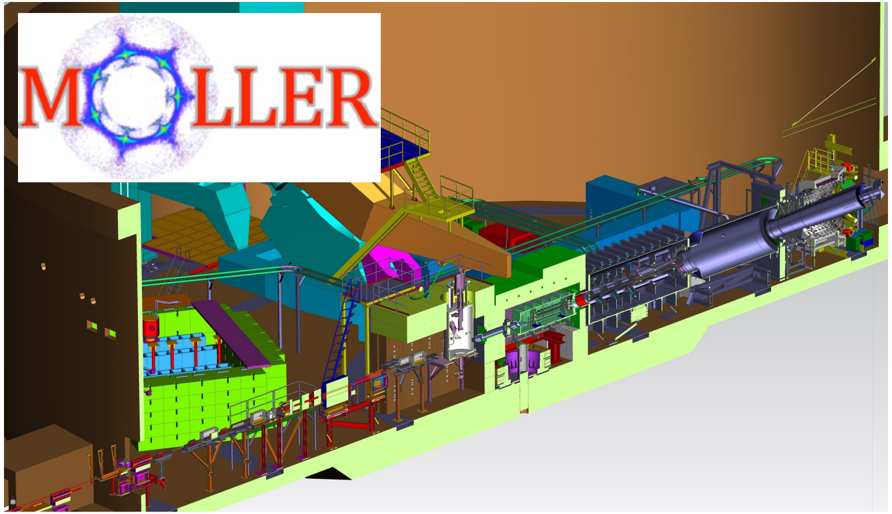
MOLLER collaboration meeting May 2023

Pion Detector



David Armstrong
Tracking System Technical Lead
William & Mary

Outline

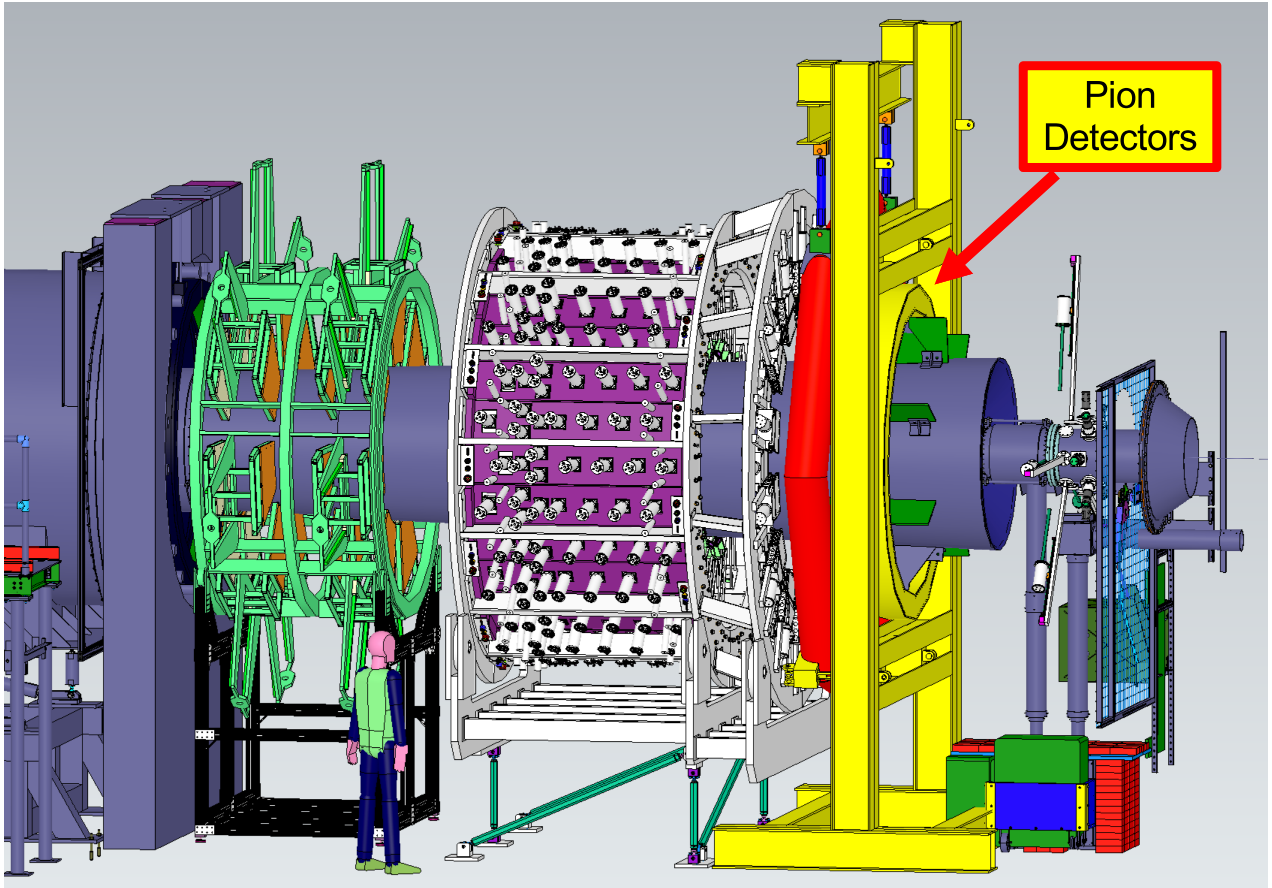
- Subsystem overview
- Beam test at Mainz
- Mechanical Design
- π/e ID with Machine Learning

- Team Members:
  - David Armstrong (W&M)
  - Wouter Deconinck (U. Manitoba)
  - Neven Simicevic (Louisiana Tech)

  PhD Students:
  - Kate Evans (W&M)
  - Elham Gorgannejad (U. Manitoba)

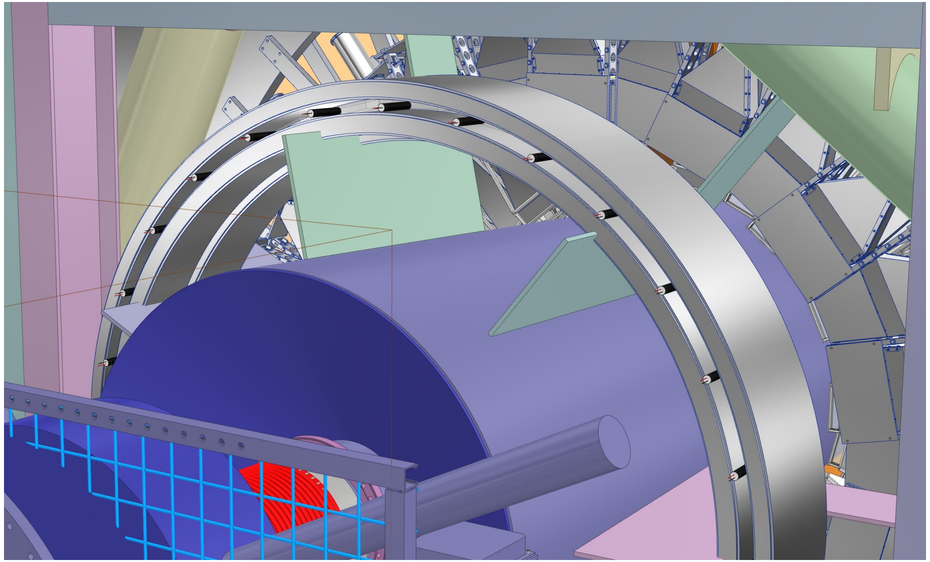
  Undergrads:
  - Gherson Gonzales (W&M)
  - Tristan Hurst (W&M)
  - Raj Seehra (U. Manitoba)

Subsystem Overview – Pion Detectors



- Modular system of acrylic Cherenkov detectors covering full azimuth
- Samples Ring 5 & Shower-max acceptance
- Downstream of Main Detectors, Shower-max Detectors
- 20 cm thick Pb “donut” to range out Moller electrons.
- Asymmetry measurement in integrating-mode
- Pion flux determination in counting-mode data-taking

Pion Detector

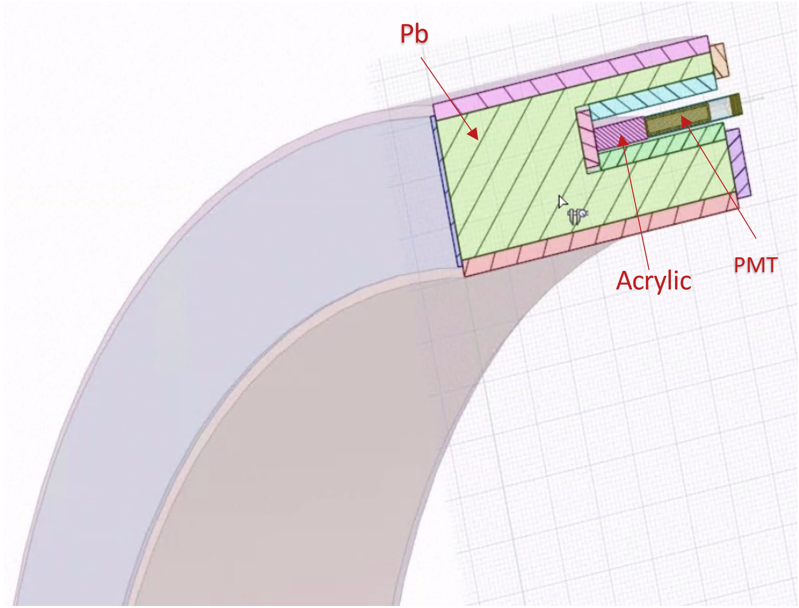


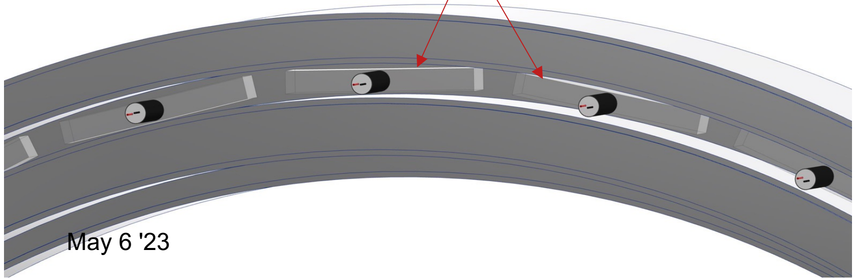
Issue: suppression of Moller electron signal
wide-angle scattered shower remnants from Moller electrons in Shower-max and other upstream materials; low-energy gammas Compton scattering in acrylic, generating small (< 3 few pe's) signals .

Solution: Encase in extended Pb donut

- 28 identical rectangular acrylic detectors:
  7 cm deep, 23 cm wide, 1" thick
- Read out via directly-coupled 1" PMT at rear (no lightguide)
- Optimized optical design:
  - maximize π/e ratio using pion directionality, and radial extent of acrylic detector
  - minimize weight/cost of Pb donut

Pion Detector





- $45\ X_0$ in direction of scattered Moller electrons
  ($9.5\ X_0$ from Shower-max, $35.5\ X_0$ from Pb donut)
- π/e ratio of photoelectrons in pion detector:
  design goal: > 50%
  achieved: 75%
- Total integrated dose: 200 kRad.
  UVT acrylic optical properties good to >1 MRad.
- Eliminates need for separate pion detector support structure
- Loose tolerance ($\pm$5 mm) on location of acrylic
- Want: $\sigma/\text{peak} < 25\ \%$, so detector response doesn't broaden asymmetry width

Pion detector tests at Mainz MAMI-B microtron Nov. 23 - 26 2022

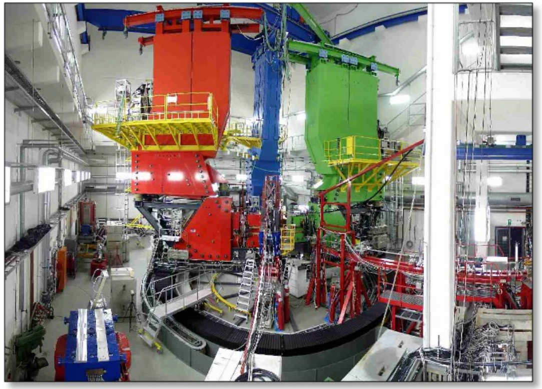
- QDC readout (CAEN V965)
- 2 Acrylic detectors studied:

  Det. A: 3.8 cm × 10.2 cm × 30 cm
  with 1.5″ PMT

  Det. B: 3.8 cm × 10.2 cm × 20 cm
  with 1.5″ PMT

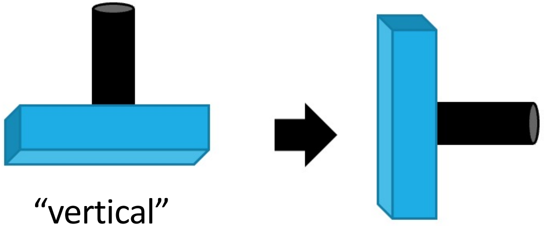
  c.f. Design Pion detector:
  2.5 cm × 7.0 cm × 23 cm
  with 1.0″ PMT

885 MeV Electron Beam



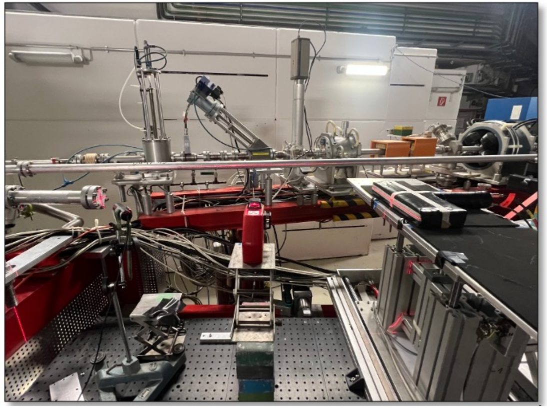
https://en.wikipedia.org/wiki/Mainz_Microtron

GEANT 4 scaling of photoelectron signal:
Design/Det. B = 0.65



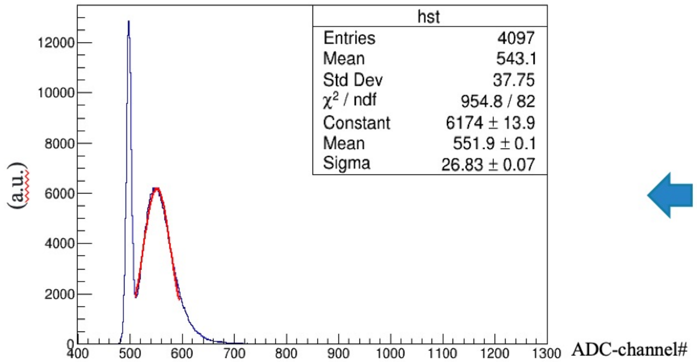
"vertical"

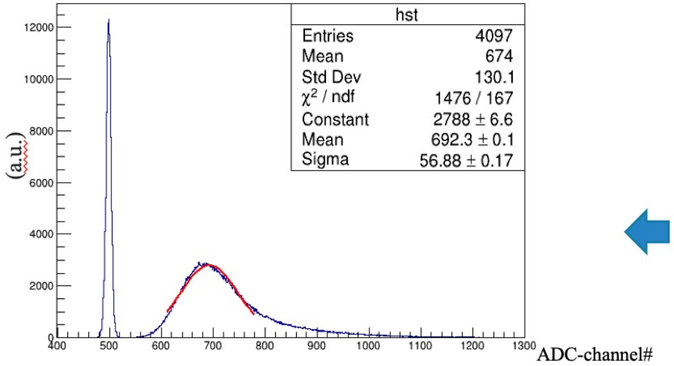
"horizontal"



Pion detector tests at Mainz - spectra

Beam Tests





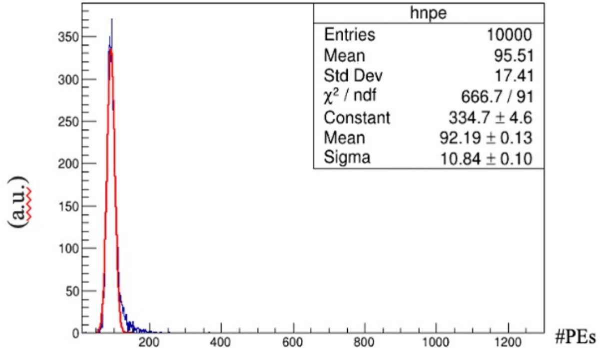
The ratio of Min#PEs[1]=3.3

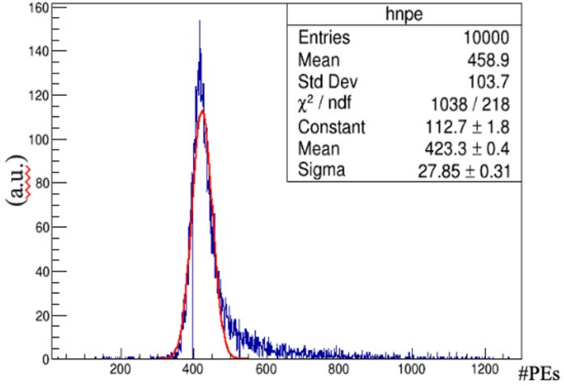
[1]Min# PEs = 1/(sigma/peak-pedestal)^2)

Configuration (1) vertical

Configuration (2) horizontal

Simulations



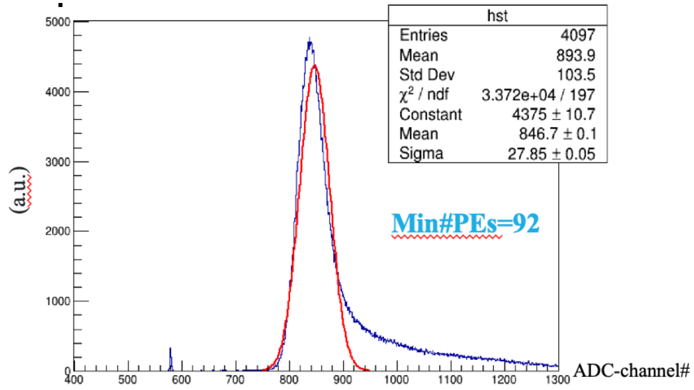


The ratio of #PEs[2]=3.5

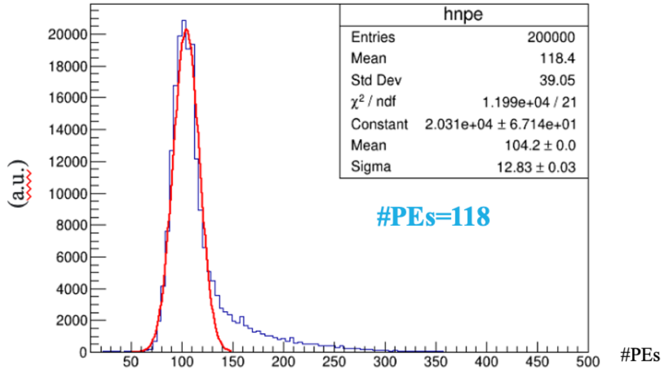
[2]#PEs= ratio of the mean values

Pion detector tests at Mainz

Beam tests



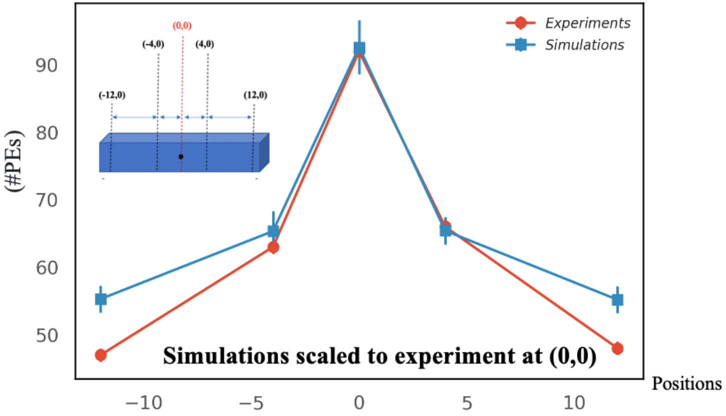
Simulations



Discovered that acrylic used was UVA (UV absorbing) not UVT (UV transparent).

Simulations modified here to use UVA.

#PEs in Different Positions



Success in benchmarking GEANT 4 simulations

PMT and Acrylic comparisons: simulation

Factors that might affect the results	Experiment
Spectral Range: UVA-Lucite	400-700 nm
Spectral Range: UVT-Lucite	300-700 nm
Quantum Efficiency: Default PMT	22% @ 290nm
Spectral Range: Default PMT	200-800 nm
Quantum Efficiency: Borosilicate PMT	27% @ 390nm
Spectral Range: Borosilicate PMT	300-650 nm

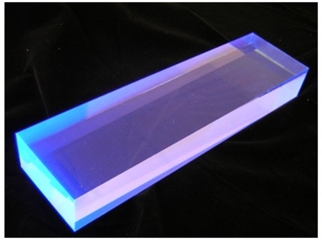
Full simulations (Pi/e) vs standalone simulations(#PEs)	Pi/e * Full Simulation	#Pes Standalone Simulation
Default QE, UVT- Lucite	70.97%	89
Default QE, UVA- Lucite	63.64%	55
Borosilicate QE, UVT- Lucite	75.34%	111
Borosilicate QE, UVA- Lucite	60.00%	65

These results use desired pion detector geometry, with 1” PMTs

Mechanical Design - prototyping

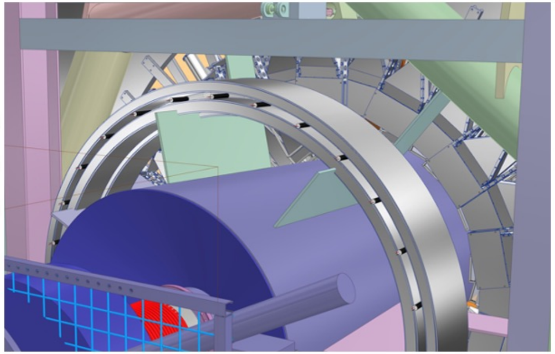
Elham Gorgannejad:

For "Det B" from Mainz beam tests



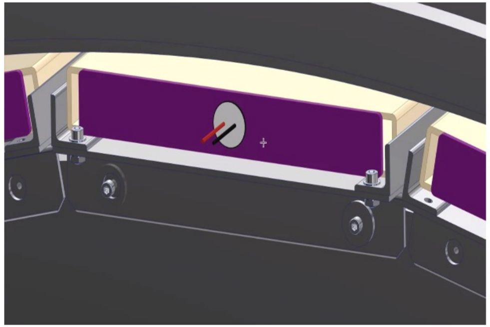
8*4*1.5 inches
38*100*200 mm

Light tight box
3D printing parts



High Voltage Hamamatsu
Photomultiplier H3178-51, 1.5 inch

Holder
Machining parts



Mechanical Design - prototyping

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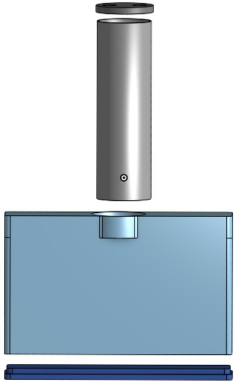
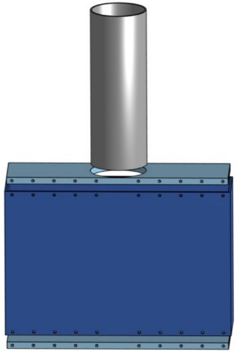
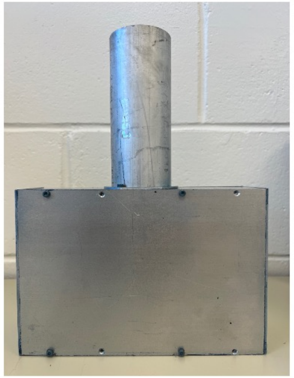


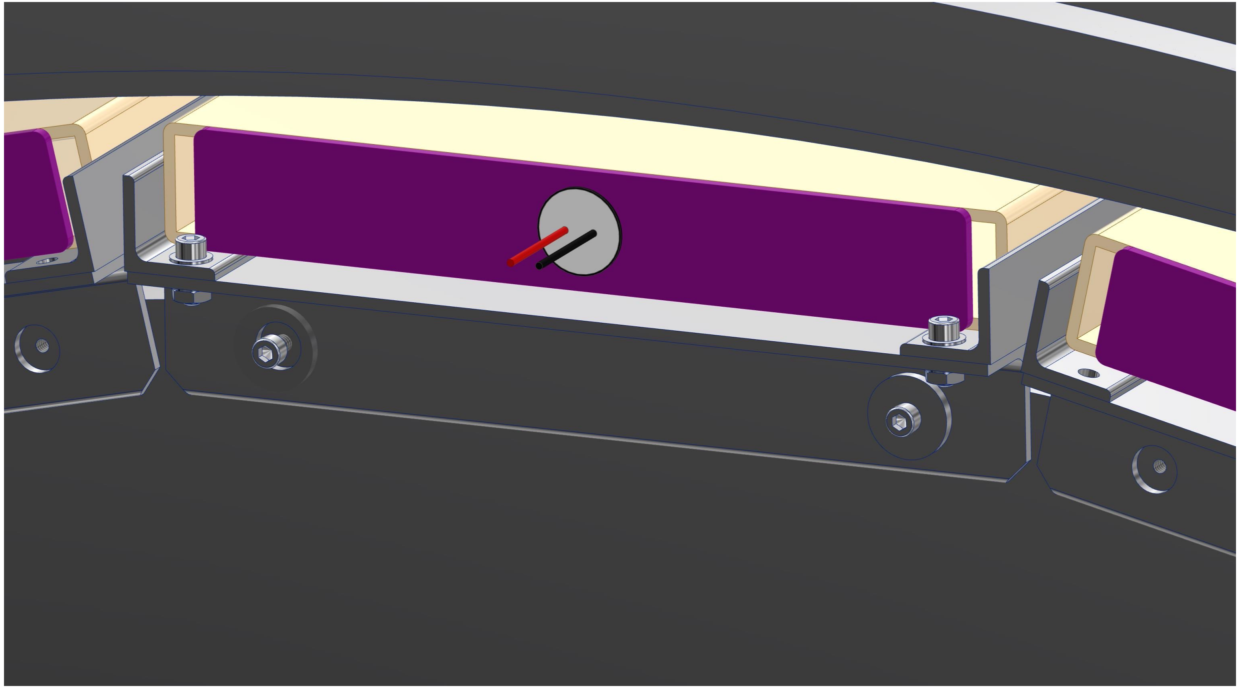
Holder
Machining parts





Mechanical Design – mounting concept

Larry Bartoszek concept:



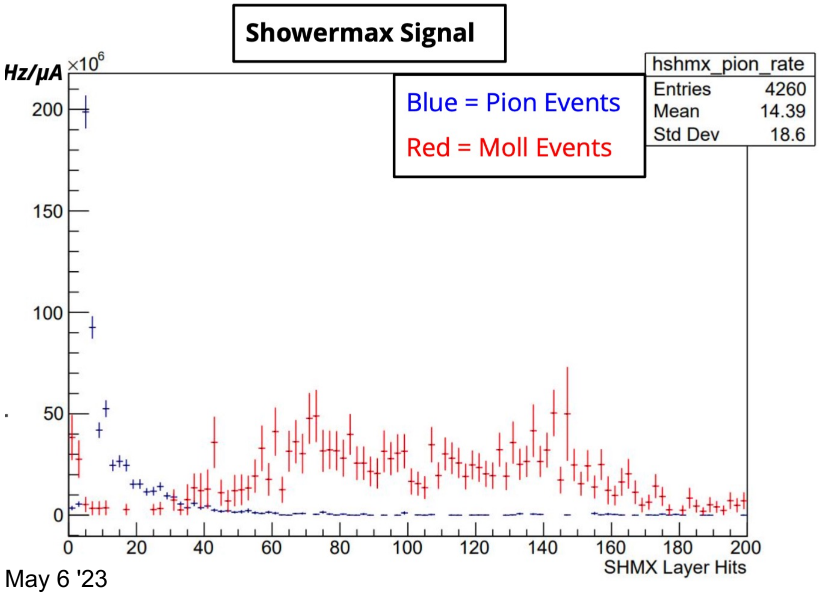
To Do:
tweak acrylic size, minimize wall thickness for box to ensure fit in the pion donut enclosure

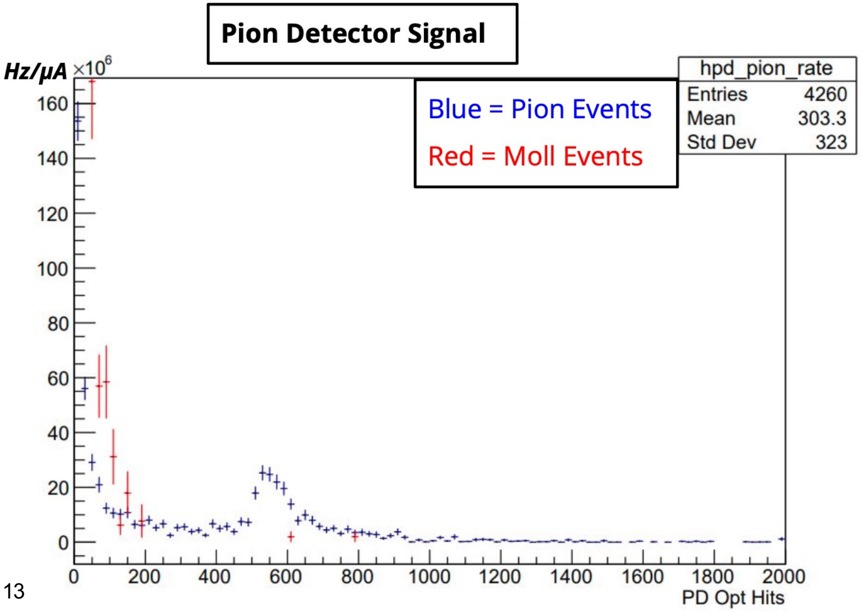
Pion Flux measurement

$$A_{PV}^{SHMX} = A_{PV}^{Mol} f_{Mol}^{SHMX} + A_{PV}^{\pi} f_{\pi}^{SHMX}$$

(similar for Ring 5

$$A_{PV}^{PD} = A_{PV}^{Mol} f_{Mol}^{PD} + A_{PV}^{\pi} f_{\pi}^{PD}$$

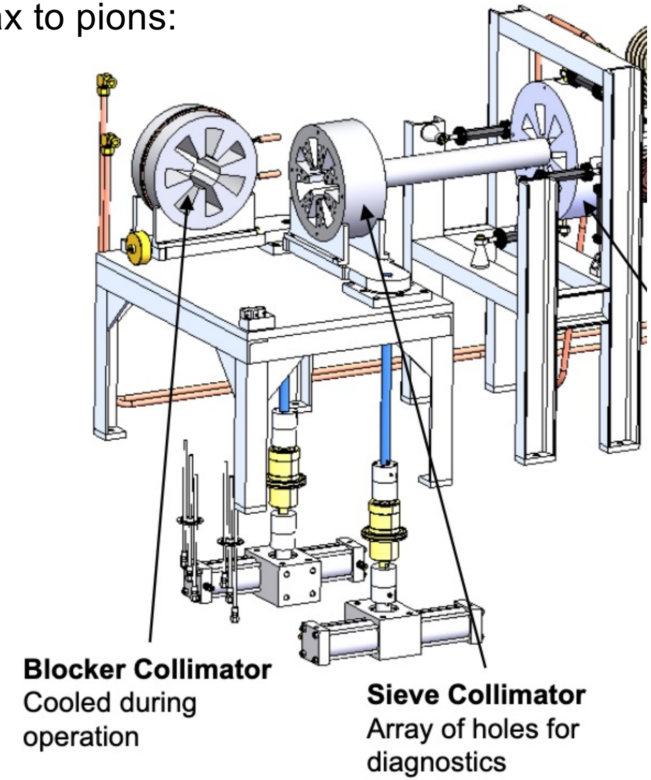




Pion Flux measurement – Blocker enhancement

- Additional mode to verify response of Pion Detector and Shower-max to pions:
  - insert Blocker collimator (20 X_0 W/Cu)
  - Suppress π^- flux at main detectors by $\times 0.55$
  - Suppress e^- flux at main detectors by $\times 10^{-4}$
- Shower-max signal: roughly equal mix of π^-/μ^- and e^-
- Pion Detector: essentially pure π^-/μ^-

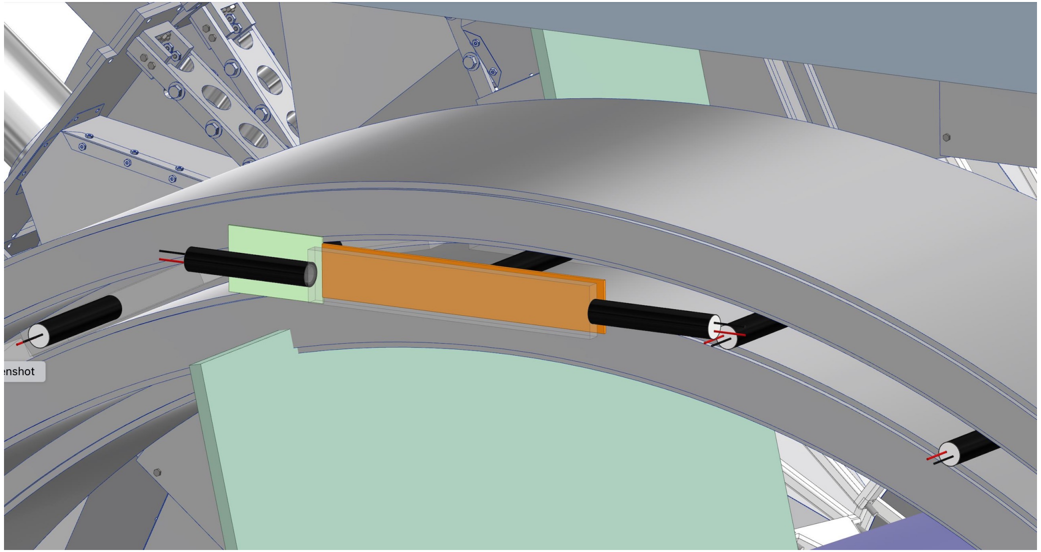
To do: detailed GEANT 4 simulations



Pion Exit Scintillator?

- In Counting Mode, could we improve f^{π} determination by adding a Pion Exit Scintillator?
- Investigated in GEANT 4 simulation by Tristan Hurst.

Conclusion: Only marginal (few %) improvement in pi/e discrimination in counting mode, but at significant cost in pion detection efficiency. We have decided not to pursue this.



Pion Flux measurement – Machine Learning

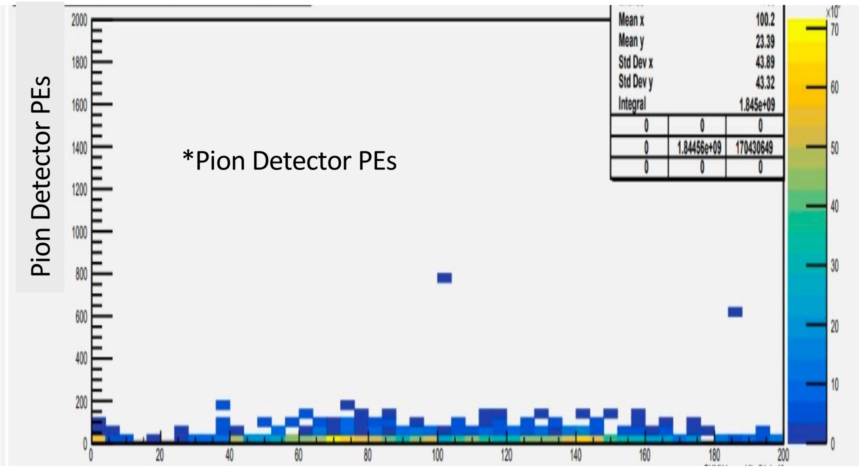
$$A_{PV}^{SHMX} = A_{PV}^{Mol} f_{Mol}^{SHMX} + A_{PV}^{\pi} f_{\pi}^{SHMX}$$

$$A_{PV}^{PD} = A_{PV}^{Mol} f_{Mol}^{PD} + A_{PV}^{\pi} f_{\pi}^{PD}$$

[similar for Ring 5]

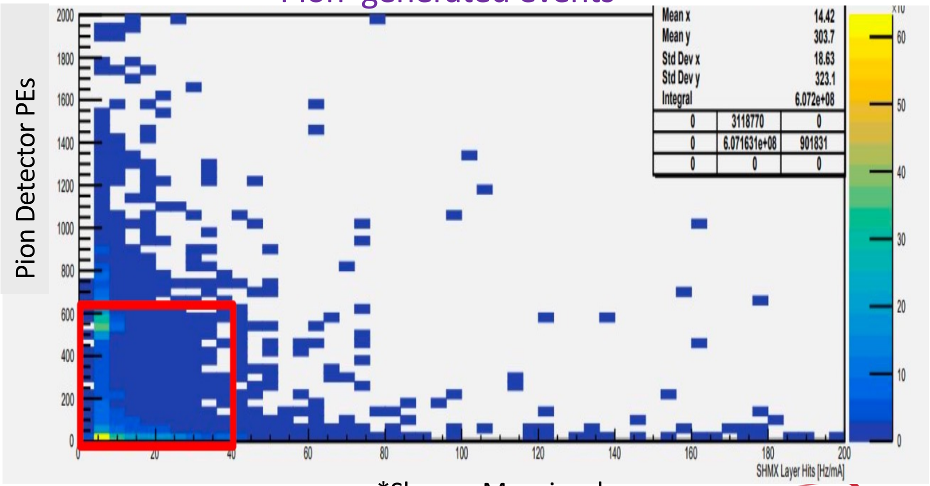
*Shower Max signal here is a proxy for optical photons: number of charged particle hits on quartz layers

Moller generated events



*Shower Max signal

Pion generated events

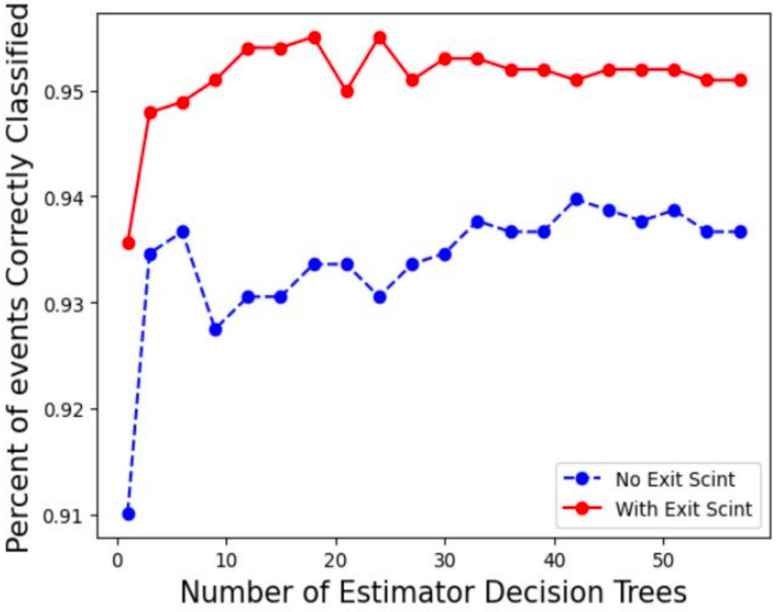


*Shower Max signal

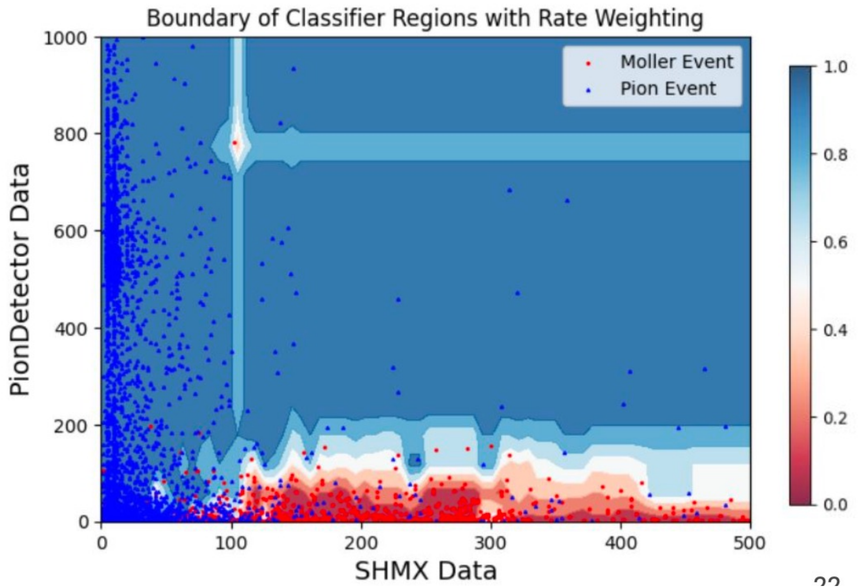
Pion Flux measurement – Machine Learning

Tristan Hurst: Random Forest Decision Tree classifier

https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier.html



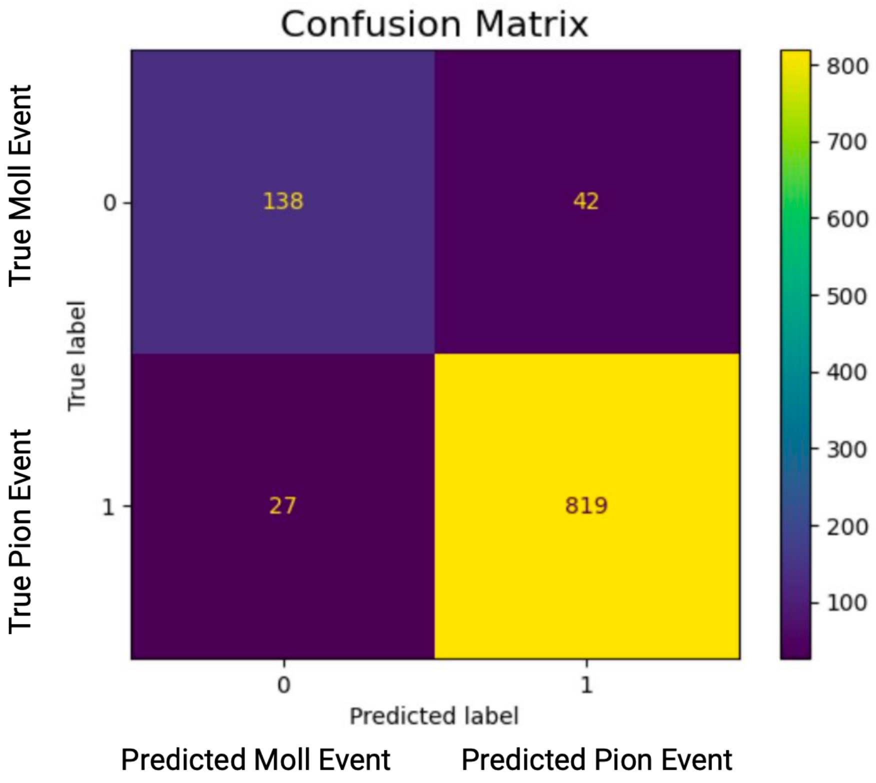
Performance = 95.1% Correctly Classified events



Pion Flux measurement – Machine Learning

Next steps for f^{π}

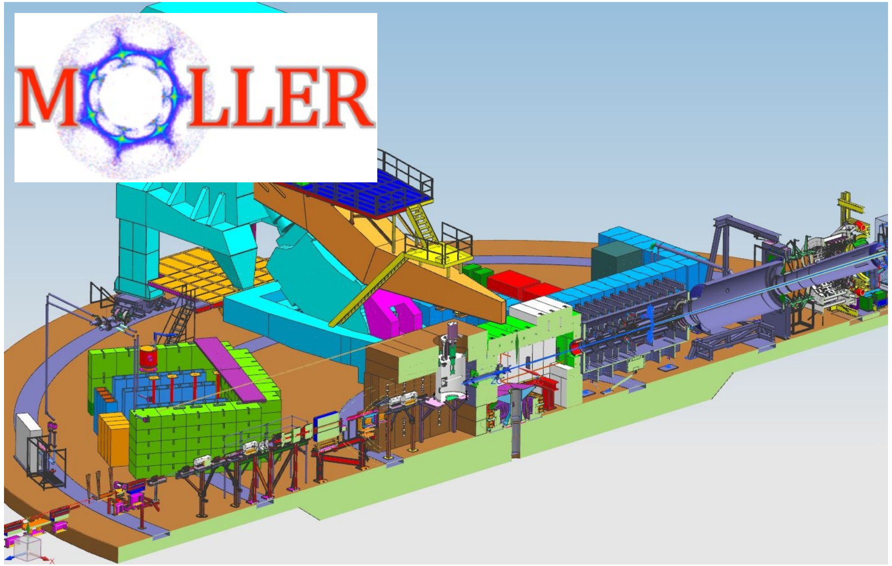
- Break up simulated data between
  open/closed/transition detectors
- add Ring 5 data
- add GEM track information
- decide on best metric for success



Pion Detector

Next steps:

- PMT model selection
- Mechanical design finalize
- 2nd prototype with final design



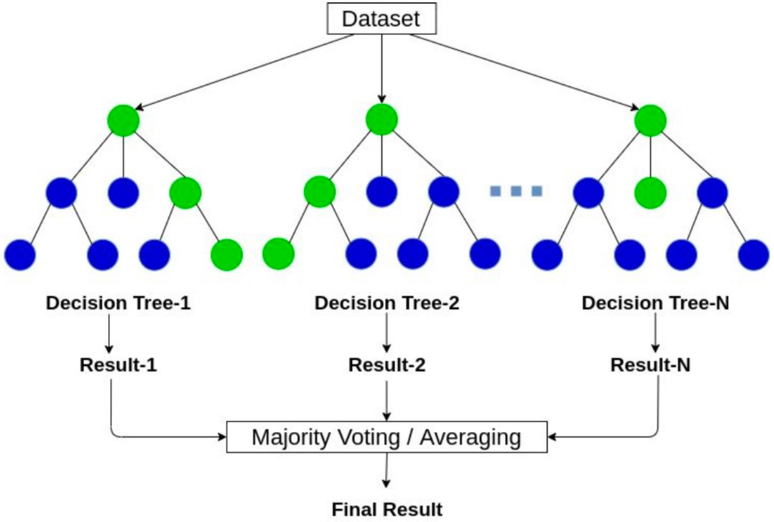
Thank You!

Questions?

Pion Flux measurement – Machine Learning

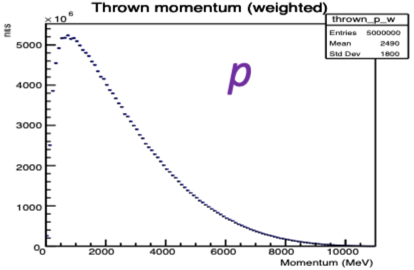
Classifier Used : Random Forest Classifier

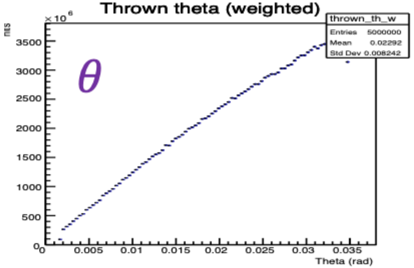
- Creates multiple decision trees using the input data
- Determines certain cuts which groups data into different branches
- When used for a classification, every tree gives an independent results, then, to determine the result of the Random Forest Classifier, the average of all the trees' decisions is the output
- Classifier returns a **probability** of the input being one type or another



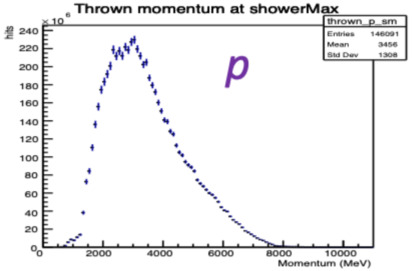
https://scikit-learn.org/stable/modules/generated/sklearn.ensemble.RandomForestClassifier.html [19]

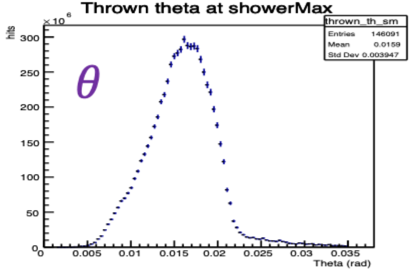
Pion Detector: Fair sampling of kinematics



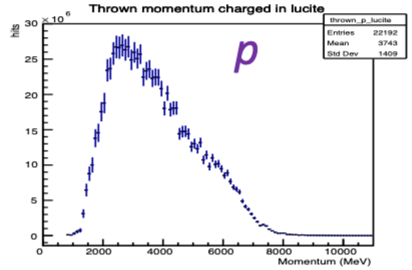


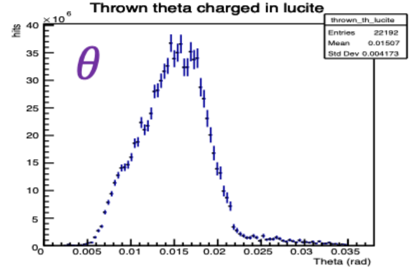
Thrown Kinematics (Wiser model)





Kinematics seen by Ring 5 & ShowerMax





Kinematics seen by Pion Detectors

Pion Detector: readout and PMT selection

- Integrating mode readout will be the same as for Main detectors and Showermax.
- Counting mode readout will use switchable-gain bases, similar to MD & Showermax (details await choice of PMT).

- 1” PMTs

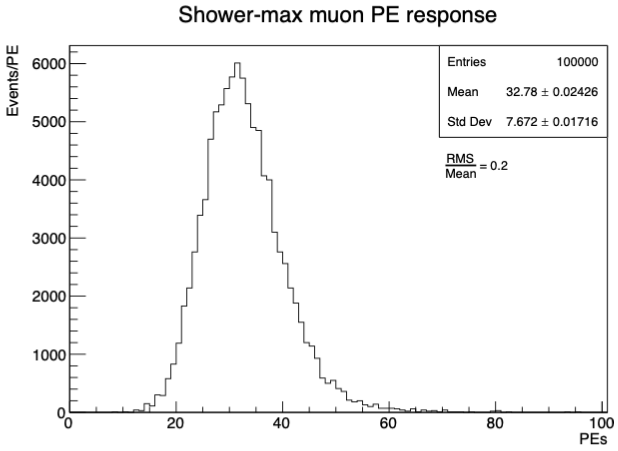
- Expected cathode current in integrating mode : 4 MHz per detector (including pi’s and e’s), folded with photoelectron response: 42 pA
- Dynamic range of the ADC: 2 V_{pp}
- Assume anode current of 500 nA to give 500 mV signal level
  - Gain at the I-to-V preamplifier: 1 MOhm
  - PMT gain: 500 nA/42 pA = 1.2×10^4 (modest gain)

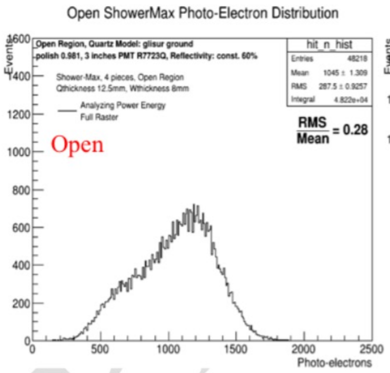
- Match optical cut-off of PMT window below cut-off of UVT acrylic (300 nm)
  $\therefore$ don’t need fused silica window, Schott glass adequate (cut off $\approx$250 nm)

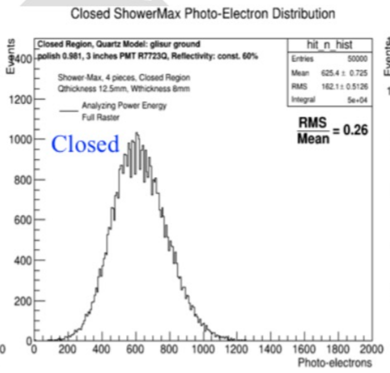
Pion Flux measurement

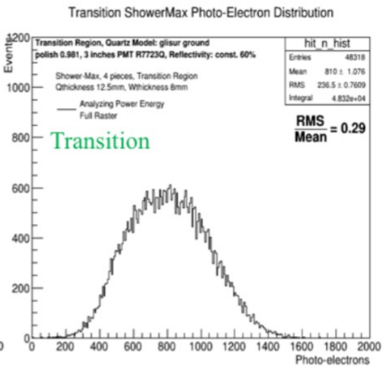
- Determine f^{π} in thin quartz detectors in Counting Mode:
  - Trigger on pion detector signal.
  - see MIP in Shower-max:

	Mean PE Response: [PEs]	
Energy	Pion	Muon
2 GeV	37	33
5 GeV	60	34
8 GeV	93	33









Software requirement: (Tracking GEMs)·(Tracking Scints)·(thin quartz)·(ShowerMax MIP)·(Pion Detector)