Commissioning and first results of the Fermilab Muon Campus

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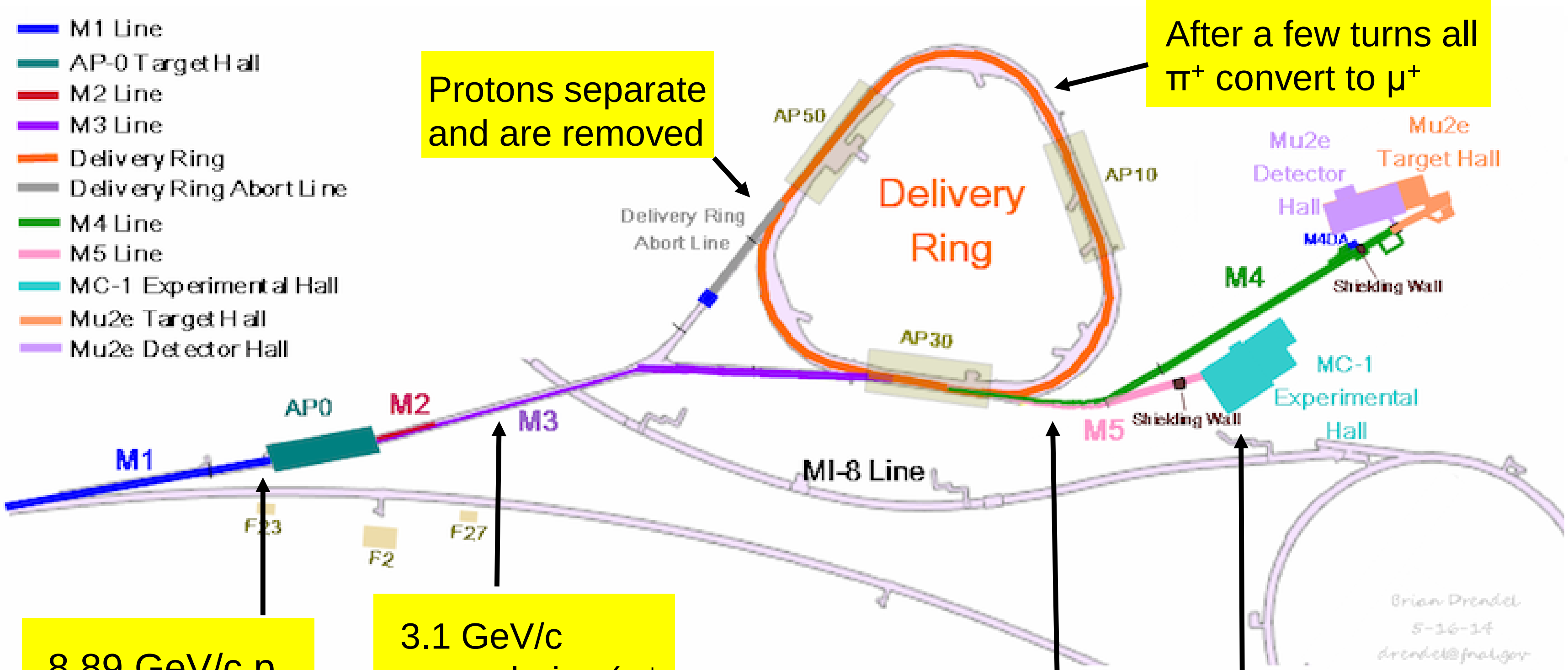
Nufact, Virginia Tech
August 17, 2018

Thanks

- Thanks to run coordinators Jim, Dean and Brian for providing me beam time to perform these measurements. We had to compete with g-2 so I know it was not easy.
- Most of the data were collected with Jim and Brian and without their exceptional skills this work could never become a reality

Muon Campus overview



Protons separate and are removed

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

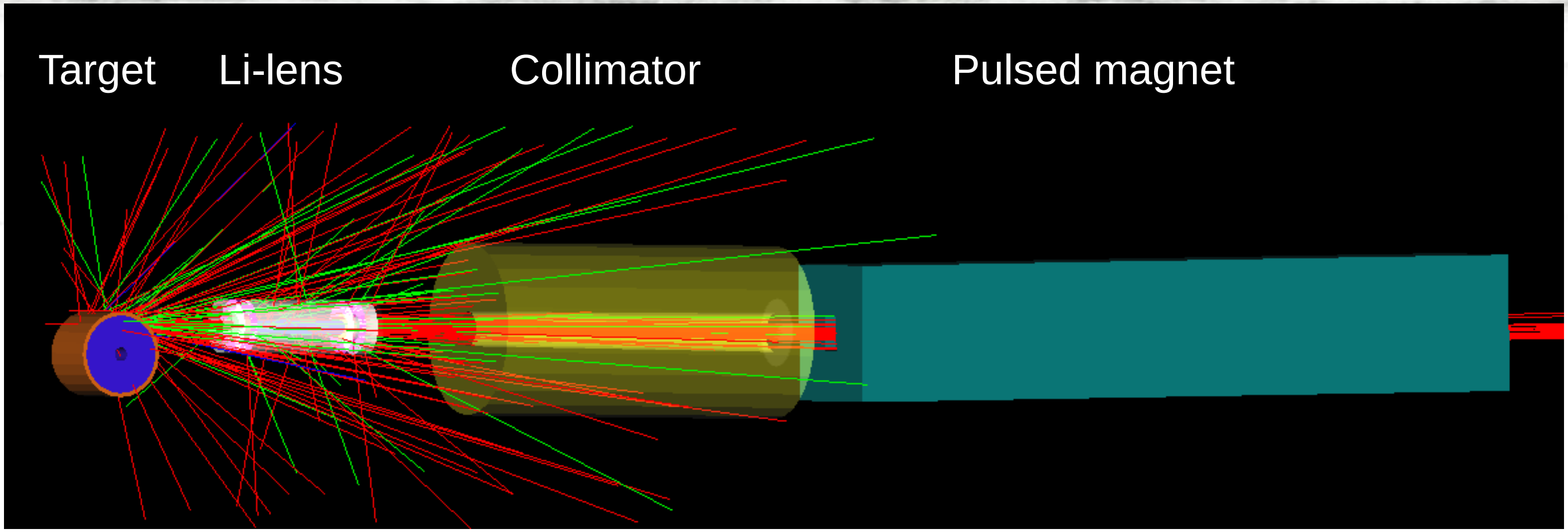
8.89 GeV/c p beam impacts the target

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

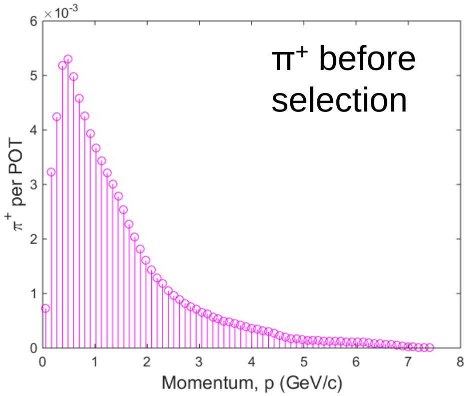
μ^+ are extracted from the ring and transferred into the storage ring via M4, M5

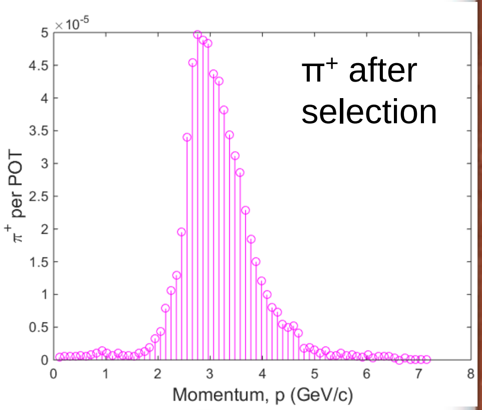
μ^+ enter the g-2 storage ring

Target station

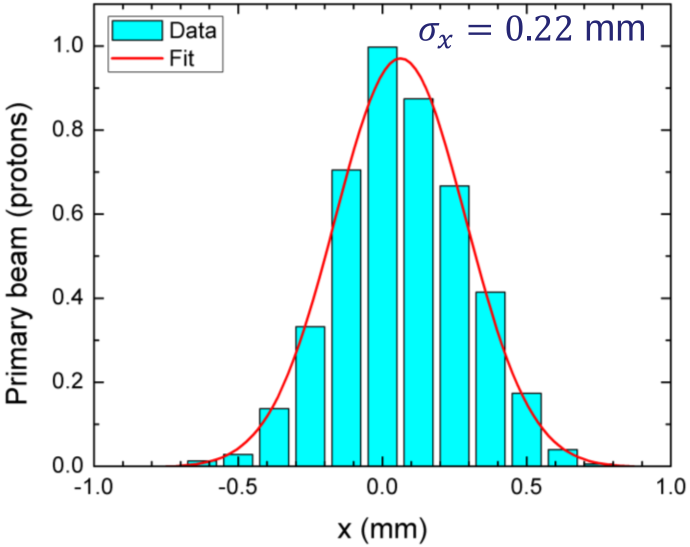


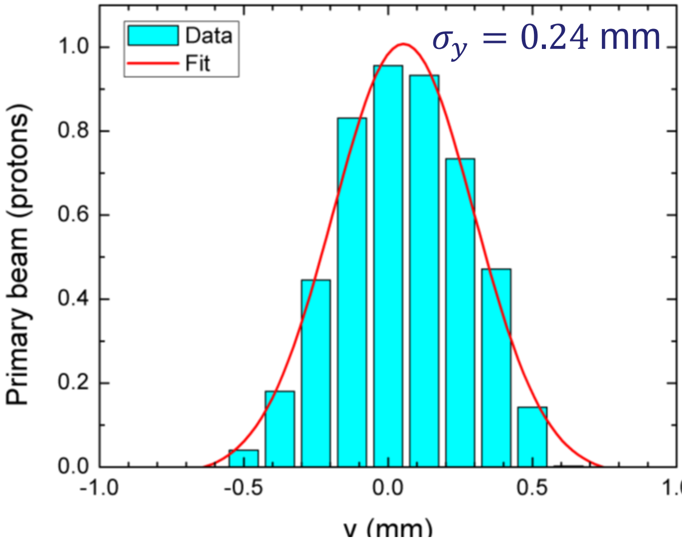
Parameter	Value
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Incoming beam momentum	8.89 GeV/c
Selection momentum	3.1 GeV/c



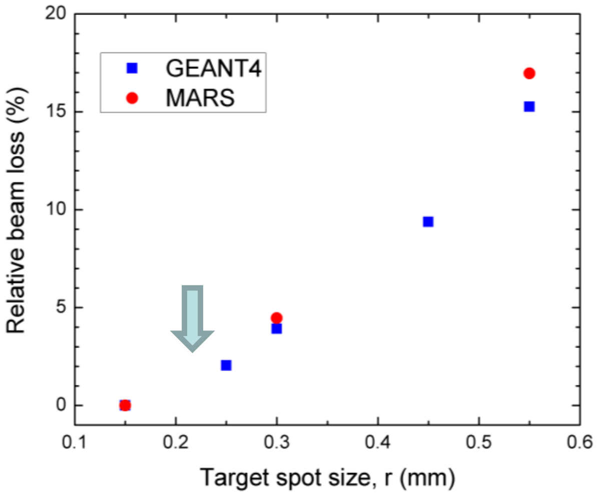


Proton beam on target





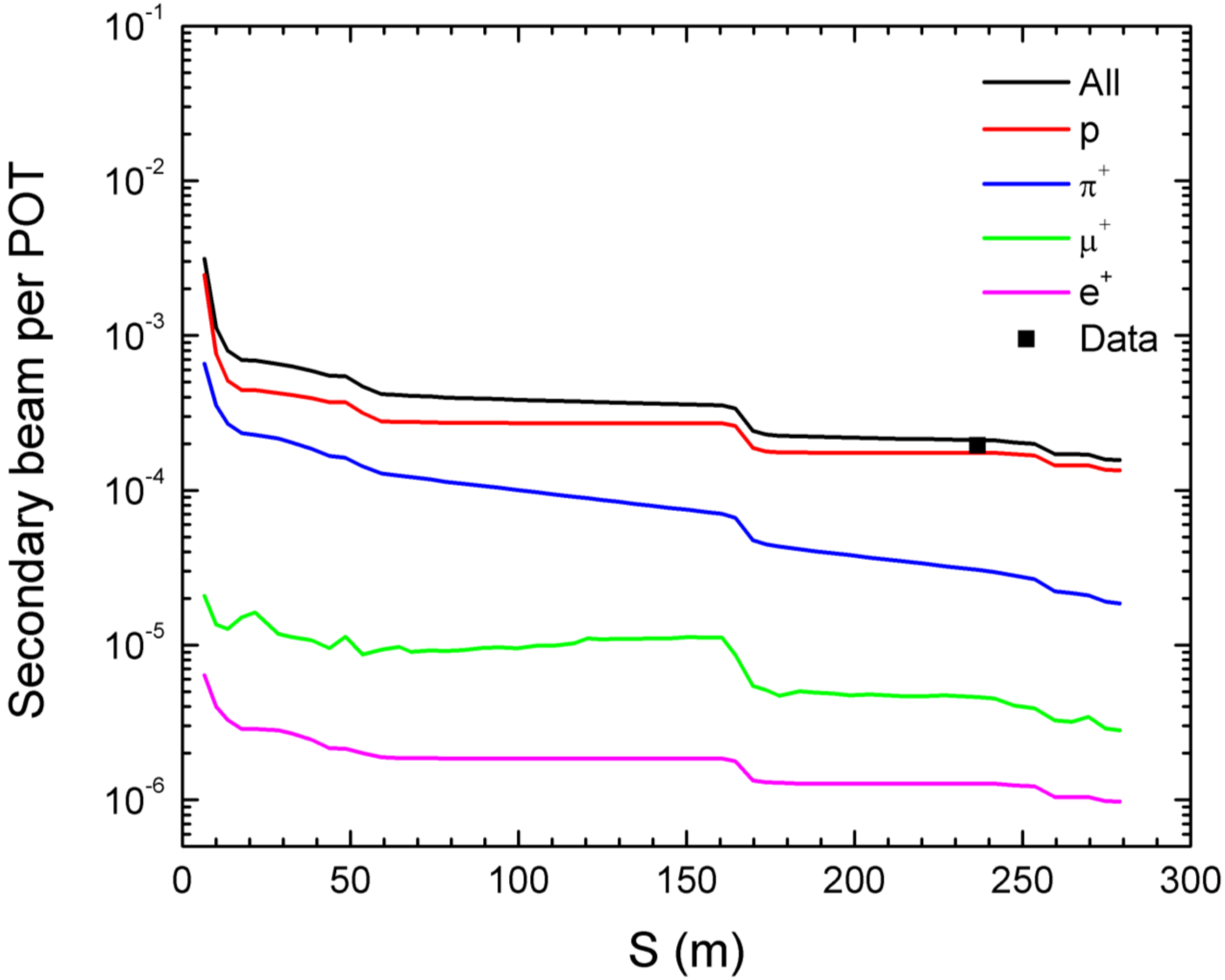
- Beam measured about ~30 cm upstream of target
- In both planes ~0.2 mm found
- Very small impact in overall performance



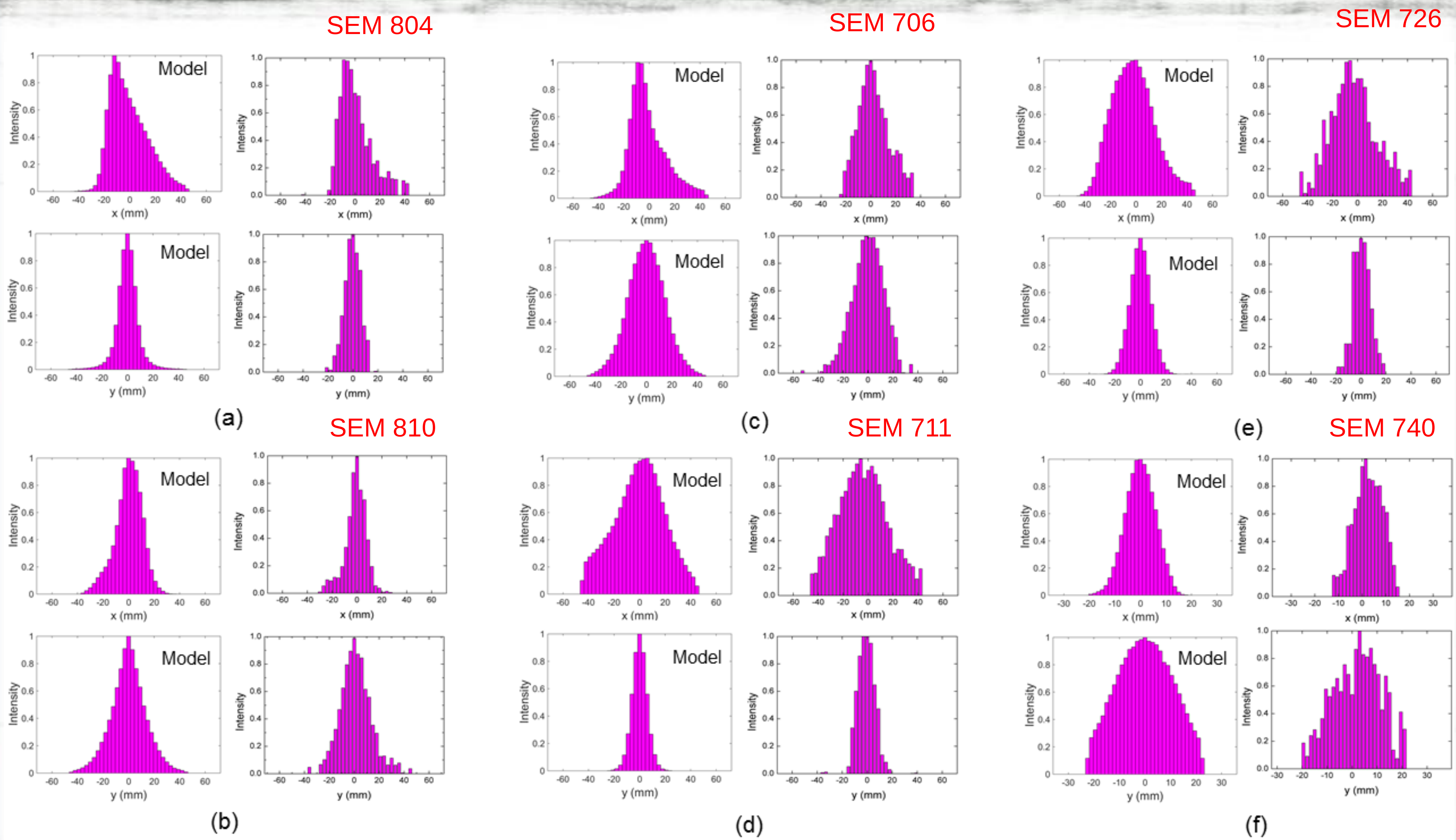
Comments about simulation model

- Started with a new MARS distribution, provided by Volodya T, that now includes positrons as well as muons produced at the lithium lens
- Fixed a couple of bugs related to apertures (like injection and extraction kicker, Q303, Q302 etc)
- Added abort kicker aperture in the model
- Added the capability to study synchrotron radiation for positrons

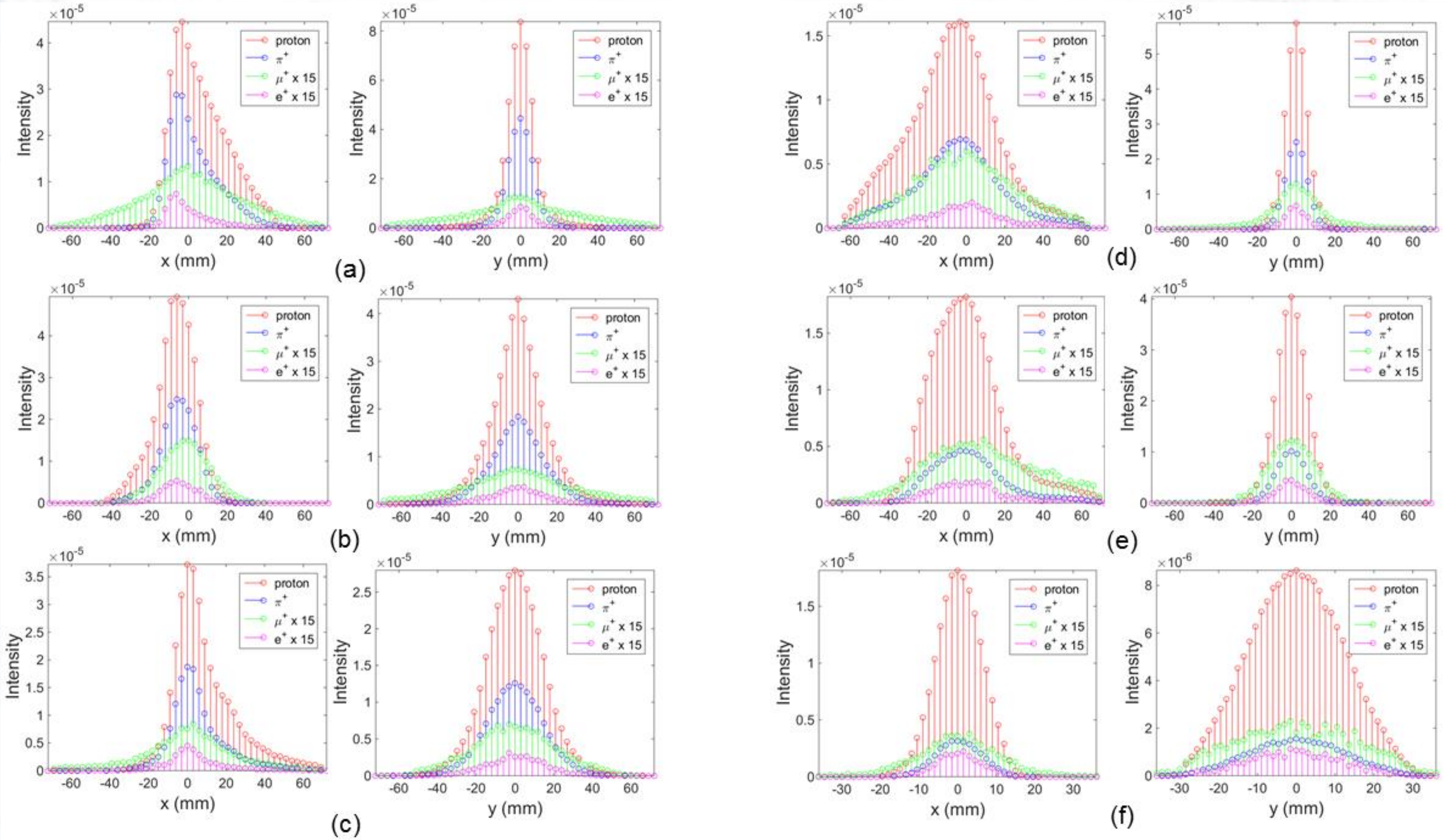
Performance within M2 & M3 lines



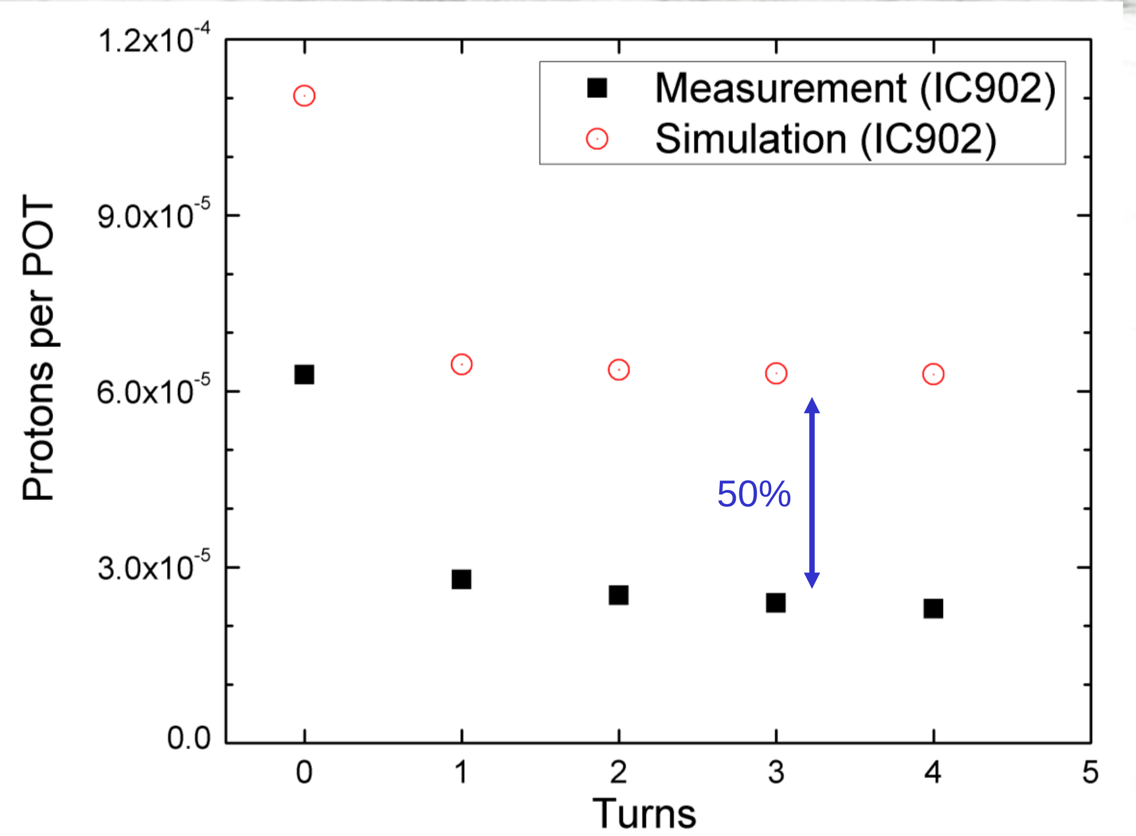
Performance within M2 & M3 lines



Performance within M2 & M3 lines



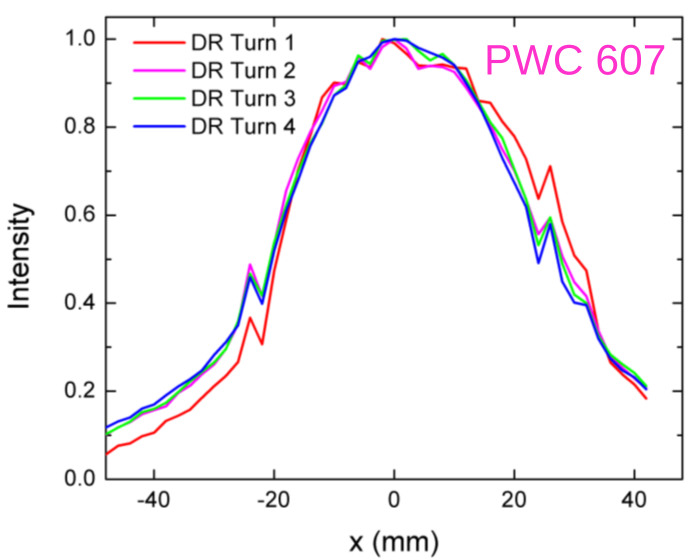
Performance in the Delivery Ring (DR)

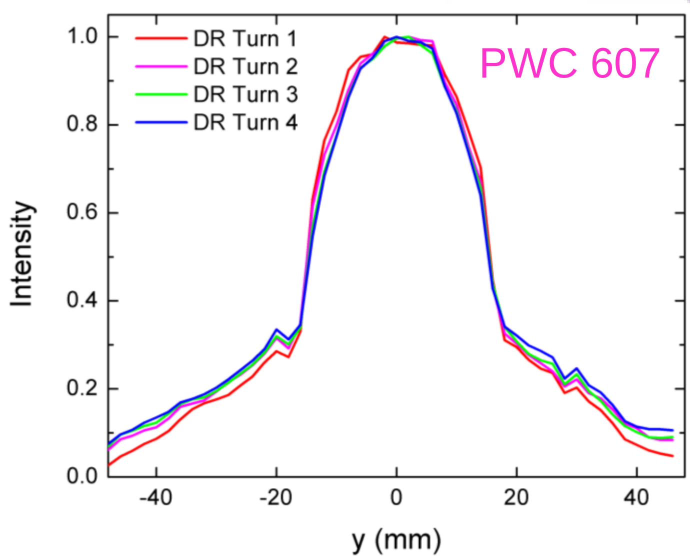


- There is a near flat 50% offset between data and simulation
- A hint that the majority of beam loss occurs between injection and straight 30

Performance in the Delivery Ring (DR)

The good news…

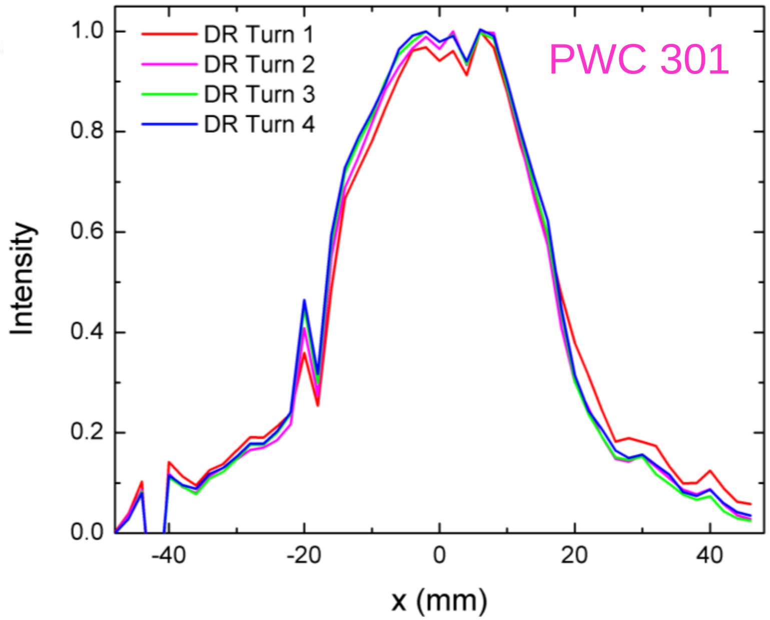




- Beam profile at PWC607 is reproducible over four turns
- This result is an indicator of good steering but <u>not</u> a indicator of good matching…
- To me this is a indicator of collimation

Performance in the Delivery Ring (DR)

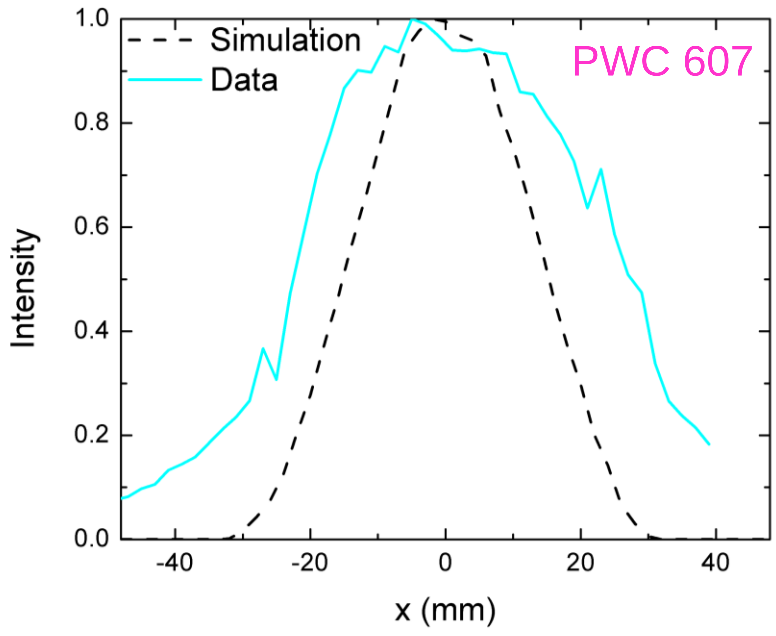
The good news…

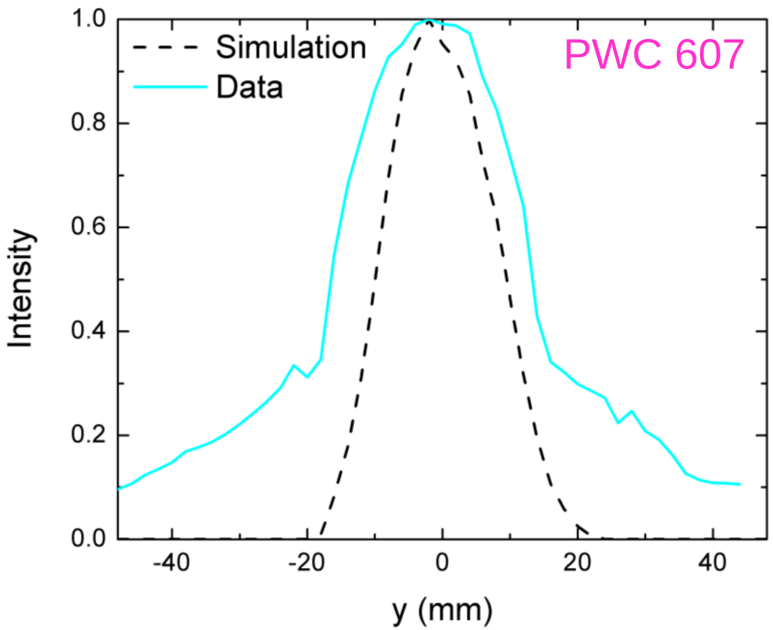


- Beam profile at PWC301 is reproducible over four turns
- This result is an indicator of good steering but not a indicator of good matching…

Performance in the Delivery Ring (DR)

The bad news…

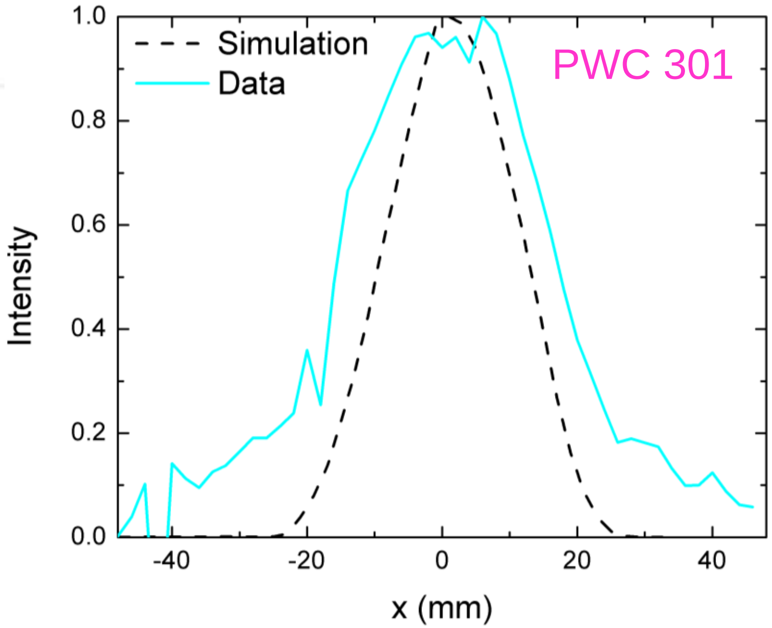




- Beam core appears wider (almost a factor of two)
- PWC profiles show long tails that are not present in the model

Performance in the Delivery Ring (DR)

The bad news…



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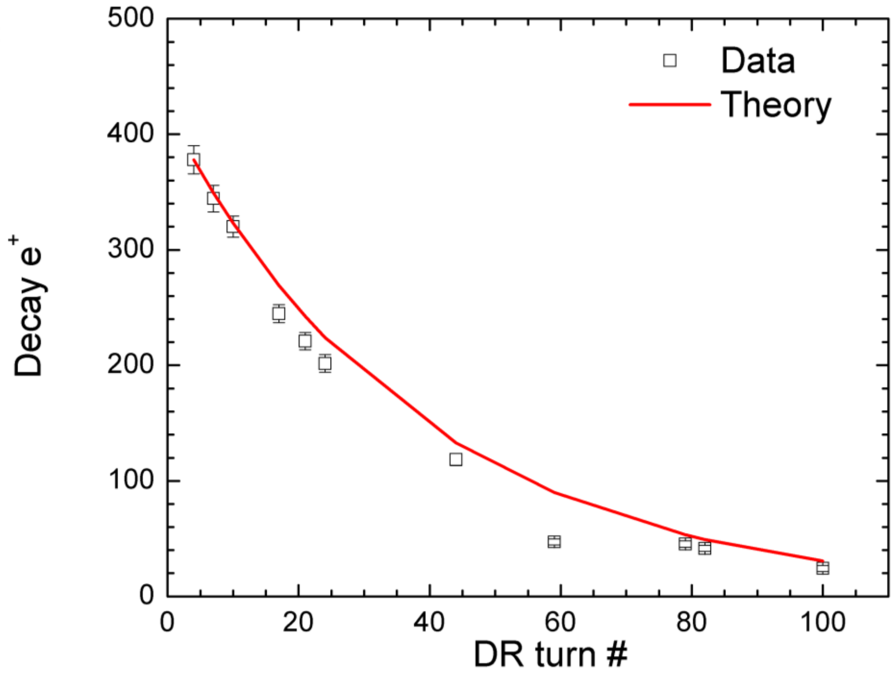
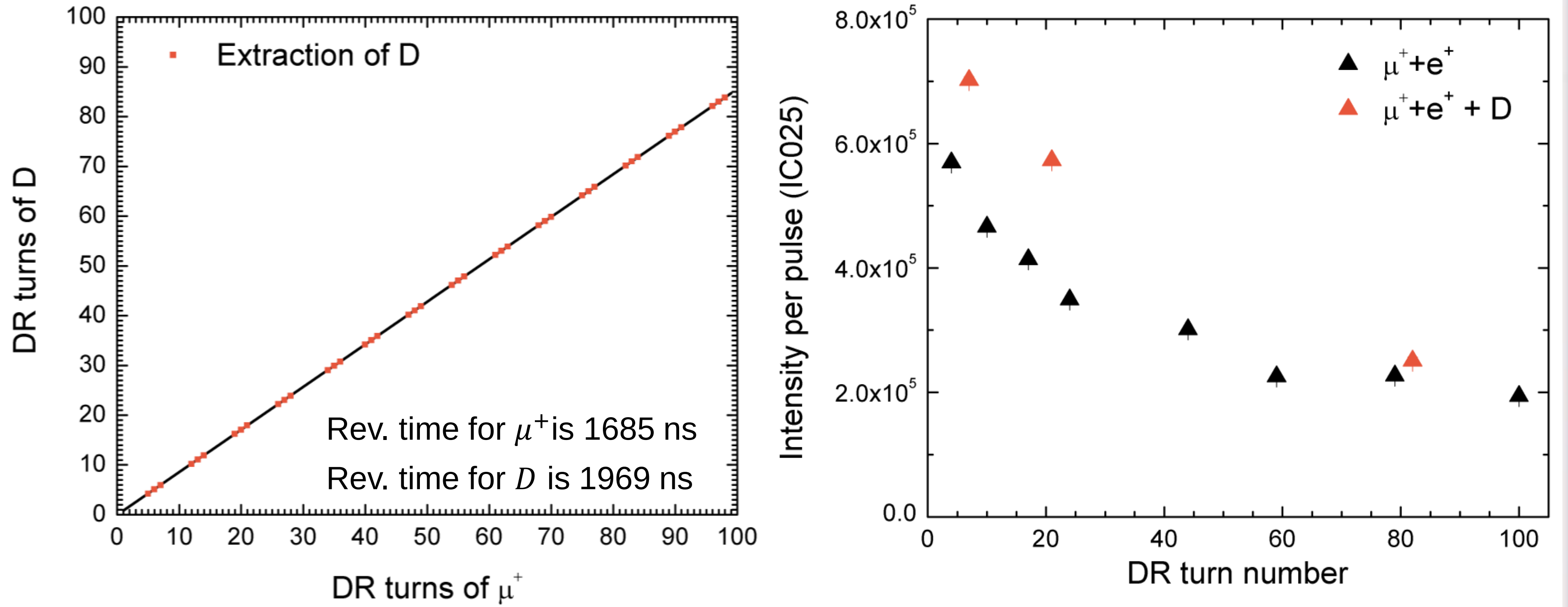
- PWC profiles show long tails that are not present in the model

Moving to 100 turns…



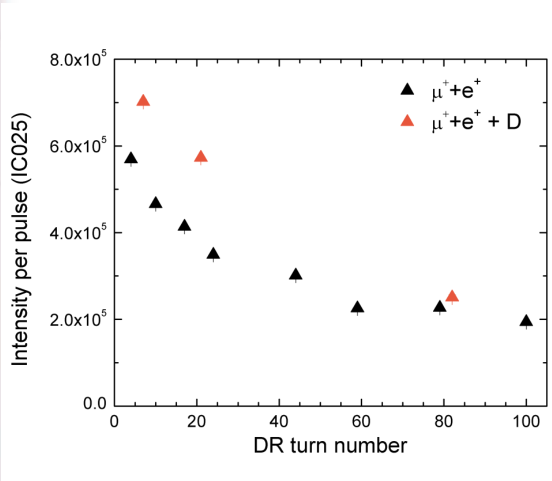
- The number of stored muons vs turns follows the decay exponential law very closely
- Another indication that the DR behaves smoothly after turn 1

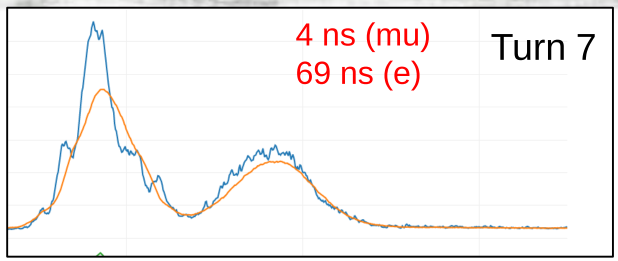
And a big surprise…

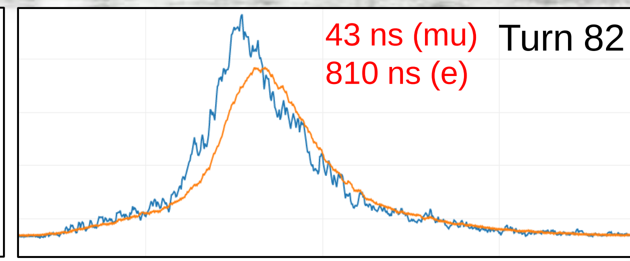


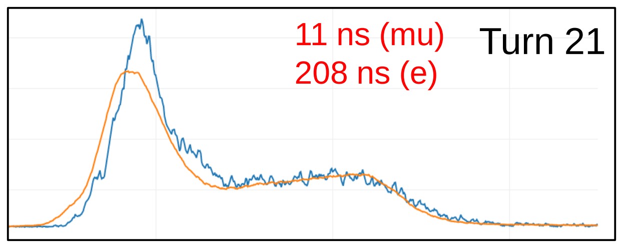
- In addition to positrons the secondary beam is contaminated with deuterons

Deuteron path length



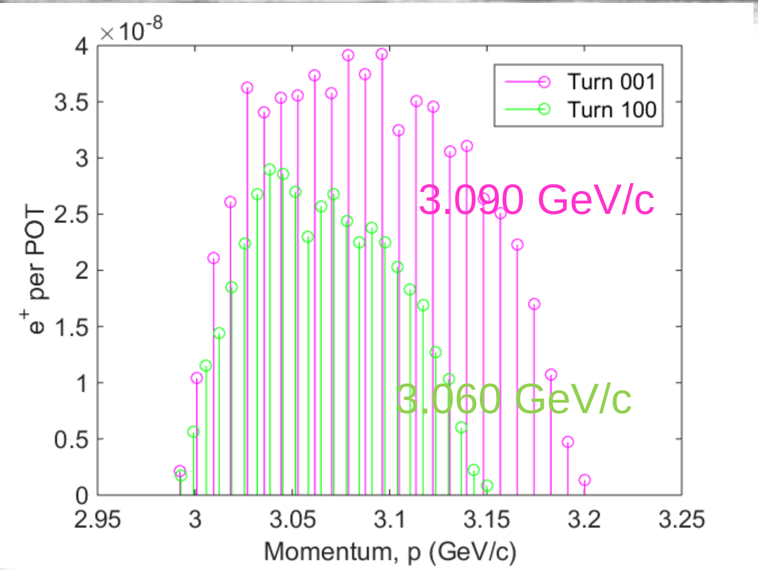


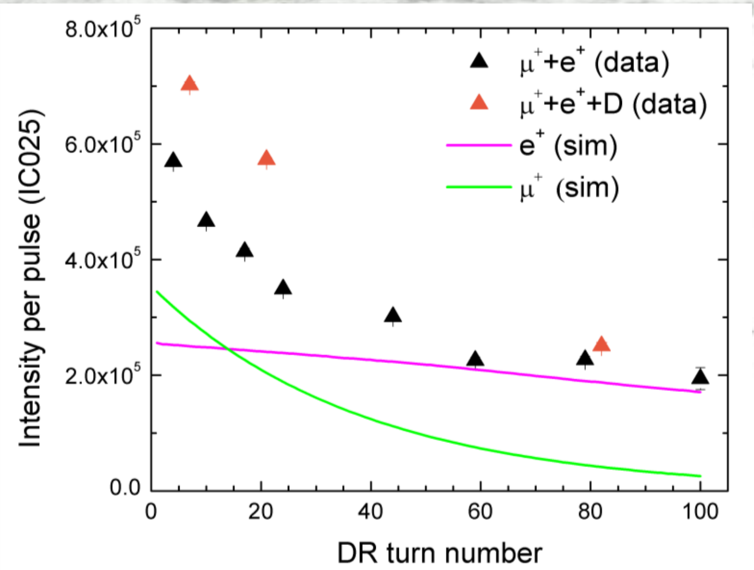




- Particles of different momentum will follow different paths and therefore will spread in time based on the formula:
- $\Delta\tau = \frac{L}{c\beta}\left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{\Delta p}{p}$
- γ is 29.3 for μ and just 1.9 for D. For the DR, α_c is 0.017 and assuming $\Delta p/p = 2\%$ we can estimate $\Delta\tau$

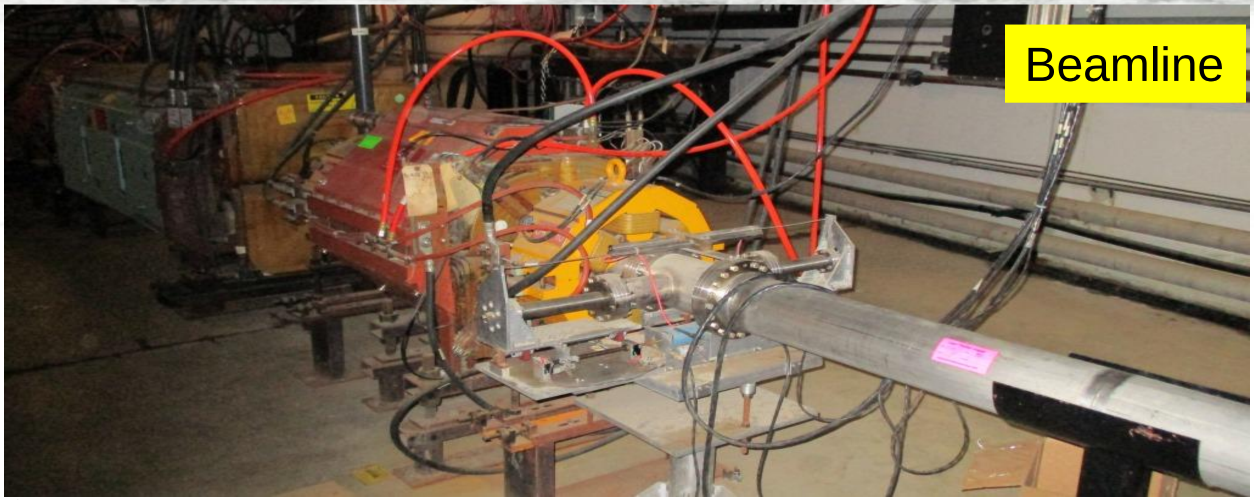
Estimate positron contamination

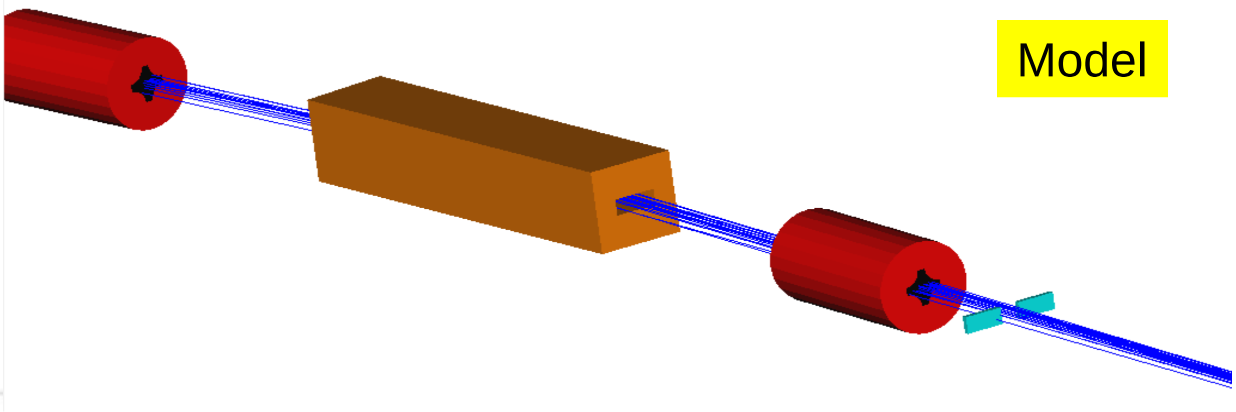




- Simulation predicts that 68% of the e^+ beam and 8% of the μ^+ beam will survive after 100 turns.
- After turn 4: $N_e + N_\mu = 5.693 \times 10^5$
- After turn 100: $\frac{68}{100} N_e + \frac{8}{100} N_\mu = 1.943 \times 10^5$
- We estimate that: $\mu^+ = 57\%$ and $e^+ = 43\%$

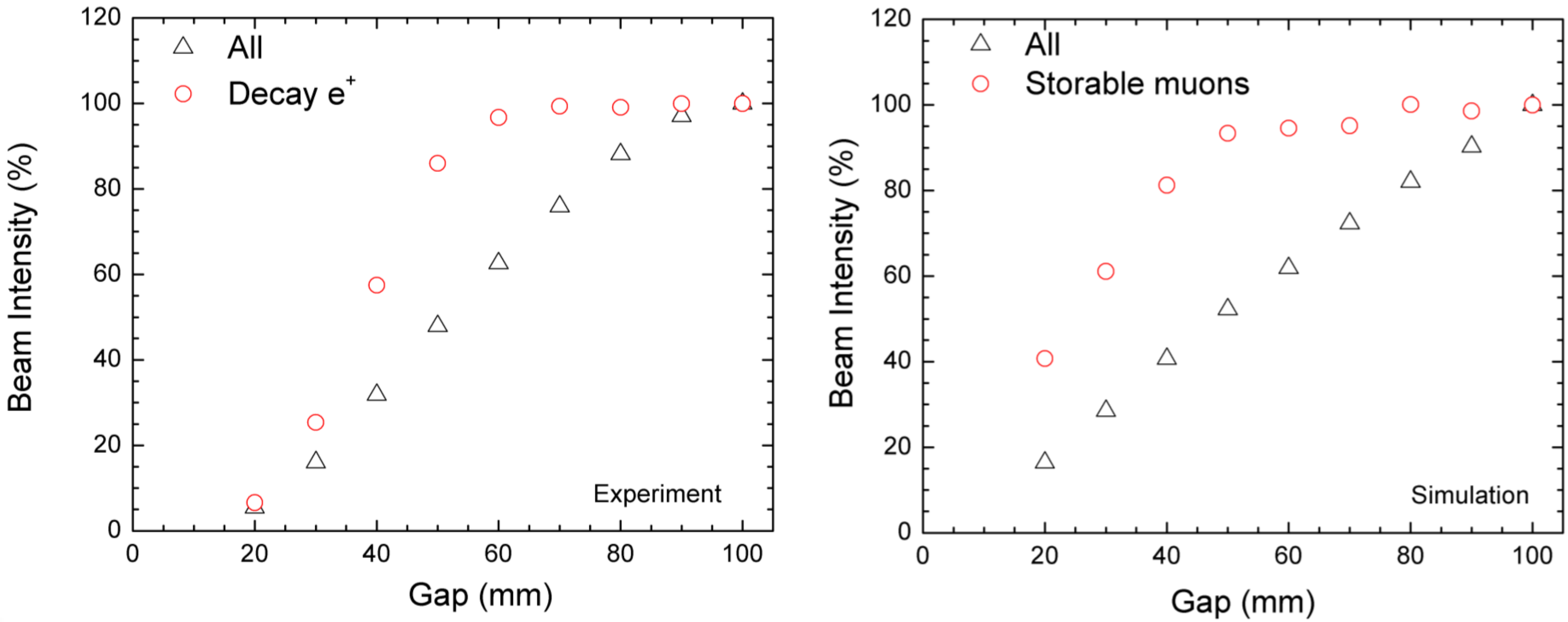
Momentum collimator commissioning





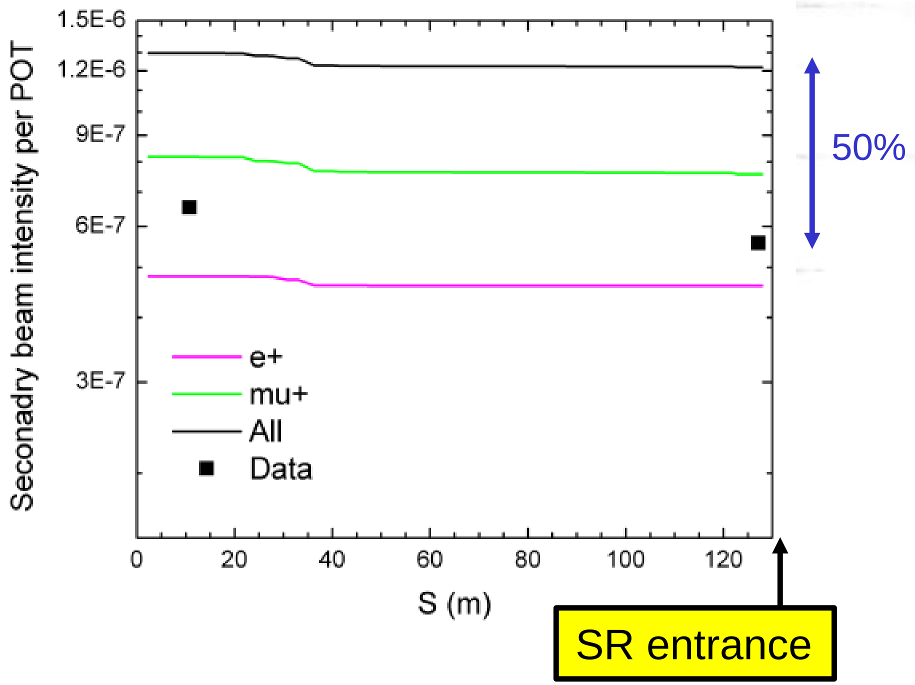
- Placed upstream of Q411 in a dispersive area ~ 1 m

Momentum collimator commissioning



- Collimator has the potential to reduce the beam intensity by more than 40% without affecting stored muons
- This trend is confirmed by the simulation model

Performance within M4 & M5 lines



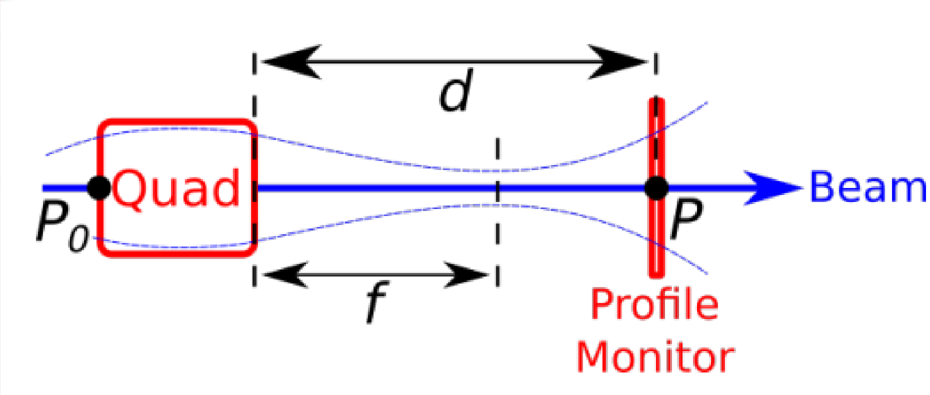
- The measured transmission along the M4-M5 line agrees with simulation (~90%)
- The measured intensity offset is the same as in the DR (~50%)

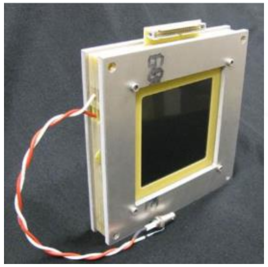
Overall performances (simulation)

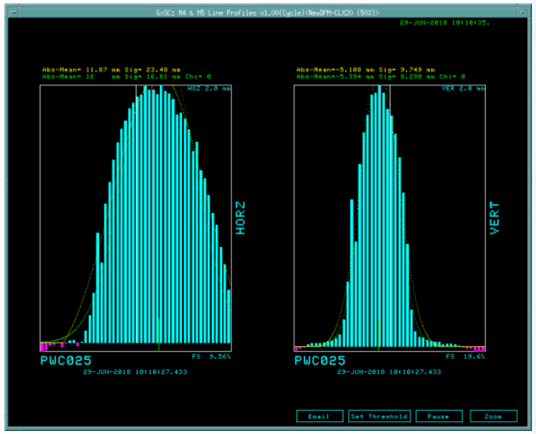
	p, all	π^+, all	μ^+, all	μ^+, $\Delta p/p=\pm 2\%$	μ^+, $\Delta p/p=\pm 0.5\%$	e^+, all
End of M3	1.35×10^{-4}	1.85×10^{-5}	2.80×10^{-6}	1.28×10^{-6}	3.52×10^{-7}	9.77×10^{-7}
DR (Turn 1)	6.61×10^{-5}	4.80×10^{-7}	9.86×10^{-7}	8.26×10^{-7}	2.28×10^{-7}	5.05×10^{-7}
DR (Turn 2)	6.55×10^{-5}	2.74×10^{-8}	9.25×10^{-7}	7.99×10^{-7}	2.23×10^{-7}	5.00×10^{-7}
DR (Turn 3)	6.52×10^{-5}	0.9×10^{-9}	8.91×10^{-7}	7.73×10^{-7}	2.17×10^{-7}	4.97×10^{-7}
DR (Turn 4)	6.50×10^{-5}	$<10^{-10}$	8.63×10^{-7}	7.51×10^{-7}	2.10×10^{-7}	4.95×10^{-7}
End of M5		$<10^{-10}$	7.57×10^{-7}	6.55×10^{-7}	1.80×10^{-7}	3.81×10^{-7}

- Simulation predicts that the concertation of e+ at the end of the beamline is 34%
- From our data analysis we found 43% which is not very far off

Quadrupole scan technique

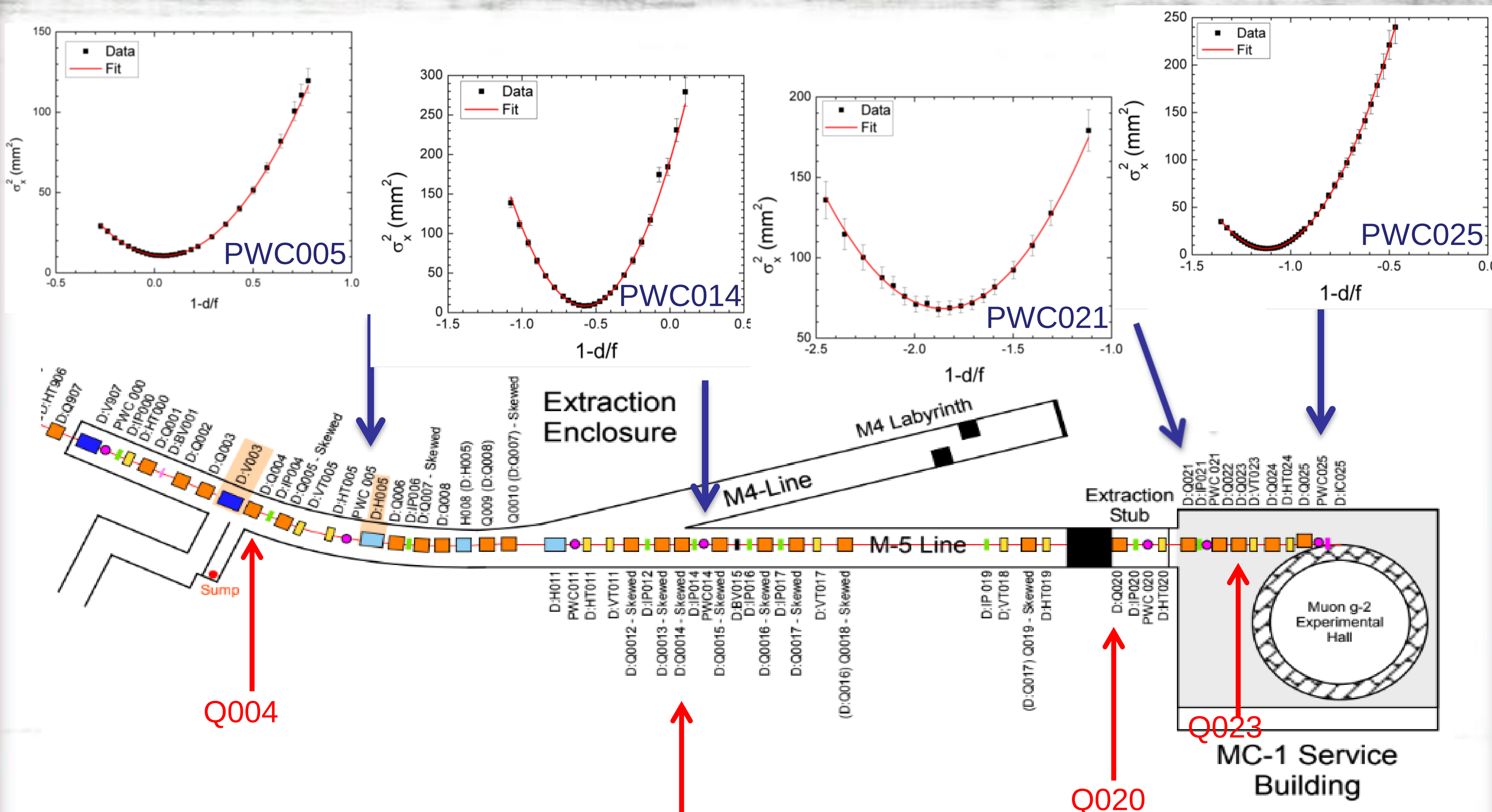






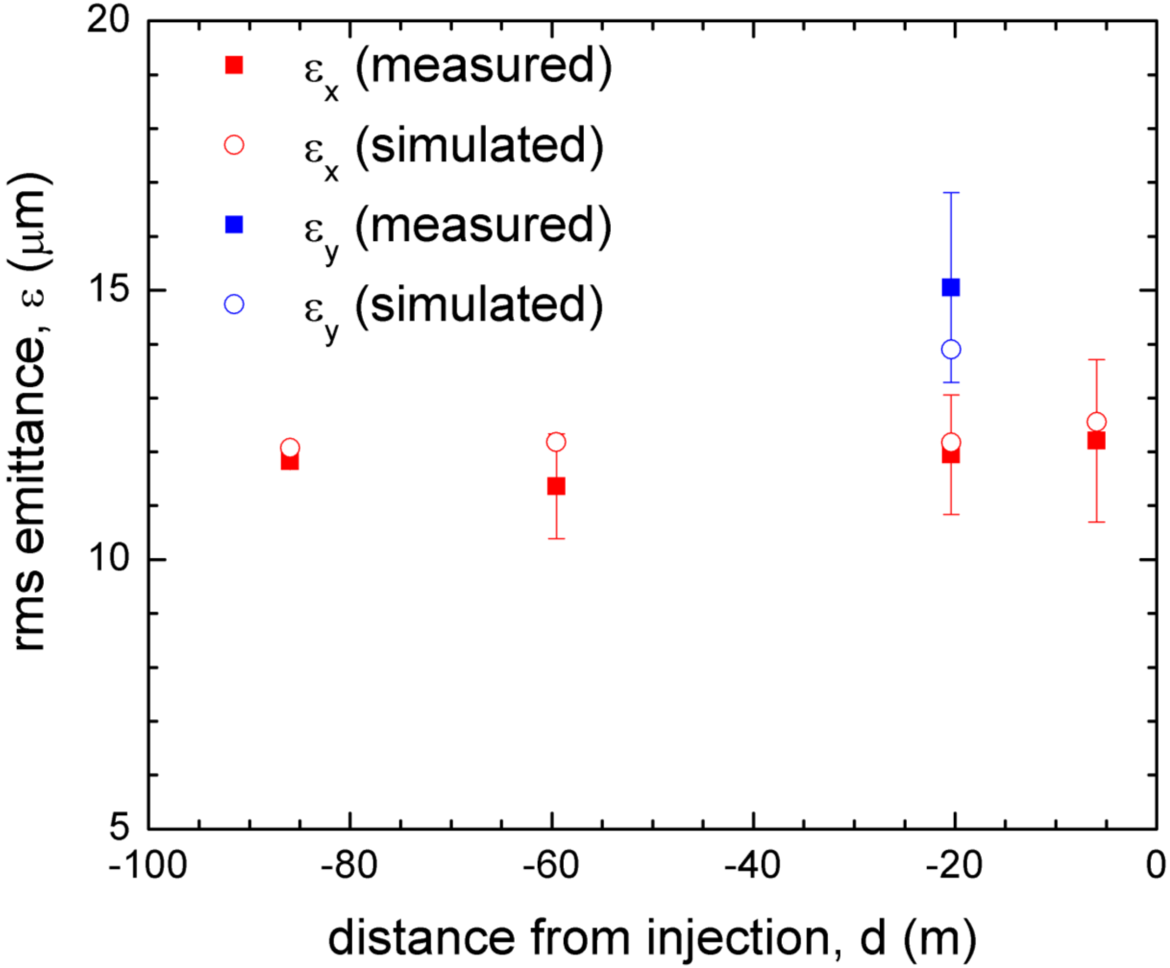
- Using a quadrupole scan we can reconstruct the beam phase-space using a handful set of beam profiles
- Allows us to measure the Twiss parameters and emittance
- Simple technique that requires no additional hardware

Measuring beam optics along the M5



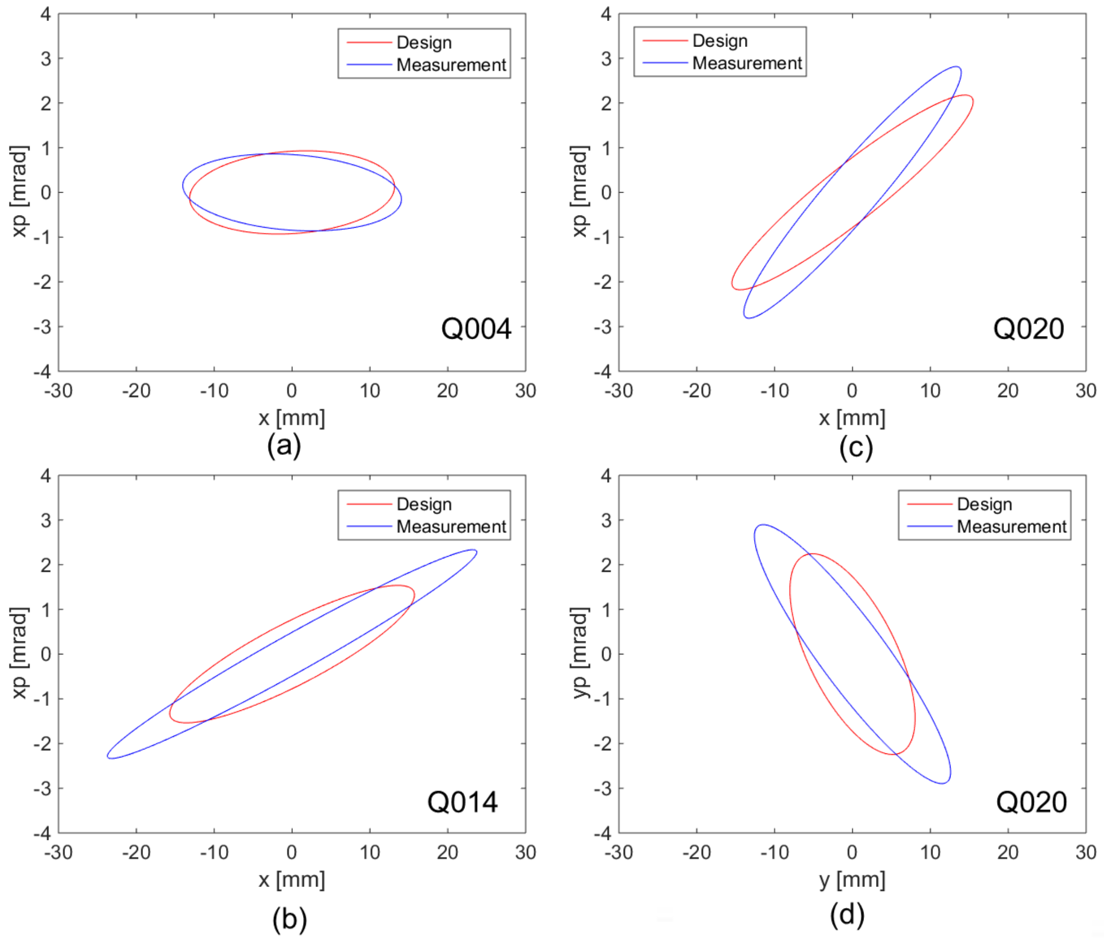
A. Ramirez, Fermilab Intern, SULI (2018)

Measuring the beam emittance



A. Ramirez, Fermilab Intern, SULI (2018)

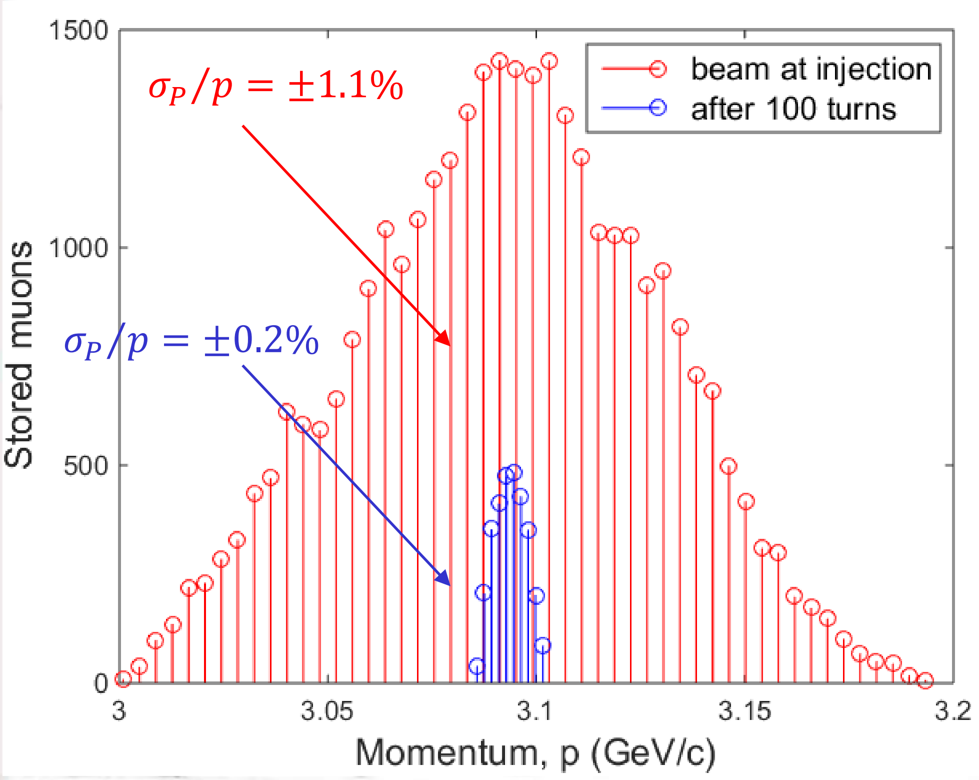
Measuring the beam phase-space



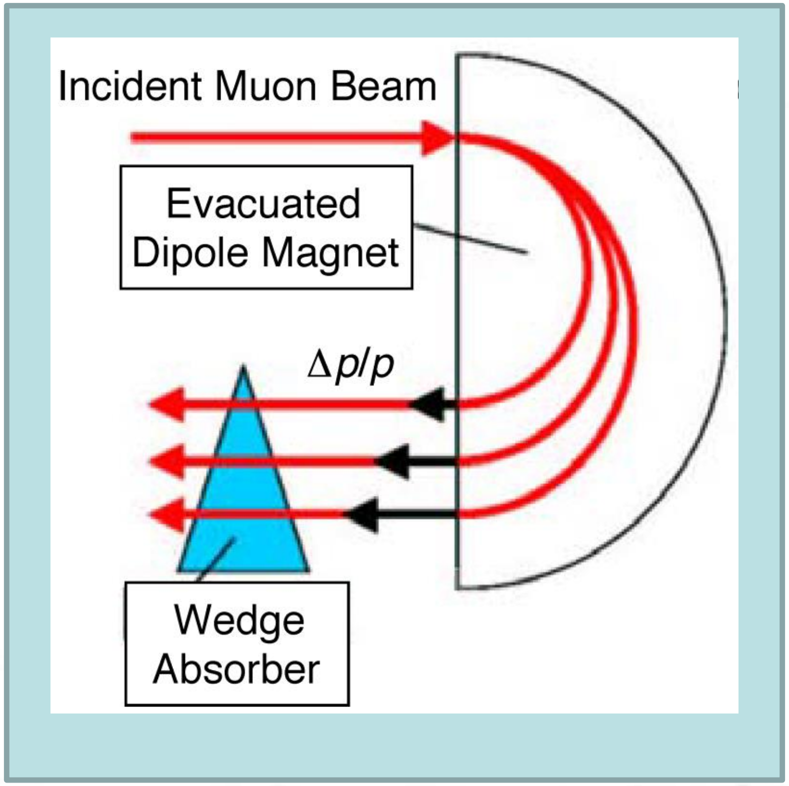
Alejandro Ramirez, Fermilab Intern, SULI (2018)

Momentum acceptance

THE PROBLEM



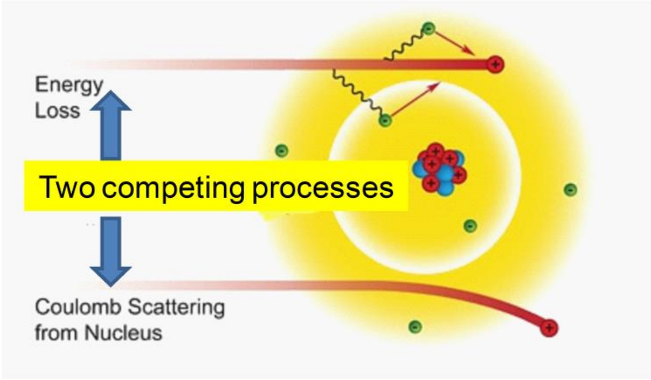
THE SOLUTION



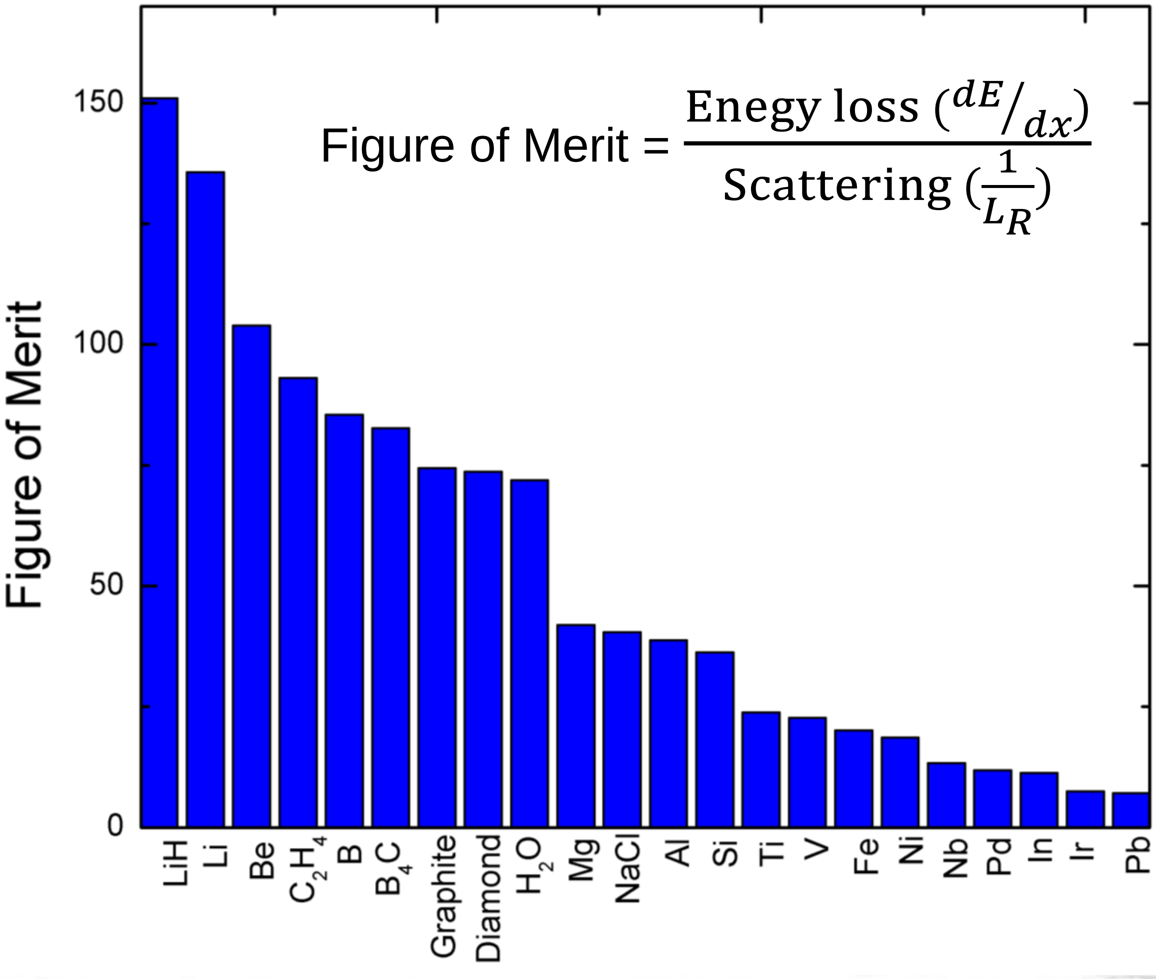
- Storage ring accepts particles only within $\sigma_p/p = 0.2\%$

Cooling requirements

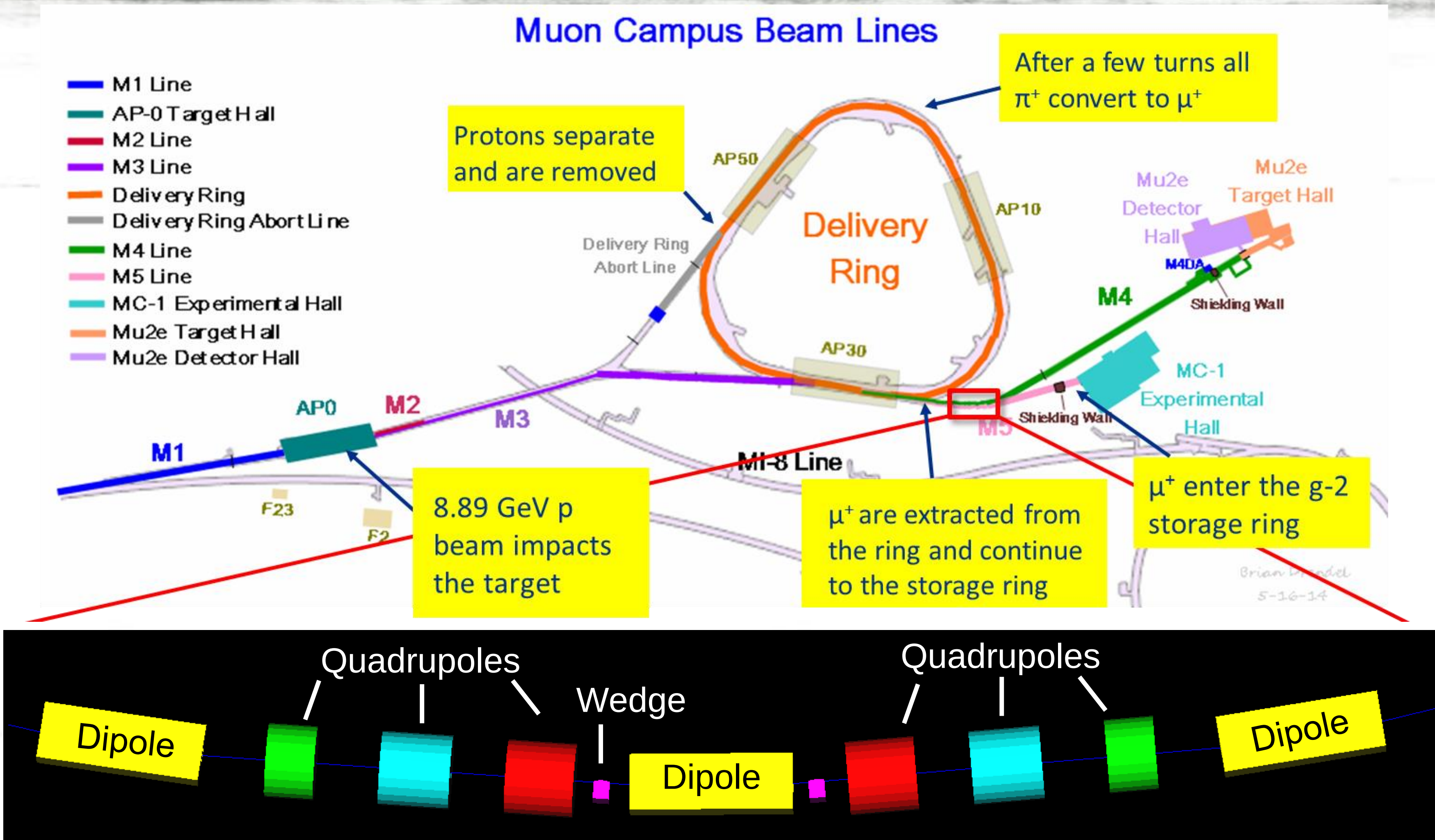
- There are competing processes involved in ionization cooling
  - Cooling from ionization of the material
  - Heating from Coulomb scattering
- We require a material with:
  - A large dE/dx
  - A large radiation length L_R
- We require a location with:
  - High dispersion
  - Low beta function



Choice of material

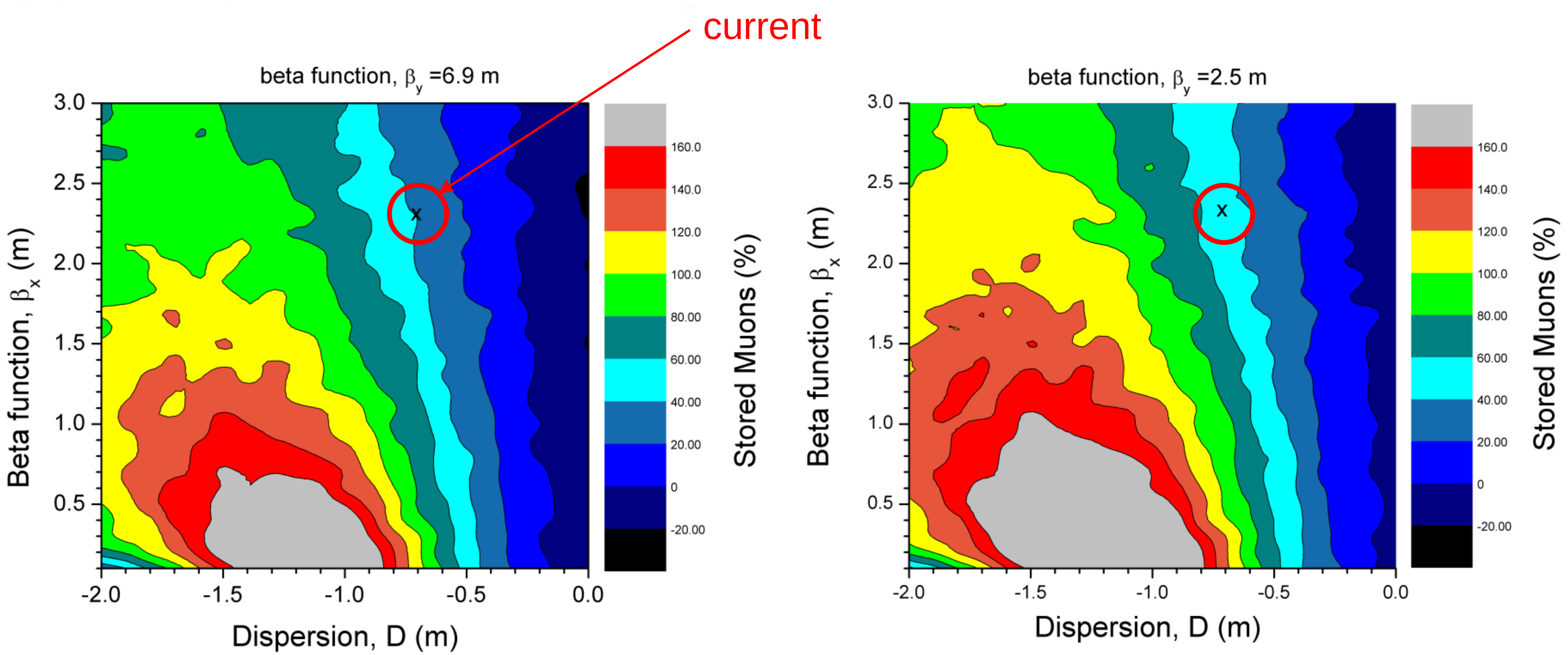


Choice of location



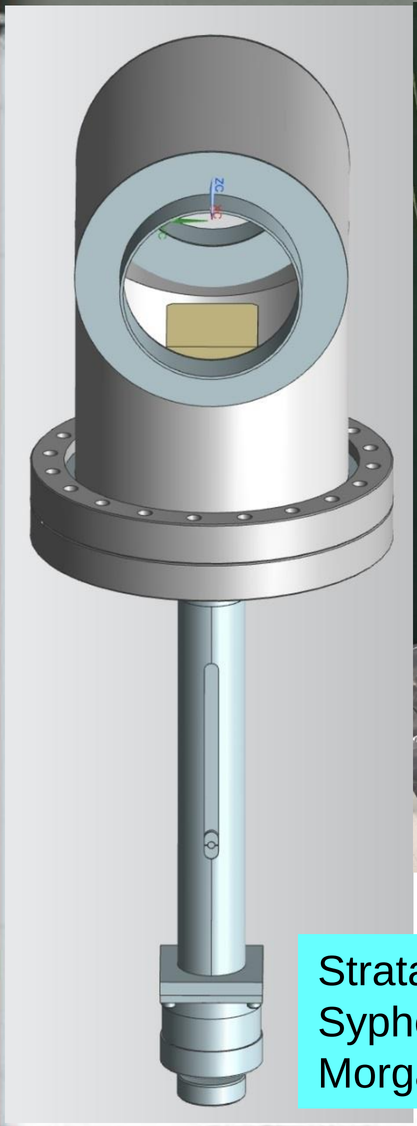
J. Bradley, Fermilab Intern, H. Edwards (2017)

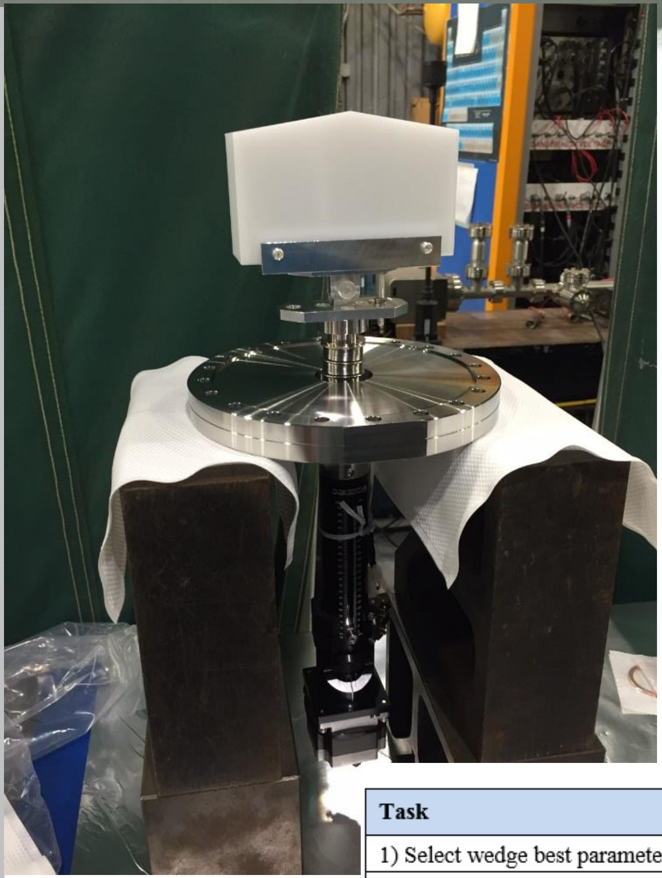
Expected performance



- Colormaps indicate the potential to increase the number of stored muons by more than 50%

Funded through Fermilab LDRD





Stratakis (PI)
Syphers (co-PI)
Morgan (coordinator)

Task	M-18	A-18	M-18	J-18	J-18	A-18	S-18	O-18	N-18
1) Select wedge best parameters	x	x							
2) M4-M5 optics optimization		x	x						
3) Engineering drawings		x	x						
4) Order parts			x	x					
5) Fabrication				x	x				
6) Installing system					x	x	x		
7) Test system							x	x	x

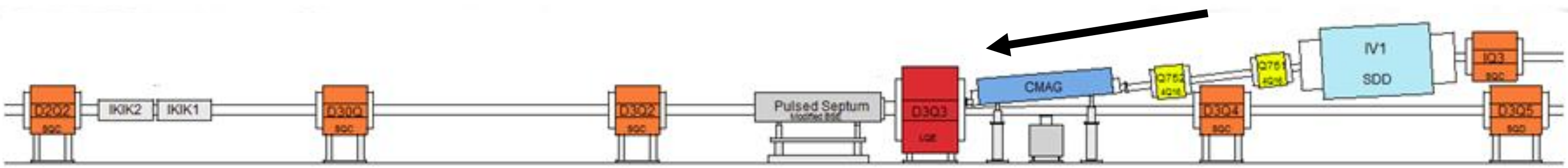
Conclusions (1)

- We see a “healthy” beam behavior for the first 200 m of the M2-M3 lines as indicated by the agreement between the simulated and measured beam profiles and the beam intensity at IC740.
- However after injection, there is a near flat 50% gap between the measured and simulated intensity
- This is accompanied with long tails on the beam distribution as well as a notable wider core compared with simulation

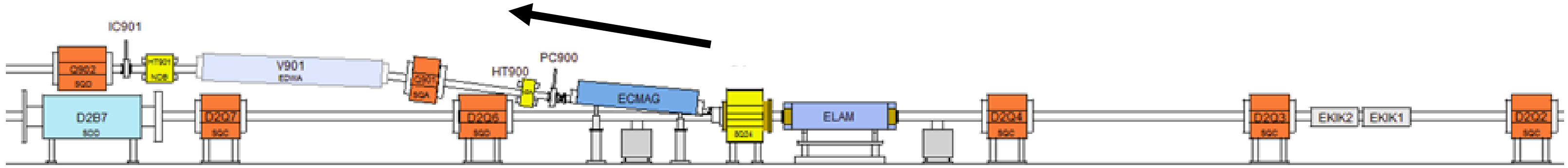
Conclusions (2)

- After the first DR turn the beam behaves very well as indicated by:
  - The muon rate from 4-100 follows closely the exponential decay law
  - The transmission in the M4-M5 lines agrees with simulation
  - The emittance and Twiss parameters agree with simulation
- All this hints that the problem is partly because of a mismatch at the end of M3 and a collimation at straight 30. I believe that extraction looks fine.
- We estimate the contamination of positrons to be ~43% which is not far from the MARS prediction ~34%

Straight 30

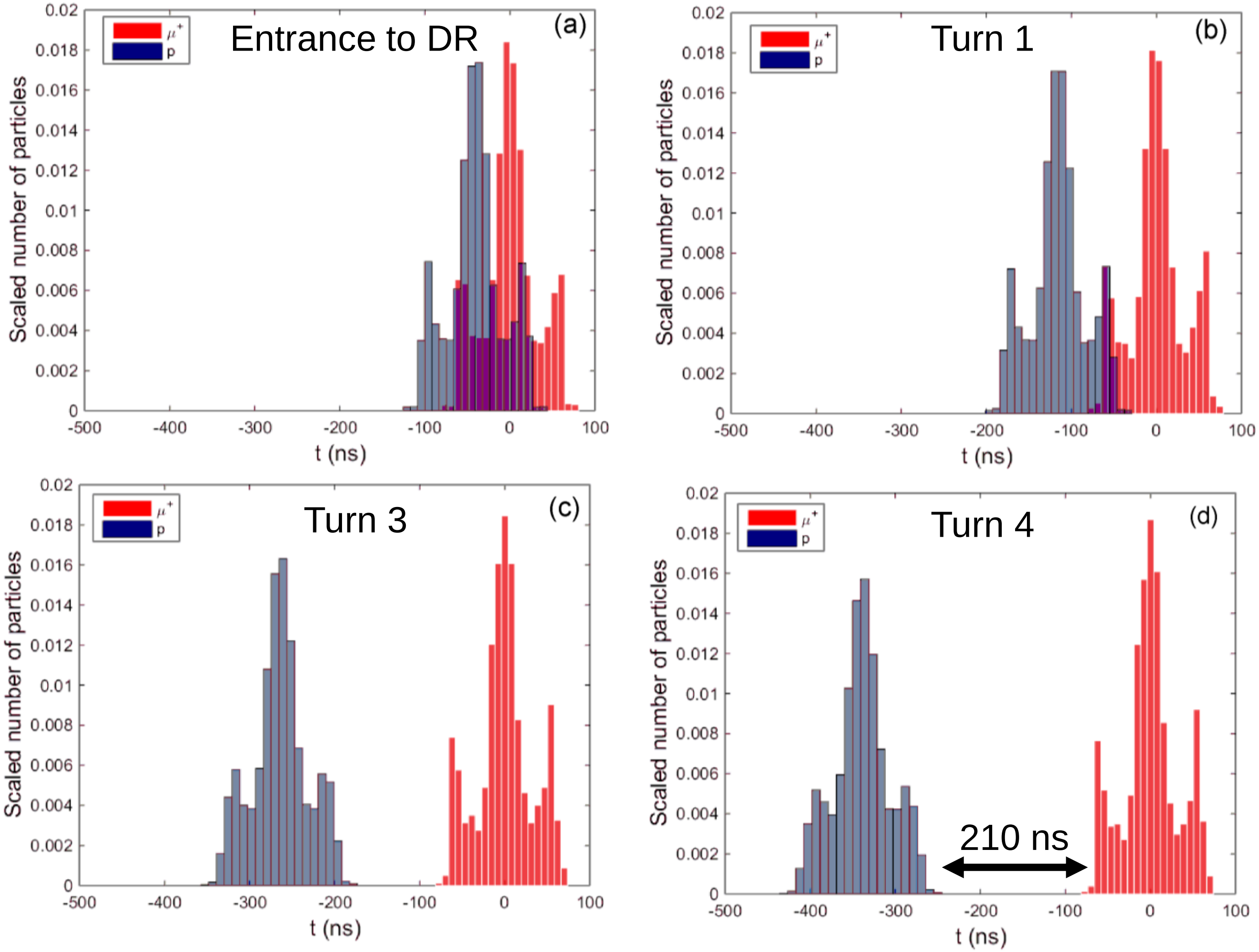


D2Q2
IKIK2
IKIK1
D30Q
D3Q2
Pulsed Septum
D3Q3
CMAG
Q752
Q751
D3Q4
IV1
SDD
IQ3
D3Q5



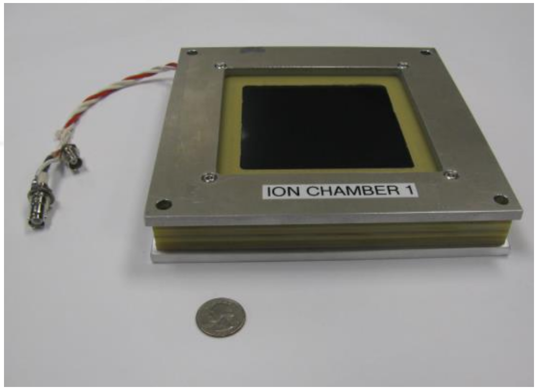
IC901
Q902
V901
D2B7
D2Q7
HT900
PC900
D2Q6
ECMAG
ELAM
D2Q4
D2Q3
EKIK2
EKIK1
D2Q2

Separation of protons

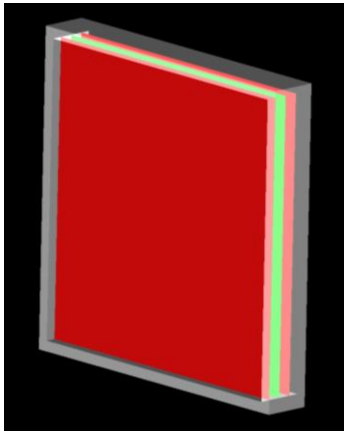


Beam control

Ion Chamber

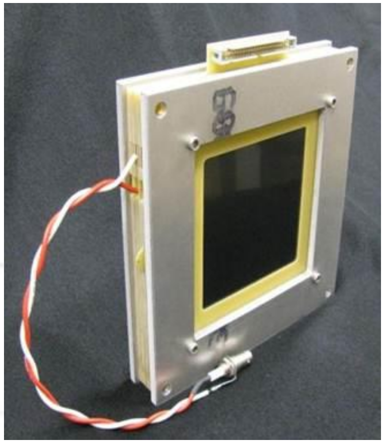


Model

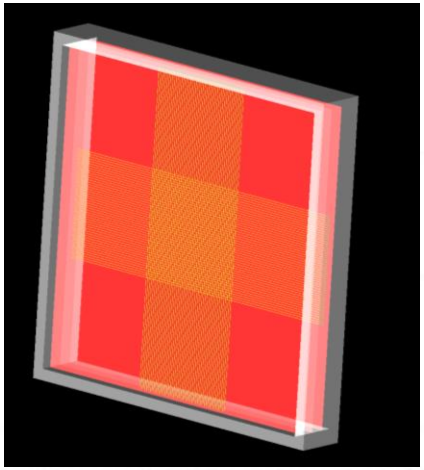


PWC IC

Proportional Wire Chamber



Model



Muon Campus simulation tools

TARGET

MARS
GEANT4

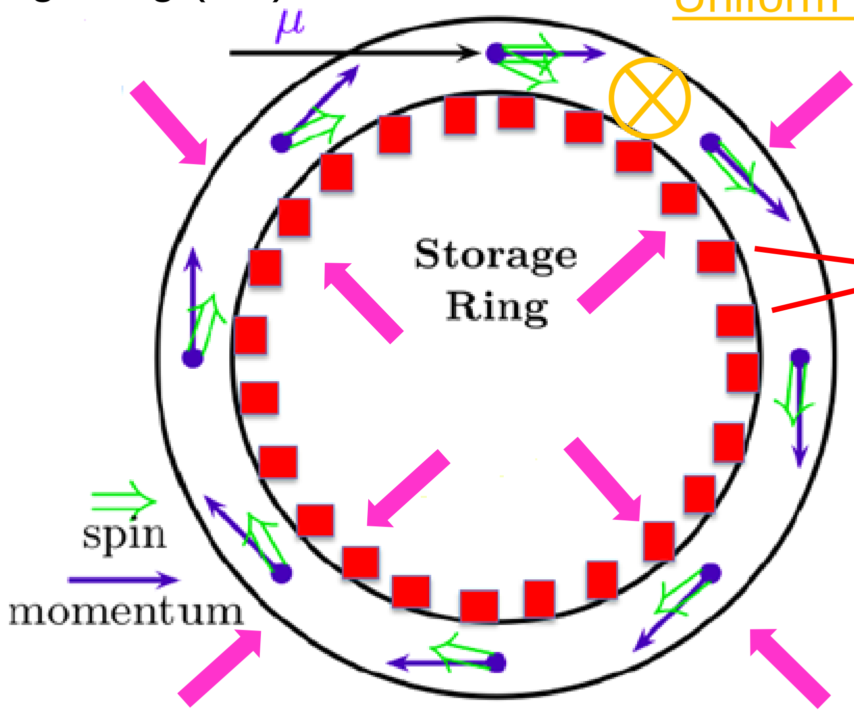
MUON CAPTURE & TRANSPORT

G4BEAMLINE
BMAD
COSY

Use at least two codes for each subsystem

Principle for measuring g-2

Inject polarized μ^+ into a storage ring (SR)



Uniform field: B=1.45 T

Electrostatic quadrupoles: For vertical focusing

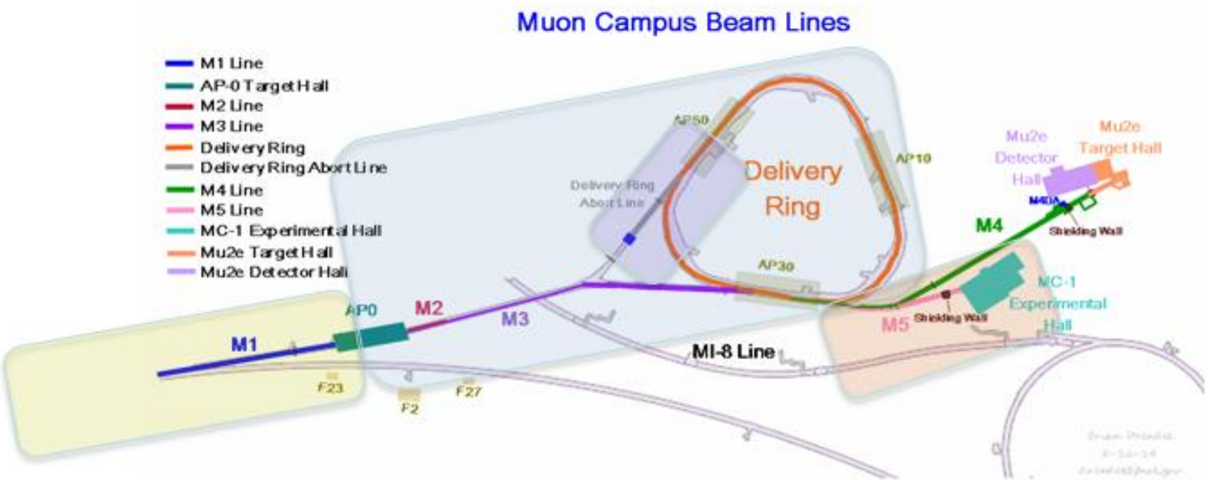
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Detectors: Detect the decay e^+. Exploit the property that direction of e^+ is strongly correlated with the direction of μ^+ spin

Zero: by using "magic" 3.1 Gev/c μ^+

Precession frequency: $\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$

Muon Campus beam diagnostics



Much of the existing Instrumentation from the Antiproton Source will be reused for g-2 operations. Beam requirements can be broken down into the following categories.

- **Primary Proton Beam (1E12):**
  - Intensity: Toroids
  - Position: BPMs, Multiwires, SEMs
  - Losses: BLMs
- **Proton-only (1E7)**
  - Intensity: Ion Chambers, Toroids*
  - Position: SEMs
  - Losses: BLMs
- **Mixed Secondary Beam (2E8 -> 1E7)**
  - Intensity: Ion Chambers, Wall Current Monitors, Toroids*
  - Position: SEMs, PWCs, BPMs*
  - Losses: BLMs
- **Muon-only (1E5)**
  - Intensity: Ion Chambers
  - Position/Profile: PWC
  - Particle Composition: Cerenkov Detector*

B. Drendel (gm2-docdb-4590)