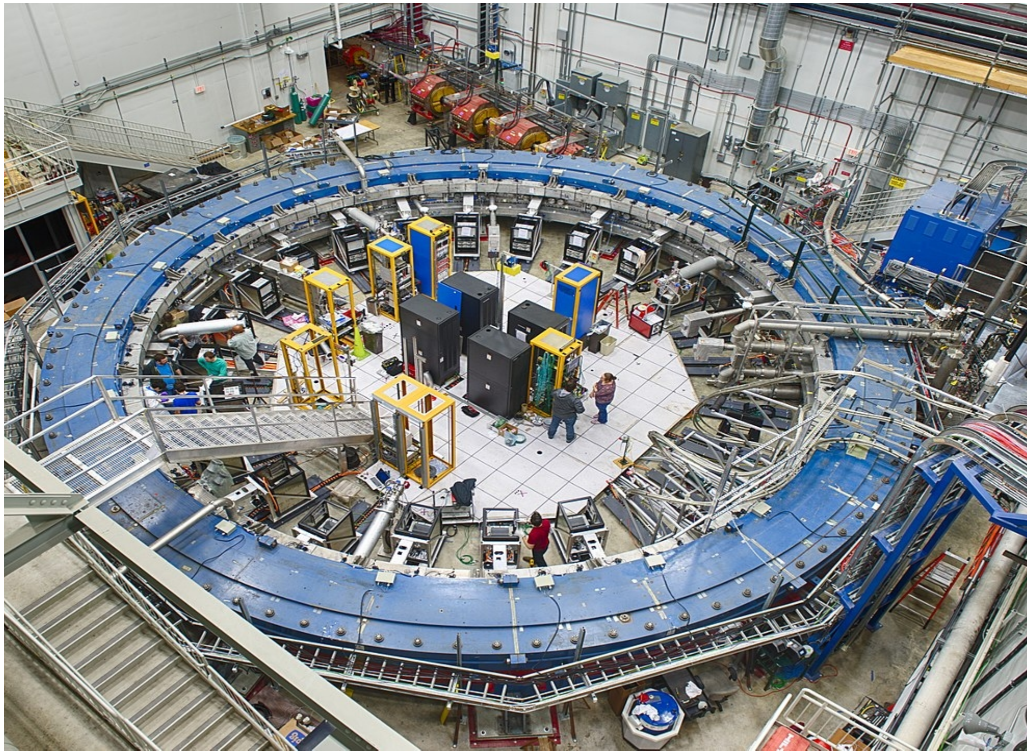


The computing of the precision Muon g-2 Experiment at Fermilab

Workshop sul Calcolo nell'I.N.F.N.
Palau – 20 May 2024

Paolo Girotti (INFN Pisa)
on behalf of the Muon g-2 collaboration

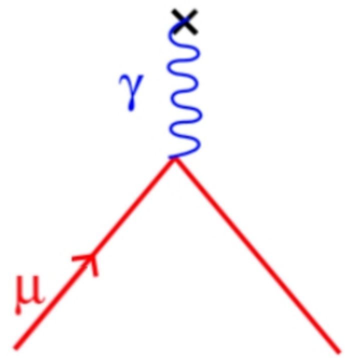
Outline

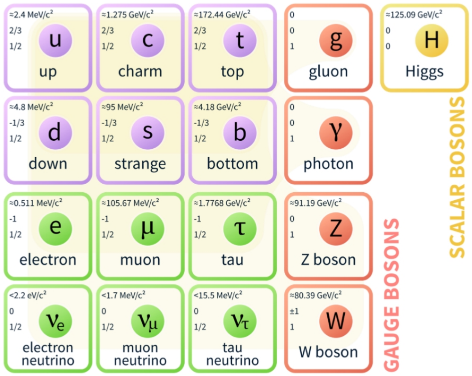
- Muon g-2 in a nutshell
- The computing of g-2
- Infrastructure and production
- Challenges and solutions

The muon g-2

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

- The magnetic moment of the muon is proportional to the g-factor
- **g** encodes all the possible virtual interactions between the muon and the magnetic field
  - With no virtual quantum interactions, **g=2**





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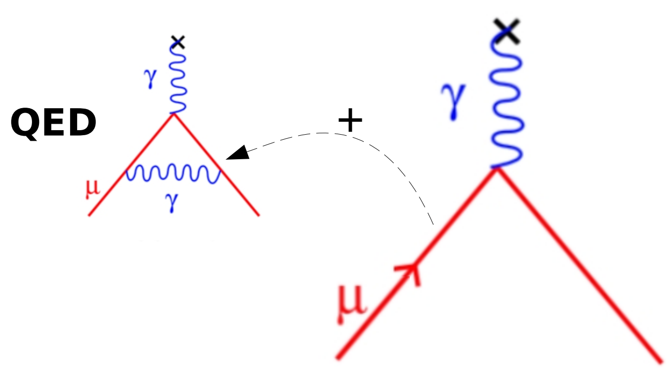

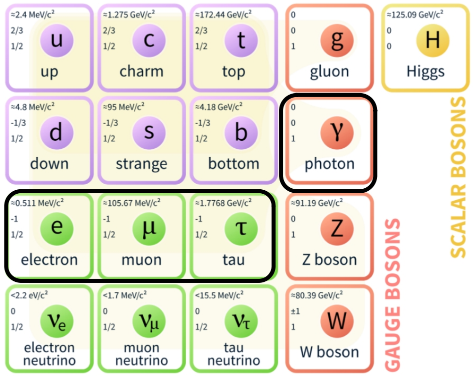

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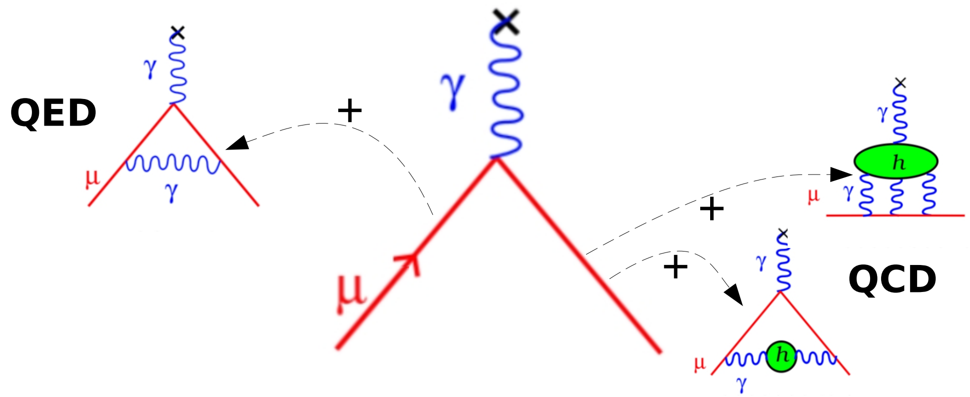

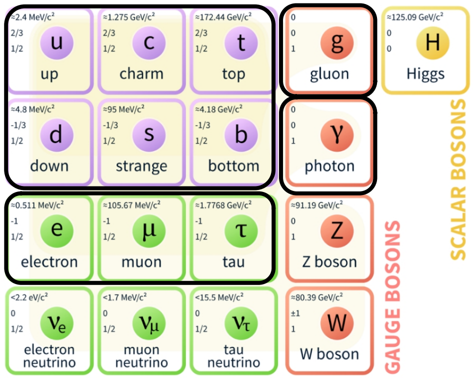

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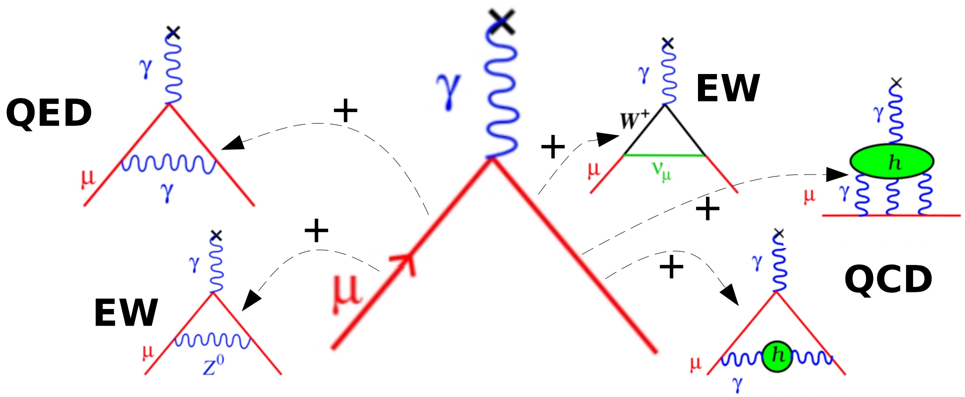
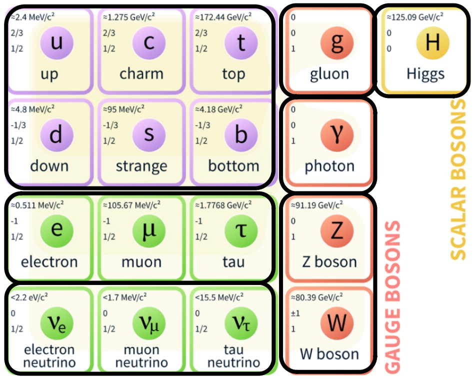
Aoyama et al. (2020)
https://doi.org/10.1016/j.physrep.2020.07.006





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  - Is there something else?

Aoyama et al. (2020)
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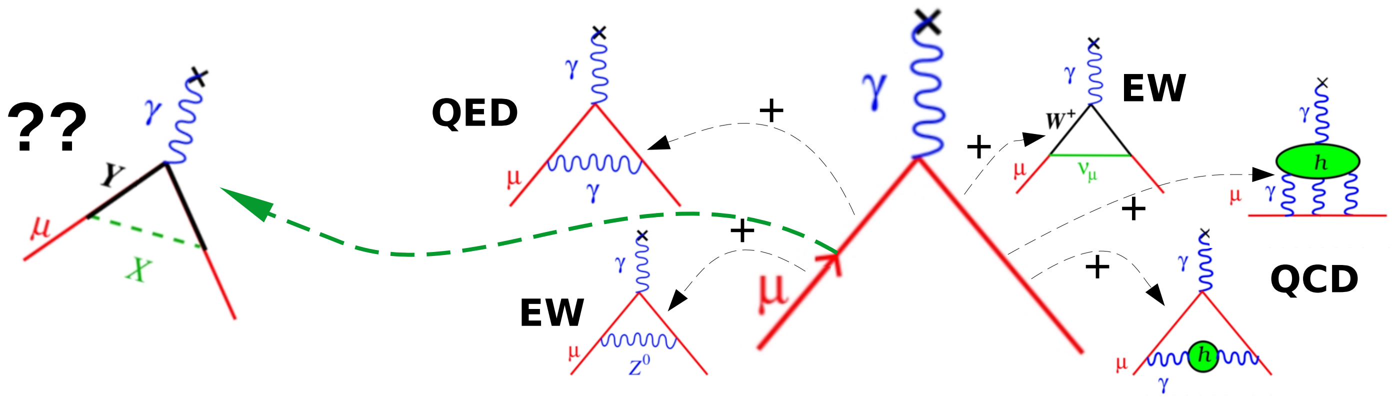
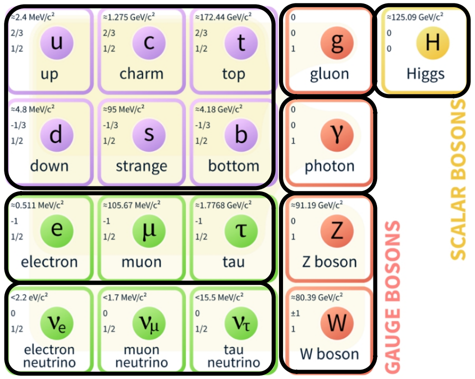
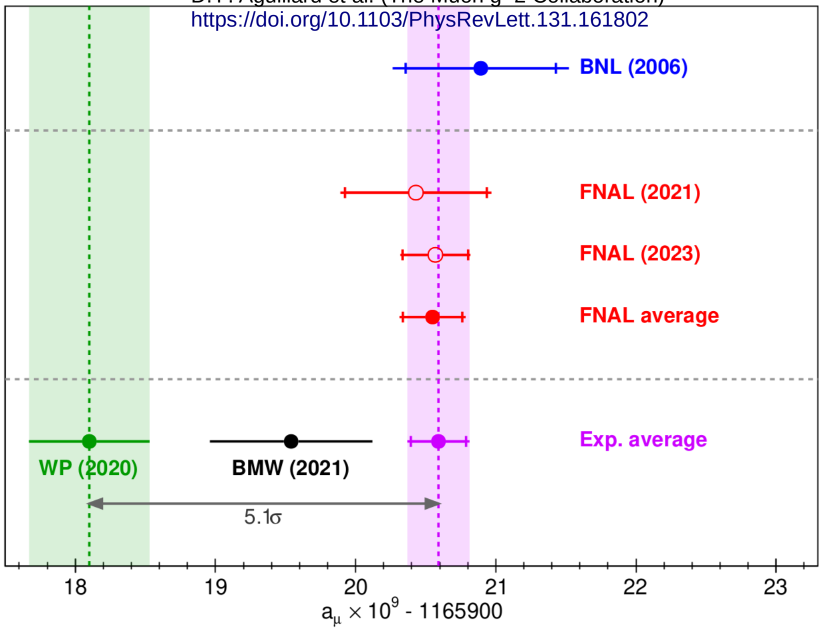


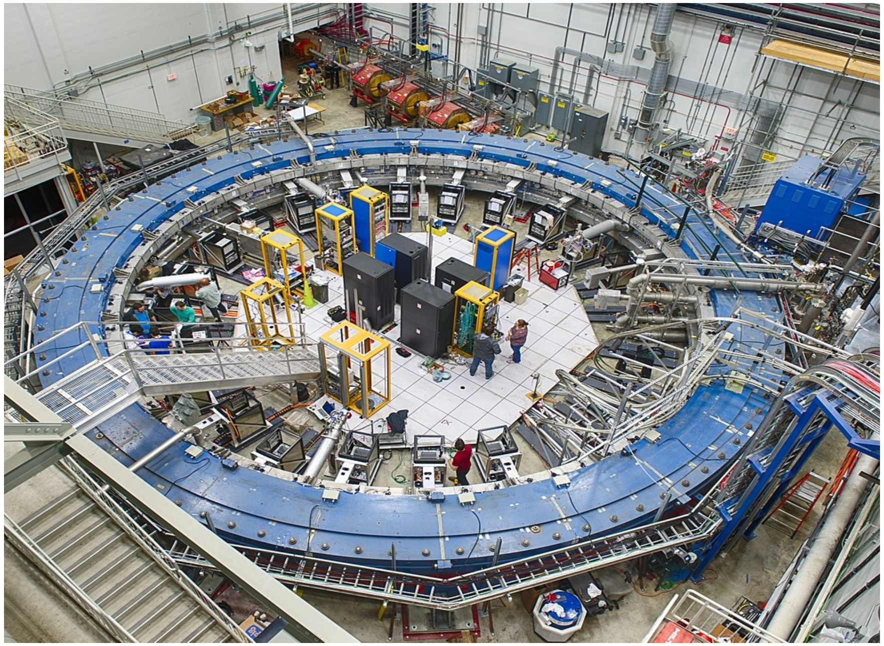


Muon g-2 Experiment

- Measurement of the Muon anomalous magnetic moment at 140 ppb
- Results published in 2021 & 2023
  - Final one expected in 2025
- >5σ tension with 2020 theory prediction

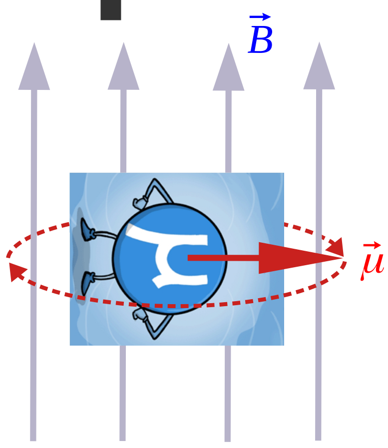
D. P. Aguillard et al. (The Muon g−2 Collaboration)
https://doi.org/10.1103/PhysRevLett.131.161802





Experimental principle

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



- Beam of polarized muons in a storage ring
- In magnetic field, the muon spin precesses slightly faster than its cyclotron frequency

$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma} \qquad \vec{\omega}_c = -\frac{e\vec{B}}{m\gamma}$$

- If we do the difference we get...

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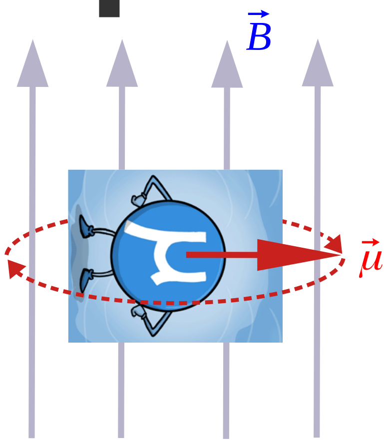

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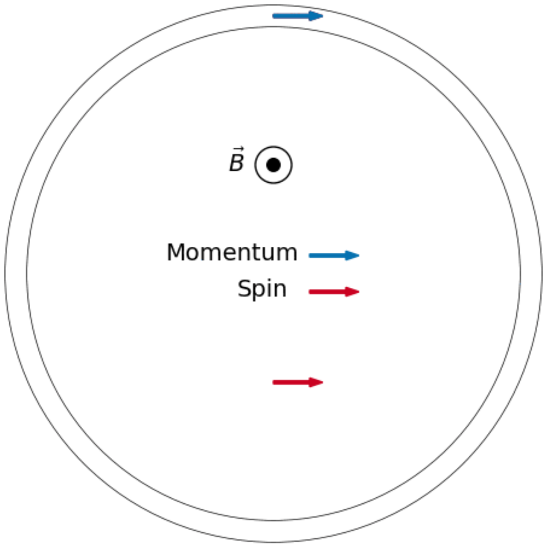
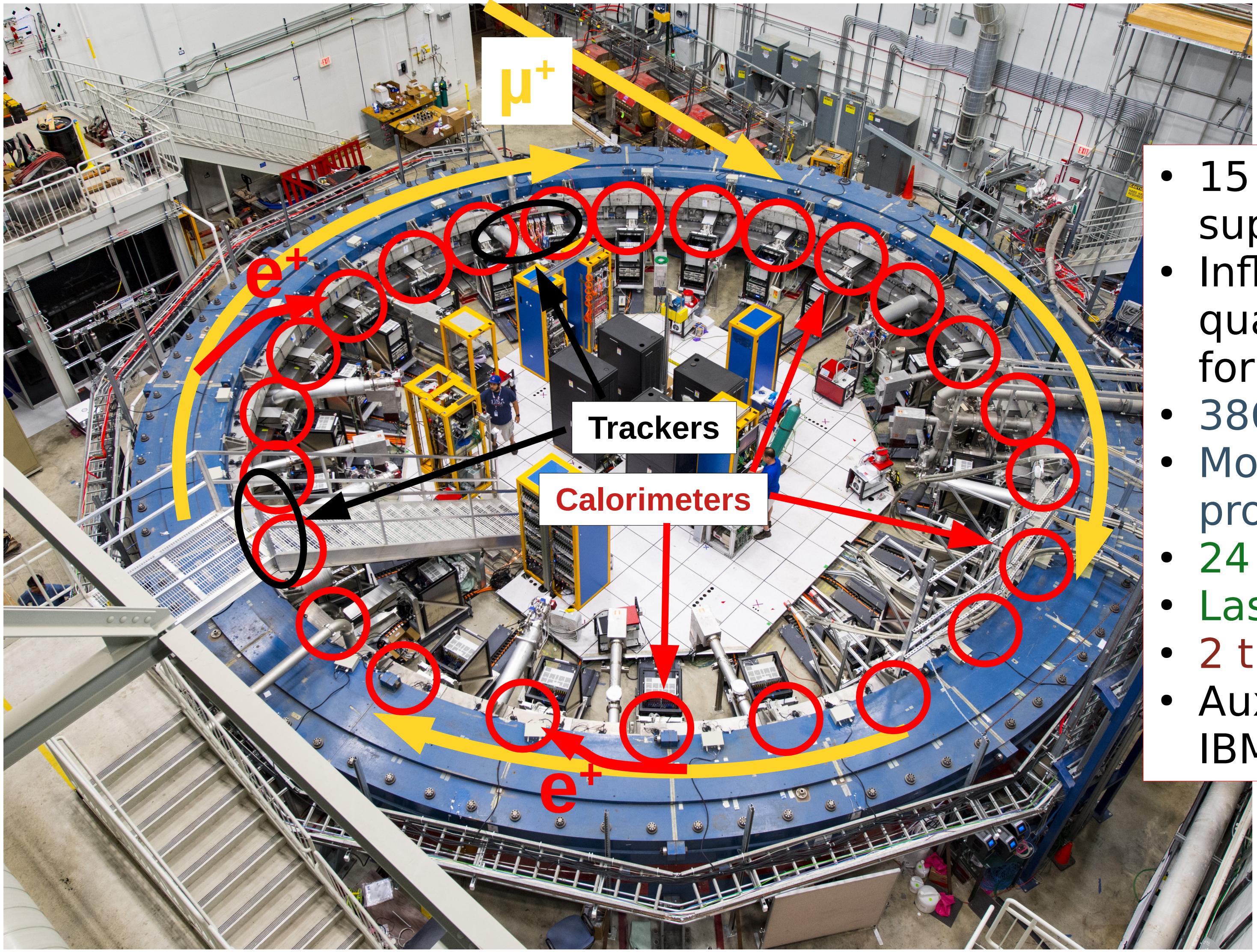
- If we do the difference we get…

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -a_\mu\frac{e\vec{B}}{m}$$

- This “anomalous” precession frequency is proportional to g-2 and to the magnetic field
- ω_a is entirely due to the virtual interactions between the muon and the field
- Measure $\boldsymbol{\omega_a}$ and **B** → obtain $\mathbf{a_\mu}$

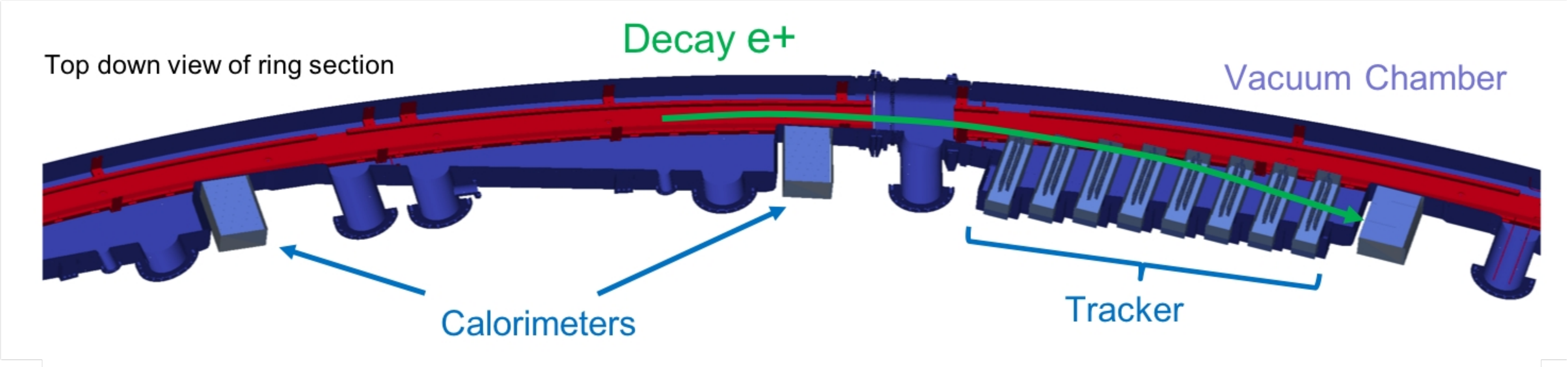


The Muon g-2 Experiment

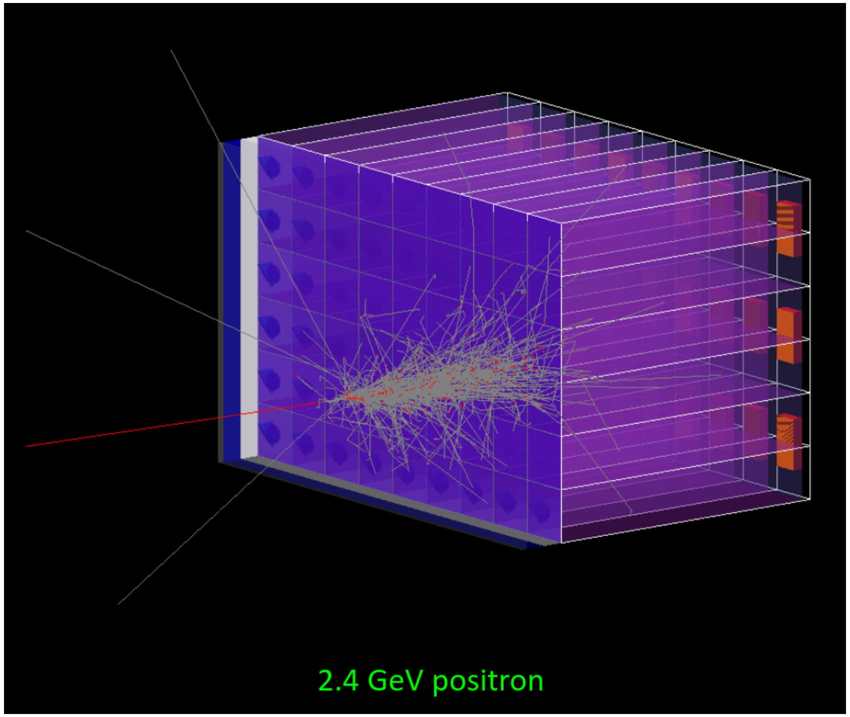


- 15 meter wide dipole superconducting magnet
- Inflector, kickers, quadrupoles, collimators for beam insertion
- 386 NMR probes
- Moving trolley with 17 probes **B**
- 24 calorimeters ω_a
- Laser calibration system
- 2 tracker stations $\rho(r)$
- Auxiliary detectors: T0, IBMs, Fiber harps

Main detectors



- 24 Electromagnetic calorimeters
  - 1296 channels digitized at 12 bit
- 2 Tracker stations
  - 2048 channels
- Calorimeter SiPMs sampled at 800 Mhz
  - 1.5 TB/s of istantaneous data rate
  - Online GPU-based trigger for pulse detection → 50 ns waveforms
  - ~1 TB / hour of raw data stored



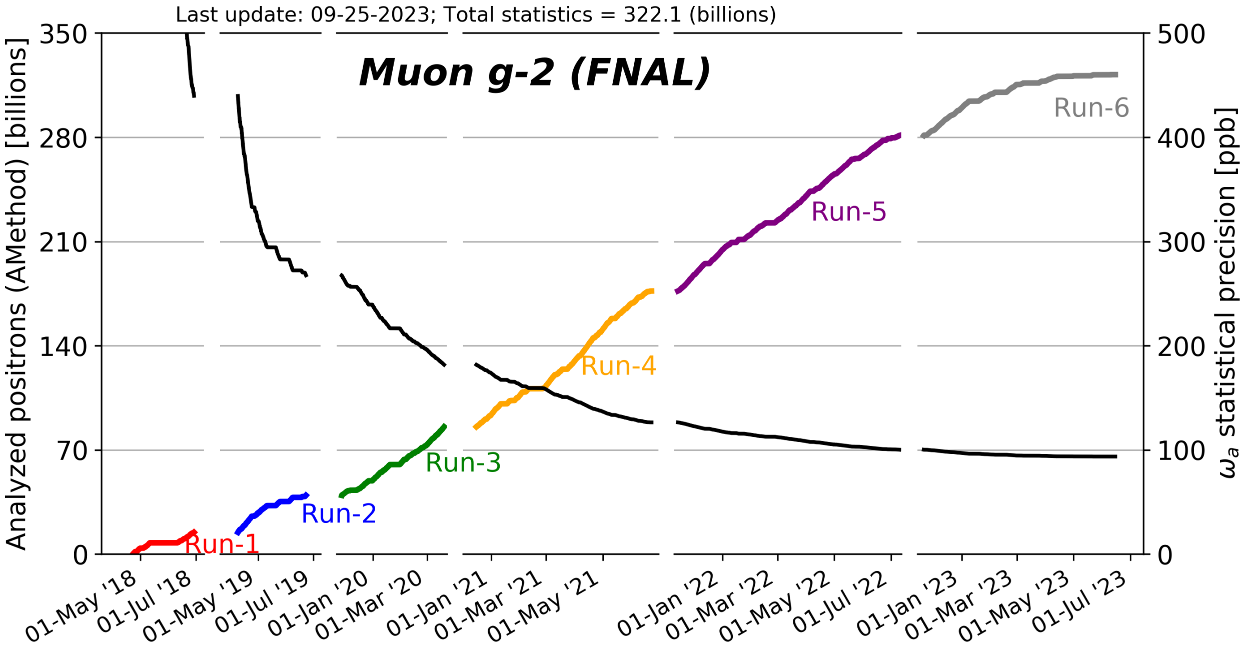
Big data

- 16 muon bunches every 1.4 s
- ~2000 muon decays over 700 μs
- ~2x10^4 s^{-1} decay detection rate
- 1 raw file (2GB) produced every ~7 s
- Six years of running

→ **~10 PB** of raw data (~5x10^6 files)

→ Simulation ~2 PB

	Raw	Reconst ructed	Nfiles [x10^3]
Run1	1.1 PB	0.3 PB	166
Run2	0.6 PB	0.6 PB	204
Run3	1.2 PB	1.3 PB	447
Run4	2.1 PB	2.4 PB	863
Run5	3.1 PB	3.4 PB	1286
Run6	1.9 PB	1.5 PB	595
Total	10 PB	9.5 PB	3500

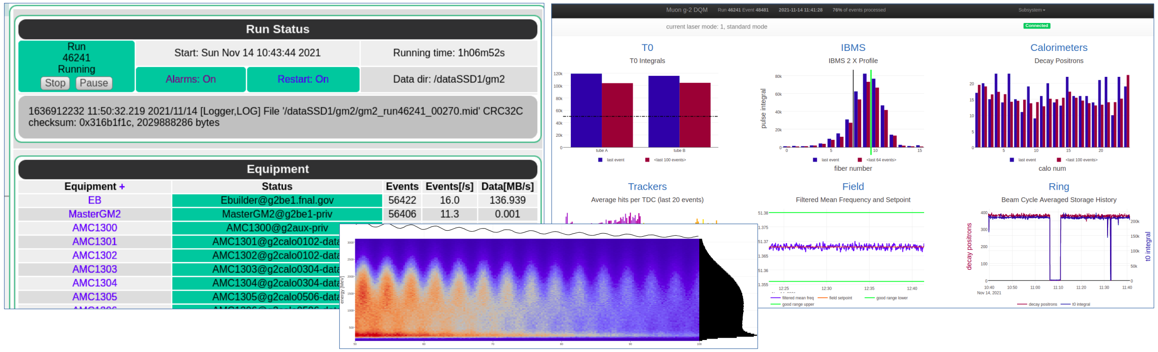


Data reconstruction

Raw data

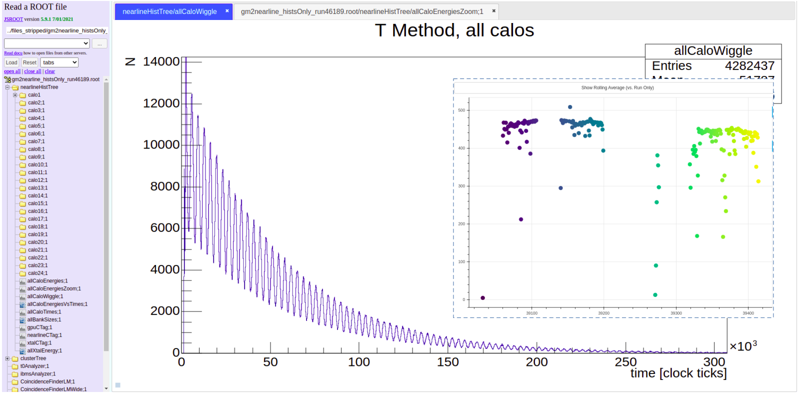
Online

- Fraction of data
- DAQ and DQM
- Instantaneous plots



Nearline

- All data
- Minimal calibration
- Results in ~30’



Offline

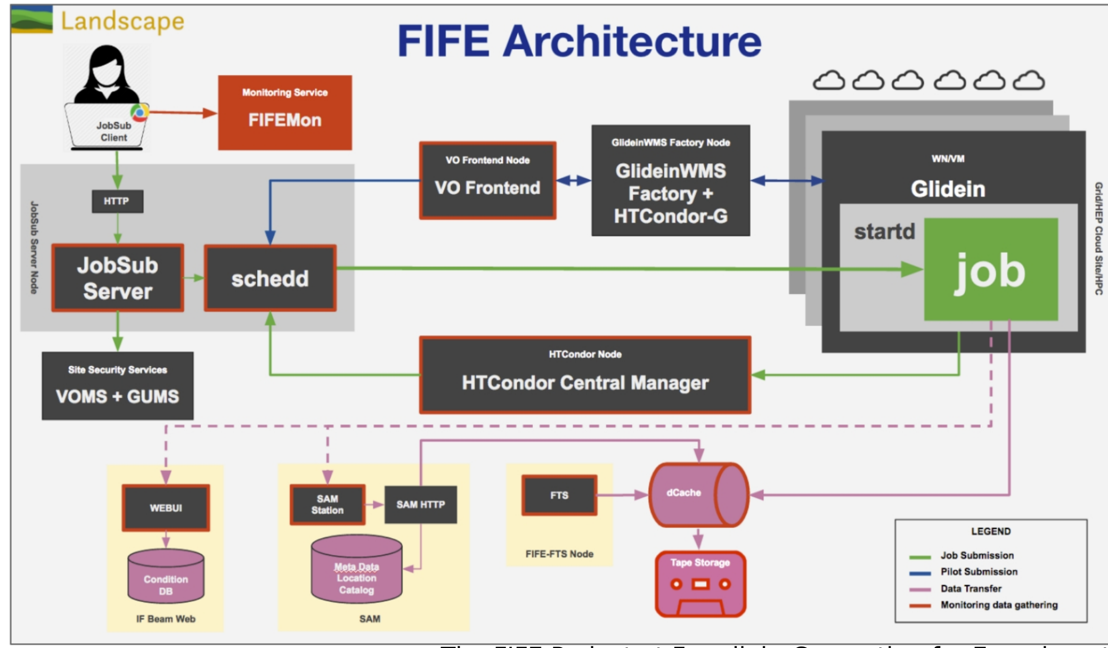
- Full calibration extracted and applied
- Multiple reconstruction techniques
- Produced on grid
- Results in ~1 year

Pre-production → Calibration → Full-production → DQC

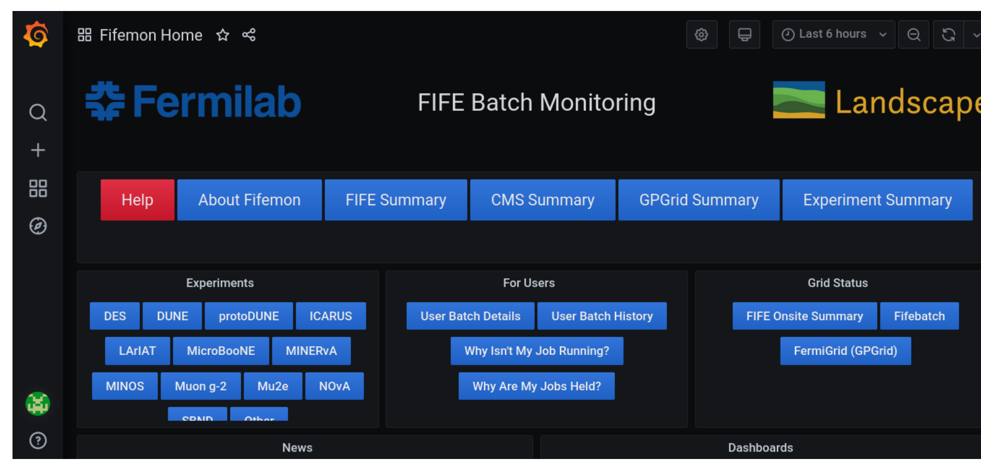
Production Operations Management System

FIFE environment

- **F**ab**r**Ic for **F**rontier **E**xperiments toolkit for data management and job submission
- SAM: metadata and datasets
- Samweb: SAM management and job progress visualization
- FTS: file detection, transfer and interface to SAM
- IFDH: high speed file transfer protocols
- Jobsub: job submission and scheduler for HTCondor
- POMS: production management
- Grafana: monitoring



The FIFE Project at Fermilab: Computing for Experiments
https://doi.org/10.22323/1.282.0176

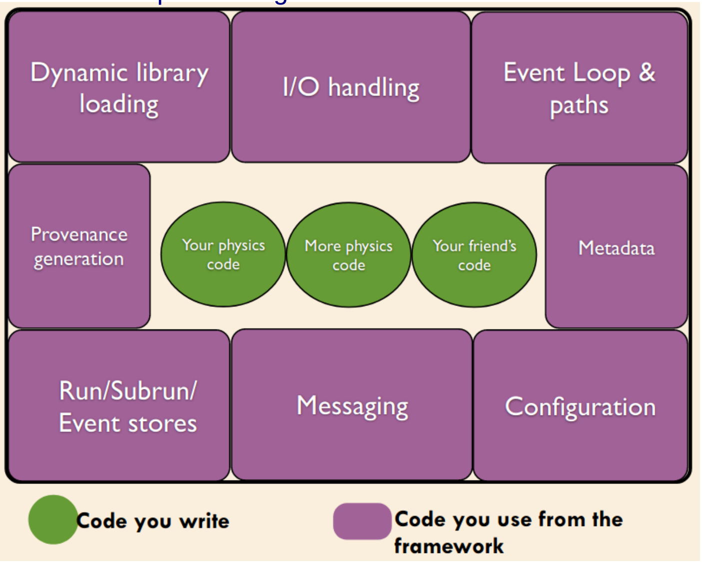


Software

- We use ***art*** framework
  - Highly modular
  - Made for HEP physics
  - Seamless transition between simulation and real data
- **ROOT/C++** based
- Version-controlled codebase
  - Hosted by Redmine
  - Now moved to GitHub
- Calibration constants stored on **PostgreSQL** conditions database
  - Based on **I**nterval **O**f **V**alidity

https://art.fnal.gov/

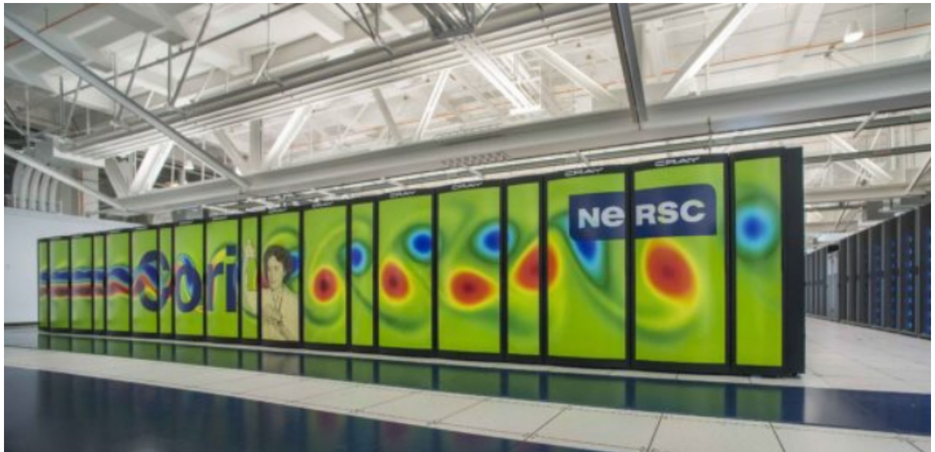
https://doi.org/10.1088/1742-6596/396/2/022020



Simulation

- Beam dynamics, detector acceptance, accurate field modeling
- Several simulation packages for the various parts of the beamline and the storage ring
  - MARS (Proton target)
  - BMAD (beamlines & g-2)
  - G4beamline (beamlines)
  - Gm2ringsim (injection & g-2)
  - COSY (g-2 storage ring)

CPU intensive (G4beamline, Gm2ringsim)



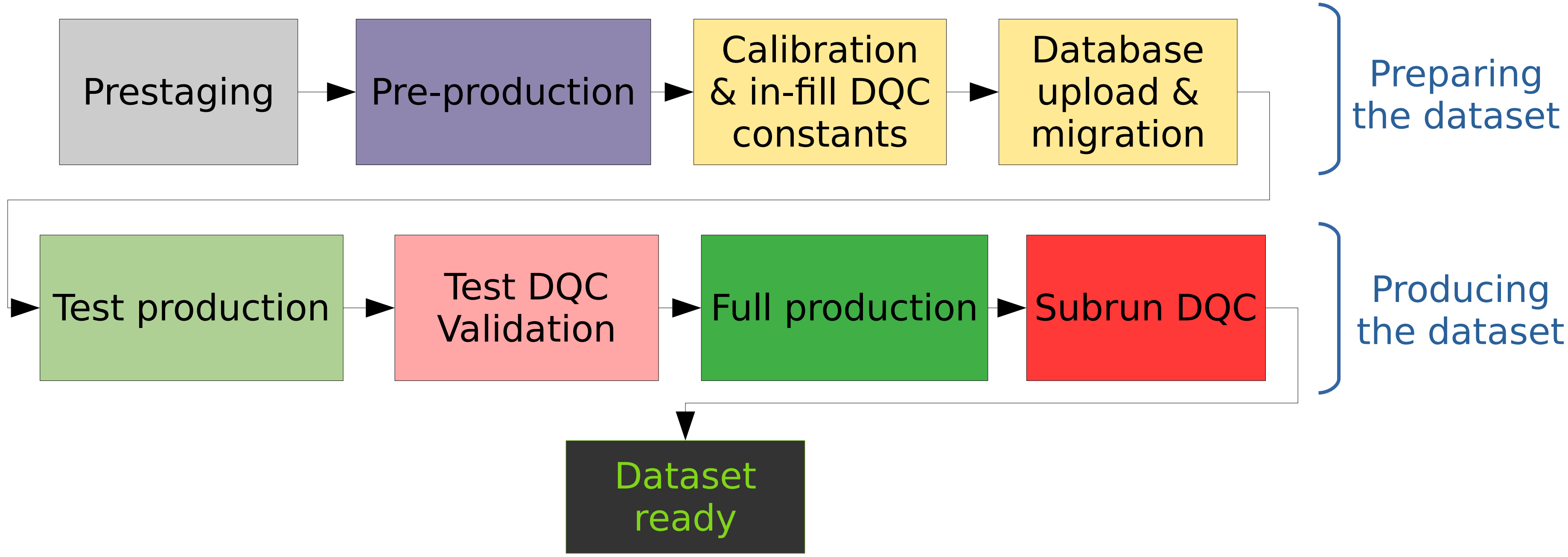
NERSC's Cori
~30 PFLOPS Cray XC40 machine

- Seamless interface between art and Geant4 developed by g-2
- Precision tracking over 200 km (up to 5000 turns in g-2 ring)
- Making use of HPC computing **@NERSC**
  - Many production completed with 10 B events

HEPCloud

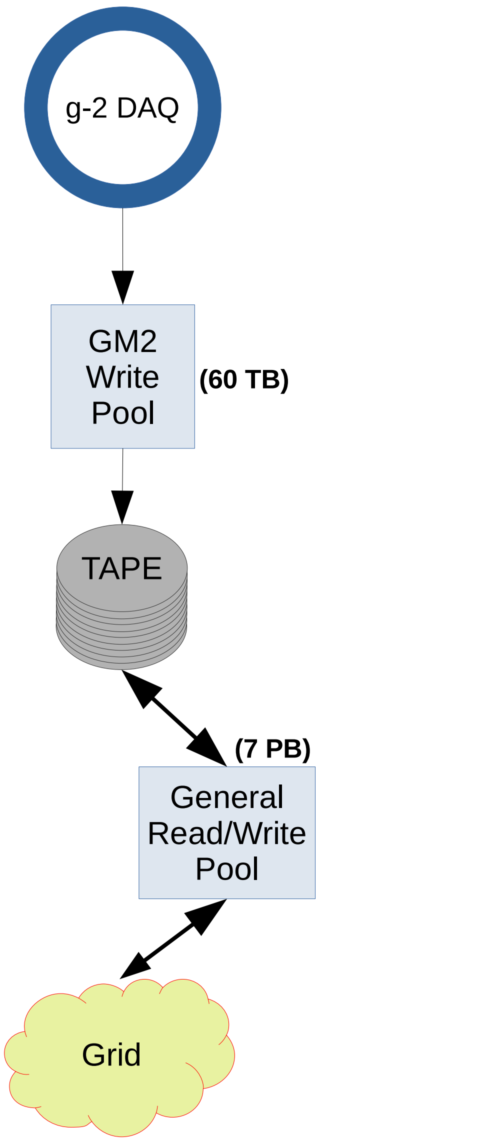
Production workflow

- Gain calibration of calorimeters is extracted from the data itself
  - Need to reconstruct the calorimeter data twice
- **Pre-production:** minimal reconstruction to extract calibrations
- **Full-production:** full reconstruction of calibrated data and DQC
- Rolling production over 85 datasets



Data staging

- Disk storage at Fermilab can’t hold all the data all the time
- First production step is to pre-stage the dataset
  - Typical dataset size: ~100k files, ~200 TiB
- Fermilab provides a common 7 PB disk pool shared by all experiments
  - Became a bottleneck for our production



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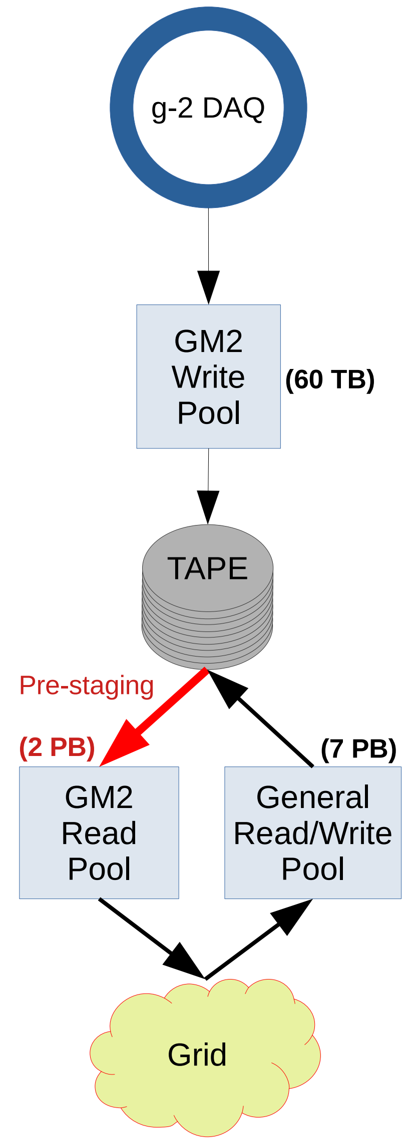
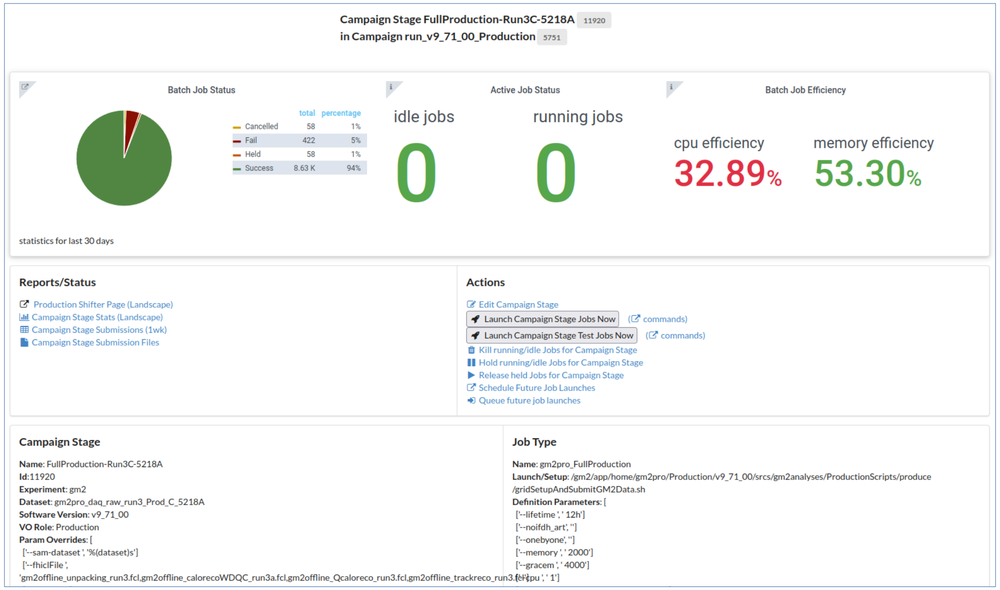
- Dedicated 1 → 1.4 → 2 PB GM2 read pool for prestaging raw files
  - Dedicated to production first, dedicated to analysis now
- Careful manual prestage scheduling
- Depending on infrastructure load, 3-6 days to prestage 200 TB of data from tape to disk

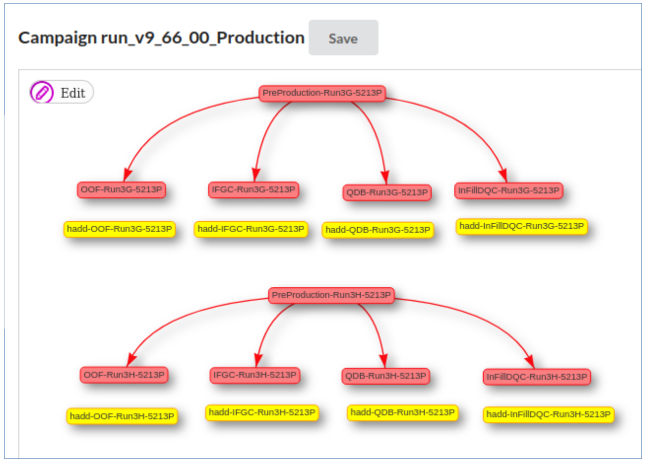


Running on GRID

- Production jobs run on **HTC Grid**
  - FermiGrid and OSG
  - 5000 reserved slots (1 thread, 2 GB) for g-2
  - Data I/O is handled by SAM, IFDH and FTS
- **POMS**
  - Excellent management service with GUI
  - Automatic slicing of dataset, sequential stages, recovery of failed jobs and scheduling
  - Addition: hybrid “gm2shifter” account with limited powers



Production Operations Management System



Challenges

- **Storage**: 10 PB of data on tape
  - Dedicated disk cache to avoid competition with other experiments
  - Prestaging scheduling
- **Computation**: 10^8 CPU hours, $5x10^6$ files
  - Parallelize reconstruction as much as possible
  - Code efficiency to use < 2 GB memory
  - Improved dataset slices and submission frequency to reduce overhead and maximize grid occupancy
- **Management** and workforce:
  - Collaboration-wide shifters
  - POMS and automatized recovery and post-processing scripts

Challenges

- **Accuracy and reliability:**
  - Multiple validation checks at several production steps
  - Periodic version-controlled software releases
- Computing intensive **simulation:**
  - Moved some of it to HPC supercomputers
- **Analysis**
  - Reduced ROOT trees/hists for analyzers
  - Reduced art skims → stored on cache
  - Institution-owned workstations and diskservers
- Slow reconstruction **turnaround**
  - Run-6 pre-production completely automatized and ran in parallel with data taking

Conclusions

- The Muon g-2 Experiment is a relatively small-sized experiment,
- All statistics contributes to the precision measurement → Big data to be processed and handled
- Data grew considerably from first to last run
  - Production improvements **increased speed by factor 5**
- Production is now complete
- Writing computing paper, expected preprint by end of year
- Final physics paper expected next year!

Dataset	N° of files	Size [TB]	Production time [days]	Rate [files/day]	Days after run ended
Run-2	267152	563	129	2071	750
Run-3	538622	1066	122	4415	794
Run-4	992005	1953	111	8937	550
Run-5	1453853	2838	141	10311	305
Run-6	748724	1760	106	7063	74

Thank you for listening!