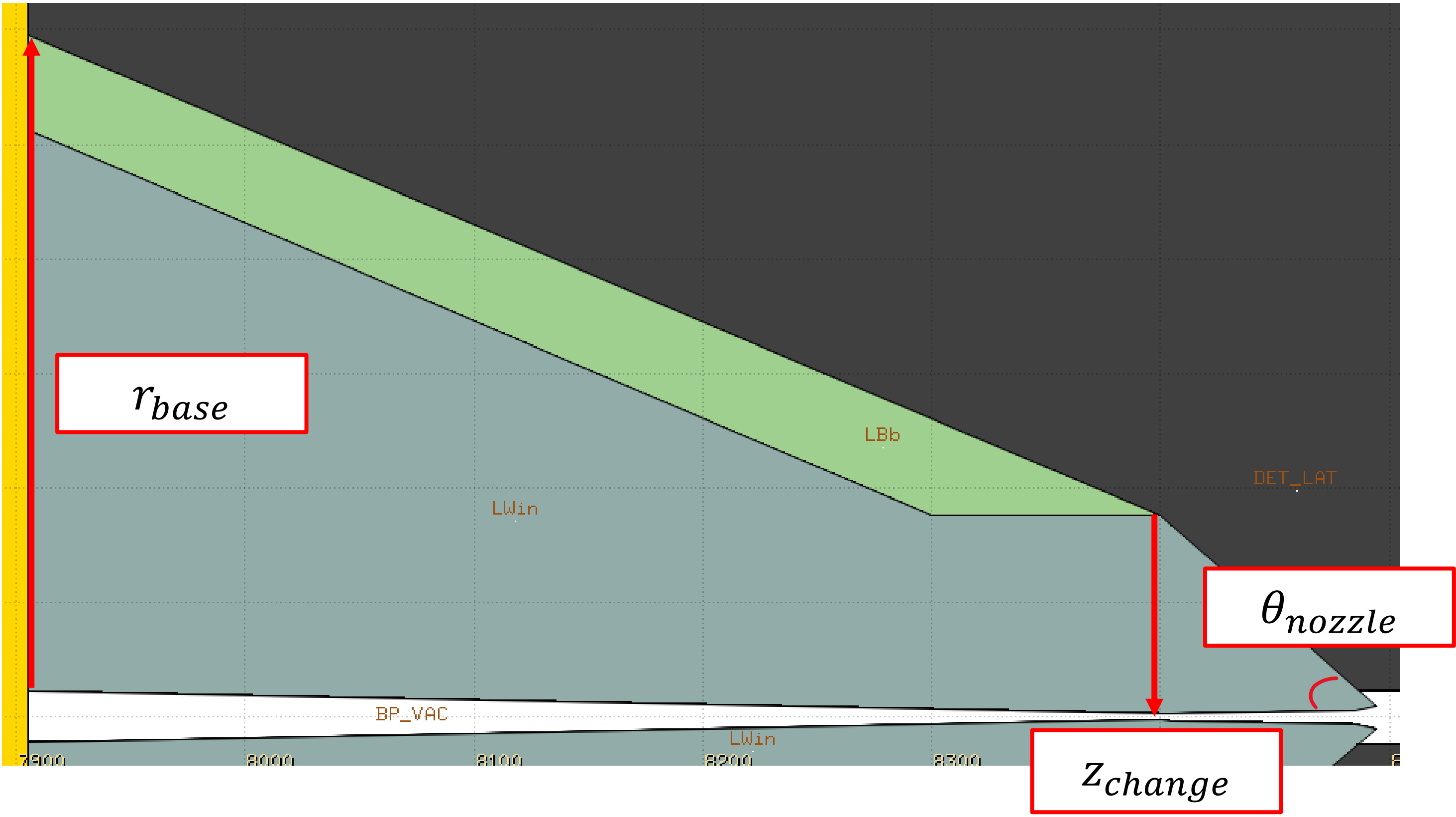
Low Statistic simulation



- 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

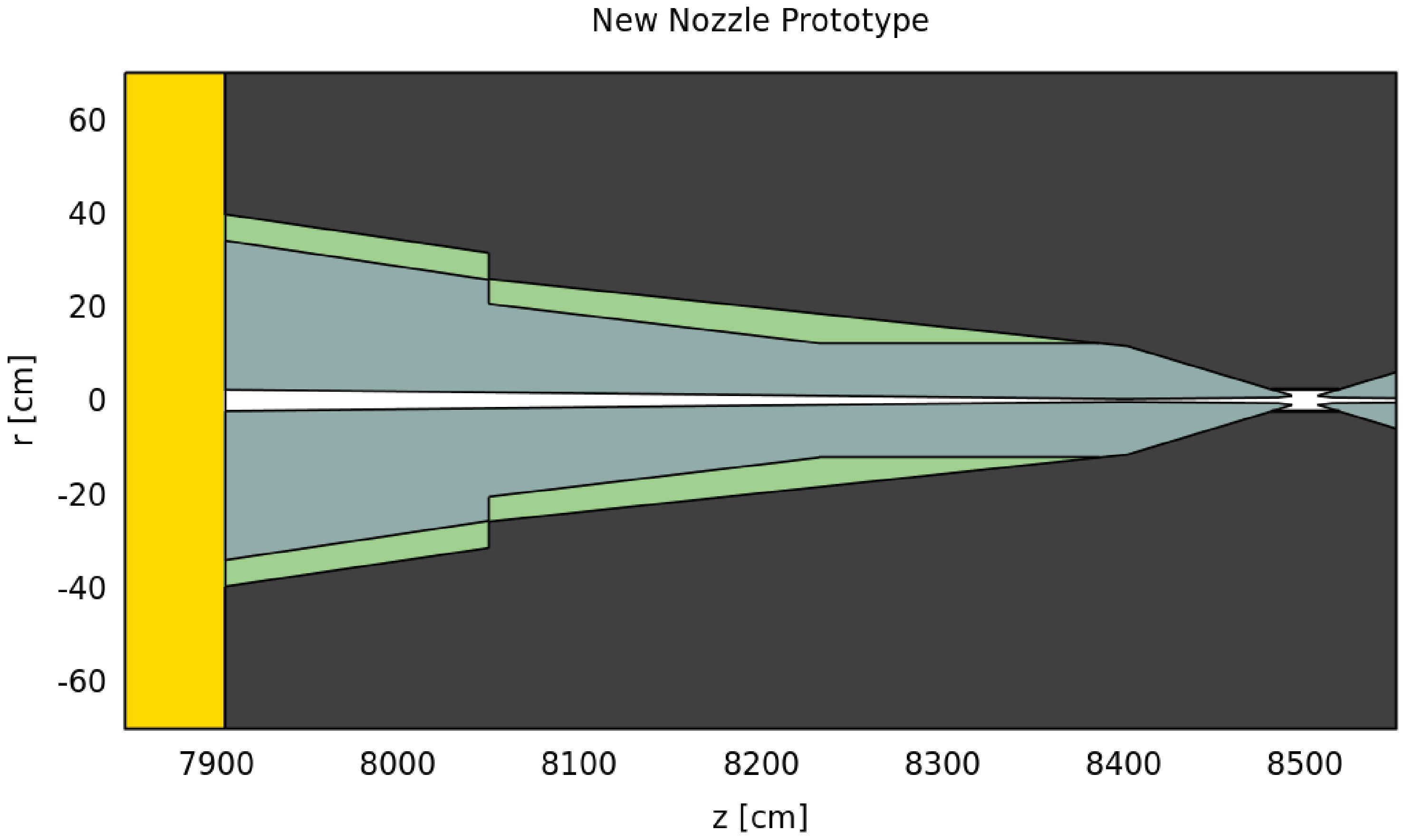
- 2*1200 simulation performed with minimum beampipe radius 0.3 (original) and 0.35
- 3 geometrical parameters:
  - $\theta_{tip} \in [3.8; 10]° \rightarrow 10$ values
  - $|z_{change}| \in [50; 200]$ cm $\rightarrow 15$ values
  - $r_{base} \in [20; 60]$ cm $\rightarrow 8$ values
- 0.02% of 1 bunch crossing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



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

Improving the ML

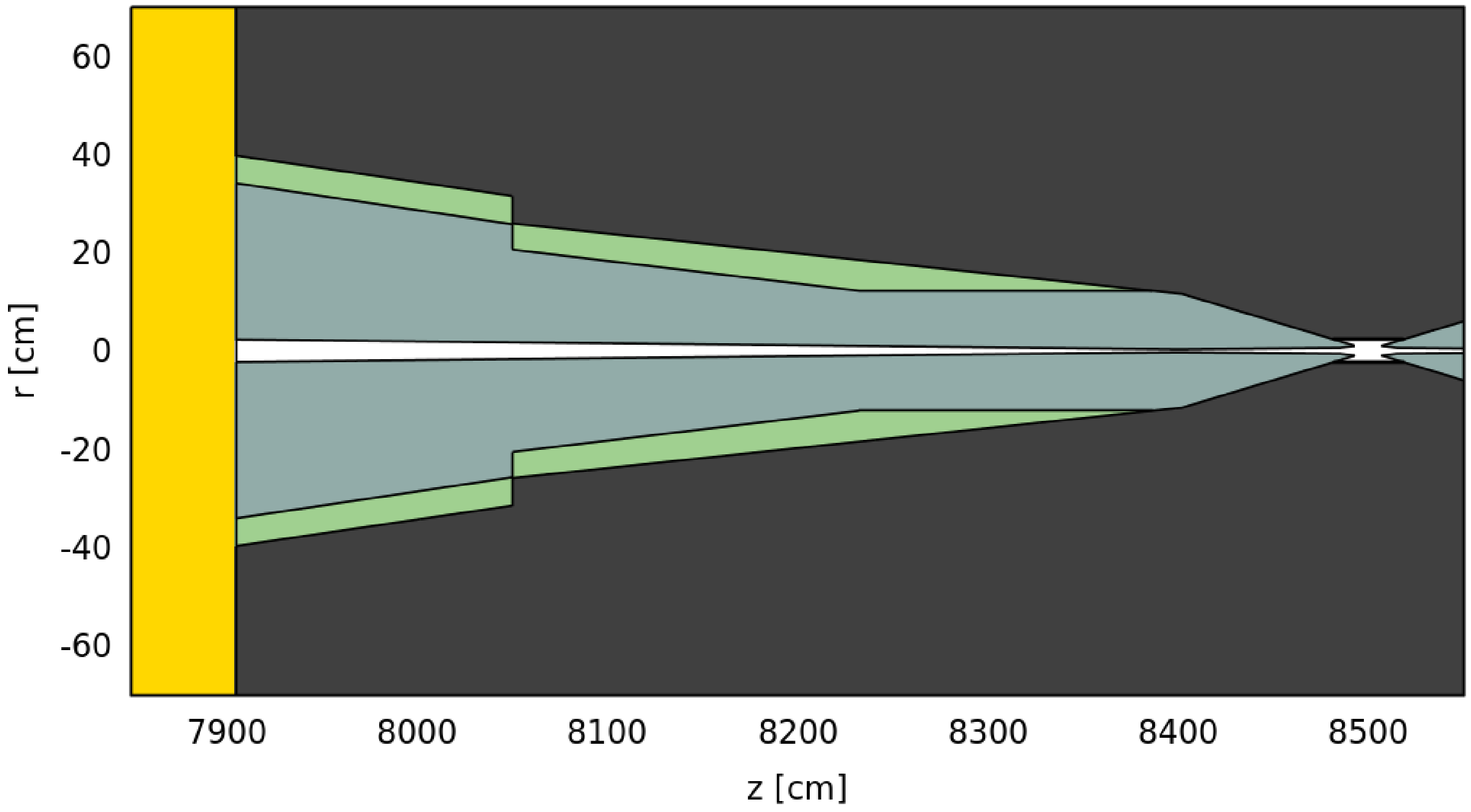
- Two new parameters:
  - $z_{step} \in [-450; -200]\ cm$
  - $r_{step} \in [0.75; 0.95] * r_{base}$
- 3125 samples (5 values per each parameter)



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)

New Nozzle Prototype



Nozzle Design XVI