Fermilab

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Single Photon Searches at ICARUS with SPINE

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U.S. DEPARTMENT of ENERGY
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ICARUS

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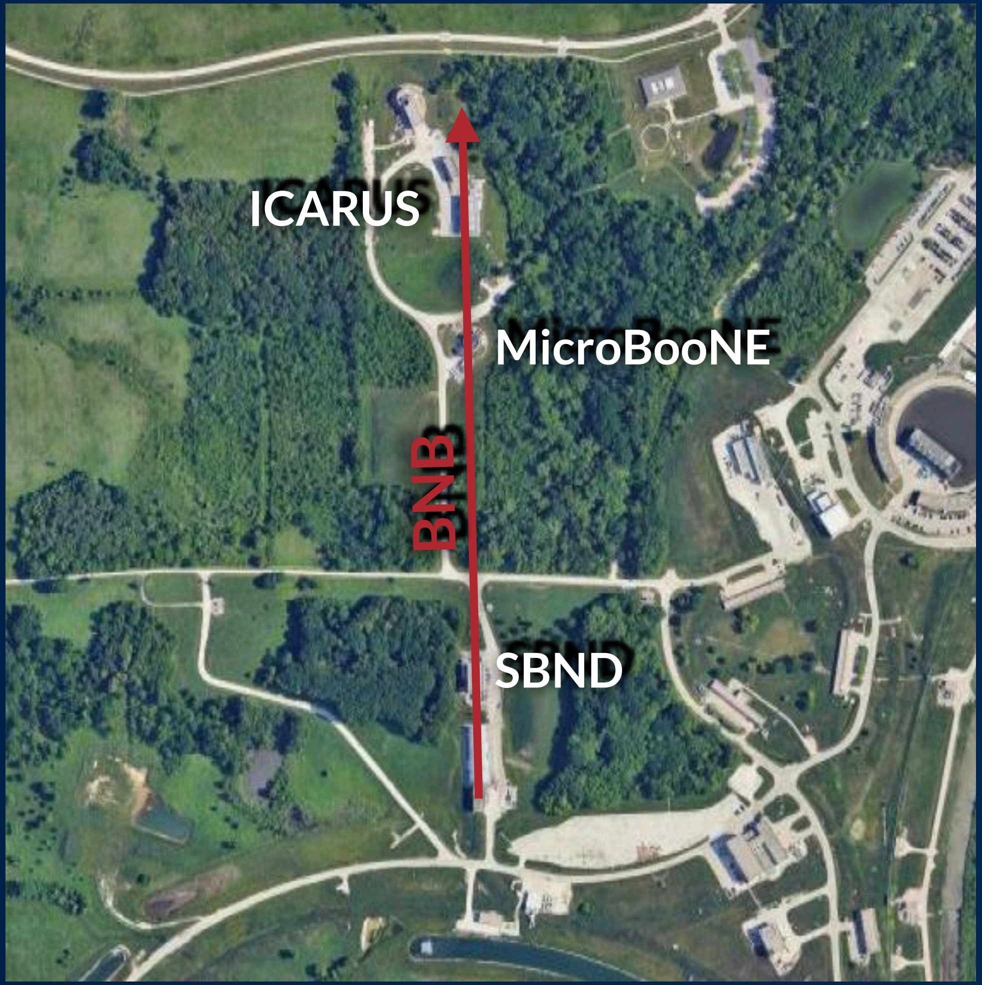
ICARUS

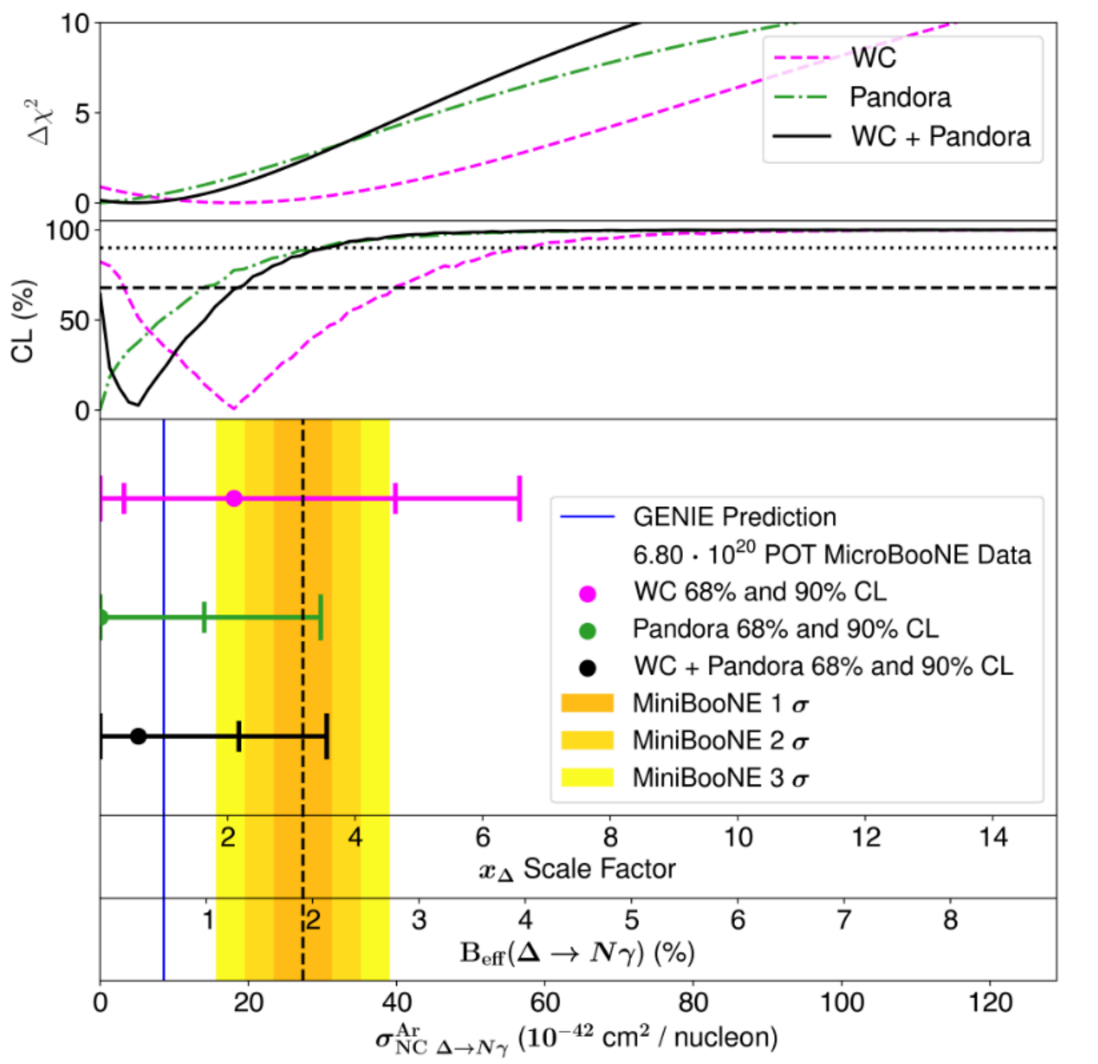
- ICARUS, MicroBooNE, and SBND are all Liquid Argon Time Projection Chamber neutrino experiments along the Booster Neutrino Beam (BNB)
- ICARUS is the furthest, 600 m from the BNB target
- ICARUS is the largest with 476 ton active mass
- ICARUS's large size makes it ideal for containing showers while rejecting out-of-detector backgrounds



Background

Why Single Photon?

- MiniBooNE, also in the BNB, saw a Low Energy Excess (LEE) of electron-like events
- The LEE could be explained by an underestimation the number of single photons events misidentified as electrons
    - NC resonance producing a Δ(1232) with a decay to a photon and a nucleon
    - NC $\Delta \rightarrow N\gamma$
- MicroBooNE published results which are consistent with this explanation, but are not definitive
- ICARUS is in a good position to help answer this question



arXiv:2502.05750v2

Background

Efficiencies

- The NC $\Delta \to N\gamma$ channel is a rare process with an estimated branching ratio near 0.5%
- MicroBooNE reported a total of 19.64% efficiency across multiple selection methodologies
- Improving our selection efficiency for these single photon events can lead to increased sensitivity to this rare process

TABLE I. Efficiency and purity summary. The rightmost column shows the efficiency and purity for a union of all four selections; note that the combined efficiency is less than the sum of the four efficiencies, because some events can be selected by both reconstructions. Efficiency is calculated as the fraction of simulated true NC $\Delta \to N\gamma$ events in the fiducial volume which enter the final selection. Purity is calculated as the fraction of the predicted selected events which are from the NC $\Delta \to N\gamma$ process.

	WC $1\gamma Np$	Pandora $1\gamma 1p$	WC $1\gamma 0p$	Pandora $1\gamma 0p$	Combined
NC $\Delta \to N\gamma$ efficiency	4.09%	4.24%	8.79%	5.52%	19.64%
NC $\Delta \to N\gamma$ purity	9.60%	14.84%	7.50%	3.98%	6.37%

arXiv:2502.05750v2

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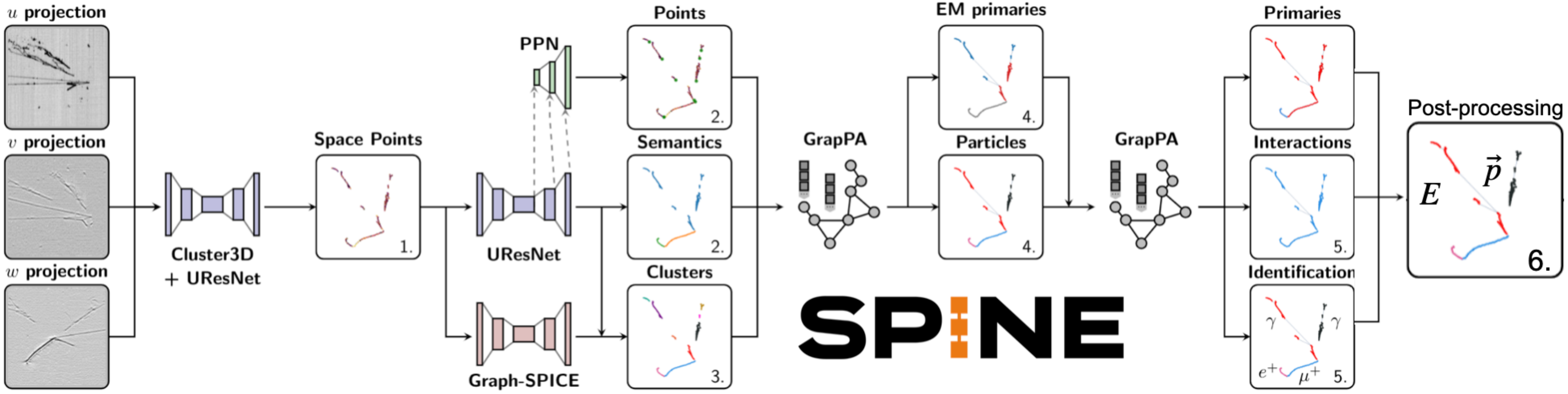
SPINE

- SPINE provides exciting opportunity to increase our reconstruction efficiency of these rare events

arXiv: 2102.01033



  - See Francois's talk from this morning
  - https://github.com/DeepLearnPhysics/spine

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1γXp Selection

Definitions

- Signal is true NC $\Delta \rightarrow N\gamma$ events with a single photon topology with any number of protons (1γXp)
    - NC $\Delta \rightarrow N\gamma \rightarrow 1\gamma Xp$
- This is a **subset** of all 1γXp final states
- Definition of 1γXp
    - 1 photon above 25 MeV
    - No electrons, muons, or charged pions above 25 MeV
    - Any number of protons

- Fiducial vertex requirement
    - 25 cm from X-/Y-faces of the detector
    - 30 cm from Z-face closest to the beam
    - 50 cm from Z-face furthest from the beam
- Containment
    - All reconstructed space points at least 5 cm from the edges of the detector
- Cuts are optimized for NC $\Delta \rightarrow N\gamma$
    - Many π^0 events are topologically 1γXp, but are physics background

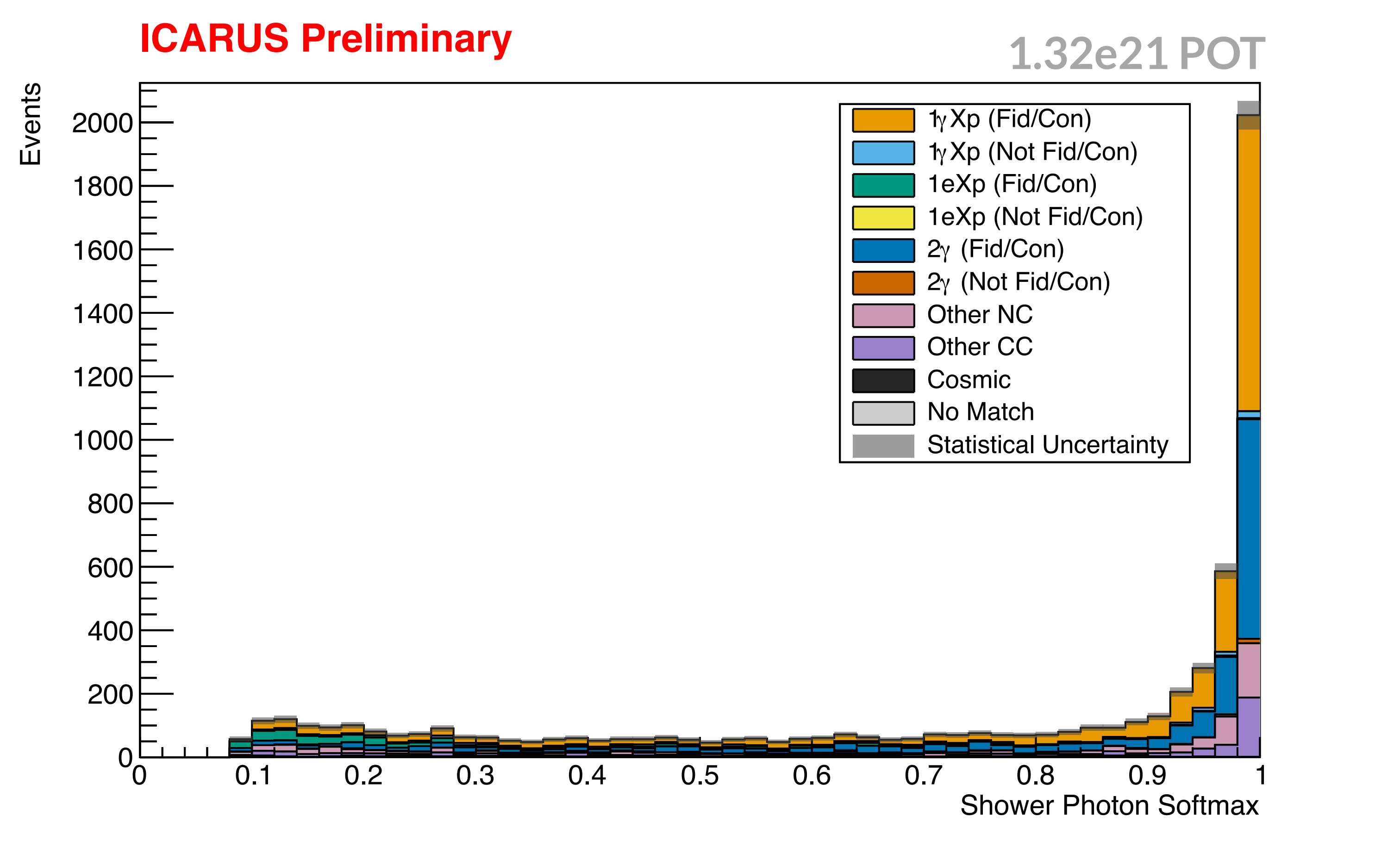
1γXp Selection

Selection Stages

- **Preselection**
  - Fiducial vertex
  - Contained event
  - Event matched to an optical flash within beam window
  - Single shower topology, 1γXp or 1eXp
- **Photon/Electron separation**
  - Primary photon softmax > 0.092
  - Start dE/dx > 3.645 MeV/cm
  - Shower axial spread > -0.005
  - Shower direction spread < 0.068

Photon Identification

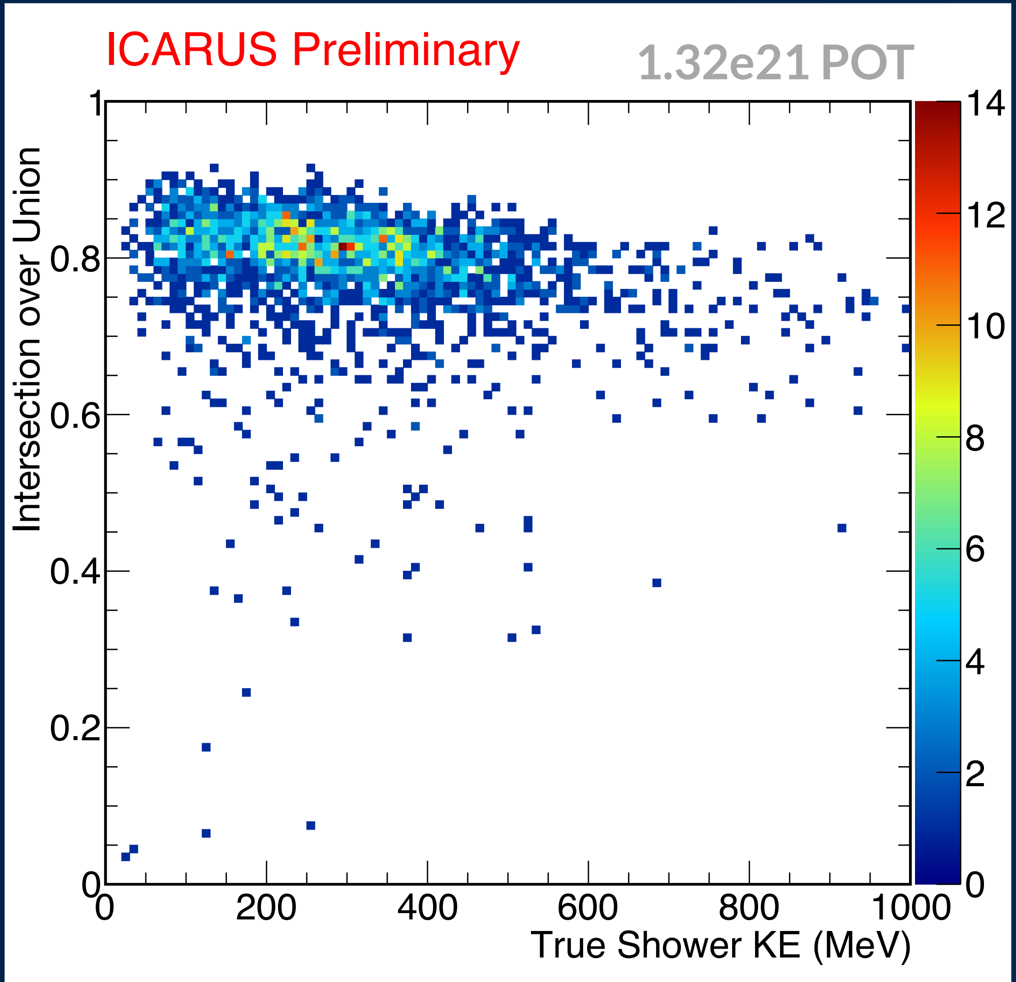
- Right more photon-like, left more electron-like
- Long tail in photon softmax ID score
- Could cut tighter, but want more inclusive selection to boost efficiency for rare processes



Shower Reconstruction

Shower Reconstruction for Selected 1γXp

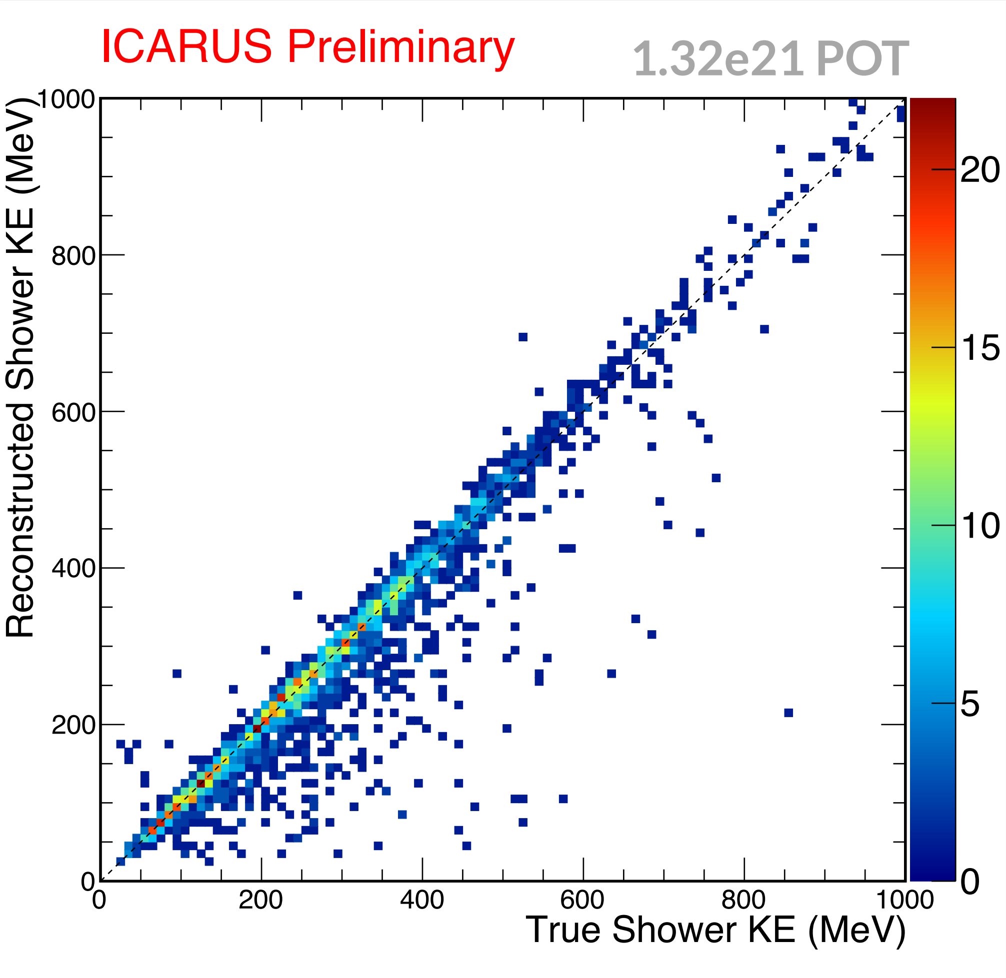
- Intersection over Union
  - Measure overlap in the space points associated with the true photon shower and with the reconstructed photon shower
  - $\dfrac{\mathscr{P}_{\text{true}} \cap \mathscr{P}_{\text{reco}}}{\mathscr{P}_{\text{true}} \cup \mathscr{P}_{\text{reco}}}$
- We are well reconstructing our photon showers



Shower Reconstruction

Shower Reconstruction for Selected 1γXp

- The kinetic energy (KE) for the photon shower in truth and reconstruction match very well
- Reconstruction holds well over all energies

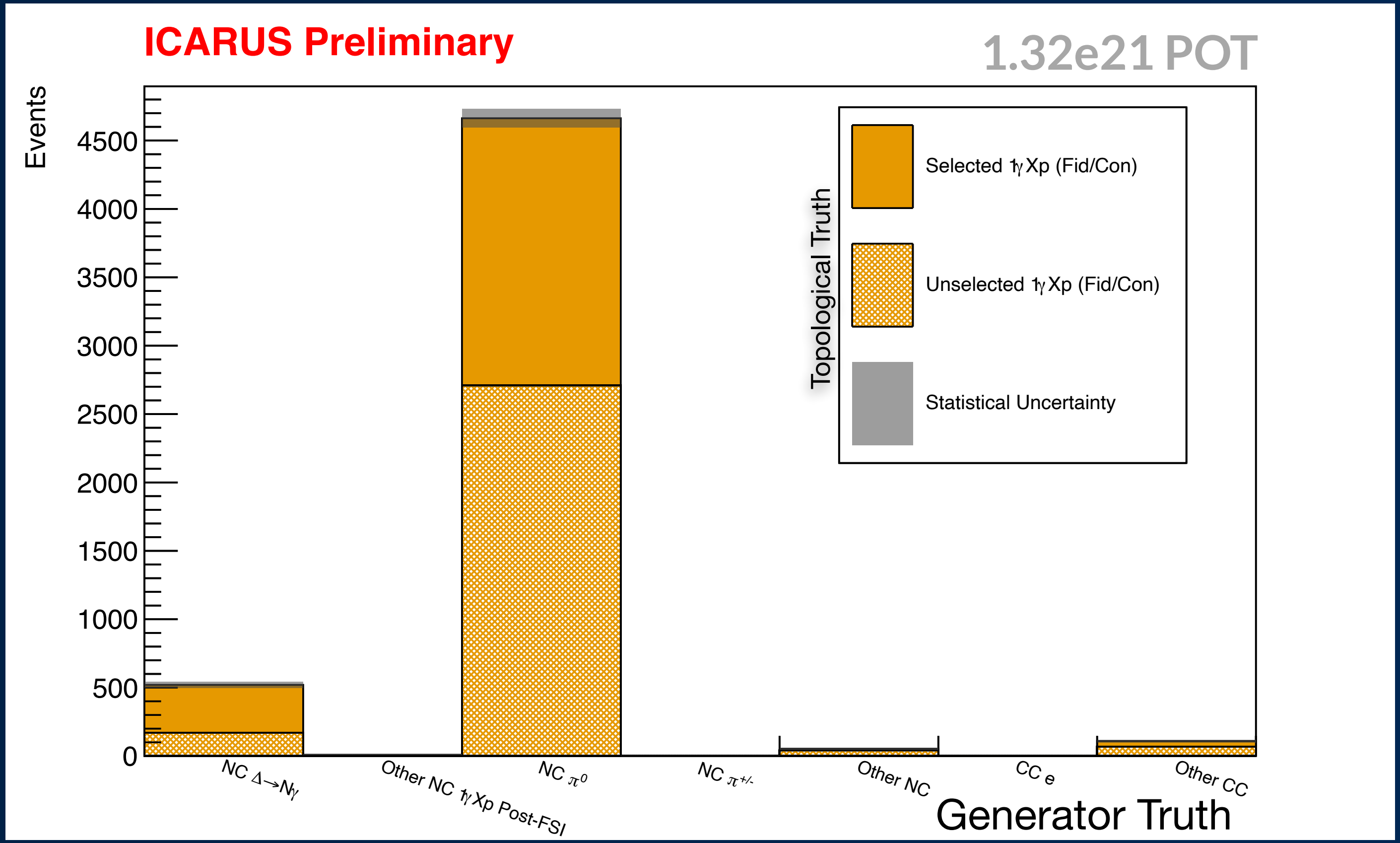


Selection Efficiency

1.32e21 POT	Selected NC Δ→Nγ	Selected Background	NC Δ→Nγ Efficiency	NC Δ→Nγ Purity
Preselection	462	15571	88.8%	2.9%
Photon/ Electron Separation	372	5757	71.5%	6.1%

1.32e21 POT	Selected 1γXp	Selected Non-1γXp	1γXp Efficiency	1γXp Purity
Preselection	3348	12685	62.5%	20.9%
Photon/ Electron Separation	2371	3758	44.3%	38.7%

True Fiducial/Contained 1γXp



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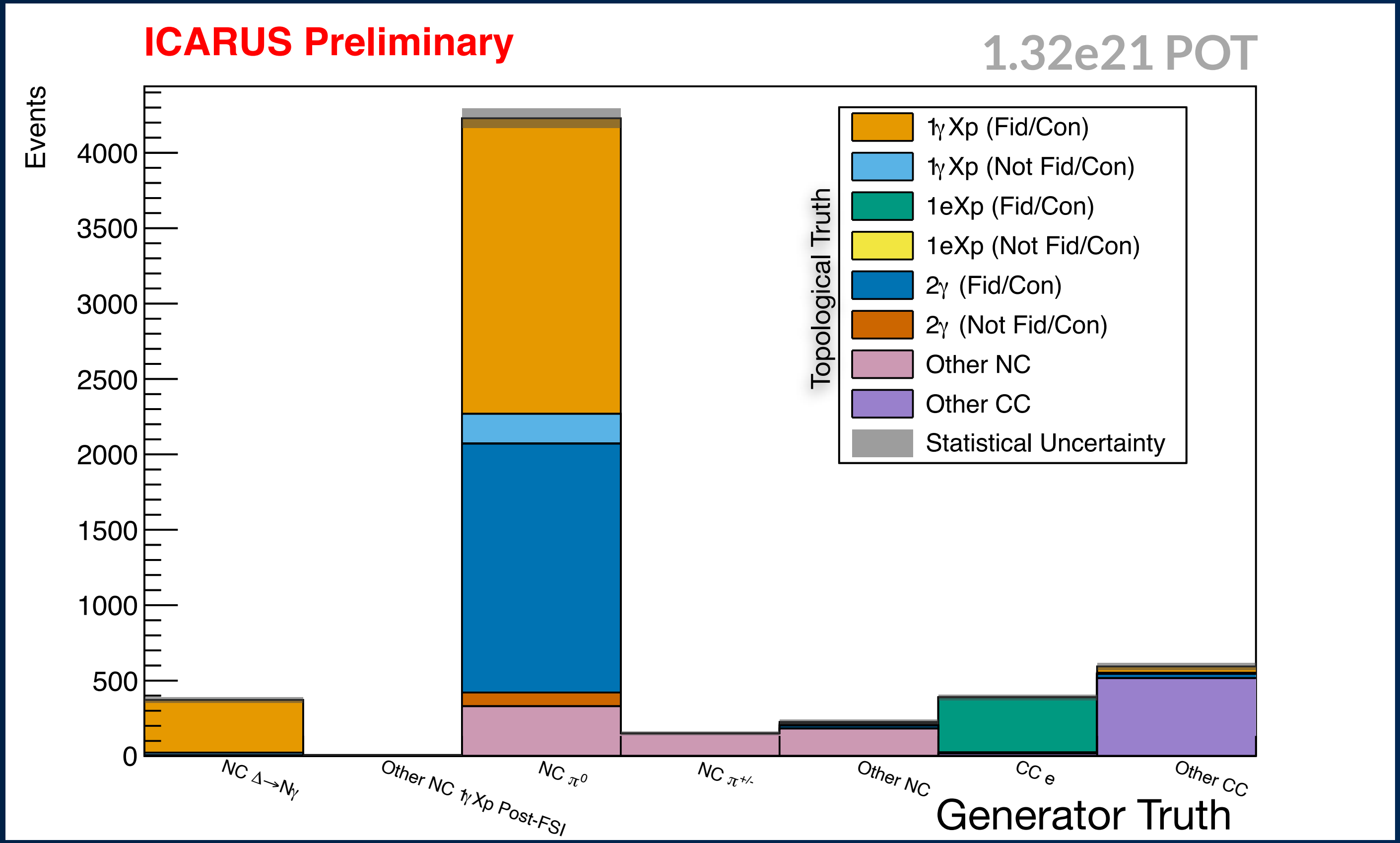
Selection Efficiency

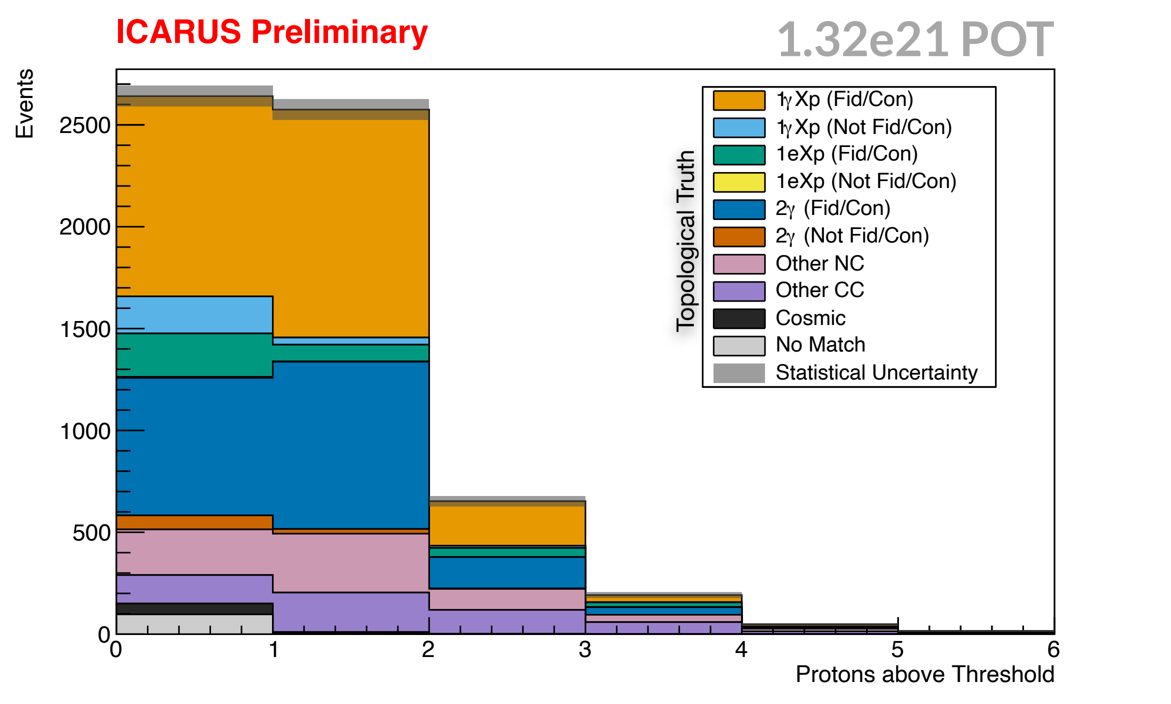
True Topology	Fraction of Selection
1γXp (Fid/Con)	38.6%
1γXp (Not Fid/Con)	7.3%
1eXp (Fid/Con)	6.1%
1eXp (Not Fid/Con)	0.1%
2γ (Fid/Con)	27.6%
2γ (Not Fid/Con)	1.5%
Other NC	10.9%
Other CC	8.7%
Cosmic	0.9%
No Truth Match	1.7%

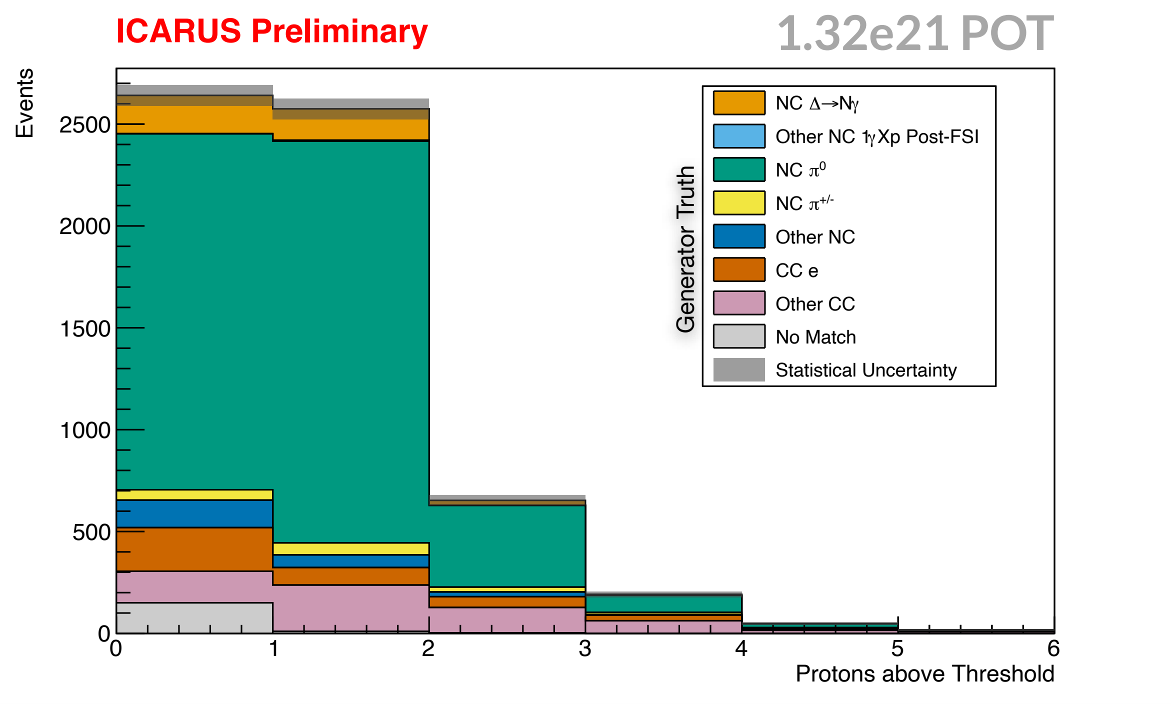
Reconstructed 1γXp Events



Proton Counts

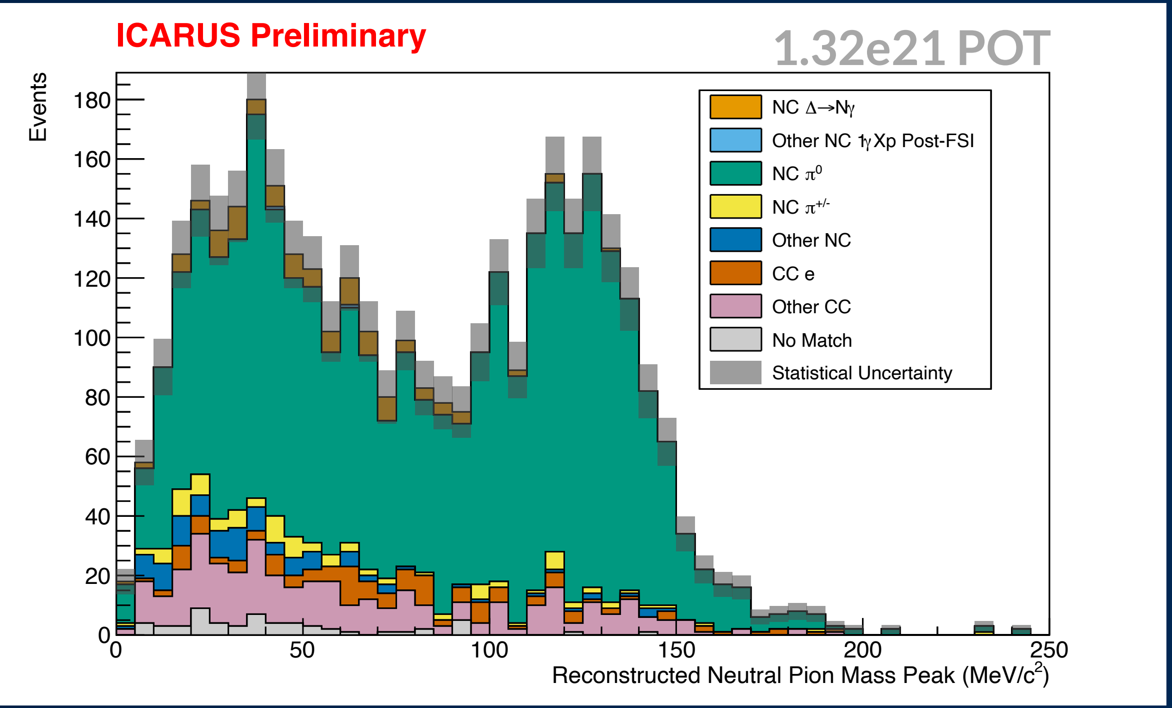
- Counting protons above 50 MeV
- The 0 proton and 1 proton subsections are both performing similarly
- Potentially could get better performance restricting to a 1γ0p + 1γ1p selection
- Does not include dirt backgrounds which may dilute 1γ0p selection





Constrain/Cut π^0 Backgrounds

- Constraining the π^0 backgrounds in a important challenge to tackle
- We are able to well SPINE reconstruct the pion mass peak
- We plan to use this to constrain the backgrounds, but this work is still ongoing



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Summary

- First looks at performing a single photon selection with SPINE look promising
- Selected showers are well reconstructed
- Excellent efficiency in single photon selection
    - 71.5% compared to 19.64% for MicroBooNE
- Both 1γ0p and 1γ1p topologies perform well
- Improvements can still be made in photon/electron discrimination
- Large π^0 backgrounds need to be constrained/reduced, but this is expected
- Expect more coming soon

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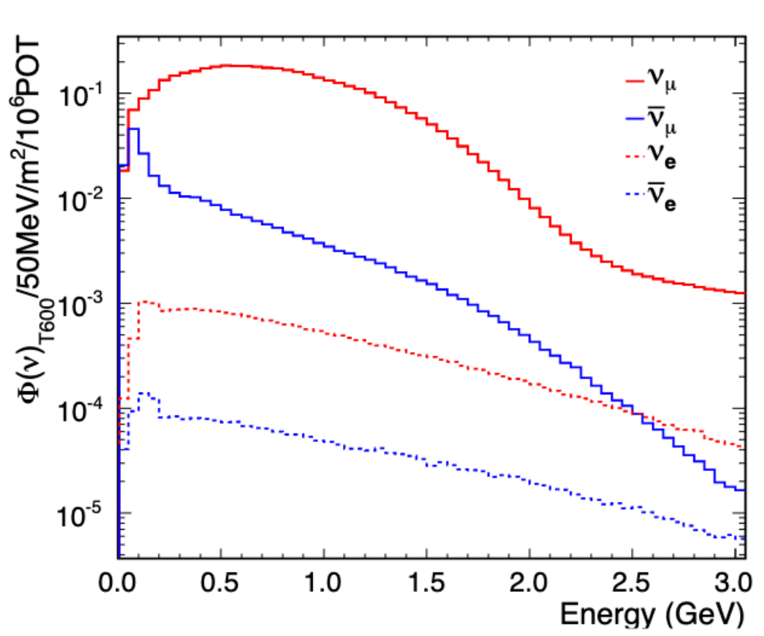
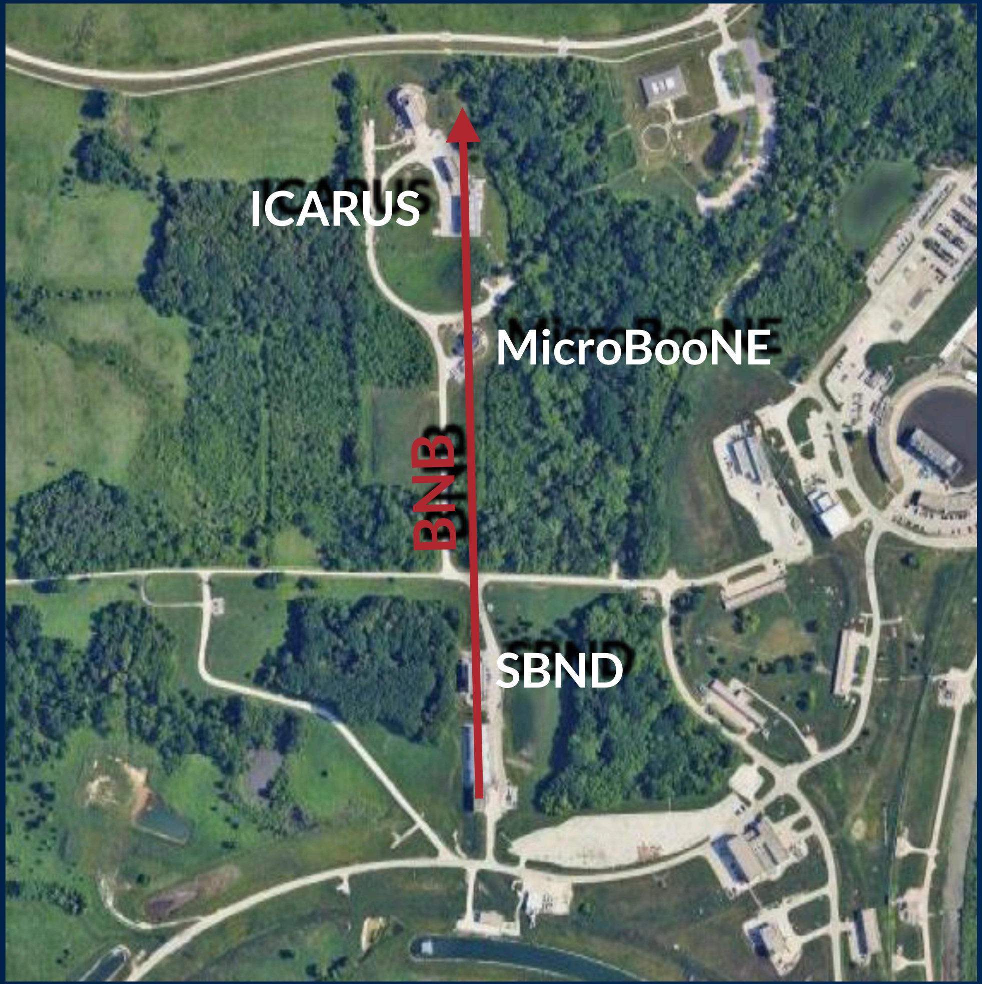
ICARUS @ SBN

BNB

- ICARUS is 600m from the BNB target
- Booster Neutrino Beam is produced the decaying mesons produced from 8 GeV protons on a beryllium target
- Produces neutrinos peaked at ~0.7 GeV



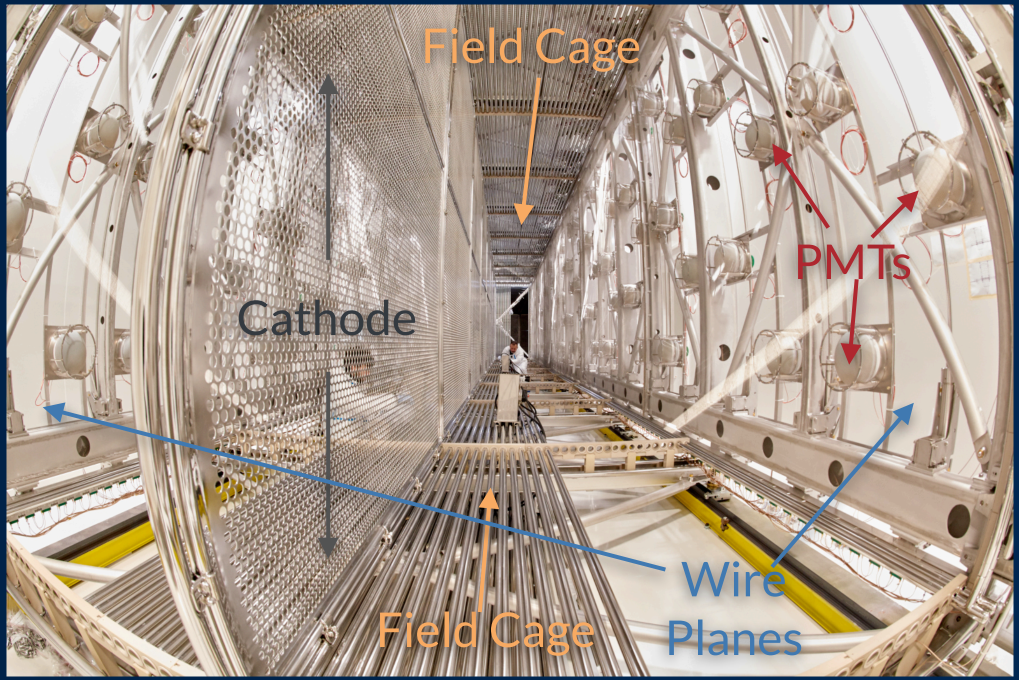
doi:10.48550/arXiv.1503.01520

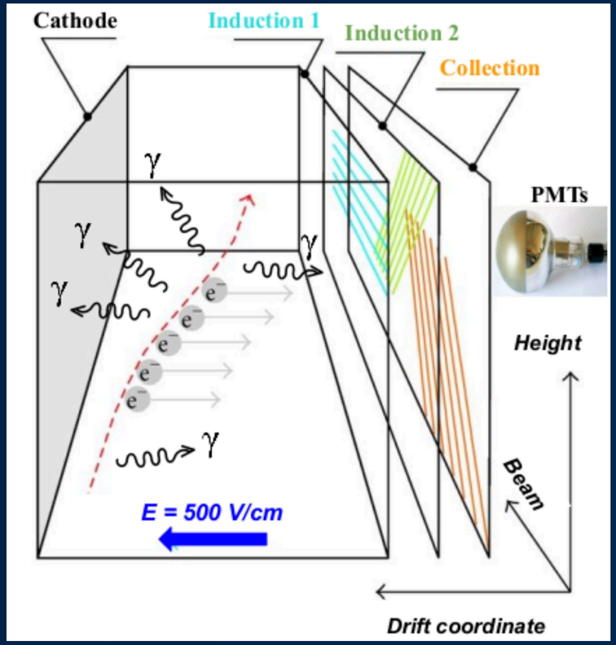


ICARUS T600

What is in a Neutrino Detector?

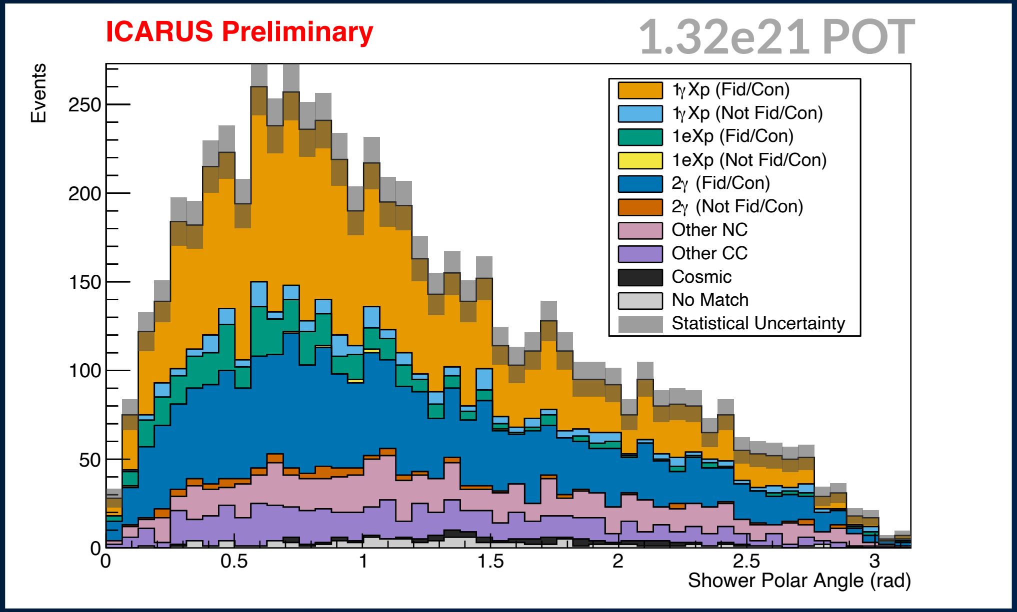
- Two cryostats. each with two Liquid Argon Time Projection Chambers (LArTPC)
    - Shared cathode between LArTPCs
    - 3 Wire Planes per LArTPC
        - Wires 0°, ±60° from vertical
    - 500 V/cm drift electric field
- 760 tons (476 ton active mass)
- 360 photomultiplier tubes (PMT)
- Cosmic Ray Tagger (CRT) system surrounds the cryostats to remove cosmogenic backgrounds

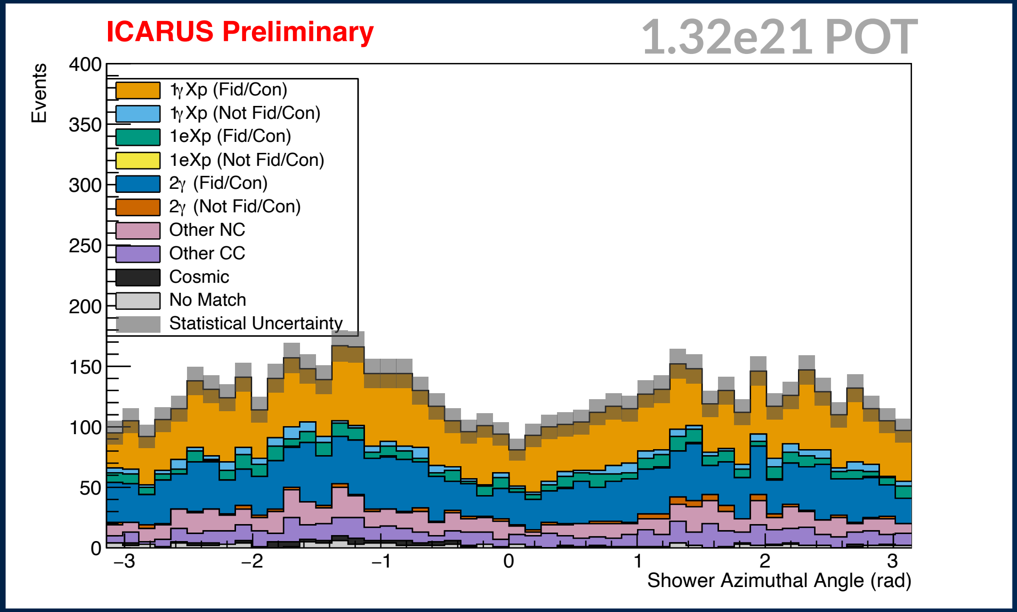




Shower Angles

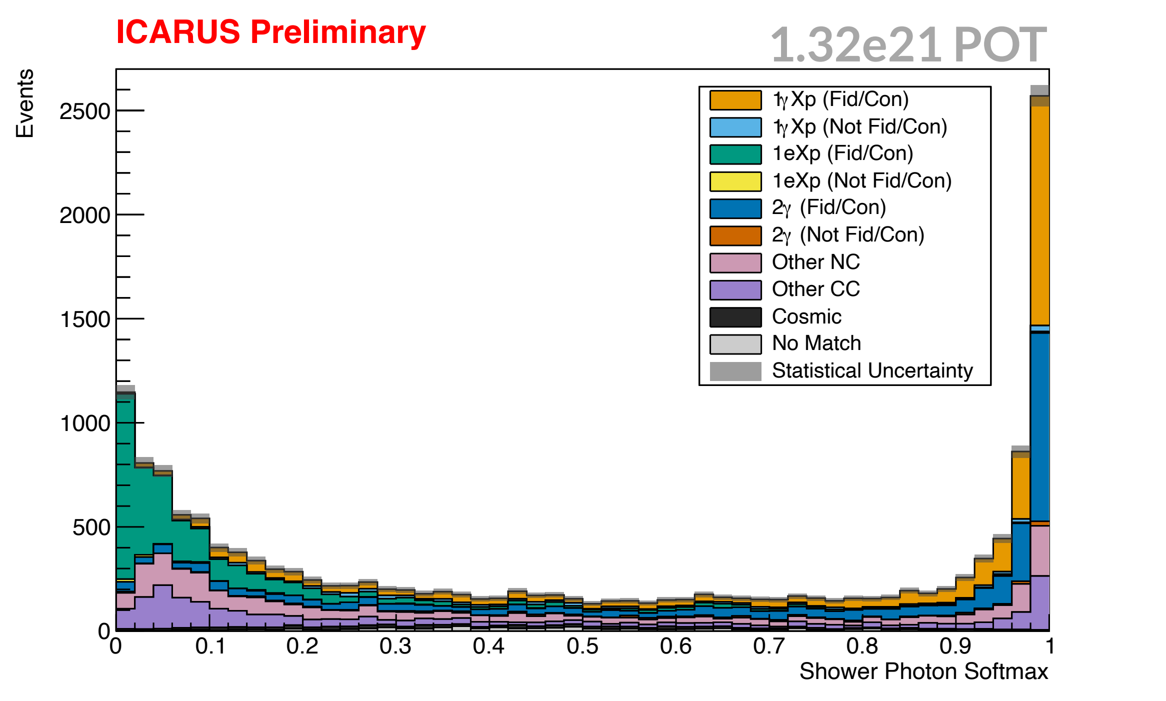
Angular Distributions for Primary Shower

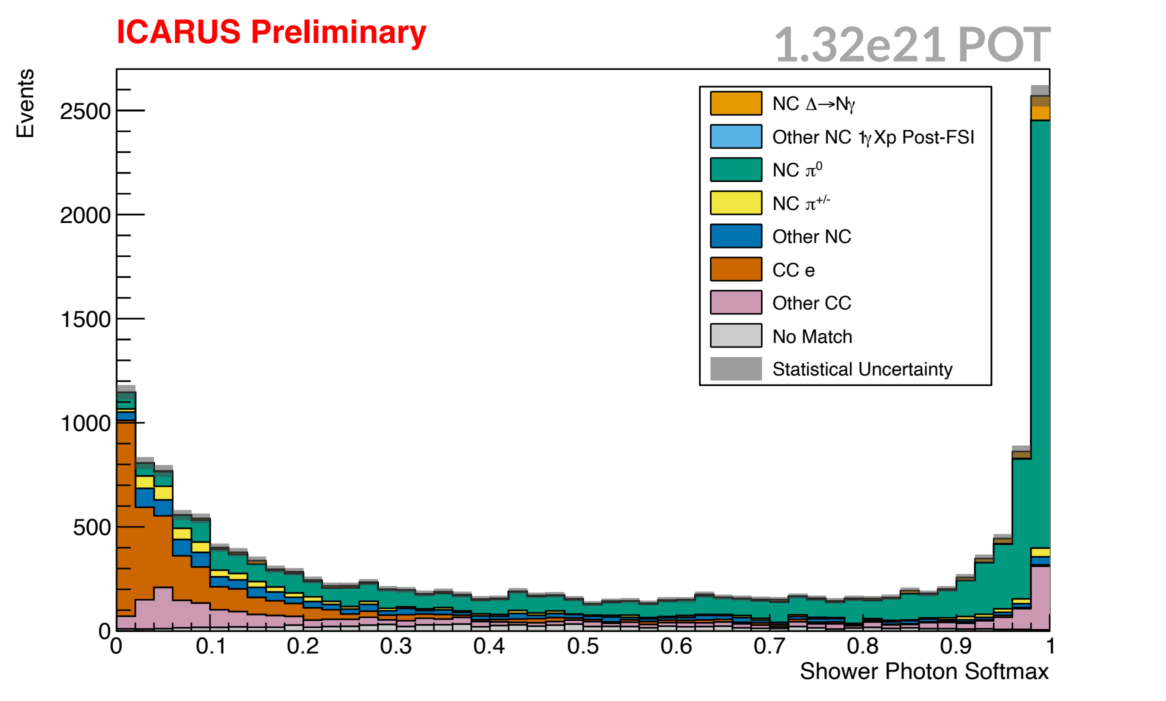




Photon Softmax

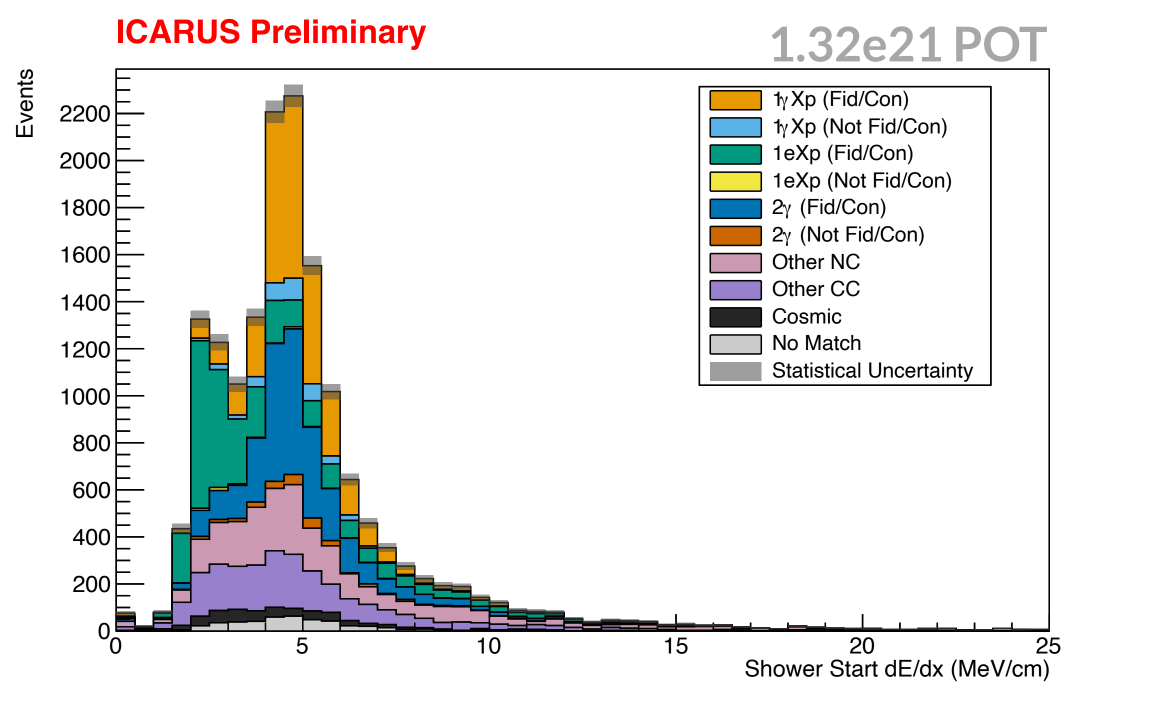
Before photon/electron separation cuts

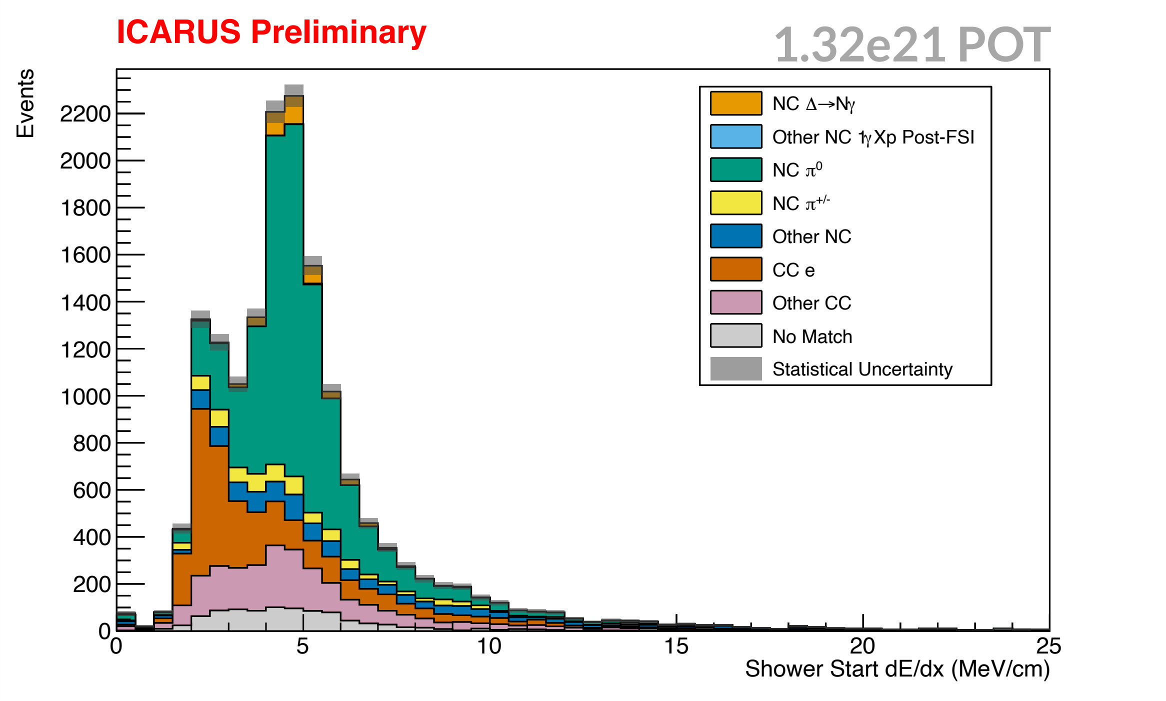




Start dE/dx

Before photon/electron separation cuts





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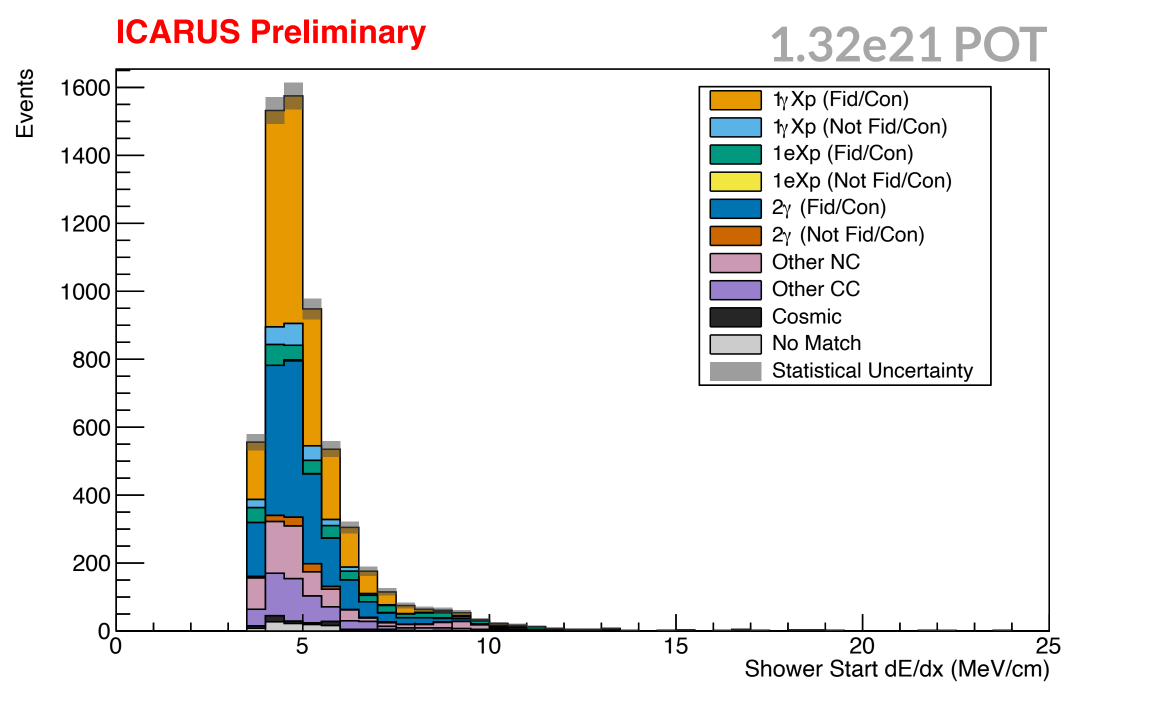
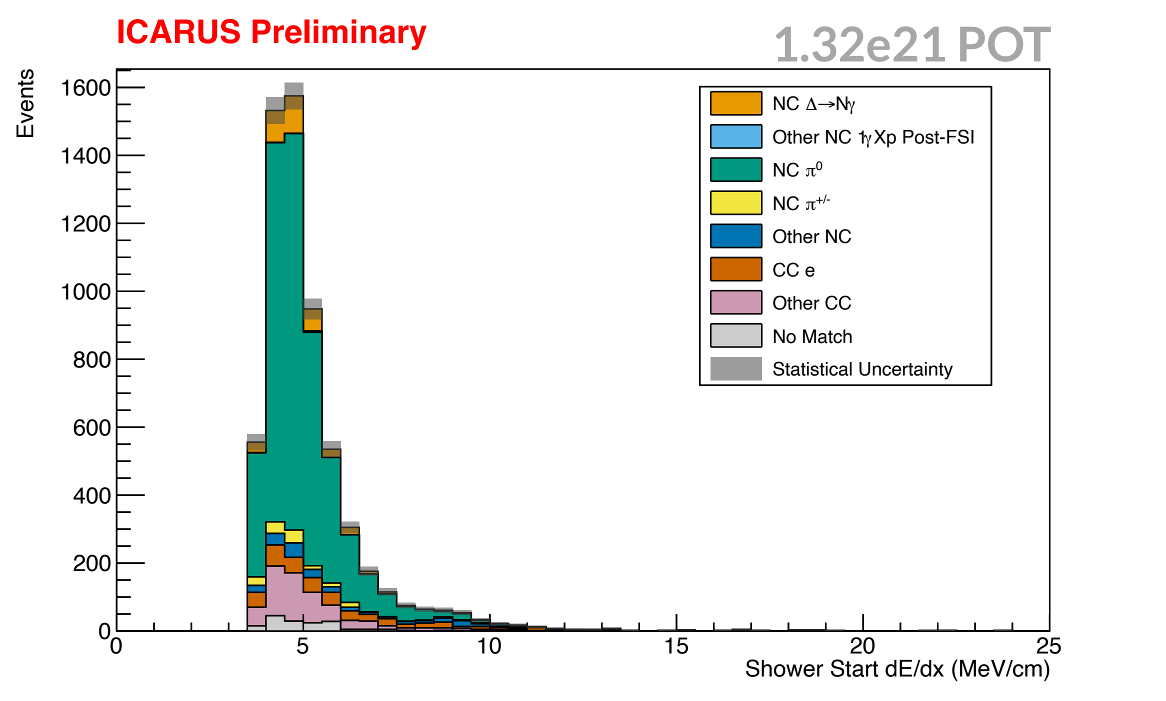
Start dE/dx

After photon/electron separation cuts





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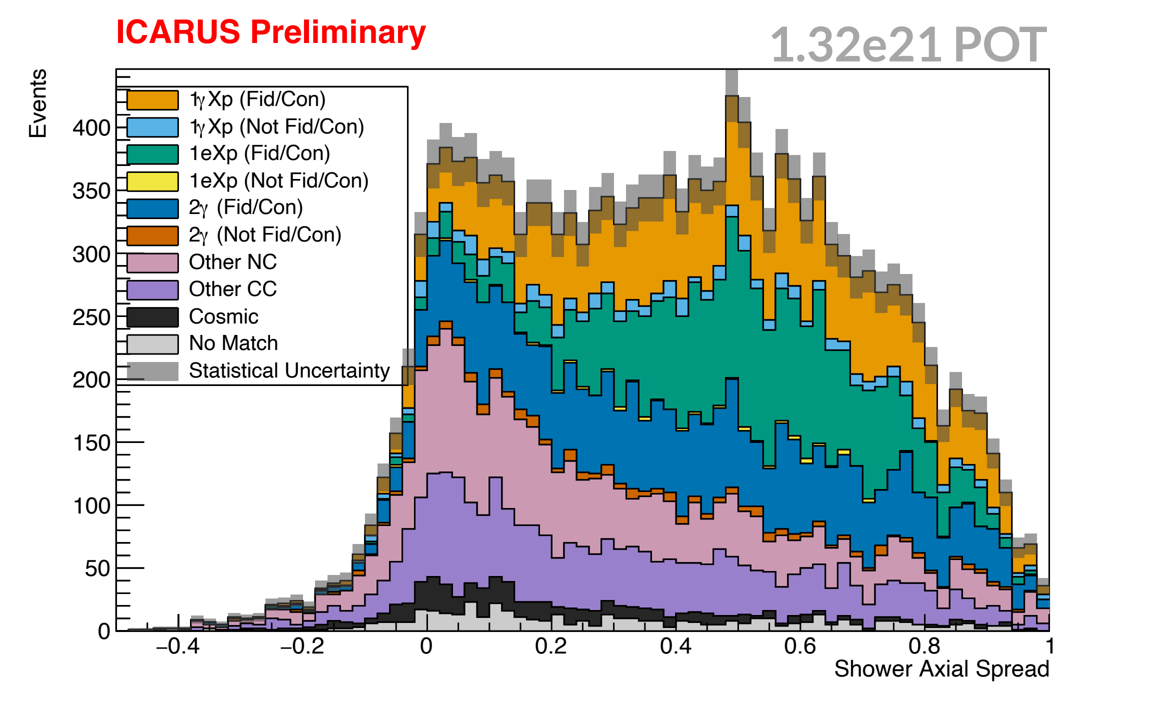
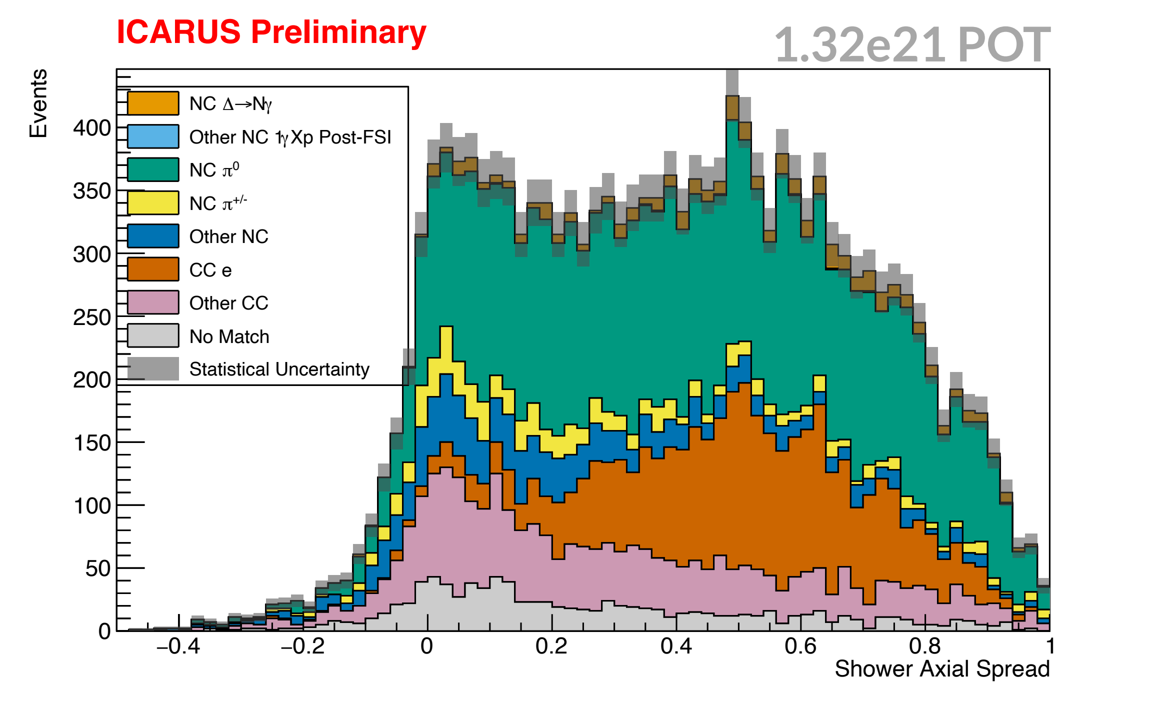
Axial Spread

Before photon/electron separation cuts





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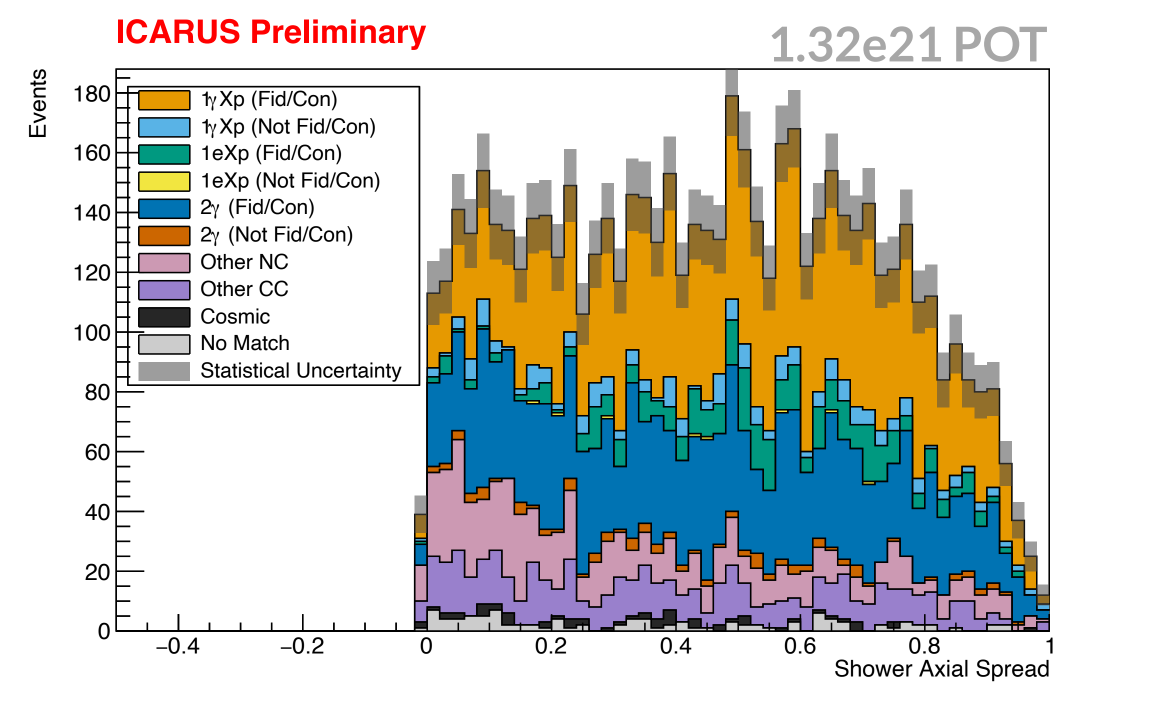
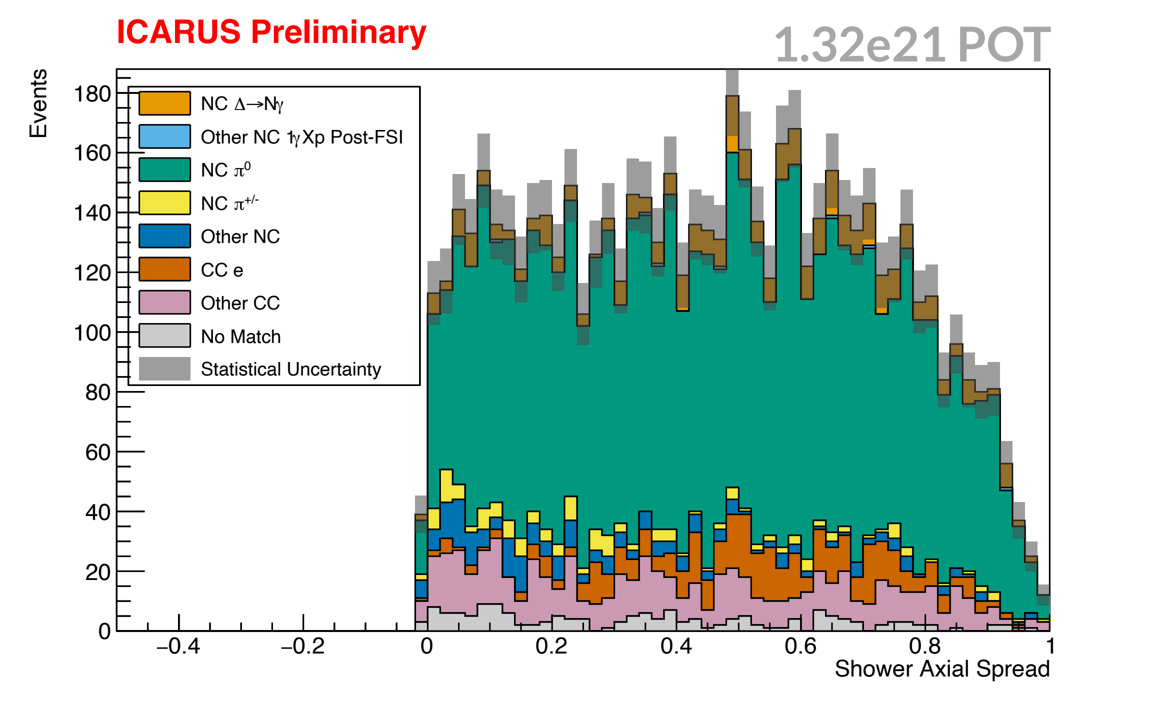
Axial Spread

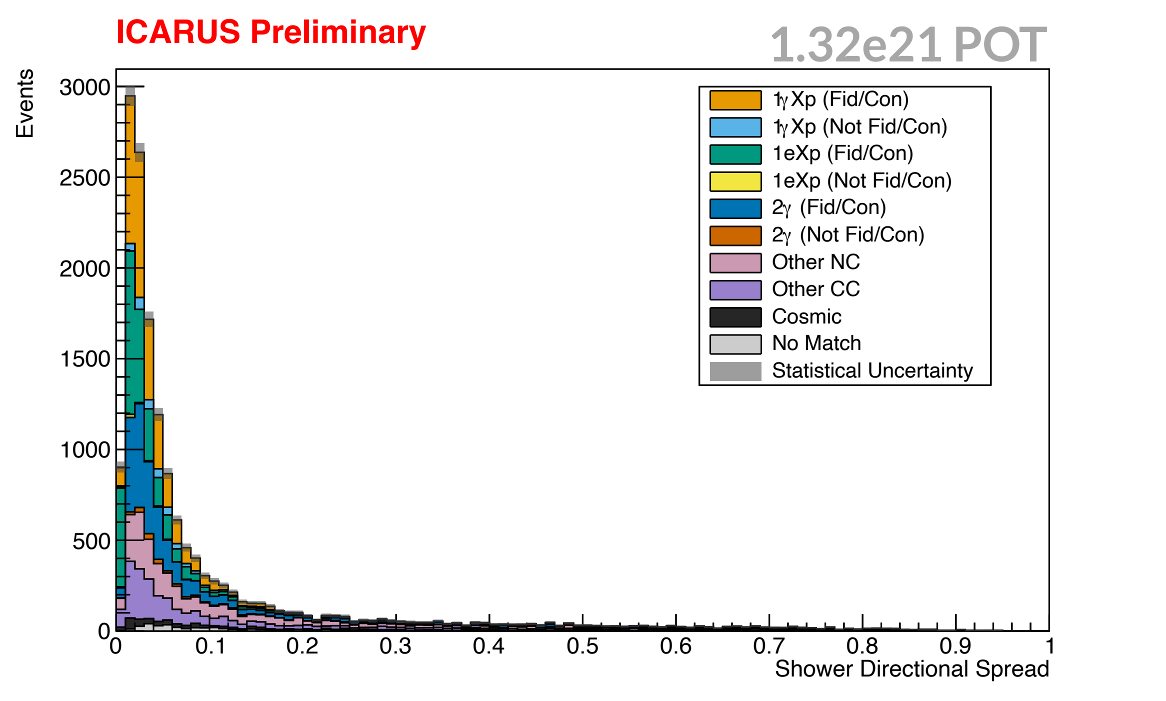
After photon/electron separation cuts

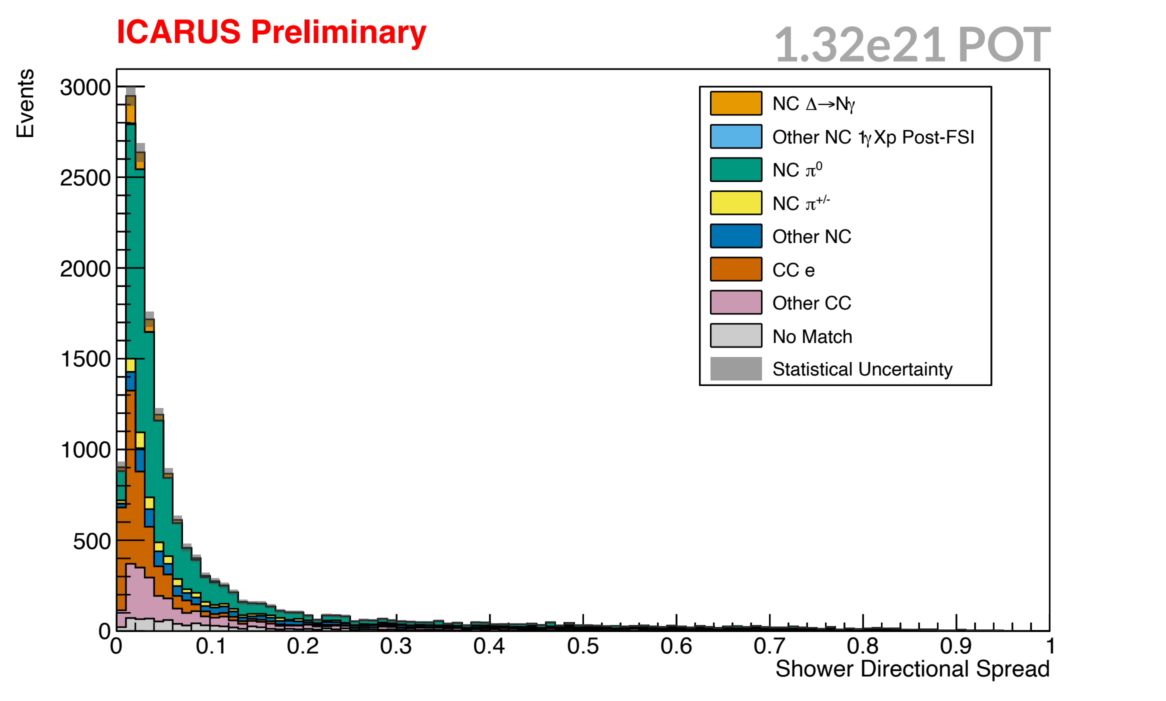




Directional Spread

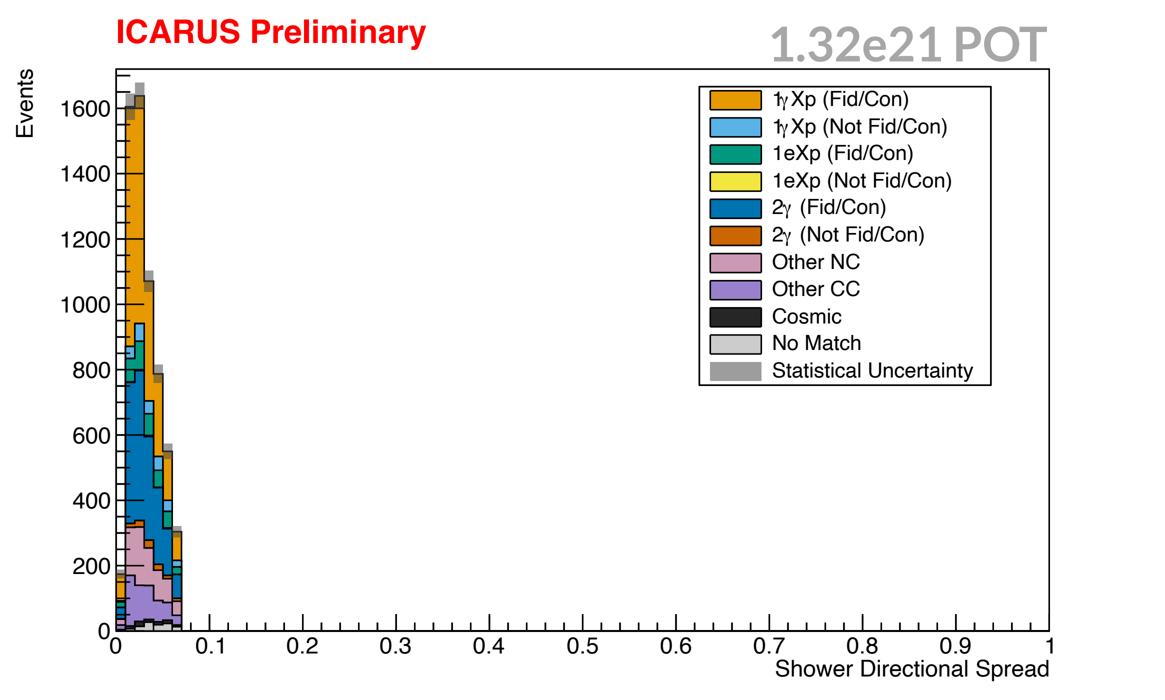
Before photon/electron separation cuts

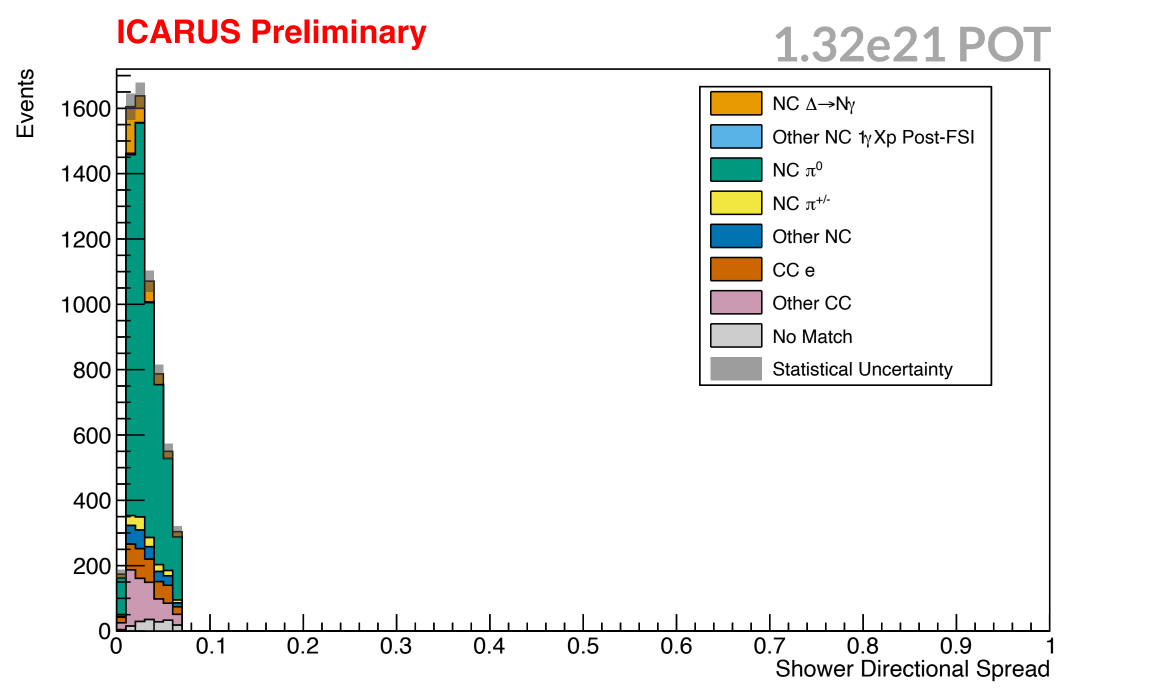




Directional Spread

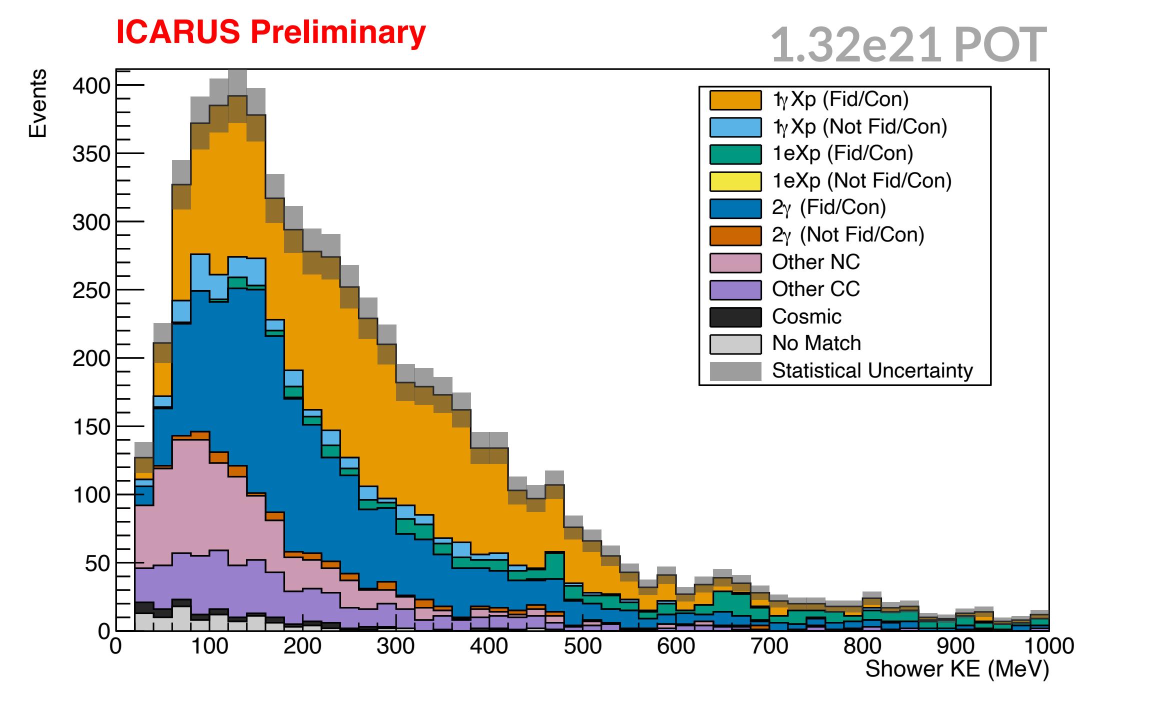
After photon/electron separation cuts

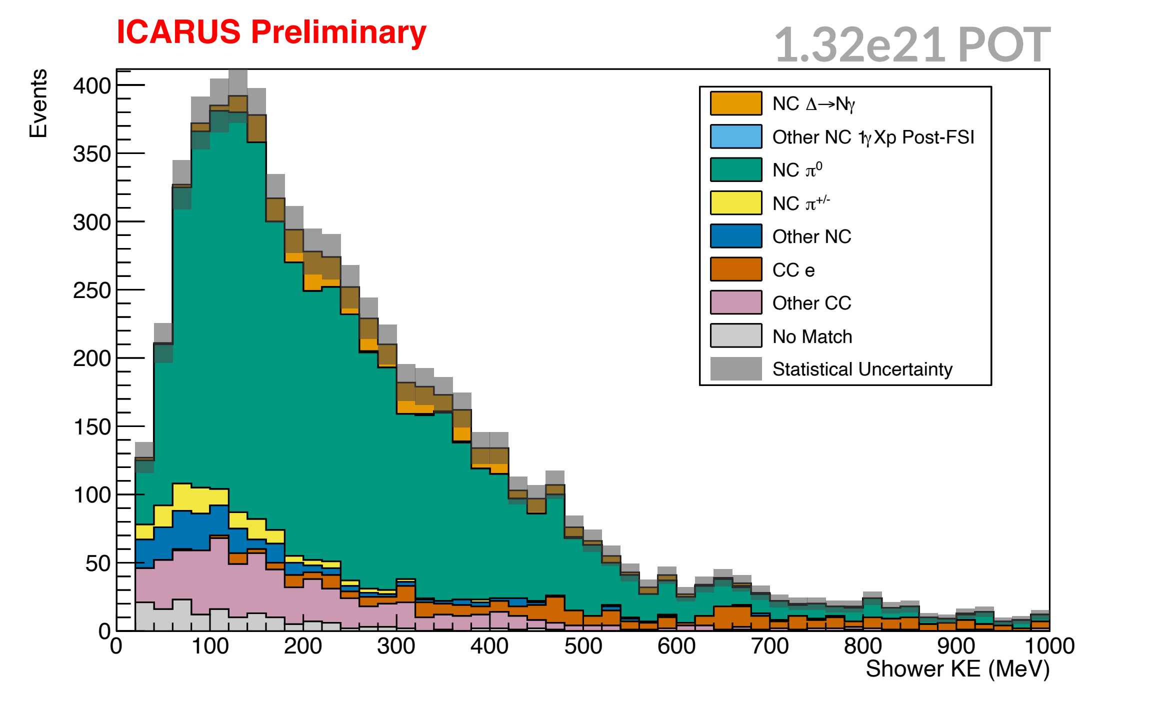




Shower KE

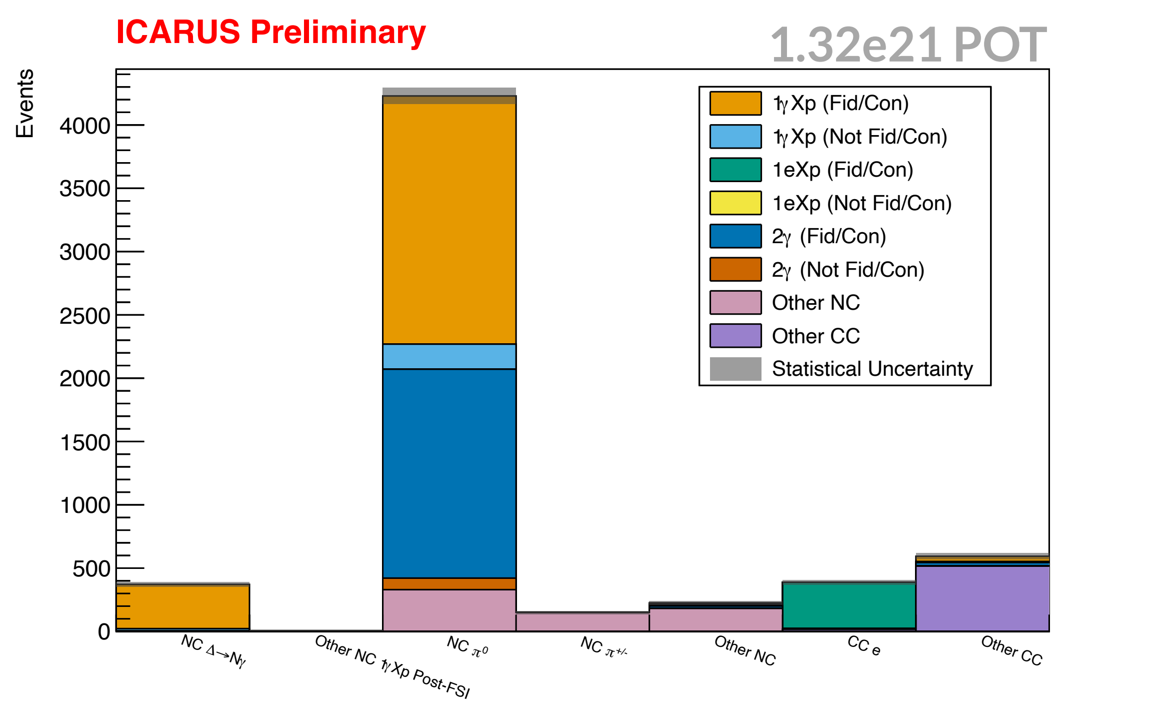
After photon/electron separation cuts

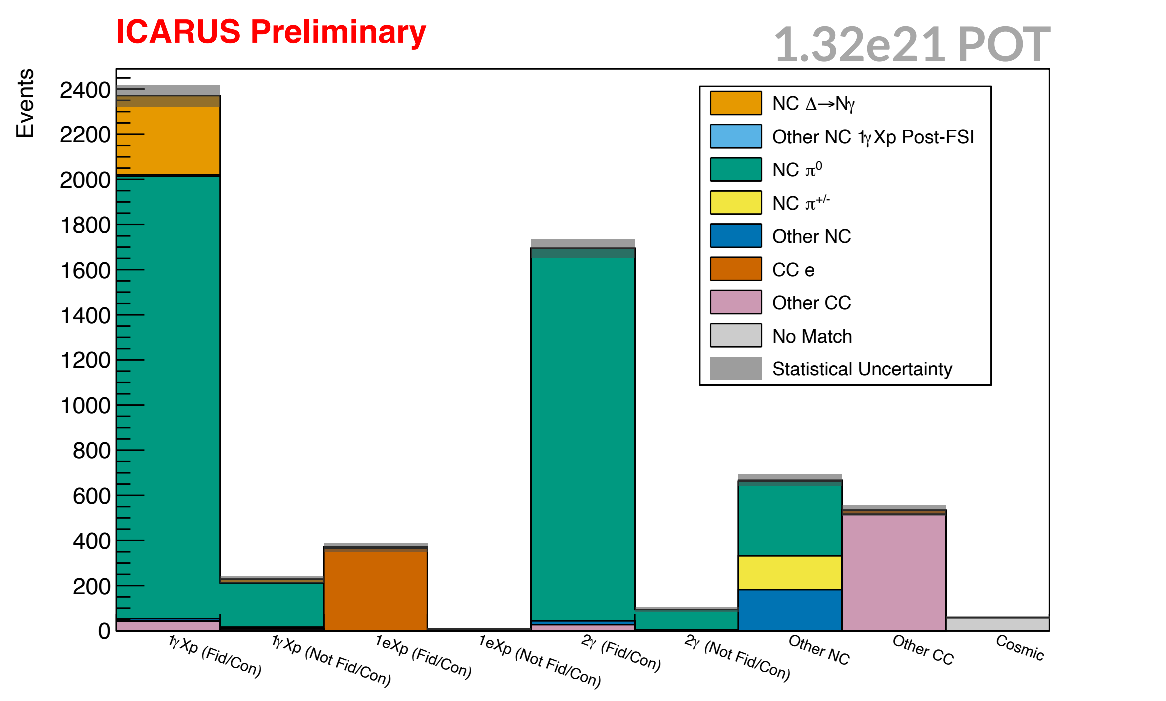




Truth Breakdown

After photon/electron separation cuts





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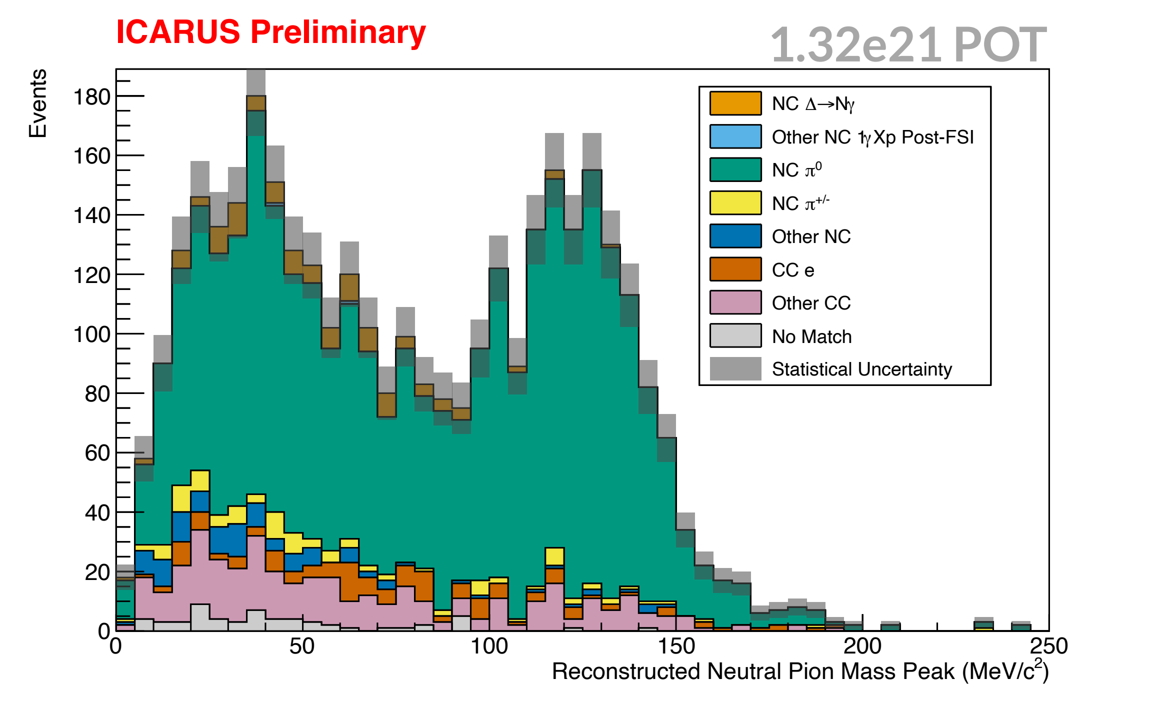
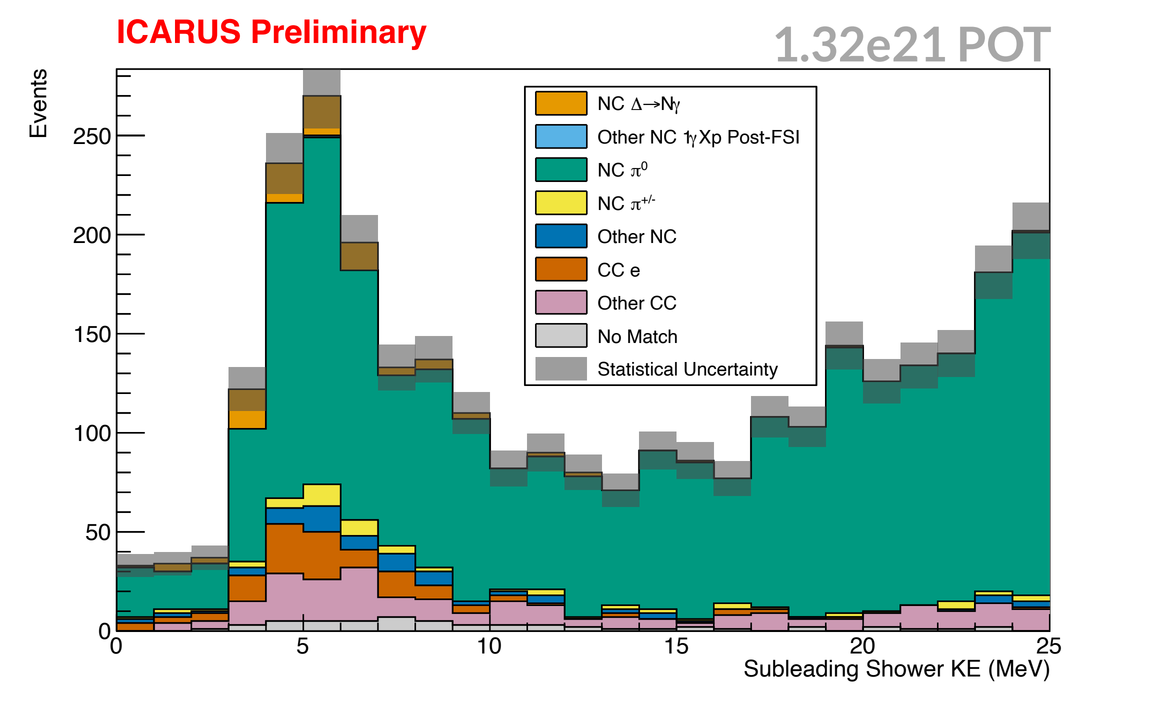
Constrain/Cut π^0 Backgrounds

After photon/electron separation cuts





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