MINERvA Neutrino Masterclass

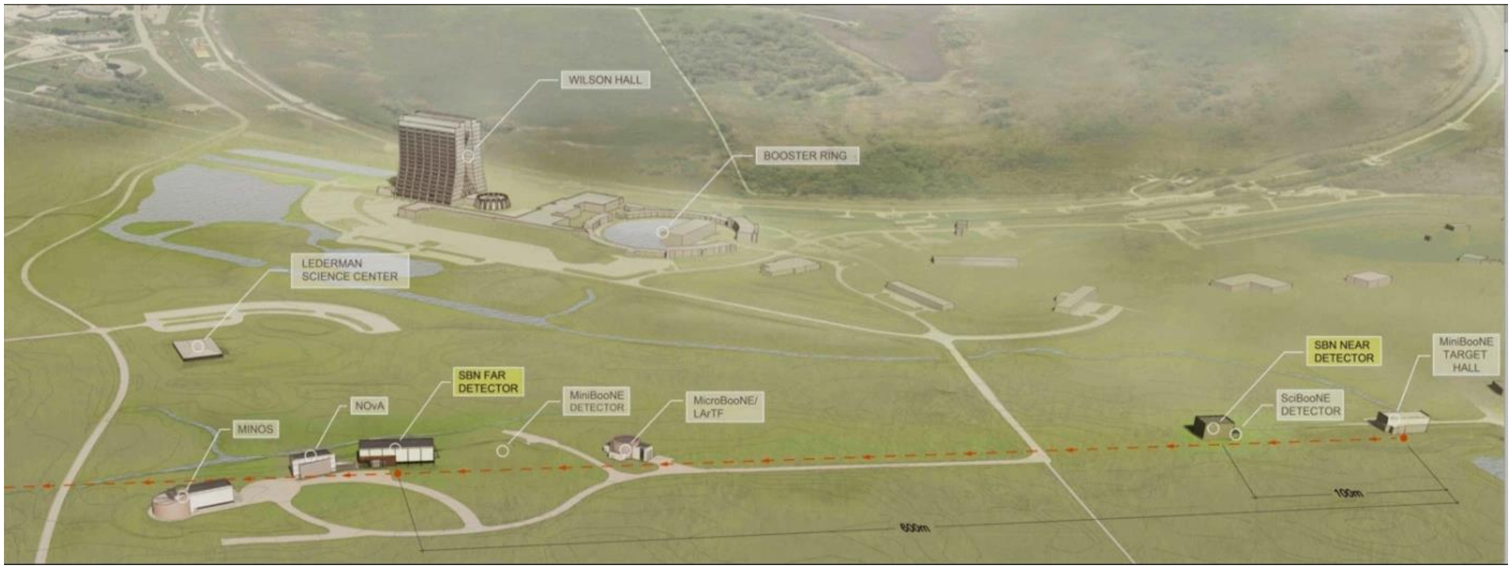
Masterclass Hands on Particle Physics

Introducción al ejercicio

Michel Sorel (III) & Avelino Vicente (V)

26 de marzo de 2026

Fermilab

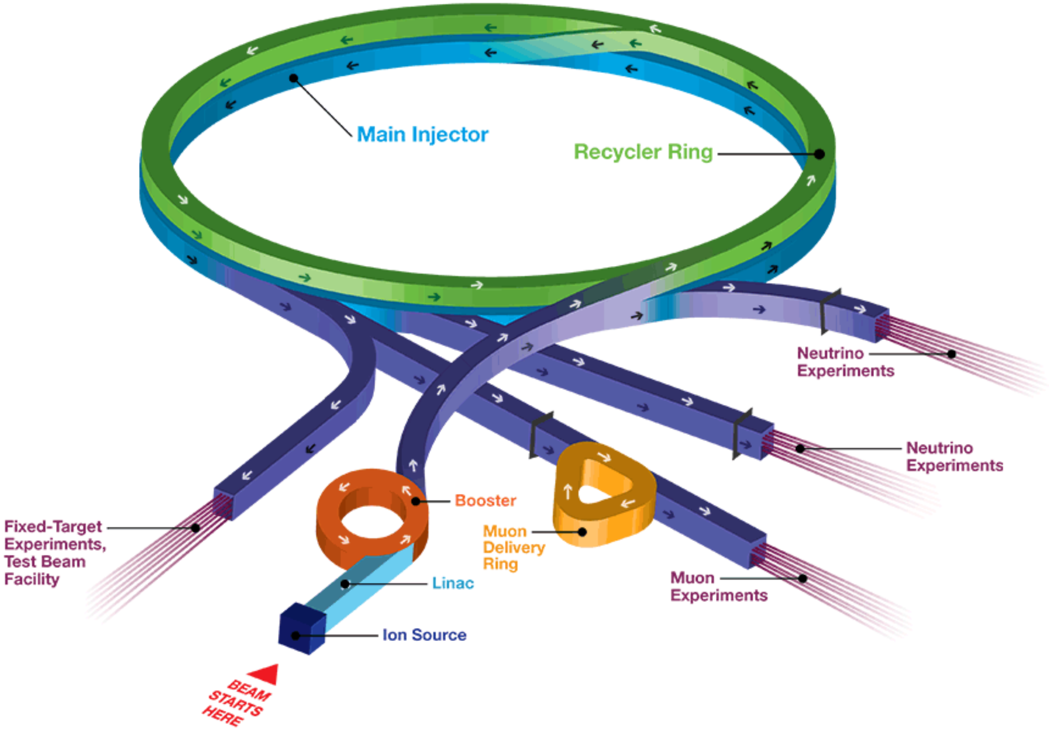


The Fermi National Accelerator Laboratory (Femilab) is the place to be to study neutrinos. The short- and long-baseline programs investigate all sorts of neutrino behaviors and shed light on the nature of the universe.

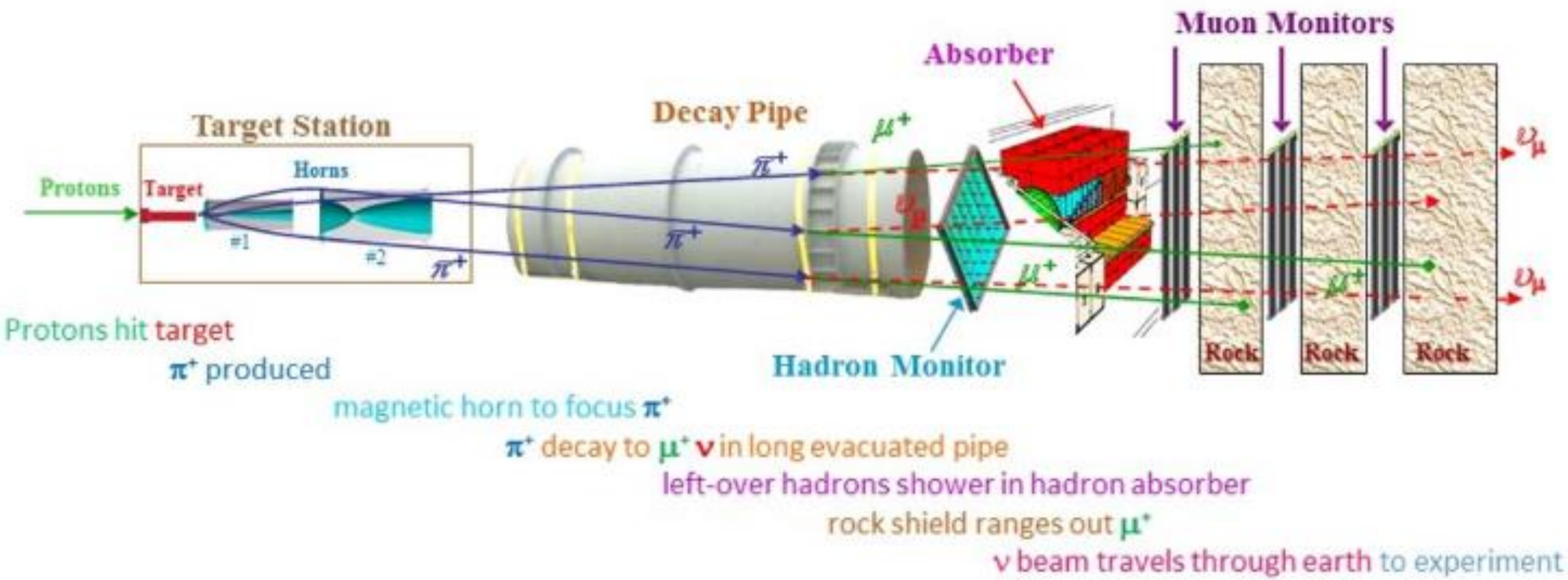
Fermilab

The Fermilab Main Injector sends protons to a targets for different purposes. Some are sent to create neutrino beams.

Fermilab Accelerator Complex

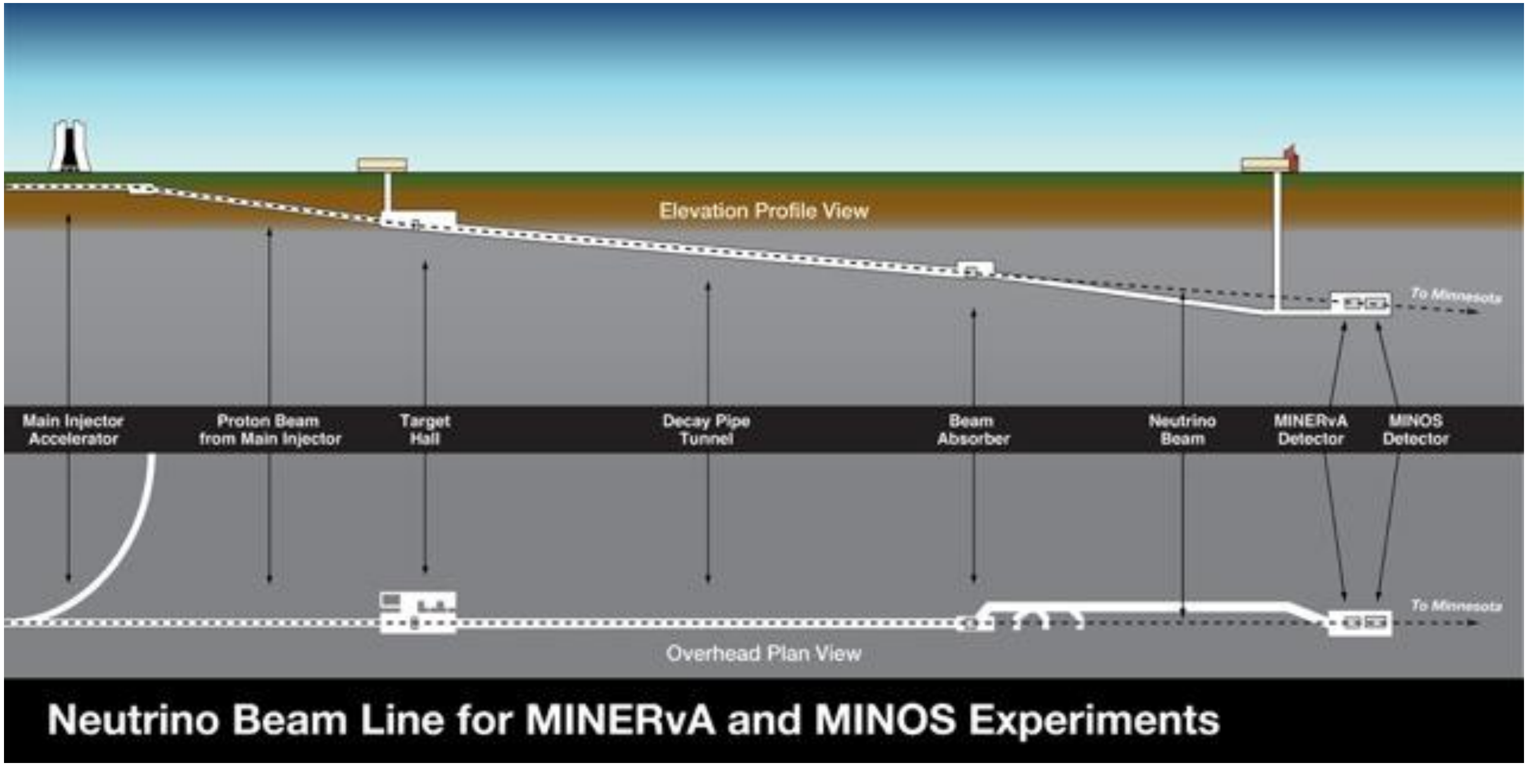


MINOS and MINERvA



protons → target → pions → muons + neutrinos → neutrino beam

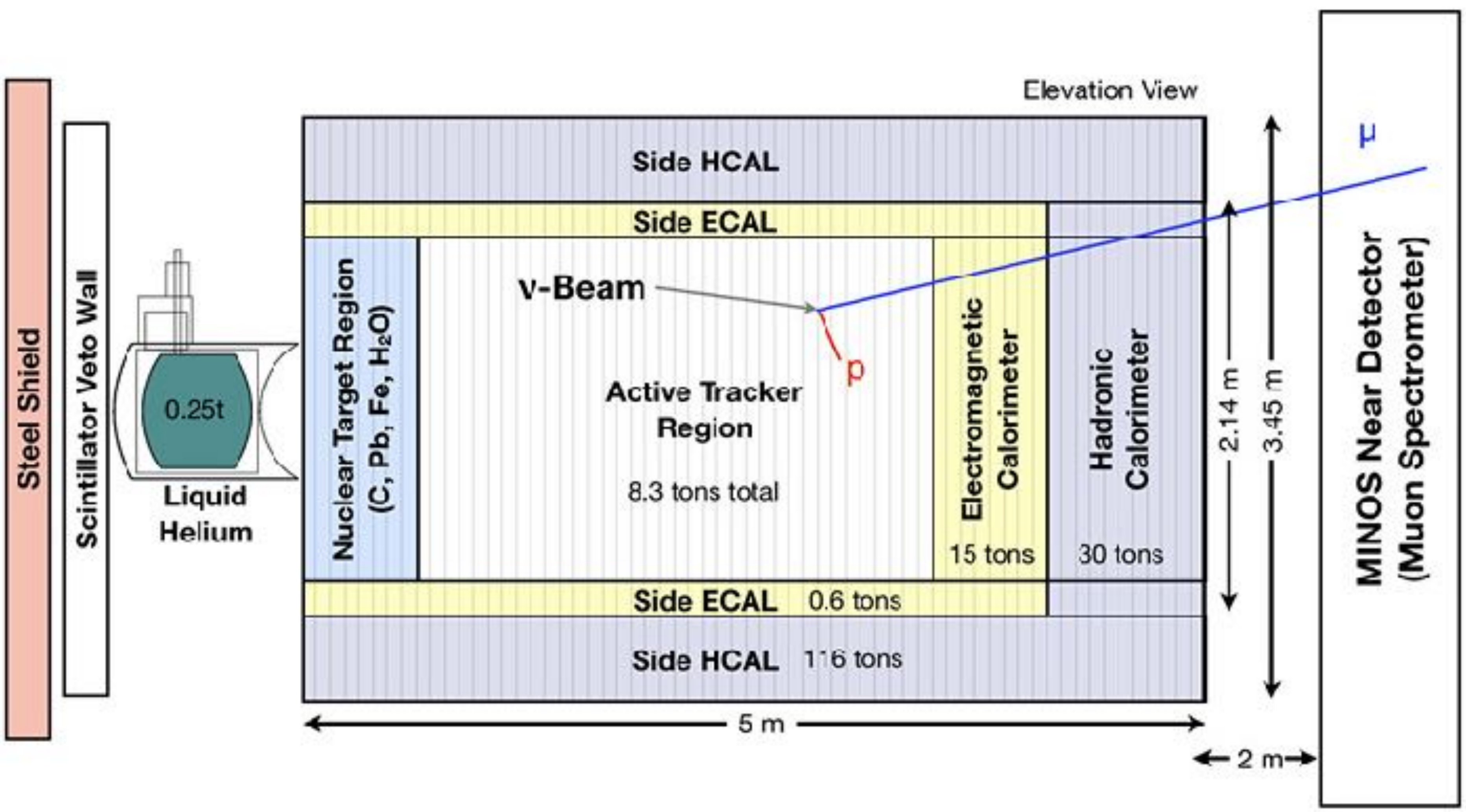
MINOS and MINERvA



Neutrinos for MINOS were measured once at Fermilab and again in a lab in Minnesota; that experiment is ended. MINERvA continues.

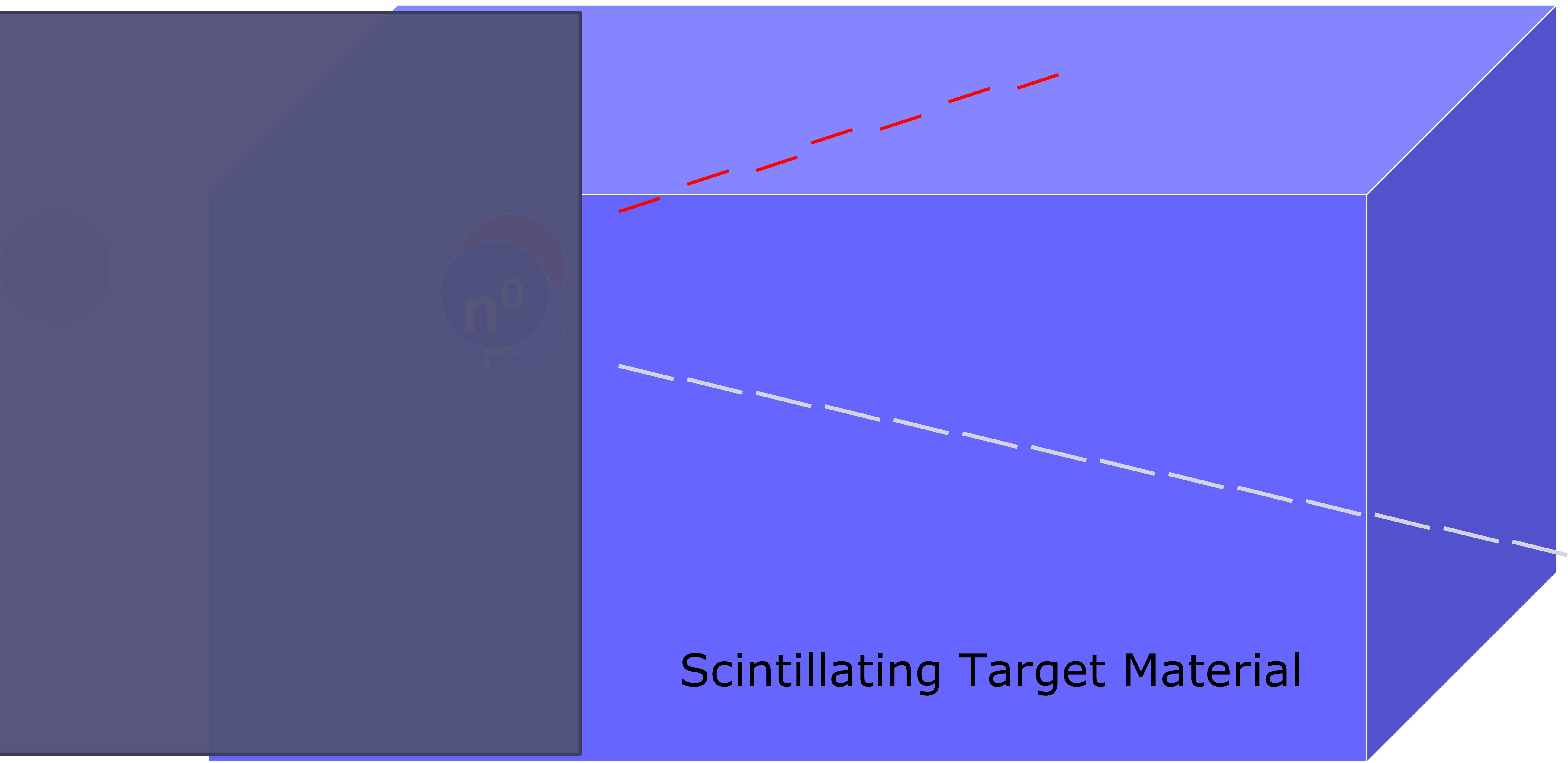
MINERvA masterclass measurement

- The **MINERvA masterclass** measurement enables you to examine actual events from the MINERvA detector in the MINOS neutrino beamline at Fermilab
- It enables you to draw conclusions based on categorization of the data and the kinematics of the interactions



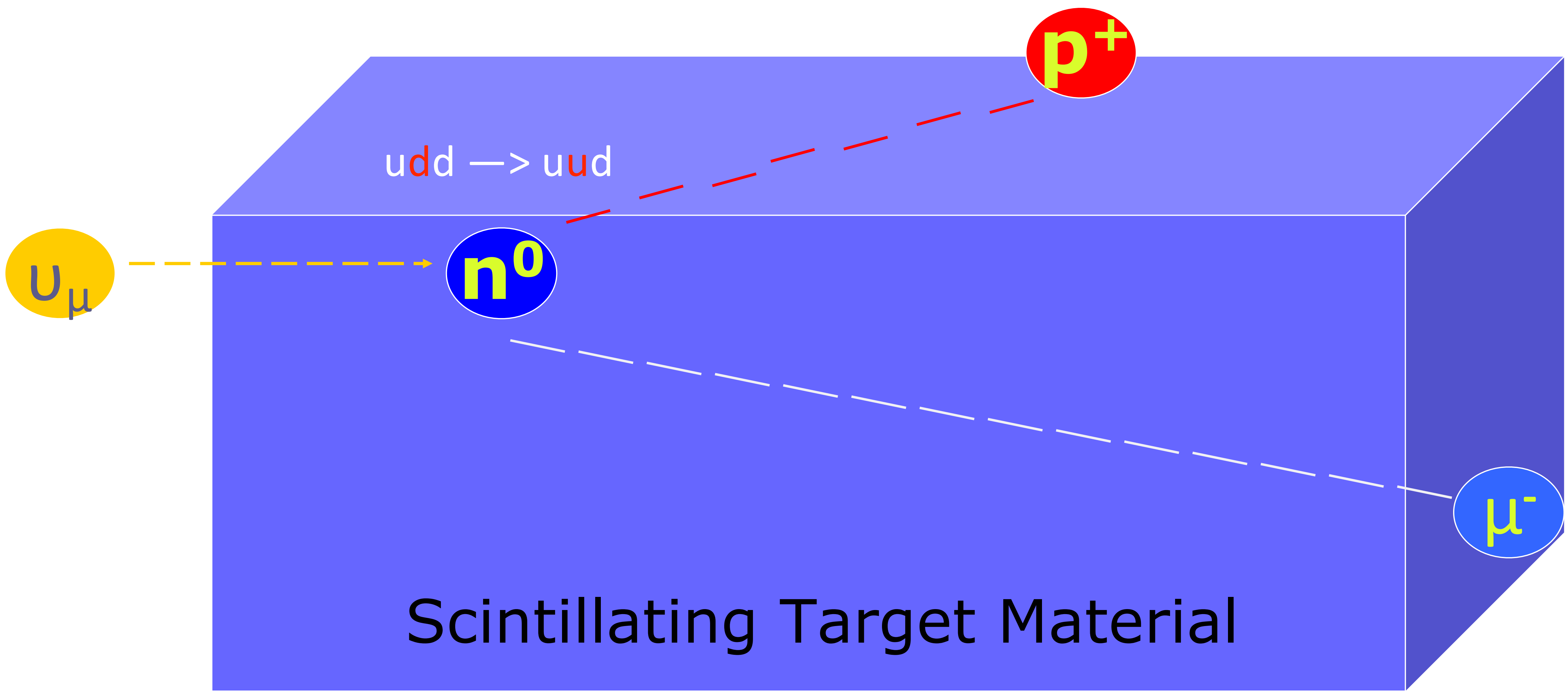
MINERvA's Principal Interaction Of Interest (What we see)

A proton and muon "appear" out of nowhere in the scintillating target



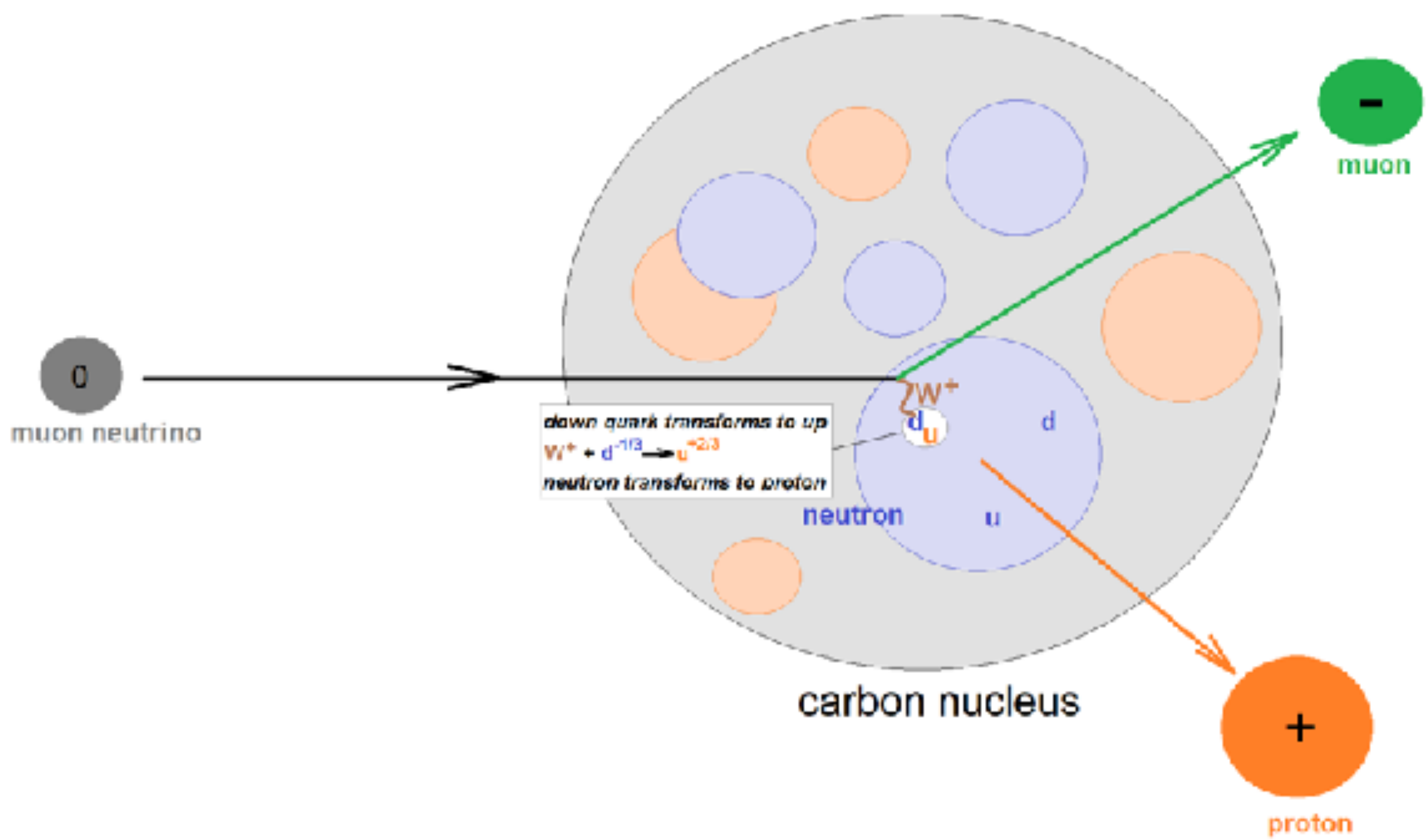
What's Going On?

- A neutrino with kinetic energy strikes a neutron at 'rest' in the nucleus of an atom…
- Which causes one of the neutron's down quarks to flip "up" (udd) to (uud) … transforming it to a proton!
- Simultaneously, a muon is generated as the neutrino annihilates



Signal and background events

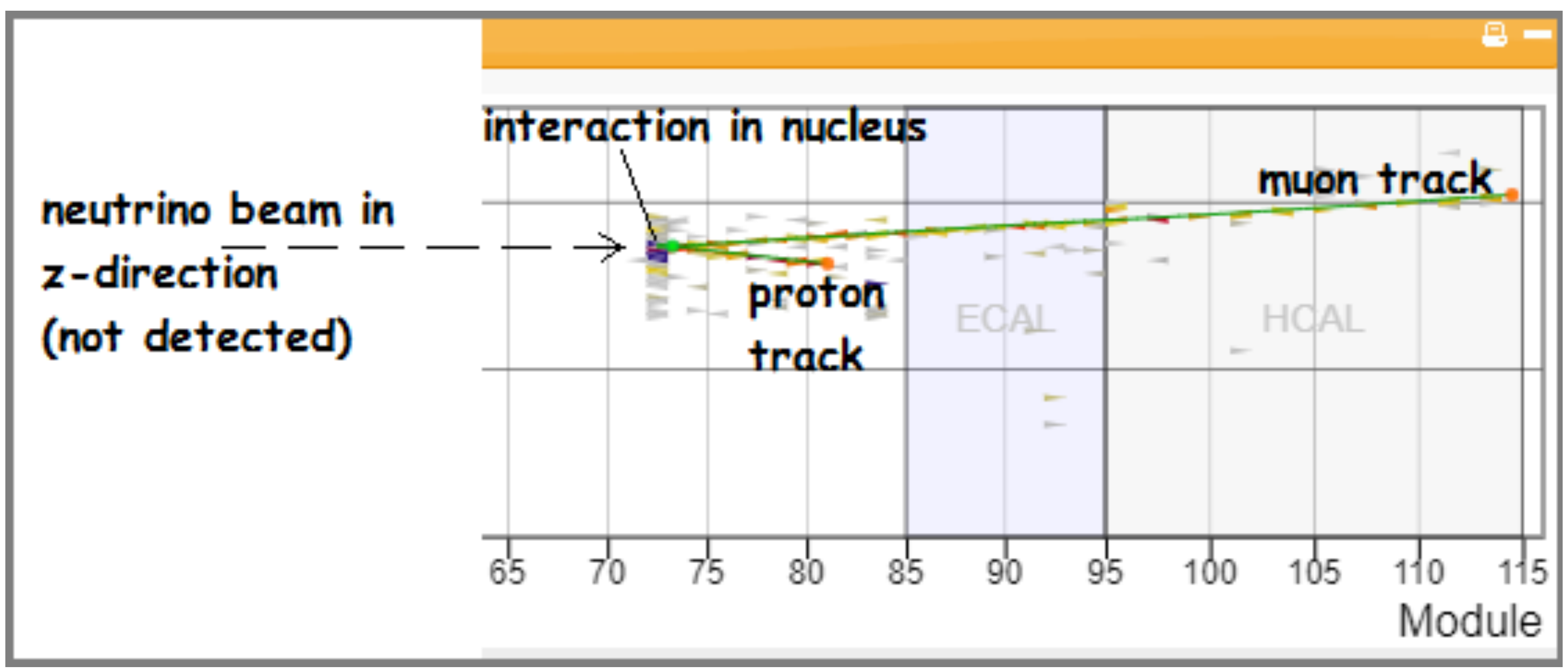
- There are both **background** and **signal** events
- In each **signal** event, a neutrino penetrates a nucleus in carbon target and undergoes a weak interaction with a neutron in that nucleus
    - ➡The neutrino interacts with the neutron to become a muon, causing the neutron to become a proton!



- **Background** event: any other event type

Interaction kinematics

- While **MINERvA** cannot directly detect the neutrino, it detects and measures the kinematics of both the muon and the proton that emerge from the interaction
- You can find this kinematic information with **Arachne**, the MINERvA event display that you will use to visualize the events.
- You will then put this information into a spreadsheet which applies conservation of momentum to give the momentum of the system prior to the interaction in three dimensions.



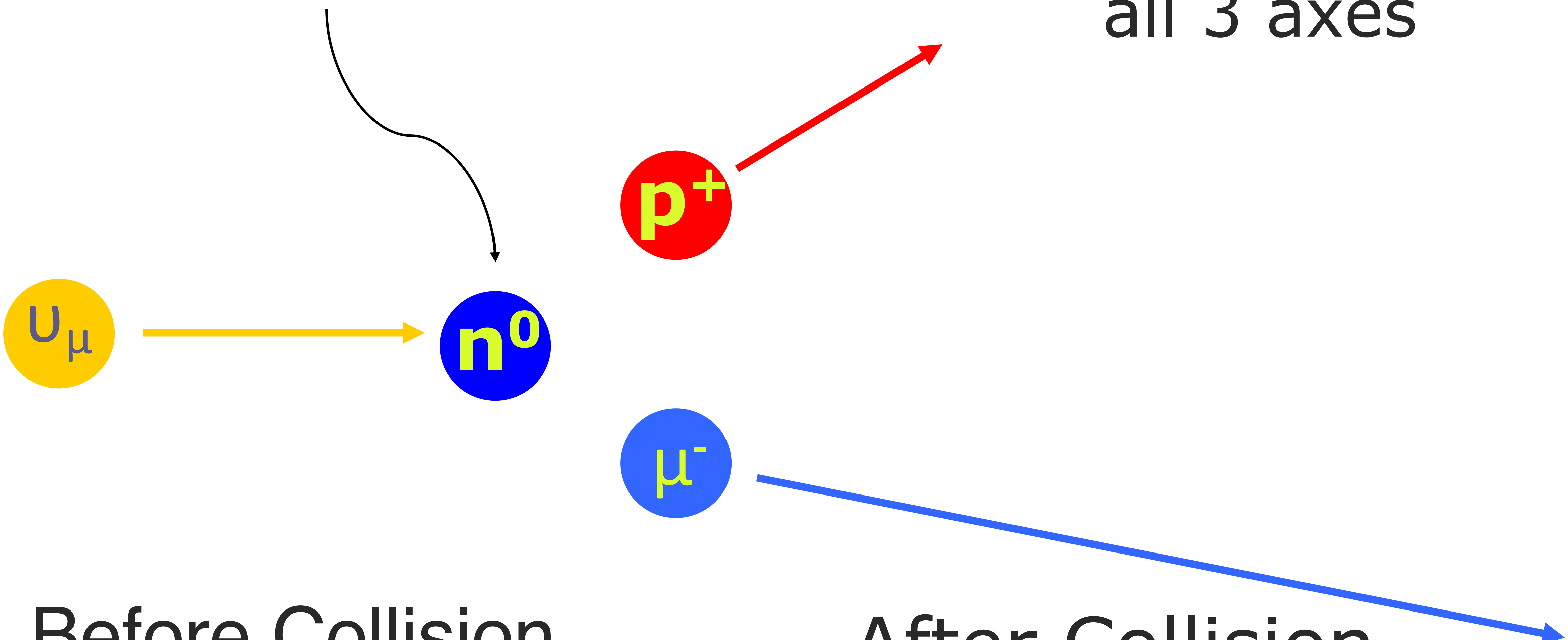
Masterclass objectives

- Determine which events are **signal** events *(from which effective measurements may be made)* and which events are **background** (that cannot be used for measurements).
- Apply conservation of momentum and energy to measure the approximate **energy of a neutrino beam** from the Fermilab accelerator complex.
- Apply conservation of momentum and energy to measure the **properties of neutrons** in nuclei of atoms in the target of a neutrino beam.

Momentum Conservation

At the position and time of the interaction **only!**

Momentum is conserved in all 3 axes

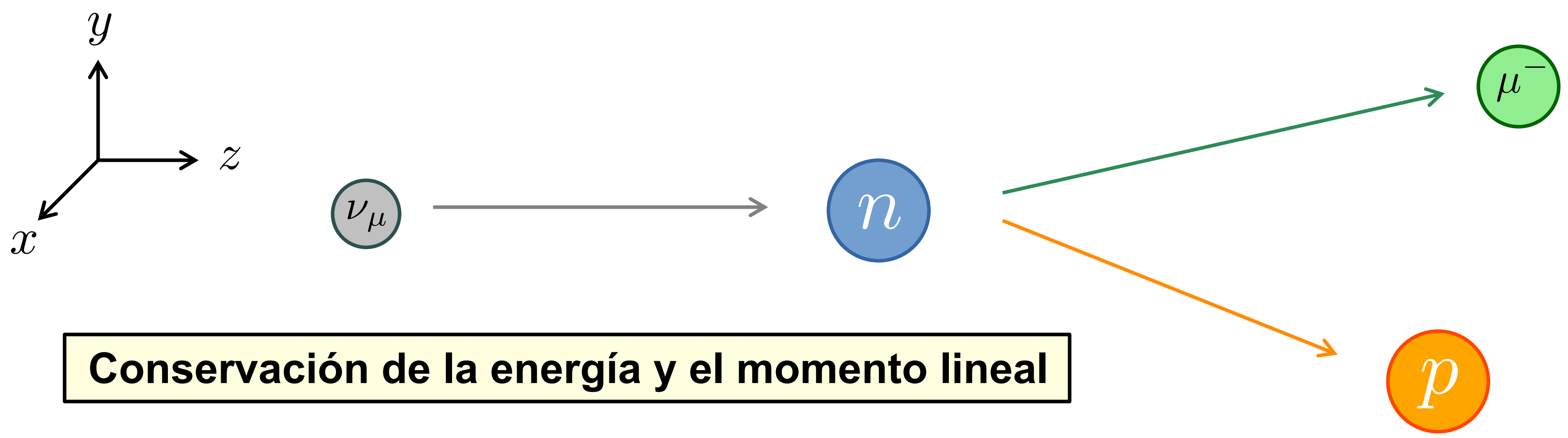


Before Collision

After Collision

$$p_{neutrino} + p_{neutron} = p_{proton} + p_{muon}$$

Cinemática: $\nu_\mu \, n \rightarrow \mu^- \, p$



Conservación de la energía y el momento lineal

⟶ **4 ecuaciones**

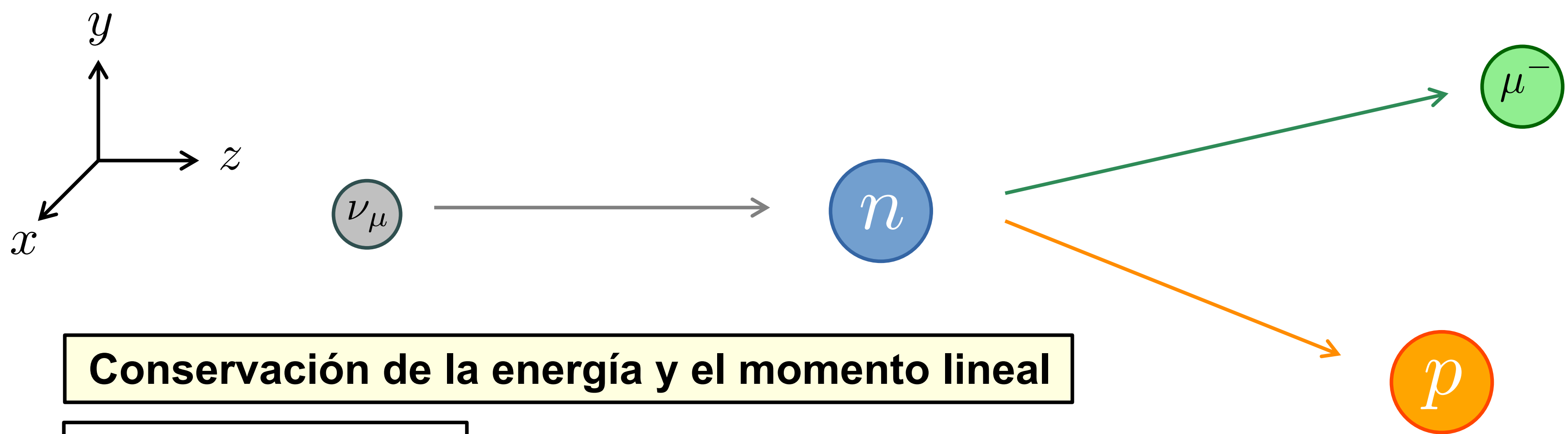
$$E_\nu + E_n = E_\mu + E_p$$

$$(p_x)_\nu + (p_x)_n = (p_x)_\mu + (p_x)_p$$

$$(p_y)_\nu + (p_y)_n = (p_y)_\mu + (p_y)_p$$

$$(p_z)_\nu + (p_z)_n = (p_z)_\mu + (p_z)_p$$

Cinemática: $\nu_\mu\, n \rightarrow \mu^-\, p$



Conservación de la energía y el momento lineal

Además:

$$E^2 = (\vec{p}\,c)^2 + \left(m\,c^2\right)^2$$

c : velocidad de la luz

⟶ **4 ecuaciones**

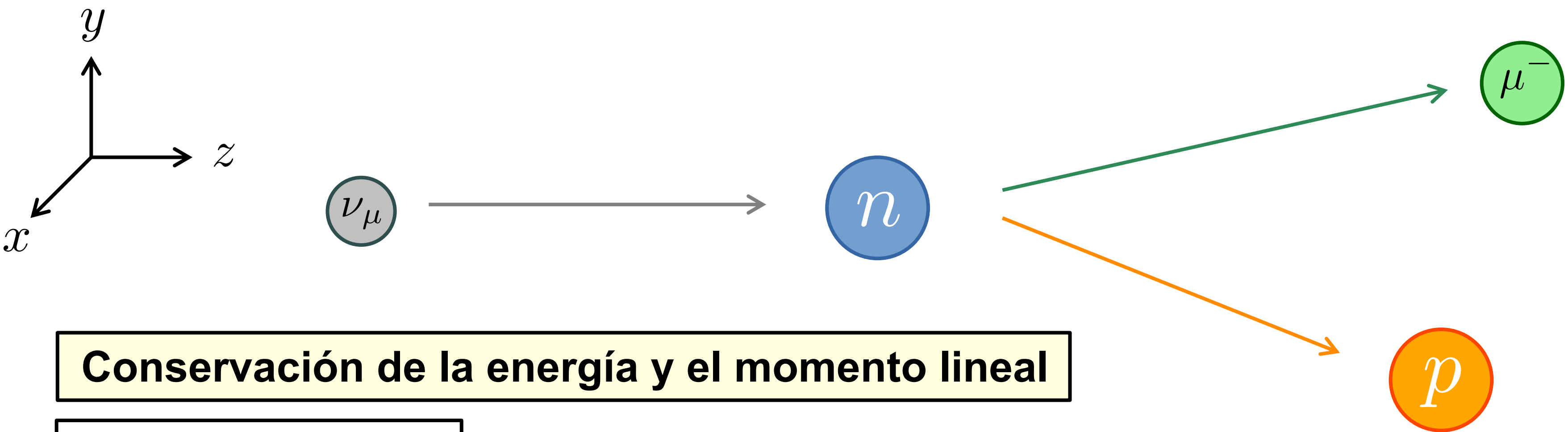
$$E_\nu + E_n = E_\mu + E_p$$

$$(p_x)_\nu + (p_x)_n = (p_x)_\mu + (p_x)_p$$

$$(p_y)_\nu + (p_y)_n = (p_y)_\mu + (p_y)_p$$

$$(p_z)_\nu + (p_z)_n = (p_z)_\mu + (p_z)_p$$

Cinemática: $\nu_\mu \, n \rightarrow \mu^- \, p$



Conservación de la energía y el momento lineal

Además:

$$E^2 = (\vec{p}\,c)^2 + \left(m\,c^2\right)^2$$

c : velocidad de la luz

→ **4 ecuaciones**

$$\sqrt{m_\mu c^2 + (p_x)^2_\mu c^2 + (p_y)^2_\mu c^2 + (p_y)^2_\mu c^2} \qquad \sqrt{m_p c^2 + (p_x)^2_p c^2 + (p_y)^2_p c^2 + (p_y)^2_p c^2}$$

$$E_\nu + E_n = E_\mu + E_p \quad \Rightarrow \quad (p_z)_\nu \, c + m_n \, c^2 = E_\mu + E_p$$

$$(p_x)_\nu + (p_x)_n = (p_x)_\mu + (p_x)_p \quad \Rightarrow \quad (p_x)_n = (p_x)_\mu + (p_x)_p$$

$$(p_y)_\nu + (p_y)_n = (p_y)_\mu + (p_y)_p \quad \Rightarrow \quad (p_y)_n = (p_y)_\mu + (p_y)_p$$

$$(p_z)_\nu + (p_z)_n = (p_z)_\mu + (p_z)_p \quad \Rightarrow \quad (p_z)_\nu + (p_z)_n = (p_z)_\mu + (p_z)_p$$

4 incógnitas

Unidades de medida

$$E^2 = (\vec{p}\,c)^2 + \left(m\,c^2\right)^2$$

masa $\quad [\,m\,] = [\,E\,]/c^2$

momento $\quad [\,p\,] = [\,E\,]/c$

energía $\quad [\,E\,] = \mathrm{MeV} = 10^6\,\mathrm{eV} = 1.6\ \times 10^{-13}\,\mathrm{J}$

El **electronvoltio** (eV) es una unidad muy habitual en física de partículas

1 eV = energía cinética que adquiere un electrón al acelerarse en una diferencia de potencial de 1 V

Ejemplo: $m_p \approx 939\,\mathrm{MeV}/c^2 \approx 1.7 \times 10^{-27}\,\mathrm{kg}$

First Step: Open files and assigned data

The entire MINERvA masterclass measurement runs online in a browser.

- Use **Google Chrome** to open the corresponding data set:

Data Group A: http://go.uv.es/mamtor/minerva_a

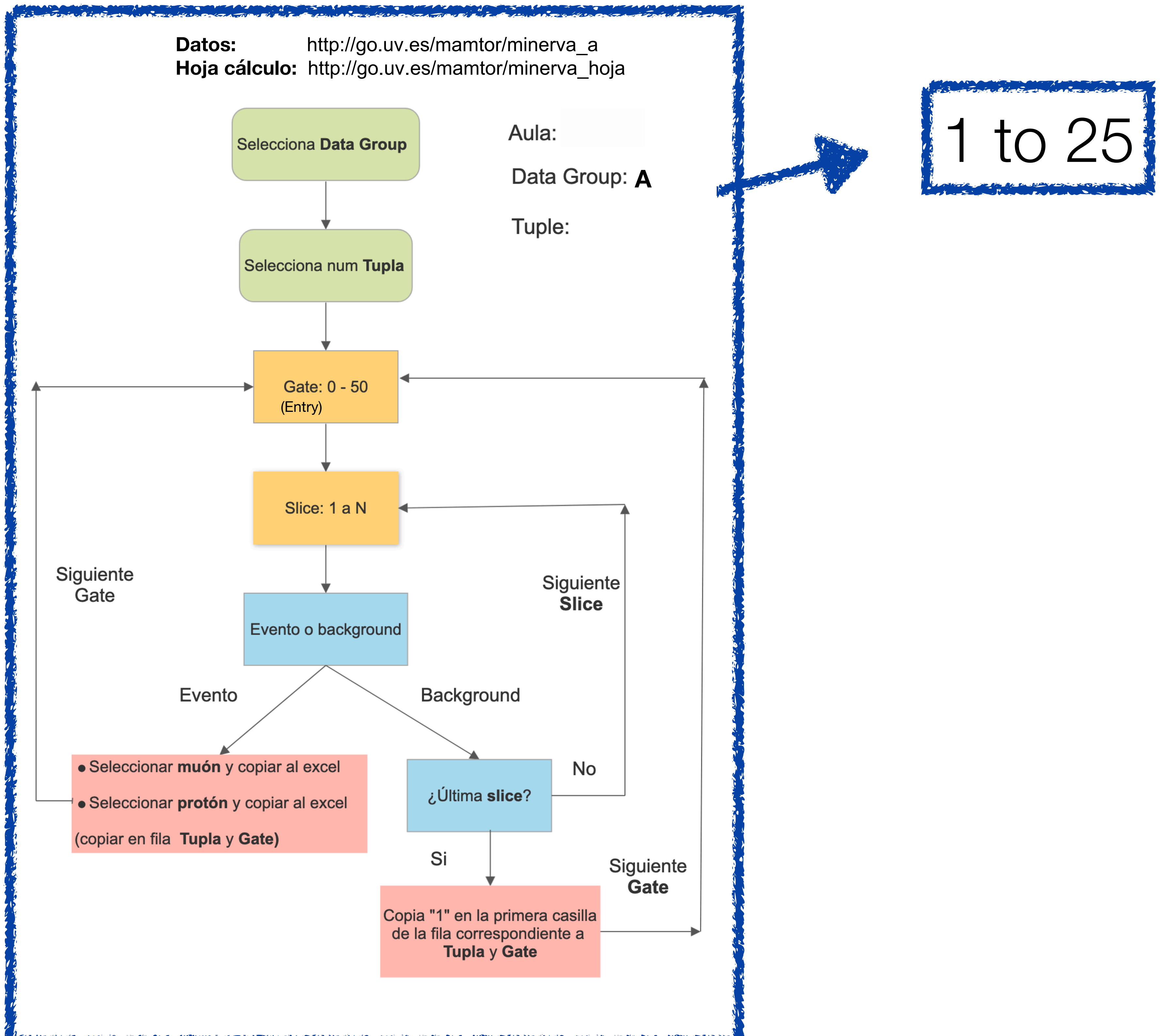
- Each student is assigned a unique **mergedTuple** (a 50-event dataset)

- We will use the **Arachne event display** to visualize, select and analyze the events

- We will use **Google Sheets** to fill kinematic information, make plots and extract results:

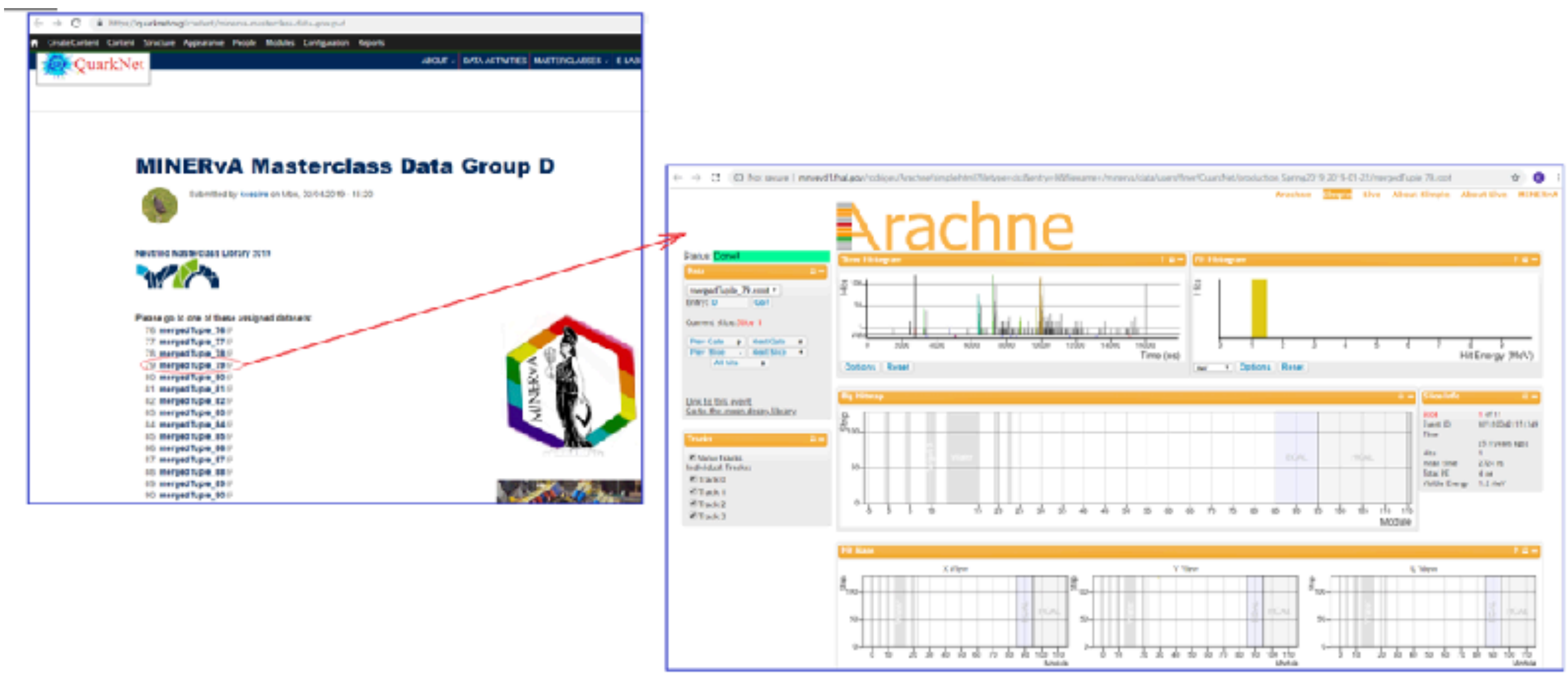
  ➡ http://go.uv.es/mamtor/minerva_hoja

First Step: Open files and assigned data



Second Step: Open and use Arachne

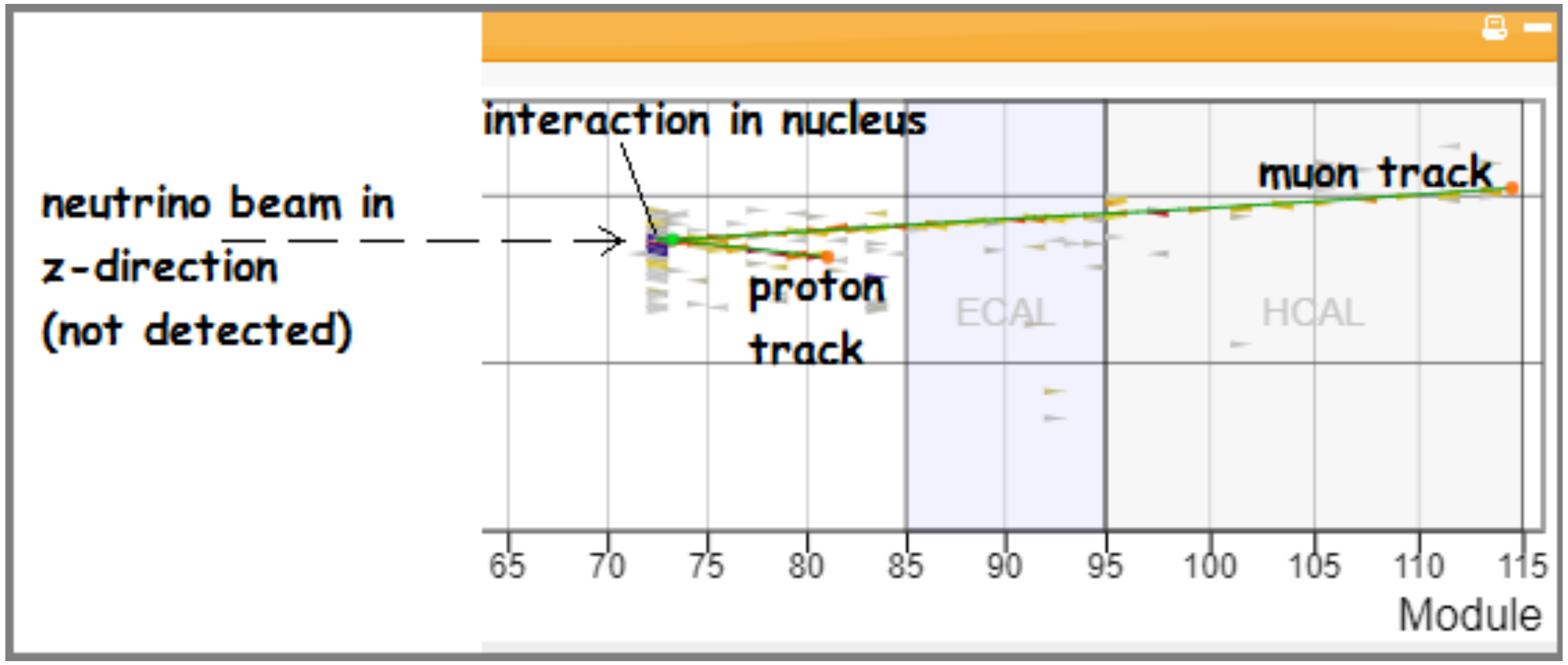
- When you click on your assigned mergedTuple, Arachne will open in a new tab



- Arachne will open at the initial time **Slice** in the first **Gate** (or event, shown as **Entry** 0; the next Gate will be Entry 1, etc.).
- In most cases, it will not initially show the event you are looking for. You must find it, if it is there, advancing from Slice to Slice within the Gate.

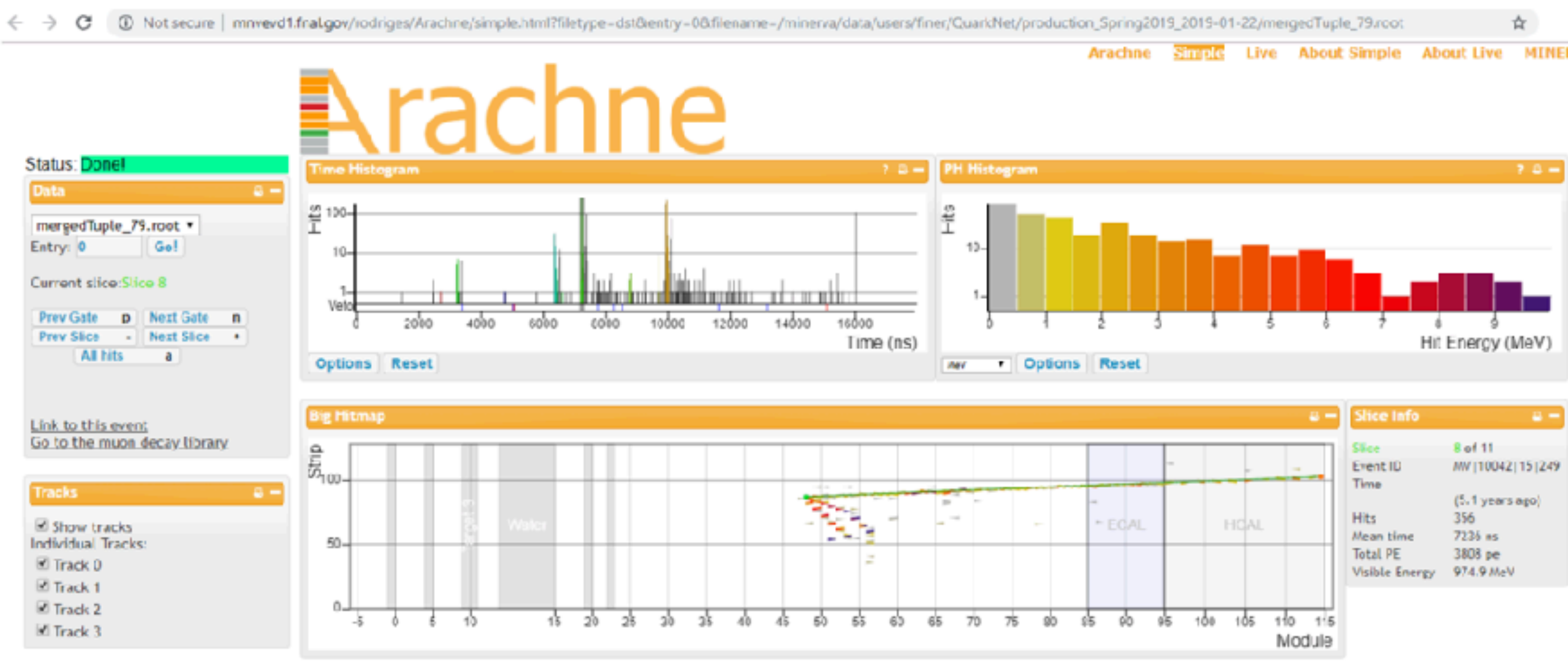
Second Step: Open and use Arachne

- You choose **Next Slice**, which moves to a slightly later time in the Gate with each click. The progress can be seen in the Time Histogram in Arachne.
- You advance the Slice until you find an instance of **one long track** and **one short track** coming from a common vertex. This is the actual event you seek:



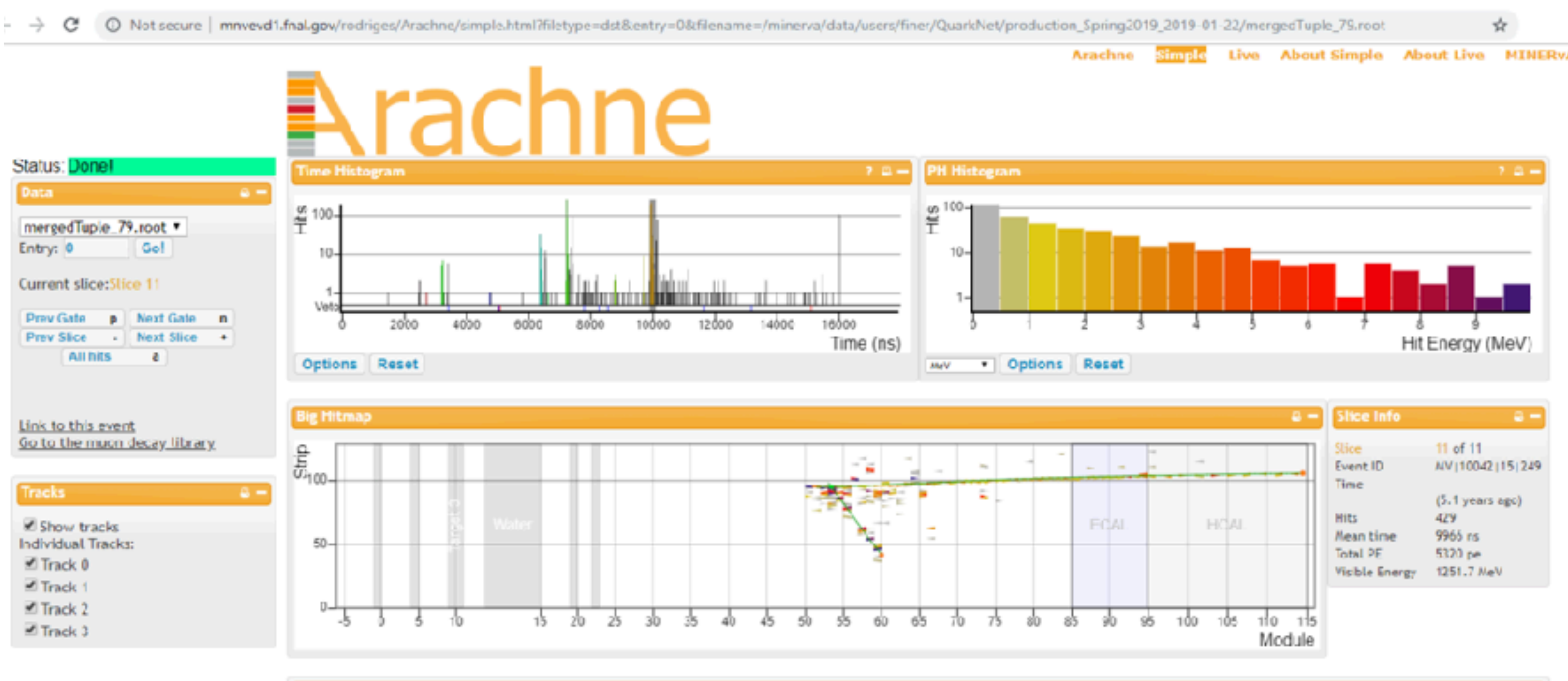
Second Step: Open and use Arachne

- In this particular **Gate**, we find two possible events but both are **background**.
- The first one, in **Slice 8** of 11, has two short tracks rather than one:



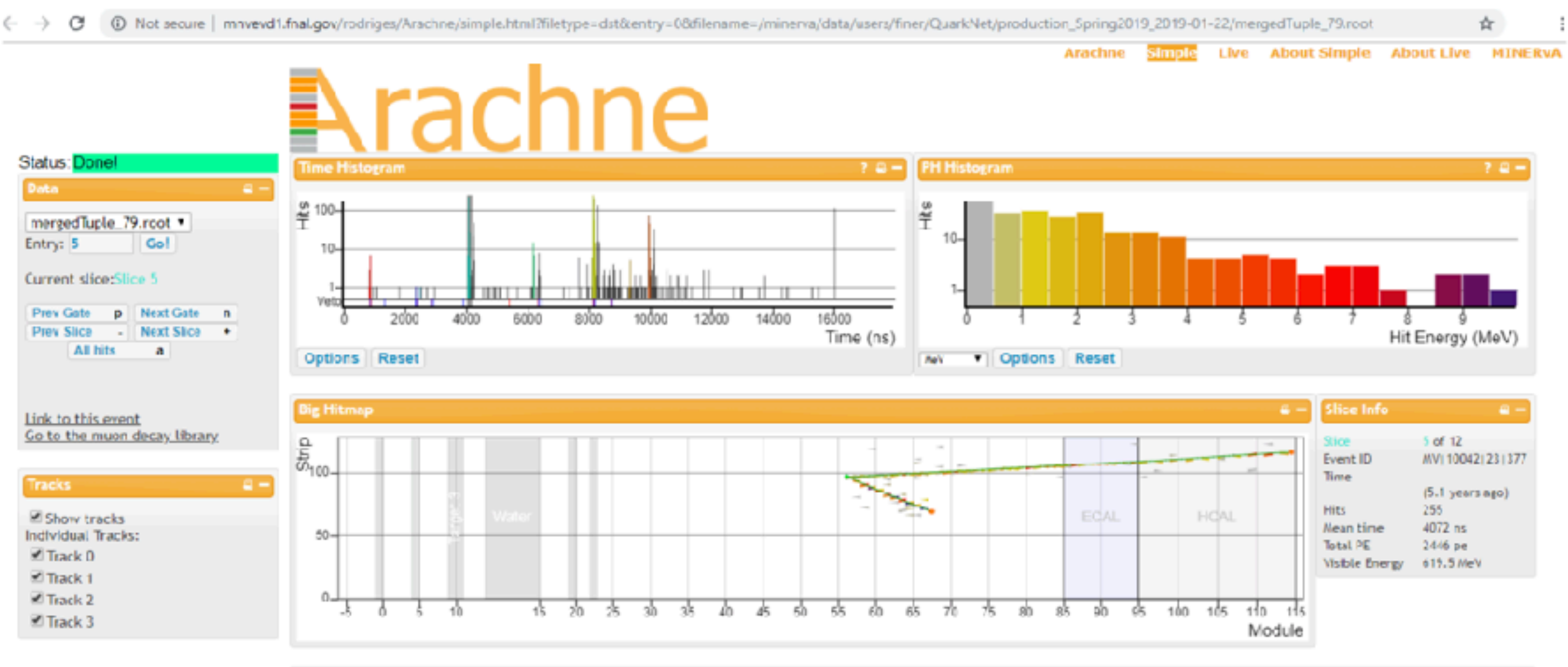
Second Step: Open and use Arachne

- The second one, in **Slice 11** of 11, has a an extra track which appears to go backwards (negative z direction) from the vertex, plus several lines of red and orange dots also coming from the same place.



Second Step: Open and use Arachne

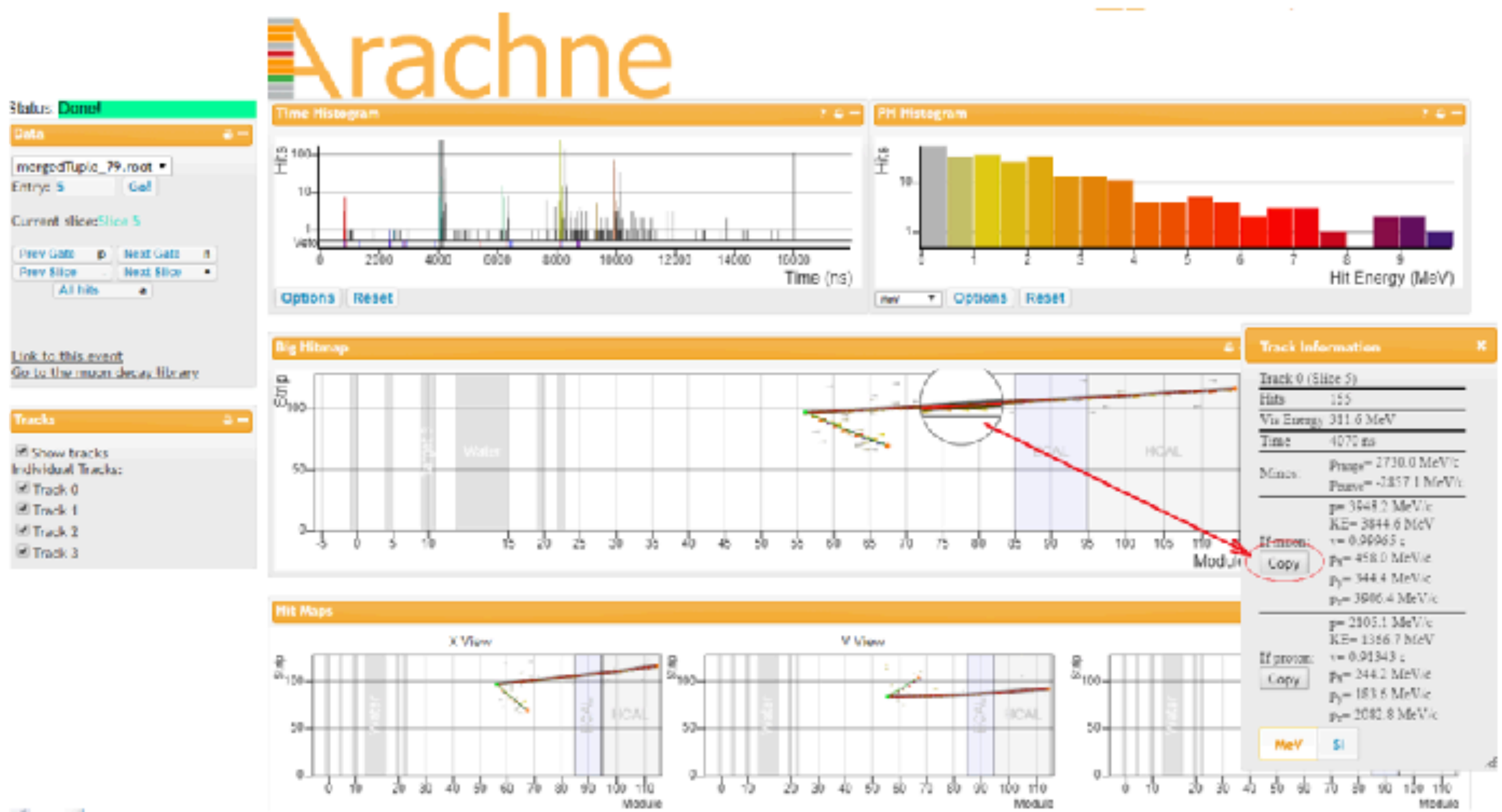
- Here is an example of a good **signal event**:



- Note we are in a different Gate!
- This is close to a "classic" event: one clear long track for the **muon** and one clear short track for the **proton**.

Second Step: Open and use Arachne

- Now you must find the **kinematics** from each track. Here we pick the long muon track:



- When you choose a track, the **Track Information box** pops up. Because this is a **muon**, you choose the Copy button for a muon.
- This copies the kinematic data for the muon to the computer clipboard.

Third Step: Enter data into the spreadsheet

- Track information is then pasted at the appropriate place in the **Valencia(A/B/F/G) Google sheet**, in this case in the row for **mergedTuple 79**, **Entry 5** and in the column under Muon KE (MeV):

Kinetic energy [MeV], velocity [c] and momentum [MeV/c]

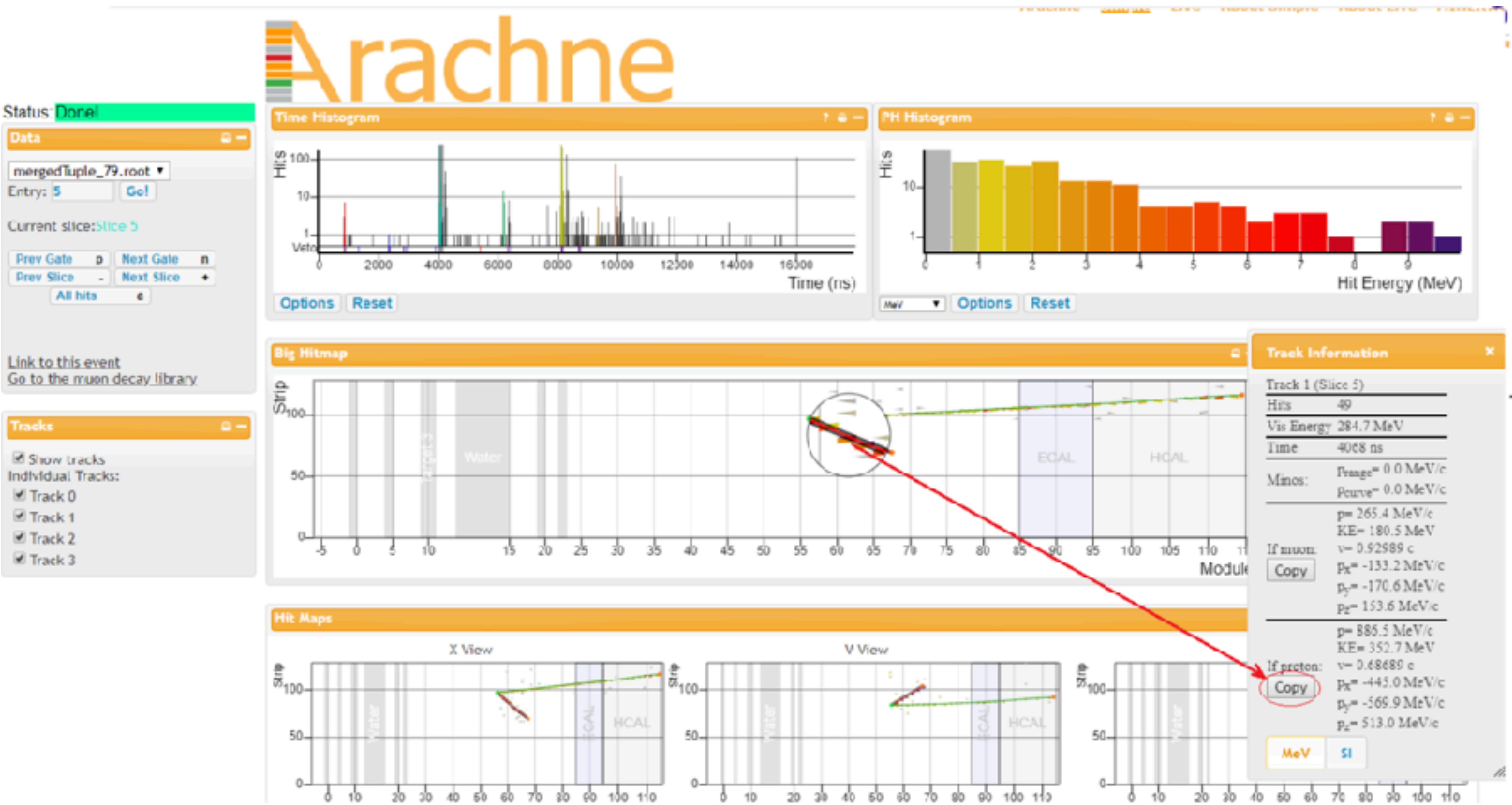
3															
4	merged		Background	Signal Event	Muon					Proton					Net
5	Tuple	Entry	(enter a 1)	Slice No	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	px (Me
154	78	38			2,463.00	0.99917	127.87	-451.51	2,527.66	250.63	0.61	282.26	73.04	659.32	
155	78	39			4,180.98	0.9997	-290.25	322.75	4,262.65	4,180.98	1	-290.25	322.75	4,252.65	
156	78	40			2,783.10	0.99934	-181.33	-468.2	2,842.18	299.54	0.65	40.96	609.33	527.92	
157	78	41													
158	78	42			3,467.68	0.99957	311.9	-624.25	3,502.30	1,219.51	0.9	169.69	-339.63	1,905.48	
159	78	43			6,862.50	0.99989	579.99	-95.45	6,941.36	330.54	0.67	-61.04	308.27	794.1	
160	78	44			70.27	0.80069	56.54	-31.5	124.52	158.34	0.52	228.67	-127.41	503.58	
161	78	45			4,687.34	0.99976	-602.76	-335.44	4,741.27	158.34	0.52	228.67	-127.41	503.58	
162	78	46			2,879.91	0.99938	-359.07	-127.86	2,957.39	1,286.94	0.91	-249.61	-86.47	2,000.18	
163	78	47			3,890.06	0.99965	295.03	433.85	3,959.00	1,397.32	0.92	-158.47	232.33	2,120.09	
164	78	48			5,784.31	0.99984	370.25	-586.18	5,847.42	169.58	0.53	-245.29	271.65	460.9	
165	78	49			3,074.27	0.99945	-228.59	-303.83	3,154.71	1,432.36	0.92	-156.6	-208.15	2,151.23	
166	78	50			5,756.19	0.99984	326.56	-411.38	5,836.57	5,784.31	1	370.25	-586.18	5,847.42	
167															
168															
169															
170															
171	79	0													
172	79	1			125.64	0.89036	111.97	-12.75	171.56	260.46	0.62	405.75	-46.31	623.59	
173	79	2													
174	79	3			2,745.79	0.99932	-396.07	-157.90	2,816.76	1,493.01	0.92	-311.93	-124.42	2,210.35	
175	79	4			235.04	0.60049	337.93	-438.13	435.93	235.04	0.6	337.93	-438.13	435.93	
176	79	5			3,844.64	0.999645564	457.9591639	344.430018	3,905.44						
177	79	6													
178	79	7													
179	79	8													
180	79	9													
181	79	10													
182	79	11													
183	79	12													
184	79	13													

mergedTuples1to25 | mergedTuples26to50 | Copy of mergedTuples51to100 | videocon plots

Add Slice No. too

Third Step: Enter data into the spreadsheet

- For the same signal event, you then choose and copy **proton track** information:



Third Step: Enter data into the spreadsheet

- Then paste the **proton kinematics** in the next cell to the right of the muon numbers:

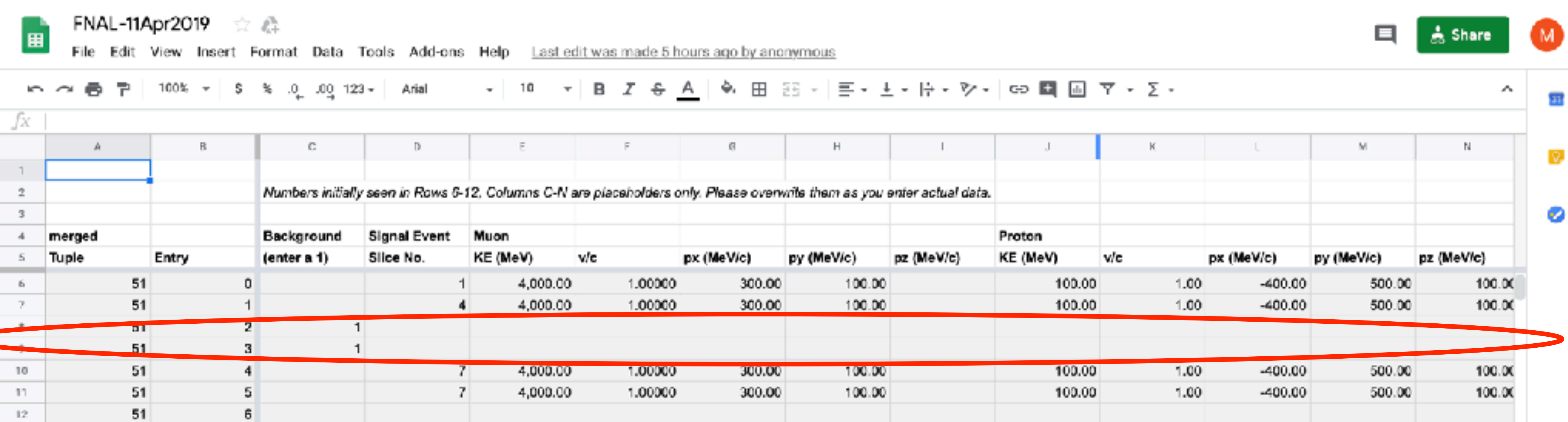
	merged		Mucn					Proton					Net	Net	nu-beam
	Tuple	Entry	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	px (MeV/c)	py (MeV/c)	pz (MeV/c)
154	78	38	2,468.00	0.99917	127.87	-451.51	2,527.66	250.63	0.61	282.26	73.04	669.32	410.13	-378.47	3,196.98
155	78	39	4,180.08	0.9997	-290.25	322.75	4,262.65	4,180.08	1	-290.26	322.75	4,262.65	-580.50	645.50	8,525.30
156	78	40	2,783.10	0.99934	-181.33	-468.2	2,842.18	299.54	0.65	40.96	609.33	527.92	-140.37	141.13	3,370.10
157	78	41													
158	78	42	3,467.68	0.99957	311.9	-624.25	3,502.30	1,219.51	0.9	169.69	-339.63	1,905.48	481.59	-9[illegible]3.68	5,407.78
159	78	43	6,862.50	0.99989	579.99	-95.45	5,941.85	330.54	0.67	-61.04	308.27	794.1	518.95	2[illegible]2.82	7,735.96
160	78	44	70.27	0.80069	56.54	-31.5	124.62	158.34	0.62	228.67	-127.41	503.58	285.21	-[illegible]58.91	628.10
161	78	45	4,687.34	0.99976	-602.76	-335.44	[illegible],741.27	158.34	0.52	228.67	-127.41	503.58	-374.09	-462.85	5,244.85
162	78	46	2,879.91	0.99938	-369.07	-127.86	2,957.39	1,286.94	0.91	-249.61	-86.47	2,000.18	-618.68	-214.33	4,957.57
163	78	47	3,890.06	0.99965	-295.93	433.85	3,[illegible]56.00	1,397.32	0.92	-158.47	232.33	2,120.09	-454.40	666.18	6,079.09
164	78	48	5,784.31	0.99984	370.25	-586.18	5,[illegible]47.42	169.58	0.53	-246.29	271.65	460.9	123.96	-314.53	6,308.32
165	78	49	3,074.27	0.99945	-228.59	-303.83	3,1[illegible]4.71	1,432.36	0.92	-156.6	-208.15	2,161.23	-385.19	-511.98	5,315.94
166	78	50	5,756.19	0.99984	326.56	-411.38	5,83[illegible].67	5,784.31	1	370.25	-586.18	5,847.42	696.81	-997.56	11,684.09
167															
168															
169															
170															
171	79	0													
172	79	1	125.64	0.89036	111.97	-12.75	171.66	260.46	0.62	406.75	-46.31	623.59	[illegible]18.72	-59.06	795.25
173	79	2													
174	79	3	2,745.79	0.99932	-396.07	-157.98	2,816.75	1,493.81	0.92	-311.93	-124.42	2,218.35	-708.00	-282.40	5,035.11
175	79	4	235.04	0.50049	337.93	-438.13	435.93	235.04	0.6	337.93	-438.13	435.93	675.86	-876.26	871.86
176	79	5	3,844.64	0.999646564	457.9591639	344.430018	3,906.44	352.6635494	0.686893643	-445.034096	-569.8872402	512.9732787	12.93	-225.46	4,419.41
177	79	6													
178	79	7													
179	79	8													
180	79	9													
181	79	10													
182	79	11													
183	79	12													
184	79	13													

mergedTuples1to25 · mergedTuples26to50 · Copy of mergedTuples51to100 · videocon plots · Sum: -148.5976145

- Note that the spreadsheet automatically calculates **Net px**, **Net py**, **nu-beam pz**

Third Step: Enter data into the spreadsheet

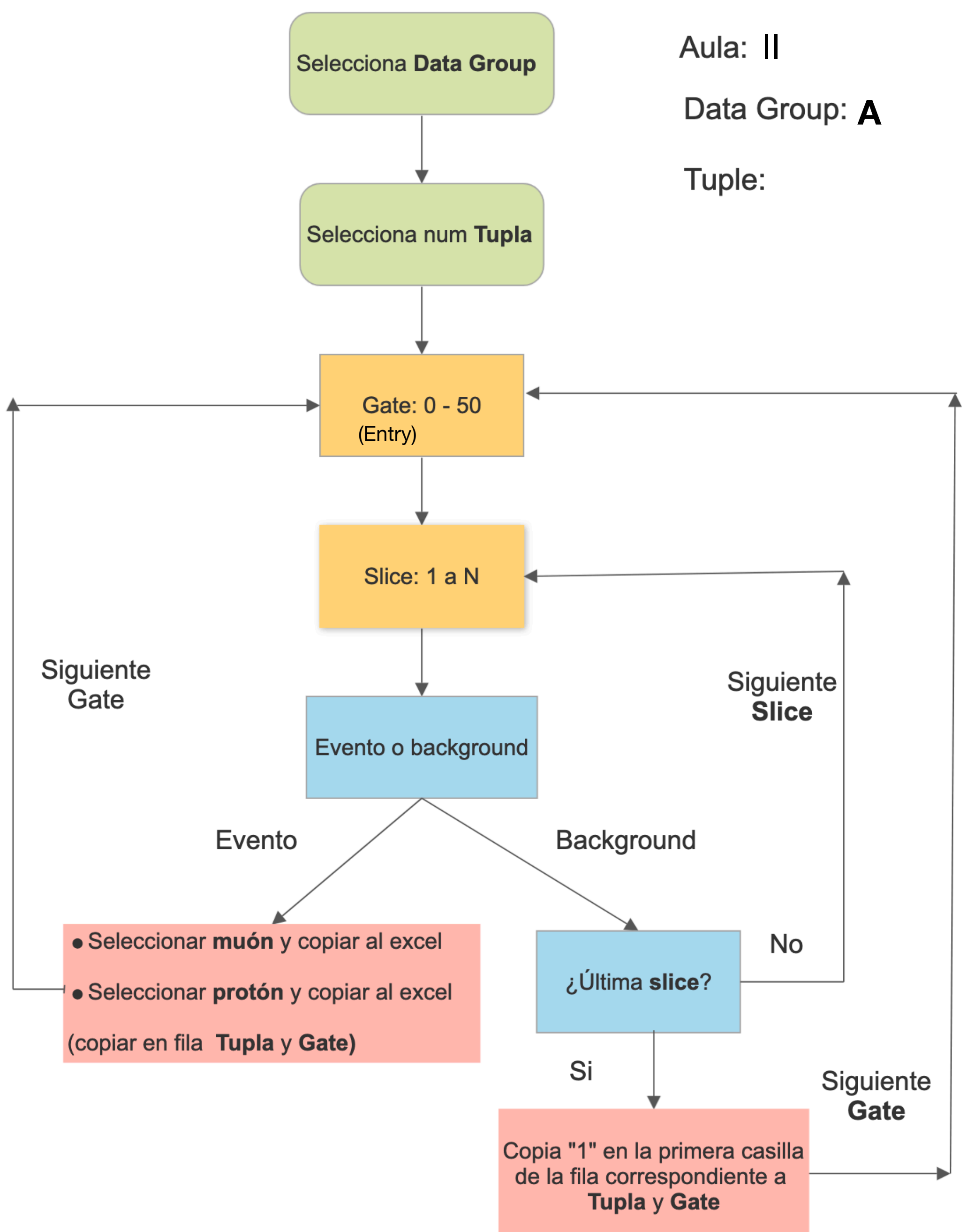
- Repeat this for all **50 entries** (or gates)
- Put a “**Background = 1**” for entries with no signal events in any time slice, leaving empty muon and proton cells



Numbers initially seen in Rows 6-12, Columns C-N are placeholders only. Please overwrite them as you enter actual data.

merged Tuple	Entry	Background (enter a 1)	Signal Event Slice No.	Muon KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	Proton KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)
51	0		1	4,000.00	1.00000	300.00	100.00		100.00	1.00	-400.00	500.00	100.00
51	1		4	4,000.00	1.00000	300.00	100.00		100.00	1.00	-400.00	500.00	100.00
51	2	1											
51	3	1											
51	4		7	4,000.00	1.00000	300.00	100.00		100.00	1.00	-400.00	500.00	100.00
51	5		7	4,000.00	1.00000	300.00	100.00		100.00	1.00	-400.00	500.00	100.00
51	6												

Datos: http://go.uv.es/mamtor/minerva_a
Hoja cálculo: http://go.uv.es/mamtor/minerva_hoja



Practice Data:

http://go.uv.es/mamtor/minerva_test

Esta tarde discutiremos los resultados obtenidos

13:00-14:30- Comida (Cafetería ETSE)

<u>Salón de actos (Edificio Cabecera, Parc Científic)</u>

14:30-14:50 - Introducción a la Facultat de Física
14:55-15:15 - Introducción al IFIC
15:15-16:00 - Comentario de resultados
16:00-17:00 - Videoconferencia con Fermilab