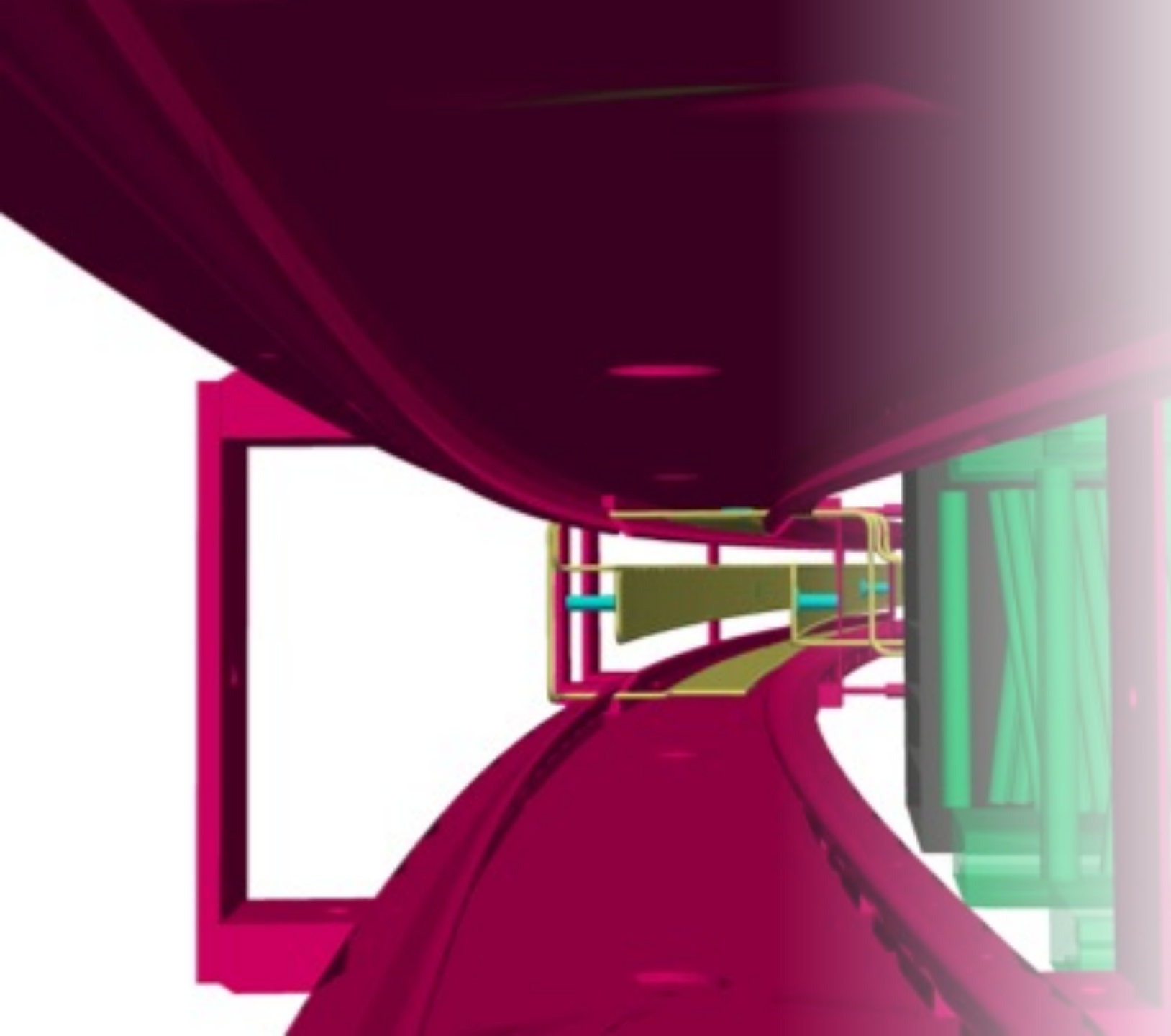


Simulations for the Muon g –2 Experiment at Fermilab

Anna Driutti

University and INFN Pisa

Simulation Contributions to a_μ :

$$a_\mu = \underbrace{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}_{\text{ratio of frequencies } (R_\mu) \text{ measured by us}} \underbrace{\frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}_{\text{fundamental factors (combined uncertainty 25 ppb)}}$$

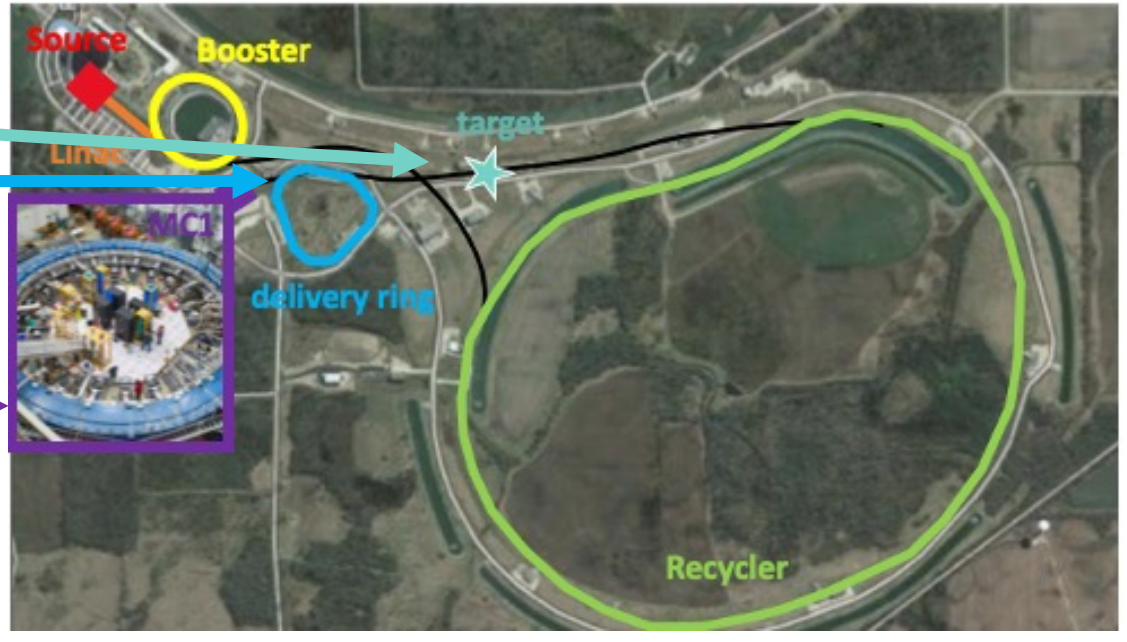
$$R_\mu = \left(\frac{\overbrace{f_{clock} \cdot \omega_a^{meas}}^{\omega_a} \cdot (1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{beam dynamics corrections}})}{\underbrace{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi)}_{\tilde{\omega}'_p(T_r)} \cdot \underbrace{(1 + B_k + B_q)}_{\text{field corrections}}} \right)$$

$M(x,y,\phi)$: Muon Distribution

- for **beam dynamics corrections**
- to propagate the **muon distribution** around the ring

- Simulations include Muon Campus and Muon g –2 storage ring:

- **Target Station:** p-bunches are collided with target to produce π^+ which are collected if their momentum is 3.1 GeV/c (±10%)
- **Beam Transport and Delivery Ring:** magnetic lenses select $\pi^+ \rightarrow \mu^+\nu_\mu$ then μ^+ are separated from p and π^+ in circular ring
- The polarized μ^+ are ready to be injected into the **storage ring**



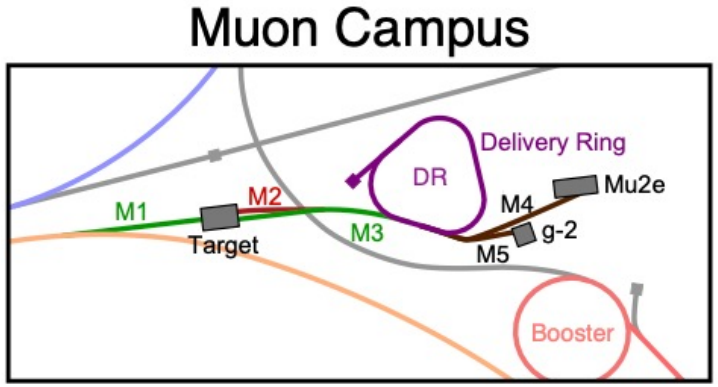
Simulations Overview

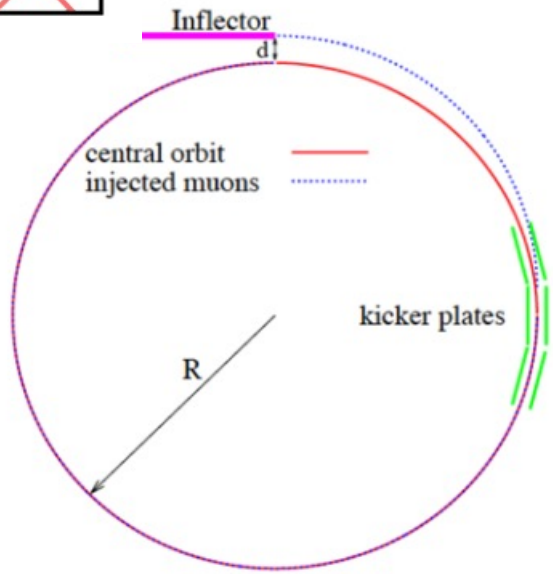
- Main simulation tools:
  - **MARS**
  - **G4BEAMLINE**
  - **BMAD**
  - **COSY**
  - **GM2RingSim**

Muon Campus Simulation

Input for:

Storage Ring Simulation





- simulations are cross-checked against benchmarks and against each other
- I'll briefly describe all the simulations but in this talk focus on GM2RingSim since it is the tool we contribute the most.

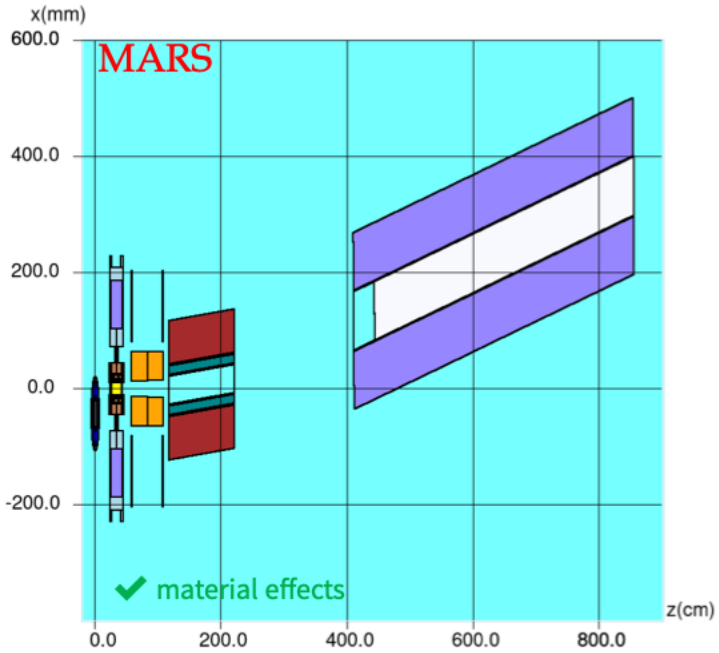
Simulations Overview

- Main simulation tools:

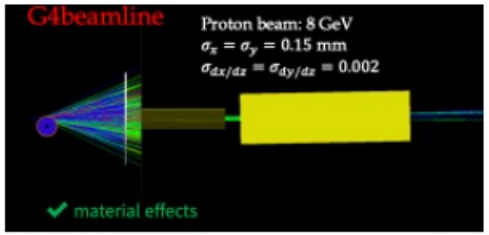
  - **MARS**
  - **G4BEAMLINE**

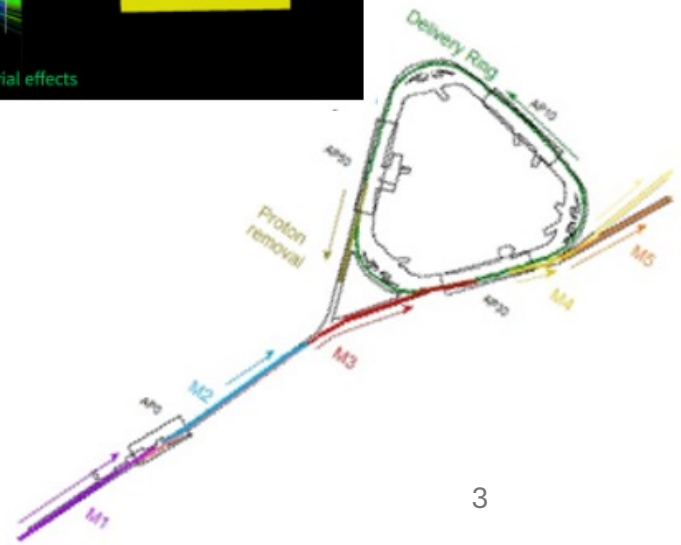
Muon Campus Simulation

➢ **MARS** simulates:
- interaction of proton beam with the target
- distribution of downstream secondary particle



➢ **G4BeamLine** is based on GEANT4, optimized for beamlines simulations and includes:
- particle interactions $e.g.$., pion-muon decay
- muon spin precession
- interactions with materials
- also used to simulate proton-target collisions





Simulations Overview

- Main simulation tools:

  - **MARS**
  - **G4BEAMLINE**

  Muon Campus Simulation

  - **BMAD**

  Storage Ring Simulation

➢ **BMAD**:

- used to simulate particles from Muon Campus beamlines to ring
- models injection into ring storage ring
- tracks particle momentum and spin interactions with fields but no interactions with materials

Simulations Overview

- Main simulation tools:

  - MARS
  - G4BEAMLINE

  - BMAD

  - COSY
  - GM2RingSim

Muon Campus Simulation

Input for:

Storage Ring Simulation

➢ **COSY**: dedicated package in COSY INFINITY
- tracks orbit-spin particle coordinates via transfer maps
- does not include injection into storage ring
- initial beam: from Muon Campus simulations or tracker data

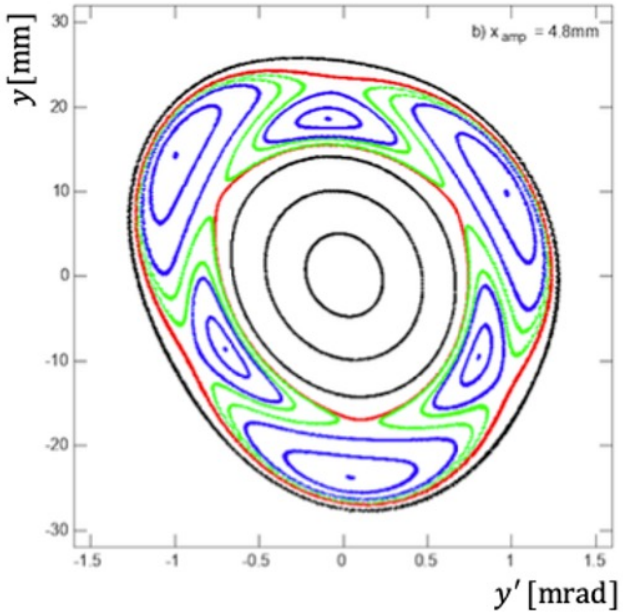
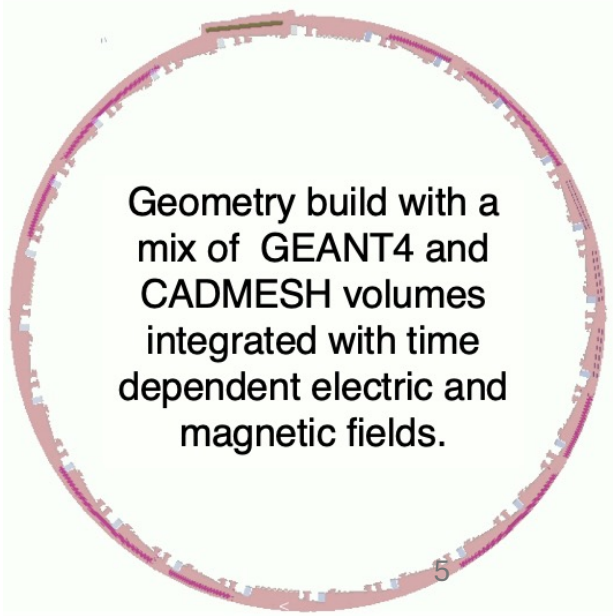


Figure 3.44: Stroboscopic tracking in the vertical phase space illustrating orbit behavior with two period-3 fixed point structures present [101], for ESQ voltage at 18.3 kV. Trajectories in blue and green colors are examples of muons (within the ring admittance and momentum acceptance) with highly modulated vertical amplitudes. Picture by courtesy of Adrian Weisskopf.

➢ **GM2RingSim**: based on GEANT4
- implemented within ART framework
- simulates injection into storage ring and interactions with materials and fields
- includes several particle guns
- initial beam from Muon Campus simulations



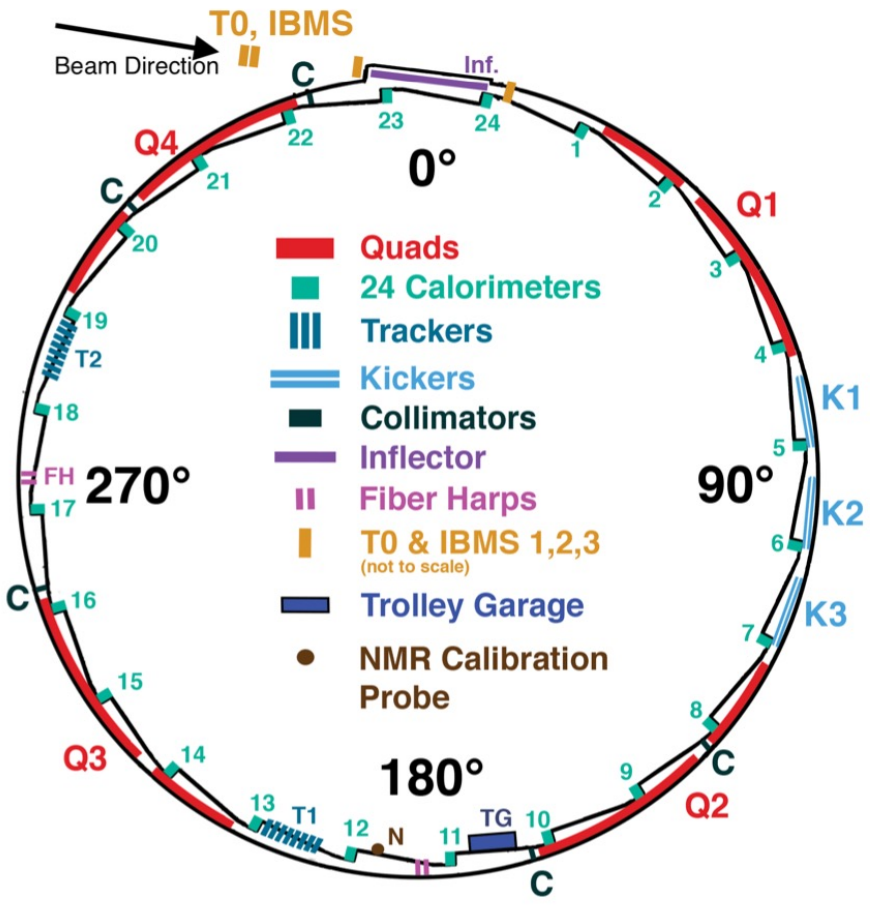
GM2RingSim Simulation

ACTIVE DETECTORS

- Calorimeters
- Fiberharps
- IBMS
- Strawtrackers
- *Ghost planes in parallel world*

ELECTROMAGNETIC FIELDS

- Backleg hole
- Inflector
- Dipole + higher multipole + fringe + radial field in the storage region
- Quad fields (no RF yet)
- Kicker

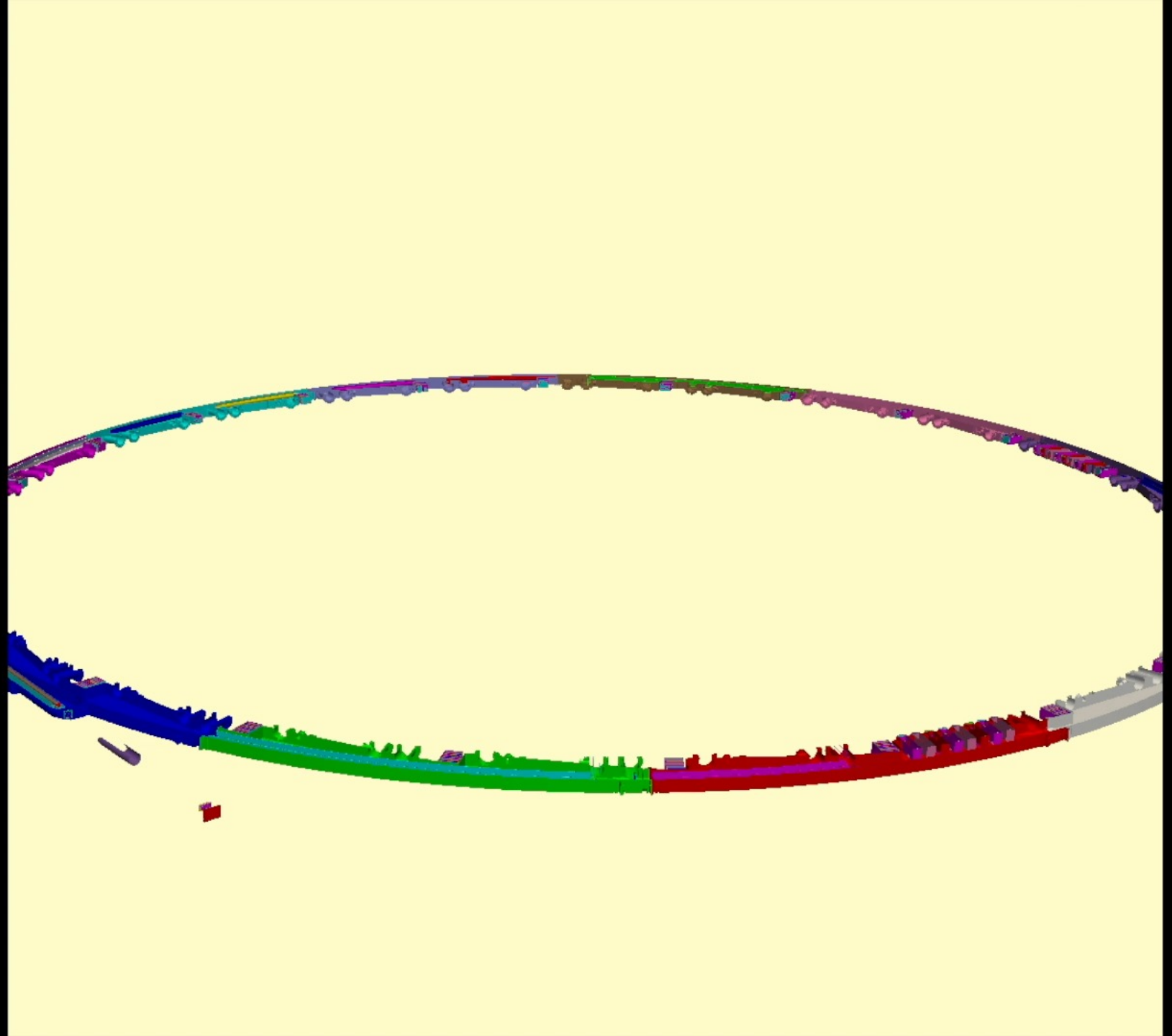


PASSIVE COMPONENTS

- Collimators
- Inflector magnet
- Kicker plates
- Poletip and cryostat
- Quad plates
- Trolley rails
- Vacuum Chambers

GUNS

- Gas gun
- Beam Gun
- Stored Muon Gun
- Lost Muons Gun



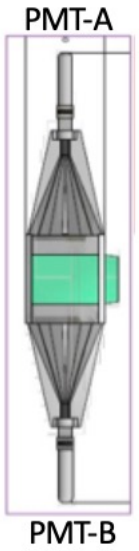
GM2RingSim Simulation Steps

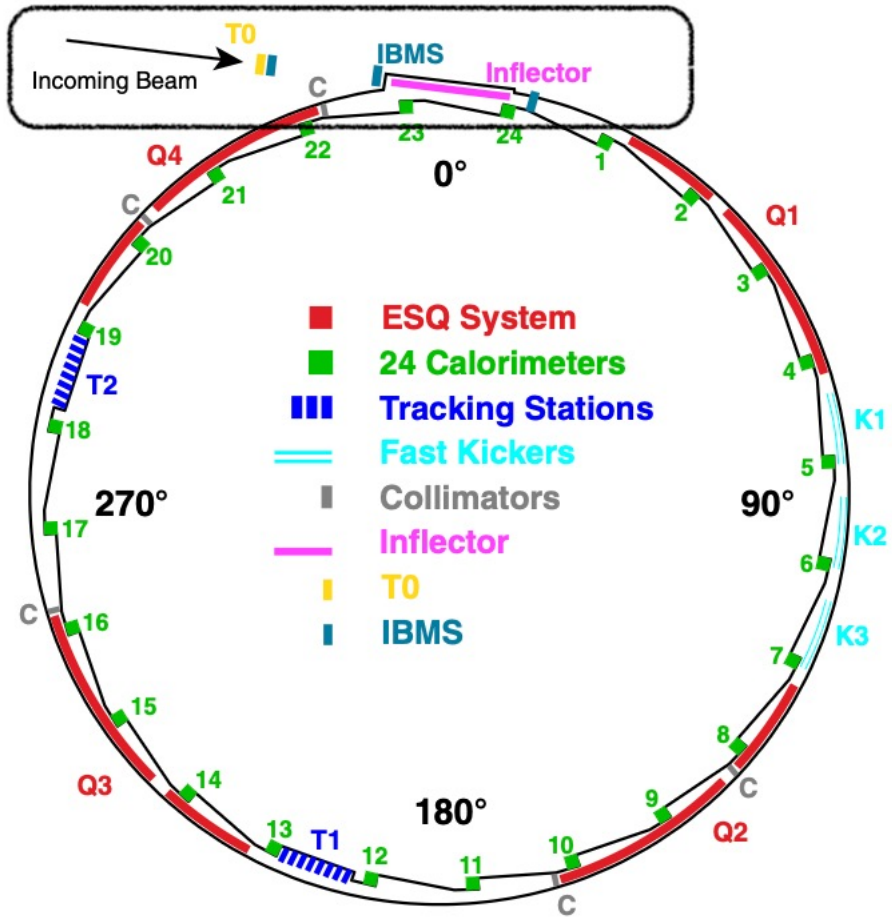
- Tuning the parameters according to run condition — Anna + Elia + Simulation Group
  - Run-1: a,b,c,d ; Run-2 ; Run3 a-b
  - On going Run-4 ; Run-5, Run-5 RF1, Run-5 RF2 ; Run-6
- Production — Anna + Simulation Group
  - Gus Gun Sample
  - Beam Gun: Nominal + at least 2 systematic simulations samples
  - Stored/Lost Muons Samples
- Studies
  - Phase –Acceptance Systematic ⟸ Anna + Elia
  - Spin-Transverse Coordinate Correlation
  - Time-Momentum Systematic
  - Lost Muons ⟸ Anna + Francesco

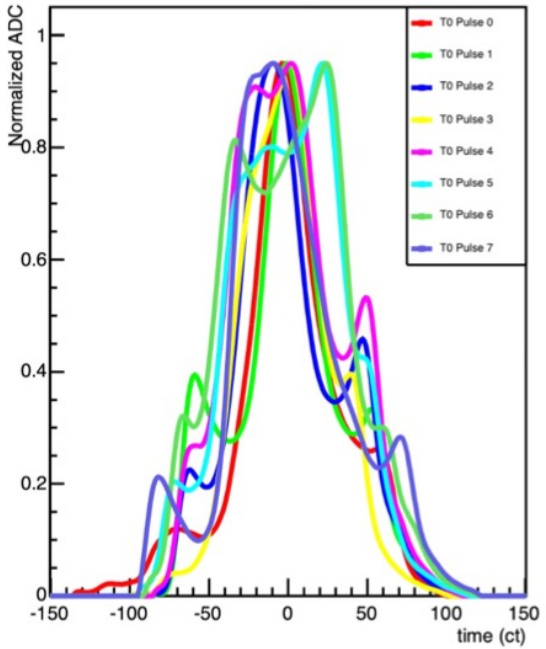
GM2RingSim Injection Tuning

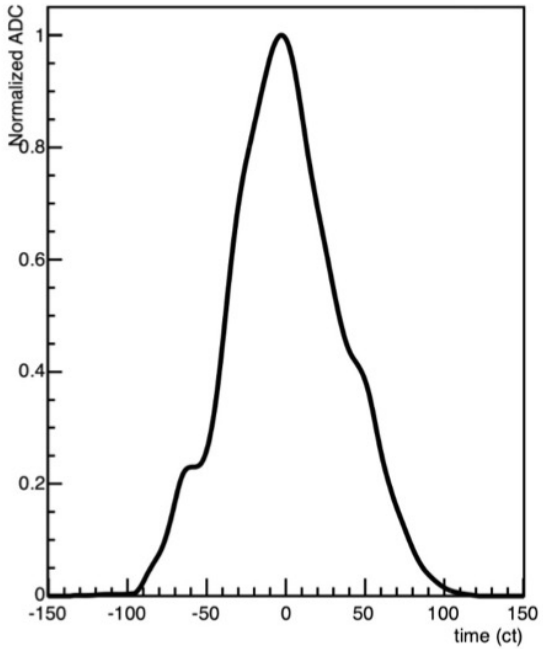
1. Inject muons at T0 scintillator
   - Start with beam spatial, momentum and spin distributions from Muon Campus Simulation at the end of M5.
   - Reweight time to reflect T0 data for that run (possible to run with separate or average pulses)

[Elia B. implemented this for Runs 2 & 3]





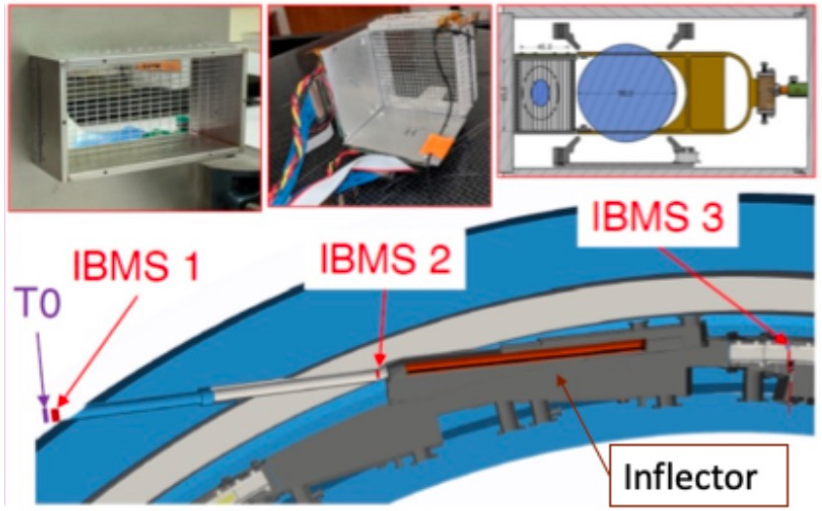


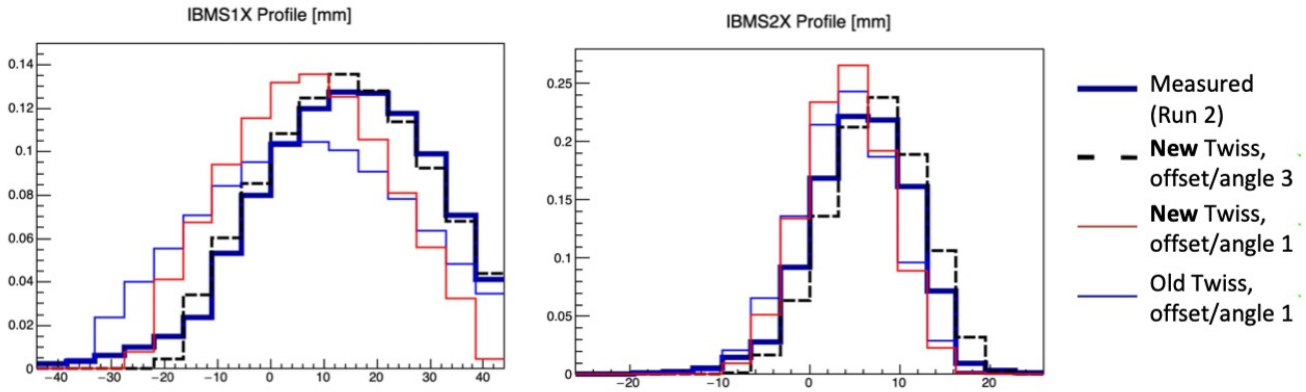


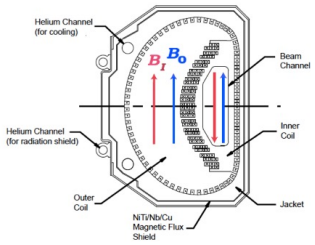
GM2RingSim Injection Tuning

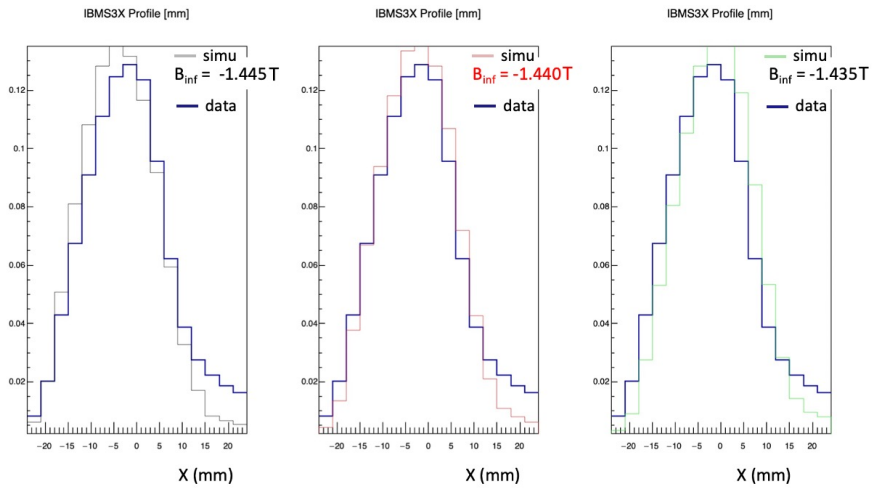
2. **Fine-tune of injection** using comparison with IBMS Data :
   - **Inflector field** tuned matching with IBMS3

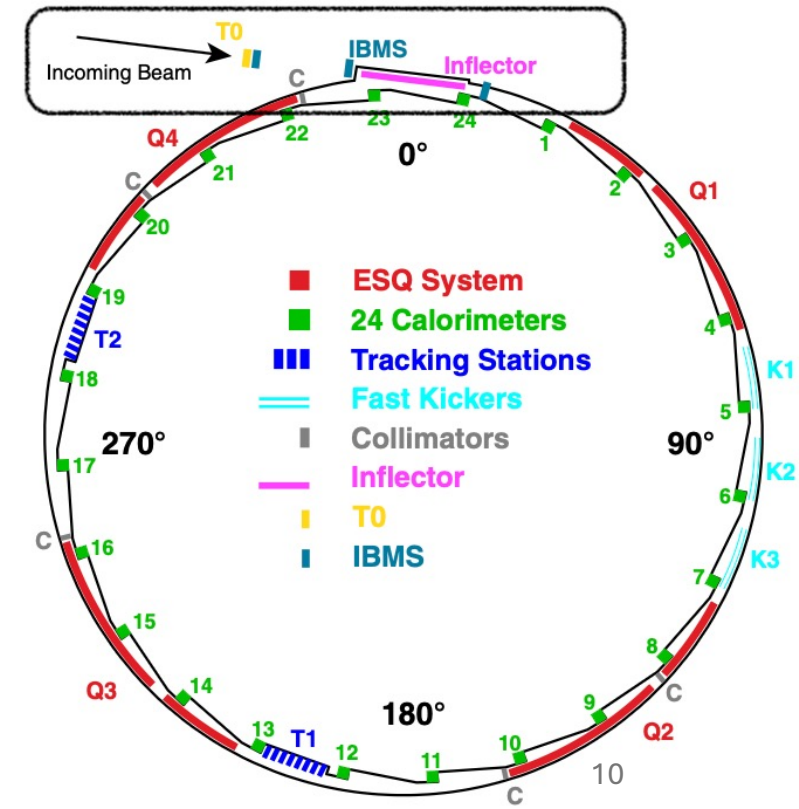
[Anna + Simulation and IBMS Team]





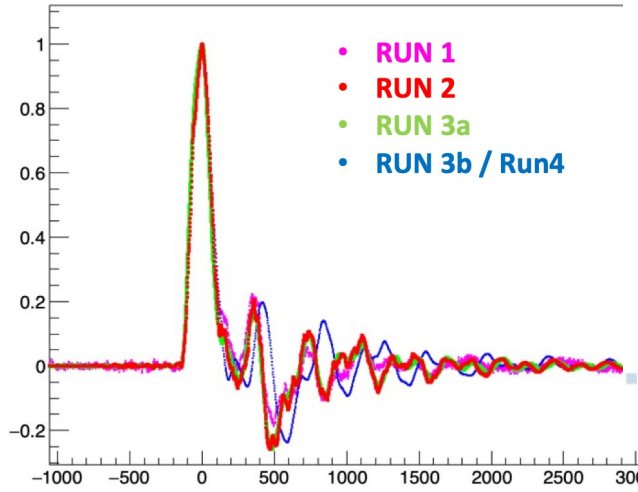


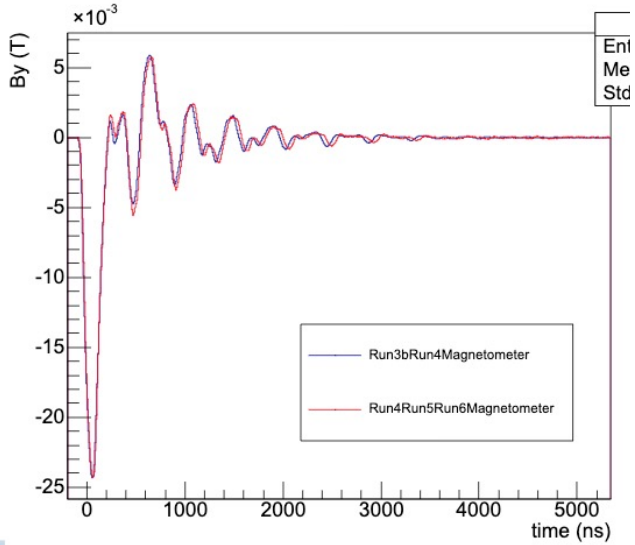




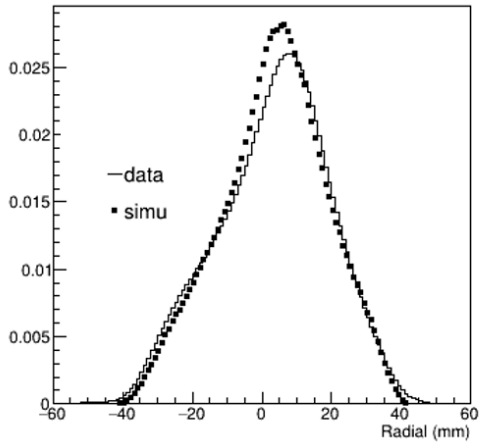
Kickers and Quads in GM2RingSim

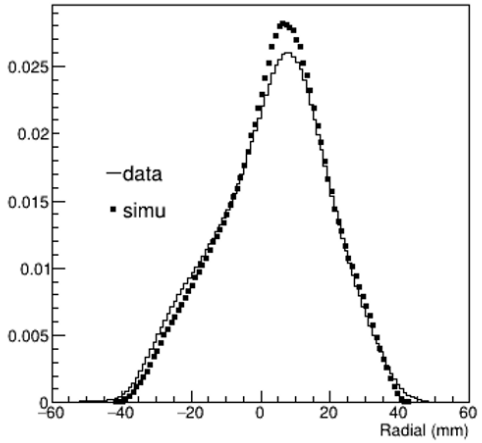
- **Kicker pulse shape** from dedicated magnetometer measurements: for Run-4-5-6 from INFN_Magnetometer Measurement (see Paolo's talk)



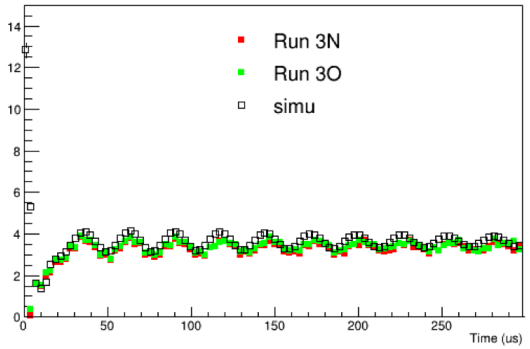


- **Kickers magnetic field strength** from measurements and fine-tune using comparison with tracker data

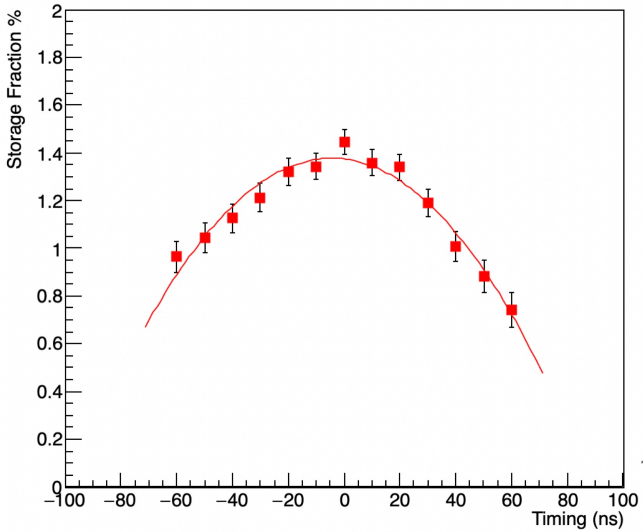




- **Quad field index** tune to match radial oscillations

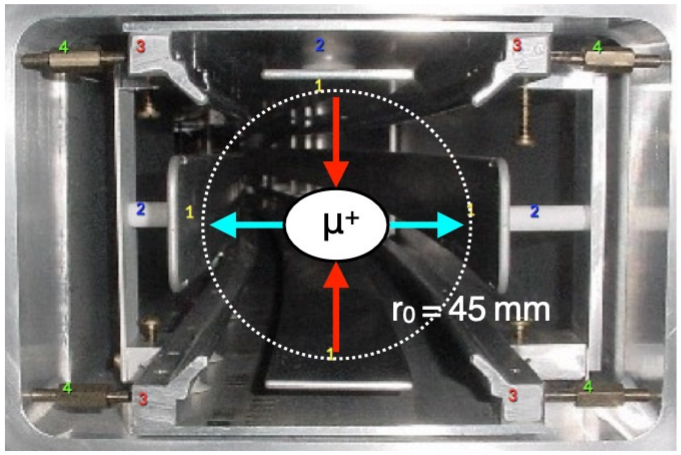


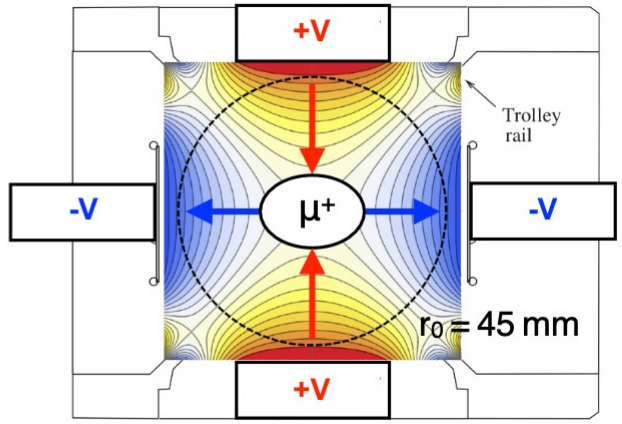
- **Kickers timing** respect to the injected beam adjusted from a simulation scan to maximize number of muon stored (similar to the experiment)



Electrostatic and Magnetic fields in GM2RingSim

- **Electrostatic Quadrupoles Field**
  - → implemented as multipole expansion
  - → evolved dynamically through scraping periods after injection
  - → RF implementation is now ongoing





Magnetic Field in the storage region

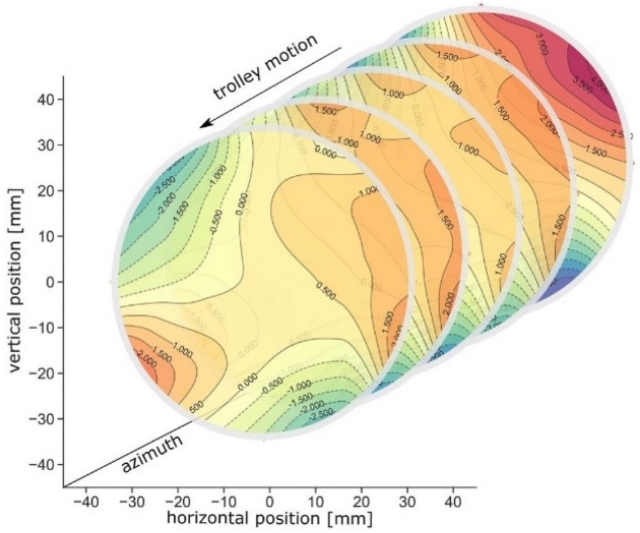
→ pure dipole magnetic field with multi-pole perturbations from field data from trolley runs

→ implementation of multi-poles perturbations for Run 4-5-6 is ongoing now

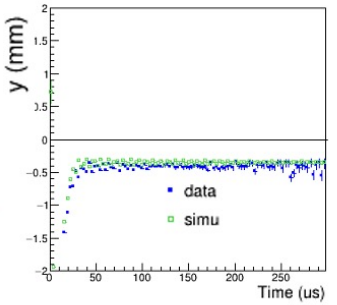
→ radially dependent fringe field from measurement and fine-tune using comparison with tracker data

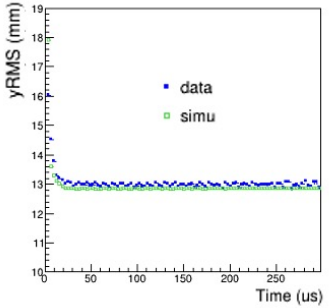
→ next step

Trolley Maps



Comparison with tracker data





Main Productions

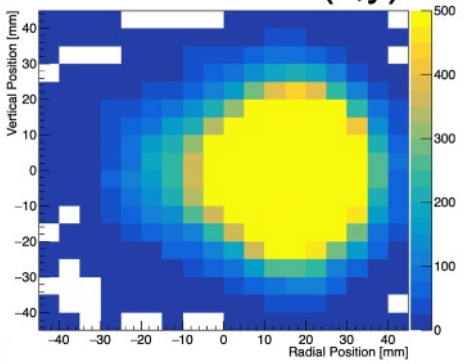
Run 1, 2+3 Simulation Production Summary

RUN	GUN	MUON DECAY	#EVTS (B)	RUNNING TIME	DISK (PB)	NOTES
1	Beam	ON	1/0.22	49/85 days @ 2k slots	0.339/0.327	First large-scale production with good/bad resistors.
1	Beam	OFF	0.11	110 days @ 2K slots	0.183	60Hr, 9Day, HighKick, Endgame nominal and systematic error productions. Trees stored on persistent.
1	Gas	e^+	10.8	139 days @NERSC	0.8	High fidelity calorimeter/tracker acceptance maps
1	Gas	e^+	0.10	4 days @2k slots	0.002	Tracker acceptance
2	Beam	OFF	1.07	1070 days @ 2K slots	1.78	Run 2 nominal + systematic error productions. Trees stored on persistent.
2	Gas	e^+	8.5	27 + 26 days @2K slots	0.001	Gun and analysis tree runs sequentially. 71 days total including pauses. Final product are analysis trees saved on persistent.
2	LM Beam	OFF	1.0	7 days	15 MB	Gun output written to scratch , only trees stored.
3	Beam	OFF	0.078	78 days @2K slots	0.13	Run 3A-G, 3I-L, 3M, 3NO, nominal + systematic error productions. Trees stored on persistent.

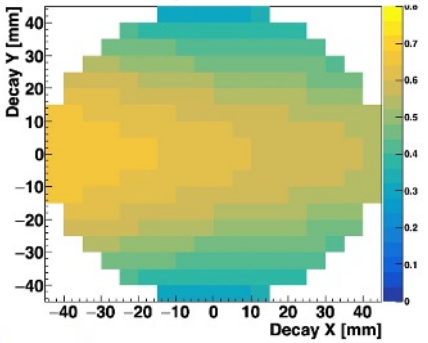
Studies: Phase-Acceptance

$$\phi_a(t) = \tan^{-1}\frac{\sum_{ij} M(x_i,y_j,t)\cdot\varepsilon(x_i,y_j)\cdot A(x_i,y_j)\cdot\sin\left(\phi_a(x_i,y_j)\right)}{\sum_{ij} M(x_i,y_j,t)\cdot\varepsilon(x_i,y_j)\cdot A(x_i,y_j)\cdot\cos\left(\phi_a(x_i,y_j)\right)}$$

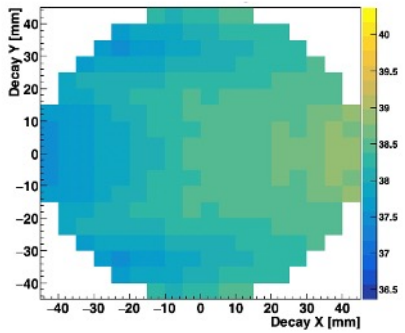
Muon location (x,y)



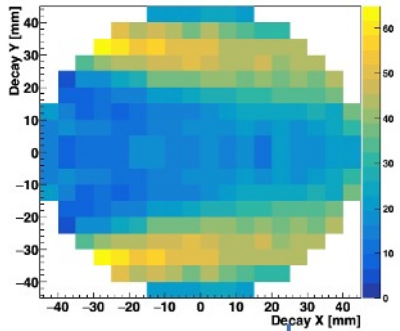
Calorimeter detection prob.



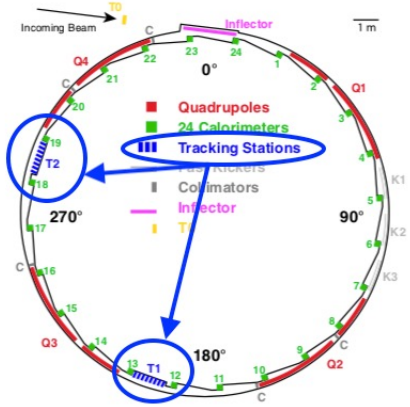
<E> dependent weighting



average phase

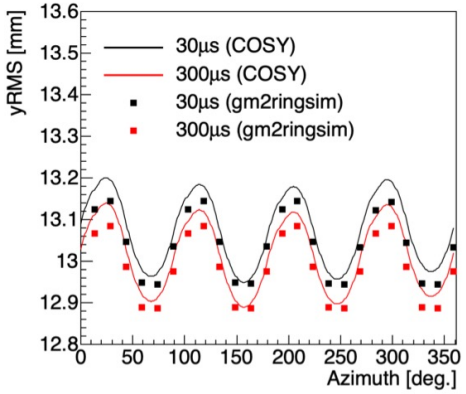


Tracker data

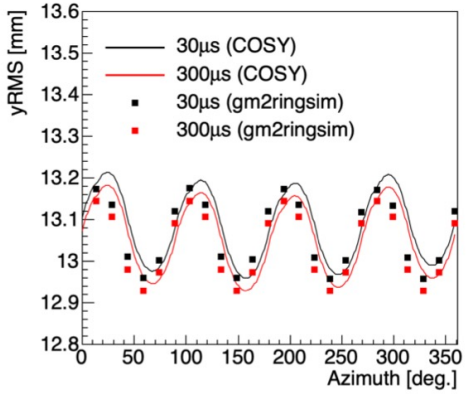


~10B events of GM2RingSim Simulation

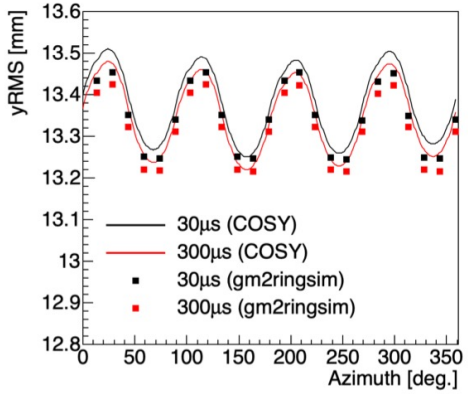
Run-2



Run-3a



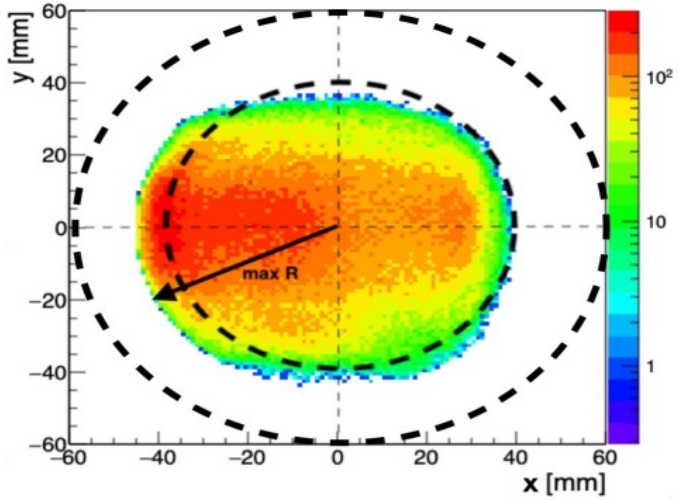
Run-3b

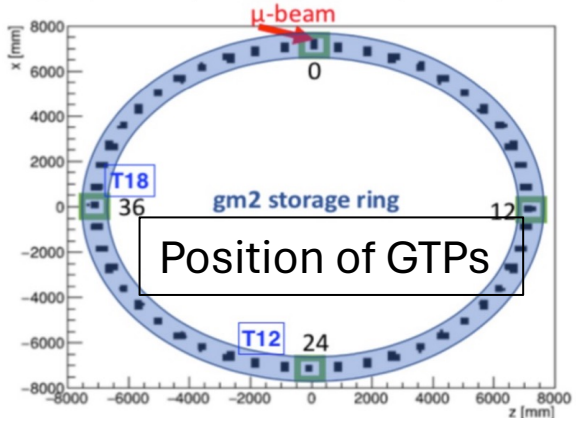


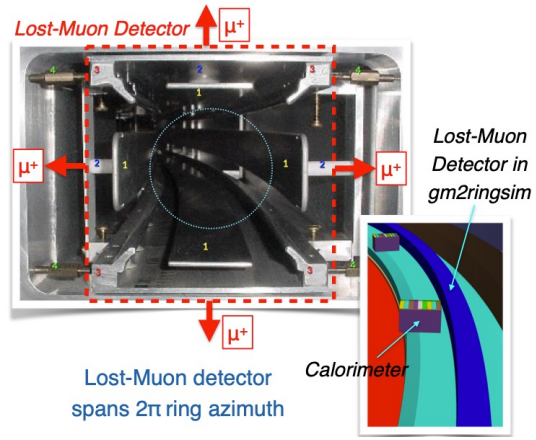
Studies: Lost Muons

- Lost Muon Gun allows us to generate a LM-enriched samples
  - ➢ Twiss pars. as input allows to guess max radial position of the muon r_{max} and select only muons that will probably hit a collimator;
  - ➢ Muons that hit a collimator and are lost can be tagged and studied using calorimeters, Ghost tracking planes and lost muon ghost detector
- Last summer generated a sample of 1B events with the Lost Muon Gun tuned with **Run-2 nominal conditions and decay OFF**.
  - ➢ Statistics was not enough to have a conclusive analysis (F. Confortini GM2-doc-29839)
  - ➢ We are currently working on improving the efficiency of the simulation and to produce large samples
  - ➢ Next step is to try to reproduce the «lost muon bump» changing the radial field parameters and to tune and test the Lost Muon Gun for the Run-3/4/5/6 settings

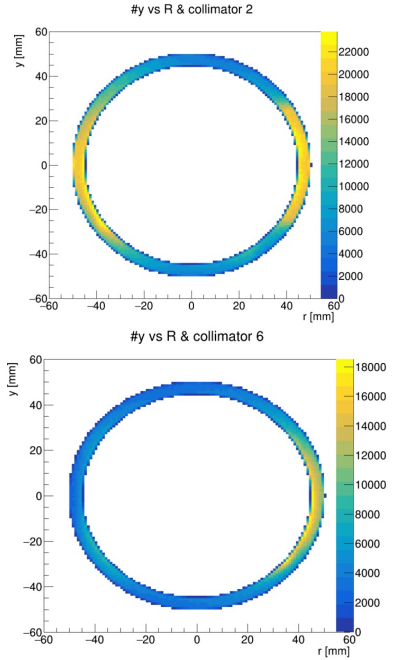
Collimators r = 45 mm



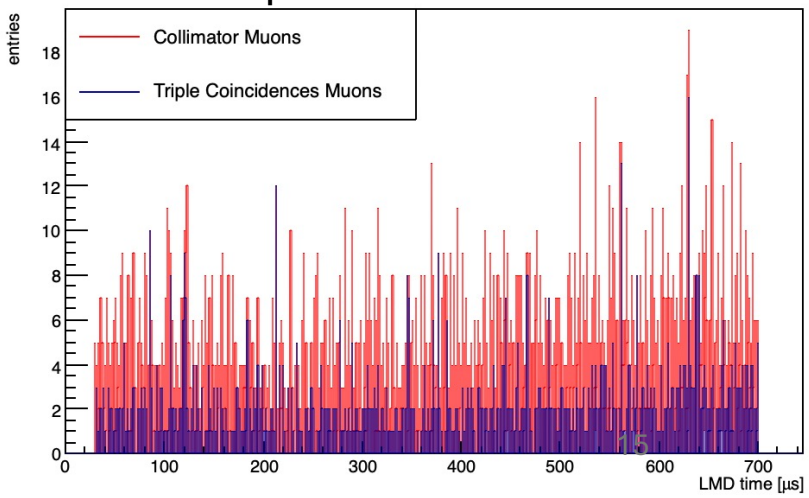




Position of Collimator hits



LM Time spectrum



Summary and Conclusion

- Simulation tools are crucial for understanding the dynamics of the muons inside the ring, especially for next result since the Run4-5-6 have much more statistics and part of the Run-5/6 have new beam dynamics due to the RF
- We are involved in all the aspect of the simulation: tuning, production and studies
- The main challenge is the production of high-statistics samples in a reasonable amount of time.. I hope in September to show some results from the studies!