Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

QUICK SUMMARY, STATUS, AND NEXT STEPS

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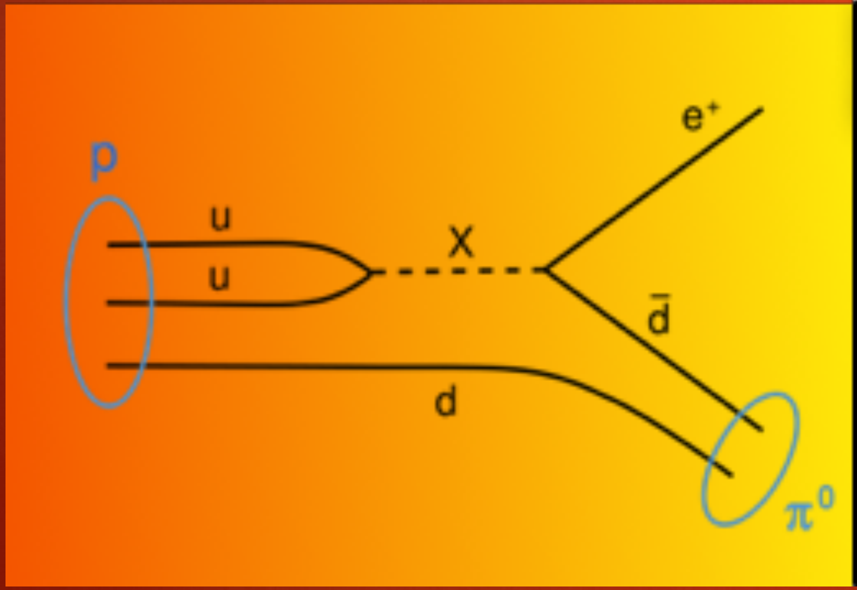
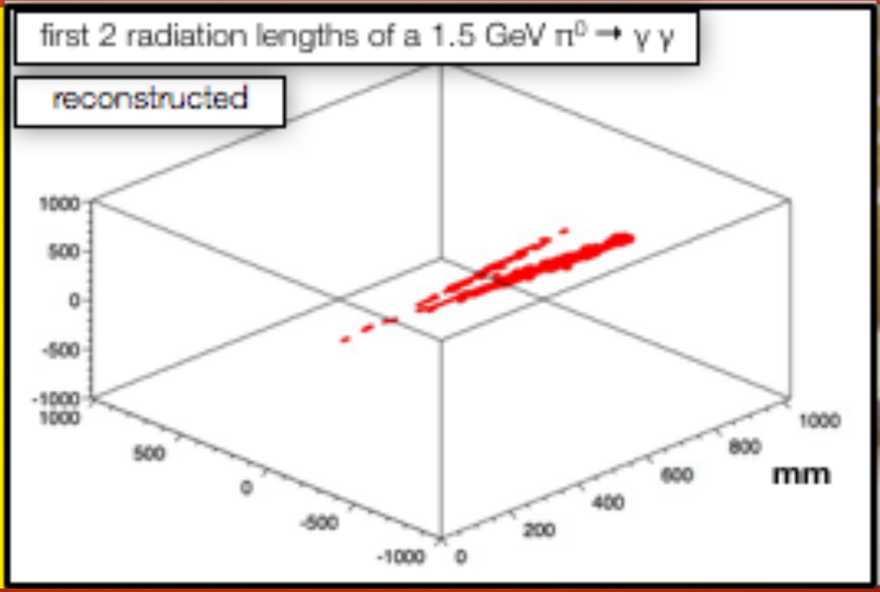
Iowa State University

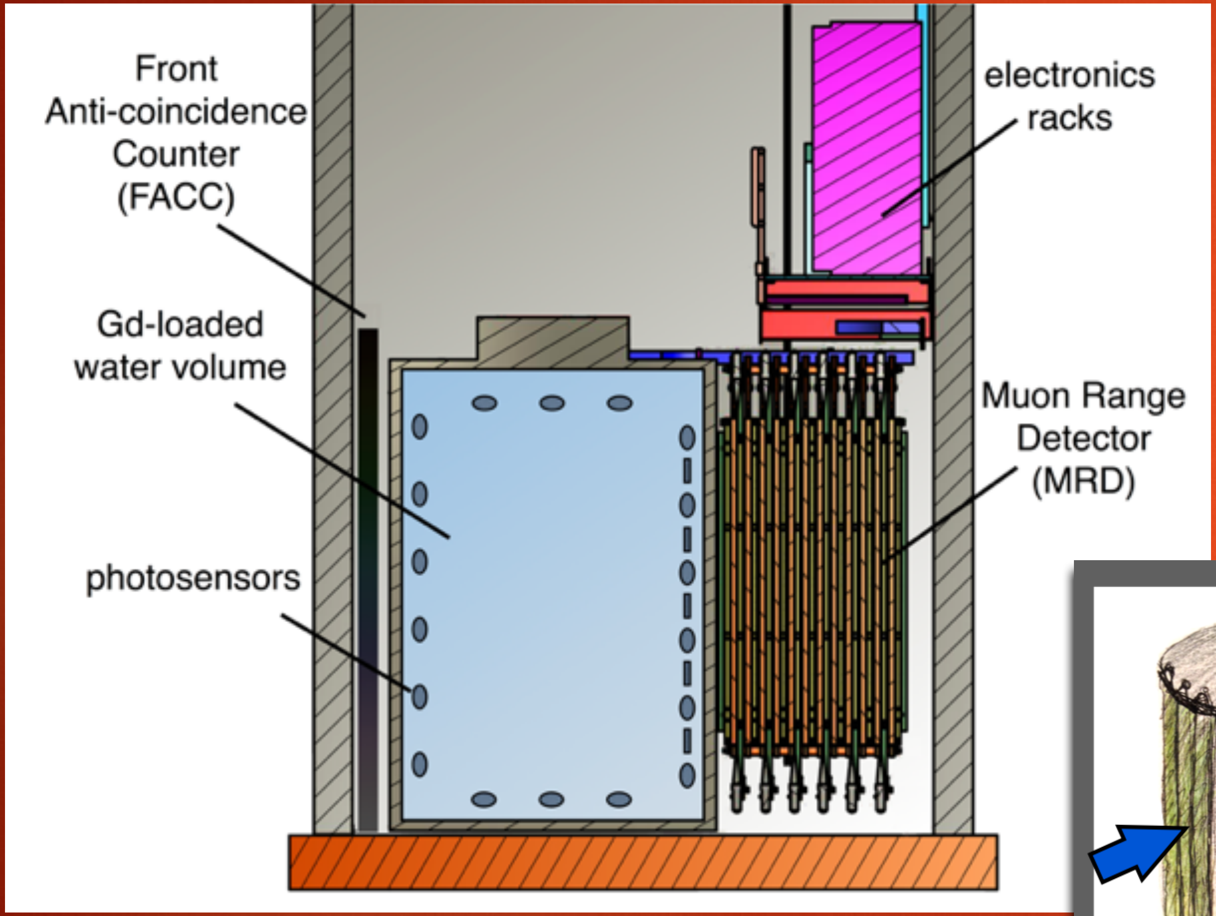
What is ANNIE

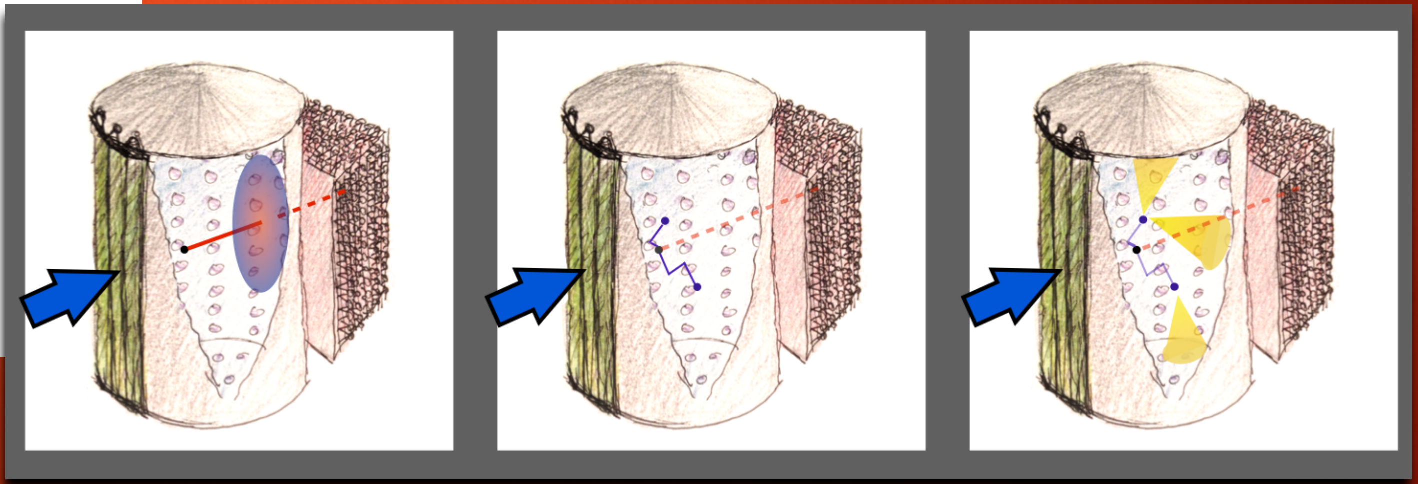
- An Active experimental effort at Fermilab
- Will measure the final state neutron multiplicity of neutrino interactions in relation to lepton kinematics, reconstructed energy, and q^2.
- A detector R&D effort – first implementation of fast photodectors (LAPPDs) and waveform sampling electronics in a Gd-loaded Water Cherenkov





What is ANNIE

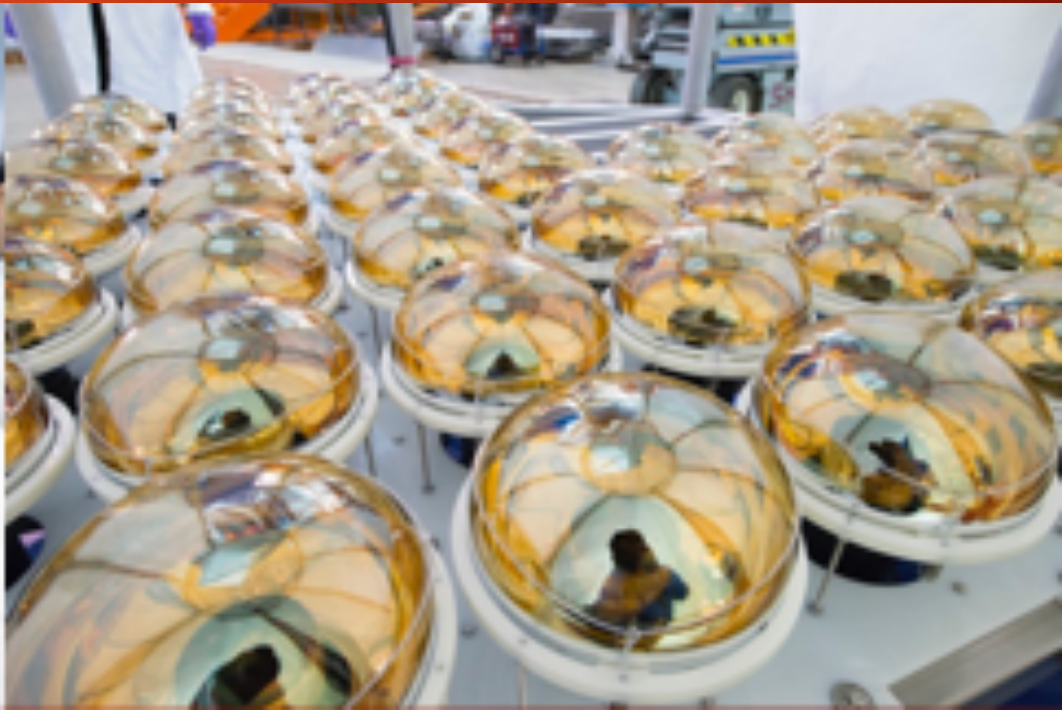




The Phases of ANNIE

- Construction of tank and Infrastructure (complete)





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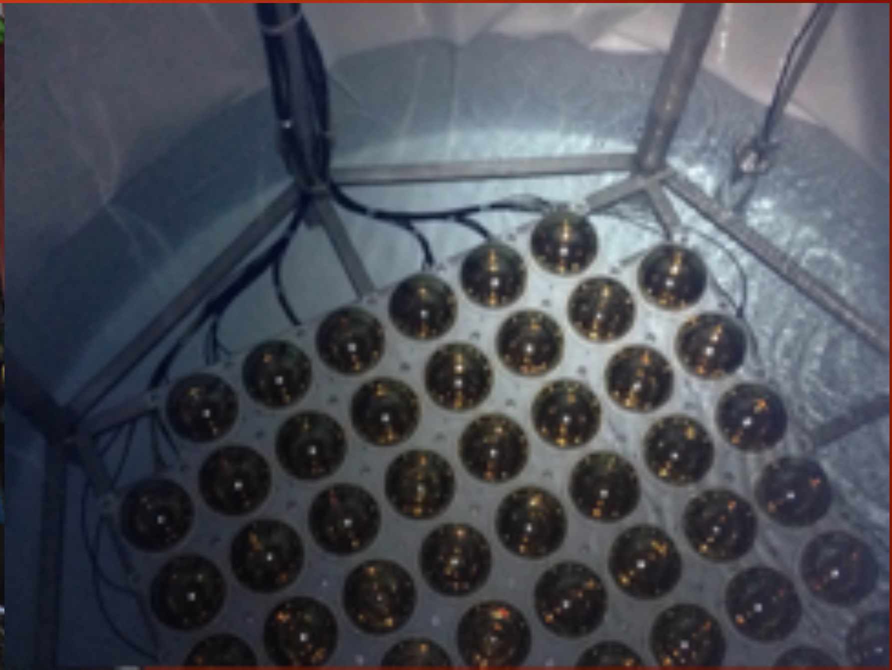

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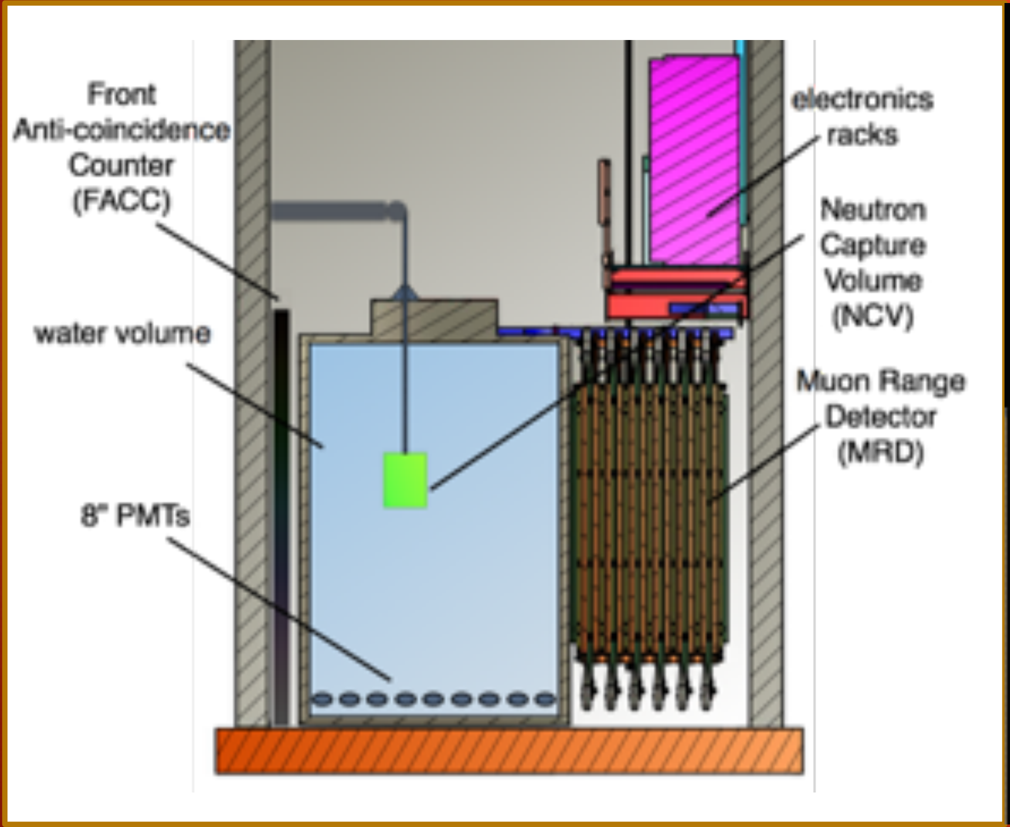
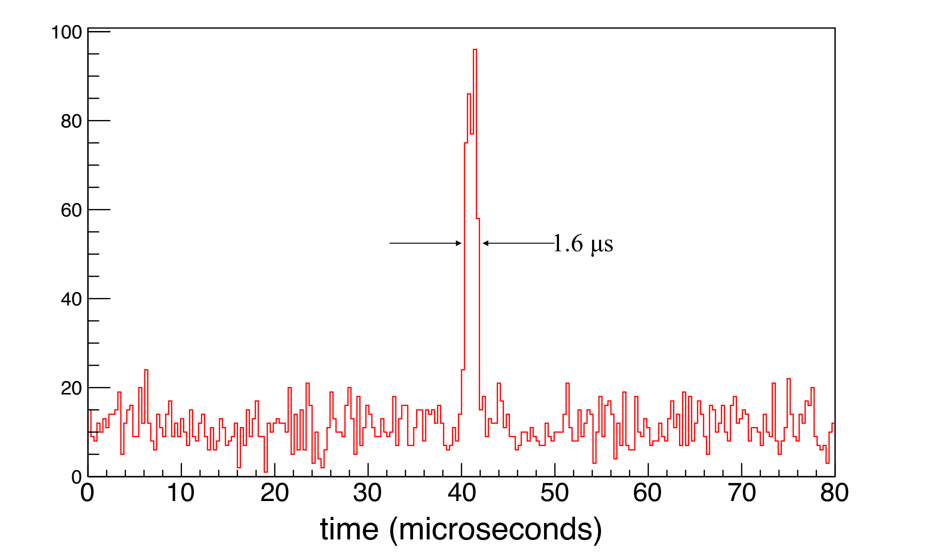
- Construction of tank and Infrastructure (complete)
- Phase I: Measurement of Background Neutrons (in progress)





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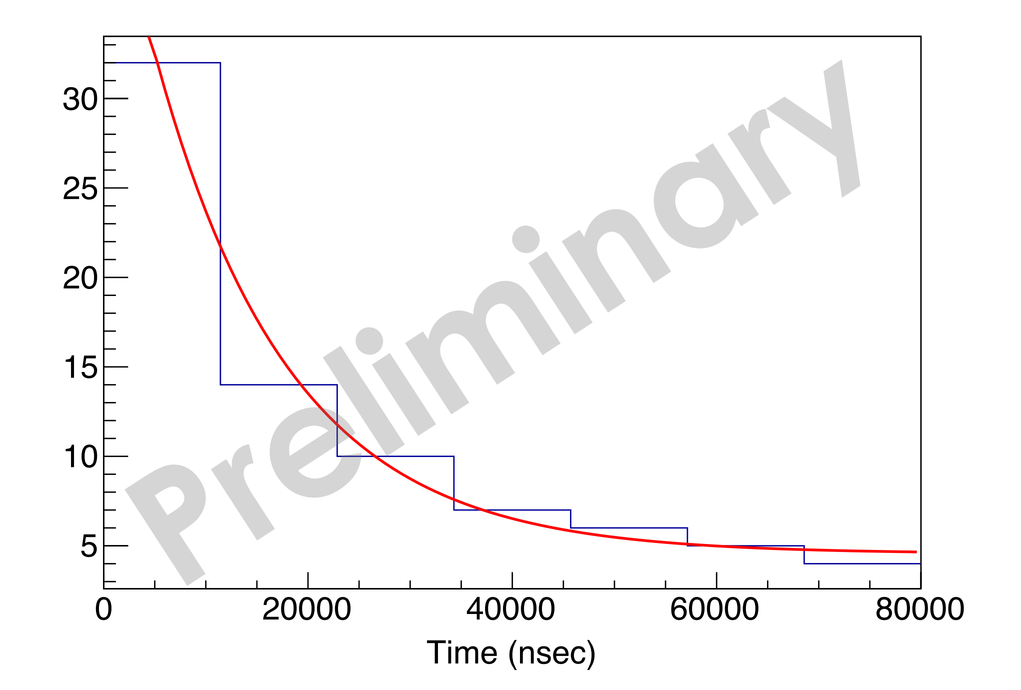
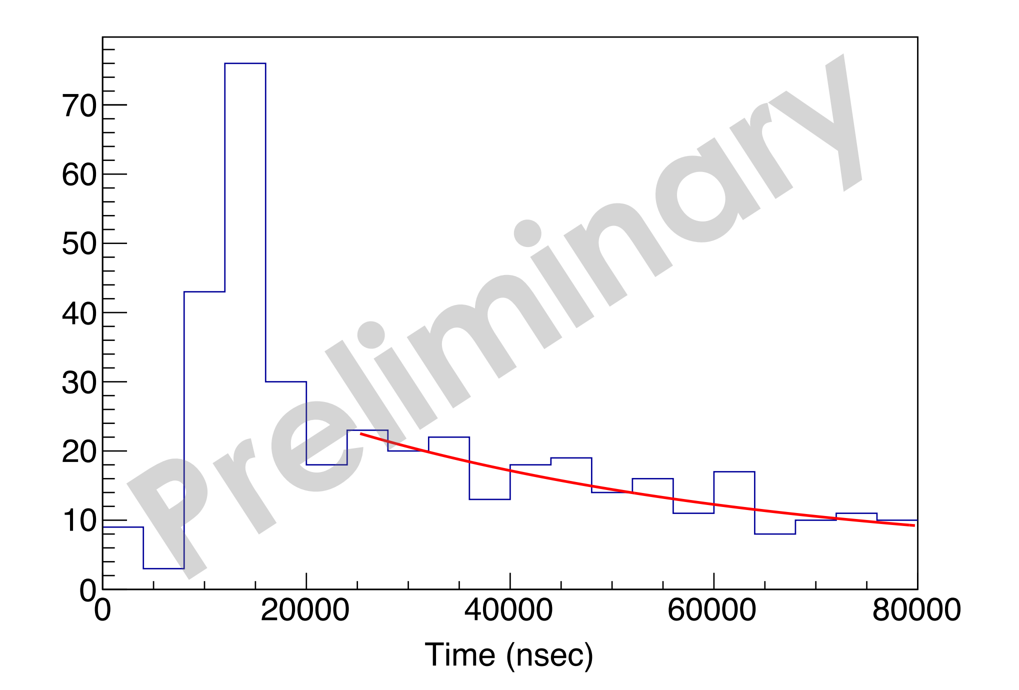
Neutron source



Beam



The Phases of ANNIE

- Construction of tank and Infrastructure (done)
- Phase I : Background Neutron Measurement (in progress)
  - Phase IB: Procurement, LAPPD testing and readiness, PSEC electronics integration (funded by DOE and in progress)



The Phases of ANNIE

- Construction of tank and Infrastructure (done)
- Phase I : Background Neutron Measurement (in progress)
  - Phase IB: Procurement, LAPPD testing and readiness, PSEC electronics integration (funded by DOE and in progress)
- Phase II: Physics Upgrade (Summer/Fall 2017)
  - Add LAPPDs, Gd, more PMTs, more electronics channels

ANNIE Physics

- Is the presence of neutrons a good handle for rejecting inelastics the fake CCQE?
  - Can we experimentally observe a hardening of the reconstructed energy distribution in ANNIE
- What is the relationship between neutron abundance and muon kinematics in CCQE-like events?
- What is the relationship between neutron abundance among other event classes (NC, events with observed pions, etc)?

Characterization of CCQE Backgrounds in Genie MC

INCREASING THE FIDELITY OF RECONSTRUCTED NEUTRINO ENERGY

Carlos Blanco, University of Chicago

Work with Dr. Richard Hill, Dr. Matt Wetstein

CCQE-Like Events: Generator level vs Detector Level

- General Criteria: No; Pions, Kaons, Gammas, Etc…) in the "final" state
- Generator Level: "Final" state is particles after intranuclear scattering (i.e. after being sufficiently far away from vertex)
- Detector Level: "Final" state is particles likely to be detected after taking into account:
  - Cherenkov thresholds
  - Secondary neutron production
  - Neutron detection efficiency

*Truth Level = Genie interaction labels as defined prior to final state interactions.

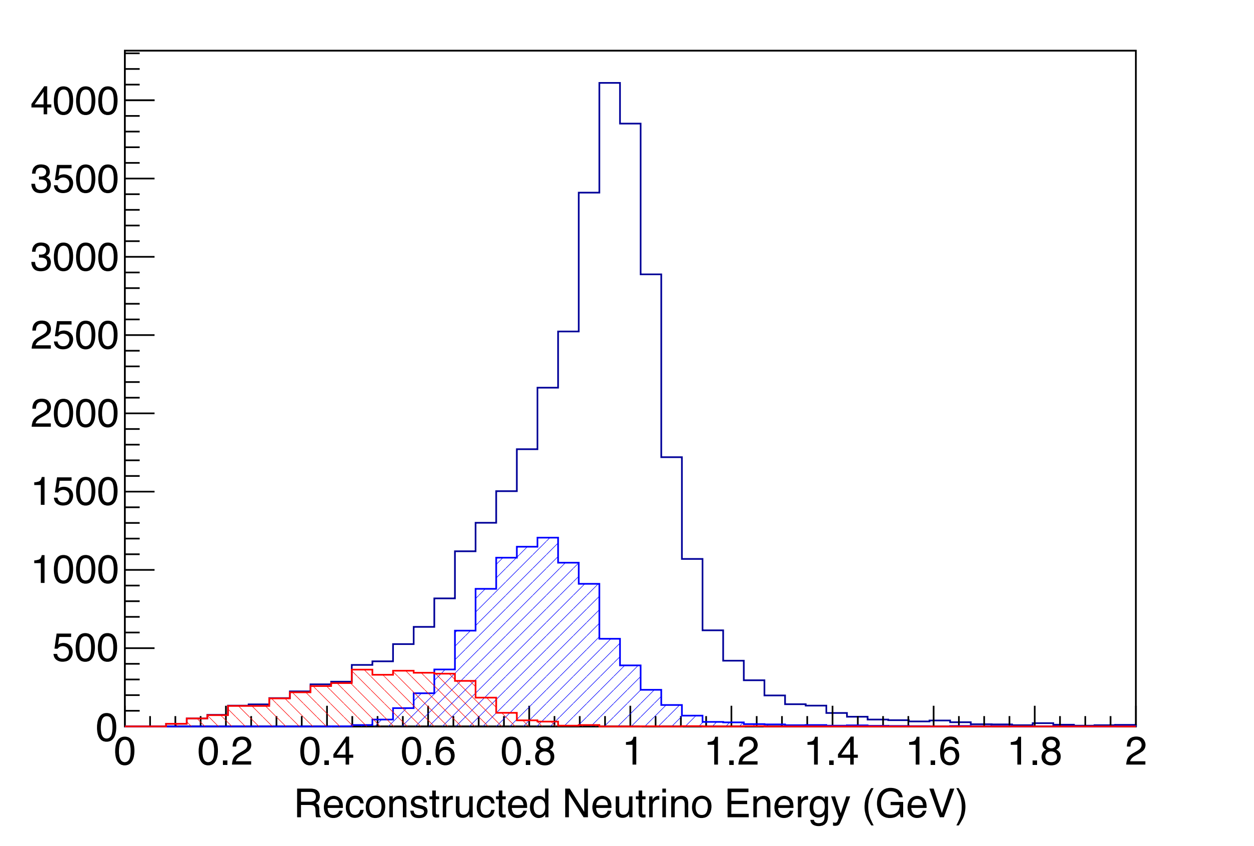
Reconstructing Energy

Presupposing elastic scattering off a nucleon.

M_n = mass of neutron
ΔM = nucleon mass difference
E_B = constant nuclear removal energy
E_μ = energy of outgoing muon
Θ_μ = angle off longitudinal axis of muon

$$E_\nu^{\text{rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + m_\mu^2 + \Delta M^2)}{2\left[M_n - E_B - E_\mu + |\vec{k}_\mu| \cos\theta_\mu\right]}$$

Reconstructed Energy in GENIE



200K 1 GeV neutrinos on water target

Only CCQE-like Events analyzed
-Generator Level

MEC and other non-CCQE backgrounds, tend to smear and bias E_{rec} downward

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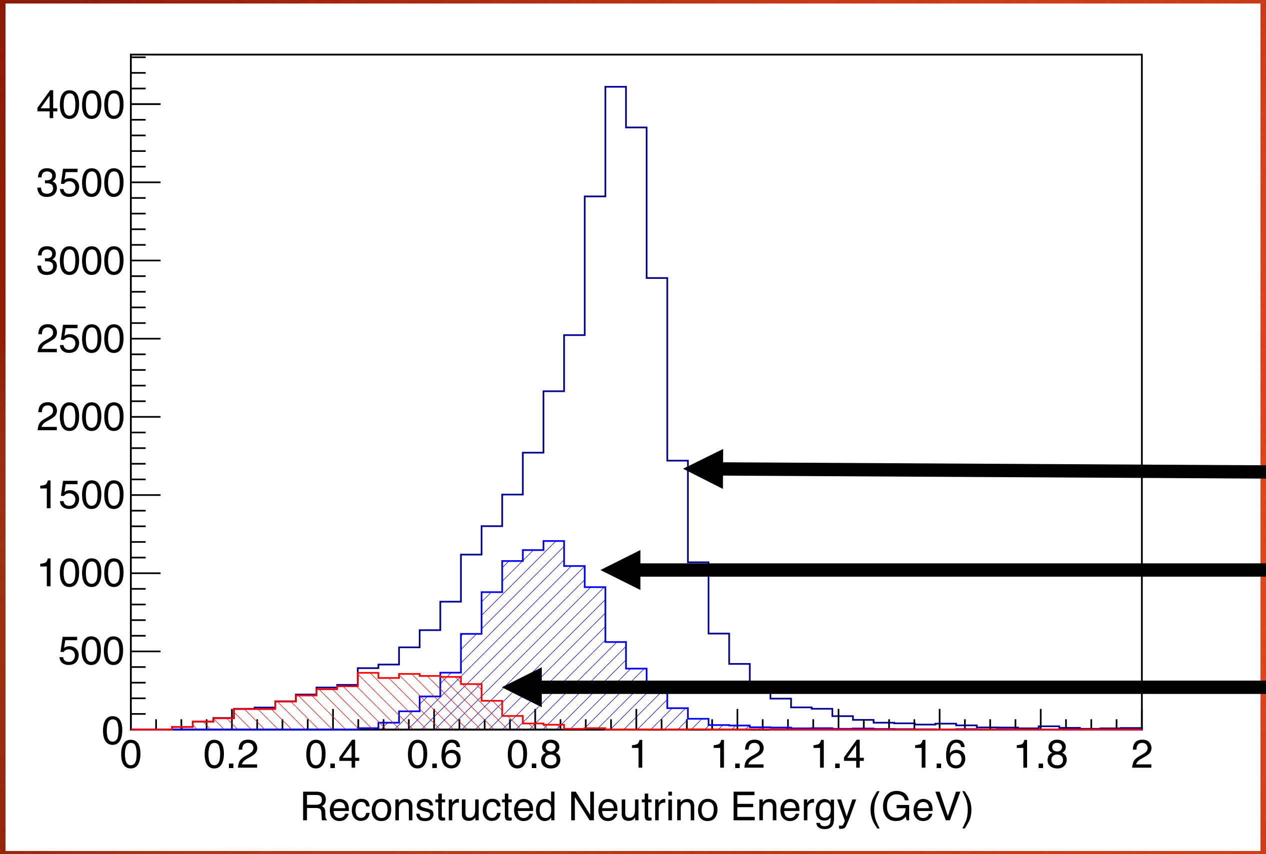


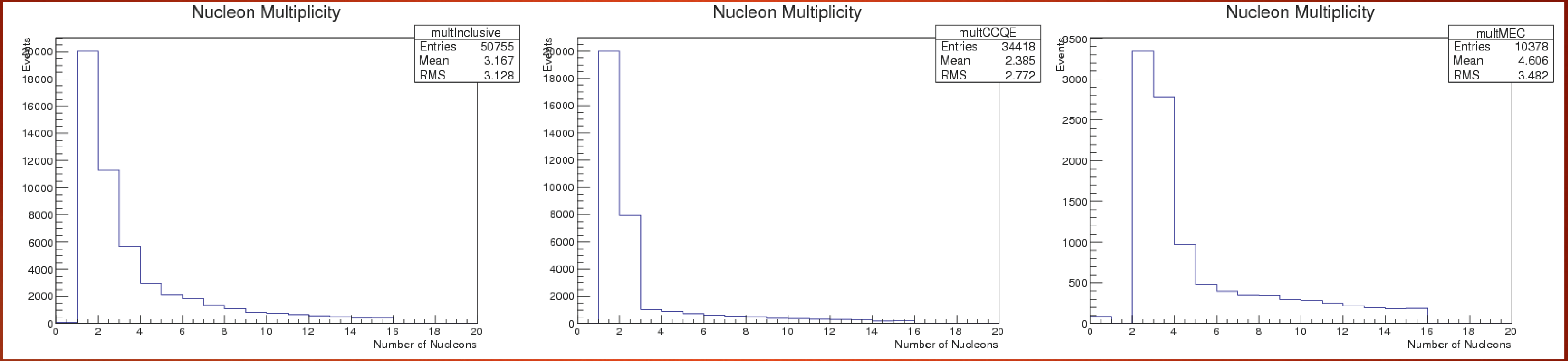
Inclusive data sample

MEC

other inelastic CCQE-like events (mostly stuck pions)

MEC and other non-CCQE backgrounds, tend to smear and bias E_{rec} downward

Nucleon Multiplicity of Reactions



Inclusive sample

True CCQE sample

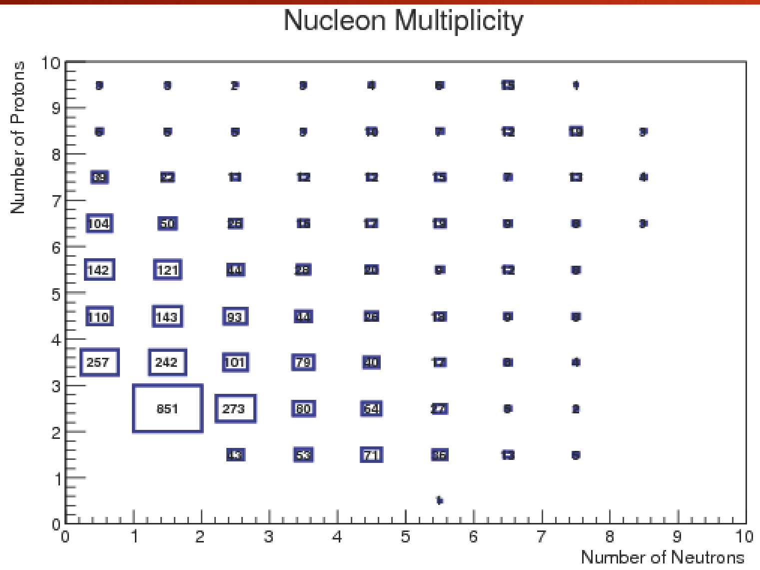
MEC sample

Truth-level CCQE sample peaked at 1 nucleon
MEC sample peaked at 2 nucleons

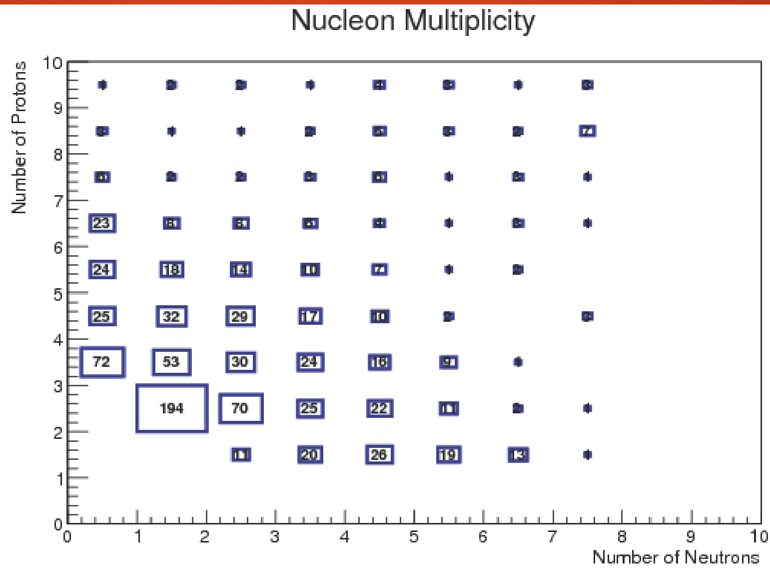
What about the other backgrounds (previous red curve)?
This includes
-Resonant single pion production
-Deep inelastic scattering

*GENIE creates n-p:n-n = 4:1 in MEC events @1 GeV

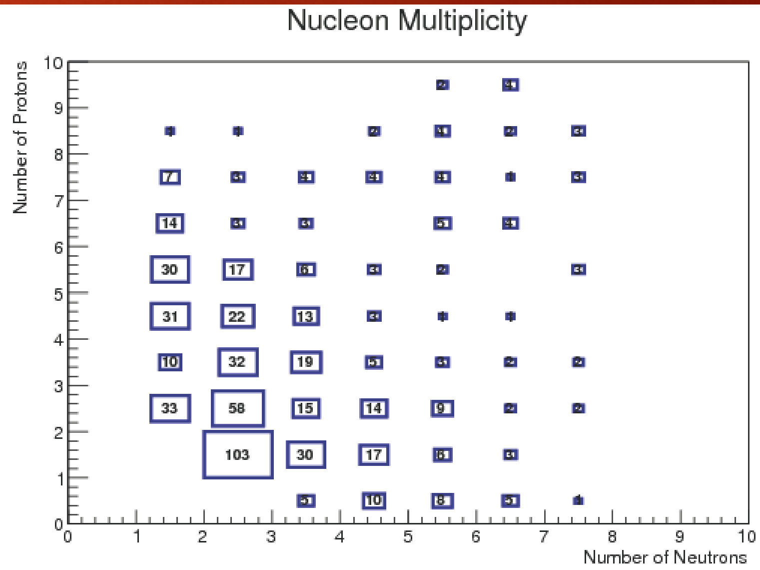
Reabsorbed pions produce neutrons *most* of the time…



Reaction 70



Reaction 71



Reaction 72

$$\nu_\mu\, p \to \mu^-\, p\, \pi^+, \qquad \overline{\nu}_\mu\, p \to \mu^+\, p\, \pi^- \qquad (70)$$

$$\nu_\mu\, n \to \mu^-\, p\, \pi^0, \qquad \overline{\nu}_\mu\, p \to \mu^+\, n\, \pi^0 \qquad (71)$$

$$\nu_\mu\, n \to \mu^-\, n\, \pi^+, \qquad \overline{\nu}_\mu\, n \to \mu^+\, n\, \pi^- \qquad (72)$$

*Only neutrino modes are considered

-These constitute most of the inelastic non-MEC background

-Genie produces at least 3 nucleons in SPP events: one from initial reaction & two from pion absorption

-Two nucleons from pion absorbtion are due to P-conservation

Neutron Multiplicity in Backgrounds and Signal

Interaction Fraction	Inclusive	0 Neutron Sample	1 Neutron Sample	More Than 1 Neutron Sample
Truth-level CCQE	67.80%	91.99%	46.65%	37.29%
MEC	20.45%	4.44%	37.37%	37.44%
Single Pion Prod.	10.12%	3.13%	14.15%	21.22%
Deep Inelastic Sc.	1.47%	0.23%	1.74%	3.89%
Misc. Final State Int.	0.16%	0.21%	0.09%	0.16%
Total Breakdown	**100%**	**100%**	**100%**	**100%**

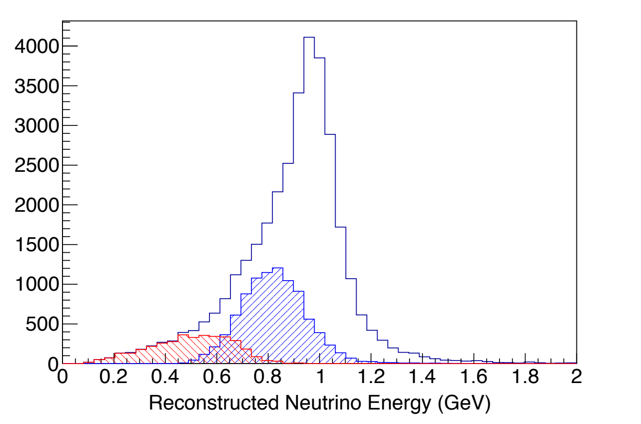
Event samples are broken up into classes of neutron multiplicity in the final state. 0 neutron sample is dominated by true-CCQE events

Interaction Fraction	0 Neutron Sample	1 Neutron Sample	More Than 1 Neutron Sample	Total Breakdown
True-level CCQE	69.57%	17.94%	12.49%	**100%**
MEC	10.84%	47.61%	41.55%	**100%**
Single Pion Prod.	15.87%	36.48%	47.65%	**100%**
Deep Inelastic Sc.	8.12%	31.12%	60.76%	**100%**
Misc. Final State Int.	62.35%	15.29%	22.35%	**100%**

Event samples are broken up into classes of reaction type. True-CCQE is dominated by events with 0 final state neutrons. MEC events are dominated by events with 1 or more final state neutrons.

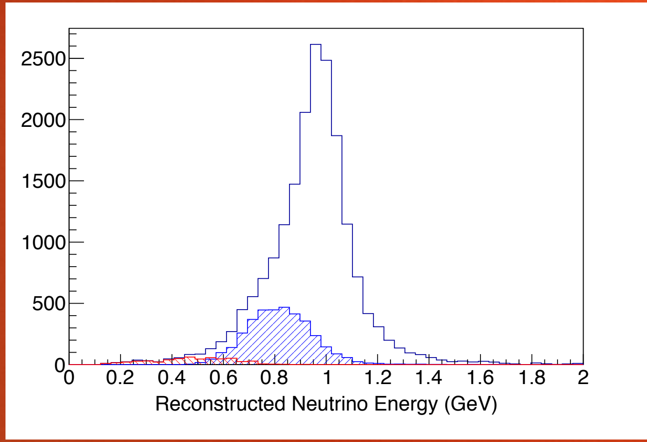
Using Neutrons to improve E_{rec}

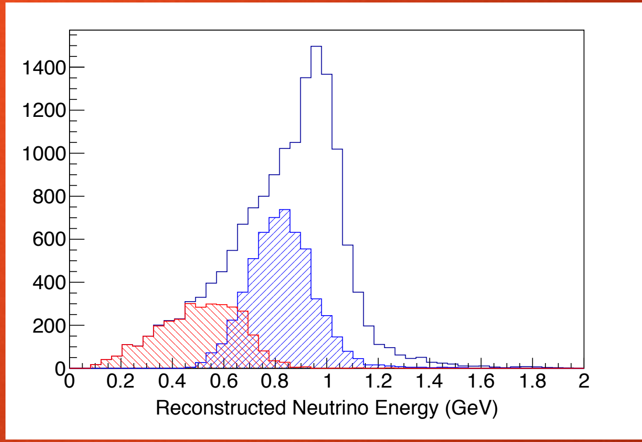
1 GeV



inclusive

0 Neutrons

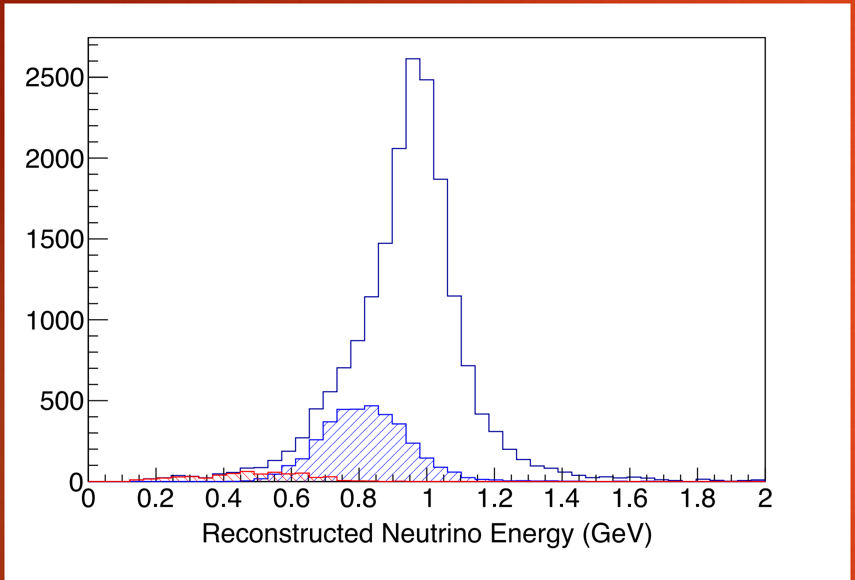




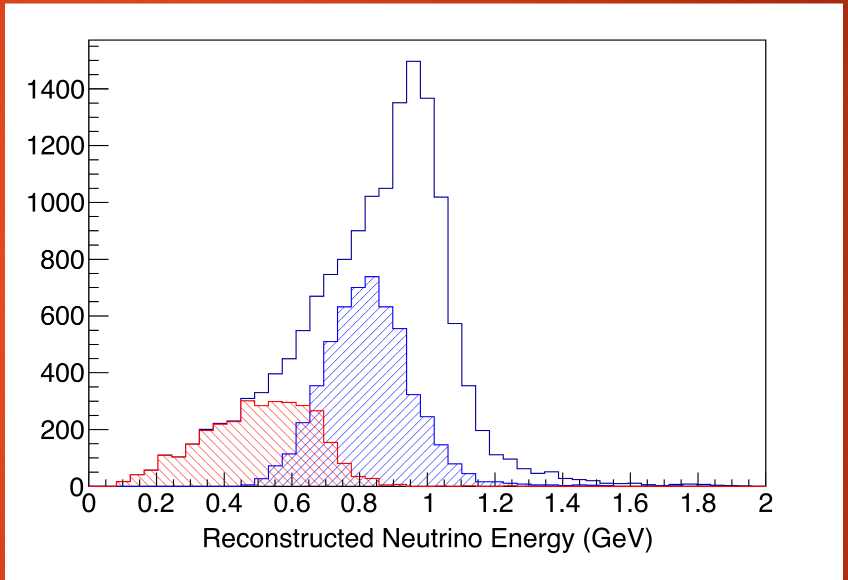
>0 Neutrons

Rejecting events with neutrons provides a purer CCQE sample and reduces the downward bias on energy. Most of the improvement comes from rejecting stuck pions

Using Neutrons to improve E_{rec}



Zero Neutrons



One or More Neutrons

1 GeV

Rejecting events with neutrons provides a purer CCQE sample and reduces the downward bias on energy. Most of the improvement comes from rejecting stuck pions

GENIE MC: Modeling Neutrino events in ANNIE

- Latest release (as of Aug., 2016) of GENIE-MC: V2.10.6
- Flux: Booster neutrino beam
- Geometry: File designed for the ANNIE detector in SciBoone Hall.
- Exposure: 4.73×10^{20} POTS
- Using CCMEC-Flag
- NP:NN Ratios generated: (2,4,6,8,10):1

GENIE MC: Modeling Neutrino events in ANNIE

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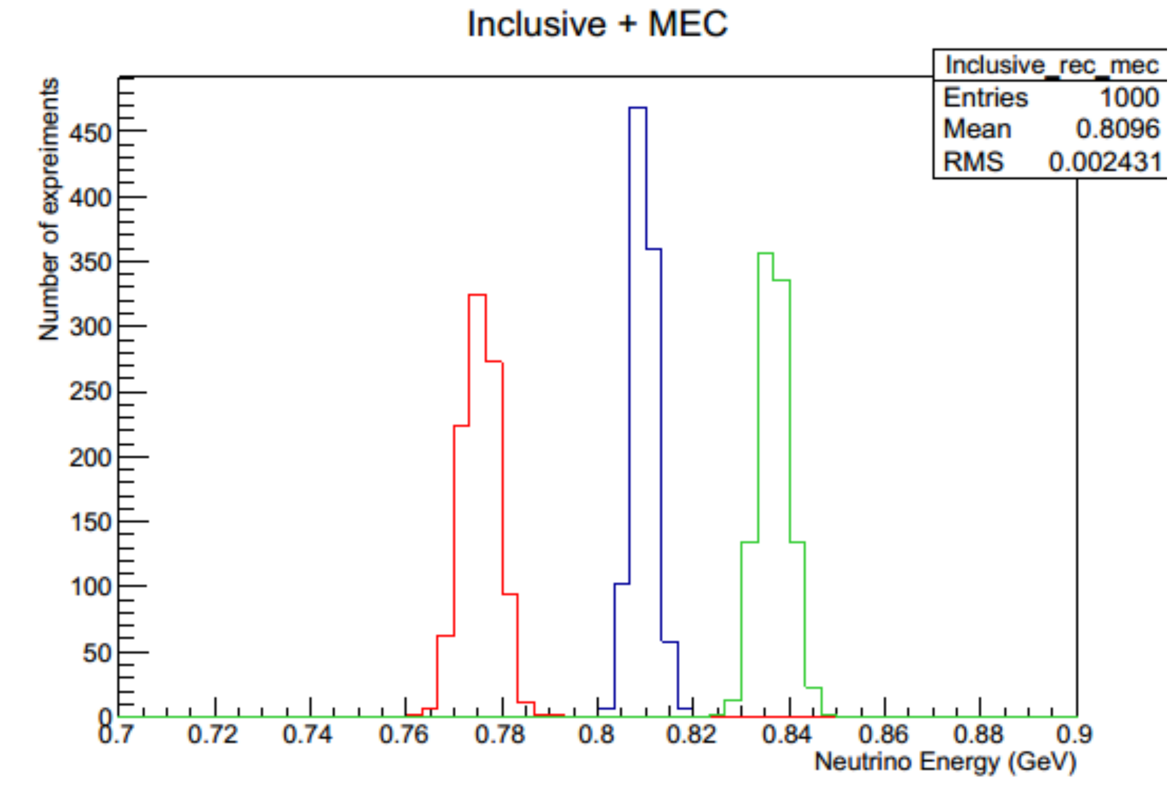
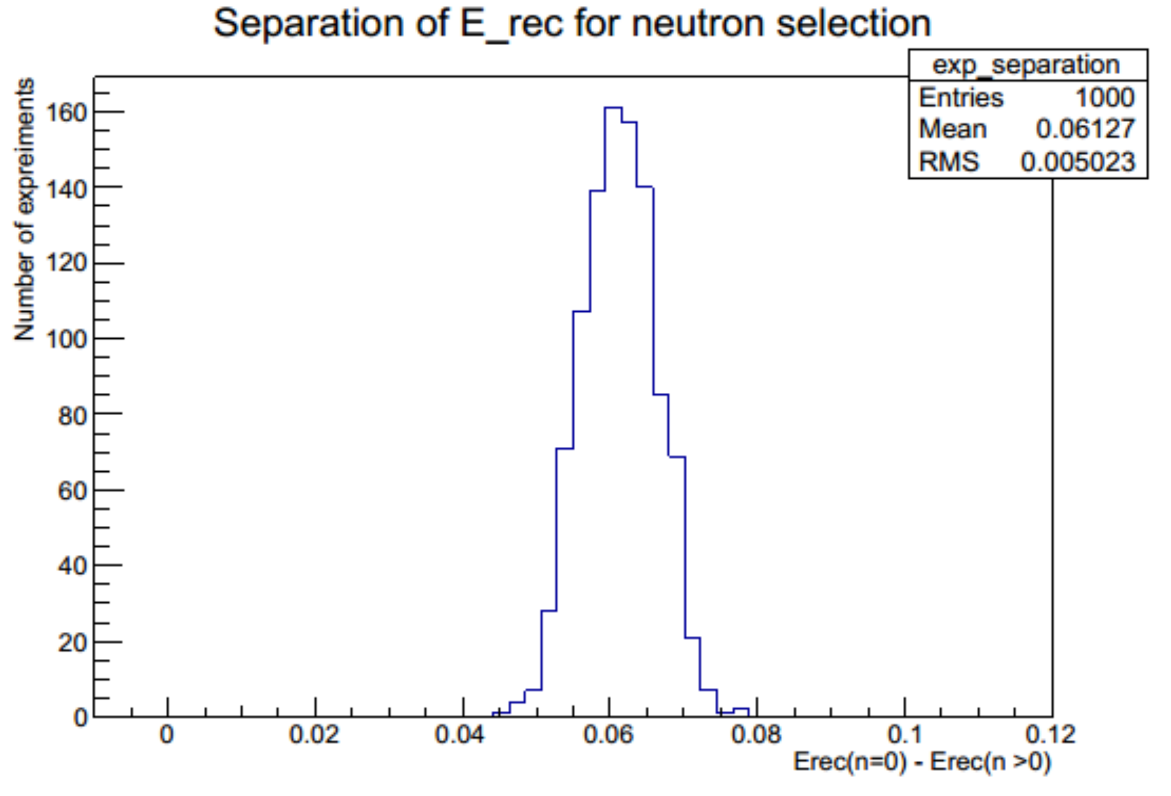
Paired-Mean Statistical Analysis

- Conduct 1000 “pseudo-experiments”; N=1000
  - Each experiment consisting of (n) events: n = 10%, 1%, 0.1% of 10^{20} POTS Data set. ~ n ≈ 80K, 8K, 800.
  - Run CCQE-like selection and energy reconstruction
  - Calculate average neutrino energy for $N_{neutrons} = 0$ and $N_{neutron} > 0$
  - Compare results using pairwise-mean strategy.

Results of Statistical Analysis: Generator-Level

Red: N > 0, Green = 0, Blue = Inclusive





- np:nn = 4:1 n = ~80K, Statistical significant at >99%

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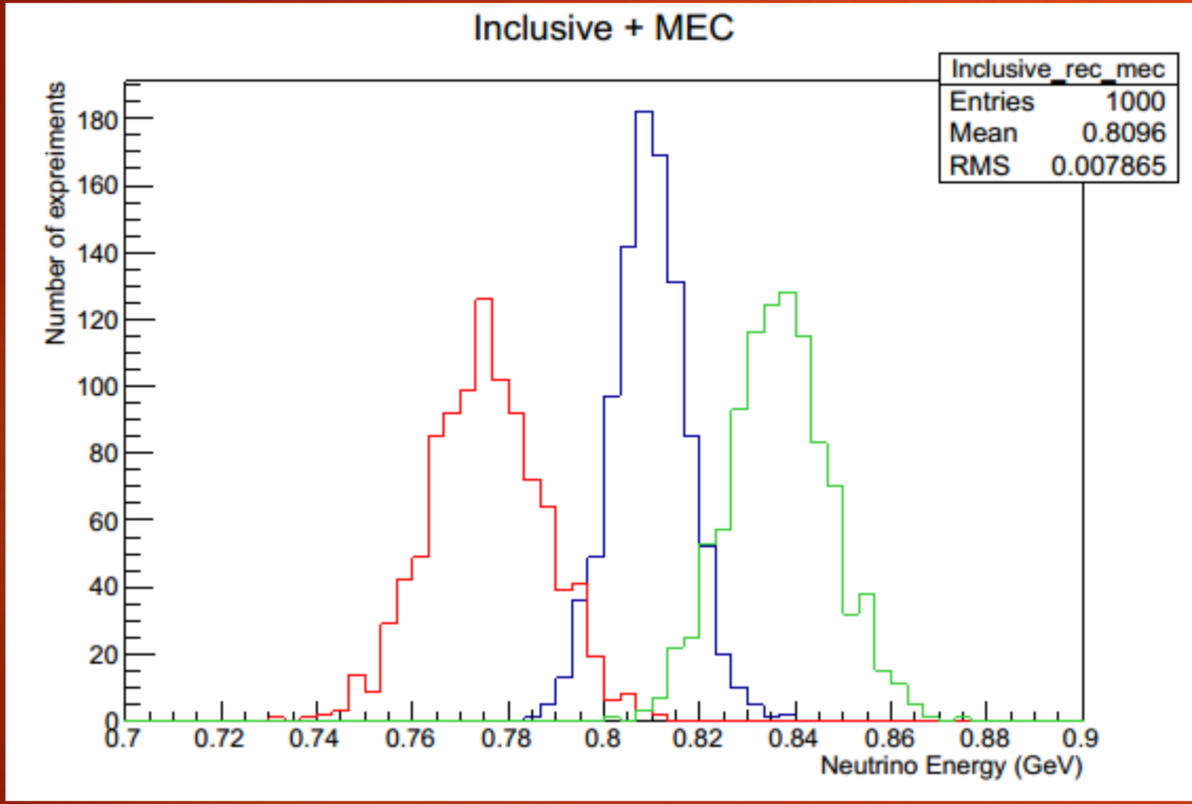
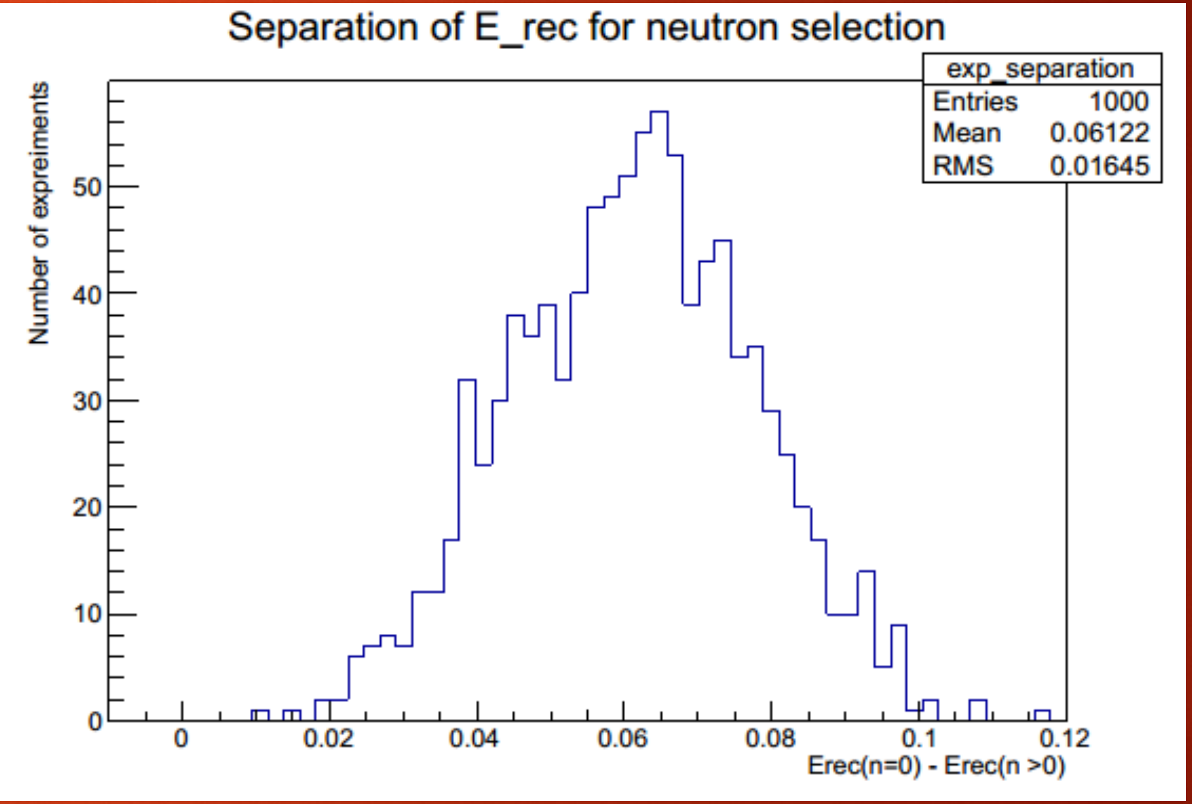
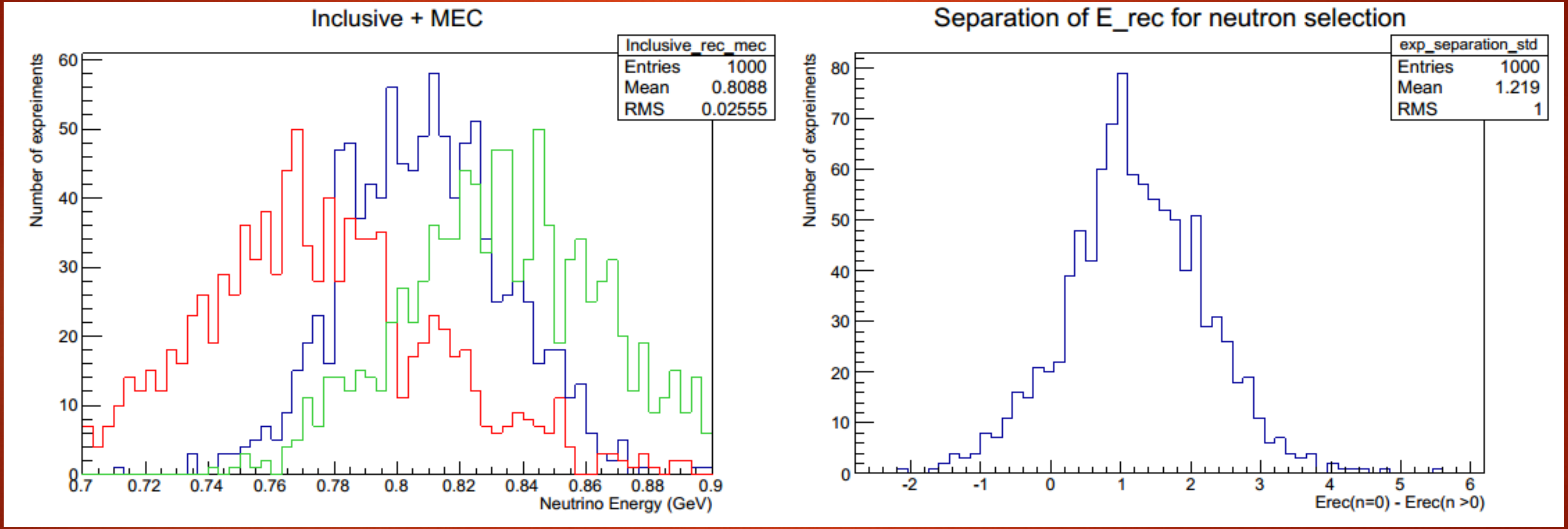




- np:nn = 4:1 n = ~8K, Statistical significant at >99%

Results of Statistical Analysis: Generator-Level

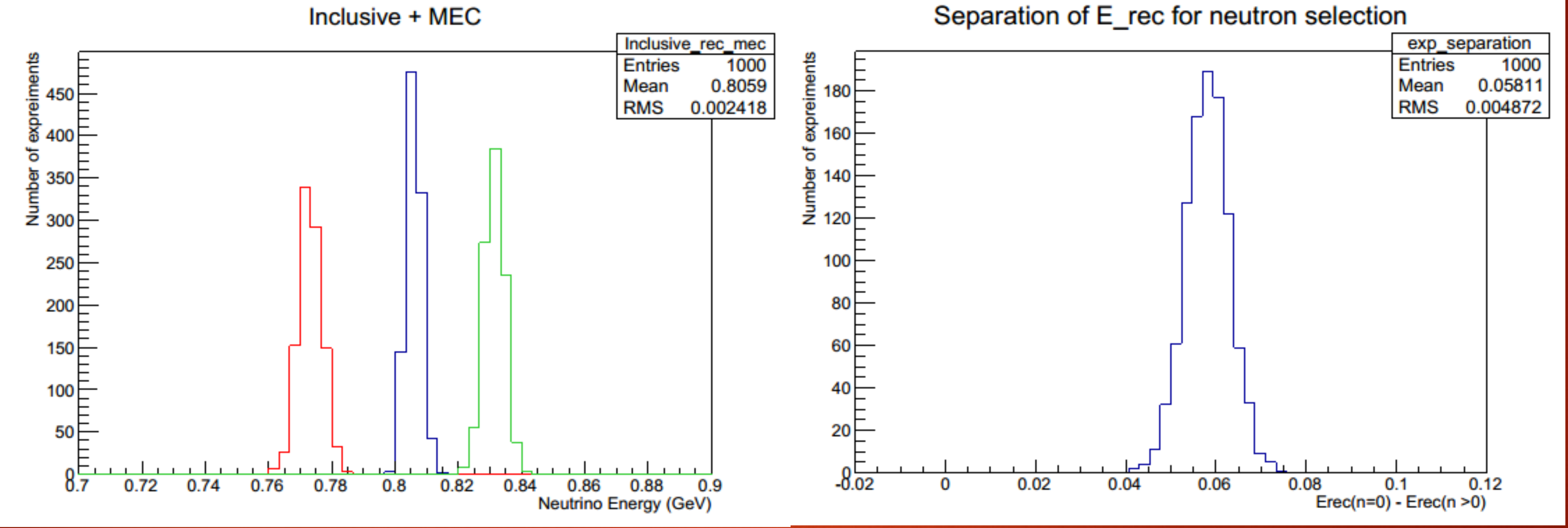
Red: N > 0, Green = 0, Blue = Inclusive



- np:nn = 4:1 n = ~800, only statistical significant at ~90%
- Alpha=0.05 Cutoff at around n = ~1600 (i.e. 9×10^{17} POTS)

Results of Statistical Analysis: Generator-Level

Red: N > 0, Green = 0, Blue = Inclusive



- np:nn = 10:1 n = ~80K, statistical significant > 99%
- Thus, increased energy reconstruction fidelity is possible across large range of MEC ratios!

Tentative Conclusions

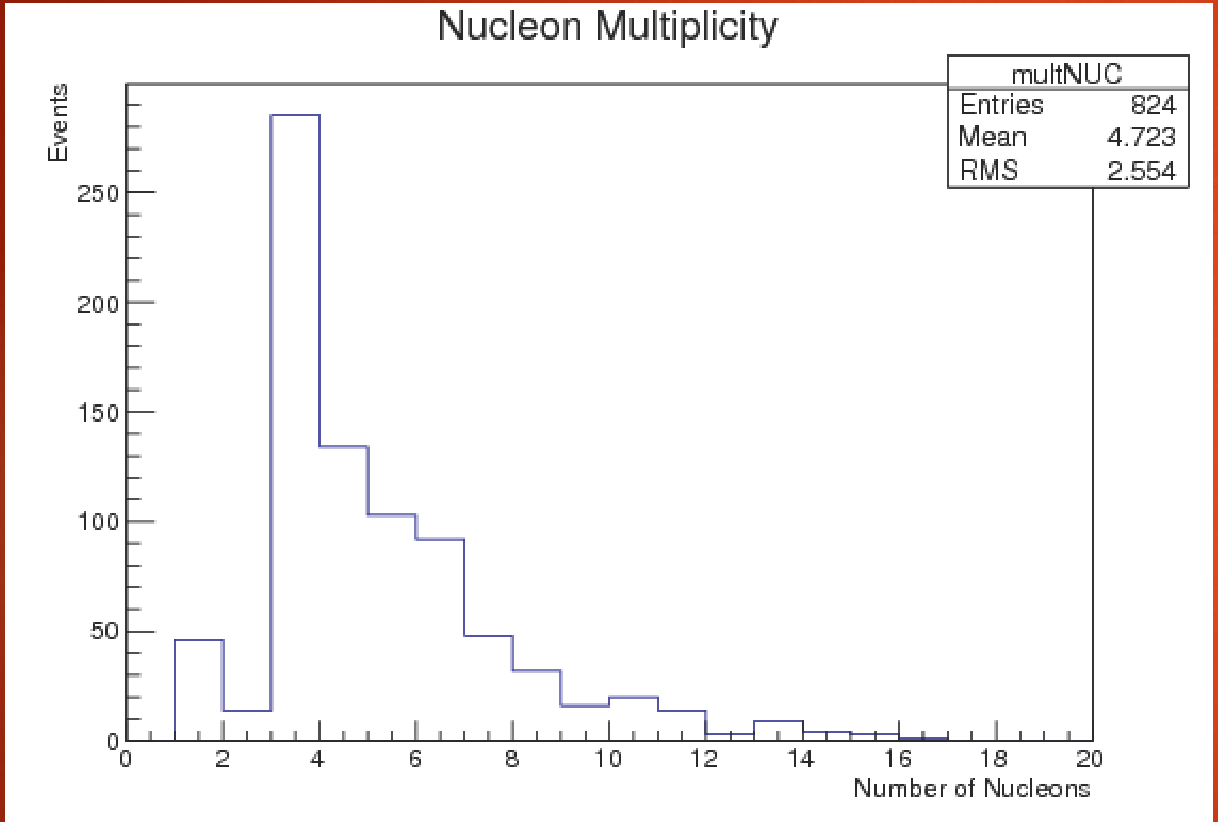
- Neutrino truth-level CCQE events are peaked at 0 final state neutrons
- Single pion production, deep inelastic scattering, and MEC are peaked at 1 or more final state neutrons
- Neutron tagging is most effective on stuck pion backgrounds
  - which typically produce neutrons and
  - have the largest biasing effect on the reconstructed energy distribution.
- ANNIE should be able to observe and demonstrate this effect with statistical significance

Open Questions and Potential Next Steps

- What impact does the n-p:n-n pair ration have on the analysis?
  - Can we potentially discriminate MEC ratios?
- What impact does the nuclear model have on the analysis?

- NEXT STEPS
  - Detector-level analysis
  - NP:NN pair analysis

Nucleon Multiplicity of Minor Backgrounds



Sample of Deep inelastic scattering and other processes with nuance code = 0.

Deep inelastic scattering and other minor inelastic processes make up ~10% of background and are beyond the scope of this study for now. However, they are observed to be peaked at 3 nucleons.

These constitute the remaining inelastic, non-MEC backgrounds observed.

Booster Neutrino Beam Flux