UNIVERSITY OF CAMBRIDGE

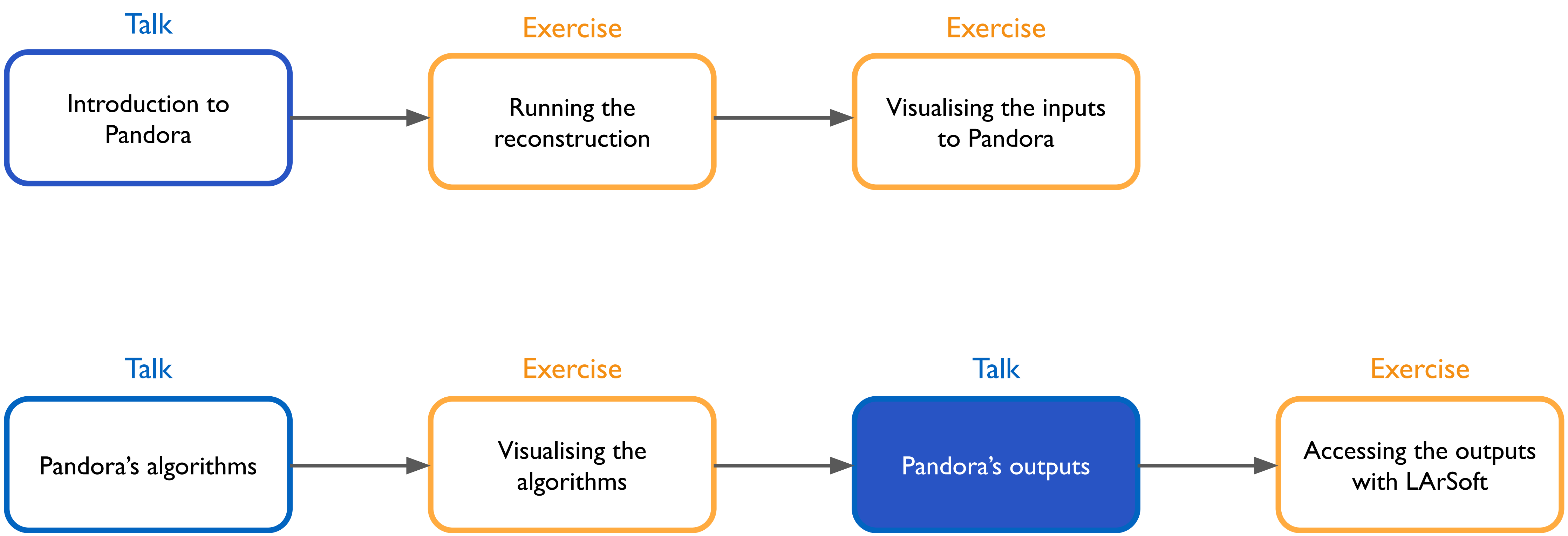
6th UK LArTPC Software Analysis Workshop

Reconstruction Outputs

Steve Dennis for the Pandora Team

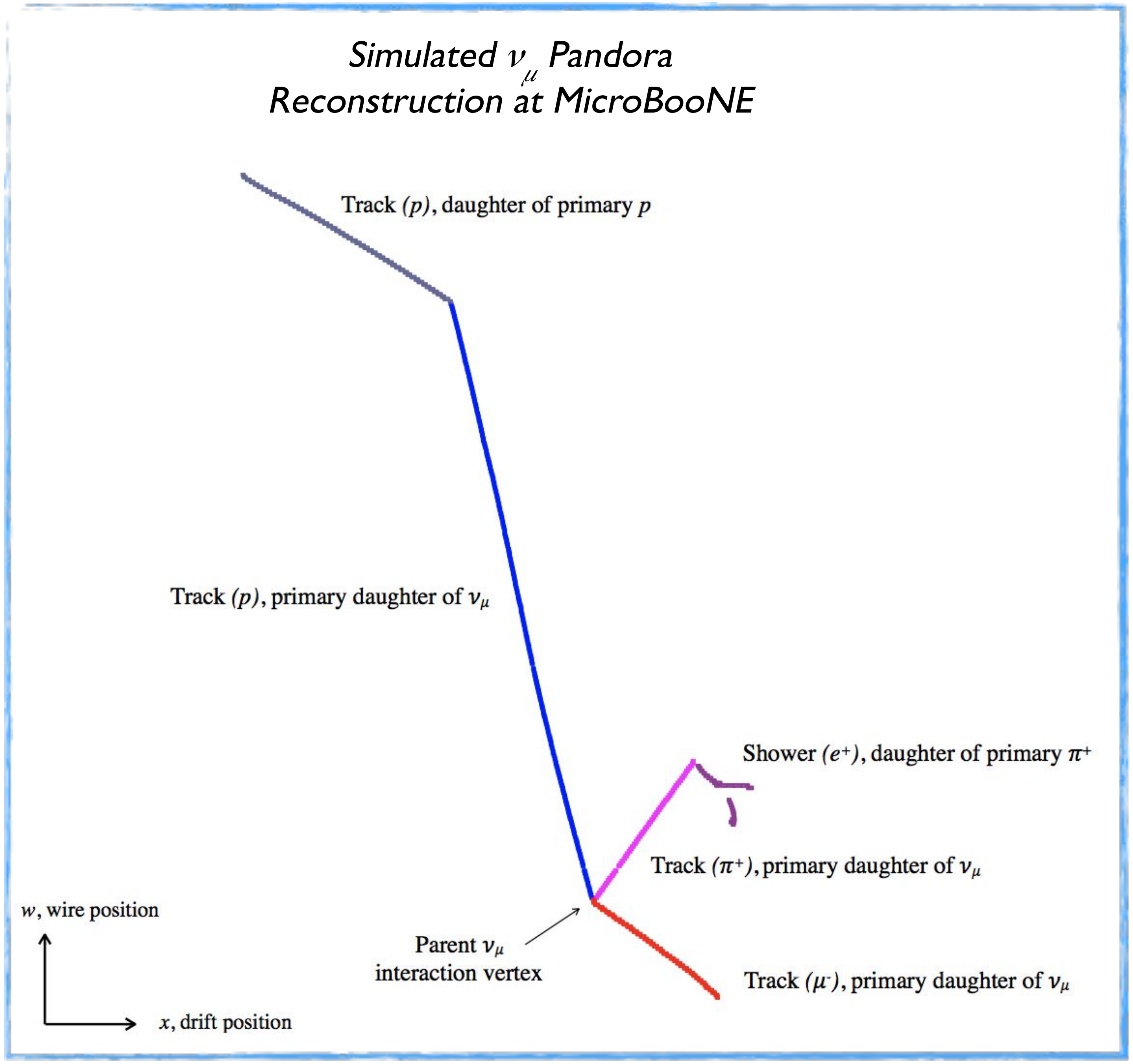
2nd November 2021

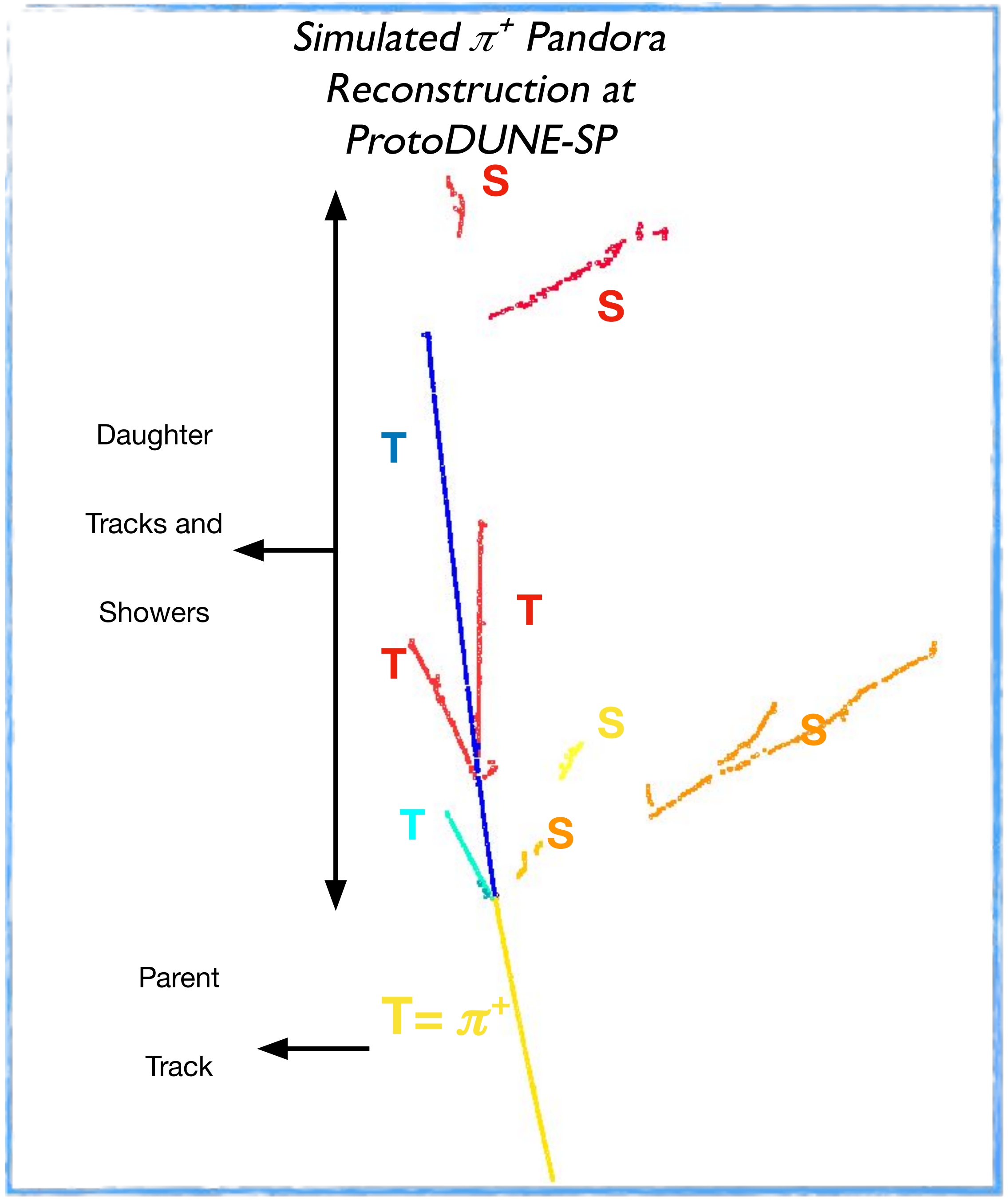
This lecture was developed by John Marshall, Warwick



A key reference: Eur. Phys. J. C (2018) 78: 82

Use 3D clusters to organise particles into a hierarchy, working outwards from interaction vtx:





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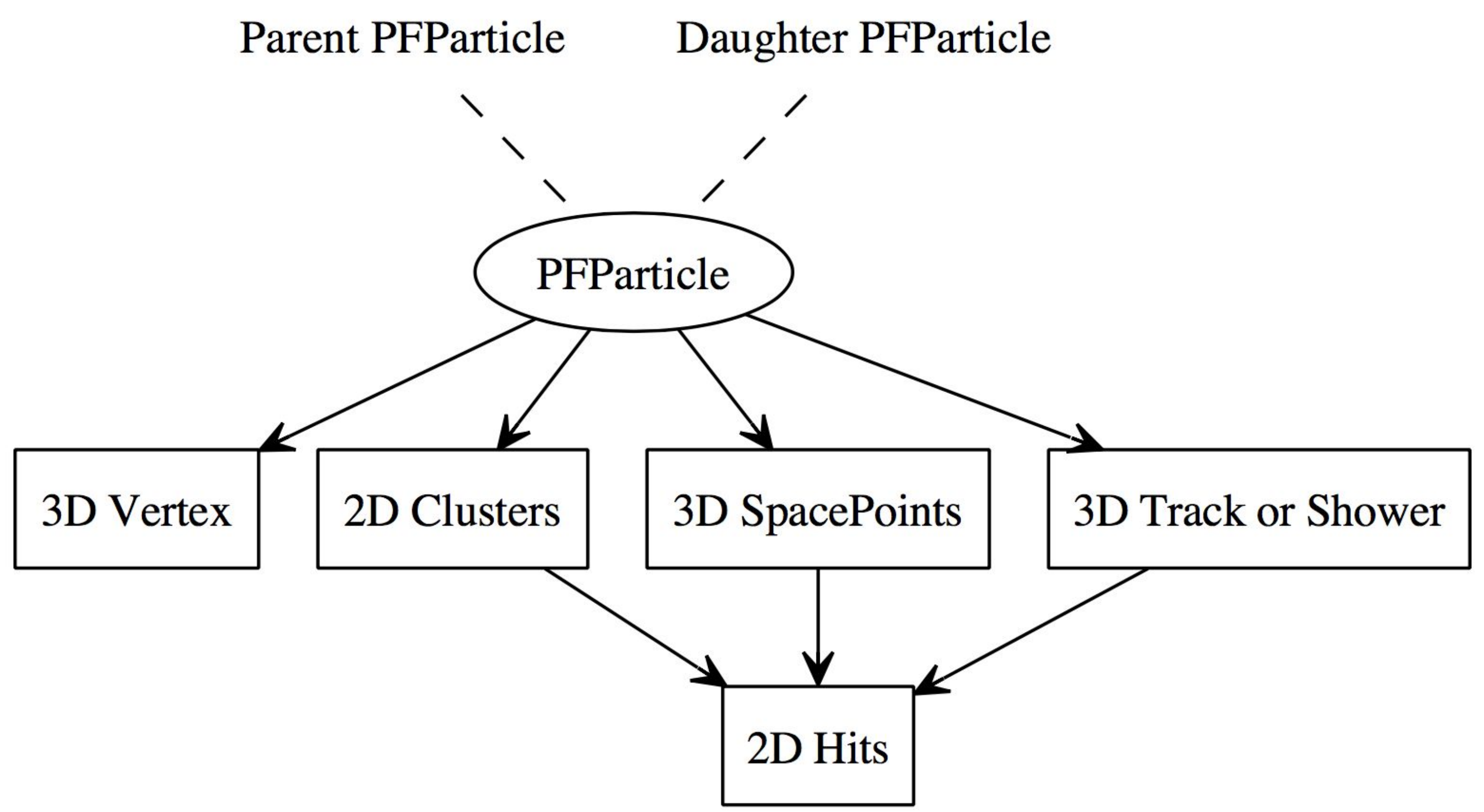
- Must translate output from Pandora Event Data Model to LArSoft Event Data Model. The key output is the PFParticle (PF ⇒ Particle Flow):
  - Each PFParticle corresponds to a distinct track or shower and is associated to 2D clusters.
  - 2D clusters group hits from each readout plane, and are associated to the input 2D hits.
  - PFParticles also associated to 3D spacepoints and a 3D vertex.
  - PFParticles placed in a hierarchy, with identified parent-daughter relationships.
  - PFParticles flagged as track-like or shower-like.

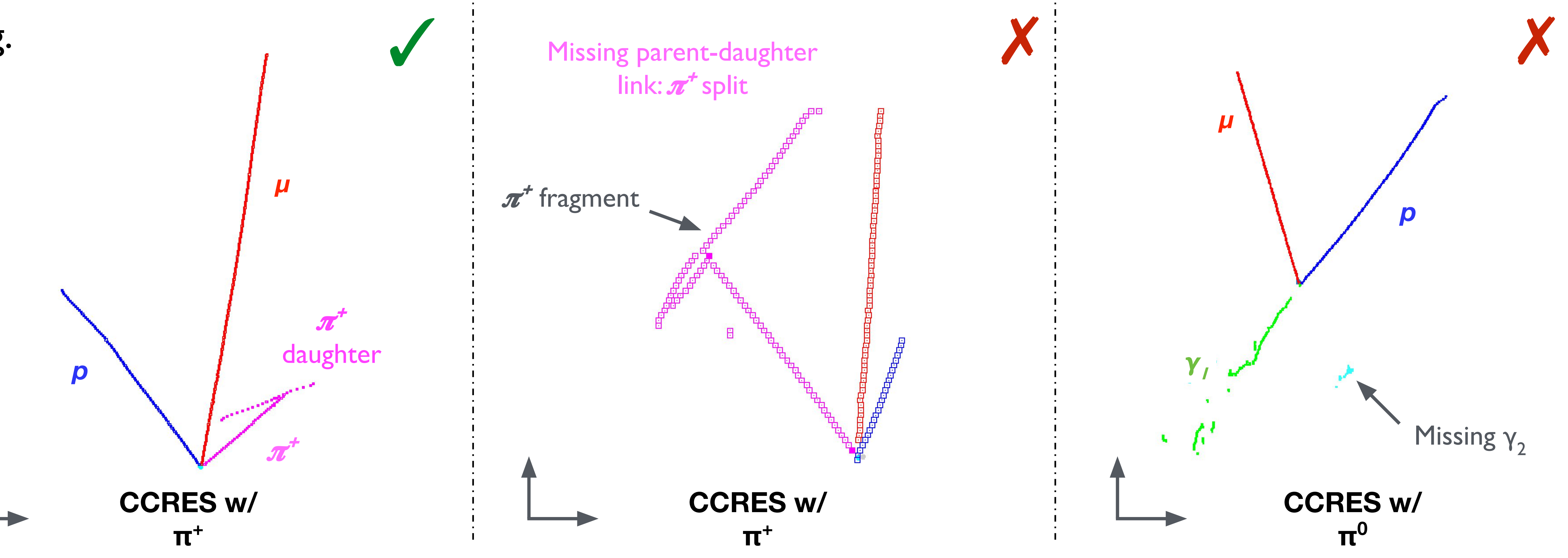


Just the most important outputs shown here

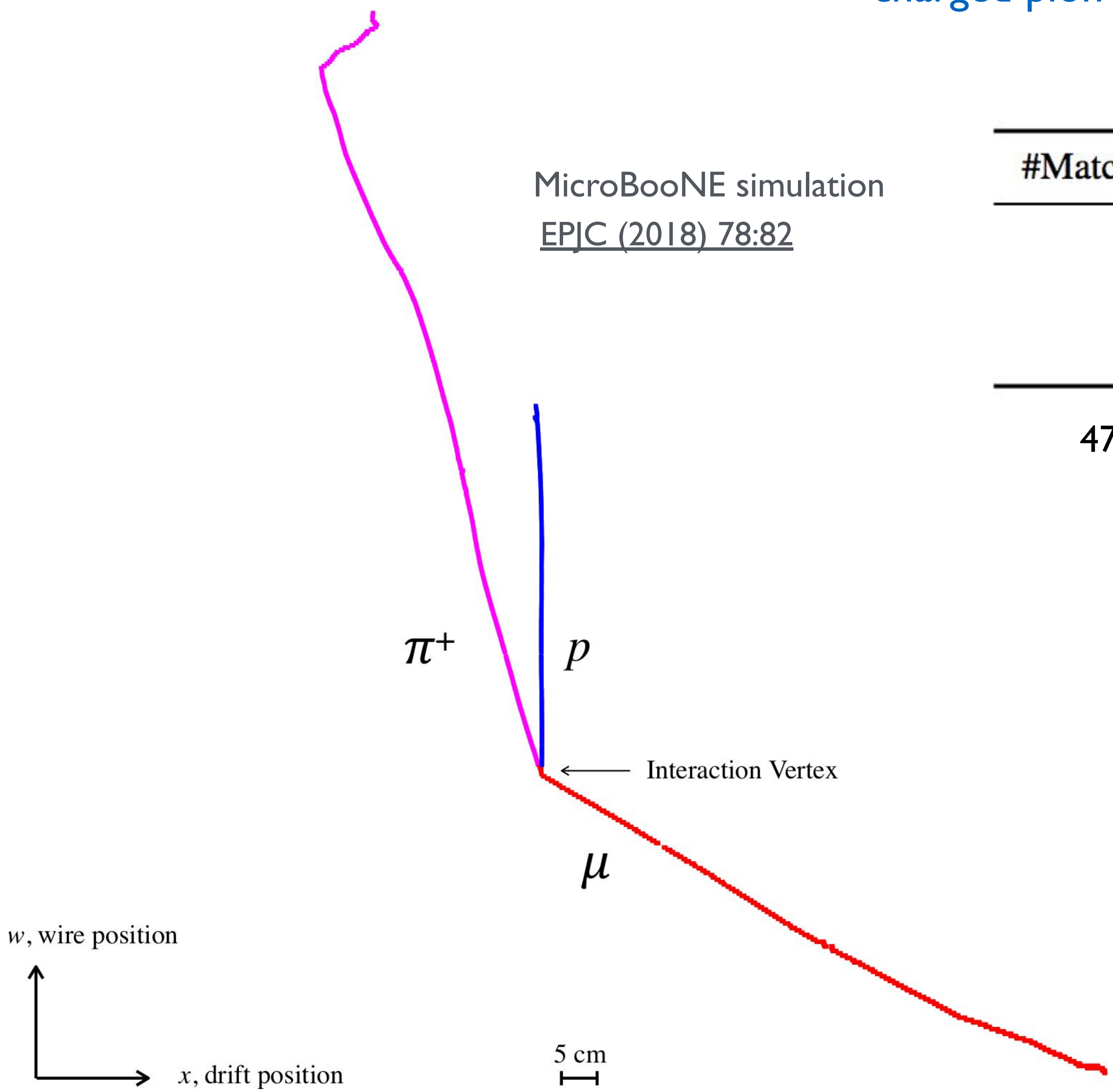
Will work with these products soon in analyzer tutorial

- Assess performance for simulated MicroBooNE events, using a selection of event topologies.
- Examine fraction of events deemed "correct" by ***very strict*** pattern-recognition metrics:
    - Consider exclusive final-states where all true particles pass simple quality cuts (e.g. nHits)
    - Correct means exactly one reco primary particle is matched to each true primary particle

E.g.



Three-track topology: CC ν_μ interactions with resonant charged pion production:



MicroBooNE simulation
EPJC (2018) 78:82

#Matched Particles	0	1	2	3+
μ	3.5%	95.1%	1.4%	0.0%
p	9.0%	86.8%	4.0%	0.3%
π^+	6.9%	80.9%	11.4%	0.8%

47,754 events, 70.5% have exactly one reco particle matched to each target.

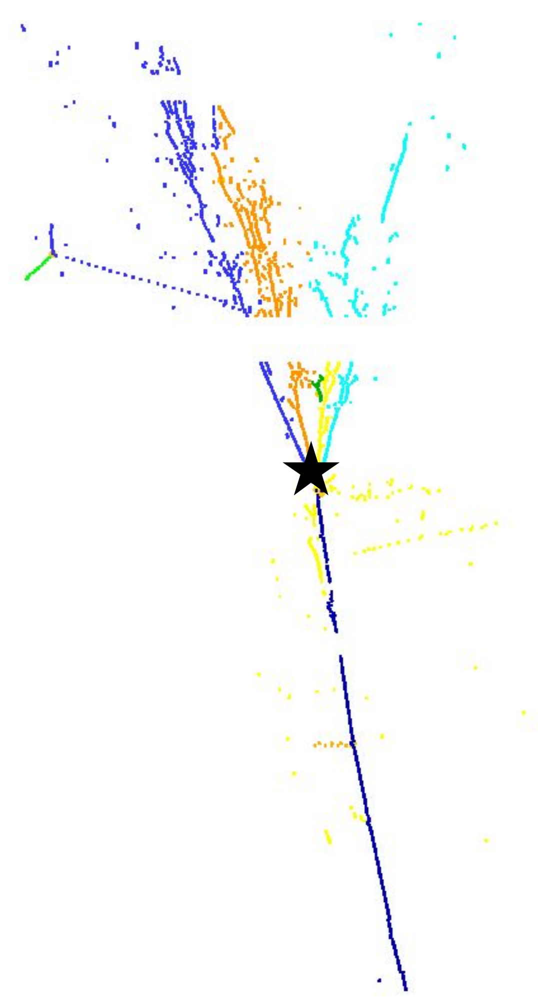
- Performance for μ and p similar to that reported for quasi-elastic events.
- π^+ interactions can lead to hierarchy of visible particles. If reconstructed separately (without parent-daughter links), π^+ is reportedly split.

1.1 GeV ν_μ

- We have used a multi-algorithm approach to create two algorithm chains:

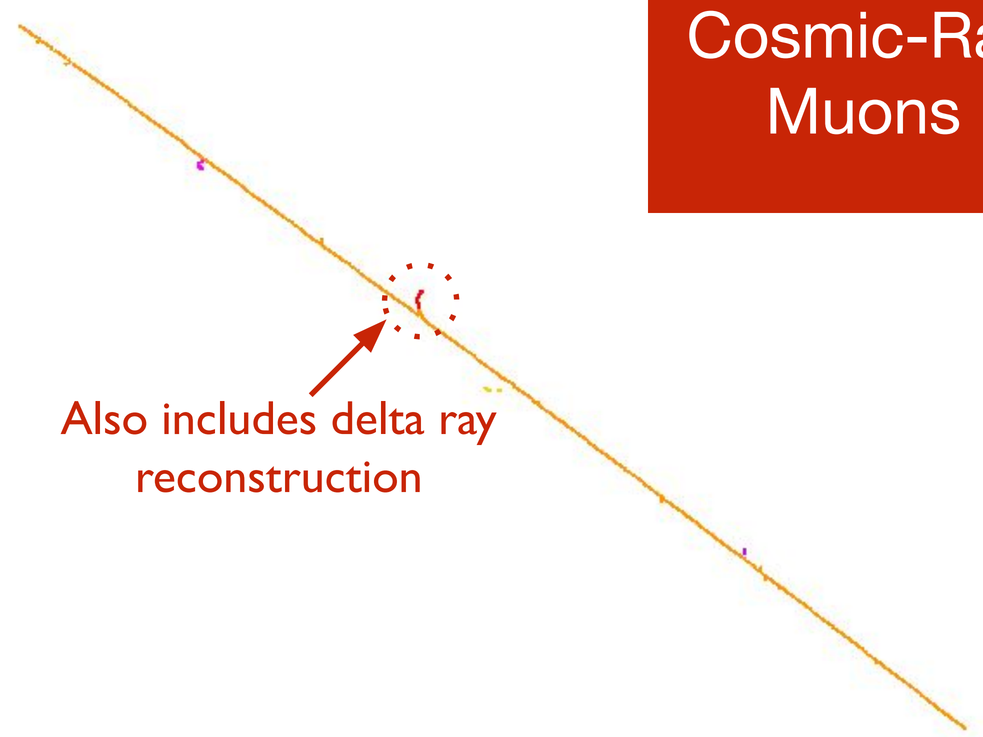
Consolidated reconstruction uses these chains to guide reconstruction for all use cases:

Cosmic rays ✔, Multiple drift volumes ✔, Arbitrary wire angles ✔, 2 or 3 wire planes ✔



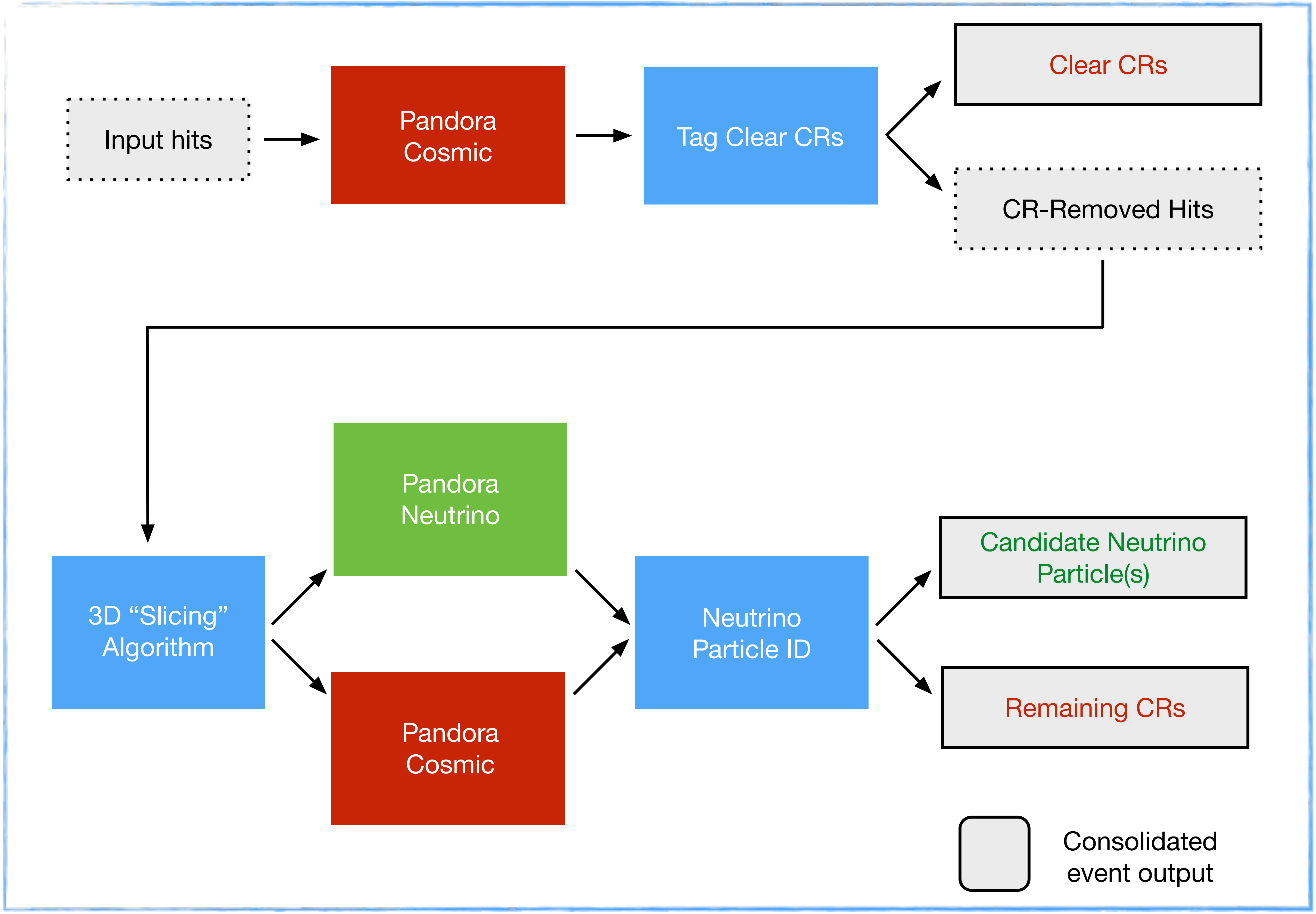
Neutrino (or TestBeam)

Target reconstruction of particles emerging from an identified vertex ★



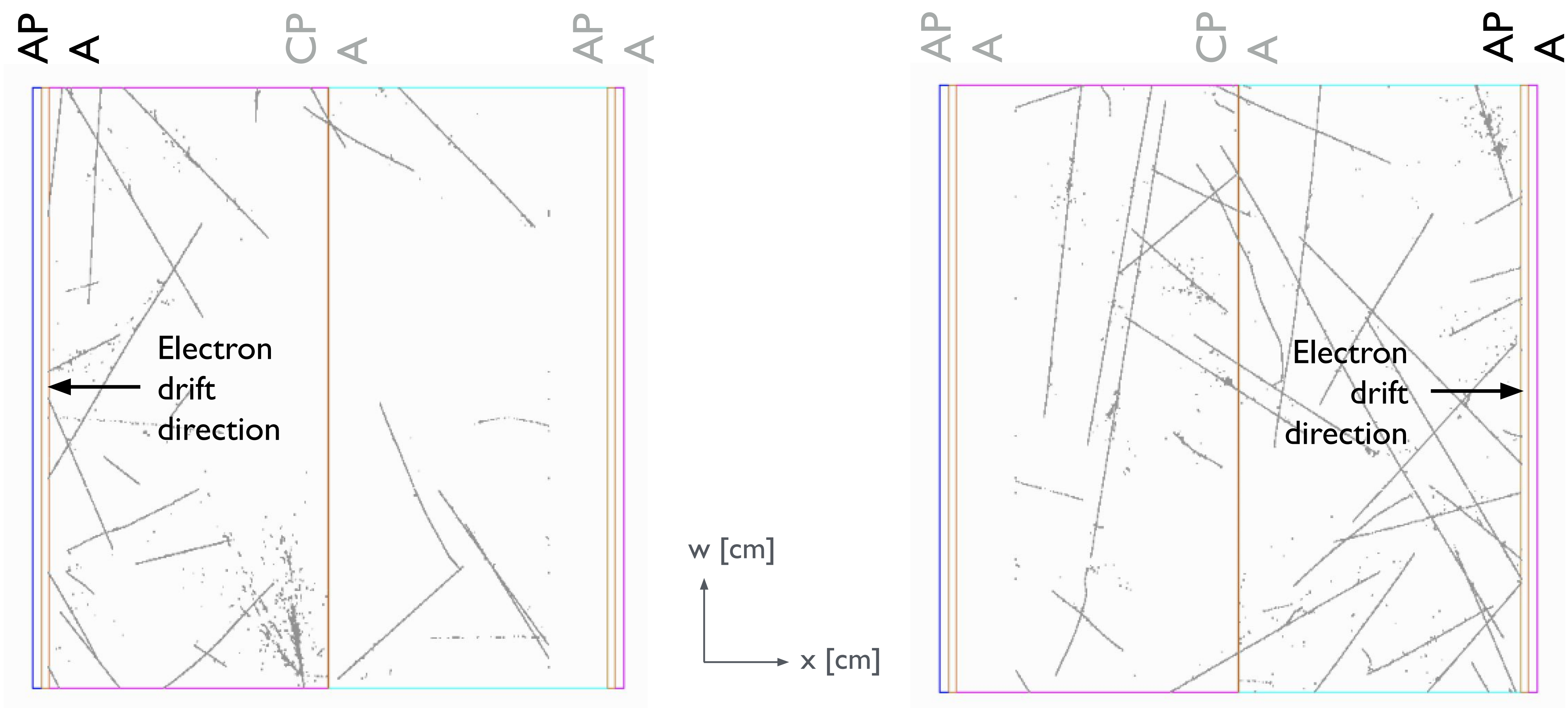
Cosmic-Ray Muons

Target reconstruction of straight-line particles in detector (e.g. cosmic-ray muons)



Input hits
Pandora Cosmic
Tag Clear CRs
Clear CRs
CR-Removed Hits
3D "Slicing" Algorithm
Pandora Neutrino
Pandora Cosmic
Neutrino Particle ID
Candidate Neutrino Particle(s)
Remaining CRs
Consolidated event output

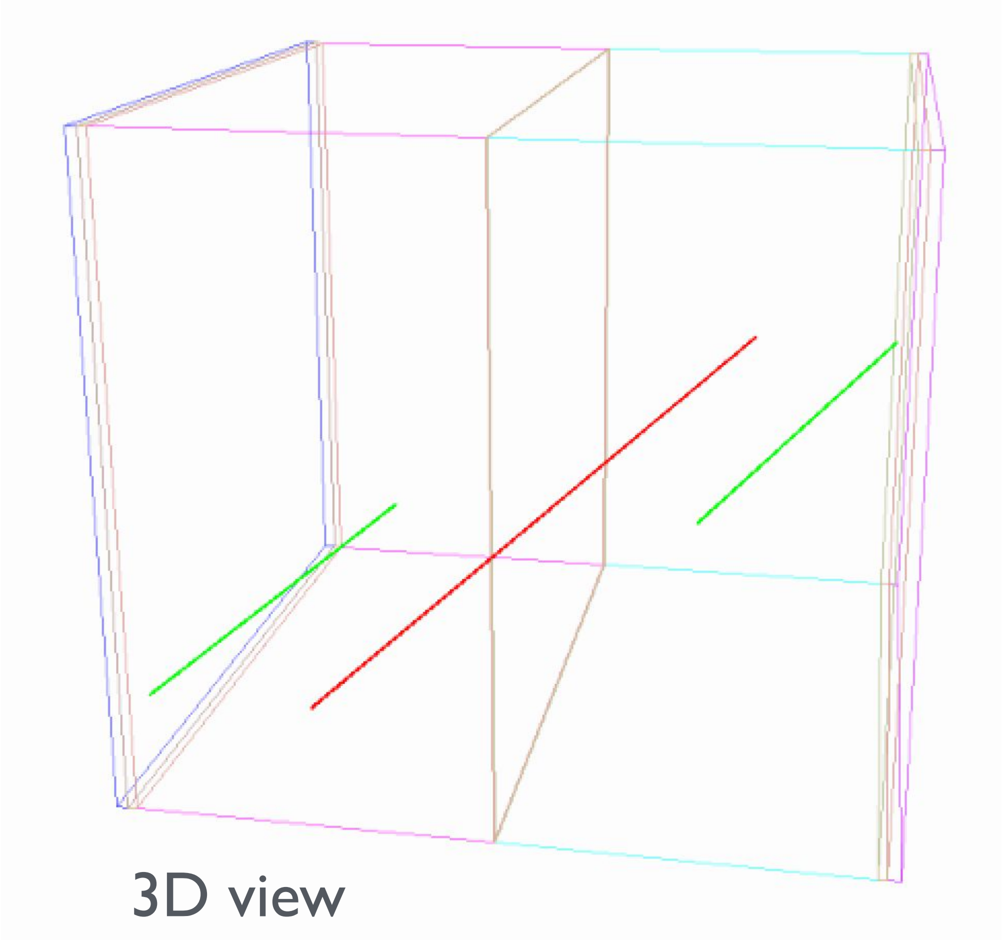
- Single Phase DUNE Far Detector prototype, exposed to test beam at CERN
- Multiple "drift volumes", complex topologies and significant cosmic-ray backgrounds:
    - An ideal testing ground for LArTPC pattern recognition

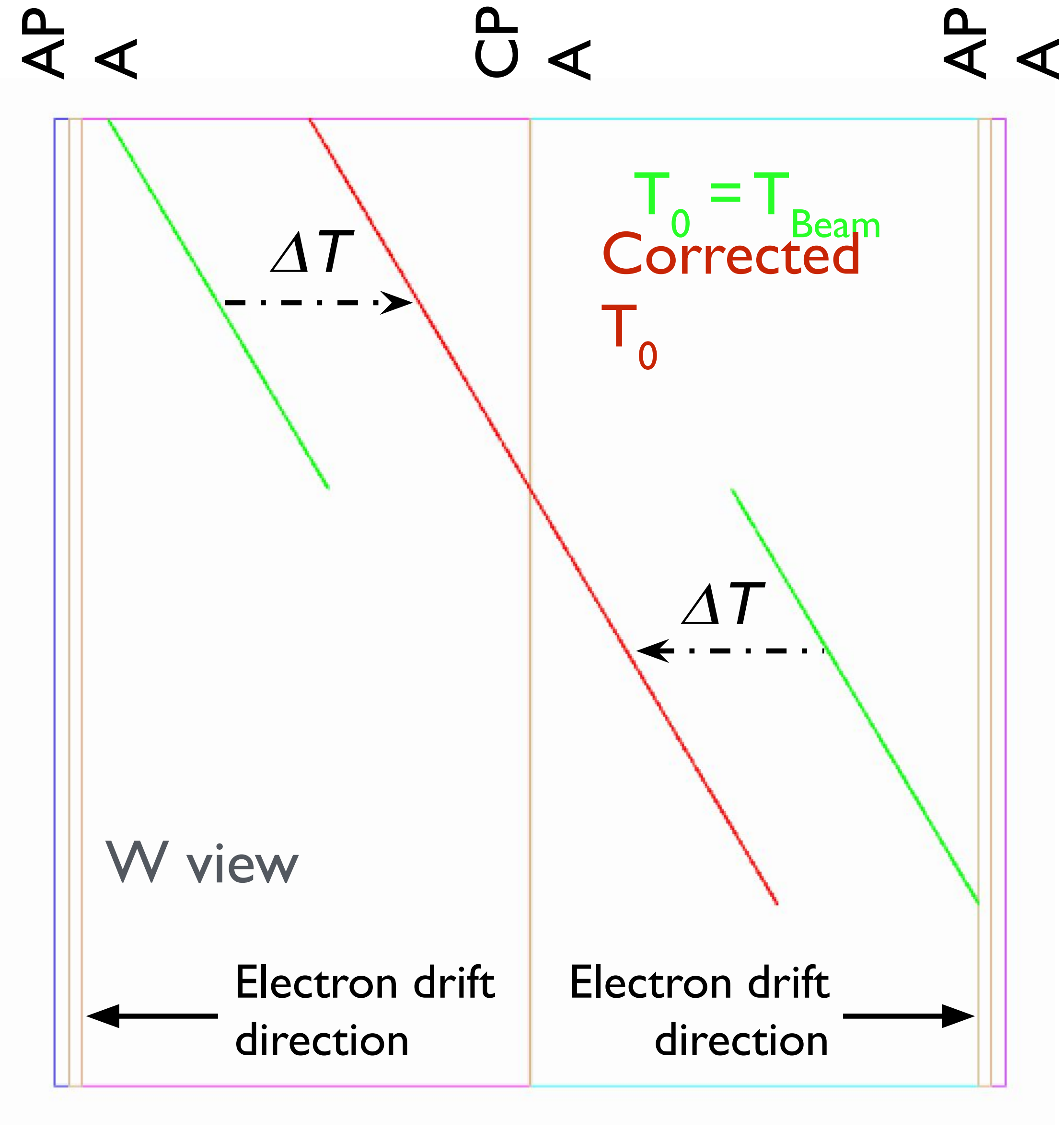


APA: Anode Plane Assembly
CPA: Cathode Plane Assembly

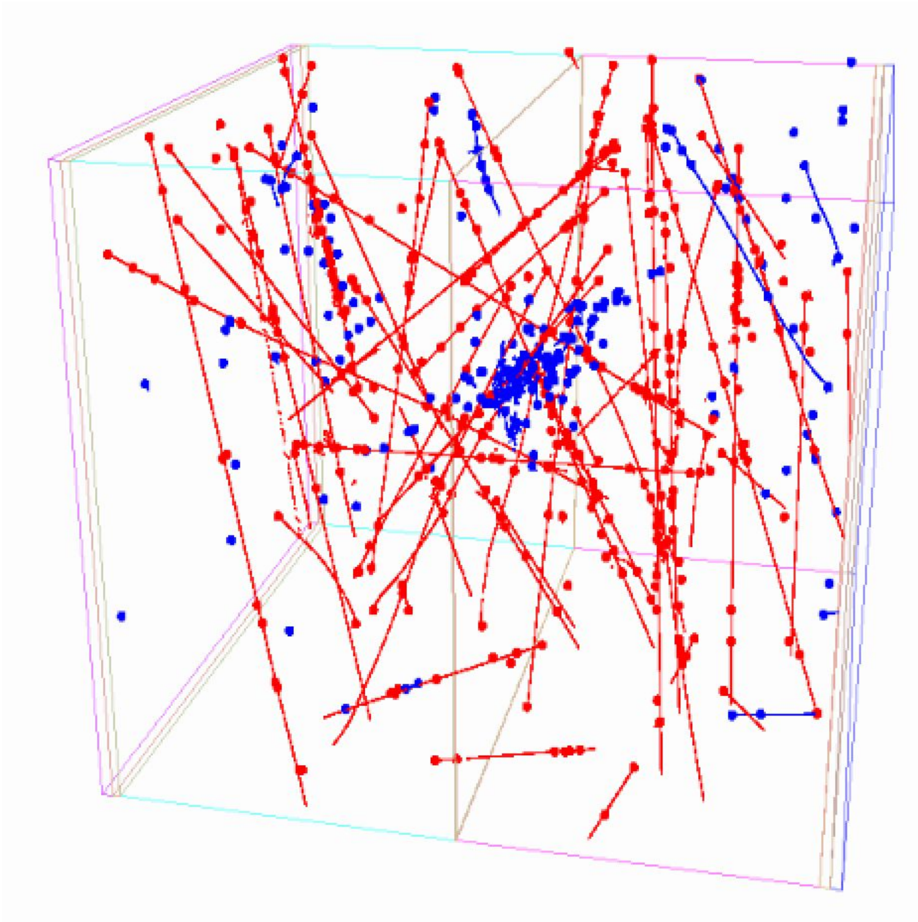
1. Reconstruct cosmic-ray muons independently for each volume of detector

- In a LArTPC image, one coordinate derived from drift times of ionisation electrons:
  - But, only know electron arrival times, not actual drift times: need to know start time, T_0
  - For beam particles, can use time of beam spill to set T_0, but unknown for cosmic rays
  - Place all hits assuming $T_0=T_{Beam}$, but can identify T_0 for any cosmic rays crossing volumes





2. Stitch together any cosmic rays crossing between volumes, identifying T_0

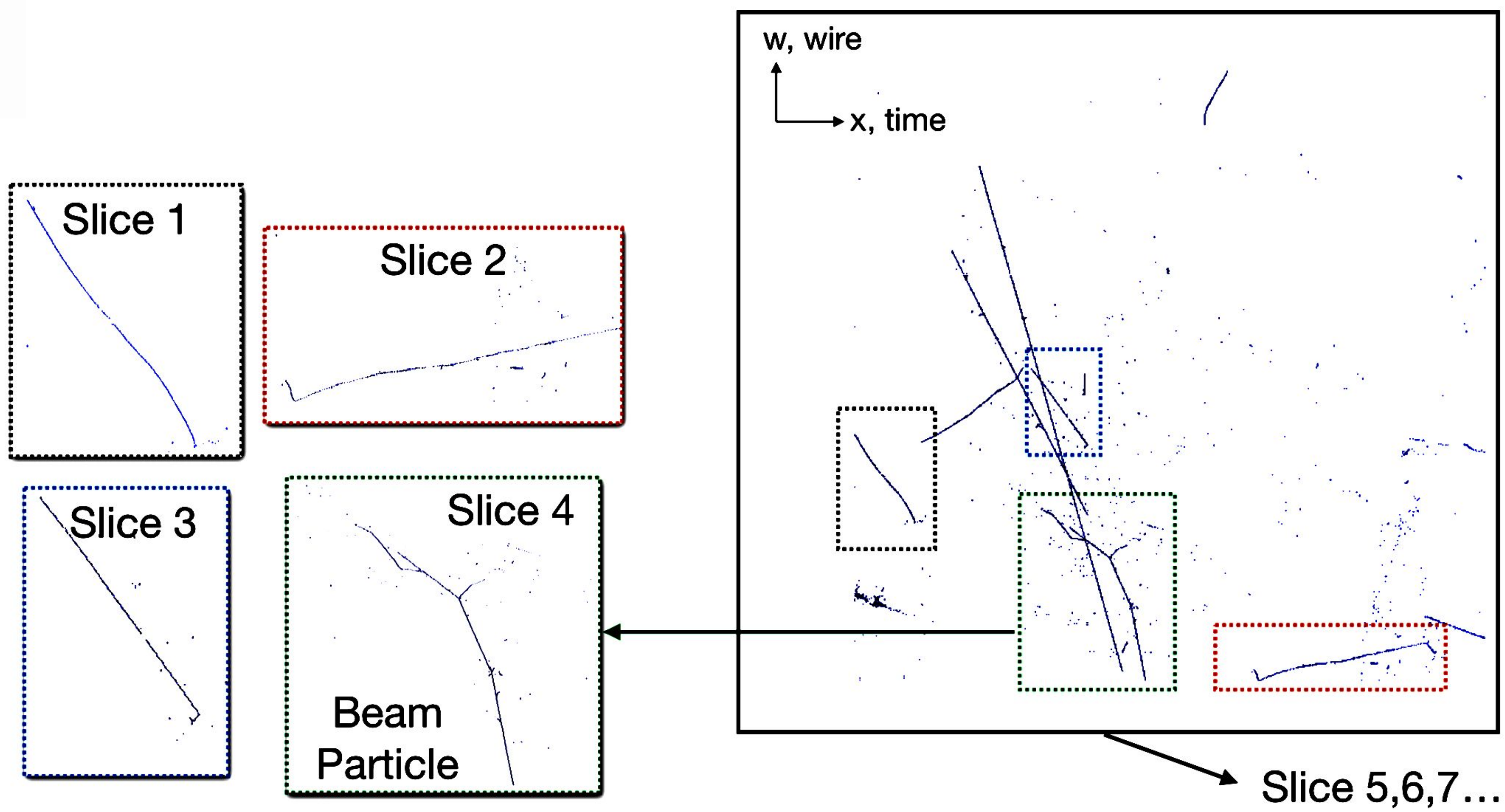


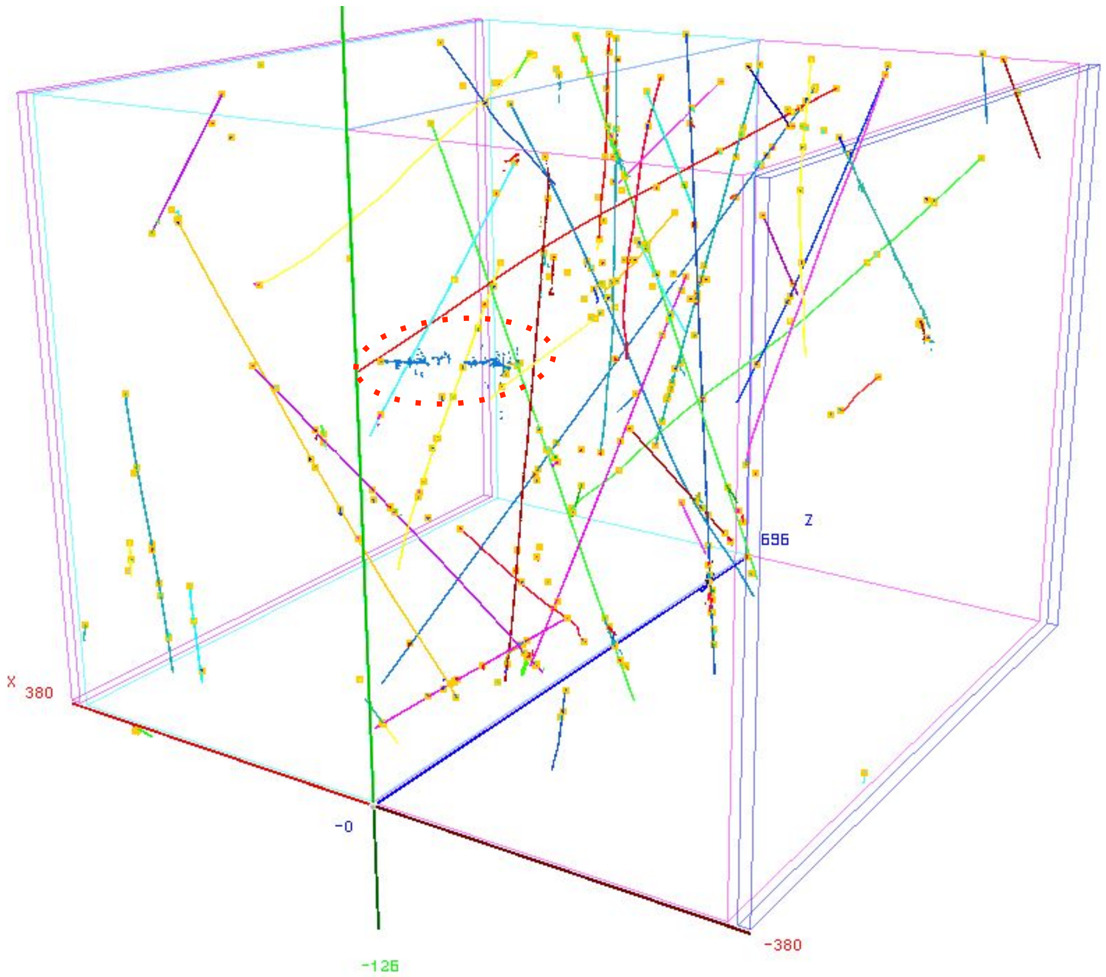
3. Identify clear cosmic rays (red) and hits to reexamine under test beam hypothesis (blue)

Clear cosmic rays:

- Particles appear to be "outside" of detector if $T_0 = T_{Beam}$
- Particles stitched between volumes using a $T_0 \neq T_{Beam}$
- Particles pass through the detector: "through going"

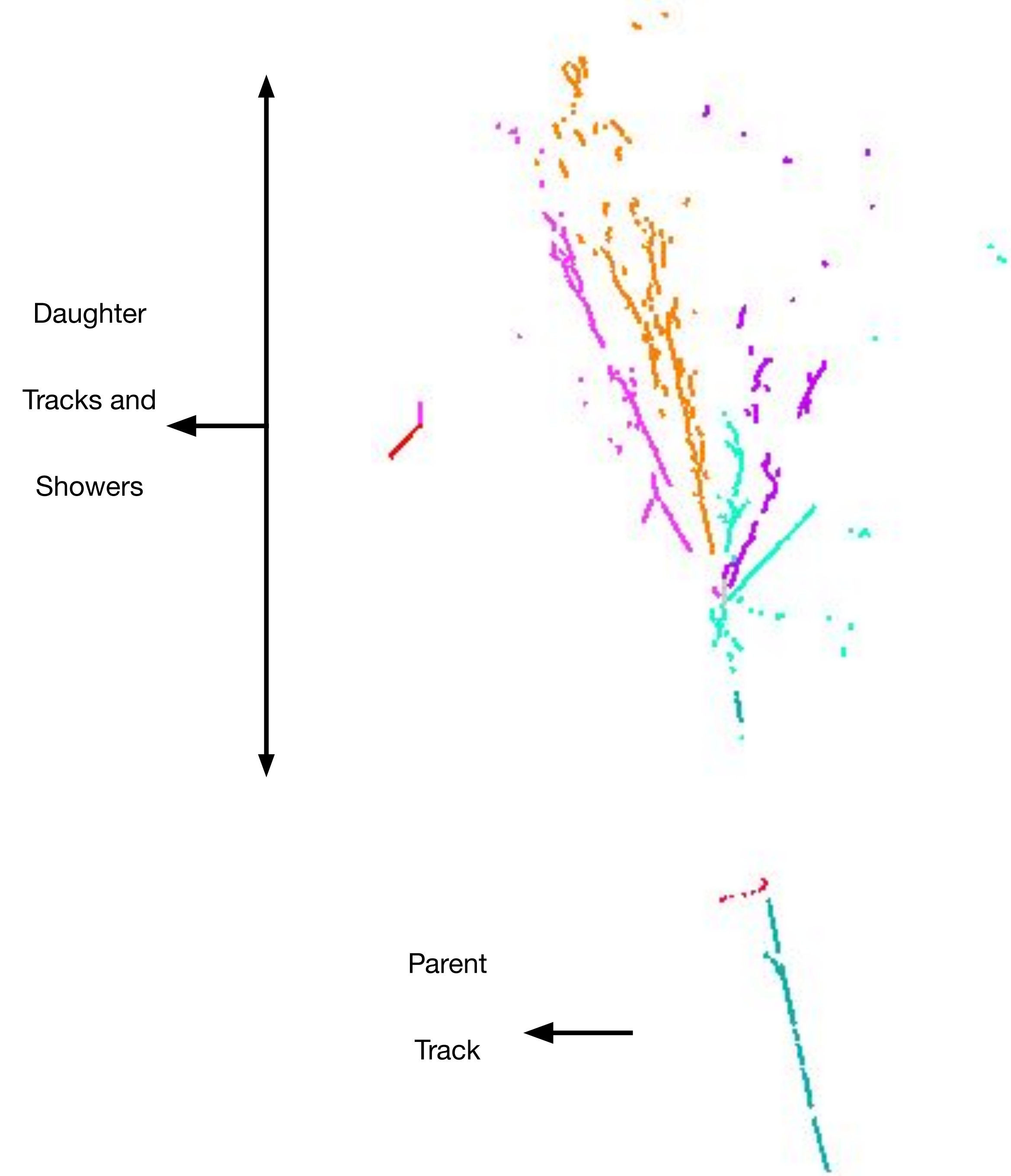
- Slice/divide blue hits from separate interactions
- Reconstruct each slice as test beam particle
- Then choose between cosmic ray or test beam outcome for each slice





E.g. Reconstruction output: test beam particle (electron)

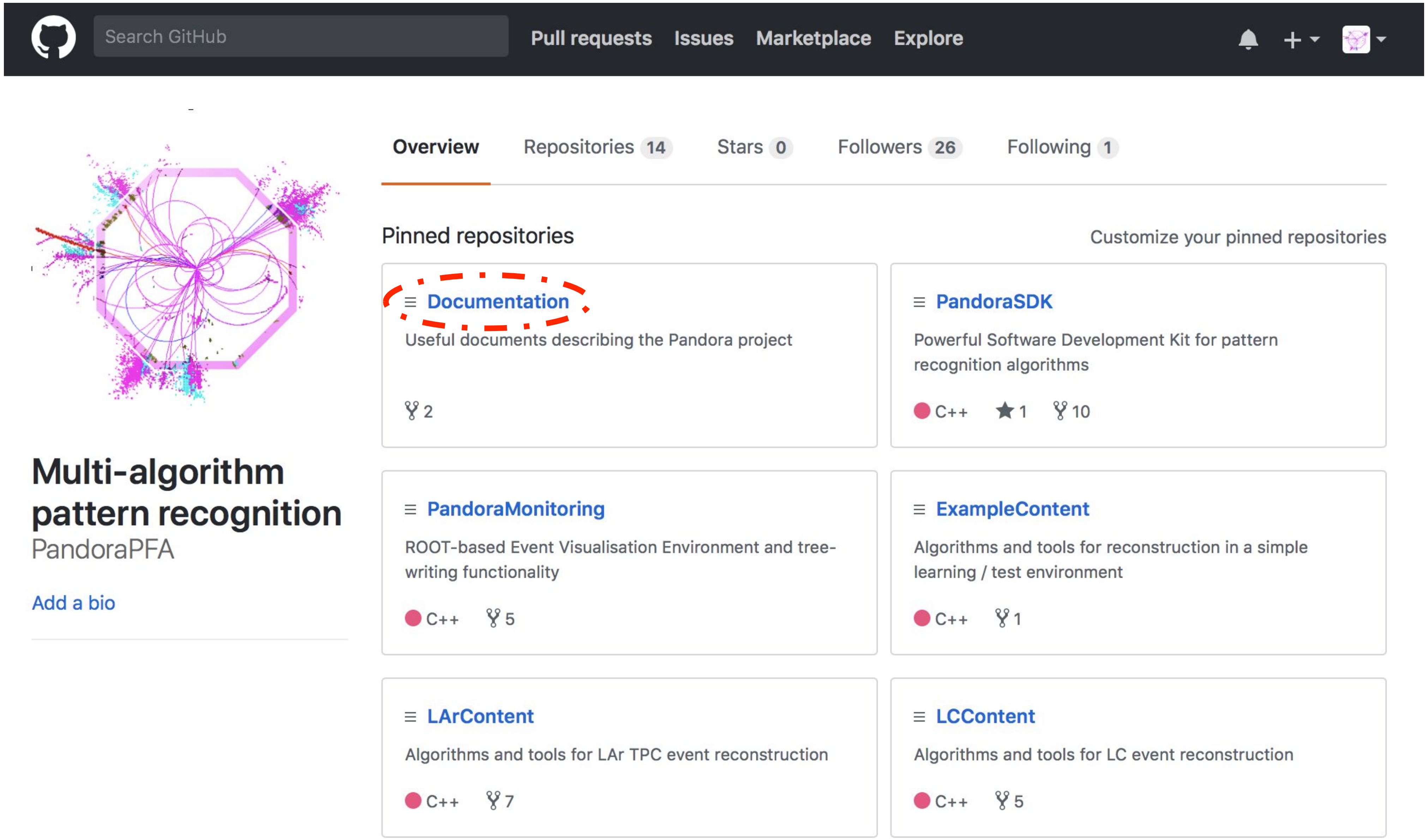
and: N reconstructed cosmic-ray muon hierarchies



E.g. Test beam particle: charged pion

- The use of Liquid Argon technology is one of the cornerstones of the current and future neutrino programmes.
- High-performance reconstruction techniques are required in order to fully exploit the imaging capabilities offered by LArTPCs:
  - Pandora multi-algorithm approach uses large numbers of decoupled algorithms to gradually build up a picture of events.
  - Output is a carefully-arranged hierarchy of reconstructed particles, each corresponding to a distinct track or shower.

We will now try working with the Pandora outputs, creating an analyzer module



Look for our channel on your experiment's Slack!

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Additional slides

1. Determine target MCParticle associated to each hit
   - Use MCParticle hierarchy to determine primary "targets" for reco
   - Associate hits to target MCParticle making largest E contribution

Target MCParticles must satisfy quality cuts

Reco/MCParticles matches must satisfy quality cuts.

2. Match reco particles to target MCParticles
   - For each combination of reco particle and target MCParticle, find the number of shared hits; fold all daughter particles, in both reco and MCParticle hierarchies, back into parent primaries
   - Interpret raw/comprehensive matching information to clarify pattern recognition performance:
     i. Find strongest (most shared hits) match between any reco particle and target MCParticle
     ii. Repeat step i, using reco and MCParticles at most once, until no further matches possible
     iii. Assign any remaining reco particles to target MCParticle with which they share most hits

3. Define performance metrics
   - Efficiency: Fraction of target MCParticles with at least one matched reco particle
   - Completeness: Fraction of MCParticle true hits shared with the reco particle
   - Purity: Fraction of hits in reco particle shared with the target MCParticle

     - Match exactly one reco particle to each target MCParticle ⇒ Event is "correct"

- In practice, some MCParticles not reconstructable. Targets must satisfy quality cuts:
- ≥15 hits in total, at least five hits in at least two views.
- Target must deposit >90% E in these hits.
- Plus, ignore all hits which are downstream of far-travelling neutron in MC hierarchy.

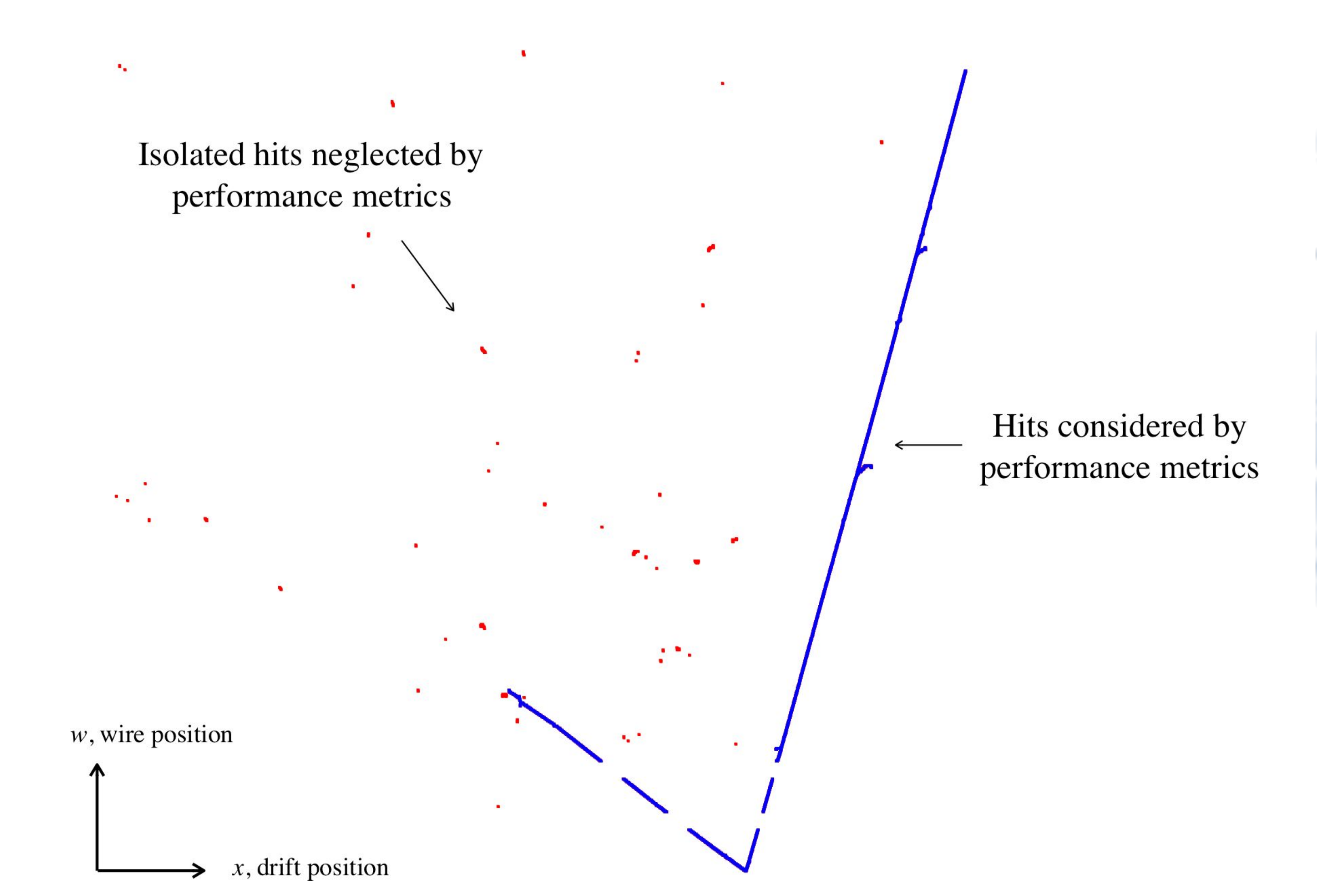


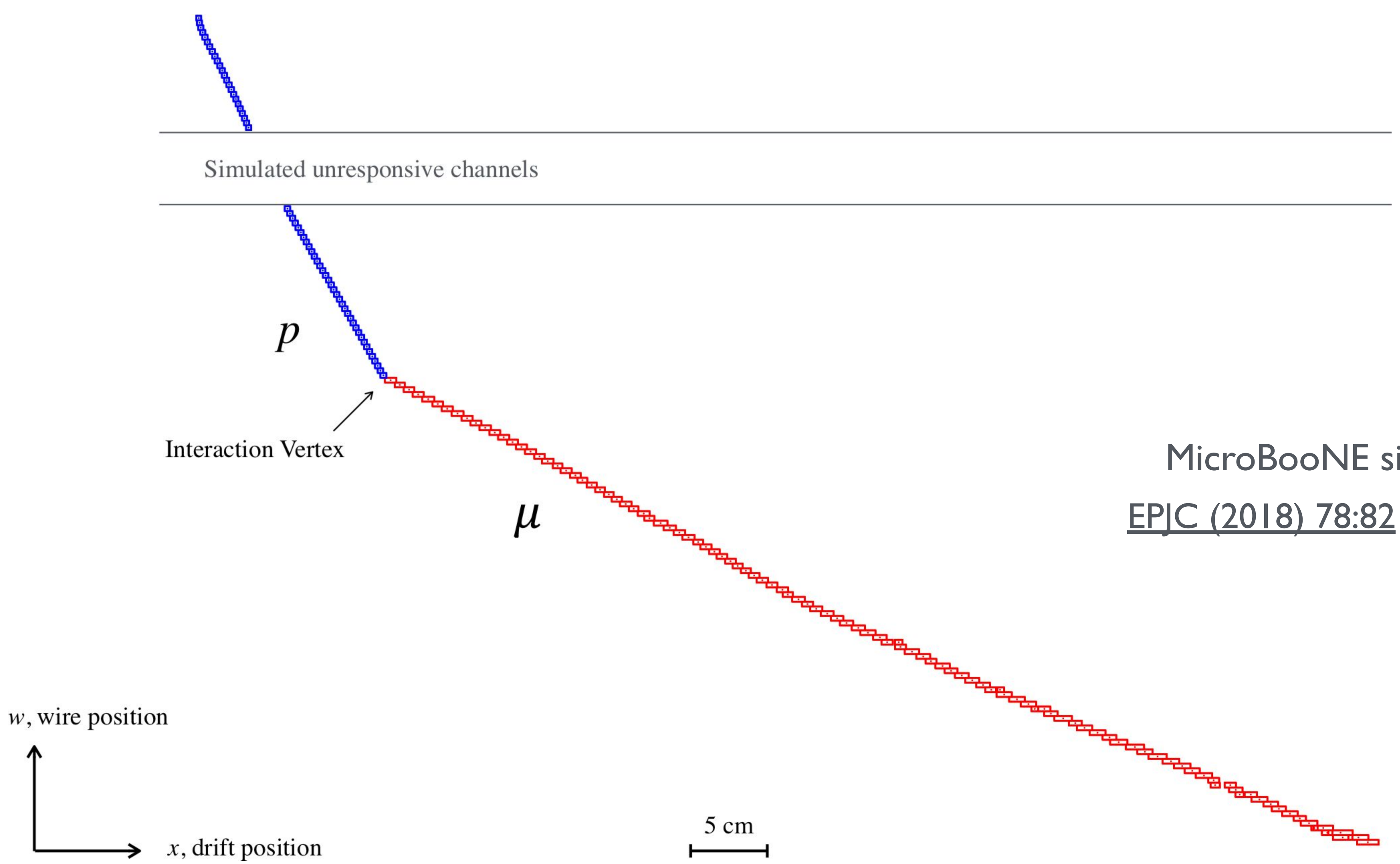
Fig. 8: The hits that are considered (blue) and neglected (red) in the construction of pattern recognition performance metrics for a typical CC ν_μ event at MicroBooNE. By considering the MCParticle hierarchy, hits that will likely form part of an isolated and diffuse topology are not used to identify or characterise the reconstructable target MCParticles in an event.

Clean topology: ν_μ CC QE interactions with xactly one reconstructable muon and one constructable proton in visible final state:

No cosmic rays here

#Matched Particles	0	1	2	3+
μ	1.3%	95.8%	2.9%	0.1%
p	8.9%	87.3%	3.6%	0.2%

53,168 events, 86.0% have exactly one reco particle matched to each target.



MicroBooNE simulation

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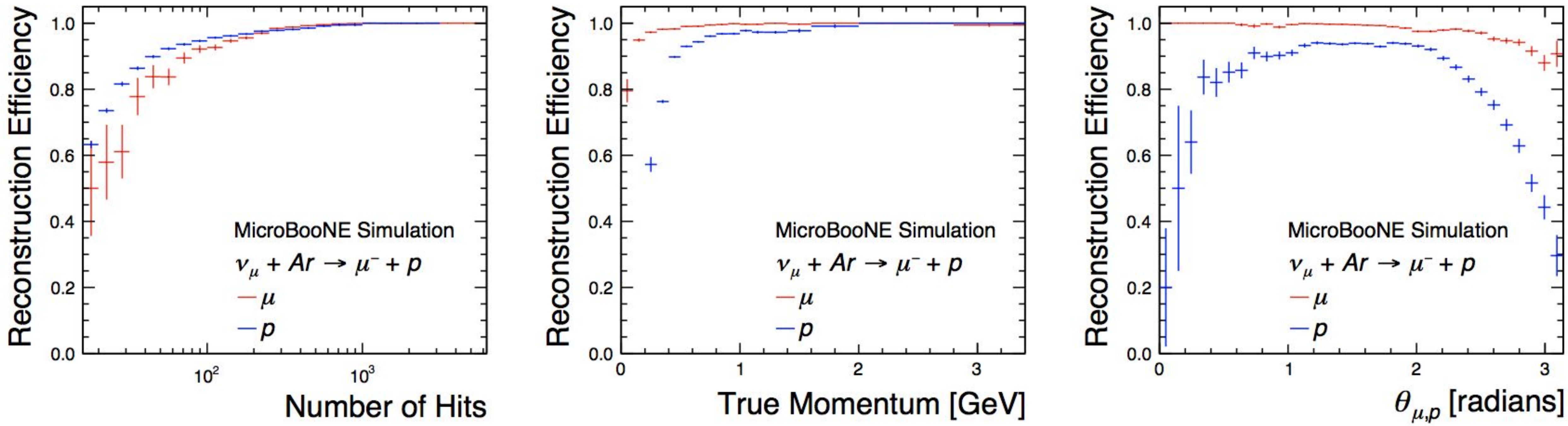
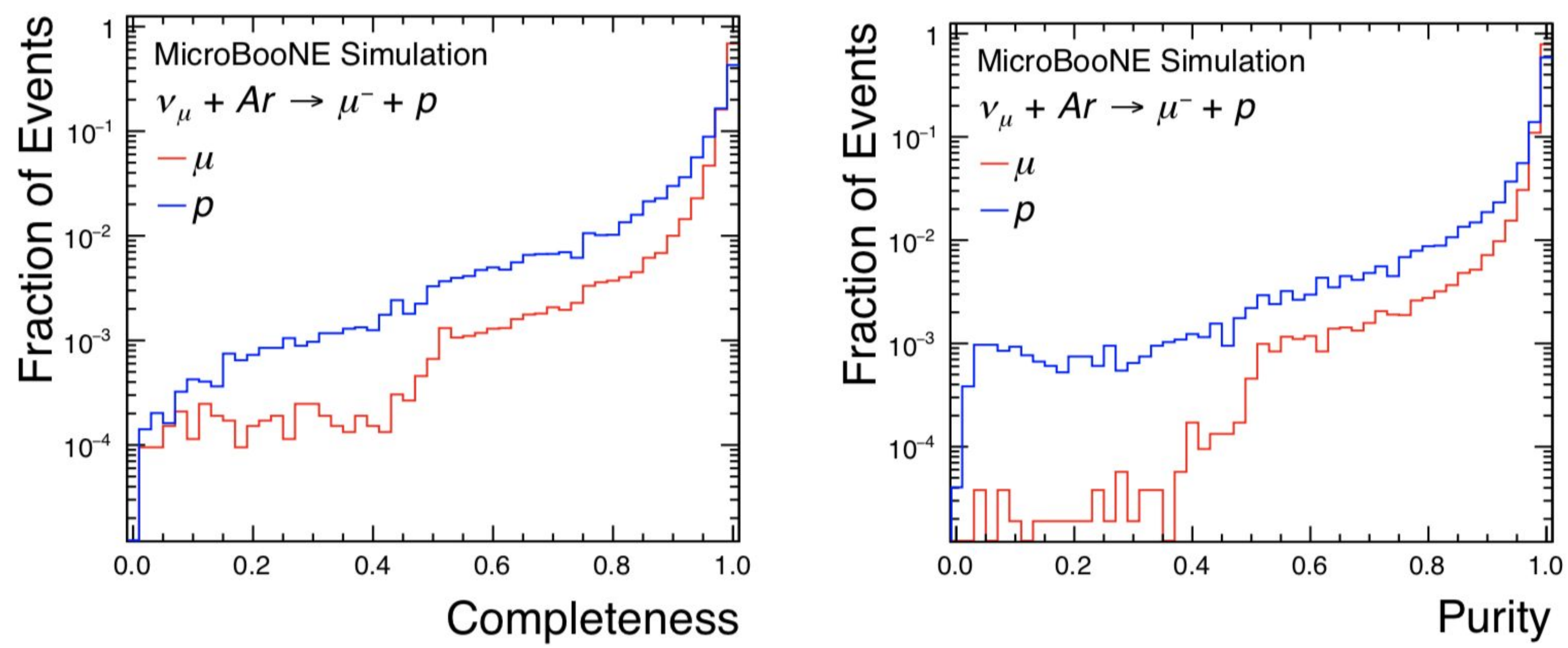
520 MeV ν_μ



- The most common failure mechanism is merging muon and proton into a single reconstructed particle.
- Single particle is matched to target with which it shares most hits, which will preferentially be the muon.



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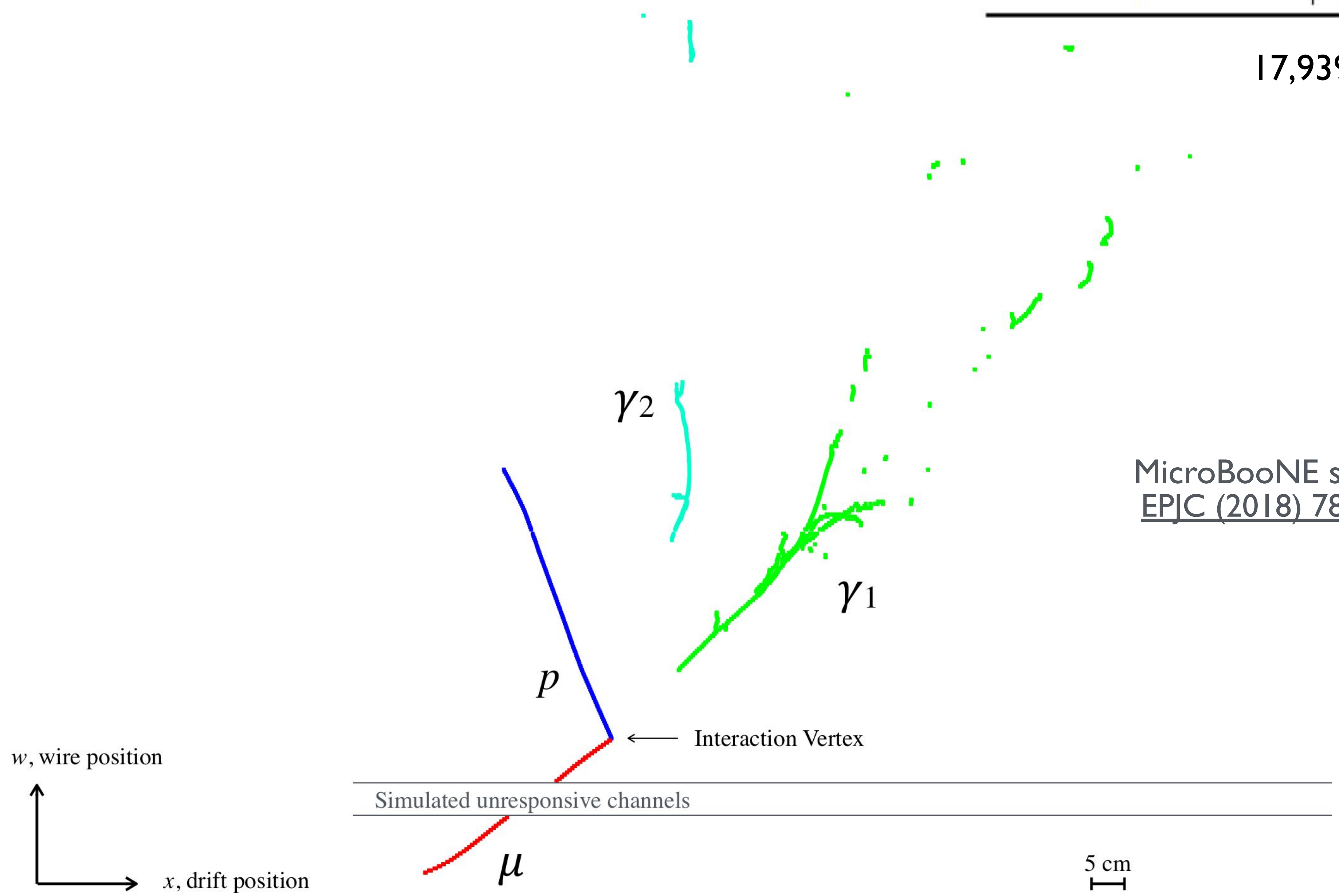
Two-photon topology: CC ν_μ interactions with sonant neutral pion production:

#Matched Particles	0	1	2	3+
μ	3.7%	94.8%	1.5%	0.0%
p	9.9%	85.5%	4.3%	0.3%
γ_1	6.8%	88.0%	4.8%	0.4%
γ_2	29.9%	66.4%	3.6%	0.2%

17,939 events, 49.9% have exactly one reco particle matched to each target.

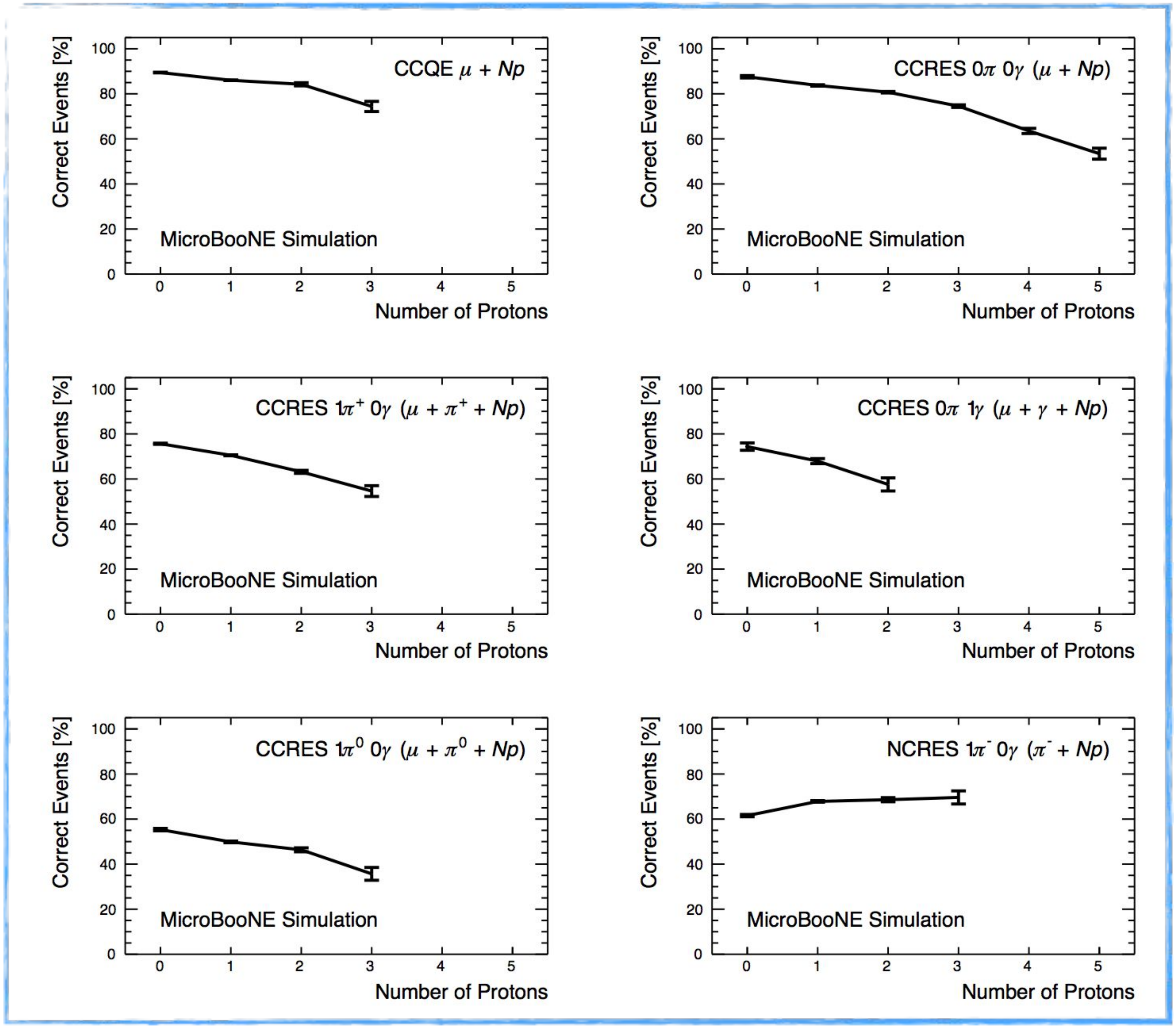
#hits γ_1 > #hits γ_2



MicroBooNE simulation
EPJC (2018) 78:82

1.4 GeV ν_μ

- Assess larger selection of exclusive final states using correct event fraction.
- Recall aim: a general purpose reconstruction for diverse event topologies.



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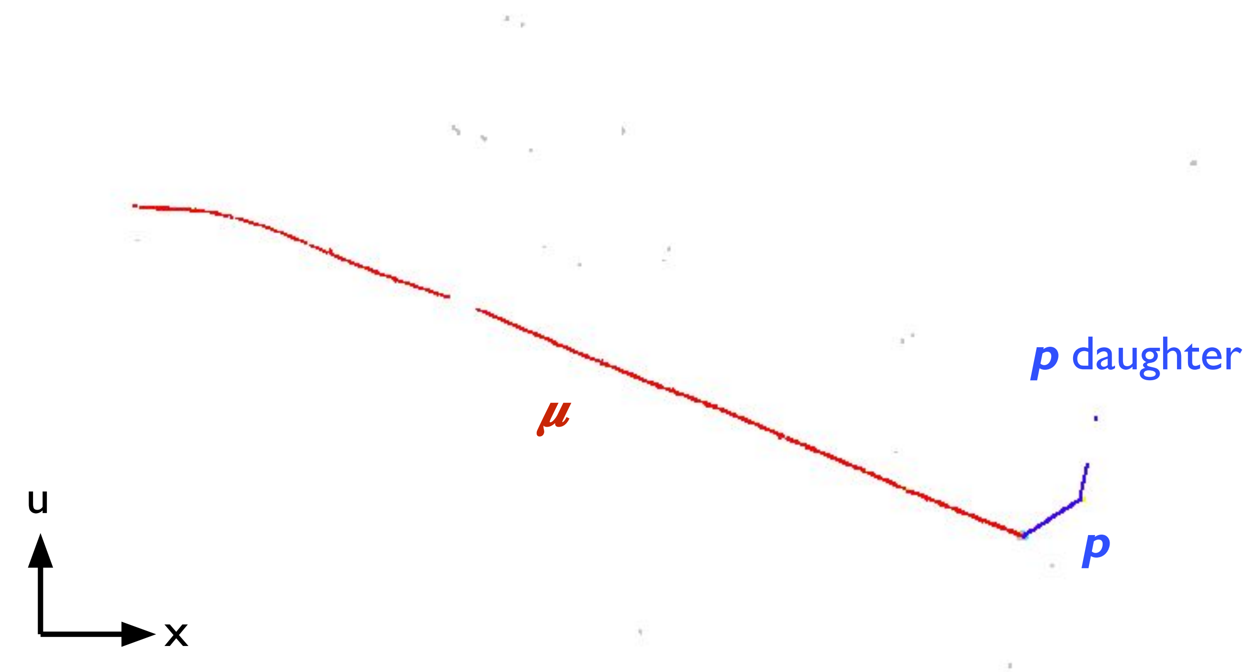
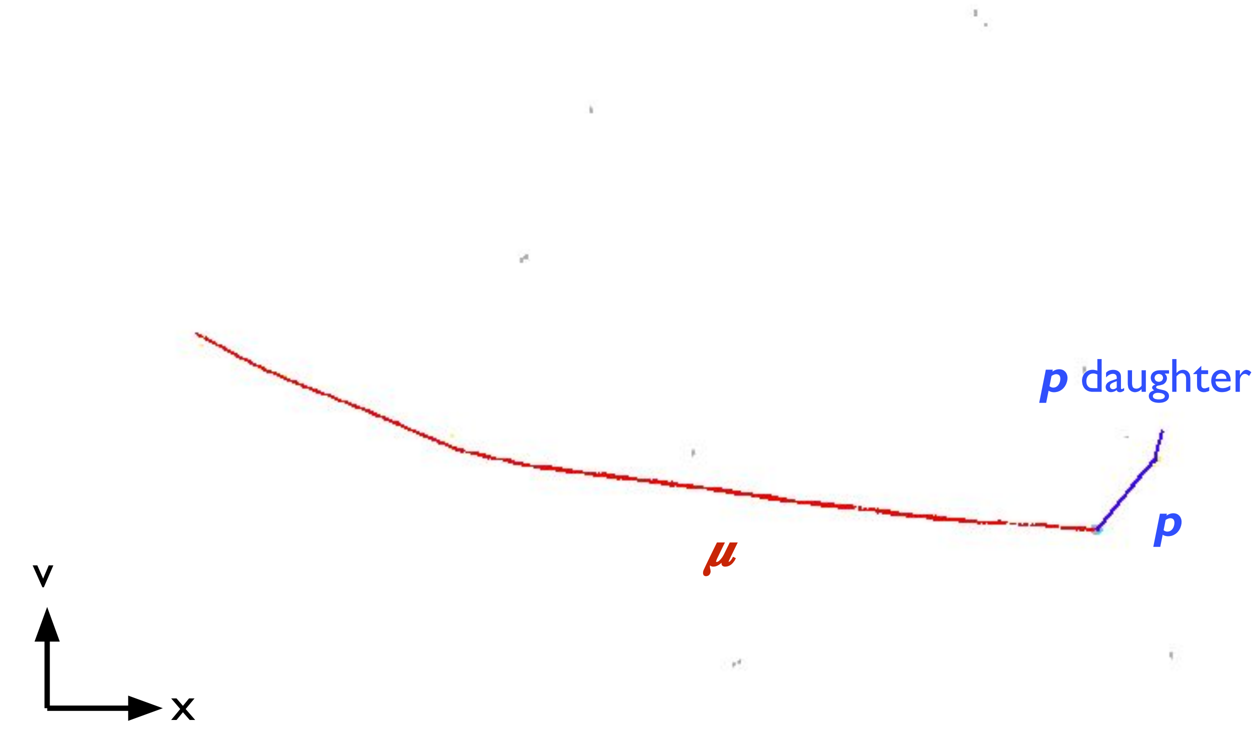
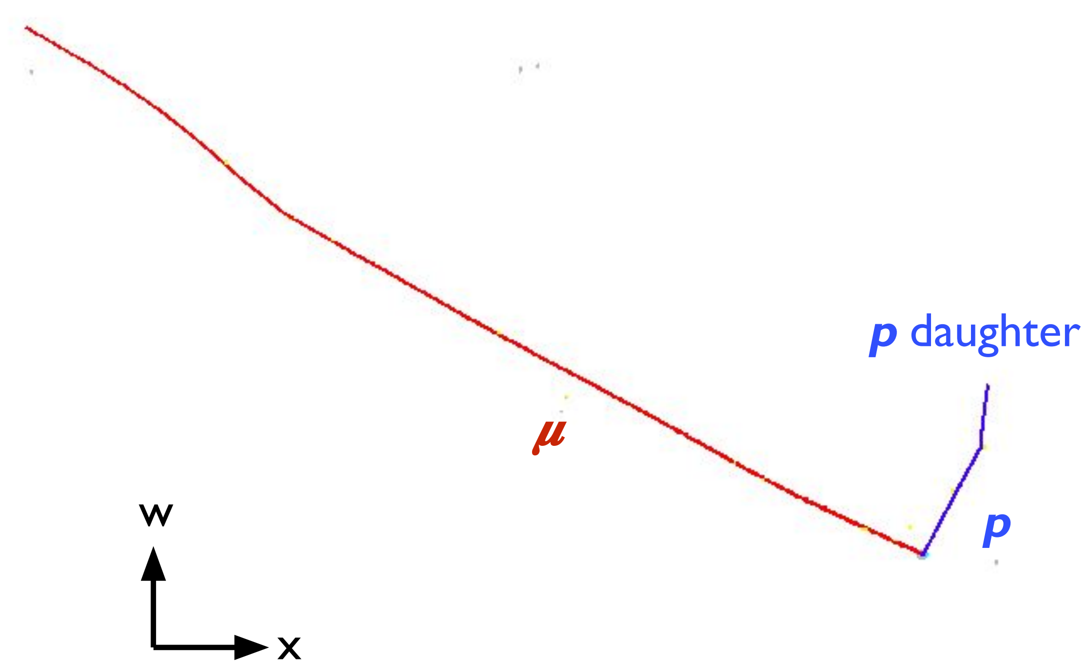




Deemed correct

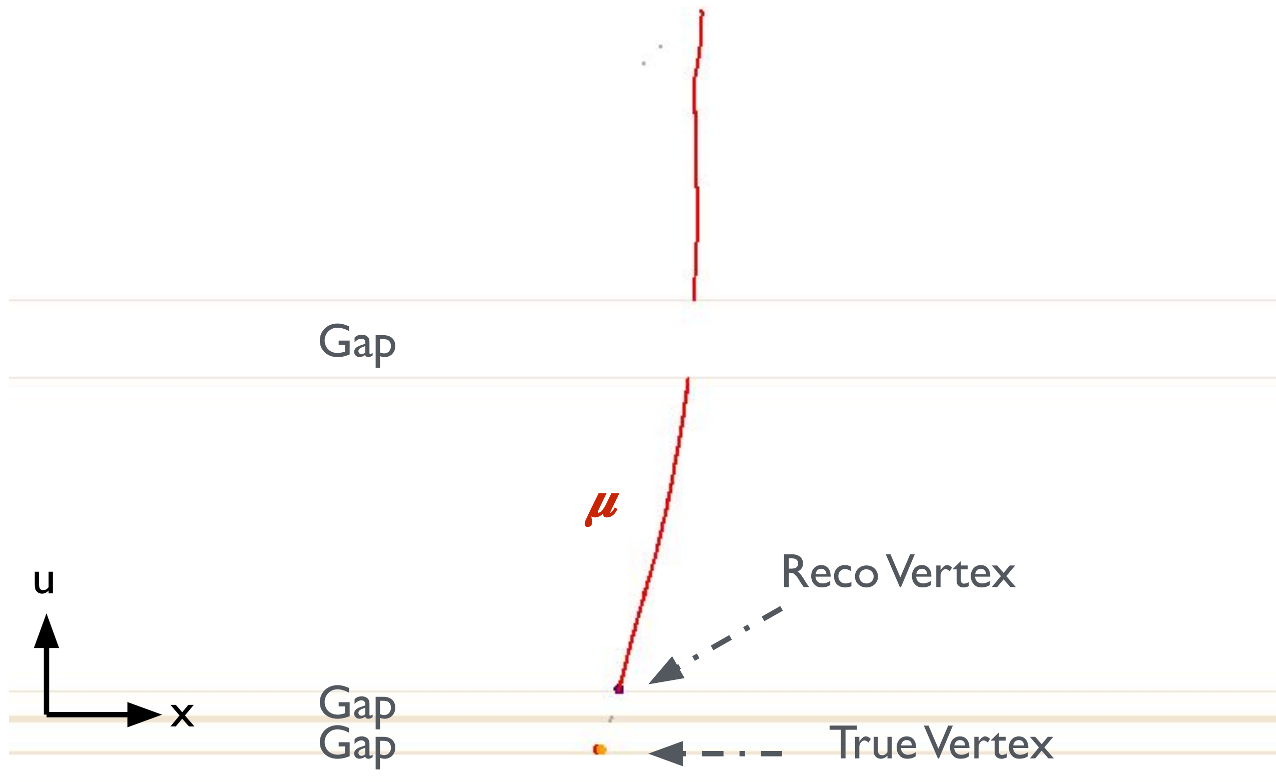


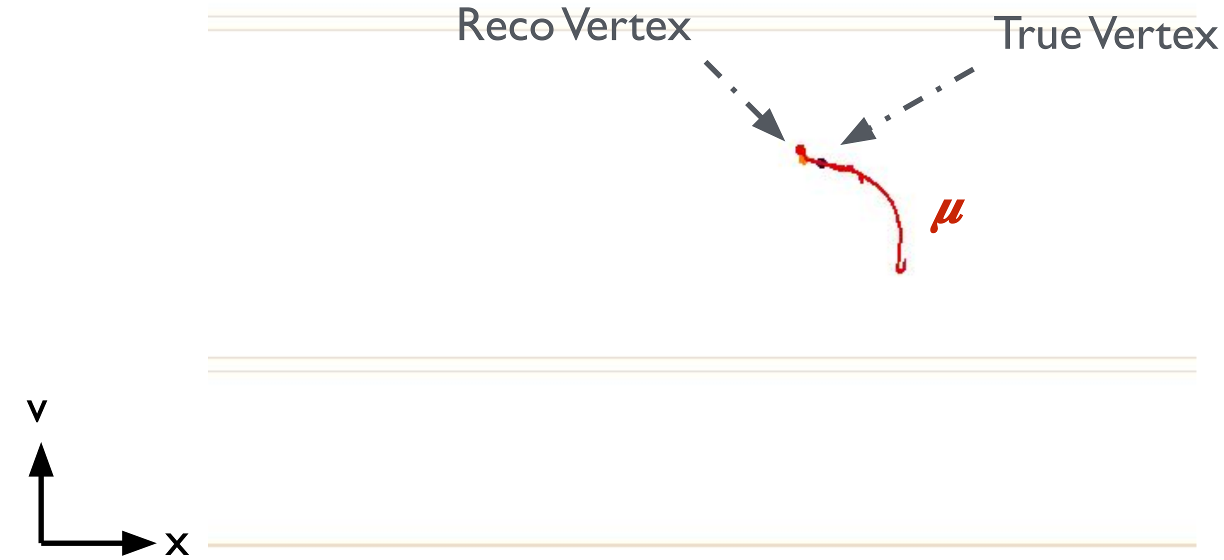
---PROCESSED-MATCHING-OUTPUT---
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

Primary 0, PDG 13, nMCHits 1153 (333, 392, 428)
-MatchedPfo 0, PDG 13, nMatchedHits 1150 (332, 392, 426), nPfoHits 1154 (332, 393, 429)

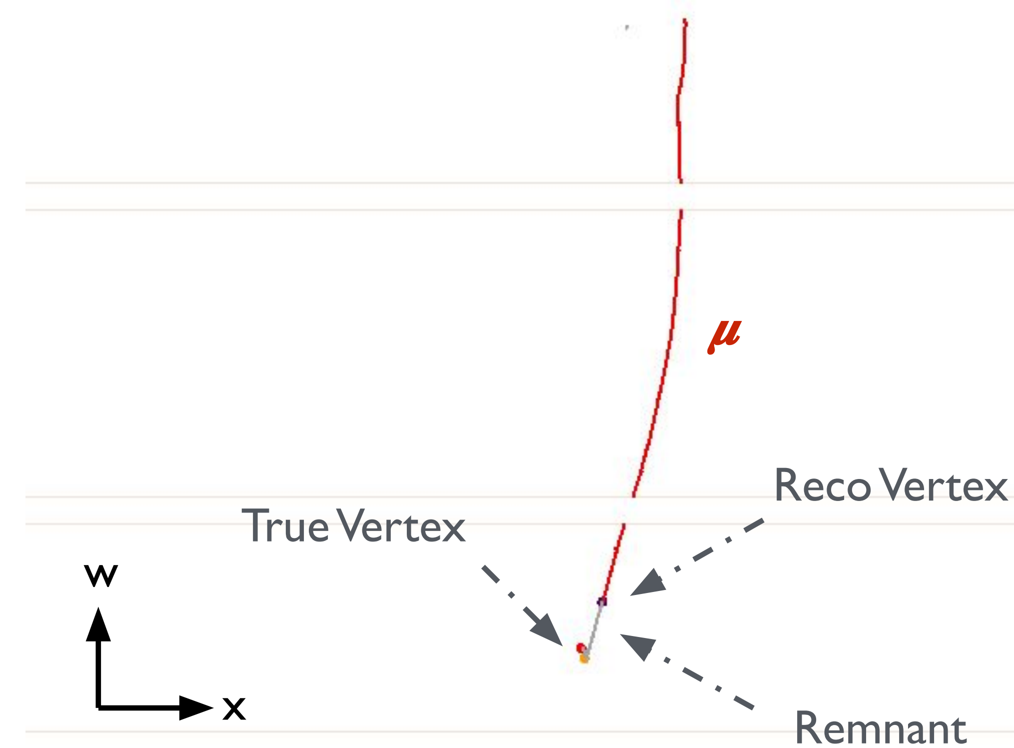
Primary 1, PDG 2212, nMCHits 383 (101, 121, 161)
-MatchedPfo 1, PDG 13, nMatchedHits 267 (61, 76, 130), nPfoHits 267 (61, 76, 130)

Is correct? 1





Work to do: vertex incorrect (gap influence)



---PROCESSED-MATCHING-OUTPUT---
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

Primary 0, PDG 13, nMCHits 834 (377, 97, 360)
-MatchedPfo 0, PDG 13, nMatchedHits 793 (372, 95, 326), nPfoHits 801 (372, 103, 326)

Primary 1, PDG 2212, nMCHits 15 (0, 7, 8)

Is correct? 0
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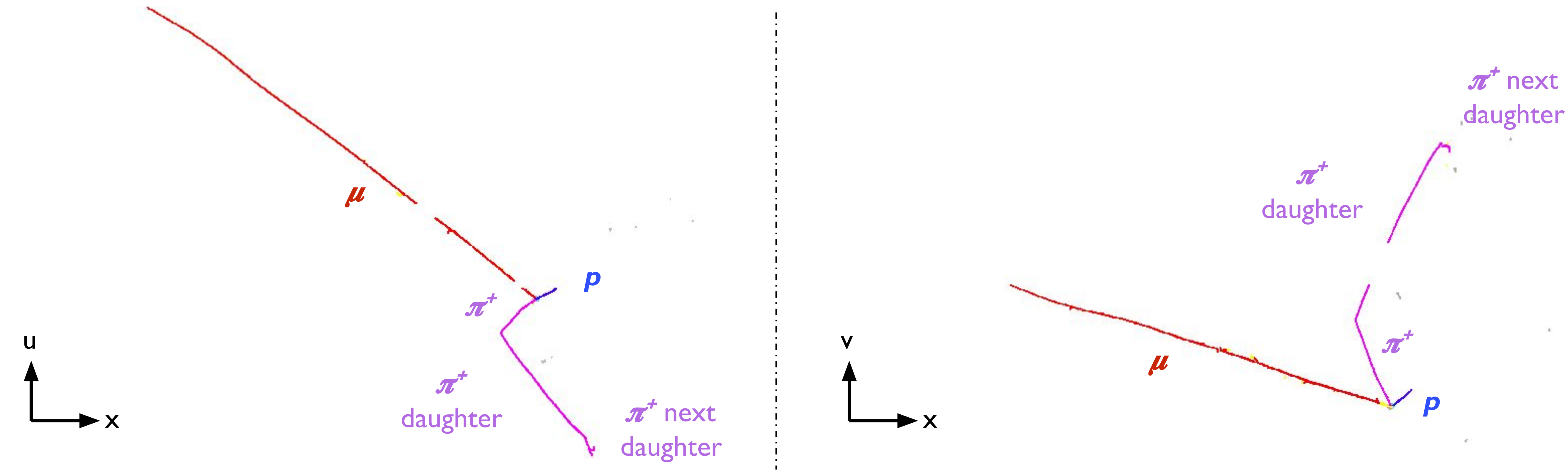


Deemed correct

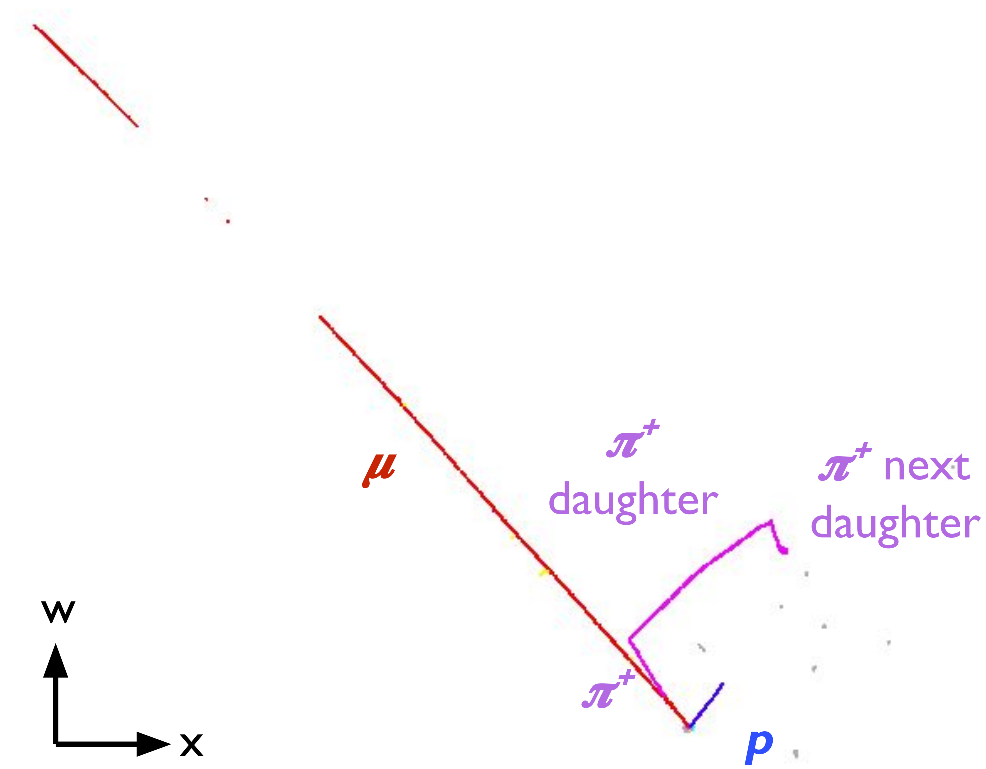
---PROCESSED-MATCHING-OUTPUT---
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

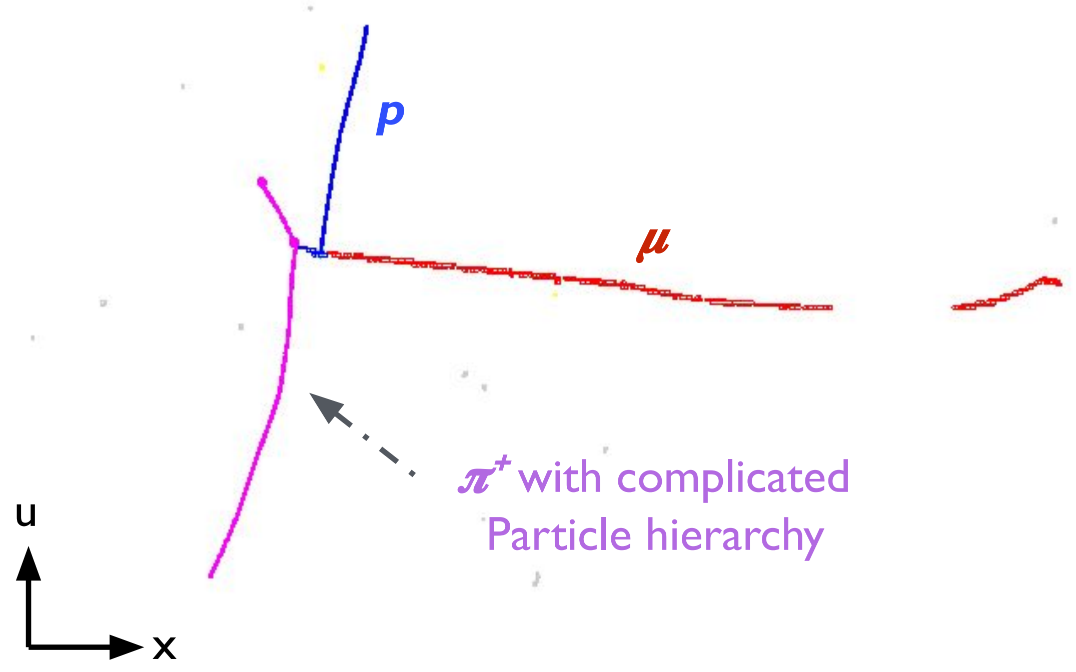
Primary 0, PDG 13, nMCHits 904 (322, 241, 341)
-MatchedPfo 0, PDG 13, nMatchedHits 900 (322, 237, 341), nPfoHits 919 (322, 239, 358)

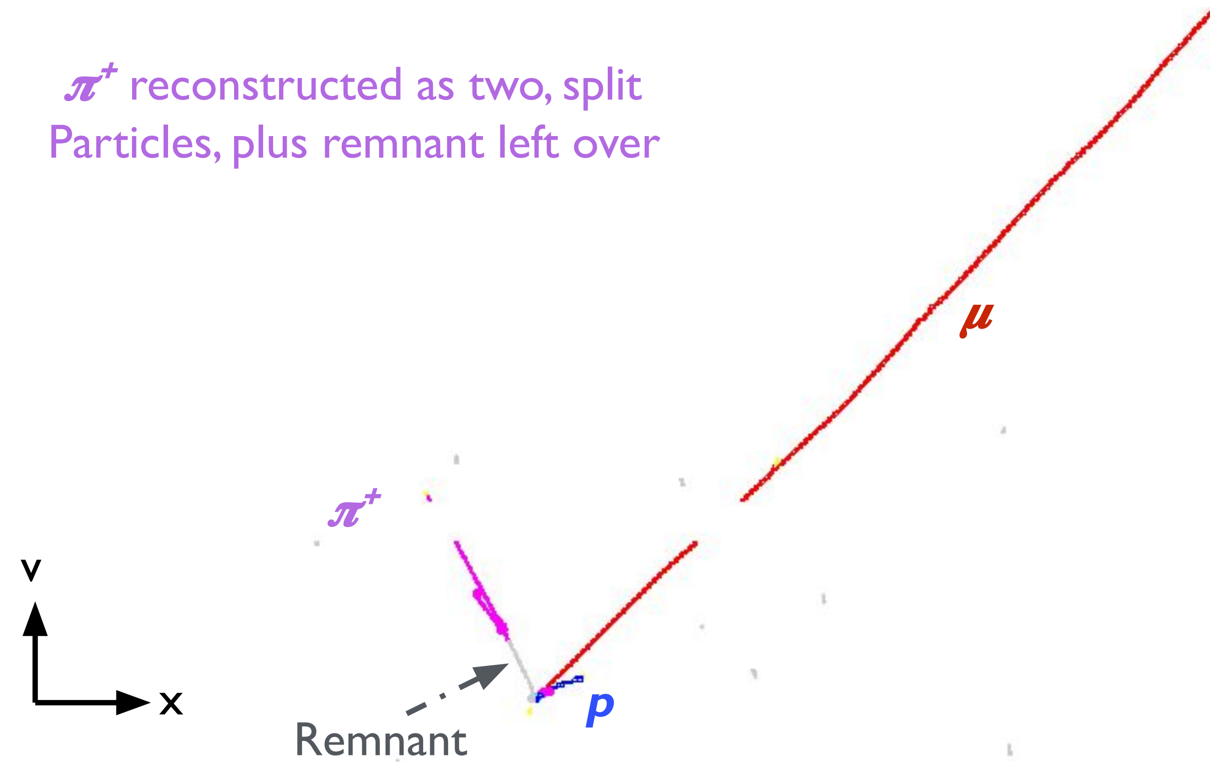
Primary 1, PDG 211, nMCHits 656 (199, 281, 176)
-MatchedPfo 1, PDG 13, nMatchedHits 600 (187, 268, 145), nPfoHits 608 (187, 274, 147)

Primary 2, PDG 2212, nMCHits 66 (13, 21, 32)
-MatchedPfo 2, PDG 13, nMatchedHits 62 (13, 19, 30), nPfoHits 62 (13, 19, 30)

Is correct? 1







Work to do: parent-daughter link missing, remnant Cluster

```
---PROCESSED-MATCHING-OUTPUT-----------------------------------------------------------------
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

Primary 0, PDG 13, nMCHits 712 (138, 284, 290)
-MatchedPfo 0, PDG 13, nMatchedHits 705 (135, 282, 288), nPfoHits 709 (136, 282, 291)

Primary 1, PDG 211, nMCHits 491 (197, 120, 174)
-MatchedPfo 1, PDG 13, nMatchedHits 246 (133, 43, 70), nPfoHits 246 (133, 43, 70)
-MatchedPfo 4, PDG 13, nMatchedHits 114 (25, 15, 74), nPfoHits 119 (25, 18, 76)

Primary 2, PDG 2212, nMCHits 202 (90, 13, 99)
-MatchedPfo 2, PDG 13, nMatchedHits 193 (90, 7, 96), nPfoHits 197 (94, 7, 96)
-(Below threshold) MatchedPfo 3, PDG 13, nMatchedHits 6 (0, 3, 3), nPfoHits 12 (4, 5, 3)

Is correct? 0
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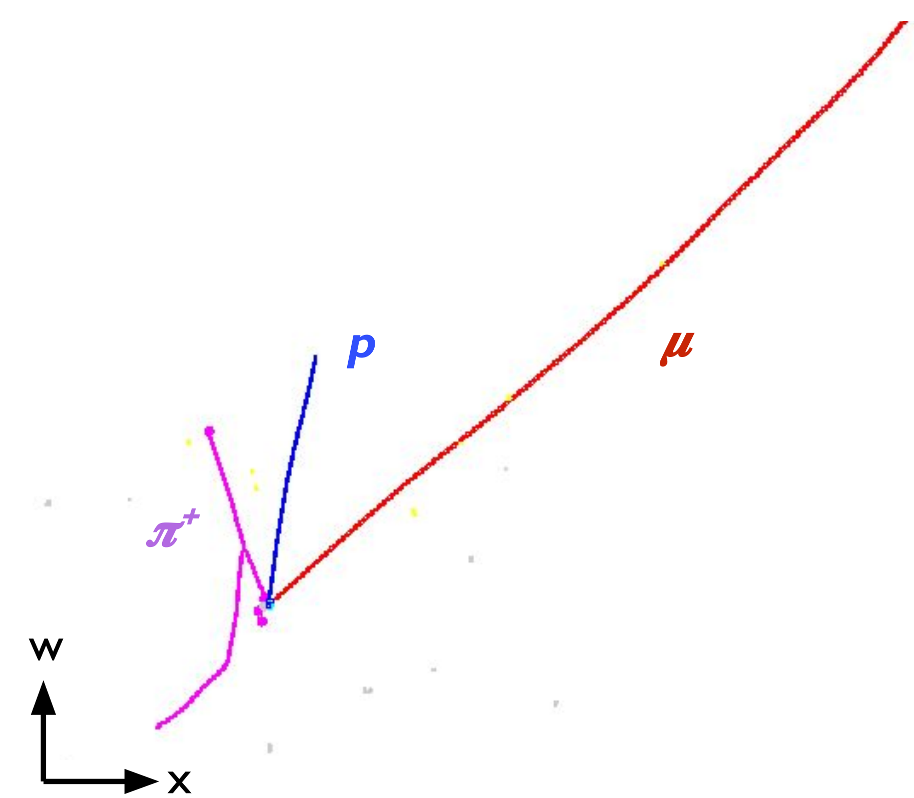

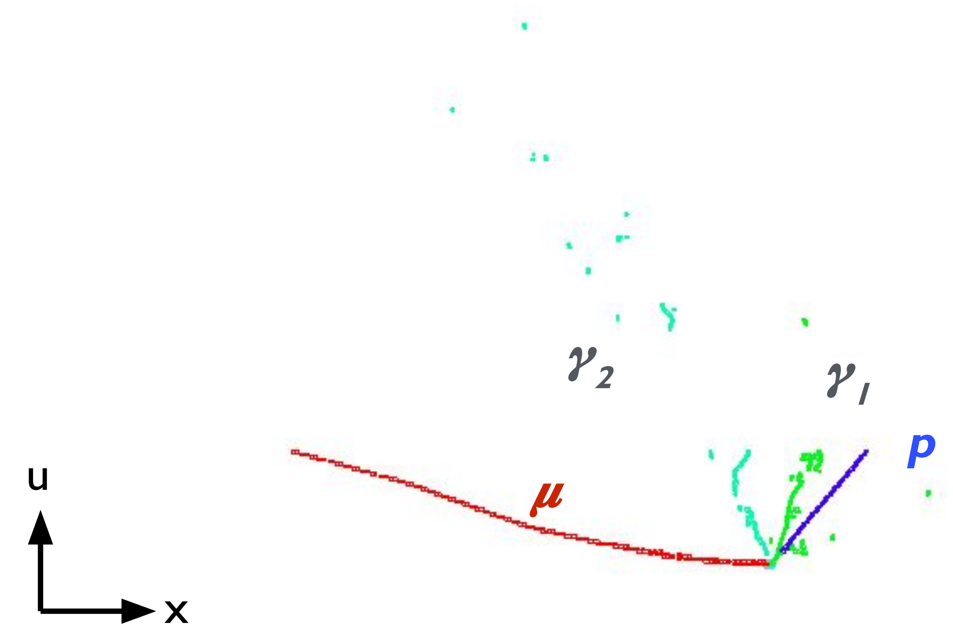

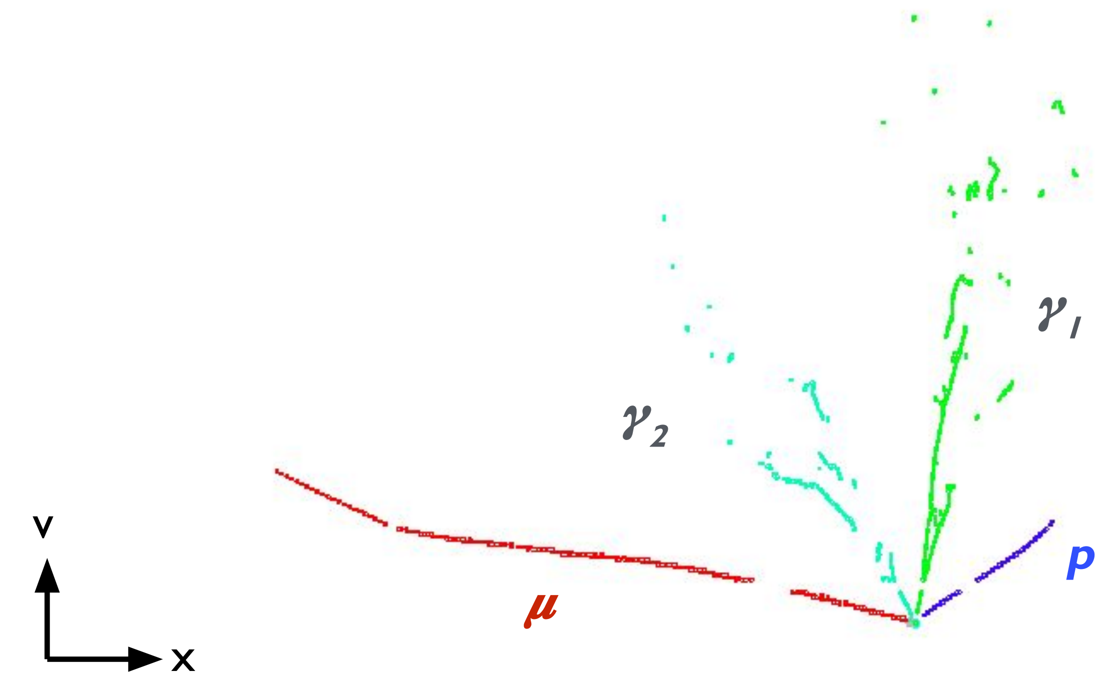

Deemed correct

```
---PROCESSED-MATCHING-OUTPUT-------------------------------------------------------------------
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

Primary 0, PDG 22, nMCHits 705 (103, 270, 332)
-MatchedPfo 0, PDG 11, nMatchedHits 660 (86, 252, 322), nPfoHits 674 (88, 260, 326)
-(Below threshold) MatchedPfo 4, PDG 13, nMatchedHits 12 (3, 9, 0), nPfoHits 14 (5, 9, 0)

Primary 1, PDG 22, nMCHits 432 (79, 136, 217)
-MatchedPfo 1, PDG 11, nMatchedHits 409 (73, 124, 212), nPfoHits 410 (73, 125, 212)

Primary 2, PDG 13, nMCHits 354 (80, 134, 140)
-MatchedPfo 2, PDG 13, nMatchedHits 336 (80, 124, 132), nPfoHits 336 (80, 124, 132)

Primary 3, PDG 2212, nMCHits 181 (41, 36, 104)
-MatchedPfo 3, PDG 13, nMatchedHits 177 (39, 34, 104), nPfoHits 183 (41, 34, 108)

Is correct? 1
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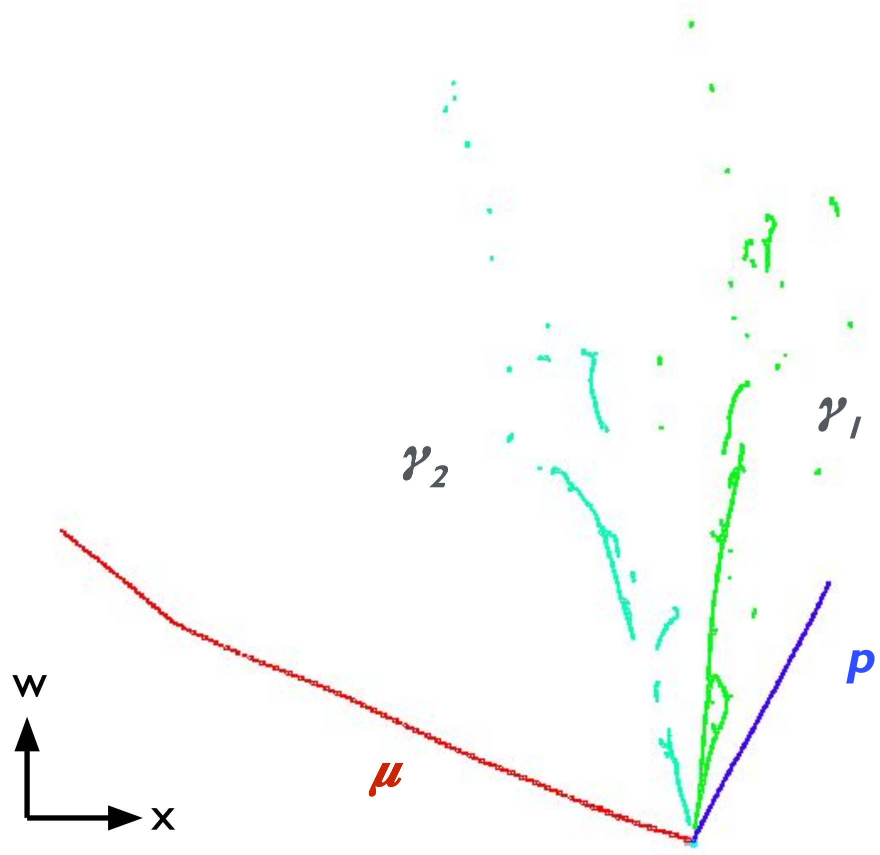

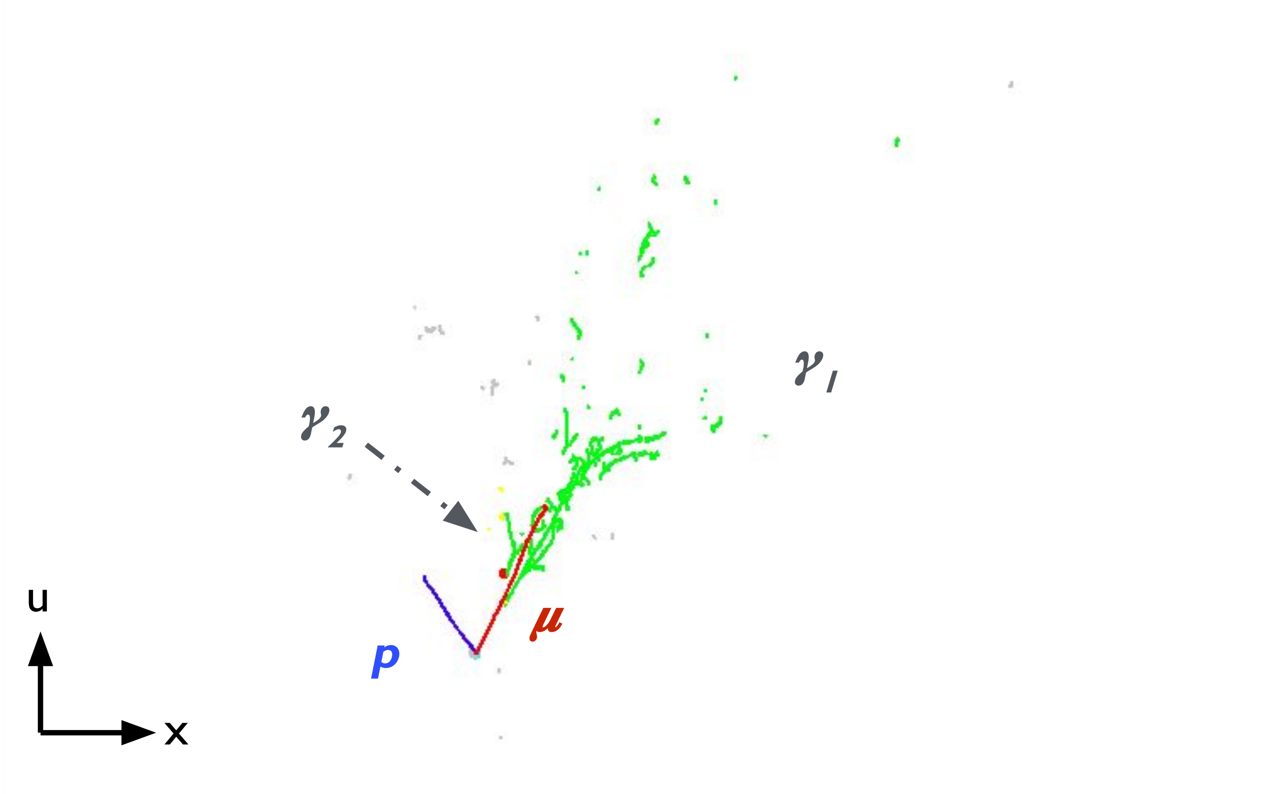

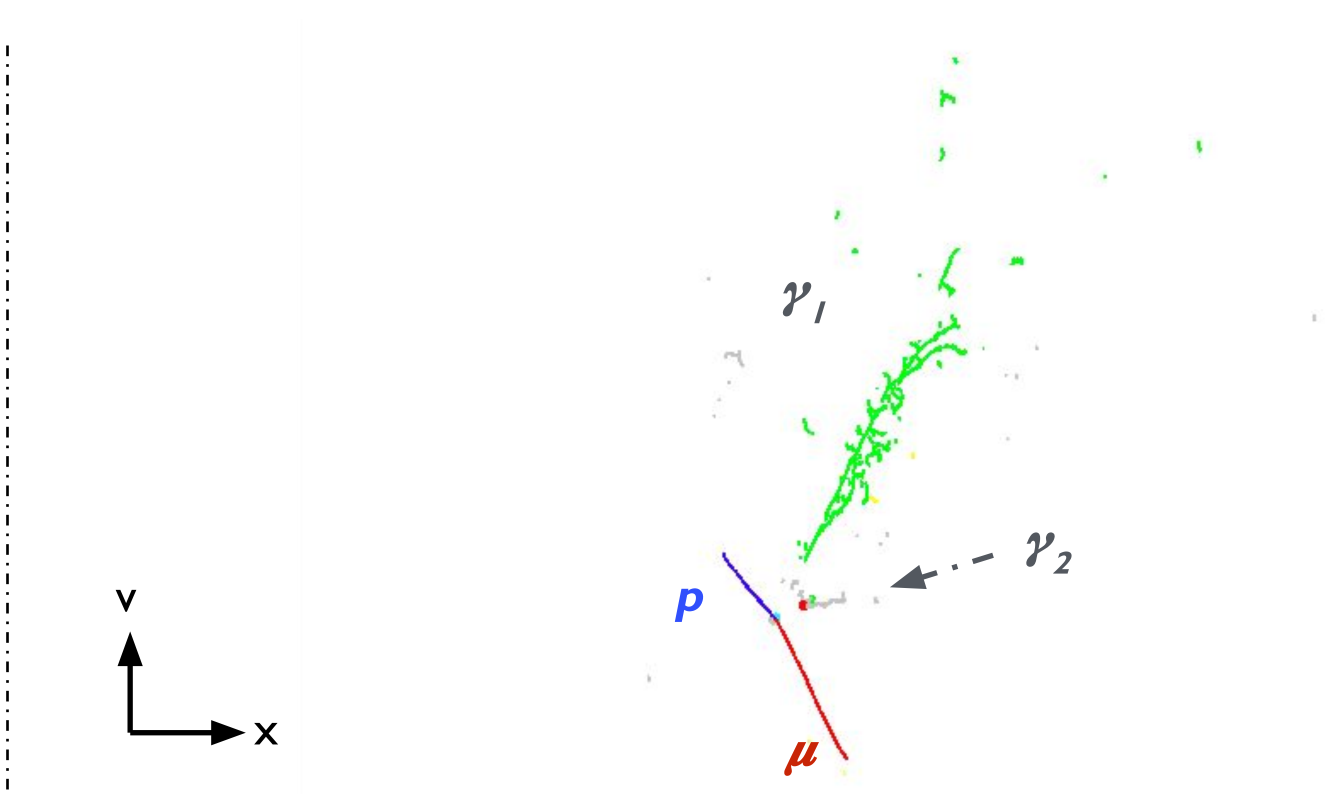

Work to do: γ_2 merged into γ_1

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---PROCESSED-MATCHING-OUTPUT--------------------------------------------------------------------
-
MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

Primary 0, PDG 22, nMCHits 1803 (544, 582, 677)
-MatchedPfo 0, PDG 11, nMatchedHits 1674 (494, 535, 645), nPfoHits 1827 (560, 542, 725)

Primary 1, PDG 22, nMCHits 224 (75, 50, 99)

Primary 2, PDG 13, nMCHits 213 (89, 88, 36)
-MatchedPfo 1, PDG 13, nMatchedHits 209 (87, 88, 34), nPfoHits 215 (90, 89, 36)

Primary 3, PDG 2212, nMCHits 196 (54, 47, 95)
-MatchedPfo 2, PDG 13, nMatchedHits 173 (46, 40, 87), nPfoHits 174 (46, 40, 88)

Is correct? 0
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