Neutrino reconstruction analysis at ICARUS detector

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As part of the ICARUS Collaboration

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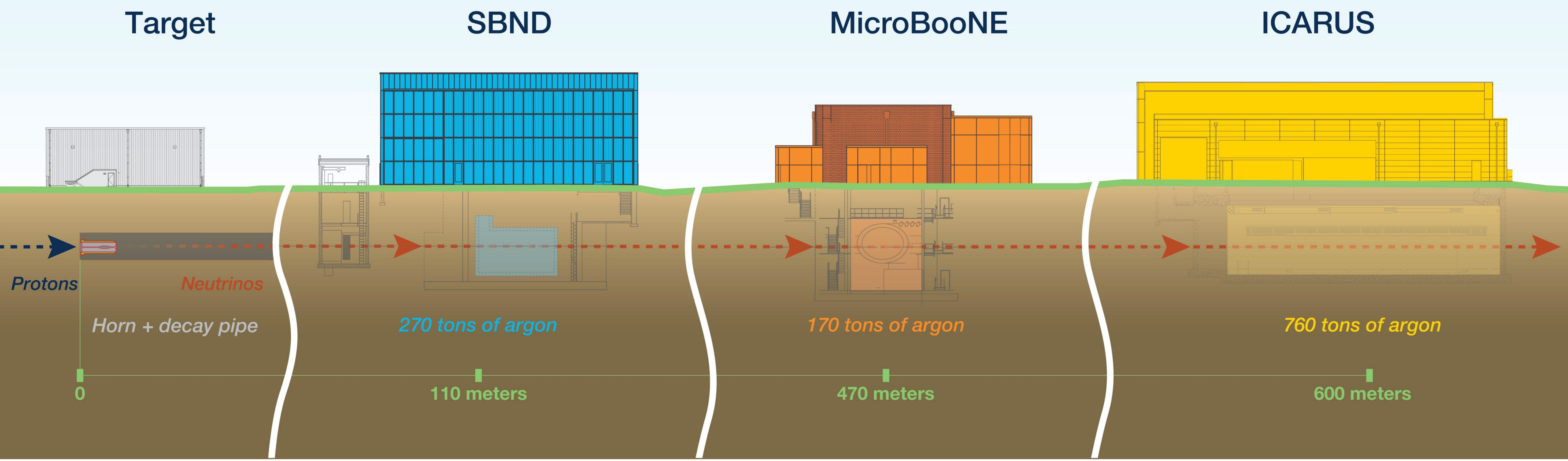
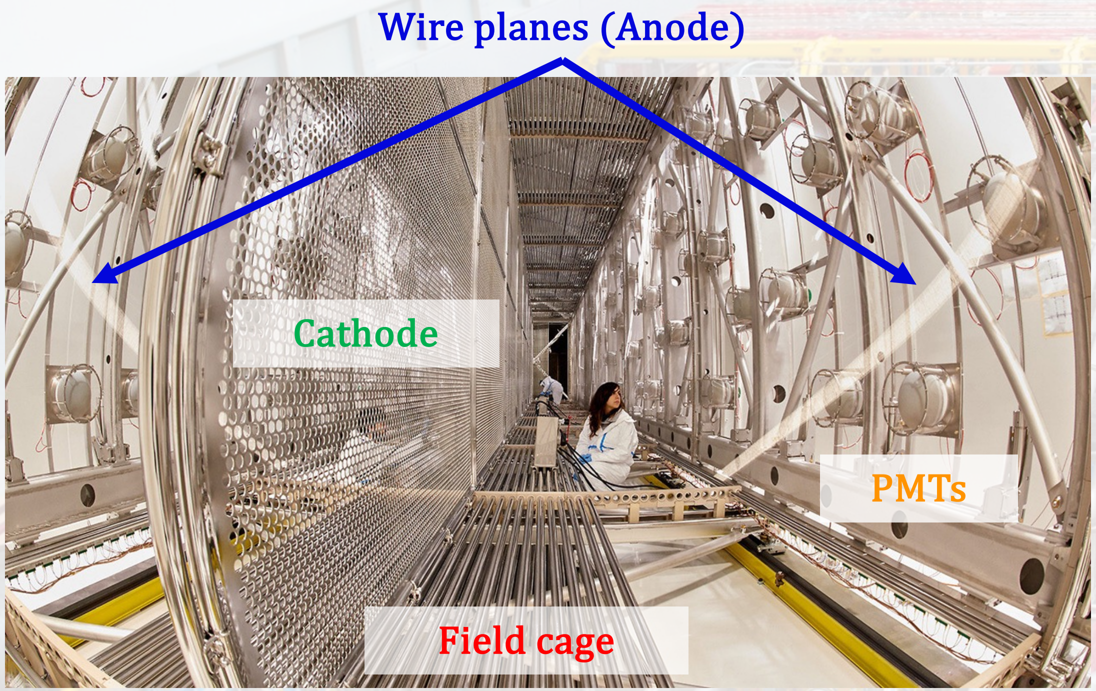
Short-Baseline Neutrino Program at Fermilab



- 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 (LArTPC detectors)

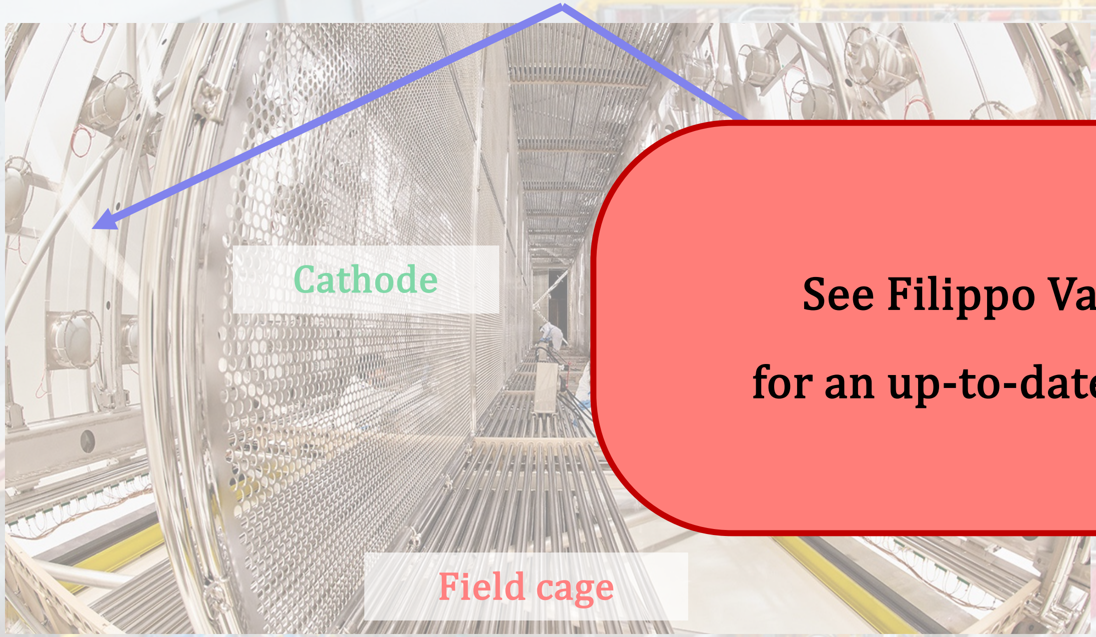
The ICARUS detector



Inside ICARUS: internal view of one cryostat

- Uniform Liquid Argon time-projection chamber (LArTPC) detector
- First large LArTPC, still one of the largest in operation
  - 2 Identical modules with 476 t total active mass
- Self-triggering detector, with precise 3D imaging and calorimetric capabilities
- Previous operation at LNGS, ICARUS moved to FNAL after overhauling phase at CERN and INFN Labs

The ICARUS detector



Inside ICARUS: internal view of one cryostat

- Uniform Liquid Argon time-projection chamber (LArTPC) detector
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  476 t total active mass
- precise 3D imaging and
- Previous operation at LNGS, ICARUS moved to FNAL after overhauling phase at CERN and INFN Labs

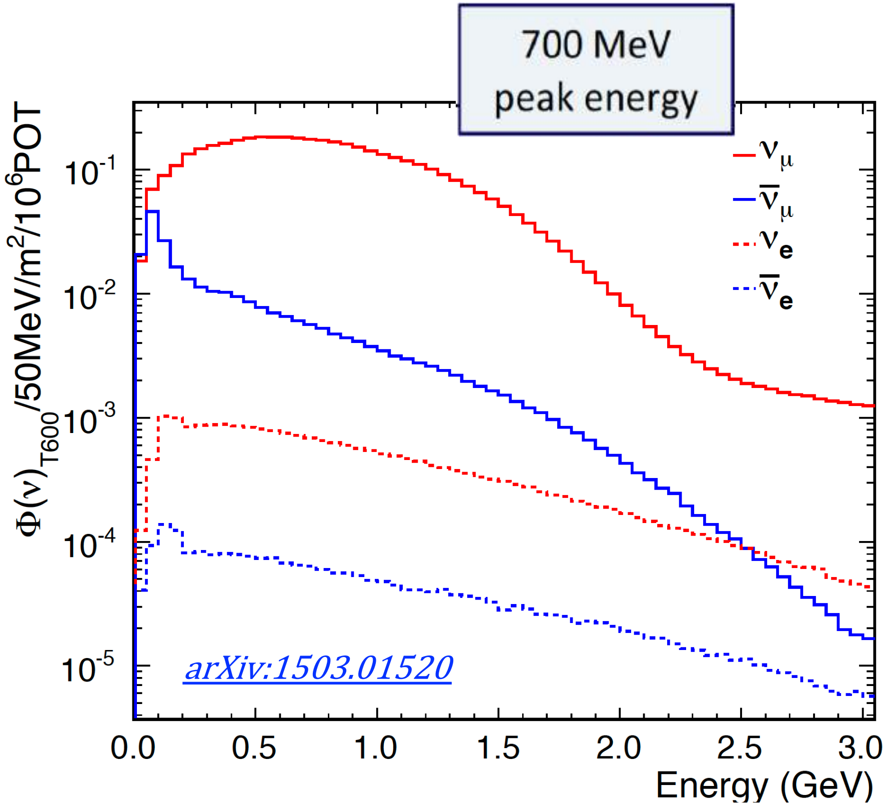
See Filippo Varanini's talk tomorrow

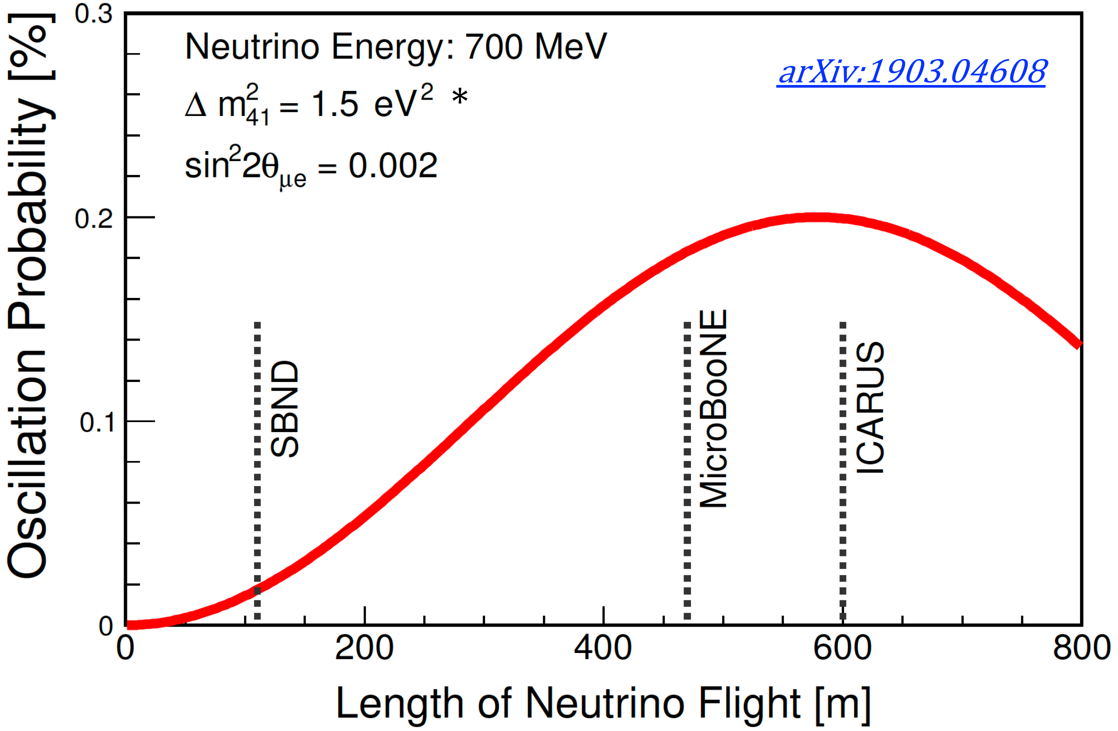
for an up-to-date review of SBN program!

Short Baseline Neutrino Program at FNAL

- BNB is a well characterized ν_μ-beam, able to produce ν and $\bar{\nu}$ beams with low ν_e contamination

(0.5 % ν_e content)



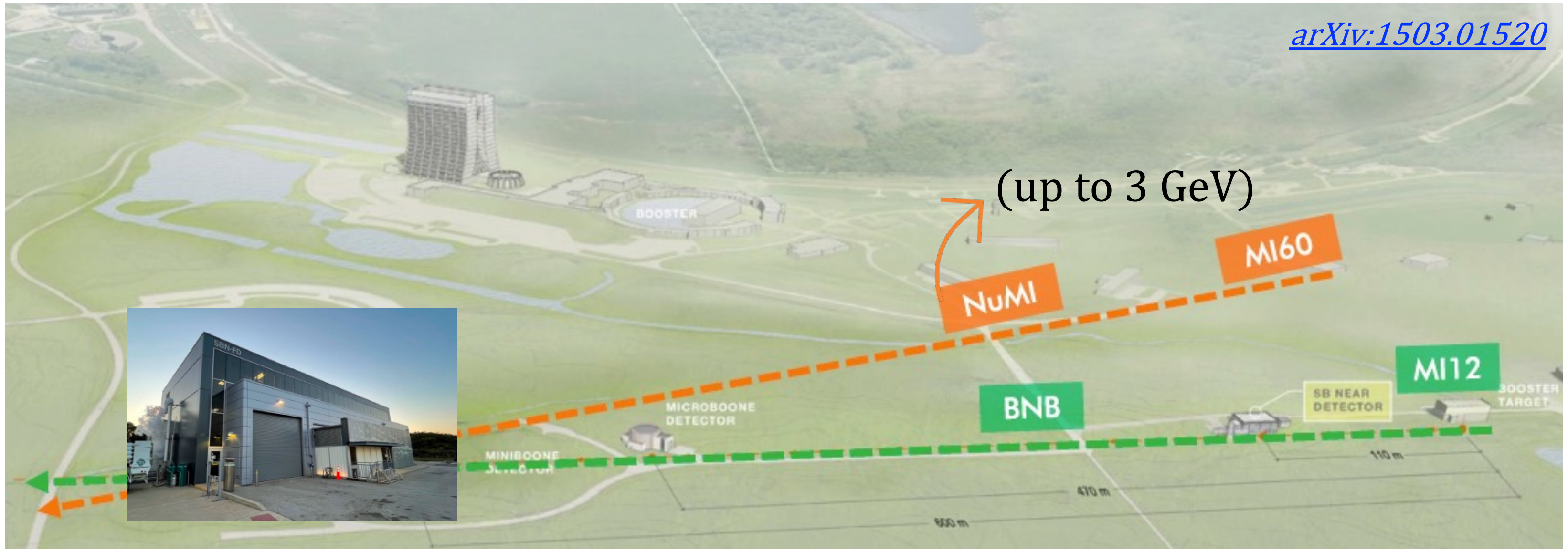


*Using best fit values

Short Baseline Neutrino Program at FNAL

- BNB is a well characterized ν_μ-beam, able to produce ν and $\bar{\nu}$ beams with low ν_e contamination
- ICARUS is also exposed off-axis to the NuMI beam and can access the ν_e rich component of the spectrum
- 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 sterile neutrinos

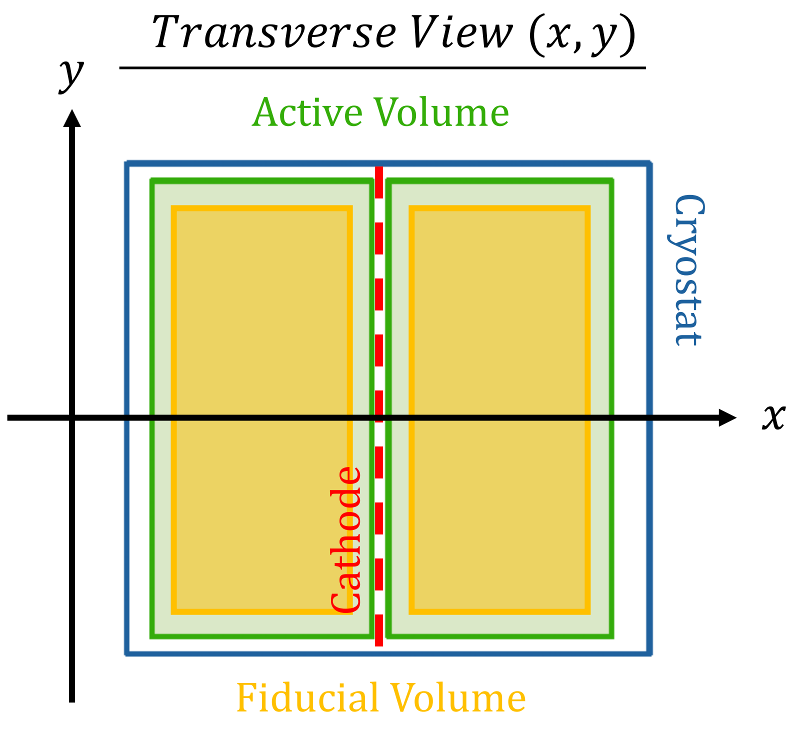
NEUTRINO-4 experiment has claimed the observation of sterile neutrino oscillations at high Δm^2 ⇢ ICARUS has started taking data alone to address it



Neutrino event selection

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



- To further simplify, we can consider $1\mu 1p$ candidates

4. Only 1 proton $L_p > 1$ cm produced at the primary vertex

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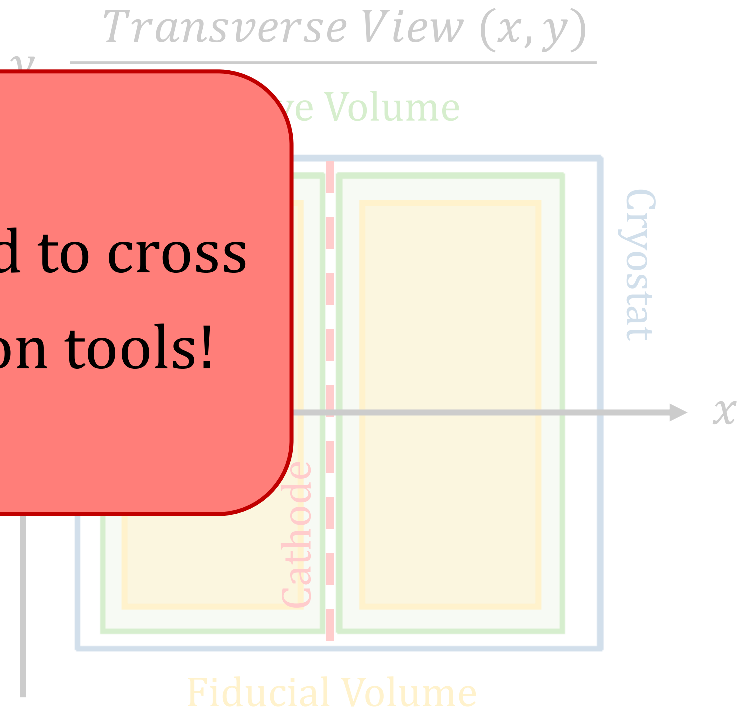
1. ν **vertex** should b… cm apart from… from the upstre…
2. **Fully containe…** 5 cm of the LAr…
3. Stopping muon…



Visually selected events can be used to cross check our **automatic** reconstruction tools!

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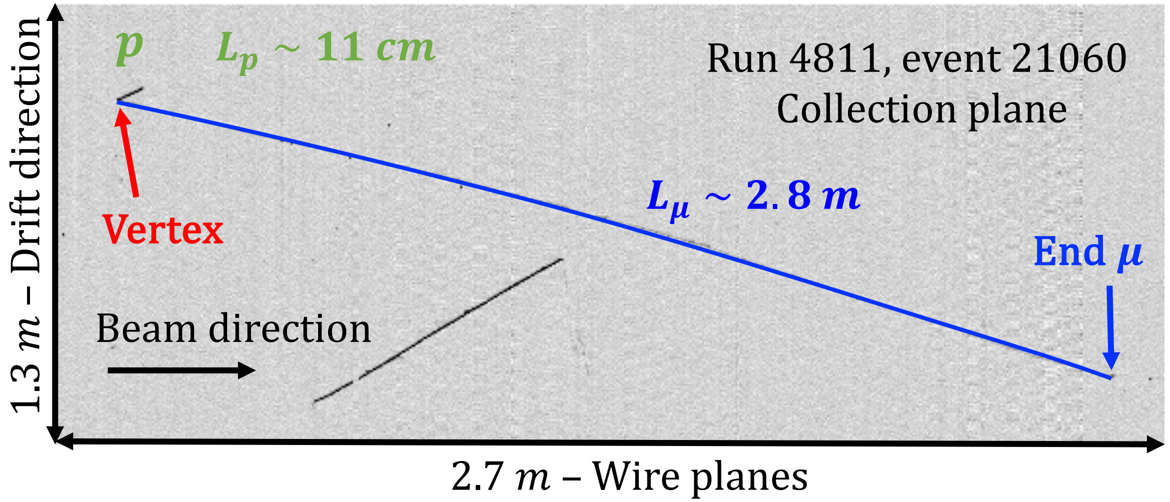
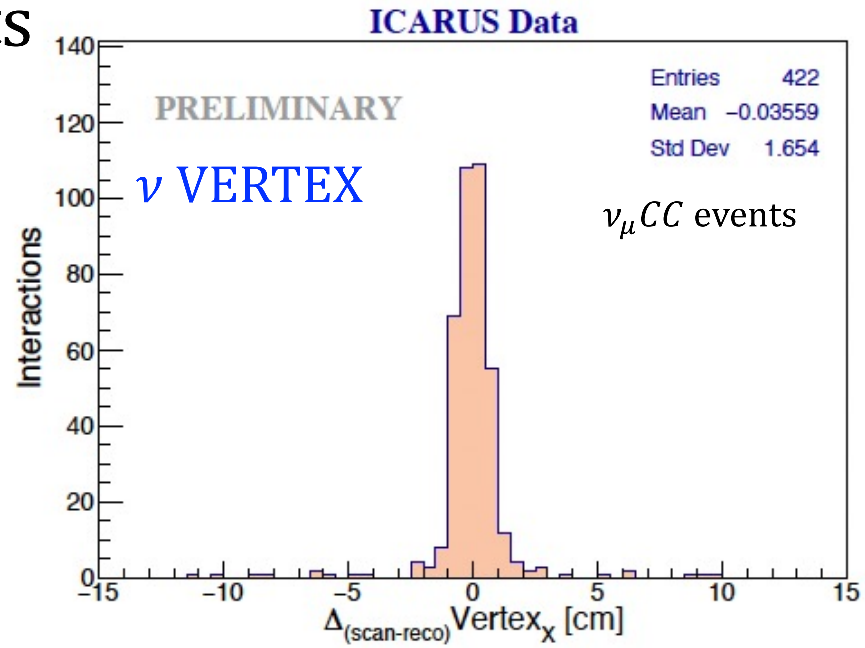
Event reconstruction with visually selected events

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



- Comparison of scan interactions with their automatic reconstruction for muon tracks
- In ~ 70% of the cases the reconstructed vertex and end position of the muon are within 15 cm from the scanned information



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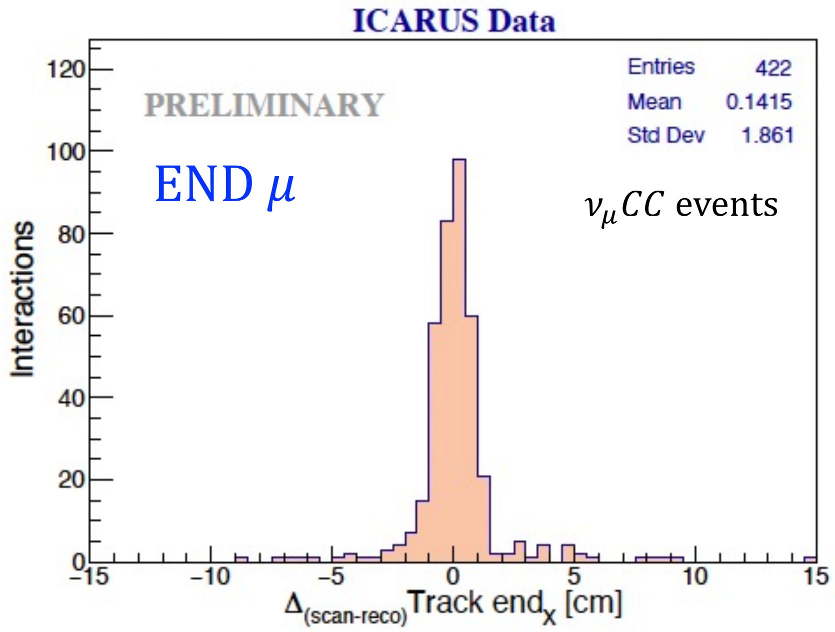
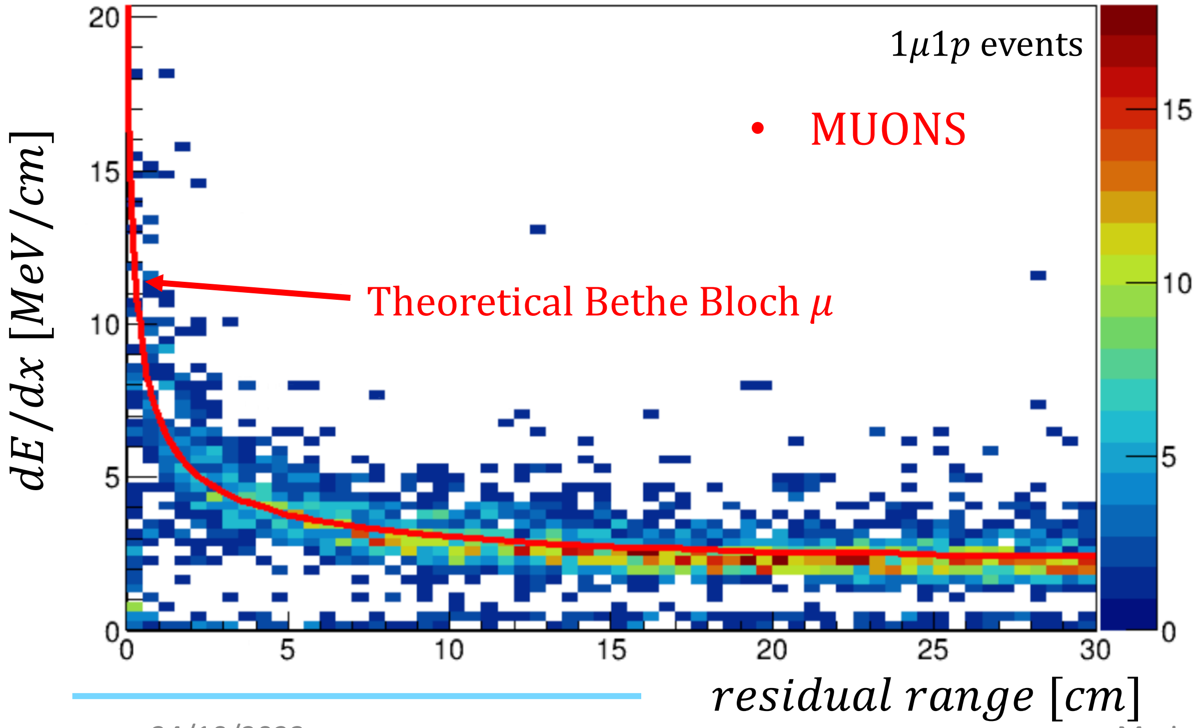
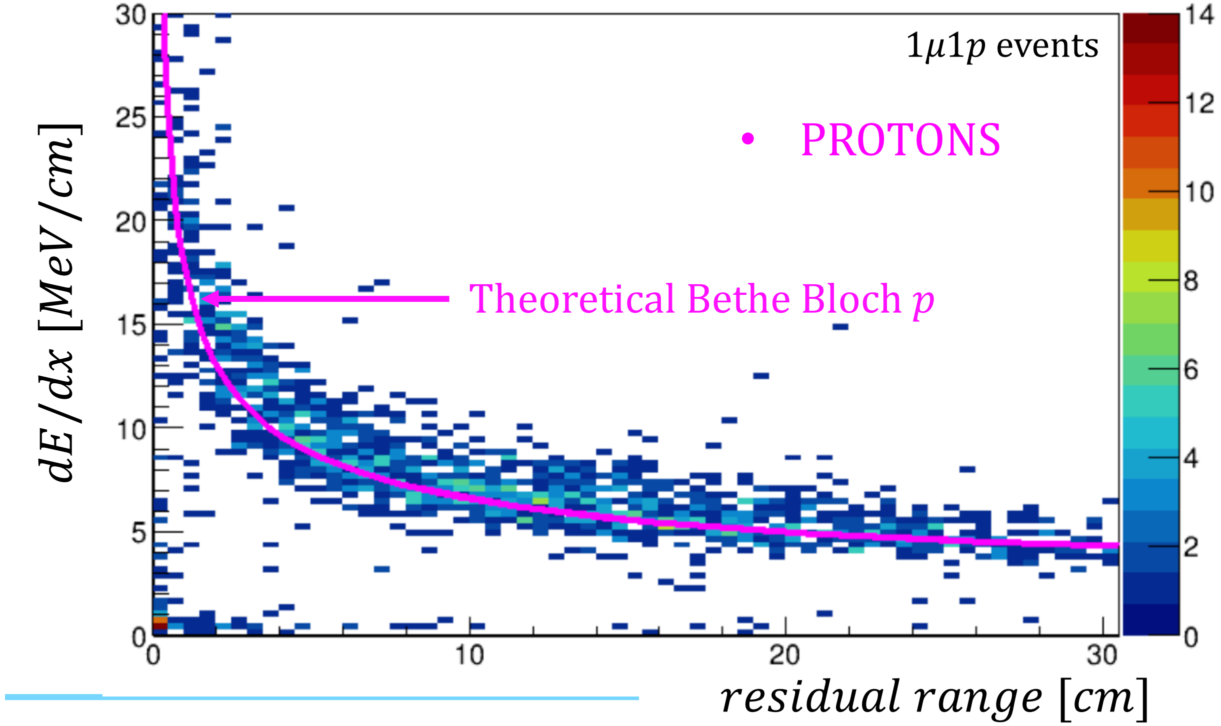


Particle identification

- The identification of the ν interactions requires a Particle Identification (PID) tool to effectively recognise the particles at the primary vertex
- The current algorithm relies on the comparison between the measured dE/dx vs residual range along the track with the theoretical profiles from different particles (μ, p, K, π)
- The χ^2 fit is performed considering **only** the last 25 cm of the track

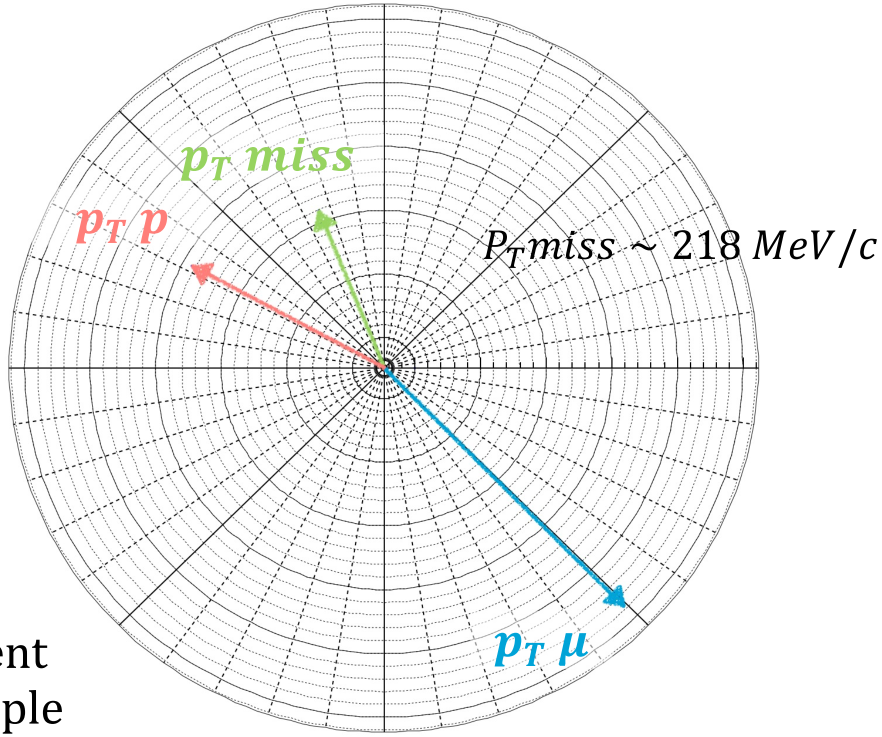




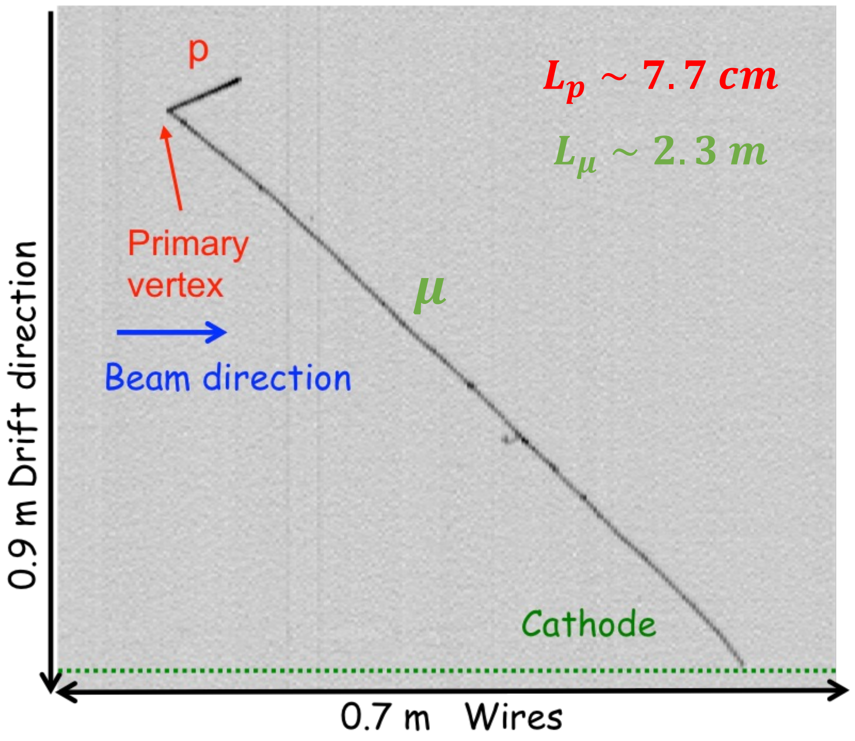
Neutrino transverse momenta

- **Well reconstructed** events are selected and the μ and p momenta computed from their range
- Kinematic event reconstruction is obtained through the total transverse momentum
- The transverse momentum of genuine $\nu_\mu CCQE$ events ⇢ dominated by the Fermi momentum in Ar nuclei

Transverse momenta $[MeV/c]$



1 event example



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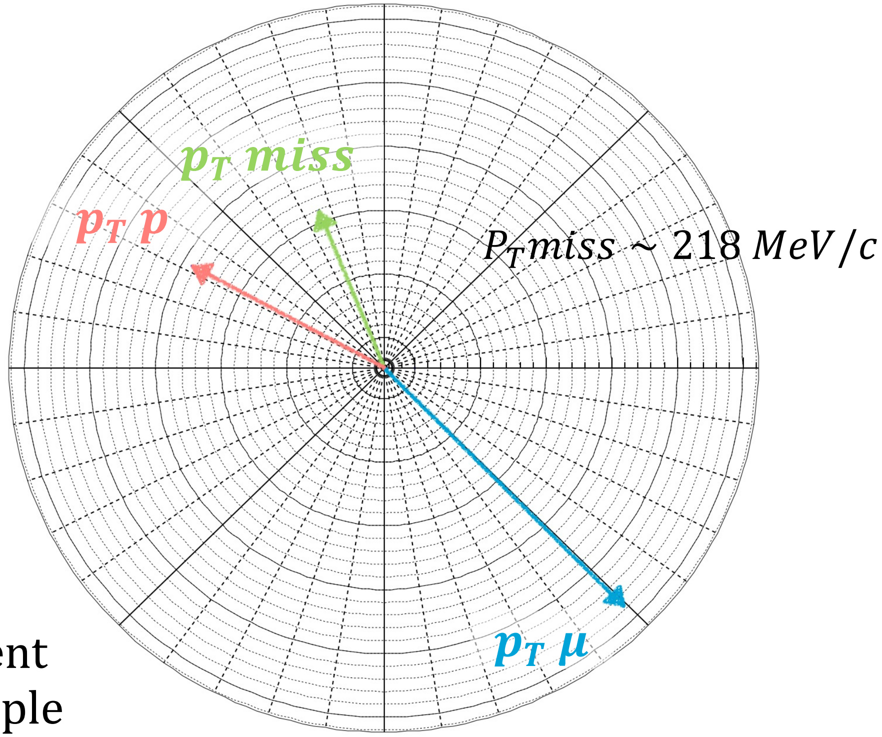

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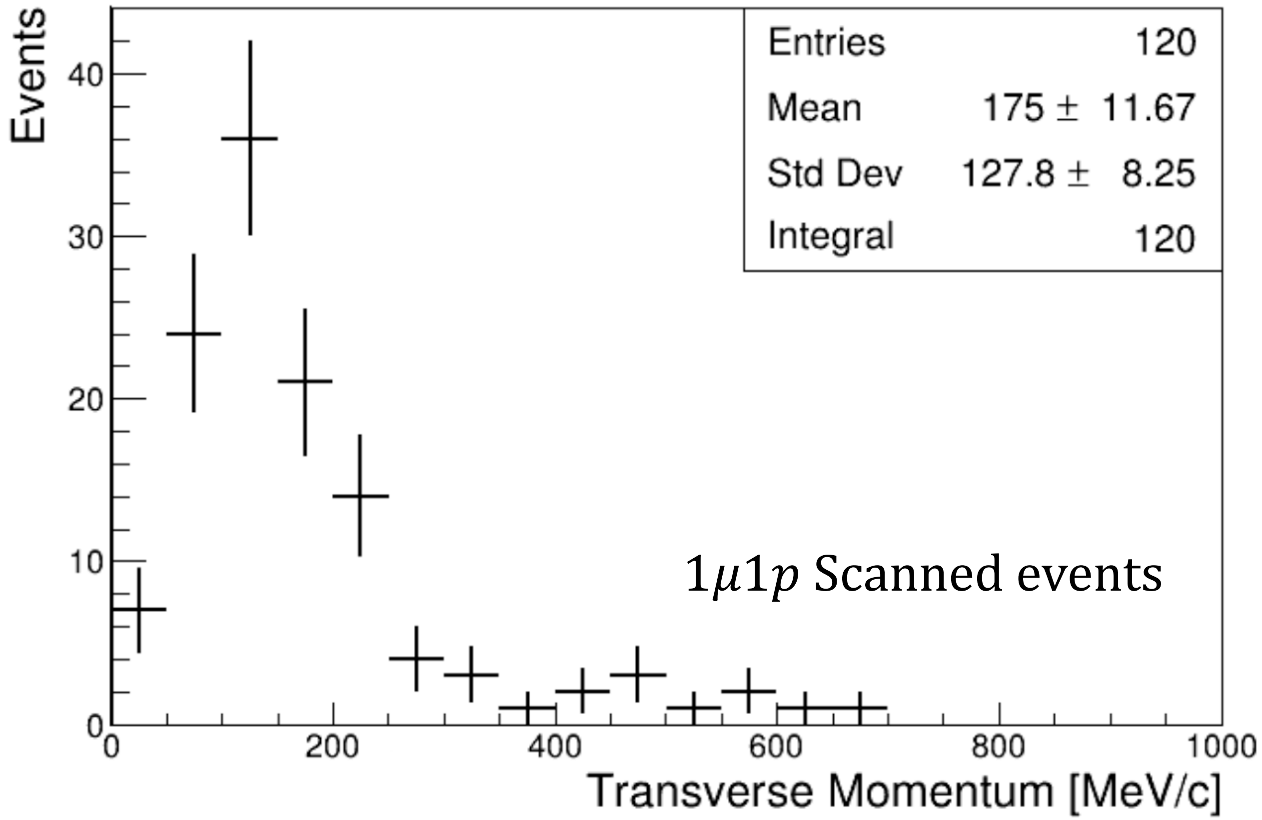
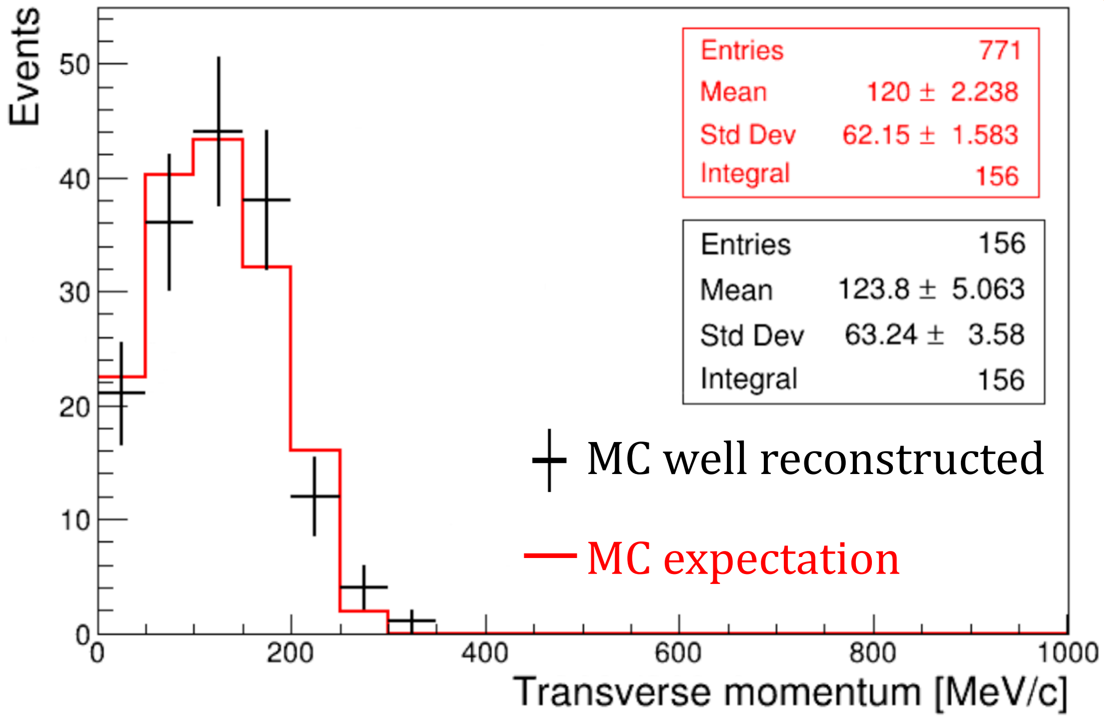


$1\mu1p$ Scanned events

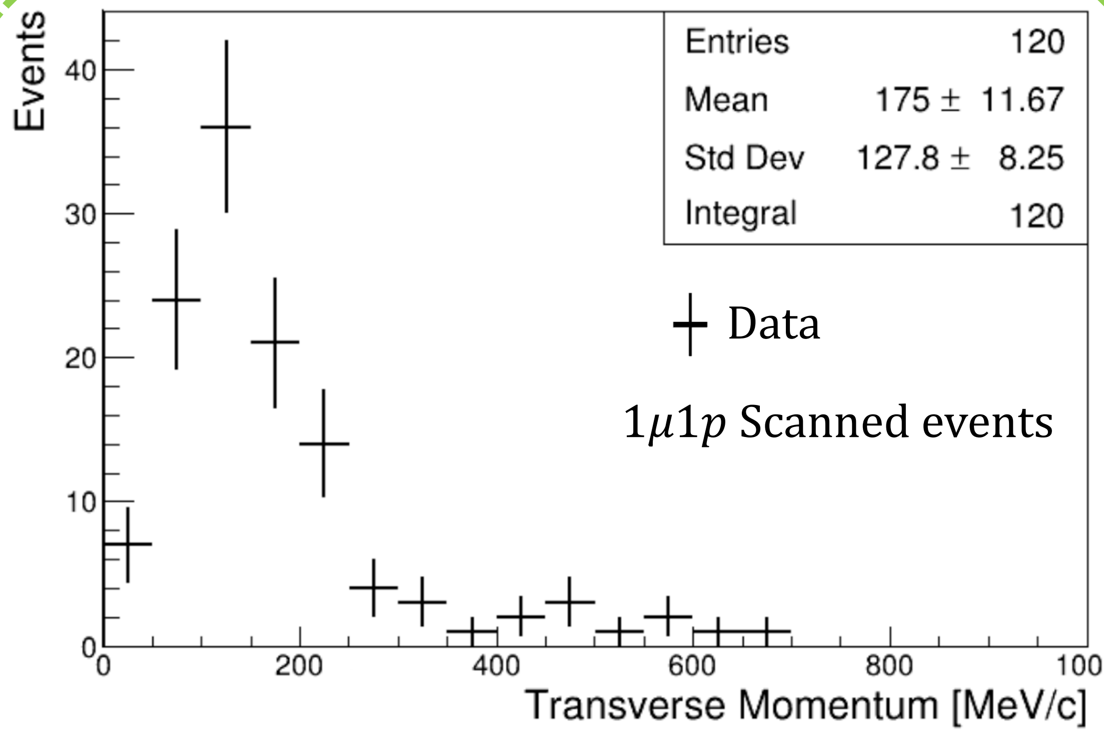
Monte Carlo comparison

- Reproduce same analysis with true $1\mu 1p$ MC events ($\sim 8\%$)



Black dots: Neutrino transverse momenta for well reconstructed MC events

Red line: true values scaled to number of black entries



Black dots: Neutrino transverse momenta for well reconstructed **data** events

Monte Carlo comparison

- It is clear from the transverse momenta plot that we are missing something…
- The visual scanning is really helpful tool to evaluate the performance of the selection and reconstruction algorithms, but it also has some limitations
  - All particles are identified based on their ionization. Hence, it is possible that different **hadrons** are wrongly classified as protons
  - Very **short** protons are not visible ⇢ mis identified as $1\mu 1p$ candidates
  - **Neutrons** and $\sim$ MeV **photons** produced at primary vertex are very difficult to recognize, unless they do some interaction

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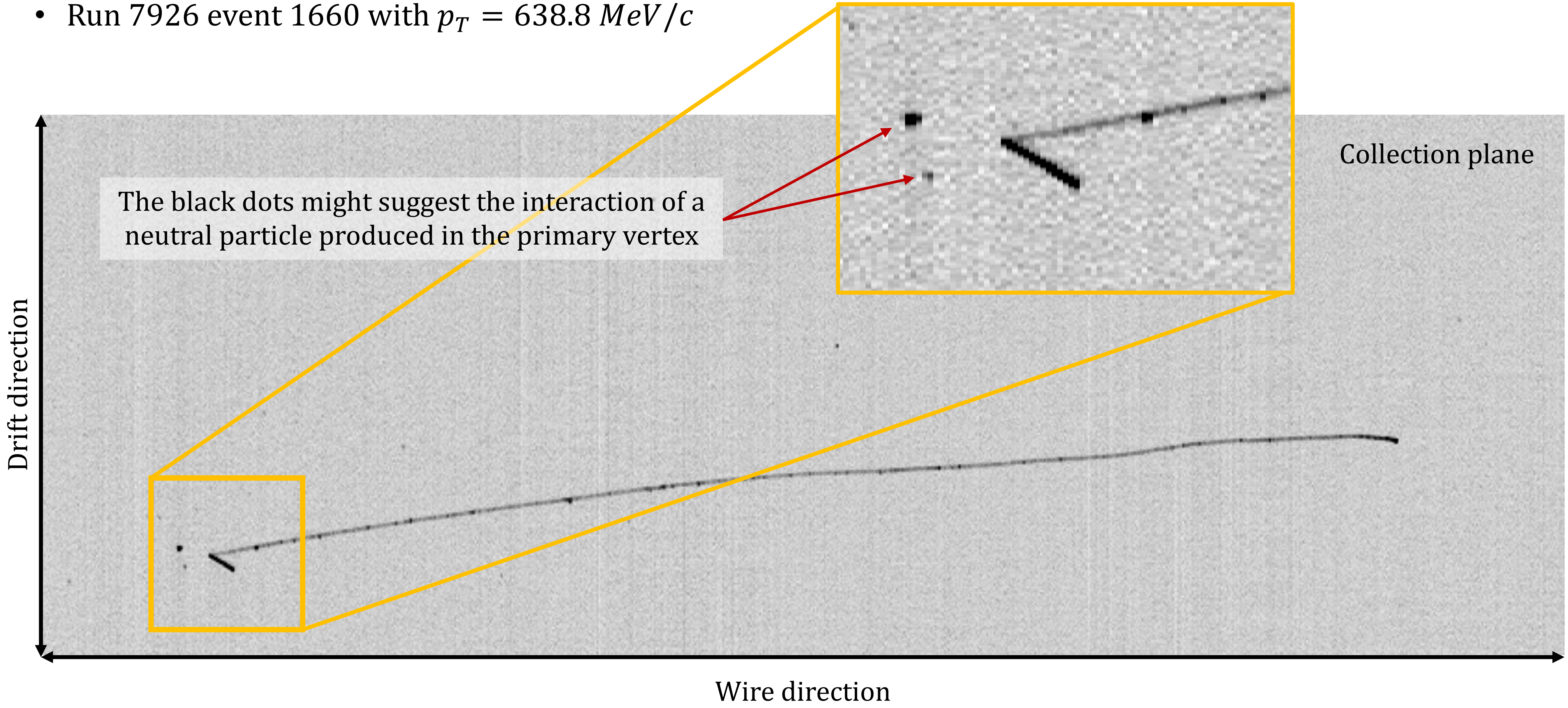
  - **Neutrons** and ~ MeV **photons** produced at primary vertex are very difficult to recognize, unless they do some interaction

Need to establish a visibility condition for protons, neutrons and photons to have a more accurate comparison between MC and real data

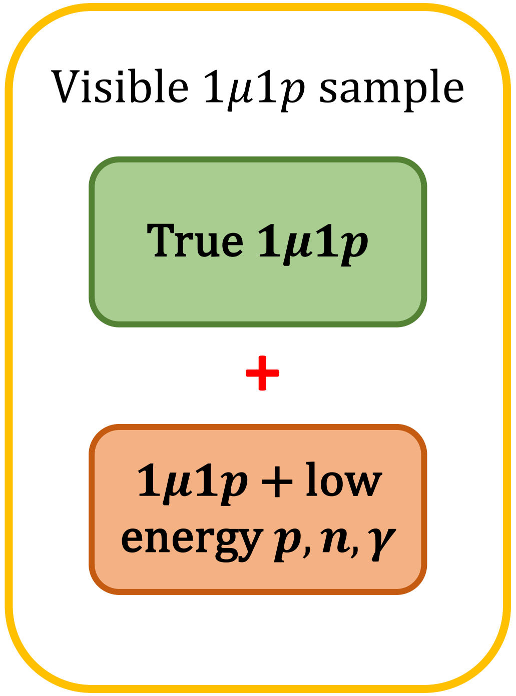
High transverse momentum event

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



Signal definition of $1\mu 1p$

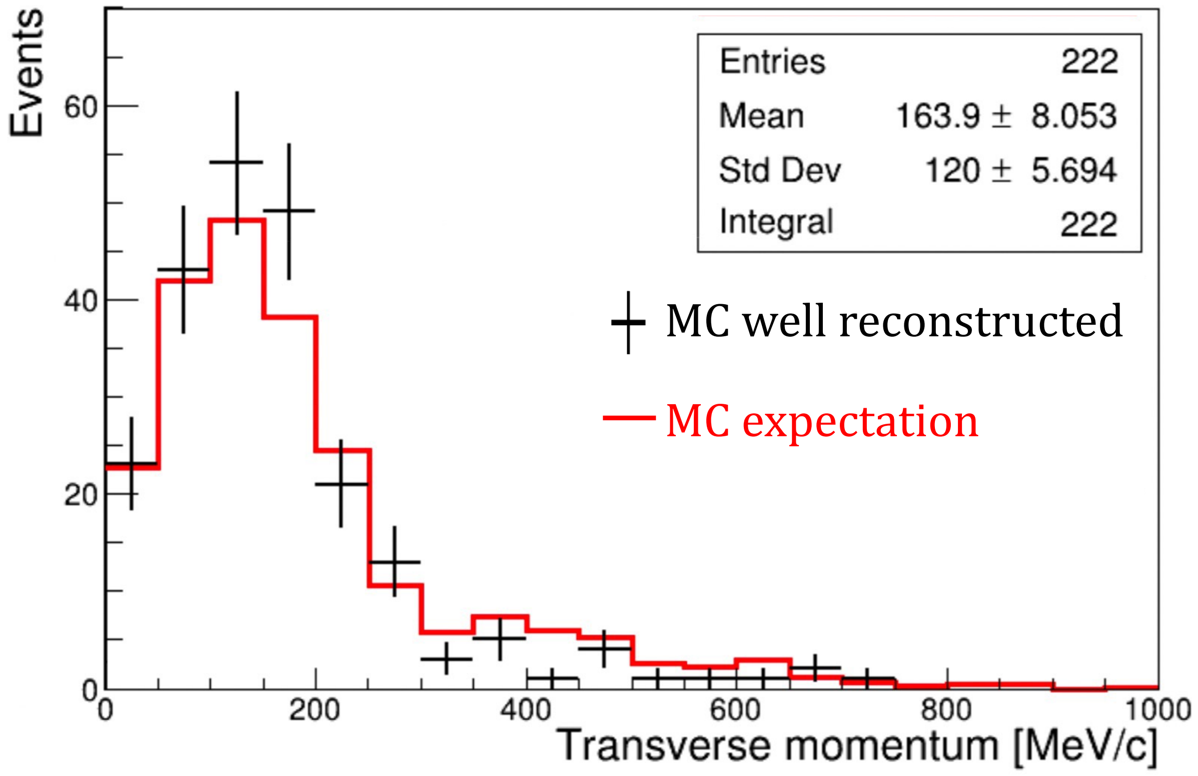
- Sample of "**Visible $1\mu 1p$**" events are defined as
  - $\nu_\mu CC$ events with the interaction vertex inside the fiducial volume
  - Only 2 visible particles coming out from the primary vertex
    - Primary proton is visible if $\mathrm{E_k} > 25MeV$ ($\sim$ $6mm$)
    - Primary neutron is visible if $\mathrm{E_{dep}} > 25MeV$
    - Primary photon is visible $\mathrm{E_{dep}} > 10MeV$
  - The 2 "visible" tracks need to be 1 muon and 1 proton
  - Visible particles both fully contained within 5cm from the active borders
  - Muon and proton lengths of at least 50 cm and 1 cm respectively



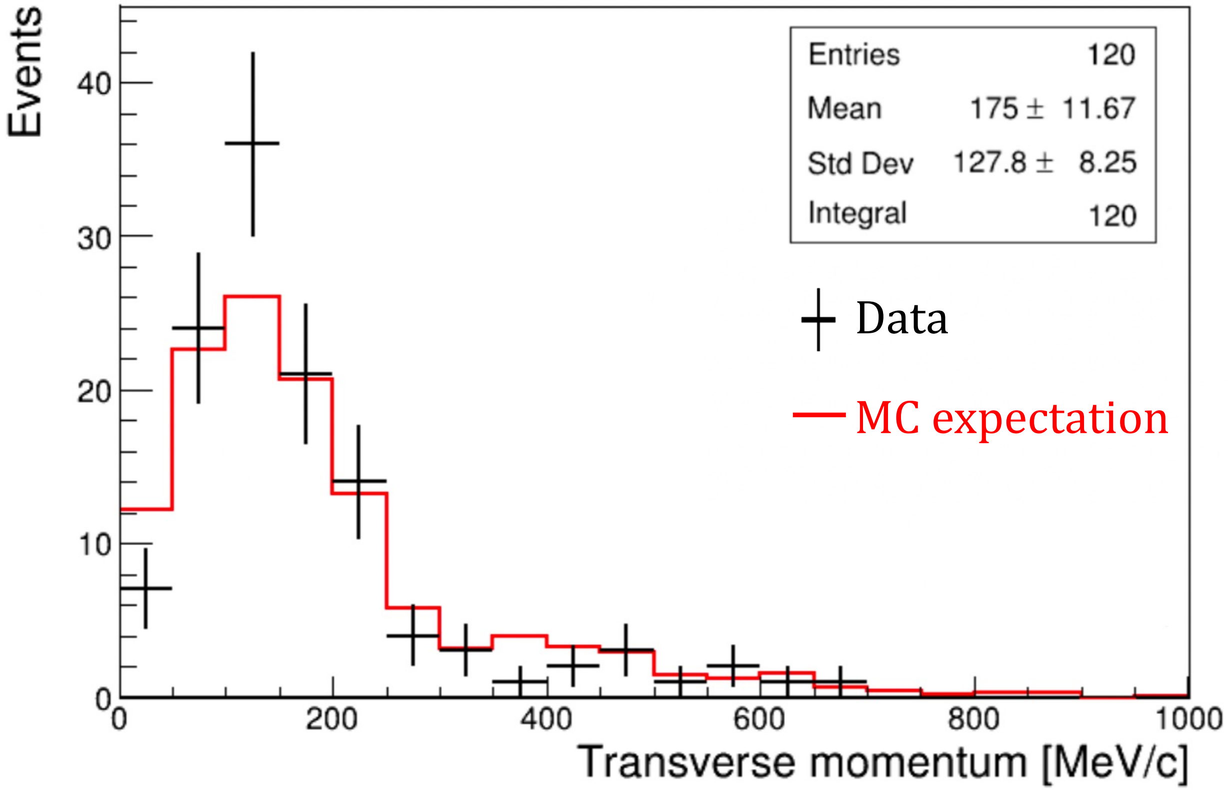
Monte Carlo cross check

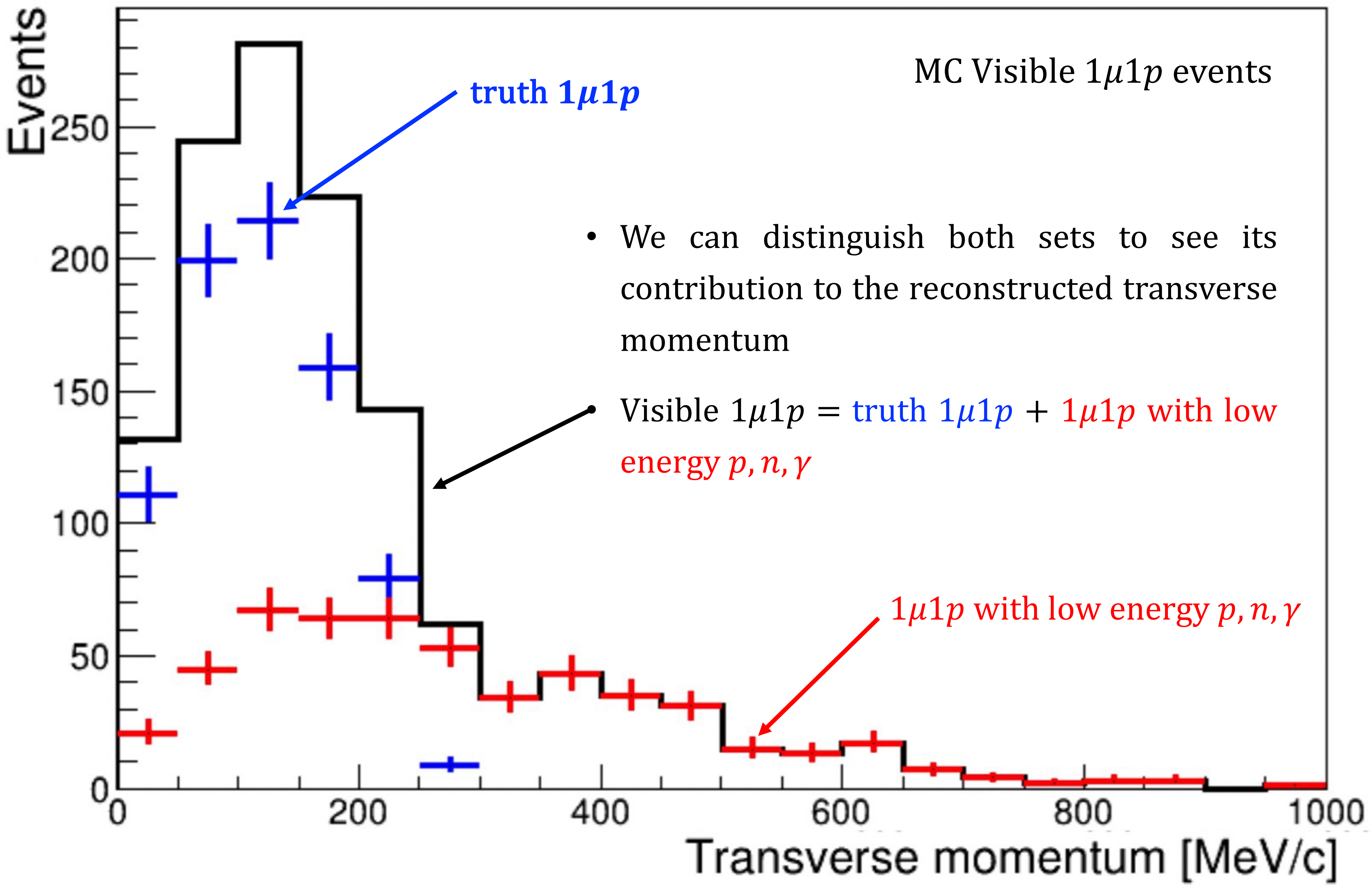
- With the new definition ⇢ better agreement between neutrino transverse momentum (MC) and data

Visible $1\mu1p$ events



Data $1\mu1p$ events

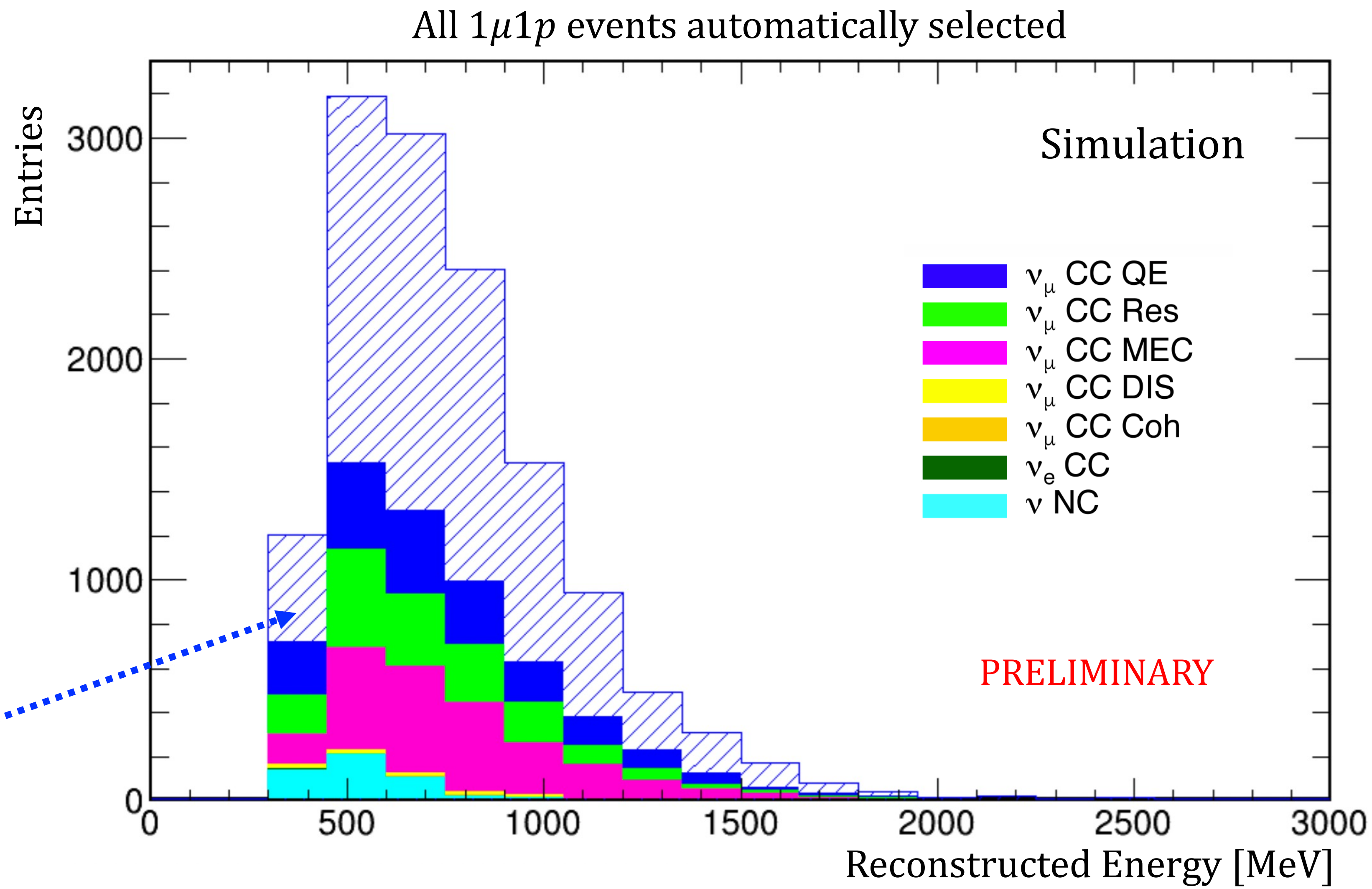




- We can distinguish both sets to see its contribution to the reconstructed transverse momentum
- Visible $1\mu1p$ = truth $1\mu1p$ + $1\mu1p$ with low energy p, n, γ

Automatic selection

- Due to the large number of collected events an automatic procedure to select $1\mu1p$ is mandatory
- A lot of effort is ongoing to maximize its efficiency and purity



These are the selected QE events which are $1\mu1p$

Conclusions and perspectives

- Preliminary results were obtained proving ICARUS' capability to perform calorimetric studies and particle identification ⇢ essential for oscillation studies
- Detailed study on MC events were performed and work is ongoing to improve the signal definition
- Collected neutrino candidates are being used to further develop and tune an automatic selection + reconstruction software tools to analyse $\nu_\mu CC$ events
- Efforts are underway to measure the energy of neutrinos and its resolution

THANK YOU!

ICARUS Collaboration at SBN

P. Abratenko[19], A. Aduszkiewicz[21], F. Akbar[23], M. Artero Pons[15], J. Asaadi[24], M. Babicz[2], W.F. Badgett[5], L.F. Bagby[5], B. Baibussinov[15], B. Behera[4], V. Bellini[7], O. Beltramello[2], R. Benocci[13], J. Berger[4], S. Berkman[5], S. Bertolucci[6], M. Betancourt[5], K. Biery[5], M. Bonesini[13], T. Boone[4], B. Bottino[8], A. Braggiotti[15], J Bremer[2], S. Brice[5], V. Brio[7], C. Brizzolari[13], J. Brown[5], H. Budd[23], A. Campani[8], A. Campos[27], D. Carber[4], M. Carneiro[1], H. Carranza[24], D. Casazza[8], A. Castro[3], M. Cicerchia[15], S. Centro[15], G. Cerati[5], M. Chalifour[2], A.Chatterjee[26],D. Cherdack[21], S. Cherubini[11], N. Chitirasreemadam[25], T. Coan[18], A. Cocco[14], M. R. Convery[17], S. Copello[16], A. De Roeck[2], S. Di Domizio[8], D. Di Ferdinando[6], L. Di Noto[8], M. Diwan[1], S. Donati[25], J. Dyer[4], S. Dytman[22], S. Dolan[2], F. Dolek[27], L. Domine[17], R. Doubnik[5], F. Drielsma[17], C. Fabre[2], A. Falcone[13], C. Farnese[15], A. Fava[5], F. Ferraro[8], F. Garcia[17], C. Gatto[14], M. Geynisman[5], D. Gibin[15], A. Gioiosa[25], W. Gu[1], M. Guerzoni[6], A. Guglielmi[15], S. Hahn[5], A. Heggestuen[4], B. Howard[5], R.Howell[23], J. Hrivnak[2], C. James[5], W. Jang[24],L. Kashur[4],W. Ketchum[5], J.S. Kim[23], D.H. Koh[17], U. Kose[2], J. Larkin[1], G. Laurenti[6], G. Lukhanin[5], A. Maria[26], C. Mariani[27], C. Marshall[23], S. Martinenko[1], N. Mauri[6], A. Mazzacane[5], K.S. McFarland[23], D.P. Mendez[1], G. Meng[15], A. Menegolli[16], O.G. Miranda[3], D. Mladenov[2], A.Mogan[4], N. Moggi[6], N.Montagna[6], A. Montanari[6], C. Montanari[5,b], M. Mooney[4], G. Moreno Granados[3], J. Mueller[4], M. Murphy[27], D. Naples[22], M. Nessi[2], T. Nichols[5], S. Palestini[2], M. Pallavicini[8], V. Paolone[22], R. Papaleo[11], L. Pasqualini[6], L. Patrizii[6], G. Petrillo[17], C. Petta[7], V. Pia[6], F. Pietropaolo[2,a], F. Poppi[6], M. Pozzato[6], A. Prosser[5], G. Putnam[20], X. Qian[1], A. Rappoldi[16], R. Rechenmacher[5], L. Rice[22], E. Richards[22], F. Resnati[2], A.M. Ricci[25], A.Rigamonti[2], G.L. Raselli[16], M. Rosemberg[19], M. Rossella[16], C. Rubbia[9], G. Savage[5], A. Scaramelli[16], D. Schmitz[20], A. Schukraft[5], F. Sergiampietri[2], G. Sirri[6], J. Smedley[23], A. Soha[5], L. Stanco[15],J. Stewart[1],N.B. Suarez[22], H.Tanaka[17], M. Tenti[6], K.Terao[17], F. Terranova[13], V.Togo[6], D.Torretta[5], M.Torti[13], Y.T. Tsai[17], S.Tufanli[2], T. Usher[17], F.Varanini[15], S. Ventura[15], M.Vicenzi[1], C. Vignoli[10], B.Viren[1], D. Warner[4], Z. Williams[24], P. Wilson[5], R.J. Wilson[4], J. Wolfs[23], T. Wongjirad[19], A. Wood[21], E. Worcester[1], M. Worcester[1], M. Wospakrik[5], H. Yu[1], J. Yu[24], A. Zani[12], C. Zhang[1], J. Zennamo[5], J. Zettlemoyer[5], S. Zucchelli[6], M. Zuckerbrot[5]

1. Brookhaven National Lab., USA
2. CERN, Switzerland
3. CINVESTAV, Mexico,
4. Colorado State University, USA
5. Fermi National Accelerator Lab., USA
6. INFN Bologna and University, Italy
7. INFN Catania and University, Italy
8. INFN Genova and University, Italy
9. INFN GSSI, L'Aquila, Italy
10. INFN LNGS, Assergi, Italy
11. INFN LNS, Catania, Italy
12. INFN Milano, Milano, Italy
13. INFN Milano Bic. and University, Italy
14. INFN Napoli, Napoli, Italy
15. INFN Padova and University, Italy
16. INFN Pavia and University, Italy
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21. University of Houston, USA
22. University of Pittsburgh, USA
23. University of Rochester, USA
24. University of Texas (Arlington),USA
25. INFN Pisa and University, Italy
26. Ramanujan Faculty Phys. Res. India
27. Virginia Tech Institute

a On Leave of Absence from INFN Padova
b On Leave of Absence from INFN Pavia

Spokesperson: C. Rubbia, GSSI

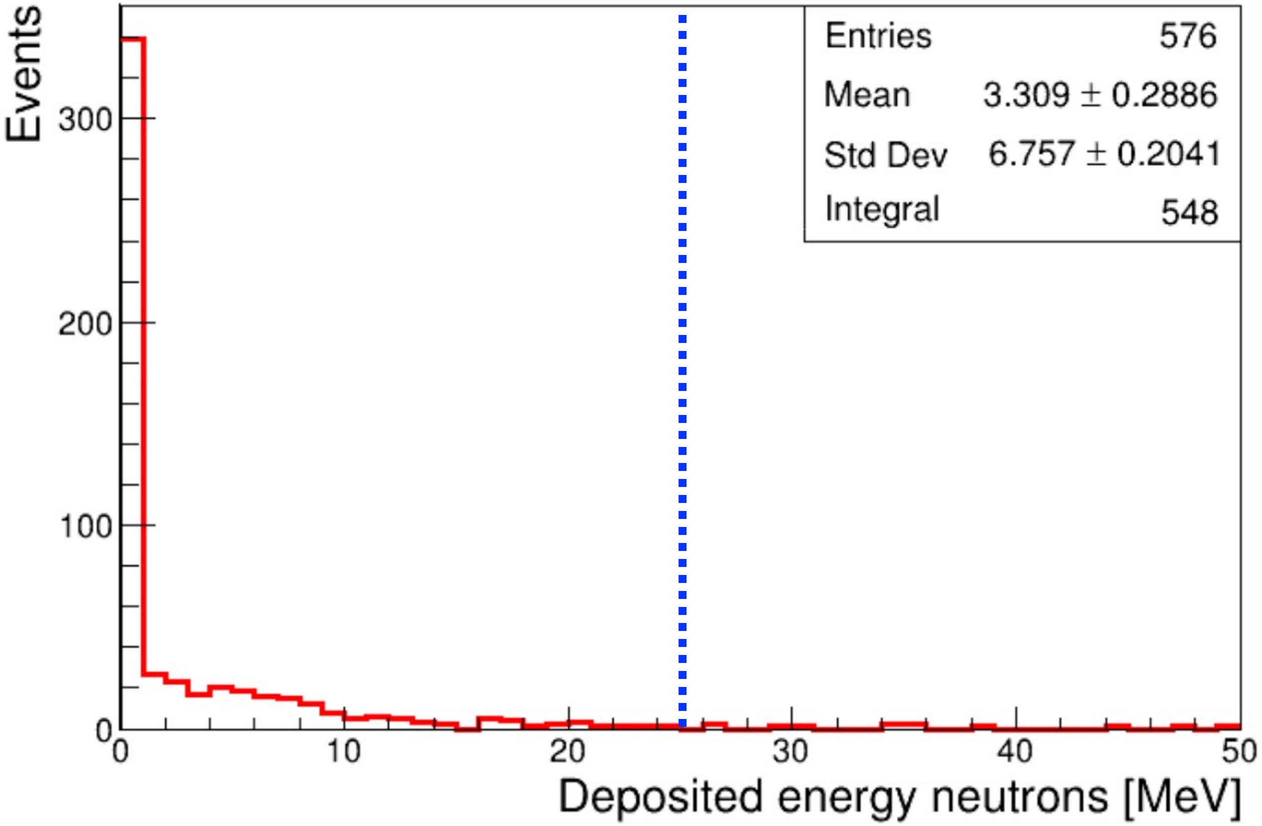
12 INFN groups, 12 US institutions, CERN, 1 Institution from Mexico and India

BACKUP SLIDES

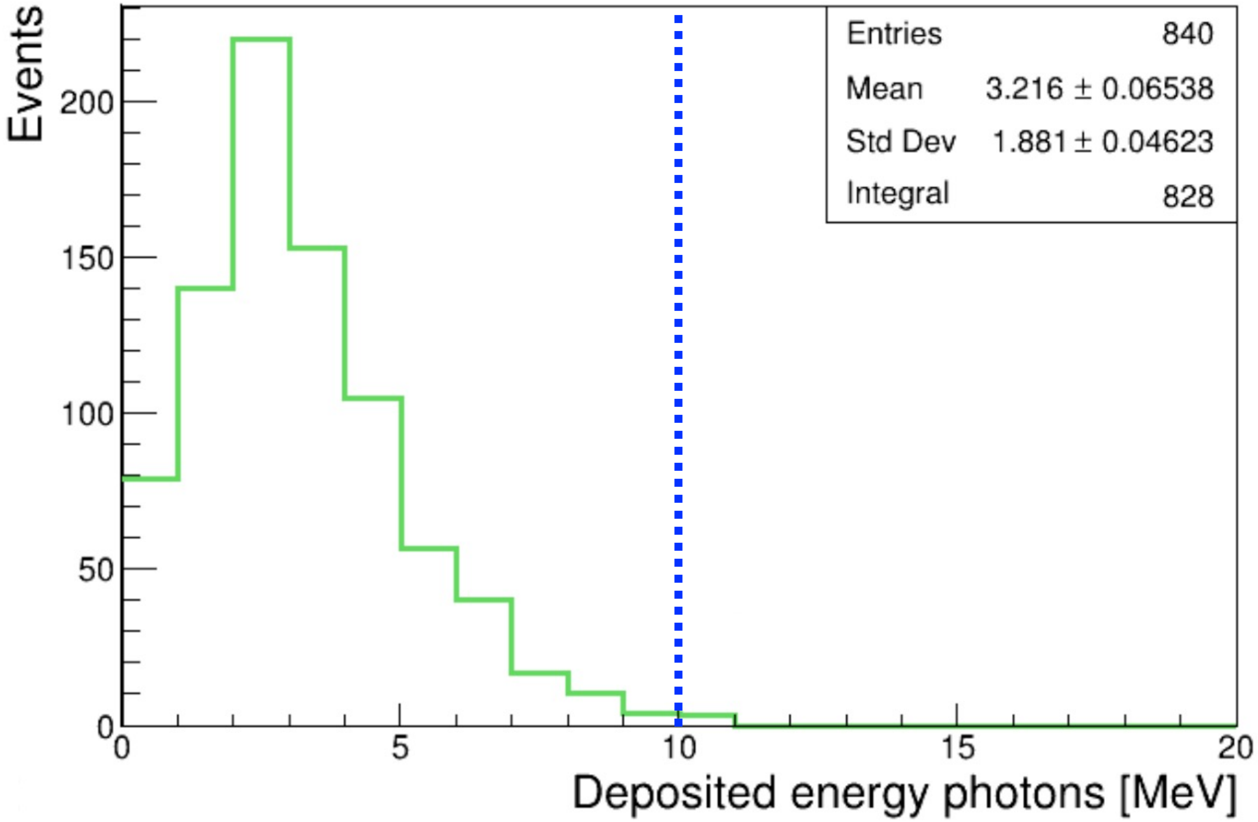
Imaging
Cosmic
And
Rare
Underground
Signals

- 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 = $10\ MeV$



- **Well reconstructed** event means:
  - Reconstructed vertex in agreement with the information from the scanning/MC within 2 cm
  - The muon track should be recognized as primary particle in the interaction
  - The muon track should start within 2 cm from the reconstructed vertex
  - The muon track should end within 2 cm from the scanning/MC position
  - The particle identification (PID) algorithm should correctly classify the muon track
  - The start/end point of the proton should be well recognized, similarly to the muon
  - The PID algorithm should correctly identify the proton track as a proton candidate