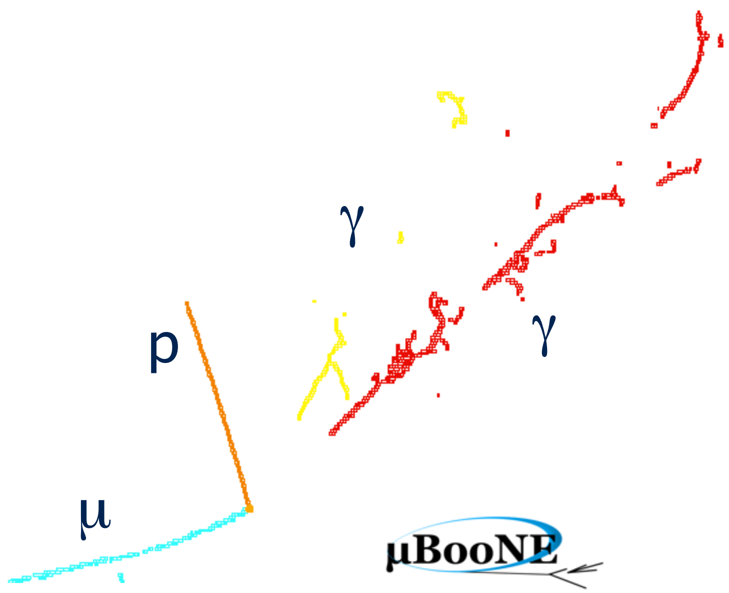
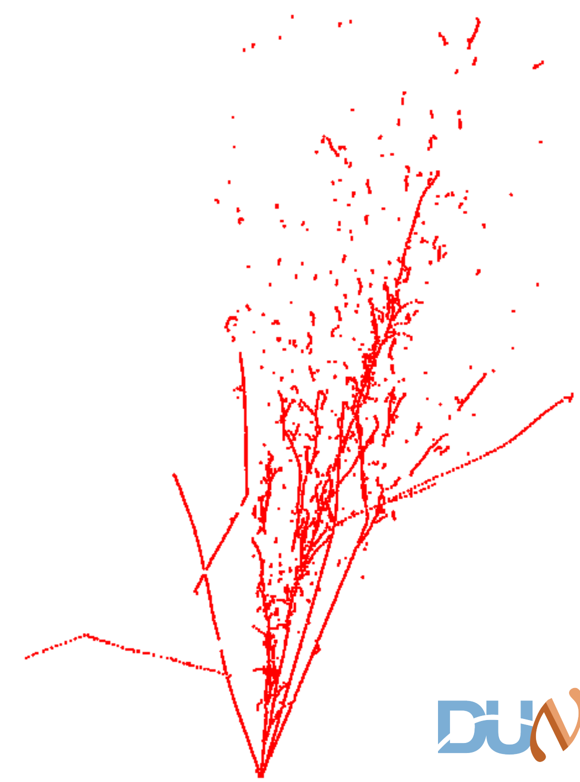


Pandora

LArTPC Reconstruction



Overview

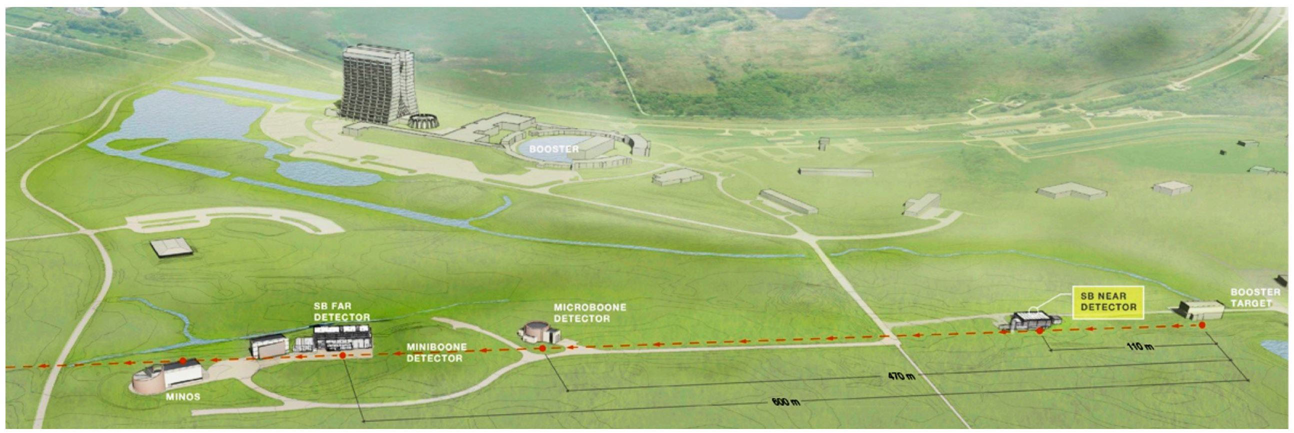
1. LArTPC detectors and event reconstruction
2. Pandora multi-algorithm approach to pattern recognition
3. Description of key Pandora LArTPC algorithms
4. Performance for neutrino interactions in MicroBooNE
5. Handling LArTPCs w/ multiple volumes and cosmic-ray backgrounds

Key references: **Eur. Phys. J. C (2018) 78: 82**
and **Eur. Phys. J. C (2015) 75: 439**

Introduction

One of the key technologies in the current and future neutrino physics programmes is the Liquid-Argon Time-Projection Chamber (LArTPC)

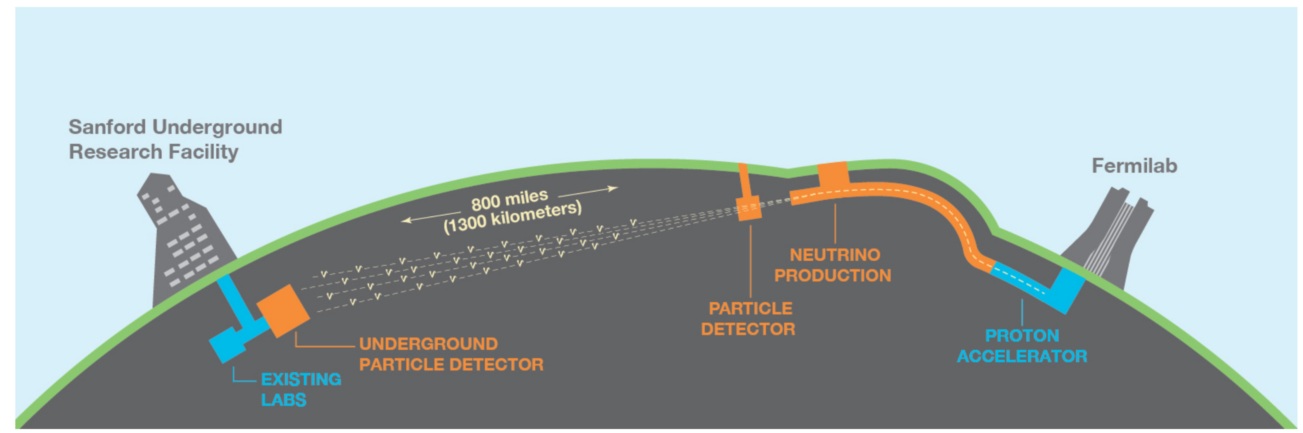
Short-baseline programme



ICARUS MicroBooNE SBND

- Three LArTPC detectors located along the Booster Neutrino Beam (BNB) at Fermilab
- Main goal is to investigate the potential sterile neutrino signals from LSND and MiniBooNE
- Precision cross-section measurements for neutrino interactions on argon

Long-baseline programme



ProtoDUNEs DUNE

- Neutrino oscillation physics:
  - Discover CP violation in the leptonic sector
  - Resolve mass hierarchy
  - Test three-flavour paradigm
  - Precision parameter measurement
- Proton decay
- Supernova neutrinos

LArTPC Detectors

- Charged particles, e.g. produced in neutrino interactions, deposit ionisation trails in liquid argon.
- Ionisation electrons drift in an applied electric field.
- In a single-phase LArTPC, the electrons are detected by a series of wire planes.
- Single-phase LArTPC detectors:
  - Past: ICARUS, ArgoNeuT
  - Current: MicroBooNE, LArIAT
  - Coming soon: SBND, ICARUS@SBN, ProtoDUNE

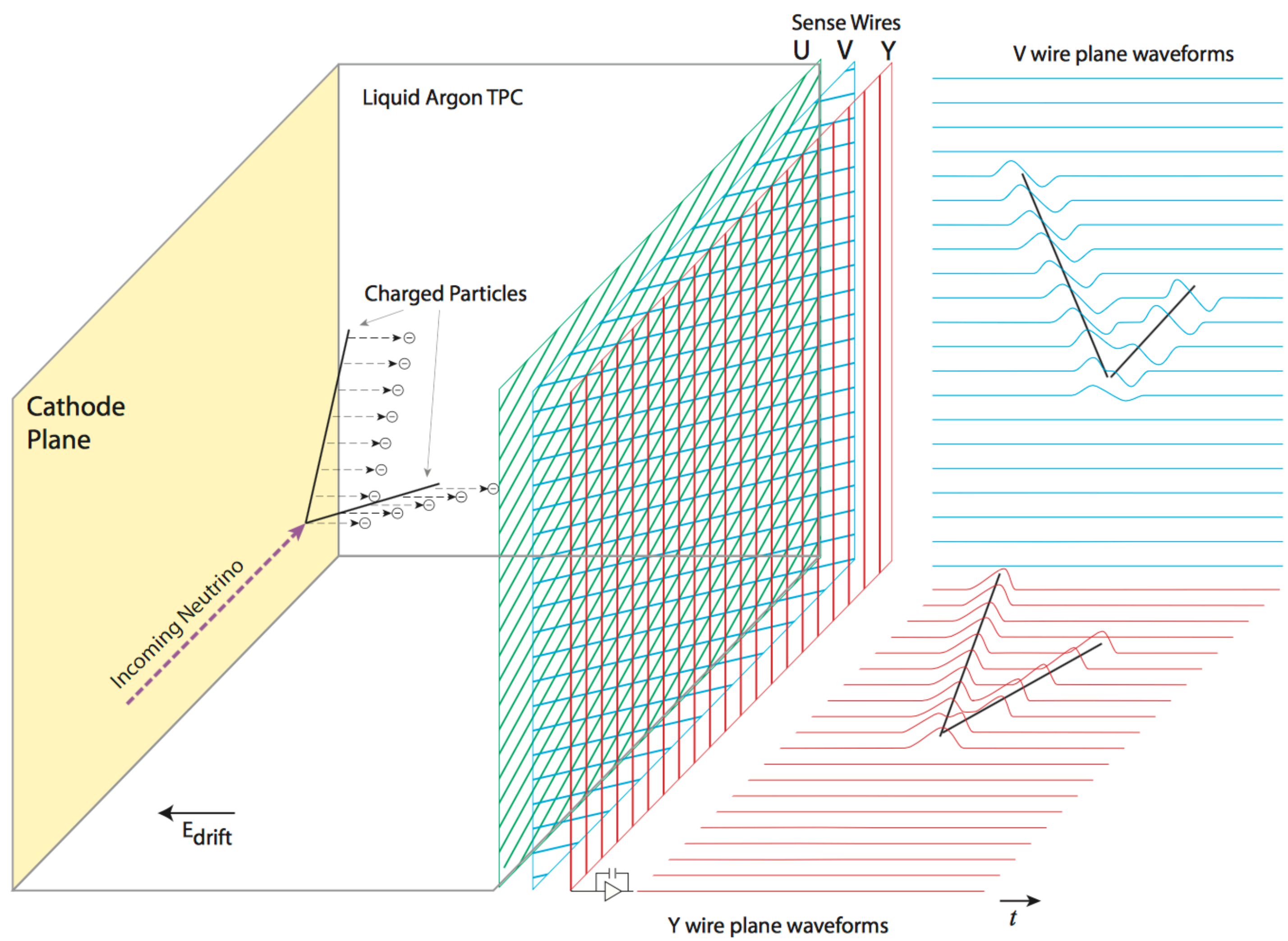
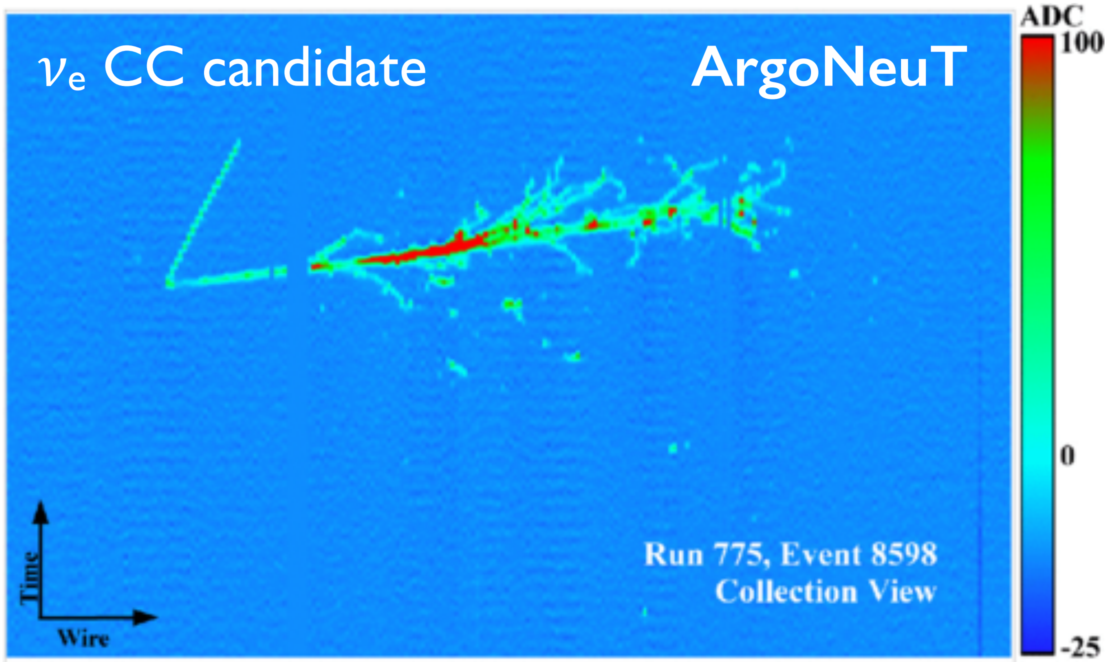
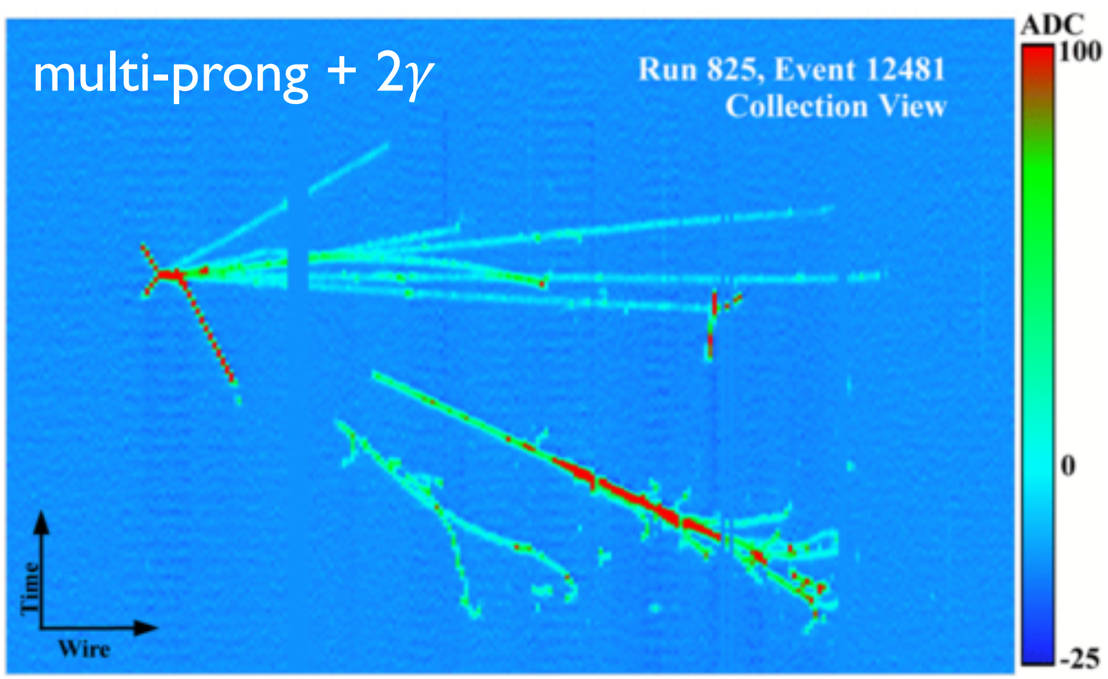


Figure: arXiv:1612.05824

Why Liquid Argon?





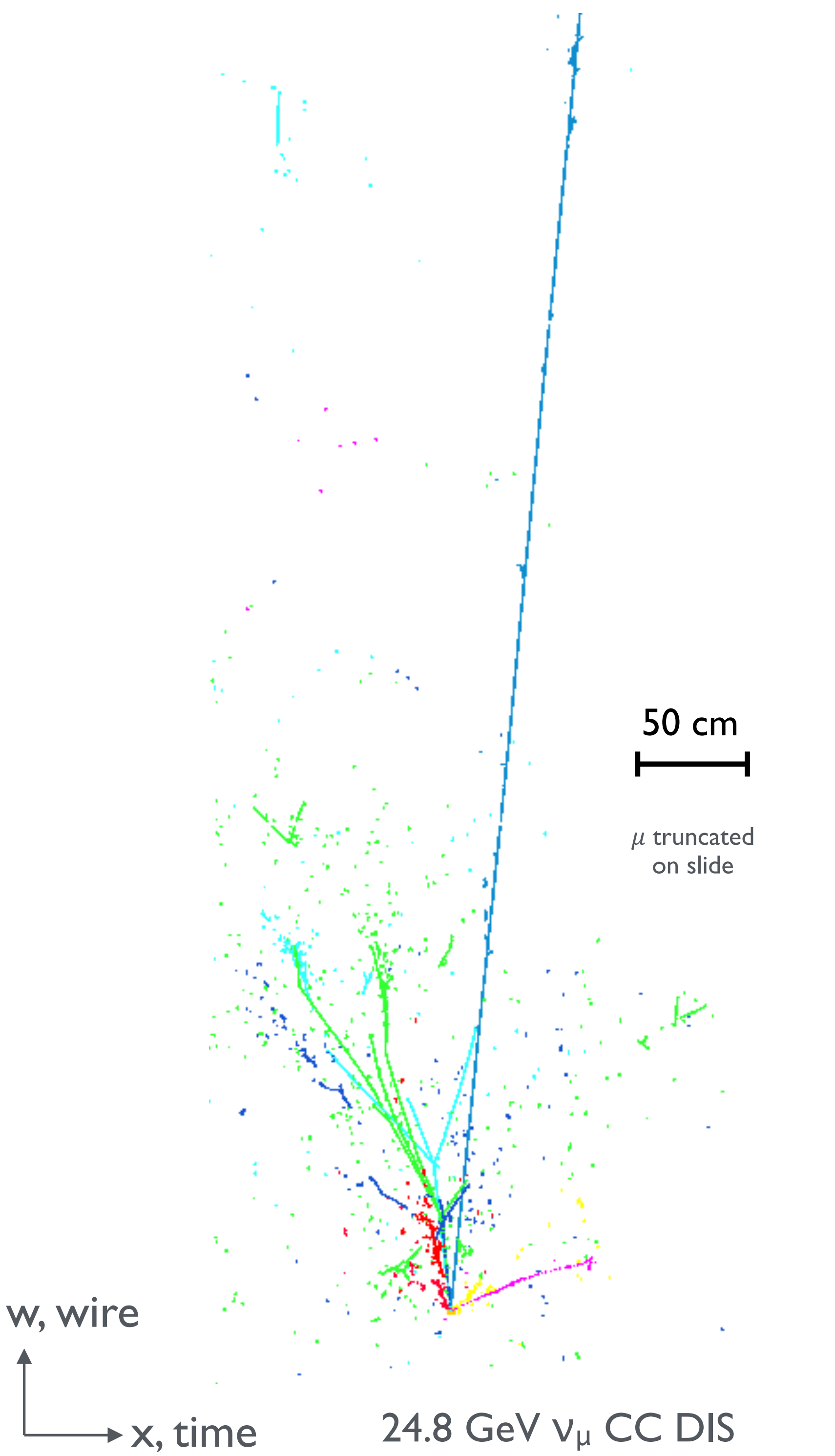
R. Acciari *et al*, Phys. Rev. D 95, 072005 (2017)

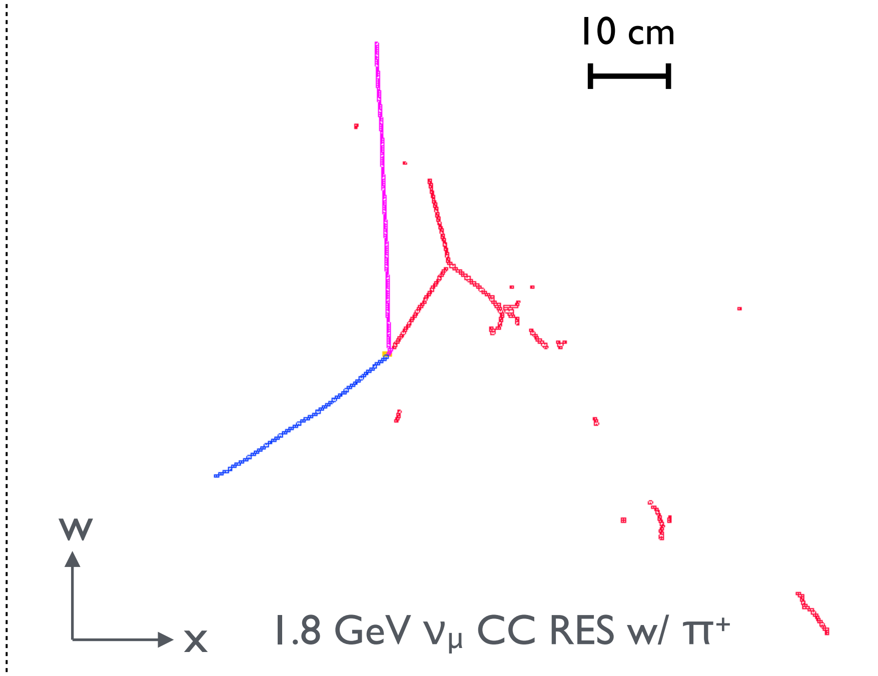
- **LArTPC detectors are fully active and fine grain, offering superb spatial and calorimetric resolution:**
  - **Reconstruction of multi-prong final states.**
  - **Particle identification:**
    - **$\mu/p/K$ in particle tracks**
    - **e/γ in electromagnetic showers**
- **Potential for high efficiency and low backgrounds in most channels**
- **Scalable to multi-kiloton masses.**

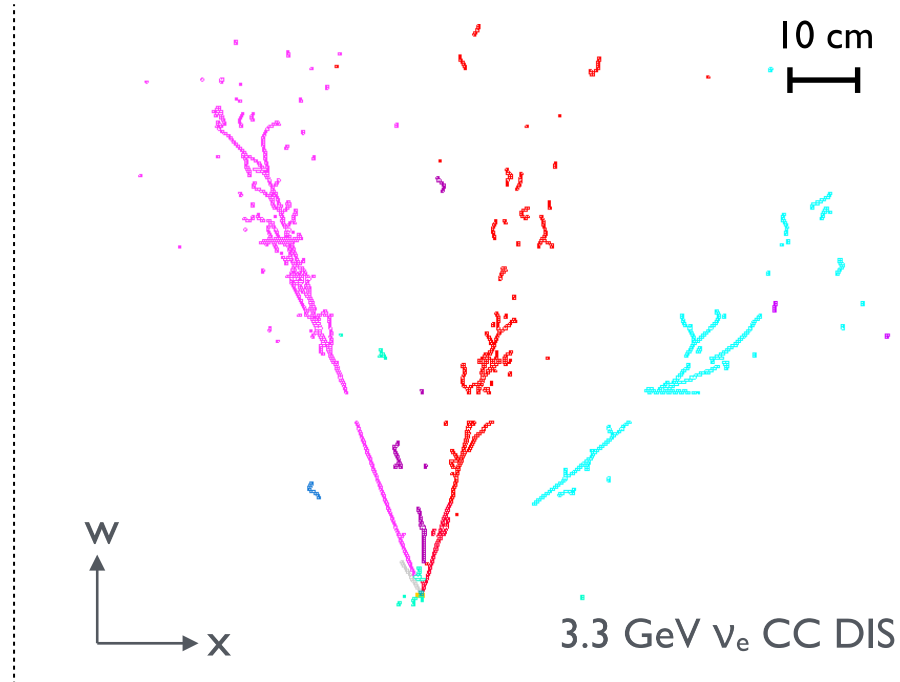
LArTPC Pattern Recognition

It is a significant challenge to develop automated, algorithmic LArTPC pattern-recognition

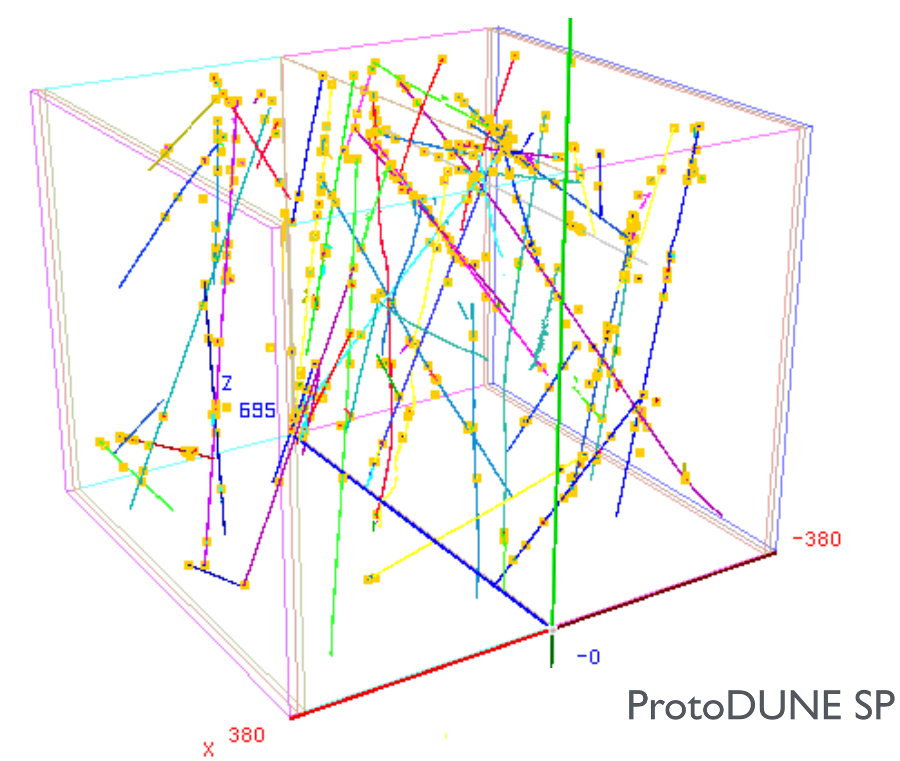
- Complex, diverse topologies:







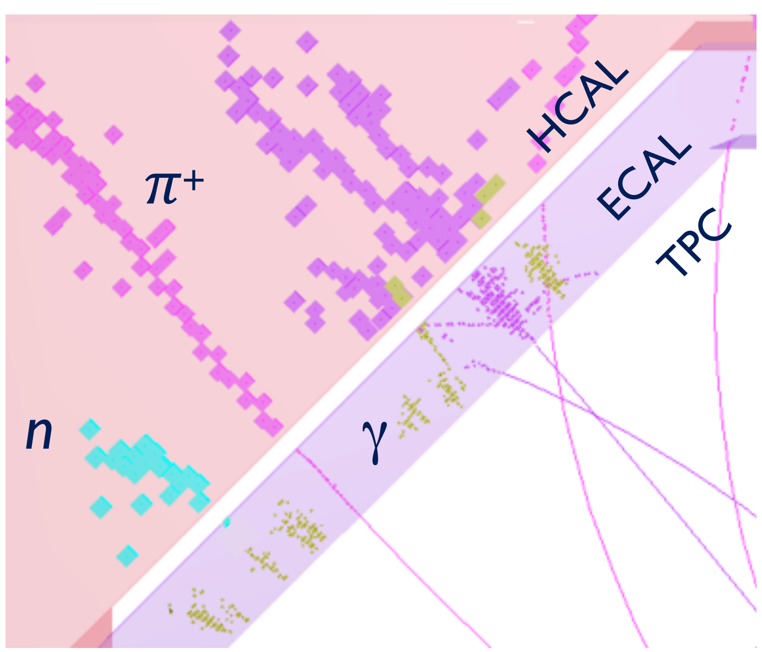
- Also, LArTPCs have long exposures, due to lengthy drift times (up to few ms).
- Significant cosmic-ray muon background in surface-based detectors.



Multi-Algorithm Pattern Recognition

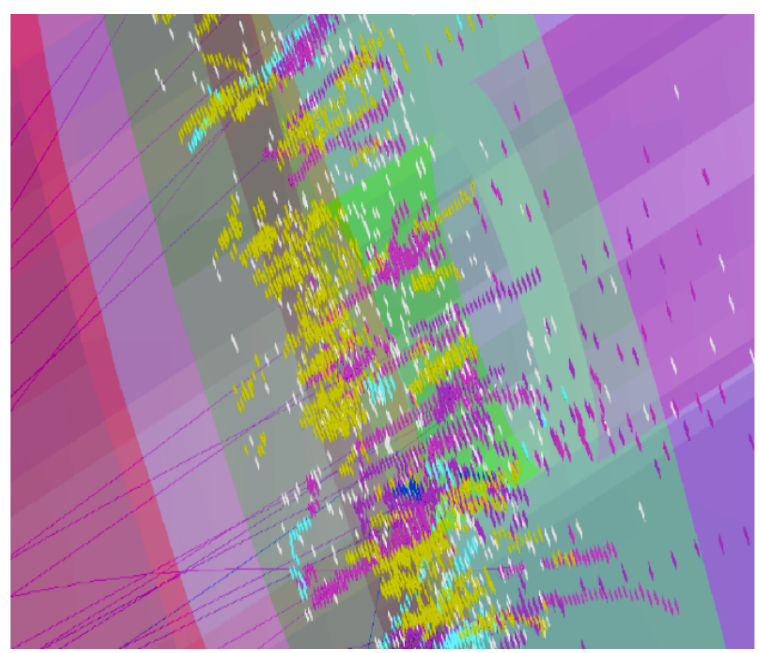
- **Single clustering approach is unlikely to work for such complex topologies:**
  - Mix of track-like and shower-like clusters

- **Pandora project has tackled similar problems before, using a multi-algorithm approach:**
  - Build up events gradually
  - Each step is incremental - aim not to make mistakes (undoing mistakes is hard…)
  - Deploy more sophisticated algorithms as picture of event develops
  - Build physics and detector knowledge into algorithms



Typical ILC event topologies - 3D

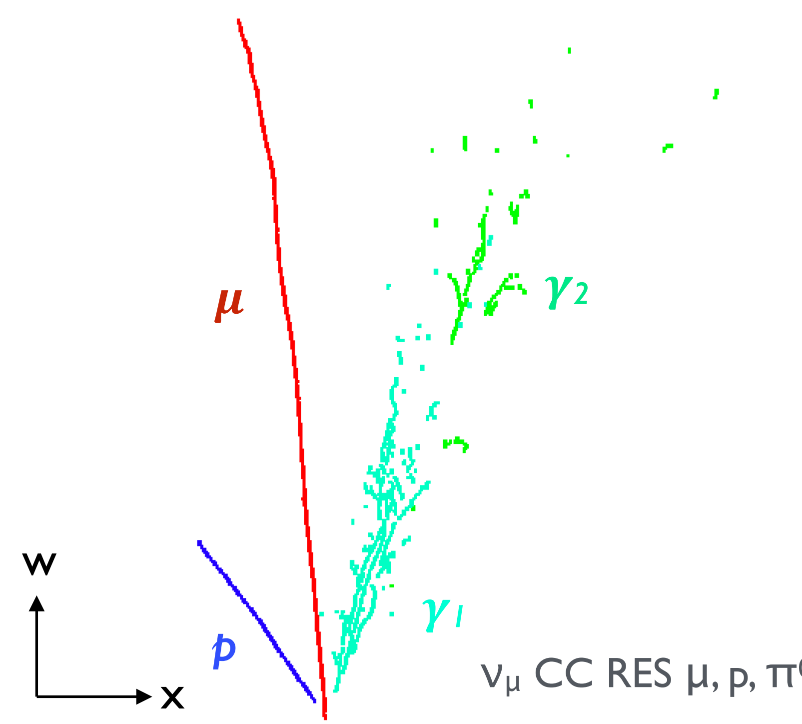
NIMA.2009.09.009 NIMA.2012.10.038



Typical showers in CMS HGCAL - 3D

LHCC-P-008

Typical LArTPC event topology - 3 x 2D



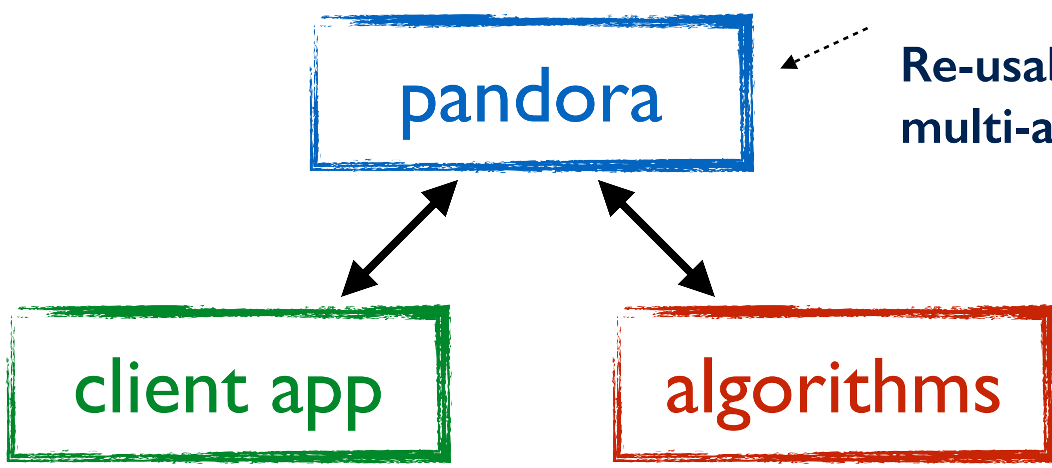
pandora: Implementation

Multi-algorithm event reconstruction rather difficult to implement. Pandora Software Development Kit engineered specifically to support this approach:

1. Easy for users to provide the "building blocks" that define a pattern-recognition problem.
2. Logic to solve pattern-recognition problems is cleanly implemented in algorithms.
3. Operations to access or modify building blocks, or create new structures, are requested by algorithms and performed by Pandora.

pandora sdk and visualisation

Re-usable libraries support multi-algorithm approach



larpandora

Handles input/output LArSoft↔Pandora

larpandoracontent

137 algorithms and tools, specifically for LArTPC usage

EPJC (2015) 75: 439

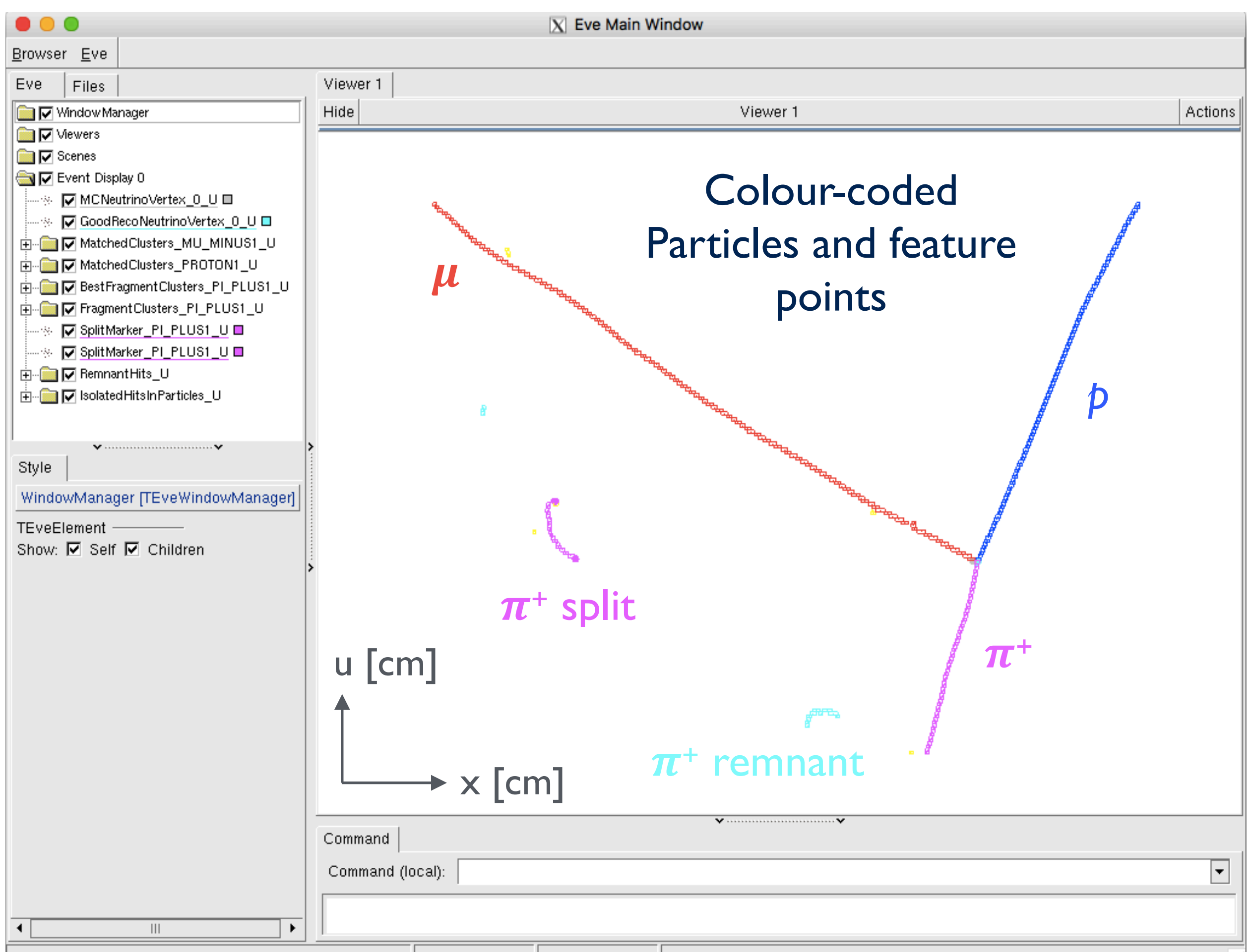
github.com/PandoraPFA

Algorithm 1 Cluster creation pseudocode. The logic determining when to create new Clusters and when to extend existing Clusters will vary between algorithms.

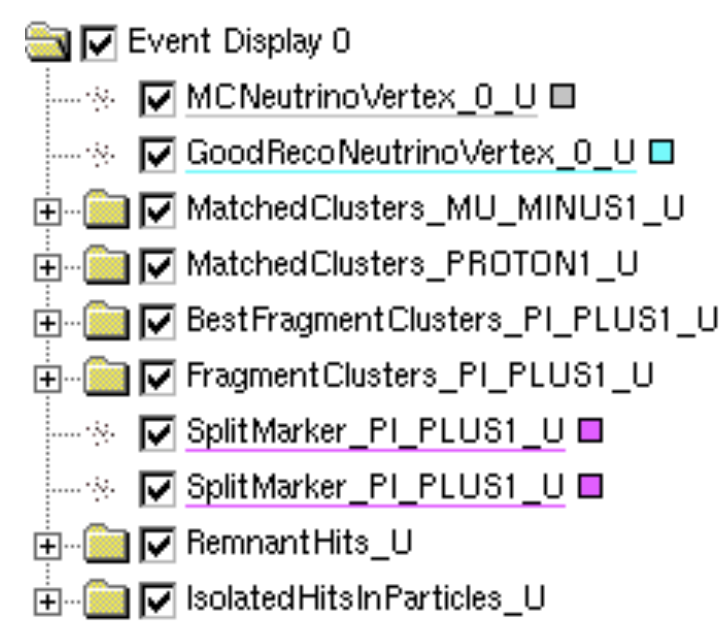
```
procedure CLUSTER CREATION
    Create temporary Cluster list
    Get current CaloHit list
    for all CaloHits do
        if CaloHit available then
            for all newly-created Clusters do
                Find best host Cluster
            if Suitable host Cluster found then
                Add CaloHit to host Cluster
            else
                Add CaloHit to a new Cluster
    Save new Clusters in a named list
```

Simplified **algorithm** implementation

- **Pandora provides a visualisation toolkit, which is vital for algorithm development. Translates Pandora objects to ROOT TEVE objects for in-algorithm display:**
  - Algorithms can easily pop up custom displays for visual debugging. Can choose e.g. which clusters to display, in which colours, can add guiding markers, lines, etc.
  - We typically develop Pandora algs visually, working with just a few events and displaying all relevant objects/constructs, before scaling up for higher-stats testing.



E.g. add just a few lines of code to a validation algorithm, to visualise quality of reconstruction:



larpandora: Input Hits

Pandora uses the output from an external hit-finding module to derive 3x2D images:

Single phase: known wire positions [cm] vs. recorded positions from drift times [cm]

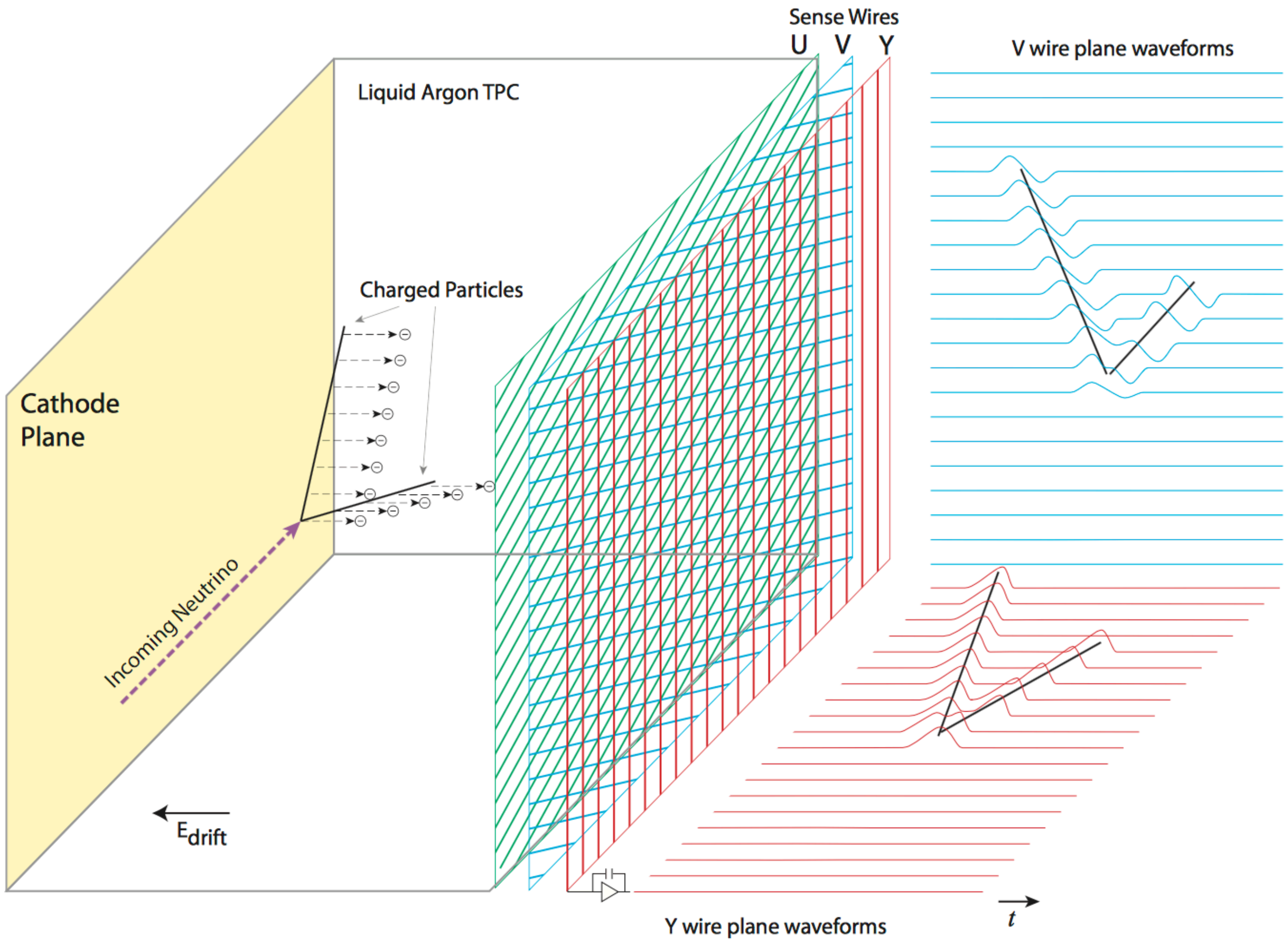
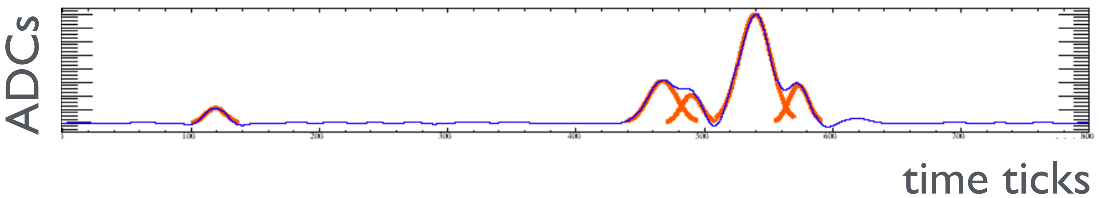


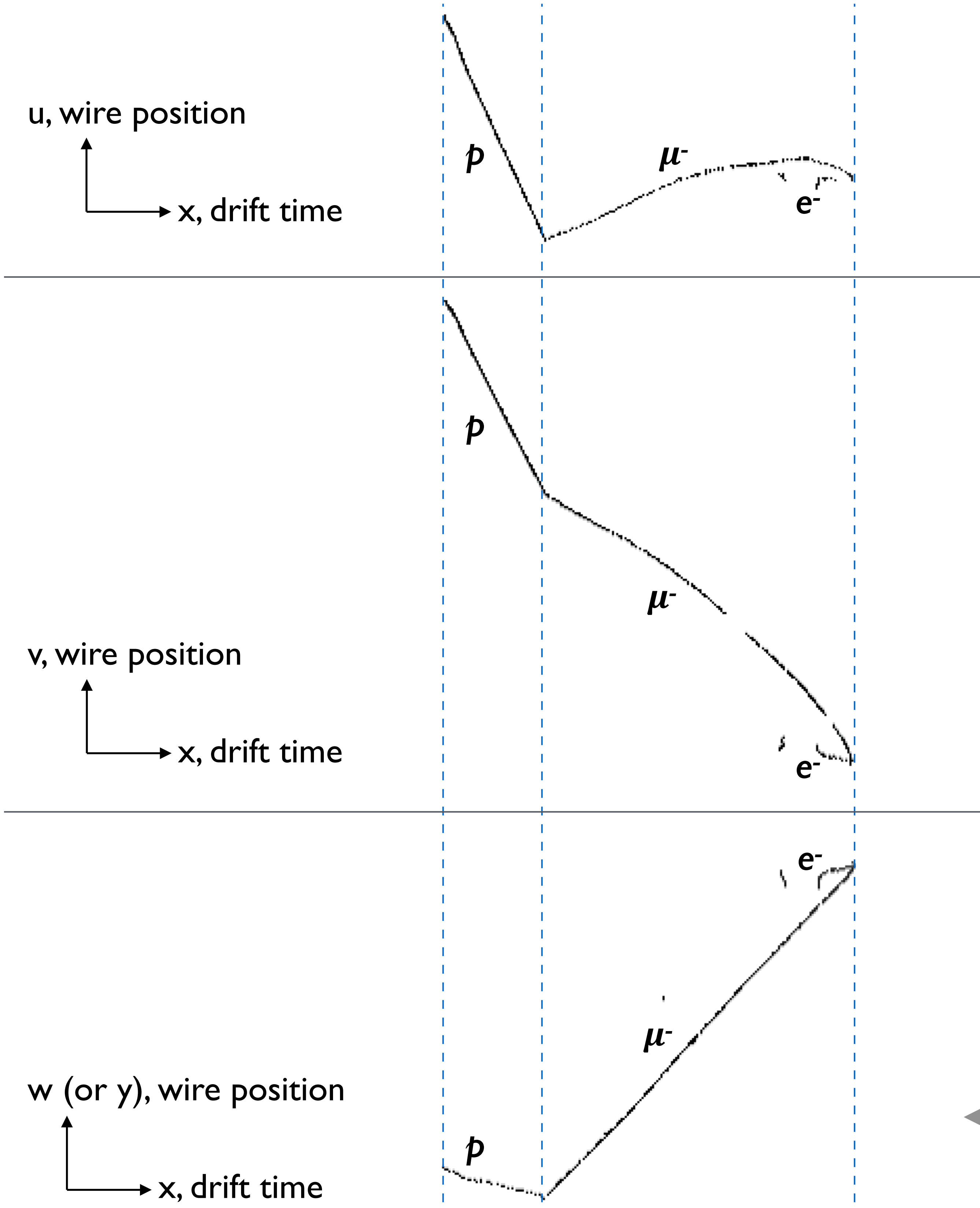
Figure: arXiv:1612.05824

- Fit pulses with N Gaussians where N is the number of peaks in a pulse.
- Each Gaussian represents a single hit, even if from a pulse w/ multiple peaks

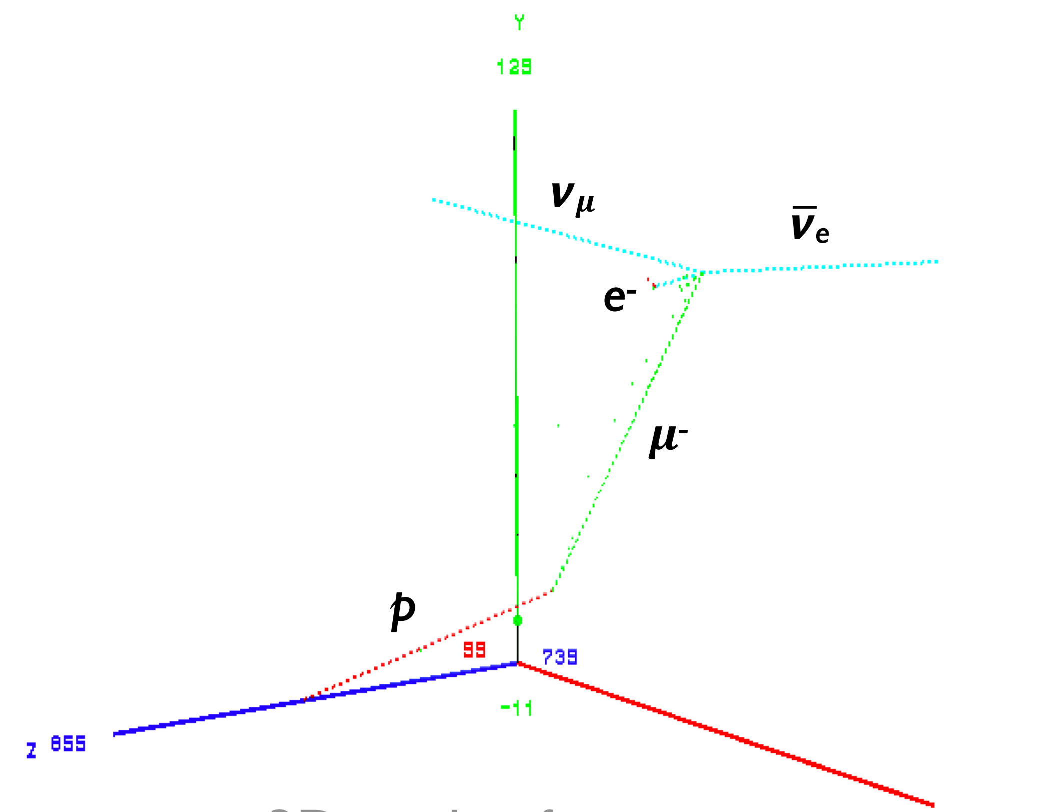


e.g. for an individual wire

larpandora: Input Hits



E.g. CC QE: ν_μ + Ar → p + μ^-



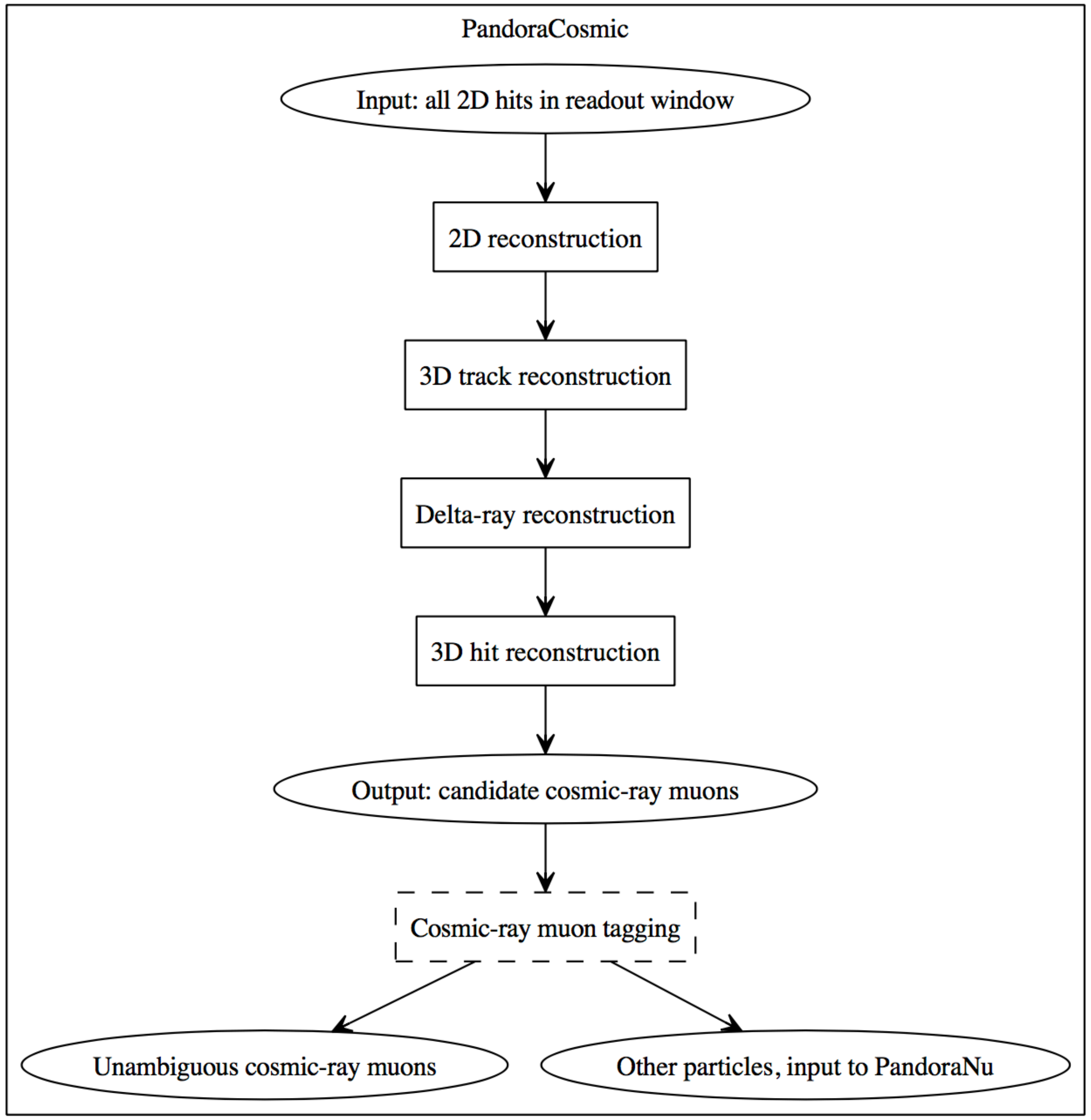
3D truth information

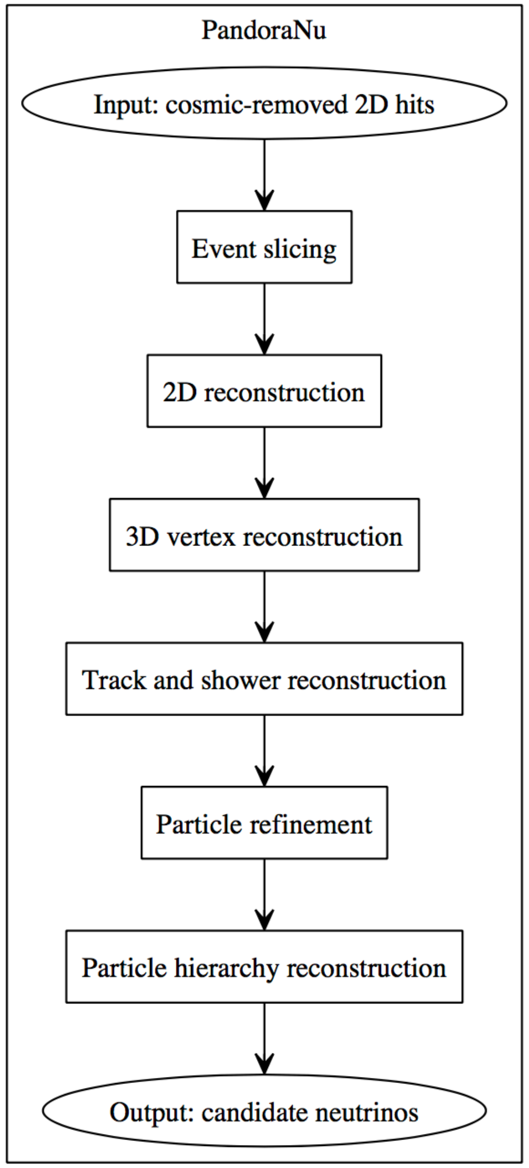
← Three 2D representations with common x coordinate, derived from drift time

larpandoracontent: Algorithm Chains

- **Two Pandora algorithm chains created for LArTPC use, with many algs in common:**
  - **PandoraCosmic:** strongly track-oriented; showers assumed to be delta rays, added as daughters of primary muons; muon vertices at track high-y coordinate.
  - **PandoraNu:** finds neutrino interaction vertex and protects all particles emerging from vertex position. Careful treatment to address track/shower tensions.

Initially use a two-pass approach: Input to PandoraNu excludes hits from unambiguous cosmic rays.

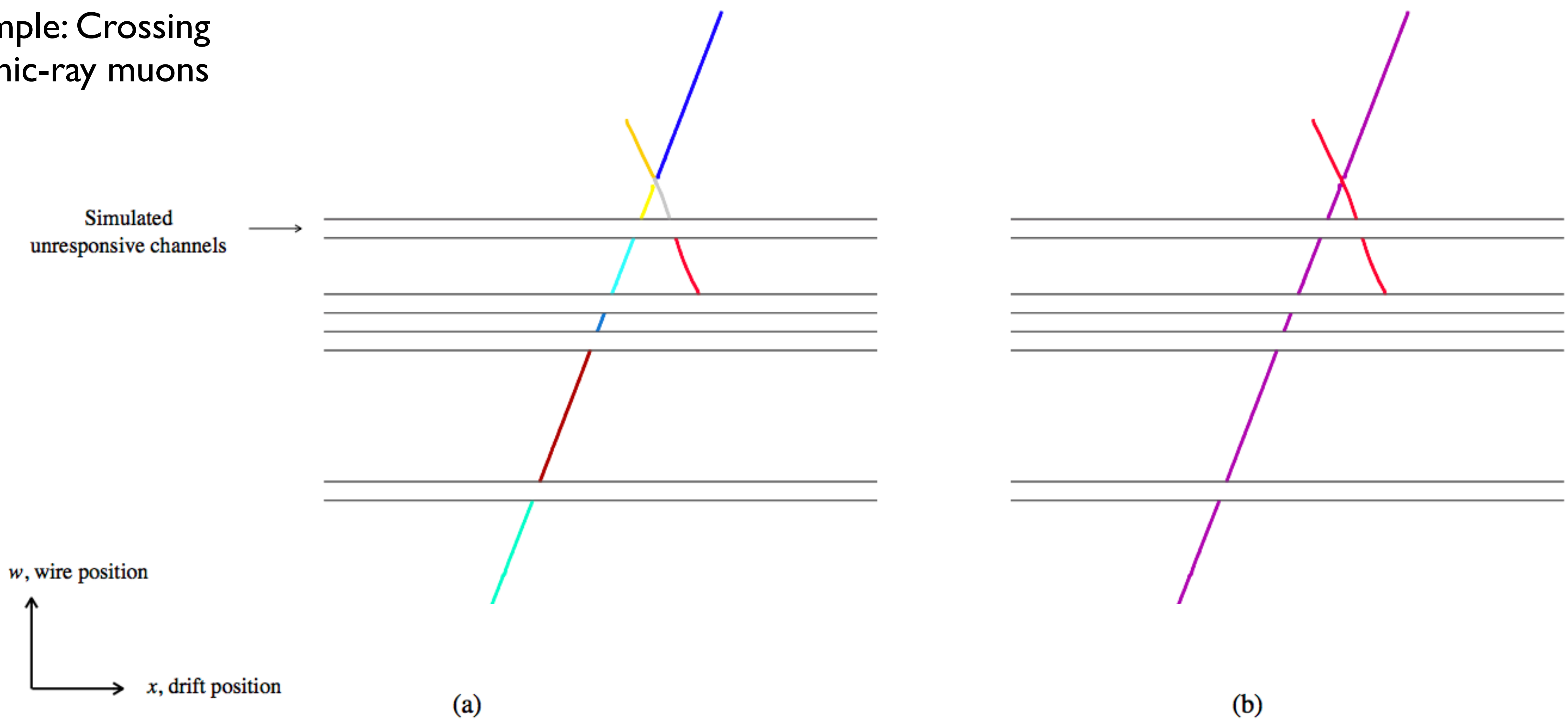




Cosmic-Ray Muon Reconstruction - 2D

- For each plane, produce list of 2D clusters that represent continuous, unambiguous lines of hits:
  - Separate clusters for each structure, with clusters starting/stopping at each branch or ambiguity.
- Clusters refined by series of 15 cluster-merging and cluster-splitting algs that use topological info.

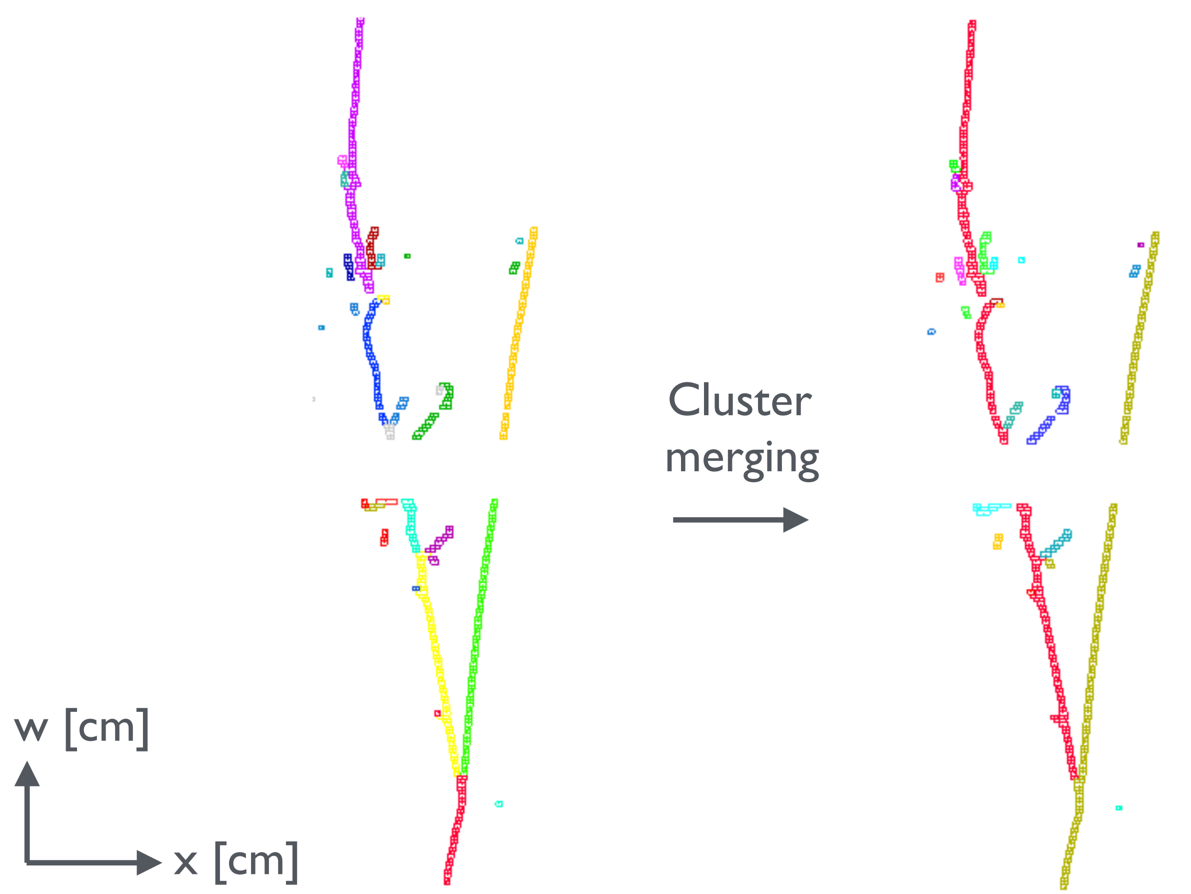
Example: Crossing cosmic-ray muons



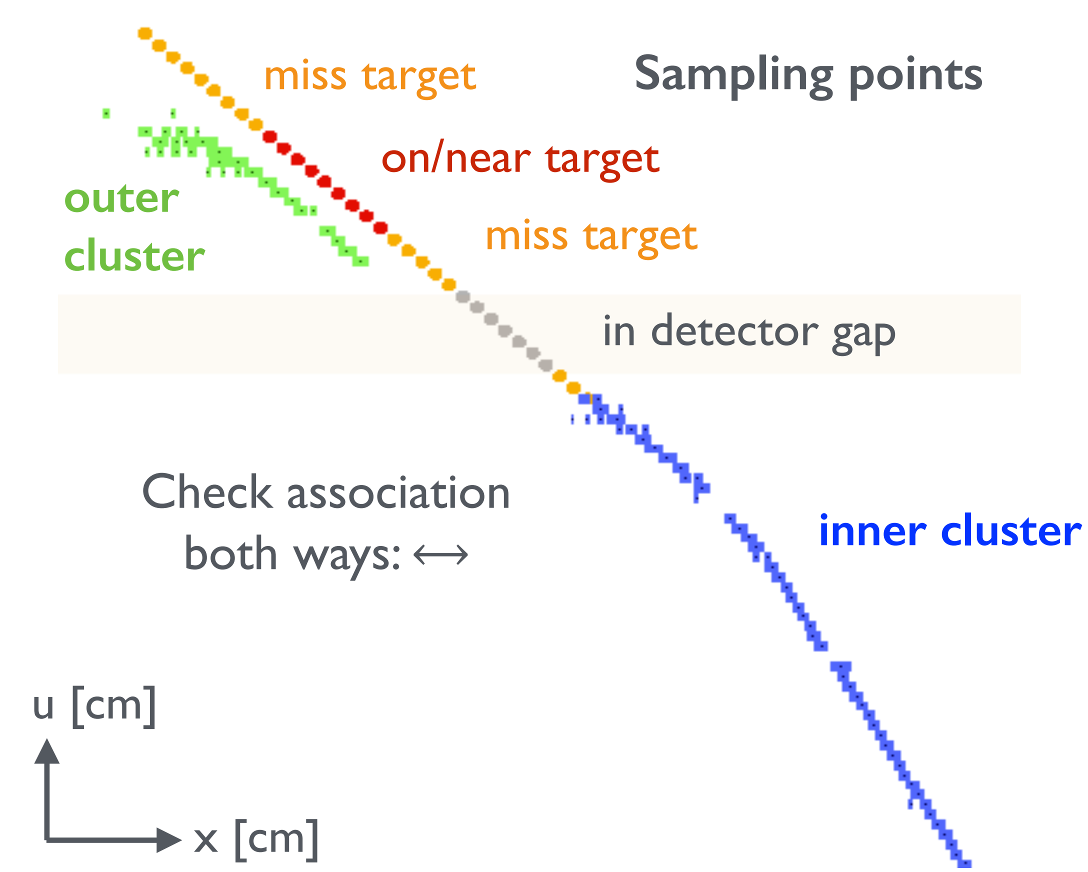
Topological Association - 2D

- **Cluster-merging algorithms identify associations between multiple 2D clusters and look to grow the clusters to improve completeness, without compromising purity.**
  - The challenge for the algorithms is to make cluster-merging decisions in the context of the entire event, rather than just by considering individual pairs of clusters in isolation.
  - Typically need to provide a definition of association (for a given pair of clusters), then navigate forwards and backwards to identify chains of associated clusters that can be safely merged.

E.g. LongitudinalAssociation

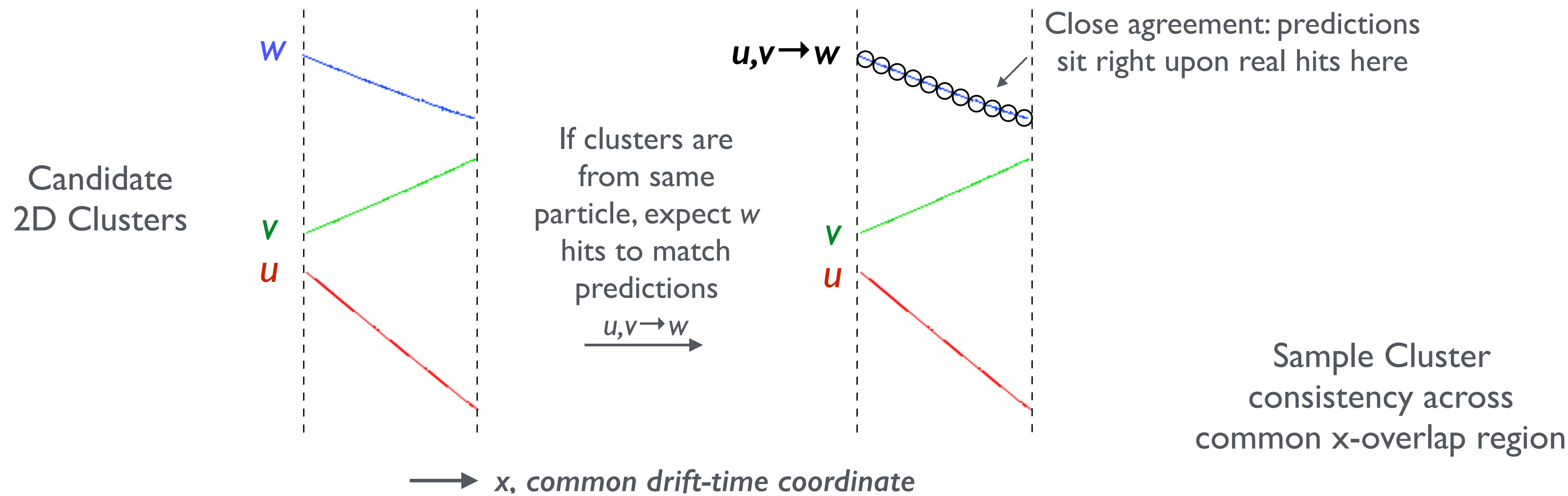


E.g. CrossGapsAssociation



Track Pattern Recognition - 3D

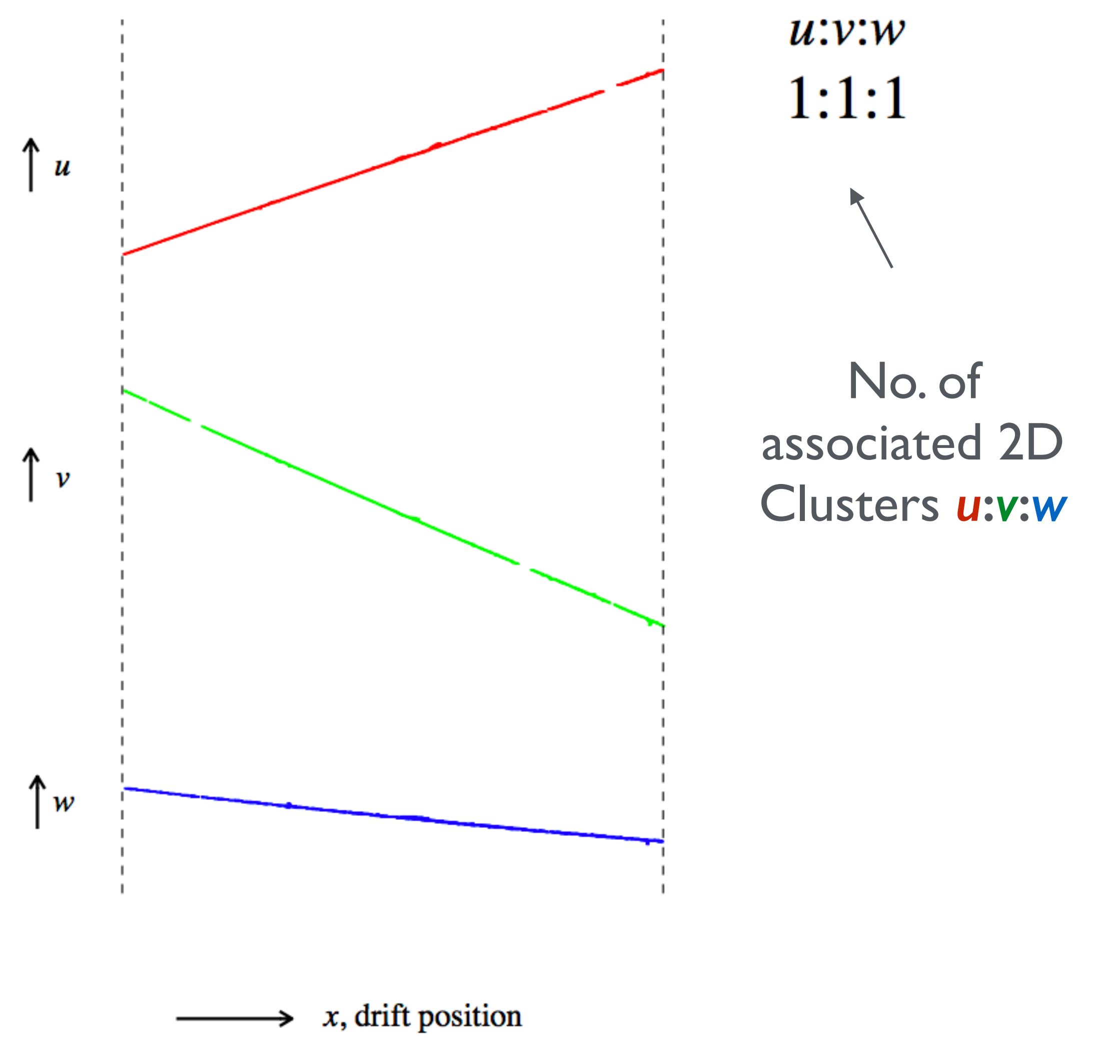
- **Our original input was 3x2D images of charged particles in the detector.**
- **Should now have reconstructed three separate 2D clusters for each particle:**
  - Compare 2D clusters from *u*, *v*, *w* planes to find the clusters representing same particle.
  - Exploit common drift-time coordinate and our understanding of wire plane geometry.
  - At given *x*, compare predictions {$u,v \rightarrow w$; $v,w \rightarrow u$; $w,u \rightarrow v$} with cluster positions, calculating χ^2



Store all results in a **"tensor"**, recording *x*-overlap span, no. of sampling points, no. of "matched" sampling points and χ^2. **Documents all 2D cluster-matching ambiguities.**

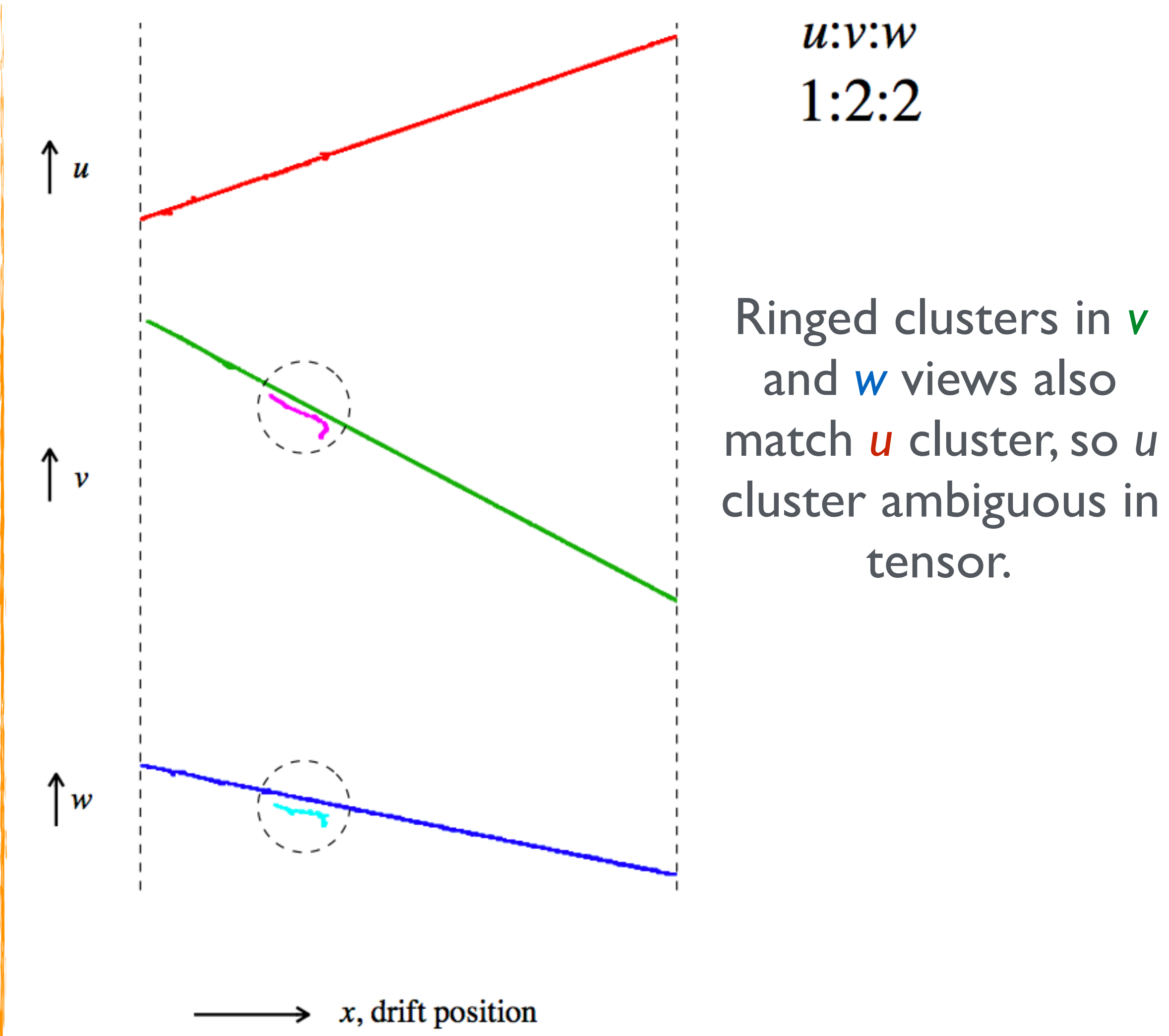
Track Pattern Recognition - 3D

Tensor stores overlap details for trios of 2D clusters. Tools make 2D reco changes to resolve any ambiguities. If a tool makes a change (e.g. splits a cluster), all tools run again.



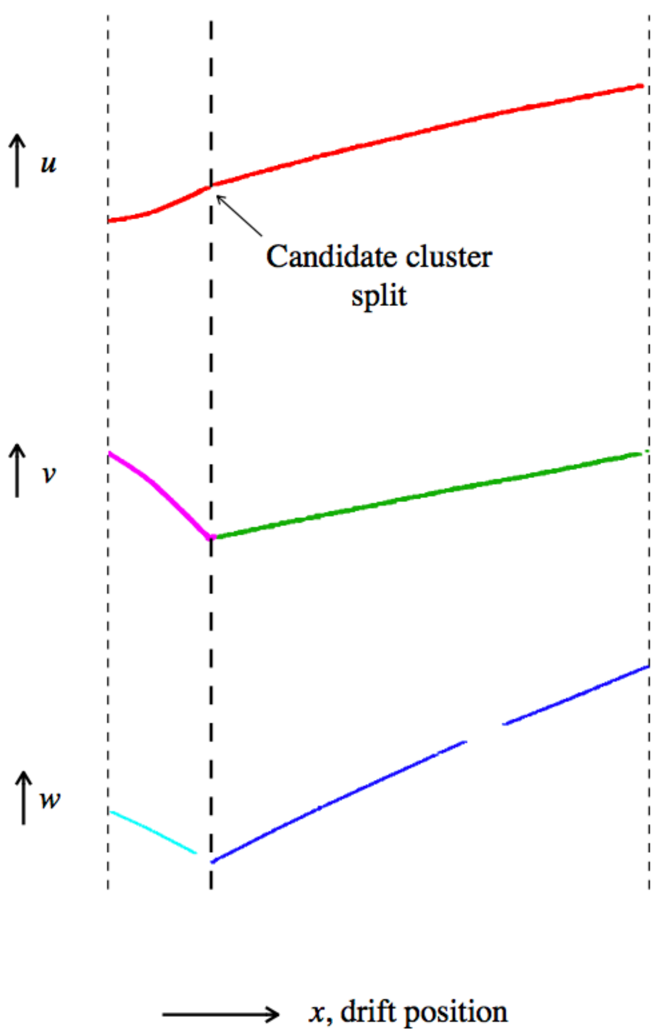
Find unambiguous elements in the tensor, demanding that the common x-overlap is 90% of the x-span for all three clusters.

Clear Tracks Tool



Resolve **obvious** ambiguities: clusters are matched in multiple configurations, but one tensor element is much "better" than others.

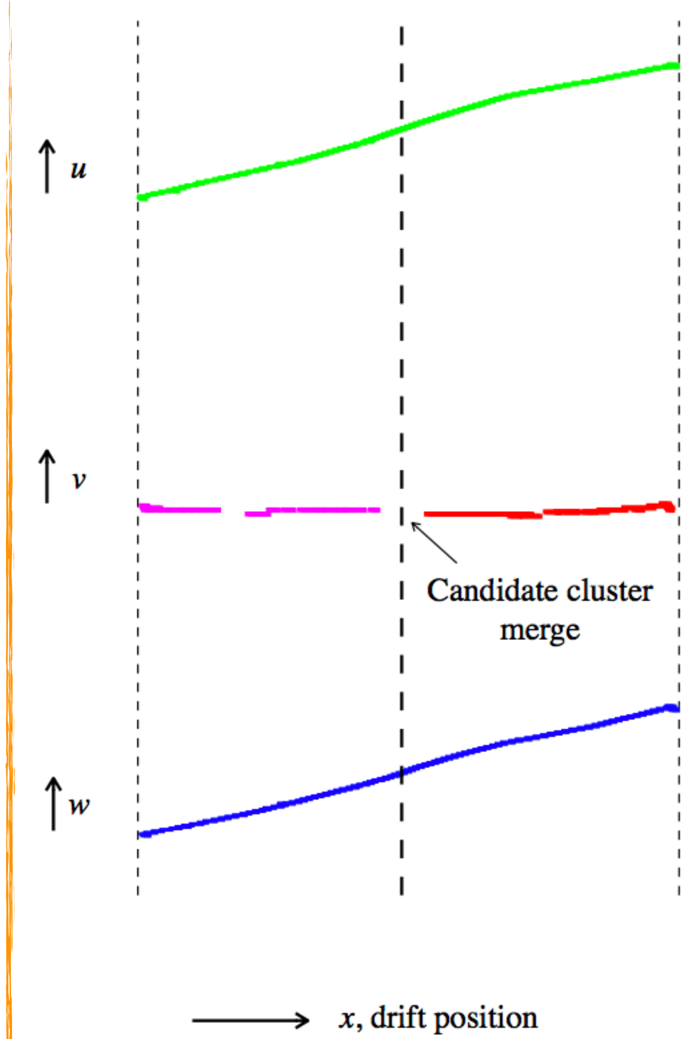
Long Tracks Tool



u:*v*:*w*
1:2:2

Two clusters in *w* and *v*, matched to common *u* cluster. **Split *u* cluster.**

Overshoot Tracks Tool



u:*v*:*w*
1:2:1

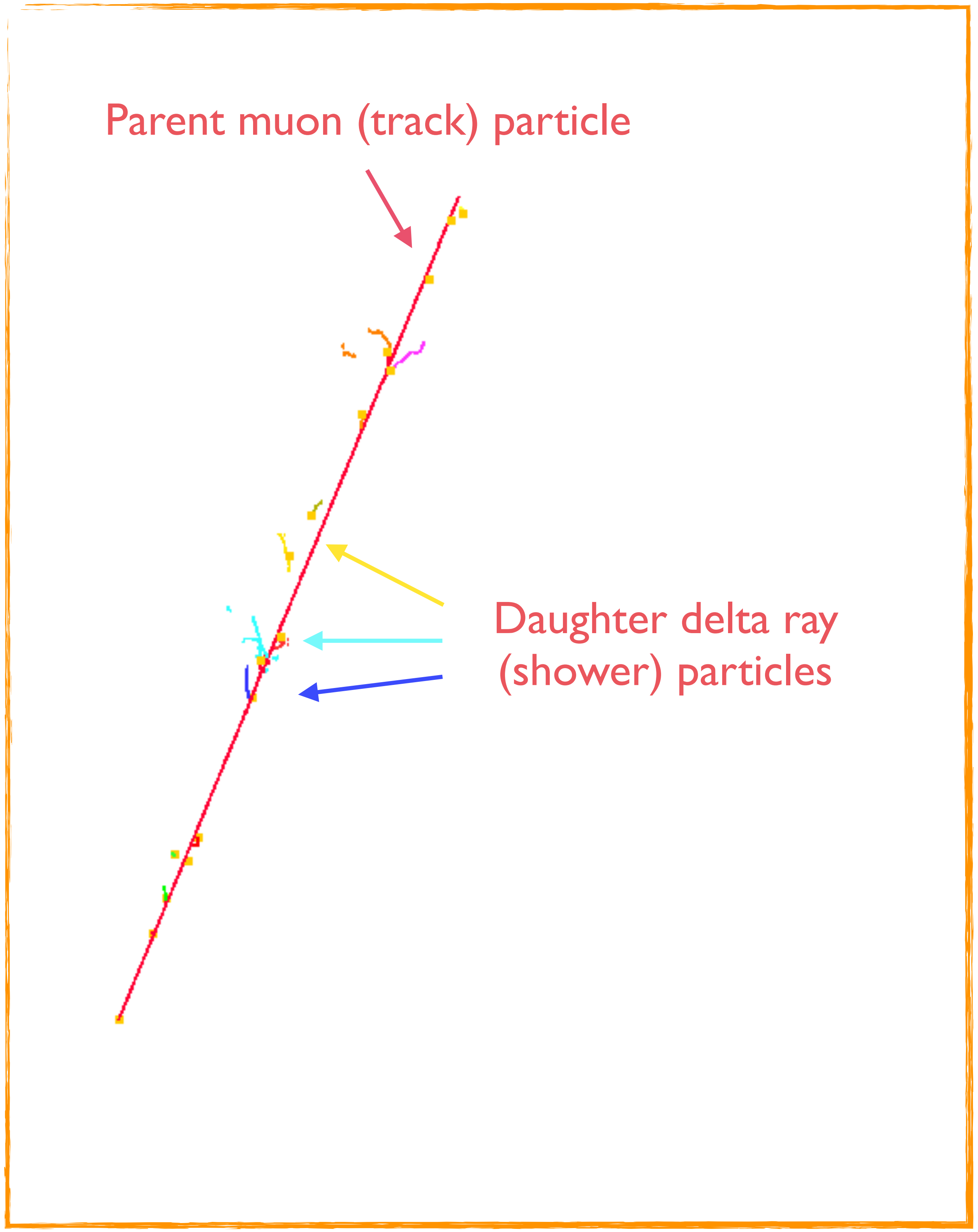
Two clusters in *v* view, matched to common clusters in *u* and *w* views. **Merge *v* clusters.**

Undershoot Tracks Tool

- Use all connected clusters to assess whether this is a true 3D kink topology.
- Modify 2D clusters as appropriate (i.e. merge or split) and update cluster-matching tensor.
- Initial ClearTracks tool then able to identify unambiguous groupings of clusters and form particles.

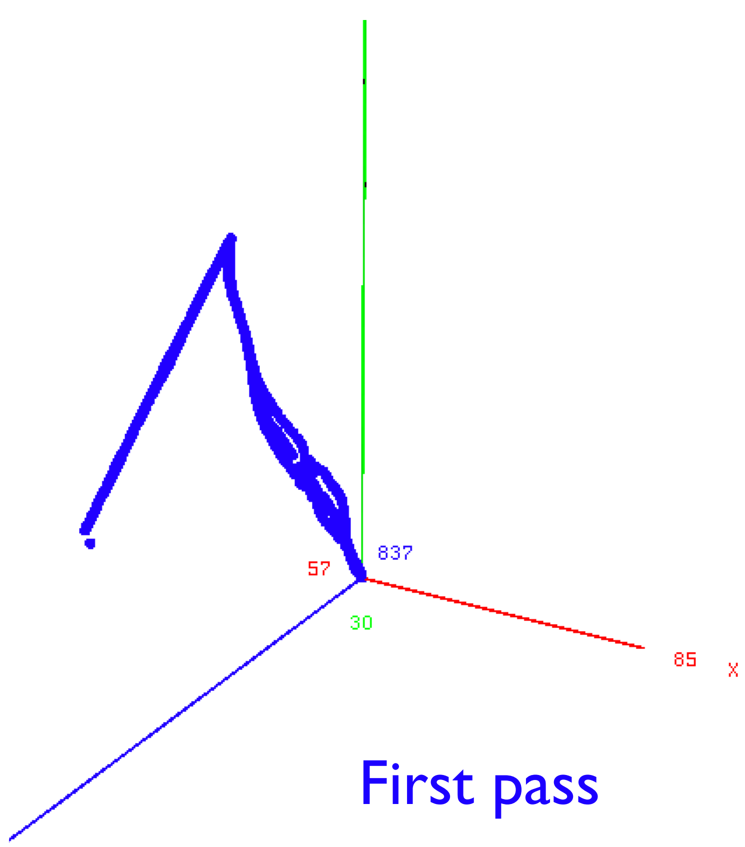
Delta-Ray Reconstruction - 2D, 3D

- **Assume any 2D clusters not in a track particle are from delta-ray showers:**
  - Simple proximity-based reclustering of hits, then topological association algs.
  - Delta-ray clusters matched between views, creating delta-ray shower particles.
  - Parent muon particles identified and delta-ray particles added as daughters.



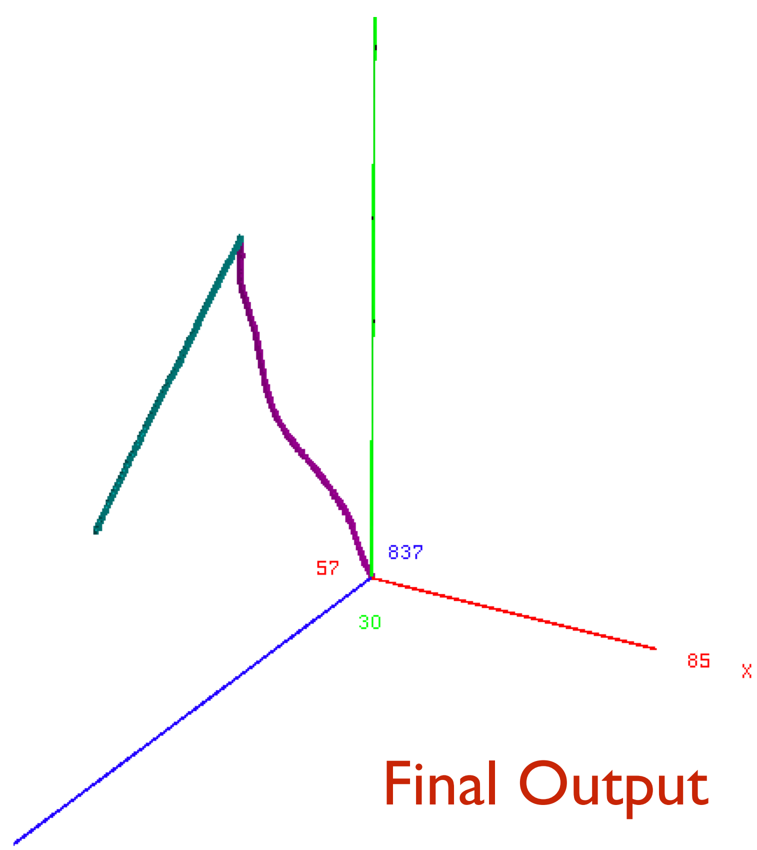
3D Hit/Cluster Reconstruction

- For each 2D Hit, sample clusters in other views at same *x*, to provide u_{in}, v_{in} and w_{in} values
- Provided u_{in}, v_{in} and w_{in} values don't necessarily correspond to a specific point in 3D space
- Analytic expression to find 3D space point that is *most consistent* with given u_{in}, v_{in} and w_{in}
  - $\chi^2 = (u_{out} - u_{in})^2 / \sigma_u^2 + (v_{out} - v_{in})^2 / \sigma_v^2 + (w_{out} - w_{in})^2 / \sigma_w^2$
  - Write in terms of unknown *y* and *z*, differentiate wrt *y*, *z* and solve
  - Can iterate, using fit to current 3D hits (extra terms in χ^2) to produce smooth trajectory



First pass

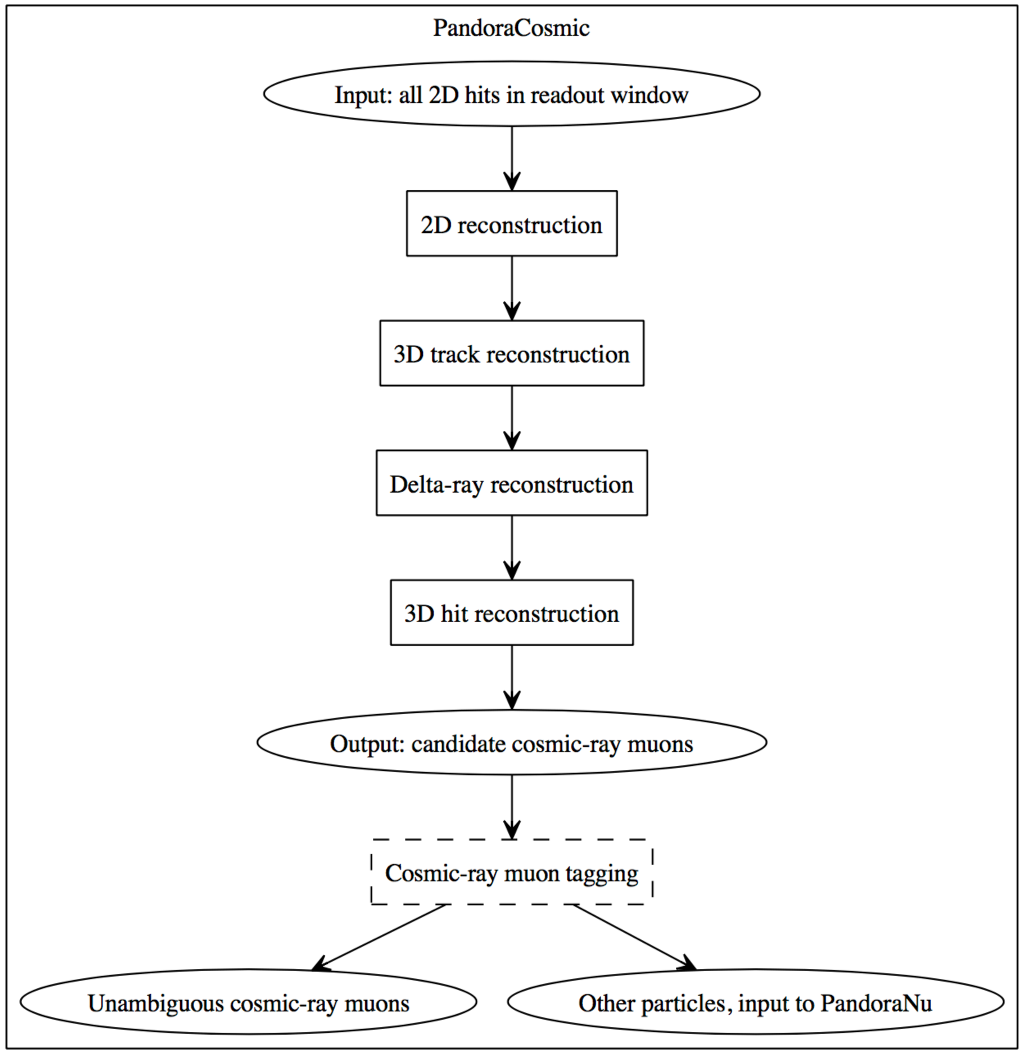
→

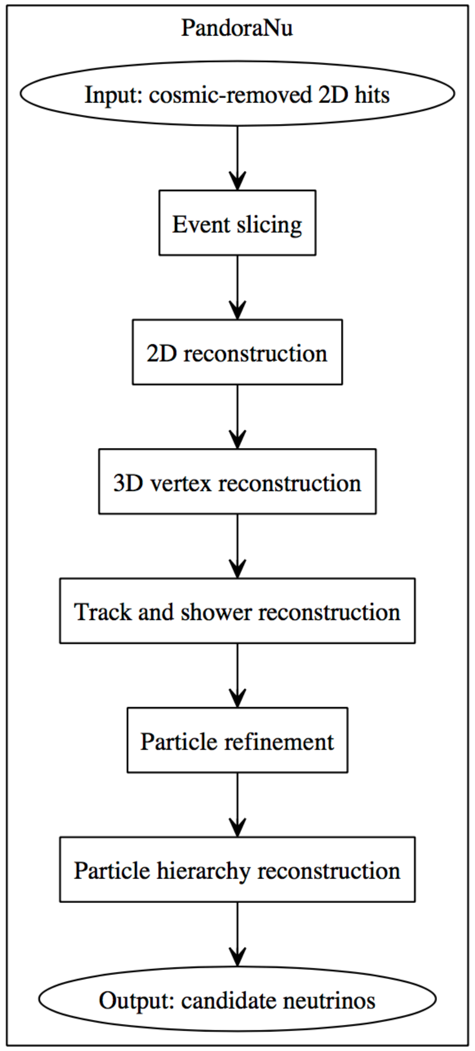


Final Output

Animated gif

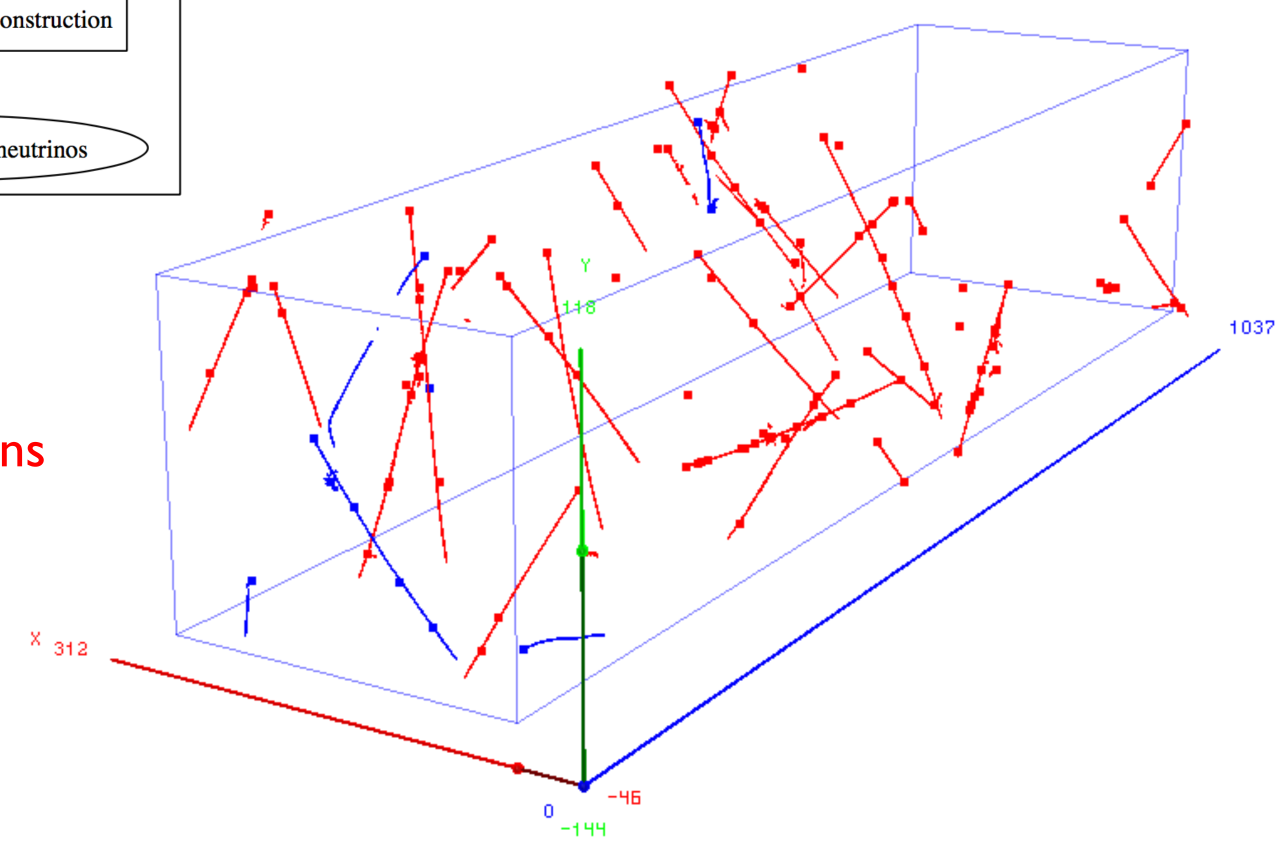
PandoraCosmic → PandoraNu





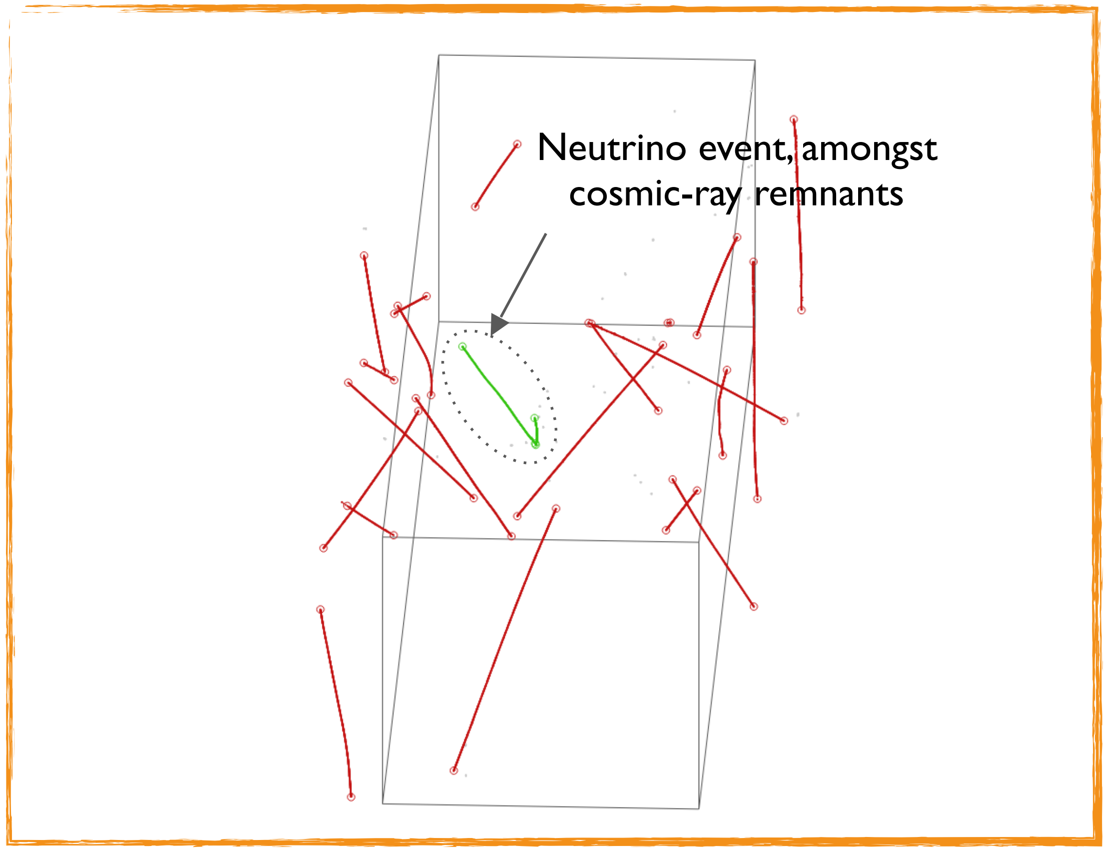
Other particles, input to PandoraNu

Unambiguous cosmic-ray muons

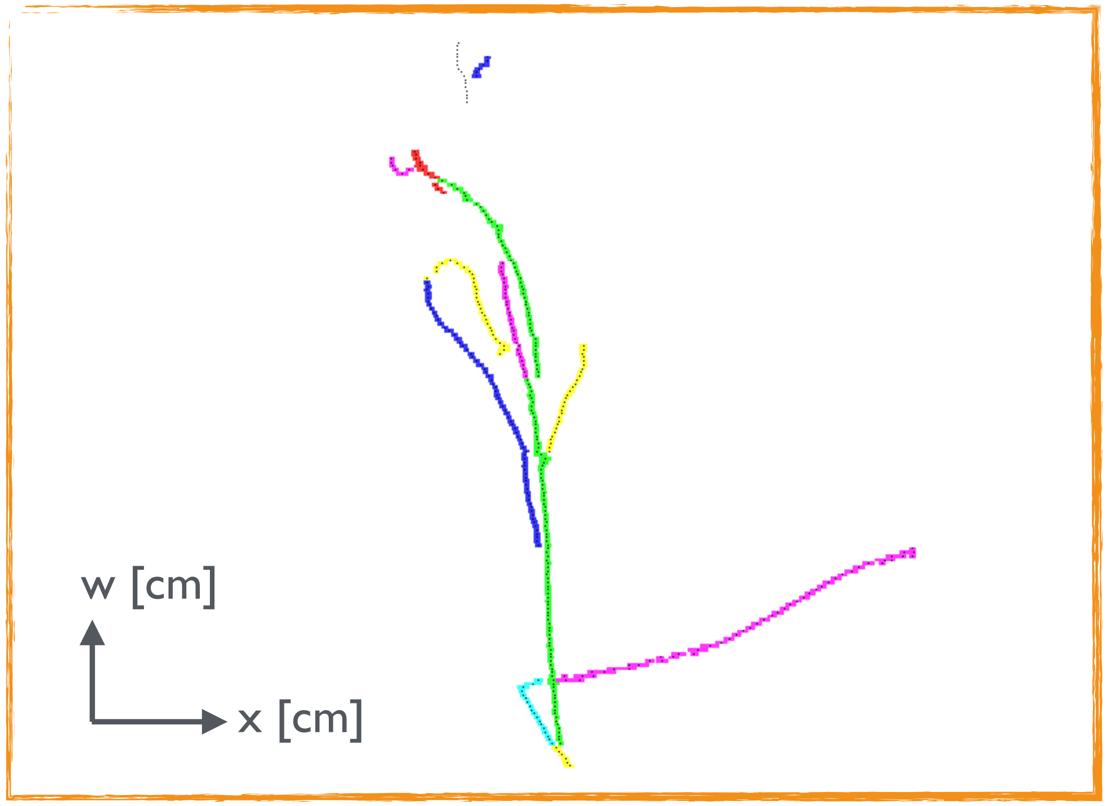


Neutrino Reconstruction

- **Must be able to deal with presence of any cosmic-ray muon remnants.**
  - Run fast version of reconstruction, up to 3D hit creation
  - "Slice" 3D hits into separate interactions, processing each slice in isolation.
  - Each slice ⇒ candidate neutrino particle.

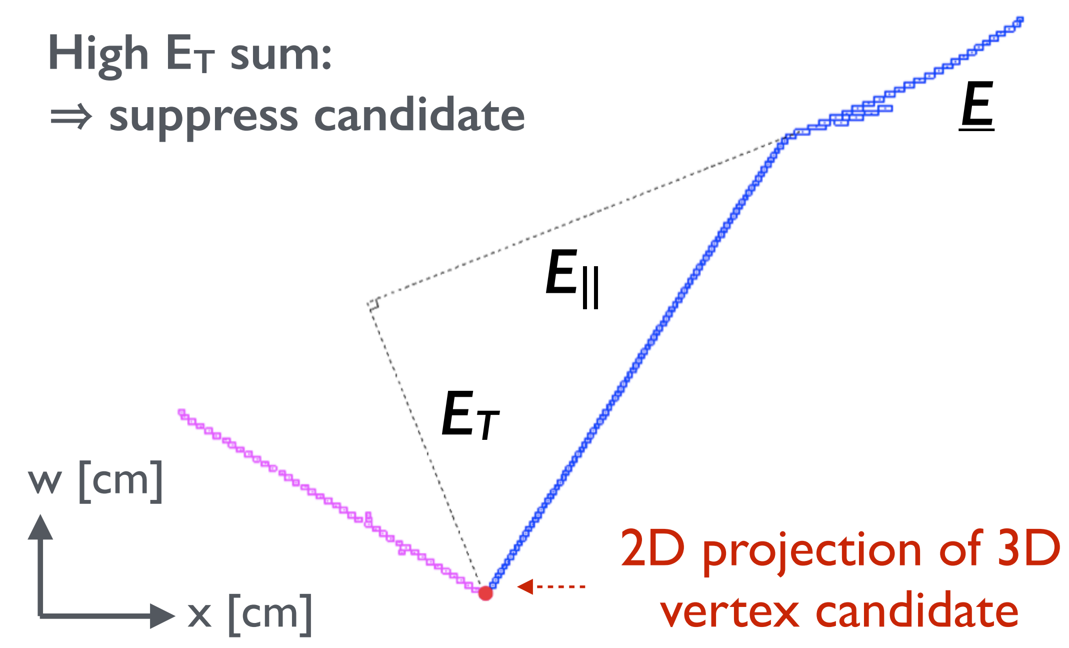


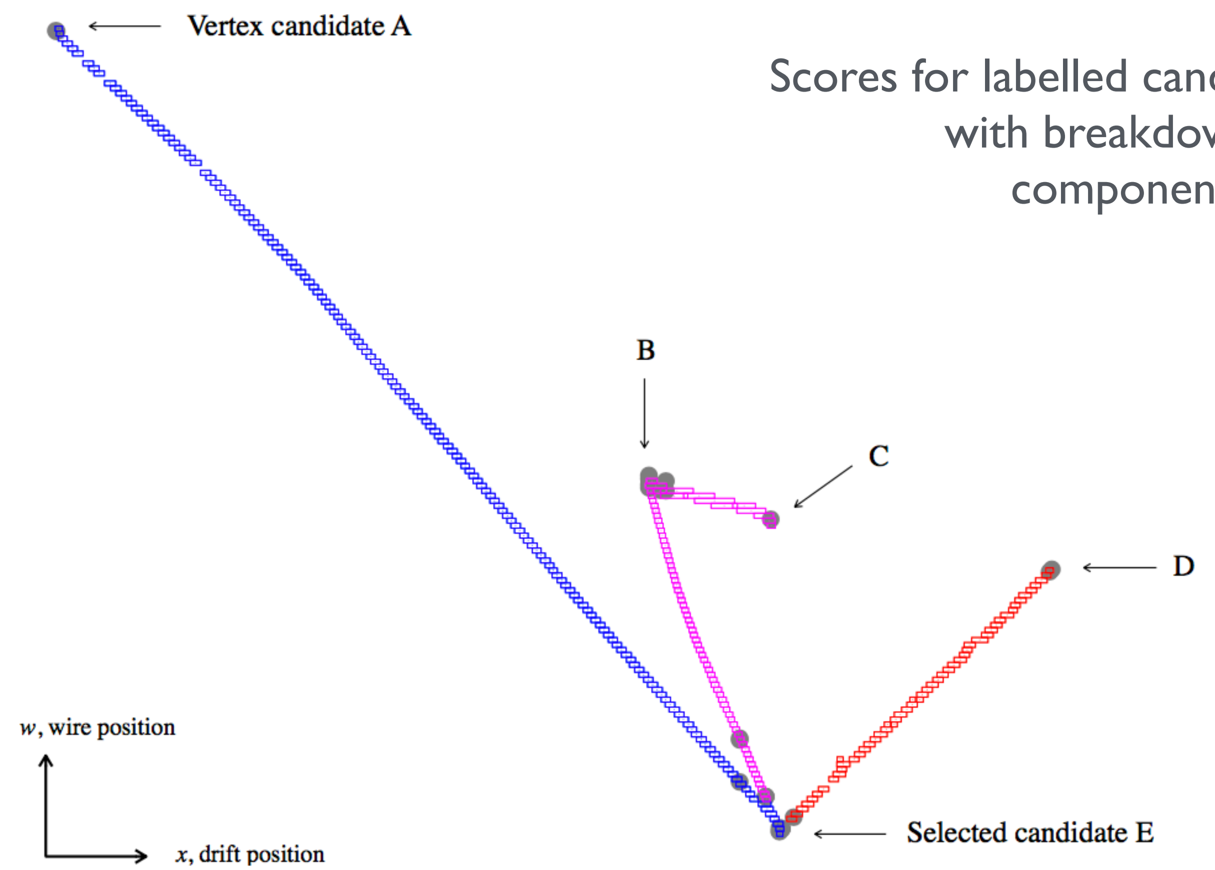
- **Neutrino pass reuses track-oriented clustering and topological association.**
  - Topological association algs must handle rather more complex topologies.
  - Specific effort to reconstruction neutrino interaction vertex.
  - More sophisticated efforts to reconstruct showers.



Search for neutrino interaction vertex:

1. Use pairs of 2D clusters to produce list of possible 3D vertex candidates.
2. Examine candidates, calculate a score for each and select the best.





Scores for labelled candidates, with breakdown into component parts:

Candidate	S	$S_{\text{energy kick}}$	$S_{\text{asymmetry}}$	$S_{\text{beam deweight}}$
A	4.9E-07	3.5E-06	1.00	0.14
B	1.3E-02	3.1E-02	0.99	0.42
C	1.1E-03	2.4E-03	0.95	0.46
D	5.7E-10	1.1E-09	1.00	0.52
E	9.0E-01	9.0E-01	1.00	0.99

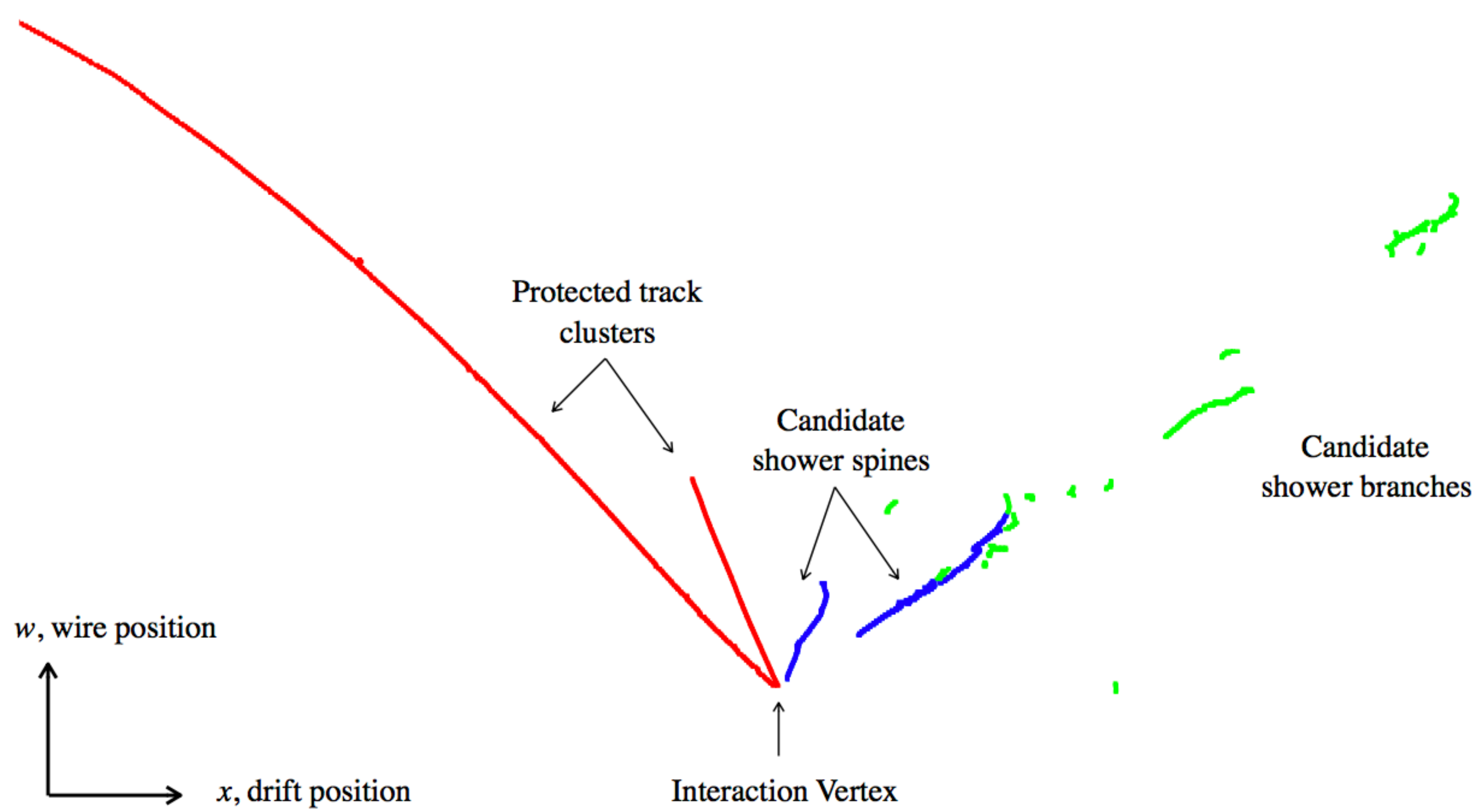
Downstream usage:

- Split 2D clusters at projected vertex position.
- Use vertex to protect primary particles when growing showers.

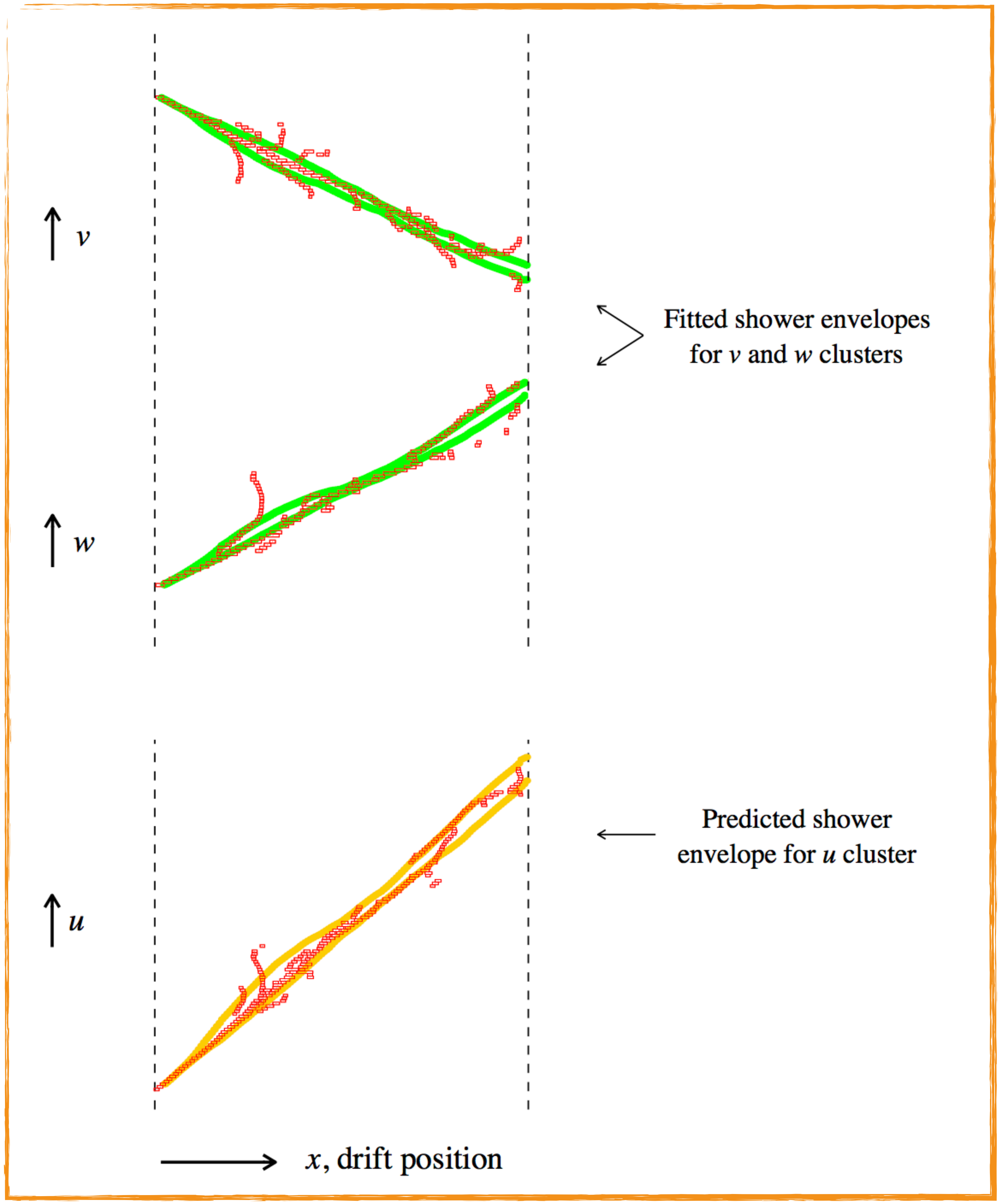
Shower Reconstruction - 2D

Track reconstruction exactly as in PandoraCosmic, but now also attempt to reconstruct primary electromagnetic showers, from electrons and photons:

- Characterise 2D clusters as track-like or shower-like, and use topological properties to identify clusters that might represent shower spines.
- Add shower-like branch clusters to shower-like spine clusters. Recursively identify branches on the top-level spine candidate, then branches on branches, etc.



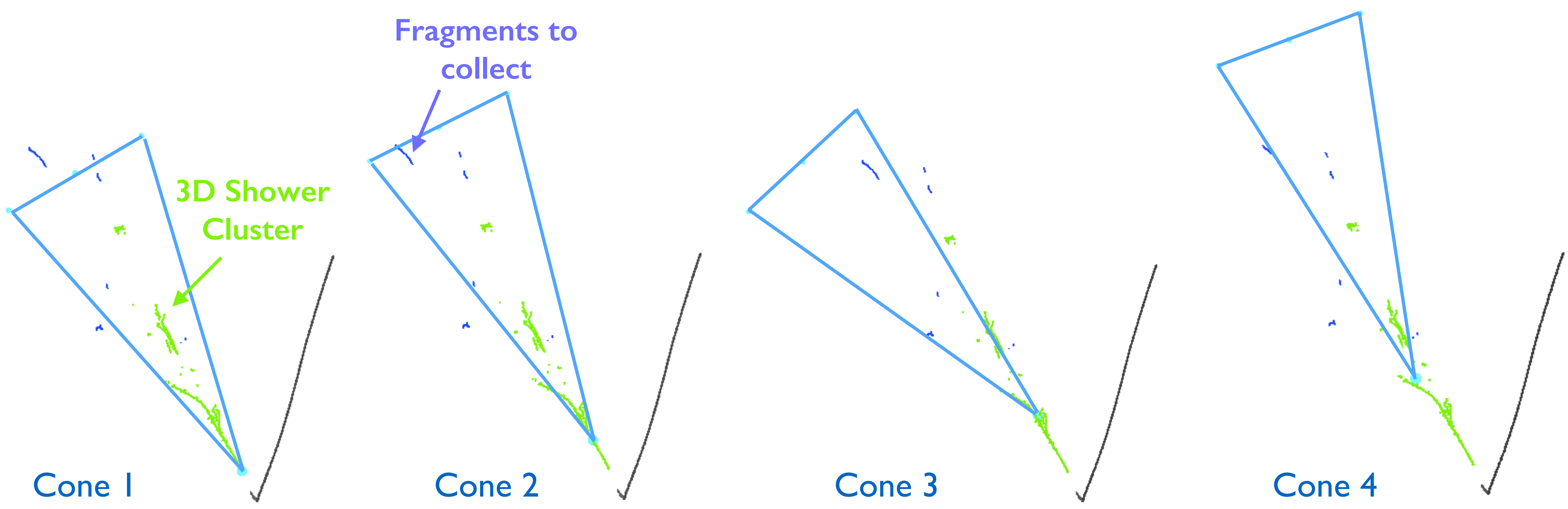
- **Reuse ideas from track reco to match 2D shower clusters between views:**
  - Build a tensor to store cluster overlap and relationship information.
  - Overlap information collected by fitting shower envelope to each 2D cluster.
  - Shower edges from two clusters used to predict envelope for third cluster.



Particle Refinement - 2D, 3D

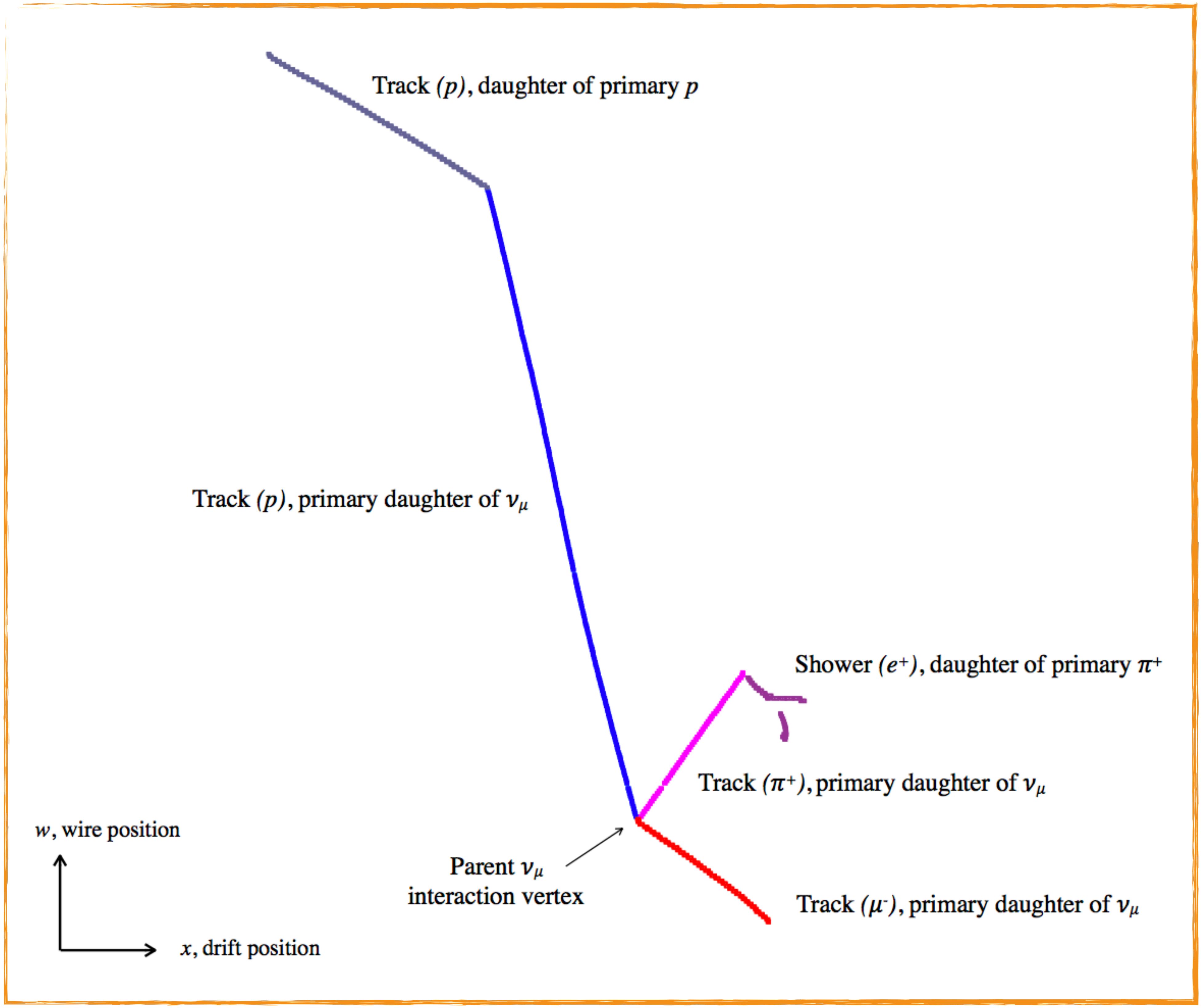
Series of algs deal with remnants to improve particle completeness (esp. sparse showers):

- Pick up small, unassociated clusters bounded by the 2D envelopes of shower-like particles.
- Use sliding linear fits to 3D shower clusters to define cones for merging small downstream shower particles, or picking up additional unassociated clusters.
- If anything left at end, dissolve clusters and assign hits to nearest shower particles in range.



Particle Hierarchy Reconstruction - 3D

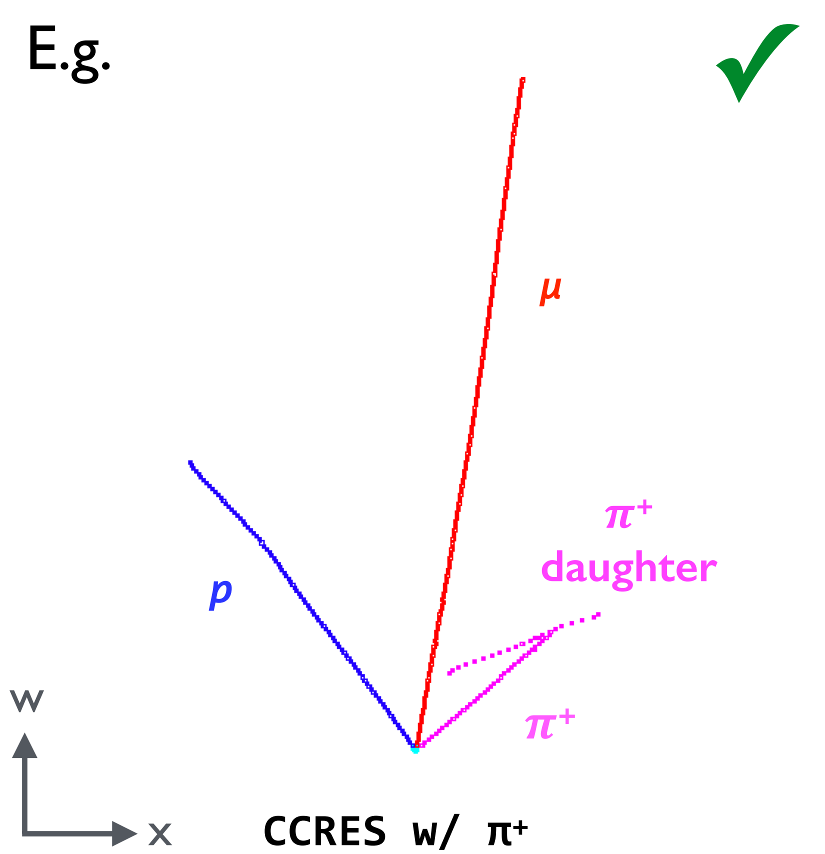
Finally, use 3D clusters to organise particles into a **hierarchy**, working outwards from 3D interaction vertex.

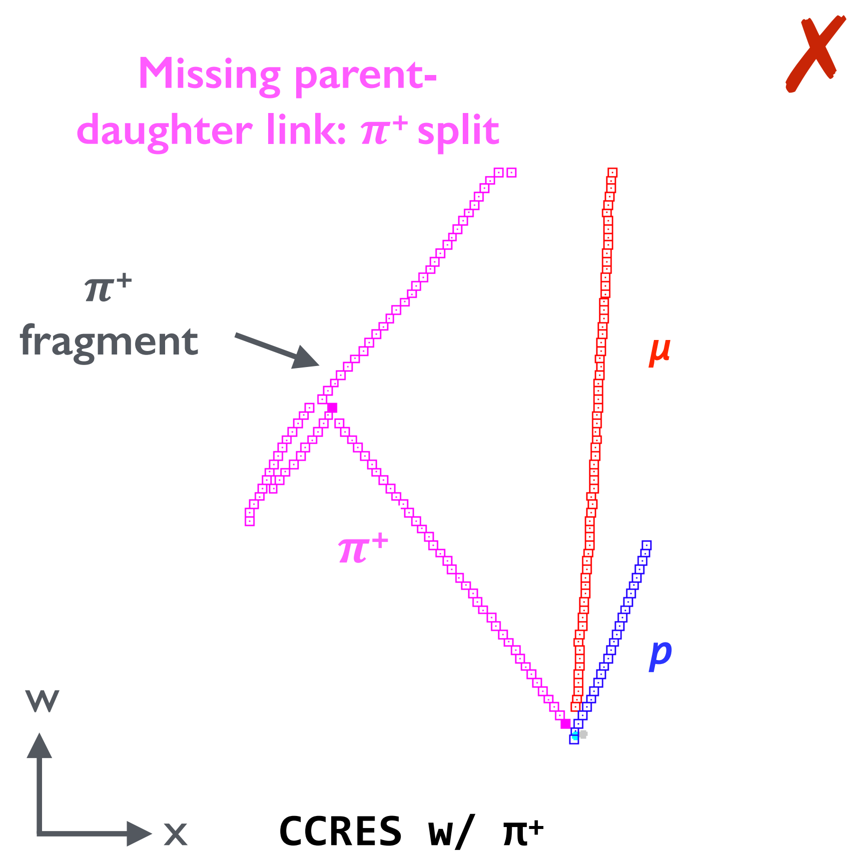


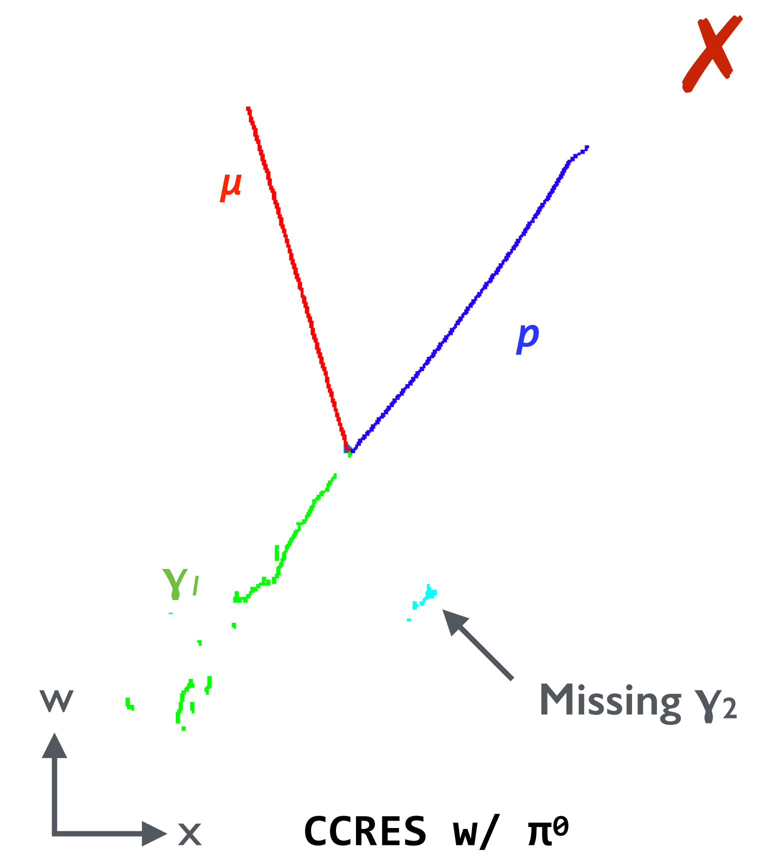
Pandora Performance Metrics

- Assess performance for simulated **MicroBooNE** events, using a selection of event topologies.
- Results published in **EPJC (2018) 78:82** and showcase v03.02.00 of LArTPC algs (Feb 2017).
- Examine fraction of events deemed “correct” by our ***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.







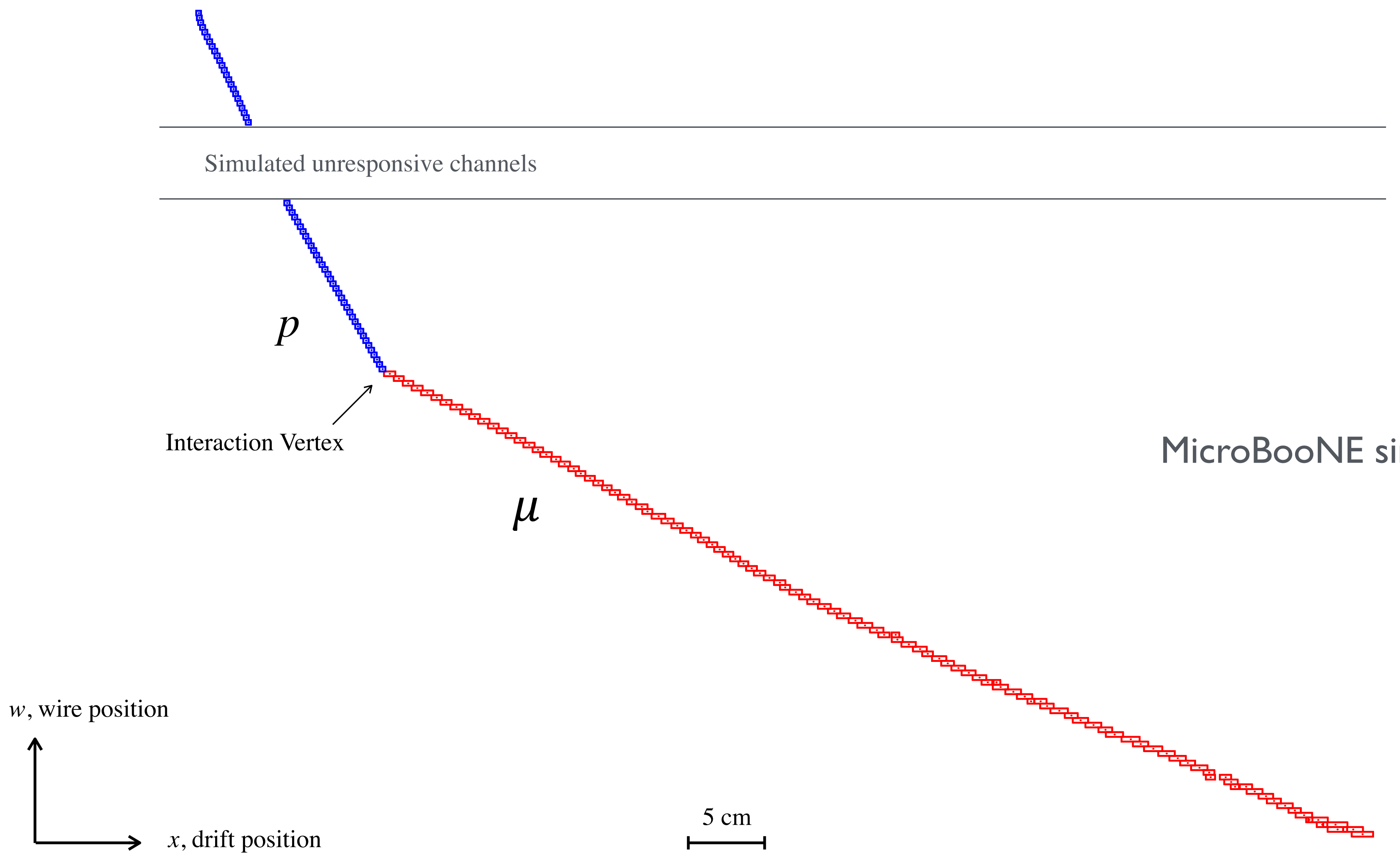
BNB CC QE: $\nu_\mu + \text{Ar} \rightarrow p + \mu^-$

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

No cosmic rays yet

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

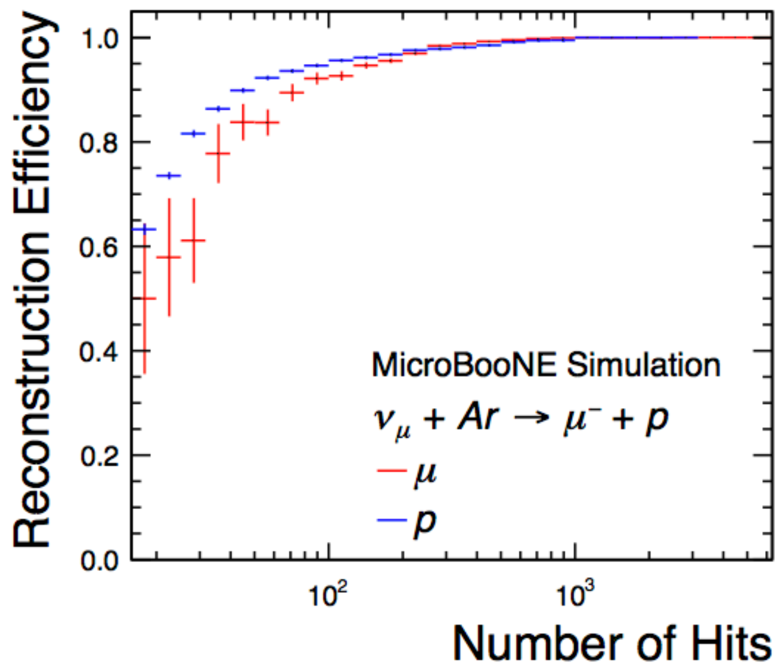
53,168 events, 86.0% have exactly one reco particle matched to each target.

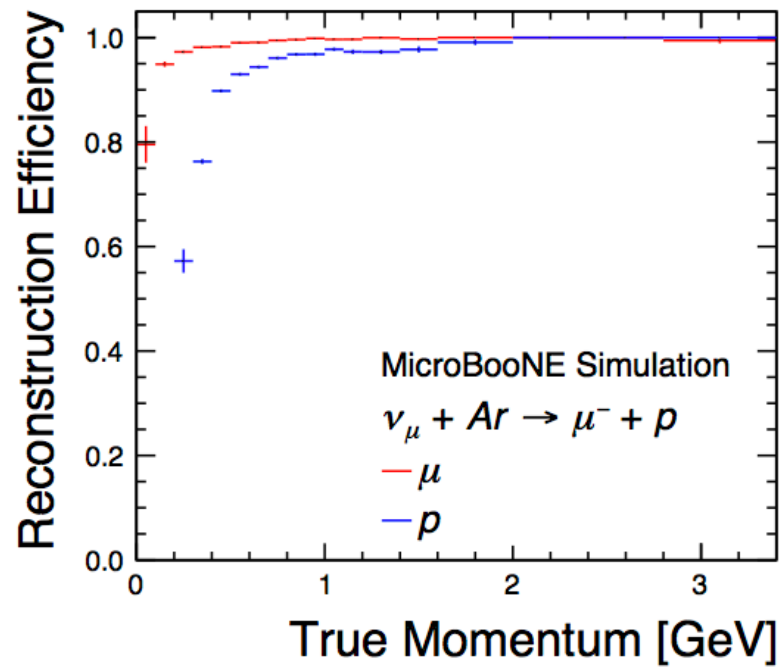


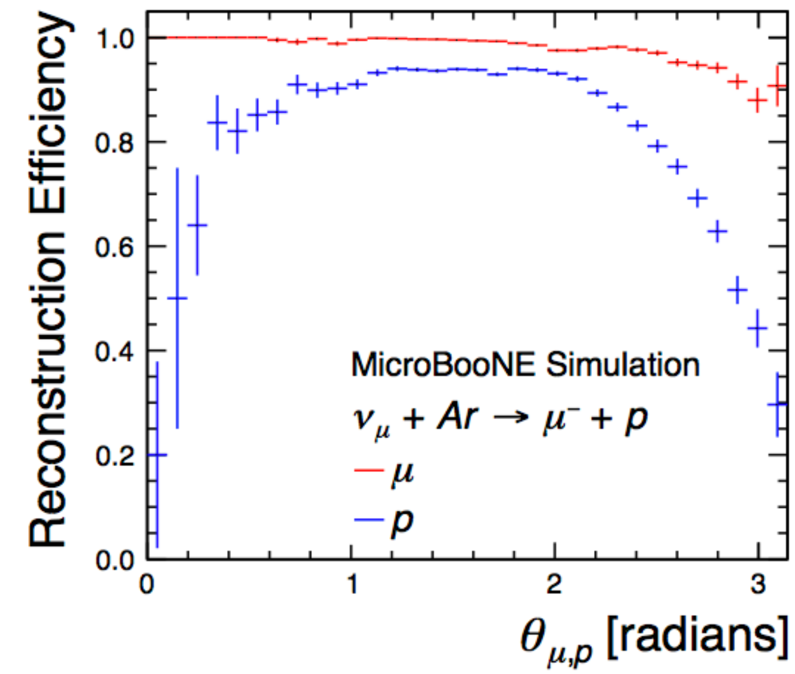
MicroBooNE simulation

520 MeV ν_μ

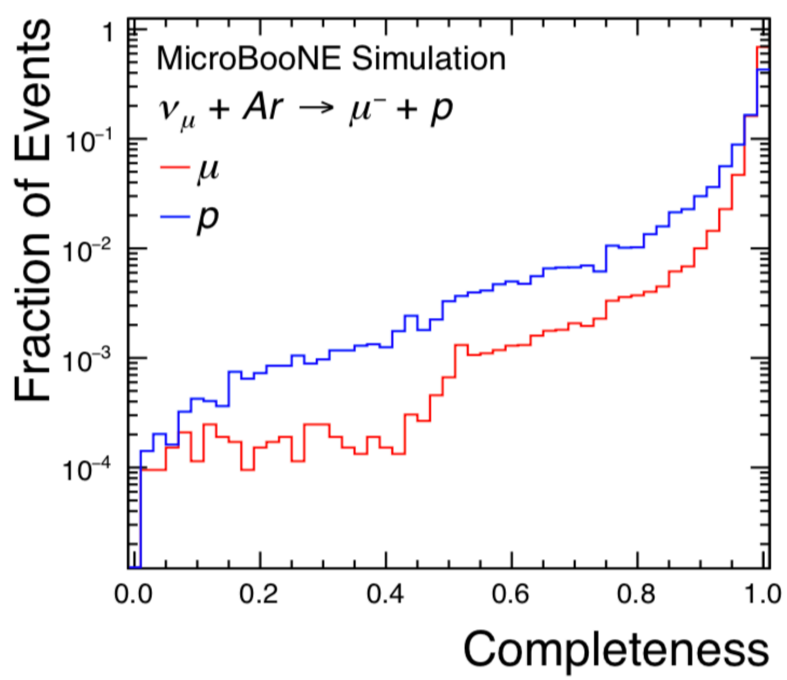
BNB CC QE: $\nu_\mu + Ar \rightarrow p + \mu^-$

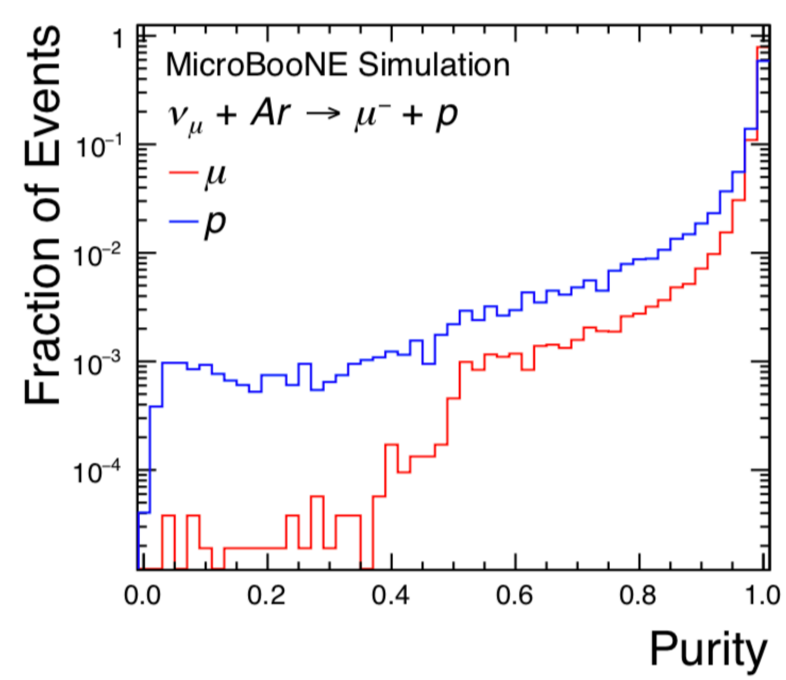




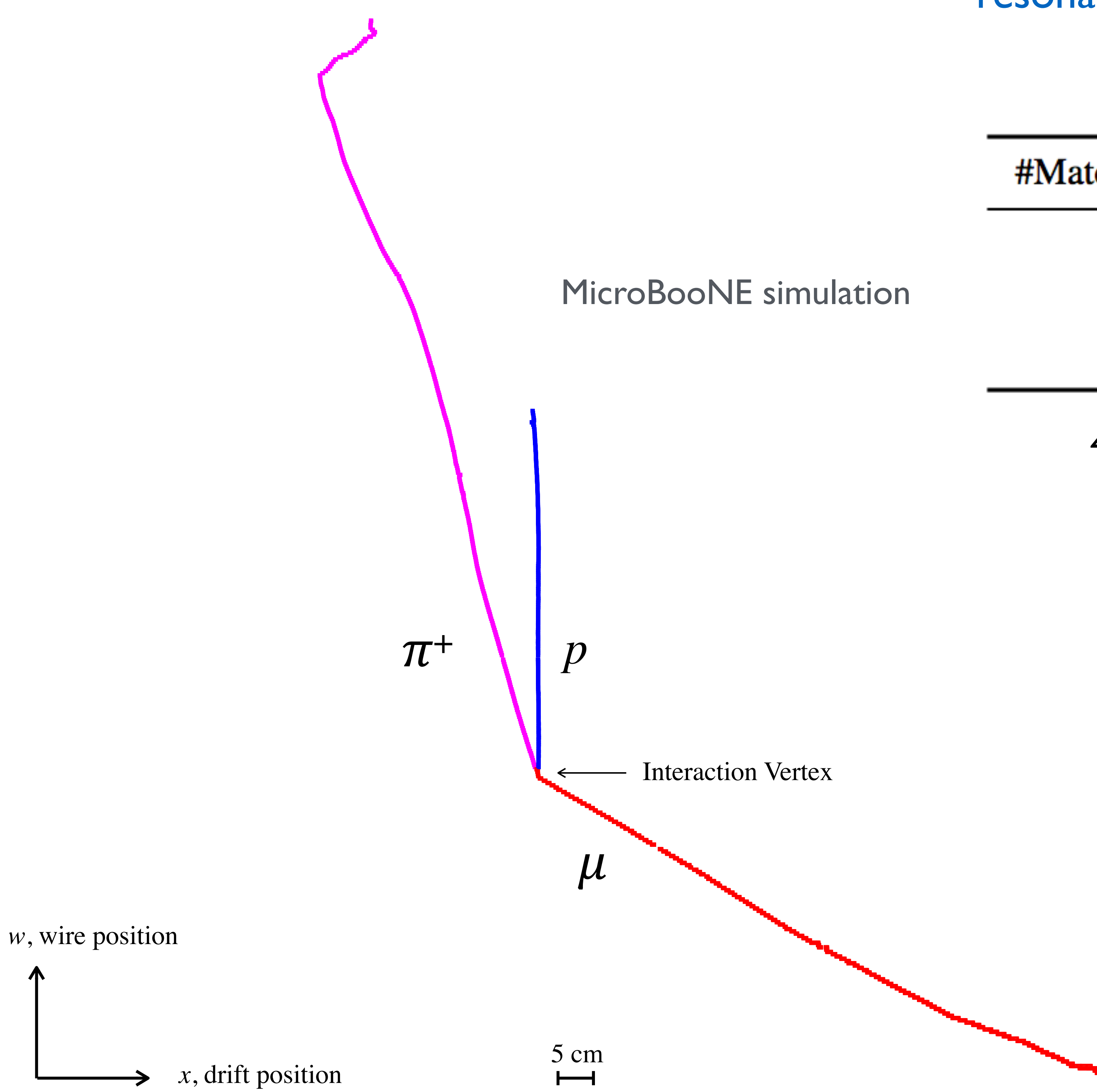


- The most common failure mechanism is merging muon and proton into a single reconstructed particle.
- Single particle is matched to target with which it shares most hits, which will preferentially be the muon.





BNB CC RES: $\nu_\mu + Ar \rightarrow \mu^- + p + \pi^+$



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

#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.

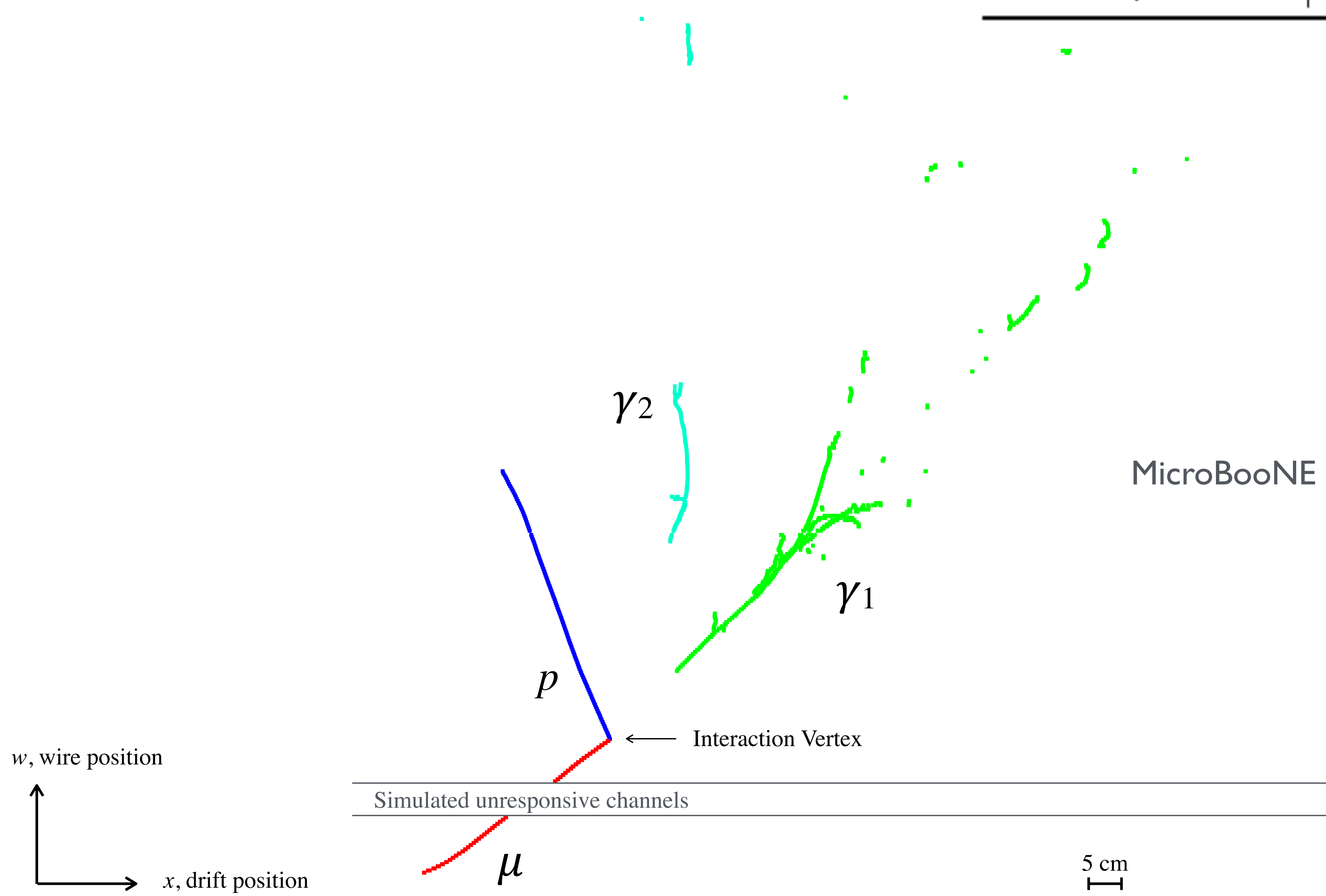
1.1 GeV ν_μ

Two-photon topology: CC ν_μ interactions with resonant 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

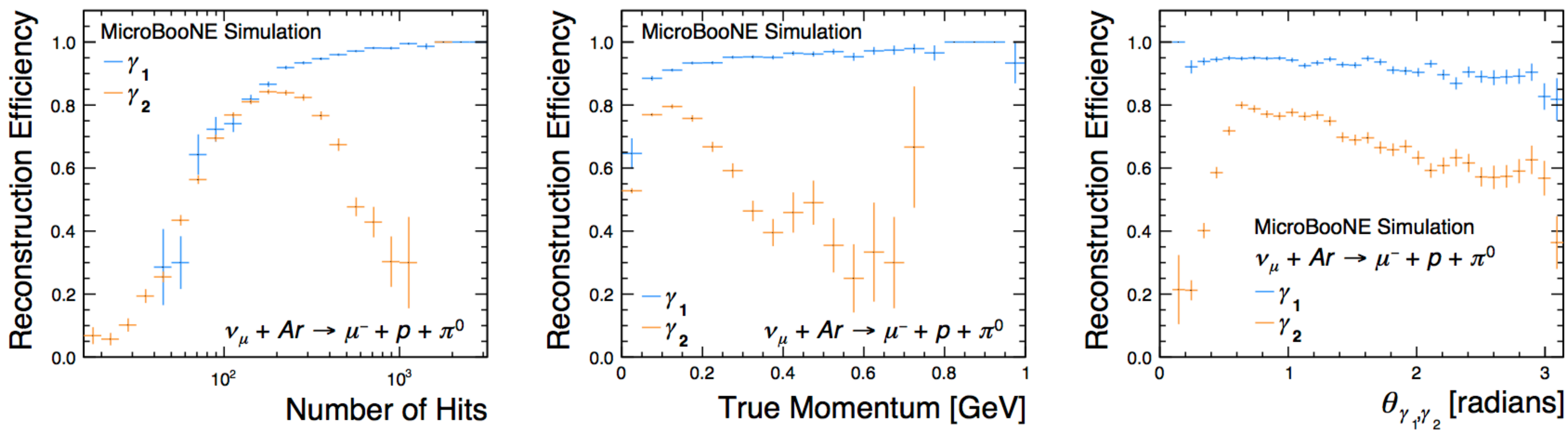


MicroBooNE simulation

1.4 GeV ν_μ

BNB CC RES: $\nu_\mu + Ar \rightarrow \mu^- + p + \pi^0$

#hits γ_1 > #hits γ_2



- Performance for muons and protons essentially as seen before.
- Efficiency for γ_1 (larger shower) rises with number of true hits. Efficiency for γ_2 initially shows same rise, but then falls away as the two showers are frequently merged into a single particle, matched to γ_1
- Efficiency for γ_2 very low when opening angle between photons is small and showers coincident. Then rises as opening angle increases and showers appear as separate entities; maximal for angle of ~36°

Selection of Exclusive Final States

- Assess larger selection of exclusive final states using correct event fraction.
- Fraction of events w/ exactly one reco particle matched to each target MCParticle.

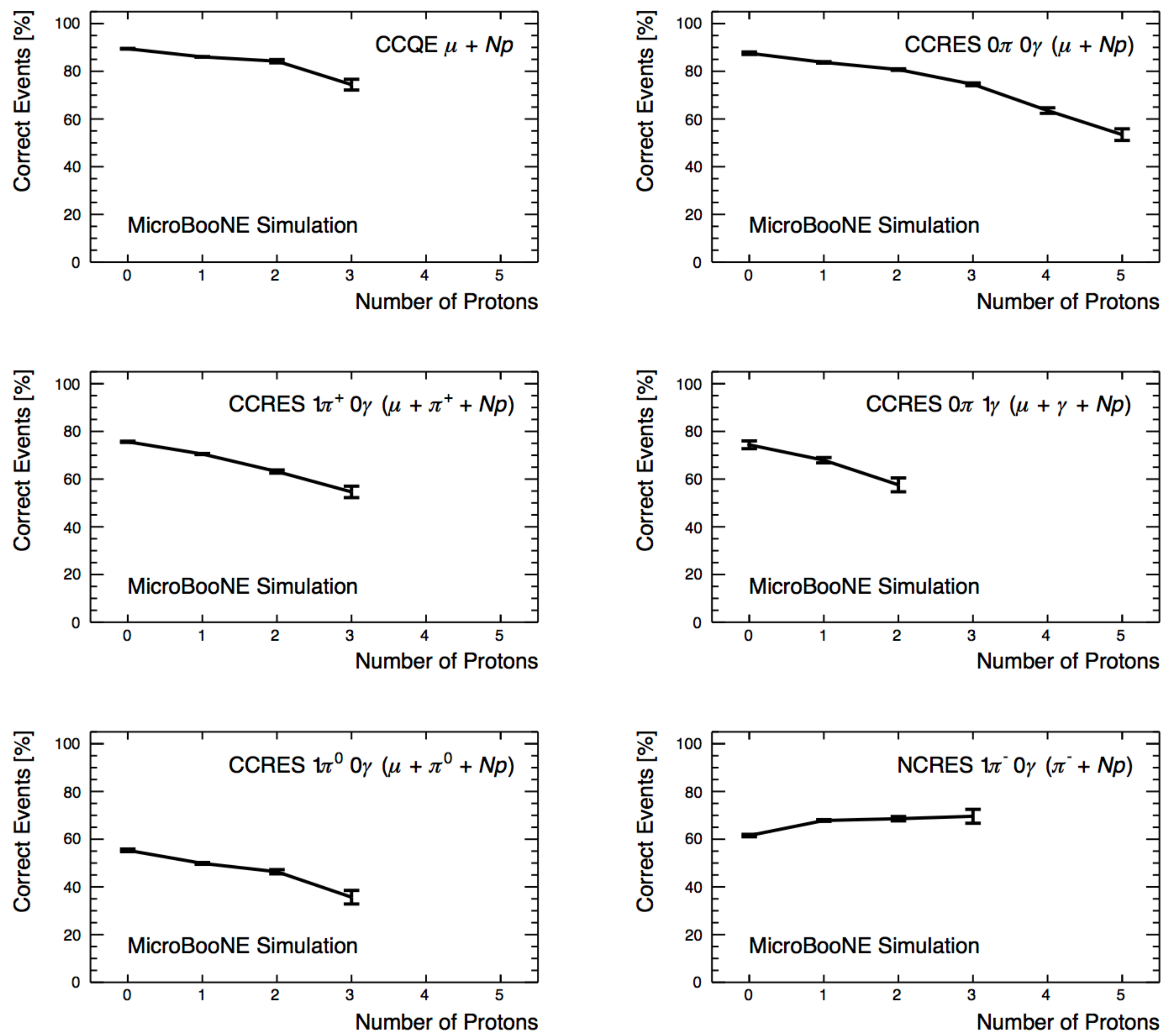


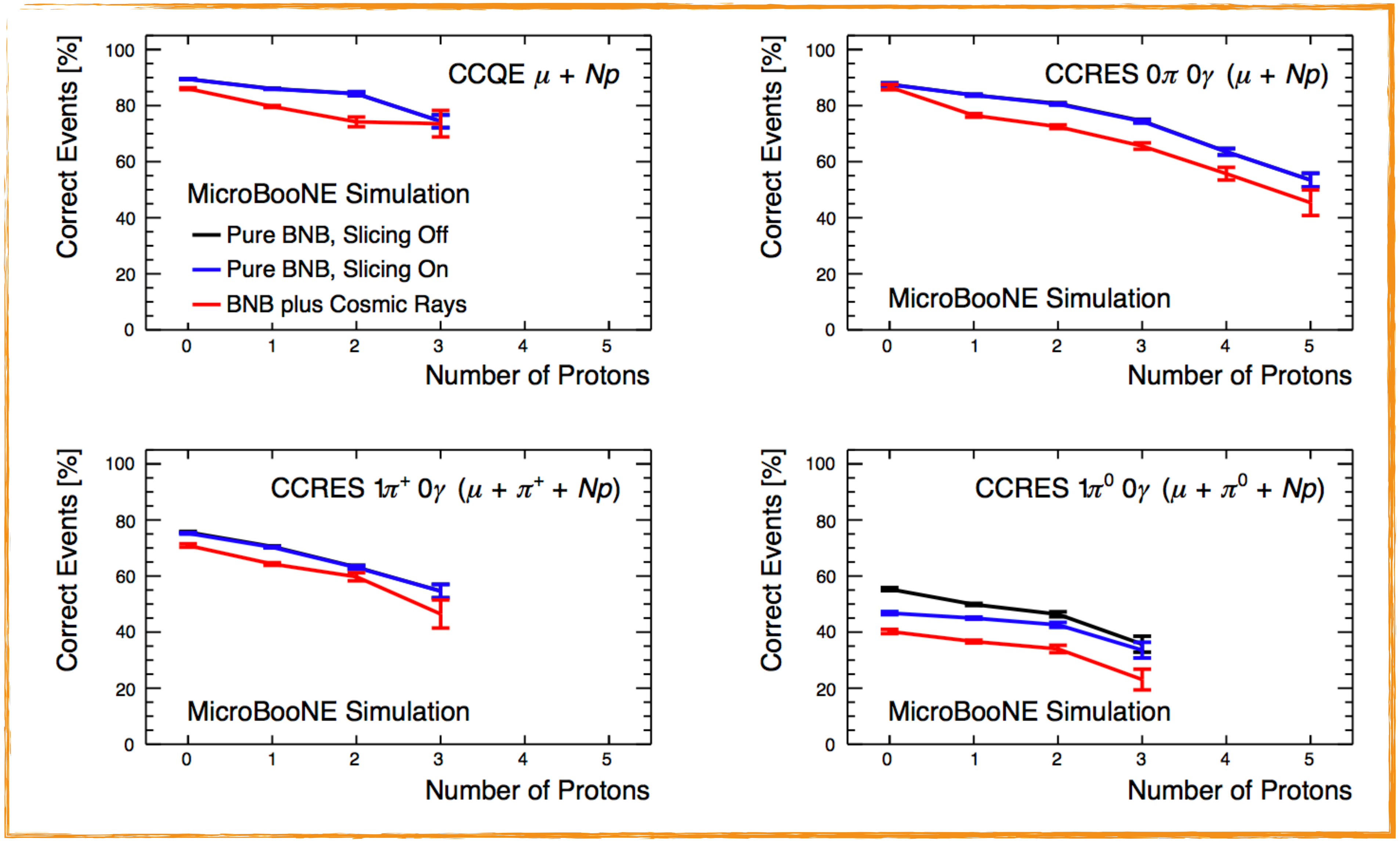
Fig. 19: The fraction of events deemed to have correct pattern recognition, shown for a selection of different BNB interactions with exclusive final states. For each interaction type (and combination of final-state leptons, pions or photons), the correct event fraction is displayed as a function of the number of final-state protons. Correct events are those deemed to have exactly one reconstructed particle matched to each target MCParticle.

Impact of Cosmic-Ray Muon Background

CCQE	μ (5.9 ± 0.2)%	$\mu + 1p$ (7.7 ± 0.2)%	$\mu + 2p$ (10.5 ± 1.2)%
CCRES $0\pi\ 0\gamma$	μ (5.1 ± 0.6)%	$\mu + 1p$ (8.2 ± 0.4)%	$\mu + 2p$ (10.1 ± 0.4)%
CCRES $1\pi^+\ 0\gamma$	$\mu + \pi^+$ (8.6 ± 0.4)%	$\mu + \pi^+ + 1p$ (10.3 ± 0.3)%	$\mu + \pi^+ + 2p$ (11.1 ± 0.9)%
CCRES $1\pi^0\ 0\gamma$	$\mu + \pi^0$ (15.0 ± 0.5)%	$\mu + \pi^0 + 1p$ (15.4 ± 0.3)%	$\mu + \pi^0 + 2p$ (17.8 ± 1.0)%

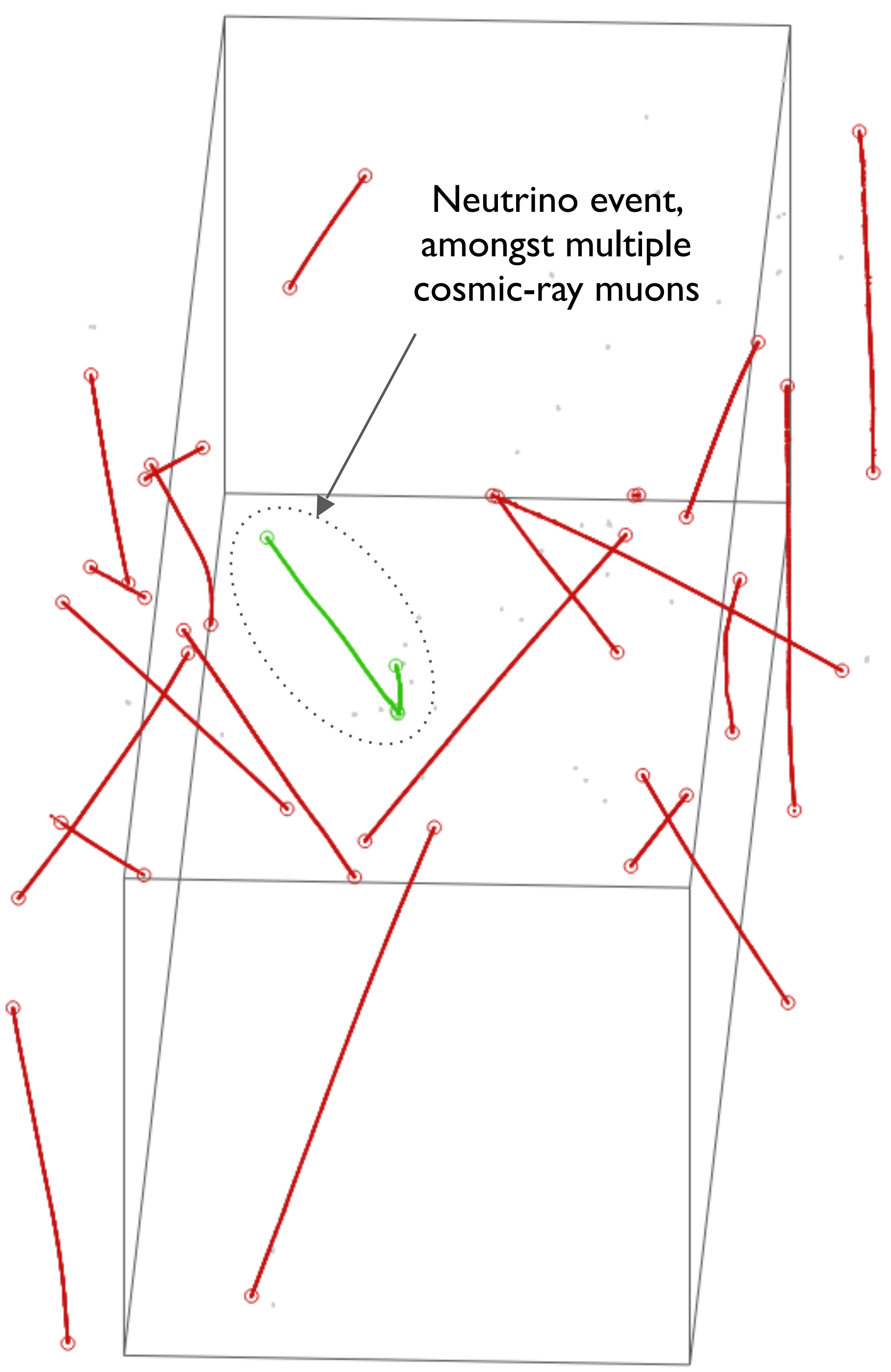
- Fraction of events damaged by cosmic-ray muon removal, for BNB interactions with exclusive final states.
- Damaged: >10% of neutrino-induced hits removed, or sufficient hits removed to change identification of target particles.

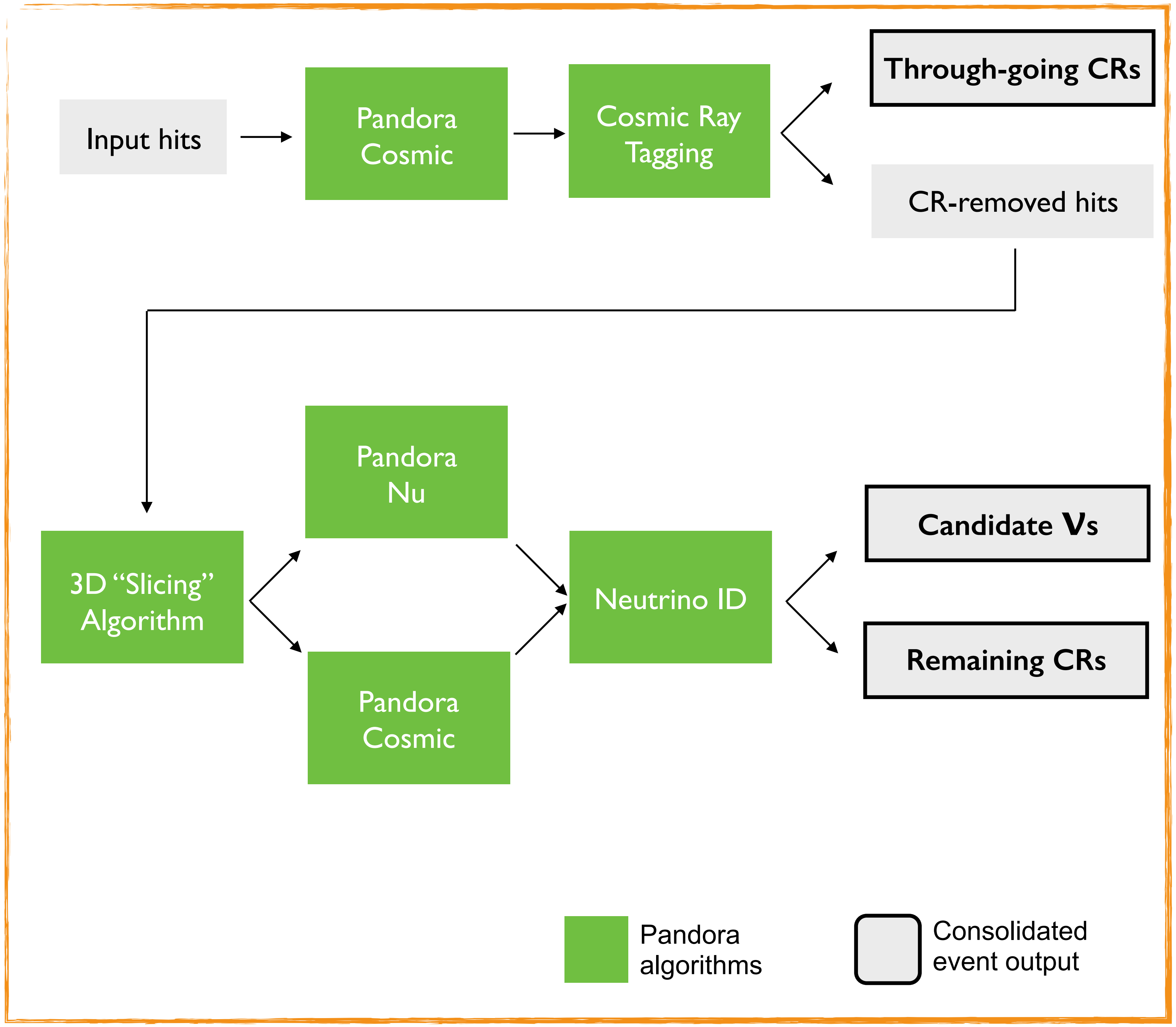
- Correct event fractions for different configurations:
- Slicing splits-up some sparse showers, harming π^0 reco.
- CR remnants cause confusion and degrade performance.



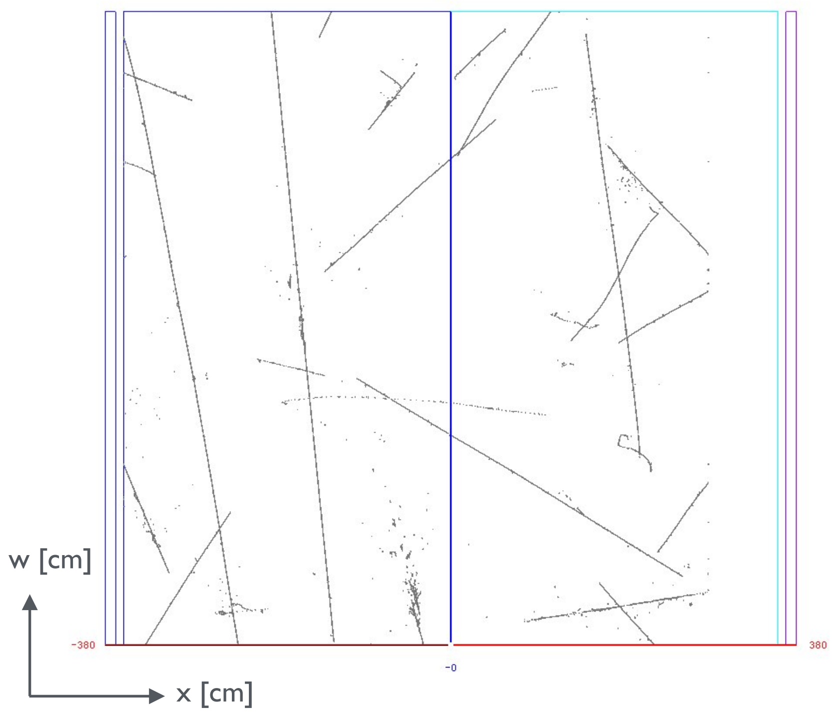
Consolidated Event Reconstruction

Current development: single, consolidated reconstruction with one (or zero) neutrino and *N* cosmic-ray muons. Compare neutrino and CR outcomes for all slices and choose best.



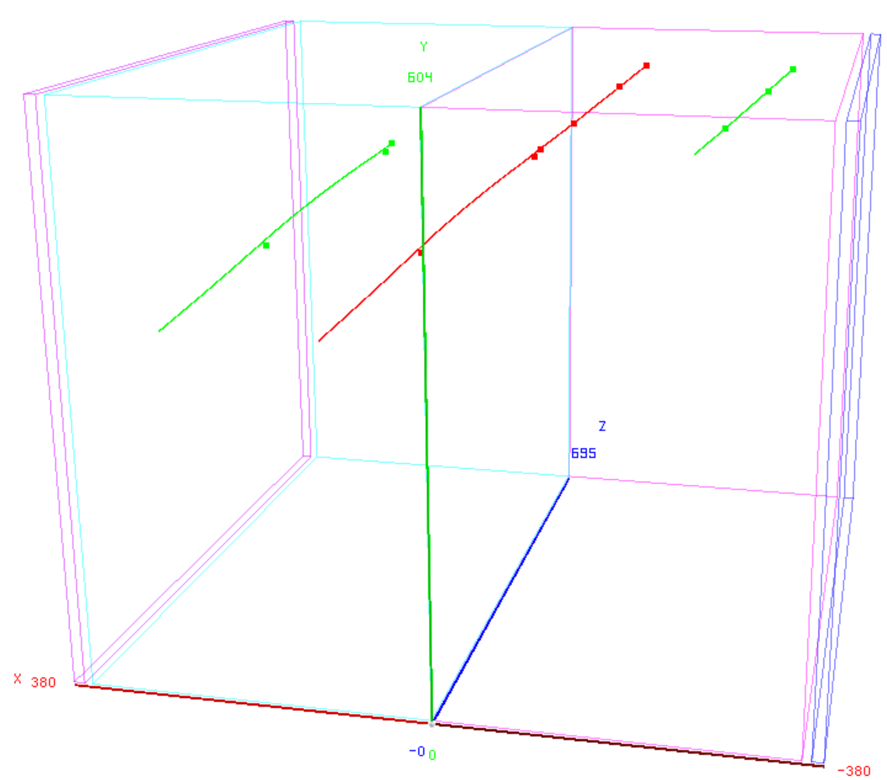


Application to ProtoDUNE SP

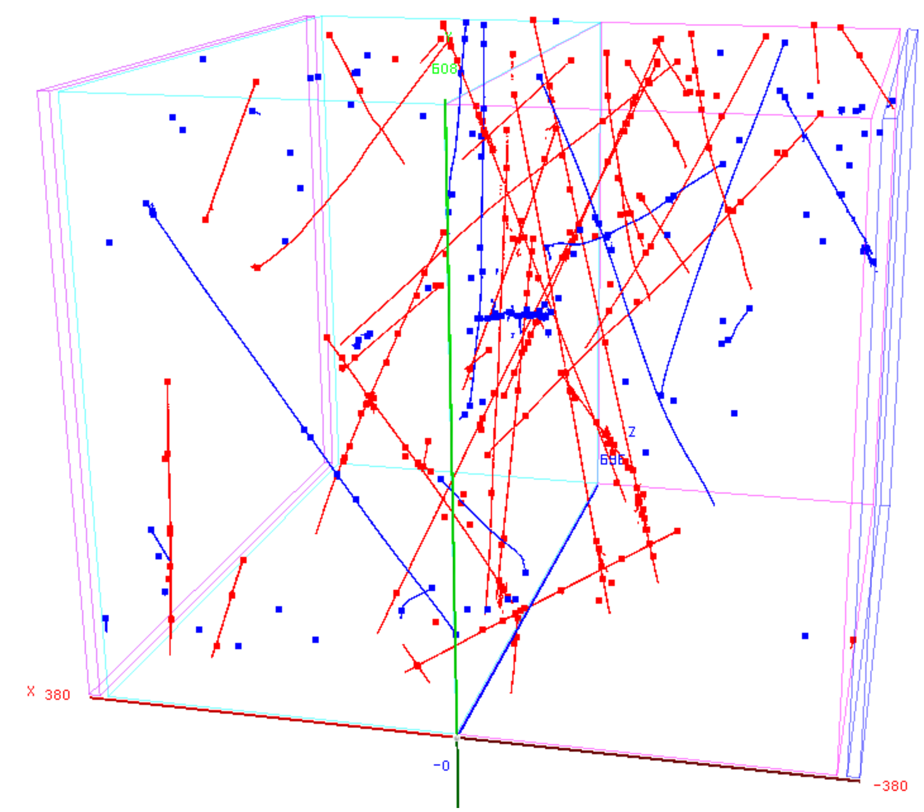


Single Phase DUNE Far Detector prototype, to be exposed to test beam at CERN. Multiple "volumes" and CR backgrounds; an ideal testing ground for PatRec

1. Independent cosmic-ray pass for each volume; readout time ⇒ image "wider" than physical volume

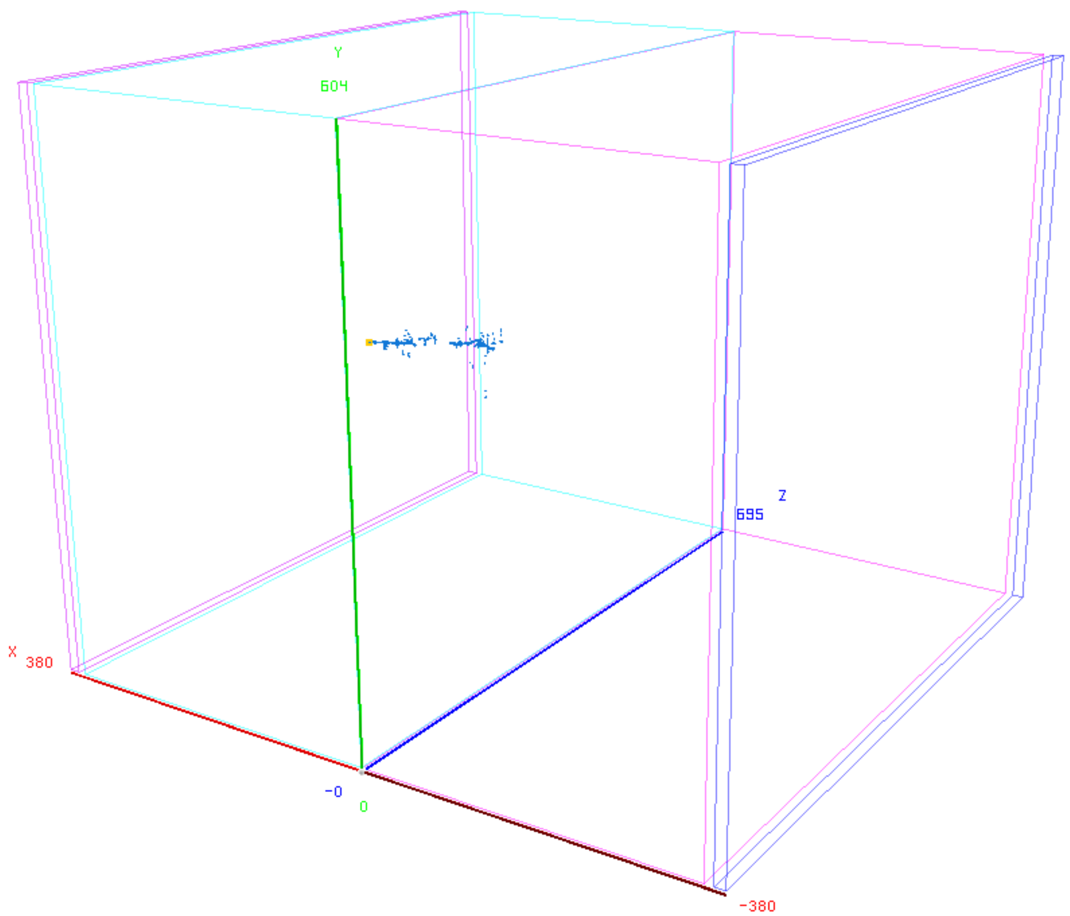


2. Stitch together any cosmic rays crossing between volumes, identifying "T0"

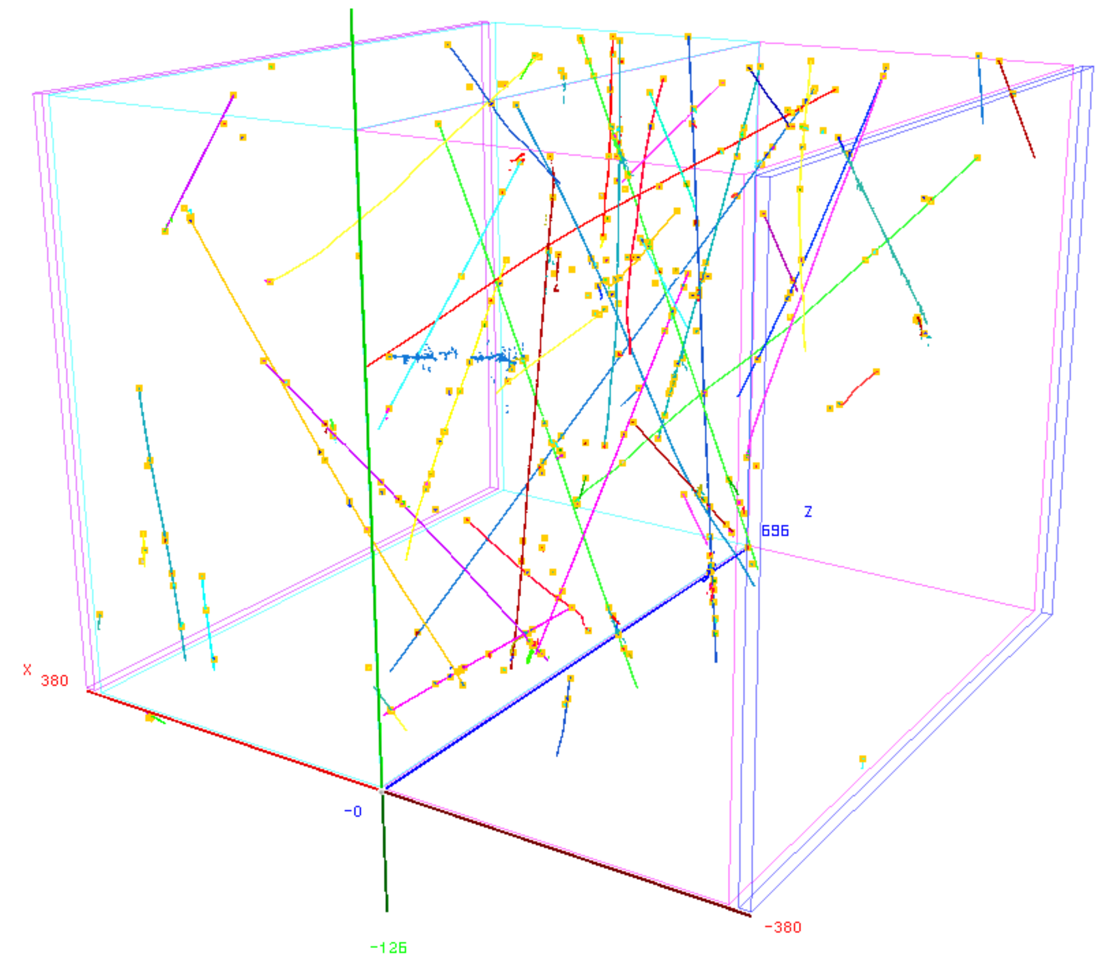


3. Flag clear cosmic rays (red) and hits to examine under both CR and nu hypotheses (blue)

Consolidated Output: ProtoDUNE SP



Output: 1 Beam particle, reconstructed and tagged

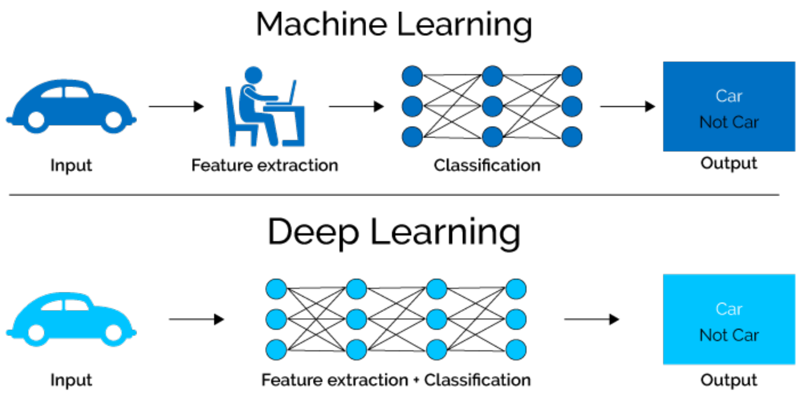


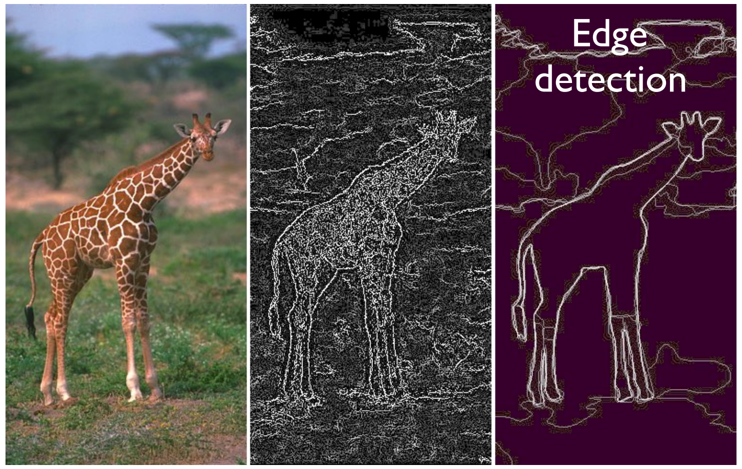
and: N reconstructed cosmic-ray muon hierarchies

Procedure is more involved, but harnesses same cosmic-ray and neutrino PatRec algorithms

Future Development

- **Embrace deep-learning approaches, which should be appropriate for LArTPC image analysis:**
  - Combine power of multi-alg and deep-learning approaches
  - Use deep learning to guide key steps in the Pandora algs
- **Use Pandora in online "fast" reconstruction opportunities, such as high-level software trigger:**
  - Fast PatRec informs decision whether to write out events
  - Pandora intrinsically fast. Reuse skeleton of existing alg chains
- **Image processing/filtering to manipulate LArTPC images prior to feature extraction:**
  - Promising technique, not yet exploited fully for LArTPCs
- **Full exploitation of Pandora for MicroBooNE, SBND, ProtoDUNE and DUNE physics programmes:**
  - Assess performance of existing algs at ProtoDUNE and DUNE
  - Add algs e.g. to handle charged-pion scattering at ProtoDUNE





Summary

- 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.
  - Pandora pattern recognition has been examined for simulated events in MicroBooNE, providing a snapshot of current performance.
  - Exciting prospects for future, via adoption of new algs and techniques.

Thanks for your attention!

Pandora LAr TPC Reconstruction

Pandora is an open project and new contributors would be extremely welcome. We'd love to hear from you and we will always try to answer your questions!

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ProtoDUNE

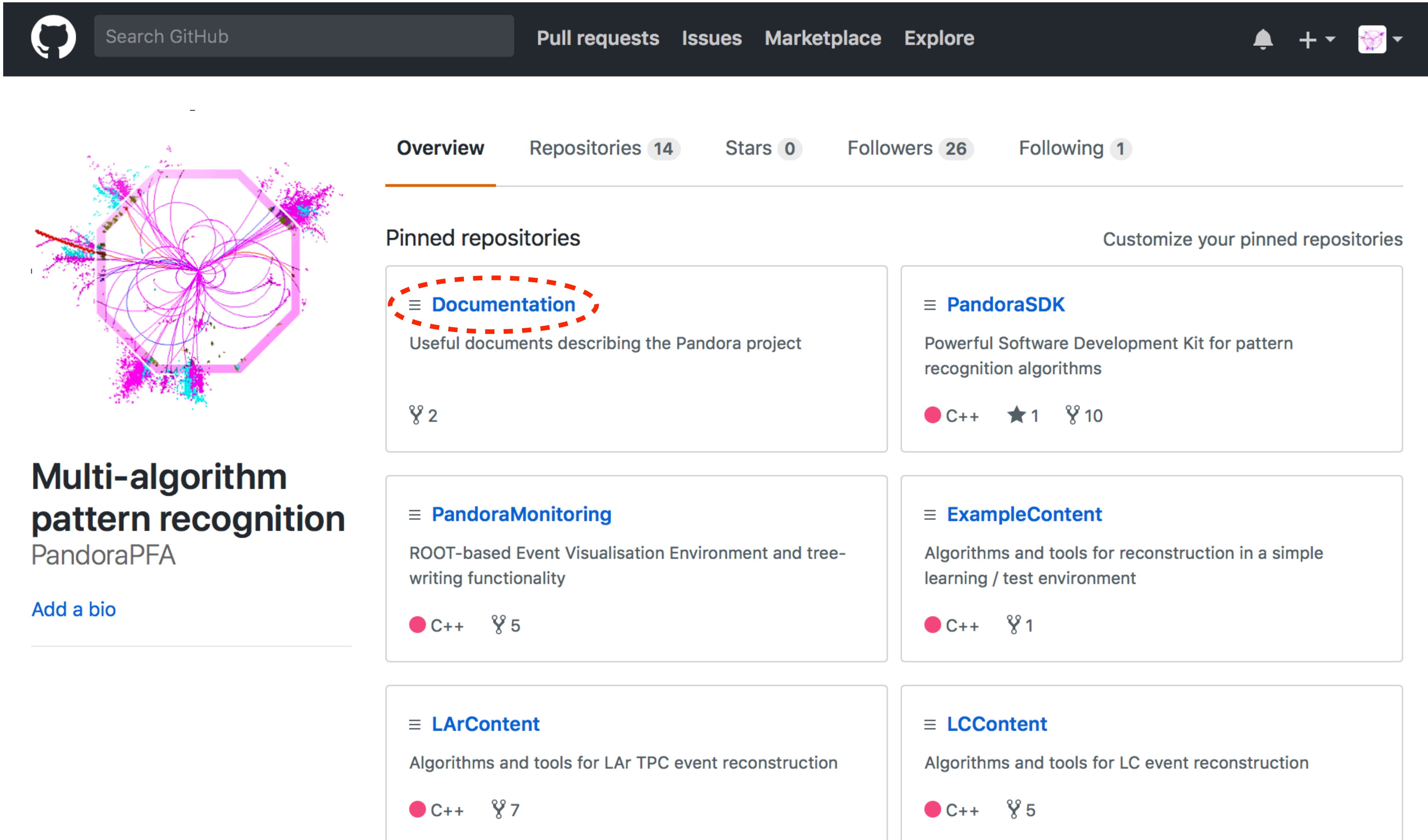
Steven Green (sg568@hep.phy.cam.ac.uk)

Please visit https://github.com/PandoraPFA

UNIVERSITY OF CAMBRIDGE

Lancaster University

https://github.com/PandoraPFA



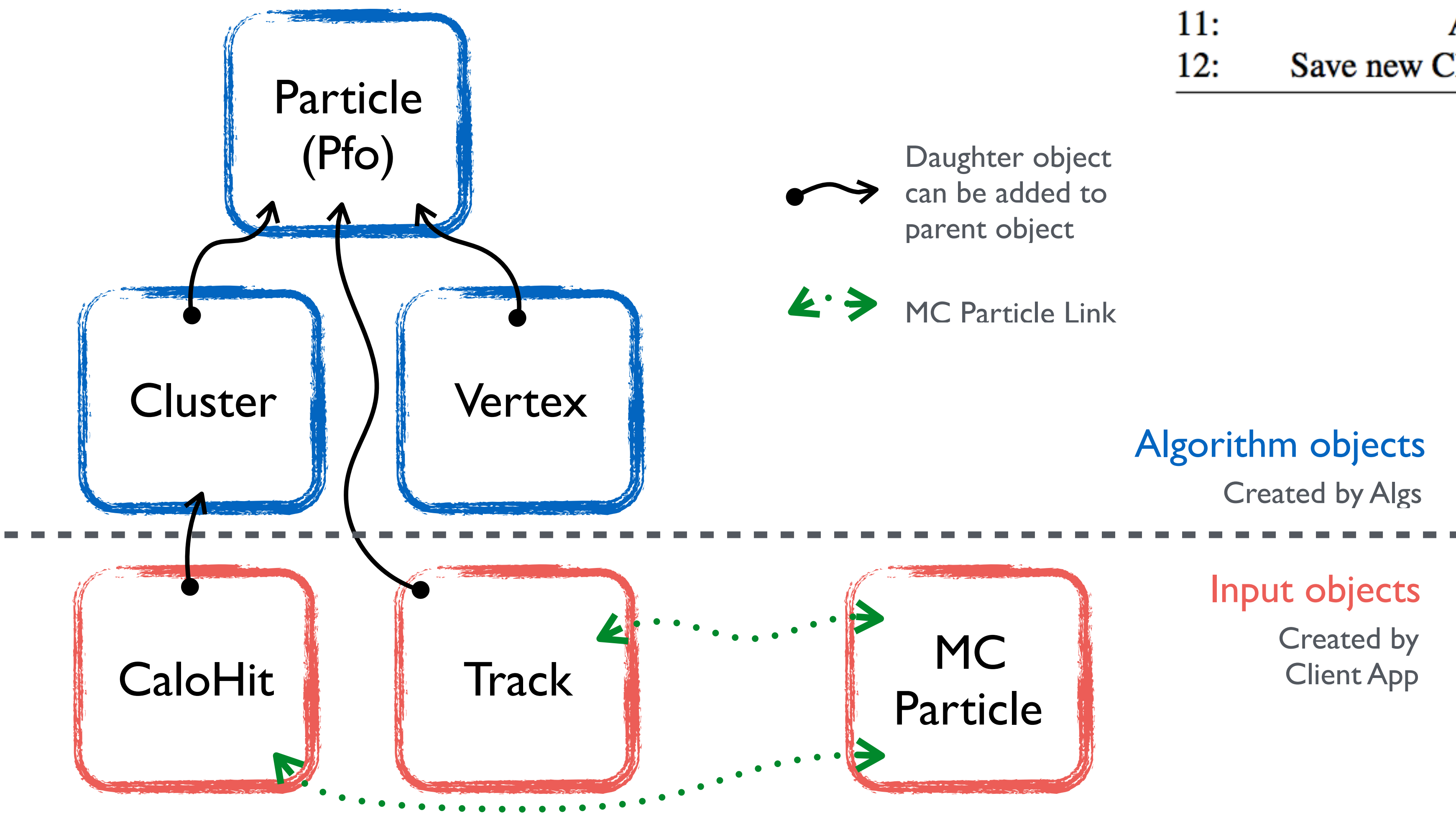
pandora: Algorithms

- Algorithms should contain the high-level logic to find patterns. Concentrate on the important bits: physics/PatRec ideas.
- They use APIs to access objects and to request Pandora to make new objects or modify existing objects (low-level impl.).

Algorithm 1 Cluster creation pseudocode. The logic determining when to create new Clusters and when to extend existing Clusters will vary between algorithms.

```
procedure CLUSTER CREATION
    Create temporary Cluster list
    Get current CaloHit list
    for all CaloHits do
        if CaloHit available then
            for all newly-created Clusters do
                Find best host Cluster
            if Suitable host Cluster found then
                Add CaloHit to host Cluster
            else
                Add CaloHit to a new Cluster
    Save new Clusters in a named list
```

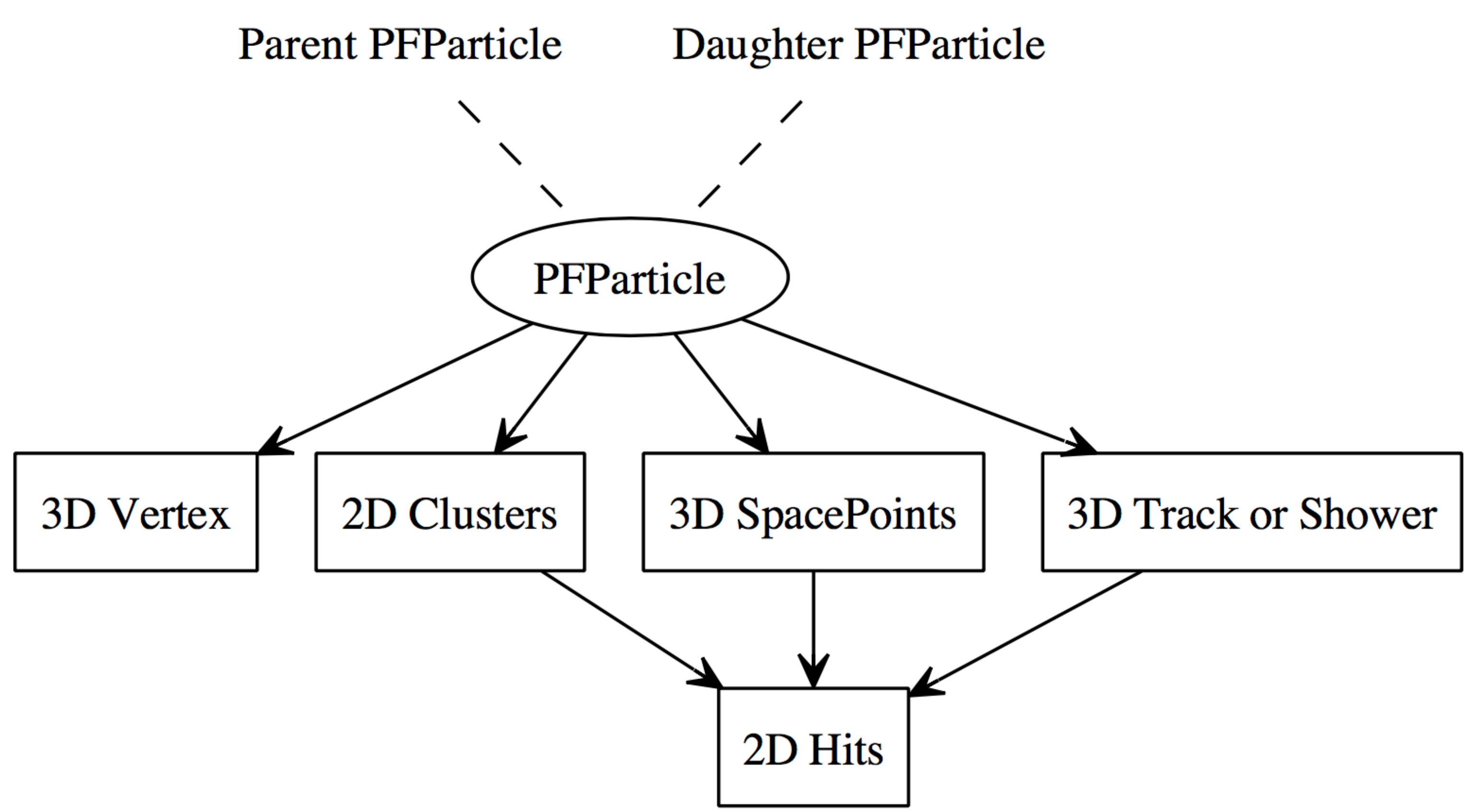
Simplified **algorithm** implementation



Generic, reusable **Event Data Model**

larpandora: Output PFParticles

- **Translate output from Pandora Event Data Model to LArSoft EDM. 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.



Performance Metrics

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.

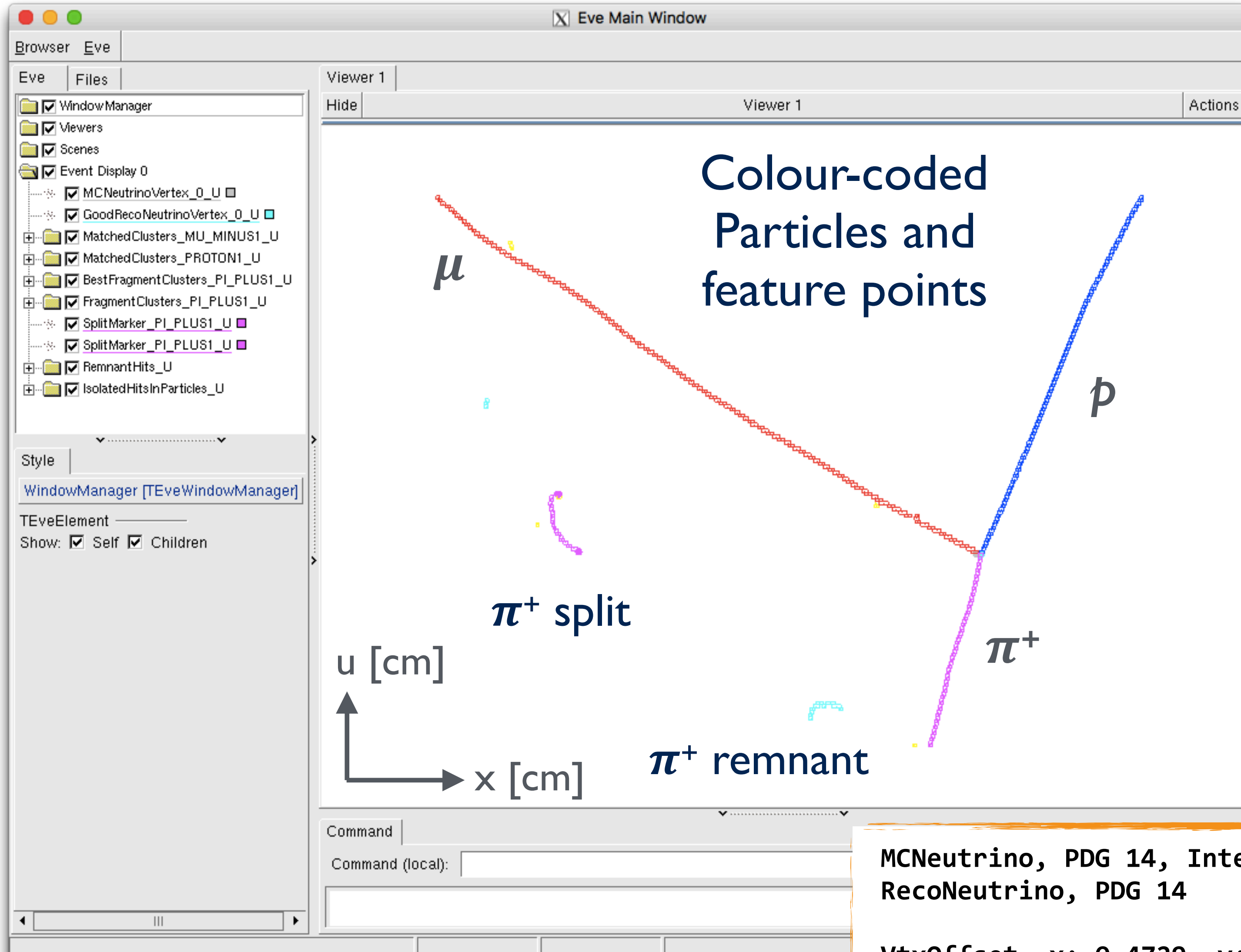
2. Match reco particles to target MCParticles

- 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

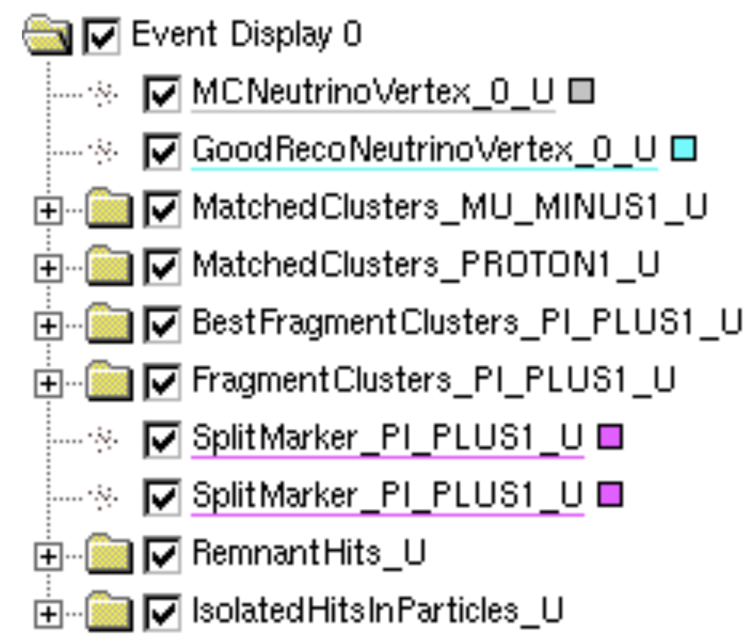
3. Define performance metrics

- 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"**

Pandora Validation Tools



Labels indicate quality of reconstruction.
Can highlight and toggle objects on/off.



Matching terminal output, shows:

- Raw Hit-matching details
- Interpreted matching details
- Requirements to define match

```
MCNeutrino, PDG 14, InteractionType 1003
RecoNeutrino, PDG 14

VtxOffset  x: 0.4729  y: 0.0803757  z: 0.0241699 length: 0.480291

MinPrimaryHits 15, MinSharedHits 5, UseSmallPrimaries 1, MinCompleteness 0.1, MinPurity 0.5

---PROCESSED-MATCHING-OUTPUT---------------------------------------------------------------
Primary 0, PDG 13, nMCHits 505 (124, 149, 232)
-MatchedPfo 0, PDG 13, nMatchedHits 505 (124, 149, 232), nPfoHits 505 (124, 149, 232)

Primary 1, PDG 2212, nMCHits 260 (118, 29, 113)
-MatchedPfo 1, PDG 13, nMatchedHits 257 (118, 27, 112), nPfoHits 257 (118, 27, 112)

Primary 2, PDG 211, nMCHits 260 (100, 92, 68)
-MatchedPfo 2, PDG 13, nMatchedHits 156 (65, 55, 36), nPfoHits 159 (65, 57, 37)
-MatchedPfo 3, PDG 13, nMatchedHits 61 (22, 21, 18), nPfoHits 61 (22, 21, 18)

Is correct? 0
```

Performance Metrics

- 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.

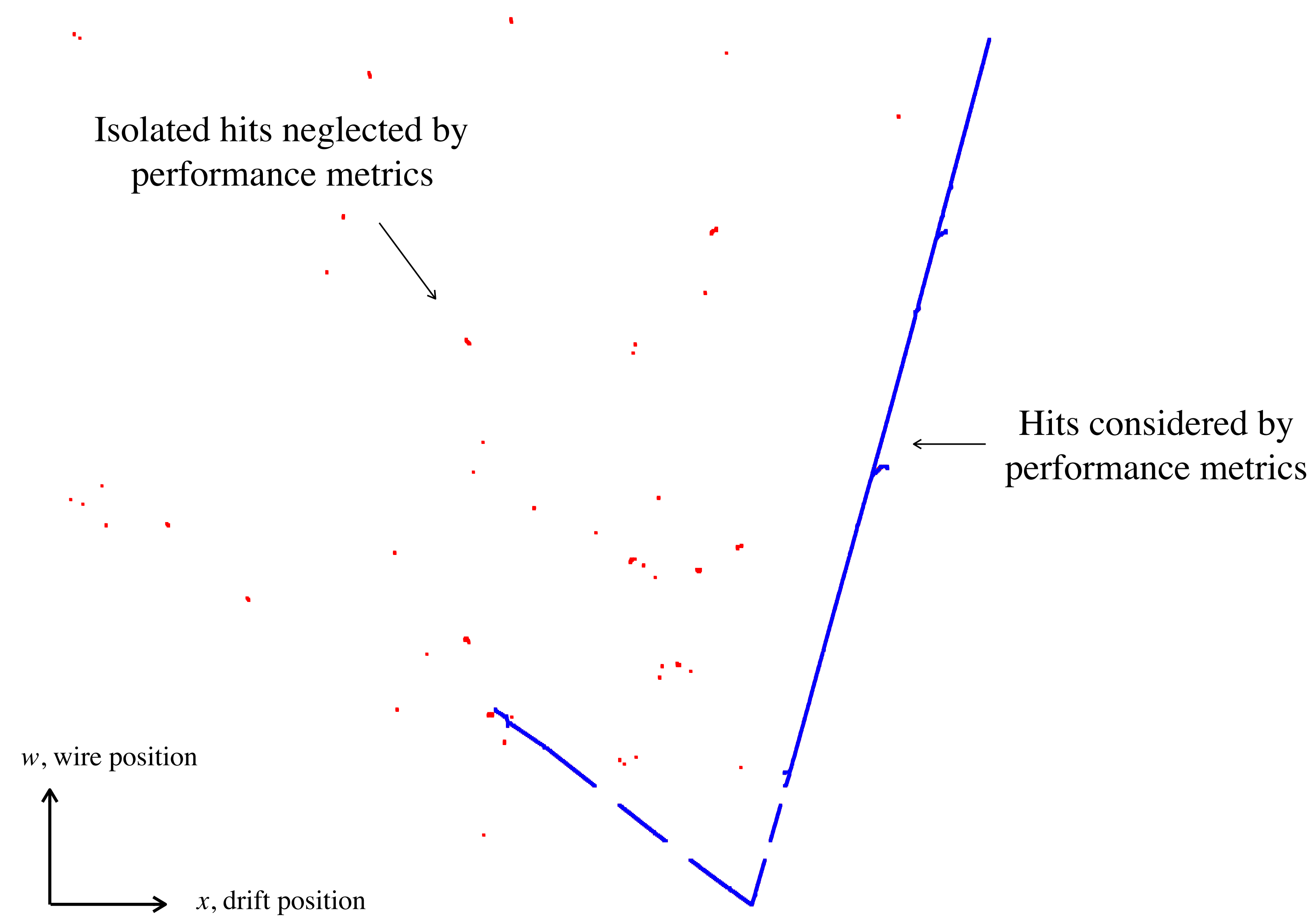
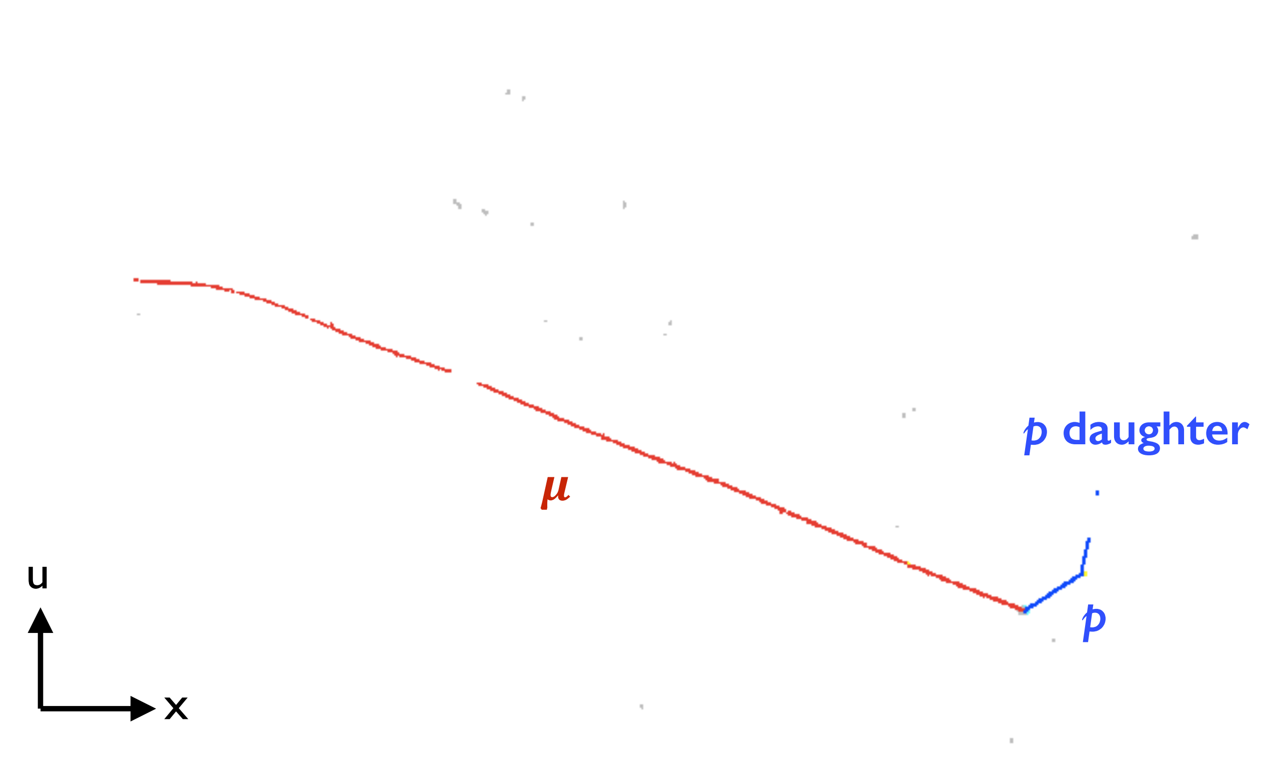
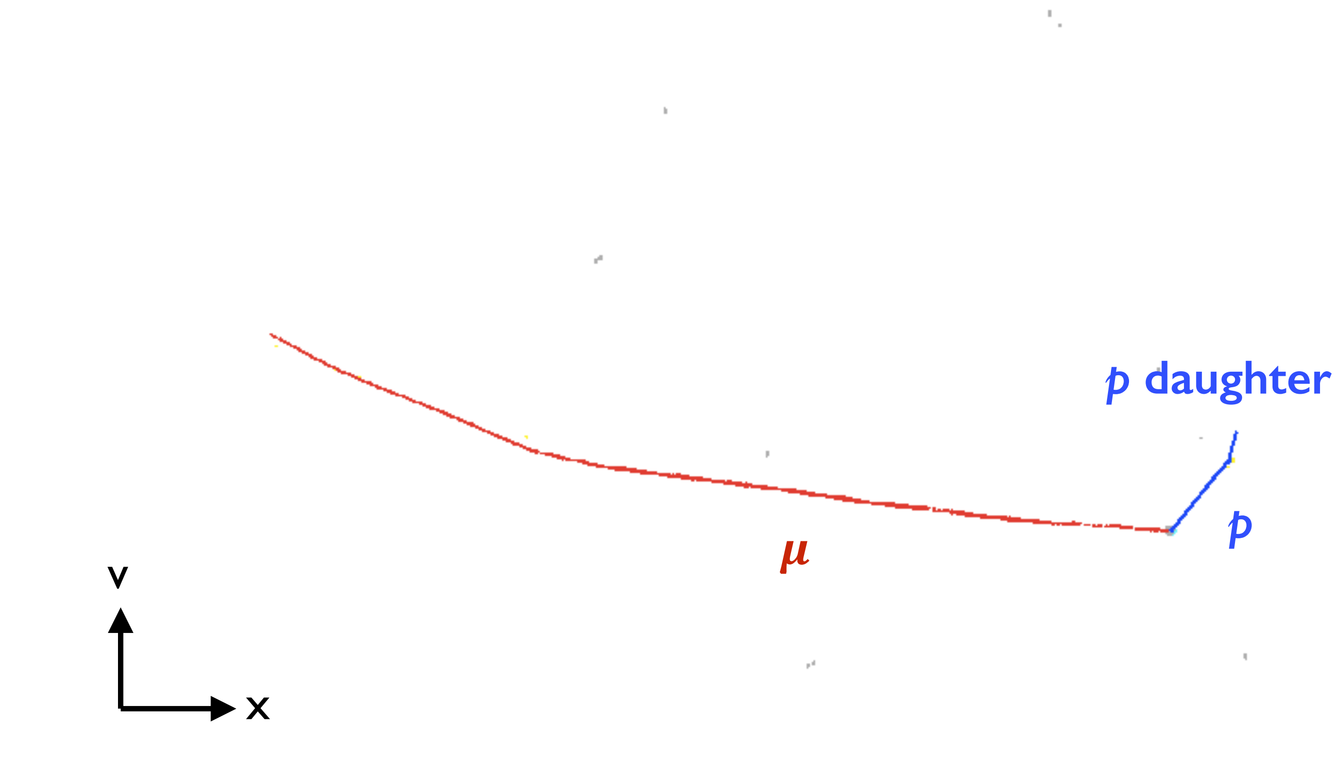


Fig. 8: The hits that are considered (blue) and neglected (red) in the construction of pattern recognition performance metrics for a typical CC ν_μ event at MicroBooNE. By considering the MCParticle hierarchy, hits that will likely form part of an isolated and diffuse topology are not used to identify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

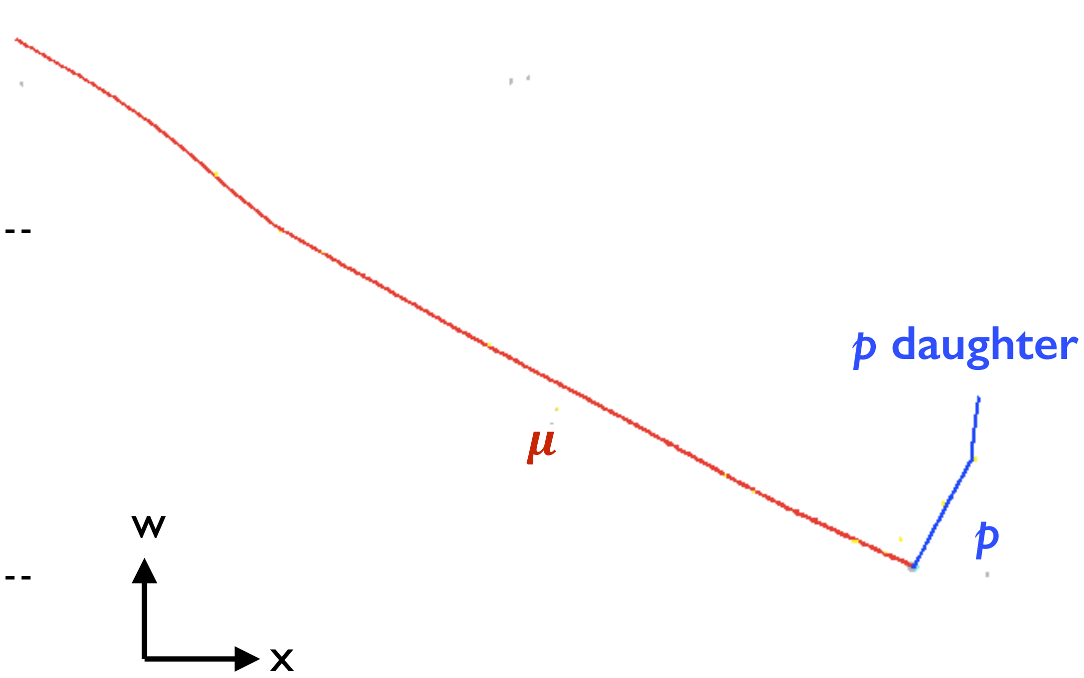
BNB CC QEL: $\nu_\mu + N \rightarrow X + p + \mu^-$



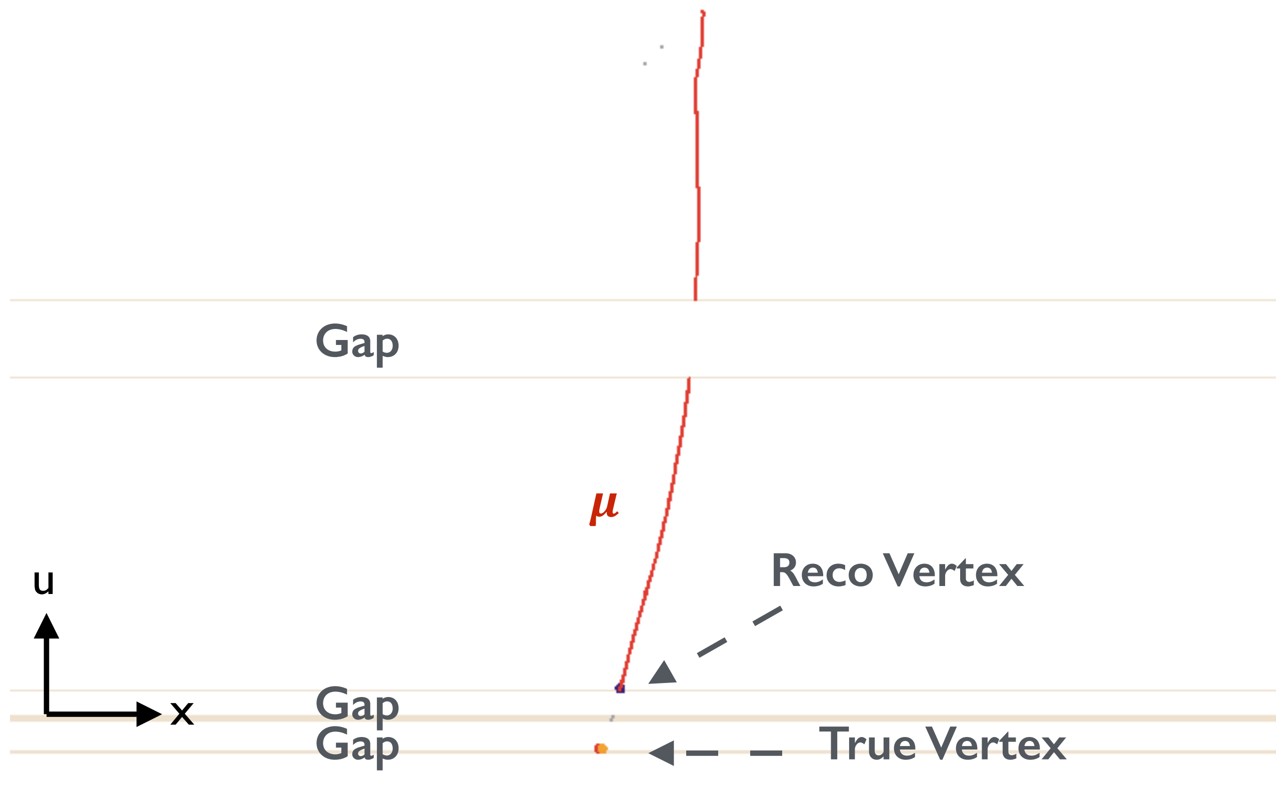


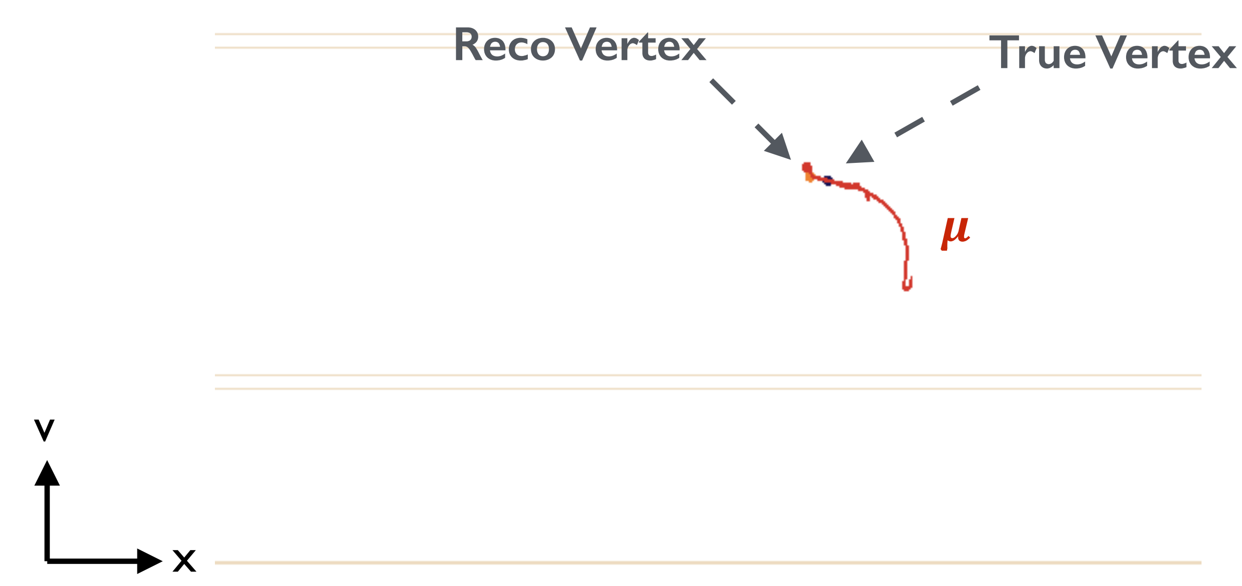
Deemed correct

```
---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
-------------------------------------------------------------------------------------------
```



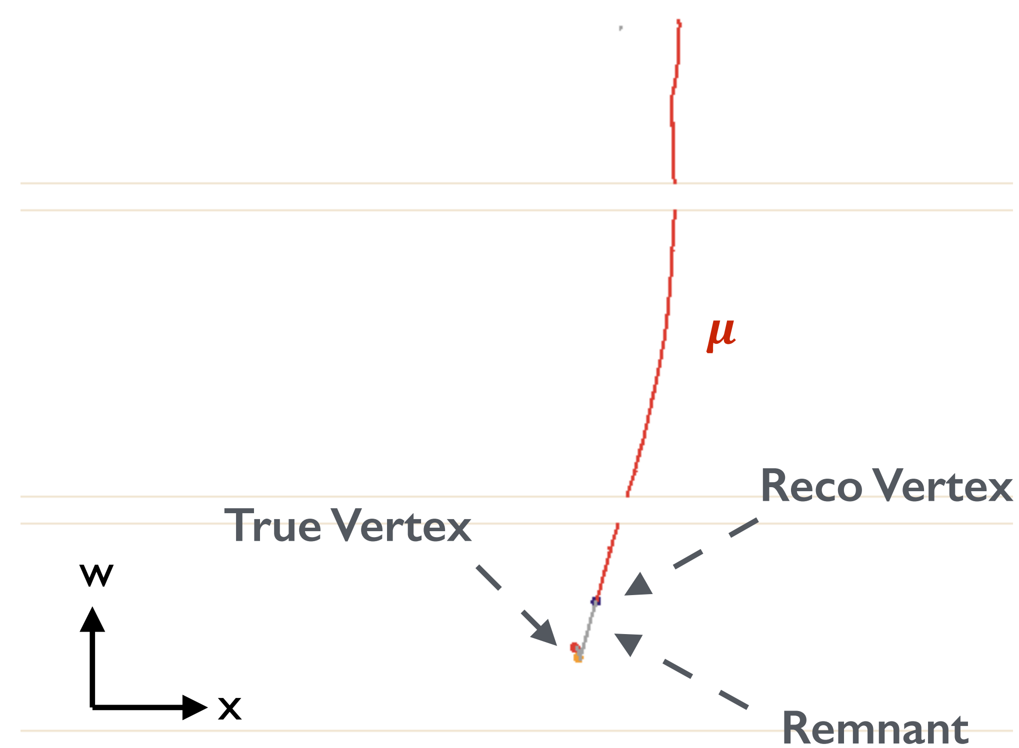
BNB CC QEL: $\nu_\mu + N \rightarrow X + p + \mu^-$



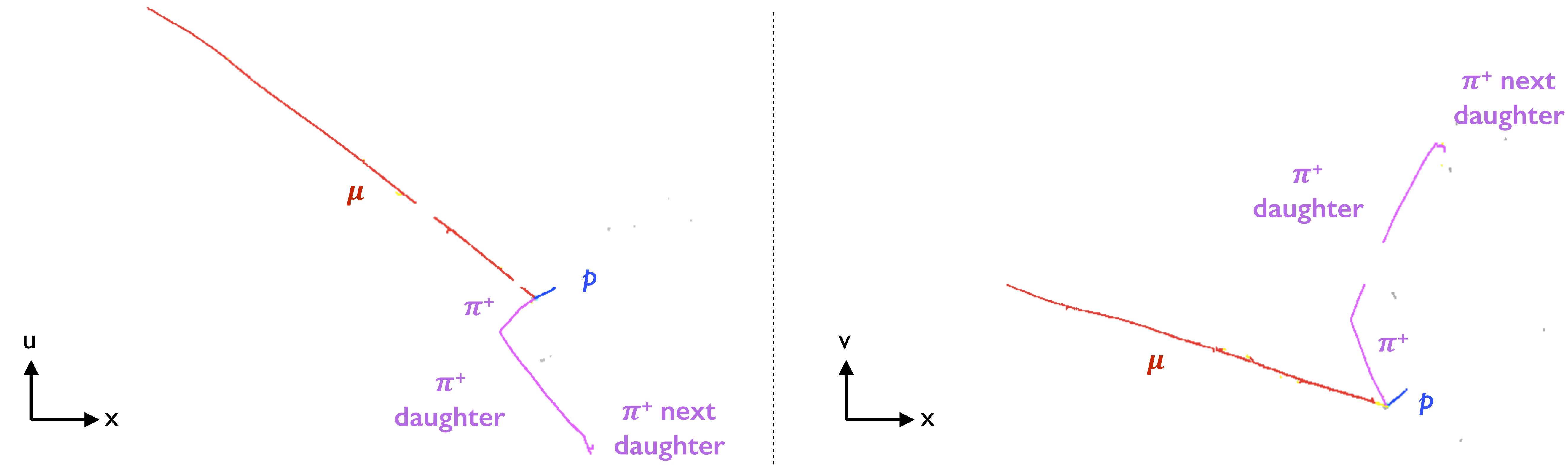


Work to do: vertex incorrect (gap influence)

```
---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
---------------------------------------------------------------------------------------------------
```

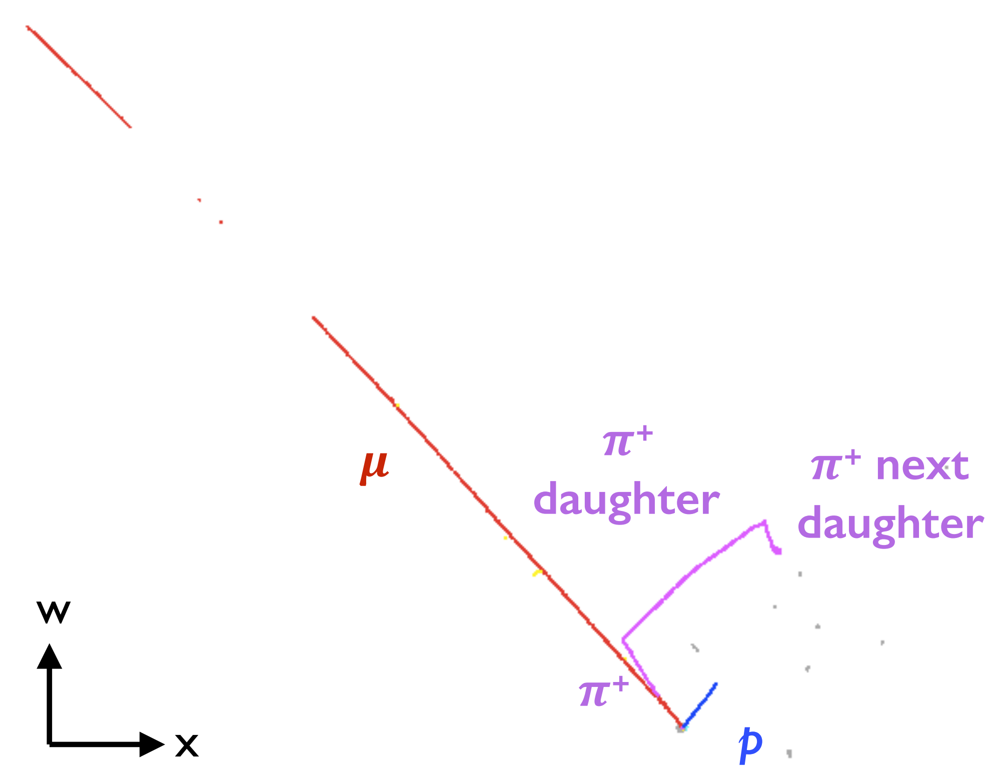


BNB CC RES: $\nu_\mu + N \rightarrow X + p + \pi^+ + \mu^-$

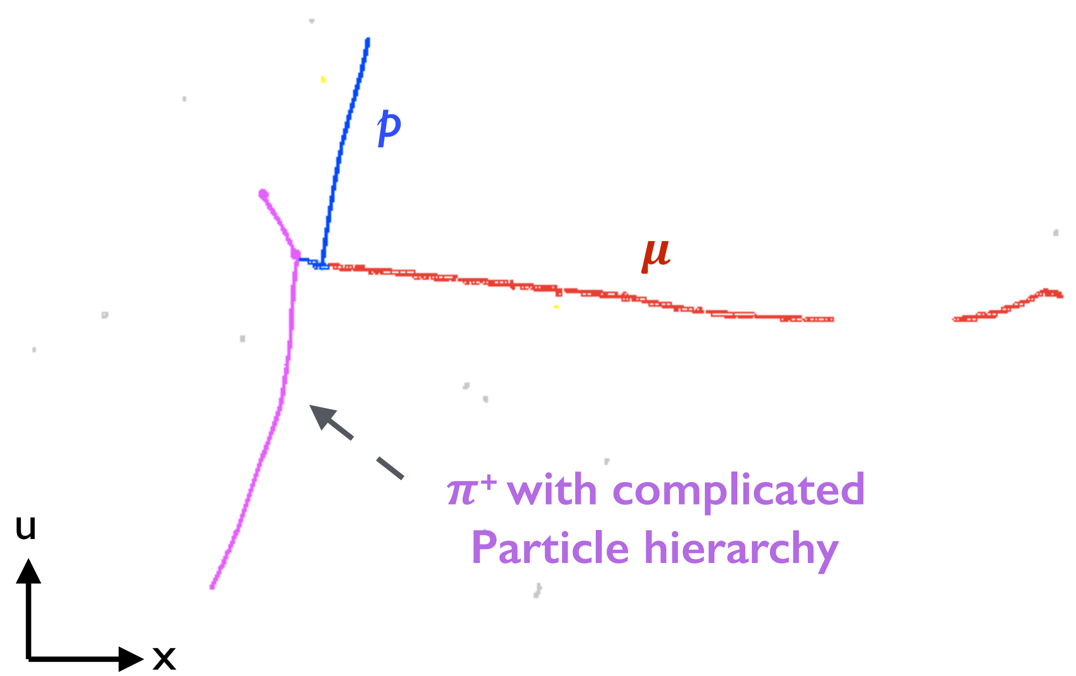


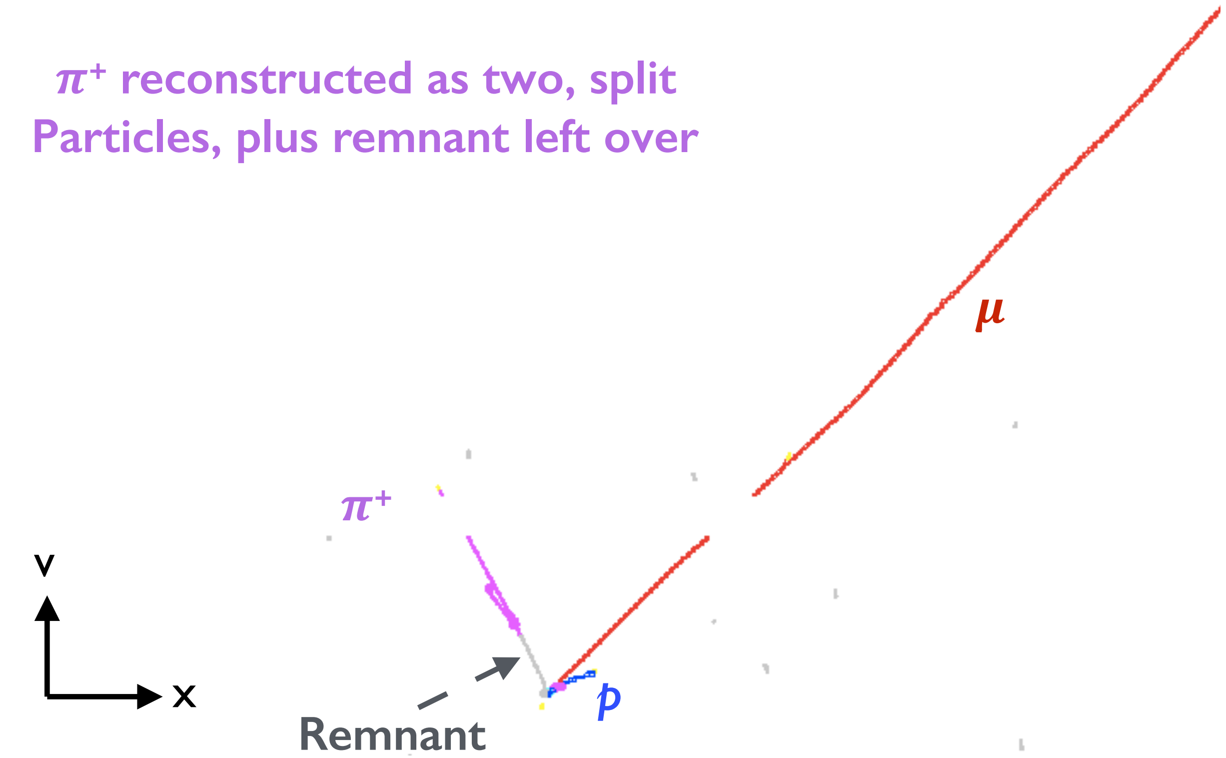
Deemed correct

```
---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
-------------------------------------------------------------------------------------------------
```



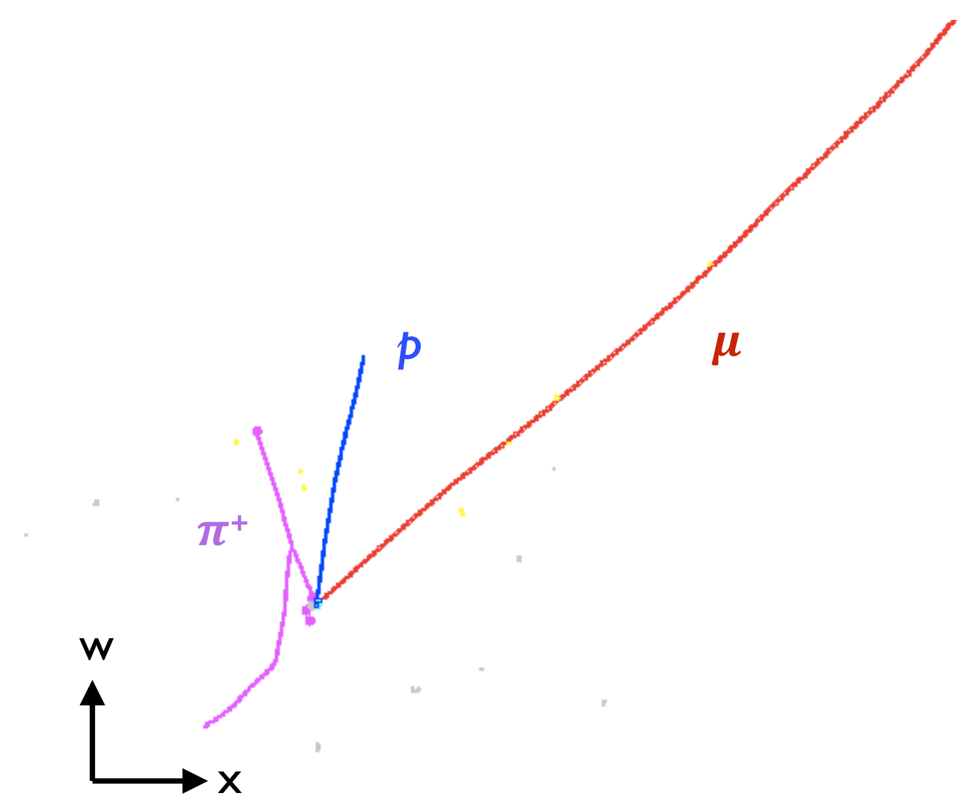
BNB CC RES: $\nu_\mu + N \rightarrow X + p + \pi^+ + \mu^-$



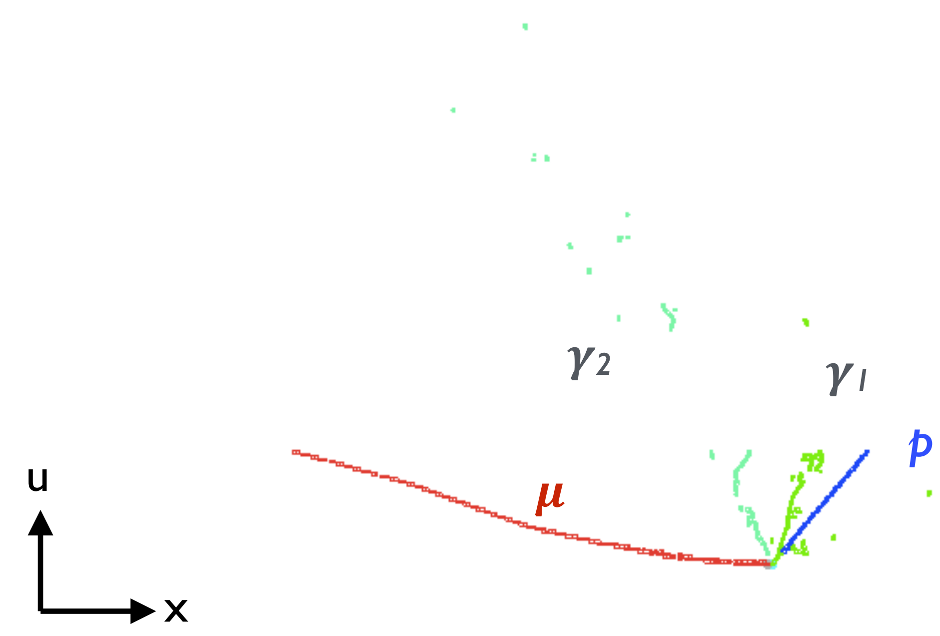


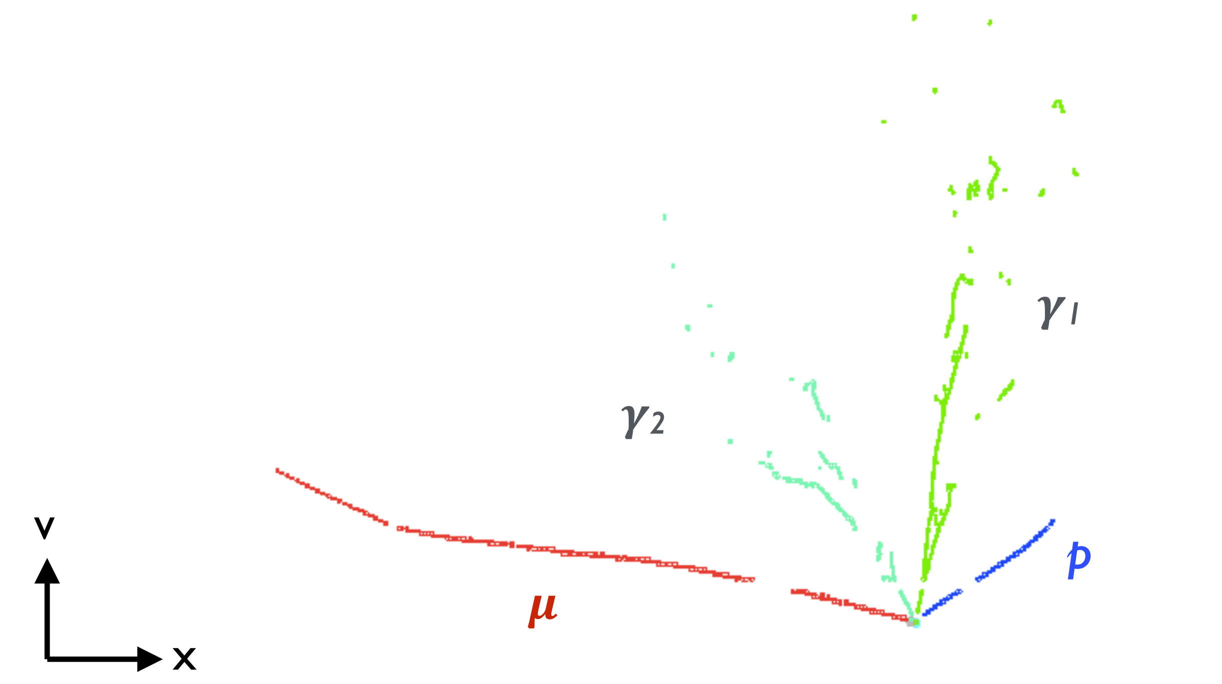
Work to do: parent-daughter link missing, remnant Cluster

```
---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
-------------------------------------------------------------------------------------------------
```



BNB CC RES: $\nu_\mu + N \rightarrow X + p + \pi^0 + \mu^-$





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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```
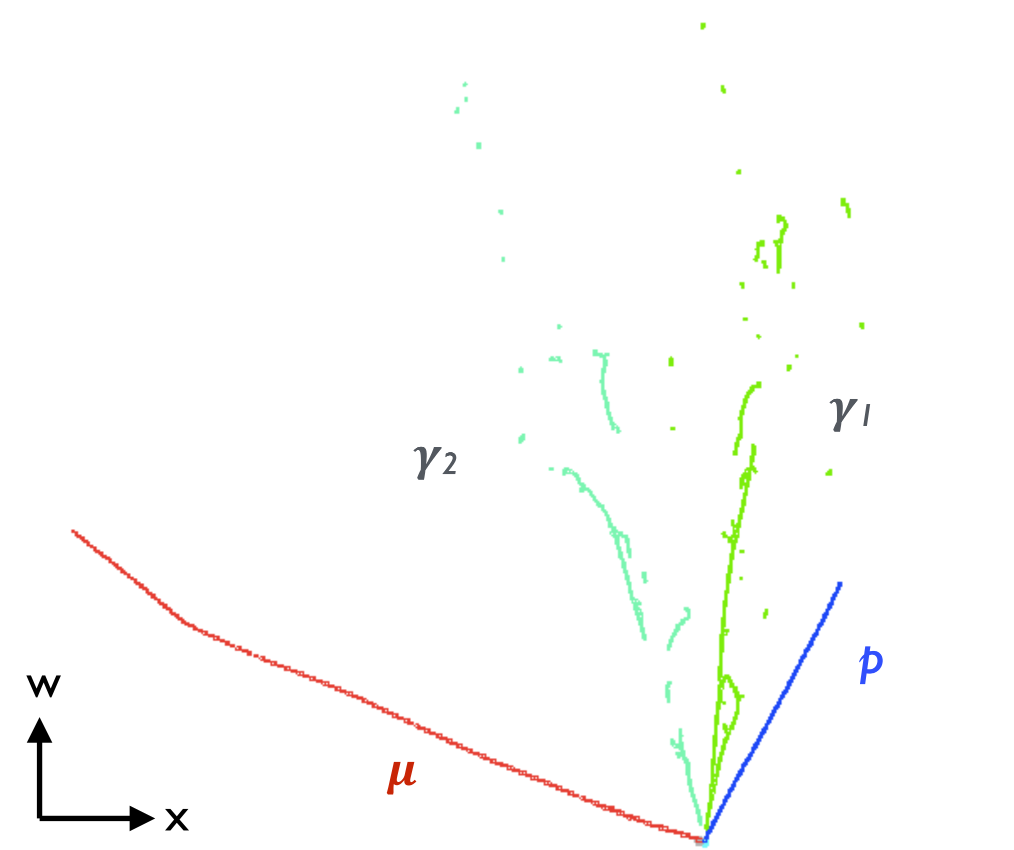
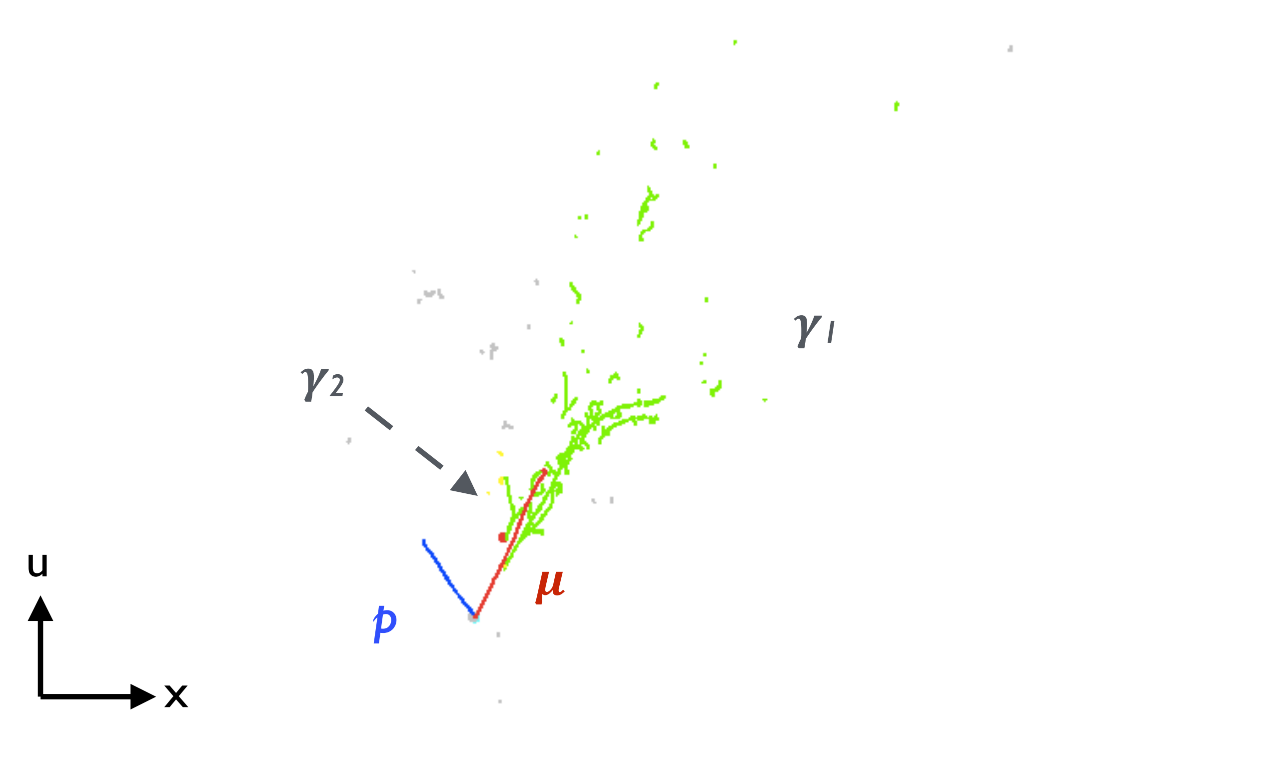
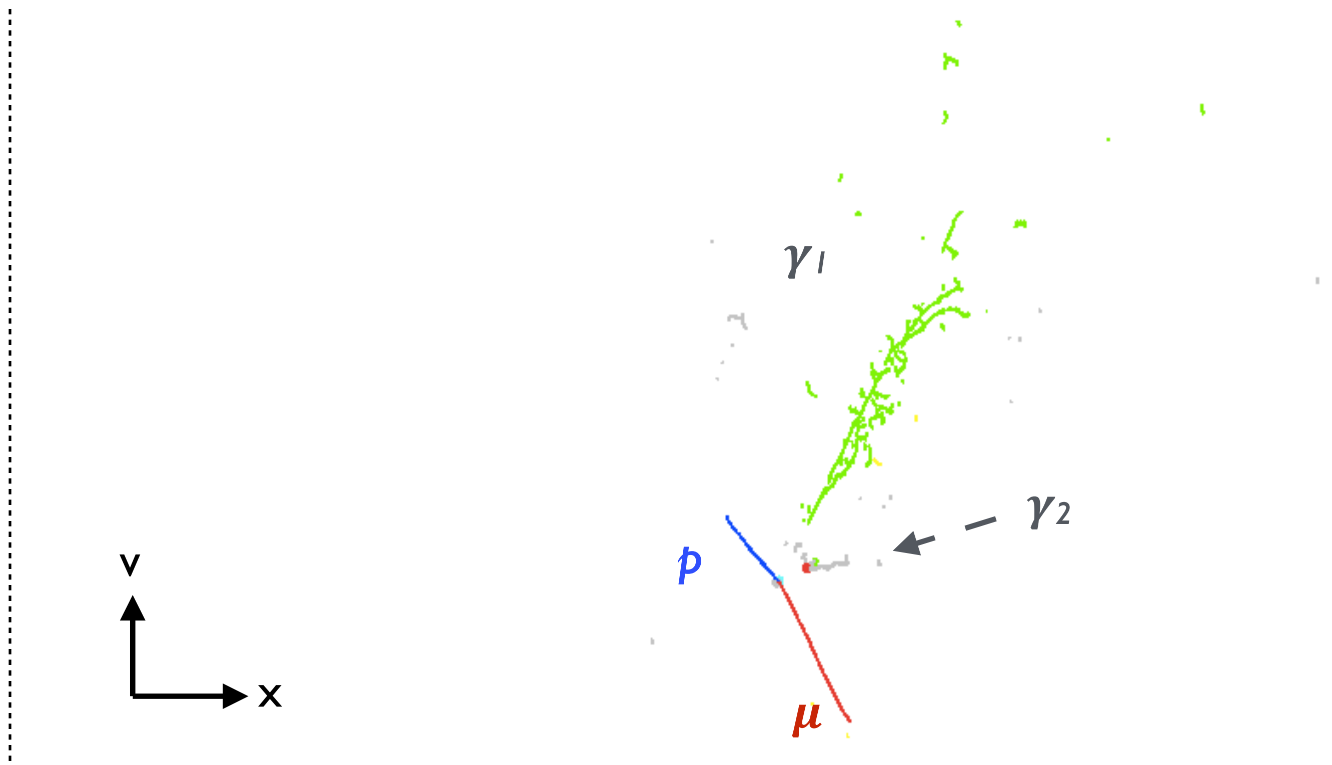
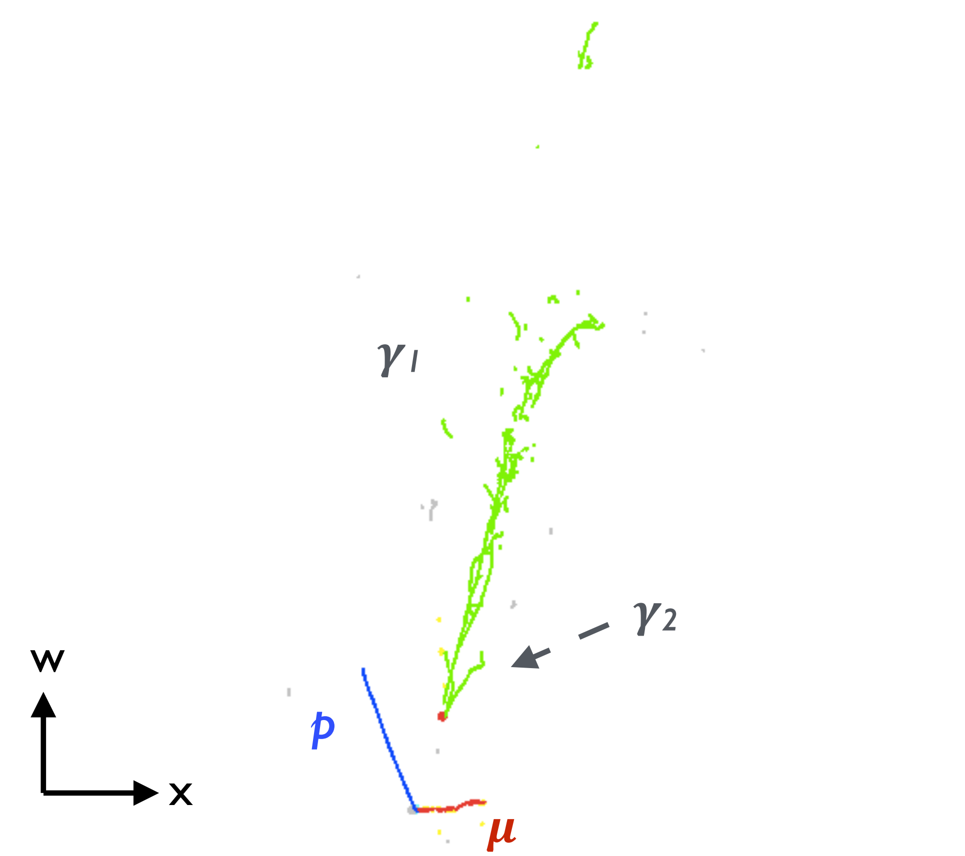





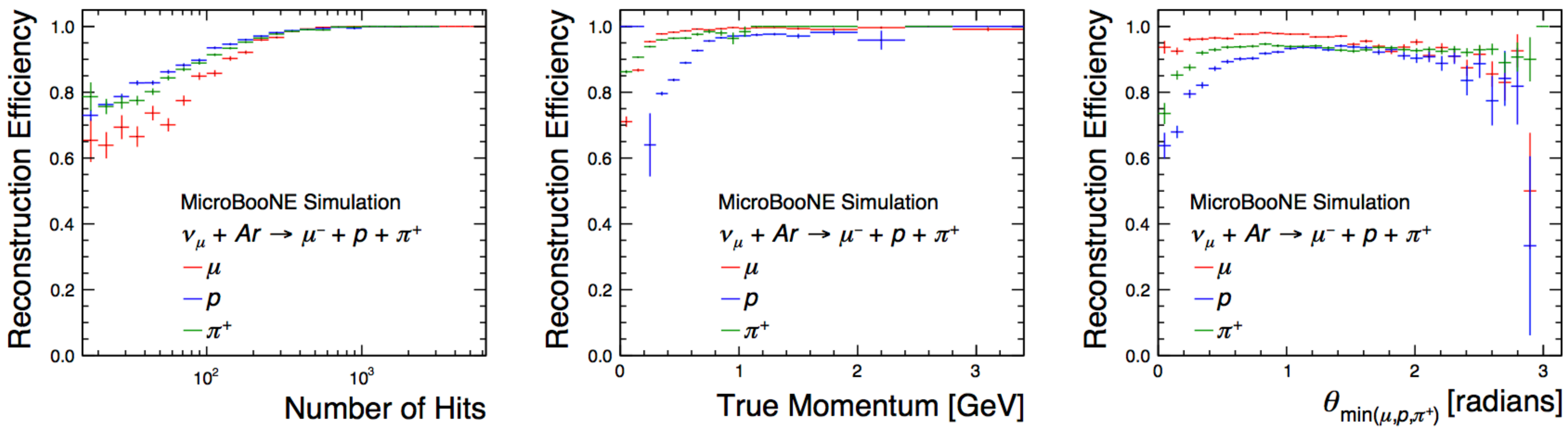


Work to do: γ_2 merged into γ_1

```
---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
------------------------------------------------------------------------------------------------
```



BNB CC RES: $\nu_\mu + Ar \rightarrow \mu^- + p + \pi^+$



- Performance for muons and protons similar to that observed for quasi-elastic events.
- Pion interactions can lead to a MCParticle hierarchy of a parent and one or more daughter. If these are reconstructed as separate primary particles (no reco parent-daughter links), pion is reportedly split up.

Vertex Reconstruction

- **The presence of additional, visible final-state particles means more information for vertexing; pointing information from tracks is, as expected, superior to that from showers.**
  - BNB CC QE ν_μ + Ar → p + μ^-: 68% of events with ΔR < 0.74 cm, 10.4% with ΔR > 5 cm
  - BNB CC RES ν_μ + Ar → μ^- + p + π^+: 68% of events with ΔR < 0.48 cm, 7.3% with ΔR > 5 cm
  - BNB CC RES ν_μ + Ar → μ^- + p + π^0: 68% of events with ΔR < 0.52 cm, 4.5% with ΔR > 5 cm

Not always so easy e.g. if μ, p back to back…