A New High Intensity Muon Beamline at the Paul Scherrer Institut

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on behalf of the HiMB Project
ETHZ UZH Physics PhD Seminar
11 Sept 2014

PAUL SCHERRER INSTITUT

Intensity Frontier Accelerator Facilities

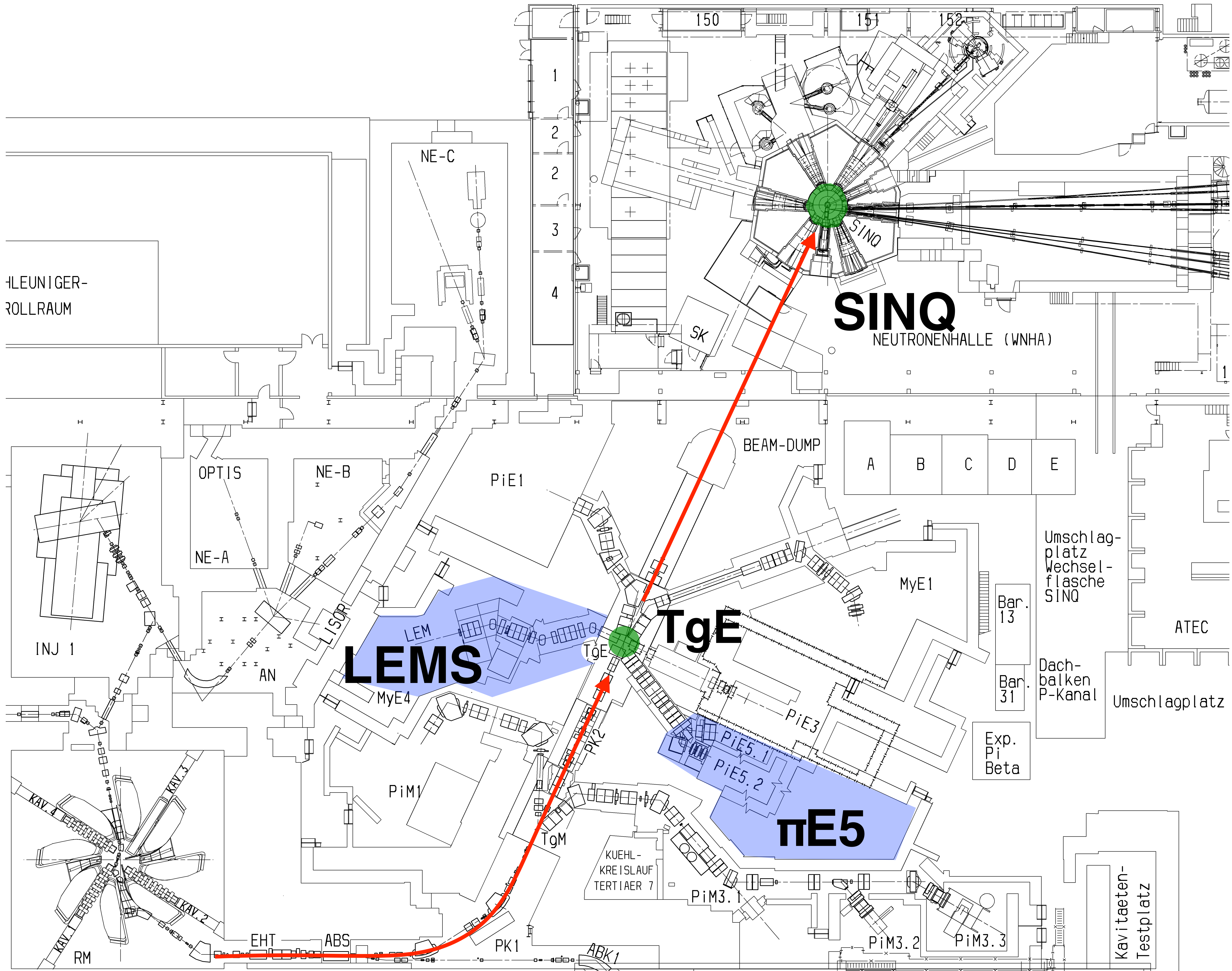
- PSI home to highest intensity DC μ^+ beam @ $10^8\ \mu^+/s$
- New cLFV experiments require significantly higher muon rates to achieve sensitivity goals
  MEG: $\mathcal{O}(6\times10^{-14})$
  Mu3e: $\mathcal{O}(10^{-16})$
- Provide a new μSR facility
- Maintain PSI leadership in high intensity muons
- Potentially: $10^{10}\ \mu^+/s$

J-PARC → $10^{10}\ \mu^-/s$

COMET: $R_{\mu e} = \mathcal{O}(10^{-17})$

Fermilab → $5\text{x}10^{10}\ \mu^-/s$

Mu2e: $R_{\mu e} = \mathcal{O}(10^{-17})$



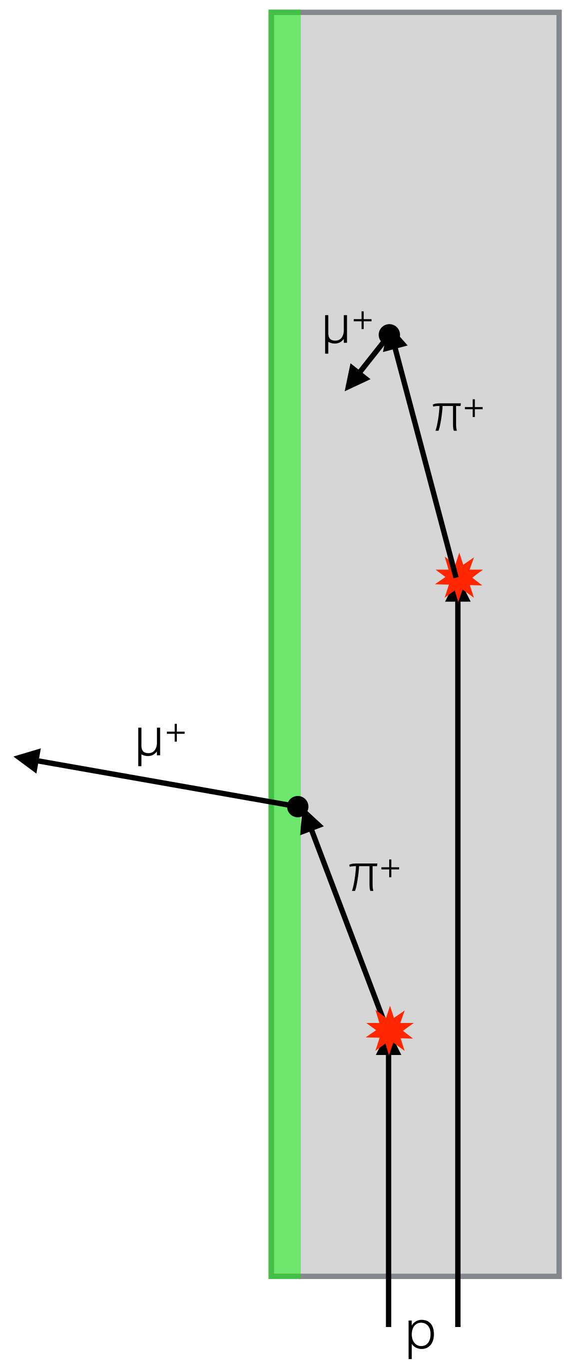
SINQ
NEUTRONENHALLE (WNHA)
TgE
LEMS
πE5
150
151
152
1
2
2
3
4
SK
NE-C
HLEUNIGER-
ROLLRAUM
OPTIS
NE-B
NE-A
PiE1
BEAM-DUMP
A
B
C
D
E
Umschlag-
platz
Wechsel-
flasche
SINQ
MyE1
Bar.
13
Bar.
31
ATEC
Dach-
balken
P-Kanal
Umschlagplatz
INJ 1
AN
LISOR
LEM
TgE
MyE4
PiE3
PiE5.1
PiE5.2
Exp.
Pi
Beta
PiM1
PK2
TgM
KUEHL-
KREISLAUF
TERTIAER 7
PiM3.1
PiM3.2
PiM3.3
Kavitaeten-
Testplatz
KAV.1
KAV.2
KAV.3
KAV.4
RM
EHT
ABS
PK1
ABK1

Pion Production and Surface Muons

- 590 MeV proton strikes nucleon in target
  $p + p \longrightarrow p + n + \pi^+$
  $p + n \longrightarrow n + n + \pi^+$
  $p + p \longrightarrow d + \pi^+$

- Pion is stopped in the target material and decays.
  $\pi^+ \longrightarrow \mu^+ + \nu_\mu$
  Those near surface of target produce monochromatic "surface muons".

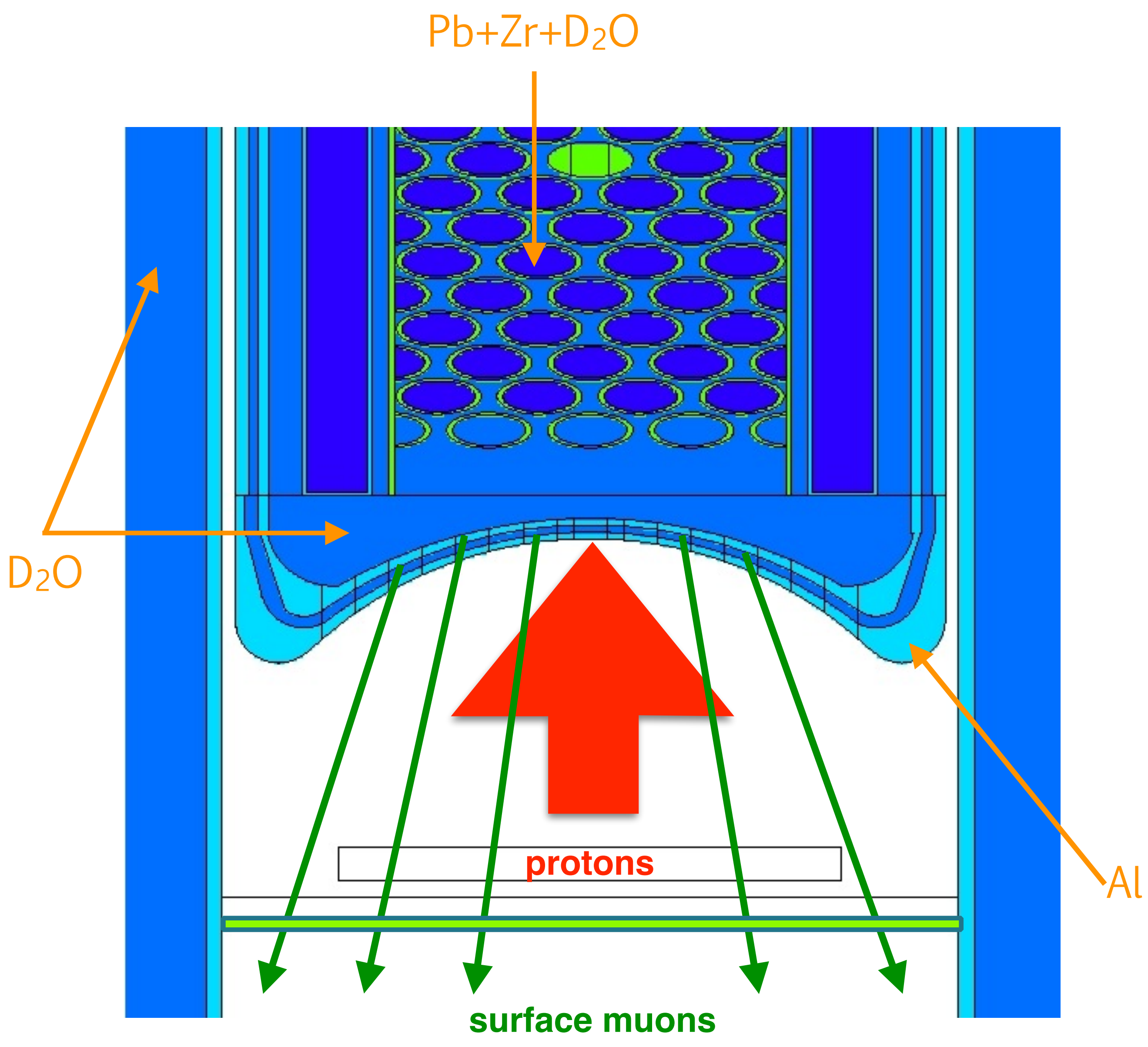
  - $P_\mu = 29.79$ MeV/c
    $E_\mu = 4.12$ MeV
    ~100% polarized



A. E. Pifer, T. Bowen, and K. R. Kendall, Nucl. Instrum. Methods 135 (1976) 39-46

HiMB Concept

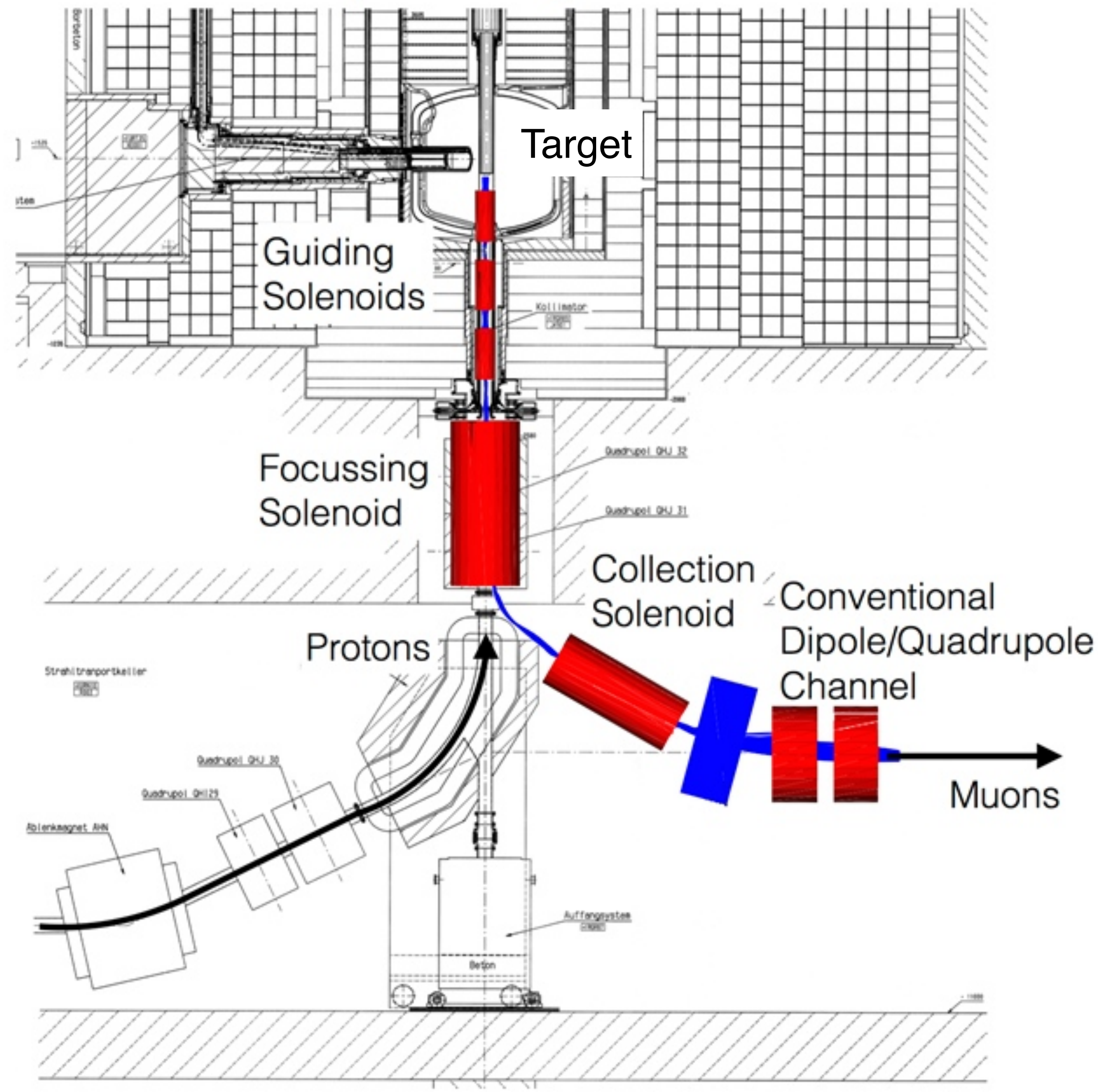
- SINQ spallation neutron source
- Pions produced in SINQ target are stopped in the Al window
- Surface muons that are produced anti-parallel to proton beam are collected

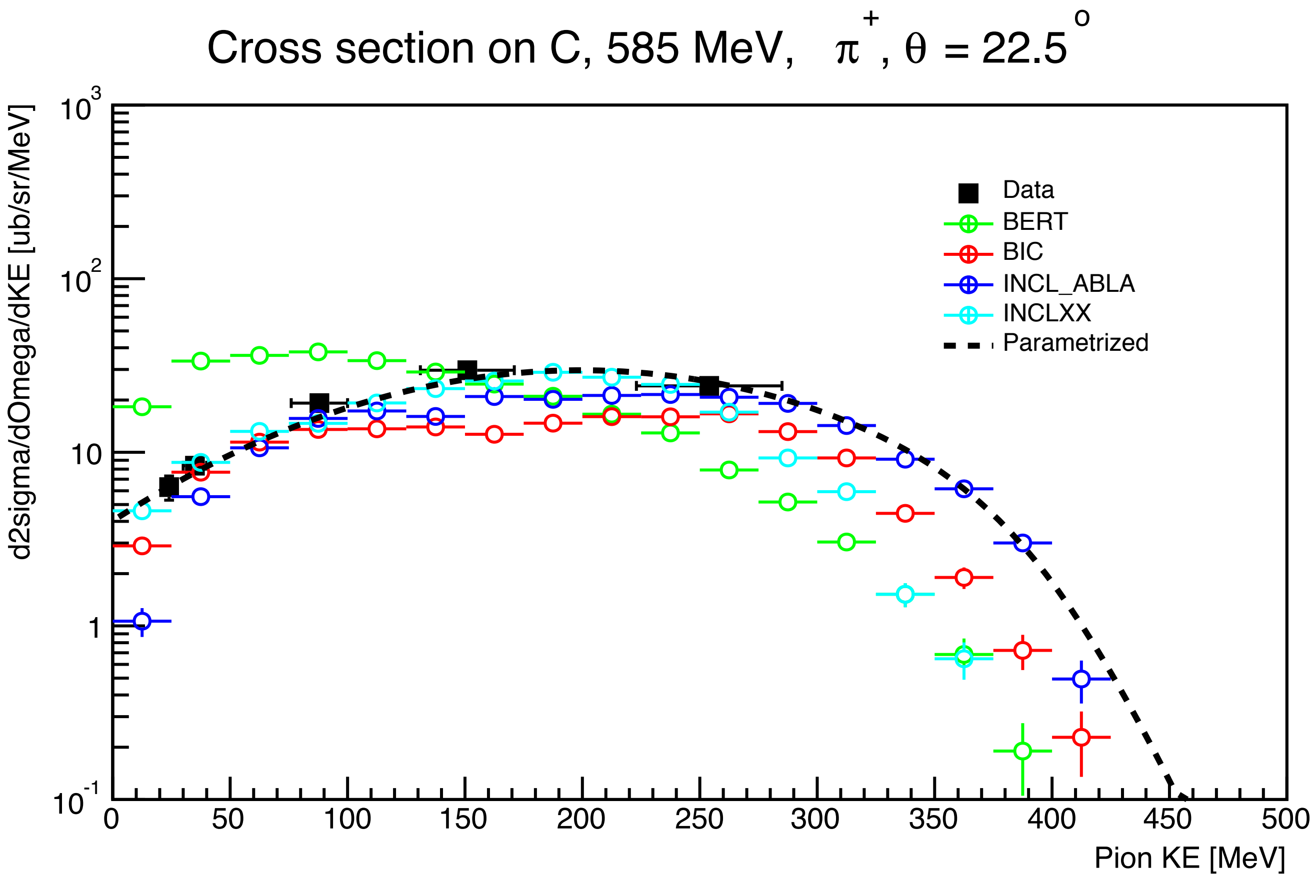


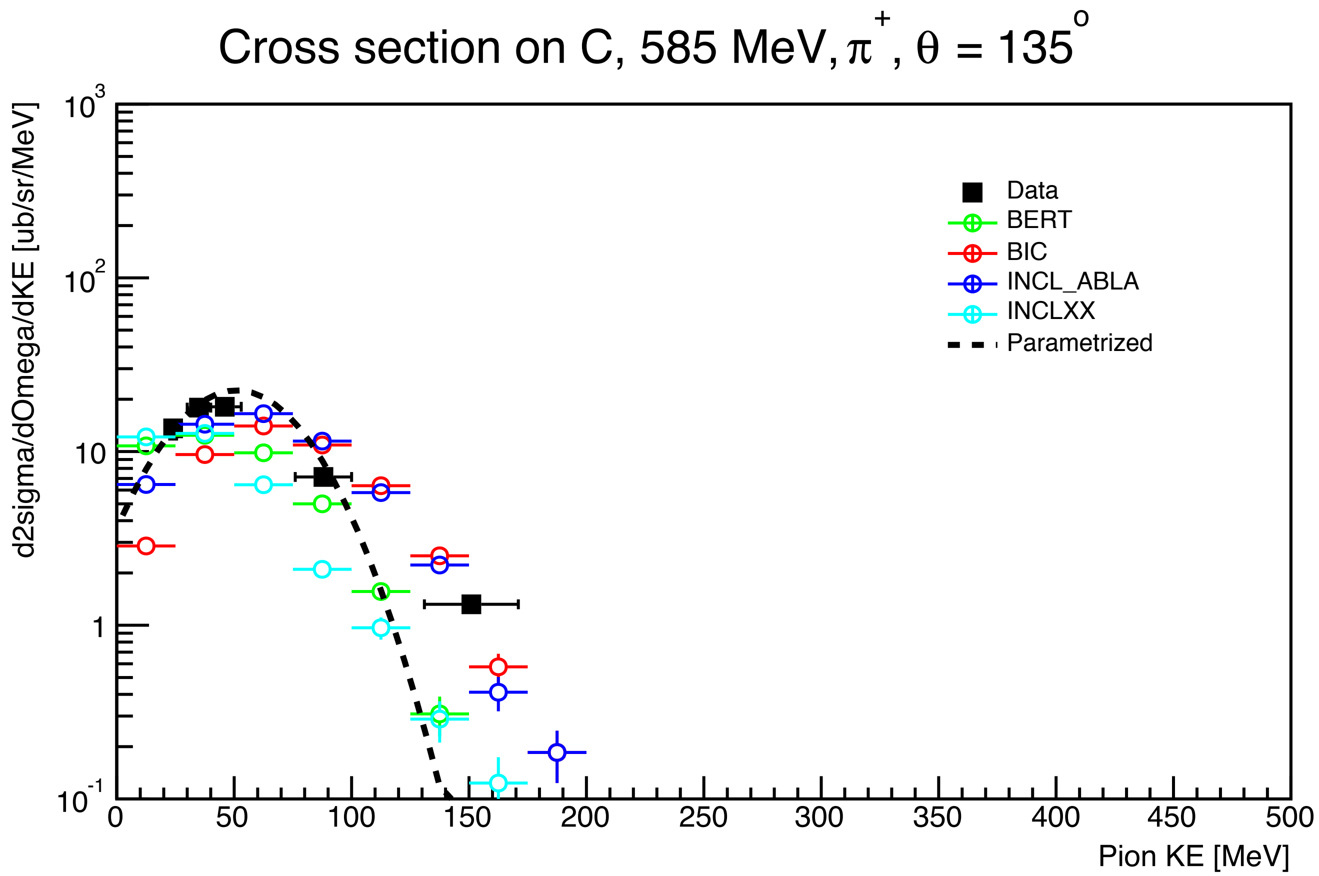
HiMB Concept

- Muons transported opposite to proton beam in solenoid channel. Extracted prior to fringe field of last bending magnet.
- Continue in a conventional beamline to experiment
- Source validation and toolset completed
- Currently studying solenoidal channel acceptance
- $R_{\mu+} = 1.2{\times}10^{11}\ \mu^+/s$ downward below source with $I_p = 1.7$ mA on SINQ

HiMB Conceptual Layout

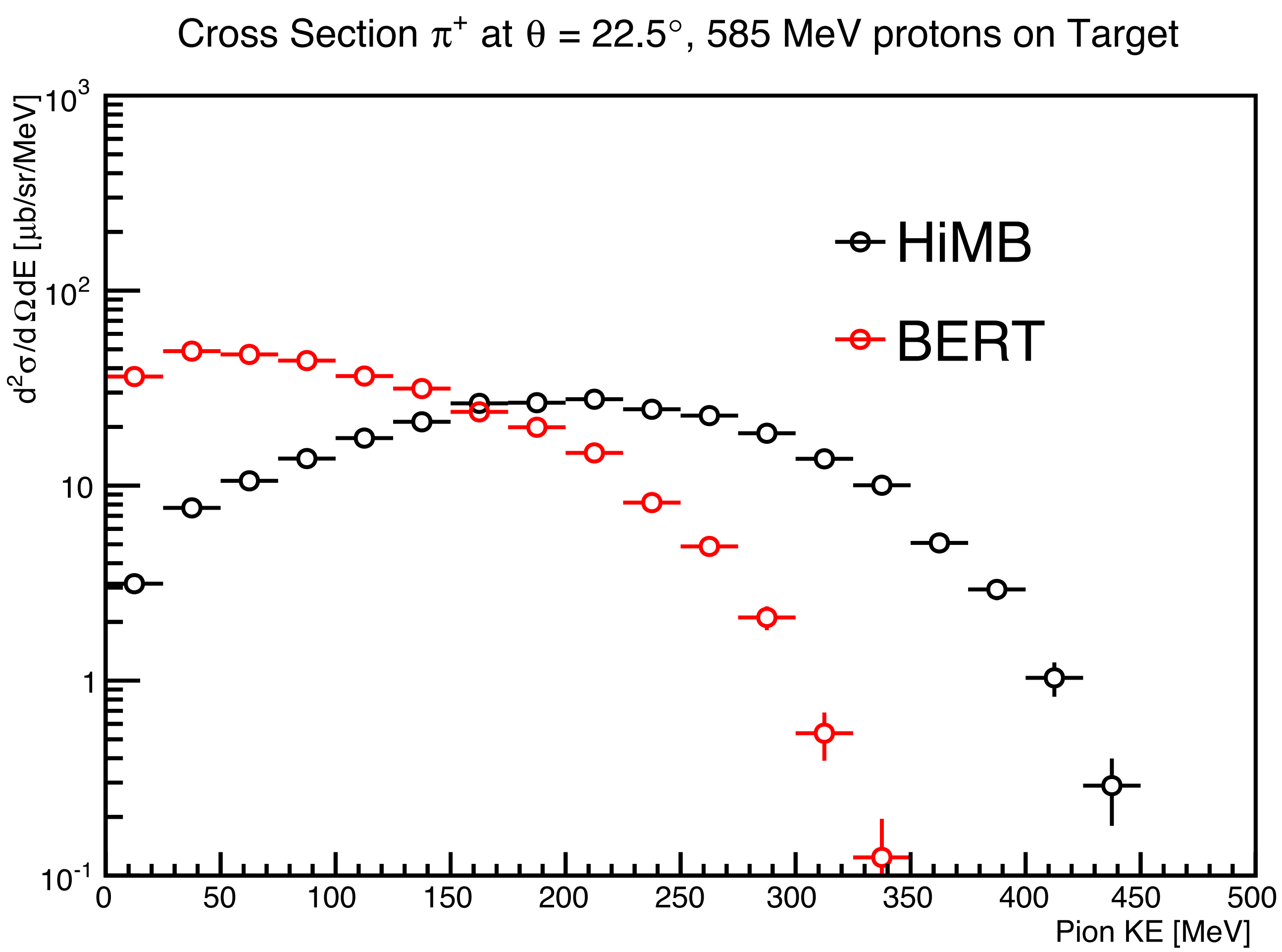


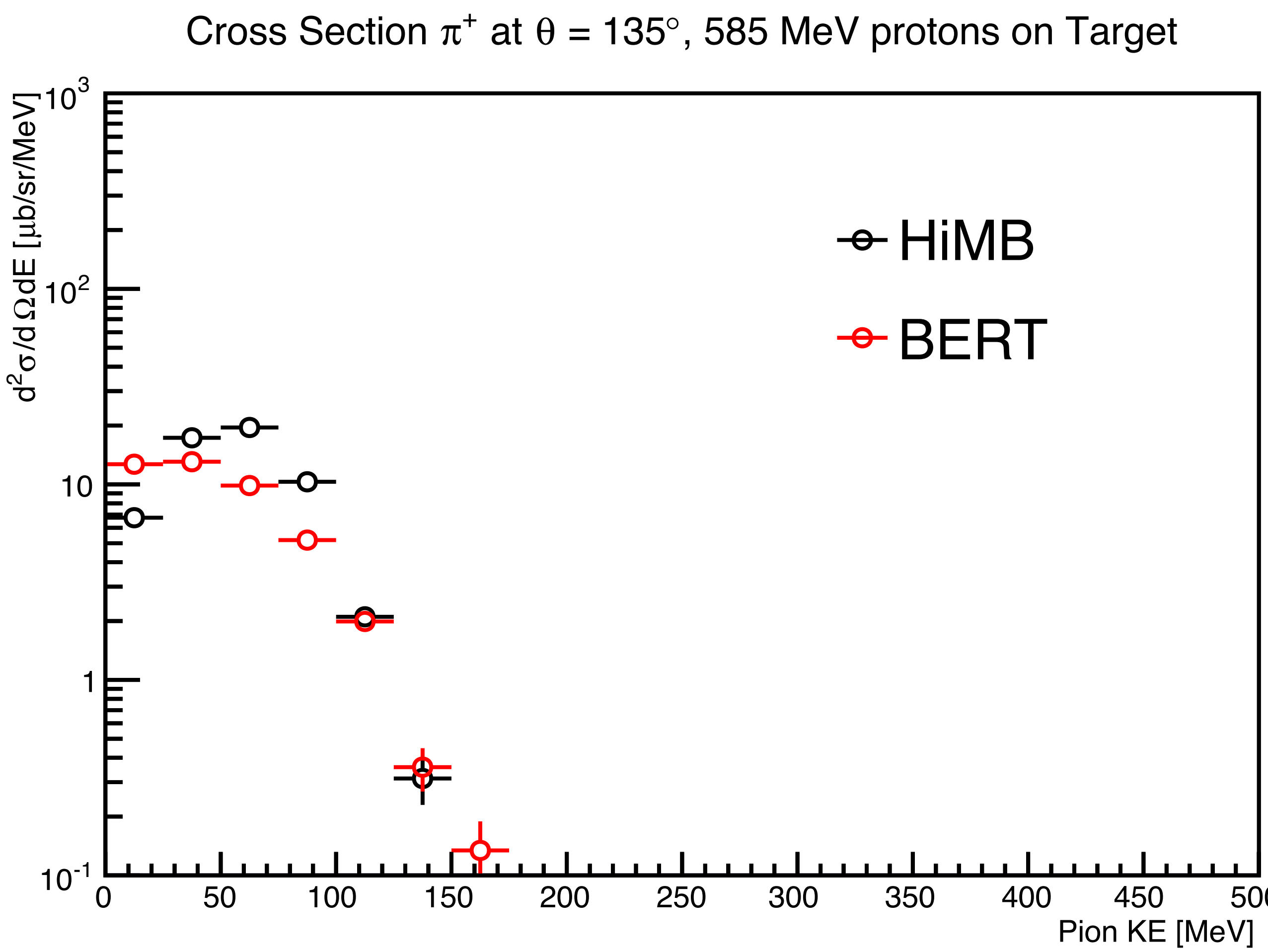




Comparison of Geant4 Models

585 MeV protons on Carbon target





R. L. Burman and E. S. Smith, Los Alamos Tech. Report LA-11502-MS

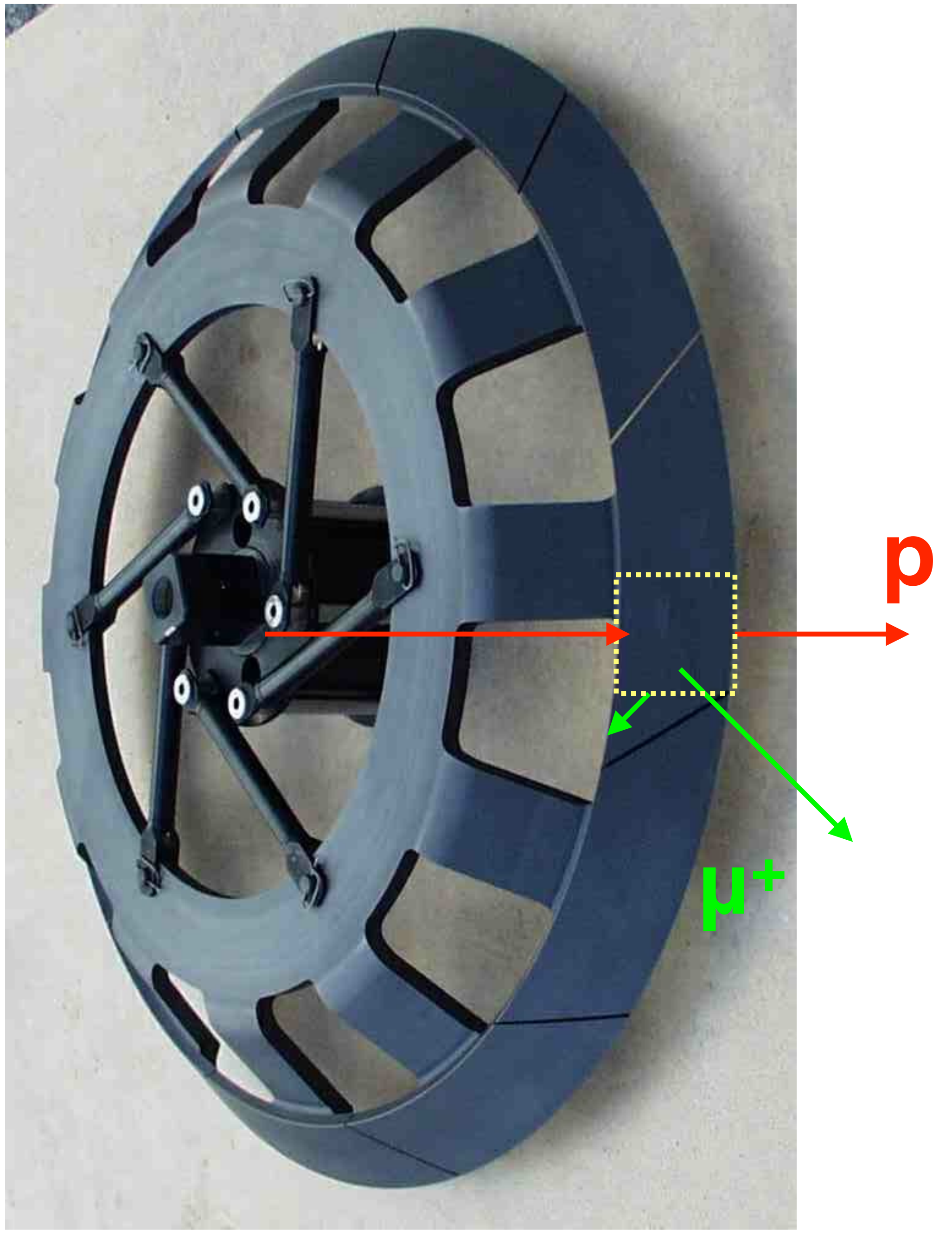
R. Frosch, J. Löffler, and C. WIgger, PSI Tech. Report TM-11-92-01

HiMB Parameterized Model

Combined parameterization of data collected at PSI and LAMPF, across all production energies and angles

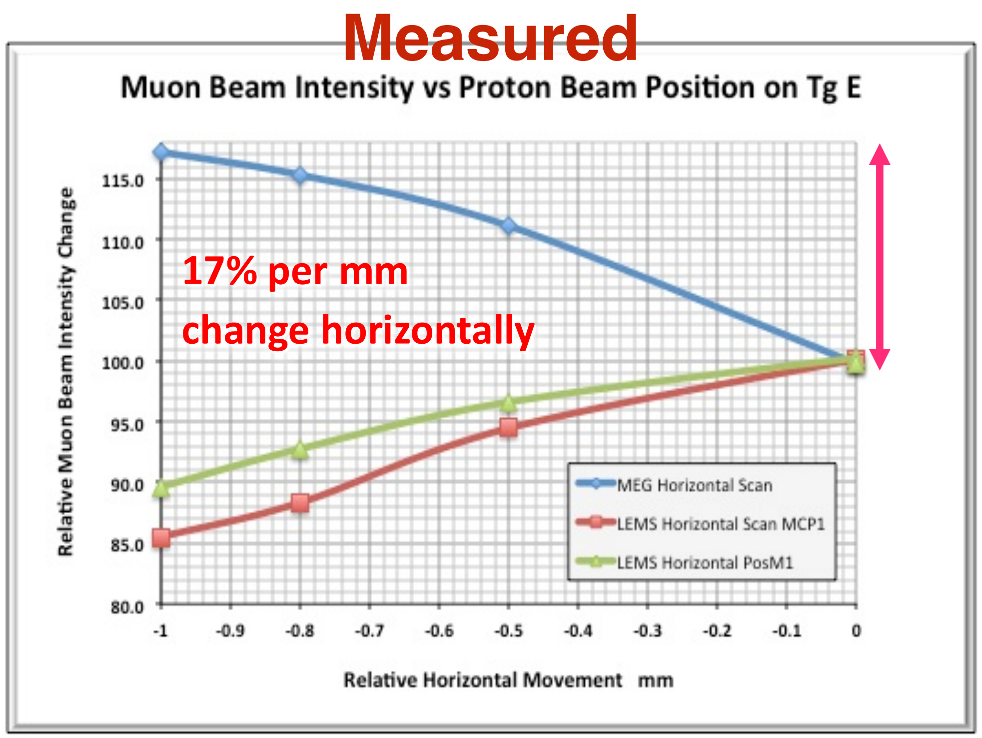
Target E at PSI

- Provides a normalization to HiMB and a validation of sim toolset
- Target E is a graphite truncated hollow cone
    - Approximated as a rectangular section in G4BL
    - Length = 40.0 mm
    - Height = 40.0 mm
    - Width = 6.0 mm



Horizontal Proton Beam Offset

- Horizontal proton beam offset from target center
- Surface muon rate measured simultaneously on opposite sides of TgE
- Higher rates as beam is brought closer to target surface
- HiMB shows better agreement between G4BL and measured rates in LEMS



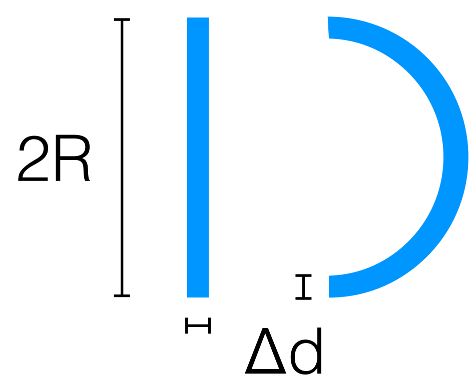
RATIO TO CENTERED BEAM

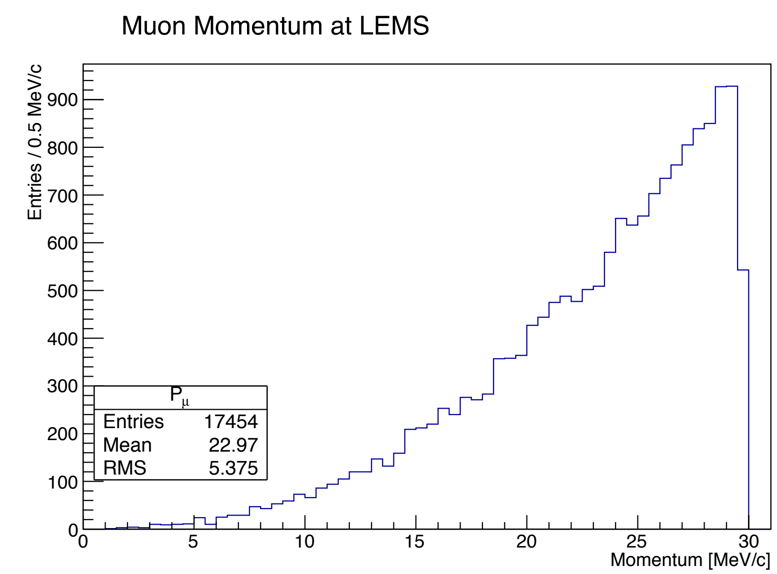
	LEMS BERT	LEMS HiMB	LEMS Data	PiE5 BERT	PiE5 HiMB	PiE5 Data
0.5 mm	0.87	0.98	0.95	1.12	1.01	1.11
1.0 mm	0.77	0.88	0.87	1.25	1.07	1.17

Radial Grooved Target

- Increasing the surface area/ volume should increase the surface muon production

- Grooves along the proton beam direction can provide this increase in surface volume

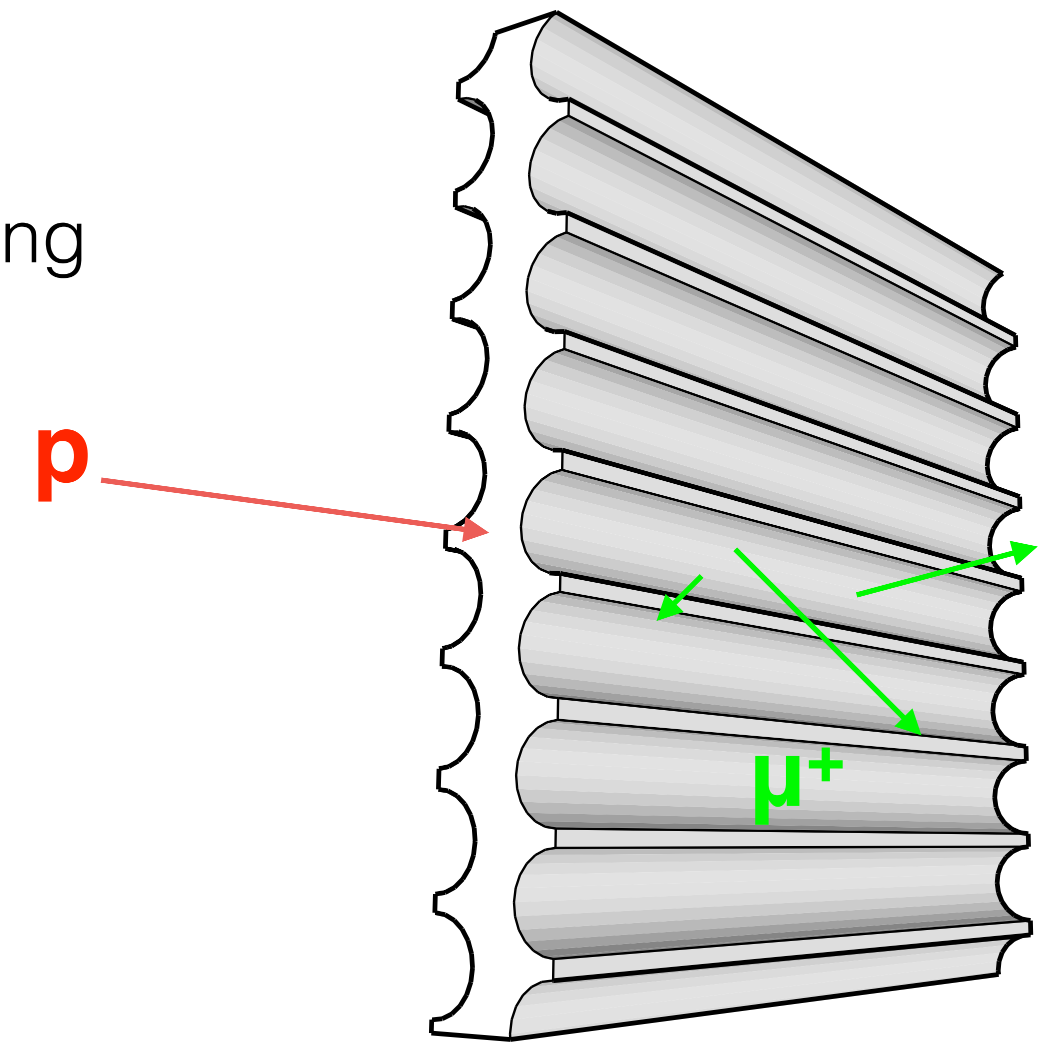


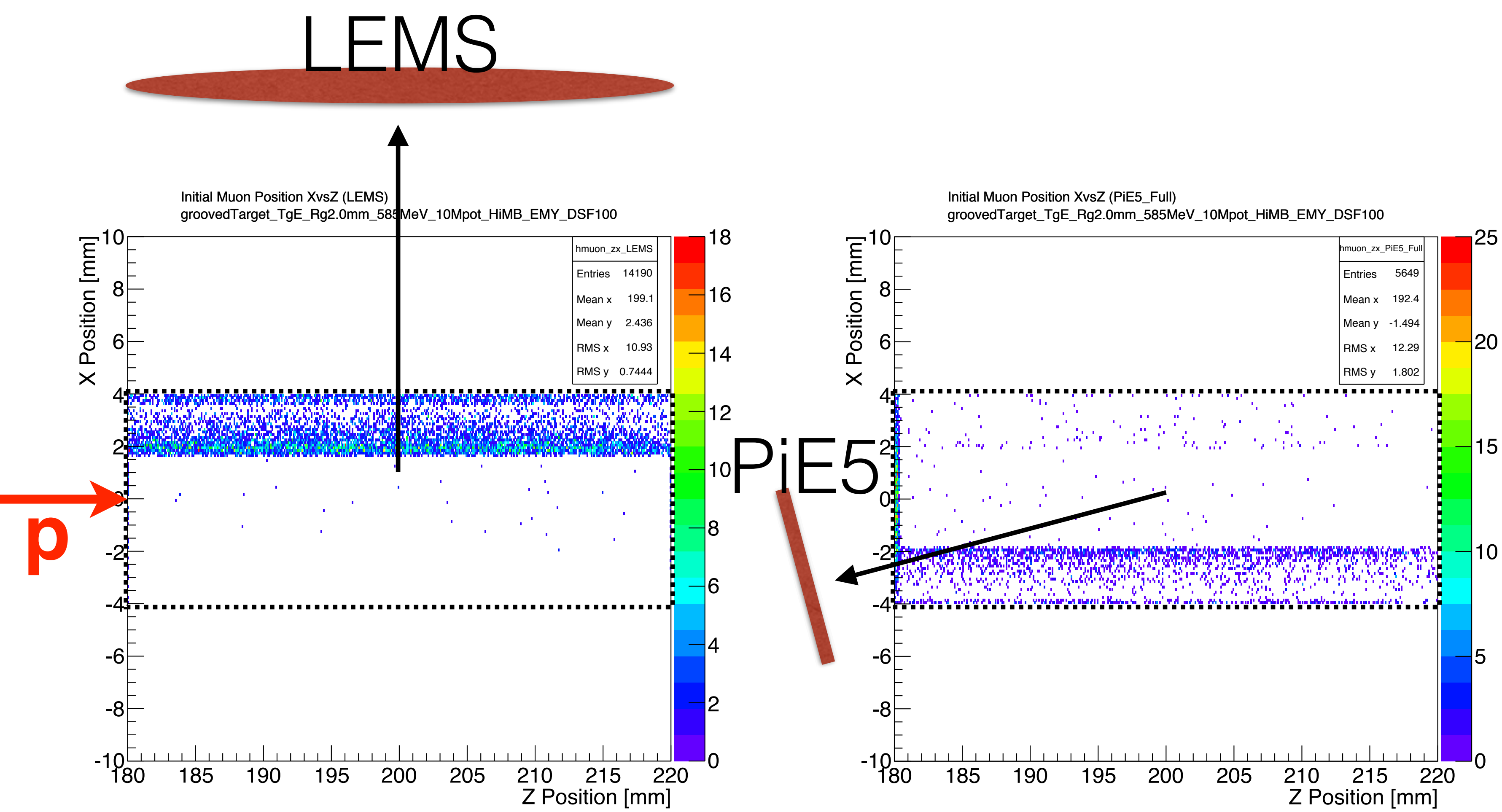


Groove Radius [mm]	Enhancement Ratio
1.0	1.35
1.5	1.40
2.0	1.45

Radial Grooved Target

- Alternate design for increasing surface muon production
- Grooves are staggered to maintain a standard target width
  - Width = 6.0 mm + R_g





Ratio to Standard

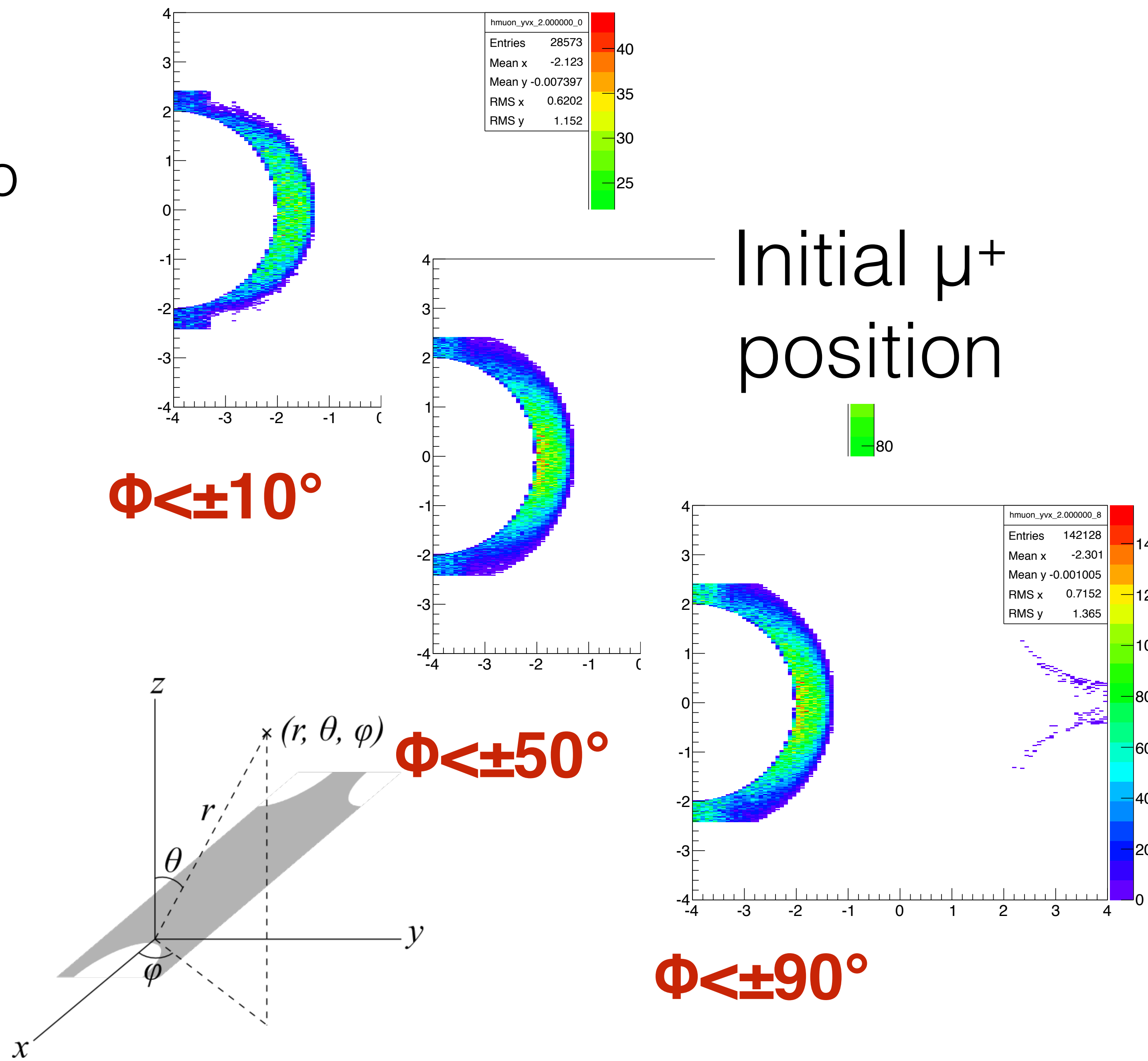
Groove Radius [mm]	LEMS	PiE5
1.0	1.02	0.99
1.5	1.02	1.02
2.0	1.04	0.99

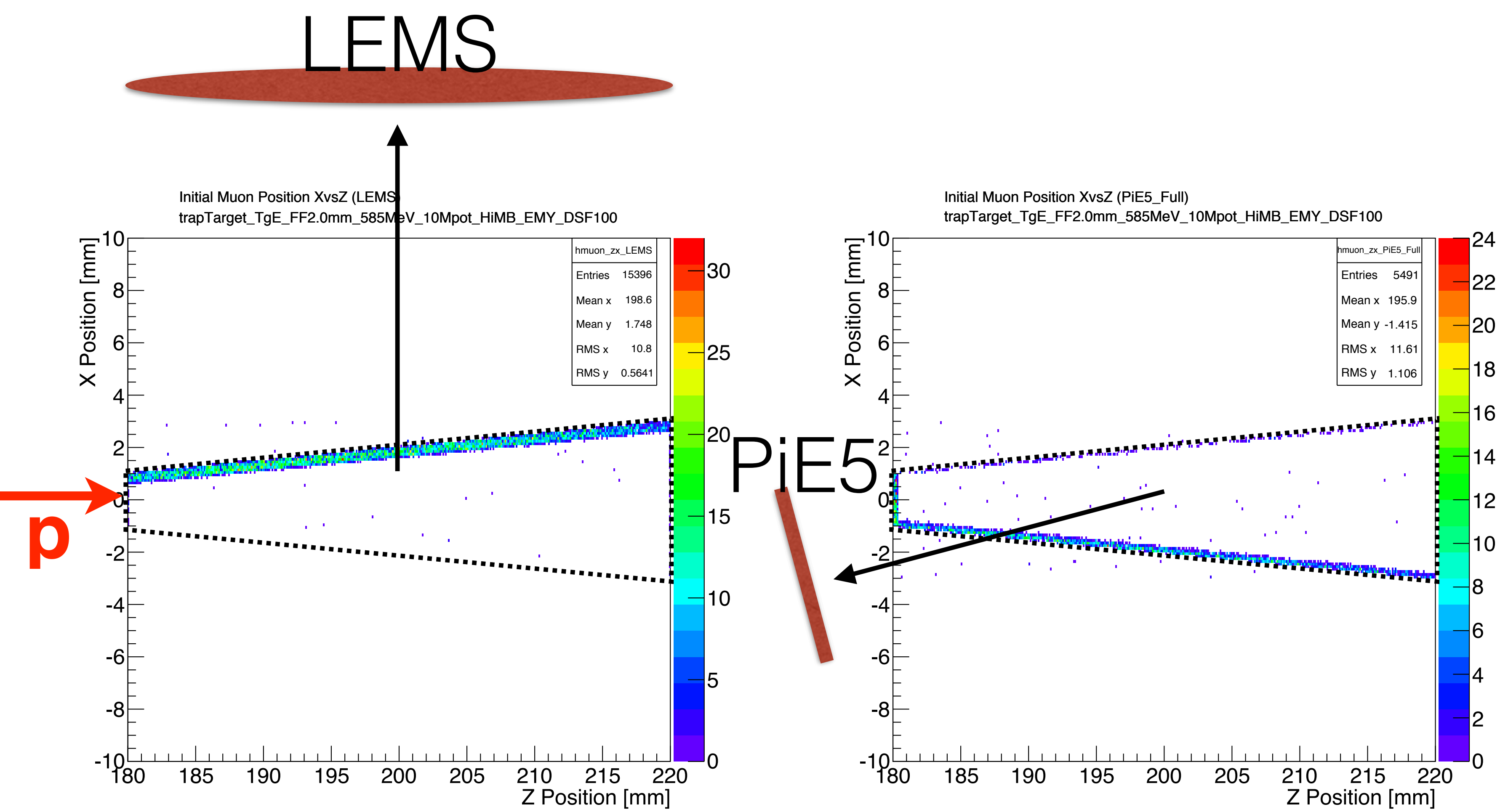
Grooved Targets

Approximately 4% enhancement for 2.0 mm groove configuration

Acceptance Depth

- The acceptance depth in a groove is at the maximum where the groove is closest to the target center
- This depth tapers near the max target width
    - Has a crescent shape for small acceptance angles (realistic for beamlines)
    - Not the full surface volume expected



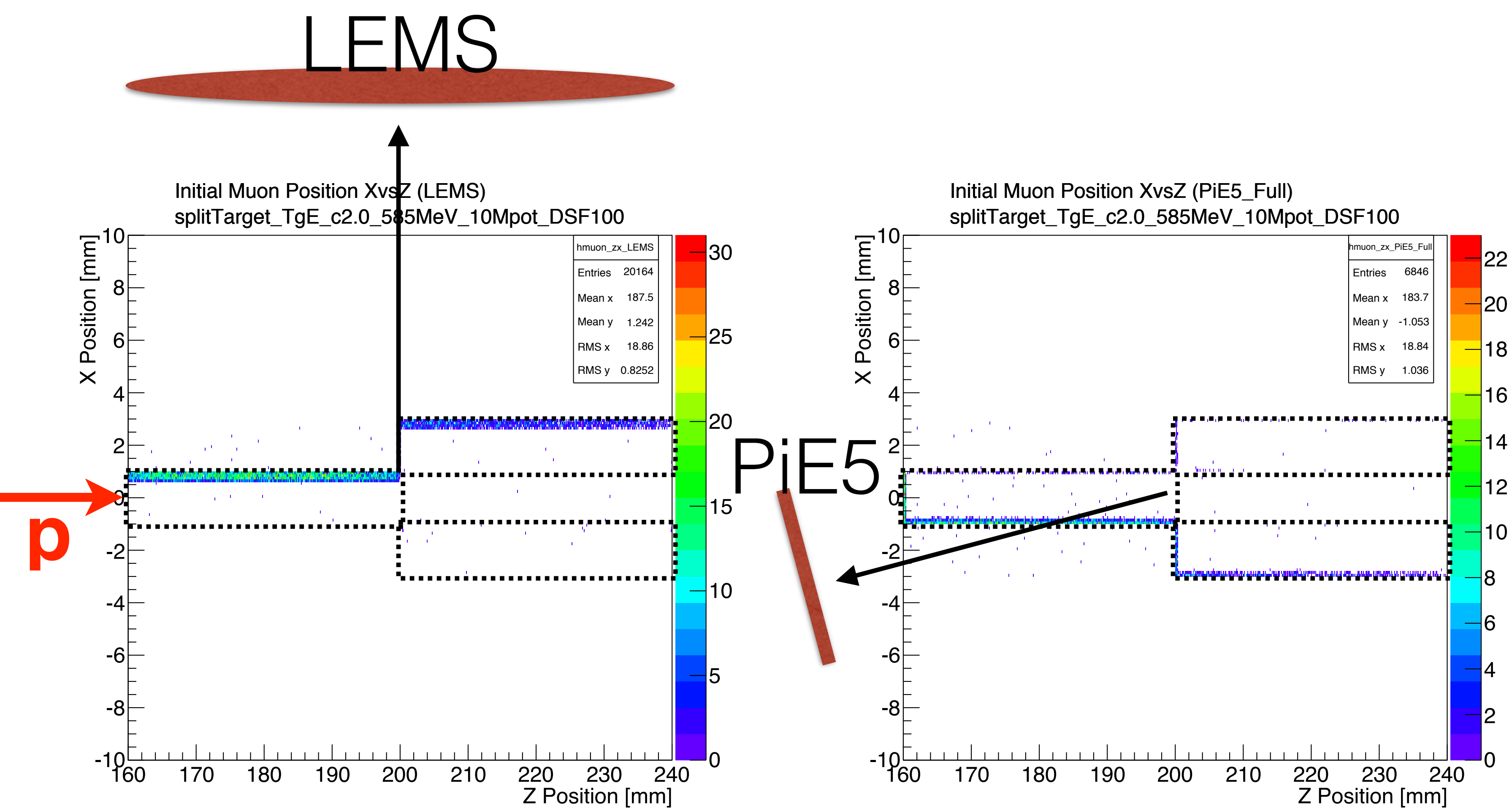


Ratio to Standard

Front Face Width [mm]	LEMS	PiE5
4.0	1.08	1.00
3.0	1.08	1.02
2.0	1.13	0.96

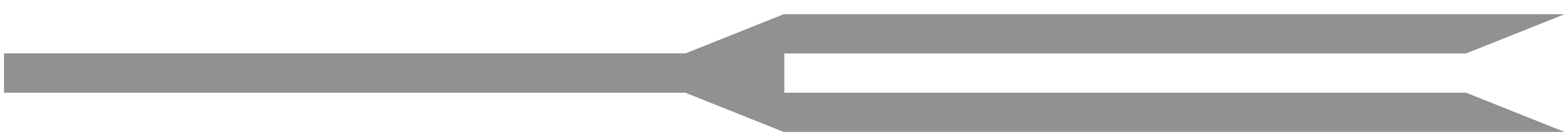
Trapezoidal Target

Approximately 13% enhancement for 2.0 mm front face target configuration



Ratio to Standard

Center Width [mm]	LEMS	PiE5
4.0	1.27	1.20
3.0	1.35	1.20
2.0	1.48	1.20



Fork Target

Approximately 50% enhancement for 2.0 mm center target width configuration

Alternate Materials

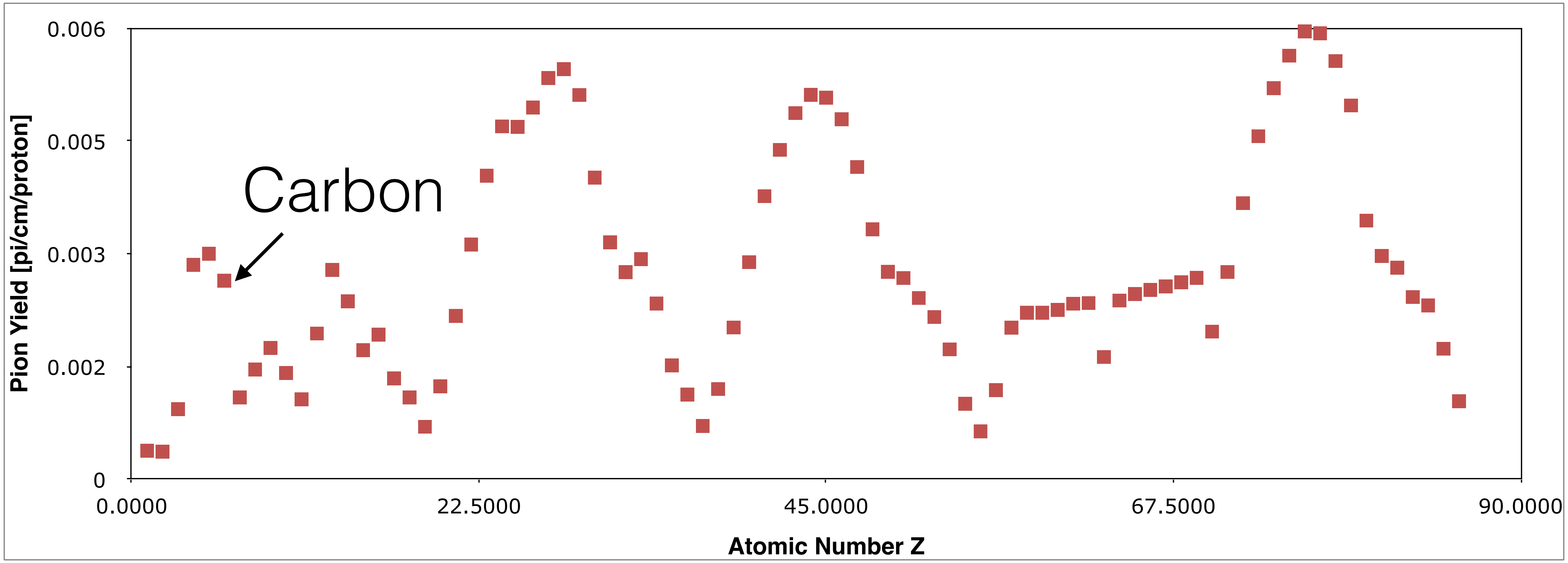
- Search for high pion yield materials → higher muon yield

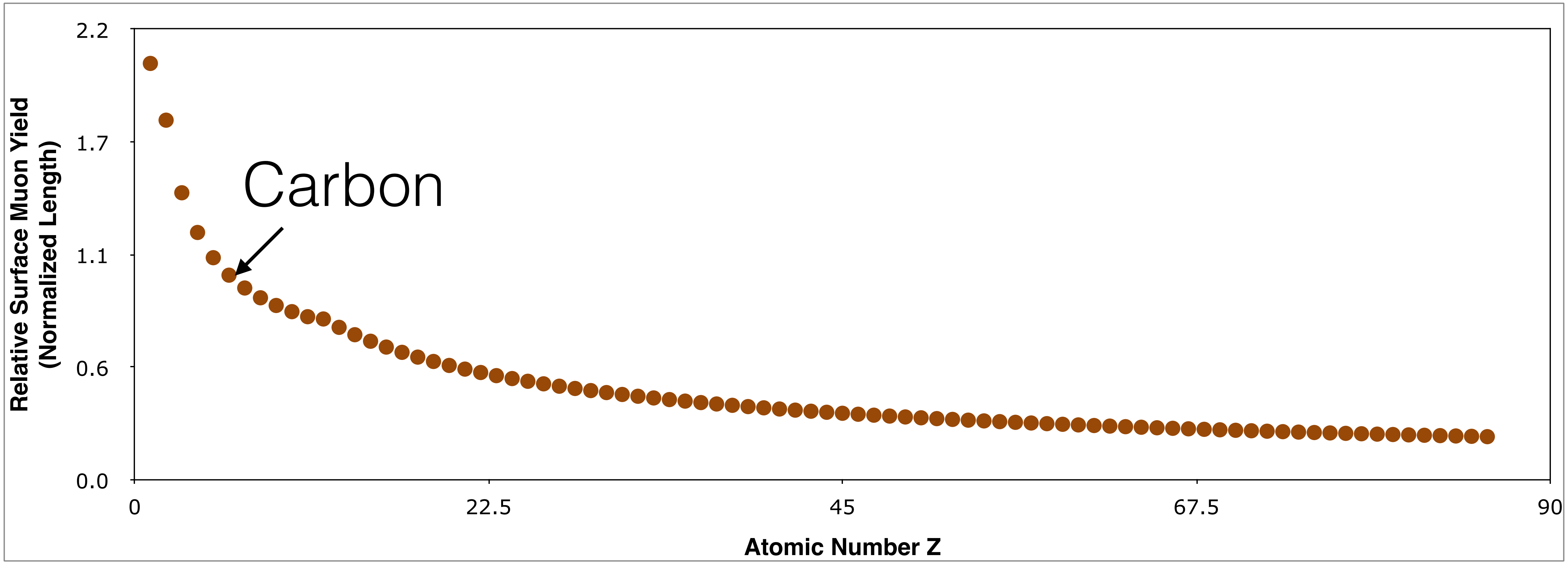
$$\text{relative } \mu^+ \text{yield} \;\propto\; \pi^+ \text{stop density} \cdot \mu^+ \text{Range} \cdot \text{length}$$

$$\propto n \cdot \sigma_{\pi^+} \cdot SP_{\pi^+} \cdot \frac{1}{SP_{\mu^+}} \cdot \frac{\rho_C (6/12)_C}{\rho_X (Z/A)_X}$$

$$\propto Z^{1/3} \cdot Z \cdot \frac{1}{Z} \cdot \frac{1}{Z}$$

$$\propto \frac{1}{Z^{2/3}}$$


Carbon
Pion Yield [pi/cm/proton]
0.006
0.005
0.003
0.002
0
0.0000
22.5000
45.0000
67.5000
90.0000
Atomic Number Z


Carbon
Relative Surface Muon Yield
(Normalized Length)
2.2
1.7
1.1
0.6
0.0
0
22.5
45
67.5
90
Atomic Number Z

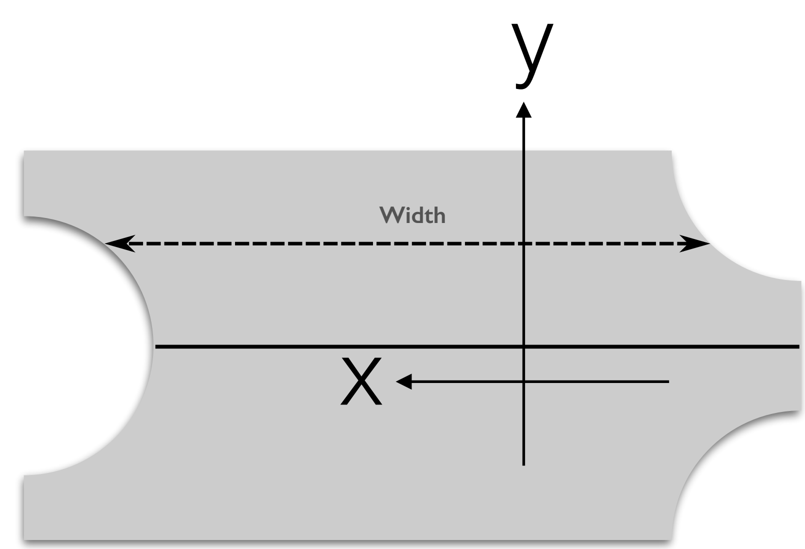
Conclusions

- HiMB project in 2-year feasibility study
  - Muon rate: 1×10^{11} μ/s from source downward
  - Currently evaluating solenoidal collection
- Parameterized π^+ cross section implemented
- Target E used as validation of G4BL
  - Possible improvements to TgE leading to higher muon rates

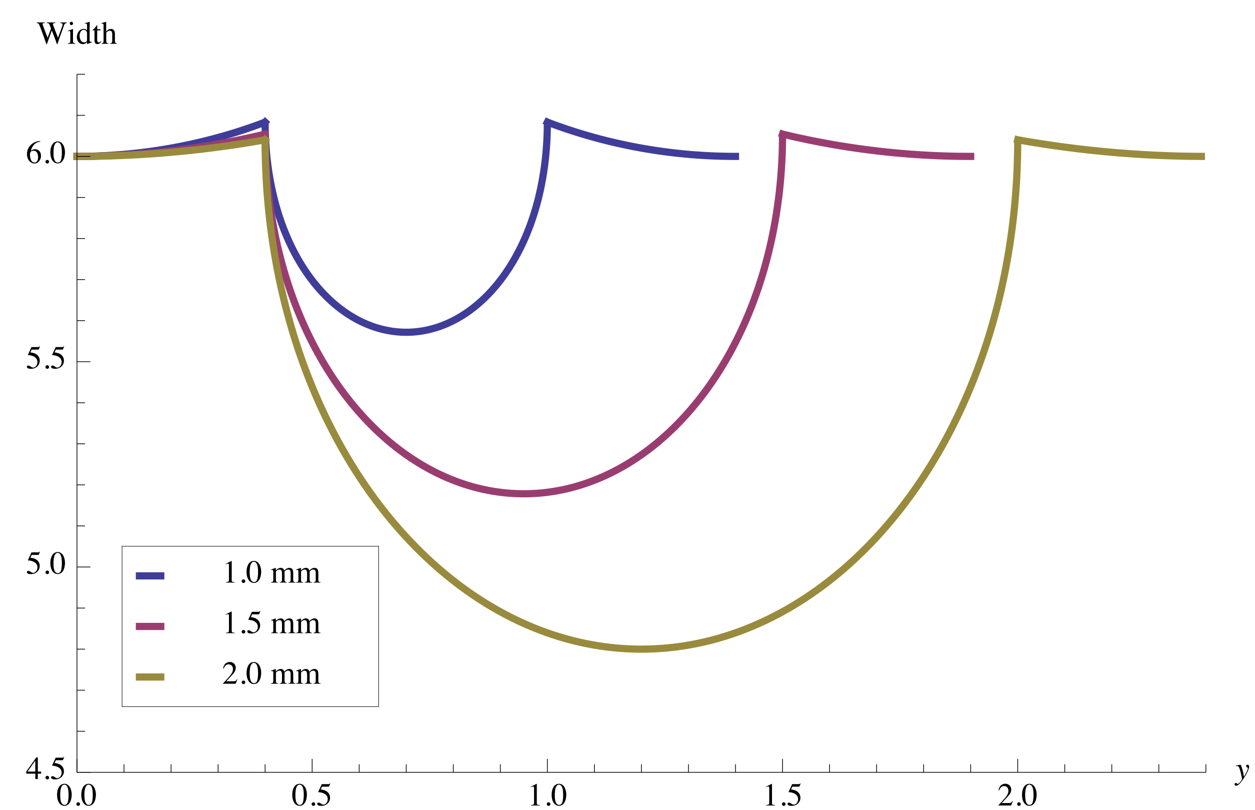
Backup Slides

Target Width

- The Target width (x-axis) varies along the y-axis
- This creates an effective width of the target that is less than the standard 6.0 mm

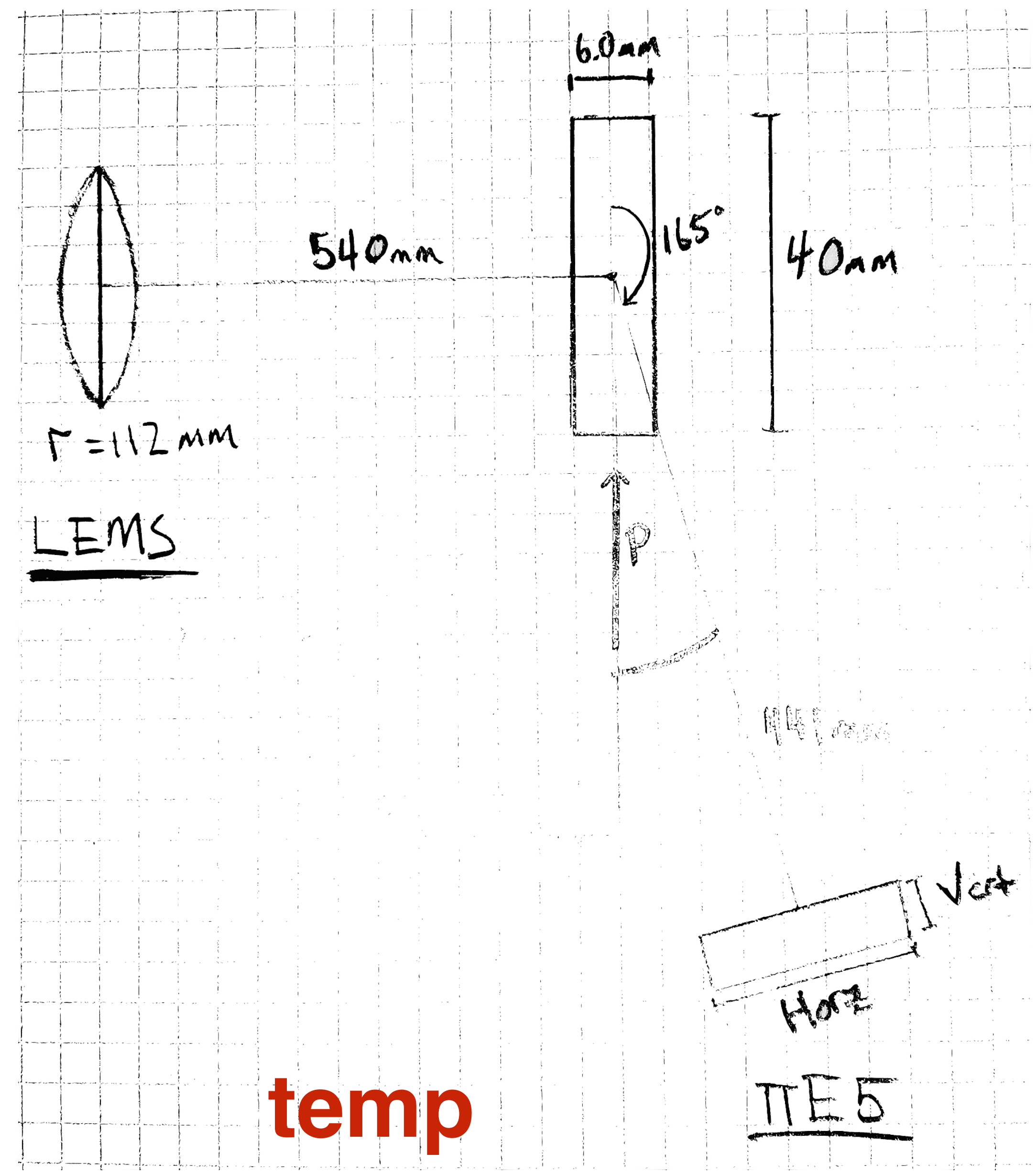


Groove Radius	Avg Target Width
1.0 mm	5.878
1.5 mm	5.64
2.0 mm	5.382
Flat	6.0



Detector Dimensions

- LEMS:
  - 540 mm from c.o.t.
  - r = 112 mm
- PiE5_Full:
  - 441 mm from c.o.t.
  - v = 79 mm, h = 353 mm



PARAMETERIZATION OF PION PRODUCTION AND REACTION CROSS SECTIONS AT LAMPF ENERGIES

by

R. L. Burman and E. S. Smith

ABSTRACT

A parameterization of pion production and reaction cross sections is developed for eventual use in modeling neutrino production by protons in a beam stop. Emphasis is placed upon smooth parameterizations for proton energies up to 800 MeV, for all pion energies and angles, and for a wide range of materials. The resulting representations of the data are well-behaved and can be used for extrapolation to regions where there are no measurements.

Inclusive π^+ Production from Carbon (T_p = 585MeV)

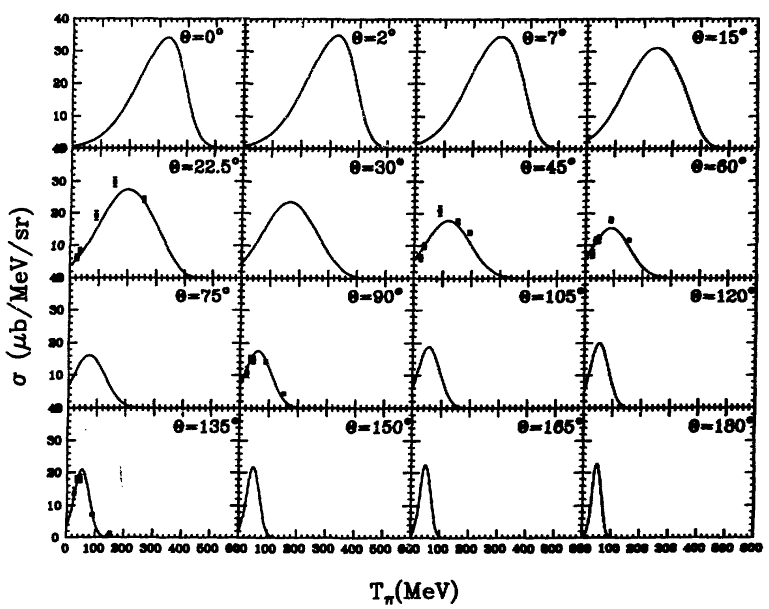


Fig. 7. The parameterization for π^+ production from carbon is compared with the data from Ref. 4.

PAUL SCHERRER INSTITUT Labor für Kern- und Teilchenphysik	Registrierung TM-11-92-01
Titel Decay of pions trapped in graphite	Ersetzt —
Autor / en R. Frosch, J. Löffler, C. Wigger	Erstellt 27.10.1992/FR11

ARCHIVEXEMPLAR 1

Unausleihbar

Abstract

This report is concerned with calculations needed for the analysis of the $p_\mu A$ experiment, in which the momentum of muons from the decay $\pi^+ \rightarrow \mu^+\nu_\mu$ of stopped pions is measured in an 'Arizona' surface muon beam. The experimental muon spectra are consistent with the assumption that the pions stopped in the graphite production target are trapped in a potential well of the form $V(r) = V_0 + \frac{1}{2}k_s r^2$, with $k_s \approx 1.0 \cdot 10^{17}\, eV/cm^2$. This potential well agrees with that recently derived by Y. Shirasu et al. for hydrogen and deuterium atoms dissolved in graphite.

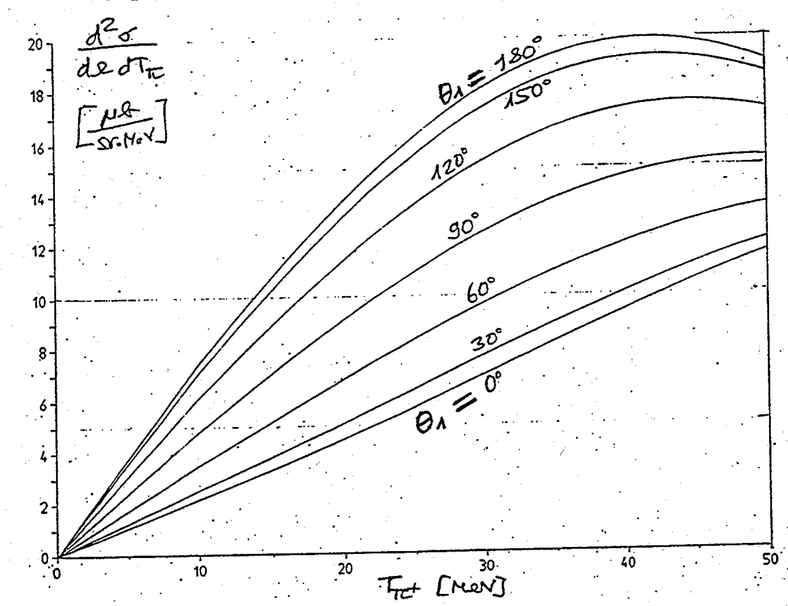
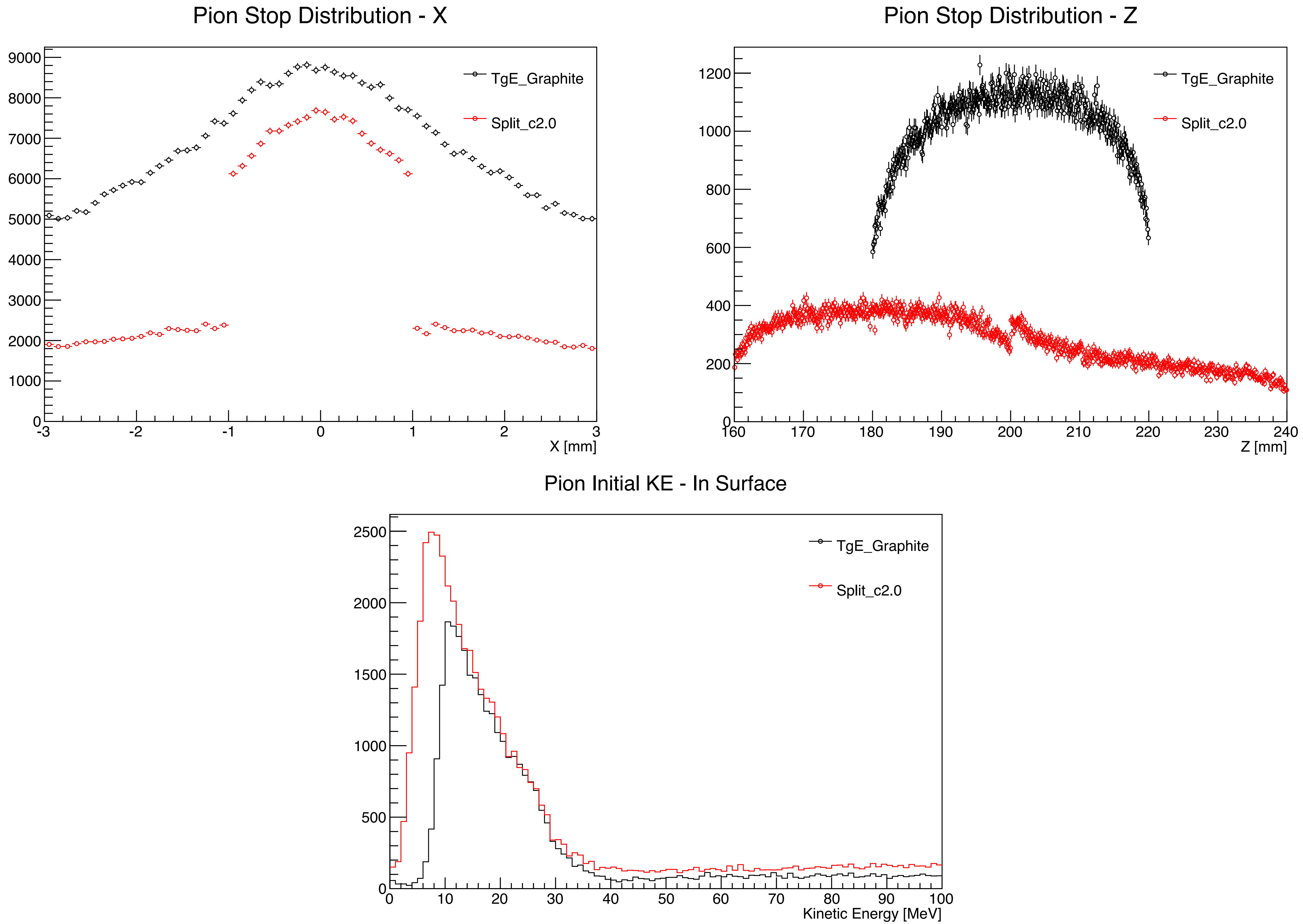
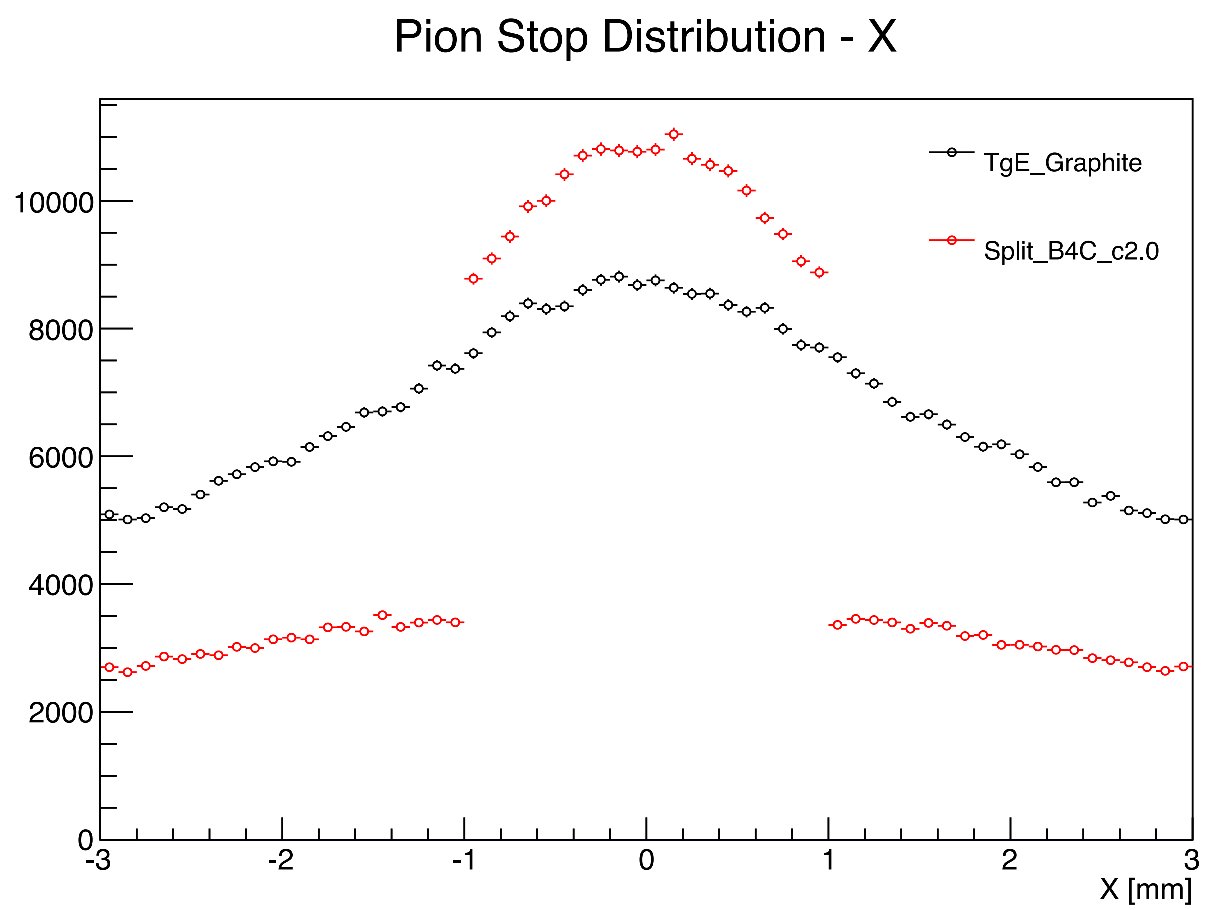


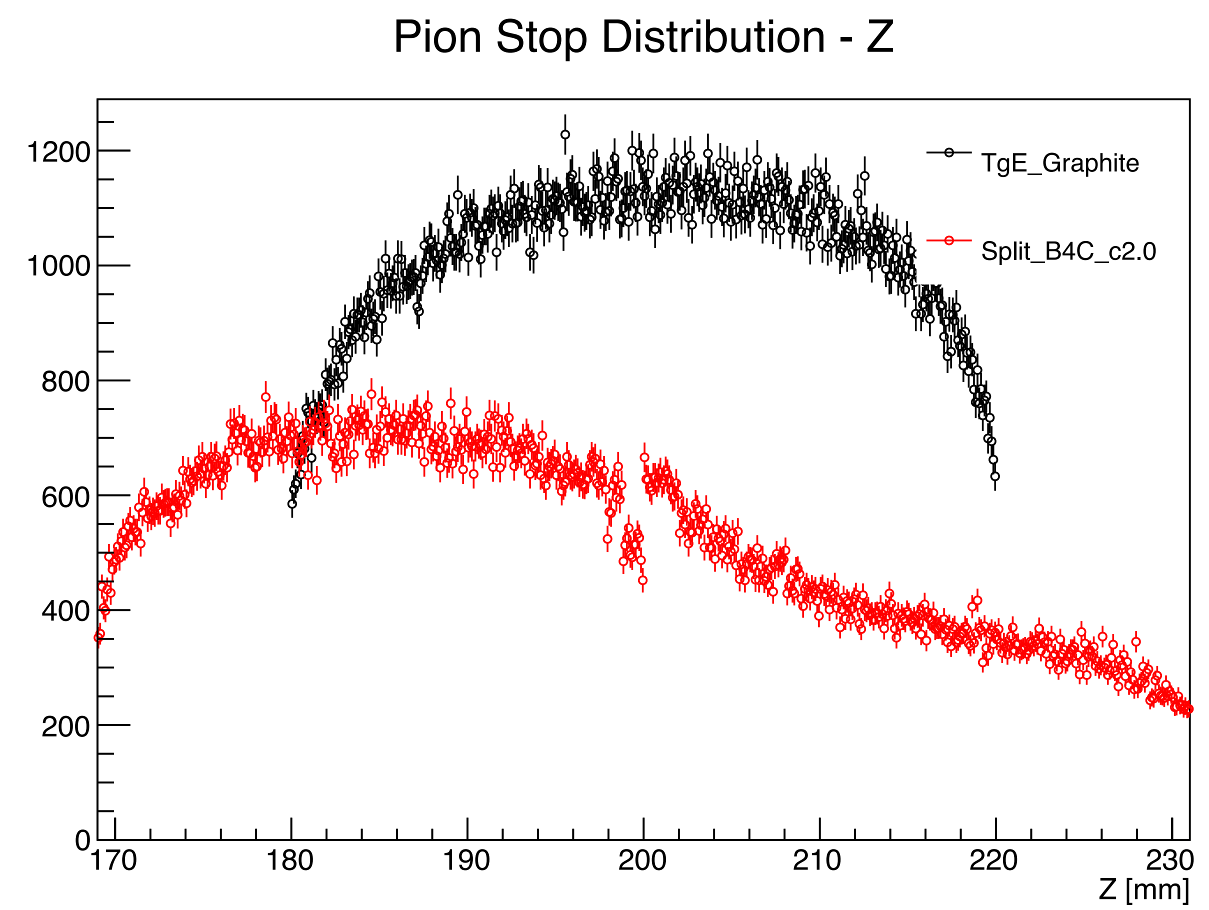
Figure 10: Differential π^+-production cross-sections according to Eq. (31), for 580MeV-protons in ^{12}C. T_{π^+}: laboratory kinetic energy of produced π^+; Θ_1: laboratory angle between proton and pion momentum vectors.

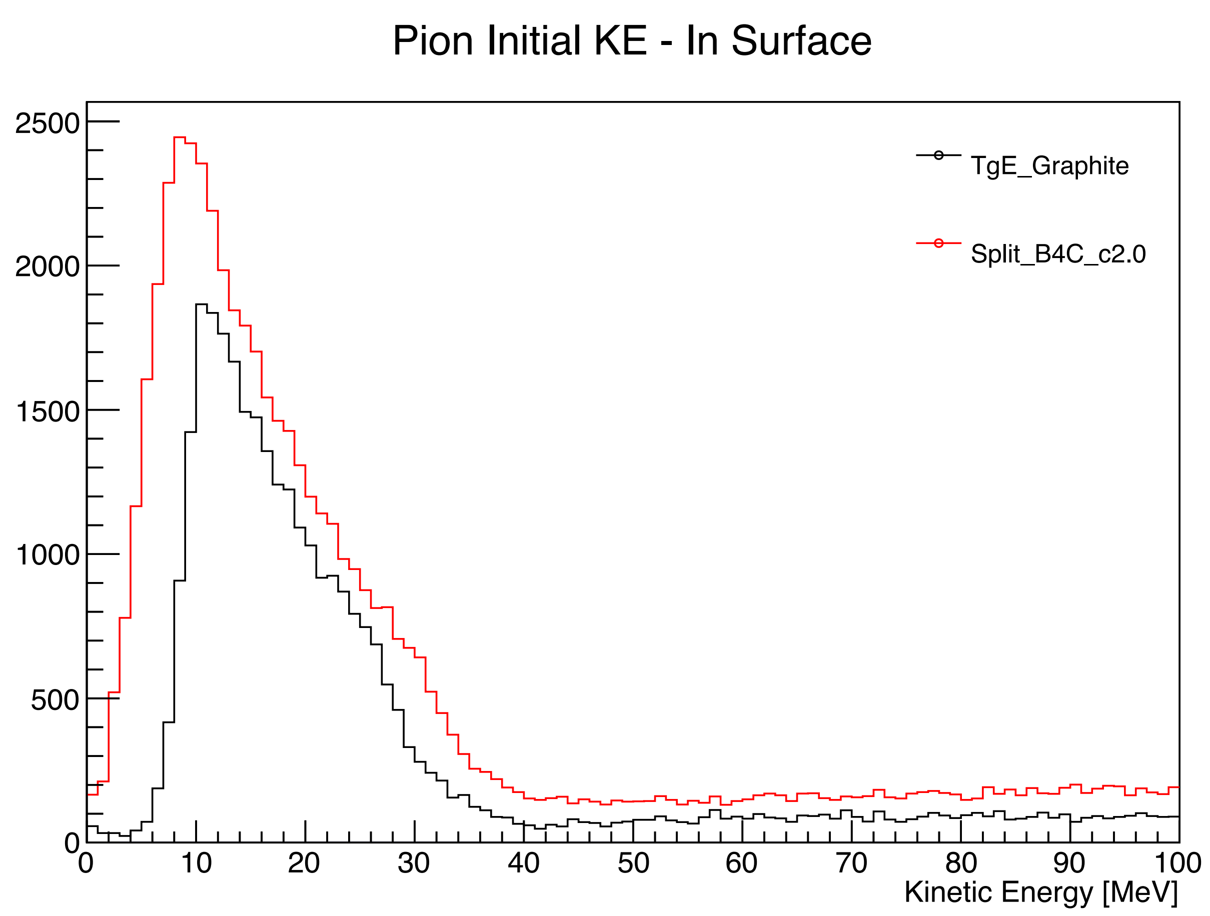
Pion production parameterization

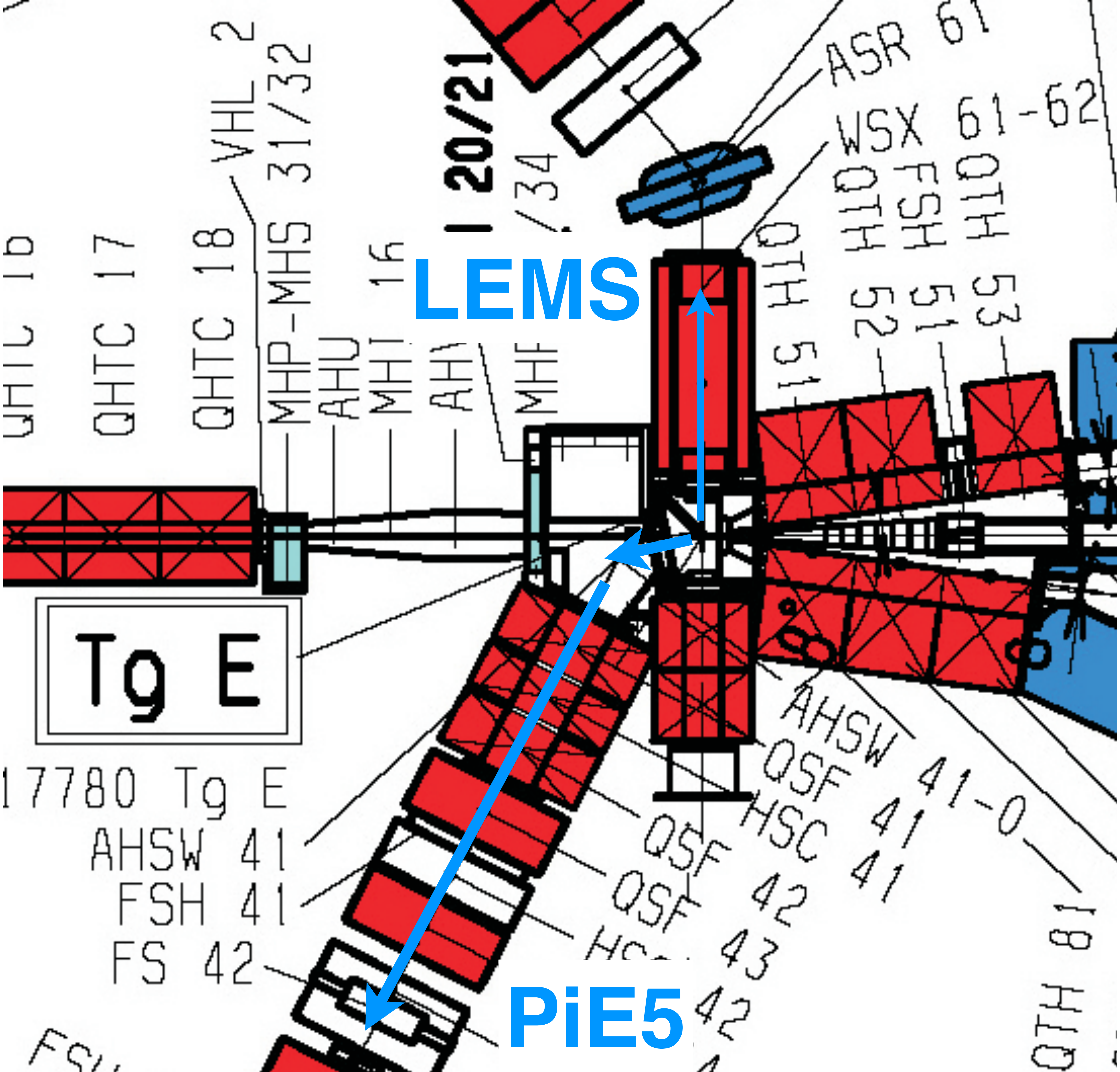


Pion Stop Distribution - X
TgE_Graphite
Split_c2.0
X [mm]
Pion Stop Distribution - Z
TgE_Graphite
Split_c2.0
Z [mm]
Pion Initial KE - In Surface
TgE_Graphite
Split_c2.0
Kinetic Energy [MeV]


Pion Stop Distribution - X
TgE_Graphite
Split_B4C_c2.0
X [mm]
-3
-2
-1
0
1
2
3
0
2000
4000
6000
8000
10000


Pion Stop Distribution - Z
TgE_Graphite
Split_B4C_c2.0
Z [mm]
170
180
190
200
210
220
230
0
200
400
600
800
1000
1200


Pion Initial KE - In Surface
TgE_Graphite
Split_B4C_c2.0
Kinetic Energy [MeV]
0
10
20
30
40
50
60
70
80
90
100
500
1000
1500
2000
2500


LEMS
PiE5
Tg E
17780 Tg E
AHSW 41
FSH 41
FS 42
QHTC 17
QHTC 18
VHL 2
MHP-MHS 31/32
20/21
ASR 61
WSX 61-62
QTH 51
AHSW 41-0
QSF 41
HSC 41
QSF 42
QTH 81