Muons, Inc.

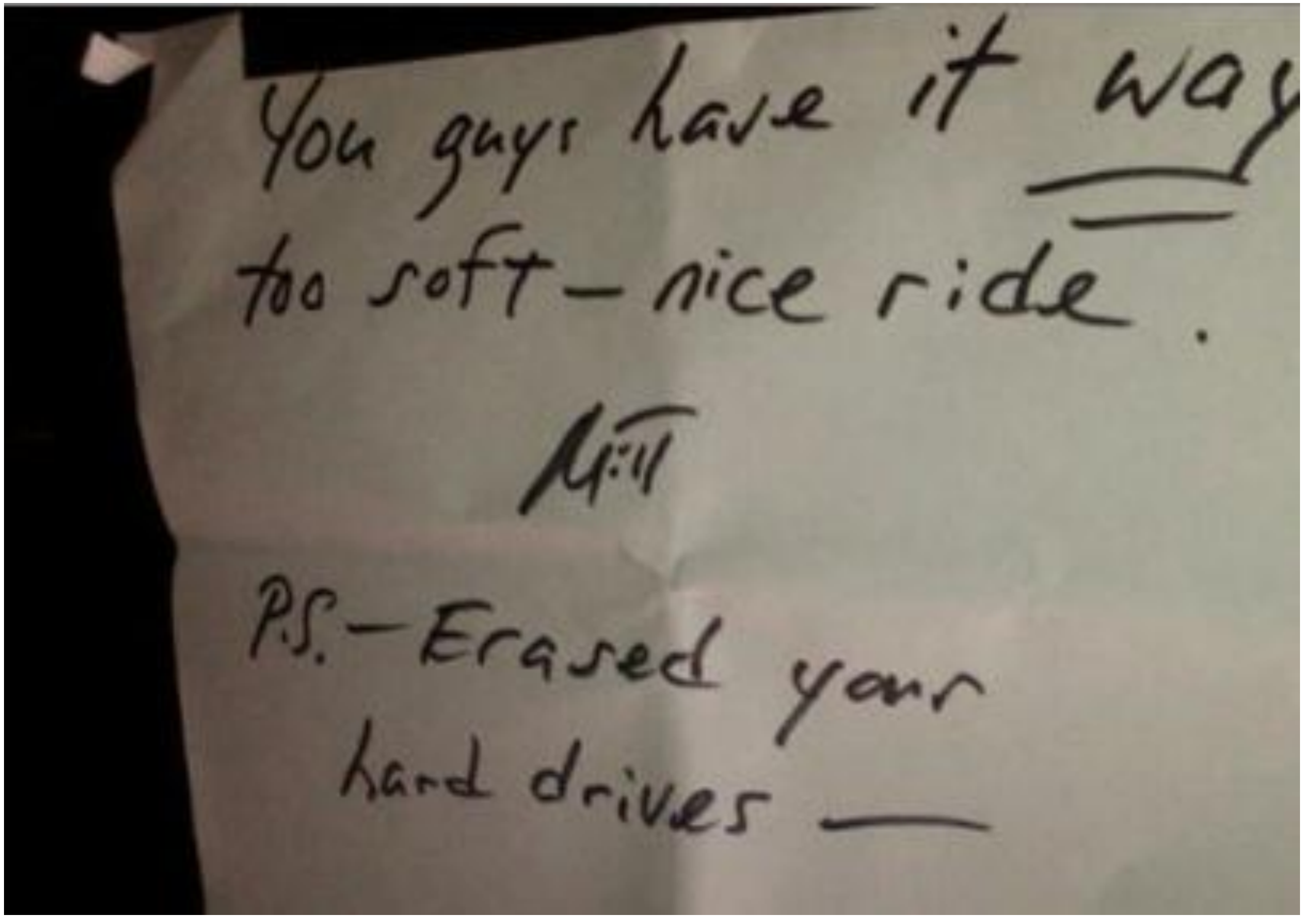
Project X Physics Study

Advanced Muon Beams @ Project X

Chuck Ankenbrandt*
Muons, Inc. Physicist
and Fermilab Scientist Emeritus
*and my colleagues, especially Cary Yoshikawa, Tom Roberts, Bob Abrams, Dave Neuffer, et al.

June 18, 2012

A coded message from Romney



By signing his name μ:π, he is obviously sending a secret message that, if elected, he will support us.

Advanced Muon Beams: Outline

- Introduction
- Dipole + Wedge (and Pion Candelabra)
- N-Ring CircUS (Circulating-beam Ultimate Source)
- Summary/Discussion/Recruiting*

***A goal of this talk is to attract talented and enthusiastic collaborators**

Introduction

- What will Project-X muon beam experimenters need?
  - High intensity
  - High duty factor
  - High purity/low contamination
  - Small emittances
  - Specific time distributions?
  - Polarization?
- Can those needs be met? And if so, how?
  - In this talk I'll describe two muon-beam system concepts
    - The Dipole + Wedge Pion Collection Scheme: status
    - The N-Ring CircUS: emergent concepts

Introduction (continued)

- The Project-X CW Linac will be able to deliver:
  - High intensity protons
  - at high duty factor
  - with specified proton time distributions
- The ideal muon beam design(s) would deliver
  - a high ratio of useful muons to incident protons
  - with high purity/low contamination
  - and small emittances,
  - while preserving, insofar as possible, the time distributions of the protons.
  - Polarization capability is necessary for some experiments.

Introduction (continued)

- Specific context (our marching orders):
  - 1-GeV protons from CW linac
  - 1 Megawatt of beam power
  - Focusing on the beam needs of a μ->e conversion experiment
    - Considerable improvement in sensitivity, and/or
    - Ability to use high-Z muon stopping targets
  - Look first at a dipole and wedge system.
- Thinking outside that box:
  - 3-GeV beam in Stage 2
  - Other experiments with other needs
  - Positive and negative pions and muons
  - Multiple muon beams from one target complex
  - Neutrino beams from circulating muon beams
  - Other muon beam system concepts

Paper at IPAC12, May, 2012

NOVEL MUON BEAM FACILITIES FOR PROJECT X AT FERMILAB

C. Ankenbrandt#, R. Abrams, T. Roberts, C. Yoshikawa, Muons, Inc., Batavia, IL 60510, USA*
D. Neuffer, Fermilab, Batavia, IL 60510, USA

Abstract

Innovative muon beam concepts for intensity-frontier experiments such as muon-to-electron conversion are described. Elaborating upon a previous single-beam idea, we have developed a design concept for a system to generate four high quality, low-energy muon beams (two of each sign) from a single beam of protons. As a first step, the production of pions by 1 and 3 GeV protons from the proposed Project X linac at Fermilab is being simulated and compared with the 8-GeV results from the previous study.

linac for further acceleration to 8 GeV. Ideas for staging Project X have recently been developed; the first stage would be a 1-GeV CW linac. The design average beam current in the CW linac is 1 mA, corresponding to beam powers of 1 and 3 MW at 1 and 3 GeV, respectively. Beam power of about a megawatt can potentially provide about two orders of magnitude increase in sensitivity for a muon to electron conversion experiment compared to the Mu2e experiment at 8 kW.

The experiment requires beam bunches spaced by about a muon lifetime. The lifetime of a stopped negative muon

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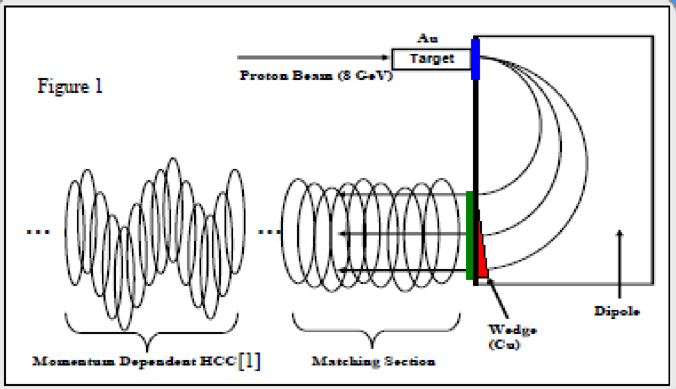
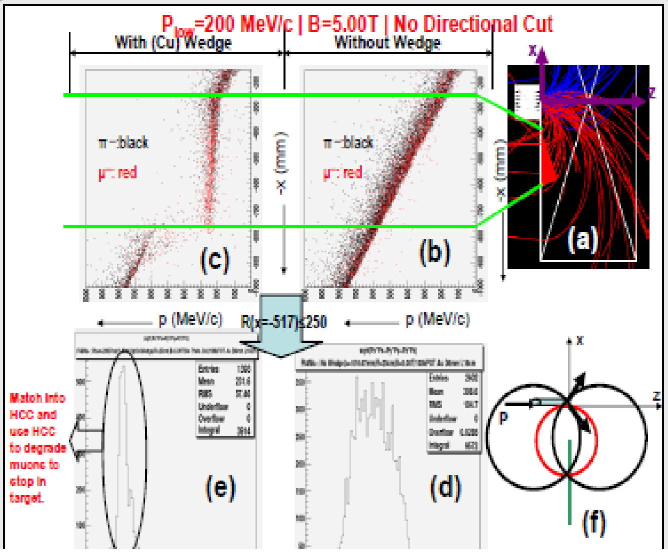




Introduction

We have been developing design concepts for future high-quality muon beam facilities driven by proton beams from the Fermilab Project X [2] linac. A variety of muon beams will be needed; one particular focus of our activities has been to provide a stopping negative muon beam for a muon-to-electron conversion experiment. (Muon to electron conversion is a charged-lepton flavor-changing process in which a muon converts directly to an electron in the field of an atomic nucleus without other particles being emitted. It is predicted to occur in some theories of physics beyond the standard model.)

A conversion experiment called Mu2e [3] has been approved and is currently being developed. It will use proton beam accelerated by the Fermilab Booster to generate muons stopping in an aluminum target. The proton energy is 8 GeV and the beam power is expected to be about 8 kW, corresponding to 1 μA of average proton beam current. The muon beam concept for Mu2e is similar to that of previously proposed (but not executed) experiments called MELC [4] and MECO [5].

Another conversion experiment following Mu2e will be an important experiment in the Project X era. If a significant signal is detected in Mu2e, then interest will turn to detecting conversion on one or more higher-Z nuclei such as gold. If, on the other hand, a convincing signal has not been detected, then the emphasis will be on achieving higher sensitivity. In both cases, a new initiative will be required because the design of the Mu2e beam and detector cannot readily be extrapolated to achieve much more demanding requirements. It is obviously desirable that any new initiative should be able to cover both possibilities, providing greater sensitivity as well as the ability to use higher-Z stopping targets effectively.

Project X is crucial for achieving the goals of the follow-on experiment. The baseline design for Project X includes a 3-GeV CW SRF linac followed by a pulsed linac for further acceleration to 8 GeV. Ideas for staging Project X have recently been developed; the first stage would be a 1-GeV CW linac. The design average beam current in the CW linac is 1 mA, corresponding to beam powers of 1 and 3 MW at 1 and 3 GeV, respectively. Beam power of about a megawatt can potentially provide about two orders of magnitude increase in sensitivity for a muon to electron conversion experiment compared to the Mu2e experiment at 8 kW.

The experiment requires beam bunches spaced by about a muon lifetime. The lifetime of a stopped negative muon in gold is less than 100 nsec, about 10 times shorter than that in aluminum. Project X includes a nimble chopper that will allow delivery of arbitrary bunch timing patterns, an important capability for these kinds of experiments.

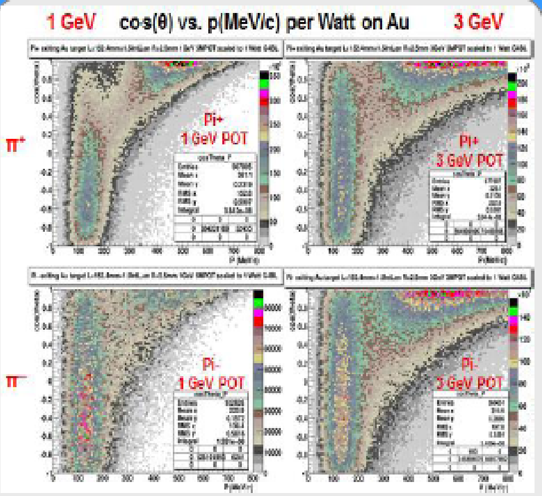


Figure 3: The fluxes of π^+'s (upper) and π^-'s (lower) exiting a gold target vs. Cos(θ) and P(MeV/c) for protons of 1 GeV (left plots) and 3 GeV (right plots). We used G4Beamline for these simulations [6].

"Candelabra Beams"

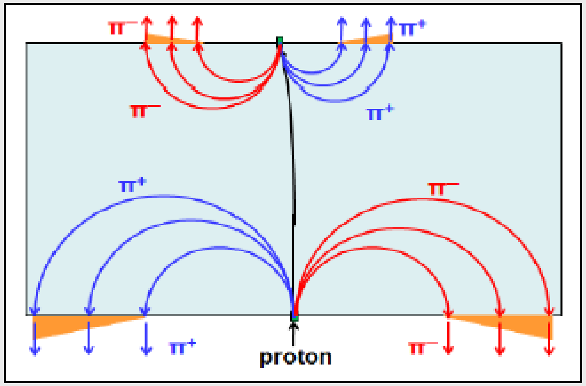


Figure 4: Layout of single dipole with two targets and four wedges to produce four monoenergetic pion beams from a single proton beam.

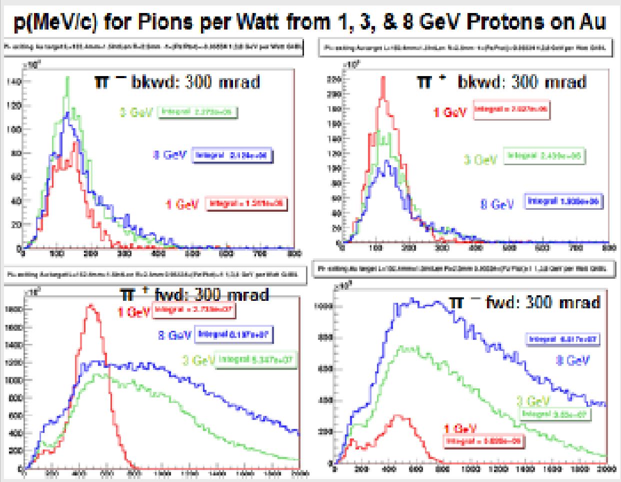
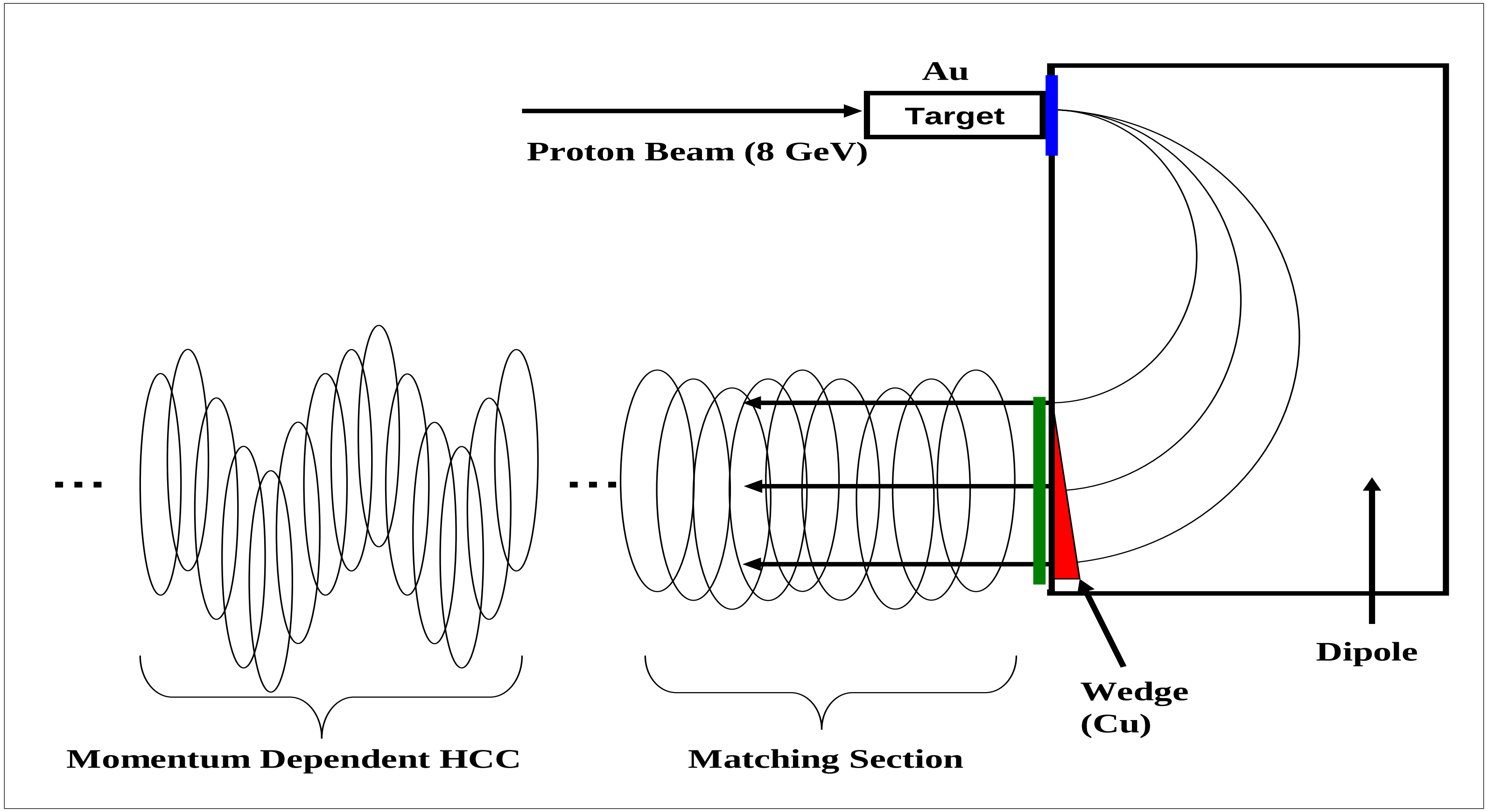


Figure 5: Momentum spectra (MeV/c) of π^+'s and π^-'s traveling forward (within 300 mrad) or backward (<300 mrad), produced by 1, 3, and 8 GeV protons. The plots are normalized to 1 watt of beam power. The placement of the plots (right/left & upper/lower) matches the location of the beams in Figure 4.

#chuck@muonsinc.com
*Work supported in part by purchase order # 605028 from Fermilab

The dipole and wedge concept

- System consists of dipole+wedge, decay volume, a single-pass cooling system, then rf recapture and deceleration., possibly followed by a tapered solenoid to the stopping target.



Dipole/wedge performance

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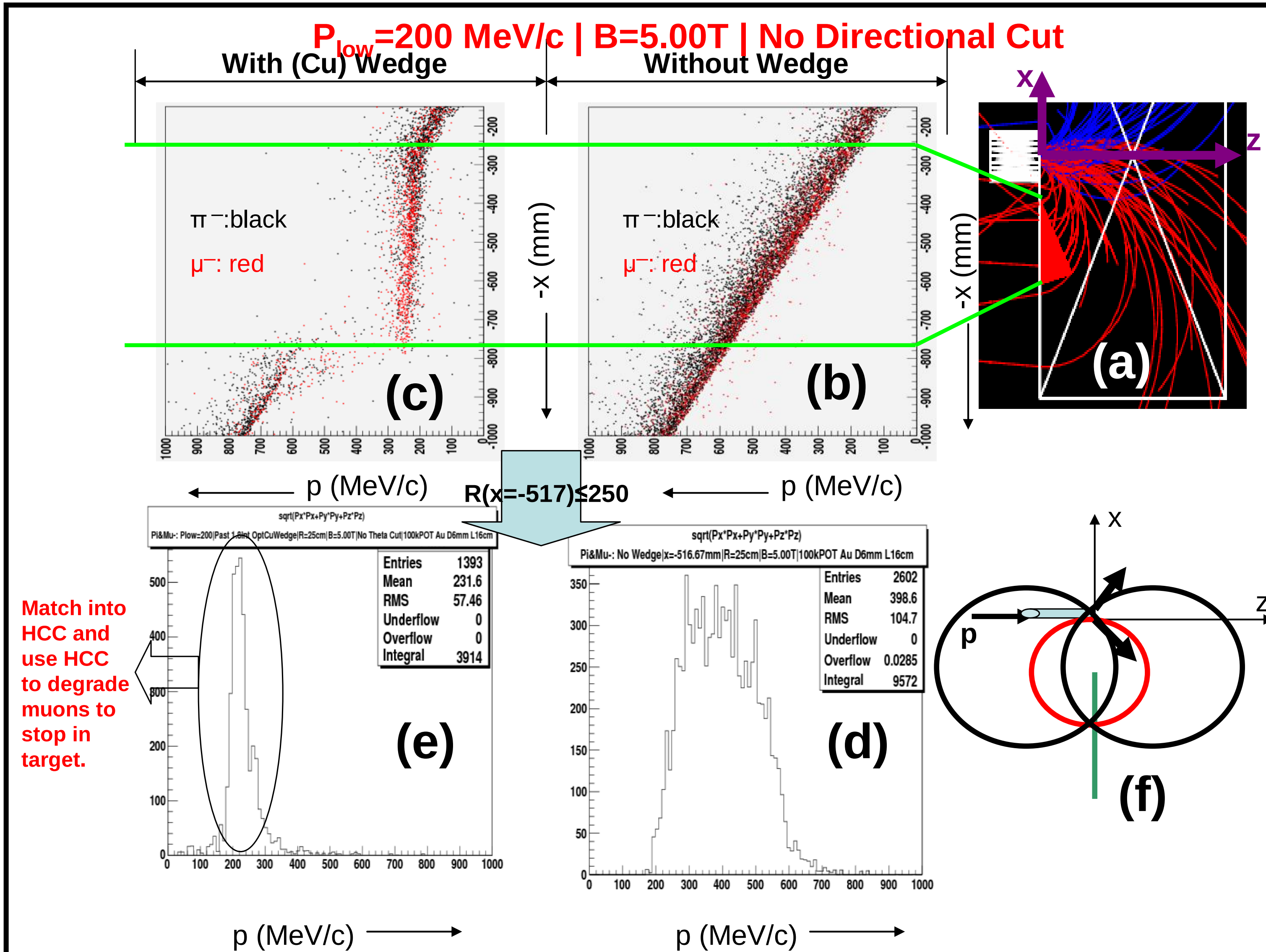
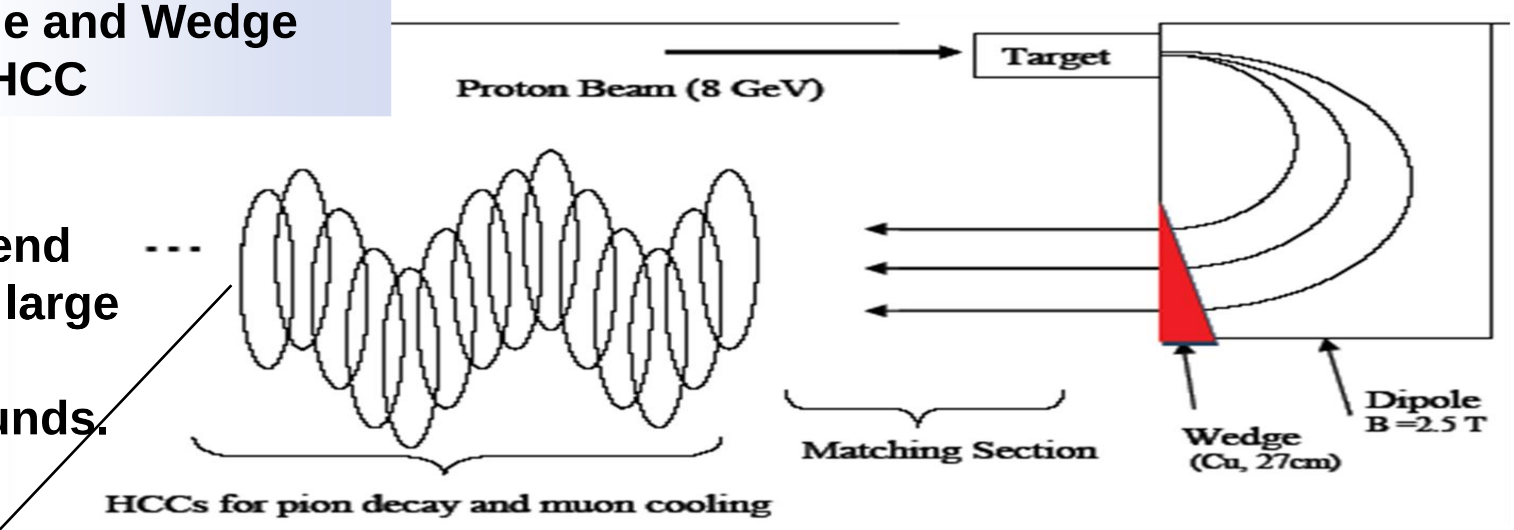
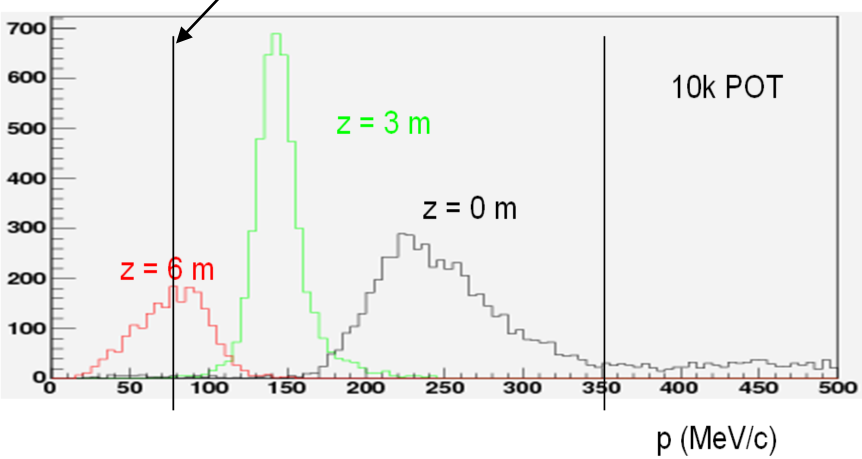


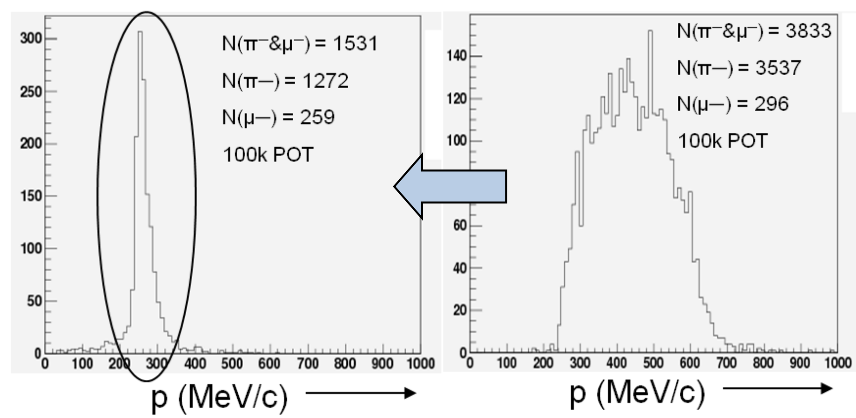
Intense Stopping Muon Beams

Dipole and Wedge Into HCC



dipole bend removes large neutral backgrounds.



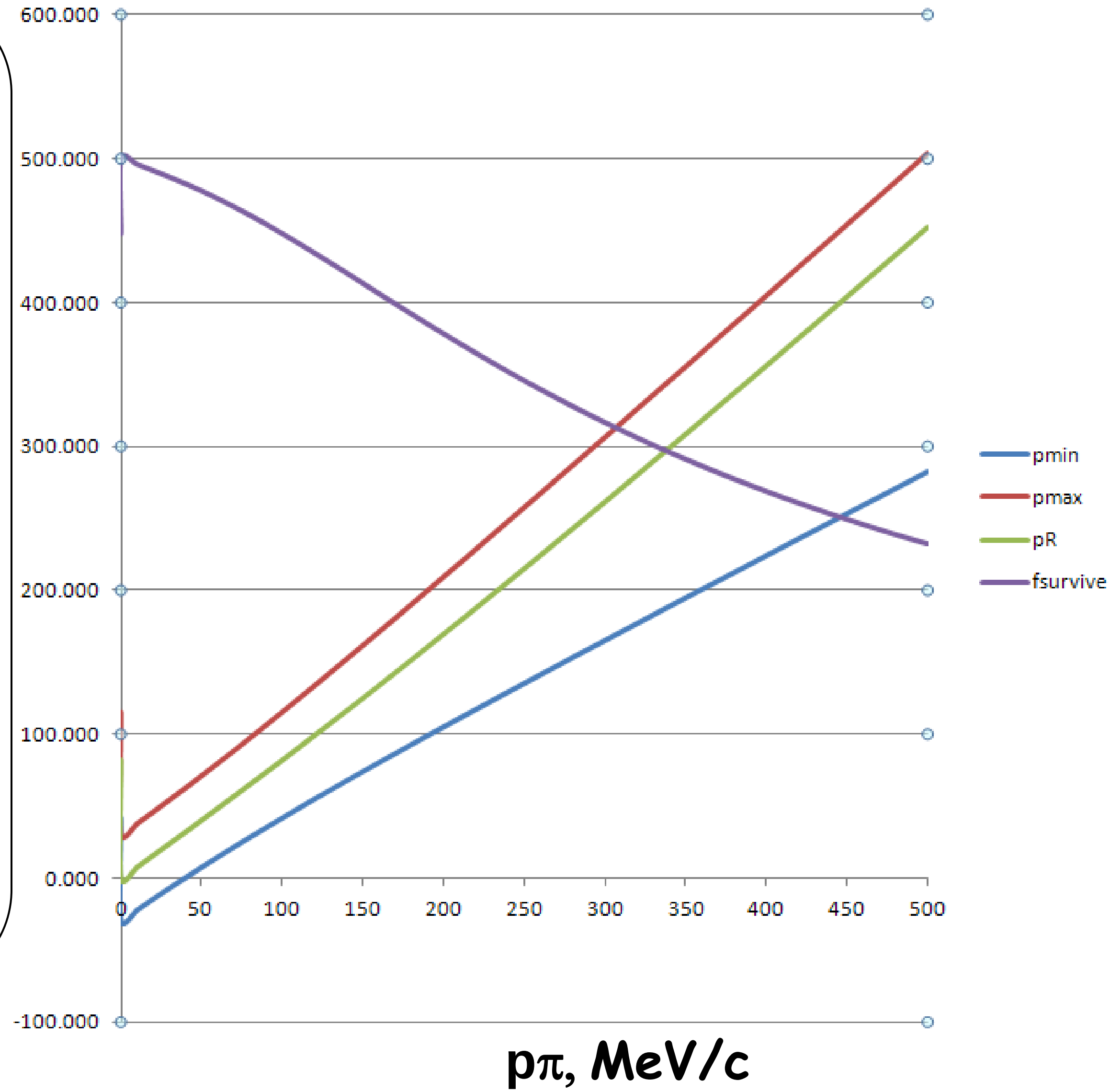


Matching into the HCC which degrades muons to stop in target

Wedge narrows P distribution

Pion Decay kinematics

pmin and pmax are the minimum and maximum muon momenta vs the parent pion momentum. pR shows the muon momentum that just survives passage through an absorber thick enough to range out the parent pions. fsurvive shows 1000* the fraction of decay muons having momenta above pR.

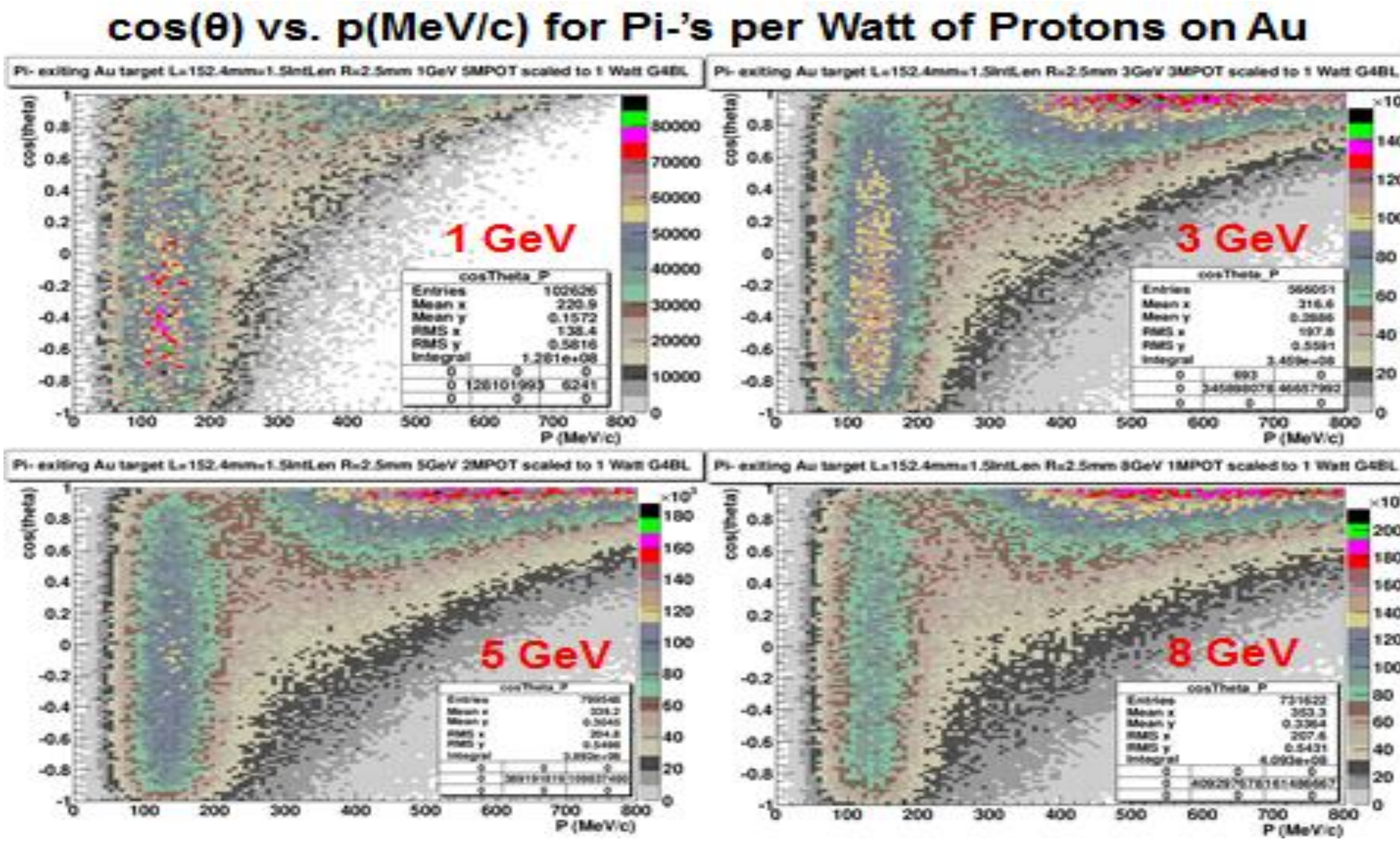


Pion Production Simulations

- Gaussian proton beam with proj. rms sizes of 1 mm
- A rod-shaped gold target
  - Radius =2.5 mm
  - Length =15.24 cm, (1.5 interaction lengths).
- The small beam and target radii were motivated by previous work of Lebedev, Mokhov, Striganov, et al.
- The results show fluxes at the target surface.
- So far, there's no magnetic field on the target.
- G4Beamline* was used for these simulations.

*T.Roberts, http://g4beamline.muonsinc.com

Negative pion fluxes vs energy



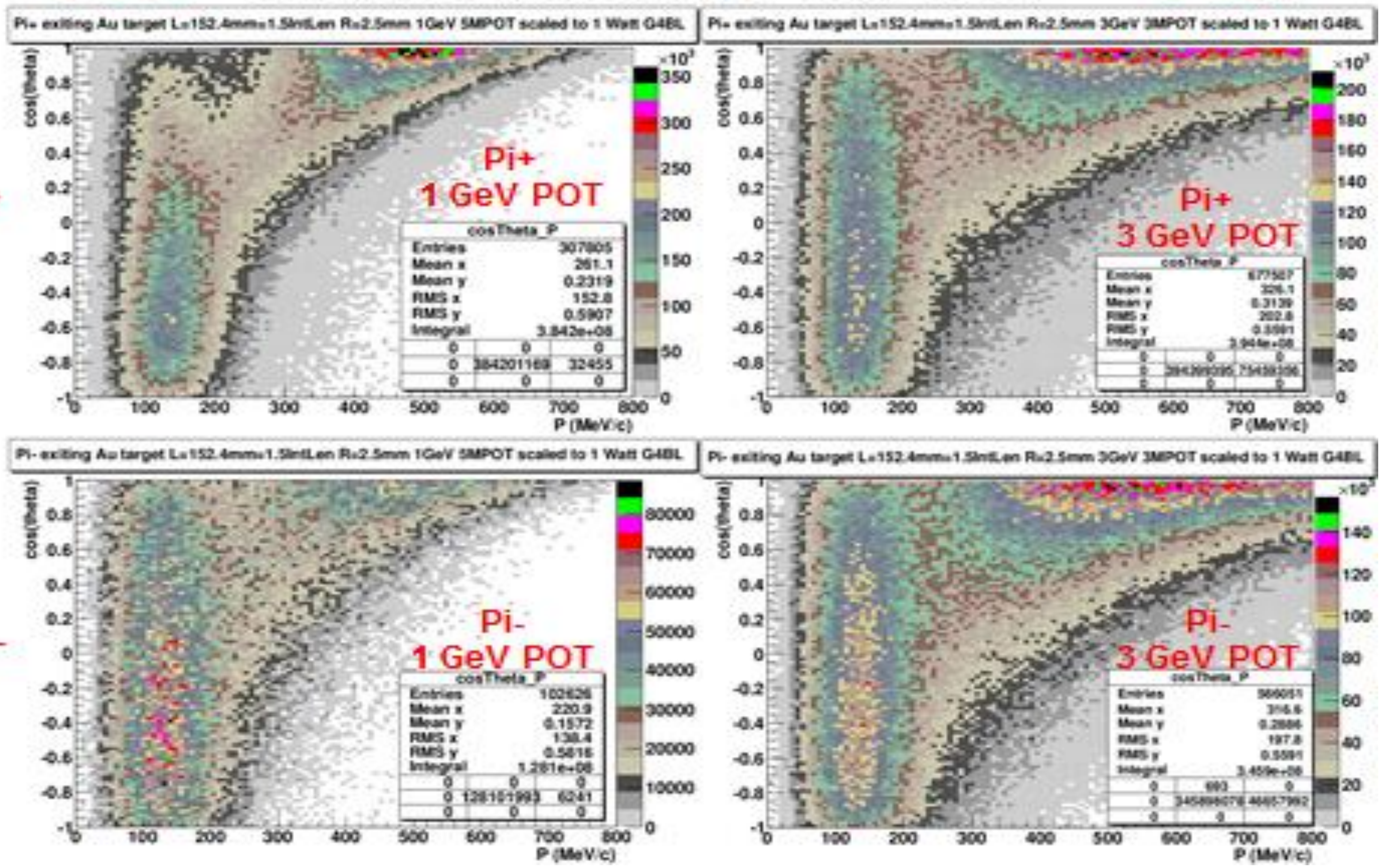
The fluxes of π⁻'s exiting a gold target vs. Cos(θ) and P(MeV/c) for protons with kinetic energy 1, 3 5, and 8 GeV.

Pion production at 1 and 3 GeV

1 GeV cos(θ) vs. p(MeV/c) per Watt on Au 3 GeV

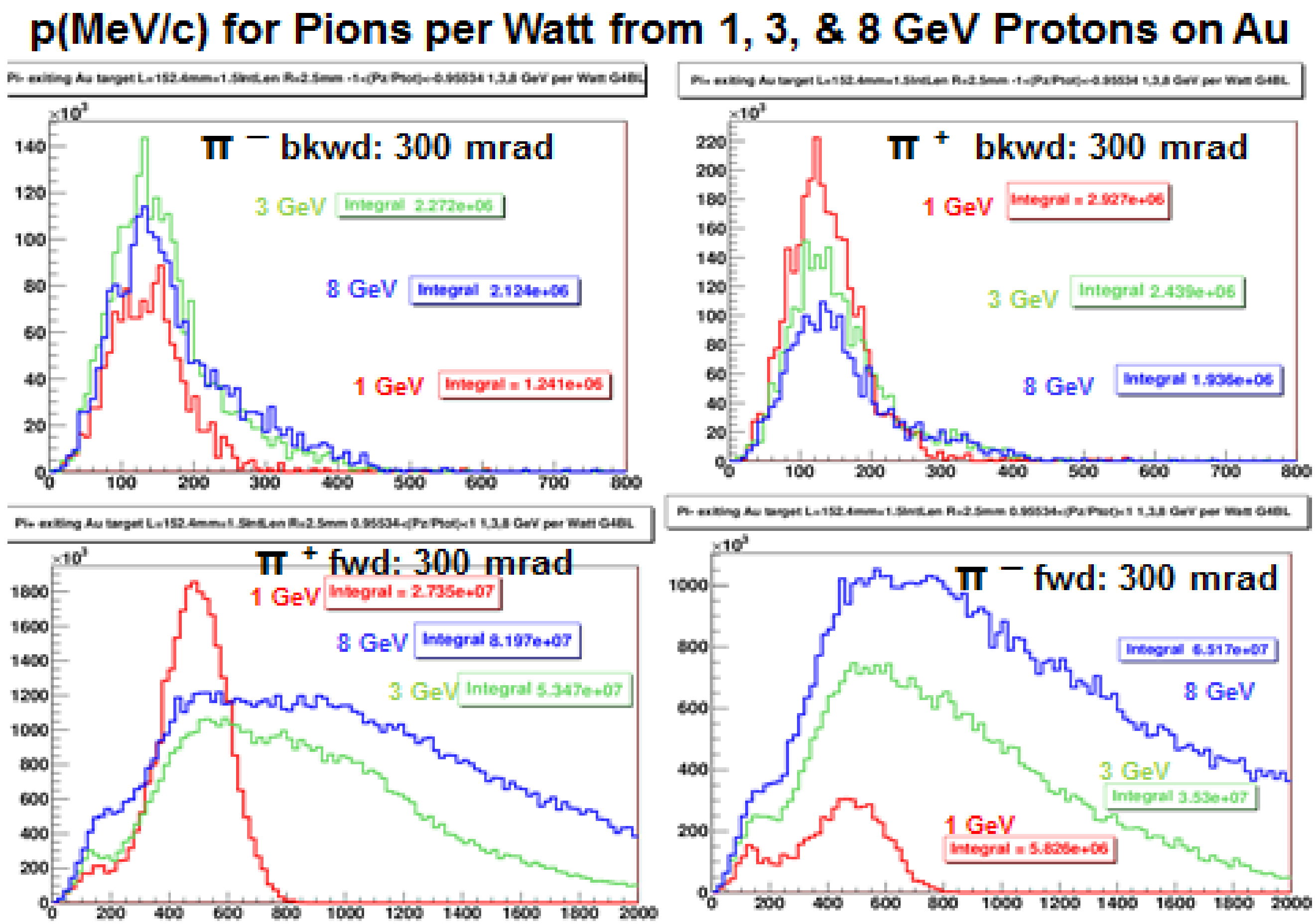
π^+

π^-



The fluxes of π^+'s (upper) and π^-'s (lower) exiting a gold target vs. Cos(θ) and P(MeV/c) for protons of 1 GeV and 3 GeV.

π momentum spectra for θ < 300 mr

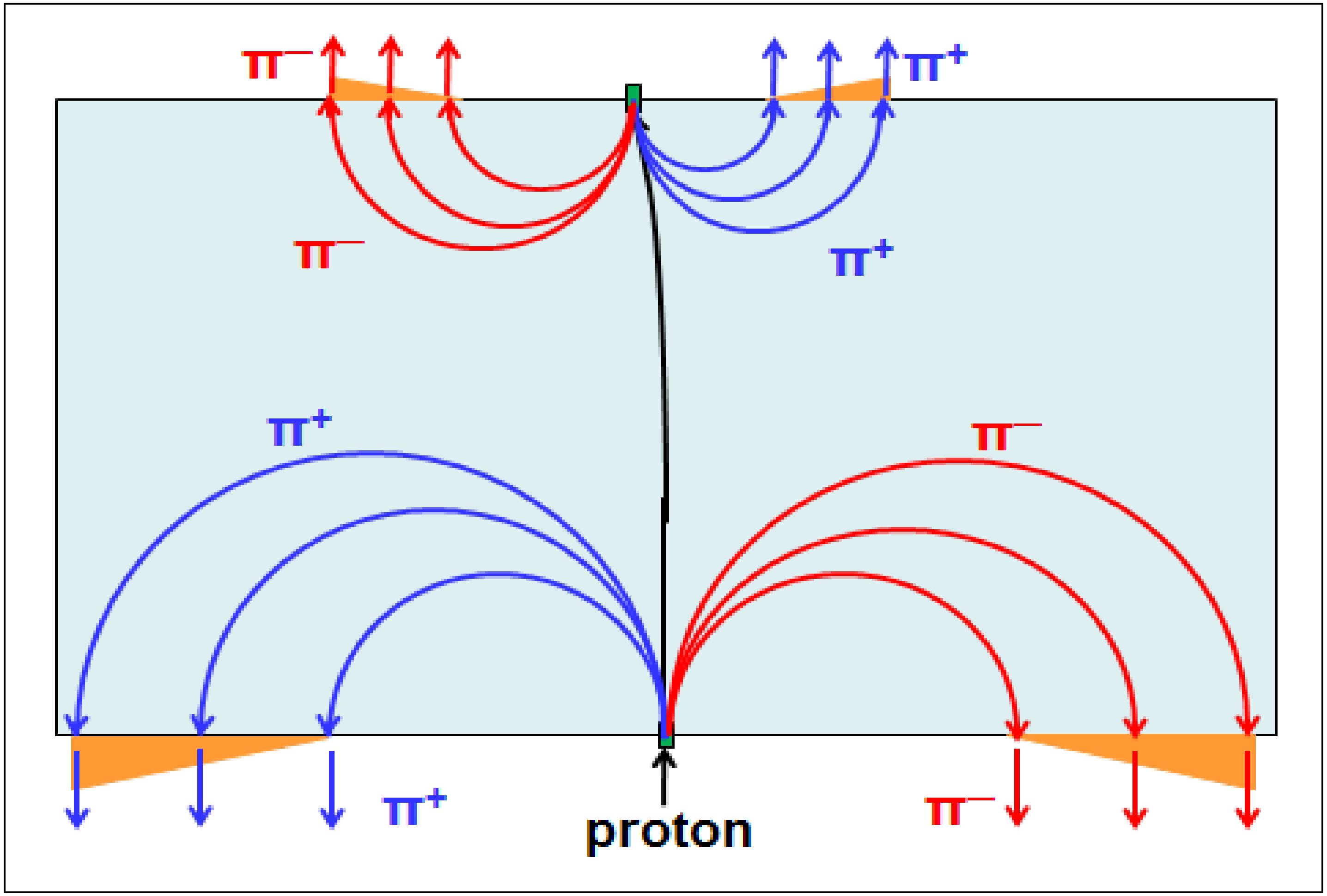


Pion Production Results

PID	Direction	KE(p) (GeV)	ΔP (MeV/c)	$N_{particle}$ per Joule
π^-	bkwd	1	50-250	1.167×10^6
π^-	bkwd	3	50-250	1.949×10^6
π^-	bkwd	8	50-250	1.683×10^6
π^+	bkwd	1	50-250	2.75×10^6
π^+	bkwd	3	50-250	2.117×10^6
π^+	bkwd	8	50-250	1.606×10^6
π^+	fwd	1	400-600	1.639×10^7
π^+	fwd	3	500-700	1.022×10^7
π^+	fwd	8	500-700	1.176×10^7
π^-	fwd	1	400-600	2.726×10^6 *
π^-	fwd	3	450-650	7.214×10^6
π^-	fwd	8	500-700	1.016×10^7

*This ratio corresponds to $N\pi/Np \sim 0.44E-3$

Candelabra complex



Layout of single dipole with two targets and four wedges to produce four mono-energetic pion beams from a single proton beam.

Comments on simulation results

- There aren't many very low-momentum pions produced.
  - Mainly just due to phase space $dV=\mathbf{p}^2 dp\, d\cos\theta\, d\phi$
  - So it's hard to produce a stopping beam directly.
- Low-energy pions have trouble escaping a thick target.
  - (This was previously pointed out by Mokhov, Lebedev, et al.)
  - The Δ resonance in πN interactions is important.
  - Ionization dE/dx causes low-E pions to range out.
- Relatively copious backward production of negative pions at low energy (should be vetted by experiment).
- 3 GeV works better than 1 GeV for π- production.
  - In a case of interest, the ratio is 2.65 for the same beam power.
- Forward production is suitable for the dipole+wedge, but the predicted rates are somewhat disappointing at 1 GeV.

A few words about rates…

- Mu2e plans to use 8 kW of 8-GeV protons (Iav=1 μA)
  - Nμ/Np ~ 2.5E-3 for Mu2e at 8 GeV (last time I looked)
- For μ->e@PX, assume 1 MW of 1-GeV protons (1 mA)
- So, 1000 times more protons, 125 times more power.
- However Nπ/Np*Ep is ~3.7 times larger at 8 GeV than at 1 GeV. So net gain is 125/3.7=33 times.
- 1 mA corresponds to 6.2E15 protons/sec.
  - That's 1.24E23 protons in 2E7 seconds.
- Nπ/Np ~ 0.44E-3 for dipole+wedge (before wedge)
  - So Nπ ~ 5E19 in a year for 1 MW of 1-GeV protons.
- Nπ/Np ~ 1.7E-3 for N-Ring CircUS
  - So Nπ ~ 2E20 in a year
- These numbers include no inefficiencies, losses, etc.

The N-Ring Circus

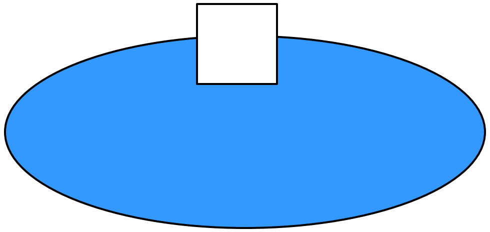
- And now for something quite different…
- and quite preliminary.

The N-Ring CircUS: System Concepts

- There's a proton storage ring and N-1 pion/muon storage rings. All fixed-energy rings.
- All rings share a common straight section; there are splitter/recombiner dipoles at the ends of that straight section. The revolution times of all rings are multiples of the fundamental 1/162.5 MHz bunch spacing of the CW linac. All rings have RF to maintain rf bunching and to restore the energy lost when the beams pass thru matter.
- H- ions come in thru a thin low-Z target in which they get stripped. A few of the resulting protons interact on the first pass; the rest are stored to recirculate thru the same target. Eventually ~all protons interact.

The NRCircUS: System Concepts (cont)

- Further absorbers on the other side of the muon rings provide faster cooling.
- Continuous extraction occurs thru a U-shaped electrostatic septum. Coherent betatron oscillations are excited by a transverse-mode deflecting rf cavity synchronous with the betatron oscillation frequency.
- It's a completely "flow-thru" system: no pulsed or ramped devices.
- After extraction, subsequent systems can provide further cooling and deceleration if necessary.



The N-Ring CircUS: Main advantages

- The thin low-Z target minimizes target reabsorption, avoids depth-of-focus (hourglass effect) problems at low beta, and functionally serves three purposes: stripper, production target, and cooling medium.
- Recirculating system allows multiple passes thru RF cavities; provides affordable multipass cooling.
- Continuous extraction allows all emittances of extracted beam to be smaller than those of the circulating beam. In principle, can reduce the 6-d emittances by a factor equal to the average number of turns before extraction.
- Multi-turn circulation before extraction reduces pion contamination, producing a pure muon beam.

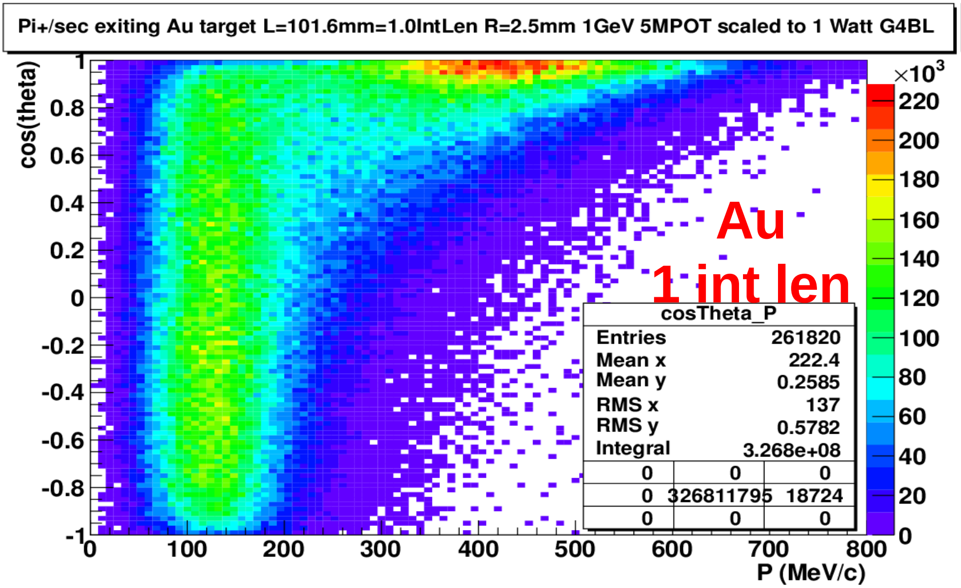
The N-Ring CircUS: Major parameters

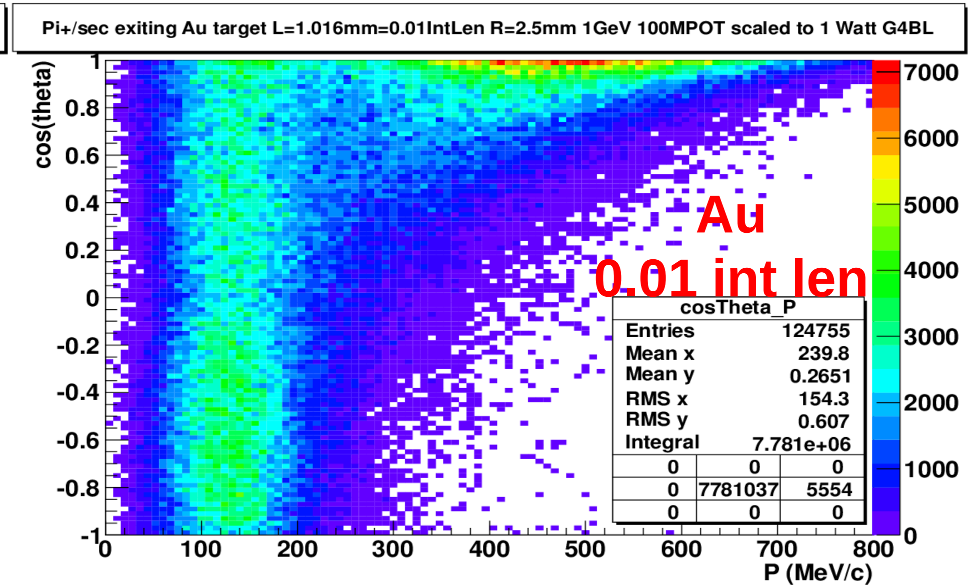
- Say N=5. Then there are 2 positive and two negative pion/muon rings, produced forward and backward, respectively. All rings operate close to transition. FFAG lattices for pion/muon rings.
- Ring sizes:
  - Size the proton ring to eventually handle 3 GeV. Say R~ 50 m, Circumference~ 300 m, Trev ~ 1 microsecond.
  - Size Pi/Mu ring circumferences to give Trev of order 3 pion lifetimes, 3% of a muon lifetime. Most pions decay before encountering additional absorber material on the other side of the ring that cools the muons.
- Energy loss per turn ~ 30 MeV. RF ring voltage ~ 100 MV.

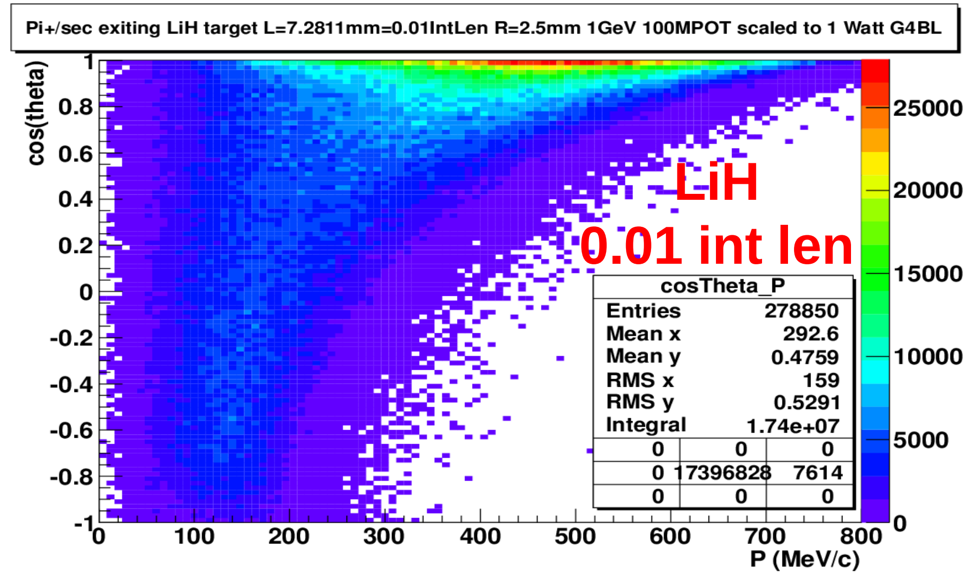
The N-Ring CircUS: Requirements

- The pion/muon rings should have enormous acceptances in transverse emittances and momentum spread so that many of the pions and resulting muons fall within the acceptances (FFAG?)
- The acceptances of the proton ring are large enough to contain the beam after it passes thru the target ~ 100 times (~one interaction length).
- The circumferences of the rings: there are some "quantization" conditions to satisfy to keep things synchronized.

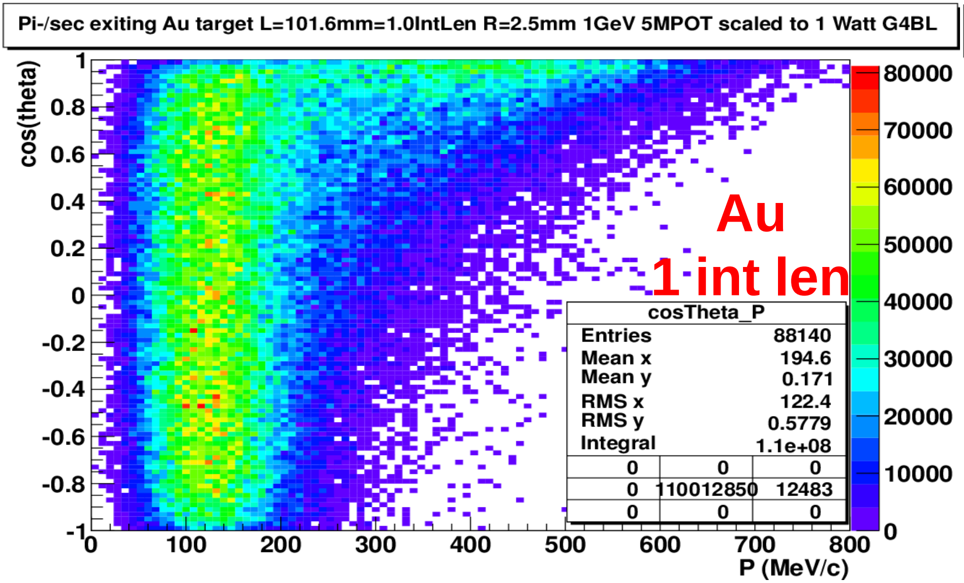
Yield of Pi+/sec per Watt

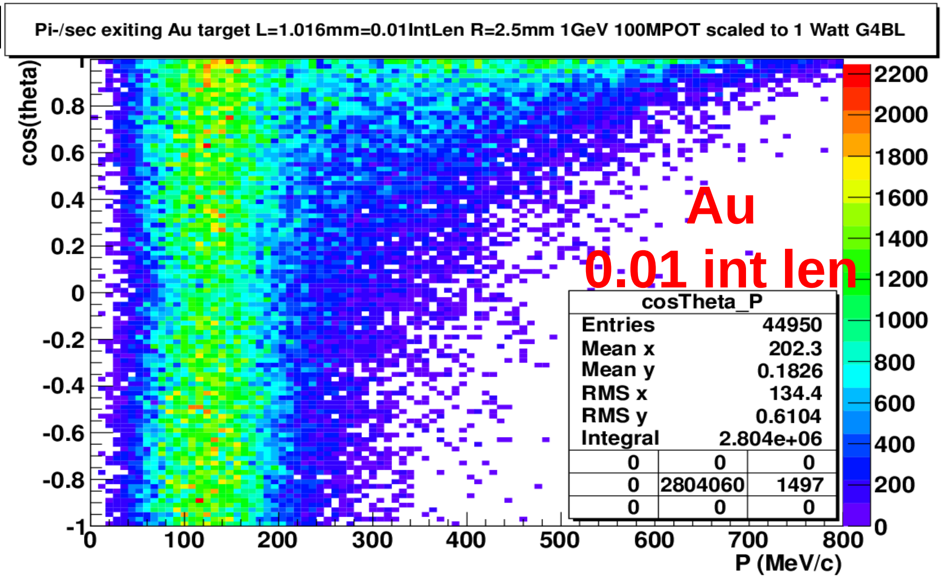


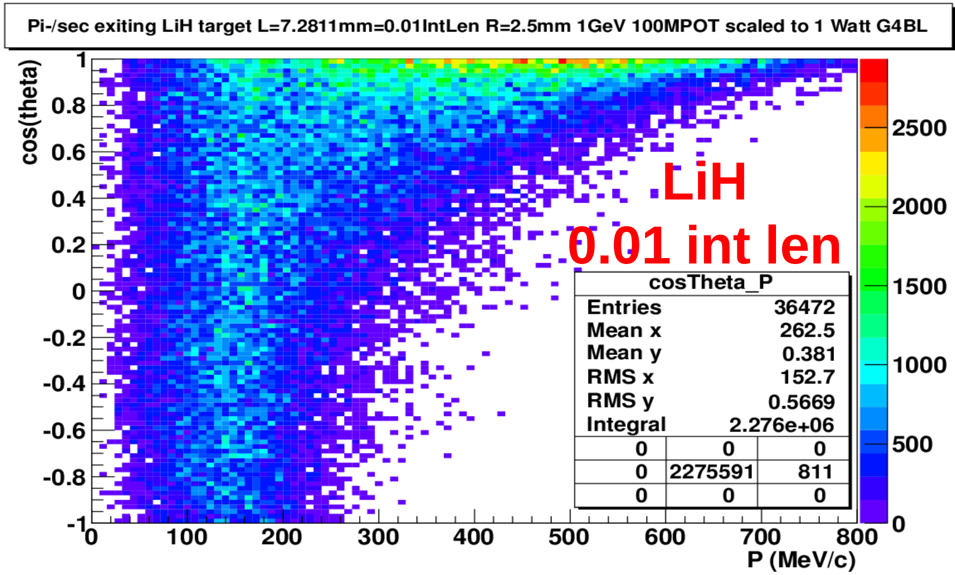




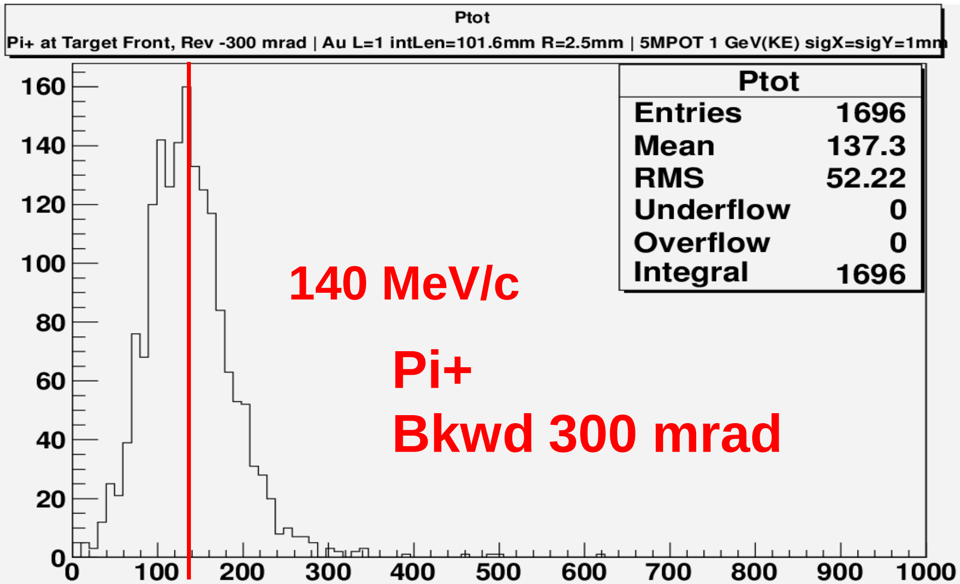
Yield of Pi-/sec per Watt

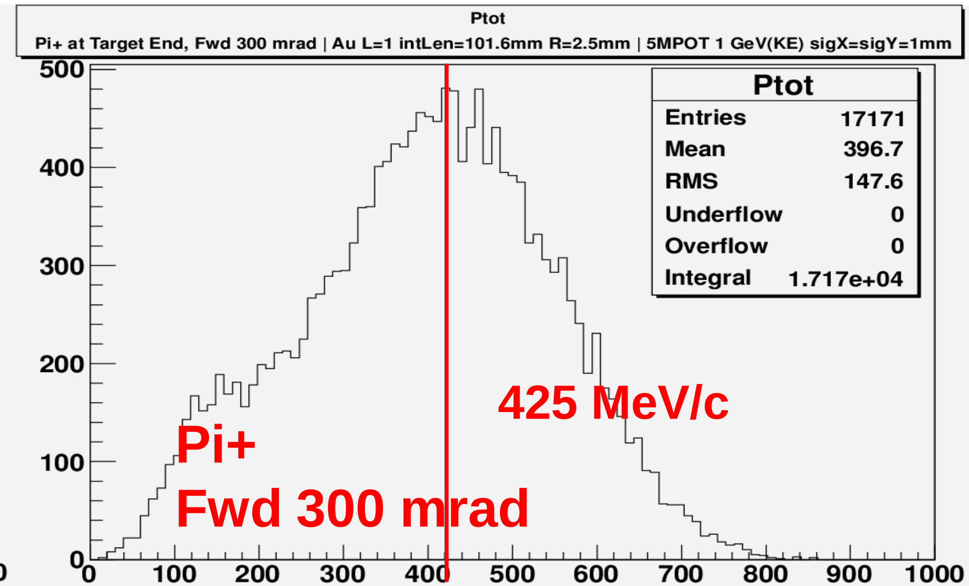


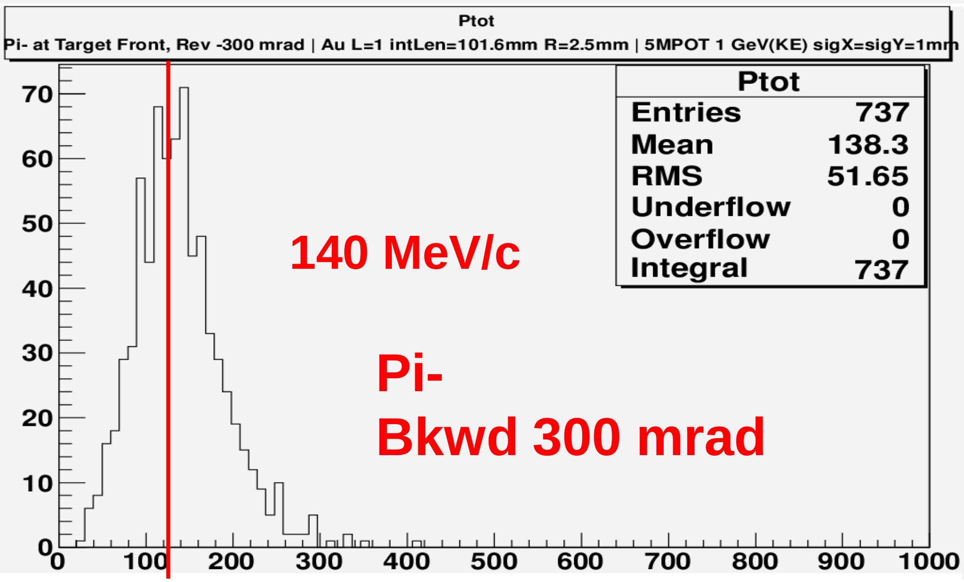


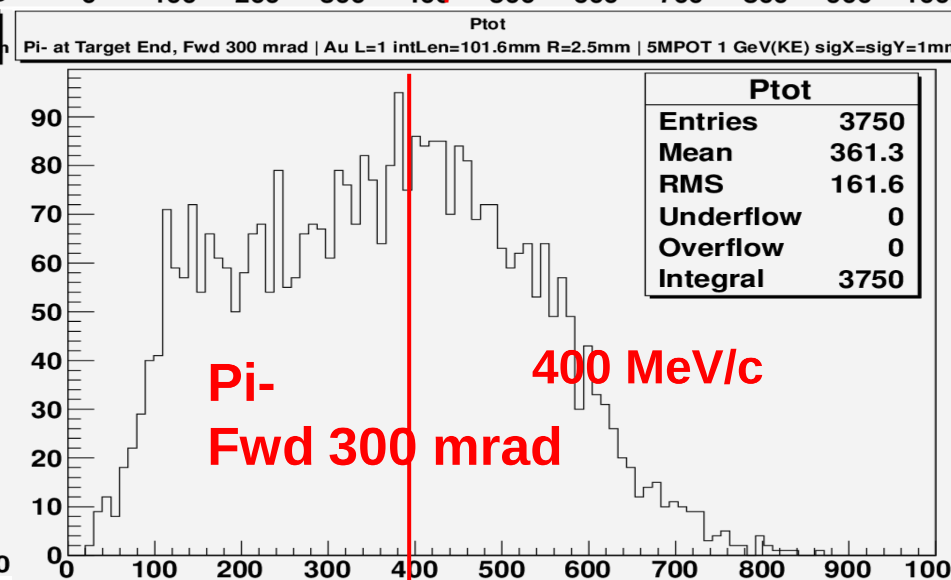


Yield per 5 MPOT on 1 λ_{int} of Au = 101.6mm

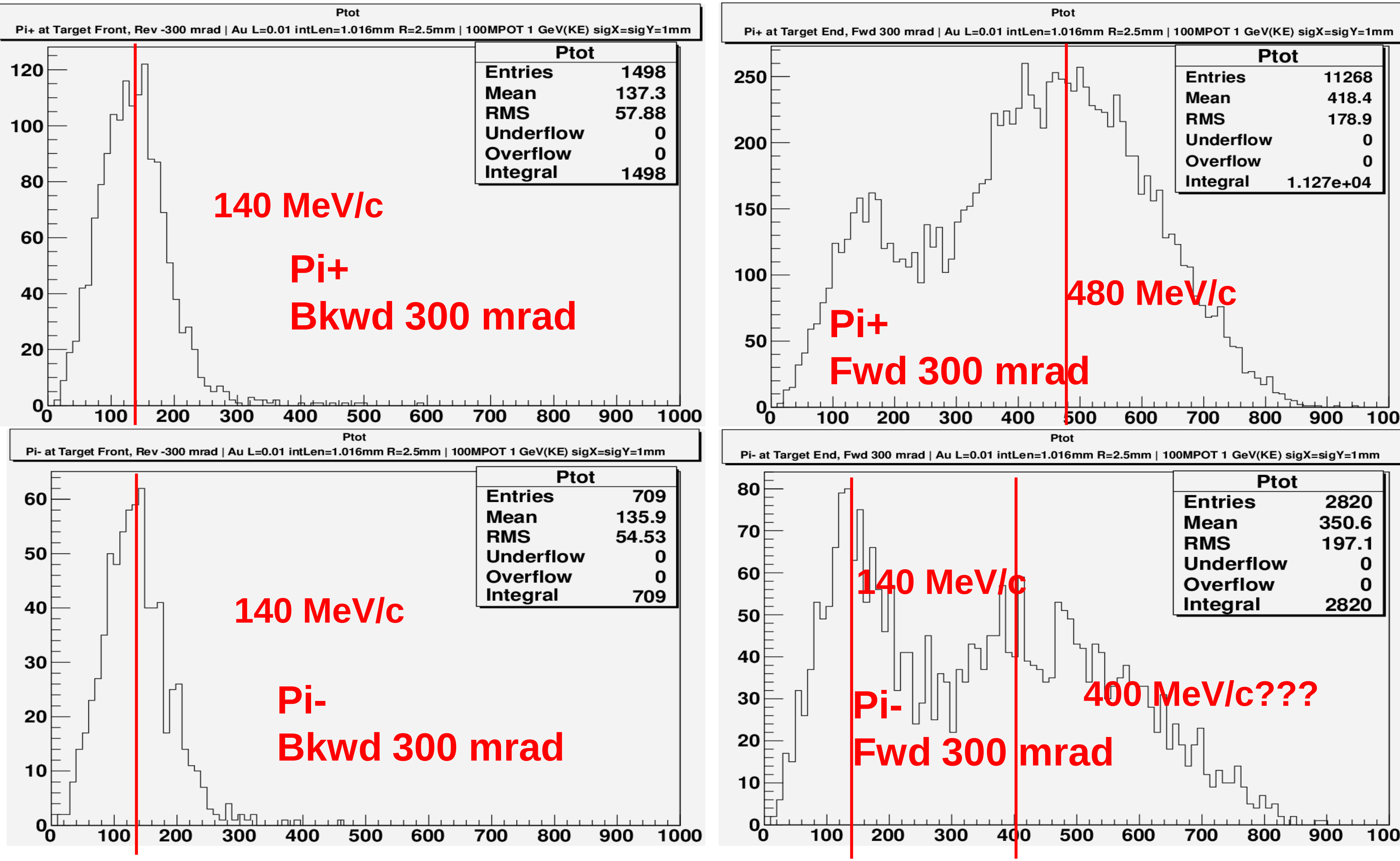




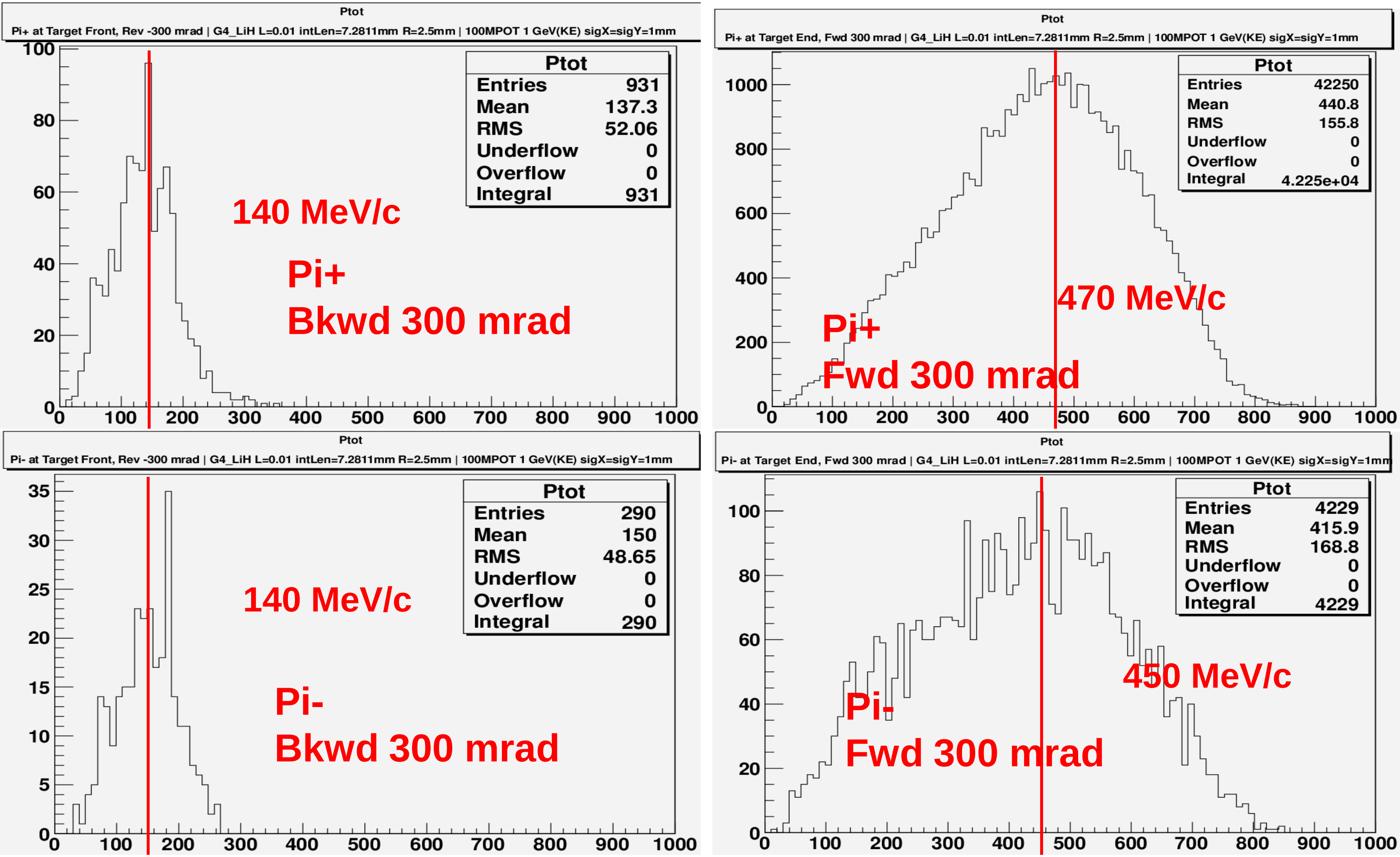




Yield per 100 MPOT on 0.01 λ_{int} of Au = 1.016mm



Yield per 100 MPOT on 0.01 λ_{int} of LiH = 7.2811 mm



Yields from IPAC12 (multiple beam energies)

PID	Dir	KE(p) (GeV)	ΔP (MeV/c)	$N_{particle}$ per Watt
π^-	bkwd	1	50-250	1.167×10^6
π^-	bkwd	3	50-250	1.949×10^6
π^-	bkwd	8	50-250	1.683×10^6
π^+	bkwd	1	50-250	2.75×10^6
π^+	bkwd	3	50-250	2.117×10^6
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π^-	fwd	3	450-650	7.214×10^6
π^-	fwd	8	500-700	1.016×10^7

Yields from 1 GeV Proton Beam

(first in each group is from the 1 GeV case in the IPAC12 table)

PID	Dir	Target Material	L_{target} (λ_{int})	ΔP (MeV/c)	$N_{particle}$/sec per Watt	$N_{particle}$/POT
π^-	fwd	Au	1.5	400-600	$2.726\text{x}10^6$	$4.368\text{x}10^{-4}$
π^-	fwd	Au	1.0	300-500	$1.946\text{x}10^6$	$3.118\text{x}10^{-4}$
π^-	fwd	Au	0.01	40-240	$6.416\text{x}10^4$	$1.028\text{x}10^{-5}$
π^-	fwd	Au	0.01	300-500	$5.299\text{x}10^4$	$8.490\text{x}10^{-6}$
π^-	fwd	LiH	0.01	350-550	$1.087\text{x}10^5$	$1.742\text{x}10^{-5}$
π^+	fwd	Au	1.5	400-600	$1.639\text{x}10^7$	$2.626\text{x}10^{-3}$
π^+	fwd	Au	1.0	325-525	$1.946\text{x}10^6$	$3.118\text{x}10^{-4}$
π^+	fwd	Au	0.01	380-580	$2.928\text{x}10^5$	$4.691\text{x}10^{-5}$
π^+	fwd	LiH	0.01	370-570	$1.201\text{x}10^6$	$1.924\text{x}10^{-4}$
π^-	bkwd	Au	1.5	50-250	$1.167\text{x}10^6$	$1.870\text{x}10^{-4}$
π^-	bkwd	Au	1.0	40-240	$8.726\text{x}10^5$	$1.398\text{x}10^{-4}$
π^-	bkwd	Au	0.01	40-240	$4.213\text{x}10^4$	$6.750\text{x}10^{-6}$
π^-	bkwd	LiH	0.01	40-240	$1.434\text{x}10^5$	$2.298\text{x}10^{-5}$
π^+	bkwd	Au	1.5	50-250	$2.750\text{x}10^6$	$4.406\text{x}10^{-4}$
π^+	bkwd	Au	1.0	40-240	$2.026\text{x}10^6$	$3.246\text{x}10^{-4}$
π^+	bkwd	Au	0.01	40-240	$8.819\text{x}10^4$	$1.413\text{x}10^{-5}$
π^+	bkwd	LiH	0.01	40-240	$7.223\text{x}10^5$	$1.157\text{x}10^{-4}$

Summary

- Two promising system concepts have been presented.
- If it works, the N-Ring CircUS has the potential to deliver what the greediest experimenters want: high flux together with excellent beam quality.
- Both the Dipole + Wedge and the N-Ring CircUS lead naturally to multiple beams from a single target station.
- The $N\pi$/Ep*Np ratios for both systems are comparable to the $N\mu$/Ep*Np of Mu2e. The N-Ring CircUS is ~ 4 times better in that regard.
- 3 GeV is significantly better than 1 GeV for negative pion production.
- It's early. There's lots of work to do. Join us!