Development of the Pandora LArTPC event reconstruction to optimise the sensitivity to CP violation at DUNE

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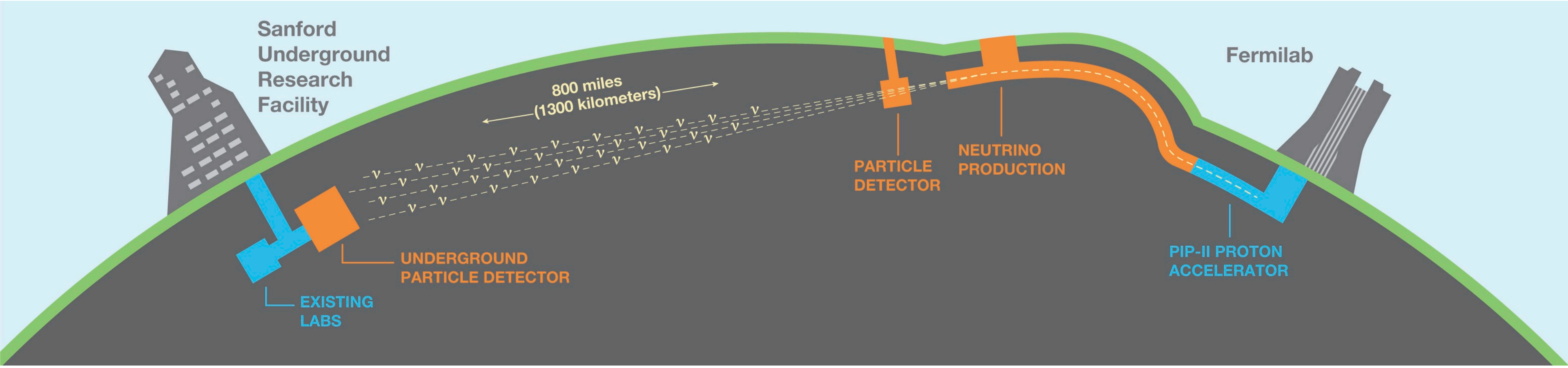
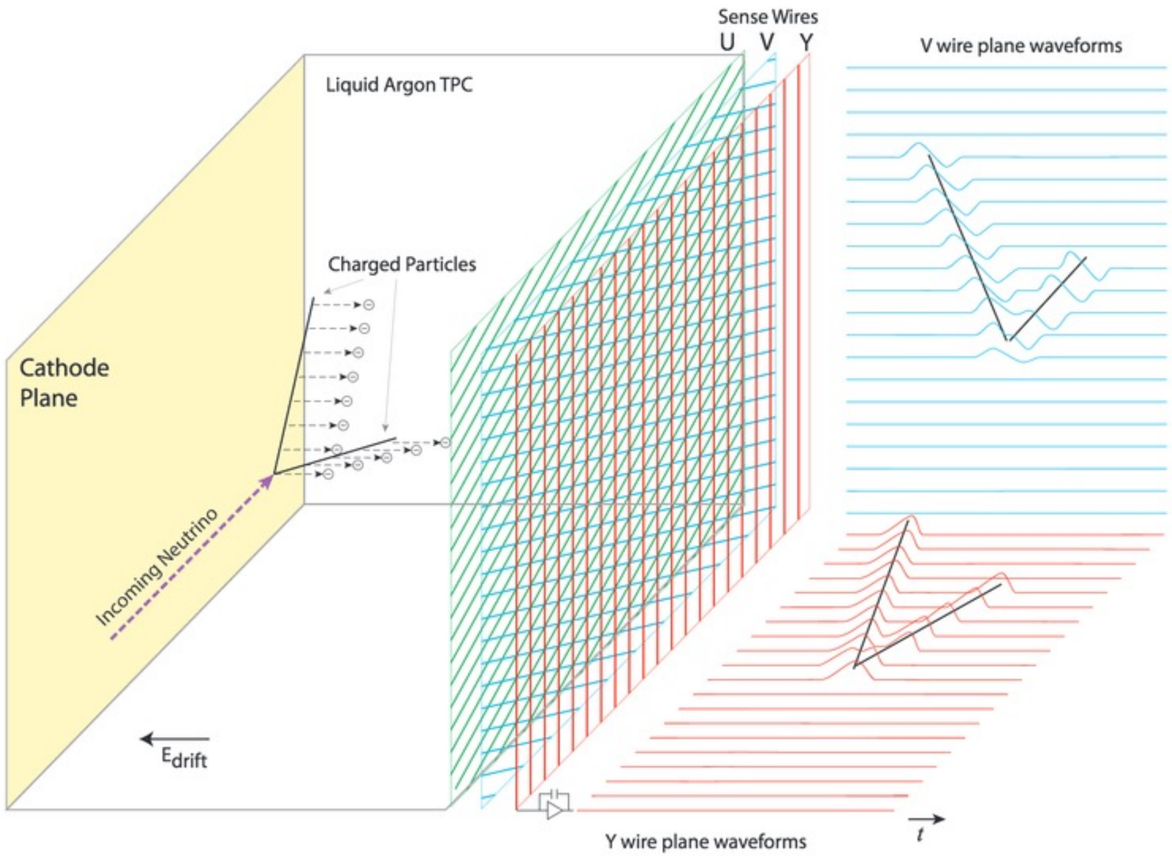
DUNE



- The far detector is planned to consist of **four 10kt fiducial mass modules** 1.5 km **underground** and 1300 km downstream of the near detector, **two** of these will be LArTPCs

- Primarily DUNE aims to:
  - precisely measure **the neutrino oscillation parameters** including the **CP violating phase δ_{CP}**
  - search for **beyond the standard model physics**
  - detect **low energy** neutrinos such as those from supernova bursts

LArTPC Operation



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- Neutrinos enter the far detector and interact with the **argon nuclei**
- Outgoing **charged** particles **ionise** the liquid argon as they traverse the detector
- An applied **electric field** drifts the ionisation electrons to a series of **wire planes** where they are detected

LArTPC Images

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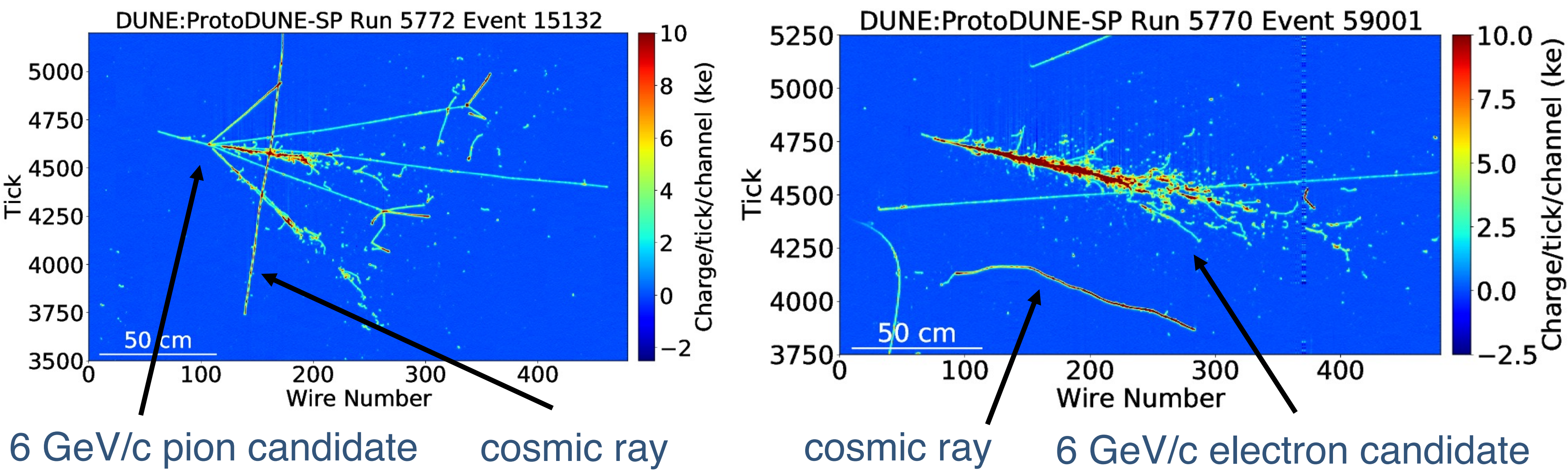
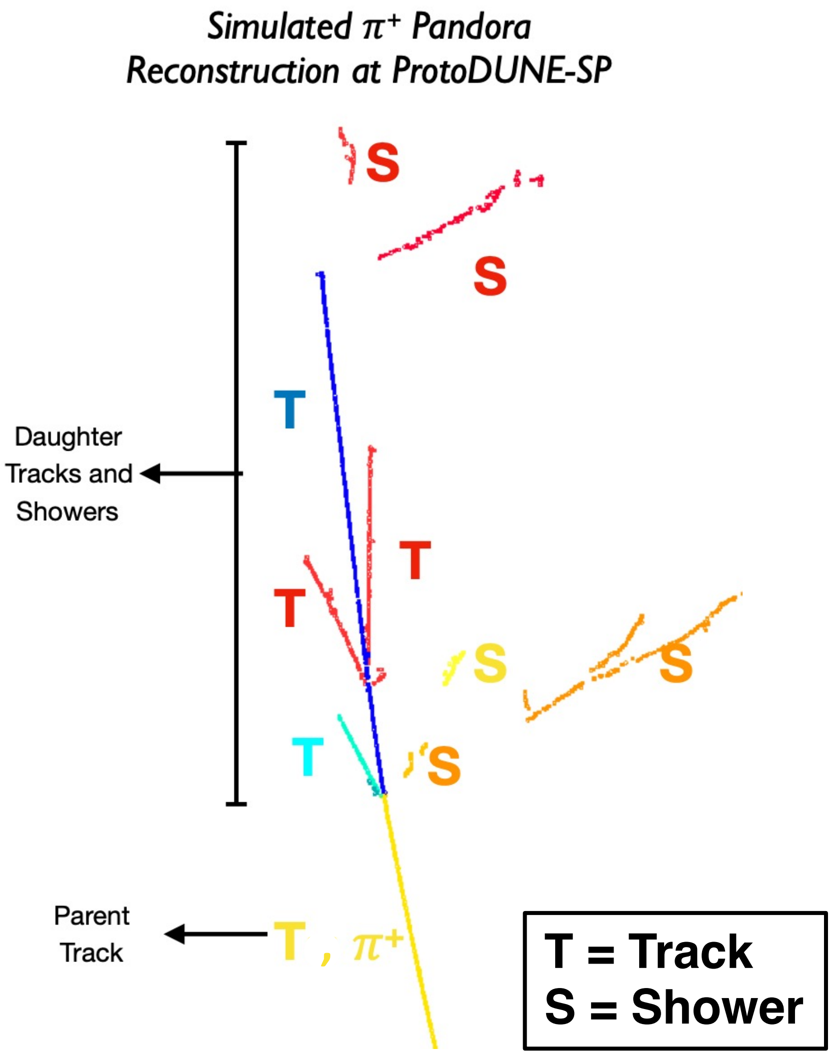


- LArTPC detectors are **fully active and fine grain**, offering **superb** spatial and calorimetric resolution
- The aim is to **identify and characterise** the visible particles in these images allowing us to perform our analyses and obtain physics results!
- To exploit such a detailed input we need a **sophisticated event reconstruction chain**

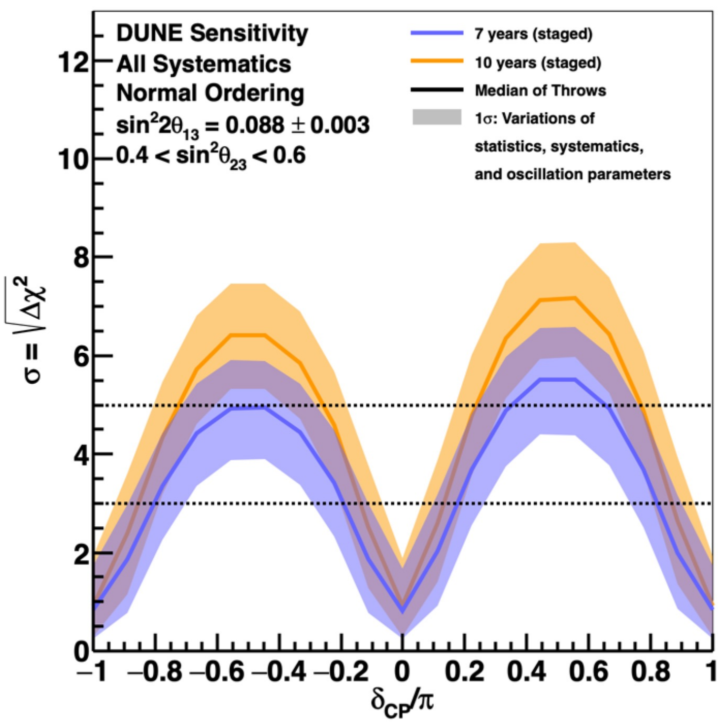
A Very Brief Reconstruction Chain Overview



- Pandora employs a **multi-algorithm approach** to pattern recognition
  - A library of traditional algorithms are applied alongside an ever growing number of **machine learning approaches** to gradually build, from the input hits, the **particle hierarchies**
  - Each particle is identified as **track** or **shower**-like
- Any necessary **high-level reconstruction** is now performed on the output of Pandora:
  - **Tracks** and **showers** are fully characterised in terms of their vertex, direction, de/dx etc
  - The **energy** is estimated
  - Anything else needed in the analysis...

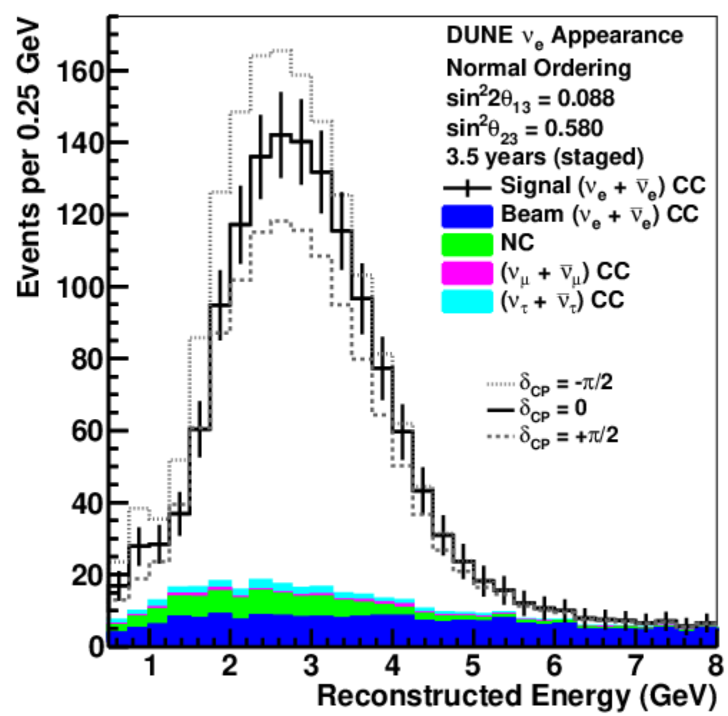
Analysis: CP Violation

- In neutrino oscillations CP violation is characterised by the **CP violating phase δ_{CP}** where CP is
  - **conserved** if $\delta_{CP} = 0, \pi$
  - **violated** if $\delta_{CP} \neq 0, \pi$
  - **maximally violated** if $\delta_{CP} = \pm \frac{\pi}{2}$



EPJC (2020) 80:978

- DUNE's sensitivity to CP violation is obtained by **simultaneously fitting** the expected $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$ energy spectra for all δ_{CP} values to the **CP conserving hypothesis**
- As we move towards the maximally violating phase, the fit to the CP conserving hypothesis becomes worse and our **sensitivity grows**

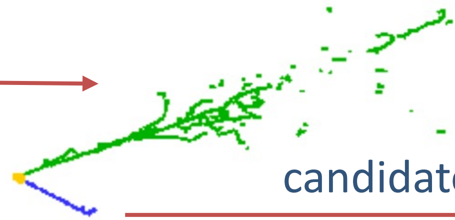


Analysis: ν_e/ν_μ selection*

* Credit to **Dom Brailsford** for initial development and continued support

- Events are selected as a result of the determined identity of the candidate leading leptons in the event (should they exist)

true signal CC ν_e event



candidate electron → **BDT*** how electron-like

candidate muon → **BDT*** how muon-like

ν_e selection

Does candidate electron look electron-like?

To remove backgrounds, does candidate muon look non muon-like?

no →

ν_μ selection

Does candidate muon look muon-like?

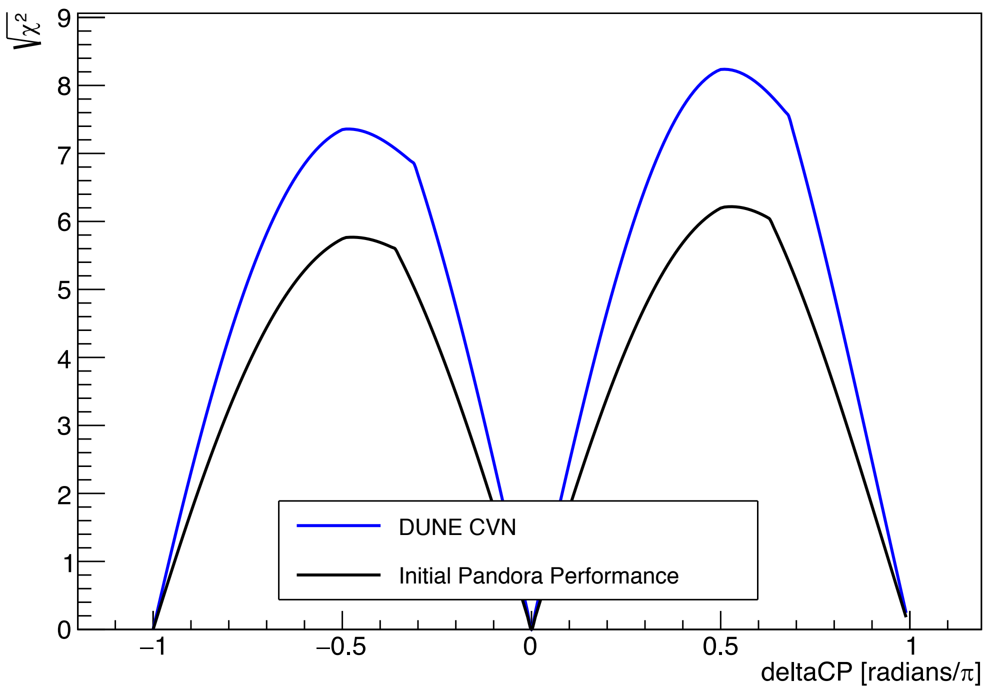
yes ↓ Fill nue energy spectra

yes ↓ Fill numu energy spectra

Initial Performance

	Nue Efficiency	Nue Purity	Nue BG Rejection	Numu Efficiency	Numu Purity	Numu BG Rejection
Pandora	60.0%	67.1%	98.6%	88.3%	87.2%	94.4%

Pandora CP Violation Sensitivity (no stats/systematics)



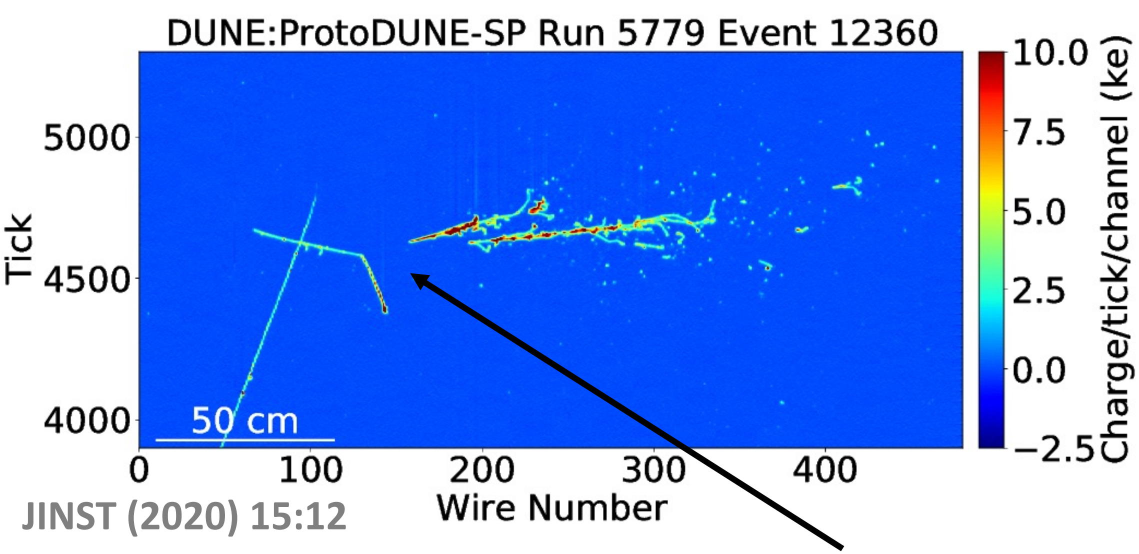
- The numu selection is very good, but the **nue selection dominates the sensitivity** and must be improved
- The Pandora **multi-algorithm** approach allows hypothesised improvements to be investigated in an **iterative** manner allowing a **specific** problem to be identified

  i.e. would a more **accurate neutrino vertex** placement result in a better sensitivity? If so, in what events? for which topologies? etc…

Leading Reconstruction Failure

- We know that the **nue selection dominates the sensitivity**, we know that our nue selection relies on our electron-like BDT being accurate, and we know that the main inaccuracy is the **BDT confusing electron with photons**

- The **initial de/dx of the shower** and the **nu-shower start displacement** is used to aid electron/photon separation – maybe this is where our improvements can be found…



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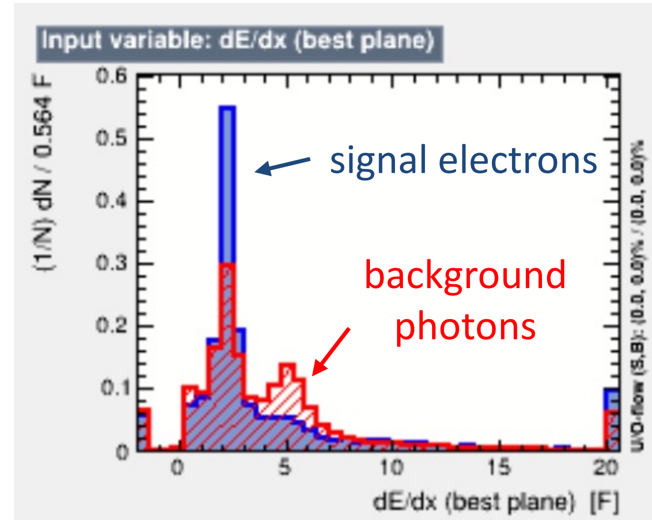
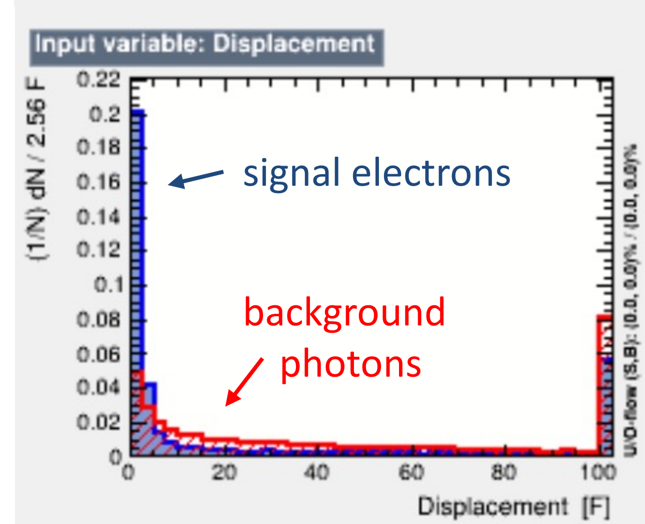
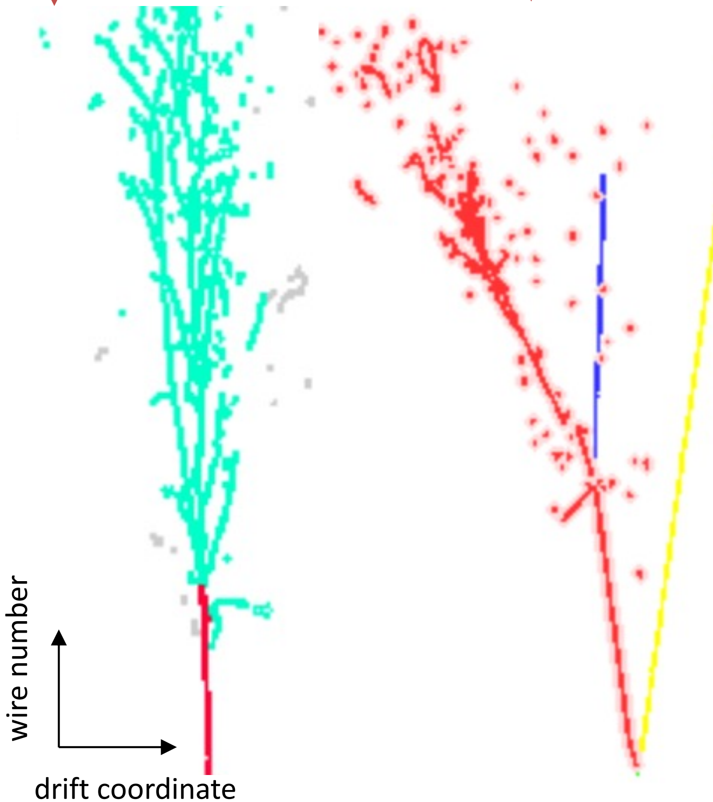
2 GeV/c pion charge exchange candidate

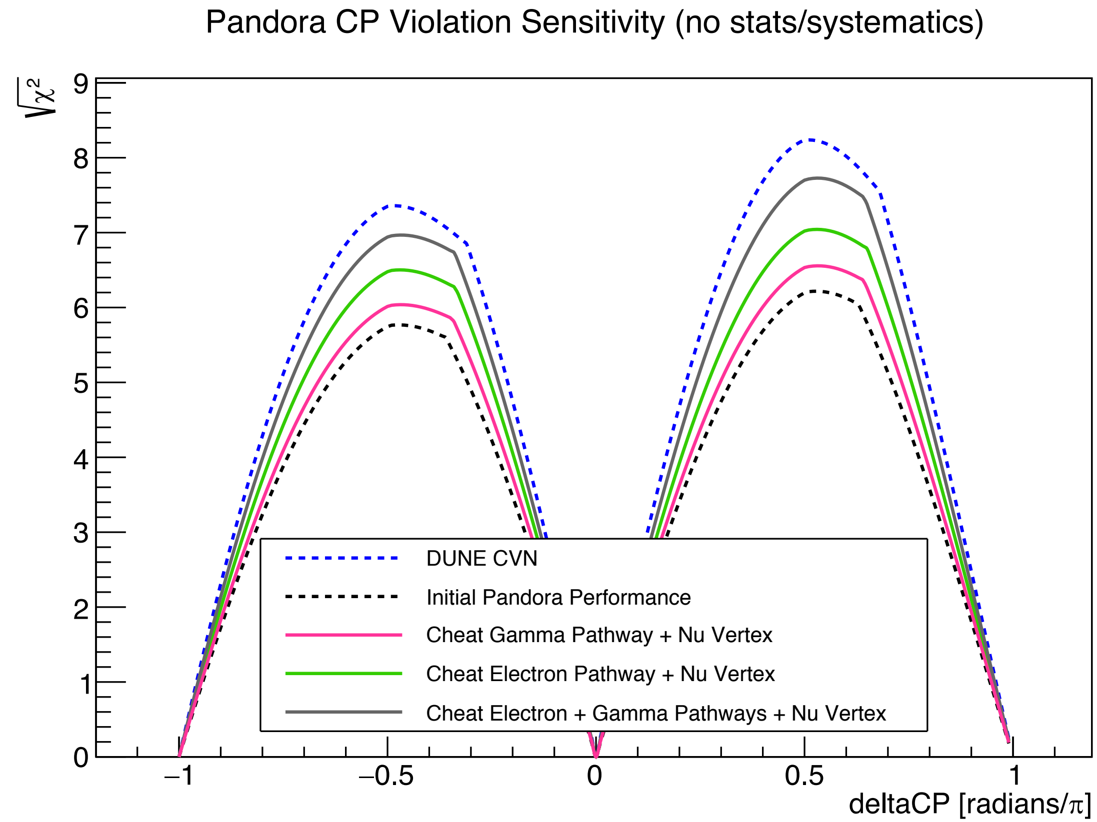




Leading Reconstruction Failure

- Let's hypothesise that to improve the sensitivity, we need to
  - Make sure that **electrons** that **should have** made their way back to the neutrino vertex **do**
  - Make sure that **photons** that **should not have** made their way back to the neutrino vertex **do not**

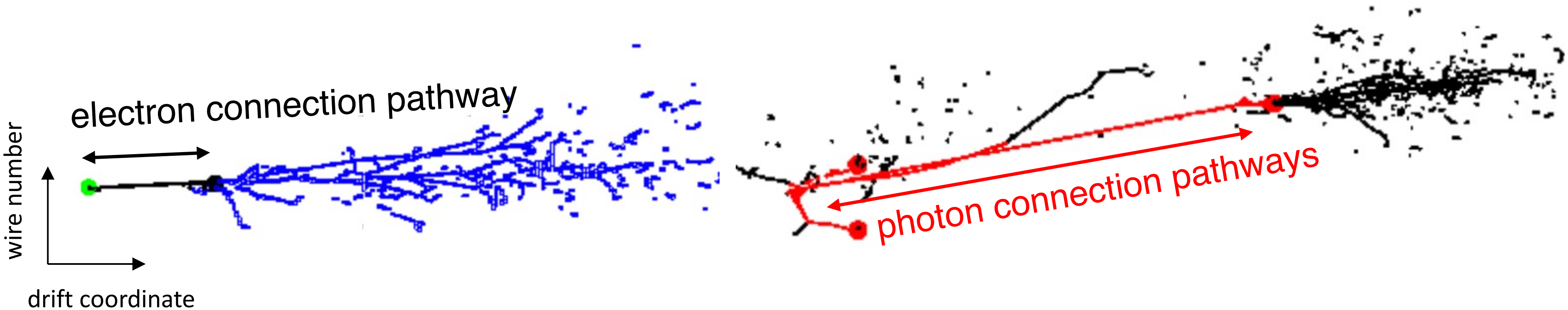




Creating an Algorithm

- The Pandora multi-algorithm approach allows us to create a **specifically designed algorithm** to fix this reconstruction failure and achieve large sensitivity gains

- In this algorithm we
  - Find the **connection pathways** that the electron (photon) should have (has) followed to get back to the neutrino vertex



  - **Decide** whether the connection should be there or not (at the moment a cheated decision but will be replaced by a BDT in future)
  - **Add in** the connection pathway, or **remove**

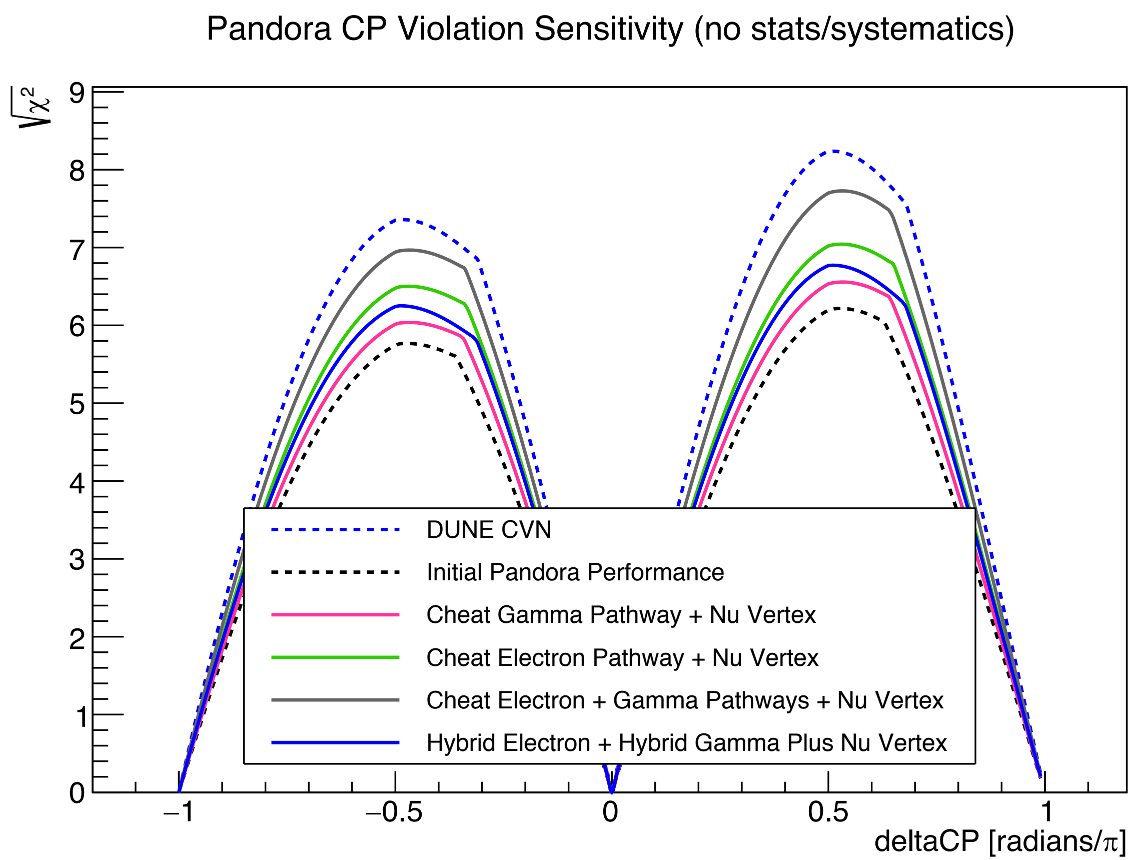
Hybrid Algorithm Performance

- The algorithm still relies on **cheating the connection pathway decision** and the **neutrino vertex placement**, so let's call this a 'hybrid' configuration

- First version performance is **looking really good!**

- We're now investigating methods of pushing the hybrid configuration **closer** to the cheated configuration and are **following many promising leads!**

- Additionally, work has started on developing the **connecting pathway BDT** to realise these sensitivity improvements



Summary

- A Pandora analysis of DUNE's sensitivity to CP violation has been illustrated

- The leading limiting reconstruction failure with respect to CP violation is the **reconstruction of the initial region of showers**

- This has motivated the development of a **hybrid electron extension tool** and **hybrid photon truncation tool** for which performance is looking very good!

- Work is now focused on replacing the **connection pathway assessment with a real reconstruction decision** by the development of a **BDT**