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Beamline Simulation Overview

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g-2 Computing Review

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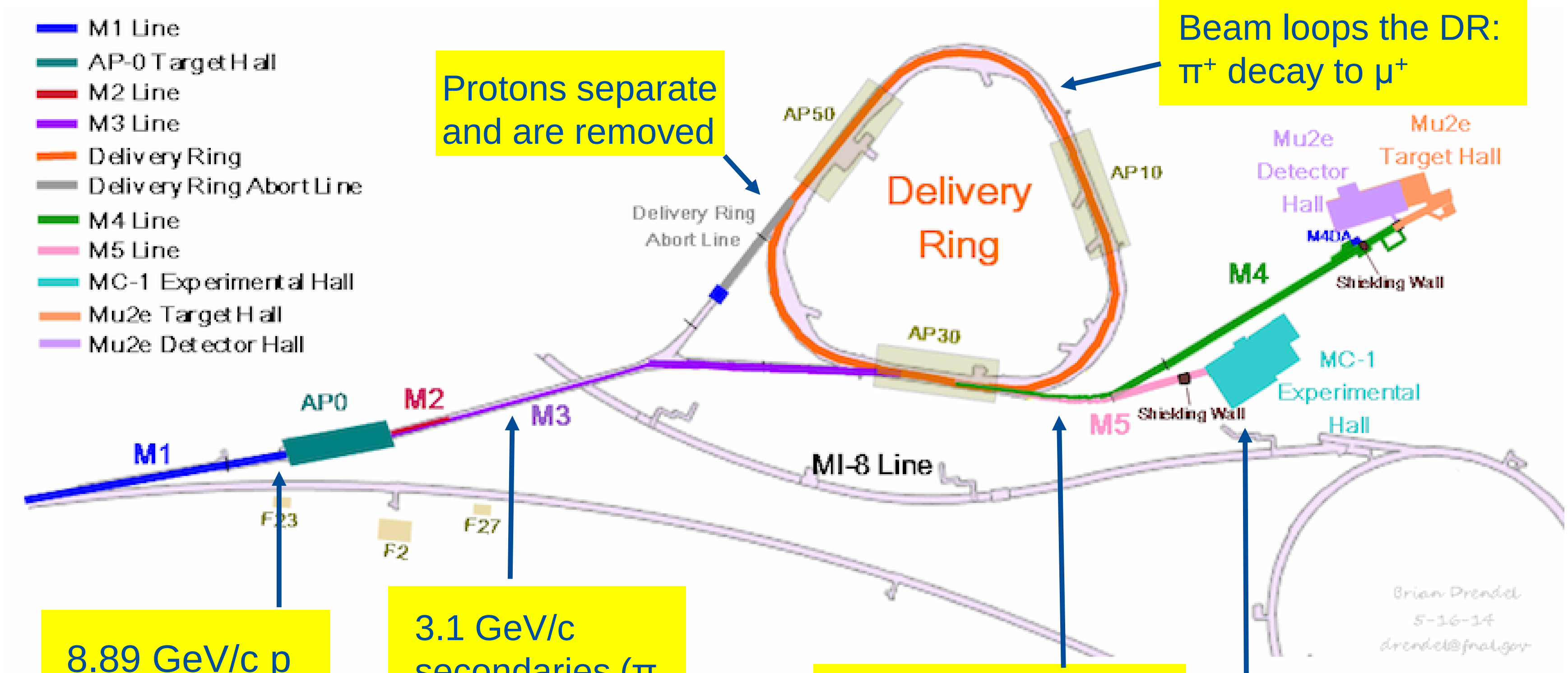
Outline

- Beamlines for the Fermilab Muon g-2 Experiment
- Requirements
- Status
  - Simulation model
  - Performance evaluation
  - Validation process
- Schedule
- Conclusion

Muon Campus beamlines

Protons separate and are removed

Beam loops the DR: π^+ decay to μ^+



8.89 GeV/c p beam impacts the target

3.1 GeV/c secondaries (π, μ, p) 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

Requirements

- **Beam at the g-2 ring entrance:**
  - Should be peaked at “magic” 3.094 GeV/c and contain as many as **possible** μ^+ **within** $\Delta p/p = \pm 0.5\%$ **or less.**
  - **Should be highly polarized (90% or better)**
- **The beamlines from the target to the g-2 ring have bends, elevation changes, complex injection & extraction schemes:**
  - **Can lead to beam losses**
  - **Can trigger error(s) on the measurement**
- **The aim of this work is to deliver an end-to-end simulation from the production target to the storage ring entrance so that the above issues can be addressed.**

Approach

- Developed simulation models for different parts of the beam lines
  - Targetry: MARS & GEANT4
  - Beamline optics: MADX, OPTIM
  - Beam and spin tracking: G4Beamline
- Multi-particle tracking using high-performance computing resources at NERSC
- Validated our results against:
  - Theoretical models & independent simulation codes
- Formed a beam dynamics study group in order to analyze results and monitor progress

Beam dynamics study group

Organizer/ host
D. Stratakis

Accelerator design
- J. Annala[1]
- M. Convery[1]
- J. Morgan[1]
- D. Stratakis[1,2,8]
- M. Syphers[1,3]

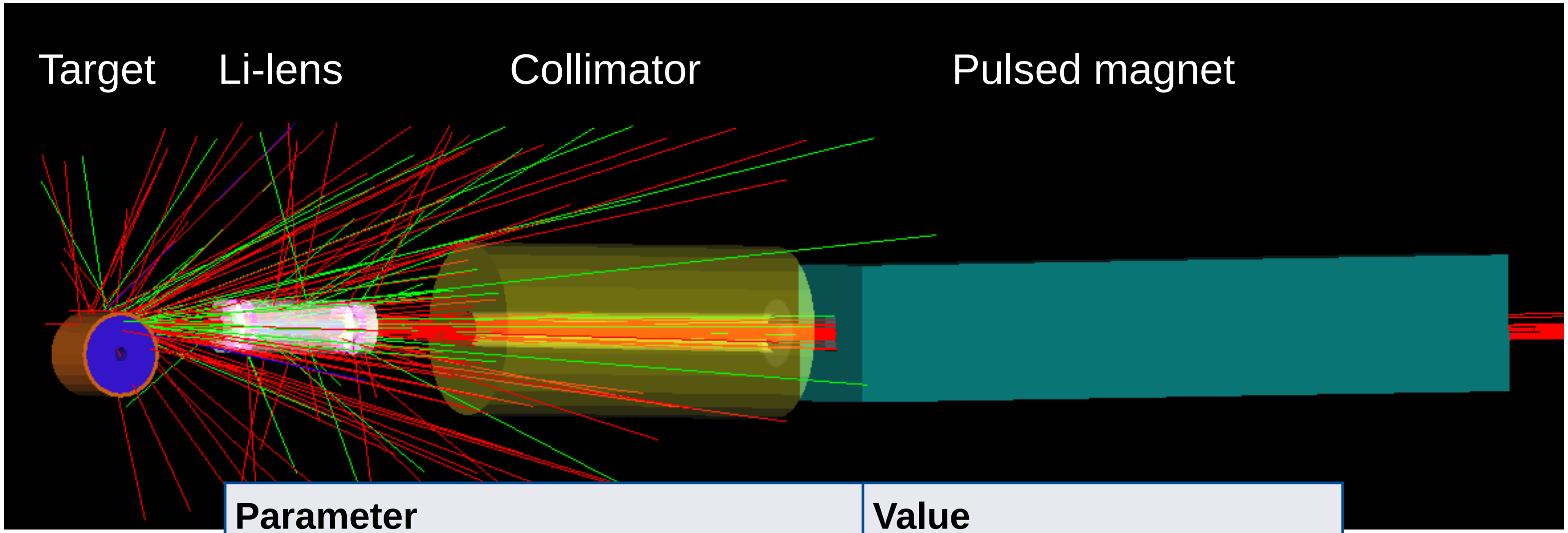
Tracking (up to the ring)
- M. Korostelev[4]
- R. Miceli[2]
- D. Stratakis[1,2,8]
- D. Tarazona[5]

Tracking (in the ring)
- M. Berz[5]
- N. Froemming[6]
- A. Herrod[4]
- J. Stapelton[1]
- S. Kim[7]

Theory
- B. Morse[8]
- J. Crnkovic[8]
- D. Stratakis[1,2,8]
- M. Syphers[1,3]
- V. Tishchenko[8]

[1]Fermilab
[2]Stony Brook University
[3]NIU
[4]Cockcroft/ Lancaster
[5]MSU
[6]Univ. Washington
[7]Cornell Univ.
[8]BNL

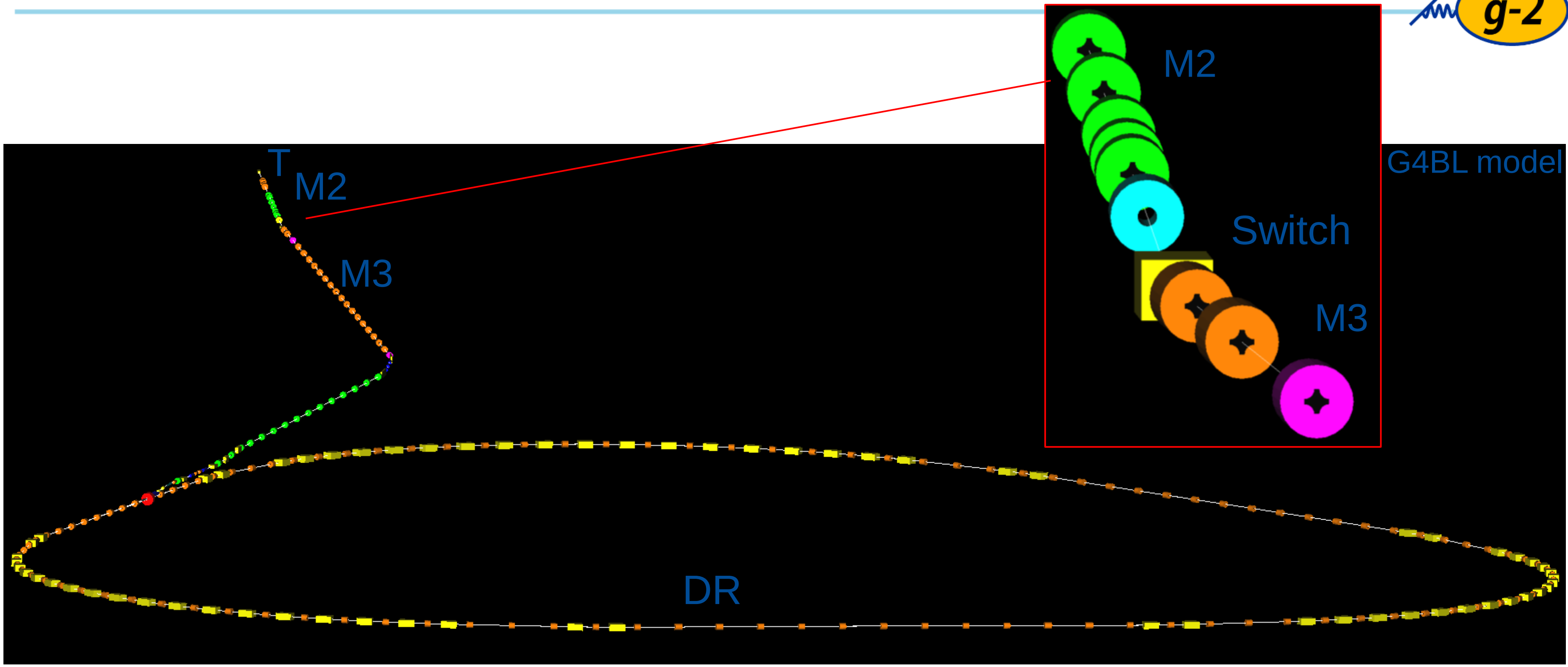
Status: Beam production target model



Parameter	Value
Intensity per pulse	10^{12}
Proton momentum	8.89 GeV/c
Secondary momentum	3.1 GeV/c
Selected particle	π^+
Beam size at target	0.15 mm
Distance between Li-lens and target	31.0 cm
Focusing field gradient of Li-lens	232 T/m

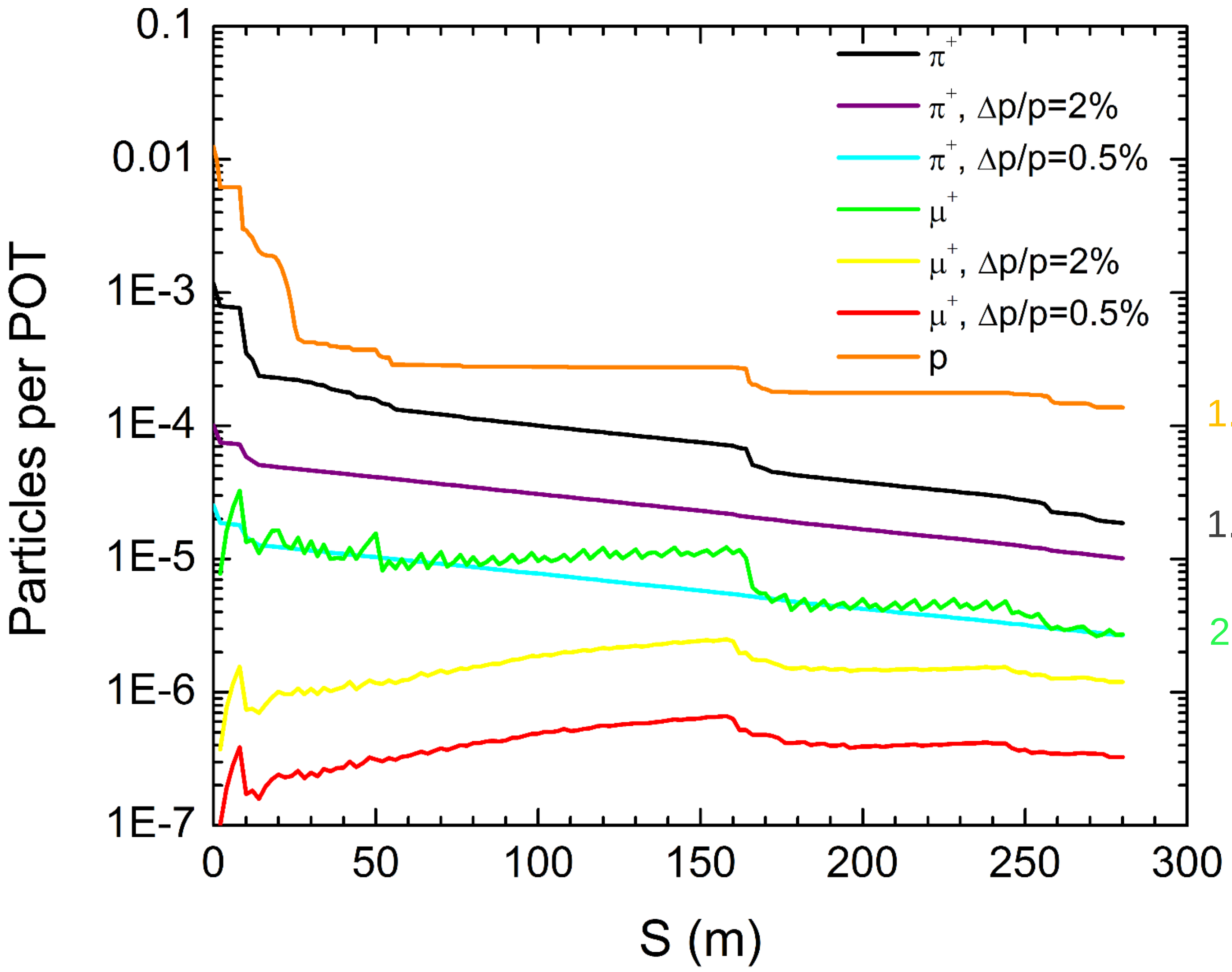
Grange et al., Muon Technical Design Report (2015)

Status: Secondary beam transport lines model



- M2 & M3 lines will carry the secondary beam from the target (T) to the delivery ring (DR)
- Generated a simulation model with G4Beamline.

Performance within M2 & M3 lines

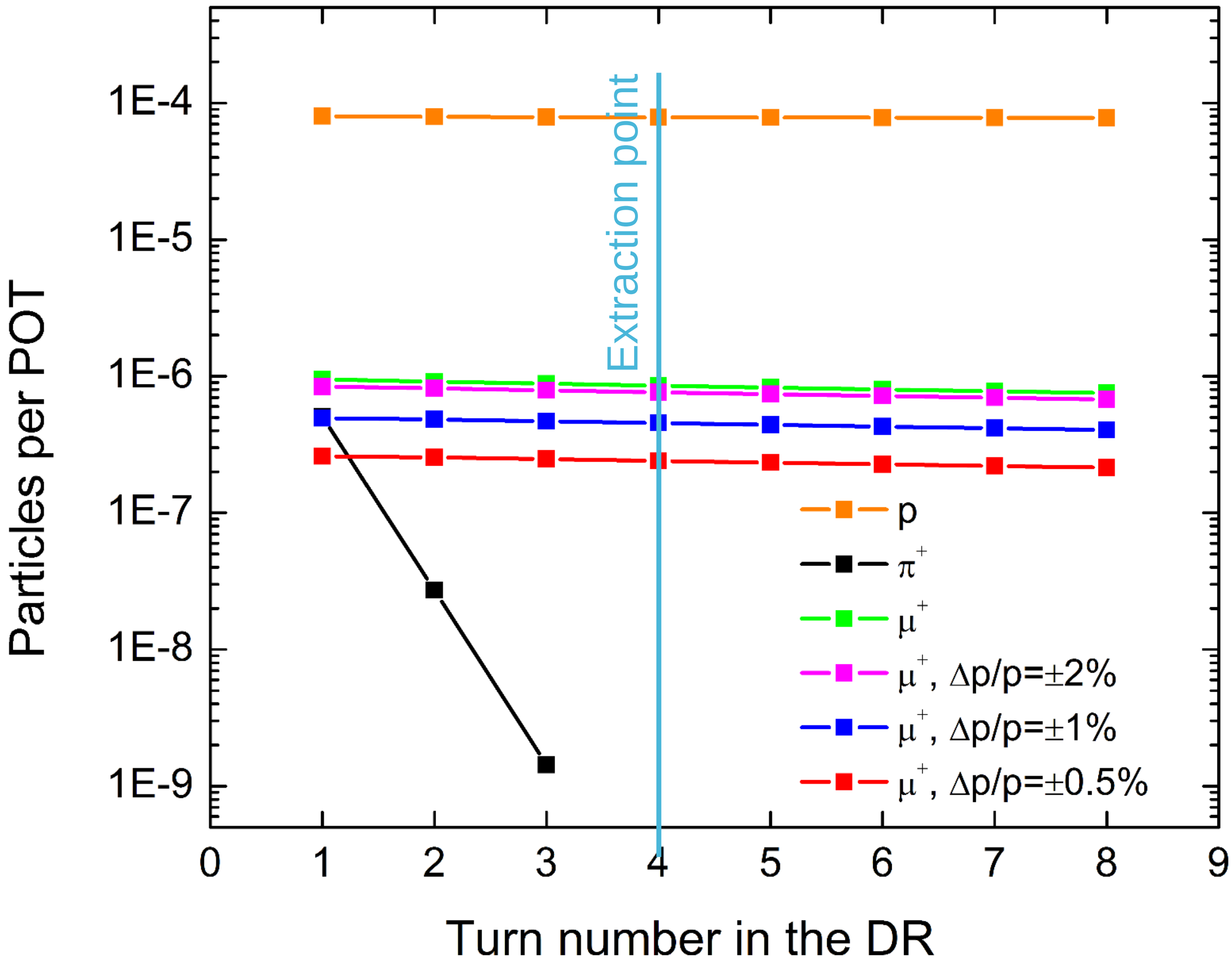


1.37x10^-4 POT

1.87x10^-5 POT

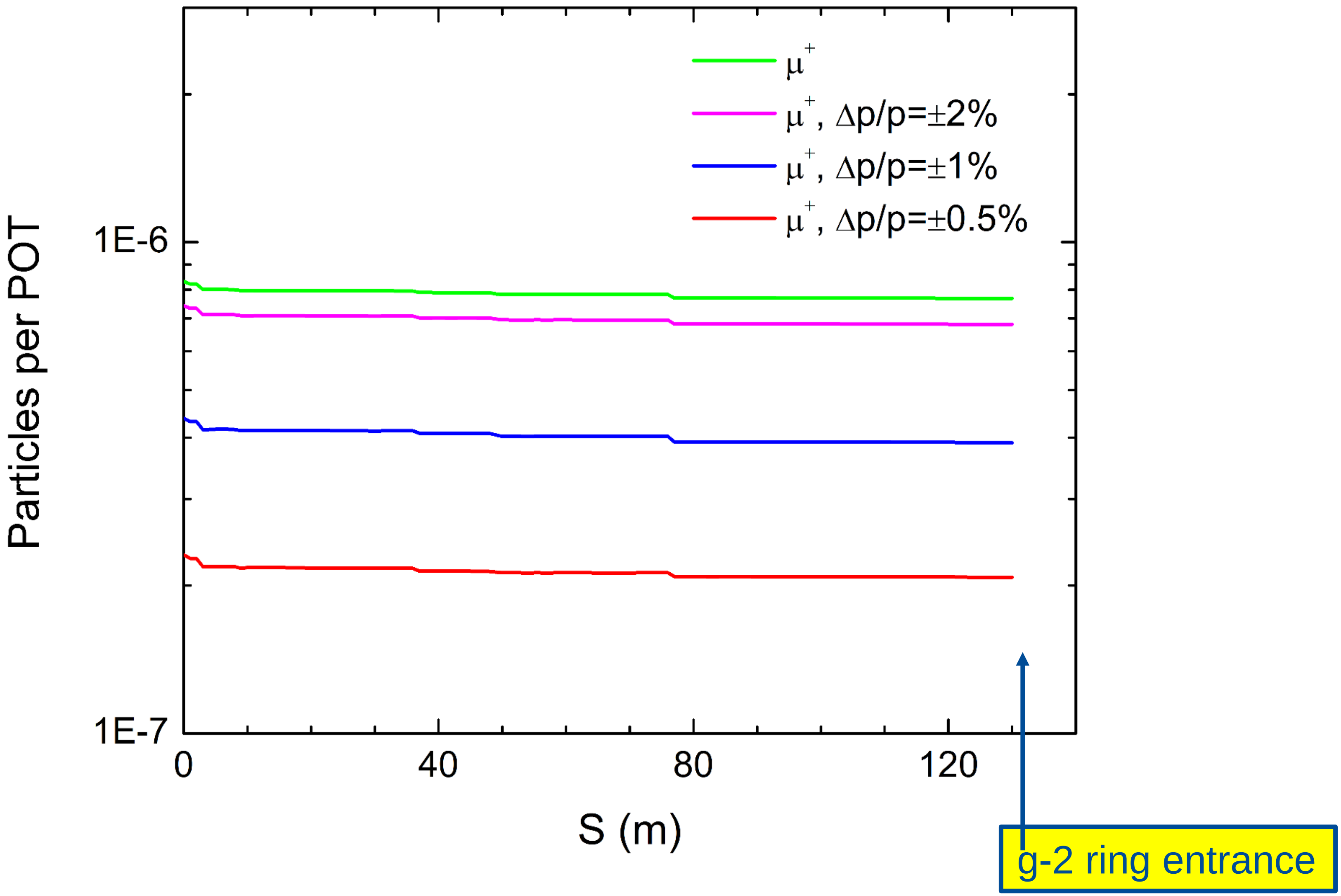
2.62x10^-6 POT

Performance within the Delivery Ring (DR)

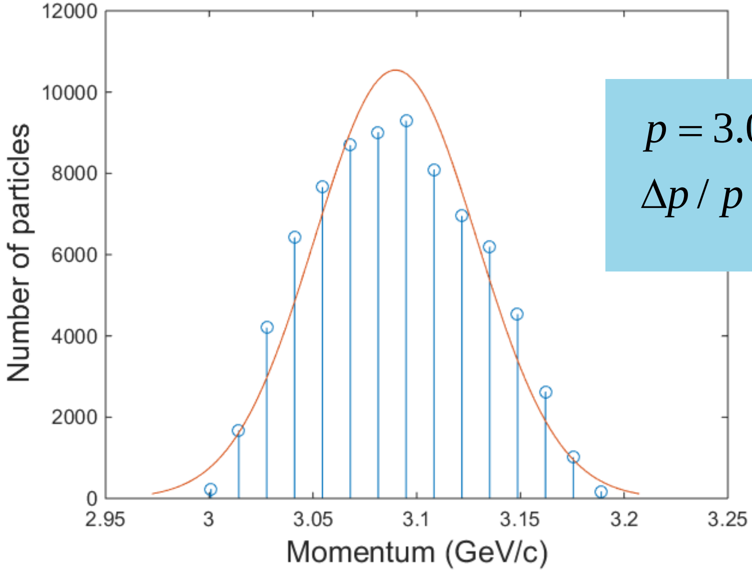


Fermilab

Performance within M4 & M5 lines



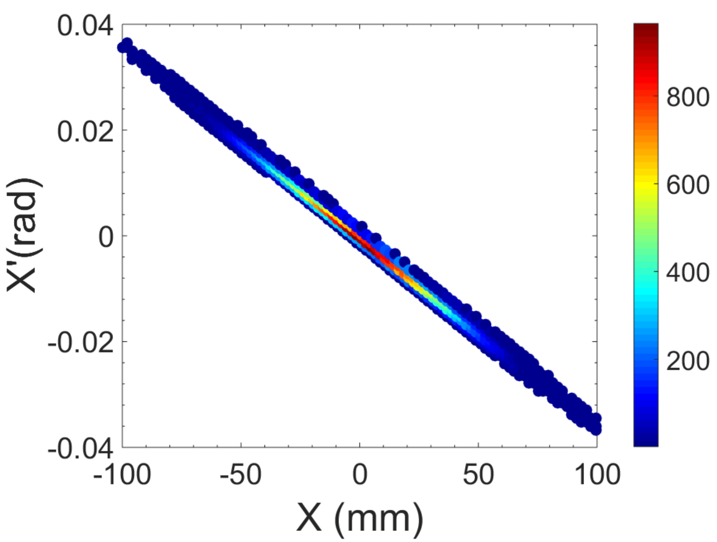
Beam at the storage ring entrance

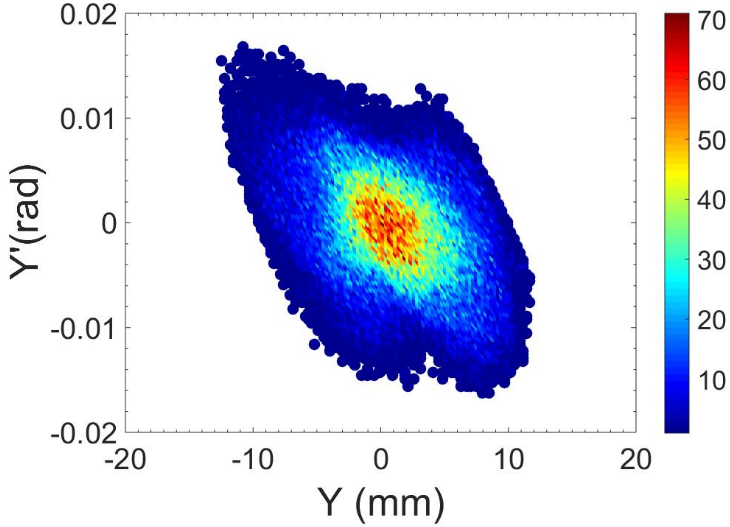


$$p = 3.090\,\mathrm{GeV}$$
$$\Delta p / p = \pm 0.012$$

New: Delivered 370,000+ particles!

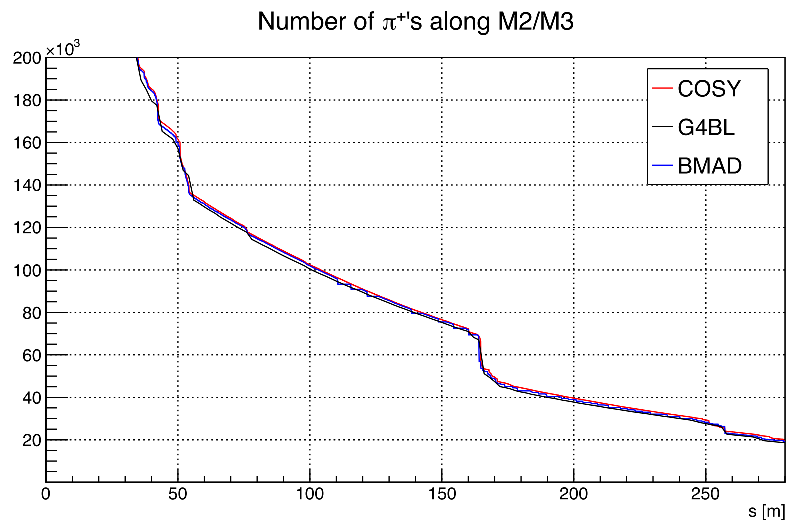
Particles	Value
Total number of muons	7.7×10^{-7} POT
Muons in $\Delta p/p = \pm1\%$	4.0×10^{-7} POT
Muons in $\Delta p/p = \pm0.5\%$	2.1×10^{-7} POT

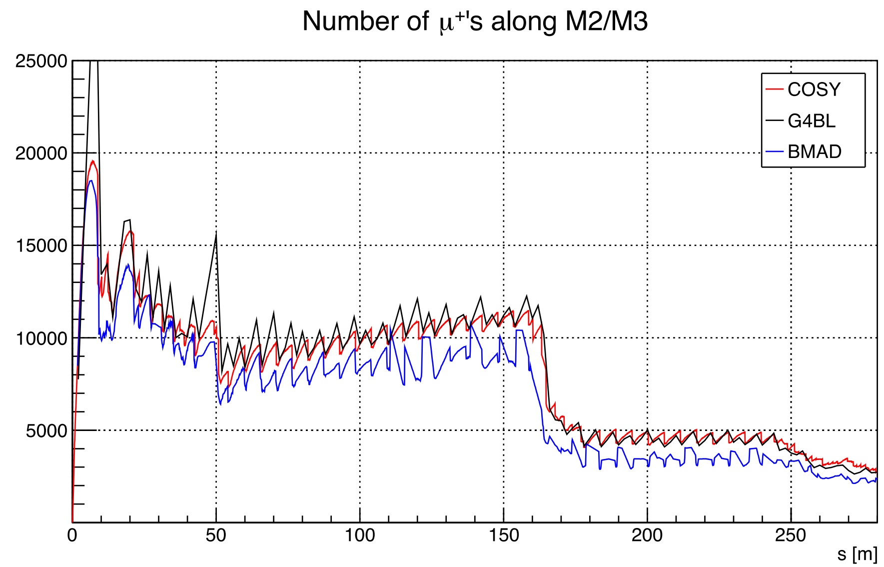




Validation

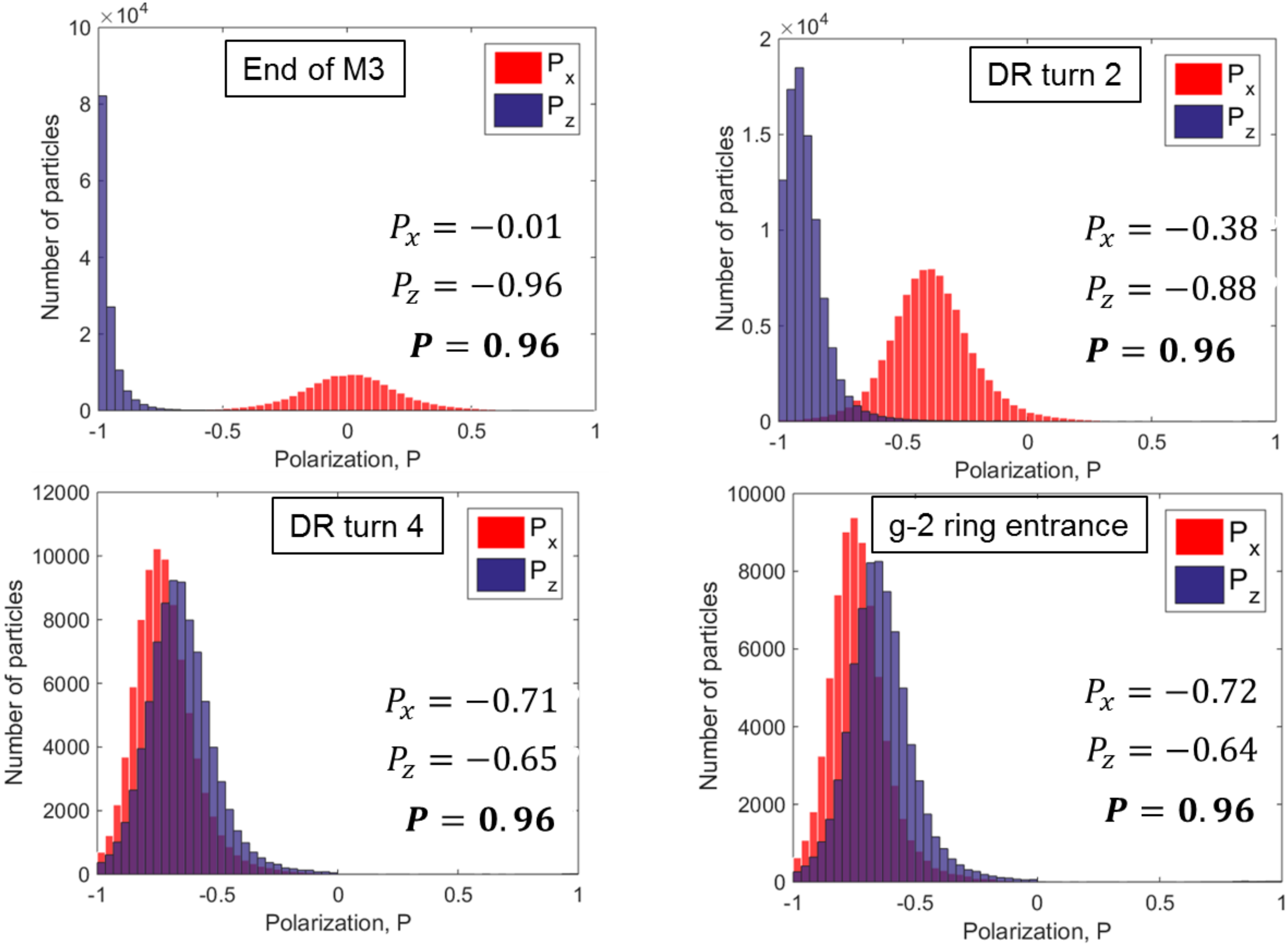
- **Compared three codes (G4Beamline, BMAD, COSY) and found good agreement!**
- **Results for the M2 & M3 lines:**



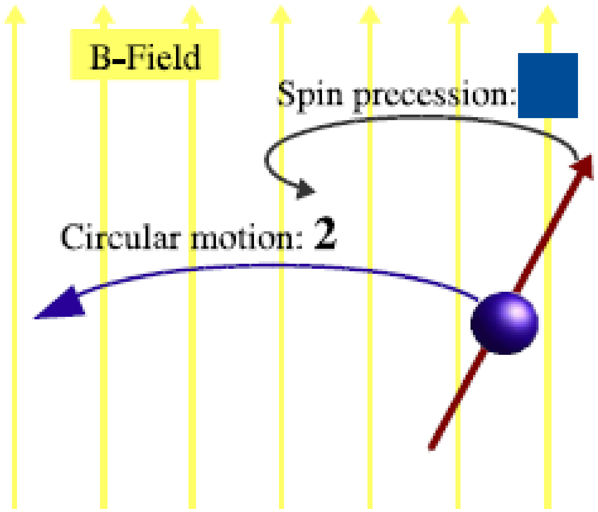


Work done by: M. Korostelev (Cockcroft, Lancaster) & D. Stratakis (FNAL) & D. Tarazona (MSU)

Spin tracking & polarization



Triggers of errors: Spin-mom. correlations

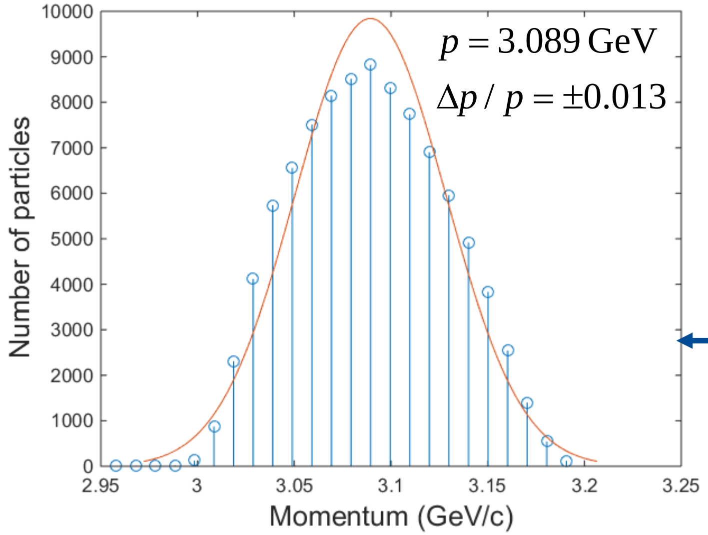


Spin precession relative to momentum:

$$\omega_a = a_\mu \frac{eB}{m_\mu c} = \gamma a_\mu \omega_c$$

Precession after N turns: $\varphi_a = 2\pi N \gamma a_\mu$

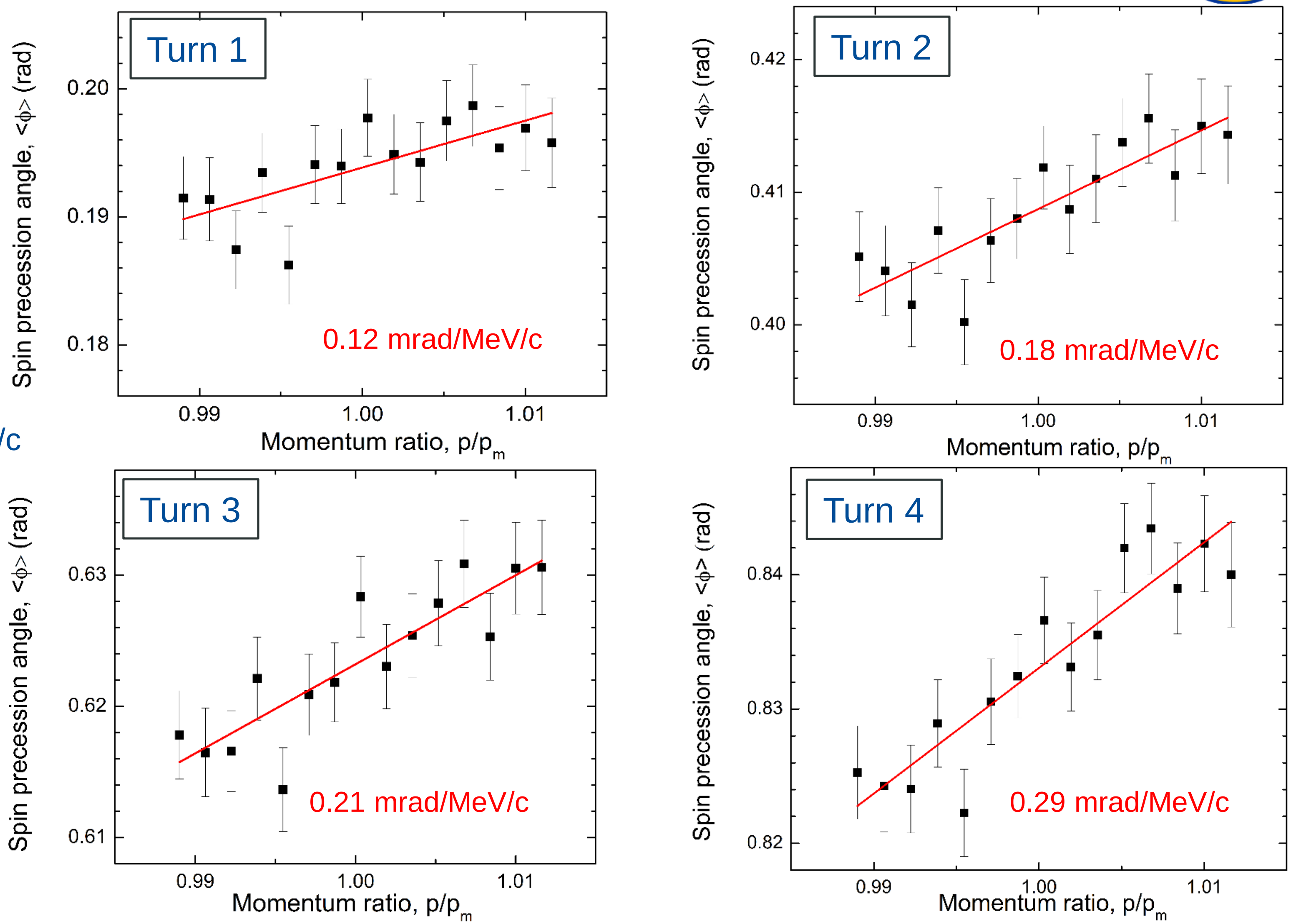
Slope of spin-momentum correlation: $\frac{d\varphi_a}{dp} = \frac{2\pi N a_\mu}{m_\mu c}$



Momentum spread after DR turn 1

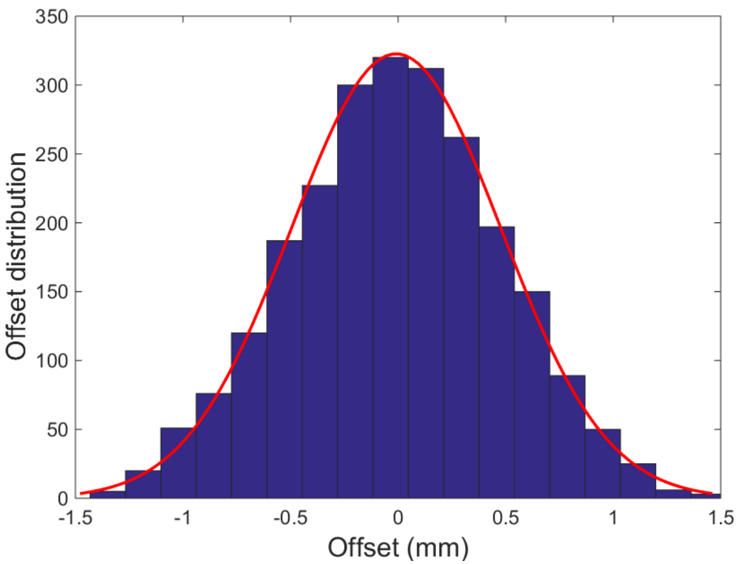
Spin-mom. correlations in the Delivery Ring

p_m : 3.094 GeV/c

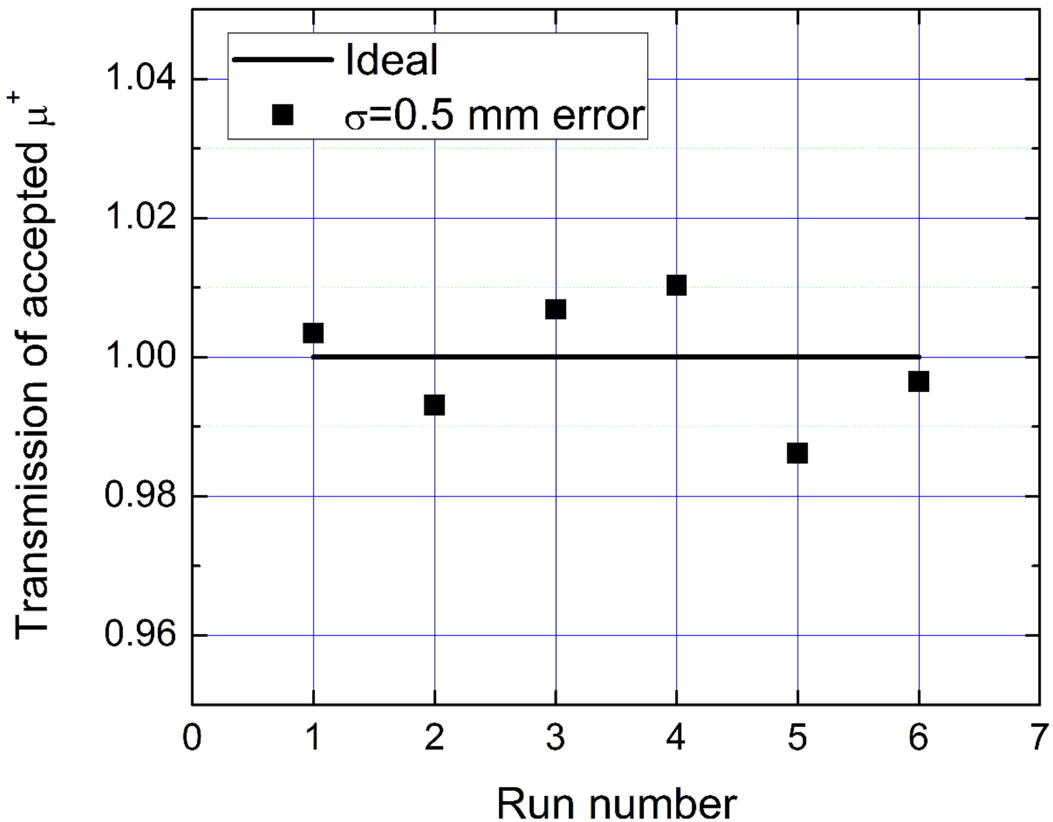


Triggers of errors: Magnet misalignments

- **Study is restricted along the M2-M3 lines only**



Error simulated as a Gaussian function (**σ=0.5 mm**) randomly distributed along magnets



Schedule (next 12 months)

- **Extend error analysis to all Muon Campus lines [Fermilab – NIU collaboration established]**
- **Include fringe fields in the analysis, particularly near injection and extraction (Fermilab – MSU collaboration)**
- **Extend the simulation into the ring (Fermilab – Cornell - UW collaboration)**
- **Theoretically and numerically, estimate the effect of the spin-momentum correlations on the measurement (Fermilab – BNL collaboration).**
- Simulate the “realistic” proton driver beam profile – **study the impact of nonlinearities.**

Conclusions (1)

- Formed a small group to study Muon Campus beam dynamics with emphasis on g-2
- Developed a end-to-end simulation model from the production target to the storage ring
- Validated it against three independent simulation codes
- Found that storage ring entrance parameters match the desired criteria:
  - The beam is >95% polarized
  - $2.1\text{x}10^{-7}$ muons per POT in $\Delta p/p = \pm 0.5\%$ and centered near magic momentum

Conclusions (2)

- Found that the Delivery Ring introduces spin momentum correlations which intensify with the number of turns. We estimate that it contributes to ~10-20 ppb error but this needs to verified with more simulations inside the storage ring
- Preliminary tolerance studies suggest that a 0.5 mm magnet displacement should not degrade the overall performance (near 1% loss)
- Delivered distributions with near 400,000 particles at the inflector. Significant improvement on the statistics of the storage ring simulations is expected.