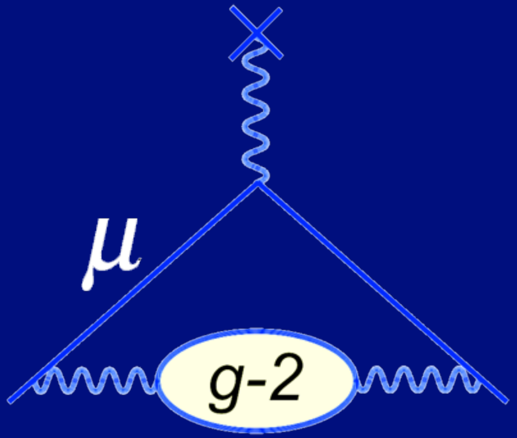
FERMILAB-CONF-24-0695-PPD-V

(Work supported by DOE.)



New Muon Campus Simulations for the Muon g-2 Experiment at Fermilab

Eremey Valetov

Michigan State University

On behalf of the Muon $g-2$ Collaboration

MICHIGAN STATE UNIVERSITY

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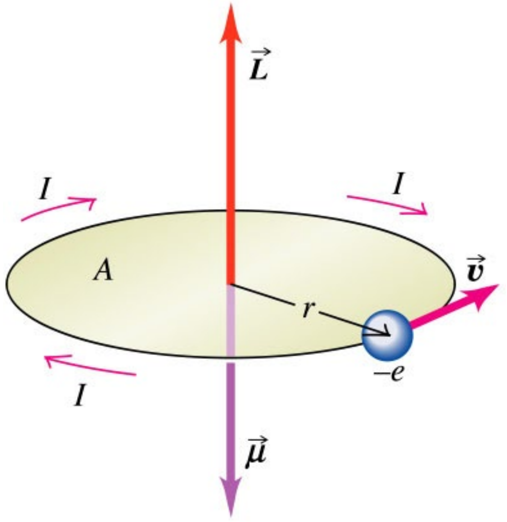
ICAP 2024, Seeheim, Germany – October 3rd, 2024

Muon Anomalous Magnetic Dipole Moment (a_μ)

$$\mu = g\frac{e}{2m}s$$

Gyromagnetic ratio equation



Classical: $g = 1$

Dirac Equation: $g = 2$

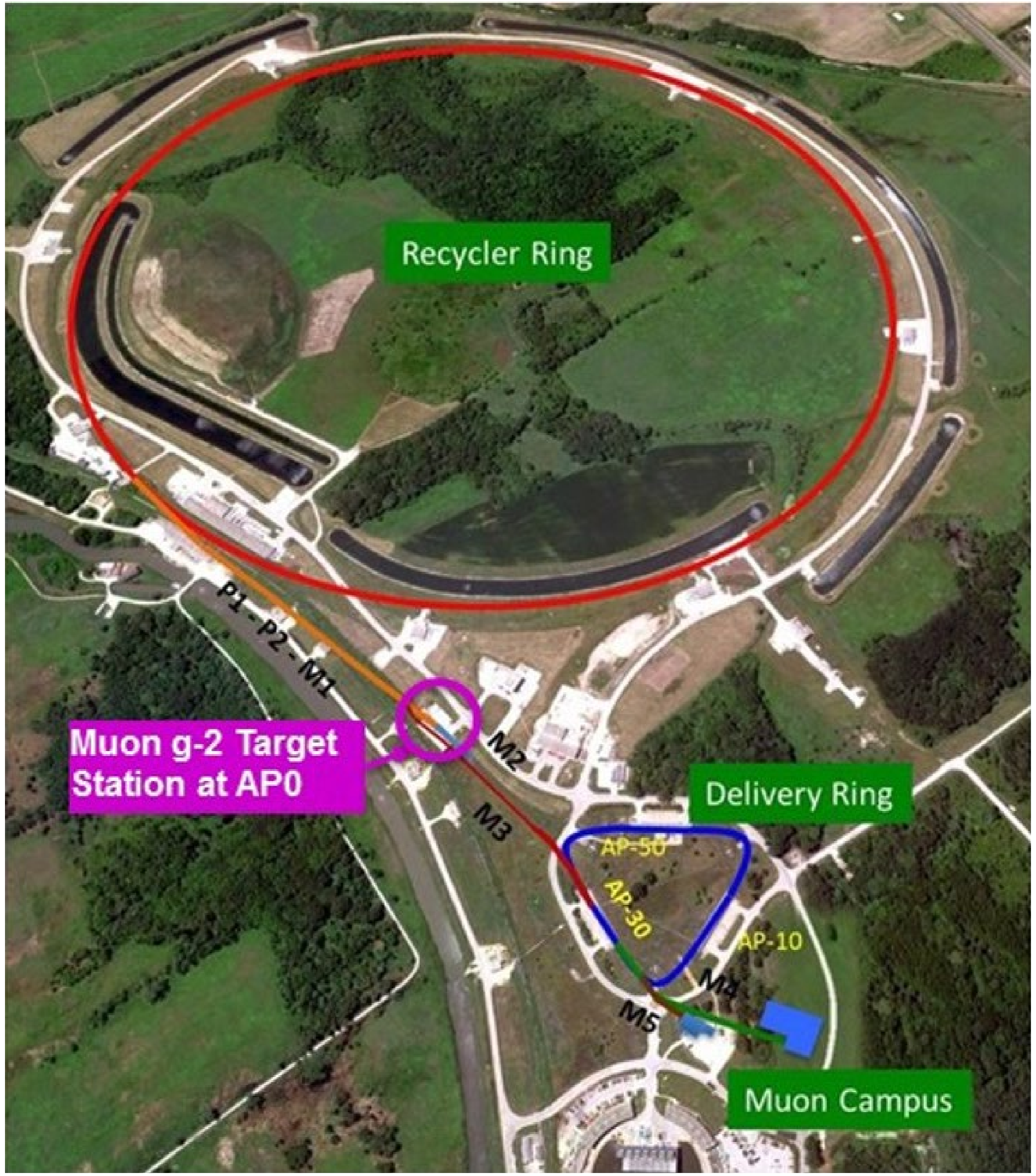
$$i\left(\partial_\mu - ieA_\mu(x)\right)\gamma^\mu\psi(x) = m\psi(x)$$

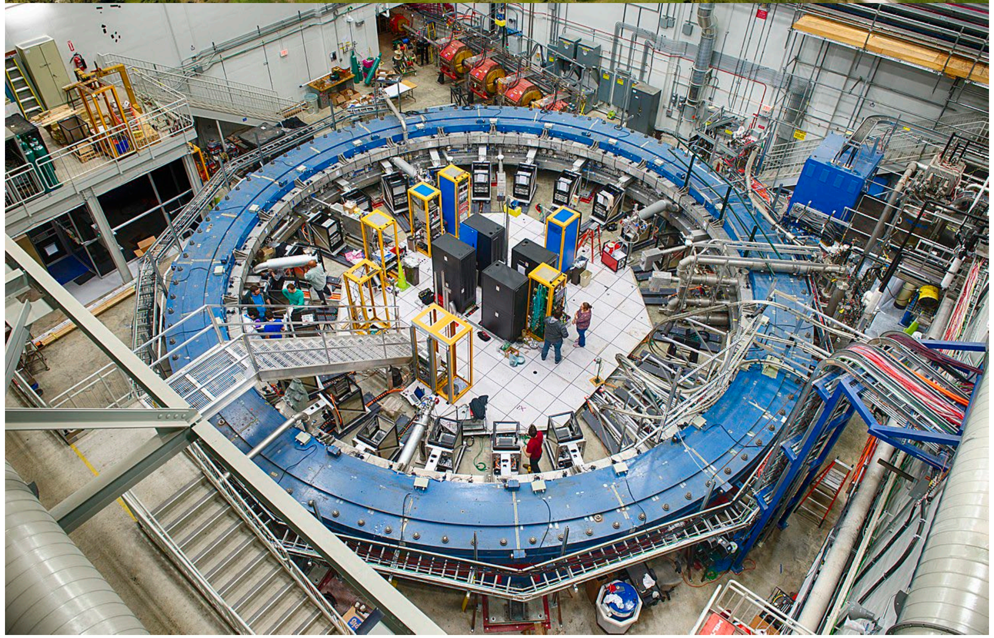
Interactions w/ quantum foam: $g > 2$

$$a_\mu = \frac{g-2}{2}$$

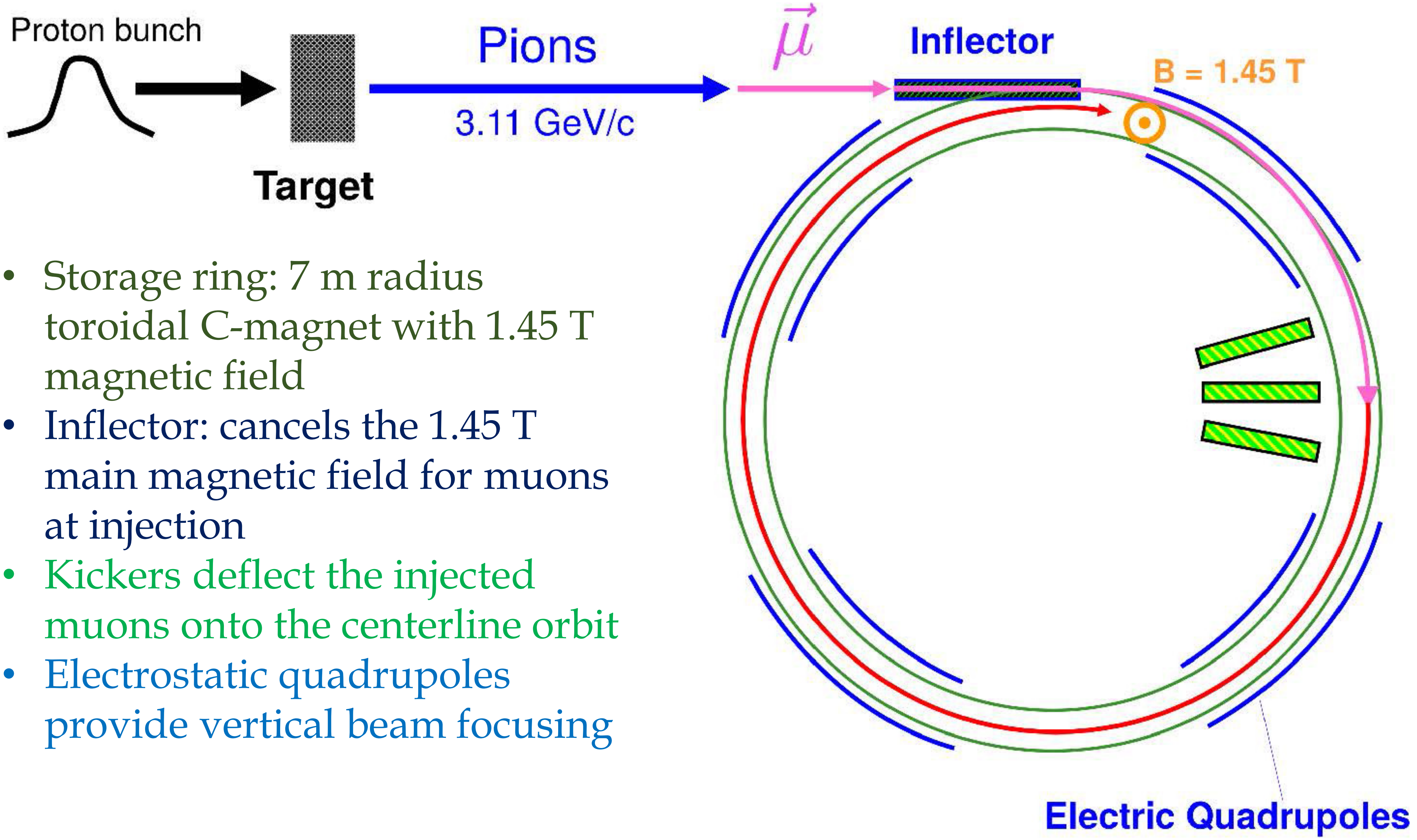
Muon anomaly

Introduction



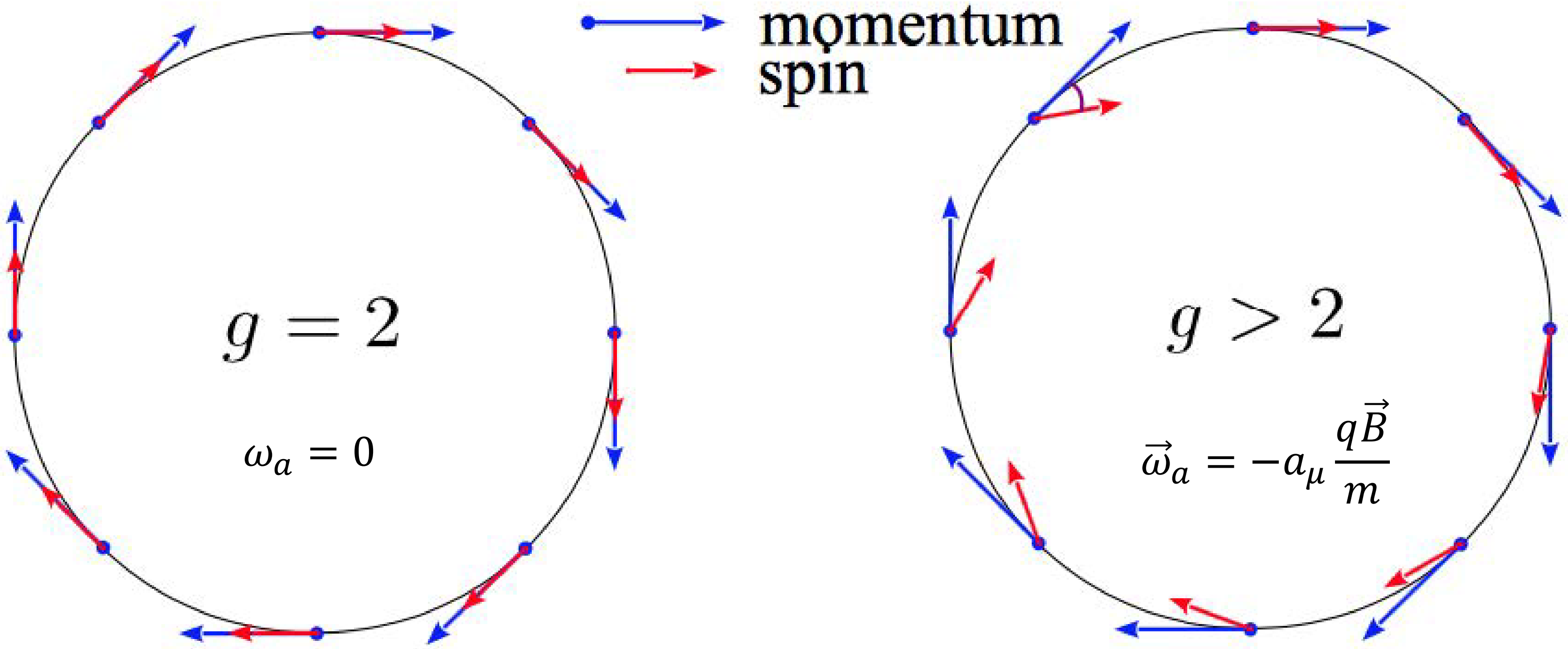


The Muon g-2 Storage Ring



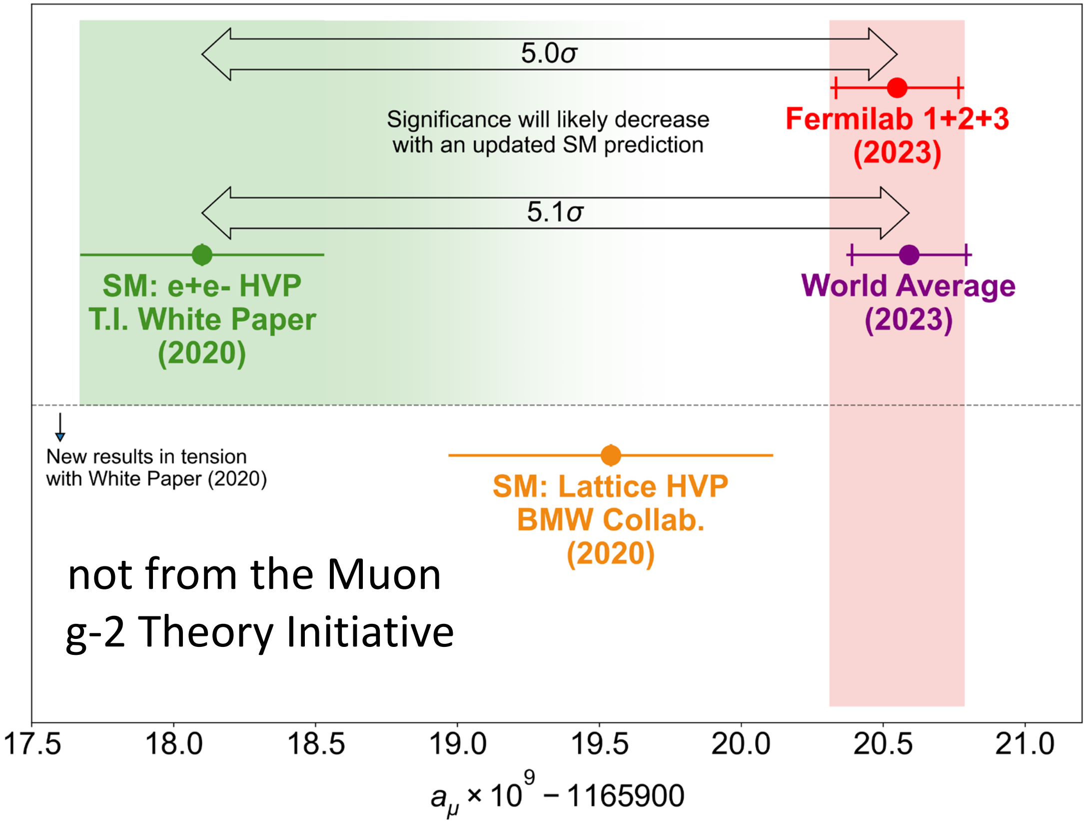
- Storage ring: 7 m radius toroidal C-magnet with 1.45 T magnetic field
- Inflector: cancels the 1.45 T main magnetic field for muons at injection
- Kickers deflect the injected muons onto the centerline orbit
- Electrostatic quadrupoles provide vertical beam focusing

a_μ Measurement Using a Storage Ring



If g=2, the angle between the magnetic moment and the momentum does not change.
If g>2, the angle between the magnetic moment and the momentum changes linearly.

Result from Runs 1-3



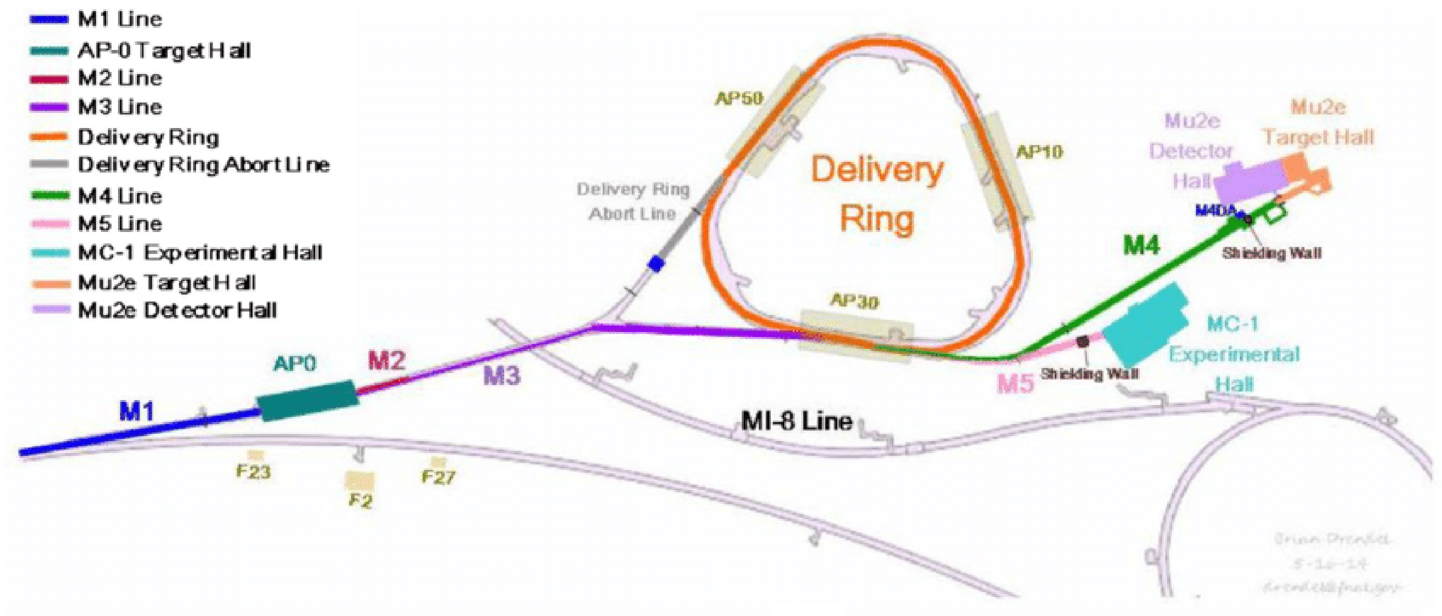
Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7°)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

a_μ (FNAL) = 0.00 116 592 055(24) [203 ppb]

a_μ (Exp) = 0.00 116 592 059(22) [190 ppb]

a_μ (Th) = 0.00 116 591 810(43) [370 ppb] **(Review by Keshavarzi, 2022)**

Beam Dynamics



(a)

(b)

Total systematic 70 ppb

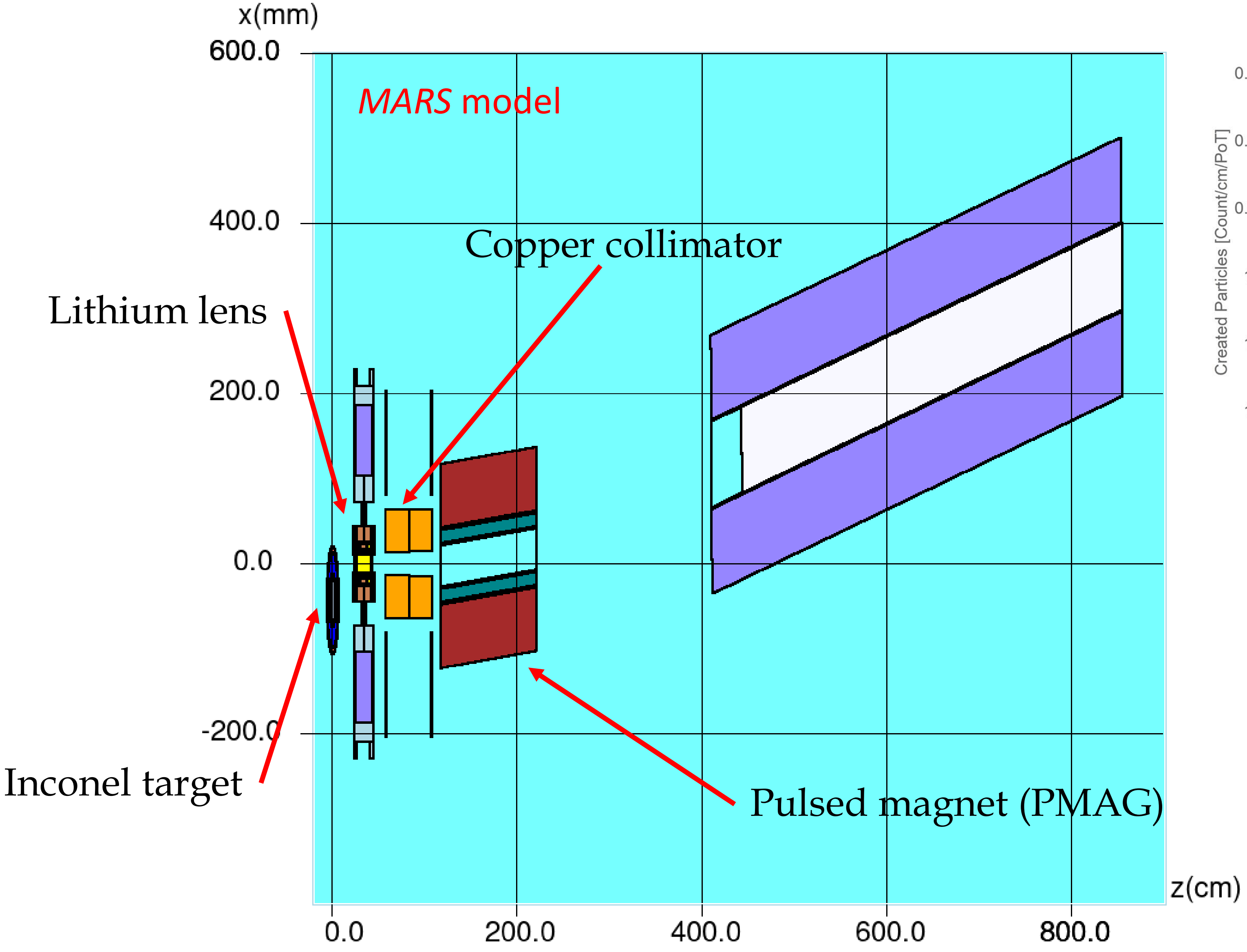
Beam dynamics: 40 ppb

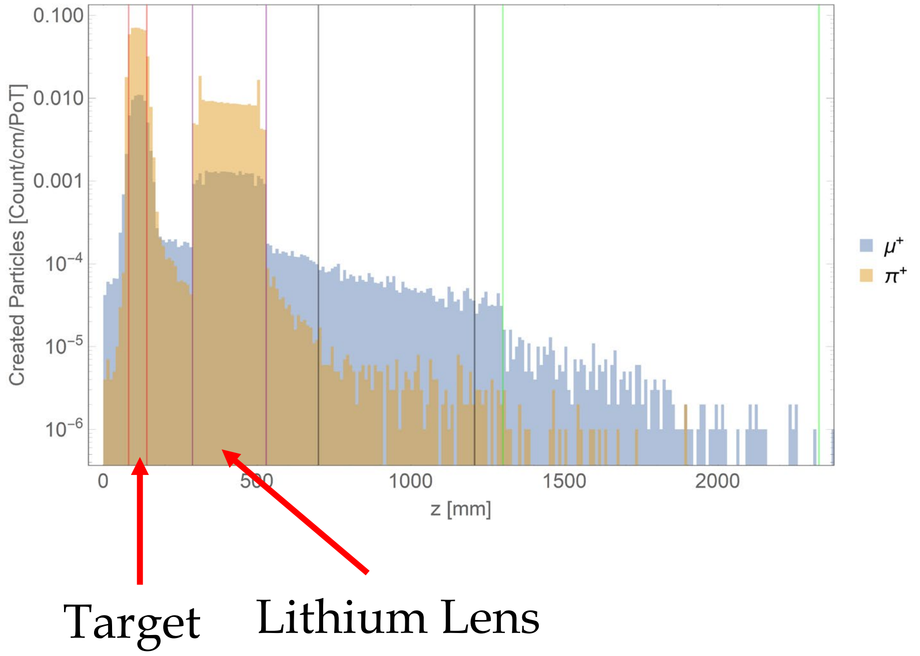
Storage ring simulations

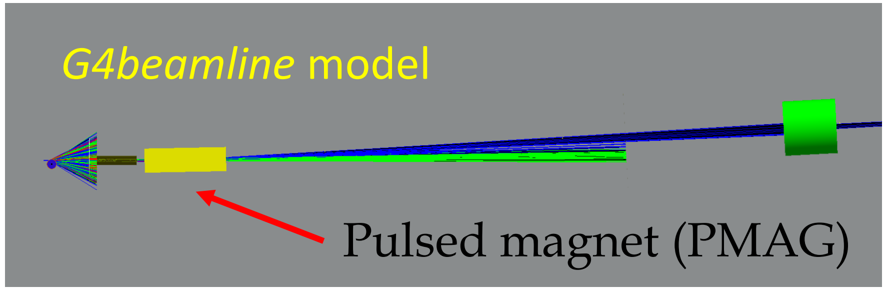
Initial muon distribution

Muon Campus simulations

Muon g-2 Target Station



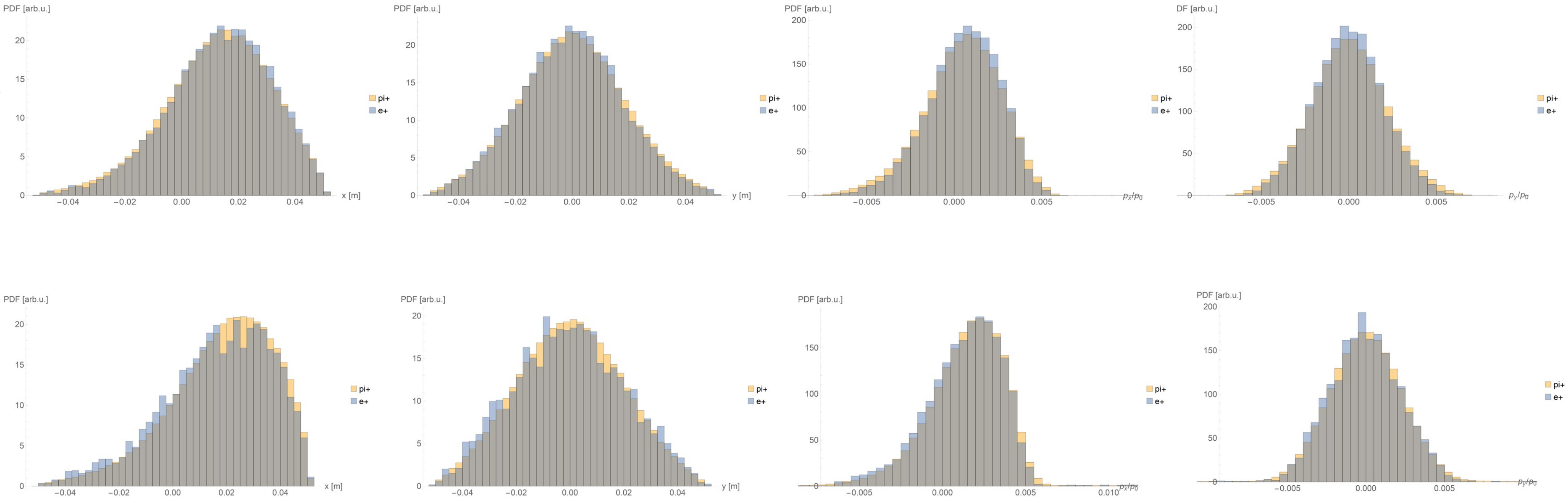




Muon g-2 Target Station

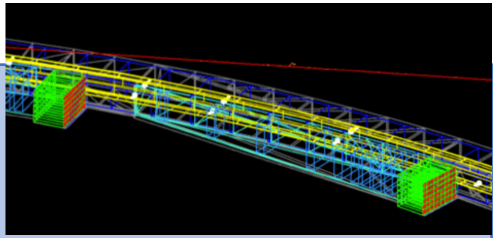
Phase space at the US end of Q801 (the first quadrupole of M2)

	x [m]	y [m]	p_x/p_0	p_y/p_0
G4beamline				
MARS15				

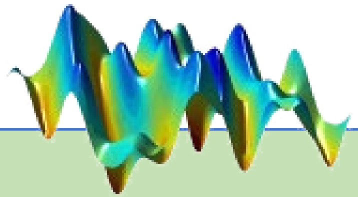


- G4beamline and MARS models of the Muon g-2 target station were carefully revised and updated
- The agreement between simulation results was improved substantially
- Notable remaining discrepancy: G4beamline-to-MARS e+ production ratio of 4.2 (accounted for)

Muon Campus and Storage Ring Simulation Codes



gm2ringsim
- Custom simulation tool
- Based on **geant4**
- **FHiCL** configuration language
- **art** event processing
- Extensive custom source code including geometry, storage ring modules, etc.



COSY INFINITY
- The most accurate storage ring model
- High-order DA transfer maps
- Accurate, Maxwellian fringe fields
- Symplectic tracking
- Electrostatic quadrupole multipole expansion up to order 24

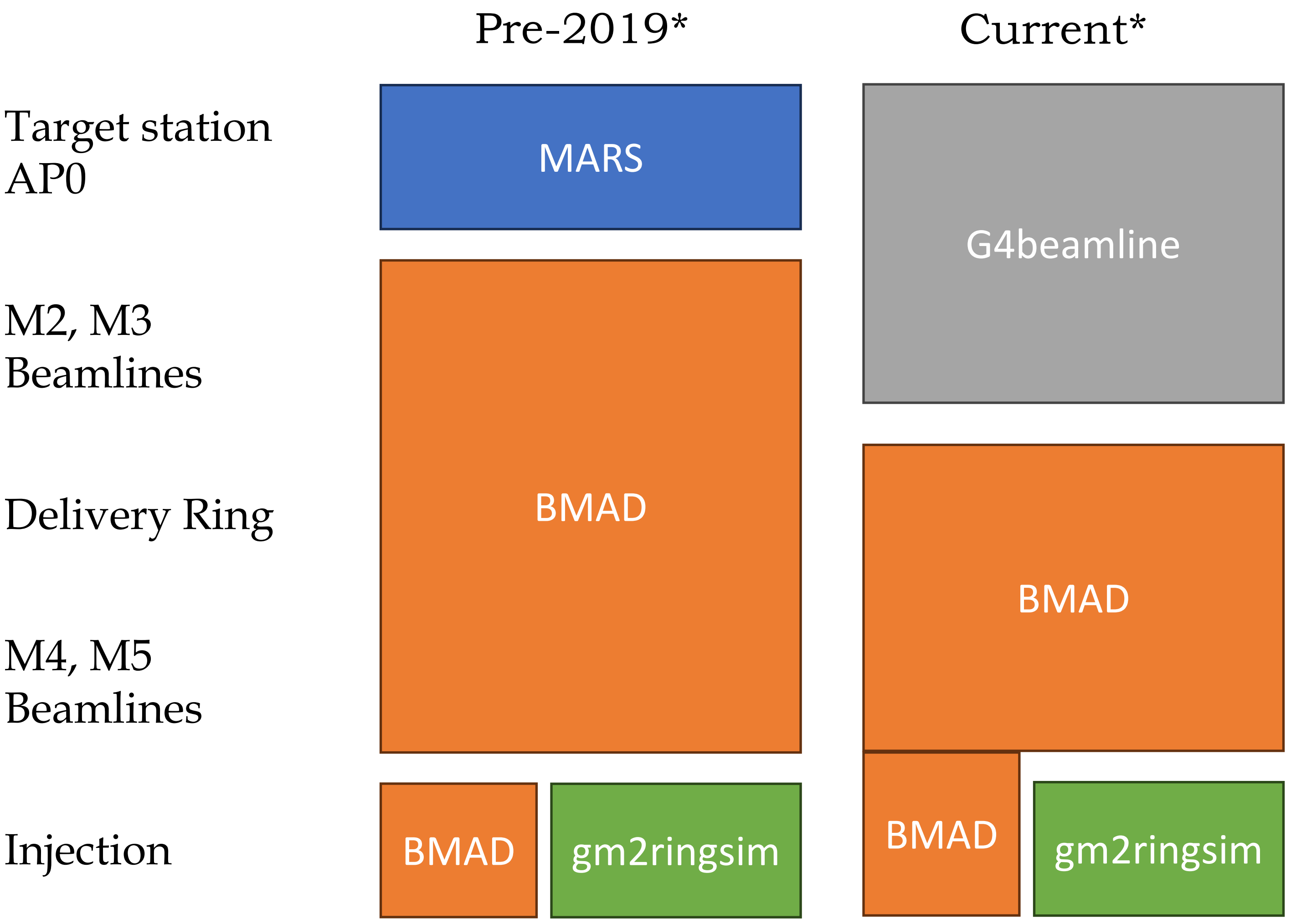
BMAD
- Similar to **MAD**, with substantial expansions
- The storage ring and the Muon Campus
- Custom pion decay code

G4beamline
- Model of the Muon Campus beamlines and target station
- Based on **geant4**
- Comprehensive physics and geometry modeling, compared to **BMAD**
- Overlapping coordinate system limitation in ring lattice modeling

MARS
- A highly accurate Monte Carlo code for modeling of radiation transport and interaction with matter
- Used for the Muon *g*-2 target station

Muon Campus Simulation Code Pipeline

Simulation pipelines



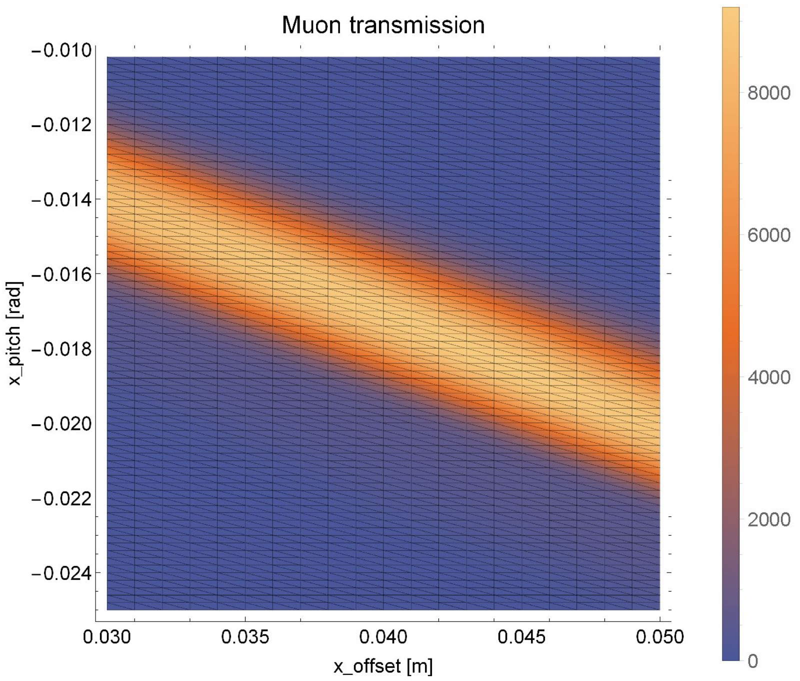
Clusters

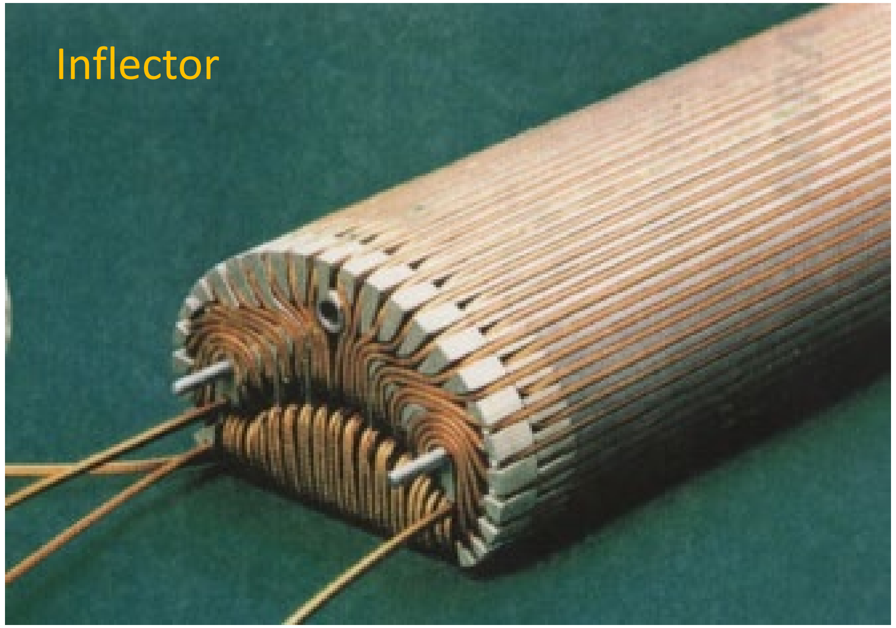
Open Science Grid

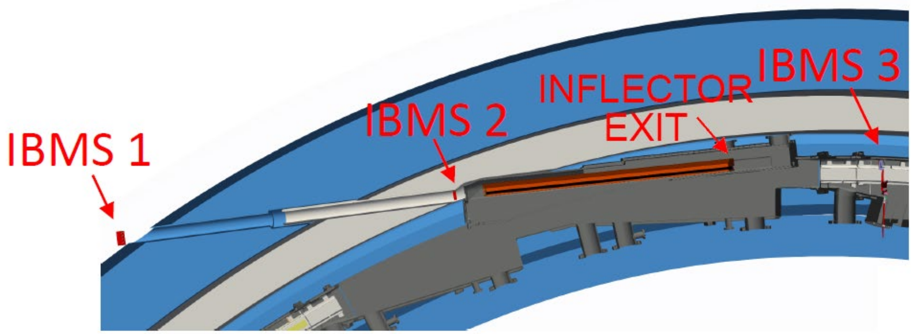
MARS: accurate particle production
G4beamline: particle physics and beamline module geometry
BMAD: beam dynamics

* This categorisation is based on high-statistics simulations. Other codes, pipelines exist.

Injection Channel



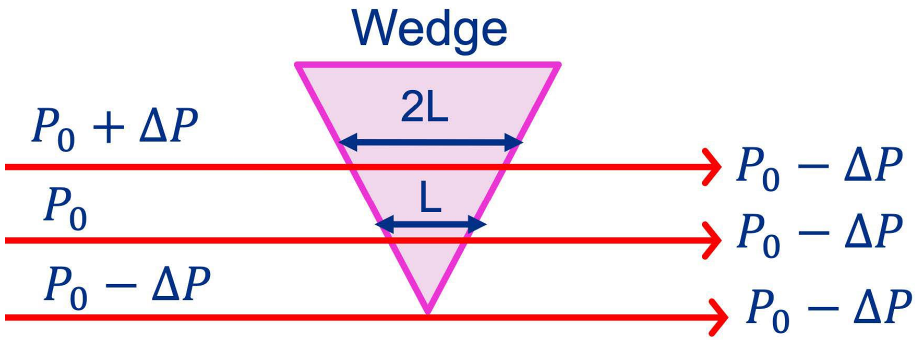


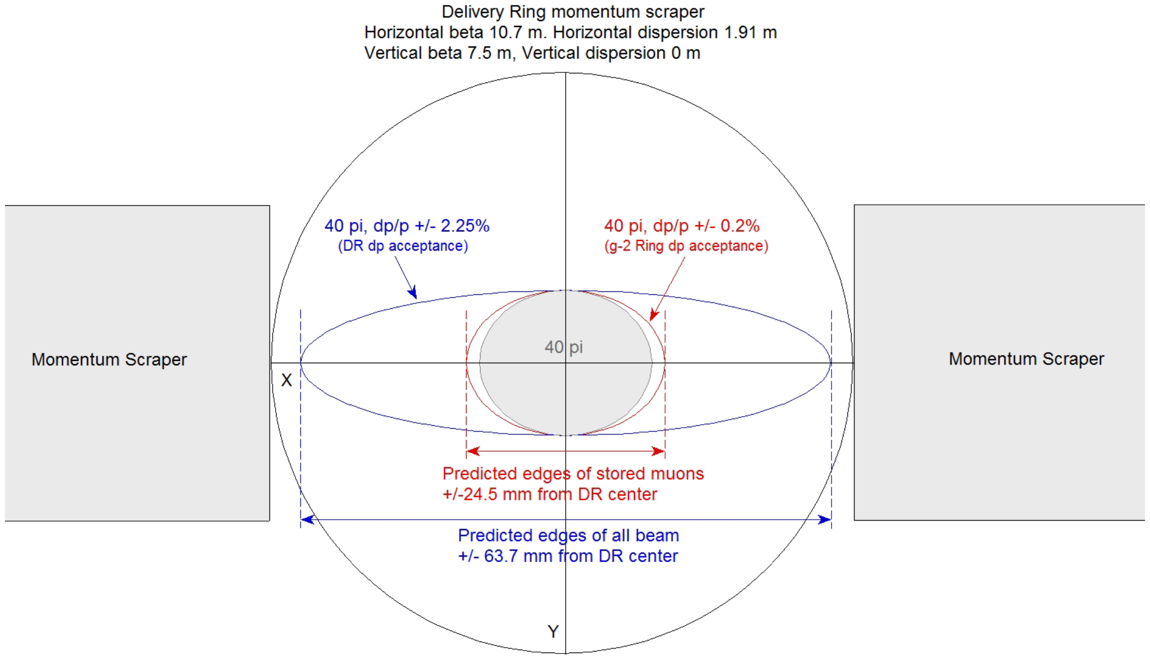


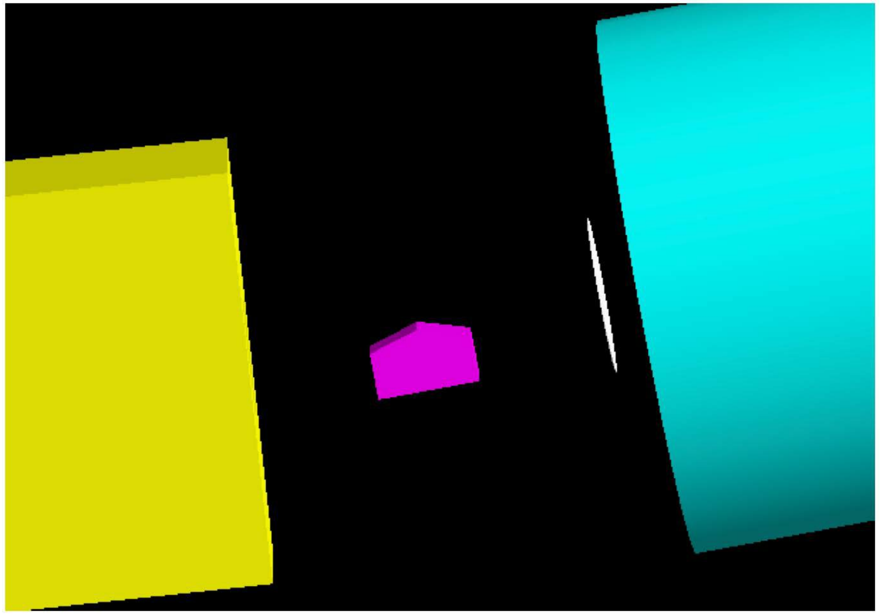
- 1.45 T bucking field to cancel main field
- Can't perturb main field by more than ~1 ppm
- Transition from large-scale (Muon Campus) to small-scale (inflector, Muon $g-2$ storage ring precision)
- Needs a careful and thoughtful approach to modelling

New Muon Campus Simulations

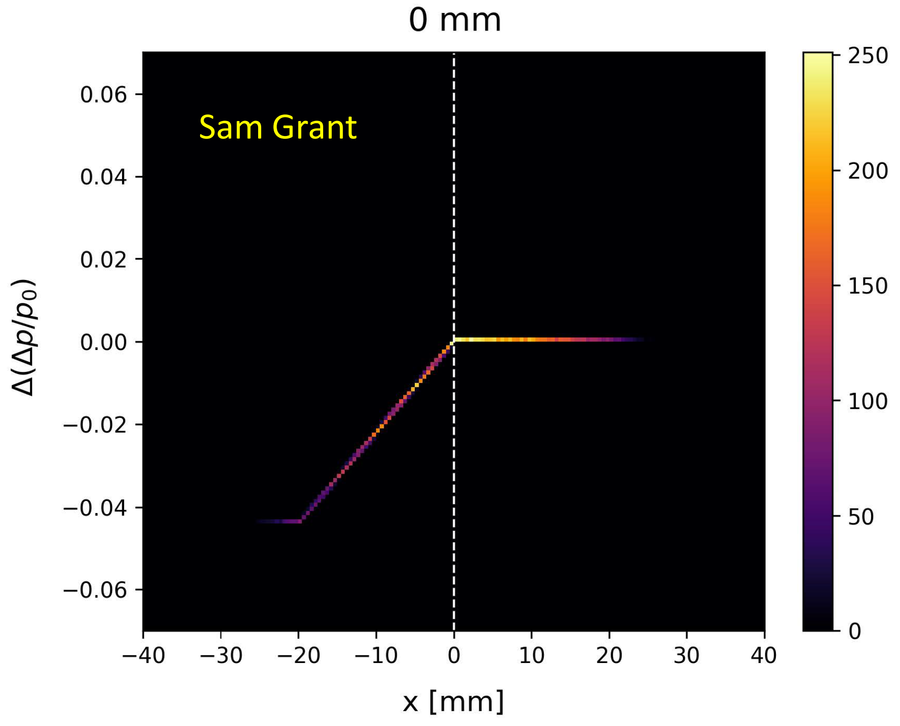
- Will be used in analyses for Runs 4-6
- Wedge in M4 for ionisation cooling
- Collimator in the Delivery Ring
- Updated quadrupole currents

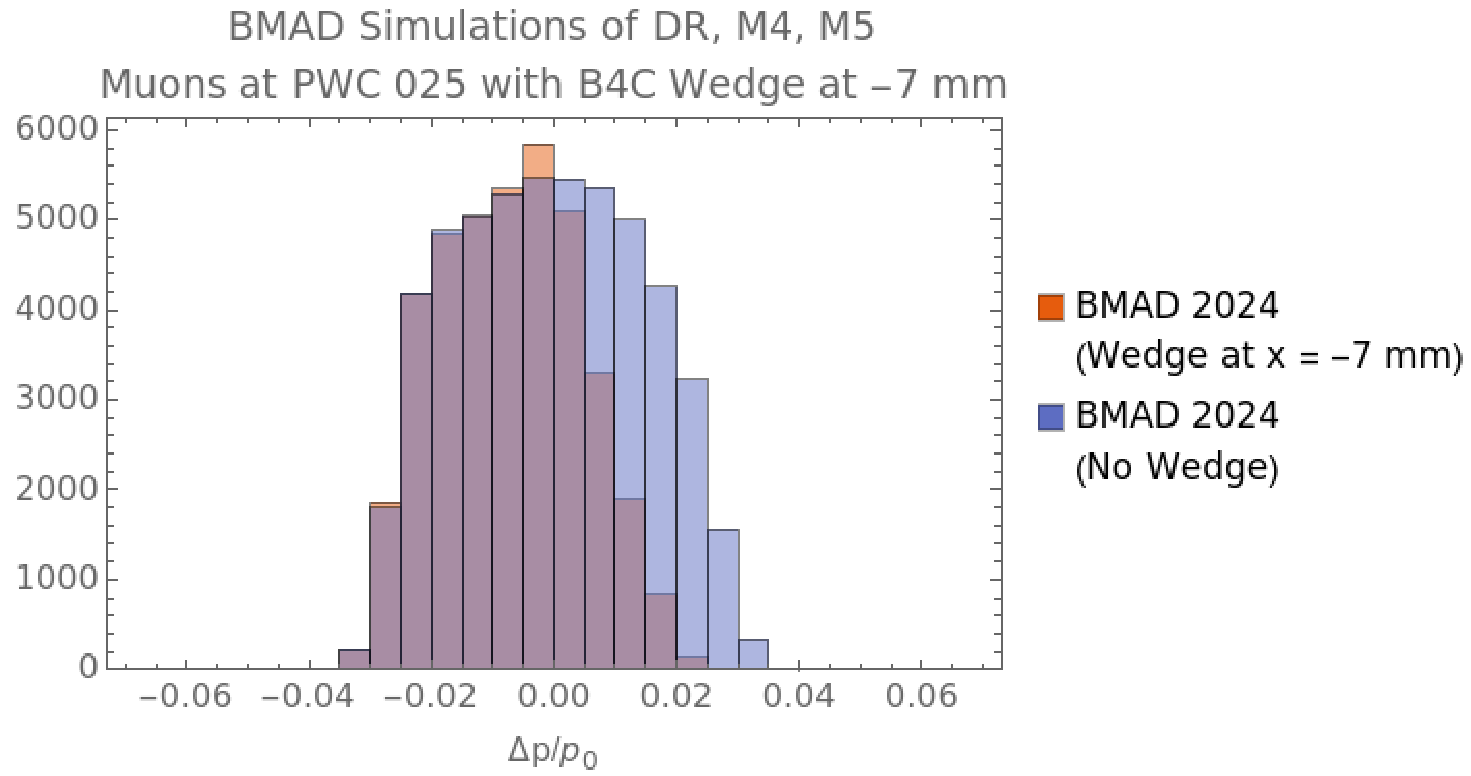






Ionisation Cooling Wedge

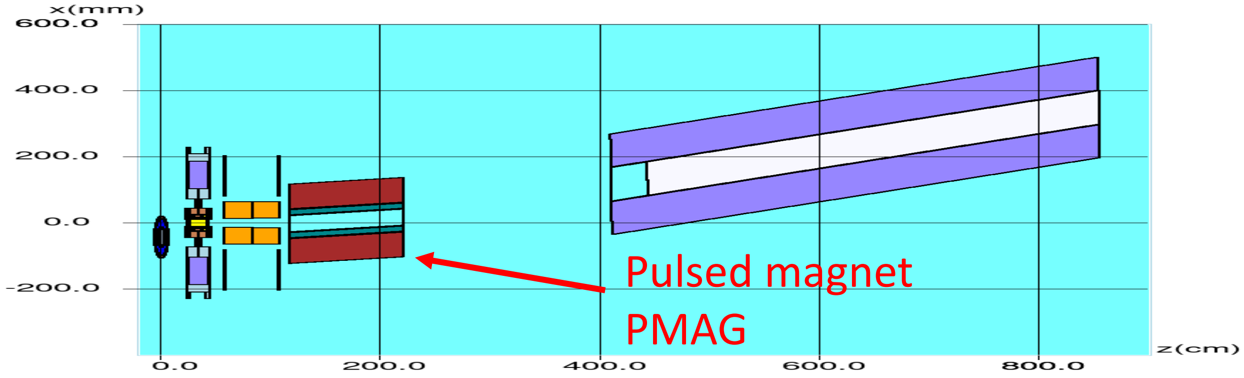




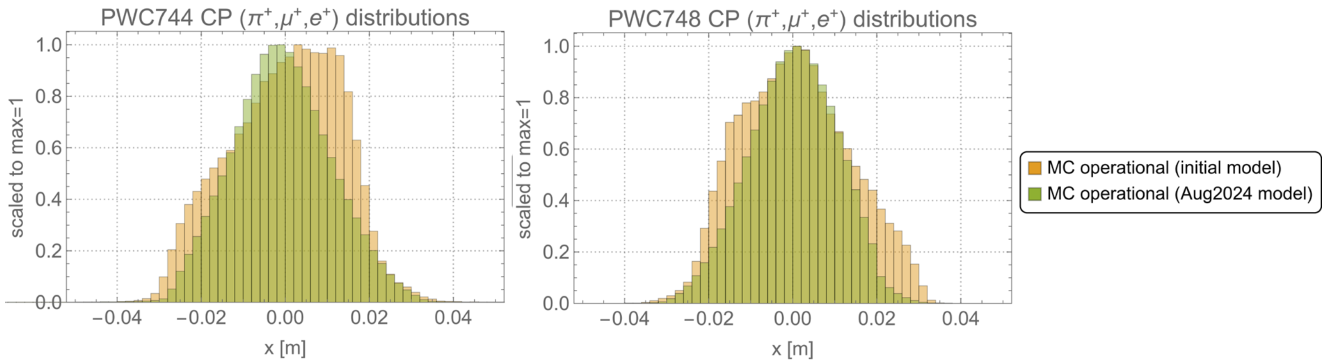
- Wedge implemented in BMAD using an extended implementation of the foil element
- *In collaboration with David Sagan (Cornell U., BMAD author) and Sam Grant (ANL)*

- Experimental increase in the muon flux: 4% [GM2-doc-24444]

Optimisation Using Glyfada

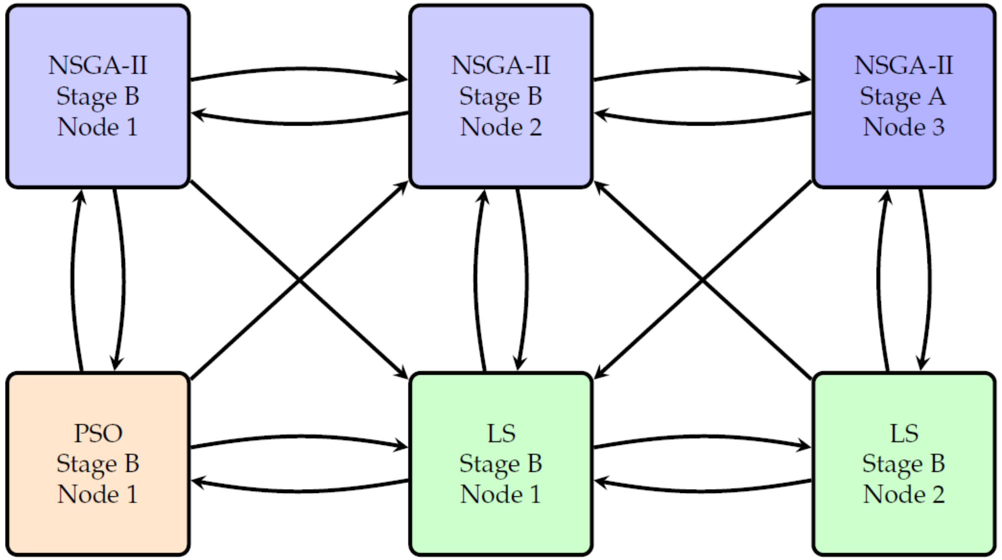


- Exact PMAG current not known from measurements
- Optimised PMAG current and some other inexact parameters using **`glyfada`**
- To match wire chamber data
- Same principle as in the control room



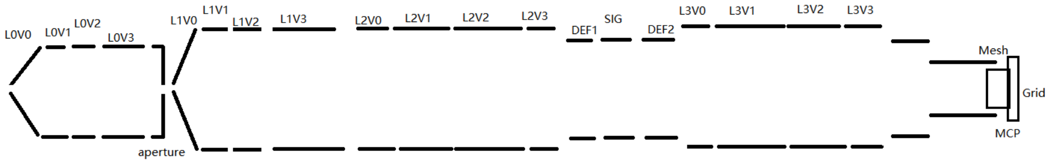
Optimiser **`glyfada`** (by E. Valetov)

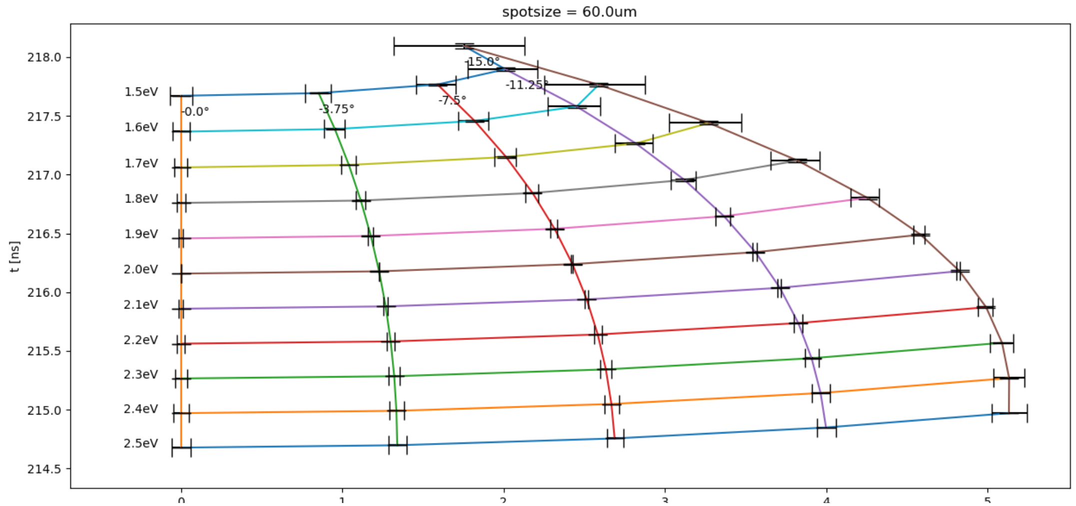
- Based on Paradis**eo** framework
- Evolutionary optimisation and local search methods
- Heterogeneous island model
- Highly effective
- Under development (α-version stage)
- Also used by author in research for PSI, LBNL, LANL, and RadiaBeam



Examples of Glyfada Applications

TOF Multimodal Electron Analyser (LBNL)

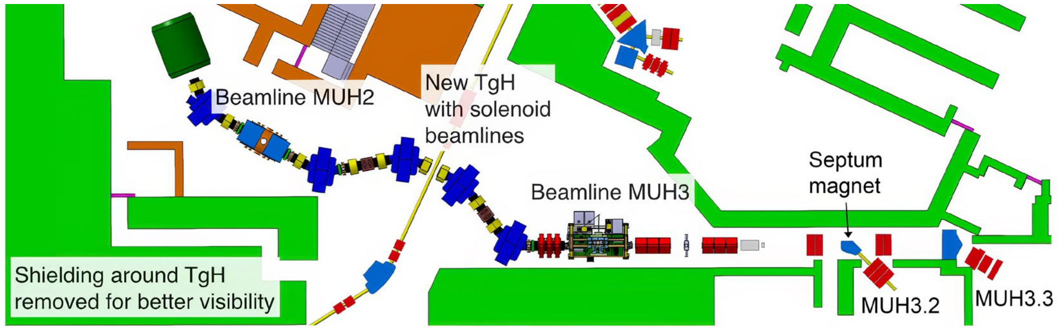


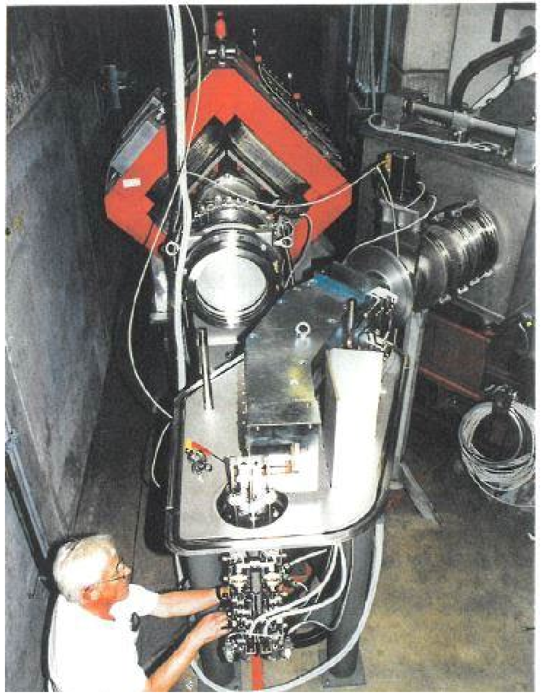


Conversion map showing aberrations at a set of energies and radii.

- Aberrations up to order 5 optimised
- Significantly better results using an early version of **`glyfada`** than using BO

High Intensity Muon Beams (PSI)





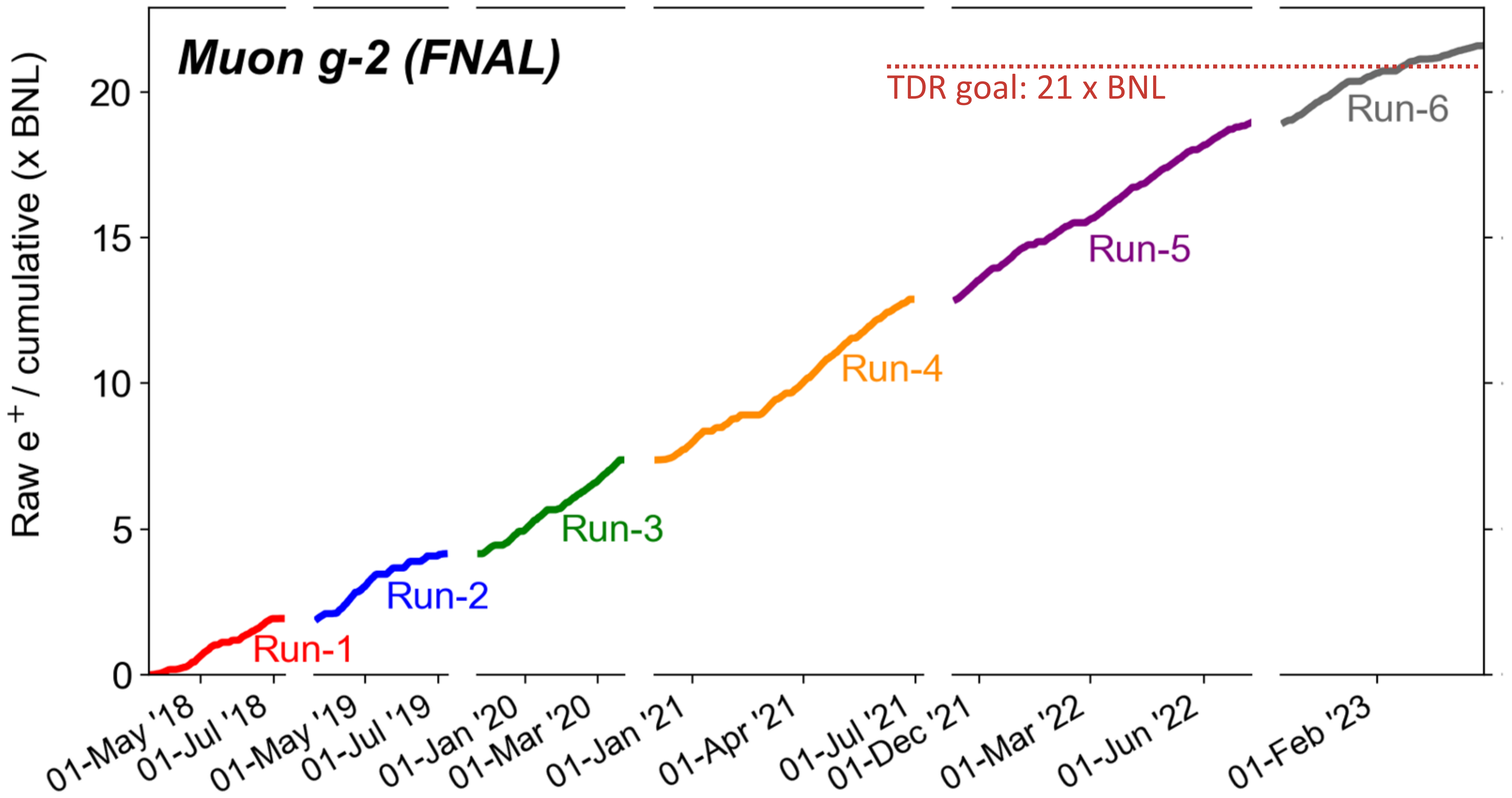
Complex final focus optimisation

- Large beam
- Two branches
- Complex septum magnet geometry
- Geometries of two collimators optimised
- **`glyfada`** optimiser: **2x** higher rate than BO (probably not typical)

New Muon Campus Simulations Status

Timeline	Steps	Facilities, methods
September 2024	G4beamline simulations of target station AP0, beamlines M2 and M3. Phase 1: 3×10^{12} protons on target	Open Science Grid
October 2024	BMAD simulations of the Delivery Ring and beamlines M4, M5: quality checks, final focus adjustements	Optimiser **`glyfada`** (Heterogeneous island method)
October 2024	BMAD simulations of the Delivery Ring and beamlines M4, M5: Phase1: 3×10^{12} protons on target	Local 32-core workstation

Data Acquisition as a Multiple of BNL Data



Conclusion

- Results based on Runs 2-3 were published in August 2023
- The experiment has completed its final Run 6 in July 2023
  - 21x more raw data than the Muon g-2 Experiment at BNL
  - Improving systematics:
    - Magnet temperature control
    - Magnetic field noise control
    - Analysis improvements (pileup reconstruction)
  - Achieved the TDR goal of 70 ppb systematic error
- Results from runs 4-6 planned to be released in 2025
  - New Muon Campus simulations for the analyses in progress
- New theory results expected in 2025

Conclusion

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

182 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

Collaboration meeting at University of Liverpool, July 2023
Photo credit: McCoy Wynne

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