Muon Cooling Experiments

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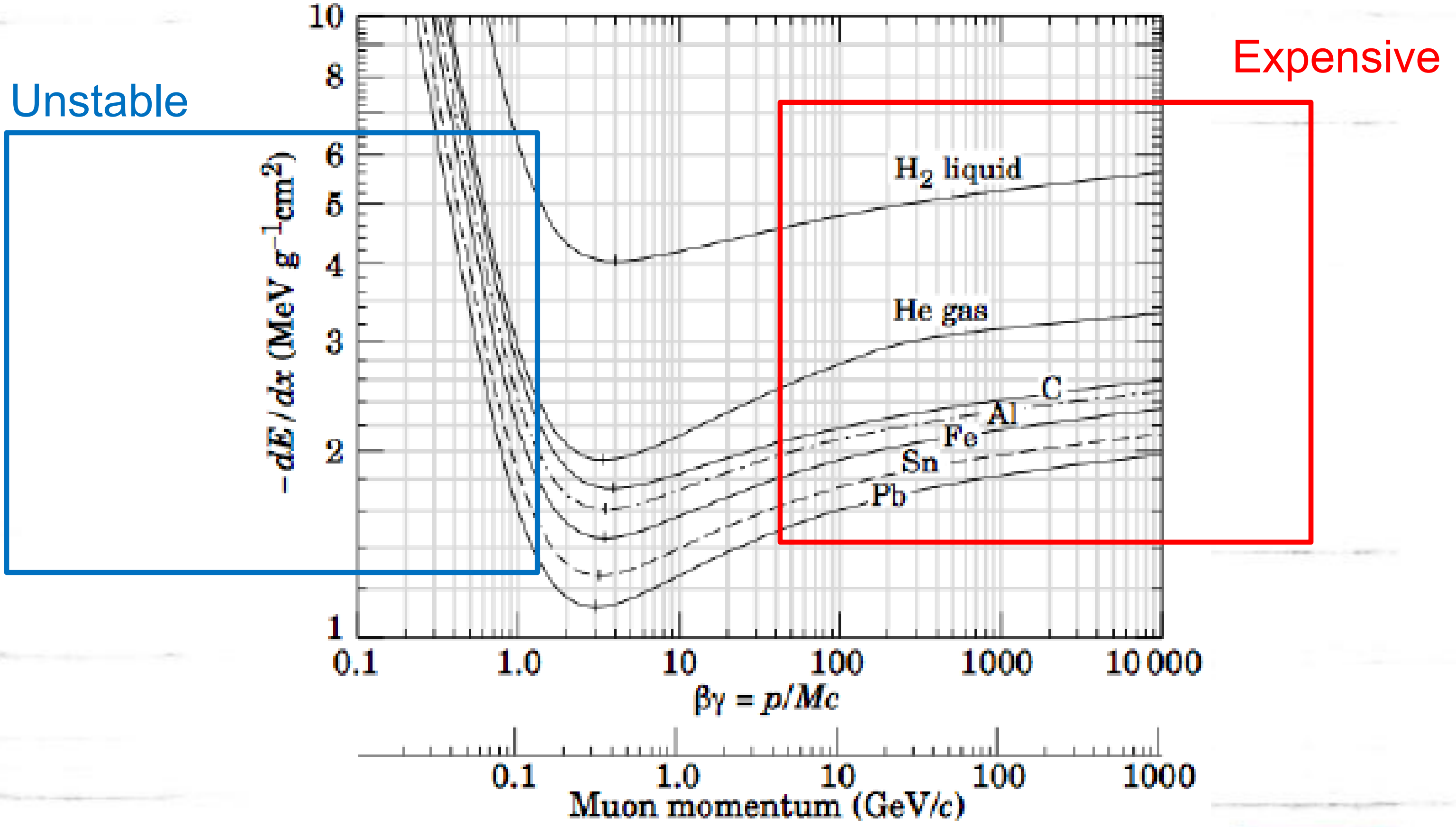
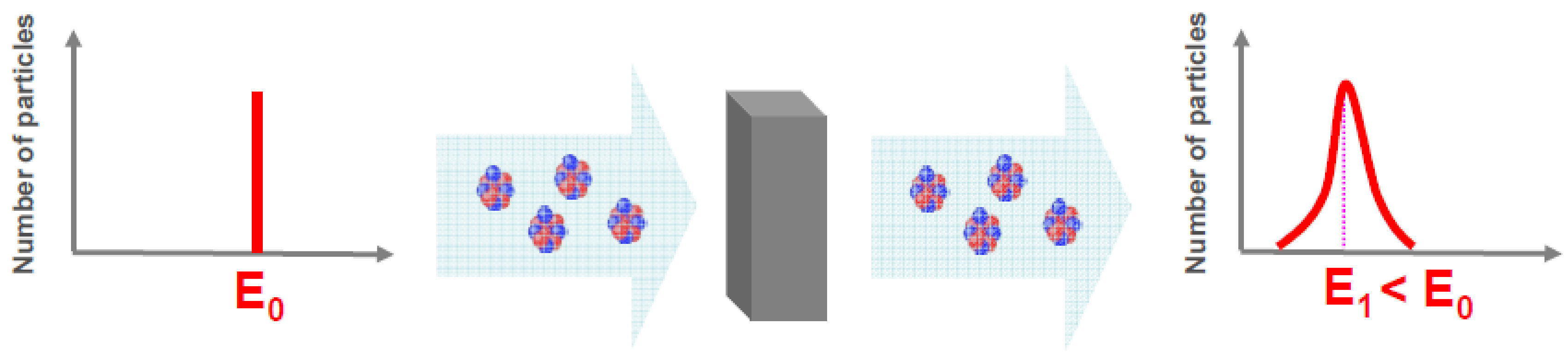
Muon Collider Accelerator School, U Chicago
August 06, 2025

Ionization (the good)

- Momentum of muons is reduced as they ionize atomic electrons in the material

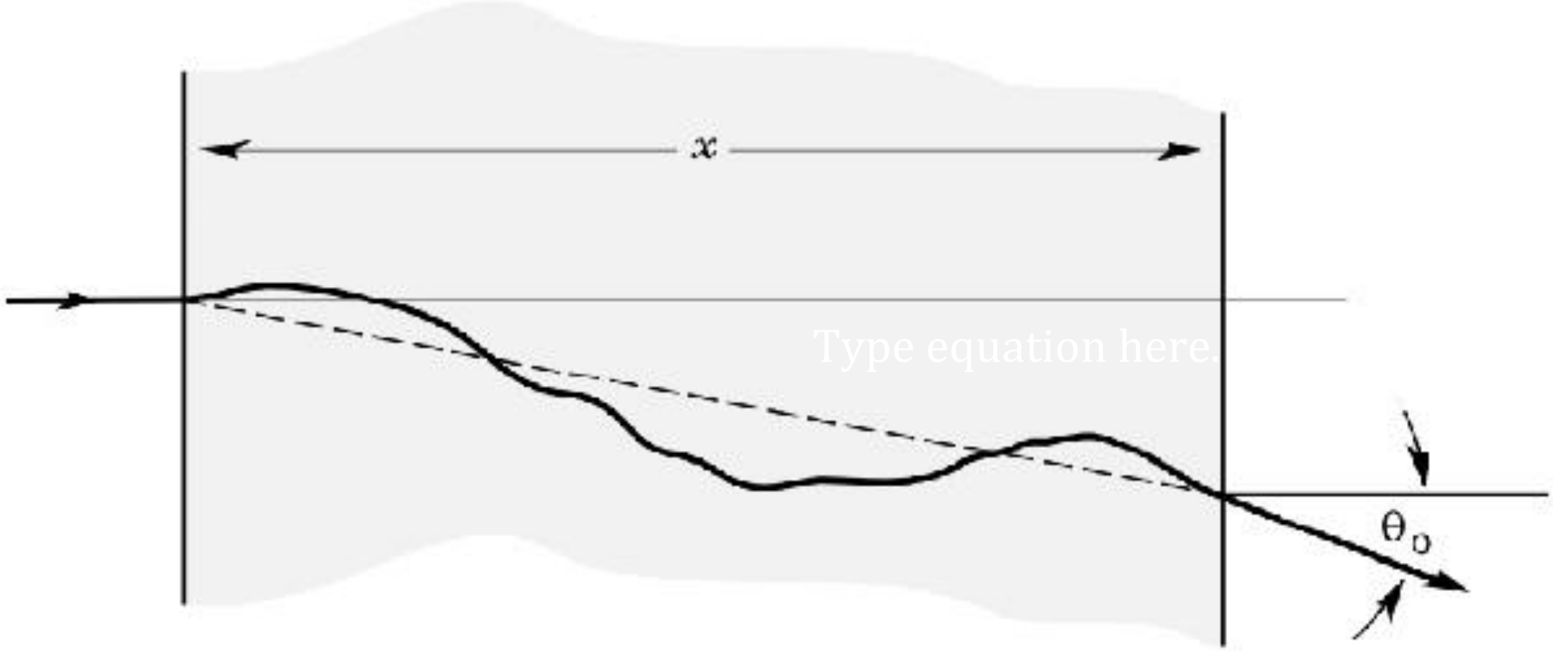


Energy straggling (the bad)



- Due to the statistical nature of ionization energy loss, large fluctuations can occur in the amount of energy deposited by a particle traversing an absorber.

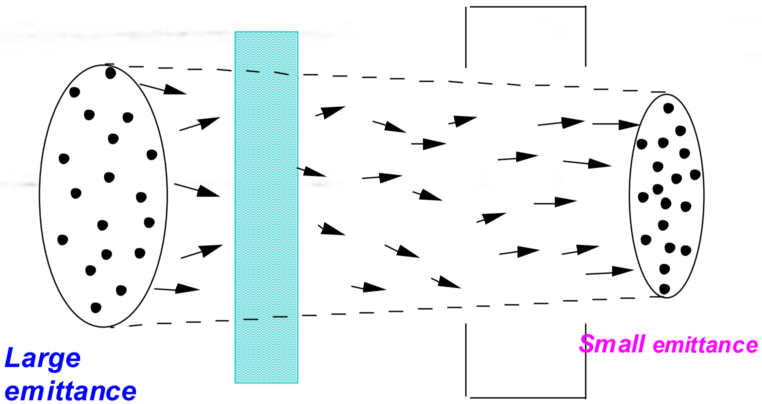
Multiple scattering (the bad)



- The angle has a roughly Gaussian distribution of width θ_0:

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{L_R}}\left[1 + 0.038\ln\left(\frac{x}{L_R}\right)\right]$$

Ionization cooling formalism (1)

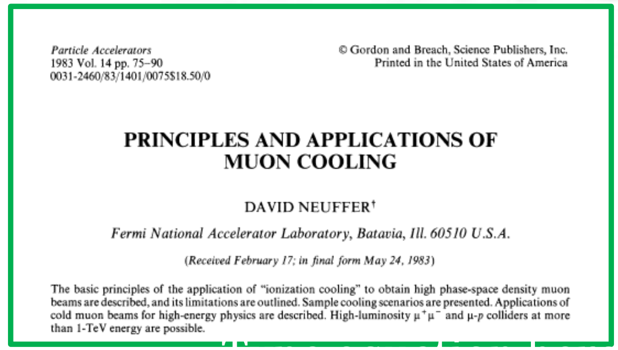


Absorber

Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Accelerator

Momentum gain is purely longitudinal


Particle Accelerators
1983 Vol. 14 pp. 75–90
0031-2460/83/1401/0075$18.50/0

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PRINCIPLES AND APPLICATIONS OF MUON COOLING

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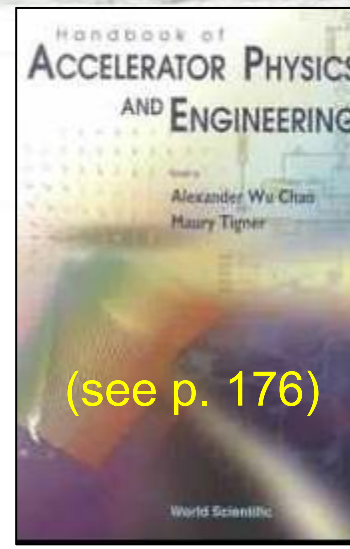
(*Received February 17; in final form May 24, 1983*)

The basic principles of the application of "ionization cooling" to obtain high phase-space density muon beams are described, and its limitations are outlined. Sample cooling scenarios are presented. Applications of cold muon beams for high-energy physics are described. High-luminosity $\mu^+\mu^-$ and μ-p colliders at more than 1-TeV energy are possible.



(see p. 176)

We like this

We like to AVOID this

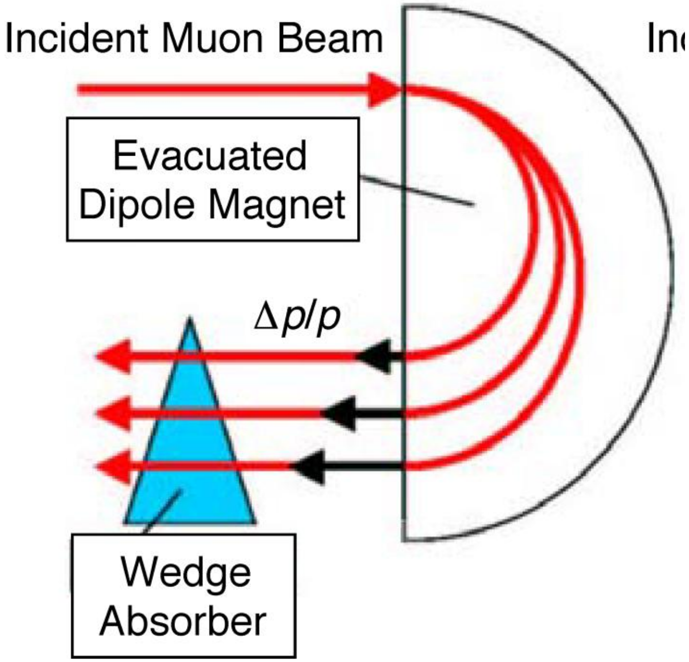
$$\frac{d\varepsilon_T}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_T + \frac{\beta\gamma\beta_T}{2}\frac{d\theta_0^2}{ds}$$

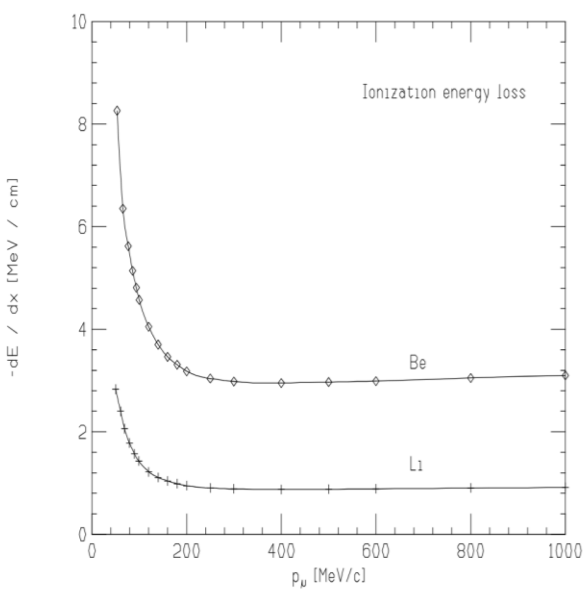
Ionization cooling formalism (2)

$$\frac{d\sigma_E^2}{ds} = -2\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E}\sigma_E^2 + \frac{d < \Delta E_{rms}^2 >}{ds}$$

We like this

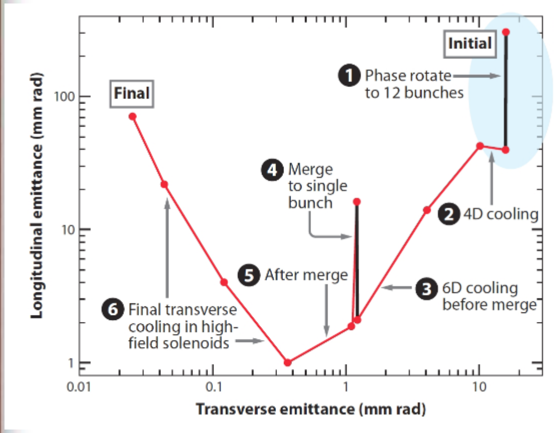
We like to AVOID this

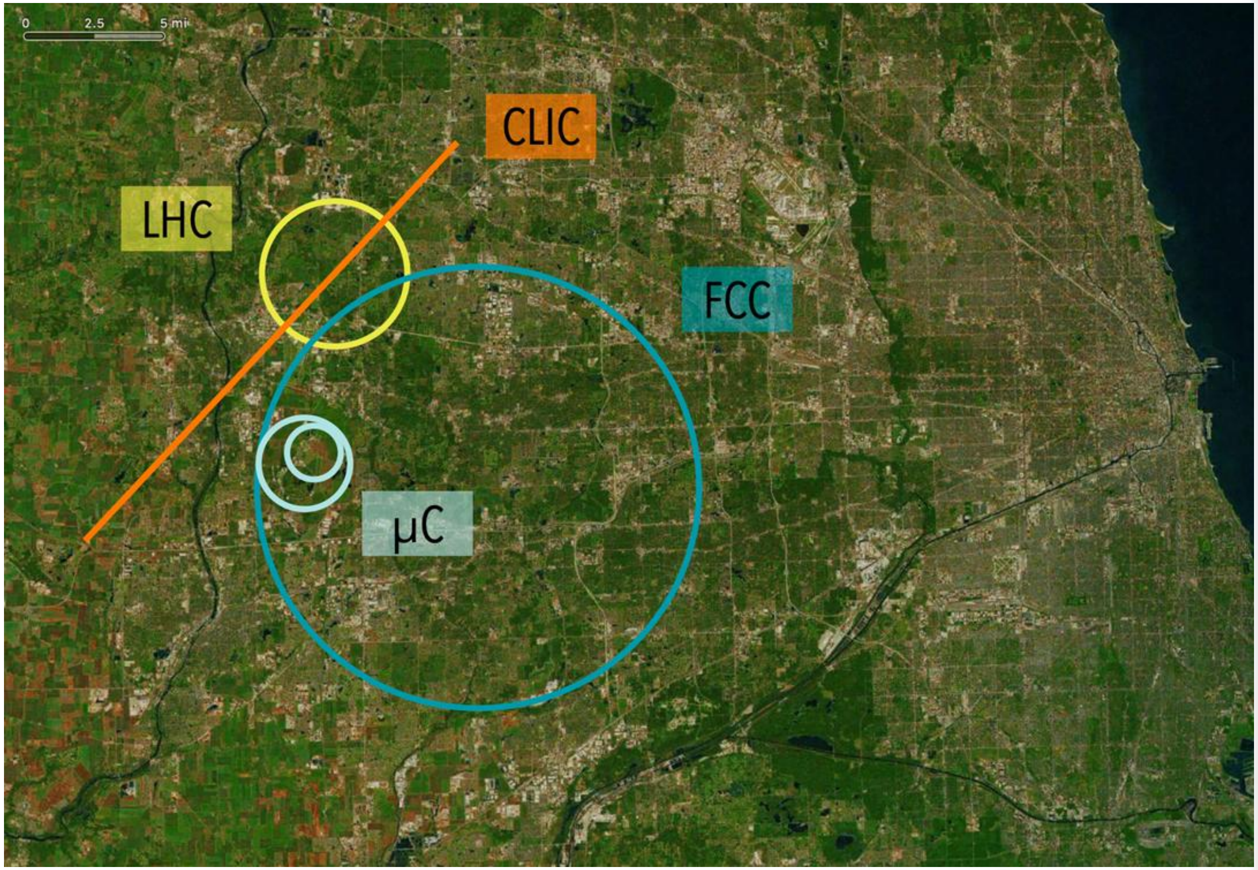




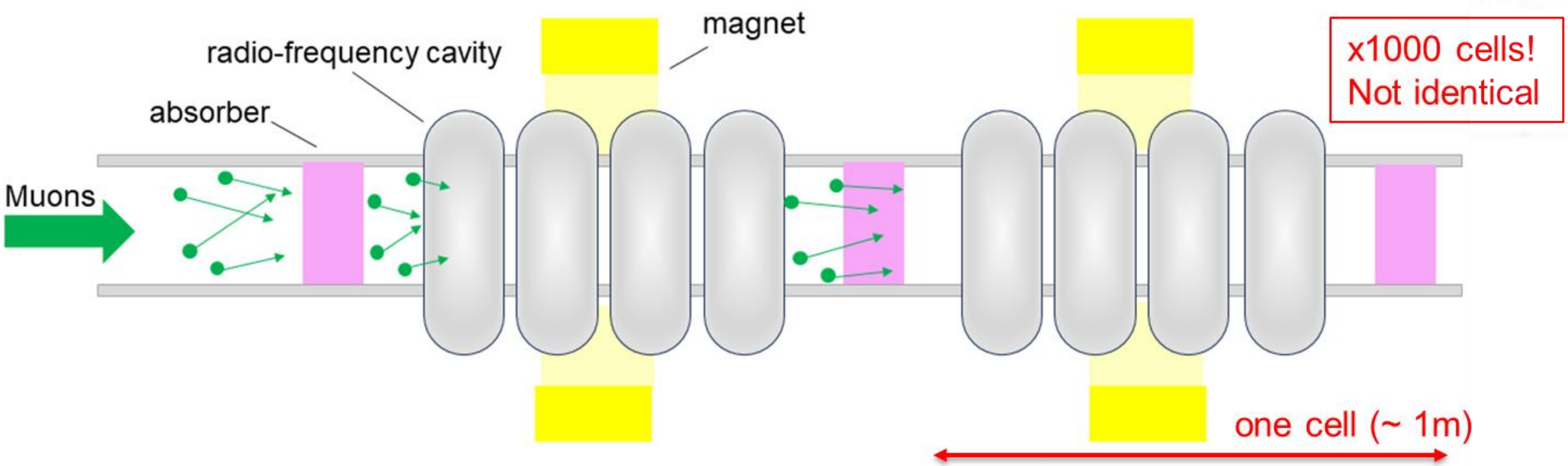
Ionization cooling application

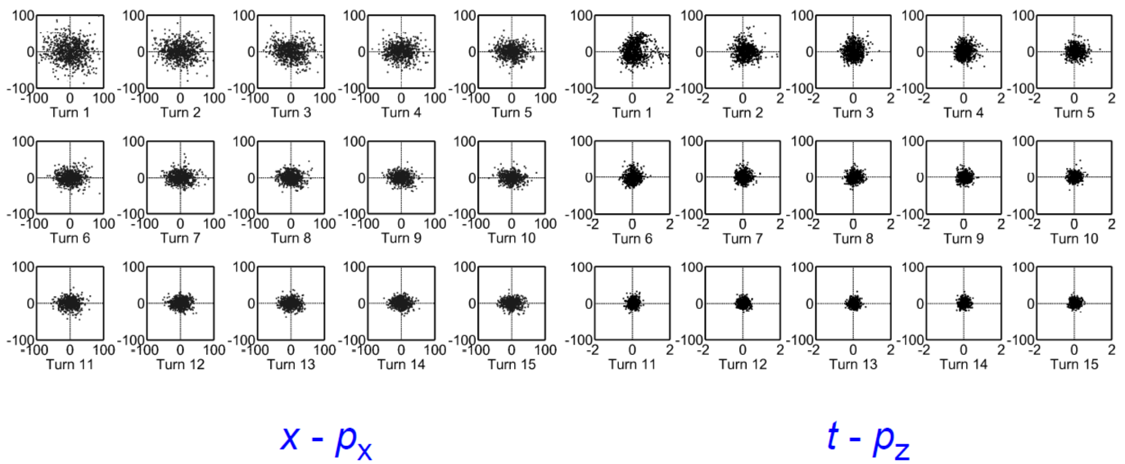
Requirement:
Reduce 6D emittance
by 5-6 orders
of magnitude





MuC ionization cooling channel



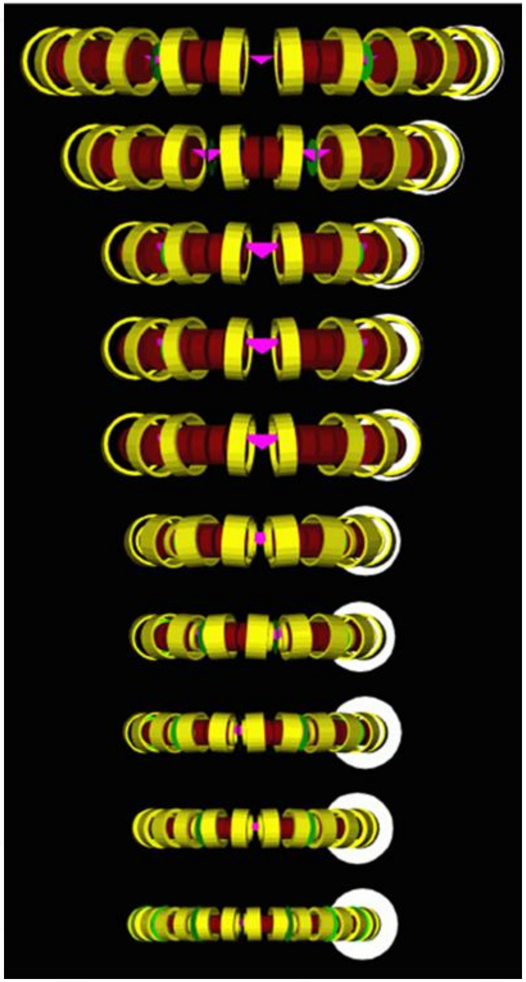


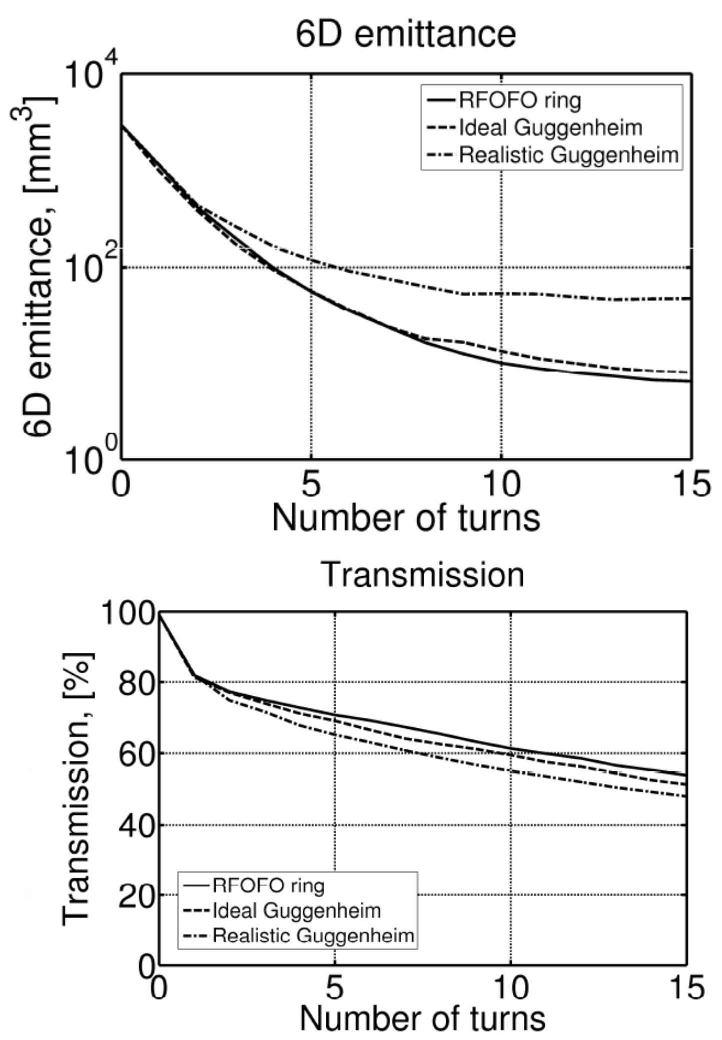
First candidate – Rings

Coils

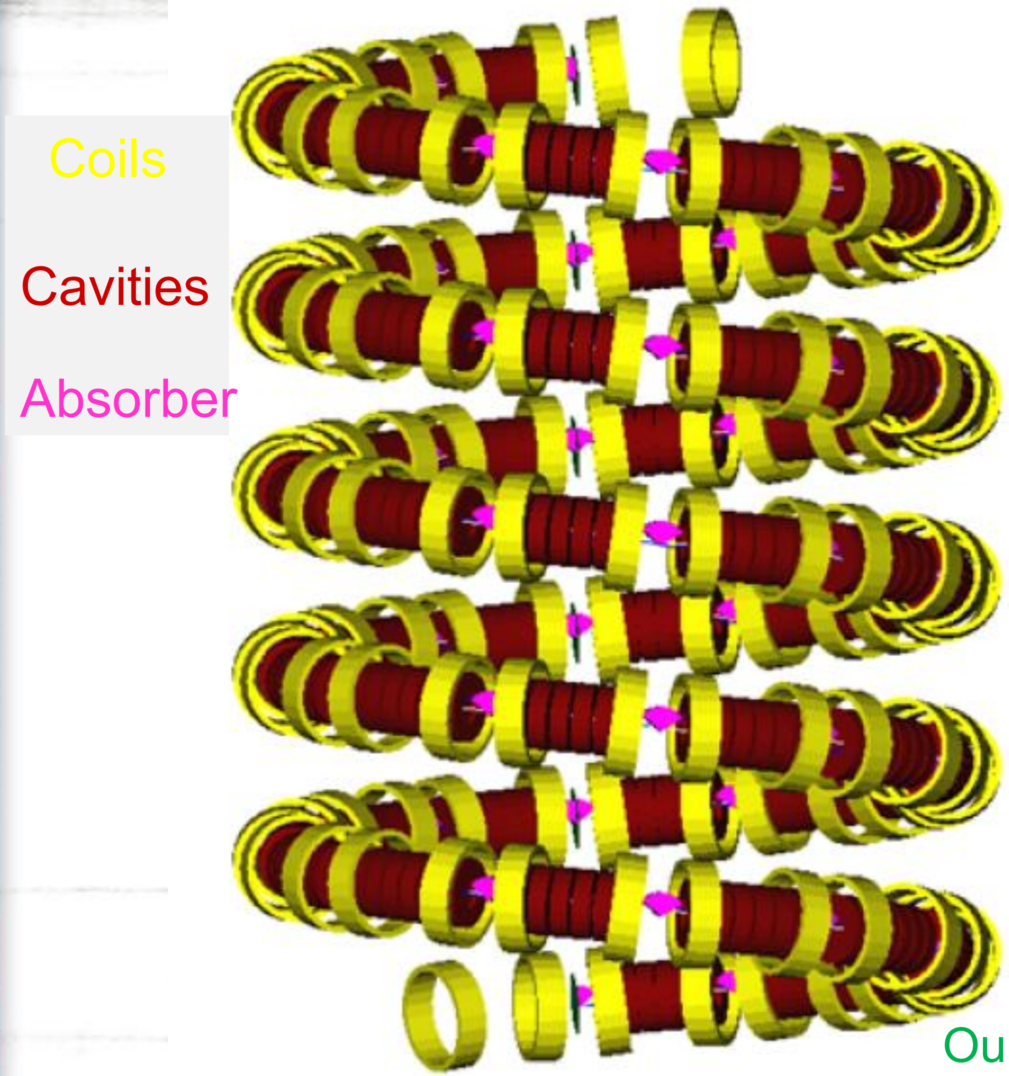
Cavities

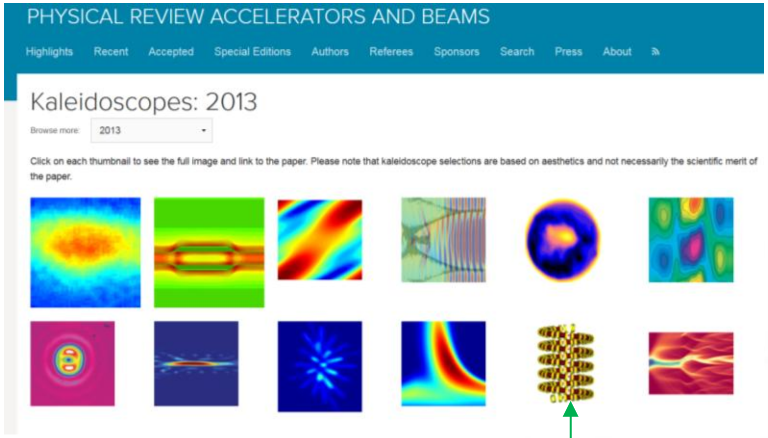
Absorber





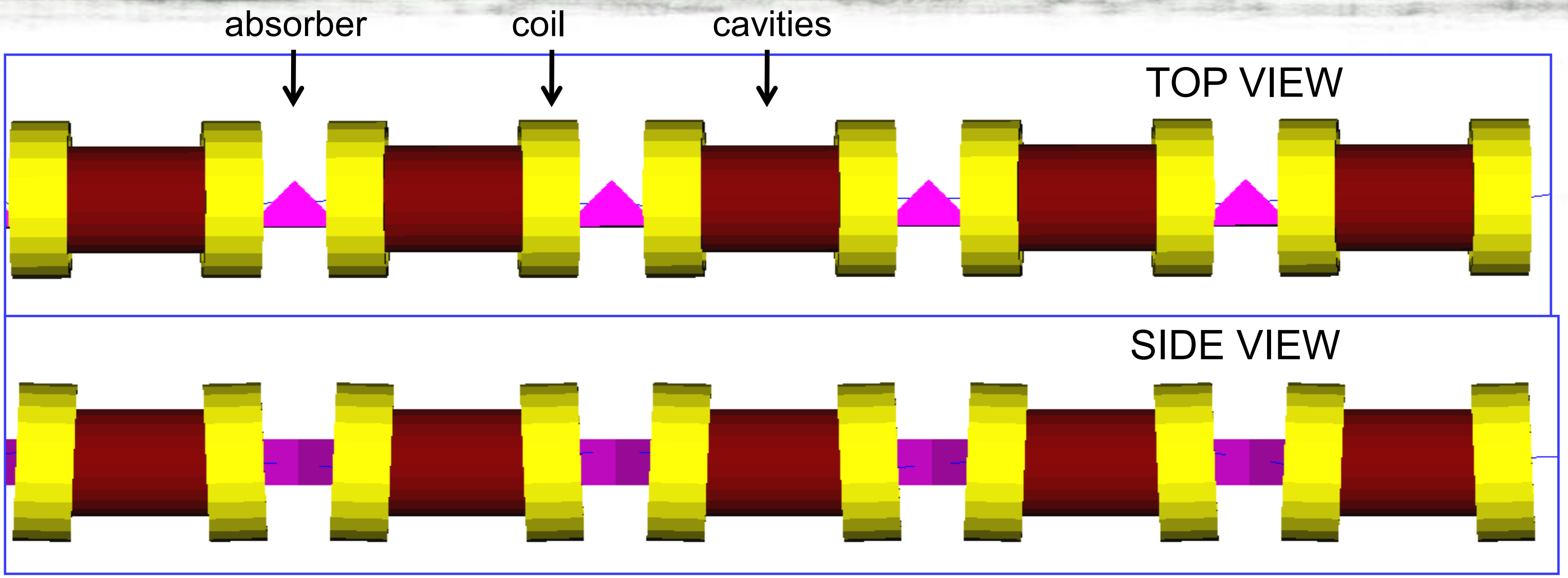
Second candidate – The Guggenheim





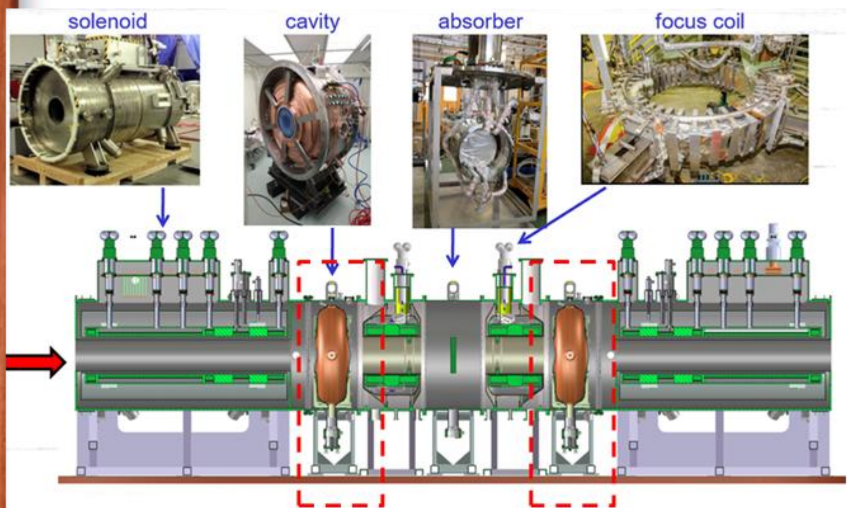
Our figure was selected for kaleidoscope

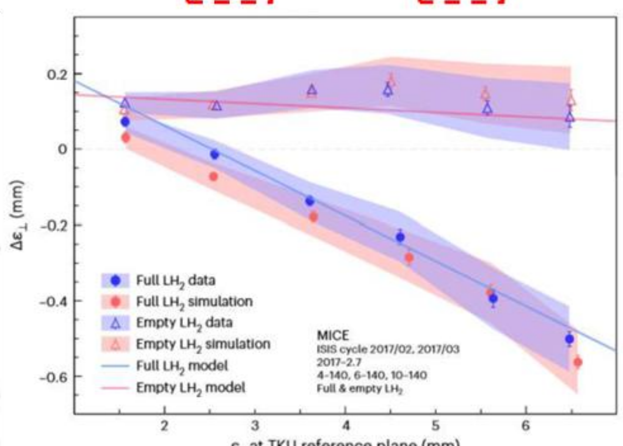
Current baseline for a MuC



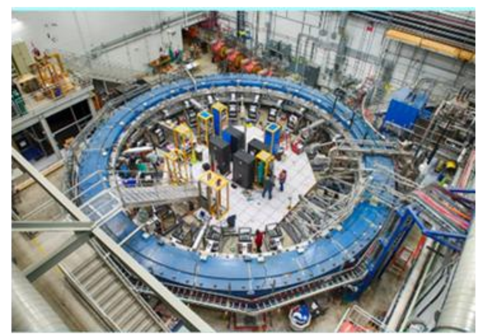
Cooling Demonstration

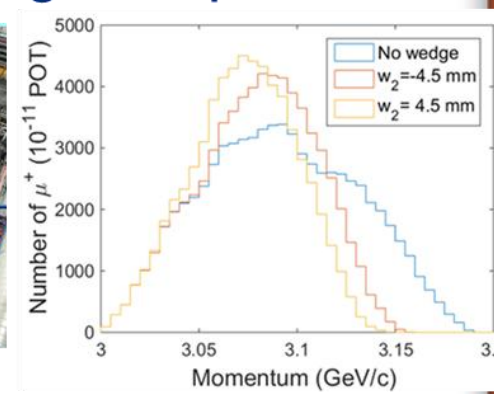
MICE Experiment

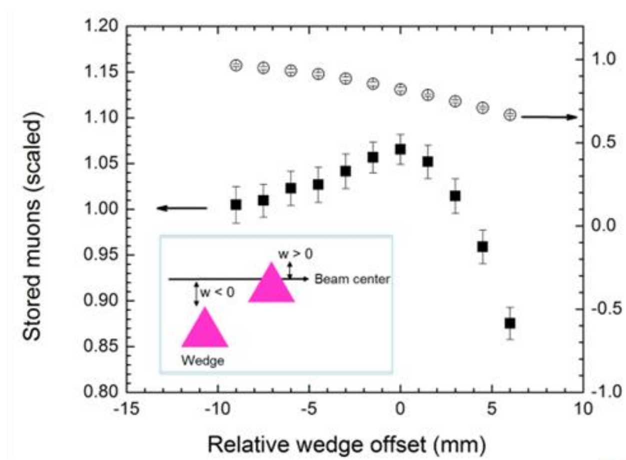


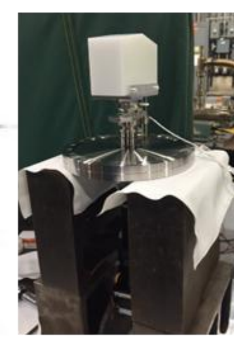


Fermilab Muon g-2 Experiment

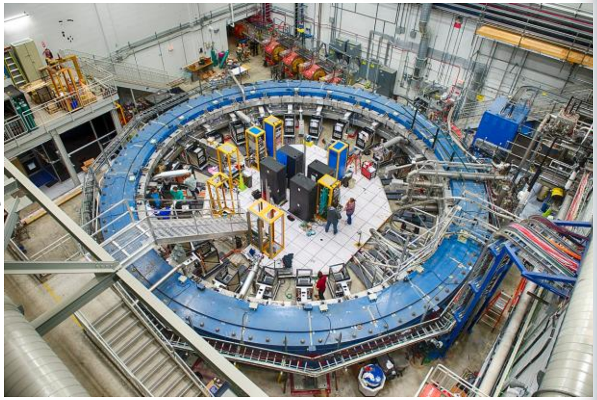






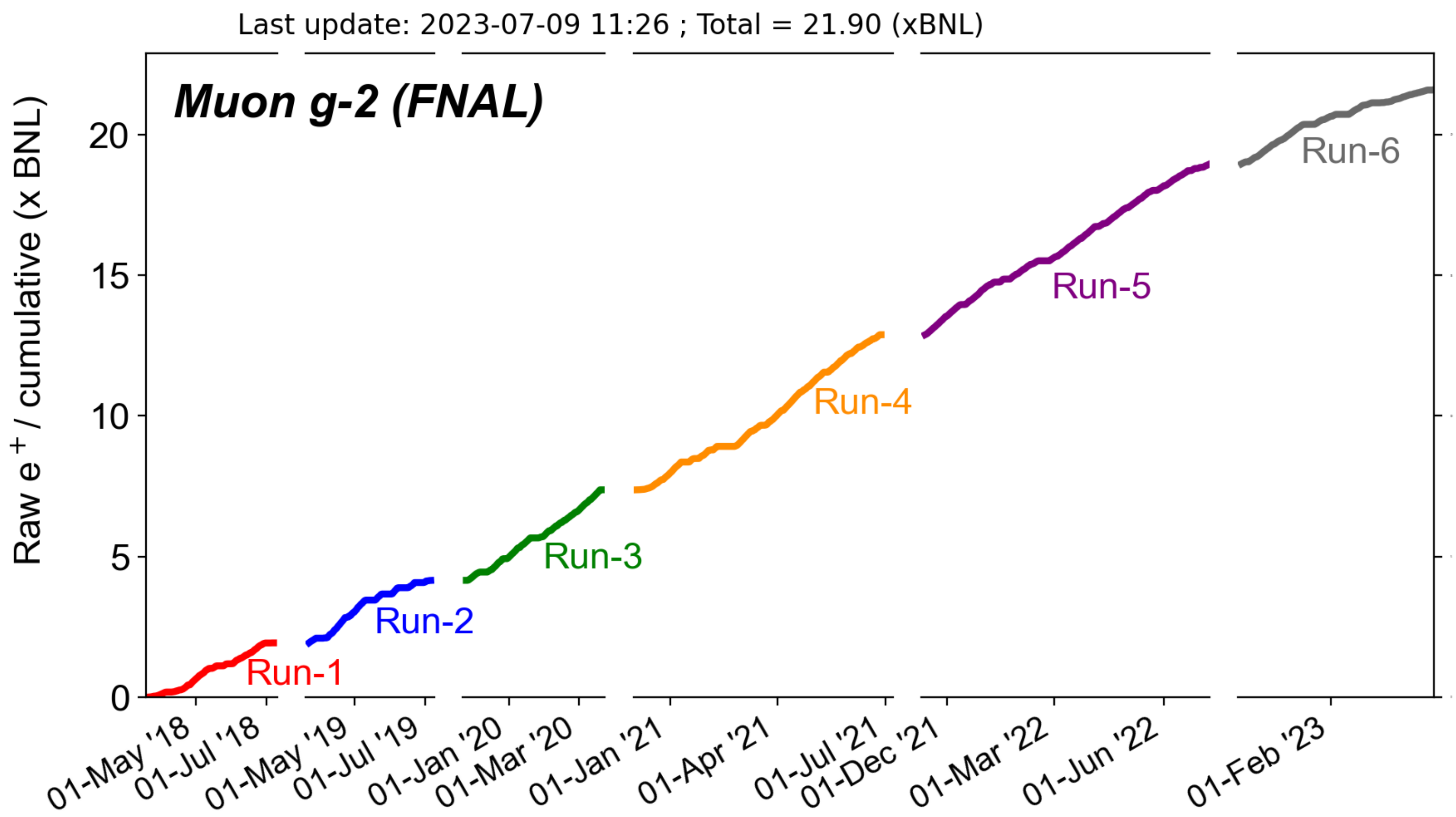


Fermilab Muon g-2 Experiment



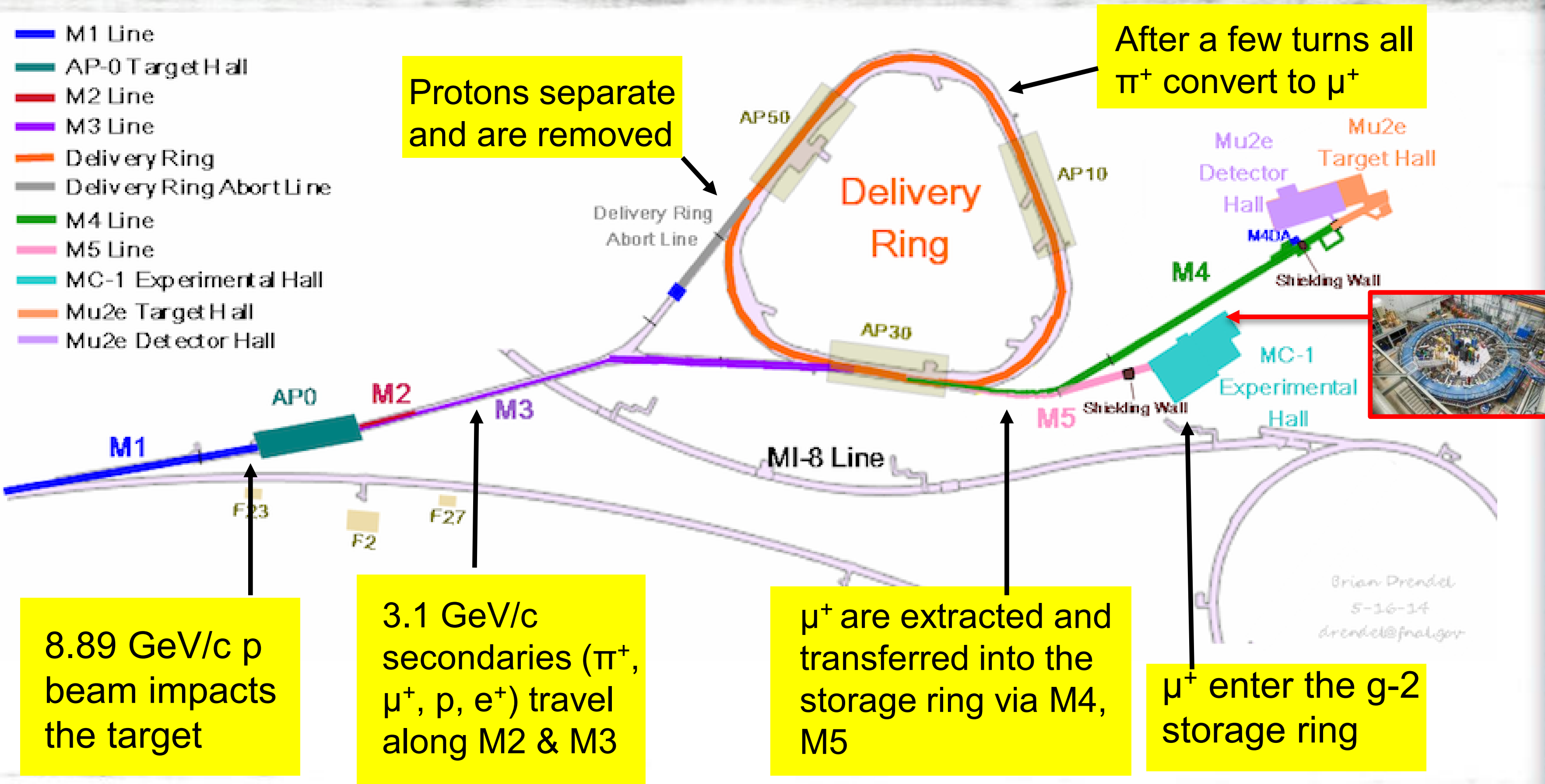
- Goal
  - Measure the muon anomalous magnetic moment (g-2) with 0.14 ppm uncertainty - a fourfold improvement of the BNL measurement (0.54 ppm)
- Approach
  - Circulate polarized muons in a uniform magnetic field and measure the precession frequency
  - 3.1 GeV/c muons to simplify Thomas-BMT equation: $\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$ (→ 0)
- Requirement
  - Requires delivery of $1.4\text{x}10^{14}$ muons in the ring which is x20 the statistics of the BNL experiment

Progress



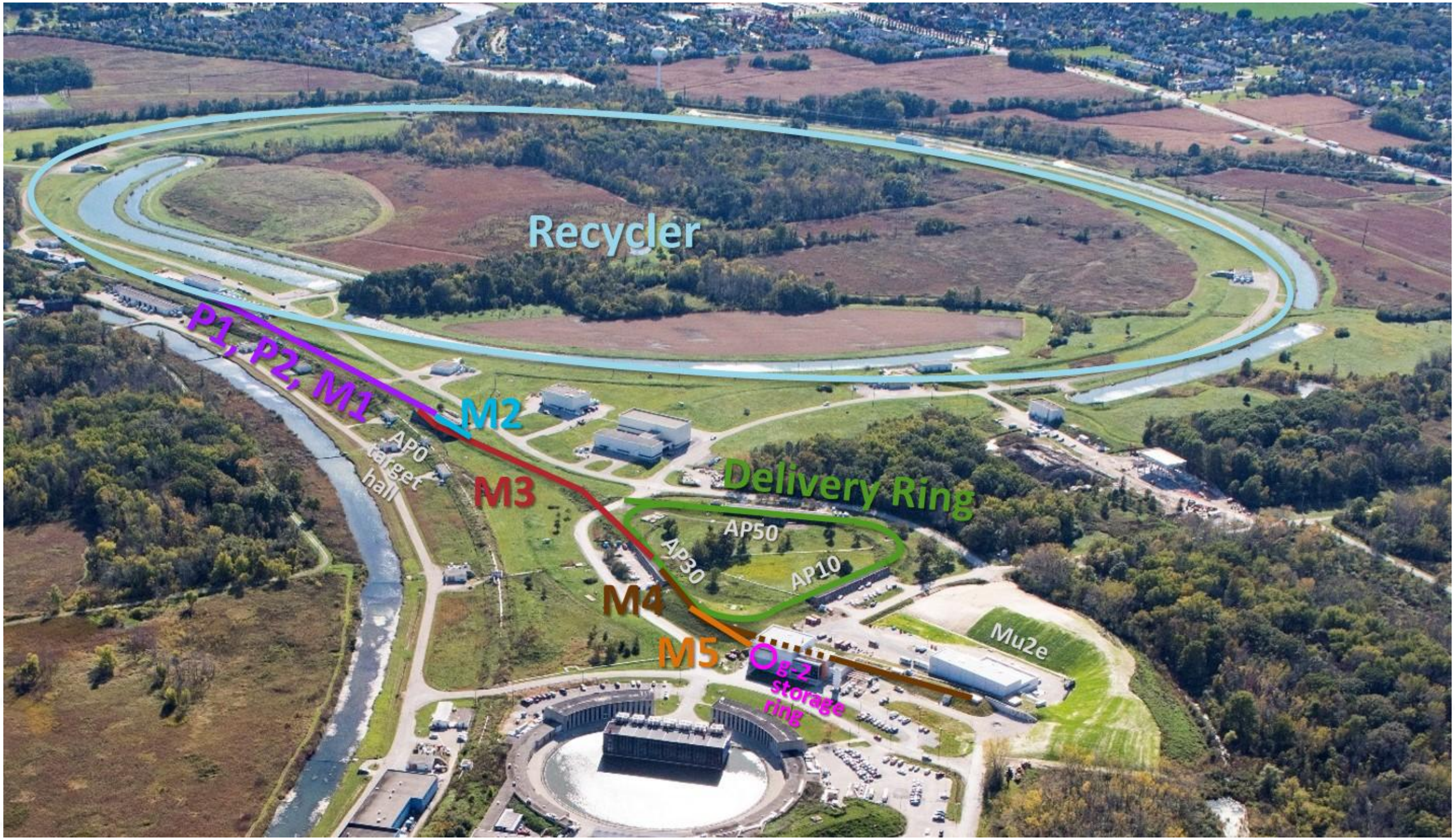
Last update: 2023-07-09 11:26 ; Total = 21.90 (xBNL)
Muon g-2 (FNAL)
Raw e + / cumulative (x BNL)
0
5
10
15
20
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Apr '21
01-Jul '21
01-Dec '21
01-Mar '22
01-Jun '22
01-Feb '23

Muon Campus

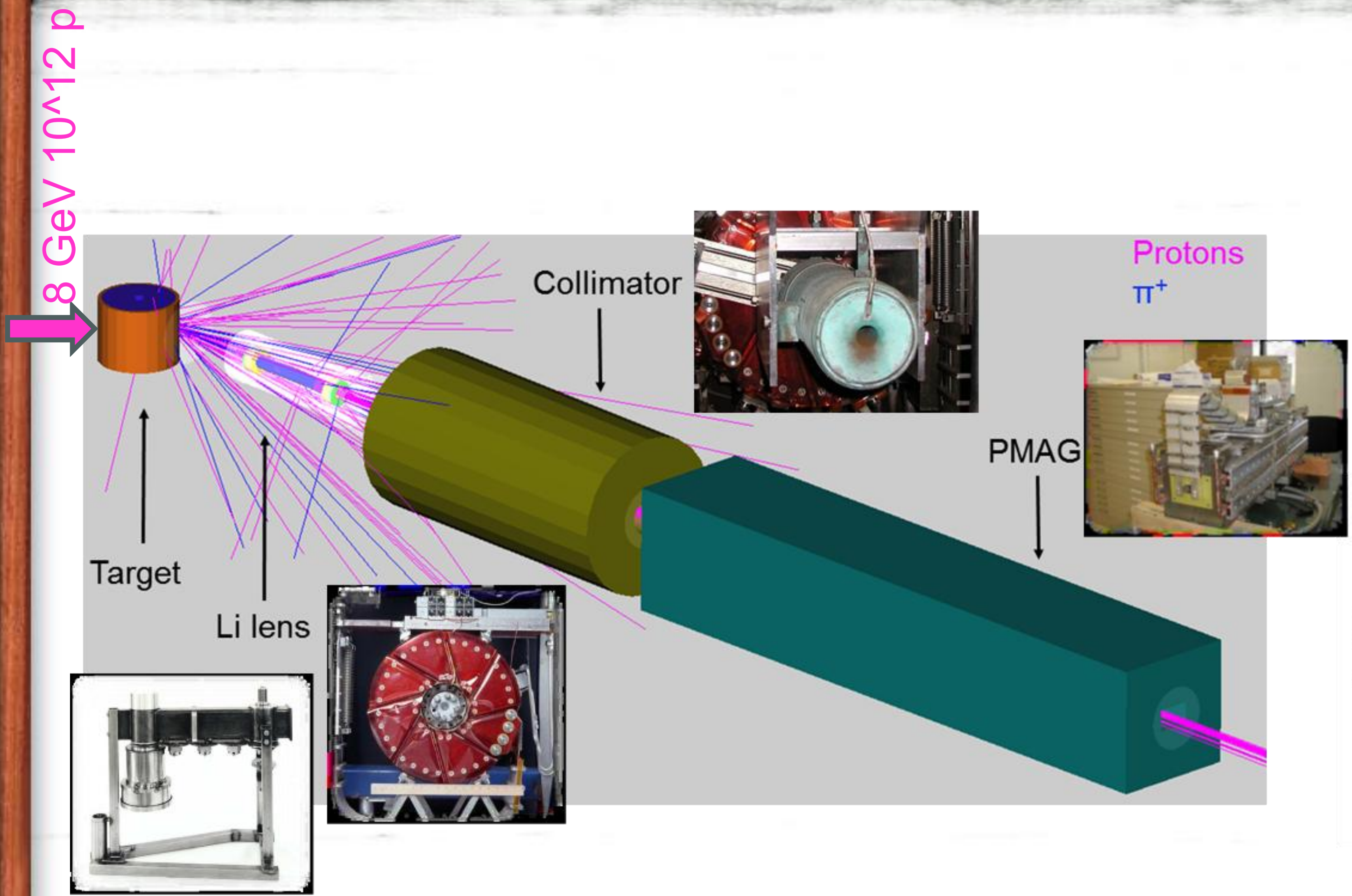


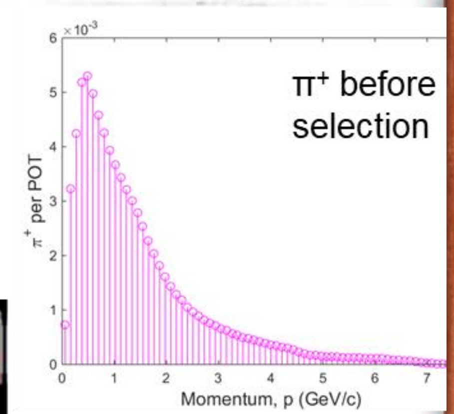
M1 Line
AP-0 Target Hall
M2 Line
M3 Line
Delivery Ring
Delivery Ring Abort Line
M4 Line
M5 Line
MC-1 Experimental Hall
Mu2e Target Hall
Mu2e Detector Hall
Protons separate and are removed
After a few turns all π+ convert to μ+
AP50
AP10
AP30
Delivery Ring
Delivery Ring Abort Line
Mu2e Detector Hall
Mu2e Target Hall
M4DA
M4
Shielding Wall
MC-1 Experimental Hall
Shielding Wall
M5
MI-8 Line
AP0
M2
M3
M1
F23
F2
F27
Brian Drendel
5-16-14
drendel@fnal.gov
8.89 GeV/c p beam impacts the target
3.1 GeV/c secondaries (π+, μ+, p, e+) travel along M2 & M3
μ+ are extracted and transferred into the storage ring via M4, M5
μ+ enter the g-2 storage ring

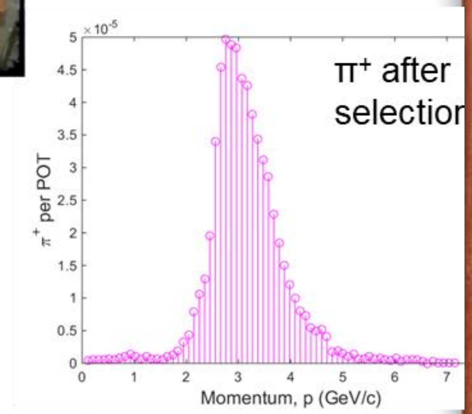
Muon Campus


Recycler
P1, P2, M1
M2
AP0 target hall
M3
Delivery Ring
AP50
AP30
AP10
M4
M5
g-2 storage ring
Mu2e

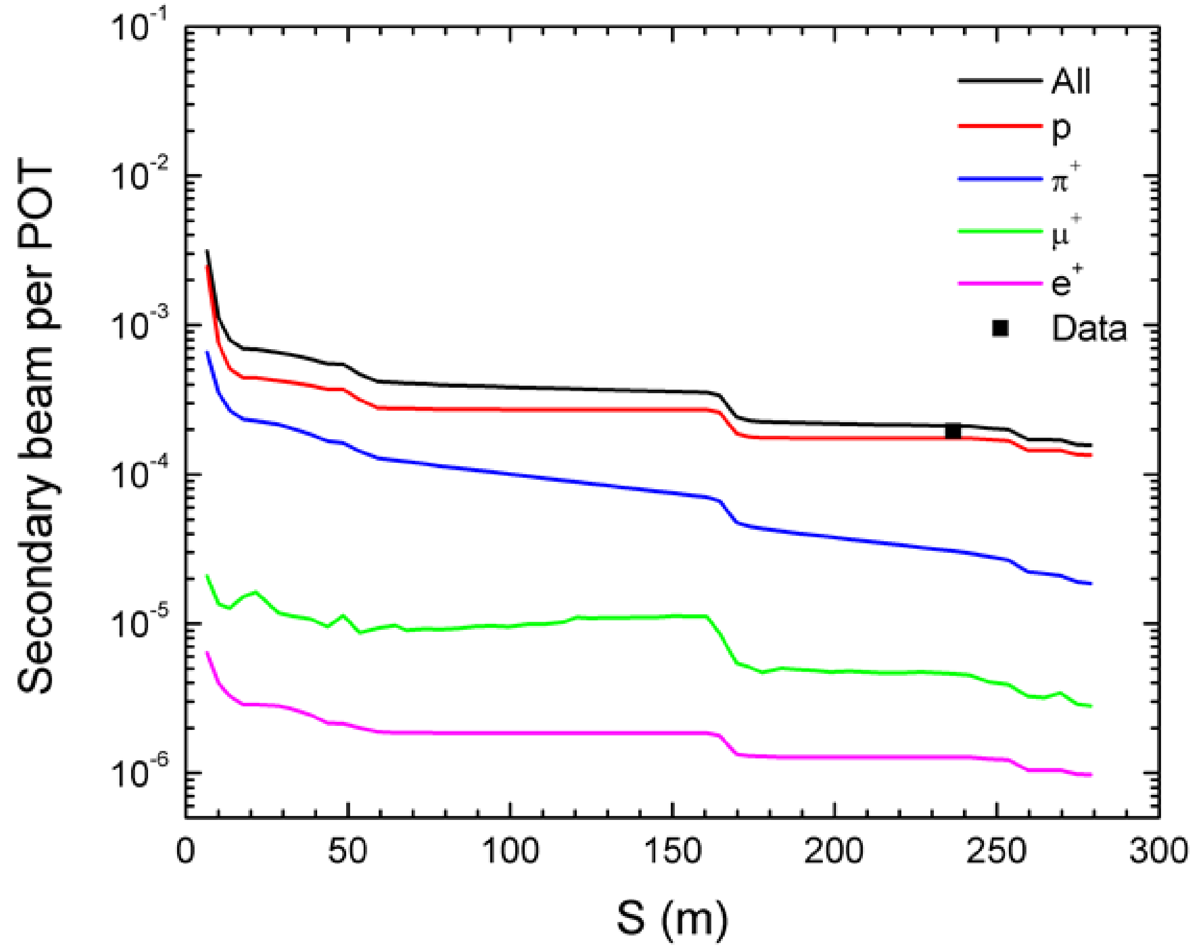
Production


8 GeV 10^12 p
Collimator
Protons
π^+
PMAG
Target
Li lens


π^+ before selection
π^+ per POT
$\times 10^{-3}$
Momentum, p (GeV/c)


π^+ after selection
π^+ per POT
$\times 10^{-5}$
Momentum, p (GeV/c)

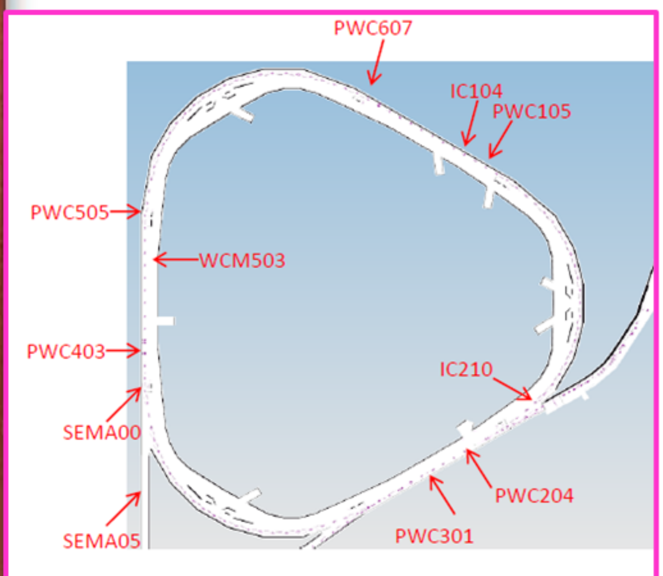
Transport

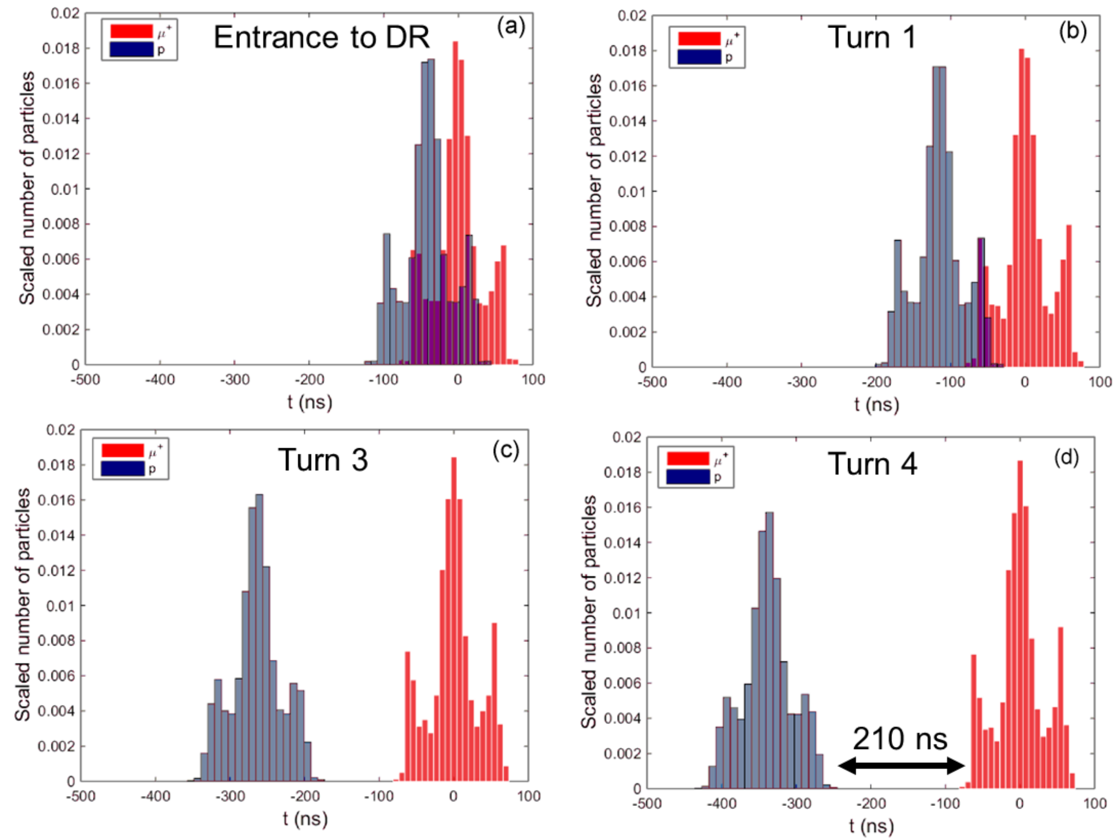


Bunch separation

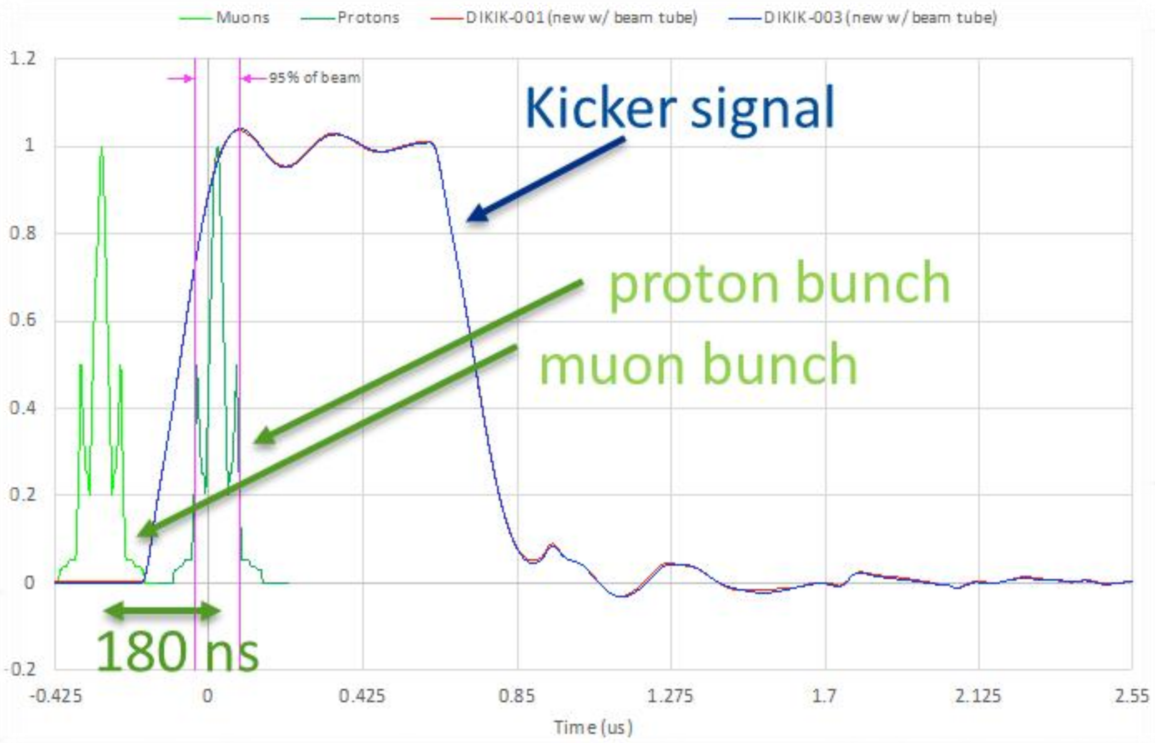
- Revolution times for 3.1 GeV/c beam:

$\mu^+, \beta = 0.999,\ T = 1685.5$ ns $e^+, \beta = 0.999,\ T = 1684.5$ ns $p,\ \beta = 0.957,\ T = 1760.2$ ns

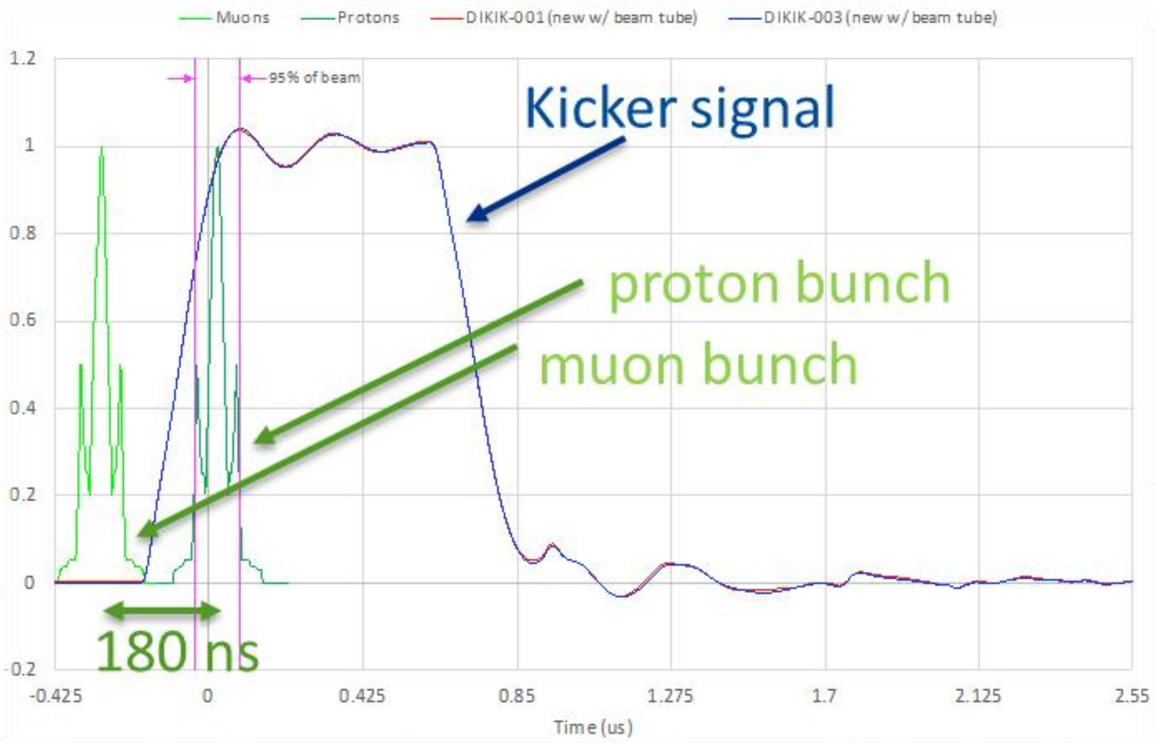




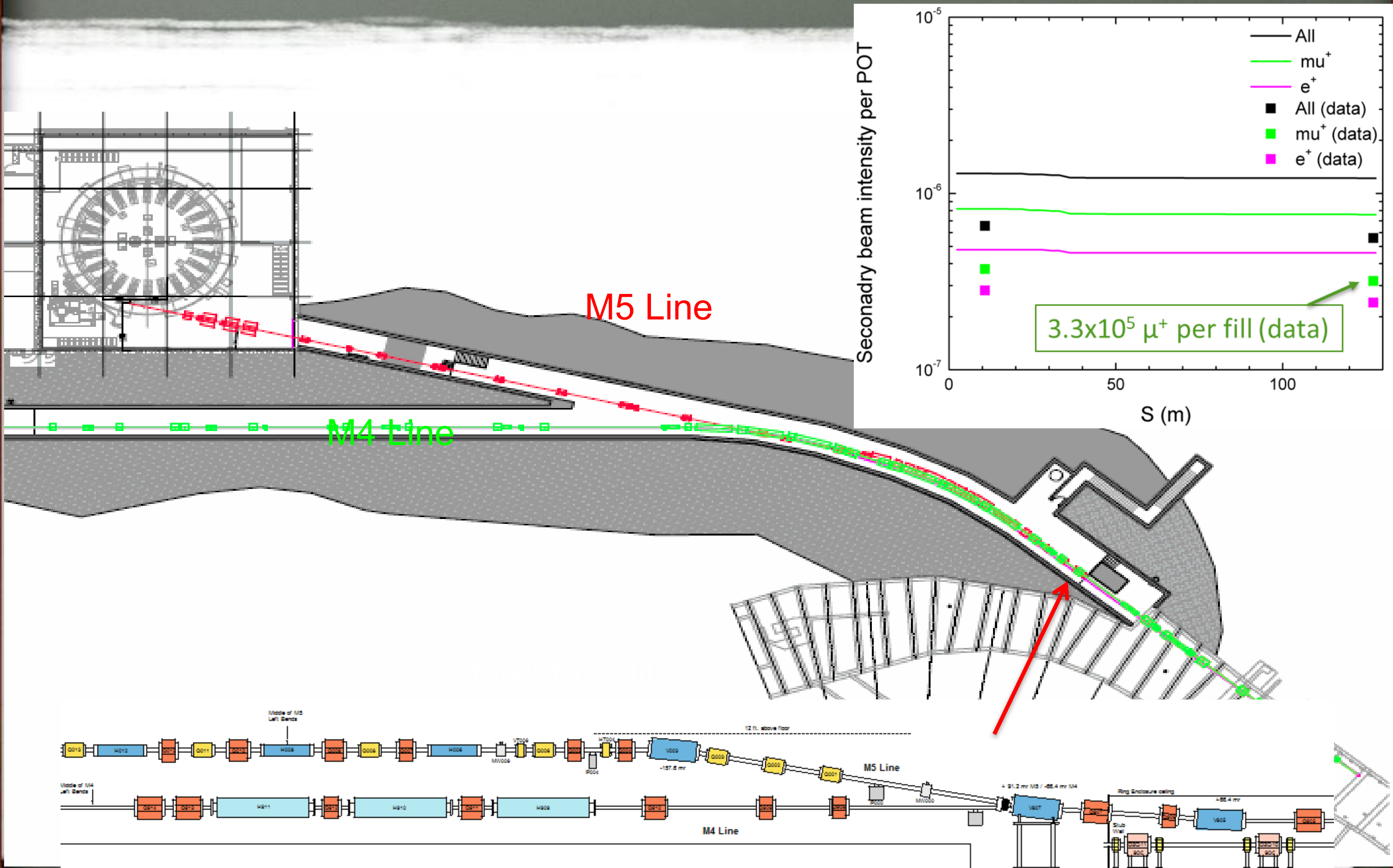
Proton removal



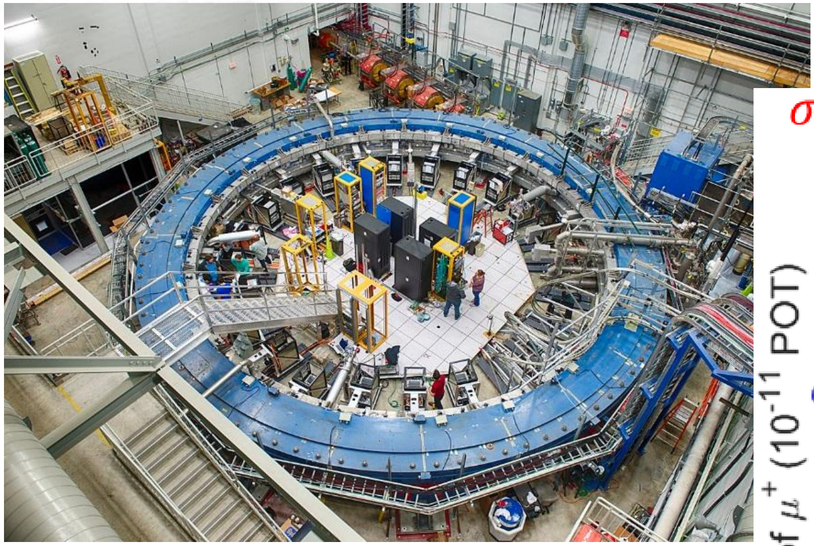
Proton removal

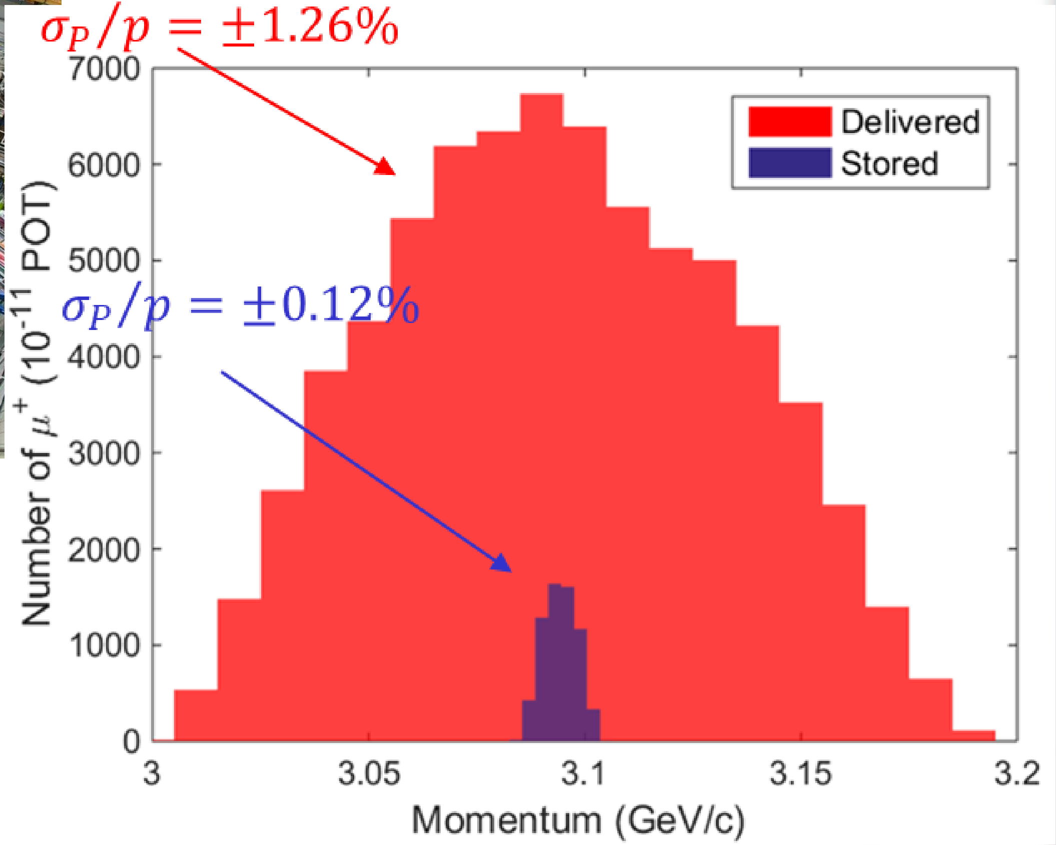


M4-M5 lines separation (top view)



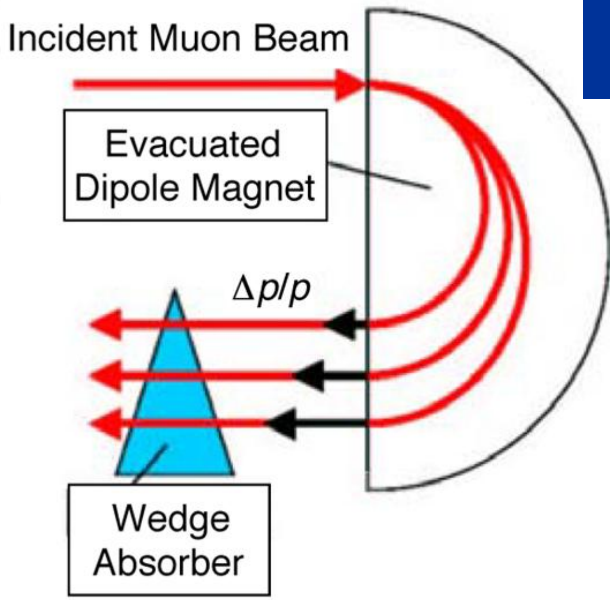
A small problem…

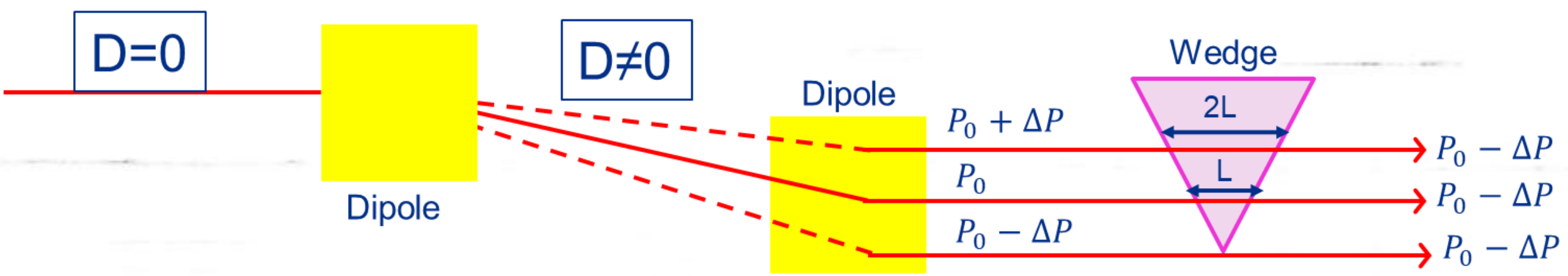




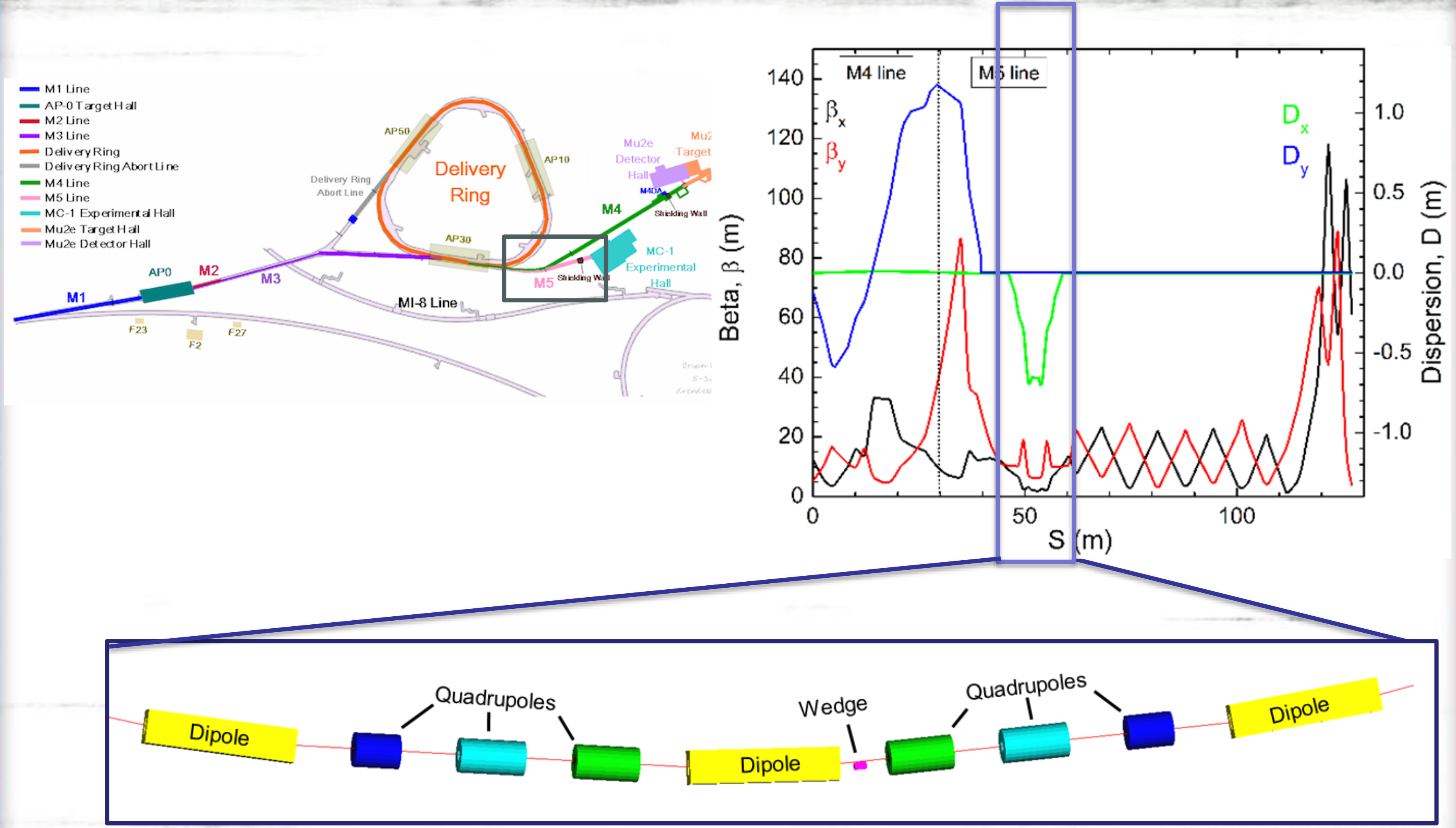
The Muon Collider Idea

LDRD at Fermilab
Laboratory Directed Research and Development

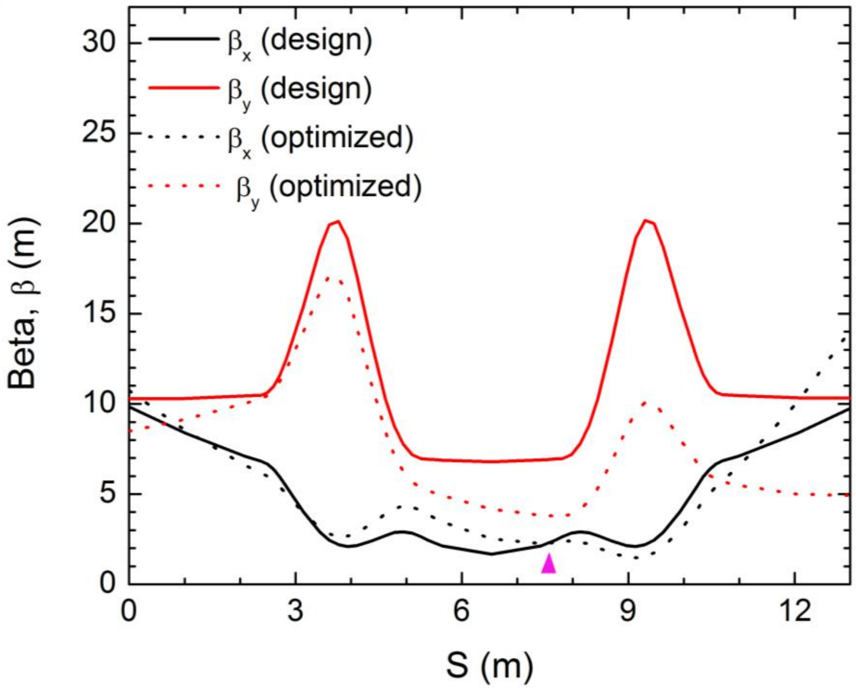


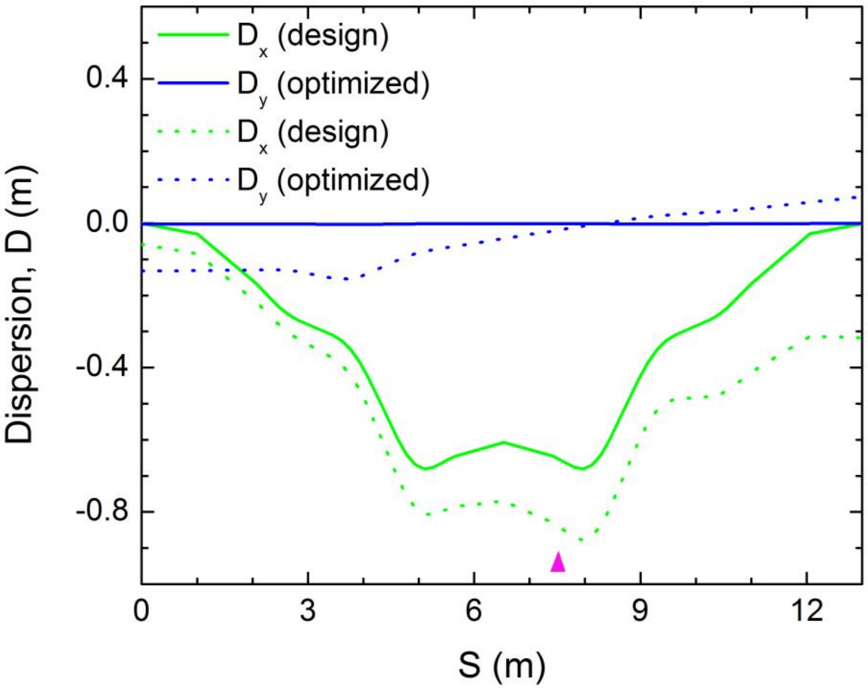


Choice of location

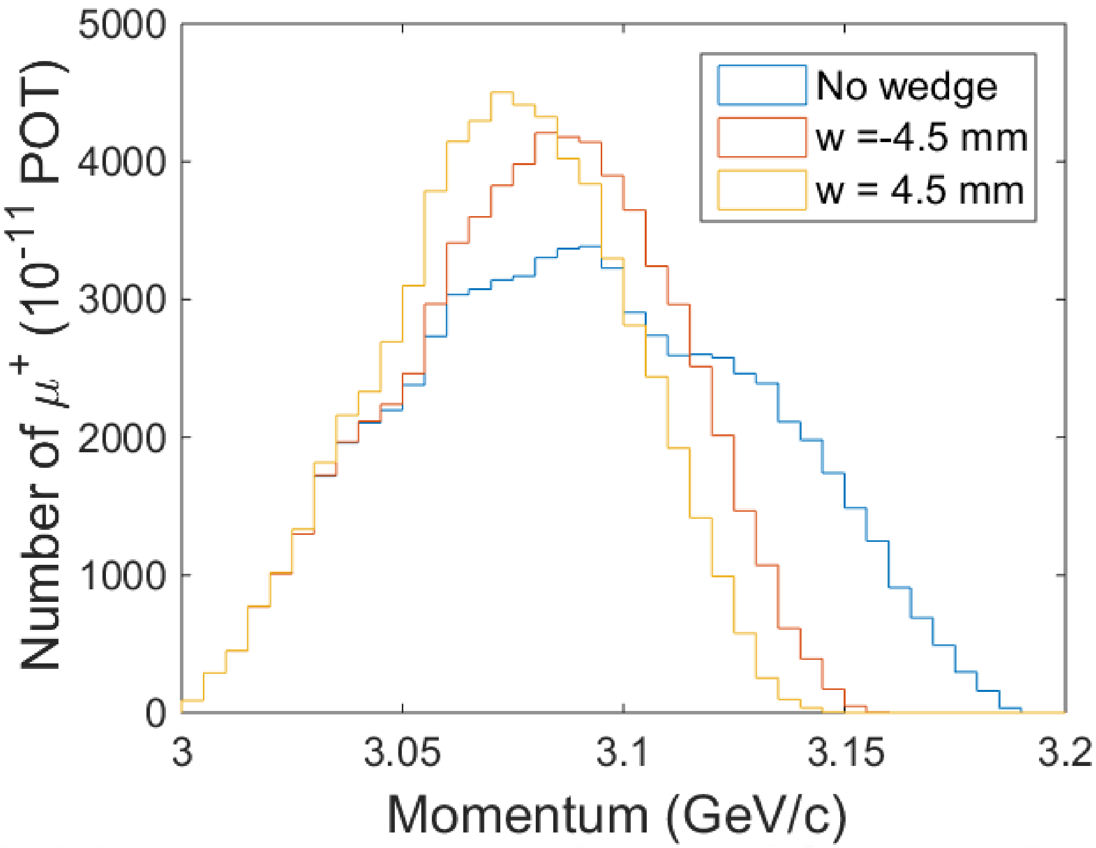


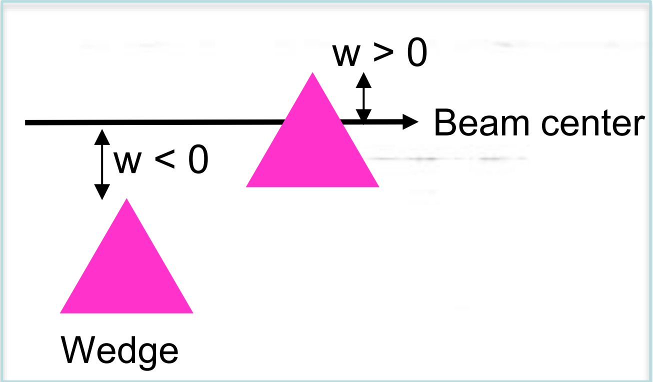
Choice of location

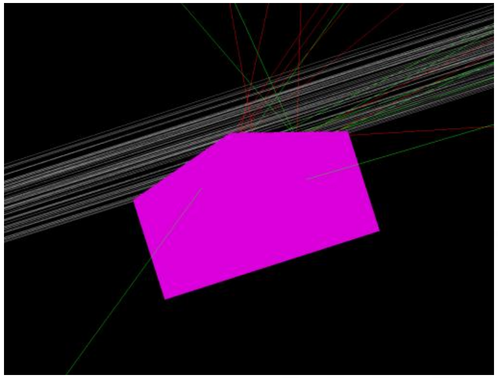




First simulation

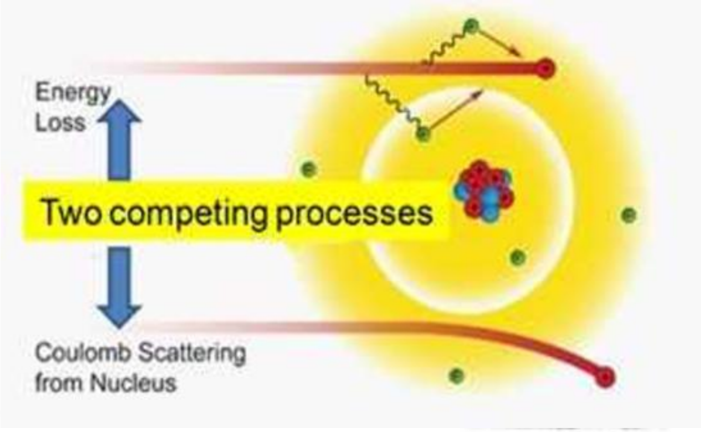






Choice of material (1)

- Mechanisms involved in the process:
  - Energy loss (contraction)
  - Multiple Coulomb scattering (expansion)
  - Energy straggling (expansion)
- We require materials with:
  - Large energy loss term
  - Large radiation length
- Beamline location with:
  - Small beta function
  - Large dispersion

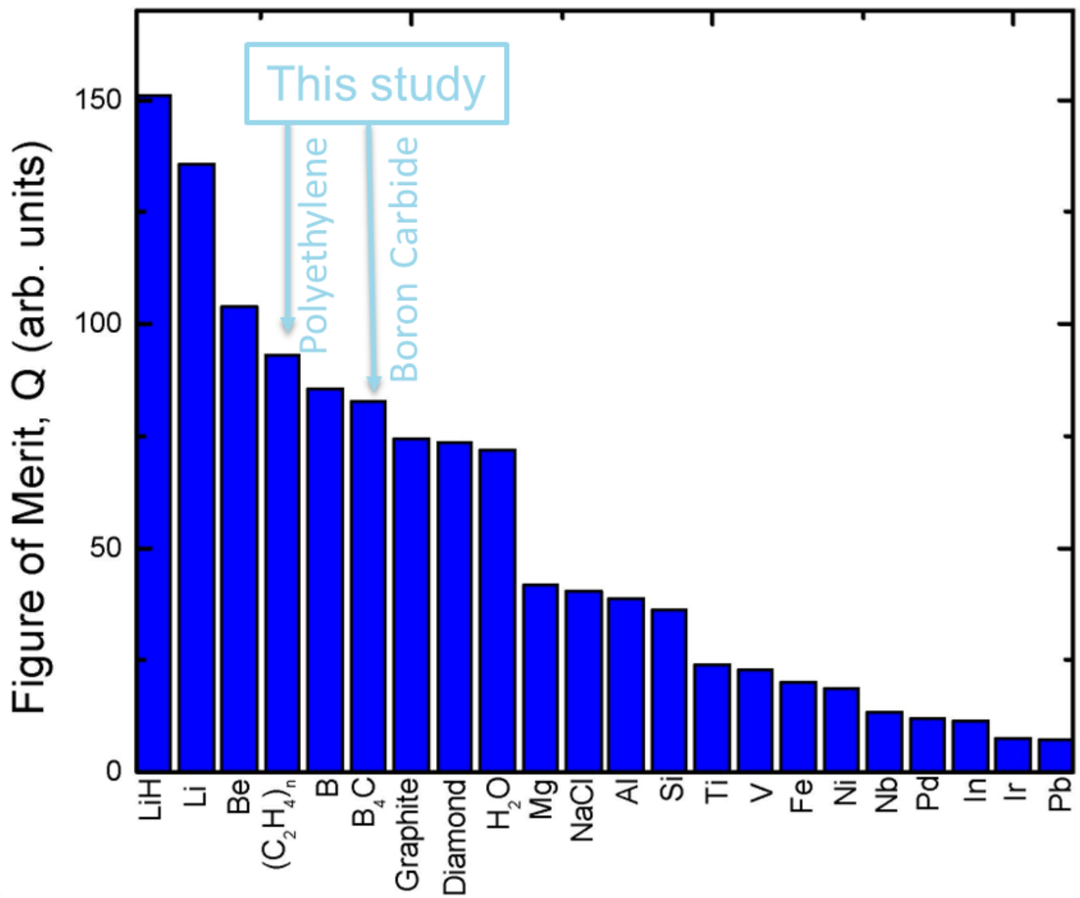


Choice of material (2)

- Q takes into account the cooling term (dE/ds) and scattering term $(1/L_R)$, i.e. $Q = L_R \times dE/ds$

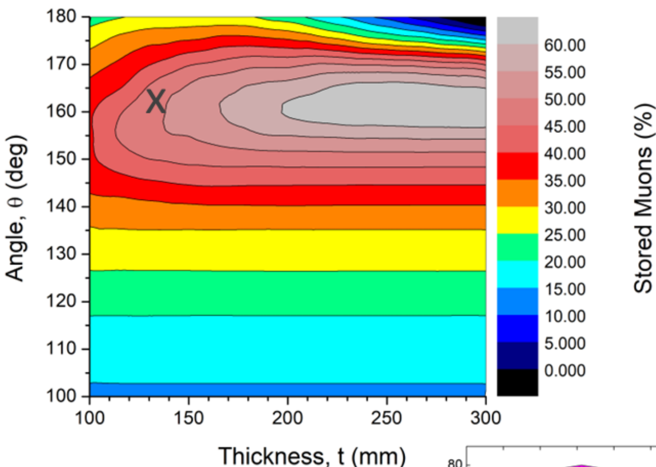
Boron Carbide (B_4C)

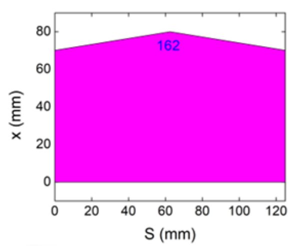
Quantity	Value	Units
<Z/A>		
Specific gravity		
Mean excitation energy		
Minimum ionization	4.157	MeV cm^{-1}
Nuclear collision length	23.12	cm
Nuclear interaction length	33.27	cm
Pion collision length	33.92	cm
Pion interaction length	46.04	cm
Radiation length	19.89	cm
Critical energy	88.08	MeV (for e^+)
Molière radius	4.659	cm
Plasma energy $\hbar\omega_p$		
Muon critical energy		



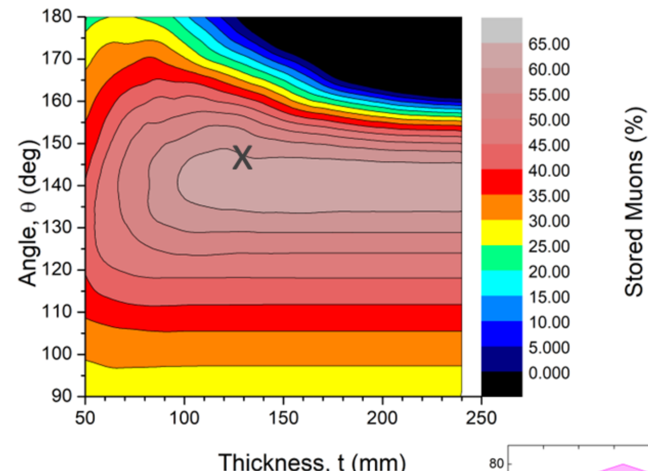
Optimum geometry

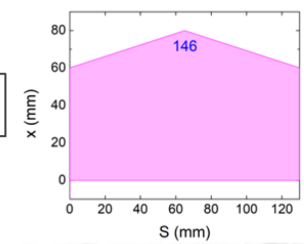
- Optimum wedge geometry was studied with a fast Monte Carlo program
- Space restrictions limit the allowable wedge length to 130 mm





Polyethylene

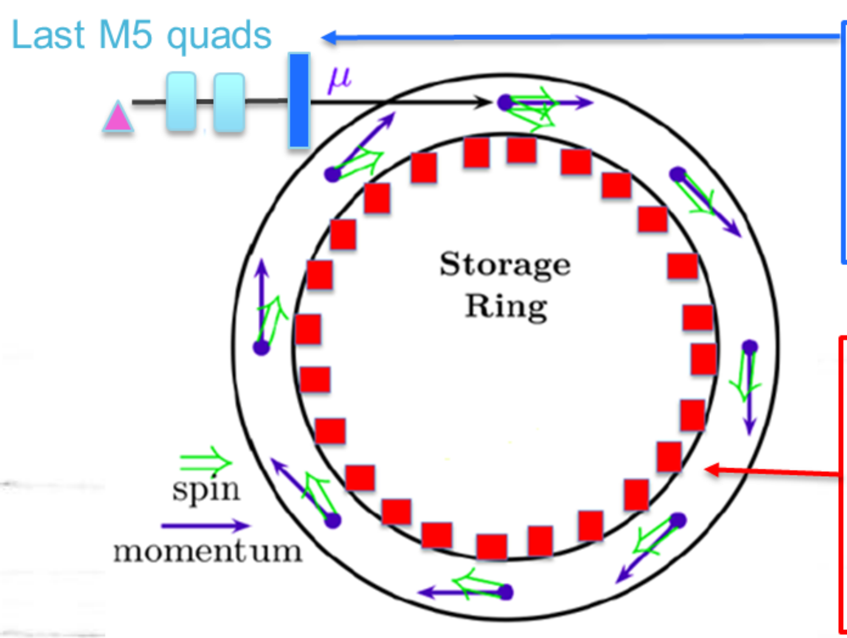




Boron Carbide

Measuring technique

- We measure beam intensity at two locations: (1) upstream of ring injection, and (2) inside the ring after thousand of turns
- Calorimeters measure only muons that fit within the ring's momentum acceptance (stored muons)



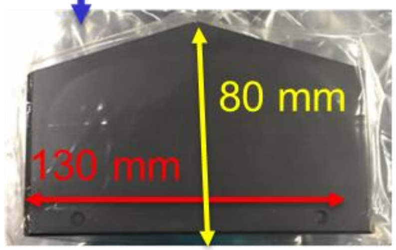
Ion Chamber: Is UPSTREAM the storage ring entrance. Measures TOTAL intensity

Calorimeters: Is INSIDE the storage ring. Measures muons WITHIN ITS ~0.1% acceptance.

Fabrication & installation

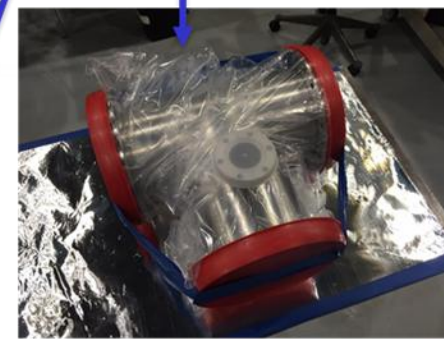
Polyethylene wedge

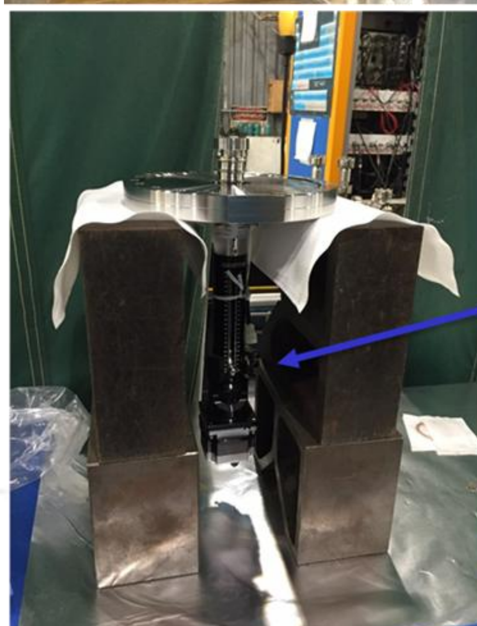
Boron Carbide wedge



New power supplies for downstream optical matching

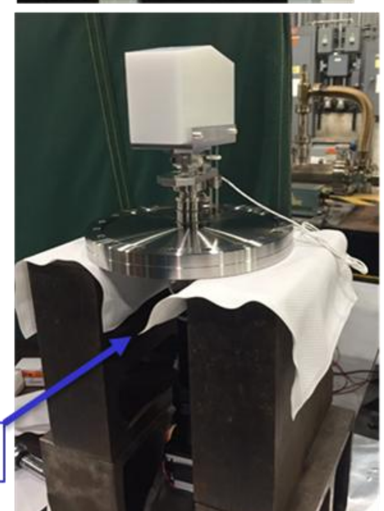
Wedge housing



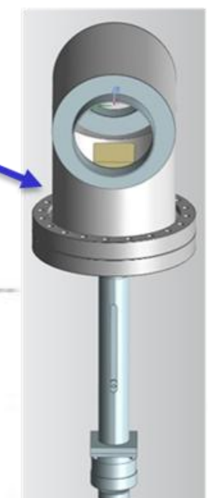


Wedge insertion actuator with submillimeter precision

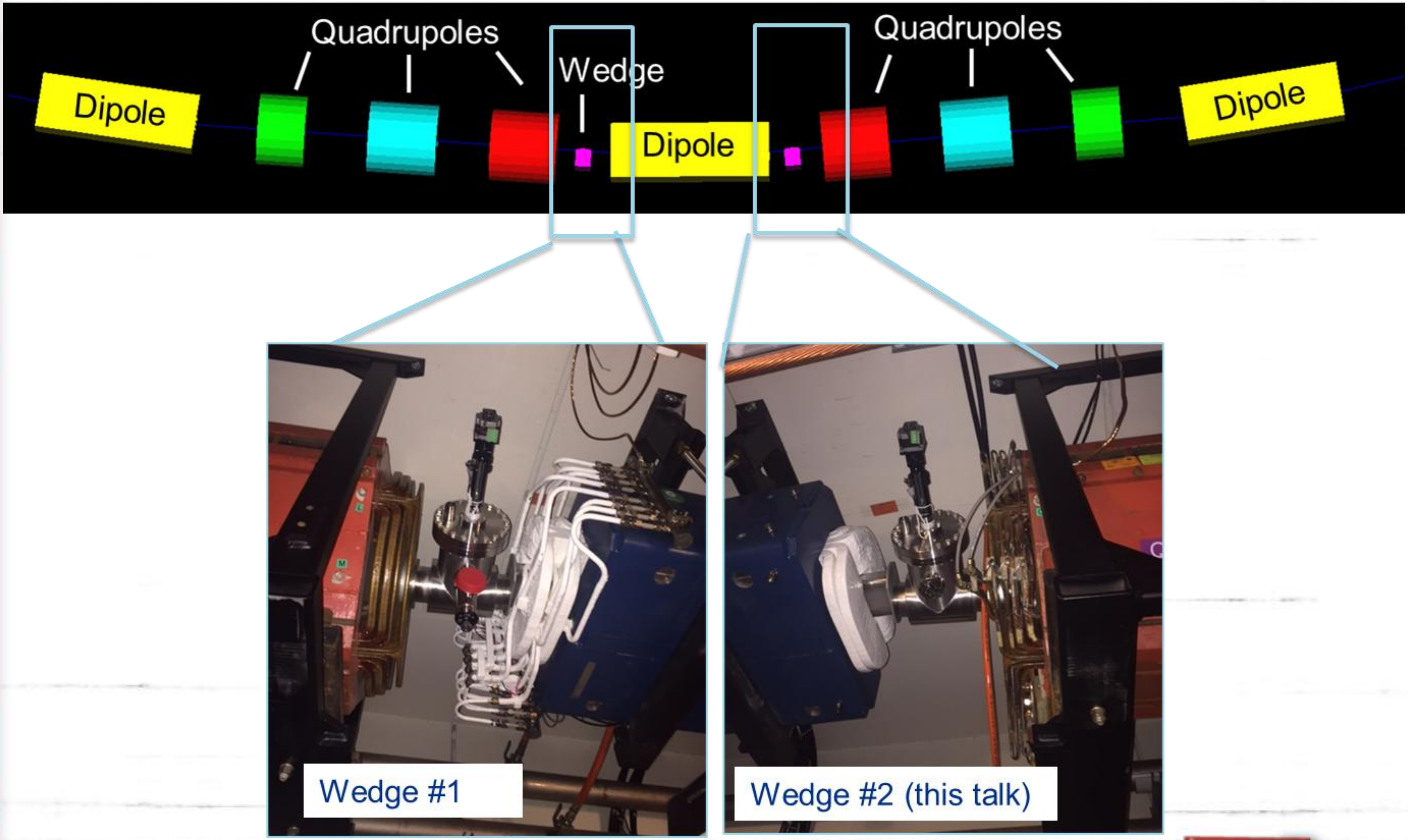
Motion-control tests



Design of complete mechanical assembly

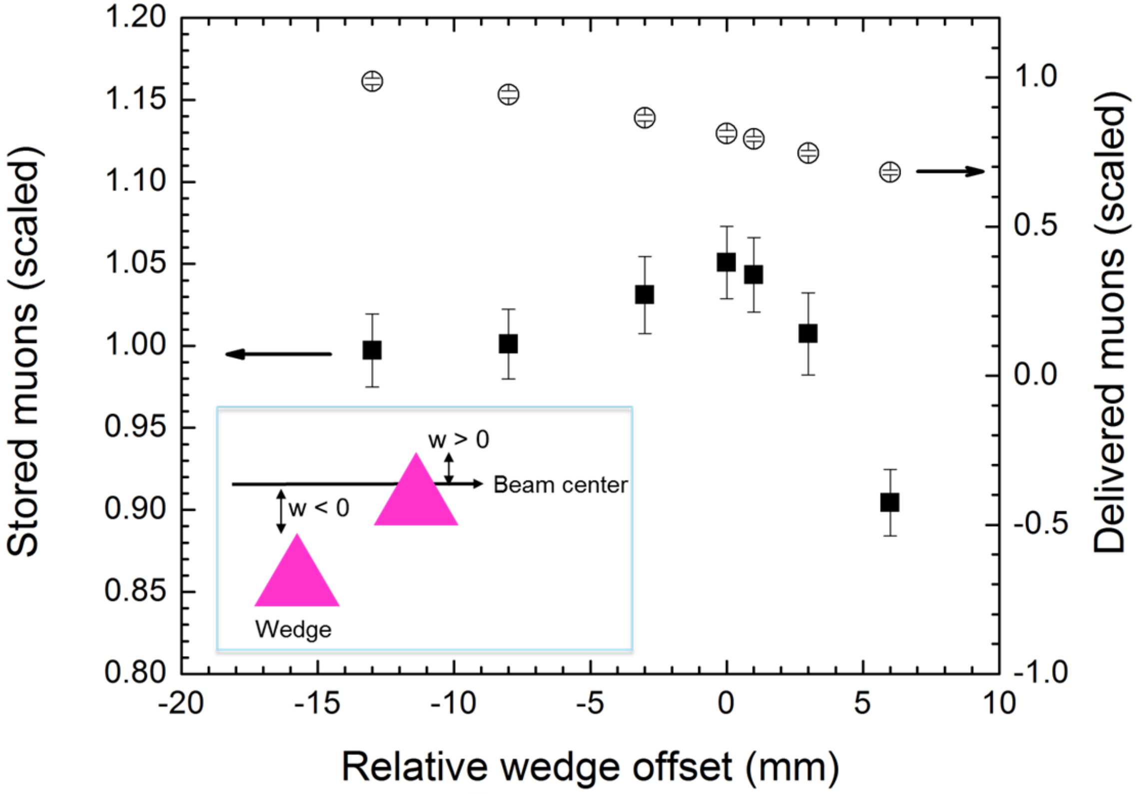


Fabrication & installation



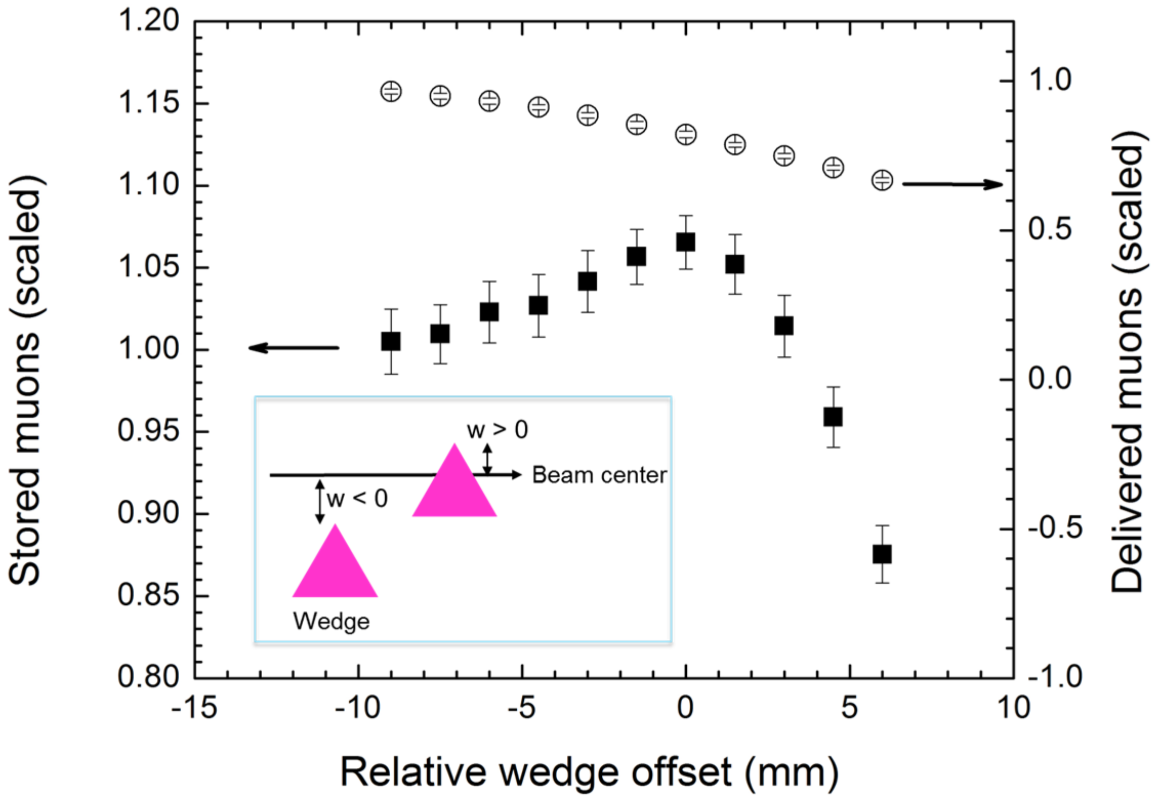
Test with a Polyethylene wedge

- A plastic wedge provided a 5% gain in stored muons



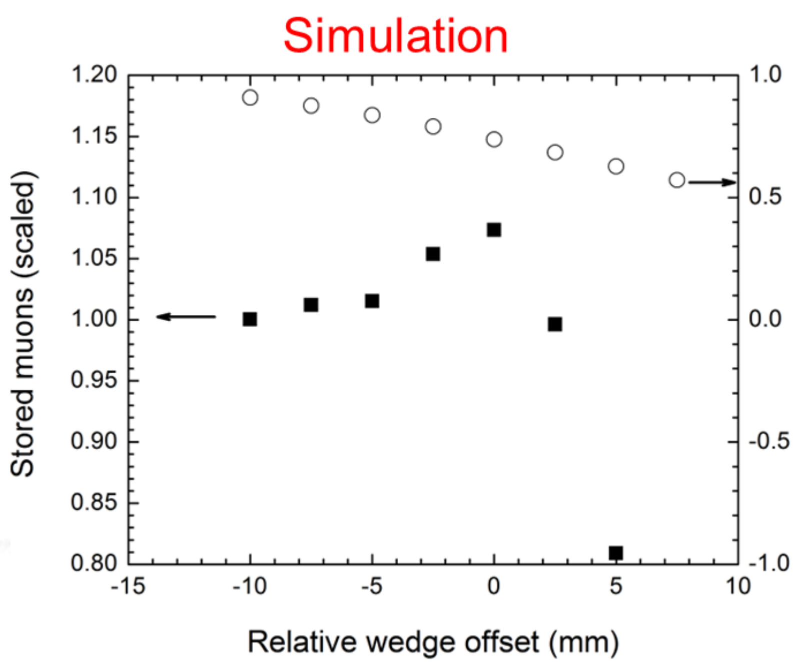
Test with a Boron Carbide wedge

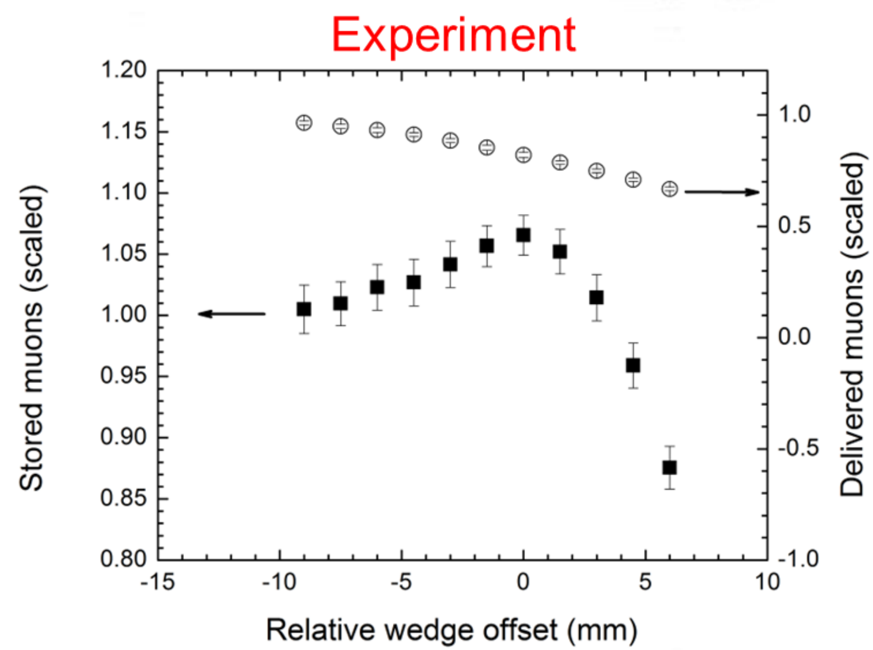
- A boron carbide wedge provided a 7% gain in stored muons



Simulation vs experiment

- The agreement between simulation and experiment is good





Thank you

Nick Amato (2019)
Master's Thesis, **NIU** (Syphers)
Title: Improved momentum spread for precision experiments using wedges

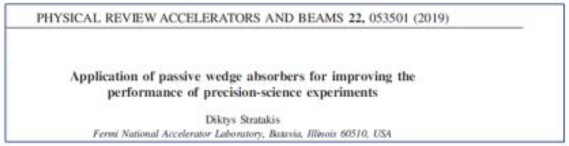
Lauren Carver (2019)
Fermilab Intern
Title: Modeling a wedge absorber for the g-2 Experiment

Jerzy Manczak (2018)
Fermilab Intern
Title: Modeling a wedge absorber for the Mu2e Experiment

Joe Bradley (2017)
Fermilab Intern
Title: Material & geometry study of a wedge absorber for the g-2 Experiment

Grace Roberts (2020)
Fermilab Intern
Title: Optimizing injection for a wedge based Muon g-2 Experiment

Ben Simons(2020)
NIU grad. student
Title: Tuning beam optics for the Muon Campus



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22**, 053501 (2019)

Application of passive wedge absorbers for improving the performance of precision-science experiments

Diktys Stratakis
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Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Realistic modeling of a particle–matter-interaction system for controlling the momentum spread of muon beams

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A parametric analysis for maximizing beam quality of muon-based storage ring experiments

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