Reconstruction studies of $1\mu 1p$ fully contained $\nu_\mu CC$ events from the Booster neutrino beam with the ICARUS detector

Imaging Cosmic And Rare Underground Signals

INTENSE Meeting

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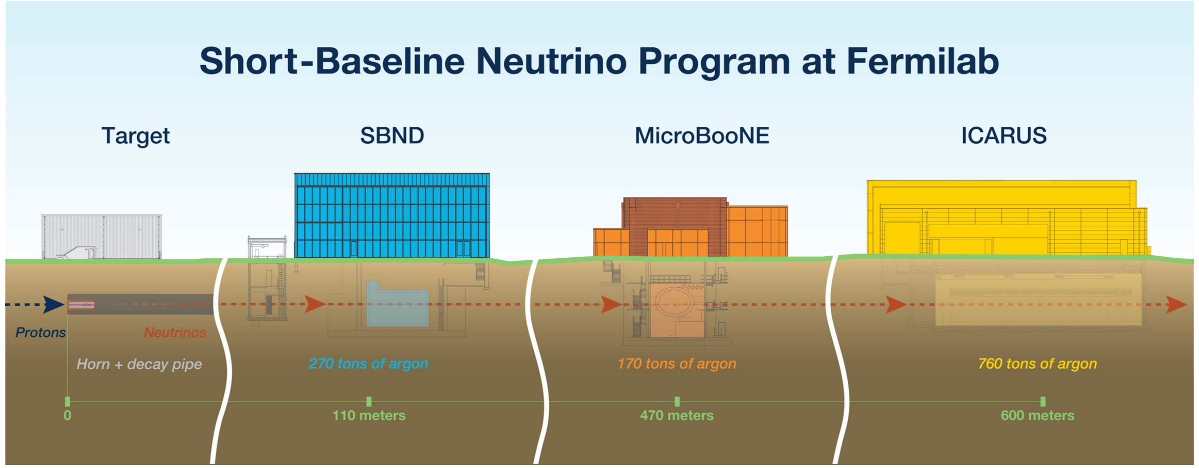
Sterile neutrino search

- Several anomalies have been observed in neutrino oscillation experiments, some of them can be explained by introducing an additional sterile neutrino state (ν_s)
- Short Baseline Neutrino (SBN) program should clarify this question by exploiting the BNB beam and comparing the neutrino interactions observed at different distances along the baseline by ICARUS and SBND



- Both ν_e appearance and ν_μ disappearance channels can be observed, granting access to study the nature of the observed anomalies and shed light on the existence of the sterile neutrino
- NEUTRINO-4 experiment has recently claim the observation of sterile neutrino oscillations, therefore ICARUS has started taking data alone to address this declaration

- A first step towards this goal is to focus on the study of ν_μCC quasi elastic interactions with the BNB

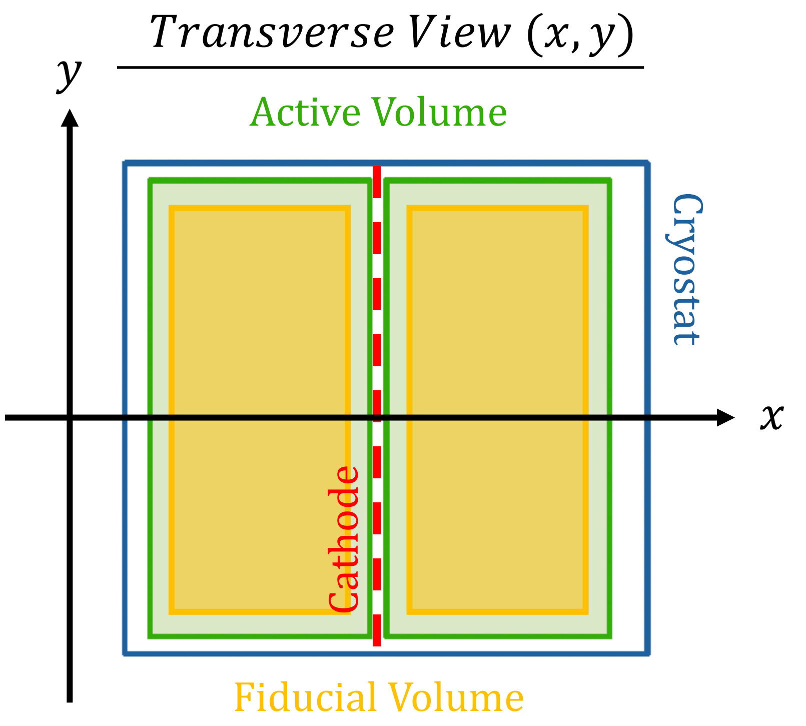
Introduction

- This is an update of my previous studies including all the new available $1\mu1p$ candidates from the visual scan effort
- Last time I reported 91 events, this sample has increased up to **520 $\boldsymbol{1\mu1p}$ candidates**
- As usual, the $1\mu1p$ sample contains a muon track longer than 50 cm and only 1 visible proton

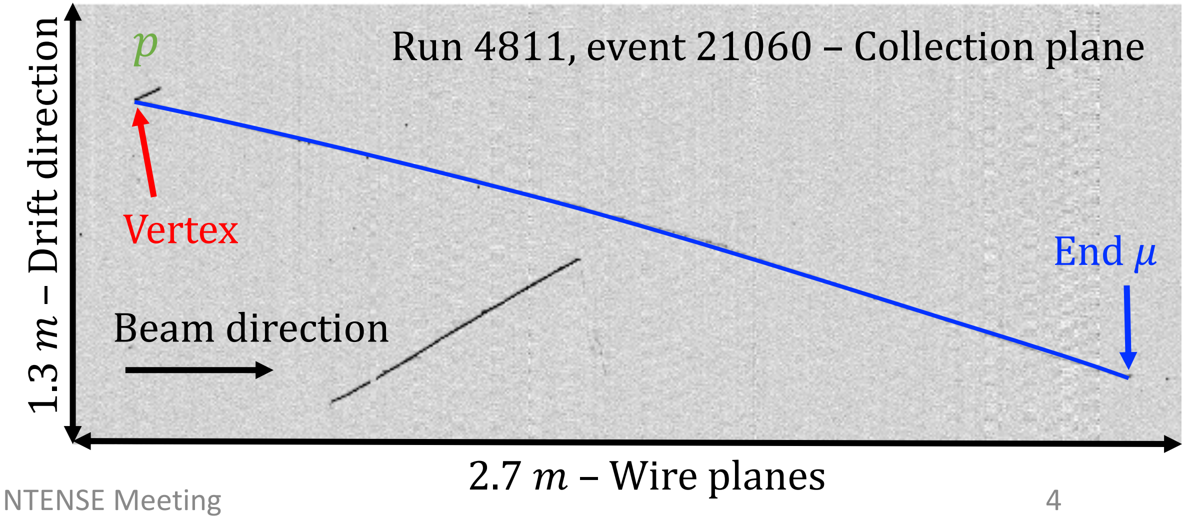
- I also had the chance to look at the BNB simulation to reproduce the analysis on MC events
- The basic idea is to extract the truth information (vertex, end muon and end proton coordinates) and feed it to the code as if it was data

ν event selection

- $1\mu1p$ candidates are selected by requiring:
  1. ν **vertex** should be inside the fiducial volume i.e., 25 cm apart from the lateral TPC walls and 30/50 cm from the upstream/downstream walls
  2. **Fully contained** interactions i.e., no signal in the last 5 cm of the LAr active volume
  3. Stopping muon of $L_\mu > 50$ cm
  4. Only 1 proton $L_p > 1$ cm produced at the primary vertex



- For each visually scanned event the 3D positions of the vertex, end muon and end proton are saved



- We have defined a set of quality requirements to evaluate the performance of our reconstruction algorithm
- Interactions tagged as clear cosmics by our pattern recognition algorithm are rejected and the muon is always considered to be the longest track within the interaction

	Data
Total events	520
Well reconstructed vertex $d(vtx_{reco} - vtx_{scan}) < 2\ cm$	405 – 78%
Muon tagged as a primary track and $L_{\mu} > 50\ cm$	400 – 77%
Well reconstructed start muon $d(start\mu_{reco} - vtx_{scan}) < 2\ cm$	353 – 68%
Well reconstructed end muon $d(end\mu_{reco} - end\mu_{scan}) < 2\ cm$	247 – 48%

- The next step would be to guarantee that the muon is properly tagged by the Particle identification (PiD) algorithm
- Due to its structure the performance of the PiD is reasonable only if we have the last part of the track available, including the characteristic rise in ionization (Bragg peak)
- We know that sometimes the reconstruction misses that part of the track, worsening the efficiency of the PiD algorithm
- A first step towards a possible mitigation could be to use the integrated energy of the last 25/12.5 cm * of the track to resolve stopping muons from bad reconstructed tracks (missing the end part of the track for any reason)
- We know the theoretical values for a stopping muon and a through going MIP

Particle/Integral up to	**25 cm**	**12.5 cm**
Stopping muon	84.87 MeV	53.16 MeV
MIP [2.2 MeV/cm]	55 MeV	27.5 MeV

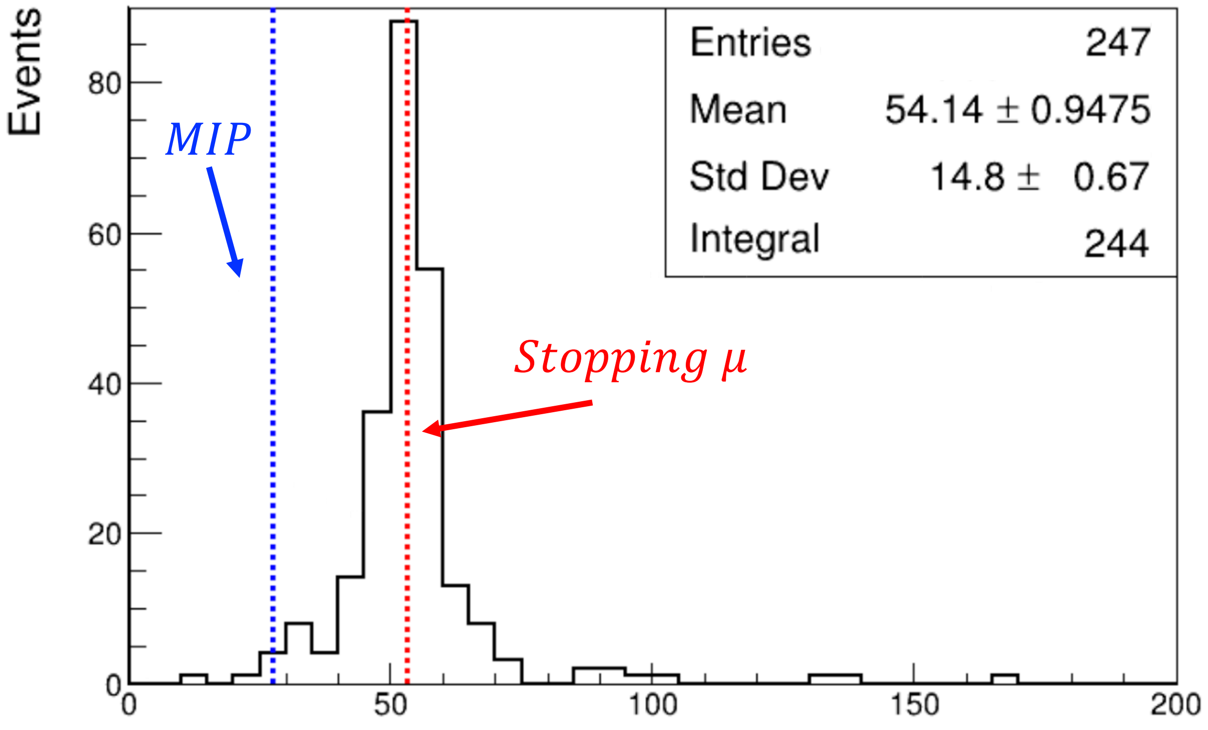
*We still need to define an optimal length over to which do the integration

Definition:

Pitch is the 3D segment of the track seen by the 3 mm wire spacing

- We define the integral as $\delta E = \sum_i \left(\frac{dE}{dx}\right)_i \times pitch_i$
- We are aware of some possible drawbacks
  1. Hits which failed to be associated with a space point will cause some underestimation
  2. Wrong measurement of pitches could cause some smearing and overestimation
- There could be some strategy to mitigate these problems
  1. Evaluate the systematic underestimation if present
  2. Use an averaged pitch if a particular value is clearly outlining
  3. Extrapolate the position of hits without space points profiting from its closest neighbours
  4. Use another view when a track is parallel to wires

Well reconstructed muons – Data sample

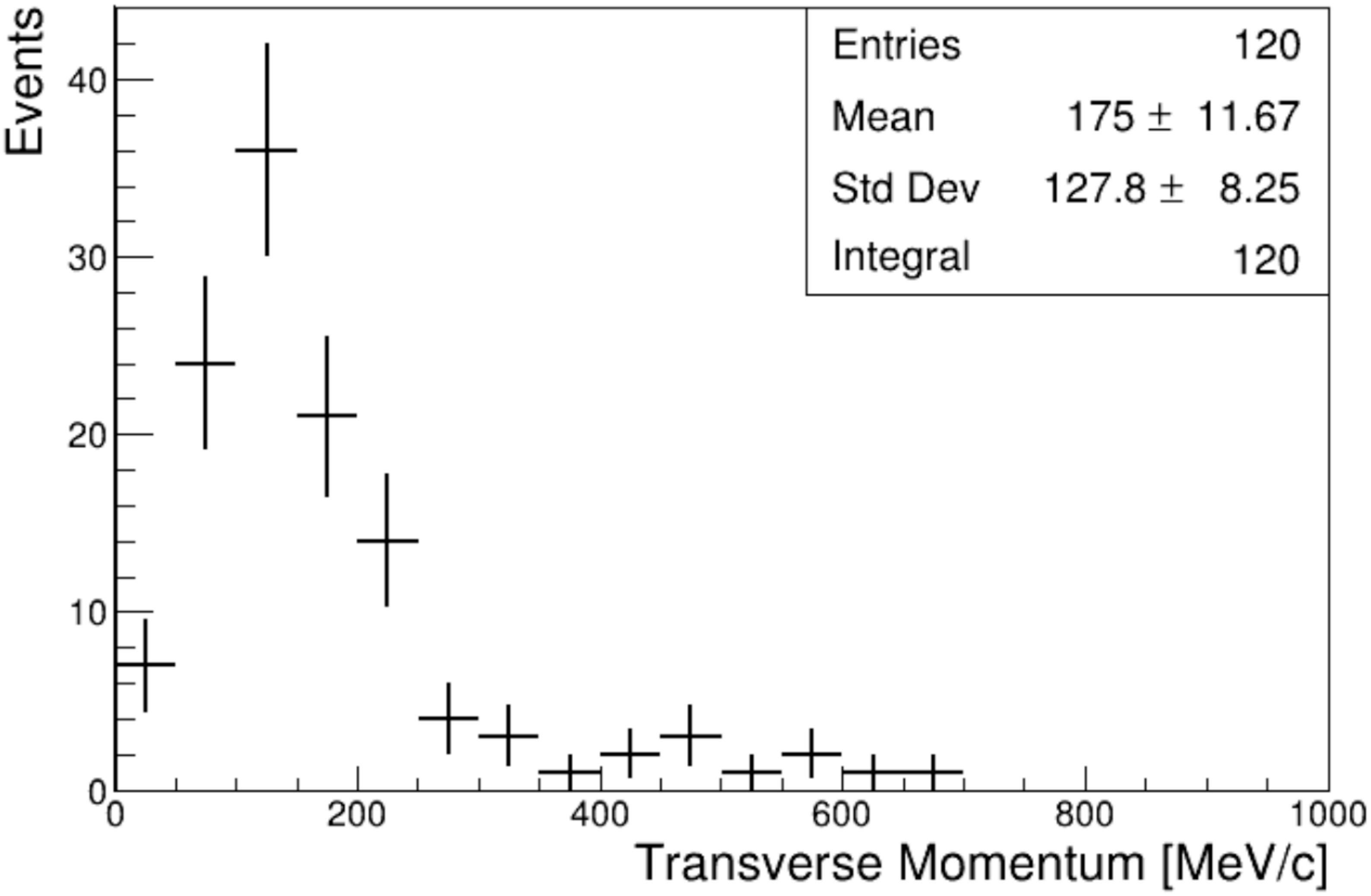


$Integral\ \delta E\ up\ to\ 12.5\ cm\ [MeV]$

	Data
Total events	520
Well reconstructed vertex $d(vtx_{reco} - vtx_{scan}) < 2\ cm$	405 – 78%
Muon tagged as a primary track and $L_{\mu} > 50\ cm$	400 – 77%
Well reconstructed start muon $d(start\mu_{reco} - vtx_{scan}) < 2\ cm$	353 – 68%
Well reconstructed end muon $d(end\mu_{reco} - end\mu_{scan}) < 2\ cm$	247 – 48%
Muon particle Identification $\chi^2_{\mu}(\mu) < 30$ & $\chi^2_{p}(\mu) > 60$	246 – 47%
Identification of proton track candidate (**)	183 – 35%
Proton well tagged by requiring $\chi^2_{p}(p) < 90$ & $\chi^2_{\mu}(p) > 30$	120 – 23%

(**) Excluding the muon, the longest remaining track needs to fulfil both conditions $d(startp_{reco} - vtx_{scan}) < 2\ cm$ and $d(endp_{reco} - endp_{scan}) < 2\ cm$

- Neutrino transverse momentum for well reconstructed events



MC Study

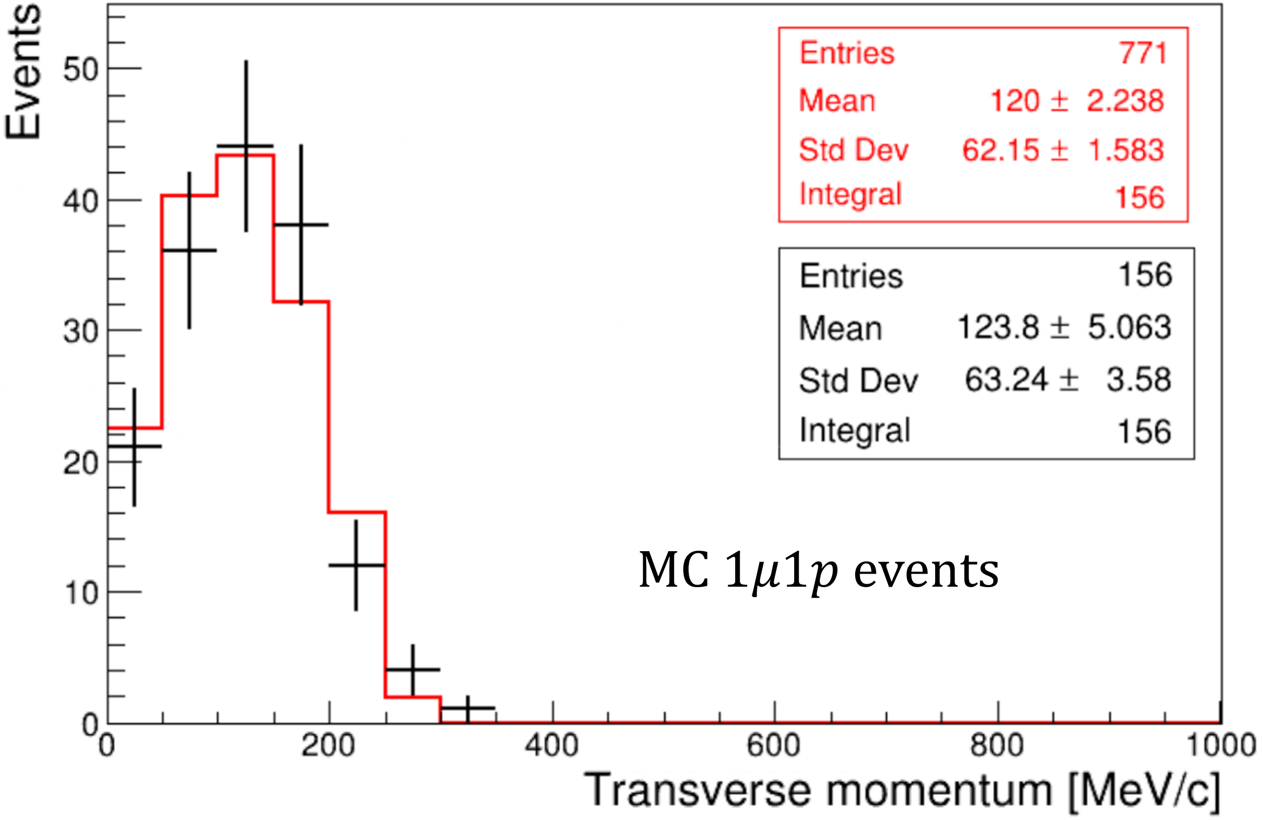
- Using the BNB simulation, I did the same analysis with truth $1\mu1p$ MC events
- The idea is to extract from MC the same information provided by the scanning group and similarly apply the analysis procedure as in the data
- The MC subsample of " **Truth $1\mu1p$**" events was selected as follow
  - $\nu_\mu CC$ events with the interaction vertex inside the fiducial volume
  - Only 2 primary tracks, 1 muon and 1 proton
  - Both particles fully contained within 5cm from the active borders
  - Muon and proton lengths of at least 50 cm and 1 cm respectively
- From 9269 $\nu_\mu CC$ events with the vertex inside the fiducial volume, we are left with 766 "Truth $1\mu1p$" ($\sim$ 8%)

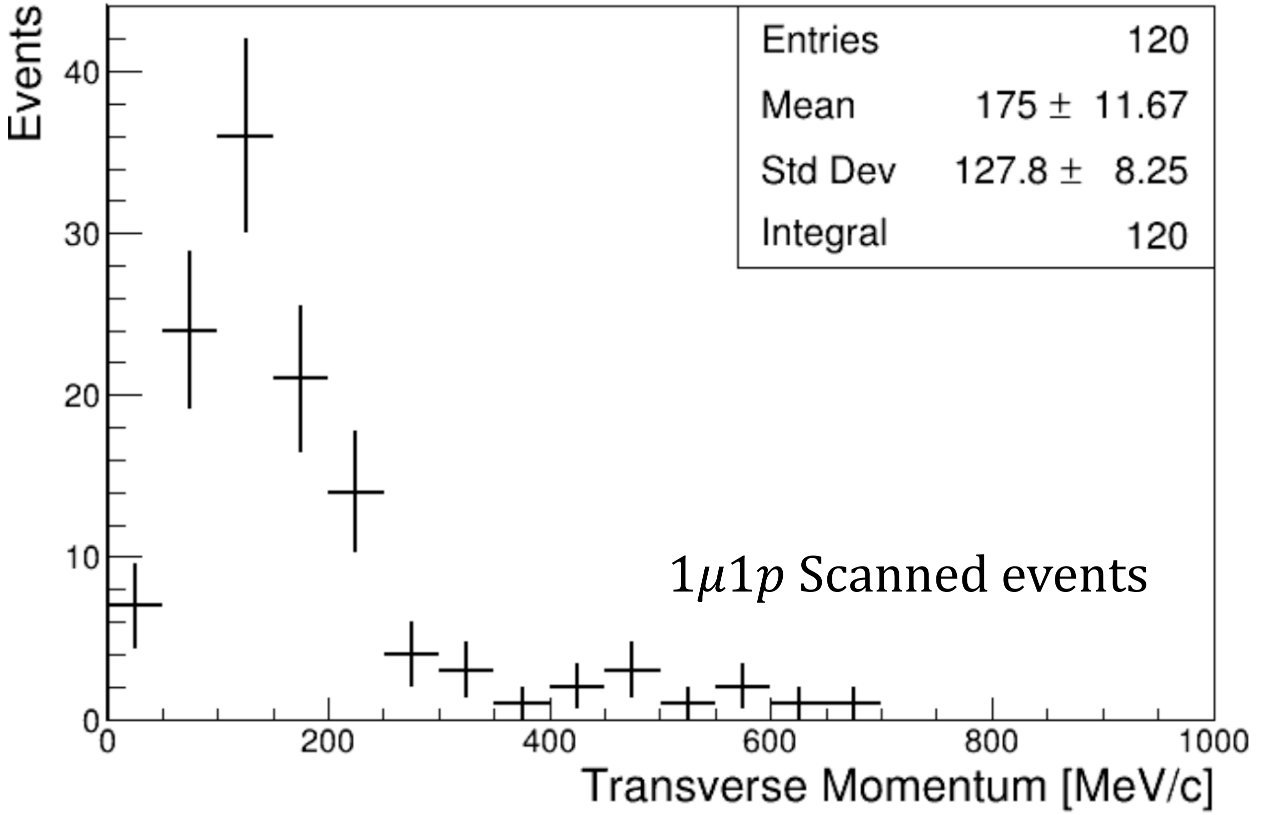
- We have already done this study in data so we can compare the results with our "Truth $1\mu 1p$" sample

	Truth $1\mu 1p$	Data
Total events	766	520
Well reconstructed vertex $d(vtx_{reco} - vtx_{true}) < 2\ cm$	579 – 76%	405 – 78%
Muon tagged as a primary track and $L_{\mu} > 50\ cm$	574 – 75%	400 – 77%
Well reconstructed start muon $d(start\mu_{reco} - vtx_{true}) < 2\ cm$	506 – 66%	353 – 68%
Well reconstructed end muon $d(end\mu_{reco} - end\mu_{true}) < 2\ cm$	344 – 45%	247 – 48%
Muon particle Identification $\chi^2_{\mu}(\mu) < 30$ & $\chi^2_{p}(\mu) > 60$	336 – 44%	246 – 47%
Identification of proton track candidate (**)	234 – 30%	183 – 35%
Proton well tagged by requiring $\chi^2_{p}(p) < 90$ & $\chi^2_{\mu}(p) > 30$	156 – 20%	120 – 23%

(**) Excluding the muon, the longest remaining track needs to fulfil both conditions $d(startp_{reco} - vtx_{scan}) < 2\ cm$ and $d(endp_{reco} - endp_{scan}) < 2\ cm$

- Neutrino transverse momentum for selected events
- Left plot: reconstructed MC events are in black, red line indicates the truth values scaled to the its well reconstructed number of events (MC)
- Right plot: Well reconstructed **data** events

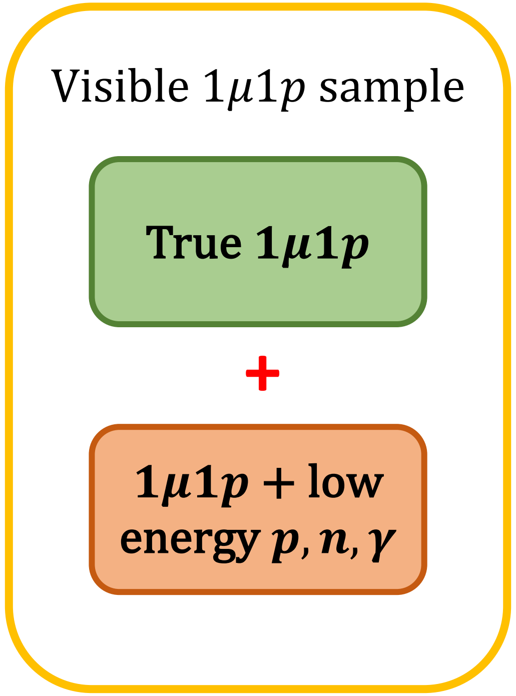




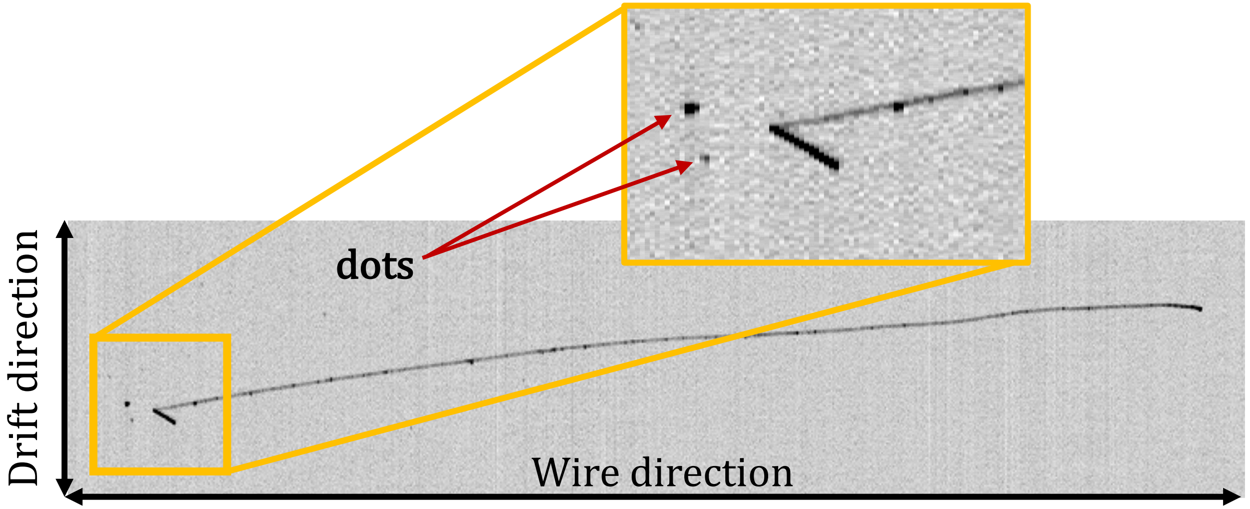
- It is clear from the transverse momenta plot that we are missing something…
- The visual scanning is really helpful to evaluate the performance of the selection and reconstruction algorithms, but it also has some limitations
  - All particles are identified by eye based on their ionization. Hence, it is possible that different hadrons are wrongly classified as protons
  - Very short protons are not visible, so these events might be mis identified as $1\mu 1p$ candidates
  - Neutrons and small photons produced at primary vertex are very difficult to recognize, unless they do some interaction
- It is mandatory to establish a visibility condition for protons, neutrons and photons to have a more accurate comparison between MC and real data
- A visual scanning of MC events has been performed to address this problem. The goal was to classify events either as a "$1\mu 1p$" or "$other$"

- 142 events were visually scanned, of which 18 were true $1\mu1p$
- The scanning result claimed 68 visually selected $1\mu1p$ candidates
- According to this information and with a more in-depth study of the additional particles produced at the primary vertex and their energy spectrum a "visible $1\mu1p$" sample was defined

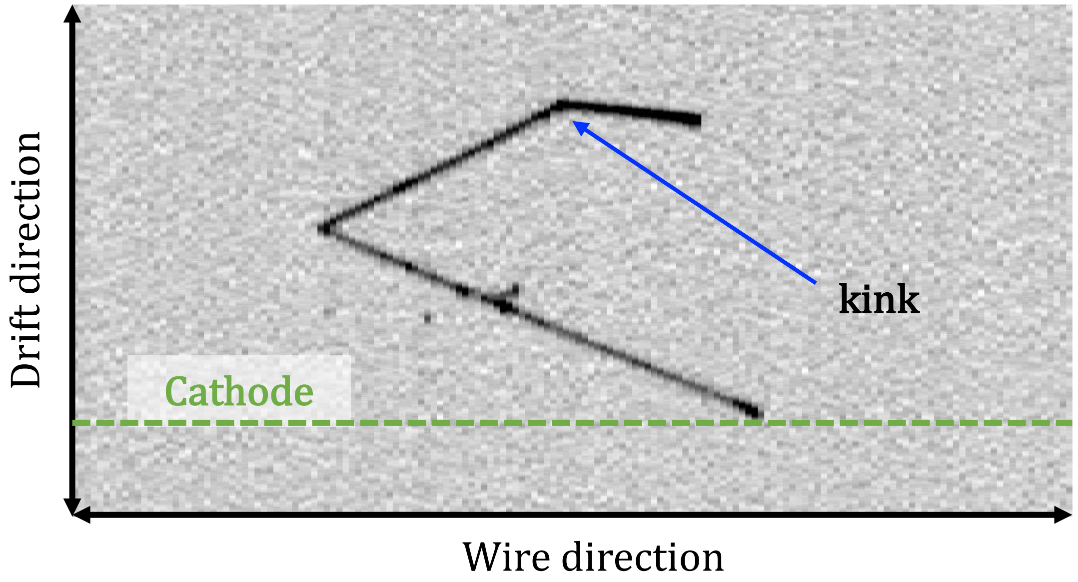
- Sample of "**Visible $\boldsymbol{1\mu1p}$**" events are defined as
  - $\nu_\mu CC$ events with the interaction vertex inside the fiducial volume
  - Only 2 visible particles coming out from the primary vertex
    - A primary proton is considered visible if its kinetic energy is above $25MeV$ ($\sim\ 6mm$)
    - A primary neutron is considered visible if the sum of deposited energy of its daughters is above $25MeV$
    - A primary photon is considered visible if its deposited energy is above $10MeV$
  - The 2 "visible" tracks need to be 1 muon and 1 proton
  - Both visible particles fully contained within 5cm from the active borders
  - Muon and proton lengths of at least 50 cm and 1 cm respectively



- 142 events were visually scanned. Truth level info:
  - 69 visible $1\mu1p$ events, of which 18 were true $1\mu1p$
  - 73 other topologies
- 68 events were visually classified as $1\mu1p$
  - 63 were visible $1\mu1p$ (containing all 18 true $1\mu1p$)
  - 5 were other: 2 neutral current events, 1 event with too short proton, 2 events with two visible protons
- 63/69 events were found. The remaining ones were classified as other due to some big kinks or the presence of black dots close to the vertex, indicating some neutral activity
- 5/68 events where visually miss classified as $1\mu1p$ when they were other interactions



The black dots might suggest the interaction of a neutral particle produced in the primary vertex

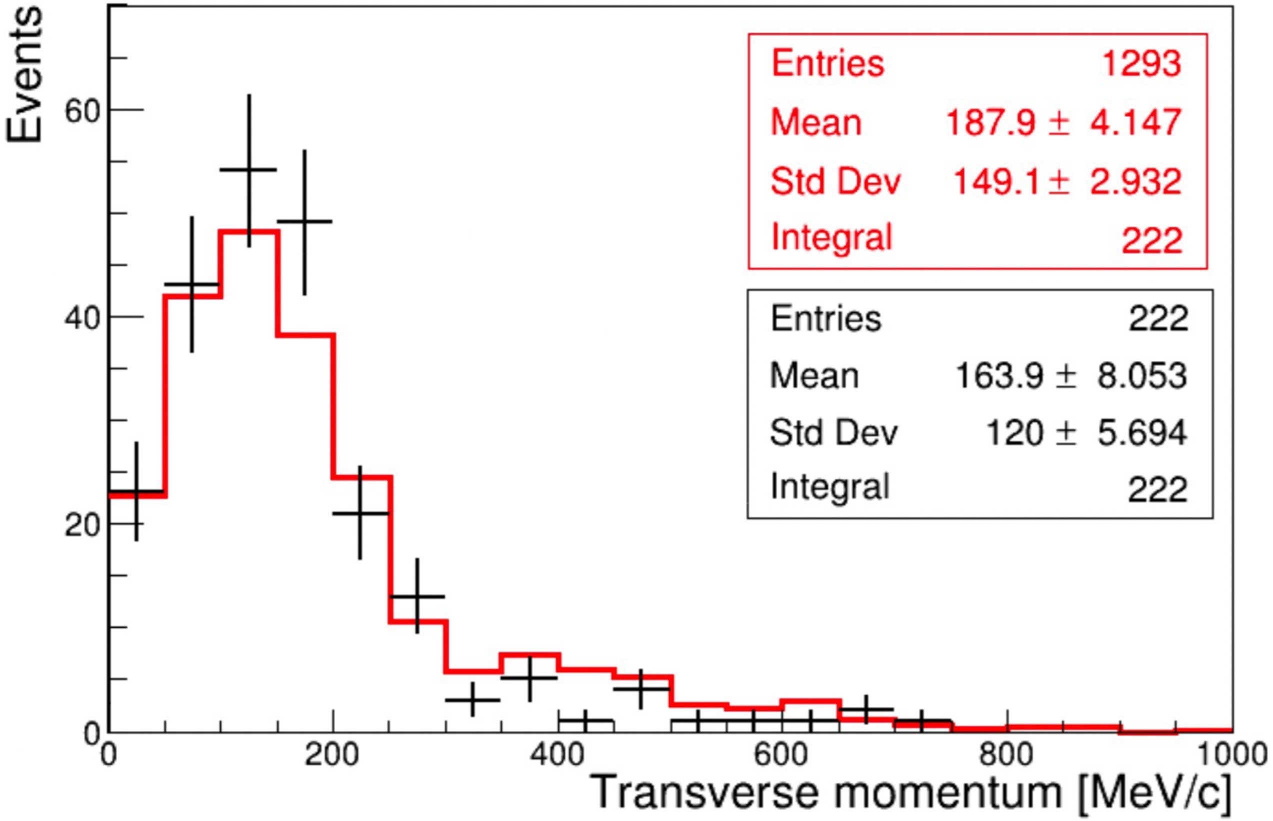


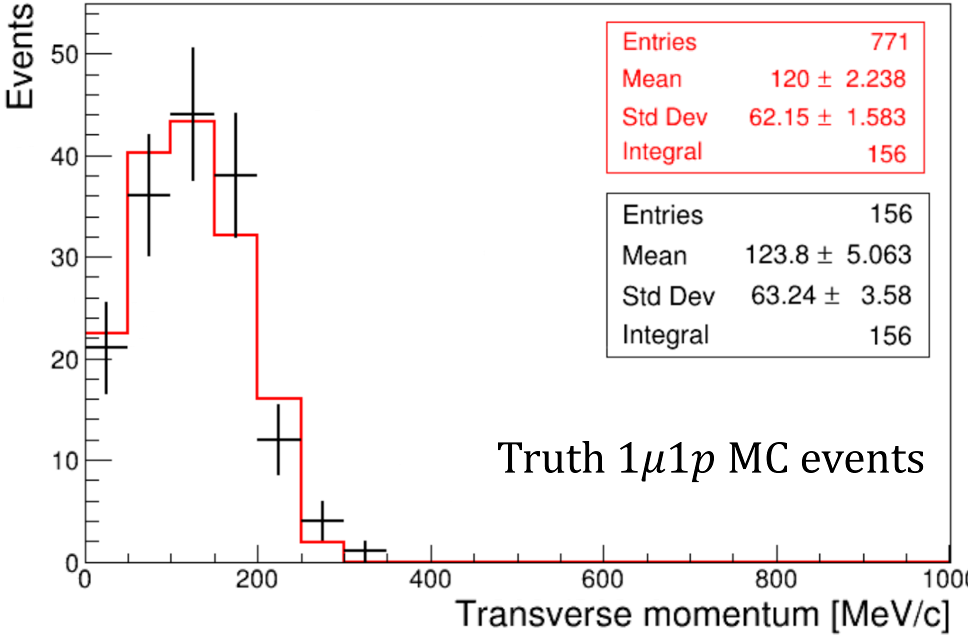
- With the new definition of "Visible $1\mu 1p$" sample we can complete the table showing the quality cuts

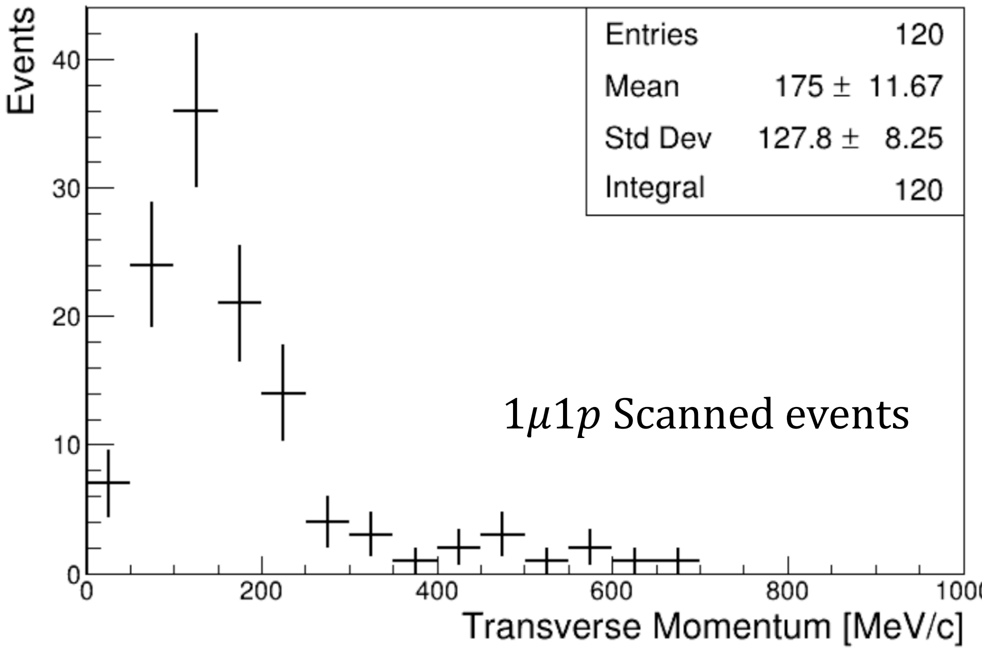
	Visible $1\mu 1p$	Truth $1\mu 1p$	Data
Total events	1293	766	520
Well reconstructed vertex $d(vtx_{reco} - vtx_{true}) < 2\ cm$	926 – 72%	579 – 76%	405 – 78%
Muon tagged as a primary track and $L_{\mu} > 50\ cm$	916 – 71%	574 – 75%	400 – 77%
Well reconstructed start muon $d(start\mu_{reco} - vtx_{true}) < 2\ cm$	792 – 61%	506 – 66%	353 – 68%
Well reconstructed end muon $d(end\mu_{reco} - end\mu_{true}) < 2\ cm$	537 – 42%	344 – 45%	247 – 48%
Muon particle Identification $\chi^2_{\mu}(\mu) < 30$ & $\chi^2_{p}(\mu) > 60$	527 – 41%	336 – 44%	246 – 47%
Identification of proton track candidate (**)	373 – 29%	234 – 30%	183 – 35%
Proton well tagged by requiring $\chi^2_{p}(p) < 90$ & $\chi^2_{\mu}(p) > 30$	222 – 17%	156 – 20%	120 – 23%

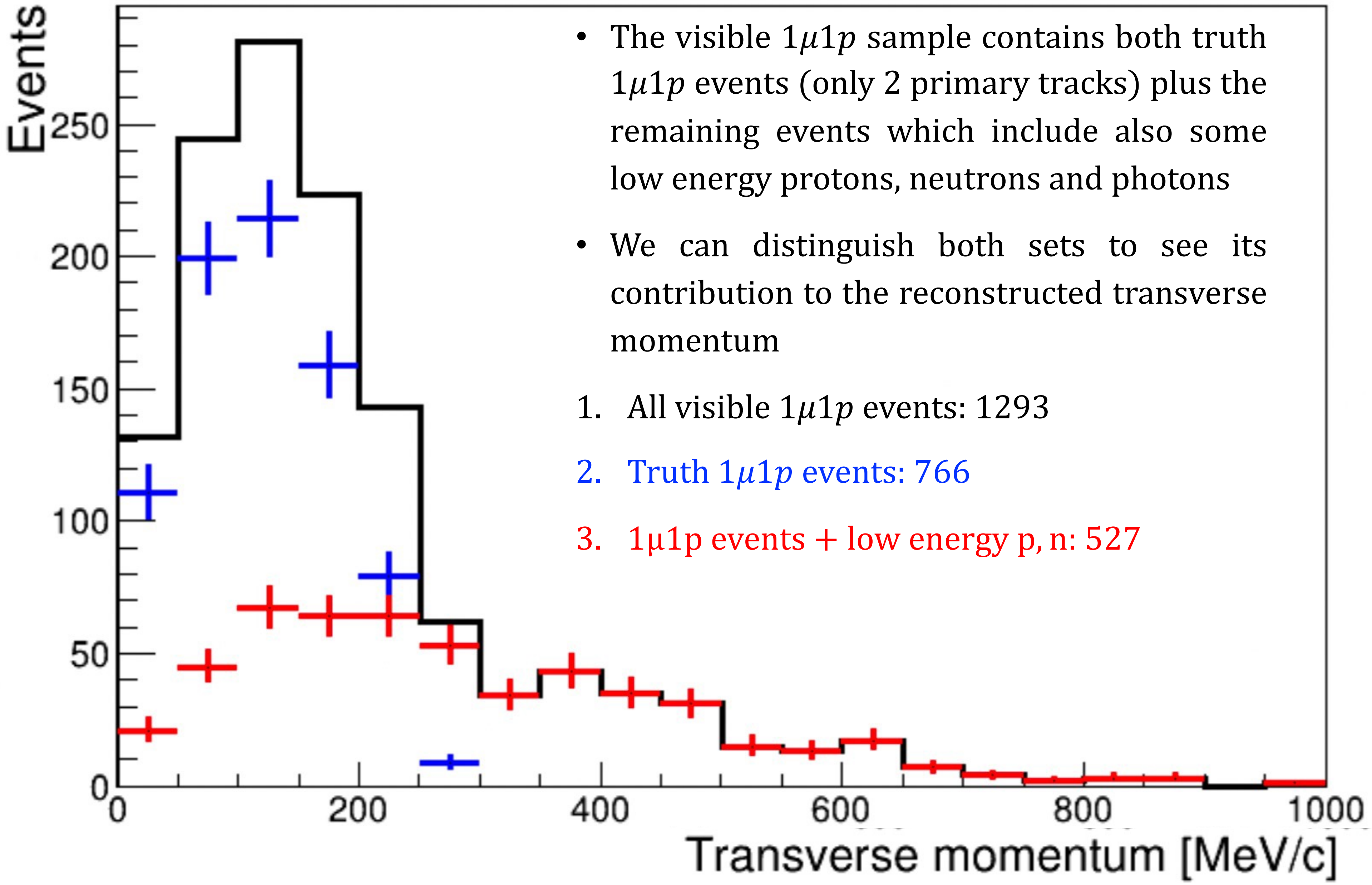
- Neutrino transverse momentum with much more similar distributions to data than before

Visible $1\mu1p$ events









- The visible $1\mu1p$ sample contains both truth $1\mu1p$ events (only 2 primary tracks) plus the remaining events which include also some low energy protons, neutrons and photons
- We can distinguish both sets to see its contribution to the reconstructed transverse momentum

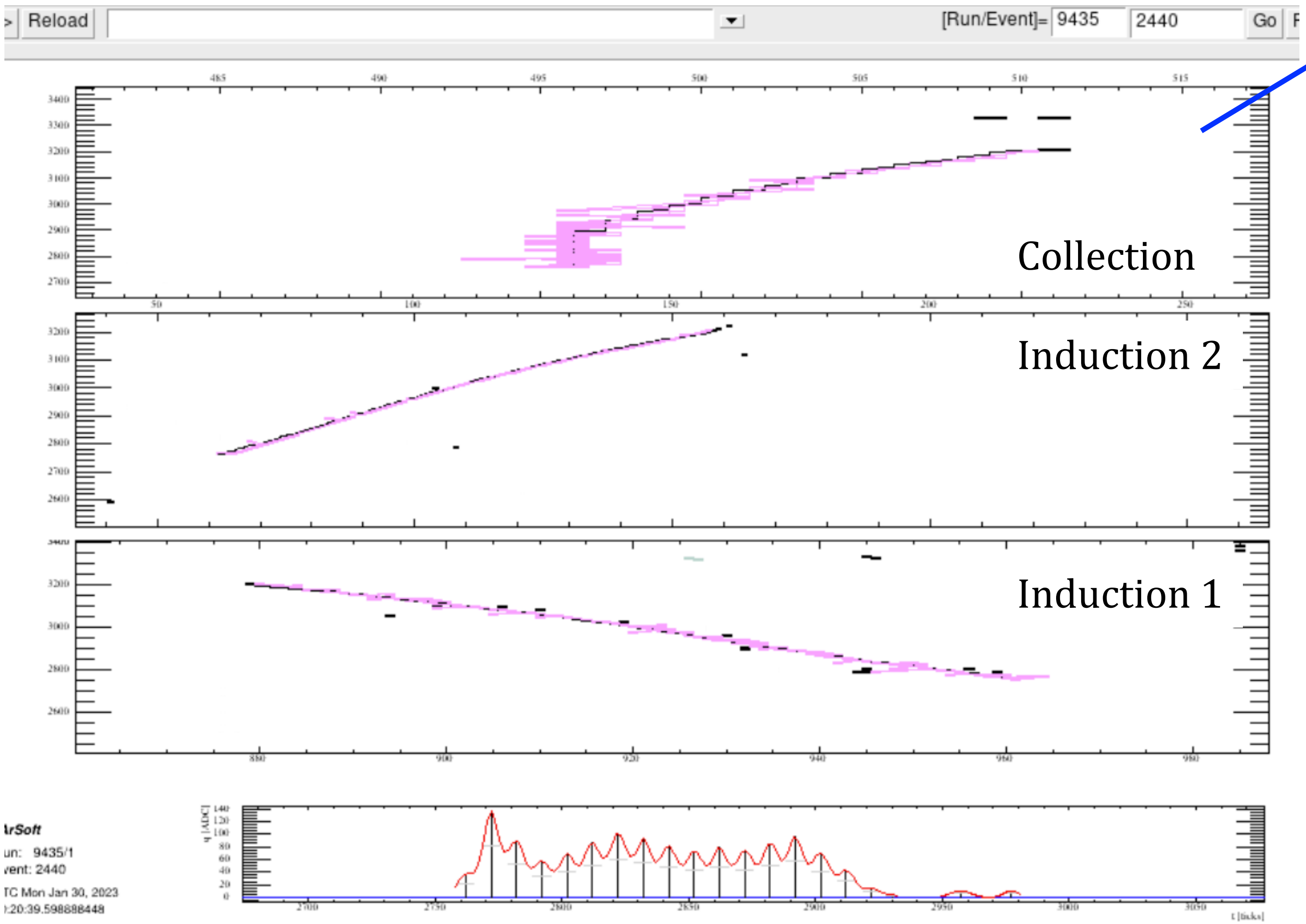
1. All visible $1\mu1p$ events: 1293
2. Truth $1\mu1p$ events: 766
3. 1μ1p events + low energy p, n: 527

Future plans

- Need to establish and optimize a solid strategy to automatically select a pure sample of well reconstructed ν
- Improve the visible definition to be as accurate as possible
- Evaluate if the transverse momenta can be a discriminating variable
- Mitigate the existing pathologies, addressing long hits treatment, broken tracks, etc
- Establish a procedure to use the pitch and integrated energy to evaluate the reconstruction quality of tracks

Backup slides

- Problems with the integrated energy: long hits causing huge pitch



wire	time [us]	rr [cm]	pitch [cm]	dedx [MeV/cm]
495	2861,1	9,31	14,02	0,28
496	2852,0	8,44	28,28	0,27
495	2847,2	7,95	49,04	0,26
496	2842,0	7,50	50,89	0,26
496	2832,0	6,71	76,71	0,25
495	2823,6	5,93	471,38	0,23
496	2822,0	5,89	370,76	0,23
497	2821,5	5,79	222,98	0,23
496	2812,0	4,95	55,69	0,26
497	2807,3	4,41	33,91	0,27
496	2802,0	4,01	41,40	0,26
497	2795,2	3,38	26,42	0,28
494	2792,3	3,29	24,99	0,24
496	2792,0	3,22	24,16	0,27
493	2791,3	2,96	29,27	0,24
497	2786,9	2,78	28,36	0,26
496	2782,0	2,28	41,71	0,27
497	2773,9	1,71	47,86	0,28
496	2772,0	1,34	76,69	0,26
495	2763,1	0,03	18,71	0,24
496	2762,0	0,01	18,40	0,26

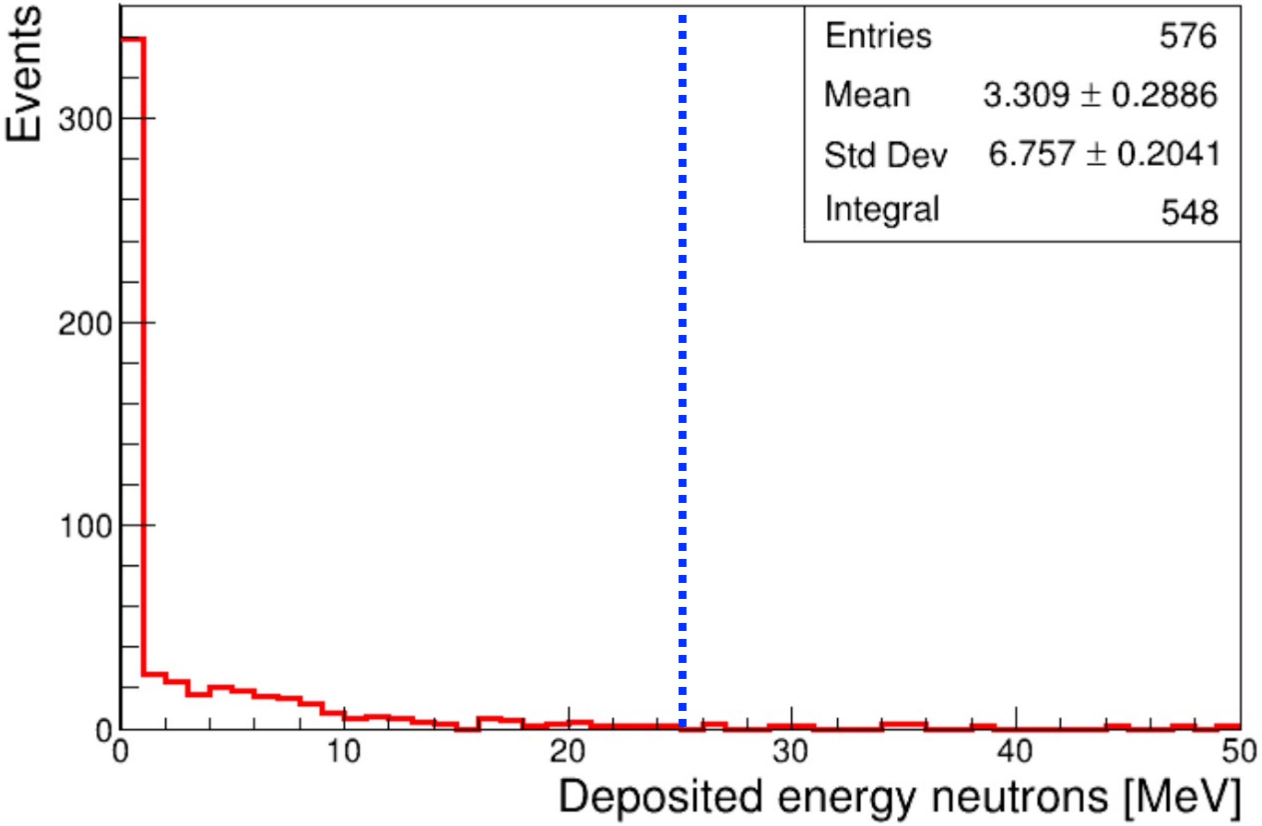
Last 10 cm just in ~ 5 wires…!

Integral for last 25 cm:

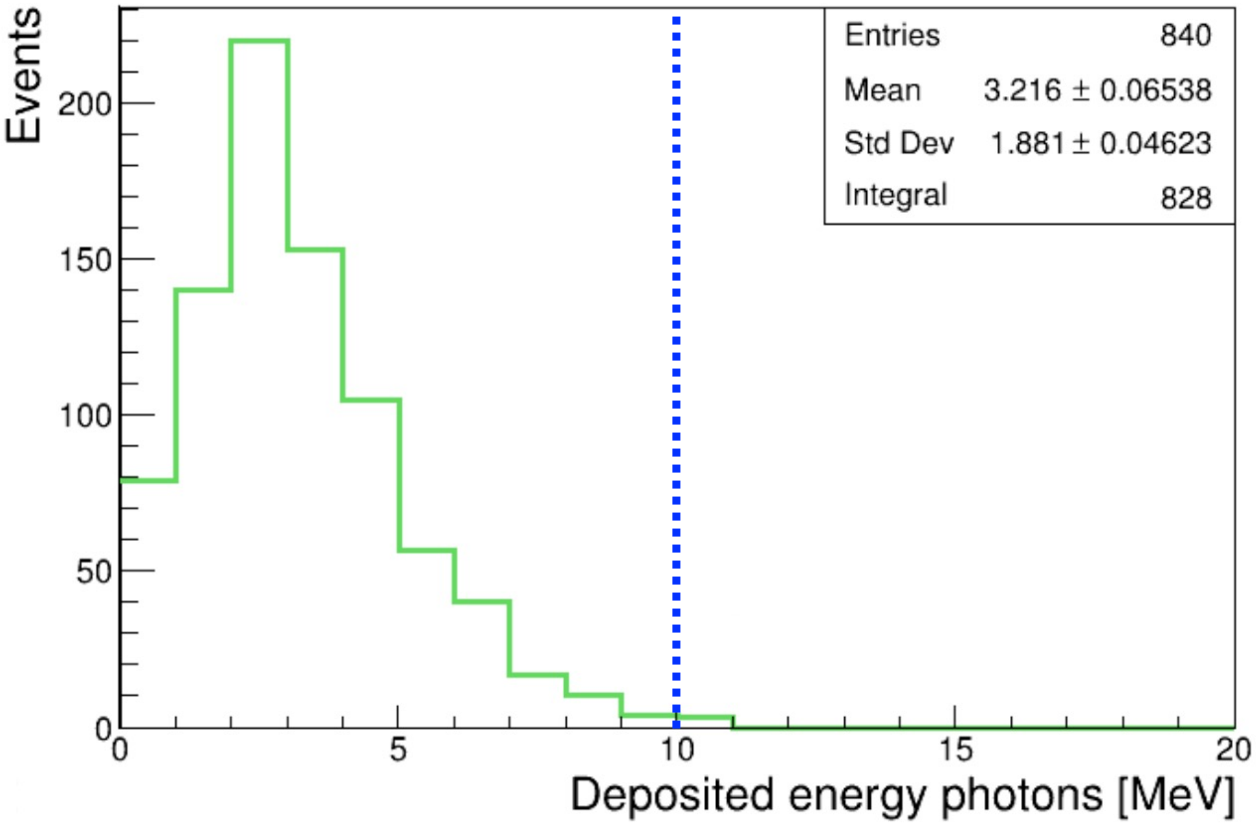
Collection	479.4 MeV
Induction 2	71.5 MeV
Induction 1	82.5 MeV

- Energy distributions for neutrons and photons exiting the primary vertex
    - Deposited energy of neutrons is defined as the sum of all deposited energy of its daughter particles

Energy threshold = 25 MeV



Energy threshold = 10 MeV



High transverse momentum events

- Run 7926 event 1660 with $p_T = 638.8\ MeV/c$