Commissioning and first results of the Fermilab Muon Campus

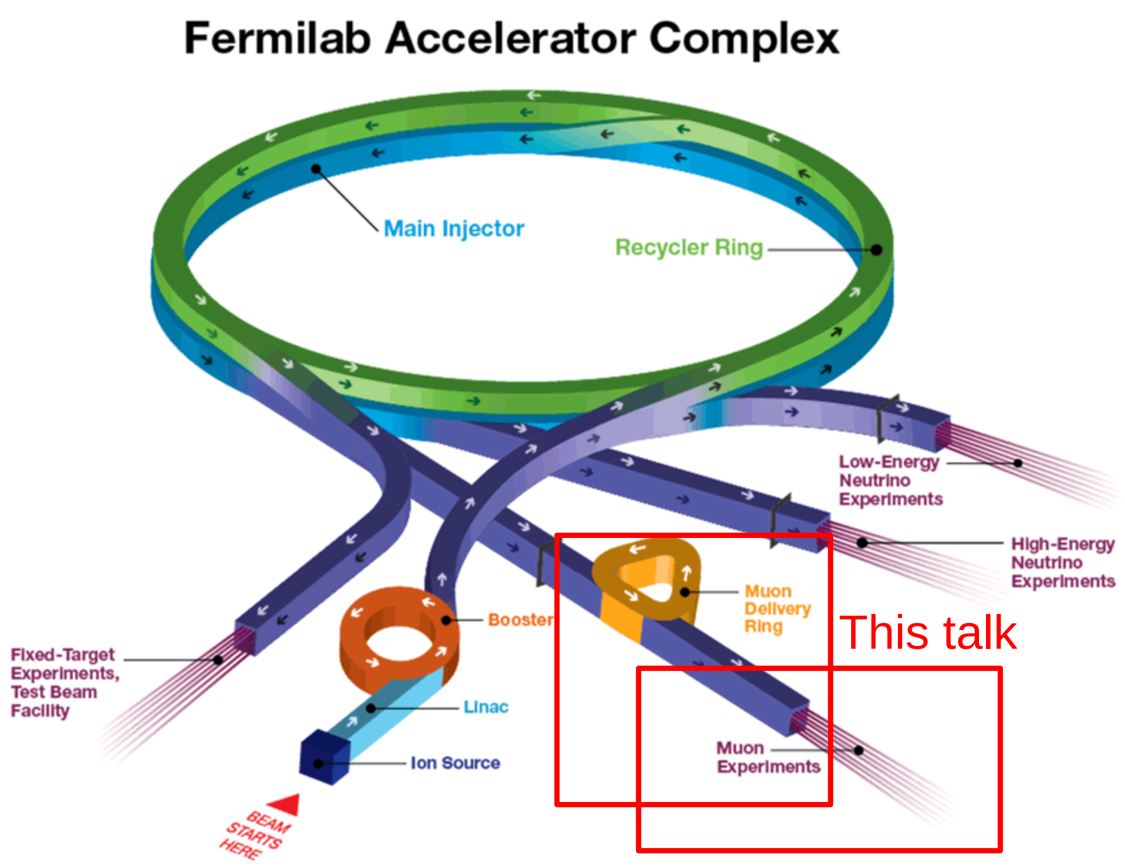
Diktys Stratakis
Fermi National Accelerator Laboratory

Nufact, Virginia Tech
August 17, 2018

Outline

- The Fermilab g-2 Experiment
- The Fermilab Mu2e Experiment
- Fermilab Muon Campus
- Commissioning the Muon Campus for the g-2 Experiment
- Comparison between data, simulations and theory
- New technologies for improving beam performance
- Future work & summary

Fermilab accelerator complex



The schedule

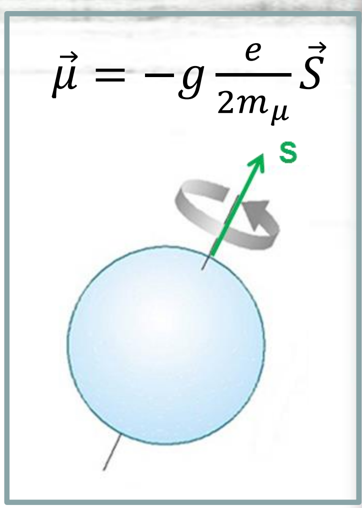
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	
LBNF / PIP II	SANFORD FNAL				DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	DUNE	ν
						LBNF	LBNF	LBNF	LBNF	LBN F	LBNF	LBNF	LBNF	LBNF	
NuMI	MI	MINERvA	MINERvA	OPEN	OPEN	OPEN	OPEN	OPEN							
		NOvA	NOvA	NOvA	NOvA	NOvA	NOvA	NOvA							
BNB	B	µBooNE	µBooNE	µBooNE	OPEN	OPEN	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	ICARUS	OPEN			OPEN	OPEN	OPEN	OPEN	
		SBND	SBND	SBND	SBND	SBND	SBND	OPEN			OPEN	OPEN	OPEN	OPEN	
Muon Complex		g-2	g-2	g-2										OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	Mu2e	LONG SHUTDOWN		Mu2e	Mu2e	Mu2e	OPEN	
SY 120	MT	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	p
	MC	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF	FTBF			FTBF	FTBF	FTBF	FTBF	
	NM4	OPEN	E1039	E1039	E1039	E1039	OPEN	OPEN			OPEN	OPEN	OPEN	OPEN	
		FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	

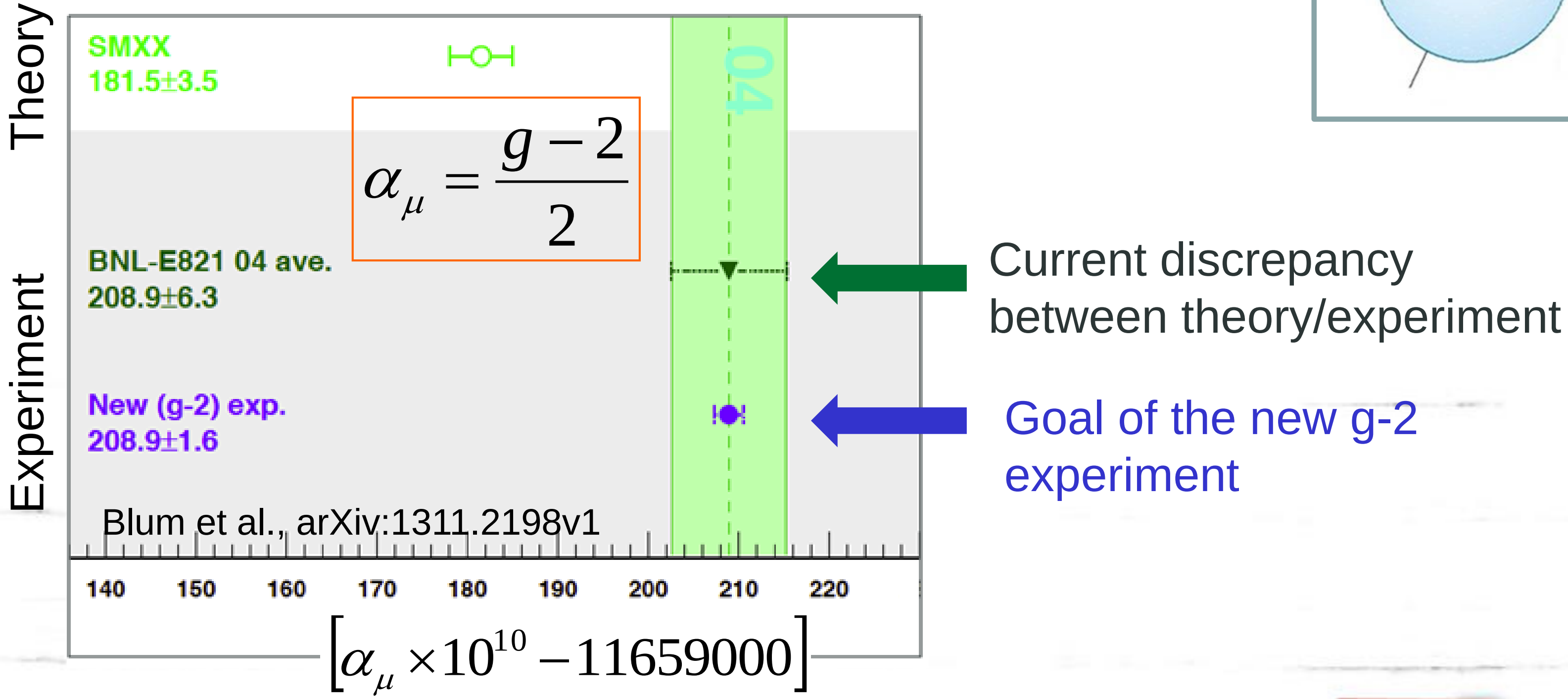
Construction / commissioning — Run — Subject to PAC review — Shutdown

Capability ended — Capability unavailable

The muon g-2 experiment

- Standard model: g_{theory}= 2.00 233 183 630 (99)
- Last measured : g_{meas} = 2.00 233 184 178 (126)
- What other physics needed for g_{theory}=g_{meas}?

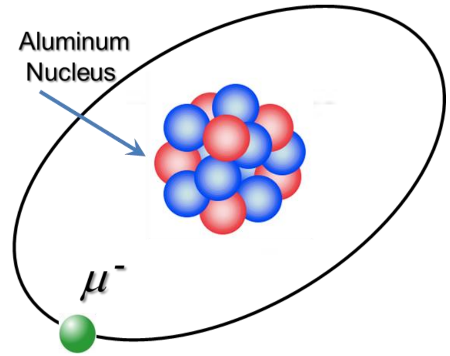




The Mu2e experiment

- Muons are stopped in a Al target and captured into an atomic orbital state of an Al nucleus. Most likely processes:
- Decay in orbit: $\mu^- \longrightarrow e^- \;\; \bar{\nu}_e \; \nu_\mu$

L_e	0	=	1	-1	0
L_μ	1	=	0	0	1



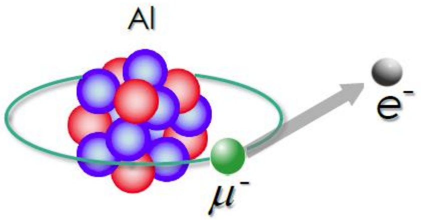
- Muon capture: $\mu^- \; N(A,Z) \longrightarrow \nu_\mu \; N(A,Z-1)$

L_μ	1	=	1

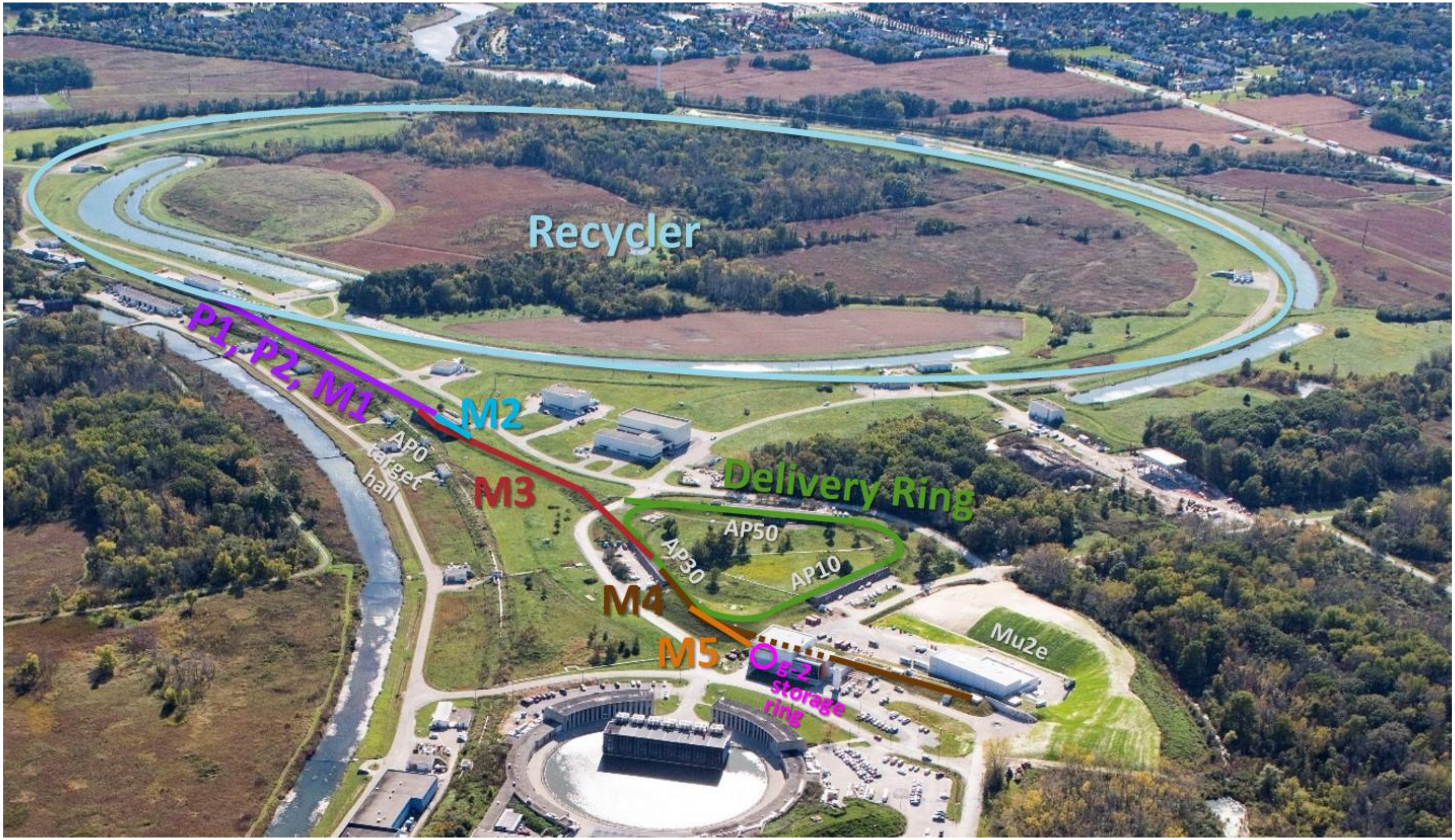
- Mu2e will for look for a neutrinoless muon to electron conversion:

$$\mu^- \; N(A,Z) \longrightarrow e^- \; N(A,Z)$$

L_e	0	≠	1
L_μ	1	≠	0



The beam source: Muon Campus



Beam delivery for g-2 and Mu2e

g-2 EXPERIMENT

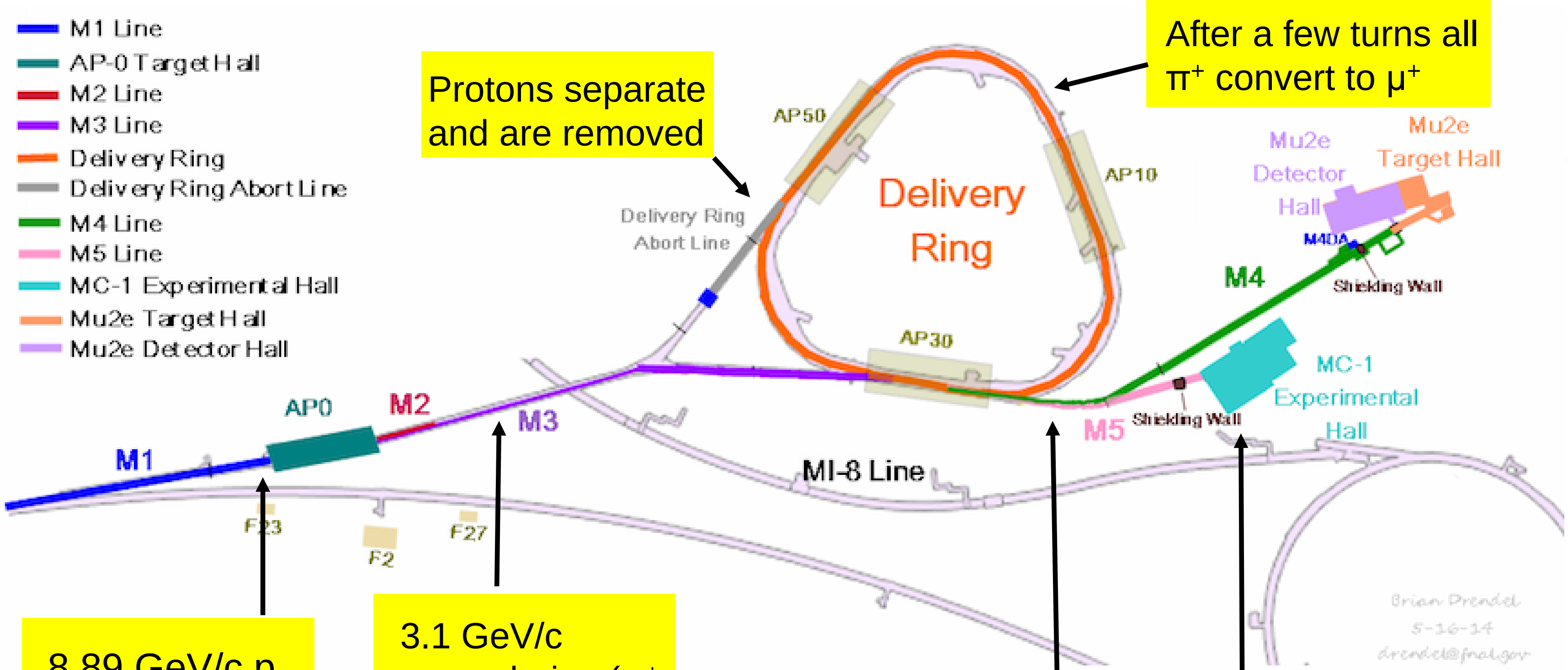
- Recycler bunches are extracted every 10 ms and directed toward the target
- Create 3.1 GeV pions and make beamline long enough for all pions to decay
- Capture 3.094 GeV muons from forward decayed pions (aim a polarization of >97%).
- Ring accepts only muons with $\Delta p/p = \pm 0.15\%$ of magic

Mu2e EXPERIMENT

- Recycle bunches are extracted every 48 ms and bypass the target
- The beam is resonantly extracted from the Delivery Ring and sent to the Mu2e target
- Eliminate out-of-time proton beam

FOCUS OF THIS TALK

Muon Campus for g-2 operations



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

Muon Campus simulation tools

- Significant effort over the last two years, to accurately estimate the pion, muon and proton rates along the Muon Campus

GOAL: Verify results with at least two codes

TARGET
GEANT4
MARS

SECONDARY BEAM TRANSPORT
G4BEAMLINE
BMAD
COSY

STORAGE RING
G4BEAMLINE
BMAD
COSY
gm2ringsim

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 111003 (2017)

Accelerator performance analysis of the Fermilab Muon Campus

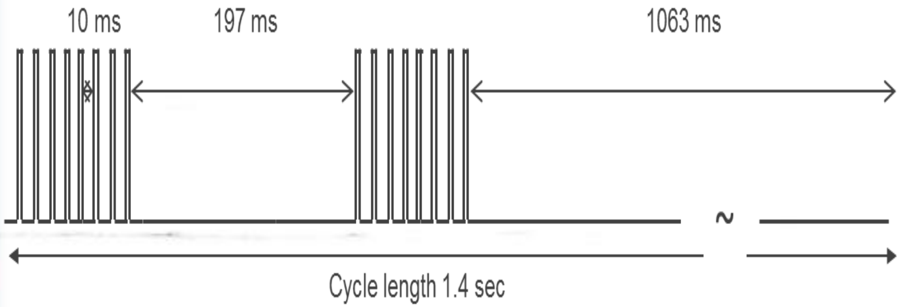
Diktys Stratakis, Mary E. Convery, Carol Johnstone,
John Johnstone, James P. Morgan, and Dean Still
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

Jason D. Crnkovic, Vladimir Tishchenko, and William M. Morse
Brookhaven National Laboratory, Upton, New York 11973, USA

Michael J. Syphers
*Northern Illinois University, DeKalb, Illinois 60115, USA,
and Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
(Received 29 March 2017; published 21 November 2017)

Beam to Muon Campus

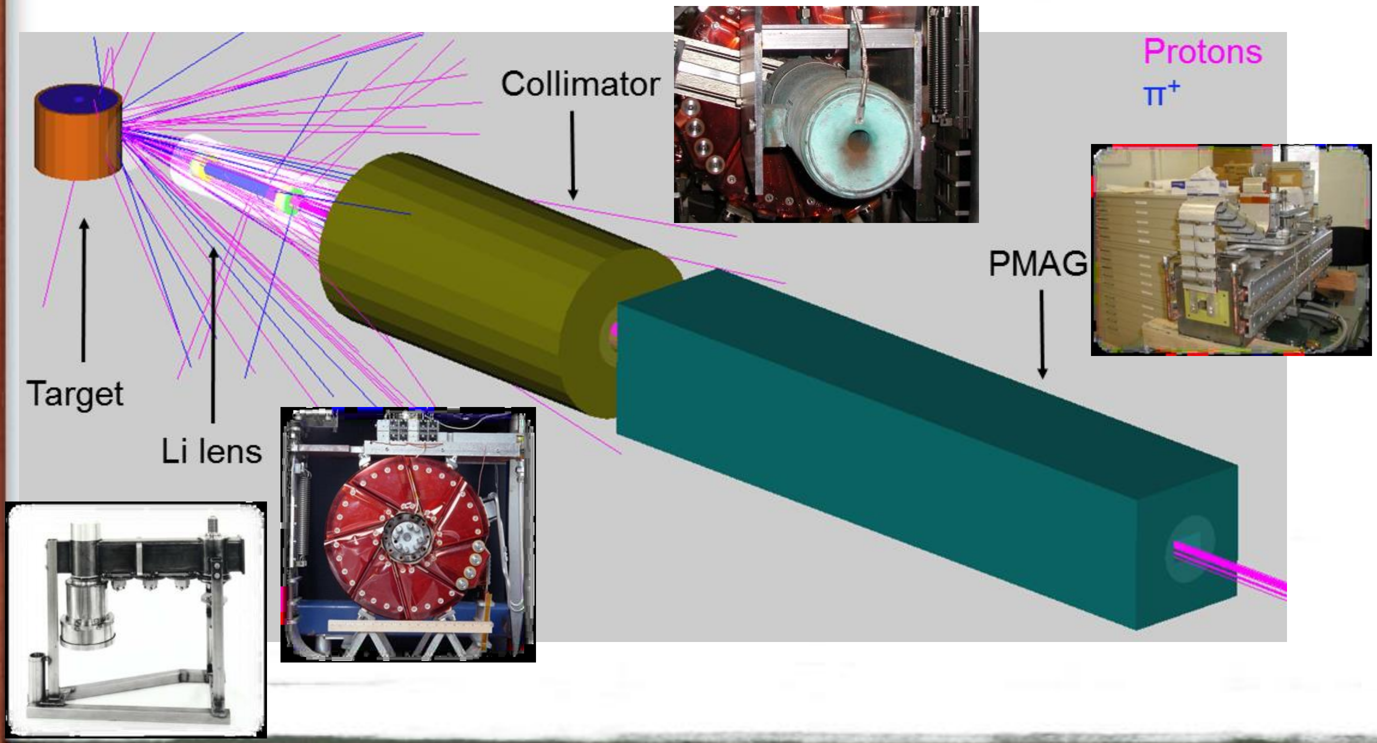
- Two booster bunches are injected into the Recycler, rebunched into 8 bunches and extracted with 10 ms intervals
- The process is repeated so that protons are sent to the Muon Campus in two groups of 8 with bursts at 100 Hz

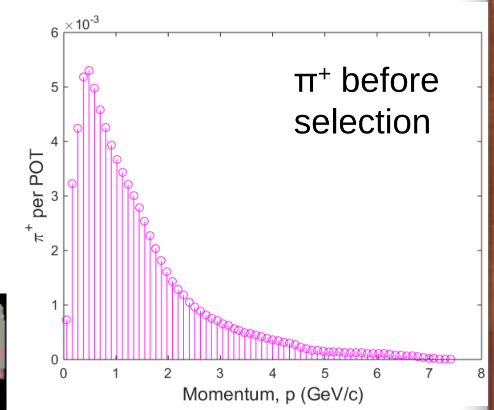


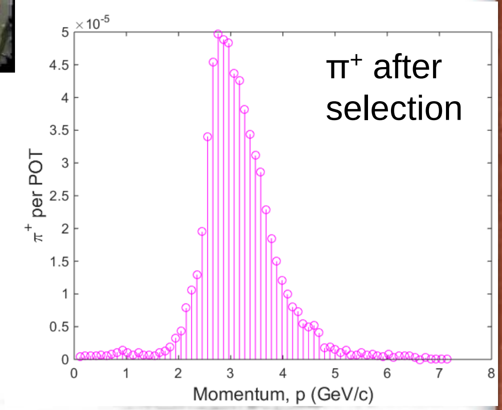
Parameter	Value
Protons on target (POT) per pulse	10^{12}
Pulse width	120 ns
Number of pulses	16
Cycle length	1.4 s
Frequency	12 Hz
Incoming beam momentum	8.89 GeV/c

Target station

- Target station consists of five main devices: production target, lithium lens, collimator, pulsed selection magnet and, beam dump

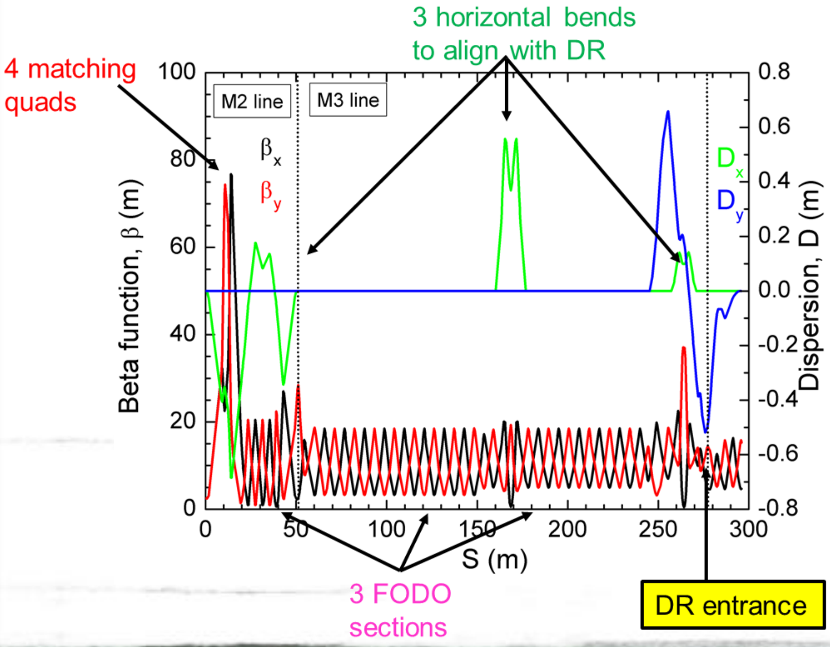


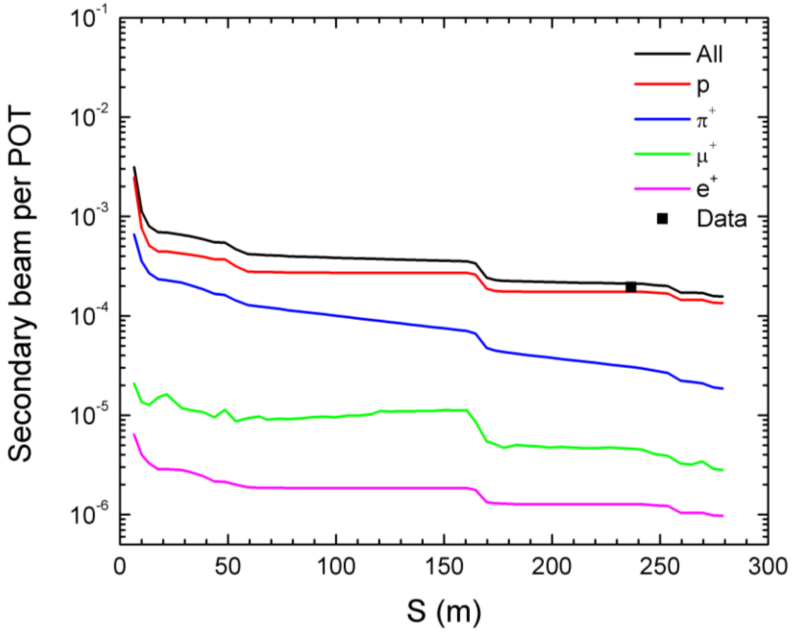




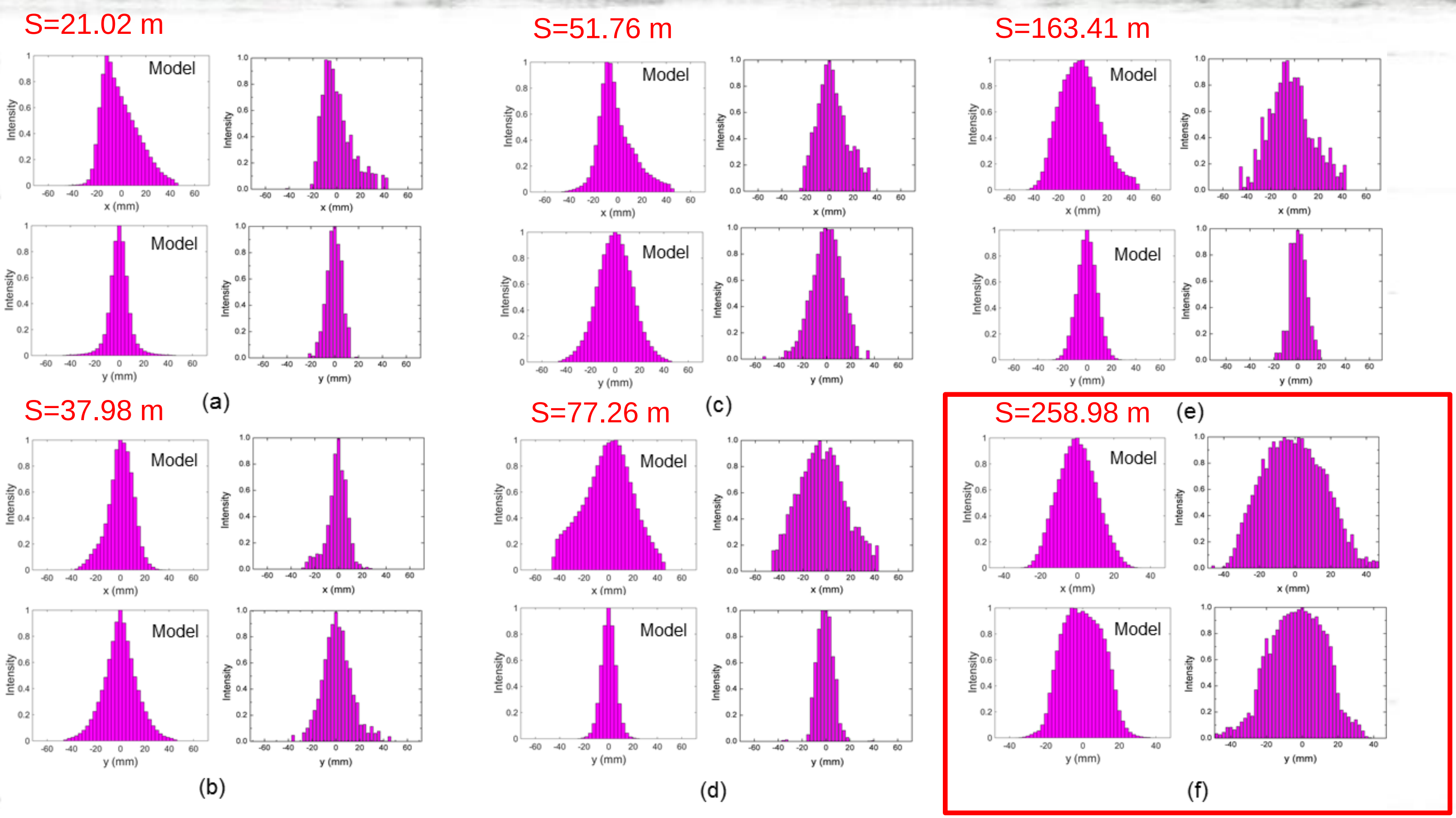
The M2 & M3 beam lines

- Designed to maintain a low beta function so that to capture as many pions and muons possible
- Mostly muons from forward decays are captured. Simulation shows that the beam is >95% polarized
- Measured intensity at the end of the line matches simulation





M2 & M3 beam lines: Data vs. Model

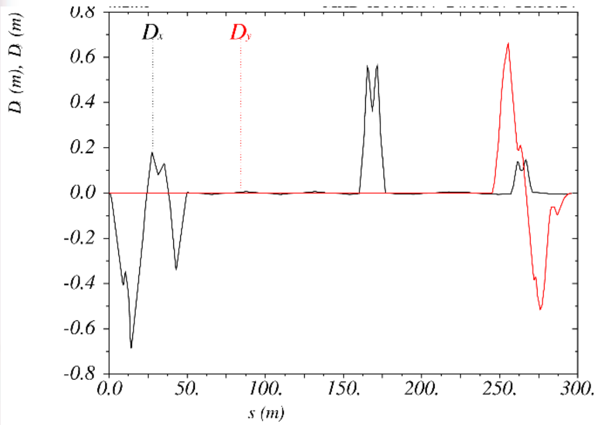


- Compared to the simulation, the beam at the end of the M3 line has a larger core and longer tails

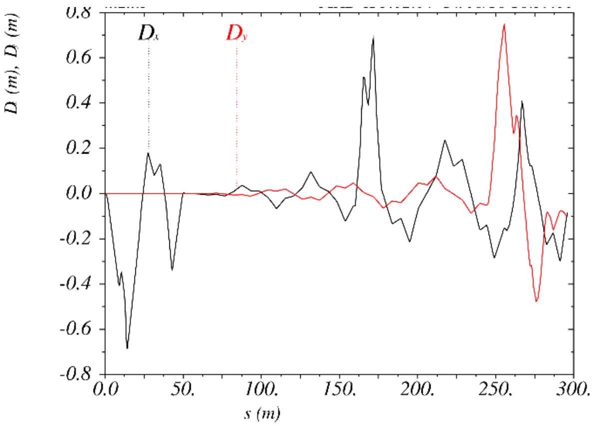
Lattice instabilities

- A small positioning error can trigger a dispersion wave which becomes amplified further downstream
- Example below show what happens if quad magnet 709 (S=66.0) is misplaced in both horizontal and vertical directions

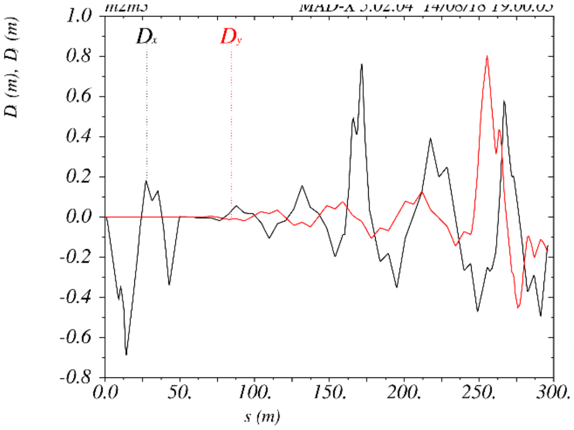
design lattice



1.5 mm

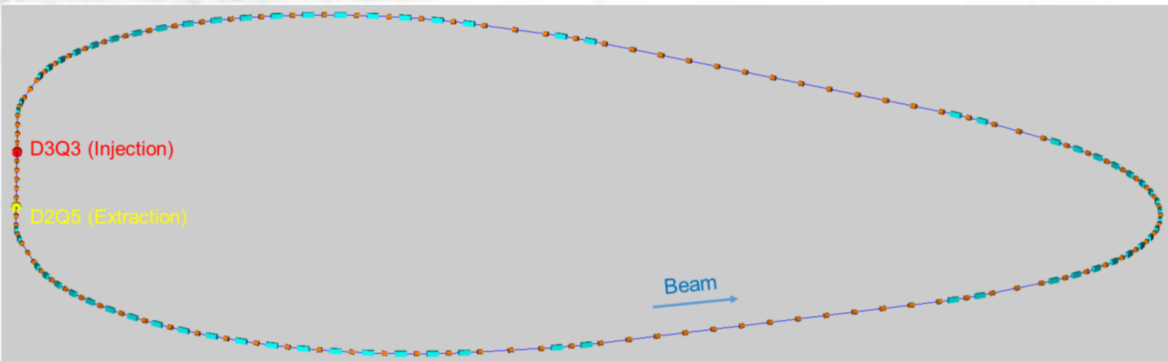


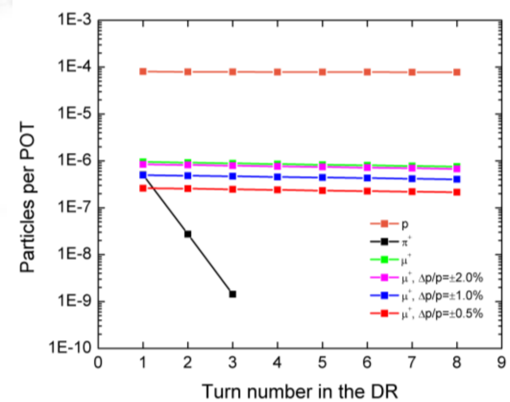
2.5 mm



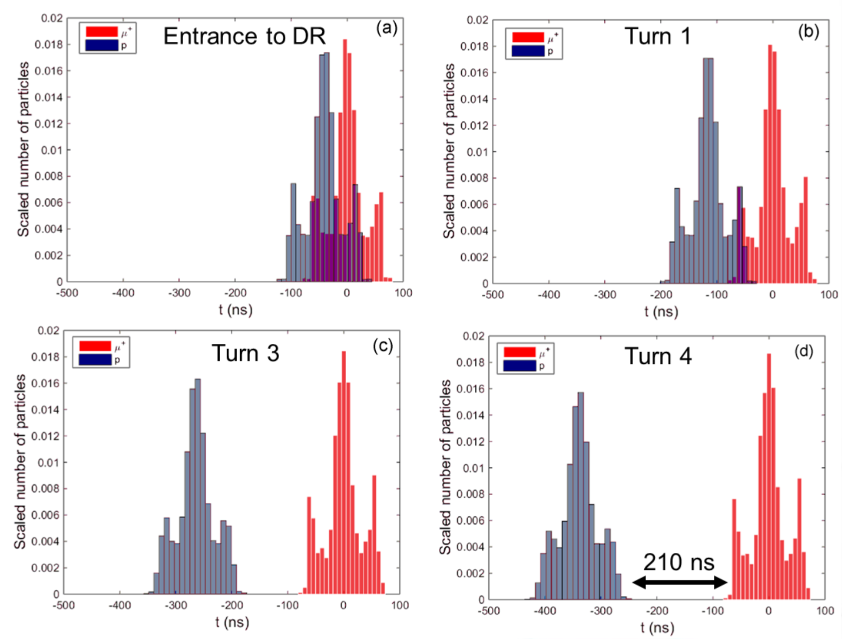
S. Romanov, priv. comm.

Delivery Ring (DR)



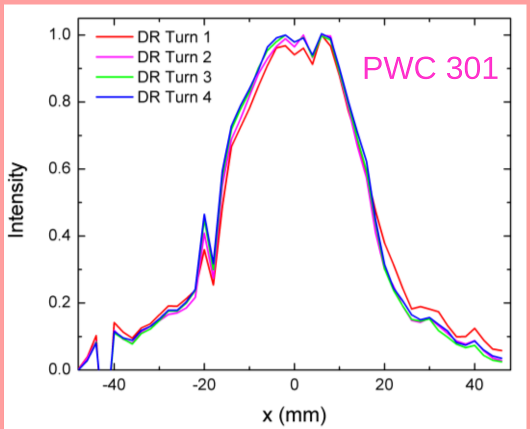


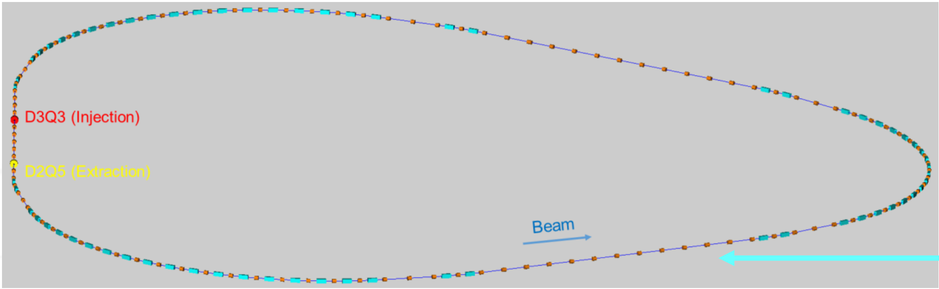
- 505 m, 57 FODO cells and 66 dipoles
- Provides enough time for the heavier protons to separate from the lighter muons
- After <u>four</u> revolutions the protons are kicked out of the beam path

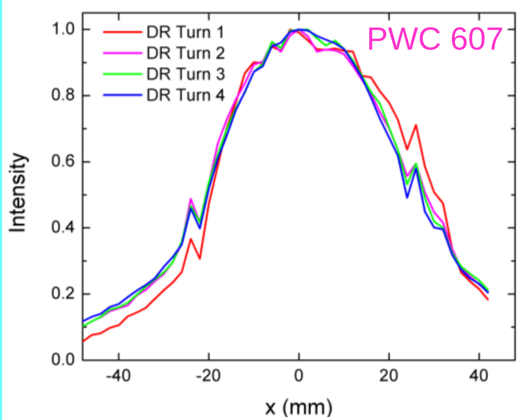


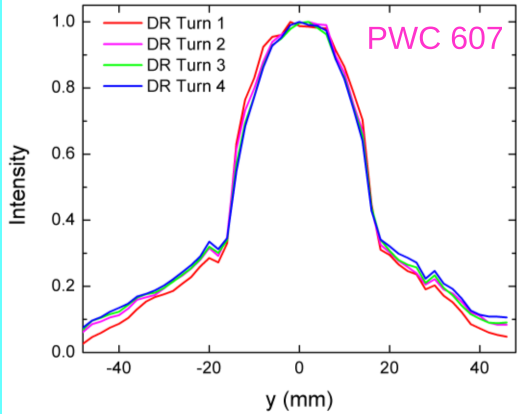
DR performance (Turns 0-4)

- Beam is proton dominated (all data before proton extraction)
- The beam profile is reproducible from turn to turn



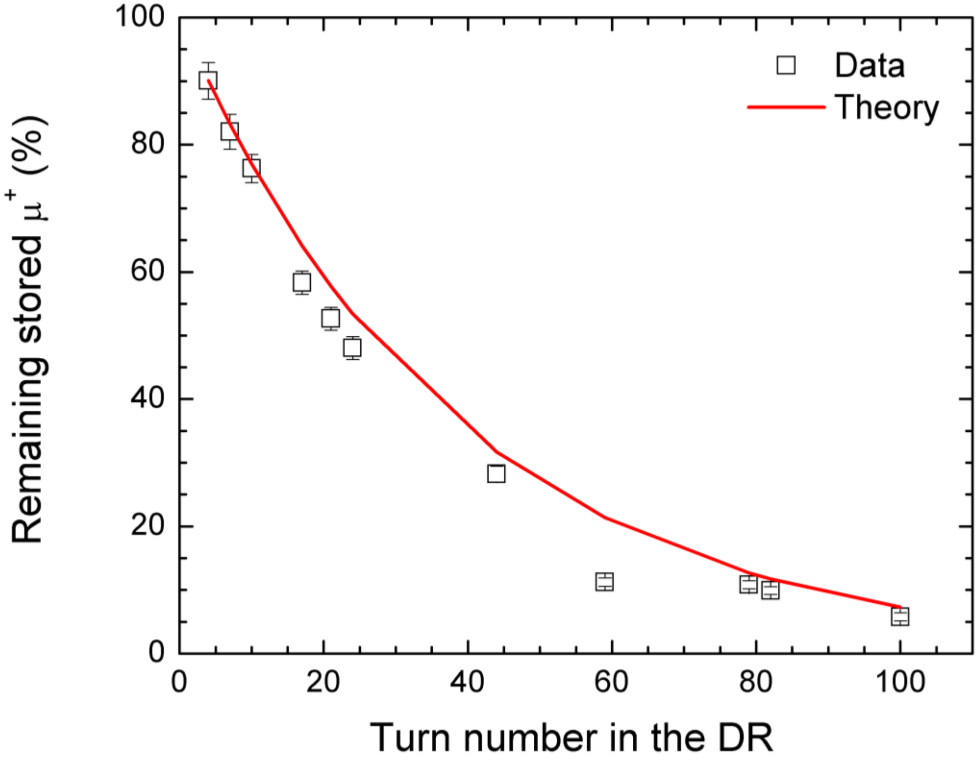






DR performance (Turns 4-100)

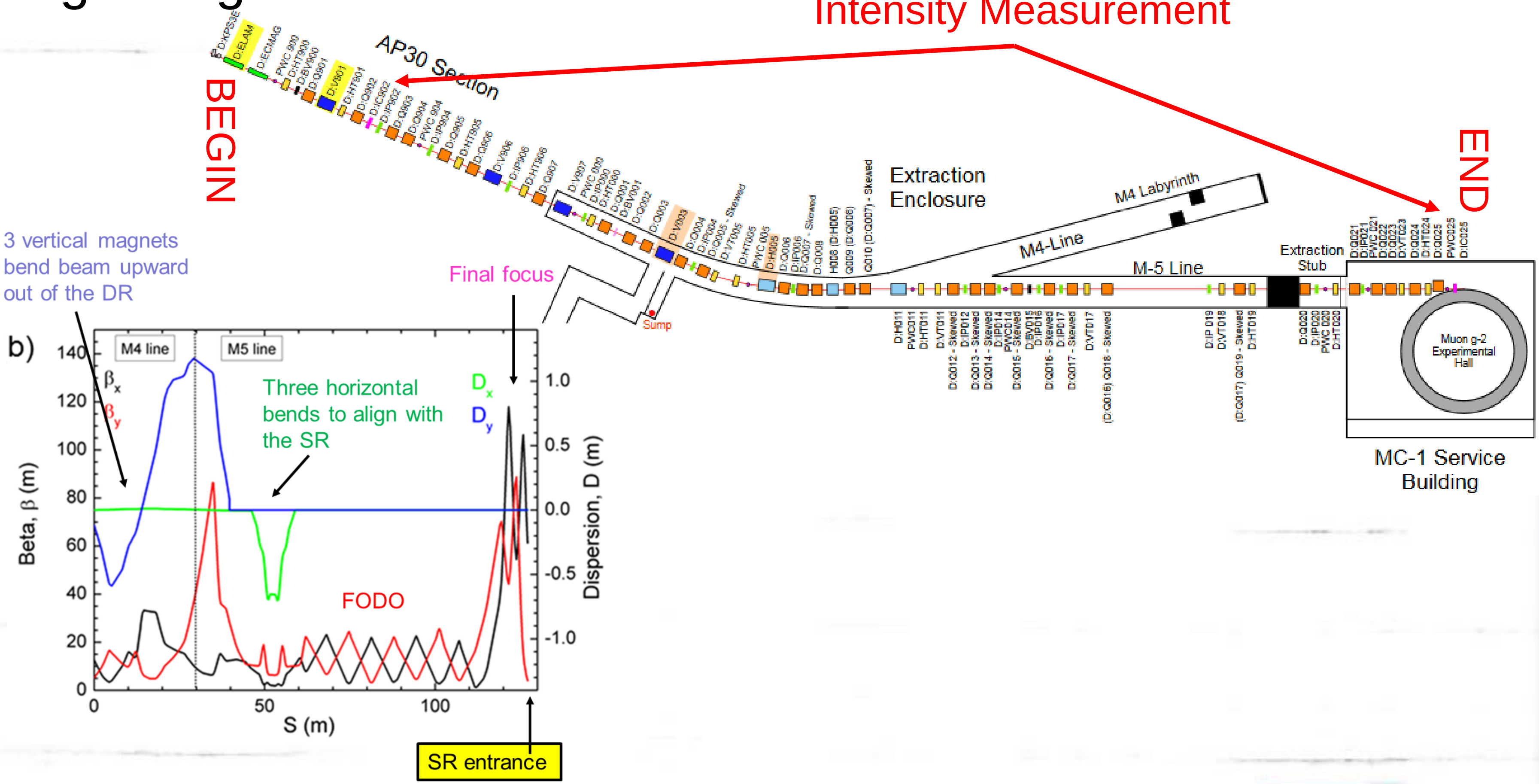
- Protons are extracted and the beam is muon dominated. Not a typical operating point but we used it to benchmark the DR



- Measurement agrees well with the exponential decay law

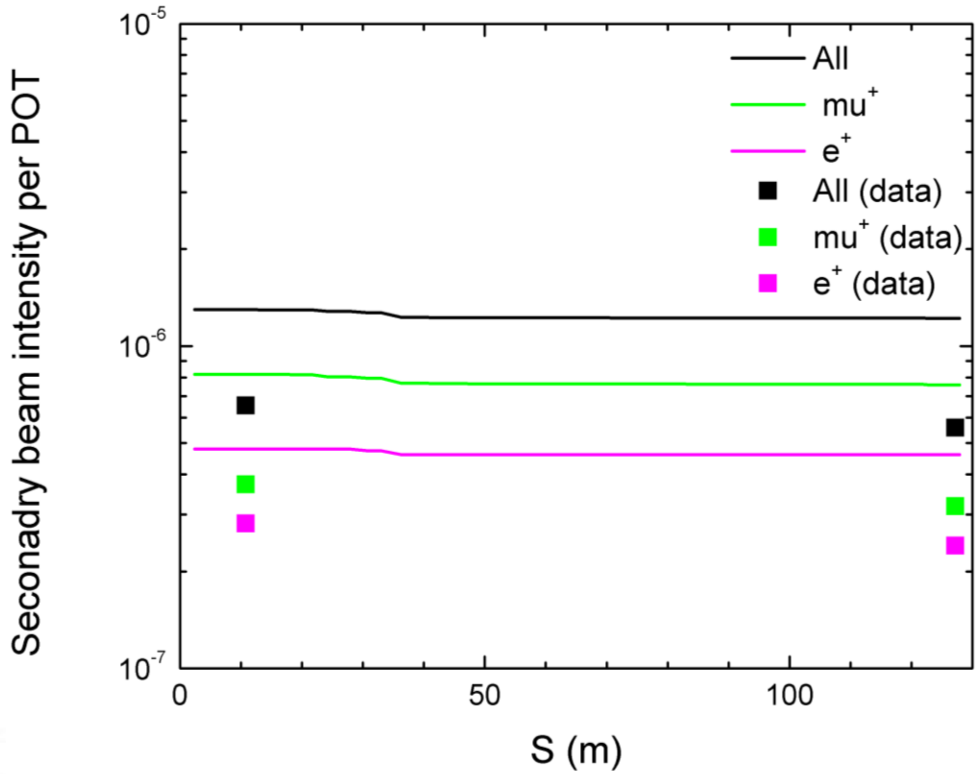
Performance within M4 & M5 lines

- 130 m long line that transports the beam from the DR to the g-2 ring

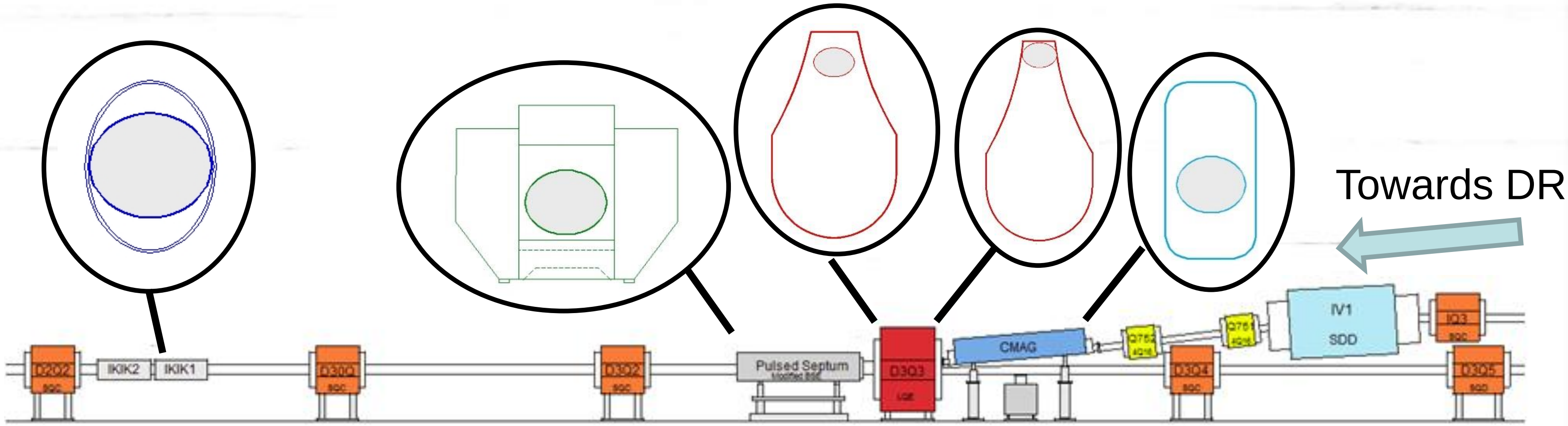


Performance within M4 & M5 lines

- Measured & simulated transmission along the M4-M5 is ~90%
- The measured mu+/e+ ratio is 57/43 and is confirmed by two independent experiments. Is close to the 60/40 from tracking



Injection & extraction to the DR scheme

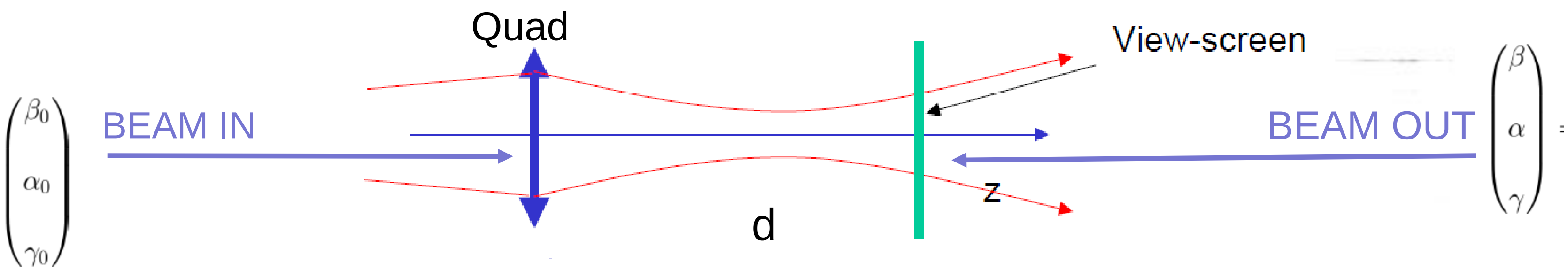


- Ideal beam barely fits through the small DR apertures
- Any upstream mismatches can lead to severe losses
- Off-momentum particles will lost at much higher numbers than magic momentum muons

Jim Morgan, priv. comm.

Measuring the beam optics

- We can estimate the Twiss parameters and emittance by measuring the beam spot size as a function of the focal length of the quad

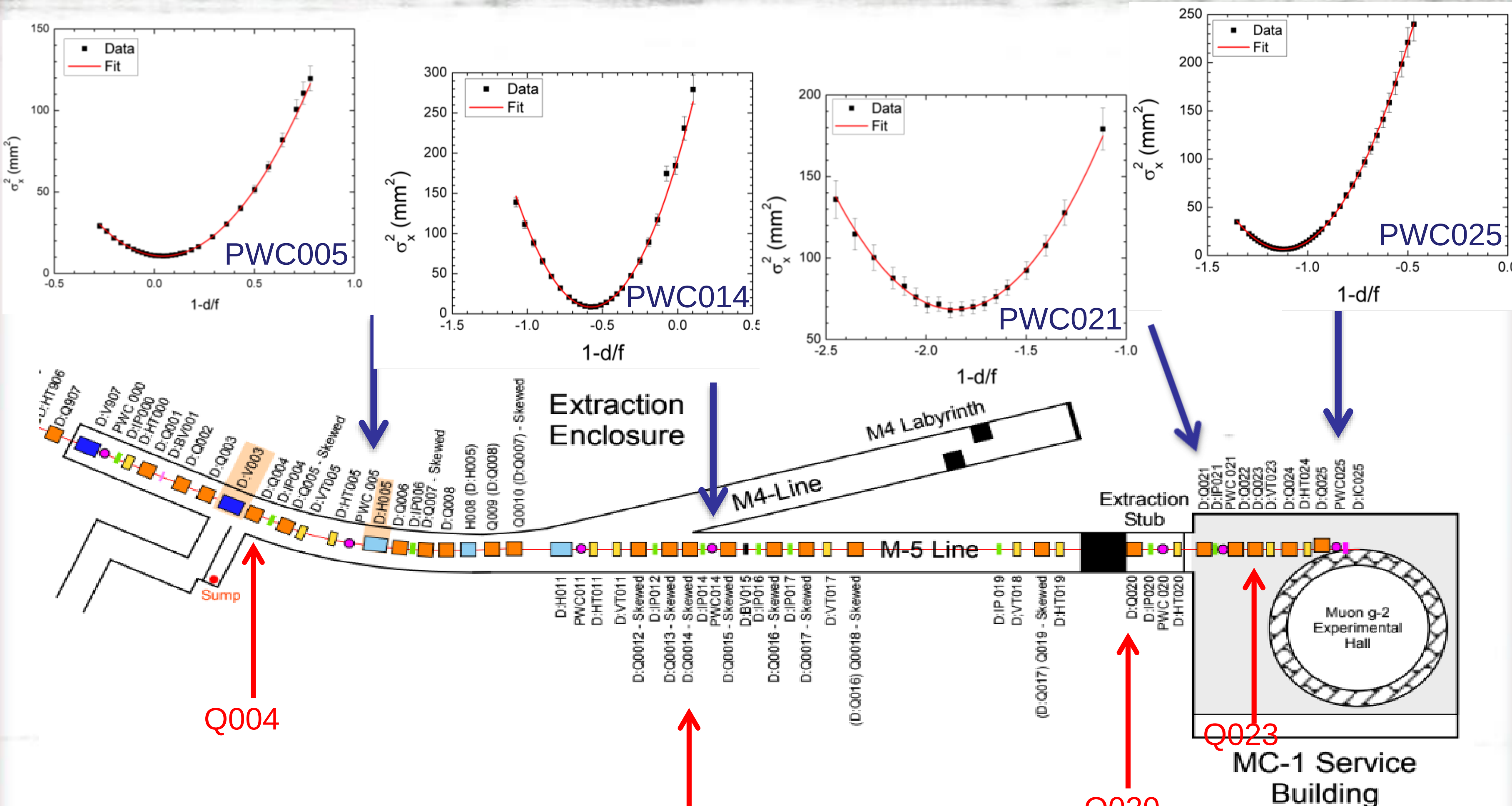


$$\begin{pmatrix} \beta \\ \alpha \\ \gamma \end{pmatrix} = \begin{pmatrix} \left(1-\frac{d}{f}\right)^2 & -2d\left(1-\frac{d}{f}\right) & d^2 \\ \left(1-\frac{d}{f}\right)\frac{1}{f} & 1-2\frac{d}{f} & -d \\ \frac{1}{f^2} & -2\frac{1}{f} & 1 \end{pmatrix} \begin{pmatrix} \beta_0 \\ \alpha_0 \\ \gamma_0 \end{pmatrix}$$

$$\sigma_x^2 = \beta\varepsilon = a\left(1-\frac{d}{f}\right)^2 2 - b\left(1-\frac{d}{f}\right)d + cd^2$$

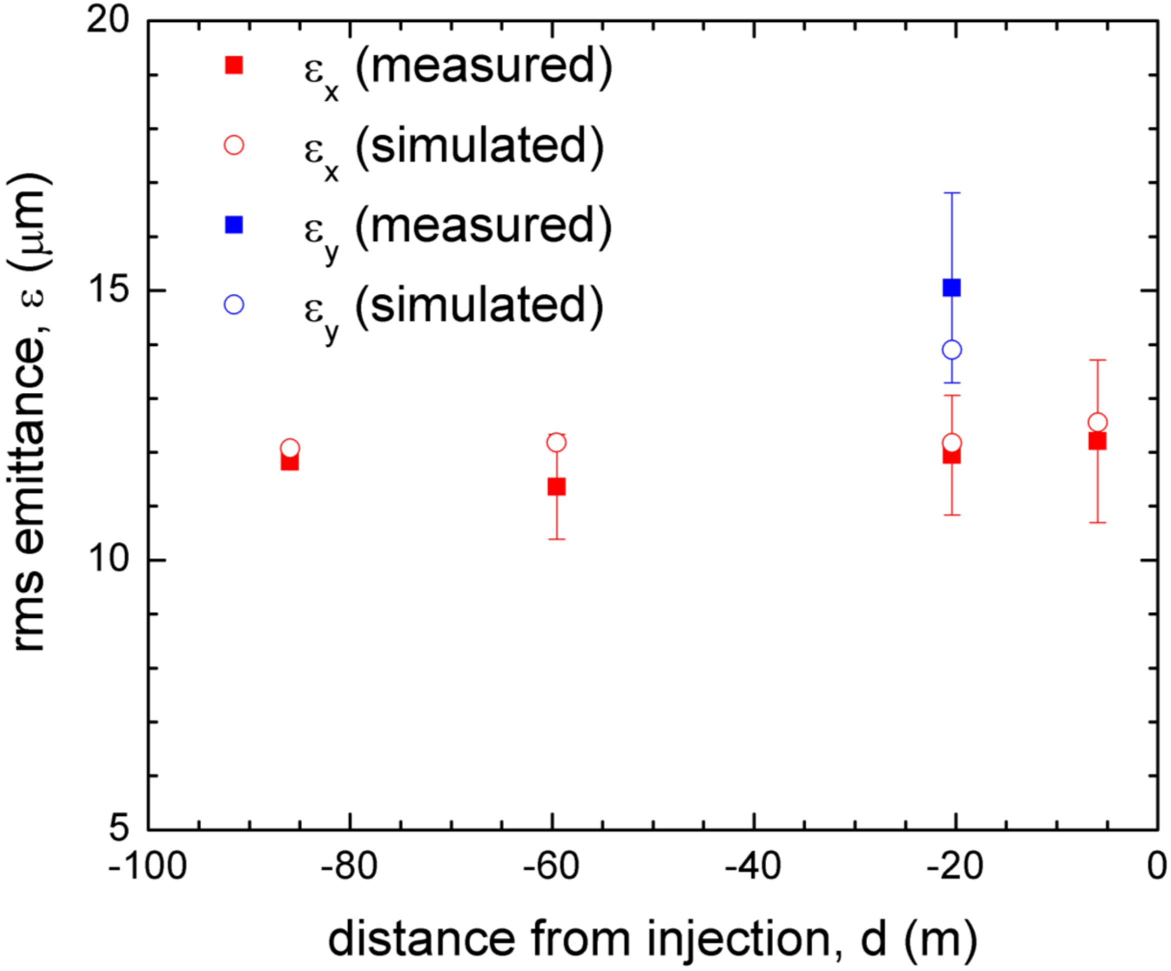
$$where \quad a = \beta_0\varepsilon \qquad b = \alpha_0\varepsilon \qquad c = \gamma_0\varepsilon$$

Optics along the M5 line



A. Ramirez, Fermilab Intern, SULI (2018)

Measuring the beam emittance

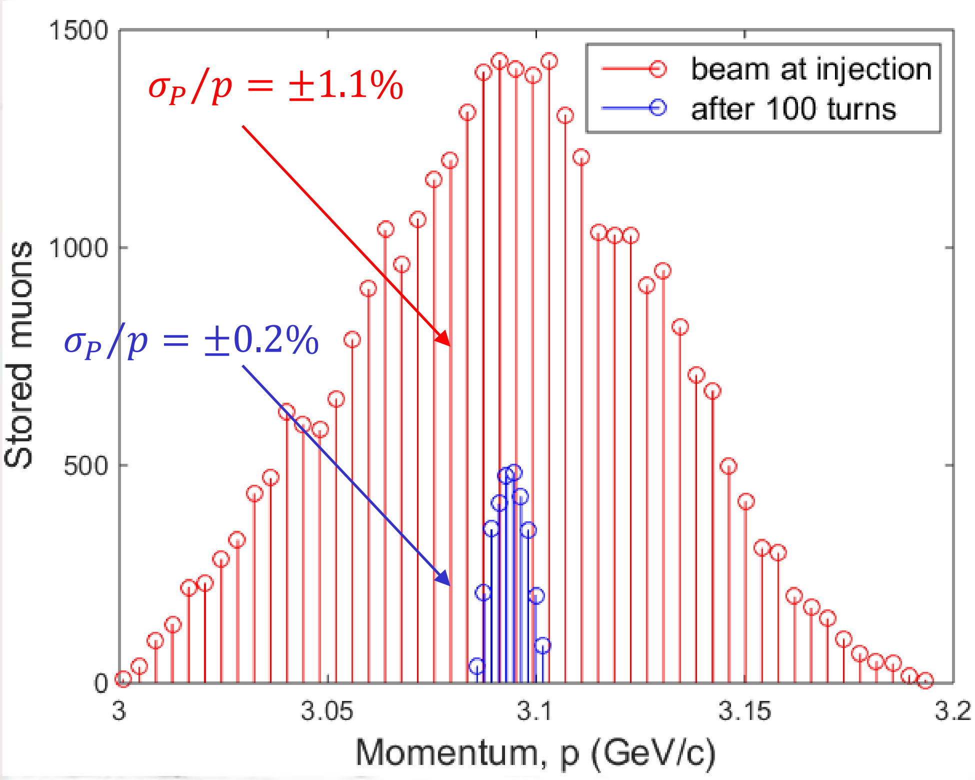


A. Ramirez, Fermilab Intern, SULI (2018)

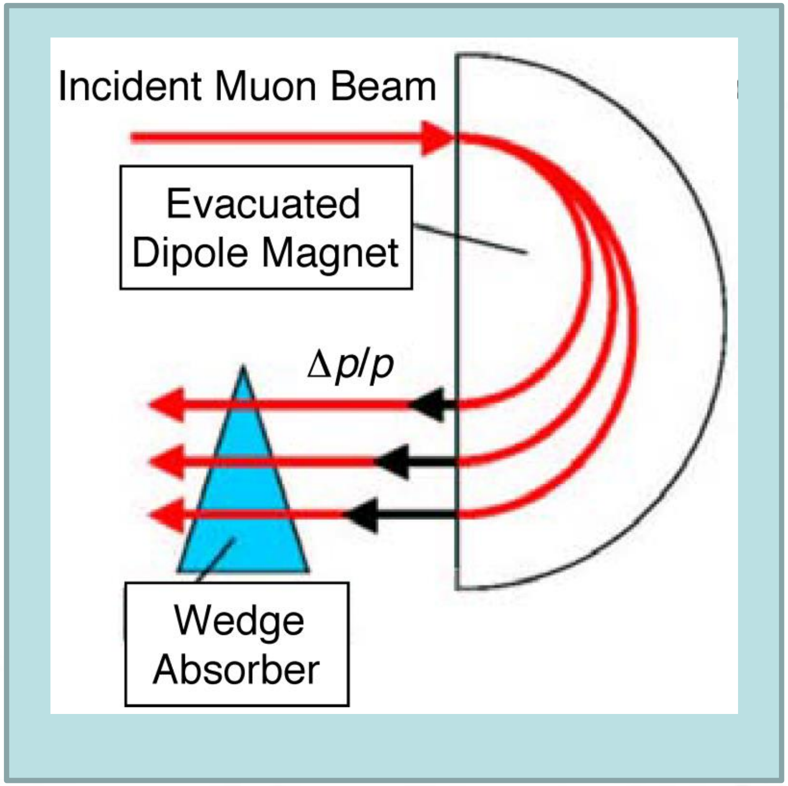
Future improvements

Momentum acceptance

THE PROBLEM



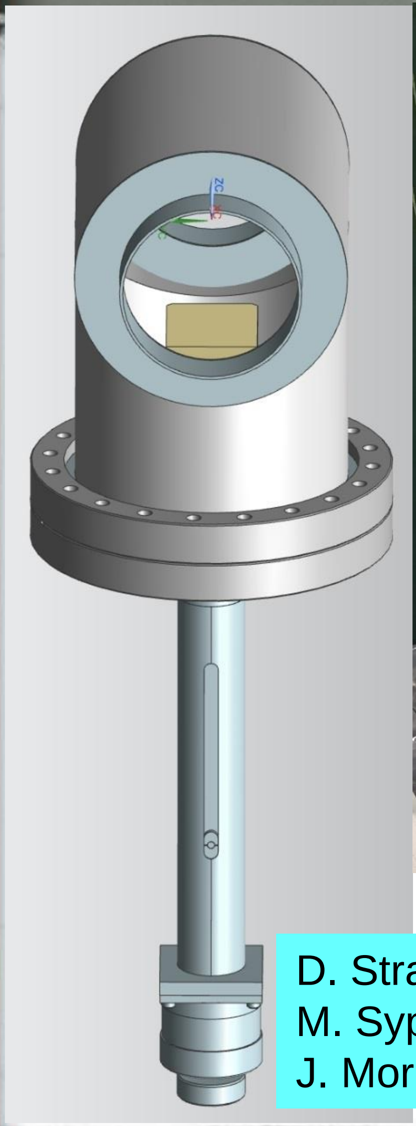
THE SOLUTION

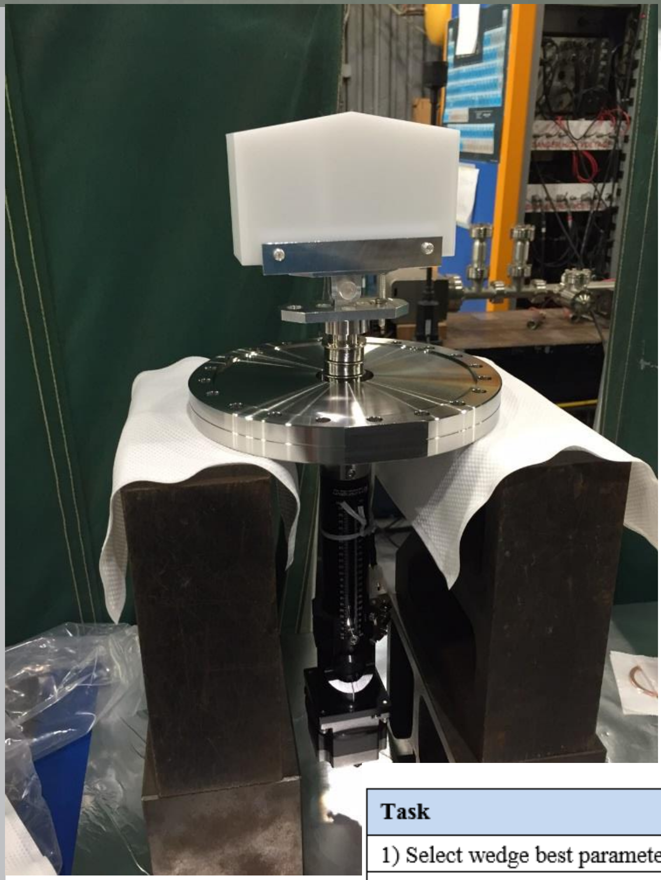


- Storage ring accepts particles only within $\sigma_p/p = 0.2\%$

Fully funded two-year program

LDRD at Fermilab
Laboratory Directed Research and Development

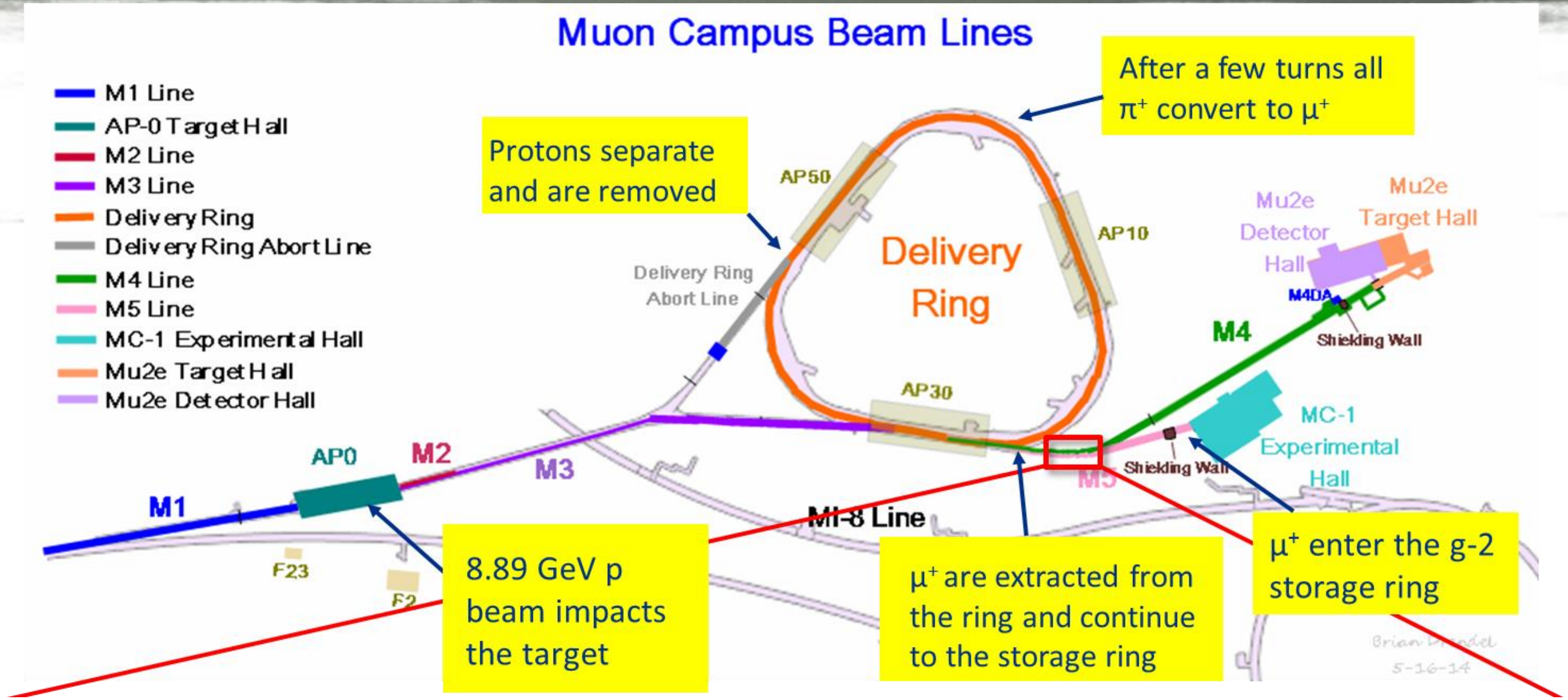


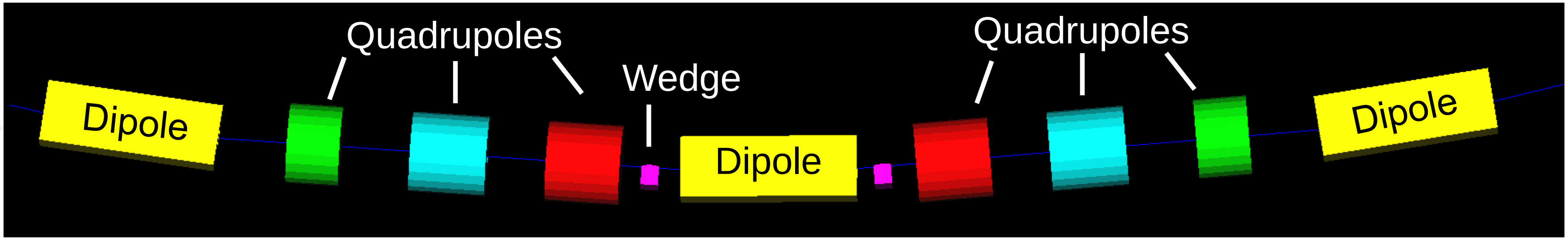


D. Stratakis (PI)
M. Syphers (co-PI)
J. Morgan (coordinator)

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

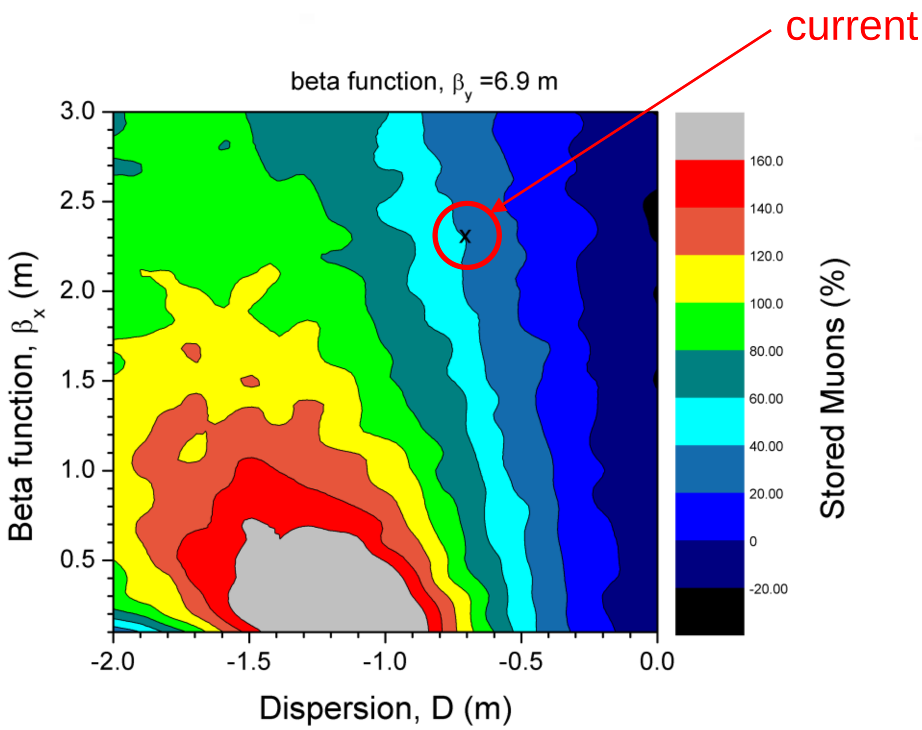
Choice of location





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

Expected performance



- Colormaps indicate the potential to increase the number of stored muons by more than 20%

Conclusions (1)

- We found "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 beam intensity
- The measured muon rate over 100 DR turns follows closely the exponential decay law suggesting minimal aperture losses in the DR
- The beam optics along the M5 line agree reasonable well with the simulation and the emittance is conserved
- Two independent measurements found the muon to positron ratio to be 57/43 which agrees well with the simulation

Conclusions (2)

- While the transmission along the M4 and M5 lines agrees well with the simulation, the beam intensity is ~40-45% less to the design value
- Likely from aperture cuts during injection in the DR due to lattice imperfections further upstream
  - Should mostly affect no-storable muons. Momentum collimators will be installed to further check this hypothesis.
- Through Fermilab's LDRD program we have been awarded a grant to design, install and test a wedge in the Muon Campus
- It will provide improvements in the number of stored muons that are required to minimize the statistical uncertainty in the Muon g-2 measurement