



Low Energy Muons at Fermilab

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Workshop on a Future Muon Program at Fermilab

California Institute of Technology, Pasadena, CA

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Strong Community interest future low energy muon experiments

LOI discussed during the 21-22 “Snowmass” community planning process for high energy physics

- lepton flavor violation
- muon decay to 3 electrons
- muonium - antimuonium
- muon hydrogen and the proton radius
- muon EDM
- muon catalyzed fusion

Letter of Interest for an Upgraded Low-Energy Muon Facility at Fermilab

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Background: A Heavy (W, Ta) target for low energy muon production

- Single pion Threshold: 280 MeV $p + p \rightarrow p + n + \pi^+$; $p + n \rightarrow p + p + \pi^-$
- Pair Threshold: 600 MeV 4 production channels @800 MeV (PIPII)

Total cross sections for π^+/π^- production beyond carbon to a good approximation are

$$\sigma_T(\pi^+) \approx 24.5 Z^{1/3}$$

$$\sigma_T(\pi^-) \approx 2.33 N^{2/3}$$

- Heavier targets favor both π^+ and π^-
- Tantalum/tungsten has a factor of 3 (8) π^+ (π^-) increase over graphite
- *NO facility is currently using a heavy production target*

TABLE XII. Total cross sections for π^+ and π^- .

Element	σ^+	σ^-	Ratio
H	13.50 ± 0.73	0.03 ± 0.01	45
D	11.42 ± 0.55	1.12 ± 0.06	10.2
Be	27.30 ± 1.40	6.49 ± 0.37	4.3
C	35.00 ± 1.80	6.64 ± 0.41	5.3
Al	53.10 ± 2.90	13.17 ± 0.90	4.0
Ti	67.00 ± 3.60	21.20 ± 1.60	3.2
Cu	77.30 ± 4.30	25.20 ± 2.0	3.1
Ag	91.60 ± 5.10	35.00 ± 3.0	2.6
Ta	101.00 ± 5.60	51.40 ± 4.70	2.0
Pb	104.20 ± 5.80	53.70 ± 4.90	1.95
Th	107.90 ± 5.90	60.40 ± 5.50	1.9

D.R.F. Cochran, *et al*, "Production of Charged Pions by 730-MeV Protons from Selected Nuclei", Phys. Rev. D 6, 3085 (1972)

Current muon beam facilities worldwide

- Fermilab currently supports muon beams for Muon $g - 2$ & Mu2e using 8 GeV protons, likewise COMET at J-PARC
- Several current muon facilities are for MuSR (μ^+ , < 30 MeV/c)
- Except for Mu2e, all production targets are light
 - 4% IL graphite targets at PSI and ISIS
 - $\leq 25\%$ IL Be target at TRIUMF
 - Graphite planned for COMET, J-PARC (Phase II maybe tungsten)
 - Tungsten at Mu2e – chosen for heat tolerance and deformation properties

Table 1: Comparison of Surface Muon Facilities and Mu2e

Facility	Max. (surface) μ rate (Hz)	Type	Comments
PSI [14]	9×10^8	CW	
TRIUMF [15]	2×10^6	CW	
MuSIC at Osaka [16]	10^8	CW	
J-PARC [17]	6×10^7	pulsed	
ISIS [17]	6×10^5	pulsed	
HIMB at PSI [13]	10^{10}	CW	(design goal)
Mu2e at Fermilab	10^{11}	pulsed	Not surface muons: $p_\mu \approx 40$ MeV/c
Mu2e with PIP-II	10^{12}	pulsed	Not surface muons: $p_\mu \approx 40$ MeV/c

Abstract

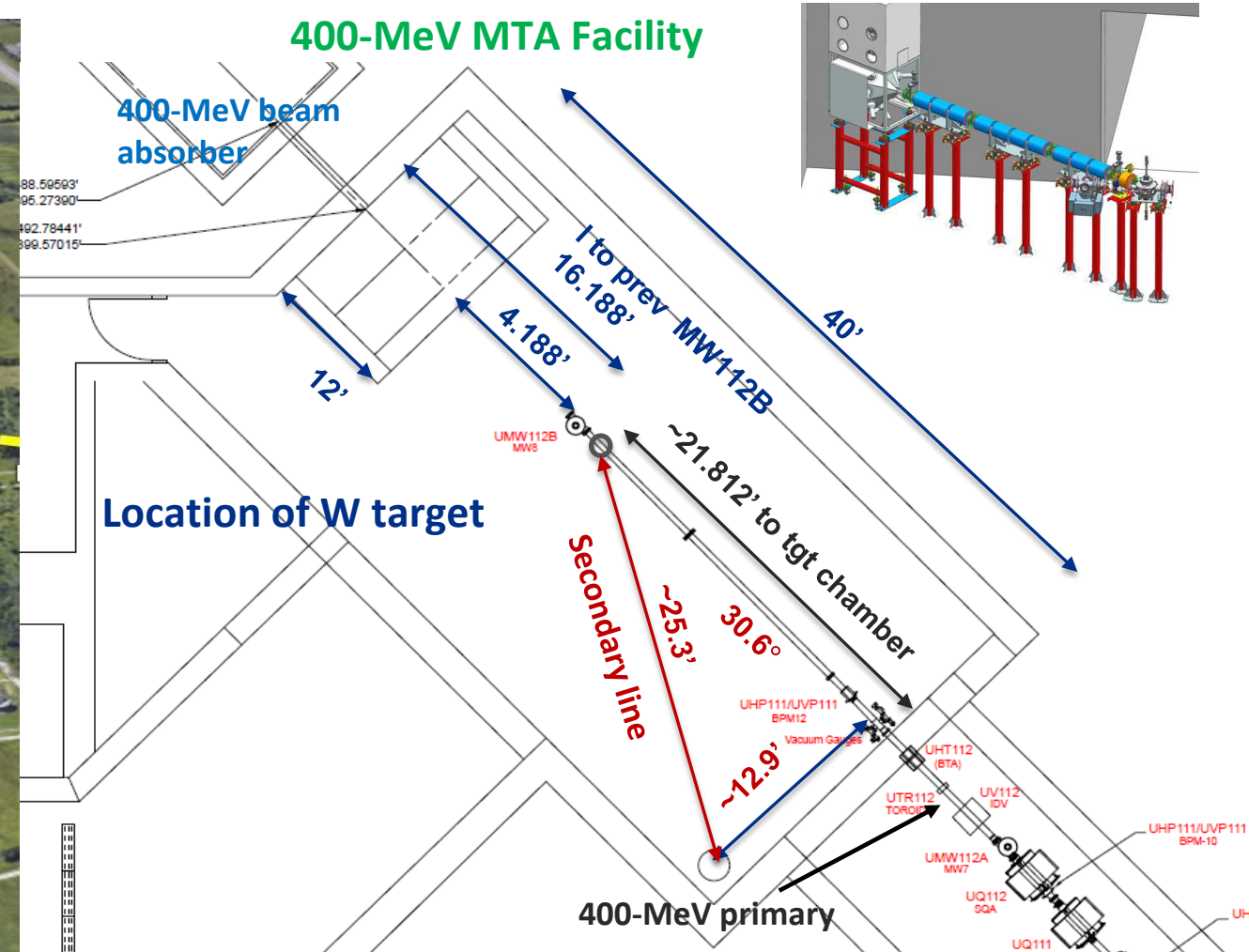
*The Fermilab Booster 400-MeV and the future PIP-II 800-MeV H- beams have the potential to produce precision, single-species secondary beams at record intensities including low energy 4-120 MeV muons, including decay-in-flight μ , μ^+ , and surface muons (μ^+). These beams can support world-class, lower-energy experiments such as charged lepton flavor violation (CLFV), HEP R&D needs such as analyses of surface damage in SRF high gradient cavities, and a recent DOE-directed initiative in muon fusion. Intense muon beams are currently produced through bombardment of a low-Z production target, **generally graphite or Be, with protons to achieve the highest production rate that minimizes the contribution of multiple scattering to the outgoing primary proton beam** – a critical specification for the downstream spallation targets at PSI, RAL and TRIUMF. Pion/muon total production cross sections increase as $Z^{1/3}$ for positive muons and $N^{2/3}$ for negative muons. **Higher mass targets such as tantalum or tungsten can potentially increase low-energy μ^+ and μ^- rates by factors of 3 and 8, respectively.** However, the muon yield is highly sensitive to the details of the target geometry and coupling to the secondary beamline collection design and orientation – low energy pion production is predominately backward and increasingly isotropic the lower the energy. The objective of this work is to study higher Z and novel target geometries combined with strategic optimization of collection and secondary beamline transport and optics to support a wide range of experiments.*

In addition to technical deliverables on the target and secondary beamline design, experiments, R&D, and other applications are being identified, particularly those that can be executed using the Fermilab 400 MeV Linac and installed in the MeV Test Area (MTA).

Fermilab LDRD: High-intensity Multi-slice Target Development

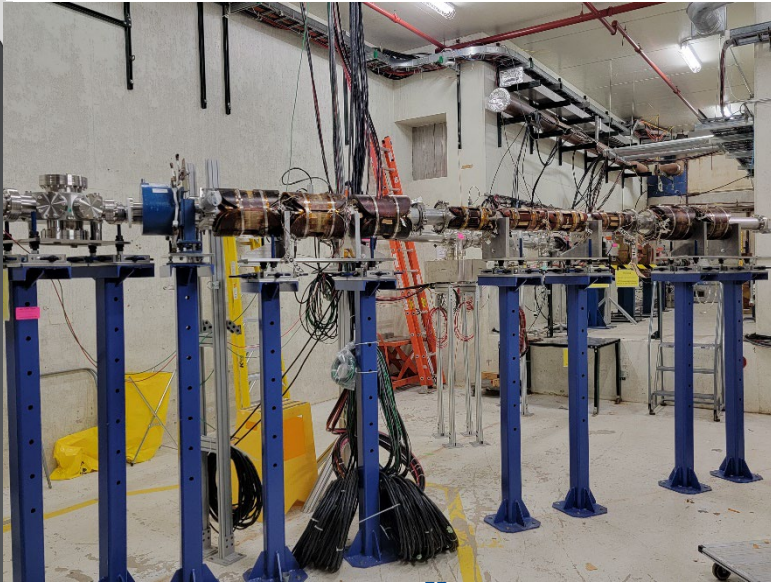
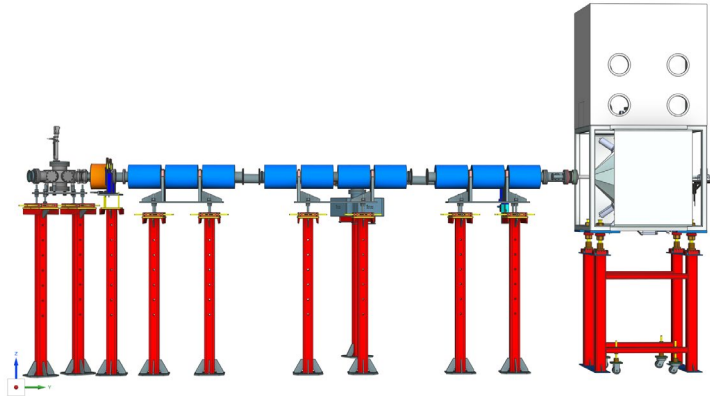
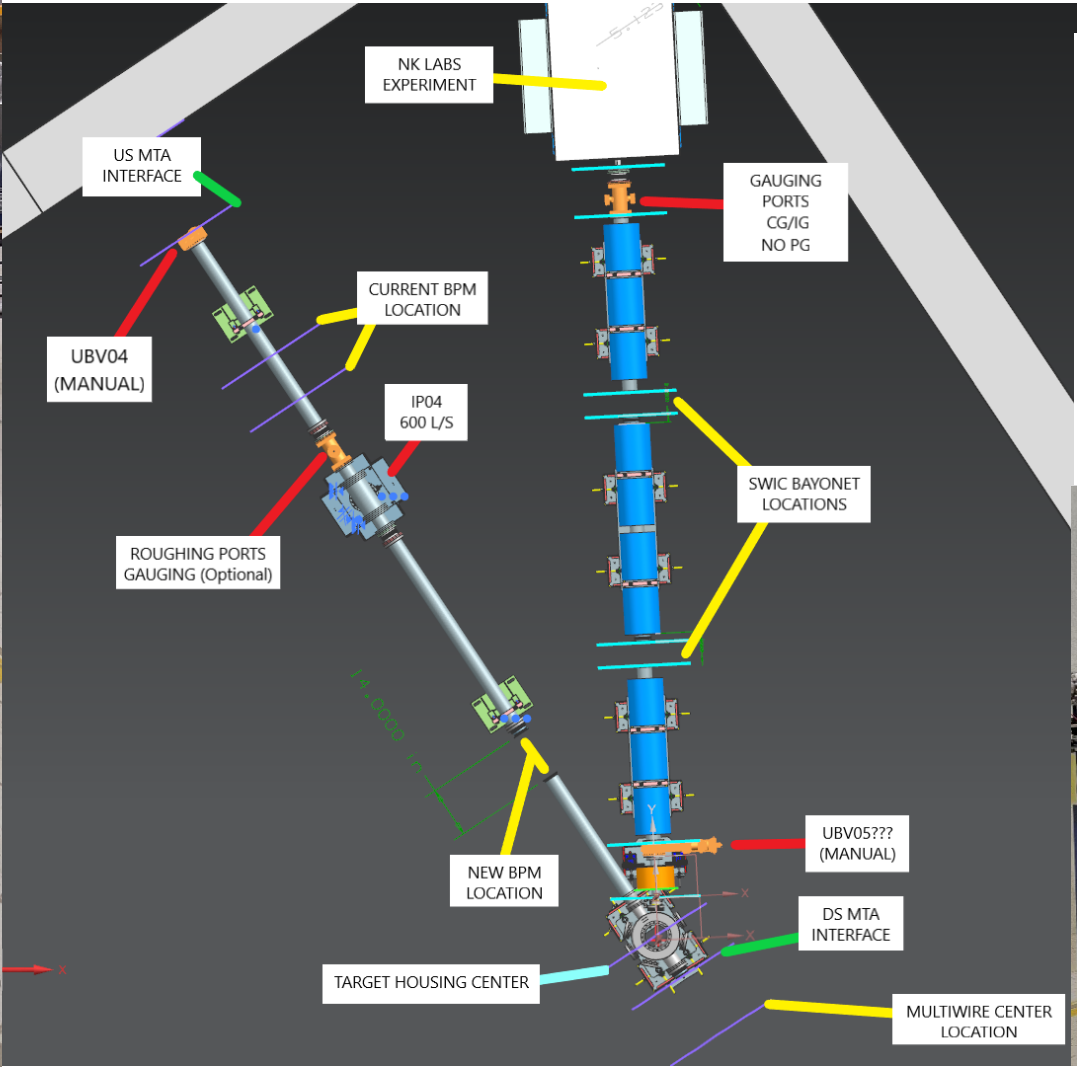
- Develop an economical approach to producing an intense multi-application low energy muon source, *both π^- and π^+*
 - *Emphasis on an intense, multi-application π^- beam*
- Provide essential R&D for muon beam planning for PIP-II era
- Develop a heavy target for lower-energy proton beams (<1 GeV)
 - *Optimize interaction length, beamline orientation and capture Ω*
 - *Optimize target geometry and orientation*
 - *Optimize # of target slices and spacing*
- Test concepts at Fermilab MTA facility at the end of the 400 MeV linac
 - ***A precision low-energy muon beamline was installed in the MTA hall during summer 2022 accelerator shutdown***
 - *Final connections, testing, and commissioning remain*
 - *Study performance compared to simulations*
 - *Support ARPA-E funded muon catalyzed fusion experiment to further quantify performance and successful application*
 - *Prepare for other muon and possibly a muonium physics experiments*

MTA Location on the Fermilab site and Exp Hall



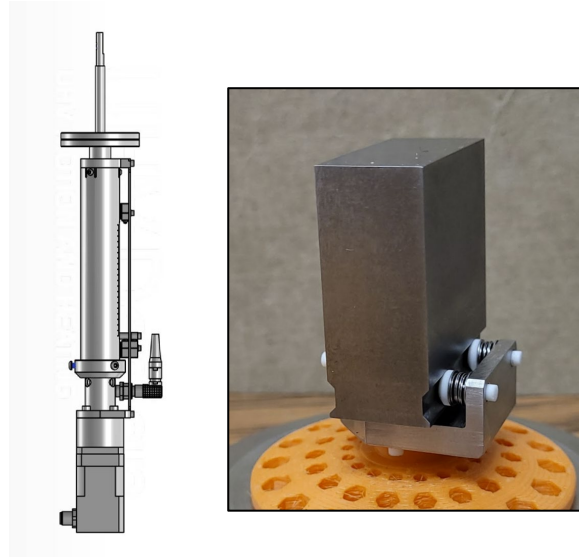
For PIP II Linac capability see E. Pozdeyev, “PIP II Linac and Possible Linac Extension,” **Booster Replacement Science Opportunities, 05/19/2020**, https://indico.fnal.gov/event/23352/contributions/185568/attachments/128433/155375/Pozdeyev_PIP2_linac_200519.pptx

The Beamline – installation complete

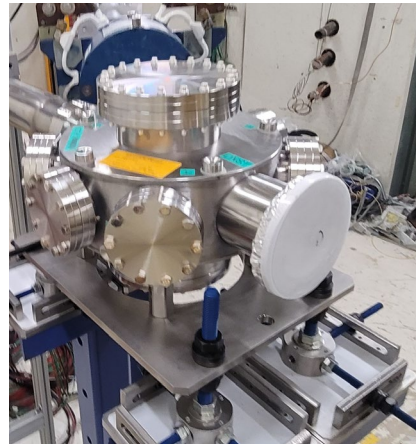


Target Optimization - Results

- Nuclear interaction models used:
- Pions are not produced beyond 4cm @400 MeV (due to energy loss)*
- Optimal integrated target length is 3 cm (solid or slices, 30% IL)*
 - 3 cm horz x 1.5 cm wide (measured) x 3 cm vertically
 - Models are giving significantly different rates and momentum distributions
 - Production peak – 100 – 150 MeV/c (A. Mazzacane)
 - Beamline retuned from 50 to 100 MeV/c

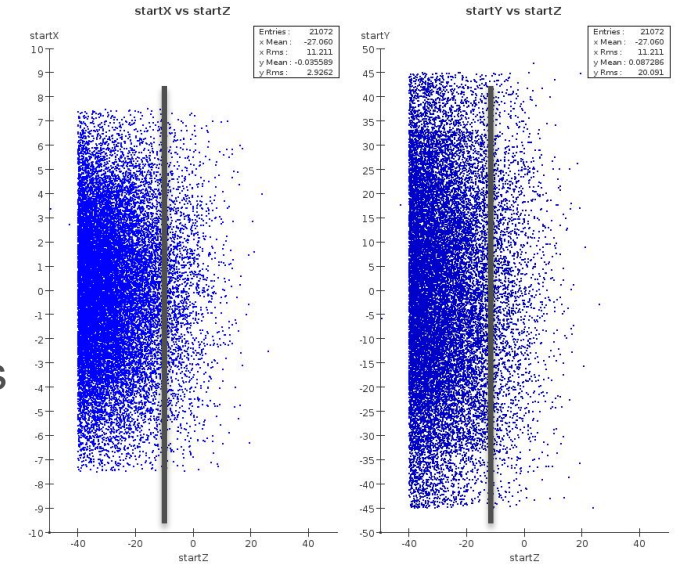
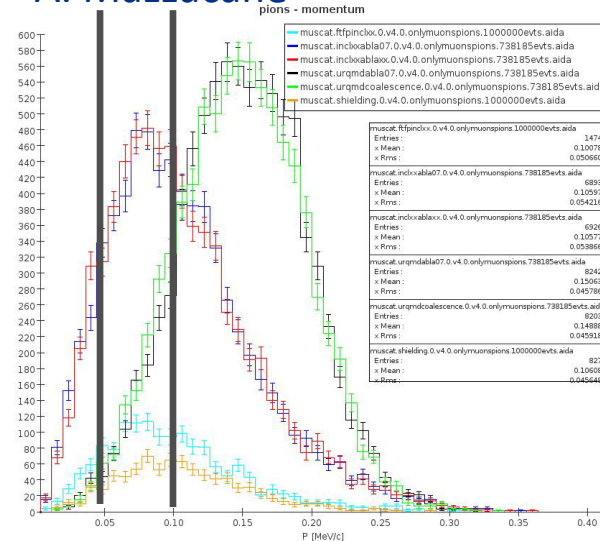


Retractable target – compatible with ITA running

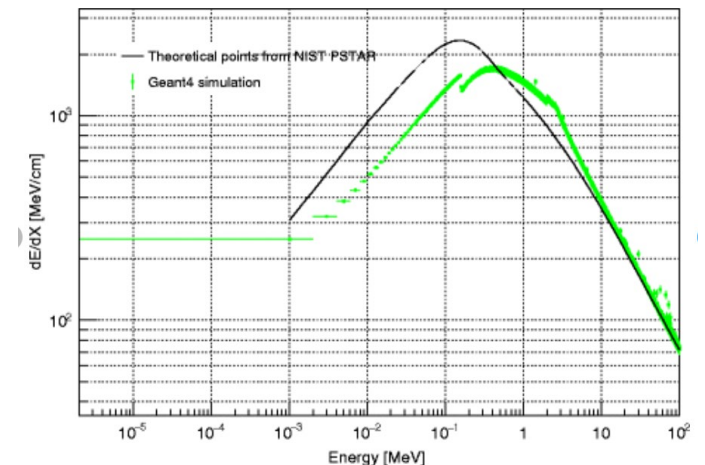


50 vs 100 MeV/c;

A. Mazzacane



Single pion 280 MeV threshold reached @4 cm; A. Mazzacane



Jasmine Tang – CCI internship project, spring 2023

- **Project Description:** *Optimize the capture and transport of a low-energy muon beam (30-50 MeV) through the decay of pions produced by 400 MeV protons directed onto a tungsten target to support physics experiments. The primary proton beam is derived from the intense 400 MeV Fermilab proton Linac. The optimization studies use the advanced G4beamline code which incorporates both charged particle dynamics and secondary particle production models and predictions. (give a link to G4beamline reference)*
- **Methodology:** The production of the initial pion beam, decay and transport is highly compute-intensive requiring POT of 10^{13} to generate hundreds of captured muons – even for low statistics give an estimate (decay and transport of $1e^8$ pions = how much time on a single processor). Since the production spectrum and distribution for a given target geometry and material is unchanged, for my project the beamline was separated and optimized independent of the production target. The methodology separates the study into two parts:
 - Production of pions from proton beam on target (graphite and tungsten have been modeled)
 - Characterize the π^- distribution in momentum and horizontal and vertical spherical angles
 - Study dependence on beamline tune with the mu- count @ end of beamline as the metric
- **Software Tools:**
 - Python, G4beamline MPI

3. Simulation setup

1. Splitting of simulations

2. G4beamline

1. Simulation file

2. Building G4beamline

3. Physics lists QGSP_BERT

4. Detector choice

3. Python

1. Generating batch jobs

2. Progress report

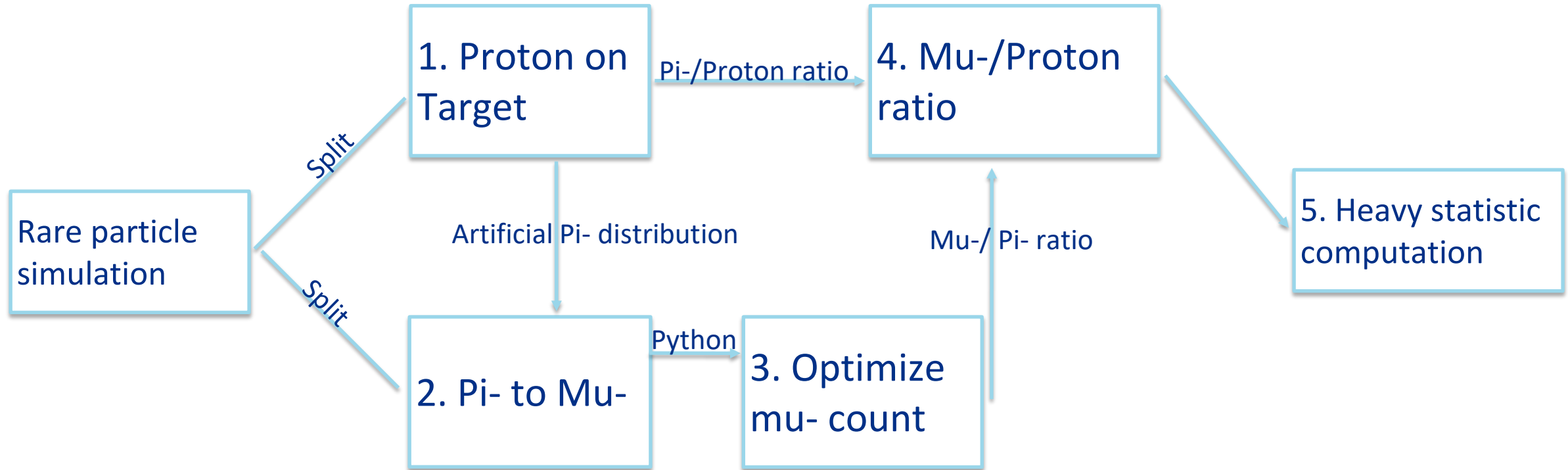
3. Loading and processing data

Simulations divided into two independent computations

Rare particle simulation <-> Unfeasible brute-force computation

Example: Running 4e9 simulation cases takes 24 hours on 12 cores for Intel i5-10400

Solution: Divide simulation into two parts; 1) production spectrum @target and 2) transport/optimization of muon capture at end of secondary beamline using 1)



Building G4beamline

Build with Ubuntu 22.04 x86.64, with MPI enabled and tweaks from User's Guides recommendation.

Docker container build for running G4beamline with MPI out of the box for high statistics computations

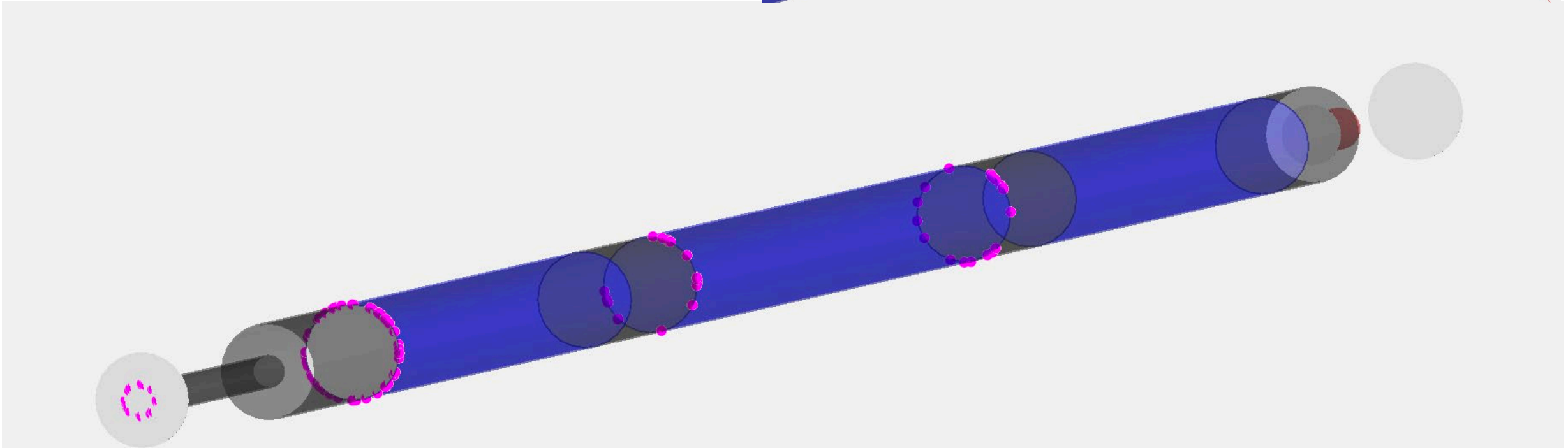
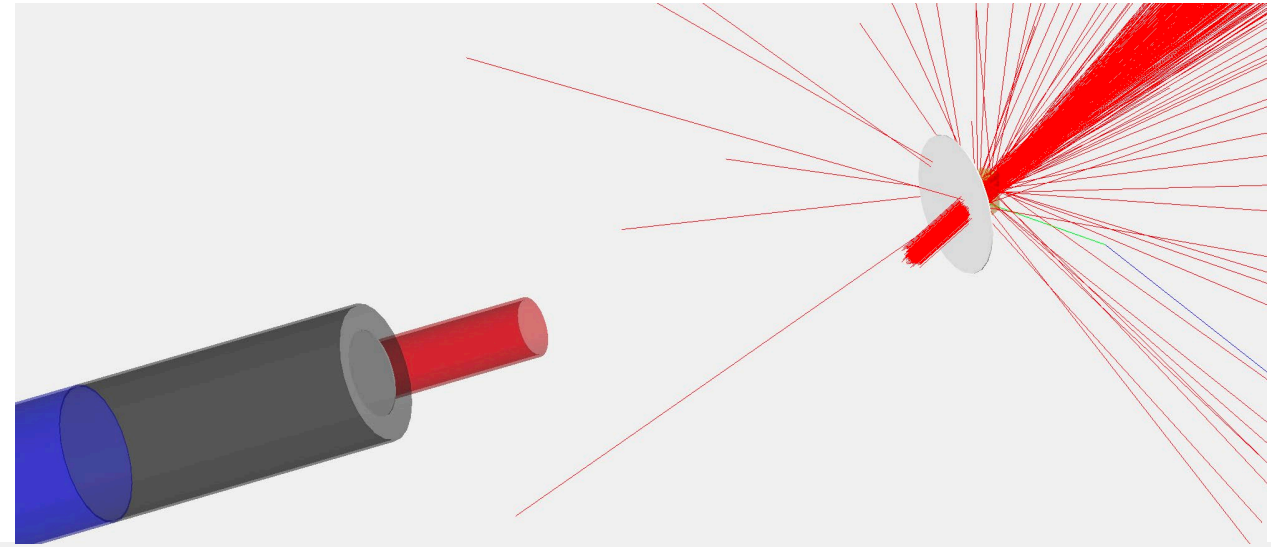
Physics List: QGSP_BERT

Virtual detectors (material free)

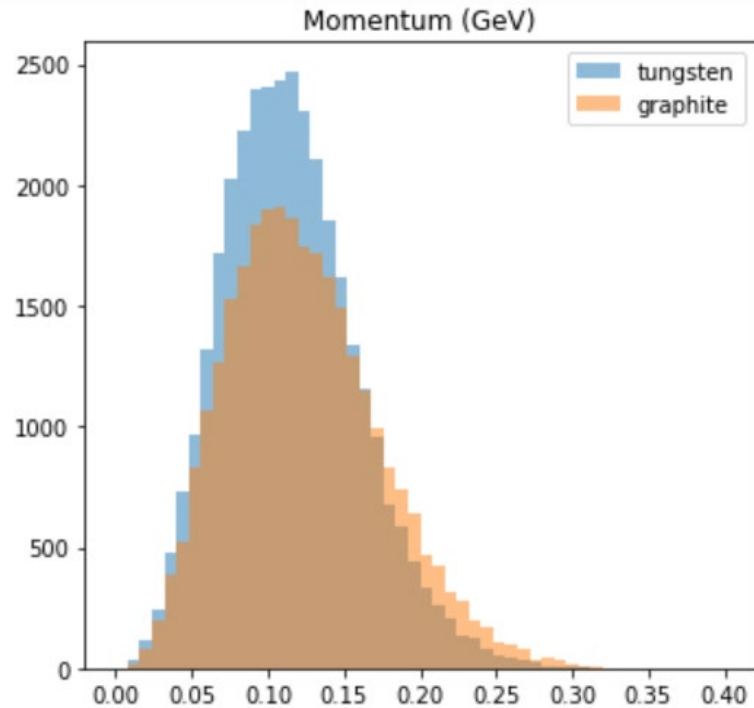
Located at different locations along the beamline and two different sizes – primary metric for muon capture is a virtual detector at the end of the beamline at the entrance to experimental apparatus

G4beamline

- Easier to use version of Geant4
- Optimized for simulating beamline
- Realistic simulations with swappable physics lists
- No C++ programming, only 1 ASCII file.
- Scriptable with Python
- Permit visualization

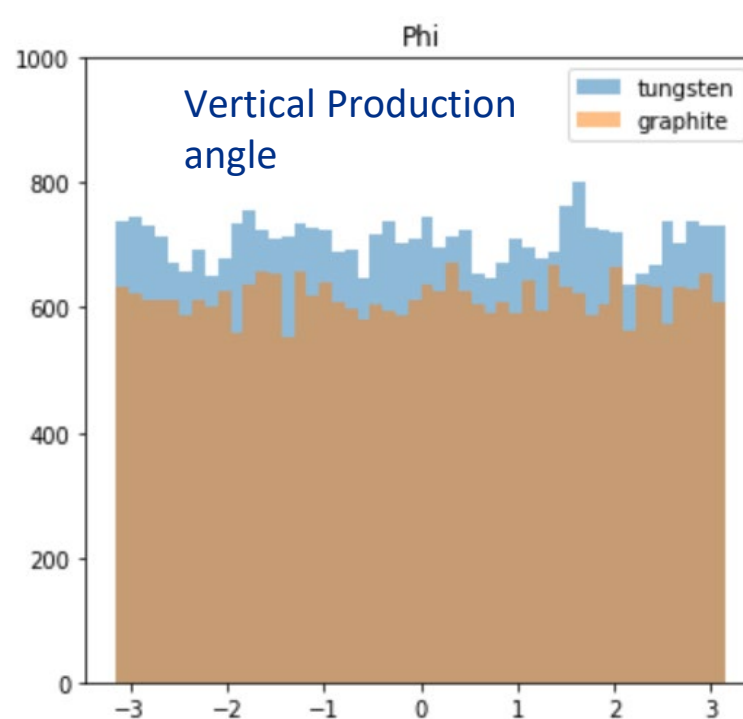


Production Spectra and Pion Distribution @Target for W and C

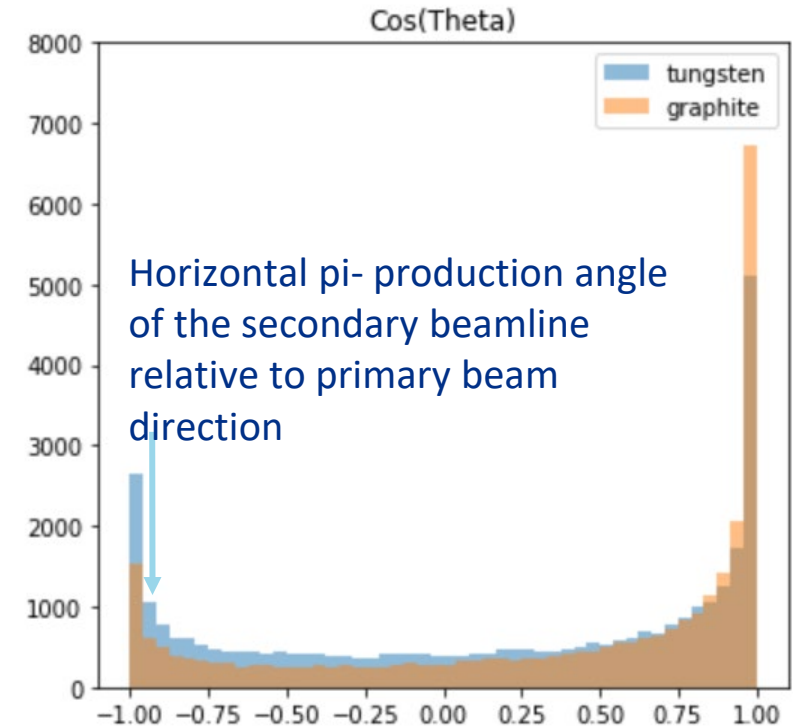


Momentum roughly follows a Gaussian distribution => Gaussian beam with mean $\sim 0.1 \text{ GeV}/c = 100 \text{ MeV}/c$ with standard deviation of $\sim 20 \text{ MeV}$

NOTE not seeing the large difference consistent with experimental data



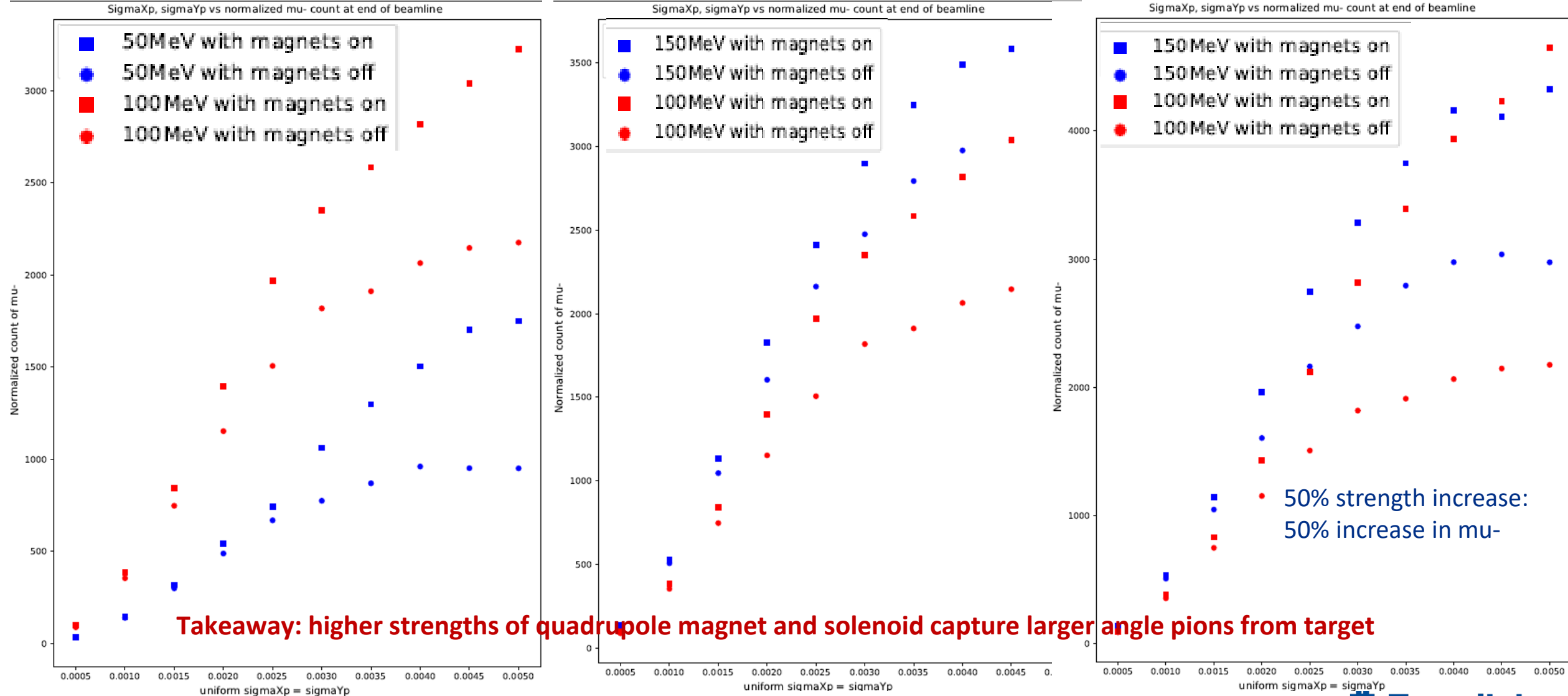
Angular distribution of pi- in the vertical plane allows a flat initial production distribution (negative sigma in angle in G4Beamline). This angle was increased sequentially to determine the maximum pion capture in angle by the secondary beamline as a function of tune.



Angular pi- distribution in the horizontal is also flat with the exception of forward and backward production angles. The cos theta of the secondary beamline is ~ 0.86 . A flat horizontal production angle can also be assumed (negative sigma).

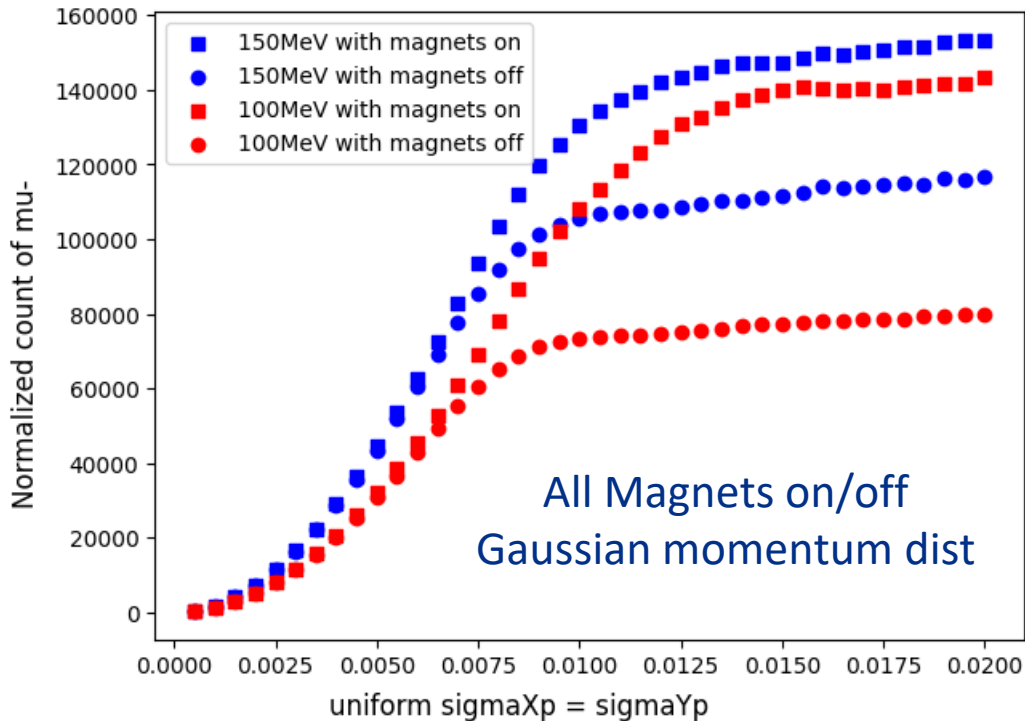
Normalized to $1e5 \pi^-$ per 20mm-mr “unit” phase space area

production spectra allows a constant density as a function of angle in vert and horz

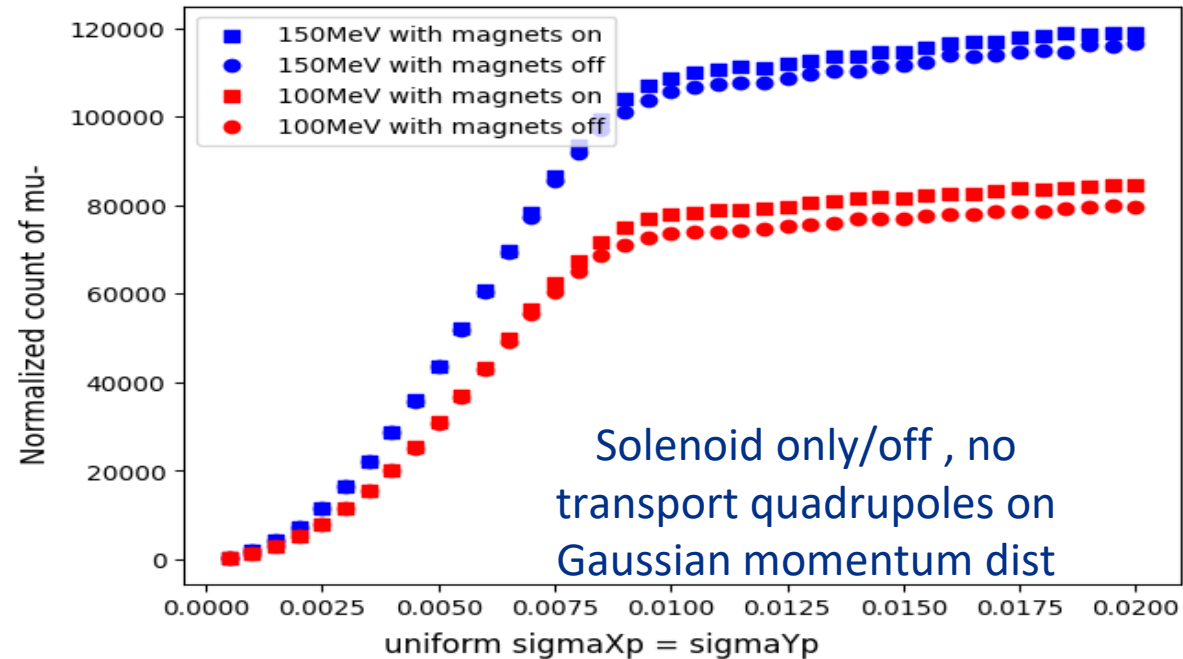


All magnets vs solenoid only - +/- 20mr pi- uniform: high statistics

SigmaXp, sigmaYp vs normalized mu- count at end of beamline (50mm rad detector)

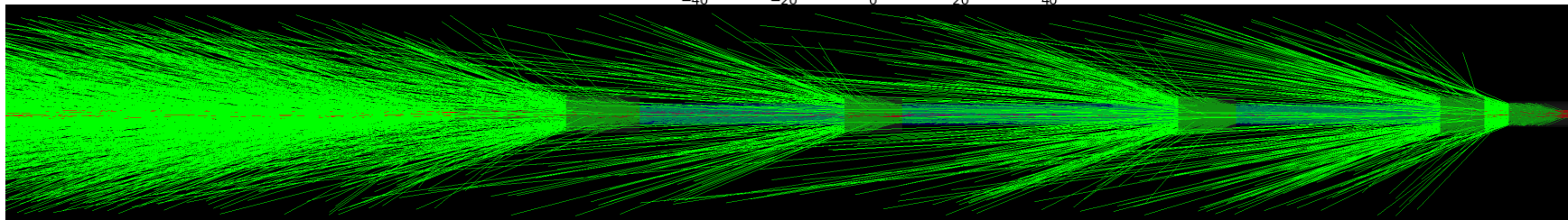
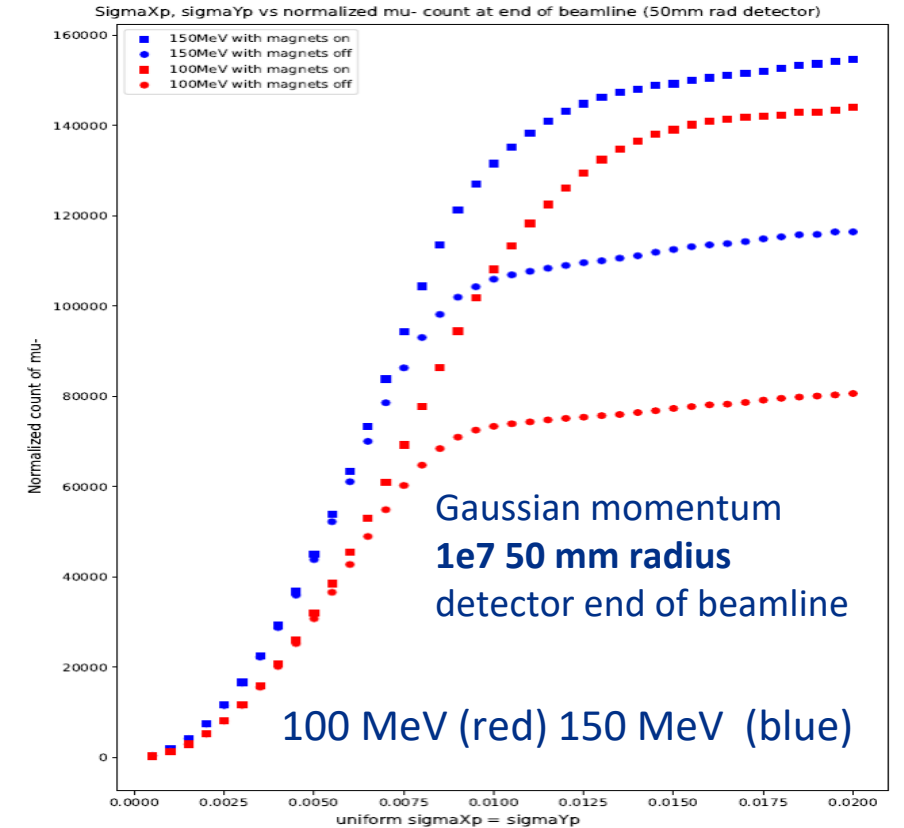
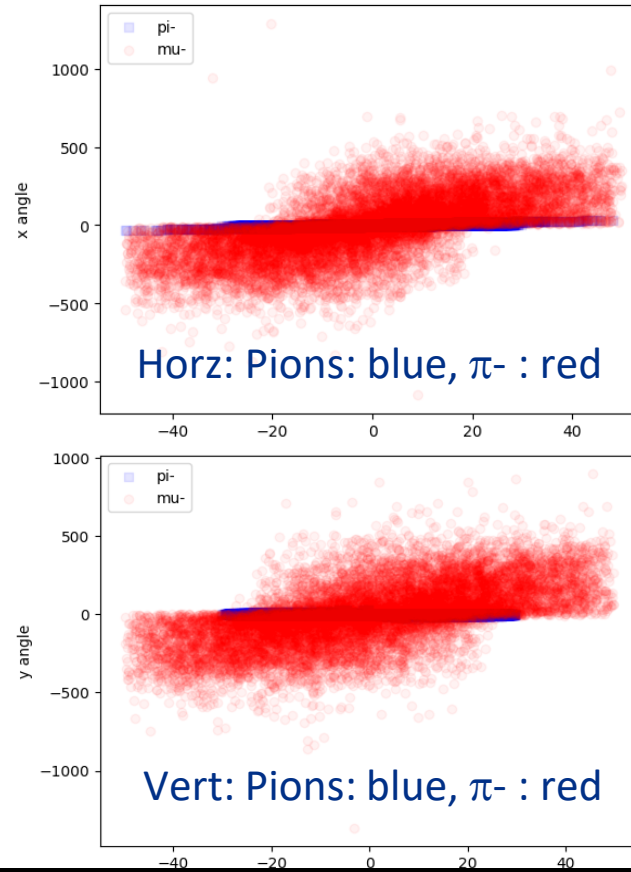
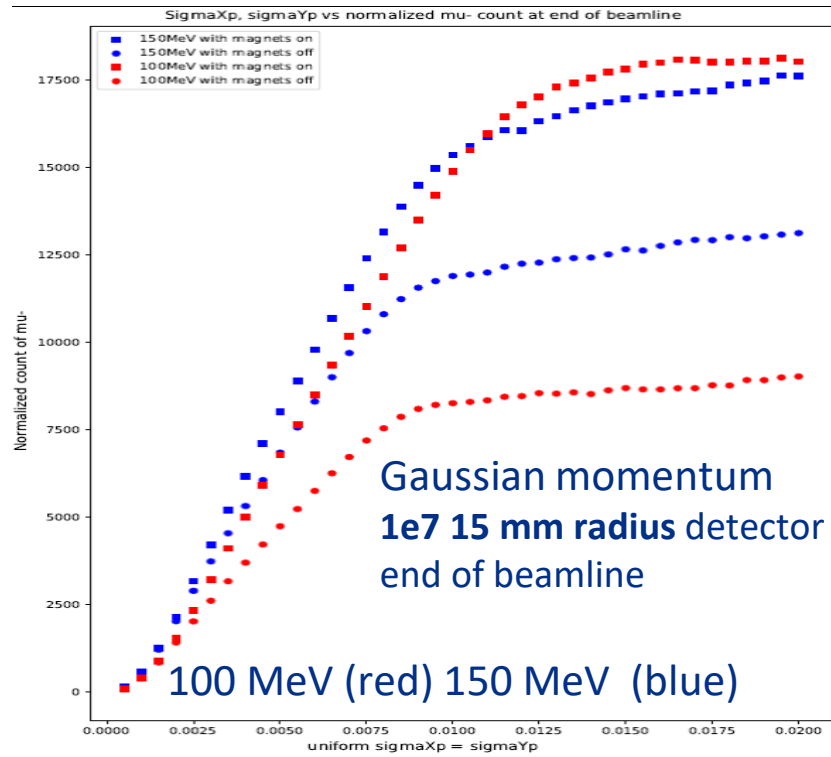


SigmaXp, sigmaYp vs normalized mu- count at end of beamline (50mm rad detector)



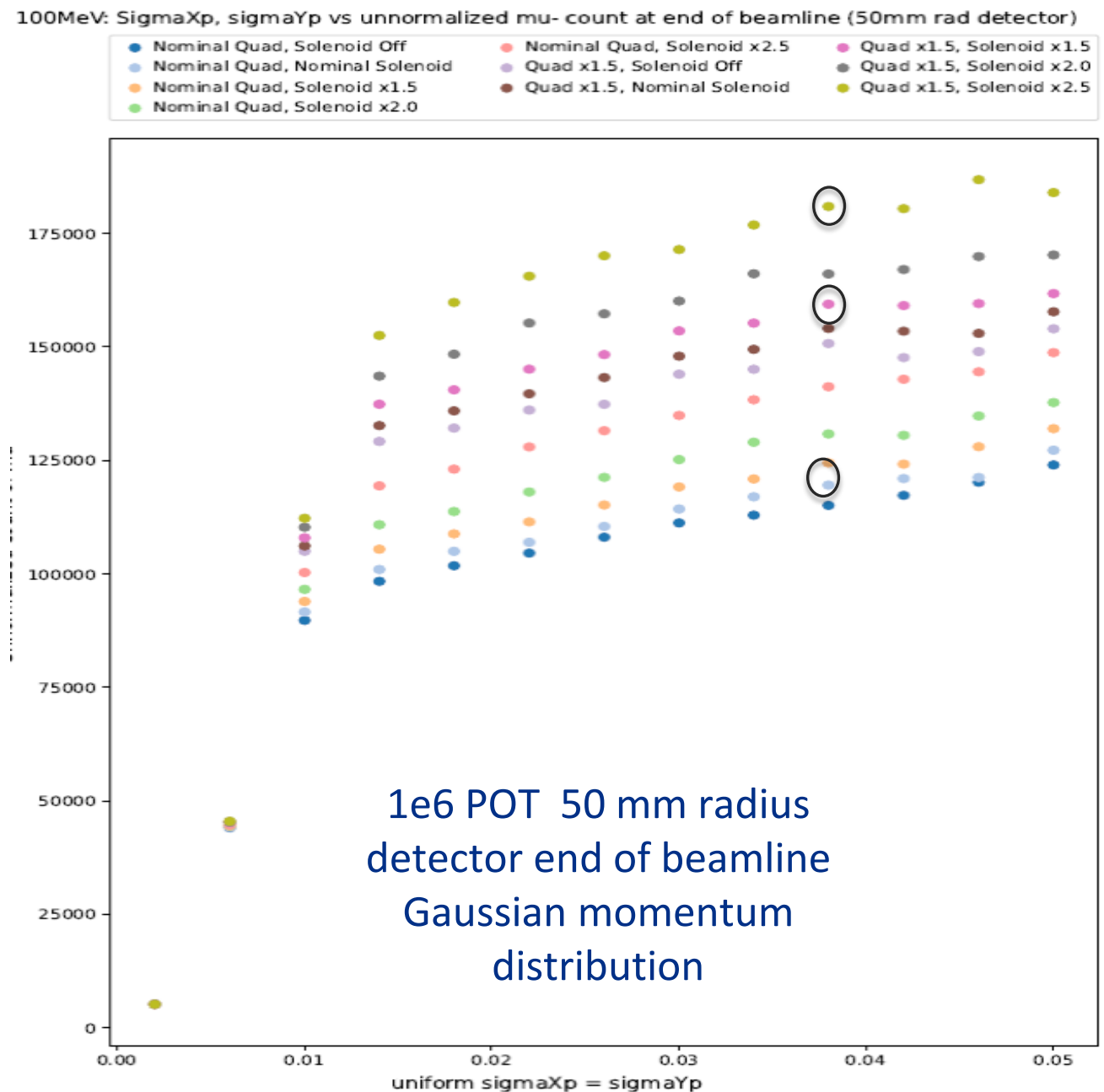
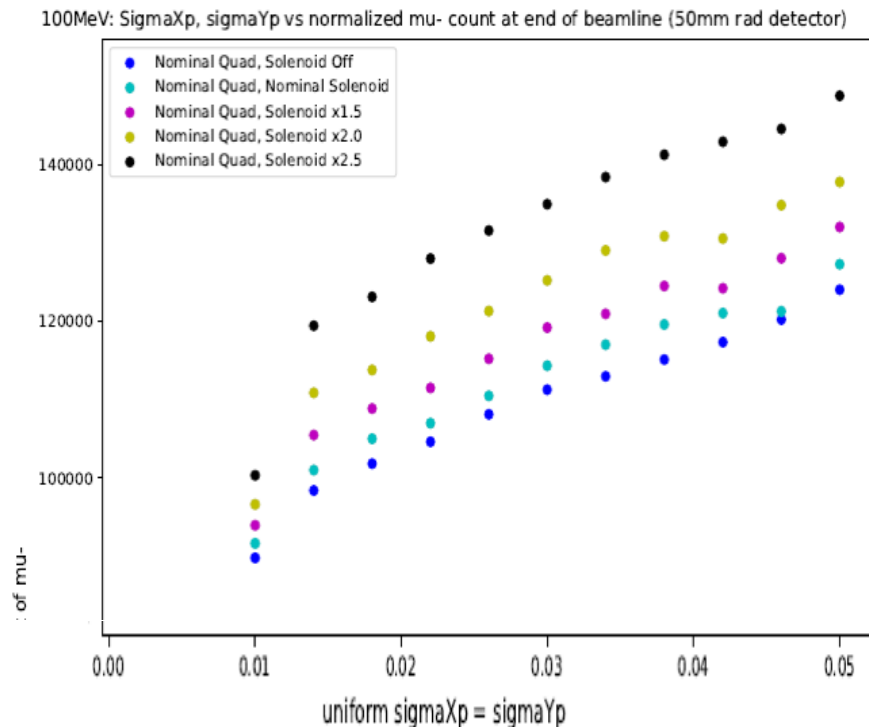
Shows strong contribution of beamline transport quadrupoles

20 mr capture, 1.5 x strength – different size detectors prop to detector area – μ^- fills the aperture
 capture \propto area (50 mm radius beampipe) – next beamline iteration will include a focusing telescope



Magnet and solenoid strength study

- Quads are beyond their op strength @1.5
- For stable optics stronger quads will require closer spacing
- We have located and been given stronger quads



Preliminary very approximate estimates – *requires a high statistics run combining production with optimized beamline*

- Captured $\mu^-/\pi^- \sim 1.4\%$ ($140\text{k } \mu^-/1\text{e}^7 \text{ POT}$) in the 4" diameter vacuum aperture @end of the line for 1.5 x nominal beamline currents
 - Scales as the square of the capture angle which scales with magnetic field strength
 - Solenoid strength can be increased by $\sim x2$
 - Stronger quads however (eventually more closely spaced) will be required to achieve $\sim x2$
 - WE NOW HAVE THESE QUADS!
- 120k/150k reduction for nominal strengths, so $\sim 1.12\%$ - using $5.2\text{e}^{-11} \mu^-/\text{POT}$ gives $5\text{e}^{-9} \pi^-/\text{POT}$ which produce a captured negative muon.
 - This increases to $\sim 1.75\%$ for peak solenoid strength and stronger quads (25% increase)
- How many muons will we make in a 32 μsec Linac pulse *under current SA*
 - 5.3×10^{12} p/pulse @32 μsec ; current SA allows 8 pulses/minute delivered in 0.5 sec: 4.2×10^{13} protons per minute
 - 2184 μ^- /minute in half a sec
 - Focusing to 1 cm radius – with stronger quads – $695 \mu^-/\text{cm}^2$ delivered in half a sec; *stronger quads: 1086 μ^-/cm^2*
- At half Linac intensity – *increases by a factor of x3375 (new SA, MTA hall will support this increase)*
- We need a high statistics run
 - Nominal currents
 - Increase all magnetic component strengths x 2
 - New line design with stronger, closely spaced quads and final focusing telescope
 - μ^+ will have x3 (decay in flight) and x 10 more surface muons

Summary

- Different hadronic models give very different yields
 - These models do not reproduce the experimental data observed between graphite and tungsten
 - Other mechanisms at work? Absorption, energy loss to escape target?
 - The experimental data was taken at 730 MeV above pair production threshold?
- 400-MeV Fermilab Linac is capable of producing world-class intensities of muon beams
 - Supports certain classes of physics experiments
- R&D can be performed for
 - Muonium experiments
 - quantum computing materials
 - future muon facilities in the PIP II era
- Critical now to initiate R&D for PIP II

- BACKUP slides

Angular Distribution of Low-energy Pion Production by 730-MeV protons

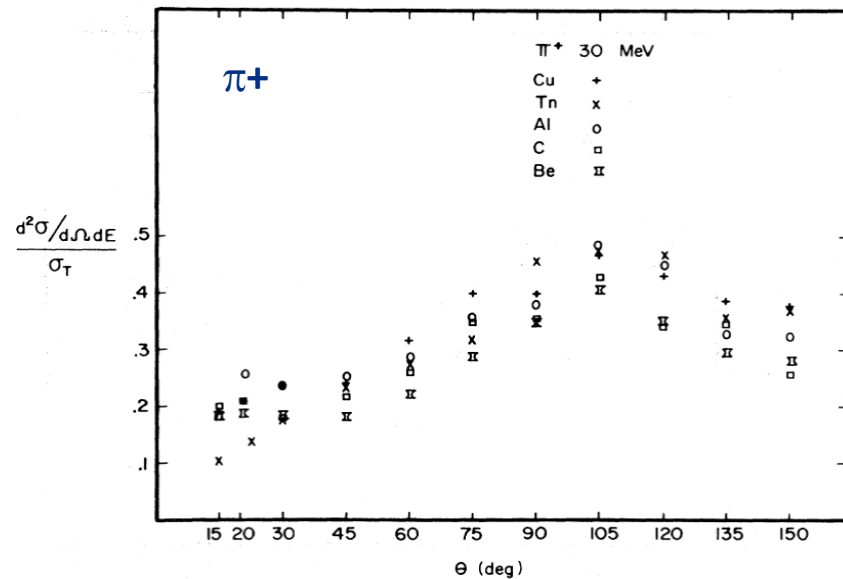


FIG. 22. $(d^2\sigma/d\Omega dE)/\sigma_T$ for 30-MeV π^+ .

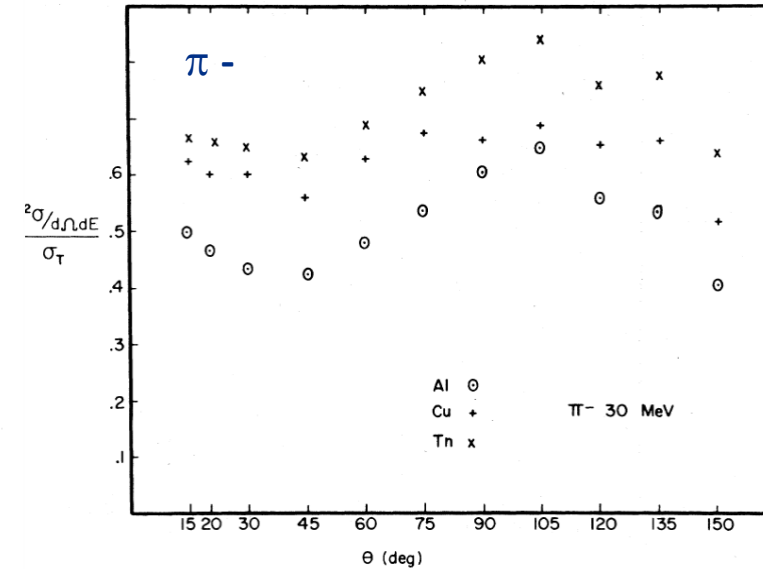


FIG. 23. $(d^2\sigma/d\Omega dE)/\sigma_T$ for 30-MeV π^- .

Differential 30-MeV pion production cross sections as a function of angle
Low-energy μ^- energy production from π^- will be \sim isotropic

D.R.F. Cochran, *et al*, "Production of Charged Pions by 730-MeV Protons from Selected Nuclei", Phys. Rev. D 6, 3085 (1972)