Bubble 1.01 for Java

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Abstract

The Bubble Chamber Program is aimed to teach basic principles of particle Physics to students by simulating events that occur in bubble chambers and accelerators. The program was written in Java at the University of Mississippi. This Documentation is intended to provide an outline of the functionality of the Software. Please submit suggestions or ideas for improvement to the author.

1 General Functionality

This section explains the functionality of the individual buttons and windows of the program.

1.1 Main Buttons Panel

The main control buttons of the Program are located under the menu bar:

- *New Run:* Initializes a new event, resets the zoom and clears the screen.
- *Rerun:* Reproduces the previous event.
- *Stop:* Stops execution of the currently running event. This may become necessary if the event does not terminate by itself, eg if the energy loss per distance is set to zero and the particles continue on a circular path within the chamber indefinitely. If the Program response start being sluggish, this is a good sign that the event has not finished and needs to be stopped using the Stop button.
- *Shuffle Colors:* This button assigns random colors to the particle tracks. Should some tracks become hard to see due to contrast, this button will assign new colors to the tracts which will become effective once the event is re-run.

1.2 Menu Bar

The Menu Bar contains the main navigation tools: *File, Mouse, Analysis and About.*

1.2.1 The File Menu

The File Menu includes the following tabs:

- *Event Type:* Opens the Properties Panel which allows modifications to the chamber by changing the magnetic field strength, adjusting the initial momentum and position of the initial event and selecting the energy loss per distance of a particle. It also allows changing between the different events.
- *Save Image:* Opens a file menu which allows you to save the current output of the screen as a JPEG image file.
- *Quit:* Terminates the program.

1.2.2 The Mouse Menu

The Mouse Menu selects between the different functionalities of the mouse.

- *Circle Fit:* Allows the user to (left) click on three different positions on the screen. The points are then connected by a circle. The program uses the magnetic field strength in the chamber to calculate a momentum from the curvature of the circle. The momentum vector is positioned at the point which was first selected. Its value is ether written out on the screen or saved in a analysis text field (see Analysis part of documentation).This allows the user to measure initial momenta of particles in the bubble chamber.
- *Zoom:* Allows the user to zoom in on a certain part of the screen. The first (left) mouse click sets the top left corner of a zoom box which then follows the mouse. The second (left) mouse click sets the bottom right corner of the zoom box and completes the zoom process. A right mouse click resets the zoom.
- *Distance* Allows the user to select two point on the screen and returns the distance between them in meters.
- *Identify Track:* Allows the user to identify a particle which produced a certain track. A text box is displayed on the track closest to the mouse. By moving the mouse over different tracks, the closest track will be identified.
- *Angle:* Allows the user to measure an angle by selecting two points on the screen. The angle is returned relative to the x-axis of the screen.

1.2.3 The Analysis Menu

The Analysis Menu opens different panels for reconstruction of the measured particles.

- *Find Particle From Decay:* Opens the main analysis window which gathers information about the momenta, mass and energies of the particles and is used to recalculate rest mass and lifetime of the decayed particles (See the examples for the supported decays in this documentation for more information on the functionality of this panel).

- *View Particle Legend:* Opens a panel which shows all particles in the chamber by color and their order of appearance. It also displays their rest mass.
- *View Supported Particles:* Opens a list of all particles which are known to the program. The list displays the name, mass, charge, decay length and track visibility of the particles.

1.2.4 The About Menu

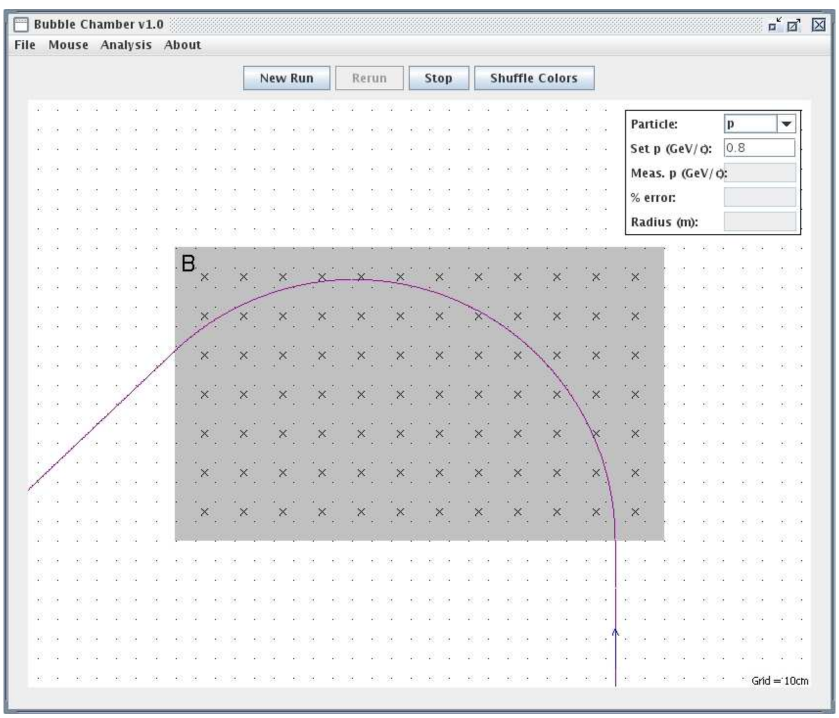
Displays brief information about the program.

2 Examples of the three supported event types

The Program has three event types aimed at different aspects of particle physics. These types are: General bending of a particle in a magnetic field (Single Particle), a particle decay in a bubble chamber focusing on the detection of the traceless lambda particle and the reconstruction of a Higgs decay in a particle detector.

2.1 The Single Particle Event

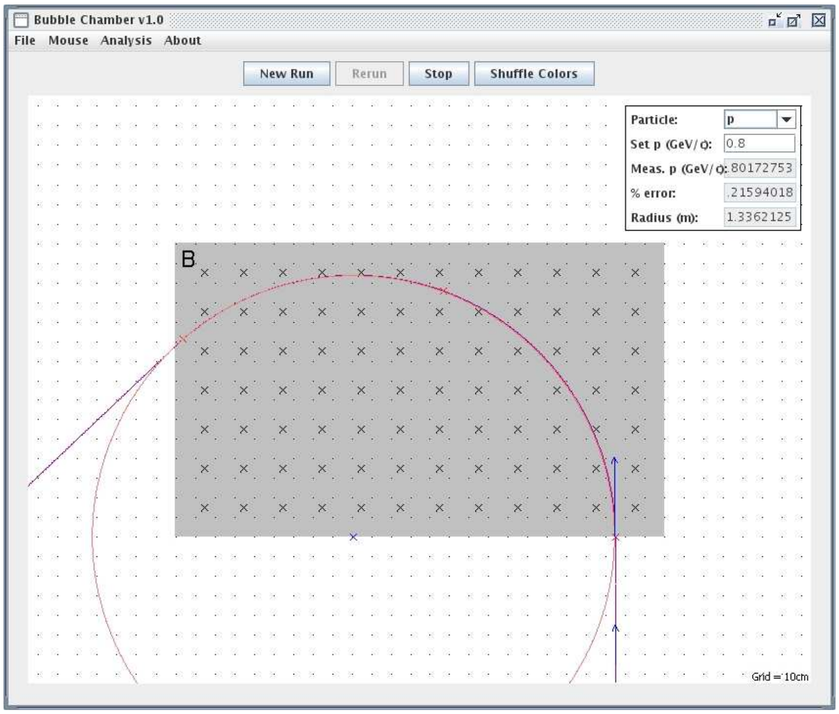
This event is selected as standard on opening the program. It can be manually selected during runtime by clicking on the *File* → *Event Type* menu and selecting *Single Particle in B-Field* in the Select collision pull down menu. This event is intended to show the effect a magnetic field has on charged and neutral particles. By clicking on the New Run button the following output should be generated:



This event is to demonstrate that charged particles experience a radial Lorenz force when entering a magnetic field region (here gray area) which causes them to curve. Outside this magnetic region they will travel in a straight path.

$$\vec{F} = q \cdot \vec{v} \times \vec{B}$$

This panel runs without energy loss (can be modified in the Properties Panel), so the curvature will be circular. By selecting *Mouse* → *Circle Fit* one can fit the circular path by selecting three points on the particle track within the magnetic region. The circle will be displayed together with the momentum vector (blue). The results of the fit will be displayed in the panel in the top left corner of the chamber screen. The following result should be produced:



The panel in the top right corner of the chamber panel shows the measured momentum and compares it to the selected momentum of the particle by displaying a percent error. This is to demonstrate that a measurement will always have some uncertainty associated with it. By changing the momentum in this panel different curvature behavior can be observed. The radius of curvature is defined by the following equation:

$$r = \frac{p}{B \cdot q}$$

Therefore a higher momentum value will result in less curvature, where as a higher magnetic field will result in more curvature.

By changing the particle type in the pull down menu of the top right panel one can explore the effect oppositely charged and neutral particles have in a magnetic field.

2.2 The Reconstruction Of The Lambda Particle

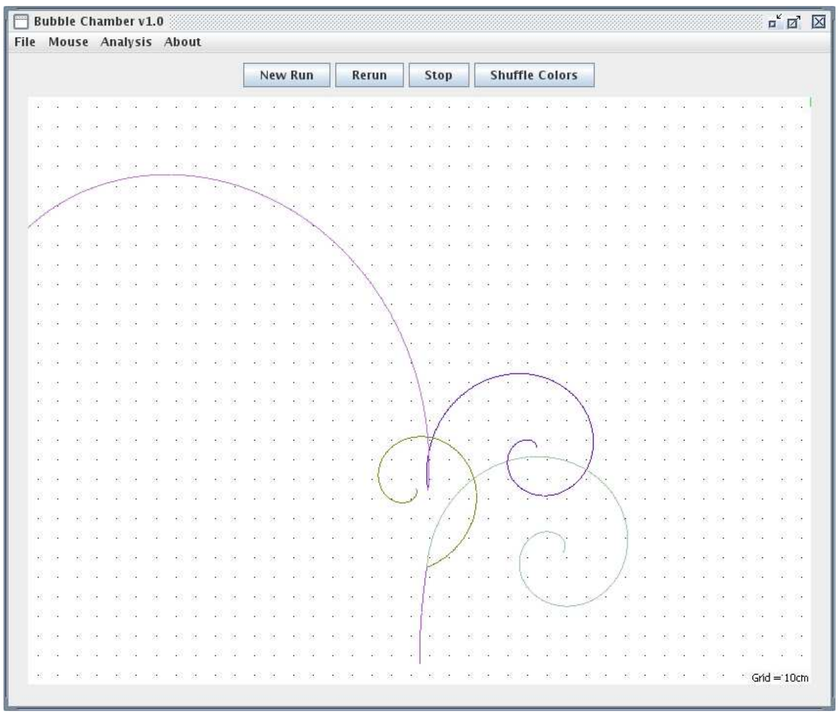
The reconstruction of the Lambda particle is the main event in the Bubble Chamber program. It simulates a negatively charged Kaon hitting a stationary proton as protons would be readily available in a bubble chamber. The collision will cause a decay into two pions and a Lambda particle. The lambda particle is uncharged and will not interact in the bubble chamber and therefore not display a track. After a certain distance of travel the lambda will decay into a proton and a pion.

This was a mystery in early particle physics since the proton and pion seemed to be created out of mid air because the neutral lambda did not show a track in the chamber. The reaction can be symbolized in the following way:

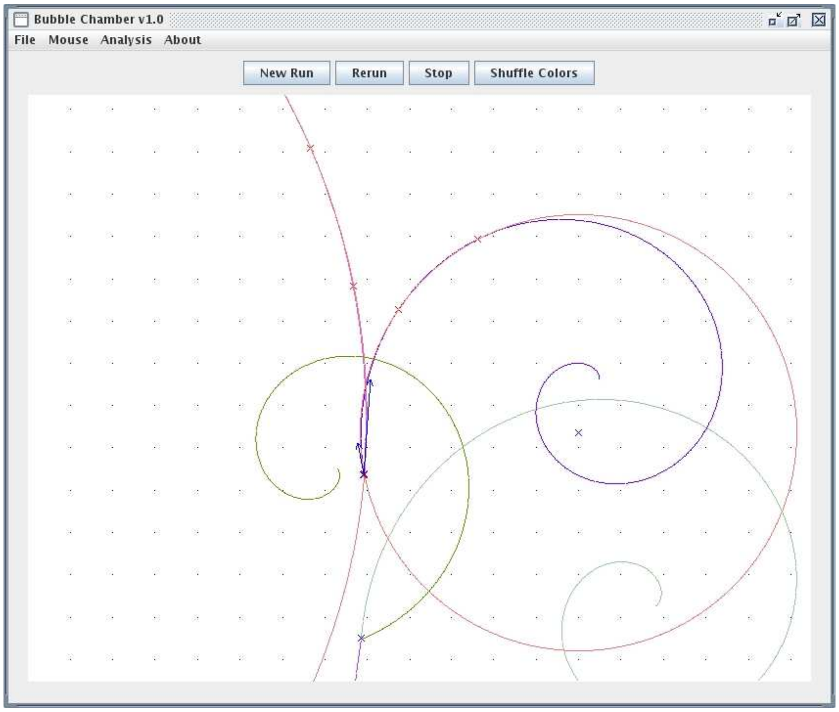
$$K^- + p \rightarrow \pi^+ + \Lambda + \pi^-$$

$$\Lambda \rightarrow p + \pi^-$$

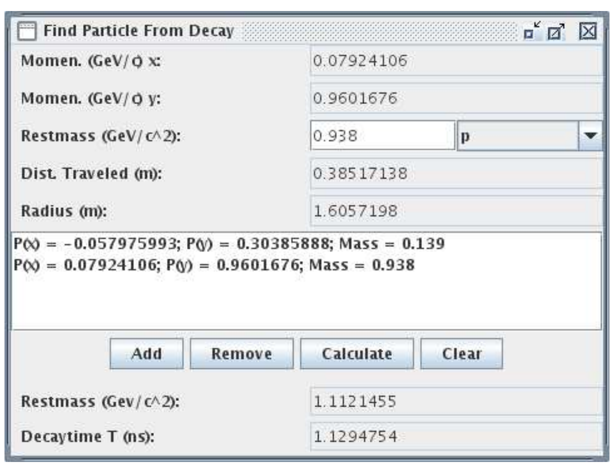
By selecting this decay process in the properties panel and clicking the new run button the following display should be generated:



One may want to go through several runs to find a decay pattern which clearly separates the lambda decay from the initial decay. For historic reasons the program is tailored to reconstruct the Lambda particle which is unseen in the chamber. In order to do so one needs to find the momentum vectors of the resulting particles (the proton and the pion). This can be done by fitting a circle to these tracks for we can assume a circular path in the early region of the tracks before the particles loose energy in the chamber an “spiral down”. To do so we first zoom into the region of interest and then apply the circle fits. The generated output should look similar to the following:



For each applied circle fit the measured momentum will be transfered into the *Find Particle From Decay* Window, which will open automatically each time a circle is fit or can be opened manually through the Analysis Menu Field. In order to uniquely identify a particle one also needs to know its rest mass. Therefore for each momentum one needs to specify the rest mass of the measured particle in the *Find Particle From Decay* Window. This can be done by entering the mass in the appropriate text field in units of GeV/c^2 or by simply typing the name of the particle (as it is defined in the *Supported Particles* List) and pressing the enter key. The Program will then look up the particle mass for you. The fully filled Find Particle From Decay window should look as follows:



Each time a particle is defined by its momentum and rest mass in the *Find Particle From Decay* Window one can add it to a list of identified particles by clicking the add button. In our case this list should include two particles in its final state (as shown) which is the pion and the proton.

In order to find the *lifetime* of the Lambda particle one should select the Distance option in the Mouse Menu and click on the path length of the Lambda particle. This is the separation between the two decay verticies. This action will then fill the *Dist. Traveled* text field in the *Find Particle From Decay* Window. This window is now completely filled and we have all the information of the decay particles and are therefore able to recalculate the mother particle which caused the decay (here this is the Lambda particle). This can be done by clicking on the Calculate button. The Window will finally show the calculated Rest mass and Lifetime of the Lambda particle in its rest frame and we have correctly discovered the Lambda particle.

Mathematically the reconstruction was done through the relativistic equation:

$$E^2 = p^2 + m^2$$

The reason for the omitted speed of light constants is due to the units used for mass and momentum and is explained in a separate document. We first find the Lambda momentum through simple vector addition:

$$\vec{p}_\Lambda = \vec{p}_{\pi^-} + \vec{p}_p$$

The Energy of the Lambda particle can be found in three steps:

$$E_p = \sqrt{{p_p}^2 + {m_p}^2}$$

$$E_\pi = \sqrt{{p_\pi}^2 + {m_\pi}^2}$$

$$E_\Lambda = E_p + E_\pi$$

Using the relativistic energy formula above we can calculate the invariant Lambda mass:

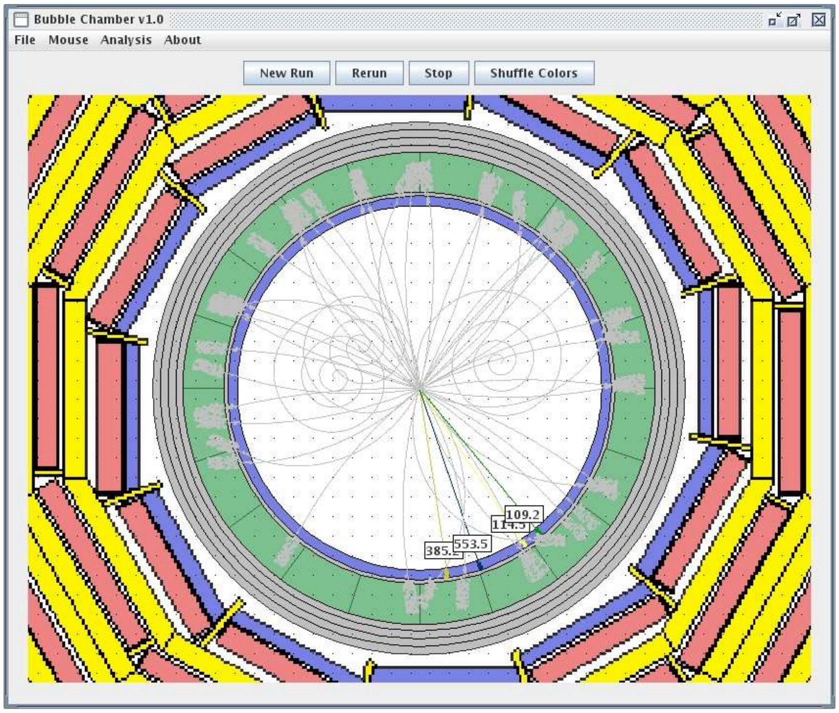
$$m_\Lambda = \sqrt{{E_\Lambda}^2 - {p_\Lambda}^2}$$

The program does these steps automatically once the *Calculate* button is pressed, but this can also be done manually using the measured data and the above formulas.

2.3 The Reconstruction Of The Higgs Particle

The Higgs particle is a very massive particle which is postulated by the Standard Model of Particles and Interactions, but has not yet been observed. Efforts are currently underway to detect this particle at the LHC (Large Hadron Collider) at the European Center for Nuclear Research (CERN) in Switzerland. Since the mass of this particle is still unknown this program makes an arbitrary assumption to set its mass to 200 GeV/c^2. This program simulates a simplified reconstruction process in the CMS detector at CERN.

By selecting the *Higgs Decay* in the Properties Panel and clicking on the *New Run* button the program should produce a similar output as shown:



The picture shown is a cut through the CMS detector at CERN with the beam line vertical to the page. The tracks of interest, which were produced in the Higgs decay are colored here. The gray tracks are background events and not of interest for us. Since the Higgs has a very high rest mass, the resulting particles have a very high momentum. This causes them to practically not bend in the magnetic field. We therefore cannot apply a circular fit to obtain their momenta. For this reason we use the calorimeters of the CMS detector to "measure" the energy of the decay particles directly. The energy readout of the particles is displayed in white boxes on the screen.

In order to reconstruct the Higgs mass we undergo the same process as before which means we need to find the momentum vectors of the particles involved. For now we assume that we know the masses of the particles involved in the decay since we can identify them in the program (*Particle Legend*). From the relativistic formula we can find the absolute value of the momenta of the particles:

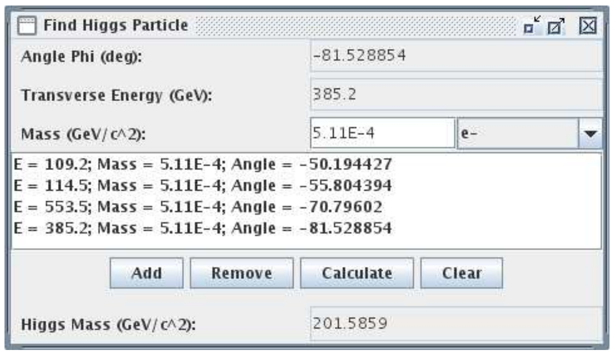
$$p = \sqrt{E^2 - m^2}$$

In order to find the momentum vector we need to use the relative angle of the particle tracks to our coordinate system:

$$p_x = p * cos(\phi)$$

$$p_y = p * sin(\phi)$$

This angle can be found by selecting the *Angle* function in the Mouse menu. Since all tracks originate from the center of the detector, this will be the starting point for the angle measurement. Click on the center of the detector (first click) and then on the outer part of the track you are investigating. This measures the Angle for this one track and places the value in the *Find Higgs Particle* Window which will open automatically or can be opened manually by selecting the *Find Particle From Decay* Menu item in the Analysis Menu. Next by clicking on the white Energy Tab associated with the track under investigation, the energy value will be transfered into the *Find Higgs Decay* window as well. The last information needed is the mass of the particle which formed the track. This value can be found from the *Particle Legend* Window or through the *Identify Track* option in the Mouse Menu. Again, typing the name of the Particle and pressing Enter will translate its name to the appropriate mass value as before. With the angle, energy and mass given, the particle is well defined and can be added to the list in the *Find Higgs Decay* by clicking the Add button. This procedure needs to be repeated for the three remaining tracks. The Find Higgs Decay Window should look as follows once fully filled:



By clicking the *Calculate* button, the program will calculate the four momentum vectors of the individual daughter particles and reconstruct the Higgs mass in the same manner as it was done in the Lambda decay.

2.3.1 The Higgs Decay Process

The Higgs particle can decay into an abundance of other particles which themselves will decay further. The Bubble Chamber program has implemented only a very brief selection of the possible decays which are shown below:

$$Higgs \rightarrow \omega^+ + \omega^-$$

$$\omega^+ \rightarrow \pi^+ + \gamma$$

or

$$Higgs \rightarrow Z + Z$$

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

And the charge conjugated reactions.

Besides the *Particle Legend* there is another way of identifying the particle type of a track, simply by looking at the detector image. Electrons (e) and photons (γ) are very light particles that show a strong electromagnetic interaction. They will therefore react within the *Electromagnetic Calorimeter* of the detector. Here this is the first ring from the inside, which is colored blue in the above picture. Since electrons are charged, they will form a visible track in the detector. The uncharged photons will be invisible and only show a reaction in the calorimeter. One can therefore distinguish between electrons and photons in the detector

Pions (π) are hadrons which are particles made of quarks. They are more massive and will react mainly in the *Hadronic Calorimeter* of the detector which is the second ring in the picture above colored green. Since Our reaction only allows pions as hadrons, a positive track in the hadronic calorimeter lets us identify this particle as a pion.

Muons (μ) are the massive version of electrons. Muons do not interact with matter much. They therefore are able to pass all the way though the detector. Therefore if the detector shows a particle leaving the image, we can identify it as a muon.

In the real experiments much more complicated identification tools need to be implemented since the collider produces an abundance of other particles which we are not considering here.

3 Time Dilation and Relativistic Effects

When dealing with highly energetic particles that travel close to the speed of light, relativistic effects such as time dilation can be observed.

3.1 Brief introduction to Special Relativity

What is *Time Dilation?* **Time dilation** is the phenomenon whereby an observer finds that another's clock which is physically identical to their own is ticking at a slower rate as measured by their own clock. This is often taken to mean that time has "slowed down" for the other clock, but that is only true in the context of the observer's frame of reference. Locally, time is always passing at the same rate. The time dilation phenomenon applies to any process that manifests change over time. (*Source: wikipedia*).

To us this means that as we are looking into the bubble chamber and are measuring the decay time of a particle, this measured decay time could be much longer than the actual lifetime of the particle. Thus the time of the particle seems to be slower than our time in the chamber.

Let us have a closer look at the Lambda particle. In particle physics, just as it is the case in radioactive decays, the decay time of a particle is not a fixed time at which a particle under all circumstances always decays, but more a statistical process in which a particle may decay sooner in one instance and later in the next. Averaged over a large number of decays we can associate a *Life Time* with this particle which gives an idea of the decay time, but can not predict a particular decay time for a single particle. This can be compared to the half life of radioactive particles. We can therefore only talk about the probability of particle decaying as time progresses. Mathematically this can be expressed as follows:

$$P(t) = 1 - e^{-t_\Lambda/\tau}$$

Were P is the probability for the particle to decay at time t and τ is the Life Time of the particle. We can see that as time progresses it becomes more likely for the particle to decay since P approaches certainty of one. The time t responsible for this process is the time seen bu the Lambda particle, not the time we measure in the Bubble Chamber, which we will refer to as t_B, as mentioned above. From special relativity these times are related by:

$$t_B = \gamma \cdot t_\Lambda$$

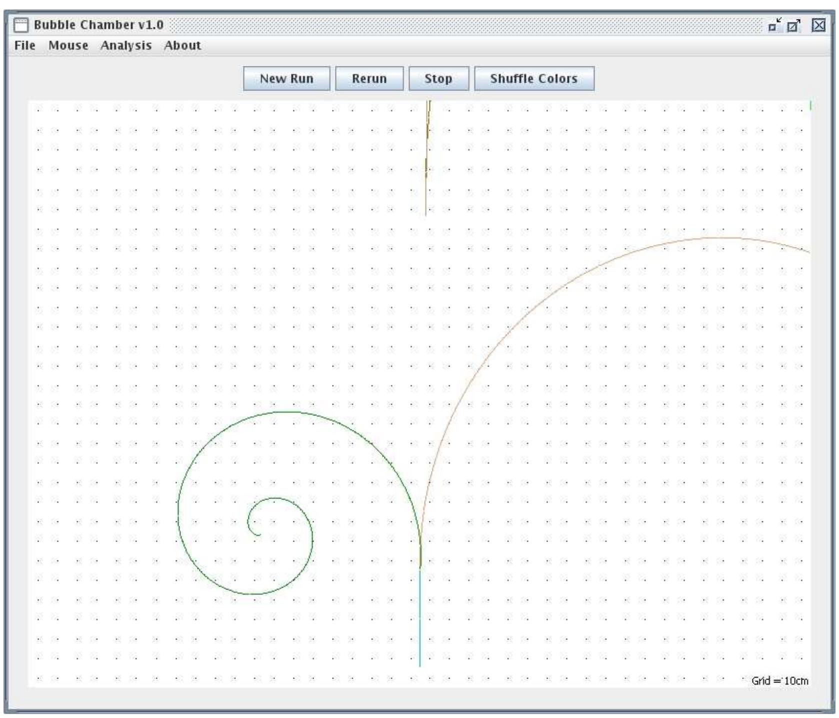
where

$$\gamma = \frac{E_\Lambda}{m_\Lambda} = \frac{\sqrt{{p_\Lambda}^2 + {m_\Lambda}^2}}{m_\Lambda}$$

We can see from these equations, that the more momentum a particle has, the greater the relativistic factor γ becomes which is responsible for the difference in time as the Lambda particle sees it t_Λ and as we measure it in the lab t_B. The clock for the Lambda particle seems to be ticking slower since $\gamma > 1$ is always the case. Therefore for high momentum particles, this time dilation can be observed in the lab.

3.2 Time Dilation in the Bubble Chamber Program

If we turn to the Lambda Decay in the bubble chamber program the Properties Panel lets us set the initial momentum for the incoming Kaon. This is set by default to $p_K = 2.0 GeV/c$. This corresponds to a γ-factor of app. 4.2. If we set the momentum to 20 GeV/c we get a γ-factor of app. 40.8, which is almost 10 times as large as before. We should therefore see a longer life of the lambda particle, meaning it will travel a further distance in the bubble chamber. This is shown in the picture below:



The long travel distance of the Lambda particle here is purely due to time dilation. One might think that a higher momentum particle will have a grater velocity and therefore cover a grater distance in the same amount of time, but we are dealing with particles which already travel close to the speed of light and no matter can be accelerated beyond the speed of light. For example a 2.0 GeV/c Kaon has a velocity of approximately 0.971*c where c is the speed of light. A 20.0 GeV/c Kaon has a velocity of 0.999*c. The difference in velocities is therefore minimal and the extra distance we observe in the Bubble Chamber is purely due to time dilation.