



Cosmic Ray Studies II

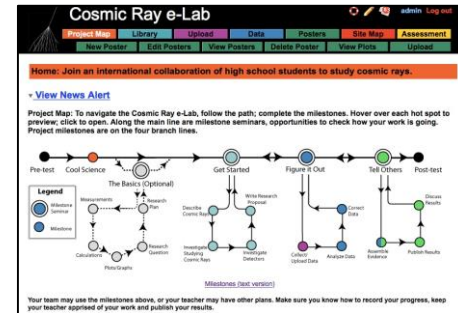
QuarkNet Student Investigations



DAQ



Detector



e-Lab

Mark Adams
Fermilab



U.S. DEPARTMENT OF
ENERGY

Office of
Science



QuarkNet



Global Cosmic Ray Effort

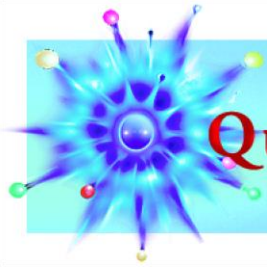
Outline

- **QuarkNet detectors around the world**
- **e-Lab data analysis tools**
- **Examples of experiments**
- **Shared data format for all outreach efforts**
- **Proposal for global cosmic ray
Measurements with and without a shared
data format**



QuarkNet Data





QuarkNet

Data Tab

Cosmic Ray e-Lab

admin Log out

Project Map Library Upload Data Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Home: Join an international collaboration of high school students to study cosmic rays.

Flux – Rate versus time

Shower – Correlate events from different DAQs.

Lifetime – Muon Lifetime

Time of Flight – Relative time between counters: speed of muon



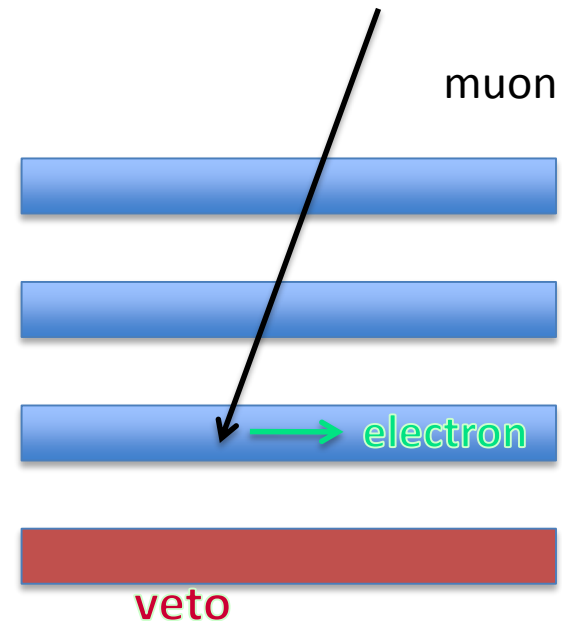
Data Analysis Flow

- Take data with cosmic ray detector.
- Define geometry of setup.
- Upload data.
- - - - - -
- Select data.
- Run an analysis.
- Save plots.
- Make poster.



Muon Lifetime

- Stack four counters.
- Program DAQ: Require three top counters to fire and veto on bottom counter.
- Record data for one week.
- Upload data file to e-Lab.
- Select data file and run “lifetime” analysis to find time between muon and next signal (electron).





Select Data

Cosmic Ray e-Lab

testJan17 Log out

- Project Map
- Library
- Upload
- Flux**
- Shower
- Lifetime**
- T of F
- View Plots
- Analyses

Choose data for lifetime study.

One way to classify objects is by measurable characteristics. All electrons have the same mass, charge and spin. What characteristics can you measure about the cosmic ray particles that reach Earth's surface? These unstable particles decay with a characteristic [signal](#) in a characteristic time. Can you measure it? If so, that characteristic is one way to determine what the particles are. Gain confidence by running a practice analysis.

Choose DAQ or experimental group.

Run analysis.

Quick Searches: [testJan17](#), [Rosen](#), [S. Peterson](#), [Fermilab Test Array](#), [Batavia](#), [IL](#)

Group: Search Data

Advanced Search

[View and Search from detector map](#)

* To speed up searches by default we are retrieving the last 3 months worth of data for the criteria you chose. You can modify your date range using the Advanced Search criteria.

Results 1 - 1 of 1 for group testJan17 (Searched 22 files in 0.219 seconds)

[Clear selected data](#)

Fermilab Test Array

Batavia, IL
22 data files: 0 blessed, 22 stacked, 844,572 total events.

▼ January 2017, 18 files Select: [All](#) [None](#)

Detector 6516, 18 files Select: [All](#) [None](#)

<input type="checkbox"/> Fri 13 2,973 events	<input type="checkbox"/> Sat 14 46,820 events	<input type="checkbox"/> Sun 15 46,503 events	<input type="checkbox"/> Mon 16 46,807 events
<input type="checkbox"/> Tue 17 39,306 events	<input type="checkbox"/> Tue 20 4,061 events	<input type="checkbox"/> Wed 21 32,313 events	<input type="checkbox"/> Thu 16 2,973 events
<input type="checkbox"/> Mon 23 9,902 events	<input type="checkbox"/> Tue 24 50,785 events	<input checked="" type="checkbox"/> Wed 25 47,273 events	<input checked="" type="checkbox"/> Wed 25 6,635 events
<input checked="" type="checkbox"/> Thu 26 51,424 events	<input checked="" type="checkbox"/> Fri 27 51,321 events	<input checked="" type="checkbox"/> Sat 28 52,102 events	<input checked="" type="checkbox"/> Sun 29 51,832 events
<input type="checkbox"/> Mon 30 50,785 events	<input checked="" type="checkbox"/> Tue 31 52,444 events		

Select files.

Analyze

Help

[Tutorial on lifetime study](#)

[Step-by-step instructions](#)

[FAQs](#)

States include provinces and countries. Enter the [abbreviation](#)

Related Milestones

[Analyze Data](#)

[Correct Data](#)

[Assemble Evidence](#)

Legend

- View data
- Rollover for more info
- Unstacked data
- Stacked data
- Blessed data
- Click to view blessing charts
- Rollover for more info
- Unblessed data
- Click to view blessing charts
- Rollover for more info
- Data has comments - Add more/View
- Add comments

You cannot select files with No Geo for Flux, Shower or Lifetime Studies.



Analysis Controls

Cosmic Ray e-Lab testJan17 Log out

Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Calculate the lifetime of muons that stop in the detector

This analysis determines the time difference between consecutive photomultiplier tube [signals](#). Two consecutive signals might be one cosmic ray muon followed by another. Two signals may also come from a muon (the first signal) which then decays into an electron, a neutrino and an anti-neutrino. The electron will create a second signal. The routine displays a histogram of the signal separations that "pass" criteria you set in a the fields below.

Gain confidence by running a practice analysis.

[Understand the graph](#)

DAQ#	You	events	events	events	events	Raw Data	Remove from analysis
6516	Fermilab Test Array Jan 25, 2017 00:00:01 UTC	798338	719968	643507	1734486	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 25, 2017 22:17:34 UTC	114080	102664	90656	243203	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 26, 2017 00:00:01 UTC	872643	785369	703202	1893371	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 27, 2017 00:00:02 UTC	888522	781367	699474	1887145	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 28, 2017 00:00:00 UTC	870676	790352	707192	1908853	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 29, 2017 00:00:00 UTC	866298	787608	708575	1910757	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 30, 2017 00:00:01 UTC	853442	769780	690422	1860017	View Statistics Geometry	<input type="checkbox"/>
6516	Fermilab Test Array Jan 31, 2017 00:00:01 UTC	885566	791868	711860	1910886	View Statistics Geometry	<input type="checkbox"/>
		(1299147 events)	6129565	5528976	4954888	13348710	<input type="checkbox"/>

List of files selected

Click **Analyze** to use the data from the buttons. Control the analysis by expanding the options below.

Analysis Controls

Coincidence level: 1

Gate width (seconds): 2e-5

Number of Bins: 40

Plot Controls

X-max: []

Y-min: []

Y-max: []

Plot Size: Medium

Plot Title: Lifetime Study

Figure caption: Data: Fermilab Test Array Jan 25-31, 2017 00:00:01 UTC
Detector: 6516
Coincidence level: 1

Fit Controls

Fitting Turn On: Yes

X-min fit: .1

X-max of fit: []

Fit Y-intercept: Yes Alpha: []

Fit Lifetime: Yes Lifetime: []

Background: Yes Background: []

Estimated time: 00:01:10

Analyze

Controls:

Coincidence requirement for electron

Time range of plot

Number of bins

Enable fitting.

Submit analysis.



Analysis Running

Cosmic Ray e-Lab testJan17 **Log out**

Project Map **Library** **Upload** **Data** **Posters** **Site Map** **Assessment**

View Data **Performance** **Flux** **Shower** **Lifetime** **T of F** **View Plots** **Analyses**

Running LifetimeStudy...



Progress:



Elapsed time: 00:00:27; estimated: 00:01:10

Perhaps queue study and look for results later.

► Analysis output



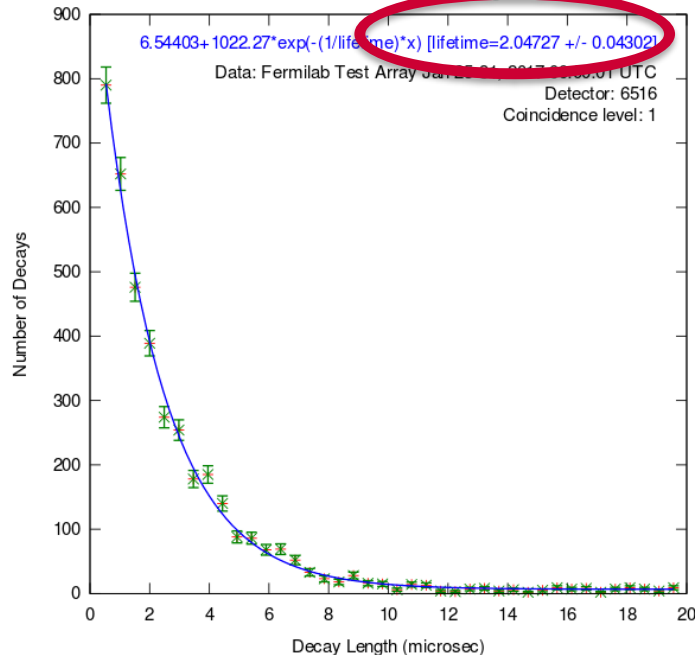
Muon Lifetime Result

Cosmic Ray e-Lab testJan17 Log out

Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Lifetime Study



3500 muon decays in 7 days

(~1 decay every 1000 muons)

Lifetime 2.05 +/- 0.04 microseconds

Random background 6.5 events per 500 ns bin

Analysis run time: 00:00:51; estimated: 00:01:10

Show [analysis director](#)
[Change](#) your parameter

Change parameters and run again.

To save this plot permanently, enter the new name you want.

Then click **Save Plot**.

(View your saved plot names)



Muon Lifetime Rerun

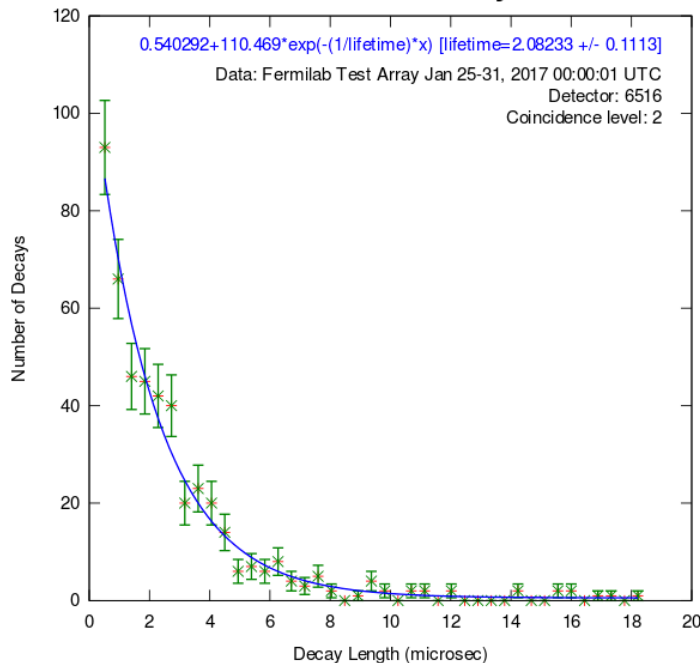
Cosmic Ray e-Lab testJan17 Log out

Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Coincidence = 2

Lifetime Study



350 muon decays in 7 days

2 hits for electron

Lifetime 2.08 +/- 0.11 microseconds

Random background 0.54 events per 500 ns bin

Slightly better signal to noise

Analysis run time: 00:00:44; estimated: 00:01:10

Show [analysis directory](#)

[Change](#) your parameters

OR

To save this plot permanently, enter the new name you want.

Then click **Save Plot**.



(View your saved plot names)



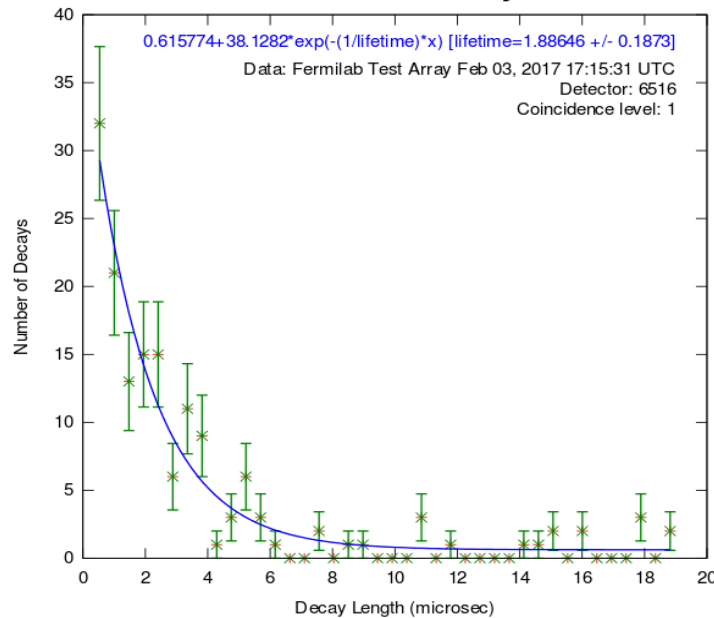
Lifetime without Veto

Cosmic Ray e-Lab testJan17 Log out

Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Lifetime Study



Short Test without Veto

140 muon decays in 2.5 hrs.

Lifetime 1.9 +/- 0.19 microseconds

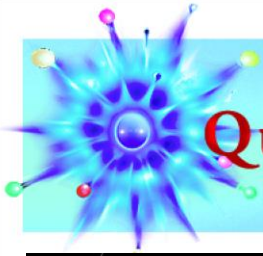
Random background 0.6 events per 500 ns bin

Background is larger:

Without veto – 140 decays with 12 background

With veto – 3500 decays with 130 background

Signal/Noise: 27 (11) with (without) veto



QuarkNet

Run Flux on Same Data

Cosmic Ray e-Lab testJan17 Log out

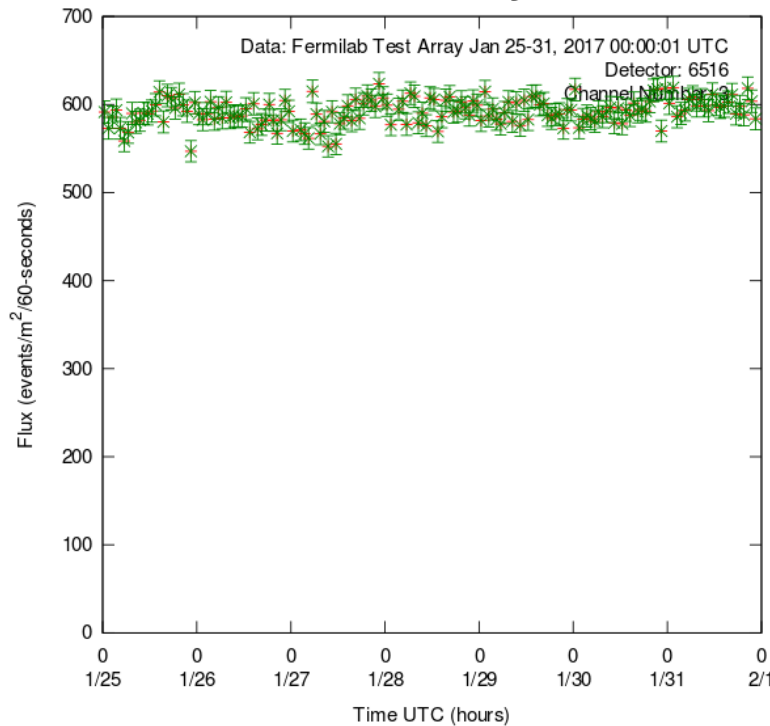
Project Map Library Upload **Data** Posters Site Map Assessment

View Data Performance Flux Shower Lifetime T of F View Plots Analyses

[View blessing plots](#)

[View interactive Flux plots](#) (Beta Version)

Flux Study



Rate versus time over 7 days
Verify that data collection looks normal.



Check Blessing Plots

Cosmic Ray e-Lab testJan17 Log out

Project Map Library Upload **Data** Posters Site Map Assessment

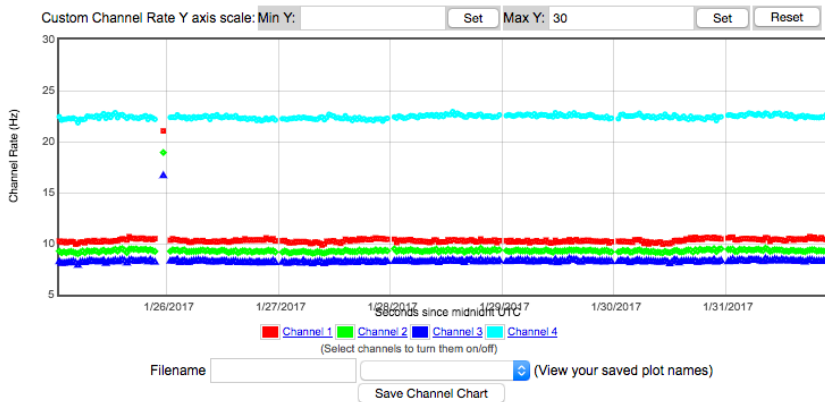
View Data Performance Flux Shower Lifetime T of F View Plots Analyses

Quality of Data Measures plus temperature and pressure information

View blessing plots by date range.

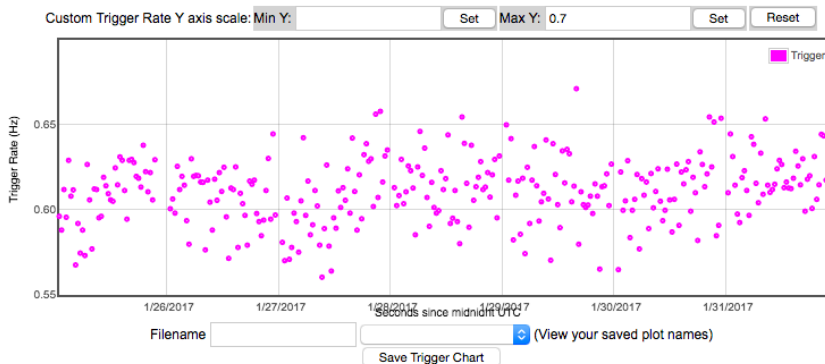
[Go back to Flux Study](#)

Rates



Frequency of individual counters independent of triggered events (scalers)

Trigger Rate



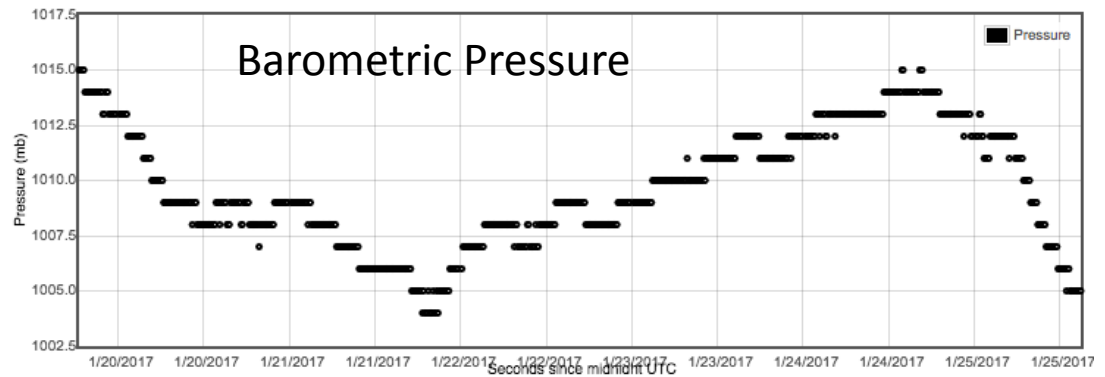
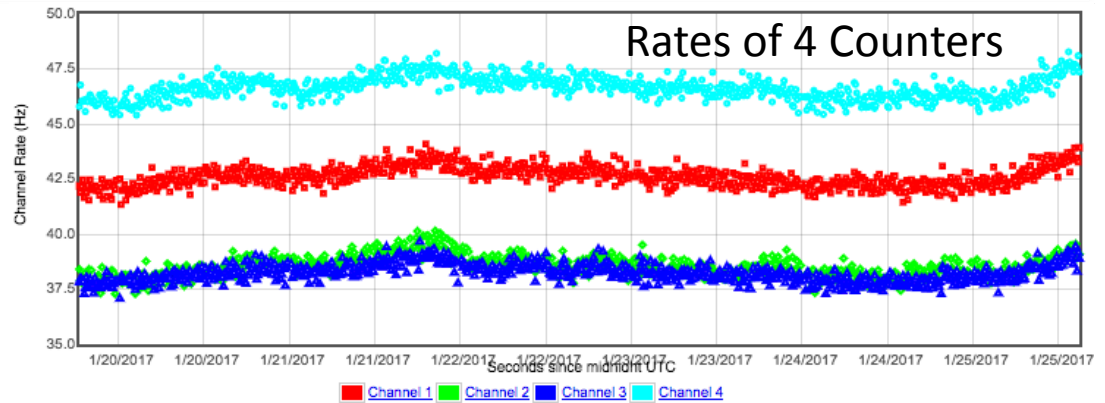
Trigger rate versus time from scalers

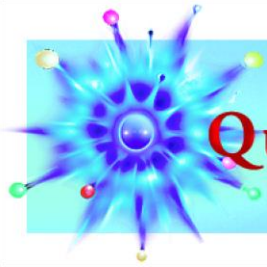


Rate vs. Pressure

Counter rates versus time inversely proportional to pressure

After correcting for barometric pressure, students can also study dependences on temperature, day/night—maybe latitude in future.



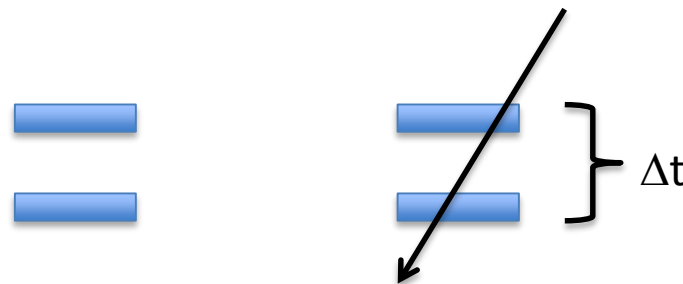


QuarkNet

Time-of-Flight Analysis

Use TOF tool to get relative timing information between counters.

Vary distance between counters in two data runs to extract the average muon speed from the means of the timing distributions.





QuarkNet

Time of Flight

Cosmic Ray e-Lab CRdata Log out

[Project Map](#) [Library](#) [Upload](#) [Data](#) [Posters](#) [Site Map](#) [Assessment](#)

[Text Version](#) [Cool Science](#) [About Us](#)

Time of Flight study

DAQ#	You're analyzing...	Chan1 events	Chan2 events	Chan3 events	Chan4 events	Raw Data
6119	Fermilab Test Array Feb 1, 2017 00:00:00 UTC Total (1 files 11793642 events)	2531632	2414049	3484173	3363788	View Statistics Geometry Compare files

Analyze the same files in [performance](#)

Click **Analyze** to use the default parameters. Control the analysis by expanding the options below.

Analysis Controls

Location: Fermilab Test Array, Batavia, IL (6119)

Event Gate (ns): 200

Channel Coincidence

Disable Soft Triggers?

Require Channels: 1 2 3 4

Channels: 1 2 3

Plot Controls

Estimated time: N/A

Measure the average muon speed.

Get relative time between all pairs of counters.

Controls:
Time range to plot
Number of counters required
Advanced controls allow software trigger logic.

Time-of-Flight Results



Cosmic Ray e-Lab

CRdata Log out

Project Map

Library

Upload

Data

Posters

Site Map

Assessment

Glossary

Resources

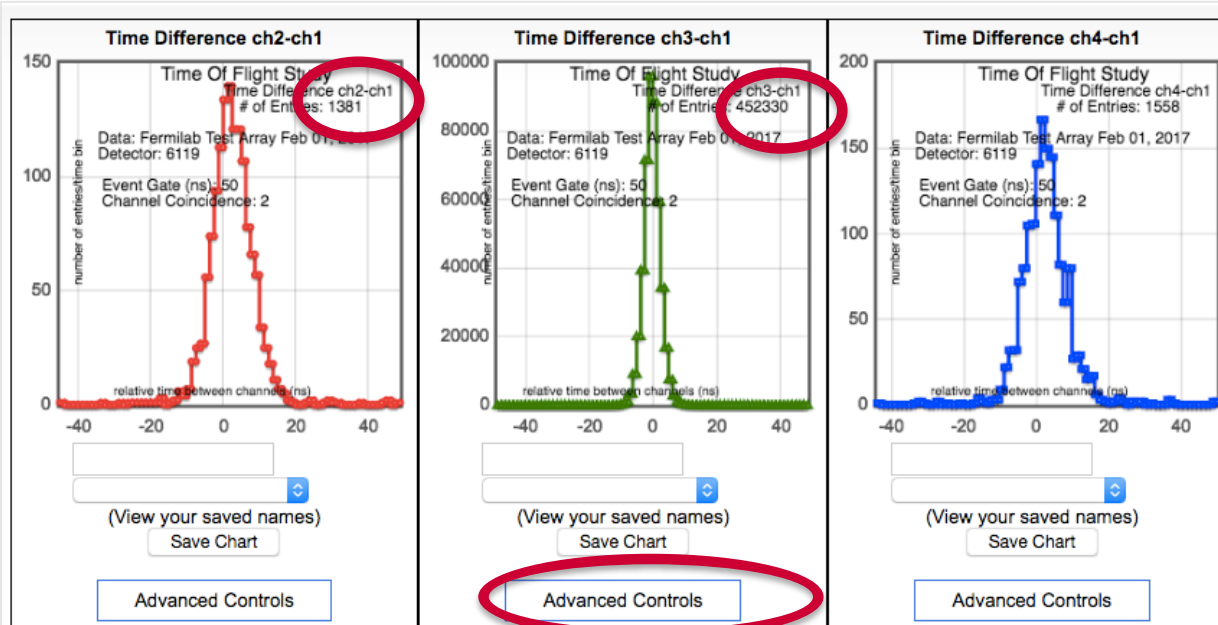
Big Picture

FAQs

Site Tips

Time of flight study result

[View all charts combined](#)



6 plots of time between counters i and j

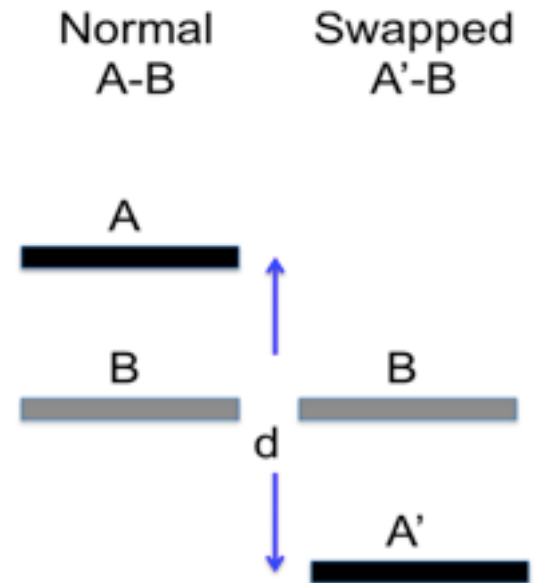
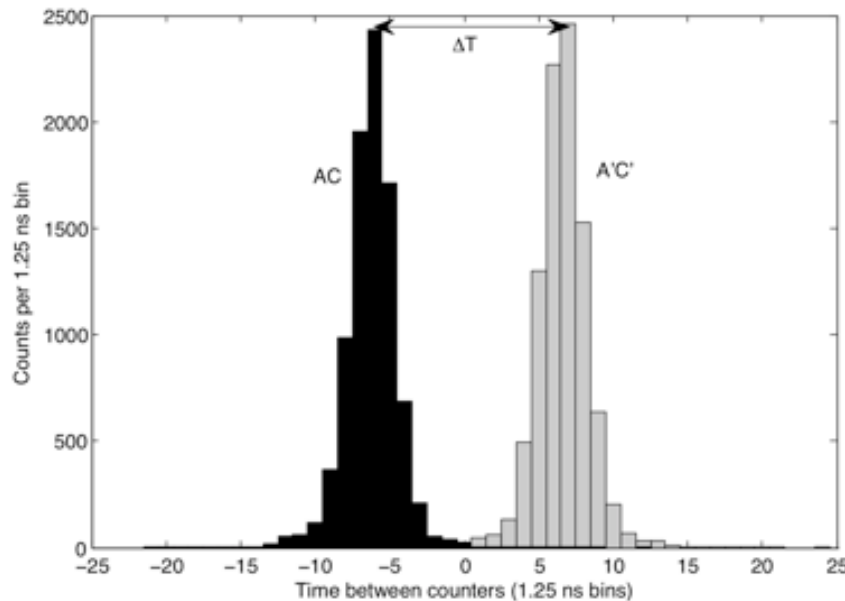
Note number of events:
Two stacks
1 over 3 and
2 over 4

Advanced controls provide fit results.



Speed

Glenbrook South High School students published a 1% measurement of the muons' average speed = $d/\Delta T$ from two configurations.

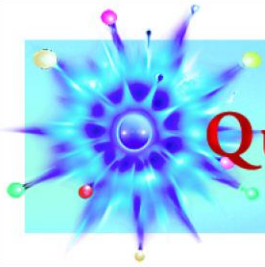




Shower e-Lab Tool

Shower enables user to search for coincidences in time in different DAQ readouts.

This can find very large showers in detectors separated by large distances or measure muon multiplicity of a large number of counters and DAQs located in a smaller space.

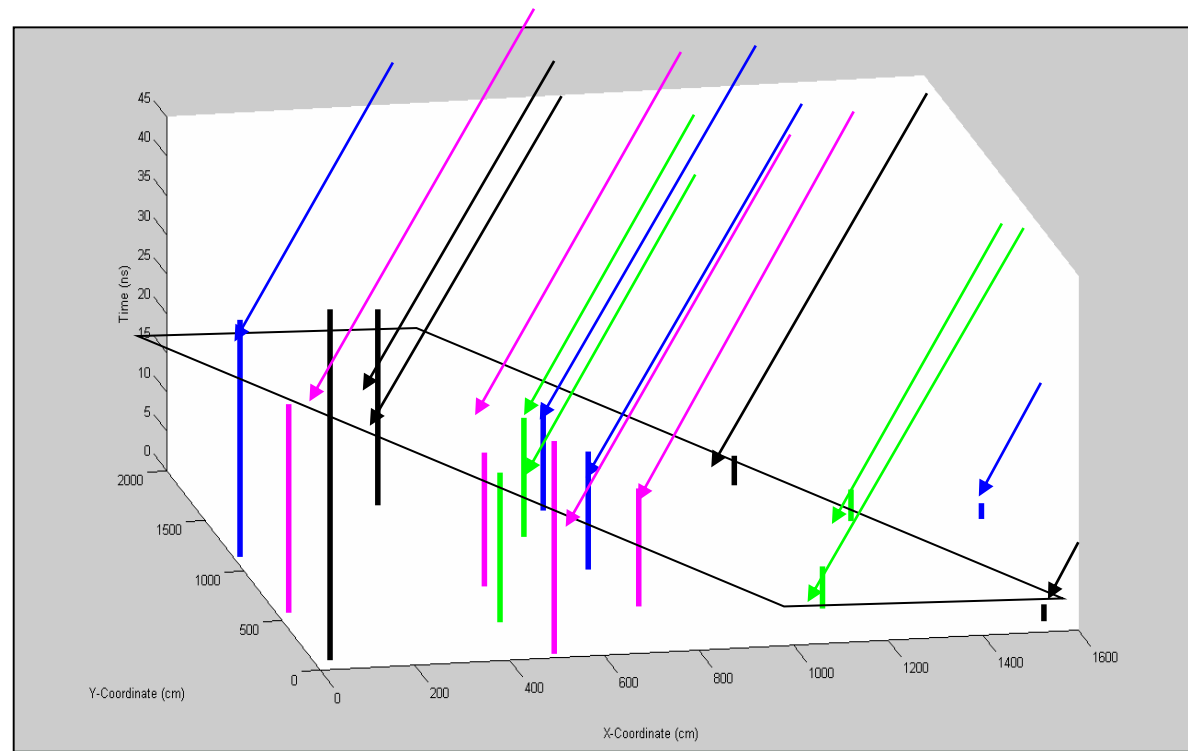


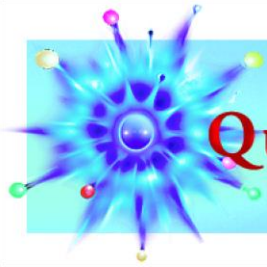
QuarkNet

Cosmic Ray Shower

**16 counters observing 16 muons in one shower
using 5 separate DAQs**

**The educational journey
required lots of
collaboration and
calibration effort.**





QuarkNet

Last Example: Time Dilation

- **Package of three counters measures muon rates at ground and on top of Sears Tower in Chicago.**
- **Muon lifetime implies few that reach roof should survive long enough to also reach ground.**
- **Result is that almost all muons reach ground.**
- **Demonstrates Einstein's time dilation (time run slower for moving objects—the muons)**





QuarkNet Data Format

Interpolate between CPU ticks.

Date: ddmmyy

Number of satellites

5A49E0F4	A6 00	00 00	27 00 00 00	59289115	000002.023	010217	A 07 0 +0081	1
5A49E0F4	00 3D	00 00	00 3C 00 00	59289115	000002.023	010217	A 07 0 +0081	
5A8F5C5C	80 00	32 00	00 00 32 00	59289115	000002.023	010217	A 07 0 +0081	
5A8F5C5D	00 00	00 00	00 00 00 27	59289115	000002.023	010217	A 07 0 +0081	2
5A8F5C5D	00 00	00 28	00 00 00 00	59289115	000002.023	010217	A 07 0 +0081	
5AA6CF4C	80 00	30 00	00 00 31 00	5AA60955	000003.031	010217	A 07 0 +0081	3
5AA6CF4D	00 00	00 00	00 00 00 27	5AA60955	000003.031	010217	A 07 0 +0081	
5AA6CF4D	00 00	00 29	00 00 00 00	5AA60955	000003.031	010217	A 07 0 +0081	

Ch 1

Ch 3

Ch 4

Universal
Time:
hhmmss

40 ns CPU counter
at trigger time

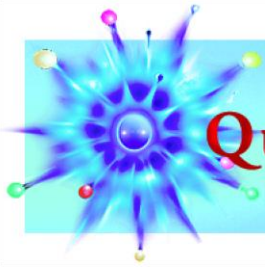
Channel 2
LE; TE
1.25 ns least counts

GPS 1 PPS
latches CPU
counter.

Absolute time accuracy of 100 ns

Relative time of counters in 1 DAQ to 1.25 ns least count

3 triggered events! Each line represents hit information in a 10 ns time slice.



QuarkNet

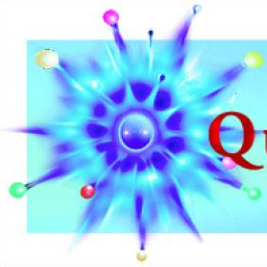
QuarkNet Data Format2

**Counter hits from triggered events stored in fraction of Julian Day:
leading edge; trailing edge; width**

**Contains corrections for counter lengths; hardware errors; counter
overflows; and correct 1 PPS**

```
#USING WIREDELAYS: ID.CHANNEL, Julian Day, RISING EDGE(sec), FALLING EDGE(sec), TIME OVER THRESHOLD
(nanosec)
6119.1 2457785 0.5000122652727026      0.5000122652729485      21.25
6119.3 2457785 0.5000122652726736      0.5000122652729919      27.50
6119.2 2457785 0.5000126299322889      0.5000126299325782      25.00
6119.4 2457785 0.5000126299322454      0.5000126299326216      32.51
6119.1 2457785 0.5000126831204167      0.5000126831207495      28.76
6119.3 2457785 0.5000126831204167      0.5000126831208073      33.75
6119.2 2457785 0.5000143909095892      0.5000143909099219      28.75
6119.4 2457785 0.5000143909096181      0.5000143909100521      37.50
-----
```

**This level of data is useful to experimenters outside of QuarkNet.
A common data format requires counter ID, time, size, position, and
orientation to neighboring counters.**



QuarkNet

Global Proposal

- **Form a collaboration of high schools.**
- **High schools take cosmic ray data and share with other sites around the world.**
- **High schools analyze data and share results with others around the world.**
- **Learn about what other groups are doing. Advertise their own experimental results.**

Does it make sense to develop a globally dispersed detector? Yes: 1. single muon rates; 2. large array correlated air showers

What could we do? Let's try!



Events That Change Muon Rates World-Wide

Without or before a common data format – SINGLE MUONS

Coordinate detector configurations and share results!

Take standard data over a long period of time: Establish baseline; perhaps correct for pressure dependence.

1. Search for change in nominal rate, e.g., due to a coronal mass

Ejection on the Sun that changes the Earth's magnetic field

When an abnormal rate is observed, send an e-mail request to detectors world-wide to capture rate histograms for a day surrounding the target time and share via a website that we can use as a logbook.

Tailored for rates from single muon setups



Events That Change Muon Rates World-Wide

Without or before a common data format – SINGLE MUONS

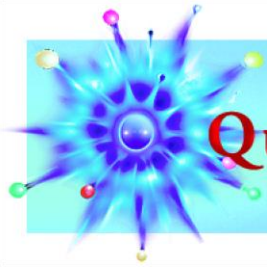
Coordinate detector configurations and share results!

Take standard data over a long period of time: Establish baseline; perhaps correct for pressure dependence.

2. Study rates versus pressure; altitude; latitude.

Website info: detector owner; rate every 20 minutes; time; latitude; longitude; stack or large array configuration; zenith angle; normal rate; comments

Tailored for rates from single muon setups



QuarkNet

Correlated Events World-Wide

Without or before a common data format – Large Array Data

3. Rare Events Study

Search for events world-wide correlated in time or for clusters of showers anywhere.

If found in any set of detectors (A) e.g., QuarkNet or HISPARC, ask groups world-wide to search for similar cluster within ~1 millisecond of the target time.

Data to share on website: detector owner; individual event times; latitude; longitude; array configuration; zenith angle; normal rate of occurrence at site B, time between A and B events



Rare Events – continued

Key is the battle against random overlaps.

Time window of search depends on rate of Rare Event A (e.g., 3 x year) and rate of second group's correlated type of event (B).

Group B might search for similar rare event over seconds, or define a less rare event and search over 10 ms.

QuarkNet example: Rare Event – 2 large arrays located outside typical air shower area (5 km apart). Rate DAQ1 and DAQ2 = 0.05 Hz leads to 0.2 random events within 10 microseconds in 3 months ($0.05 \text{ Hz} \times 0.05 \text{ Hz} \times 10^{-6} \text{ s} \times 8 \times 10^5 \text{ s}$).

User B would search at a specific time. If B rate is 0.1 Hz, 1 random event overlap would occur within 10 s search window.



With Common Format

With a common format, studies of any user with any other user's data would become much easier. A better shared logbook would need to be implemented.

Imagine a world-wide network of detectors that high school students can:

1. Monitor for rare events.
2. Mine for rate variation around the world.
3. Explore effects of latitude or pressure versus altitude.
4. Monitor the entire celestial sphere for cosmic ray variation.



Summary

- Students all over the world thrive doing research with QuarkNet cosmic ray detectors in their schools.
- It is inquiry-based learning at its best.
- Global cosmic ray experiments are well underway.
- Students understand technology and the process of science in a big collaboration.

Let's try a project! Next steps:

- **Build a closer global collaboration!**
- **Explore what global cosmic ray coverage can accomplish.**