The LPPP: A Particle Physics Simulation for Outreach

Harald Fox h.fox@lancaster.ac.uk
lppp.lancs.ac.uk

IOP 9 Sep 2025

Lancaster Particle Physics Package

http://lppp.lancs.ac.uk

Introduction

The LPPP is a project that spans more than two decades, the exact origins lost in the mist of time (a UK wide masterclass task force was at the root).

We are grateful to acknowledge several rounds of funding from STFC.

One of the main drivers was Vato Kartvelishvili, with numerous students helping, Alex Finch for neutrinos and recently PostDoc Andy Wharton working on the package.

Its latest incarnation is (??? → Java →) HTML5 + javascript for the animations. This version should be platform independent and resizable.

Our "customers" prefer a Masterclass in September. The LPPP is embedded in a standalone day where school groups join. In the future we would (also) like to join the CERN Masterclass with individual participation.

Provisional Schedule

09:15	Arrive on Campus.
09:30	Talk: Introduction to Particle Physics
10:15	Refreshments Demonstration of cloud chamber
10:45	Hands-on session in PC lab: The Lancaster Particle Physics Package: Basic kinematics of particle collisions.
12:15	Q & A sessions in small groups
12:45	Lunch break
13:45	Talk: " Particle Physics and Cosmology"
14:20	Film: "Atlas Experiment in CERN"
14:40	Talk: "The Grid - the largest computer system in the world?"
15:00	Quiz on particle physics.
15:30	Close

The Lancaster Particle Physics Package (LPPP)

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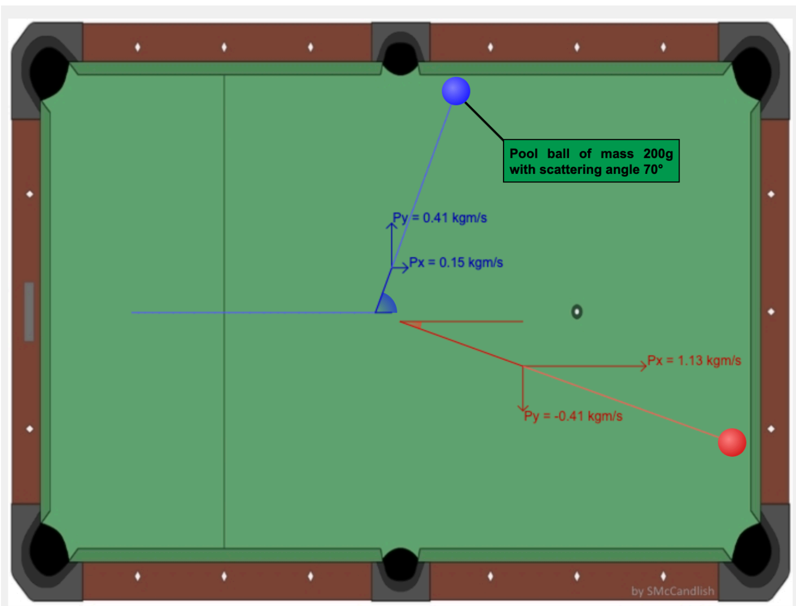
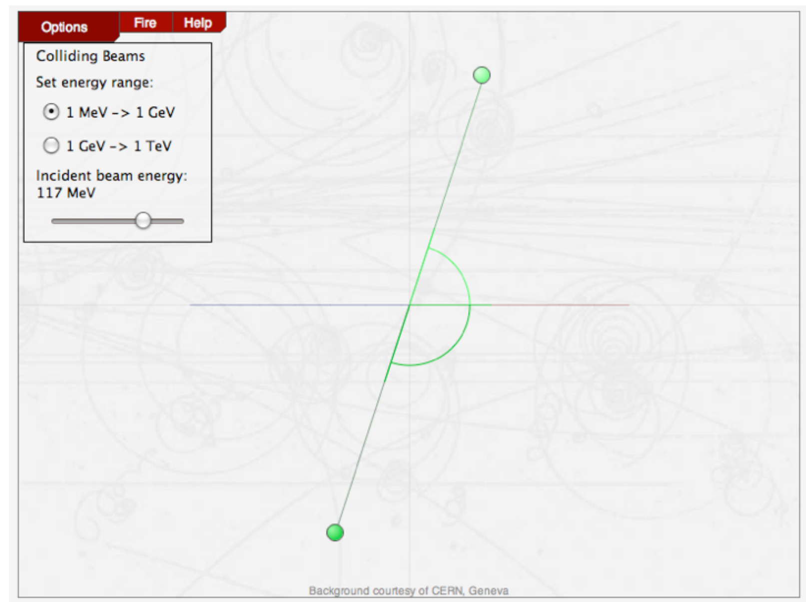
LPPP: Table of Content

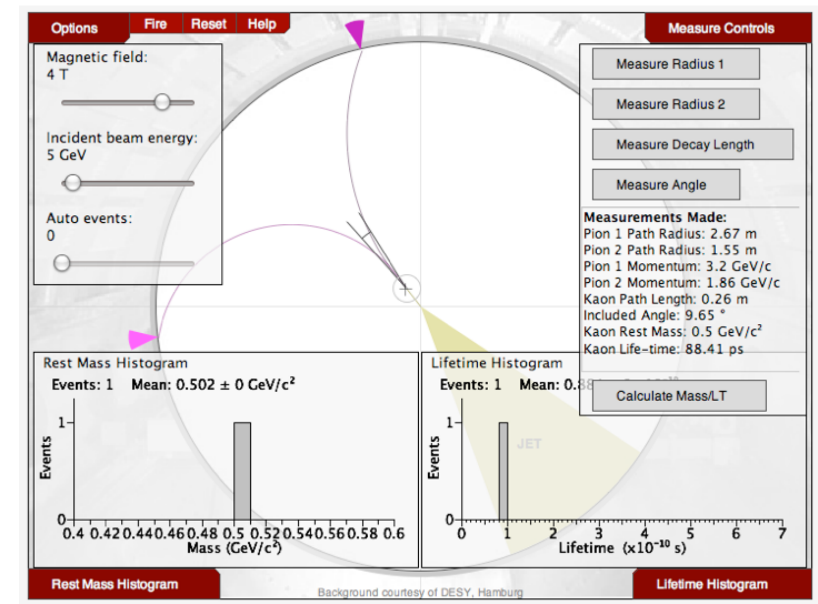
Pool



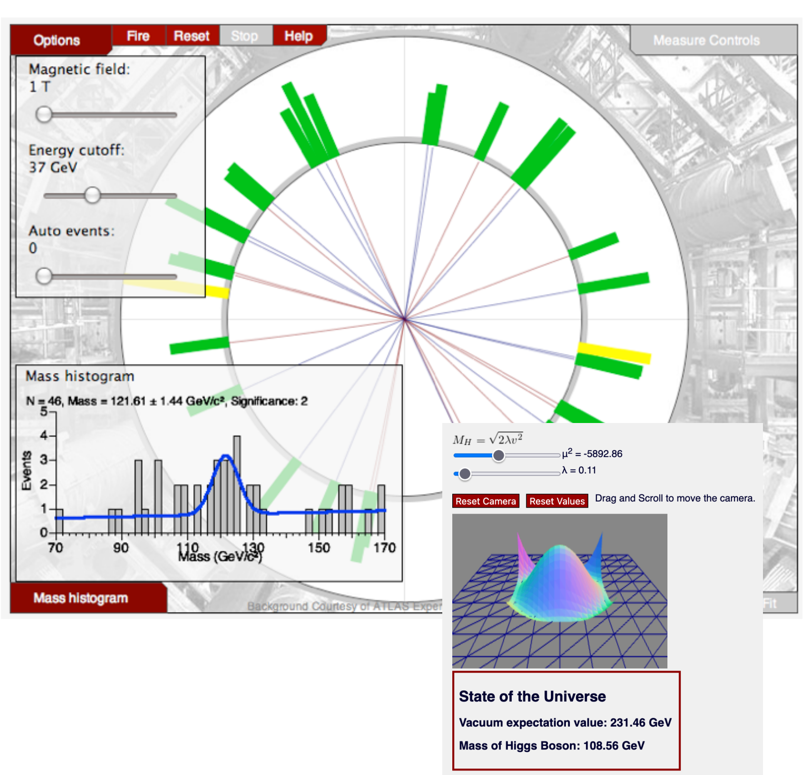
Annihilation



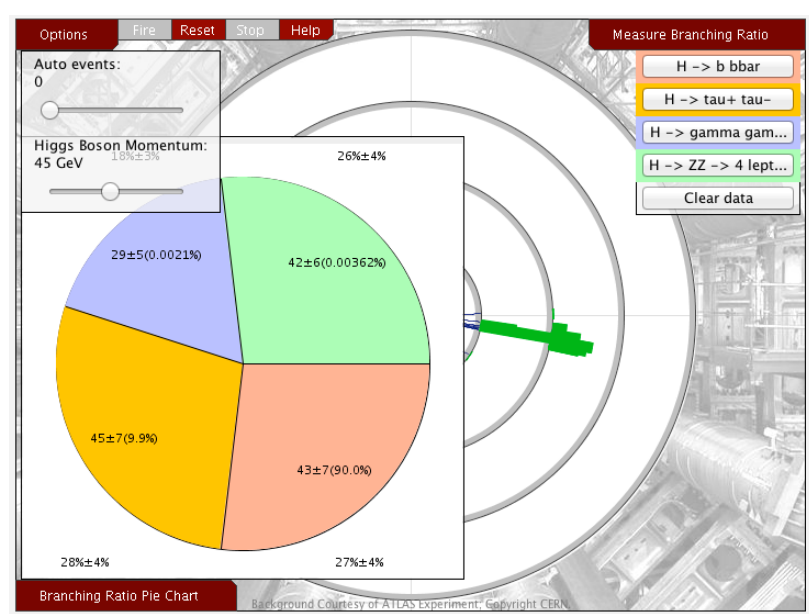
Lifetime



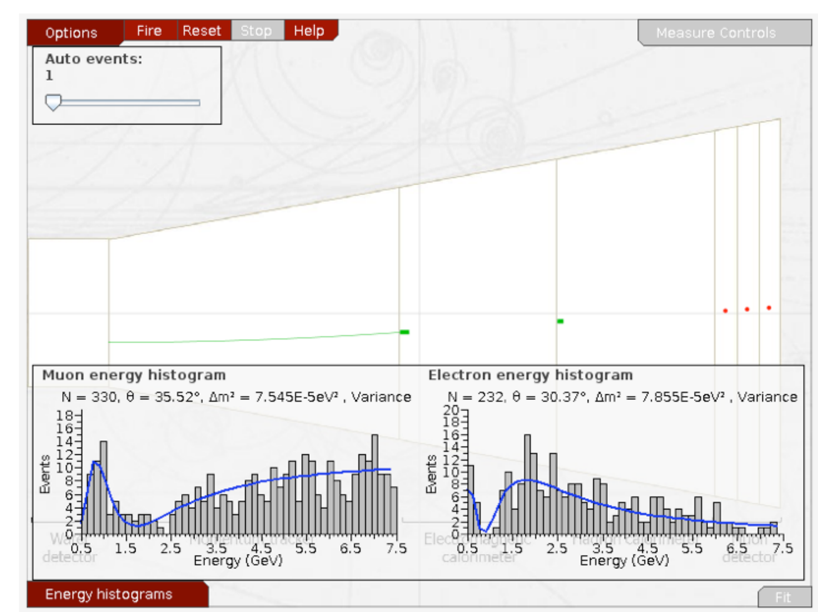
Higgs



Branching Ratios



Neutrino Mixing



LPPP: Pool

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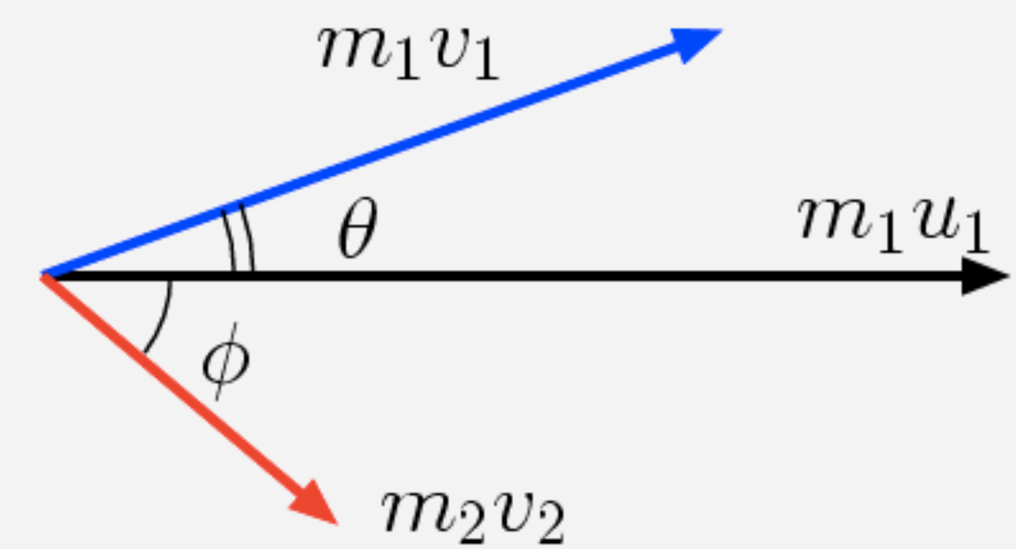
$$\frac{1}{2}m_1 u_1^2 = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 \quad \textbf{(1)}$$

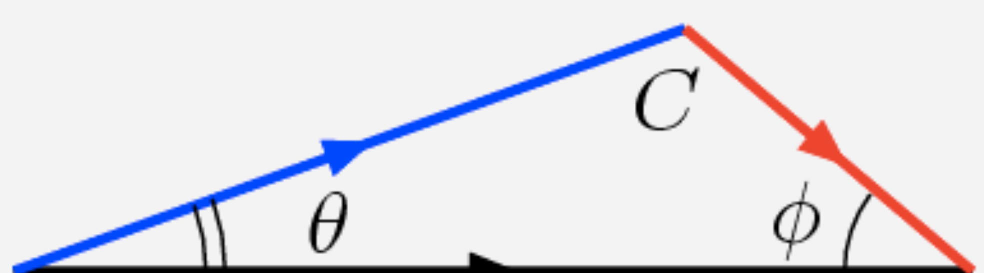
and rearrange it to give

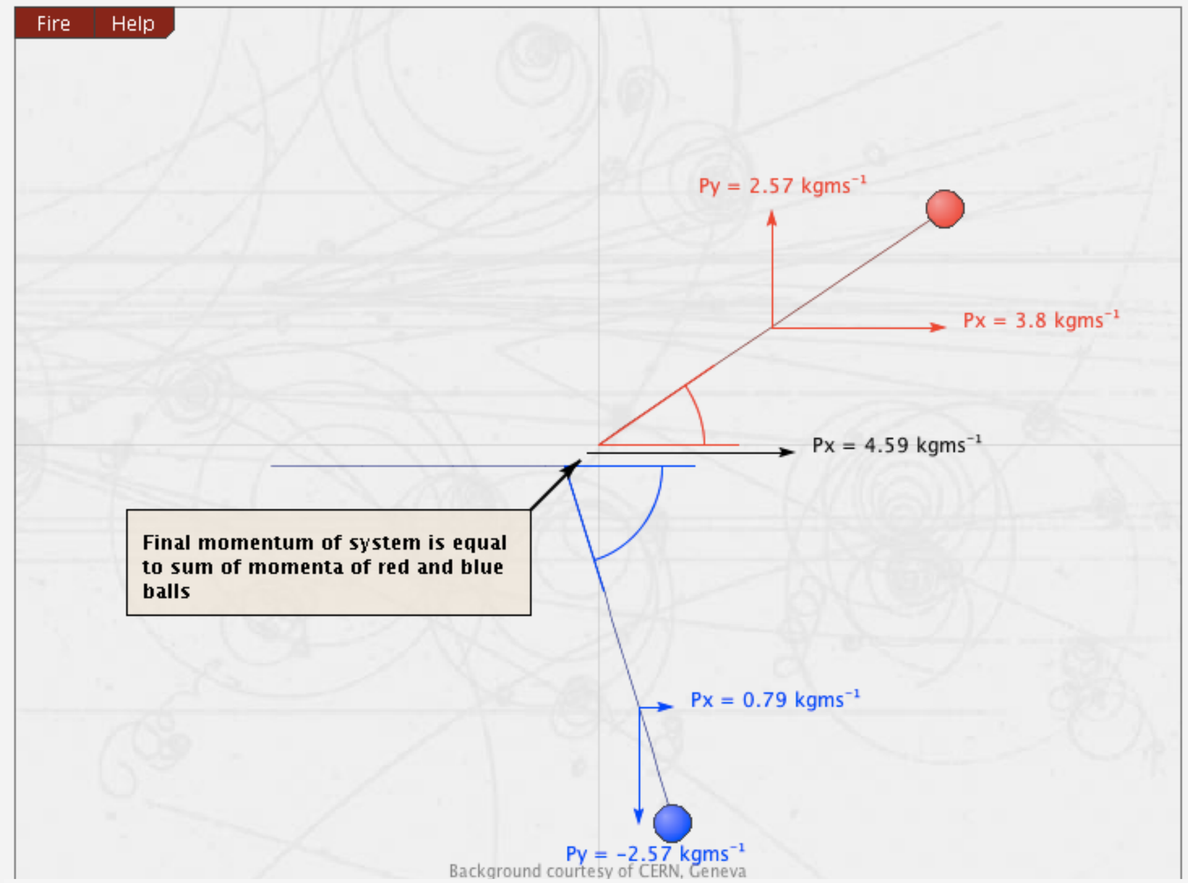
$$u_1^2 = v_1^2 + \left(\frac{m_2}{m_1}\right) v_2^2 \quad \textbf{(2)}$$

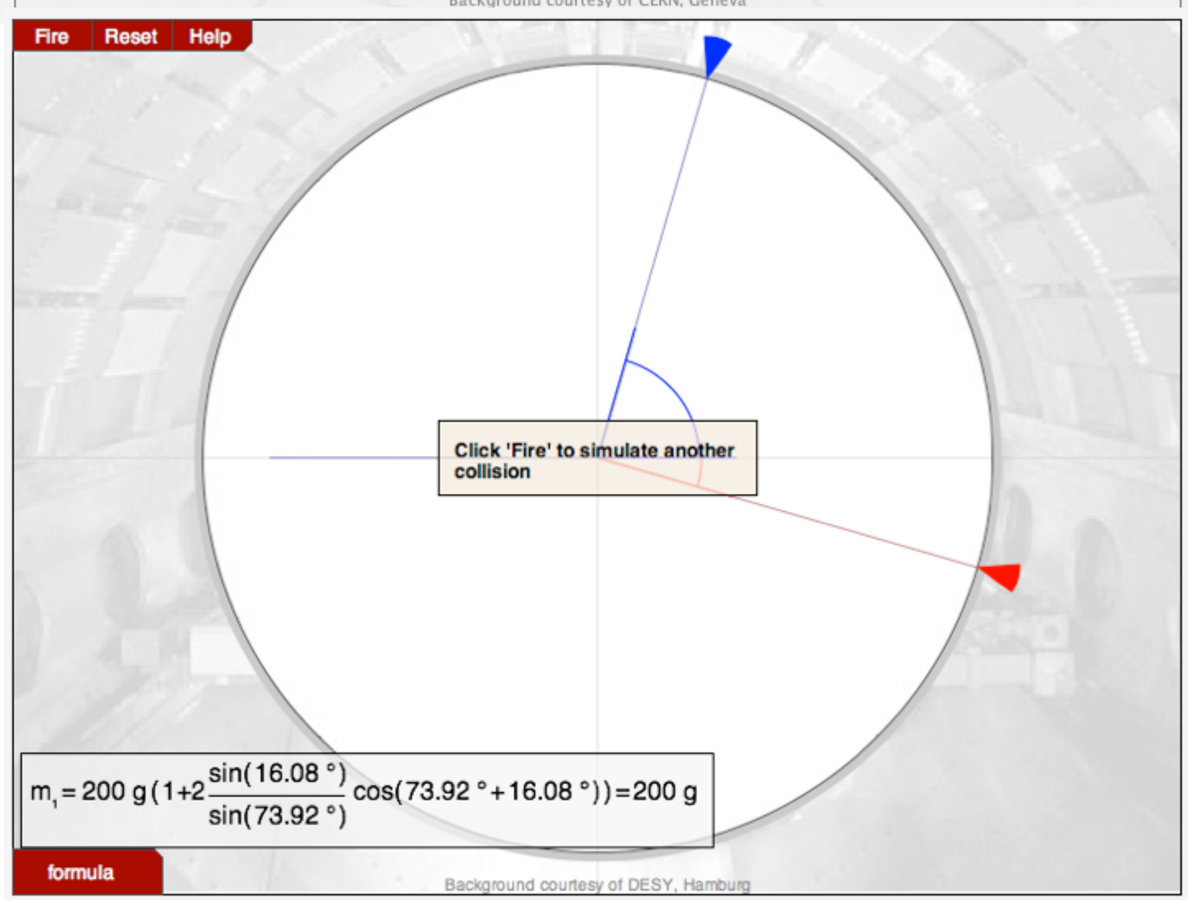
Now consider the three momentum vectors in the system.



These can be redrawn to form a closed triangle.







LPPP: Pool

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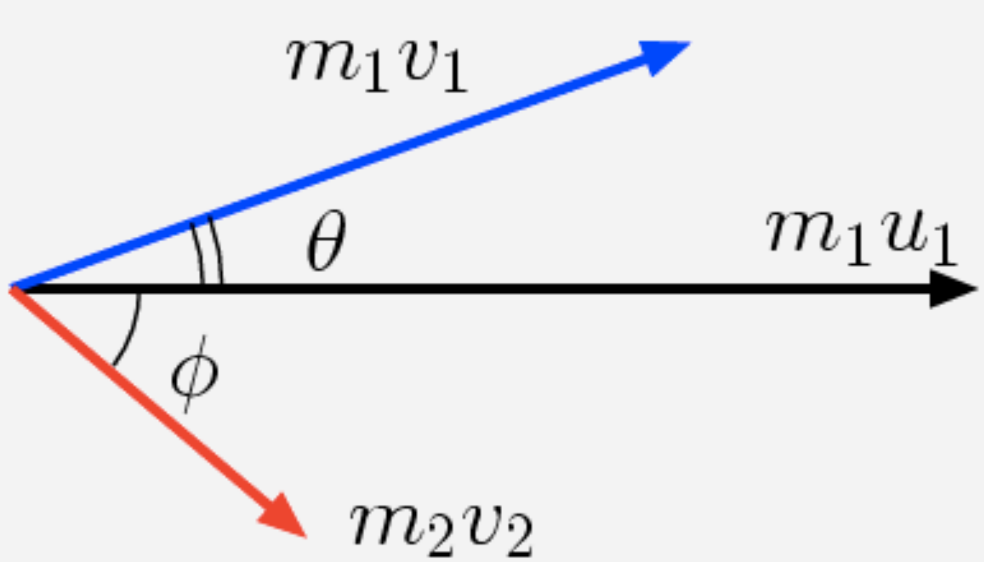

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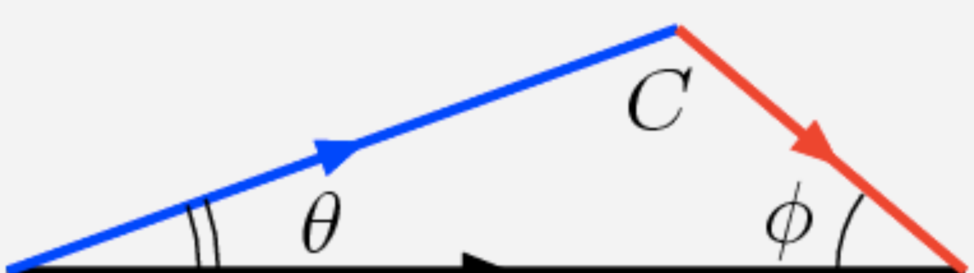
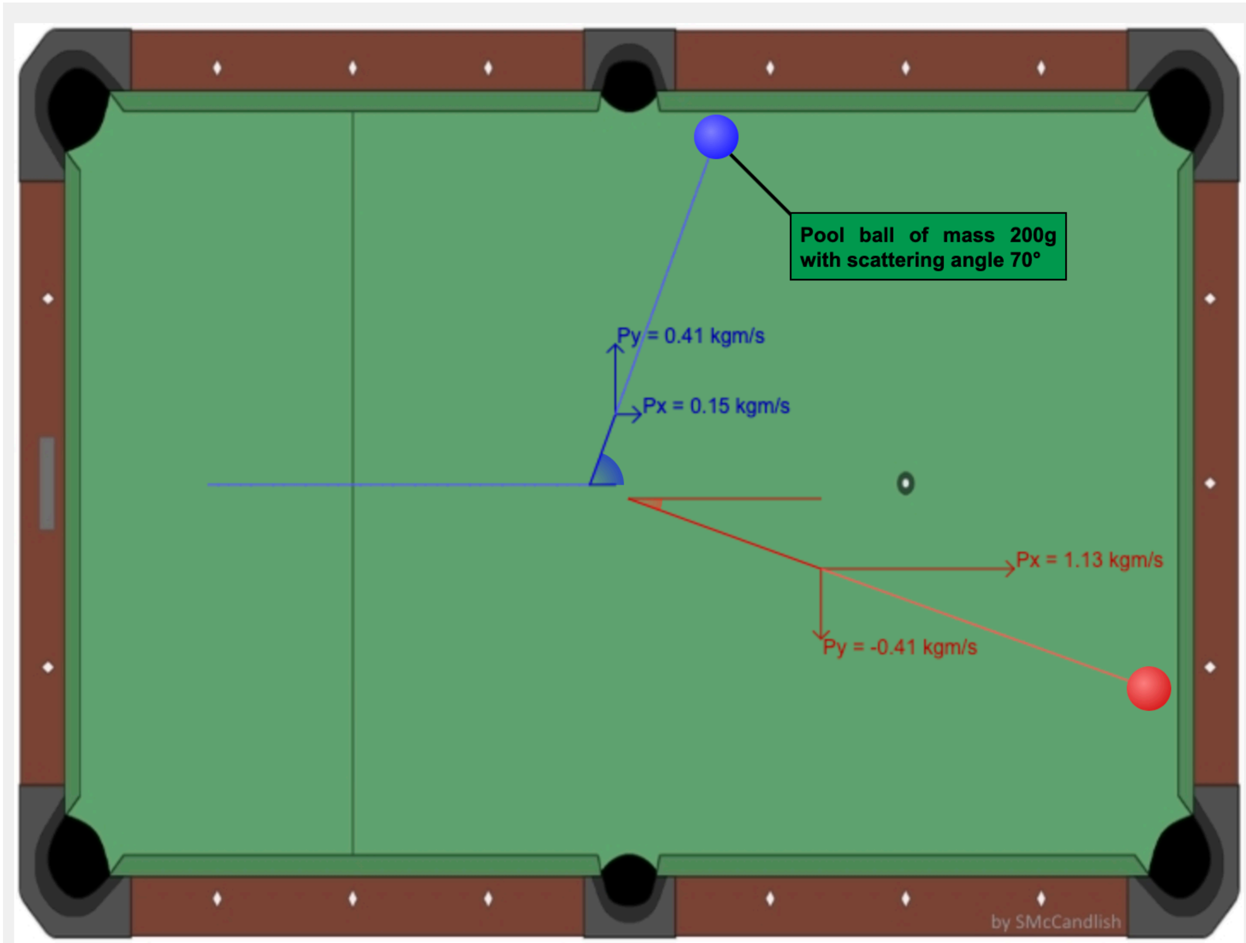
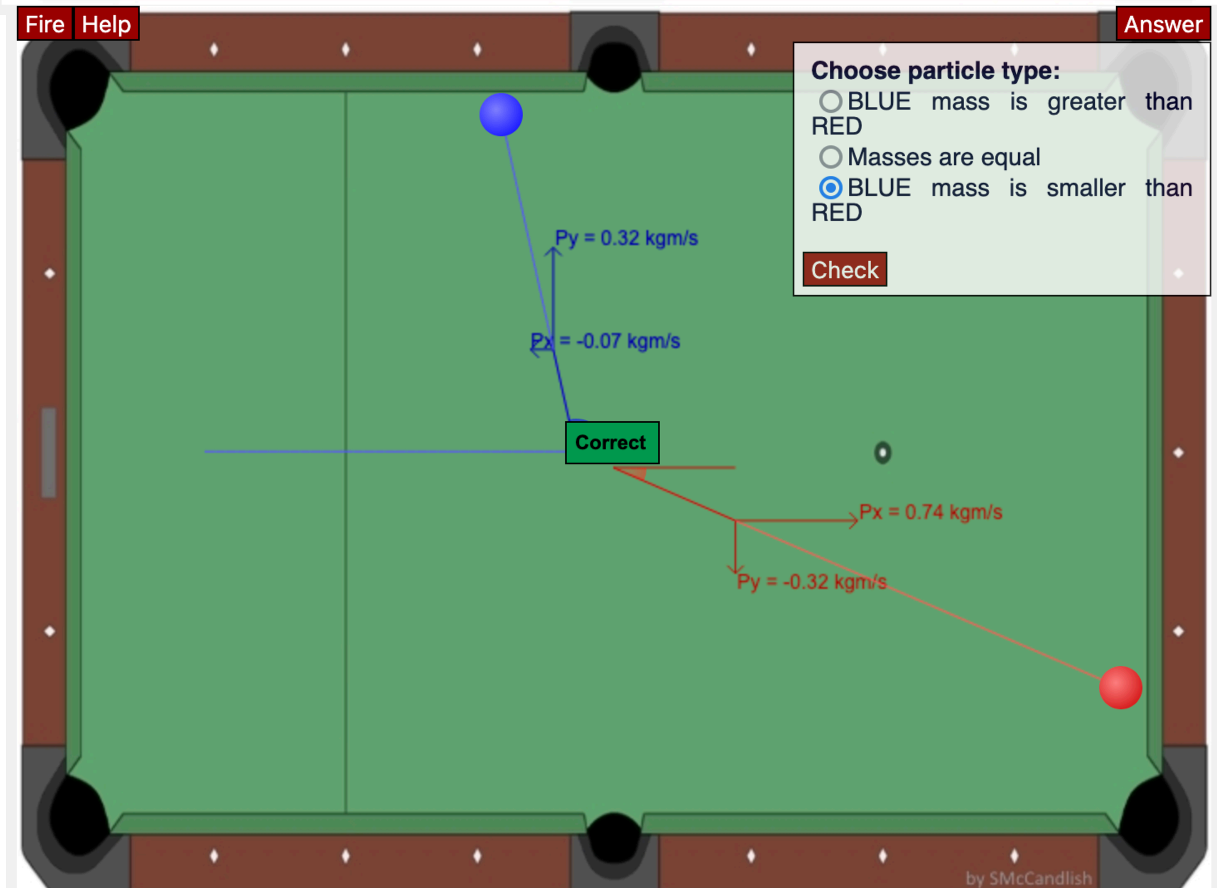






Annihilation

Introduction into relativity

$E^2=m^2+p^2$ + optional other equations

Fixed target vs collider experiment

Suppose you want to make a muon antimuon pair (μ) by colliding and annihilating a positron and an electron. (1)

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

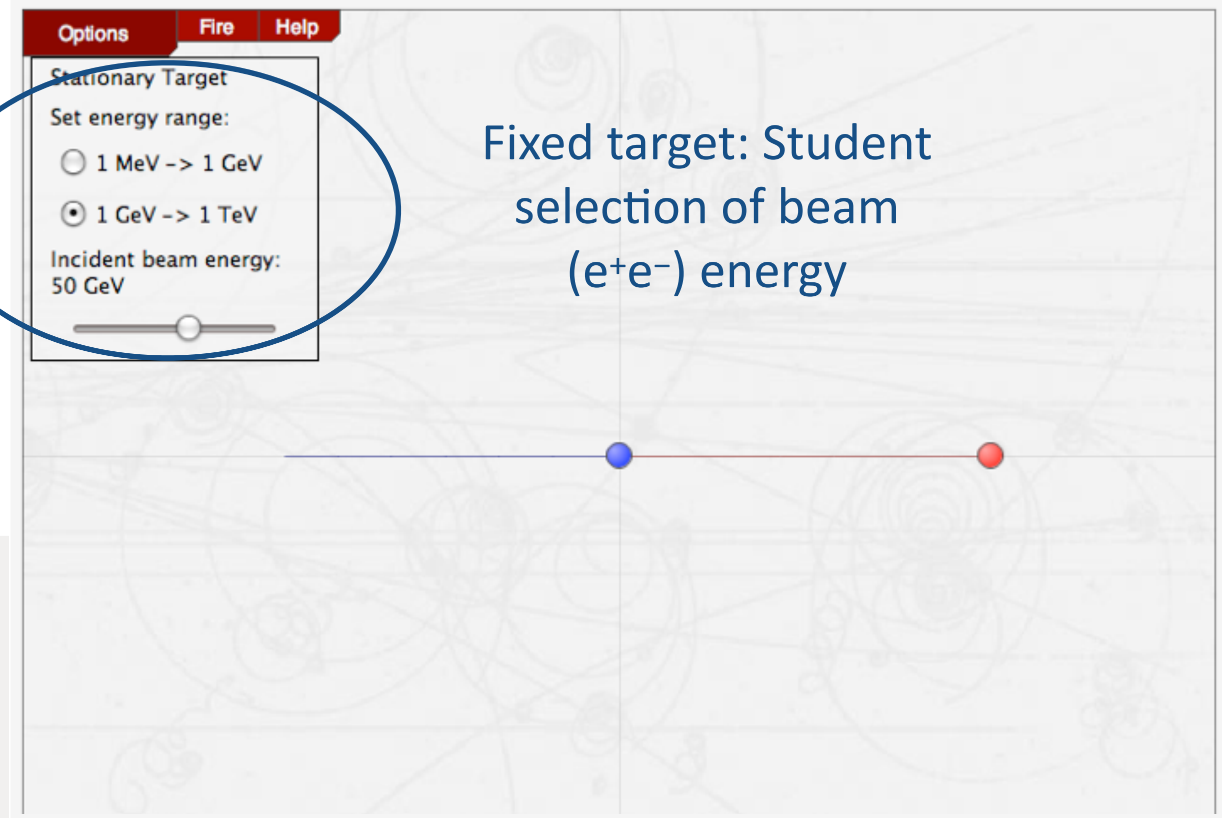
The (muon) μ particles are each about 200 times the mass of an electron, so most of the kinetic energy of the electron and positron must be used to create them.

The positron e^+ could be fired at a stationary electron (in practice the electron would be bound in an atom with kinetic energy of a few eV, which is negligible compared with the high energies involved in Particle Physics).

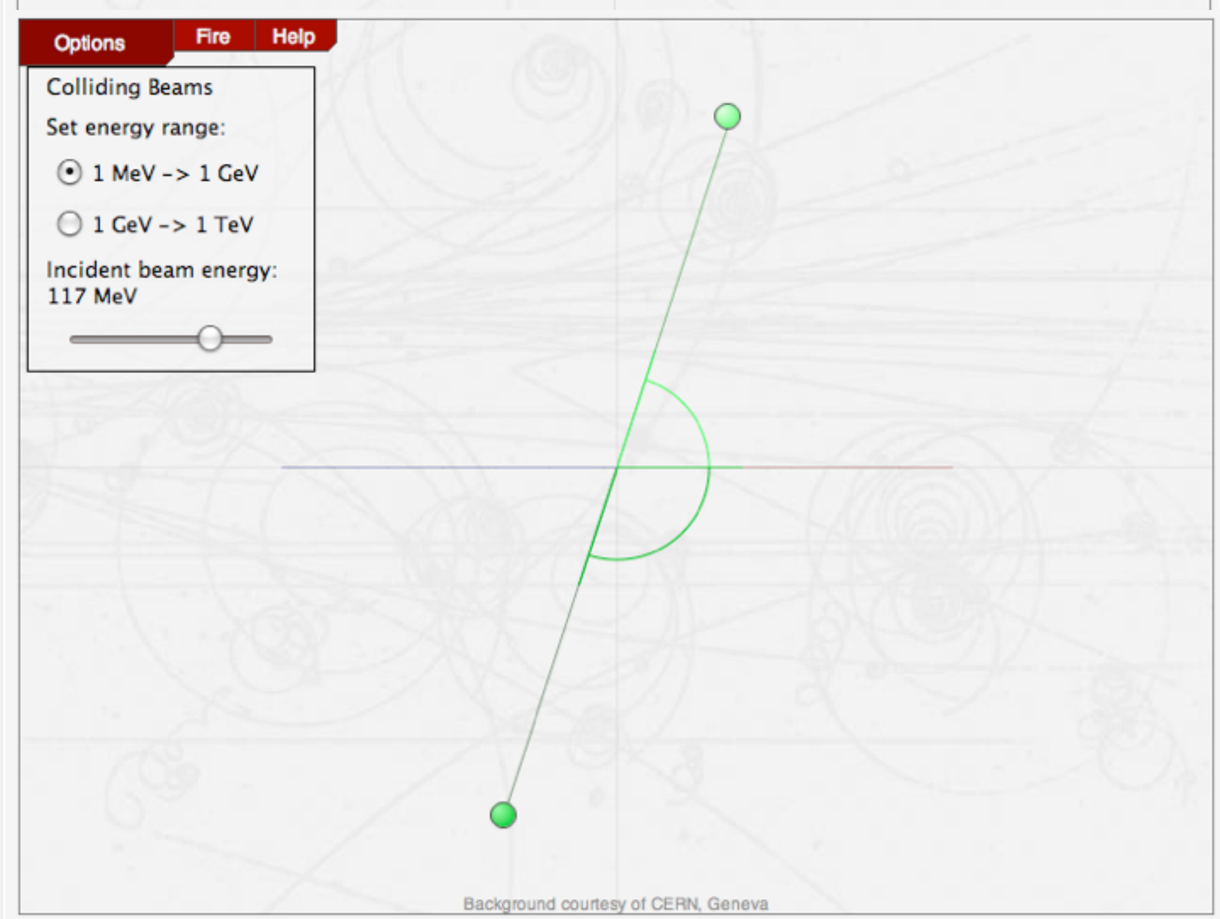
The incident positron (e^+) has momentum p_e and total energy E_e and collides with a stationary electron (e^-) thereby annihilating to produce a 'virtual photon'. The virtual photon materialises into a new e^+ and e^- pair or any other heavier particle antiparticle pair, such as μ^+ and μ^-, provided sufficient energy is available. The μ^+ and μ^- pair must have total momentum equal to p_e in order to conserve momentum in the collision.

Combining the relativistic energy and the momentum conservation equations yields the equation below: (2)

$$E_e = 2\frac{(m_\mu c^2)^2}{m_e c^2} - m_e c^2$$



Fixed target: Student selection of beam (e^+e^-) energy



Magnetic Field

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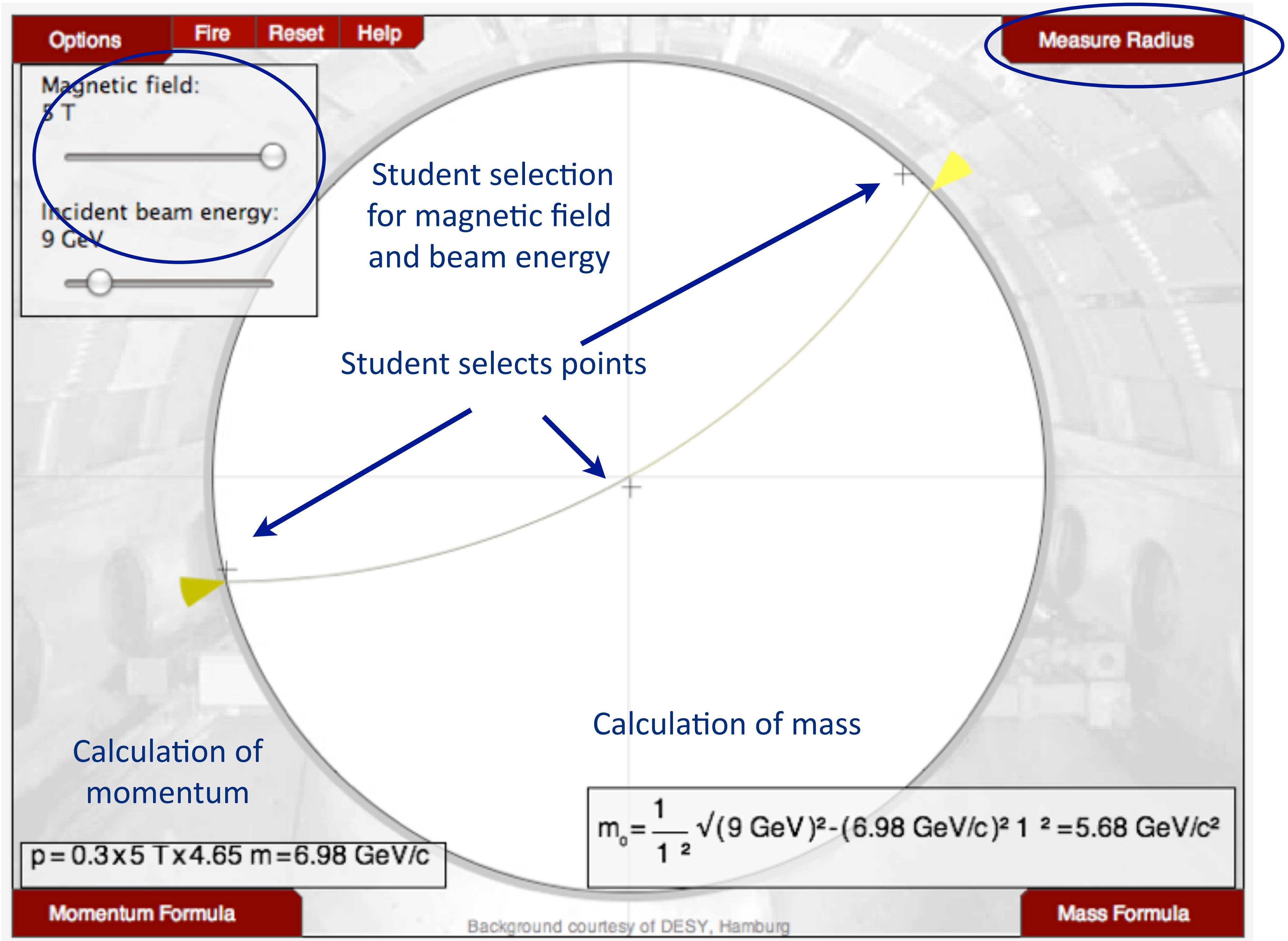
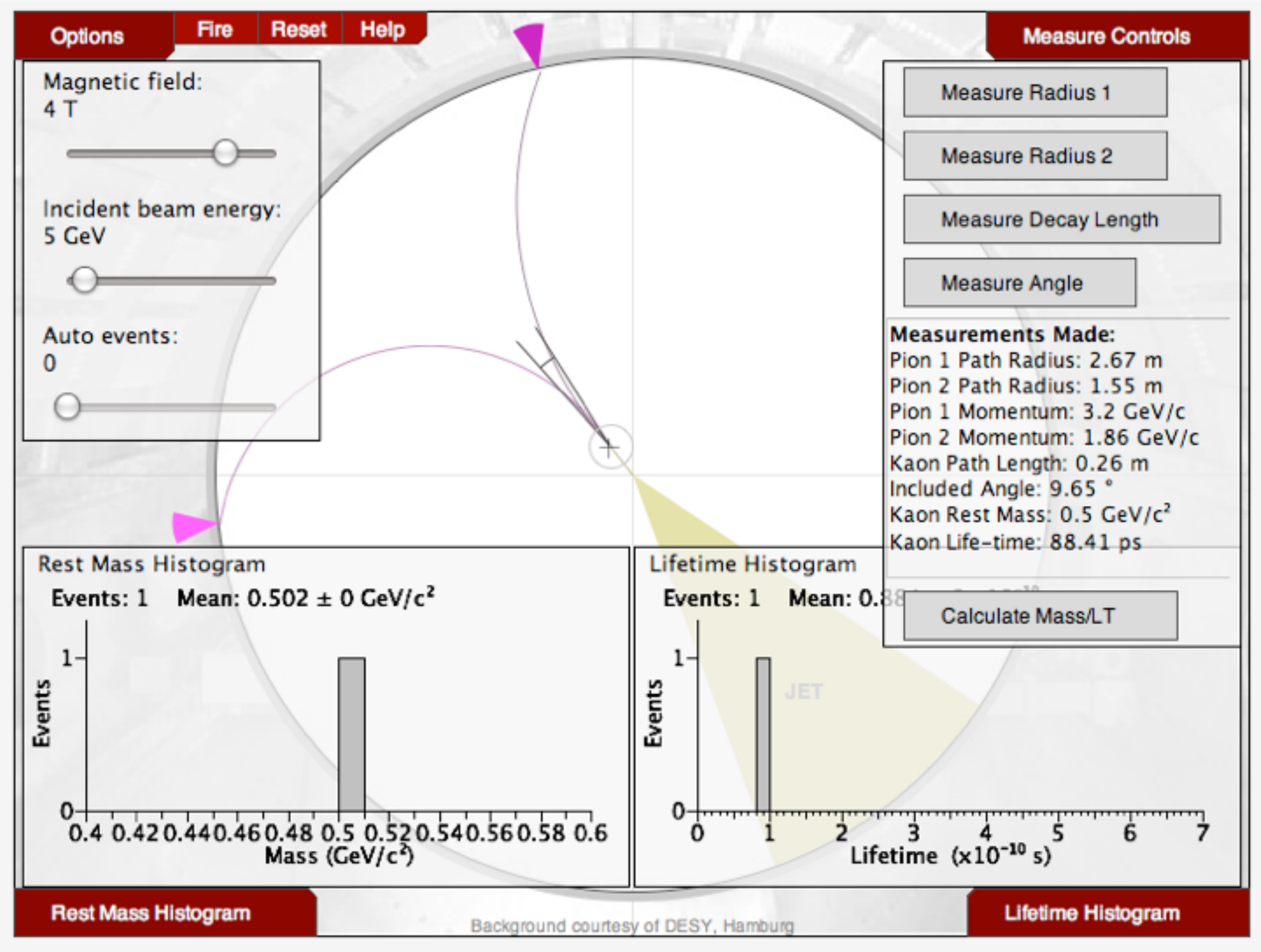
Measurement tool

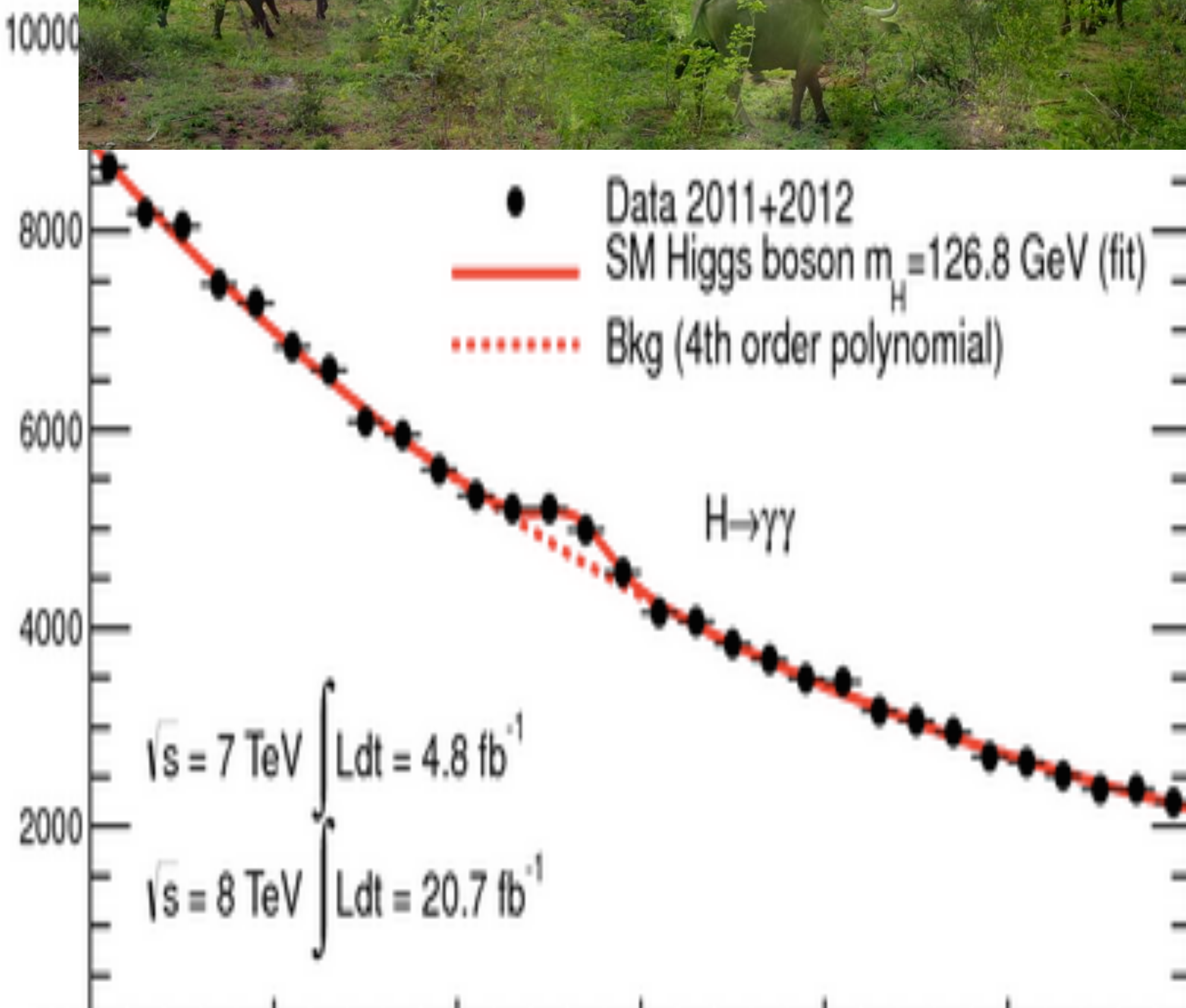


(Skipped for Masterclass)

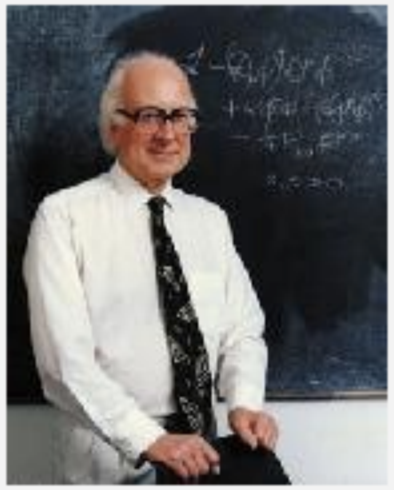
Lifetime Measurement



The Higgs Boson



The Higgs Boson

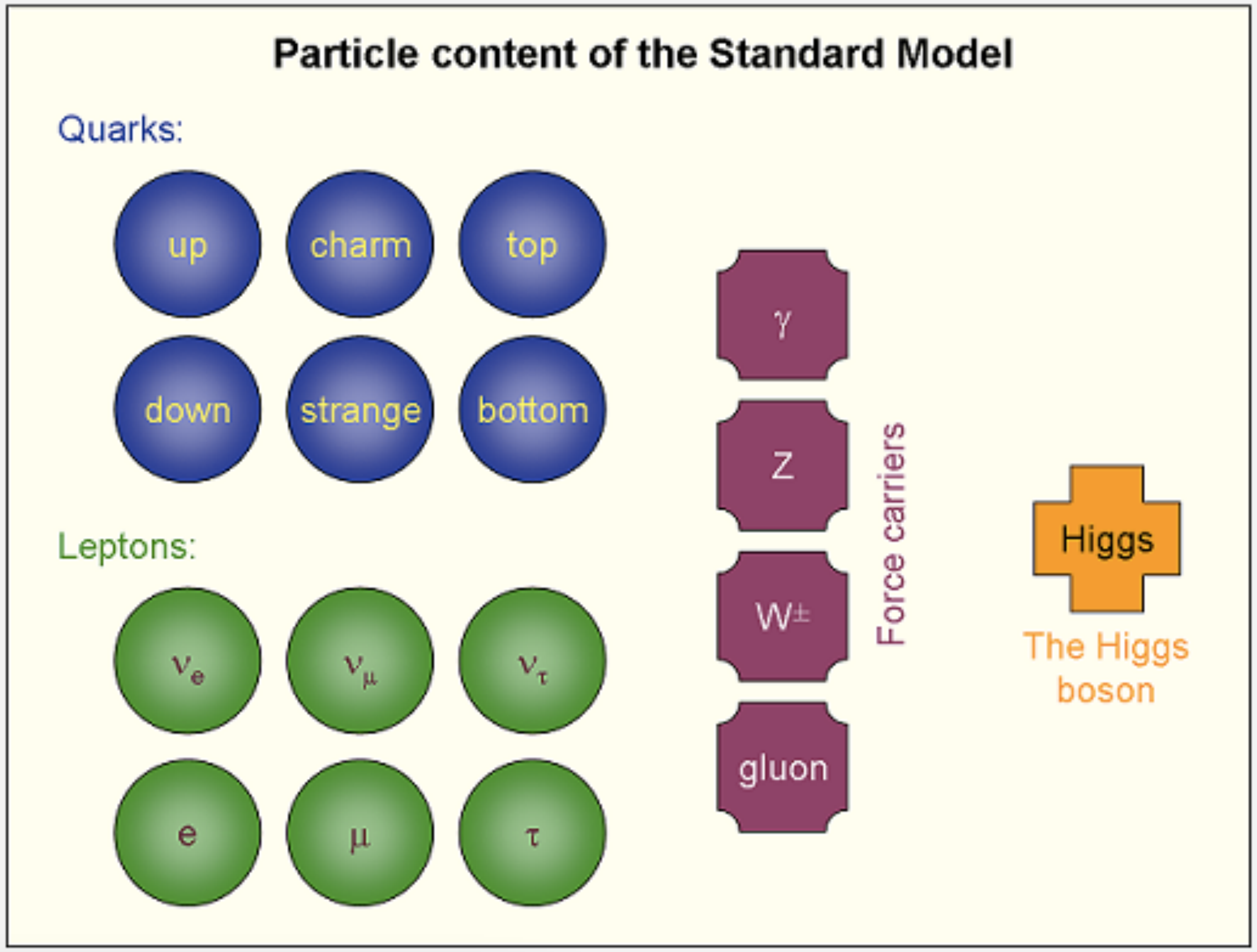


Sir Peter Higgs

The Higgs boson (named after Peter Higgs CH FRS) is predicted by the Standard Model (SM) of particle physics. The SM successfully accounts for the weak, strong and electromagnetic interactions. The need for a particle with the properties of the Higgs arises from the mathematics behind our current understanding of the electroweak forces and in particular the fact that the W and Z bosons, which mediate the weak force, have large masses. The interaction of other standard model particles with the Higgs field is thought to be the origin of the mass of those particles. The discovery of the Higgs boson with the correct properties, the final step, marks the triumph of the standard model as the theory which united the weak, strong and electromagnetic forces (but no gravitational force as of yet).

The Standard Model of particle physics is at present our best theory for explaining how the universe works on a fundamental level. It describes the interactions of the fundamental particles via three of the four fundamental forces.

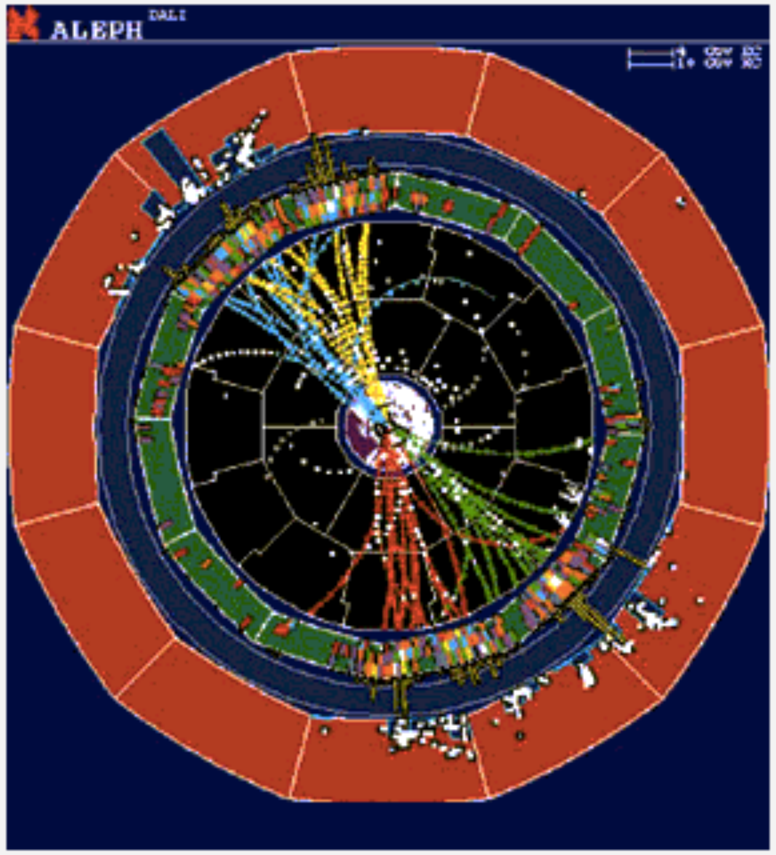
The particles are divided into two groups, *bosons* and *fermions*. The fermions (spin-half particles) are "matter" particles which make up the elements around us, and are further divided into *quarks* and *leptons*. The quarks are the constituents of hadrons, such as the proton and neutron, whilst the electron is an example of a lepton. The bosons are sometimes referred to as the "force carriers" and are responsible for the forces between particles. A force carrier is exchanged between two particles, transferring momentum and causing an interaction. The final particle is the Higgs boson, which is intimately linked to why particles have mass. See the chart below for a summary of these particles.



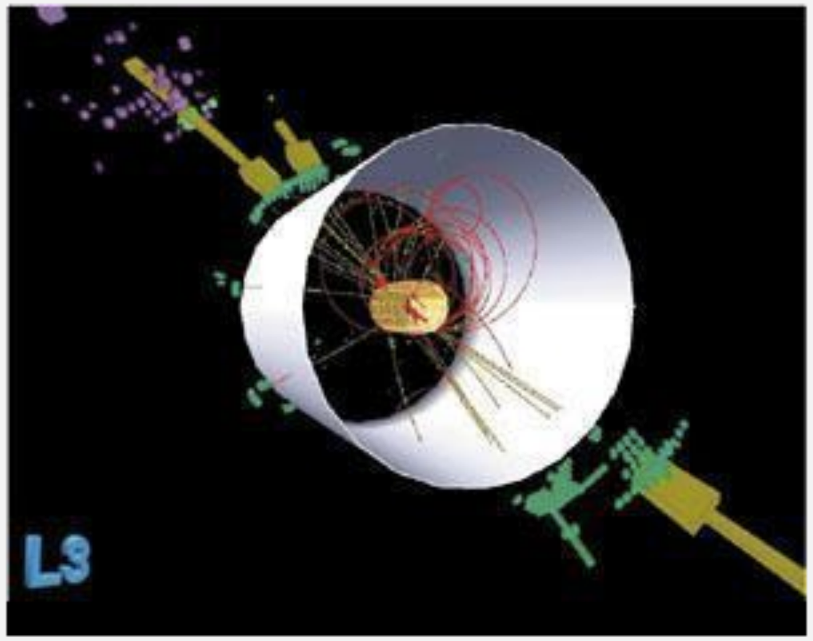
The Higgs Boson

Previous experiments provided a lower limit to the possible mass of the Higgs. It is not possible to compute the mass of the Higgs particle directly from theory. However, from precision measurements of the properties of other SM particles made at CERN, Fermilab SLAC and some other centres, it was possible to work backwards to a range of values for the Higgs mass. The LEP was able to test the possible Higgs mass range up to 114 GeV and the current consensus is that no convincing evidence for the existence of the Higgs particle was found below this energy, though several events were produced which could, possibly, be due to Higgs particle production and decay.

The event on the right, from the ALEPH detector, shows the decay of a candidate Higgs particle into four emerging sprays ("jets") of particles. The red/yellow pair and the blue/green pair emerge back to back, suggesting the production of a Higgs and a Z boson (for more information on this particular decay, see the Branching Ratios module). The image below shows a view of a candidate Higgs event from the L3 experiment. Some of the energy is dissipated as neutrinos and is therefore not visible.



Higgs candidate. ALEPH experiment CERN



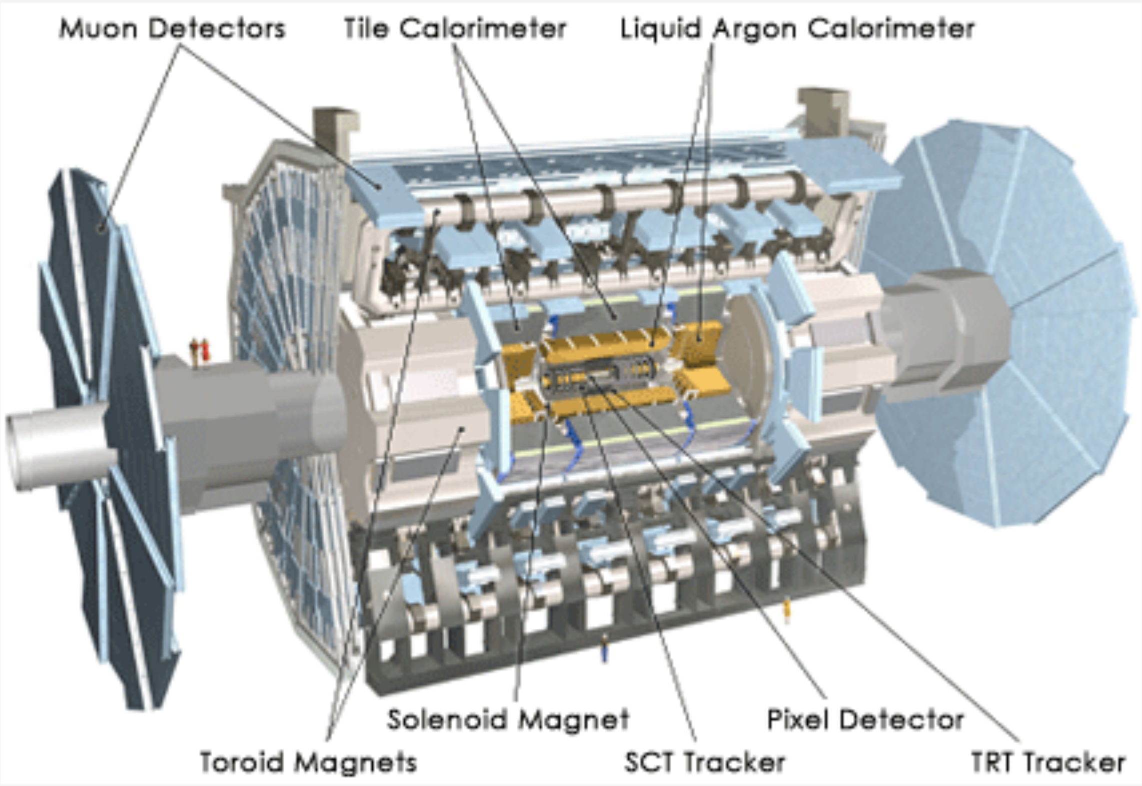
Higgs candidate. L3 experiment CERN

Current measurements would place the mass of the Higgs particle at ~125.09 ± 0.21(stat.) ± 0.11(syst.) GeV (according to a combined analysis from ATLAS and CMS in 2015, found here). This is beyond the maximum energy which the LEP was able to test (approximately 114 GeV) and required the LHC experiments to be able to test with statistically significant accuracy.

For a Higgs particle at this energy, one of the most efficient ways to detect it is by looking for the decay of the Higgs into two high energy photons (gamma rays) rays ($H \to \gamma\gamma$). This gives a distinct signature in the detector chambers which can be used to identify the Higgs boson with little background interfering.

+ Understanding Feynman diagrams

The Higgs Boson



ATLAS detector schematic

The LHC generates about 1 billion collisions per second just within the ATLAS detector. The collision sites are surrounded by vast arrays of detectors which map the 3-D structure of the debris arising from these events. From the billions of events a small group of about 200 events per second will be selected, by computer, which bear the signature of various interesting patterns, including the possible decay routes of the Higgs boson. This process is known as triggering. The current software for the LHC has in excess of 500 different triggers corresponding to various processes of interest. For more information, click here.

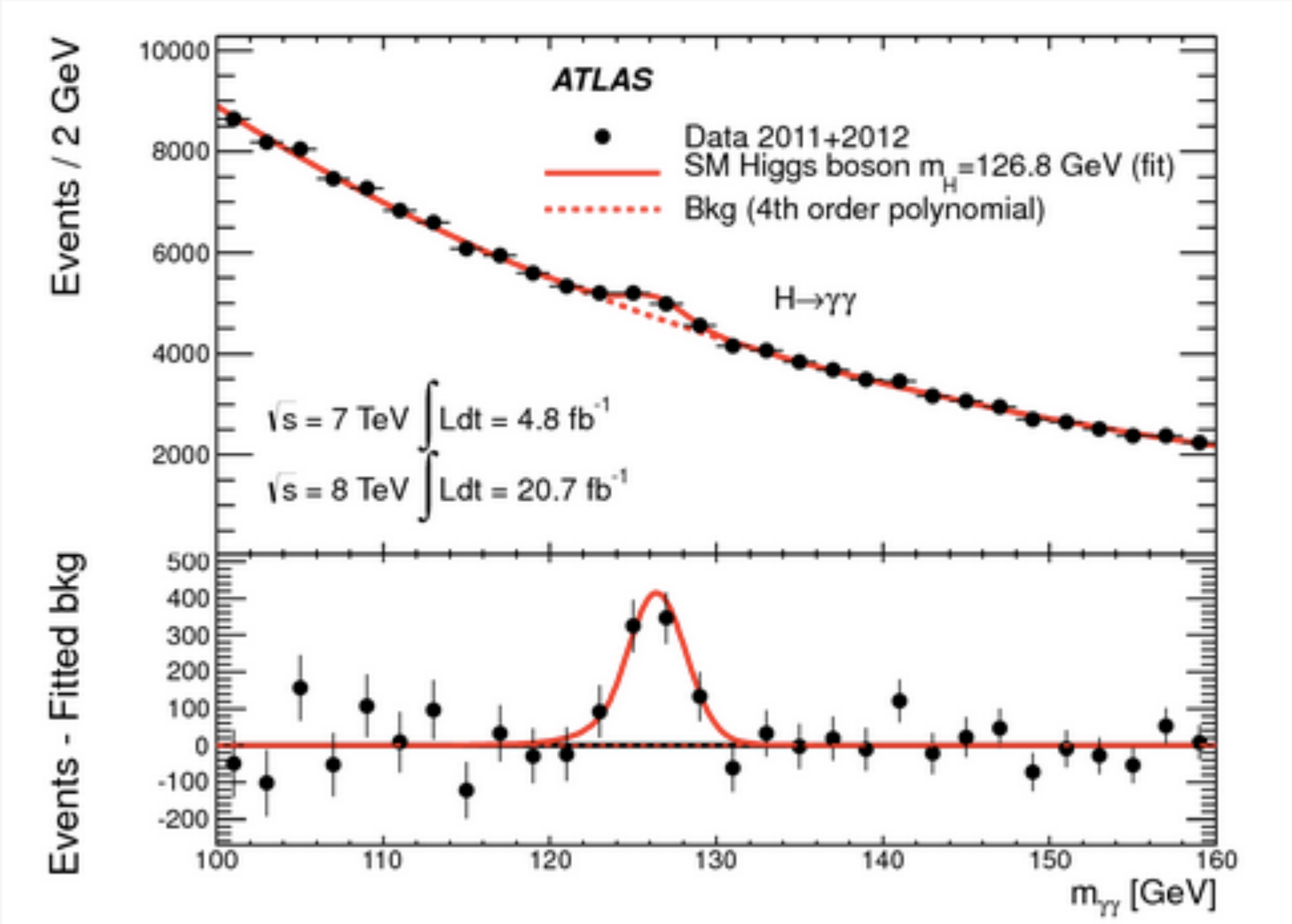
+ ATLAS Detector Details

The Higgs boson decays by several pathways. One route predicts decay into two very high energy gamma rays ($H \rightarrow \gamma\gamma$) which should leave an easily recognizable signature in the **detector**. The gamma rays would not leave a track in the central detectors but would deposit all their energy in two regions of the surrounding electromagnetic calorimeters (ECALs). Electrons and positrons also deposit their energy in the ECALs but they leave tracks in the inner detector. Other particles, such as pions and muons, will leave traces in the ECALs and in other detectors beyond the ECALs.

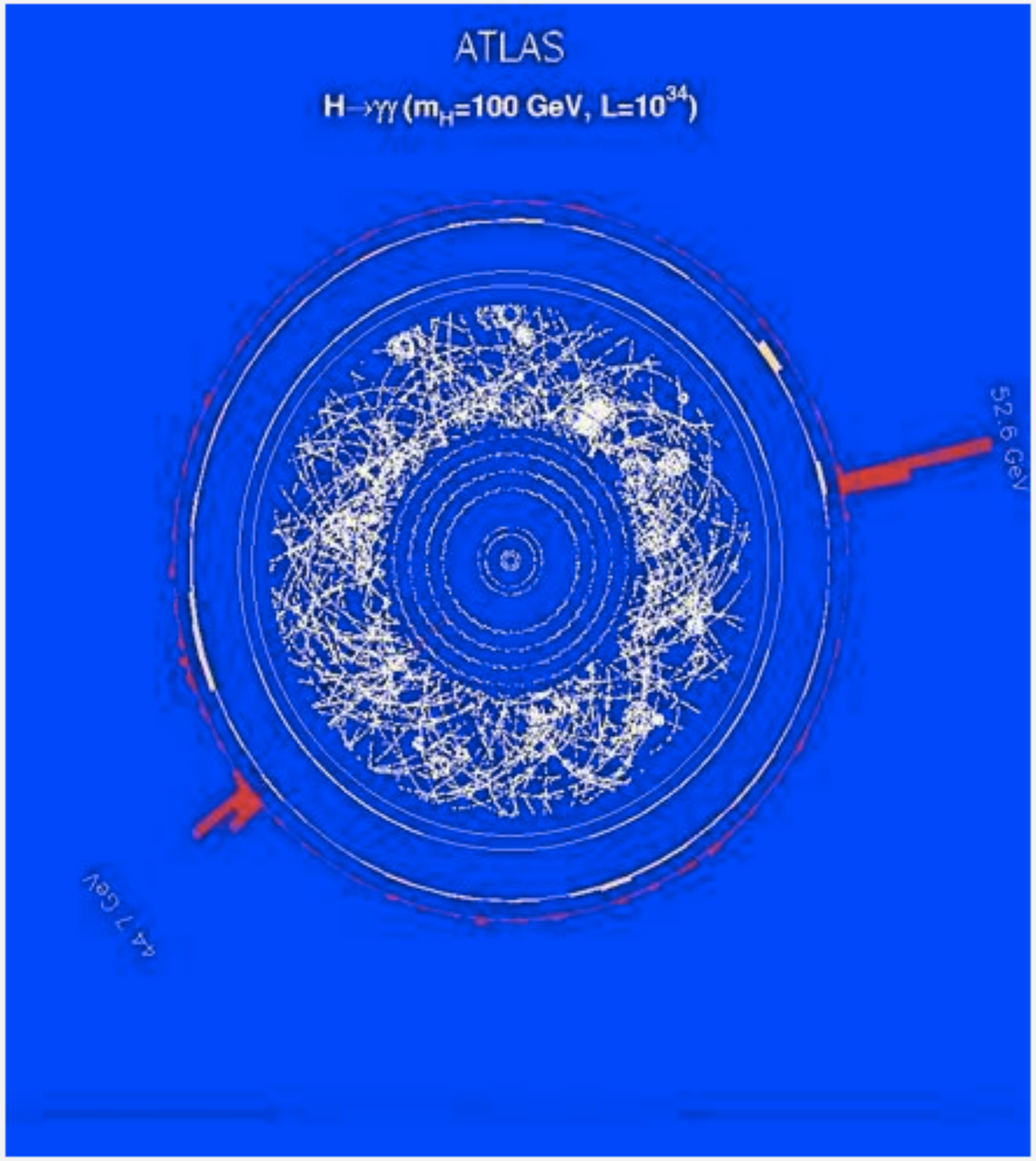
The Higgs Boson

The signature of a H→γγ decay then is exactly two energy deposits in the ECAL coming from particles which leave no tracks in the inner chamber and are completely stopped by the ECAL. The adjacent image shows a computer simulation of such an event. The energy of the photons is shown as red "towers" at the location on the electromagnetic calorimeter where the photon hits the detector. This view of the data is an end view of the detector along the beam line.

Higgs researchers will receive only the most promising events from the billions that occur each second. Many of these candidate events will contain photons from other sources. Pairs of such photons will have a wide range of masses and give a smooth continuous distribution of events above and below the Higgs mass. True Higgs events will have the two-photon invariant mass in a narrow range of masses. If sufficient candidate events can be collected then a visible Higgs peak should emerge above the background.

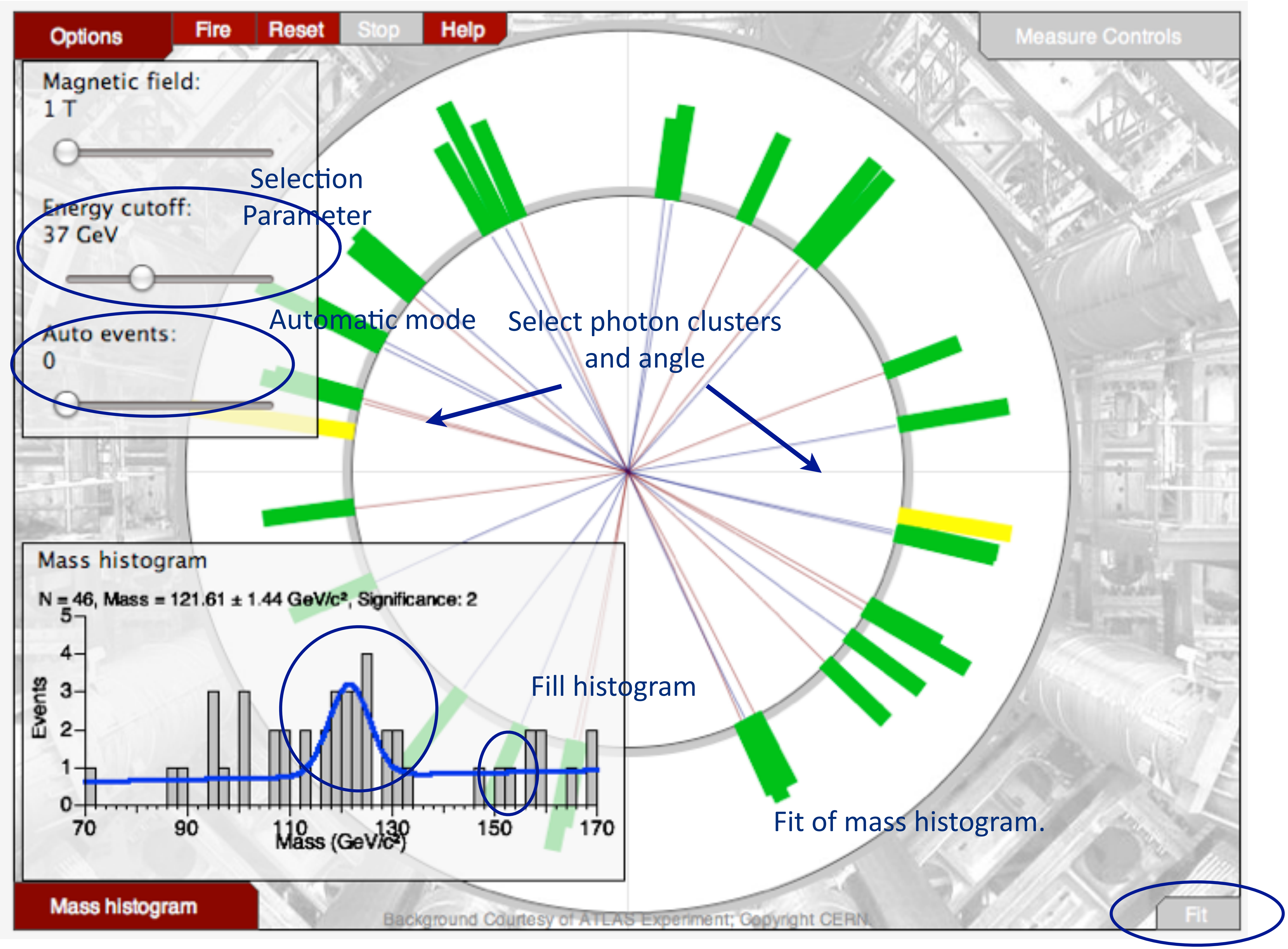


The discovery plot showing the statistically significant peak at a mass of 126.8 GeV (from 2012, for more information click here).

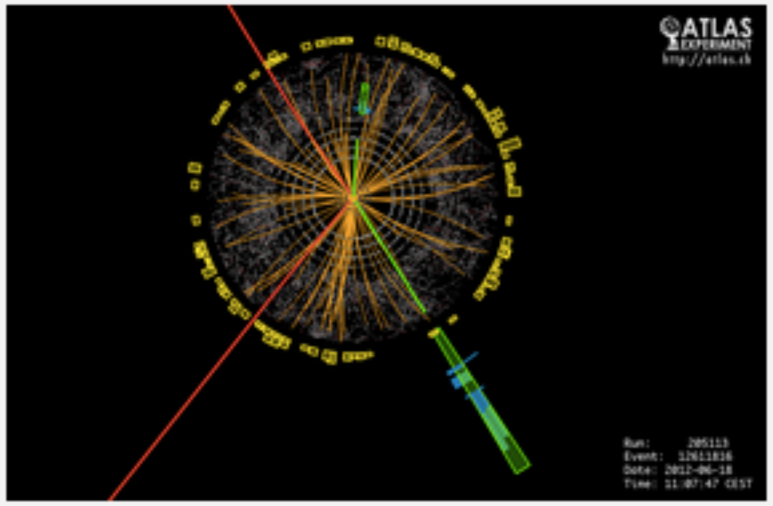


Computer simulation of a Higgs decay in the ATLAS detector

The Higgs Boson



Higgs Branching Ratio



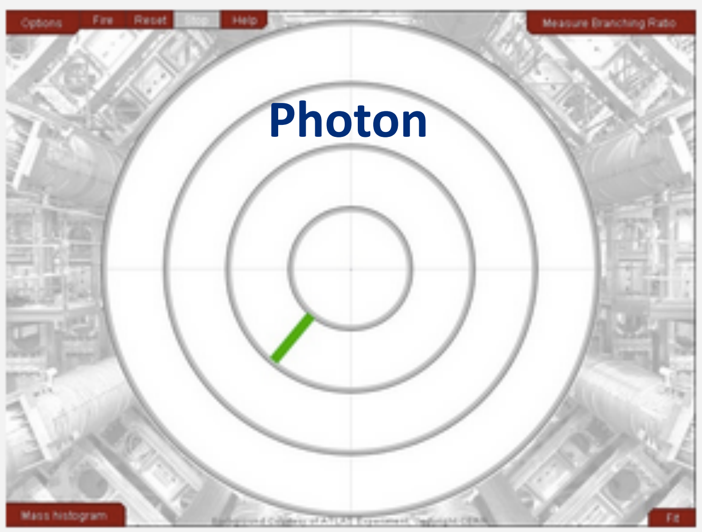
A Higgs boson being detected by the ATLAS detctor

What to look for?

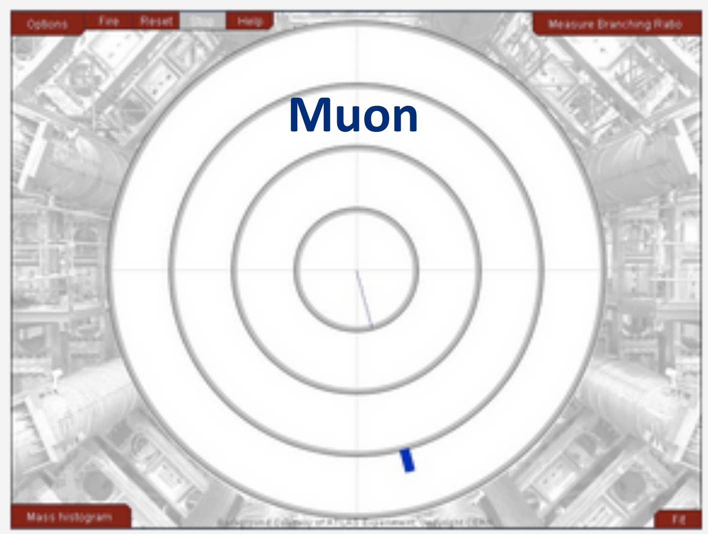
The Higgs Boson has four main decay channels:

- $H \rightarrow \gamma\gamma$ (Higgs boson to two photons 0.0229%)
- $H \rightarrow ZZ \rightarrow llll$ (Higgs boson to two Z bosons to four leptons 0.0131%)
- $H \rightarrow b\,\bar{b}$ (Higgs boson to a b-quark and anti-b-quark 56.9%)
- $H \rightarrow \tau\,\tau$ (Higgs to a tau lepton and an anti-tau lepton 6.28%)

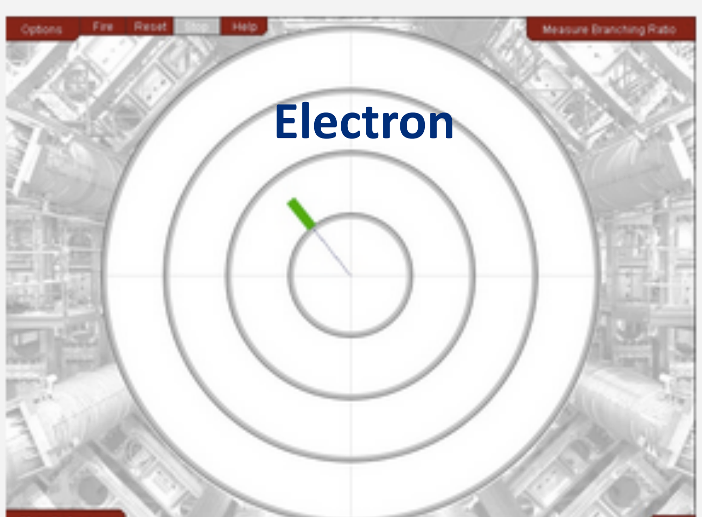
Reference: https://twiki.cern.ch/twiki/bin/view/LHCPhysics /CERNYellowReportPageBR#Higgs _2_gauge_bosons



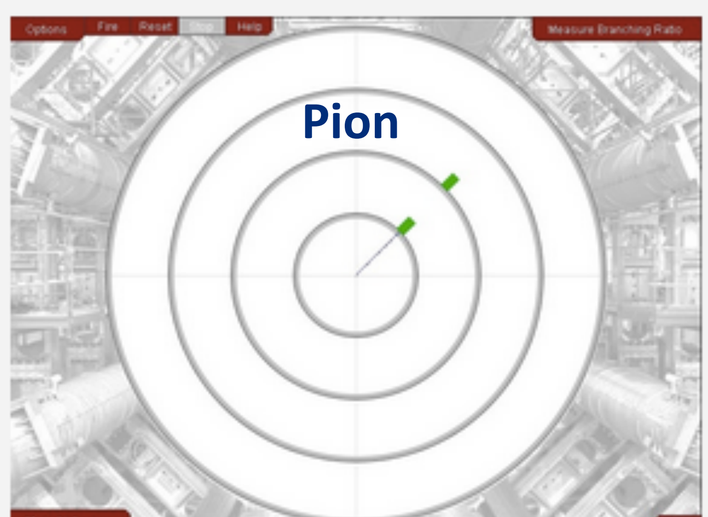
A photon being detected.



A muon being detected.



An electron being detected.



A pion being detected.

Particle ID

Higgs Branching Ratio

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The Photon

Identifying a Photon is one of the easier particles to identify as a Photon will only leave energy in the ECAL (the electromagnetic calorimeter, or in this case, the first ring). This is the nicest way to seperate them as only electrons and photons will leave energy only within the ECAL (pions deposit some energy in the ECAL and HCAL). To seperate a photon from an electron, look for a tower of energy that has no track. Neutral particles do not interact with the tracking chamber, the inner most part of the detector. Since the photon is neutral, it shall leave no track.

The Electron

The electron will interact with the tracking chamber and the ECAL (first ring) only. Therefore, to identify an electron, you are looking for a tower within the ECAL that has a track from the centre where the decay occured. Since electrons are charged they do interact with the tracking chamber, unlike photons.

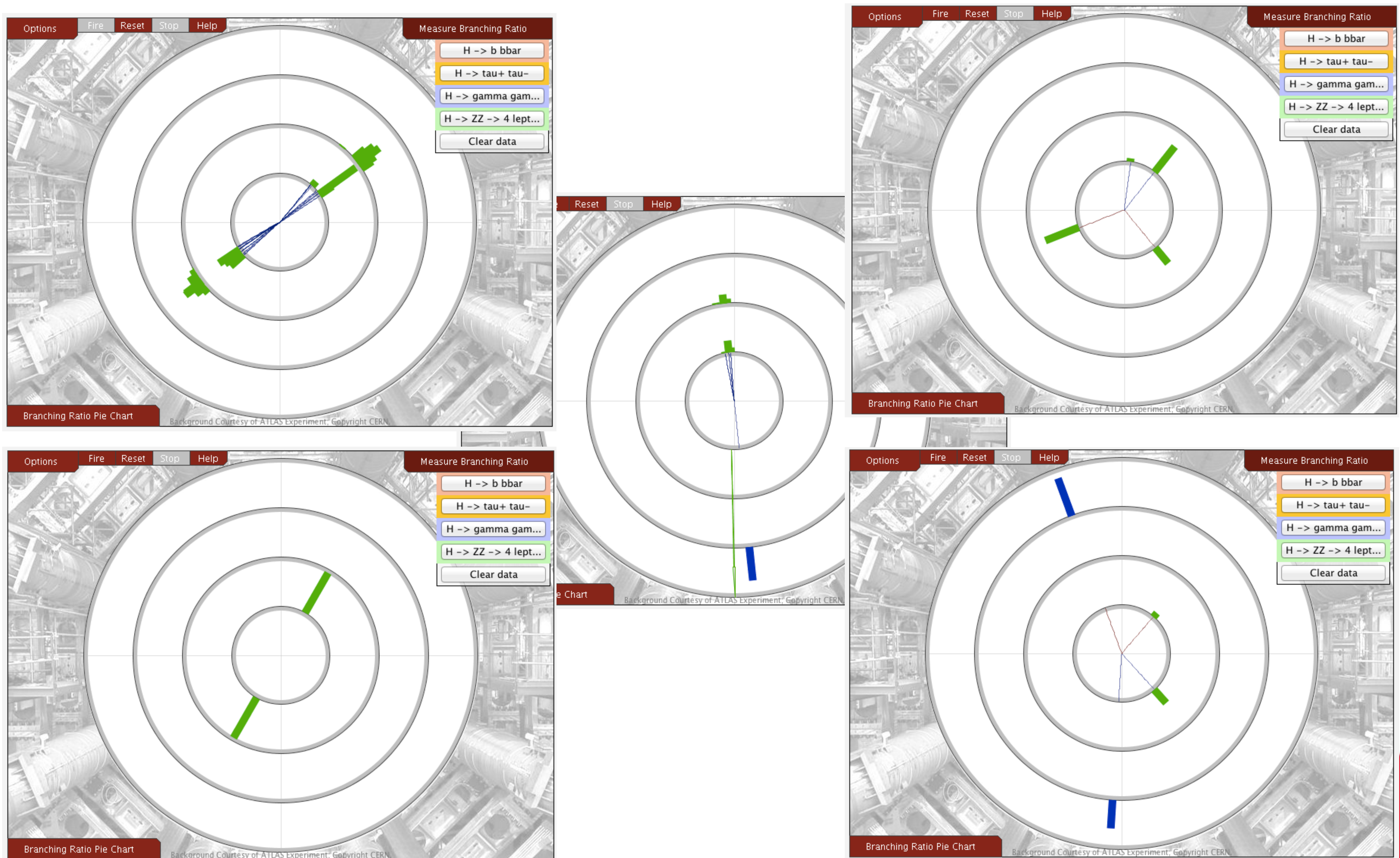
The Pion

Pions are different to electrons and photons because they interact with both the ECAL and the HCAL (Hadronic Calorimetre which is teh second ring) and so will have energy deposited in both the electromagnetic calorimeter and the hadronic calorimeter. Their tell-tale signature is two energy towers and if the pion is charged, it shall have a track. However, pions can be positive, negative and neutral resulting in them not always leaving a track.

The Muon

Muons barely interact with most of the detector and so have a special apparatus added to the outside of the detector called the Muon Spectrometre. This ring is on the outside to avoid interference with other particles. This special apparatus makes muons simpler to identify as only muons will interact with the outer most ring, as well as the tracking chamber on the inside. To highlight this, they are also shown in blue.

Higgs Branching Ratio



Higgs Branching Ratio

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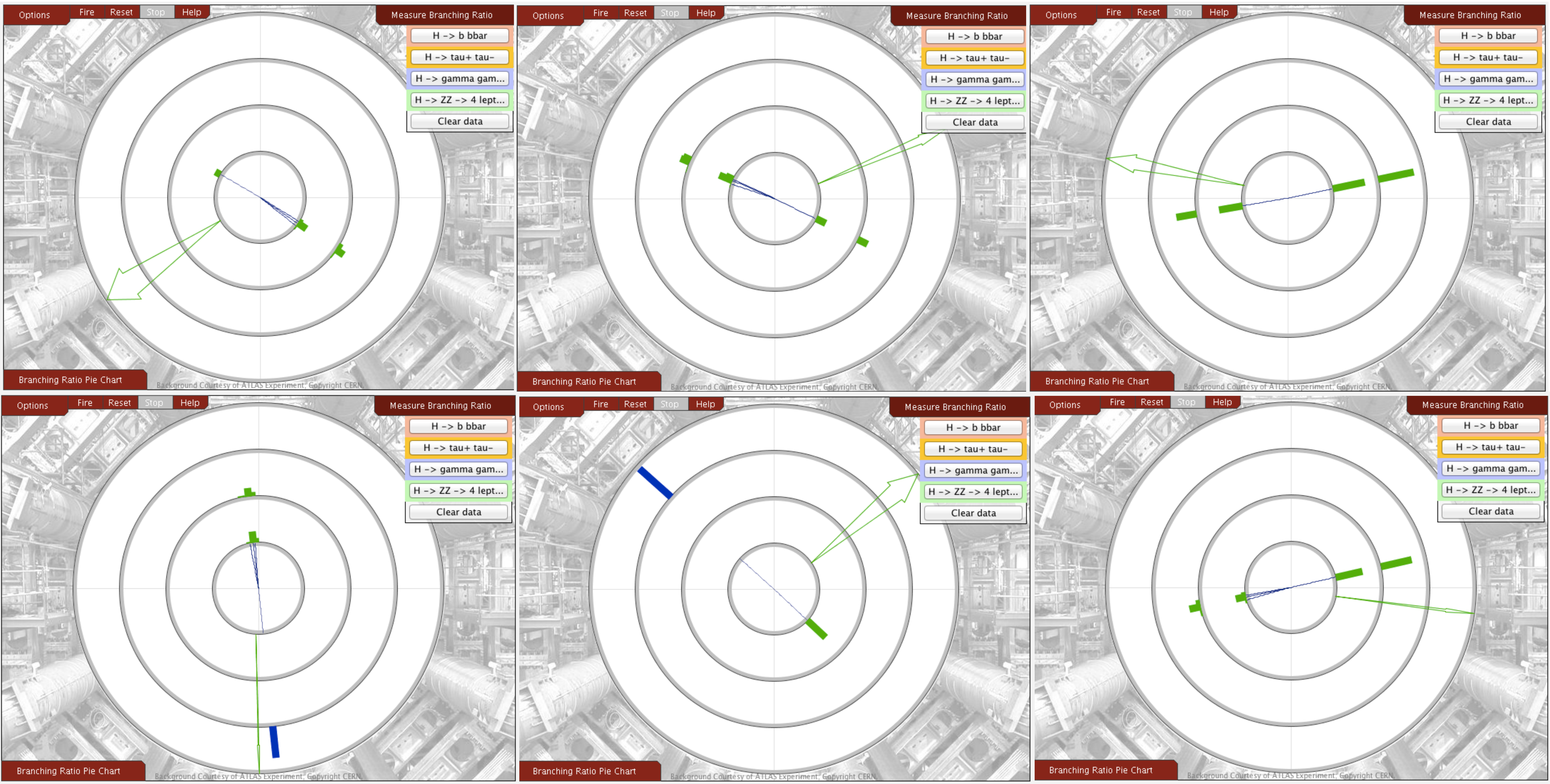
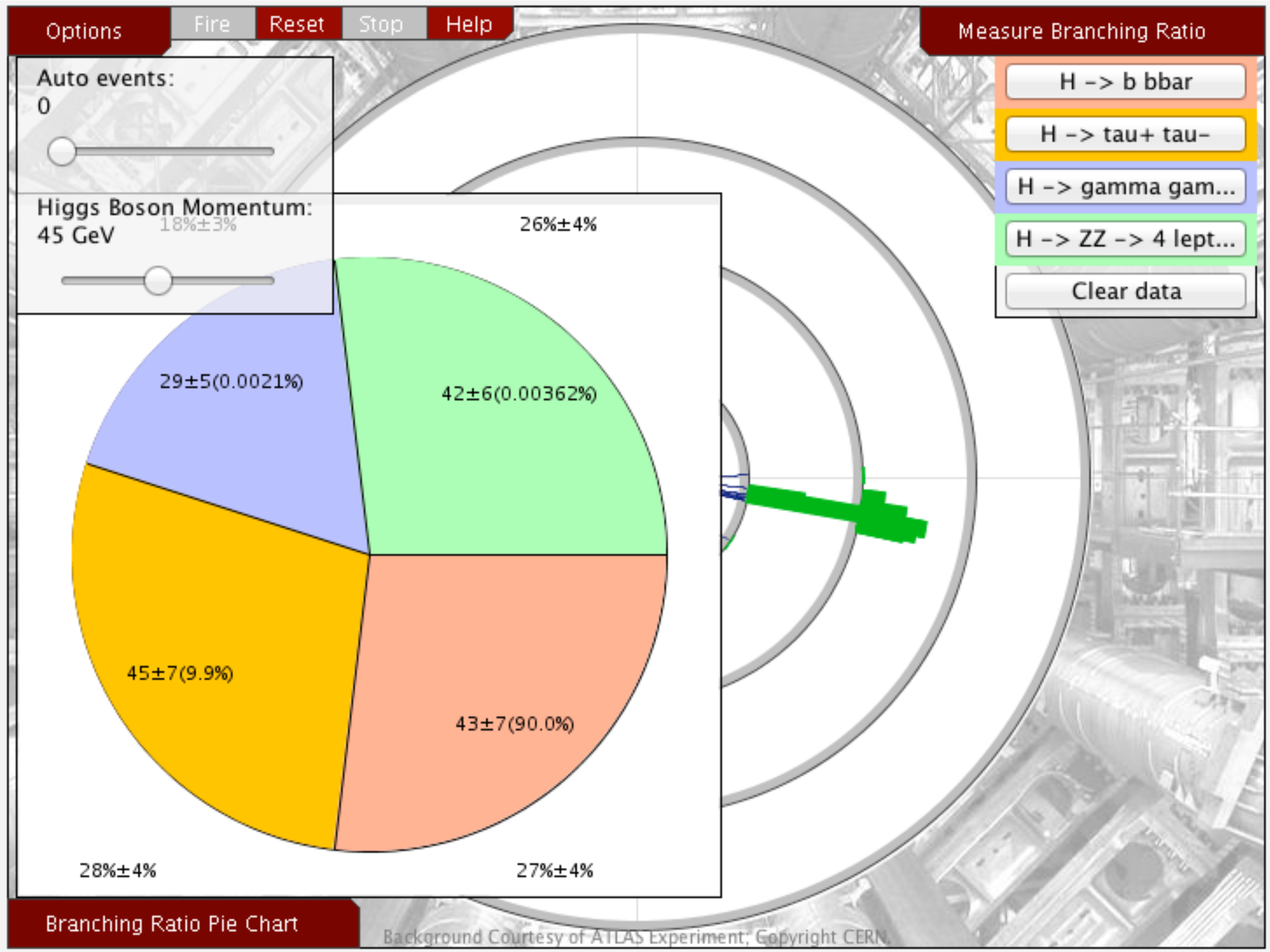


Higgs Branching Ratio



Mexican Hat Potential

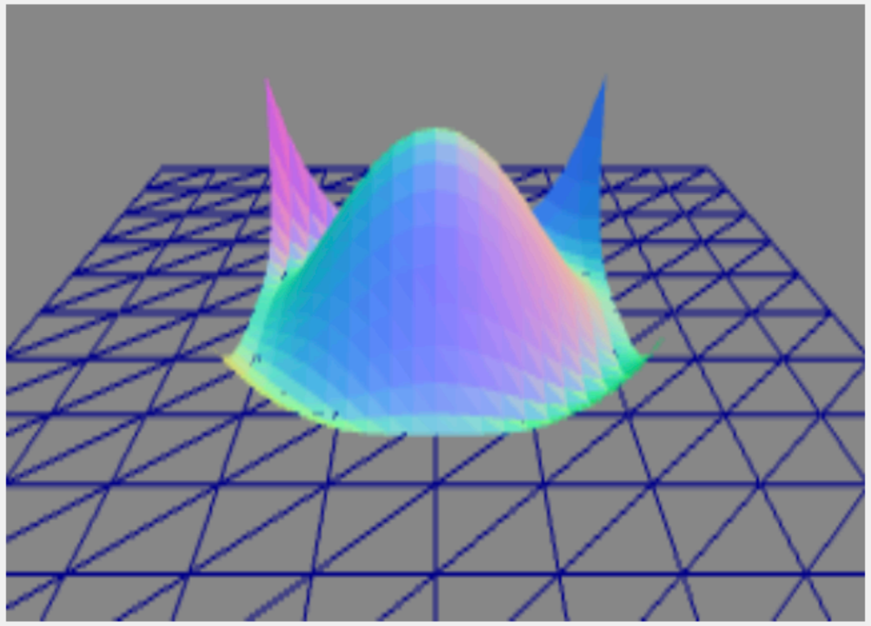
A bit of theory and let students play with the parameters:

$M_H = \sqrt{2\lambda v^2}$

μ^2 = -5892.86

λ = 0.11

Reset Camera | Reset Values | Drag and Scroll to move the camera.



State of the Universe

Vacuum expectation value: 231.46 GeV

Mass of Higgs Boson: 108.56 GeV

Neutrino Mixing

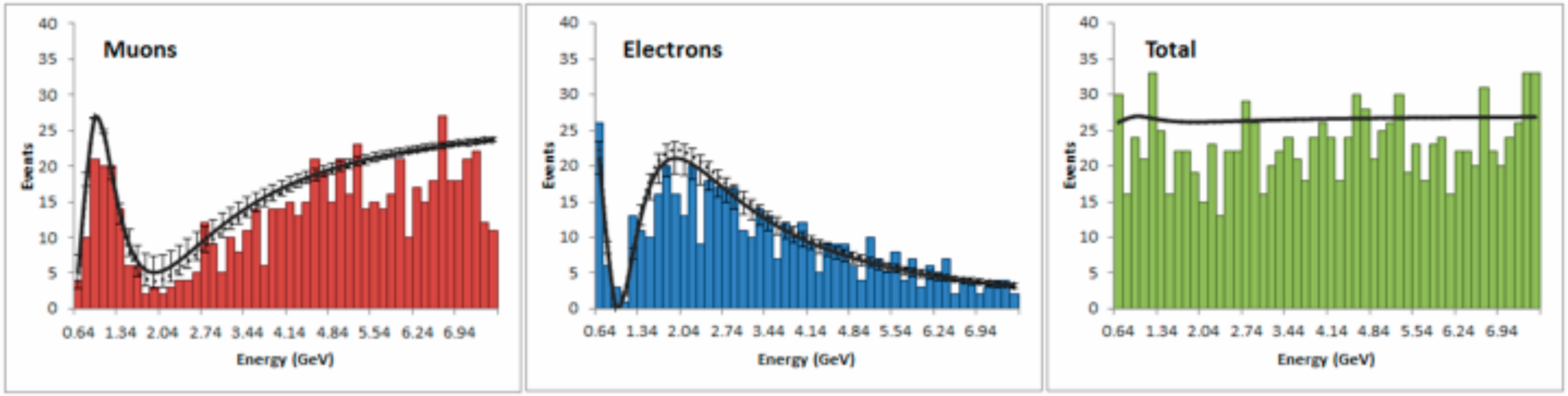
$$P_{e\to\mu} = sin^2 2\theta_{12} \sin^2\left(1.267\,\frac{\Delta m_{21}{}^2 L}{E}\,\frac{GeV}{eV^2 km}\right)$$

The neutrino mixing formula

In this formula, $P_{e\to\mu}$ is the probability that an electron neutrino will mix to a muon neutrino, θ_{12} is the mixing angle, Δm_{21} is the mass difference between a muon neutrino and an electron neutrino in eV, L is the length of the detector in km and E is the energy of the neutrino in GeV.

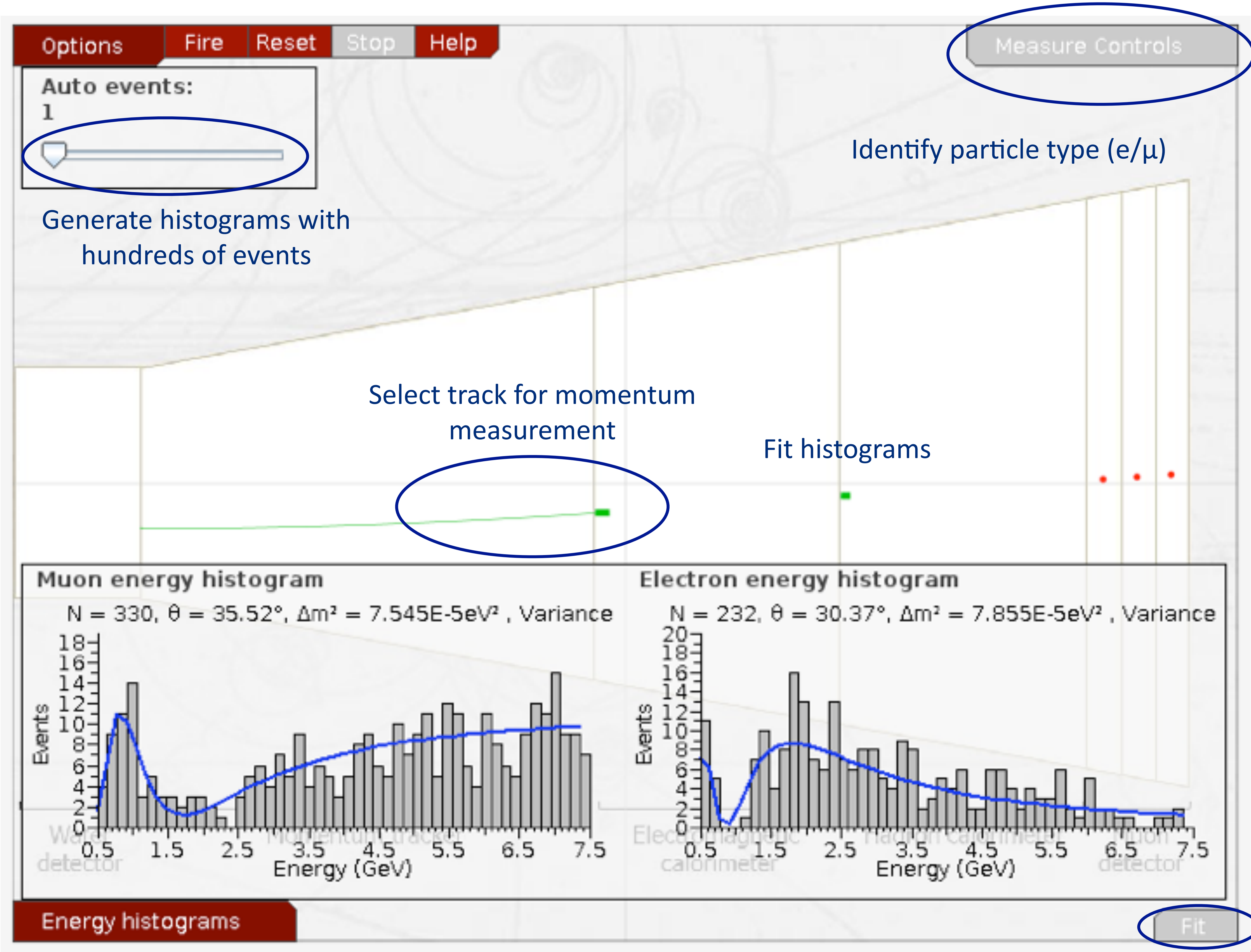
To generate the fit we vary the mixing angle, θ_{12} and the mass difference, Δm_{21} until we find the minimal value of chi squared and thus the best possible fit for the data.

We started with a uniform energy distribution of muon neutrinos but in the muon histogram (red bars) below part of the muon energy spectrum is 'missing'. The missing muons correspond with the appearance of electrons in the electrons histogram (blue bars). This is characteristic evidence of neutrino mixing. Adding the muon and electron histograms together (green bars) gives back the uniform energy spectrum we would expect if neutrino mixing had never occurred.



Histograms and fitting curves

Neutrino Mixing



Usage Statistics

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Analysing the statistics is still in its infancy.

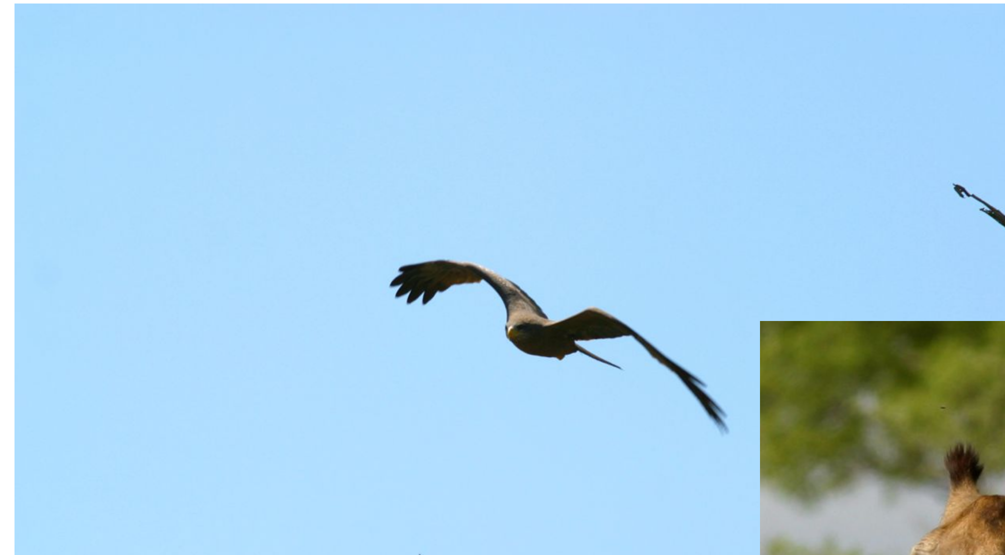
A 2½ month snapshot some time ago (might include automatic crawlers):

Main page	3012
Pool	2672
Higgs main page	3250
Higgs Measurement	1105
Neutrino theory	1123

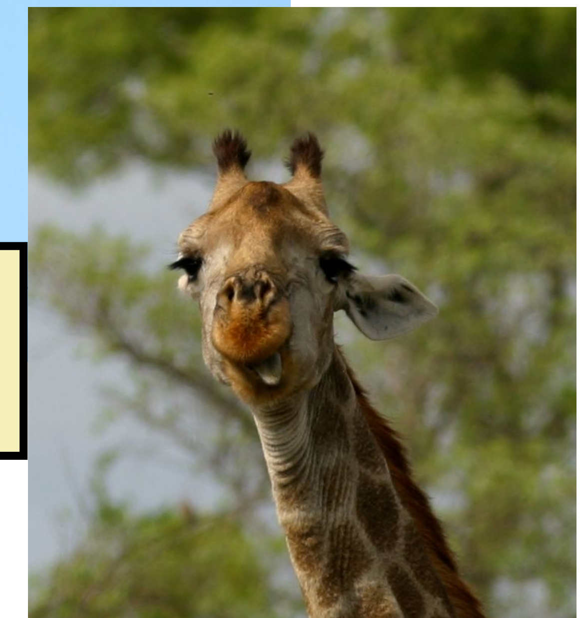
US	609
UK	519
CN	197
IN	119 …
ZA	27

You win some - you loose some

The best part of the Masterclass
is consistently the quiz

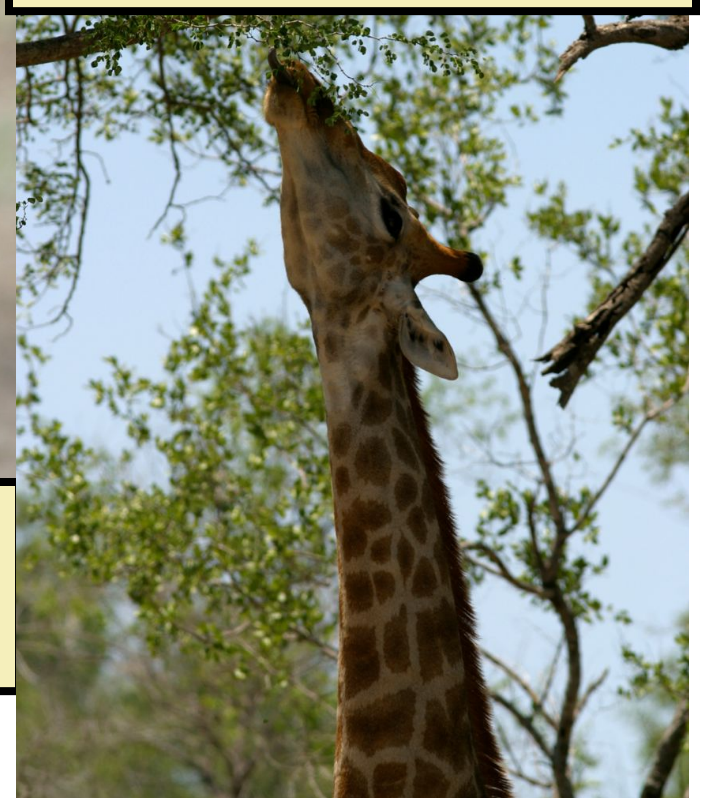


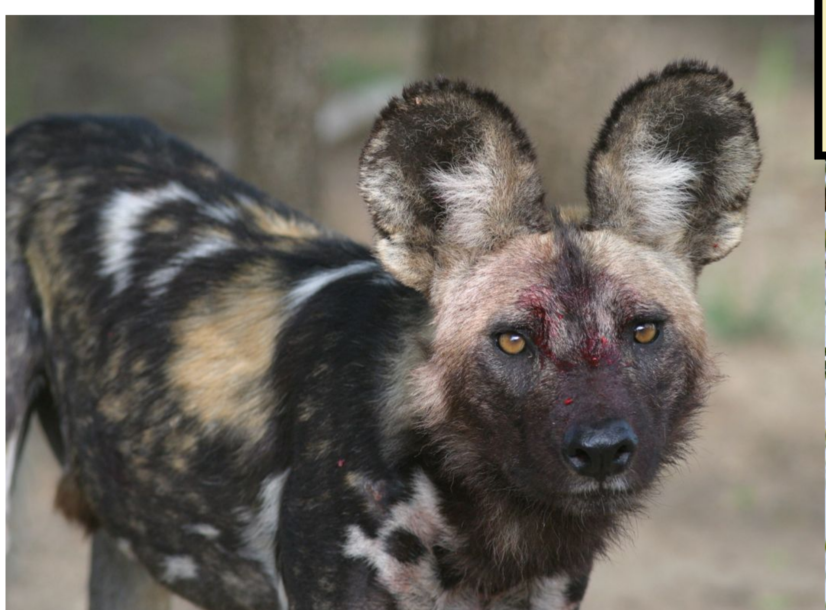
"I have learned more here
than from our visit to CERN"



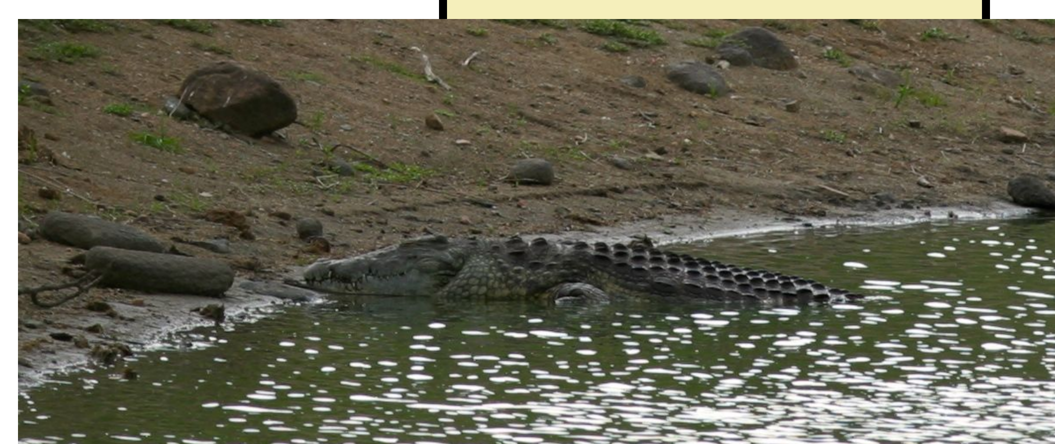
It's a bit boring

Some students are a bit
stretched by 2D momentum
conservation





Students are quite competitive to
win a "Nobel Prize" for the first 4σ
Higgs discovery.



There are always some students who do not
engage with the program.

Conclusions

LPPP can be a useful tool for students

- Students on their own
- Teacher led classes
- Stand alone Masterclasses
- Point the odd undergraduate student