Simulating Muon Filter for MUonE and MSSM Proton Collisions for Dark Matter Searches

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Contents

Part I:
Muon identification in the MUonE experiment

Anomalus magnetic moment of a muon

$$a_{\mu SM} = 116591810(43) \times 10^{-11}$$

$$a_{\mu EXP} = 116592089(63) \times 10^{-11}$$

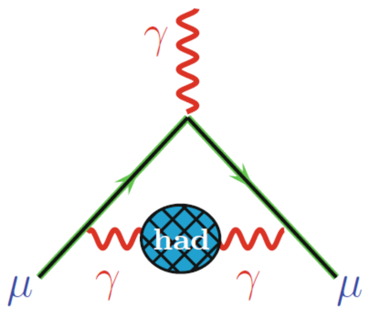
$$\Delta a_{\mu} = 279(76) \times 10^{-11} = 3.7\ \sigma$$ [1]

$$a_{\mu SM} = a_{\mu}^{QED} + a_{\mu}^{EW} + a_{\mu}^{had}$$

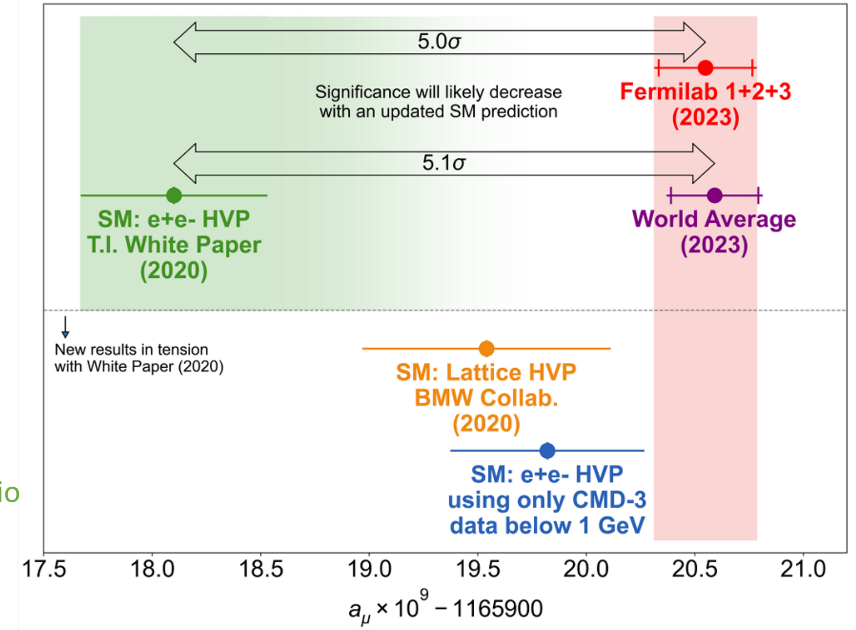
Main source of the uncertainty, influenced by the non-perturbative nature of QCD

The hadronic vacuum polarization - leading order hadronic contribution:

[2]



EPS-HEP Conference 2023., Presentation by Riccardo Nunzio Pilato, University of Liverpool



The Need for an Alternative Approach

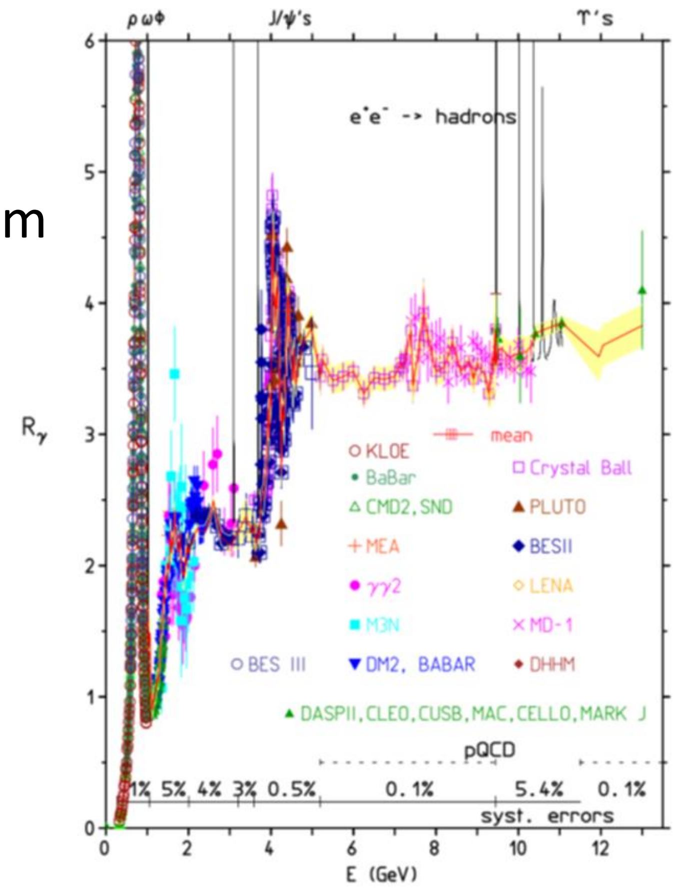
Time-like approach

- Basic concepts:
  - unitarity and causality
  - Dispersion Relation and Optical Theorem
  - direct relation to data: total hadronic cross section $\sigma(e^+e^- \to had)$

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^\infty \frac{ds}{s}\frac{1}{\pi} Im\Pi^{had}(s)K(s)$$

$$Im\Pi^{had}(s) = \frac{\alpha}{3}R_{had}(s),$$

$$R_{had}(s) = \frac{\sigma^0_{had}(e^+e^- \to had)}{4\pi\alpha^2/3s}$$



Lattice QCD

- Results have uncertainties of 2-3%, compared to 0.5-0.6% error from e^+e^- measurements

[3]

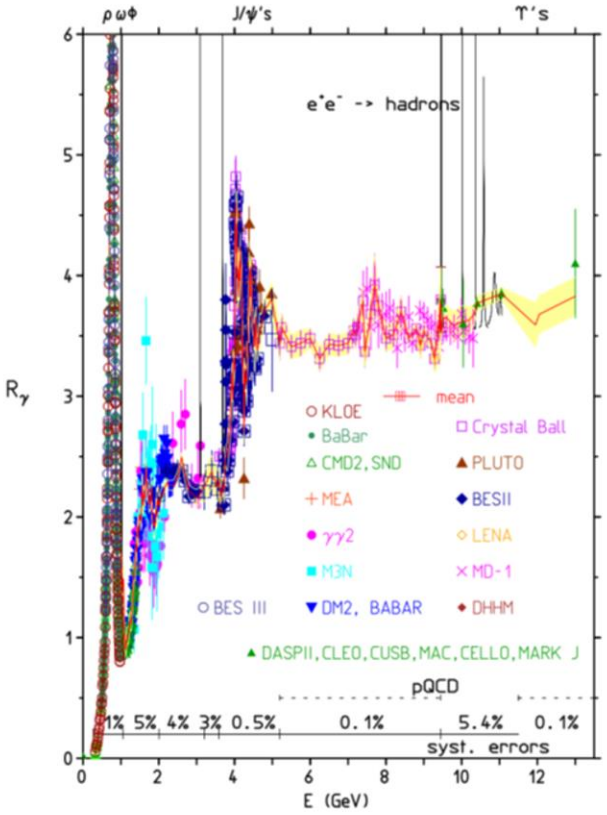
The MUonE Experiment's Approach

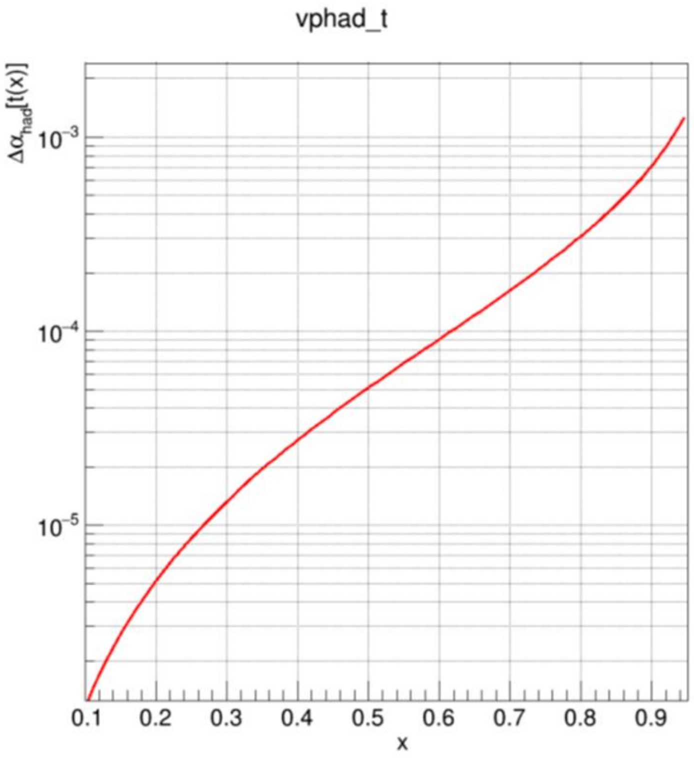
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha^{had}[t(x)]$$

$$t(x) = -\frac{x^2 m_\mu^2}{x-1} < 0$$

$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2$$



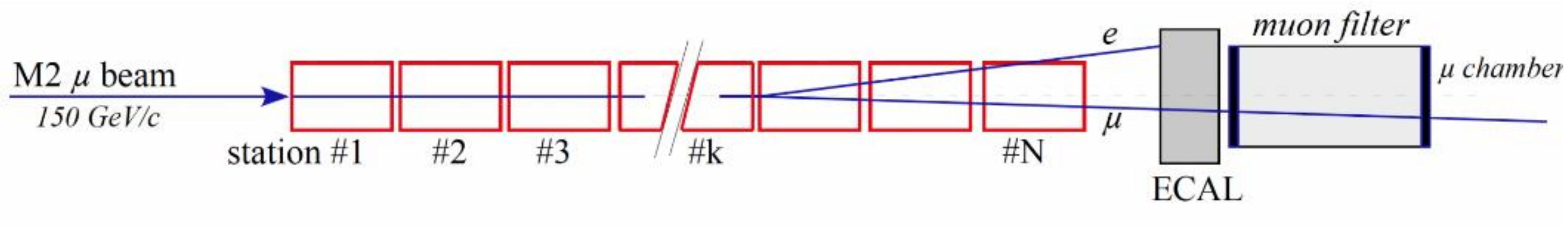


[4]

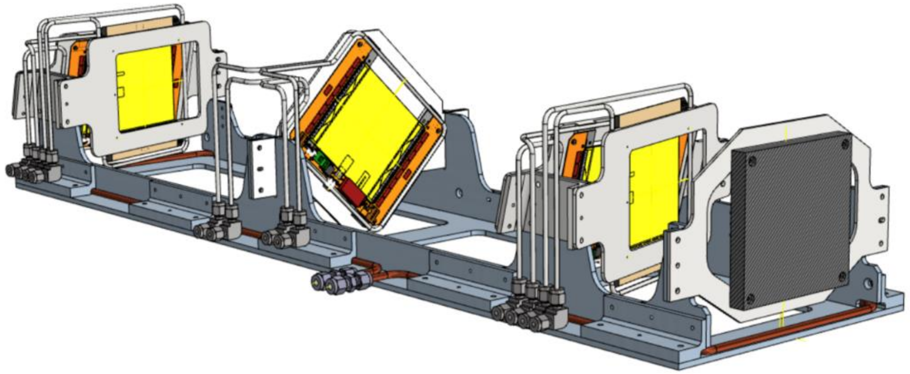
MUonE experiment

- Aims at determining the leading hadronic contribution to the muon anomalous magnetic moment by measuring the effective electromagnetic coupling in the space-like region at low momentum transfer

- Using a 160 GeV muon beam at CERN, the experiment targets a precision of $O(10^{-5})$ in measuring the shape of the differential cross section of μ−e elastic scattering



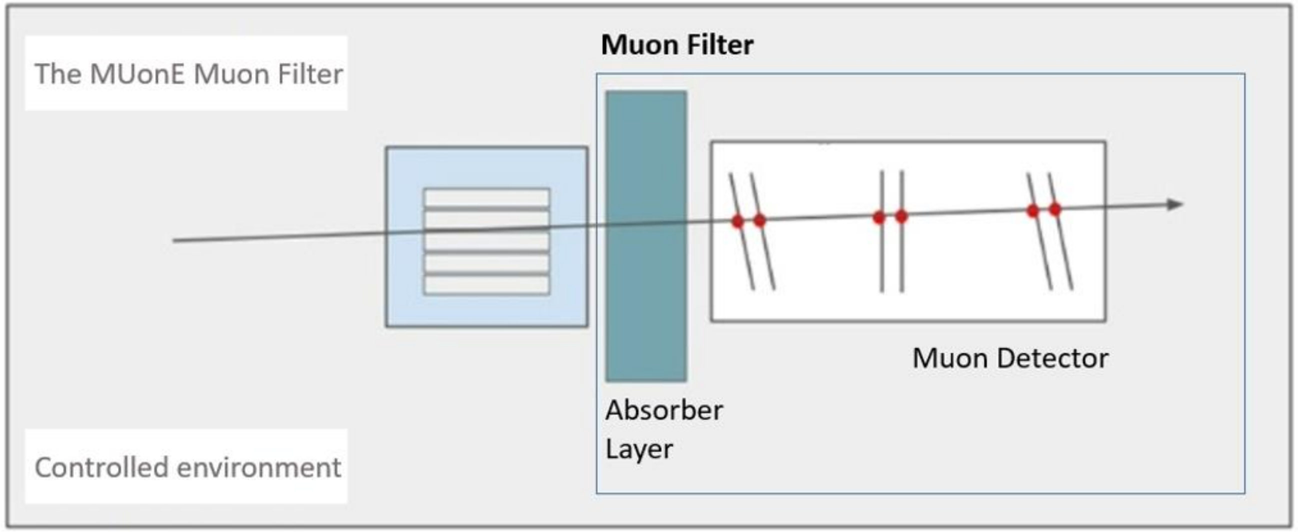
[4]

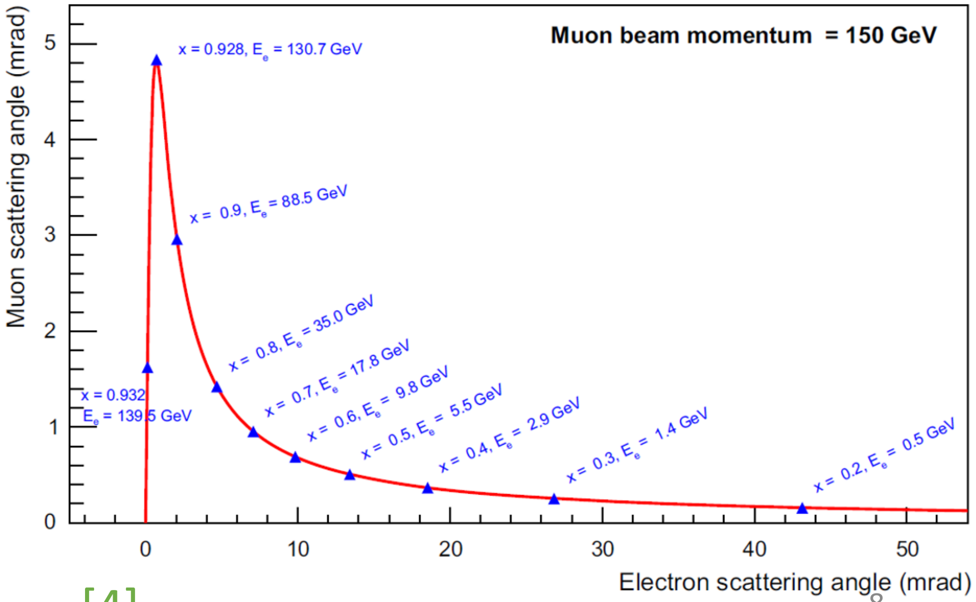


[4]

Muon filter - Importance of Precise Particle Identification

- Location: downstream of the ECAL
- Structure: a thick absorber followed by tracking planes
- Role: particle identification (PID) and correcting for potential pion contamination in the muon beam

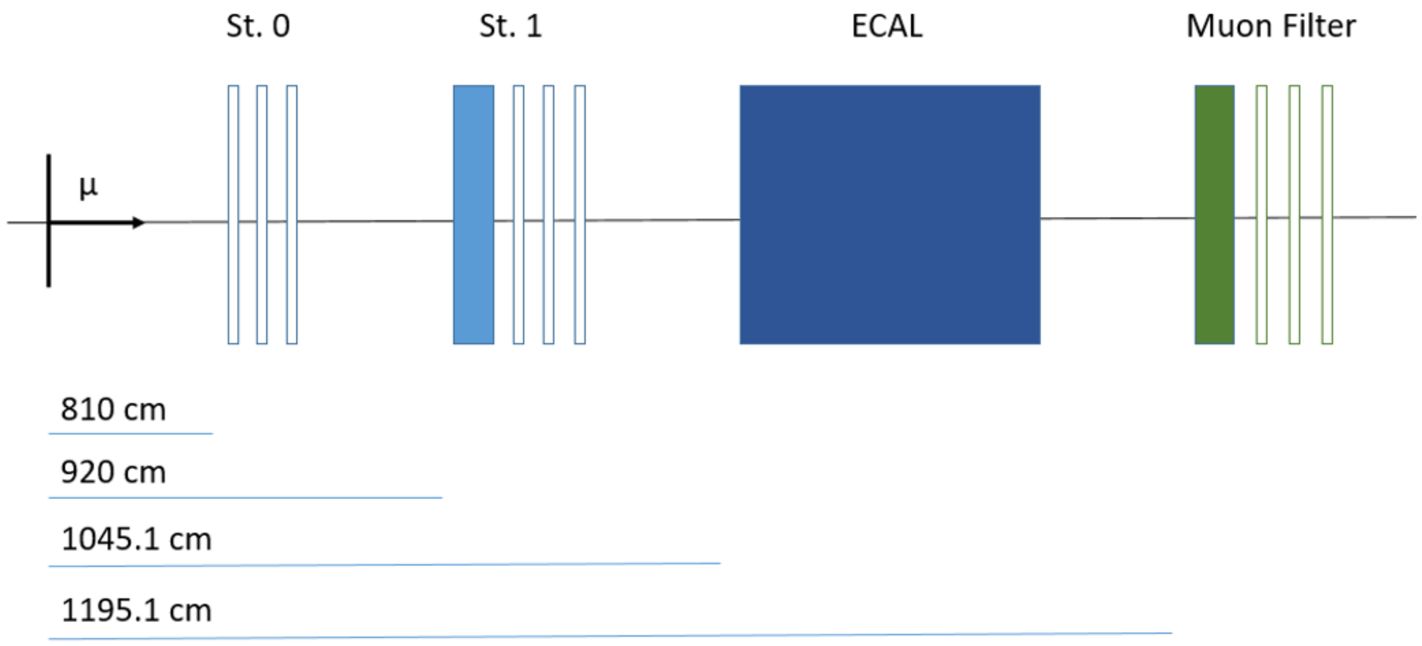




[4]

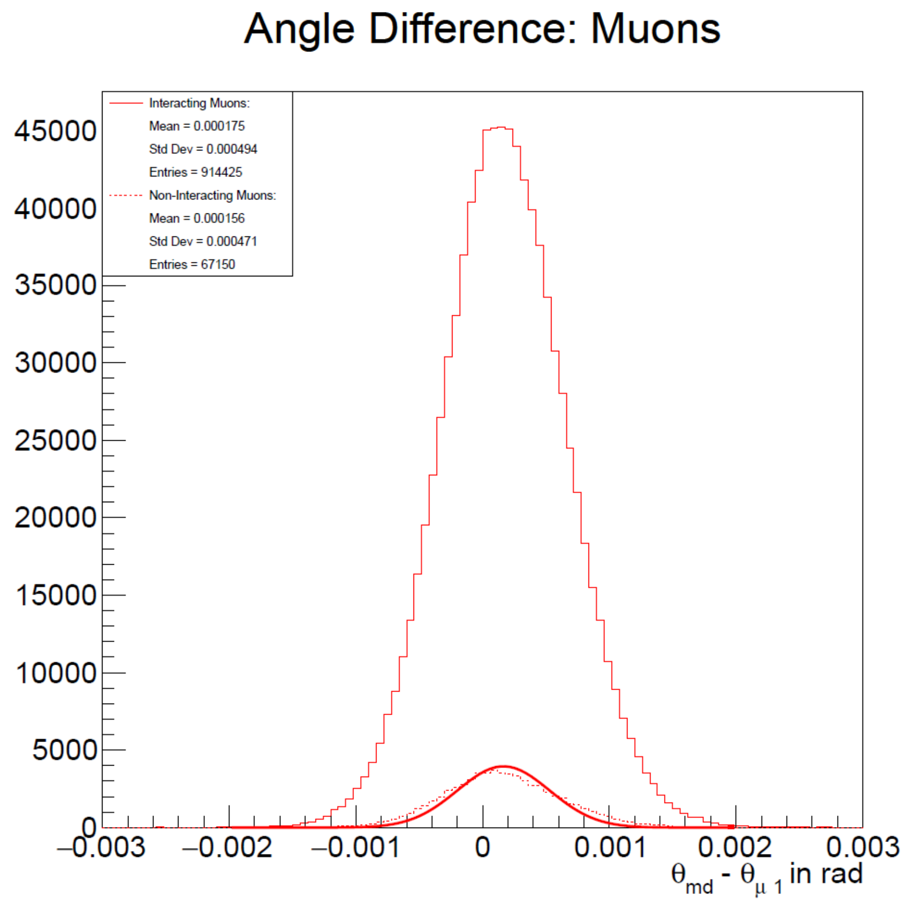
My Research – Simulations for the Muon Filter

- The main focus of the thesis: simulation of the performance of the muon filter using the *FairMUonE* software in conjunction with the *Bura* supercomputer
- 10^6 events (10^5 for Pion Contamination Study)
- Beam generator: MuonGunBeamProfile
- Interaction generator: MESMER elastic interaction

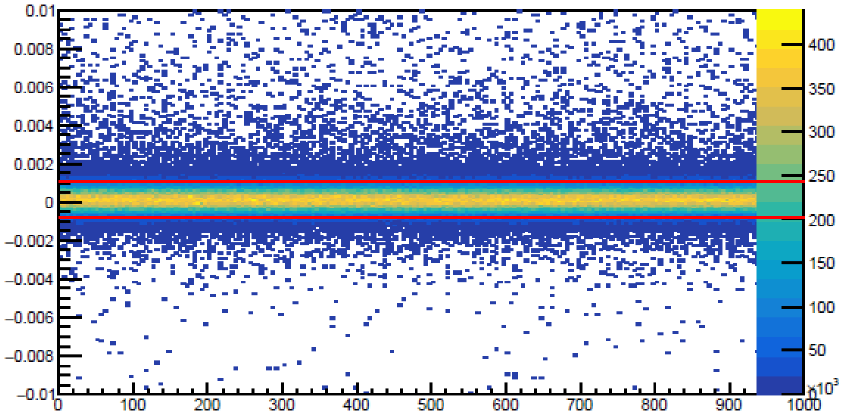


Angle Method

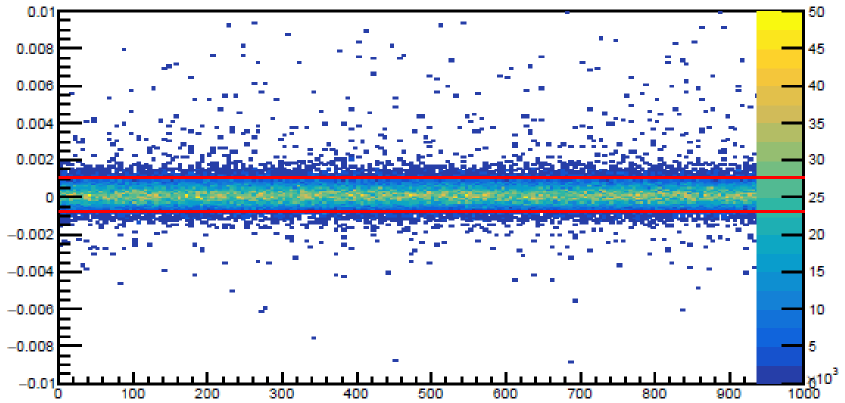
- Method for correct muon track extrapolation
- Main idea:
  - Take the distribution of muon angle differences and apply a cut-off interval of μ±σ on all of the angles reconstructed in the muon detector
  - Check whether the signal muon angle reconstructed in the muon detector is within this cut-off interval



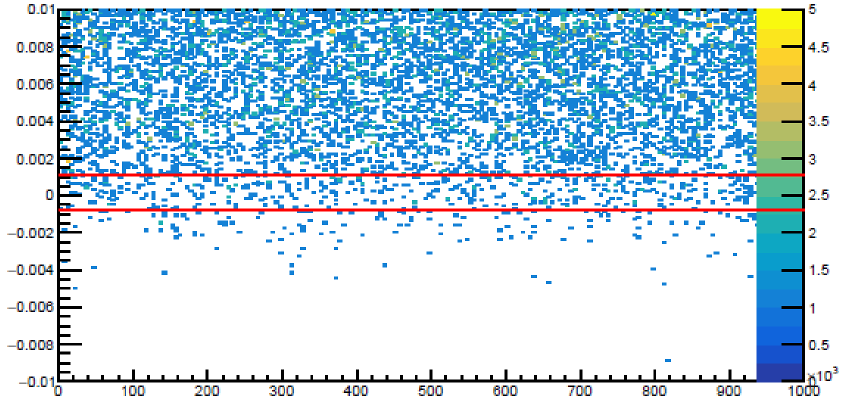
- Deviation from zero in the angle difference for non-interacting muons is due solely to Multiple Coulomb Scattering (MCS) → the analysis informs about how much background falls into the MCS uncertainty region around the muon



Interacting Muons



Non-Interacting Muons

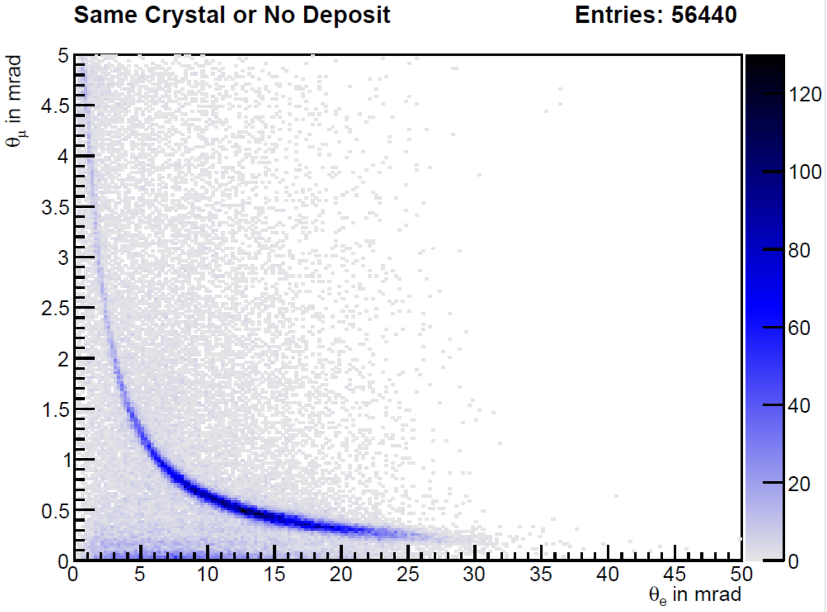


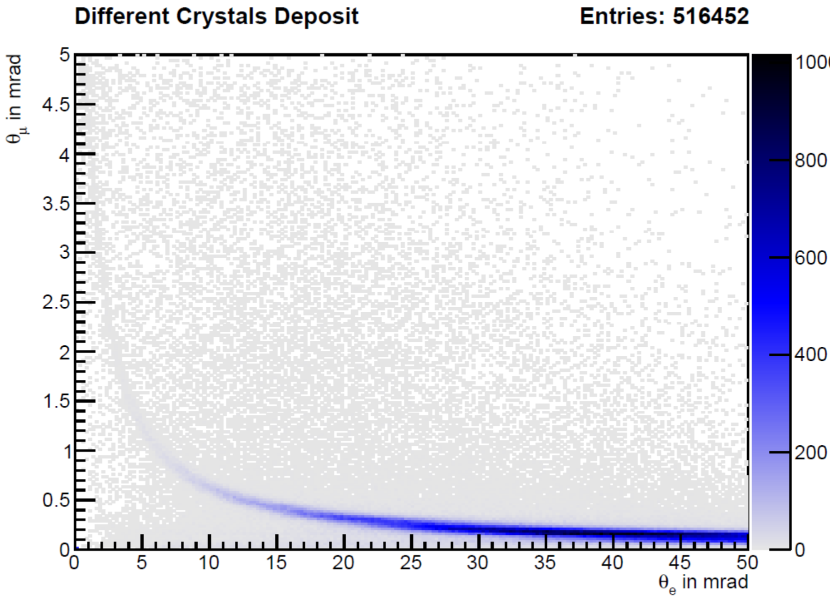
Background

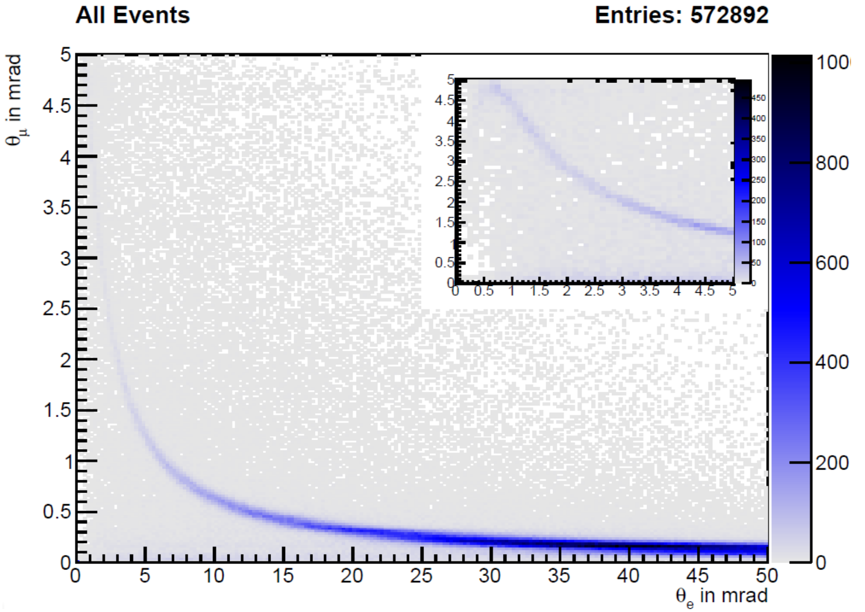
10 cm Iron	Probability	Uncertainty
Non-Interacting Muon Data, 1 Sigma Cut-Off	0.99937	4×10^{-5}
Non-Interacting Muon Data, 2 Sigma Cut-Off	0.99869	4×10^{-5}
Interacting Muon Data, 1 Sigma Cut-Off	0.99899	3×10^{-5}
Interacting Muon Data, 2 Sigma Cut-Off	0.99781	5×10^{-5}
Non-Interacting Muon Data, 1 Sigma Cut-Off, Filter Relevant Events	0.9986	4×10^{-4}
Non-Interacting Muon Data, 2 Sigma Cut-Off, Filter Relevant Events	0.9973	5×10^{-4}
Interacting Muon Data, 1 Sigma Cut-Off, Filter Relevant Events	0.9981	5×10^{-4}
Interacting Muon Data, 2 Sigma Cut-Off, Filter Relevant Events	0.996	7×10^{-3}

By comparing muon angles before and after the absorber, I achieved over **99% background rejection** with minimal muon loss.

Final correlation curve







Scenario	No Absorber (%)	1 cm Fe (%)	2 cm Fe (%)	10 cm Fe (%)
Muon Filter Required	8.78764	8.992	9.085	9.012
Muon Filter Required, Correctly Identified Events	8.75795	8.968	9.050	8.970

Scenario	No Absorber (%)	1 cm Fe (%)	2 cm Fe (%)	10 cm Fe (%)
Muon Filter Required	84.618	81.460	85.347	81.862
Muon Filter Required, Correctly Identified Events	83.7466	80.923	84.886	81.203

In **9% of all events**, the muon filter was crucial for identification. Without the filter, the ECAL alone correctly identified only **20% of ambiguous cases ($\theta_e < 5$ mrad)**.

Part II:

Probing Dark Matter at the LHC: Monte Carlo Simulations in the MSSM

Introduction

- **Research Focus:** Simulating proton-proton collisions within the MSSM framework.
- **Scenario:** Only light superparticles are a **bino-like dark matter candidate** (χ) and a **nearly-degenerate slepton** ($\tilde{l}$).
- **Challenge:** Traditional searches fail due to:
  - **Soft leptons** and **small missing transverse energy (MET)**.
  - **High background** from standard model processes like $\mathbf{t\bar{t}}$ and **WZ decays**.
- **Our Approach:**
  - Investigate an **alternative search strategy** involving an additional **radiated jet** to provide transverse boost.
  - Use **angular distributions** and other discriminatory variables to enhance signal-background separation.

Event Generation and Simulation Strategy

- $pp \to jZ \to j\bar{\tau}\tau \to j\bar{\ell}\ell\bar{\nu}\nu\bar{\nu}_\tau\nu_\tau$,
- $pp \to \bar{t}t(j) \to \bar{b}W^- bW^+(j) \to \bar{b}b\bar{\ell}\ell\bar{\nu}\nu(j)$,
- $pp \to jZZ/jW^+W^- \to j\bar{\ell}\ell\bar{\nu}\nu, j\bar{\ell}\ell\bar{\tau}\tau(\to \bar{\ell}\ell\bar{\nu}\nu + \text{jets})$

[5]

• Tools Used:

- **MadGraph & Pythia8** for event generation, simulated on the HPC.

• Signal Definition:

- Focus on **opposite-sign, same-flavor dileptons + MET**.
- Simulated with **strict decay channels** to make detection challenging.
- $qg\ (q\bar{q}) \to j\gamma^* \ /\ Z^* \to j\tilde{l}^*\tilde{l} \to j\chi\chi\bar{l}l$

Example;

Exclusive: p p > w+ w-, w+ > mu+ vm, w- > mu- vm~

Inclusive: p p > w+ w-

• Technical Parameters:

- Adjusted **xqcut** and **qcut** parameters for optimization.
- MSSM SLHA2 model used with:
  - **Smuon mass = 110 GeV**
  - **Neutralino mass = 100, 90, 80, 70, 60, 50 GeV**
  - All other particles decoupled.

• Background Approach:

- **Exclusive:** Only backgrounds that directly mimic the signal (muonic decays enforced).
- **Inclusive:** Covers a **wider phase space**, ensuring a comprehensive background study.

Event Selection and Analysis

- **Goal:** Separate signal from background by applying a series of event selection cuts.

- **Three Sets of Cuts:**
  - **Primary Cuts:** Define the event topology.
  - **Secondary Cuts:** Further reduce backgrounds, globally beneficial to all targeted mass splittings..
  - **Tertiary Cuts:** Optimize based on **mass splitting (Δm = 10–60 GeV)**, using kinematic variables.

- **Results:** Shown in tables, demonstrating how signal-to-background separation improves.

- **Analysis:** Conducted using a **custom program in MadAnalysis** to track distributions and cross-section changes.

Selection	$t\bar{t}jj$	$\tau\tau jj$	$Zjjjj$	$ZZjj$	$WZjj$	$WWjj$	S^{110}_{10}	S^{110}_{20}	S^{110}_{30}	S^{110}_{40}	S^{110}_{50}	S^{110}_{60}
Matched Production	6.1×10^5	5.6×10^4	5.2×10^7	1.3×10^4	4.2×10^4	9.5×10^4	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2
τ-veto	5.4×10^5	3.0×10^4	5.1×10^7	1.2×10^4	4.0×10^4	8.9×10^4	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2	1.9×10^2
OSSF muon	3.5×10^3	4.3×10^2	6.0×10^5	3.2×10^2	5.8×10^2	5.1×10^2	3.9×10^1	6.8×10^1	8.1×10^1	8.8×10^1	8.9×10^1	9.1×10^1
exactly 1J $P_T > 30$	6.6×10^2	2.6×10^2	7.1×10^4	9.4×10^1	1.5×10^2	1.1×10^2	7.6×10^0	1.3×10^1	1.6×10^1	1.7×10^1	1.7×10^1	1.8×10^1
Jet b-veto	1.9×10^2	2.5×10^2	7.0×10^4	8.0×10^1	1.4×10^2	1.1×10^2	7.5×10^0	1.3×10^1	1.6×10^1	1.7×10^1	1.7×10^1	1.8×10^1
$\not{E}_T > 30$ GeV	1.6×10^2	1.8×10^2	8.9×10^3	3.3×10^1	6.6×10^1	9.2×10^1	6.3×10^0	1.0×10^1	1.3×10^1	1.4×10^1	1.5×10^1	1.6×10^1

Selection	$t\bar{t}jj$	$\tau\tau jj$	$Zjjjj$	$ZZjj$	$WZjj$	$WWjj$	S^{110}_{10}	S^{110}_{20}	S^{110}_{30}	S^{110}_{40}	S^{110}_{50}	S^{110}_{60}
$m_{\ell\ell} \notin M_Z \pm 10$ GeV	1.4×10^2	1.8×10^2	6.2×10^2	2.0×10^0	1.0×10^1	7.9×10^1	6.0×10^0	9.2×10^0	1.1×10^1	1.2×10^1	1.3×10^1	1.4×10^1
$\cos\theta^*_{\ell_1,\ell_2} < 0.5$	8.1×10^1	1.6×10^2	4.7×10^2	1.4×10^0	6.7×10^0	4.5×10^1	4.8×10^0	6.9×10^0	8.0×10^0	9.0×10^0	9.5×10^0	1.0×10^1
$m_{\tau\tau} > 125$ GeV	2.7×10^1	2.3×10^1	8.7×10^1	3.0×10^{-1}	1.4×10^0	1.4×10^1	3.0×10^0	3.4×10^0	3.6×10^0	3.9×10^0	4.1×10^0	4.3×10^0
$\not{E}_T > 125$ GeV	2.9×10^0	6.6×10^{-1}	0	1.5×10^{-2}	2.2×10^{-1}	2.3×10^0	5.1×10^{-1}	5.8×10^{-1}	6.6×10^{-1}	7.1×10^{-1}	7.9×10^{-1}	8.9×10^{-1}
Jet $P_T > 125$ GeV	1.1×10^0	6.6×10^{-1}	0	1.1×10^{-2}	1.9×10^{-1}	1.7×10^0	4.9×10^{-1}	5.2×10^{-1}	5.2×10^{-1}	4.6×10^{-1}	4.5×10^{-1}	4.5×10^{-1}

Selection	$t\bar{t}jj$	$\tau\tau jj$	$ZZjj$	$WZjj$	$WWjj$	S^{110}_{10}	S^{110}_{20}	S^{110}_{30}	S^{110}_{40}	S^{110}_{50}	S^{110}_{60}
Small Mass Gap Optimization											
$1.0 < P^j_T \div \not{E}_T < 1.3$	4.5×10^{-1}	5.5×10^{-3}	2.7×10^{-3}	6.2×10^{-2}	6.6×10^{-1}	$\mathbf{4.2 \times 10^{-1}}$	$\mathbf{3.0 \times 10^{-1}}$	2.4×10^{-1}	1.8×10^{-1}	1.6×10^{-1}	1.4×10^{-1}
$\Delta\phi(\not{E}_T, j) \div \pi > 0.95$	1.8×10^{-1}	5.5×10^{-3}	2.2×10^{-3}	2.7×10^{-2}	3.8×10^{-1}	$\mathbf{4.0 \times 10^{-1}}$	$\mathbf{2.3 \times 10^{-1}}$	1.7×10^{-1}	9.6×10^{-2}	7.7×10^{-2}	6.2×10^{-2}
Events at $\mathcal{L} = 300$ fb^{-1}	52.7	1.7	0.7	8.1	113.6	**120.0**	**69.0**	51.0	28.8	23.1	18.6
$S \div (1 + B)$	-	-	-	-	-	**0.68**	**0.39**	0.29	0.16	0.13	0.10
$S \div \sqrt{1 + B}$	-	-	-	-	-	**9.0**	**5.2**	3.8	2.2	1.7	1.4

[5]

Next Steps – Machine Learning and Neural Networks

- No simple set of cuts can perfectly separate signal from background.
- Traditional cut-based methods rely on trial and error.
- Machine learning, especially **neural networks**, can optimize selection by recognizing complex patterns in kinematic variables.
- The goal is not only better event selection but also understanding why certain cuts work.
- I am currently learning about machine learning techniques to apply them in this analysis.

Part III:
Research interests and future work

Research interests and future work

- Passion for Quantum Field Theory, Particle Physics, General Relativity, and Cosmology.
- Interest in scattering amplitudes, dark matter, dark energy, and fundamental interactions.
- Aim to contribute to theoretical physics.
- Plan to stay engaged with MUonE and Ljubljana research while focusing on PhD work.

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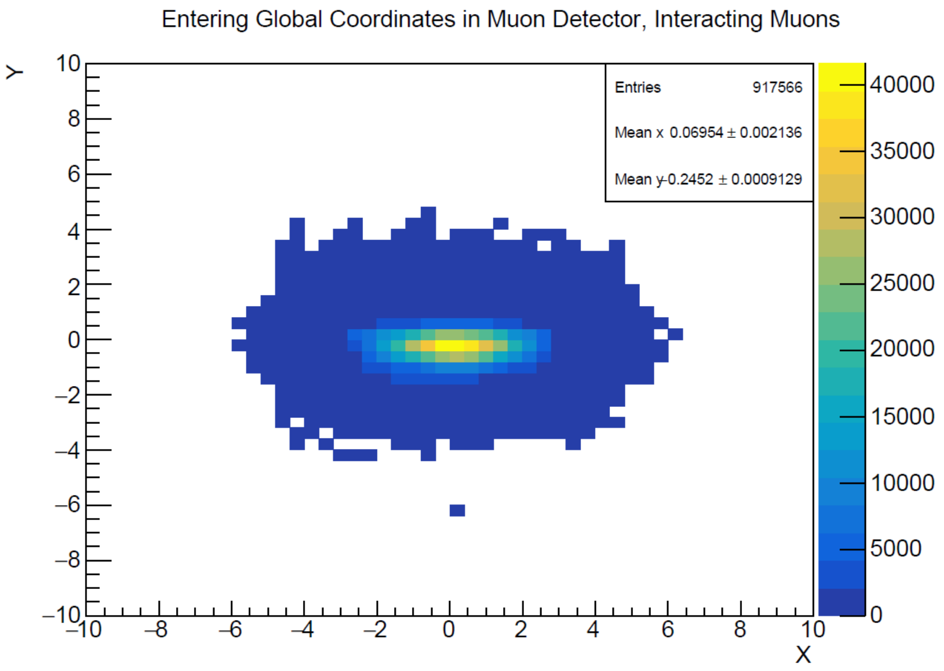
[5] Dutta, B., Fantahun, K., Fernando, A., Ghosh, T., Kumar, J., Sandick, P., Stengel, P., & Walker, 2017, Probing Squeezed Bino-Slepton Spectra with the Large Hadron Collider, arXiv:1706.05339v2

APPENDIX I: MUONE EXPERIMENT

Acceptance study

- $acceptance = \frac{reconstructed}{generated}$

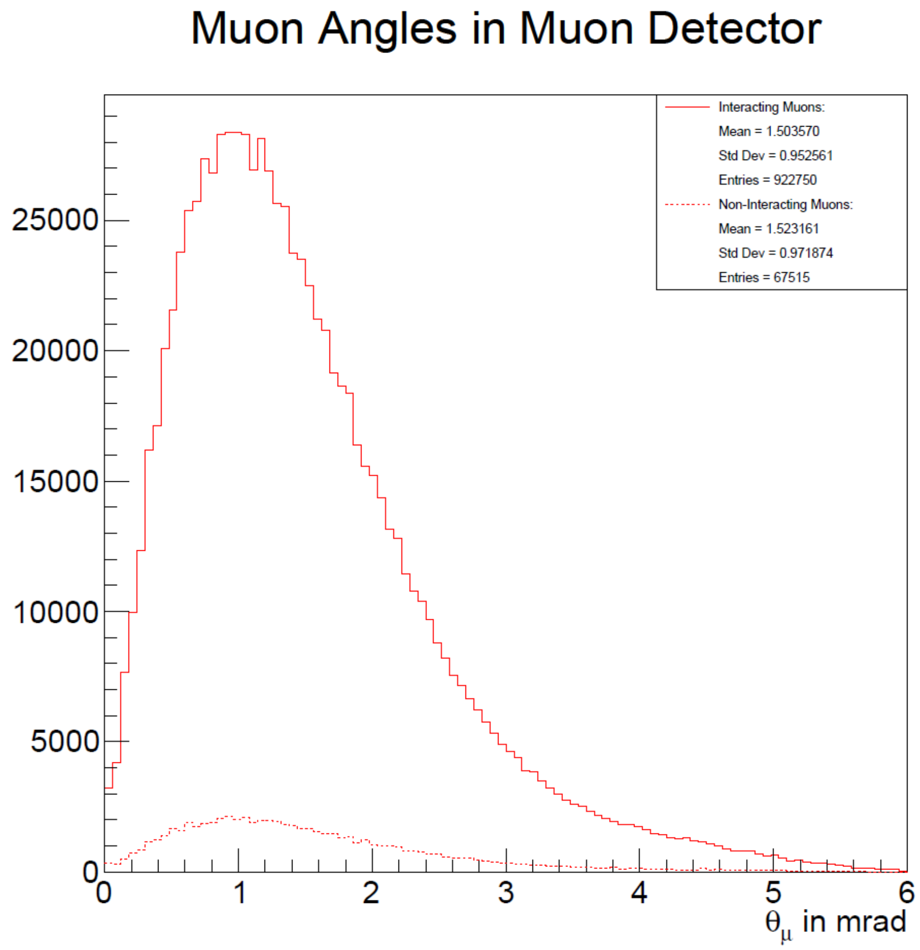
Configuration	Acceptance Station 1	Acceptance Muon Detector
No Absorber	$99.85 \pm 0.01\%$	$99.812 \pm 0.009\%$
1 cm Iron	$99.85 \pm 0.02\%$	$99.80 \pm 0.02\%$
2 cm Iron	$99.85 \pm 0.02\%$	$99.80 \pm 0.01\%$
10 cm Iron	$99.85 \pm 0.02\%$	$99.76 \pm 0.02\%$



No Absorber	Interacting outside Absorber	Non-Interacting	Interacting in Absorber
Reconstruction Inefficiency	$27 \pm 4\%$	$4 \pm 1\%$	$0 \pm 0\%$
Sensor Inefficiency	$47 \pm 4\%$	$10 \pm 2\%$	$0 \pm 0\%$
Zero Hits (Escape)	$9 \pm 4\%$	$3 \pm 2\%$	$0 \pm 0\%$
10 cm Iron	**Interacting outside Absorber**	**Non-Interacting**	**Interacting in Absorber**
Reconstruction Inefficiency	$14 \pm 4\%$	$1 \pm 1\%$	$27 \pm 4\%$
Sensor Inefficiency	$30 \pm 4\%$	$7 \pm 1\%$	$9 \pm 1\%$
Zero Hits (Escape)	$8 \pm 2\%$	$3 \pm 03\%$	$2 \times 10^{-7} \pm 4 \times 10^{-7}\%$

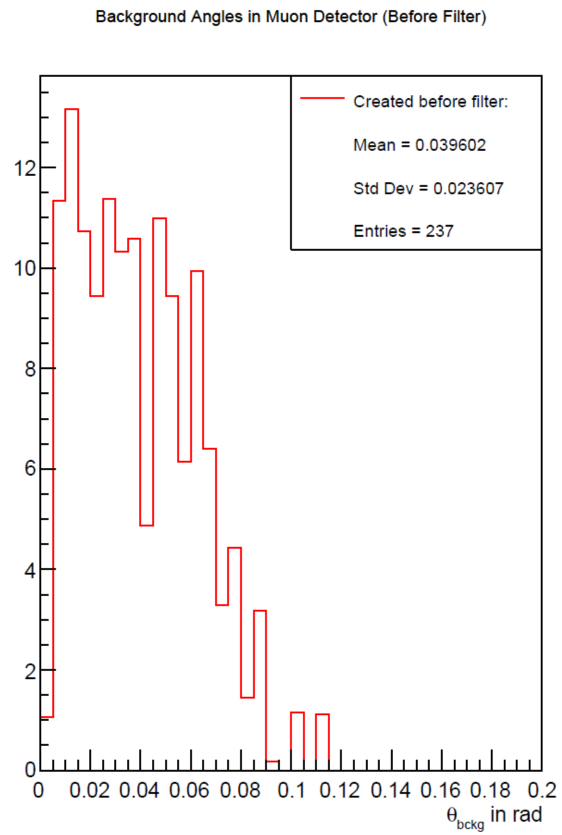
Increasing absorber thickness slightly reduced the number of detected muons in muon detector, but most losses were due to **sensor inefficiency**, not the absorber layer itself.

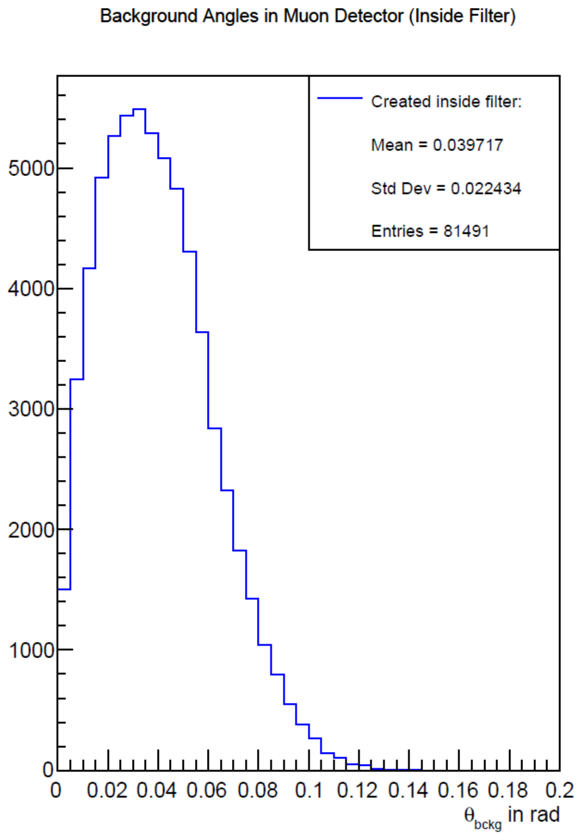
Muon and background particle angle analysis



Material	Muon Type	Mean / mrad	Std Dev / mrad
No Absorber	Interacting	1.5	0.9
	Non-Interacting	1.5	0.9
1 cm Iron	Interacting	1.5	0.9
	Non-Interacting	2.0	1.0
2 cm Iron	Interacting	1.5	0.9
	Non-Interacting	2.0	1.0
cm Iron	Interacting	2.0	1.0
	Non-Interacting	2.0	1.0

Description	No Absorber	1 cm Iron	2 cm Iron	10 cm Iron
Interacting muons	$85.8 \pm 0.2\%$	$86.4 \pm 0.3\%$	$87.5 \pm 0.1\%$	$93.2 \pm 0.1\%$
Muons interacting in Absorber	-	$7.3 \pm 0.1\%$	$14.1 \pm 0.1\%$	$53.3 \pm 0.3\%$
Non-interacting muons	$14.5 \pm 0.2\%$	$13.6 \pm 0.3\%$	$12.5 \pm 0.1\%$	$6.8 \pm 0.1\%$
Interacting muons, reconstructed in muon detector	$85.3 \pm 0.2\%$	$86.3 \pm 0.3\%$	$87.3 \pm 0.1\%$	$93.0 \pm 0.1\%$
Muons interacting in Absorber, reconstructed in muon detector	-	$7.3 \pm 0.1\%$	$14.1 \pm 0.1\%$	$53.2 \pm 0.3\%$
Non-interacting muons, reconstructed in muon detector	$14.5 \pm 0.2\%$	$13.5 \pm 0.3\%$	$12.5 \pm 0.1\%$	$6.7 \pm 0.1\%$



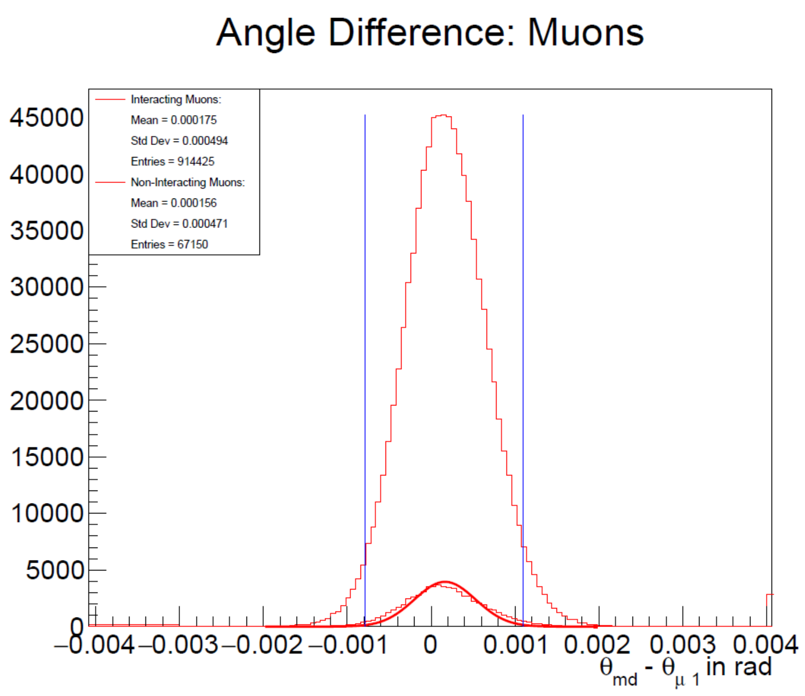


Histogram	**Mean** / rad	**Std Dev** / rad	**Entries**
Before; No Absorber	0.03	0.03	34099
Before; 1 cm Iron	0.04	0.02	18453
Before; 2 cm Iron	0.04	0.02	10728
Before; 10 cm Iron	0.04	0.02	237
Inside; No Absorber	0.0	0.0	0
Inside; 1 cm Iron	0.04	0.02	40195
Inside; 2 cm Iron	0.04	0.02	55481
Inside; 10 cm Iron	0.04	0.02	81491

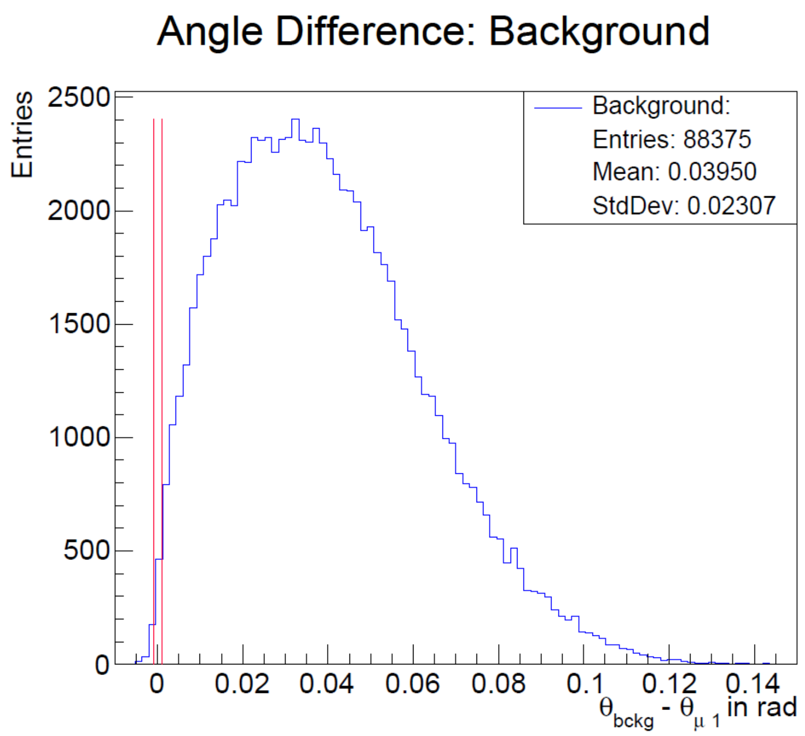
Absorbers reduce background from particles produced before them but also generated new background internally.

- Main source of background: e^+ and e^- from pair production process

Angle method



Percentage of lost muons:
Interacting: 6.0181%
Non-Interacting: 5.0040%

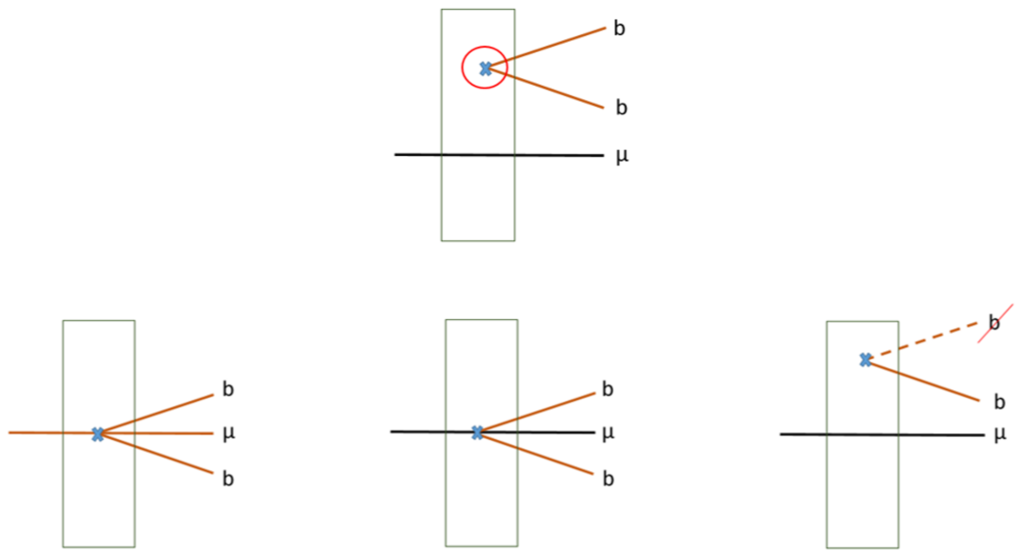


Percentage of background inside cut-off: 0.5262%

	No Absorber	1 cm Iron	2 cm Iron	10 cm Iron
Lost Interacting Muons	0.0025%	5.7833%	5.9584%	6.0181%
Lost Non-Interacting Muons	0.0018%	4.8270%	5.2950%	5.0040%
Background within line cut-off	5.1232%	0.9102%	0.7893%	0.5262%

Vertexing Method for background rejection

- Background particles reconstructed in the muon detector but originating in the absorber can be traced back to their origin, or vertex → If the vertex lies within the absorber, the corresponding track is identified as background and rejected.
- This method works only for background particles generated within the absorber.

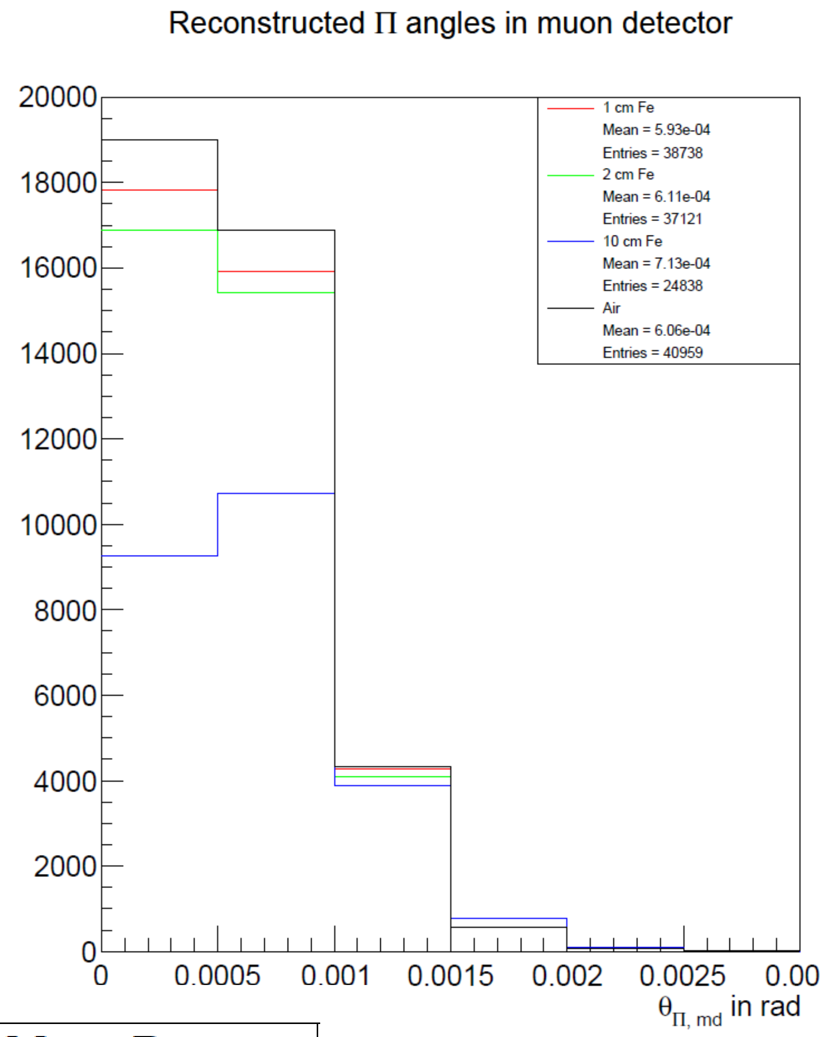


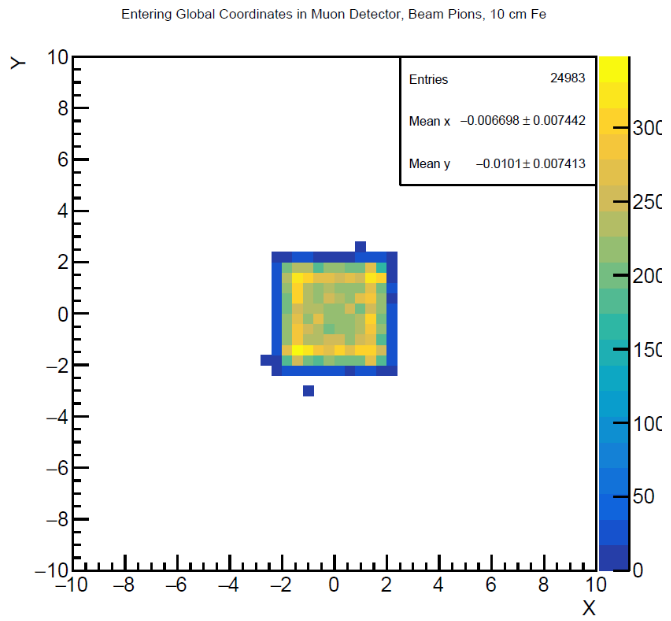
- The percentage of usable tracks in the configuration without an absorber is high, suggesting that most of the background tracks within the cut-off originate from the ECAL
- As the thickness of the absorber increases, the percentage of usable tracks rises
- While the no-absorber setup shows the highest percentage of eliminated background tracks, it is essential to consider the overall data when evaluating performance

Metric	**No Absorber**	**1 cm Iron**	**2 cm Iron**	**10 cm Iron**
Percentage of Usable Tracks	98.1245 %	41.8706 %	44.7911 %	64.9742 %
Muon-Interaction Error	44.3627 %	48.1649 %	42.6244 %	35.5949 %
Track Elimination Efficiency	16.2383 %	13.4586 %	13.4586 %	9.1120 %

Pion contamination study

- Goal: to determine the absorber layer ability to stop beam pions from reaching the muon detector.
- Updated version of FairMUonE
- 10^5 events
- Square-shaped pionic beam generator
- Future work: more realistic beam profile, consisting of a mix of muons and pions





Absorber Configuration	Station 1	Muon Detector
No Absorber	$96.2 \pm 0.2\%$	$41.0 \pm 0.3\%$
1 cm Iron	$96.2 \pm 0.2\%$	$38.7 \pm 0.3\%$
2 cm Iron	$96.2 \pm 0.2\%$	$37.1 \pm 0.4\%$
10 cm Iron	$96.2 \pm 0.1\%$	$24.8 \pm 0.4\%$