Cosmic Rays

What are they?
Where do they come from?
Let's measure for ourselves!

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Outline

- Describe Cosmic Rays - Astronomy
- What do we see on the Earth's surface?
- Cosmic Ray Muons
- QuarkNet Detector
- **Analysis – Speed of Muon**
- Use Time of Flight between detectors
- Further studies?

QuarkNet Outreach

- High Energy Physics
- CMS, ATLAS and ALICE at the LHC CERN p-p 13 TeV
- Neutrino experiments at Fermi
- Cosmic Ray Muons
- HEP detectors and techniques brought to your school (supernovae are your accelerators)
- Muons are fundamental in all of these areas

Today's Questions

What can you study with Cosmic Rays

using QuarkNet Detectors

and

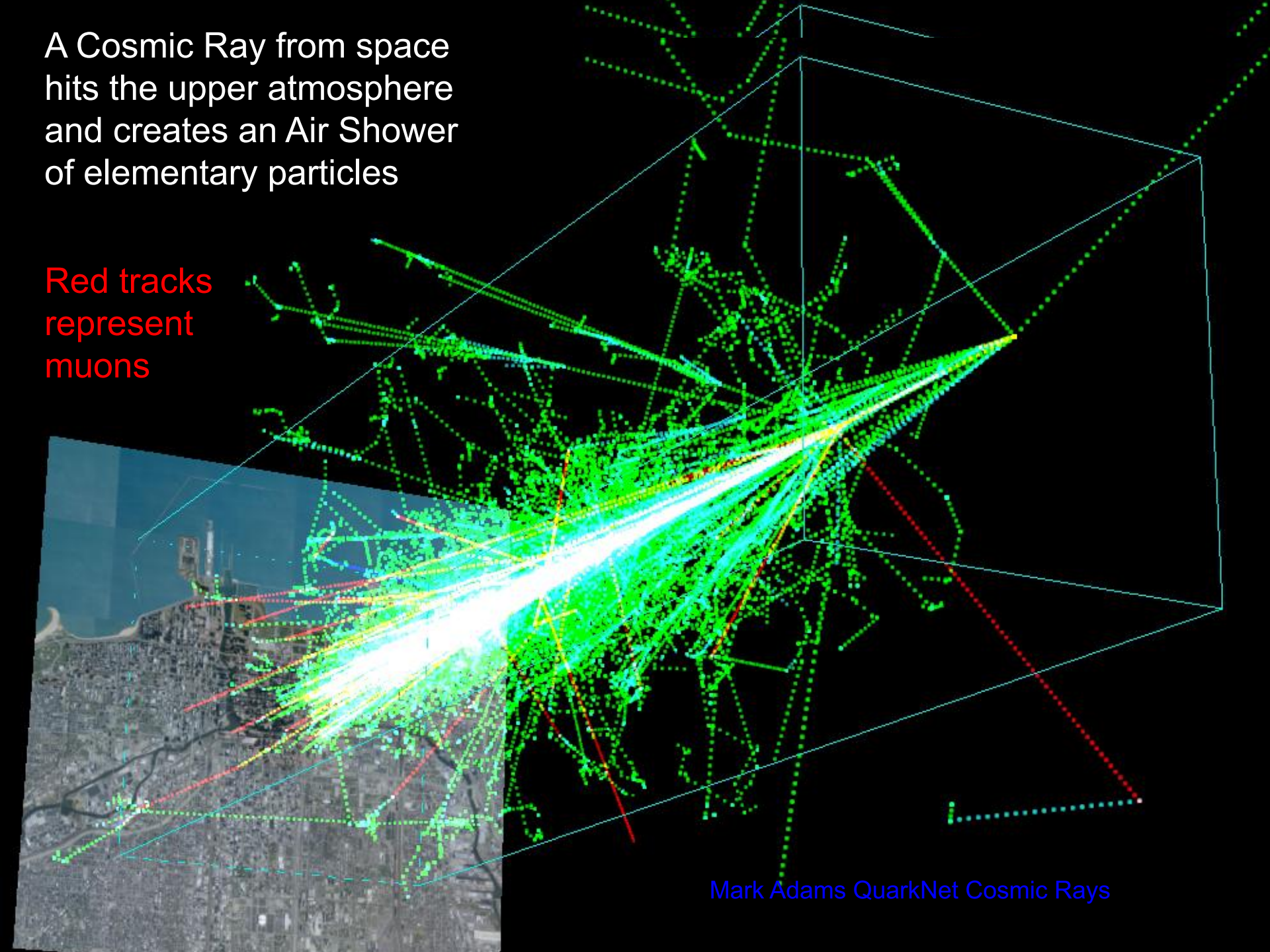
e-Lab analysis tools?

Cosmic Ray Discovery

- Cosmic Rays discovered in 1912 (Victor Hess) in balloon experiments
- Radiation higher at 5000m than at sea level – implies source hitting atmosphere
- No difference during partial eclipse – implies Sun not the source

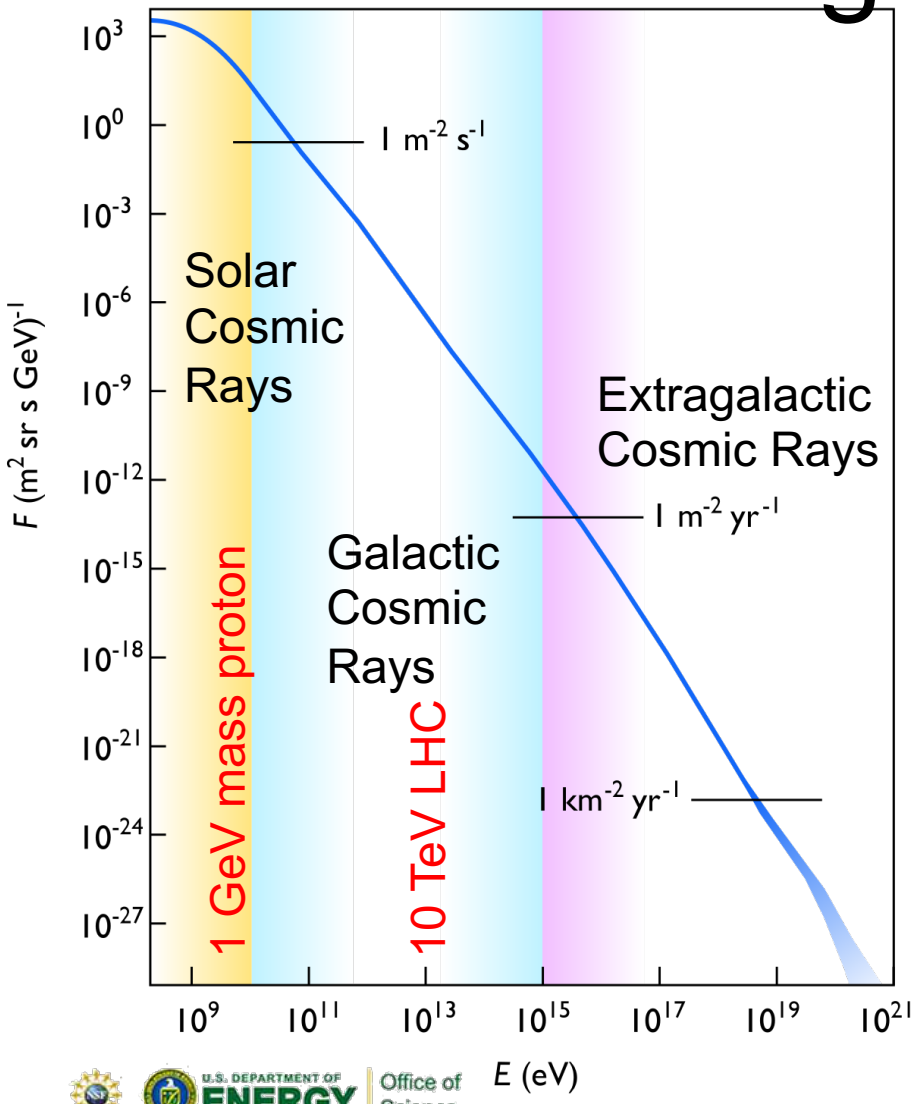
A Cosmic Ray from space hits the upper atmosphere and creates an Air Shower of elementary particles

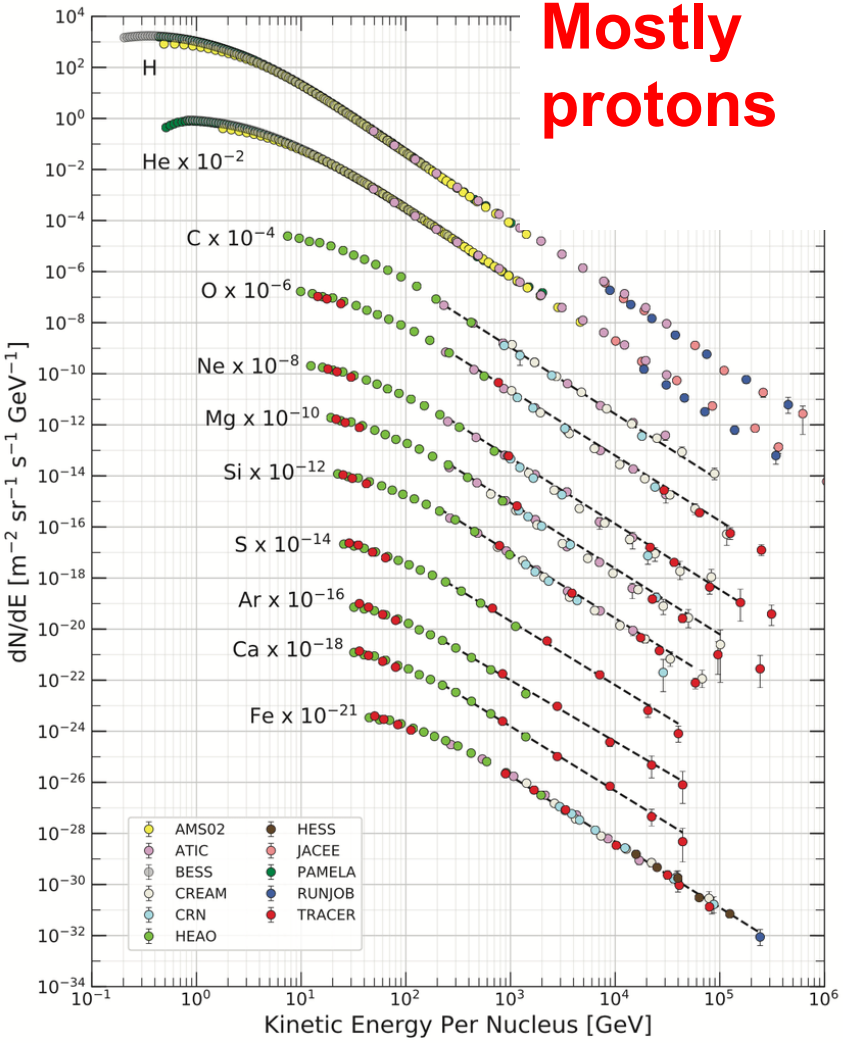
Red tracks represent muons



Mark Adams QuarkNet Cosmic Rays

Cosmic Ray Rates Hitting the Atmosphere

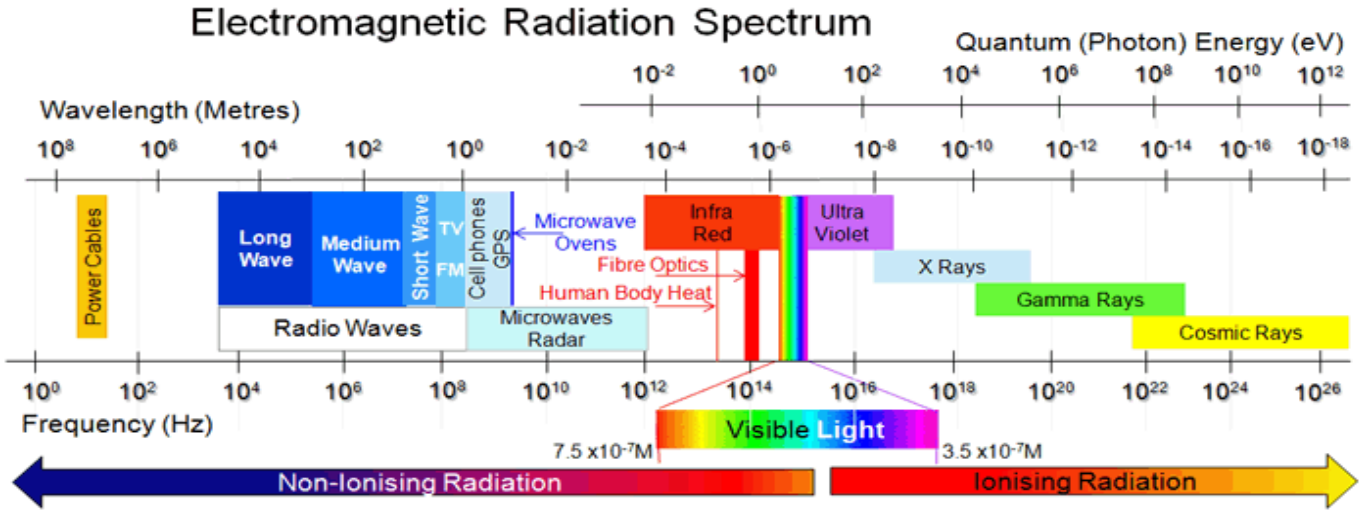




Mostly protons

How High is High Energy?

- Sun peaks with photons of energy 1 eV -atomic energies
- 1000 eV x-rays are from inner shell electron state
- 1,000,000 eV nuclear energy transitions (MeV nucleus and energies in sun's core)
- 1,000,000,000 eV gamma rays (GeV)



Energy Scales

Question – How are x-rays produced?

A. Dental office
B. Argonne Photon Light Source
C. Inner shell transitions in Heavy Elements
D. Stopping charged particles

X-rays from accelerated particles

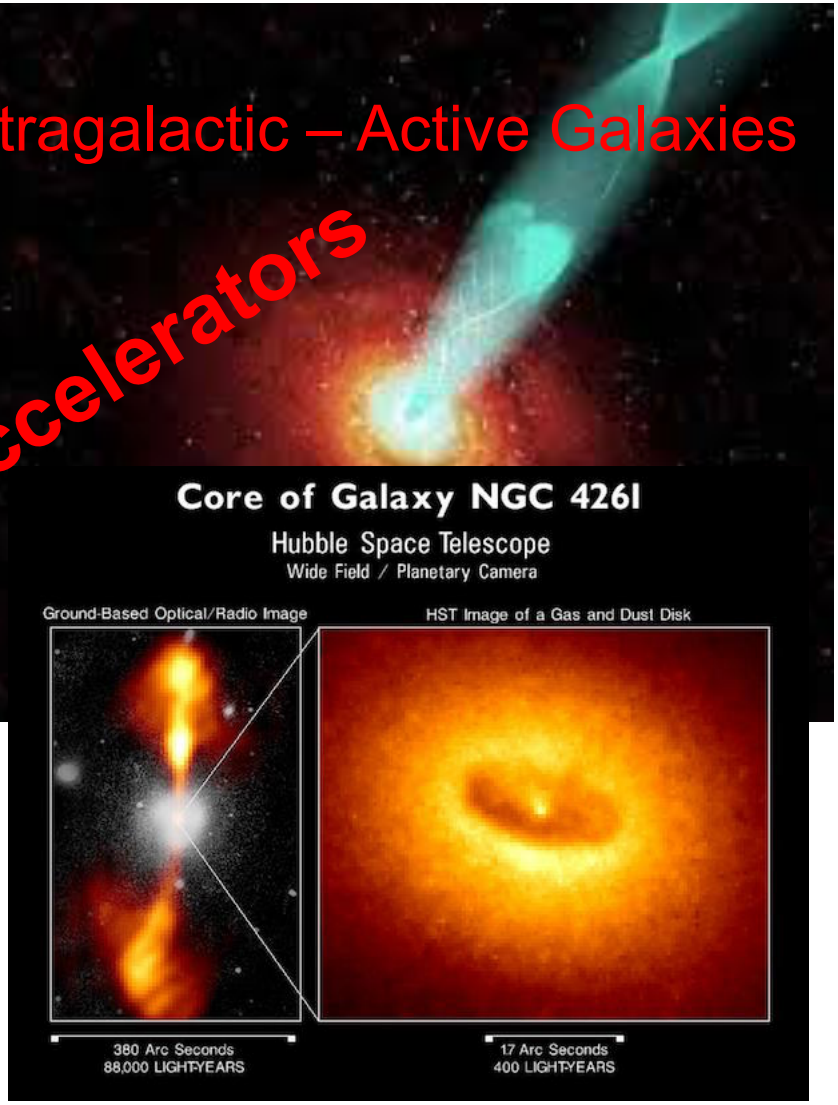
A. Dental office – HV accelerates electrons which hit metal plates, giving off x-ray photons
B. Argonne Photon Light Source – Large machine accelerates electrons; magnets **wiggle** electron paths – **Key to Covid-19 research**
C. Inner shell transitions in Heavy Elements – excited electron falls to lower inner shell state
D. Stopping charged particles – charged particles crash into material and slow down dramatically (accelerate), radiating x-ray photons –
E. Is why LEP(e+e-) didn't discover Higgs in '90s

Cosmic Ray Sources

Galactic - Supernovae

Extragalactic – Active Galaxies

Natural very high energy accelerators



Cosmic Ray Summary

Cosmic Rays are high energy nuclei (mostly proton) accelerated in some extreme condition – eventually hitting Earth's atmosphere

Galactic – Exploding massive stars

Extragalactic – Massive Black Hole accelerates particles

Weird that source of this energy is Gravity

Charged – trajectory bent by magnetic fields

Very poor telescope

Muons?

- Why haven't we discussed muons yet?
- Muons are created in the cosmic ray interactions with the atmosphere
- They have large energies (>2 GeV)

Air Showers make muons

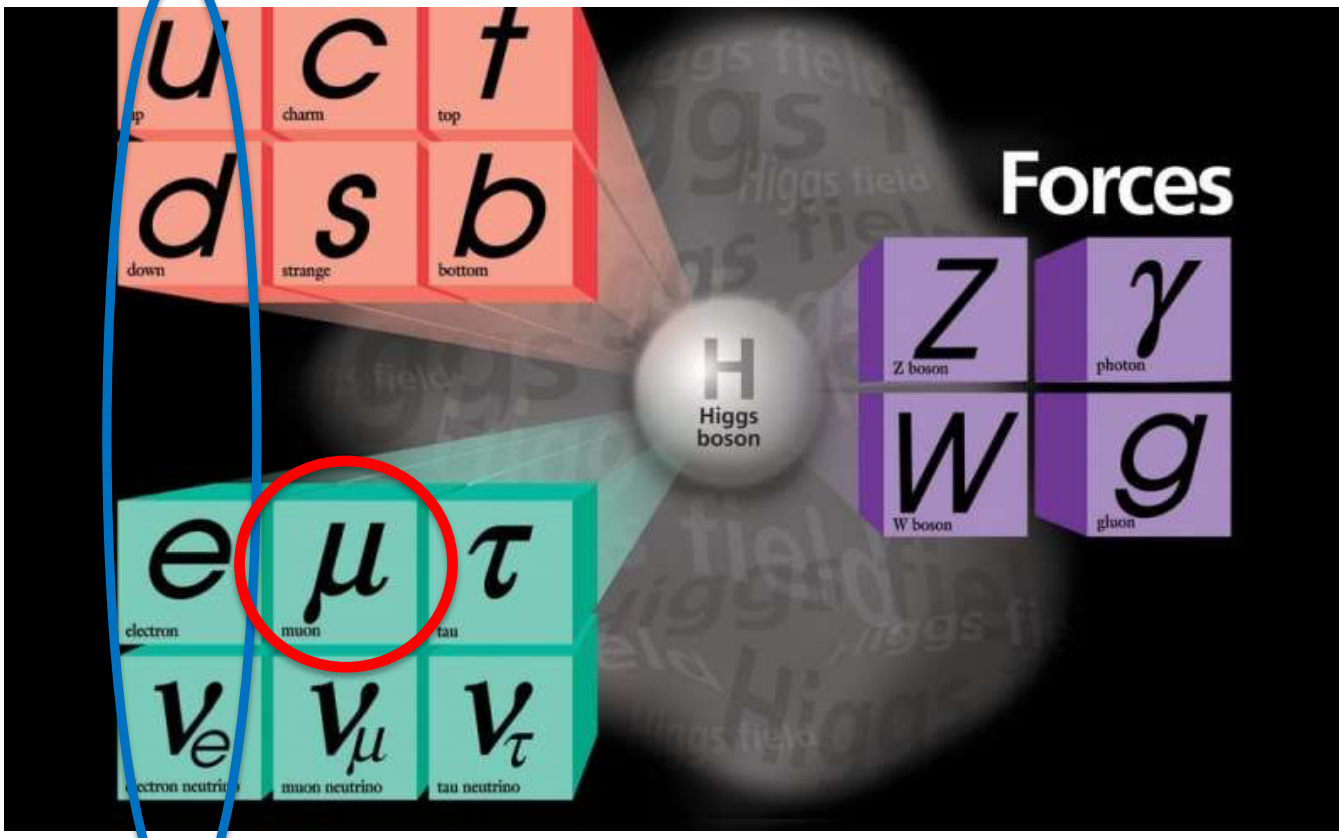
- Many particles created in collisions with atmosphere (Air Shower) ~ 15 km above surface
- Most particles interact strongly and stop
- some decay (to muons); muons live long enough to reach surface
- Muon lifetime is ~2 microseconds – at speed of light that is 600m
- Why do muons make it to ground?

(demonstrates Einstein's Special Relativity)

The Standard Model

quarks make up protons and neutrons using Strong force

leptons don't feel the strong force



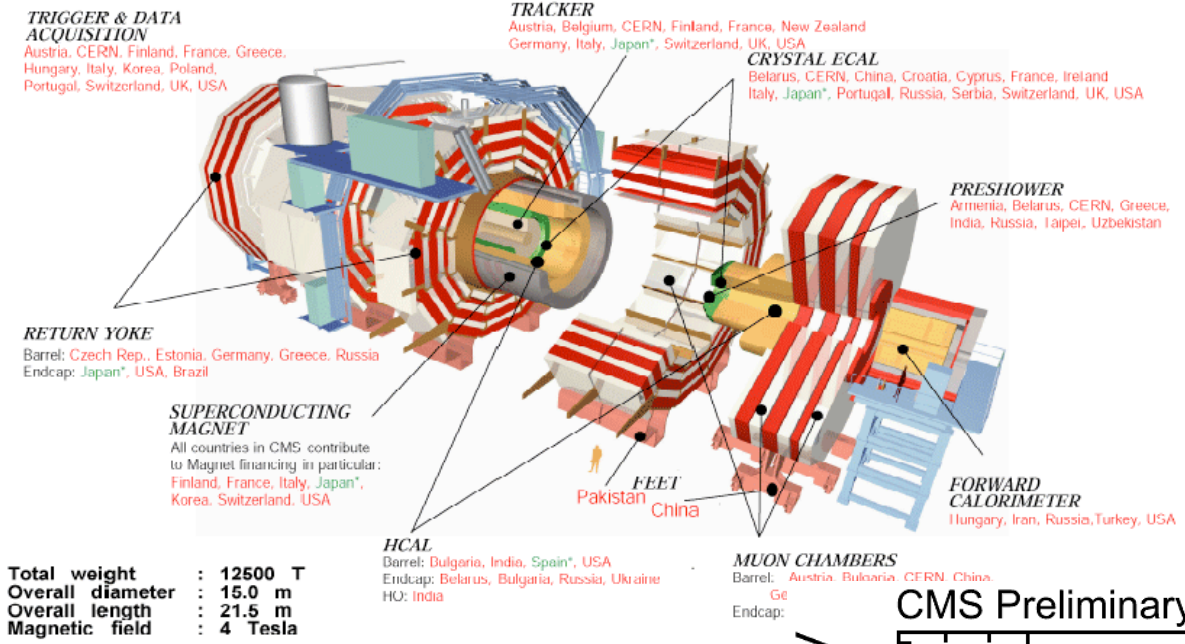
Fermions take up space

Bosons are carriers of force

Muons at the surface

- Muons discovered (identified in air showers) in 1936 (Anderson and Neddermeyer). Rabi “Who ordered that?”
- Fundamental particle: charged, unstable lepton like a heavy (0.105 GeV) electron
- Particle sweet spot –
  - does notice nuclei (lepton); Loses energy through atmosphere gradually
  - Lives long enough to reach surface
  - Massive (unlike electron) - travels far

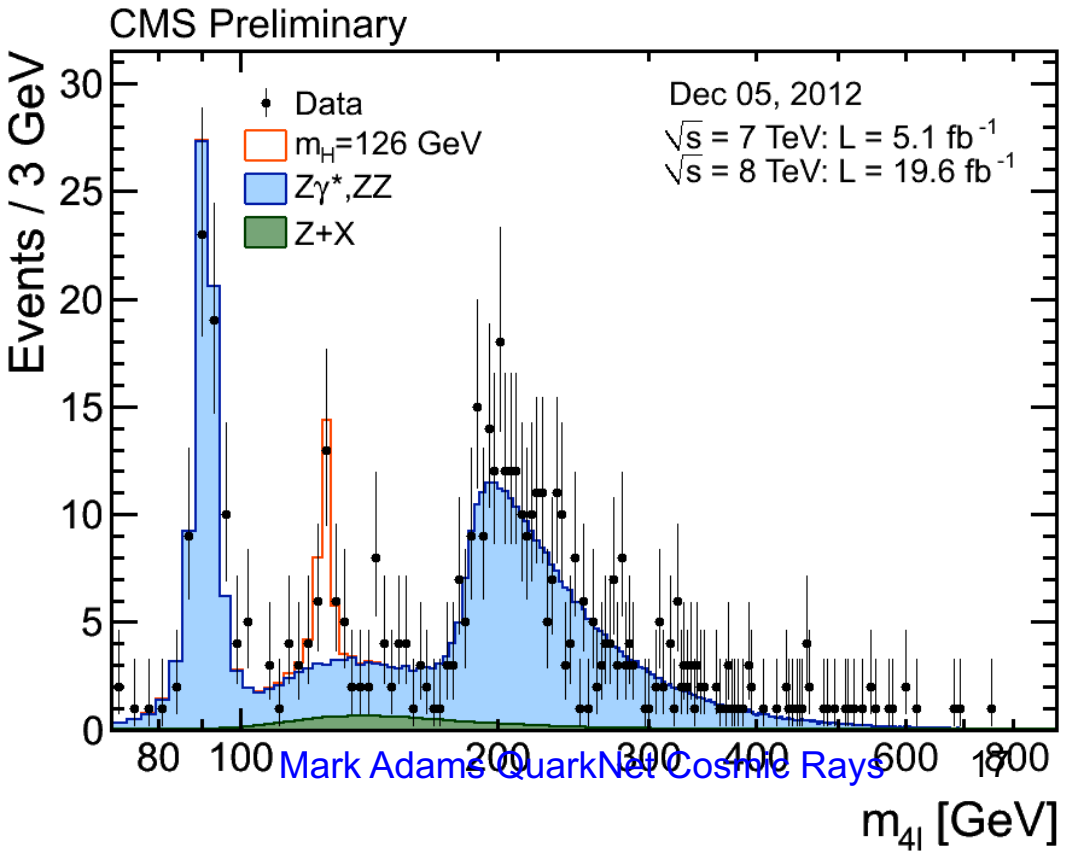
LHC experiments



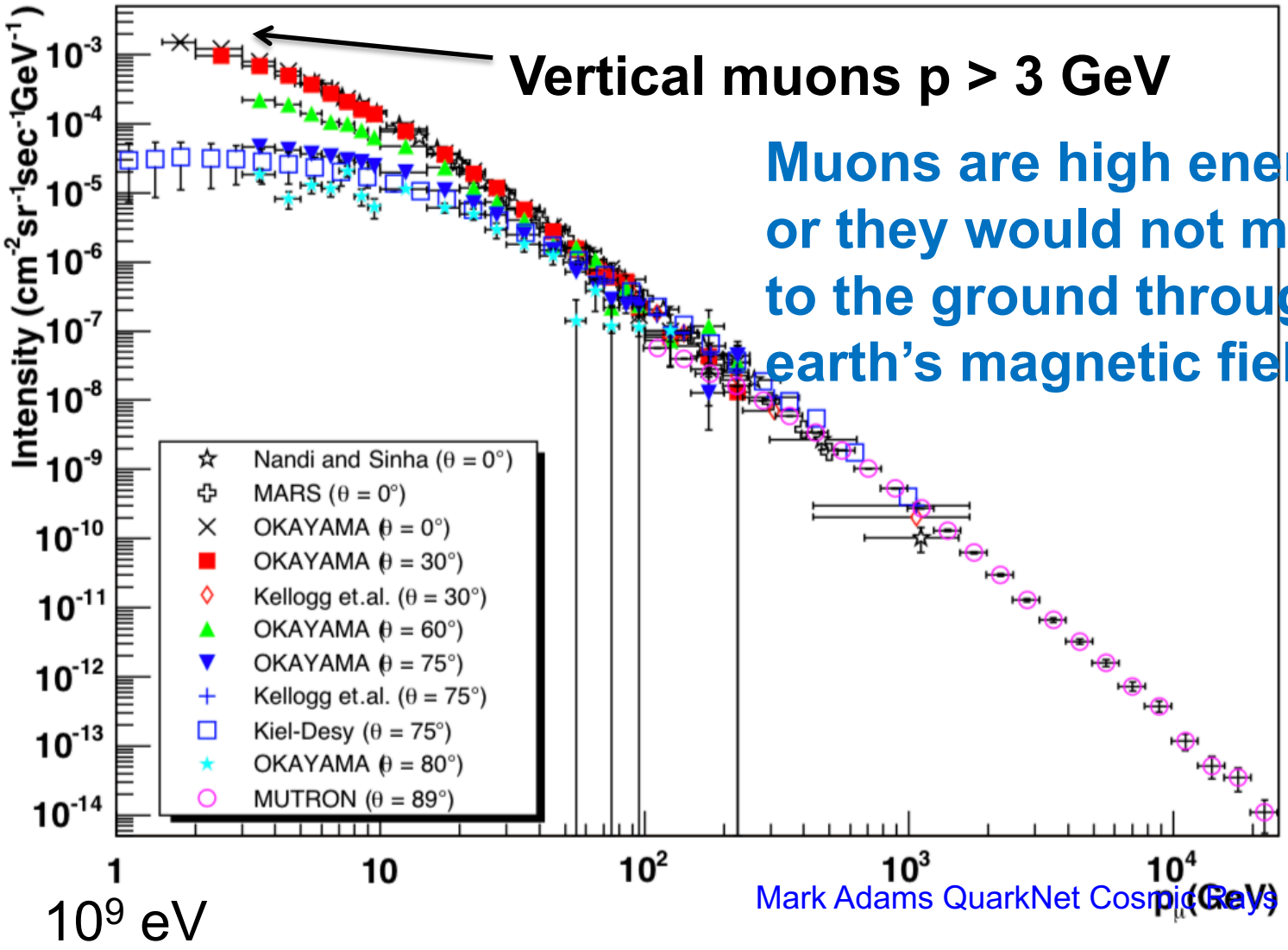
Discovery of the Higgs

4 leptons – some event = $\mu\ \mu\ \mu\ \mu$

μ at LHC is same as in Cosmics

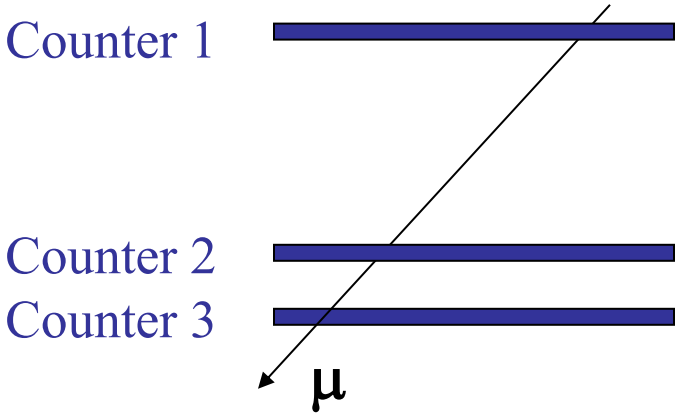


Muon momentum spectrum at surface

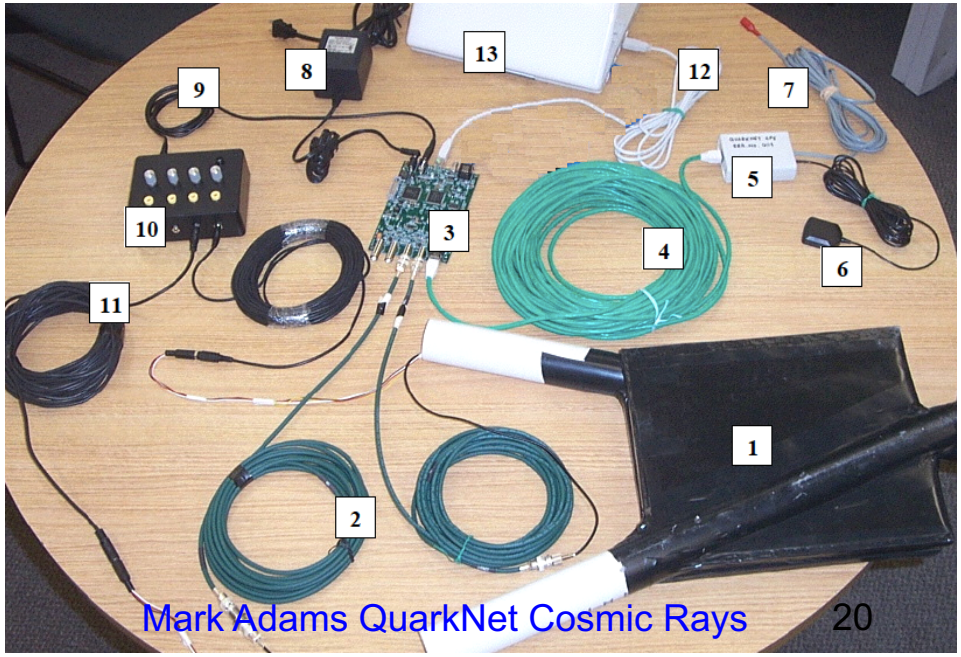


Muons are high energy, or they would not make it to the ground through the earth's magnetic field

Detector QuarkNet



- Single muon passes through all detectors
- Energy > 2 GeV
- Electronics selects events with 3 hit counters
- GPS gives absolute time
- A detector stack can point
- Measure Muon Speed with Time of Flight (TOF)



What can we measure?

Muons tell us about the cosmic rays, but we also can study the muons

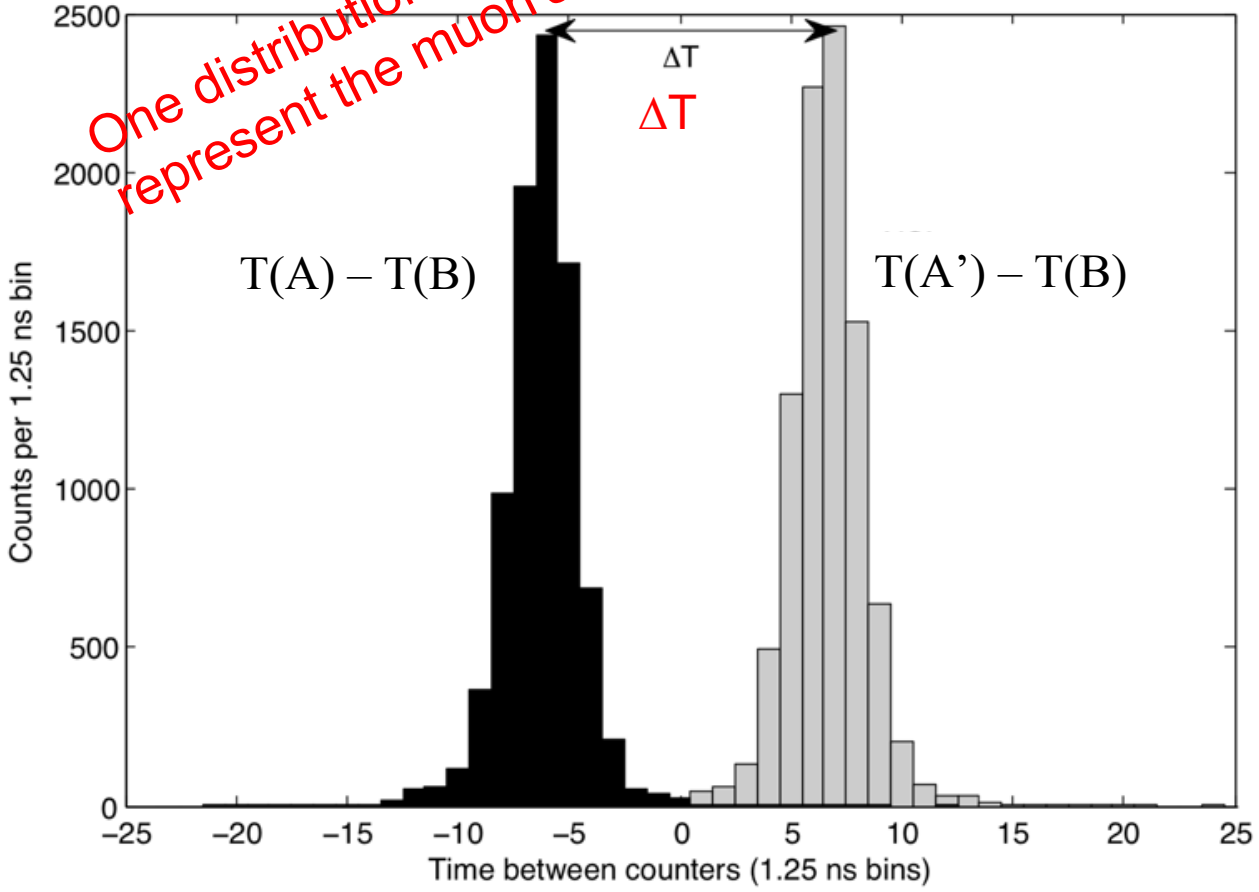
- Rates of muons over time (day/night)
- Rates of muons versus angle
- Lifetime of muon
- Size of Cosmic Ray Air Shower
- Time Dilation
- **Speed of muons**

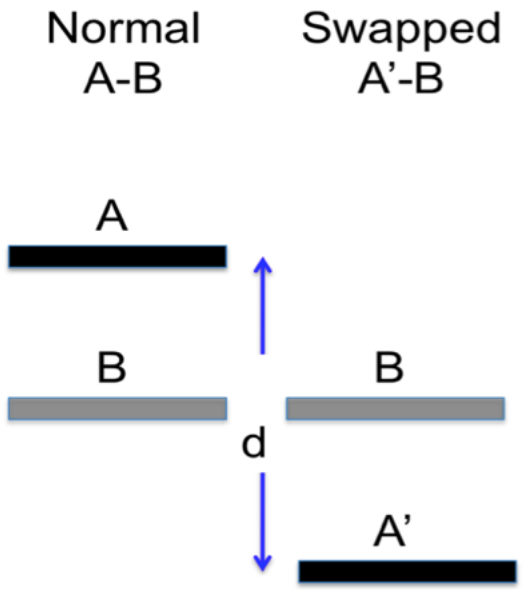
Speed of Muon

- Let's measure average speed of a collection of muons that schools have recorded with their detectors
- Ultimate speed in the universe (speed of light)
- Question to keep in mind. Why would all muons travel at the same speed?

Timing Distributions muon speed

One distribution does not represent the muon's travel time





Speed = Δz/ΔT

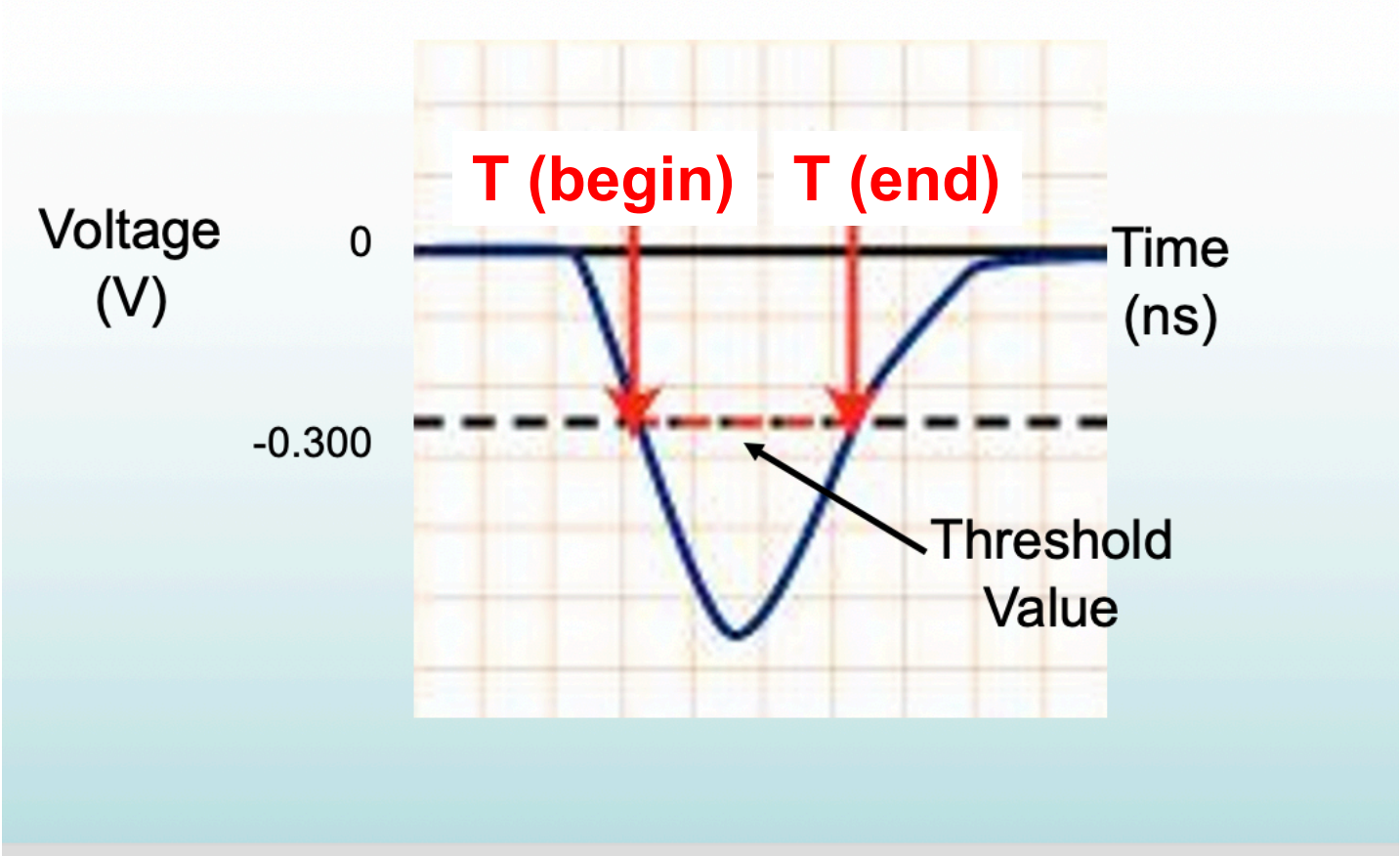
GBS HS students published a measurement of the muon's speed

Our Muon Speed Data

- We will simplify the measurement today. Our data has had their signal cable lengths artificially adjusted in software so that $\Delta T = 0$ when the counters are next to each other (i.e. no distance between the pair for the muon to travel)
- Result is that ΔT of any pair represents the travel time for the muon

Signal vs Time

Data saved: beginning and end of pulse



QuarkNet Data Format

Time of the hit of each counter recorded to 1.25 ns precision

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  1
5A8F5C5C 80 00 32 00 00 00 32 00 59289115 000002.023 010217 A 07 0 +0081  2
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  2
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  3
5AA6CF4D 00 00 00 29 00 00 00 00 5AA60955 000003.031 010217 A 07 0 +0081  3
```

Ch 1 | Ch 3 | Ch 4

40ns cpu counter at trigger time

Channel 2 LE; TE 1.25 ns Least Counts

GPS 1pps latches cpu counter

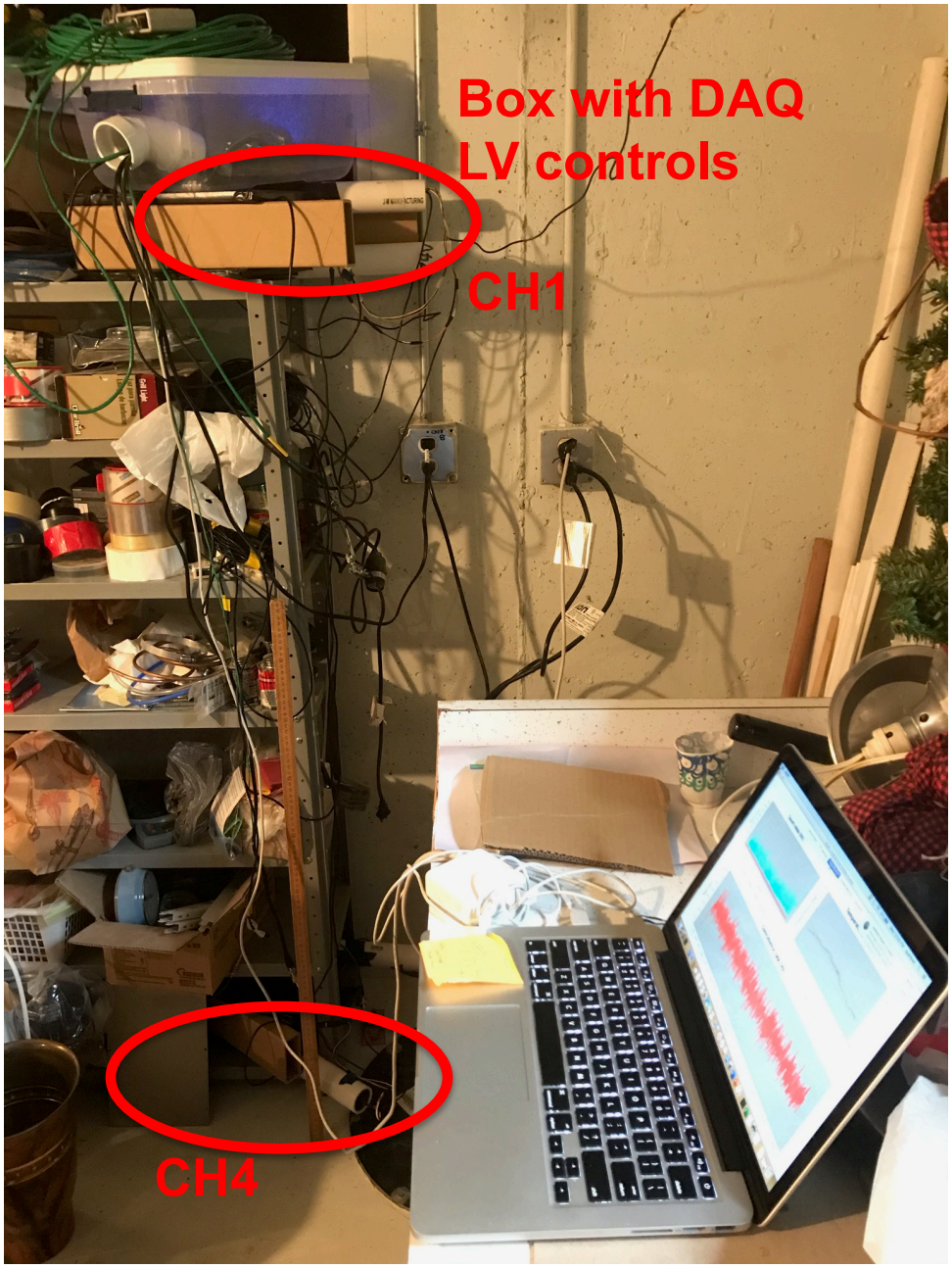
Universal Time: hhmmss

Absolute time accuracy of 100ns

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

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

- Detector 6674 in basement
- Next to sump pump that causes lots of random noise

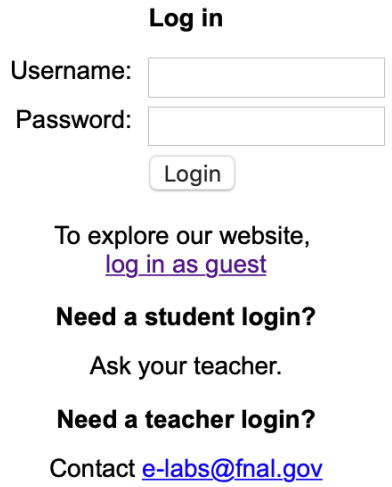


Quarknet e-Lab i2u2.org

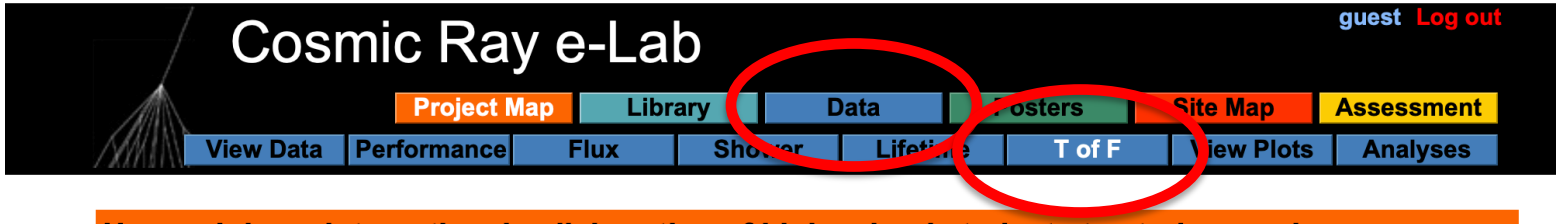
Cosmic Ray e-Lab

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

Go to i2u2.org and login in as guest



Select TOF Analysis

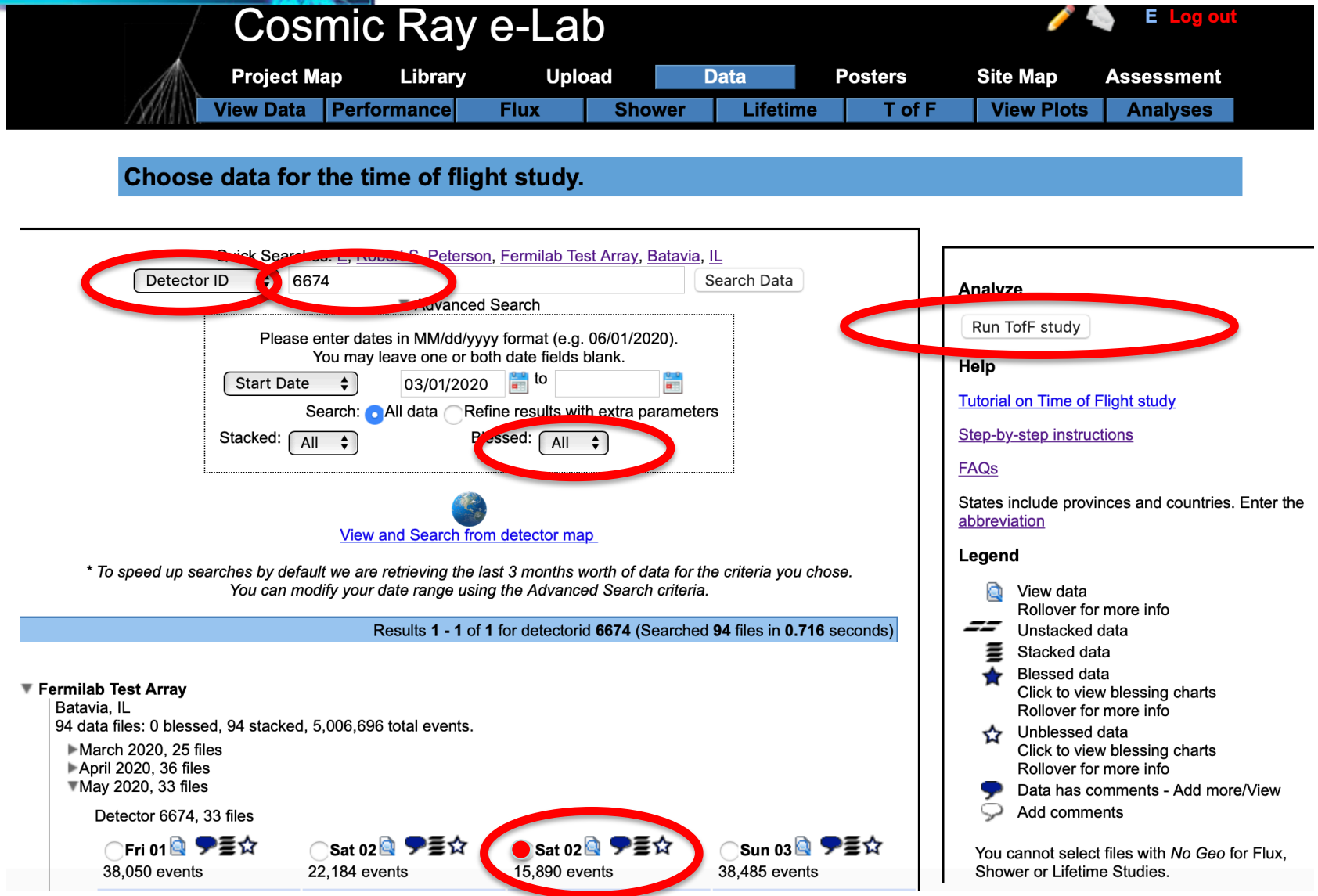


Milestones (text version)

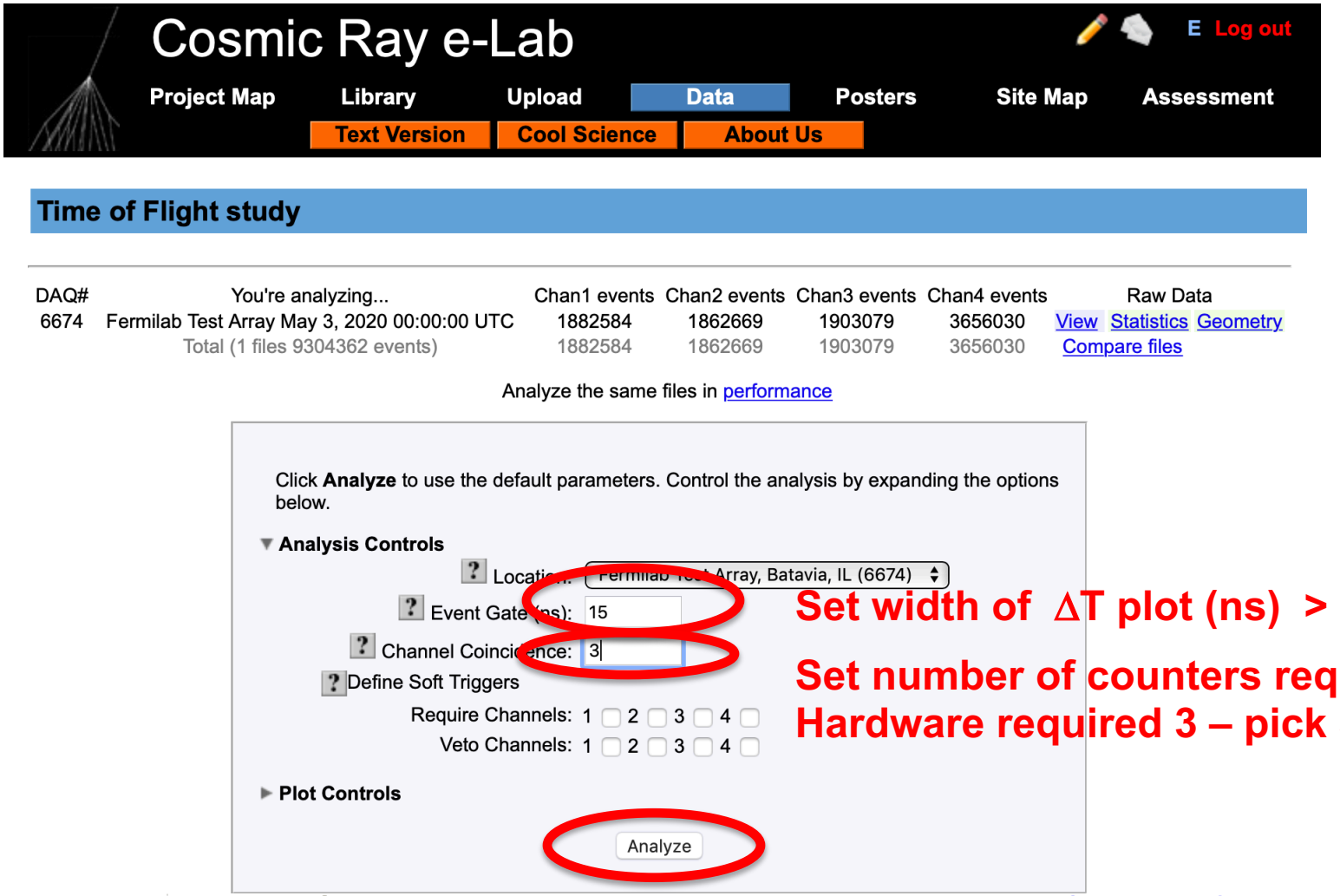
Choose different files

- Select a file of Detector 6674 on any day in April or May.
- choose a file based on the first letter of your last name:
- Adams choose ~April 1st
- Lincoln choose April 30th
- Washington choose ~ May 28th

File Selection



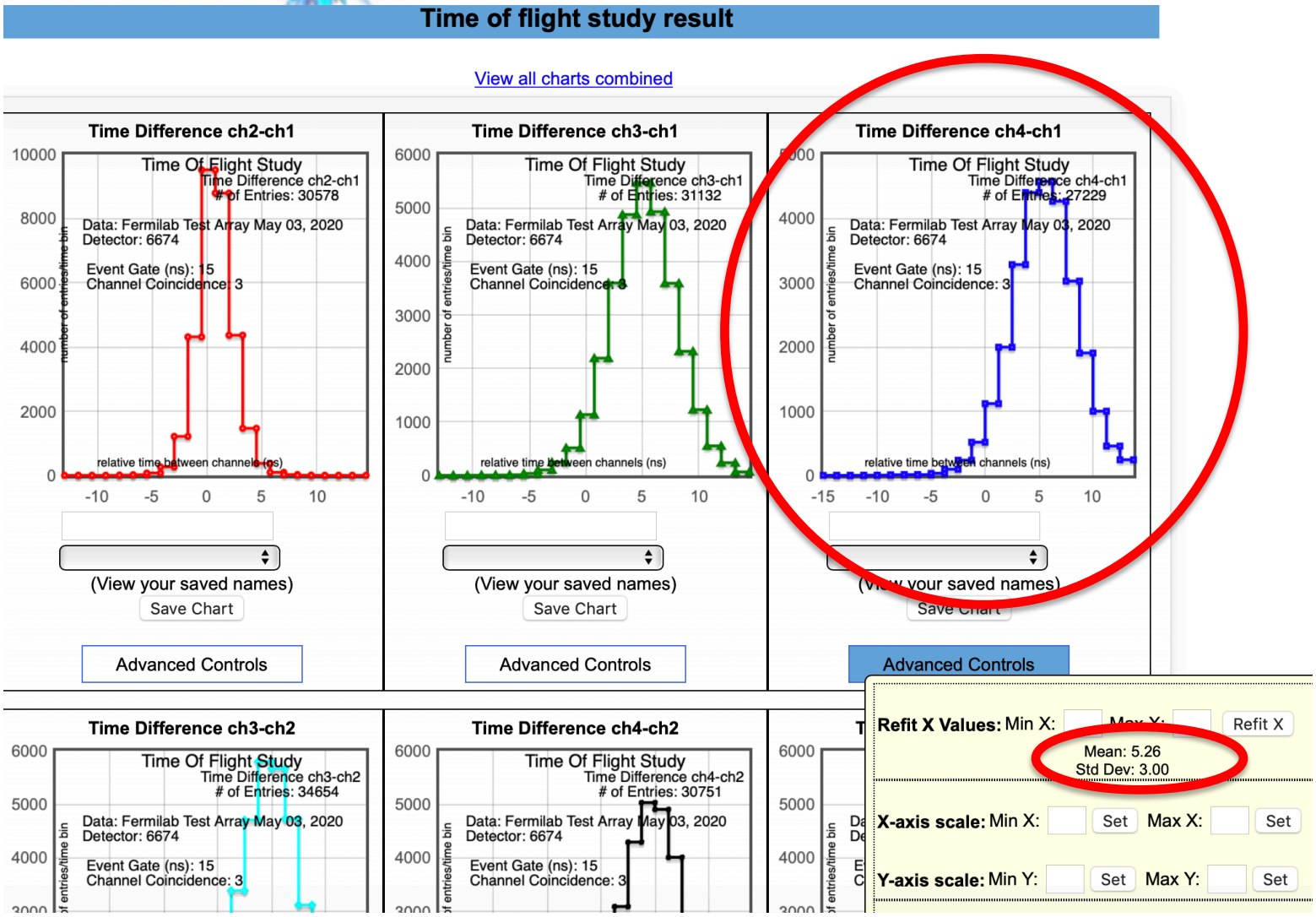
TOF Control Panel



Set width of ΔT plot (ns) > 15ns

Set number of counters required
Hardware required 3 – pick 3 or 4

TOF results


Time of flight study result
View all charts combined
Time Difference ch2-ch1
Time Of Flight Study
Time Difference ch2-ch1
# of Entries: 30578
Data: Fermilab Test Array May 03, 2020
Detector: 6674
Event Gate (ns): 15
Channel Coincidence: 3
number of entries/time bin
relative time between channels (ns)
(View your saved names)
Save Chart
Advanced Controls
Time Difference ch3-ch1
Time Of Flight Study
Time Difference ch3-ch1
# of Entries: 31132
Data: Fermilab Test Array May 03, 2020
Detector: 6674
Event Gate (ns): 15
Channel Coincidence: 3
number of entries/time bin
relative time between channels (ns)
(View your saved names)
Save Chart
Advanced Controls
Time Difference ch4-ch1
Time Of Flight Study
Time Difference ch4-ch1
# of Entries: 27229
Data: Fermilab Test Array May 03, 2020
Detector: 6674
Event Gate (ns): 15
Channel Coincidence: 3
number of entries/time bin
relative time between channels (ns)
Advanced Controls
Time Difference ch3-ch2
Time Of Flight Study
Time Difference ch3-ch2
# of Entries: 34654
Data: Fermilab Test Array May 03, 2020
Detector: 6674
Event Gate (ns): 15
Channel Coincidence: 3
Time Difference ch4-ch2
Time Of Flight Study
Time Difference ch4-ch2
# of Entries: 30751
Data: Fermilab Test Array May 03, 2020
Detector: 6674
Event Gate (ns): 15
Channel Coincidence: 3
Refit X Values: Min X:
Refit X
Mean: 5.26
Std Dev: 3.00
X-axis scale: Min X:
Set
Max X:
Set
Y-axis scale: Min Y:
Set
Max Y:
Set

Where is position information?

3 clicks to find Geometry of the file you select

Step 1

Fermilab Test Array
Batavia, IL
94 data files: 0 blessed, 94 stacked, 5,006,696 total events.
- March 2020, 25 files
- April 2020, 36 files
- May 2020, 33 files

Detector 6674, 33 files

Fri 01	Sat 02	Sa 02	Sun 03
38,050 events	22,184 events	15,890 event	38,485 events

Step 2

6674.2020.0503.0

Show metadata | Show Geometry | Show Blessing Charts | Download | Download Threshold File

Distance between counters 1 and 4:
1.595m - 0.085m = 1.51m

Step 3

Geometry for 6674.2020.0503.0

Detector Geometry

If you are using EQUIP for data acquisition, you still need to enter geometry data on this page for use in the Cosmic Ray e-lab.

GPS is @ (0,0,0).

Each point (x,y,z) represents the center of a counter.

	Active Channels:	1	2	3	4
	Cable Length (m)	Area(cm²)	x:E-W(m)	y:N-S(m)	z:Up-Dn(m)
1	0.53	750.0	0	0	1.595
2	1.85	750.0	0	0	1.488
3	3.5	750.0	0	0	0.188
4	1.2	750.0	0	0	0.085

Stacked Orientation Unstacked

Visualize geometry

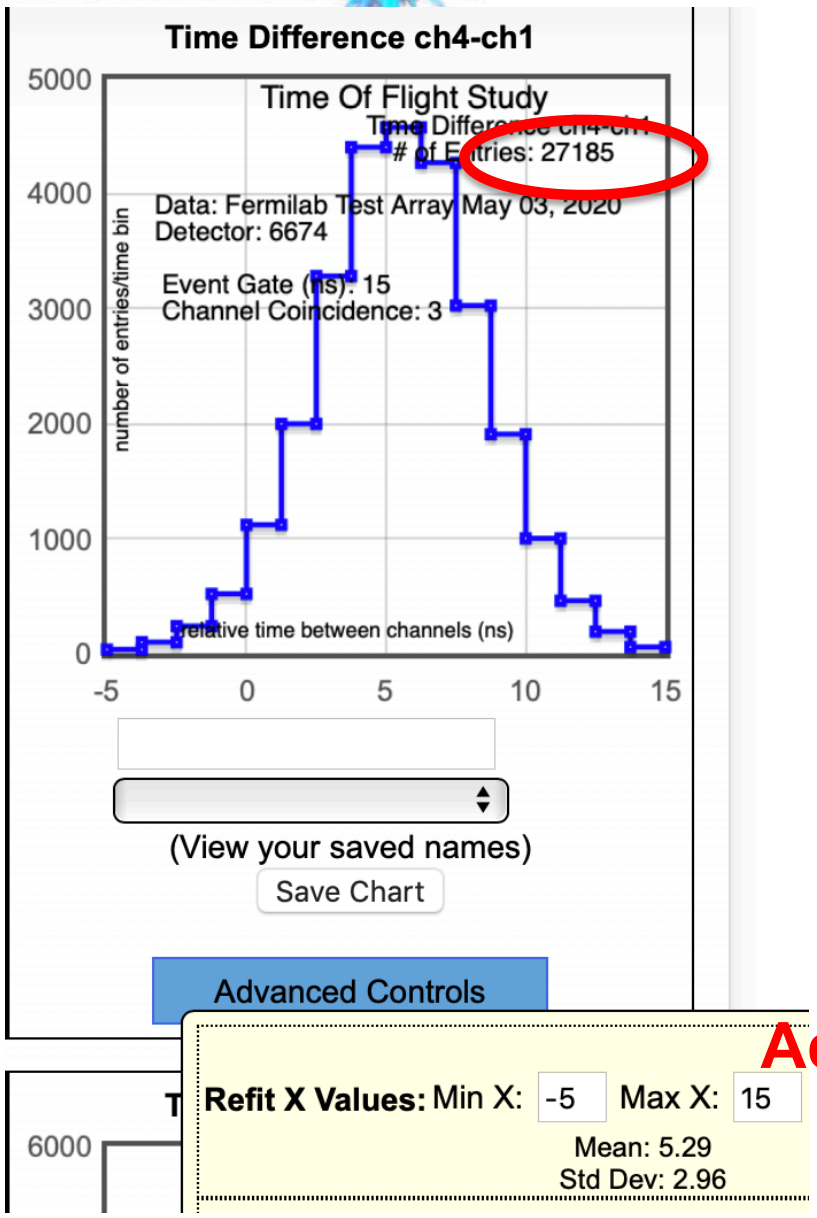
GPS Coordinates

GPS Coordinates Tutorial | Find GPS Coordinates

Latitude: 41:53.365920 N Longitude: 088:19.585297 W

U.S. DEPARTMENT OF ENERGY | Office of Science

Calculate Speed



Δt = 5.29 ns with error of 2.96 ns
Error means 68% of results fall within mean-error to mean+error:
Large error 2.33->8.25ns

Calculate the speed:
Speed = $\Delta z / \Delta t$ = 1.51m/5.29ns
Average muon speed = 2.85 x10^8m/s

Why is this result so close to accepted value of 2.95 x10^8m/s?

Error on the mean of all muons is much smaller (related to 1/sqrt(N))

Advanced Controls will show mean

You measured maximum speed in the universe!

- Please share your results via chat.
- If we combined our analyses, the measurement would improve

- Wait! –
- Why should all muons travel at the same speed?
- Baseballs, cats and cars don't.

You measured maximum speed in the universe!

- Why should all muons travel at the same speed?
- Answer is due to Special Relativity - Particles can be accelerated to very high energies but their speed asymptotically approaches c:
  - Momentum = M * v * 1/sqrt(1-v^2/c^2)
  - Related – faster particles go, longer they live as measured by us (time dilation)

Questions; Extra

- Can you improve the measurement? Share ideas via chat
- Ten muons/sec go through your body, do they hurt?

- Want to do more e-Lab studies?
  - quarknet.org analysis link https://quarknet.org/content/resources-cosmic-ray-analyses-online
  - Contact adams@fnal.gov

Conclusions

- Cosmic Rays rain down on the Earth from supernovae and Active Galaxies
- High schools use QuarkNet detectors to study cosmic rays and their resulting muons
- 100,000 files of data are available in e-Lab for all to study
- I hope you enjoyed your measurement of the maximum speed in the Universe
- I will stay around to answer your questions

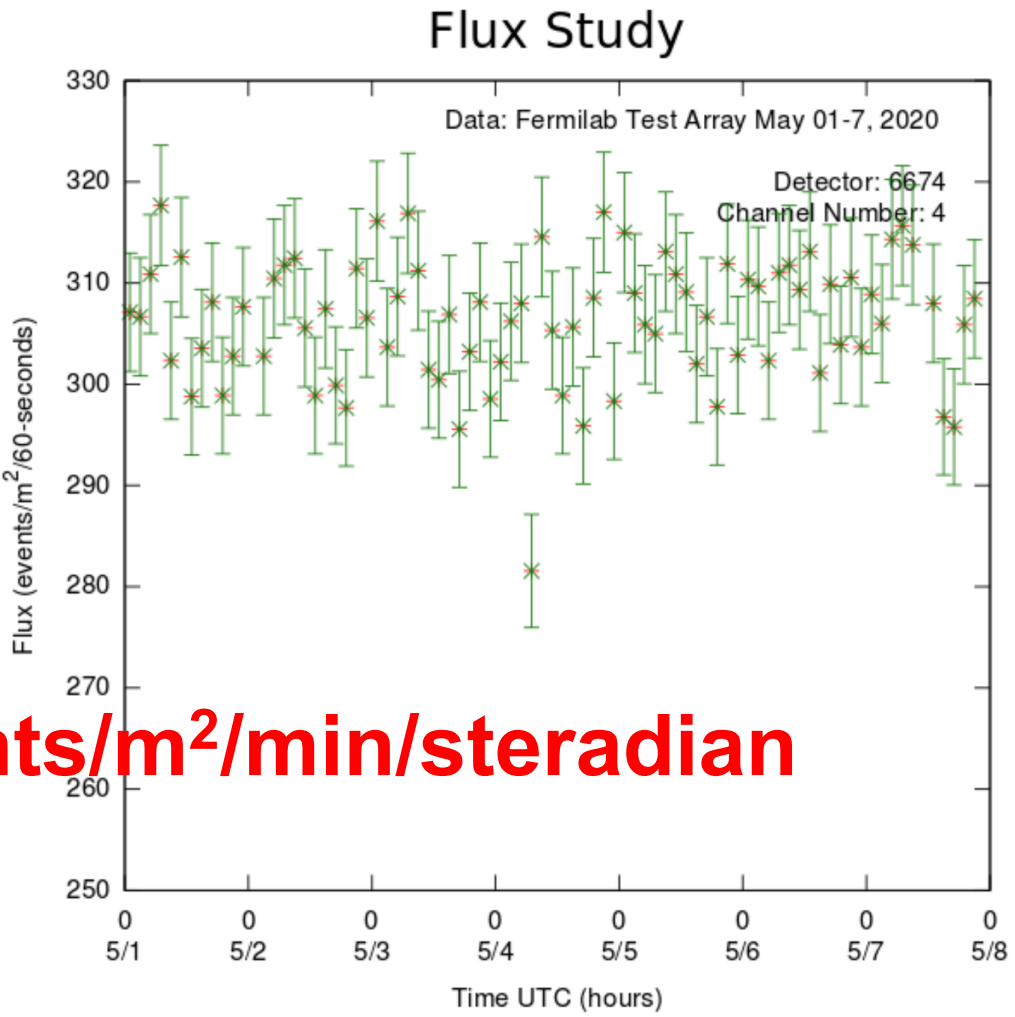
Extra Slides

Flux - Rate versus time

A week of data

Note: no big day/night effect

> Not from Sun



Number of events/m^2/min/steradian in 6-hr bins