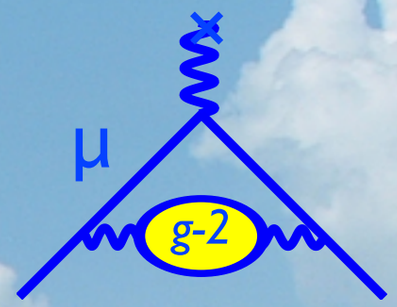
Muon g-2
Computing Projects



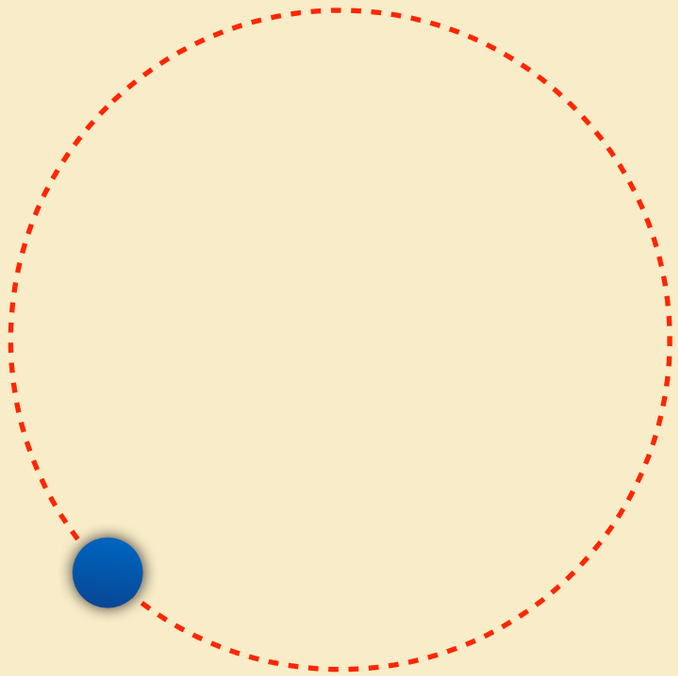
Adam Lyon, Fermilab

SCD Projects Meeting

December 18, 2013

Photo: Hogan Nguyen

Quick Primer to Muon *g-2*



A orbiting charged has angular momentum

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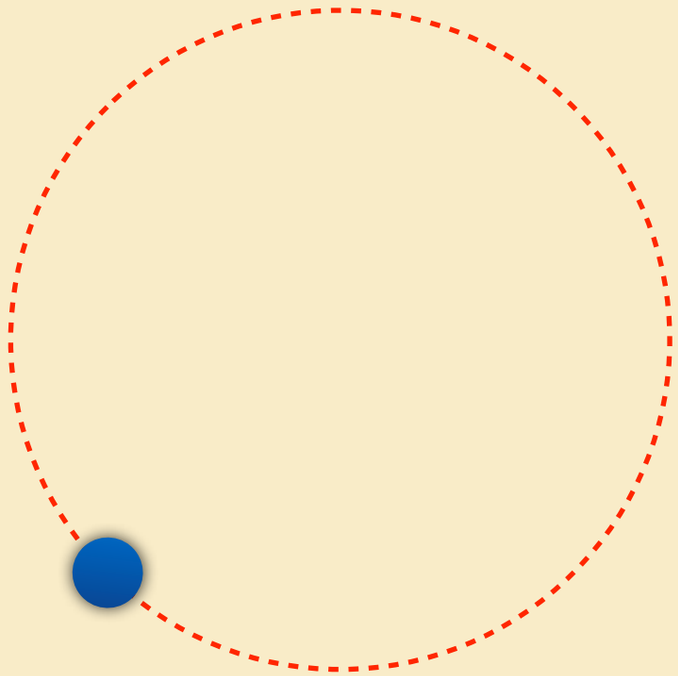

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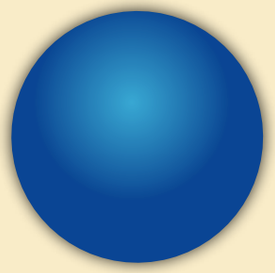

Many particles have an intrinsic angular momentum - spin

$$\vec{\mu_S} = g\frac{q}{2m}\vec{S}$$

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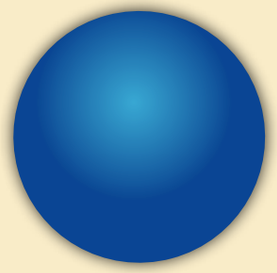

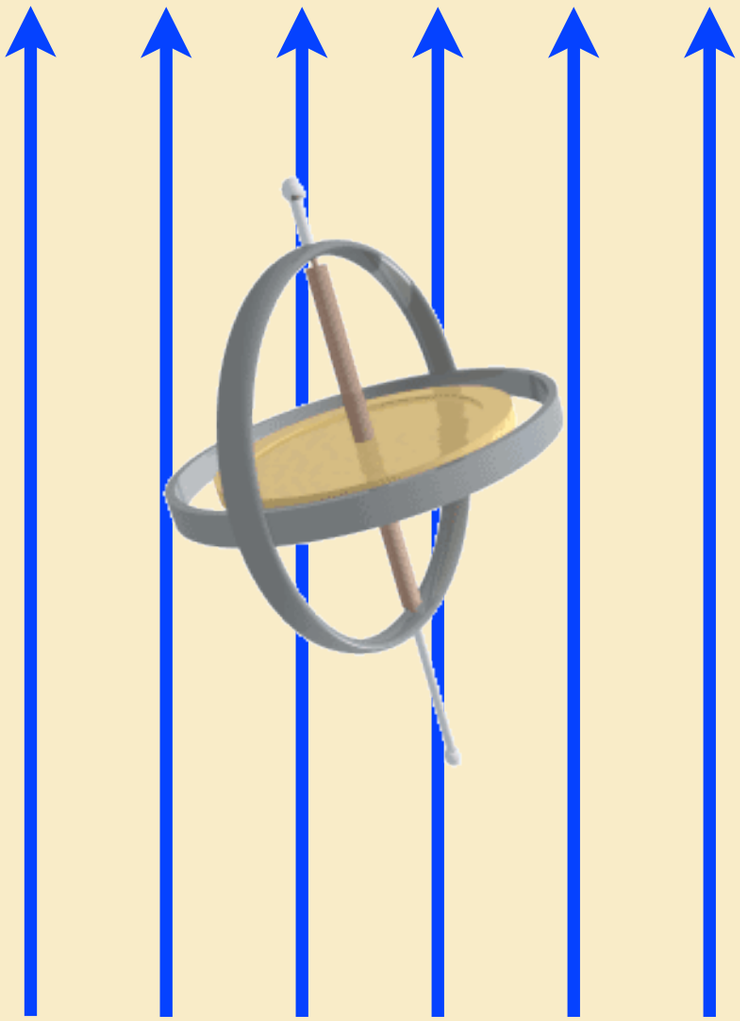

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$$\omega_s = g\frac{eB}{2mc}$$

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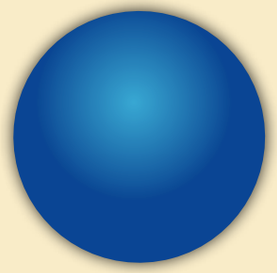
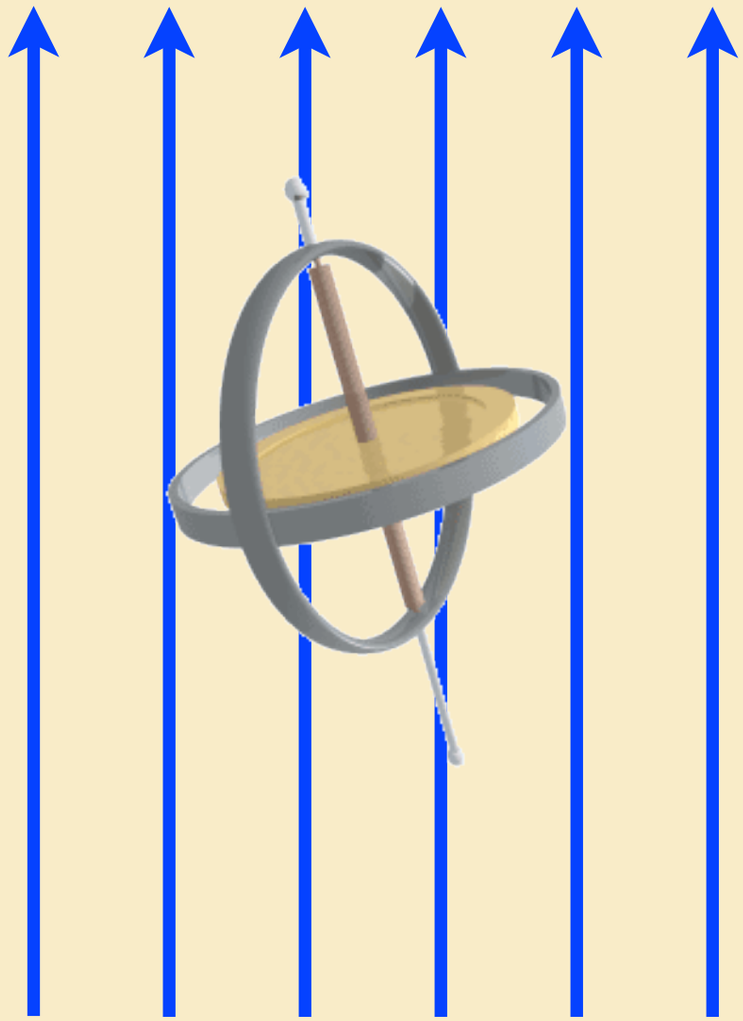




Many particles have an intrinsic angular momentum - spin

$$\vec{\mu_S} = g\frac{q}{2m}\vec{S}$$

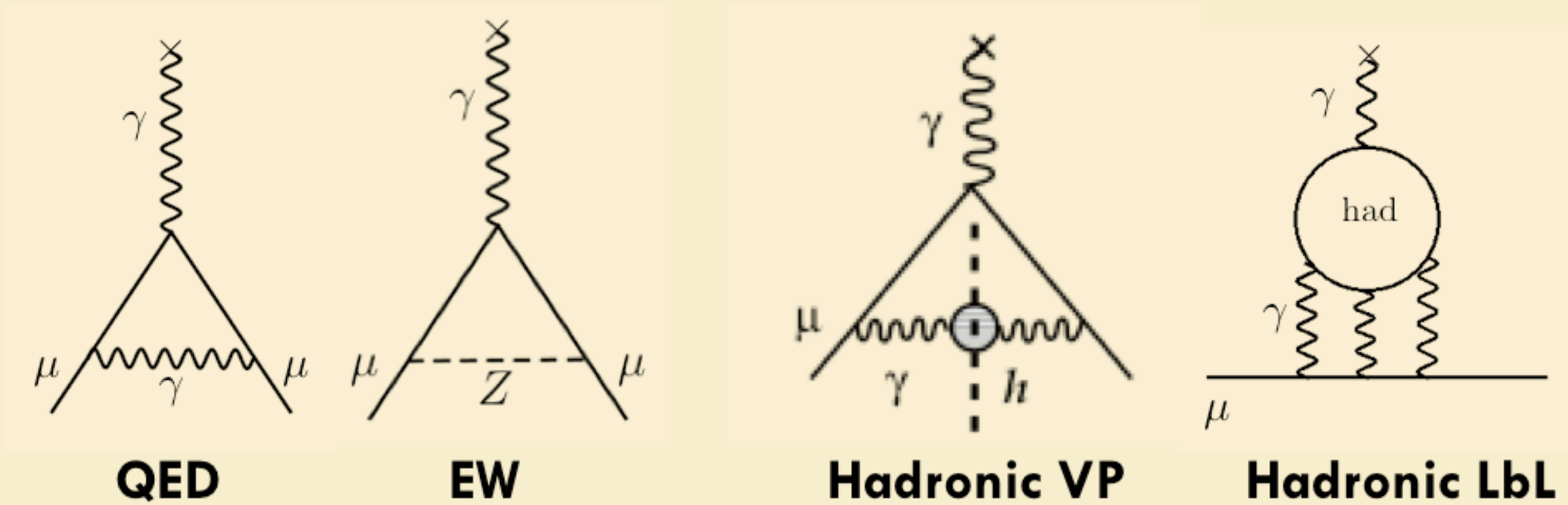
$$\omega_s = g\frac{eB}{2mc}$$

$$a = \frac{g-2}{2}$$

$$a = \frac{g-2}{2}$$ **can be calculated and measured very precisely to test the COMPLETENESS of the Standard Model**

Muons are "just right" for these studies

(muons more sensitive to more complicated physics than electrons; taus are too difficult)



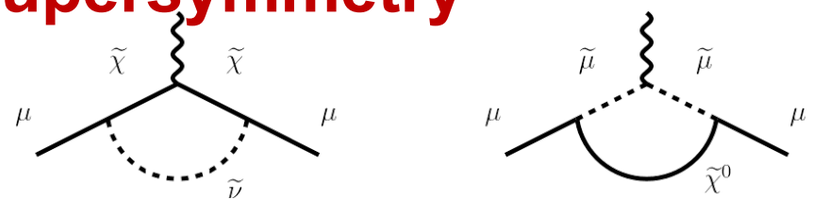
Brookhaven E821 1999-2001 (540 ppb)

$$\mathbf{a}_\mu^{\mathrm{exp}} - \mathbf{a}_\mu^{\mathrm{SM}} = \mathbf{287(80)} \times \mathbf{10^{-11}} \quad > \mathbf{3}\sigma$$

What could the new physics be?

- **Dark Photons**
  - light new vector particles V kinetically mixed with the photon

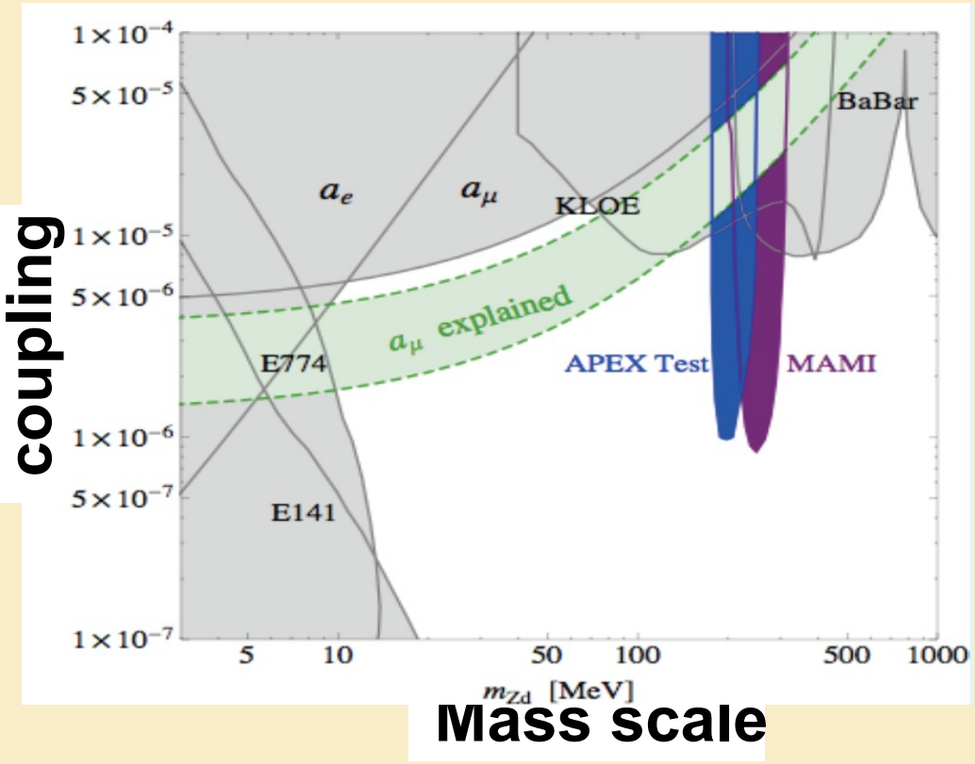
- **Supersymmetry**

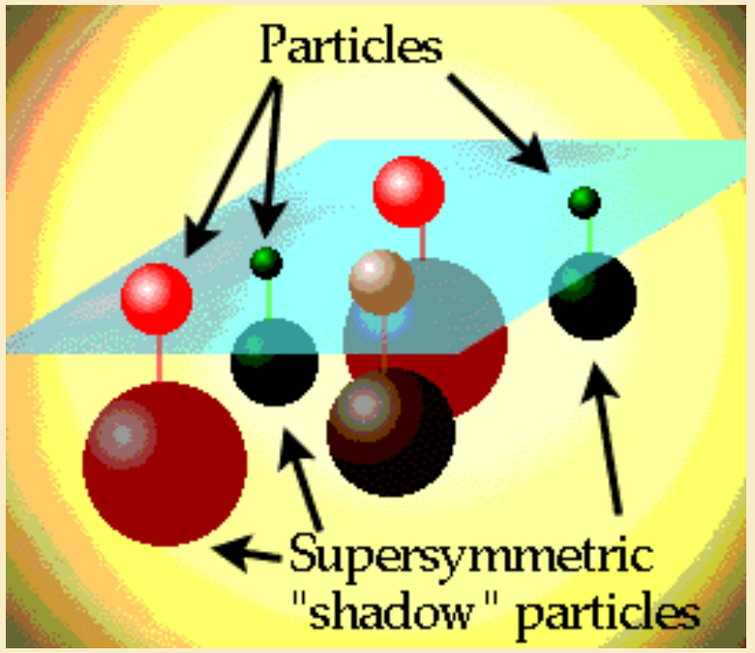


$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}} \right)^2 \tan\beta\ \text{sign}(\mu)$$

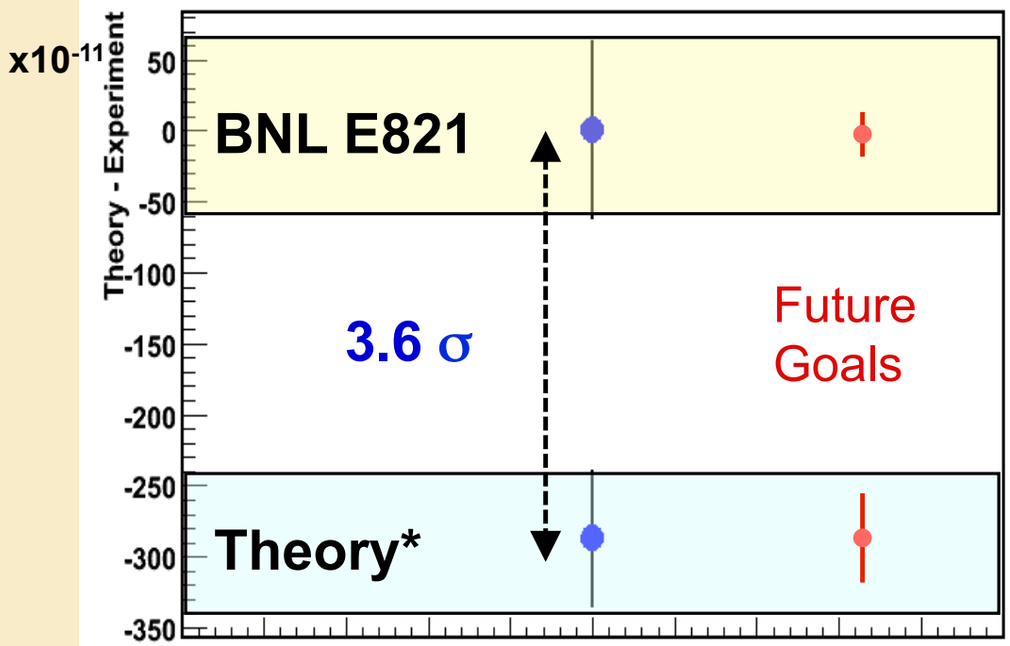
Difficult to measure at the LHC

- **The Uninvented**
  - Perhaps the most important of all





Goal is to reach discovery
Need 4-fold reduction in error



Goal: 140 ppb

7.5 σ if same central values

Expected 330 ppb

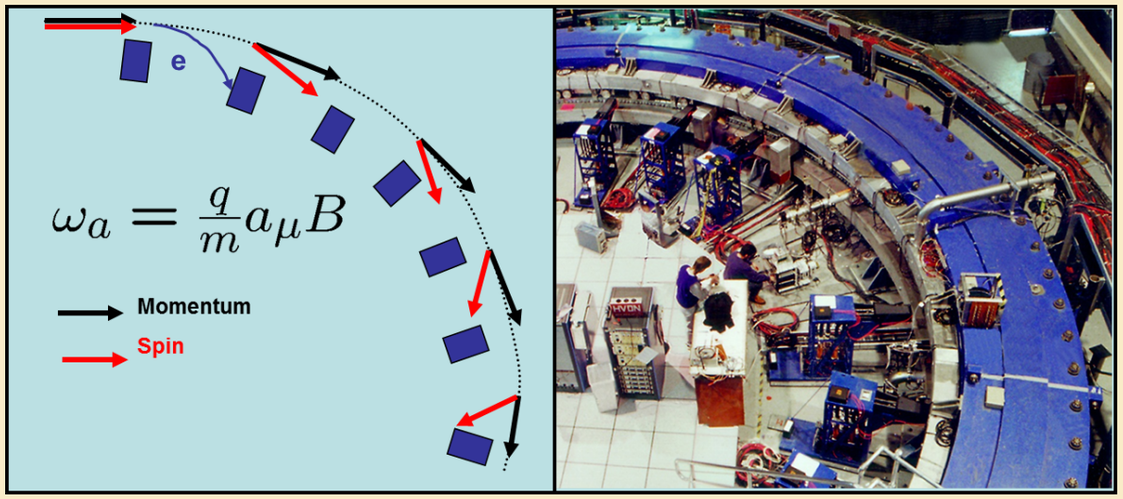
E989 Experimental Scope

Positive muons will be used to measure the muon anomaly to an absolute precision of $\delta a_\mu = 16 \times 10^{-11}$ (140 ppb). The error budget is distributed as follows:

Category	Error (ppb)	vs BNL E821
Statistical	100	x20 events
Field Systematics	70	x2 better
Precession Systematics	70	x3 better

Follow-up run using Negative Muons is a natural next phase

$$a = \frac{g-2}{2}$$ **is derived by measuring the precession of the muon spin in a very well measured magnetic field**

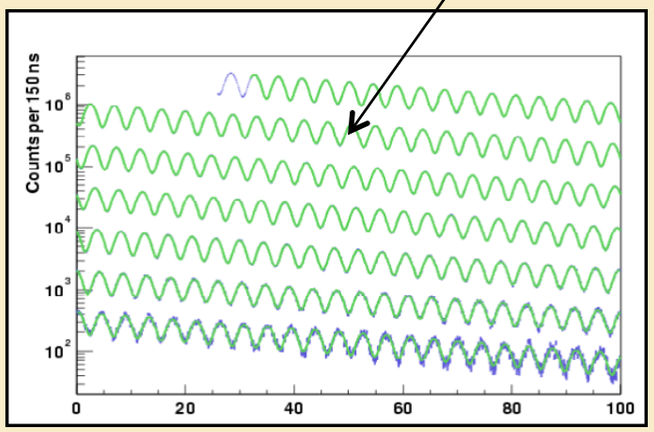


Key Improvements:

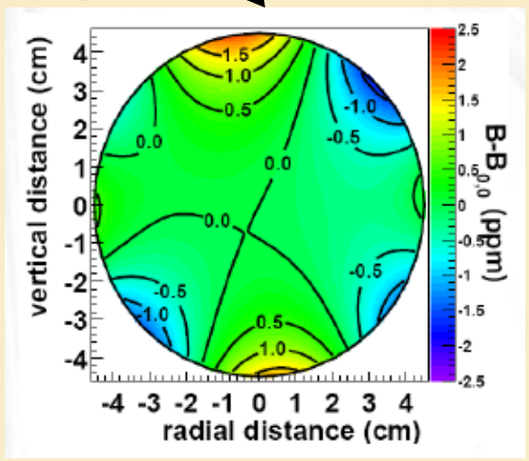
1) <u>More muons</u> more often delivered to ring

2) <u>Better muon</u> storage efficiency

$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$



Precession frequency



Average Magnetic Field

3) <u>Better modeling</u> of stored beam motion

4) Higher <u>field uniformity</u> and monitoring

5) <u>Reduced systematics</u> on precession frequency

Moving the magnet (summer 2013)

Where is it now?

MC-1

Building complete end of February 2014

Emmert returns to move ring into MC-1 in June

It takes a collaboration (FNAL E989)

Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Mississippi
- Kentucky
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

- **National Labs**
  - Argonne
  - Brookhaven
  - Fermilab
- **Consultants**
  - Muons, Inc.

Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:

- Shanghai

The Netherlands:

- Groningen

Germany:

- Dresden

Japan:

- Osaka

Russia:

- Dubna
- PNPI
- Novosibirsk

England

University College London
Liverpool
Oxford
Rutherford Lab

Korea

KAIST

FTE Committed

Survey of Collaboration for P5

Construction	Runnning	Analysis
2014 - 2016	2017-2018	2019 - 2022
91	80	68

>150 collaborators from 38 institutions

<u>Spokespersons</u>
David Hertzog (UW)
Lee Roberts (Boston)

Timeline

Activities	2013	2014	2015	2016	2017	2018	2019	2020	2021
Project Milestones									
Conceptual Design									
Preliminary Design									
Final Design									
CD-3 work									
Accelerator Improvements									
Installation Sequence									
MC-1 construction									
Magnet Construction									
Cooldown									
Shimming of Field									
Install Vacuum, other in-ring eqp									
Install Detector / Electronics									
Commissioning and Running									
Beam Tests/Commissioning									
Experiment Commissioning									
Mu + Data Taking									
Result 1									
Analysis									
Result 2									
Upgrades, Mu- Run Prep									
Mu- Running									
Result 3									

Representative, not schedule

18/24 m

Project Phase **Experiment Phase**

Some New Collaboration Structures

Now, just some suggestions. The IB and Self_Nominations are required

Group	Charge / Focus
End-to-End simulations and rate estimates **Mike Syphers** **Volodja Tishchenko**	Provide updated estimate of muon flux and muon phase space parameters to front of Inflector; including spin tracking and differential parameters from the front to the rear of the bunch; Interface with Injection Group to optimize storage rate
Injection & storage fraction **David Rubin** **Nathan Froemming**	Provide updated estimate of stored muon flux and expected stored muon phase space; estimate muon loss rate; provide interface to Simulation group regarding muon gas gun
Omega_p analysis and systematics coordinator **TBD senior** **Brendan Kiburg**	Develop analysis structure for obtaining omega_p from sets of NMR probes, trolley, etc. Group to keep eye on Field Systematic Error budget and report on perceived progress from the analysis side. Define measurement protocols (trolley run frequency, value of WFDs on select probes, etc.). Interface with Project Ring Team, DAQ Team, Slow Control.
Omega_a analysis and systematics coordinator **TBD - senior** **TBD - postdoc**	Develop analysis protocol for the near-term design phase. Includes Detector related Systematics for Gain and Pileup. Interface with Detector Team on designed hardware and performance. This team will evolve and split once real data is in sight.
Beam Physics Systematics studies **Bill Morse & TBD**	Muon loss, E and Pitch, Differential decay; CBO, New ideas and worries; Radial distribution; Interface with tracker, calo and fiber harp groups
EDM **Paul Debevec**	Physics case; implementation; statistical reach
Simulation Generation & Models **Adam Lyon** **TBD postdoc**	Build the main ART-based architecture and interface with other teams to provide productions of simulated events. Train the many young people; workshops, etc. Verification studies. Resource coordination

Computing Projects @ Muon g-2

1) Simulations and Offline
2) Development Environment
3) Interactive Analysis
4) Data Management

Simulations & Offline

Simulations played a minor role in BNL E821
(Preferred direct calculations; not part of Nucl culture)

g2migtrace written after run to explore improvements
to ring – Full Geant4 simulation of ring, dynamics, detectors

Monolithic system – Hard to alter – Hard to work together

The “killer” use case…

In g2migtrace/src/primaryConstruction.cc

```
// constructionMaterials is essentially a "materials library" class.
// Passing to to construction functions allows access to all materials

  /**** BEGIN CONSTRUCTION PROCESS  ****/

  // Construct the world volume
  labPTR = lab -> ConstructLab();
  // Construct the "holders" of the actual physical objects
#ifdef TESTBEAM
  ArcH.push_back(labPTR);
#else
  ArcH = arc->ConstructArcs(labPTR);
#endif
  // Build the calorimeters
  //  cal -> ConstructCalorimeters(ArcH);
   station->ConstructStations(ArcH);
#ifndef TESTBEAM
  // Build the physical vacuum chambers and the vacuum itself
  VacH = vC -> ConstructVacChamber(ArcH);
```

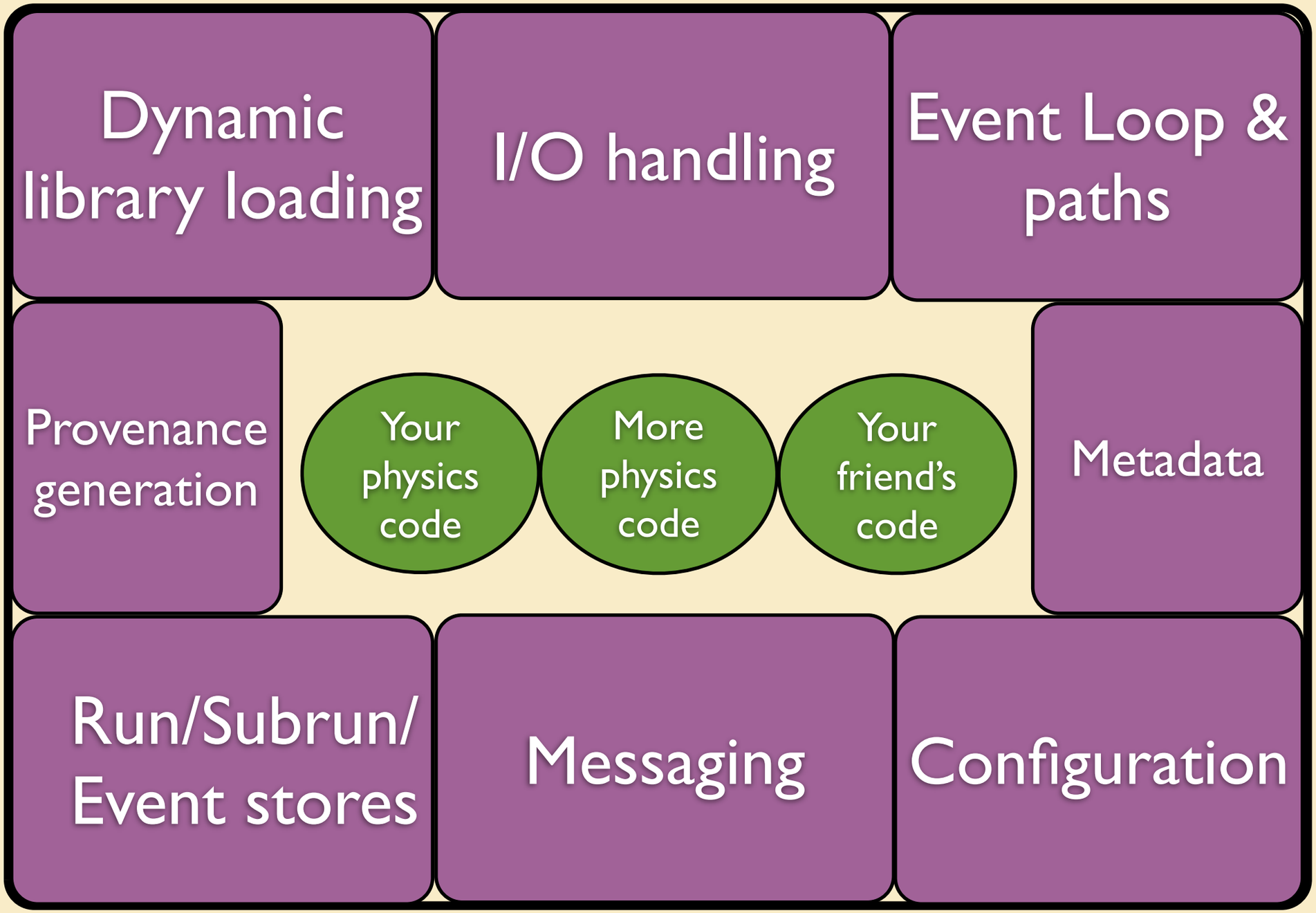
WHAT IF WE WANT TO TEST A DIFFERENT DETECTOR?

THIS CODE CRASHES IN OPTIMIZED BUILDS. #IFDEF CREATED A SUBTLE HARD TO FIND BUG

THIS KIND OF CODE IS VERY HARD TO EXCISE LATER

We can't maintain code like this and our sanity

What does the ART framework do?



Code you write

Code you use from the framework

ARTG4

Needed a generic interface layer between Geant4 and Art

Summer student Tasha Arvanitis and I set out to work on writing ArtG4 - necessary for g2migtrace port

Tasha: (then Freshman) at Harvey Mudd College [was also here as an IMSA High School student]

With some C++ experience, Tasha quickly learned ART and appreciated its capabilities

See ArtG4 Seminar

Hans Wenzel has extended ArtG4 to handle GDML

Daniel's group considering taking over support

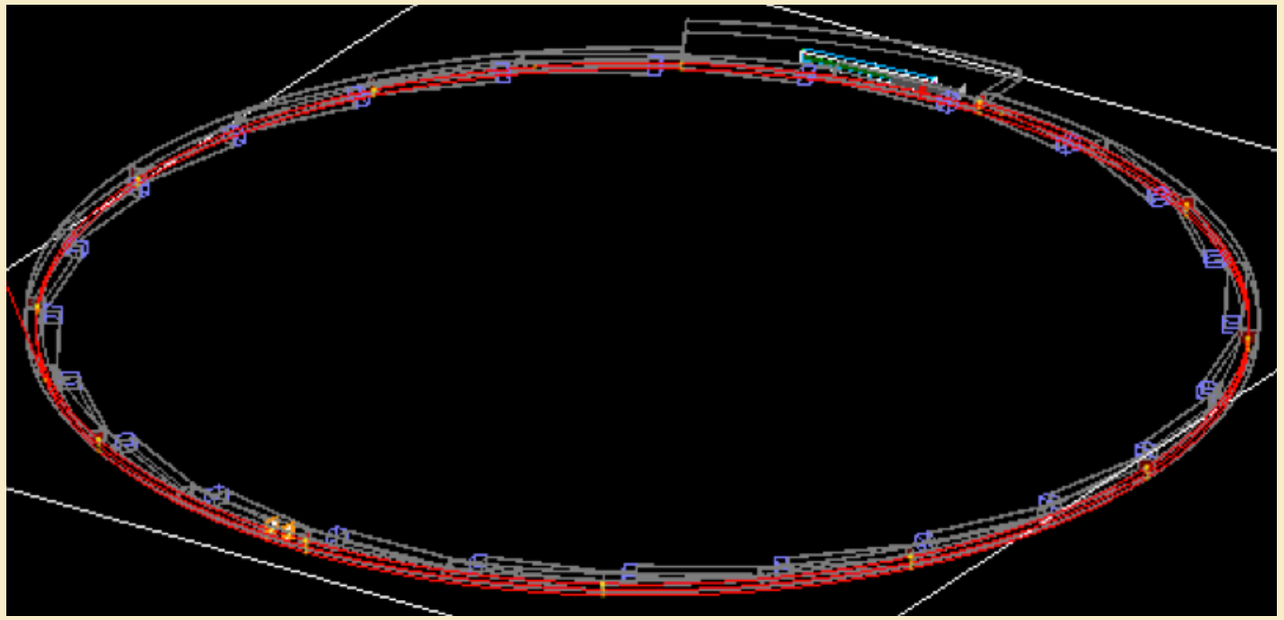
g2sim / ring + detectors simulation

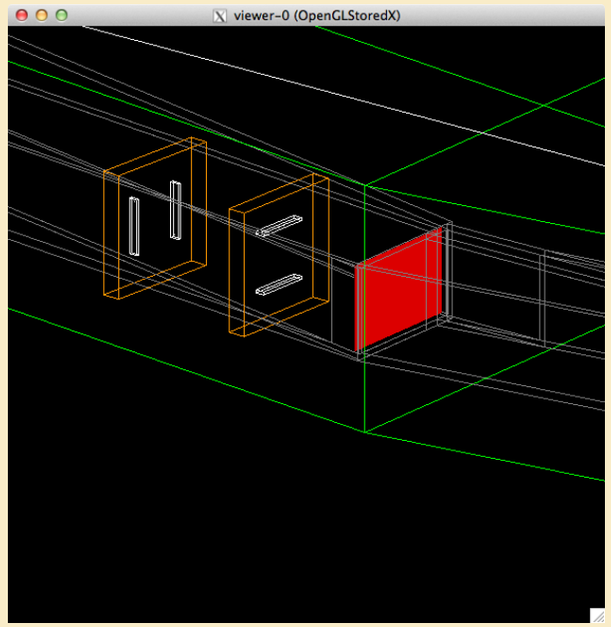
Started Oct 12

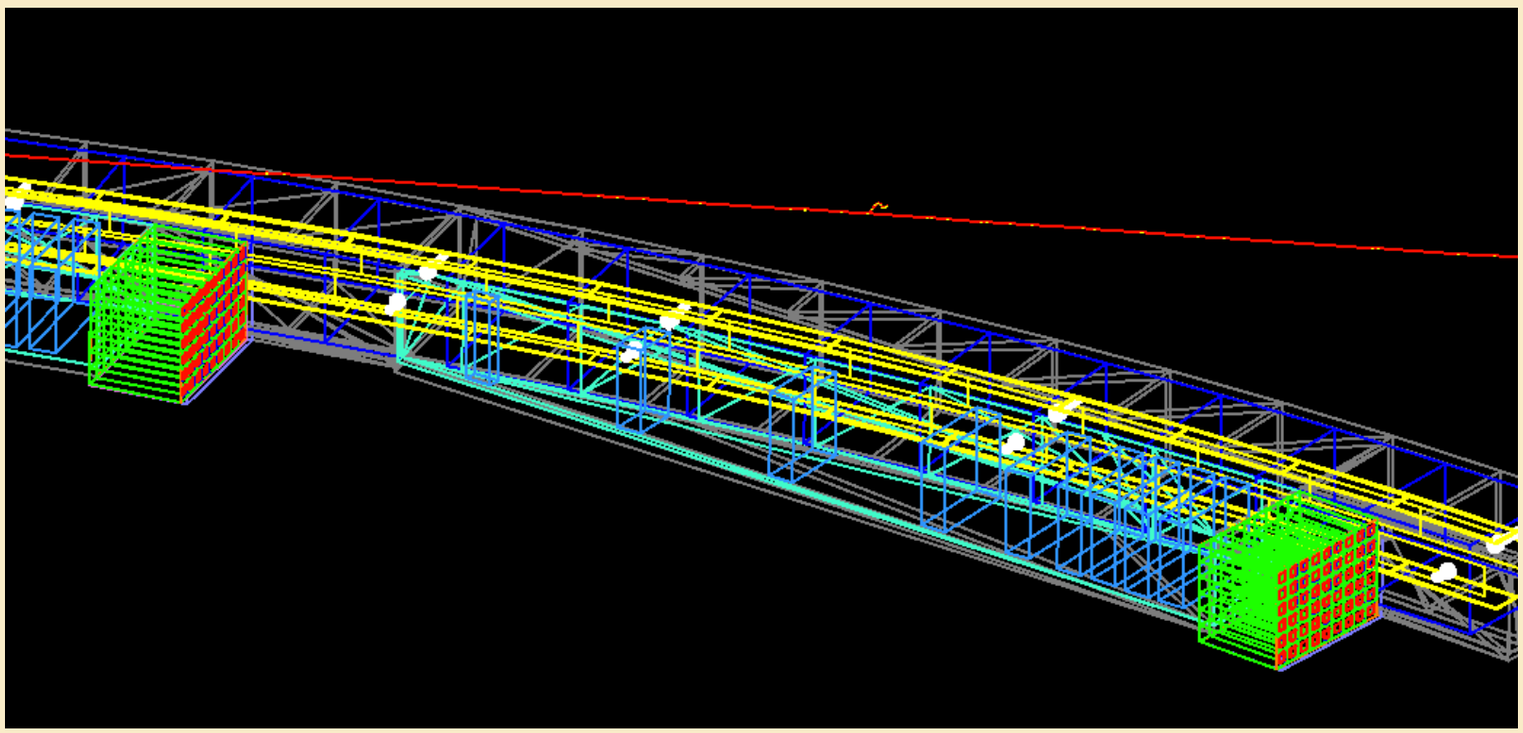
4 months with 5 active people

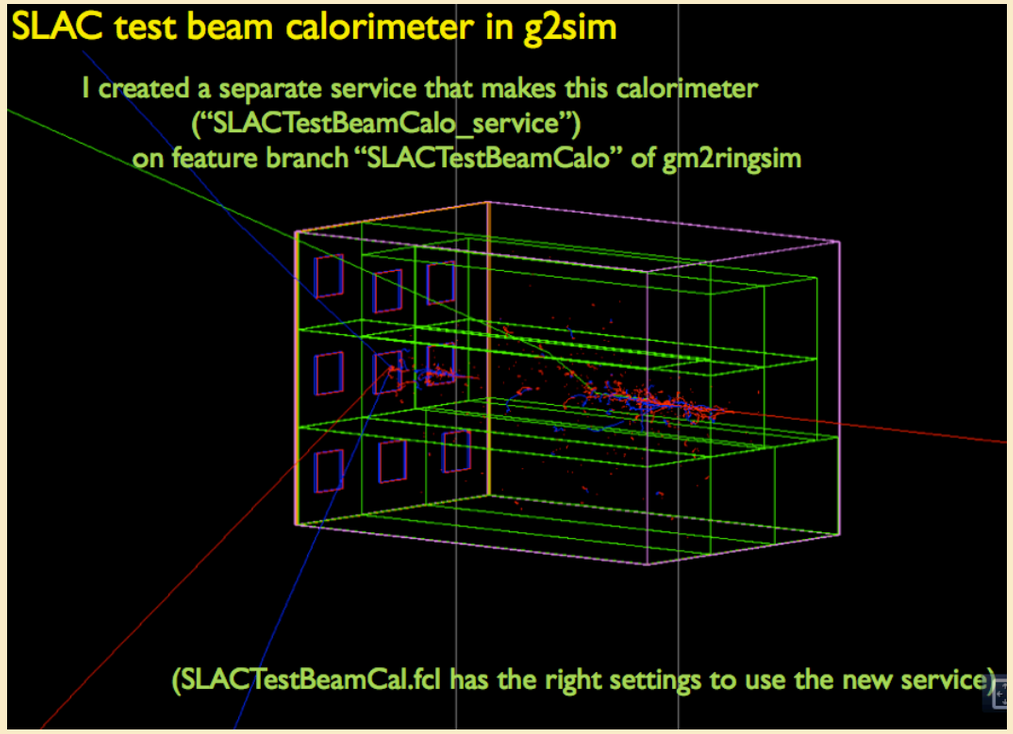
Now have many more analyzing

Art has made simulations a success

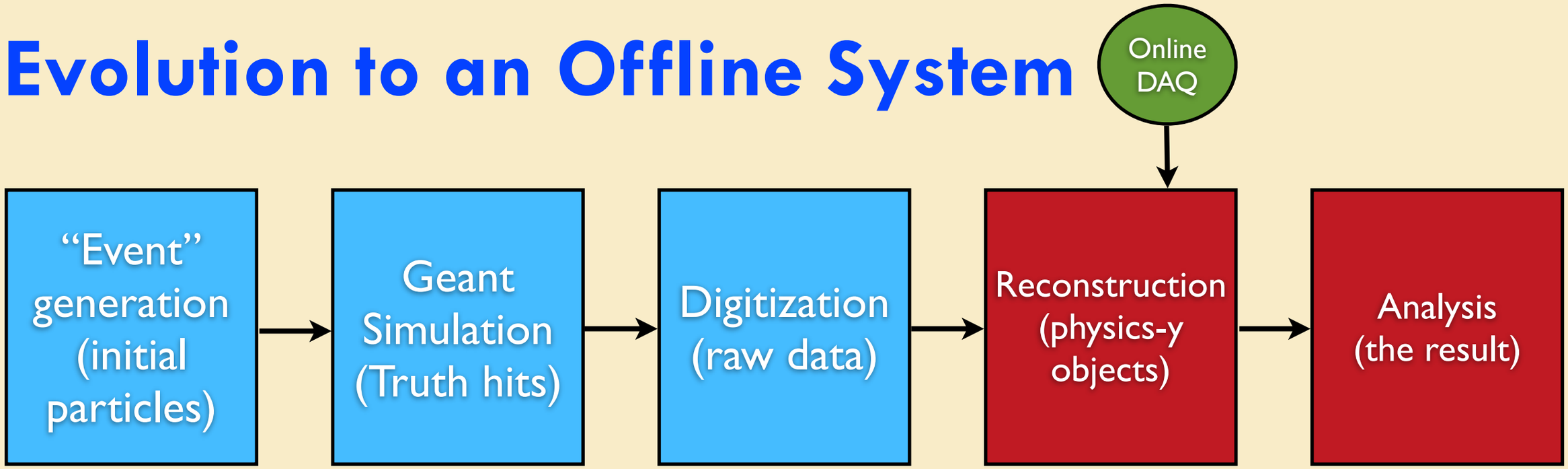








Evolution to an Offline System

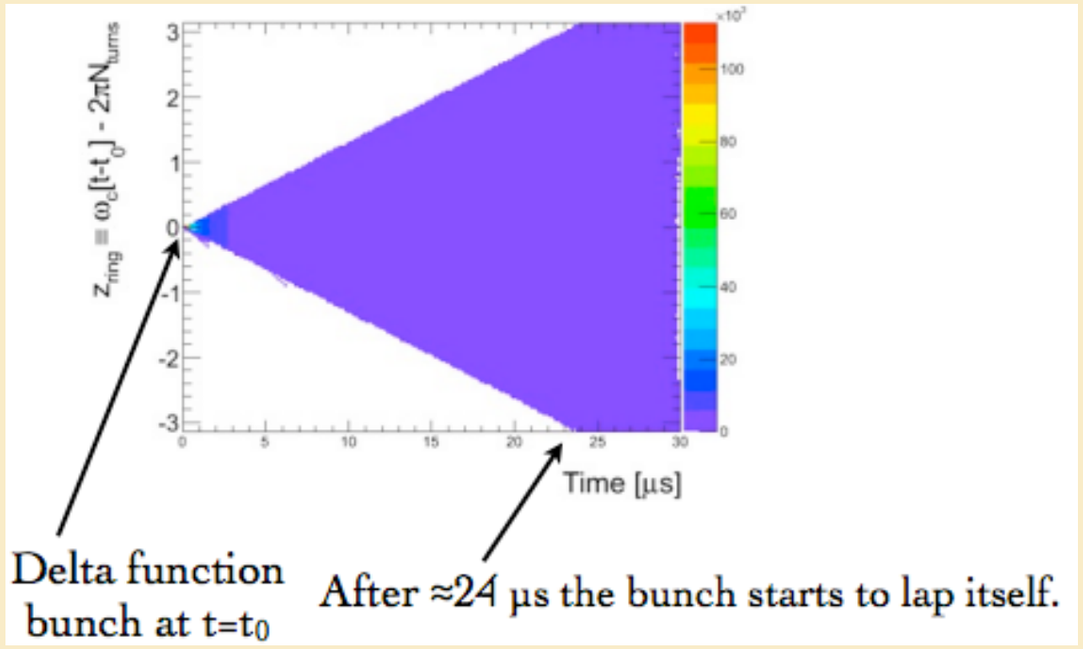


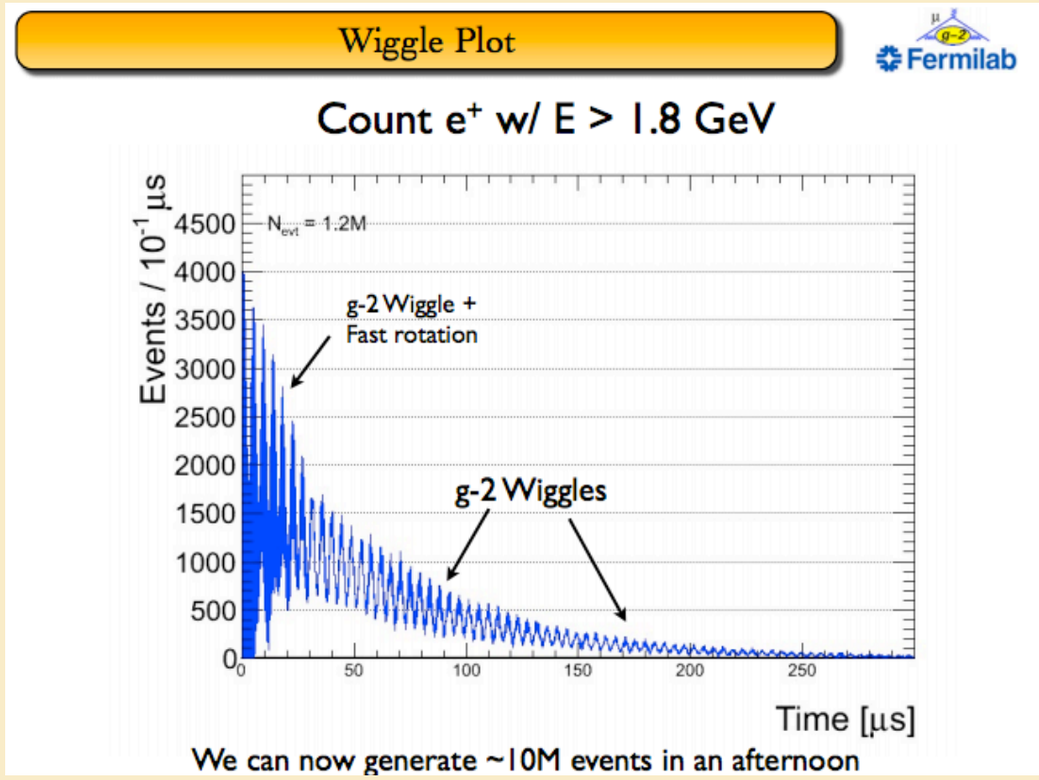
"Event" generation (initial particles)	Geant Simulation (Truth hits)	Digitization (raw data)	Reconstruction (physics-y objects)	Analysis (the result)
o Particle guns and physics models	o The ring simulation including sensitive detectors	o SiPM response o Straw response o Calibrated hits	o Fit waveforms for energy and times o Cluster finding	o All the things you do to determine omega_a
o Complete	o Outputs "Truth" hits (where particles went and how much energy they deposited where) o Detector correlations (e.g. crystal sharing) o All infrastructure complete. Used for studies	o Waveform generation o Fills and islands o Output is simulated "raw" data, like what the DAQ writes out to tape o Calorimeter campaign focusing here	o Reconstruct and fit tracks o Output is physics-y objects that can be analyzed o Tracking focusing here	o Not started yet

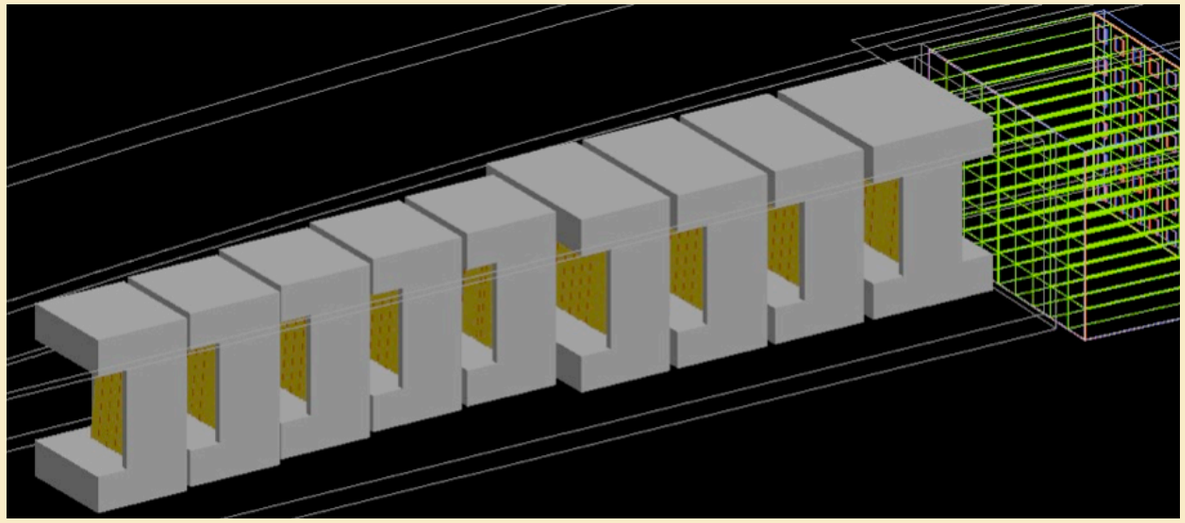
Building all of these critical tools takes major effort

Simulations and Offline Plans

- o Simulation gets beam dynamics correct
- o We're under the gun to do important studies
- o Need to complete necessary tools
- o Plan big simulation runs for summer 2014
- o Major effort from FNAL, Cornell, UW, NWU







Geometry is complicated so we use the simulation to test fit of components

g-2 Development Environment

I designed the environment in 2012 (excellent collaboration with Art team)

Principles:
- **Science demands reproducibility**
- **Consistency, flexibility**
- **Facilitate collaboration**
- **Use complicated C++ written by experts (not us)**

Implementation:
- **Art**
- **git, git-flow (simplifies and enforces a git workflow), & Redmine**
- **Take as much as possible from the Art developers and extend**
- **CMake**
- **Relocatable UPS**

Extensions:
- **Build multiple repositories simultaneously with automatic dependencies**
- **Convenience command line tool “gm2d”**
- **Local releases**
- **Mac OSX Build of Art**

Present and future work on Env

Development environment has been a big success

Now: Collaborating with LArSoft (gm2d becomes “mrb”);
We sat at a version of Art and dependencies for a year; now upgraded to latest
Distribution via CVMFS

Near future: Need to develop a release strategy and system (lots of expertise in collaboration and SCD); Automate builds

Need to explore databases (geometry, calibrations)

Challenge of Interactive Analysis

Art is geared for batch analysis

Can Art be extended for interactive analysis?
E.g. Creating plots on the fly; playing with the data

Can we avoid the proliferation of alternate (often subpar) frameworks written to get closer to Root for analysis?

Art is an ideal framework – knows the data structures; links to Root

Needs super-efficient event processing capabilities

See CS-doc-5268

Jim & Marc are exploring these issues

Connection to Big Data?

Data Management

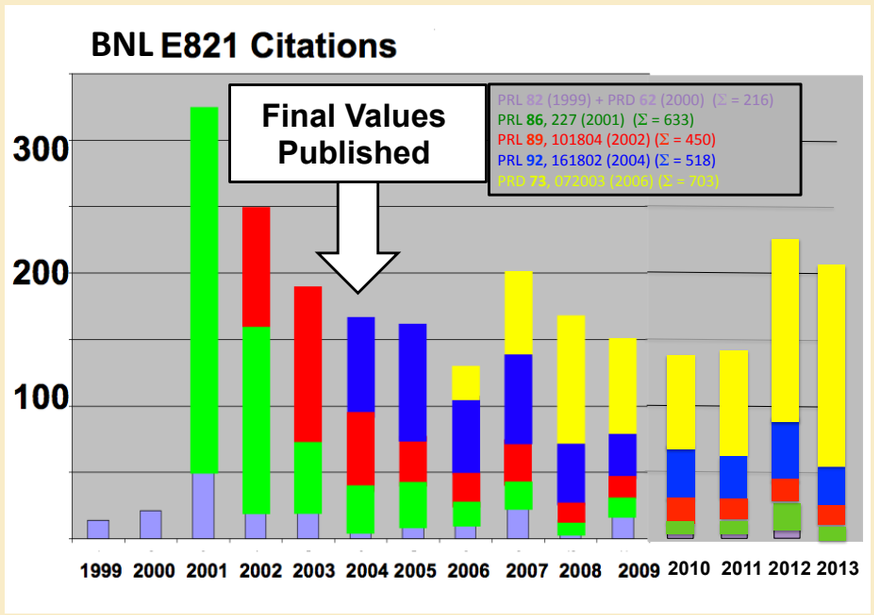
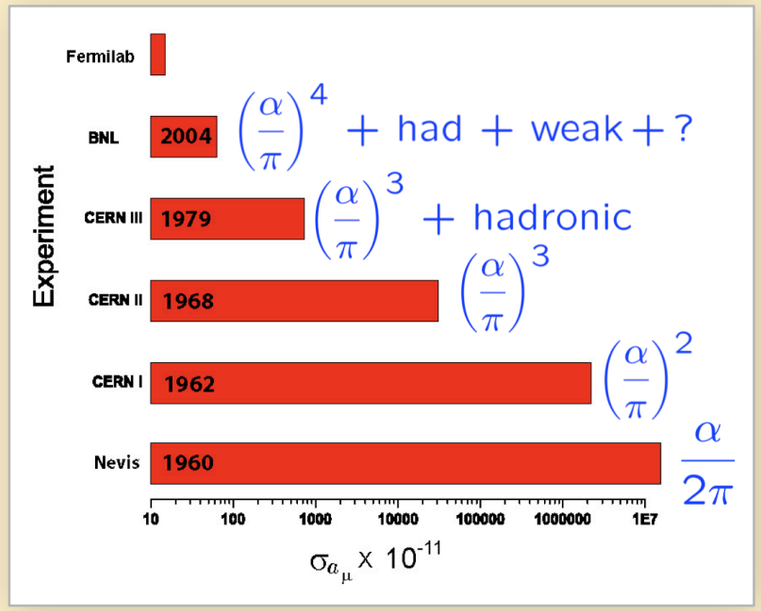
o Late to the SAM/remote processing game (NOvA, uBoone ahead of us)
o We aren't ready for it yet, but will be soon
o Several institutions interested in contributing batch slots (e.g. Cornell)

o Push on two fronts:
1) Use of xrootd (it's supposed to be the future)
2) Data-processing-as-a-service (simplify DM services to turn-key, improve user interfaces)

Summary

- Muon *g*-2 is a compelling experiment
  Is the discrepancy new physics? What is it telling us?

- Project is off to a roaring start
  reuse of equipment, experienced and fun collaboration (old+new),
  magnet move extreme success with huge PR for the lab,
  performance at CD-1 review raised the bar for readiness

- Timeline relevant to current physics priorities

- Computing challenges are important and interesting
  Heavy use of SCD tools and expertise
  Art has truly enabled our simulation & offline work and strong collaboration