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Status of $\sqrt{s} = 3 \text{ TeV}$ 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

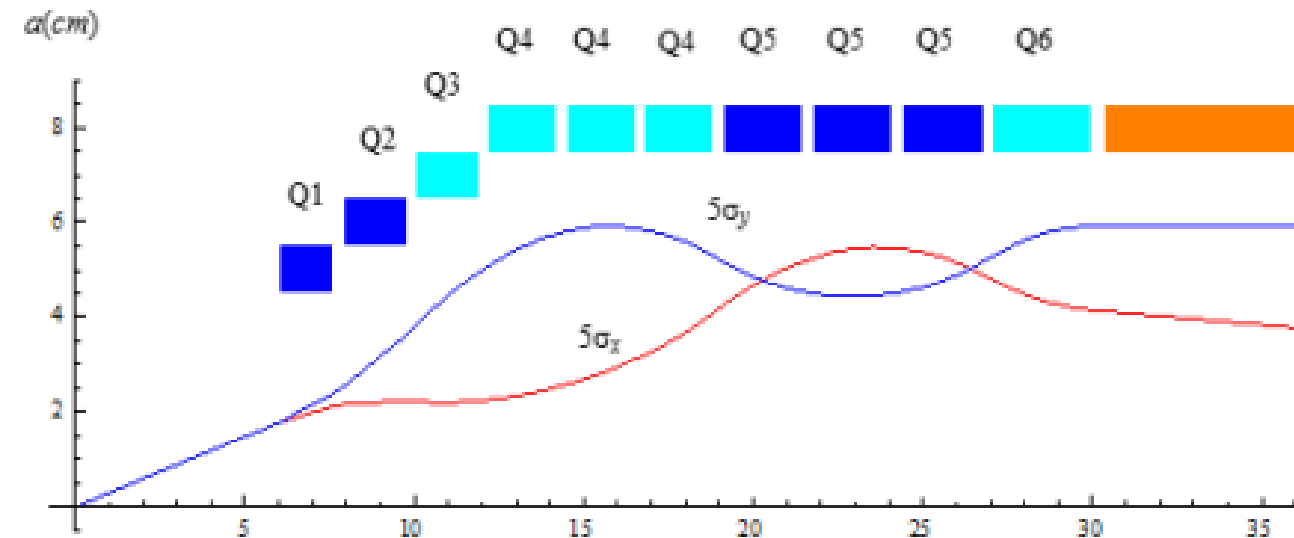
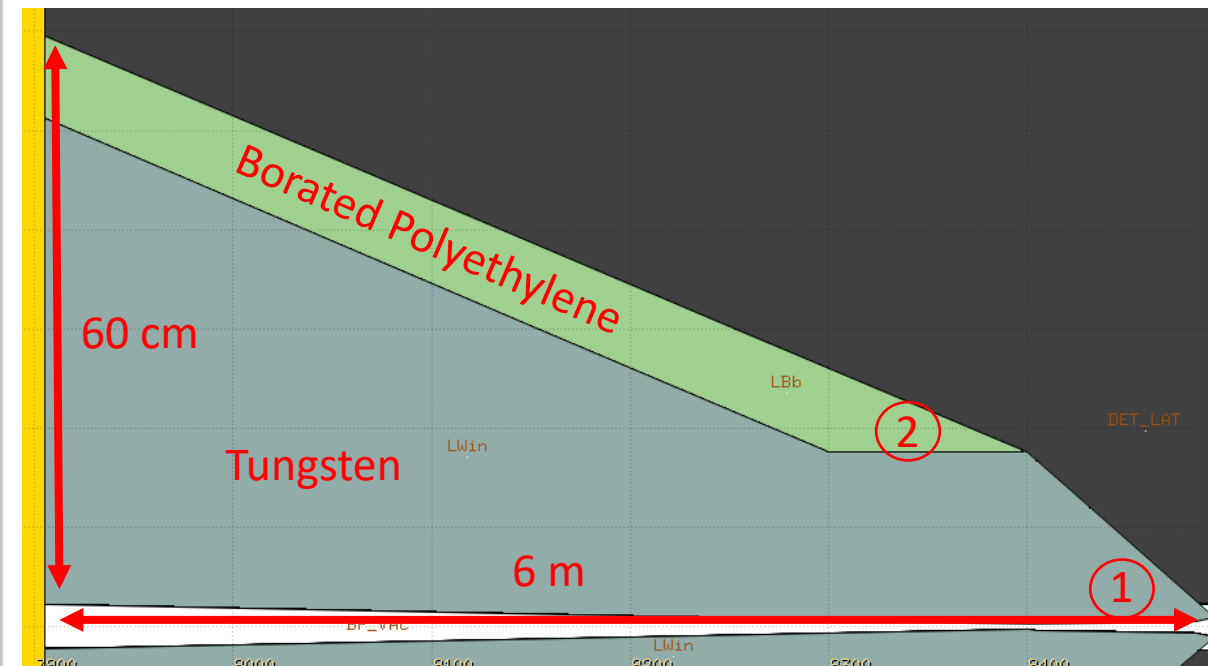
- **Pair production**

3 TeV MDI

MAP nozzle design:

- 1) 10° closest to the IP
- 2) 5° starting from $z = 100\text{ cm}$

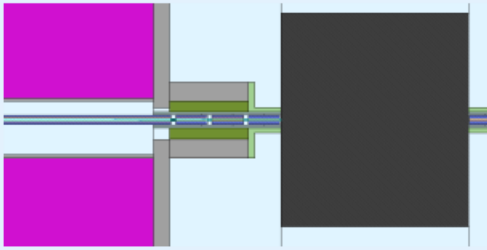
- MAP design[1] with mixed function FF quadrupoles (Cyan)



BIB simulation with FLUKA

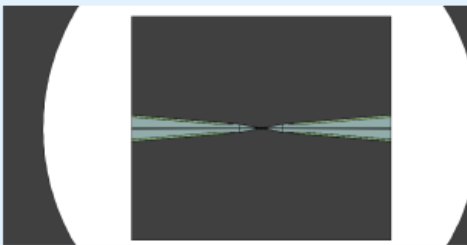
1. From muon decay to nozzle area

Machine dependent



2. Nozzle area to detectors

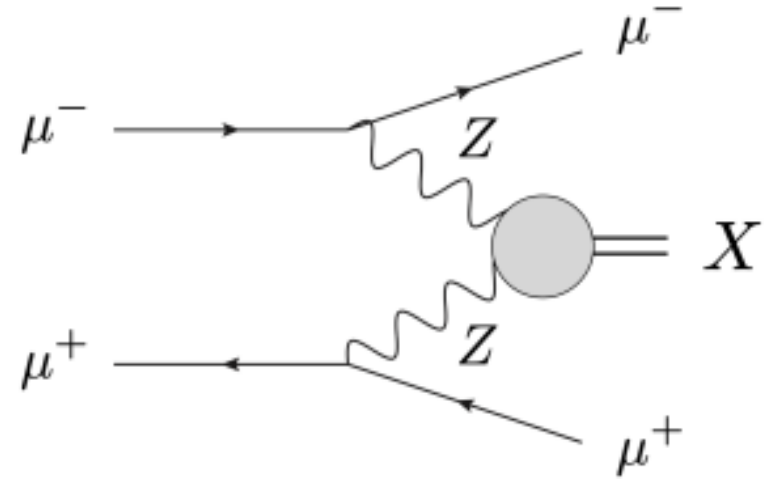
Nozzle dependent



- Generated one beam of μ^+ decays within **55 m** from the Interaction Point
 - **Energy threshold** for particles production fixed at **100 keV**
 - Particles which arrives to the nozzles are scored
-
- Propagation through the Nozzles
 - Particles who exit the nozzle and enters the detector area are scored
 - ~1.6% of one BIB event (i.e. bunch crossing) considering only 1 beam → **4 days per simulation**

Forward Muons

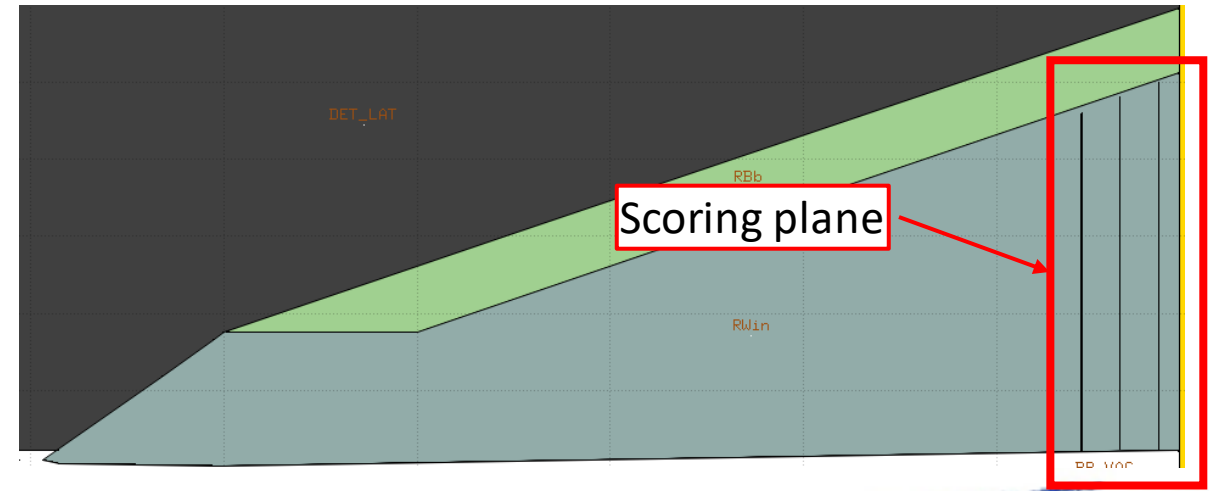
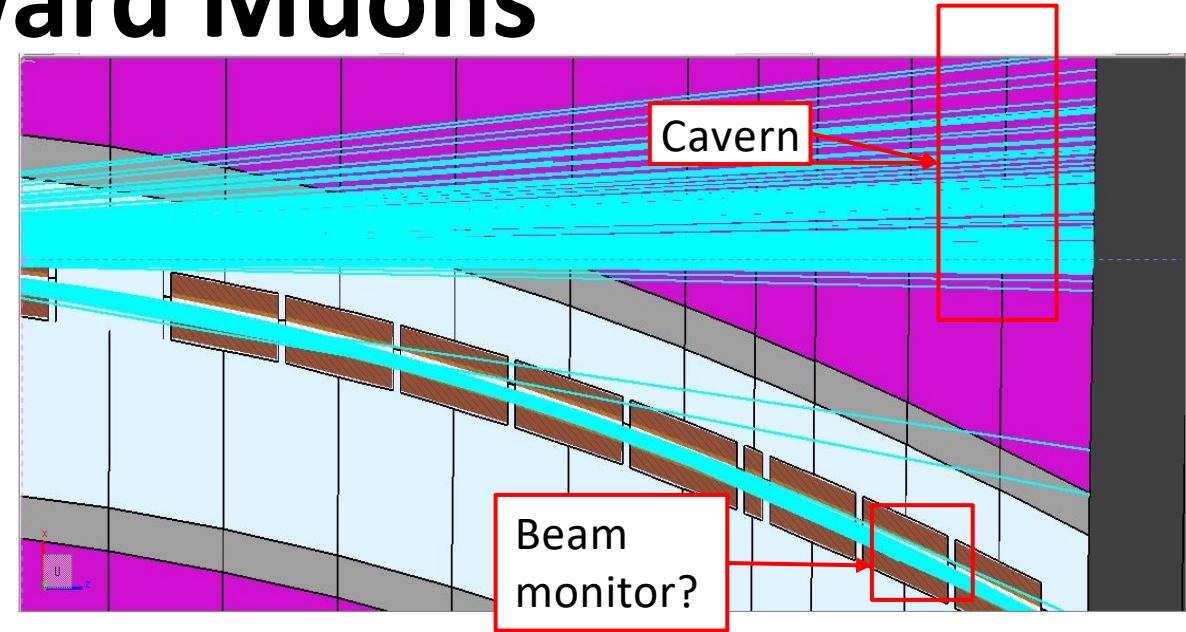
- Why are we interested in forward muons?
 - Allows to distinguish process from Z/W boson fusion
 - Allows precise measure of Higgs boson Width [2, 6]
 - New physics might have forward muons in the final state [3]



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

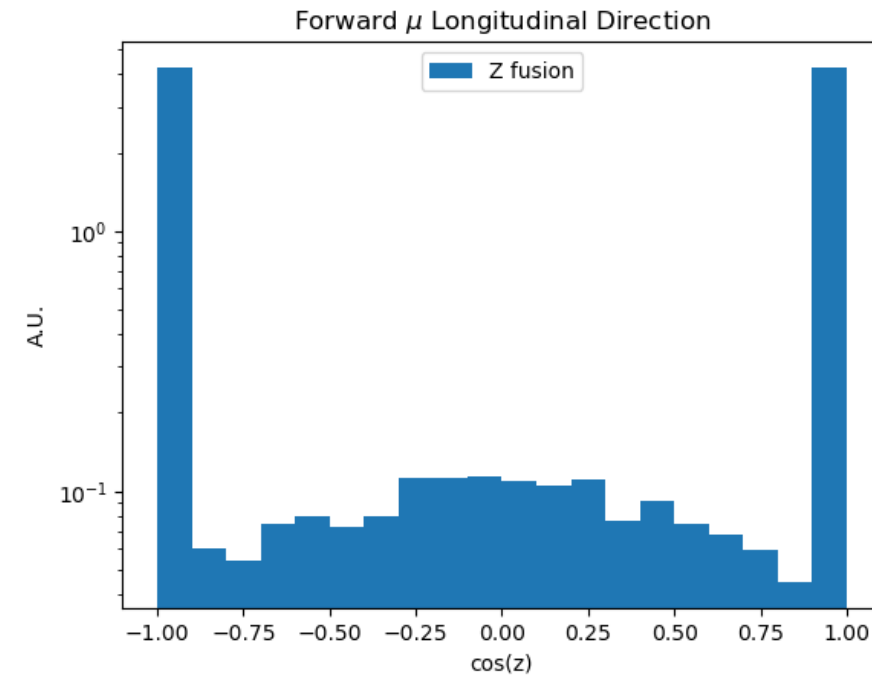
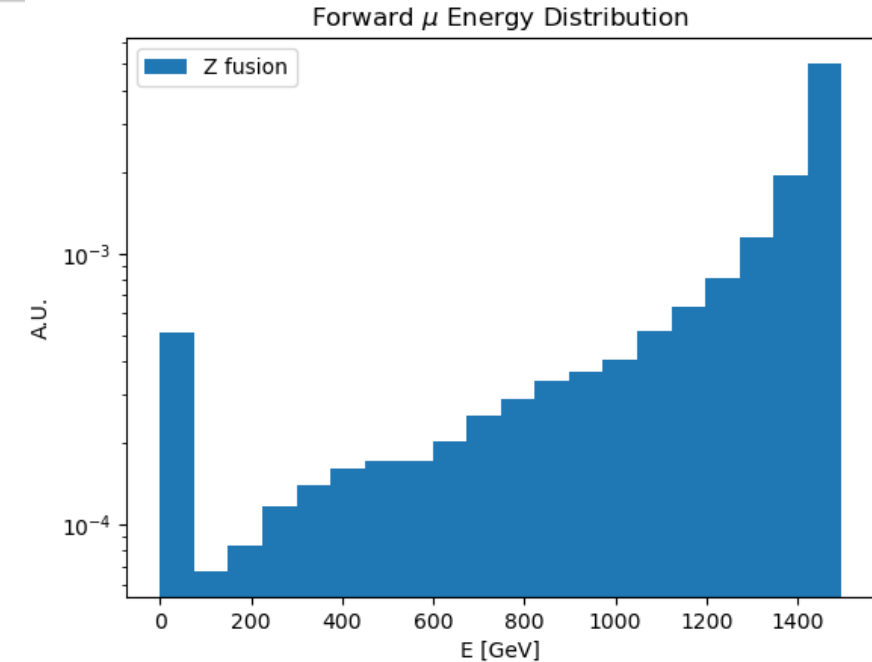


Simulated samples

- Forward muons from:

$$\mu^+\mu^- \rightarrow ZZ + \mu^+\mu^- \rightarrow H + \mu^+\mu^- \rightarrow W^+W^- + \mu^+\mu^-$$

- $2 \cdot 6.15 \cdot 10^3$ 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**



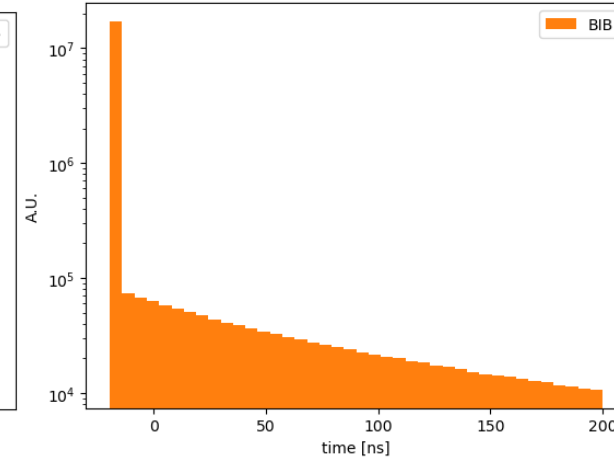
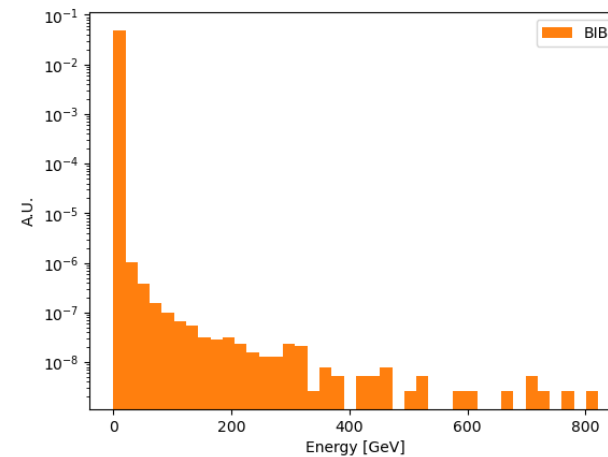
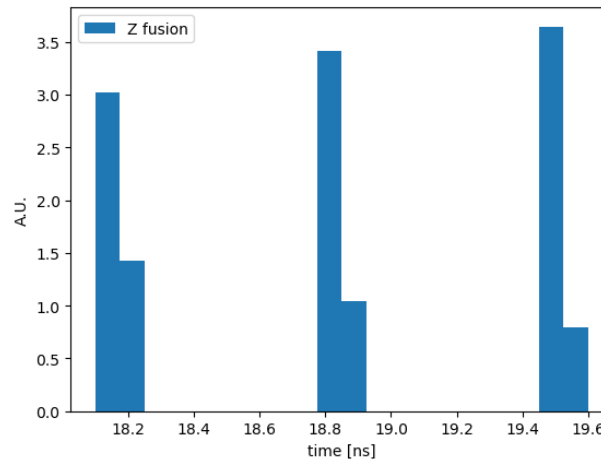
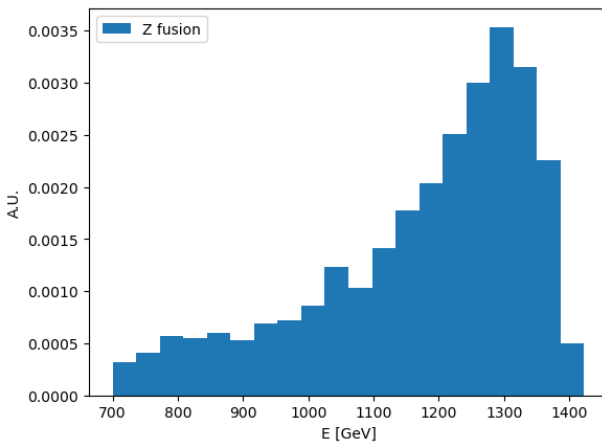
Simulation Outputs

■ Forward Muons:

- Fixed time of arrival in the layers
- Coming from IP
- High energy $\Rightarrow [0.7, 1.4] \text{ TeV}$

■ Beam Induced Background:

- Most particles arrive earlier than bunch crossing
- Time cuts discard great majority of BIB



Performance

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

Event	Layer 1	Layer 2	Layer 3
<i>BIB</i> *	$2.5 \cdot 10^4$	$2.7 \cdot 10^4$	$3.0 \cdot 10^4$
<i>Z fusion</i> **	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 [%]
<i>BIB</i> [#]	< 0.28	
<i>Z fusion</i> ^{##}	52.5	99.2

*Normalized to the bunch crossing

** 6150 events simulated

[#] 0 particles tracked, estimation on the total bunch crossing computed according to [\[1\]](#)

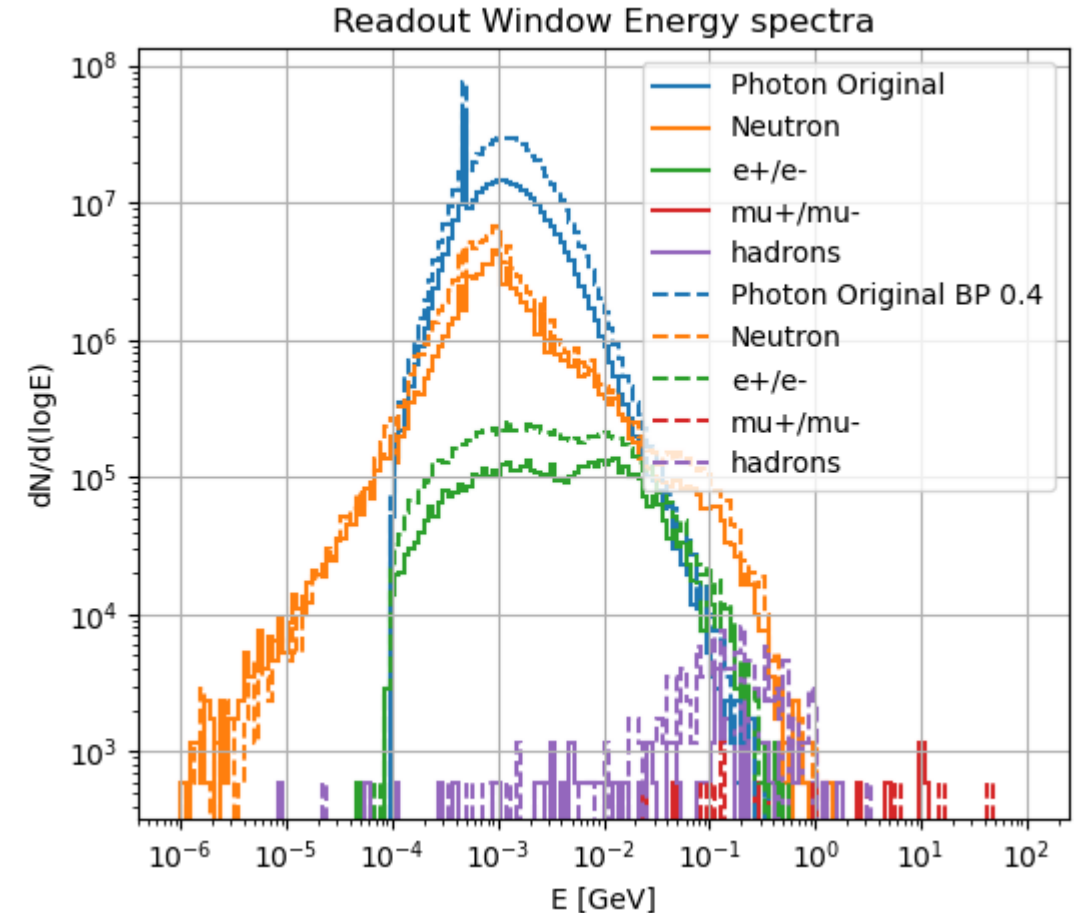
^{##} Efficiency computed on the total muon generated, i.e. 6150, not on only the ones who pass through the nozzle and the layers

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

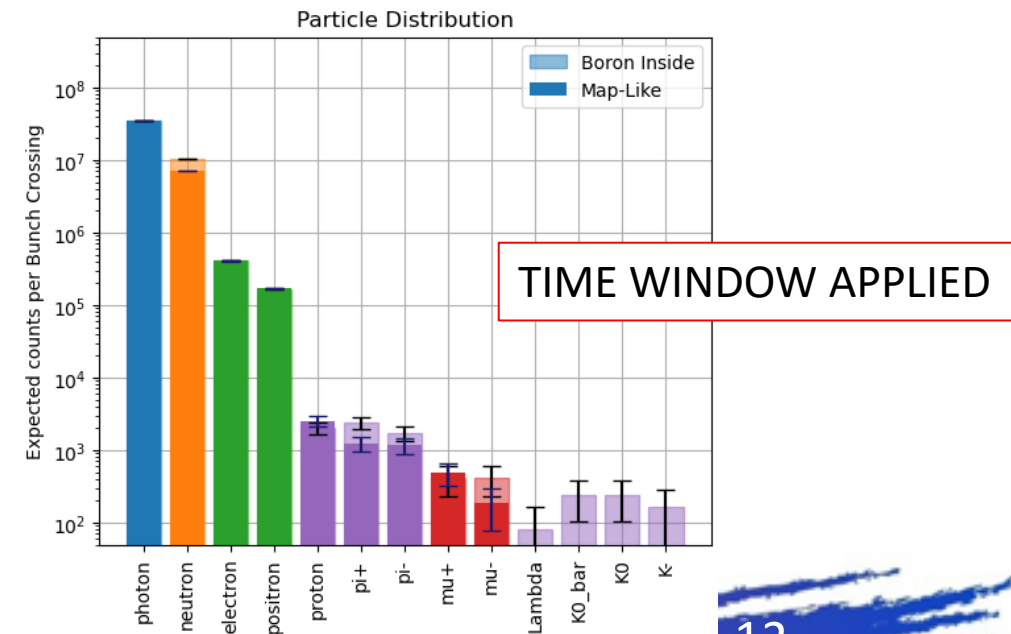
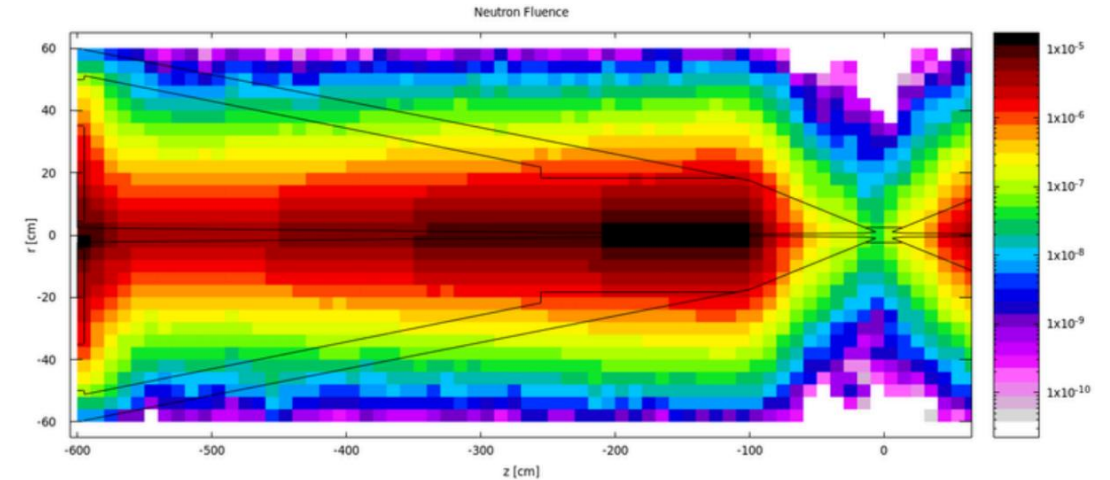
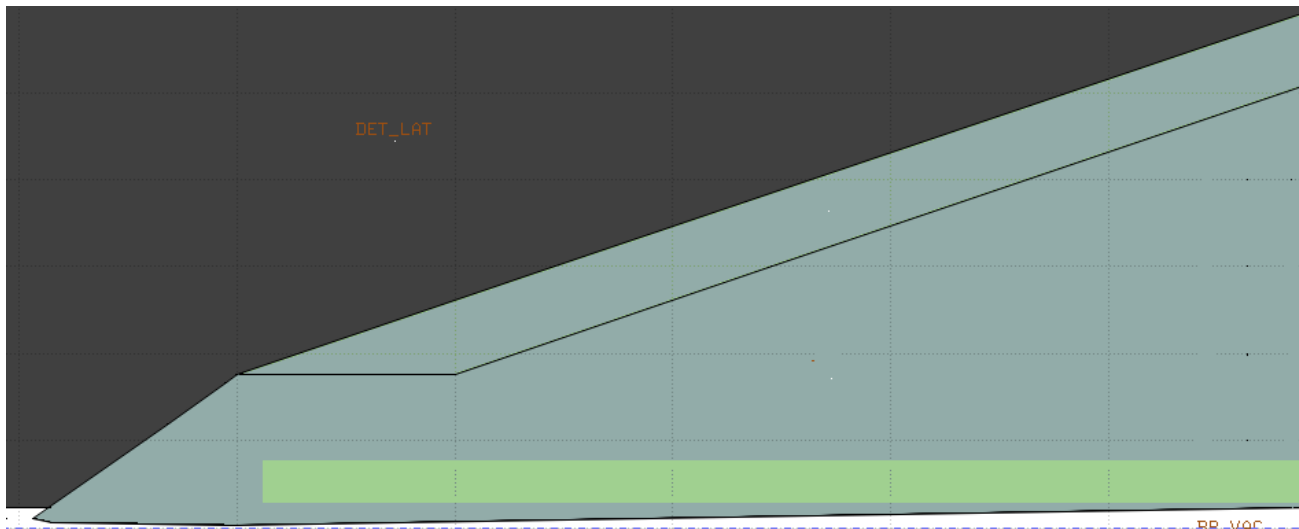
High Statistics Approach

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



High Statistics Approach

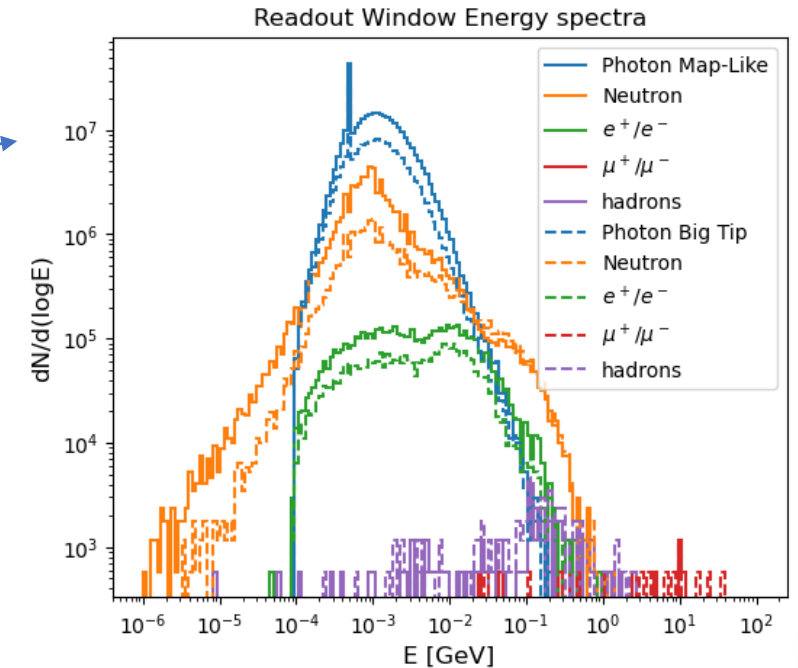
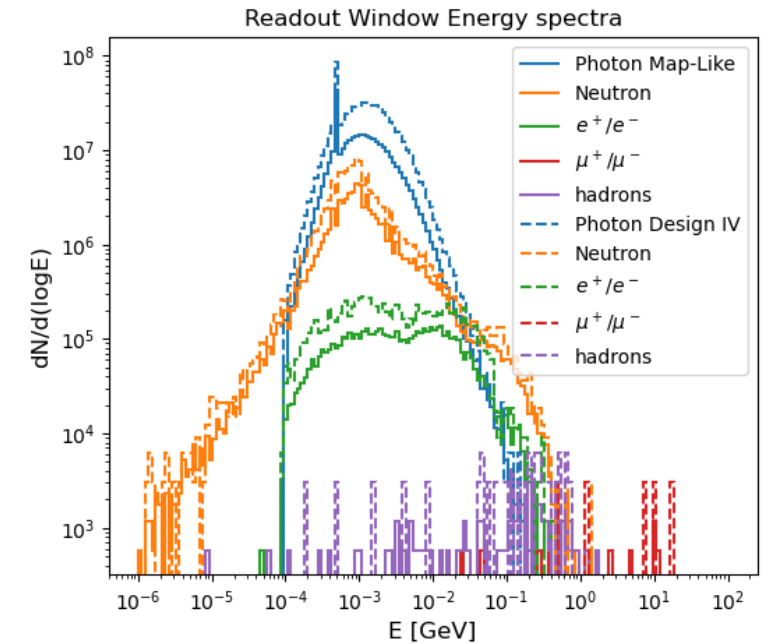
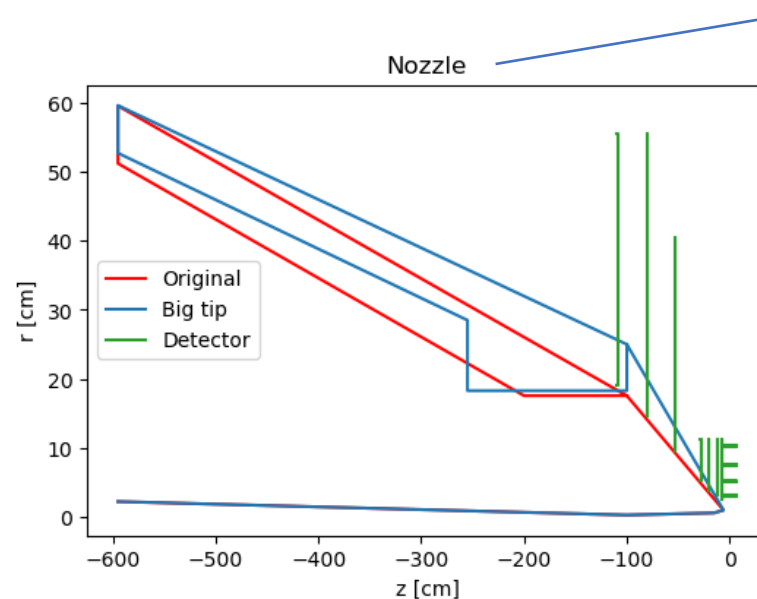
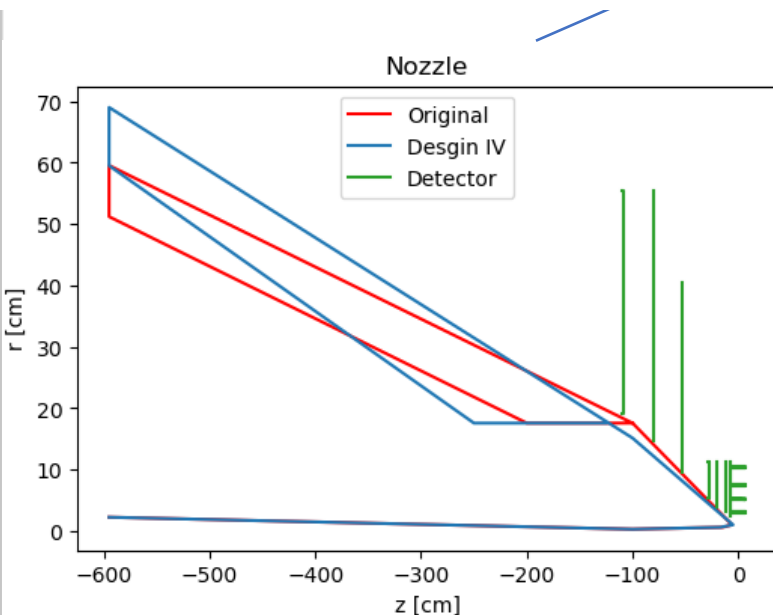
- Lessons learned:
 - The Beam Pipe cannot be touched
 - Is Boreth layer really effective?
 - Tried to put the Boreth inside the nozzle



High Statistics Approach

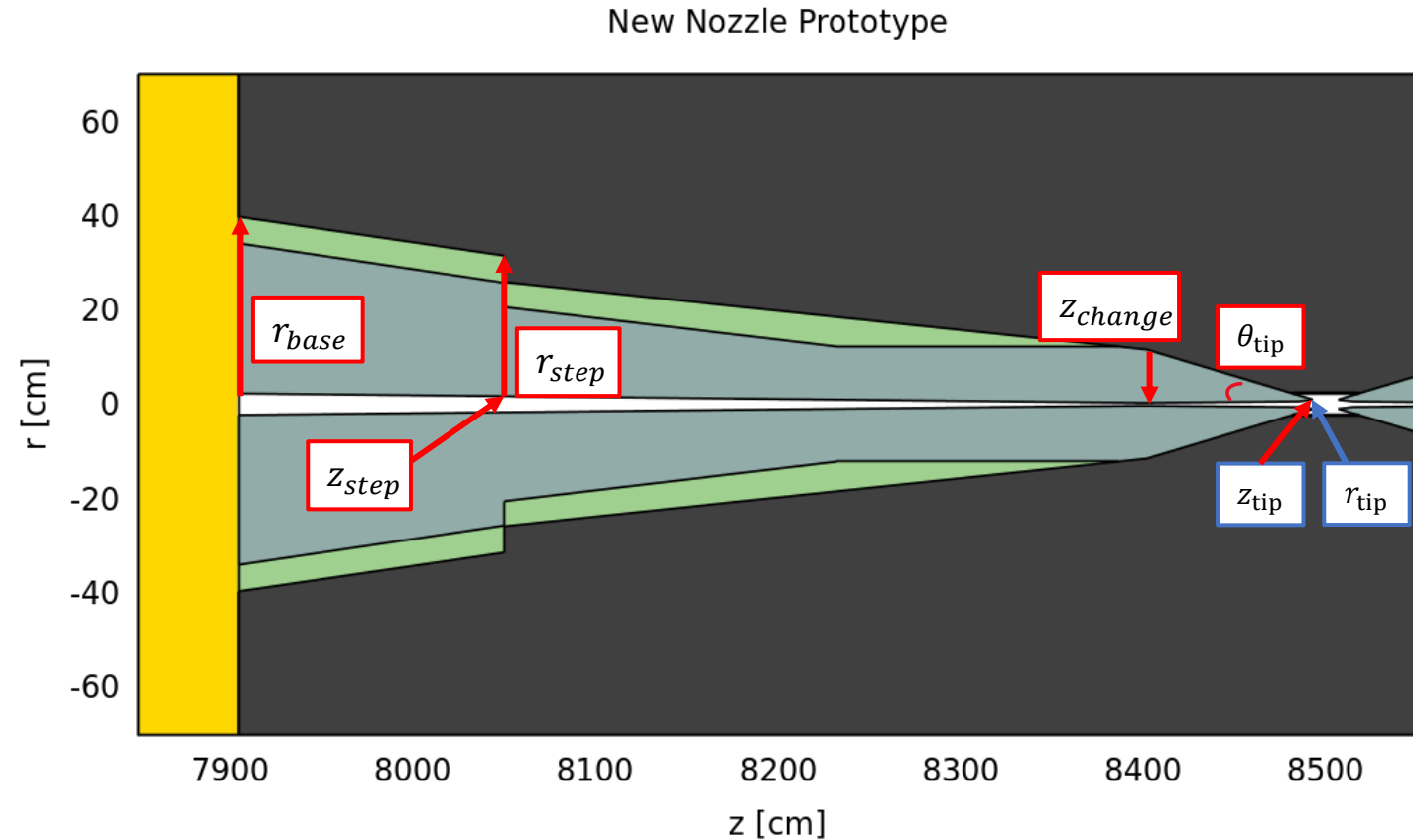
■ Lessons learned:

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



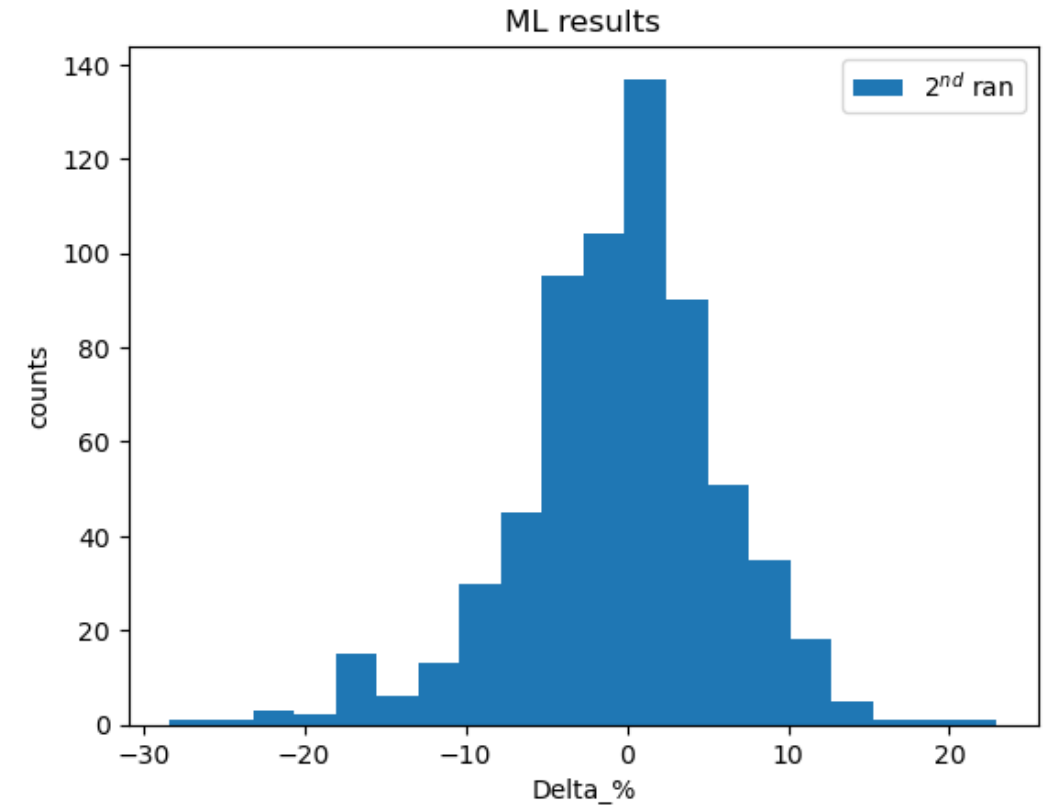
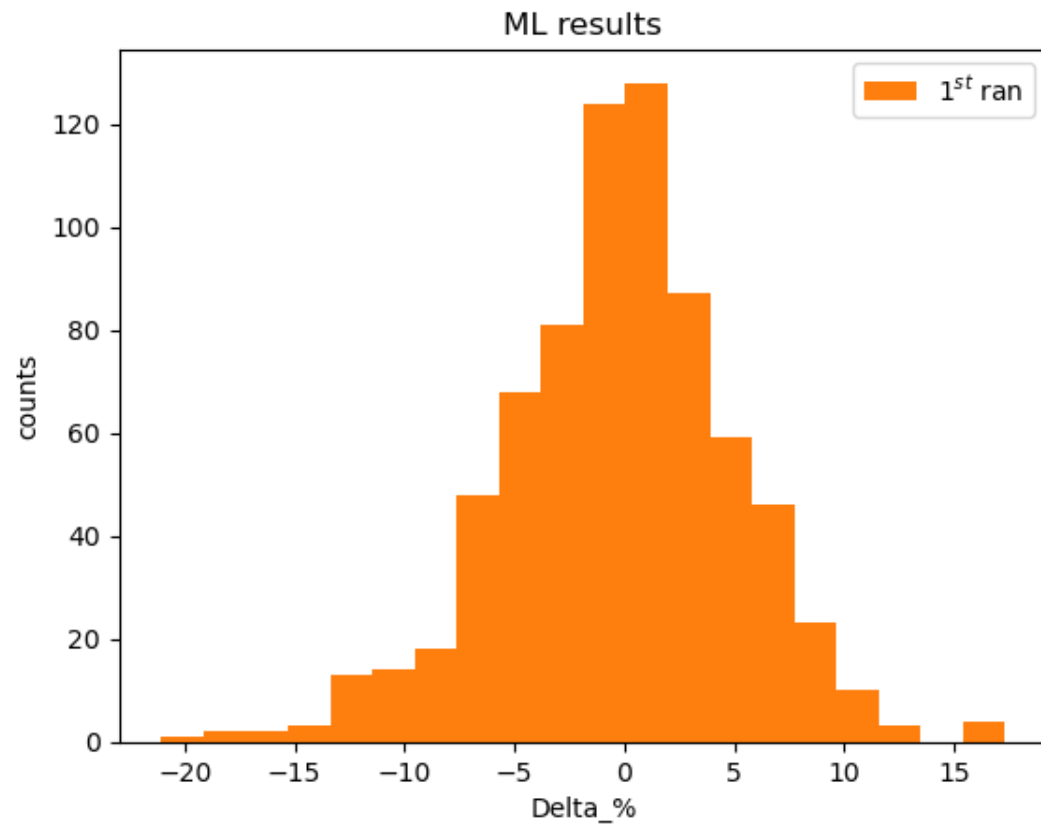
Machine Learning Approach

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

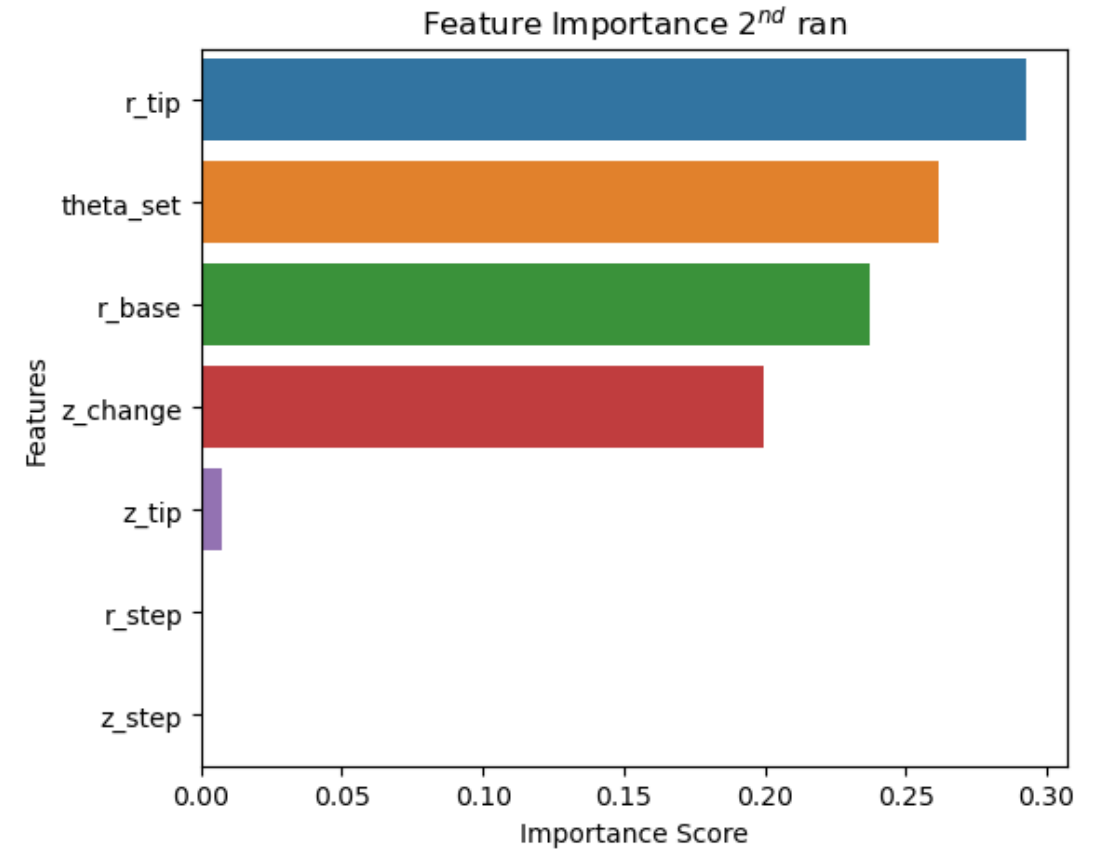
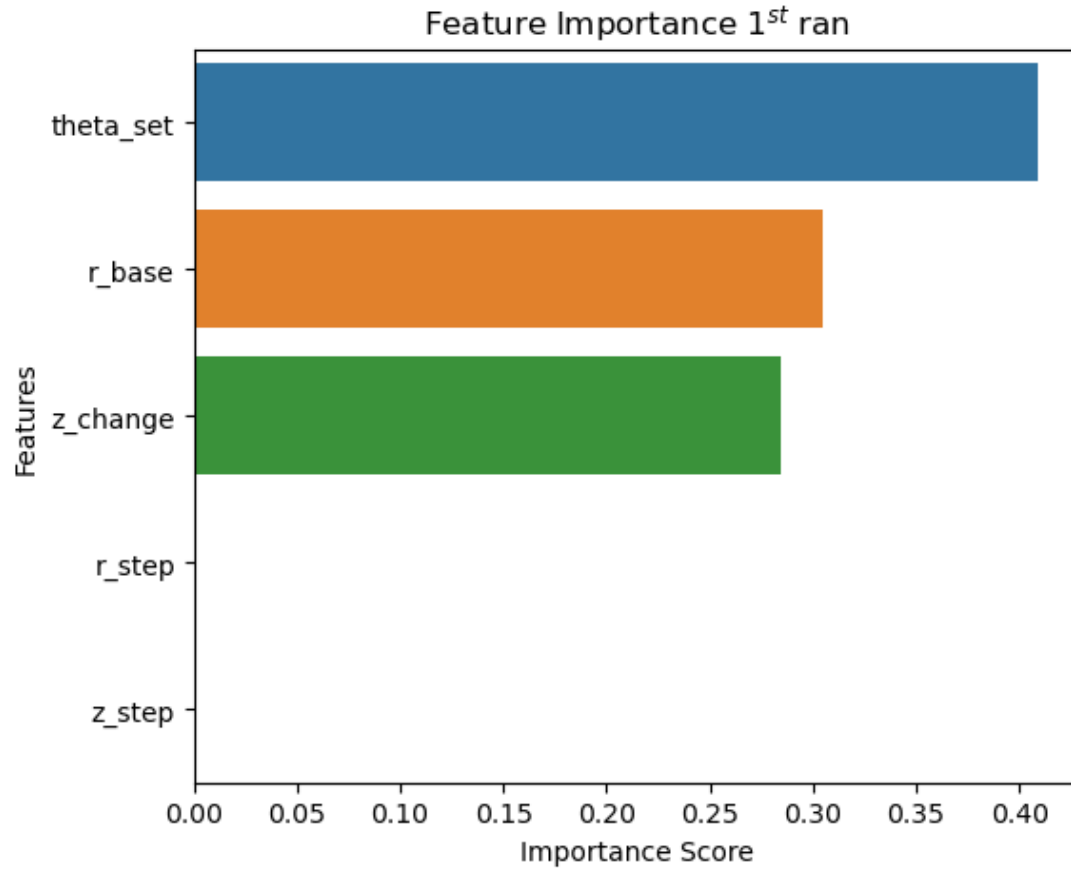


XGBoost performance

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

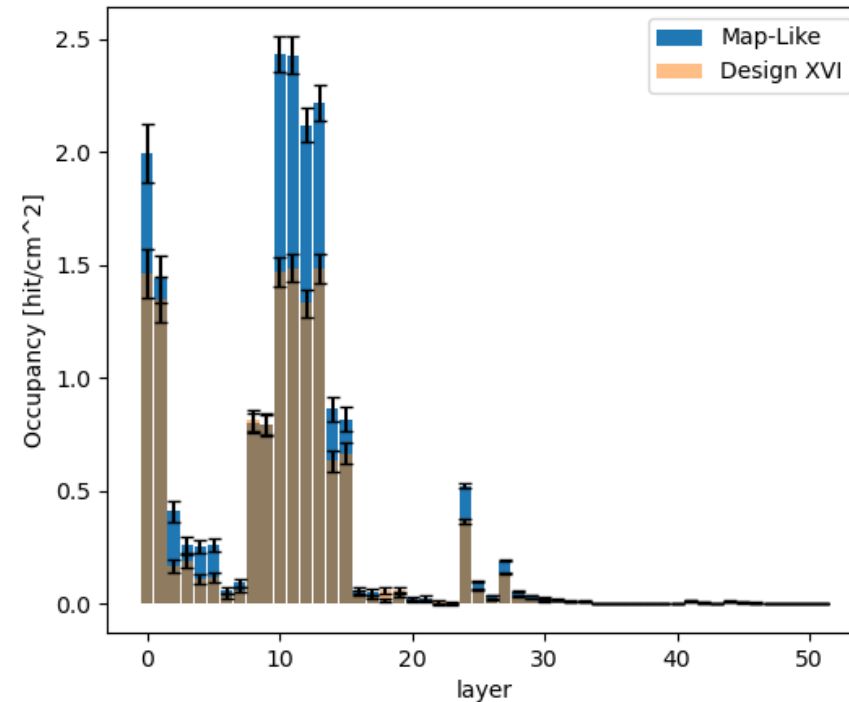
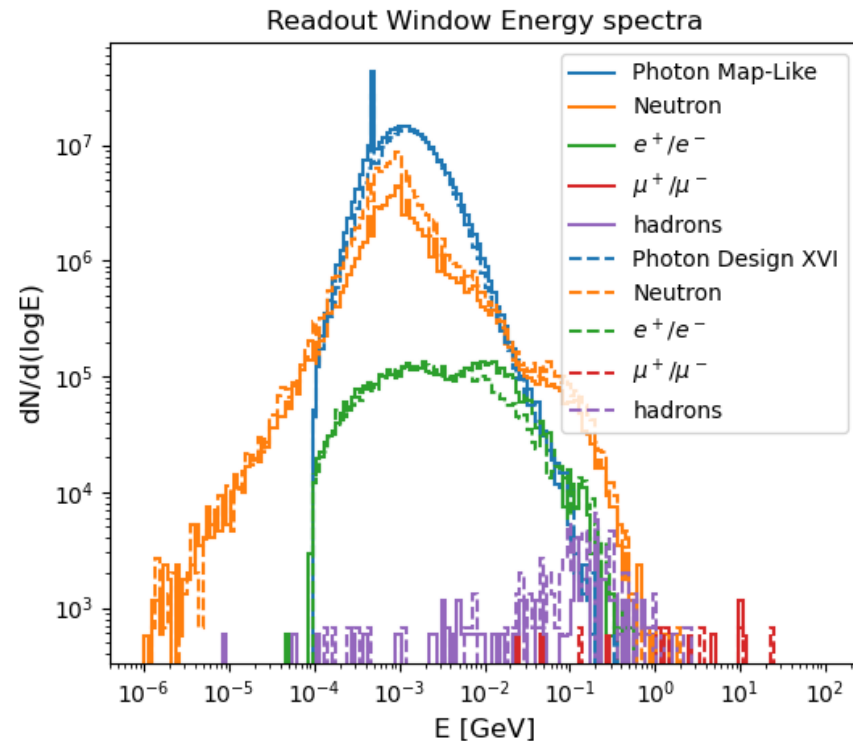


XGBoost performance



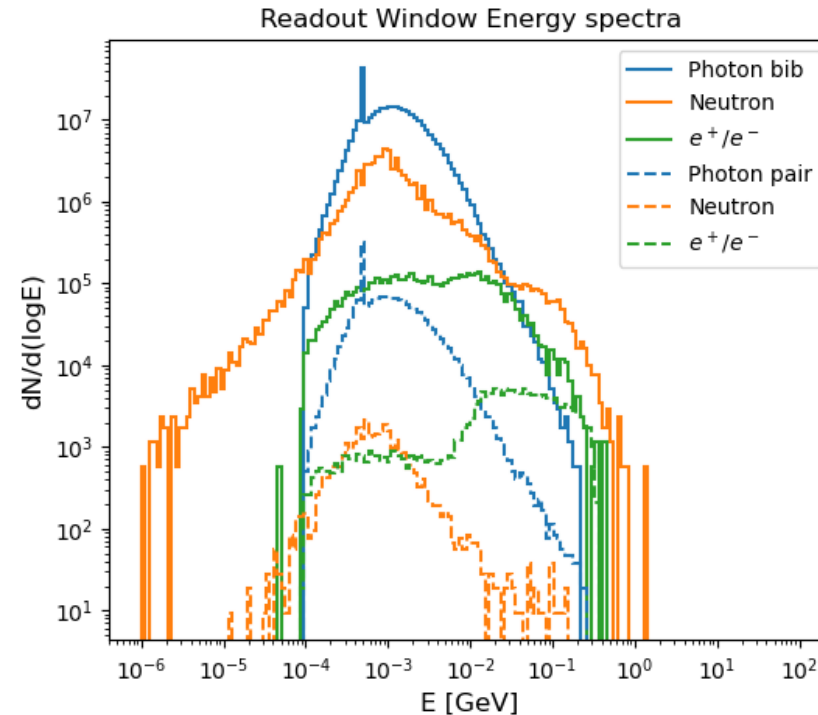
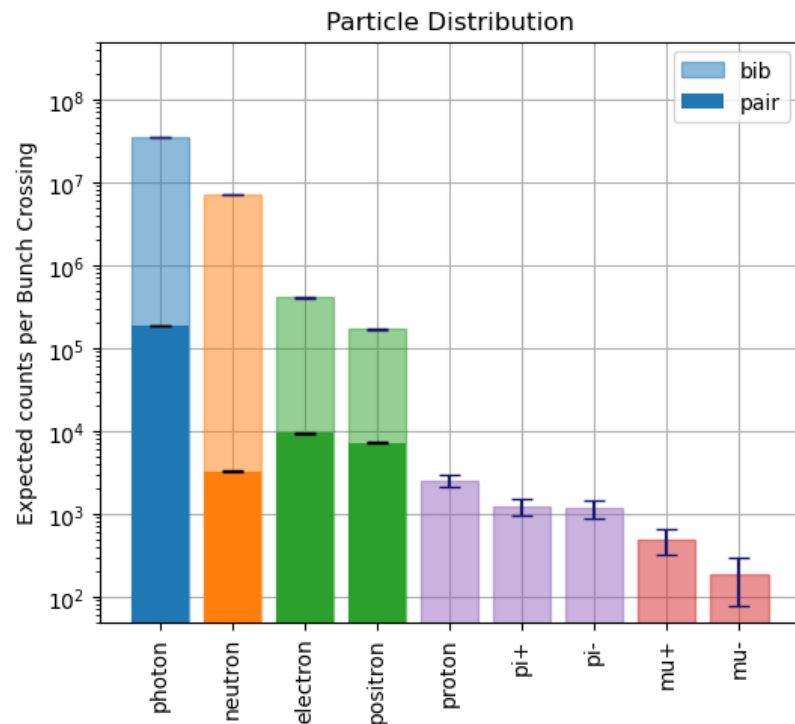
Nozzle Design XVI

- 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 their momentum

- **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](https://inspirehep.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](https://mode.github.io)
- [5] A. Baranov et al., OPTIMIZING THE ACTIVE MUON SHIELD FOR THE SHIP EXPERIMENT AT CERN, [SHIP optimization](https://SHIPoptimization.github.io)
- [6] Z. Liu, HIGGS WIDTH AND COUPLINGS AT HIGH ENERGY MUON COLLIDERS WITH FORWARD MUON DETECTION, indico.cern



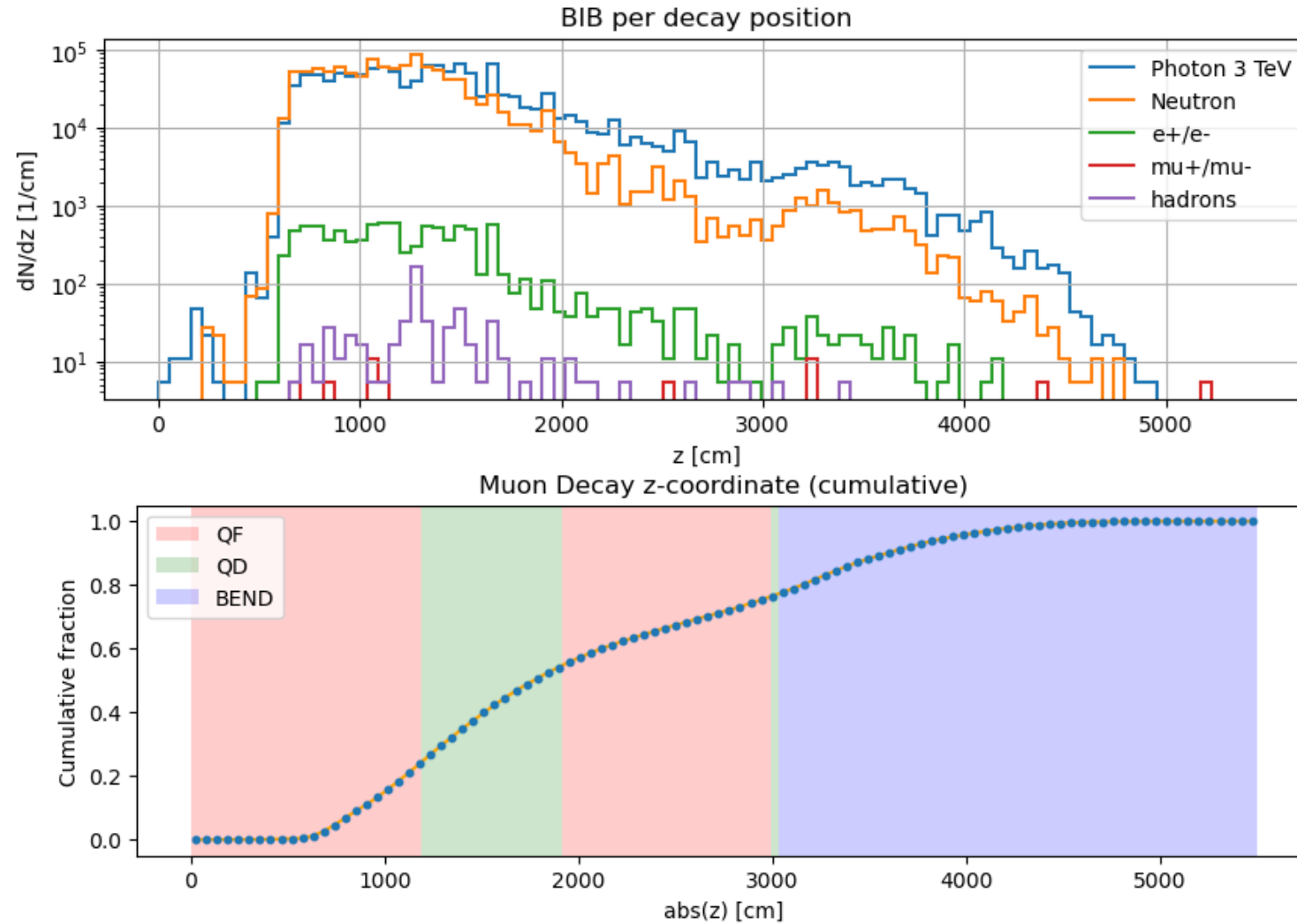
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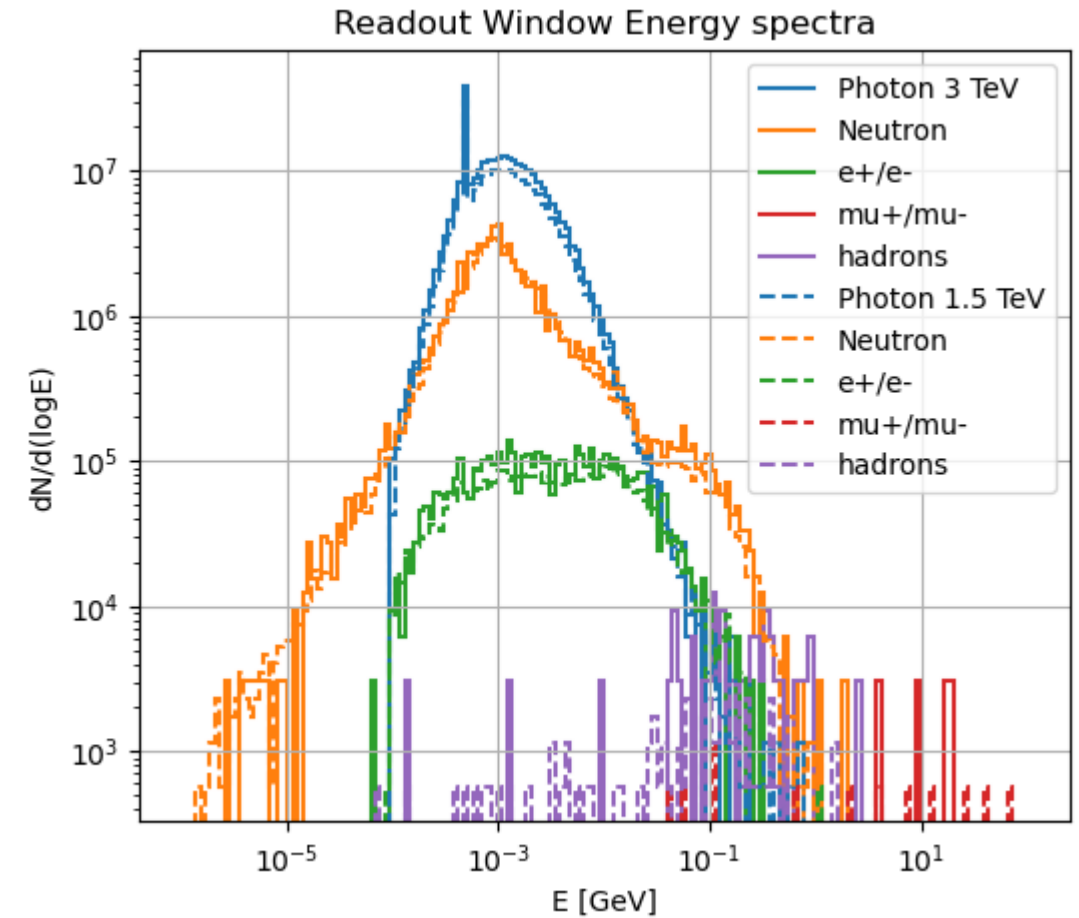
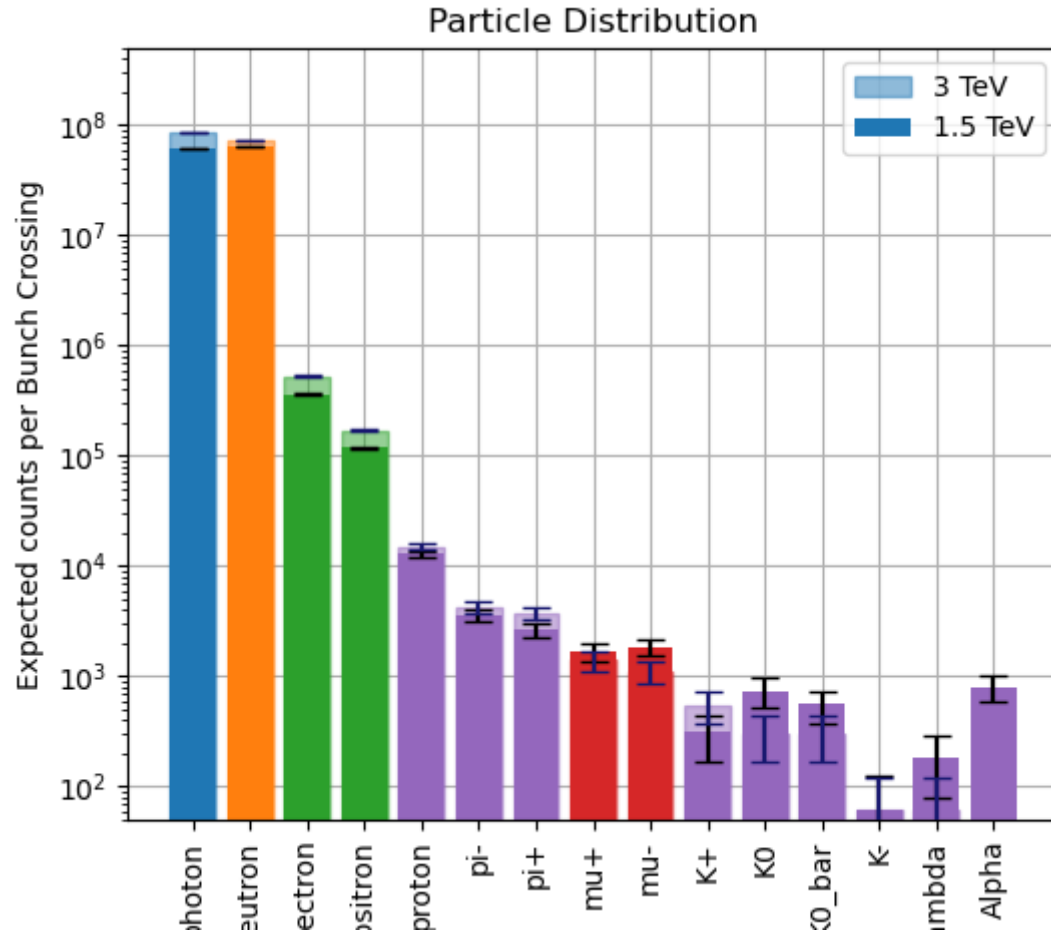
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BACKUP

Muon decay position



BIB simulation with FLUKA



Detector

hadronic calorimeter

- ◆ 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- ◆ 30x30 mm² cell size;
- ◆ 7.5 λ_I .

electromagnetic calorimeter

- ◆ 40 layers of 1.9-mm W absorber + silicon pad sensors;
- ◆ 5x5 mm² cell granularity;
- ◆ 22 X_0 + 1 λ_I .

muon detectors

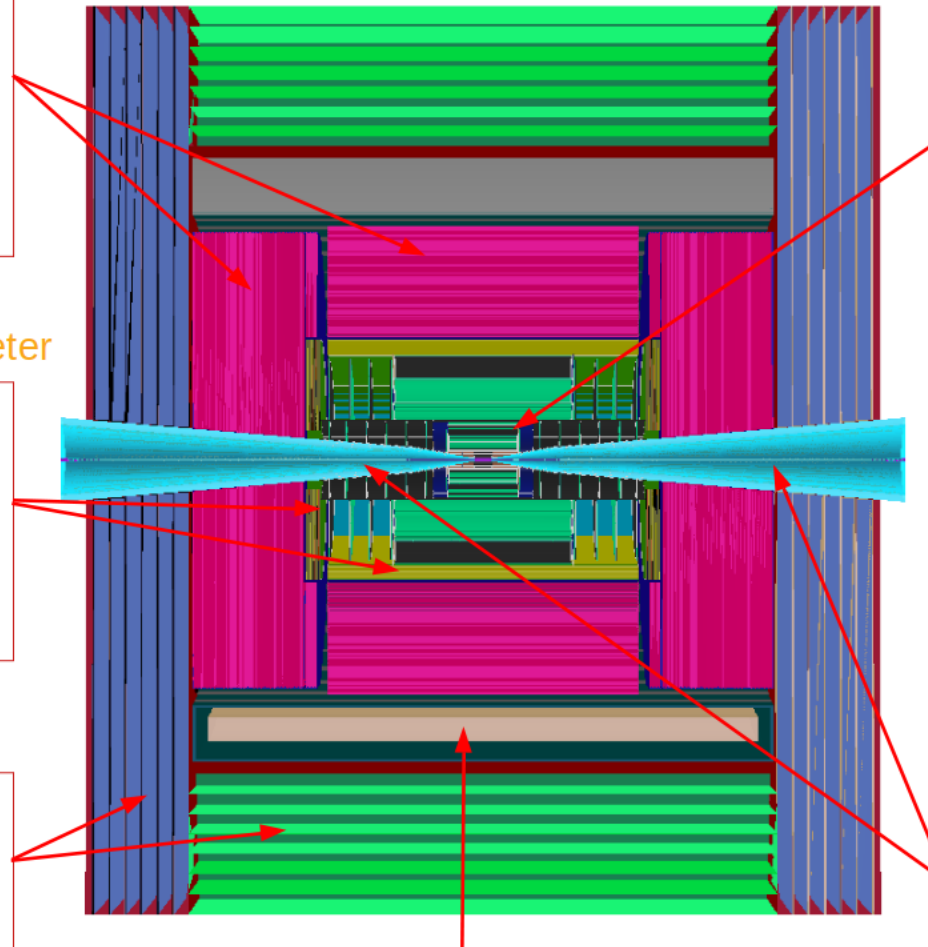
- ◆ 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- ◆ 30x30 mm² cell size.

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.

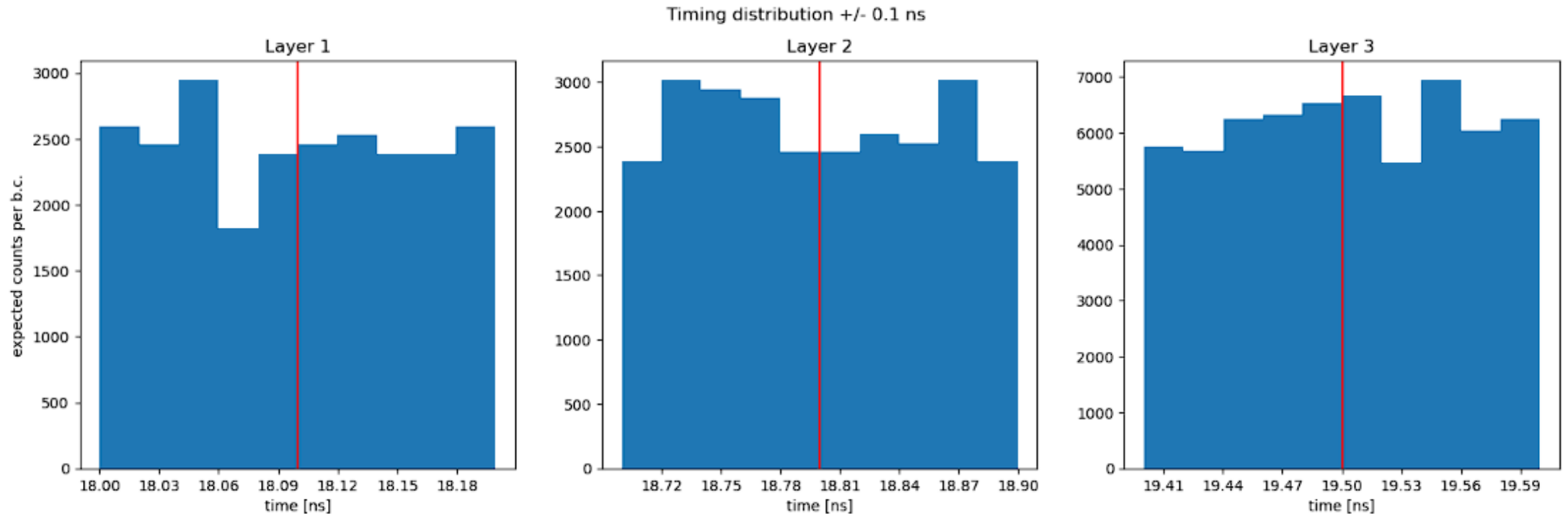


superconducting solenoid (3.57T)

BIB characteristics

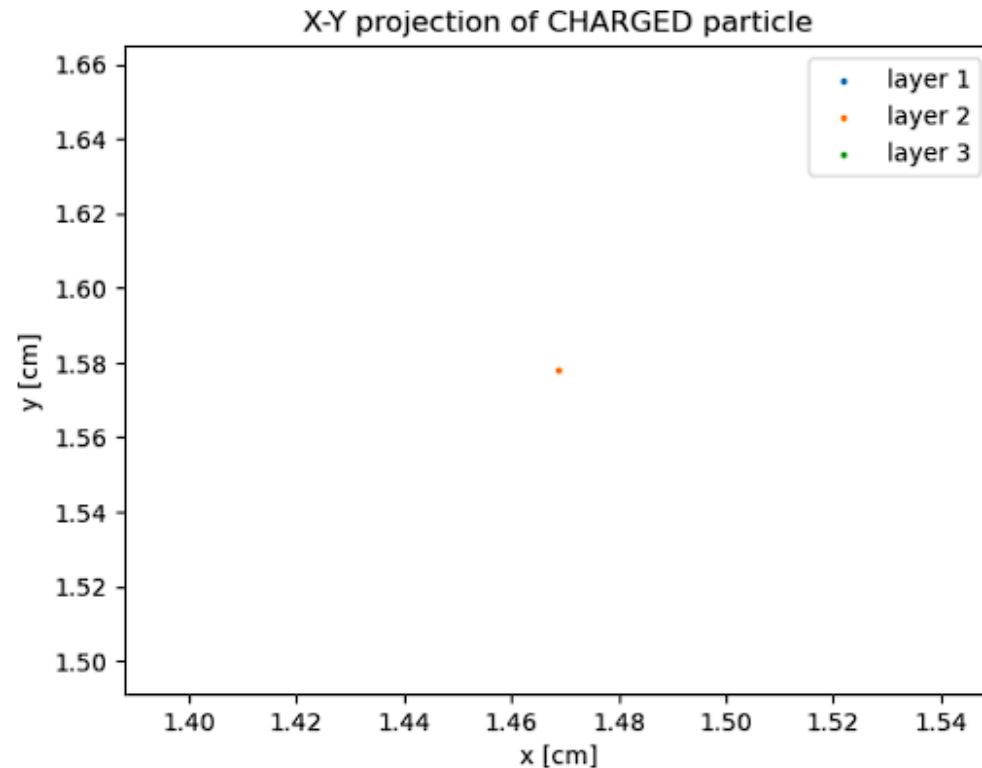
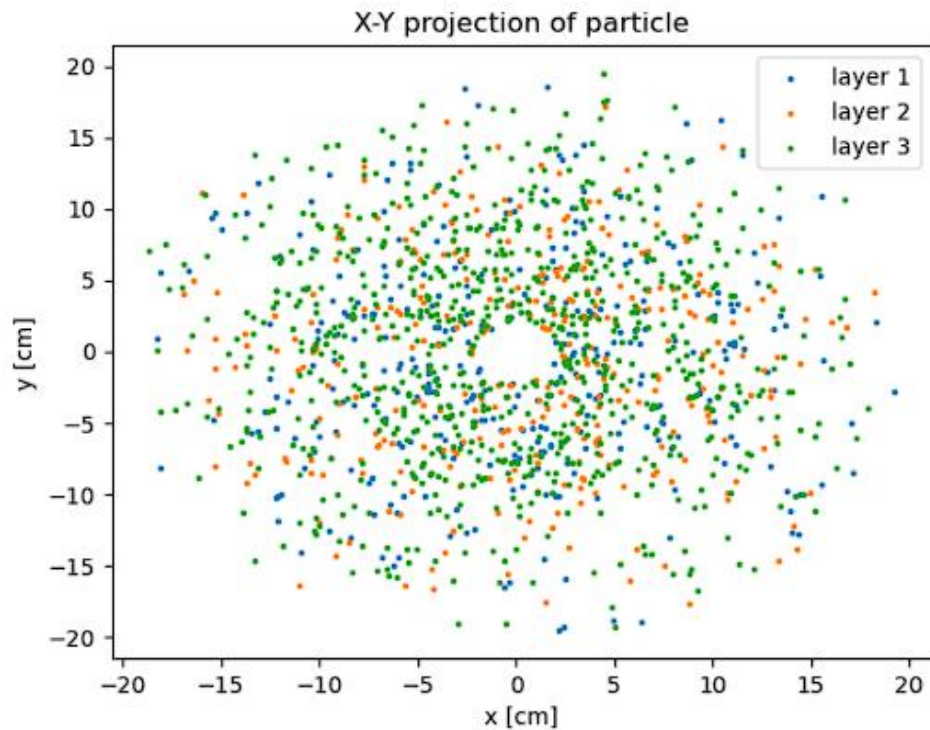
- By requiring a window of ± 100 ps with respect to the expected time of arrival in the layers

BIB reduced by 5 order of magnitudes



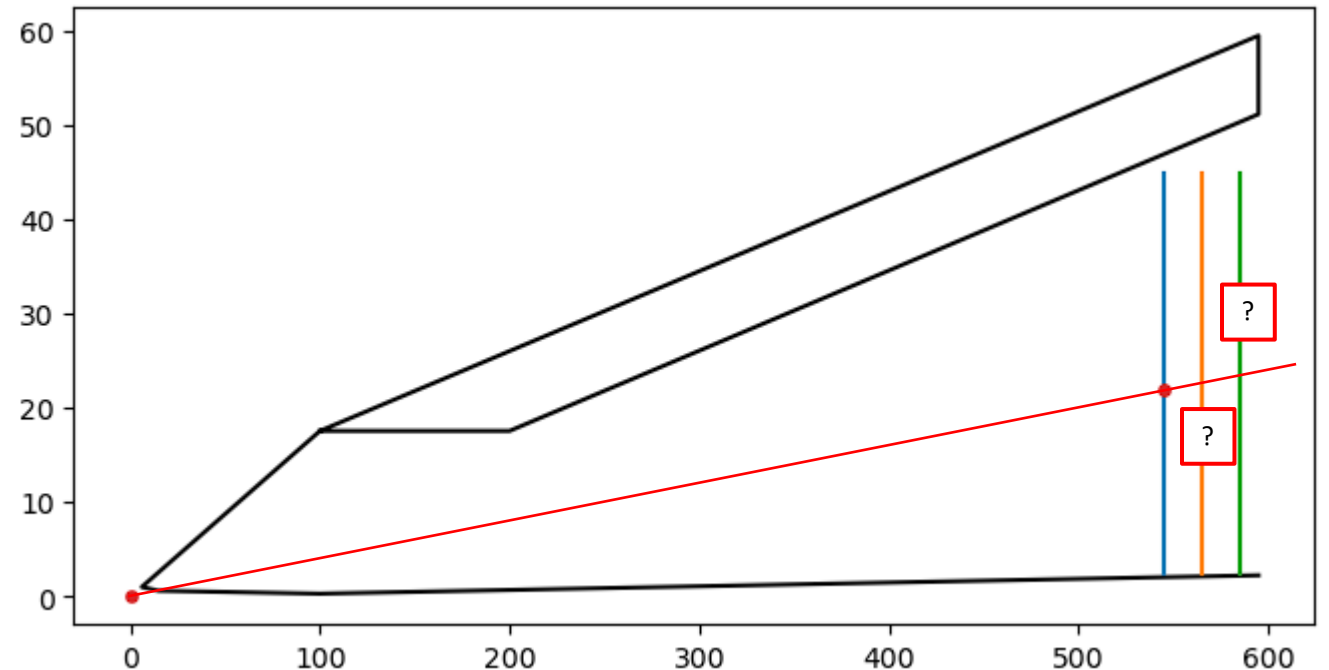
BIB characteristics

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



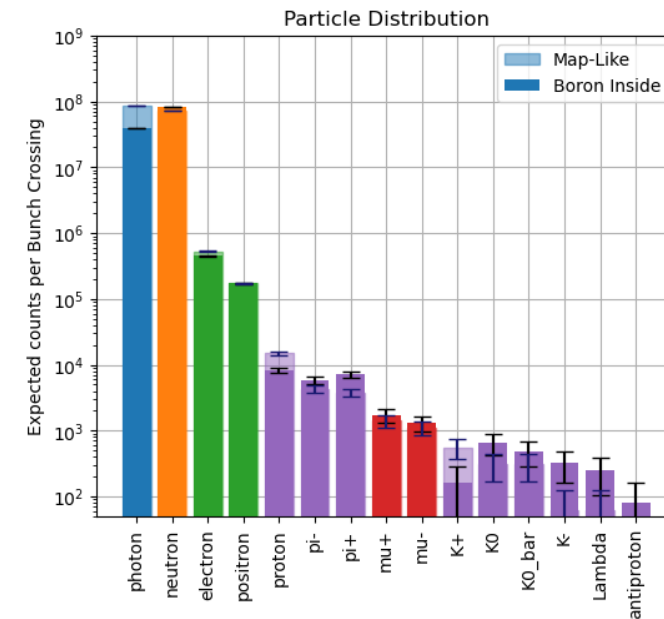
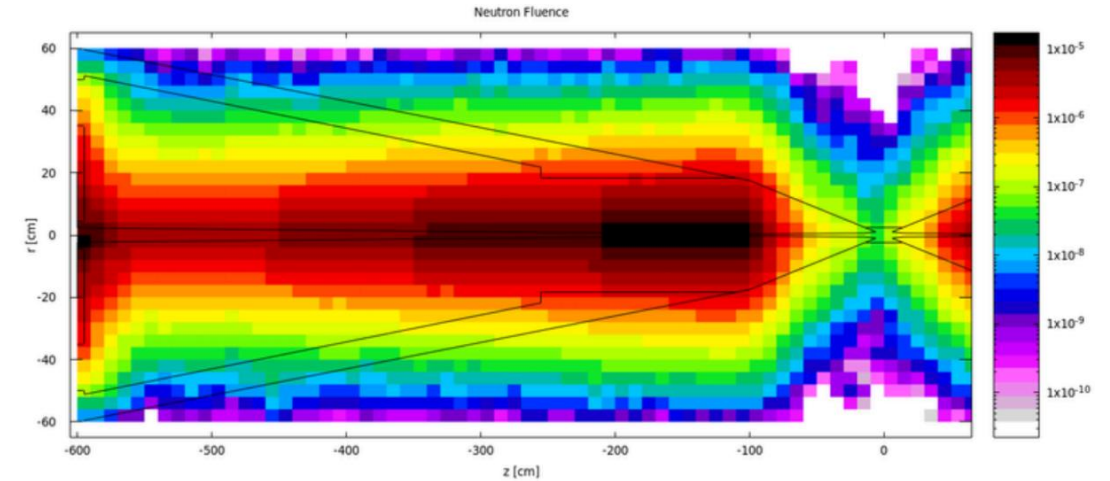
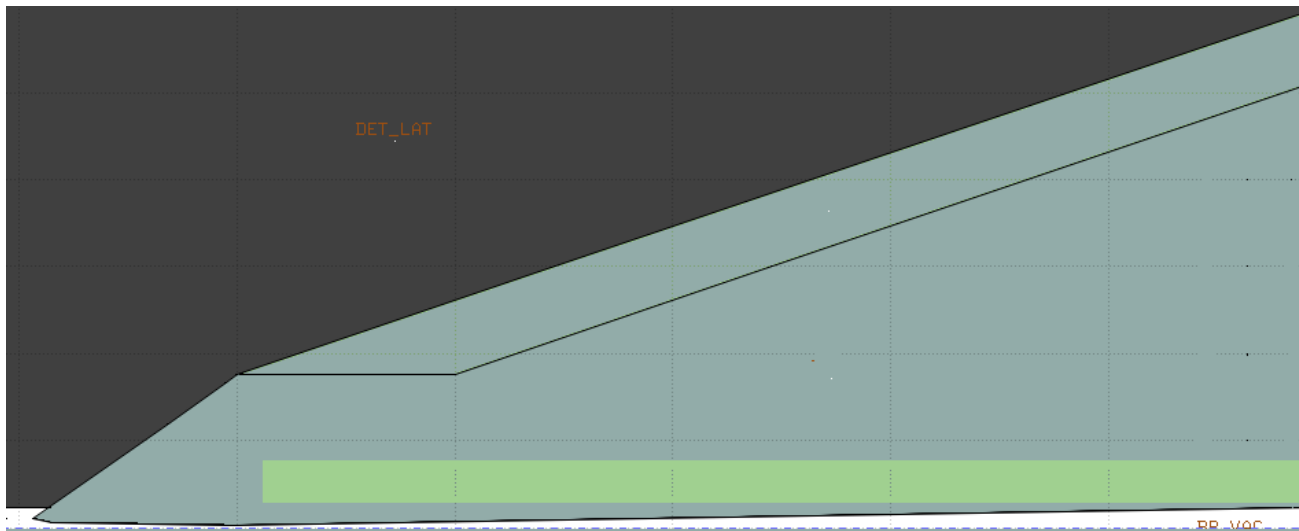
(a rough) Tracking

- Assuming that forward muons are produced at the IP, a straight line is 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 $\pm 1\text{ cm}$, the particle is tagged as a forward muon

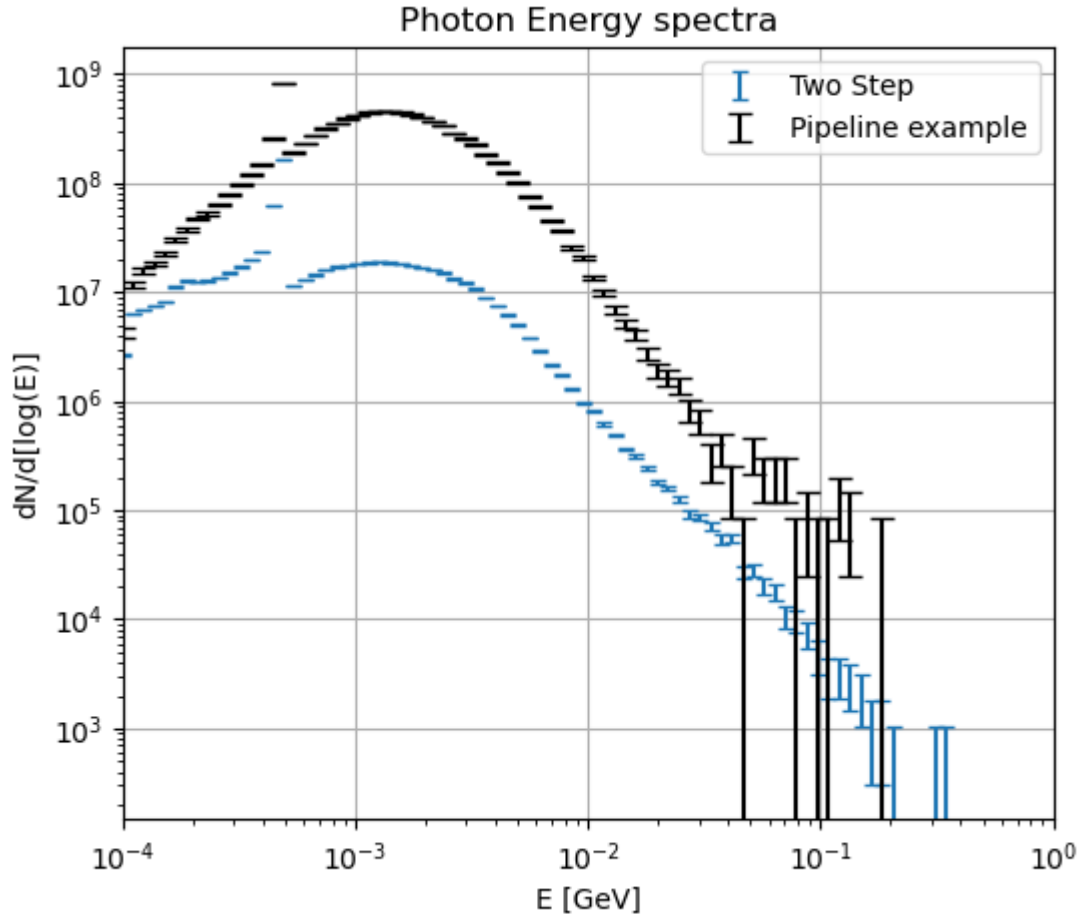


High Statistics Approach

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



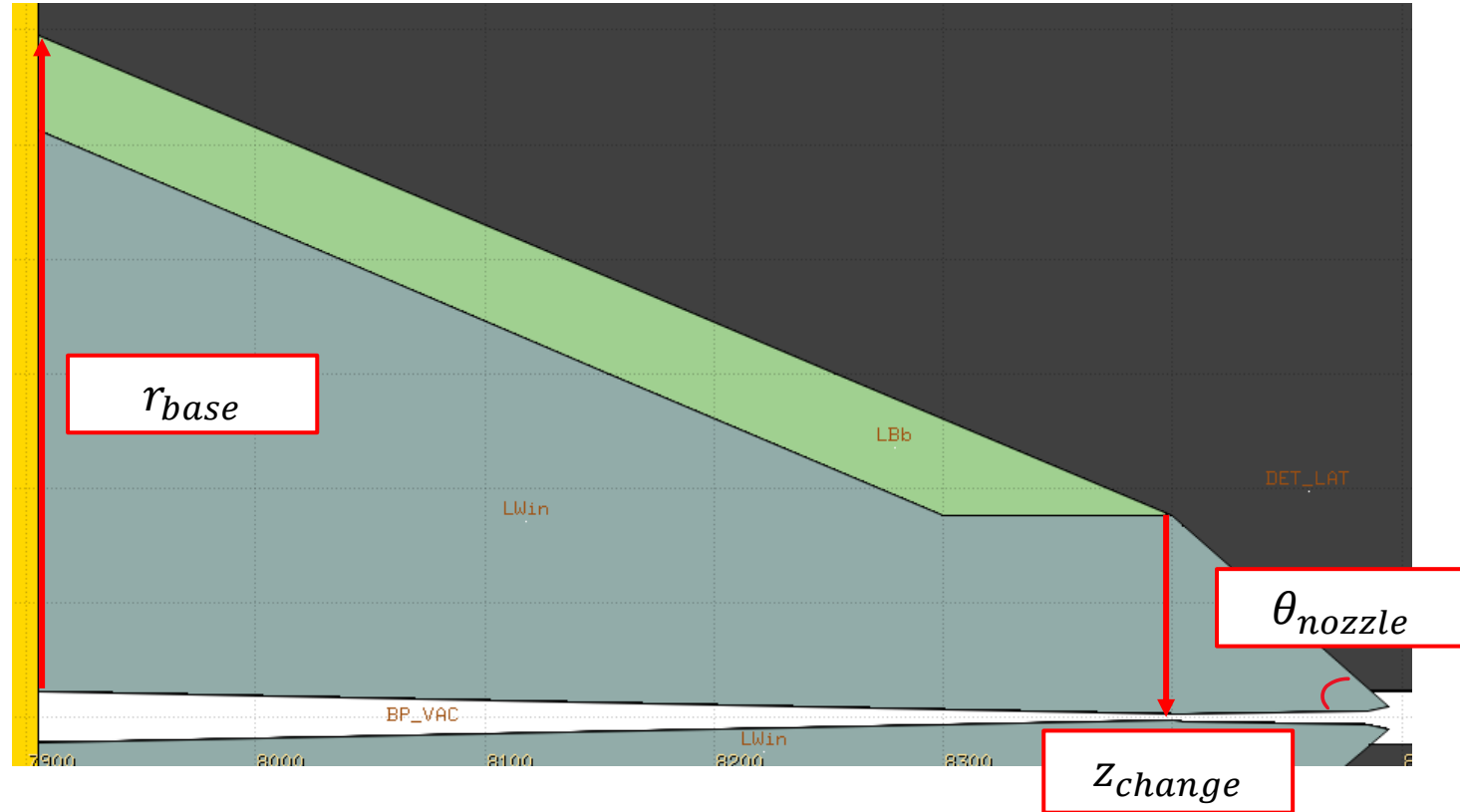
Low Statistic simulation



- 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:
 - $\theta_{tip} \in [3.8; 10]^\circ \rightarrow 10$ 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 $\rightarrow$

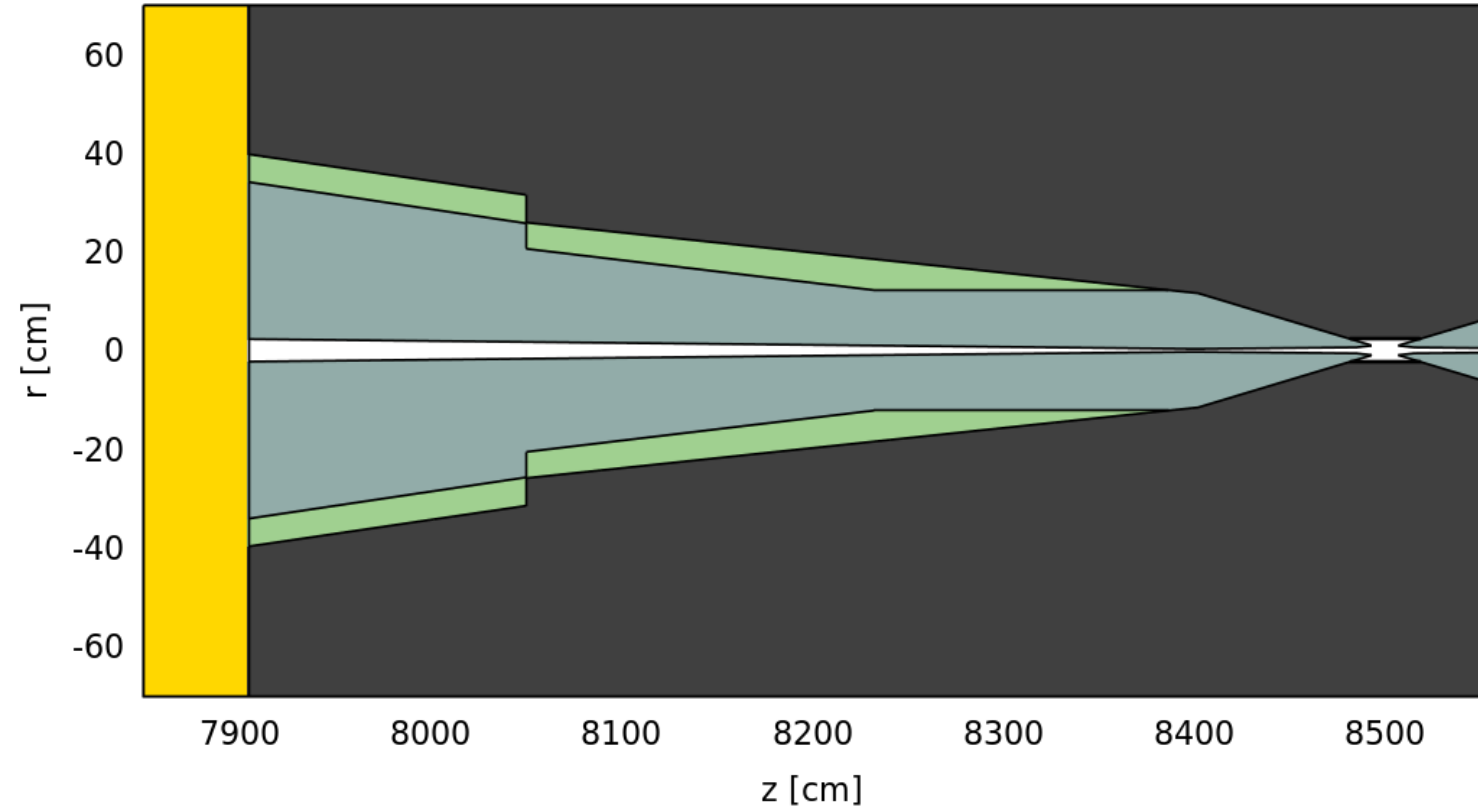


$$\theta_{nozzle} = \tan^{-1} \left[\frac{(94 \cdot \tan \theta_{tip}) \cdot r_{base} / 60}{|z_{change}| - 2} \right] \in [0.7; 18]^\circ$$

Improving the ML

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

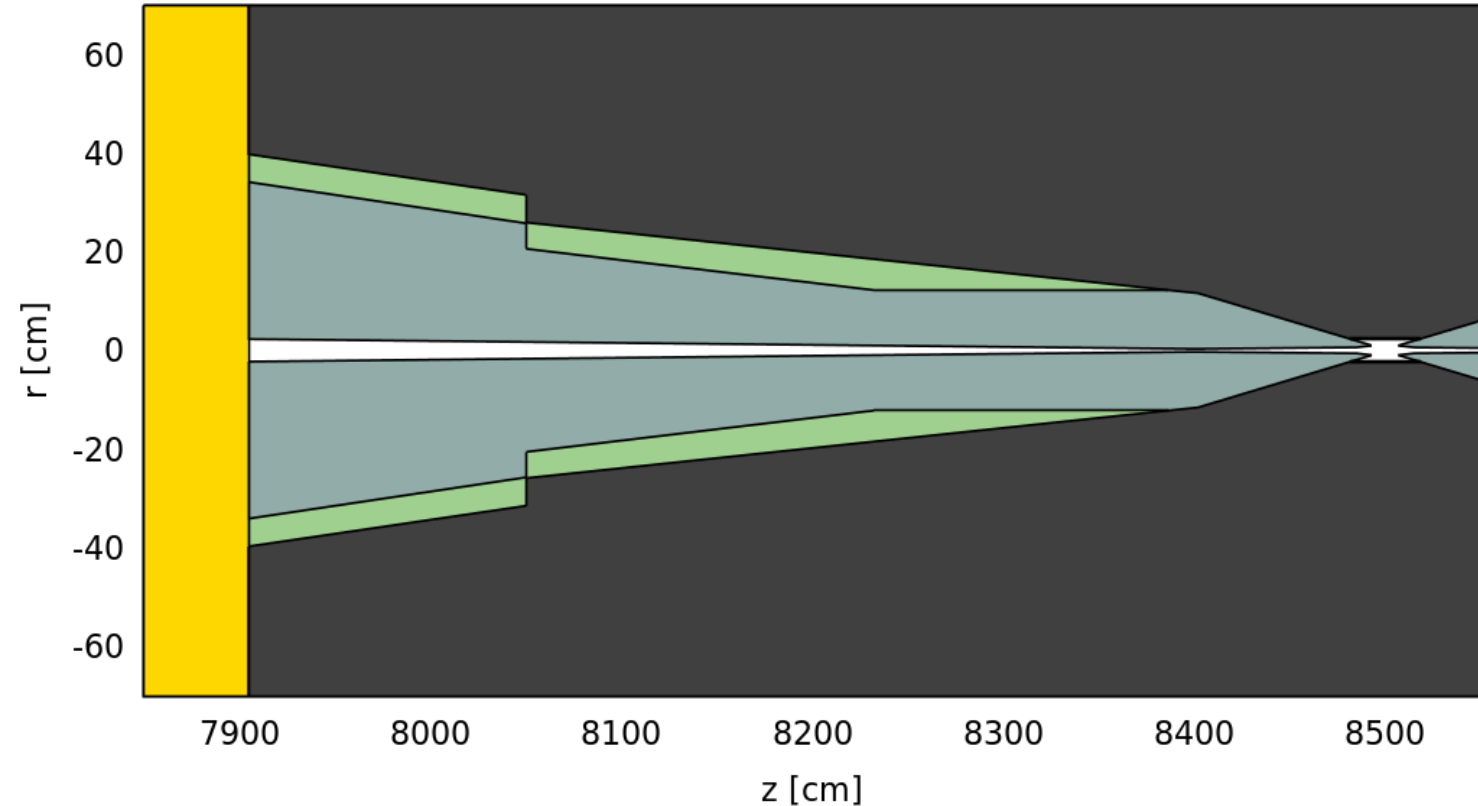
New Nozzle Prototype



Improving the ML - 2

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

New Nozzle Prototype



Nozzle Design XVI

