Tau appearance search in MINOS+

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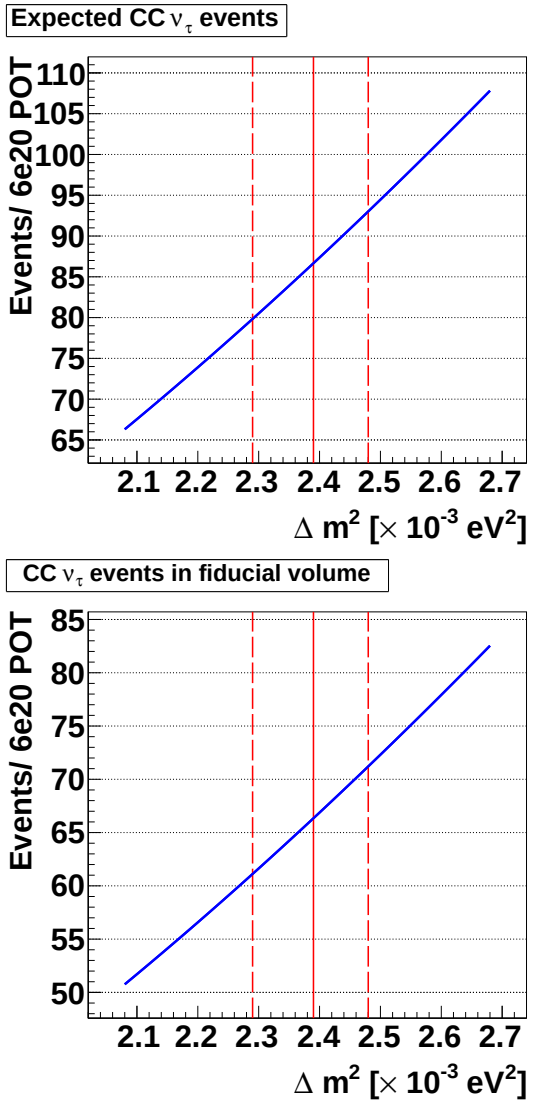
The setup

- I looked for possibilities of ν_τ appearance observation in MINOS+ (and MINOS) using Far Detector MC files (FHC only)
  - M000200N_NOVA, daikon_10, dogwood5, standard ntuples (.sntp)
  - 1467 subruns in tau files - corresponding to 9.54×10^{23} POT
  - 296 subruns in muon files - corresponding to 1.92×10^{23} POT
- I assumed two-flavor oscillation with the parameters from latest MINOS fits ($\sin^2 2\theta = 0.96 \pm 0.04$ and $\Delta m^2 = 2.39^{+0.09}_{-0.10}$ eV^2)
  - All following plots are oscillation weighted
  - No differentiation between neutrinos and antineutrinos

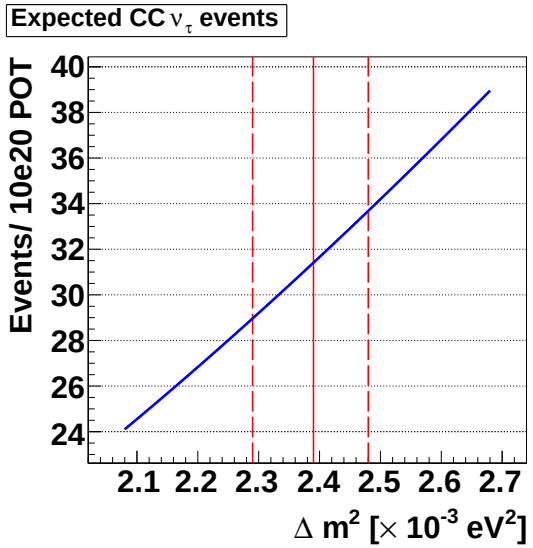
Number of expected events

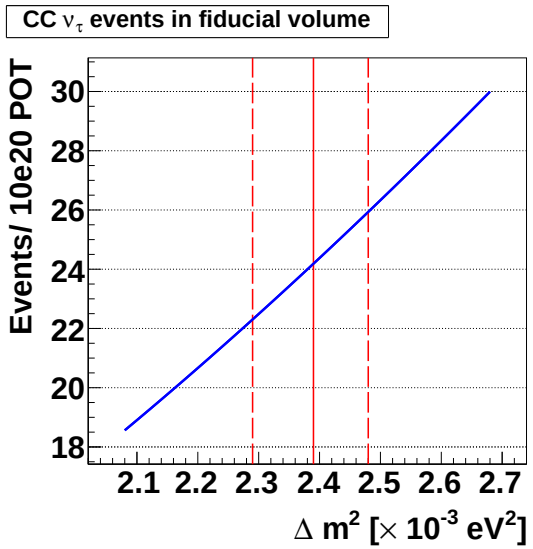
- MINOS+ event numbers are normalized for 6×10^{20} POT (planned 1-year statistics)
- 86.7 CC ν_τ events expected in the whole detector volume
- 66.5 CC ν_τ events expected in fiducial volume
- Δm^2 uncertainty leads to an error of $\sim 10\%$ and $\sin^2 2\theta$ uncertainty to $\sim 4\%$



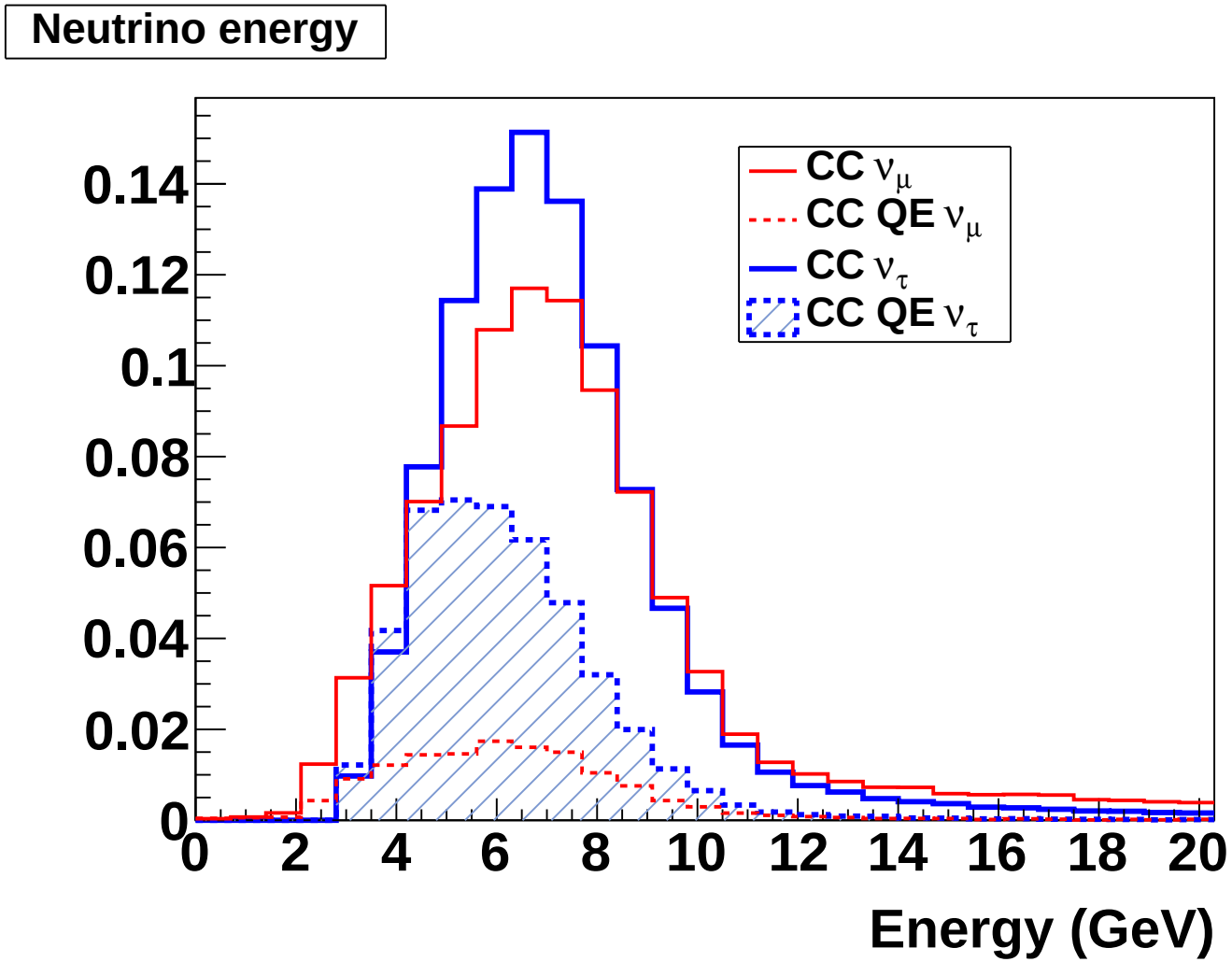
Comparison with MINOS

- For comparison: MINOS evt numbers for 10×10^{20} POT (almost whole FHC beam statistics)
- 31.5 CC ν_τ events expected in the whole detector volume
- 24.2 CC ν_τ events expected in fiducial volume





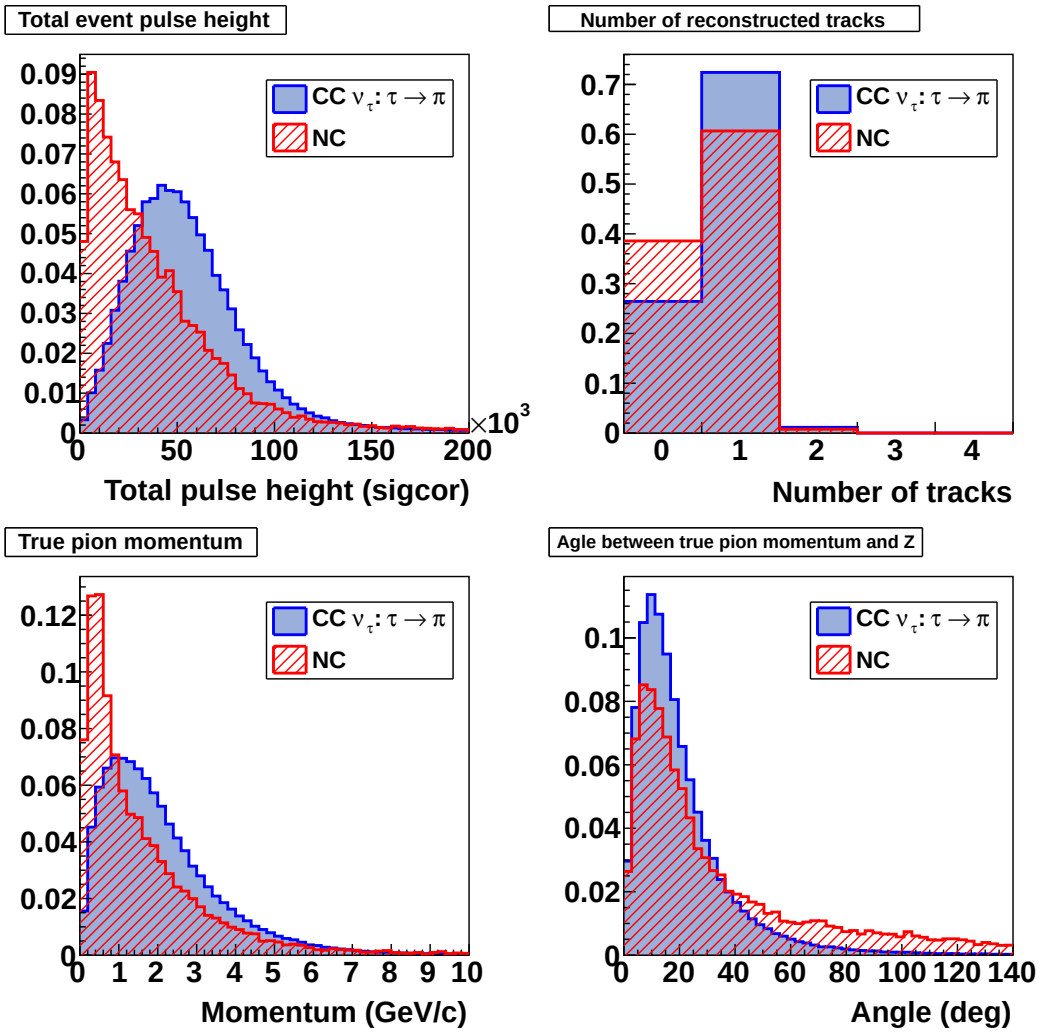
Neutrino energies at MINOS+



CC ν_μ and CC ν_τ event numbers are area-normalized

Hadron channel analysis

- Definition: charged pions among tau children (actually pion channel)
- 41.4 events expected (per year) in fiducial volume (BR: ∼62%)
- Main background from NC (1626 evts in fid vol)
- CC ν_τ evts differ from NC in total PH and reconstructed track number
- Slight differences in pion kinematics

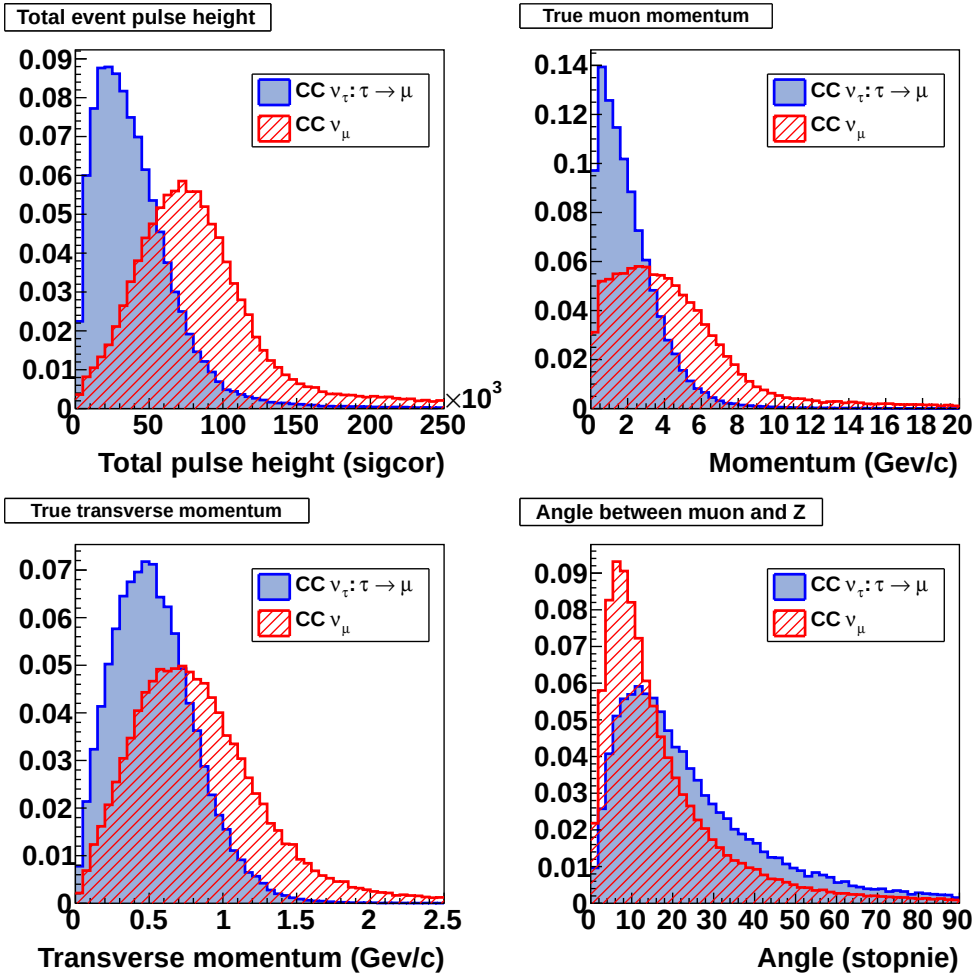


Hadron channel – summary

- Largest signal events number and pretty good S/B ratio
- Two variables with decent signal-background separation
- Pion kinematic variables:
  - Visual scanning results (DocDB-9106) shows that $\sim$25% of hadron channel CC ν_τ events have a visible pion track
  - Track reconstruction algorithm is optimized for muons
  - Reconstructed pion tracks have poor quality
- Room for improvement: more sophisticated identification variables based on event topology

Muon channel analysis

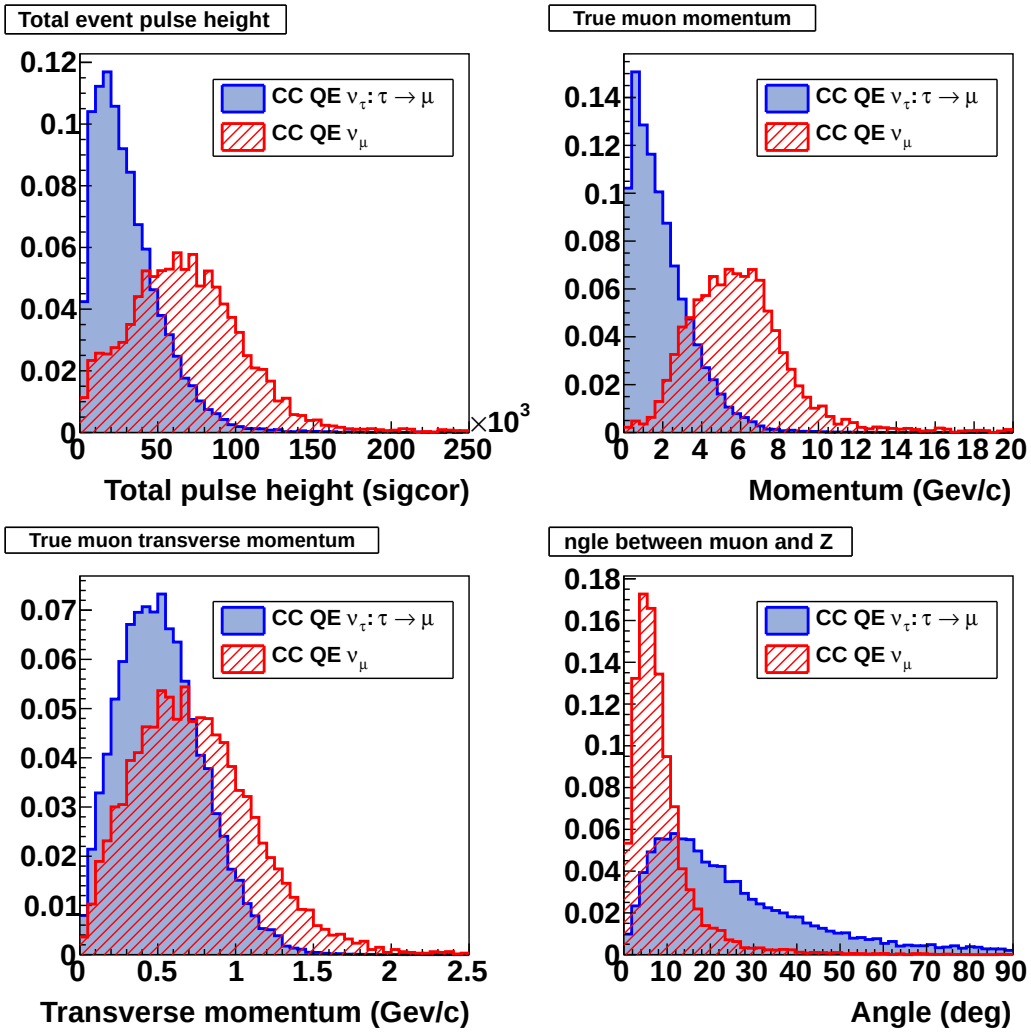
- Definition: muons among tau children
- 11,6 events expected (per year) in fiducial volume (BR: ∼17%)
- Huge background from CC ν_μ (4740 evts in fid vol)
- Significant differences in total event PH and true muon kinematics



Muon channel – QE subsample

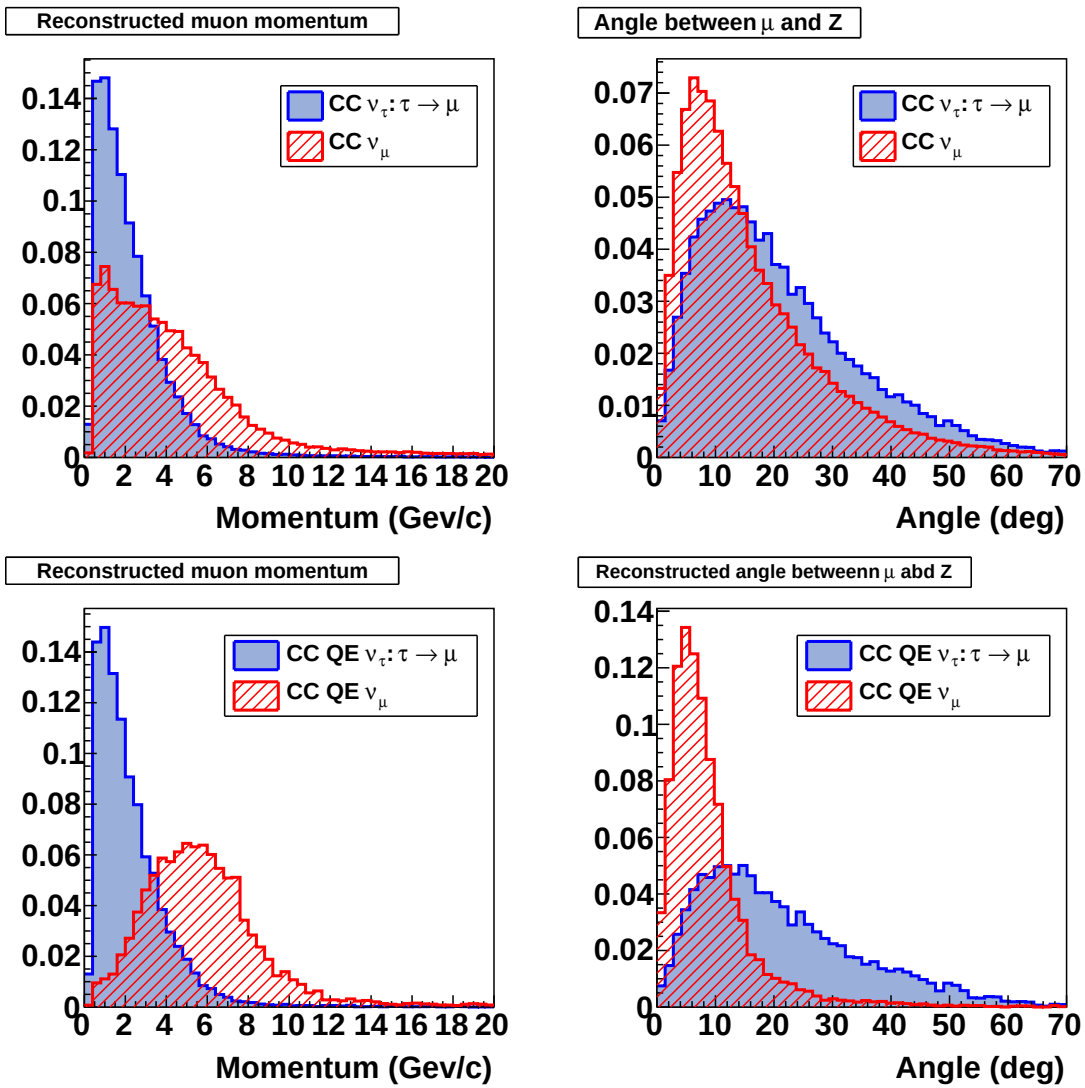
For QE interactions:

- Better S-B separation (less low energy muons from true CCQE ν_μ events)
- Better S/B ratio but less signal event
  - 4.13 CCQE ν_τ evts (36% of all CC)
  - 444 CCQE ν_μ ($\sim$9% of all CC)



Muon channel – reconstructed variables

- Assume ideal muon track selection
- Reconstructed kinematic variables don't differ much from true ones
  - First row: all CC events
  - Second row: true CCQE events



Muon channel – summary

- Good S-B separation in total PH and muon kinematic variables
- Muons are well reconstructed and with good efficiency
- Very low signal rate and S/B ratio
- For QE interactions the separation and S/B ratio are better but signal events become very scarce

CC ν_τ from muon channel selection

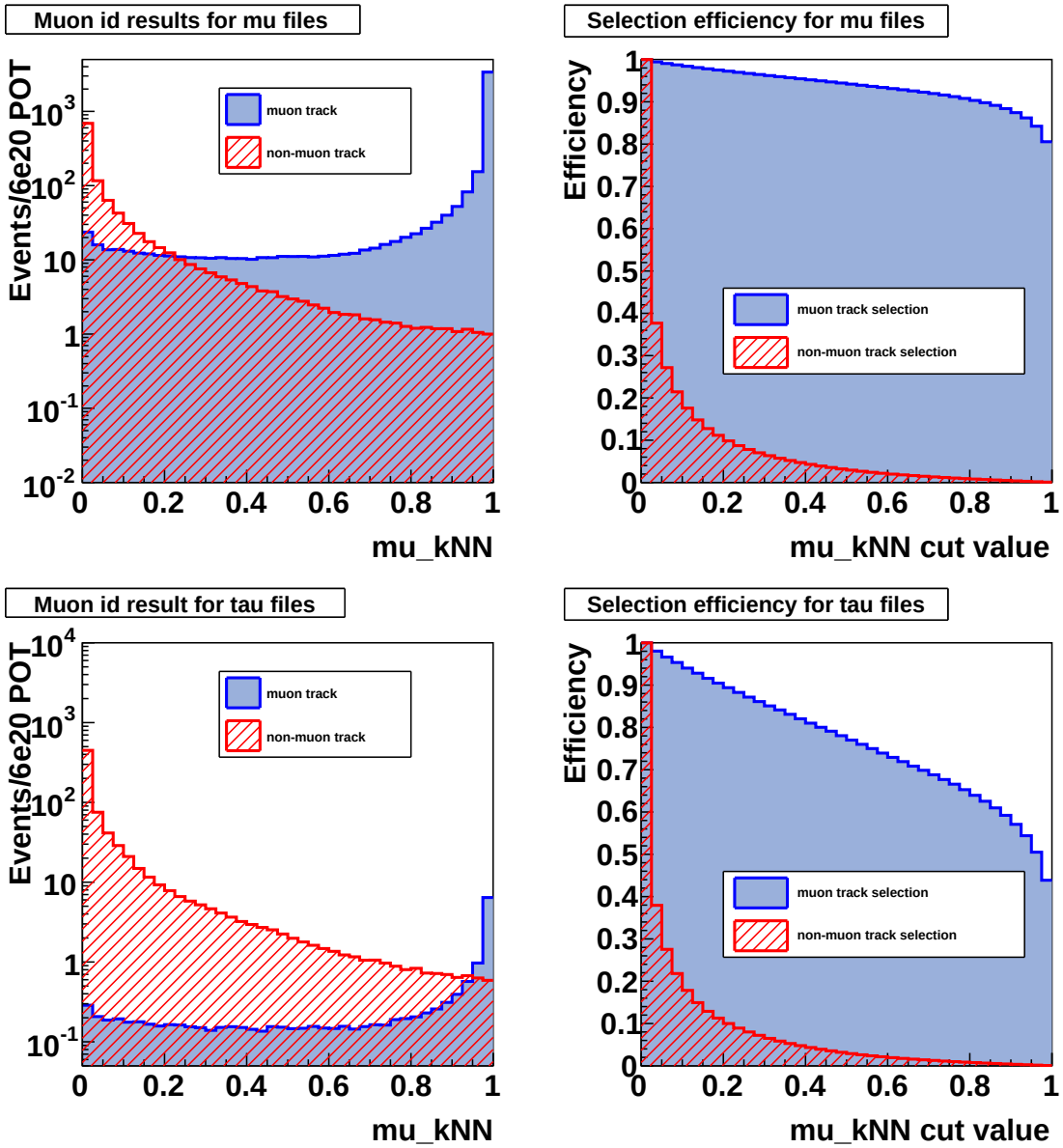
- Simple algorithm for selection of CC ν_τ events in which the tau decays into muon
- Done in four steps:
  - Preselection cuts
  - Muon tracks identification (Rustem's kNN)
  - Muon track id and QE-like selection cuts
  - CC ν_τ selection (also kNN based)

Preselection cuts and muon track identification

- $\sim$ 82% of CC ν_τ events from the muon channel have a reconstructed muon track (more than half hits comes from the muon)
- Preselection cuts:
  - Event vertex contained in fiducial volume (from CC analysis) – rejects $\sim$ 23% of all events
  - Track has to cross at least 10 scintillator planes – rejects $\sim$ 5% of signal events
- I implemented Rustem's kNN identification algorithm for .sntp files using ROOT with TMVA
  - The variables definitions are the same as in original PhD thesis
  - The number of nearest neighbors is $k = 80$
- No additional low-energy muon track identification (like Jasmine's)

Muon track identification results

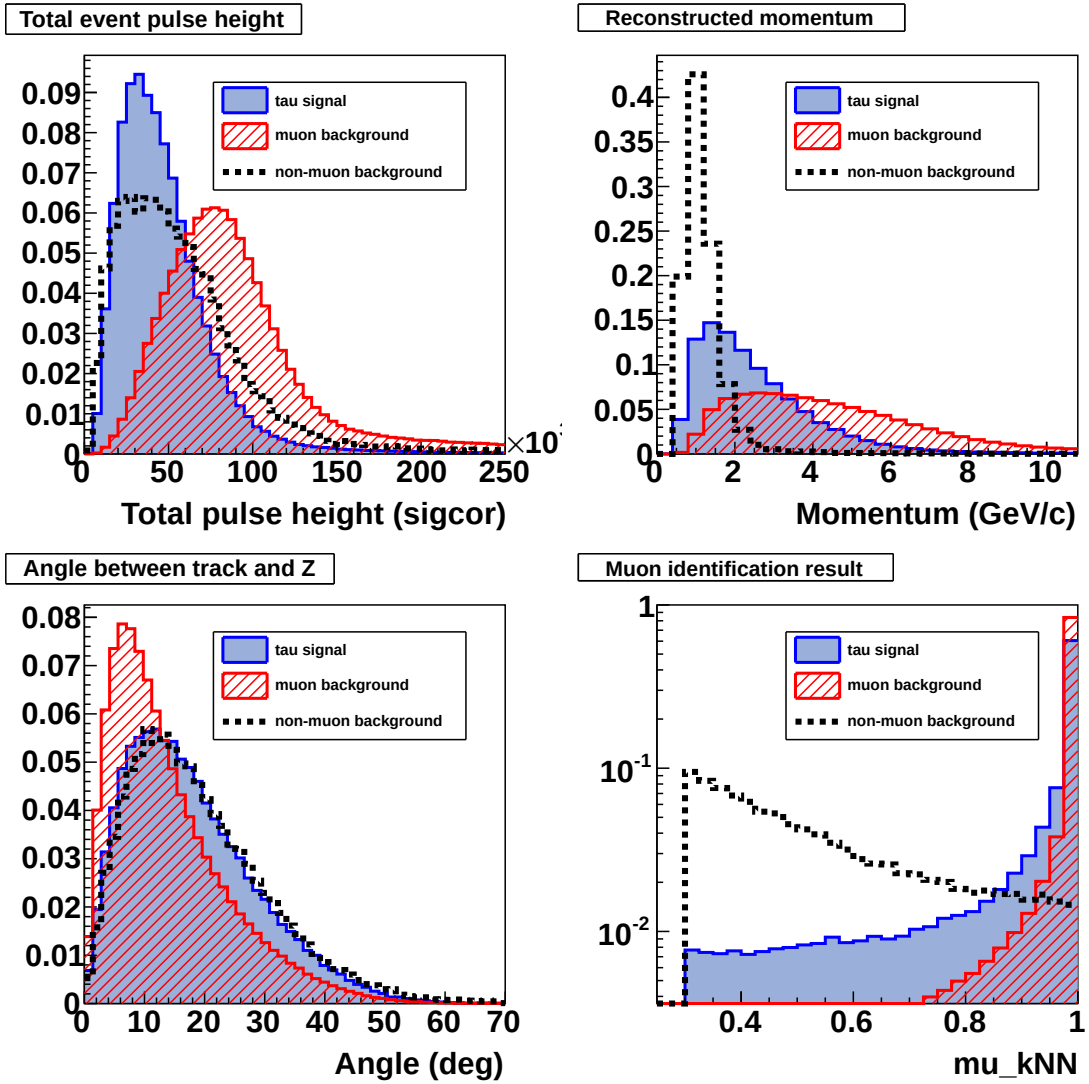
- Separate results for the muon-only files and tau-only files
- NC events are not oscillation weighted on this plots!



Cut on mu_kNN

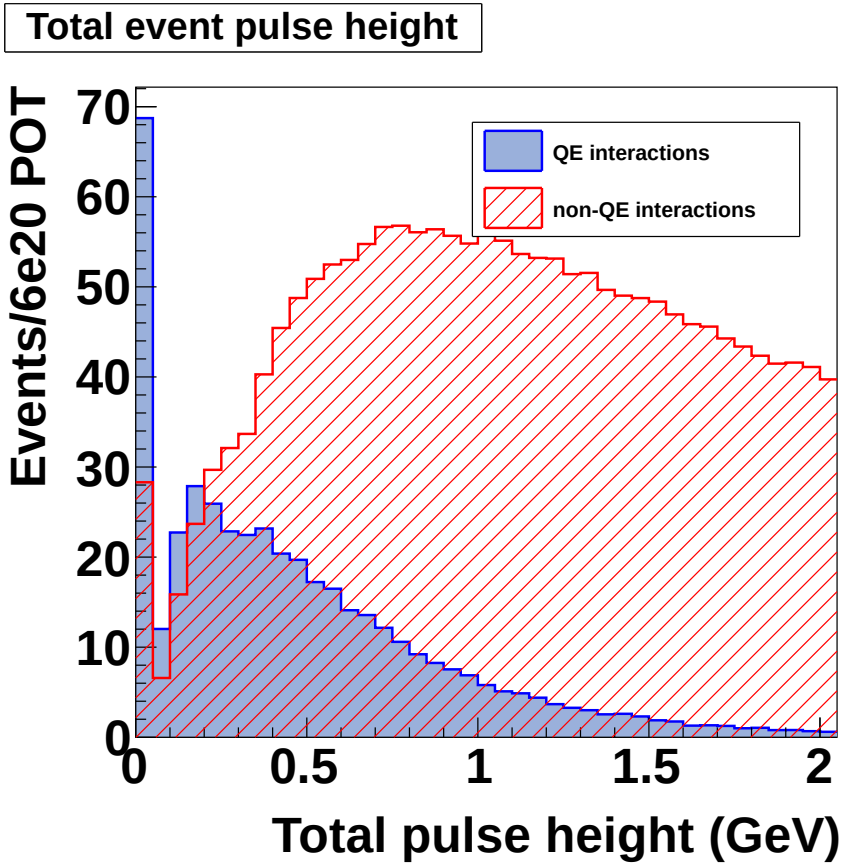
- Basic cut: mu_kNN > 0.3
- Non-muon background:
  - Resembles the signal very much
  - Can be rejected by cutting on higher values on mu_kNN
- Prepared 3 samples for different cut values

ν_τ selection variables after mu_kNN > 0.3 cut:



Cut on shower energy

- Better S-B separation and S/B ratio for QE events
- Simplest QE-like selection is cutting on reconstructed showers energy
- Prepared 4 samples for different cut values (including no cut)

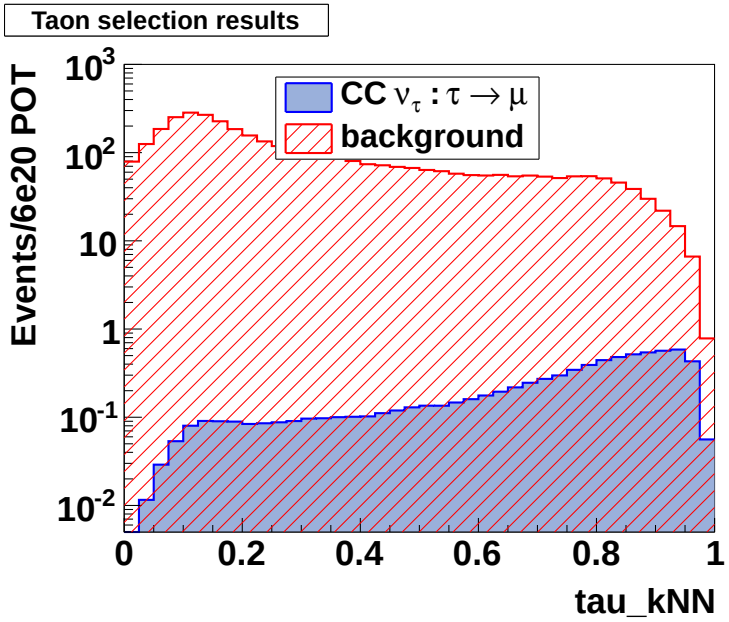


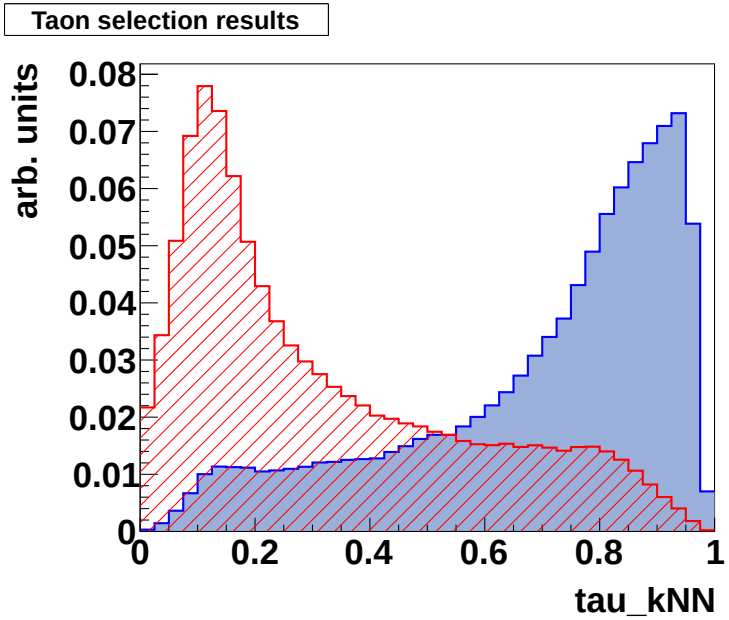
CC ν_τ: $\tau \to \mu$ selection

- Secondary selection based on kNN with three variables (total event PH, reconstructed muon momentum and reconstructed angle between muon track and Z axis)
- kNN trained on the same number of signal and background events (with oscillation weights)
- $k = 80$, no big difference for k between 40 and 120
- For any of the 12 samples (for different combinations of cuts) I searched for a cut value on the kNN result that would give maximum significance ($\frac{S}{\sqrt{S+B}}$)
- It is the largest for samples with the lowest cuts (i.e. the largest efficiency) – I'll show results for two of them

Selection results – sample 1

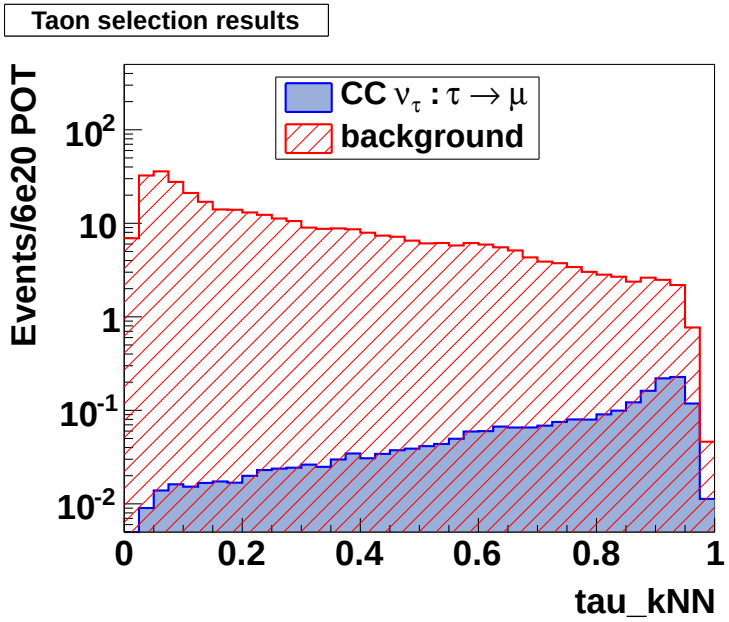
- Sample with lowest cuts: 0.3 on mu_kNN and no shower energy cut
- 2.7 $\pm$ 0.3 CC ν_τ: $\tau \rightarrow \mu$ events after cutting on tau_kNN > 0.85
- 113 $\pm$ 1 background events
- (for 6 $\times$ 10^{20} POT)

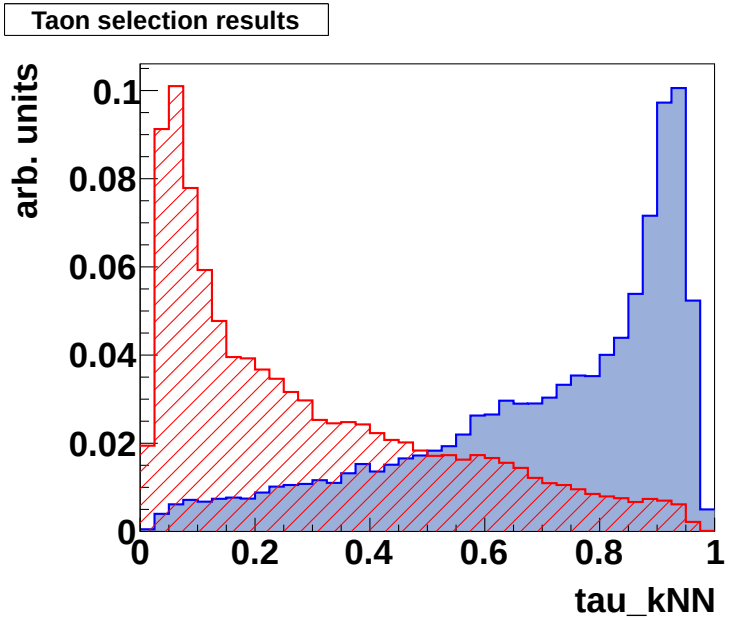




Selection results – sample 2

- Sample with 0.3 cut on mu_kNN and 375 MeV cut on shower energy
- 0.85 ± 0.09 CC ν_τ: $\tau \to \mu$ events after cutting on tau_kNN > 0.85
- 10.5 ± 0.2 background events
- (for 6×10^{20} POT)





Summary

- Complete framework needed for selection of ν_τ events has been developed
- Current selection of ν_τ events, $\tau \to \mu$ has low significance, mainly due to very low number of events
- Possible signal efficiency improvements :
  - Bigger fiducial volume
  - Add muon identification variables to identify low-energy muon tracks
- Possible improvements in background rejection :
  - Look for other variables
  - Selection using information about proton track, for QE events with pion or muon track
- Anyway the chances to observe ν_τ appearance aren't looking so bad