STT for Nuclear Effects

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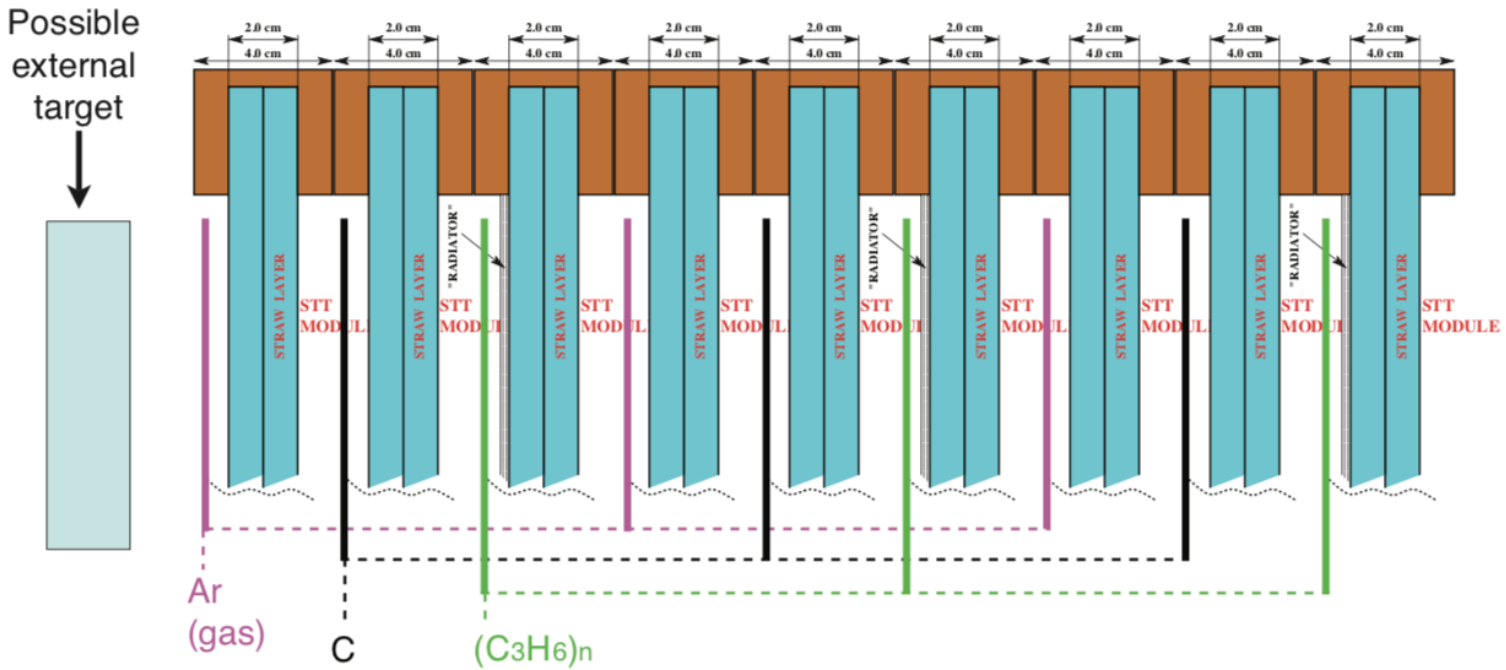
Introduction

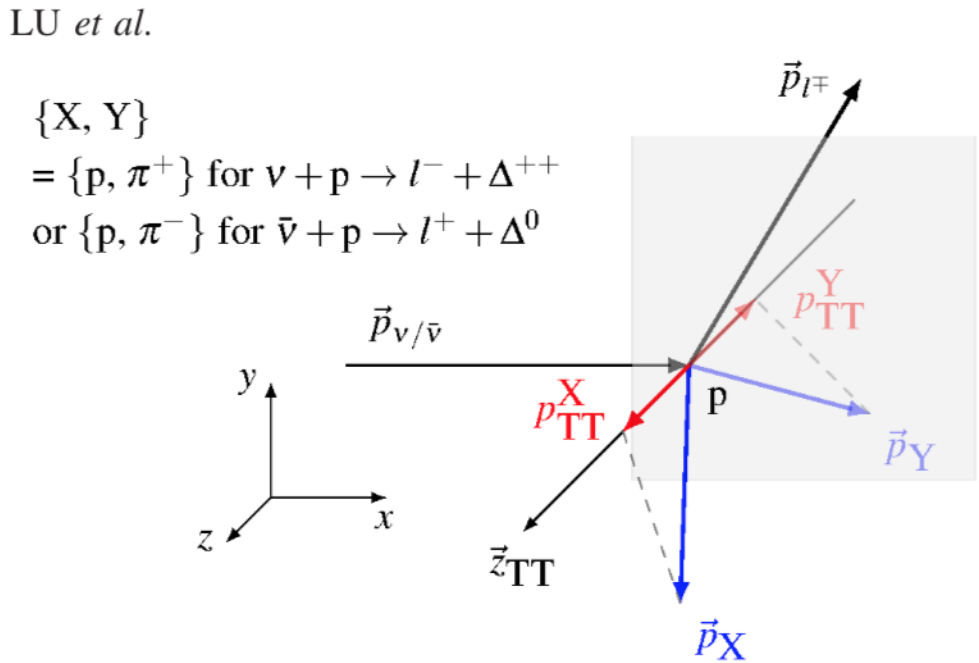
- Nuclear effects are important:
  - Neutrino energy reconstruction.
  - Can be different between neutrino and anti-neutrino.
  - Uncertainties to flux measurements.
- STT (CH2) is less affected by nuclear effects than Ar.
- STT has multiple nuclear targets and abundant free protons to constrain nuclear effects.

Nuclear Targets in STT



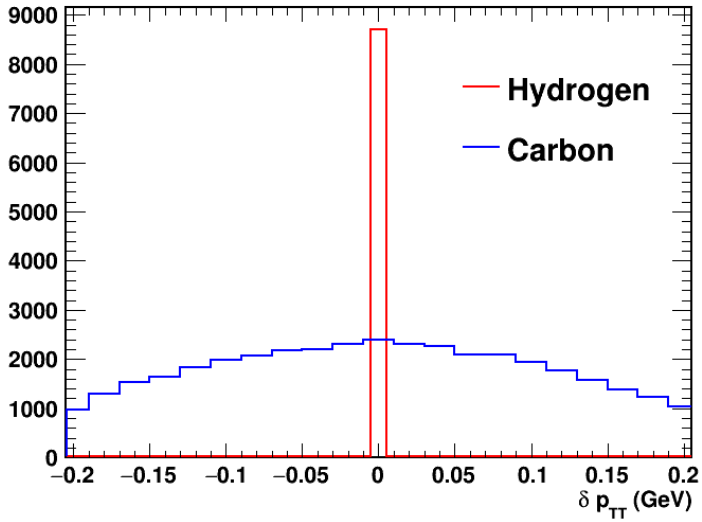
- Multiple nuclear targets can be implemented in STT: Ar, Ca, C etc.
- Subtraction of carbon from CH2 gives hydrogen target, free from nuclear effects.
- H and nuclear targets are subject to same detector response and flux uncertainties: the best way to identify/correct the bias caused by nuclear effects and reduce uncertainties.

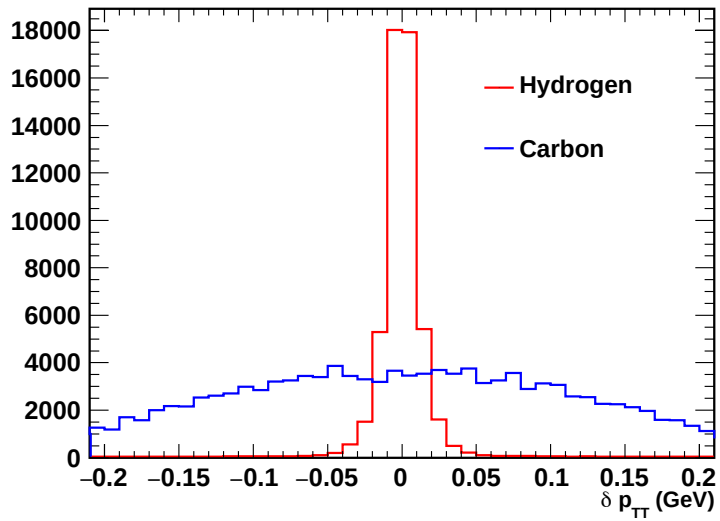
Method of Double-Transverse Kinematics



- The hadron momentum projections on the axis transverse to both neutrino and muon (double-transverse) should be balanced without nuclear effect.
- Nuclear effect causes imbalance by Fermi motion and final-state interactions.
- The imbalance δp_{TT} gives good separation power between hydrogen and nuclear targets.

Hydrogen Events Selection



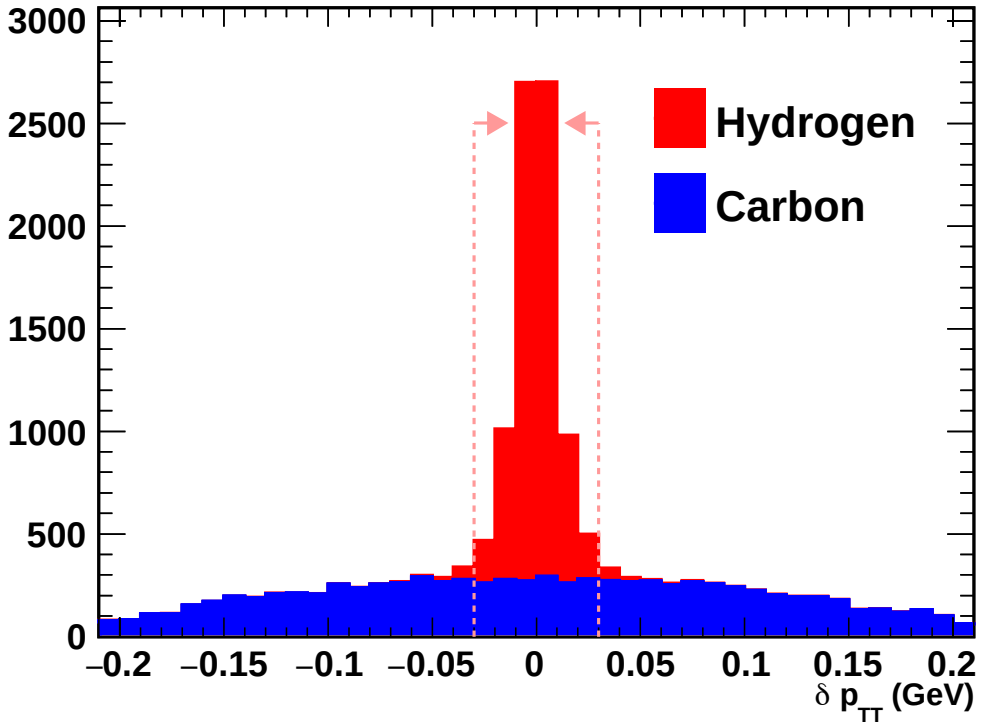


- Left: true δp_{TT}:
  - Hydrogen events peak at exactly zero.
  - The carbon events are smeared out because of Fermi motion and FSI.
- Right: reconstructed δp_{TT} (added threshold and smearing).
  - The reconstructed shape of H events is only detector effect.
  - Good resolution leads to tight cut to reduce background.

Topology and Statistics

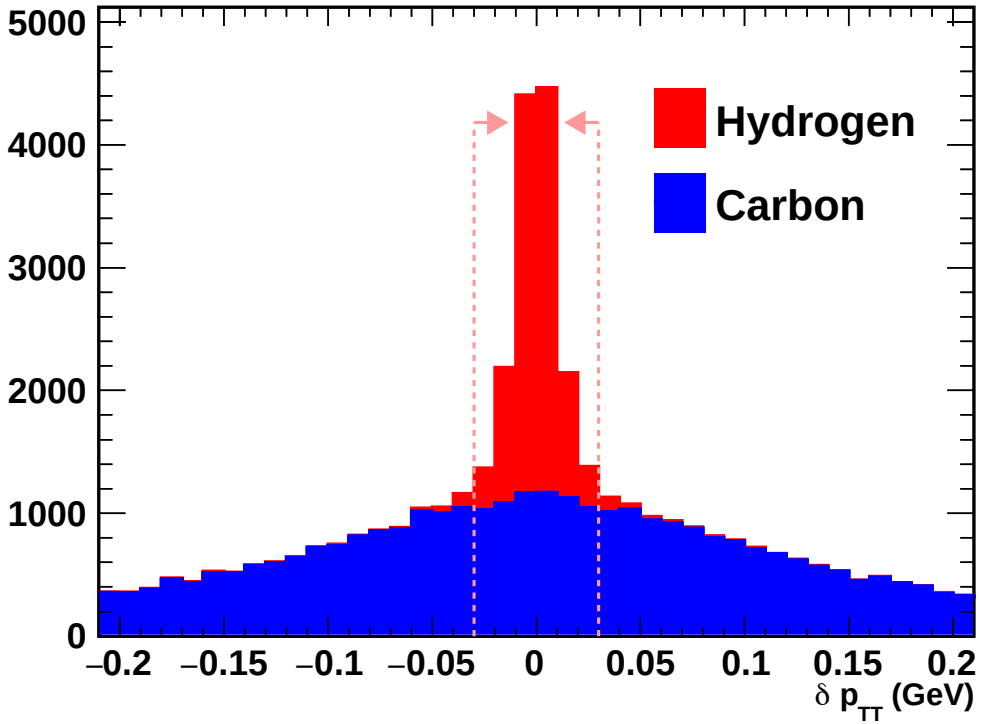
- Topologies:
  - FHC: ν_μ-CC Res ($\nu_\mu p \to \mu^- p \pi^+$).
  - RHC: $\bar{\nu}_\mu$-CC Res ($\bar{\nu}_\mu p \to \mu^+ p \pi^-$).
- Statistics, assuming 5 ton CH2, 5 year's running, 80 GeV beam:
  - 3.41 M ν_μ-CC, 1.88 M resonance in neutrino mode.
  - 2.76 M $\bar{\nu}_\mu$-CC, 1.62 M resonance in anti-neutrino mode.

Hydrogen Events Selection (FHC)



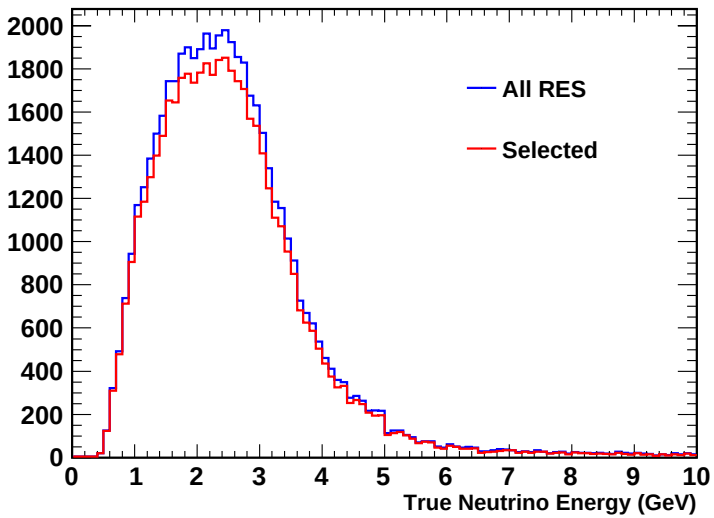
- Select 3-track ($\mu^- p \pi^+$) events with $W_{rec} < 1.4$ GeV (RES region).
- Signal region: $|\delta p_{TT}| < 0.03$ GeV.
  Background region: $|\delta p_{TT}| > 0.03$ GeV (sideband).
- Purity is $\sim$77% in signal region.

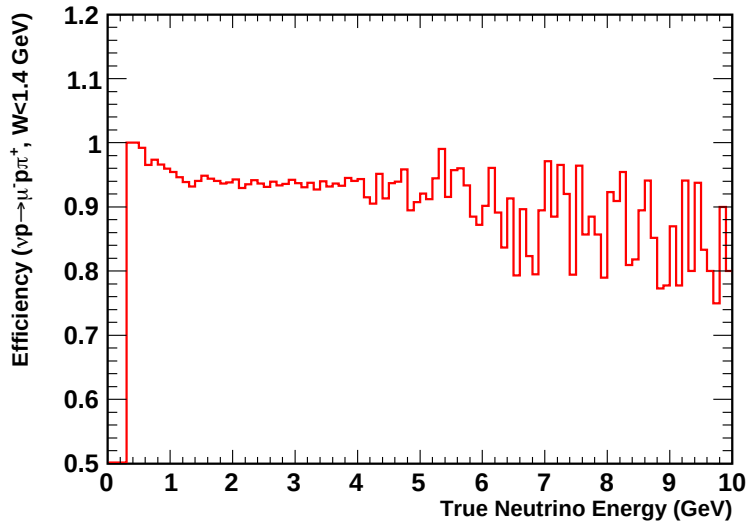
Hydrogen Events Selection (RHC)



- Select 3-track ($\mu^+ p \pi^-$) events with $W_{rec} < 1.4$ GeV (RES region).
- Signal region: $|\delta p_{TT}| < 0.03$ GeV.
  Background region: $|\delta p_{TT}| > 0.03$ GeV (sideband).
- Purity: 59%. Lower because there is another channel of RES ($\mu^+ n \pi^+$) not selected.

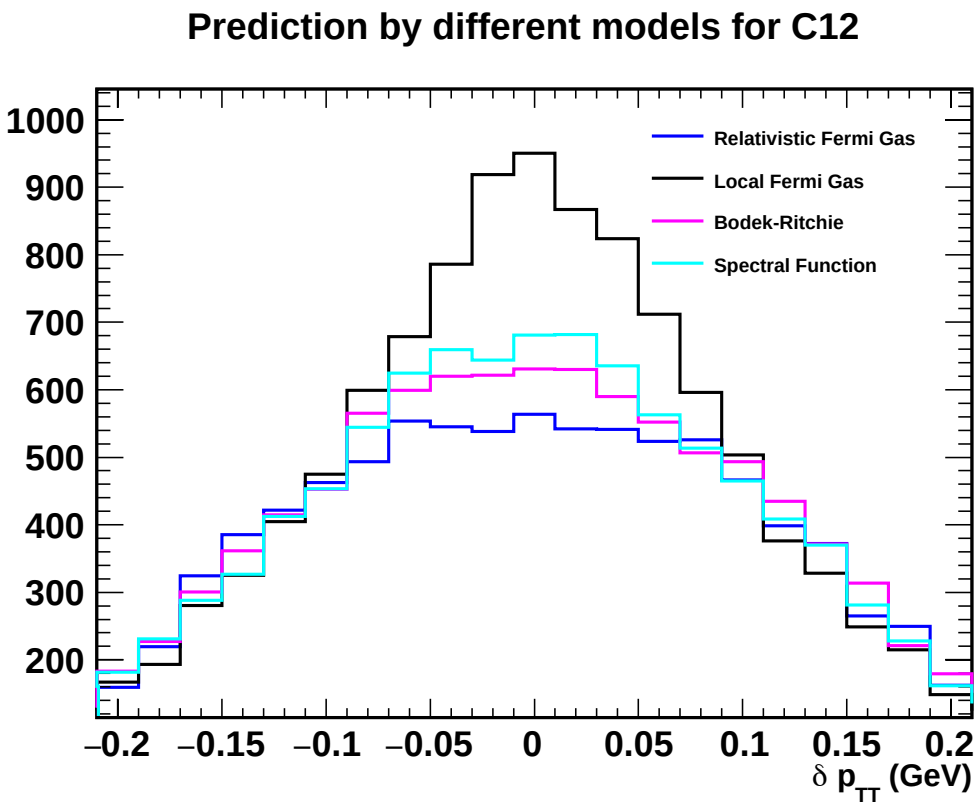
Selection Efficiency





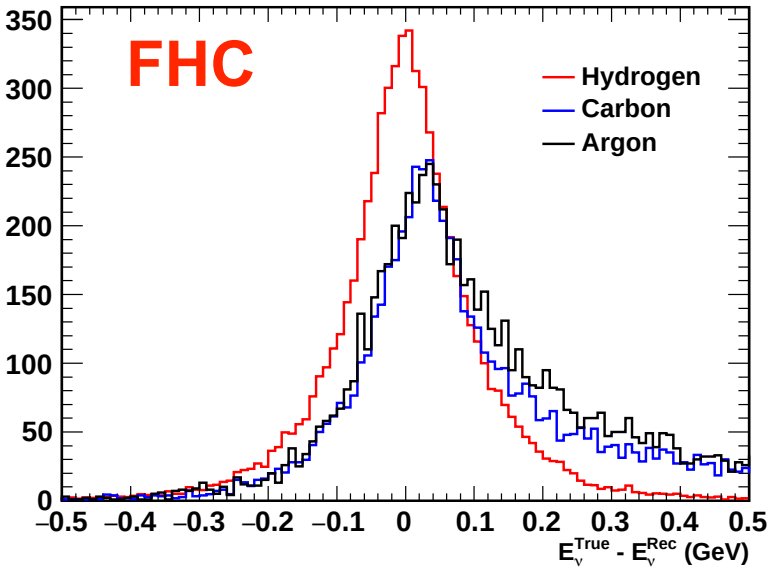
- The efficiency of selecting hydrogen RES events (true $W < 1.4$ GeV) is $\sim$94%, largely independent from incoming neutrino energy.

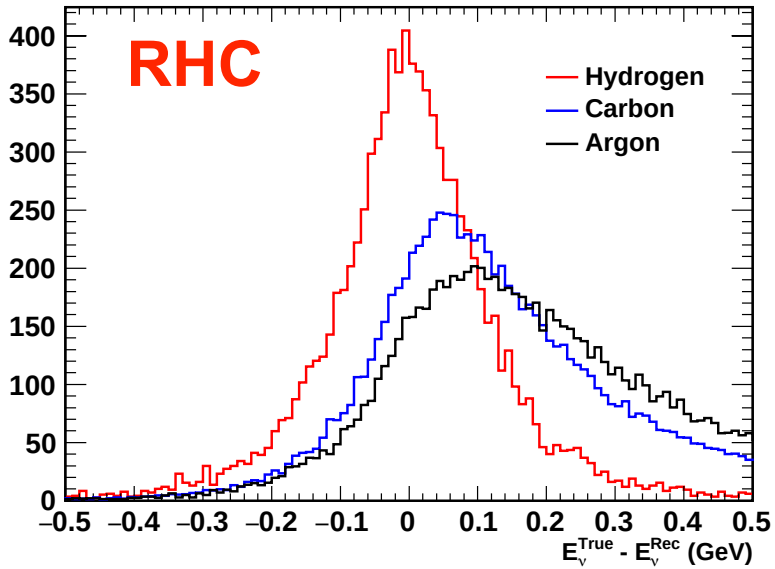
Model dependence of Background Shape



- The shape of carbon background is model-dependent.
- It is important to have dedicated carbon target (graphite) to measure the background shape.
- It also serve as a constraint on nuclear model itself.

Neutrino Energy Reconstruction

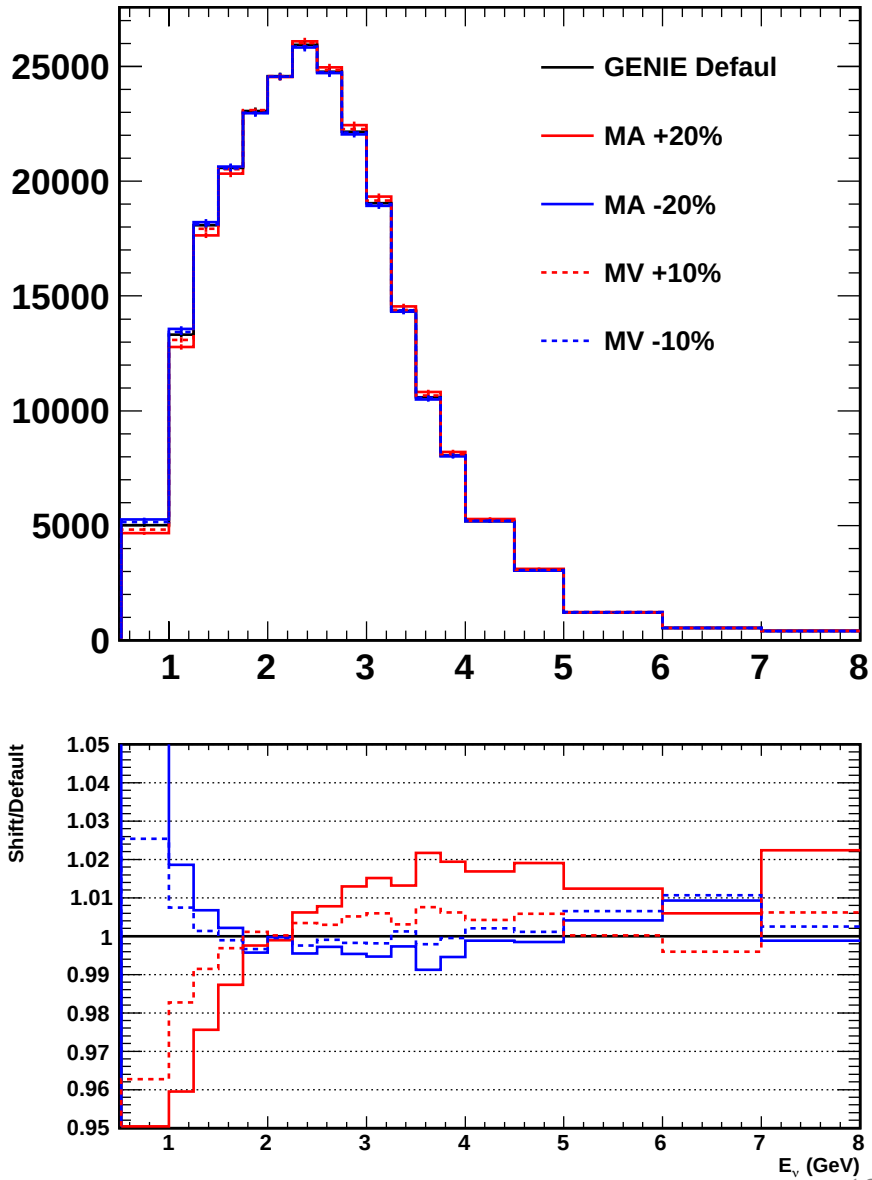




- Left: neutrino mode; Right: anti-neutrino mode.
- The hydrogen sample provide a method of reconstructing E_ν independent from nuclear effect.
- The carbon events show a difference between E_ν^{rec} and E_ν^{true}, which depends on the nuclear model used.
- Nuclear effect for Ar is even larger than carbon, especially in anti-neutrino mode.

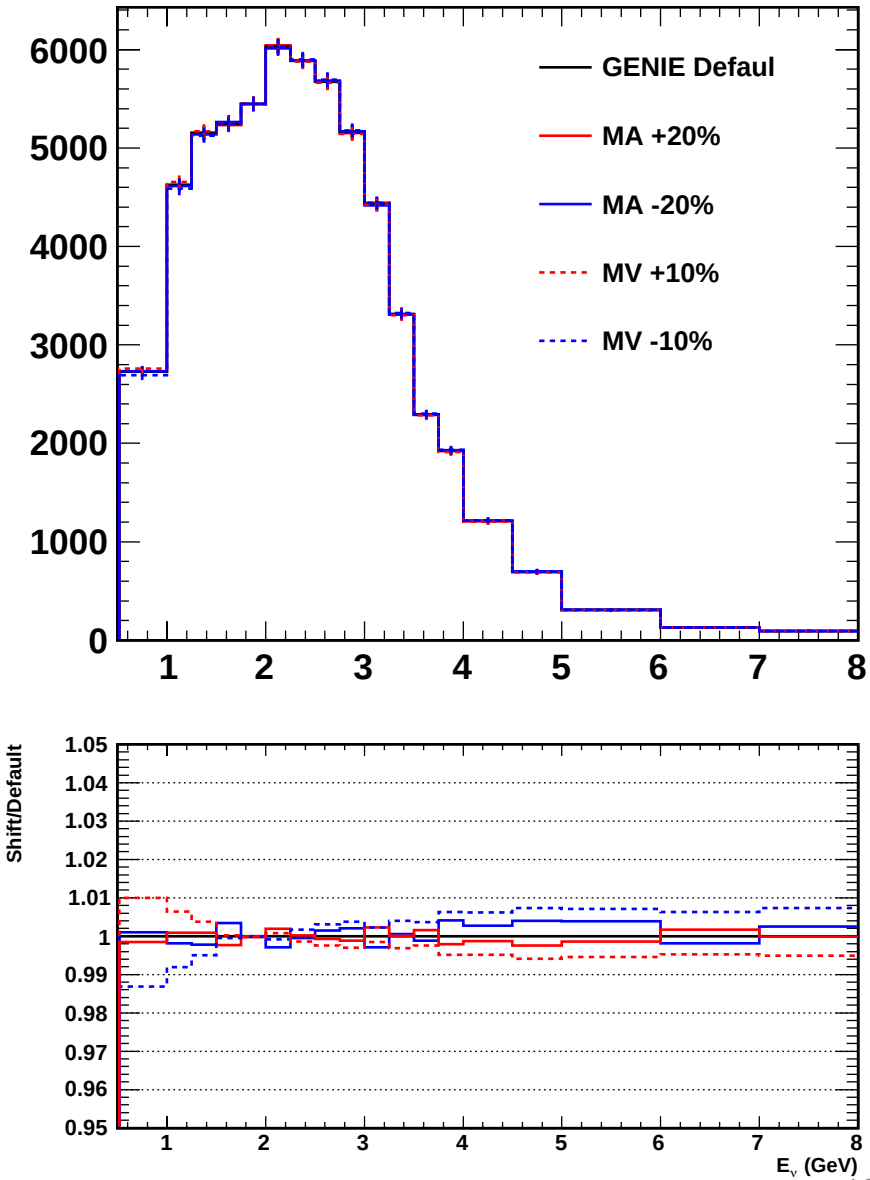
$\nu-$H Cross Section

- The cross section of $\nu-$H interactions are relatively better understood than nuclear targets.
- Changing MA and MV (Rein-Seghal RES model) doesn't change the E_ν shape much.

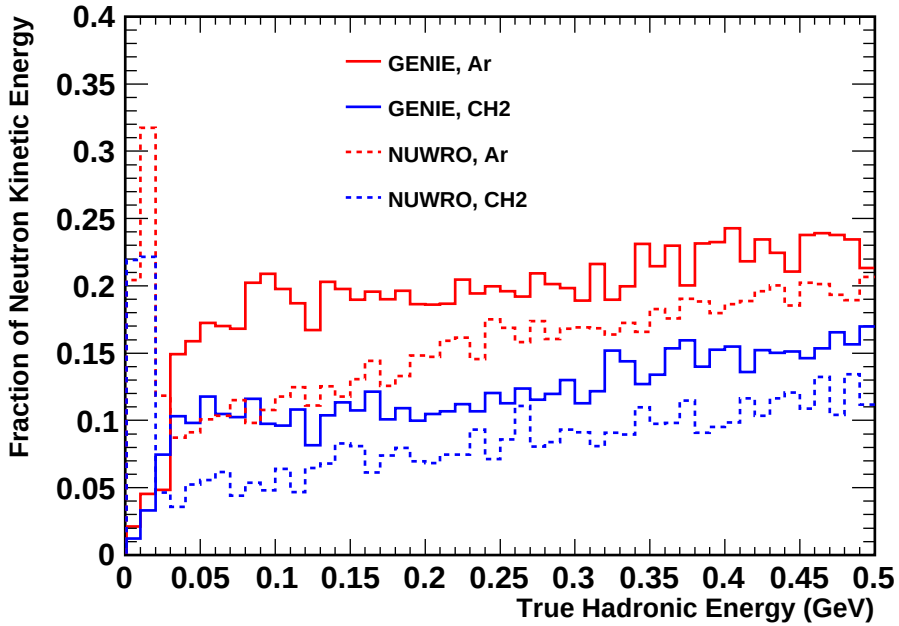


ν−H Cross Section ($\nu < 0.5$ GeV)

- Cut on ν (E_{Had}) significantly reduces the xsec uncertainties.
- There is no ambiguity in ν cut caused by neutrons.
- Efficiency is $\sim 25\%$ with $\nu < 0.5$GeV cut, 0.4 M events enough for a measurement.
- It potentially provides another channel to constrain the neutrino flux.

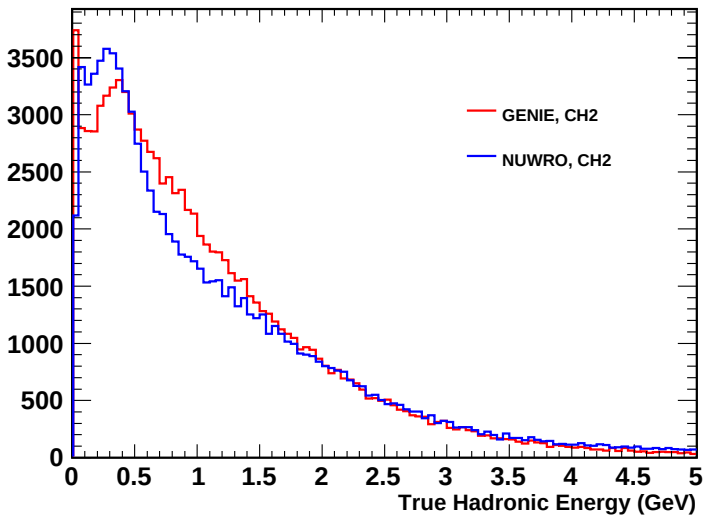


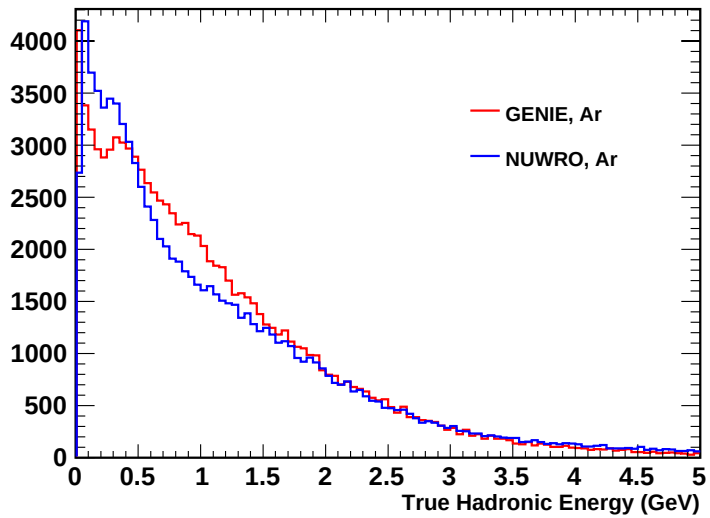
ν (E_{Had}) in Nuclear Targets



- In nuclear targets (C, Ar) a fraction of hadronic energy is carried by neutron.
- The fraction is larger in Ar than C.
- 90%-95% of the neutrons are from FSI, which is much larger in Ar.
- GENIE and NUWRO give very different predictions of neutrons.

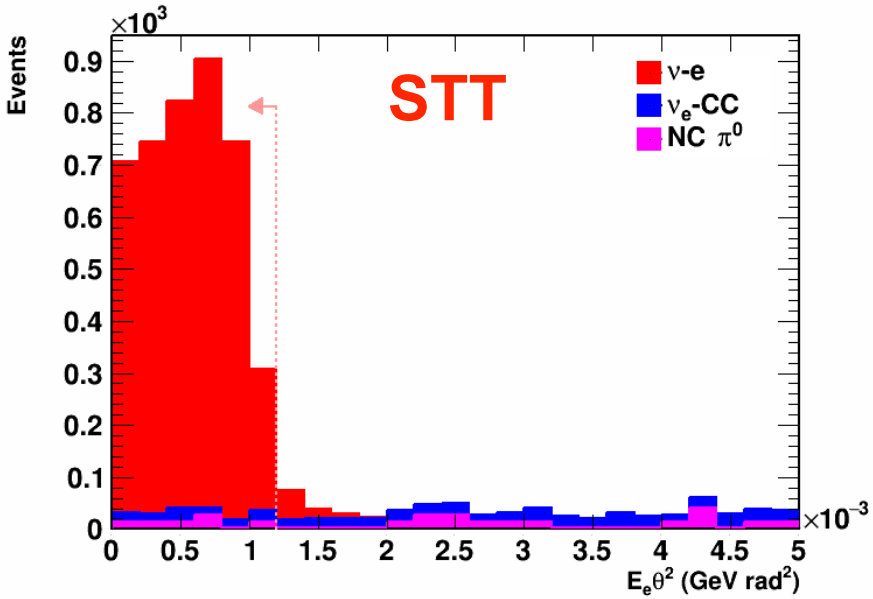
ν (E_{Had}) in Nuclear Targets

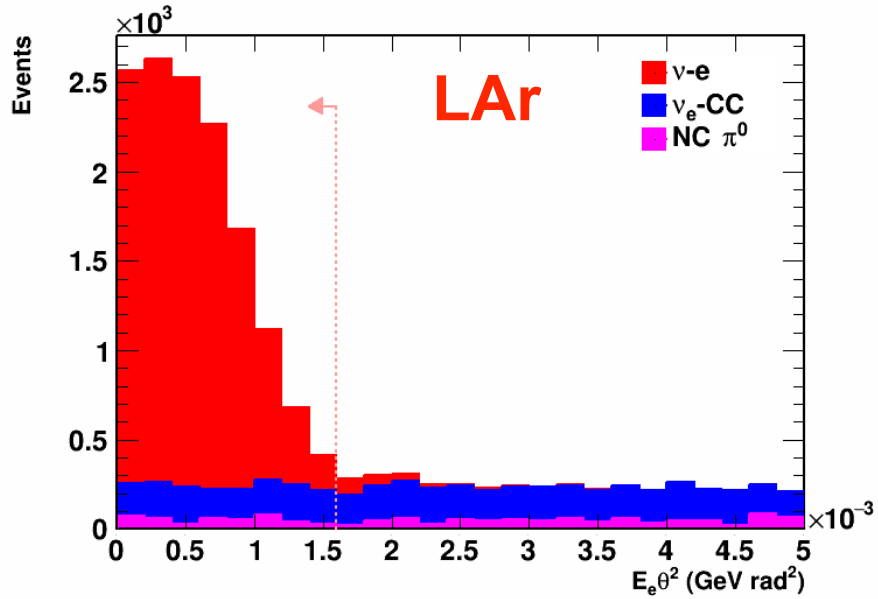




- GENIE and NUWRO give very different predictions of hadronic energy (ν), mostly due to nuclear effects.

Nuclear Effects and ν-e





- A large number of background to ν-e comes from nuclear effects (ν_e-CC with no visible proton), which is considerably larger in Ar than CH2.
- STT provides low-systematic ν-e measurement itself. The uncertainty is statistic-dominant (1.6%).
- STT also constrains nuclear effects to reduce the systematic uncertainty in LAr ν-$e$measurement, where the systematic uncertainty will be dominant (stat uncertainty on rate $<$1%).

Summary

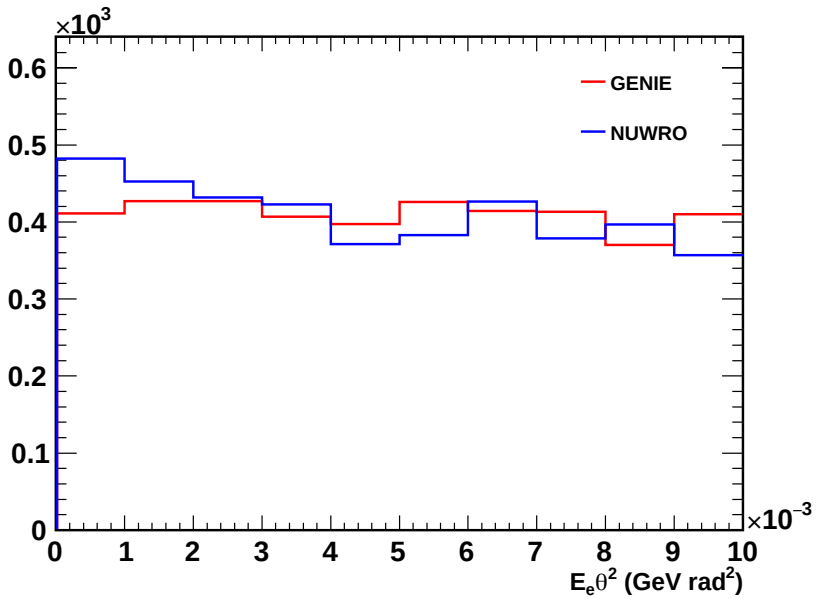
- Nuclear effects are important, especially because we use LAr.
- STT itself provides measurements less affected by nuclear effects.
- STT constrains nuclear effect by multiple nuclear targets (Ar, Ca, C...) and hydrogen, complementary to LAr measurements.
- Hydrogen is potentially a powerful tool for various studies.

Back up slides

STT Hydrogen Study

- STT performance:
  - Momentum resolution: 5%.
  - Angular resolution: 2 mrad.
  - Proton momentum threshold: 200 MeV.
  - π^+ momentum threshold: 70 MeV.
- Statistics:
  - 5 ton CH2, 5 year's running, 80 GeV beam: 3.41 M ν_μ-CC (1.88 M resonance) on hydrogen.
- This talk focus on resonance $\nu_\mu p \to \mu^- p \pi^+$ in neutrino mode (FHC).
  - Use NuWro as generator.
  - 100k CH2 event sample (mockdata).
  - Independent H and C12 samples (using same model as CH2)
  - Perform a test of signal and background normalization.

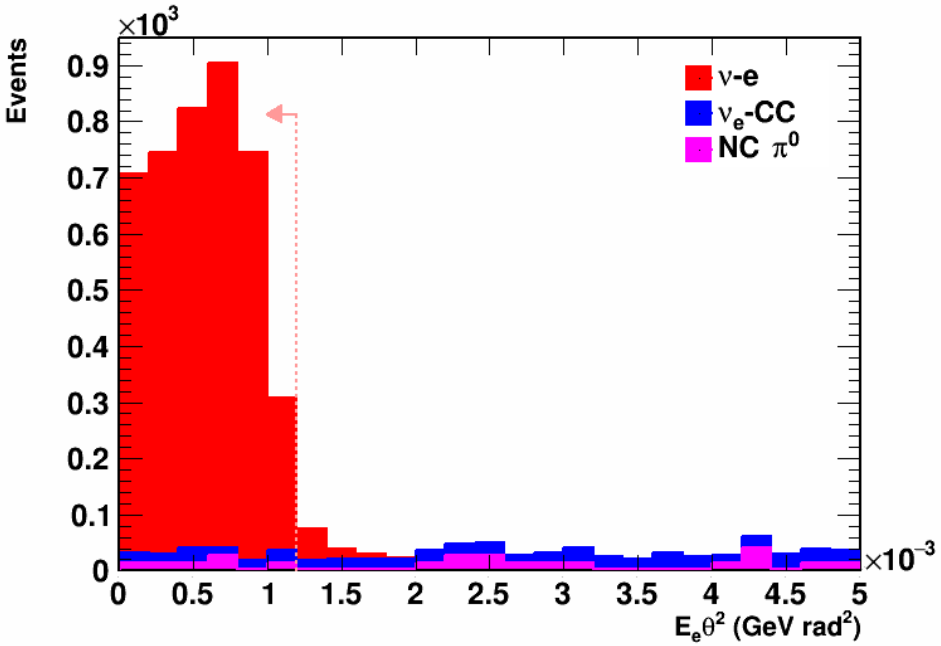
ν-e Background Shape



- Background (QE) shape differs between generators/models.

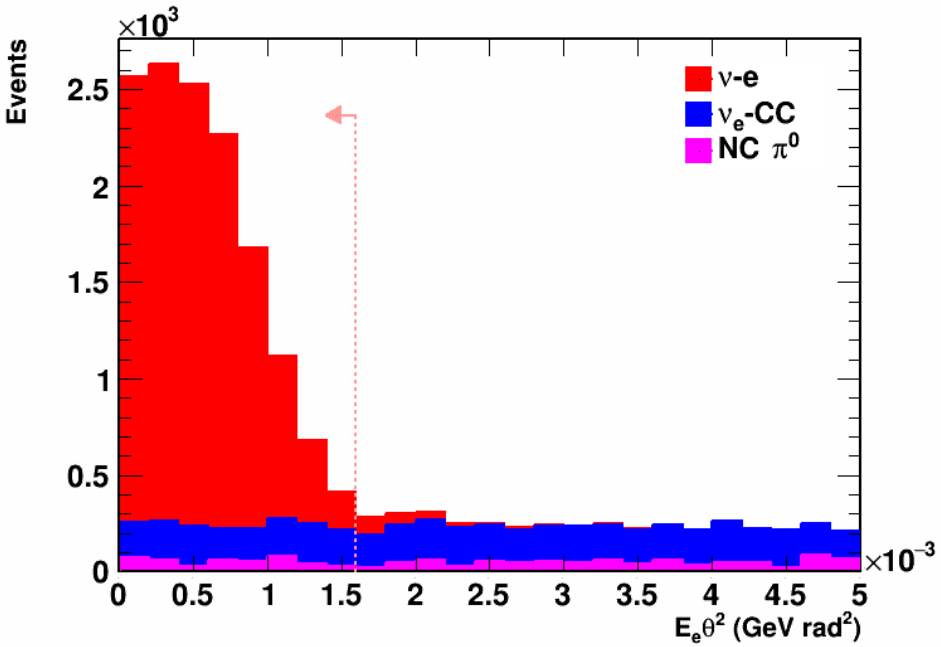
Background to ν-e (STT, 5 ton)

- Total statistics: 4.5k.
- E_e >0.15 GeV
- ν_e background:
  - No charged hadrons with kinetic energy >10 MeV.
  - No additional π^0 or γ.
- π^0 background:
  - At least one photon convert in STT.
  - Only one electron with $E_e > 150$ MeV.
  - Energy of the positrons/the other electron/the photon which doesn't convert < 50 MeV.
- Cut at $E\theta^2$ <0.0012 with 98% signal efficiency.
- Total background is $\sim$ 5%:
  - ν_e-CC: $\sim$ 3%



Background to ν-e (LAr, 25 ton)

- Total statistics: 17.7k.
- E_e >0.5 GeV
- ν_e background:
  - Total KE of charged hadrons E_{Had} <20 MeV.
  - No additional π^0 or γ
- π^0 background:
  - Second photon $E_\gamma < 50$ MeV.
  - Suppressed by 0.1 to account for e/γ separation
- Cut at $E\theta^2$ <0.0016 with 98% signal efficiency.
- Total background is 14%
  - ν_e-CC: 11%
  - NC-π^0: 3%



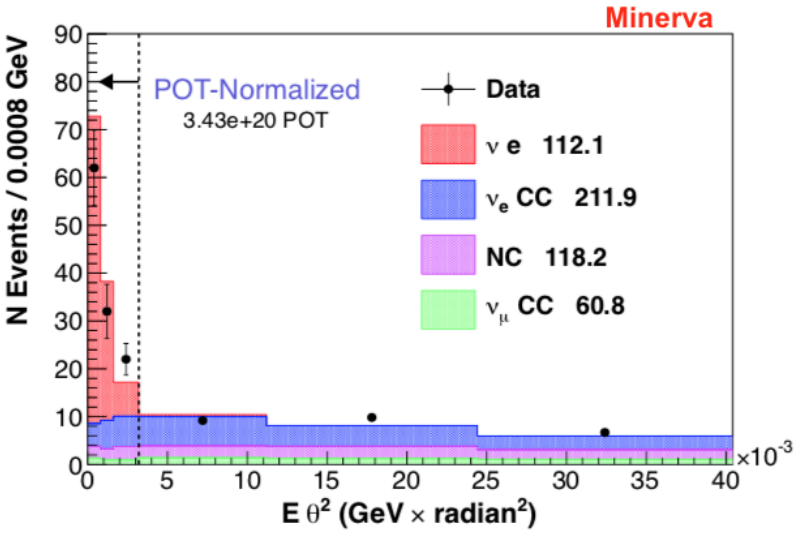
Why is the difference?

- CH2 has larger electron/nucleon ratio (8:14) than Ar (18:40): **27%** less ν-N interactions in STT to start with.
- The ν_e-CC background is greatly affected by **nuclear effects** (nucleon/pion absorption/inelastic-scattering), which is significantly larger in Ar than CH2. Ar has **40%** more ν_e-CC with no visible hardrons than CH2 according to GENIE!
- Better Angular resolution in STT leads to tighter $E\theta^2$ cut (1.2 vs 1.6 $\times 10^{-3} GeVmrad^2$): **25%** less background.
- The rest difference is because of different detector responses to charged hadrons and π^0s.

Background Uncertainty

- Statistical uncertainty on rate:
  - LAr (25 ton): 11933 events selected $\rightarrow$ 0.9%.
  - STT (5 ton): 4162 events selected $\rightarrow$ 1.6%.
- Background uncertainty: We need $\sim 7\%$ uncertainty on background modeling for 1% on ν-e (Minerva has 20/17% on QE/π^0))
- Other systematic sources like electron energy scale, reconstruction efficiency not yet included (1.8% and 2.7% in Minerva!).
- Systematic uncertainty is not negligible in DUNE ND ν-e measurement, and even dominates in the case of LAr.

Background Uncertainty



Minerva

Source	Fractional Uncertainty
Flux (simulated background)	0.2%
GENIE (not including CCQE)	2.3%
CCQE shape	3.1%
Beam angle	0.2%
Electromagnetic energy scale	1.8%
Reconstruction Efficiency	2.7%
Total Systematic Uncertainty	5.1%
Statistical Uncertainty	12.2%

- Quantitatively estimate the systematic uncertainty caused by background is difficult, depending upon exactly how to constrain the background.
- It might be illustrative to look at Minerva uncertainties on backgrounds (22% in signal region), constrained by 2 sidebands ($E\theta^2$ and dE/dx):
  - $\sim$ 21% on the CCQE shape
  - $\sim$ 17% on other background (π^0s).