ICSC
Centro Nazionale di Ricerca in HPC,
Big Data and Quantum Computing

Machine Learning Algorithms for event reconstruction in Super-Kamiokande

Spoke 2 Annual Meeting
Catania 11 Dec. 2024

Nicola Fulvio Calabria (PoliBa and INFN Bari)
for PoliBa/UniBa WP3 Task Force

Outline

- Super-Kamiokande overview
- Reconstruction in Super-Kamiokande
- Model training
- Preliminary results
- Conclusions and plans

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
Politecnico di Bari

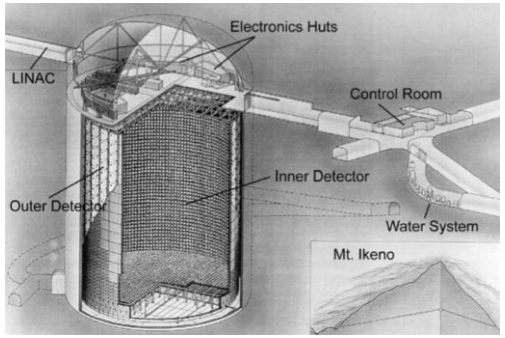
Super-Kamiokande (SK), Kamioka mine, Japan

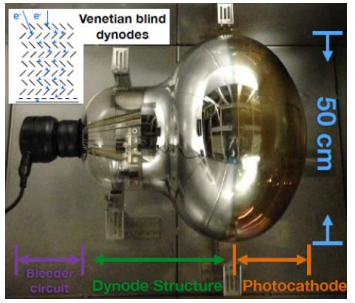
39 m x 40 m cylindric tank filled with 50 kton of ultrapure water, of which 22.5 kton inside Fiducial Volume, divided into two optically insulated sections:

- **Inner Detector (ID):** 11k 50 cm Photomultiplier Tubes (PMTs) (40% coverage) facing inwards.
- **Outer Detector (OD):** 2k 20cm PMTs facing outwards

Some research topics in SK:

- **Proton decay**
- Neutrino oscillations (2015 Nobel Prize)
- Neutrino astrophysics





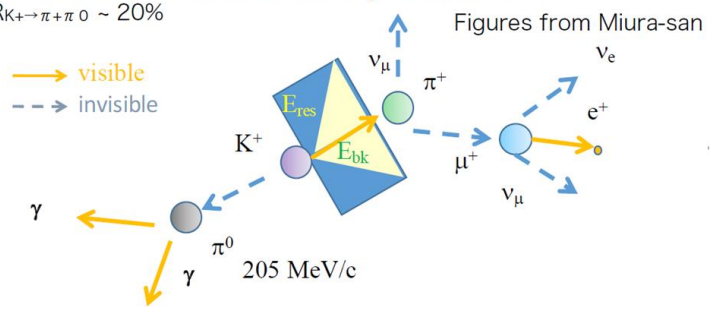
Upon trigger, for each hit PMT, charge produced and time of the hit are collected (event)

Proton decay p -> ν K^+ as a case study in SK

Partial lifetime limit: 5.9 x 10^{33} yrs

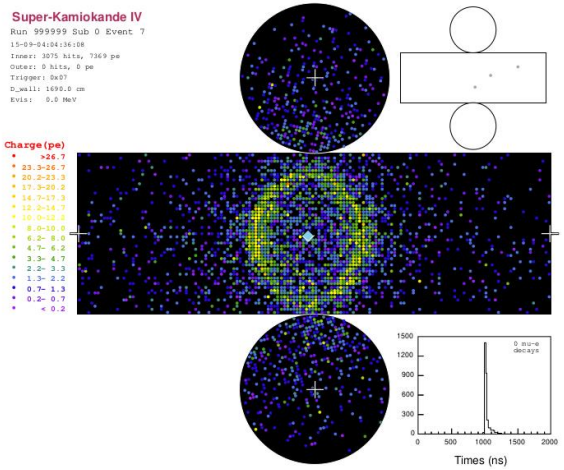
$K^+ \to \pi^+ \pi^0$: Hadronic decay channel in water

$BR_{K^+ \to \pi^+ \pi^0}$ ~ 20%

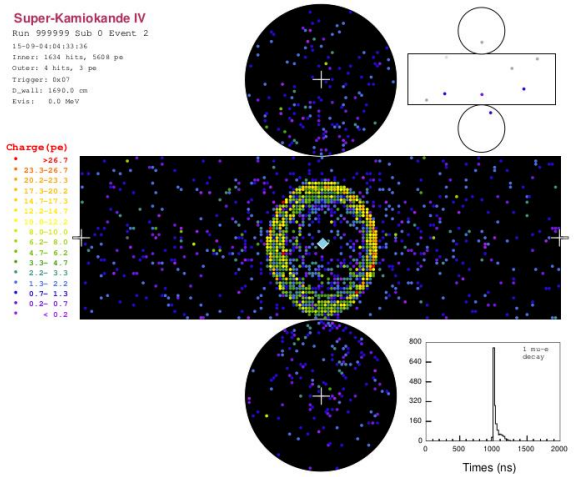


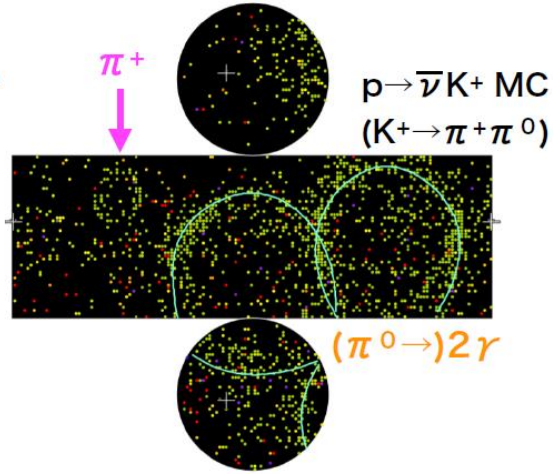
reference Study with APFit:
PHYSICAL REVIEW D90,072005 (2014)
«Search for proton decay via p→νK using 260 kiloton ·year data of Super-Kamiokande»

Showering (e-like)



Non showering (muon-like)





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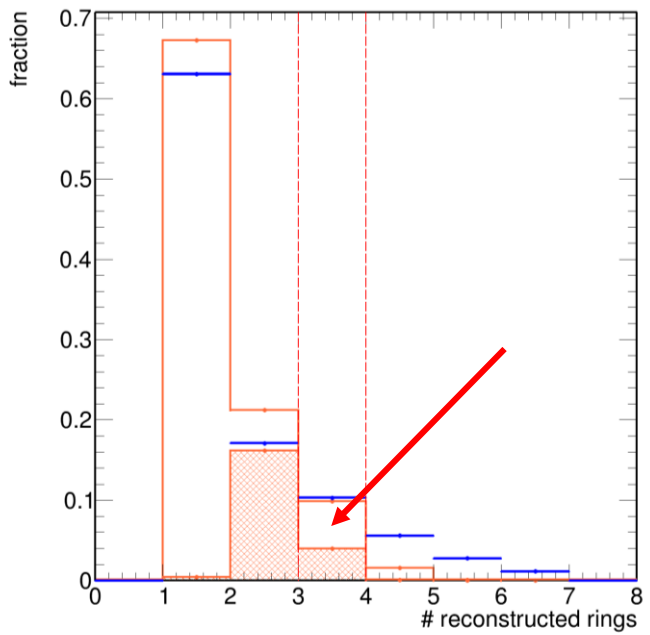
p -> ν K^+ Analysis with fiTQun (MC only)

Exposure (kton*yr)	#BG	BG sys. Err. (%)	Eff. (%)	Eff. Sys. Err. (%)
200	0.03 ± 0.02	50.9	2.9 ± 0.02	26.1



SK ATM-ν MC (background)
SK PDK MC
True $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ (hatching) (signal)

Reconstruction algorithms in SK

	APfit	fiTQun
Type of fit	Sequential (vertex, ring counting, PID, michel-e tagging)	Single log-likelihood function minimization $L(\mathbf{x}) = \prod_j^{\text{unhit}} P_j(\text{unhit}\|\mathbf{x}) \prod_i^{\text{hit}} [1 - P_i(\text{unhit}\|\mathbf{x})]\, f_q(q_i\|\mathbf{x}) f_t(t_i\|\mathbf{x})$
Used by	Super-Kamiokande	T2K, MiniBooNE, Super-Kamiokande, Hyper-Kamiokande
Max # rings	5	6
PID	$e^\pm$, $\mu^\pm$	$e^\pm$, $\mu^\pm$, $\pi^\pm$
CPU time per SK event	< 1 min/event	~ 10 min/event

fiTQun makes the reconstruction of charged kaon kinematics possible (charged pion PID)

Low-background analysis in this proton decay channel with fiTQun is possible.

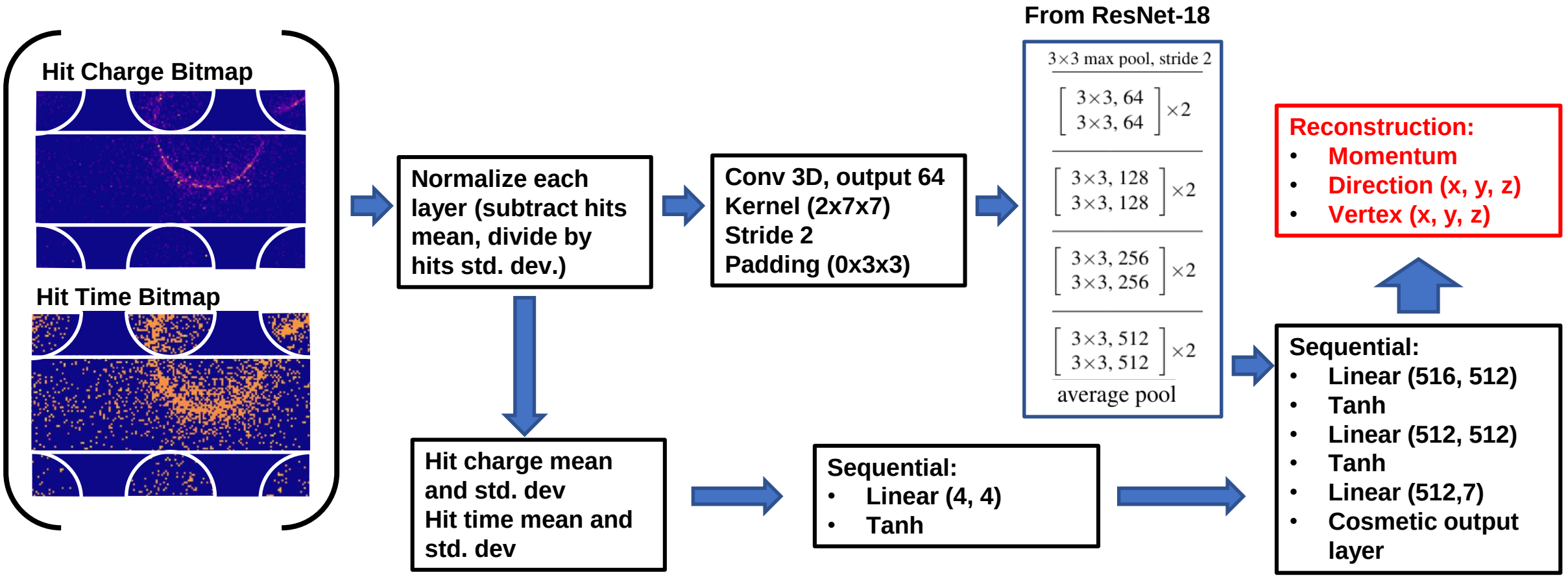
We aim to increase signal selection efficiency by improving ring detection.

Machine Learning algorithms are interesting candidates for this purpose.

Results and plot from N.F. Calabria PhD Thesis, 'Search for proton decay in Super-Kamiokande and perspectives in the Hyper-Kamiokande experiments', 2023, Università degli Studi di Napoli.

Reconstruction of electron events in Super-Kamiokande with Machine Learning

- Preliminary study using a custom ResNet-18 based Neural Network in PyTorch.



Model Training

Dataset:
4 M (Train/Validation: 80%/20%) + 1M (Test) electron events generated with SKDETSIM
Momentum: 0 – 1000 MeV/c isotropic
Vertex: uniform in ID volume with distance from wall 100 cm

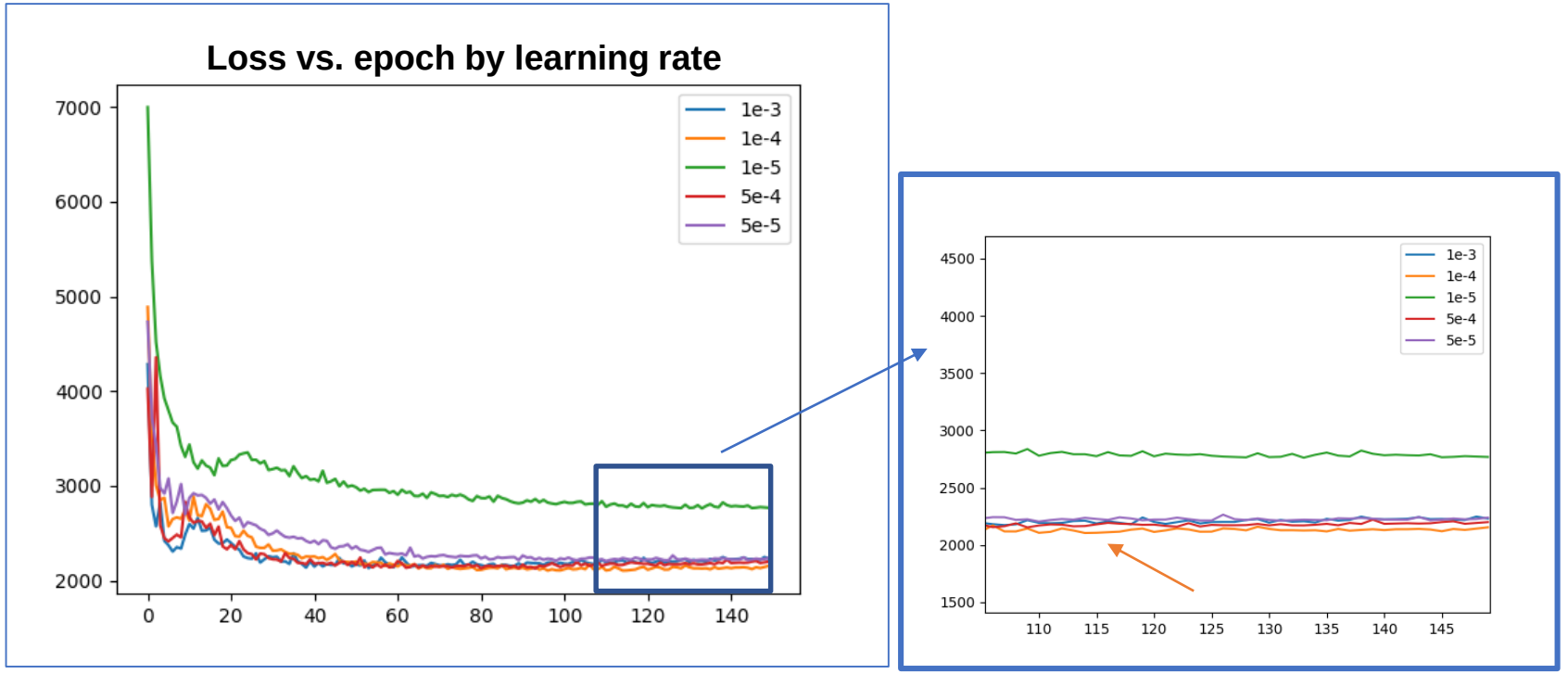
Hardware:
Tesla A100 40 GB (local server farm)

Optimizer:
ADAM

Loss:
MSELoss

Learning rate:
Coarse grid search, 150 epochs per trial

Best candidate chosen:
Learning rate $1x10^{-4}$ after 115 epochs
(~30 minutes per epoch)



Model reconstruction performance

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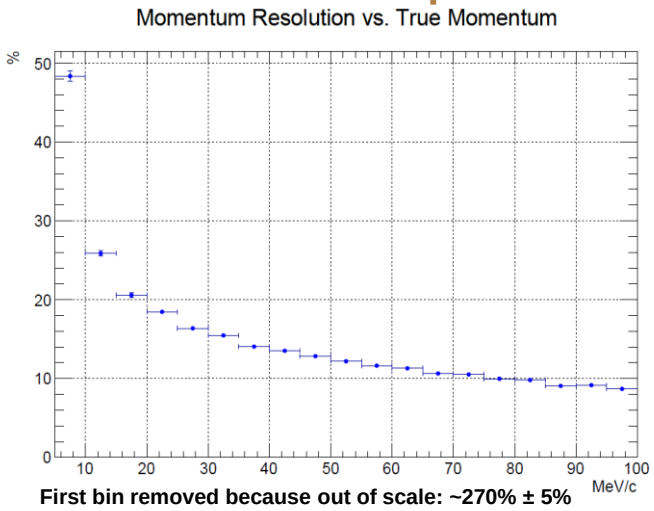
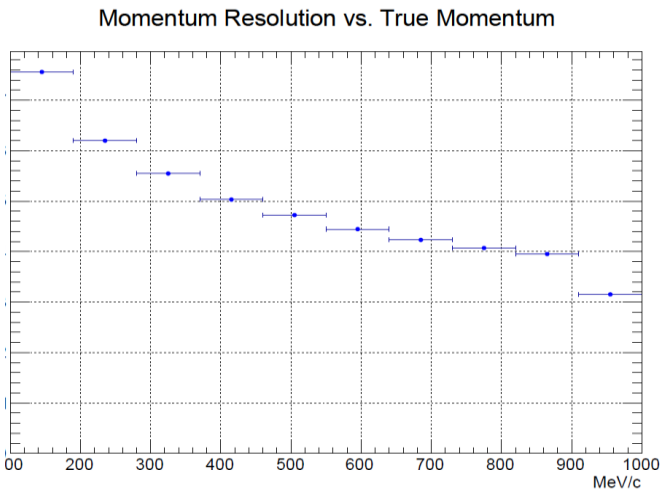
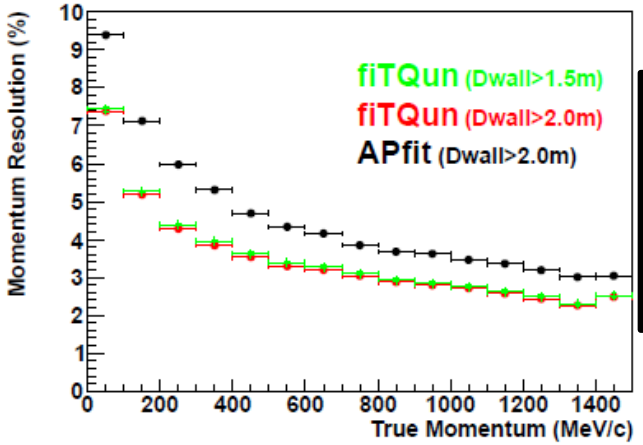


First bin removed because out of scale: ~270% ± 5%

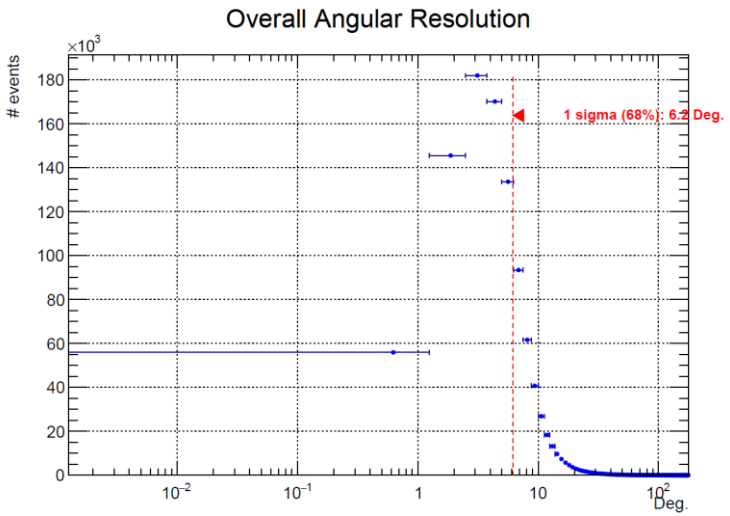


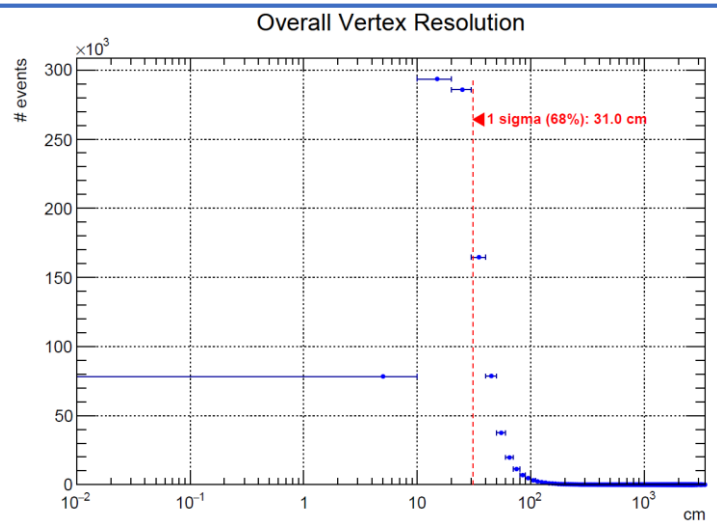


This plot and the following fiTQun references are from Y. Suda PhD Thesis «Search for proton decay using an improved event reconstruction algorithm in Super-Kamiokande», 2017.

Overall angular resolution

Model: 6.2°
fiTQun: ~3°



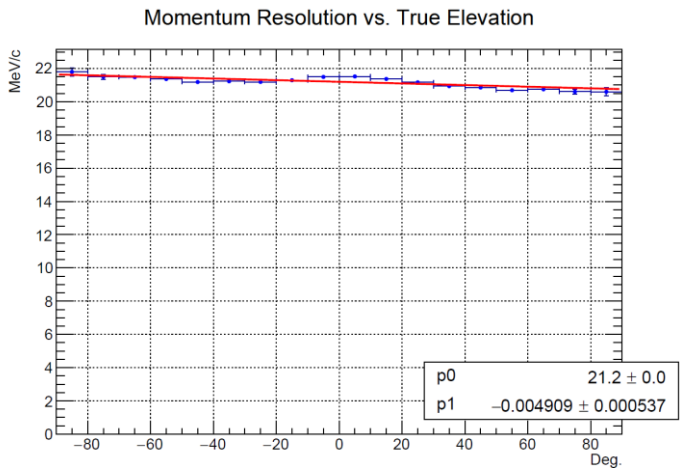


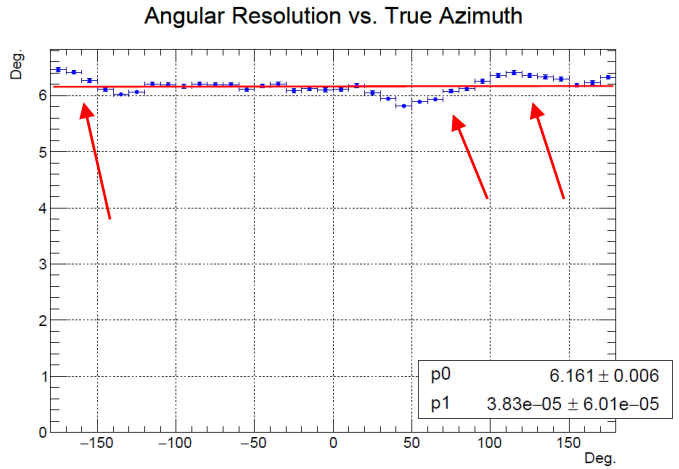
Overall vertex resolution

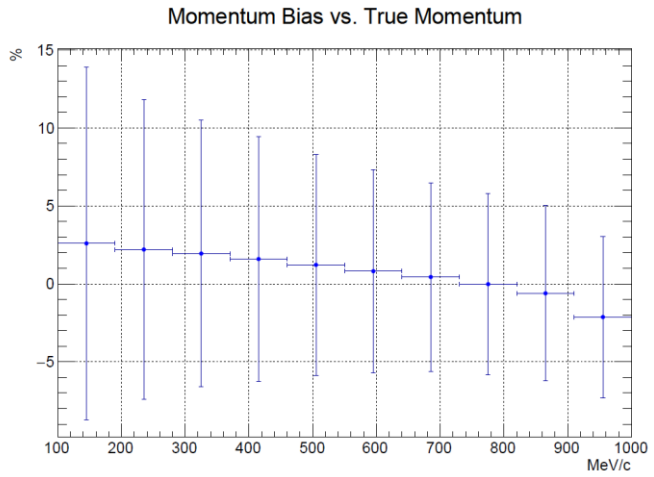
Model: 31.0 cm
fiTQun: 19.5 cm

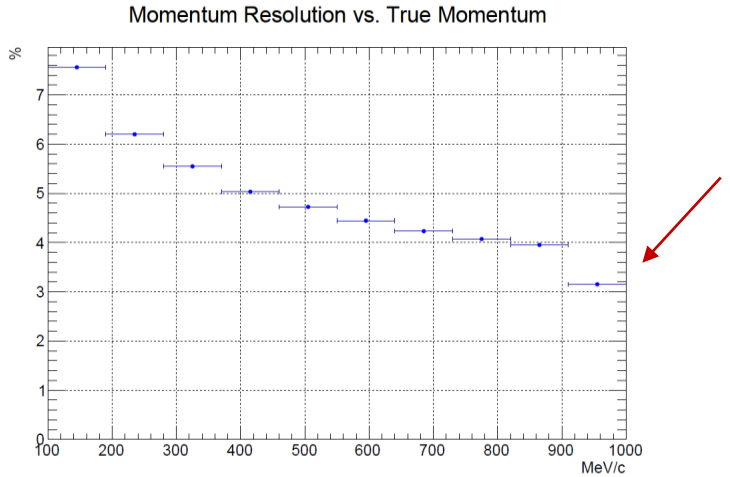
Some features to investigate

PRELIMINARY









Conclusions, plans…

- I trained and tested a preliminary Machine Learning model for reconstruction in Super-Kamiokande with an electron-only dataset
- There are some features that need to be investigated
- There is much room for improvement and optimization
- I plan to extend this study to muons and charged pions
- I presented this model at «Neutrino Physics and Machine Learning 2024», ETH Zurich, 25 – 28 June, 2024.

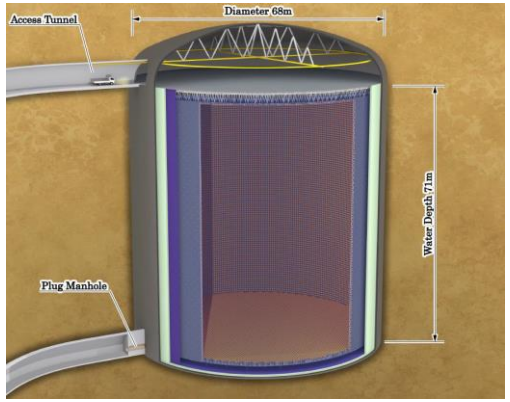
The next phase will be computationally intensive: I will use CINECA resources for that!

… and perspectives for Hyper-Kamiokande!

fiTQun will be part of the official reconstruction suite For Hyper-Kamiokande, the next generation Water Cherenkov detector (start of operations expected for 2027)

I'm porting it to GPUs using CUDA.

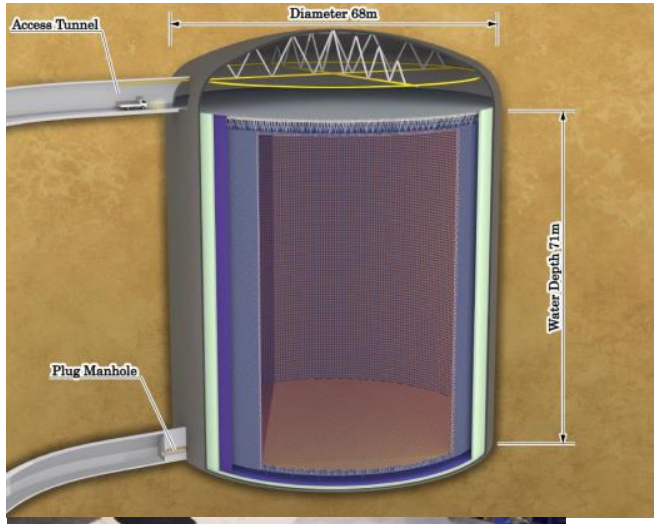
Work in progress!



"This work is (partially) supported by ICSC – Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union – NextGenerationEU"

THANK YOU!

Hyper-Kamiokande (HK) (Hida mine, Japan) and perspectives



HK is under construction: operation will begin in 2027!

- **Cylindrical tank: (68 m x 71 m)**
- **Fiducial volume: 0.19 Mton (~ 8 SK FV)**
- **20k 50 cm PMTs in the ID**
- **~ 1k composite photosensors (multi-PMT)**

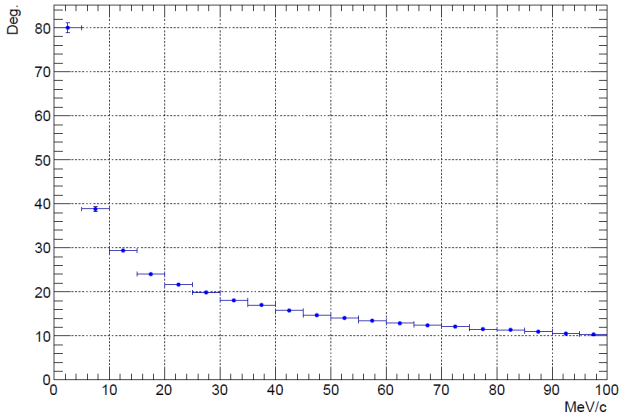
fiTQun takes 1 order of magnitude CPU time more per multi-ring HK event with respect to SK

Two possible candidate approaches:

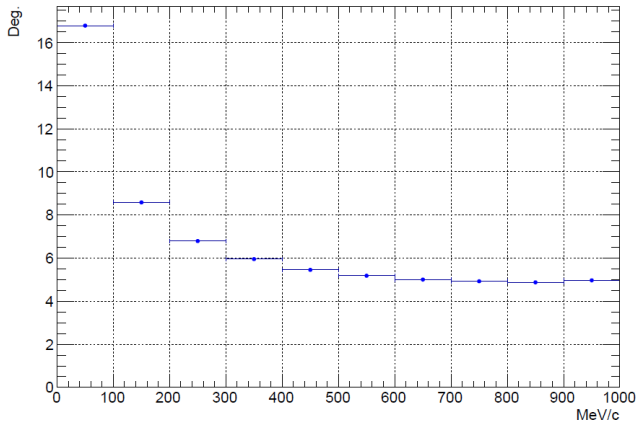
- **Port fiTQun code to run on GPUs**
- **Introduce Machine Learning algorithms for reconstruction, shifting the computational effort to training**

PRELIMINARY

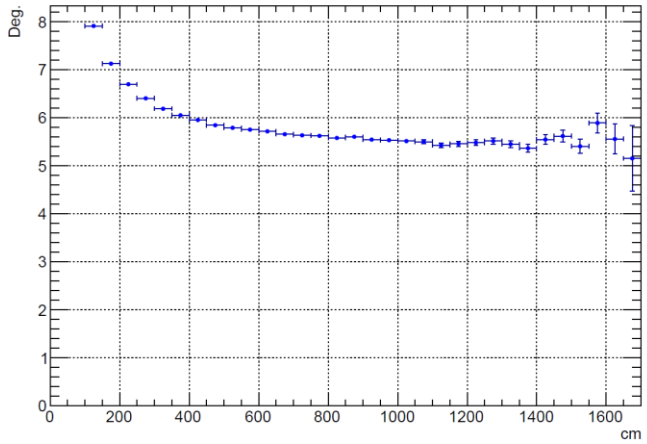
Angular Resolution vs. True Momentum



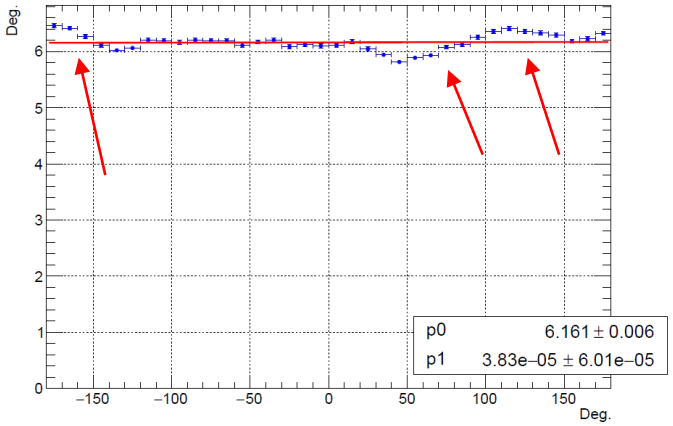
Angular Resolution vs. True Momentum



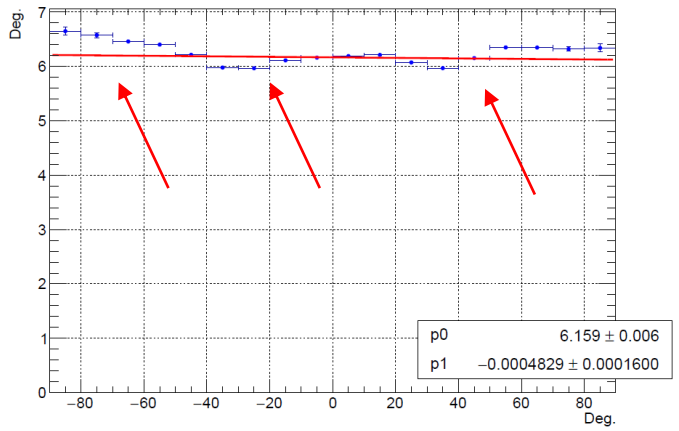
Angular Resolution vs. True Distance from ID Wall



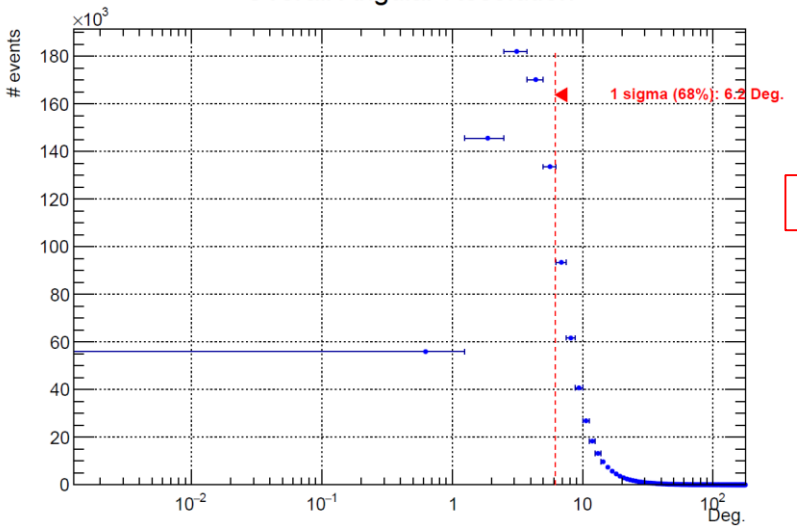
Angular Resolution vs. True Azimuth



Angular Resolution vs. True Elevation



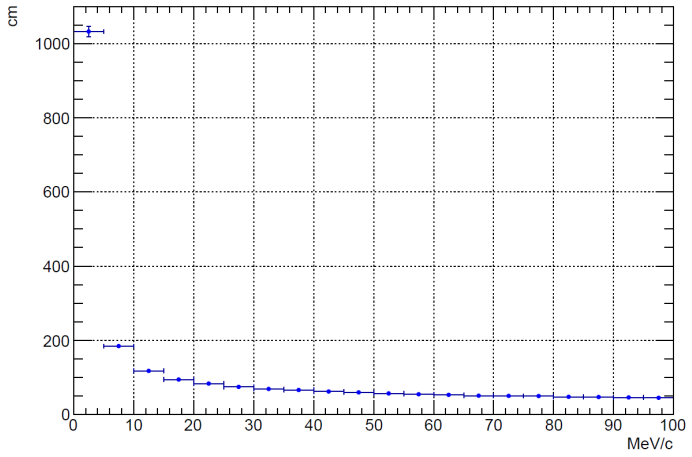
Overall Angular Resolution



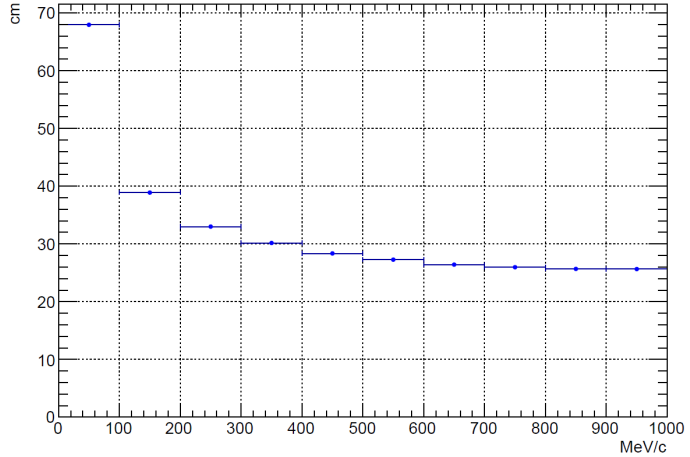
fiTQun: ~3°

PRELIMINARY

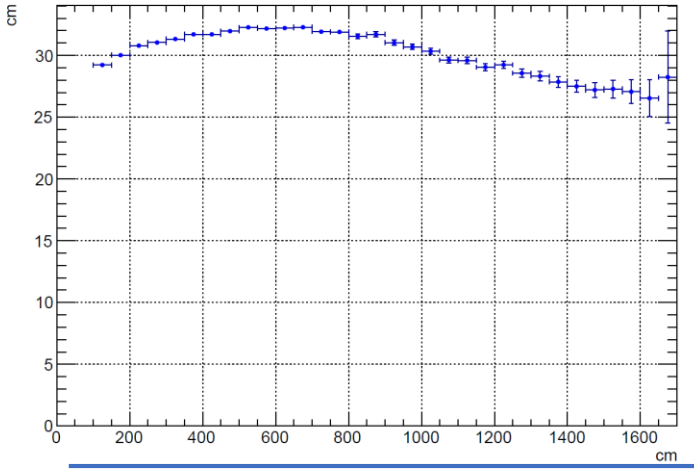
Vertex Resolution vs. True Momentum



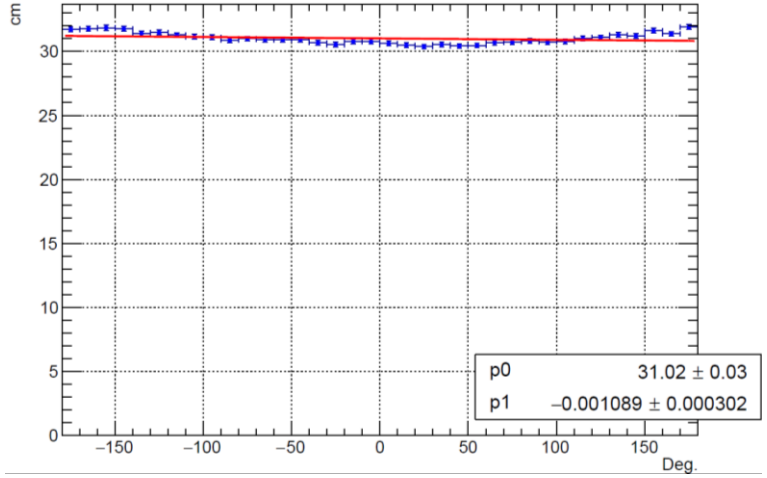
Vertex Resolution vs. True Momentum



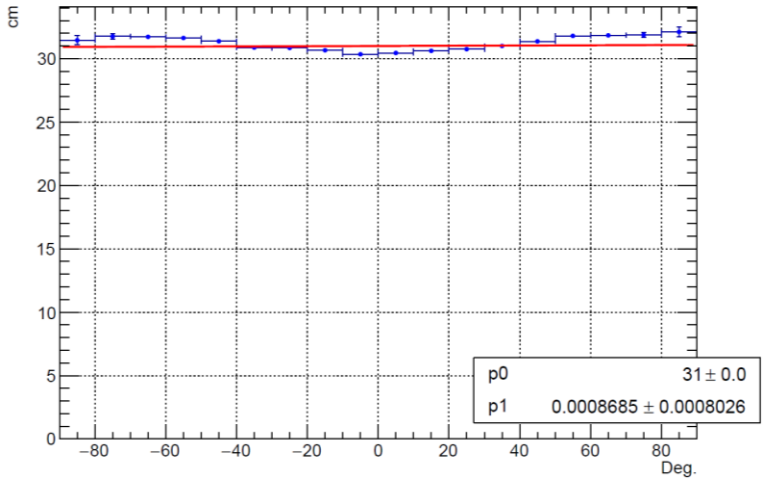
Vertex Resolution vs. True Distance from ID Wall



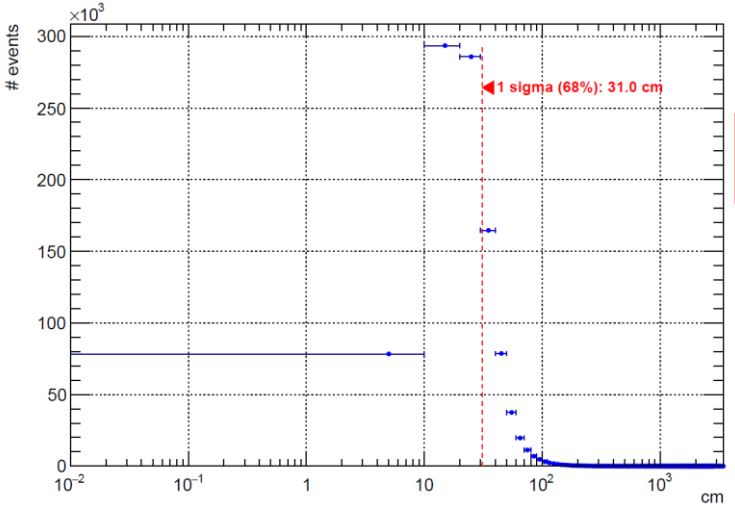
Vertex Resolution vs. True Azimuth



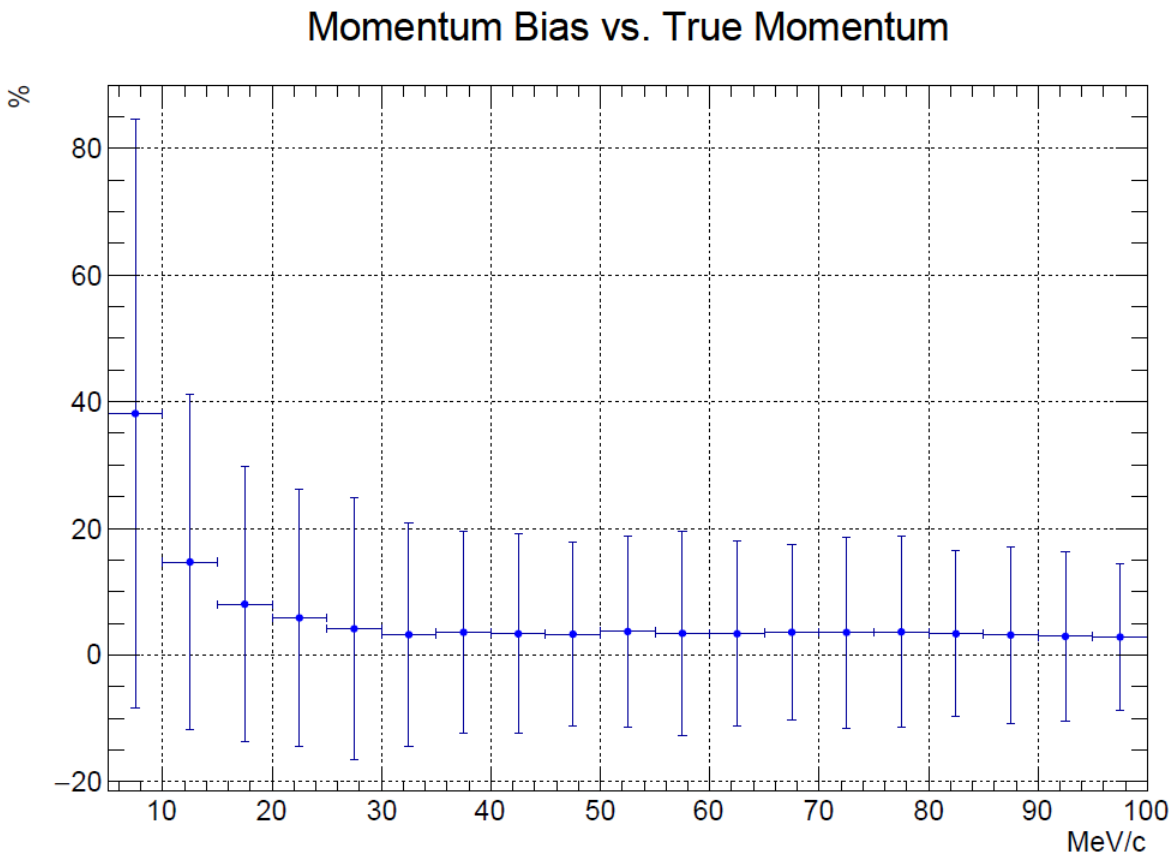
Vertex Resolution vs. True Elevation

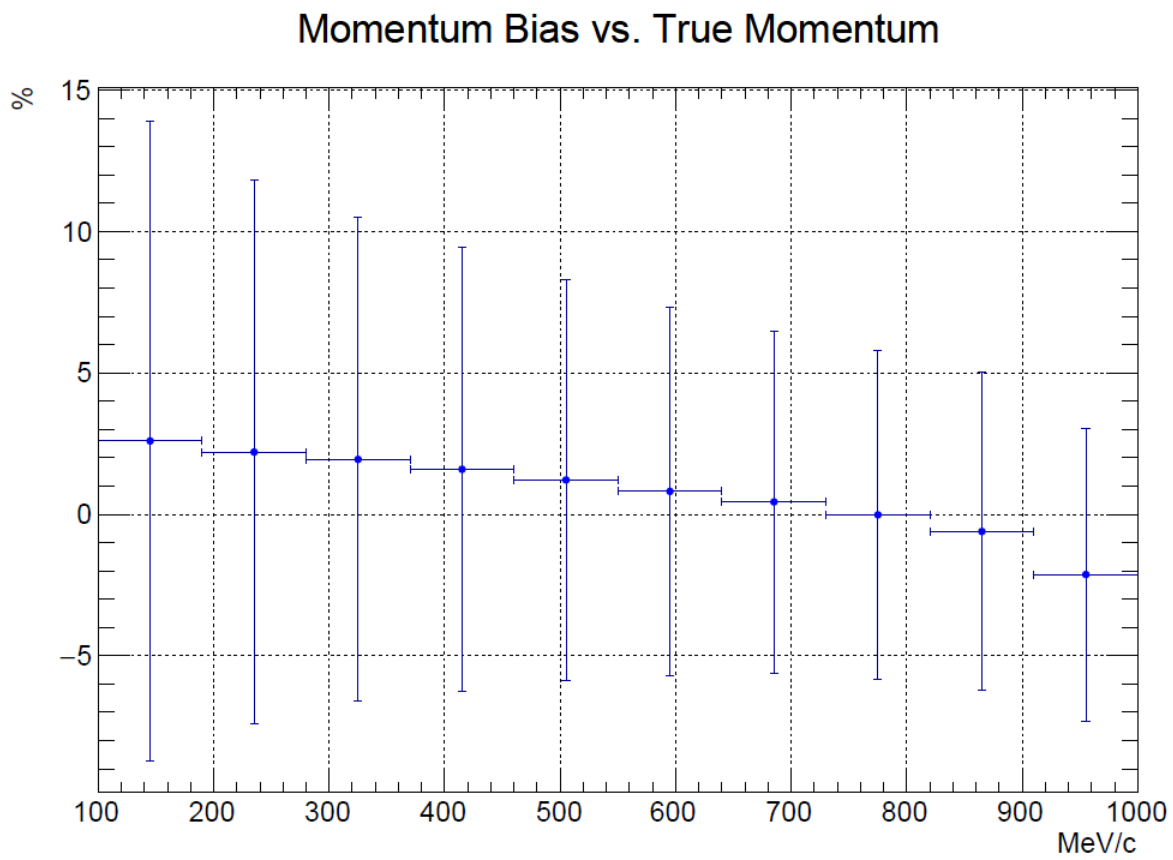


Overall Vertex Resolution



fiTQun: 19.5 cm

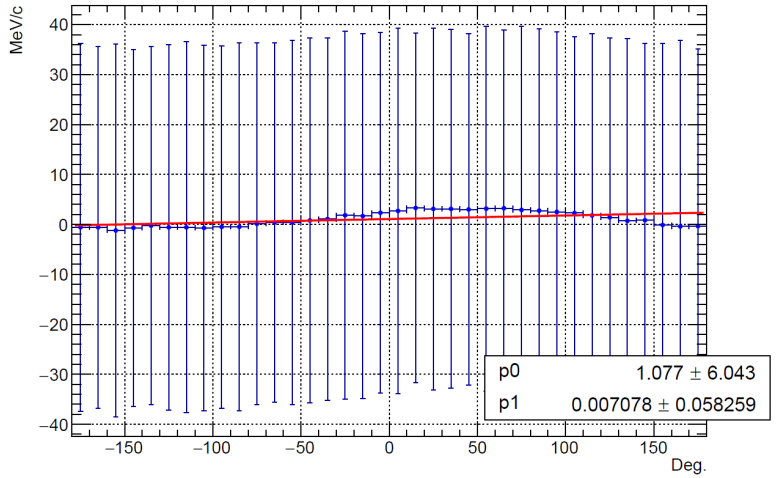




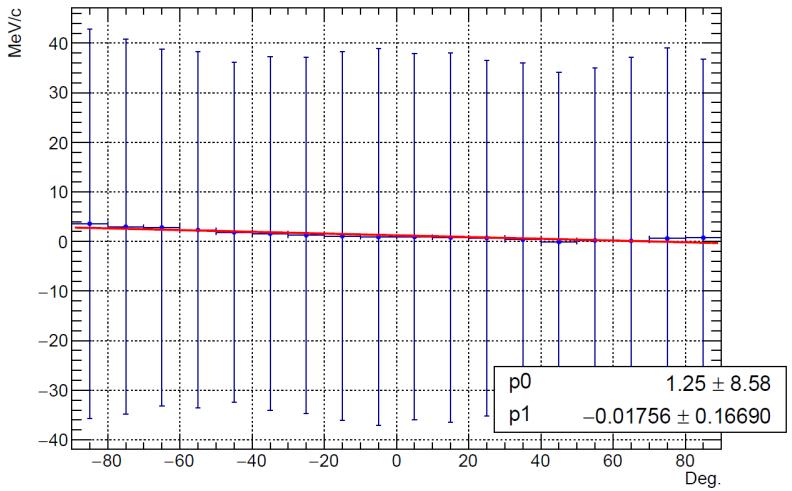
First bin removed because out of scale: ~1000% ± 15000%

PRELIMINARY

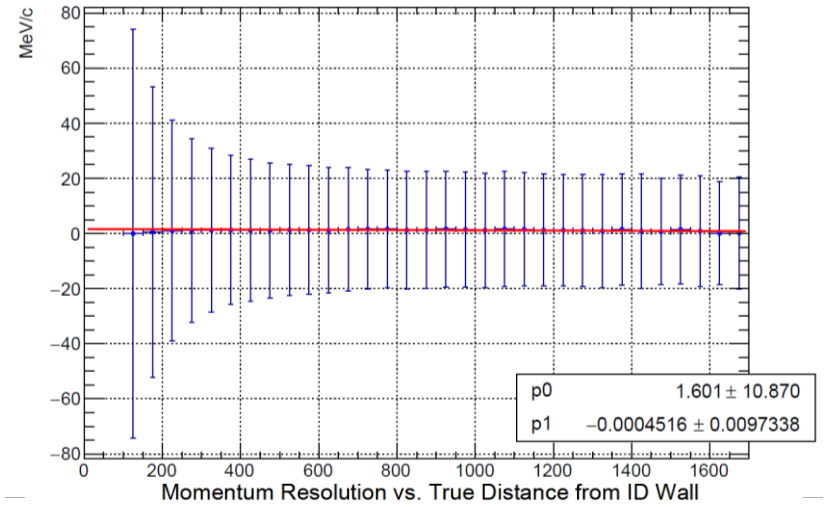
Momentum Bias vs. True Azimuth



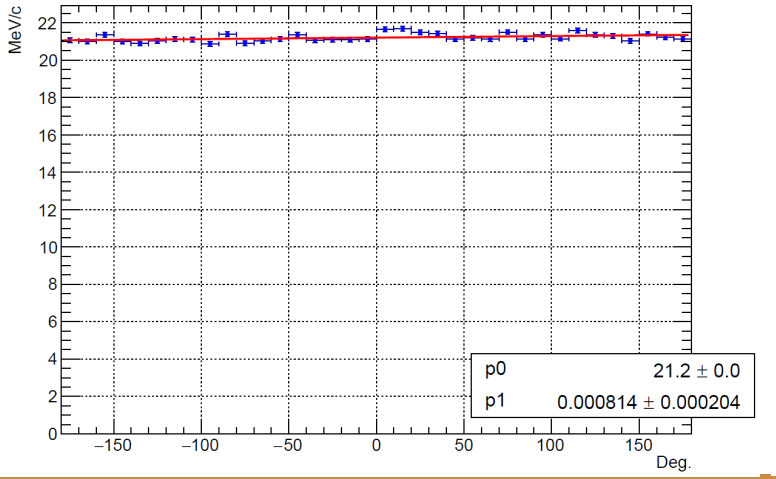
Momentum Bias vs. True Elevation



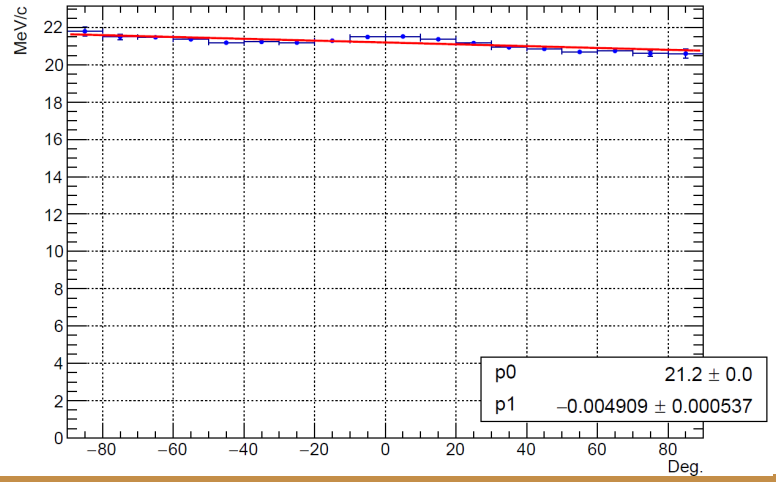
Momentum Bias vs. True Distance from ID Wall



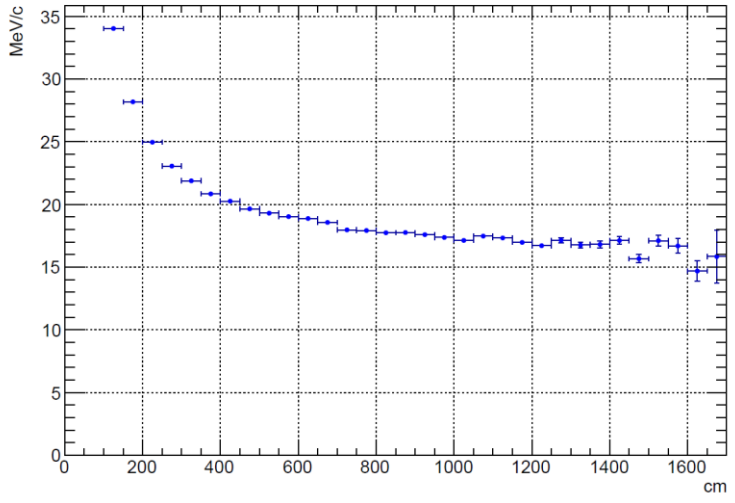
Momentum Resolution vs. True Azimuth



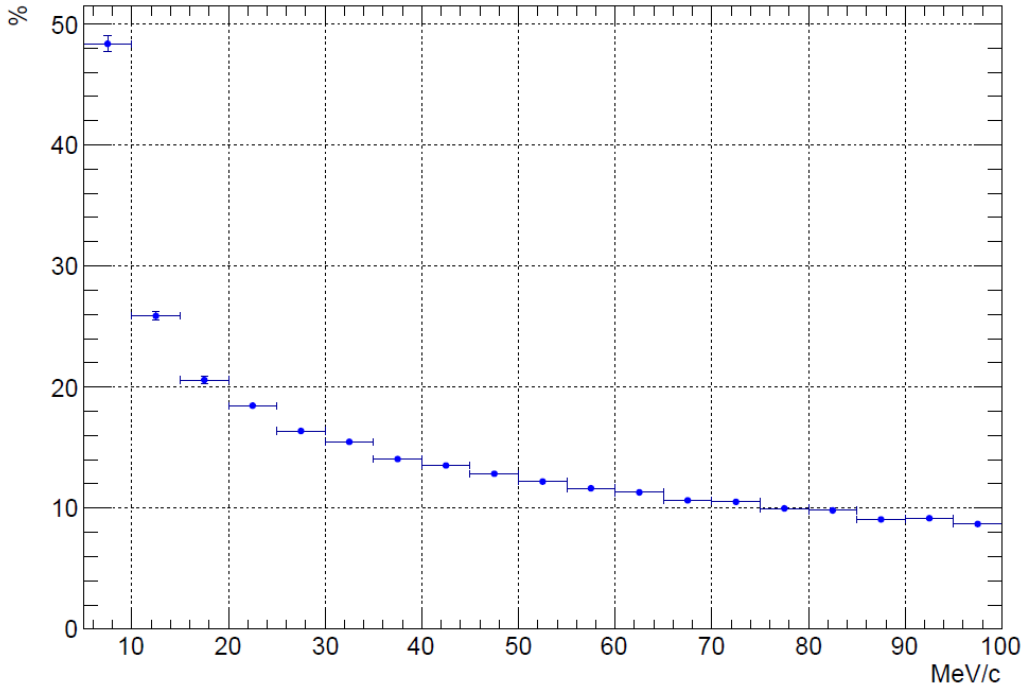
Momentum Resolution vs. True Elevation



Momentum Resolution vs. True Distance from ID Wall

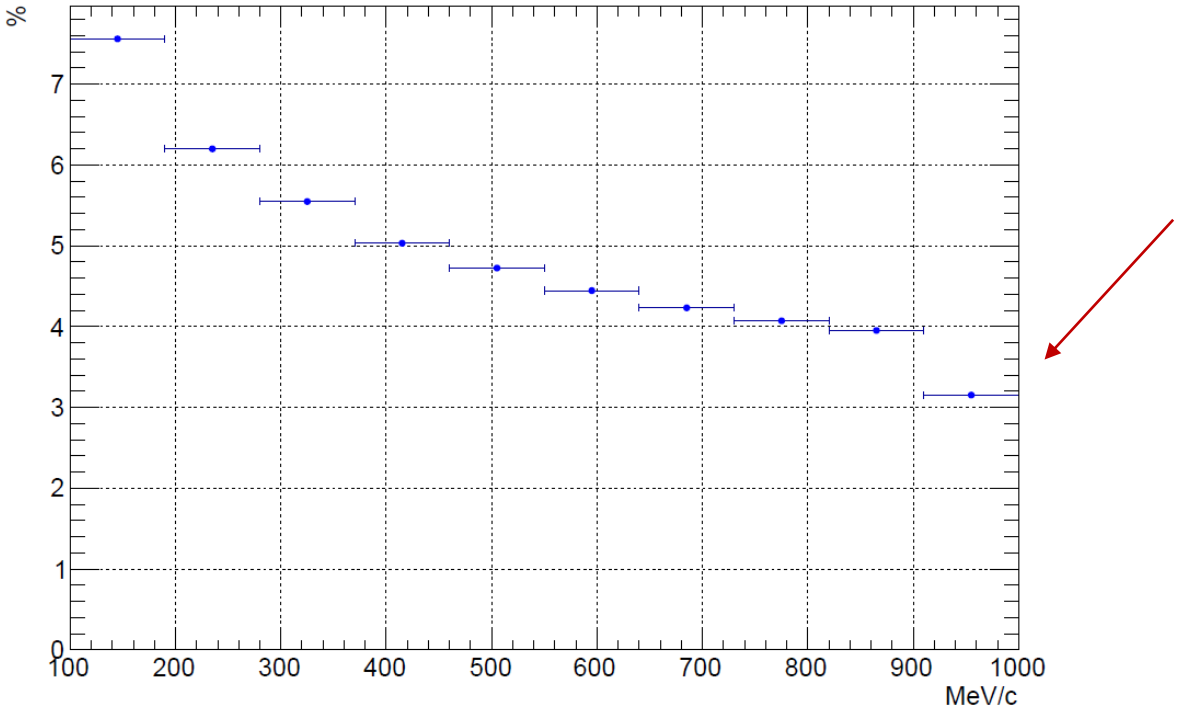


Momentum Resolution vs. True Momentum

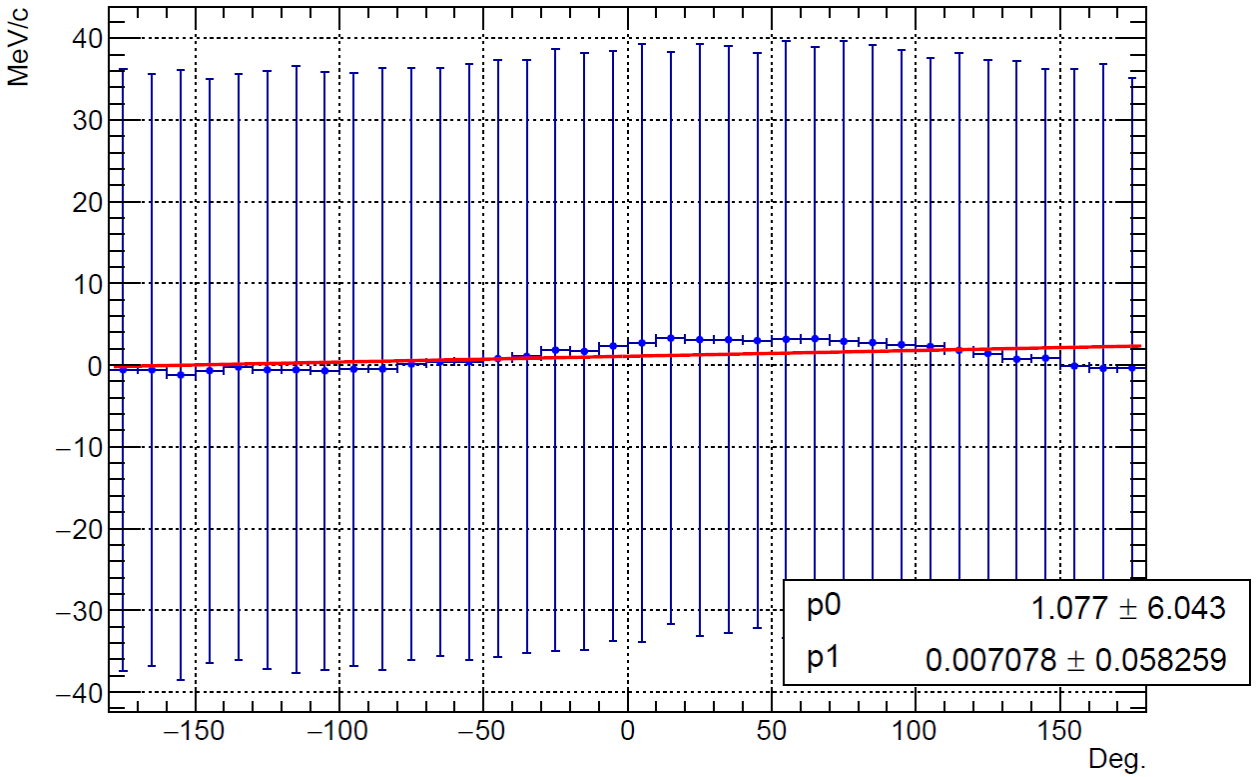


First bin removed because out of scale: ~270% ± 5%

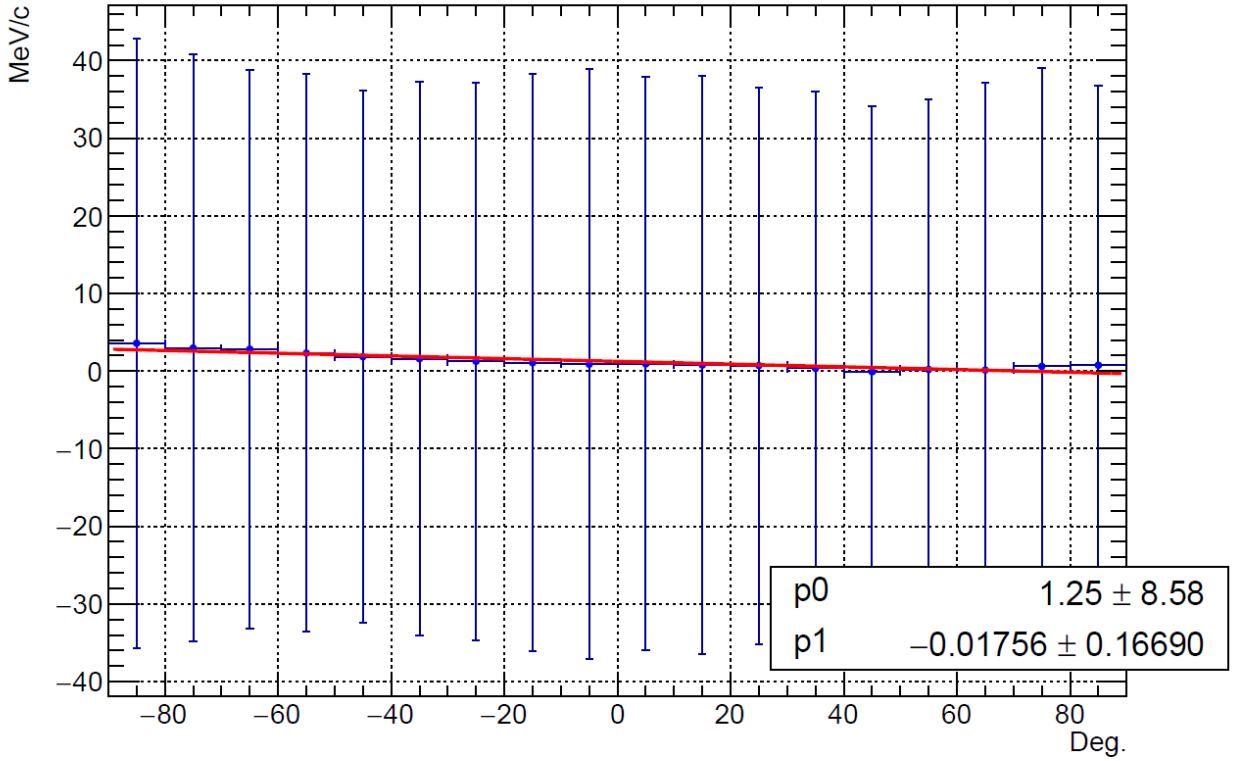
Momentum Resolution vs. True Momentum



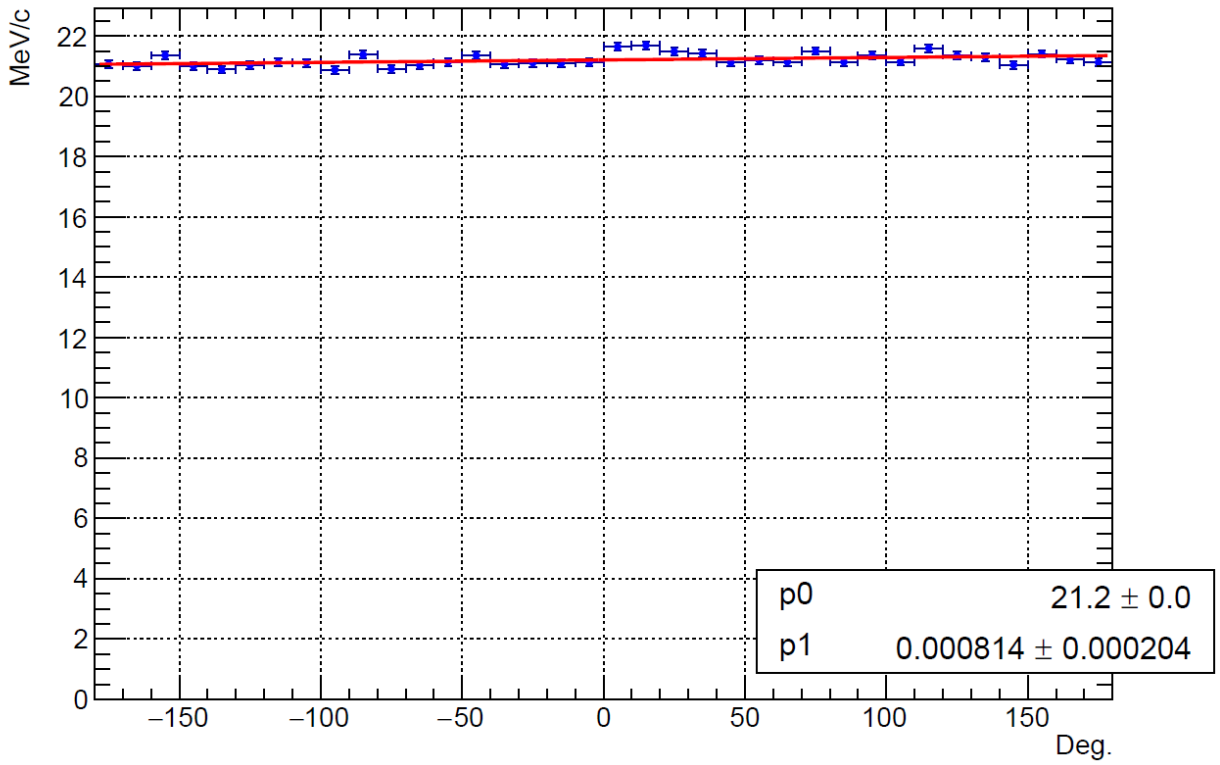
Momentum Bias vs. True Azimuth



Momentum Bias vs. True Elevation



Momentum Resolution vs. True Azimuth



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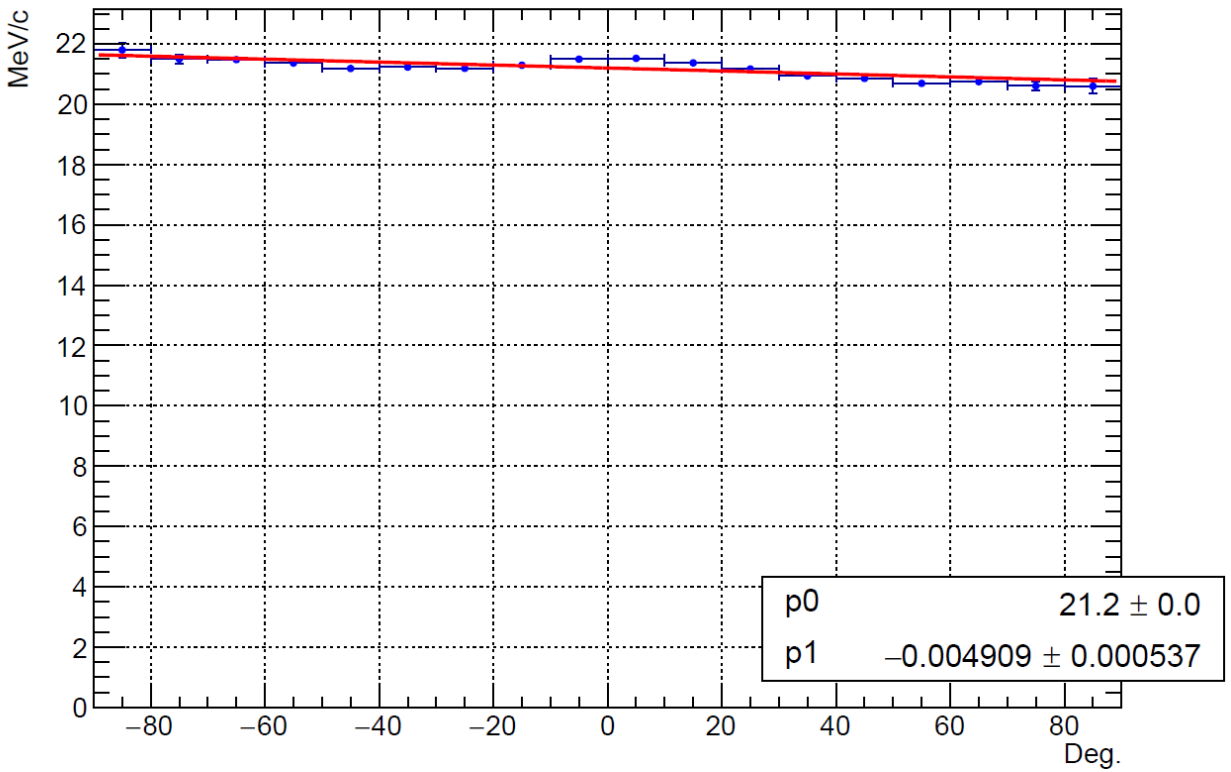
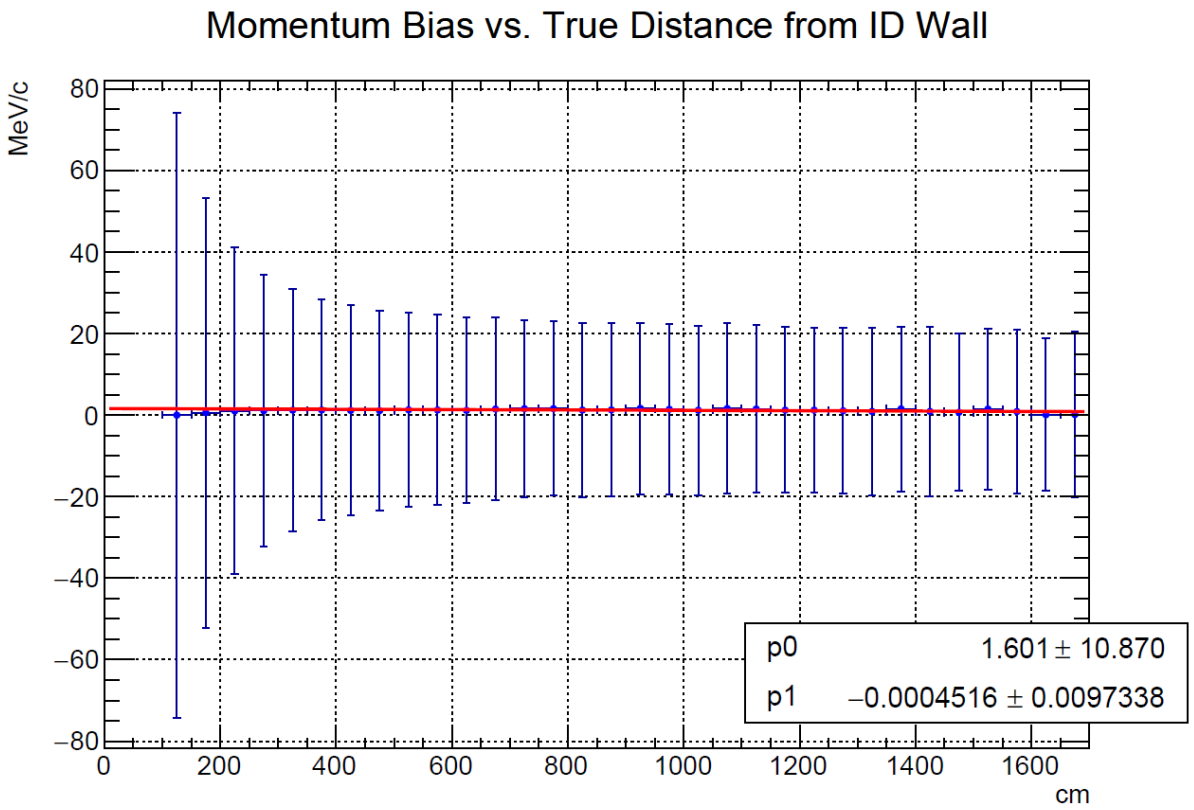
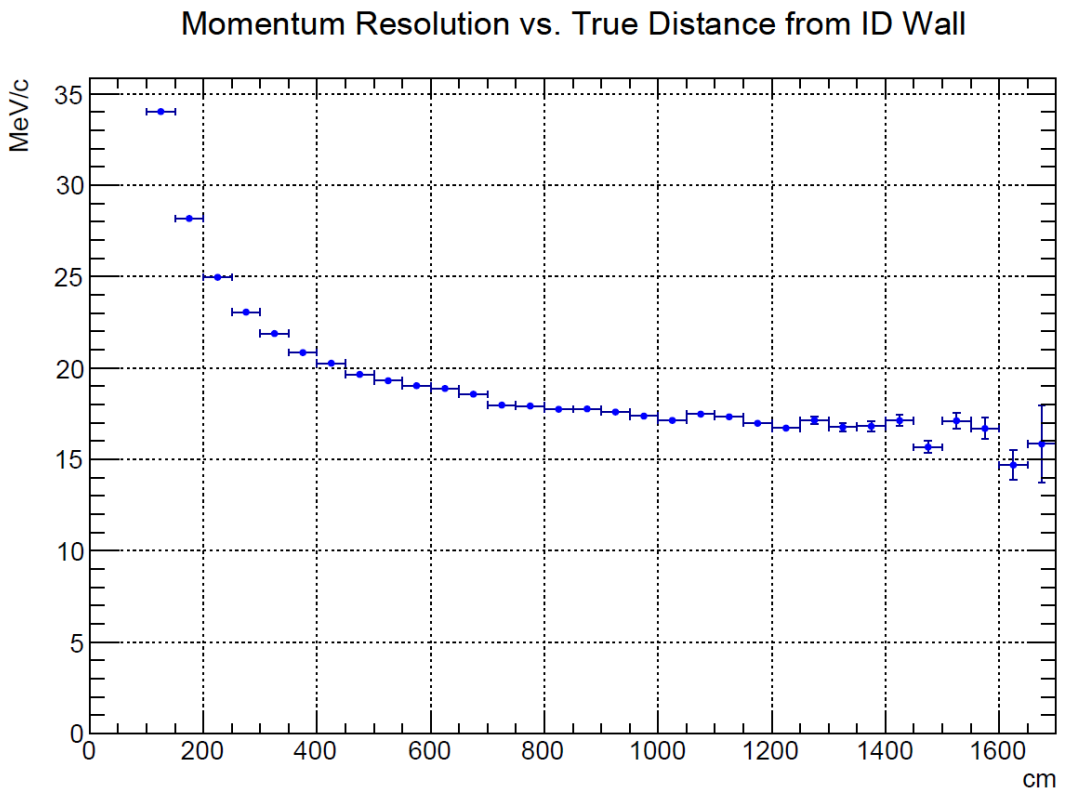
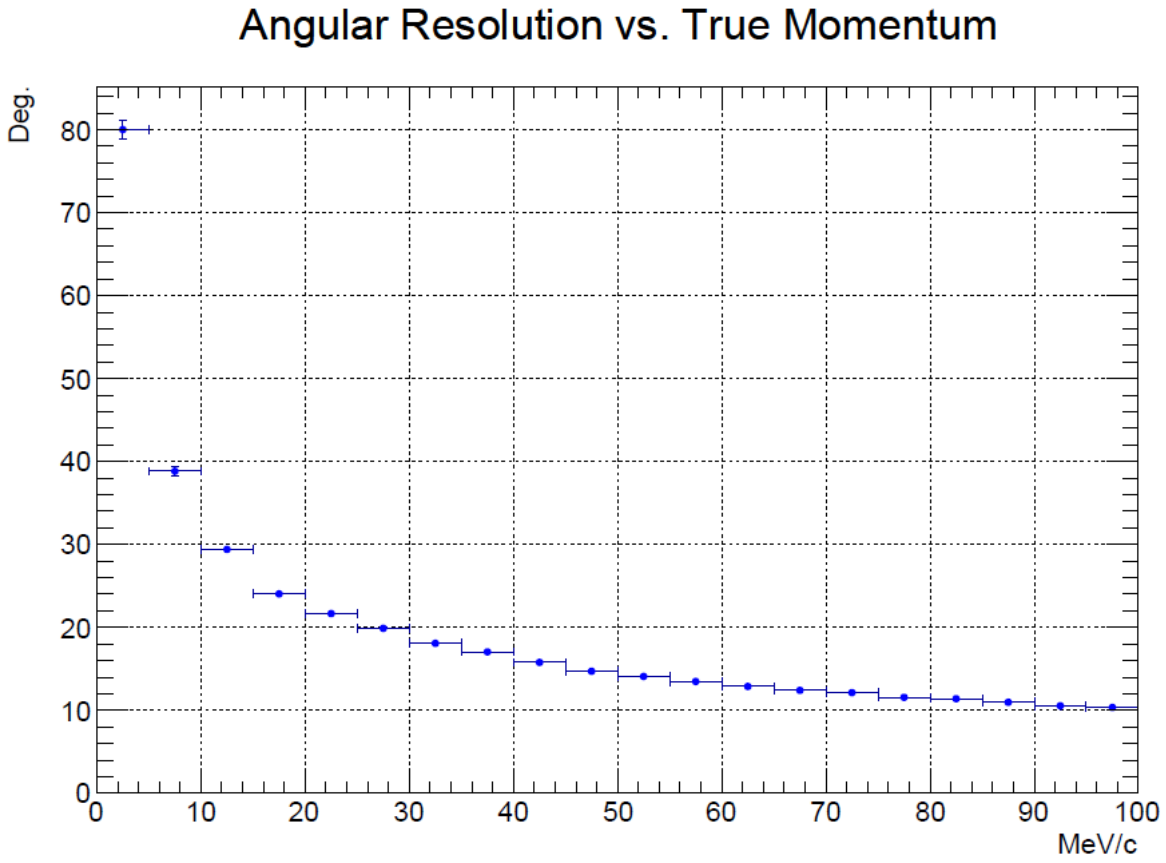
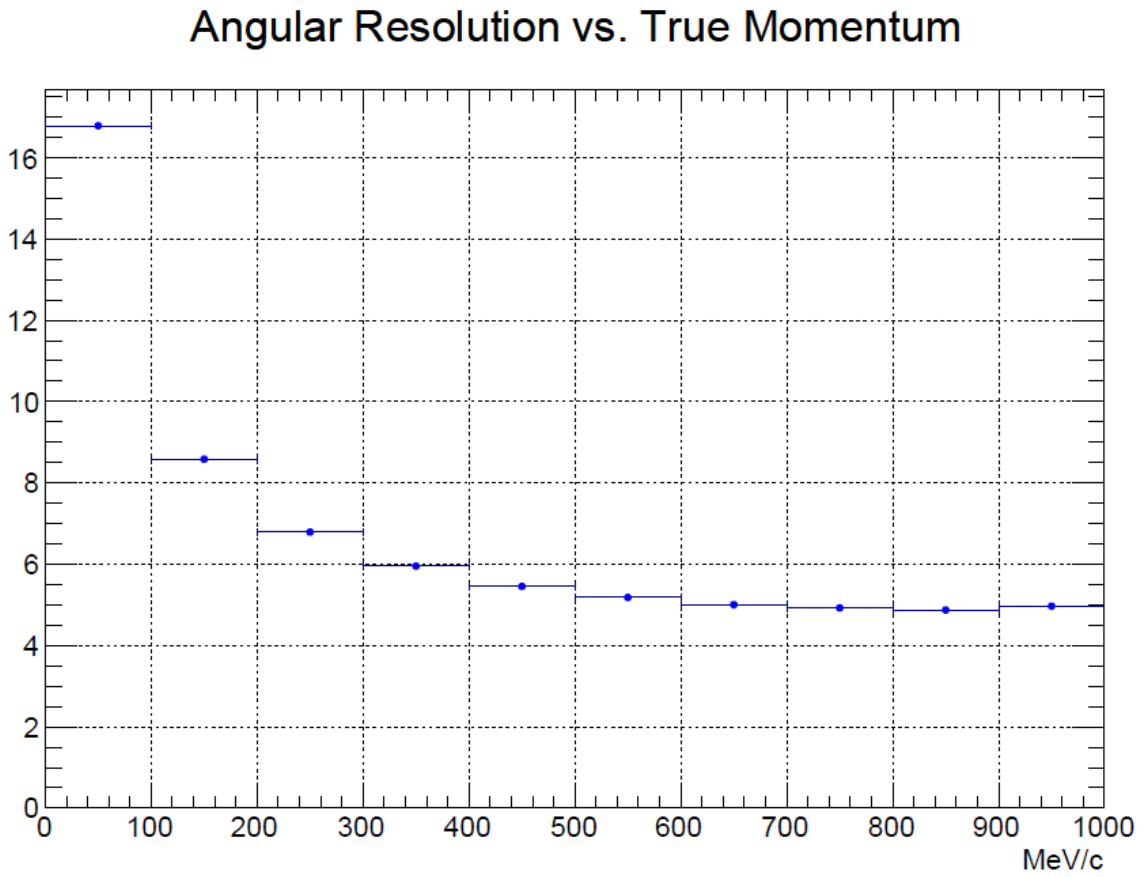


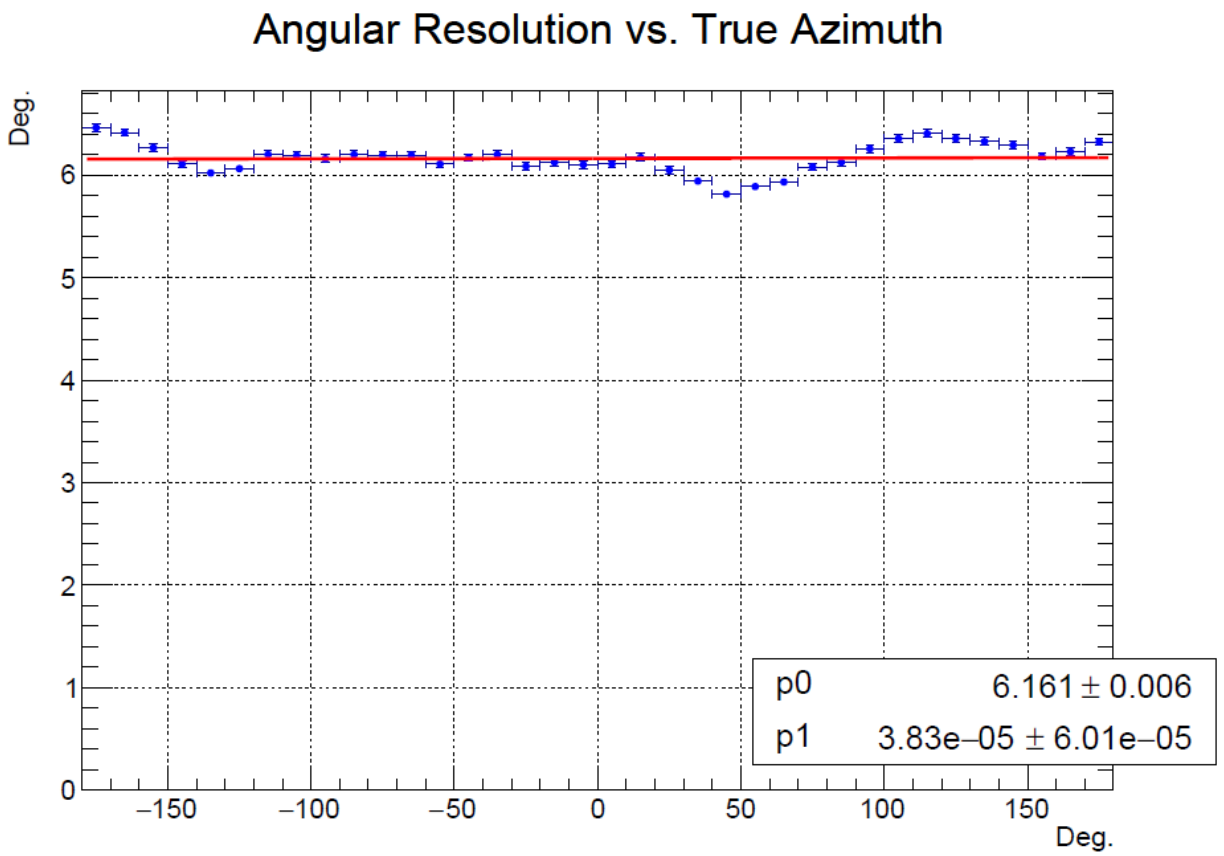

Momentum Bias vs. True Distance from ID Wall
MeV/c
80
60
40
20
0
−20
−40
−60
−80
0
200
400
600
800
1000
1200
1400
1600
cm
p0 1.601 ± 10.870
p1 −0.0004516 ± 0.0097338

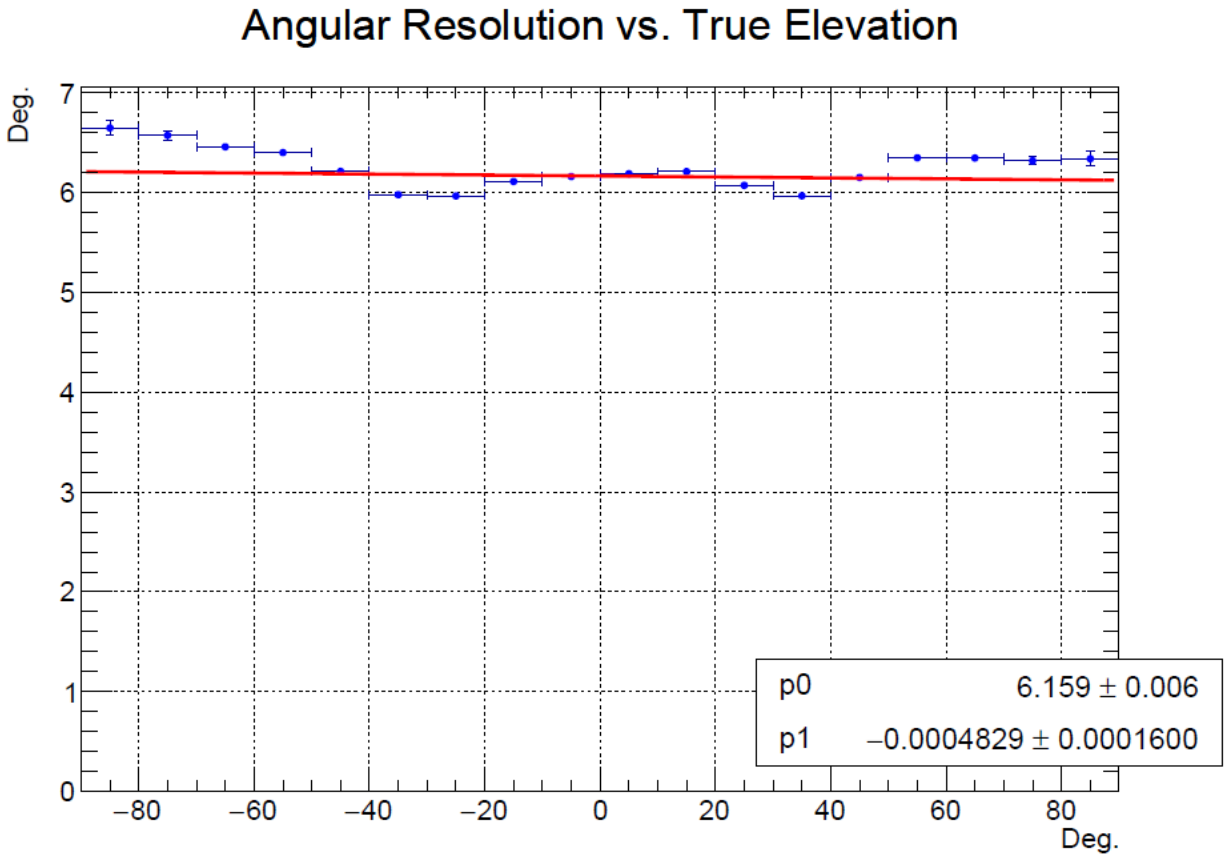

Momentum Resolution vs. True Distance from ID Wall
MeV/c
35
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
cm

Direction reconstruction

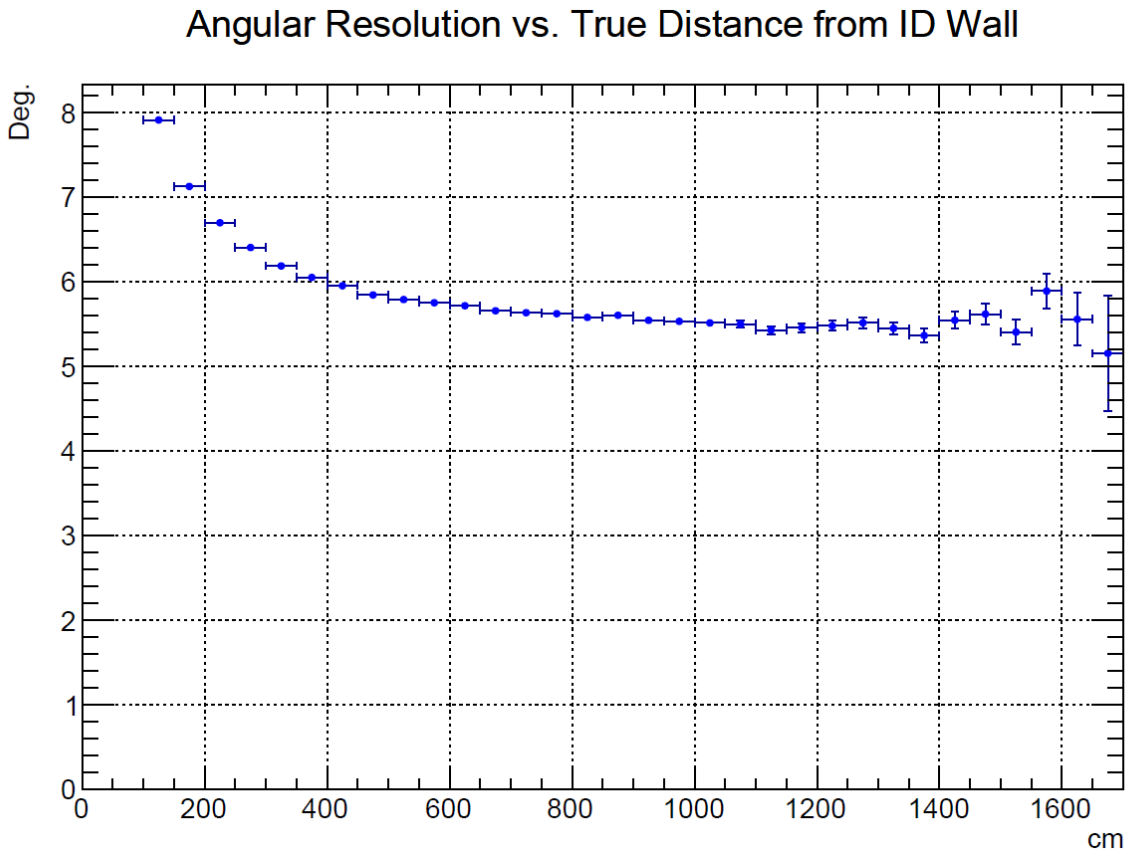


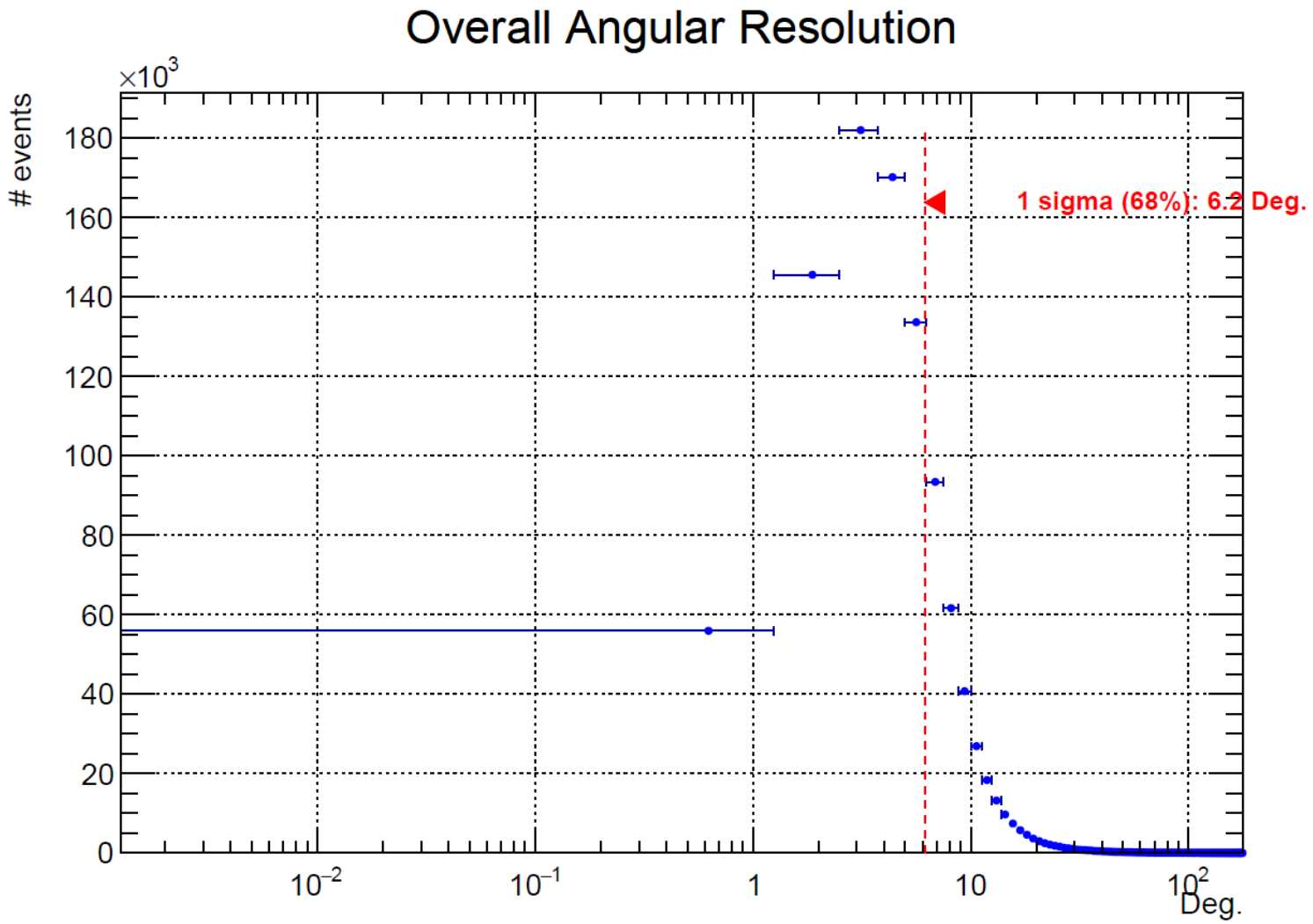


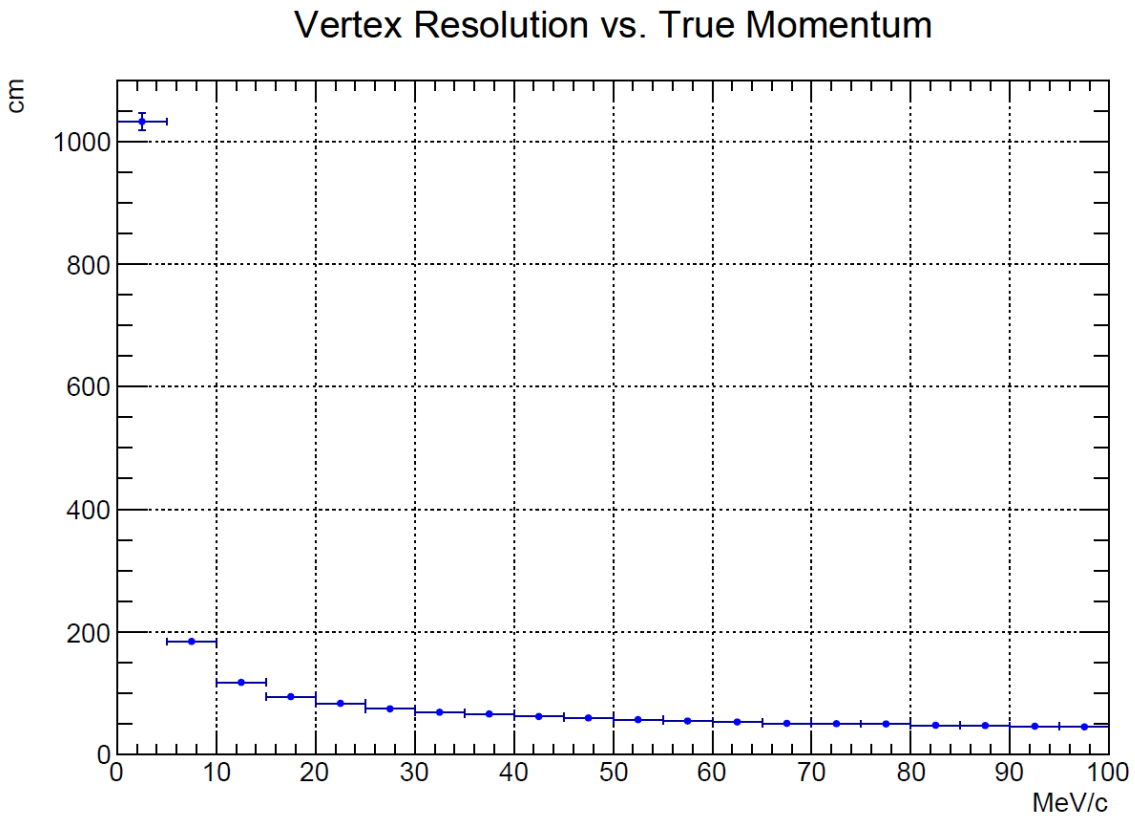

Angular Resolution vs. True Azimuth
Deg.
Deg.
p0 6.161 ± 0.006
p1 3.83e−05 ± 6.01e−05

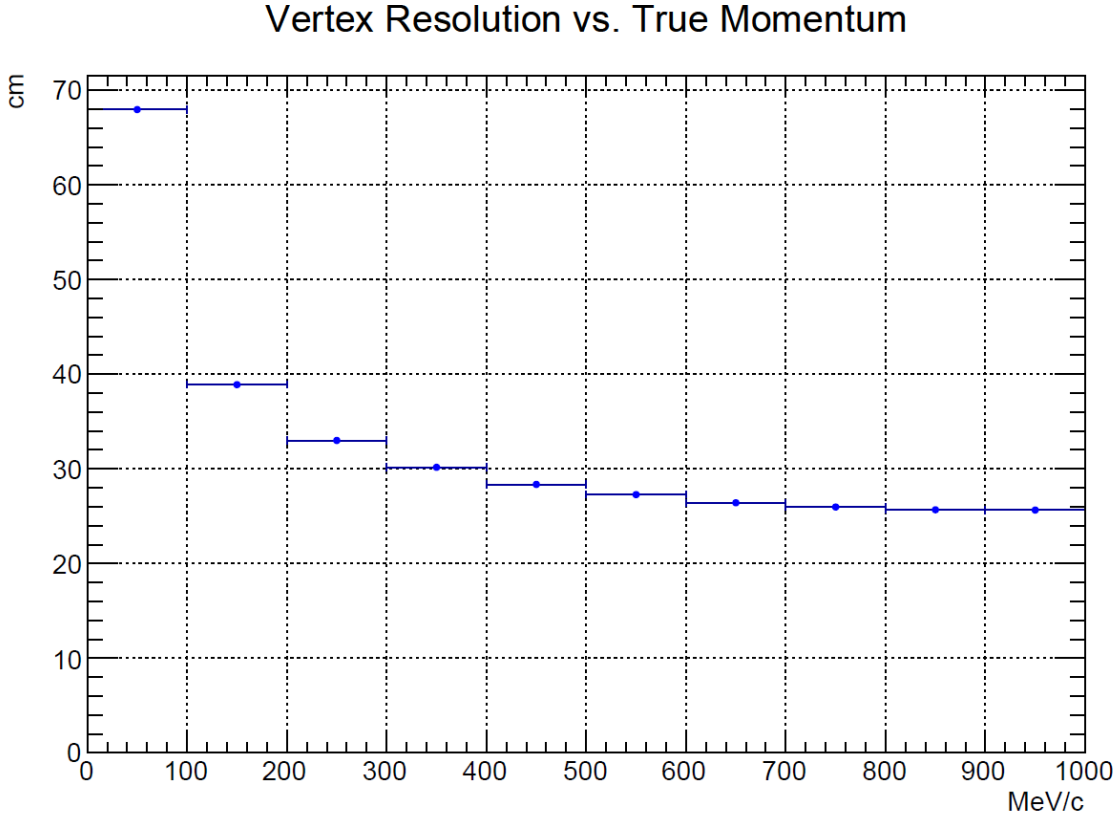

Angular Resolution vs. True Elevation
Deg.
Deg.
p0 6.159 ± 0.006
p1 −0.0004829 ± 0.0001600

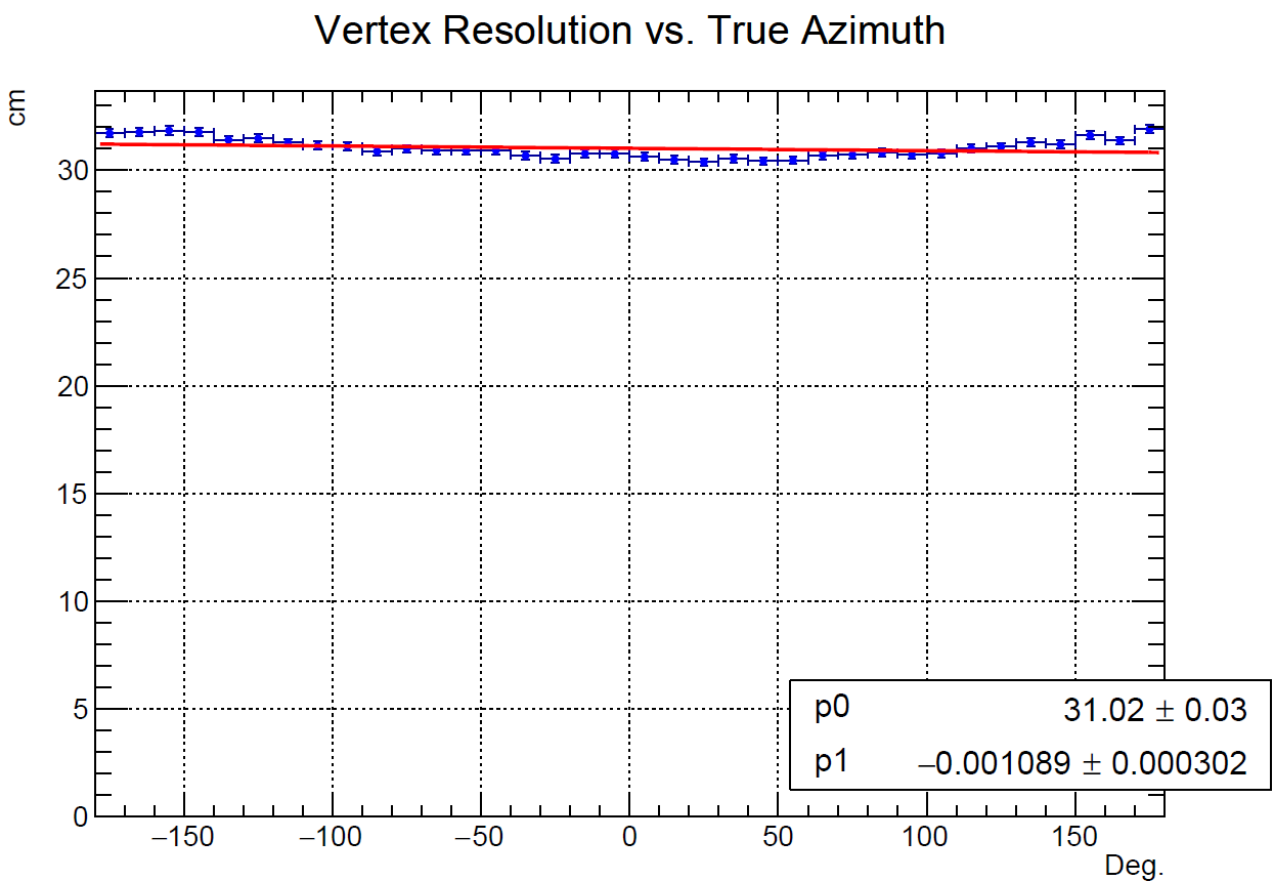
Direction reconstruction

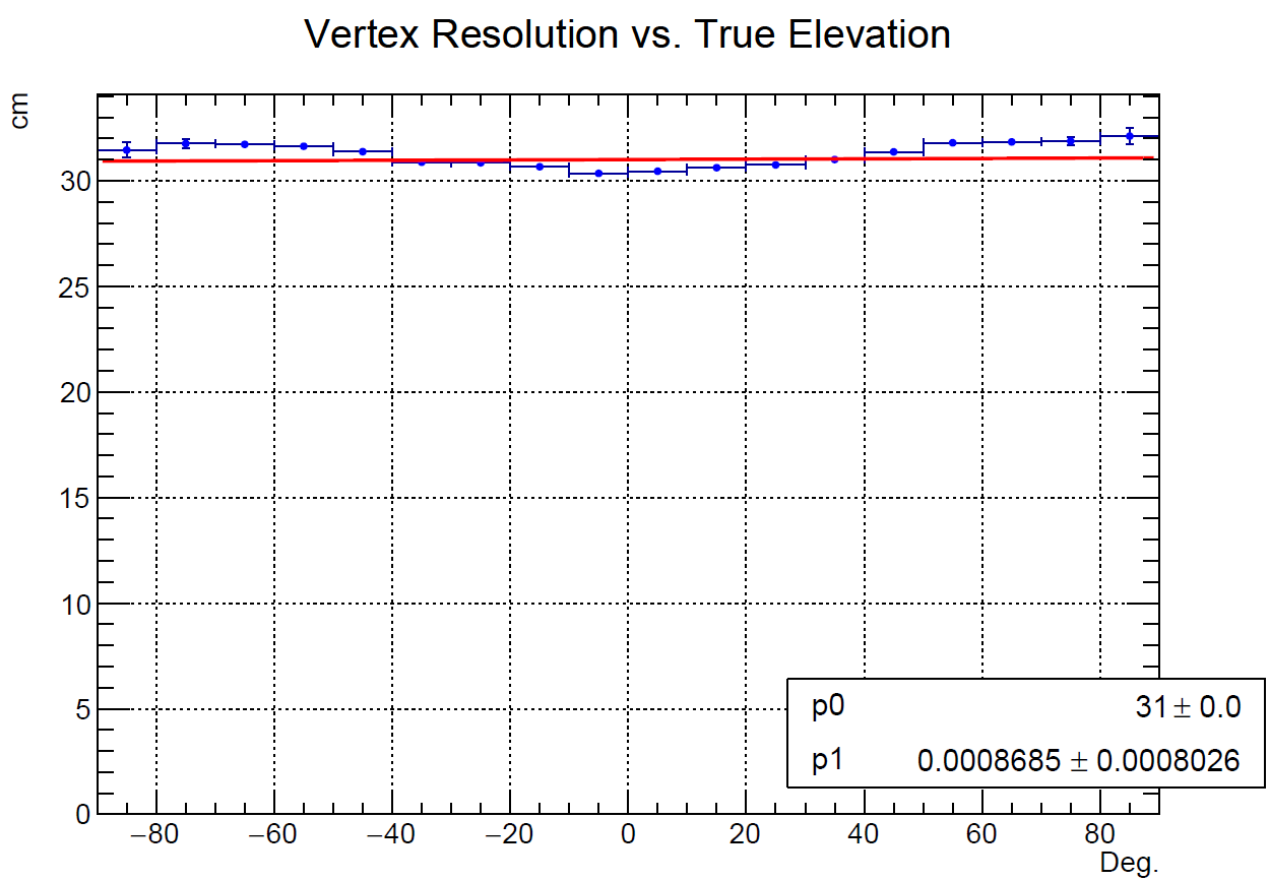


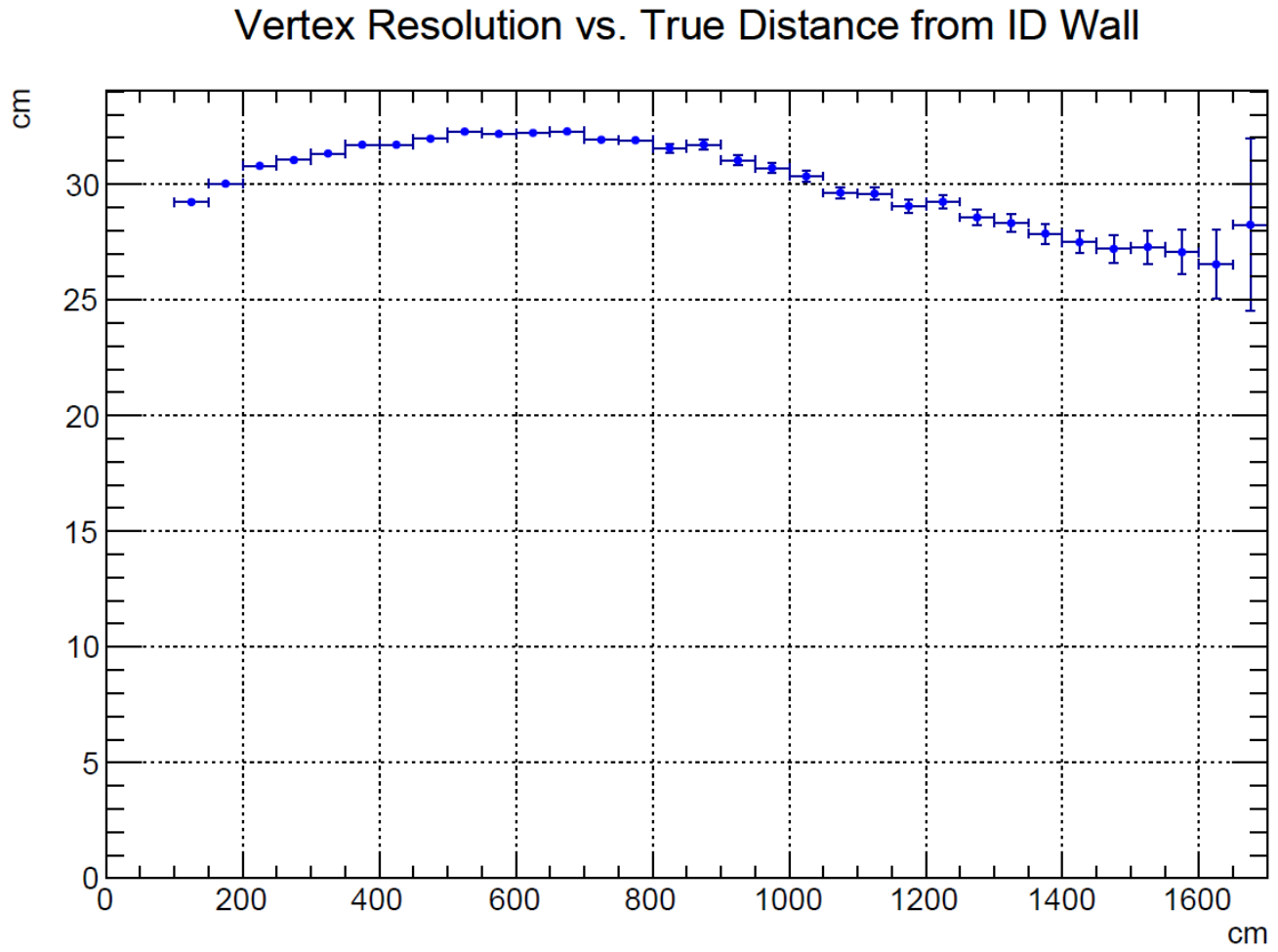

Overall Angular Resolution
×10^3
events
180
160
140
120
100
80
60
40
20
0
1 sigma (68%): 6.2 Deg.
10^-2
10^-1
1
10
10^2
Deg.

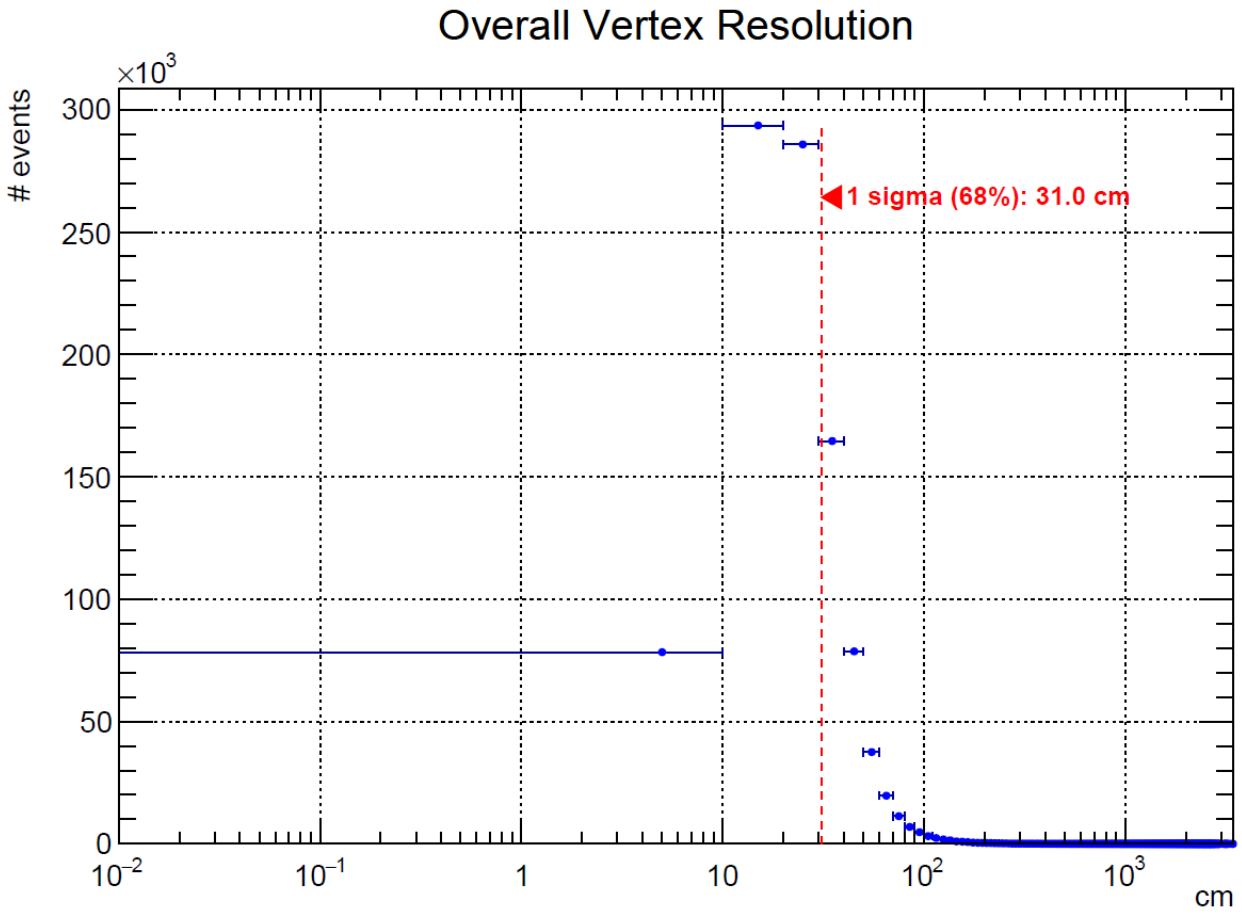

Vertex Resolution vs. True Momentum
cm
1000
800
600
400
200
0
0
10
20
30
40
50
60
70
80
90
100
MeV/c


Vertex Resolution vs. True Momentum
cm
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
700
800
900
1000
MeV/c

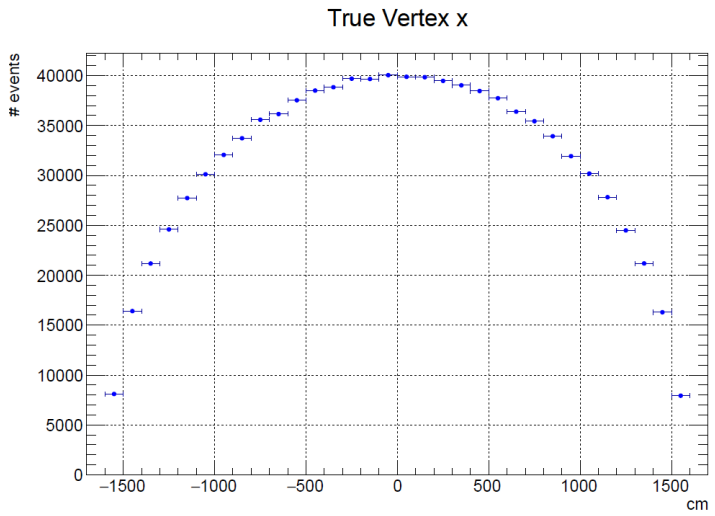

Vertex Resolution vs. True Azimuth
cm
30
25
20
15
10
5
0
−150
−100
−50
0
50
100
150
Deg.
p0 31.02 ± 0.03
p1 −0.001089 ± 0.000302

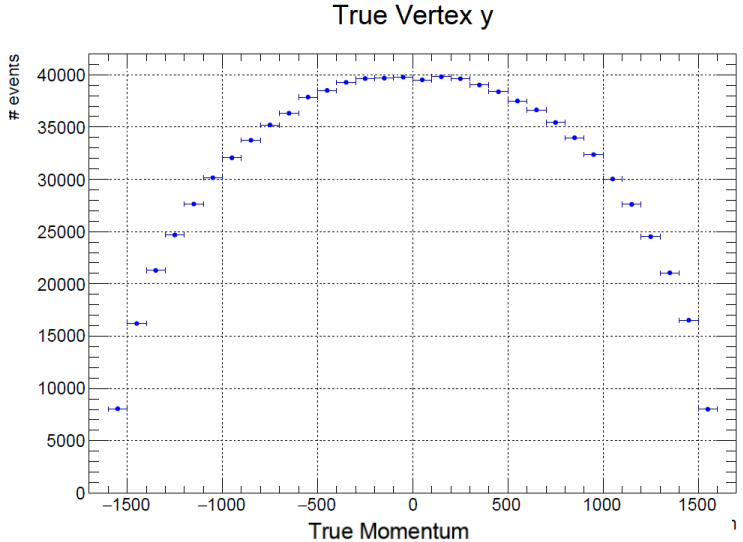

Vertex Resolution vs. True Elevation
cm
30
25
20
15
10
5
0
−80
−60
−40
−20
0
20
40
60
80
Deg.
p0 31 ± 0.0
p1 0.0008685 ± 0.0008026

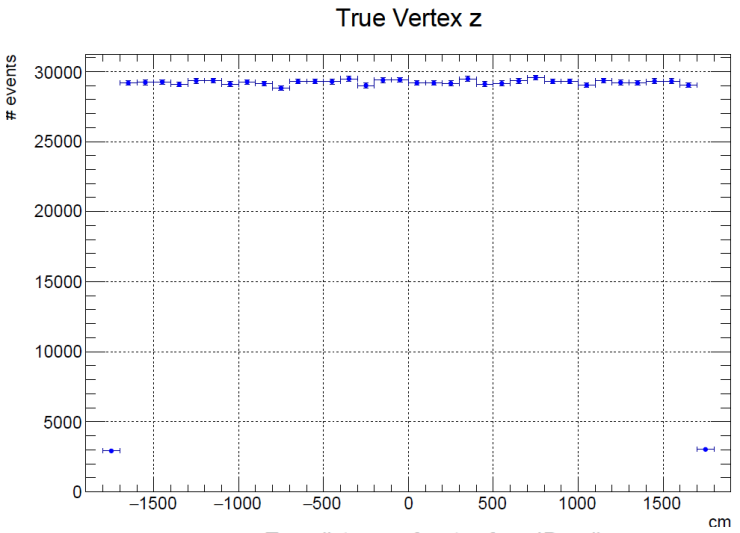

Vertex Resolution vs. True Distance from ID Wall
cm
30
25
20
15
10
5
0
0
200
400
600
800
1000
1200
1400
1600
cm

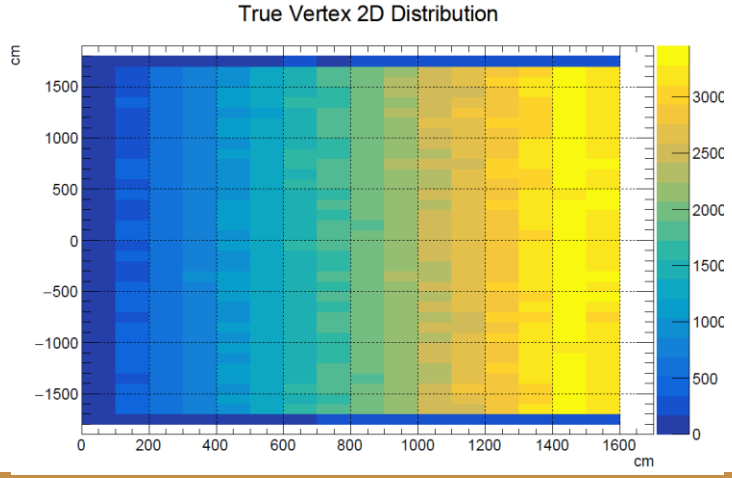

Overall Vertex Resolution
×10^3
events
300
250
200
150
100
50
0
1 sigma (68%): 31.0 cm
10^-2
10^-1
1
10
10^2
10^3
cm

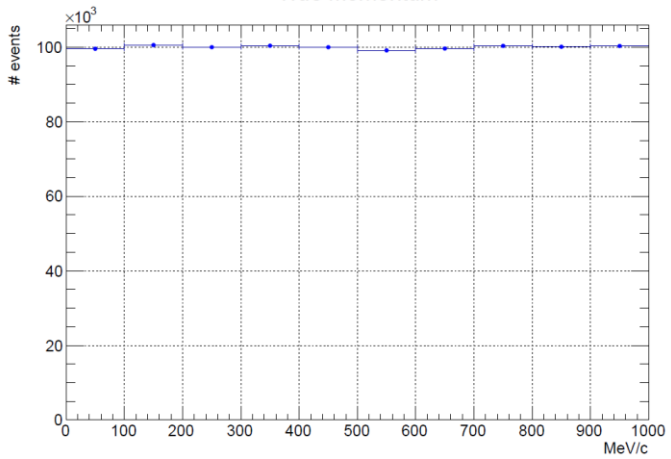
Test dataset MC truth check

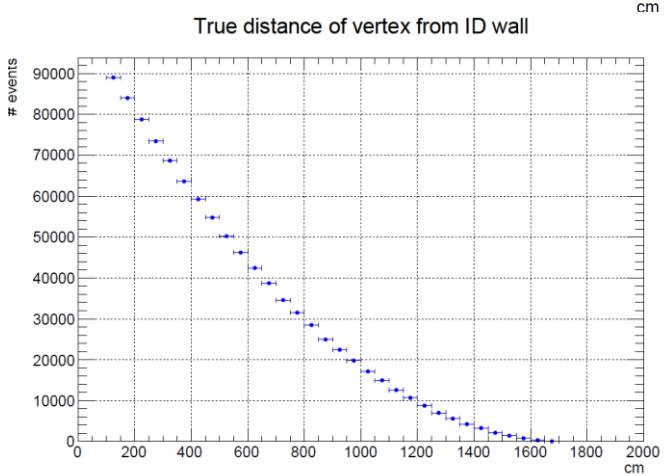












Test dataset MC truth check