Beam analysis for secondary beams (Part II)

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PHYS 790D, NIU, DeKalb, IL (Fall 2019)
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Outline

- Review of particle-matter physical processes for muons
- Review of the theoretical framework of ionization cooling
- Application of ionization cooling to the Fermilab Muon g-2 Experiment
- Design considerations:
  - Choice of location
  - Choice of material
  - Choice of length and angle
  - Choice of optics
- Simulated performance

Particle-matter interactions

- Particles can interact with:
  - atoms/molecules
  - Atomic electrons
  - nucleus
- Leads to several interaction processes:
  - Ionization
  - Multiple scattering
  - Energy loss (Bremsstrahlung)
  - Hadronic showers

Muons

- Carry the same electrical charge as electrons
- Like electrons and unlike protons, muons are elementary particles
  - Do not feel the strong interaction, meaning no hadronic showers
- Muons are ~200 times heavier than electrons
  - Are not affected by Bremsstrahlung at most energies
- As a result, muons can travel “untouched” for very long distances inside materials

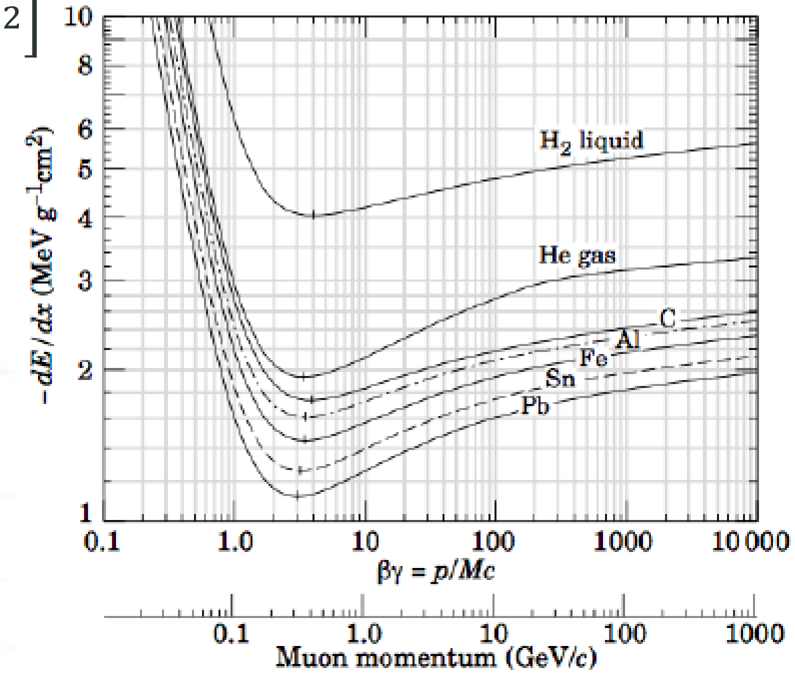
Ionization

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

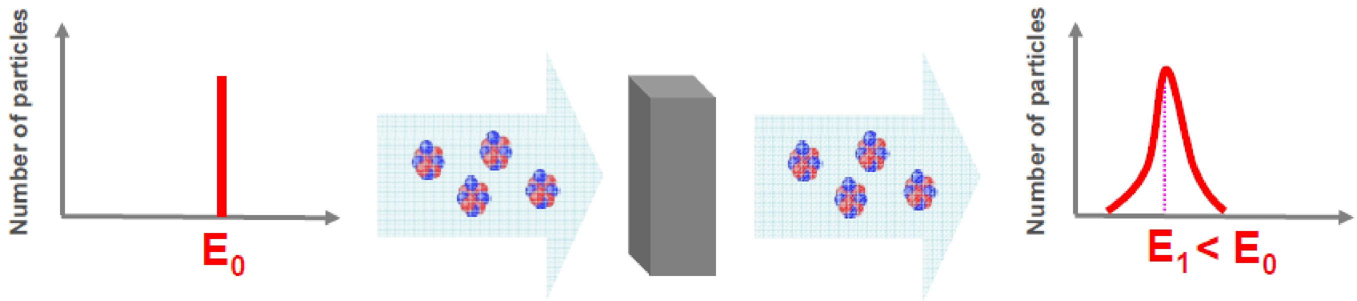
- Average energy loss is given by Bethe-Bloch formula

$$\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\left[\frac{1}{\beta^2}\ln(K\gamma^2\beta^2) - 1 - \frac{\delta}{2\beta^2}\right]$$

- Ionization term (dE/dx):
  - Depends on material density
  - Does not depend on the mass of the incident particle
  - Minimum at $\beta\gamma \approx 3$

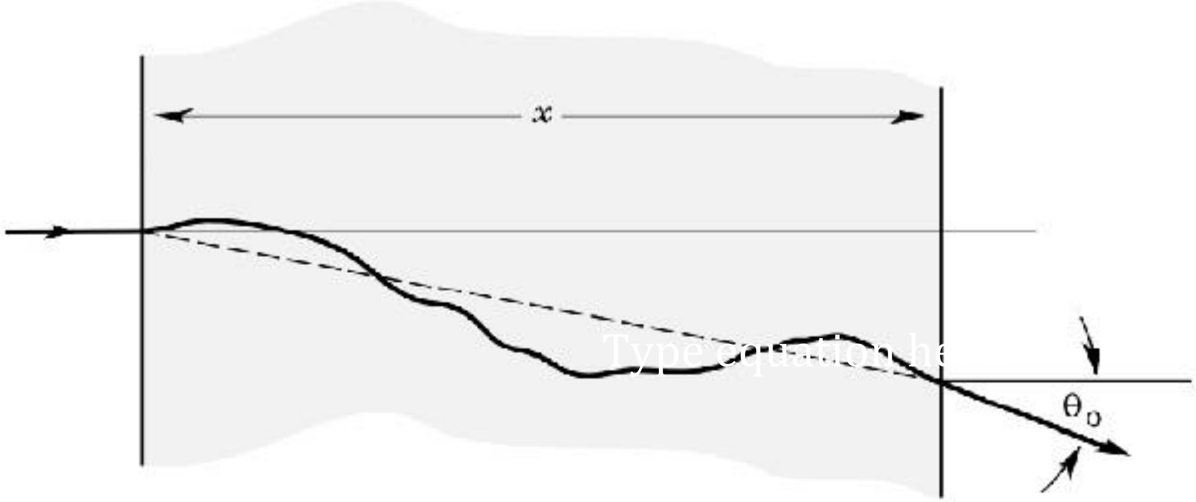


Energy straggling



- 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.
- Was first described by Landau (another Nobel prize winner). Straggling increases rapidly for materials with high electron density and very energetic beams.

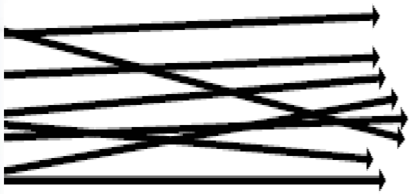
Multiple scattering

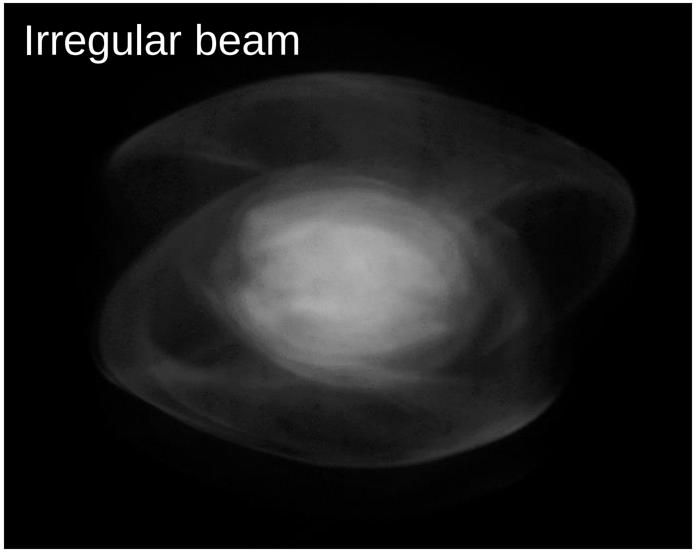


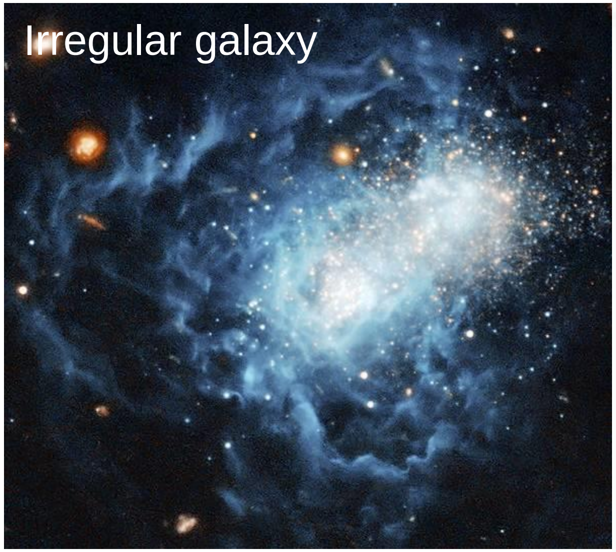
- Muon will be deflected due to Coulomb scattering from nuclei
- The angle has a roughly Gaussian distribution of width θ_0:

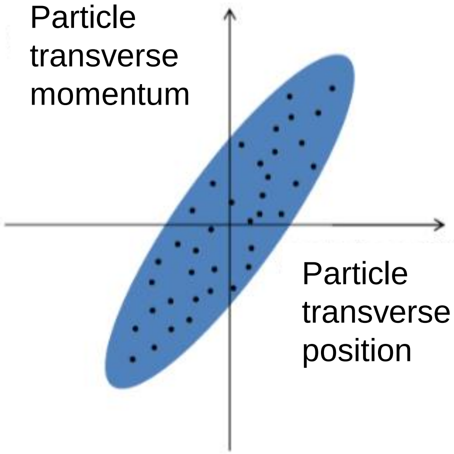
$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\sqrt{\frac{x}{L_R}}\left[1 + 0.038\ln\left(\frac{x}{L_R}\right)\right]$$

Defining beam quality



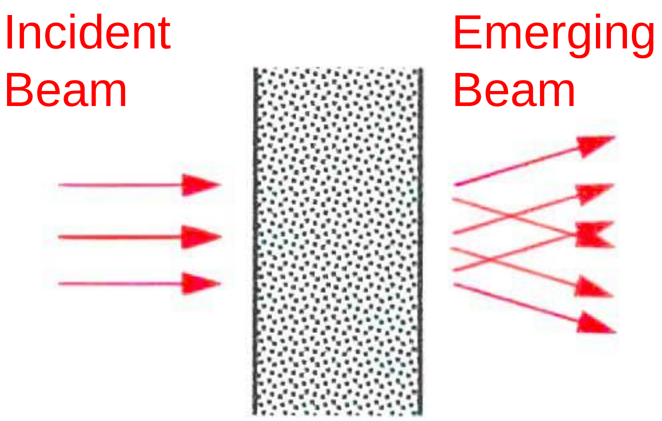






- Beam quality measures:
  - emittance (ε): volume of phase-space
  - Brightness (B): density of phase-space
- We desire high brightness & low emittance beams

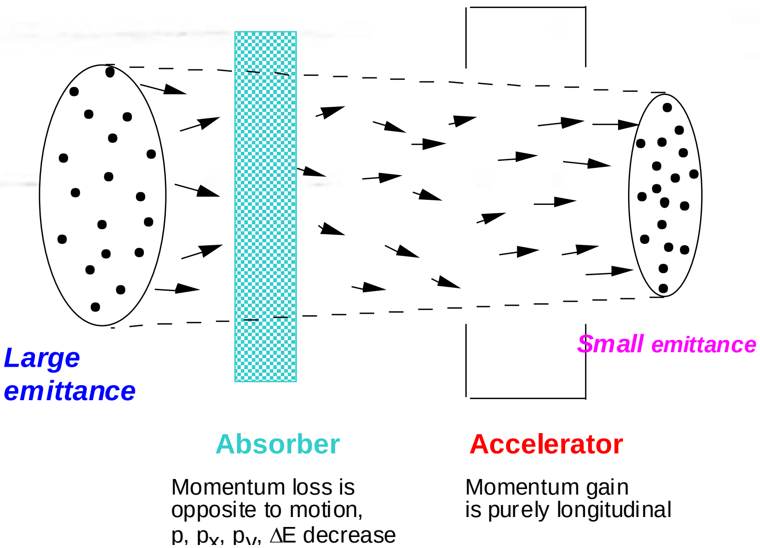
Emittance growth from scattering

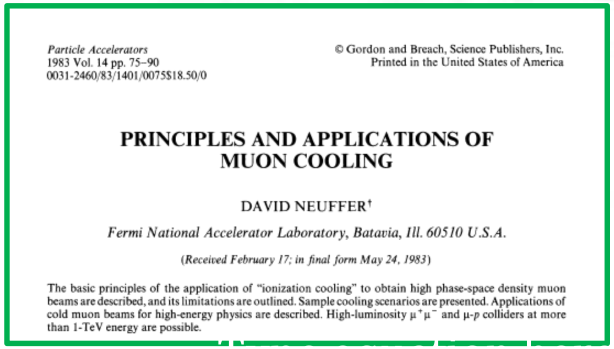


M. Syphers, GM2-doc-2343

- For an individual particle after scattering: $x' = x_0' + \Delta\theta$
- Taking second order moments:
  - $\langle x^2 \rangle = \langle x_0^2 \rangle$
  - $\langle x'^2 \rangle = \langle (x_0' + \Delta\theta)^2 \rangle$
  - $\langle x x' \rangle = \langle x_0 x_0' \rangle$
- The new emittance after scattering is: $\epsilon = \langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2$ or $\epsilon = \epsilon_0 \sqrt{1 + \frac{\langle x_0^2 \rangle \theta_{rms}^2}{\epsilon_0}}$
- Emittance growth depends on size and material

Ionization cooling formalism (1)




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

PRINCIPLES AND APPLICATIONS OF MUON COOLING

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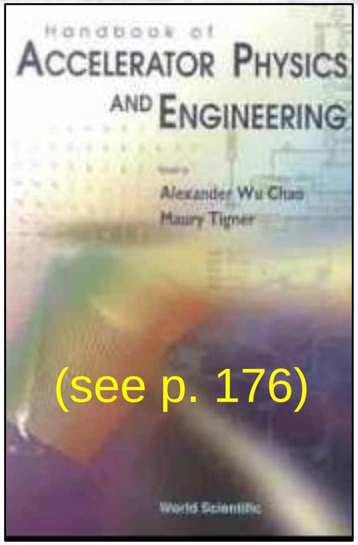
Fermi National Accelerator Laboratory, Batavia, Ill. 60510 U.S.A.

(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.



Cooling term — Multiple scattering term

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

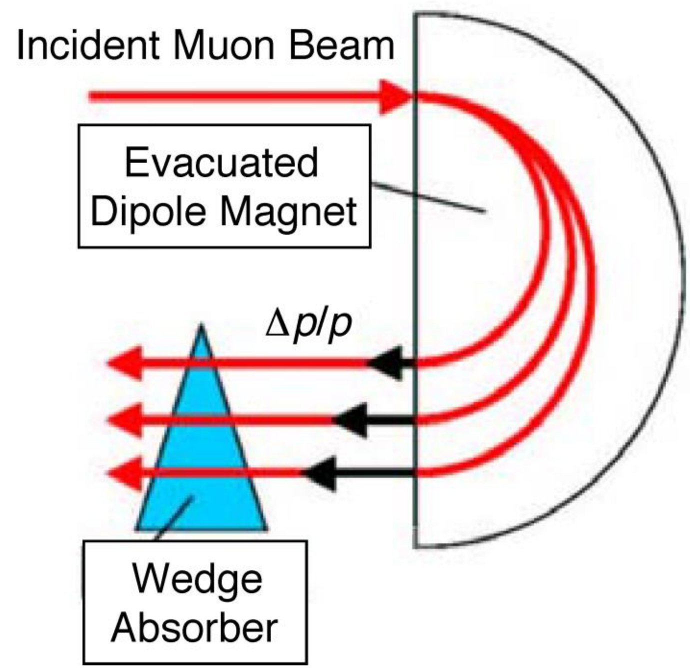
- Cooling is enhanced with good focusing & dense materials with high radiation length
- BUT we cool transverse only!

Ionization cooling formalism (2)

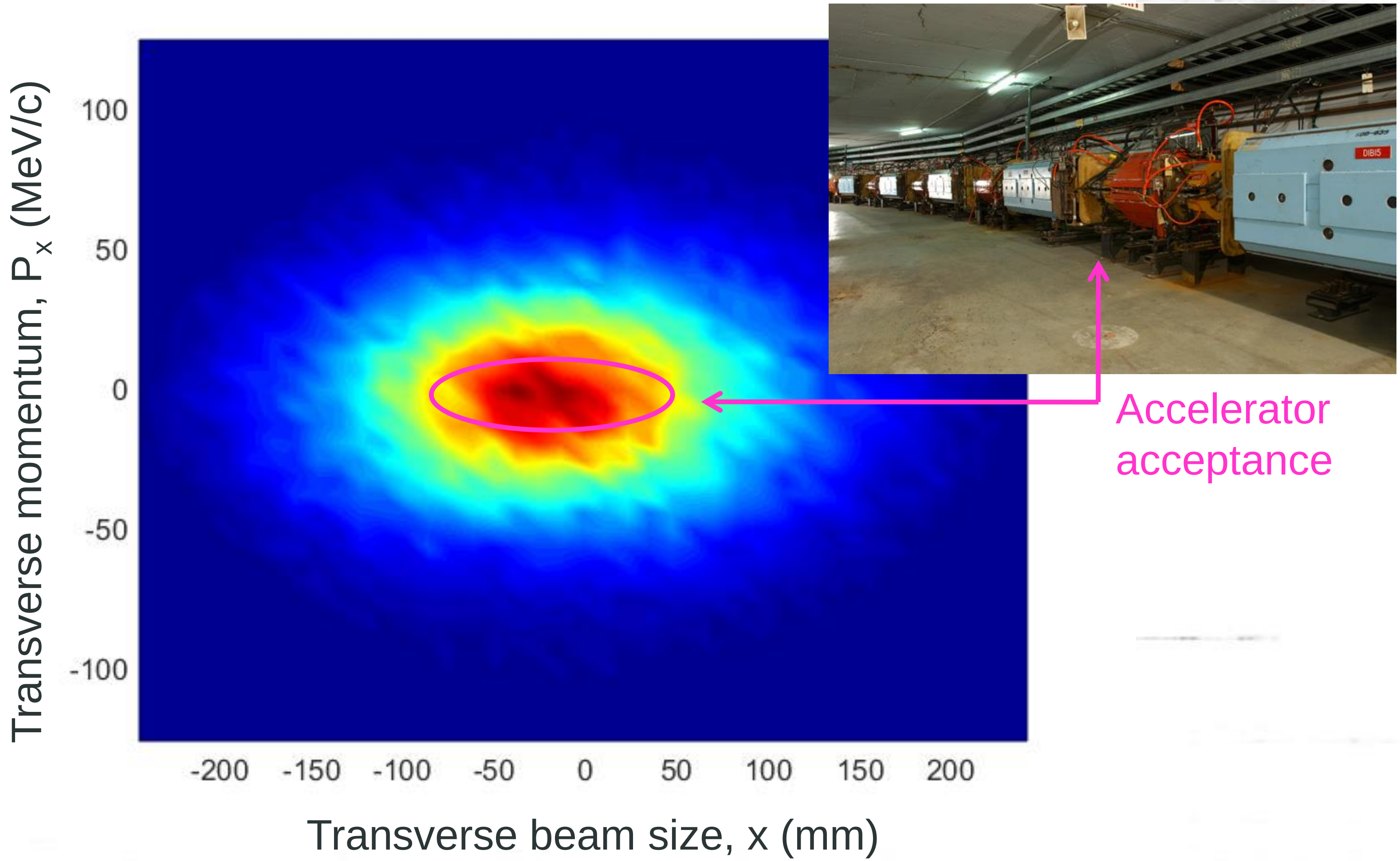
Cooling term   Straggling term

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

- Cooling occurs only if derivative: $$\frac{\partial\left(\frac{dE}{ds}\right)}{\partial E} > 0$$
- Ionization loss does not naturally provide adequate longitudinal cooling
- Can be enhanced, if it is arranged that high energy muons lose more energy than low energy ones.

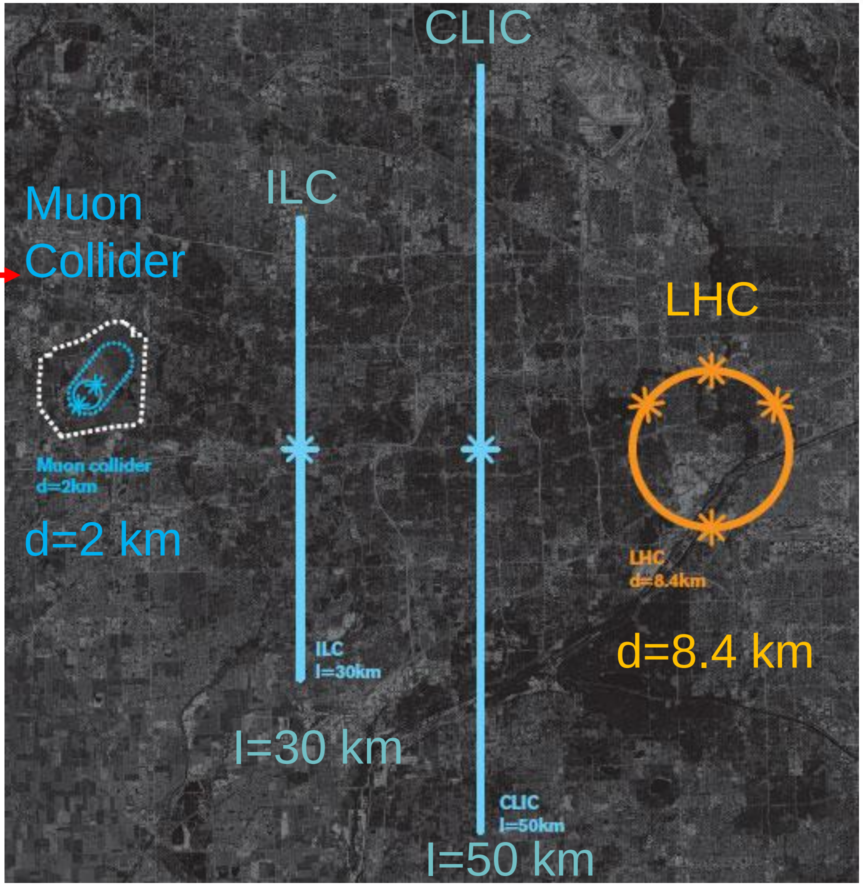


Muon beam at birth



History of ionization cooling (1)

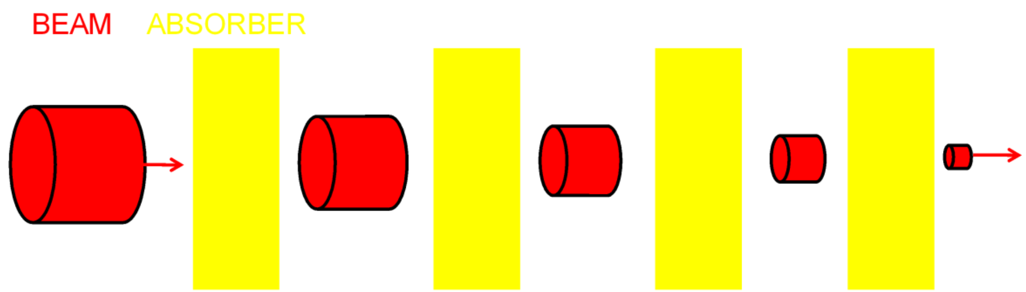
Requirement:
Reduce 6D emittance by at least 5 orders of magnitude



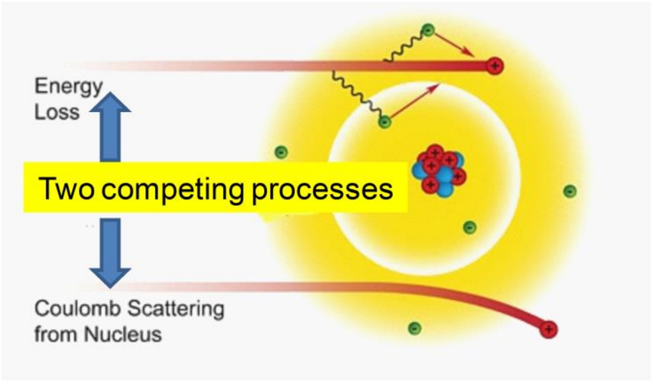
- As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision probe of fundamental interactions

Concept of ionization cooling (1)

- The concept:

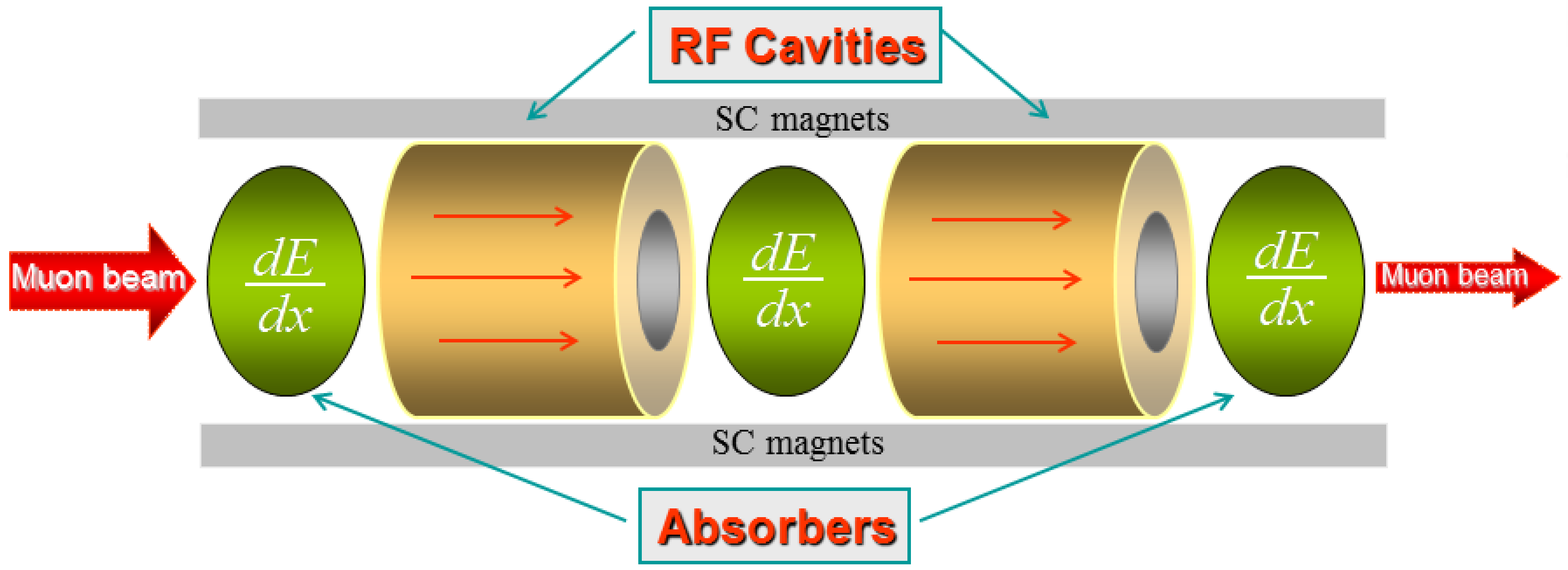


- The physics processes:



- Cooling improves if:
  - Absorber is a low Z material
  - The beam is well focused in the absorber
- But, one more thing is missing...

History of ionization cooling (2)



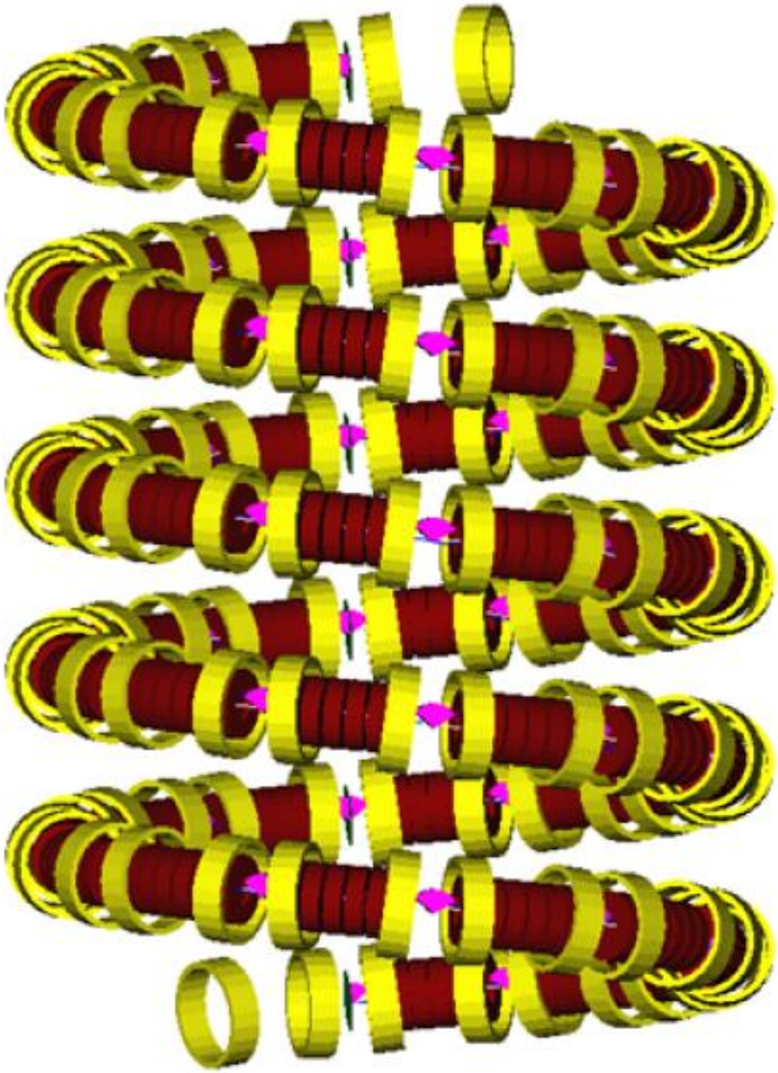
- Restore the lost momentum in z with a longitudinal E-field
- A pillbox cavity is placed adjacent to the absorber

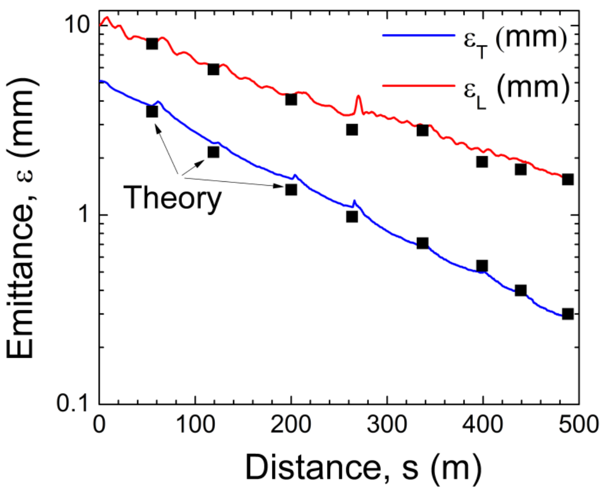
First candidate – Guggenheim channel

Coils

Cavities

Absorber





Community acceptance

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **16**, 091001 (2013)

Tapered channel for six-dimensional muon cooling towards micron-scale emittances

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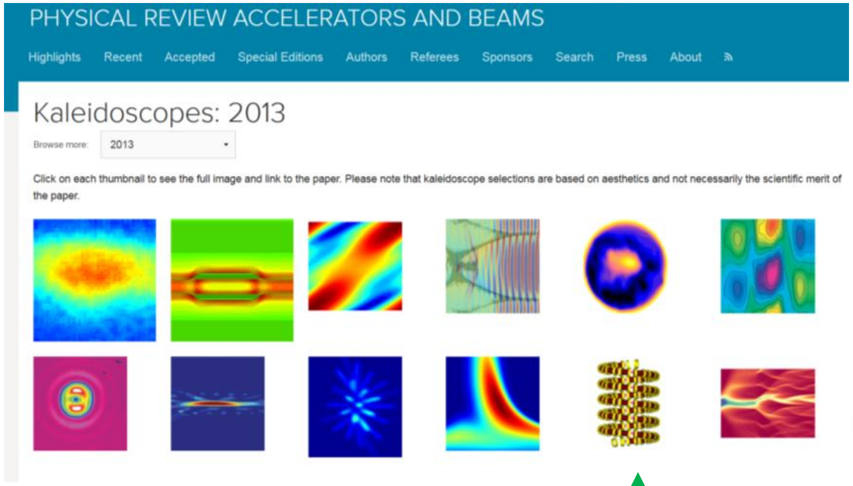
(Received 19 June 2013; published 23 September 2013)

A high-luminosity muon collider requires a significant reduction of the six-dimensional emittance prior to acceleration. Obtaining the desired final emittances requires transporting the muon beam through long sections of a beam channel containing rf cavities, absorbers, and focusing solenoids. Here we propose a new scheme to improve the performance of the channel, consequently increasing the number of transmitted muons and the lattice cooling efficiency. The key idea of our scheme is to tune progressively the main lattice parameters, such as the cell dimensions, rf frequency, and coil strengths, while always keeping the beam emittance significantly above the equilibrium value. We adopt this approach for a new cooling lattice design for a muon collider, and examine its performance numerically. We show that with tapering the cooling rate is not only higher than conventional designs, but also maintains its performance through the channel, resulting in a notable 6D emittance decrease by 3 orders of magnitude. We also review important lattice parameters, such as the required focusing fields, absorber length, cavity frequency, and voltage.

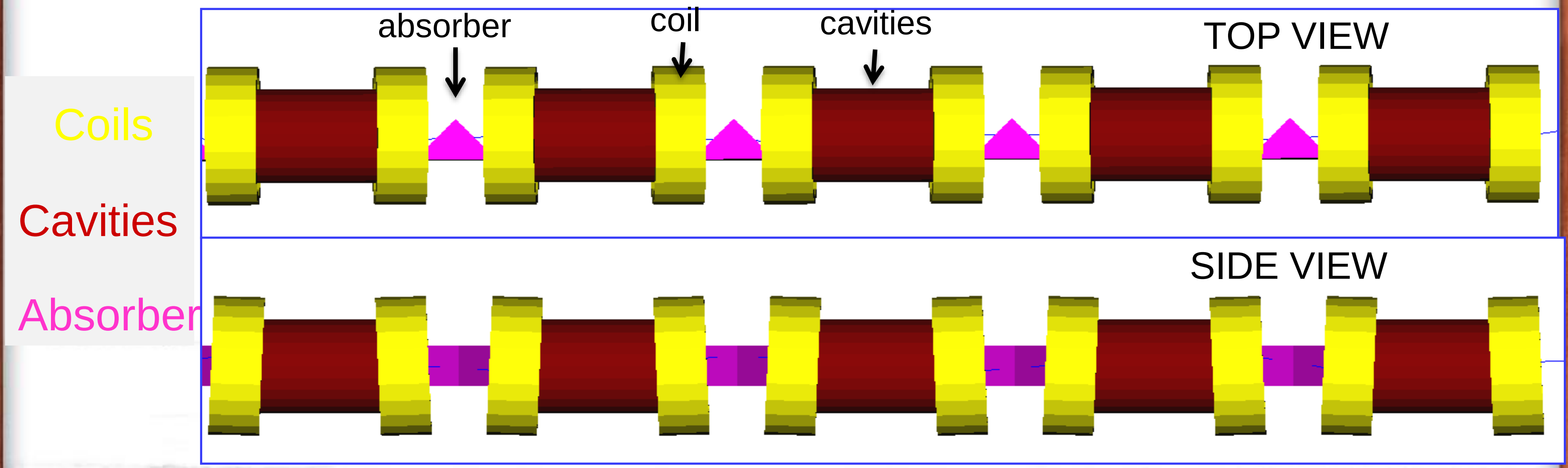
Distinguished as an
“Editor’s suggestion” paper



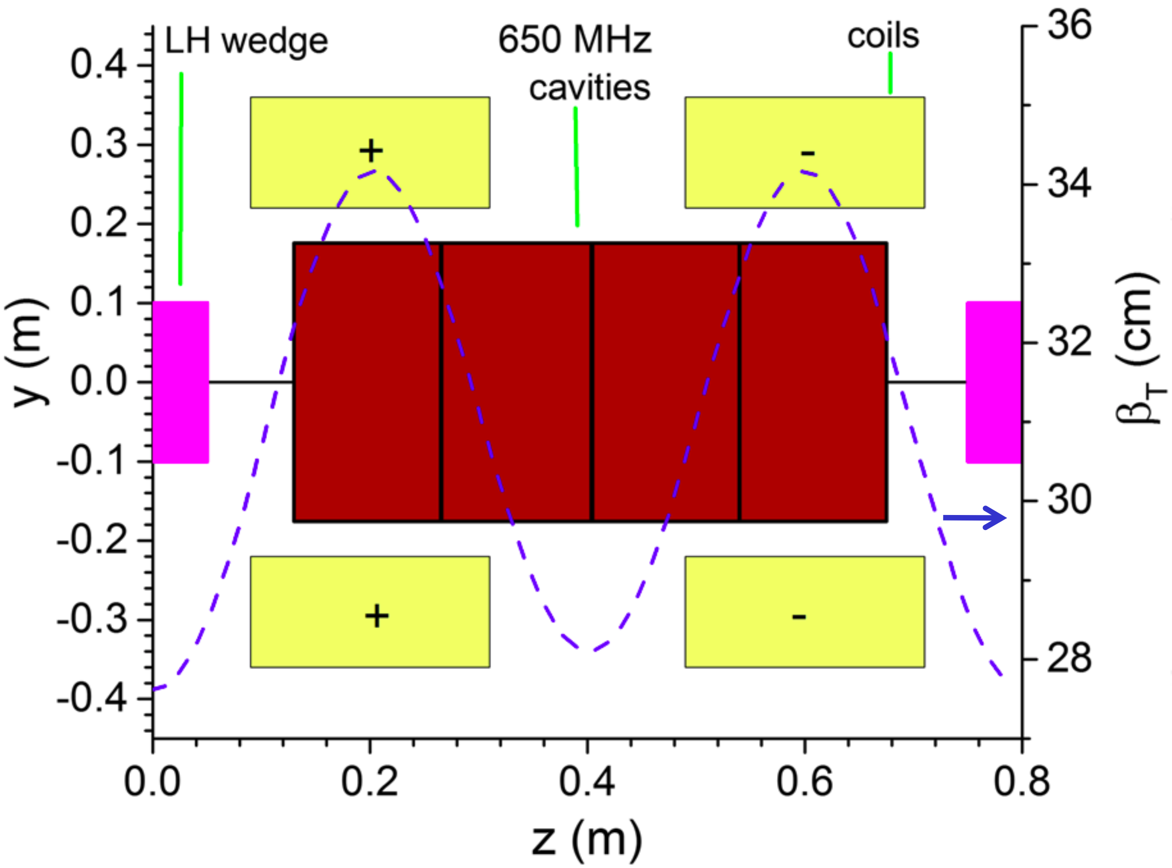
Our figure was selected for kaleidoscope

A better design…

- Straight geometry (vs. spiral) simplifies construction and relaxes several technological challenges
- Its length will depend on the application

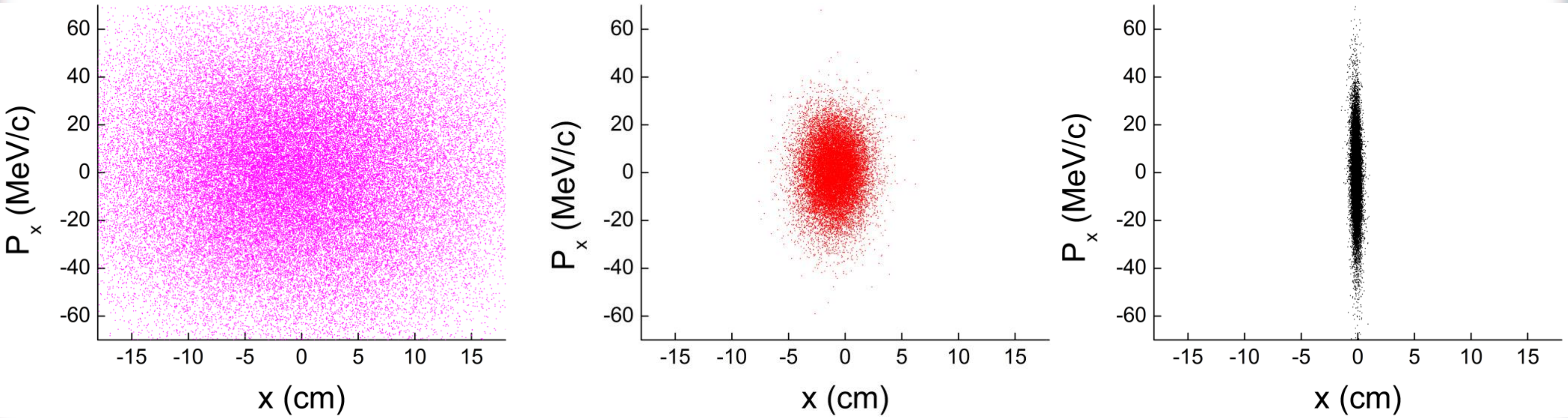


One cooling cell



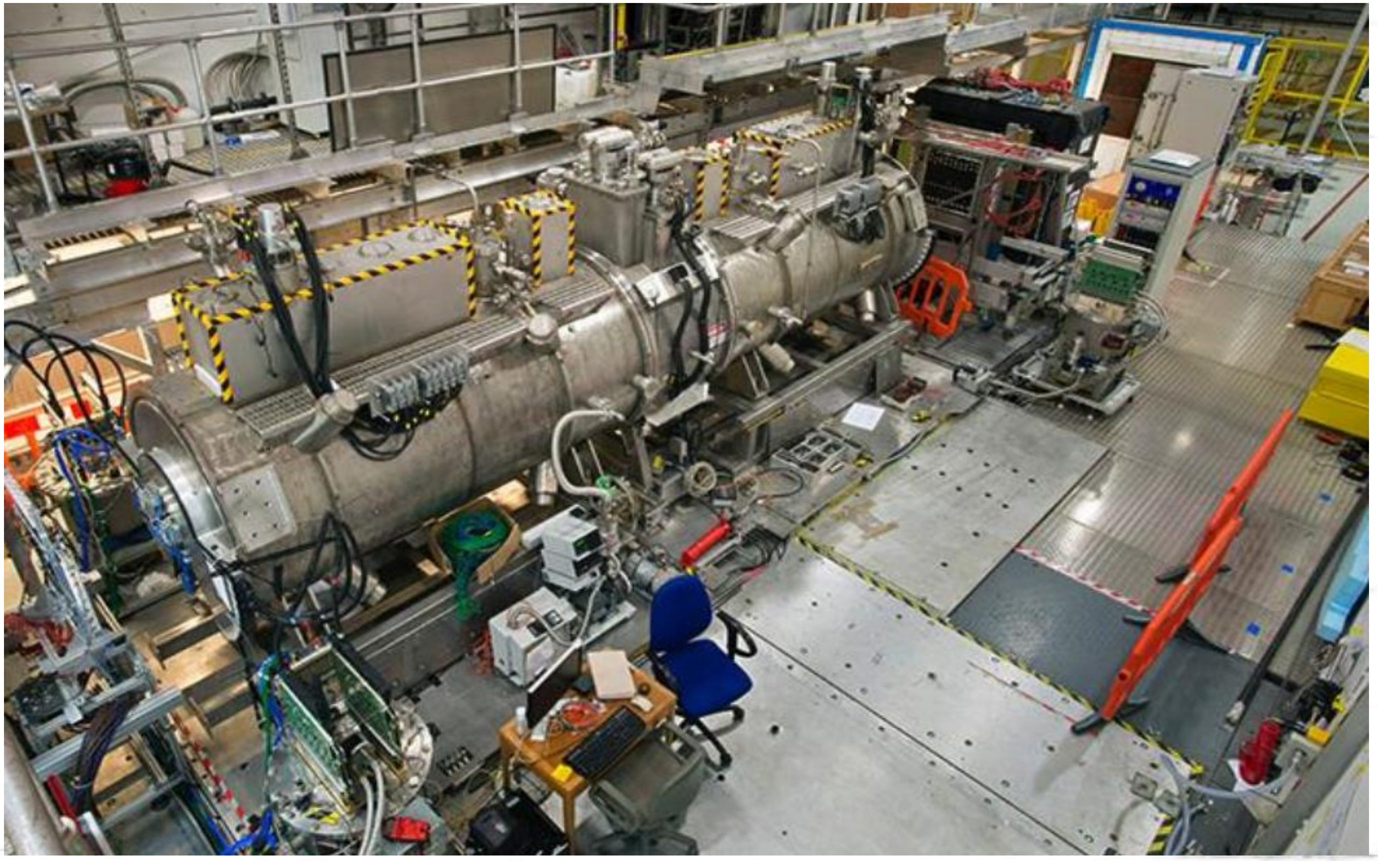
Performance: phase-space reduction

BEGIN INTERMEDIATE END



Muon ionization cooling experiment (1)

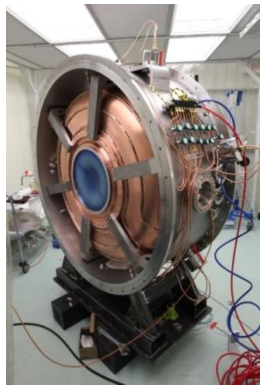
- Demonstration of ionization cooling at Rutherford Appleton Laboratory, UK (US-UK sponsored).



Muon ionization cooling experiment (2)

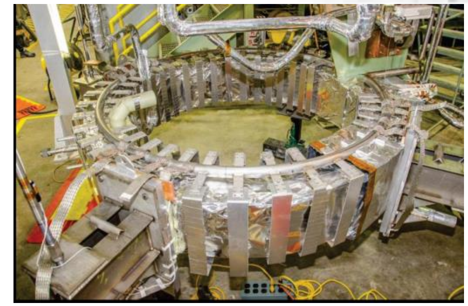
solenoid

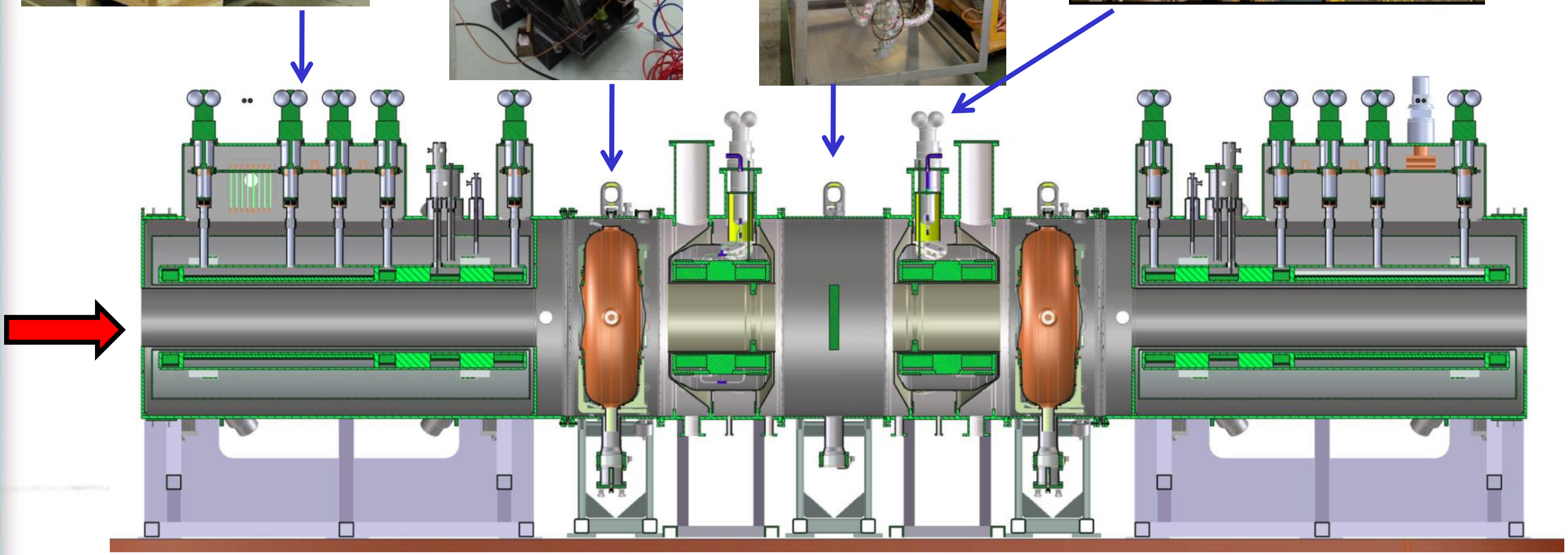
201 MHz cavity



absorber

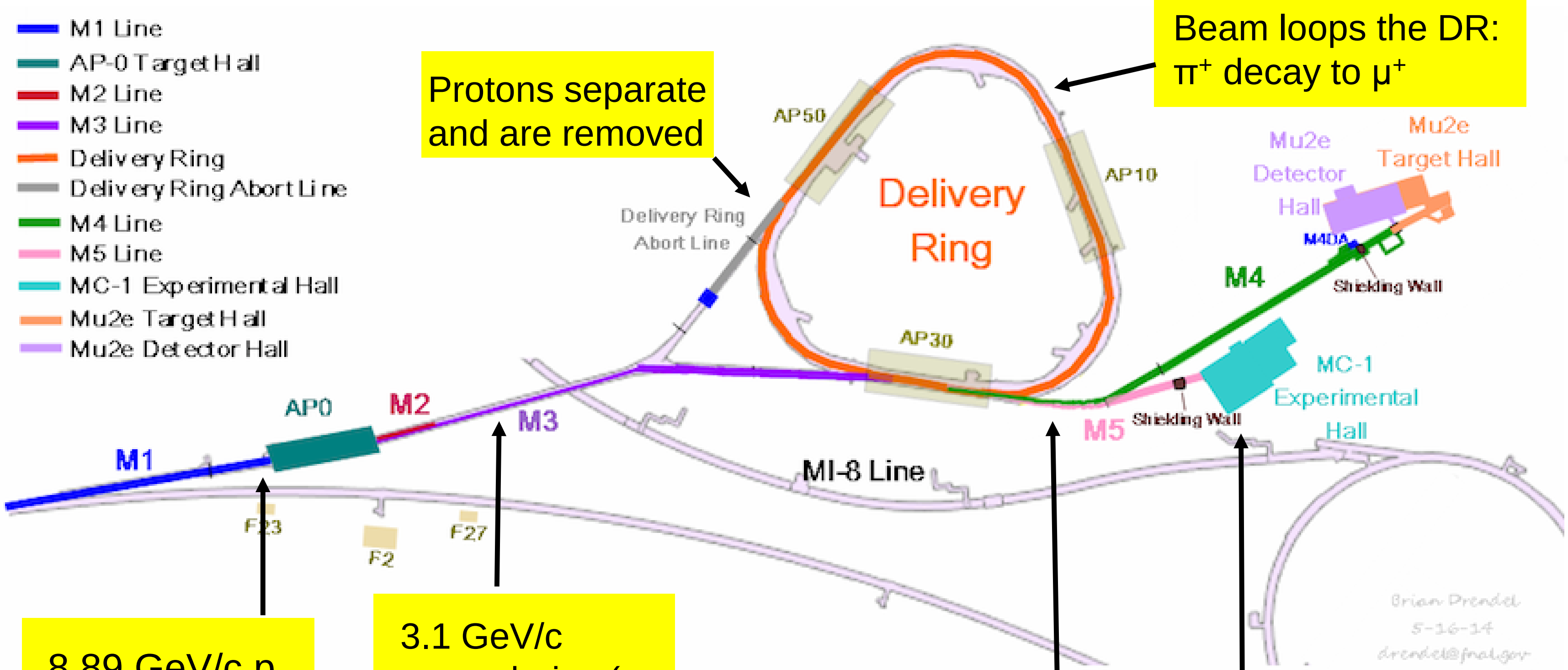
focus coil





- Experiment complete. Demonstrated transverse cooling ~6%

Fermilab Muon Campus accelerator



Protons separate and are removed

Beam loops the DR: π^+ decay to μ^+

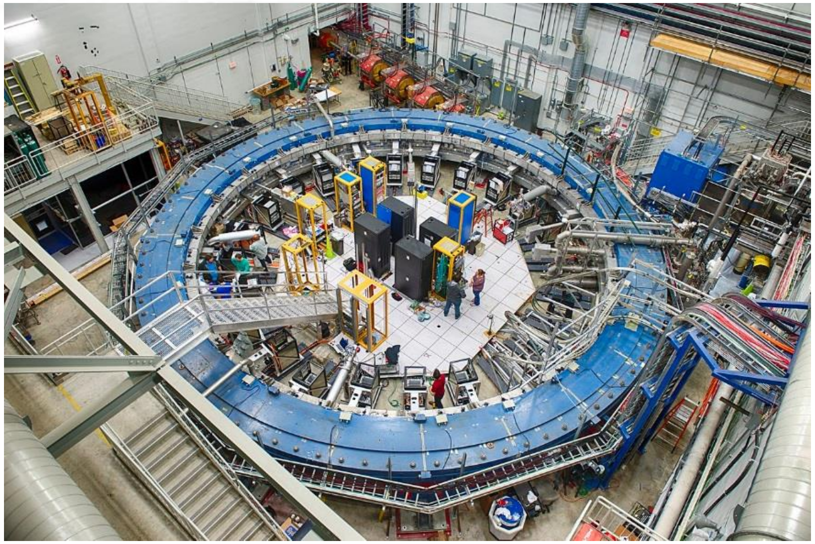
8.89 GeV/c p beam impacts the target

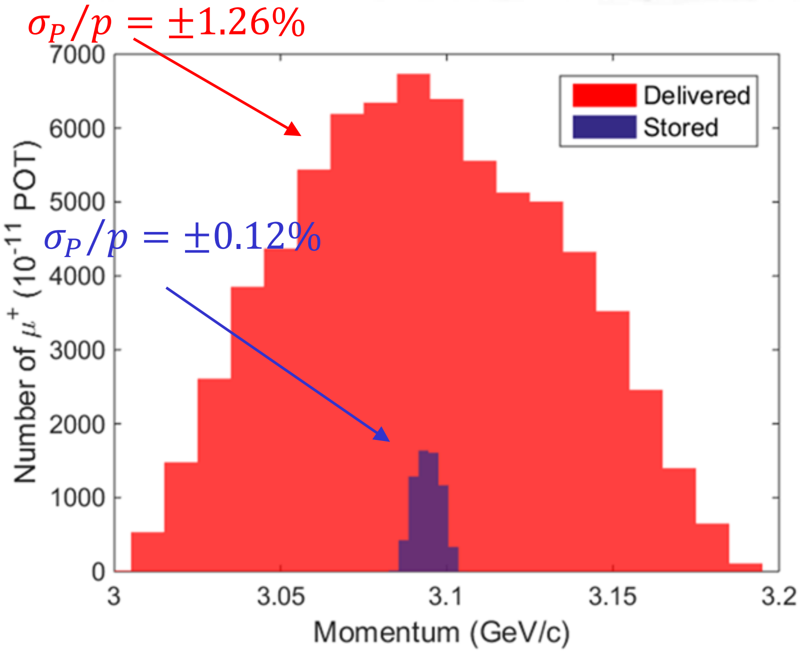
3.1 GeV/c secondaries (π, μ, p) travel along M2 & M3

μ^+ are extracted from the ring and transferred into the storage ring via M4, M5

μ^+ enter the g-2 storage ring

Motivation for the Muon g-2 Experiment



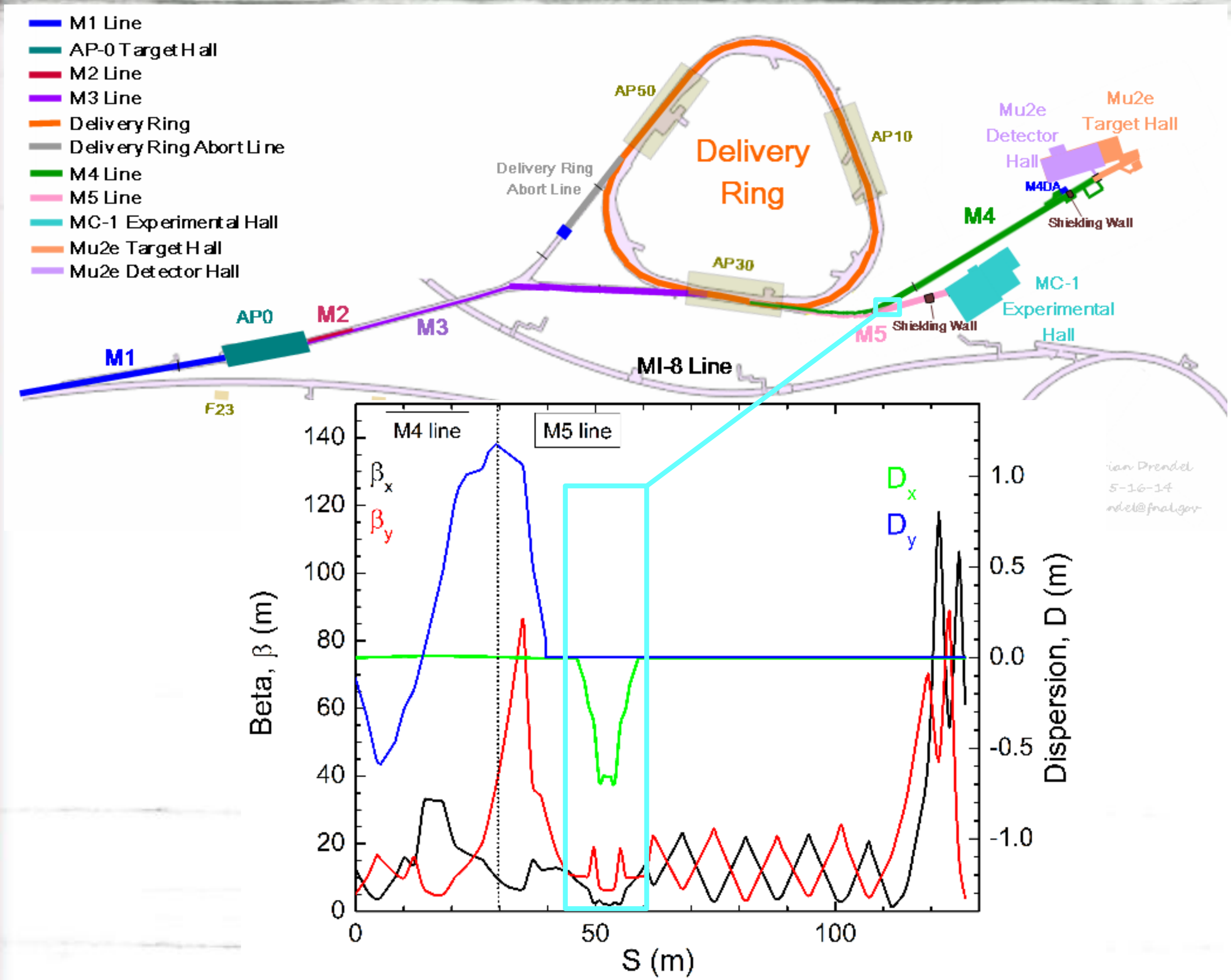


- Statistical uncertainty of the measurement dependents on muon intensity. Essential to place as many muons as possible into a stable orbit in the ring.
- The ring accepts only a fraction of the delivered muons

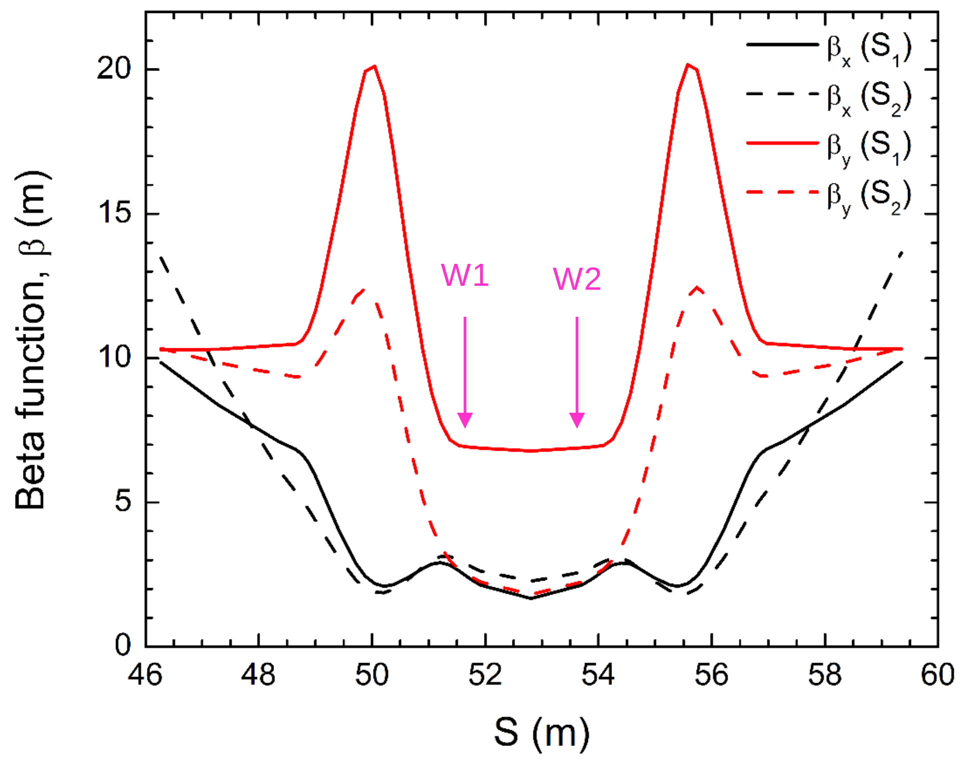
Choice of location (1)

- For practicality, it is highly desirable to build the system without modifying the existing Muon Campus beamline
- Absorber is expected to trigger emittance growth & mismatches so it is preferred to place it downstream of both injection to DR & extraction from DR areas wherein the narrowest apertures exist.
- Pick the last horizontal bend string in the M5 line. There are two more advantages for this selection:
  - Beam is free of protons and the remaining muons are at low rates, hence energy deposition is at negligible levels
  - Considerable dispersion and relatively low beta functions (next slide)

Choice of location (2)



Choice of location (3)

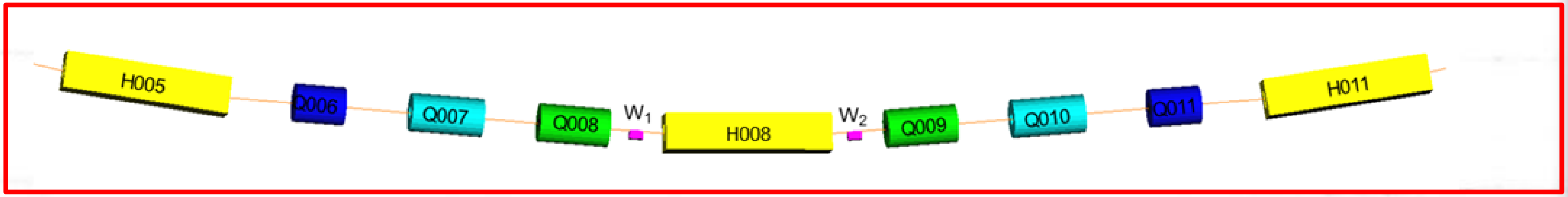


Two alternative solutions for the beam optics:

– TDR (baseline) solution S_1

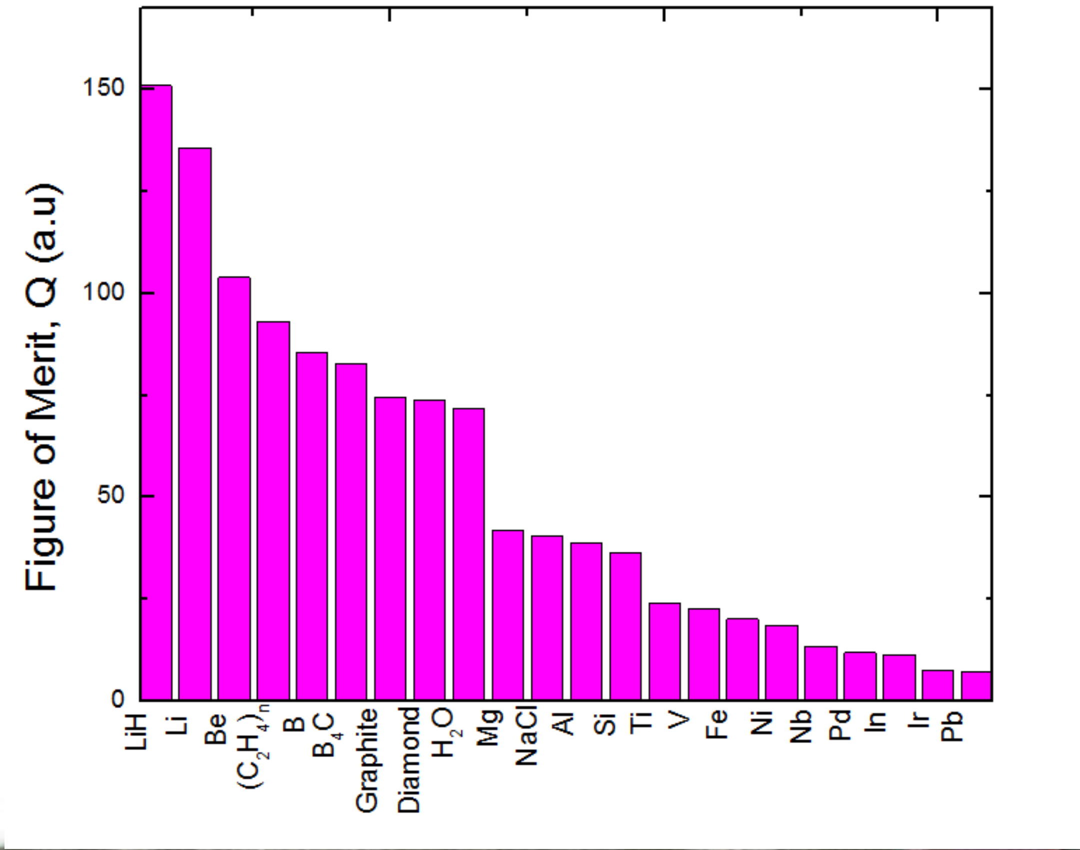
– Modified solution S_2 that has similar properties to S_1 but much lower vertical beta function

– Dispersion is in the 0.65 - 0.75 m range



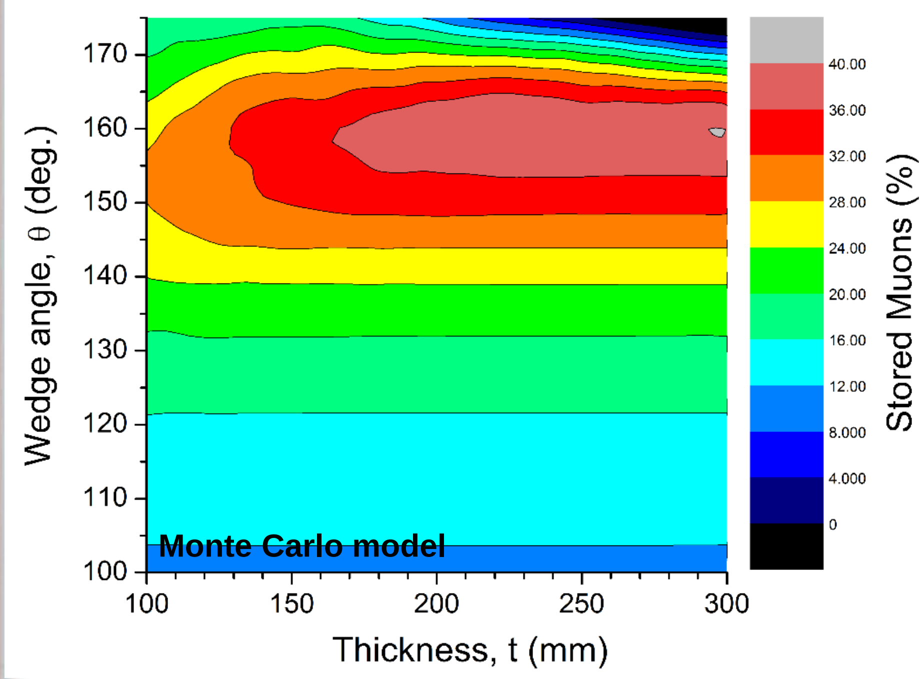
Choice of material

- We can establish a merit factor Q, that takes into account the cooling term (dE/ds) and scattering term $(1/L_R)$, i.e. $Q = L_R \times dE/ds$

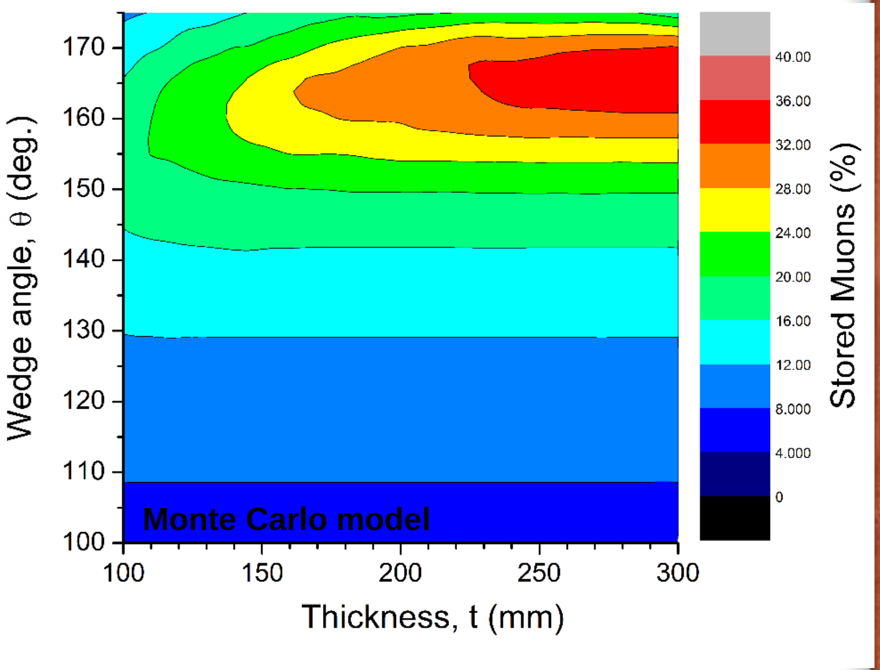


Choice of angle and length (1)

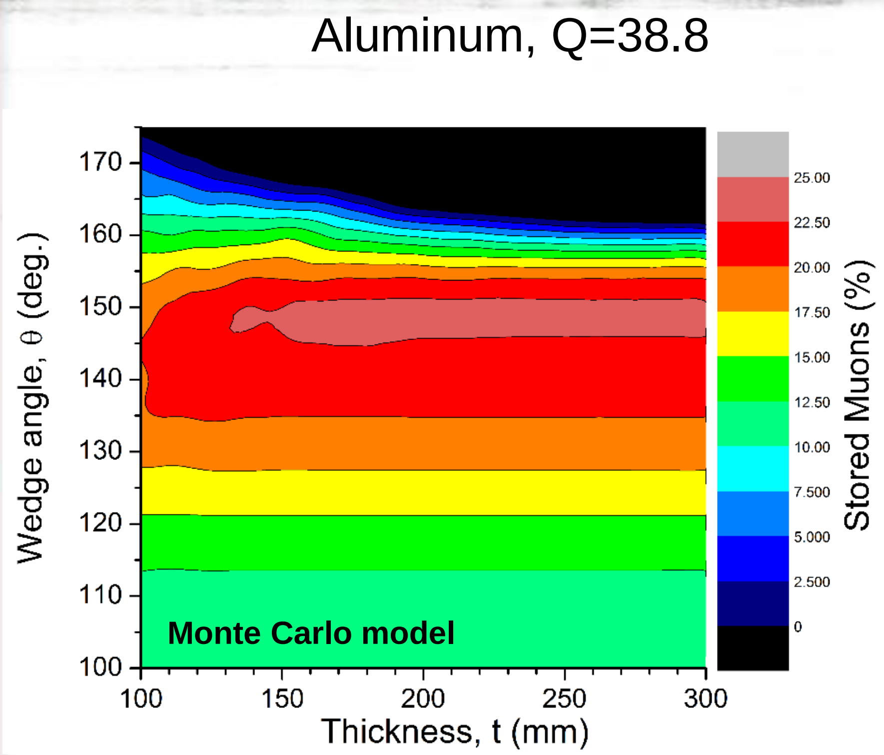
Beryllium, Q=104.0

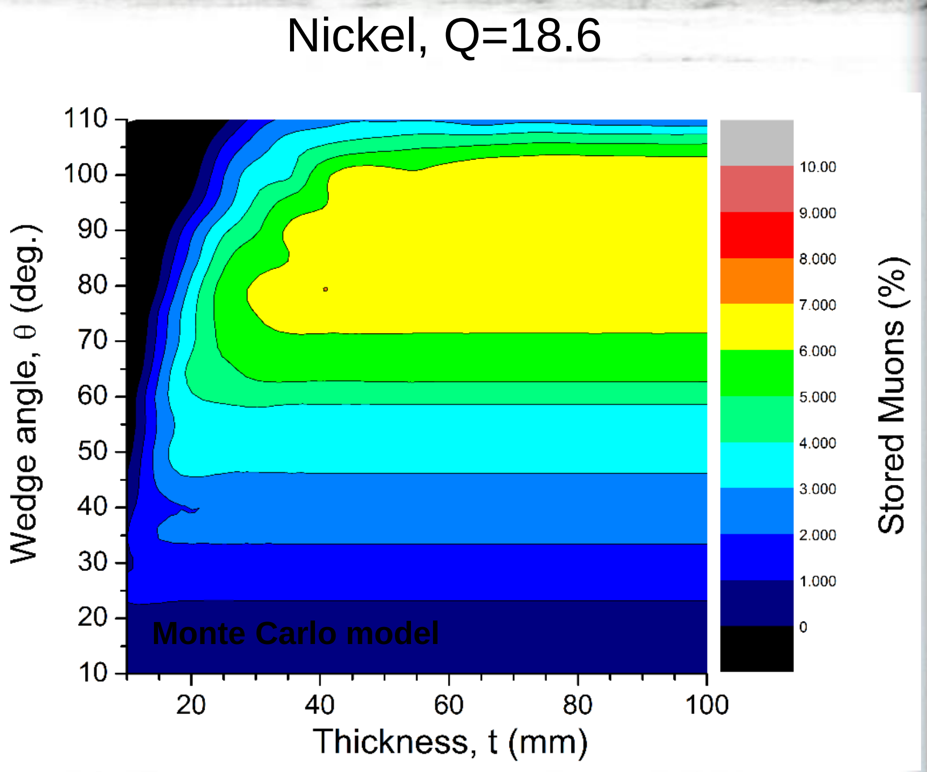


Polyethylene, Q=93.1



Choice of angle and length (2)

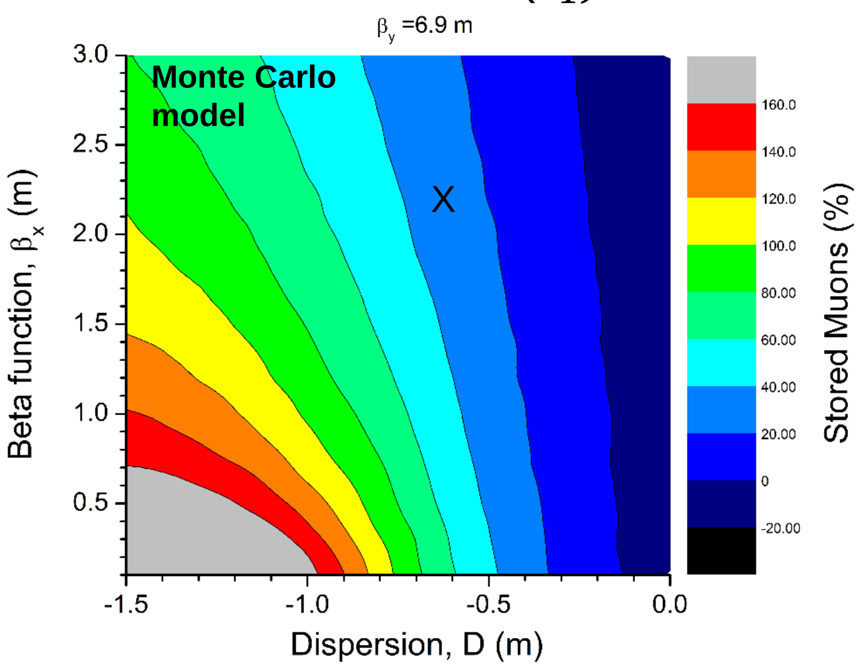




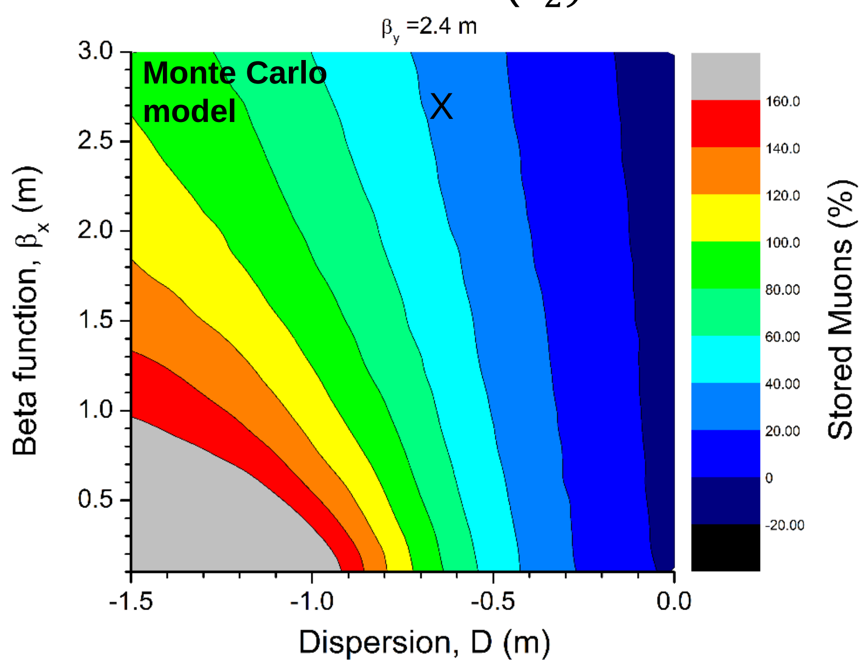
- Colors and performances are not same for the two plots!

Choice of optics

Solution 1 (S_1) – TDR



Solution 2 (S_2) - Carol

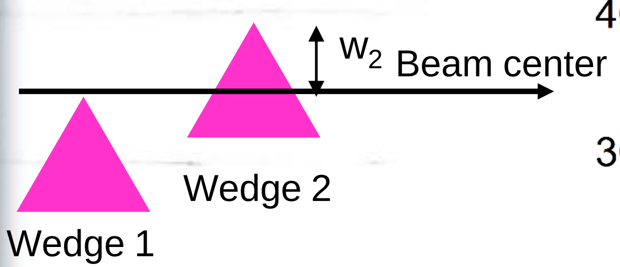


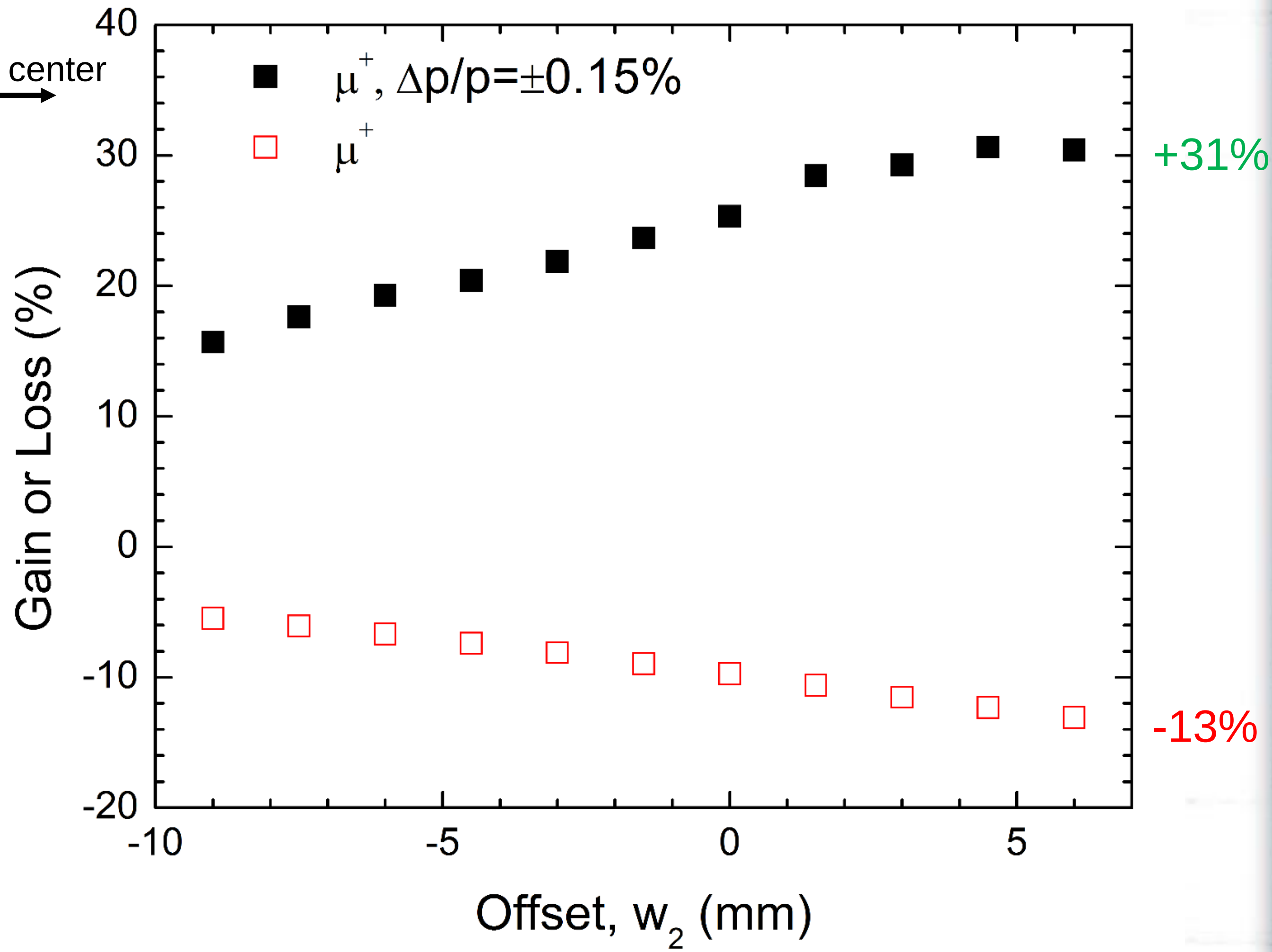
- While a point with D >1 & beta <1 is preferred, with the tools available (hardware, magnets) points (x) are currently possible
- Monte Carlo assumes perfect matching & injection and no straggling. More detailed simulation in the next slides

Simulations

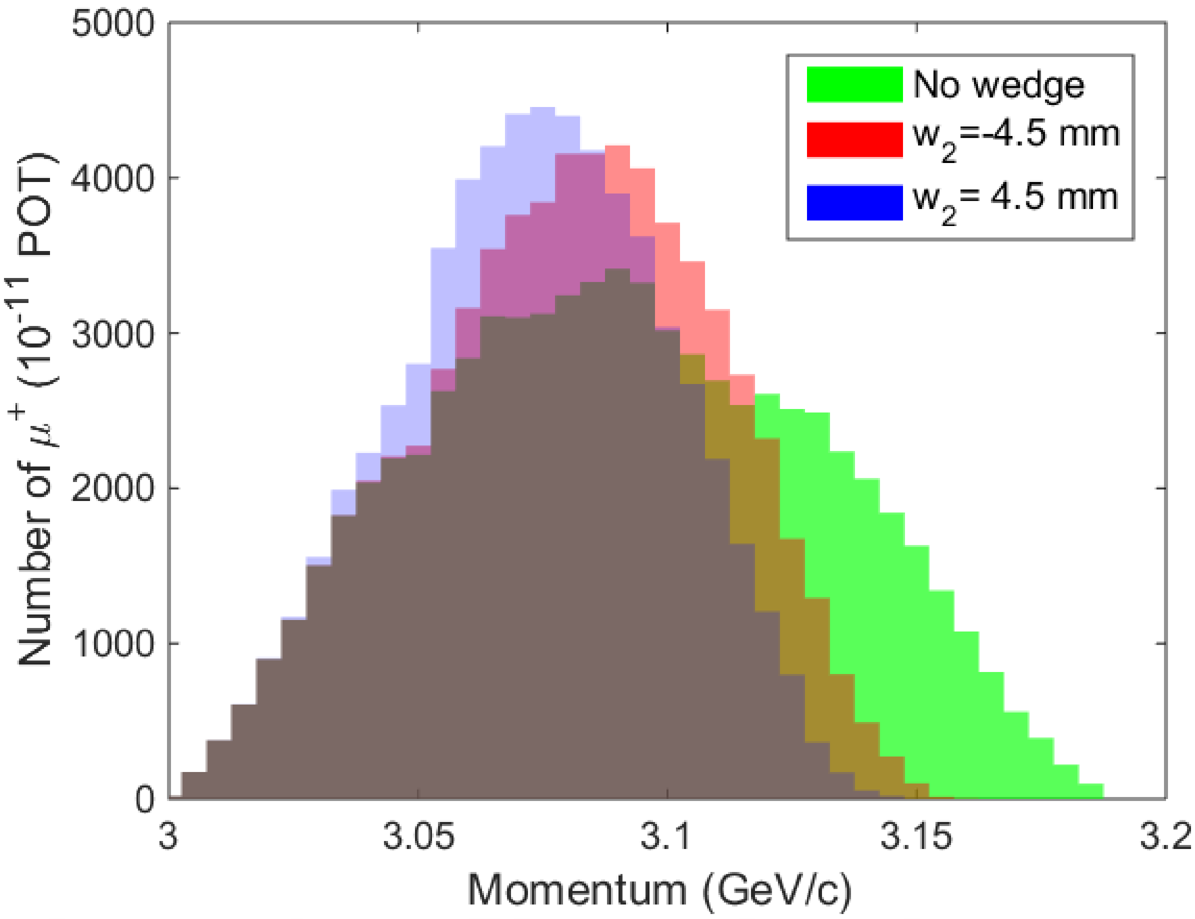
- Monte Carlo model provides a good first-order estimate. However, to further access feasibility of the wedge system it must studied under more realistic assumptions
- Use G4beamline, a Geant4 based code, that incorporates key particle-matter physical processes (energy loss, straggling, multiple scattering) as well as includes decays and spin precession
- All simulations start at ECMAG using a realistic beam distribution that is the outcome of an end-to-end simulation from the target

Performance at the end of M5 (1)

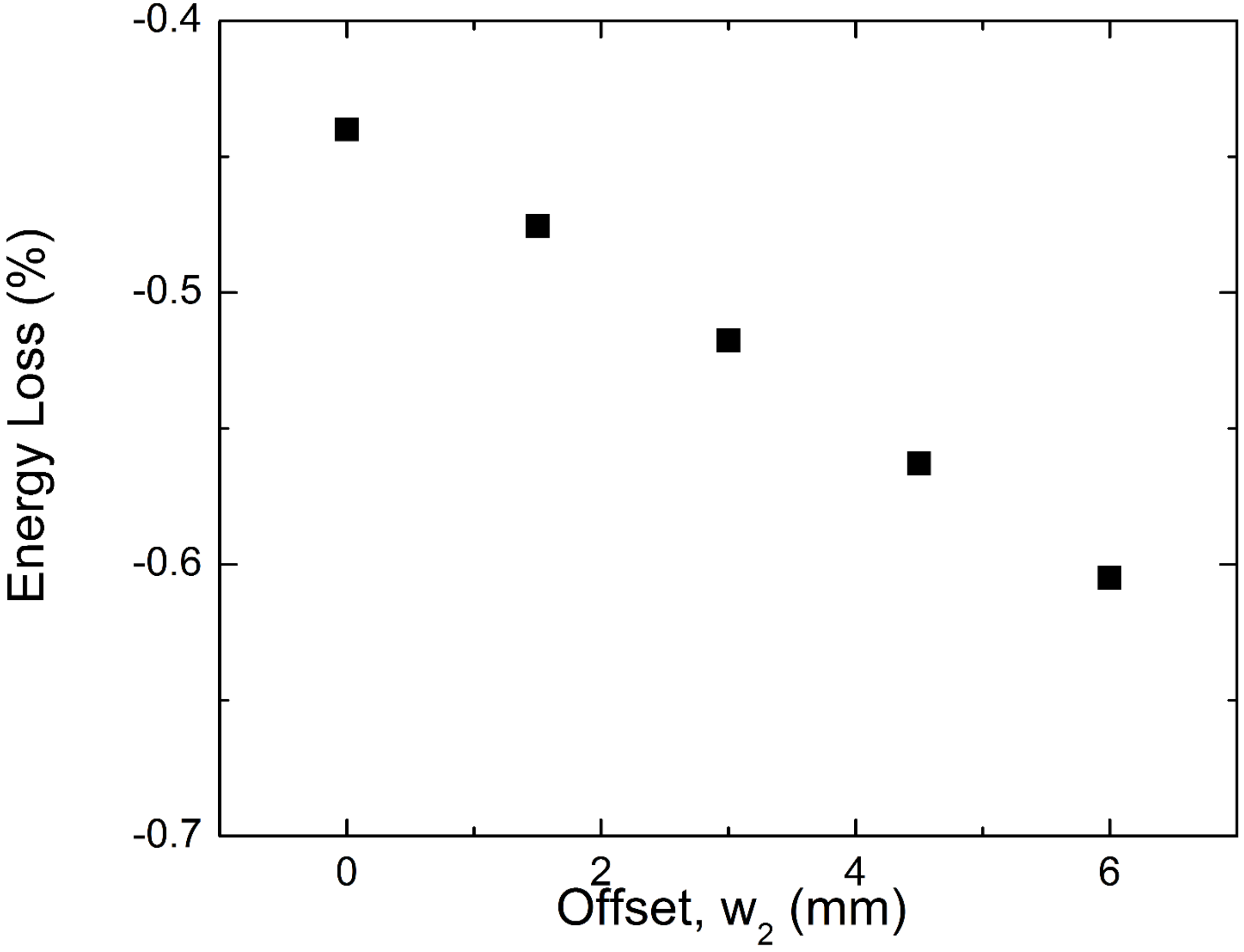




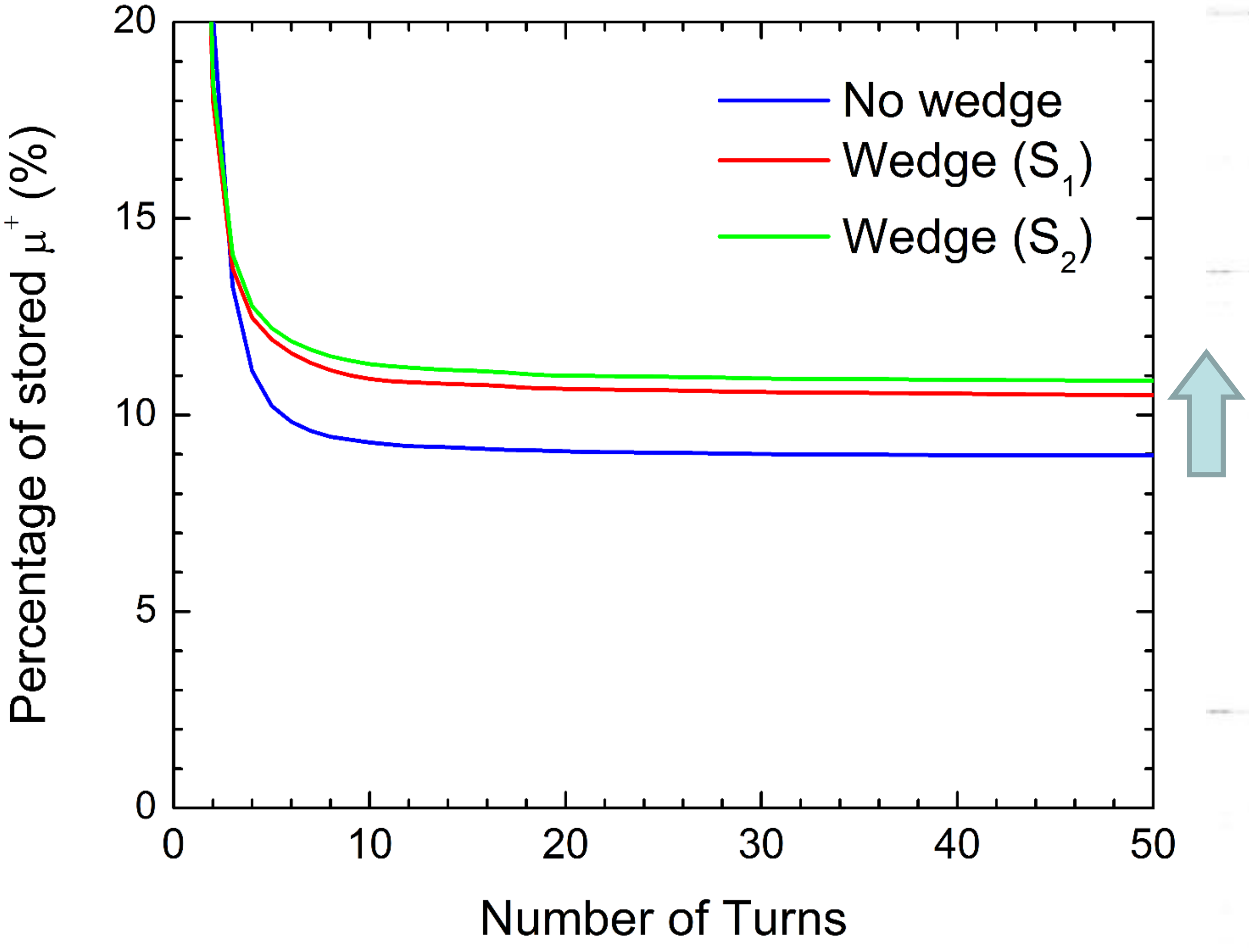
Performance at the of M5 (2)



Performance at the of M5 (3)



Storage ring performance

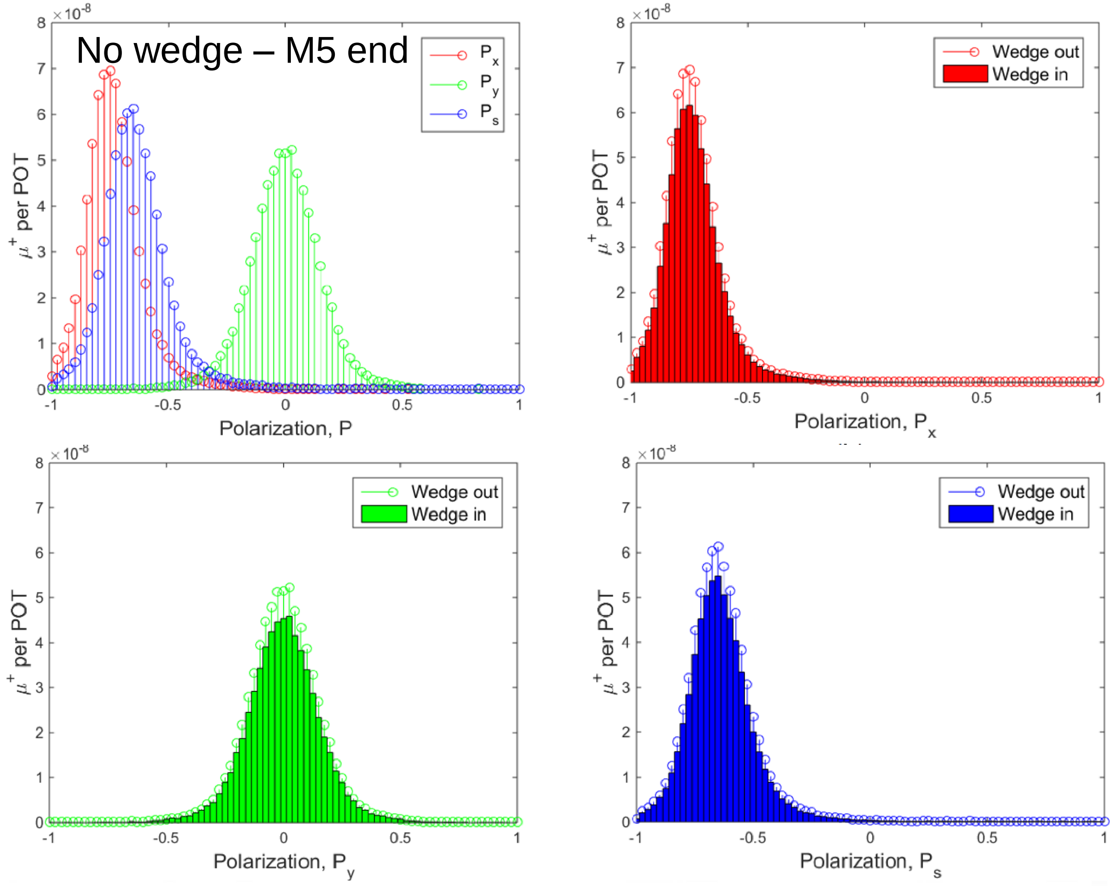


Gain: 21%

Acceptance limits

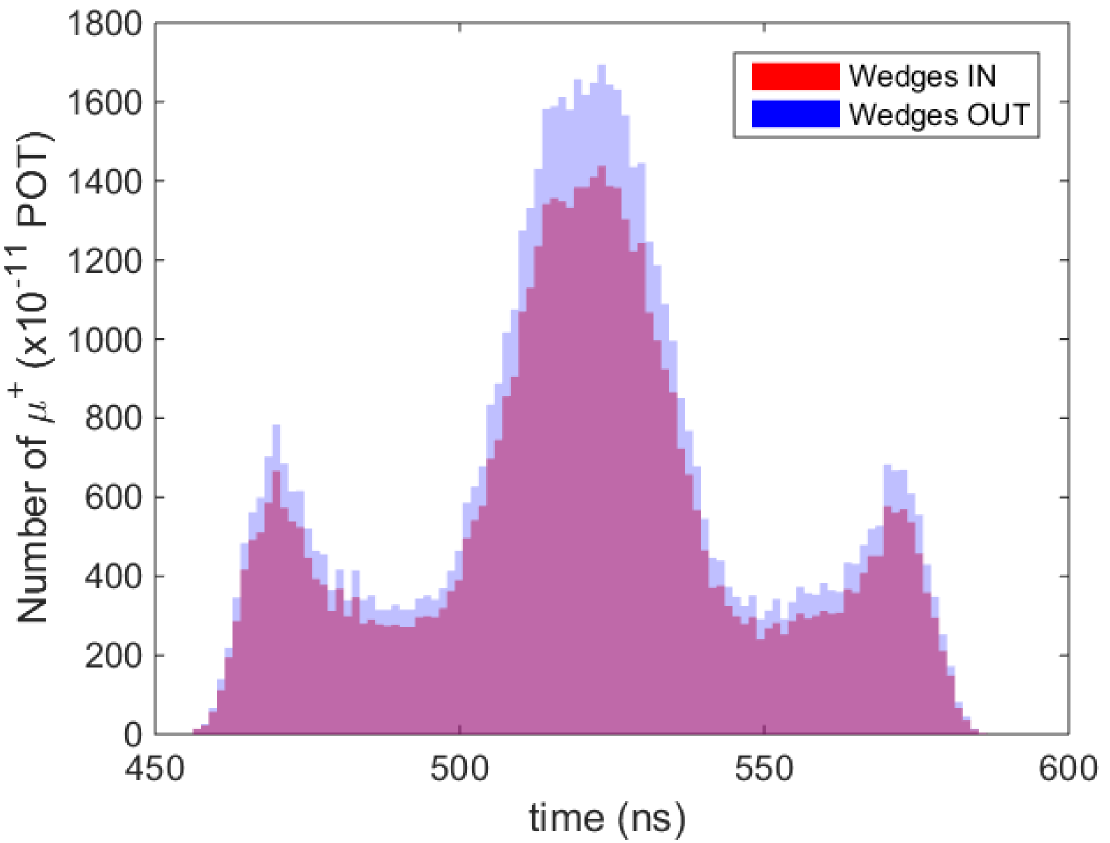
- Assuming 27.2 kV operation for the quads, the peak beta functions in the ring are $\beta_x = 8.0\ \mathrm{m}$ and $\beta_y = 18.0\ \mathrm{m}$
- The beam is constrained into a 45 mm aperture
- Therefore acceptance limits are $A_x = 253\ \mu m$ and $A_y = 112\ \mathrm{\mu} m$
- This may explain the better performance for solution S_2

Influence in muon polarization

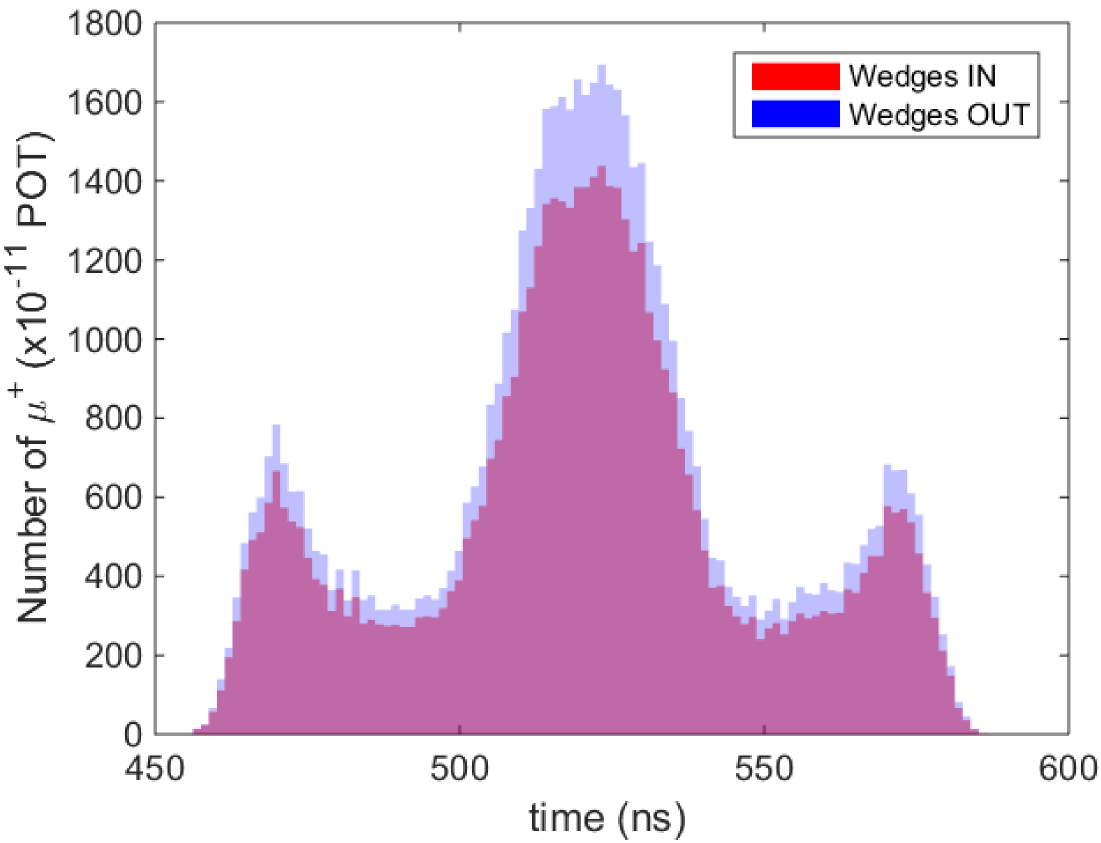


- The wedge has a negligible effect on polarization and therefore can be safely inserted along the beam path.

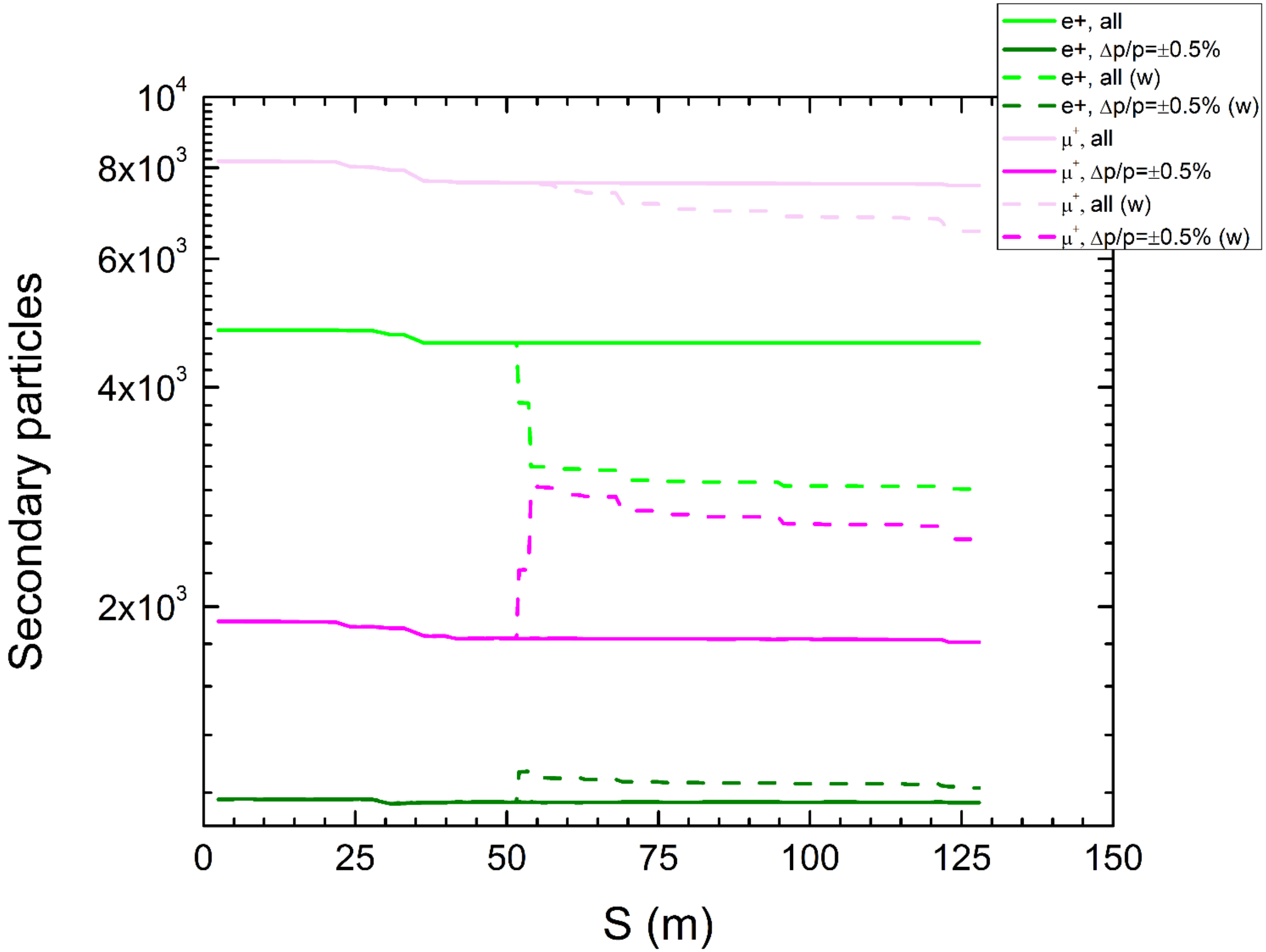
Influence in time profile



Influence in time profile



Positron removal?



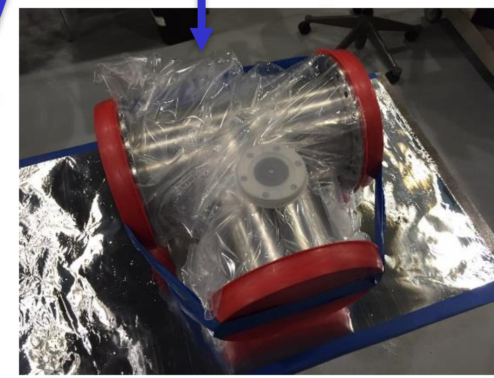
Fabrication and installation progress

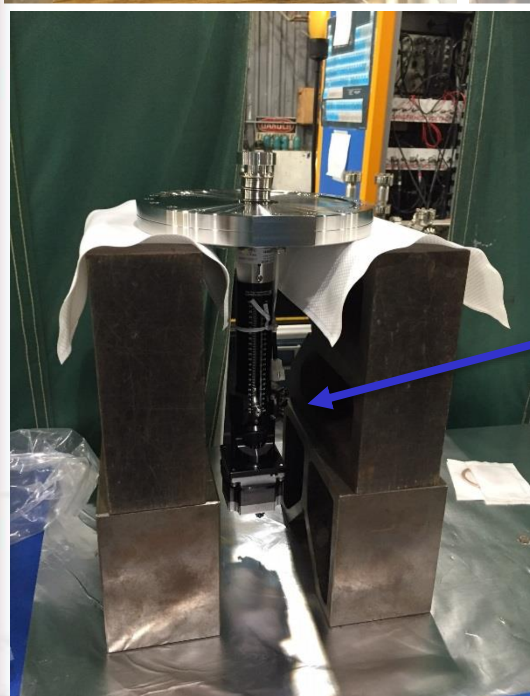
Polyethylene wedge

Boron Carbide wedge

New power supplies for downstream optical matching

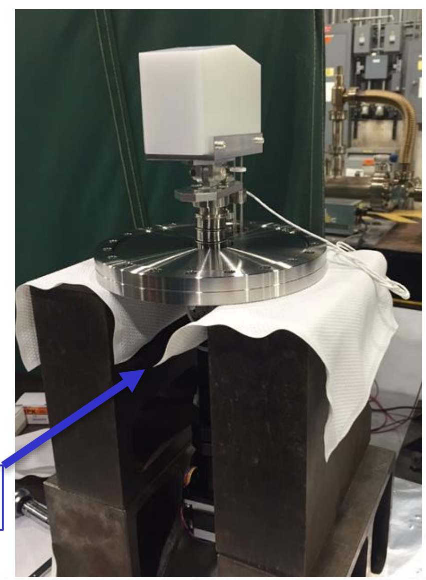
Wedge housing



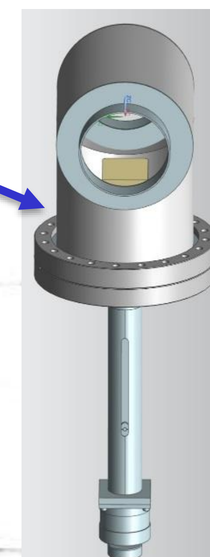


Wedge insertion actuator
with submillimeter precision

Motion-control tests

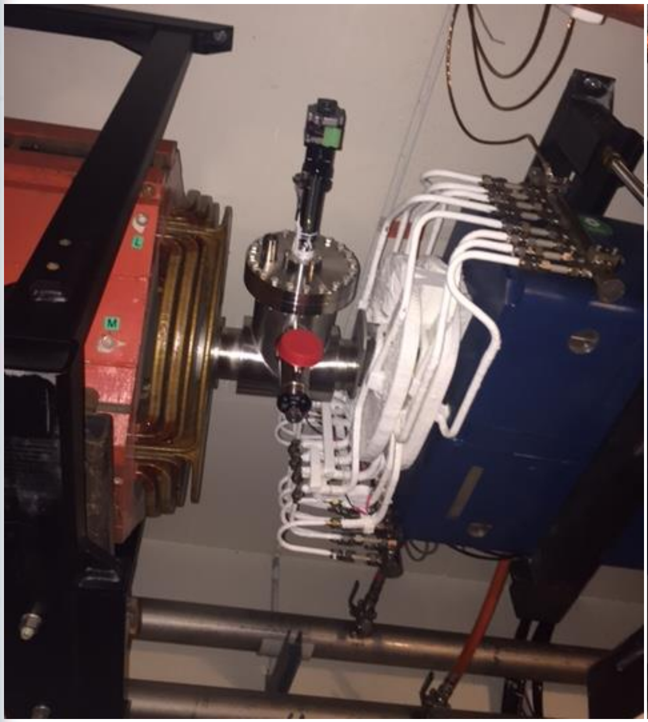


Design of complete mechanical assembly

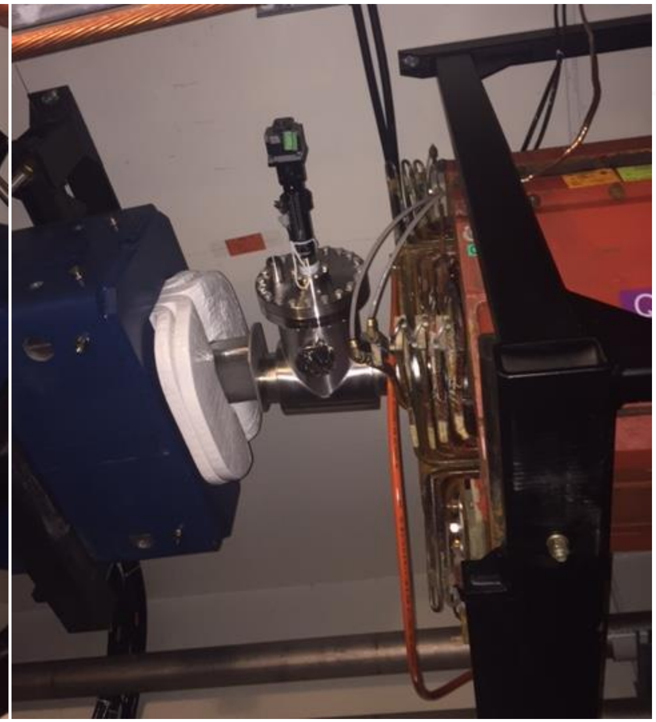


Wedges in Muon Campus

M5, Wedge 1



M5, Wedge 2

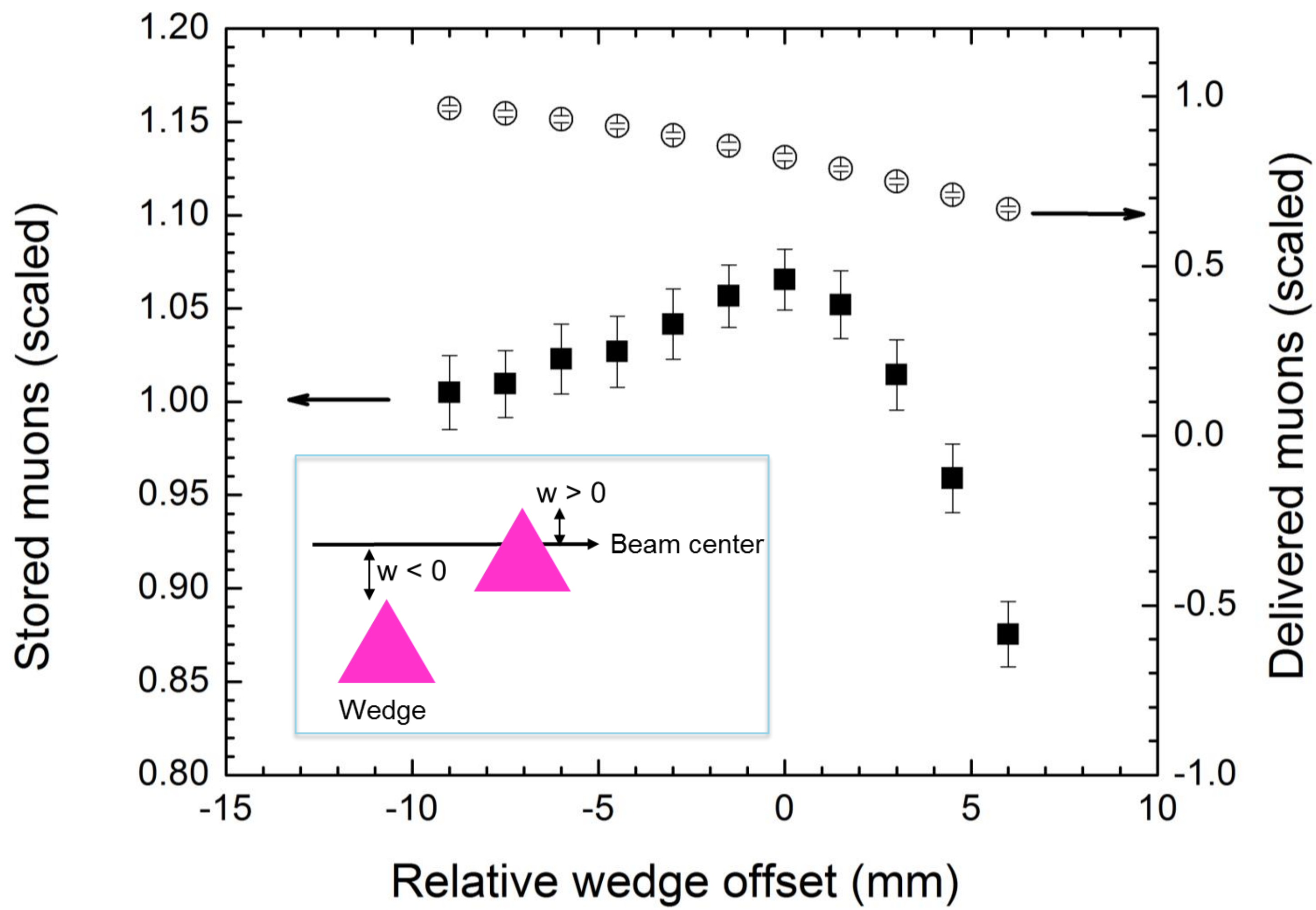


DR Wedge

- Special thanks to Jim Morgan for monitoring the fabrication and installation process

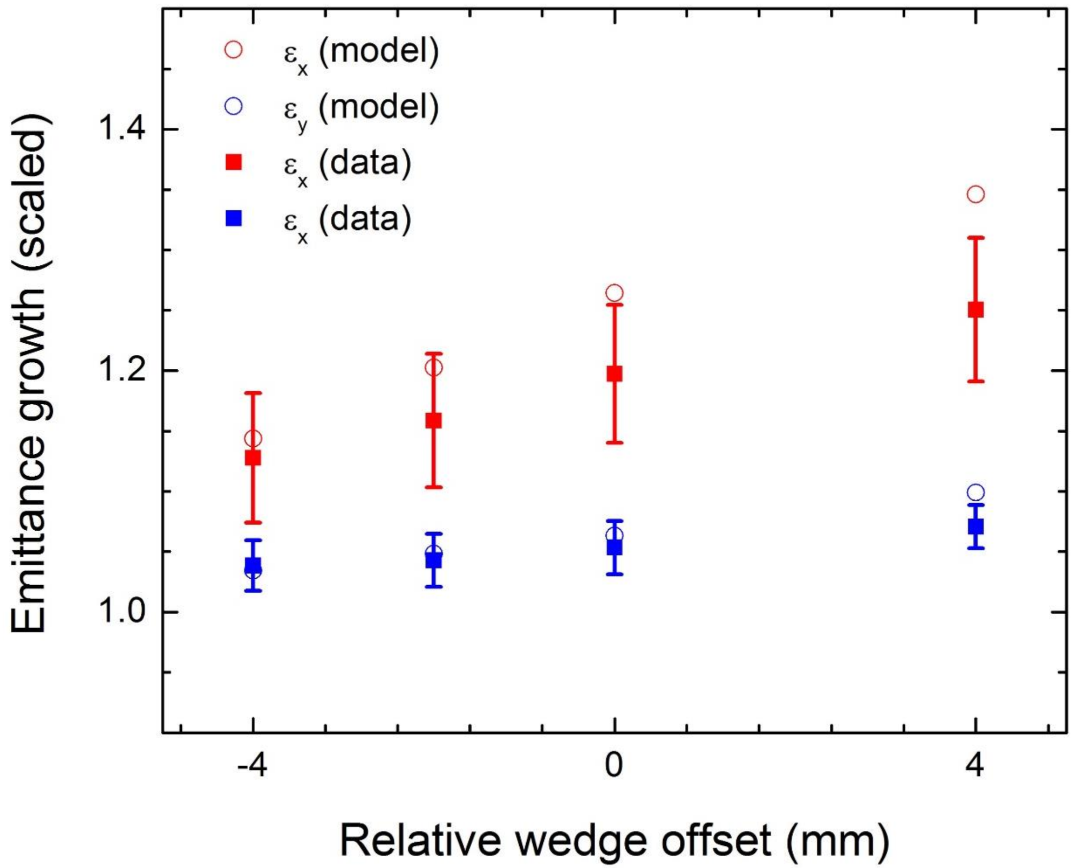
Test with a Boron Carbide wedge

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



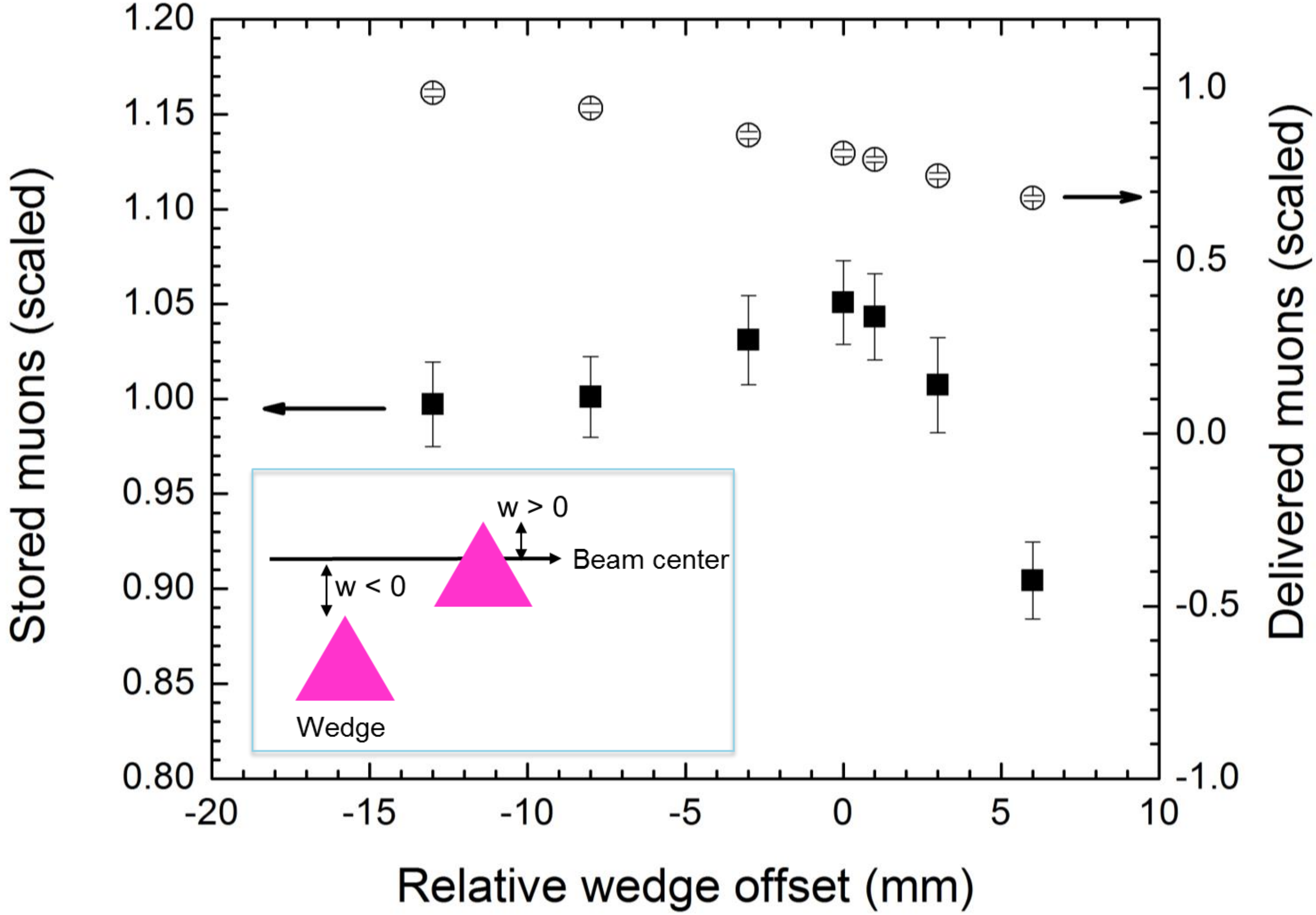
Emittance exchange

- While the momentum spread reduces, the transverse emittance grows as a result of the emittance exchange



Test with a Polyethylene wedge

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



Fermilab

Possibilities for improvement

- Lattice designs that will provide a higher dispersion and lower beta function could improve the performance of the wedge