Target studies/Shielding

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Review for the MTA Secondary Line
August 23, 2021

A few words about me

- Joined AD three weeks ago
- Worked at INFN, PSI, SLAC, FNAL
- Experience in particle physics, detector R&D, operations, projects:
    - BaBar (Data analysis of semileptonic $B \rightarrow D^{o}\ l\ \nu$ decays with ML techniques)
    - MEG (offline framework)
    - ILC (Physics and detector studies for the LoI and the TDR)
    - ADRIANO multiple readout calorimeter (R&D,Test Beams,data analysis)
    - CDF (Data analysis with ML techniques)
    - Muon Collider (Physiscs and detector studies for Snowmass 2013)
    - ORKA (Simulations for proposal and for Snowmass 2013)
    - REDTOP (proponent)
    - OPOS (Group Leader)
    - POMS (Project Manager)
    - CI (Project Manager)
    - Liaison (Experiments, Directorate)
    - Affiliations DB (Manager, Admin)

Outline

- The Physics of Pion/Muon Production
- Classes of Particle-Matter interaction MC Simulations
- Monte Carlo Simulation Frameworks
- Geometry Implementation/Visualization
- Target Studies
- Shielding Assessment Addendum
- Summary

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Introduction

Studies

Outline Detailed

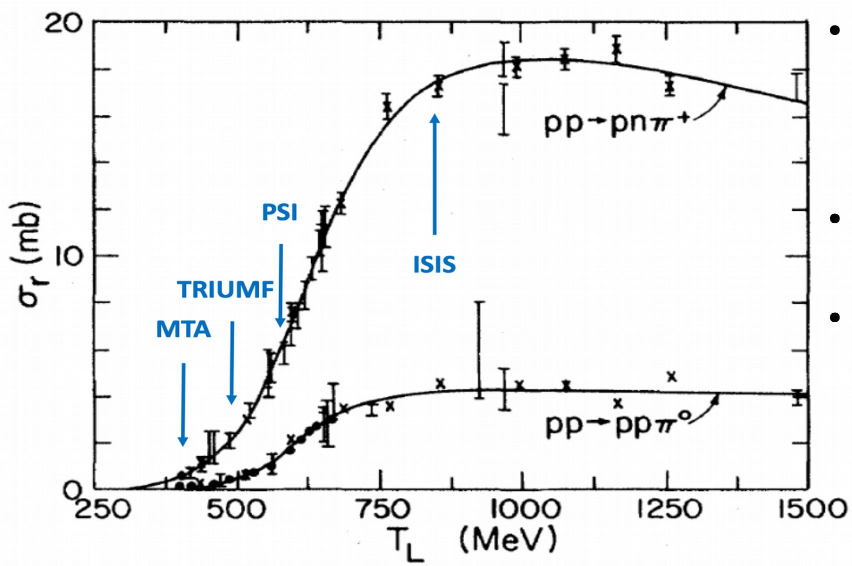
- The Physics of Pion/Muon Production
- Classes of Particle-Matter Frameworks
  - Particle transport programs vs Particle-nucleus hadronic scattering models
  - Limitations of particle-nucleus hadronic scattering models
- Monte Carlo Simulation Frameworks
  - GenieHad
  - SLIC
  - JAS3/ROOT
- Geometry Implementation/Visualization
  - LCCD/GDML
  - ROOT
- Target Studies
  - Implemented geometries
  - Simulation strategy
  - Momentum and origin of produced π^-
  - Momentum and direction of π^- at the entrance of the MTA secondary beamline
- Shielding Assessment Addendum
  - MTA Facility
  - Working plan
- Summary

The Physics of the Pion/Muon Production

- Single pion production thresold is 280 MeV, for pair is 600 MeV
- The single production cross section increases with the energy of the beam and begins to level around 800 MeV.
- Two facilities at Fermilab are candidates at producing high-intense pion/muon beams:
  - 800 MeV PIP II linac
  - 400 MeV MTA linac

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



- Charged pions production cross section were measured using the 730-MeV proton beam from the Berkely LBNL cyclotron 6 on various target nuclei, from hydrogen to lead.
- Heavier targets favor both π^+ and π^- production as shown in the table of total cross sections
- For the pion production at MTA, Tungsten is used as target material.

W was not part of the LBNL target materials:
Need to extrapolate for ARPA

Classes of Particles-Matter Frameworks for Hadronic Interactions

Particle transport programs

- Each particle is transported trough the material and interacted continuously
- Scattering takes into account the surrounding material
- Interactions at each steps need to be parametrized to limit CPU
- Few frameworks available

Particle-nucleus hadronic scattering models

- Single interaction between two particles (i.e. proton and nucleus)
- Nucleus is isolated and in vacuum
- Probe is propagated inside the nucleus: very slow programs not suited for transport code (except for Incl++ which is parametrized)
- Many models available (usually developed by nuclear theorists)

Particle transport programs

Geant4

- Largest share of users
- Relatively fast
- Multiple nuclear interaction models available trough physics list
- Choice of physics list depends on applications
- Open source
- For HEP applications, generally considered OK for simulations of energy deposited inside the detectors, not for the study of hadronic interaction products

MARS15

- Based on LAQGSM (Los Alamos version of the quark-gluon string model)
- Nuclear interaction of probe-target very well described
- Source not available
- For HEP applications, generally considered excellent for study of hadronic interaction products

FLUKA

- Same as MARS15, but based on DPMJET-III model
- Source not available

Particle-nucleus hadronic scattering models

- Multiple models available:
  - Urqmd
  - Dpmjet-III
  - Incl++
  - Gibuu
  - Jam
  - Phsd
  - Pythia
  - QGSM/LAQGSM
  - PHITS
- Probe is transported inside the nucleus: usually very slow
- Very accurate determination of scattering products
- Mostly used by intermediate energy experiments (<5 GeV) where the nuclear interaction is very complex (non-perturbative, presence of intranuclear-resonances, string theory not well applicable)
- Models act differently: in general experimenters use multiple models and get a range of predictions
- **All open source except for LAQGSM**

Limitations of particle-nucleus hadronic scattering models

- The target is a standalone nucleus surrounded by vacuum rather than being part of the materials in the apparatus;
- No geometry aware: the target nucleus is positioned in the origin of the reference frame, rather than everywhere in the apparatus;
- The beam and the target are well-defined species, while the beam and the materials in the experimental apparatus are composed of multiple species;
- Except for the Incl++ case, the nucleons in the final state are returned to the user as a list of free (un-aggregated) particles rather than physical fragments.
- Output format is non-standard

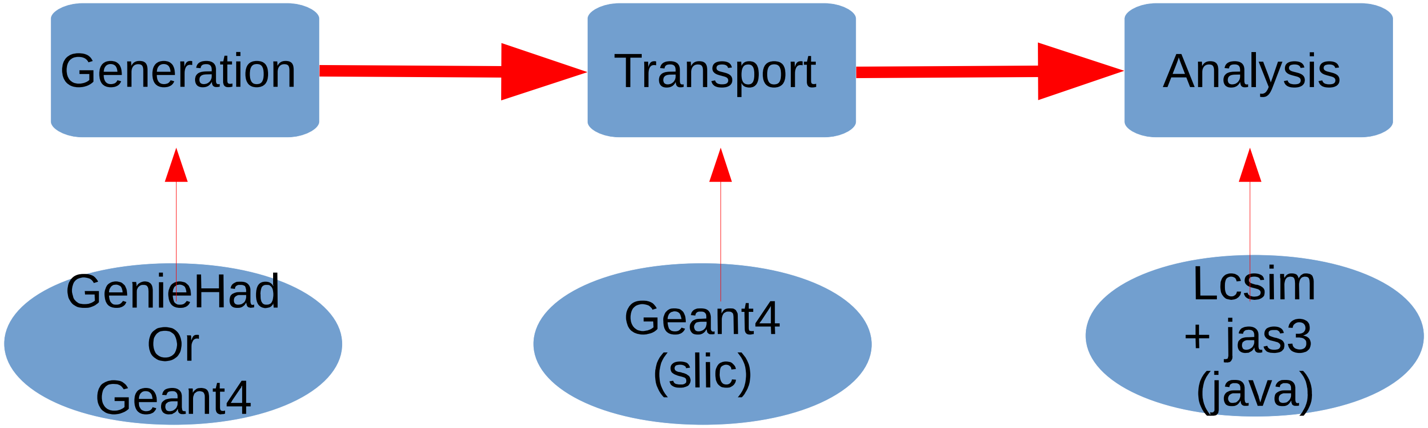
Overcoming the limitations – GenieHad

- GenieHad was developed for overcoming the limitations of standalone particle-nucleus hadronic scattering event generators
- It consists of a collection of interfaces to several external generators
- It uses the description of the geometry and the beam, and the I/O systems (both based on the ROOT framework) of the well established GENIE event generator.
- Several libraries interface the generation process to external nuclear scattering engines and to clusterization, evaporation/de-excitation programs.
- The user selects the nuclear and the evaporation models at run time via xml-based input cards.
- Event output in several formats:
    - Stdhep
    - Slcio
    - Hepevt
    - Lhe
    - root

Products of primary scattering (elementary particles and nuclear remnants) need to be fed into a particle transport code simulating the rest of the apparatus

MC Simulation Framework – Steps and Toolkits

- The simulation of the interaction of the projectile on target (event simulation) is efficiently factorized in steps.
- Each step can be processed by the appropriate program that takes into account the specific case and complexity



Advantages:

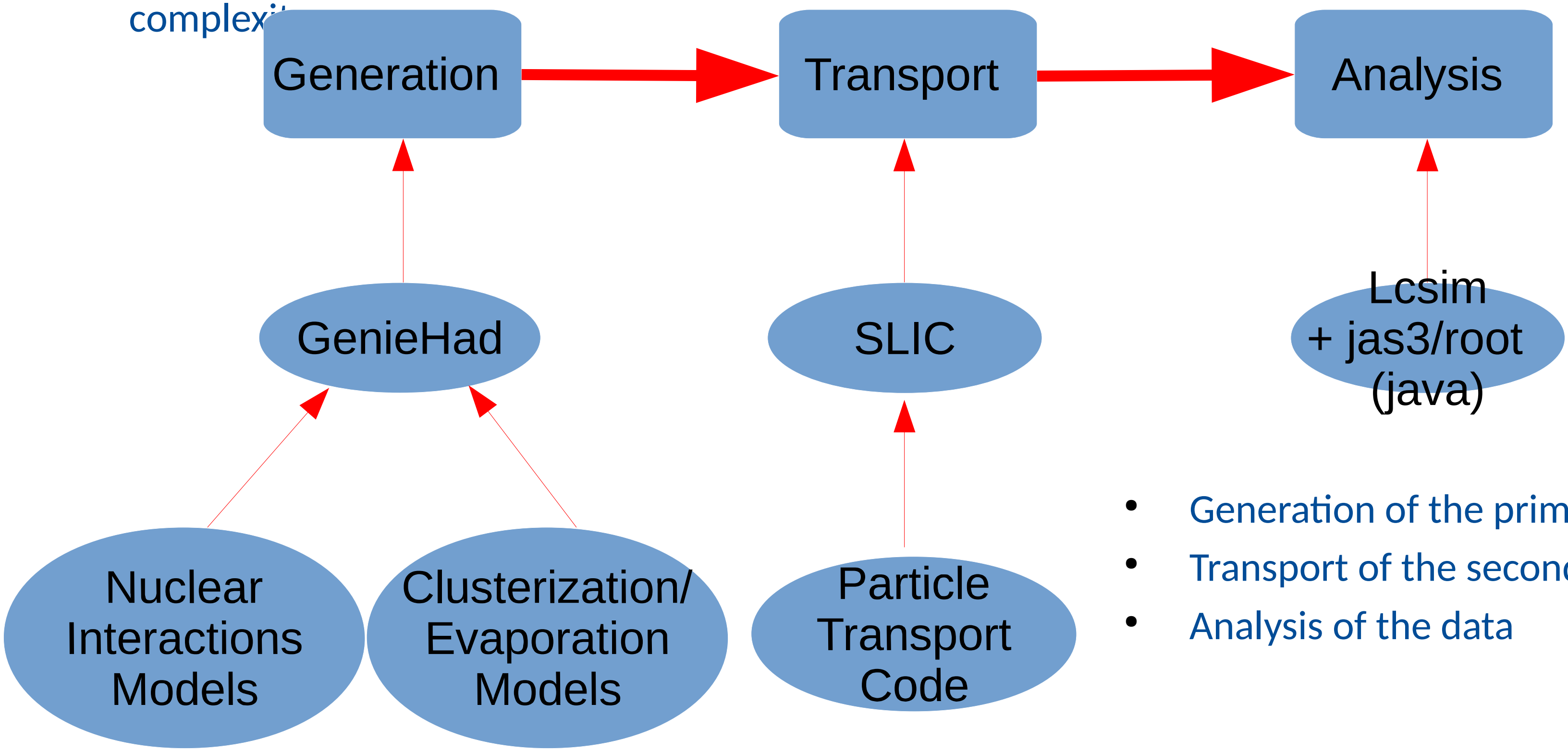
- It allows to compare several hadronic interaction models among them and vs Geant4

Disadvantages

- Two-step process
- Hadronic model only applied to primary interaction

Simulation Strategy for Thin Targets:

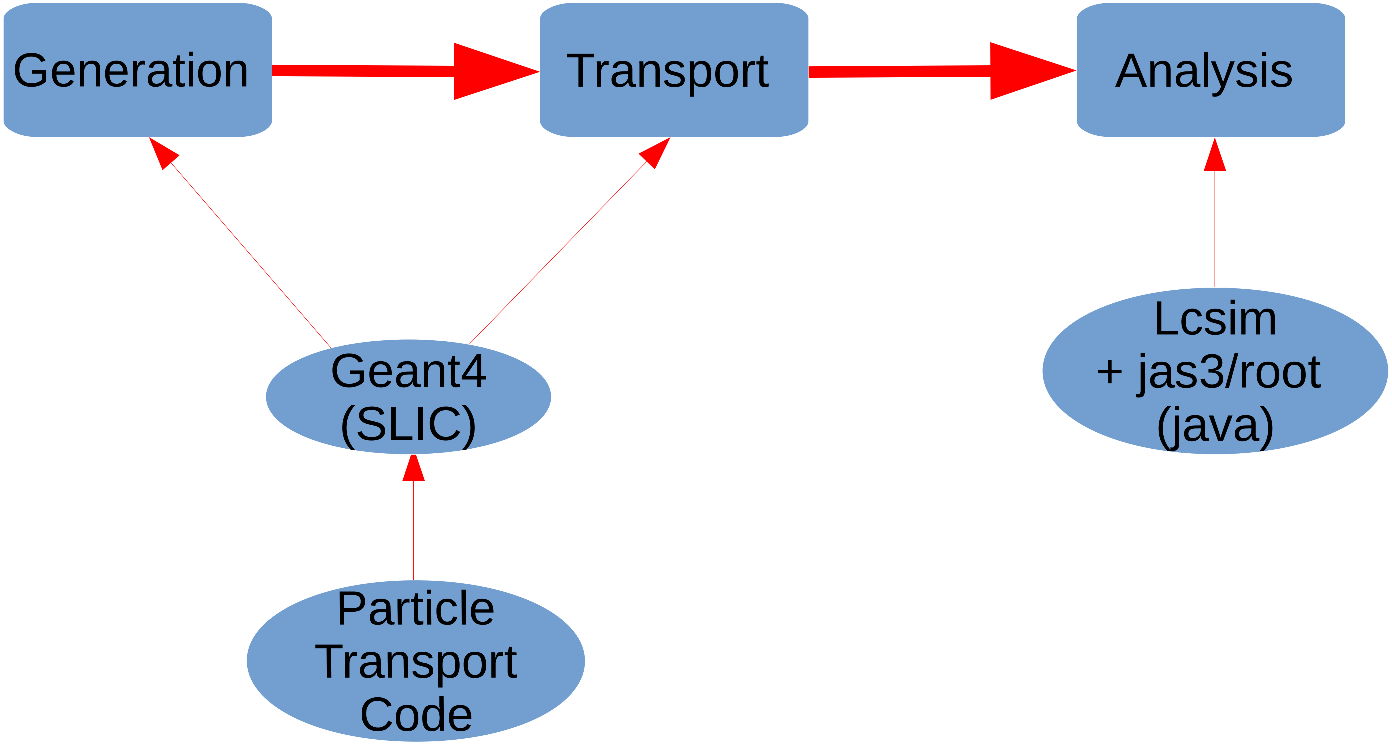
- The simulation of the interaction of the projectile on target (event simulation) is efficiently factorized in steps.
- Each step can be processed by the appropriate program that takes into account the specific case and complexi



- Generation of the primary interaction
- Transport of the secondary particles
- Analysis of the data

Simulation Strategy for Thick Targets

- Combination of EM, inelastic hadronic scattering and coherent process (charge exchange, capture, fission, etc.) needs to be continuosly taken into account when a particle traverses matter
- Correct simulation of thick targets requires a full particle trasport framework



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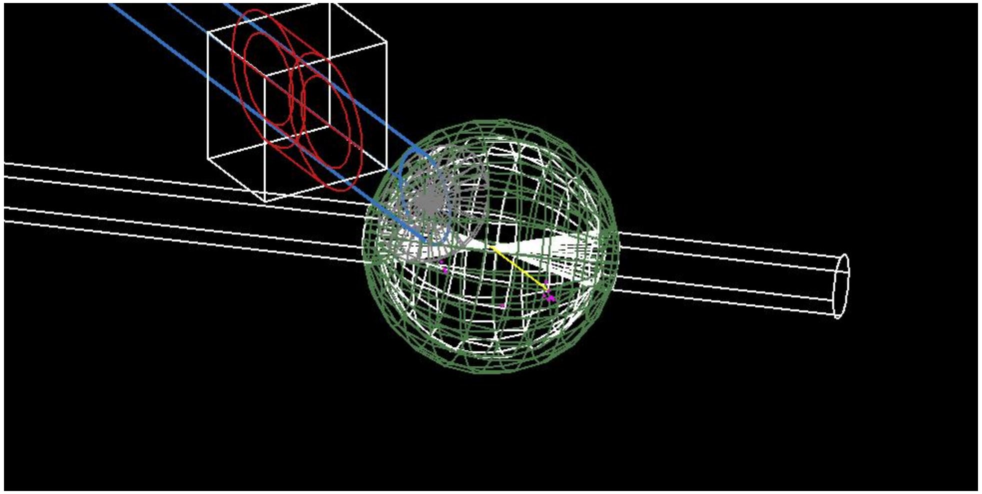
Geometry Implementation and Visualization

LCCD/GDML

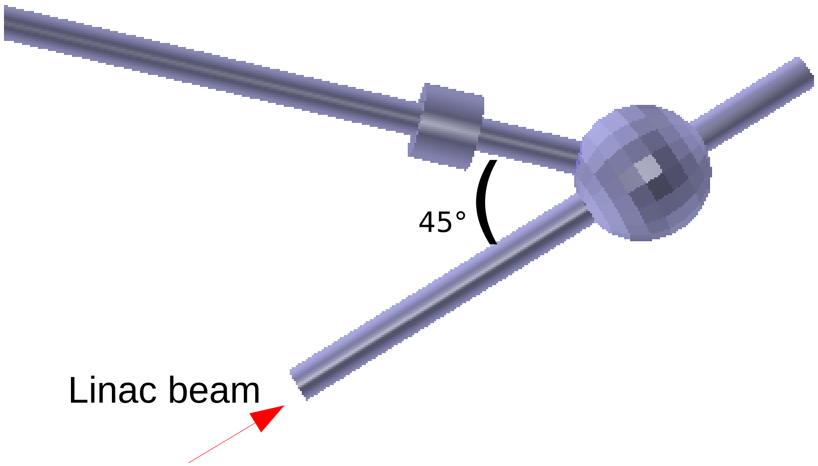
- The detector geometry is described using the Linear Collider Detector Description (LCDD). This system allows end users to create complex detector geometries in a standard XML format.
- The LCDD is based on the Geometry Description Markup Language (GDML) that is supported by GEANT4 and ROOT both as imput and output

ROOT

- ROOT has a geometry package for building, browsing, navigating and visualizing detector geometries.

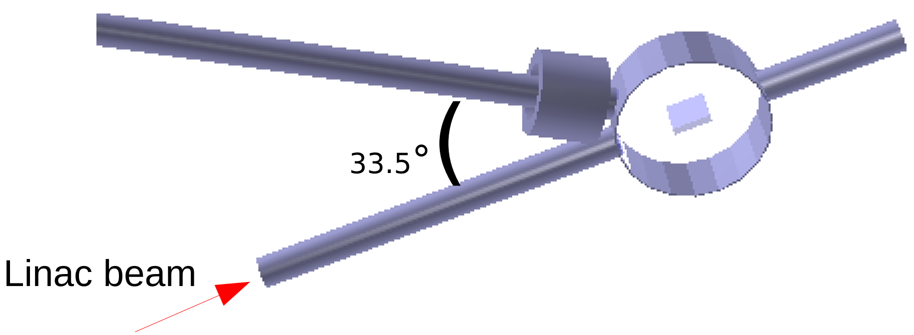


Target Studies - Implemented Geometries



- Latest implementation of the geometry (bottom picture)
- Cylindrical production chamber
- Secondary beamline @146.5° angle
- Solid W target (1.5x9x8)cm^3 (80% IL)

- Early implementation of the geometry before defined officially (top picture)
- Spherical production chamber
- Secondary beamline @135° angle
- Three W slices (20x20x3.3)mm^3 each (~10% IL) oriented 45° to the proton beam

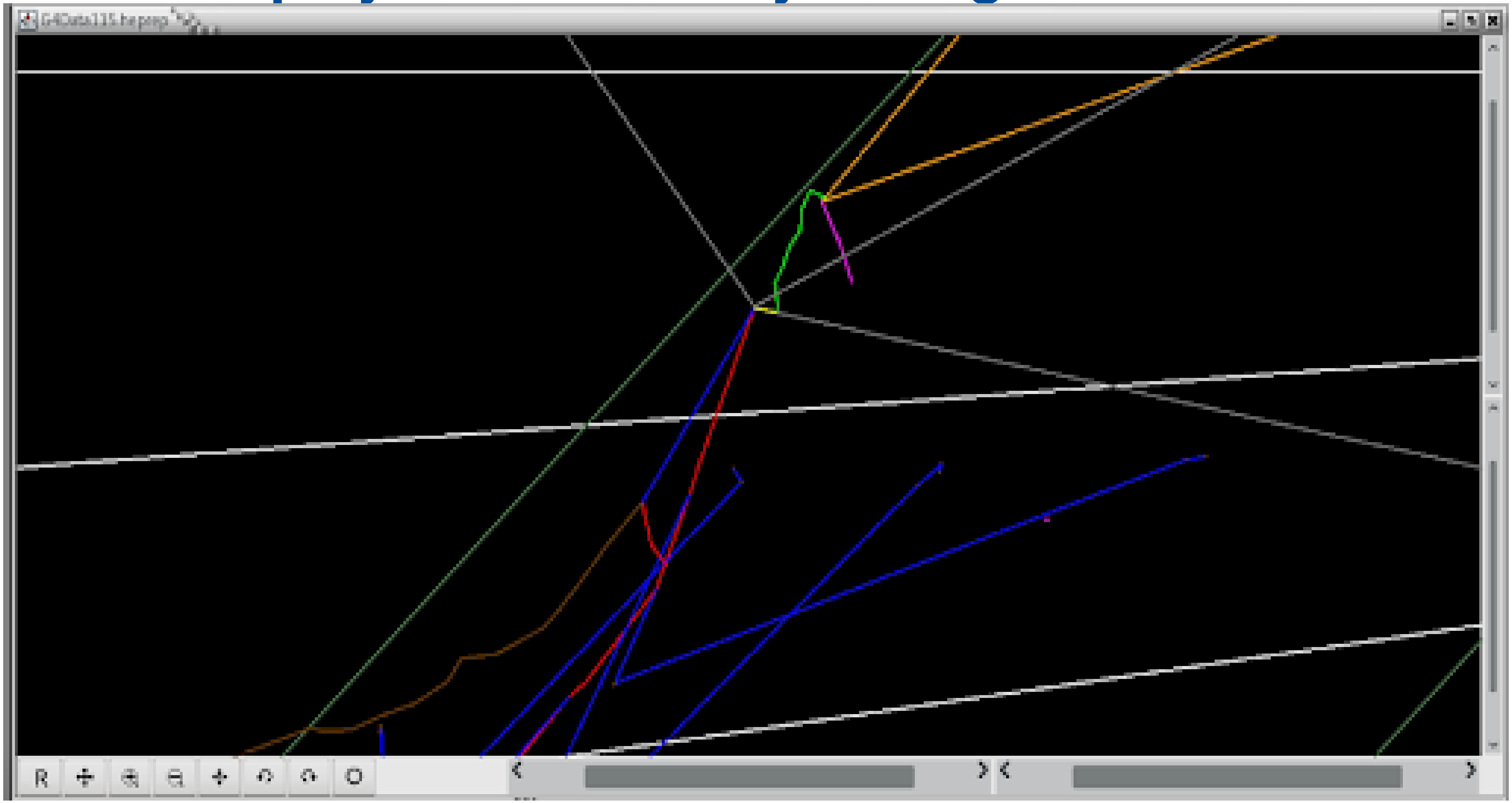


Summary of implemented geometries and simulation models

Version	Target	Extraction line	Chamber	Simulations Geniehad	Simulations Geant4
V3.1	3 x 3.3 mm (slanted)	-45^{o}	Spherical, 20mm thick	Urqmd Incl++ Gibuu Jam Phsd	Shielding FTPF_INCL
V3.2	3 x 10 mm (slanted)	-33.5^{o}	Spherical, 20mm thick Incl++	Incl++*	Shielding FTPF_INCL FTPF_INCL_HP
V4.0	1 x 80 mm	-33.5^{o}	Cilindrical 1/8” thick	Urqmd Incl++*	Shielding FTPF_INCL

*For reference only

Event display – Muon decay in target

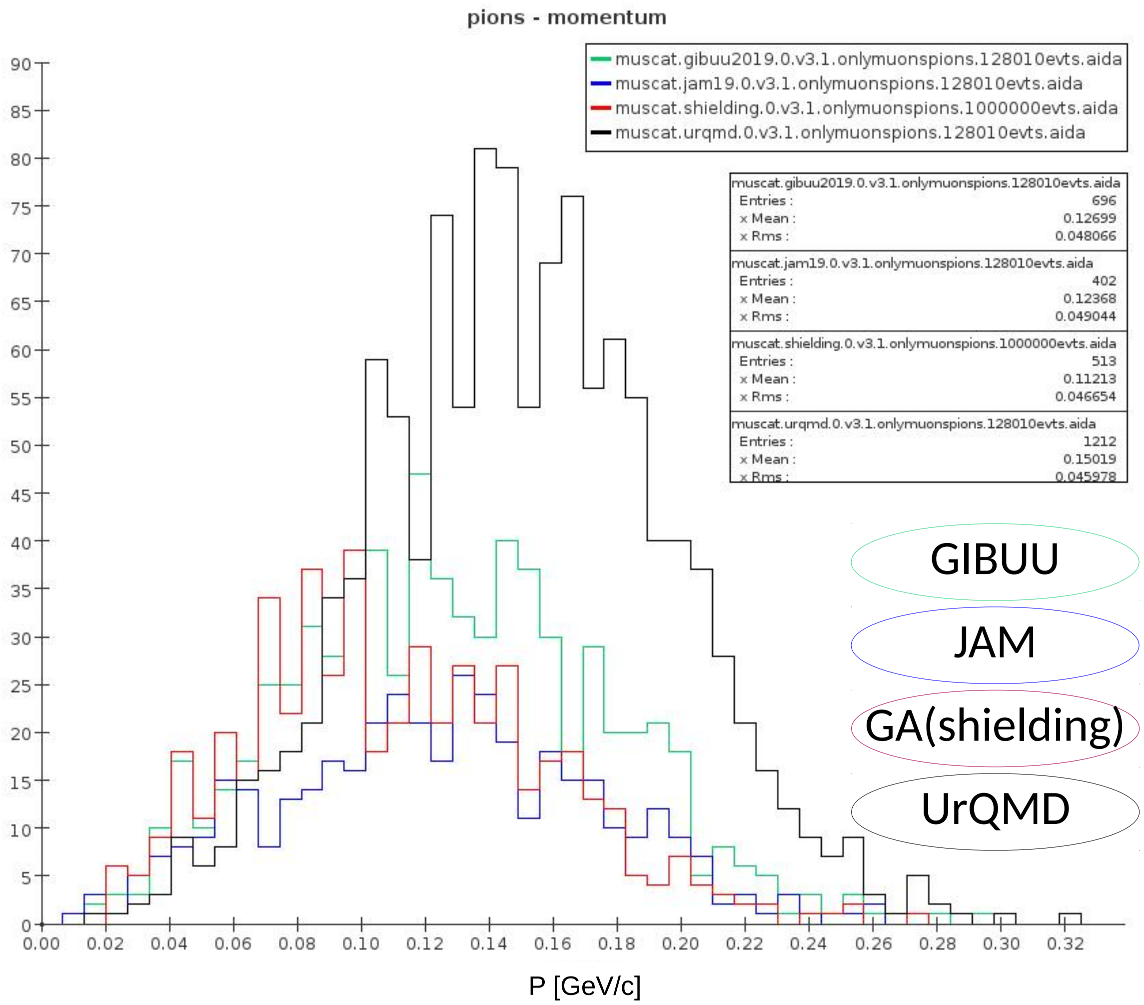


UrRQMD (inelastic only)

Magenta:p, Green:π, Orange:n, Yellow:μ, Red:e, Gray:ν, Blue:γ

Geometry v3.1

Three 3.3 mm Slices W Target Studies – π^- Momentum



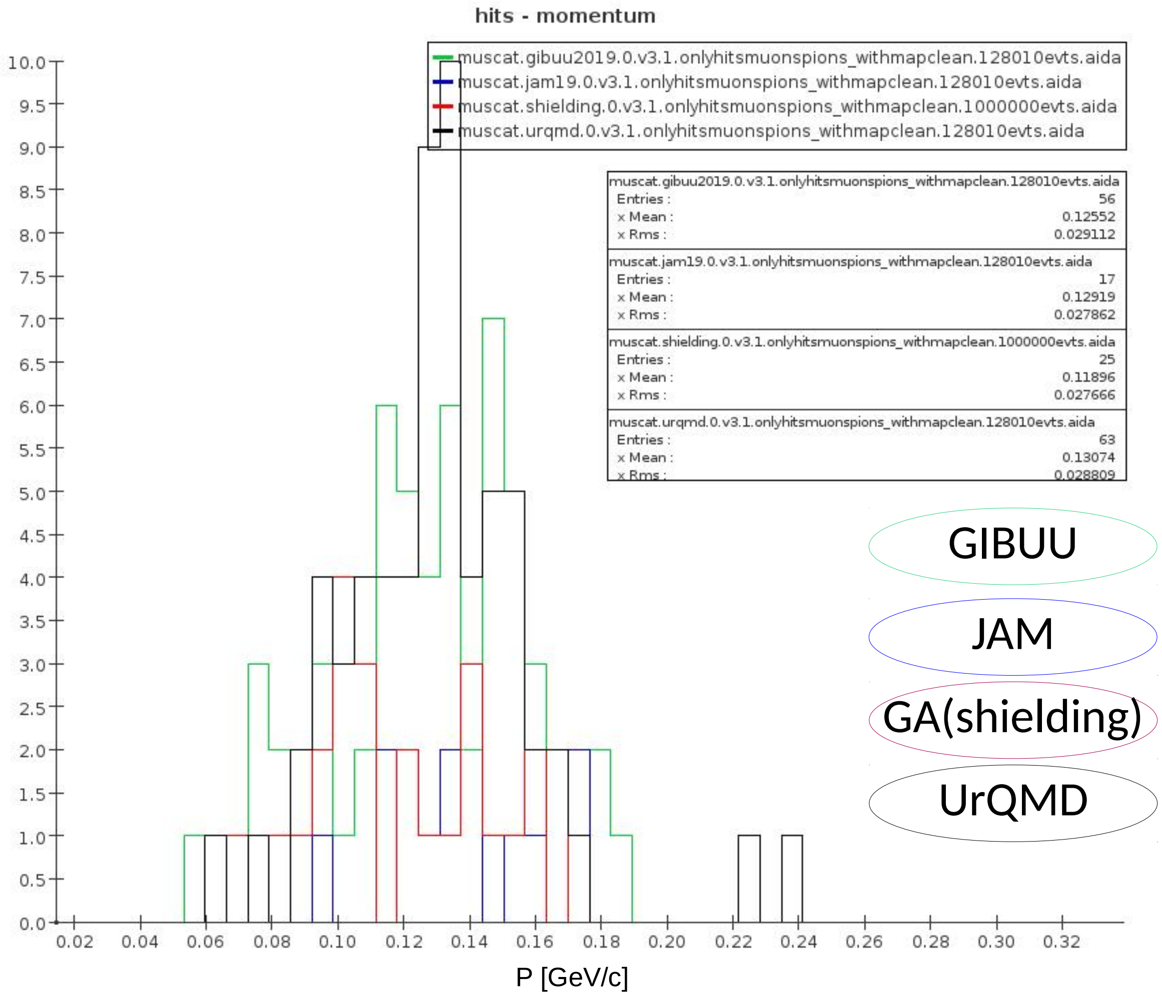
1M POT

Beam:
E_k=(400 ± 1) MeV
$\sigma_x=\sigma_y$=500 μm

Three 3.3 mm Slices W Target Studies – π^- Momentum at the entrance of the transport line

Geometry v3.1

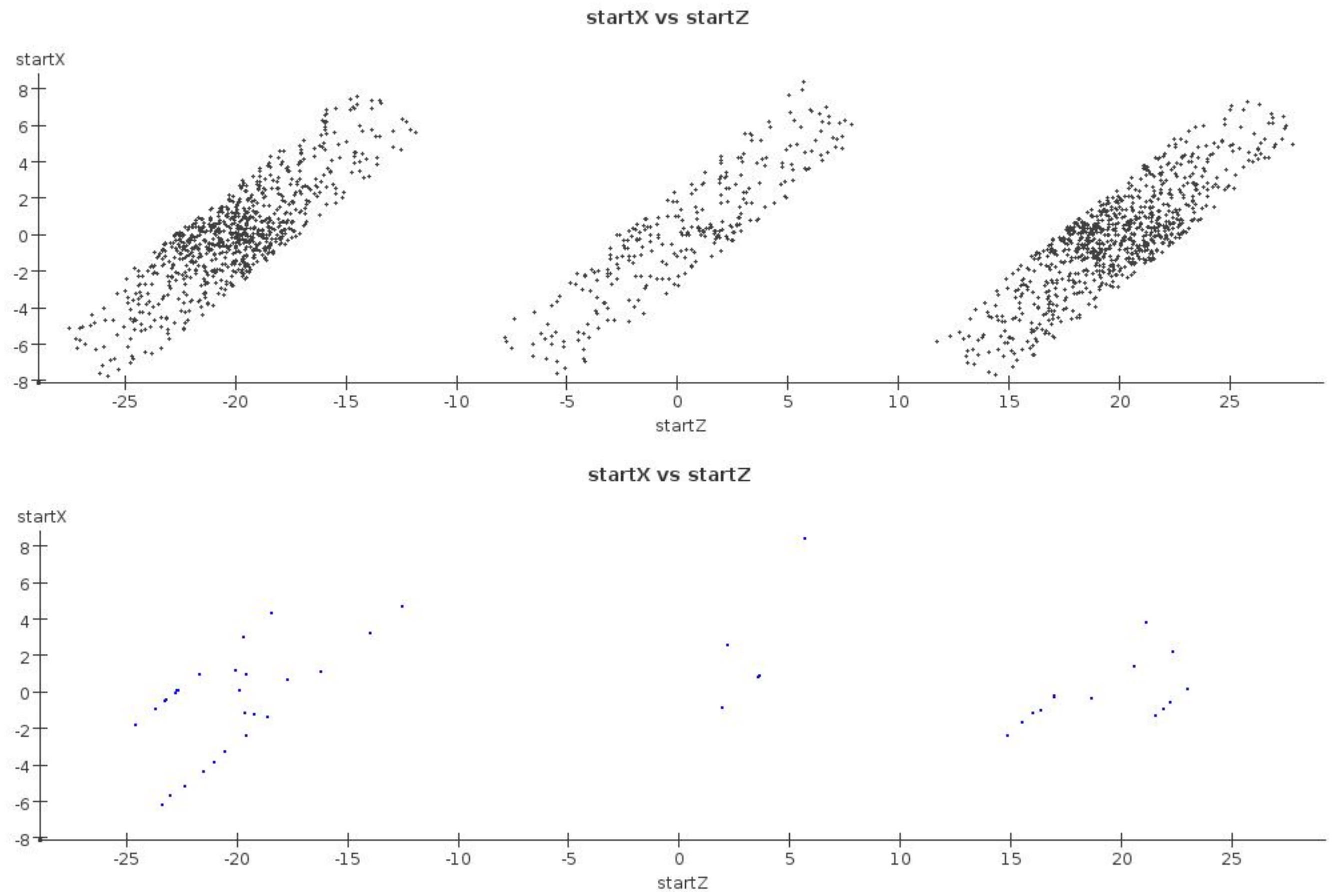
1M POT



Beam:
E_k=(400 ± 1) MeV
$\sigma_x=\sigma_y$=500 μm

Geometry v3.1

Three 3.3 mm Slices W Target Studies – π^- Origin



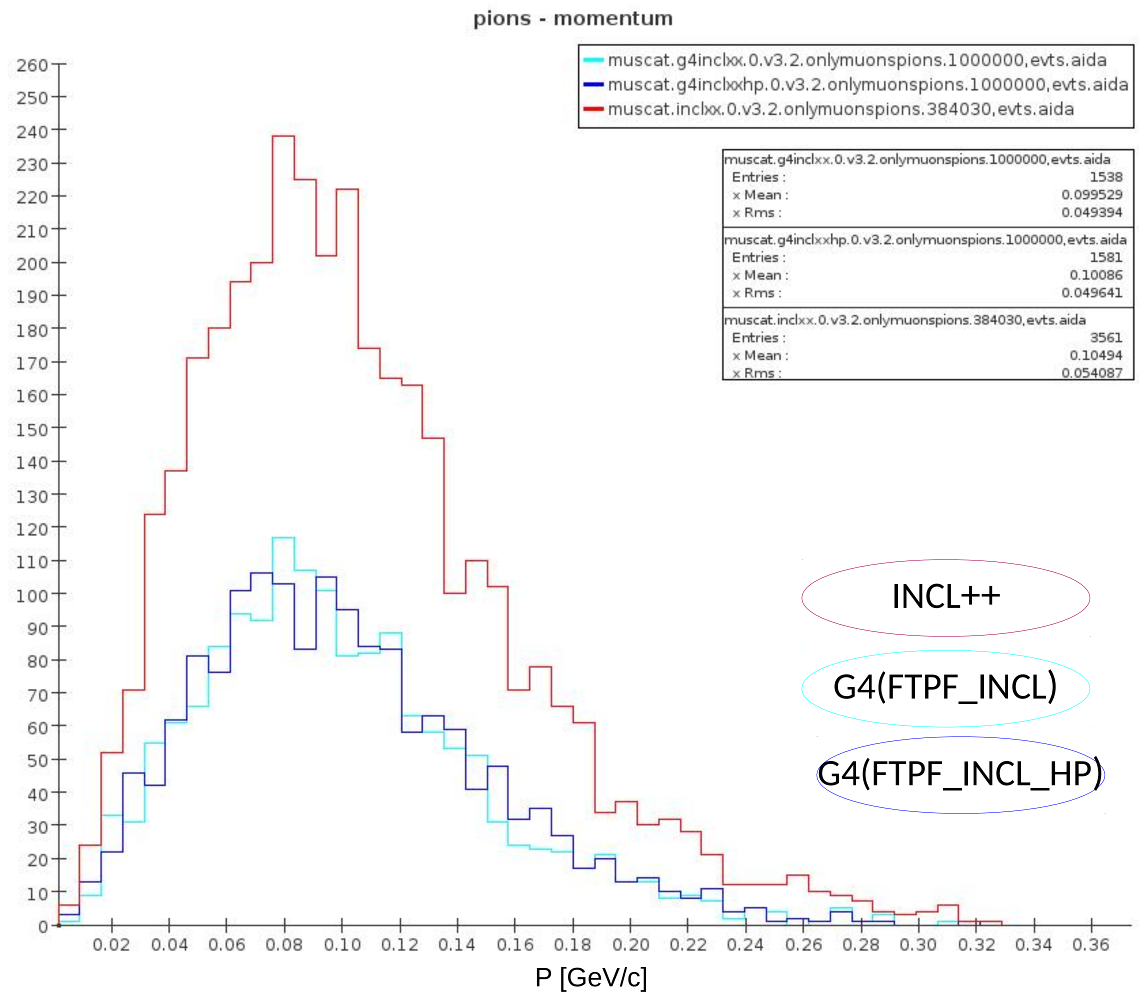
3.3 mm thick target slices

93% W, 6.1% Ni, 0.9% Fe (17.8 g/cm^3) (~ 10 Λ_{int})

Fermilab

Geometry v3.2

Three 10 mm Slices W Target Studies – π^- Momentum



1M POT

Beam:

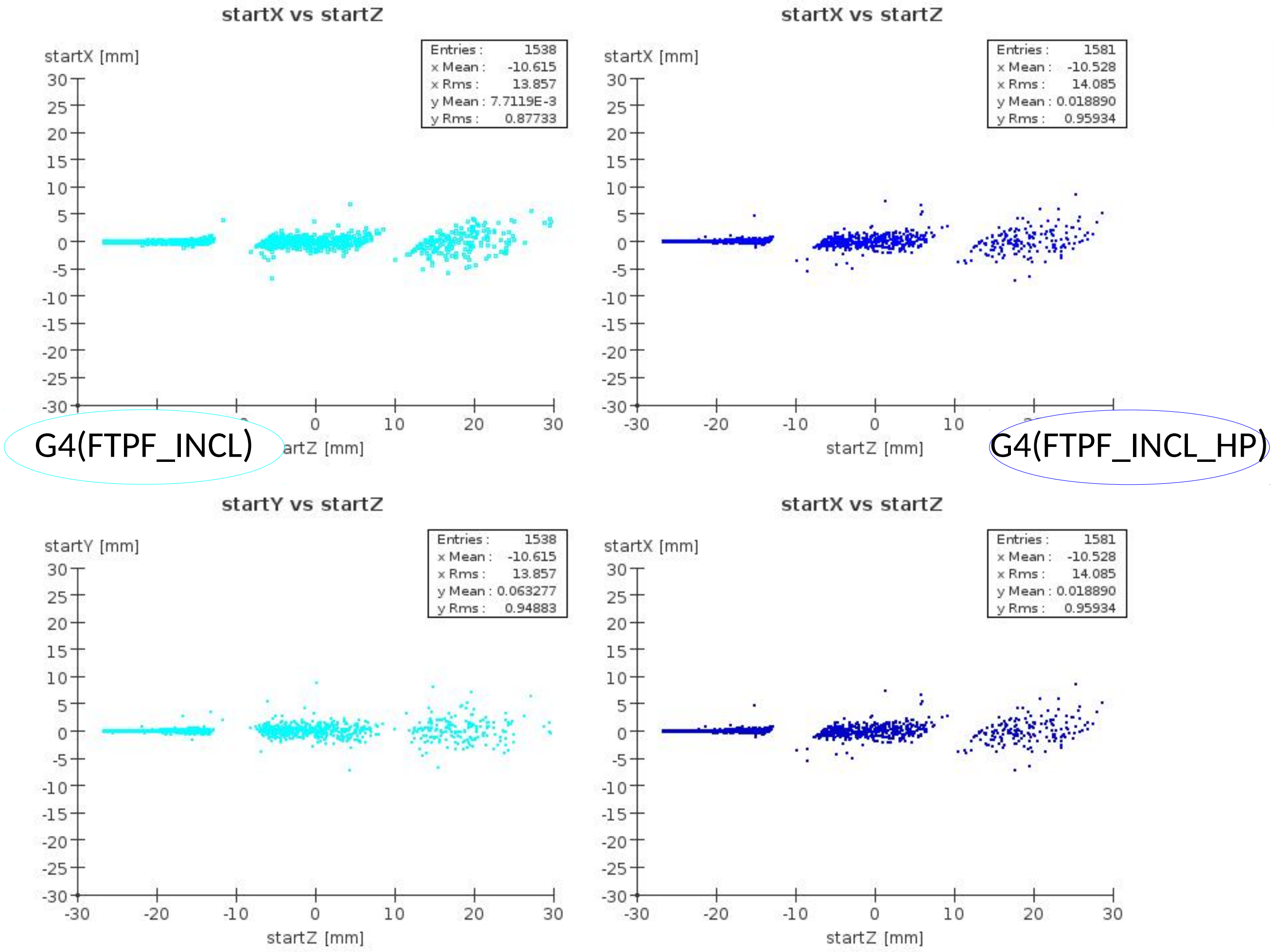
E_k=(400 ± 1)MeV

σ_x=σ_y=500μm

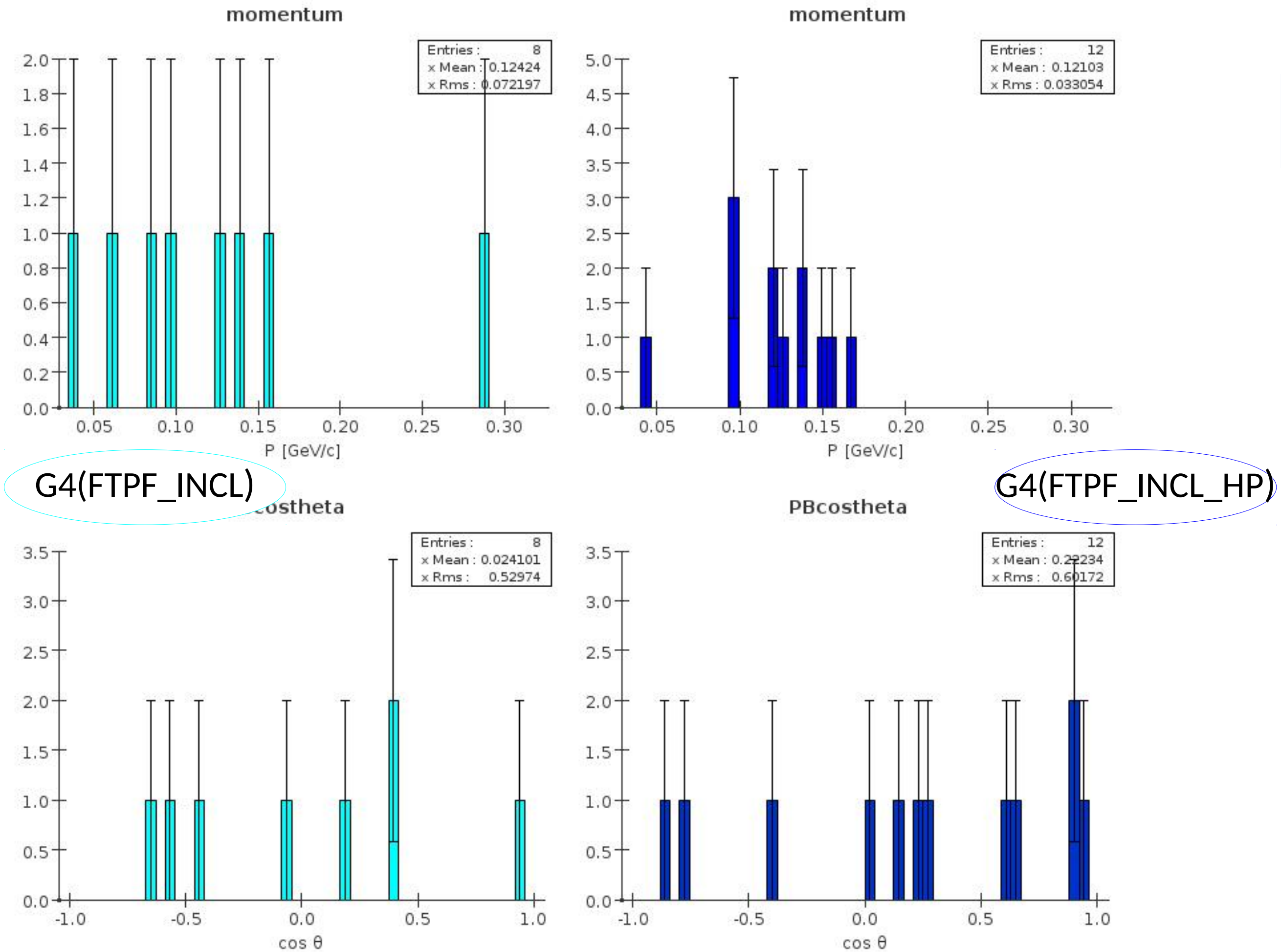
Geometry v3.2

Three 10 mm W Slices Target Studies – π^- Origin

1M POT

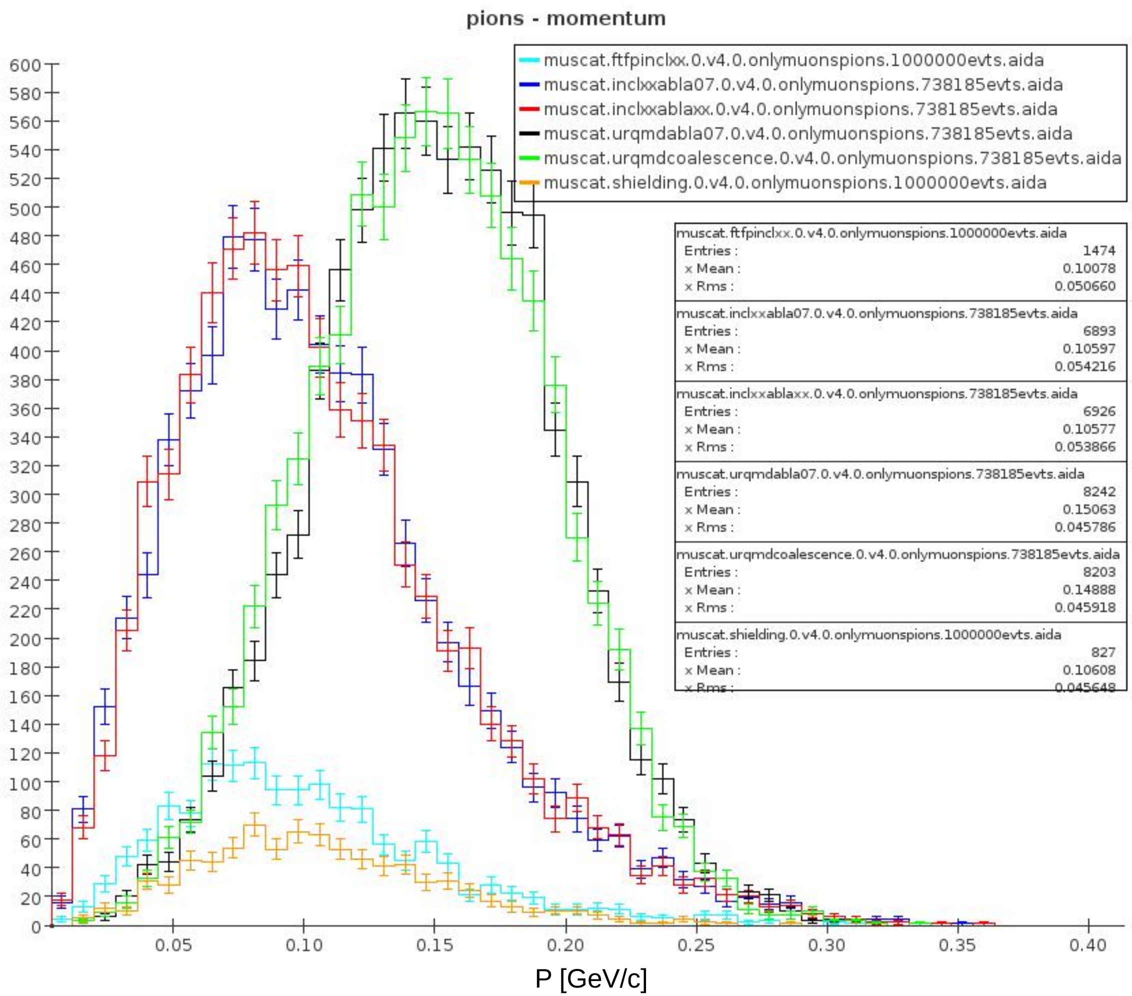


Three 10 mm Slices W Target Studies – π⁻ at the entrance of the transport line



1M POT

Solid 80 mm W Target Studies* – π^- Momentum



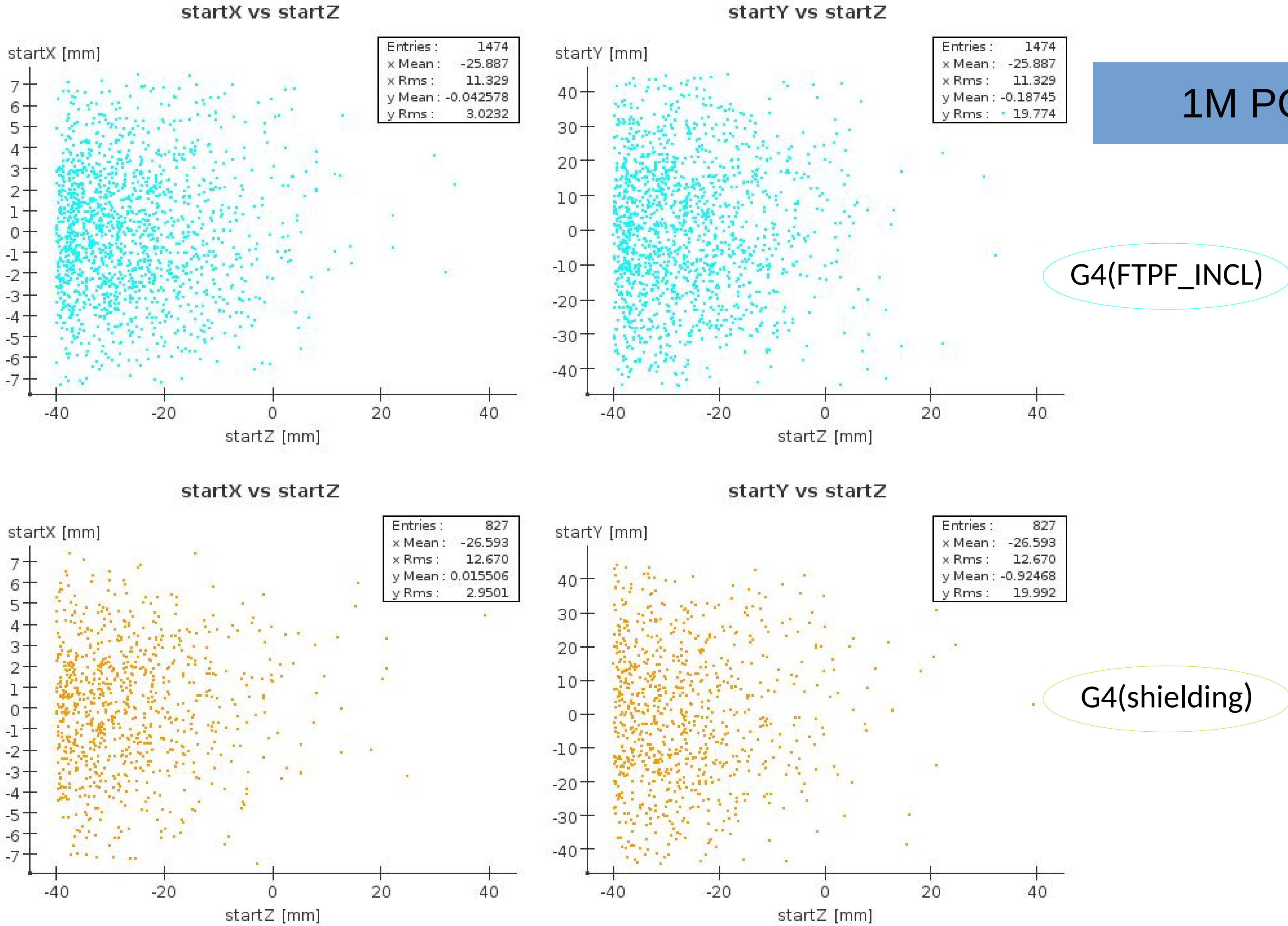
1M POT

Beam:
E_k=(400 ± 1)MeV
σ_x = 3 mm
σ_y =24 mm
cut at 95%

*For reference only

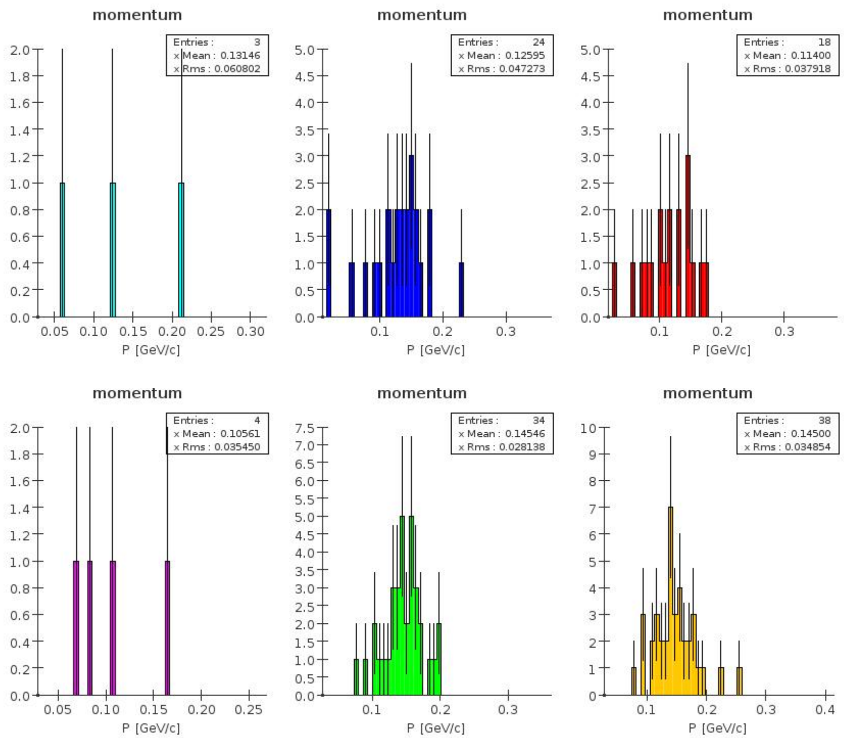
Solid 80 mm W Target Studies – π⁻ Origin

1M POT



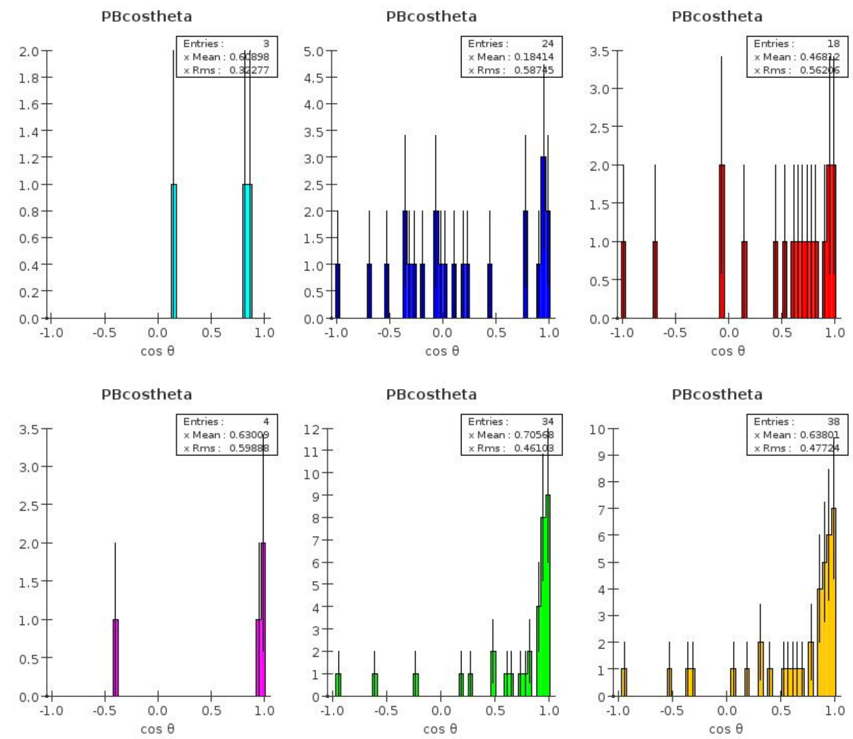
Geometry v4.0

Solid 80 mm W Target Studies* – π^- at the entrance of the transport line



1M POT

*For reference only

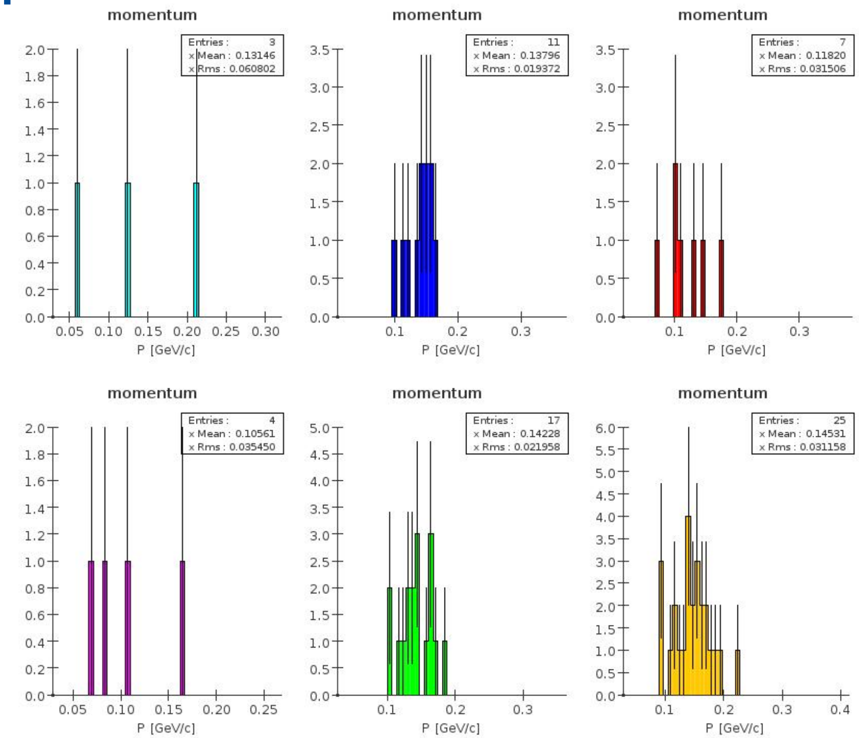


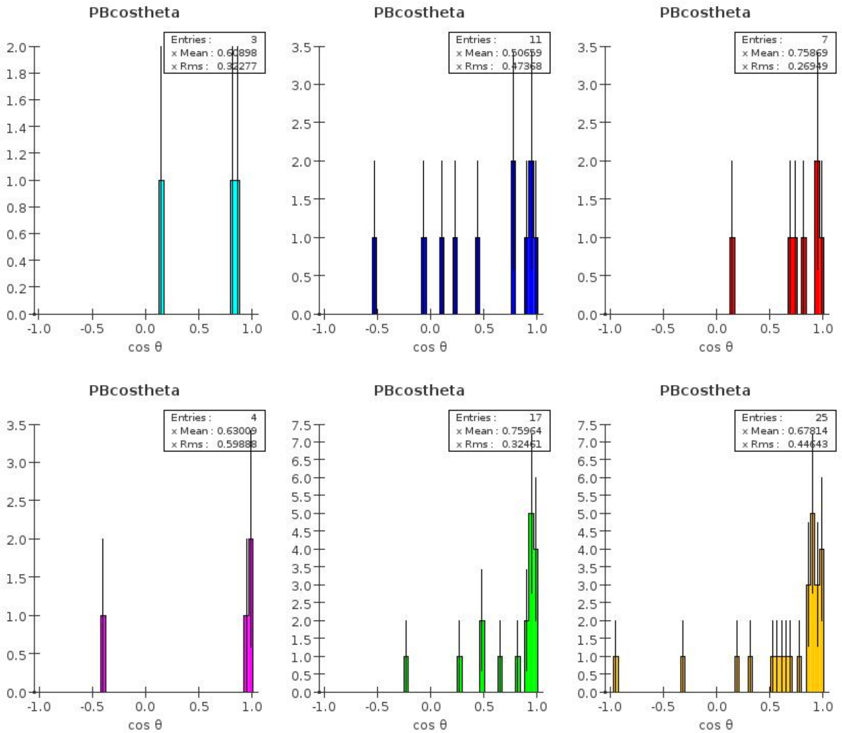
- Geant4 (FTPF_INCL)
- INCL++ & abla07
- INCL++ & abla++
- Geant4 (shielding)
- UrQMD & abla07
- UrQMD & coalescence

Solid 80 mm W Target Studies –
π^- at the entrance of the Transport Line produced within 3 cm of target

Geometry v4.0

1M POT





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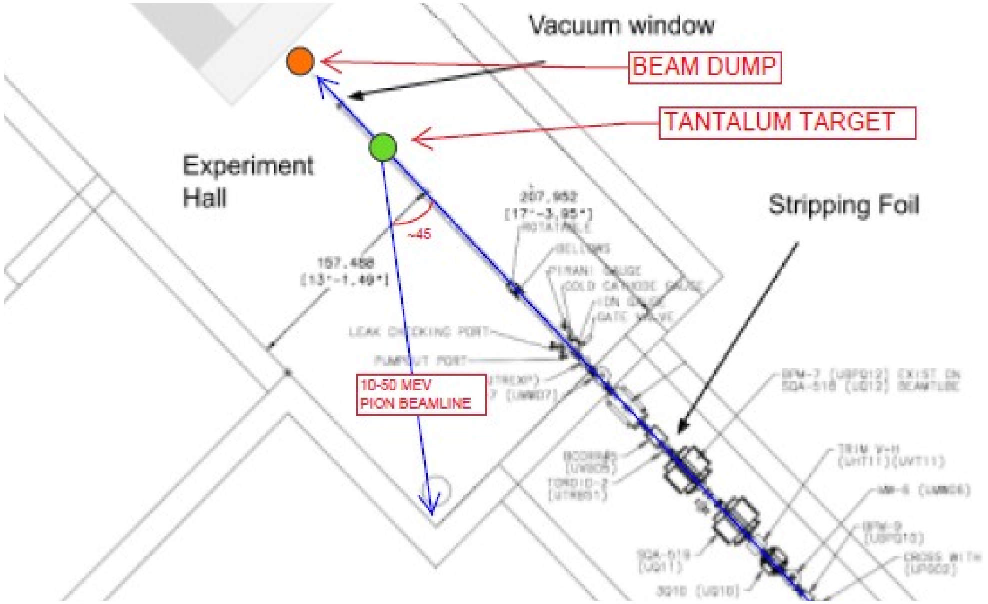
Shielding Assessment Addendum - MeV Test Area (MTA)

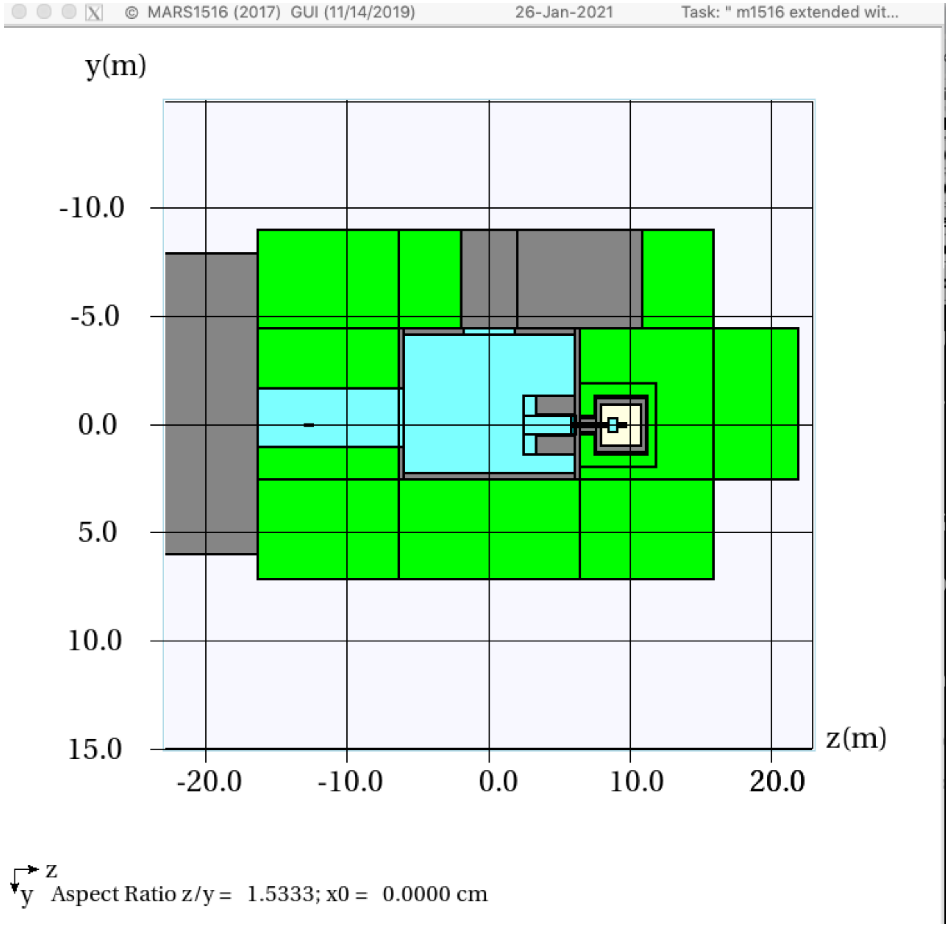
- The MTA provides 400 MeV proton beam at high average rate for irradiation studies on material and particle detectors
- The beamline is the same as for the previous MuCOOL facility with the addition of an electron stripping foil
- The beam emerges at the end of the beamline from a metal vacuum window and continues through air into a Shielding Cave
- Target material can be irradiated in this volume surrounded by three feet of concrete shielding blocks

Parameter	Value	Unit
Kinetic Energy	401.5	MeV
Energy Spread	1	MeV
RF Structure	201.24	MHz
Bunch Length	0.208	ns
Max Pulse Length	80	µs
Max Particles Per Bunch (28 mA)	0.88×10^{9}	
Max Particles Per Pulse	1.6×10^{13}	
Peak Current	28	mA
Avg Current	38	µA
Max Beam Power	15.7	kW
Beam Emittance (99%)	8	mm-mrad



Working Plan

- The analysis of the MTA shielding will be done using MARS
- Calculations will be performed under normal operations conditions and accident scenario (beam trajectory and beam intensity accident)
- Work already started to implement the needed geometry in MARS
- Will include the new target station and secondary beamline



Summary Yield at the entrance of the transport line

Beam Parameters

Kinetic Energy	MeV	400±1
Number of Proton/Pulse	-	1.4E+13
Frequency	Hz	15

π^- yield for G4 simulations

3 x 3.3 mm slices – v3.1	
Gibuu2019	1176E+6 π/sec
Jam19	357E+6 π/sec
Geant4(shielding)	525E+6 π/sec
UrQMD	1323E+6 π/sec
3 x10 mm slices – v3.2	
Geant4(FTPF_INCL)	168E+6 π/sec
Geant4(FTPF_INCL_HP)	252E+6 π/sec
8 mm solid – v4.0	
Geant4(FTPF_INCL)	61E+6 π/sec
Geant4(SHIELDING)	81E+6 π/sec

Work in progress

Backup Slides

Simulation Strategy – Work in Progress - Plans

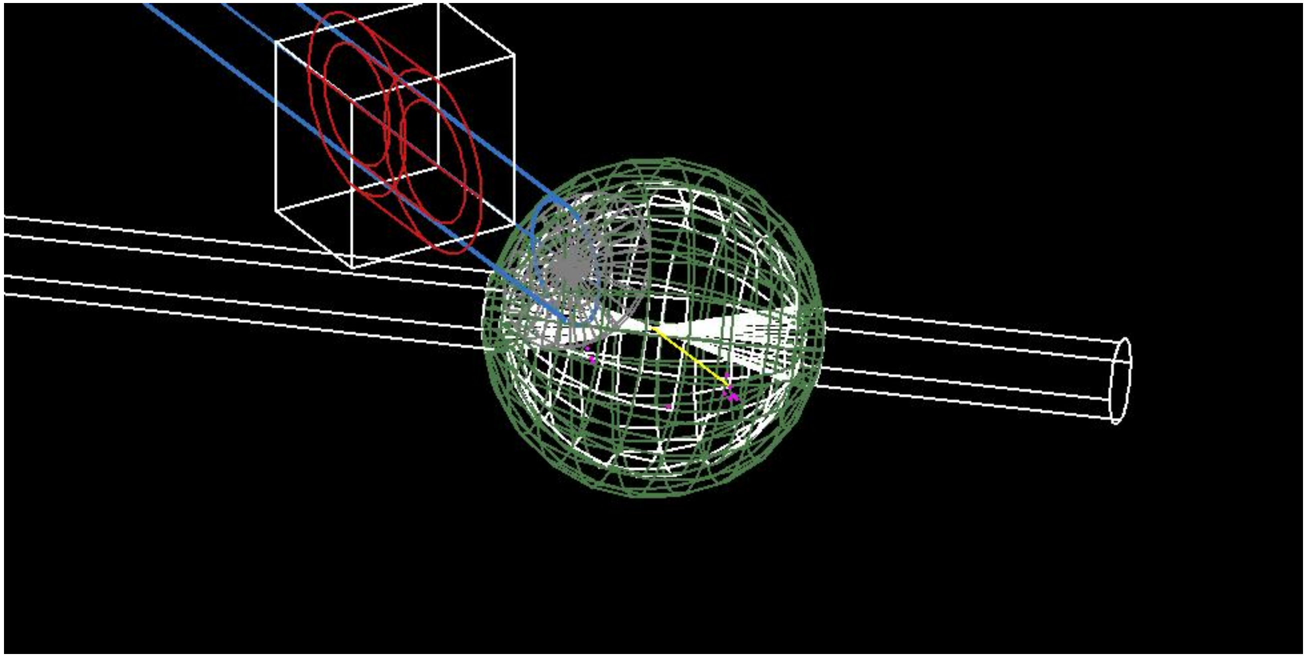
The simulation strategy has been defined as follows.

- Primary interactions are simulated using GENIEHad and comparing four different models of nuclear interactions (for details see: https://redtop.fnal.gov/the-geniehadevent-generation-framework/):
    - GiBUU 2019
    - INCL++ (the last version, released a few months ago)
    - PHSD 4.0
    - UrQMD 3.4
    - DPMjet-III (future plans)
    - JAM (future plans)
- Primary particles are then fed into GEANT4 for particle transport and decay (complex magnetic field can be included with a field map).
- New GDML geometry of the beam pipe, production chamber, solenoid and target is in place. Work already started to include the geometry of the entire enclosure (thanks to the previous work with MARS – Jason StJ)
- Goal is to compare with MARS when the new version is available (per communication with Nikolai M.)

Comparison of Models

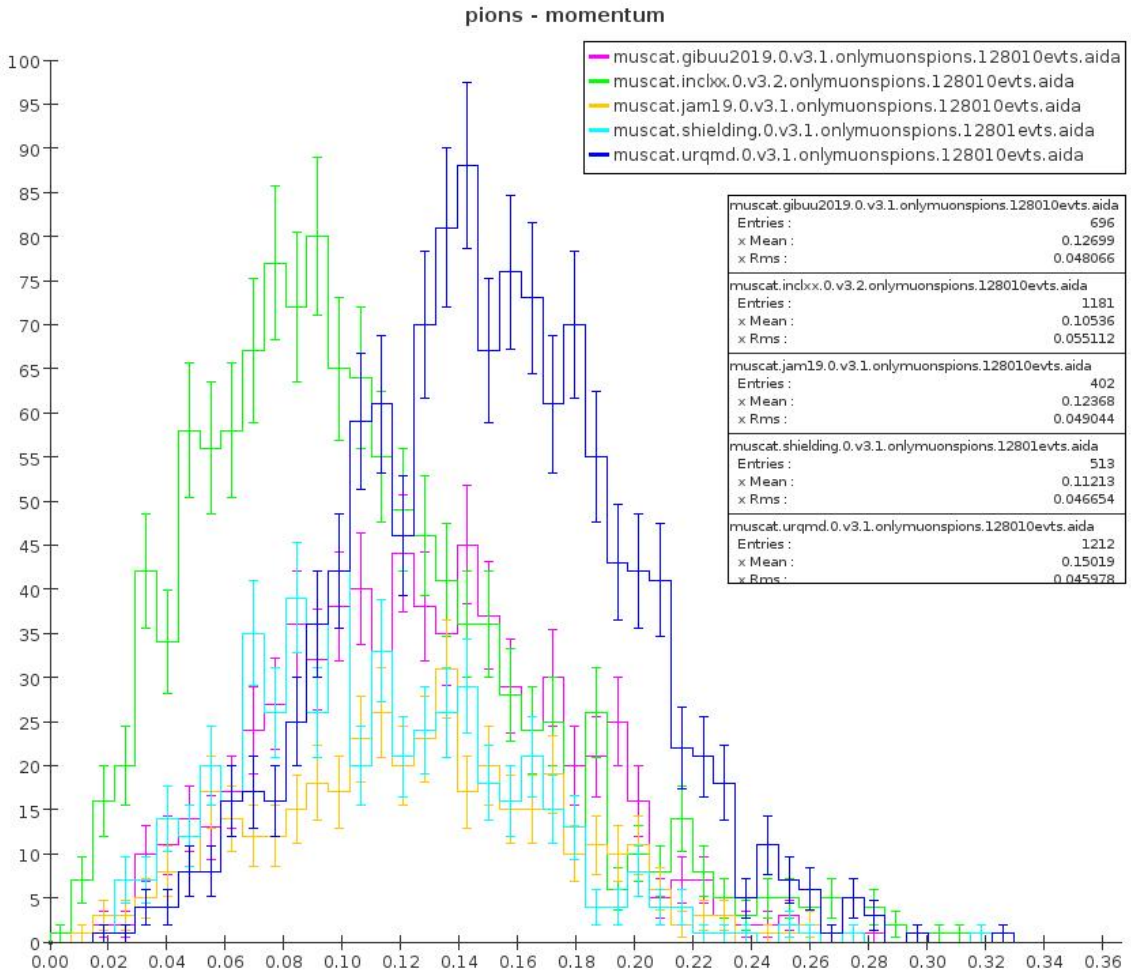
Model	Version	Interaction xsection	Elastic Interaction	Evaporation model
INCL++	6.3	Internal	NO	ABLA++
UrQMD	3.4 (2015)	Parametrized	NO	COALESCENCE(GEM)
GiBUU	2019	Parametrized	NO	COALESCENCE(GEM)
PHSD	4.0 (2018)	Parametrized	YES	ABLA 0.7
JAM	1.9 (2020)	Internal	YES	COALESCENCE(GEM)
DPMjet	III	Parametrized	NO	COALESCENCE(GEM)

Implemented Geometry



The entrance of the solenoid is 0.4064 m from the center of the target @135 deg angle
The solenoid is physically 14 cm long

Thin Slices Target Studies – π^- Momentum



Summary

- The machinery is in place and working
- Possibility to compare different hadron models and simulation with data
- The first step is to optimize the target material, geometry and orientation, number of slices and distances.
- Only INCL++ and UrQMD will be used for the optimization (10x faster that other models)
- Other models used only to estimate the range of the results
- Gdml geometry is implemented
- Several scores detectors added to control particle fluxes
- Momentum distribution of produced pions is consistent among models, but DPMjet (under investigation)
- Preliminary simulation doesn’t include the solenoid magnetic field, more work needs to be done
- Preliminary studies indicate the solenoid is too far.

Backup slides

JAS3 and ROOT

- JAS3[4] is a flexible, extendable, experiment-independent interactive data analysis framework
- JAS3 is written in Java and makes extensive use of FreeHEP libraries

- ROOT[5] is a framework for data processing, born at CERN
- ROOT is written in C++ and it is widely used by experiments