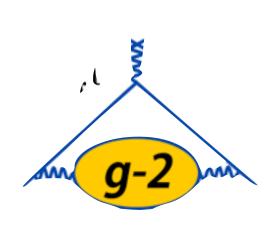


Data Acquisition with GPUs for Muon g-2 at Fermilab

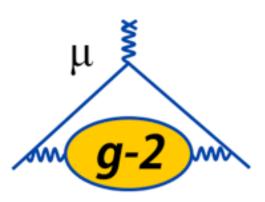
Wes Gohn University of Kentucky 2 August 2017

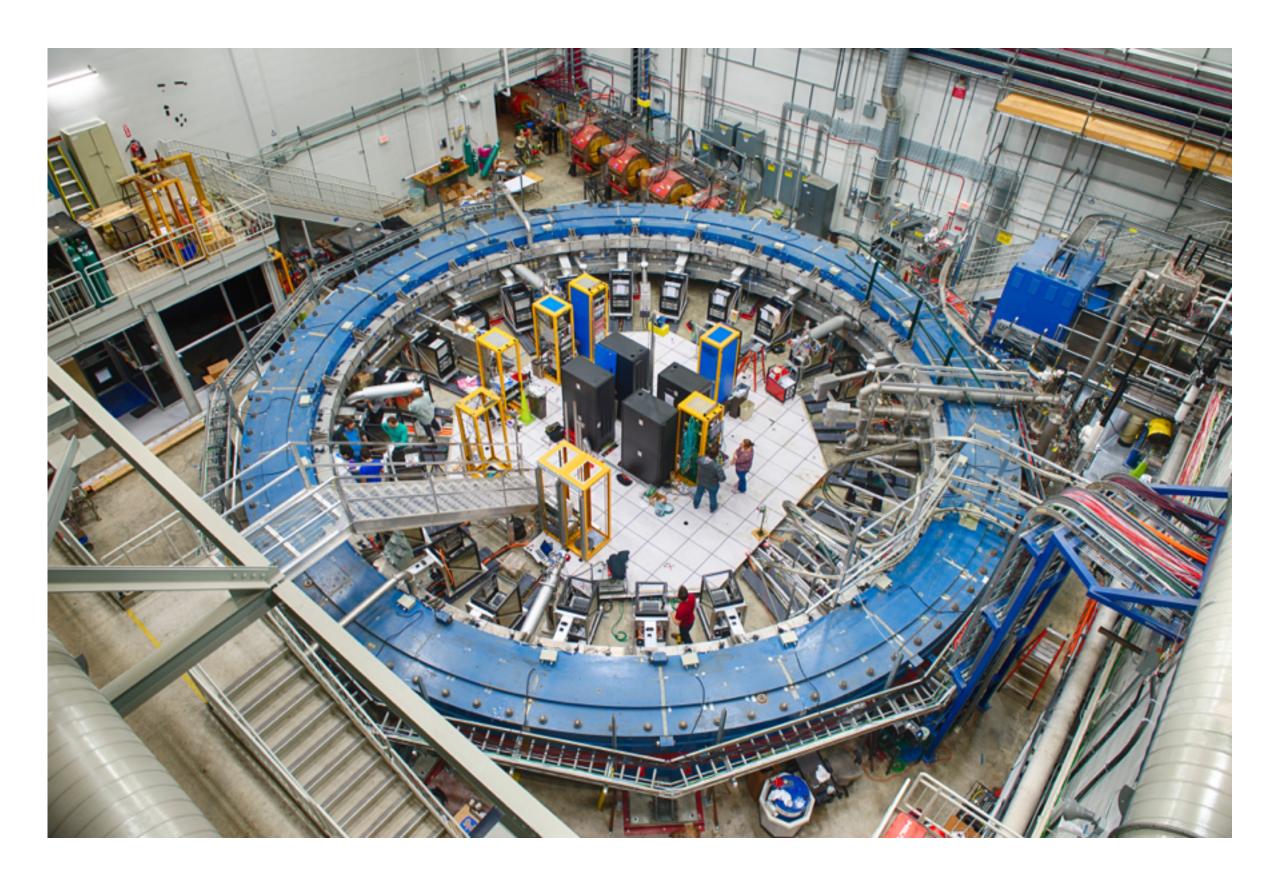




Muon g-2 Experiment Overview

- Goal is to measure the anomalous magnetic moment of the muon to 140 ppb, which is a factor of 4 better than has been previously measured.
- Muon fills are injected into the ring at a rate of 12 Hz.
- The precession frequency of the muons is measured by detecting decay positrons in 24 segmented calorimeters inside the ring.
- We finished a five-week commissioning run on July 7.



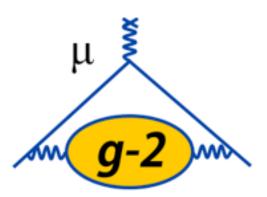






g-2 Detector Systems

- 24 Calorimeters
 - 1 uTCA crate for each calorimeter
 - 54 channels * 24 calos = 1296 channels of digitized data.
 - Data provided by 12 Cornell waveform digitizers.
- 4 Fiber Harps
 - 7 channels * 4 harps = 28 channels
 - Data provided by Cornell waveform digitizers
- Quads and Kickers
 - Write 4 quad channels and 15 kicker channels
 - Data provided by Cornell waveform digitizers
- 3 Trackers
 - Data from Multihit TDCs sent from FC7s in a uTCA crate
- IBMS and quads
 - Running on CAEN digitizers
- Slow control SCS3000 devices



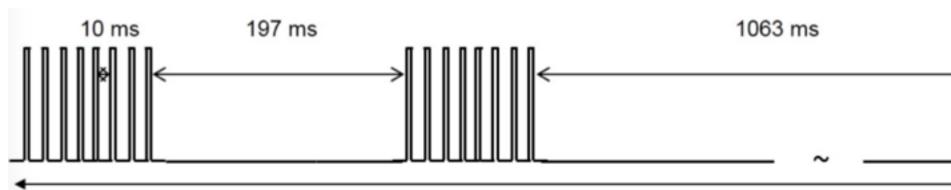






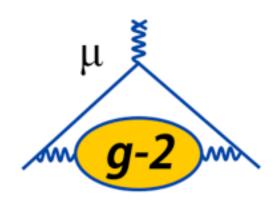
Rate requirements

• Accommodate 12 Hz average rate of muon fills that consist of sequences of eight successive 700 μ s fills with 10 ms fill-separations.



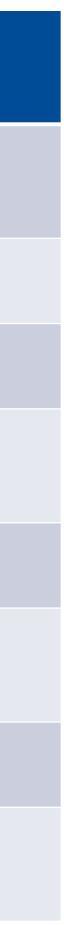
Cycle length 1.4 sec

- Time-averaged rate of raw ADC samples is 20 GB/s, which must be reduced by a factor of 100.
- Data is processed in GPUs to accomplish this task.
- Total data on tape after 2 years of running will be 10 PB.



Source	MB Per Fill	MB Per Second
Raw data	1,600	19,400
T-Method	9.4	112.5
Q-Method	4.0	48.5
Prescaled Raw	1.6	19.4
Tracker	0.75	9
Laser Monitor	0.08	1
Auxiliary	0.33	4
Event Builder:	16.2	194.4

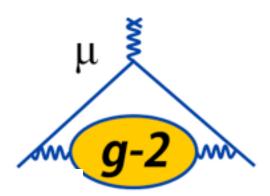


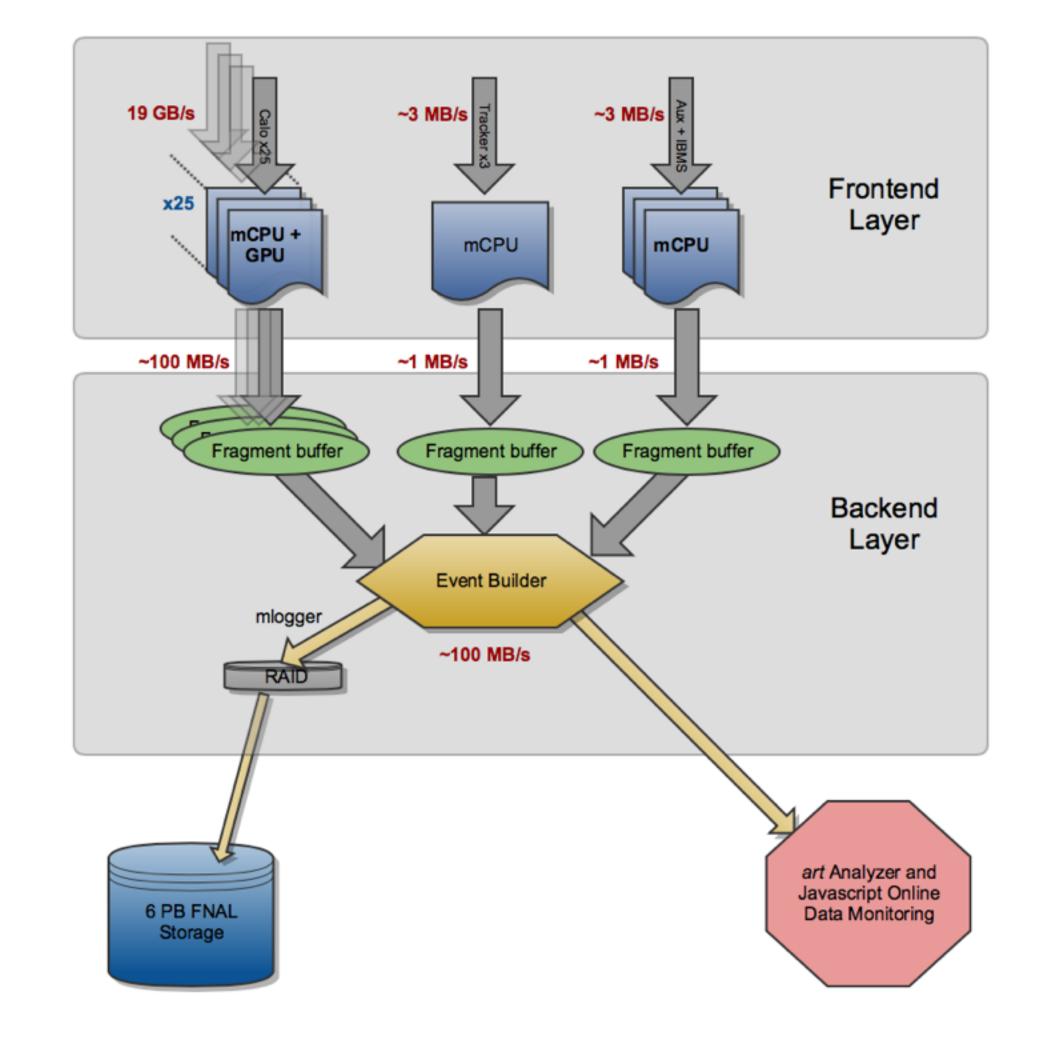




DAQ Design

- Layered array of commodity, networked processors
- Frontend layer for readout of detectors.
- Backend layer for assembly of event fragments.
- Slow control layer.
- Online analysis layer using art+JS.
- Field DAQ operates independently, but with a similar design.



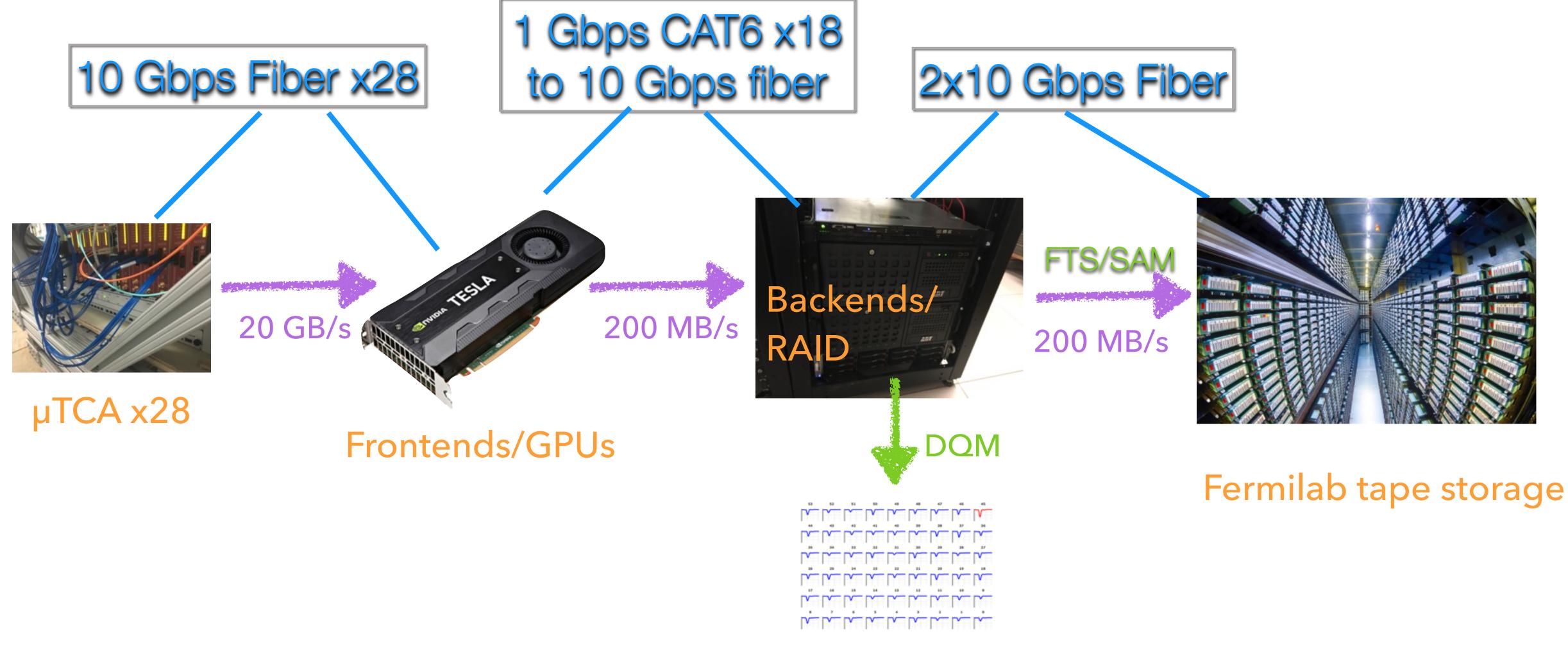




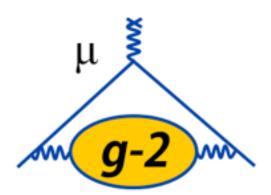




Data Flow



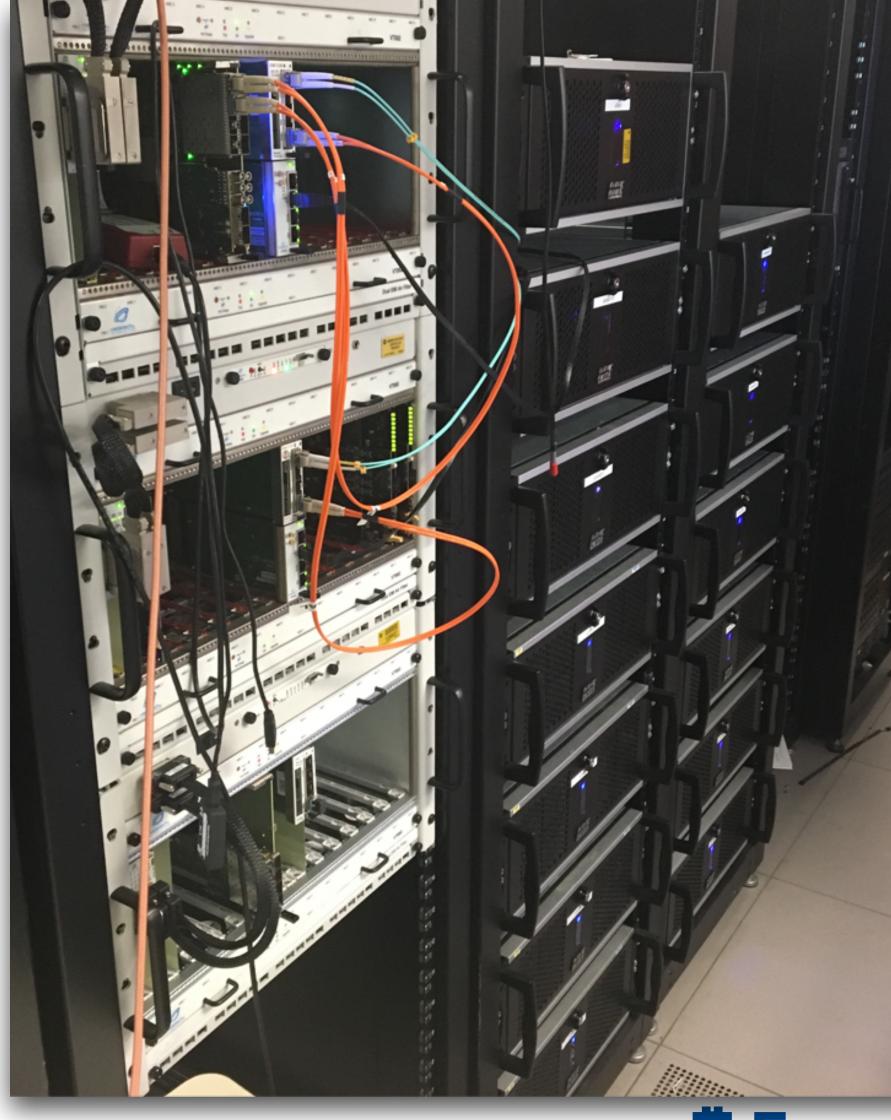
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DAQ Hardware

- The DAQ hardware includes:
 - 17 frontend machines
 - 5 backend machines
 - 2 dedicated near line analysis machines
 - 3 computers for HV control
 - 3 servers
 - 24 beagle bones running slow controls
- Each frontend contains two Nvidia Tesla K40 GPUs
 - 2880 CUDA cores at 740 MHz
 - 288 GB/s memory bandwidth
 - 12 GB on board memory
 - ECC memory protection
- 70 TB RAID for temporary data storage.



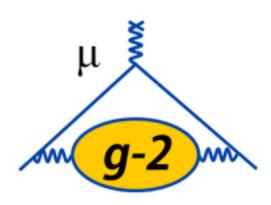






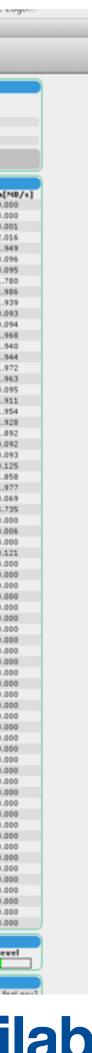
MIDAS Software

- MIDAS is a DAQ software package developed at PSI and TRIUMF and used by T2K, SCDMS, MEG, and many other experiments.
- Provides a web-interface for control of the experiment, data logging, and event building.
- We write frontend code in C++ and CUDA that processes the data and sends it to the event builder.
- 32 fast frontends reduce data volume for each event by a factor of 100 and store data in Midas banks.
- 35 slow control frontends process slow data.
- Includes alarm system and sequencer.
- Software configuration is dumped to a JSON file and saved to a PostgreSQL database at the end of each run.



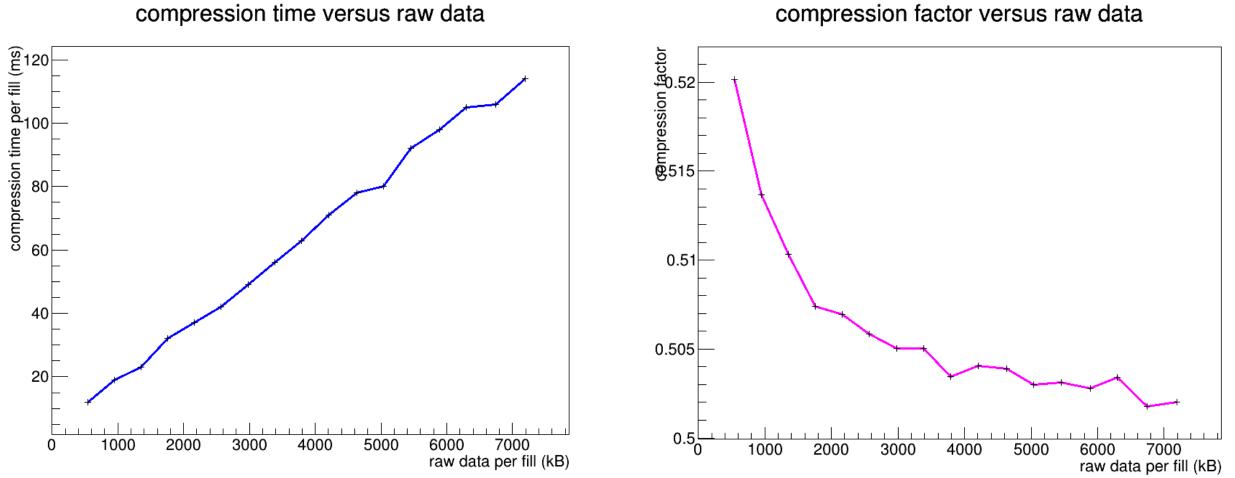
	Test Restart Fast Frontends		
	ChanMap Straw Tracker Power Straw Tracker 1	Settings WFDS	
Run	Run Status Start: Wed Jun 28 05:38:50 2017		ing time: 0h2
1618 Ala Running Experimen	t Name: GM2	Da	ta dir: /data2/
Stop git hash: CCC Run St			
	FO] channel /data2/gm2/gm2_run01618_47.mic	writer chain: CRC	32C I CRC32
Equipment +	Equipment Status	Events	Events[/s]
MasterGM2	MasterGM2@g2be1.fnal.gov	1222	0.7
EB AMC1300	Ebuilder@g2be1.fnal.gov AMC1300@g2aux-priv	1221 1223	0.0
AMC1301	AMC1301@c2calo0102-data	1223	1.0
AMC1302	AMC1302@g2calo0102-data	1222	0.7
AMC1303	AMC1303@g2cale0304-data	1221	0.7
AMC1304 AMC1305	AMC1304@g2cale0304-data	1221 1222	0.7
AMC1306	AMC1305@g2calo0506-data AMC1306@g2calo0506-data	1223	1.0
AMC1307	AMC1307@g2calo-spare-priv	1222	0.7
AMC1308	AMC1308@g2calo-spare-priv AMC1309@g2calo0910-data	1221	0.7
AMC1309	AMC1309@g2cale0910-data	1221	0.7
AMC1310	AMC1310@g2cale0910-data	1222	0.7
AMC1311 AMC1312	AMC1311@g2calo1112-data AMC1312@g2calo1112-data	1222	0.7
AMC1313	AMC1313@g2calo1314-data	1223	1.0
AMC1314	AMC1314@g2calo1314-data	1222	0.7
AMC1315	AMC1315@g2calo1516-data	1221	0.7
AMC1316	AMC1316@g2calo1516-data	1223	0.7
AMC1317 AMC1318	AMC1317@g2calo1718-data AMC1318@g2calo1718-data	1222	0.7
AMC1319	AMC1319@gColo1920-data	1222	0.7
AMC1320	WWC7350@d5calo1456-04ta	1221	0.7
AMC1321	AMG1321@g26802122-08ta	1221	0.7
AMC1322	AMC1322@g2calo2122-data AMC1323@g2calo2324-data	1221	0.7
AMC1323 AMC1324	AMC1323@g2cale2324-6ata	1222	0.7
AMC1325	AMC1324@g2calo2324-data AMC1325@o2laserdao-data	1225	0.7
AMC1326	AMC1325@g2laserdaq-data AMC1326@g2aux-priv	1221	0.7
StrawTrackerLVandSC03	StrawTrackerLVandSC03@g2tracker1.fnal.go	W 0	0.0
StrawTrackerDAQ	StrawTrackerDAQ@g2tracker0.fnal.gov	1221	0.7
StrawTrackerHV03	StrawTrackerHV03@g2tracker1.fnal.gov	0	0.0
IBMS Detector CaloSC01	18MS Detector@g2ibms-priv CaloSC01@g2sc-priv	1223	0.7
CaloSC02	CaloSC02@p2sc-priv	0	0.0
CaloSC03	CaloSC03@g2sc-priv	0	0.0
CaloSC04	CaloSC04@g2sc-priv	0	0.0
CaloSC05	CaloSC05@g2sc-priv	0	0.0
CaloSC06 CaloSC07	CaloSC06@g2sc-priv CaloSC02@g2sc-priv	0	0.0
CaloSC08	CaloSC07@p2sc-priv CaloSC08@p2sc-priv	0	0.0
CaloSC09	CaloSC09@g2sc-priv	0	0.0
CaloSC10	CaloSC10@c2sc-priv	0	0.0
CaloSC11	CaleSC11@g2sc-priv	0	0.0
CaloSC12	CaloSC12@g2sc-priv	0	0.0
CaloSC13 CaloSC14	CaloSC13@g2sc-priv	0	0.0
CaloSC15	CalaSC140g2sc-priv CalaSC150g2sc-priv	0	0.0
CaloSC16	CaloSC16@g2sc-priv	0	0.0
CaloSC17	CaleSC17@e2sc-priv	0	0.0
CaloSC18	CaloSC18@g2sc-priv	0	0.0
CaloSC19 CaloSC20	CaloSC19@p2sc-priv CaloSC20@p2sc-priv	0	0.0
CaloSC21	CaloSC20@g2sc-priv CaloSC21@g2sc-priv	0	0.0
CaloSC22	CaloSC22@g2sc-priv	0	0.0
CaloSC23	CaleSC23@g2sc-priv	0	0.0
CaloSC24	CaleSC24@g2sc-priv	0	0.0
ESQ_slow ESO	ESQ_slow@g2quad-01 ESQ@g2quad-02-priv	1729	1.0
ESQ	Ok	173	0.0
mscb110	Ok	29	0.0
mscb13e	Ok	2871	0.0
mscb319	Ok	29	0.0
mscb323	Ok	29	0.0
KickerSC_mscb282 mscb174		29	0.0
Beam	Beam@g2sc-priv	346	0.3
	Logging Channels		



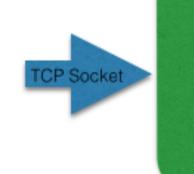


Calorimeter-GPU Frontend

- Each frontend process reads data from one uTCA crate over 10 Gb ethernet with TCPIP.
- Frontend is multithreaded with mutex locks.
- Data is processed in Nvidia Tesla K40 GPUs using CUDA code that is integrated into the frontend.
- Midas banks are losslessly compressed using zlib.
- Full configuration of the uTCA crate is performed via the MIDAS ODB.



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TCP Thread

Read and unpack data from TCP socket and copy to ring buffer.

GPU Thread

Memcpy to GPU and Process data

MFE Thread

Pack and send data to **MIDAS** banks and DQM

MIDAS Ban







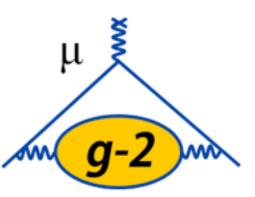


Why GPUs?

- The GPUs dramatically improve performance by parallelizing processing.
- Technology was developed for commercial applications, so it is well supported.
- Easier to code in C++ than to learn specialized language.
- Without GPUs, we could not keep up with our data rates.



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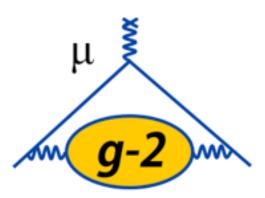


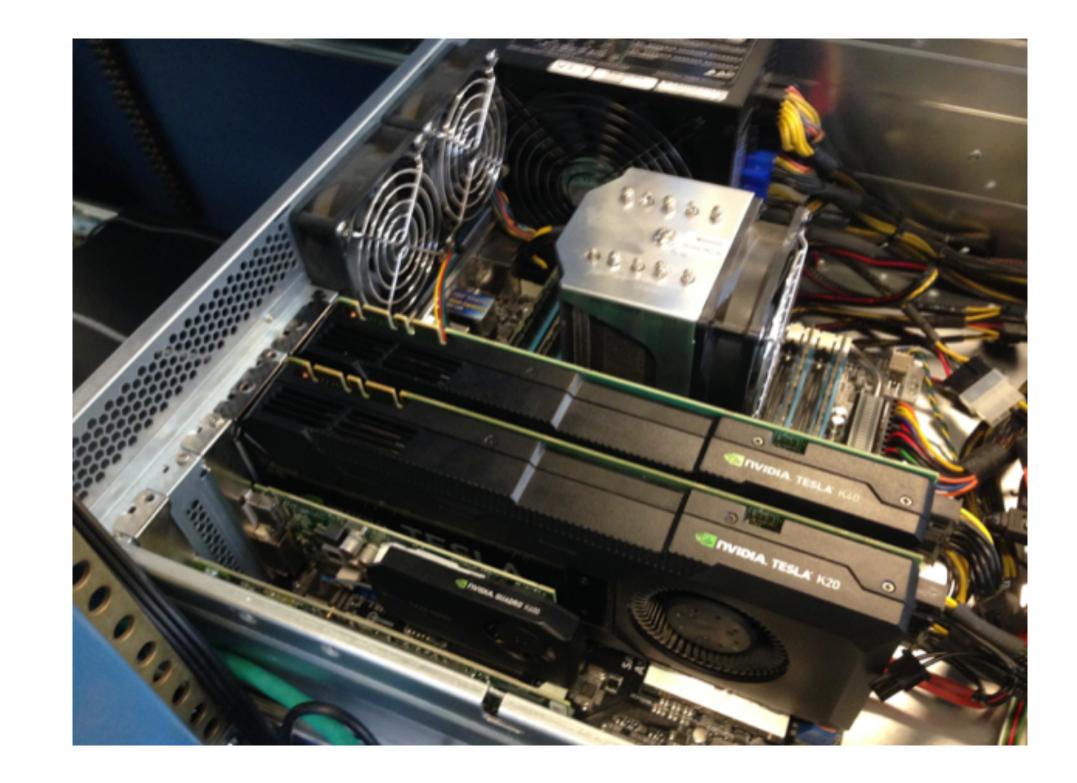




GPU Processing

- The frontend includes CUDA routines for data processing.
- Each GPU processes data from one calorimeter.
- Raw fill is copied to GPU memory, where it is reduced using T-method (island chopping), Q-method (histogramming), pedestal calculation, and template fitting.
- The output of each process is written in one MIDAS bank.

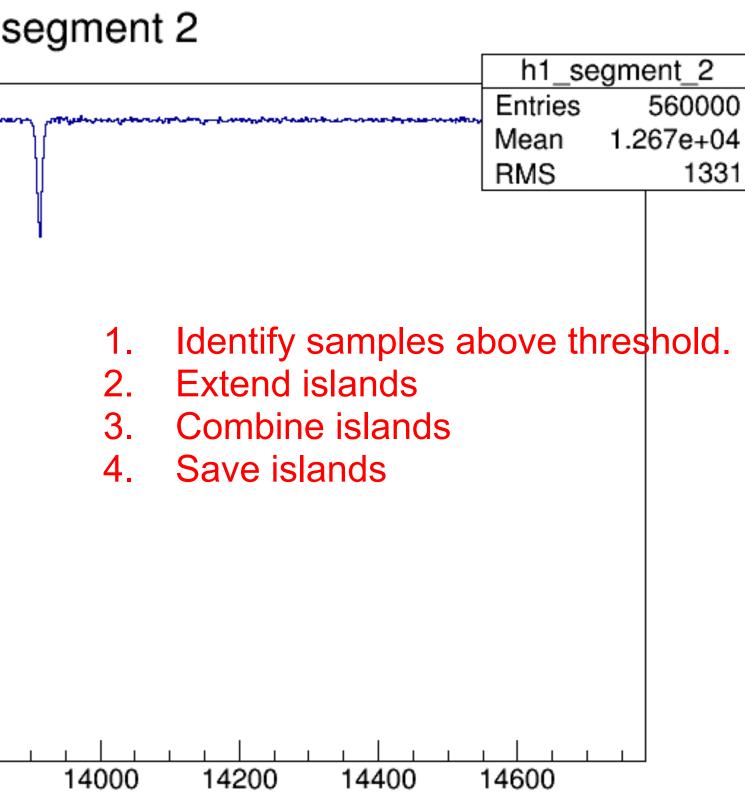


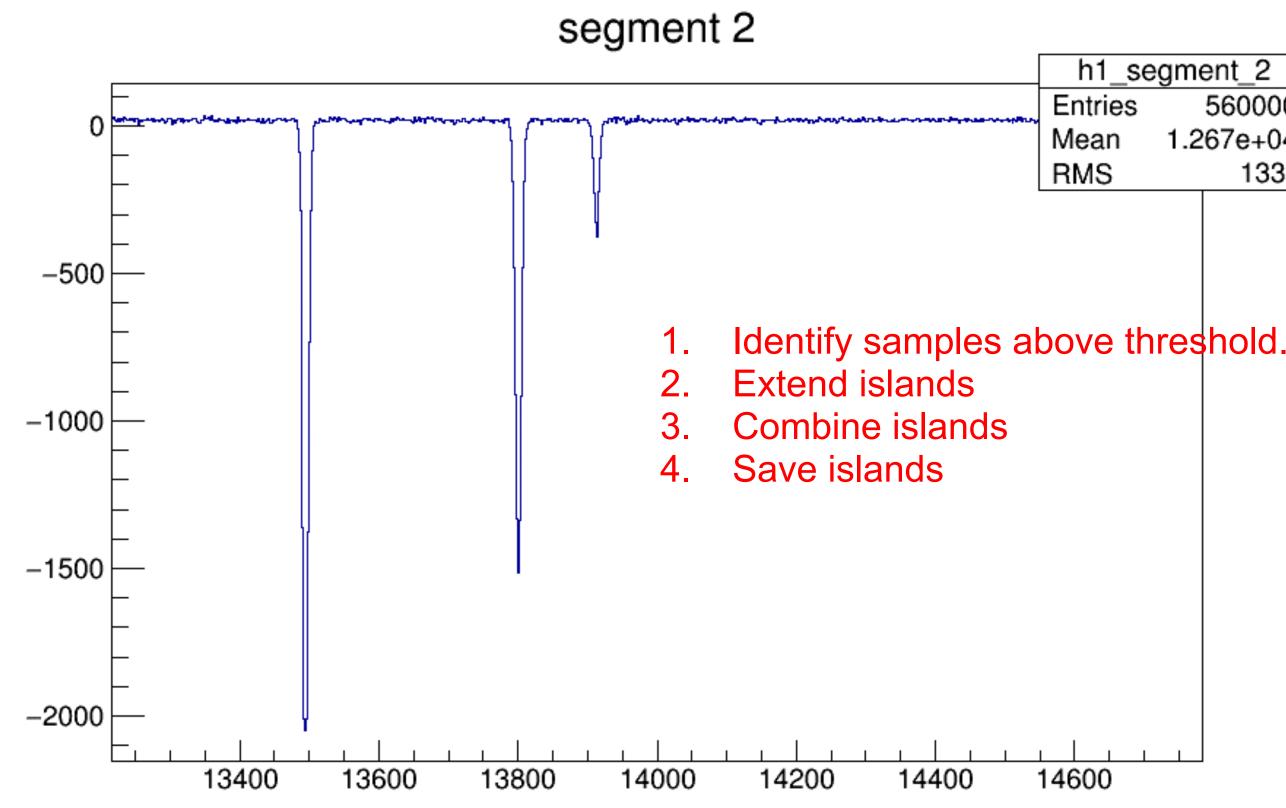


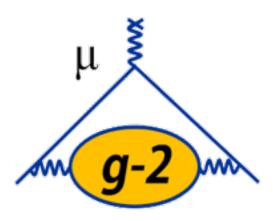




- Identify and save regions of the waveform containing positron hits.
- A typical waveform will have ~180 islands.



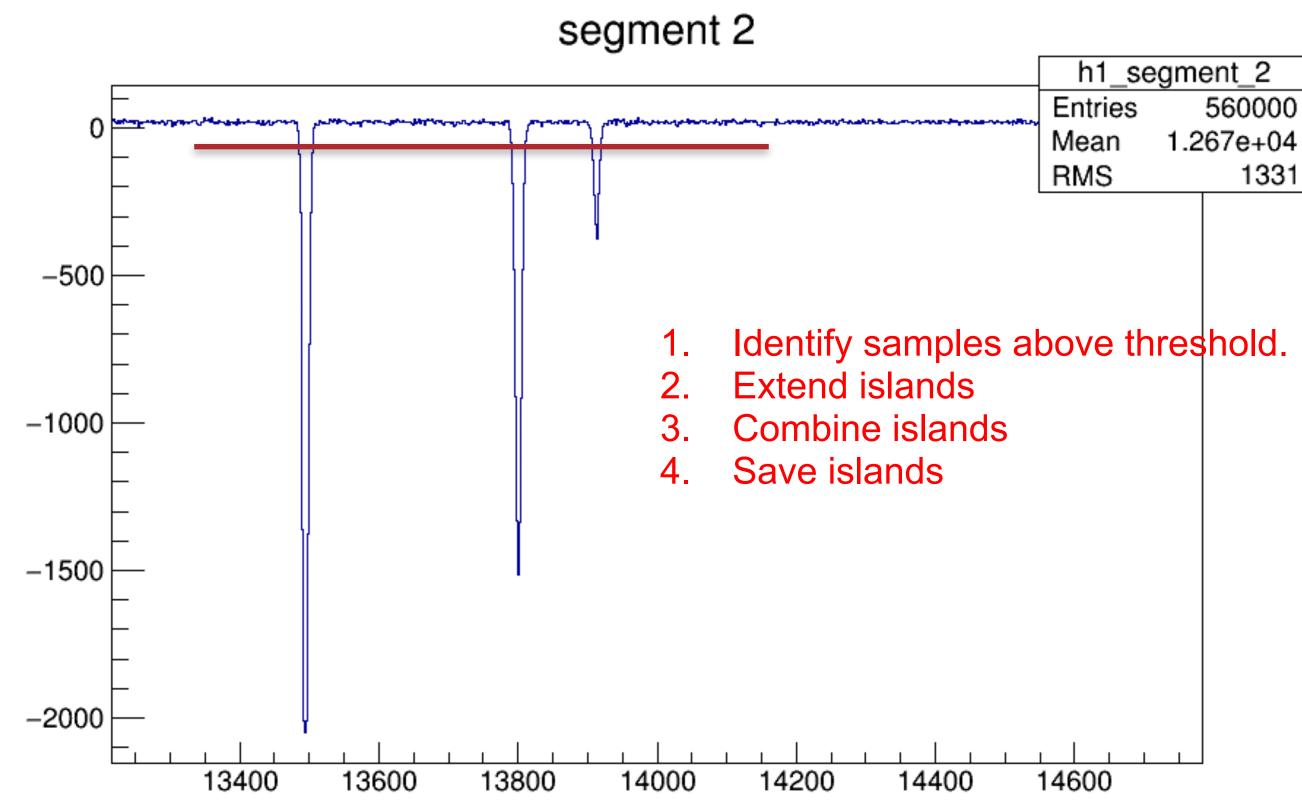


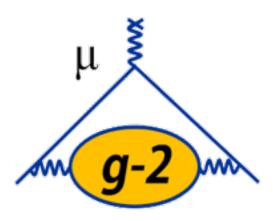






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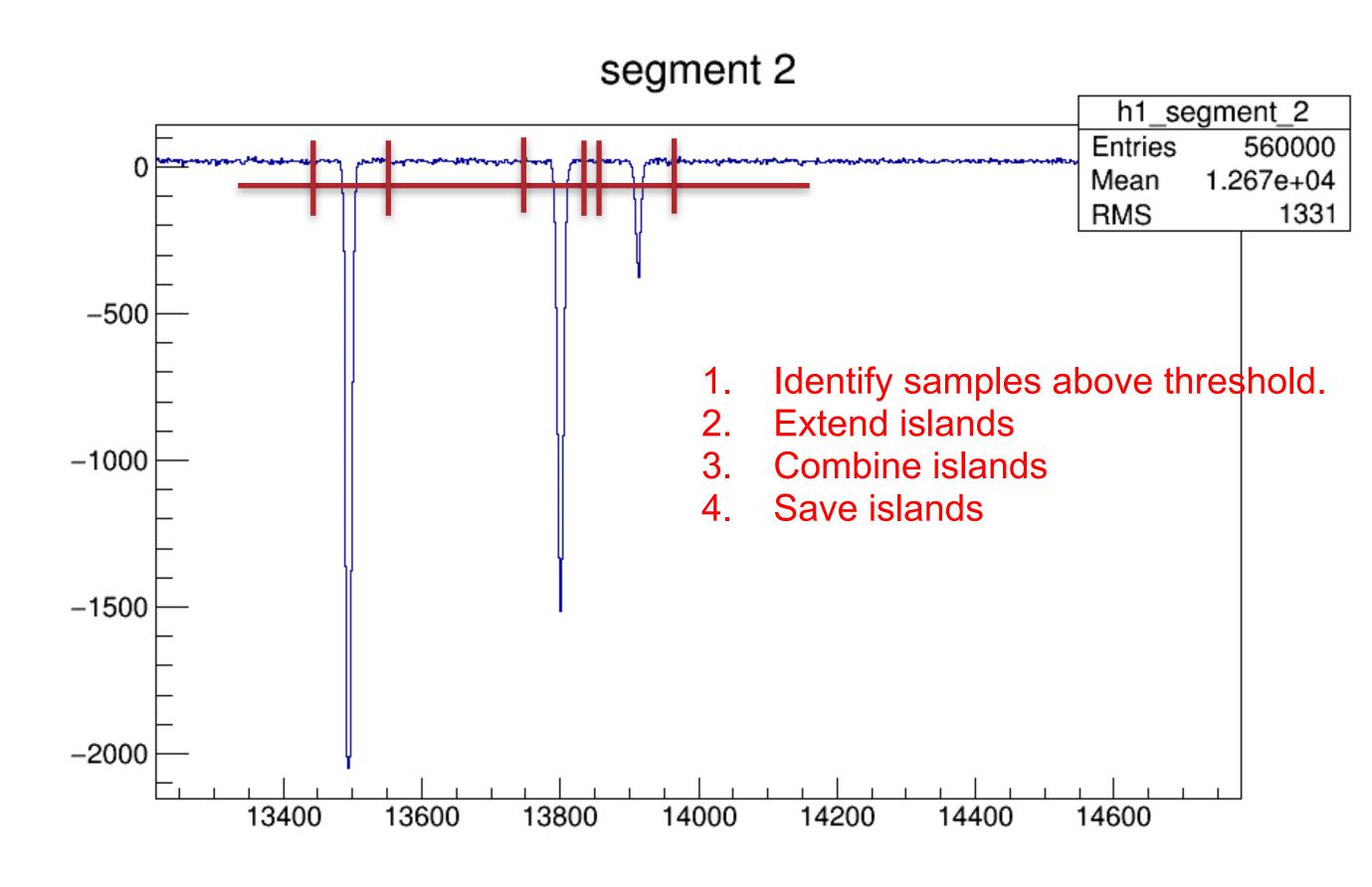


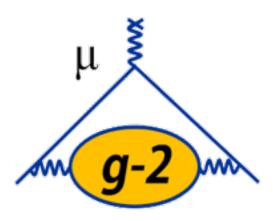






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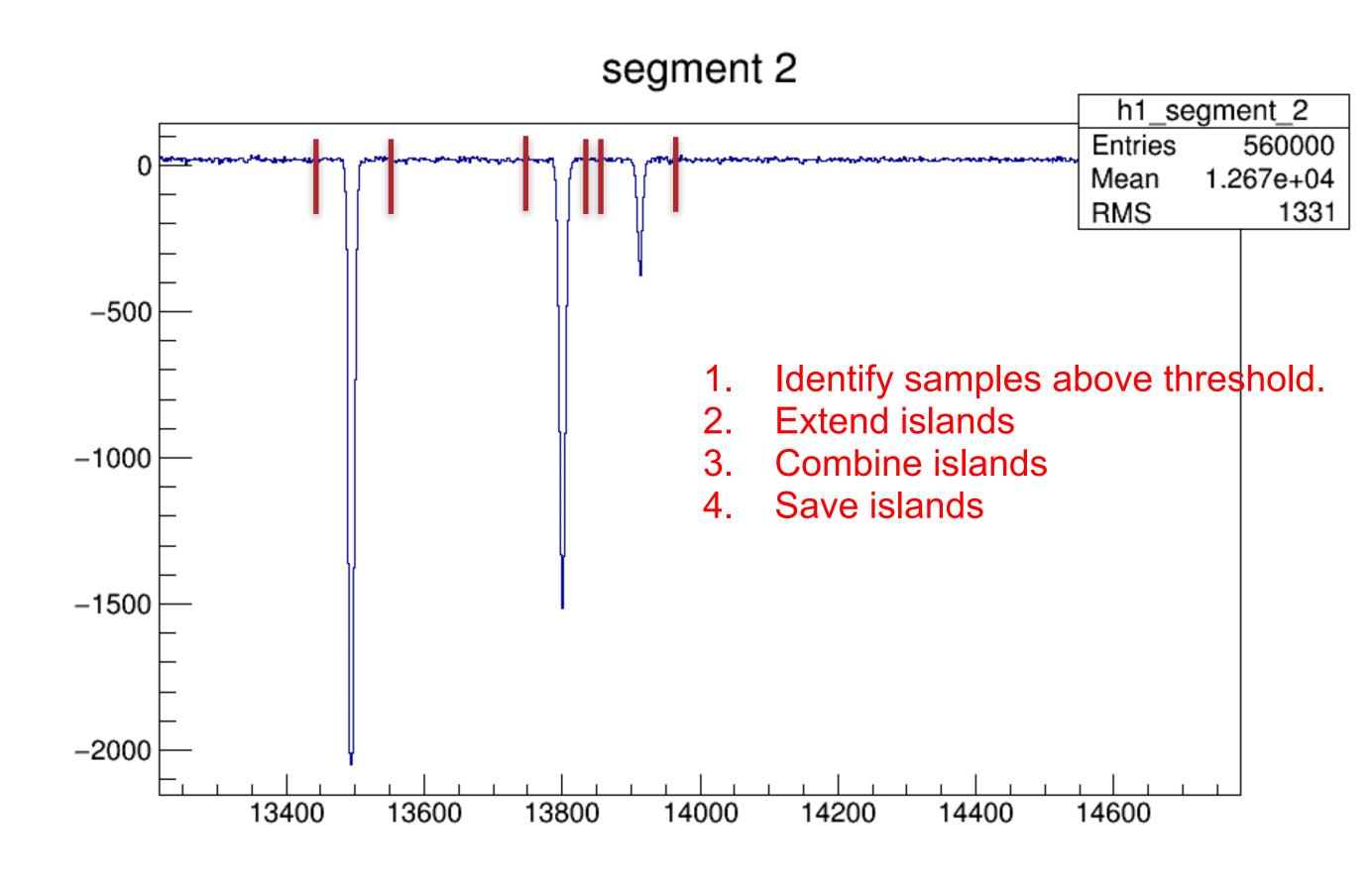


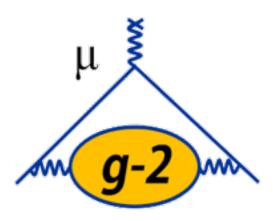






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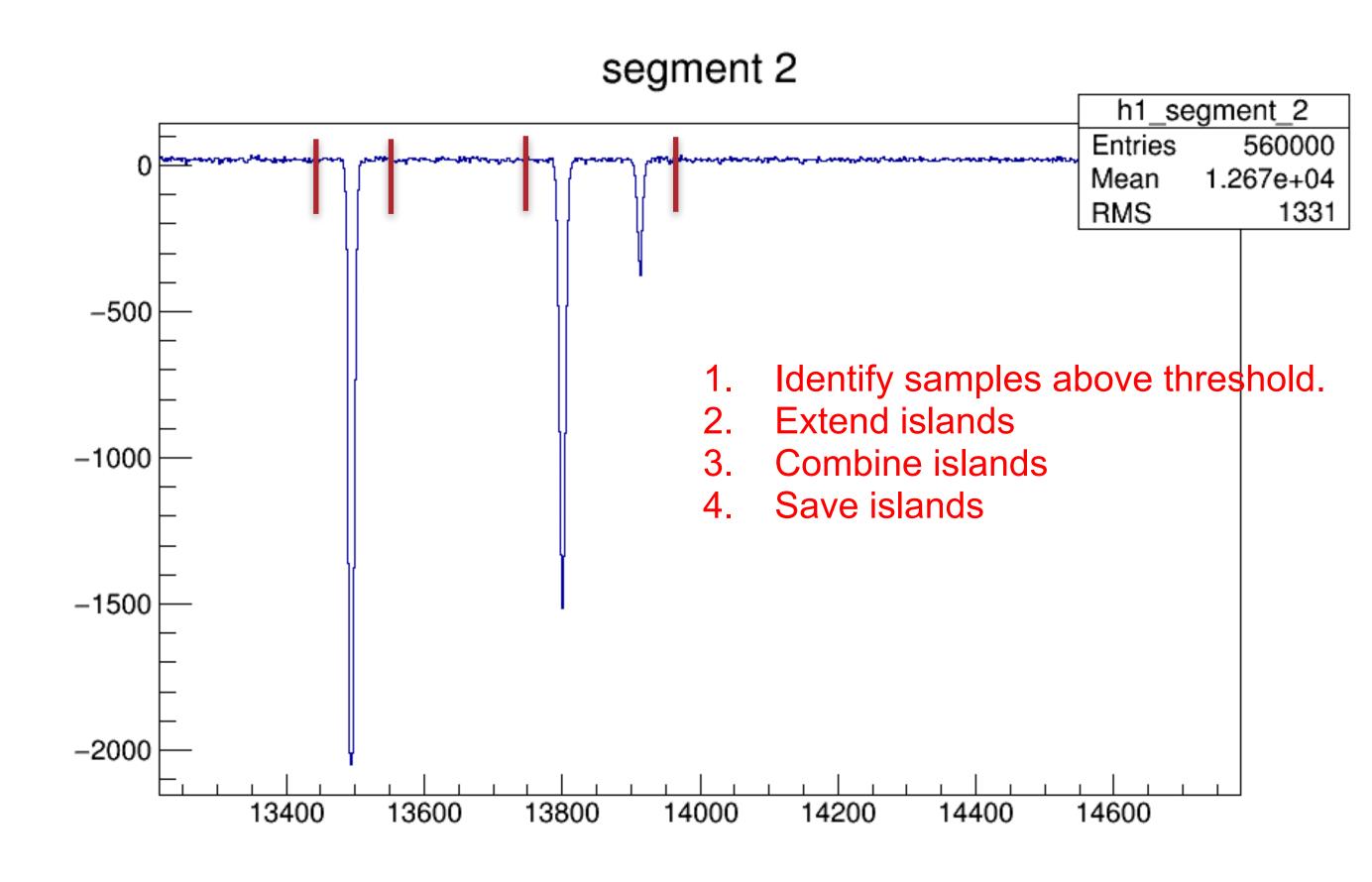


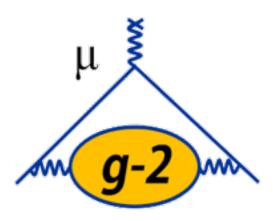






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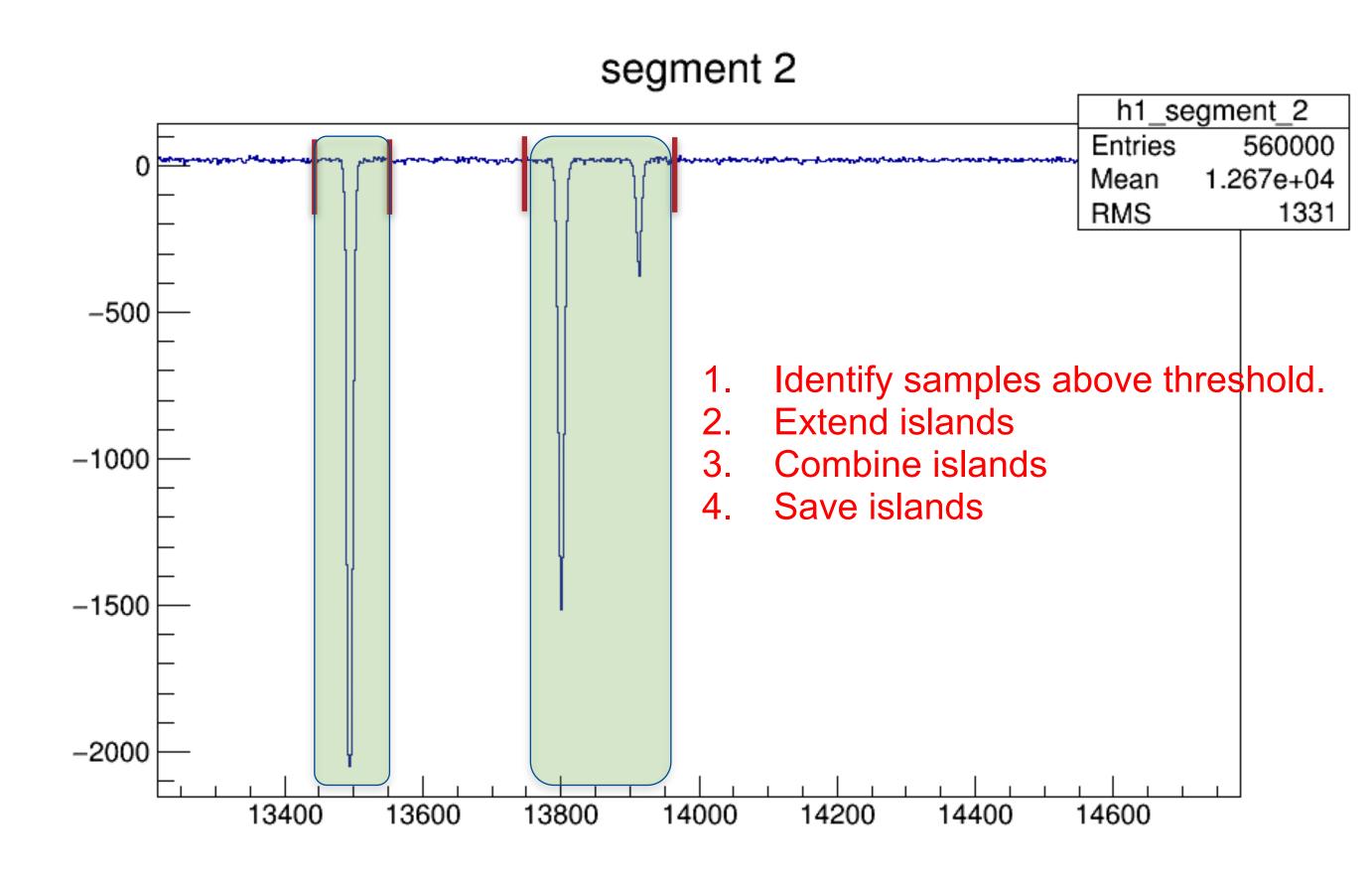


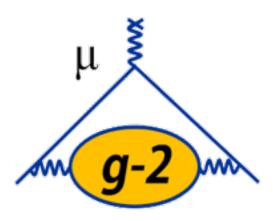






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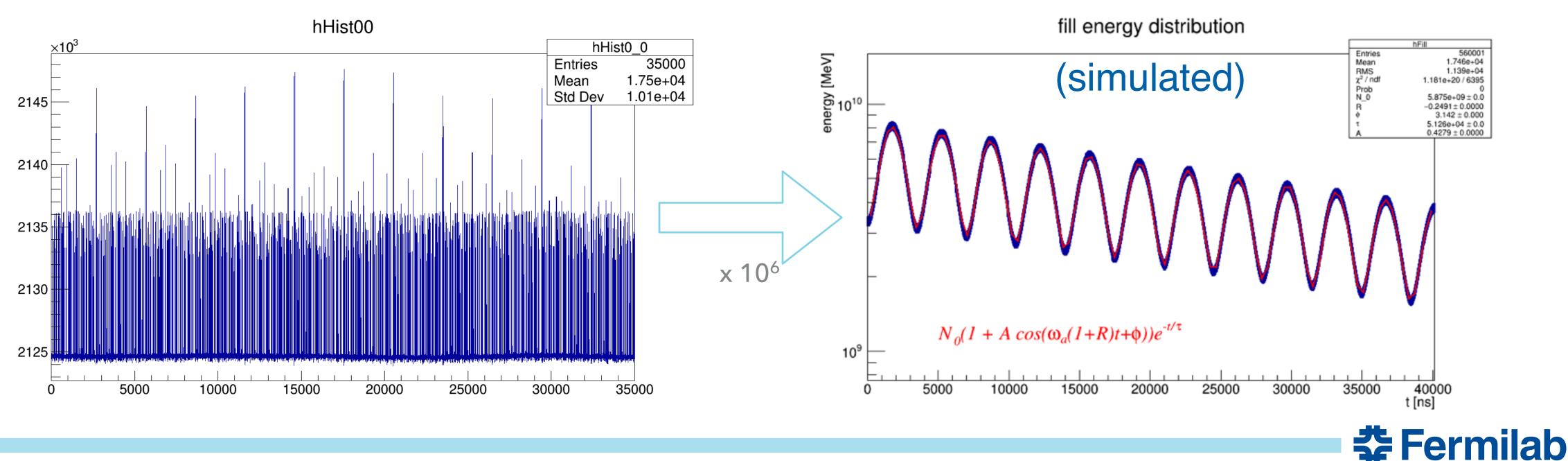




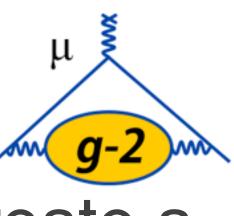


Q-method

- Full waveforms are decimated in time and summed over many fills to create a histogram that is saved in the data file.
 - i.e. If we decimate in time by 10 and flush every 100 fills, we reduce the data rate by a factor of 1000, so from 20 GB/s to 20 MB/s.
- Use smaller bins at lower times and wider bins at later times to insure that we can extract the pedestal.



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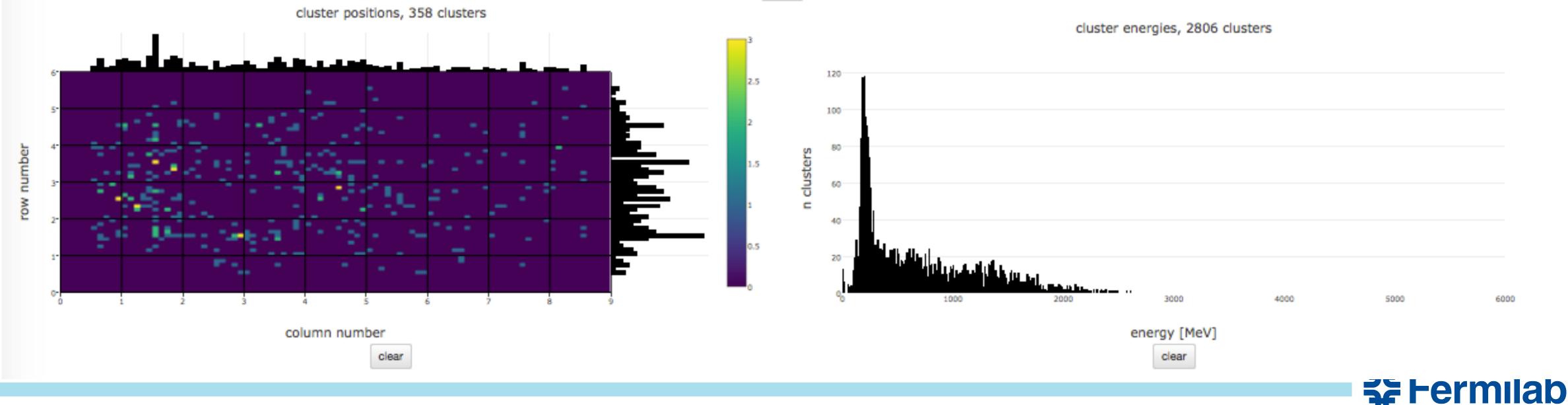




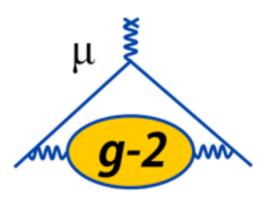


GPU Template Fits

- above a certain threshold.
- chopped islands.
- Reduces the processing necessary in the online DQM.



What we get from the DAQ Wes Gohn 14

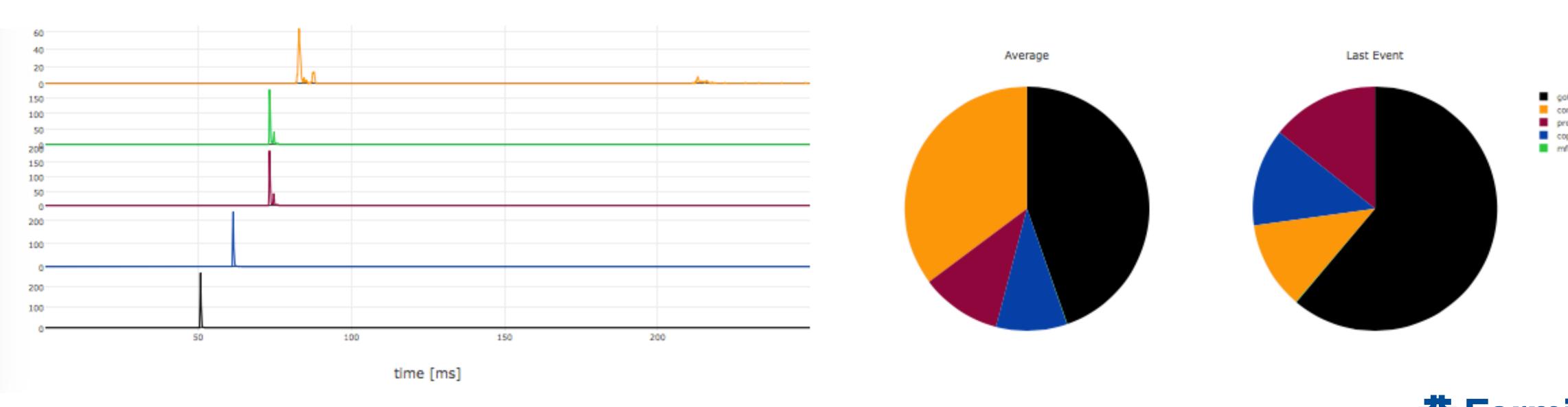


• Fit templates are loaded into the GPU memory and used to fit each peak

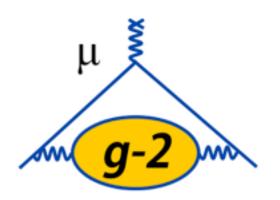
A bank containing the fit results will be saved for each fill in addition to the

Processing time

- Processing time in the GPU is very small.



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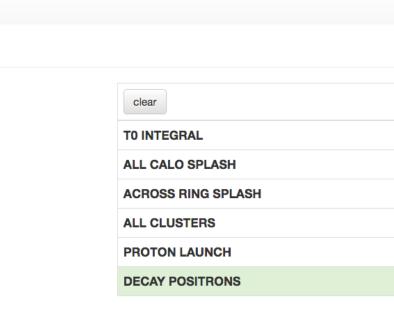
Must process each event in 83 ms to keep up with average beam rate of 12 Hz. • Most time is spent reading data from TCP socket and copying it to the GPU.

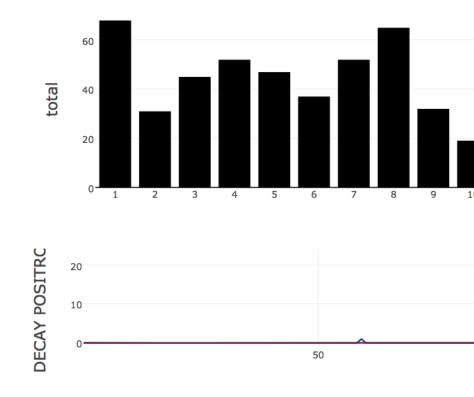




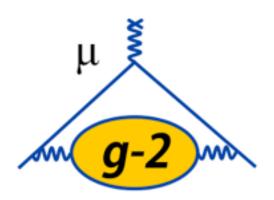
Data Quality Monitor

- Online DQM streams data from MIDAS mserver.
- Uses existing art modules to process the data.
- Data is extracted from the art job using ZeroMQ and published to a web GUI using node.js and plotly.

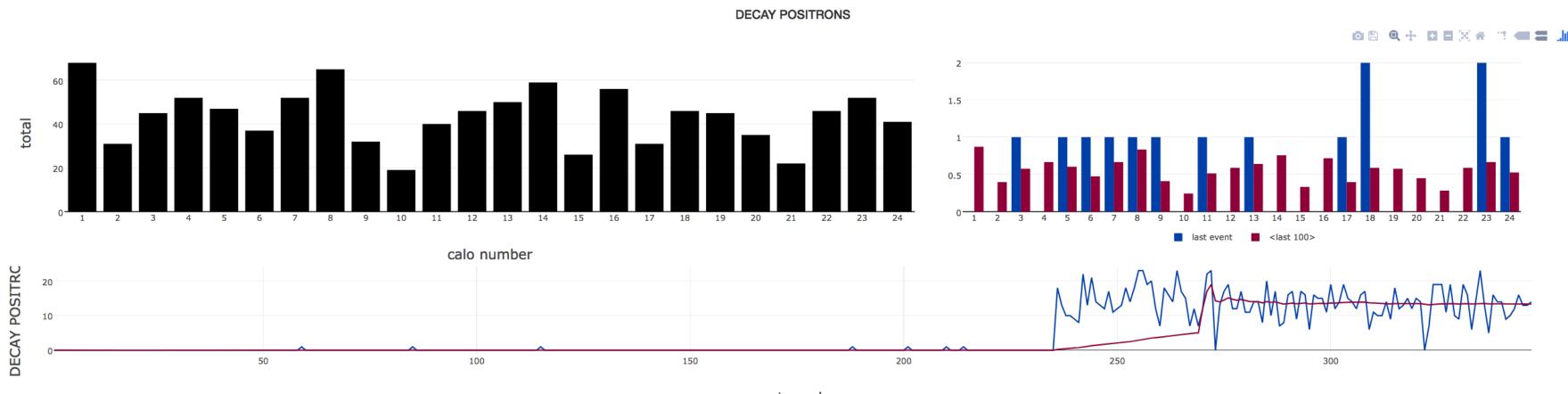




100



100% of events processed Subsystem-Bun 1911 Event 348 Muon a-2 DQM Connected Select Calo recon kicker timino **CTAG** high gain T0 trace LAST NFILLS TOTAL AVG (last 100) 78 5.03e+6 6.48e+4 6.45e+4 650.4 78 50733 666 -100 78 3657 49 46.9 ₽ –150 78 239 189.1 14749 78 7189 112 92.2 -200 78 13.4 1043 14 25.4k 25.6k 26.2k 25.8k time [clock ticks]



Fermilab

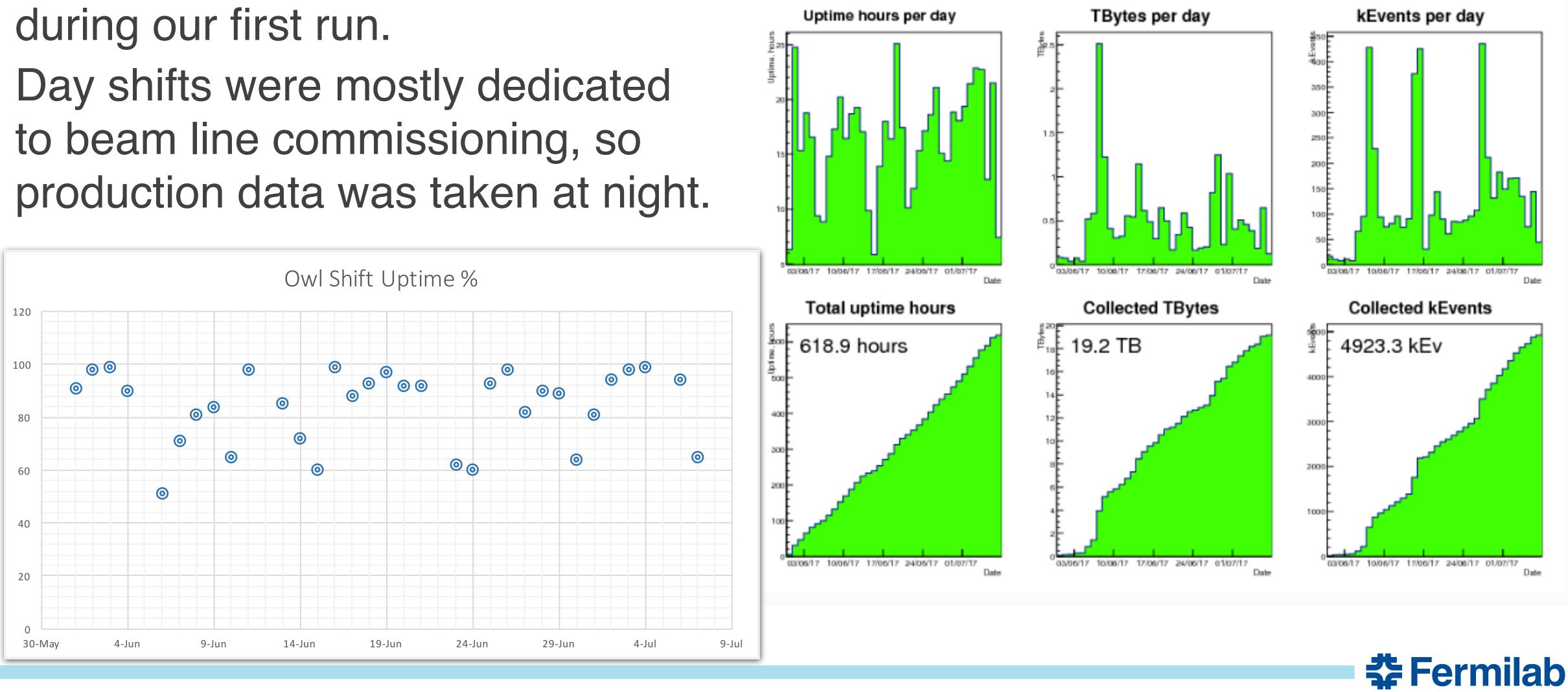
event number





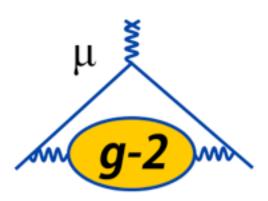
DAQ Performance During First Run

- The MIDAS DAQ performed well during our first run.
- Day shifts were mostly dedicated to beam line commissioning, so



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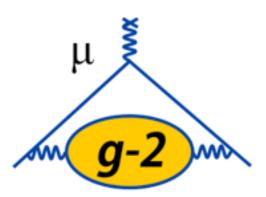
W. Gohn I U. of Kentucky I DAQ for Muon g-2

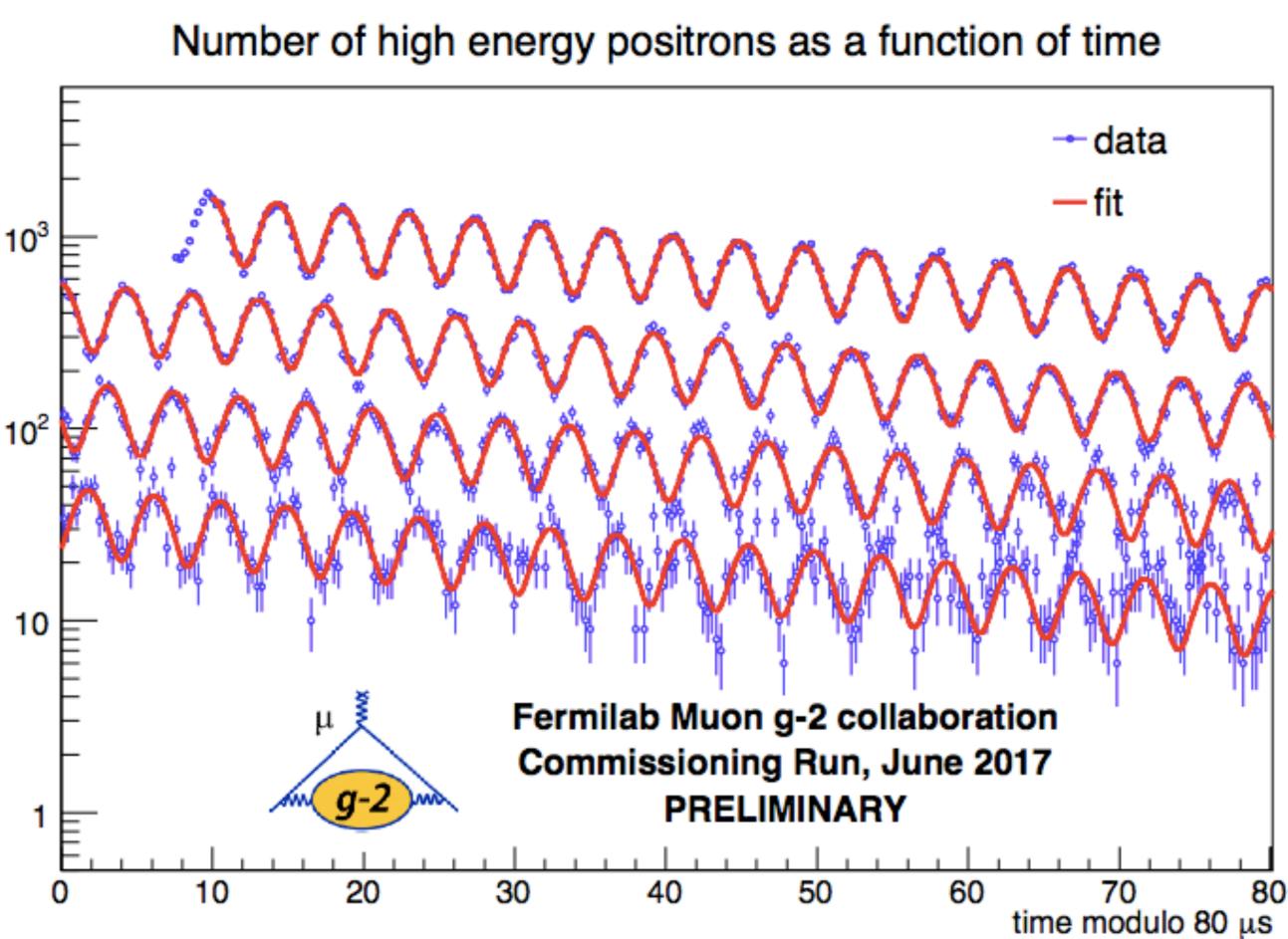


Muon G-2 data taking

Summary

- The DAQ for Muon g-2 at Fermilab has been fully installed and performed well during commissioning.
- The DAQ hardware includes 17 frontend machines, 5 backend machines, 2 dedicated line analysis machines, 3 computers for slow control, 3 servers, and 24 beagle bones runni 67 MIDAS frontends.
- Takes an input data rate of 20 GB/s, and redu that to < 200 MB/s in the event builder via GP processing and lossless compression.
- Commissioning run in June 2017 yielded first "wiggle plot" created from ~700k positrons.

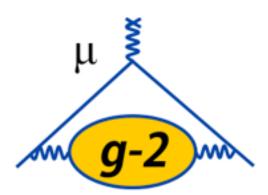








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Backup

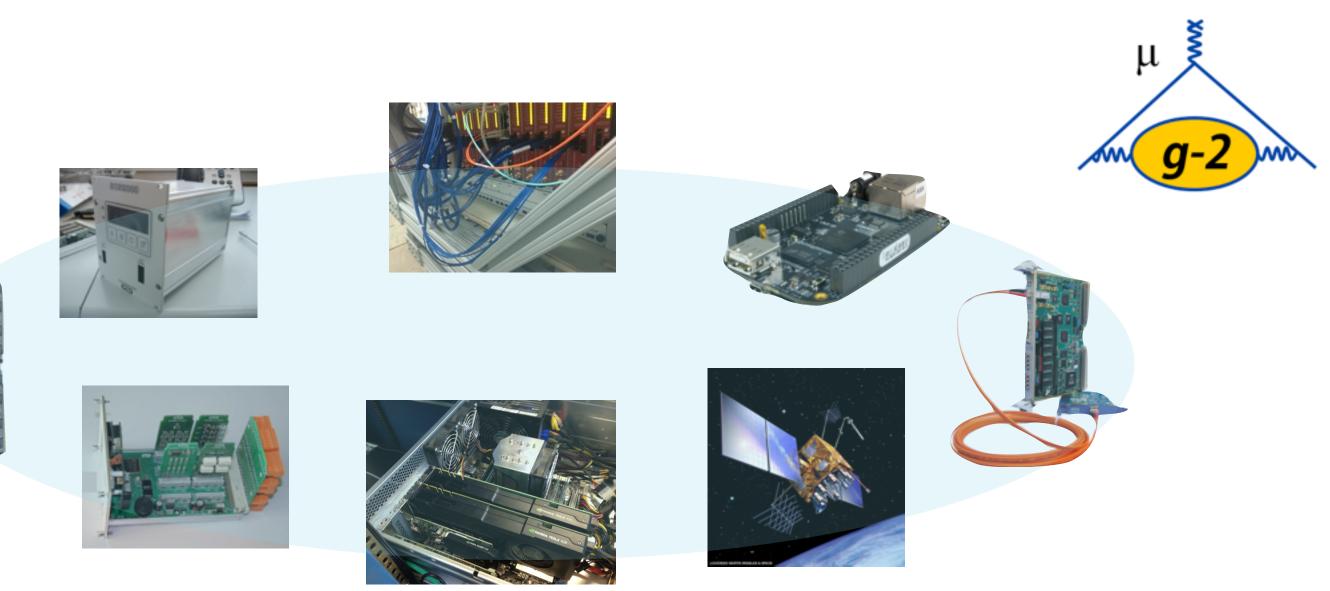








- The DAQ must assemble data from an "Internet of things" to form a complete picture of each muon fill.
- Expect an average data rate of 12 Hz for muon fills, plus some laser and pedestal fills.
- This provides data at a rate of 20 GB/s, which must be reduced via processing of data in GPUs.

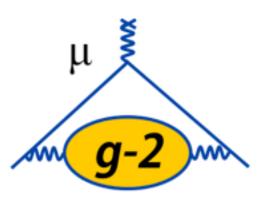






Input sources

- Digitization is performed in custom uTCA based waveform digitizers. Each digitizer runs at 800 MSPS, so each time bin is 1.25 ns, and a 700 us fill
- is 560,000 clock ticks.
- Each uTCA crate contains 12 WFD5s or 60 channels of digitization.
 - Crate 0 reads data from the clock and control center (CCC)
 - Crates 1-24 each read data from one calorimeter (+ spare channels)
 - Crate 25 reads data from the laser system
 - Crate 26 reads data from the Auxiliary detectors (Harps, Quads, and Kickers)
 - Crate 27 reads data from the three tracker detectors.
- Data from each crate is sent to a DAQ computer via a dedicated 10 Gb fiber. The total data rate is 20 GB/s.
- The data is then processed in Nvidia K40 GPUs.



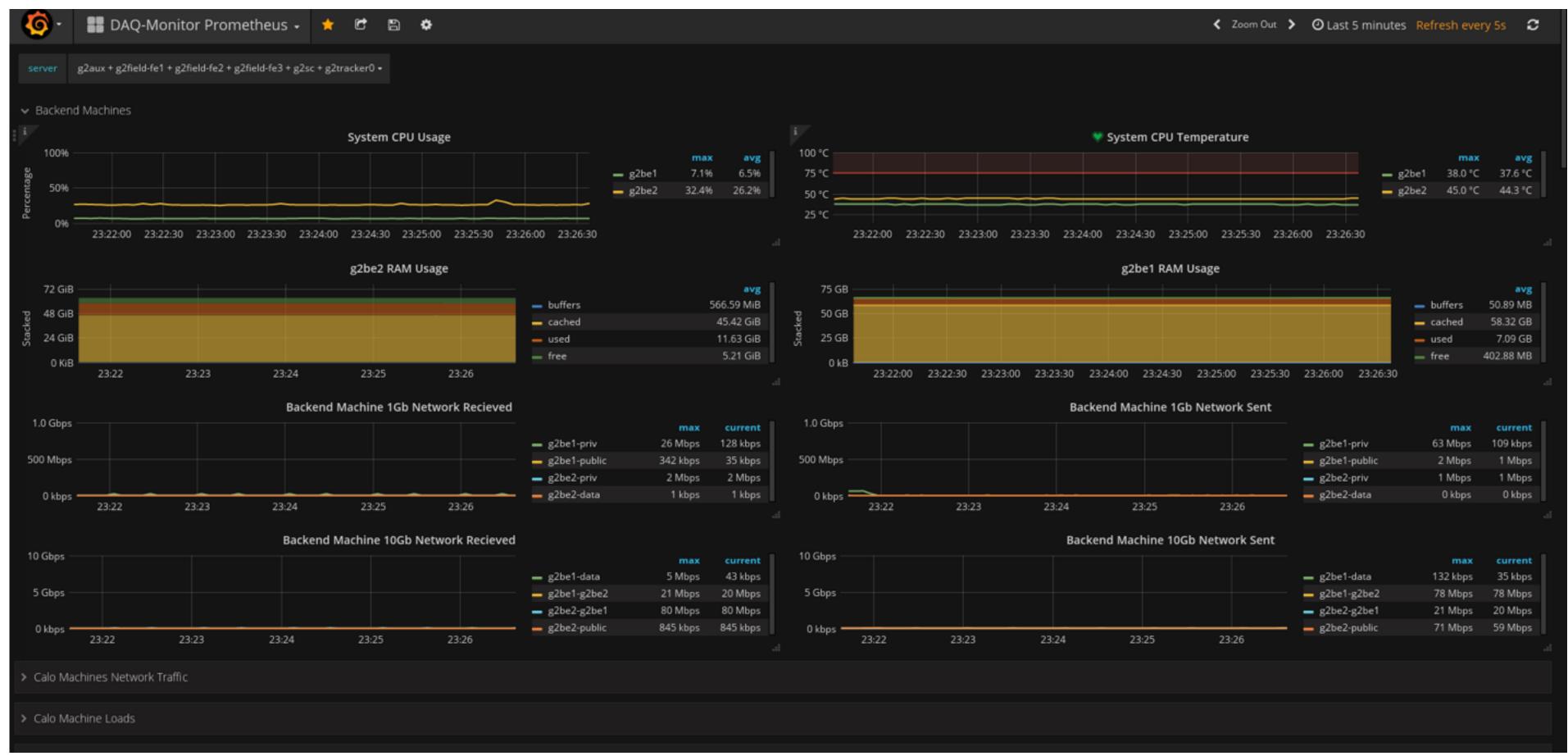




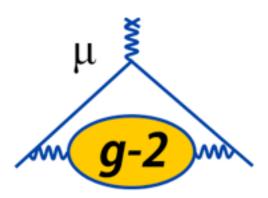


DAQ Health Monitor

 Monitored health of DAQ systems using netdata for system monitoring, prometheus for short term data storage, and grafana to display data.



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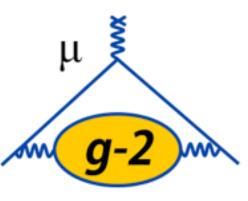
Fermilab



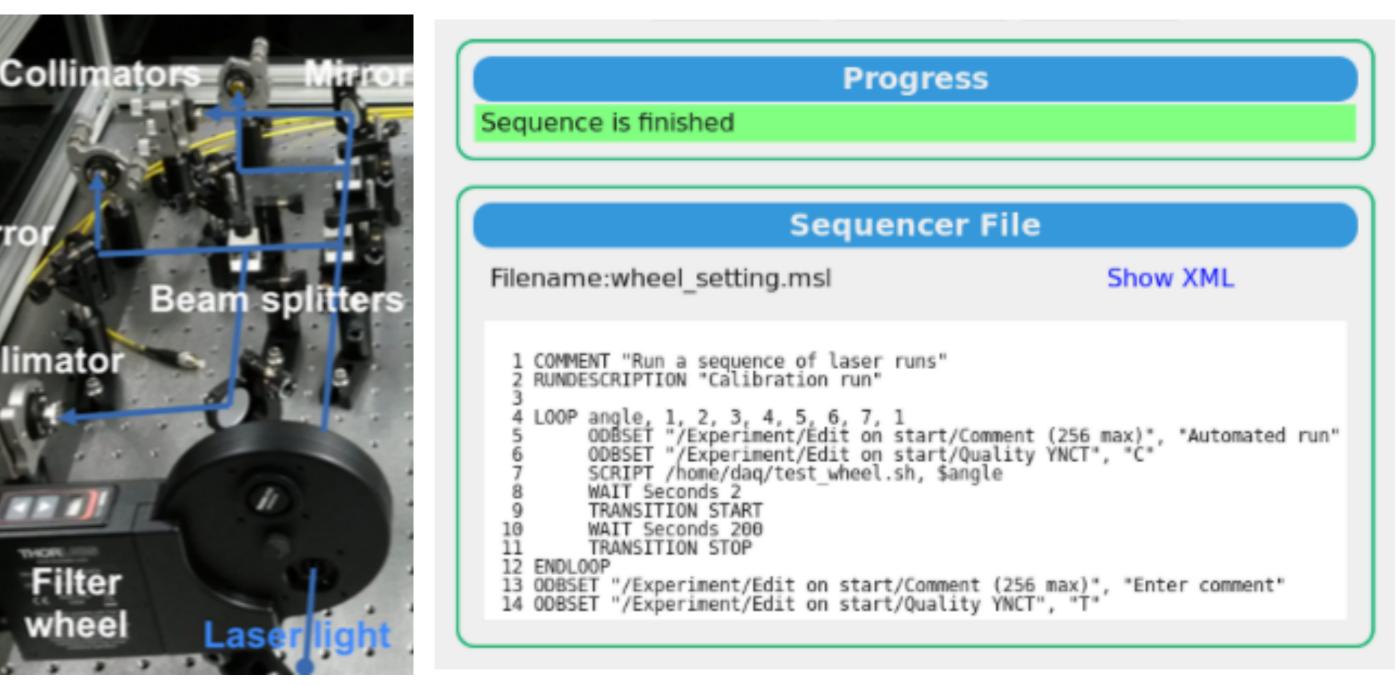
MIDAS Sequencer

- scans and bias voltage scans.
- A typical sequence would be:
 - Execute script to move wheel.
 - Update ODB values
 - Take data for 10 minutes
 - Repeat





The sequencer was used extensively for calibration runs such as filter wheel

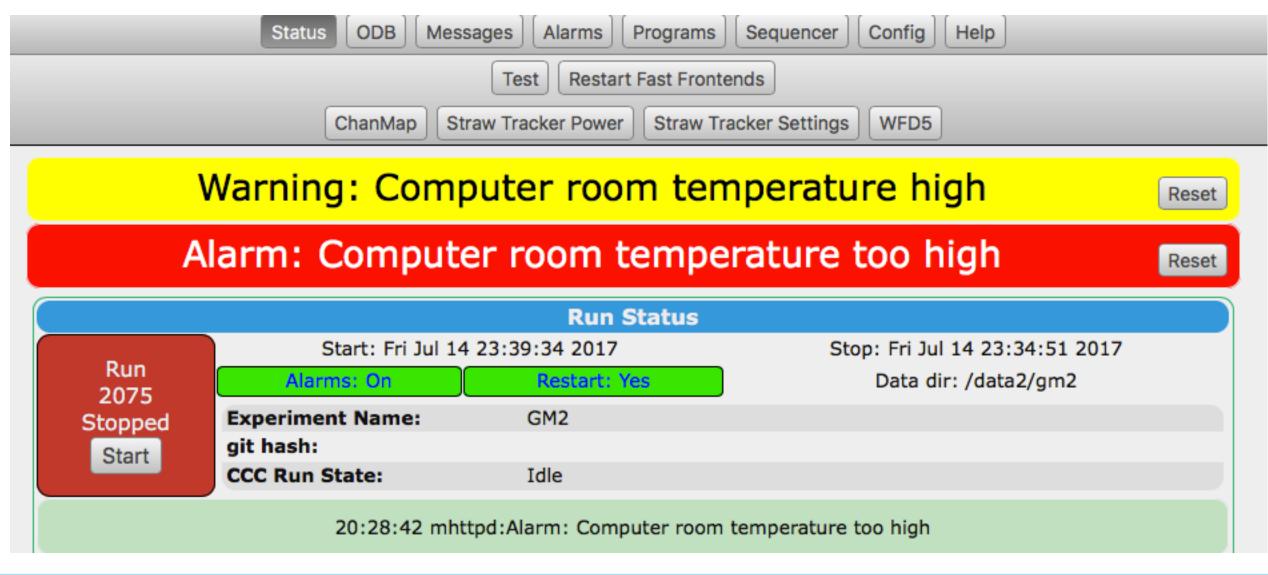




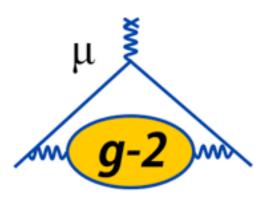


MIDAS Alarms

- The MIDAS alarm system was used as the primary alarm system.
- Alarms were set on temperatures and voltages from MSCB devices.
- Other slow frontends set alarms automatically when encountering an error. Periodic alarm reminded shifters to perform shift checks.
- Had problems at first with alarm audio, which was traced to a recent lack of mp3 support in scientific linux — this was later rectified with a recent update.



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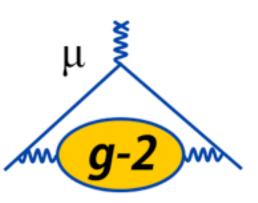


Custom Controls Page

- is very cumbersome.
- masse. Status ODB Messages Chat Al

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		AN	4C130	~) • T	Q01	⊜ то	02	0
		/E	quipr	ne	nt/AM	1C1	300/	Set	ti
Channel #	Rider	01	Rider	02	Rider	03	Rider	04	R
00	-200	*	-200	*	-200	*	-200	*	-
01	-200	*	-200	*	-200	^	-200	*	-
02	-200	*	-200	*	-200	~	-200	*	-
03	-200	*	-200	*	-200	*	-200	*	-
04	-200	*	-200	*	-200	*	-200	*	-
								Enat	ble
			/	/Eq	uipm	en	t/AM	C13	30
Channel #	Rider	- 01	Rider	- 02	Rider	- 03	Rider	- 04	R
00		5)))	
01		1)))	
02		1)))	
03		1)))	

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• With this number of frontends, configuring settings via the standard ODB tree

A set of custom Javascript pages were written to manipulate ODB values en

arms) [P	rogram	s	History		MSCB) [s	equence	er	Config		Help			
TQO	з	TQ04		Thr	eshc	old C	et x	-segmt)et y-seg	gmt]			
		01/0	lala		Ch			(/h la ma	- la	- 1-1					
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200	•	-200	^	-200	\$	-200	\$	-200	\$	-200	•	-200	~	-200	^
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200	\$	-200	\$	-200	\$	-200	\$	-200	\$	-200	\$	-200	\$	-200	\$
200	*	-200	\$	-200	^	-200	*	-200	^	-200	-	-200	^	-200	^
200	\$	-200	^	-200	^	-200	\$	-200	^	-200	\$	-200	^	-200	^
															_
	Char	n used	Po	ositive c	ross	ing									
0/S	etti	ings/	Rid	erXX	/Cł	nanne	elX.	X/ena	abl	ed					
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	W	RITE to	ODB												



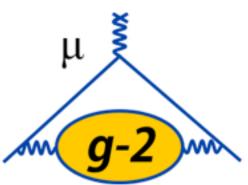


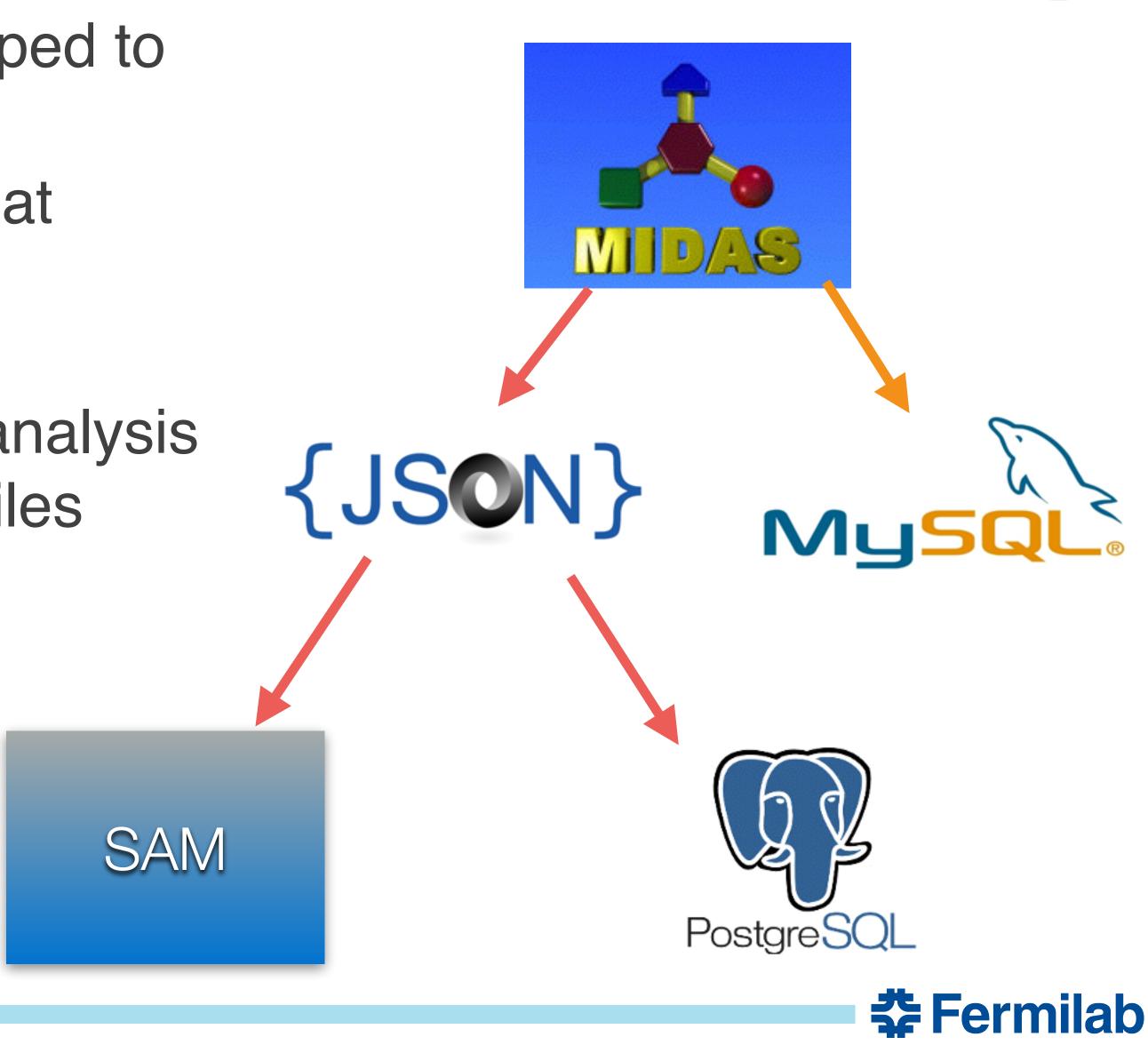




MIDAS ODB Archive

- At each end of run, the ODB is dumped to a JSON file.
- A python routine is then executed that imports the entire JSON file into a PostgreSQL database.
- Metadata that is used in the offline analysis is also extracted from these JSON files using python plugins.



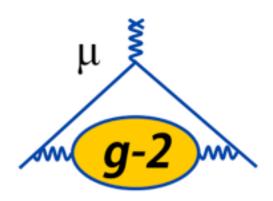


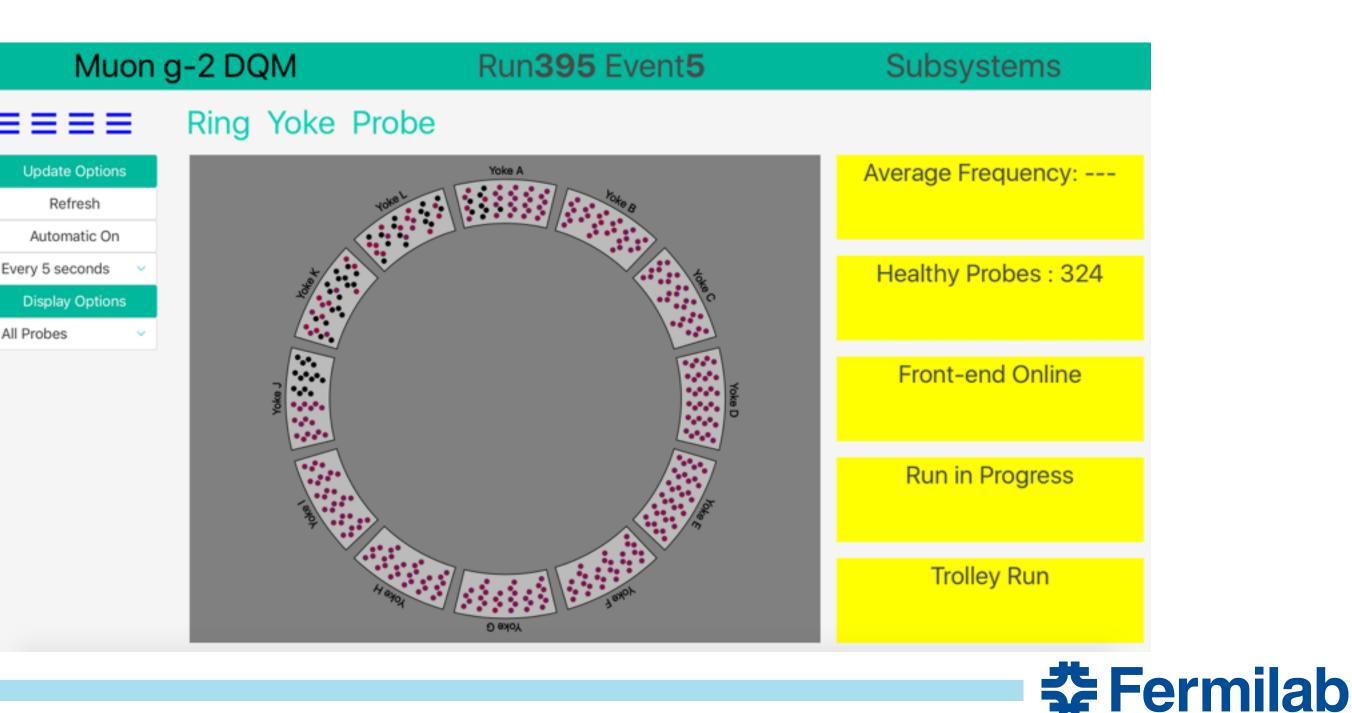
Field DAQ

- Field DAQ runs in independent MIDAS experiment.
- Contains seven asynchronous frontends reading data from fixed magnetic field probes and from a trolley that periodically transverses the ring to perform precision measurements of magnetic field.
- Data is correlated with the fast DAQ offline using GPS timestamps.

Status ODB Messages Alarms Programs History MSCB Help Restart Front-Ends Restart Logger Restart Server Restart DQMs										
Trolley Control Plunging Probe Control										
Run Status										
Kull	tart: Thu Jun 1 08:52:27 2017		nning time: 0h r: /home/newg							
Dunning		Data ui	r. /nome/newş	jz/gilizbata/						
	periment Name: g2-field bliey Status: n									
	ney status.									
09:19:00 [Fixed Probes, DEBUG] issued trigger										
	09:19:00 [Fixed Probes,DEE	UG] issued	l trigger							
	09:19:00 [Fixed Probes,DEB	UG] issued	l trigger							
	09:19:00 [Fixed Probes,DEB Equipme	-	l trigger							
Equipment		-	Events[/s]	Data[MB/s]						
Equipment Fixed Probes	Equipme	nt		Data[MB/s] 0.995						
Fixed Probes	Equipme Status	nt Events	Events[/s]							
	Equipme Status Fixed Probes@g2field-fe2-priv	nt Events 398	Events[/s] 0.3	0.995						
Fixed Probes TrolleyInterface	Equipme Status Fixed Probes@g2field-fe2-priv Frontend stopped	nt Events 398 0	Events[/s] 0.3 0.0	0.995						
Fixed Probes TrolleyInterface GalilFermi	Equipme Status Fixed Probes@g2field-fe2-priv Frontend stopped Frontend stopped	nt Events 398 0 0	Events[/s] 0.3 0.0 0.0	0.995 0.000 0.000						
Fixed Probes TrolleyInterface GalilFermi Surface Coils	Equipme Status Fixed Probes@g2field-fe2-priv Frontend stopped Frontend stopped Frontend stopped	Events 398 0 0 0	Events[/s] 0.3 0.0 0.0 0.0	0.995 0.000 0.000 0.000						
Fixed Probes TrolleyInterface GalilFermi Surface Coils Monitor	Equipme Status Fixed Probes@g2field-fe2-priv Frontend stopped Frontend stopped Frontend stopped Frontend stopped	nt Events 398 0 0 0 0	Events[/s] 0.3 0.0 0.0 0.0 0.0 0.0	0.995 0.000 0.000 0.000 0.000						
Fixed Probes TrolleyInterface GalilFermi Surface Coils Monitor Fluxgate	Equipme Status Fixed Probes@g2field-fe2-priv Frontend stopped Frontend stopped Frontend stopped Frontend stopped Frontend stopped Frontend stopped	nt Events 398 0 0 0 0 0 0 0	Events[/s] 0.3 0.0 0.0 0.0 0.0 0.0 0.0	0.995 0.000 0.000 0.000 0.000 0.000						
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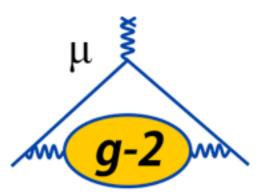




Slow Controls

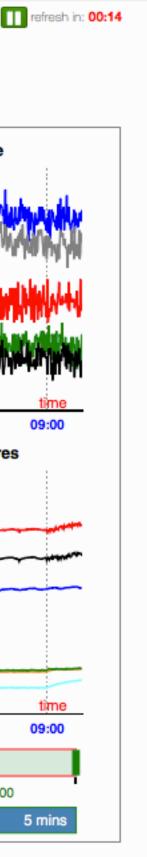


- DAQ includes six SCS3000 mscb devices.
- 24 beaglebones reading slow control data from calorimeters.
- HV and LV frontends for tracker system.
- Slow frontend reading magnet properties from IFIX via an OPC client.
- Beamline frontend periodically reading output of beam components from database.
- Slow control data is stored in a Postgres database and displayed using a custom Django web display.



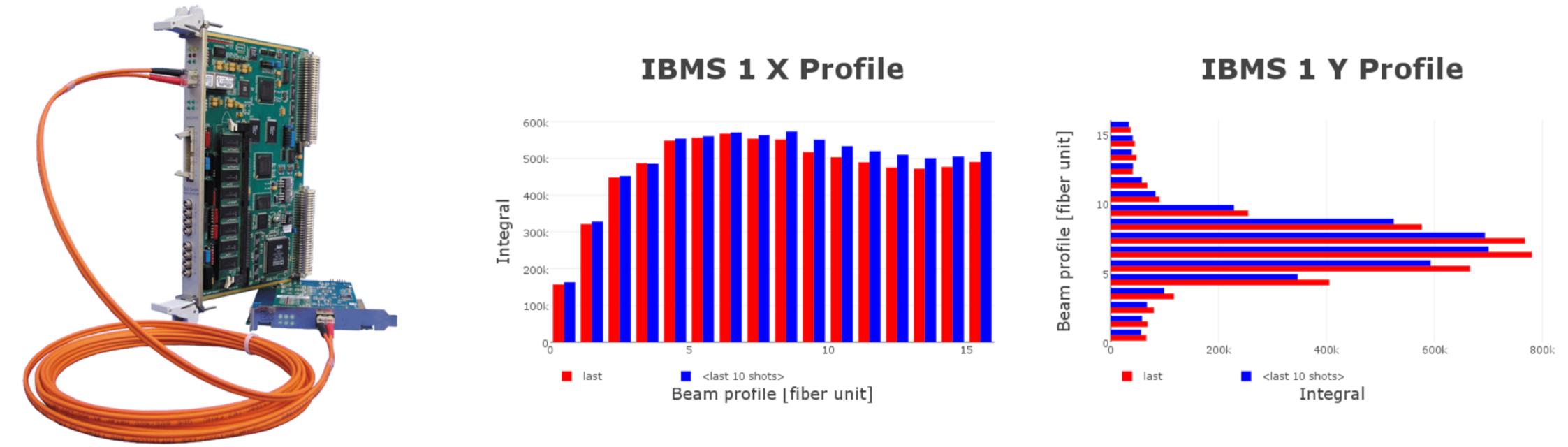


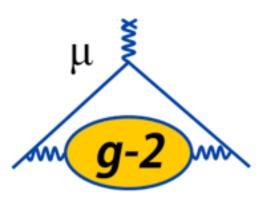




IBMS Frontend

- Data from the inflector beam monitoring system (IBMS) is read out via a CAEN digitizer.





A custom MIDAS frontend was written to integrate this detector into the DAQ.

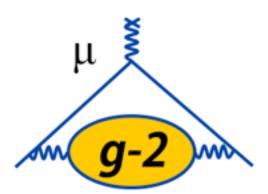


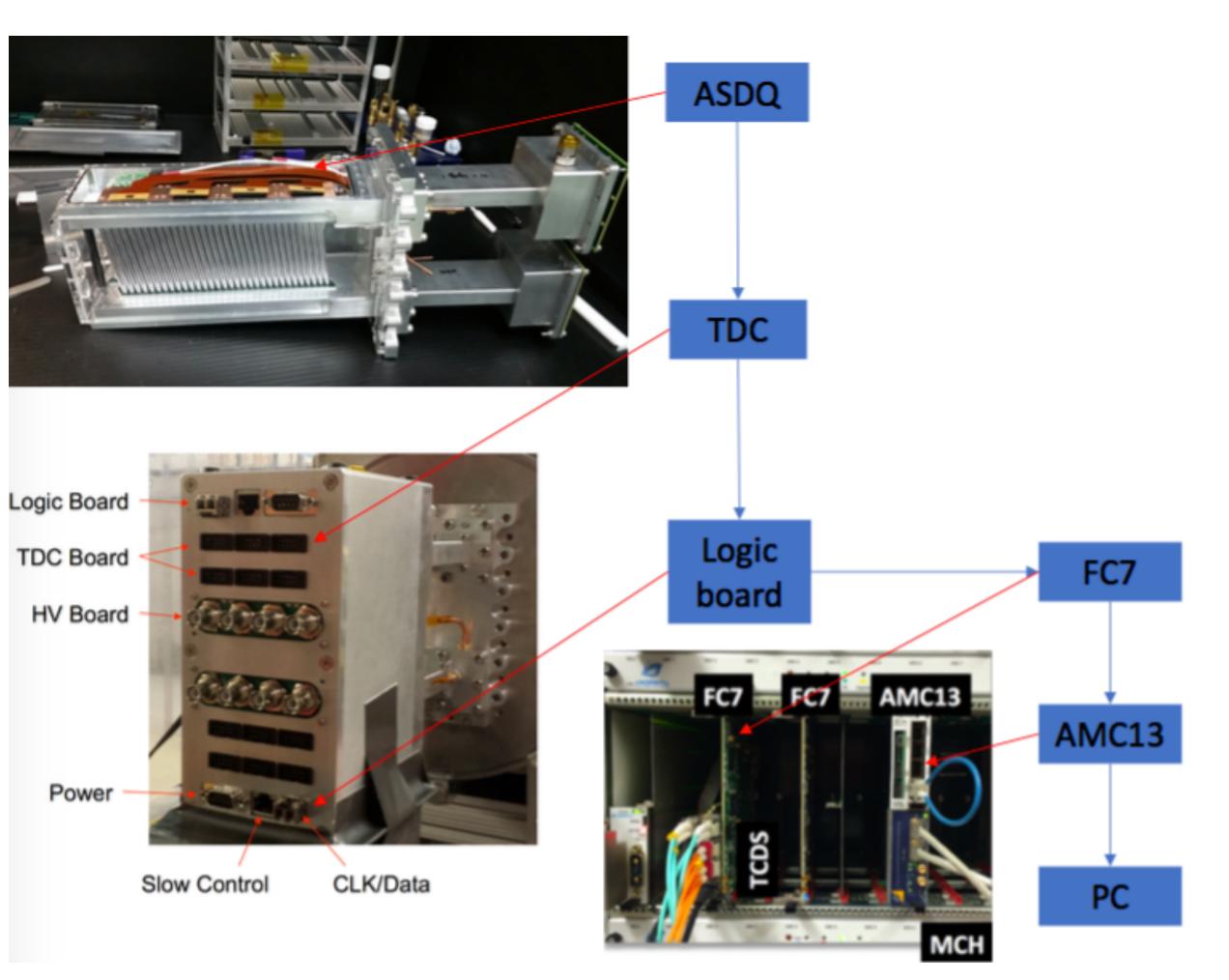




Tracker Frontend

- Three tracker stations will be read via one uTCA crate.
- Reads data from AMC13.
- Instead of digitizers, data comes from multihit TDCs that are read via FC7 cards.





(Thanks R. Chislett for the diagram)



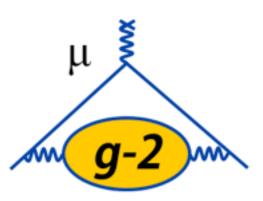


MasterGM2 frontend

- Communicates with other frontends using RPC calls.
- Provides begin of run and end of run RPCs to all frontends.
- Provides end of fill trigger to synchronous frontends.
- Configures clock and control system.
- Reads trigger times from Meinberg GPS unit and writes them to a MIDAS bank.



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Event builder

ODB Equipment of each frontend.

Online Database	Browser			
Find Create Delete Crea	ate Elog from this	page		
/ Equipment / AMC1308 / S	Settings / Glo	bals /	Enable he	oral
Key	Value	+		
sync	n			
use AMC13 simulator	n	and the second		
GPU Device ID	2 (0x			
Send to Event Builder	y y			
Shelf configuration	rider			
FE lossless compression	n			
raw data store	У			
raw data prescale	1000 (0x38	8)		
raw data prescale offset	8 (0×8)			

- Total EB rate maxed out at > 1.2 GB/s (limited by network bandwidth)
- The event builder combines up to 270 banks for each event.



Modified event builder to change how it is enabled — now done entirely in

