



MINERvA Neutrino Masterclass

Masterclass Hands on Particle Physics

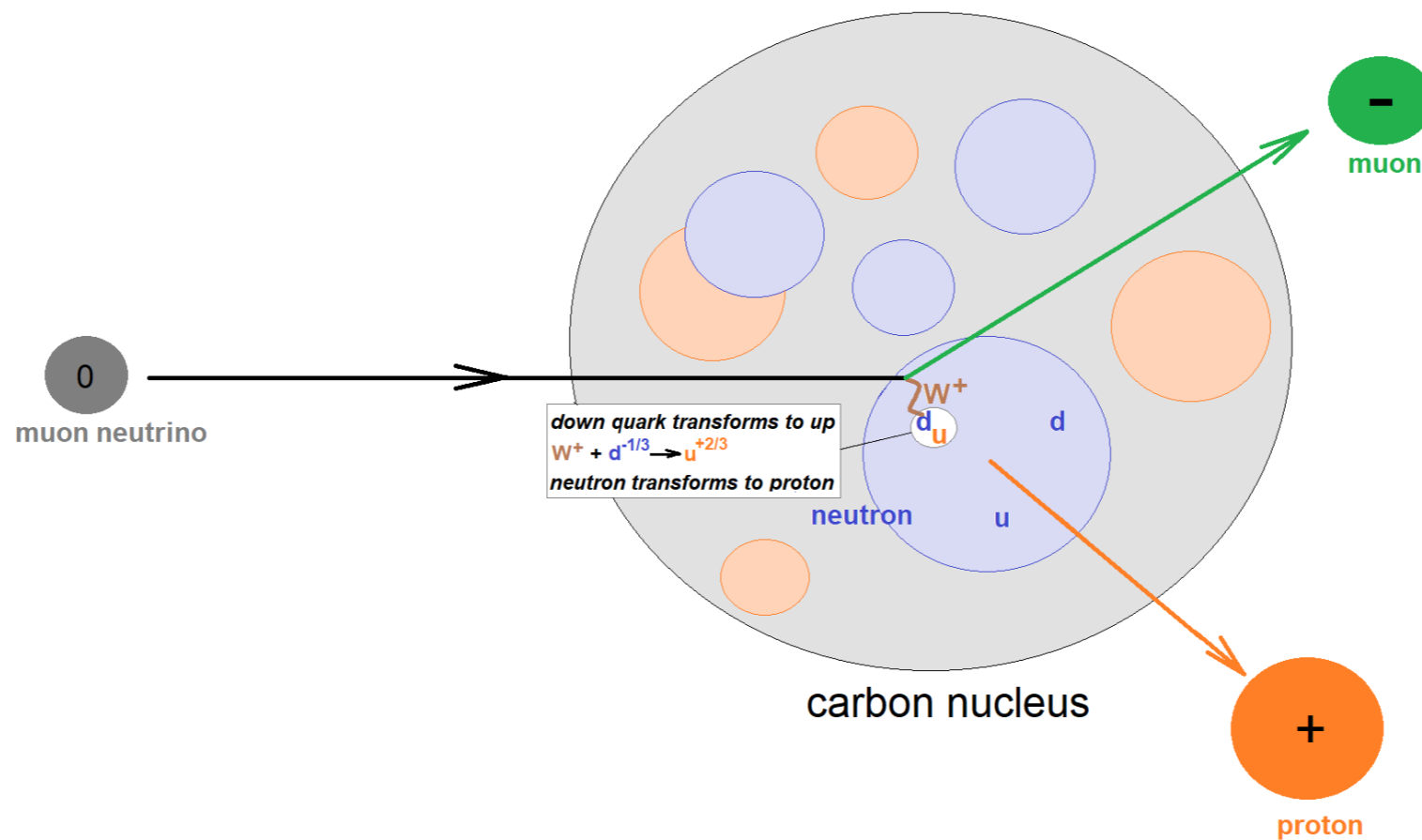
# Comentario de resultados

Mariam Tórtola

26 de marzo de 2026

# Signal and background events

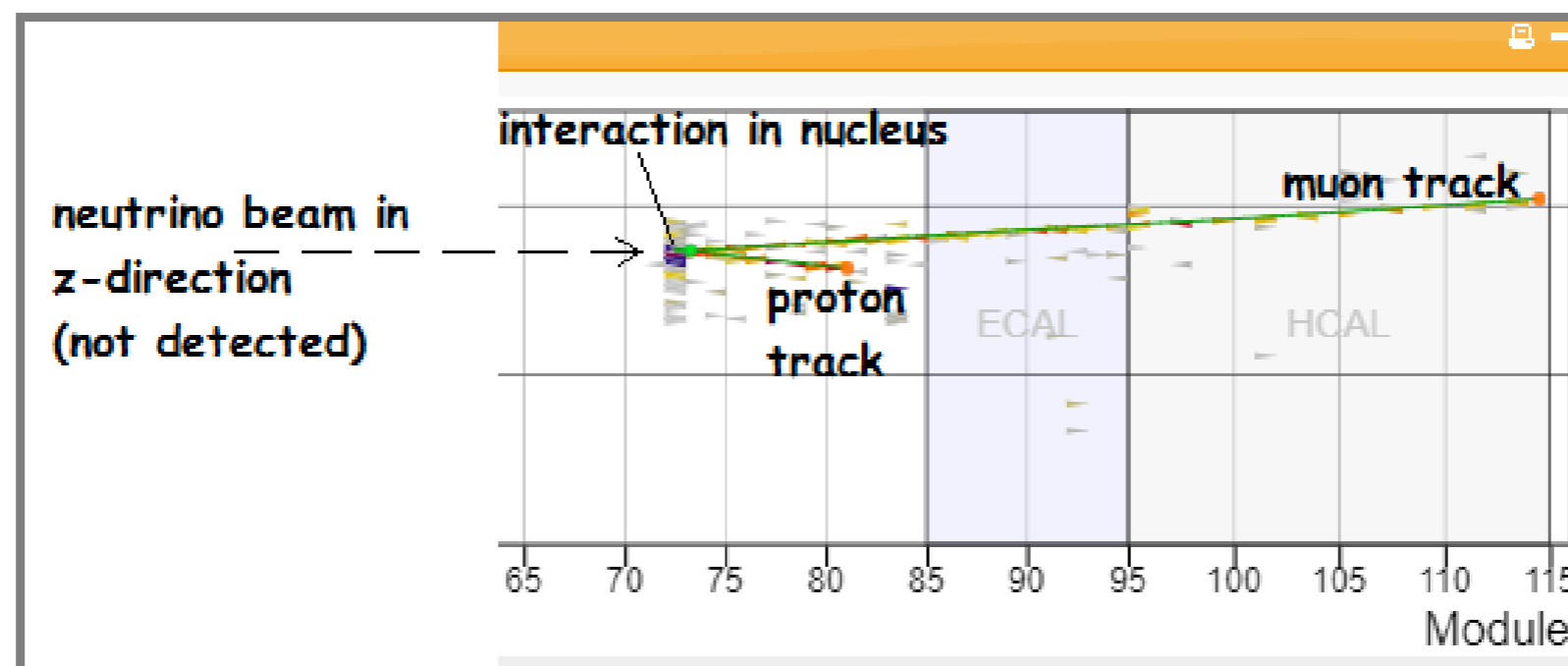
- There are both **background** and **signal** events
- In each **signal** event, a neutrino penetrates a nucleus in carbon target and undergoes a weak interaction with a neutron in that nucleus
  - The neutrino interacts with the neutron to become a muon, causing the neutron to become a proton!



- **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.

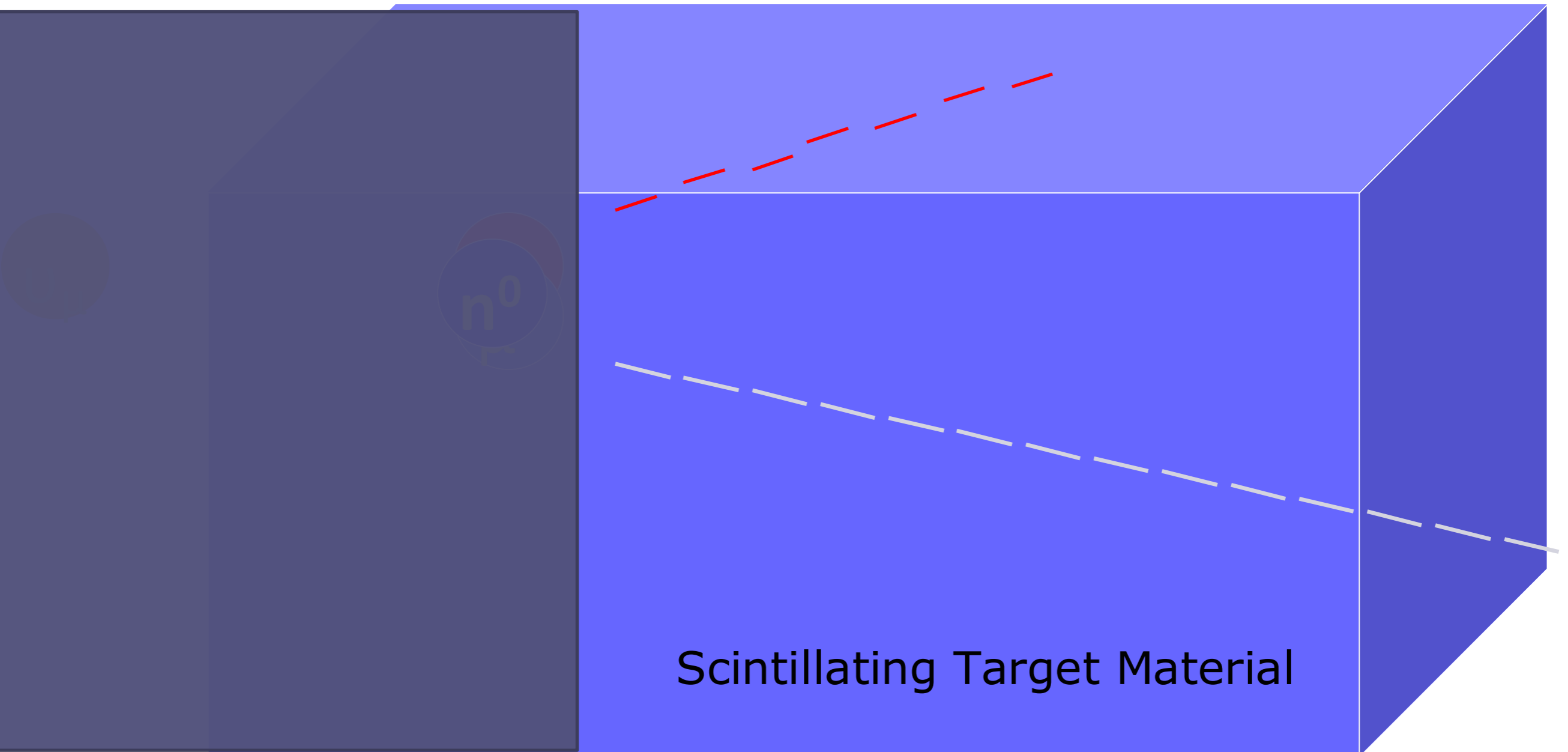


# MINERvA's Principal Interaction Of Interest (*What we see*)



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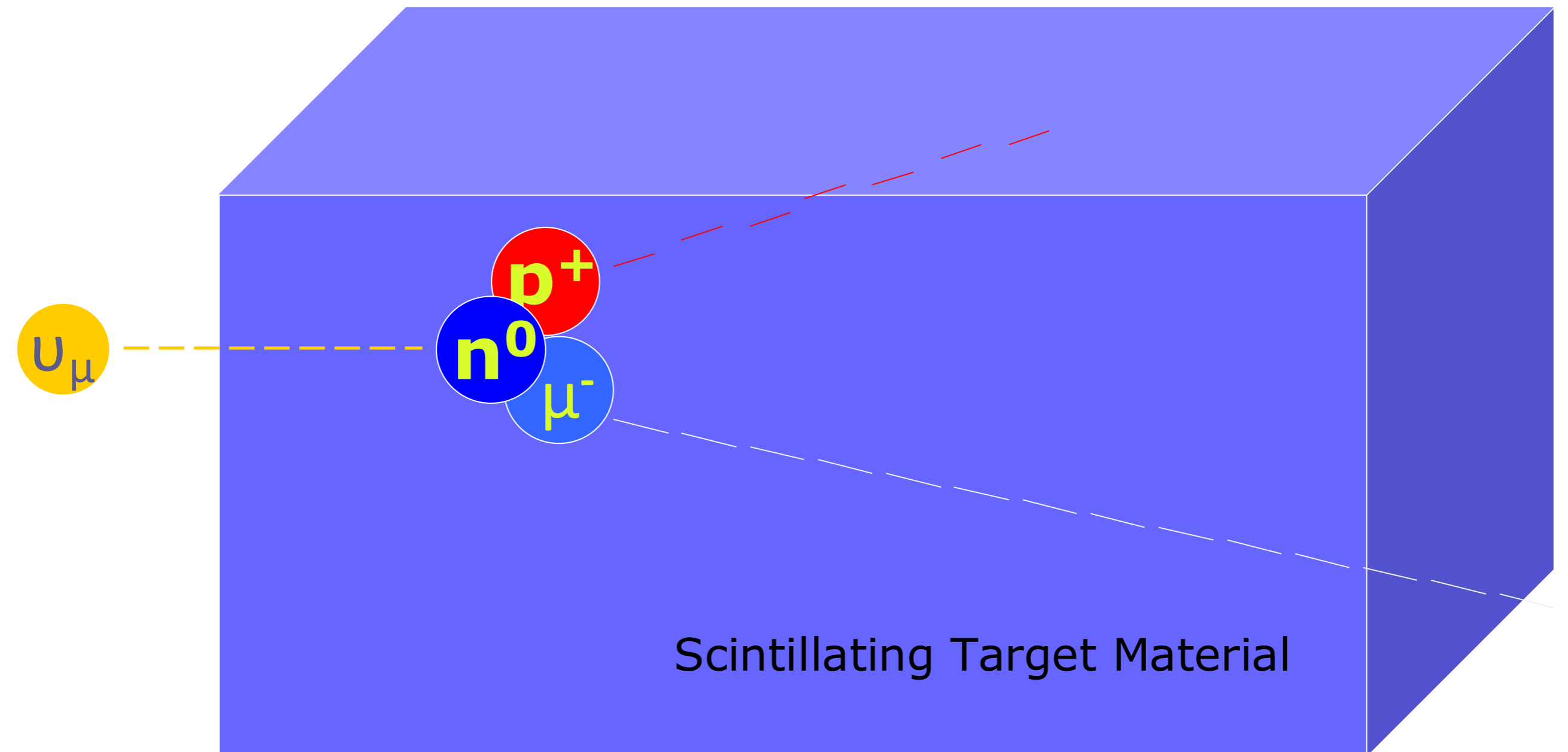
A proton and muon “appear” out of nowhere  
in the scintillating target



# MINERvA's Principal Interaction

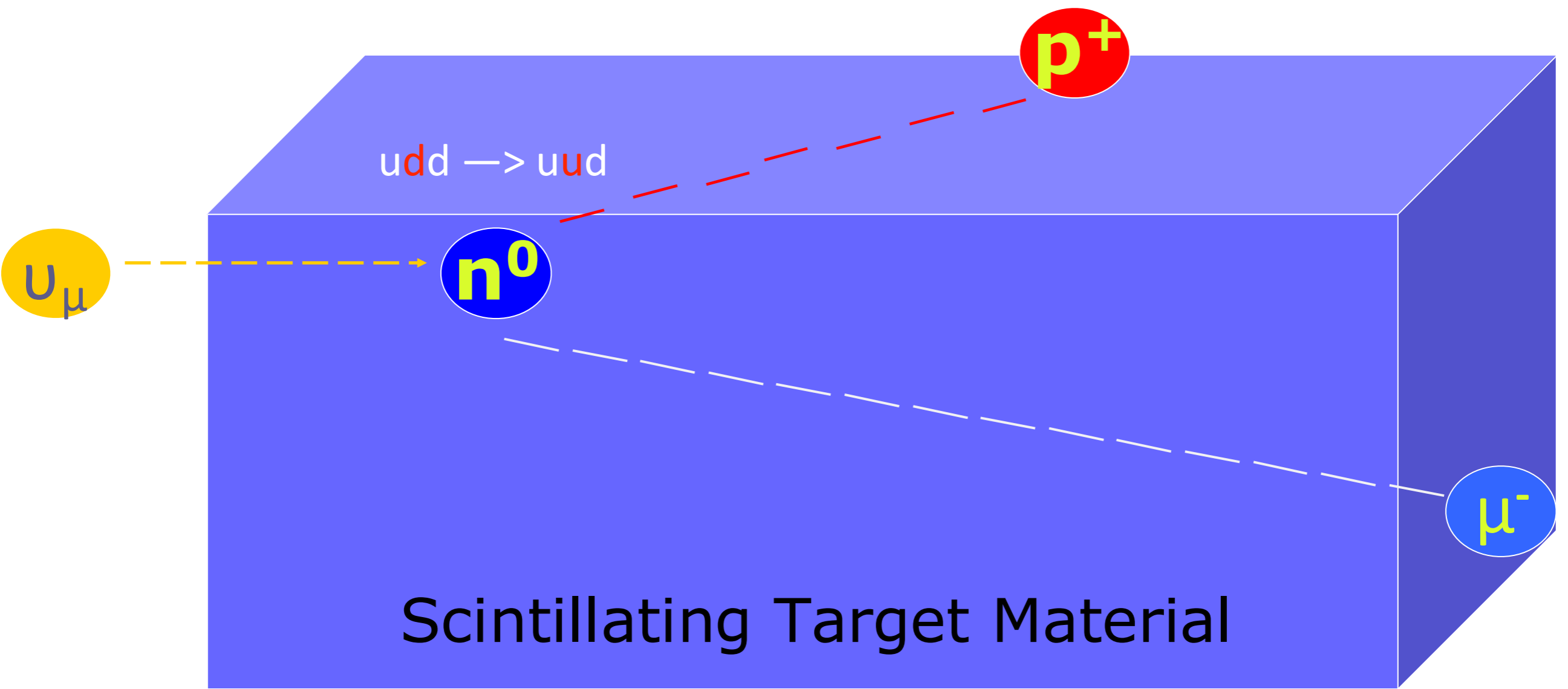
Of Interest (**Revealed**)

**neutrino + neutron  $\rightarrow$  proton + muon**

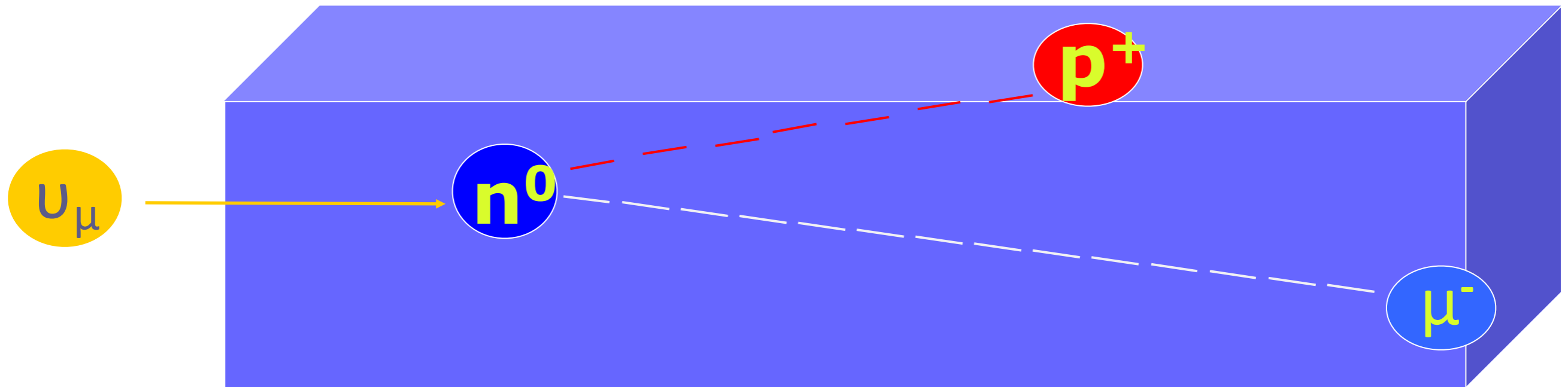


# What's Going On?

- 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



# What's Going On?



- Also, there is a net gain of mass & a loss of energy during the interaction ( $E = \Delta mc^2$ )
- Some of the neutrino's pre-collision kinetic energy changes into new mass (the muon) and some is transferred to the kinetic energies of the muon and proton.

# Masterclass objectives

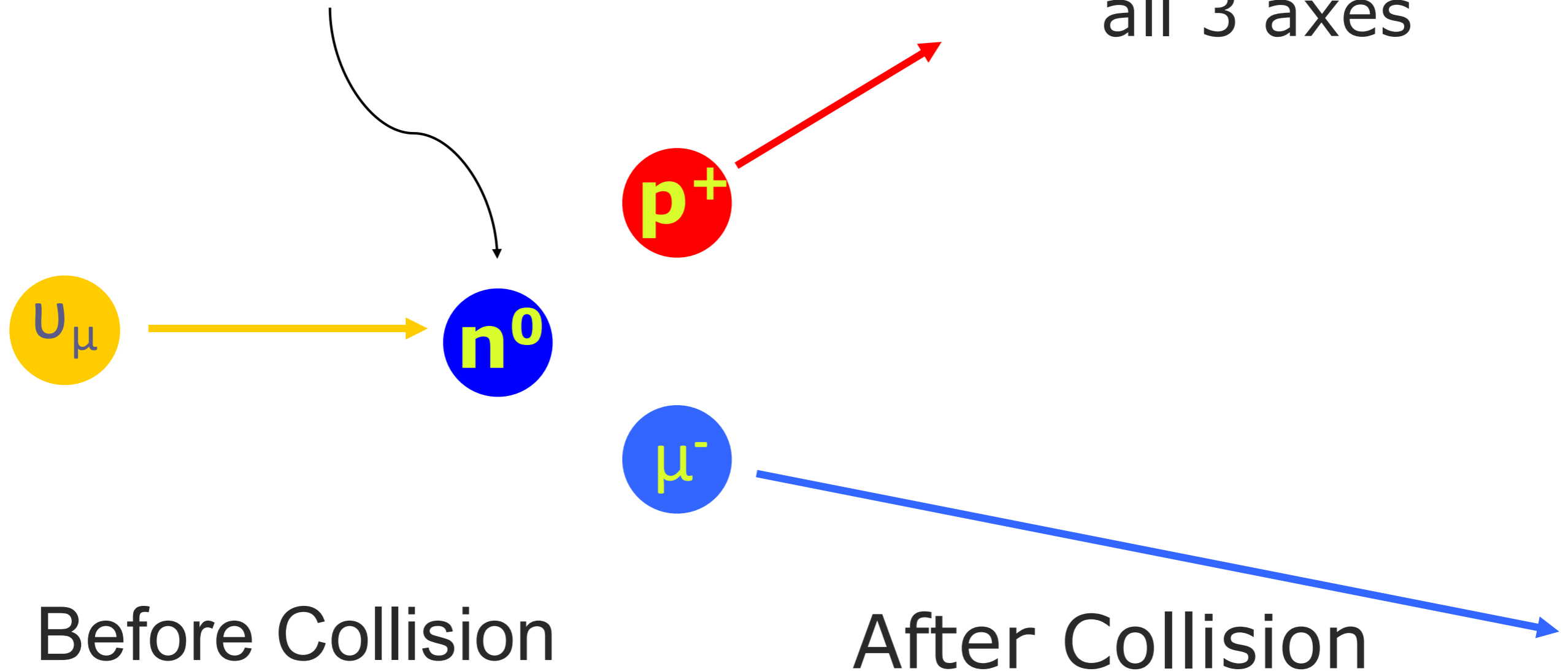
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- Determine which events are **signal** events (*from which effective measurements may be made*) and which events are **background** (that cannot be used for measurements).
- Apply conservation of momentum and energy to measure the approximate **energy 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!**

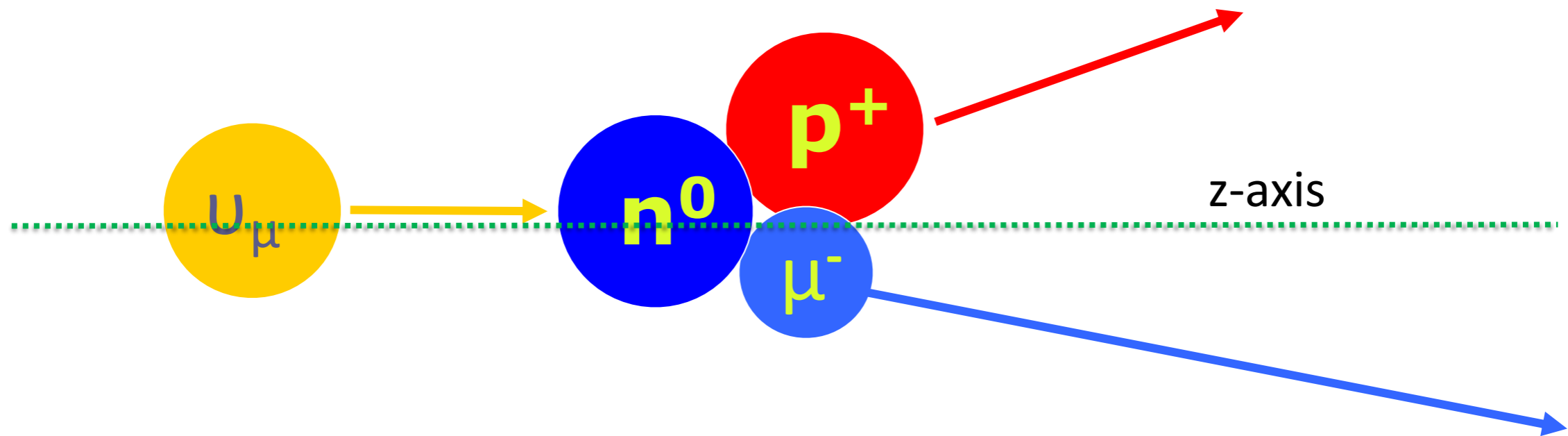
Momentum is conserved in all 3 axes



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

# Momentum Conservation

The beam is aimed so that neutrinos only have momentum in the z-axis!



$$\mathbf{p}_{\text{neutrino}} + \mathbf{p}_{\text{neutron}} = \mathbf{p}_{\text{proton}} + \mathbf{p}_{\text{muon}}$$

In the z-axis:  $\mathbf{p}_{\text{neutrino}} = \mathbf{p}_{\text{proton}} + \mathbf{p}_{\text{muon}}$

# Momentum Conservation

In the z-axis:  $p_{\text{neutrino}} = p_{\text{proton}} + p_{\text{muon}}$

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Cells initially seen in Rows 6-9, Columns C-N are placeholders only. Please overwrite them as you enter actual data. Cells below (Columns O, P, and Q) contain form

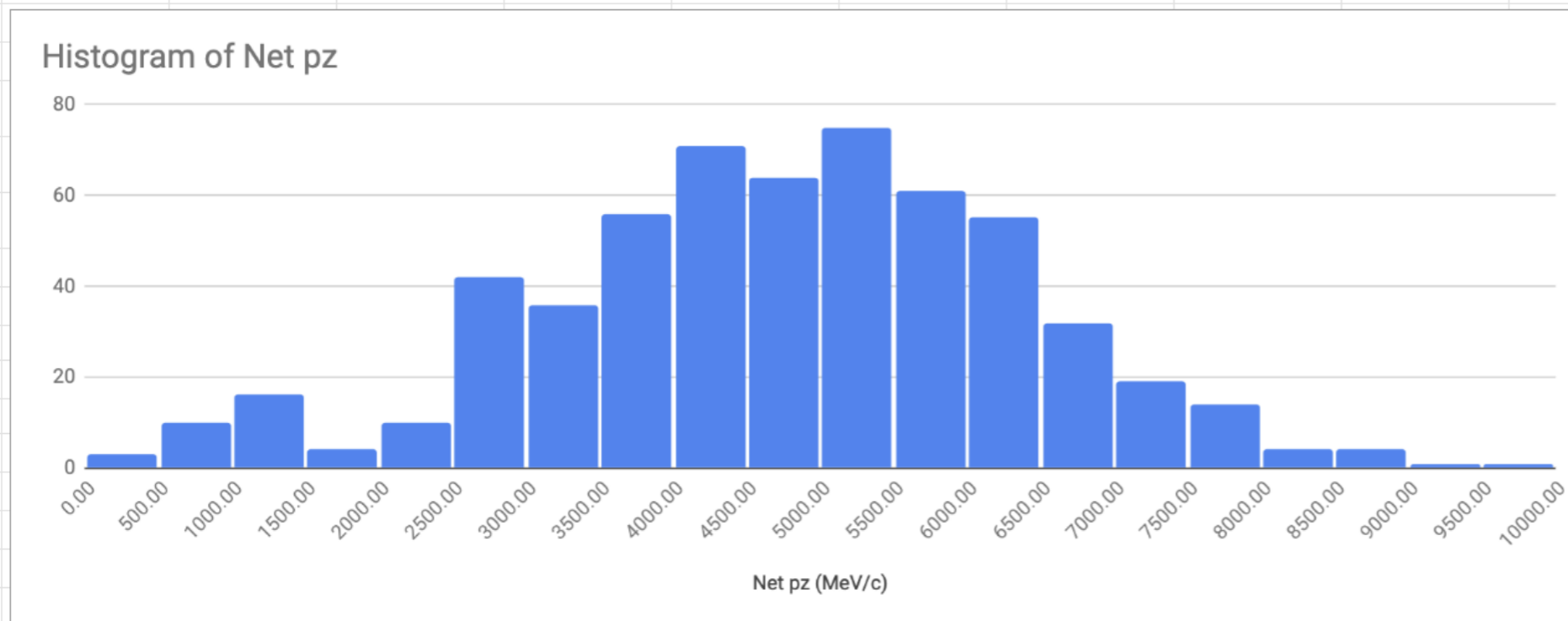
merged	ground	Signal Event	Muon	Proton	Net	Net	nu-beam									
Tuple	Entry	a 1)	Slice No.	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	KE (MeV)	v/c	px (MeV/c)	py (MeV/c)	pz (MeV/c)	px (MeV/c)	py (MeV/c)	pz (MeV/c)
1	0		8.00	3,900.91	1.00	216.88	-618.13	3,950.59	149.67	0.51	-404.93	168.17	333.0	-188.05	-449.96	4,283.
7	1	1	6	3657.228461	0.9996104682	481.1571926	-404.2494757	3,707.88	229.23	0.60	-377.94	366.27	453.4	103.21	-37.98	4,161.
8	1	2	13	5433.205762	0.999820258	305.8229353	450.1413187	5510.403178	222.54	0.59	-276.19	-252.49	571.8	29.63	197.65	6,082.
9	1	3	4	2789.784268	0.9993419497	-387.6257508	-83.01515678	2865.589942	317.1095393	0.6644360457	589.2264459	259.7579881	529.899932	201.60	176.74	3,395.
10	1	4	16	3,256.78	0.99951	296.85	-621.23	3,288.84	331.88	0.67	-691.93	226.69	450.0	-395.08	-394.54	3,738.
11	1	5	1	4,303.67	0.99972	-103.46	-484.88	4,379.44	151.40	0.51	-25.26	388.02	394.65	-128.72	-96.86	4,774.
12	1	6	1													
13	1	7	16	4,685.40	0.9997597532	477.5293491	252.9459501	4,758.66	129.9290636	0.4780447288	377.5155437	231.3060912	254.1810209	855.04	484.25	5,012.
14	1	8	12	3,737.62	0.9996266001	-600.6682665	-27.70212263	3,793.83	100.6545082	0.4294483008	-311.3805579	56.40446148	314.3562823	-912.05	28.70	4,108.
15	1	9	3	4,848.45	0.999775311	-295.4307845	257.0810679	4,936.83	138.8654079	0.4912003088	66.94732257	408.0054534	329.9162209	-228.48	665.09	5,266.
16	1	10	10	5,703.09	0.9998365752	-474.3692348	-89.88577369	5,787.03	132.451618	0.4818282709	429.8556261	129.3239493	254.01	-44.51	39.44	6,041.
17	1	11	1	4,423.82	0.9997311957	-268.6516708	-310.446515	4,508.95	138.2201278	0.4902730271	315.7212772	358.8118567	223.561826	315.72	358.81	223.
18	1	12	2	1,495.91	0.9978468197	471.9893509	79.2221565	1,524.09	253.9384696	0.6170124695	-7.308542741	41.89963611	734.2099979	464.68	121.12	2,258.
19	1	13	1													
20	1	14	3	5968.814264	0.999850563	411.6492861	-458.6319542	6041.555785	201.5686747	0.5678697201	-318.4285188	417.114398	378.6708619	93.22	-41.52	6,420.
21	1	15	4	5,935.67	0.9998489186	-334.7303114	-222.6615757	6,026.36	340.2139228	0.6793261568	296.6579432	266.1358802	771.4613344	-38.07	43.47	6,797.
22	1	16	6	3095.915258	0.9994618329	505.3873747	-148.0682539	3155.549537	361.0675456	0.6918342247	-109.0857395	-201.3911907	869.0652321	396.30	-349.46	4,024.
23	1	17	5	5,102.75	0.9997967206	-123.3501849	-467.8972533	5,184.15	428.9783452	0.7274270972	402.8763775	-421.8996347	805.2807702	279.53	-889.80	5,989.
24	1	18	3	4,418.65	0.9997305799	614.2480472	-116.6250692	4,479.00	241.6544384	0.6064152697	-569.261259	205.8403261	381.1980759	44.99	89.22	4,860.
25	1	19	1													
26	1	20	2	2,430.83	0.9991423822	474.4661225	206.4491596	2,480.26	216.2790297	0.5827820969	133.9362614	357.8620846	553.6351549	608.40	564.31	3,033.
27	1	21	15	5609.308424	0.9998311668	396.7338001	283.2996877	5692.507298	330.1919794	0.6730075067	-556.1958358	-385.950933	519.7643371	-159.46	-102.65	6,212.
28	1	22	12	4309.795476	0.9997171287	173.1898586	-695.6785874	4354.931765	402.31	0.7142993076	-179.4135308	713.3972245	612.74	-6.22	17.72	4,967.
29	1	23	1													
30	1	24	1													
31	1	25	9	3,573.89	0.9995926165	-15.82238301	615.0232122	3,625.56	237.7528978	0.6029398099	192.5382952	-424.0572708	534.4673167	176.72	190.97	4,160.
32	1	26	13	5588.667733	0.9998299403	-206.0610921	-555.2936103	5661.803166	241.85	0.6065851845	228.4296524	523.0015086	431.84	22.37	-32.29	6,093.

Valencia - DG A Valencia - DG B Valencia - DG F Valencia - DG G videocon plots

[http://go.uv.es/mamtor/minerva\\_hoja](http://go.uv.es/mamtor/minerva_hoja)

# Momentum Conservation

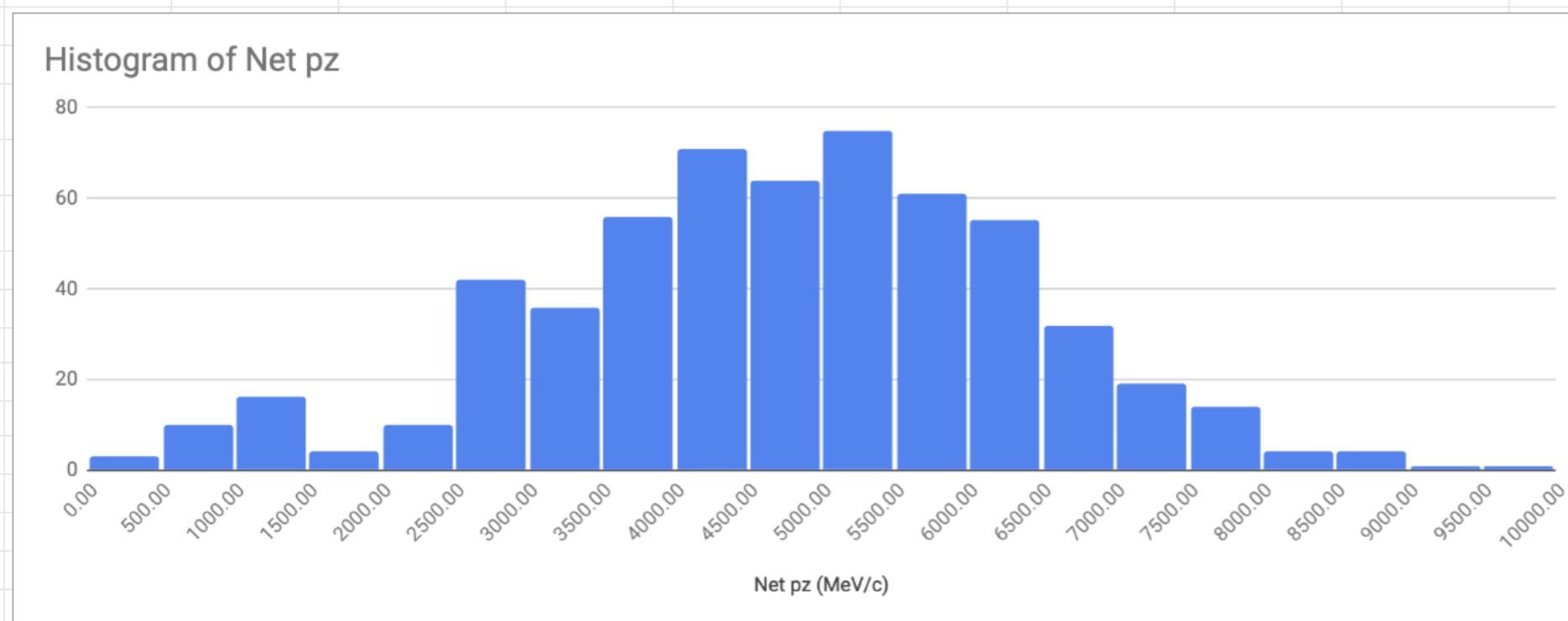
In the z-axis:  $p_{\text{neutrino}} = p_{\text{proton}} + p_{\text{muon}}$



Avg pz = 4,790.89 MeV/c  
Med pz = 4,842.17 MeV/c  
StdDev= 1735.003 MeV/c

# Momentum Conservation

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Avg pz = 4,790.89 MeV/c  
Med pz = 4,842.17 MeV/c  
StdDev = 1735.003 MeV/c

$$\text{Avg } p_z = \sum_{i=1}^N \frac{p_z^i}{N}$$

**Average or mean value**

**Med pz = median**

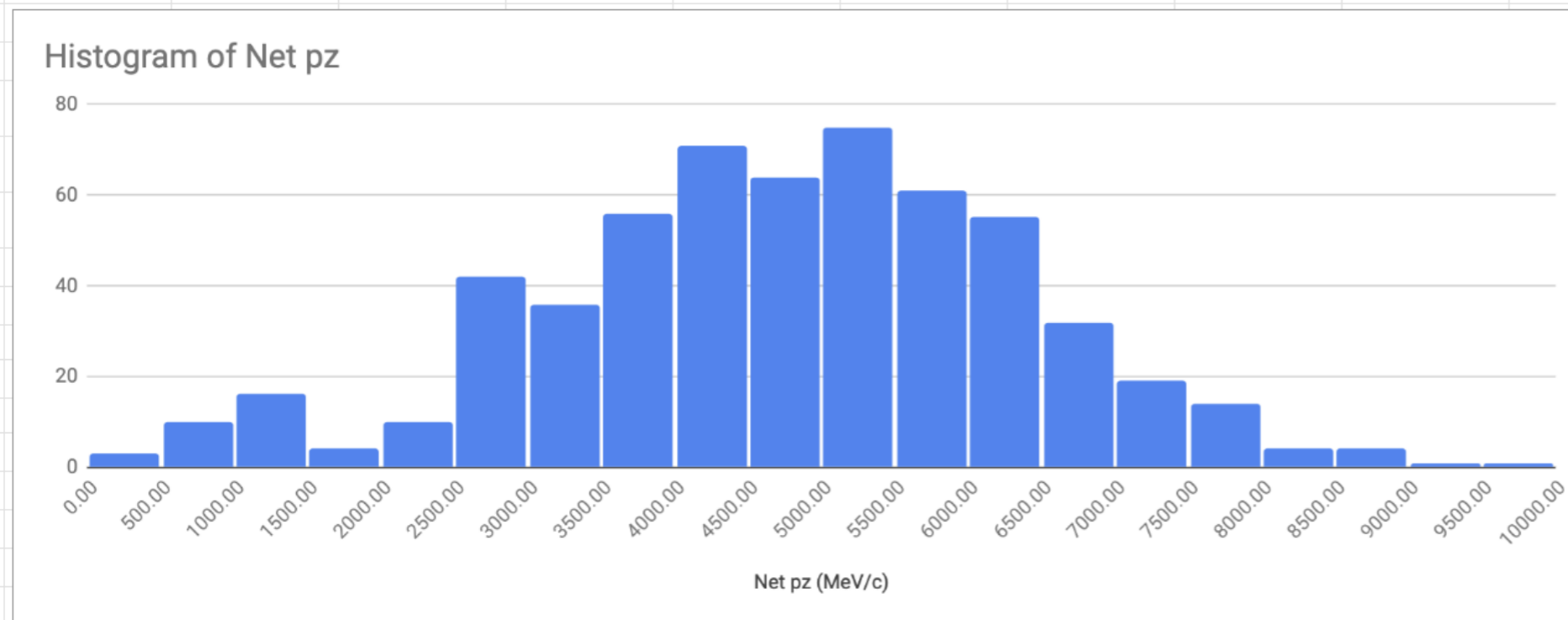
**central value in a distribution**

**StdDev = standard deviation**

**dispersion of the data**

# Momentum Conservation

In the z-axis:  $p_{\text{neutrino}} = p_{\text{proton}} + p_{\text{muon}}$



Avg pz = 4,790.89 MeV/c  
Med pz = 4,842.17 MeV/c  
StdDev= 1735.003 MeV/c

⇒ We can reconstruct the initial **neutrino momentum**

$$E^2 = p^2c^2 + m^2c^4$$

For neutrinos:  $pc \gg mc^2$

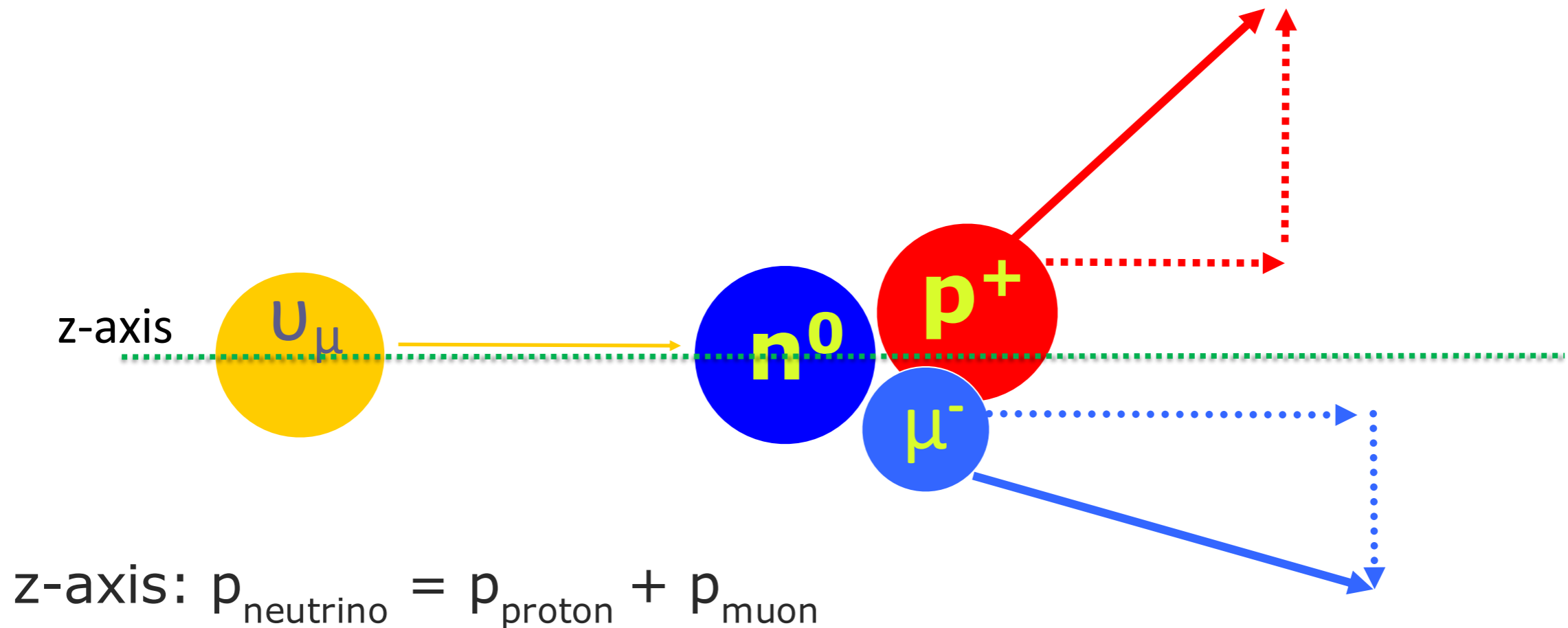
⇒

$$E_{\text{beam}} = p_{\text{neutrino}} c$$

⇒

**initial neutrino energy**

# Momentum Conservation

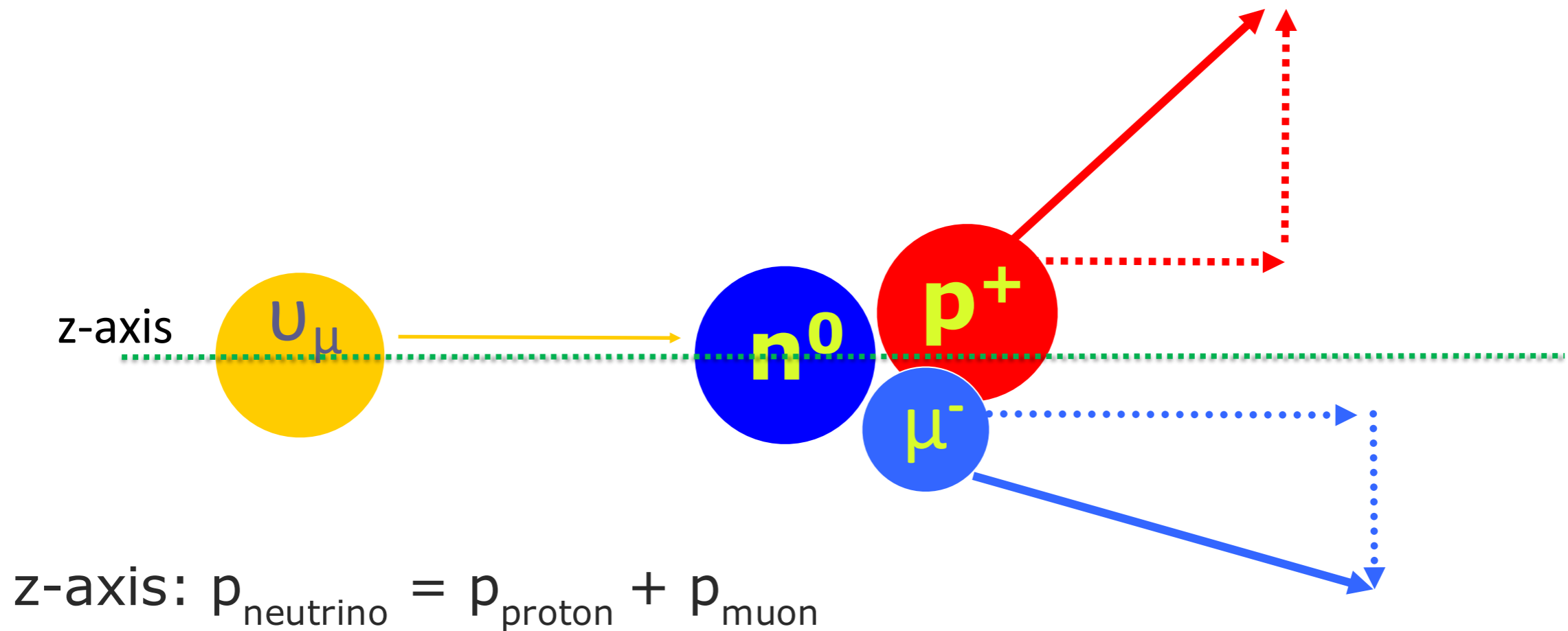


If the target neutron is totally at rest...

... then in the x-axis & y-axis

$$p_{\text{proton}} + p_{\text{muon}} = 0$$

# Momentum Conservation



If the target neutron has **motion**...

... then in the x-axis & y-axis

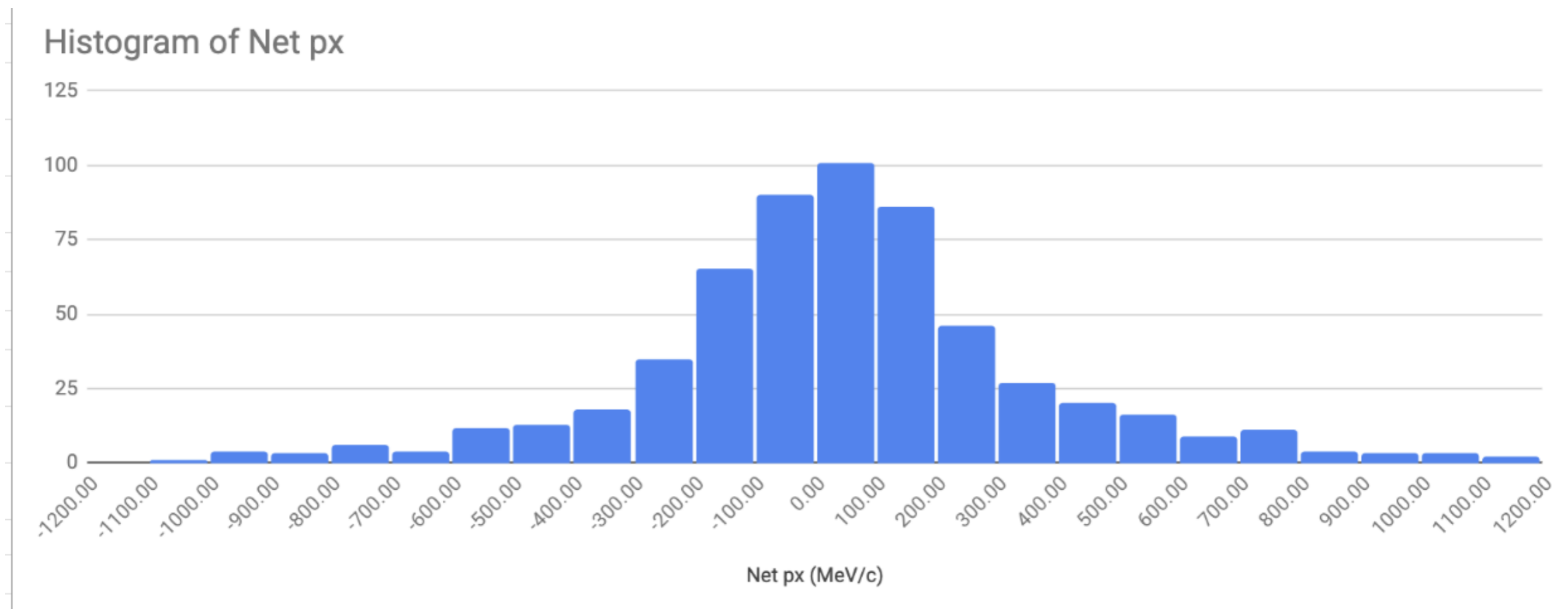
$$p_{\text{proton}} + p_{\text{muon}} \neq 0$$

# Momentum in x-y directions

x-y axis:  $p_{\text{neutron}} = p_{\text{proton}} + p_{\text{muon}}$

$p_{\text{proton}} + p_{\text{muon}} \approx 0$

Histograms net  $p_x$



⇒ distribution centered in 0

$\Delta p_x = 336.7 \text{ MeV/c}$

⇒ width of the distribution of  $p_x$  :  $\Delta p_x$

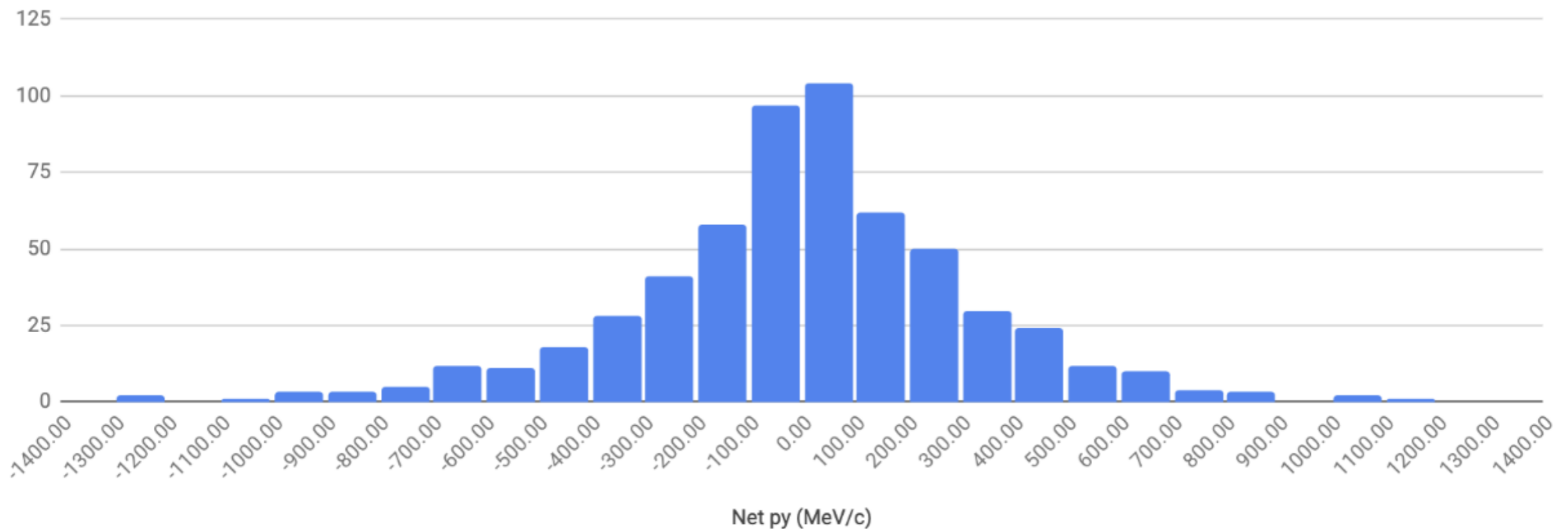
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$$p_{\text{proton}} + p_{\text{muon}} \approx 0$$

Histograms net  $p_y$

Histogram of Net  $p_y$



⇒ distribution centered in 0

$$\Delta p_y = 323.6 \text{ MeV/c}$$

⇒ width of the distribution of  $p_y$  :  $\Delta p_y$

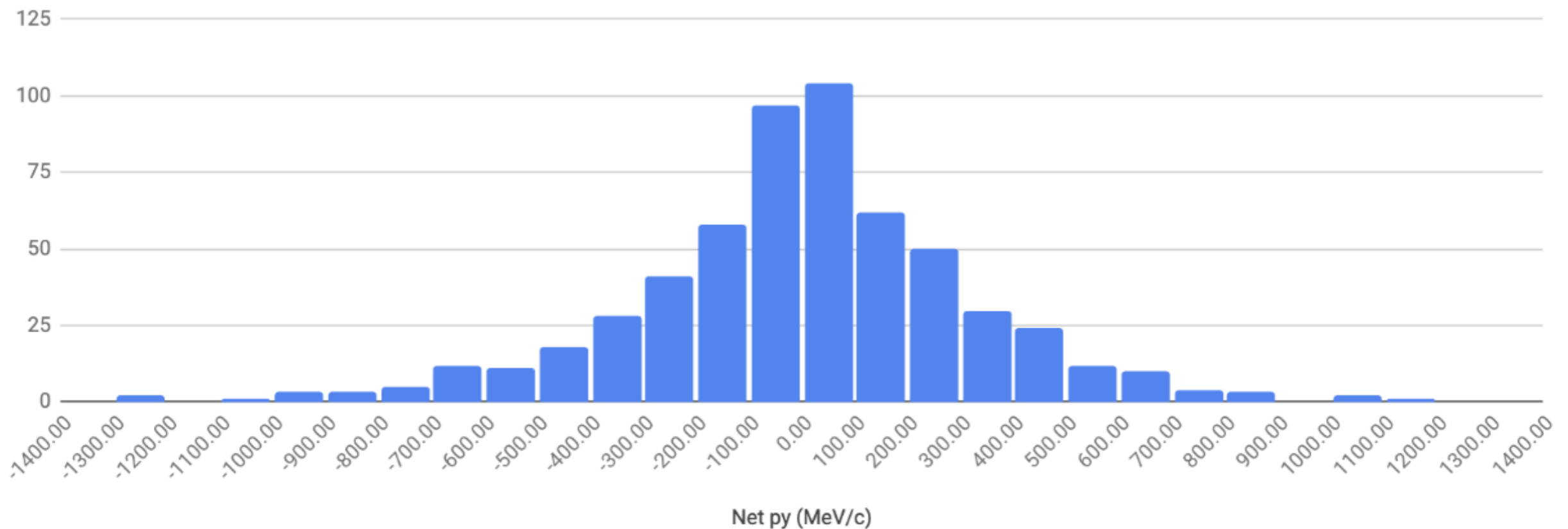
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Histograms net  $p_y$

Histogram of Net  $p_y$



⇒ distribution centered in 0

⇒ width of the distribution of  $p_y$  :  $\Delta p_y$

**But: neutron at rest!!**

Origin of neutron momentum ?

# Origin of neutron momentum ?

1) Classical thermal equilibrium of neutrons with atoms in the scintillator

$$T = 300K \rightarrow \langle KE_n \rangle = \frac{3}{2} k_B T = 3.9 \times 10^{-8} \text{ MeV}$$

$$\langle p_n \rangle = \sqrt{2m_n \langle KE_n \rangle} = 8.5 \times 10^{-3} \text{ MeV}/c$$

**Too small!!**

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$$\langle p_n \rangle = \sqrt{2m_n \langle KE_n \rangle} = 8.5 \times 10^{-3} \text{ MeV}/c$$

2) **Heisenberg uncertainty principle** and neutron confinement in the nucleus

$$\Delta p_x \Delta x \geq h/4\pi \rightarrow \Delta p_x = (100 \text{ MeV} \cdot \text{fm}/c) / \Delta x$$

**Better, but still  
small**

$$\Delta x = 2 \cdot R = (1.25 \text{ fm}) A^{1/3} = 5.7 \text{ fm} \rightarrow \Delta p_x \geq 18 \text{ MeV}/c$$

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3) **Fermi gas**: exclusion principle applied to neutrons confined in the nucleus

$$\rightarrow p_{\text{Fermi}} = \left( \frac{3\pi^2 N}{V} \right)^{1/3} = 241 \text{ MeV}/c$$

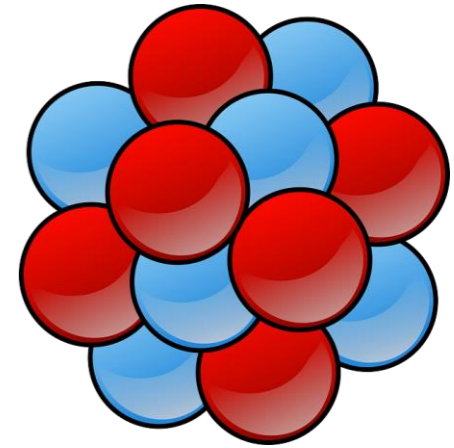
**Typical value of transverse moment in MINERvA**

# Estimation of the radius of the nucleus

The results on transverse momentum of the neutron can be used to estimate the size of the **carbon nuclear radius**.

⇒ We can compare our results with the average radius of a nucleus with A nucleons:

$$R = R_0 A^{1/3} = (1.25 \text{ fm}) A^{1/3} \rightarrow R(\text{C}, A=12) = 2.9 \text{ fm}$$



1) **Heisenberg** uncertainty principle:

$$\Delta p_x \Delta x \geq h/4\pi \rightarrow R \approx \Delta x = (100 \text{ MeV} \cdot \text{fm}/c) / \Delta p_x$$

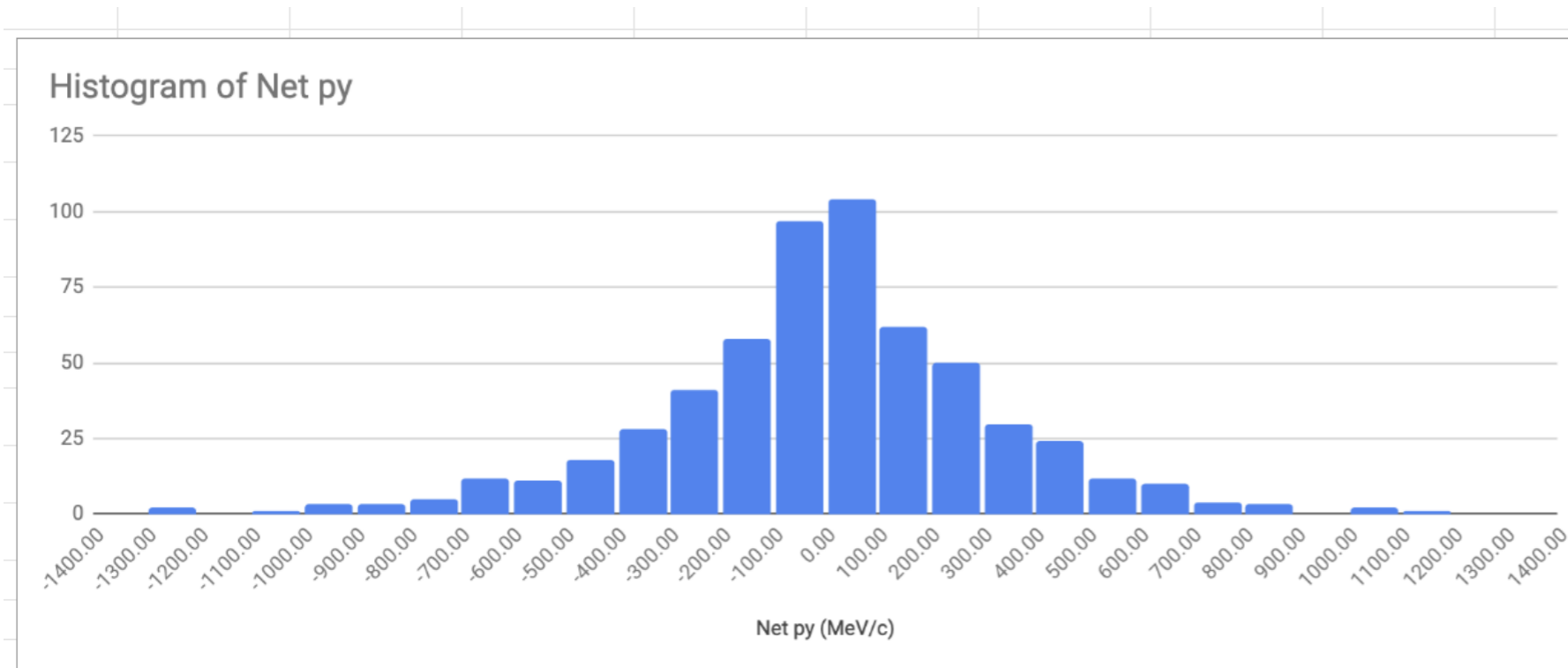
**Estimation of R**

2) **Fermi gas** approximation: neutrons must obey the exclusion principle

$$p_{\text{Fermi}} = \left( \frac{3\pi^2 N}{V} \right)^{1/3} \rightarrow p_{\text{Fermi}}(^{12}\text{C}) \simeq \frac{300 \text{ MeV}/c}{R_0}$$

**Estimation  
of  $R_0$**

# Momentum Conservation in x-y



Calculated:

Std Dev = 323.64 MeV/c

delta-y = 0.31 fm (Heisenberg)

delta-y = 0.93 fm (Fermi Gas)

Visual:

(FWHM/2) =

Std Dev = 250.00

delta-x = 0.40 fm (Heisenberg)

delta-x = 1.20 fm (Fermi Gas)

$$\Delta p_x, \Delta p_y \Rightarrow \Delta x, \Delta y$$

**Estimation of C  
nuclear radius R and R<sub>0</sub>**

$$R = R_0 A^{1/3} = (1.25 \text{ fm}) A^{1/3} \rightarrow R(\text{C}, A=12) = 2.9 \text{ fm}$$

$$R_0 = 1.25 \text{ fm}$$

[http://go.uv.es/mamtor/minerva\\_hoja](http://go.uv.es/mamtor/minerva_hoja)



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Masterclass Hands on Particle Physics

# Videokonferencia

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<https://go.uv.es/mamtor/videoconf>