ProtoDUNE Neutron Study Update

David Rivera

University of Pennsylvania

November 21, 2019

Motivation

- Missing/Invisible Energy:
  - Neutrons can carry away a significant portion of the energy for an event
    - Visible energy from neutrons can be delayed and/or manifest as seemingly uncorrelated energy depositions in the detector
  - Energy resolution is limited by our ability to reconstruct and account for all missing energy
    - average missing energy varies with interaction type
    - Event-to-event fluctuations
- In ProtoDUNE, the beam instrumentation offers measurement of the incident beam particle momentum
  - + PID --> Energy measurement
- For DUNE we will have a wide-band neutrino beam ~ few GeV range

ProtoDUNE vs. DUNE

- ProtoDUNE
- Surface detector
  - High cosmic rate
- Charged particle test-beam
- h + A -> many final states

DUNE

- Underground
  - Large decrease in cosmogenic backgrounds
- Long-baseline neutrino detector
- $\boldsymbol{\nu}$ + A -> lepton + X + hadronic

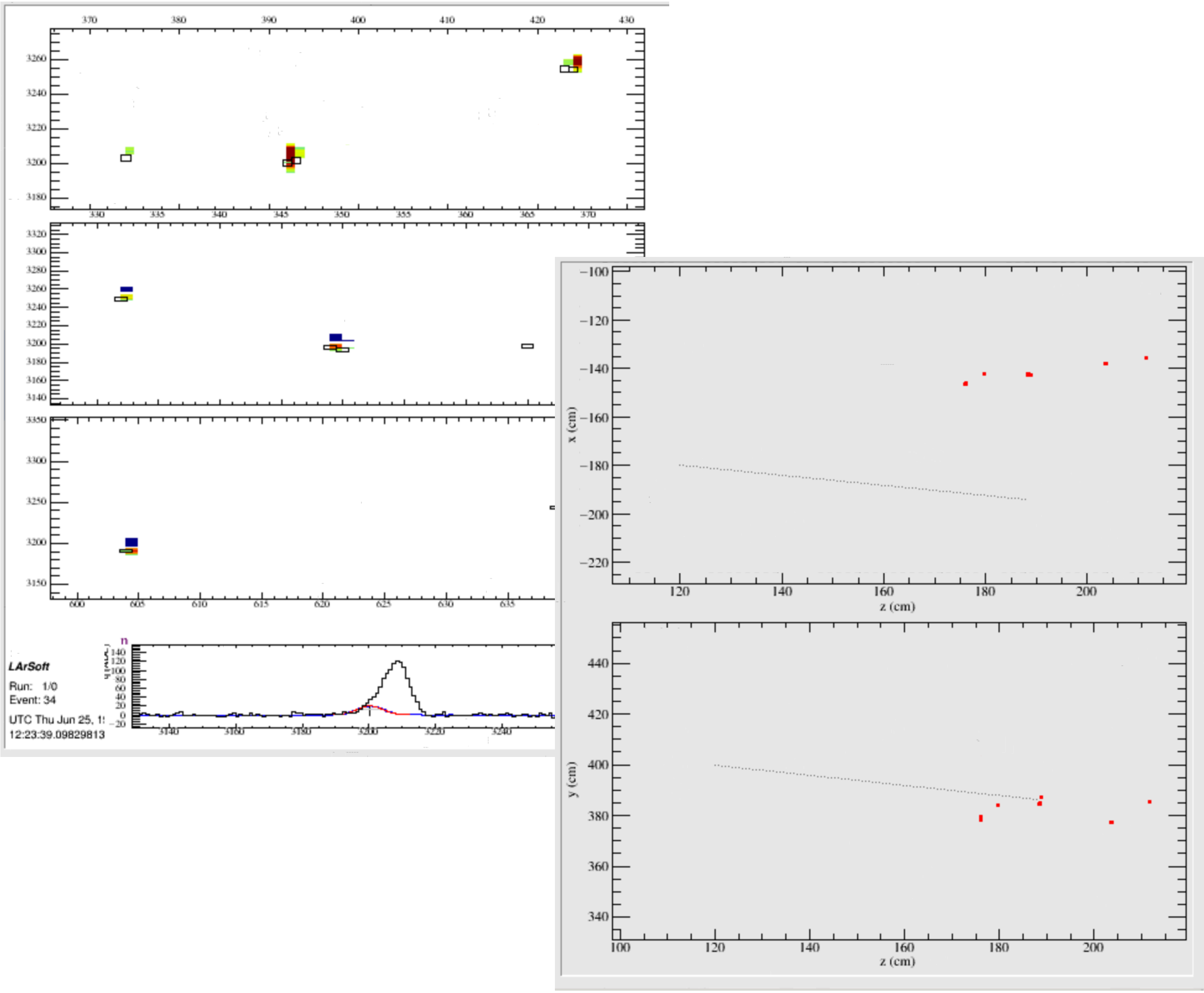
- h = incident hadron
- hadronic = primary hadronic component
- A = Ar-40
- X = post-interaction nucleus

How do we "see" neutrons?

- Quick Answer: Indirectly
- Neutron interactions in LAr typically include:
  1. Elastic scattering
  2. Inelastic scattering
  3. Capture
- Neutrons produce visible energy via:
  - Inelastic scattering resulting in charged particle final states
    - E.g. Charge exchange (n+A -> p + X)
  - De-excitation gammas - Inelastic scattering resulting in excited nuclear states which subsequently decay, emitting photons (Ar* -> Ar + N$\boldsymbol{\gamma}$)
  - Neutron Capture : n + 40Ar -> 41Ar + N$\boldsymbol{\gamma}$
    - ~O(200$\boldsymbol{\mu}$s)
    - $\boldsymbol{\Sigma}$E$_{\gamma}$ = 6MeV

Photon detection

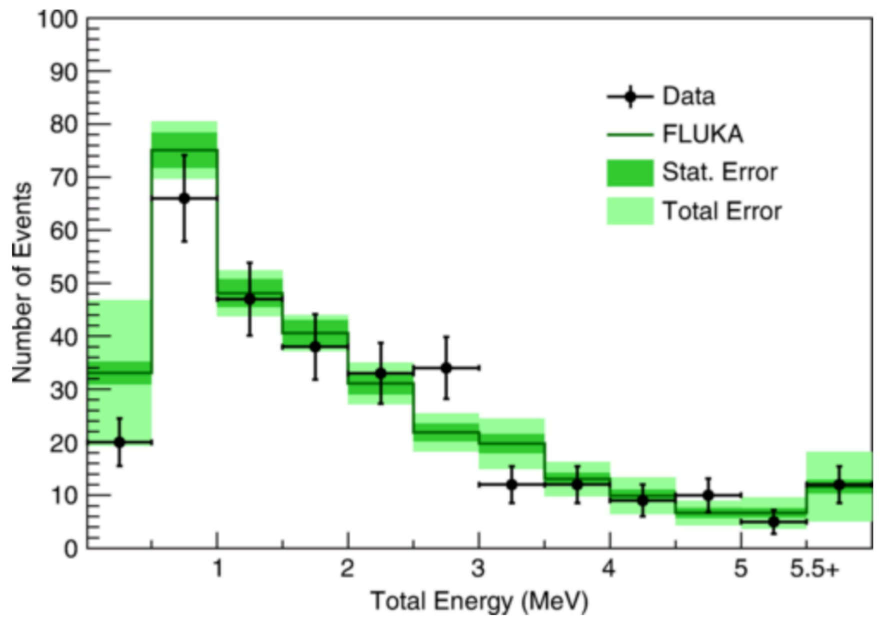
- Both inelastic scattering and neutron capture can produce photons which can further displace the energy carried away by neutrons
- These (few MeV) photons typically Compton scatter with electrons which are a proxy for neutron visible energy

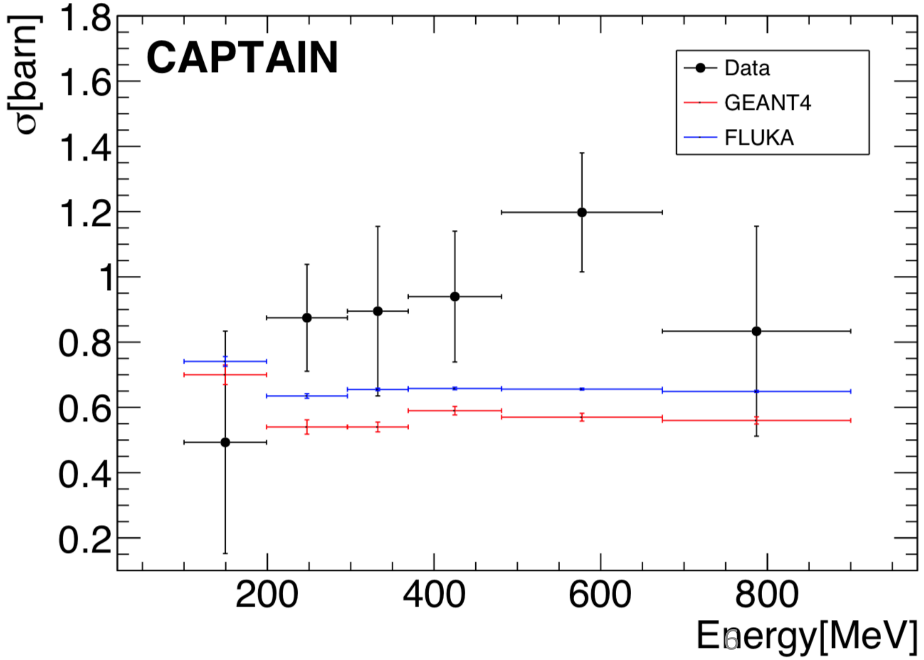


Thermal neutron capture. Kinetic energy = 0.025eV

Other Experiments

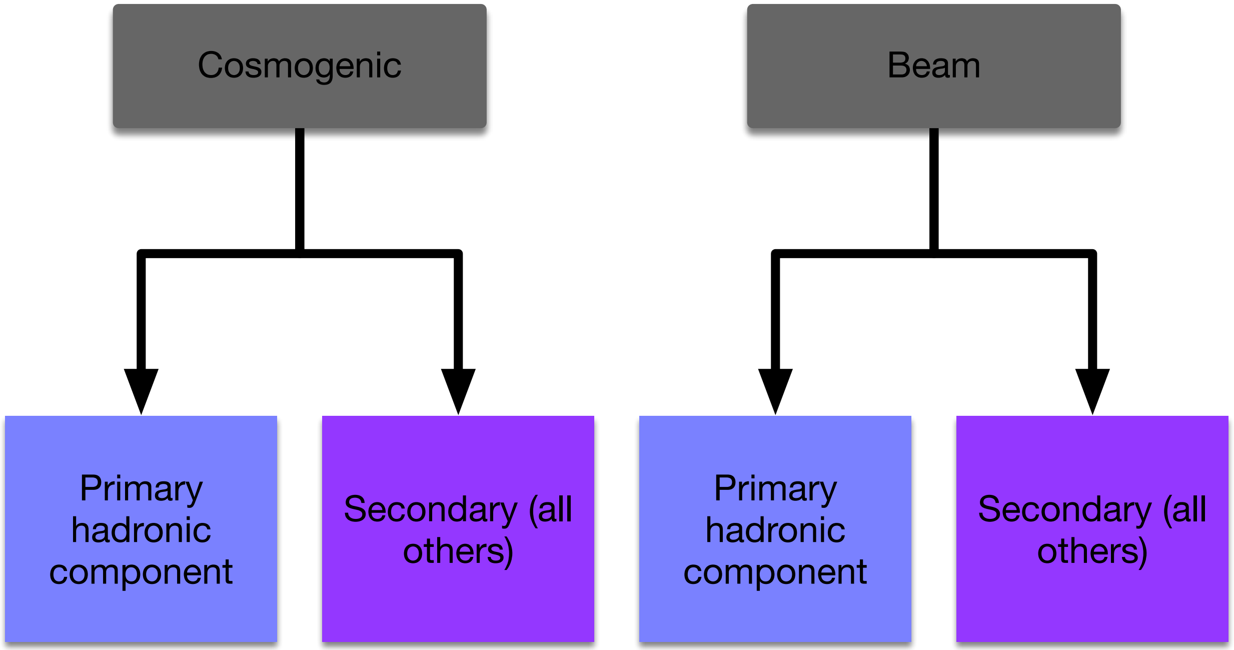
- The ArgoNeut collaboration has demonstrated reconstruction of low energy physics -> there is hope for being able to reconstruct the blips from de-excitation/capture gammas
  - https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.012002
- At ProtoDUNE energies, neutrons can carry away a significant portion of the energy and can be identified via charge exchange
- MiniCaptain collaboration recently published neutron cross-section paper
  - Main detection mechanism for neutrons in their 100-800MeV neutron beam was via identification of proton candidates from inelastic scattering
  - https://arxiv.org/abs/1903.05276





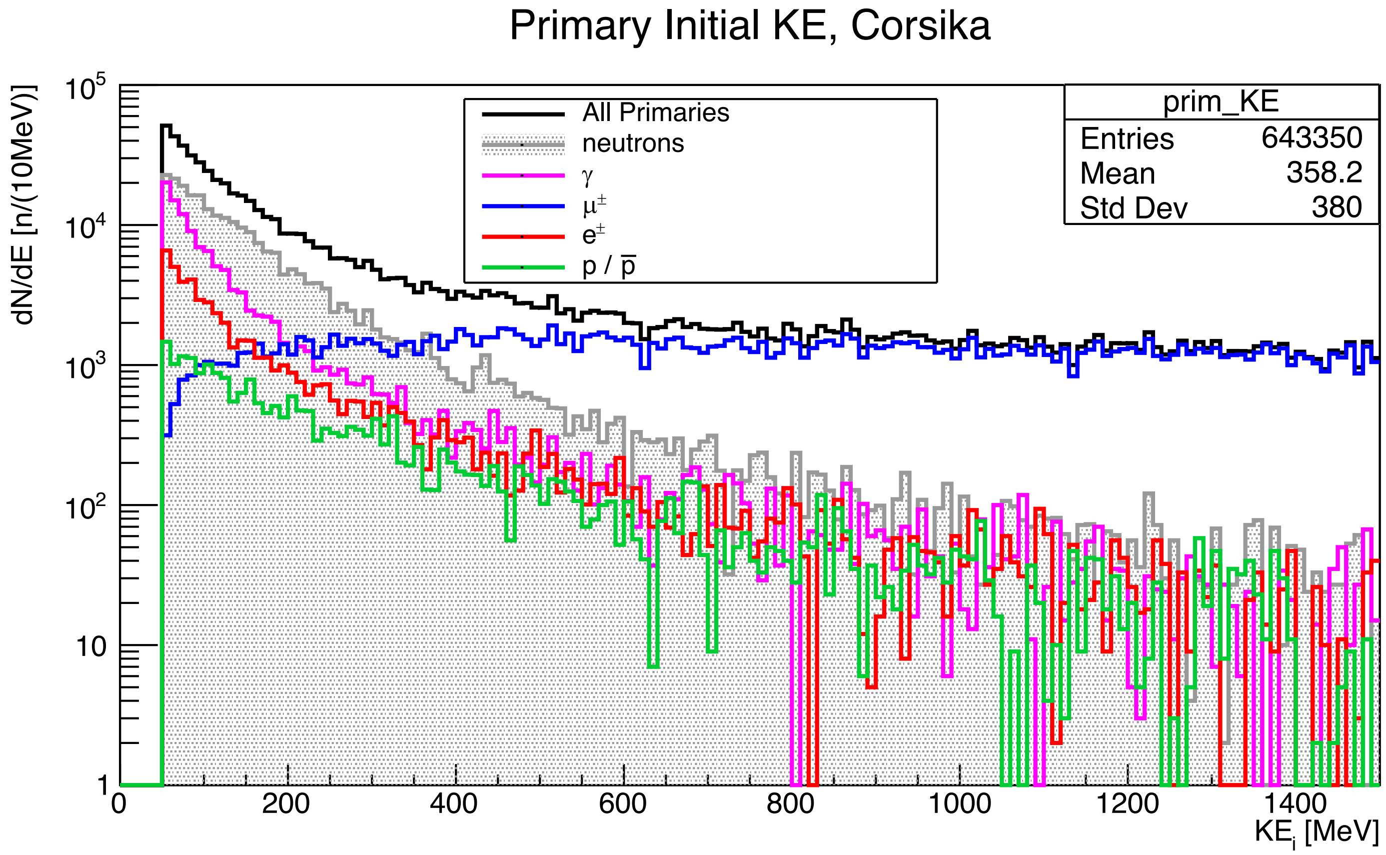
Backgrounds

- The neutron background has both a cosmogenic and a beam-induced component
- Each of which have a primary and a secondary component
  - Primary – neutrons that enter the detector
  - Secondary – neutrons produced by secondary interaction by particles such as muons within the detector



Corsika

- Corsika – simulates air showers from cosmic rays
- Integrated into Larsoft by M. Bass (see [1])
- There is a 50 MeV energy cut on all generated particles:
  - MCC11 less reliable for low energy studies
  - Have generated my own Corsika-only samples



[1] https://indico.fnal.gov/event/10893/contribution/3/material/slides/0.pdf

Changes

- Problems with larsim/LArG4 (Legacy):
  - Neutrons decays in the ProtoDUNE foam
  - Scintillation EndProcess() even for neutrons(!)
- Refactored framework – I enabled the use of the refactored larg4 in the ProtoDUNE simulation chain (see my collaboration meeting talk) as an alternative to Legacy
  - No more neutron decays or overuse of Scintillation process
  - Access to reference physics lists e.g. QGSP_BERT_HP

Some definitions

- **Candidates:** the protons and $e^{\mp}$ that deposit visible energy and *can be* from neutron origin
- **Progenitor:** The candidate's ancestor (from the notion of "parentage" in larsoft; mother and daughter particles)
- **Provenance:** the reaction chain yielding the candidate protons, electrons, or positrons. For example:
  - **Signal proton provenance :** $n + {}^{40}_{18}Ar \rightarrow X + p$
  - **Signal $e^{\mp}$ provenance** : $n + {}^{40}_{18}Ar \rightarrow X + \gamma \rightarrow X + e^{\mp}$
- X represents everything else
- I will typically neglect the nuclei when noting the provenance
  - E.g. : $(n + {}^{40}_{18}Ar \rightarrow X + p) \leftrightarrow (n \rightarrow p)$

Backgrounds

True neutron backgrounds

- Candidates that have the same ***provenance*** as the signal but with neutrons that are not from the primary particle in question (e.g. π^+)
  - These backgrounds have a primary and secondary neutron component
- E.g. :
  - Primary cosmic neutrons
  - Beam-induced neutrons ("punch-through" from collisions with the target)
  - neutrons from photo-nuclear breakup: $\gamma + {}^{40}_{18}Ar \rightarrow X + n$
    - These photons themselves can be from e^- Bremsstrahlung
    - Photons from π^0 decays

Backgrounds (continued)

- Backgrounds = neutron backgrounds + Other
- Others = candidates from any provenance and without a neutron progenitor
  - E.g. : ($e^{\pm} \rightarrow \gamma \rightarrow e^{\mp}$) or ($\pi^{+} \rightarrow p$)
- I will be focusing on the (signal + neutron backgrounds) for this talk

Analysis Approach

- Monte Carlo study
- Simple approach, focusing on TPC simulations (no photon simulation)
- Start with hits (hitpdune – disambiguated gausshit)
- All hits are backtracked to the trackID contributing the largest portion of the deposited energy and the provenance is determined

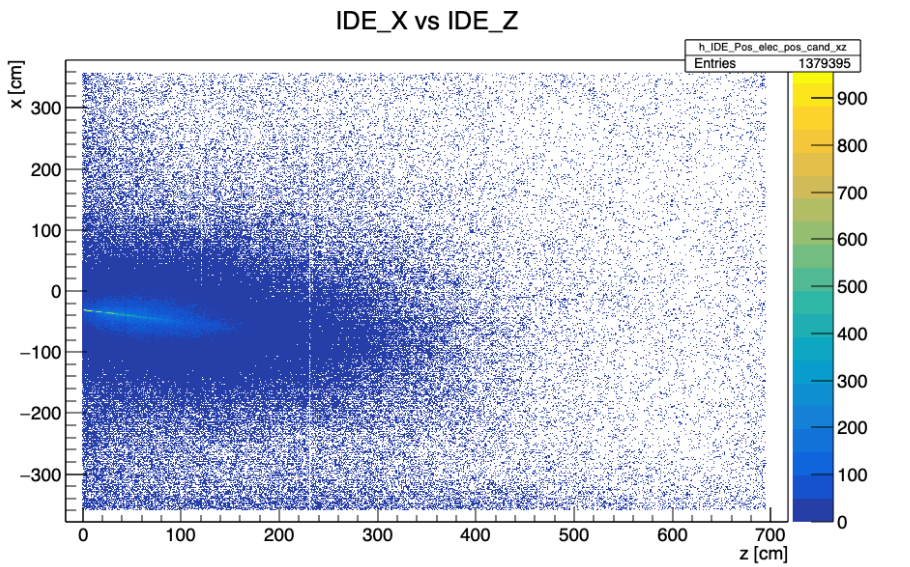
Samples

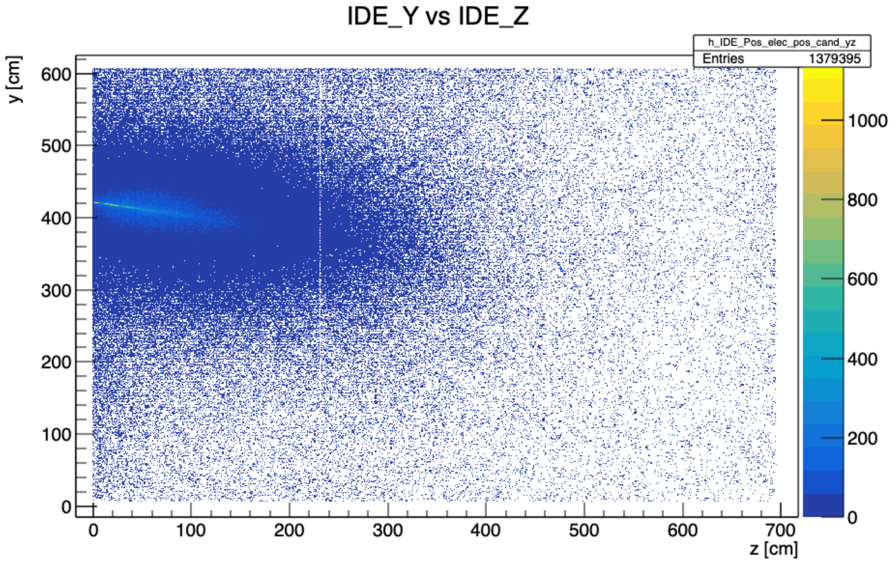
- Particle gun (single π^-, 10k evts)
- CORSIKA (600 full cmc simulation)
- 1GeV Negative Beam + beam backgrounds (12k evts)

Negative 1GeV pion, single particle (10k events)

$e^{\pm}$ Candidate Energy Depositions

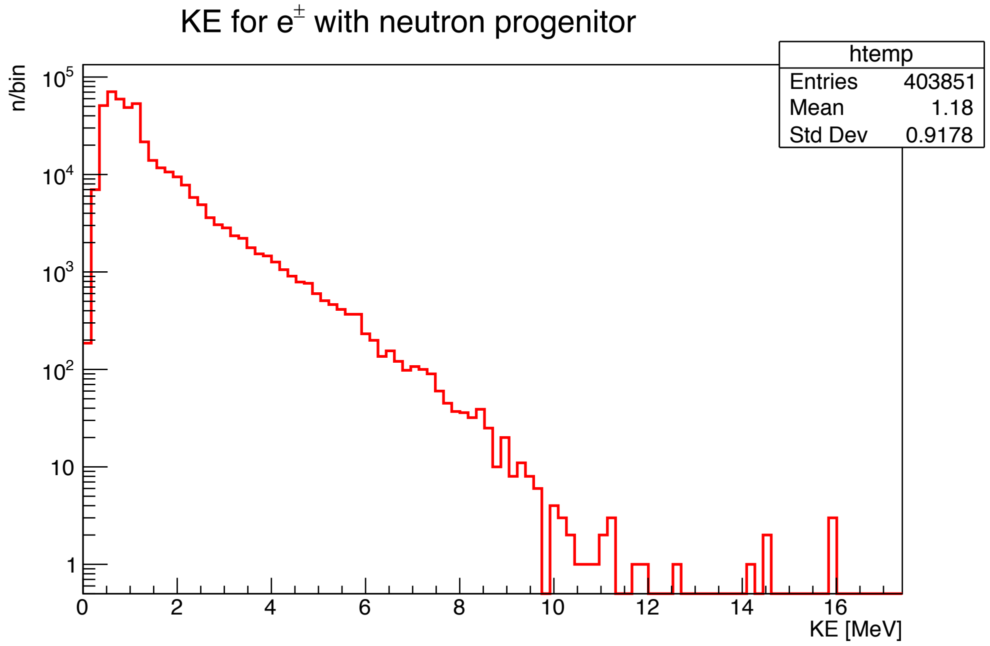
- Only pi- are simulated
- 10,000 events
- All electrons/positrons included
- Includes electrons from hadronic ionization from the pi- themselves

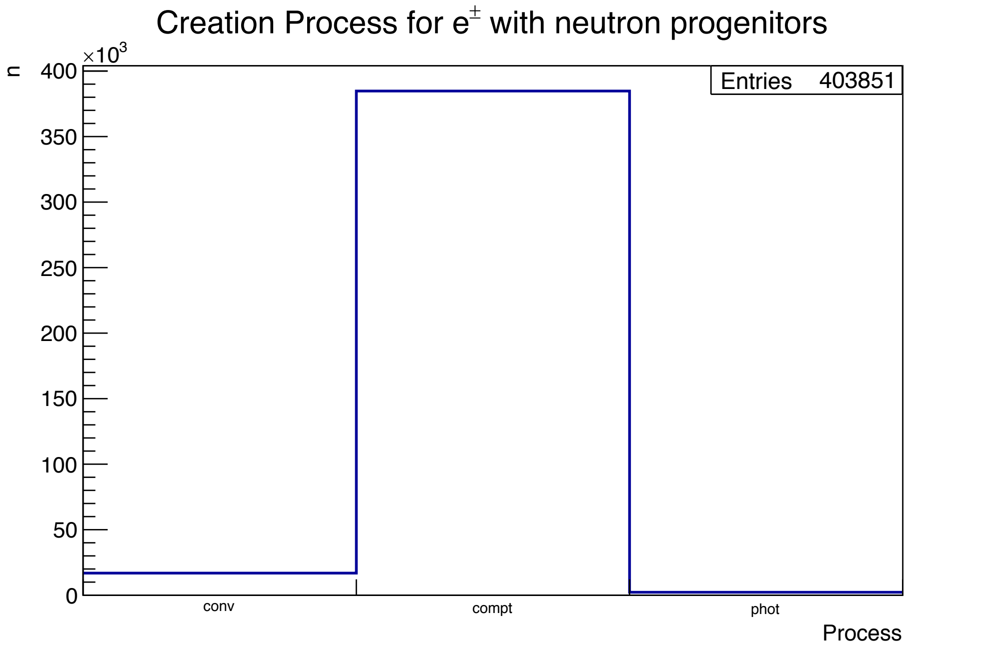




Signal e±

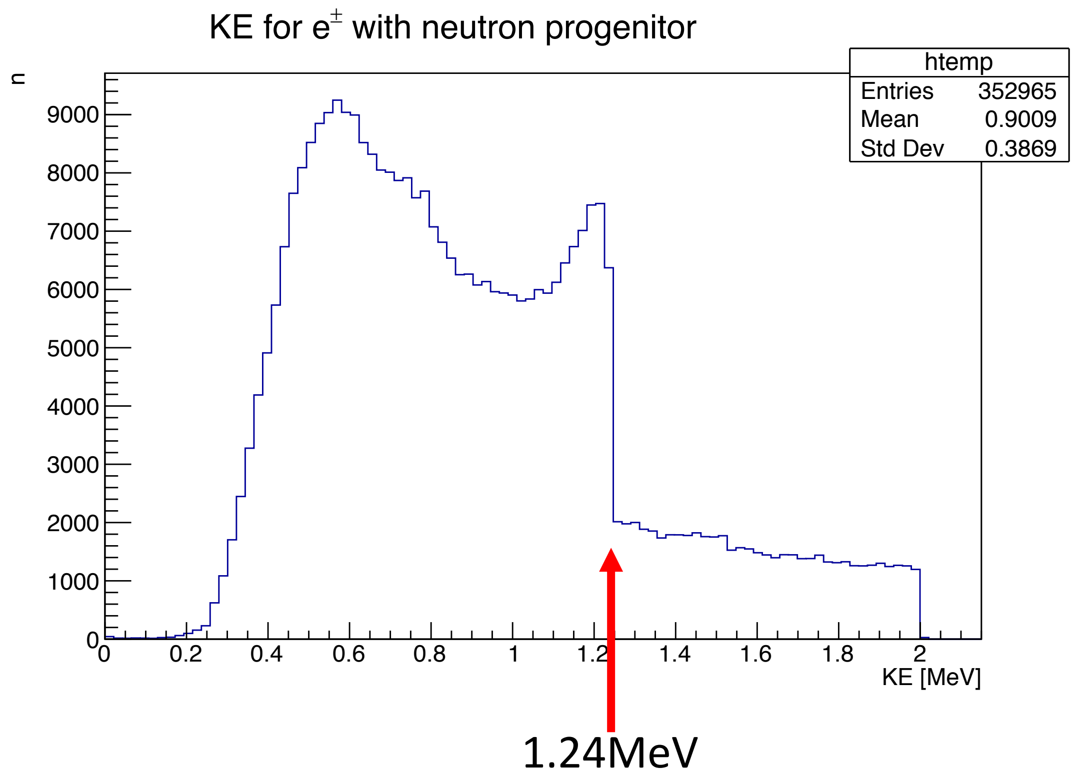
- $e^{\pm}$ from de-excitation / capture gammas with neutron progenitors are low energy
  - Very few above 10MeV
  - Mostly produced through Compton scatters
- conv – photon pair - production
- phot – photoelectrically produced





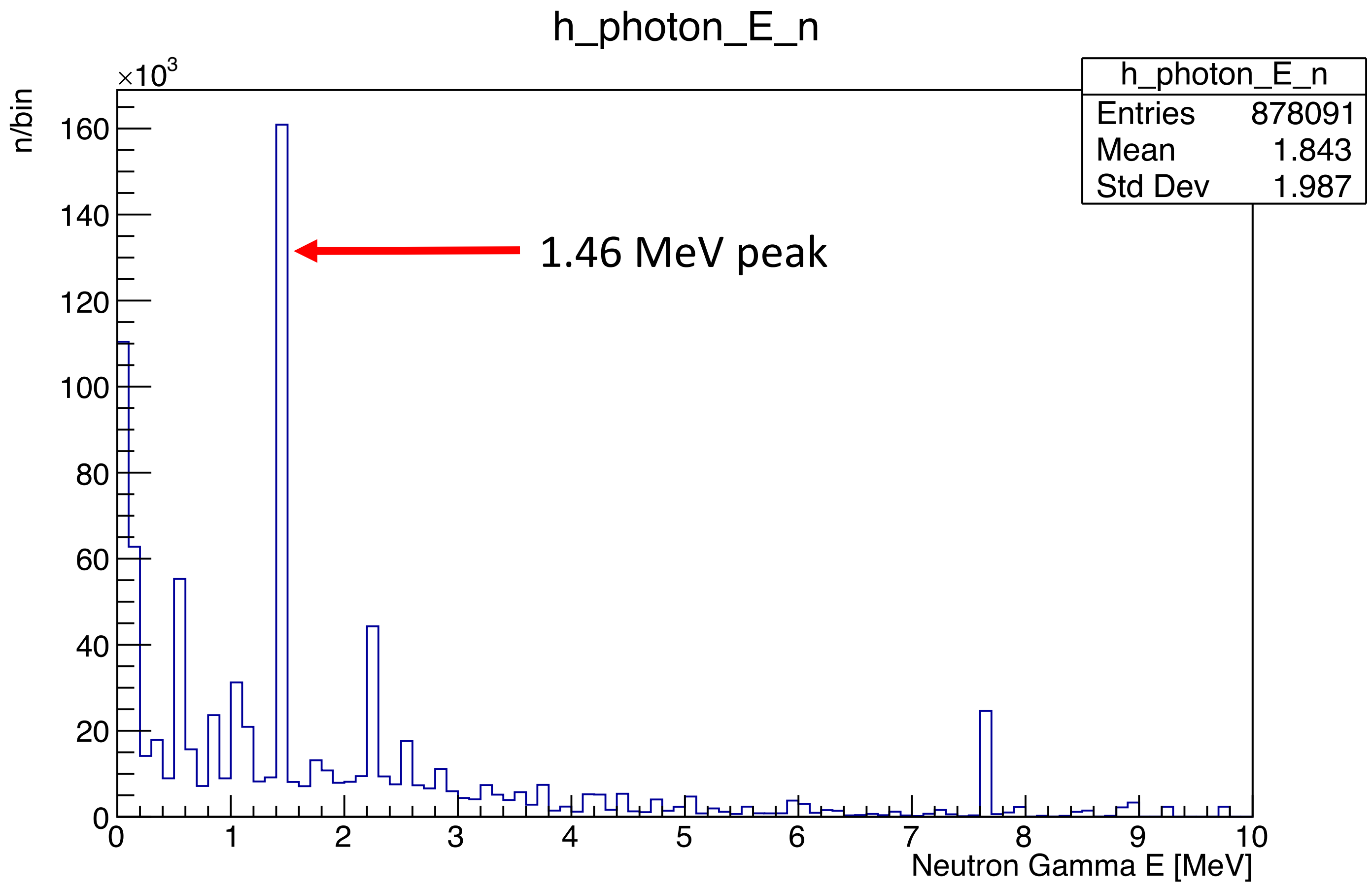
Compton edge

- ^{39}Ar has a 565keV endpoint (200 keV peak)
- ~1/5 of these e^{\pm} have kinetic energies below 565keV
- Large Compton edge around 1.24 MeV is predominantly from Ar40 transitions from 1st excited state to the ground state (see next slide)

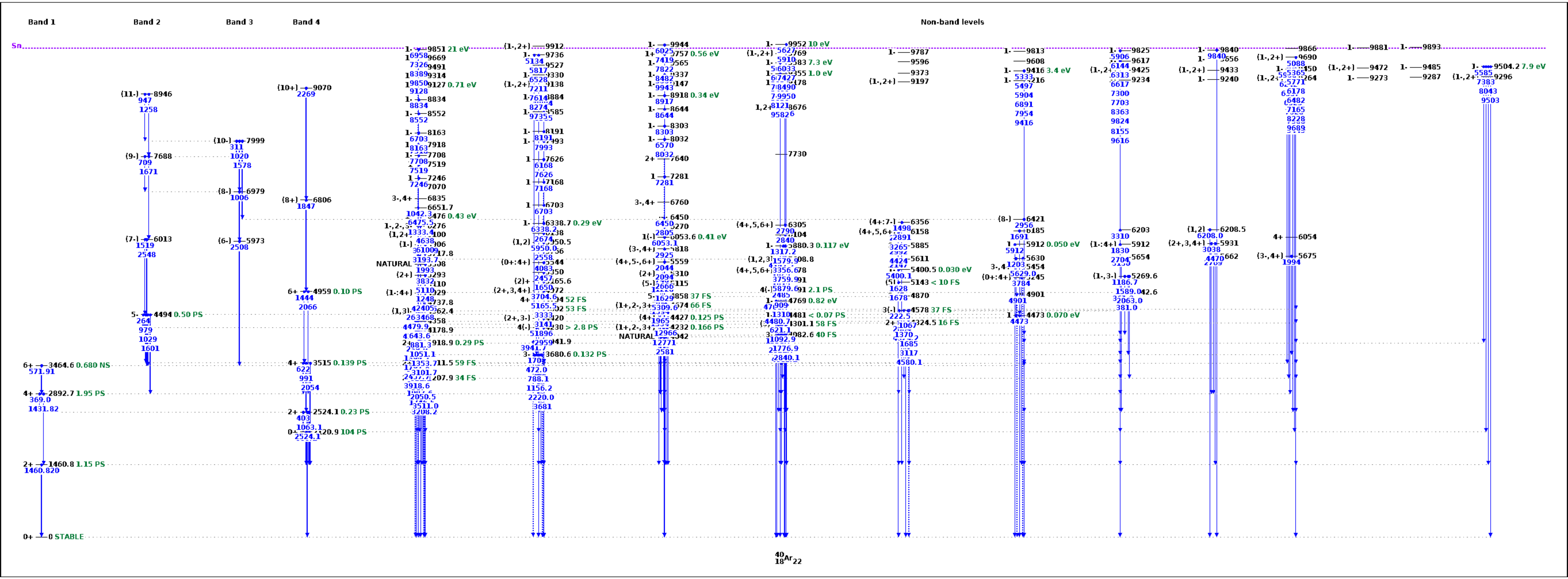


Photon energies from neutron processes

- Includes photons from both neutron-inelastic and neutron capture processes



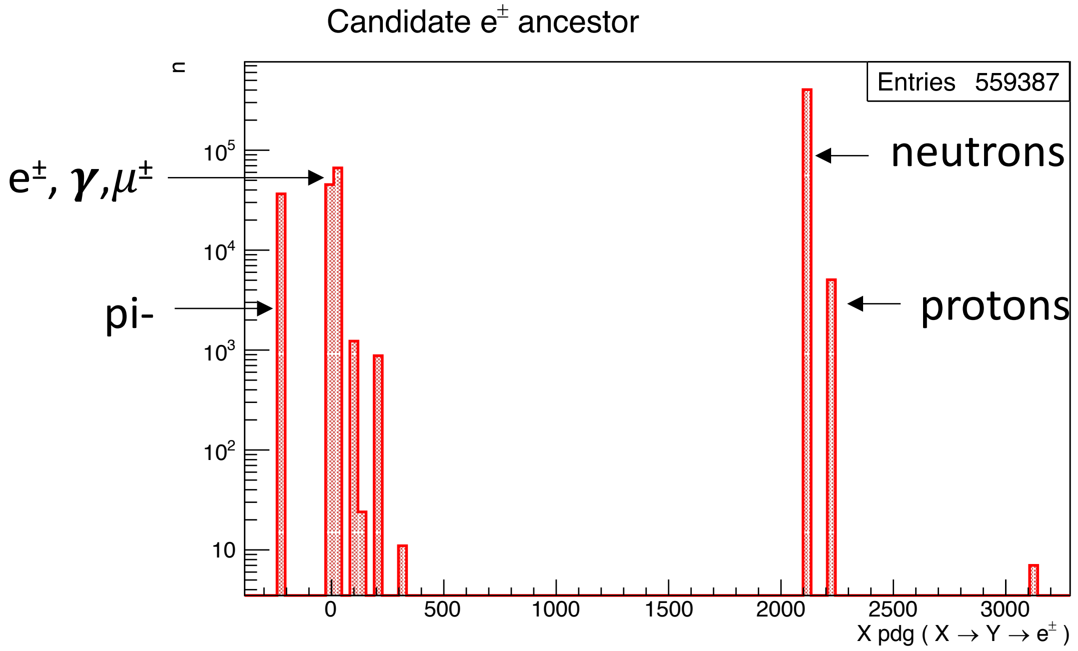
Argon-40 Energy Levels



- 1st excited state: 1.46MeV

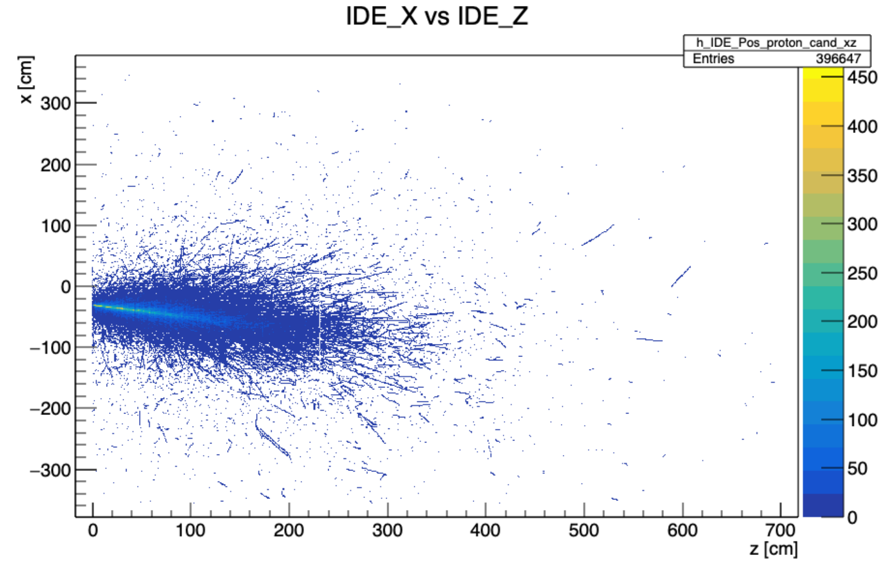
Background e± candidates

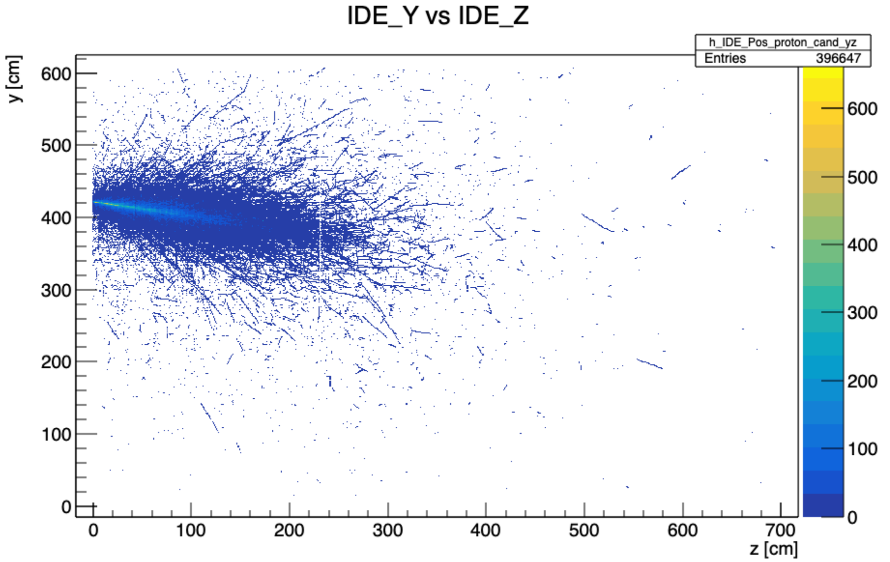
- Including all e± all descending from the primary beam pi-
- 5.5% are ionization e- from the passage of the pion itself (secondary e-, no grandmother particle)



Proton candidate energy deposits

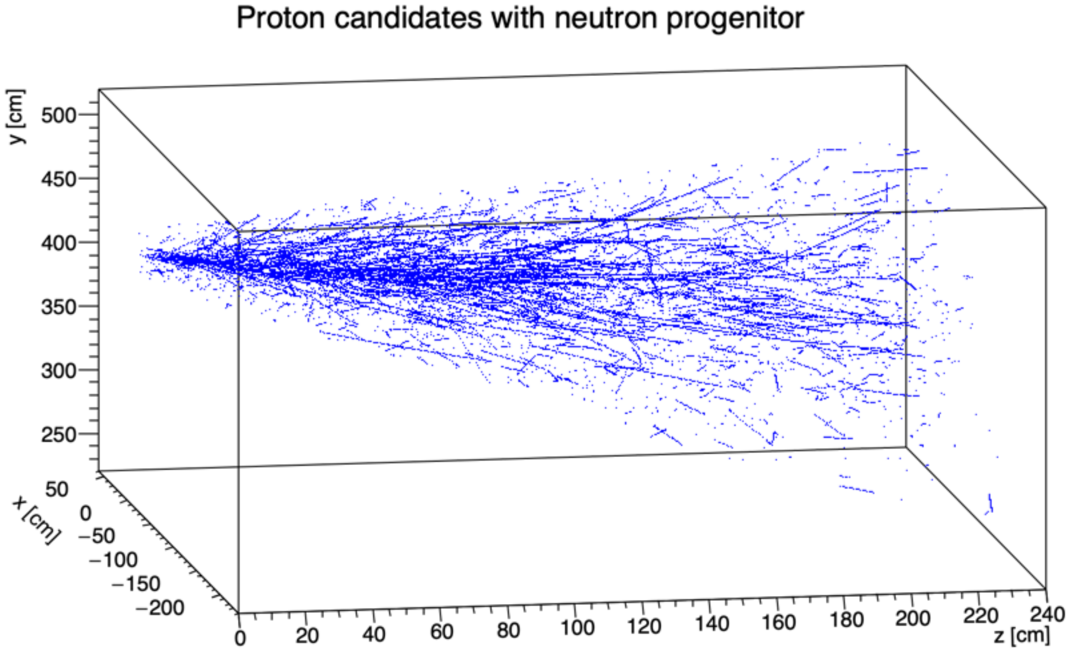
- Only pi- are simulated
- 10,000 events
- Protons with neutron and non-neutron mothers
- Large majority of these are from pi- inelastic interactions





Cone cut for protons from 1GeV, pi-

- Cone cut:
  - Right Cone with axis in the beam direction
  - z < 230cm, only candidates contained within the first APA
- Protons from pi- inelastic scattering not considered bkg since these have connected pi- and proton tracks
- Protons from neutrons are topologically separate from primary pi- tracks



Number of candidates hits (1GeV, pi- only sample, 10k evts)

Elec/positron	Non-neutron and not from muon ionization or hadronic ionization (A)	Non-neutron but from muon or hadronic ionization (B)	With neutron progenitor (S)	Total (T = A+B+S)	Avg. signal candidate hits per event (S/10k)	Signal/bkg (S/(A+B))
Cone cut	172607	55858	252839	481304	25.3	1.1
Cone cut + 565 keV < KE < 10 MeV	160123	55799	225965	441187	22.6	1.0

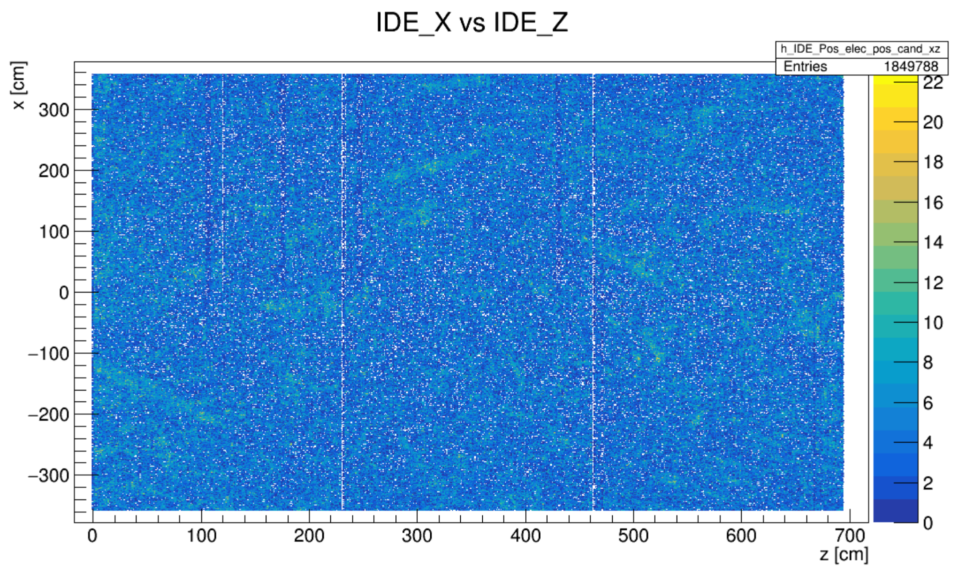
proton	Non-neutron (not really bkg*)	With neutron progenitor (S)	Total	Avg. signal protons hits per event (S/10k)
Cone cut	273952	33282	307234	3.3
Cone + KE>21 MeV	265738	26762	292500	2.7

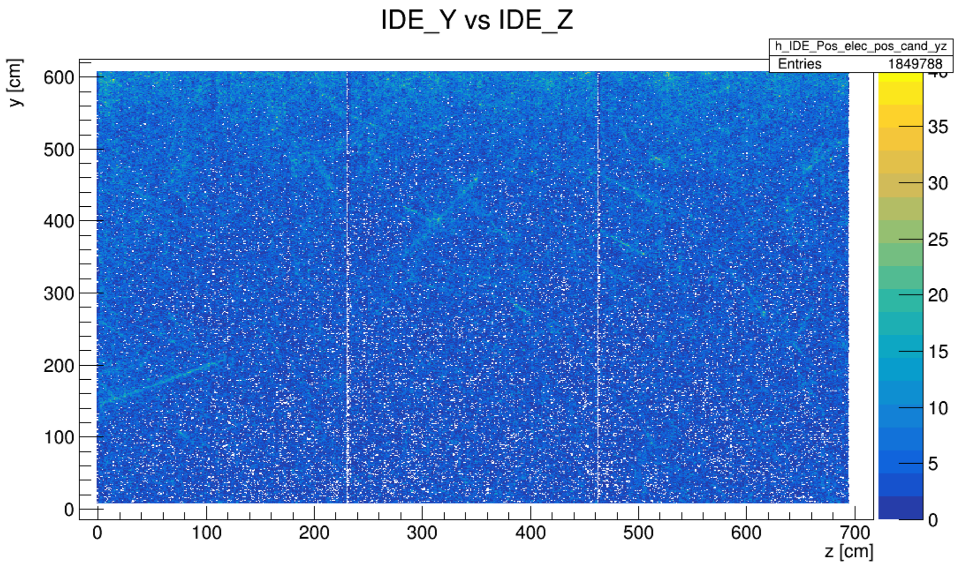
* For $\pi \rightarrow p$ expect no separation between incoming pion and outgoing proton, whereas protons from neutrons will have separation

Full CORSIKA, CMC 600 events (Purely Background)

e$^{\pm}$ candidate depositions

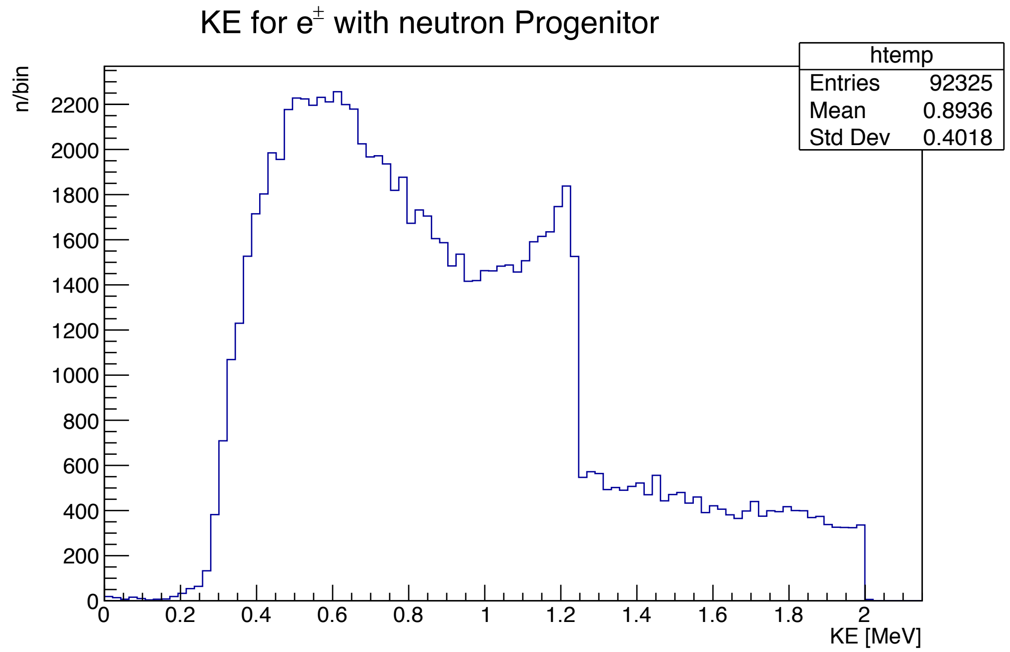
- All electrons/positron ionization depositions
- 600 events with the full Constant Mass Composition Model from our Corsika generator in ProtoDUNE





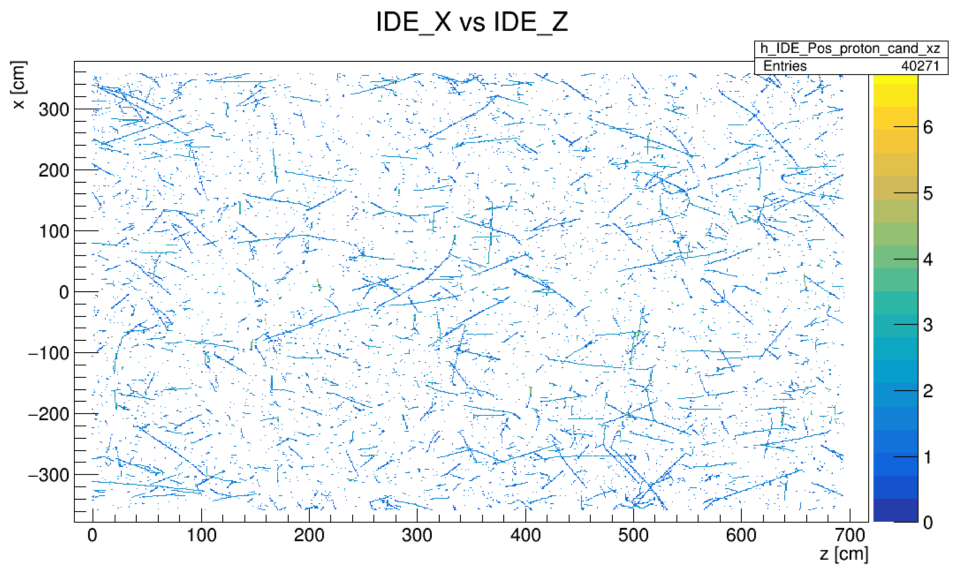
Low Energy $e^{\pm}$

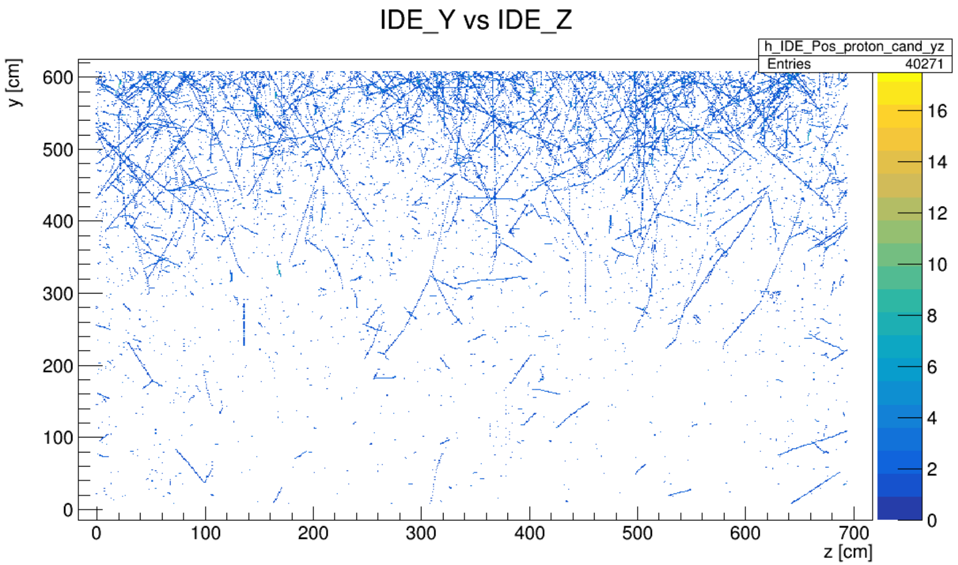
- Kinetic energies for $e^{\pm}$ candidates with neutron progenitor
- Compton edge also visible here (from neutron bkg)



Proton candidate energy depositions

- Includes all protons:
  - Primary, secondary, and higher order protons
- Purely background

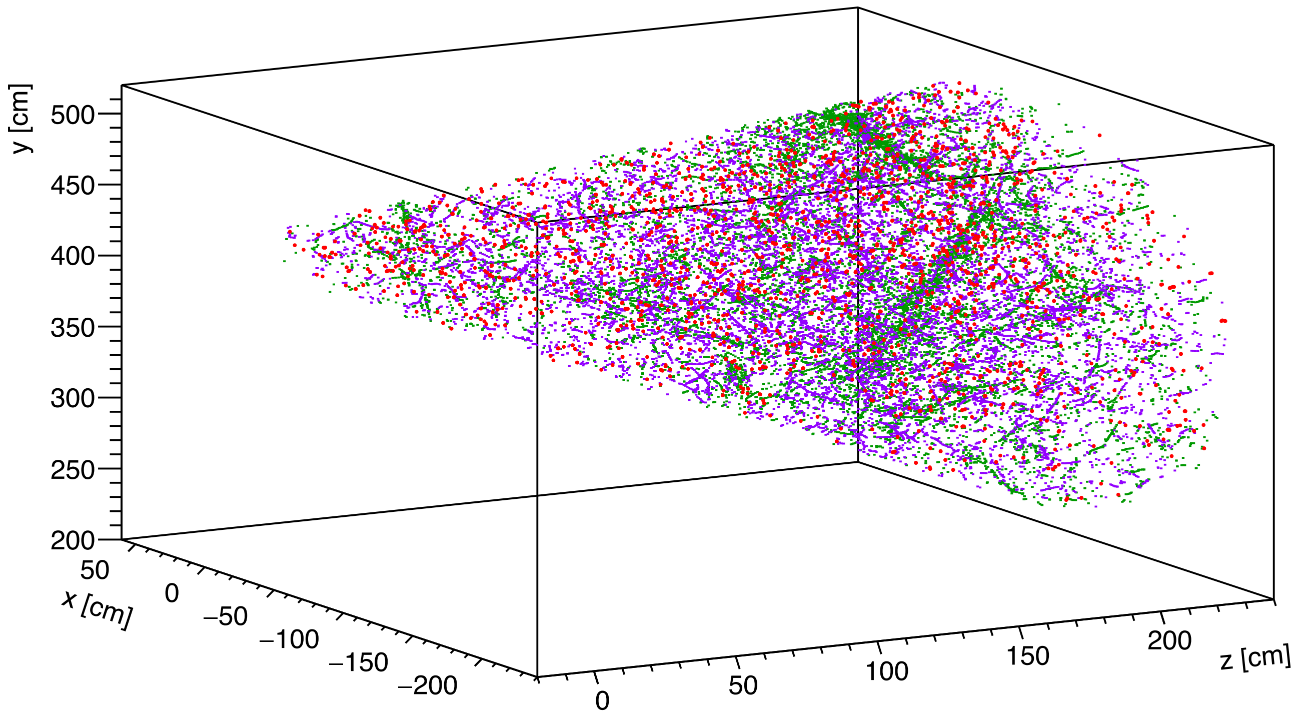




Cone cut on $e^{\pm}$ candidates

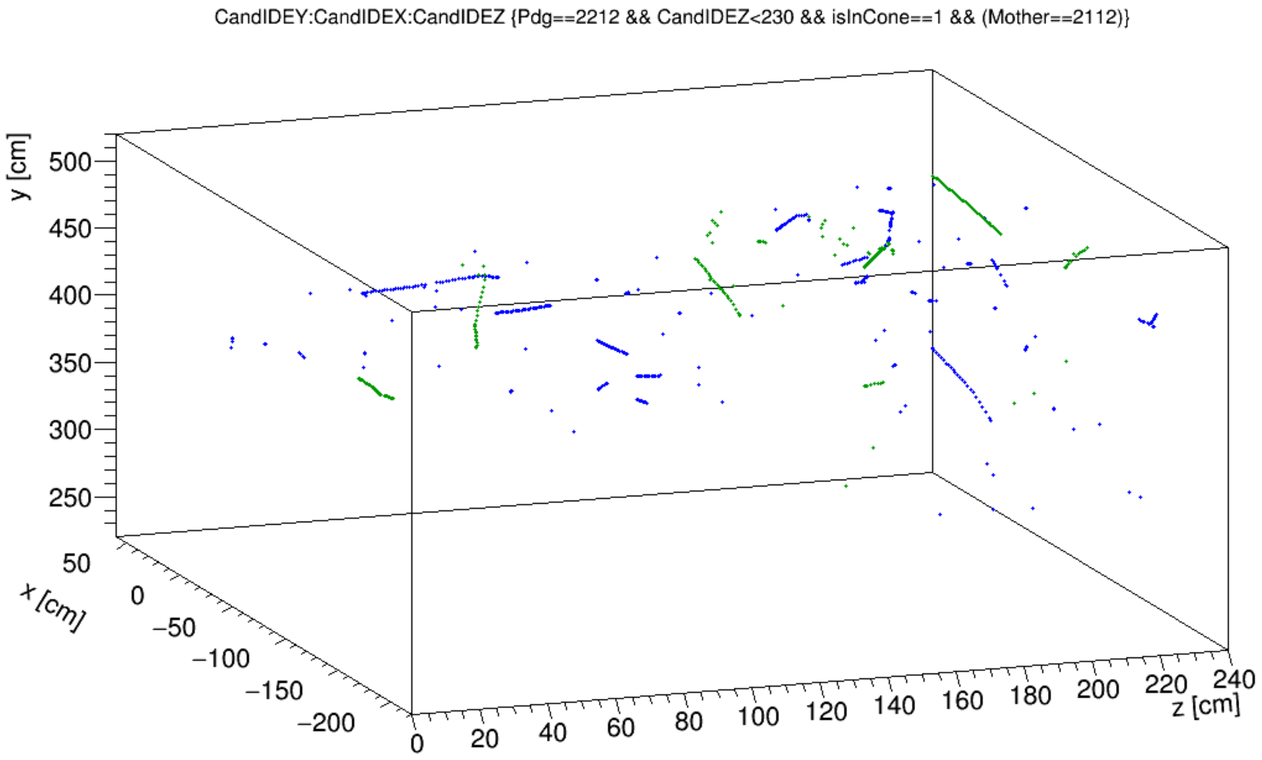
- 600 Corsika evts
- Two cuts:
  - z < 230cm, only candidates contained within the first APA
  - KE < 10MeV
- Red = $e^{\pm}$ with neutron progenitor (true neutron bk)
- Magenta = $e^{\pm}$ from muon or hadronic ionization
- Green = all other $e^{\pm}$

Candidate Ionization Deposition Event locations



Cone cut on cosmic bkg proton candidates

- Only protons in z < 230 cm
- Cone cut along beam direction
- 600 evts
- All bkg proton candidates distributed within 74 of the 600 events
  - Most of the cone cuts in the 600 evts have no protons from cosmic backgrounds
- Blue = protons with neutron progenitor (true neutron component)
- Green = protons from all other provenances



Number of candidate hits, cosmics, 600 evts

Elec/positron	Non-neutron and not from muon ionization or hadronic ionization (A)	Non-neutron but from muon or hadronic ionization (B)	With neutron progenitor (C)	Total (D = A+B+C)	Avg. per event (D/600)
Cone cut + KE<10MeV	9007	5594	2160	16761	27.9
Cone cut + 565keV < KE < 10MeV	8157	5566	2006	15729	26.2

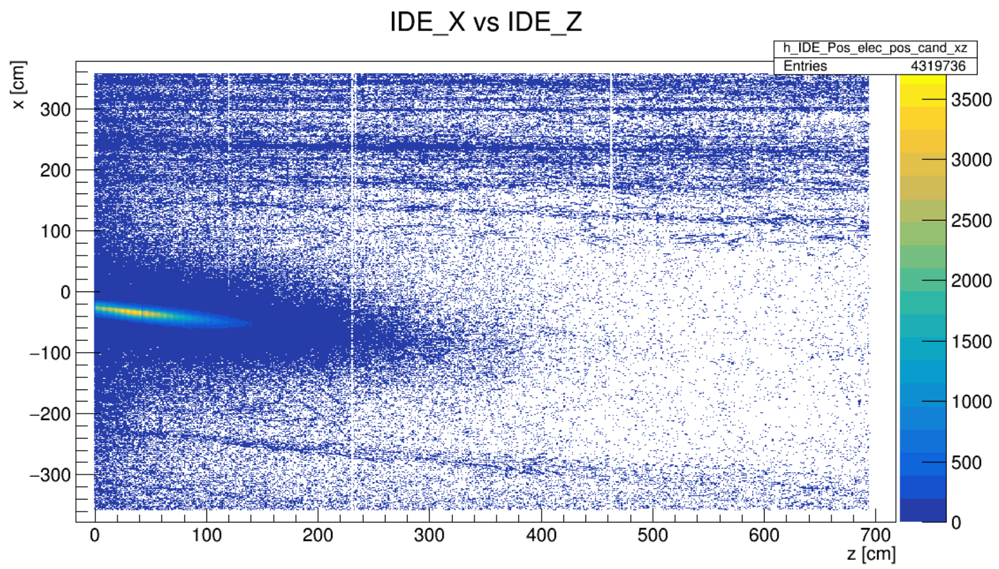
proton	Non-neutron (A)	With neutron progenitor (B)	Total (C=A+B)	Avg. per event (C/600)
Cone Cut	0	360	360	0.6
Cone cut + KE > 21MeV	0	298	298	0.5

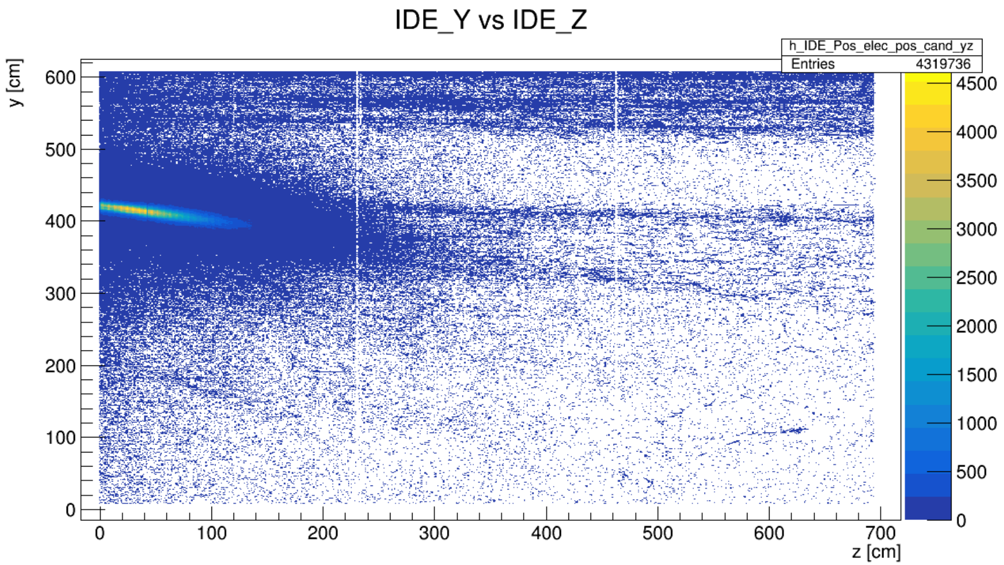
BACKUP

Beam + Beam Bkg, 12k events (2300 pi-)

e$^{\pm}$ candidates depositions

- 12000 events
- Includes mainly beam electrons
- 2300 pi- events
- Beam backgrounds e.g. halo muons and punch-through neutrons





All proton candidates

- Most protons come from the 2300 pi- events