Muon Beams at Fermilab

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NuFact 2021 (online)
9 September 2021

Outline

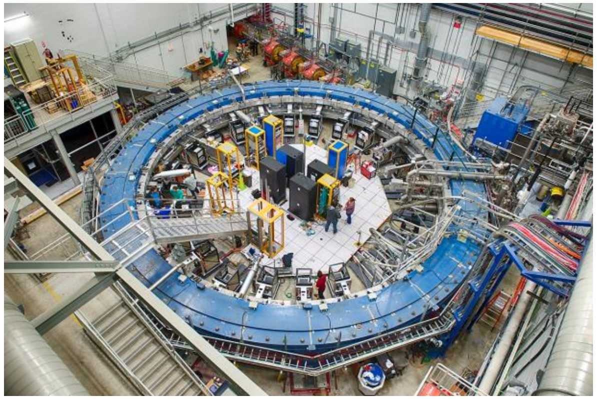
- Overview of the Fermilab Muon Campus
- Commissioning experience of the Muon Campus
- Operational experience of the Muon Campus
- Comparison between data, simulation and theory
- Strategies to improve performance
  - Using passive wedge absorbers
  - Using an open-ended inflector design
- Summary

Motivation

- In the next decade Fermilab will host two world-class precision science experiments:
  - The **Muon g-2 experiment** will determine with high precision the anomalous magnetic moment of the muon.
  - The **Mu2e experiment** will improve the sensitivity on the search for a neutrinoless conversion of a muon to an electron.
- A dedicated accelerator facility to provide beams to both experiments has been designed and constructed at Fermilab
- The Muon g-2 experiment will precede the Mu2e experiment
- In this talk, I will discuss the commissioning and operational effort of this accelerator facility for the Muon g-2 Experiment

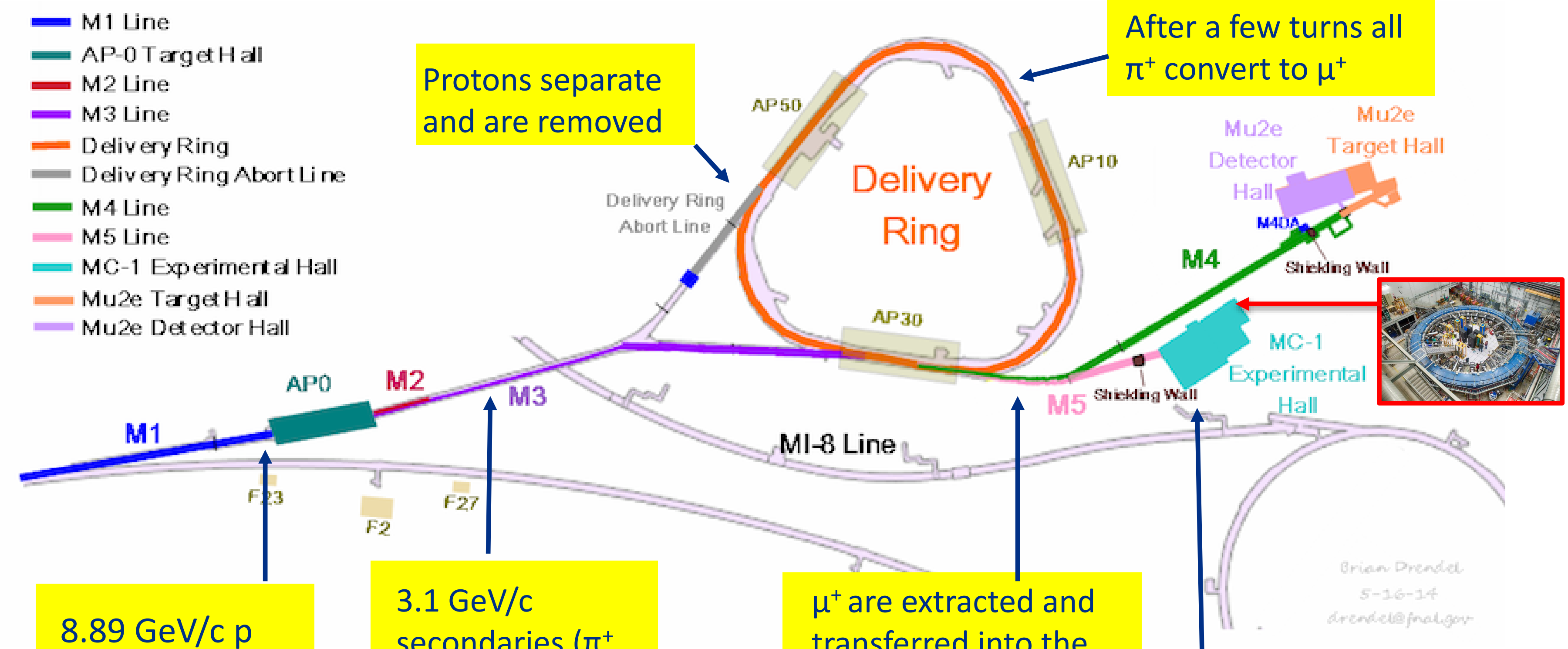
Fermilab Muon g-2 Experiment

- 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: $\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \vec{\beta} \times \vec{E}\right]$
- Requirement
  - Requires delivery of $1.4\text{x}10^{14}$ muons in the ring which is x20 the statistics of the BNL experiment

Muon Campus layout



After a few turns all π^+ convert to μ^+

Protons separate and are removed

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

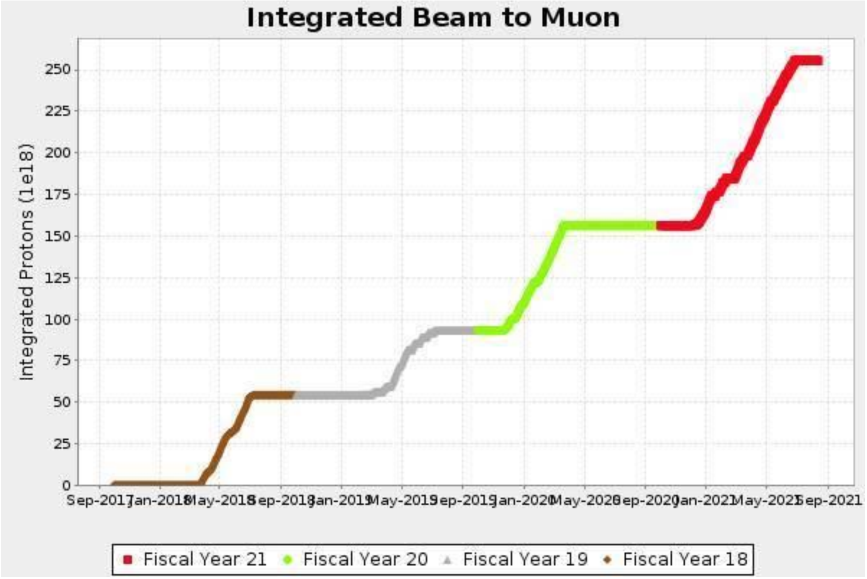
- The delivered muon beam is free of protons and pions, which created a major background in the BNL experiment

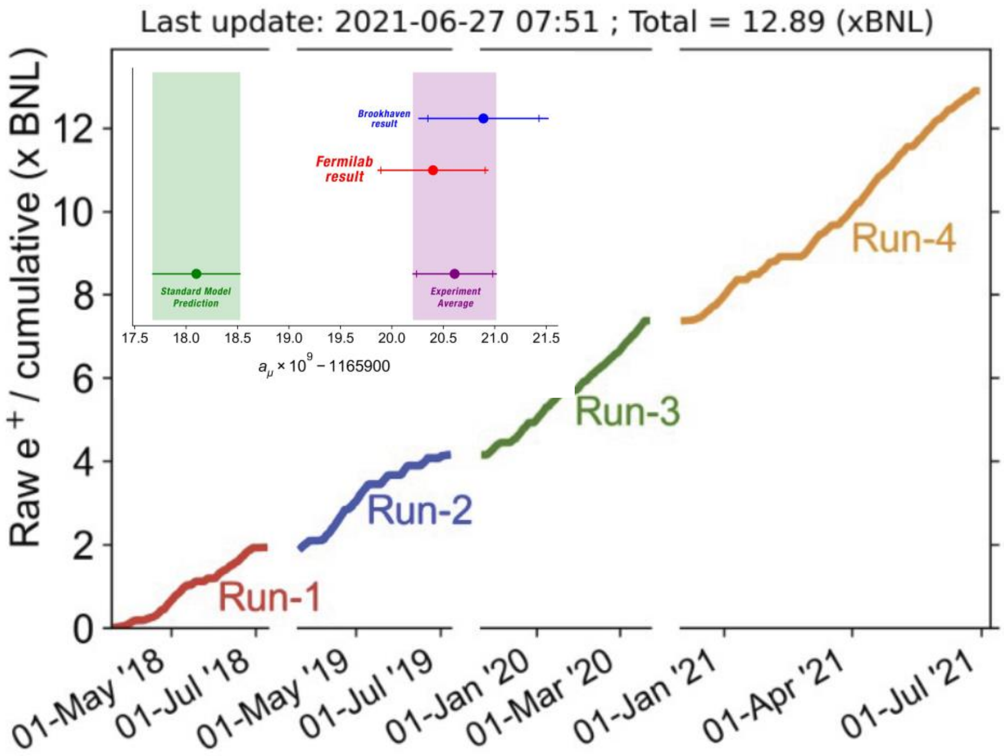
Milestones of the Muon Campus

- Started accelerator installation in May 2013
- Started beam commissioning in Apr. 2017
- Stored the first muons in the storage ring in May 2017
- Completed commissioning phase and begun normal operations for the Muon g-2 Experiment in Dec. 2017
- Completed Run 1 (2018), Run 2 (2019), Run 3 (2020) and Run 4 (2021). Routinely collect 1x BNL statistics per month. >12x BNL collected so far.
- Released first results in April 2021
- End of FY23 Muon g-2 stops. Mu2e physics run begins.

Performances

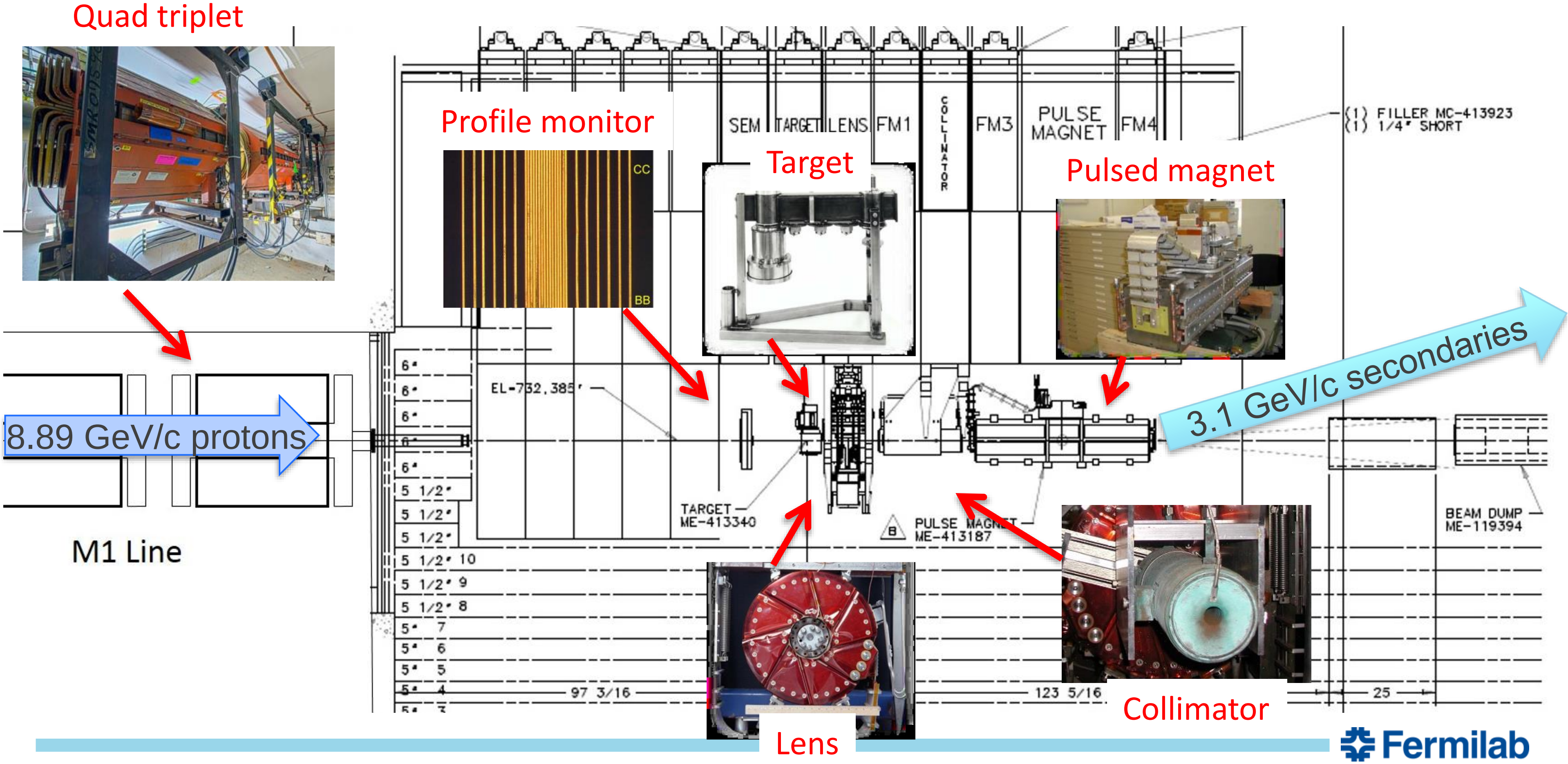
- Muon Campus delivers 3.2e07 muons per protons on target
- So far, 8e13 muons have been injected into the storage ring
- We estimate that 2e12 have been stored inside the ring





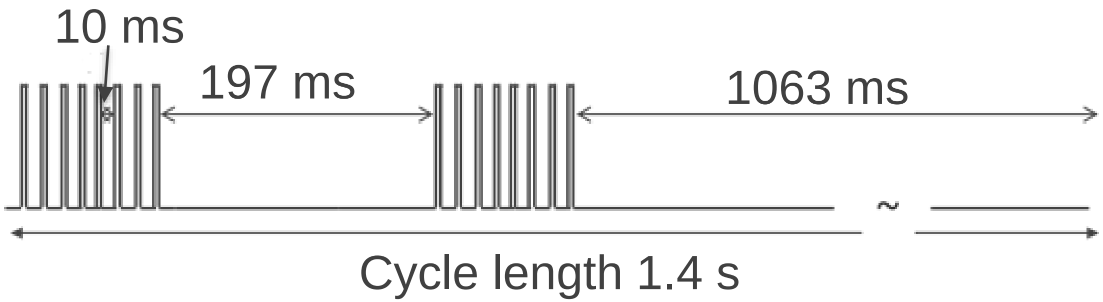
Target station

- Includes a target, Li lens, collimator, pulsed magnet & dump
- Flexible quad triplet upstream to adjust primary beam size

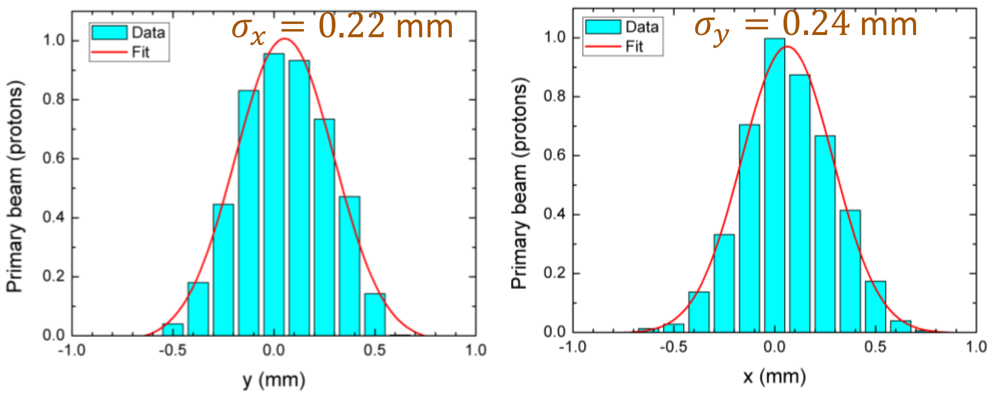


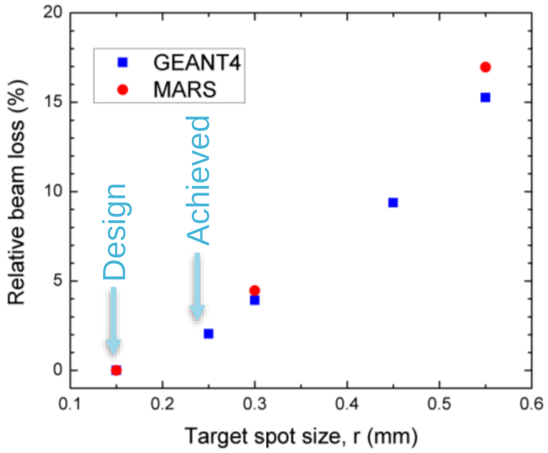
Primary beam on production target

- Bunch coalescing of incoming beam via four 2.5 MHz cavities shapes bunches to the desired length and intensity
- Performance sensitive to beam spot size on target



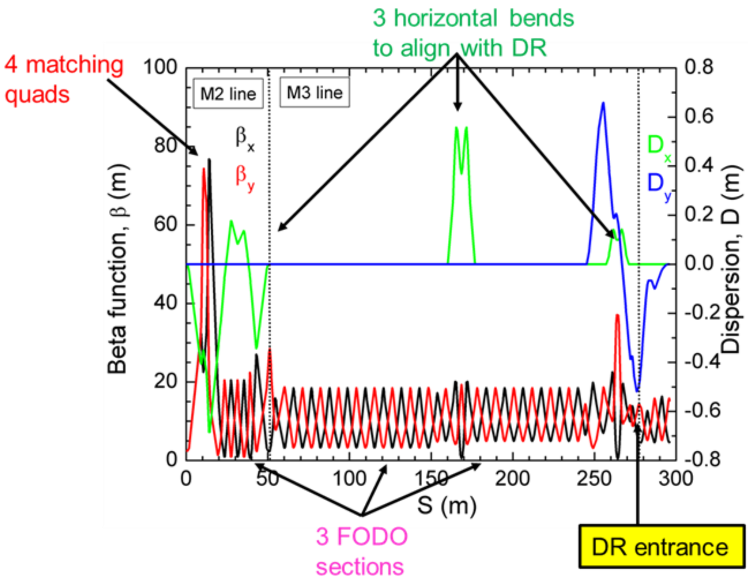
Parameter	Value
Protons on target (POT)	10^{12} per pulse
Pulse width	120 ns
Number of pulses	16
Bunch average frequency	11.4 Hz
Primary kinetic energy	8 GeV

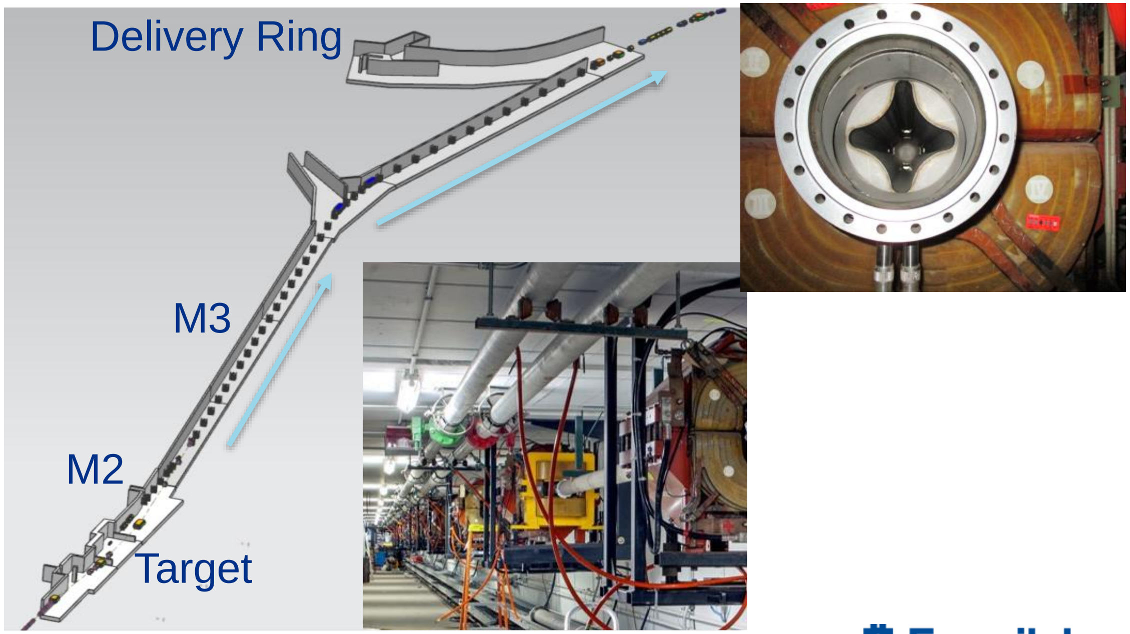




Muon capture and transport lines (M2-M3 lines)

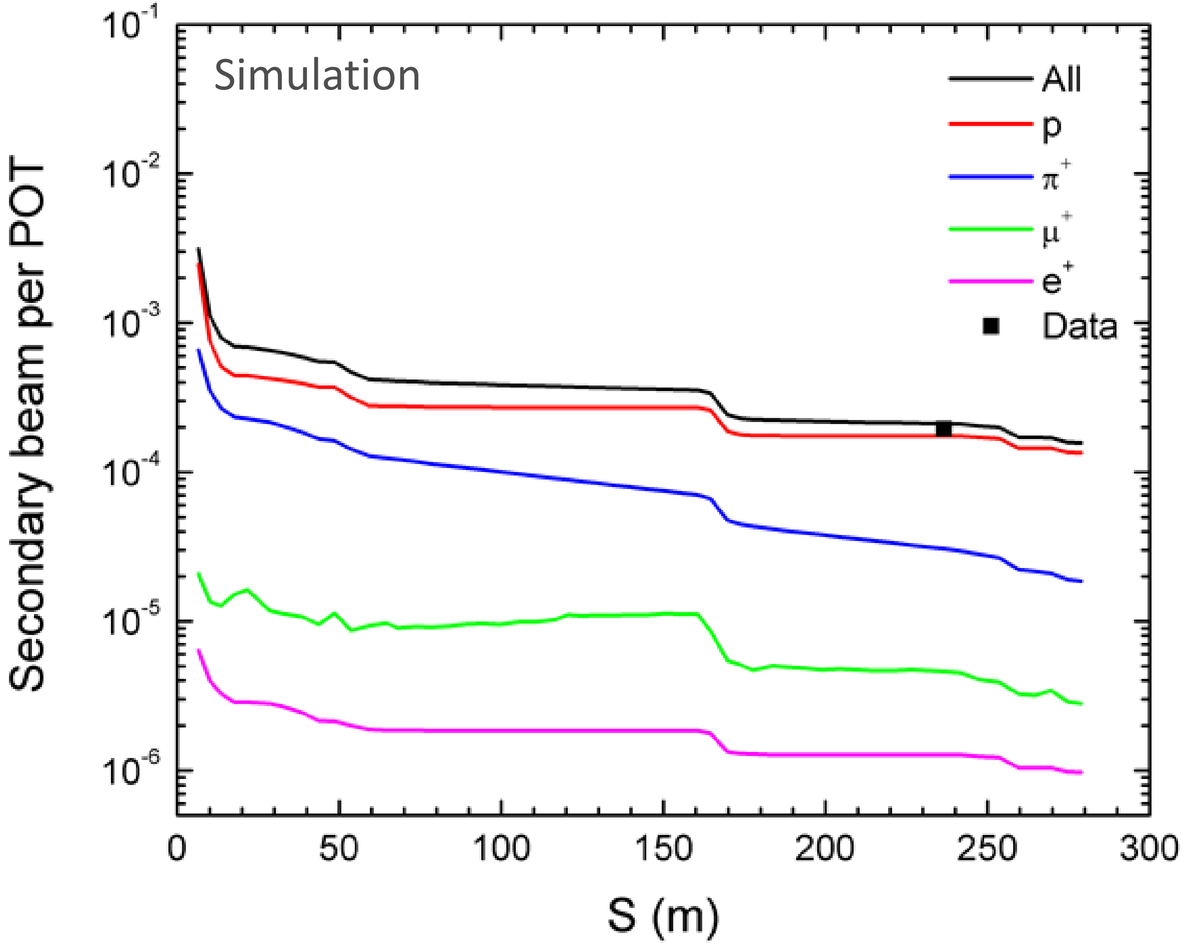
- Beamlines have a high magnet density with large aperture quadrupoles to maximize capture of pions and muons
- Mostly muons from forward decays are accepted and the polarization is 90%
- 70% of the pions are expected to decay along the M2-M3 lines





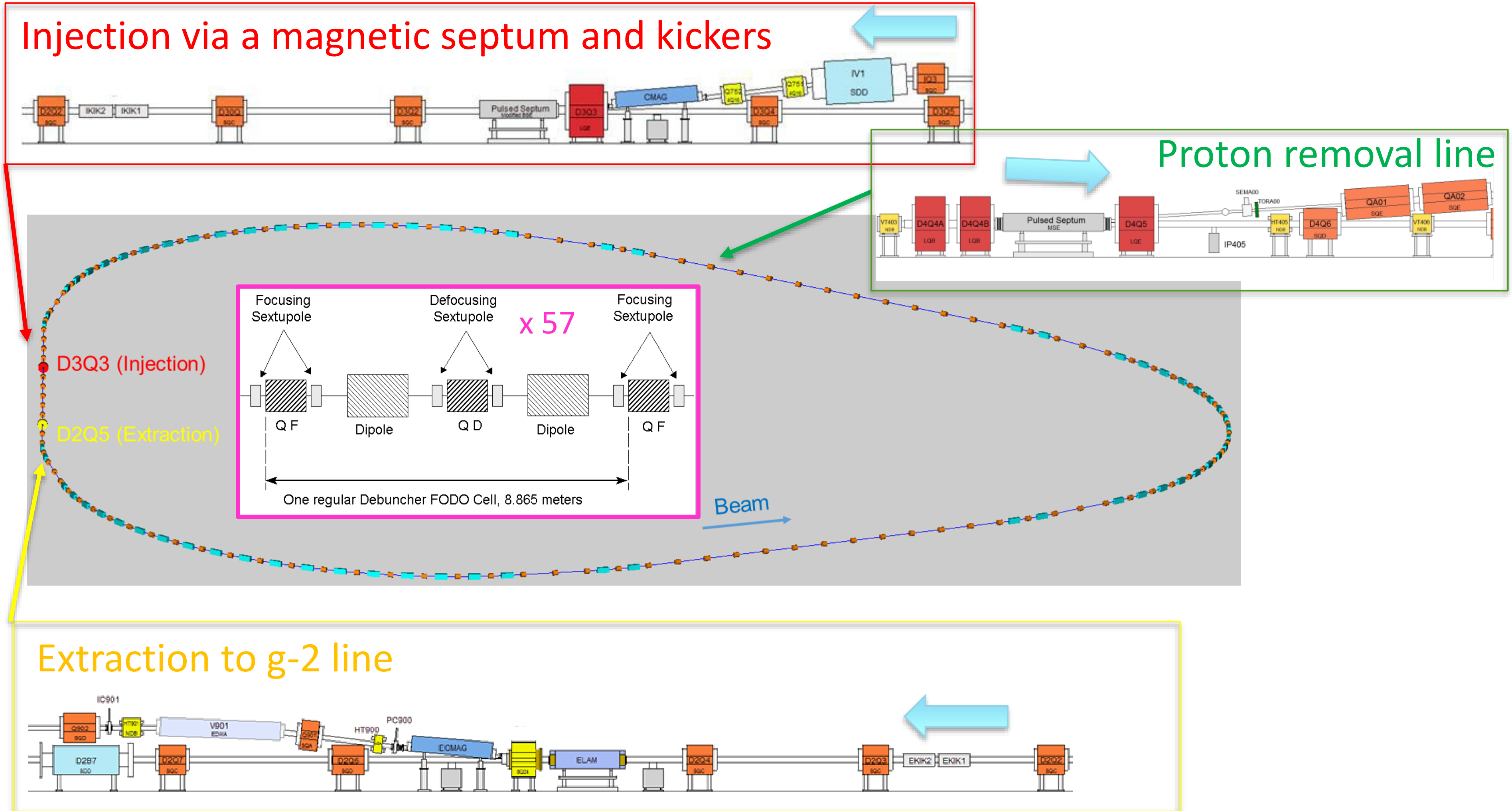
Beam performance along the M2-M3 lines

- Measured intensity at the end of the line matches simulation



Delivery Ring (DR)

- DR is 505 m long and contains 57 FODO cells with 66 dipoles



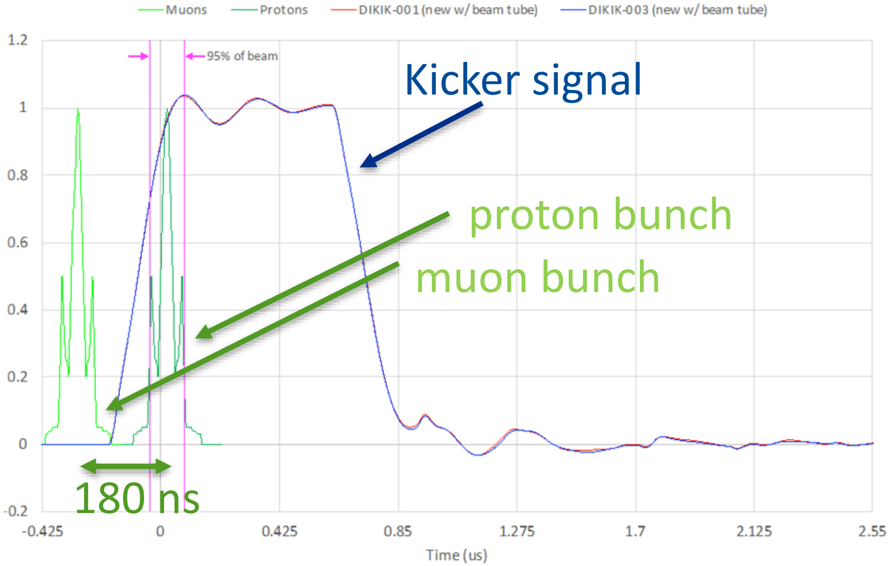
Injection via a magnetic septum and kickers

Proton removal line

Extraction to g-2 line

Proton removal

- Muon and proton bunches separate by 75 ns per turn
- Kicker rise ~180 ns; protons removed during turn 4
- Remaining beam extracted to g-2 after turn 4
- Commissioned in Dec 2017

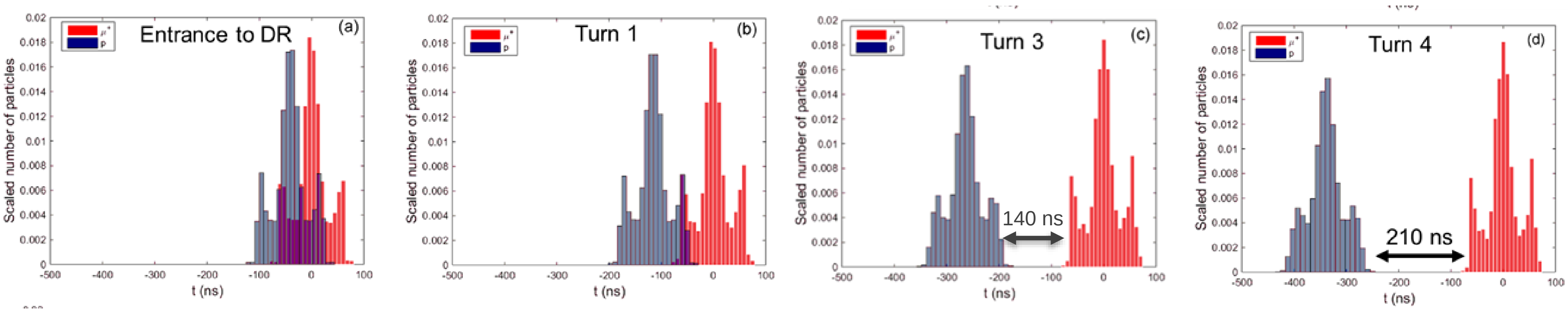


Kicker signal

proton bunch

muon bunch

180 ns



Entrance to DR

Turn 1

Turn 3

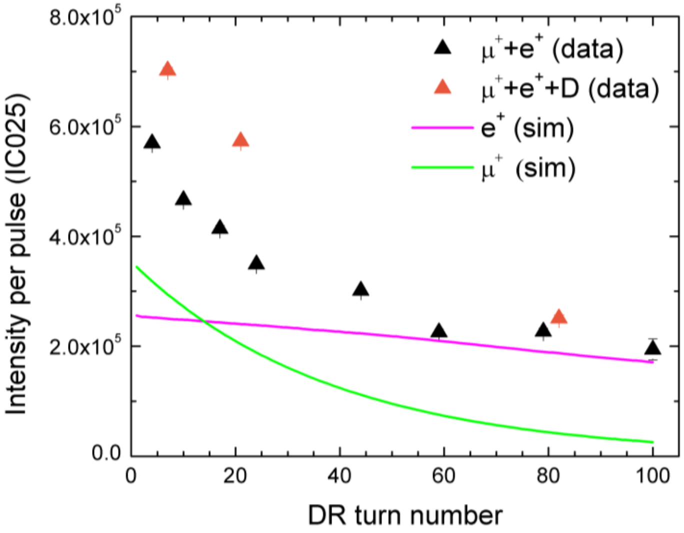
140 ns

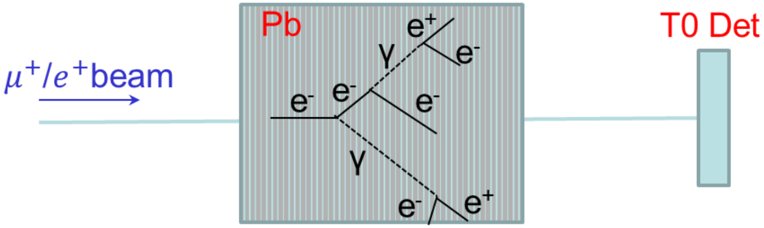
Turn 4

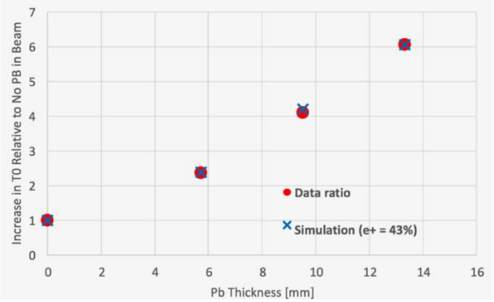
210 ns

Measuring positron rates

- Protons were extracted at turn 4; increased to 100 turns to find the e$^+$ rate
- After 100 turns, 31% of e^+ are lost due to synchrotron radiation
  - Turn 4: $N_e + N_\mu = 5.69 \times 10^5$
  - Turn 100: $\frac{69}{100} N_e + \frac{7}{100} N_\mu = 1.94 \times 10^5$
  - $\mu^+ = 57\%$ and $e^+ = 43\%$
- Independent test with a variable thickness Pb block gave same result!

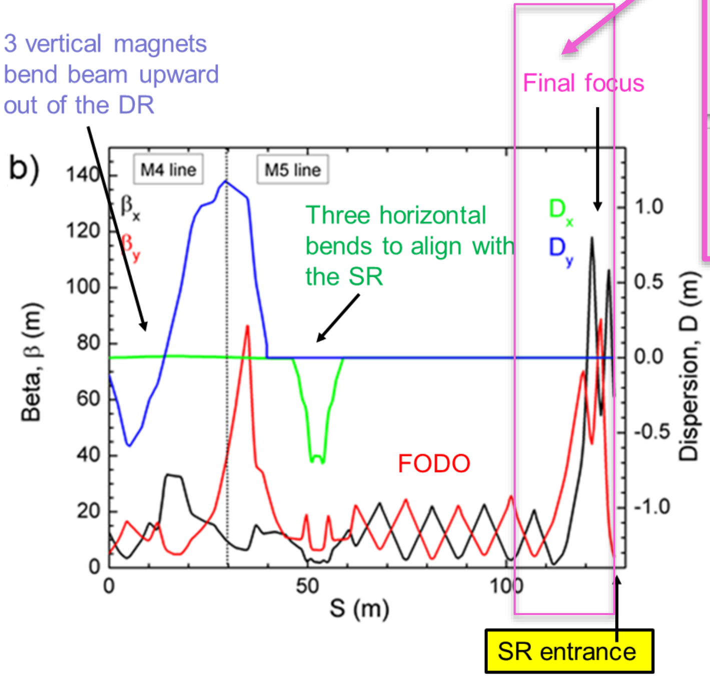






Muon transport to g-2 line (M4-M5 lines)

- 127 m long and transports beam from the DR to the g-2 ring

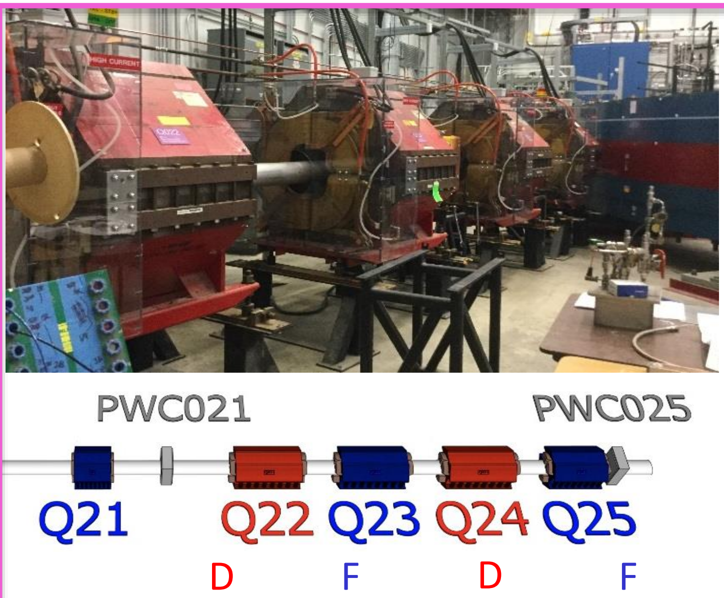

3 vertical magnets bend beam upward out of the DR

Final focus

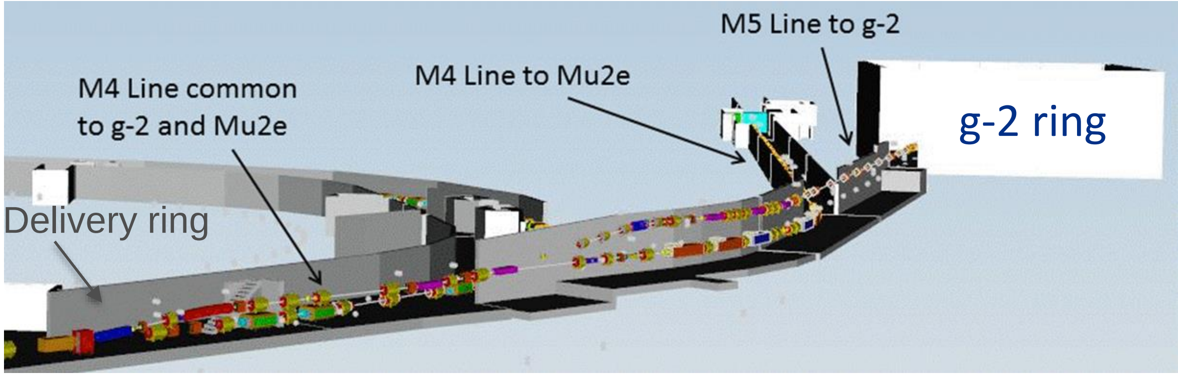
Three horizontal bends to align with the SR

FODO

SR entrance

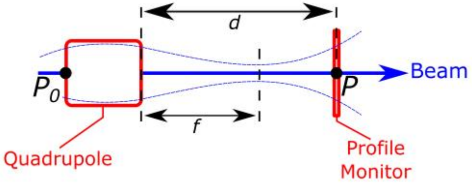


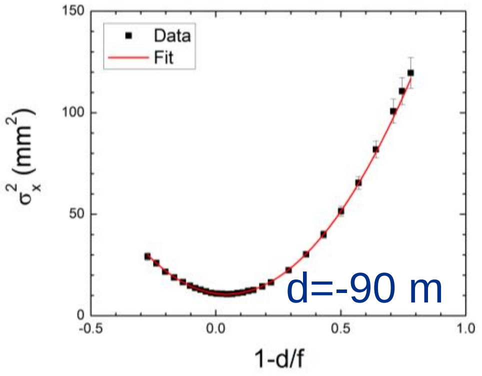
Tunable final focus to optimize injection into the ring

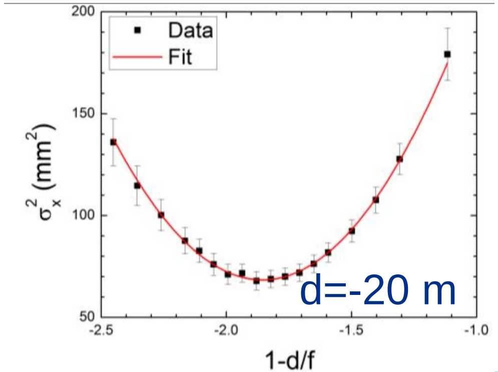


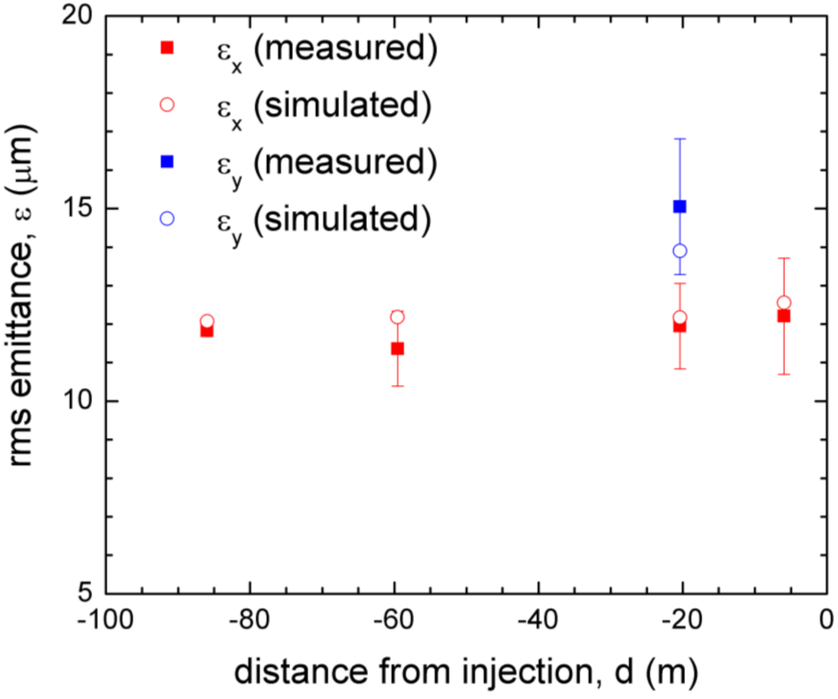
Optics measurements along the M4-M5 lines

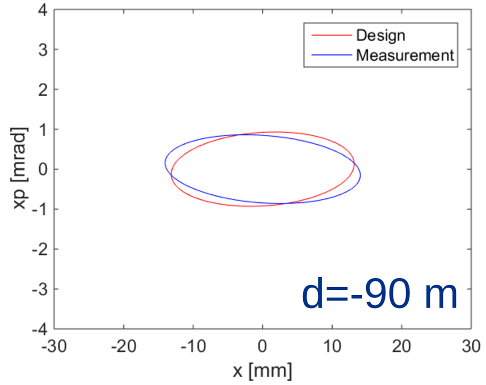
- We measured the beam optics along several locations. Measured emittance agrees well with design parameters.

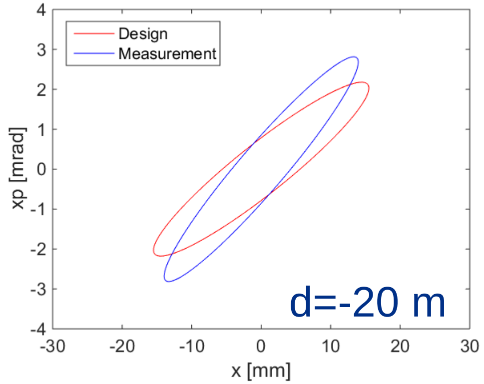






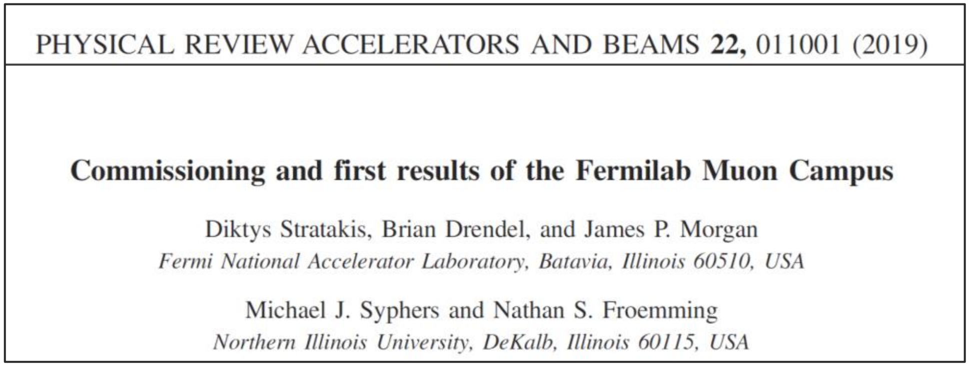






Transmission along the M4-M5 lines

- Good news:
  - Simulation and data show 90% transmission along the M4-M5
  - Measured mu+/e+ ratio (57/43); tracking (60/40)
- More attention needed:
  - Transmission along the Muon Campus is 60% of the design



PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 011001 (2019)

Commissioning and first results of the Fermilab Muon Campus

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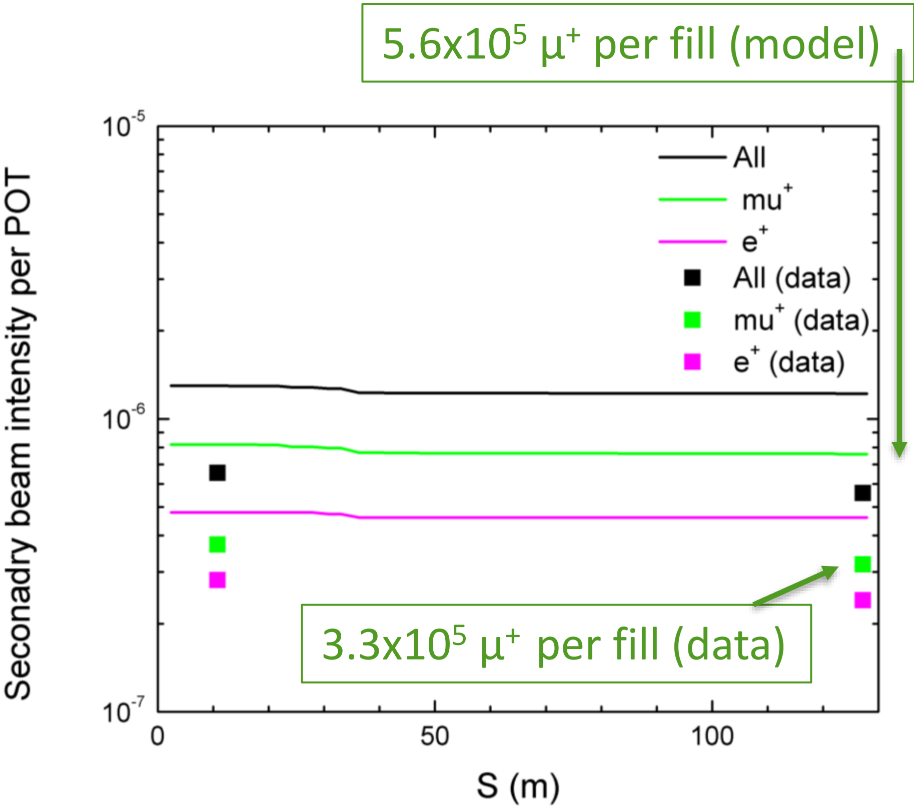


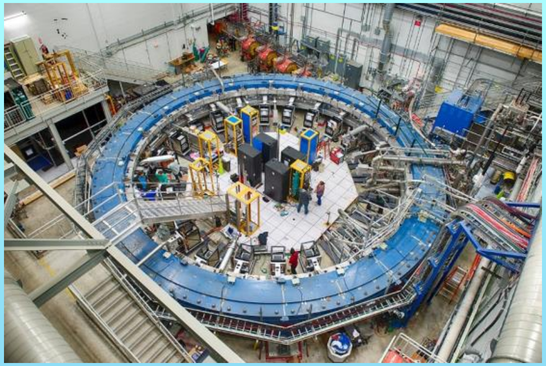
$5.6\text{x}10^5$ μ^+ per fill (model)

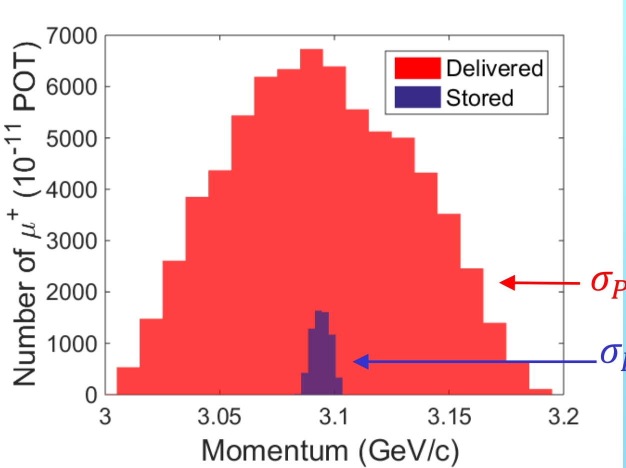
$3.3\text{x}10^5$ μ^+ per fill (data)

Performance enhancement with passive absorbers

- The g-2 ring accepts only a fraction of the delivered muons

CURRENT SCHEME

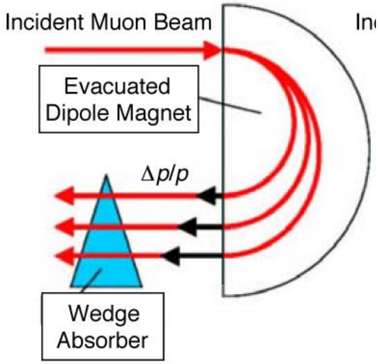


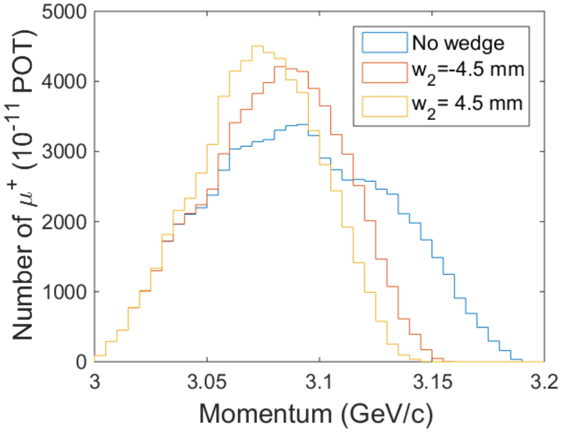


$\sigma_P/p = \pm 1.26\%$

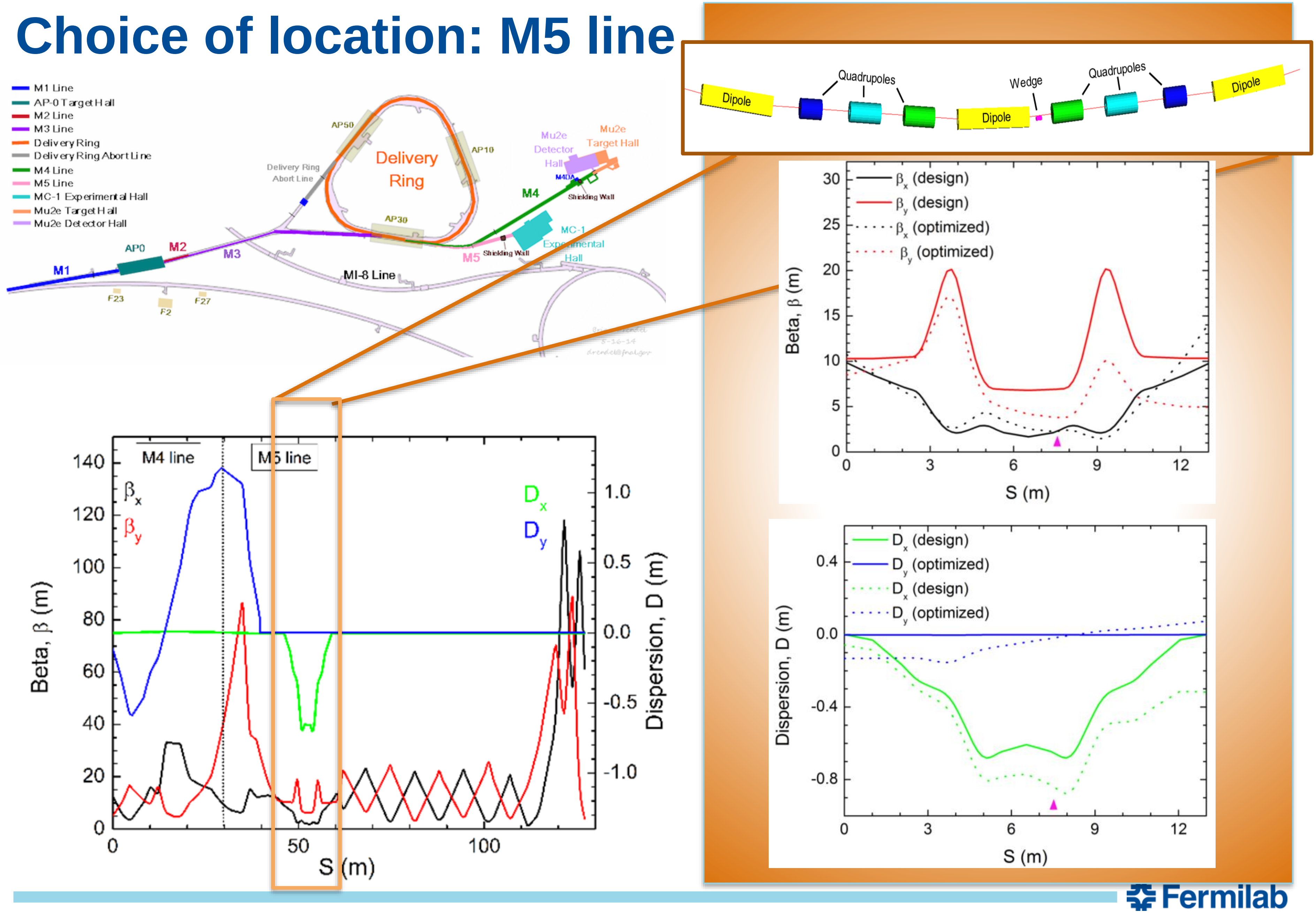
$\sigma_P/p = \pm 0.12\%$

IMPROVED SCHEME





Choice of location: M5 line

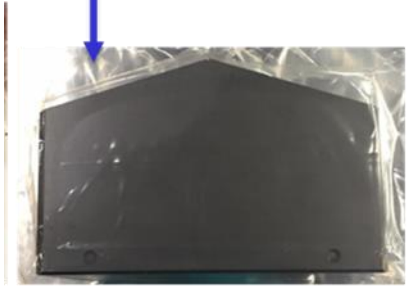


Proof-of-principle test with a passive wedge

- Proof-of-principle experiment designed and carried out.

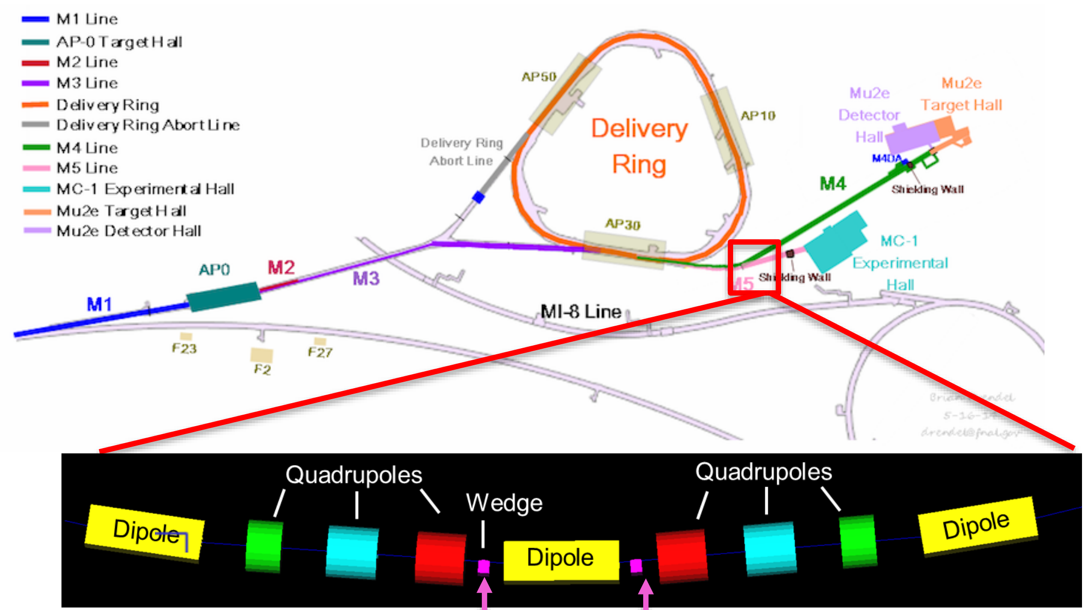
Polyethylene wedge

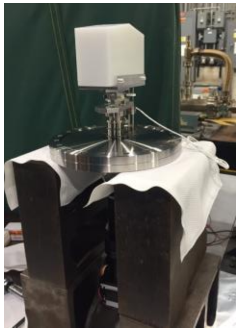
Boron Carbide wedge



LDRD at Fermilab

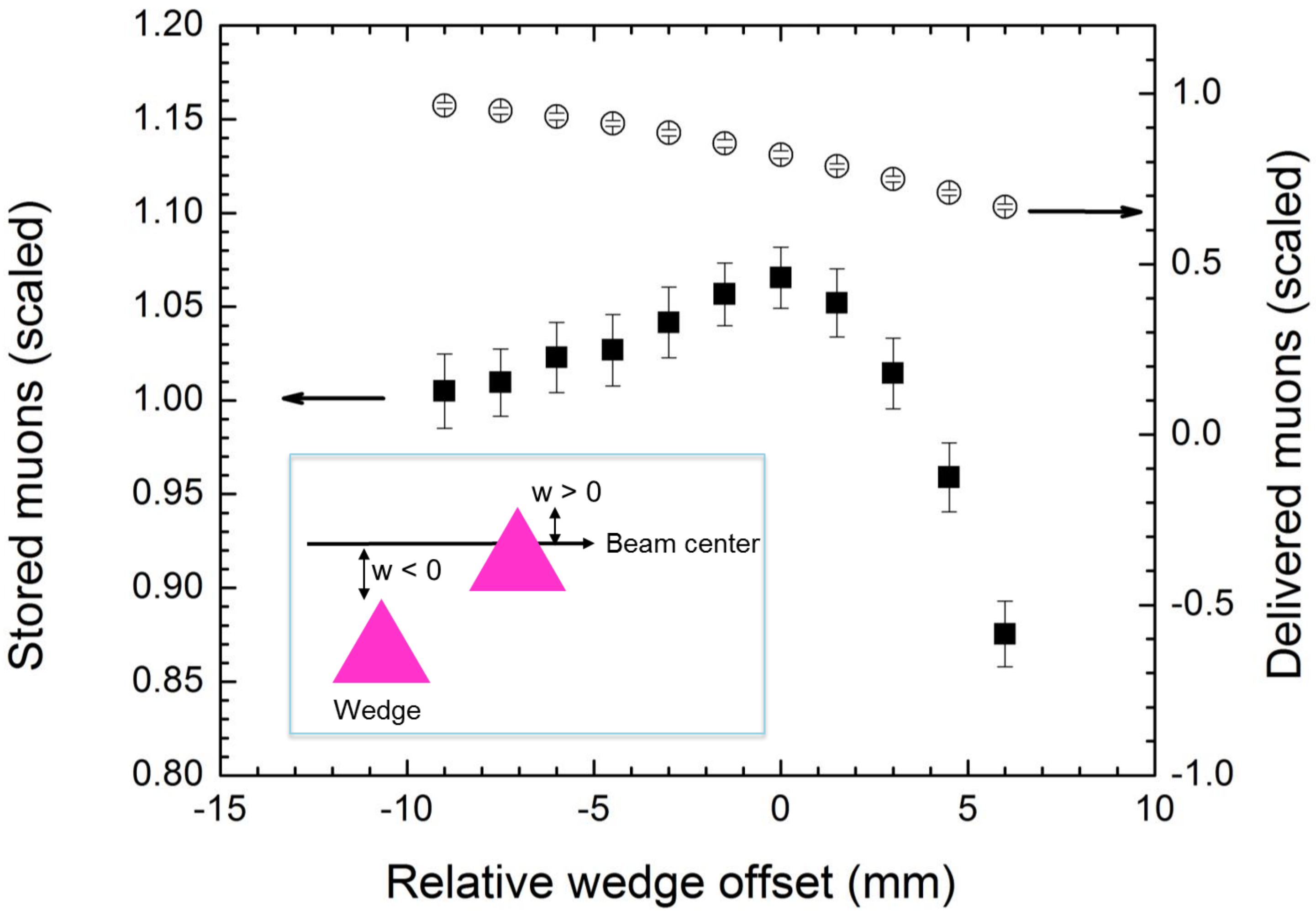
Laboratory Directed Research and Development





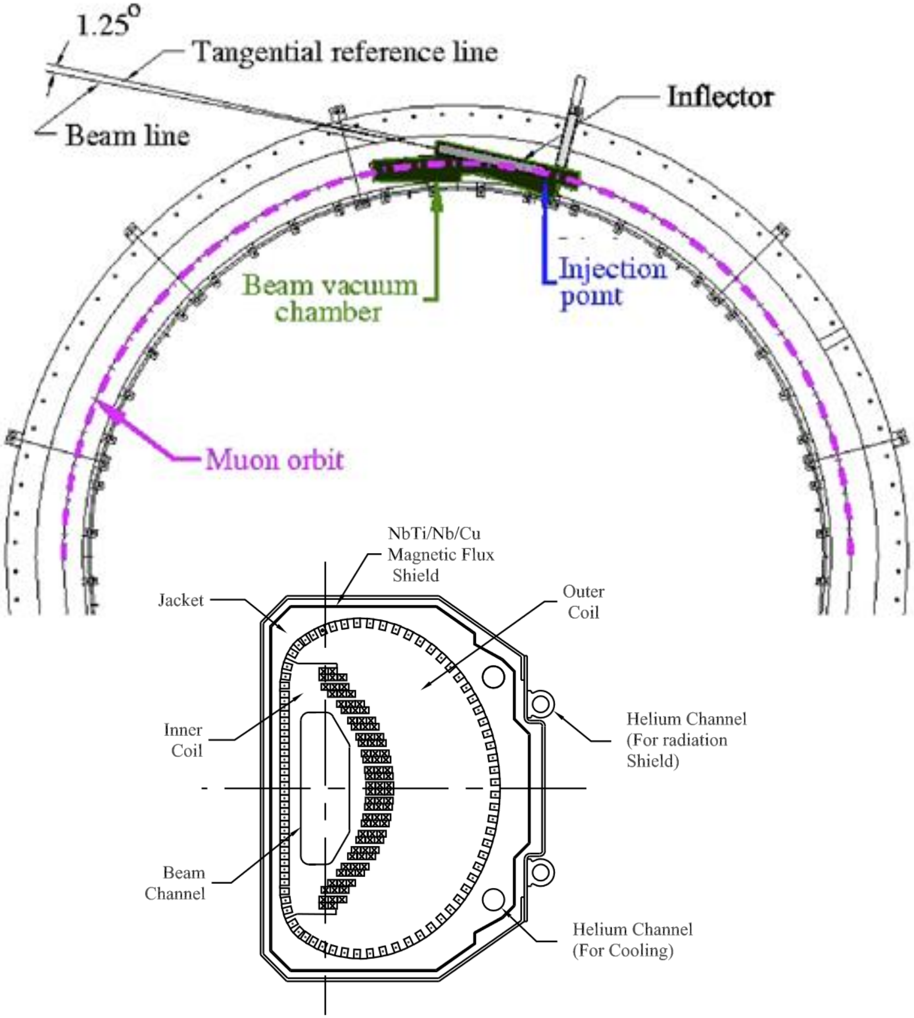
Test with a Boron Carbide wedge

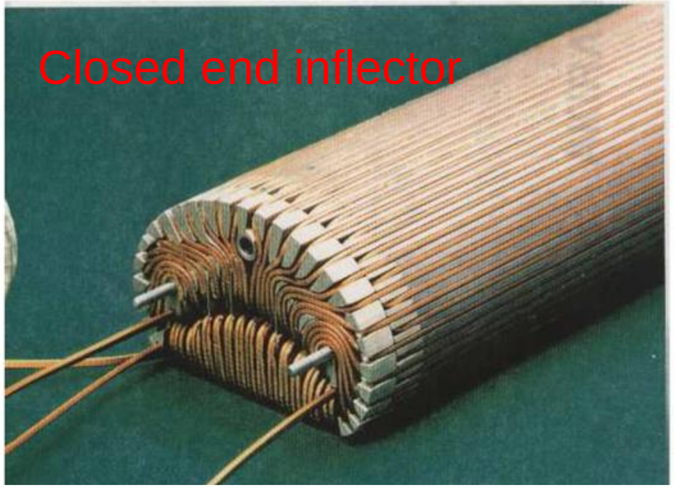
- A boron carbide wedge provided a 7% gain in stored muons



Modifications of the inflector design

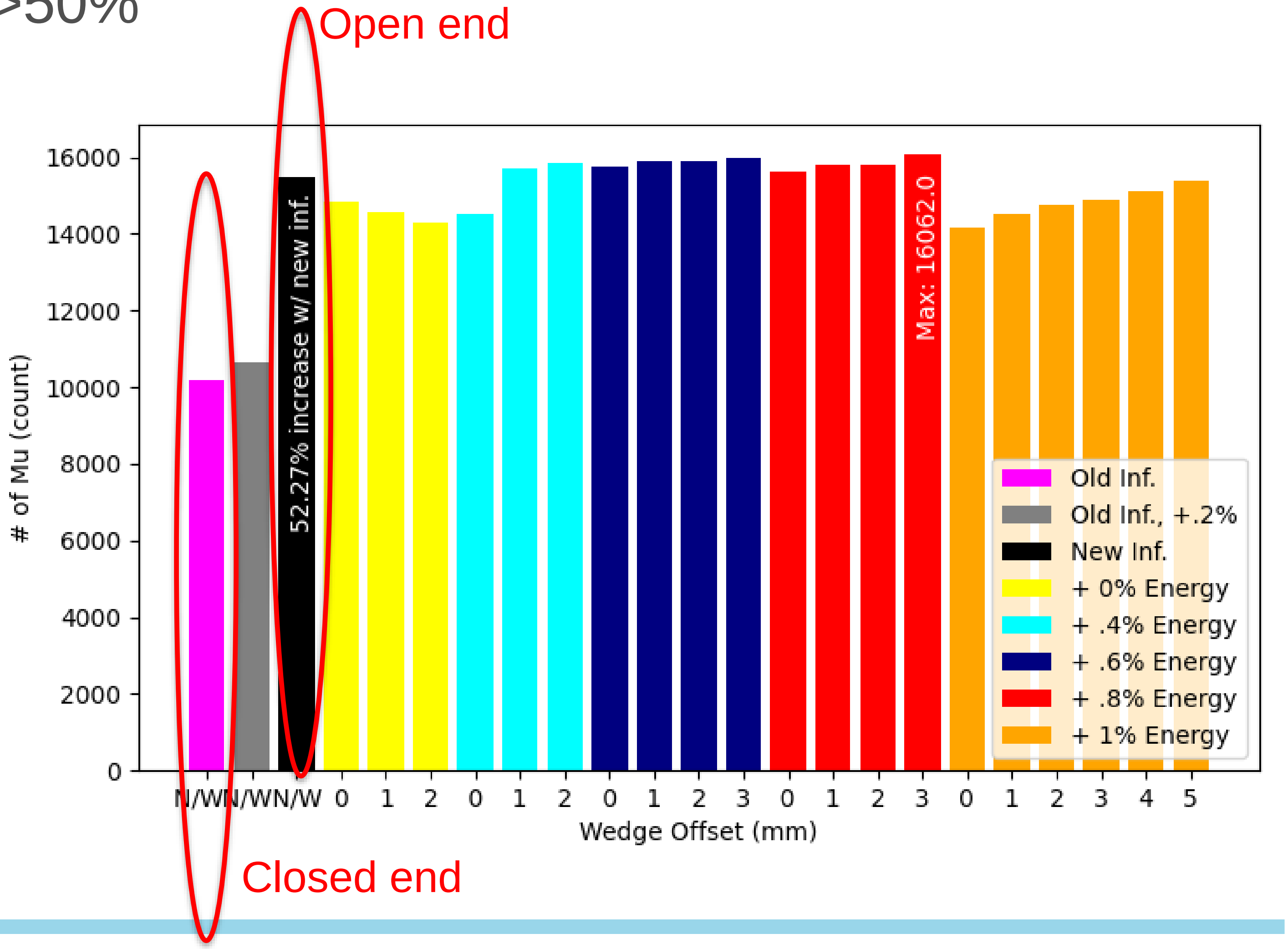
- Current inflector uses the closed-end design





Performance with open-end inflector and wedge

- Adding an open ended design can increase the stored muons by >50%



Summary

- An accelerator facility to provide beams to both g-2 and Mu2e experiments has been designed and constructed at Fermilab
- The facility has been commissioned and is now in the operation phase for the Muon g-2 Experiment
- It currently delivers roughly 1x the BNL statistics per month. Experiment will complete at 20x the BNL statistics
- A passive wedge system has been designed and commissioned for improving performance. Showed up to 7% improvement on stored muons
- The current plan is to run in this mode for two more years while in parallel doing commissioning tests for Mu2e beam delivery, when an opportunity exists.