MDI Optimization for $\sqrt{s} = 3\ TeV$ Muon Collider

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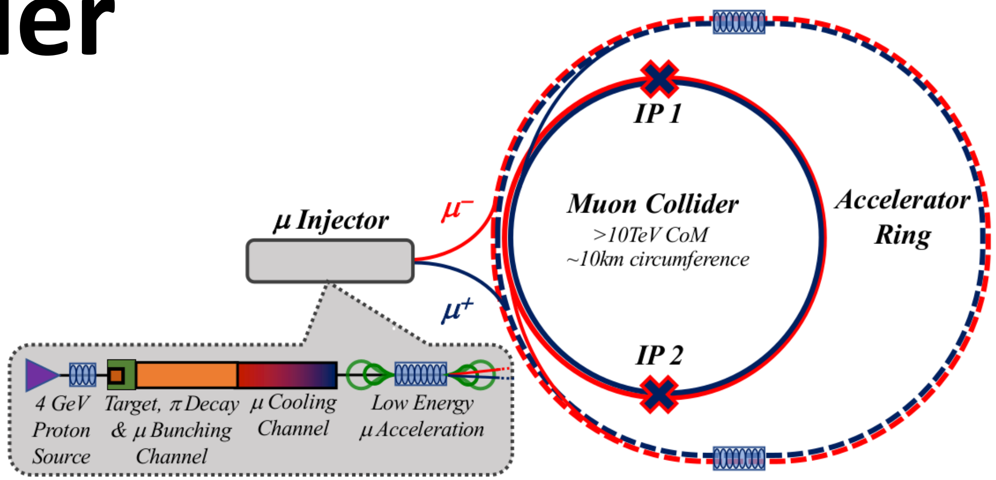
Outline

- **Introduction**
  - Muon Collider
  - Beam-Induced Background
  - Machine Detector Interface (MDI)
- **Forward Muon Detection**
  - Physics Case
  - Instrumenting the MDI
  - Simulation and performance
- **MDI Geometry Optimization**
  - Discussion of different approaches
    - By hand parameters tuning
    - Machine Learning studies
  - New geometry properties
  - New geometry effects on Beam-Induced Background

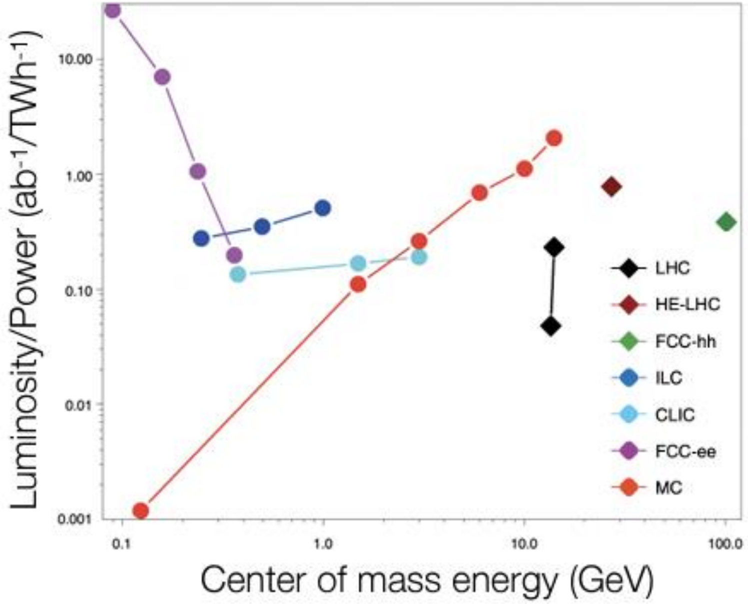
Muon Collider

- **Motivation**
  - Both a precision and high energy collider
  - Luminosity scales with energy
  - Cost effective and sustainable machine
- **Challenges**
  - Muon beam production, cooling and acceleration
  - **Beam Induced Background**
  - Neutrino flux

[3]



[1]

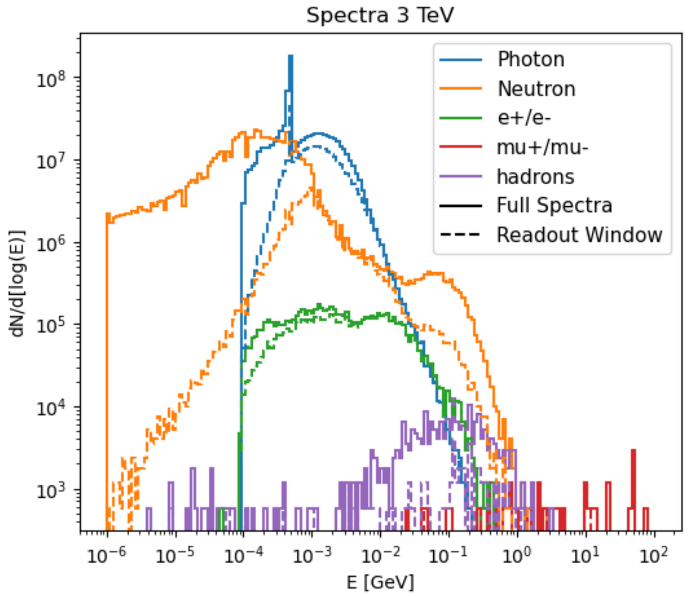


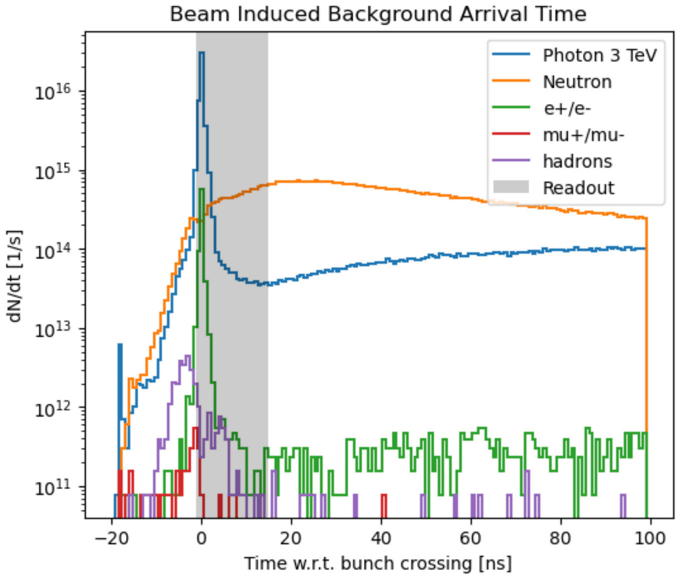
[2]

Beam Induced Background at $\sqrt{s} = 3\ TeV$

- $2.34 \cdot 10^5$ *expected decays/meter* each bunch crossing
- Decay products interact with the machine
- Intense flux of **low energy** particle reaches the detector
- Arrival Time distributed with respect to bunch crossing
- **Mitigation strategies**:
  - Shielding in the Machine Detector Interface
  - Readout window of $[-1, +15]\ ns$

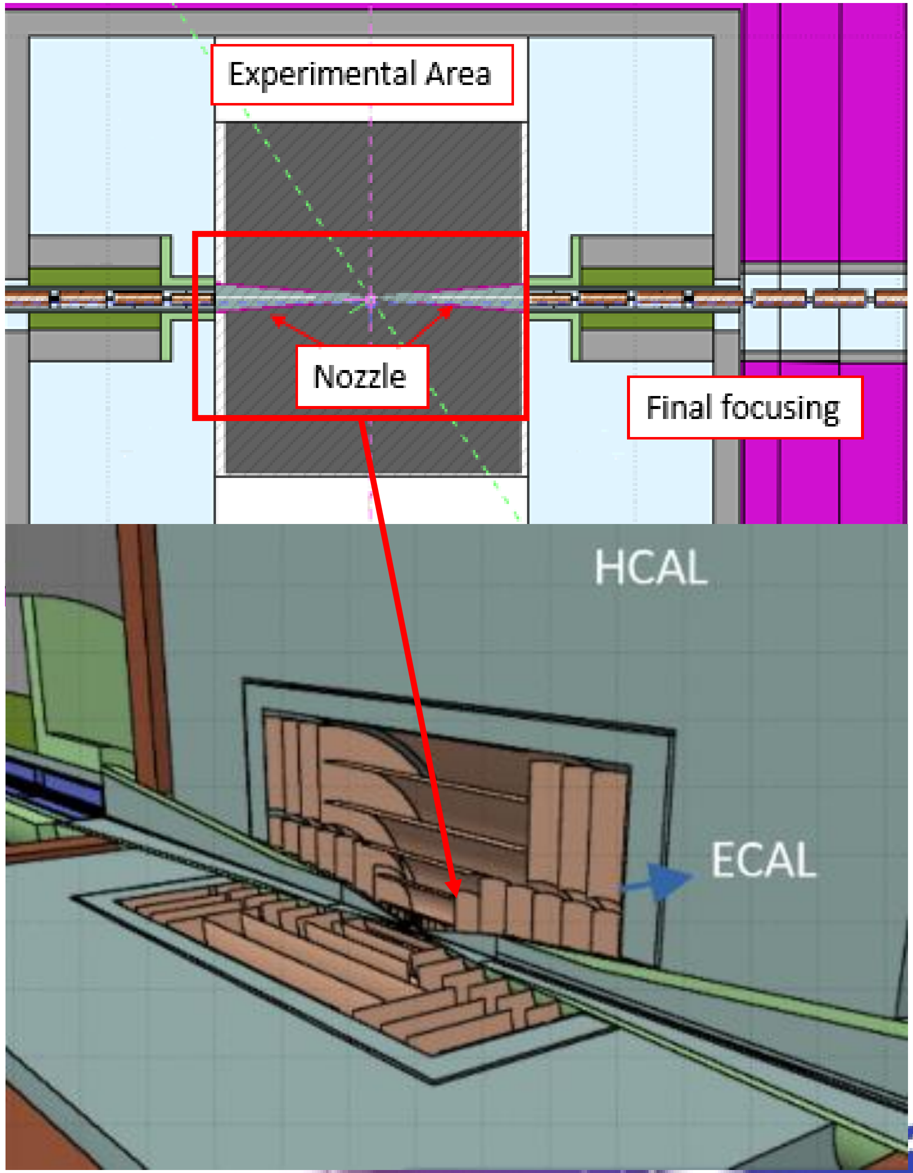
Particle	Expected Flux
$Photon$	$8.48 \cdot 10^7$
$Neutron$	$7.35 \cdot 10^7$
e^+/e^-	$7.00 \cdot 10^5$





Machine Detector Interface (MDI)

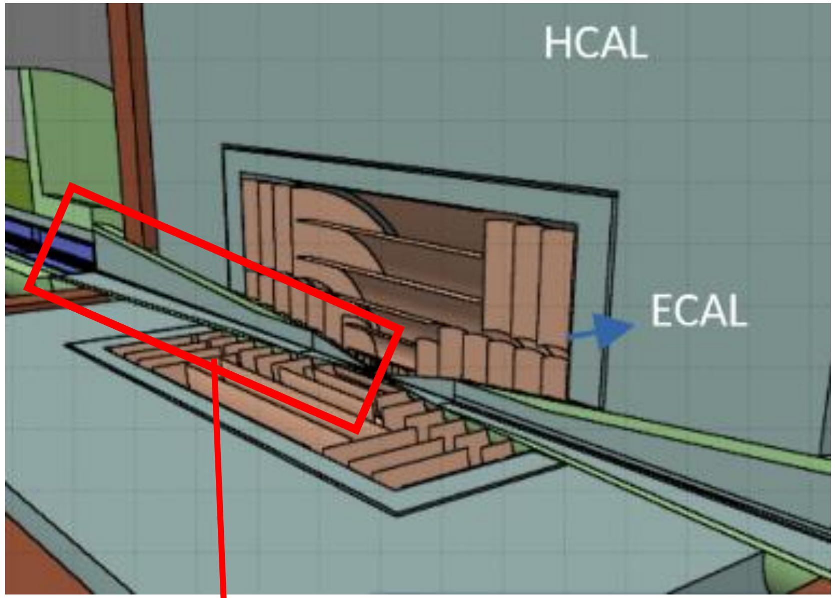
- MDI includes final focusing and Interaction Region
- Shielding nozzle are a unique feature of the Muon Collider*:*
  - Introduced to mitigate the BIB
  - They reduce the detector acceptance
- MDI implemented in FLUKA to simulate the BIB

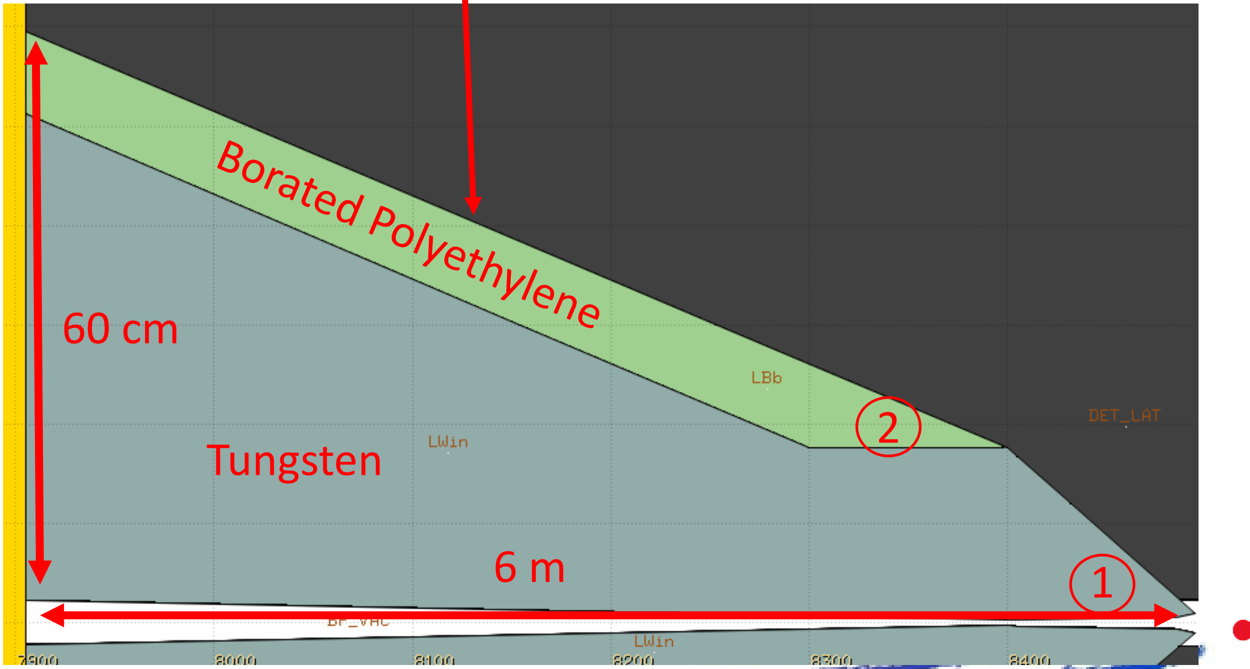


Courtesy of D. Calzolari

Shielding Nozzle

- Shielding nozzle designed by MAP collaboration for $\sqrt{s} = 1.5\ TeV$
- Nozzle material:
  - Tungsten core to absorb high energy incoming particle
  - Borated polyethylene coat for neutron absorption
- Nozzle geometry:
  1. $10°$ closest to the IP
  2. $5°$ starting from $z = 100\ cm$





Goal of the study

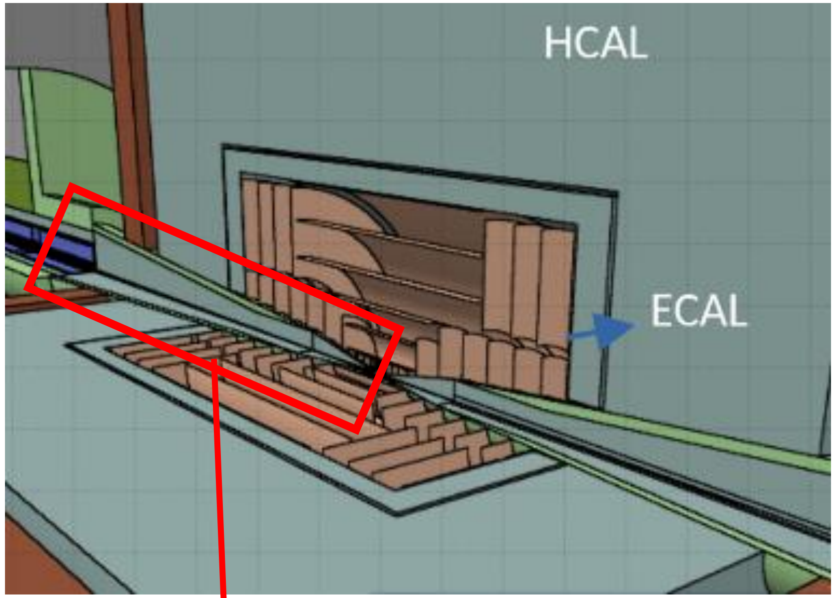
- **Optimize the geometry** for $\sqrt{s} = 3\ TeV$

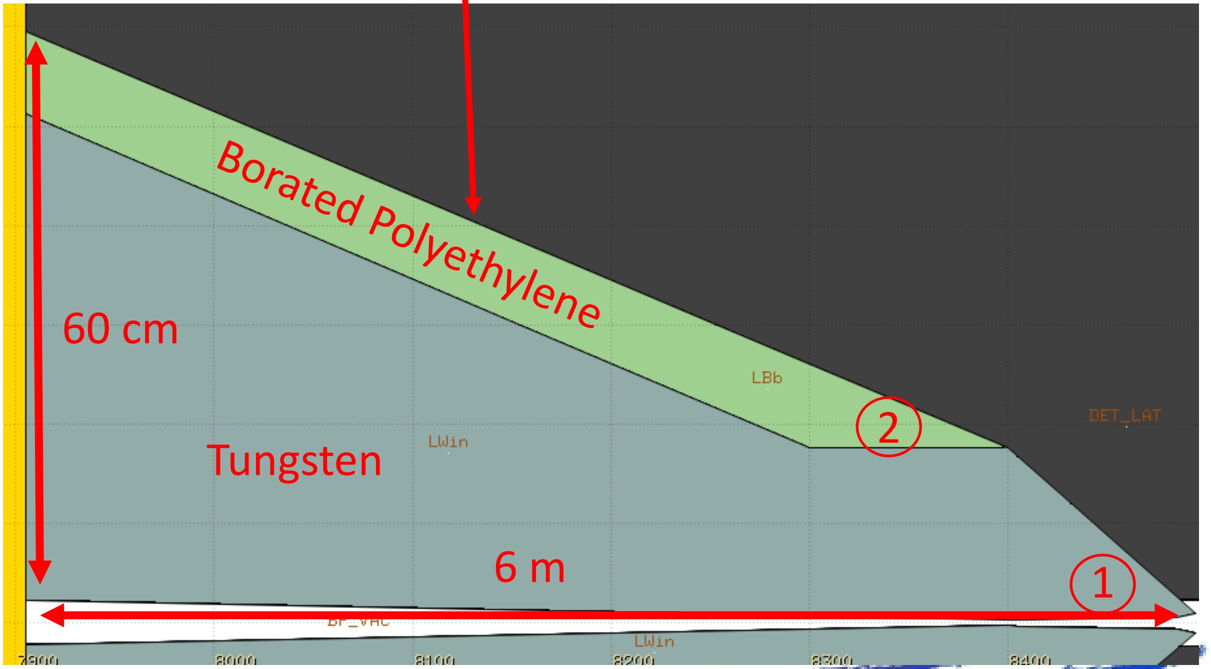
  Muon Collider:

  - Reduced the BIB flux entering the detector area
  - Maximizing the detector acceptance

- **Instrumenting the nozzle**:

  - Feasibility study for detectors in the nozzle to detect forward muons

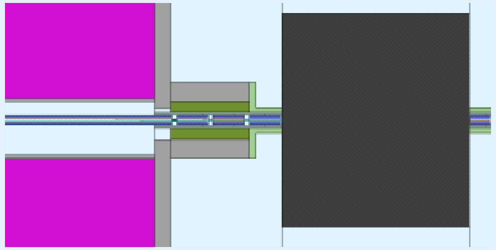




BIB simulation with FLUKA

1. From muon decay to nozzle area

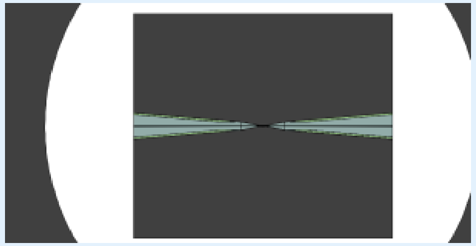
Machine dependent



- 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

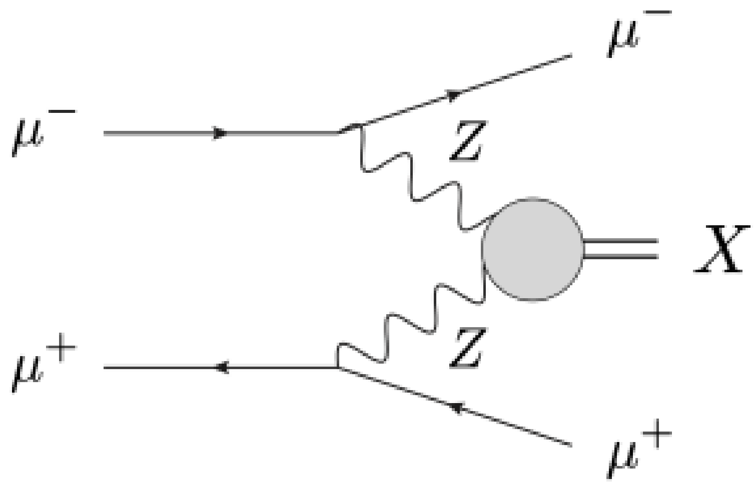


- Propagation through the Nozzles
- Particles who exit the nozzle and enters the detector area are scored
- $\sim$1.6% of one BIB event (i.e. bunch crossing) considering only 1 beam $\rightarrow$ $\mathbf{4\ days}$ **per simulation**

Pictures from D. Calzolari

Forward Muons

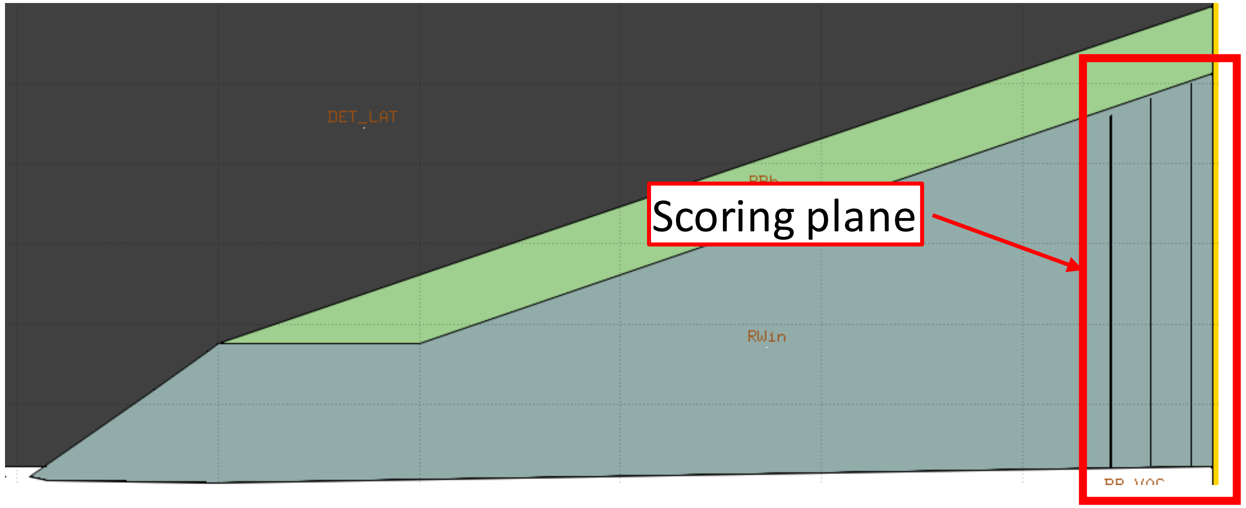
- **Physics Case**
  - Allows to distinguish process from Z/W boson fusion
  - Allows precise measure of Higgs boson Width [4]
  - New physics might have forward muons in the final state [5]



Z Boson fusion with forward muon production[3]

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

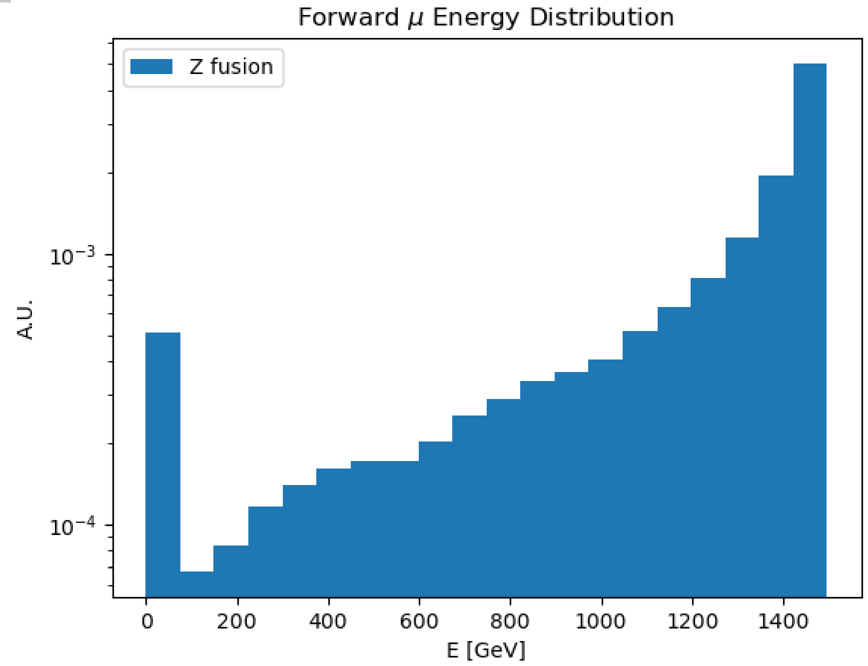
Simulated samples

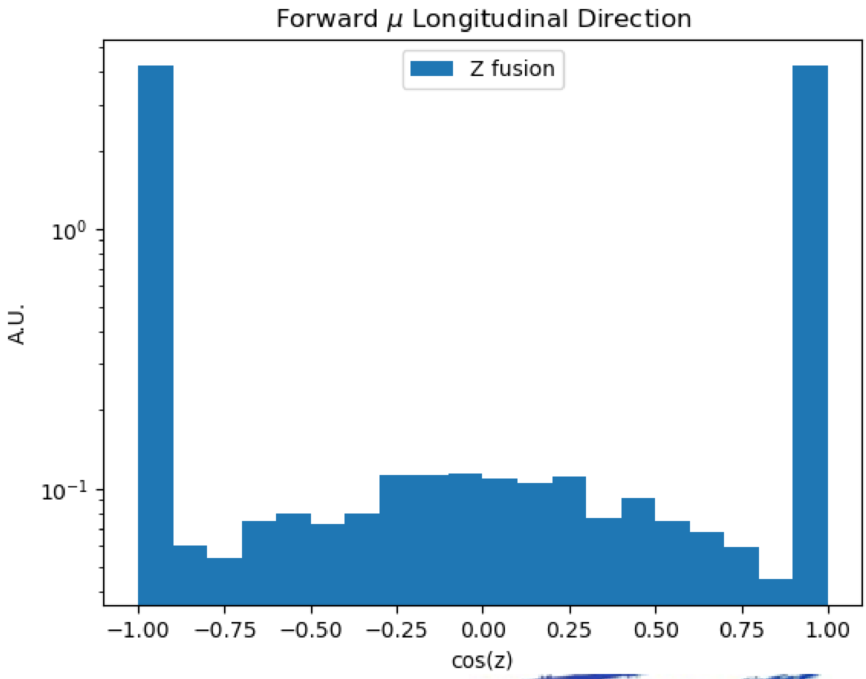
- **Forward muons from:**

$$\mu^+\mu^- \to ZZ + \boldsymbol{\mu^+\mu^-} \to \mathrm{H} + \boldsymbol{\mu^+\mu^-} \to W^+W^- + \boldsymbol{\mu^+\mu^-}$$

  - $6.15 \cdot 10^3$ Montecarlo events simulated with WHIZARD
  - 1 forward muon per event simulated with FLUKA

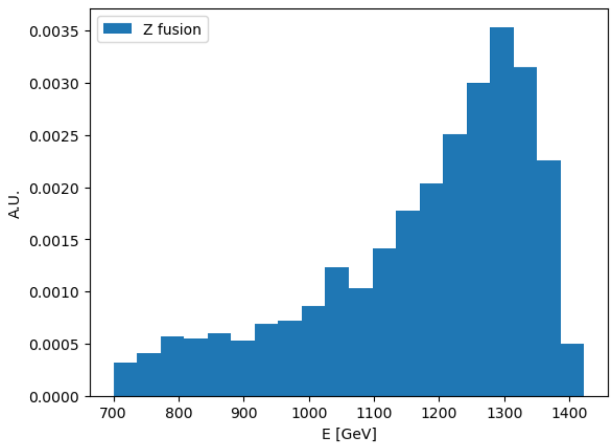
- **Beam Induced Background:**
  - 1.4 % of bunch crossing simulated
  - Particles crossing the silicon layers are scored
  - Silicon layers do not reproduce a detector behavior

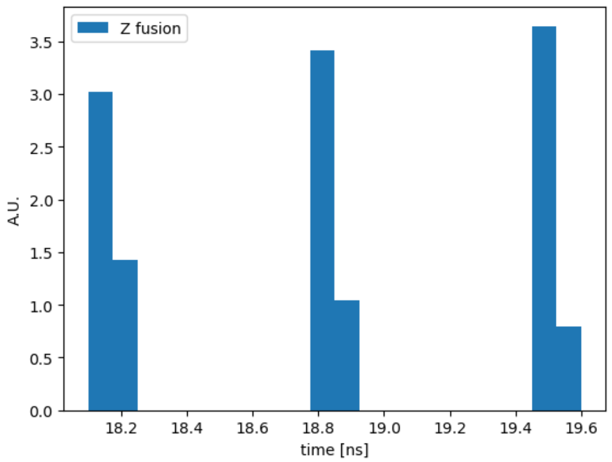


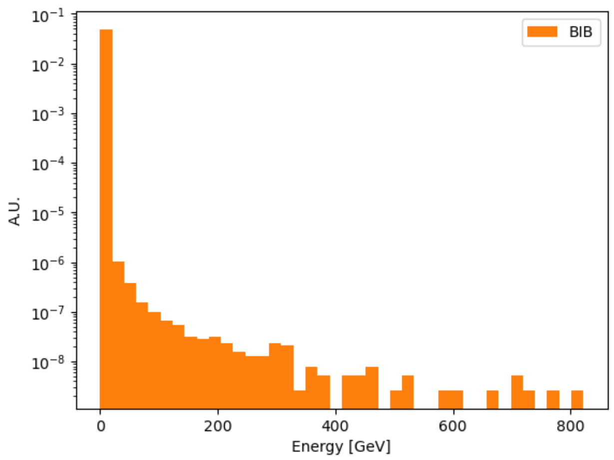


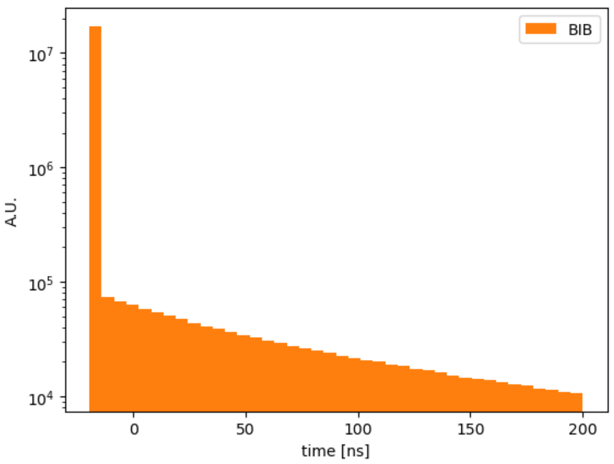
Simulation Outputs

- **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:

- **Forward Muons:**
  - 53% enters the nozzles
  - 99% of forward muons in the nozzles correctly tracked

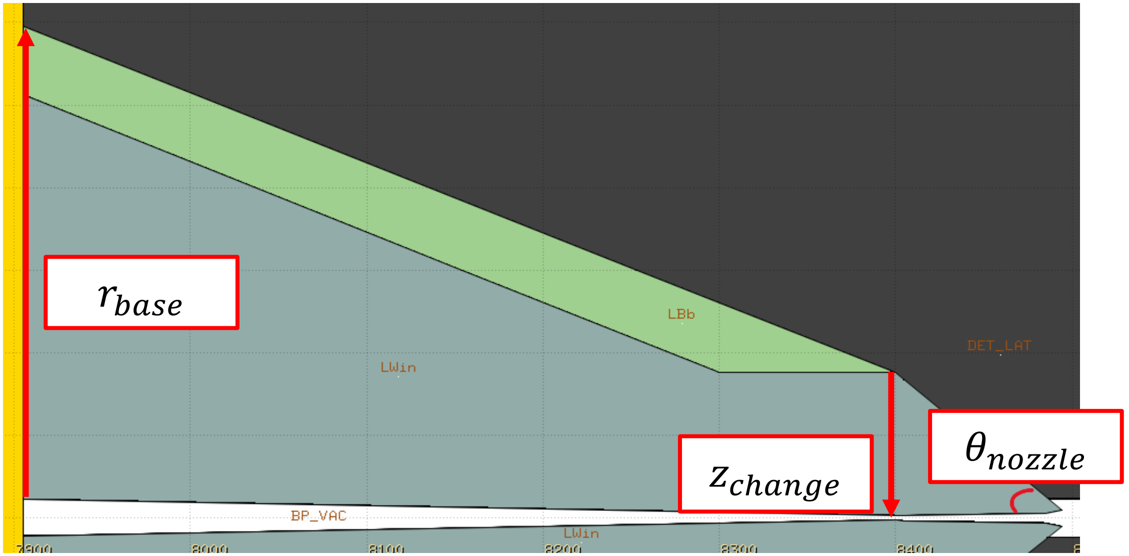
52.5% Overall tagging efficiency

- **BIB:**
  - 0 fake forward muon tagged

*Normalized to the bunch crossing
** 6150 events simulated

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

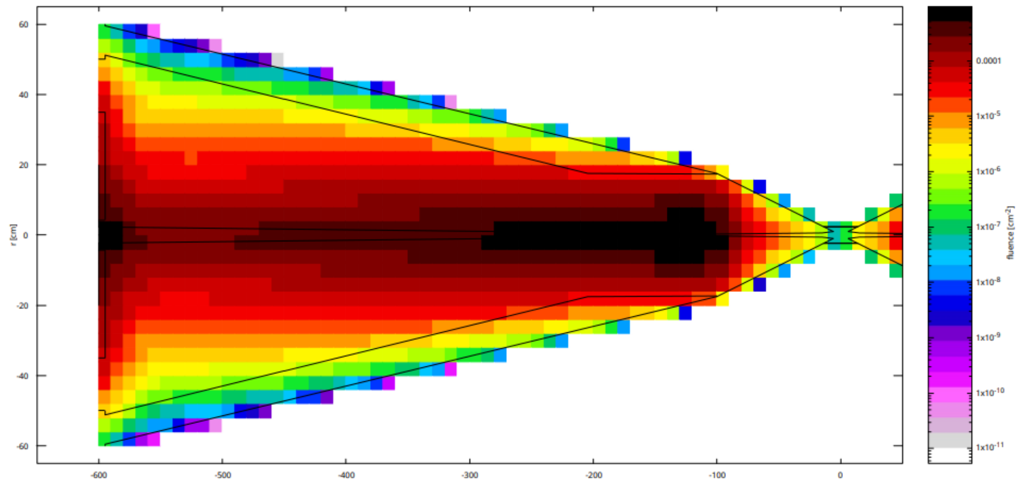


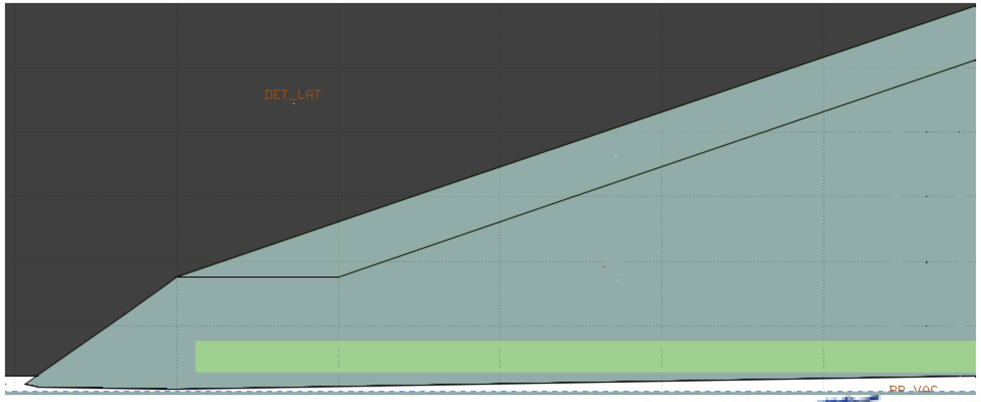
- **Figures of merit:**
  - Occupancy on the tracking system
  - Integrated flux of particles entering the Detector area

Manual Tuning Results

- **Method:**
  - 1.6% of 1 bunch crossing BIB simulated with FLUKA
  - Event reconstruction in the Tracking System to evaluate occupancy
  - Several configuration tested starting from MAP designed
  - Investigated the effectiveness of borated polyethylene coat on nozzle surface
- **Results:**
  - $O(1\ cm)$ modification of the nozzle **tip strongly impact the BIB**
  - Further from the Interaction Point, the amount of tungsten can be reduced
  - A **layer of tungsten outside the coat** further reduces photon and e^+/e^- flux in the detector

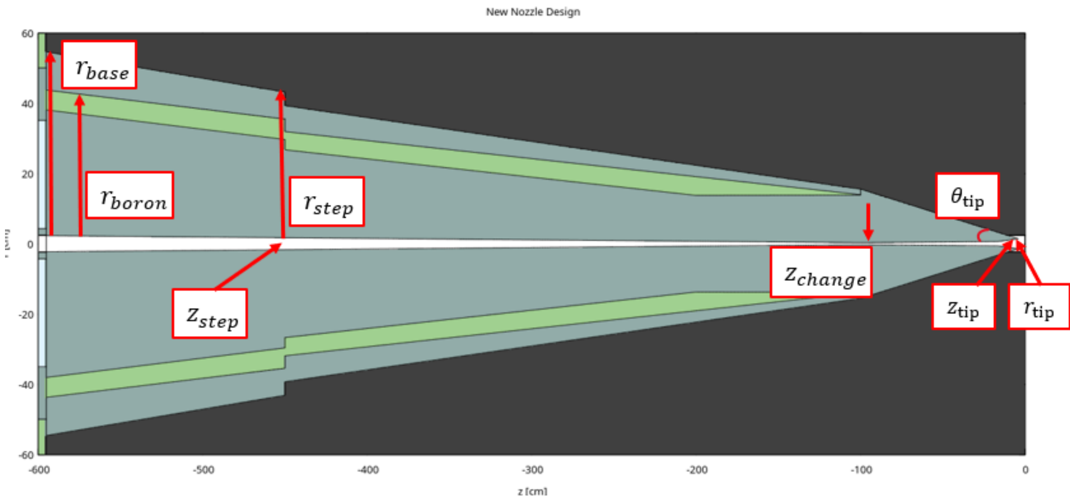
Neutron Fluence

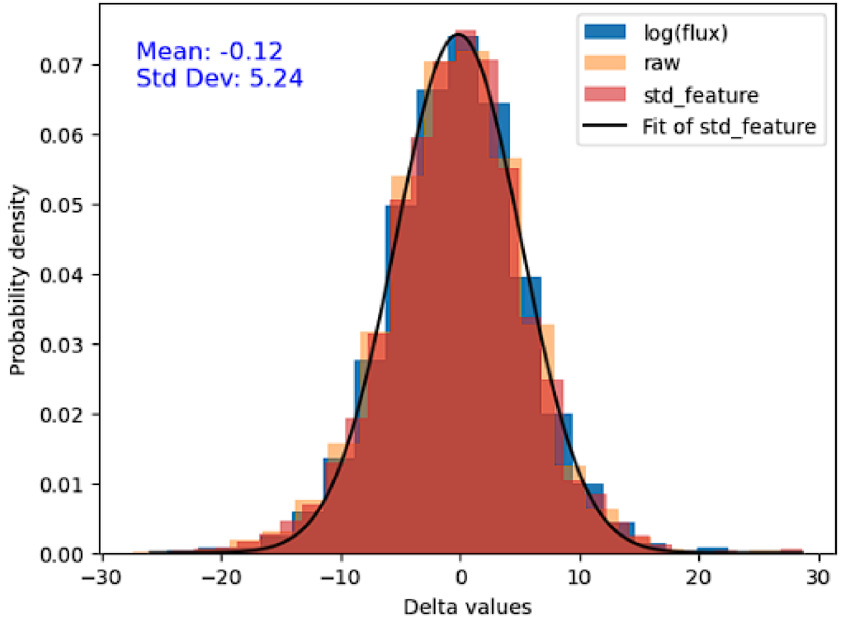




Machine Learning results

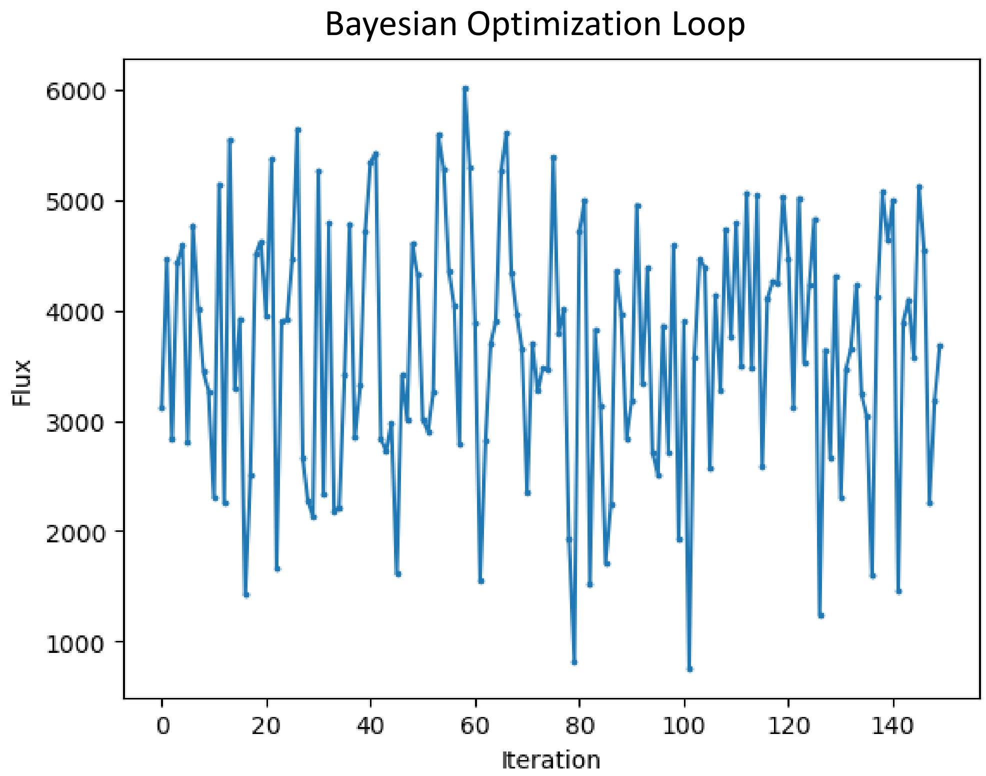
- **Method:**
  - Nozzle geometry described by 8 parameters
  - $\sim$13000 FLUKA simulation performed considering 0.02% of a bunch crossing varying the parameters
  - Several ML model trained and data transformation techniques applied
  - Models evaluated according to $\Delta[\%] = \frac{Flux_{true} - Flux_{predicted}}{Flux_{true}} * 100$
- **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: $\overline{\Delta} = -0.12\%, \sigma = 5.24\%$





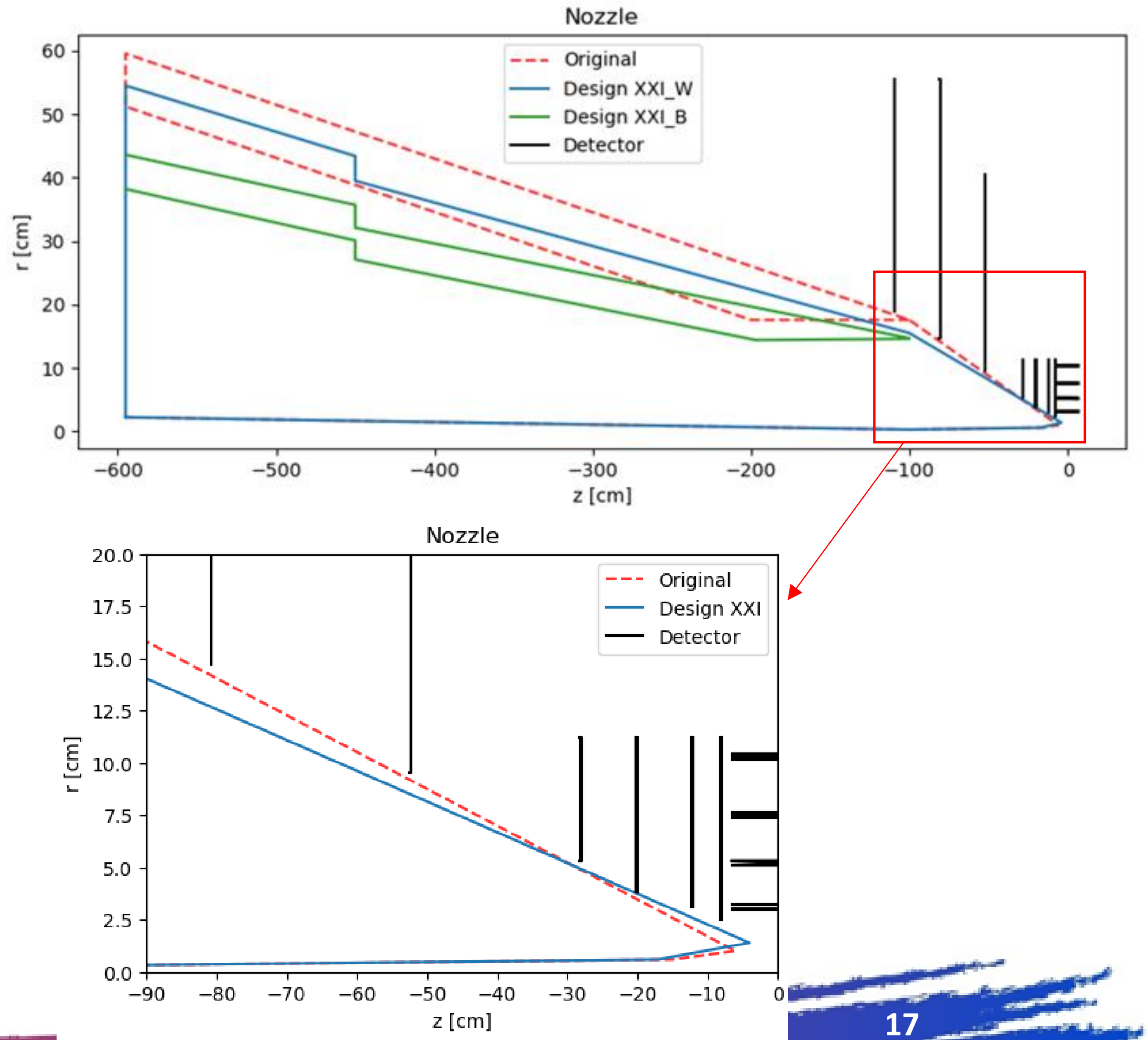
Bayesian Optimization Results

- **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



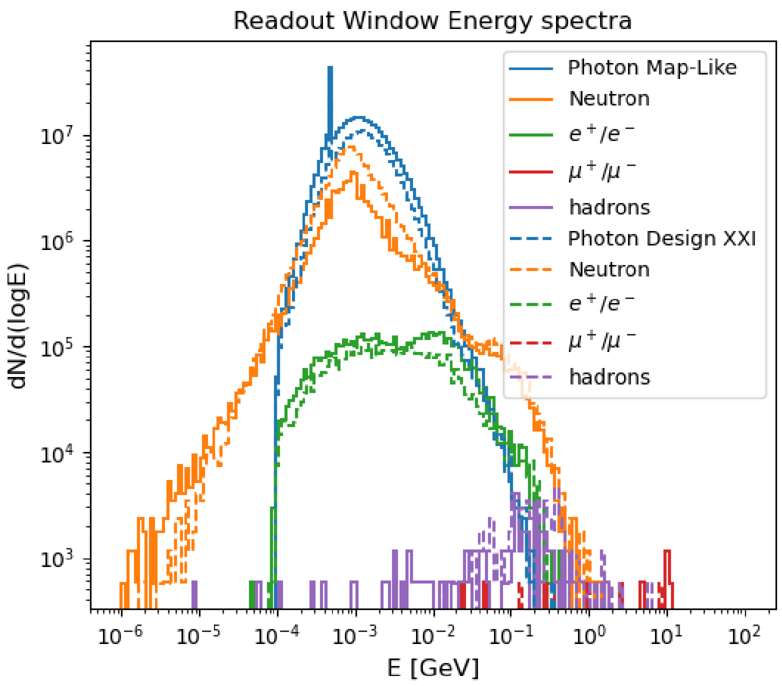
Optimized Geometry

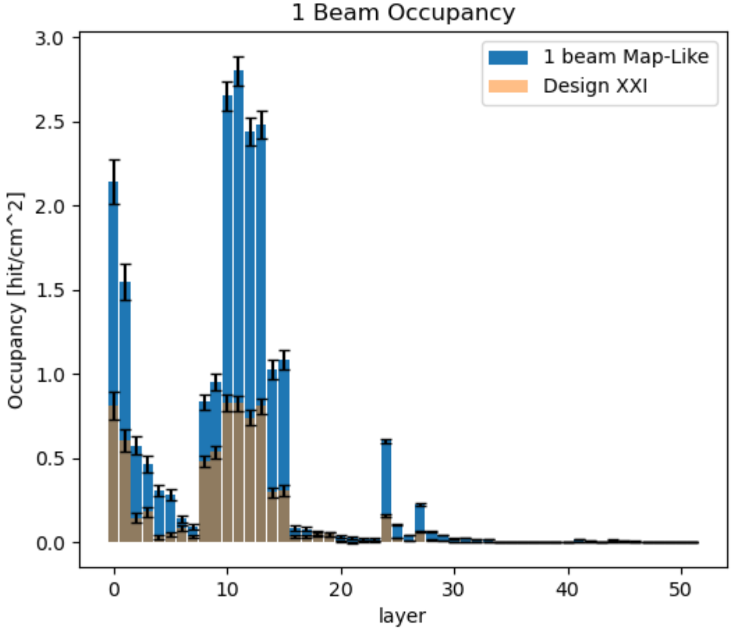
- Considering both Manual Tuning and Machine Learning studies a new design has been achieved
- **Main features:**
  - Base radius reduced
  - Nozzle body further reduced starting at 450 cm from the IP
  - Borated polyethylene coat moved under a layer of tungsten
  - Tip moved few millimeters further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



Optimized Geometry

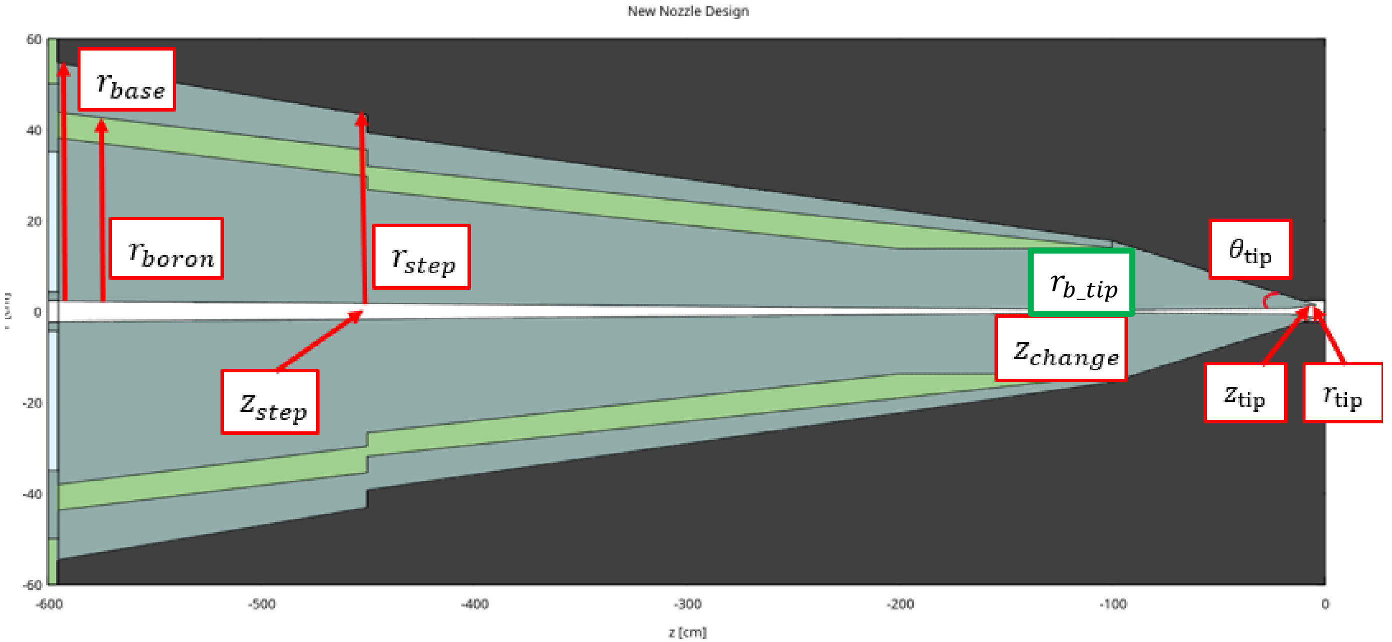
- **Beam-Induced Background:**
  - Reduced photon and e^+/e^- flux
  - Reduced occupancy in the tracking system
  - Increased neutron flux
- **Overall consideration:**
  - Easier to sustain
  - Less material needed
  - Increased detector acceptance
  - BIB impact on tracking system and ECAL reduced
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





Next Steps

- Full BIB reconstruction in the Detector
- A 9th parameters will be considered
- Increasing statistics for Bayesian optimization loop
- Commercially available tungsten alloy to be studied
- Definition of a complex **figure of merit**



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

Thank you for your attention

Reference

- [1] C. Accettura et al., Towards a Muon Collider, arxiv.org
- [2] K. Long, D. Lucchesi, M. Palmer, N. Pastrone, D. Schulte, V. Shiltsev, Muon Colliders: Opening New Horizons for Particle Physics, arxiv.org
- [3] C. Accettura et al., Interim report for the International Muon Collider Collaboration, arxiv.org
- [4] P. Li, Z. Liu, K. Lyu, HIGGS WIDTH AND COUPLINGS AT HIGH ENERGY MUON COLLIDERS WITH FORWARD MUON DETECTION, arxiv.org
- [5] M. Ruhdorfer, E. Salvioni, A. Wulzer, INVISIBLE HIGGS FROM FORWARD MUONS AT A MUON COLLIDER, arxiv.org
- [6] Y. Alexahin, E. Gianfelice-Wendt and V. Kapin, MUON COLLIDER LATTICE CONCEPTS, Iopscience.iop.org

Backup

Muon Collider Parameters

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

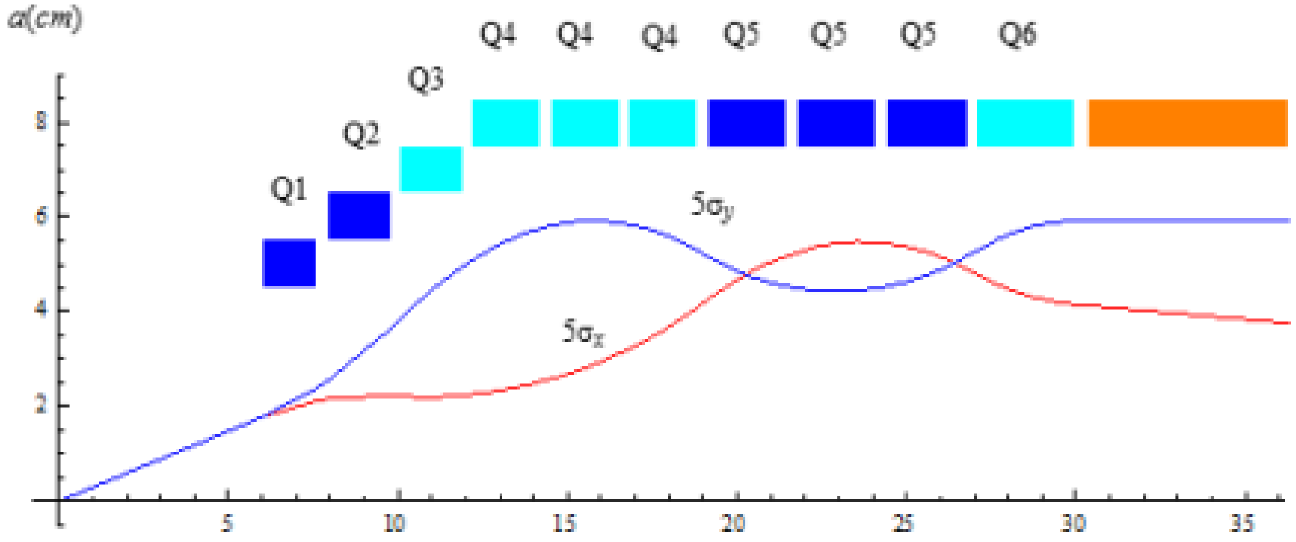
Note: currently focus on 10 TeV, also explore 3 TeV

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

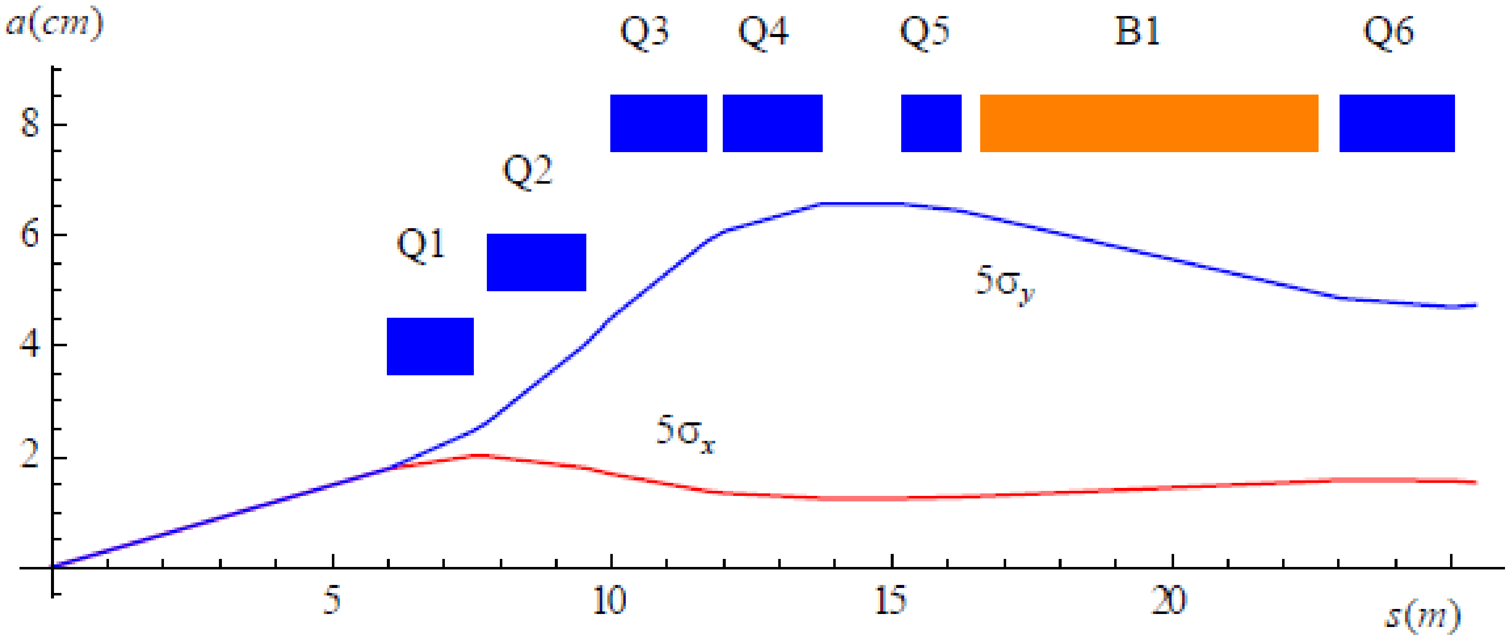
Parameter	Unit	3 TeV	10 TeV	14 TeV	CLIC at 3 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40	2 (6)
N	10^{12}	2.2	1.8	1.8	
f_r	Hz	5	5	5	
P_{beam}	MW	5.3	14.4	20	28
C	km	4.5	10	14	
<B>	T	7	10.5	10.5	
ε_L	MeV m	7.5	7.5	7.5	
σ_E / E	%	0.1	0.1	0.1	
σ_z	mm	5	1.5	1.07	
β	mm	5	1.5	1.07	
ε	µm	25	25	25	
$\sigma_{x,y}$	µm	3.0	0.9	0.63	

3 TeV Design

- Final Focusing MAP design[6] with mixed function quadrupoles (Cyan)

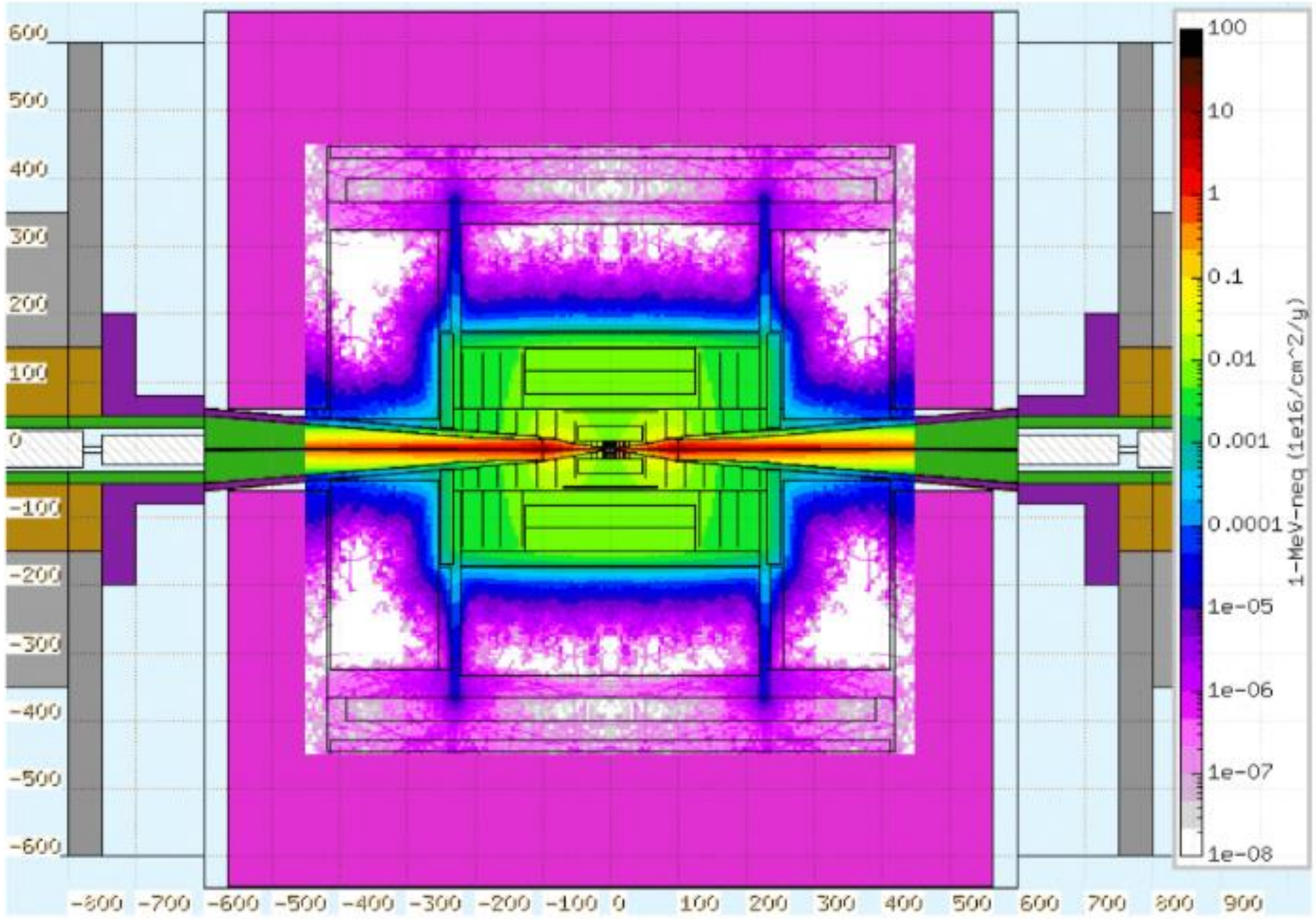


$\sqrt{s} = 1.5\,TeV$ Design



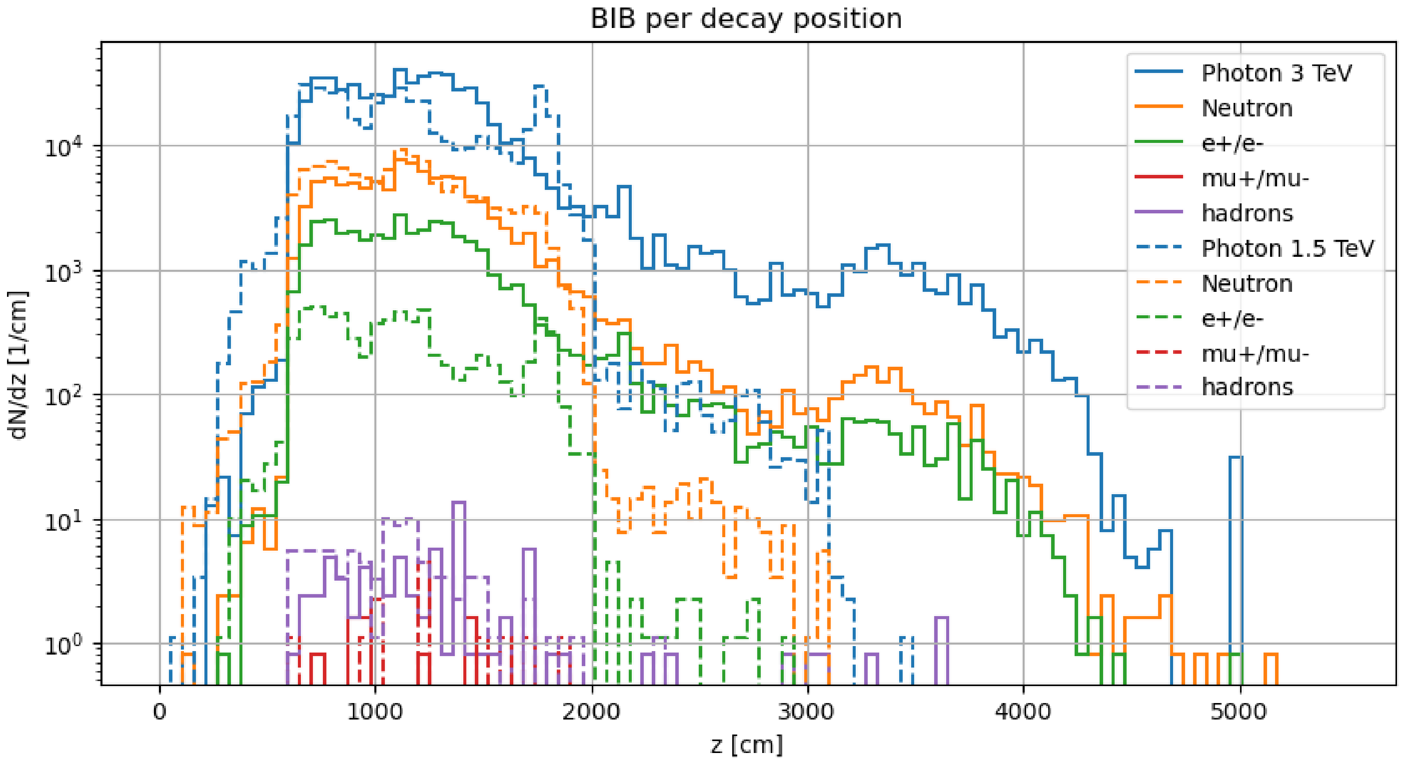
Dose

- Considering 200 operational days/year, 1-MeV-neq fluence is expected to be:
  - $\sim 10^{14-15}\ cm^{-2}y^{-1}$ in the tracker
  - $\sim 10^{14}\ cm^{-2}y^{-1}$ in the electromagnetic calorimeter

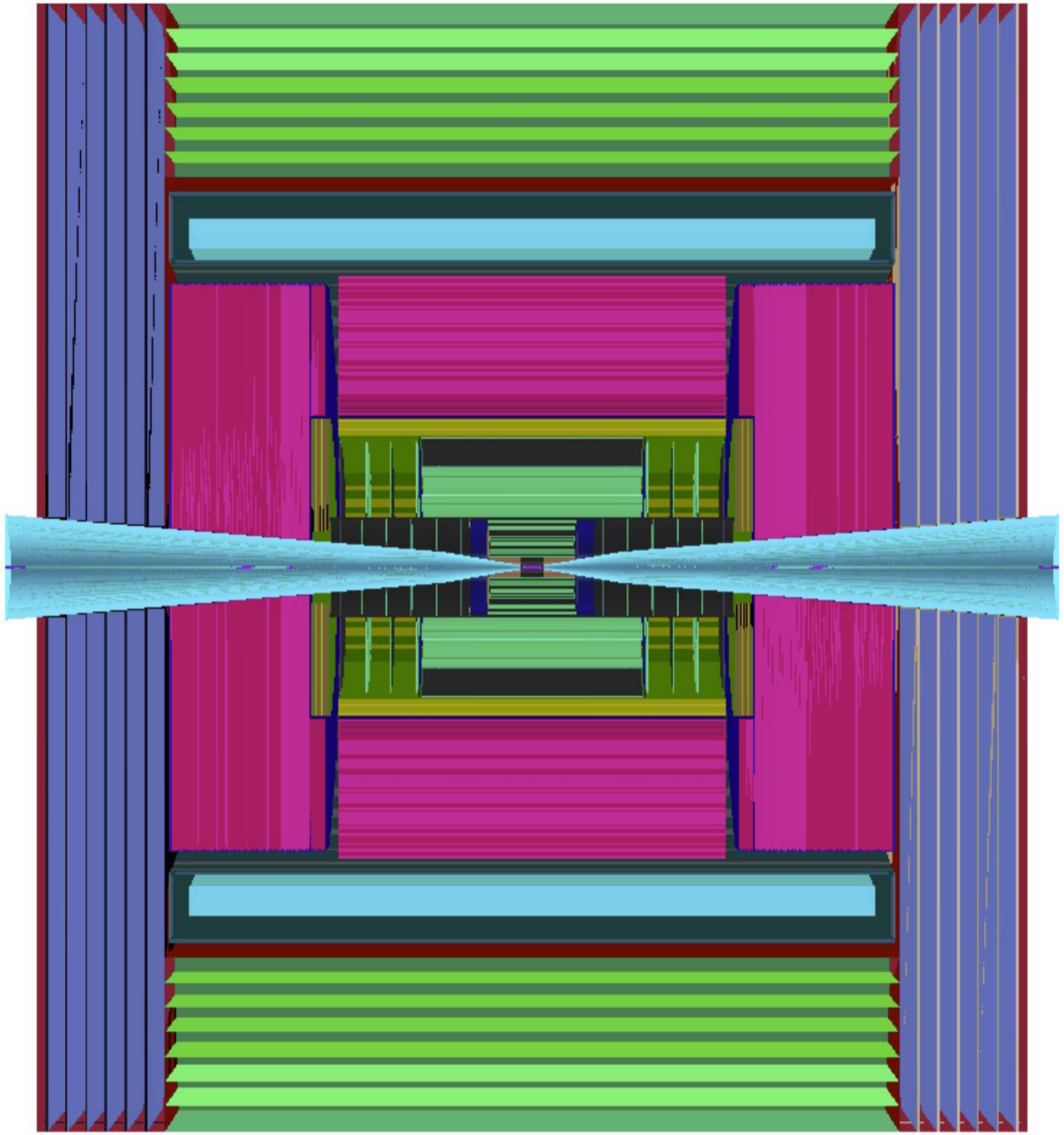


Muon decay position

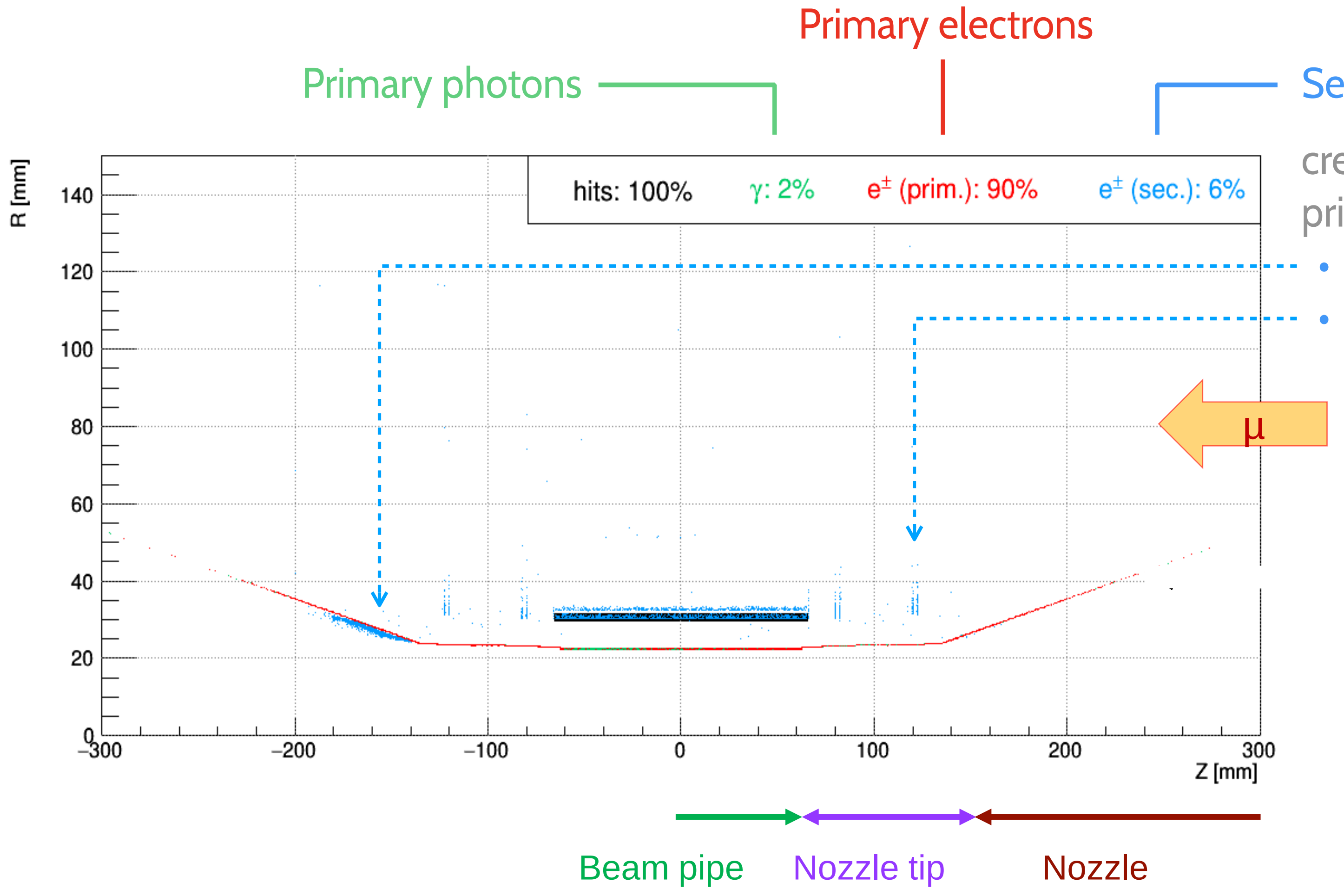
- Muon decays up to 55 m cause BIB in the detector for the $\sqrt{s} = 3\ TeV$ case
- In the $\sqrt{s} = 1.5\ TeV$ it is enough to consider decays from 35 m



Detector



Occupancy in the tracker

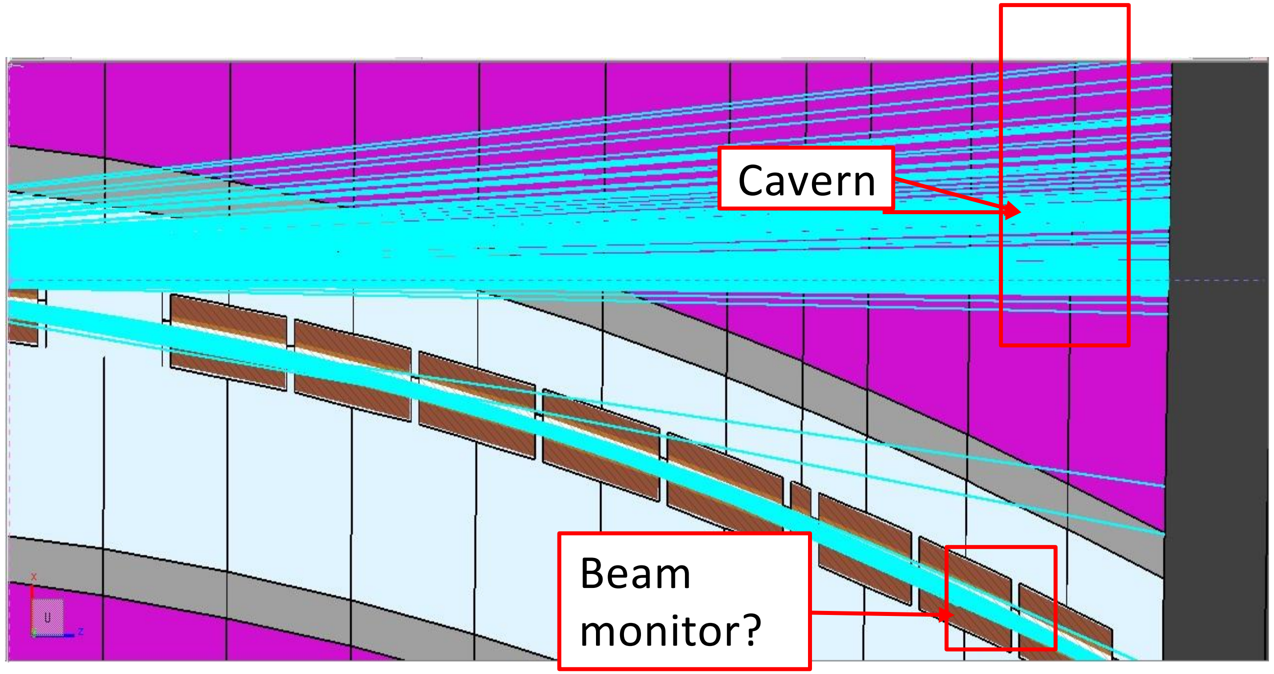


created by interaction of primary photons with:

- MDI material
- detector material

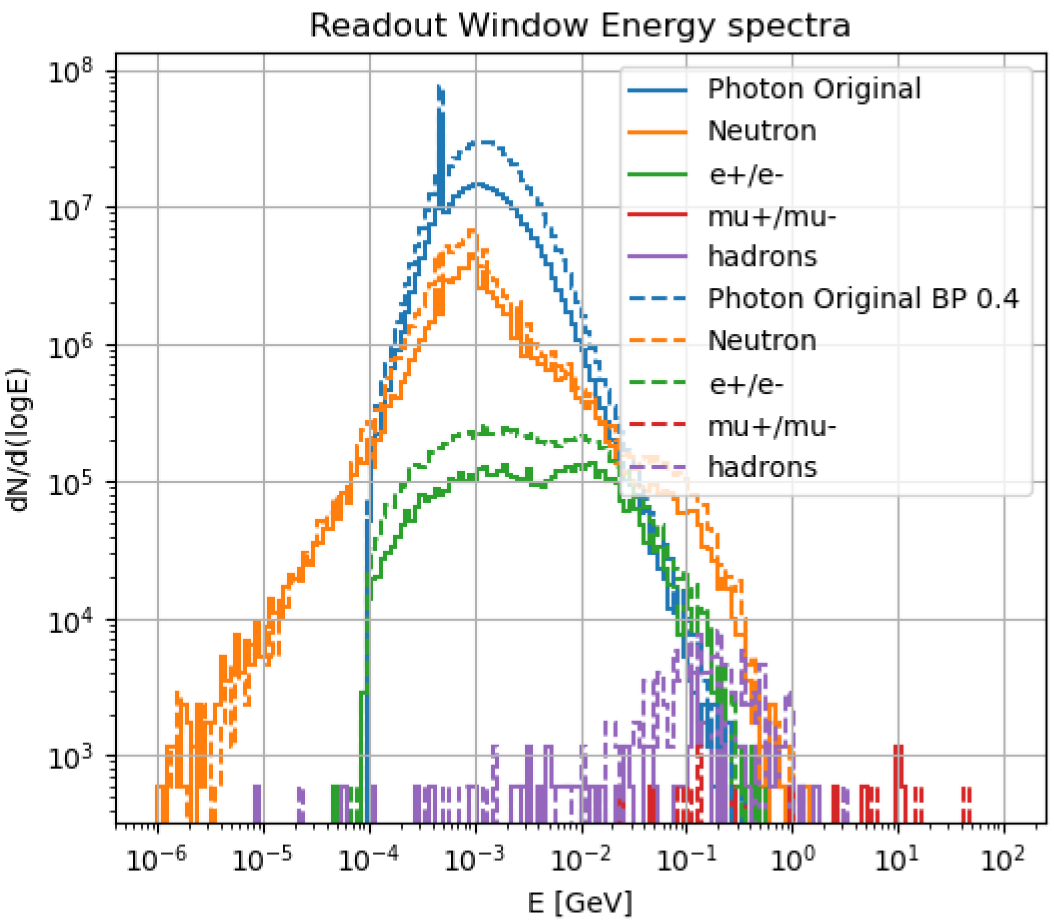
Detecting Forward Muons

- Instrumenting the cavern: Large detector, clean environment



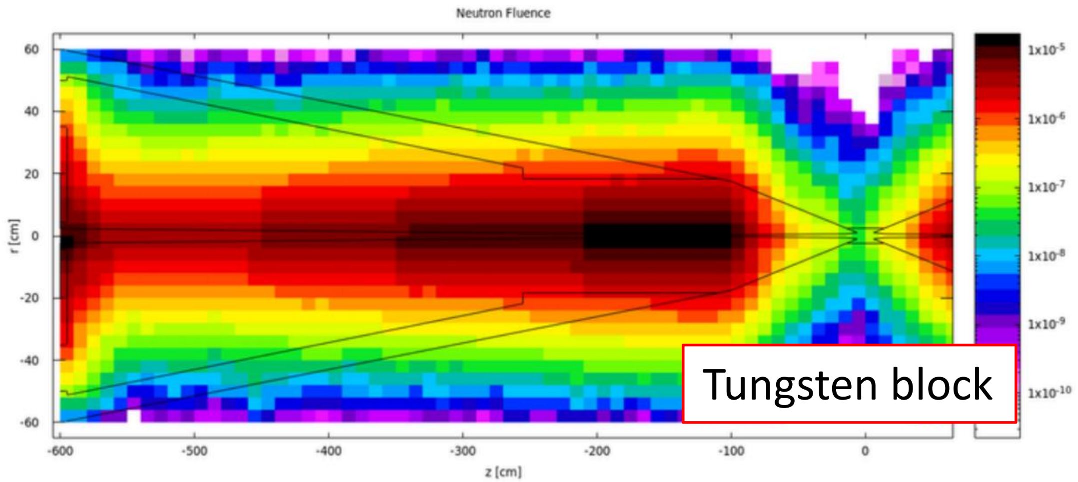
High Statistics Approach

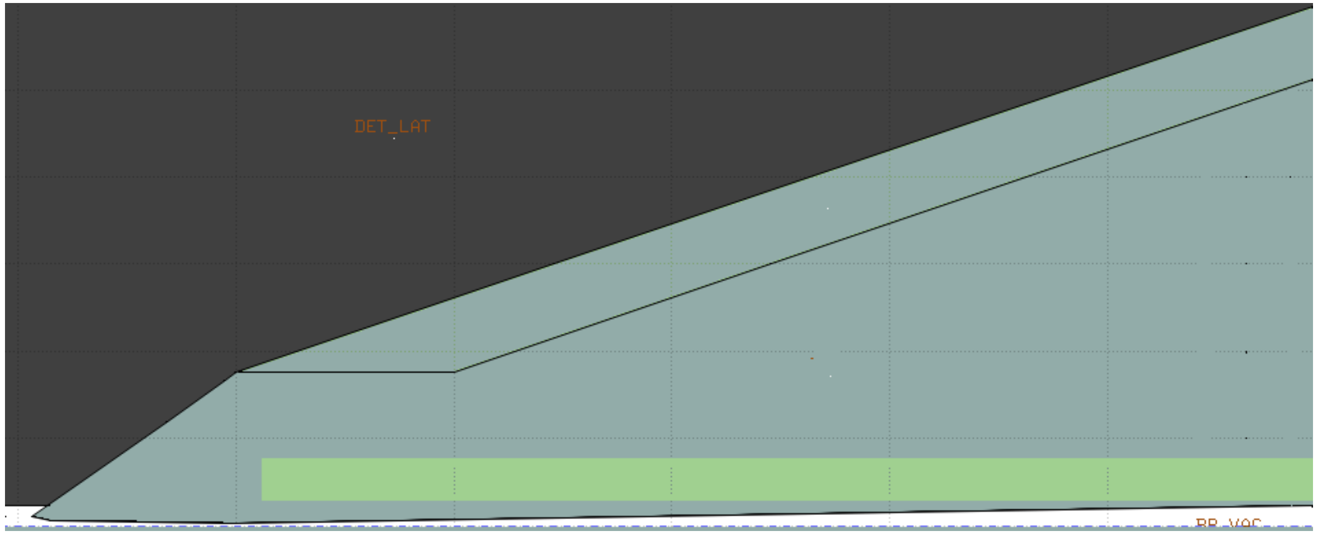
- Lessons learned:
  - The Beam Pipe cannot be touched, by increasing the minimum nozzle internal radius from $0.3 \rightarrow 0.4\ cm$, BIB increase by a factor 2

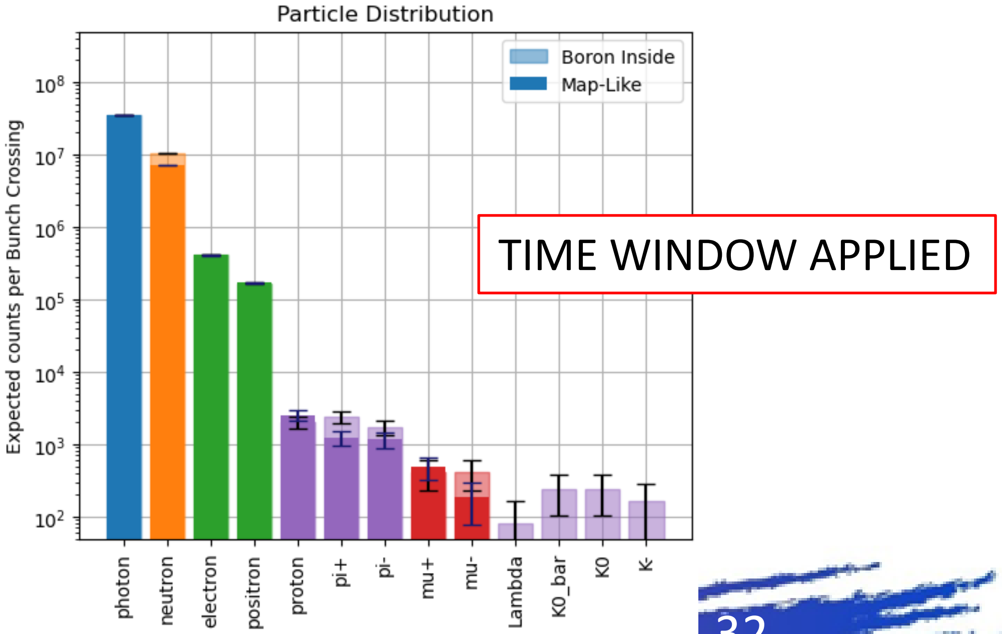


High Statistics Approach

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

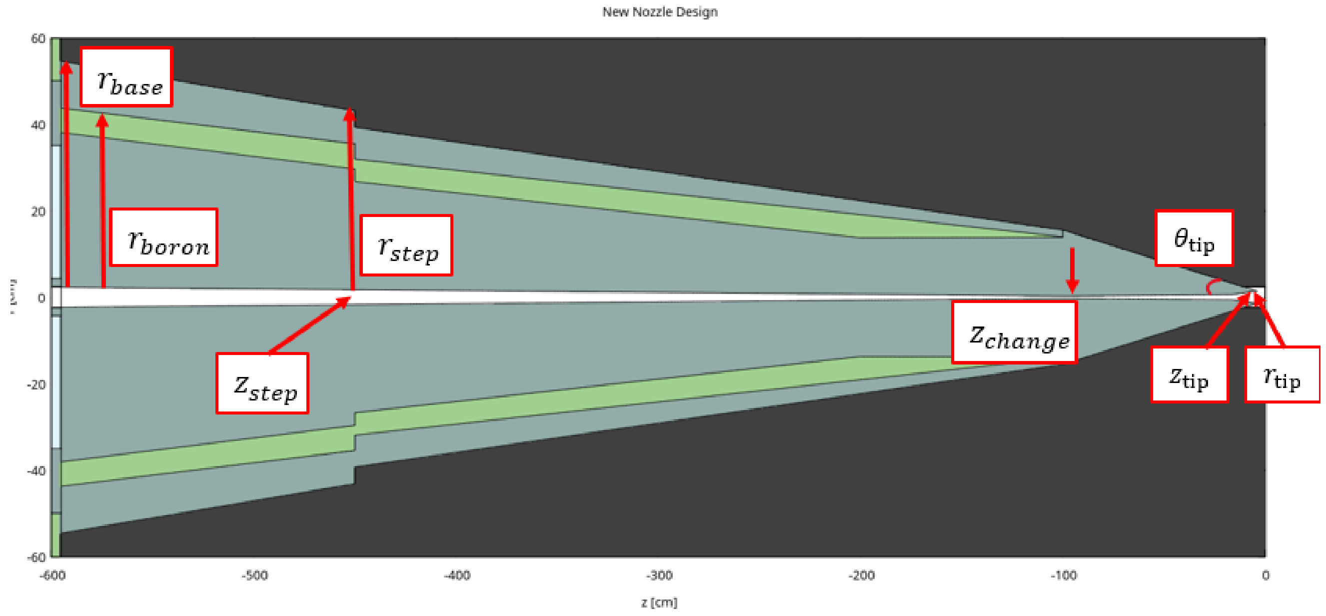






Statistics and Parameters

- **Statistics**
  - Low → 0.02% of bunch crossing
  - Medium → 0.6% of bunch crossing
  - High → 1.6% of bunch crossing
- **Parameters:**
  - $\theta_{tip} \in [0.126, 0.174]$ degree
  - $r_{base} \in [45, 60] cm$
  - $r_{boron} \in [0.8, 0.95]\%$ of r_{base}
  - $z_{step} \in [-450, -250] cm$ from IP
  - $r_{step} \in [0.75, 0.95]\%$ of r_{base}
  - $z_{change} \in [-130, -80] cm$ from IP
  - $z_{tip} \in [-6, -4] cm$ from IP
  - $r_{tip} \in [0.6, 1.4] cm$

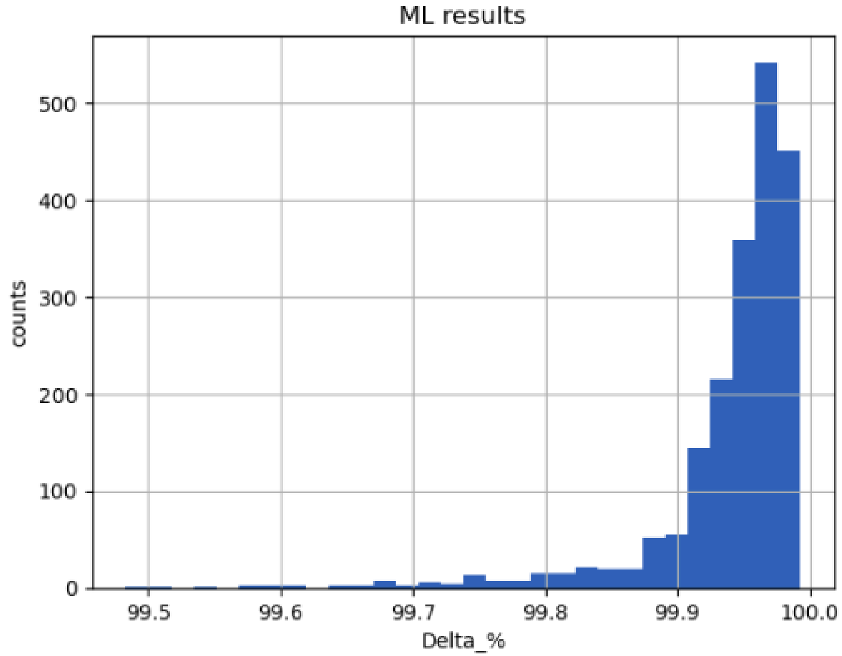


- **Key concepts:**
  - Layer of tungsten outside the boron
  - Last $\sim 100\ cm$ geometry most impacting
  - **Small changes impact strongly the BIB**

Hard ML results

- XGBoost regressor to predict the flux from the parameters to:
  - Perform in short time large amount of pseudo-simulation
  - Do a Bayesian optimization without running FLUKA
- Flux in 2 o.o.m range, so log applied → no effect
- Applied scalers (std, min-max) → removed outliers
- $Delta[\%] = \frac{Flux_{true} - Flux_{predicted}}{Flux_{true}} * 100$
- Tried a pytorch NN model, but did not achieve any result

```python
class NeuralNetwork(nn.Module):
    def __init__(self, ninputs, device=torch.device("cpu")):
        super().__init__()
        #self.flatten = nn.Flatten()
        self.linear_relu_stack = nn.Sequential(
            nn.Linear(ninputs, 512),
            nn.BatchNorm1d(512),
            nn.ReLU(),
            nn.Linear(512,128),
            nn.BatchNorm1d(128),
            nn.ReLU(),
            nn.Linear(128,64),
            nn.BatchNorm1d(64),
            nn.ReLU(),
            nn.Dropout(p=0.2),
            nn.Linear(64, 1)
        )
        self.linear_relu_stack.to(device)
```



Hard ML results

- XGBoost regressor to predict the flux from the parameters to:
  - Perform in short time large amount of pseudo-simulation
  - Do a Bayesian optimization without running FLUKA
- Flux in 2 o.o.m range, so log applied → no effect
- Applied scalers (std, min-max) → removed outliers
- Prediction correct within 10% with best model
- Tried a pytorch NN model, but did not achieve any result

```python
class NeuralNetwork(nn.Module):
    def __init__(self, ninputs, device=torch.device("cpu")):
        super().__init__()
        #self.flatten = nn.Flatten()
        self.linear_relu_stack = nn.Sequential(
            nn.Linear(ninputs, 512),
            nn.BatchNorm1d(512),
            nn.ReLU(),
            nn.Linear(512,128),
            nn.BatchNorm1d(128),
            nn.ReLU(),
            nn.Linear(128,64),
            nn.BatchNorm1d(64),
            nn.ReLU(),
            nn.Dropout(p=0.2),
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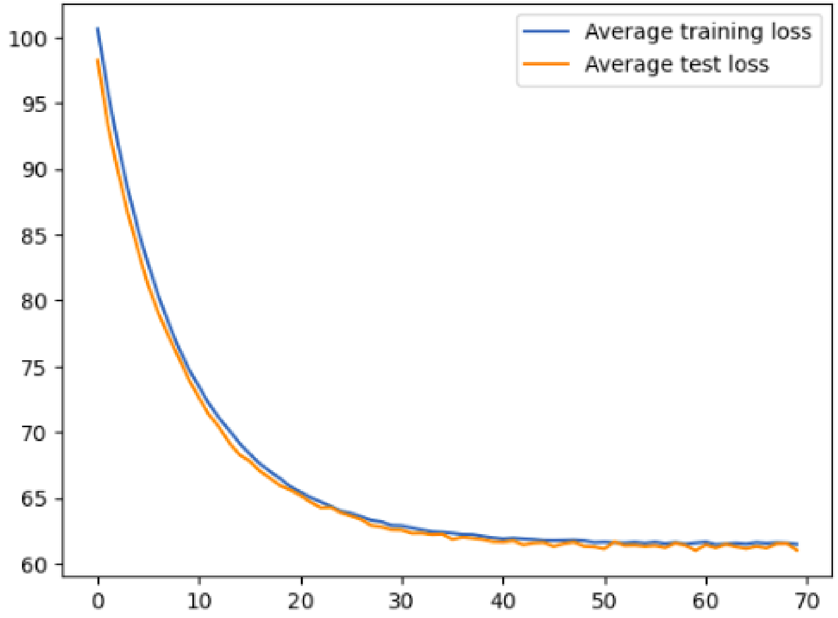
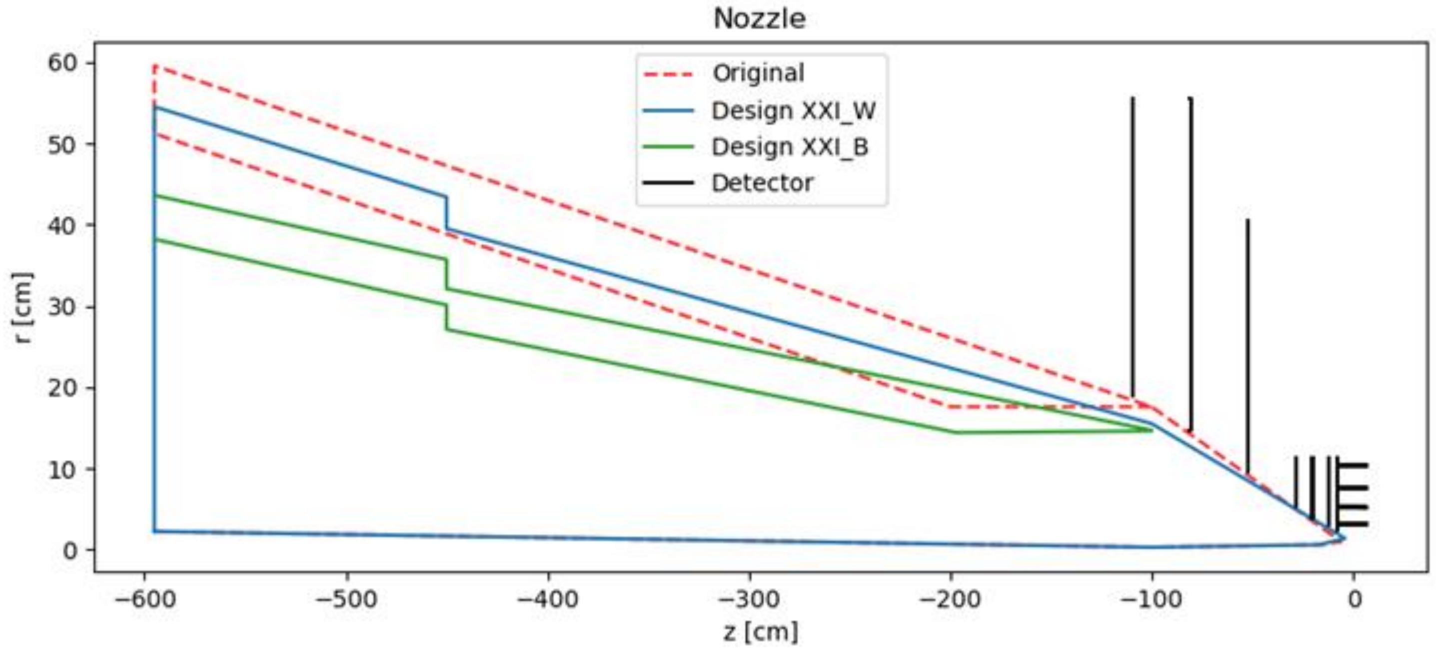


Optimization Results

- Combining XGBoost analysis and by-hand simulations, an improved design has been achieved
- BIB energy spectrum after readout window applied (left)
- Occupancy on the vertex detector (right)
- Plots compare the new geometry with the original one from MAP



Flux per bunch crossing

Particle	MAP Design	Design XXI
photons	$3.45 \cdot 10^7$	$2.27 \cdot 10^7$
neutrons	$7.18 \cdot 10^6$	$1.34 \cdot 10^7$
e^+/e^-	$5.75 \cdot 10^5$	$4.19 \cdot 10^5$

	MAP Design	Design XXI
Layer 0	2.14	0.81
Layer 1	1.54	0.61

Occupancy for 1.6% of bunch crossing

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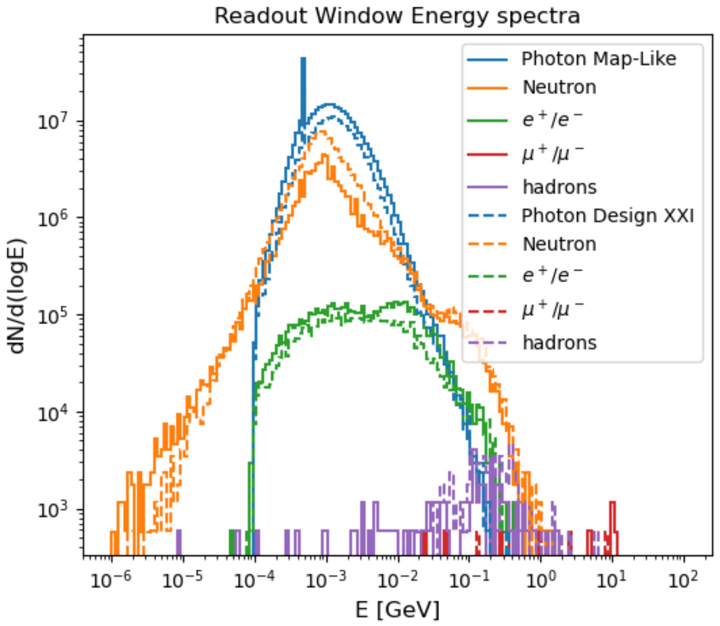

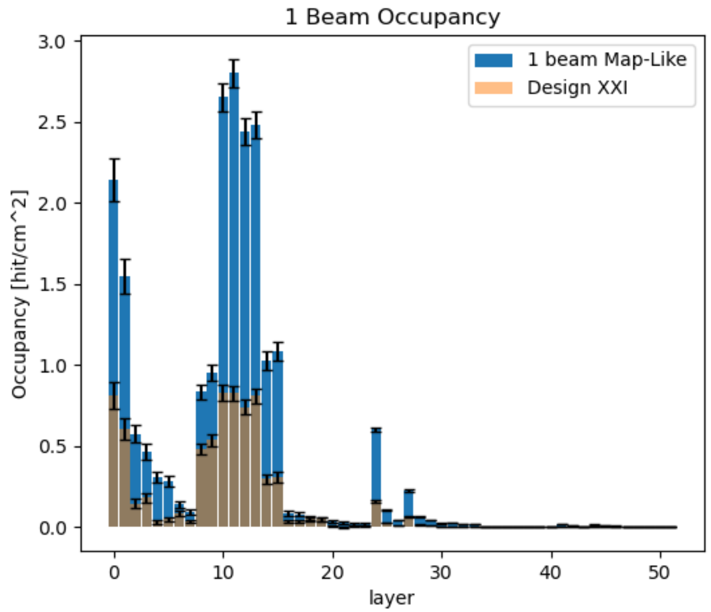

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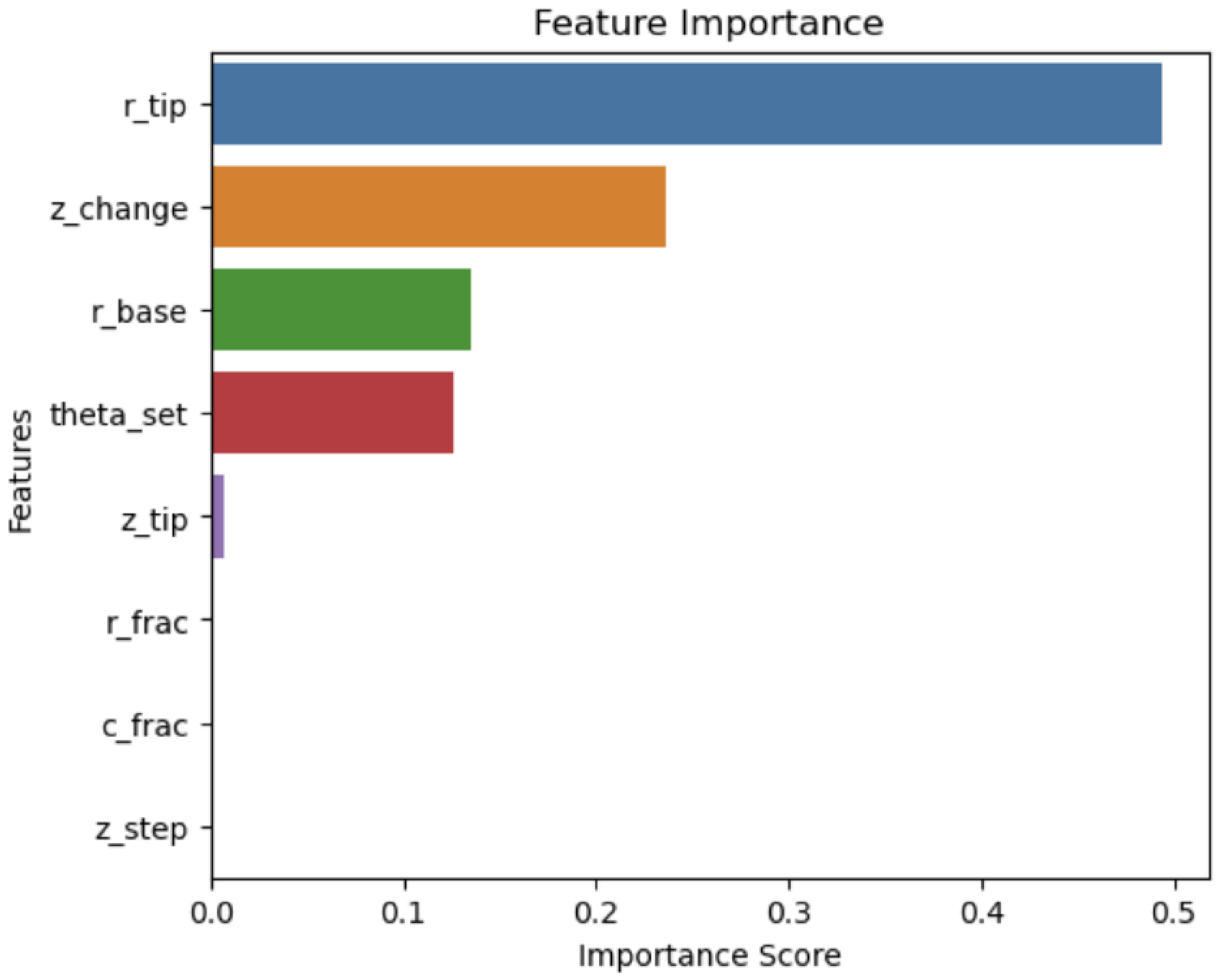
Hard ML results

- Feature Importance with XGBoost regressor



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%)