$\nu_\mu \rightarrow \nu_\tau$ Appearance in μBooNE

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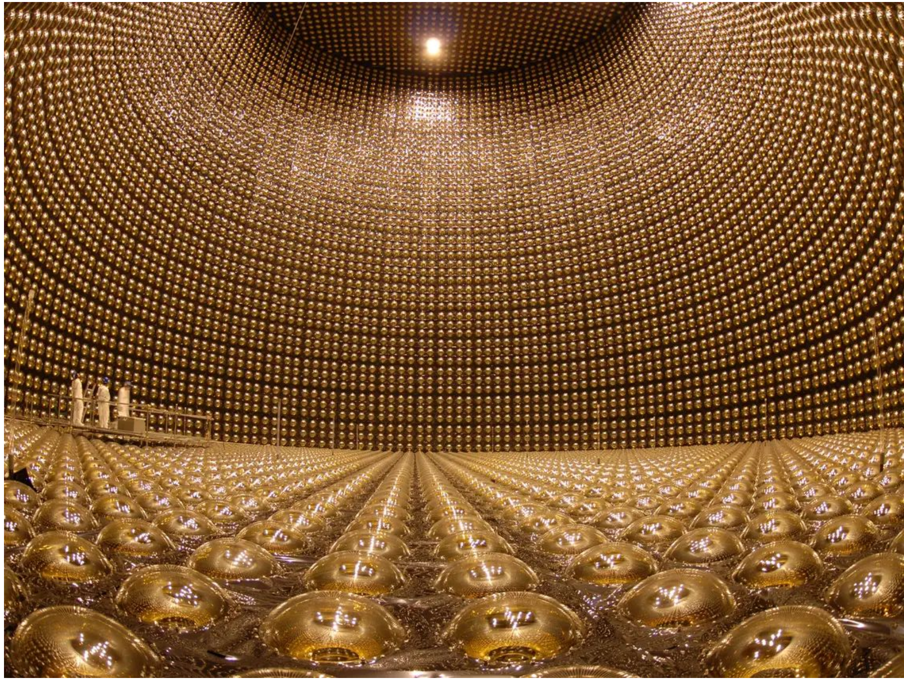
What is a neutrino?

- The “little neutral one”
- Extremely abundant, rarely interacting particle
  - Did you know that there’s about 100 billion going through your thumbnail every second?
- Three flavors within the Standard Model - ν_e, ν_μ, ν_τ



[1]

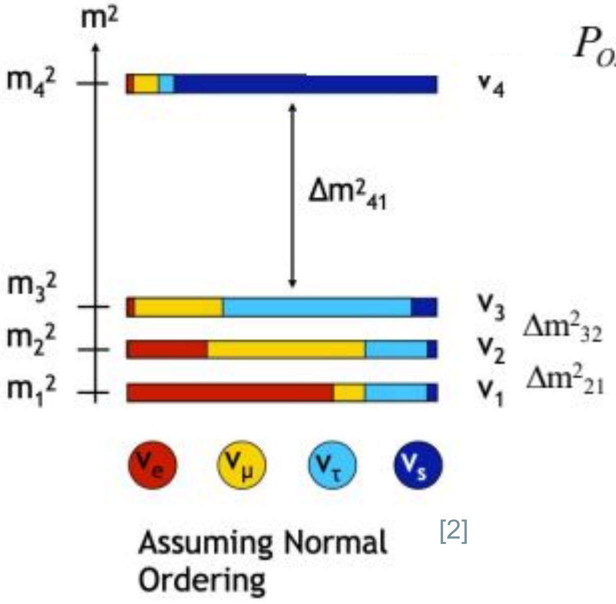
- **Hot topic in physics - lots of current & upcoming big neutrino experiments!**

Neutrino Oscillations + Sterile Neutrinos

We know about the three neutrino flavors in the SM… but what if there was a fourth?

Several neutrino experiments have seen anomalies which suggest the existence of another type of neutrino, the **sterile neutrino.**

$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$



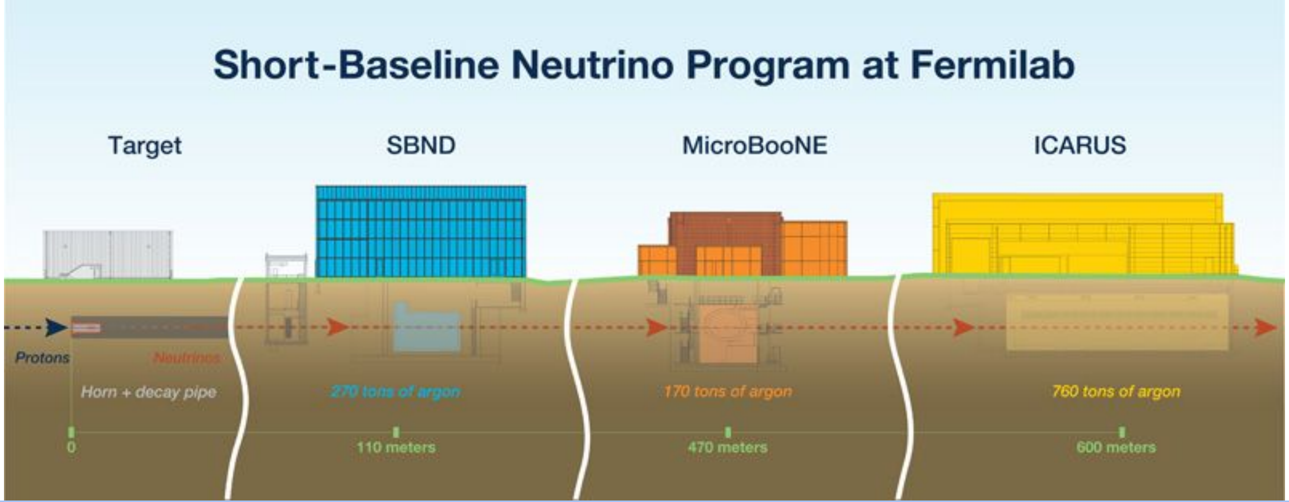
[2]

How do we look for sterile neutrinos?

- ν_μ disappearance ($\nu_\mu \to \nu_s$)
- ν_e disappearance ($\nu_e \to \nu_s$)
- ν_e appearance ($\nu_\mu \to \nu_e$)
- ν_τ appearance ($\nu_\mu \to \nu_\tau$)

MicroBooNE & the SBN Program

- 170 ton liquid argon time projection chamber (LArTPC)
- 1 of 3 detectors in the Short Baseline Neutrino (SBN) program at Fermilab
- SBN Goal: Investigate the possibility of light sterile neutrinos through $\nu_\mu \rightarrow \nu_e$ oscillations



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Booster Neutrino Beam (BNB)

The Boo in μBooNE

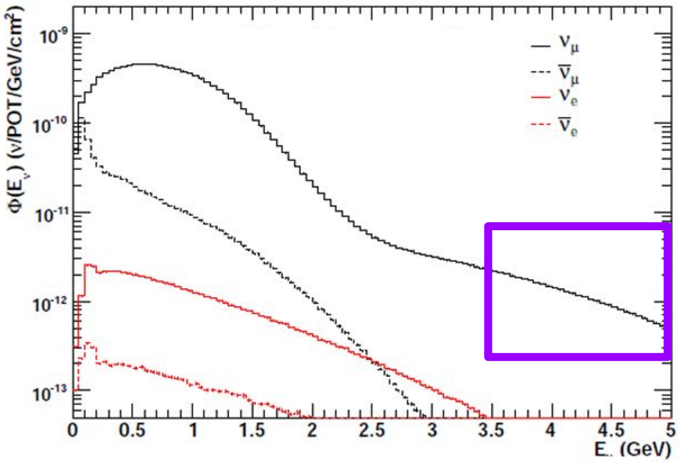
8 GeV protons on Beryllium target

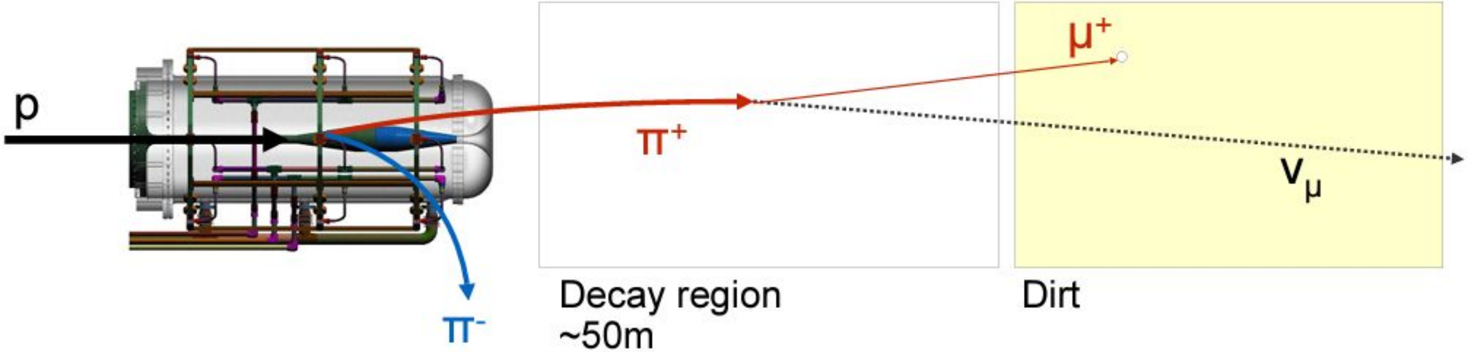
5 Hz w/ $5 \cdot 10^{12}$ protons per pulse

$> 99\%\ \nu_\mu$ & $< 1\%\ \nu_e$

Mean energy < 1 GeV

BNB Neutrino Flux





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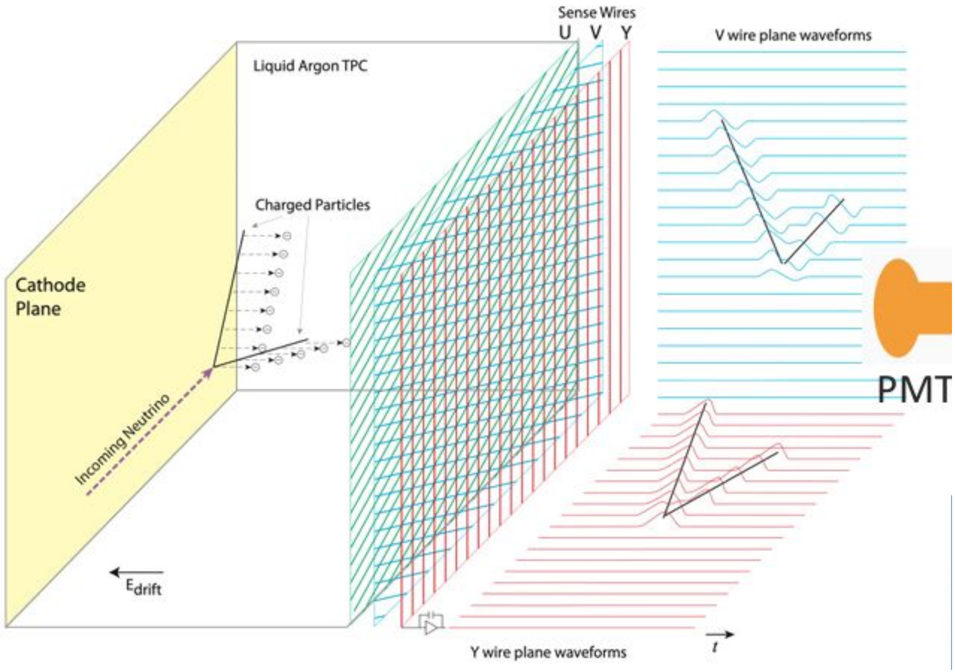
Liquid Argon Time Projection Chambers (LArTPCs)

Liquid argon serves as the nuclei target for neutrino-nucleon interactions.

Why Argon? Because it is

- Dense
- Cheap
- Inert

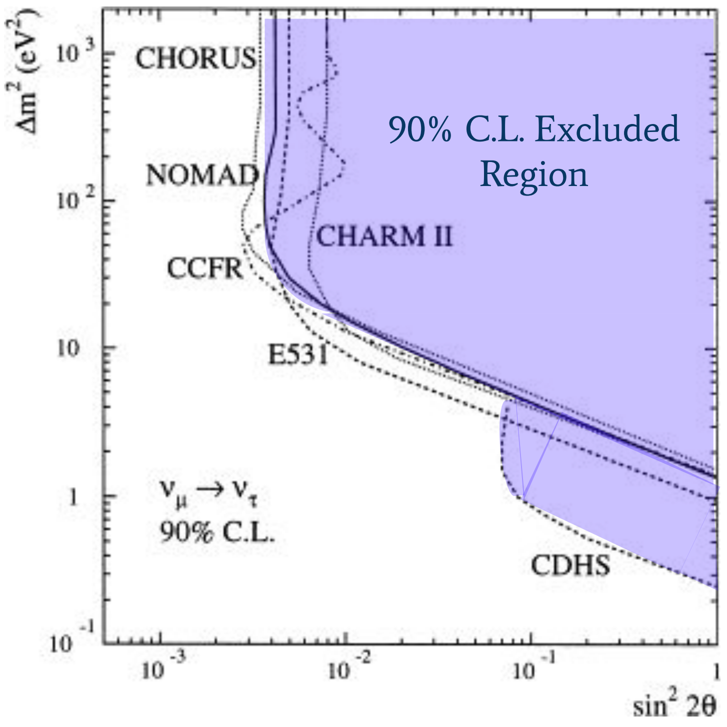
Stay tuned for Josiah's presentation to learn more...



$\nu_\mu \to \nu_\tau$ Oscillation Sensitivity

- MicroBooNE initially looked for evidence of $\nu_\mu \rightarrow \nu_e$ oscillation
  - No evidence thus far, albeit with low sensitivity
- Previous experiments have done searches for $\nu_\mu \rightarrow \nu_\tau$
  - NOMAD[5]
  - CHORUS[6]
- Preliminary kinematics search in DUNE[7]
- First opportunity to do so with μBooNE data !!
- Can be expanded to the greater SBN program.

$$P_{Osc} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 L / E\right)$$



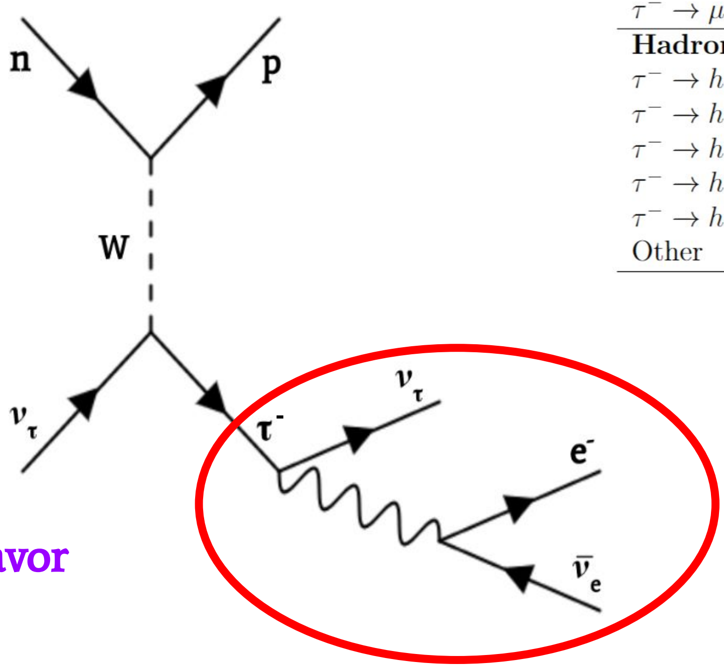
Neutrino Charged Current Interactions

Neutrino interacts with a neutron, knocking out a proton and producing it's charged lepton cousin.

Energy threshold for tau production is 3.5 GeV.

Allows us to identify the flavor of the incident neutrino.

ν_τCC Interaction + τ^--Decay



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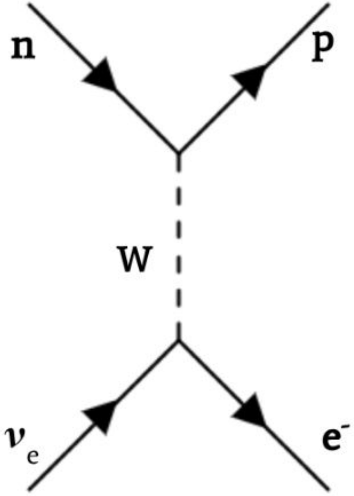
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$		4.8
Other		3.3

[8]

Hadronic decays difficult to reconstruct... and muon decay has too much background → focus on electron decay mode.

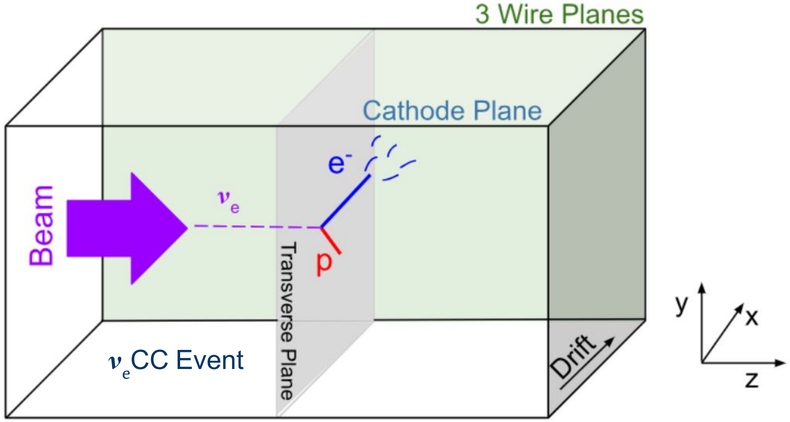
ν_τCC Signal vs. ν_eCC Background

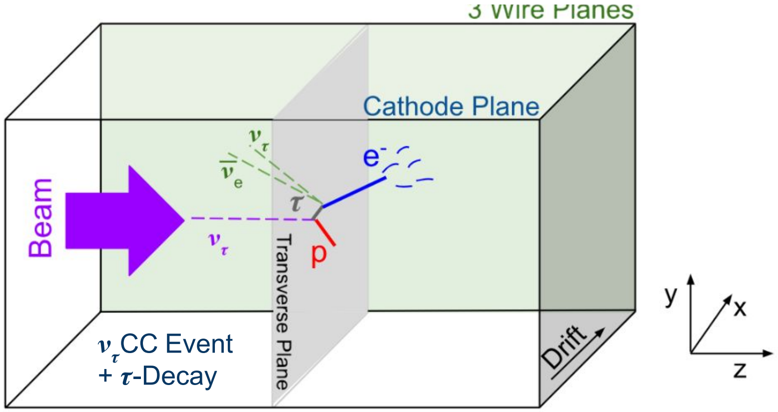
Background comes from ν_eCC interactions which also create a final state proton and electron.



ν_eCC Interaction

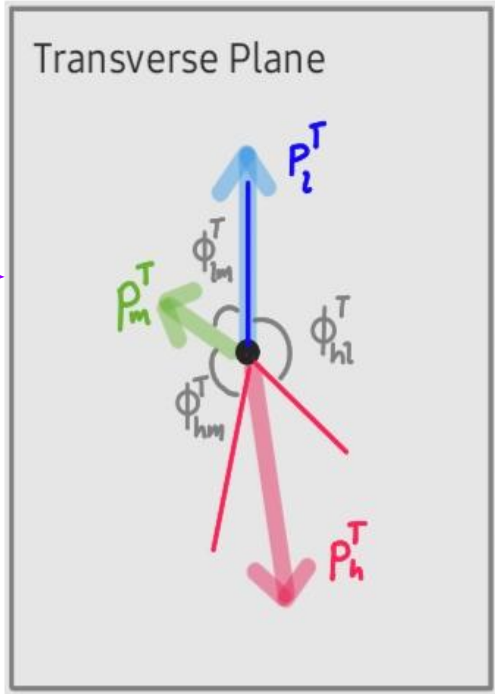
Extra outgoing neutrino and antineutrino from tau decay affect the momentum of the outgoing particles.



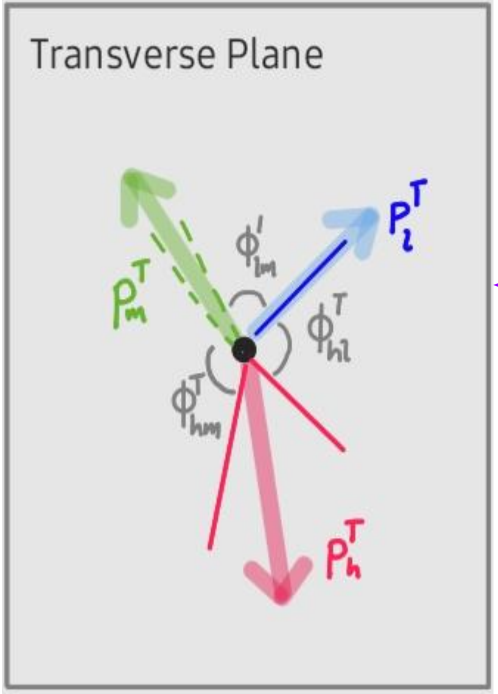


ν_τCC vs. ν_eCC Kinematics

ν_eCC Interaction



ν_τCC Interaction



Little missing transverse momentum*

Larger missing transverse momentum

* From Fermi momentum of the neutron.

Kinematic Variables

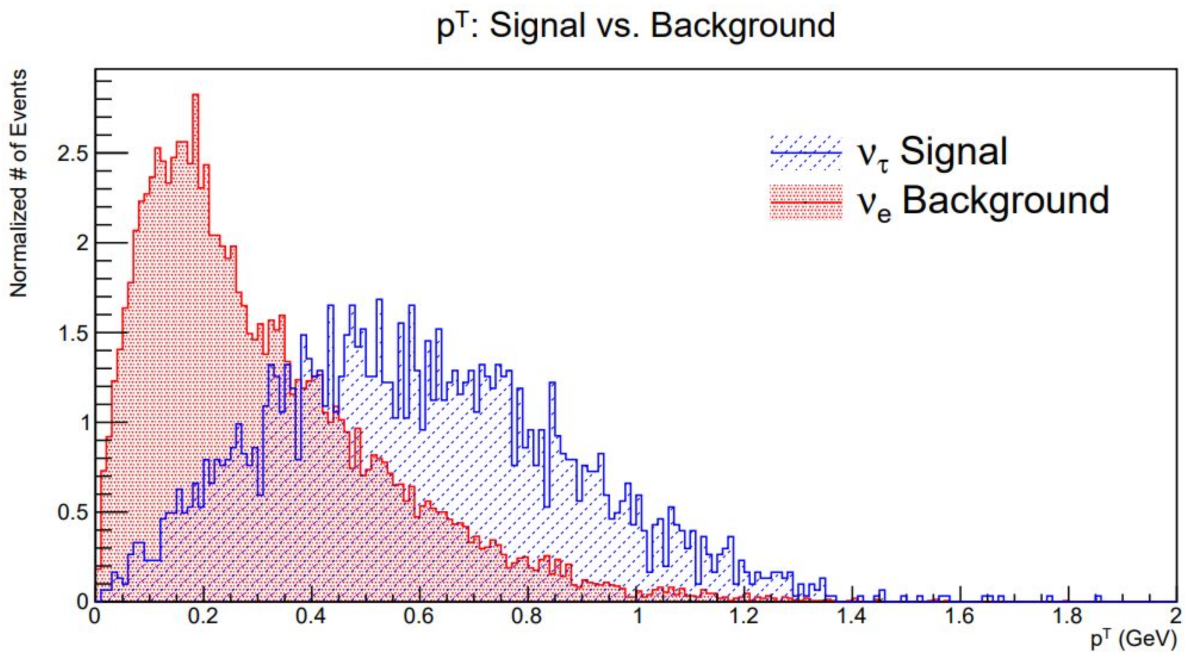
Seven main kinematic variables:

- p_p^T: transverse momentum of exiting proton(s)
- p_e^T: transverse momentum of exiting electron
- p^T: total transverse momentum of final state electron and proton(s)
  - p_m^T: negative of p^T
- ϕ_{lm}: angle between electron momentum and missing transverse momentum
- ϕ_{lh}: angle between electron momentum and total proton momentum
- ϕ_{hm}: angle between total proton momentum and missing transverse momentum
- KE_{lep}: kinetic energy of exiting electron

Monte Carlo Truth-Level Analysis

GENIE (Generates Events for Neutrino Interaction Experiments)

~20,000 events each for signal (100% Osc.) and background (intrinsic beam)

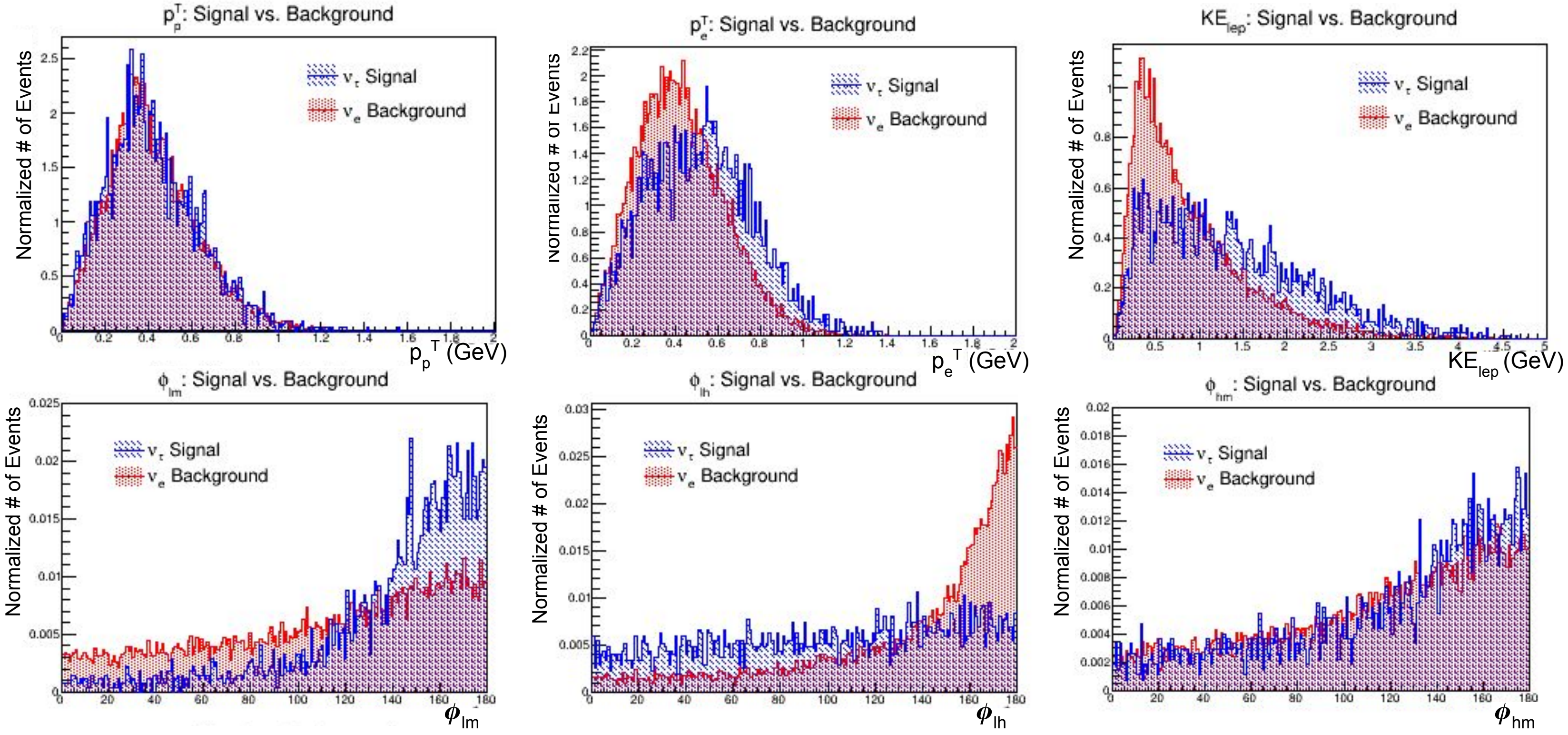


Optimize selection based on truth-level information.

If we could reconstruct everything perfectly, what do the kinematics look like?

Study how distributions and correlations between variables differ between signal and background.

Distributions for the other six kinematic variables, all can tell us valuable information.



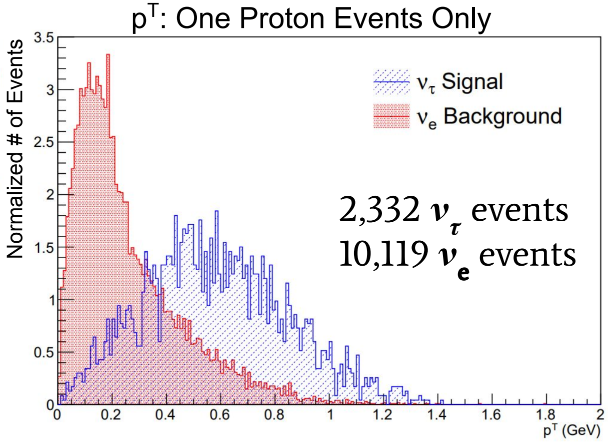
How do we optimize event selection?

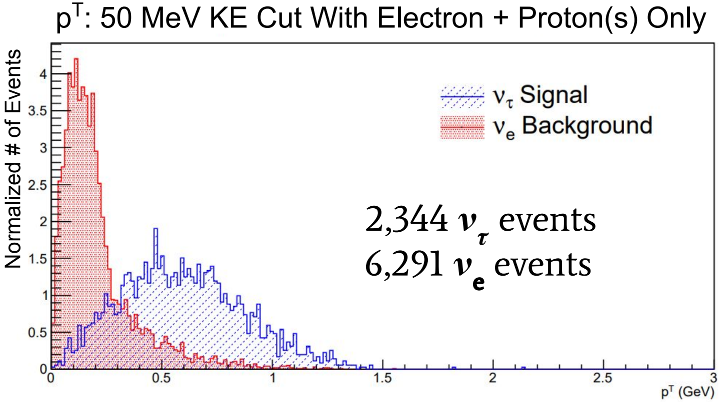
Place cuts on event characteristics - trying to improve the ratio of signal to background events.

Could be based on:

- Kinetic energy of the protons
- Number of final state protons
- Are there other final state charged particles (pions, kaons, etc)

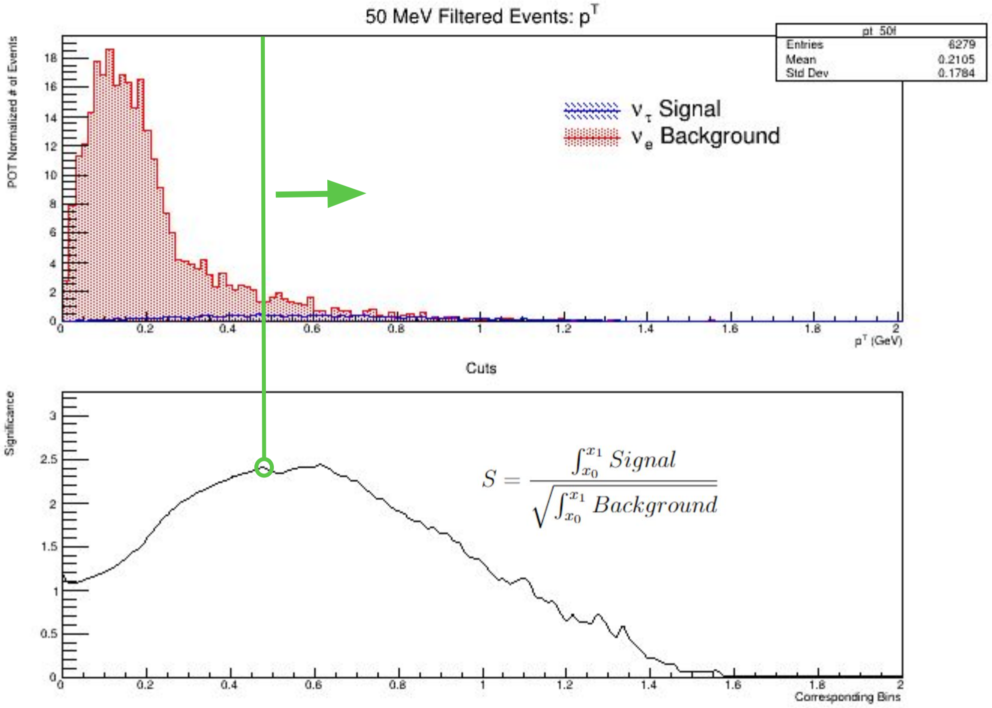
Many, many different selection themes!





How to optimize selection for a single variable?

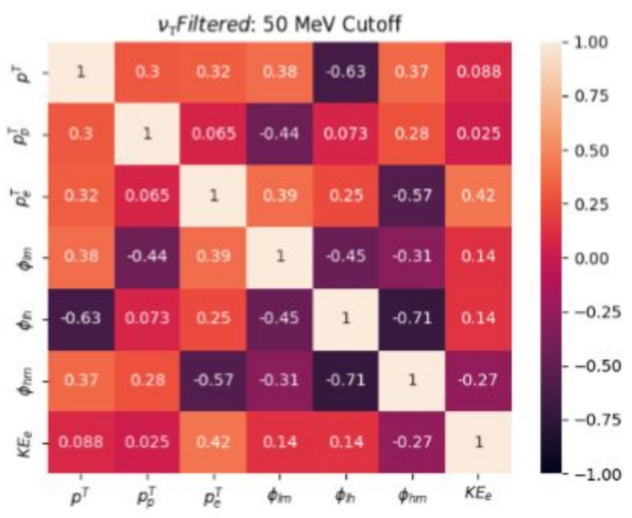
- Optimize based on statistical significance
- Event # is normalized to true MicroBooNE POT (protons on target)
- Based on plot, would cut all events with p^T below ~0.45 GeV



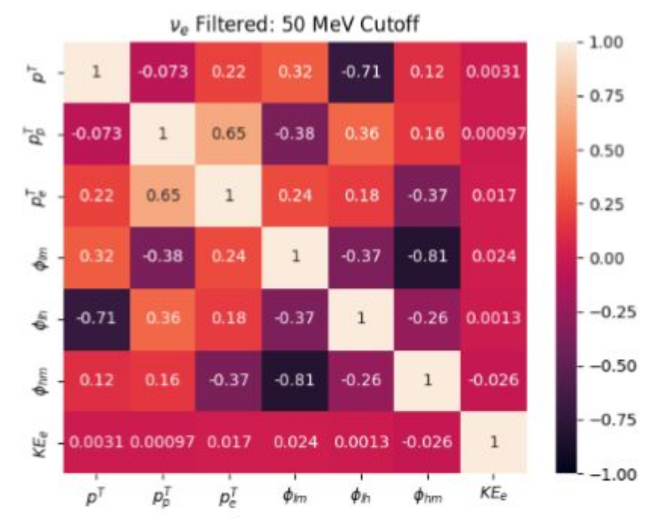
Variable Correlations

- Correlation matrices of all 7 defined kinematic variables.
- See which variables correlate differently for signal and background - indicates where to look when making 2D selections.

Signal



Background



2D Selections

The more clustered the red is the better!

Cut out as much red as you can while keeping as much blue as you can.

Top:

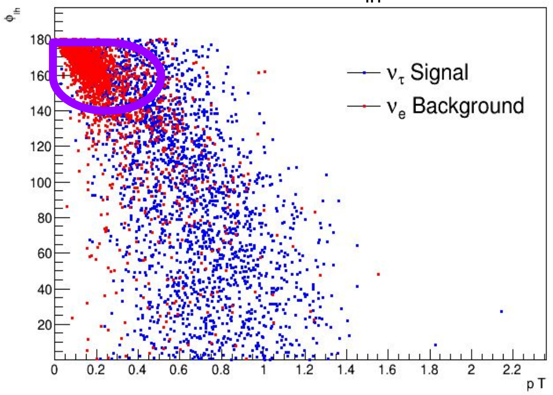
95% of background rejected, but also over 50% of signal rejected.

18 ν_τ events → 8 ν_τ events
299 ν_e events → 15 ν_e events

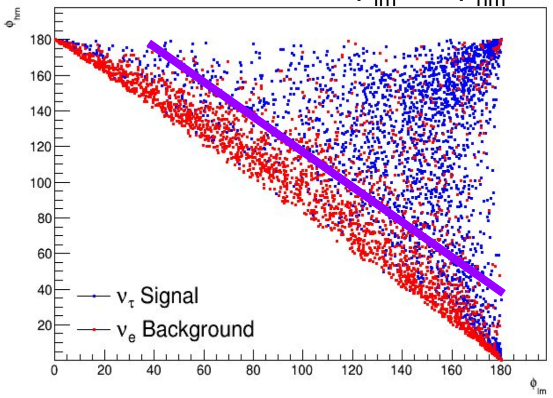
Bottom:

Around 80% background rejected, but 78% of signal remaining.

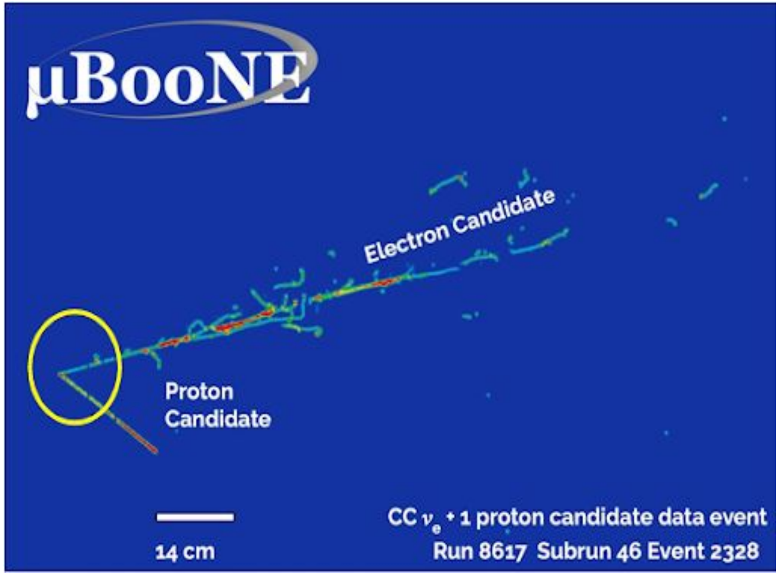
50 MeV Filtered: ϕ_{lh} vs. p^T



50 MeV Filtered: ϕ_{lm} vs. ϕ_{hm}



Reconstruction Analysis



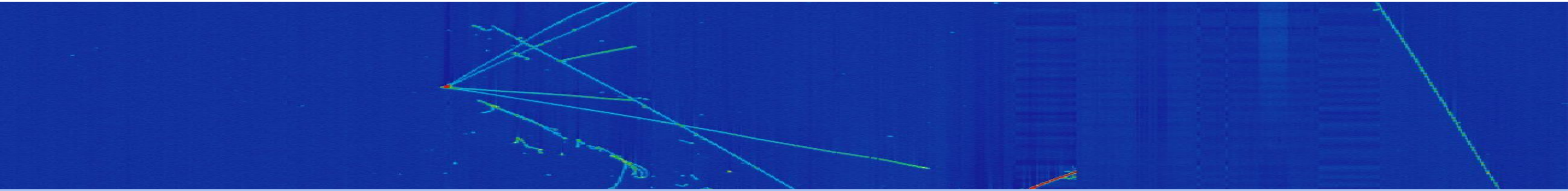
- After truth-level analysis - see how the same selections hold up using reconstruction information.
  - Recreate plots and make adjustments to selections.
- Much better representation of real MicroBooNE data.
- Need efficient selections for identifying proton-like and electron-like events.
- Preliminary reconstruction information distributions can be found in my report.

Conclusion & Next Steps

- We now have developed tools to optimize selection for $\nu_\mu \rightarrow \nu_\tau$ oscillation in MicroBooNE. Kinematics selections based on truth-level analysis give us information about the underlying mechanics of signal and background events.
- Particle identifying selections allow preliminary kinematics studies with reconstruction information.
- Actual detection of $\nu_\mu \rightarrow \nu_\tau$ excess will be very difficult to see in MicroBooNE alone, very few signal events means low significance even if they are there. However, there is still hope for the greater SBN program.

Next Steps

1. BDT training for track recognition → Better selection efficiency
2. Refine selection algorithm for reconstructed simulation
3. Test the algorithm on the full MicroBooNE MC and real data to look for any discrepancies
4. Expand to the full SBN program
5. Evaluate the first sensitivity for $\nu_\mu \rightarrow \nu_\tau$ oscillations in MicroBooNE and SBN!



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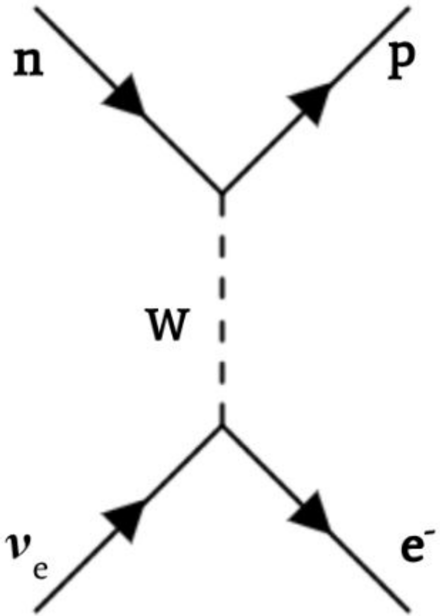
Neutrino Charged Current Interactions

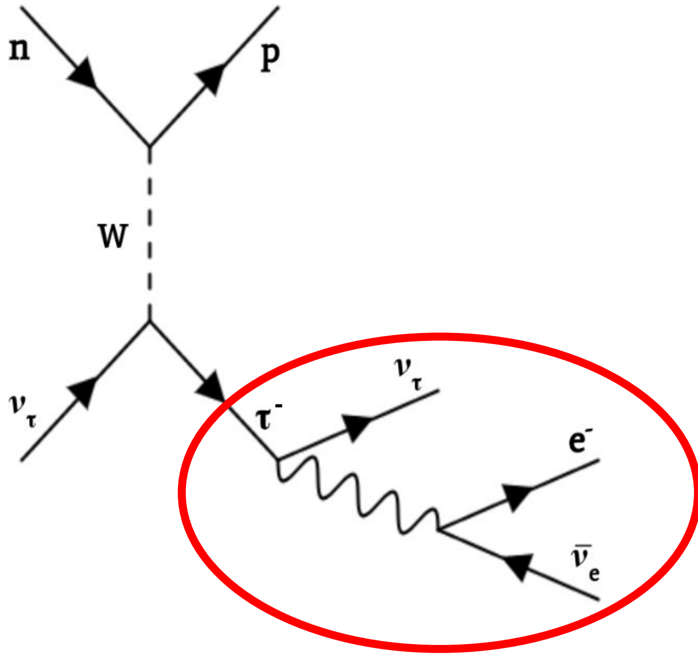


ν_eCC Interaction

Neutrino interacts with a neutron, knocking out a proton and producing it's charged lepton cousin.

Energy threshold for tau production is 3.5 GeV.

Allows us to identify the flavor of the incident neutrino.



ν_τCC Interaction + τ-Decay

Neutrino Oscillations + Sterile Neutrinos

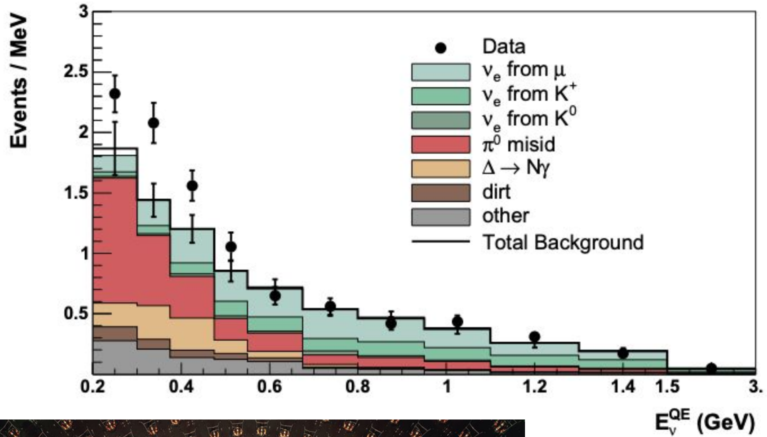
What do all of these anomalies mean?

Points towards new physics beyond the Standard Model!

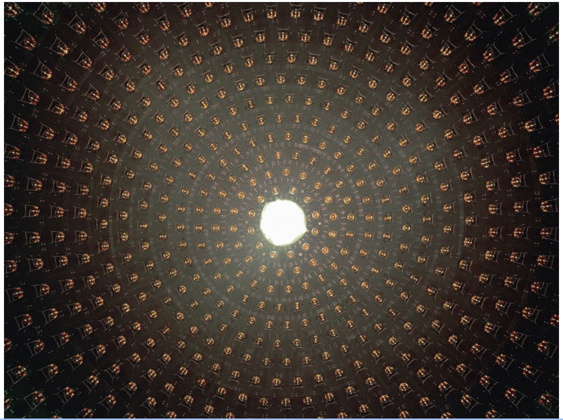
Most investigated theory is that of the sterile neutrino, an additional particle to the three flavors known in the SM.

Even more difficult to detect than ordinary neutrinos!!

- Primary Goal: Investigate the anomalous mass-squared difference of the Los Alamos Liquid Scintillator Neutrino Detector (LSND)
- Ended up with another anomaly! - an excess of electron-like events at low energies
- What is the source of the extra events?
  - Single electron or single photon at neutrino interaction vertex

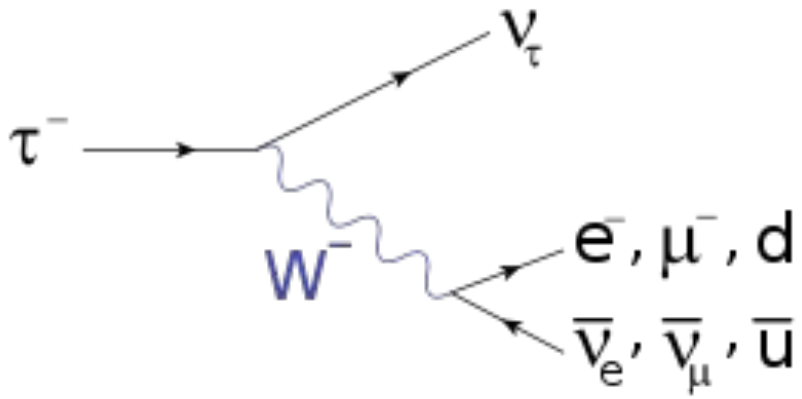


Wanwei Wu, 2023.



ν_τCC: τ-Decay Branches

- Only concerned with leptonic decay pathways
- ν_μ flux is much too high to have a chance of detecting a ν_τ to any significance
- ν_e flux is much lower, giving a low background for the electron decay pathway for a ν_τ event



Decay Mode	Resonance	Branching Ratio (%)
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Other		3.3

Monte Carlo Truth-Level Analysis

GENIE (Generates Events for Neutrino Interaction Experiments)

~20,000 events each for signal and background

Accounts for the neutrino-nucleon interactions as well as the Fermi momentum.

Study the kinematic differences at truth-level, without the uncertainty of reconstruction.

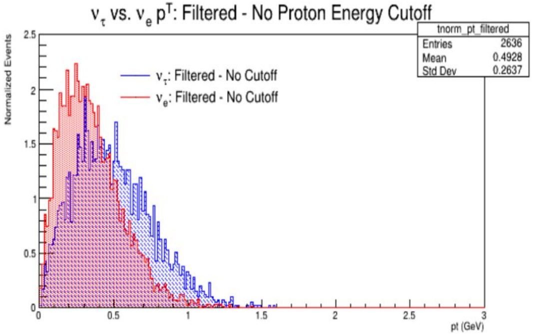
How do we optimize selection?

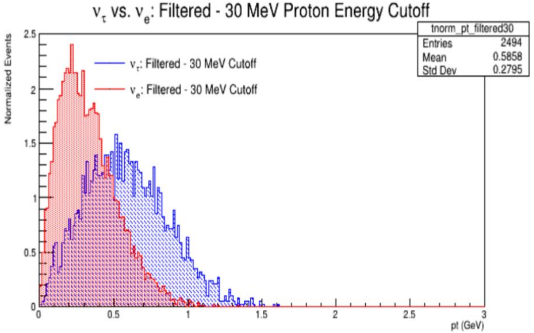
The goal is to find the best separation and reduce background as much as possible.

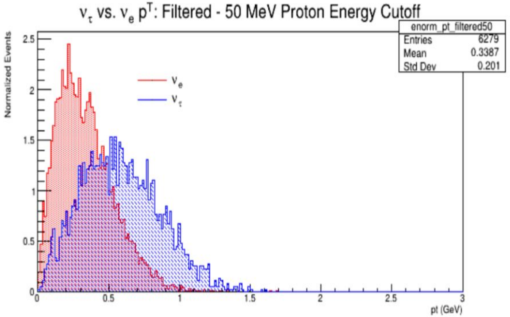
Place cuts on the events and kinematic variables.

Could be based on:

- Kinetic energy of the protons
- Number of final state protons
- Are there other final state charged particles (pions, kaons, etc)







Many, many different filtering/inclusion themes!

POT Normalization

- MicroBooNE POT (Protons On Target):
  - Runs 1-3: 6.8 E20
  - Runs 1-5: 1.32 E21
- POT required for GENIE to produce 20k events:
  - $\boldsymbol{\nu}_{\tau}$: 1.51 E23
  - $\boldsymbol{\nu}_{e}$: 2.56 E22
- Simulation POT much higher → Need to normalize MC data down to the proper MicroBooNE POT
- High $\boldsymbol{\nu}_{\tau}$ CC interaction threshold means not very many actual $\boldsymbol{\nu}_{\tau}$ events would have been seen by MicroBooNE, if any.