Commissioning and First Results of the Fermilab Muon Campus

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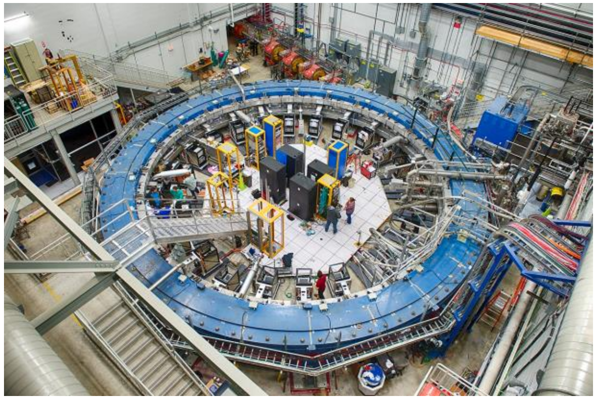
Outline

- 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
- 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

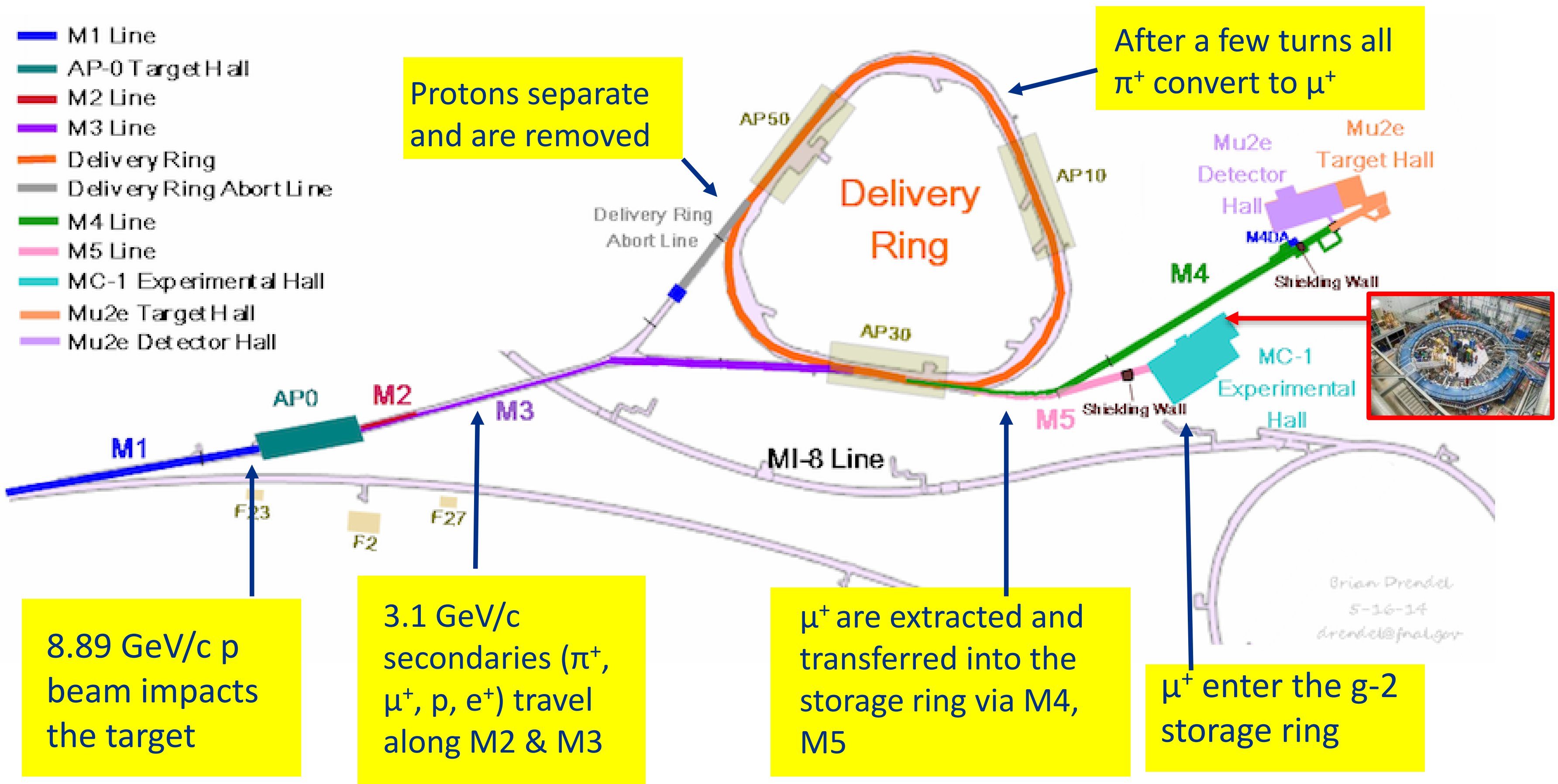
Fermilab Muon g-2 Experiment



- 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 1.4×10^{14} muons in the ring which is x20 the statistics of the BNL experiment

See talk:
Syphers, WEYYPLS1

Muon Campus layout



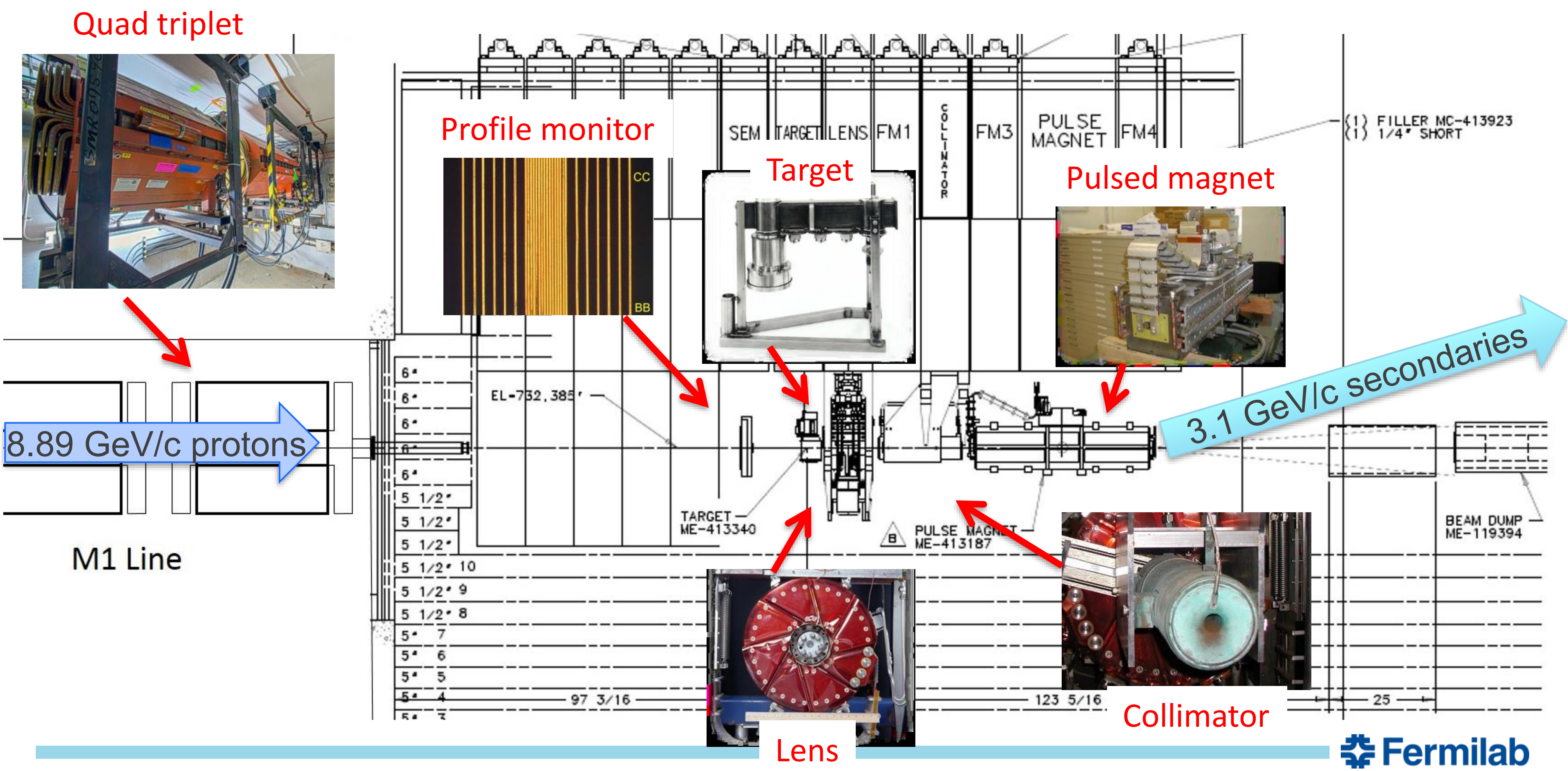
- The delivered muon beam is free of protons and pions, which created a major background in the BNL experiment

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 where the Muon g-2 Experiment has collected 2x the BNL statistics in Jul 2018
- Started Run 2 in Mar. 2019 and we now routinely collect 1x BNL statistics per month

Target station

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



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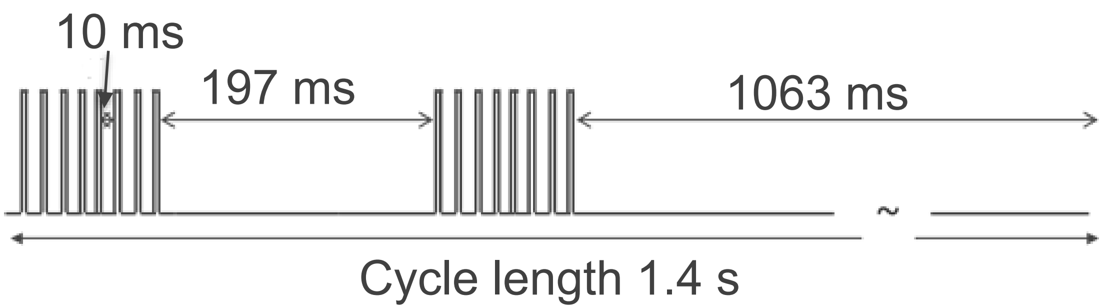
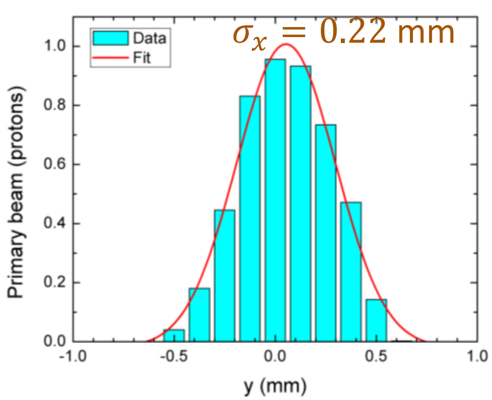
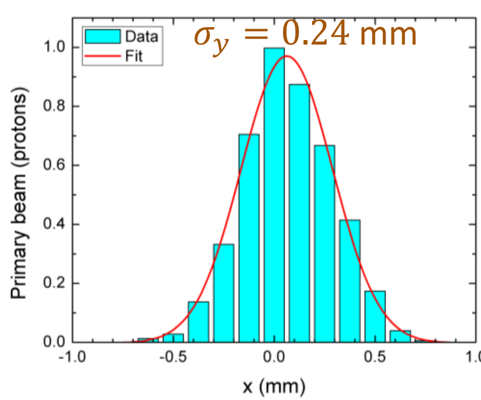
Primary beam on production target

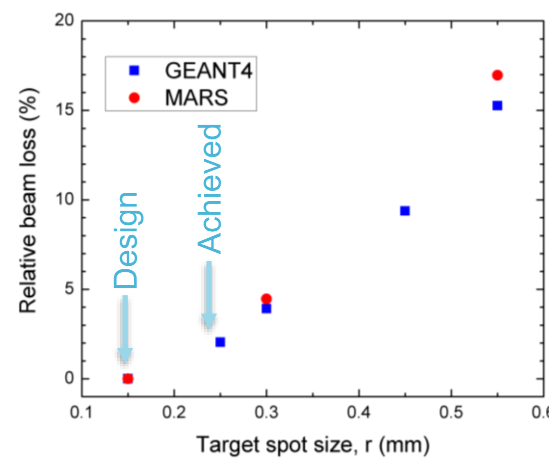
- Bunch coalescing of incoming beam via four 2.5 MHz cavities shapes bunches to the desired length and intensity
- Performance sensitive to beam spot size on target



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

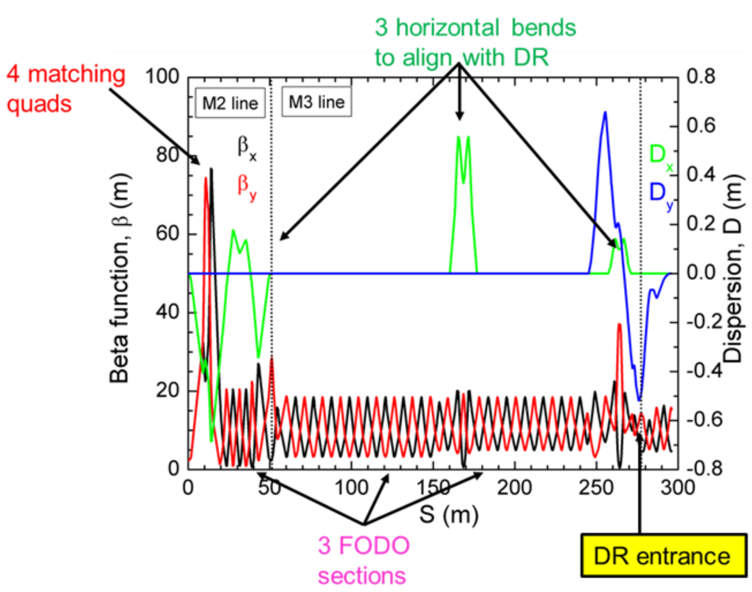


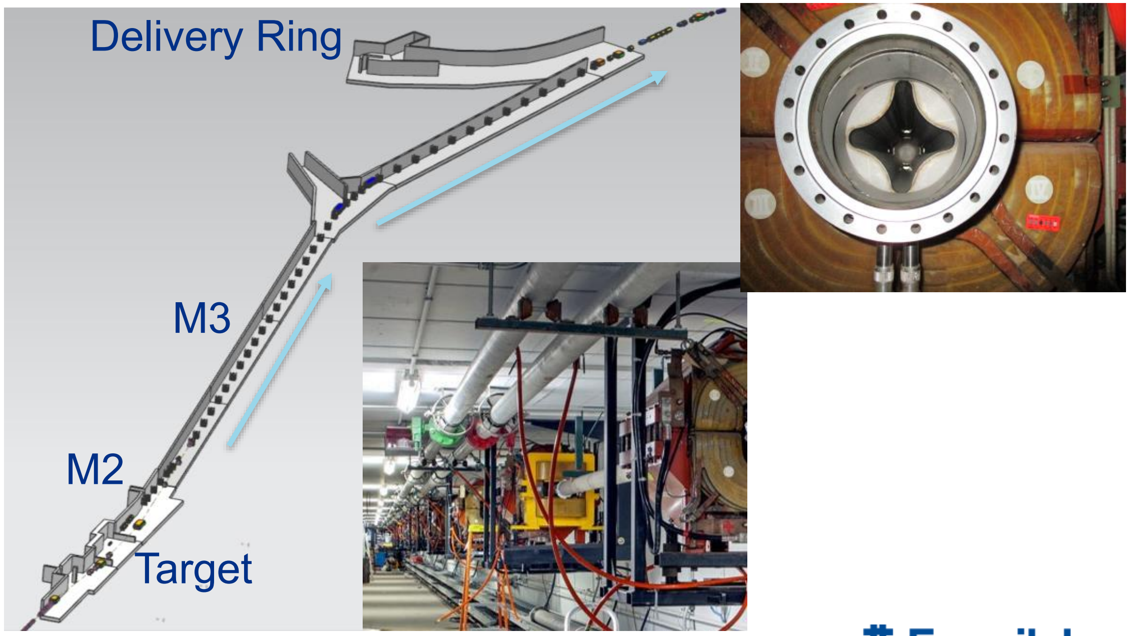




Muon capture and transport lines (M2-M3 lines)

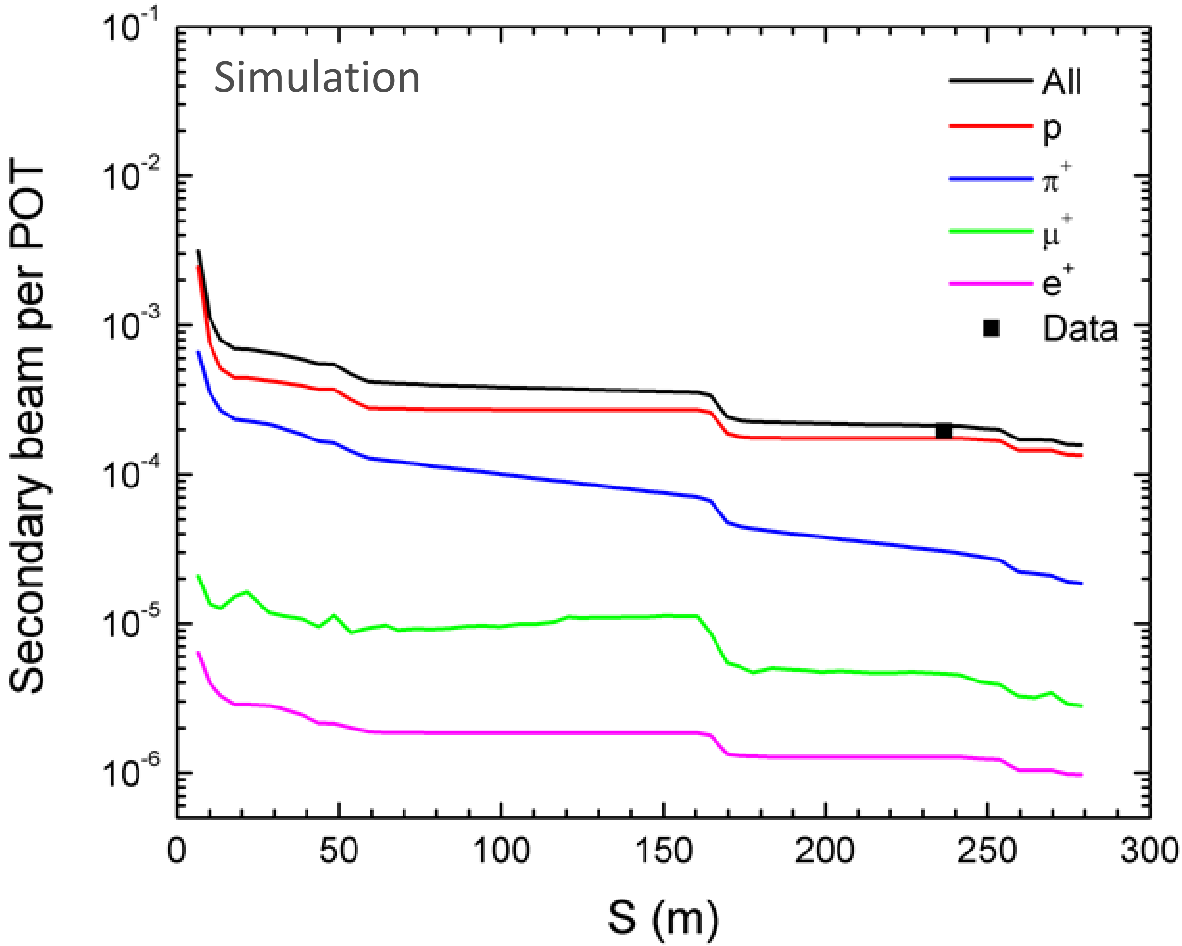
- Beamlines have a high magnet density with large aperture quadrupoles to maximize capture of pions and muons
- Mostly muons from forward decays are accepted and the polarization is 90%
- 70% of the pions are expected to decay along the M2-M3 lines





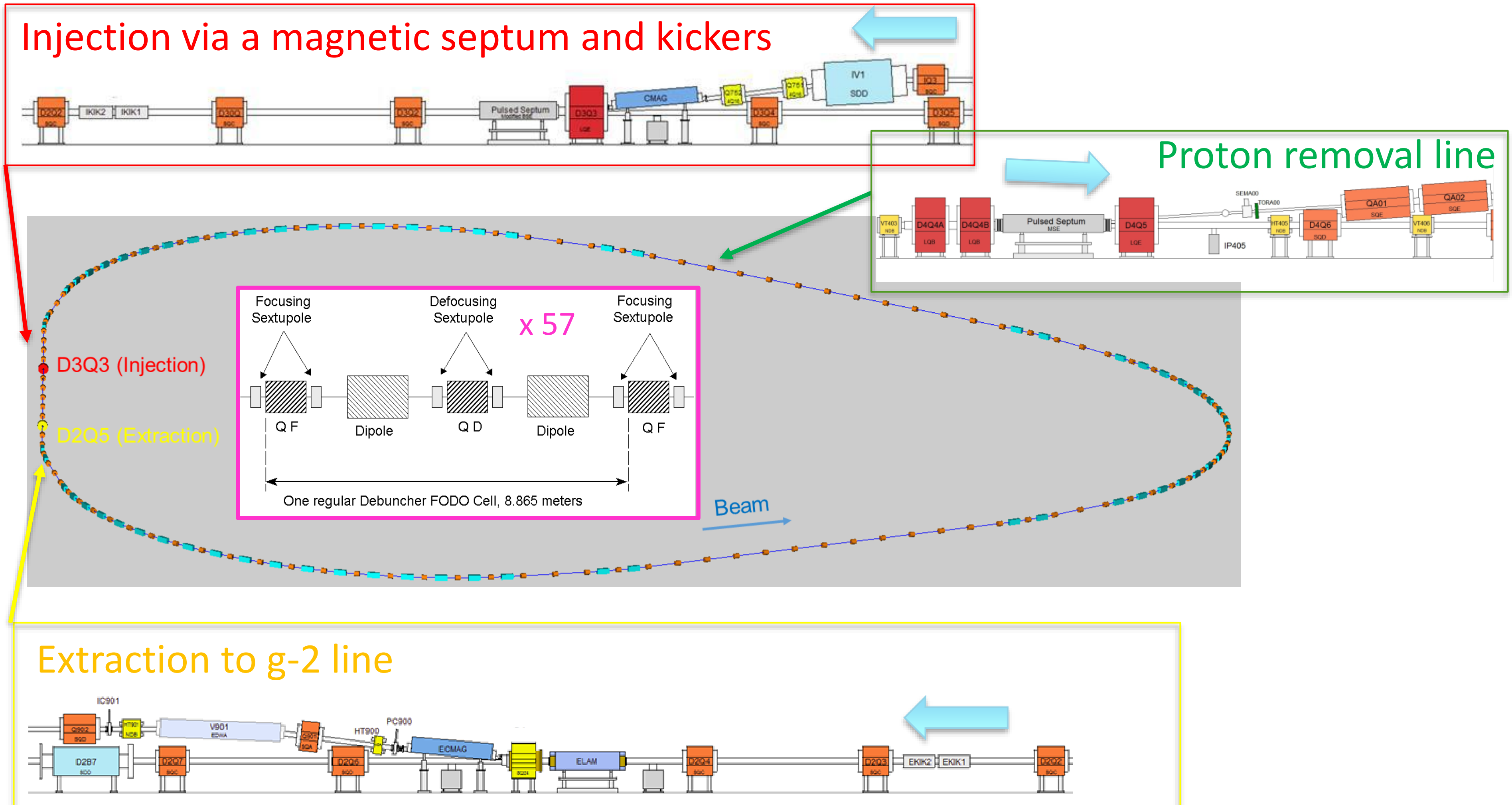
Beam performance along the M2-M3 lines

- Measured intensity at the end of the line matches simulation



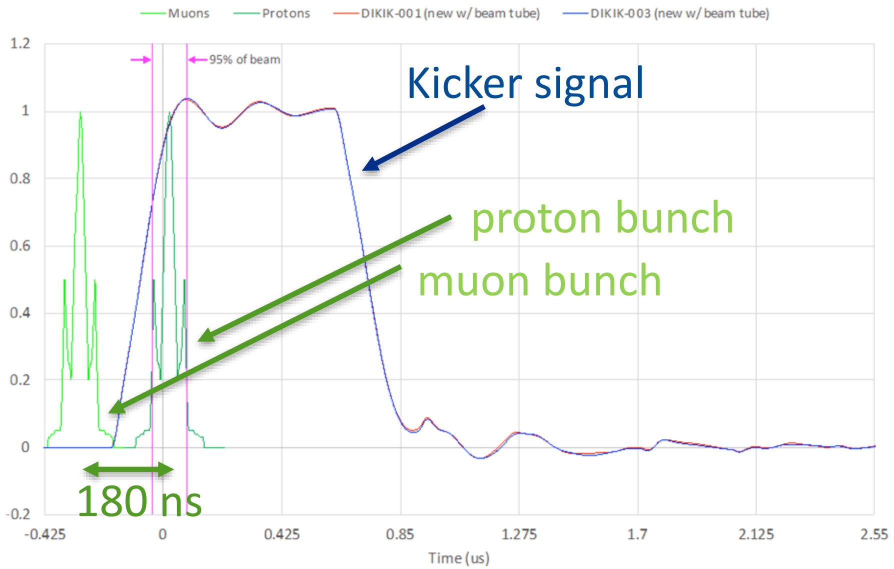
Delivery Ring (DR)

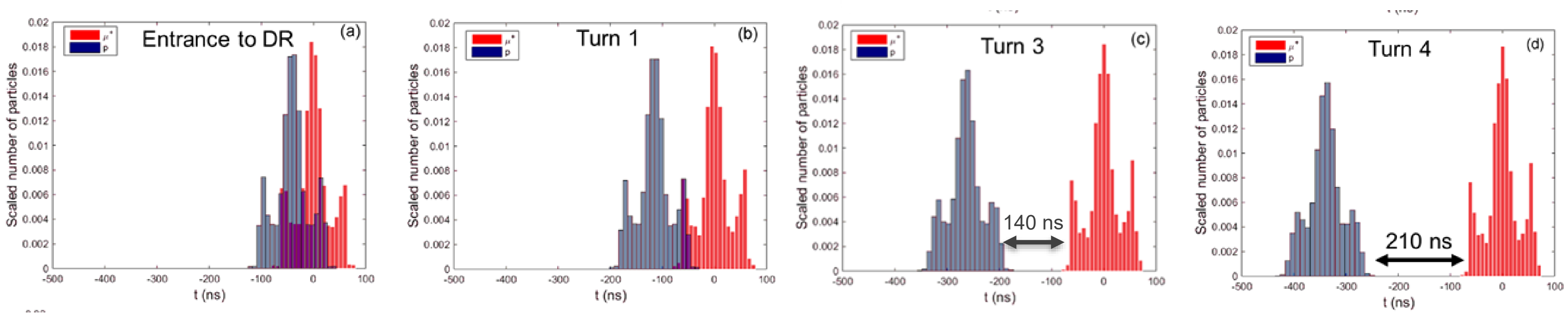
- DR is 505 m long and contains 57 FODO cells with 66 dipoles



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





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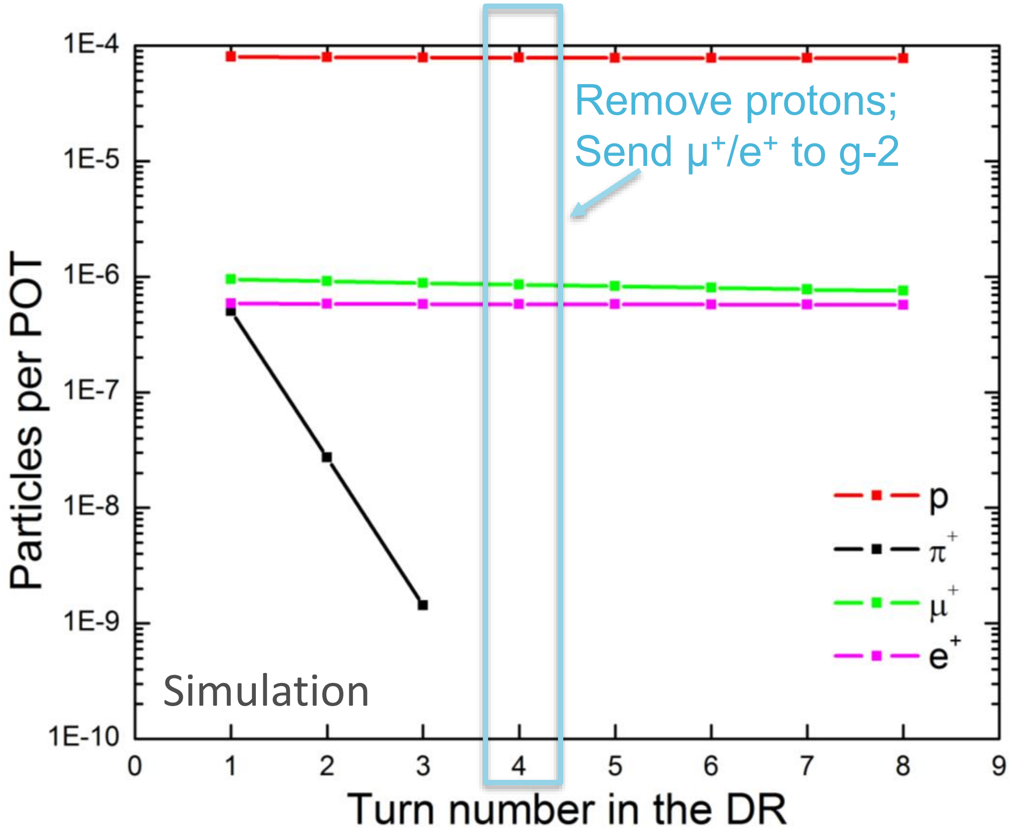
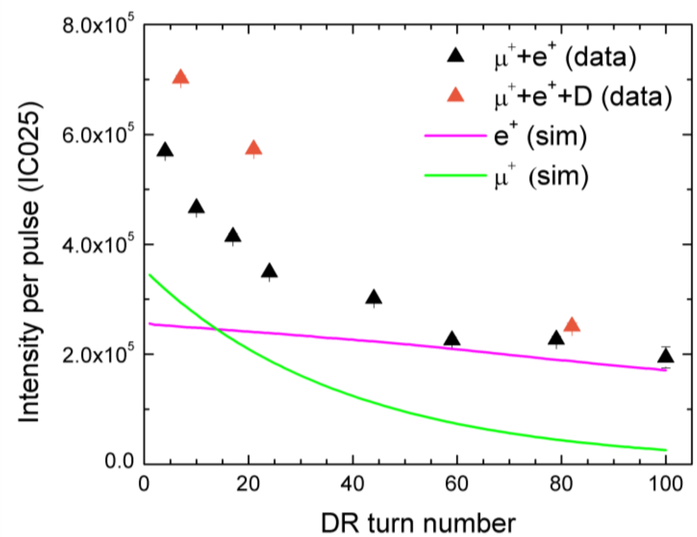
Delivery Ring simulated performance

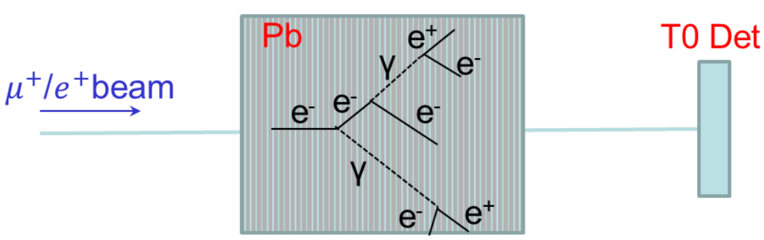
- Secondary protons dominate. Pions <1% after three turns
- A considerable amount of "target born" e^+ is present which needs to be determined in order to evaluate performance

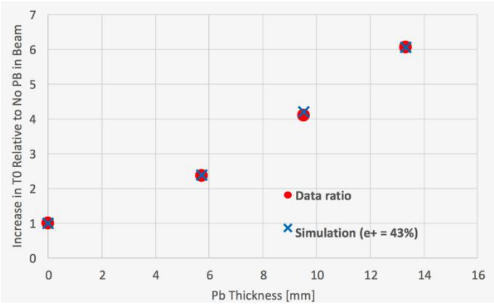


Measuring positron rates

- 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!







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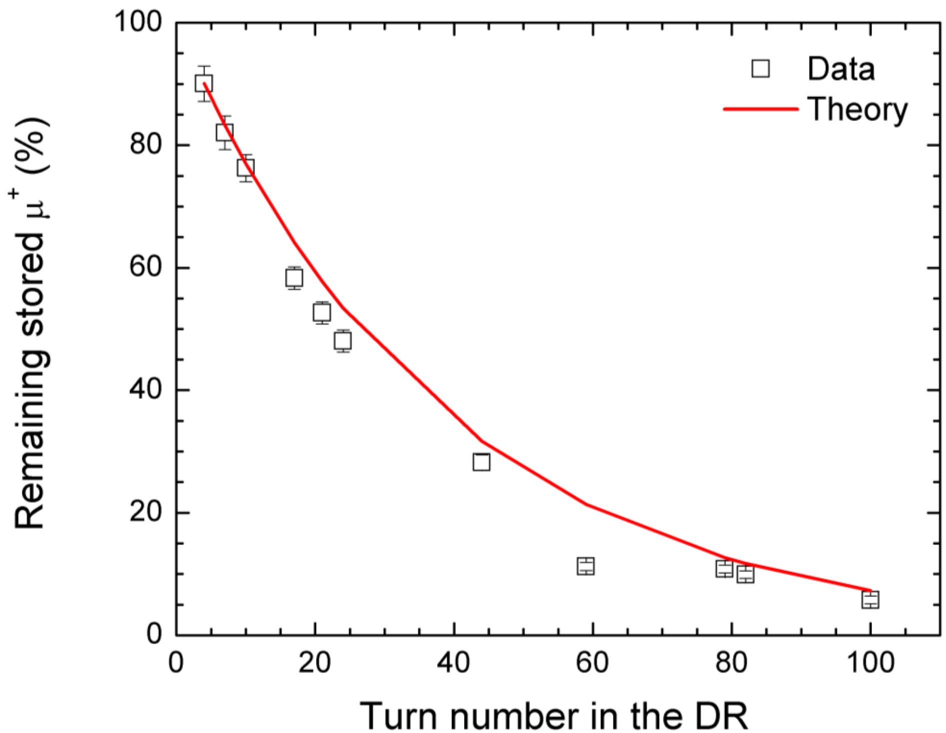
Transmission of muons along the Delivery Ring

- We measured the muons stored inside the g-2 storage ring as a function of the DR turn number
- Measured muon life time was $\tau = (60 \pm 1)$ μs instead of 64 μs. This suggests unwanted beam losses in the DR



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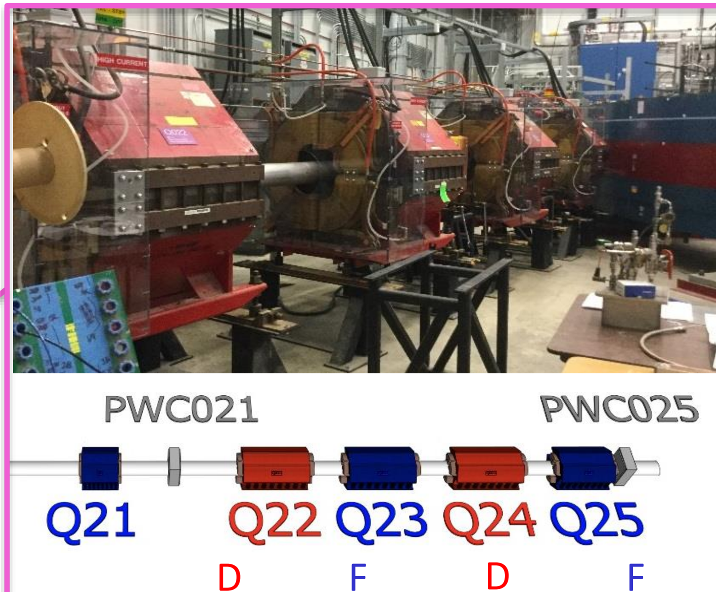
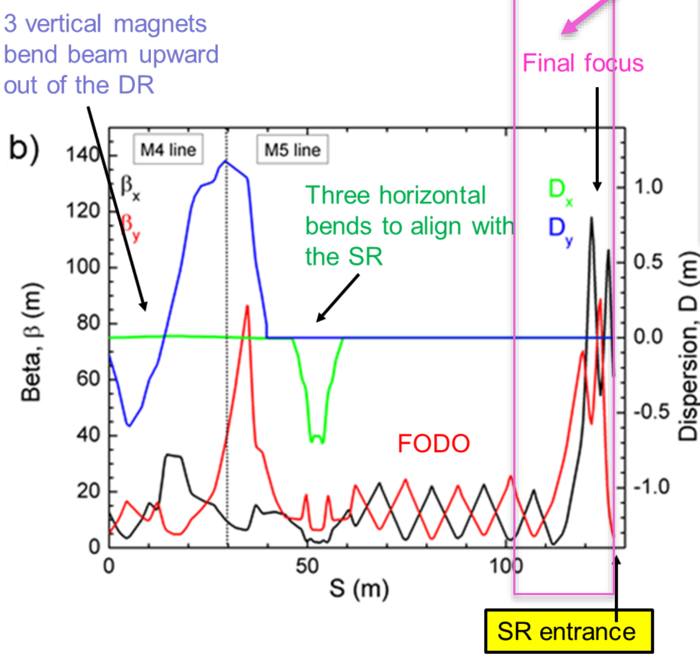
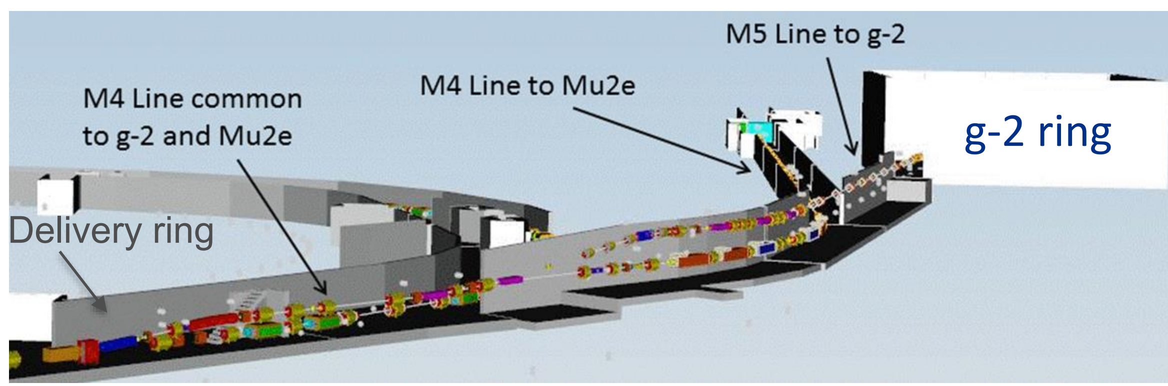
Muon transport to g-2 line (M4-M5 lines)

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



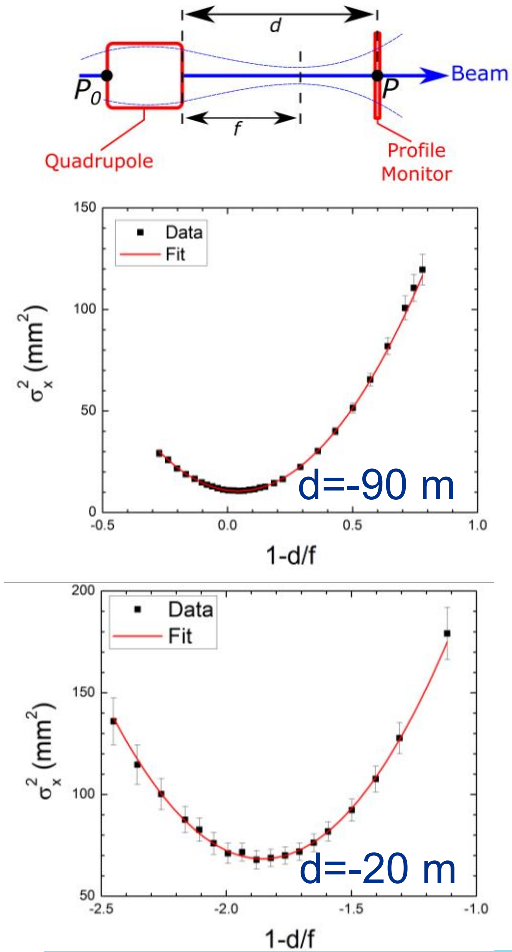
Tunable final focus to optimize injection into the ring

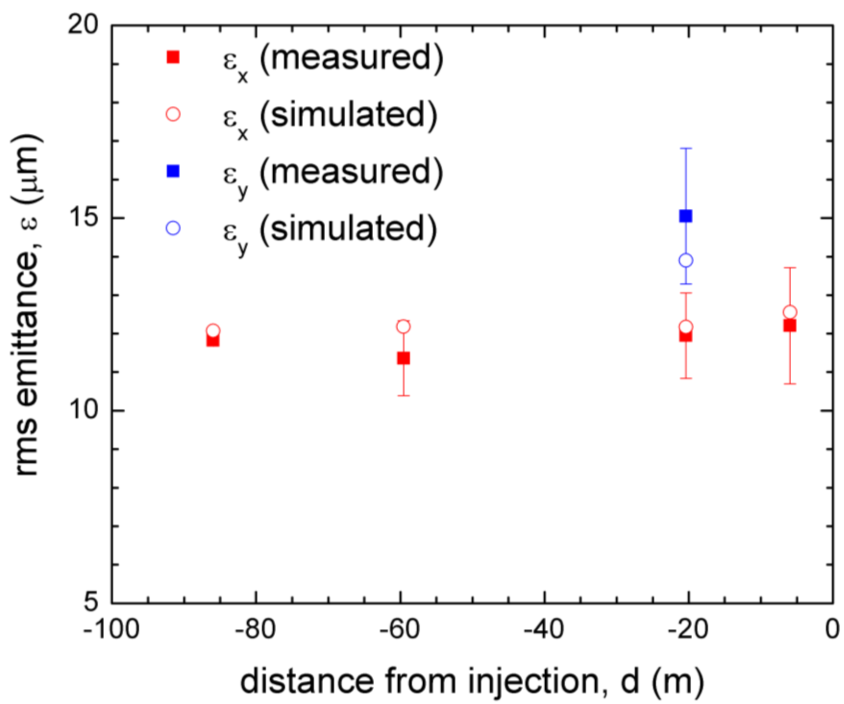


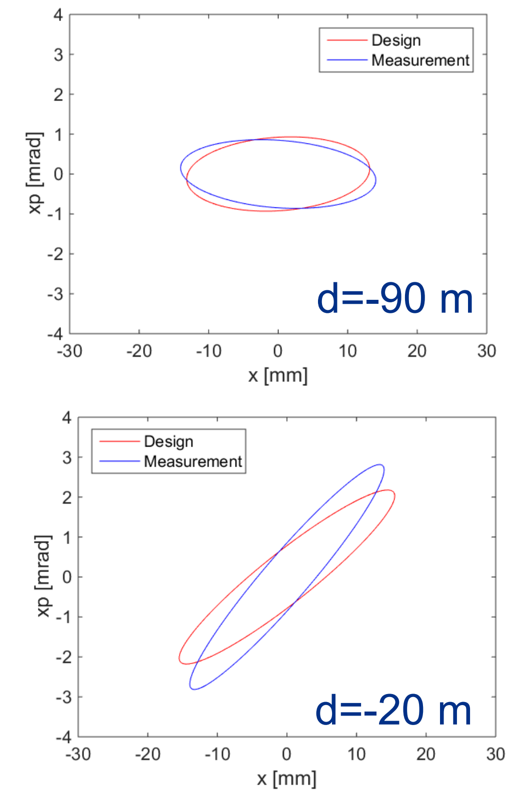


Optics measurements along the M4-M5 lines

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

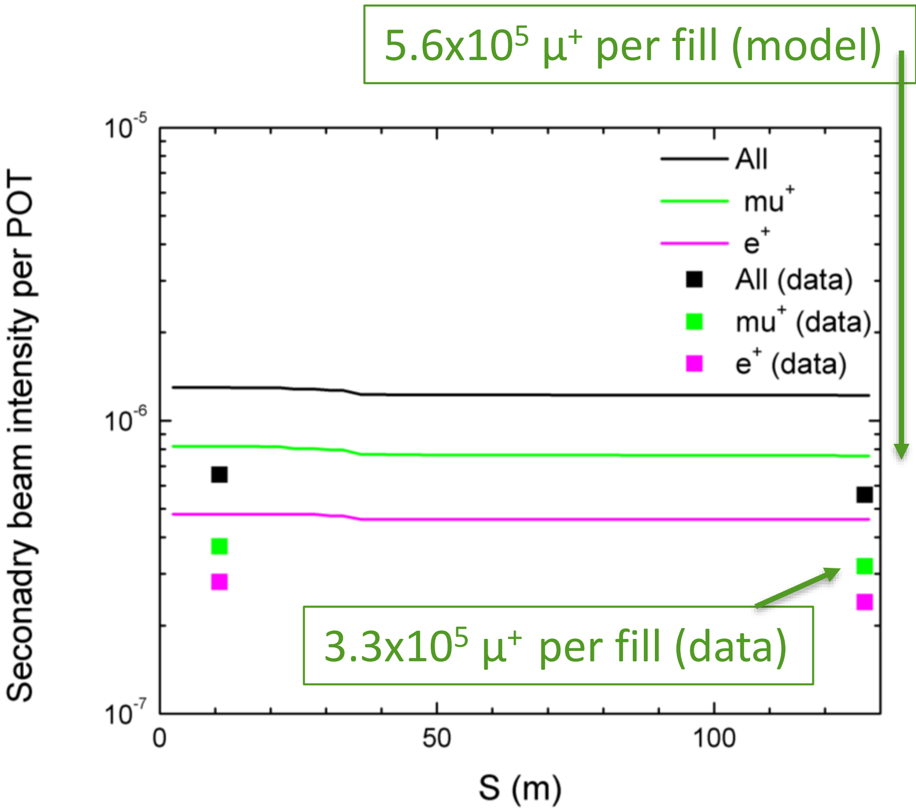






Transmission along the M4-M5 lines

- 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
  - Partly from some simplifications of the simulation model but also from unwanted losses during injection and circulation in the DR

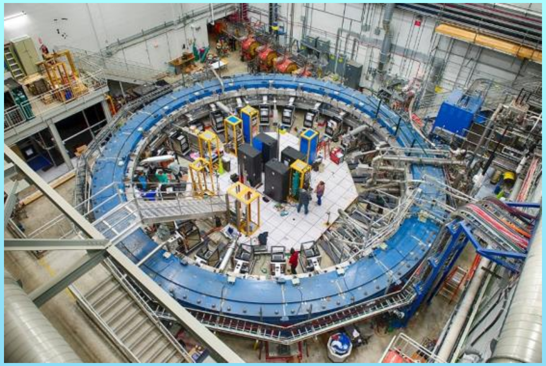


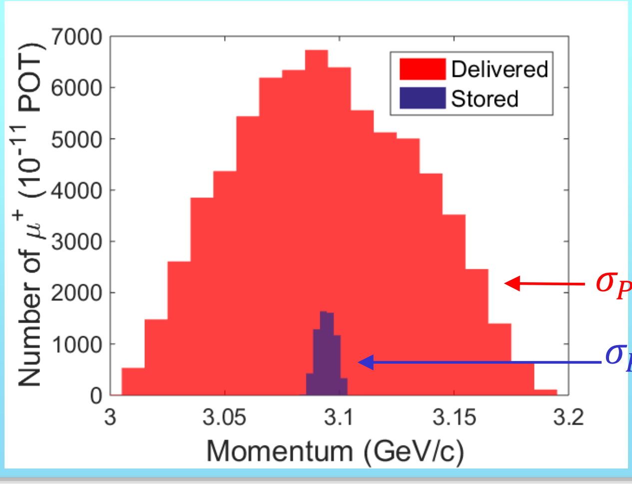
- The Muon Campus delivers 1 x the BNL statistics per month

Performance enhancement with passive absorbers

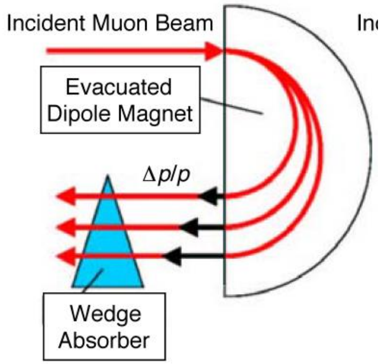
- The g-2 ring accepts only a fraction of the delivered muons

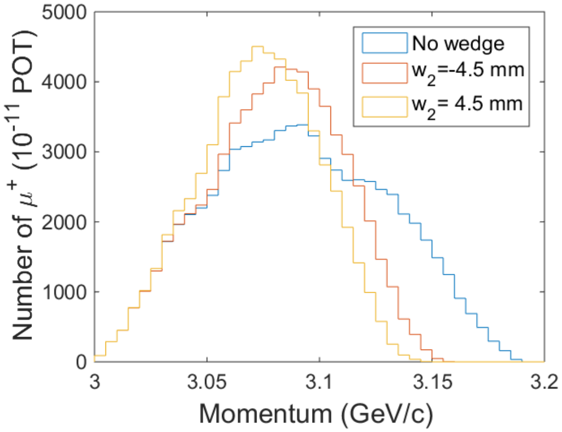
CURRENT SCHEME





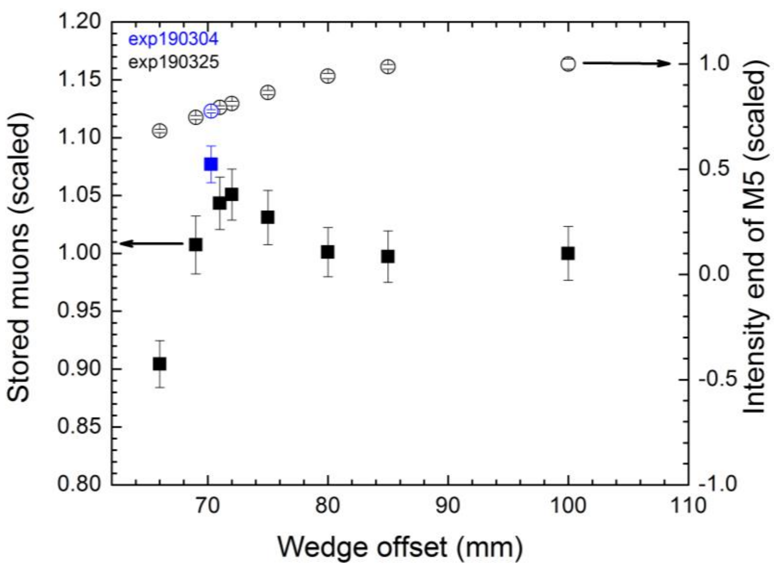
IMPROVED SCHEME

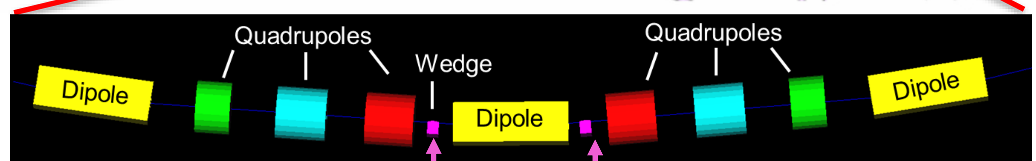


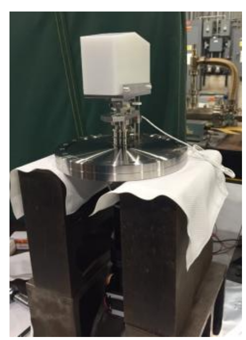


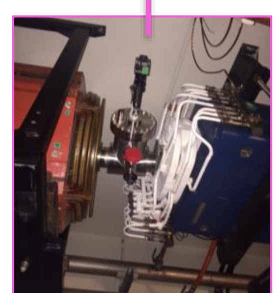
Proof-of-principle test with a polyethylene wedge

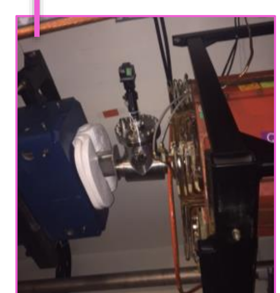
- Proof-of-principle experiment carried out. Demonstrated a gain up to 8% in stored muons with a polyethylene wedge.











LDRD at Fermilab
Laboratory Directed Research and Development

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 plan for mitigation of the observed beam losses during injection and circulation in the DR is underway
  - Improved diagnostics and instrumentation installed to aid analysis
- A passive wedge system has been designed and commissioned for improving performance. First test showed a up to 8% improvement on stored muons