Muon Campus At Fermilab

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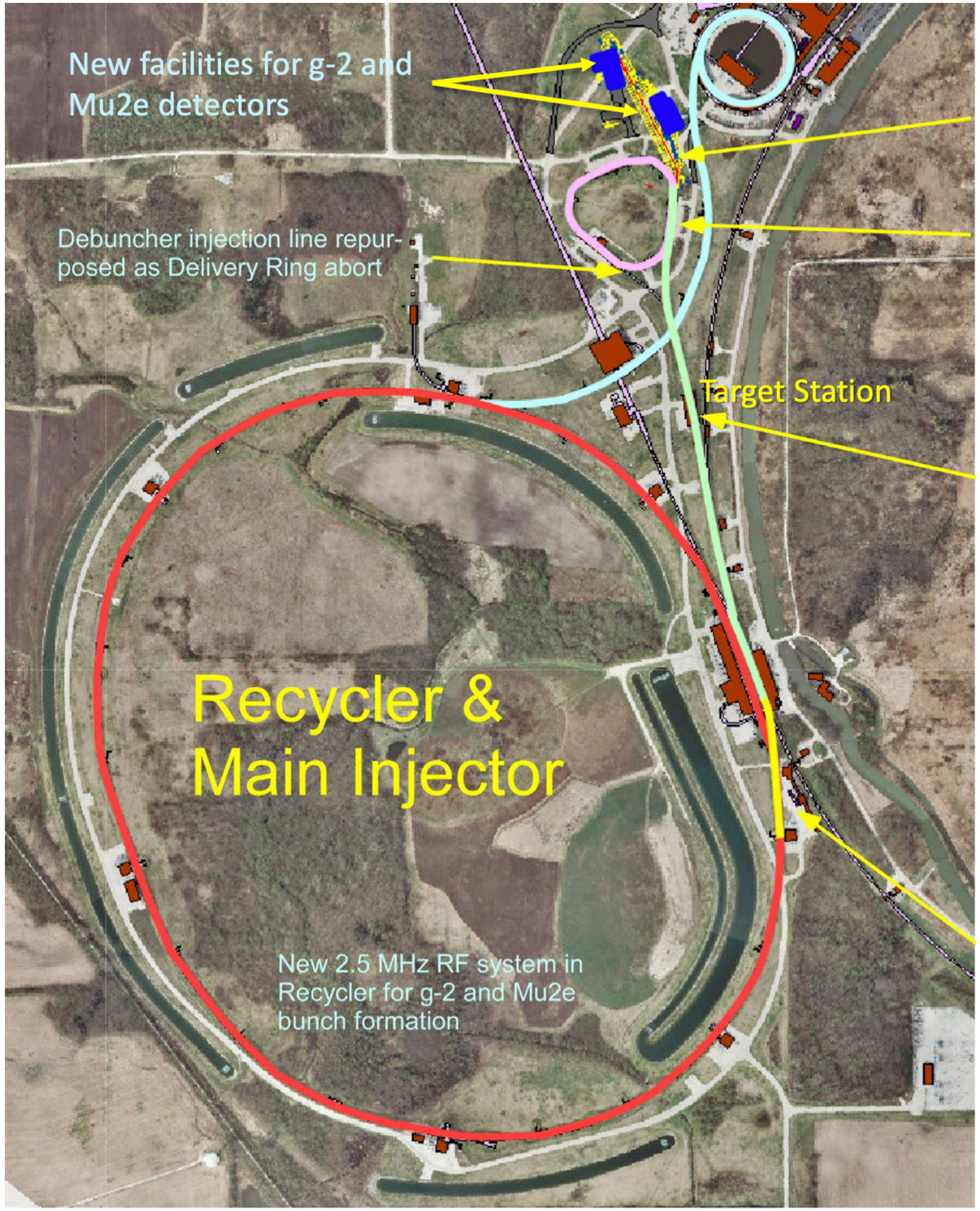
FPCP

27 May, 2022


Mu2e
MC-1
Muon g-2
Muon Campus:
Present Day

Antiproton source →Muon Campus



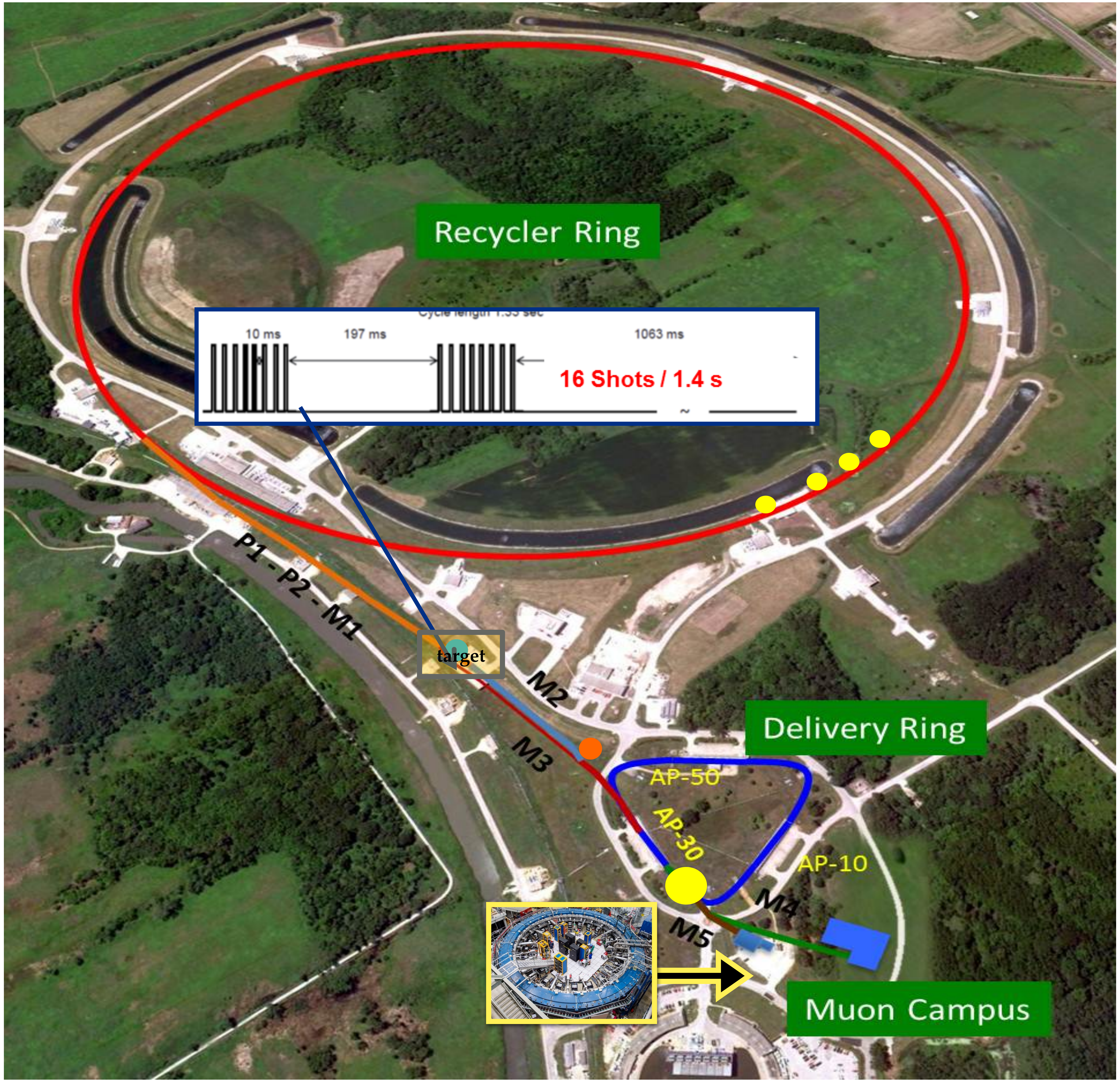
M4, M5 beamlines to transport beam to Muon g-2, Mu2e

Antiproton accumulator ring removed,
Debuncher reused as Delivery Ring

120 GeV protons on target for antiproton production
Replaced by
8 GeV protons on target for muon production for g-2
& 8 GeV transport for Mu2e bypassing target

120 GeV extraction from Main Injector for antiproton stacking
Replaced by
8 GeV extraction from Recycler for Muon campus

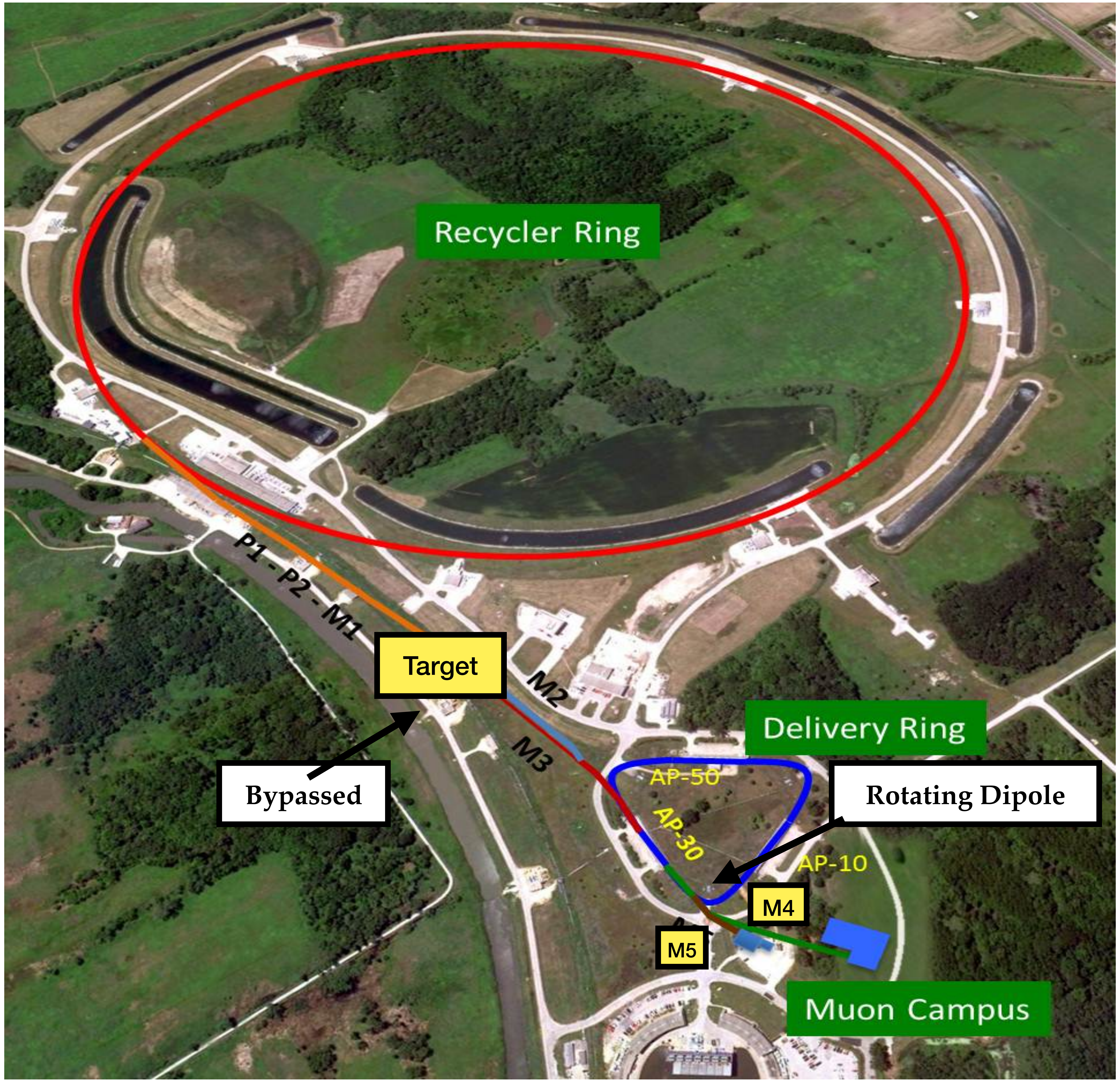
Muon g-2 Beam



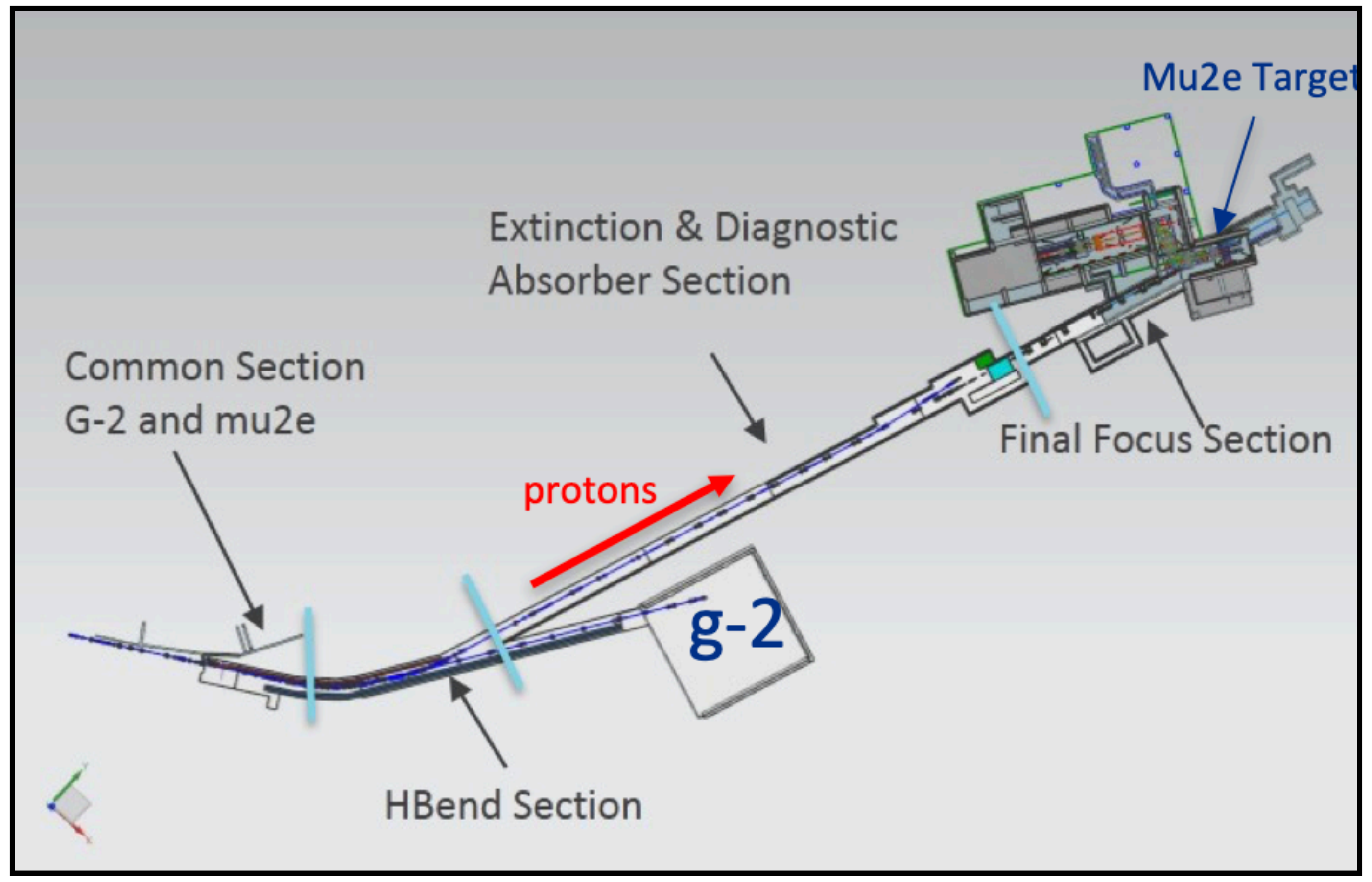
- Short batches of 8 GeV protons into Recycler
- Each batch divided into 4 bunches of 10^{12} protons
- Extract each bunch at a time and directed to target
- Long beam line channel to collect $\pi \rightarrow \mu$
- $p/\pi/\mu$ beam enters Delivery Ring (DR); protons kicked out; π decay away
- **μ enter storage ring**

Mu2e Beam

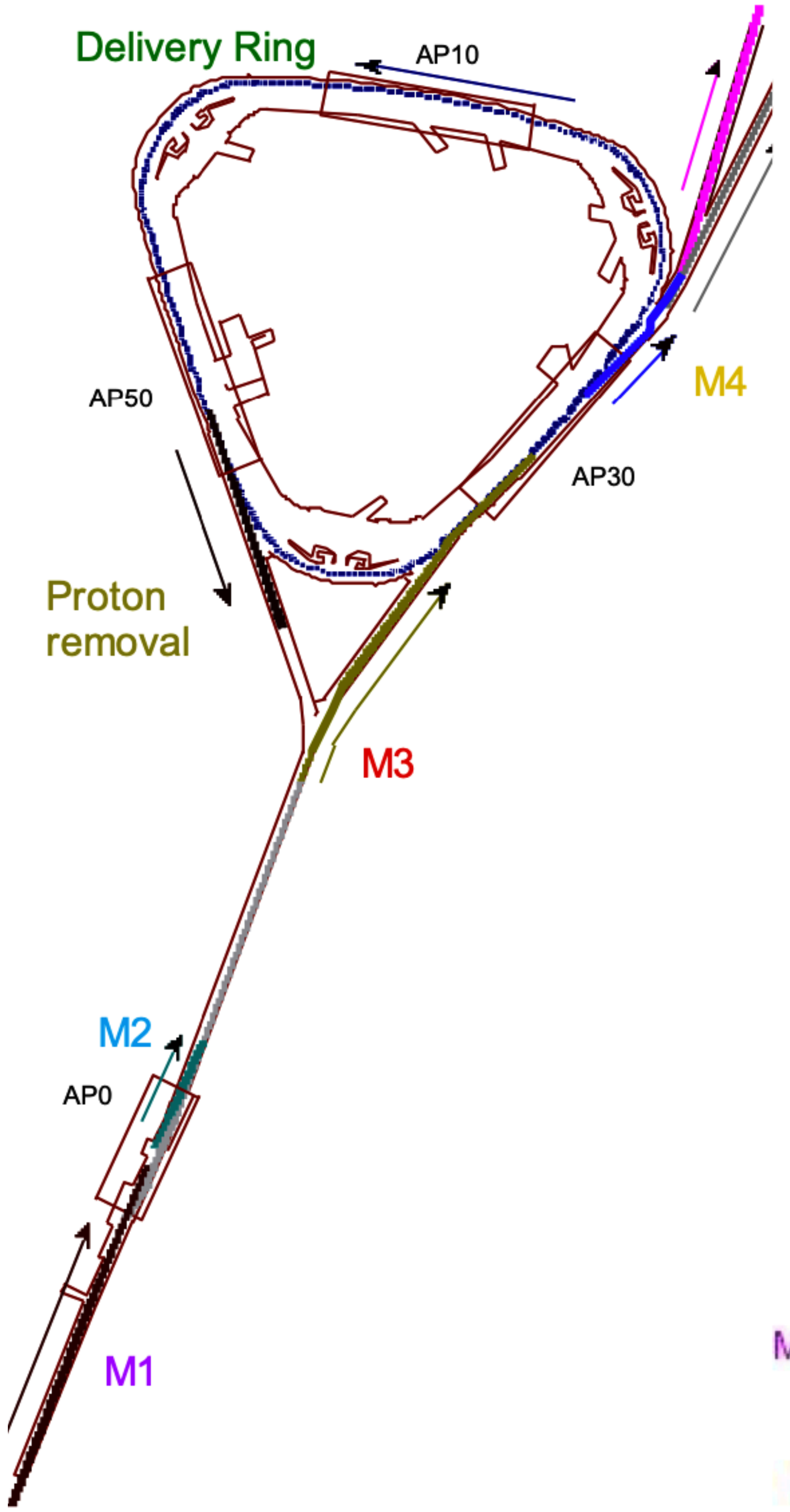
- Delivery of proton beam for Mu2e is similar to that of g-2
- 8 GeV transport for Mu2e bypassing target
- Each proton bunch synchronously transferred to DR where beam is resonantly extracted to Mu2e proton target via M4 beamline
- A vertical dipole is rotated to direct beam to Mu2e via M4 line rather than to g–2 via M5 line



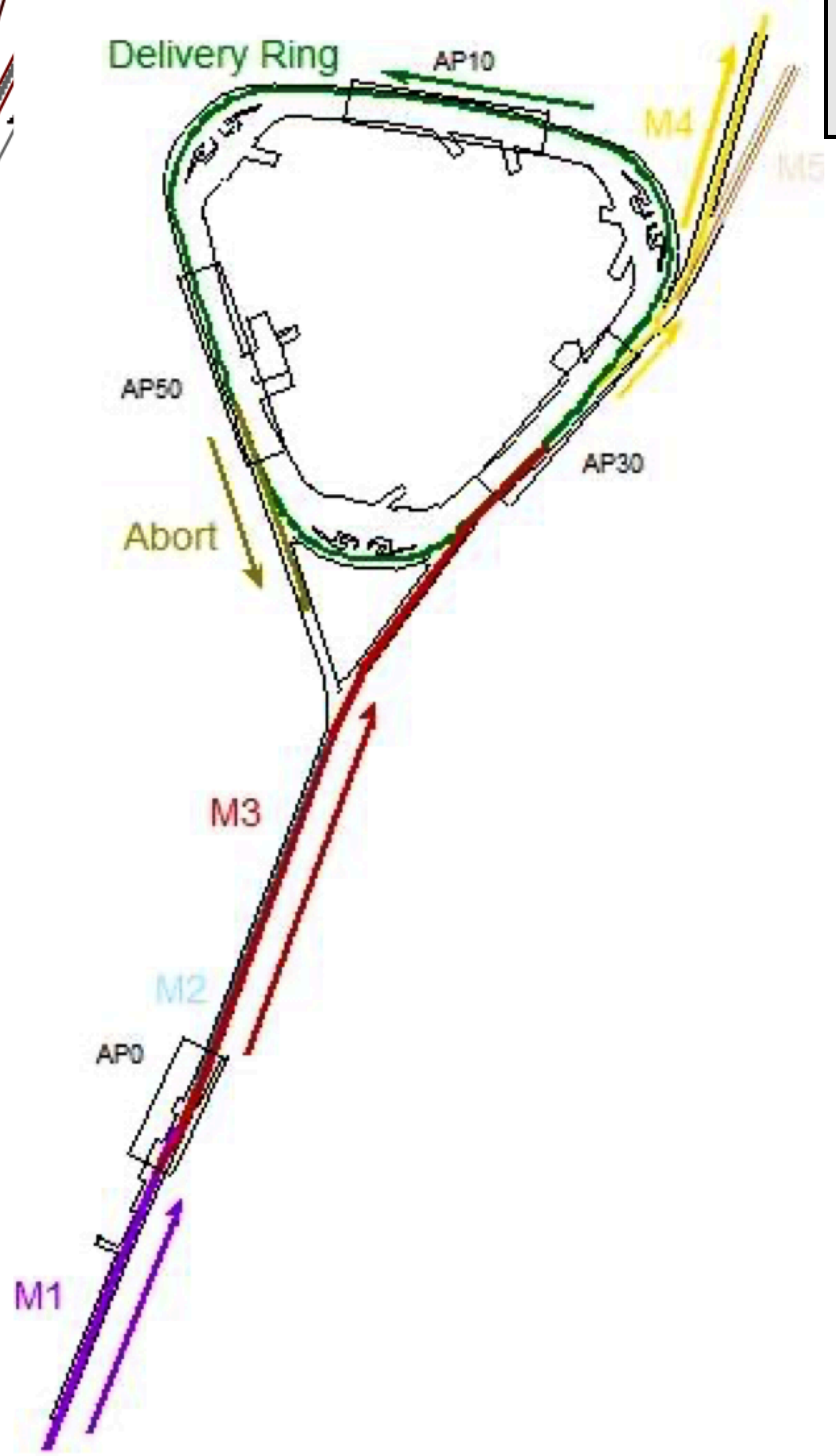
Differences b/w g-2 & Mu2e



- 8.89 GeV/c proton beam from Recycler transported to AP-0 target station
- A 3.1 GeV secondary beam transported through M2 & M3 to DR
- Beam takes 4 turns around DR
- Single turn extraction into M4 & M5 to g-2 ring



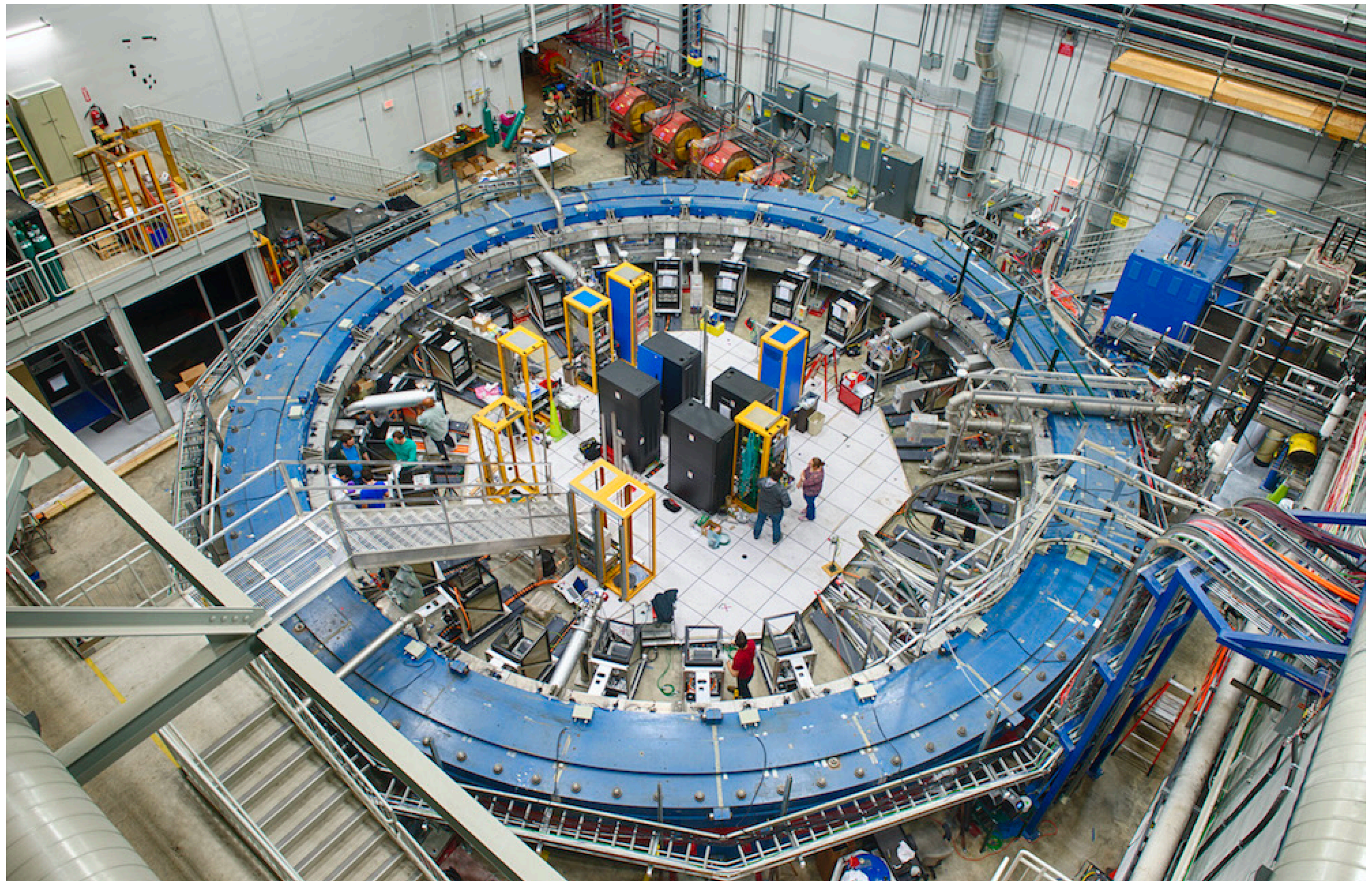
g-2 operations



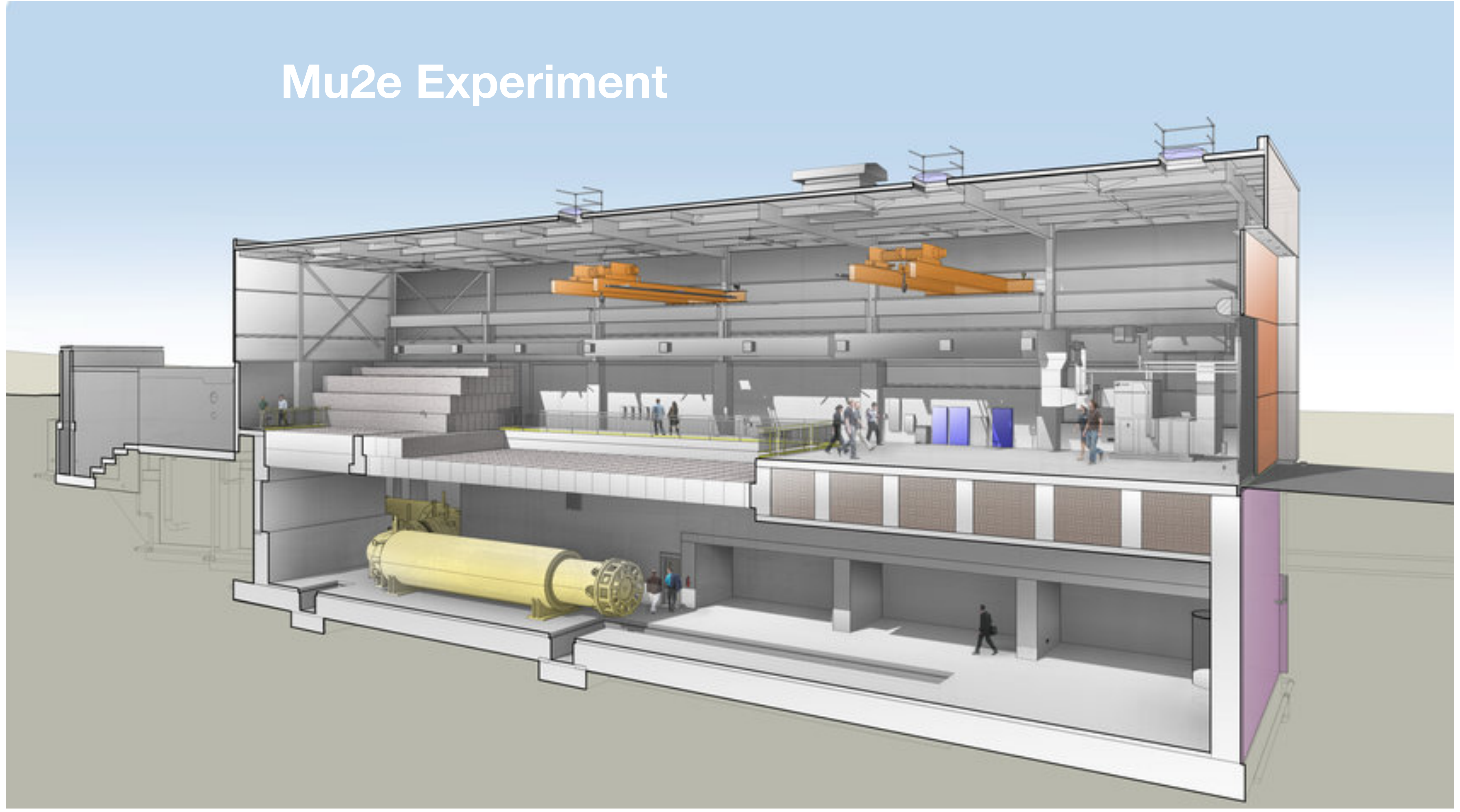
Mu2e operations

- 8.89 GeV/c proton beam bypasses Target Station and through M3 to DR
- Protons resonantly extracted from DR over 43 ms into M4 Line
- Protons transported through M4 to Mu2e target

Muon Campus Experiments: Muon g-2, Mu2e



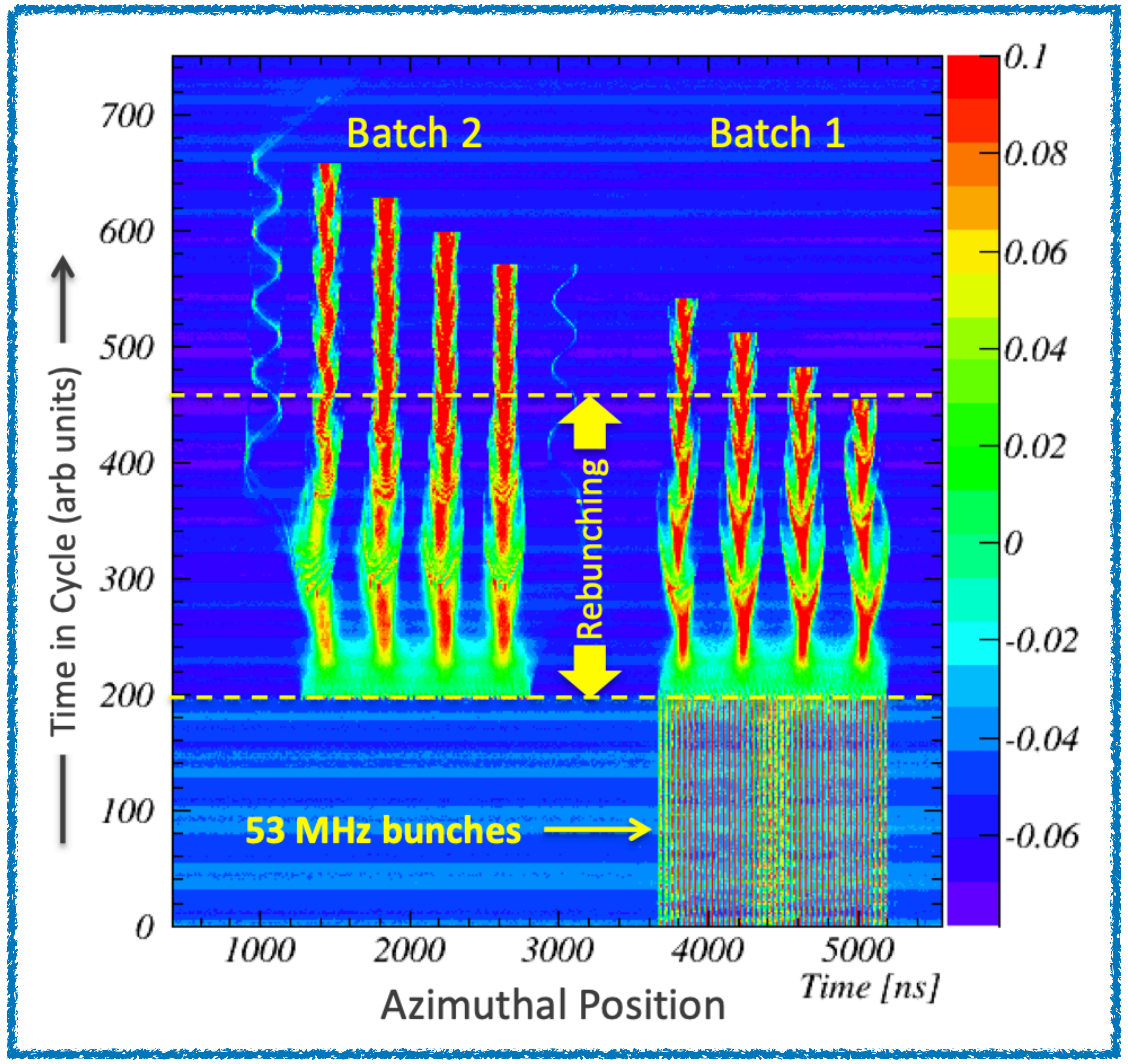
- Highly accurate test of Standard Model
- Looks for significant deviation
- Esra Barlas's talk on Experimental review of g-2

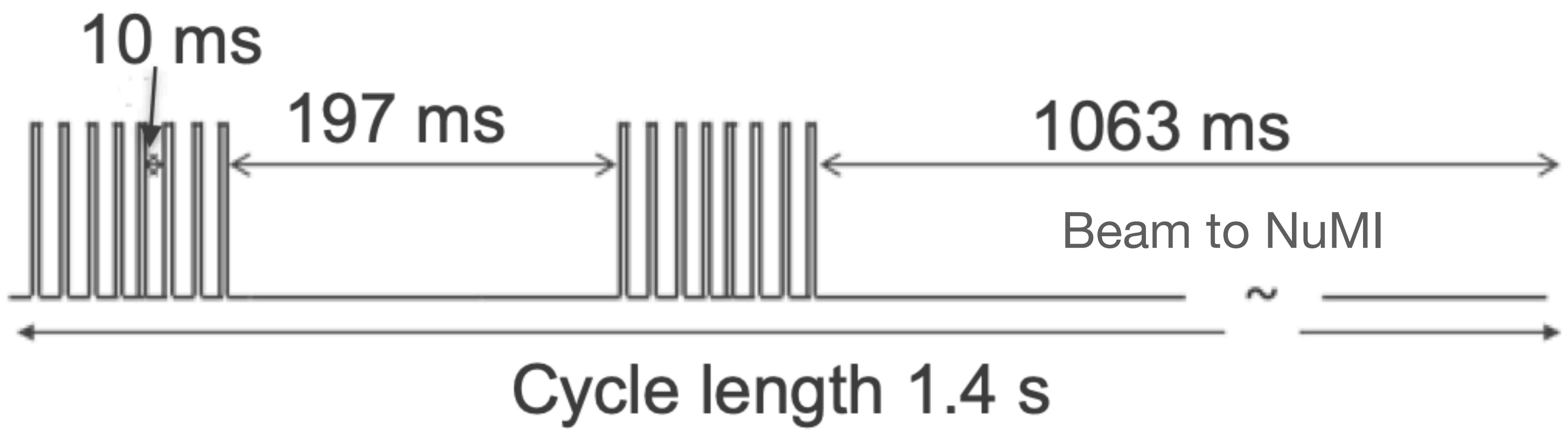


- Looks for rare processes using high intensity muon beam
- Talk by Mete Yucel on "A Search for New Physics in the Lepton Sector: Charged Lepton Flavor Violation and the Mu2e Experiment"

Muon g-2 Beam Delivery Details

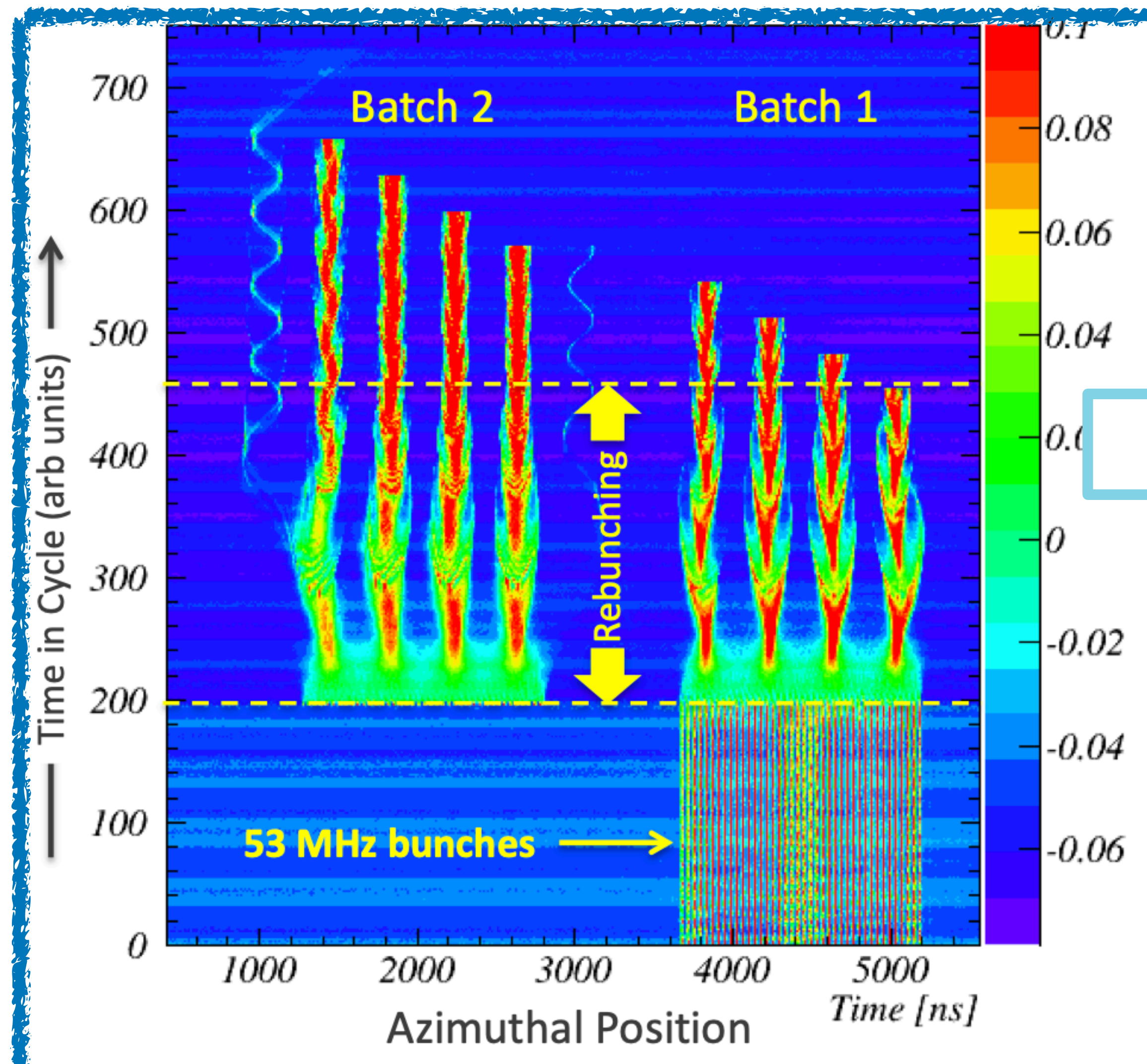
Recycler Ring 2.5 MHz Rebunching



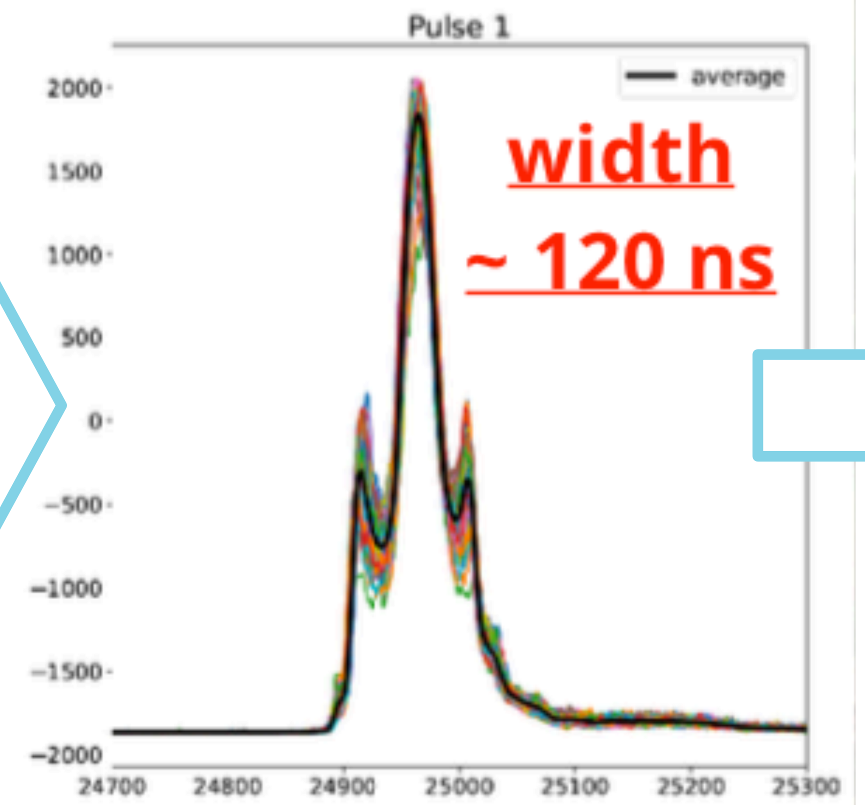


- First batch(4×10^{12} protons) injected into Recycler at t = 0
  - 84 53 MHz bunches/batch
- Second batch injected at t = 200
- Rebunching ramp plays immediately after 2nd bunch injected
  - 53 MHz RF turned off
  - Adiabatic bunching with 2.5 MHz for 90 ms
- After rebunching, 8 2.5 MHz bunches are circulating in Recycler
  First bunch (10^{12} protons) extracted to g–2 target at t = 460
- 2.5 MHz bunches extracted, one-at-a-time, every 10ms

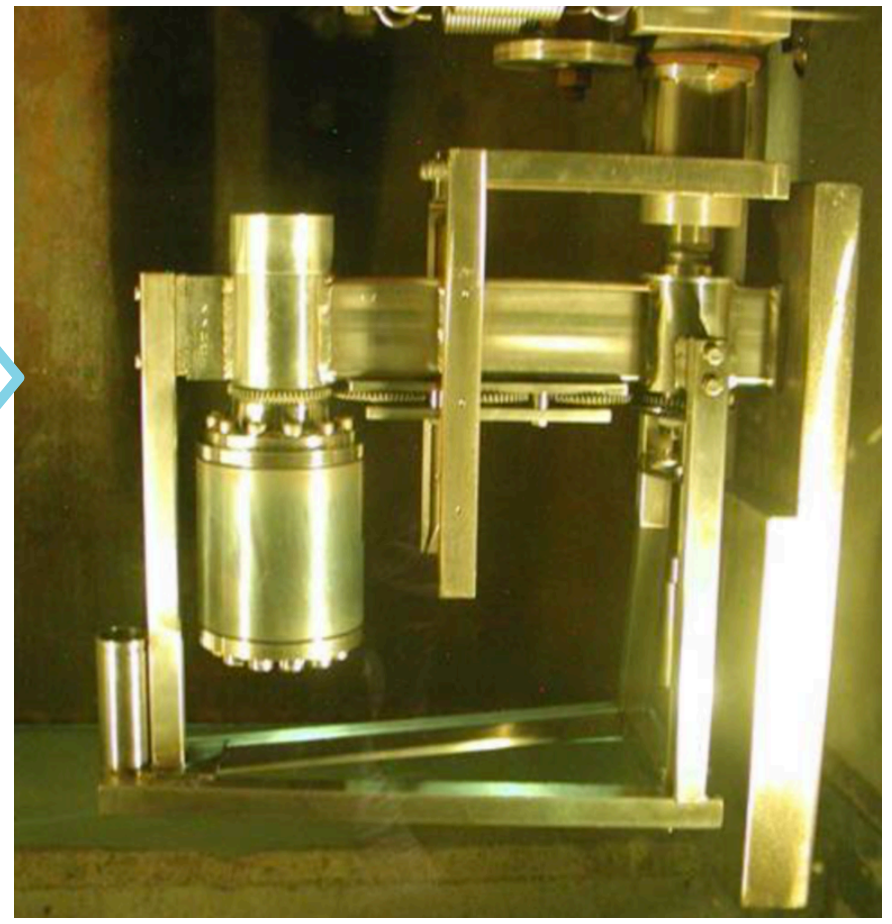
Proton Beam on Target



Recycler Ring 2.5 MHz Rebunching

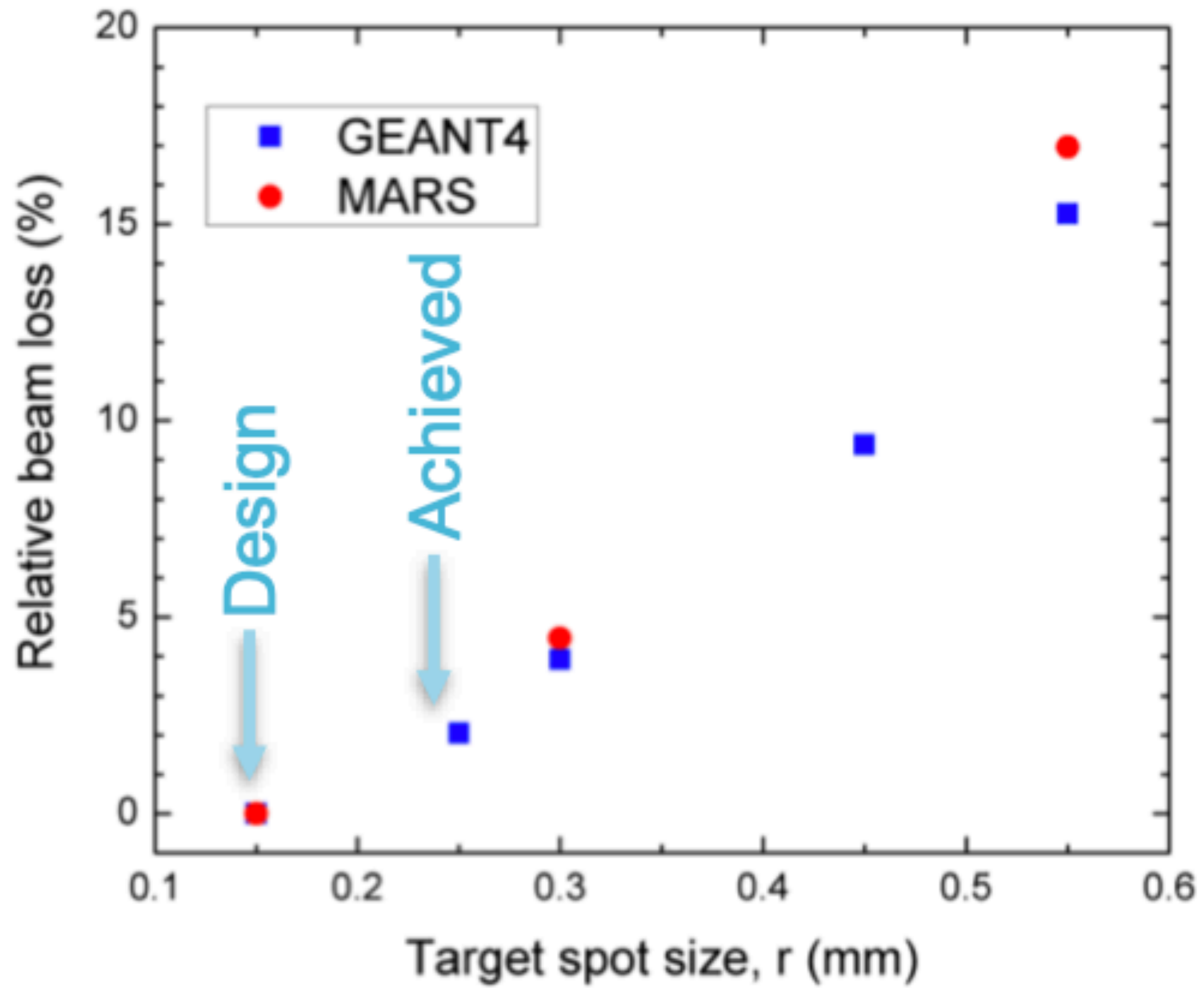


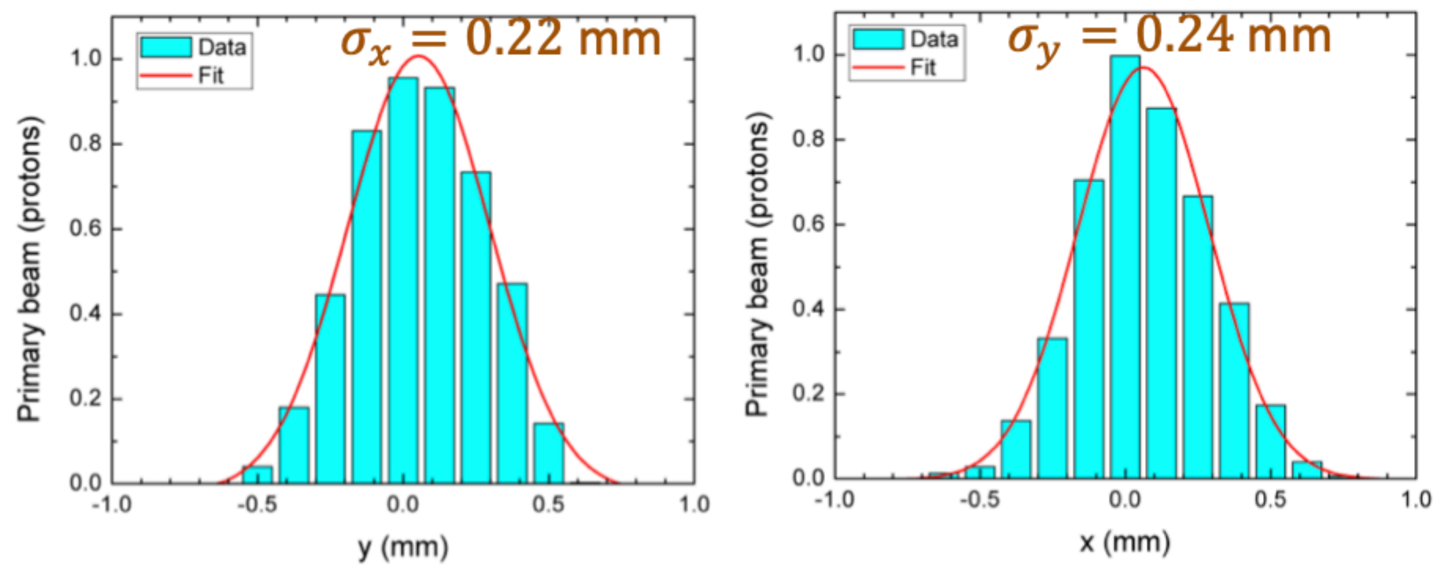
120-ns wide,
8 GeV proton bunch



Inconel (Nickel alloy) target
(from Tevatron Run-II)

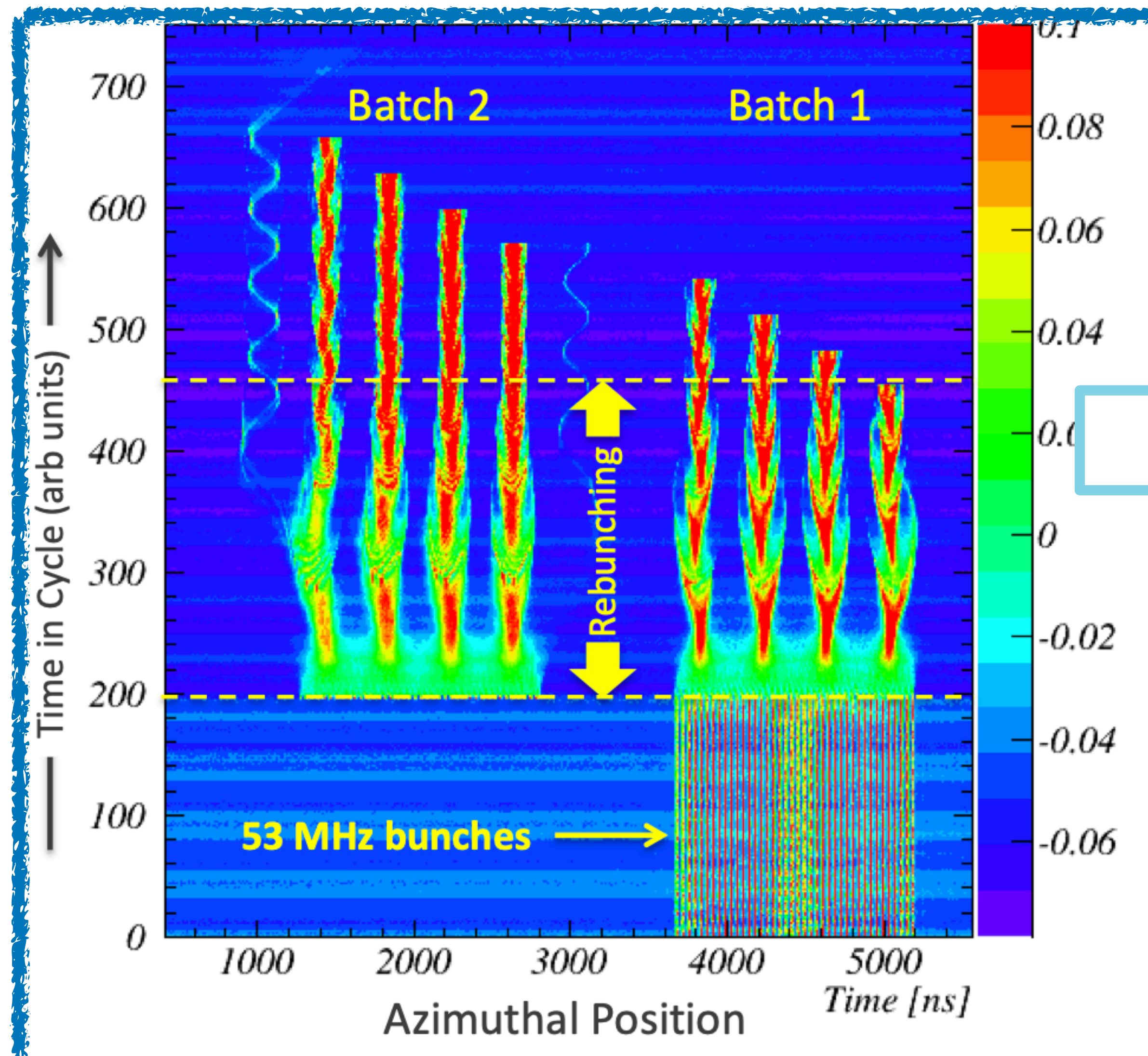
Parameter	Value
Protons on target (POT)	10^{12} per pulse
Pulse width	120 ns
Number of pulses	16
Bunch average frequency	11.4 Hz
Primary kinetic energy	8 GeV



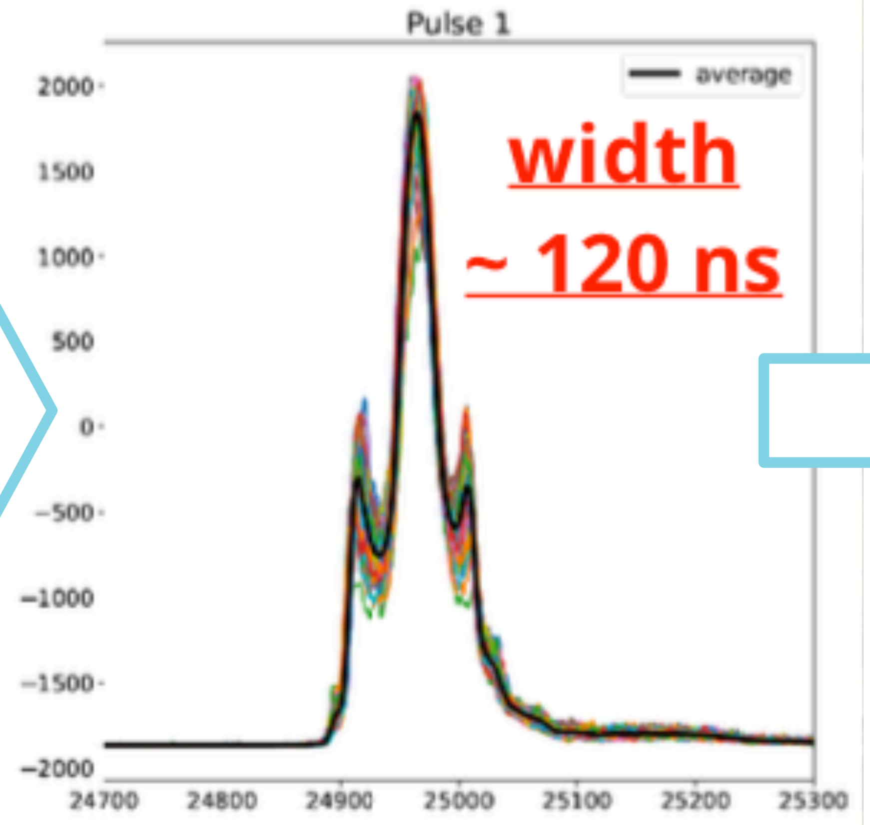


- Performance sensitive to beam spot size on target

3.11 GeV/c Pions Selection



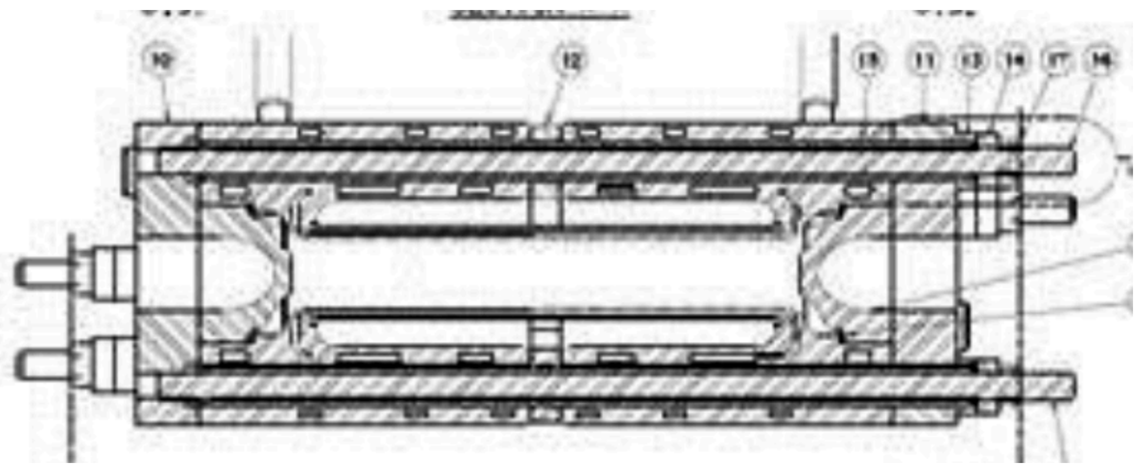
Recycler Ring 2.5 MHz Rebunching



120-ns wide,
8 GeV proton bunch

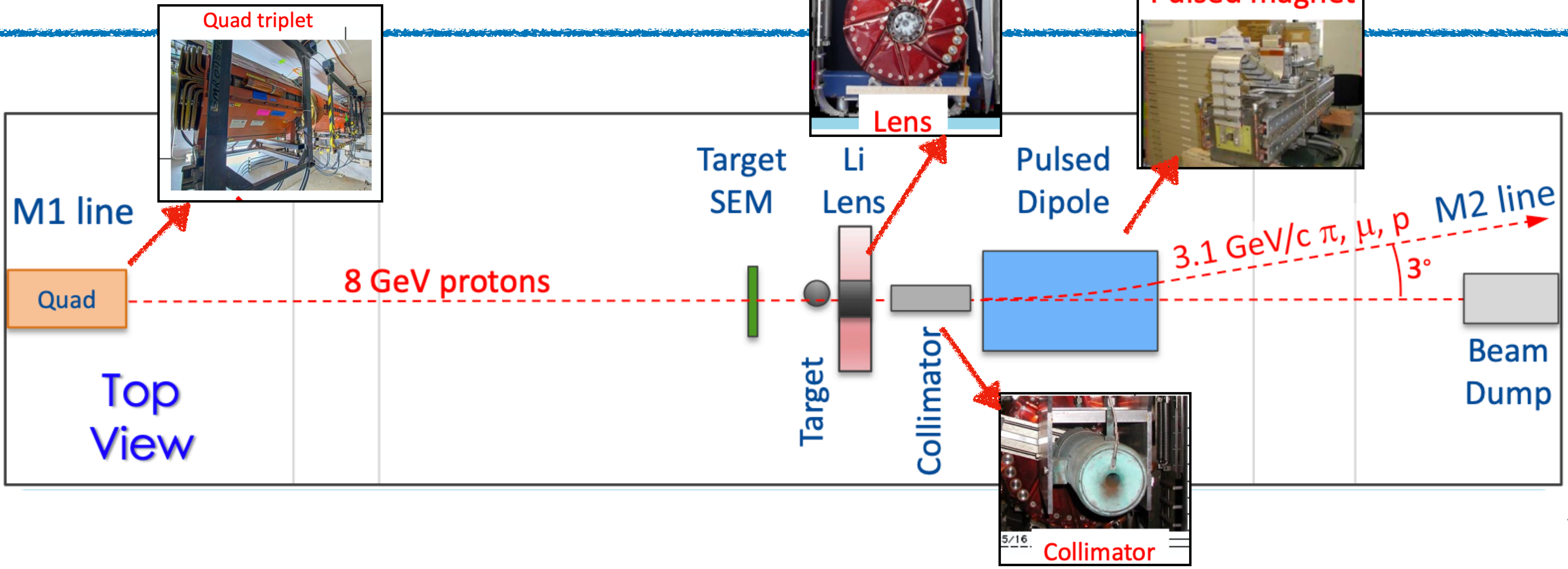
Inconel (Nickel alloy) target
(from Tevatron Run-II)

π

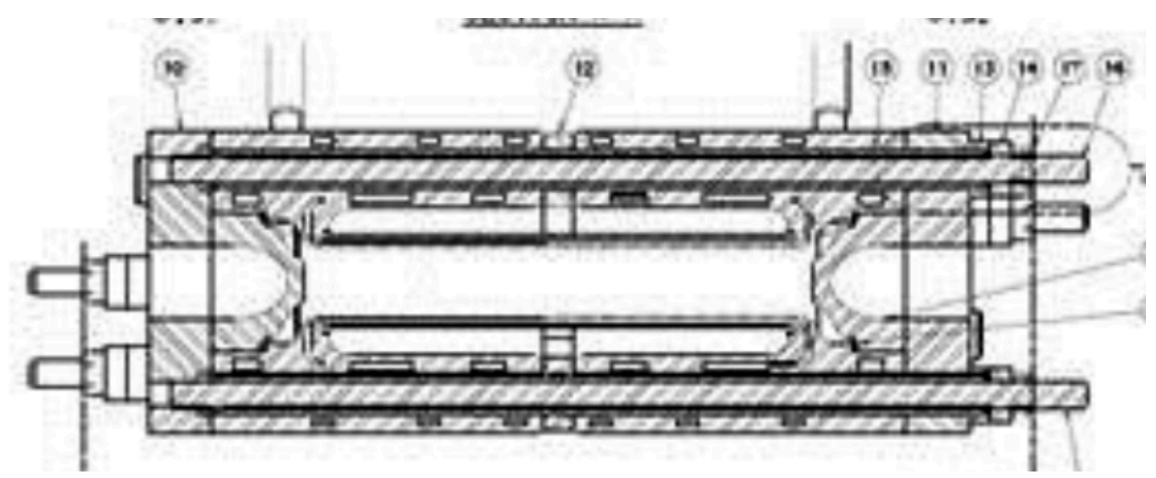


Li Lens focuses particles,
Pulsed Magnet selects
p = 3.11 GeV/c pions

- Flexible quad triplet upstream to adjust primary beam size
- Secondaries focused by lithium lens & momentum-selected by pulsed dipole magnet ~3.11 GeV/c

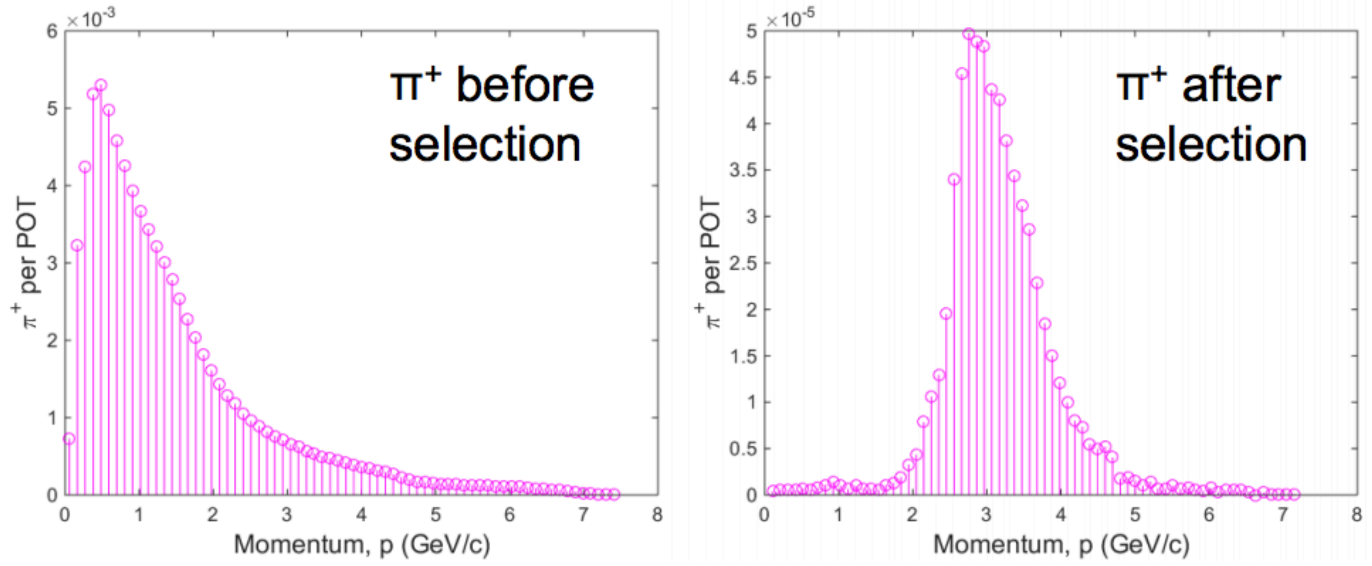


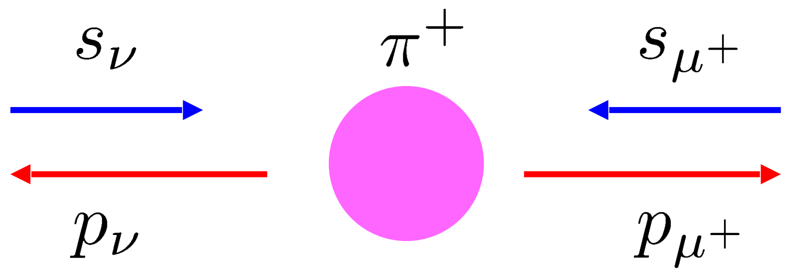
Muon Capture & Transport Lines (M2-M3 Lines)



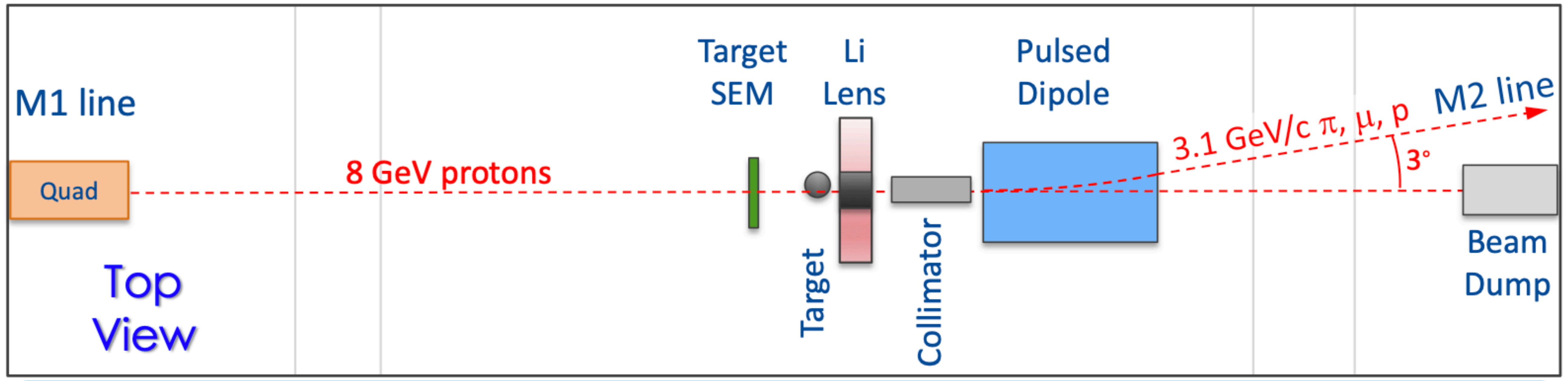
long path for π decay to μ

Li Lens focuses particles,
Pulsed Magnet selects
p = 3.11 GeV/c pions

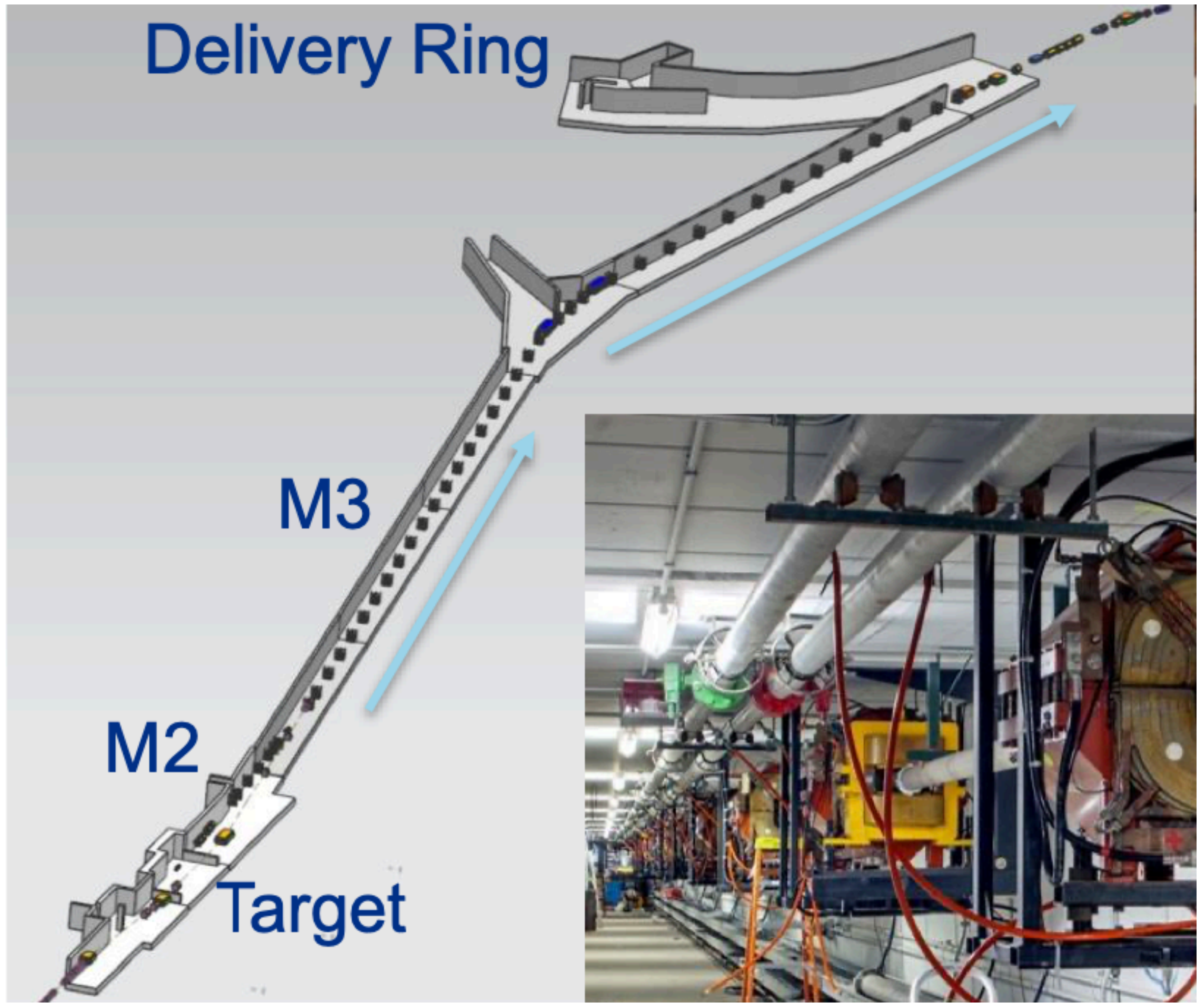




capture 3.09 GeV/c μ^+ =>
90% polarized beam



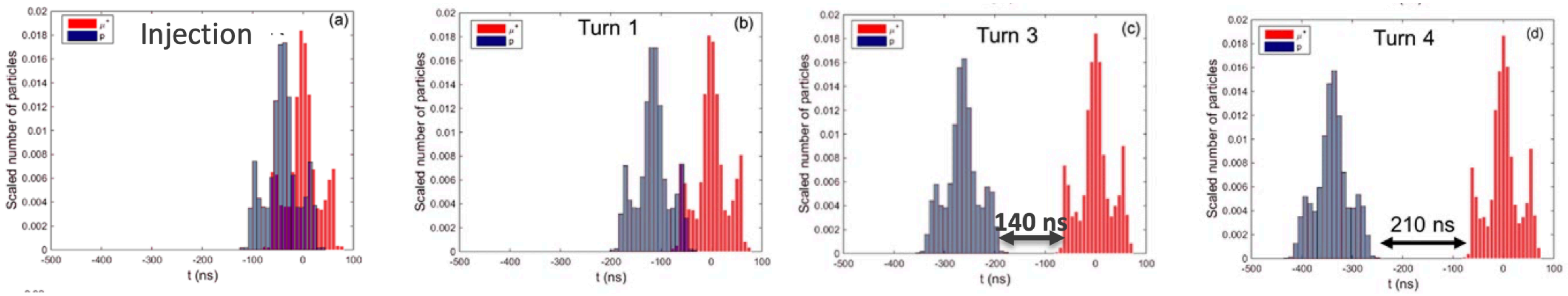
- Beamlines have high magnet density with large aperture quadrupoles
- Mostly muons from forward decays accepted & 90% polarization achieved
- 70% of pions expected to decay along M2-M3 lines



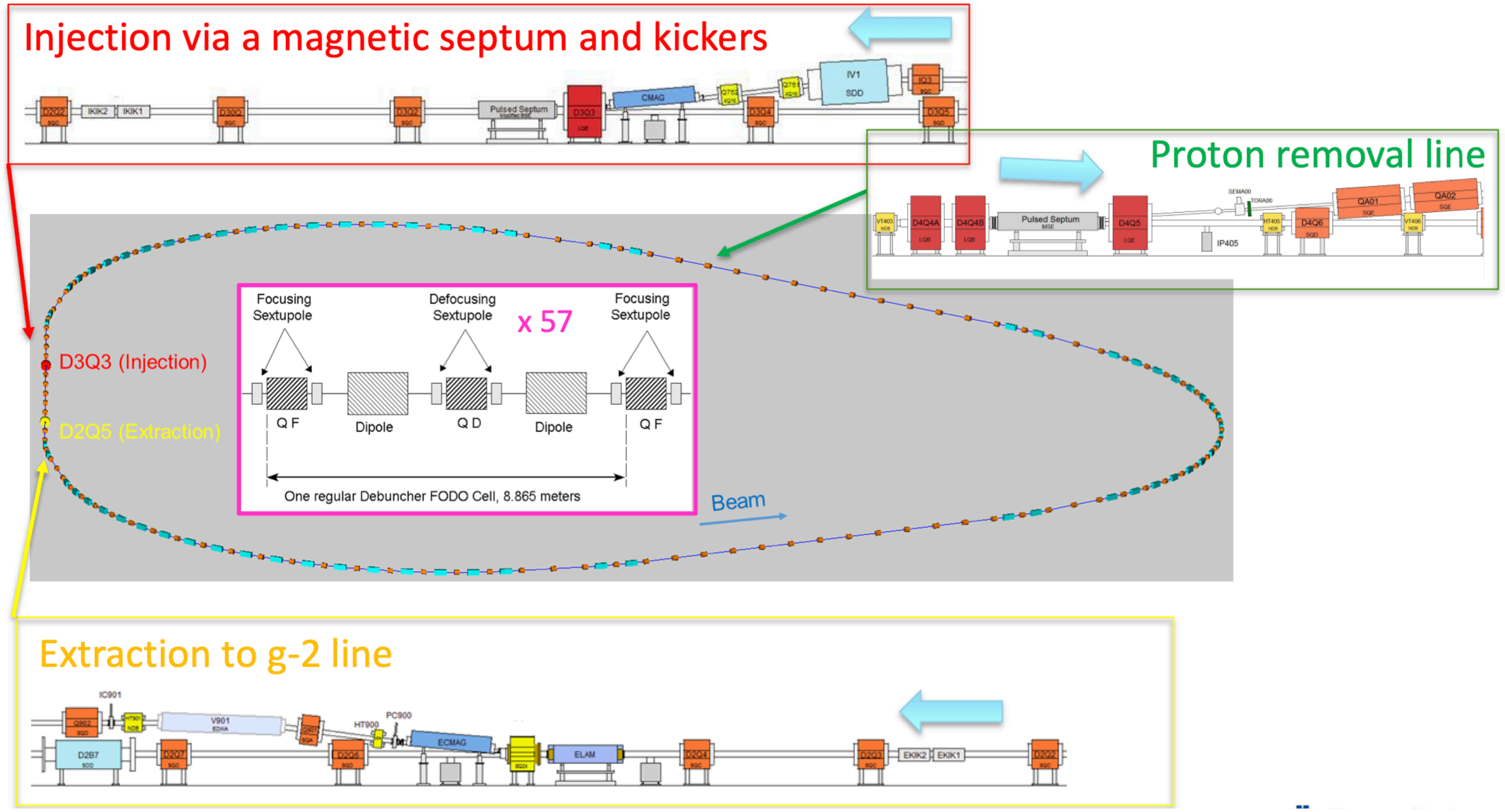
Proton Removal

Delivery Ring

has μ, π, p
4 turns separates contaminants



muons to g-2

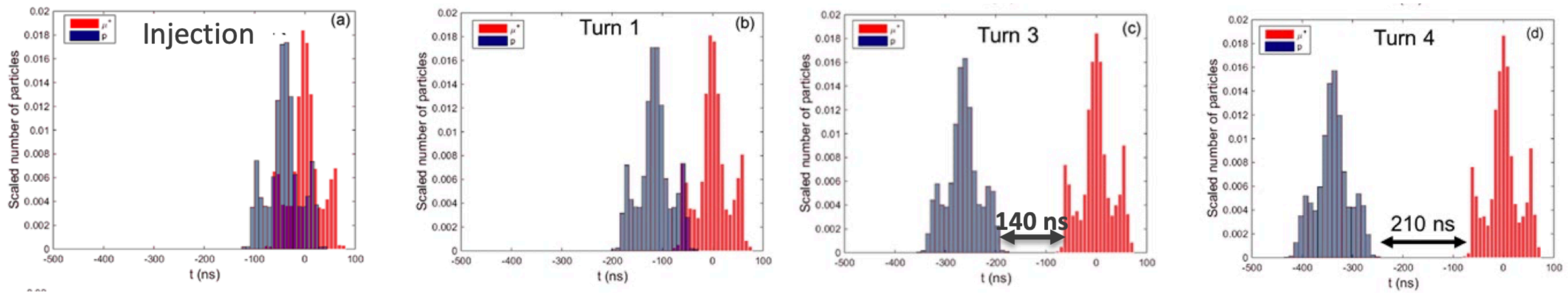


- Secondary Beam transferred to Delivery Ring
- At Delivery Ring injection beam composition:
  - -89% protons
  - -8% pions
  - -2% muons
- After 4 turns, only protons and muons remain
- Protons sent to beam dump prior to extraction of remaining muons to g-2

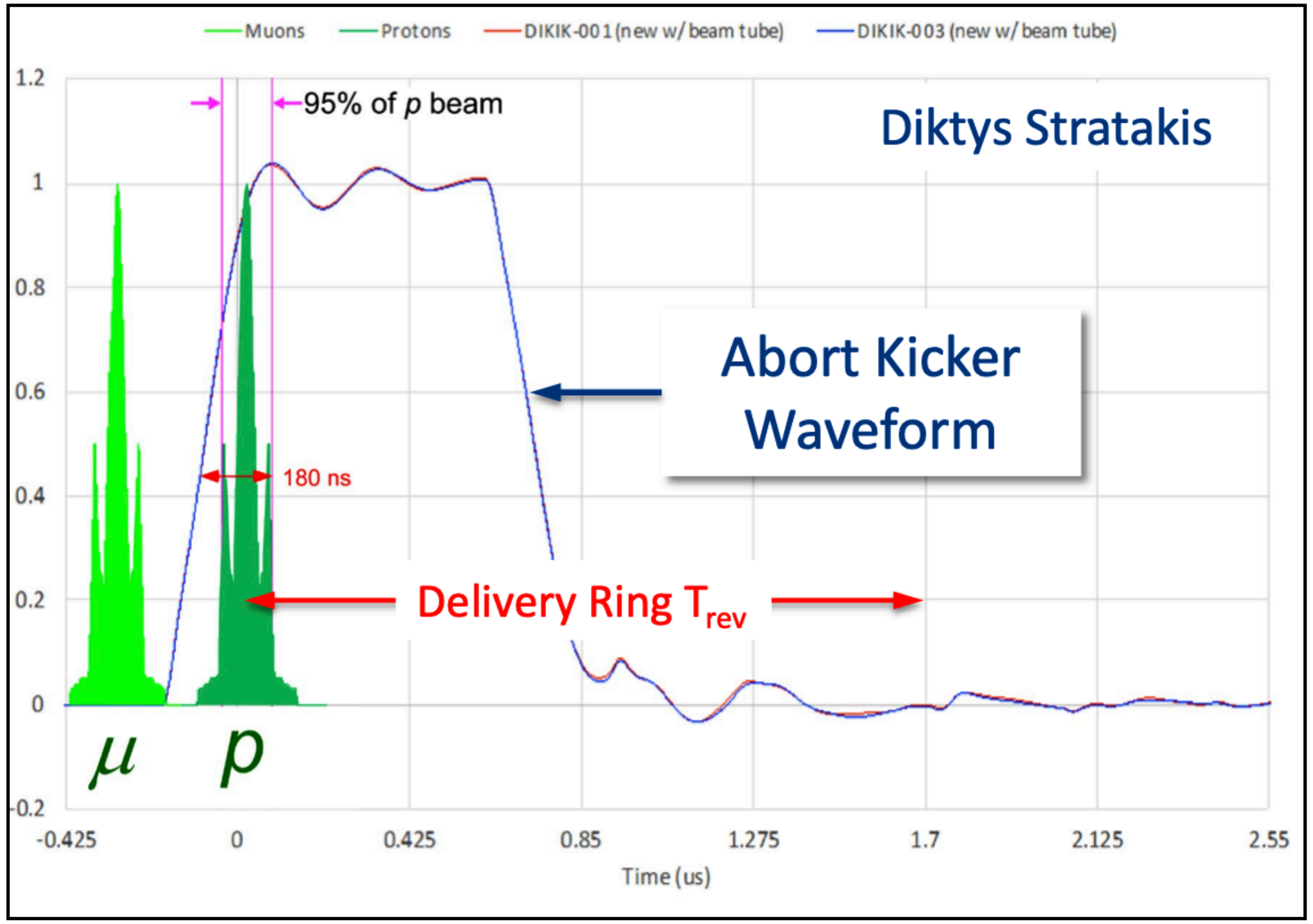
Proton Removal

Delivery Ring

has μ, π, p
4 turns separates contaminants

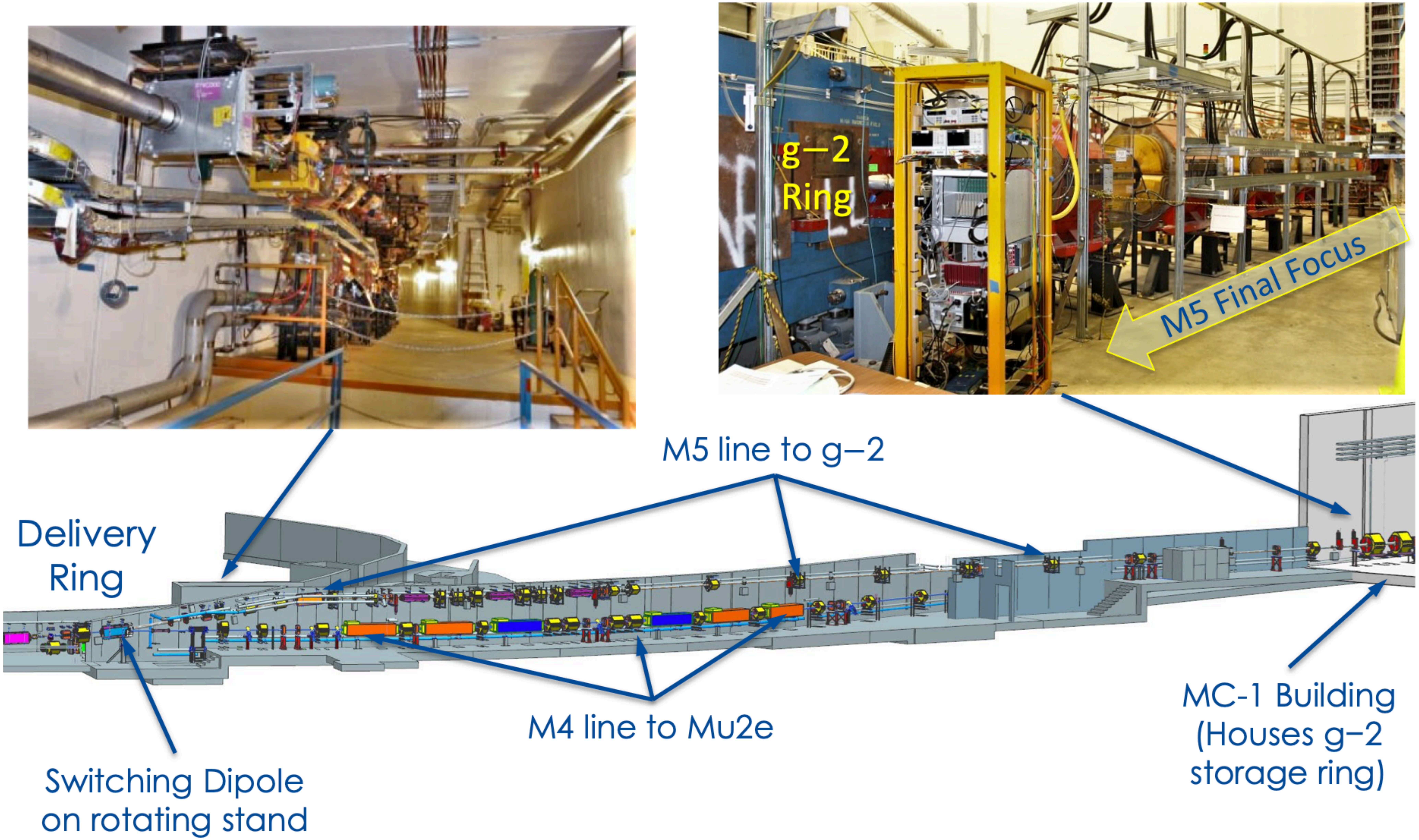


muons to g-2

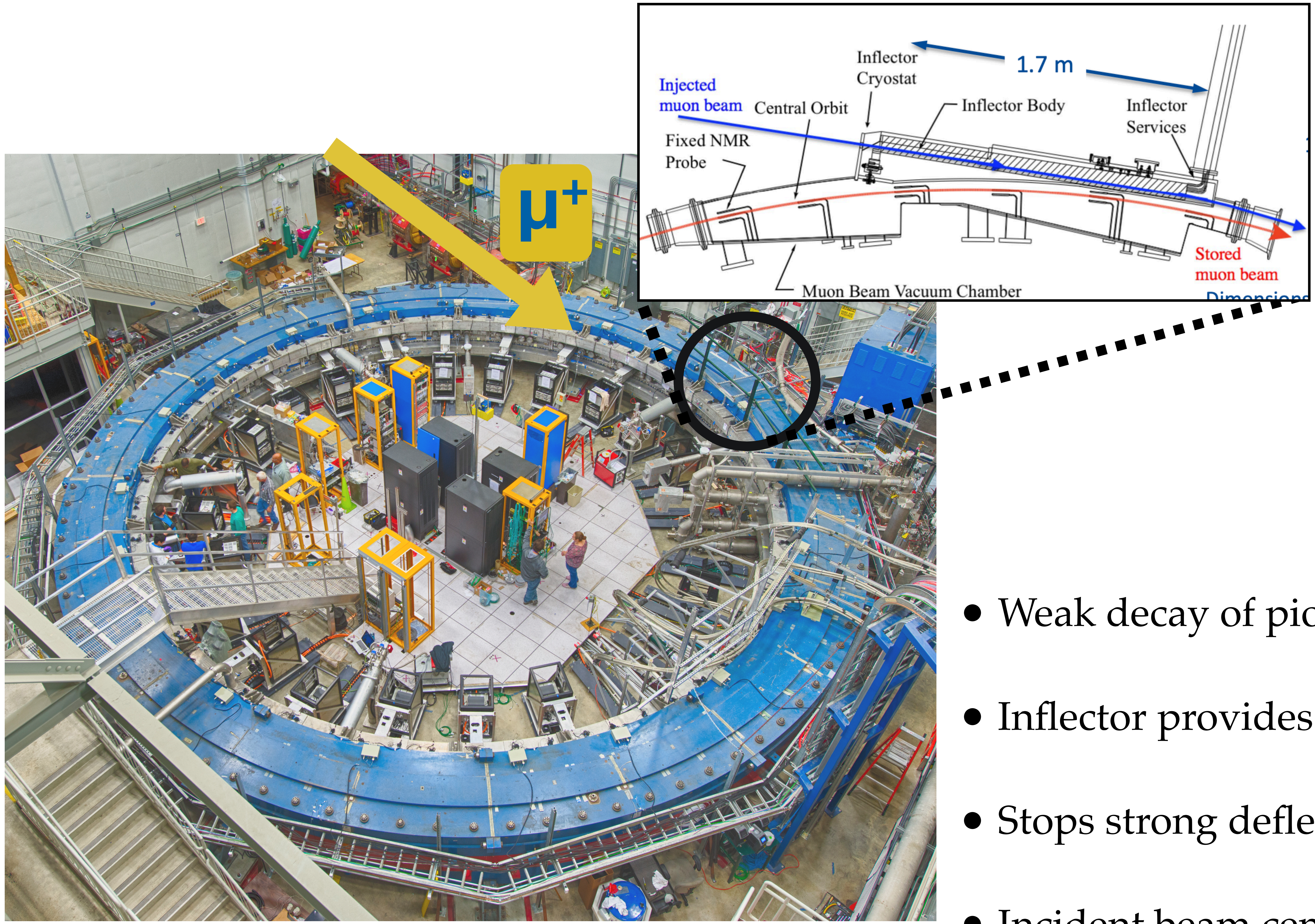


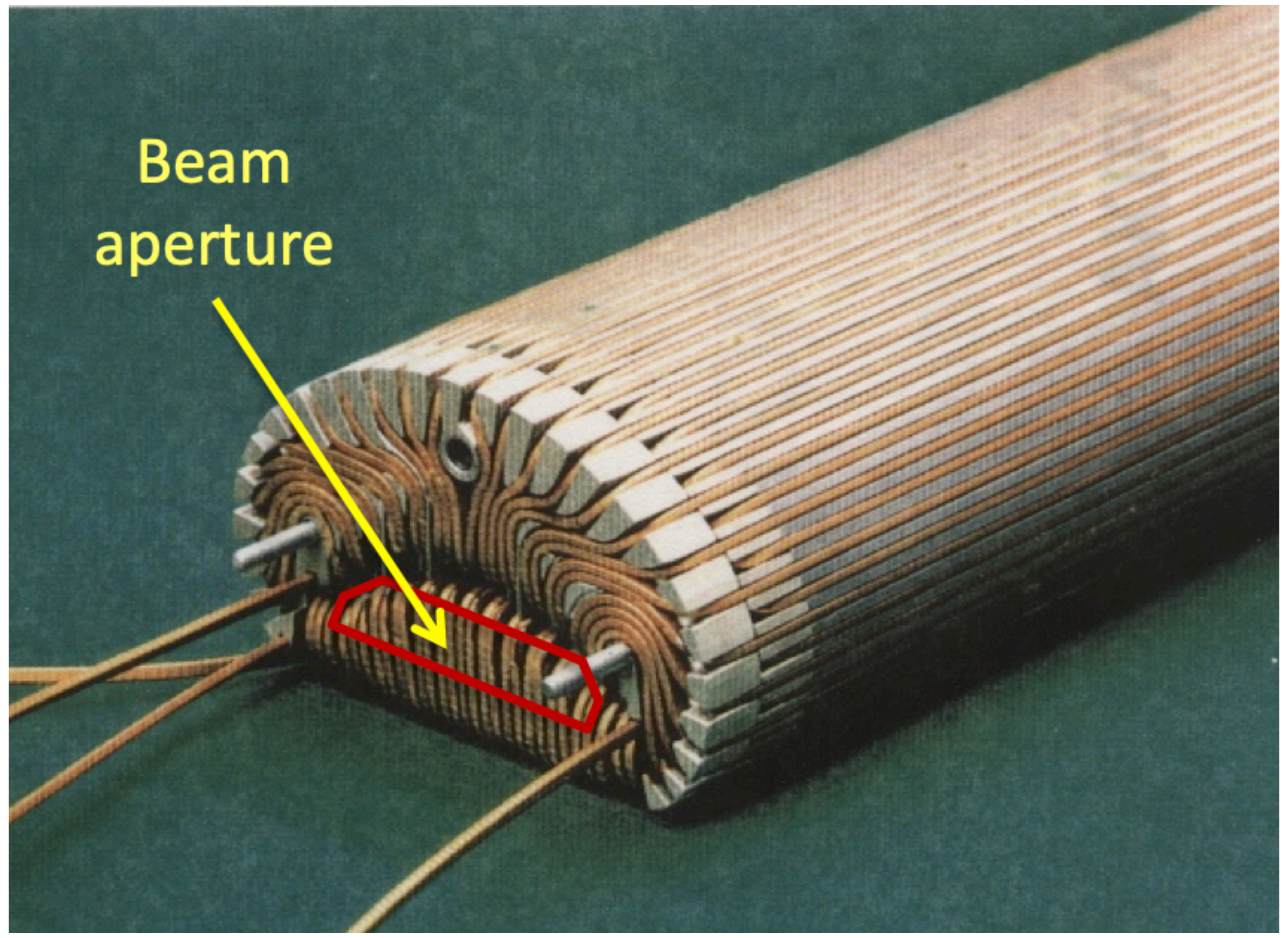
- Kicker rise ~180 ns; protons removed during turn 4
- Remaining beam extracted to g-2 after turn 4

Transport from Delivery Ring to g-2 Ring



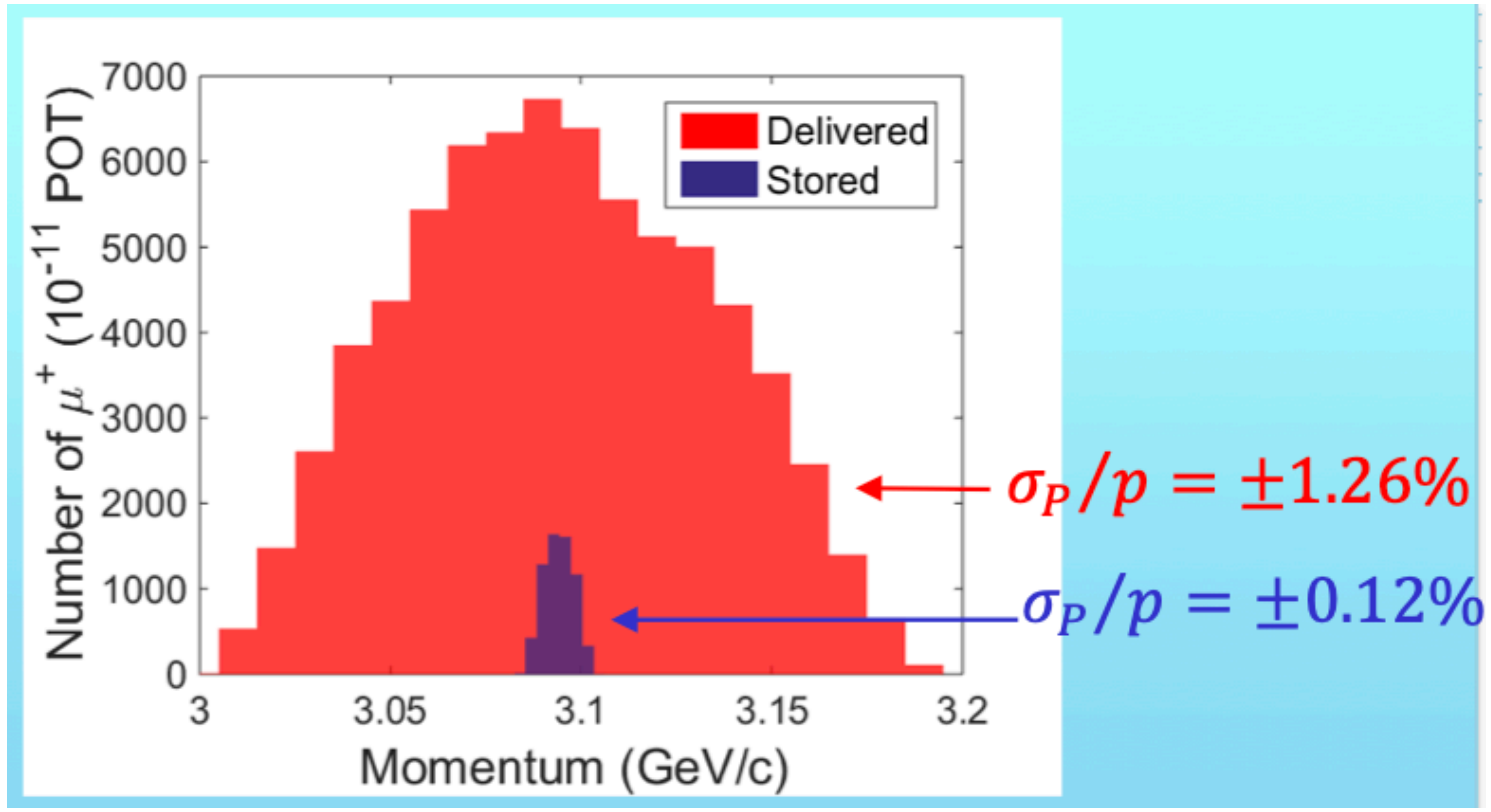
Injection into g-2 Storage Ring



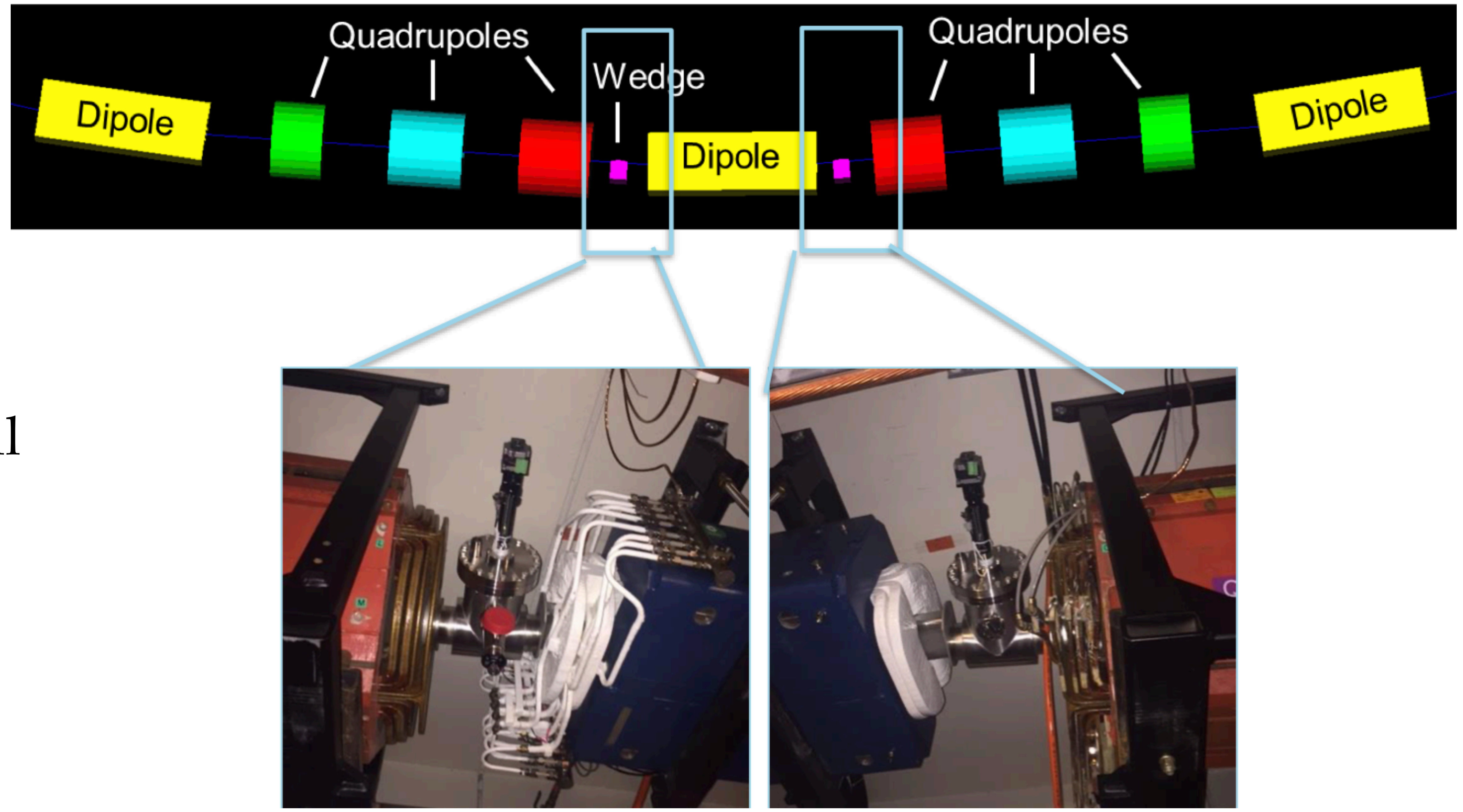


- Weak decay of pions produces highly polarized muon beam
- Inflector provides field free region to deliver beam to edge of storage region
- Stops strong deflection of the beam
- Incident beam center 77 mm off from storage region center
- Muon transmission efficiency is 2-4%

Performance Enhancement



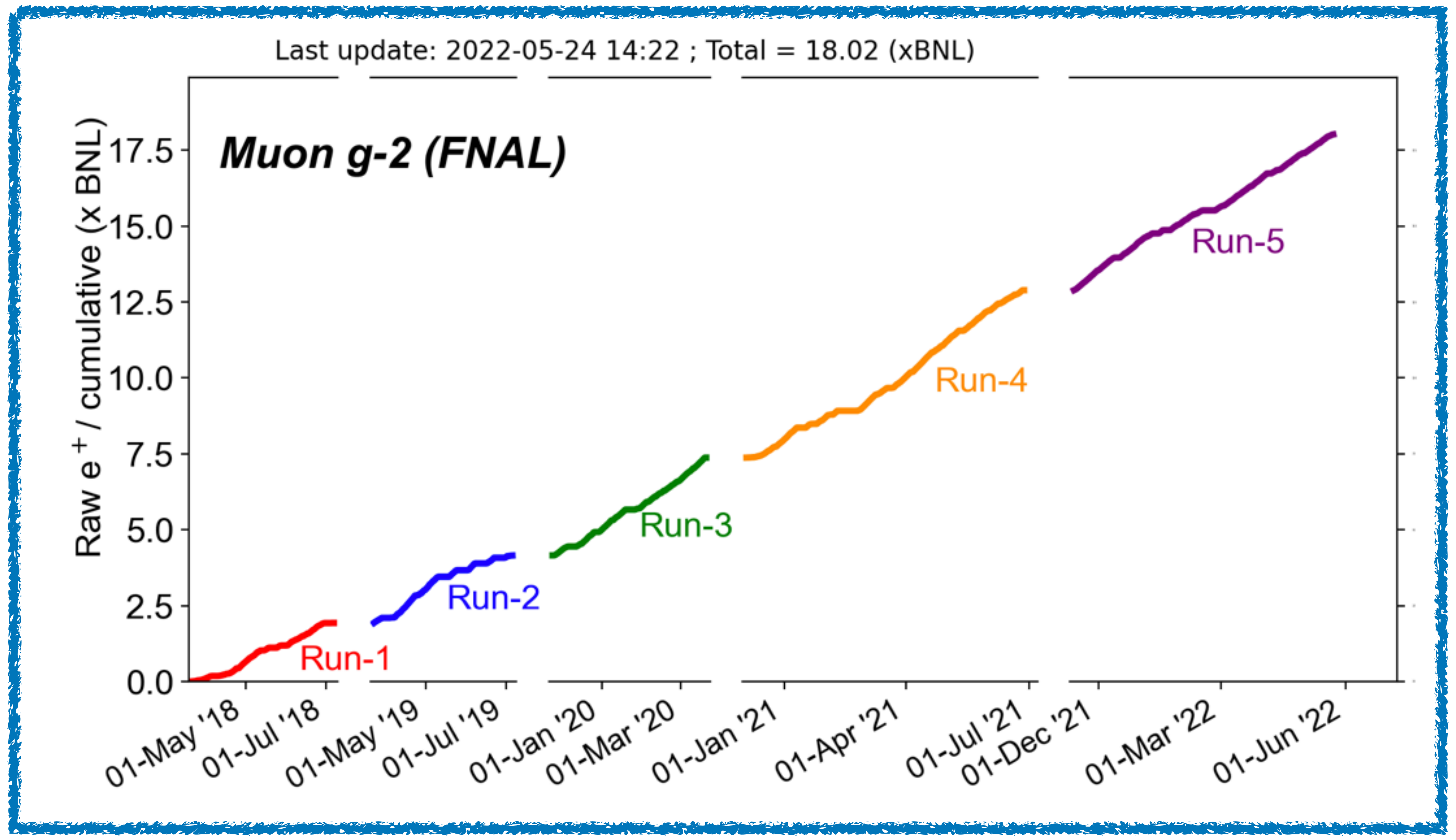
- g-2 ring accepts only a fraction of delivered muons
- Goal : provide as many muons within magic momentum (~3.1 GeV/c) band



- Proposal to reduce momentum spread in M4/M5:
  - Supported by Fermilab's LDRD program: to design, install and test a wedge in Fermilab's muon campus, system installed and commissioned
  - Primary test before g-2 Run2: up to a 7% improvement on stored muons

Courtesy Diktys Stratakis

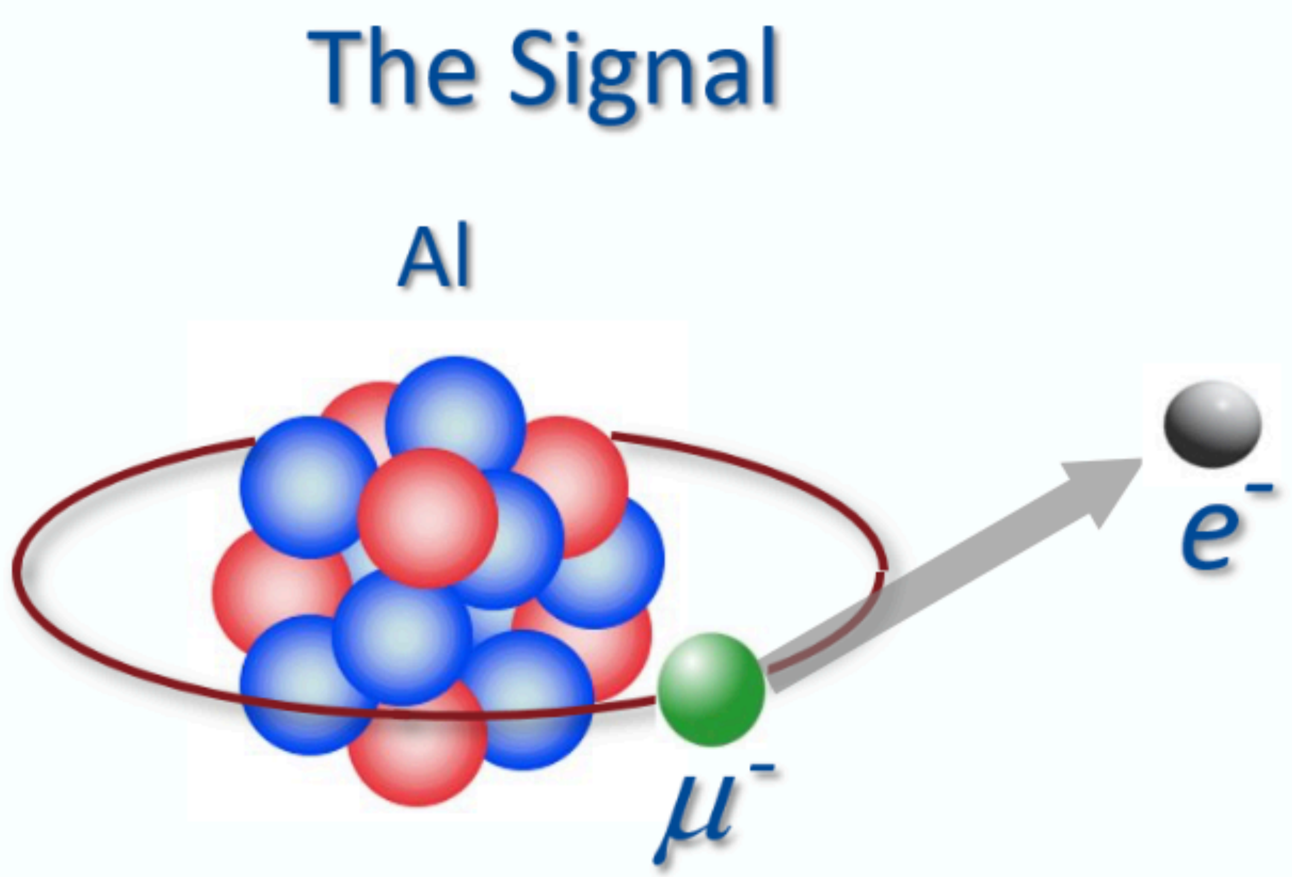
g-2 Status & Future Plans



- Run1 is about the 6% of E989 total budge
  - In November 2021 Run5 started
  - Accumulating 5.1 BNL up to now
- Final goal for Run5 is ~19 BNL
- Next year a μ^- Run likely - reduce uncertainty in anomalous magnetic moment of negative muon by a factor of two
- Plan to acquire equivalent of a four BNL-sized data set in a seven-month period
  - Required polarity change of main power supplies, trims
  - Polarity change of kickers and septa
  - At target station: original Pbar design, μ^- is normal polarity
- Polarity change planned during summer shutdown 2022 prior to running

Mu2e Beam Delivery Details

Mu2e Proton Beam Time Structure

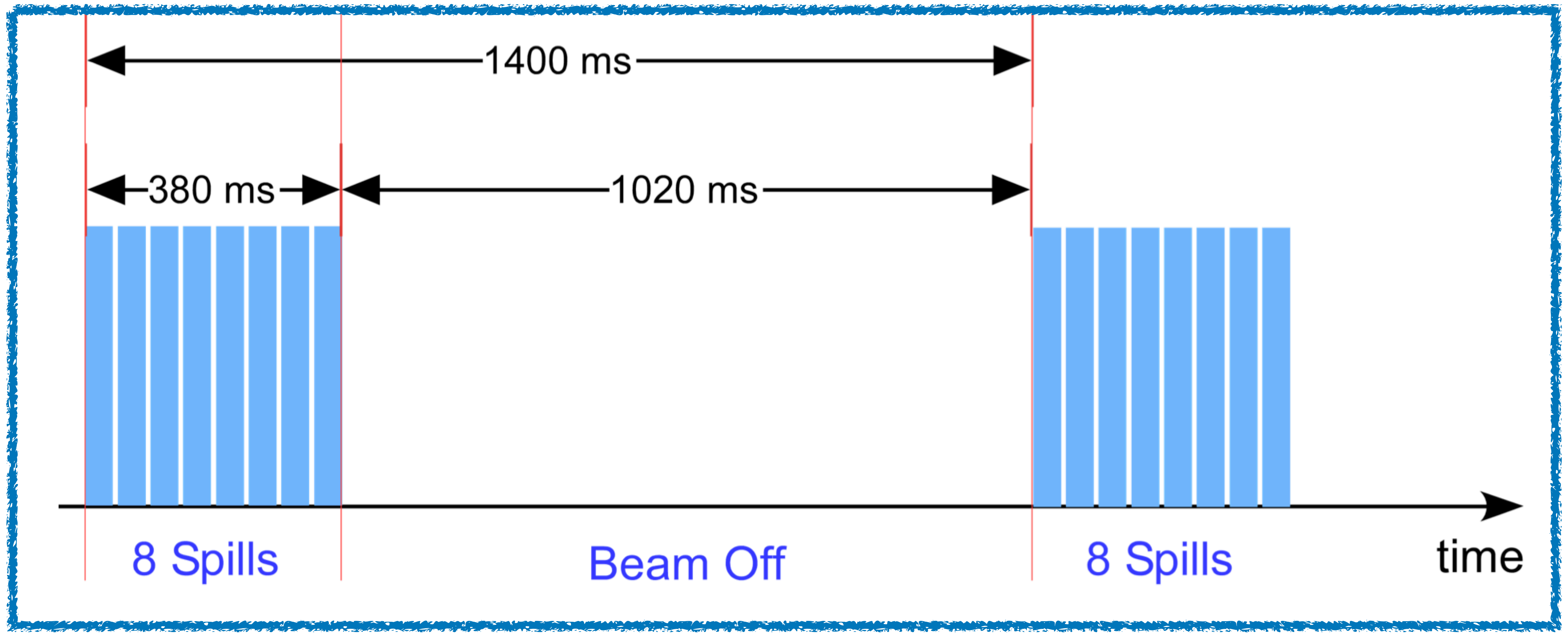


$$\mu^- N \rightarrow e^- N$$

L_μ: 1 0

L_e: 0 1

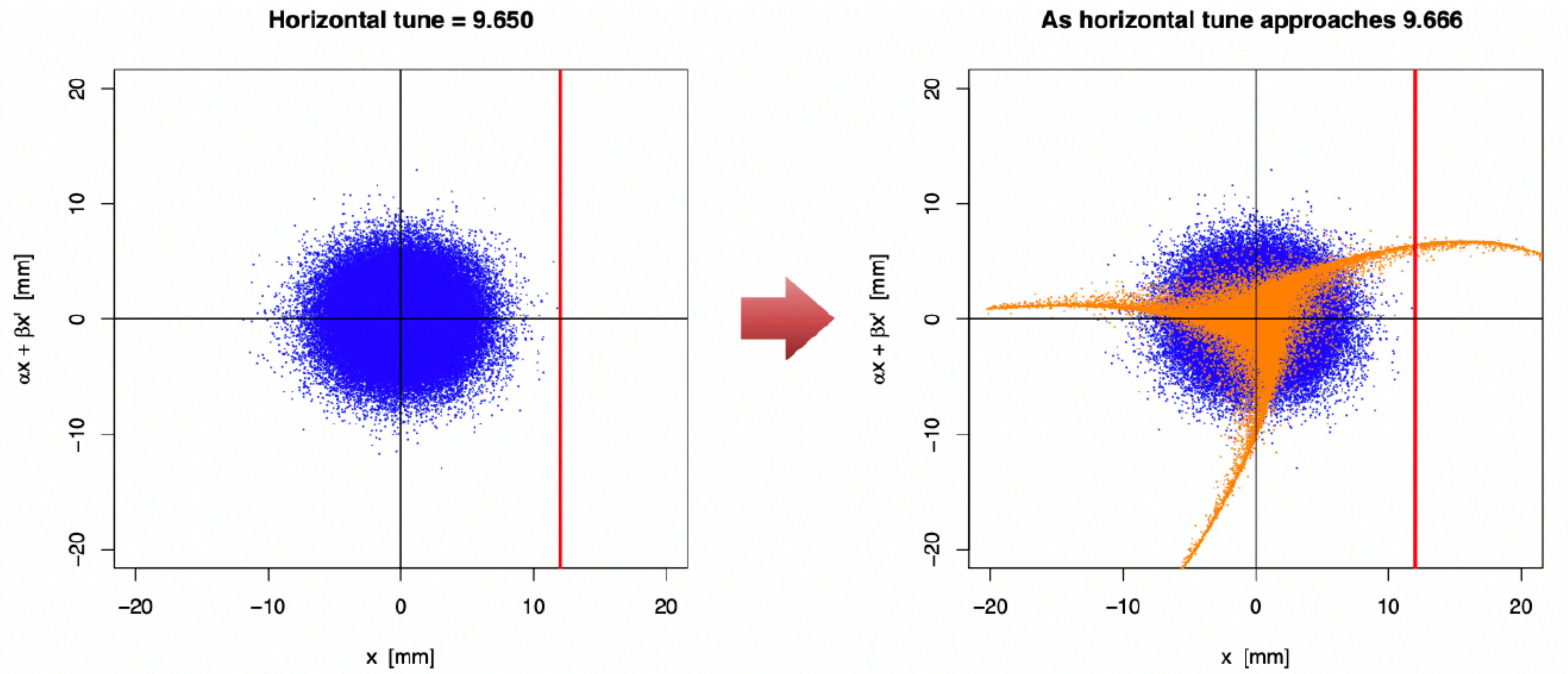
Both L_μ and L_e are not conserved in this process



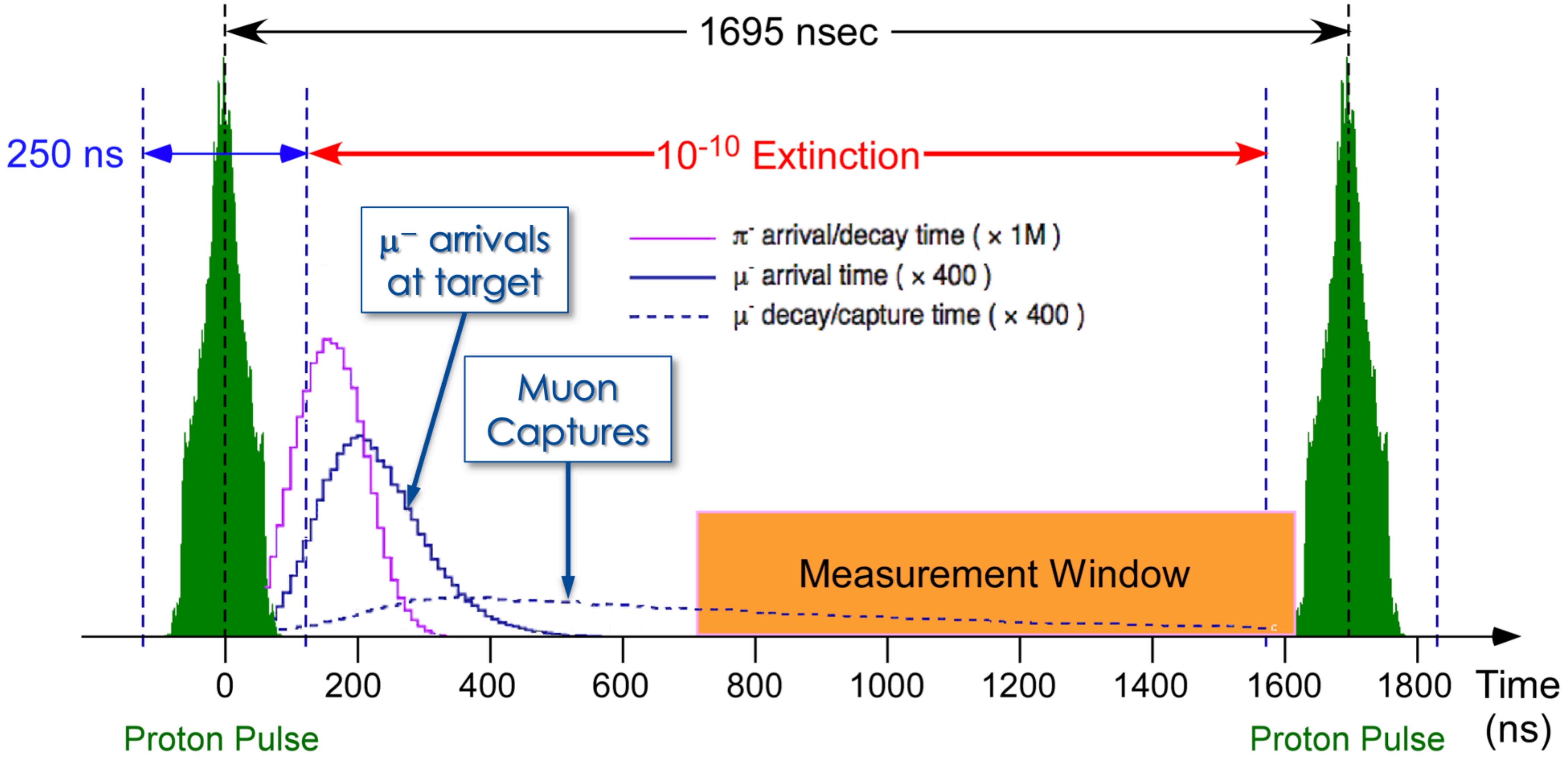
- Each of 8 bunches from Recycler slow spilled to Mu2e over an interval of 380 ms
- Each spill 43 ms long with a 5 ms reset between spills
- After 8th spill, Recycler used for NuMI/NOvA slip-stacking

Resonant Extraction

- Use nonlinear (sextupole) magnets to drive a harmonic instability
- Extract unstable beam as it propagates outward
  – Standard technique in accelerator physics



Reduction of Prompt Backgrounds



3^{rd} Order Resonance Extraction

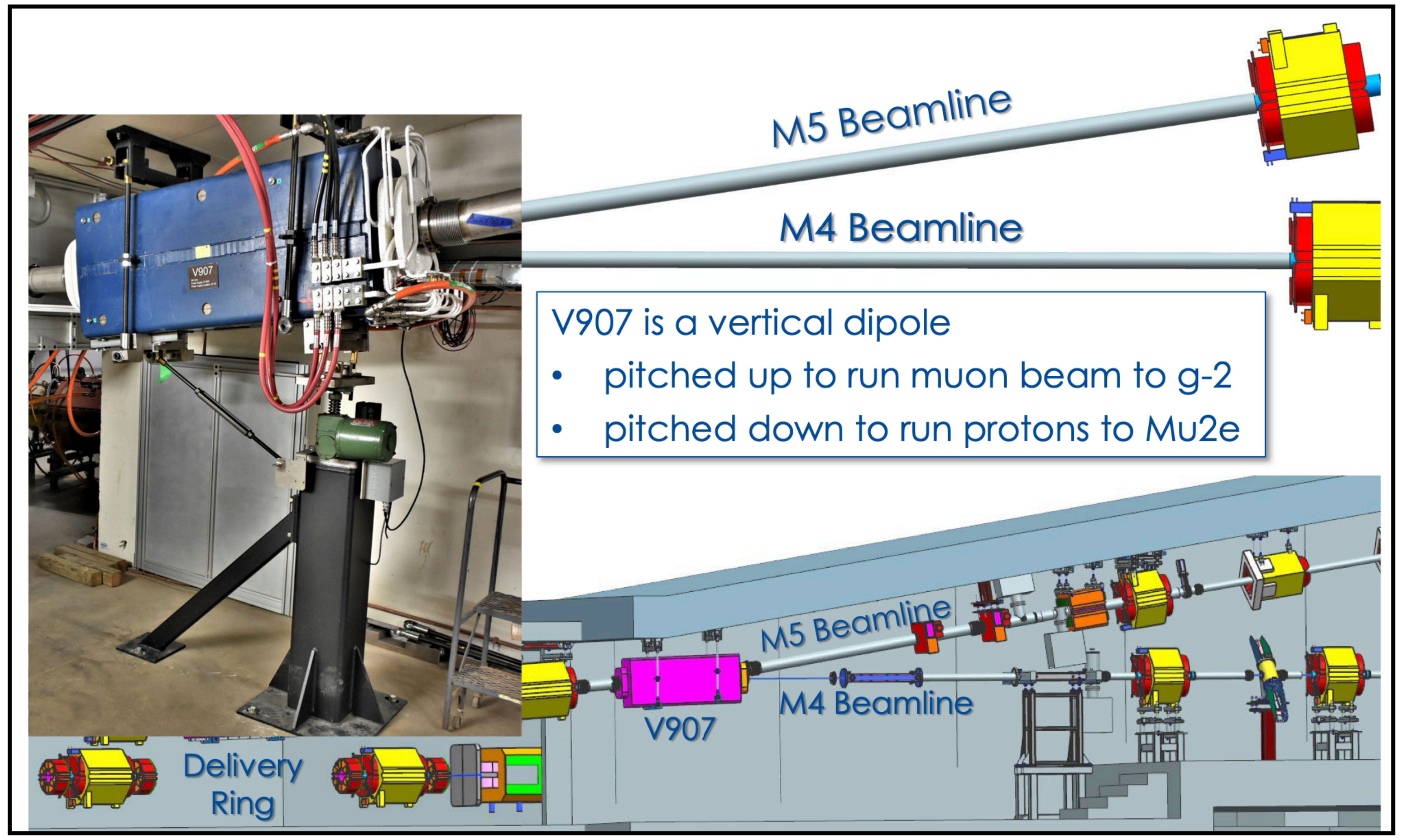
Quadrupoles drive a 1/3 integer resonance in horizontal tune

Sextupoles induce a controlled beam instability

Septum peels off a micro bunch on each turn

To control spill rate uniformity during resonant extraction, RF knockout technique used

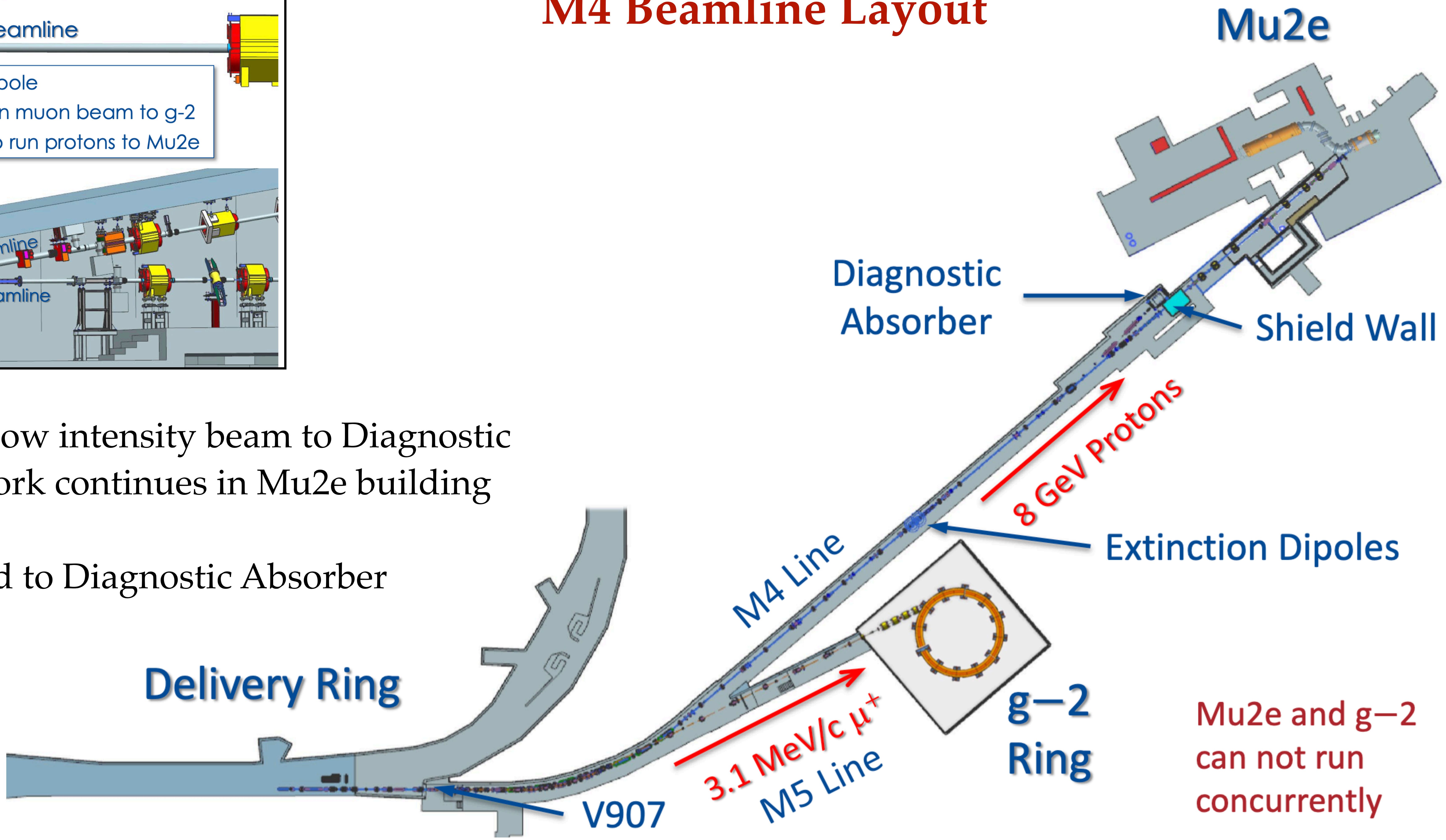
Proton Beam Transport from DR to Mu2e



- A shield wall allows running low intensity beam to Diagnostic Absorber while installation work continues in Mu2e building

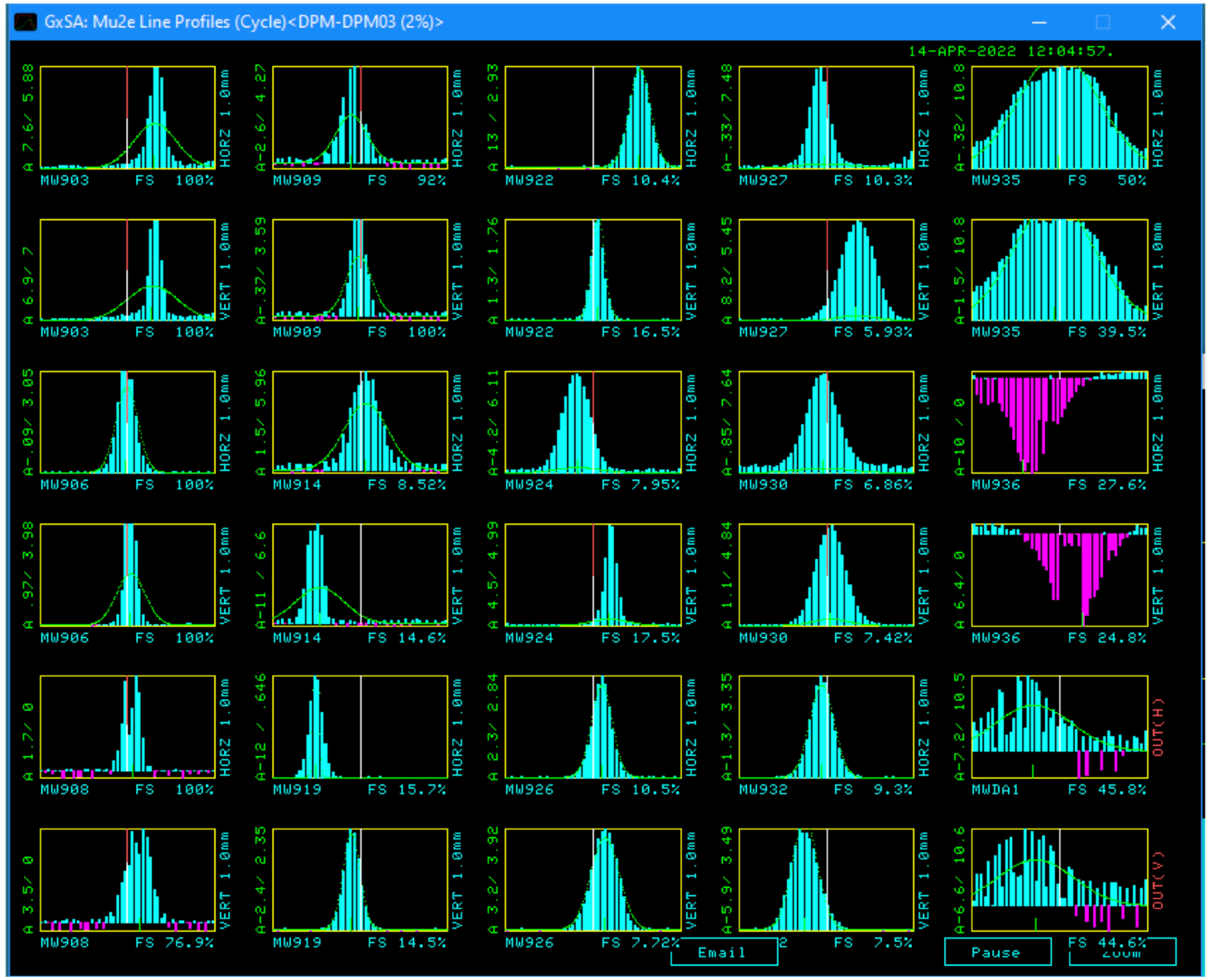
- Installation of M4 is completed to Diagnostic Absorber

M4 Beamline Layout

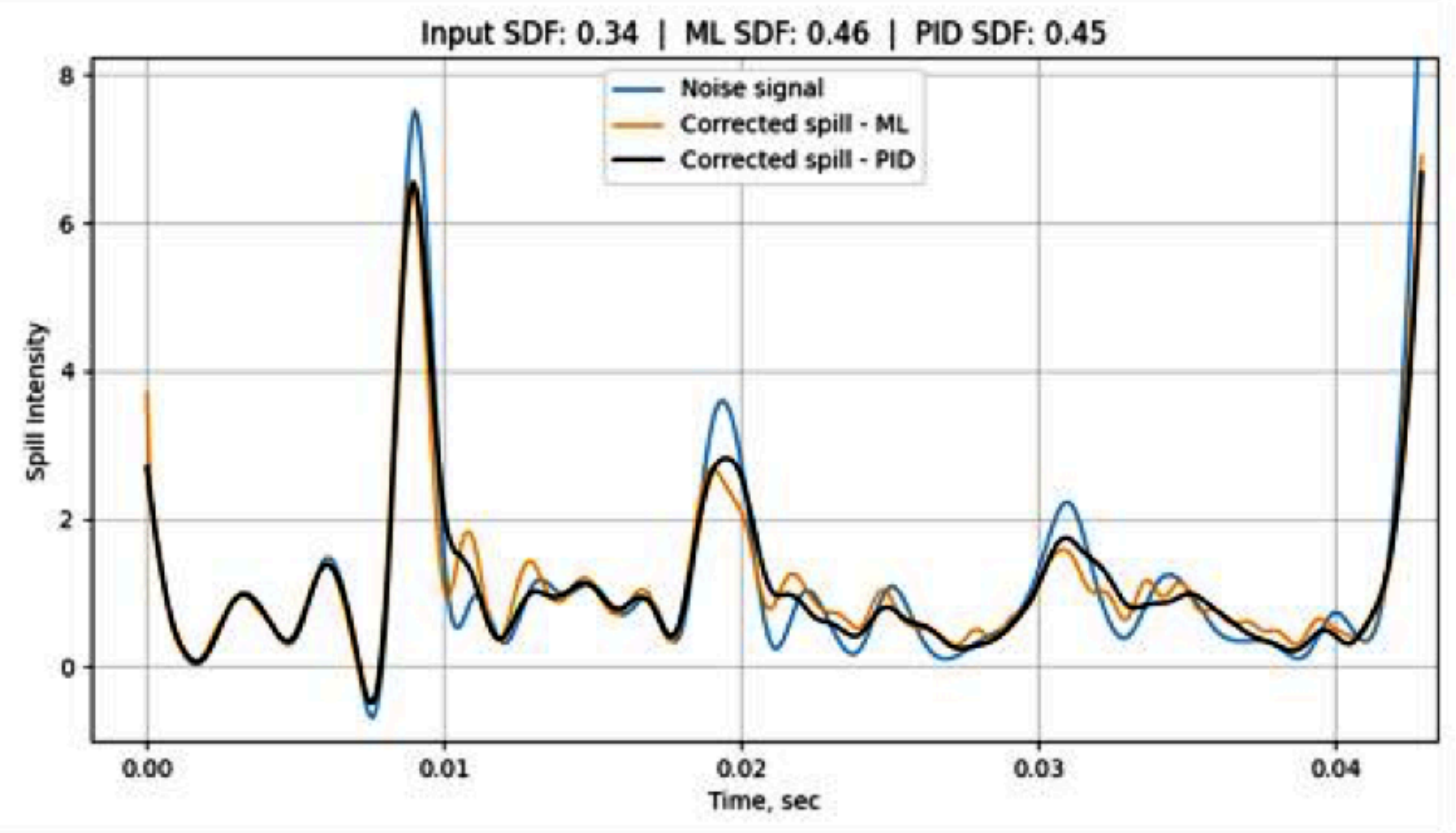


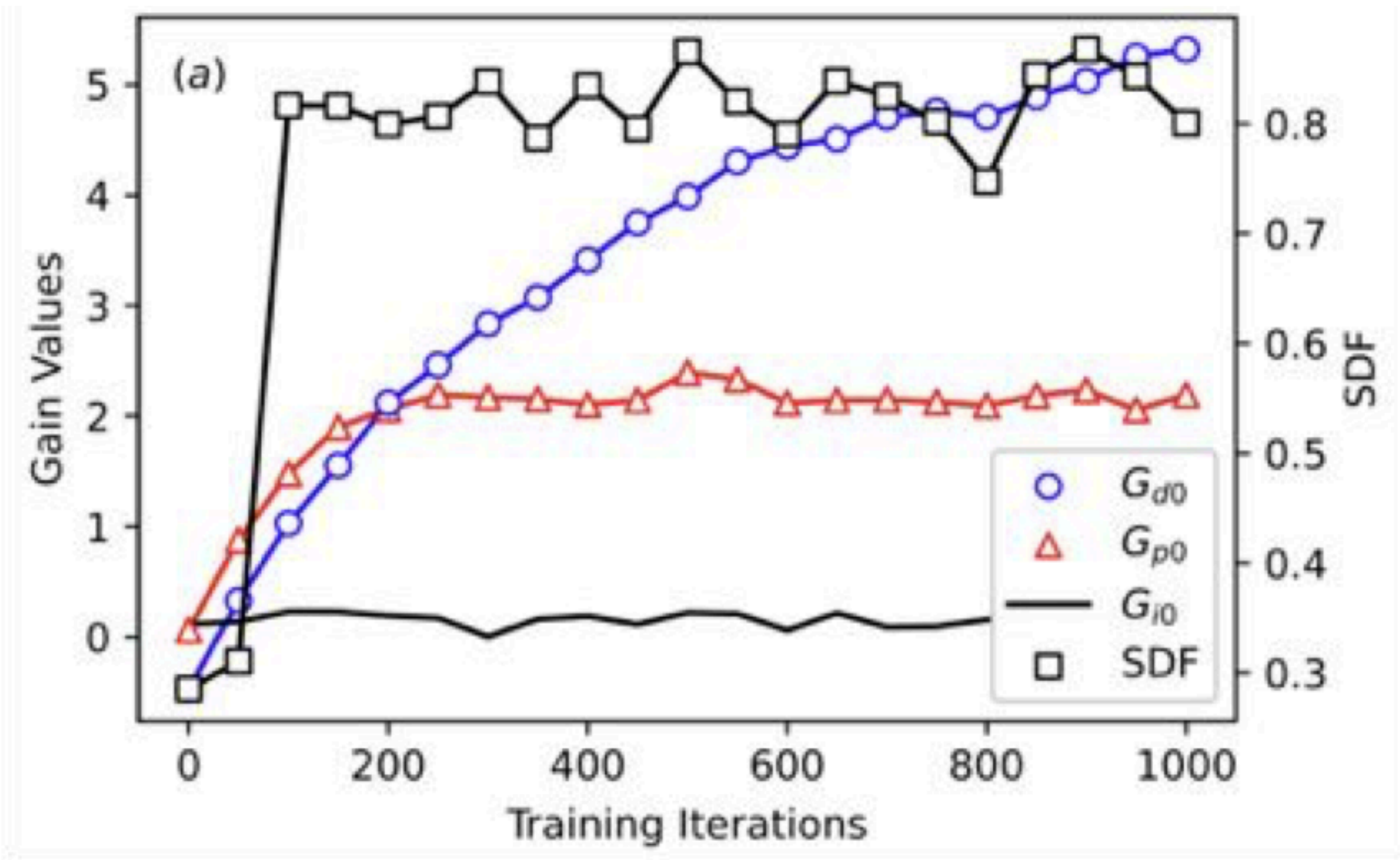
Beam Commissioning to Mu2e Diagnostic Absorber

- Commissioned beam to Diagnostic Absorber for first time!
- Along M4 line, multi wires at strategic locations to monitor the beam profiles
- See beam to all of them suggests that we had sent beam to diagnostic absorber successfully
- Satisfies Mu2e project key performance parameter
- Plan to upgrade a toroid in diagnostic absorber line so to monitor beam intensity



New Ideas: Machine Learning Spill





Comparing different ML regulation schemes: optimized PID regulator vs ML regulator

READS (Real-Time Edge AI for Distributed Systems):

- Improve real-time spill regulation with reinforcement learning algorithms for guided operations optimization
  - » Increases Spill Duty Factor of slow spill extraction

Courtesy A. Narayanan & M. Thieme, IPAC'21, THPAB243

Fermilab

New Ideas: Unique Proton Target

Unique target has been built

» Testing of target at AP0, with Mu2e like beam underway

- Radiatively cooled
- Peak temperature = 1130°C (@ 8 kW proton beam power)
- Variable length segmented core and fins to control longitudinal temperature profile
- Extended mounting bars on outside ring to minimize bending moment on target
- Stopped muon yield = 0.0015 μ/POT

Work underway on Mu2e target remote handling

Beyond Mu2e: Potential Experiments

- Mu2e II: Searching for Muon Conversion in the PIP II Era - will utilize 100 kW beam

- PIP-II will power both DUNE & other experiments like Mu2e-II

- Many other ideas to build short-, medium-, and long-term muon-based experiments were discussed at

  - "Potential Fermilab Muon Campus & Storage Ring Experiments workshop" (https://indico.fnal.gov/event/48469/)

  - "Muon Properties and Related Topics III" workshop (https://indico.fnal.gov/event/52525/)

Summary

An accelerator facility to provide beams to both g-2 and Mu2e experiments has been designed and constructed at Fermilab

- Facility has been commissioned in 2017 and is now in operation phase for Muon g-2 since Experiment since 2018

- It currently delivers roughly 1x the BNL statistics per month. Experiment will complete at 20x the BNL statistics

- A passive wedge system shows up to 7% improvement on stored muons

- μ^- mode is not compatible with Mu2e mode –run for 7 months before switching to Mu2e mode

- Current plan is to run g-2 until 2023 while in parallel doing commissioning tests for Mu2e beam delivery opportunistically