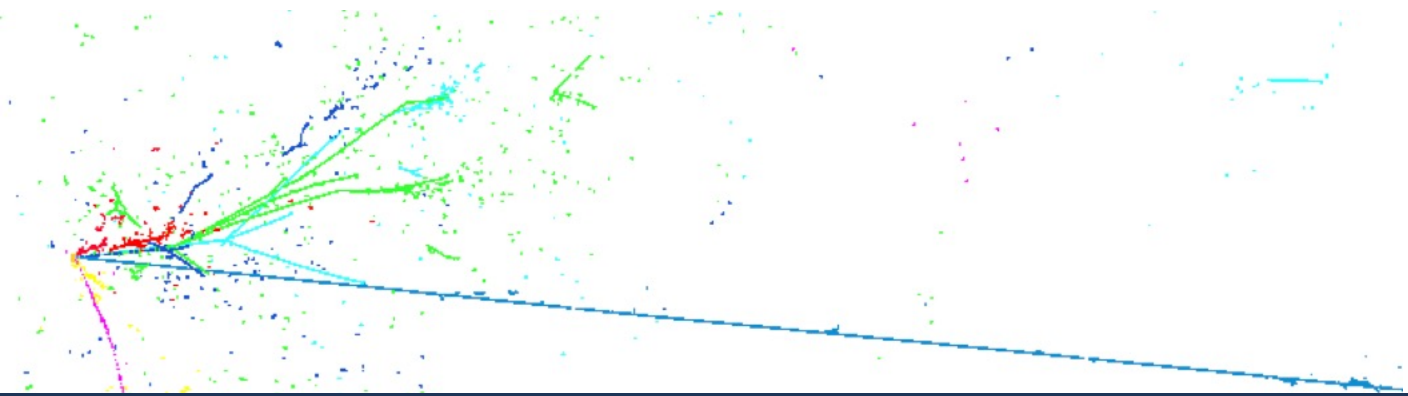


The Pandora reconstruction for the DUNE experiment

Maria Brigida Brunetti

5 May 2021 @ The University of Birmingham

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

WARWICK THE UNIVERSITY OF WARWICK

Key Points

- Many open questions in **neutrino physics**
- What answers can we get with **long-baseline oscillation** experiments?
- Why the **Liquid Argon Time Projection Chamber** technology?
- The **DUNE** experiment, and the far detector prototypes
- The challenges of **event reconstruction**
- The **Pandora** approach to pattern recognition
- Reconstruction with Pandora: **performance and prospects**

Neutrino Open Questions

- Is there CP violation in the lepton sector?
- What is the neutrino mass ordering?
- What are the mass differences and mixing angles?

  → *Long-baseline oscillation experiments*

- What are the absolute neutrinos masses?

  → *Tritium beta decay endpoint*

- Are neutrinos Dirac or Majorana particles?

  → *Neutrinoless double beta decay ($0\nu\beta\beta$)*

- Why are neutrino masses so small?
- Are there sterile neutrinos?

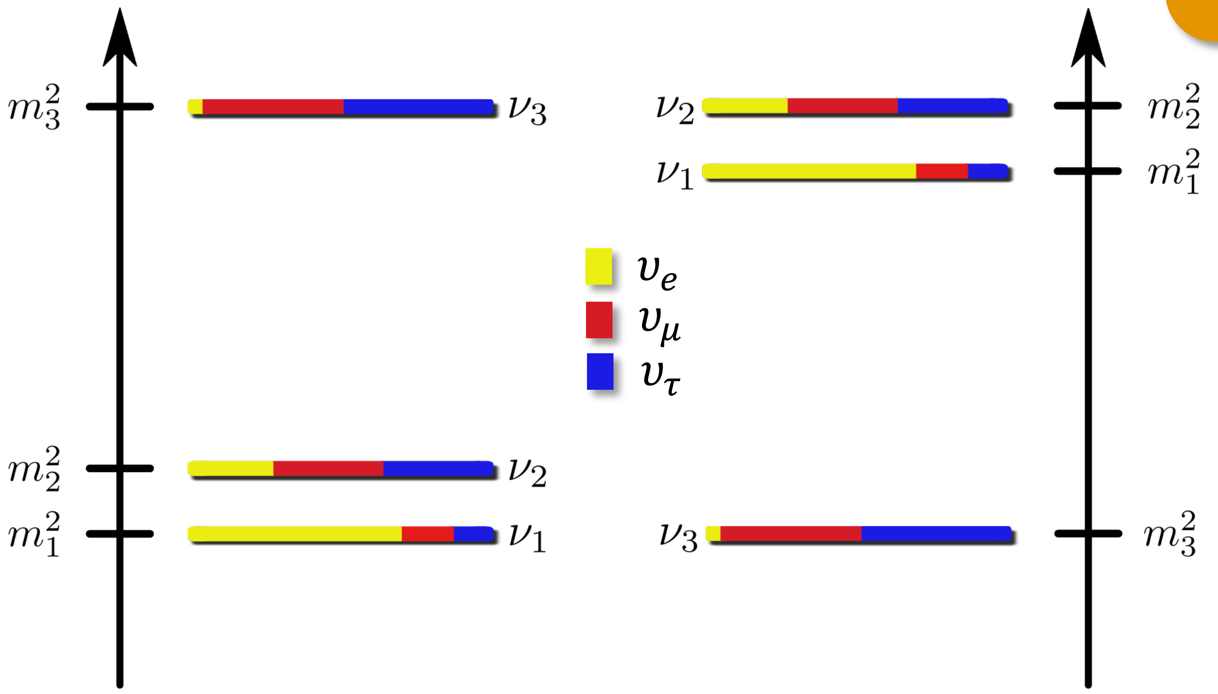
  → *Accelerator and reactor oscillation experiments*

Neutrino Mass Hierarchy

$m_{1,2,3}$ = mass eigenstates

$m_{e,\mu,\tau}$ = interaction eigenstates

- We have observed neutrino oscillations, thus we know at least two neutrinos are massive



- $m_2 > m_1$ by convention
- Two possibilities for m_3

$\boldsymbol{m_3 > m_2}$ (NORMAL) $\boldsymbol{m_3 < m_1}$ (INVERTED)

- Many ways to tackle this question: long-baseline oscillation experiments, β and $0\nu\beta\beta$ decays, cosmological observables…
- For **long baselines**, oscillation probability is modified by matter (MSW effect) in a different way for neutrinos and antineutrinos → compare to find sign of Δm_{13}^2

CP Violation in Lepton Sector

- Standard Model only has one known source of CP violation so far: Cabibbo-Kobayashi-Maskawa (CKM) matrix phase in quark sector
- But we know neutrinos have mass and leptons mix, because we have observed oscillation
- Is there a CP-violating phase similar to the CKM one in Pontecorvo-Maki-Nagasawa-Sakata (PMNS) matrix?
- How large is δ? ($\delta_{CKM} \sim 68°$)

Can compare amplitudes with **long-baseline oscillation experiments :**

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})\ ?$$

Two-flavour oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$c_{13} = \cos\theta_{13}$, $c_{13} = \sin\theta_{13}$

$\boldsymbol{\delta_{CP} \neq 0, \pi}$ → **CP violation**

Neutrino Oscillations

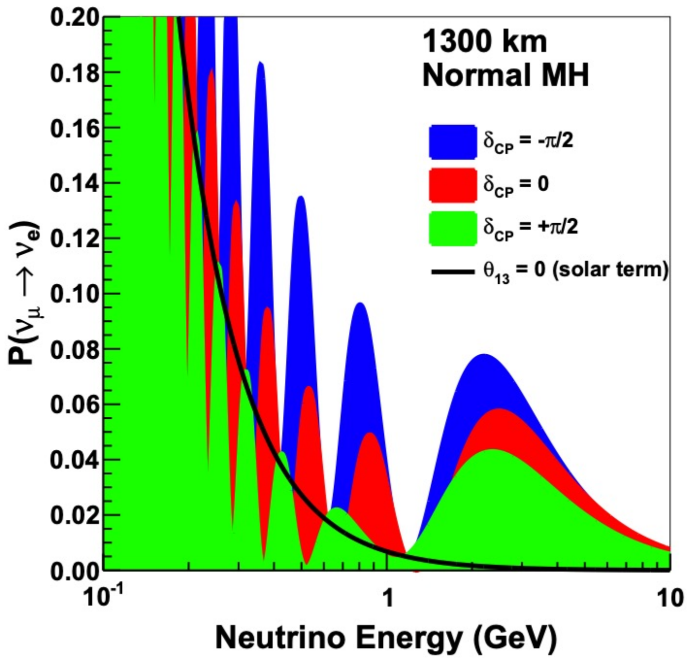
2-flavour appearance probability

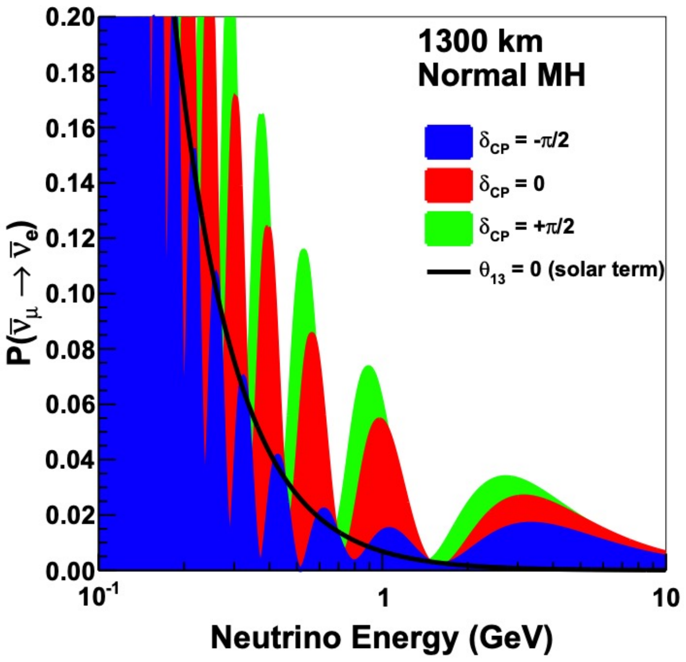
PHYSICS

$$P_{\upsilon_\alpha \to \upsilon_\beta}(\mathrm{L,E}) = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)\mathrm{L(km)}}{\mathrm{E(GeV)}}\right)$$

EXPERIMENT

Must disentangle different effects! Spectra shapes impacted by matter effects (larger for longer baselines), mass ordering, δ_{CP}, mixing angles…



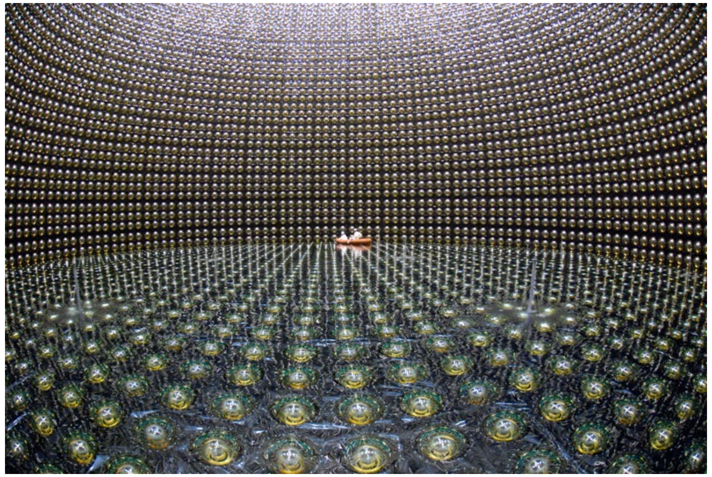


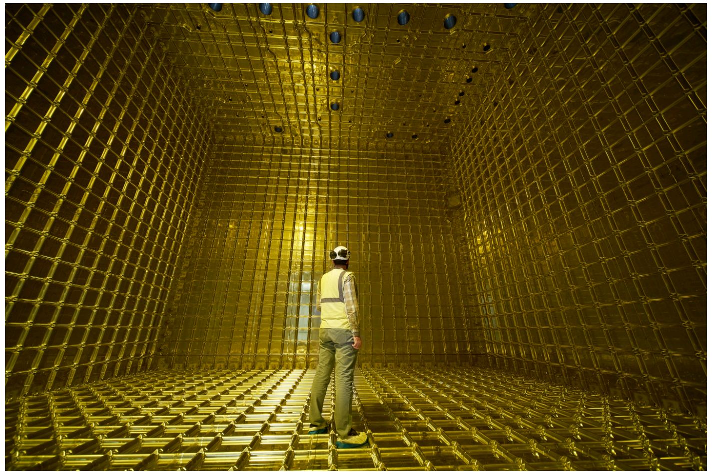
υ_e appearance spectra for normal mass hierarchy, for different values of δ_{CP}, for a 1300 km baseline, for neutrinos (left) and antineutrinos (right)

DUNE conceptual design report
arXiv:1512.06148 [physics.ins-det]

Neutrino Experiment Design

- Oscillation experiments are an excellent tool to tackle many open questions. Many parameters to be chosen!
- **Beam parameters**
- **Two baseline choices**:
  - Short baseline (precise cross section measurements, appearance/disappearance anomalies, near detectors)
  - Long baseline (mass hierarchy, CP violation)
- **What detector technology**?
  - Water Cherenkov detectors (e.g. HyperK)
  - Liquid argon time projection chambers (e.g DUNE)





This talk: Reconstruction of interactions in Liquid Argon Time Projection Chambers (LArTPCs)

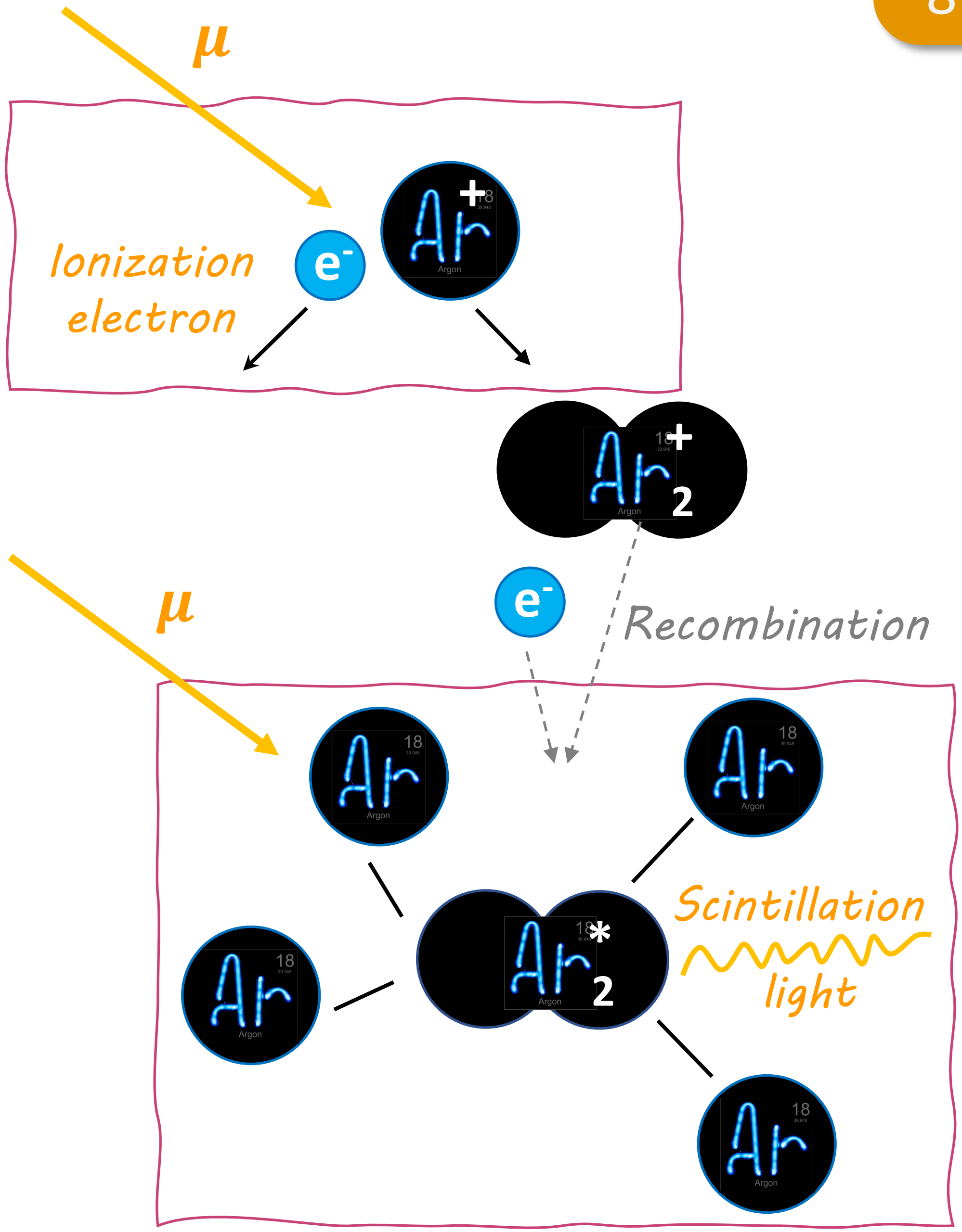
Why Liquid Argon?

- **Noble elements:** large use in particle physics experiments (neutrino oscillation and interactions, dark matter searches, $0\nu\beta\beta$ searches)

- Two energy loss mechanisms:
  - **Scintillation**: transparent to their own scintillation light
  - **Ionization:** stable → low e^- capture → long drift

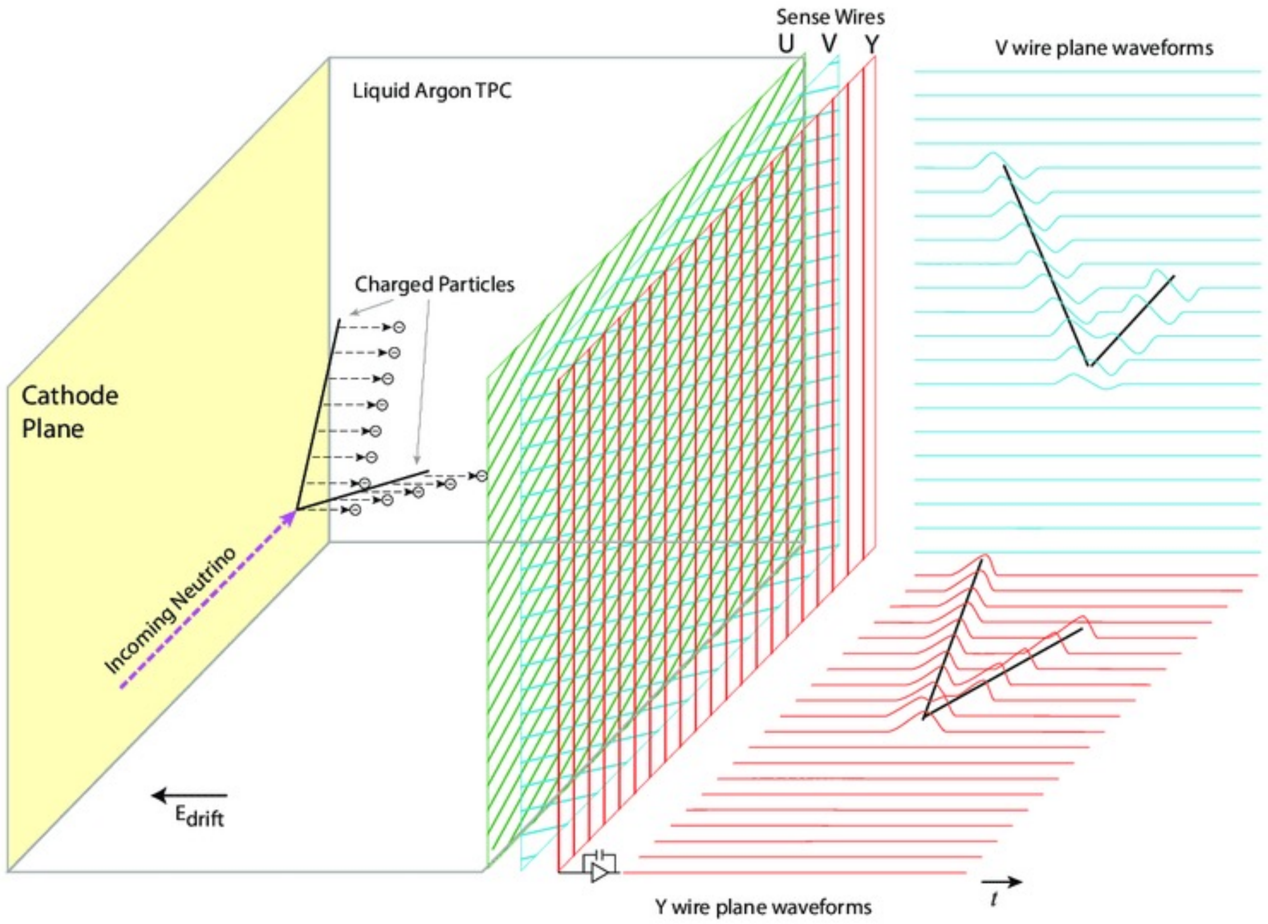
- **Very good dielectrics**: can sustain high electric fields

- **Argon:** high light yield, cheap/easy to obtain, best suited for ~ GeV neutrinos



LArTPCs

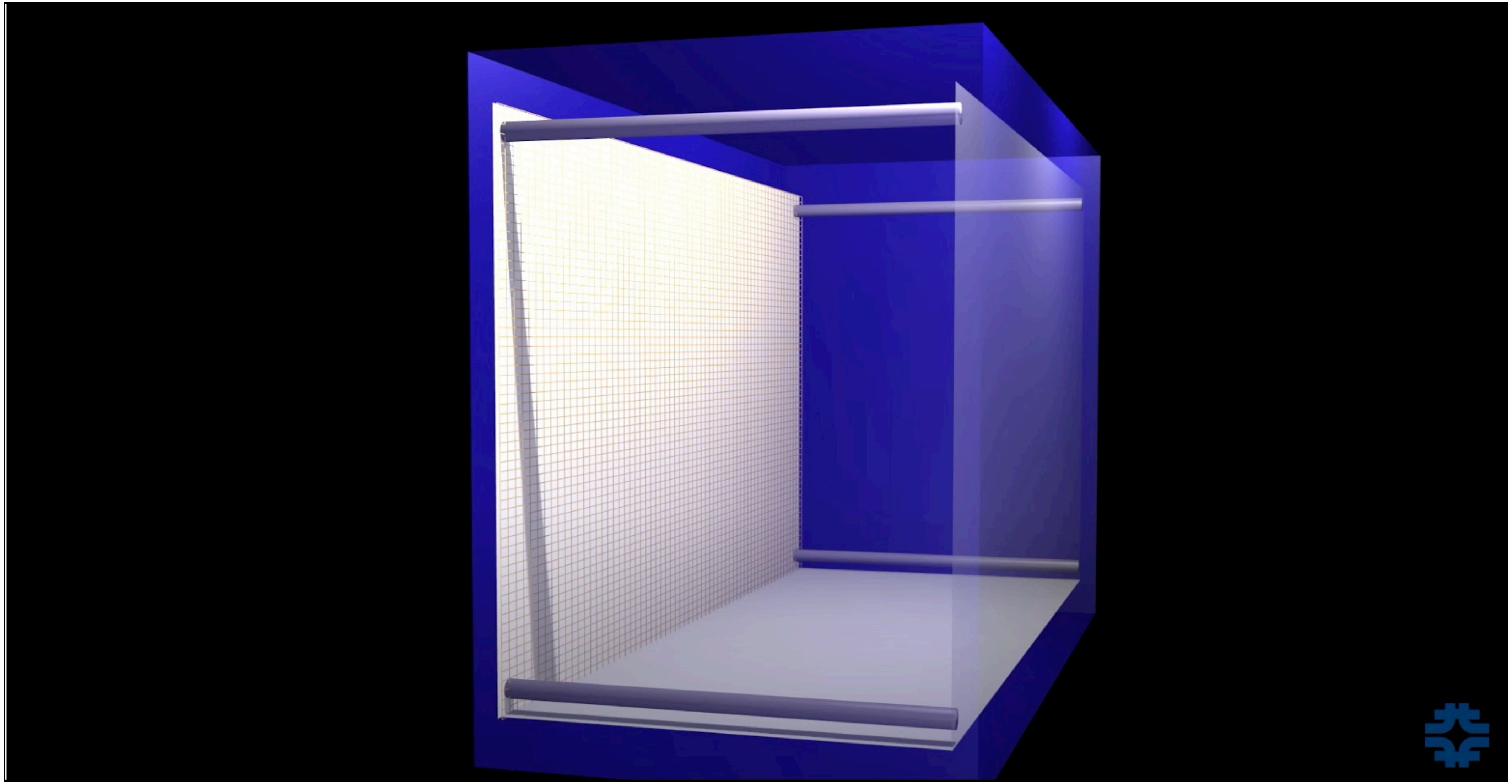
- Proposed by C. Rubbia in 1977, now well-established technology for neutrino experiments
- Use **scintillation** and **ionization** to find 3D position of particles and interactions
- Drift charge recorded by several readout (RO) wire planes, with different orientations
- Each RO plane forms a 2D image (wire ID, common drift coordinate)
- Light collected by photomultipliers



Sketch of the MicroBooNE detector

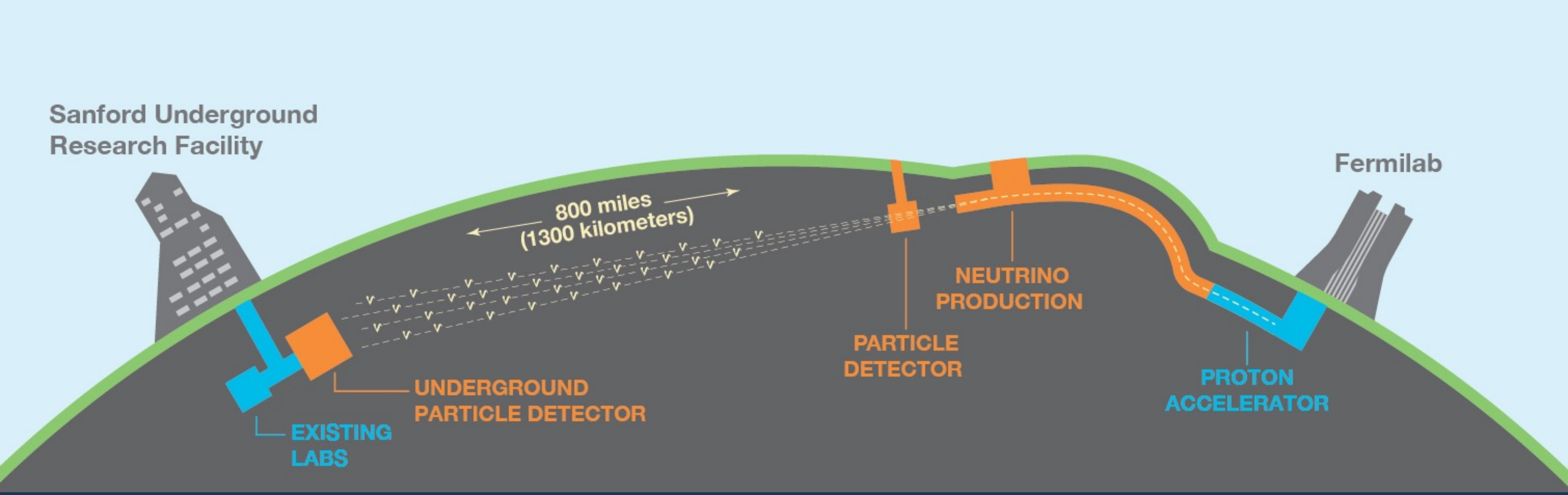
A Two-View Example

(credits: Fermilab)



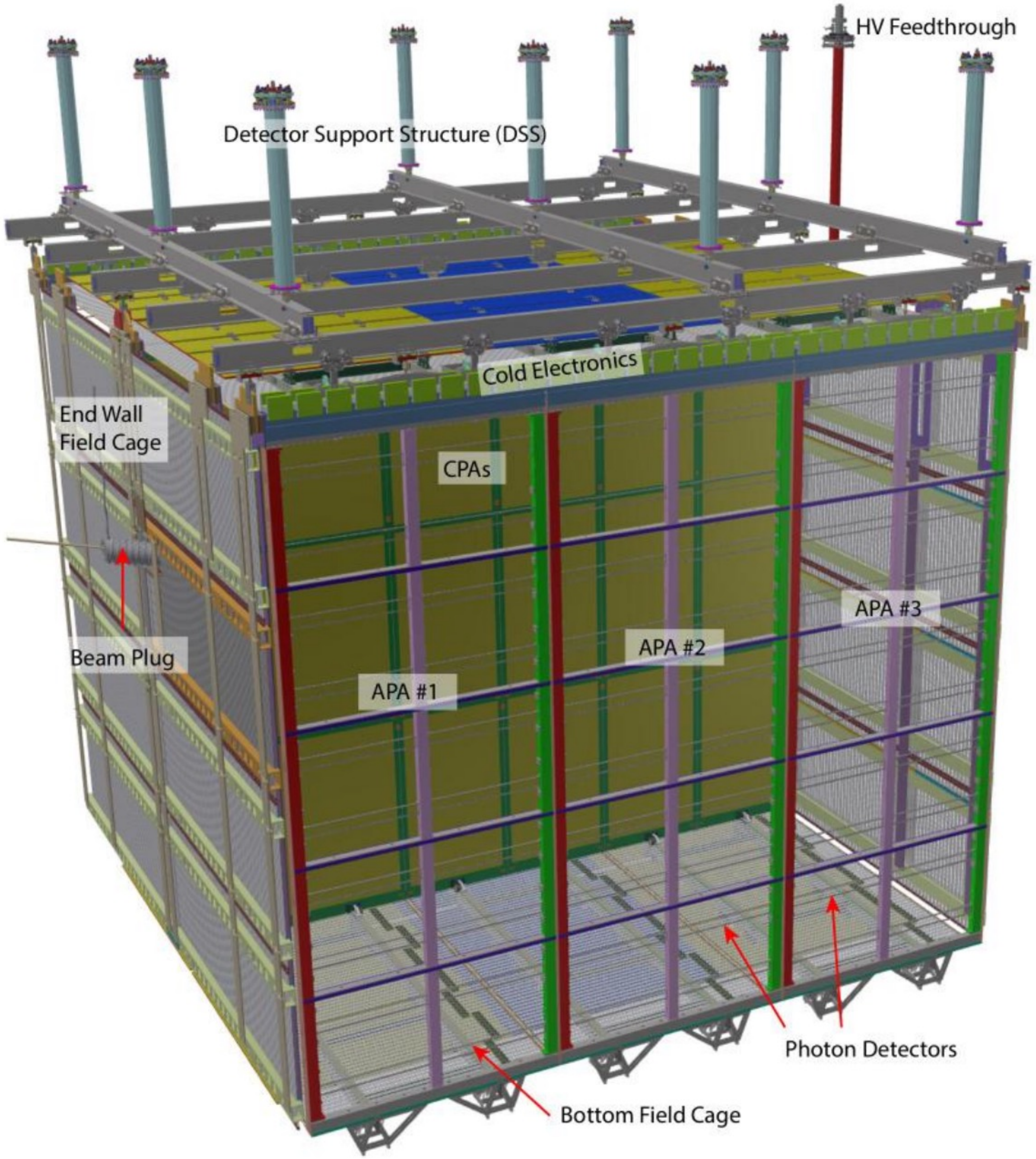
Long-baseline Programme

- Three near detectors, four 10-kton fiducial volume LArTPC modules at far site
- Broad physics programme: CP violation in lepton sector, three-flavour paradigm, neutrino mass hierarchy, neutrinos from supernova, proton decay, …
- Two prototypes at CERN: ProtoDUNE Single and Dual Phase



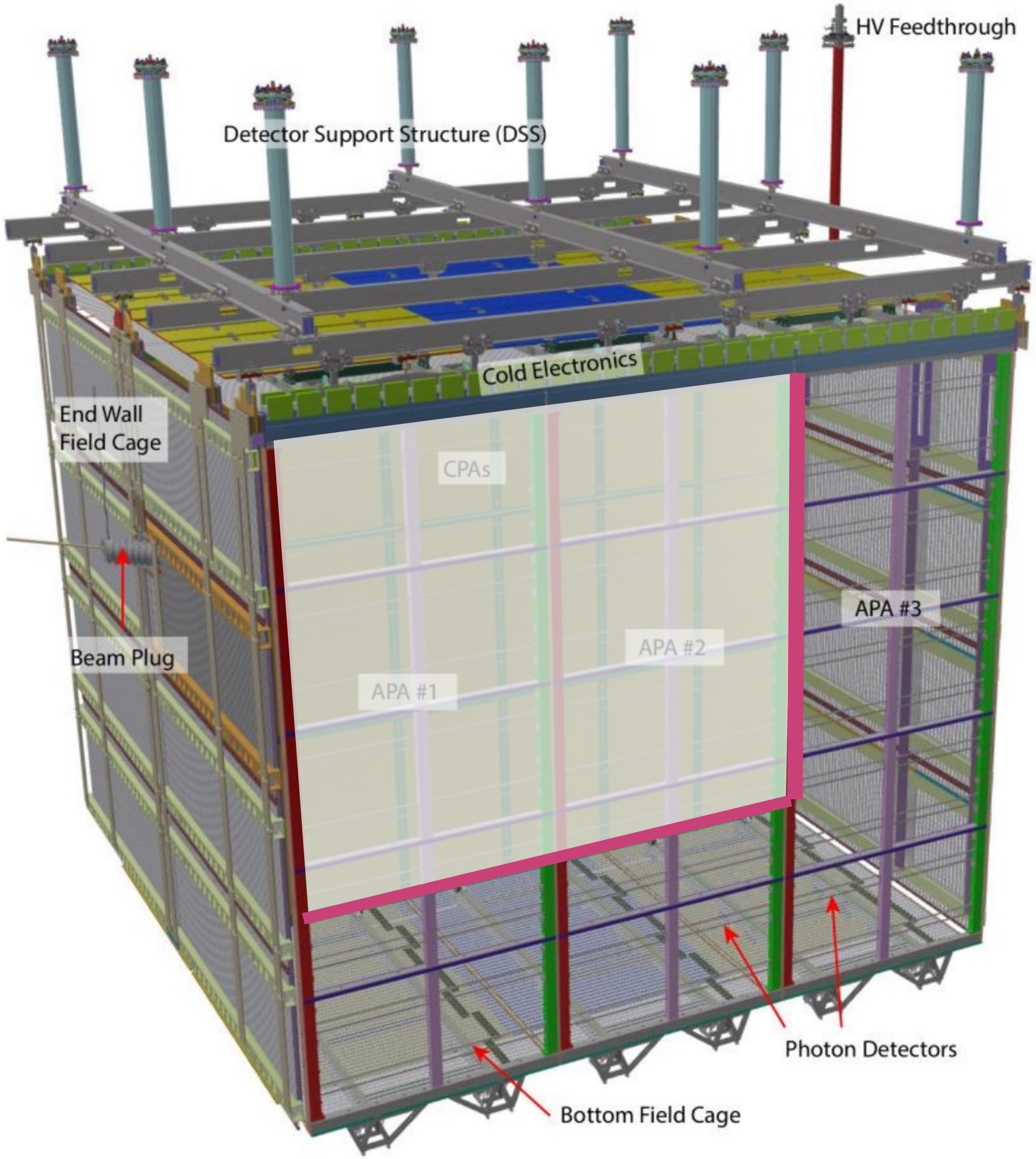
ProtoDUNE-SP

- 420 t single-phase LArTPC prototype at CERN for the DUNE FD
- Total active volume: $(6.1 \times 7 \times 7.2)$ m^3



ProtoDUNE-SP

- 420 t single-phase LArTPC prototype at CERN for the DUNE FD
- Total active volume: $(6.1\times7\times7.2)$ m^3
- Two 3.6 m deep drift volumes: **central cathode plane** between two anode planes



ProtoDUNE-SP

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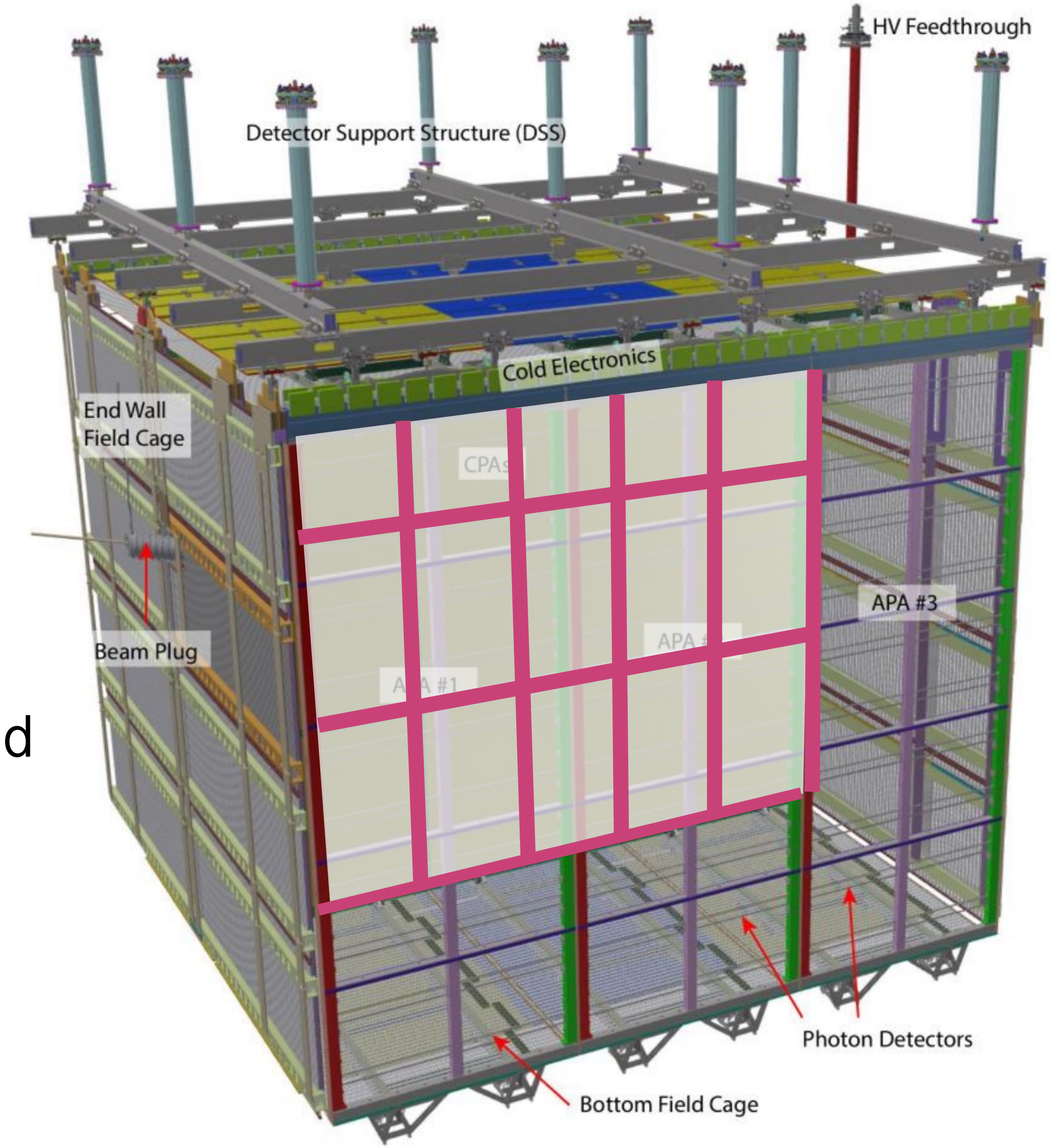
- Two 3.6 m deep drift volumes: central cathode plane between two anode planes

Cathode plane:

Array of 18 modules $(1.18\times2)\ m^2$

Held at -180 kV, provides 500 V/cm drift field



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- 420 t single-phase LArTPC prototype at CERN for the DUNE FD
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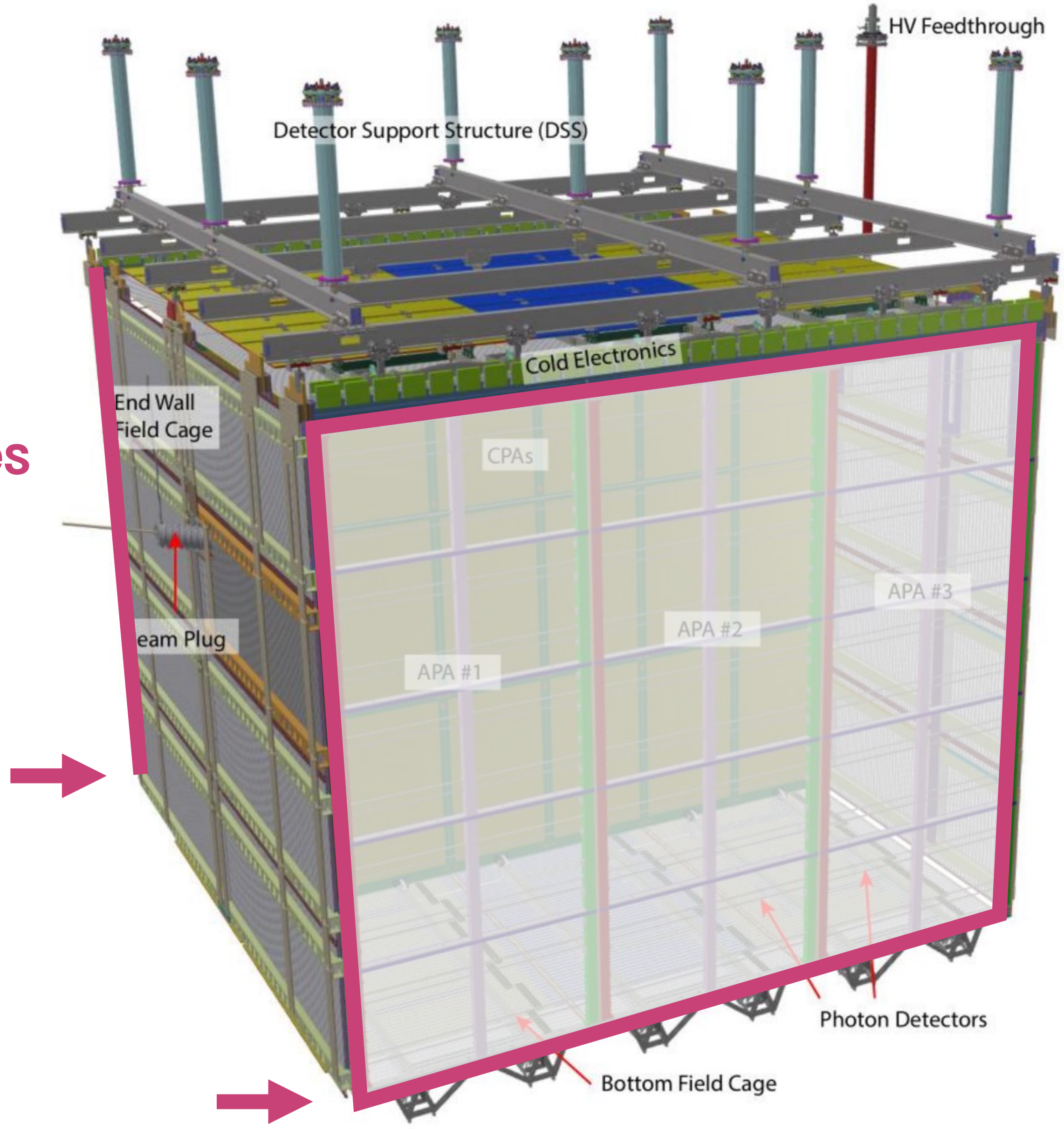
- Two 3.6 m deep drift volumes: central cathode plane between two **anode planes**



ProtoDUNE-SP

- 420 t single-phase LArTPC prototype at CERN for the DUNE FD
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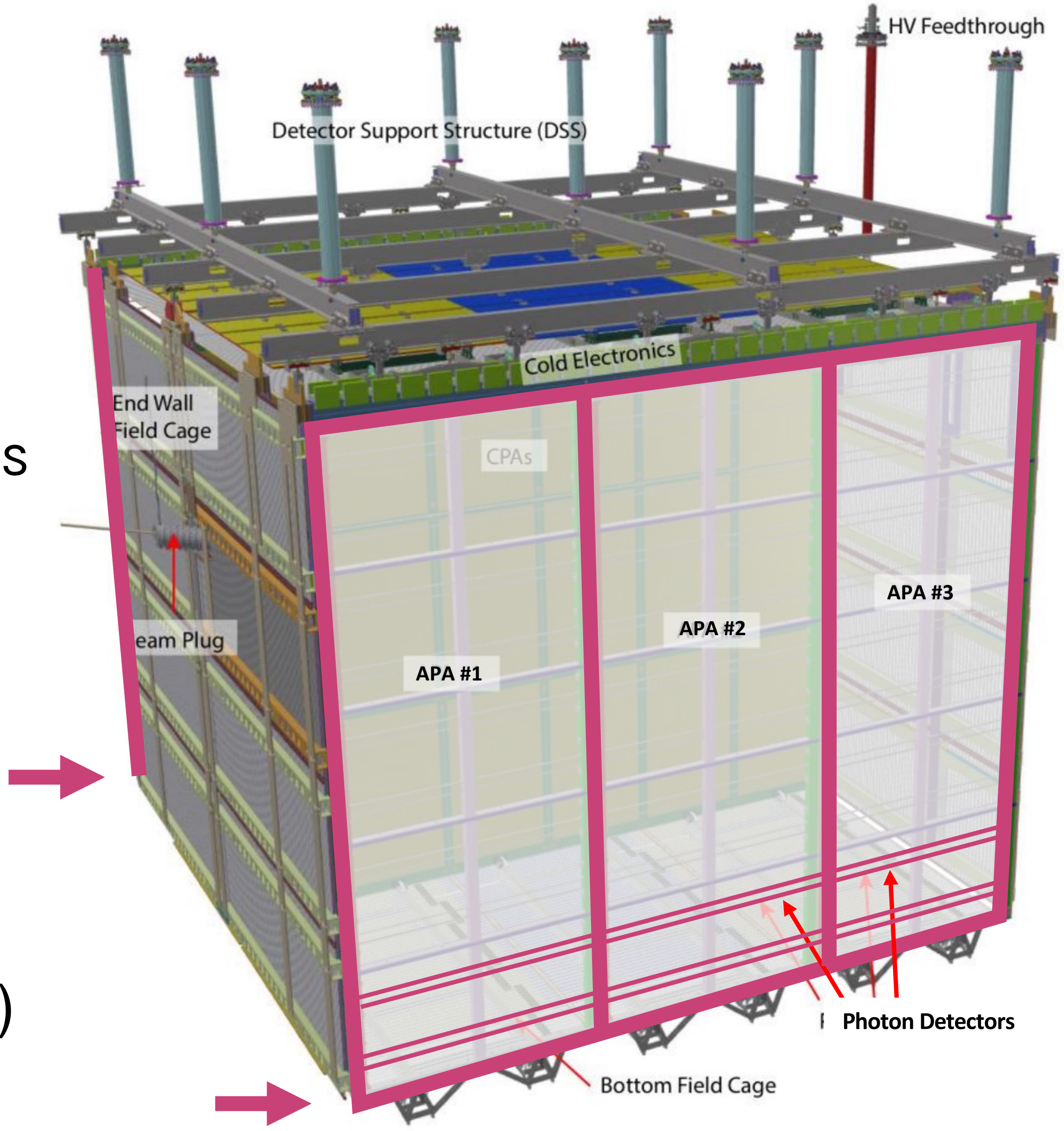
- Two 3.6 m deep drift volumes: central cathode plane between two anode planes

Anode plane:

Three adjacent Anode Plane Assemblies (**APAs**) $(6\times2.3)\ \mathrm{m}^2$ wide

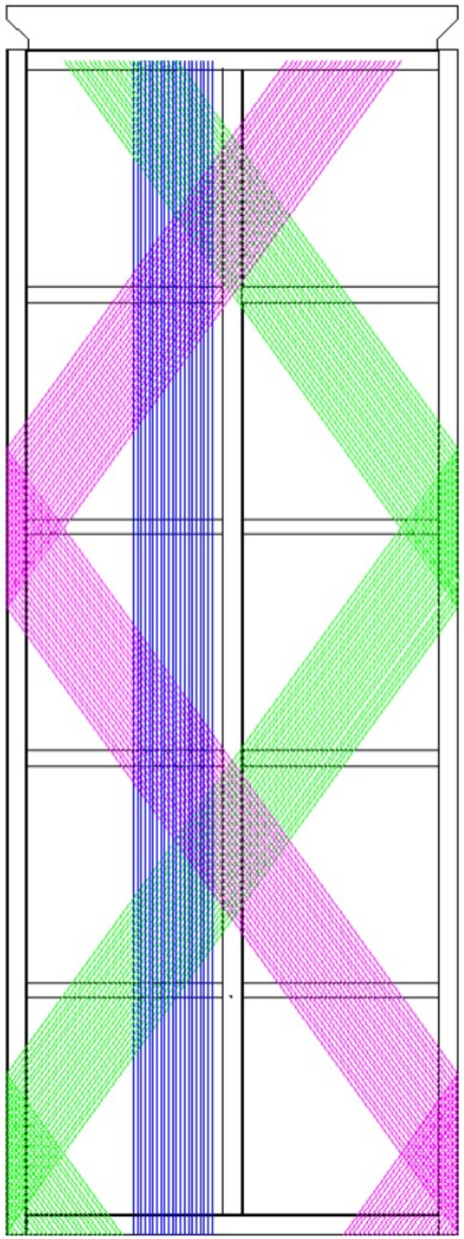
The Photon Detection system (**PDS**) is integrated into the APAs: bar-shaped light guide and wavelength-shifting (WS) layer, coupled to silicon photomultipliers (SiPMs)



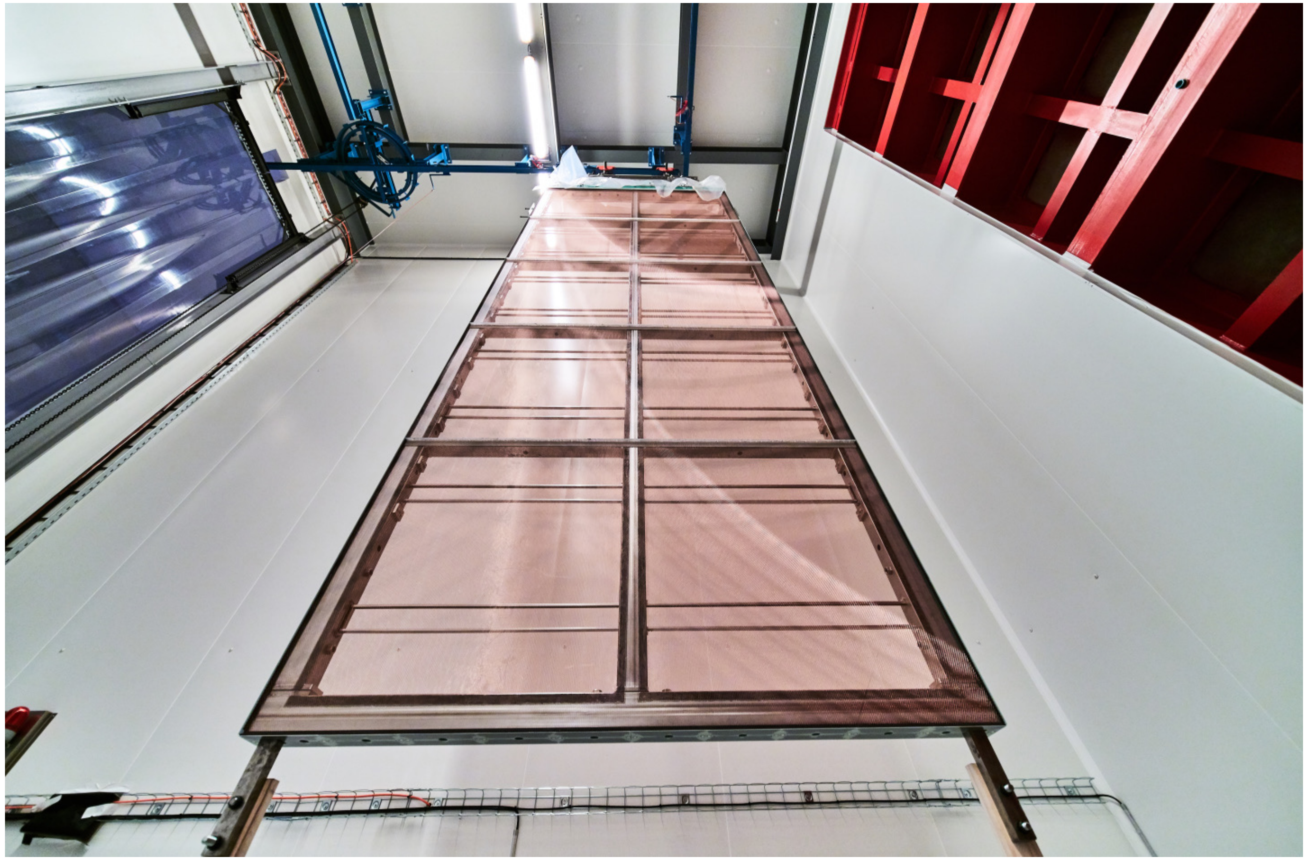
APAs

- A frame holds three parallel planes of wires oriented at different angles
- Two induction planes (U and V) at 35.7° degrees and a **collection plane** with vertical wires
- Pitch: 4.67 mm (U and V), 4.79 (W) – 2560 readout channels
- Each wire plane yields a 2D (wire coordinate, drift coordinate) image
- Key feature for reconstruction (will say more in following slides)
- Leading production role by the UK

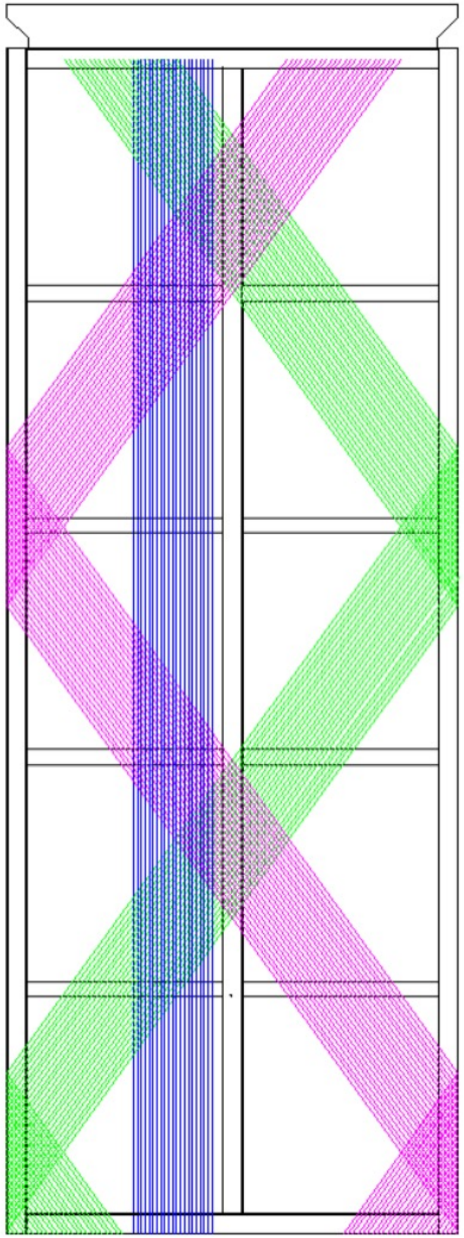
→ Reconstruction will rely on 3 × 2D images!



APAs

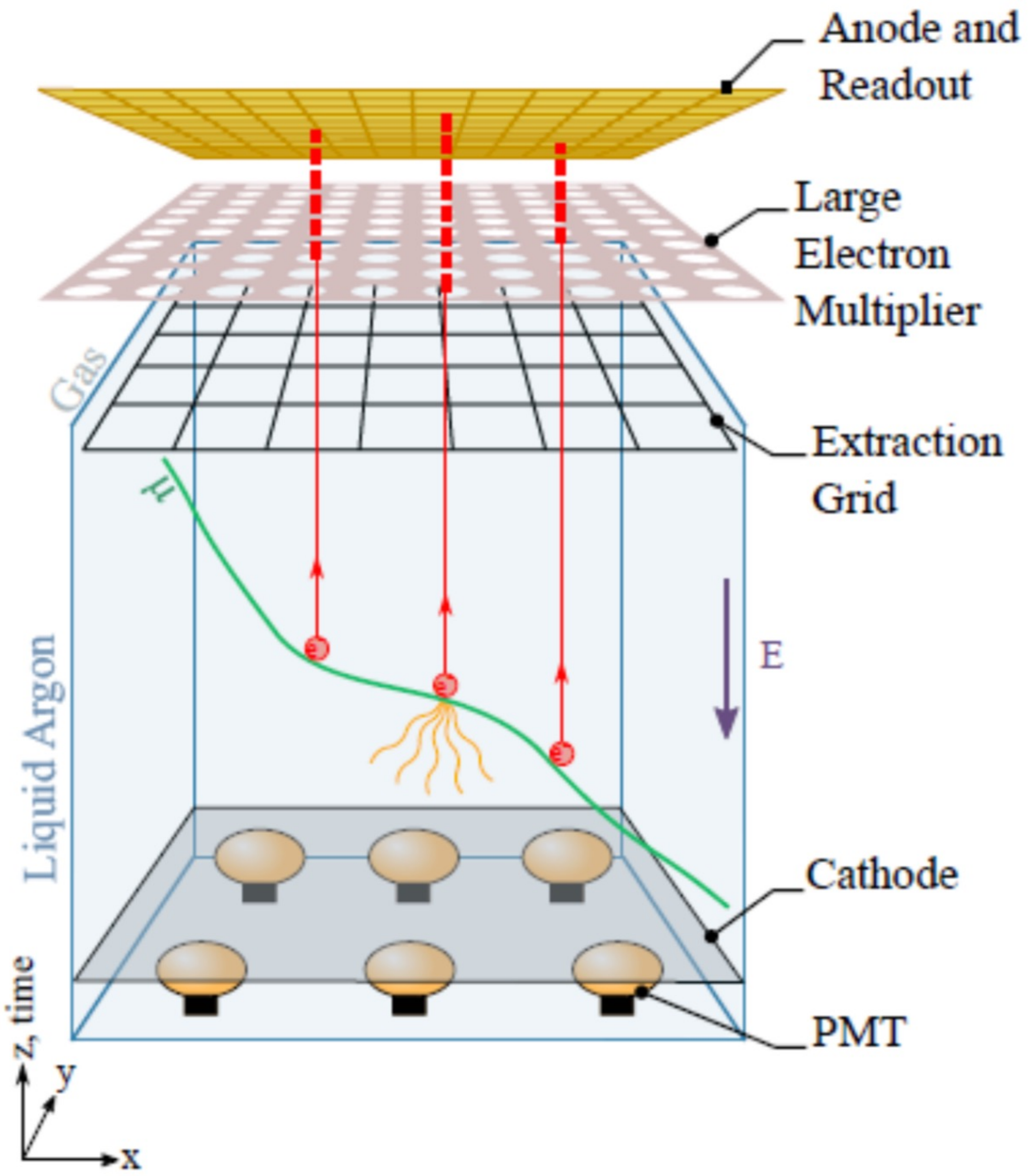


First APA ready to be installed in the protoDUNE-SP detector
Photograph: Ordan, Julien Marius



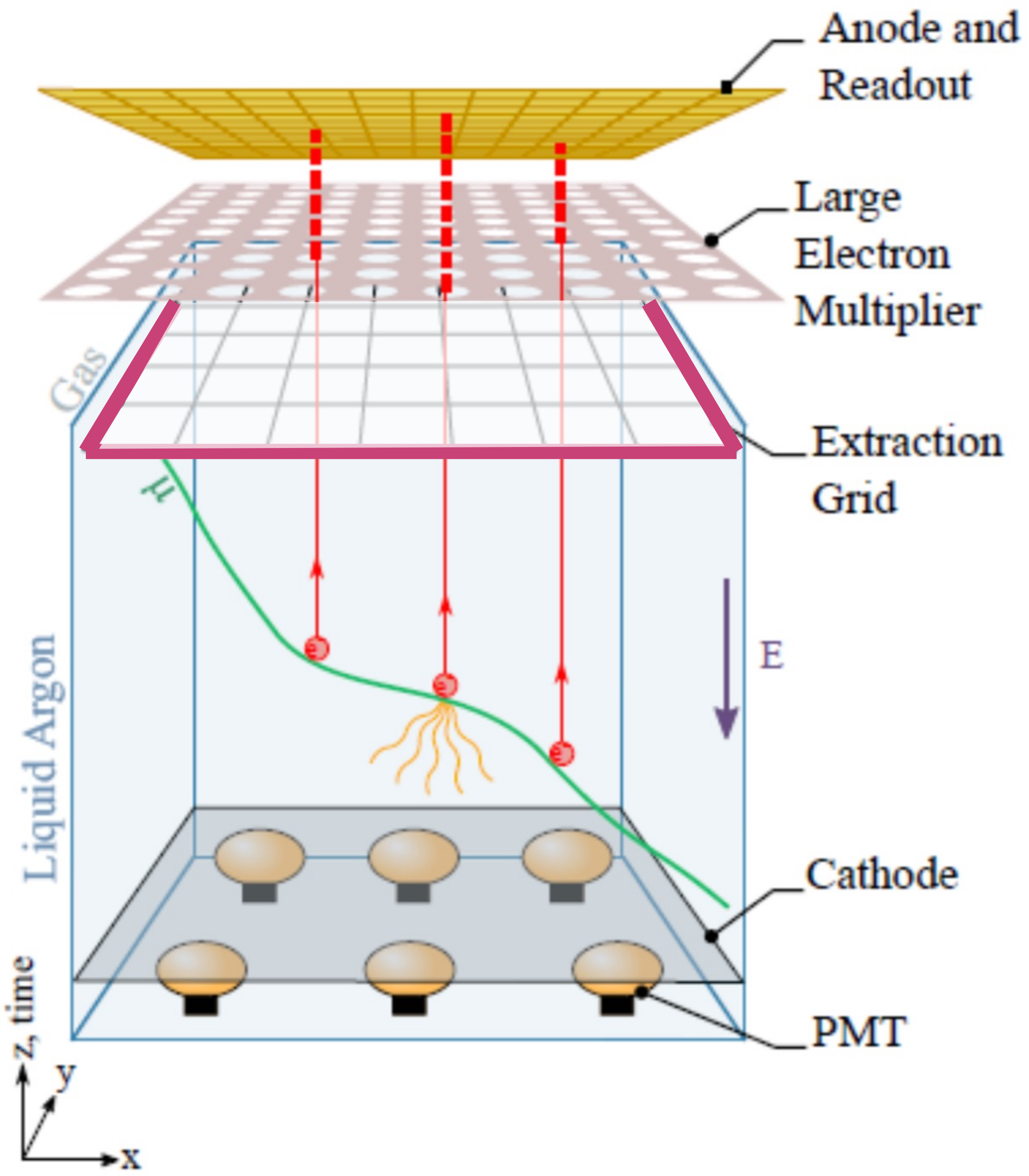
ProtoDUNE-DP

- 300 t dual-phase LArTPC prototype at CERN for the DUNE FD
- Vertical drift and one single TPC with active volume: $(6\times6\times6)\ \mathrm{m}^3$



ProtoDUNE-DP

- 300 t dual-phase LArTPC prototype at CERN for the DUNE FD
- Vertical drift and one single TPC with active volume: $(6\times6\times6)\ \mathrm{m}^3$
- **Ionization event → 3D position**
- Ionization electrons drift vertically towards extraction grid and charge readout planes (**CRPs**)

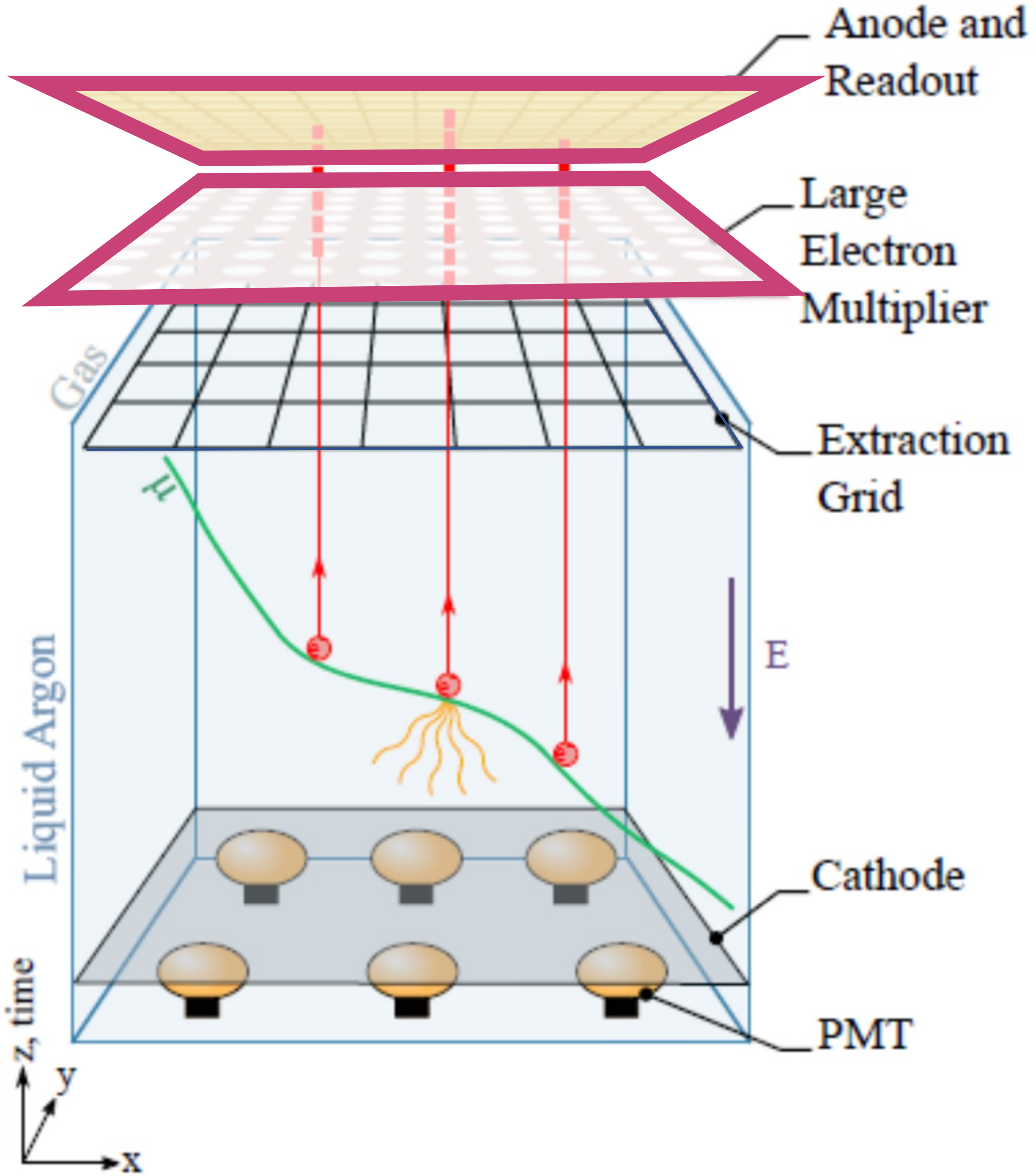


ProtoDUNE-DP

- 300 t dual-phase LArTPC prototype at CERN for the DUNE FD
- Vertical drift and one single TPC with active volume: $(6\times6\times6)\ \mathrm{m}^3$
- **Ionization event → 3D position**
- Ionization electrons drift vertically towards extraction grid and **charge readout planes** (**CRPs**)

CRP = sandwich of **anode**
(two strip-based collection views)
+ 36 Large Electron Multipliers (LEMs)

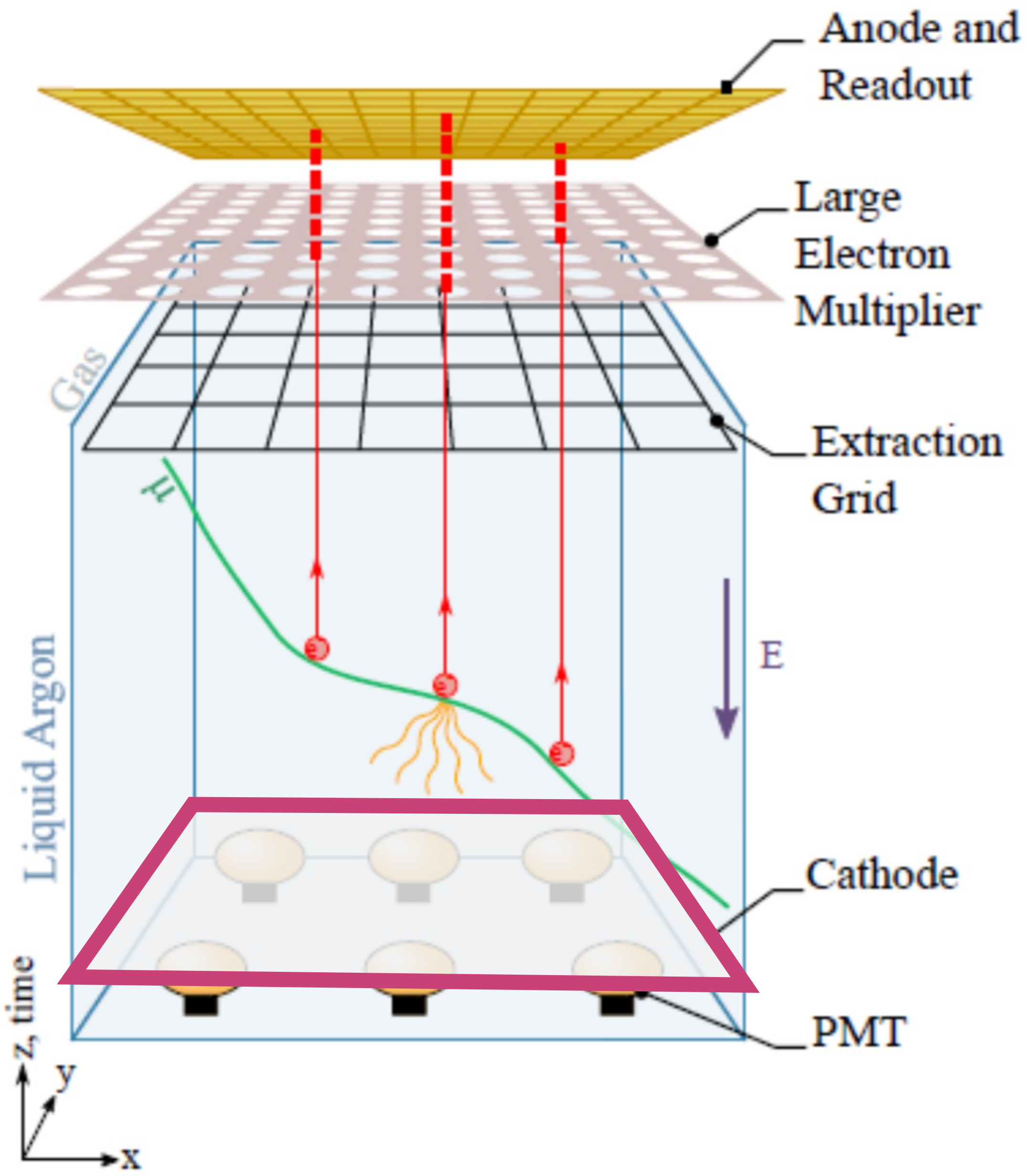
→ Reconstruction will rely on 2 × 2D images!



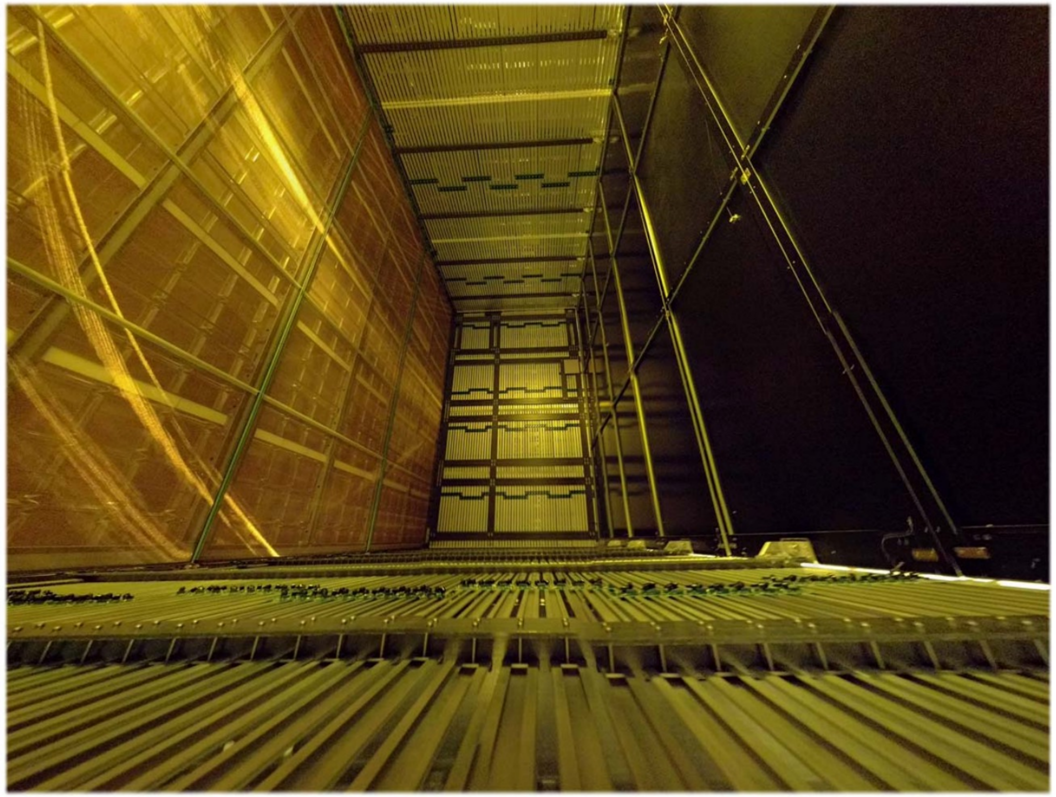
ProtoDUNE-DP

- 300 t dual-phase LArTPC prototype at CERN for the DUNE FD
- Vertical drift and one single TPC with active volume: $(6\times6\times6)\ \mathrm{m}^3$
- **Ionization event → 3D position**
- Ionization electrons drift vertically towards extraction grid and charge readout planes (**CRPs**)
- **Scintillation light → event timing**

Array of 36 photomultiplier tubes (**PMTs**) below **cathode** detect scintillation light

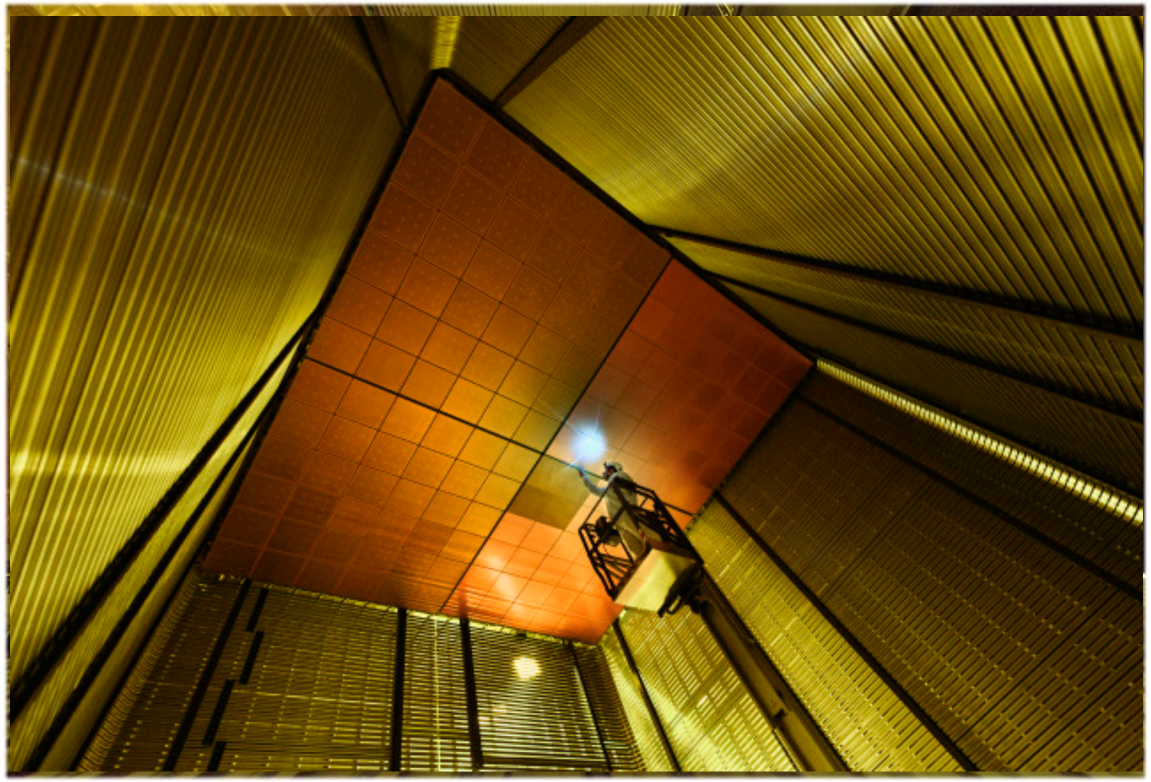


ProtoDUNE photos



A ProtoDUNE-SP drift volume

DUNE Project Monthly Status Report March 2018



Inside ProtoDUNE-DP

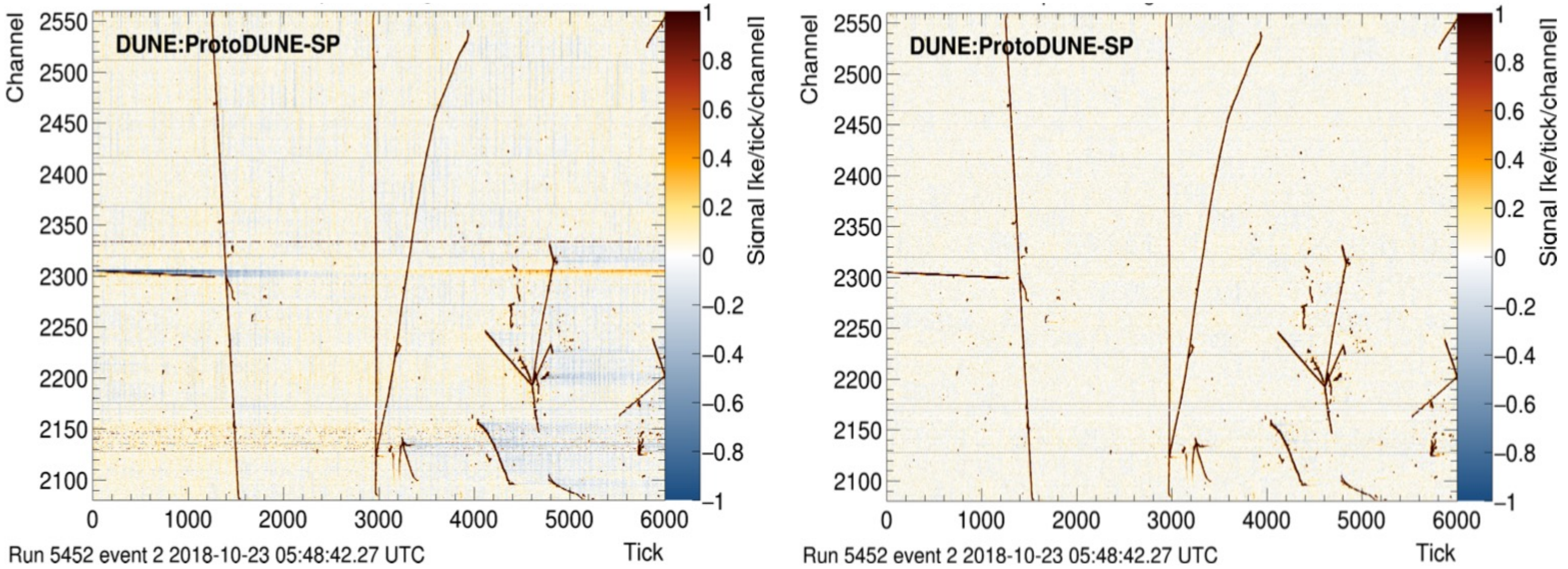
cds.cern.ch/images/CERN-PHOTO-201902-023-1

How to go from raw data to physics quantities for analysis?

- **Data preparation: ADC counts → charge waveform**

Evaluation of pedestals, charge calibration, mitigation of readout issues, tail removal, noise suppression

Background reduction on collection plane
(a): after pedestal subtraction/calibration
(b): After ADS/time mitigation and tail/noise removal
JINST 15 (2020) P12004



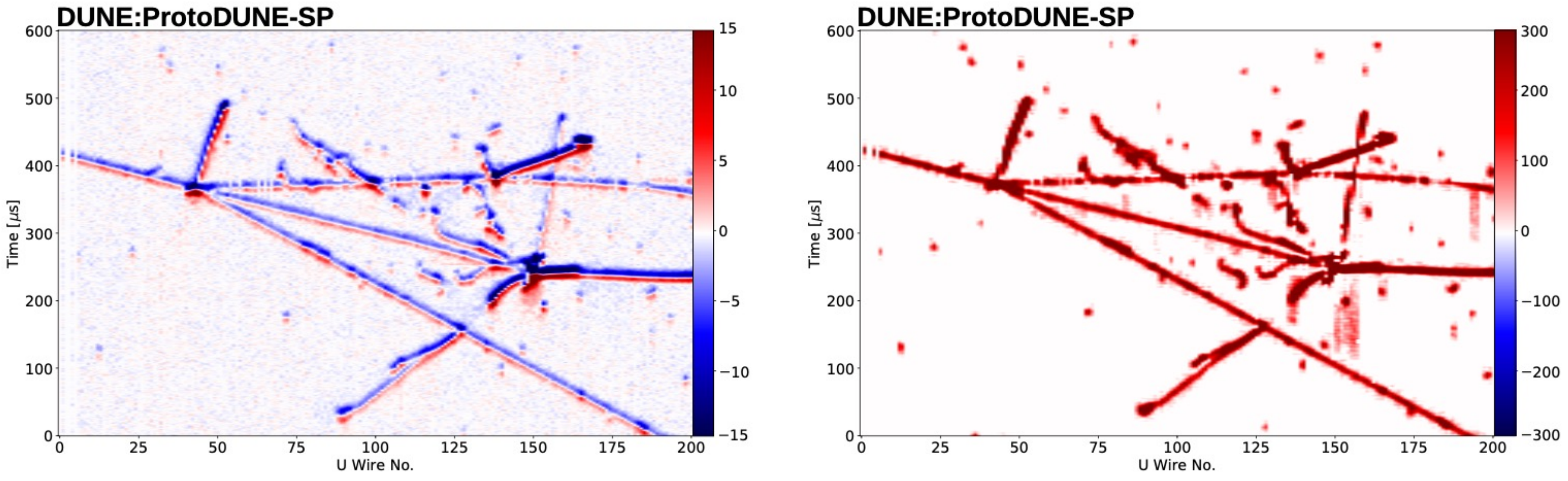
Event Reconstruction Chain

How to go from raw data to physics quantities for analysis?

- **Signal processing: charge waveform → arrival time and position**

Deconvolve drift field and front-end electronics response

Interaction vertex from 7-GeV beam particle (induction plane)
(a): raw waveform ADC counts
(b): ionization charge after 2D deconvolution
JINST 15 (2020) P12004



(a) After Noise Filtering (b) After Deconvolution

Event Reconstruction Chain

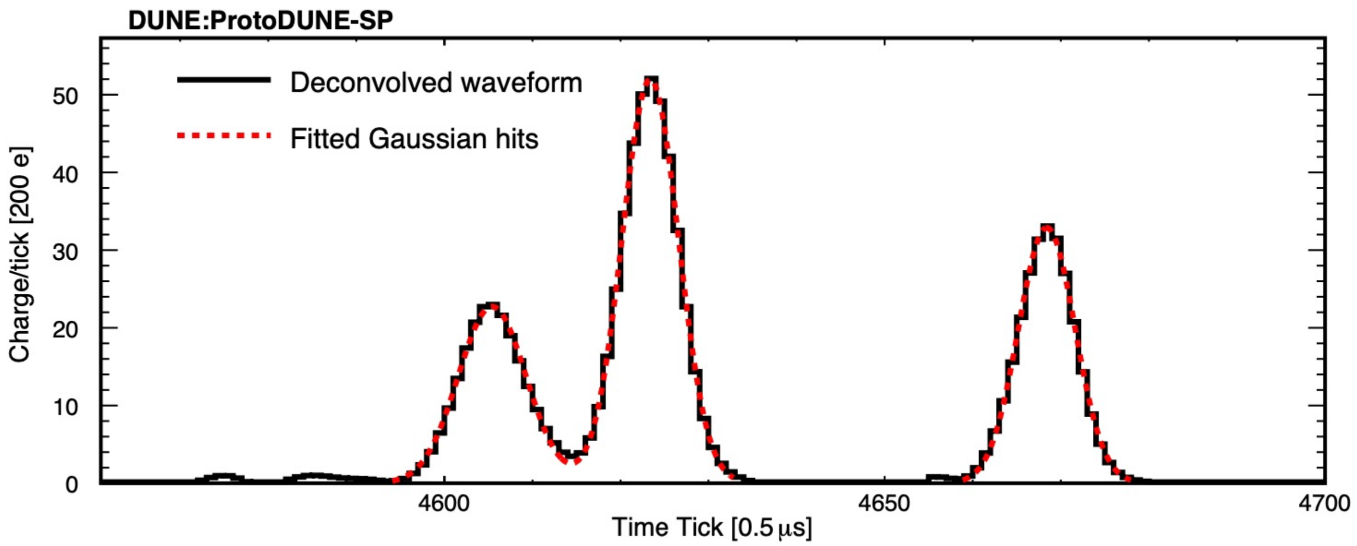
How to go from raw data to physics quantities for analysis?

- **Low-level event reconstruction: hit finding**

Find peaks in wire waveforms and fit them to Gaussians

Hit: charge deposition on a single wire at a single time

Example of reconstructed waveform on a single wire (ProtoDUNE-SP data)
JINST 15 (2020) P12004



Event Reconstruction Chain

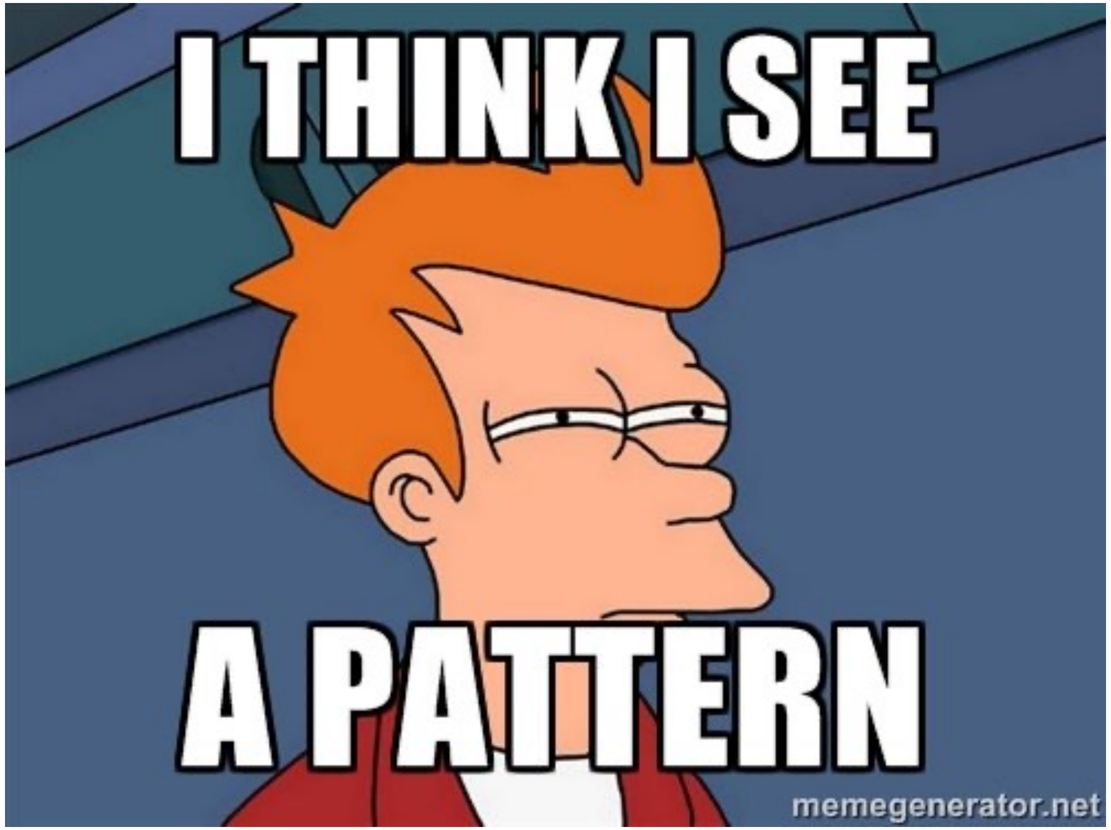
How to go from raw data to physics quantities for analysis?

- **Pattern recognition:**
  the bit you do by eye!

(A lot about that in the next slides…)

- **High-level characterization**

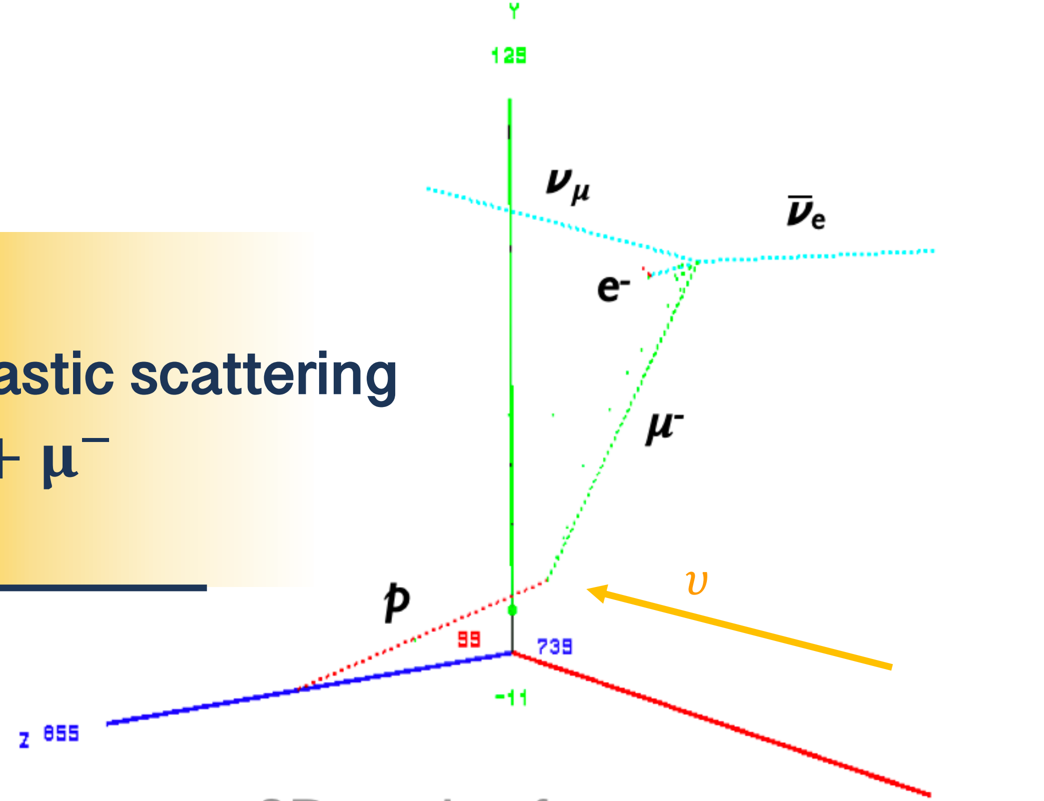
Particle ID, neutrino flavour and interaction type, energy…



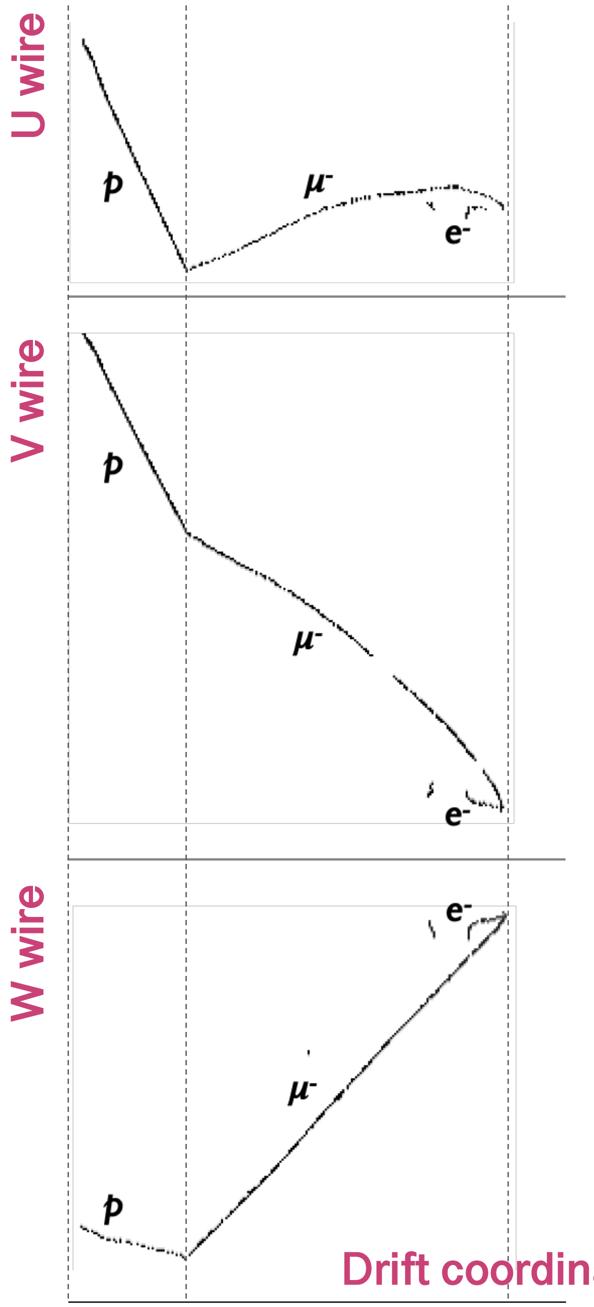
Inputs to Pattern Recognition

- **2D hit representations** in the plane of **wire/strip number** versus **common x coordinate**, derived from drift time

Example
Charged current quasi elastic scattering (CC QE) $\nu_\mu + Ar \rightarrow p + \mu^-$
followed by muon decay



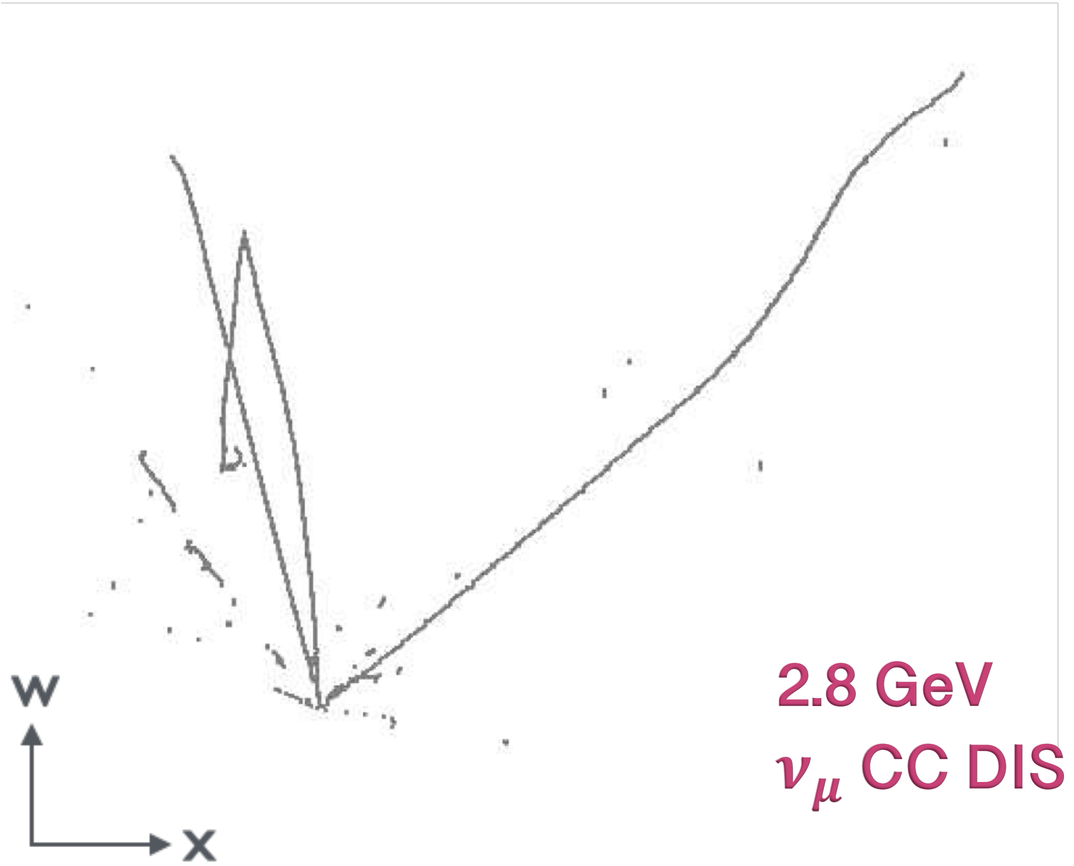
3D truth information

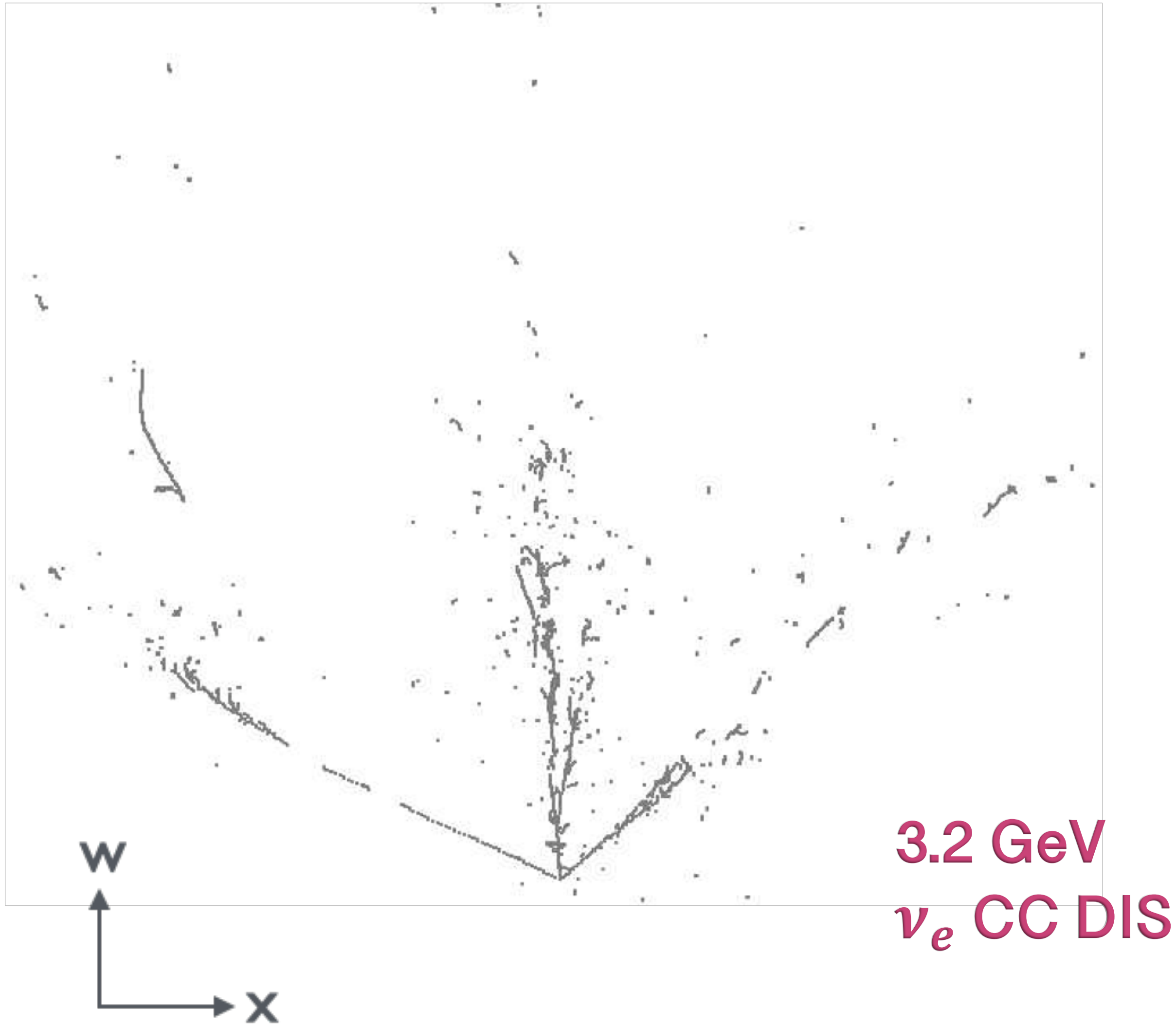


Drift coordinate

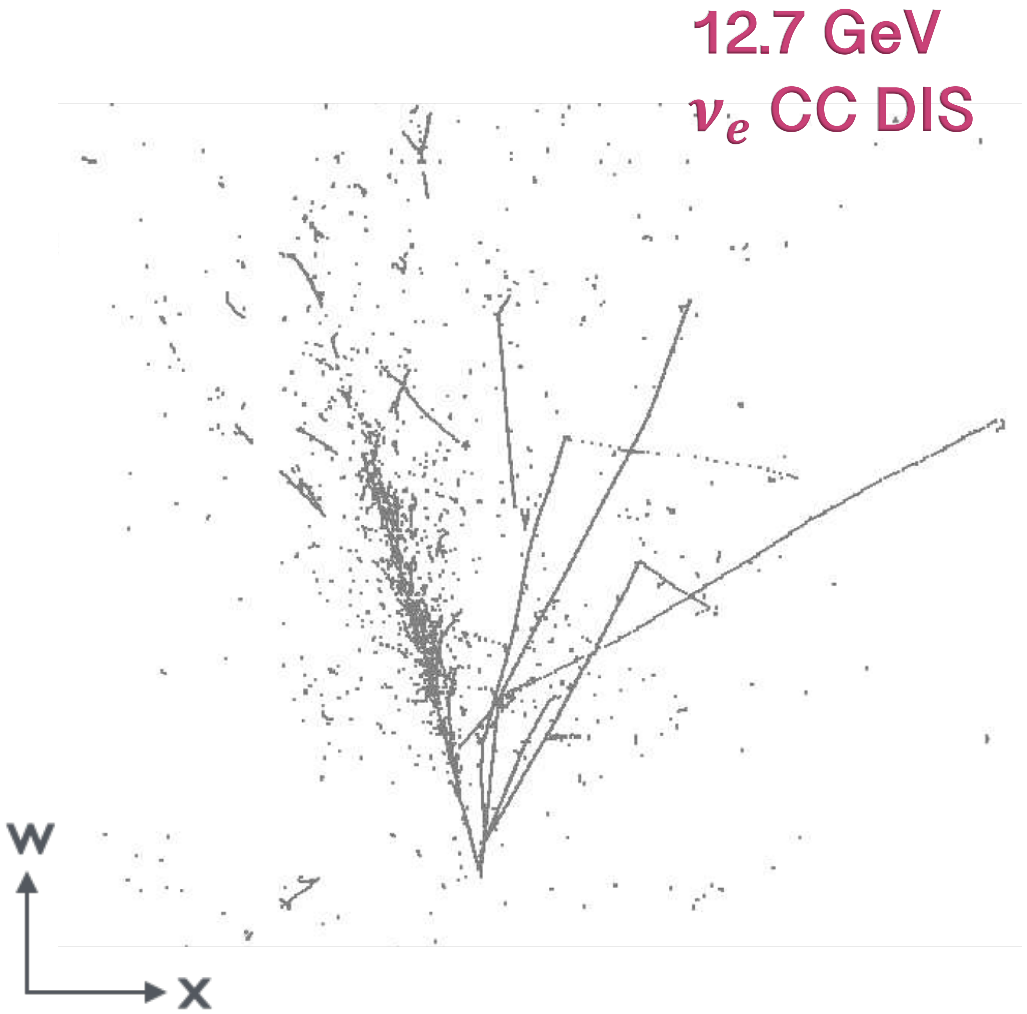
Pattern Recognition Challenges

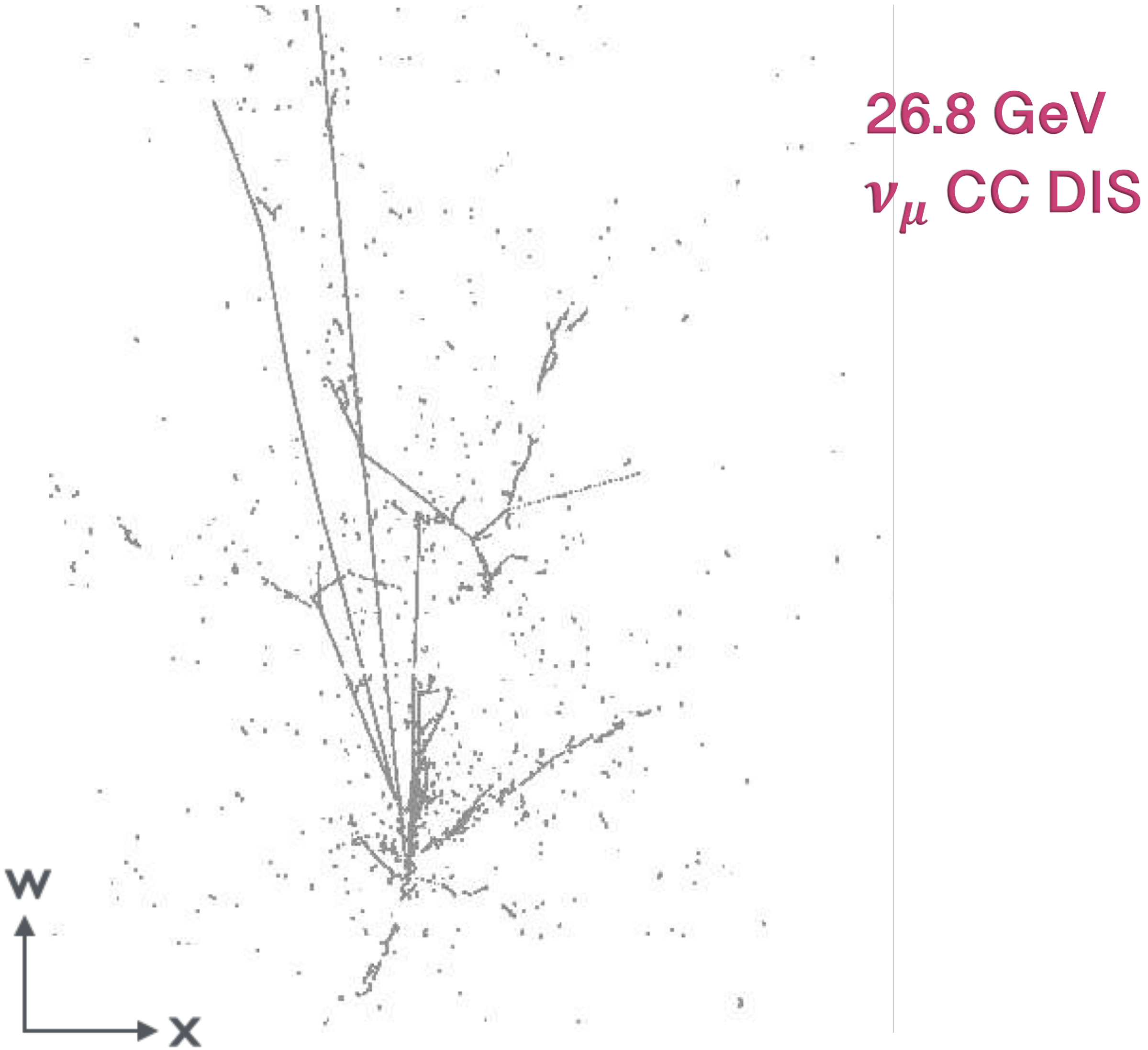
Complex, diverse topologies





Pattern Recognition Challenges

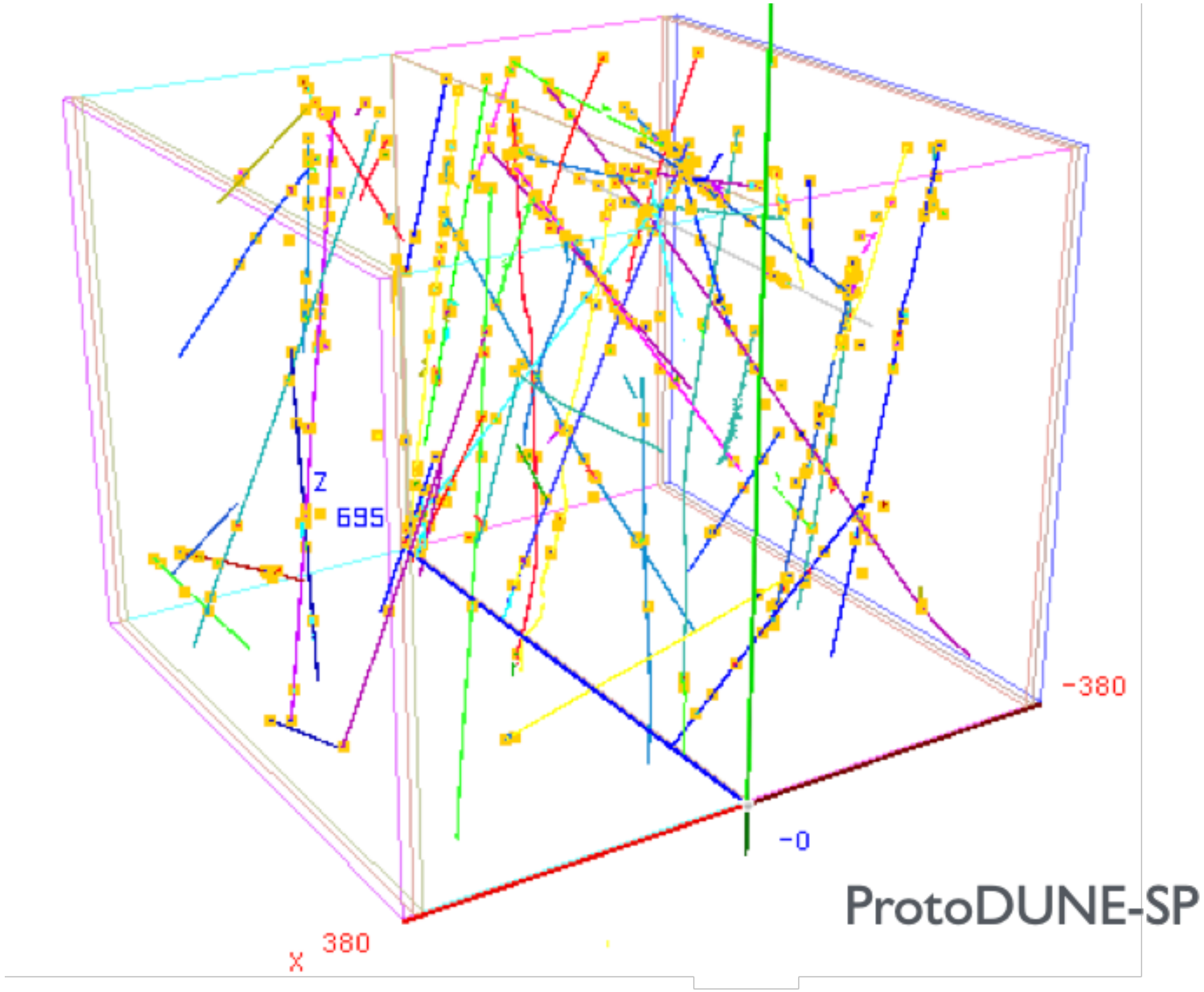




Pattern Recognition Challenges

- Long exposures due to lengthy drift times (~ms)
  → significant cosmic ray background in surface-based detectors

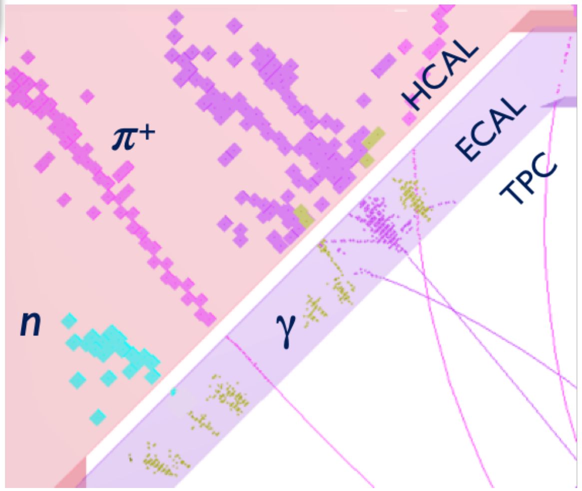
Single clustering approach unlikely to work for such complex topologies!



The Pandora Multi-Algorithm Approach

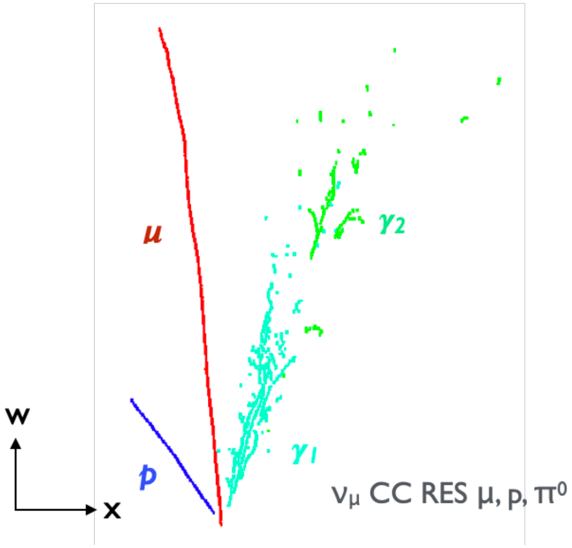
- Pandora uses a **multi-algorithm** approach
  - Build up events gradually
  - Large numbers of algorithms, each addressing specific event topologies - more sophisticated as picture of event develops
  - Each step is incremental - aim not to make mistakes
  - Build physics and detector knowledge into algorithms

"Tried and tested" approach:
ILC/CLIC, SBND, Icarus, MicroBooNE…



Typical ILC event topologies - 3D
NIMA.2009.09.009 NIMA.2012.10.038

BNB interaction at MicroBooNE - 3 x 2D



Two Main Algorithm Chains

Two chains created for LArTPC use, with many algorithms 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/TestBeam

- Nu chain used for neutrino interactions at the DUNE FD, test beam chain used for ProtoDUNE
- **Very similar chains**: find interaction vertex and protect all particles emerging from vertex position
- Careful treatment to address track/shower tensions

More than 140 algorithms in total

Two Main Algorithm Chains

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2D Reconstruction

3D Track Reconstruction

Delta-Ray Reconstruction

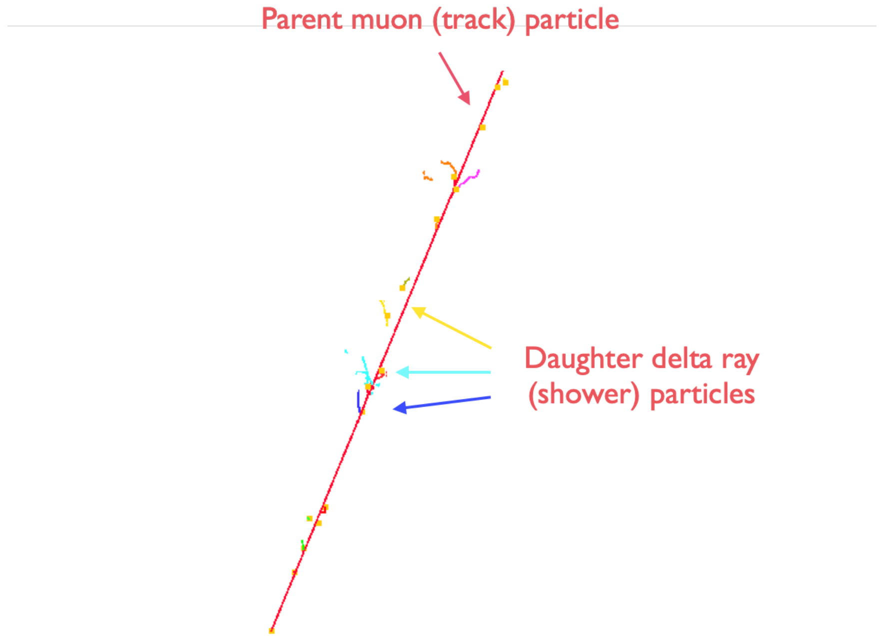
3D Hit Reconstruction

More than 140 algorithms in total

Two Main Algorithm Chains

Two chains created for LArTPC use, with many algorithms in common

PandoraCosmic



- 2D Reconstruction
- 3D Track Reconstruction
- Delta-Ray Reconstruction
- 3D Hit Reconstruction

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Two Main Algorithm Chains

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2D Reconstruction

3D Track Reconstruction

Delta-Ray Reconstruction

3D Hit Reconstruction

More than 140 algorithms in total

Two Main Algorithm Chains

Two chains created for LArTPC use, with many algorithms in common

- 2D Reconstruction
- 3D Vertex Reconstruction
- Track and shower Reconstruction
- Particle Refinement
- Particle Hierarchy Reconstruction

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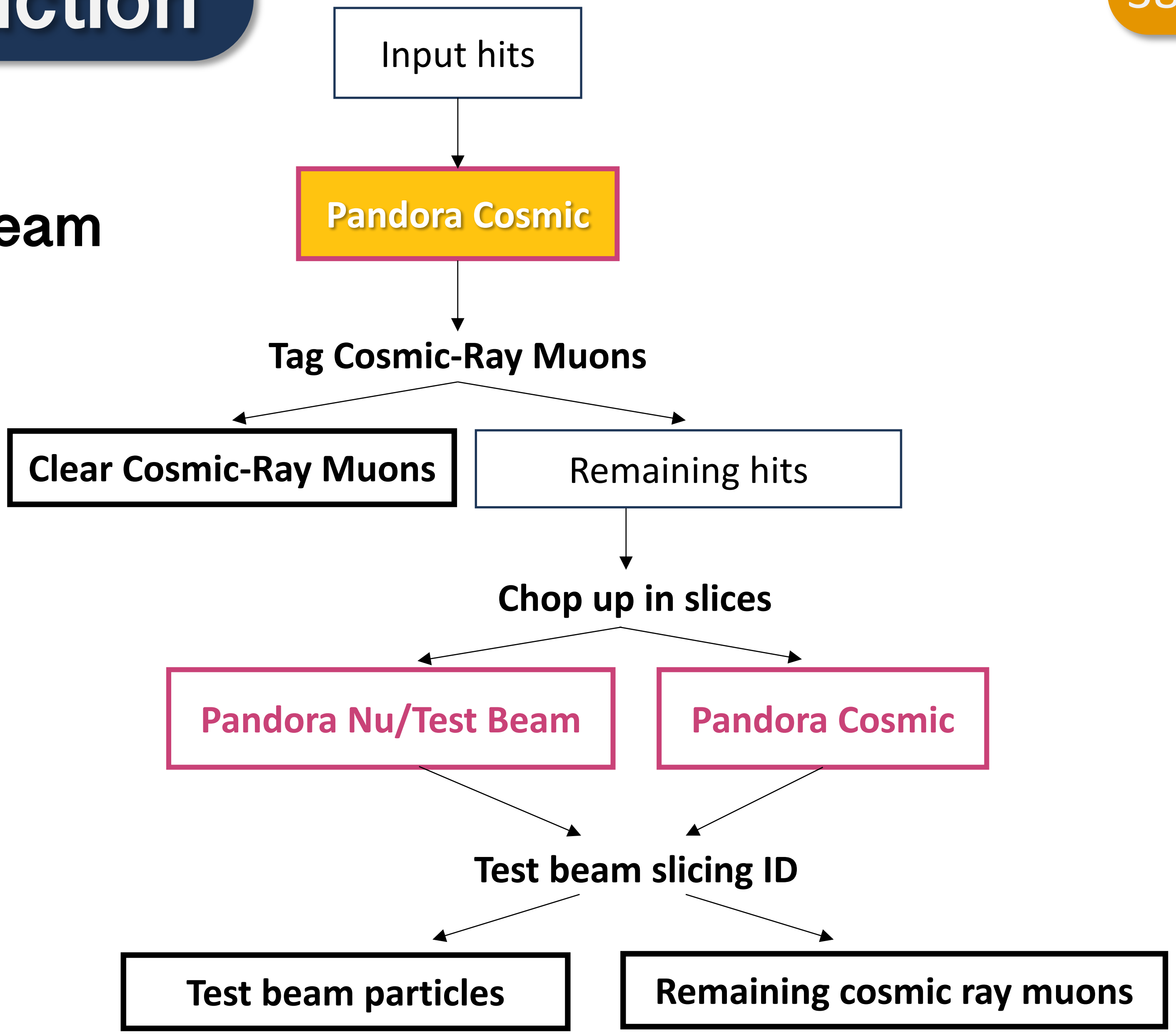
- Nu chain used for neutrino interactions at the DUNE FD, test beam chain used for ProtoDUNE
- **Very similar chains**: find interaction vertex and protect all particles emerging from vertex position
- Careful treatment to address track/shower tensions

More than 140 algorithms in total

Consolidated Reconstruction

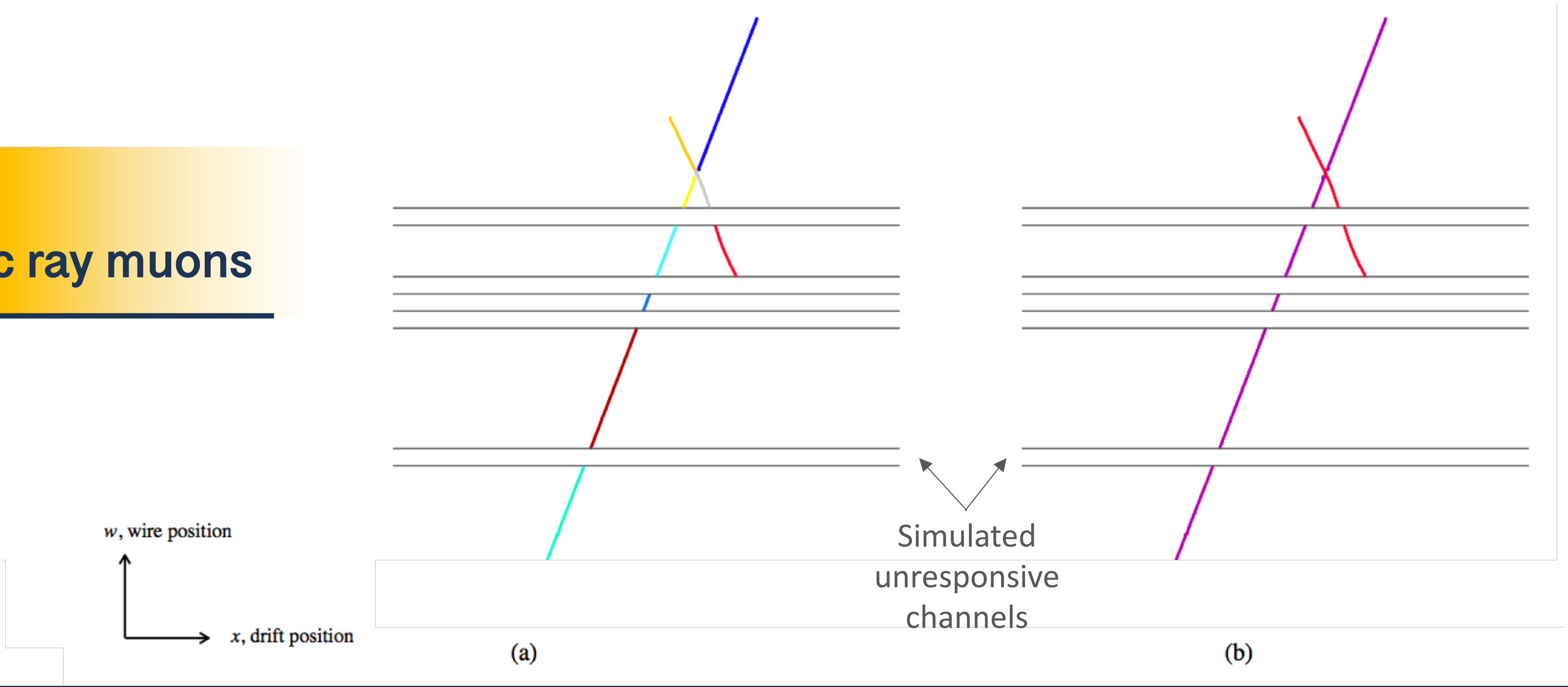
- Two algorithm chains:
  Cosmic and Neutrino/**Test Beam**

1. Cosmic reconstruction on all particles
2. Clear cosmic muons tagged
3. 3D slicing on remaining hits
4. Cosmic and Test Beam reconstruction on each slice
5. Best output selected



- 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 algorithms

Example
Crossing cosmic ray muons



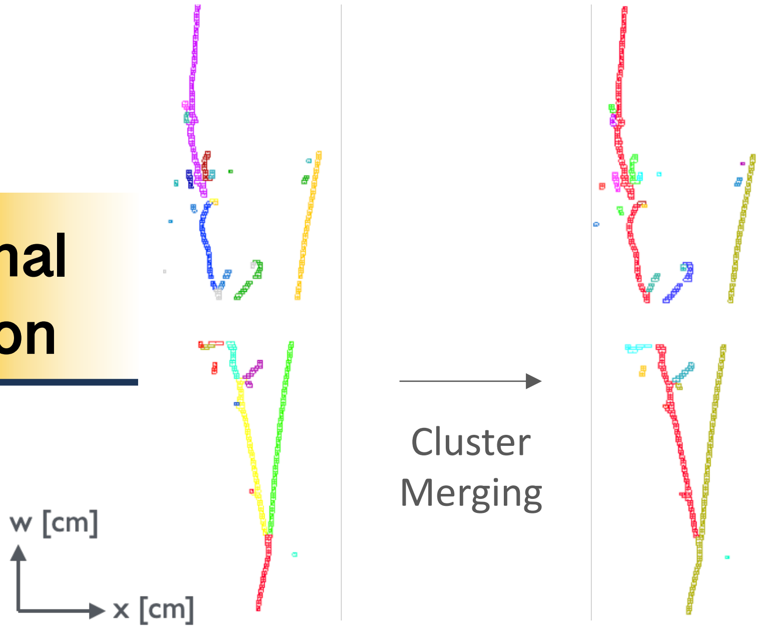
2D Topological Association

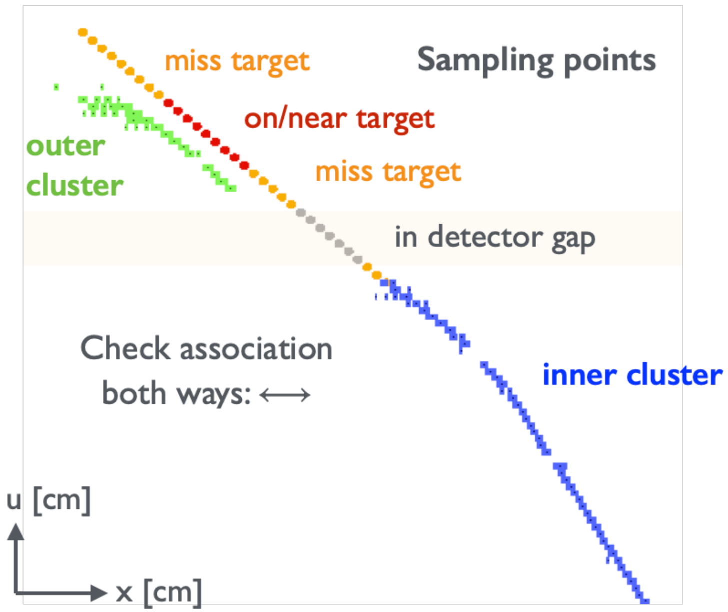
- E.g. **cluster-merging algorithms** identify associations between multiple 2D clusters → grow the clusters to improve completeness, without compromising purity

$$\text{Completeness} = \frac{\#\text{ shared MC}-\text{reco hits}}{\#\text{ hits in MC particle}} \qquad \text{Purity} = \frac{\#\text{ shared MC}-\text{reco hits}}{\#\text{ hits in reco cluster}}$$

- Make cluster-merging decisions in the context of the **entire event**

Longitudinal Association

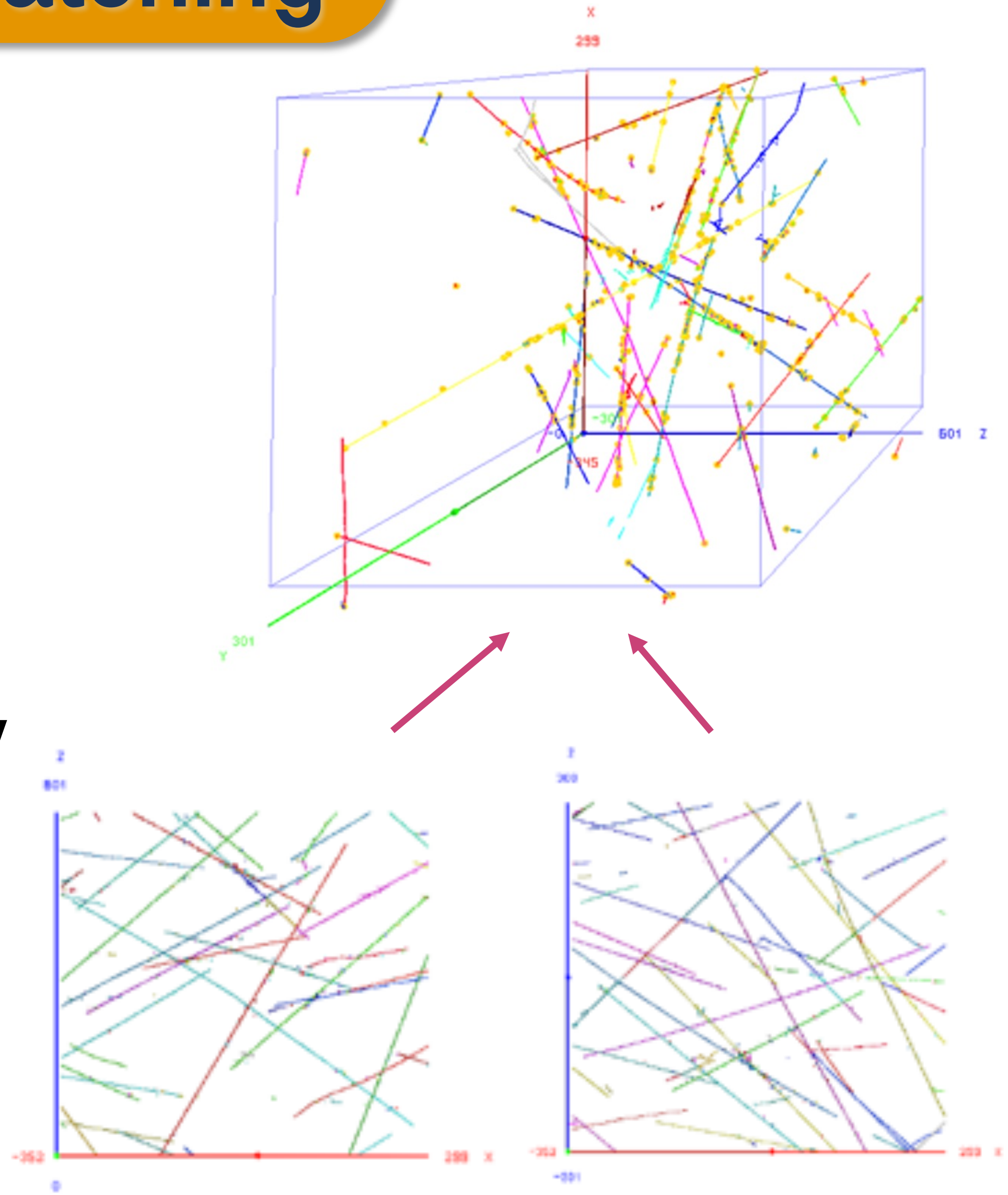




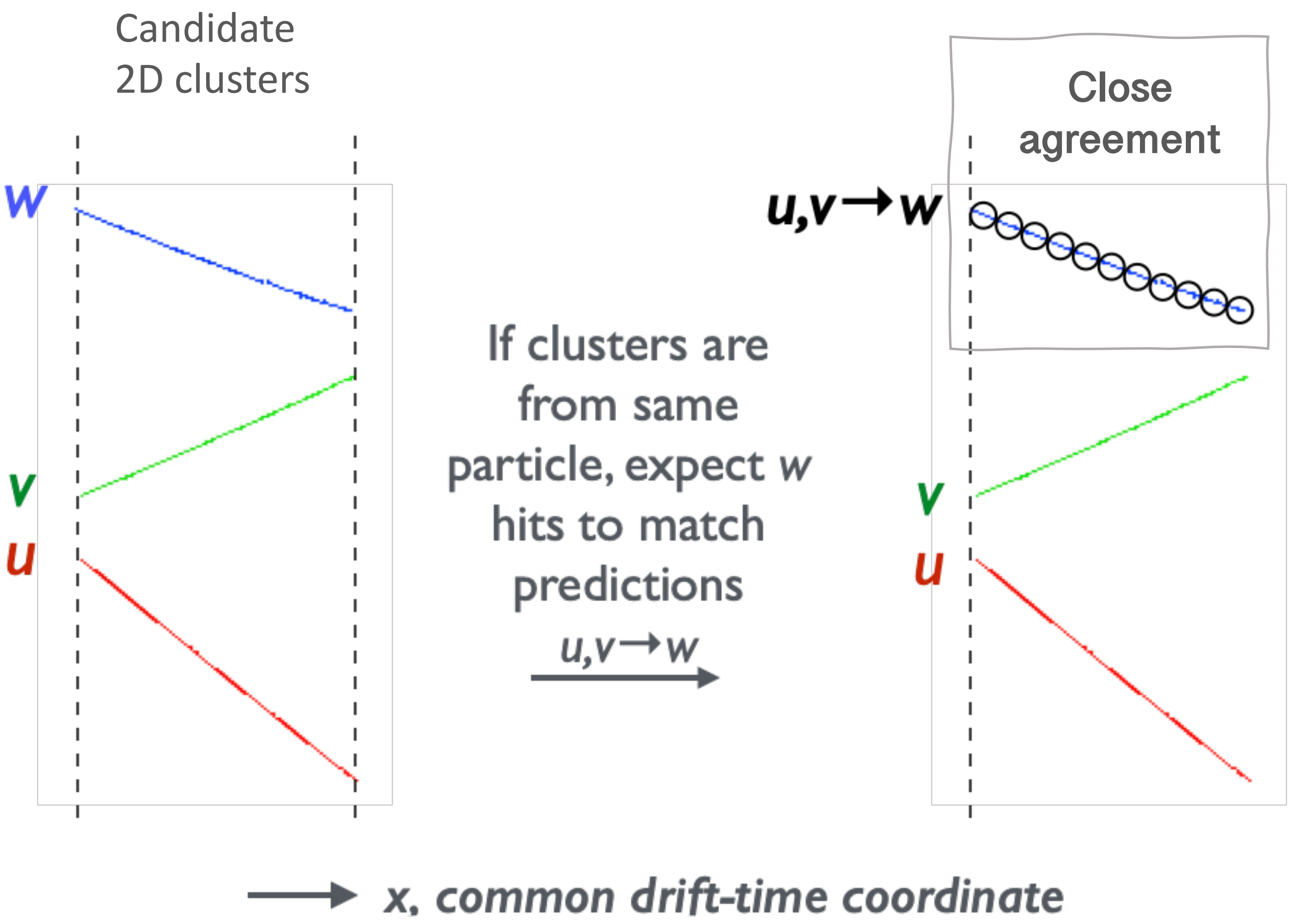
CrossGaps Association

2D → 3D Matching

- **Aim:** **match 2D clusters across views to reconstruct 3D trajectories**
- Only two non-parallel views required, but **redundant information** often necessary to correctly identify matches
- In three-view detectors such as ProtoDUNE-SP we exploit the **redundancy** to match clusters between views
- For two-view detectors such as ProtoDUNE-DP, we utilise **calorimetric information**



- Three separate 2D clusters for each particle
- Compare 2D clusters from three planes to find those representing same particle
- Exploit common drift-time coordinate and wire plane geometry
- In overlap region, compare predictions with cluster positions { *u*, *v* → *w*, *v*, *w* → *u*, *w*, *u* → *v* }

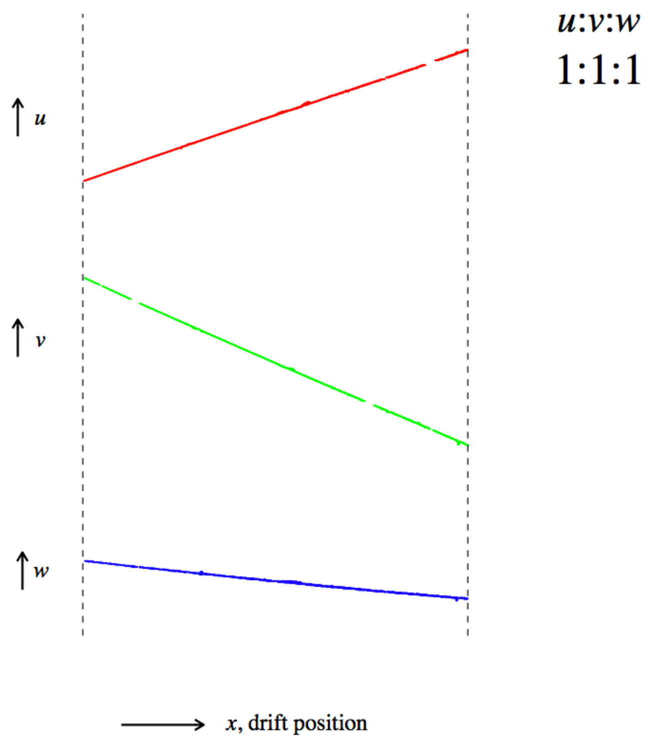


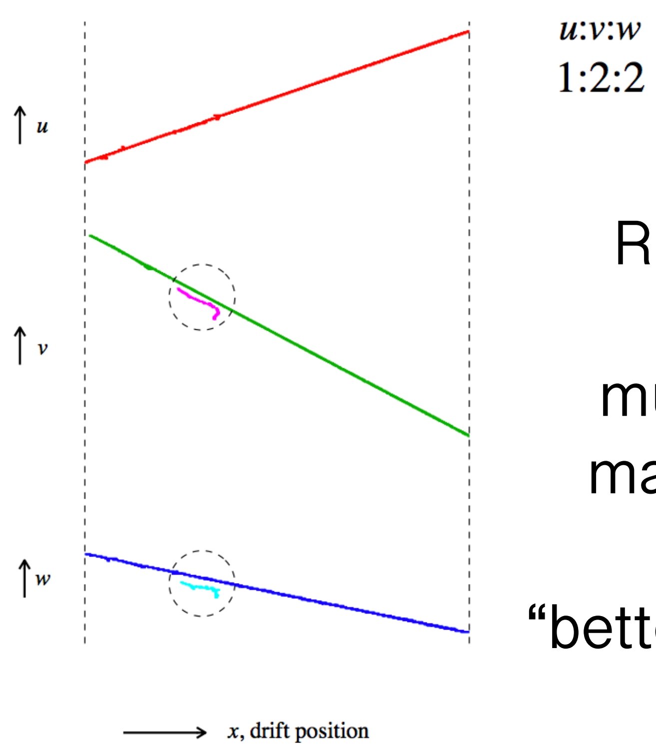
Calculate χ^2 and store all results in 3D array with overlap span and n. sampling points

- Tools use information in 3D array to make 2D reconstruction changes to **resolve any ambiguities**. If a tool makes a change (e.g. splits a cluster), all tools run again.

Clear Tracks Tool

Find unambiguous elements demanding common x-overlap > 90% for all three clusters.





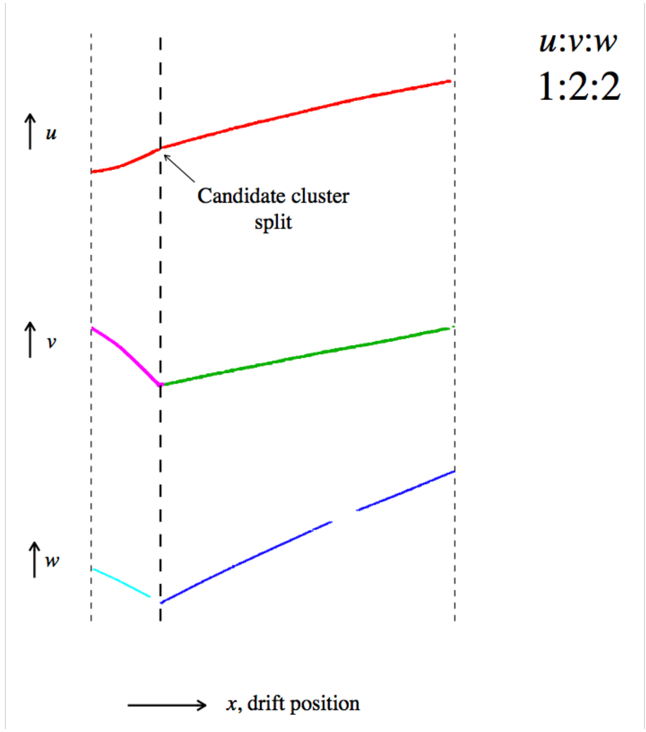
Long Tracks Tool

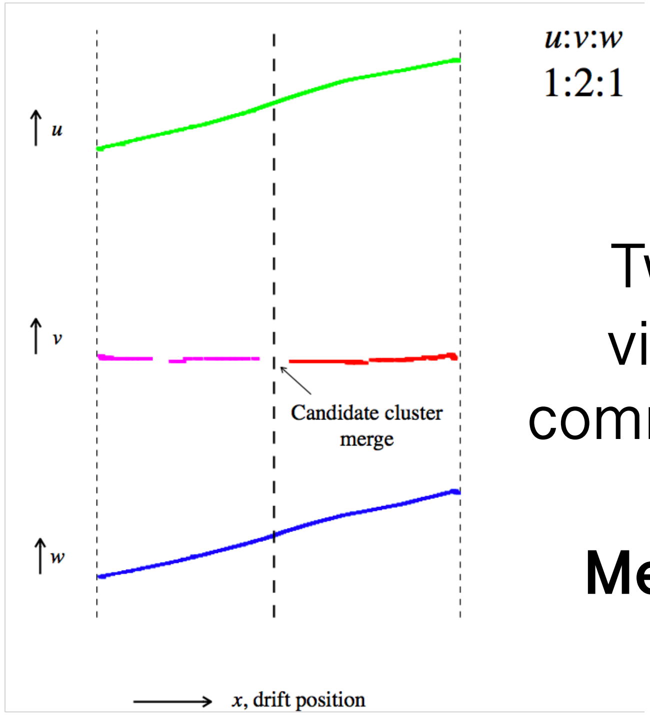
Resolve **obvious** ambiguities: multiple possible matches, but one element much "better" than others

- 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 details

Overshoot Tracks Tool

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



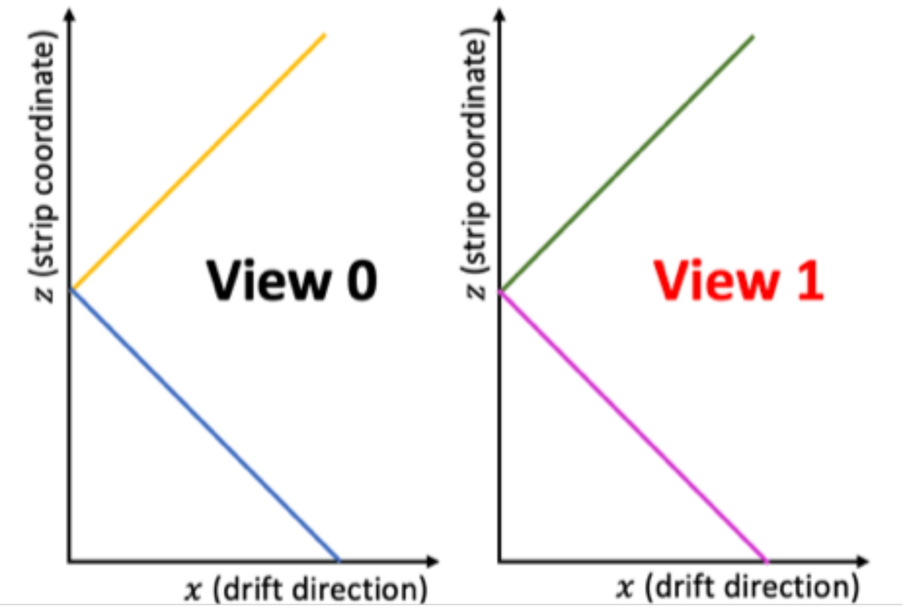


Undershoot Tracks Tool

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

- 2 Views only : **no redundancy** to be exploited, can only match end points
  → the reconstruction can struggle to make correct matches

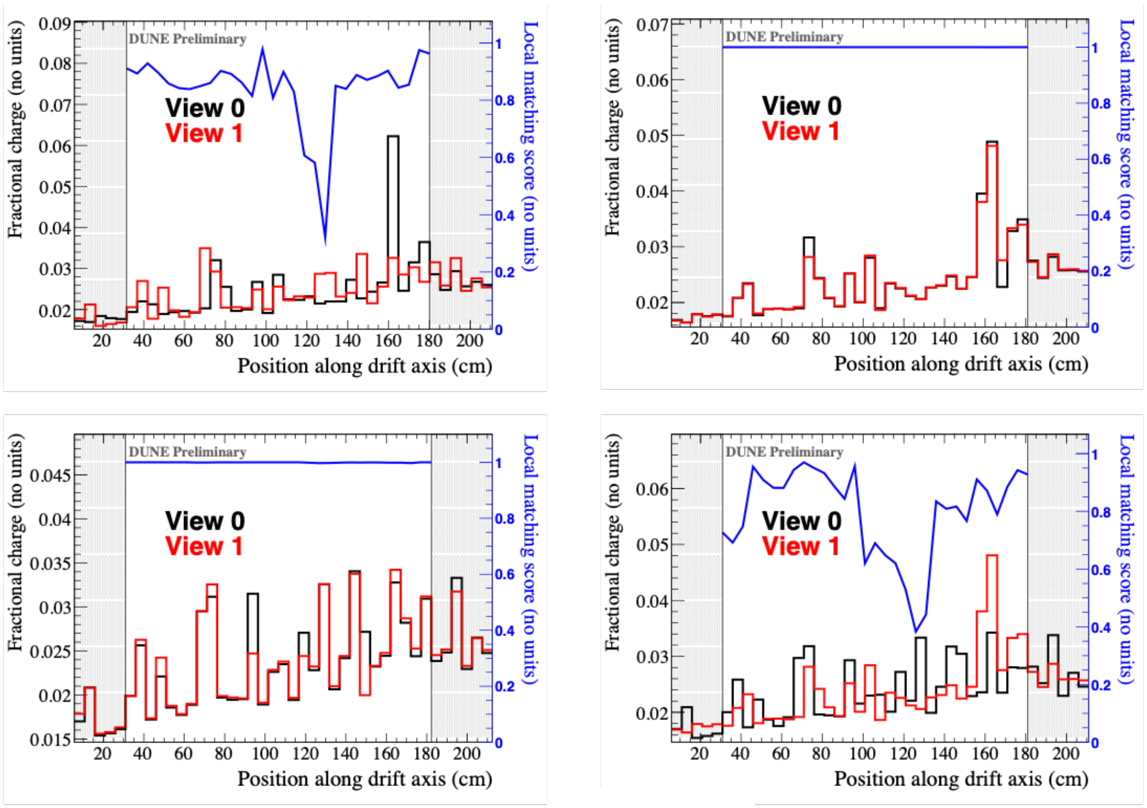
- Example: di-muon particle gun Monte Carlo event in ProtoDUNE-DP



Calorimetric matching procedure

- Identify all cluster combinations
- For each combination, identify overlap region in drift coordinate

- For each possible pair, build fractional charge profiles
- Slide an 11-bin wide window across the profiles, and for each calculate **local matching score**: L = 1 - p-value*
associated to centre of profile region under window (blue curve)
- If correct match, L consistently close to 1
If wrong match, L uniform between 0 and 1
- **Locally matched fraction =** fraction of L values above threshold (0.99)



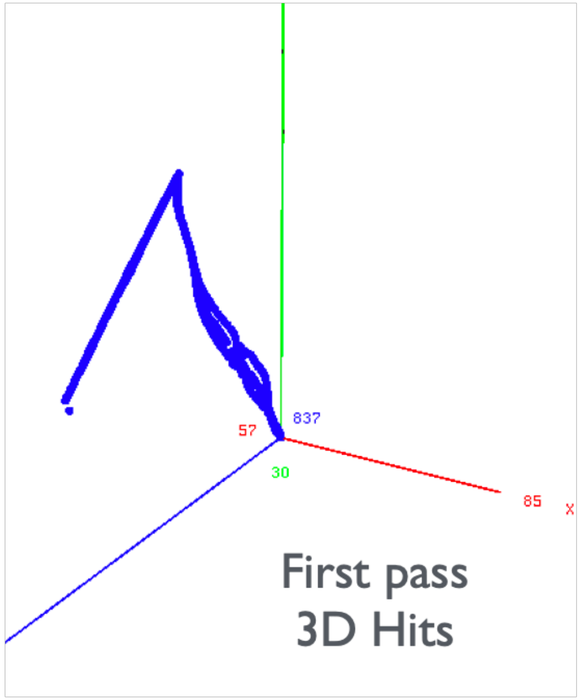
Di-muon particle gun Monte Carlo particle event in ProtoDUNE-DP

Store all results in 2D array with locally matched fraction, n. locally matched points, etc.

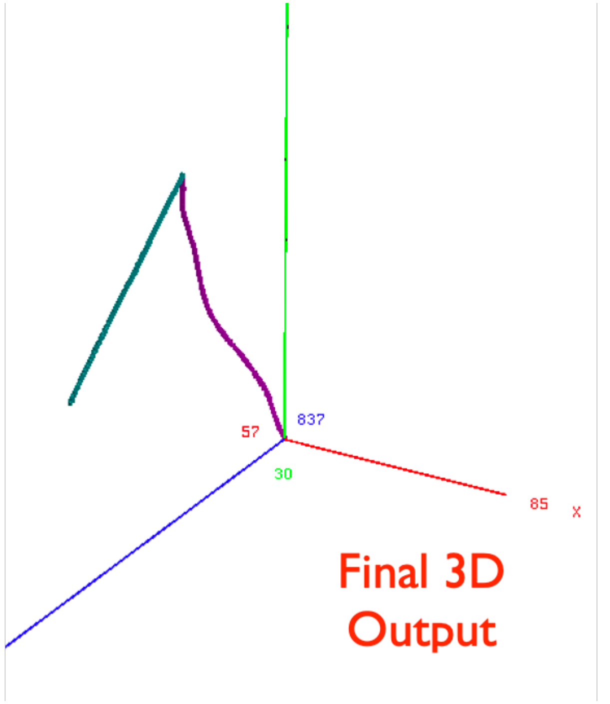
*(p-value for measuring a correlation coefficient (*r*), assuming true *r*=0)

3D Space Points

- 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}



→

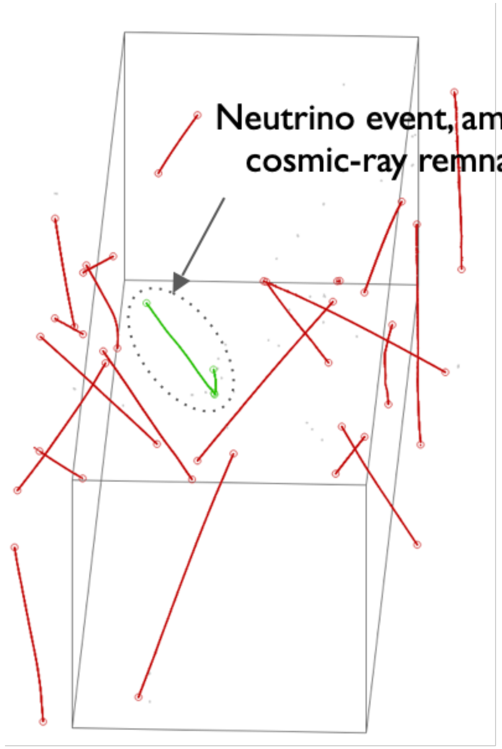


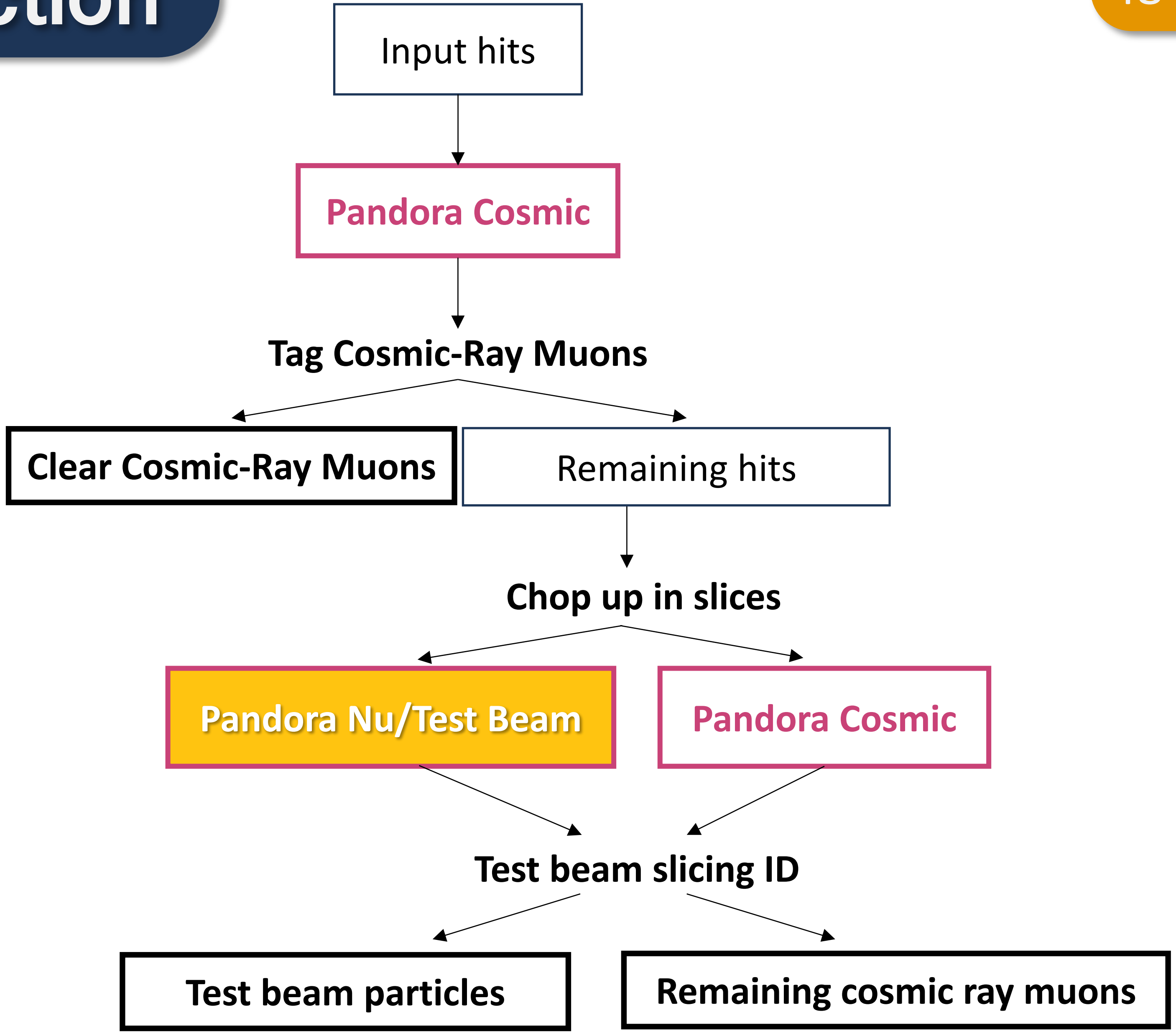
$$\chi^2 = (u_{out} - u_{in})^2/\sigma_u^2 + (v_{out} - v_{in})^2/\sigma_v^2 + (w_{out} - w_{in})^2/\sigma_w^2$$

- 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

Consolidated Reconstruction

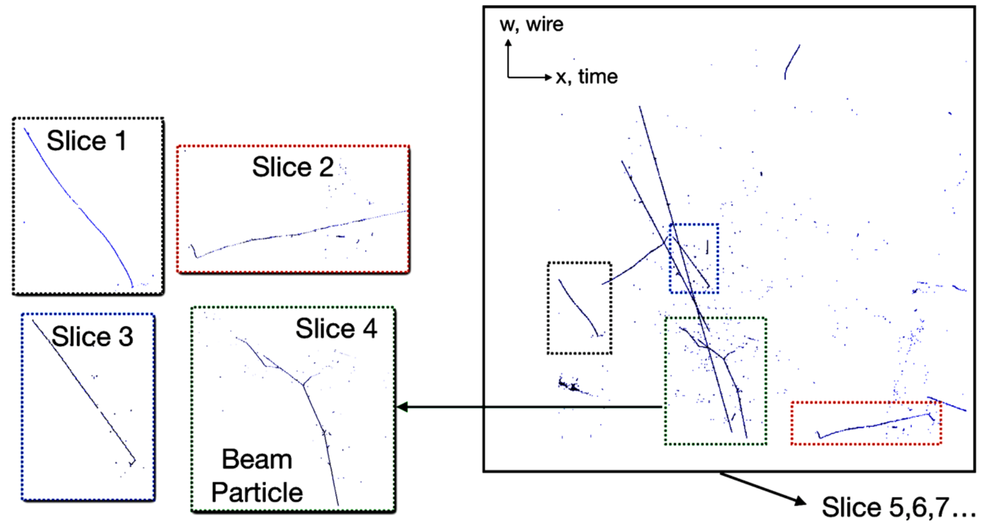
- After cosmic reconstruction is performed, clear cosmic rays are tagged;
- Must be able to deal with presence of any cosmic-ray muon remnants!

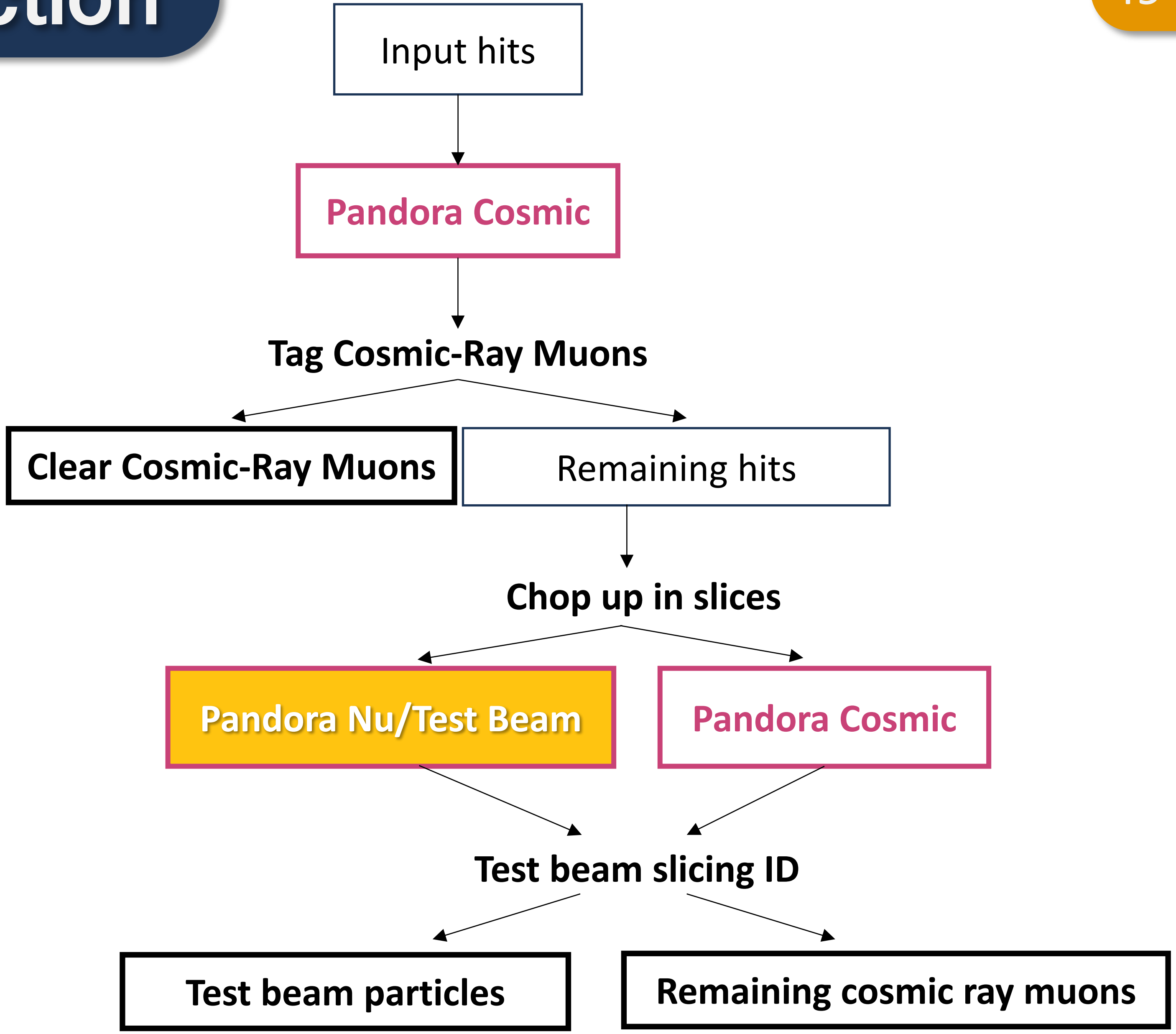




Consolidated Reconstruction

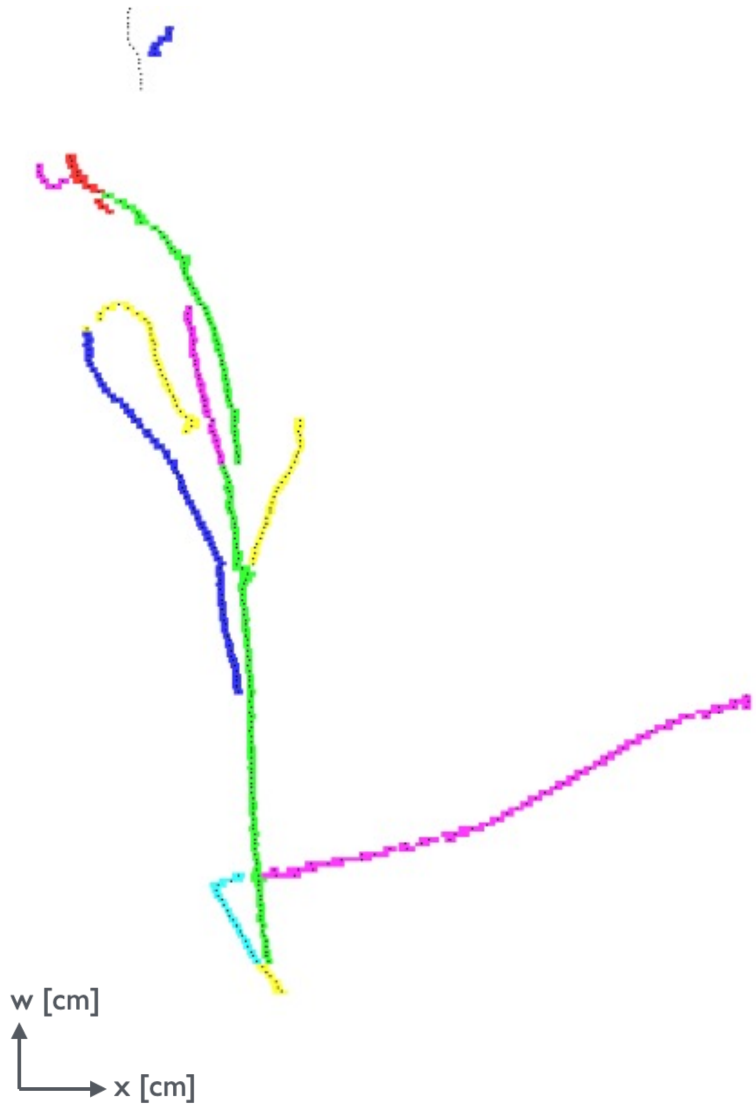
- "Chop up" remaining 3D hits into separate slices, one per interaction, and process each slice in isolation;
- Each slice ⇒ candidate neutrino particle. Cosmic and neutrino reconstructions both run on each slice!





Neutrino pass reuses track-oriented clustering and topological association

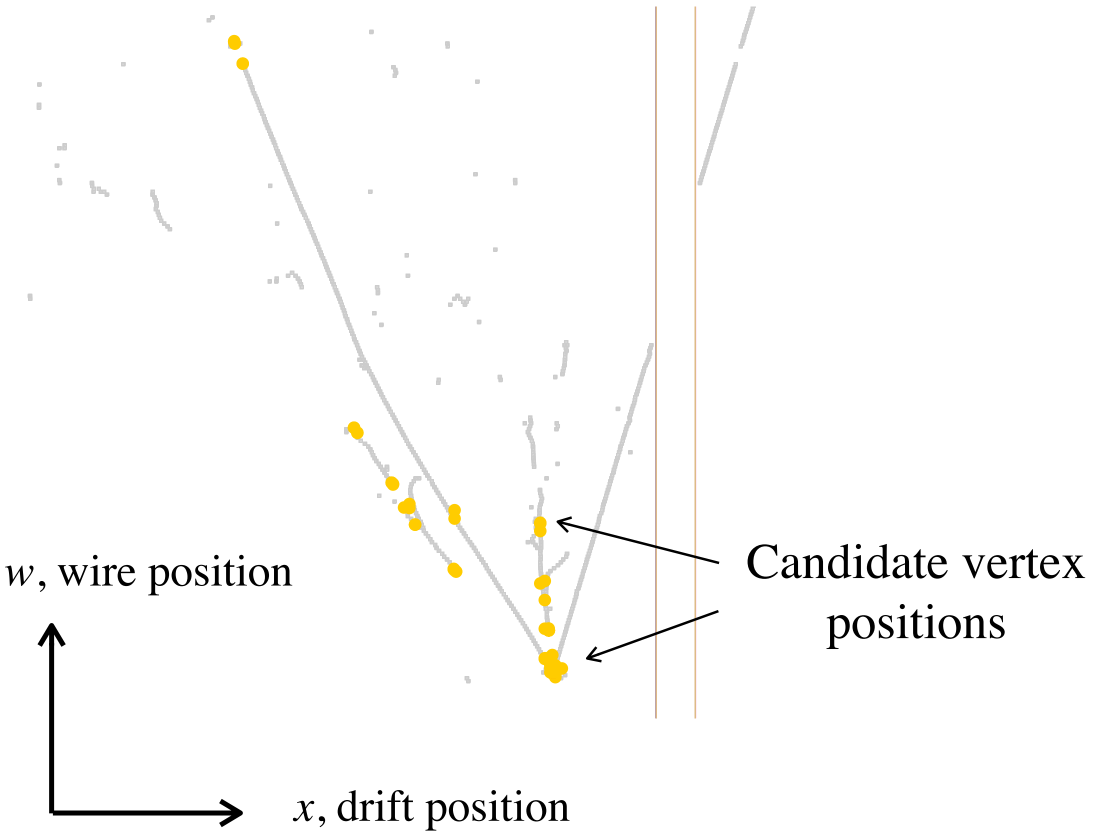
- Track reconstruction identical as in the cosmic chain
- Topological association algorithms must handle rather more complex topologies
- Specific effort to reconstruct neutrino interaction vertex
- More sophisticated efforts to reconstruct showers



Vertex Reconstruction

Search for neutrino interaction vertex

- Use pairs of 2D clusters to produce list of possible 3D vertex candidates
- Examine candidates, calculate a score for each and select the best
- Selection uses Boosted Decision Trees and Convolutional Neural Networks

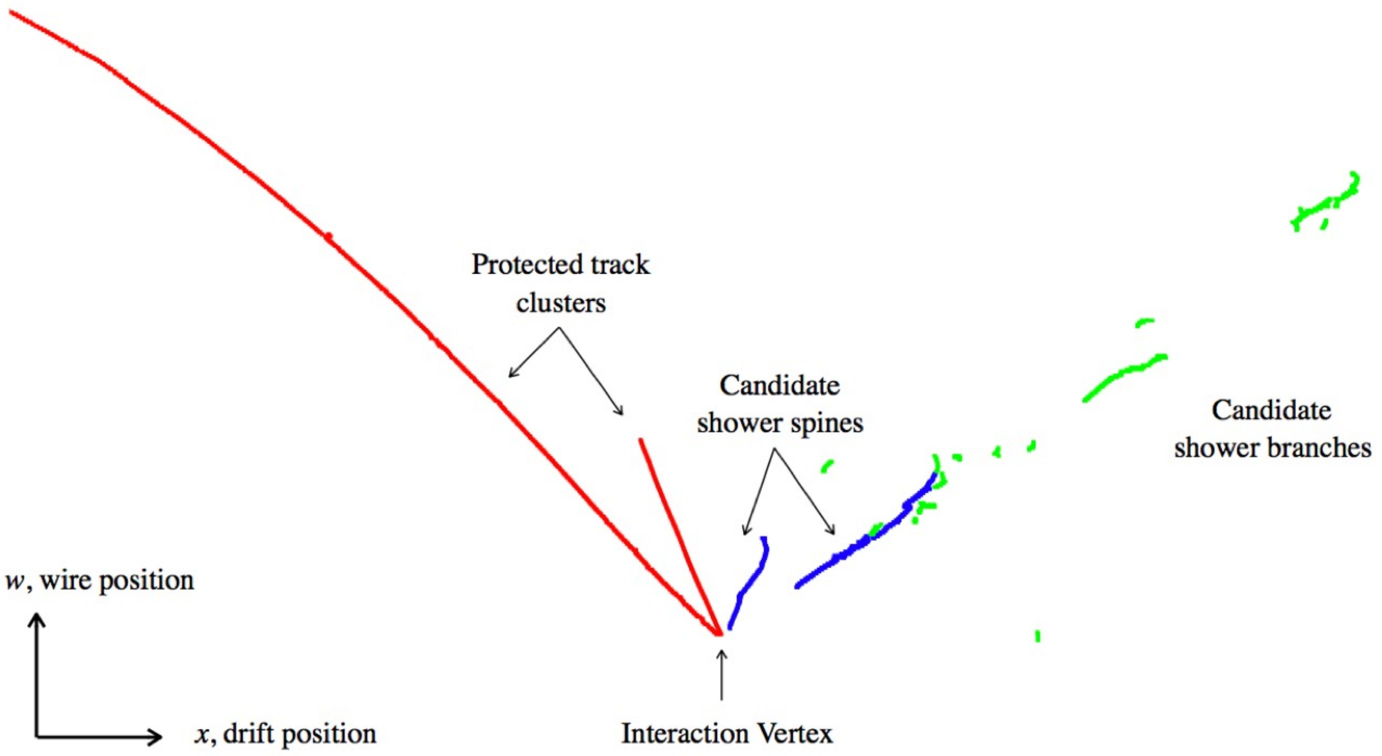


Vertex used to split 2D clusters and protect primary particles when growing showers

Shower Reconstruction 2D

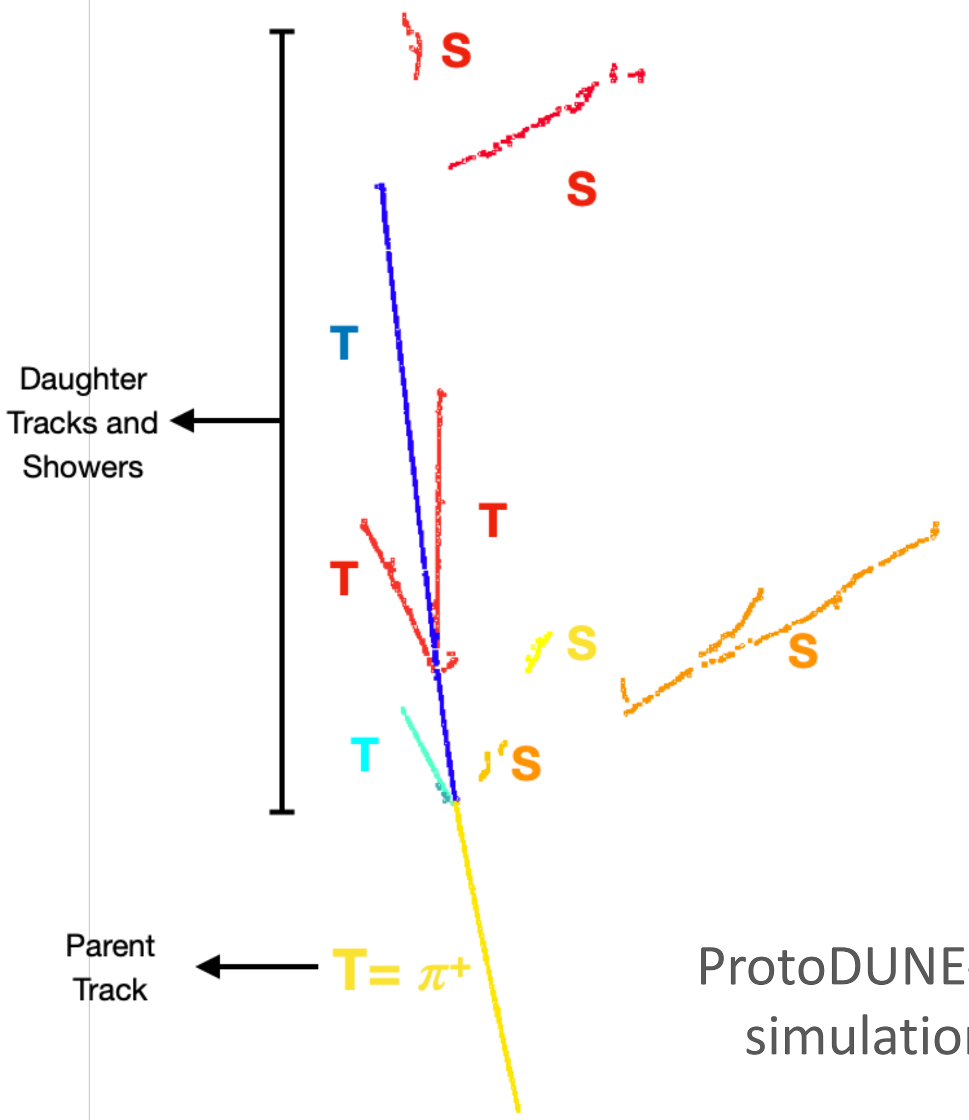
Attempt to reconstruct primary electromagnetic showers, from electrons and photons

- Characterise 2D clusters as track-like or shower-like
- Use topological properties to identify 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.



Particle Hierarchy Reconstruction

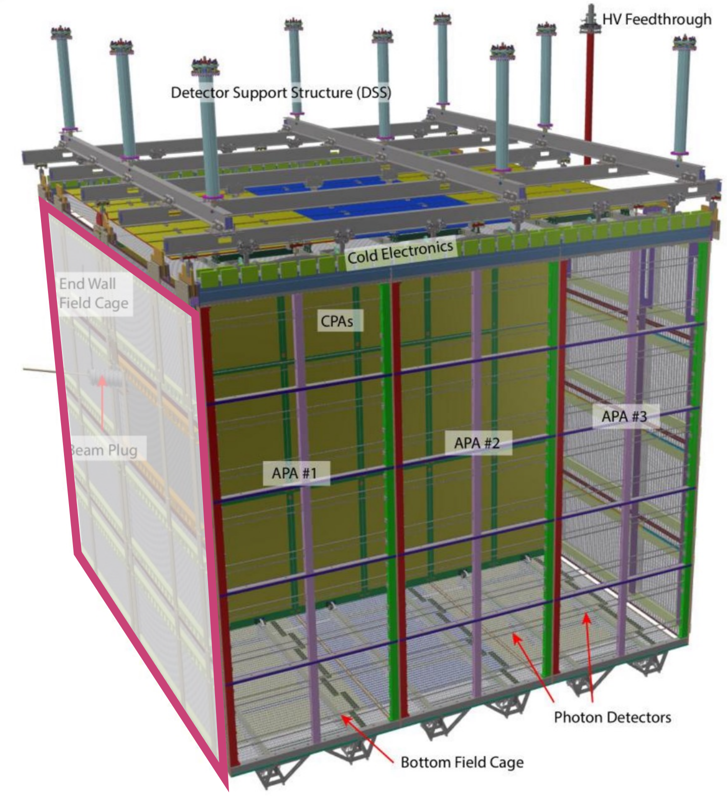
Use 3D clusters to organise particles into a hierarchy, working outwards from interaction vertex

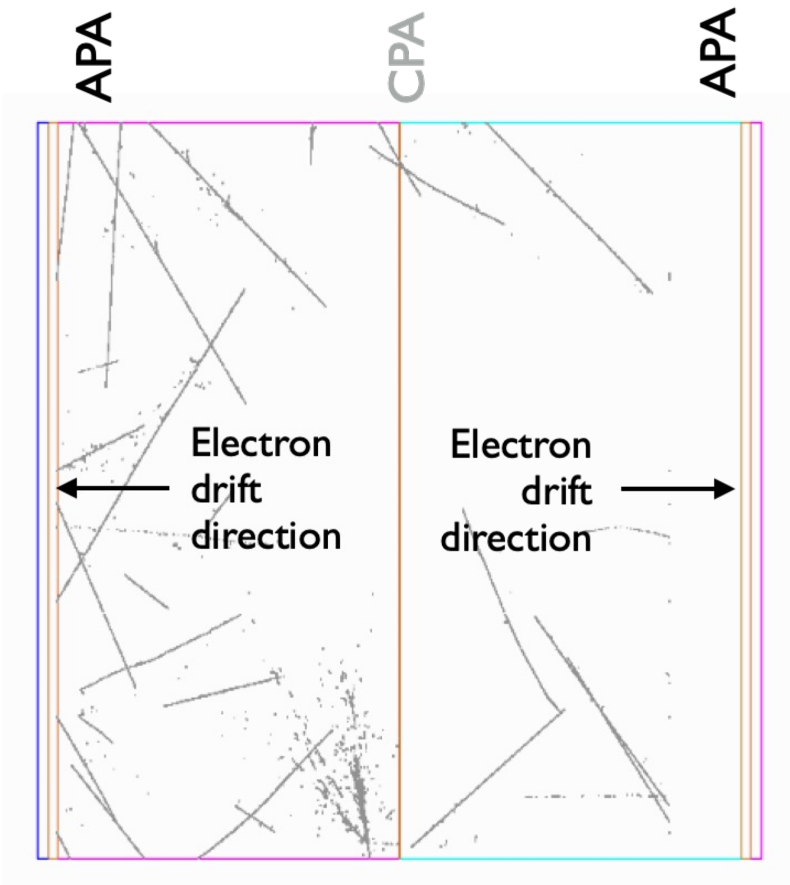


ProtoDUNE-SP simulation

ProtoDUNE-SP Reconstruction

Multiple drift volumes, complex topologies (CERN test beam) and significant cosmic-ray background (surface detector)





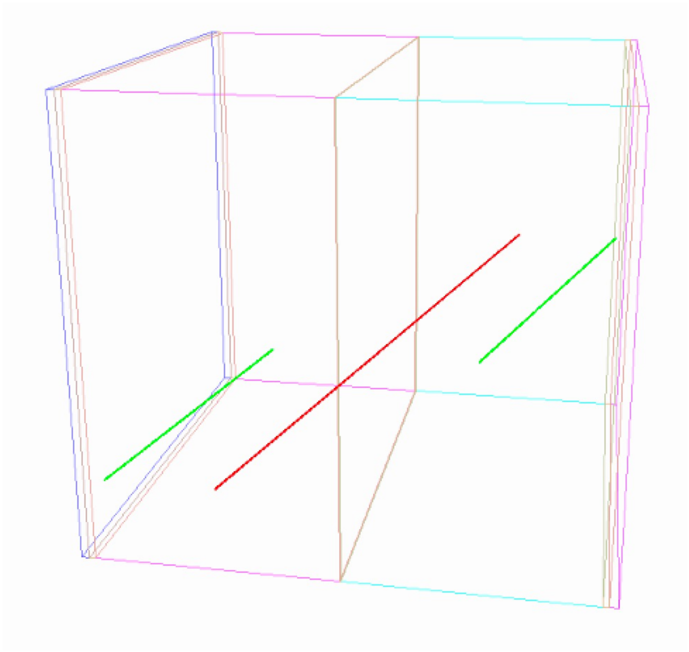
An ideal testing ground for LArTPC pattern recognition

Reconstruction is first performed in each drift volume separately

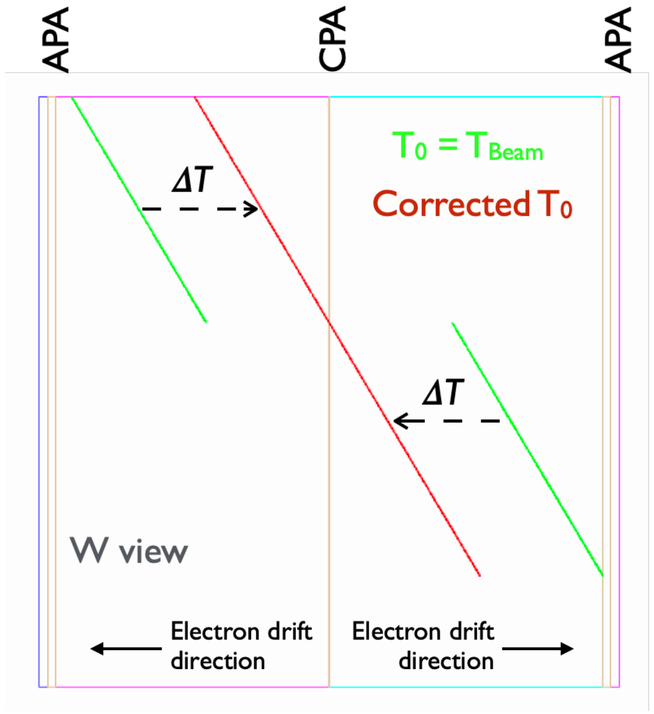
Stitching and T0 Identification

In a LArTPC image, one coordinate derived from drift times of ionisation electrons

- **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



Stitch together any cosmic rays crossing between volumes, identifying T_0

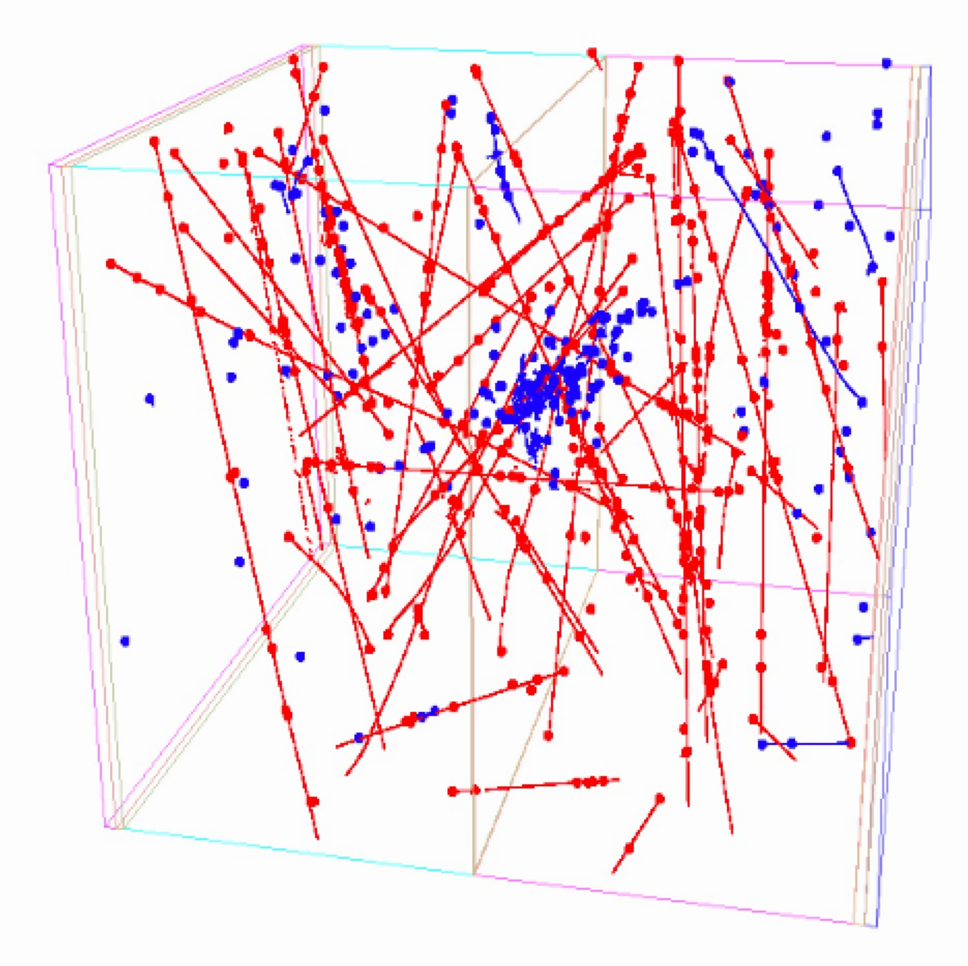


Cosmic Ray Tagging

Identify clear cosmic rays (red) and hits to re-examine under test beam hypothesis (blue)

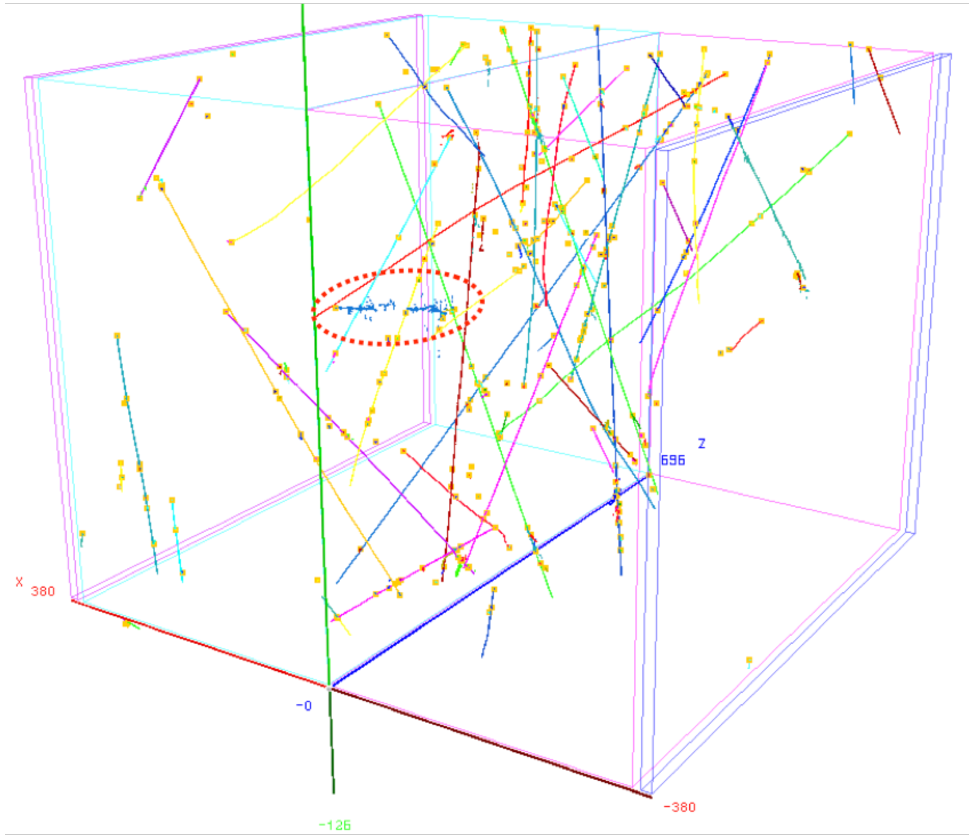
Clear cosmic rays:

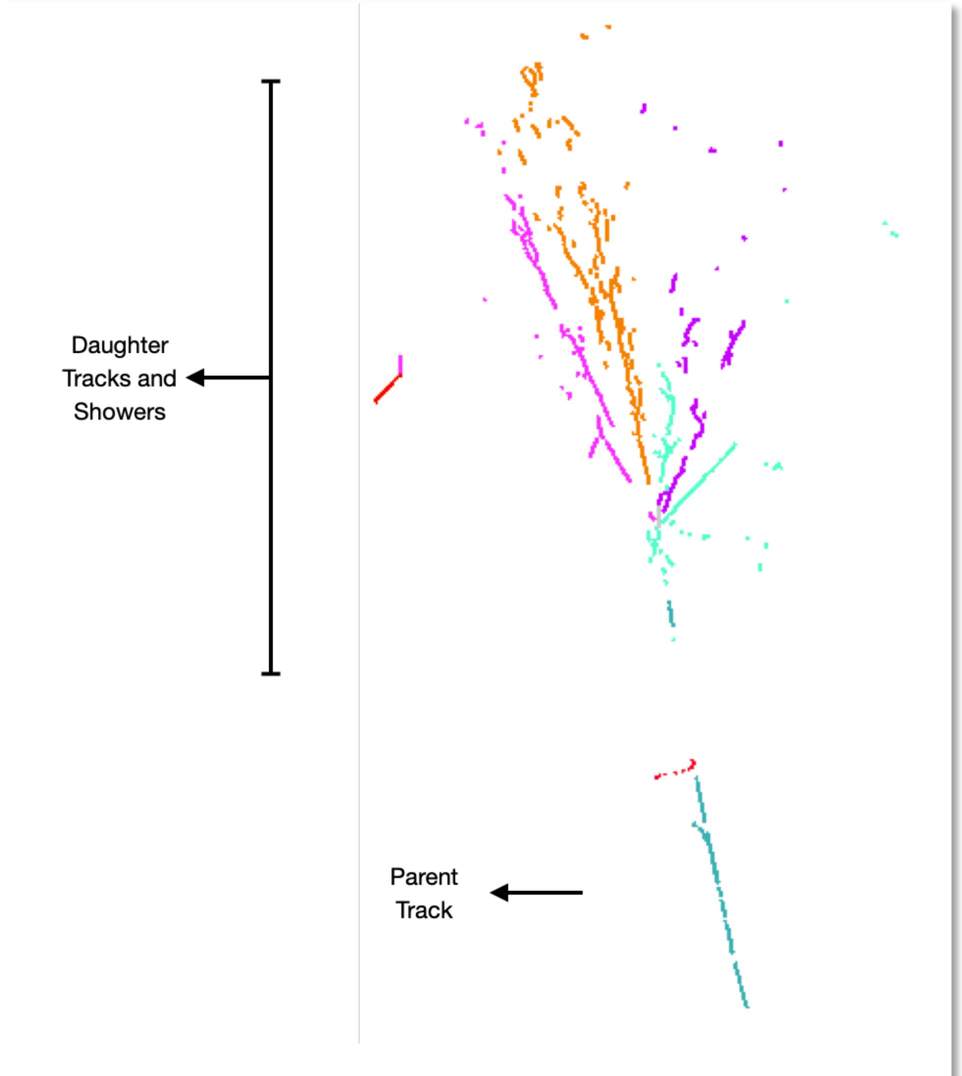
- Particles appear to be "outside" of detector if $T_0 = T_{beam}$
- Particles stitched between volumes using a $T_0 \neq T_{beam}$
- Particle passes through the detector top to bottom



Consolidated Output

Example Reconstruction output:
test beam particle (electron)
and: N reconstructed cosmic-ray muon hierarchies

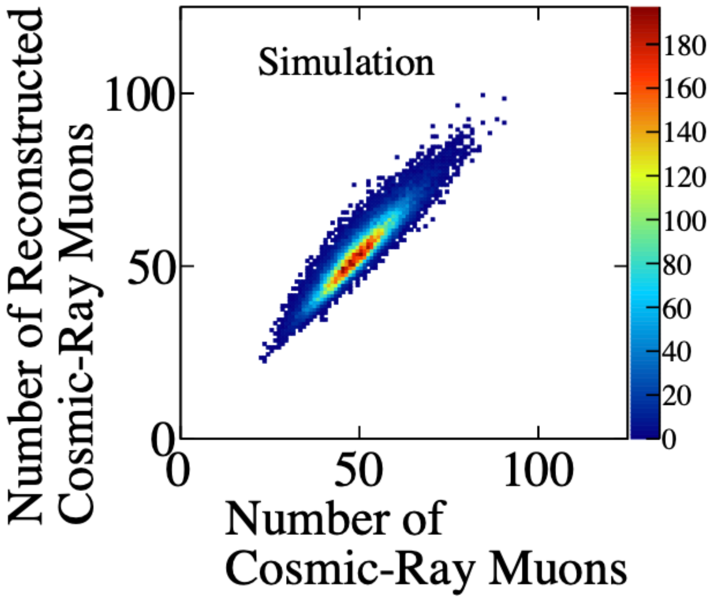


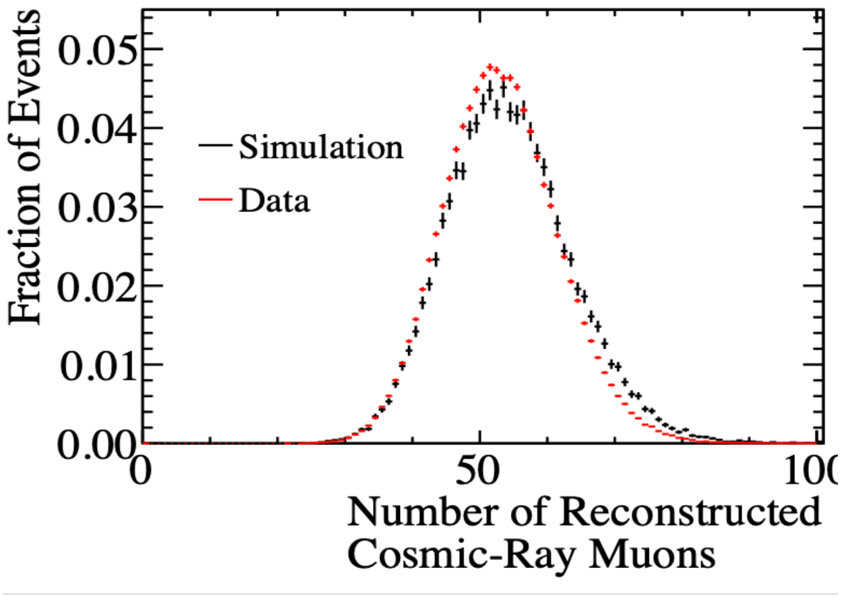


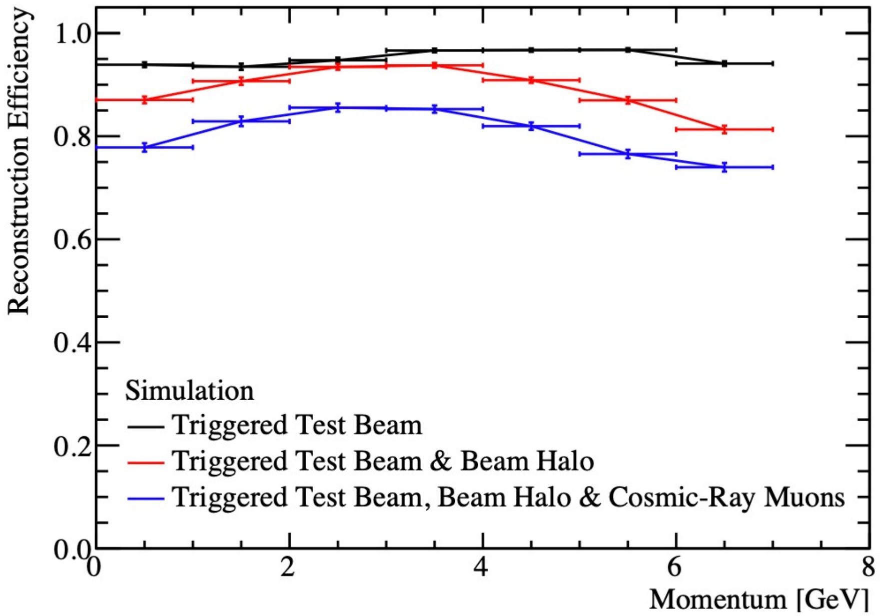
Example test beam particle: charged pion

PD-SP Reconstruction Performance

arXiv:2002.03005 **[hep-ex]**







- **Completeness**

Fraction hits shared by MC particle with its best matched reconstructed particle

- **Purity**

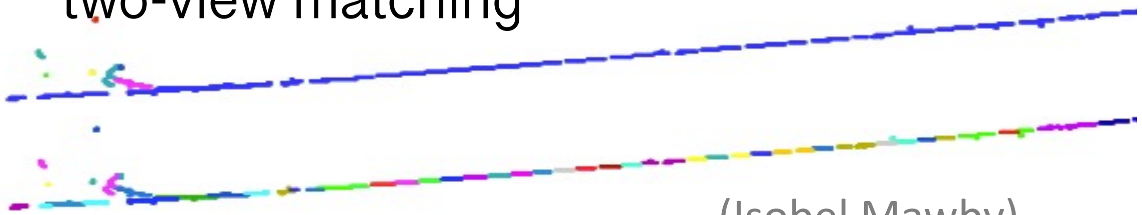
Fraction hits shared by reconstructed particle with its best matched MC particle

- **Efficiency**

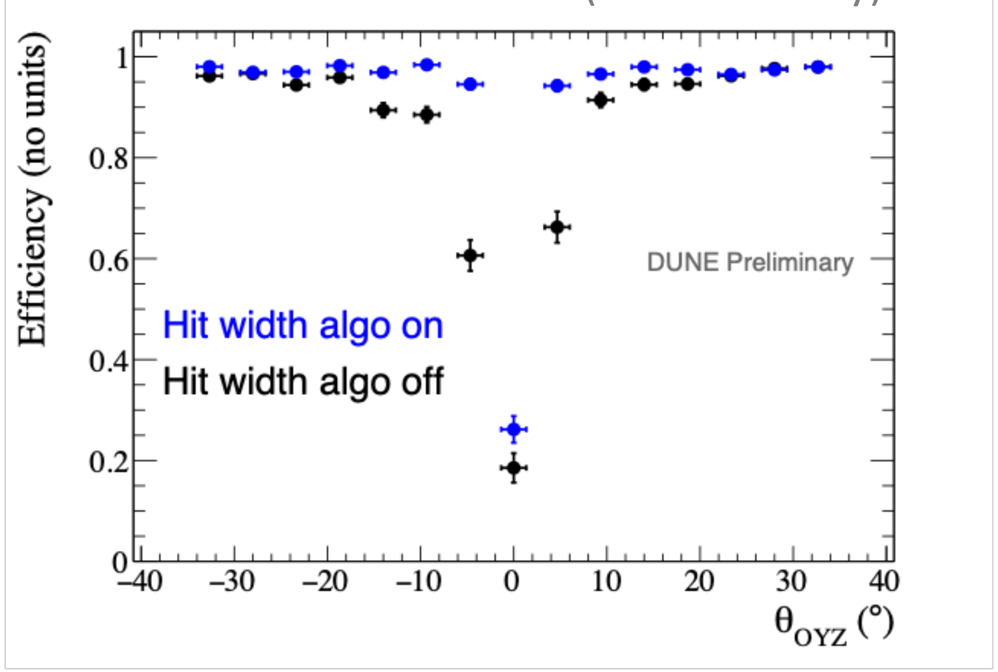
Fraction of MC particles of a given type with at least one matched reconstructed particle with no. hits > 5, completeness > 10%, purity > 50%

PD-DP Reconstruction Progress

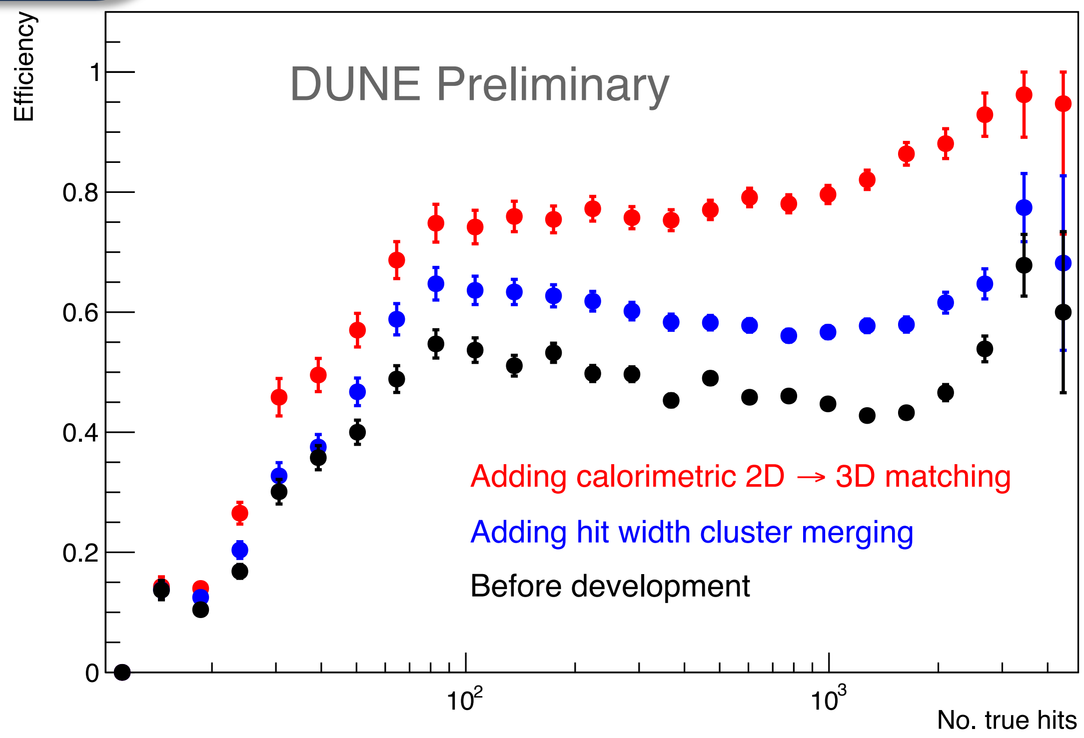
- Reconstruction for PD-DP work in progress
- Large improvements already obtained with hit width cluster merging and calorimetric two-view matching



(Isobel Mawby)



Efficiency vs No. true hits



- **Correct cosmic ray fraction**

Number of cosmic rays for which each MC particle is matched to exactly one reconstructed particle

46% → 57% → 76%

Summary

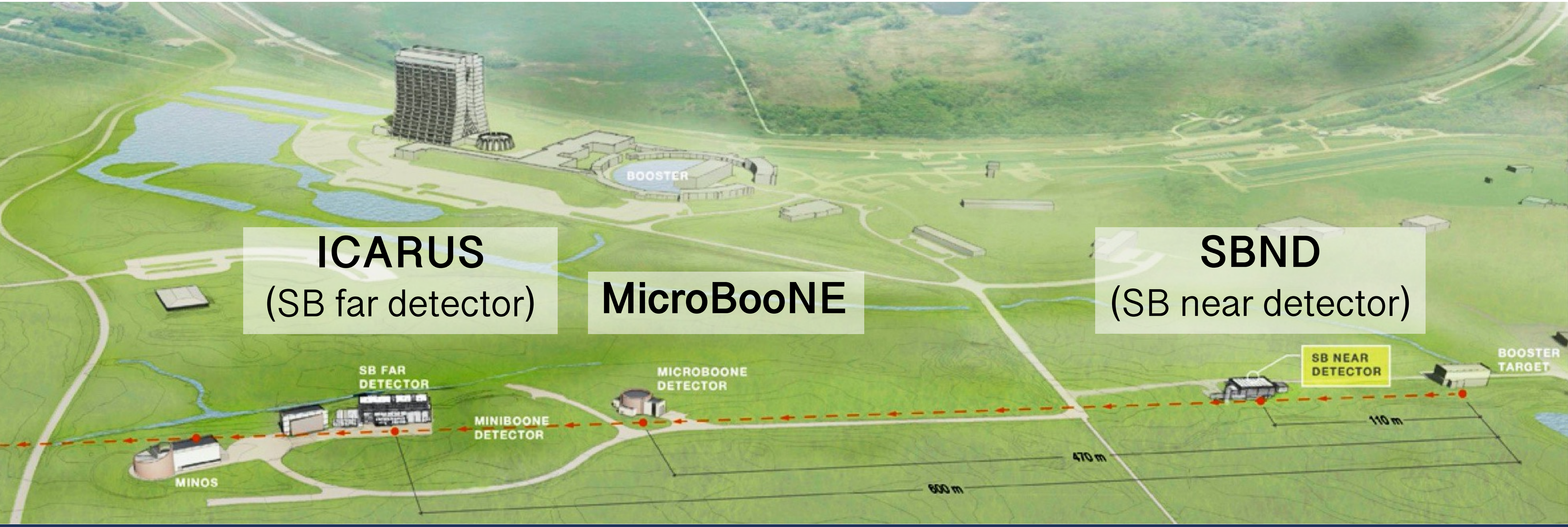
- **The Liquid Argon TPCs is a key technology** in current and future **neutrino experiments**
- Two prototypes, ProtoDUNE Single and Dual Phase, built and tested at CERN
- **State-of-the-art reconstruction is of crucial importance** to enable precision measurements at DUNE
- **Pandora's multi-algorithm approach** allows to gradually build up a picture of events, and carefully forms hierarchies of particles generated at each interaction
- Pandora has been used successfully for the reconstruction of ProtoDUNE-SP data
- Recent work has shown **high quality reconstruction can be achieved for two-view detectors** as well

Thank you for listening!
☺

Spares

Short-baseline programme

- Three LArTPC detectors at the Booster Neutrino Beam (BNB) at Fermilab
- Investigate low-energy excess seen by LSND and MiniBooNE (sterile neutrino?)
- Precision cross-section measurements for neutrino interactions on argon



PMNS vs CKM

PMNS

NuFIT 5.0 (2020)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

PDG 2020

CKM

$$\theta_{13} = (0.2 \pm 0.006)^\circ$$
$$\delta_{CP} = (68.5 \pm 2.5)^\circ$$

(asymmetric errors in reality)

Mass differences

$$\Delta m^2_{21} \sim 7.5 \times 10^{-5}\mathrm{eV}^2$$
$$\Delta m^2_{32} \sim \Delta m^2_{32} \sim 2.4 \times 10^{-3}\mathrm{eV}^2$$

DUNE oscillation physics

$$\begin{pmatrix}\upsilon_e\\ \upsilon_\mu\\ \upsilon_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & e^{i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{-i\delta}s_{13} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\upsilon_1\\ \upsilon_2\\ \upsilon_3\end{pmatrix}$$

Atmospheric υ
Long-baseline υ (accelerator)

Short-baseline υ
Long-baseline υ (accelerator)

Solar υ

Table 14.6: Experiments contributing to the present determination of the oscillation parameters.

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\|\Delta m^2_{31,32}\|$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\|\Delta m^2_{31,32}\|$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\|\Delta m^2_{31,32}\|$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

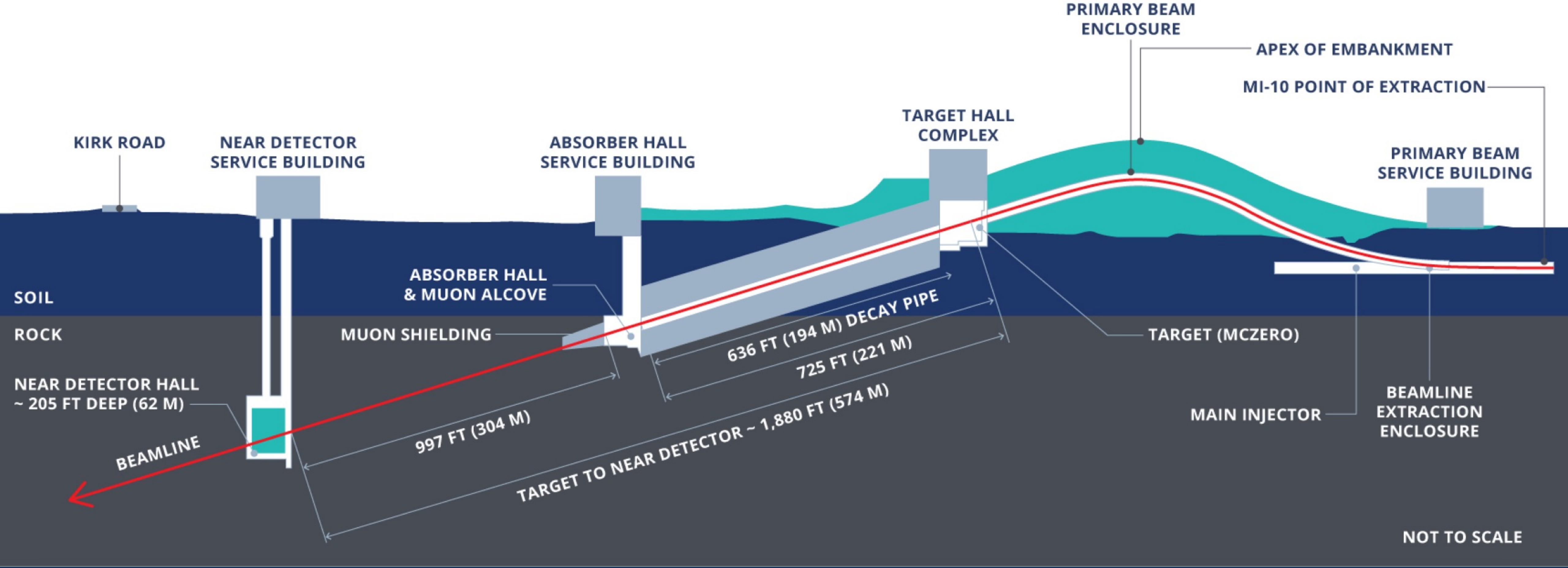
- Overconstrain 3-flavour paradigm
- $\sin^2\theta_{13}$ via the electron neutrino appearance channel $\nu_\mu \rightarrow \nu_e$ with precision approaching reactor measurements
- Broadband on-axis beam → characterise L/E oscillation behaviour with smaller systematics than atmospheric oscillation experiments
- Sensitive to new neutrino mass eigenstates
- Tests of Lorentz-invariance in the neutrino sector
- High energy beam → study $\nu_\mu \rightarrow \nu_t$

Long-Baseline Neutrino Facility (LBNF)

- Deliver the world’s most intense neutrino beam
- Proton Improvement Plan-II (PIP-II)
- Upgrade of existing facilities (higher energy LINAC, protons per bunch, bunches…)
- Going from 700 kW to 1.2 → 2.4 kW

Long-Baseline Neutrino Facility (LBNF)

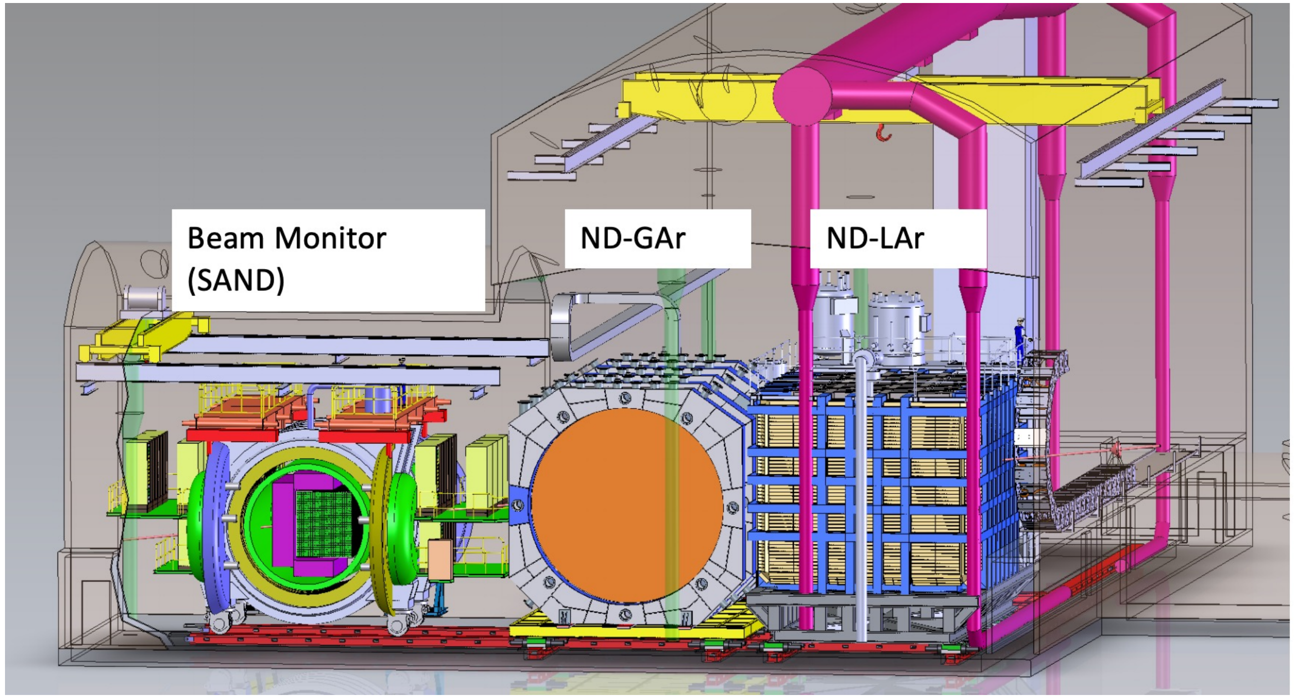
- Neutrino bem is completely new, from primary beam extraction to decay pipe and absorber



DUNE Near Detector

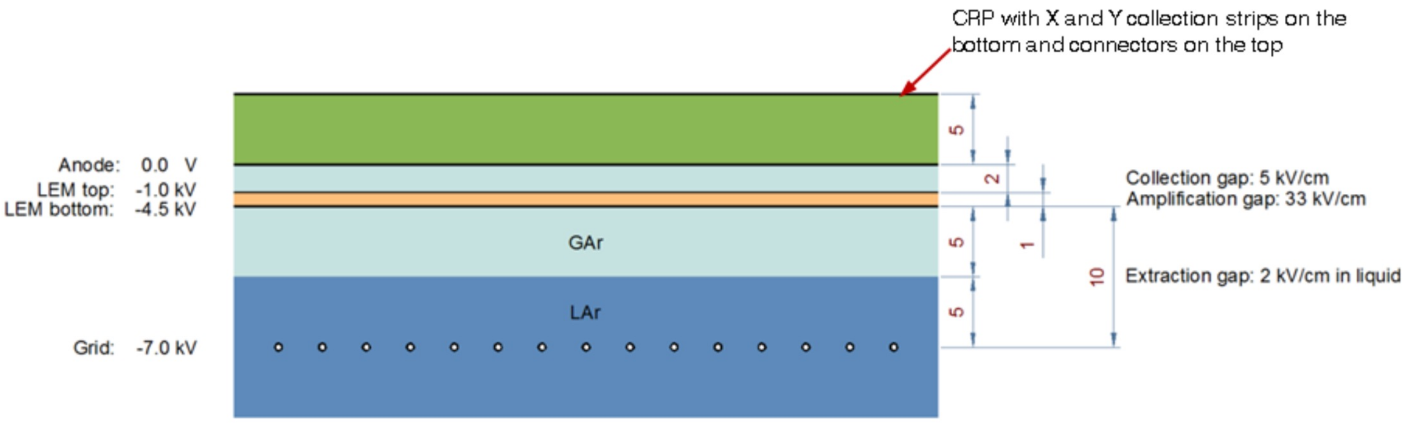
- An on-axis beam monitor (SAND)
- A multi-purpose high-pressure GAr detector
- A pixelated LAr TPC

} Installed on a movable platform



CRPs

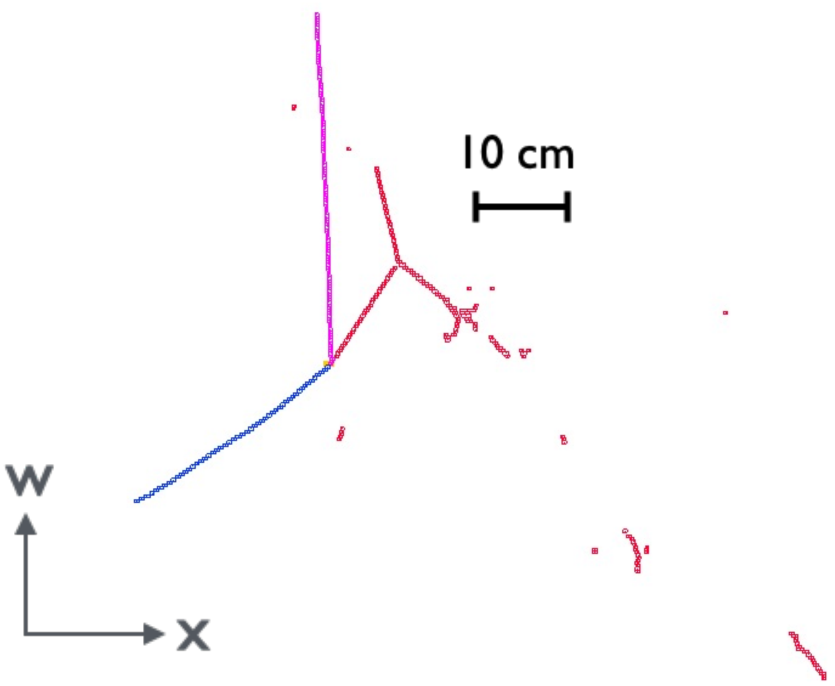
- Ionization electrons reach extraction grid just below liquid-gas interface
- Strong E field extracts electrons into gas phase
- Amplification stage: large electron multipliers with high field regions (**LEMs**)
- 2D anode (two strip-based collection views with 3.125 pitch, each forming a 2D image) → **Reconstruction will rely on only two 2D images!**



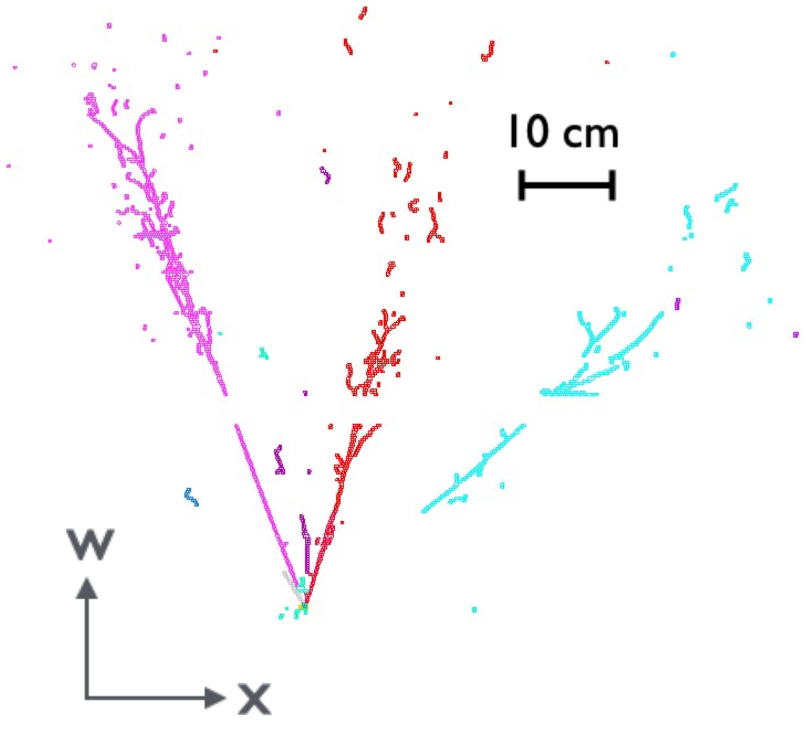
- 1 CRP = sandwich of 36 LEMs + 1920 RO channels. ProtoDUNE-SP: 4 CRPs

Pattern recognition challenges

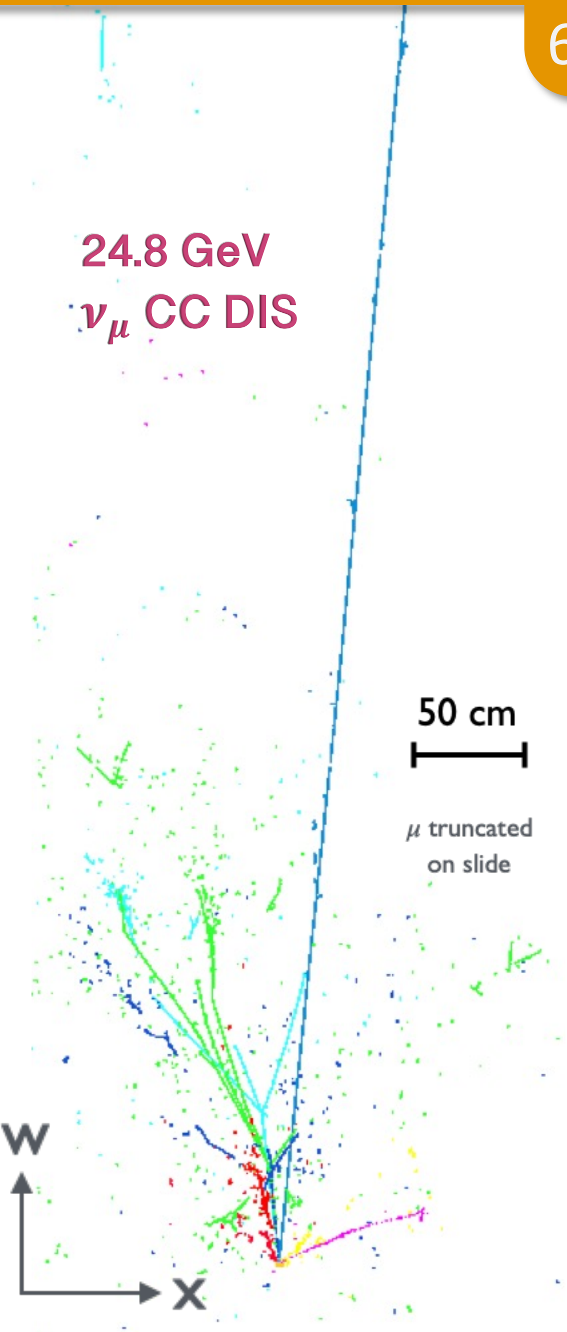
- Complex, diverse topologies



1.8 GeV
ν_μ CC RES W/π^+



3.3 GeV
ν_e CC DIS

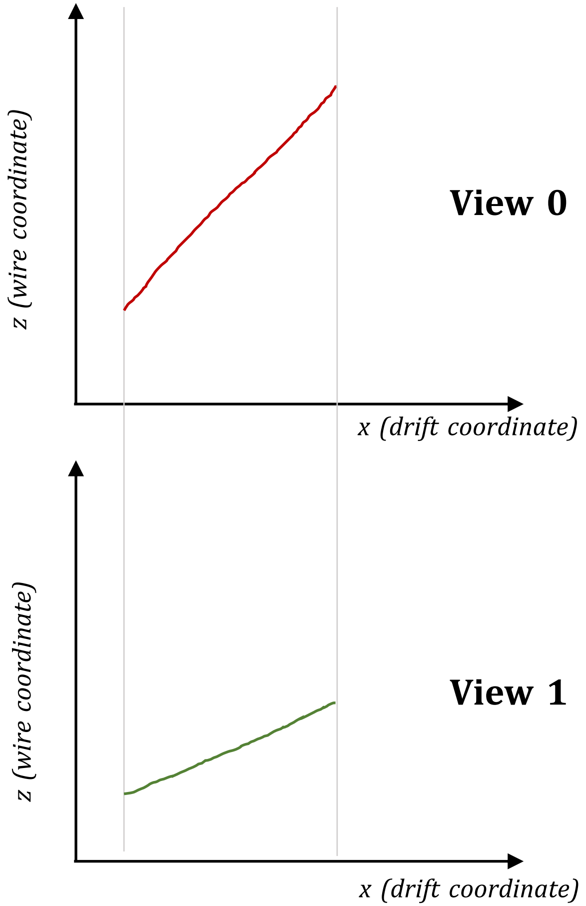


24.8 GeV
ν_μ CC DIS

Two-view matching tools

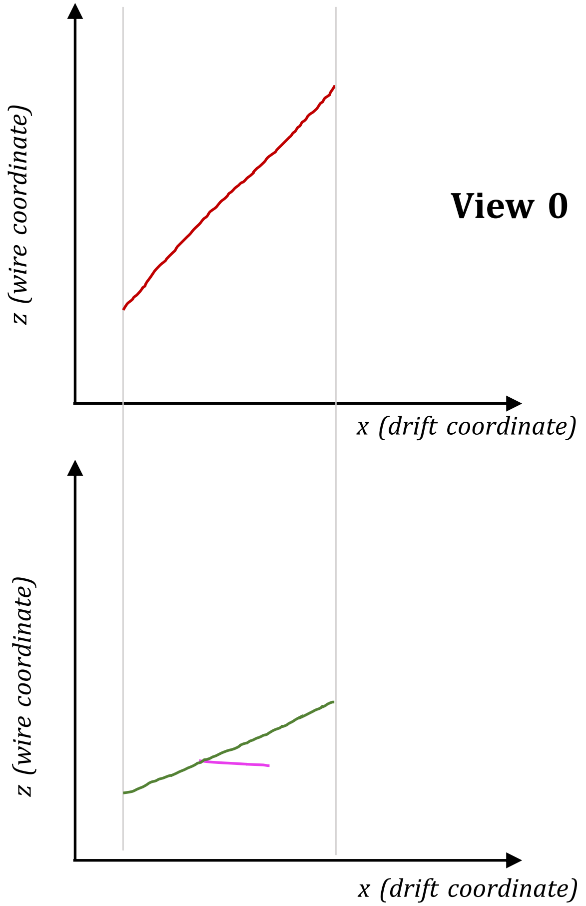
Clear Tracks tool

Non-ambiguous matching



Long Tracks tool

Obvious ambiguities matching



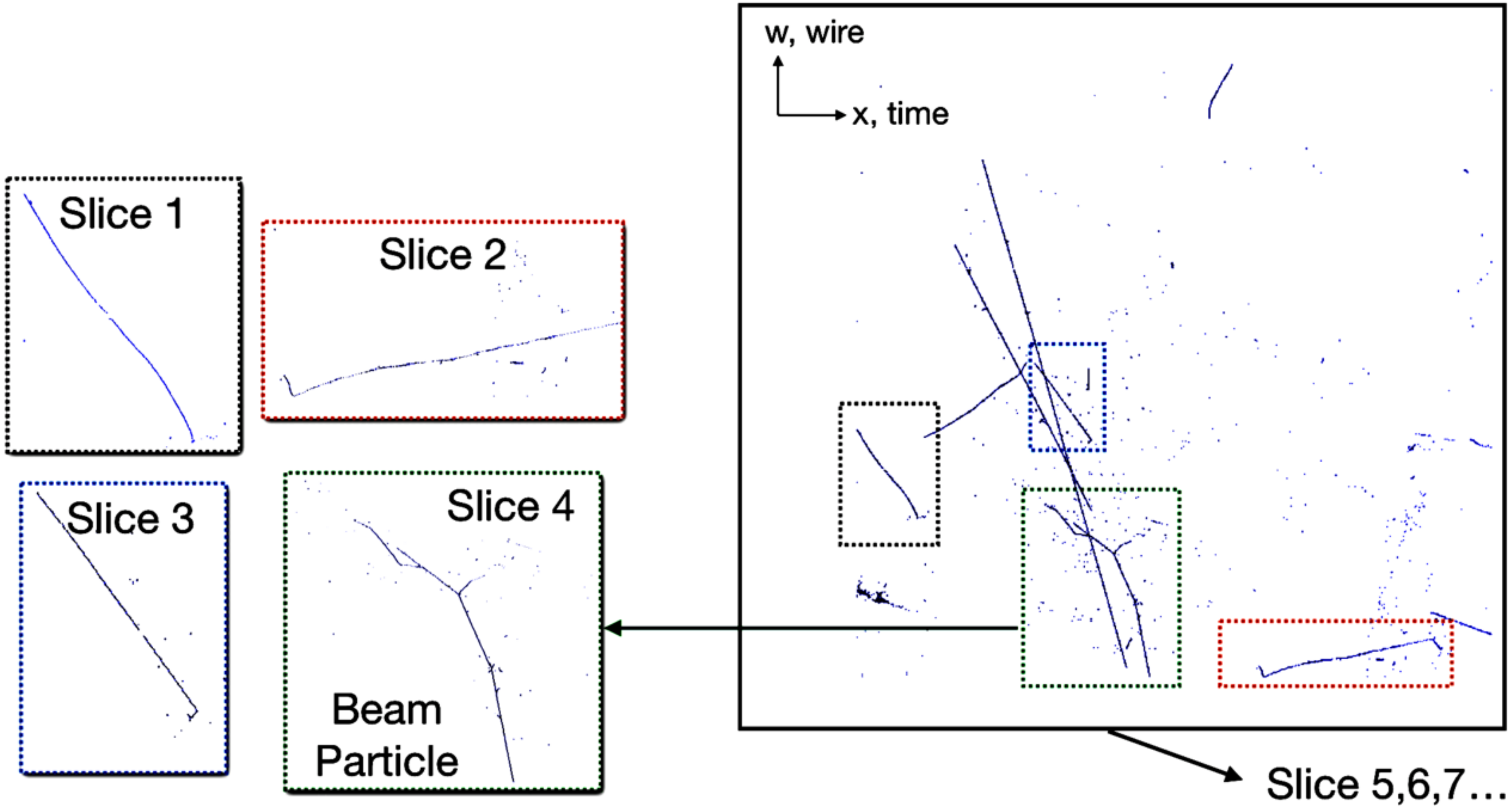
Simple Tracks tool

Best match based on ranking

- **Locally matched fraction**
  The fraction of local matching scores above a threshold
- **Matching score**
  Calculated as the local matching score, over whole overlap region
- **Number of matched points**
  The number of local matching scores above a threshold

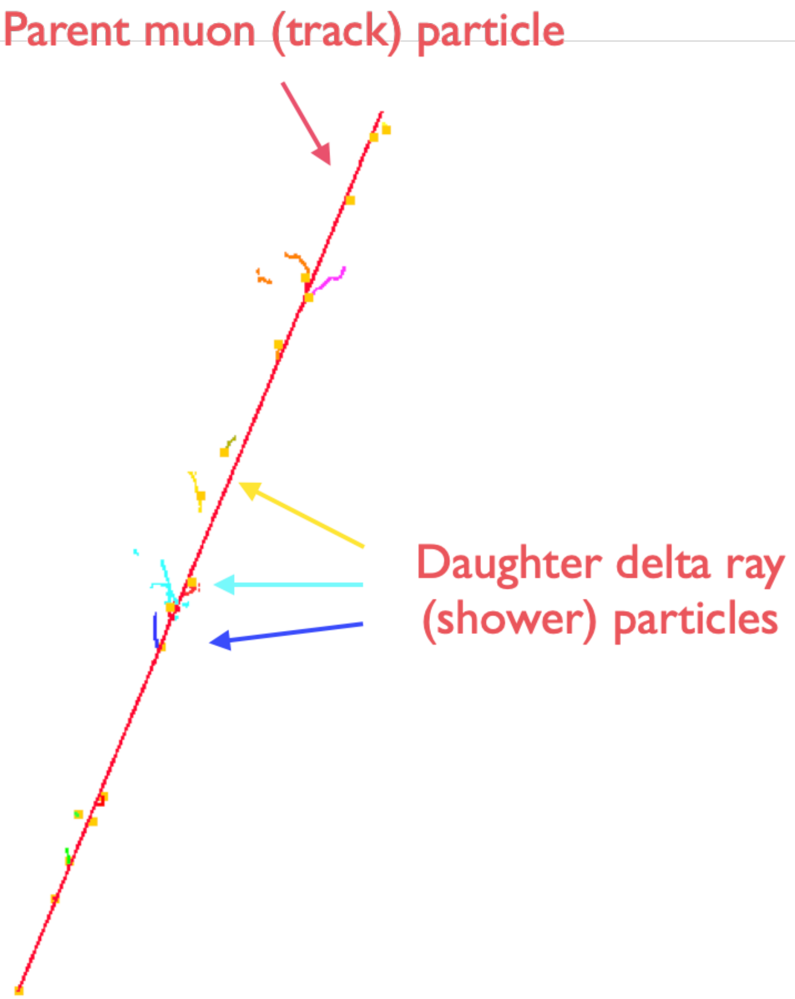
Slicing

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



Delta-ray Reconstruction (2D, 3D)

- Assume any 2D clusters not in a track particle are from delta-ray showers
- Delta-ray clusters matched between views, creating delta-ray shower particles
- Parent muon particles identified and delta-ray particles added as daughters

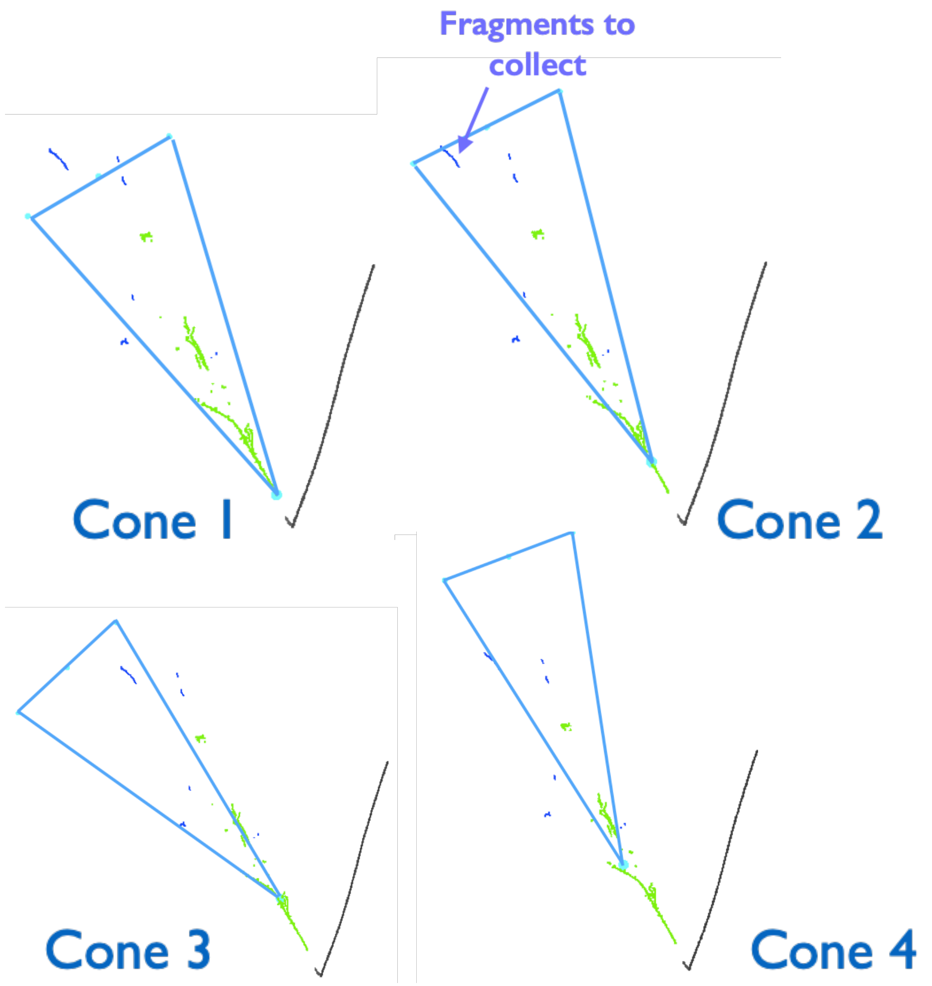


Particle Refinement 2D/3D

A series of algorithms deals with remnant clusters to improve particle completeness

Example
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



Machine Learning in Pandora

- Various machine learning (ML) techniques employed in Pandora and by high-level characterization making use of Pandora products

A few examples…

- BDTs used to label slices as cosmics or nu/beam
- BDTs used for track/shower ID
- CNNs and BDTs used for vertexing
- CNNs used for PID
- Semantic segmentation for hit-wise track/shower ID being explored, with potential use for vertexing too

Machine Learning in Pandora

Semantic segmentation

Assign track and shower probability to each pixel

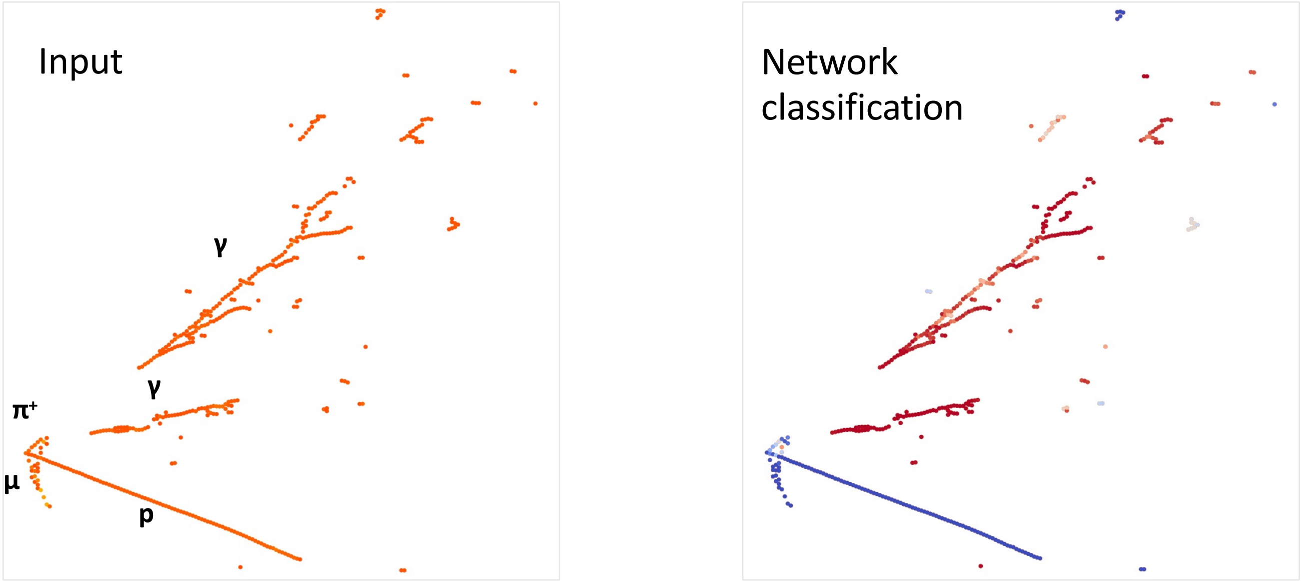


Fig: Input hits and network track (blue) and shower (red) classification for W view

True\Net	Shower	Track
Shower	91.1%	8.9%
Track	6.5%	93.5%
Σ	100%	100%

Tab: Confusion matrix for U view

True\Net	Shower	Track
Shower	92.2%	7.0%
Track	7.8%	93.0%
Σ	100%	100%

Tab: Confusion matrix for V view

True\Net	Shower	Track
Shower	92.3%	6.8%
Track	7.7%	93.2%
Σ	100%	100%

Tab: Confusion matrix for W view

- Provisional proof of concept to identify primary vertex via semantic segmentation
- Region-finding capability already evident
- Longer-term aim to find secondary vertices too

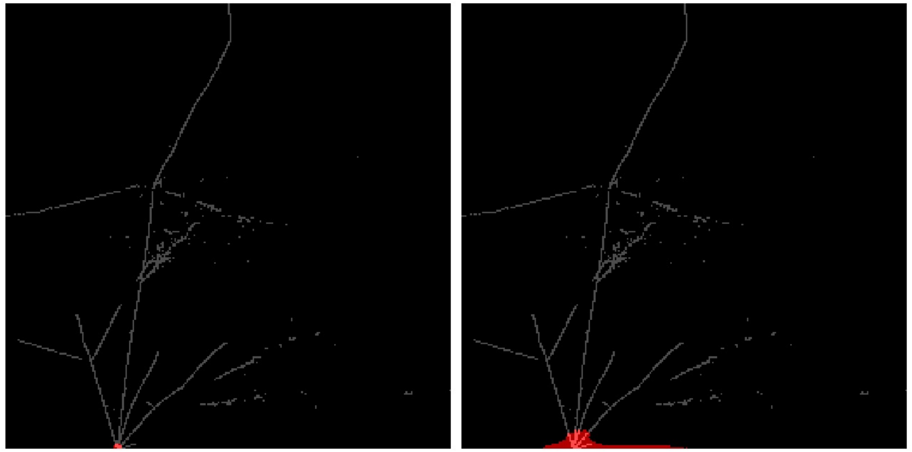


Fig: Left) Input hits and true vertex. Right) Network vertex classification

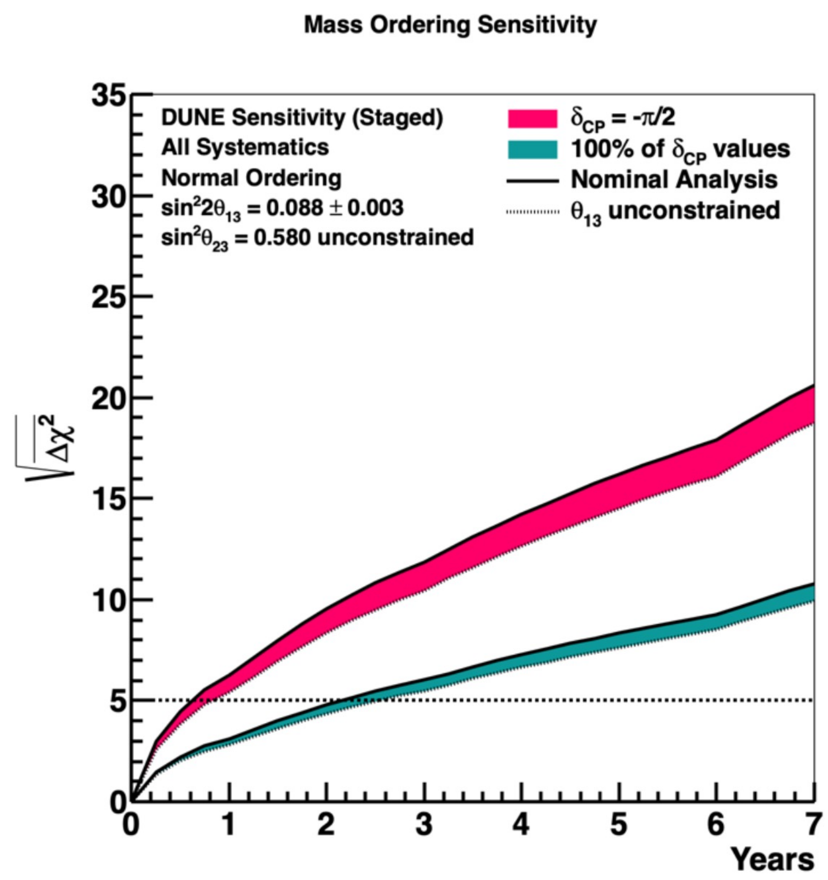
Credits: Andy Chappell

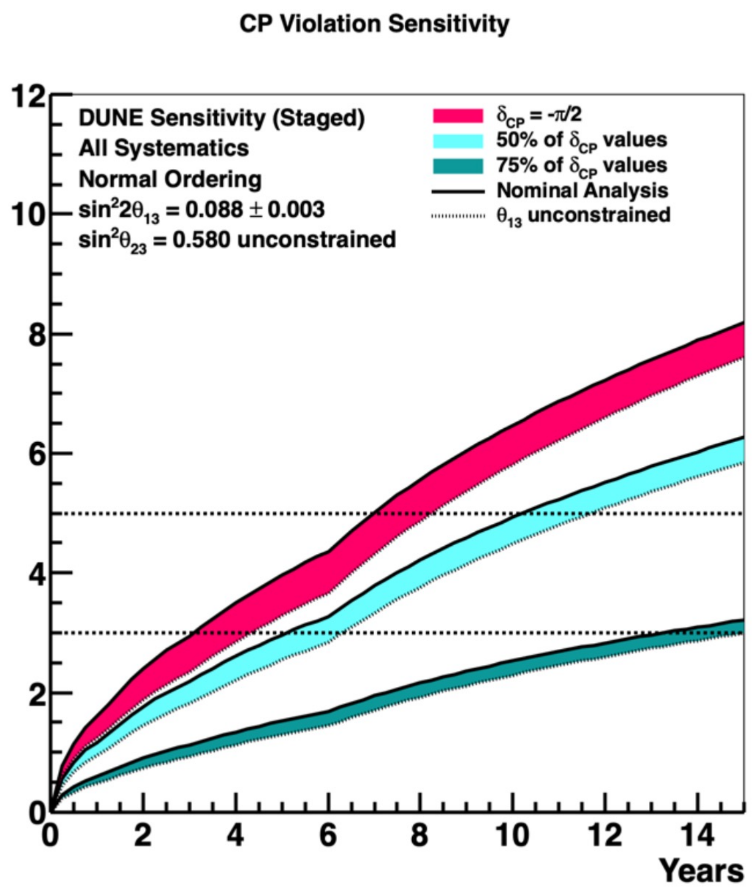
Timescales

- First two FD modules completion ~ 2024
- Beam operational ~ 2026
- Last module ~ 2027

Significance from test statistics $\Delta\chi^2$:

$$\begin{aligned}
\Delta\chi^2_{MH} &= \chi^2_{IH} - \chi^2_{NH} \text{ (true normal hierarchy)}, \\
\Delta\chi^2_{MH} &= \chi^2_{NH} - \chi^2_{IH} \text{ (true inverted hierarchy)}, \\
\Delta\chi^2_{CPV} &= Min[\Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = 0), \Delta\chi^2_{CP}(\delta^{test}_{\mathrm{CP}} = \pi)], \text{ where} \\
\Delta\chi^2_{CP} &= \chi^2_{\delta^{test}_{\mathrm{CP}}} - \chi^2_{\delta^{true}_{\mathrm{CP}}}.
\end{aligned}$$





Significance of the DUNE determination of mass ordering (left, normal ordering) and CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) for different δ_{CP} values, as a function of time in calendar years. True normal ordering is assumed.

DUNE Far Detector Technical Design Report
arXiv:2002.03005v2 [hep-ex]