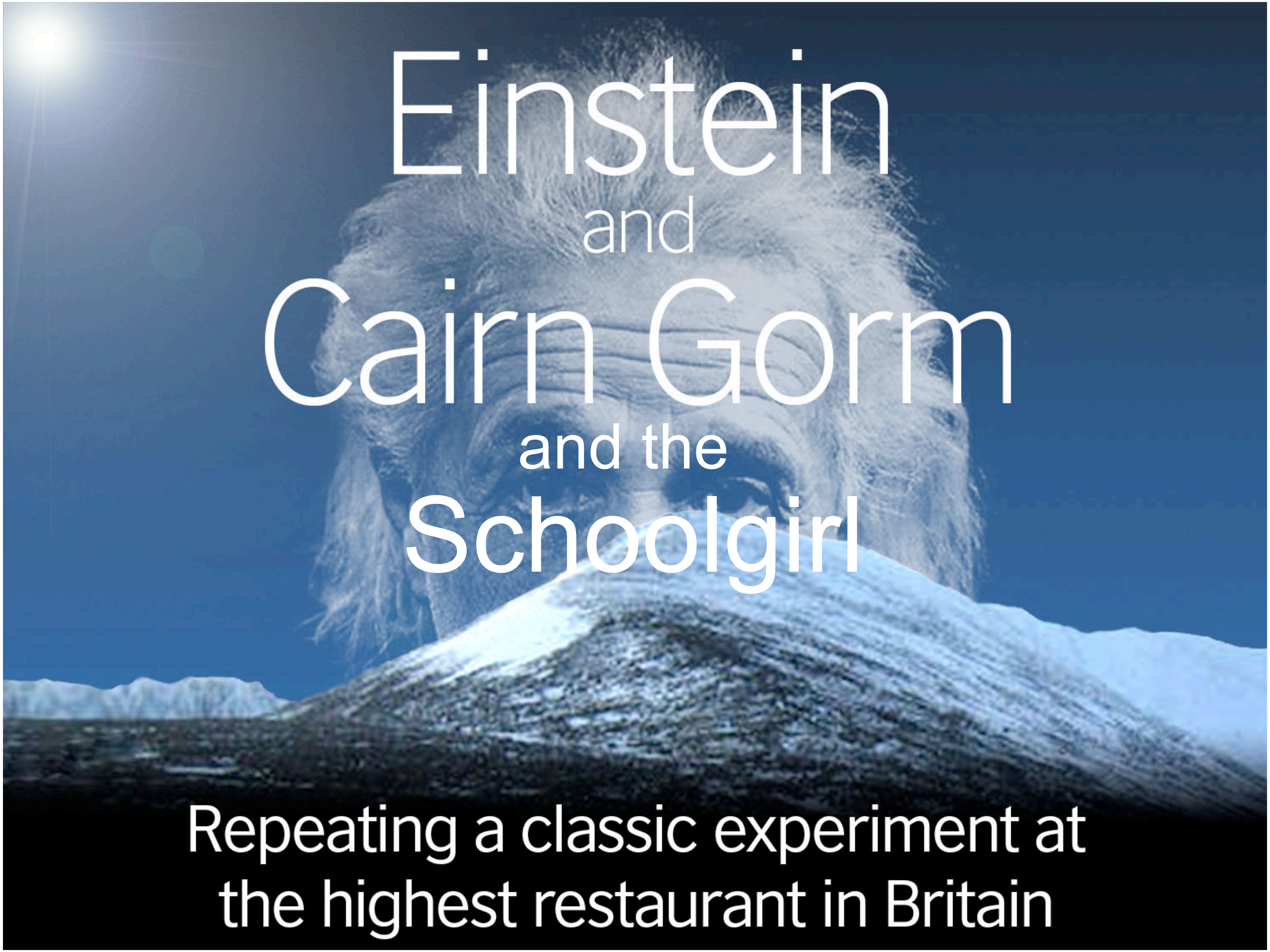
Einstein
and
Cairn Gorm
and the
Schoolgirl
Repeating a classic experiment at
the highest restaurant in Britain

pp̄4s̄s

Funded by **PPARC** to take Particle Physics to Scottish Schools

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The Scottish Science Technology Roadshow

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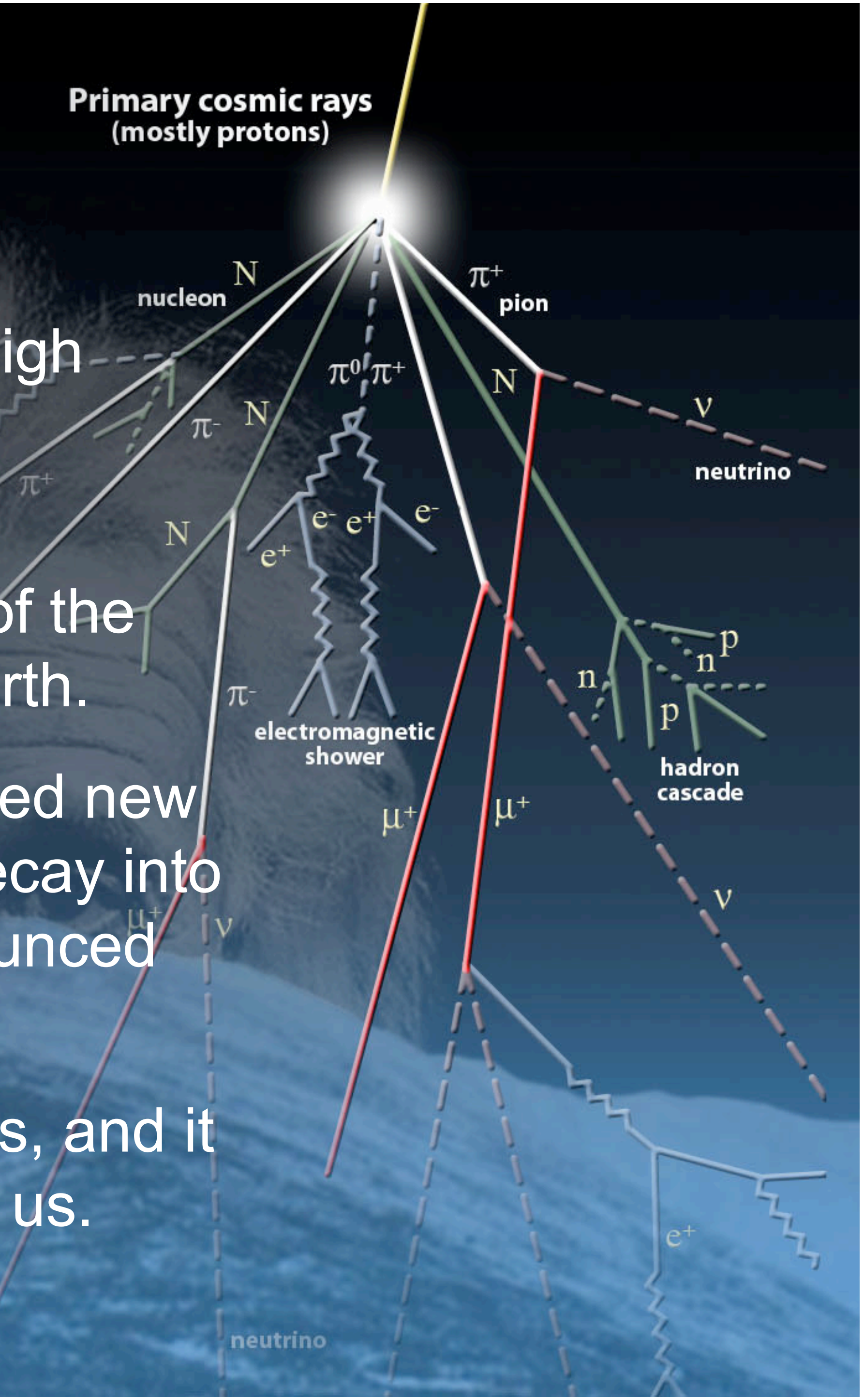
The Muon Lifetime Experiment

- This experiment detects muons created by the collision of cosmic ray particles from space with the upper atmosphere.
- We can make a variety of measurements, including a test of one of the predictions of Einstein's Special Theory of Relativity.
- By running the experiment near sea-level, as well as at the Cairn Gorm top station, we are able to confirm one of Einstein's basic statements:

The faster you go, the slower time will pass…

Cosmic Rays

- These are particles moving at high speeds, which strike the upper atmosphere.
- As shown opposite, the debris of the collisions rain down towards Earth.
- Some of the debris are short-lived new particles, called pions, which decay into others, including muons (pronounced “mew-ons”).
- The muons continue downwards, and it is these particles which interest us.



Secondary Cosmic Rays

Primary cosmic ray interactions produce pions and kaons

$$p + p \rightarrow p + p + \pi^{+} + \pi^{-} + K^{+} + K^{-} \ldots\ldots$$

Decays of pions and kaons produce positive and negative muons (and associated neutrinos and anti-neutrinos)

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \qquad K^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \qquad K^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu}$$

We detect some of these muons --

the neutrinos are not seen by our detector!

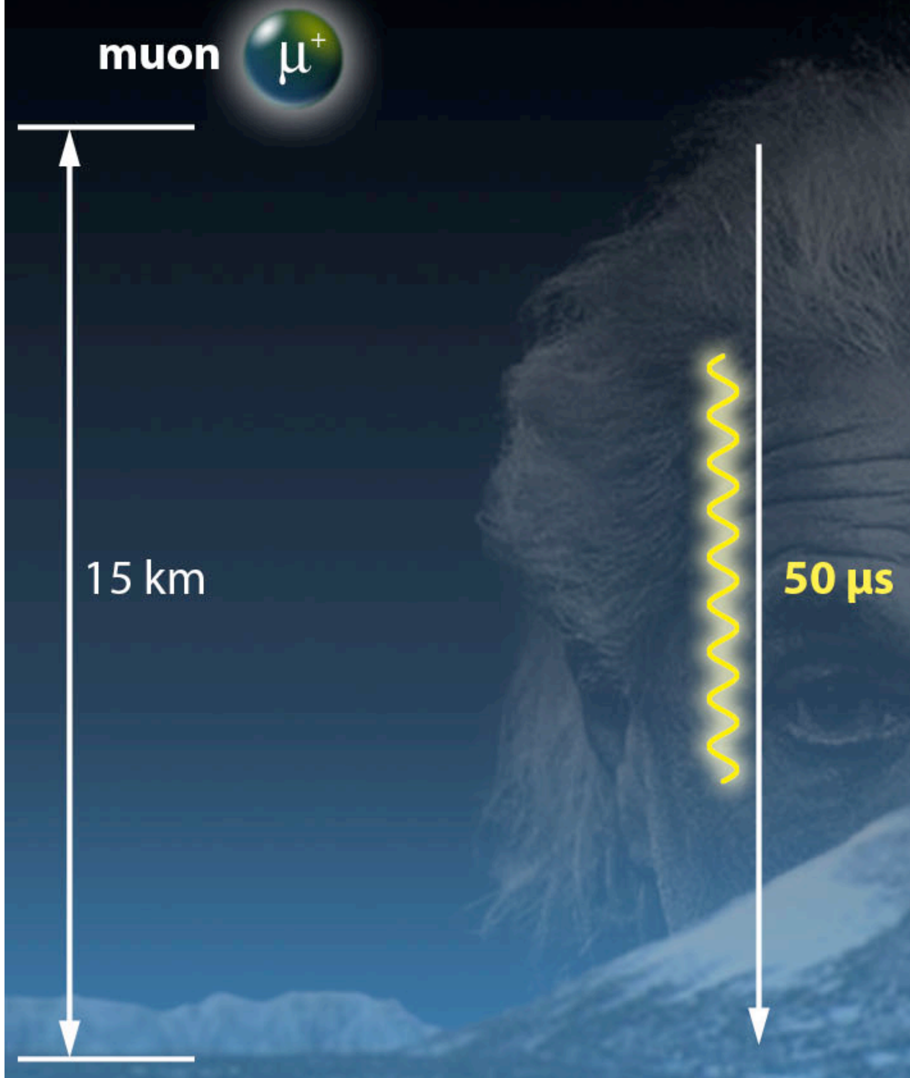
Muons

- Most people are aware of the basic building blocks of all atoms: protons, neutrons and electrons.
- There are many other particles, however, and most of them are *very* short-lived. One in particular is the muon.
- Muons have exactly the same charge as the electron, but are 187 times more massive. They belong to the same family: *leptons.*
- Whereas electrons can exist forever, muons can only exist for about 2.2 microseconds (2.2 μs).
- In comparison, an eye-blink is 30,000 μs.

electron

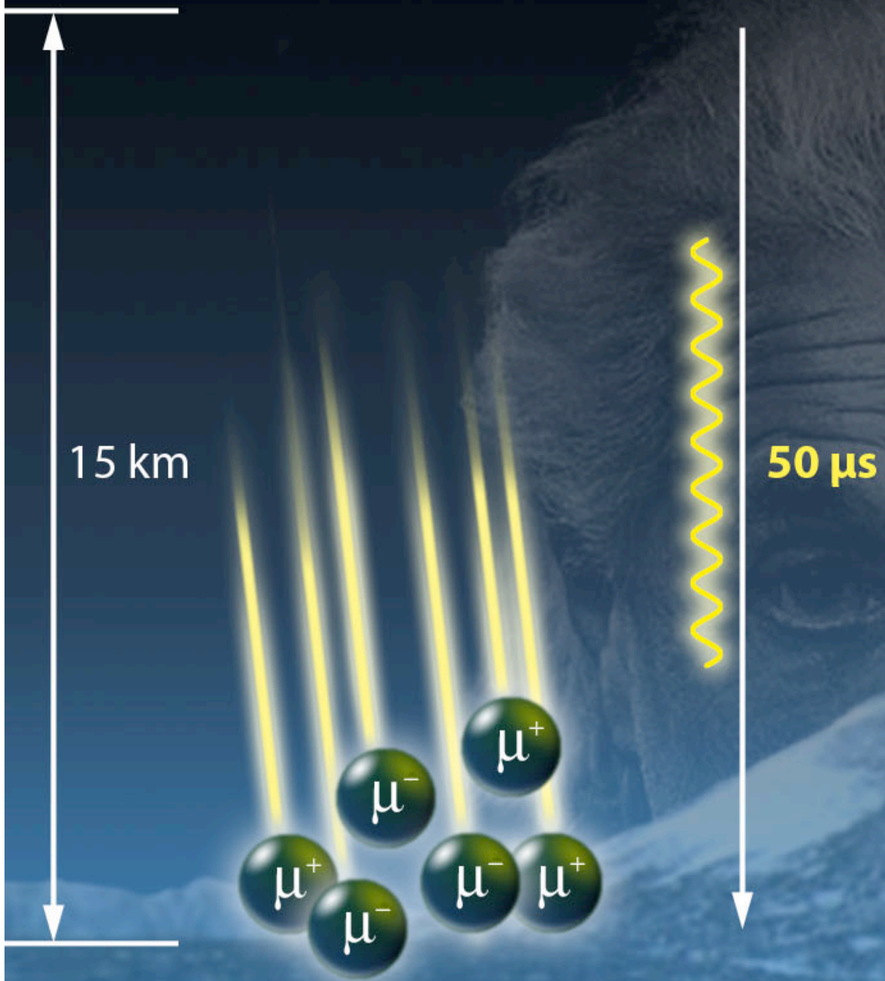
muon

Long-lived Muons?



- Most muons are created at an average height of 15 km in the upper atmosphere.
- Nothing can travel faster than light, which takes 50 µs to reach the surface from this height.
- Muons live on average only 2.2 µs before decaying.

Long-lived Muons?



- Most muons are created at an average height of 15 km in the upper atmosphere.
- Nothing can travel faster than light, which takes 50 μs to reach the surface from this height.
- Muons live on average only 2.2 μs before decaying.
- The probabilty for a muon to survive this journey is about one in ten thousand million!
- So… we should see almost no muons at the surface of the Earth
- BUT… we can detect *many* muons
- Why?

Einstein and Relativity

- The answer comes from Albert Einstein’s

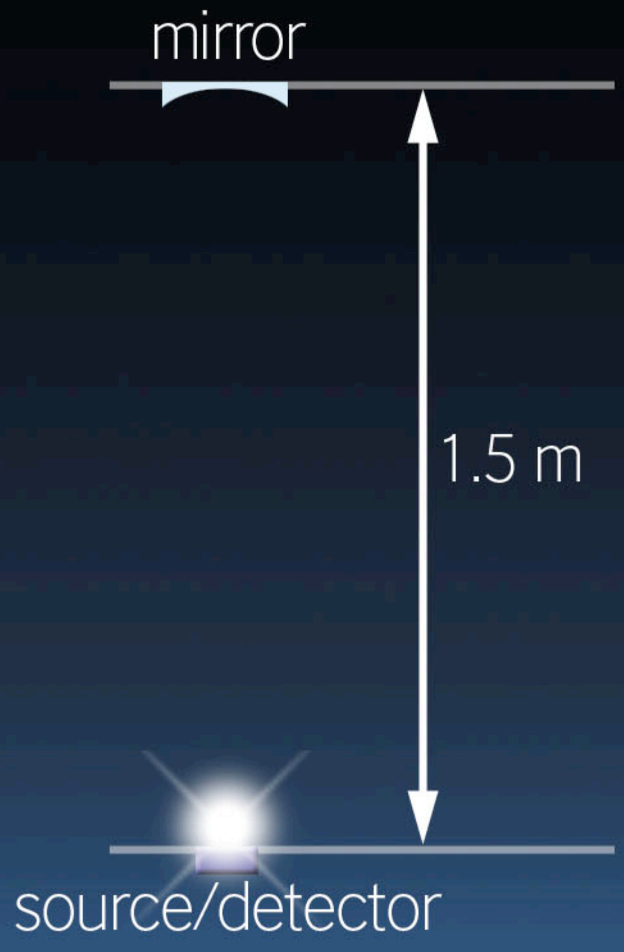
Special Theory of Relativity.

- One of its many predictions is the key for us here:

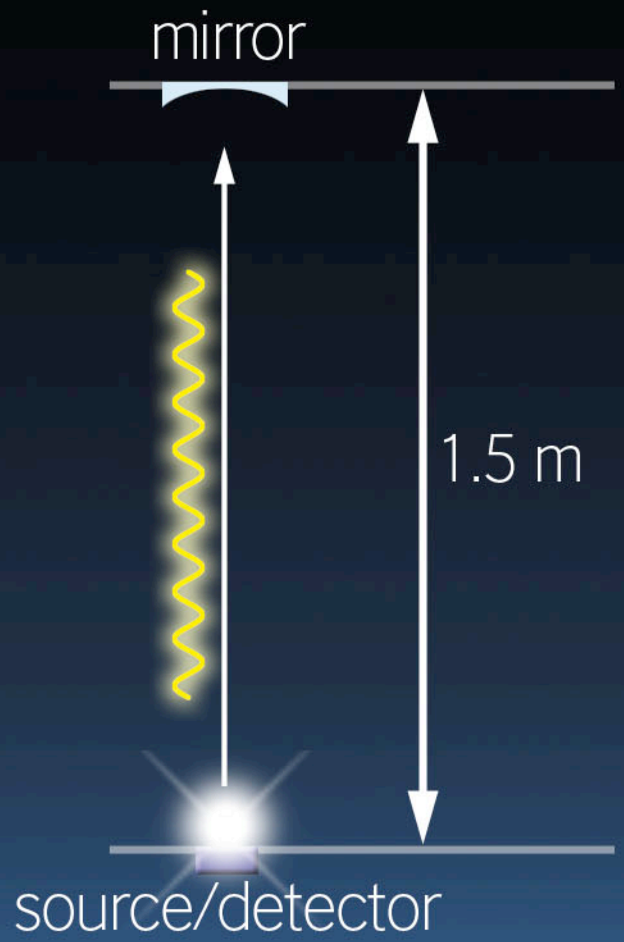
Time slows down for moving objects

- The effect is only significant when objects move *very* fast - the muons that come to a stop and decay in our experiment setup move at over 98% of the speed of light.
- Time slows down significantly for these moving muons.

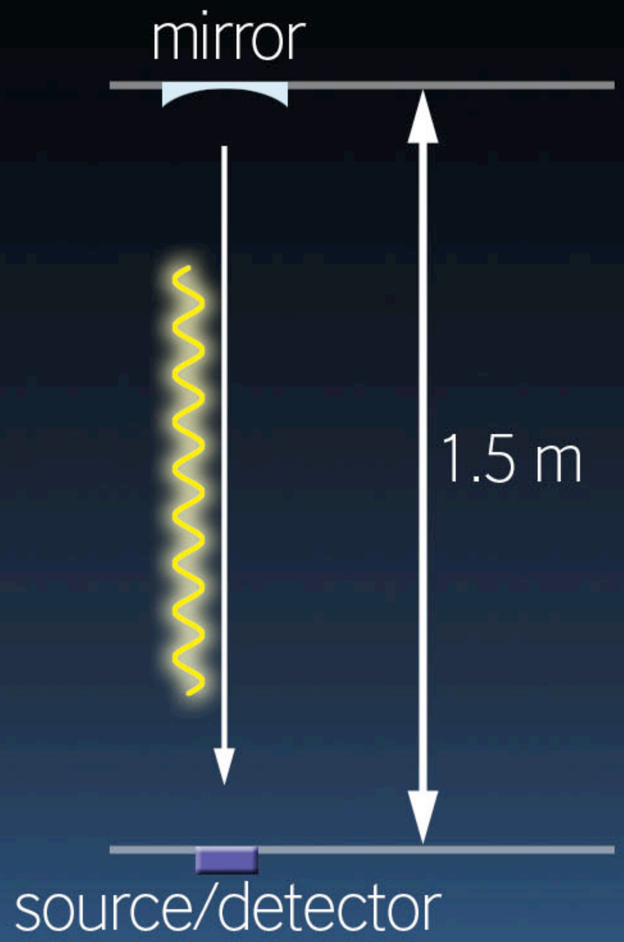
Person inside the train:



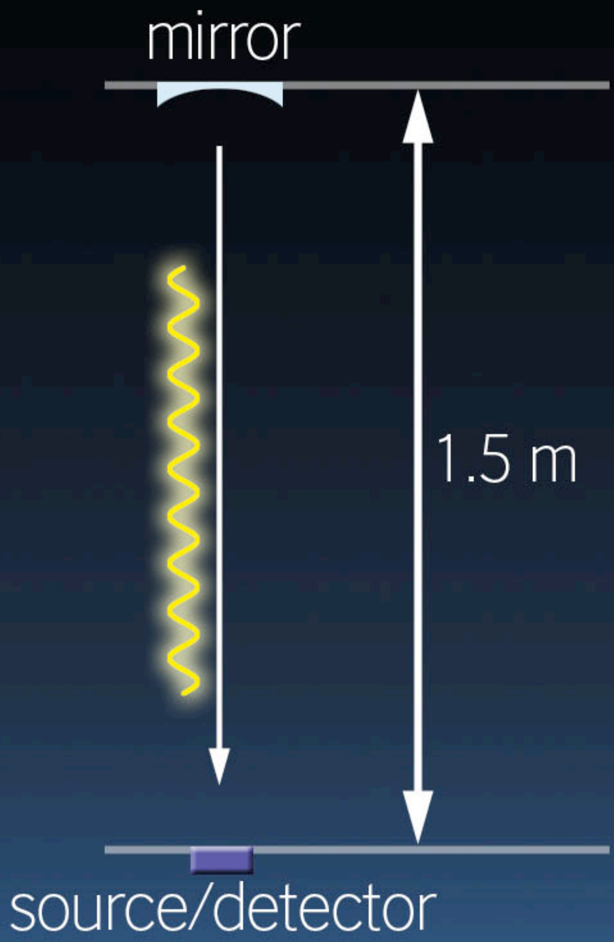
Person inside the train:



Person inside the train:



Person inside the train:

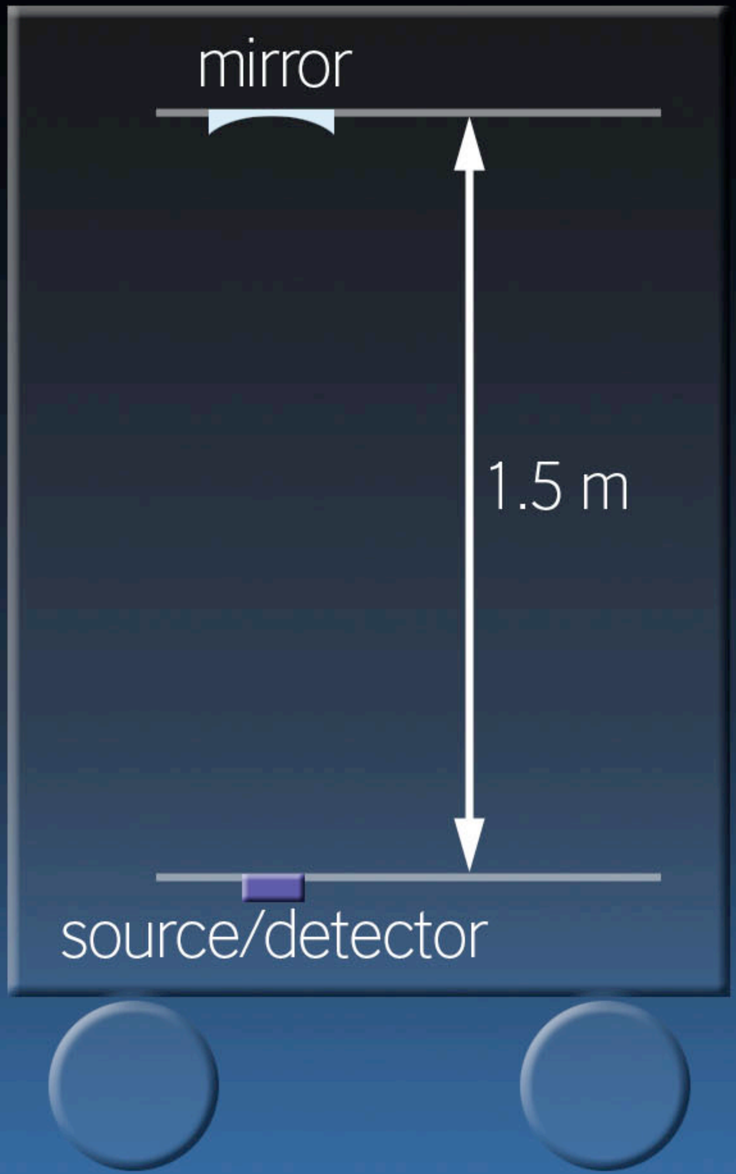


Total light path = 3m

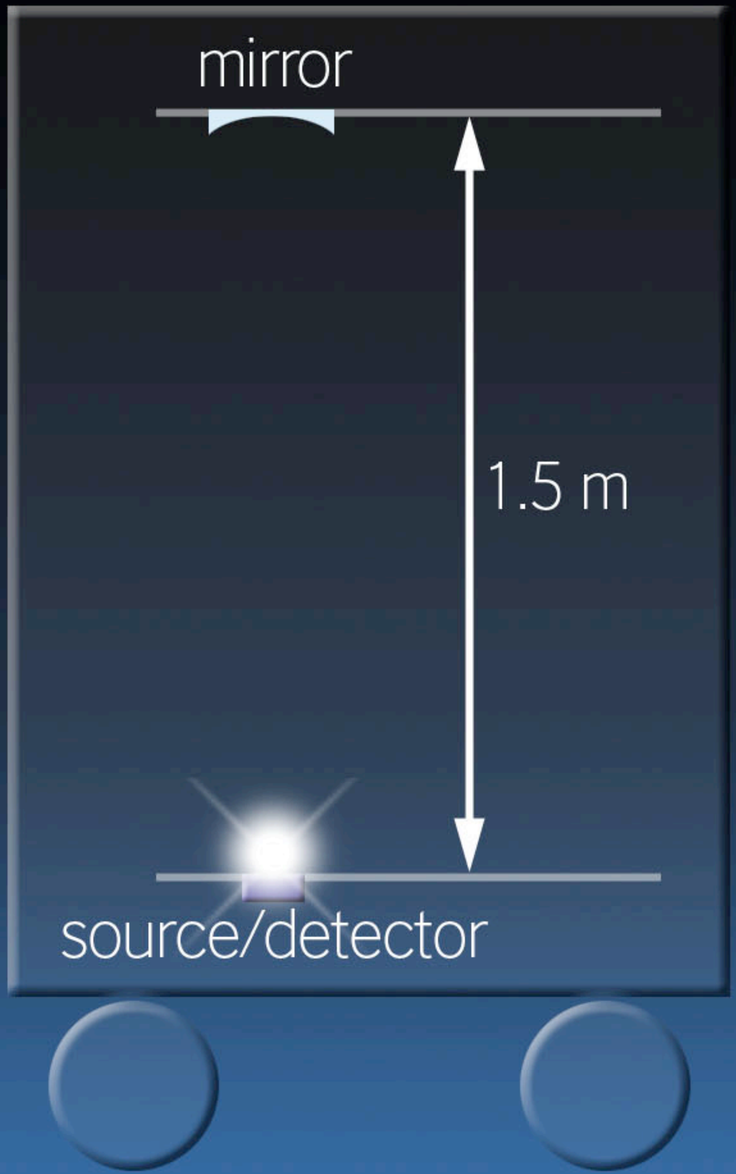
Light travels ~ 3×10^8 m/s

Clock tick = 10^{-8} s = 10 ns

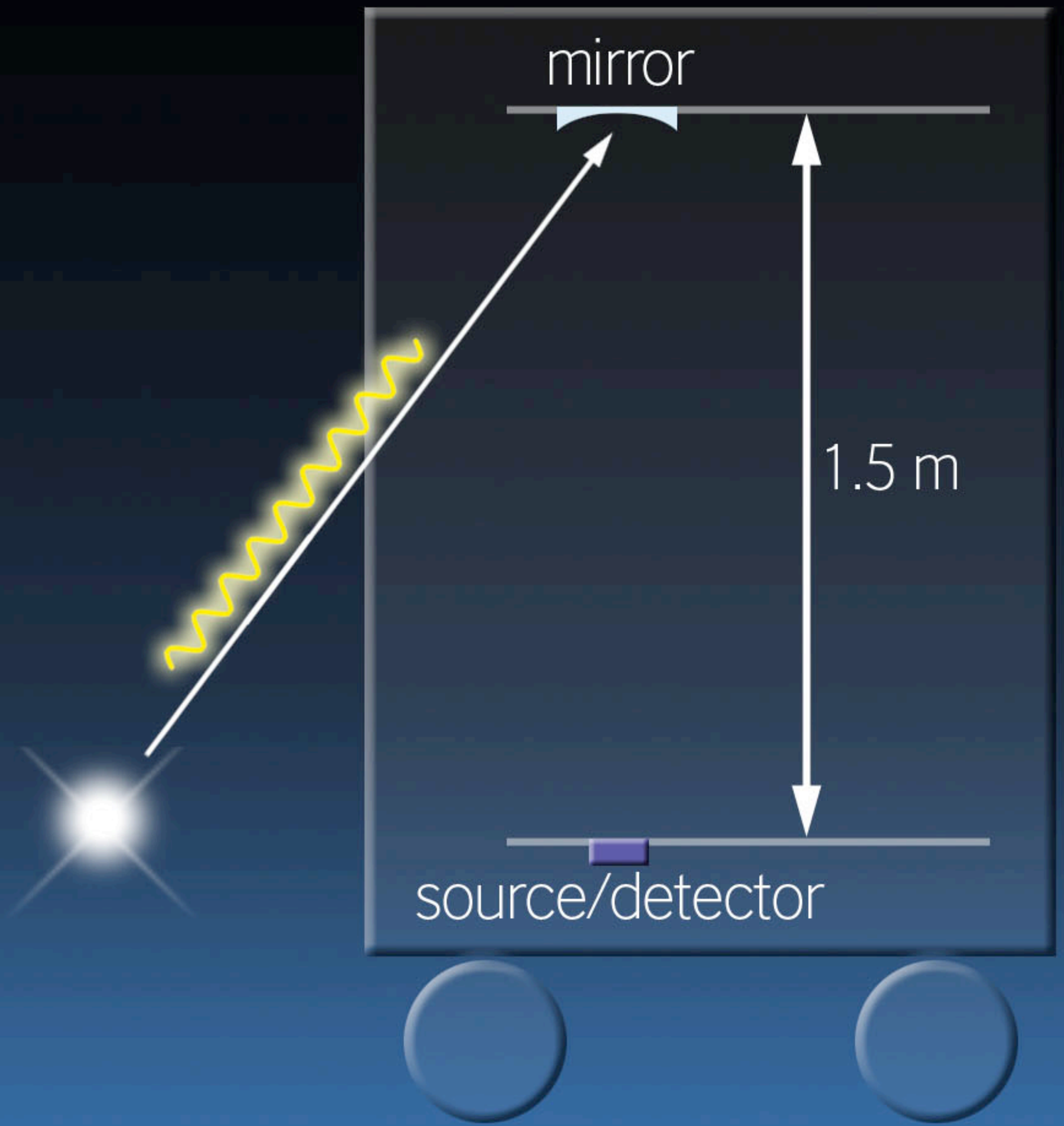
Person standing outside the train:



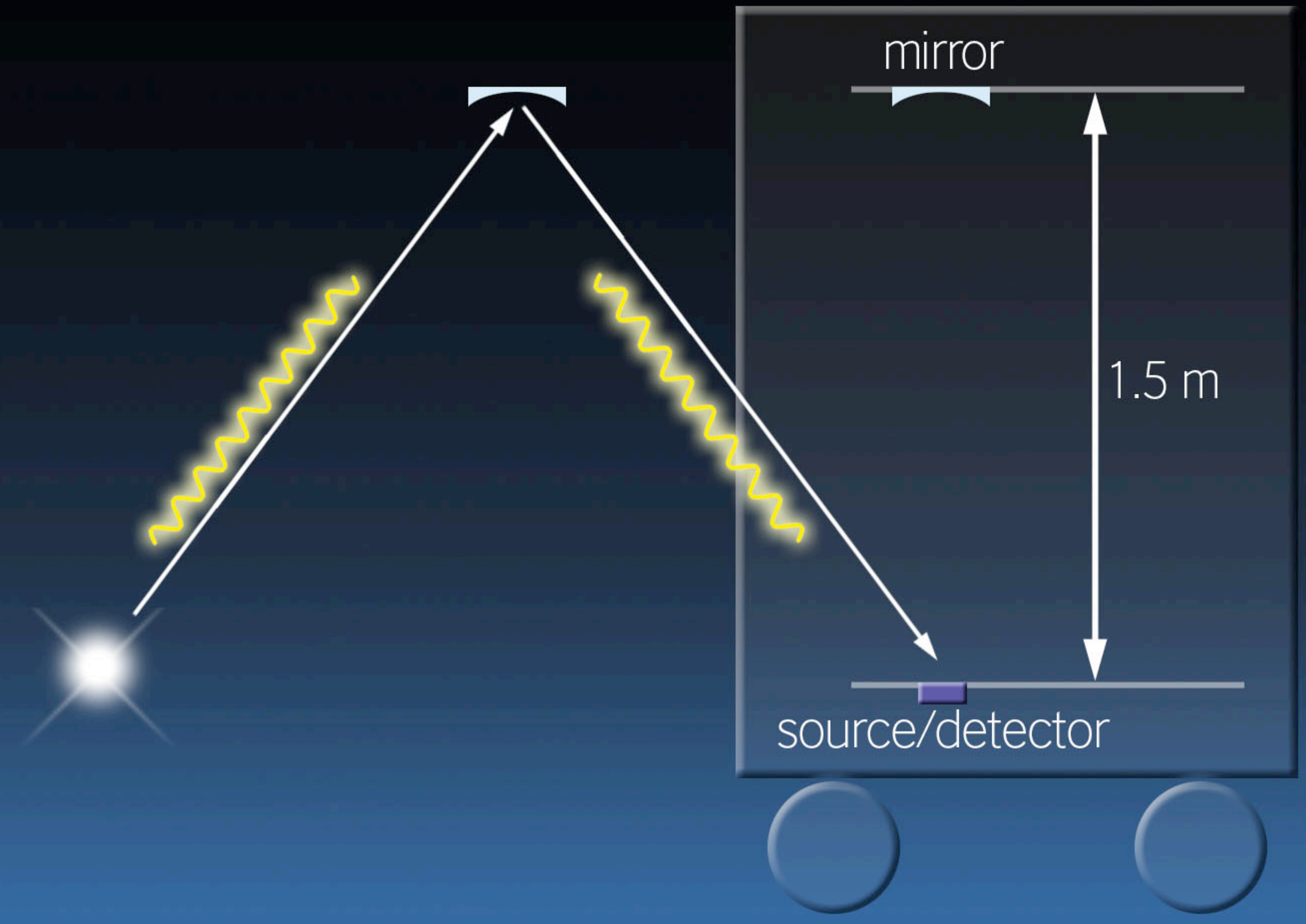
Person standing outside the train:



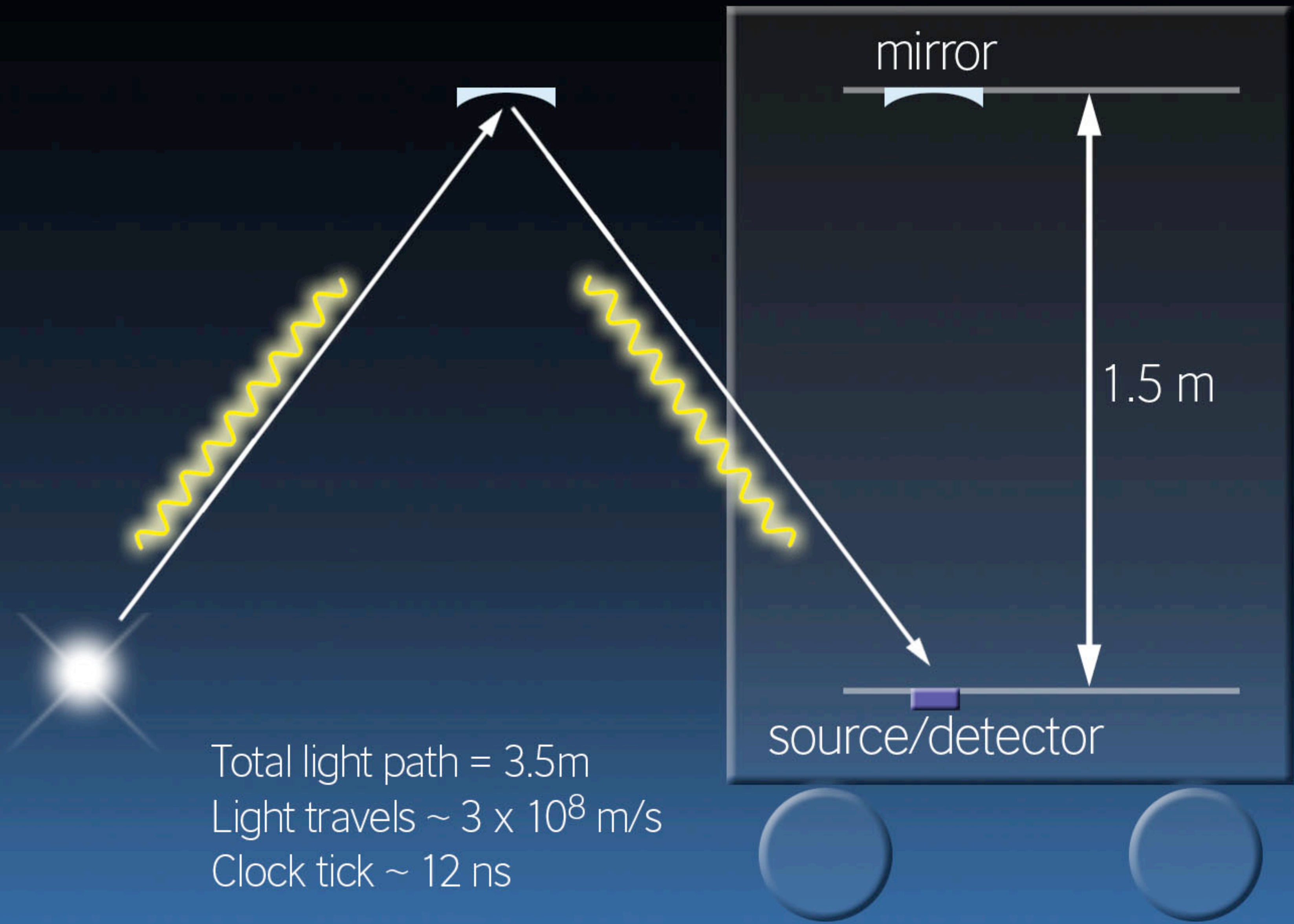
Person standing outside the train:



Person standing outside the train:



Person standing outside the train:



Time Dilation Factor

We can calculate how time slows down for moving objects using the factor gamma

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

We will show the calculations giving us the speed of the muon and the corresponding factor gamma later.

Einstein and Relativity

Our experiment detects muon decays.

By comparing the measured muon decay rates at sea-level, and at Cairn Gorm (nearly 1 km higher), we can check the predictions with and without the effect of time dilation

Let's now look at the equipment used in the experiment…

The Muon Lifetime Experiment

- Shown here are Ingrid Burt, from Beeslack High School in Penicuik, and Alan Walker from The University of Edinburgh, her supervisor.
- Ingrid carried out a feasibility study into using this equipment to make time dilation measurements, as part of a Nuffield Foundation scholarship.
- She's now continuing the work as part of her 6th year physics project.

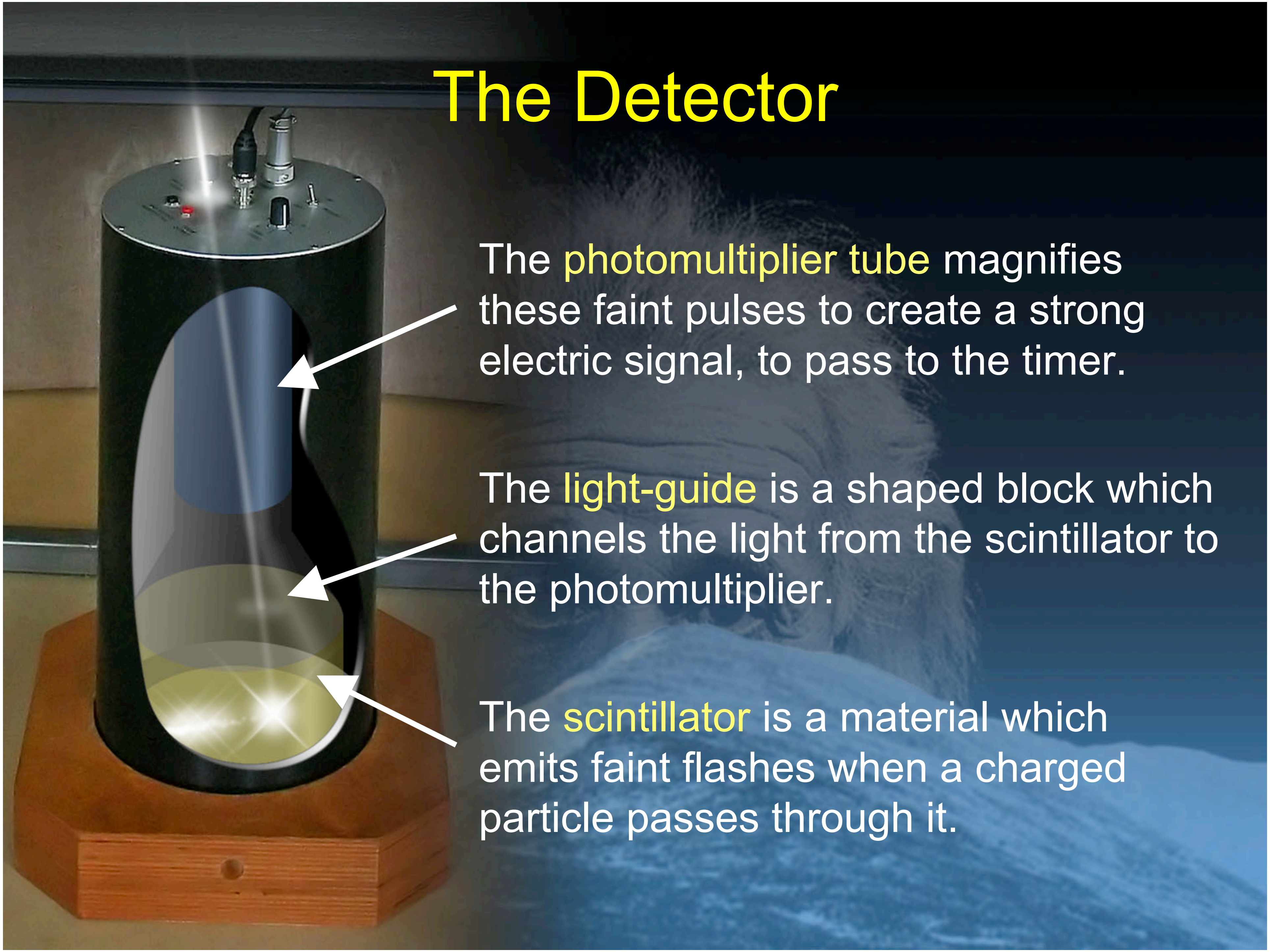
Muon Experiment at Cairn Gorm

The Muon Detector Installation

- A view of the experiment at Cairn Gorm. On the tower shelving, and under the steel table you can see our muon detection apparatus. It comprises three main parts:
    - •The Detector
    - •The Data Aquisition
    - •The Analysis Program

The Detector

- The muon detector is the black cylinder under the steel sheeting.
- It detects the muons as they pass through (or stop) in the detector, and signals their presence to the rest of the experiment.
- There are three main parts to the detector…


The Detector
The photomultiplier tube magnifies these faint pulses to create a strong electric signal, to pass to the timer.
The light-guide is a shaped block which channels the light from the scintillator to the photomultiplier.
The scintillator is a material which emits faint flashes when a charged particle passes through it.

The Data Acquisition Unit

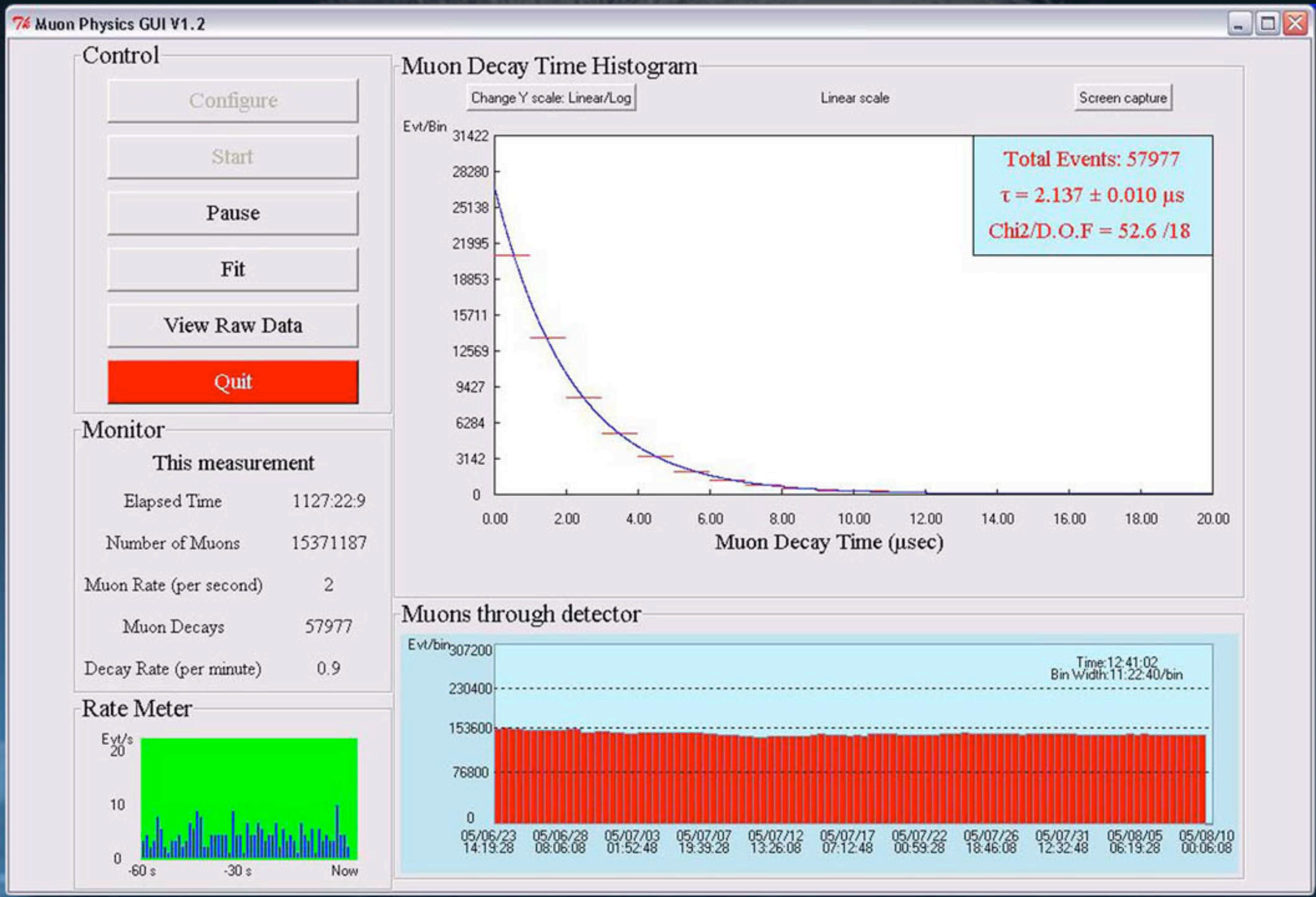
- The signals from the detector are sent to the central electronics unit.
- It is looking for a particular type of signal: TWO flashes of light, spaced less than 20 microseconds apart.
- These flashes show that a muon entered the detector triggering the first flash, slowed down and stopped.
- It decays into an electron (and two neutrinos), that escapes from the detector and triggers the second flash.
- The unit measures the time between the flashes, and sends this information to the analysis program.

The Analysis Program

- This is the software running on the laptop. It takes the timing signals, and displays a variety of results:
  - A graph of the decay times
  - A fit to the muon lifetime
  - The rate of decay of the muons (decays per minute)
- It is the last of these that is the most important value to measure in this experiment.

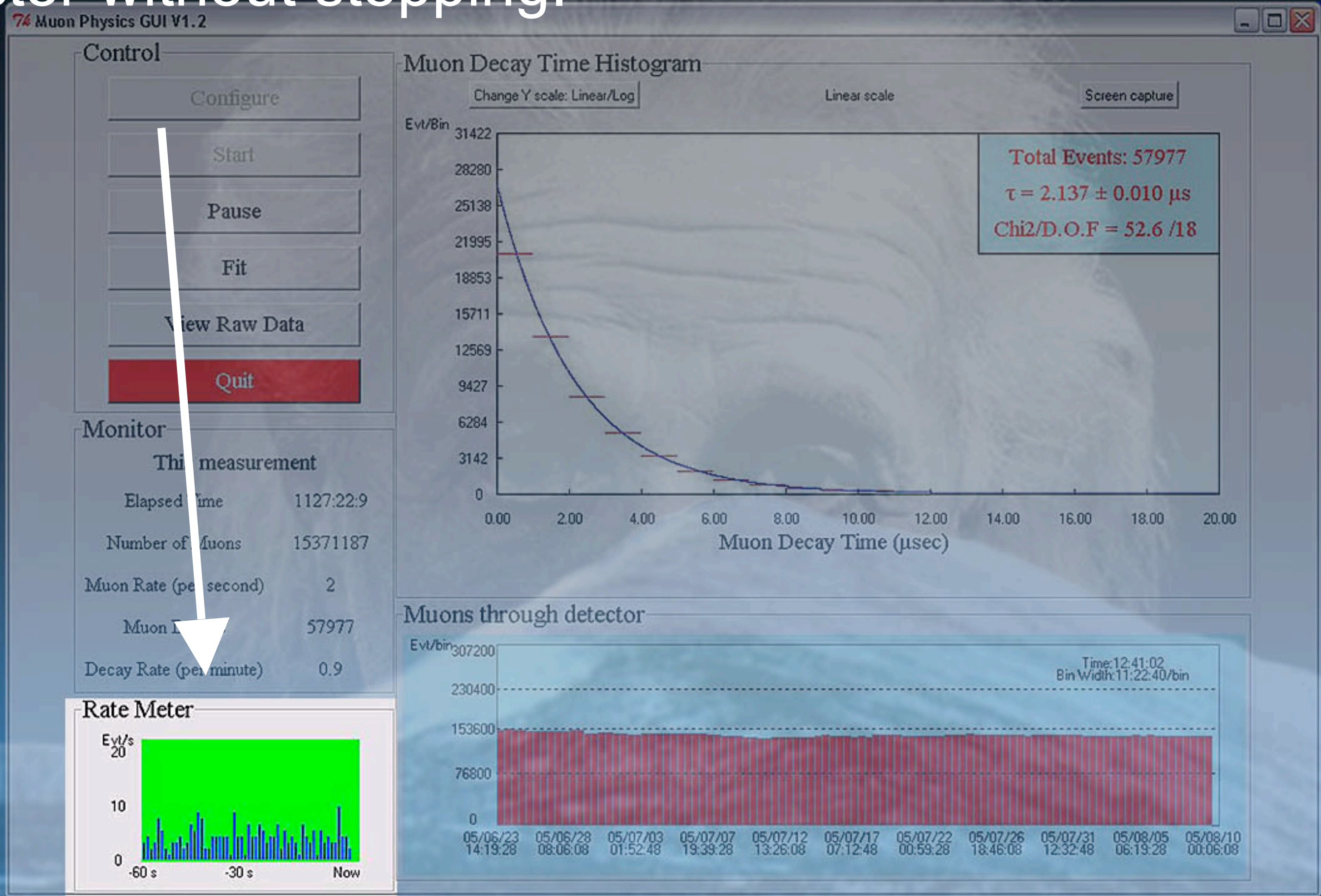
The Analysis Program

The screenshot below shows the continually updating results, as the experiment progresses.



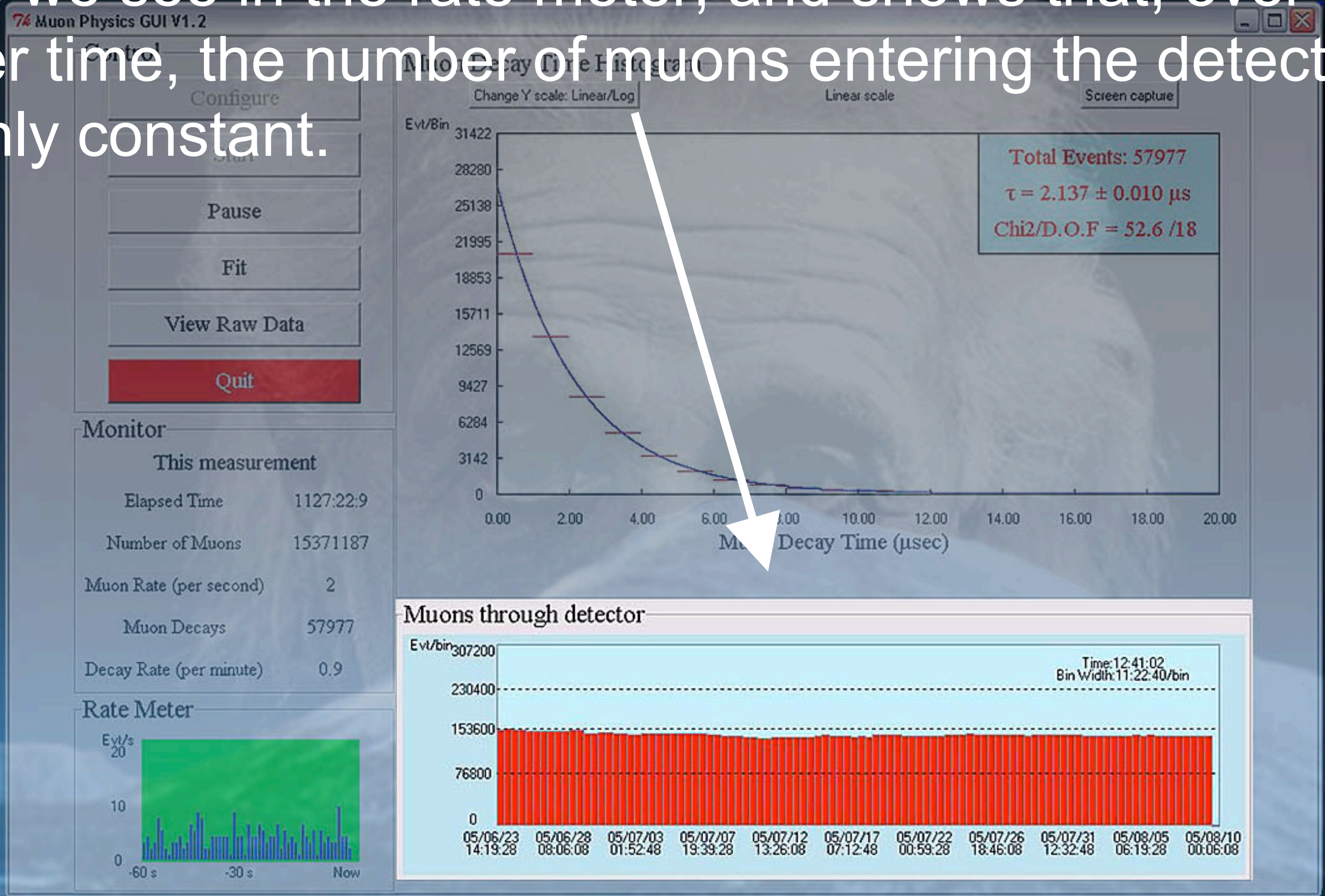
The Analysis Program

At bottom left is the current number of muon events per second. This includes muons which pass through the detector without stopping.



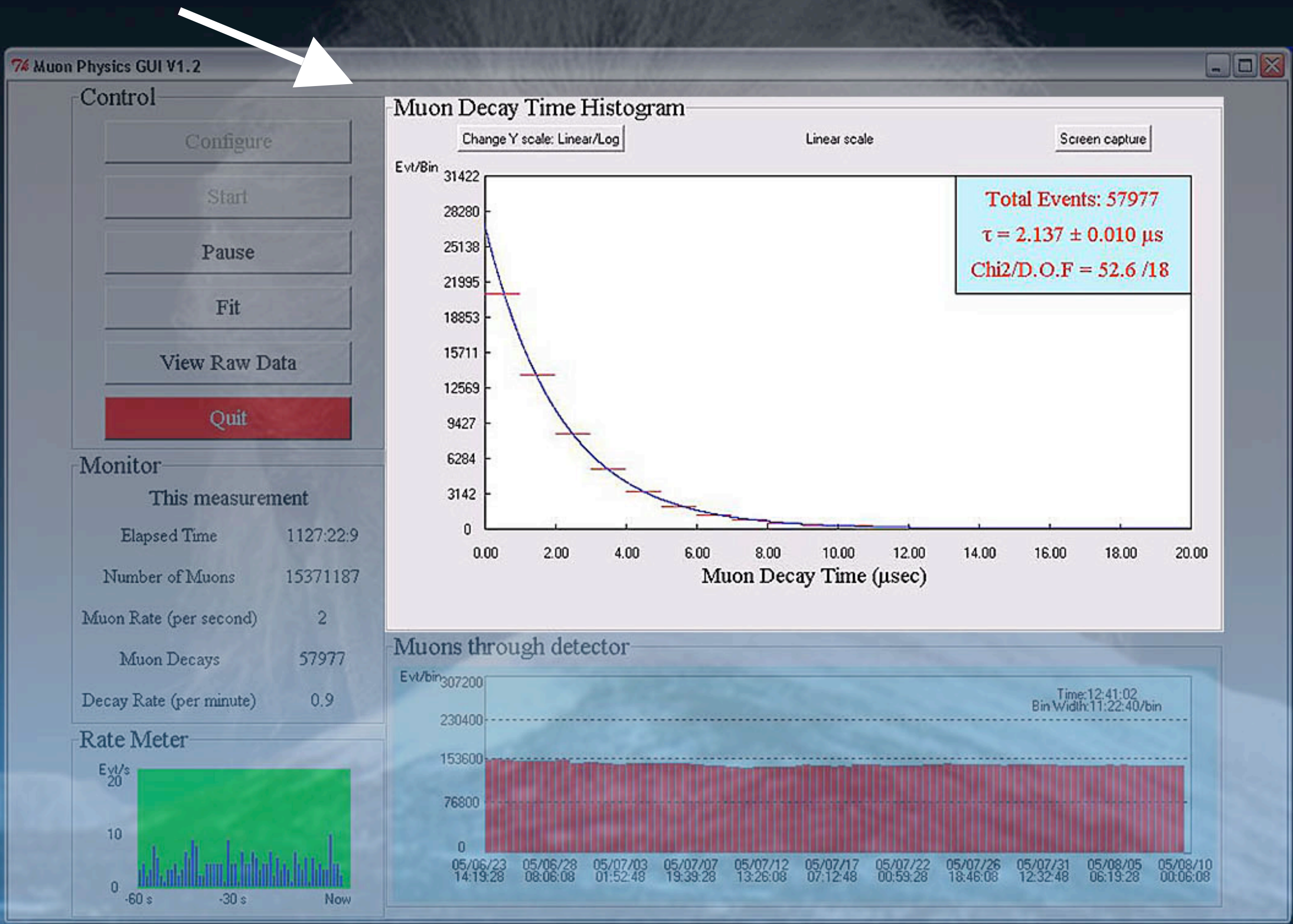
The Analysis Program

This graph displays the number of muons detected in equal time intervals. This smooths out the random arrival times we see in the rate meter, and shows that, over a longer time, the number of muons entering the detector is roughly constant.



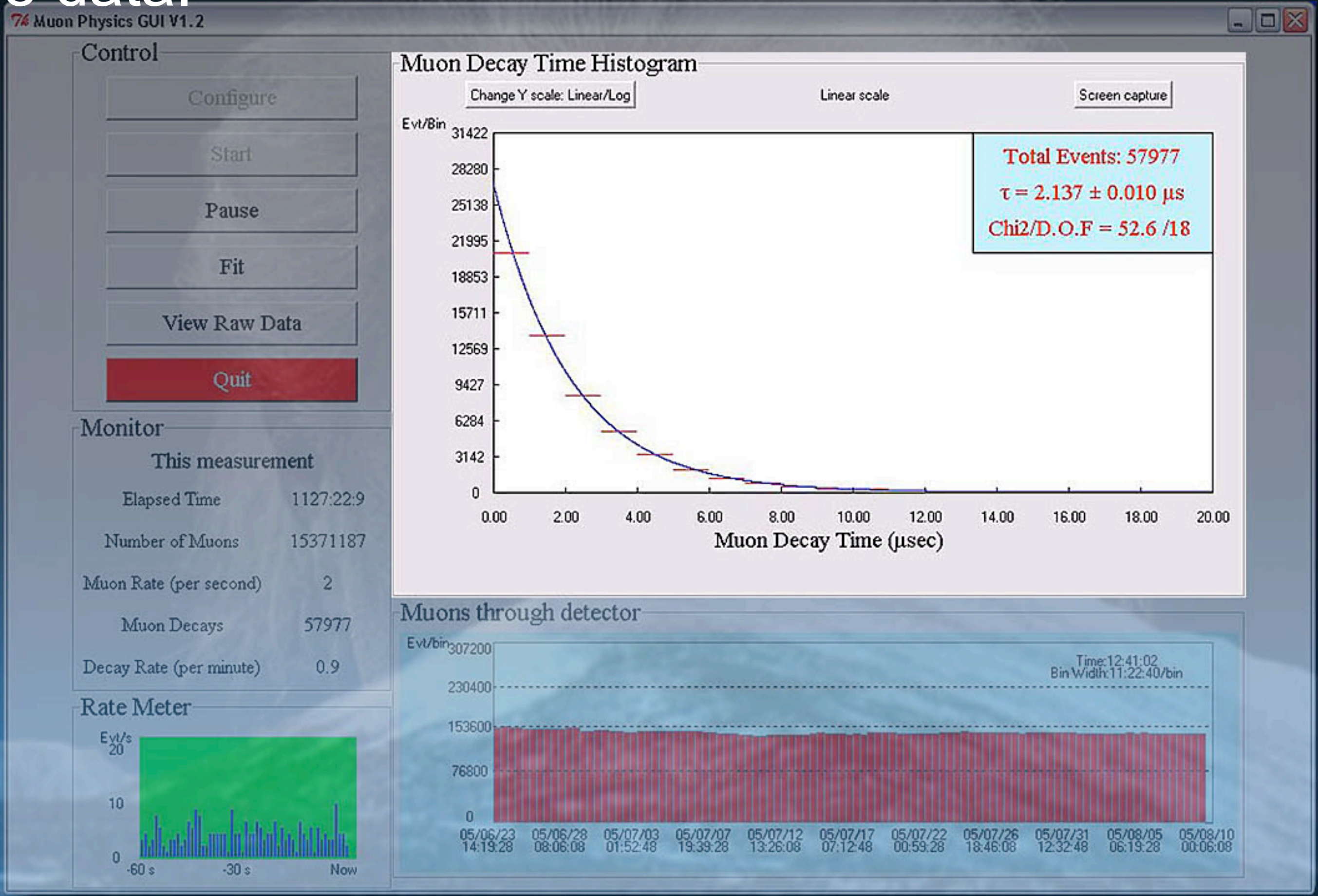
The Analysis Program

This graph plots the number of decays (double flashes) of muons in the detector.



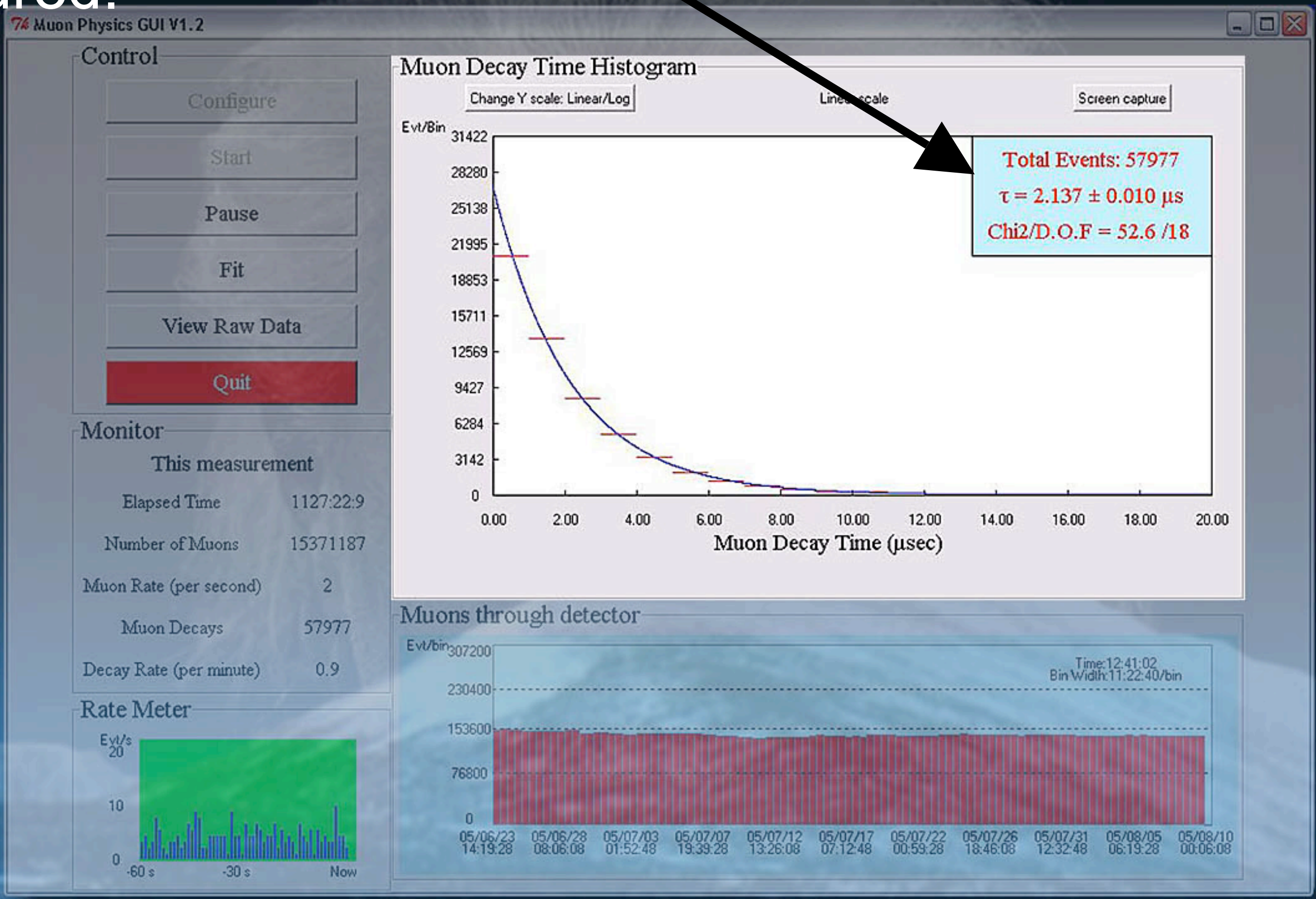
The Analysis Program

The horizontal axis shows the decay time for each double flash. The solid line shows the exponential decay law that fits the data.



The Analysis Program

From the fitted curve, we can extract the average life (lifetime) of a muon -- 2.137 µs when this screen was captured.



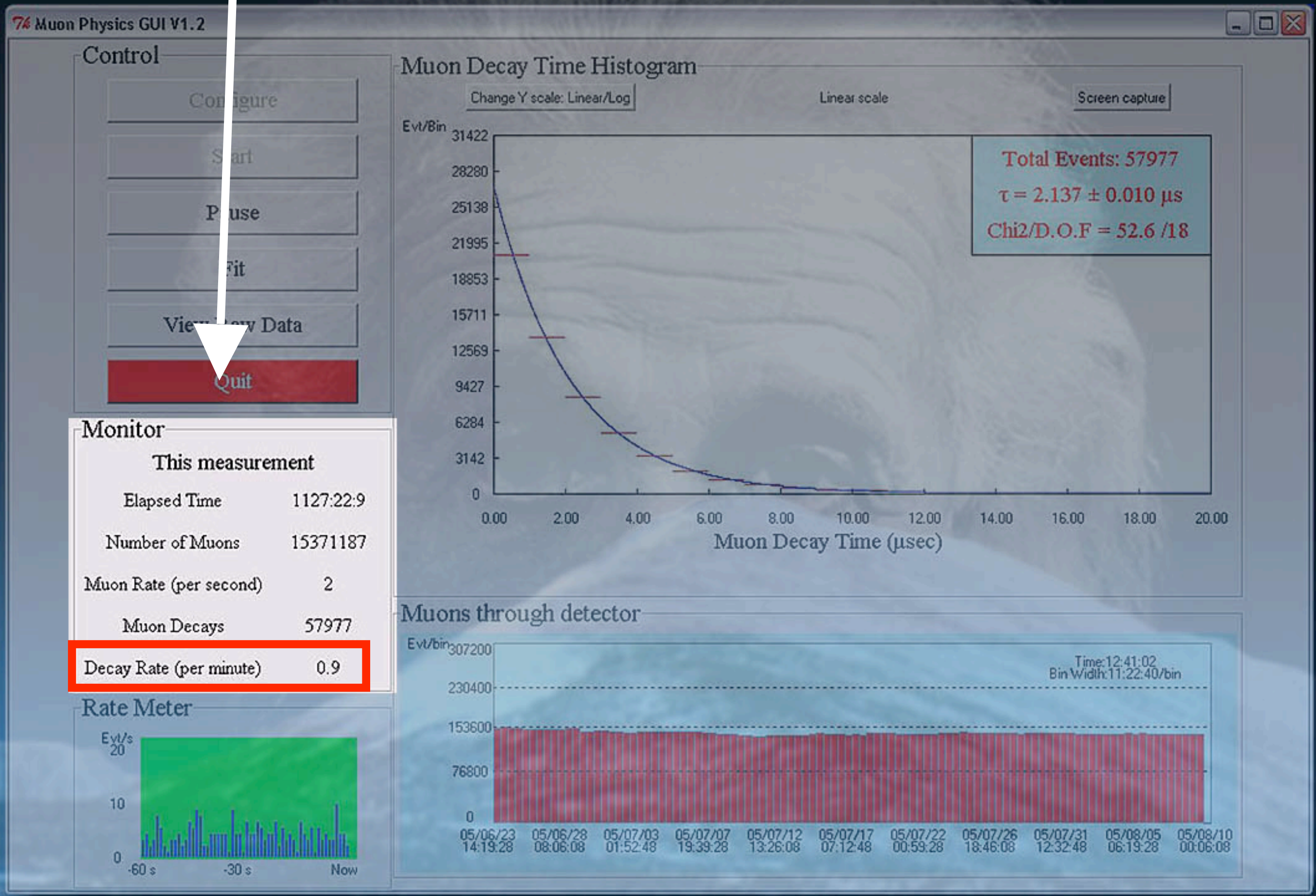
Muon Decay Times

- The longer the experiment ran, the more data (more muon decays in the detector) was collected, and the more precise was the lifetime measurement.
- In a long run at the University of Edinburgh, we measured the lifetime to be 2.134 microseconds.

- *(NB: This less than the value measured in a vacuum as negative muons can also undergo muon capture in the scintillator, reducing the mean lifetime for all muons.)*

The Analysis Program

Here the most important quantities are displayed, including the number of muon decays per minute.



Measurements at Cairn Gorm

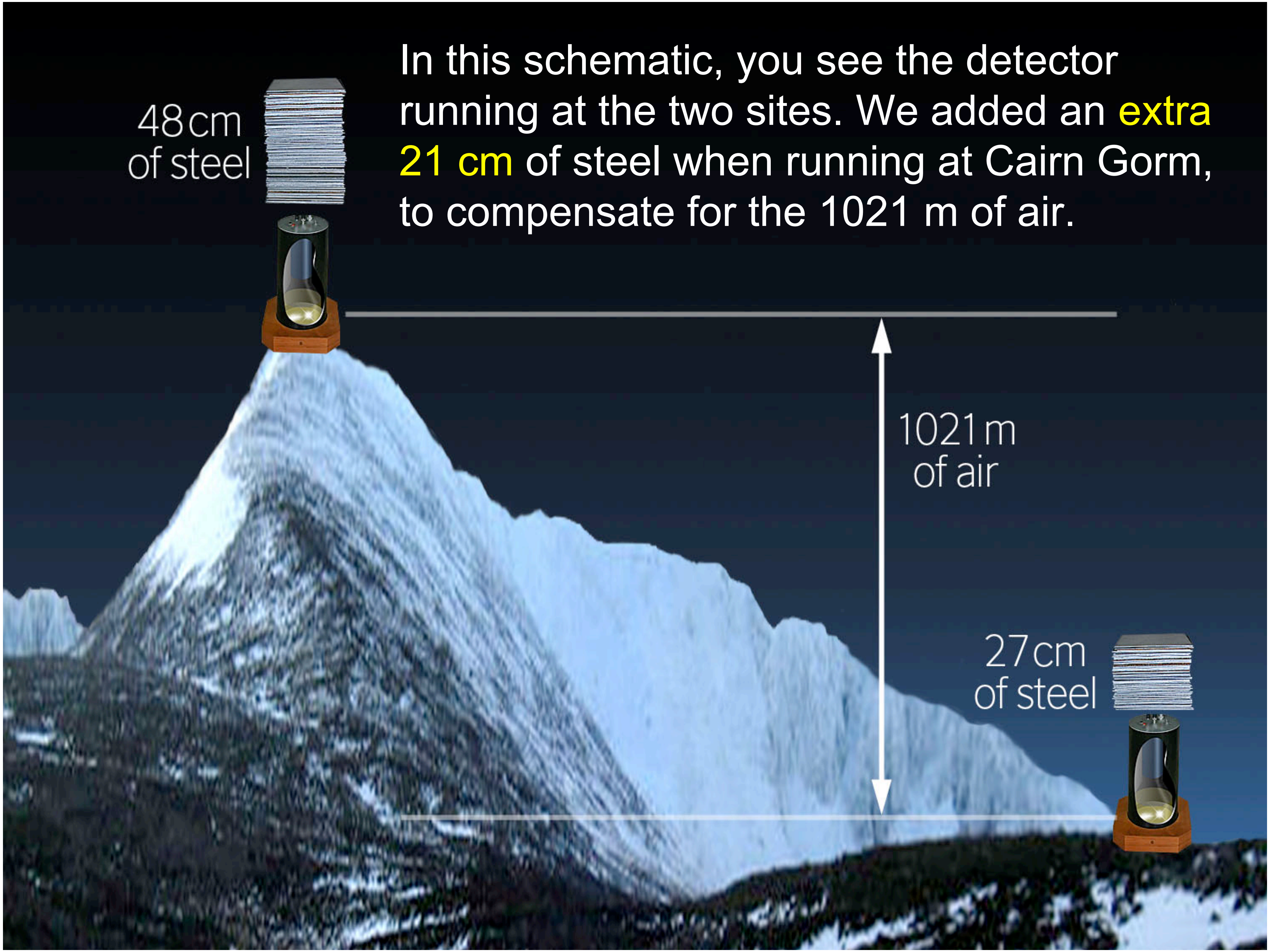
- Two measurements of muon decay rates are required:
  - one at (or near) sea level;
  - one at altitude.
- The comparison of the decay rates at these two locations, should verify the effect of time dilation, and show that muons are surviving longer as they are moving so fast.
- There’s another complication, however:
  - THE ATMOSPHERE

Measurements at Cairn Gorm

- Cairn Gorm is nearly 1 km higher than the King's Buildings in Edinburgh, where our first measurements were made.
- That means 1 km of extra air through which the muons have to travel, to get to the detector in Edinburgh.
- This air will absorb energy from the muons, slowing them down.
- This means that the detector would not be measuring decays rates of muons with the same energies at the two sites.

The Steel Plates

- We had therefore to compensate for the missing 1 km of air.
- This is one of the reasons why the STEEL PLATES were placed above the detector:
- It turns out that about 21 cm of steel absorbs the same energy as 1021 m of air…


In this schematic, you see the detector running at the two sites. We added an extra 21 cm of steel when running at Cairn Gorm, to compensate for the 1021 m of air.
48 cm of steel
1021 m of air
27 cm of steel

We placed the (48 cm) of steel above the detector for the following reason…

The Steel Plates

- The calculations of the predicted muon decay rate is more accurate when we sample higher energy muons as their higher energy means that their speeds are nearer that of light.
- The scintillator, however, only stop fairly low energy muons; high energy ones just zip straight through.

The Steel Plates

- By placing lots of steel plate above the detector, we absorbed the energy of the faster muons, slowing them down sufficiently to be stopped in our detector scintillator.
- The more steel, the more precise are the predictions. There was, however, a limit to how much we could take to the Ptarmigan Station! (The stack of 96 plates weighs over a third of a tonne…)

Our Expectations

- We carried out our first experimental run at the University of Edinburgh, and made our first measurements of the muon decay rate.
- Having calculated how much steel was needed to compensate for the increase in altitude, we took the kit to Cairn Gorm, and ran the experiment until November 3rd.

Our Expectations

- Our Edinburgh result was:
  - **•1 muon decay per minute**
- If time dilation is not taken into account, we would expect to see a decay rate at Cairn Gorm of:
  - **•5 muon decays per minute**
- Ingrid’s calculations suggested that, if Einstein is correct, and time slows down when you move fast, the result at Cairn Gorm would be:
  - **•1.3 muon decays per minute**

The Bethe -Bloch Equation

As a charged particle travels through matter it slows down by transferring some of its energy to nearby atoms, causing excitation or ionisation.

Detailed calculations of the energy lost by a muon in air, steel and the scintillator were performed using the well-understood Bethe-Bloch formula:

$$\frac{dE}{dx} = -4\pi\rho N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\gamma^2\beta^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

The losses depend on the velocity of the muon (beta is v/c). Ingrid performed these calculations iteratively with Microsoft Excel using appropriate formulae in adjacent cells.

The Bethe -Bloch Calculations

TABLE A3

Losses in scintillator (PVT), standard Bethe Bloch equation, density correction (BBv3)

BB coeff.	muon mass MeV	electron mass MeV	Z/A	I eV	density gm/cm^3	hnup eV	rho	-C	X0	X1	a	m
0.1716	105.6584	0.5110	0.5414	64.7000	1.0320	21.5400	1.9290	3.1997	0.1464	2.4855	0.1610	3.2393

Distance	Total	Kinetic	Energy	Total	gamma	beta	p	p/mc	Tmax	Tmax0	X	delta
	Energy	Energy	Loss	Loss								
cm	MeV	MeV	MeV	MeV			MeV/c		MeV	MeV		
0	159.1389	53.4805		0.0000	1.5062	0.7478	119.0021	1.1263	0.6576	0.6625	0.0517	0
6.25	140.2130	34.5546	0.1707	18.9259	1.3270	0.6574	92.1738	0.8724	0.3948	0.3974	-0.0593	0
12.5	105.6586	0.0002	2.4129	53.4803	1.0000	0.0021	0.2209	0.0021	0.0000	0.0000	-2.6797	0

Energy at the top of scintillator required to reach Top/Middle/Bottom of Scintillator:-												
	Total	Kinetic			Gamma	Beta	p	p/mc				
	Energy	Energy										
Top	105.6584	0.0000			1.0000	0.0000	0.0000	0.0000				
Middle	140.2530	34.5946			1.3274	0.6576	92.2345	0.8730				
Bottom	159.1389	53.4805			1.5062	0.7478	119.0021	1.1263				

Here beta = v /c. With no shielding muons stopping in§scintillator have speed between 0 and 3/4 the speed of light.

The Bethe -Bloch Calculations

TABLE B3

Losses in iron, standard Bethe Bloch equation, density correction (BBv3)

BB Coeff.	muon mass MeV	electron mass MeV	Z/A	I eV	density gm/cm^3	hnup eV	rho	-C	X0	X1	a	m
1.1257	105.6584	0.5110	0.46556	286.0000	7.874	55.1720	2.5040	4.2911	-0.0012	3.1531	0.1468	2.9632

Distance (cm)	Total Energy	Kinetic Energy	Energy Loss	Total Energy Loss	Gamma	Beta	p	p/mc	Tmax MeV	Tmax0 MeV	X	delta
0	720.6505	614.9921		0.0000	6.8206	0.9892	712.8629	6.7469	22.9967	23.7725	0.8291	1.3134
49.3	159.1390	53.4806	1.4822	561.5115	1.5062	0.7478	119.0022	1.1263	0.6576	0.6625	0.0517	0.1475

Energy at the top of scintillator required to reach Top/Middle/Bottom of Scintillator:-								
Using BBv2	Total Energy	Kinetic Energy			Gamma	Beta	p	p/mc
Top	105.6584	0.0000			1.0000	0.0000	0.0000	0.0000
Middle	140.2530	34.5946			1.3274	0.6576	92.2345	0.8730
Bottom	159.1389	53.4805			1.5062	0.7478	119.0021	1.1263

Energy at the top of iron required to reach Top/Middle/Bottom of Scintillator:-								
Using BBv2 49.3cm Fe	Total Energy	Kinetic Energy		Energy at bottom of Fe	Gamma	Beta	p	p/mc
Top	693.0868	587.4284		105.6585	6.5597	0.9883	684.9859	6.4830
Middle	707.3330	601.6746		140.2534	6.6945	0.9888	699.3971	6.6194
Bottom	720.6505	614.9921		159.1385	6.8206	0.9892	712.8629	6.7469

These abbreviated spreadsheets show that the speed of muons passing through 49.3 cm of steel and then stopping in the scintillator is in the range 0.9883c and 0.9892c

The Bethe -Bloch Calculations

Energy at the top of scintillator required to reach Top/Middle/Bottom of Scintillator:-								
Using	Total	Kinetic			Gamma	Beta	p	p/mc
BBv3	Energy	Energy						
Top	105.6584	0.0000			1.0000	0.0000	0.0000	0.0000
Middle	140.2534	34.5950			1.3274	0.6576	92.2351	0.8730
Bottom	159.1389	53.4805			1.5062	0.7478	119.0021	1.1263

Energy at 0m of atmosphere with 49.3 cm Fe to reach Top/Middle/Bottom of Scintillator:-								
Using	Total	Kinetic	Energy at	Energy at	Gamma	Beta	p	p/mc
BBv3	Energy	Energy	top of Fe	bottom of Fe				
Top	693.0868	587.4284	716.4120	105.6585	6.5597	0.9883	684.9859	6.4830
Middle	707.3330	601.6746	731.6441	140.2534	6.6945	0.9888	699.3971	6.6194
Bottom	720.6505	614.9921	745.8256	159.1385	6.8206	0.9892	712.8629	6.7469

Energy at 1021 m of atmosphere with 28.3 cm Fe to reach Top/Middle/Bottom of Scintillator:-								
Using	Total	Kinetic	Energy at	Energy at	Gamma	Beta	p	p/mc
BBv3	Energy	Energy	top of Fe	bottom of Fe				
Top	689.9295	584.2711	506.5561	105.6588	6.5298	0.9882	681.7910	6.4528
Middle	704.9631	599.3047	520.0832	139.5189	6.6721	0.9887	697.0002	6.5967
Bottom	718.9635	613.3051	532.7482	157.9953	6.8046	0.9891	711.1574	6.7307

These abbreviated spreadsheets show that the speed of muons passing through 1021m of air, 28.3cm of steel and then stopping in the scintillator is in the range 0.9882c and 0.9891c

The Bethe -Bloch Calculations

The muons that stop and then decay in the scintillator at both the top and bottom stations have speeds between 0.9882 and 0.9891 of the speed of light. With such precise speeds we can accurately calculate (iteratively) the effect of time dilation.

Below we show a snapshot of the calculation but missing out most of the steps!

TABLE D3

Losses in Air, Iron and Scintillator using standard Bethe Bloch equation, density correction (BBv3)

				Loss			t(NR)	t(R)	NR	R	NR	R
Air Height m												
1021	0	718.9635		0.0000	6.8046	0.9891	0.00	0.00	1.0000	1.0000	1.0000	1.0000
21	100000	497.9955	21.7063	220.9680	4.7133	0.9772	3.39E-06	5.85E-07	0.8565	0.9690	0.2145	0.7666
0	102100	493.4543	4.5412	225.5092	4.6703	0.9768	3.46E-06	6.00E-07	0.9679	0.9931	0.2076	0.7613
Steel	0	493.4543		0.0000	4.6703	0.9768	0.00	0.00	0.9679	0.9931	0.2076	0.7613
Steel	28.3	159.1389	1.4971	334.3154	1.5062	0.7478	3.73E-06	6.58E-07	1.0000	1.0000	0.2075	0.7612
Scintillator	0	159.1389		0.0000	1.5062	0.7478	0.00	0.00	1.0000	1.0000	0.2075	0.7612
Scintillator	12.5	105.6583	2.4131	53.4806	1.0000	#NUM!	3.73E-06	6.59E-07	1.0000	1.0000	0.2074	0.7610

From this table we can see that the reduction in rate of muon decays detected between the Ptarmigan Station and King's Buildings is predicted to be 0.76 with time dilation, but 0.21 without!

The Predictions of the Bethe -Bloch Calculations

- The reduction in rate with no time dilation is 0.20
- The reduction in rate taking into account time dilation is 0.76
- The difference between these is a factor of 3.67
- The measured rate at 76m elevation is 1 decay per minute
- At Cairn Gorm Ptarmigan Station at 1097m elevation:-
- without time dilation the predicted rate is 4.87 decays per minute
- with time dilation the predicted rate is 1.31 decays per minute

What did the display show at the end of the run?

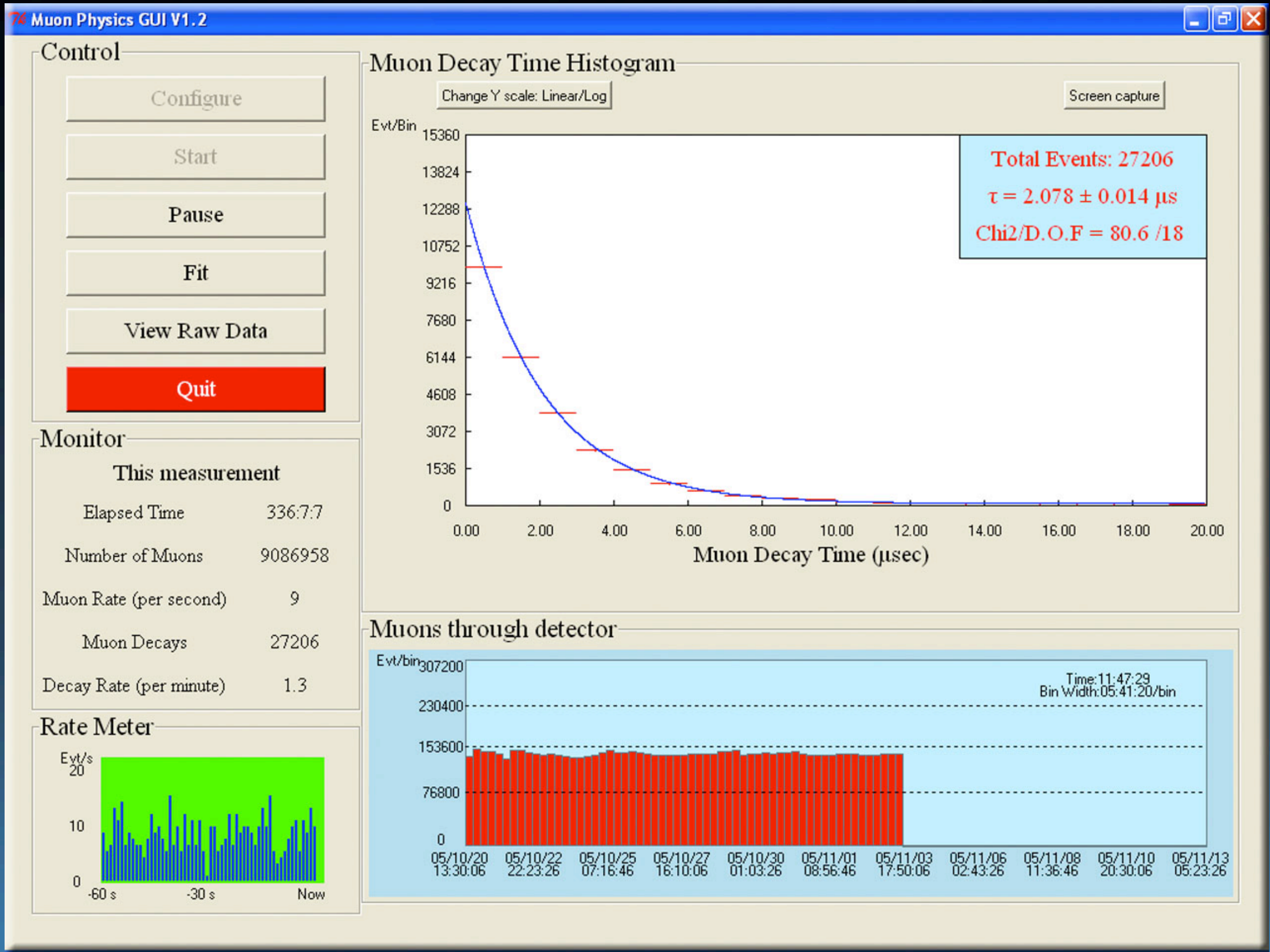
1.3 decays per minute

Was Einstein correct?

1.3 decays per minute << 5 decays per minute

Well done Albert!

The Final Screenshot at Cairn Gorm



This shows clearly the rate of 1.3 muon decays per minute.

Our thanks particularly to the staff of SCI-FUN Mark Reynolds, Brian Cameron, and Michael Palmer for their enormous help in construction and setting up.

To the Andy Downie and the staff of the School of Physics Mechanical Workshop for their technical help in constructing parts of the experimental apparatus, but in particular for cutting and filing the 96 plates of steel!

Finally thanks to those whose support and enthusiasm for the project has been our reward.

Thanks to you all!

Our thanks

We at SCI-FUN would like to thank all those at Cairngorm Mountain Ltd who, through their time, assistance and enthusiasm, made this project possible.

We would also like to thank the Particle Physics and Astronomy Research Council, for their contribution to the funding of our experiment.

The top station, Cairn Gorm