Simulation for Muon g-2

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Computing Readiness Review

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Physics Needs

- Physics dictates the requirements of our simulation
- Some of our needs are unique within particle physics

<u>Goals</u>

1) Characterize muon storage/loss at injection and throughout fill
2) Develop/test calorimeter reconstruction algorithms
3) Develop/test tracker reconstruction algorithms
4) Support SiPM gain studies
5) Exercise offline data analyses workflow
6) Commissioning analyses

Simulation Framework(s)

We must precisely characterize:

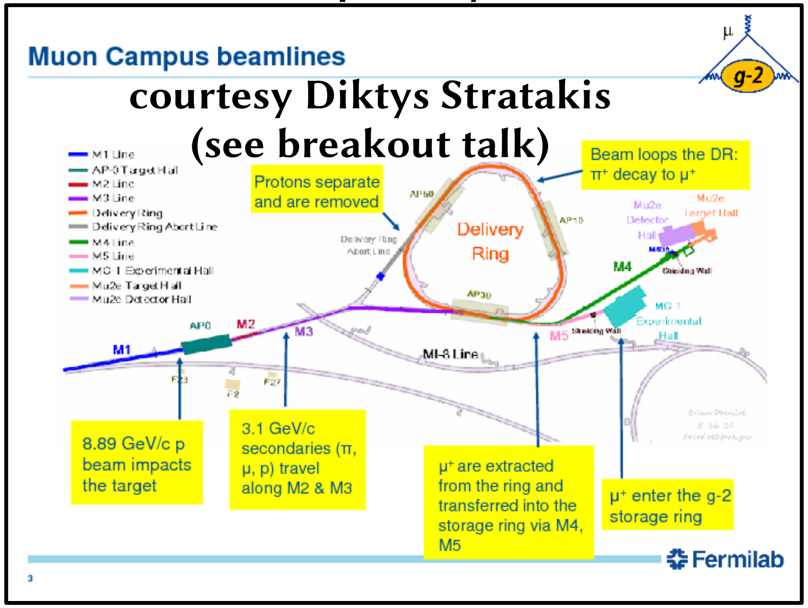
- phase-space of injected muons (strongly affects storage efficiency)
- spin distribution at injection (and correlation with momentum)
- muon distribution in storage region (convoluted with B field to obtain precession frequency)
- time-dependent fields (tuning storage efficiency using kicker/quads)
- material geometries (especially near storage region)
- detector response and resolution

Break problem into multiple stages:

- G4Beamline (proton target, beamline propagation, pion decay in booster ring, and muon delivery to MC1)
- gm2ringsim (muon injection into ring, fine-tuning of orbital radius and muon phase space, muon decay to positrons, and their signal in our detectors)

G4Beamline

- End-to-end Geant simulation from proton target to muon delivery to MC1
  - Track beam **(including polarization)** through beam lines and delivery ring
  - Must account for multiple bends, elevation changes, and injection/extraction schemes
- Works with other tools to simulate production on target and beamline optics
- **Critical** to understand **spin-momentum correlation** at storage ring entrance (measurement systematic on precession frequency)
- Also delivery efficiency (normalization)
- Independent of art, gm2ringsim
- Cross-checked with other tools
- Using NERSC resources successfully
- (More details in Diktys' talk)



gm2ringsim

- Geant4 simulation of ring, fields, muon behavior in storage, and signal in our detectors
  - includes realistic material geometry and electromagnetic fields
- Accompanies our art analysis framework
- Under development since ~2013
- Really four separate packages/repositories (for now)
  - artg4: generic Geant4 interface to art
  - gm2geom: describes geometry of our experiment
  - gm2ringsim: Geant4 driver (via artg4) using gm2geom
  - gm2dataproducts: all art records produced by our experiment
- Soon: most packages will likely be merged into a single repository for reasons discussed in Adam's computing overview

gm2ringsim Event Generation

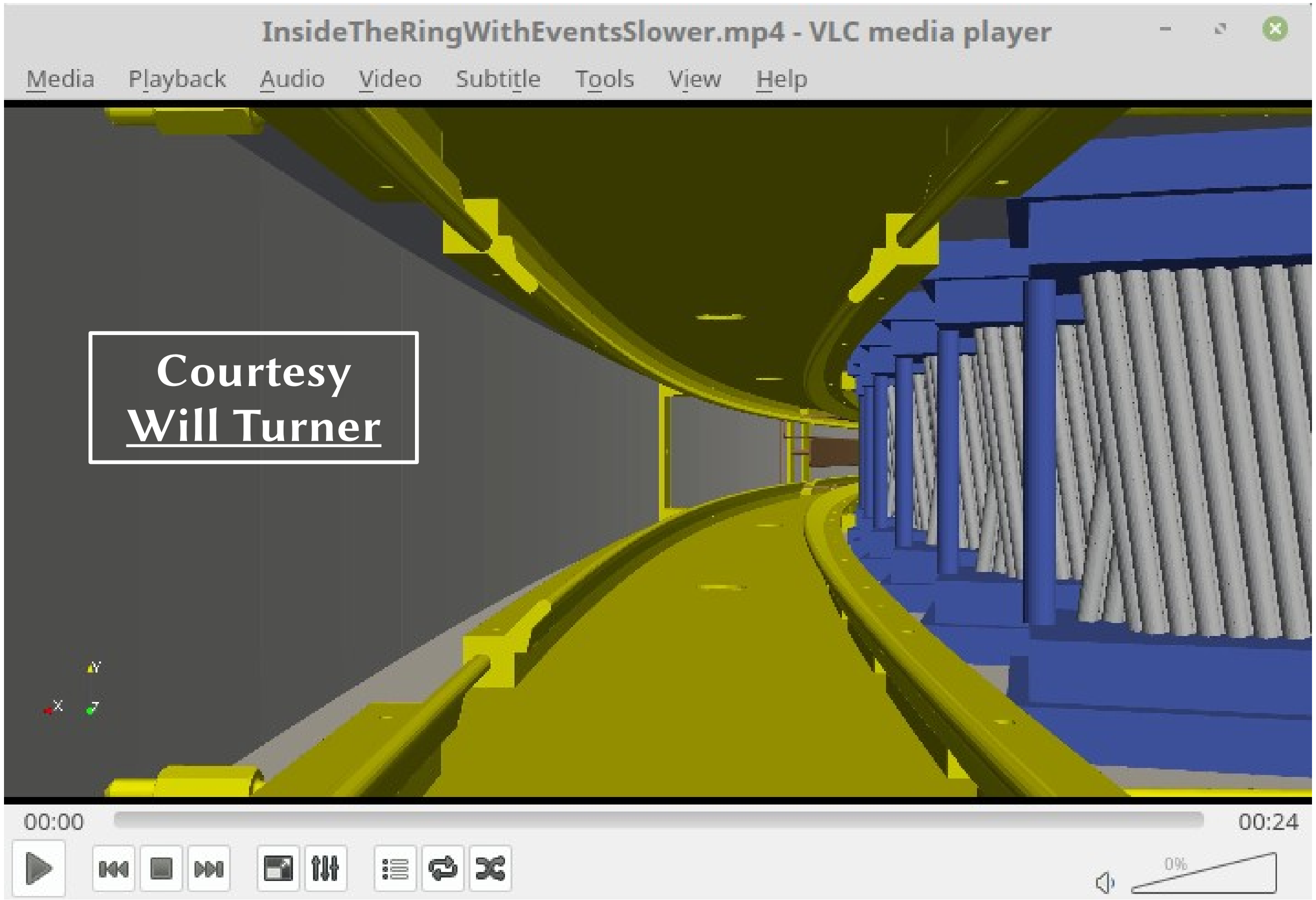
- **Event generation** is simply particle injection using Geant ‘particle guns’
- Muon Guns: high-fidelity, full simulation of muon propagation from some fixed starting point
  - specify phase space and spin
  - shoot muons from various stages (inflector entrance or exit, or at end of G4Beamline)
- Muon Gas Guns: parametrically emulate muon storage, behavior, and decay in ring
  - skip muon propagation to save simulation time (for fast studies of background and other effects)
  - inject muon at decay time
- Particle Bomb: isotropic multi-species source
  - designed to test Geant geometry

gm2ringsim Geometry

- Unique challenge: we have complex structures **very close to the beam**
  - necessary due to requirements on size, field(s), cooling, and instrumentation
  - this is particularly important for study of muon loss
- Standard approaches (using native Geant volumes or GDML) do not sufficiently describe these structures
- Geometry development has accelerated recently due to Cadmesh
- **Cadmesh** allows us to import native CAD file formats (STL, PLY, others) directly into Geant-manageable geometry
  - this is as close as Geant can get to 'the real thing'
  - does not require "intermediate file format conversion using commercial software"[arXiv:1105.0963]
  - this fixed a **serious roadblock** to our geometry implementation
  - represents a **unique contribution from g-2** to physics simulation methods
- For more details, see Leah's geometry talk

[Overhead View of Ring]

A Brief Tour…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Courtesy
Will Turner
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gm2ringsim

- The simulation has **already been used for successful studies**, well before its implementation is complete
- These studies regularly influence the experiment's design (hardware **and** software)
- Highlights of a few results:
  - Quadrupole, inflector design studies
  - Calorimeter signal study
  - Tracking/EDM studies
- We have remaining development goals that are **crucial** to our measurement
- Current implementation campaign focuses on these goals
-

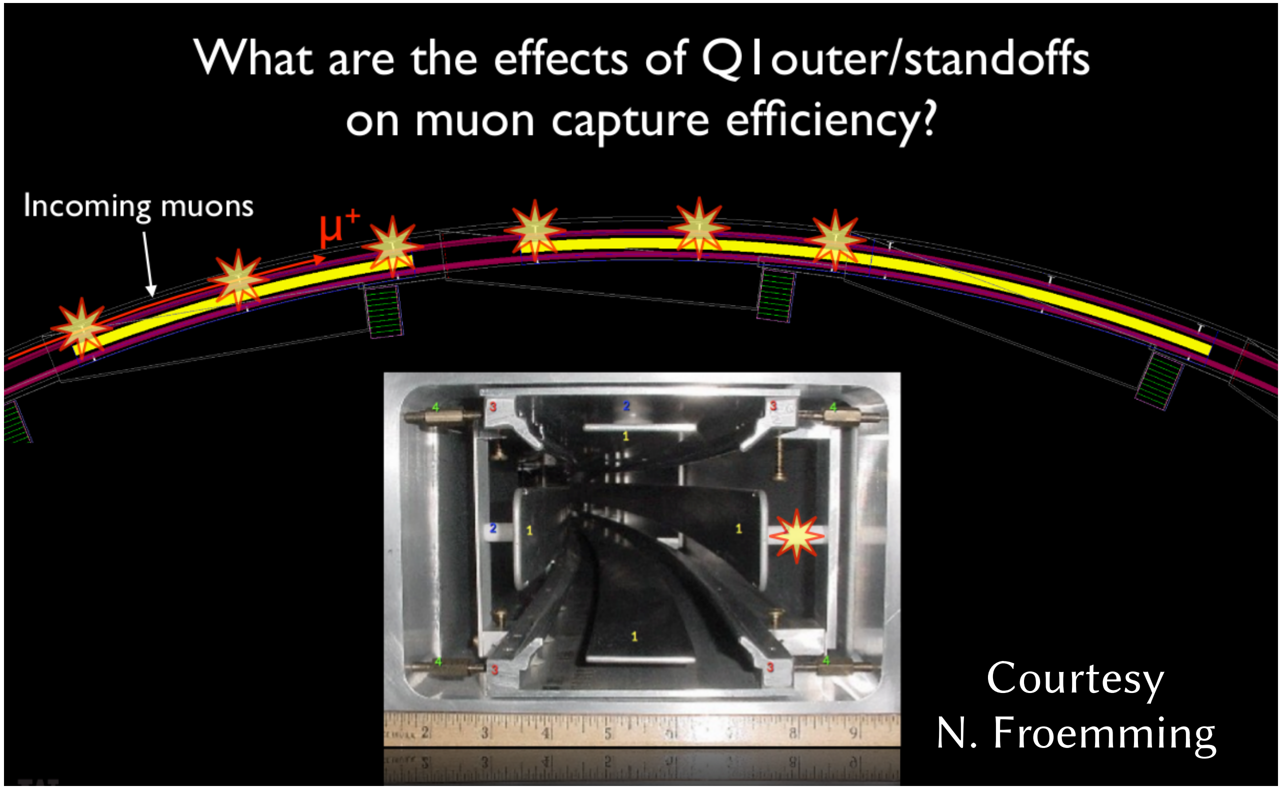
Selected gm2ringsim Studies

Quad Plates and Standoffs

Nathan Froemming 2015

Problem: muons exit inflector and hit quadrupole plates (and the 'standoffs' which support them)

Originally thought to impede beam at level of ~few percent

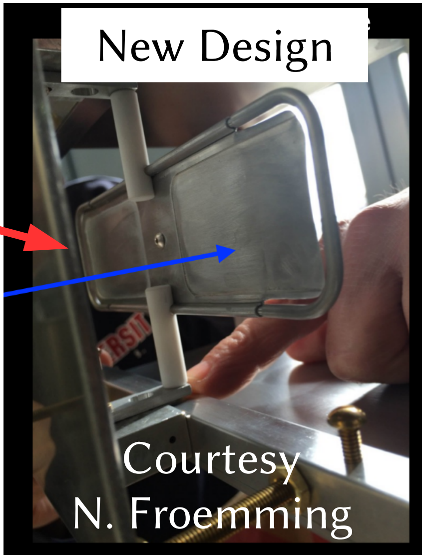


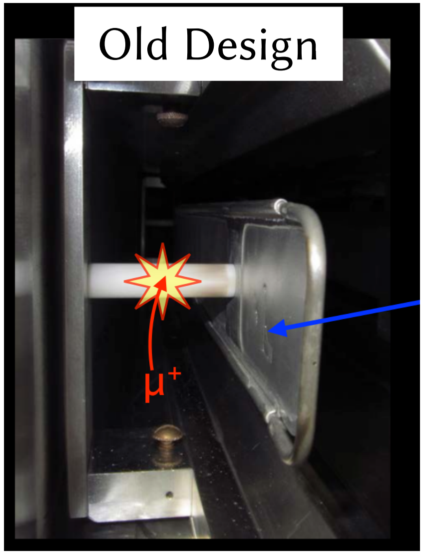
Selected gm2ringsim Studies

Quad Plates and Standoffs

Nathan Froemming 2015

- Study with gm2ringsim tested different standoff design
  - allow unobstructed muon passage behind plate!
- Muon storage efficiency jumped from 2.31% to 2.84%
  - **this is a 23% increase in data**
- Similar problem: beam passes **through** Q1 outer plate
  - thin aluminum plate, but still contributes to loss
- Same study also tested materials:
  - build plate from lower-Z material, cover in aluminum
  - boosts 2.84% storage efficiency to 3.34%
- **45% data increase in total**
- **Simulation results have informed hardware design**
- Simulation materials have been updated as well



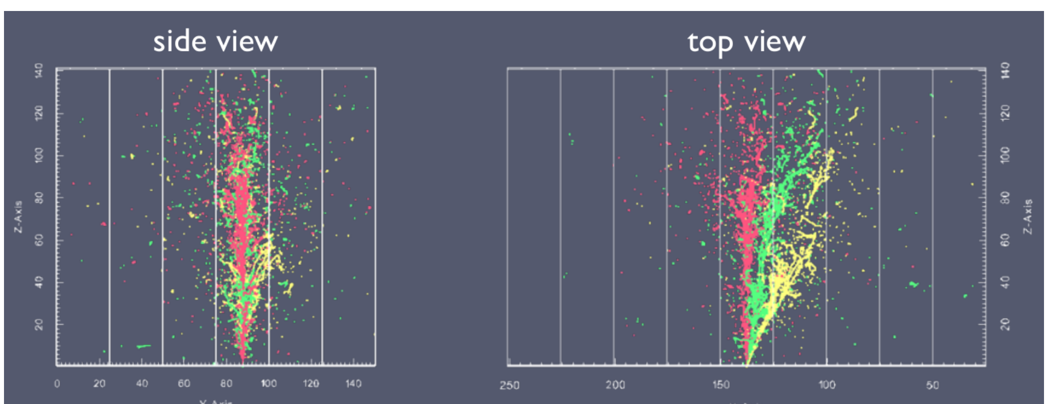


Selected gm2ringsim Studies

Calorimeter Cluster Position

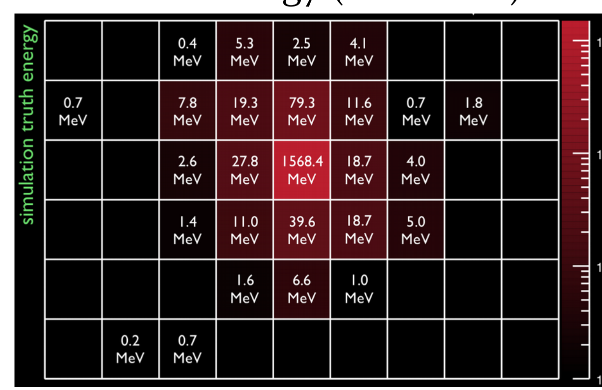
David Sweigart 2016

- Calorimeter tested with electron beam at SLAC
- Before test run, David surveyed methods reconstructing **position** and **angle** of beam from crystal data
- This was critically important to **fast-turnaround analysis** in test run
- Required **Geant simulation of EM cascade** in crystals
- Method with best performance worked **out of the box** for real data



Courtesy David Sweigart

truth energy (front view)



Courtesy David Sweigart

Selected gm2ringsim Studies

Tracking and/or EDM Studies

plot(s)

a couple of general points...

Physics Needs

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Muon Loss and Storage Efficiency

- Muon beam momentum spread is **much** wider than the maximum 'momentum acceptance' of our storage ring
- We are forced to accept **~95% muon loss** in injection and first turn in storage
  - 94% vs 97% would be a **potential factor of two in useful statistics**
- Beam injection: study storage efficiency as a function of:
  - kicker pulse strength and timing
  - quadrupole scraping to 'clean up' muon phase space
- 'Lost Muon' signal
  - use simulation to relate loss to a measurable signal (don't just trust simulated storage efficiency)
  - need a high-fidelity signal as a proxy for measurement of storage efficiency
  - muon coincidence in consecutive calorimeters (and background for this signal)

Muon Loss and Storage Efficiency

Status

- Preliminary studies of kicker timing have been done in gm2ringsim
  - ‘fakes’ propagation through inflector (injects muons at inflector exit)
  - uses 2D field map (swept through ring azimuth to generate 3D field)
- Studies of materials (quad plates, collimators) mostly finished
- Lost muon signal: studies of multi-calorimeter coincidence have started

Plans

- Finish gm2ringsim studies, including
  - propagation from ‘upstream’ through inflector
  - implement 3D kicker/quadrupole fields
  - test kicker timing and various quad scraping programs
  - finish calorimeter coincidence study

Develop/Test Calorimeter Reconstruction

- Energy/time/angular resolution
- Develop and test
  - pulse fitting algorithms in crystals
  - cluster-finding algorithms (combining crystal pulses)
  - identification of ‘pile-up’ (coincident positron hits) and background
- Test performance of these algorithms using SLAC data
  - tested calorimeter prototype in SLAC’s electron beam (June 2016)
  - this test **exercised software** as well
  - analysis implemented **within art** using gm2ringsim (with flexibility of artg4)
  - compare SLAC data to calorimeter simulation

Develop/Test Calorimeter Reconstruction

Status

- ongoing work characterizes efficiencies of pulse fitting and clustering
  - pulse-fitting is robust
  - temporal clustering is working well, spatial clustering needs more work

Plans

- finish main fitting/clustering algorithms
- work on ‘pile-up’ identification algorithms
- test performance **with background** from secondaries
- experiment with alternative/independent algorithms
  - maybe even machine learning for clustering

Develop/Test Tracker Reconstruction

- We need algorithms for track-fitting straw signals
  - muon decay position is unknown (so it can't be used for fitting algorithms)
- Use tracks to reconstruct muon spatial distribution in storage region
  - method will rely on simulated spatial distribution as we **cannot directly measure** muon distribution
  - target: extract this distribution shape with accuracy to sub-mm level
- Understand track-finding efficiency in relation to
  - **non-uniform magnetic field in tracker region**
  - particle energy, and chosen signal threshold
  - muon decay location, number of planes hit, vertical pitch
  - background from lost muons and low-energy secondaries

Develop/Test Tracker Reconstruction

Status

- currently characterizing signal generated in straws
- track-fitting algorithms under development

Plans

- finalize generated signal in straws (ongoing)
- finish developing/testing tracking algorithms (ongoing)
- reconstruction of injected muon beam is waiting on track-fitting (waiting on above)
- See Tammy's talk for more information

Exercise Offline Data Handling

- Generate a **large simulated sample**
- Use this sample to:
  - ensure an analysis path is implemented by Day 1
  - test full-scale handling of our data
- Analyses not mentioned above: spin precession, fast rotation, pitch correction, betatron oscillations
- Status: early production of large data sets has enabled high-statistics preliminary analysis
- Plans:
  - production team: large, high-quality muon simulations
    - full muon propagation, spin evolution
    - generate and digitize signals for ‘mock data’
  - use ‘mock data’ to develop art analyzer modules
    - pitch correction, spin precession needed by turn-on
    - fast rotation and betatron oscillation studies soon afterward

Commissioning Analyses

- [‘Simulation verification’ test runs (what can we measure on Day 1 that will tell us if the simulation is getting things right?)]
- Troubleshooting/diagnostic signals (how can we directly test the performance of the ring on Day 1?)
  - Fiber Harps and Inflector Beam Monitoring System (IBMS) are critical diagnostics
  - scan field timing parameters, compare storage efficiency to simulation
- Characterize effects from misalignments of our fields
- Status:
  - fiber harp analyses beginning now (FiberHarpGun)
  - IBMS hardware still under construction
- Plans:
  - IBMS needs g2ringsim for design decisions **and** analysis modules for Day 1

[Schedule/Timeline]

- [MDC_Tasks.ods]

Conclusion

- Simulations have already been critical for understanding urgent design and operational issues
  - complementary end-to-end checks (from proton target to signal in our detectors)
  - G4Beamline: dedicated, high-fidelity sim for generation of muon beam
  - gm2ringsim: detailed muon interactions with materials, fields, and detectors in storage ring
- gm2ringsim is currently under heavy development (see commit history from Adam's talk)
  - analysis and physics goals drive current implementation efforts
  - we have a structured task list
  - our timeline is acheivable

BACKUP SLIDES
(and/or scrap material)

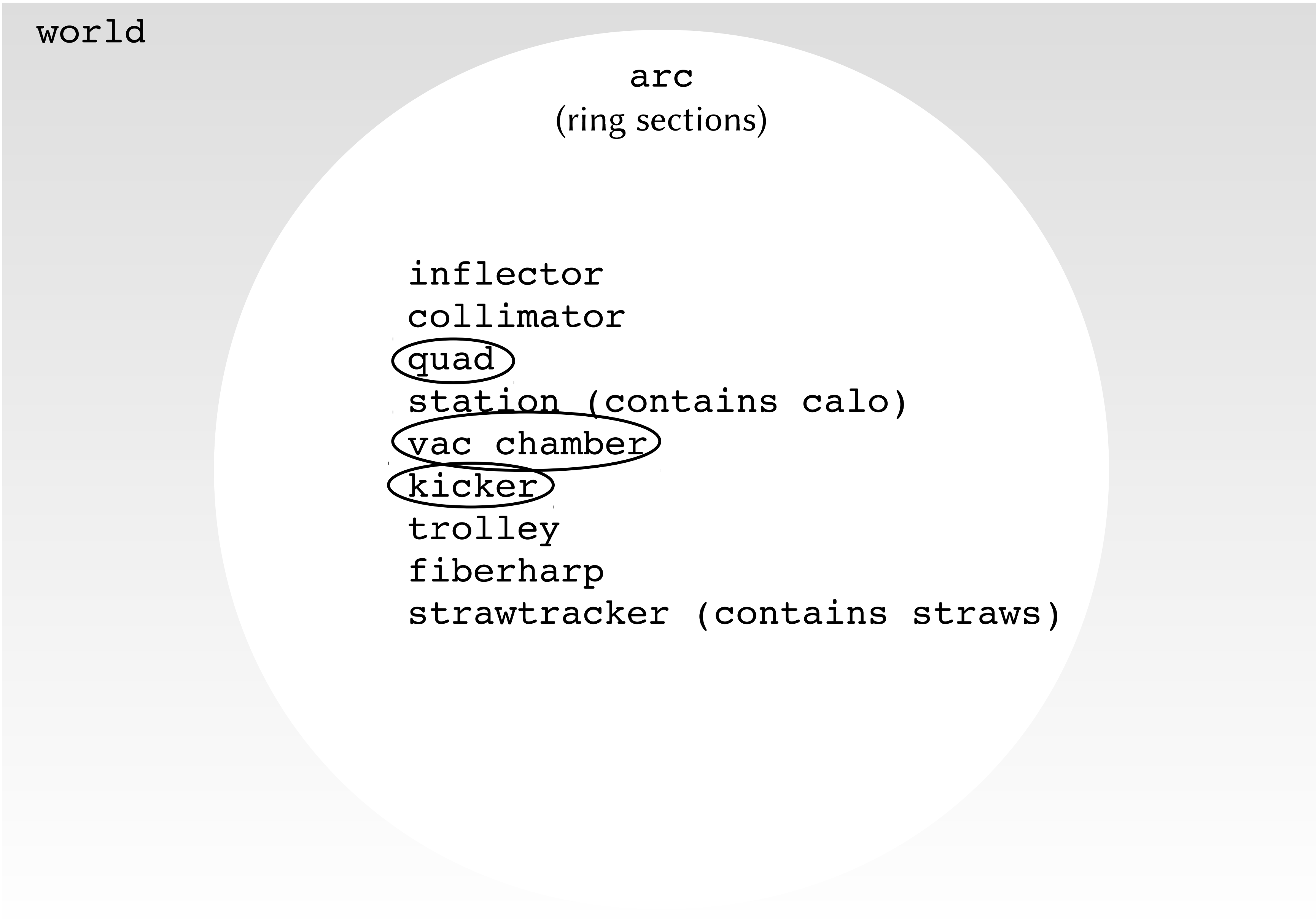
Geant Geometry Heirarchy

`world`

`arc`
(ring sections)

```
inflector
collimator
quad
station (contains calo)
vac chamber
kicker
trolley
fiberharp
strawtracker (contains straws)
```

EM Fields and Geant Geometry (Old Scheme)



Unified EM Fields

Subgoals

<u>Major analysis goals above require:</u>

- **accurate geometry** for all components near storage region, including vacuum chamber and detectors
- **high-quality interactive visualization capabilities** showing hits on ring components and detectors
- **static field(s):** main dipole field and its fringe field outside of storage region
- **time-varying fields** in beam kickers and focusing/scraping quadrupoles
- **Muon Gas Gun** includes fast rotation, CBO, and spin orientation
- can produce **realistic calo crystal pulses** with appropriate statistical smearing and proper energy sharing among crystals
- produce primary and secondary **tracker hits** (background)
- produce **fiber harp and IBMS hits** for beam injection studies
- **verification package:** standard set of physics/statistics checks (see Renee's talk)
- **standardized art records** from simulation

Subgoals I: Geometry

- Geometry must be implemented accurately to simulate muon behavior inside and outside the ideal storage region
- Muons can collide with any components near beam storage region (inflector, quad/kicker plates and standoffs, trolley rails, vacuum chamber)
- Muon trajectories can be affected by calorimeters, trackers, and their housings and accessories
- Proper positioning is important for accurate simulation of signal from tracker straws, Inflector Beam Monitoring System (IBMS), and fiber harps
- Fiber harps with **and** without mass
- Interactive, high-quality visualization capabilities showing detector geometry and hits (artvtk is neat)

Subgoals II: Fields

- static fields:
  - main dipole field and its fringe field outside of storage region
  - our detectors are located within this highly non-uniform fringe field, and it will affect their performance
- time-varying fields:
  - kicker fields tunable to ~10 nanoseconds (for beam injection studies)
  - implement quadrupole scraping (for beam injection studies)
  - specific checks on Geant's handling of quickly-varying fields
    - our experiment will test this much more than most experiments

Subgoals III: Beam Dynamics

- Muon Gas Gun includes fast rotation, CBO, and spin orientation
  - this is mostly verified by Tom Studdard's pass at pitch correction analysis
- Muon Injection Guns (currently under development) exhibit betatron oscillations and fast rotation automatically

Subgoals IV: Detectors

- calorimeters can produce pulses with appropriate statistical smearing and proper energy sharing among crystals:
  - this depends on accurate geometry as well as implementation of materials and EM processes in these materials
  - find something about most recent progress (Kim, Aaron)
- trackers can produce both primary hits and secondary hits (background)
  - Tammy has some work on this?
- fiber harps and IBMS produce hits for beam injection studies

Subgoals V: Verification and Checks

- **verification package:** standard set of physics/statistics checks
- **visualization tools**:
  - Paraview (via heprep-to-vtk conversion plugin)
  - artvtk: write out VTK geometry natively for each detector and art data product

SiPM Gain Response

- SiPMs have nonlinear gain which depends on history
- Our total signal tracks exponential muon decay distribution
- **Therefore, nonlinear gain is driven by a signal which changes by orders of magnitude over a fill**
  - Geant will **NOT** simulate SiPM gain from physics
- Current studies model SiPM gain analytically, and test this model given intensity and time distribution of incident photo-electrons
  - gm2ringsim can **simulate these intensities and time distributions**, and their **relation to deposited energy**
- These inputs will allow studies to optimize corrections for SiPM gain
- Status: not started
- Plans: results from gm2ringsim early enough to facilitate gain studies well before arrival of muons

[include somewhere II]

- ArtG4 makes the simulation extremely flexible and this has been a big success (e.g. used for SLAC and tracker test beams). [we are the only experiment using ArtG4)
- things unique to g-2:
  - GDML cannot satisfy our geometry construction requirements. (We are one of the only experiments not using GDML - need to explain why)
  - We have complicated geometry and that complication matters - using CadMesh to mitigate
  - We have complicated changing magnetic fields
- We can visually verify our geometry with ParaView (of course this isn't the only way we verify).
- Spin tracking (have found bugs in Geant that have been fixed)

[include somewhere III]

- We have flexible and precise particle guns
- We shoot single muons; need to aggregate into fills with art later
- We have digitization for SiPMs and straws
- We have a verification package
- Time estimates for running
- We have done optimization studies (get info from Adam)