Atmospheric Neutrino Energy and Angle Reconstruction

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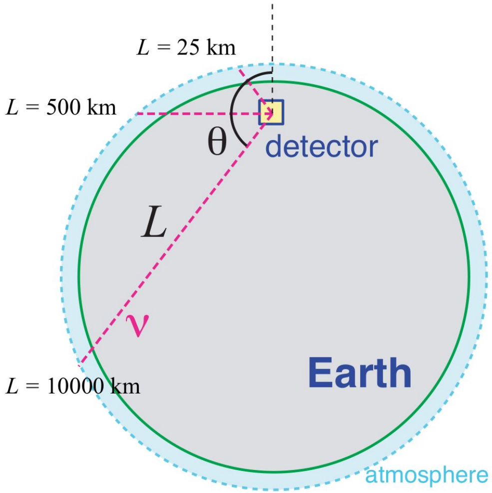
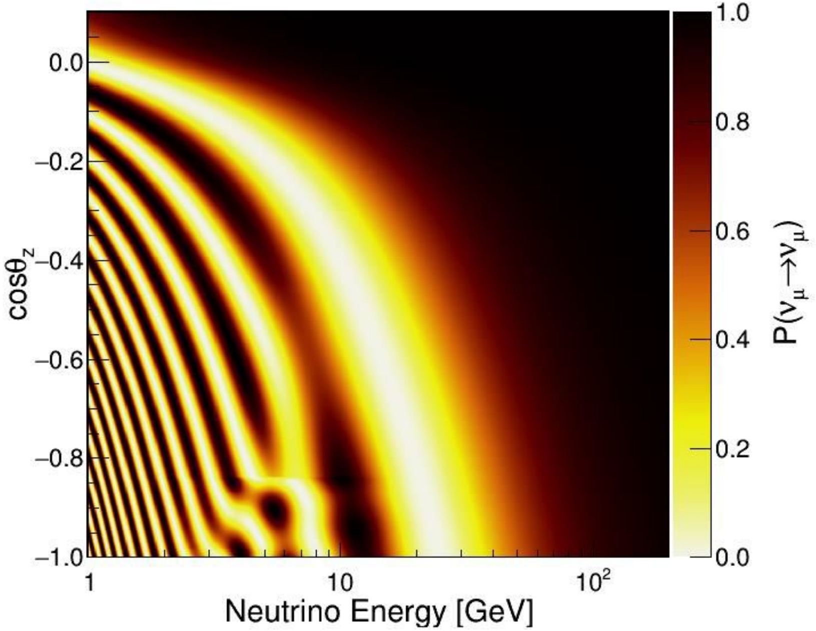
Reconstruction of atmospheric neutrinos

- Atmospheric neutrinos:
  - Wide energy range and baseline allows for oscillation analysis (sterile, δ_{CP}, …)
  - Energy and zenith angle reconstruction is necessary

- Energy reconstruction performance needs to be checked in a wider range w.r.t. beam neutrinos

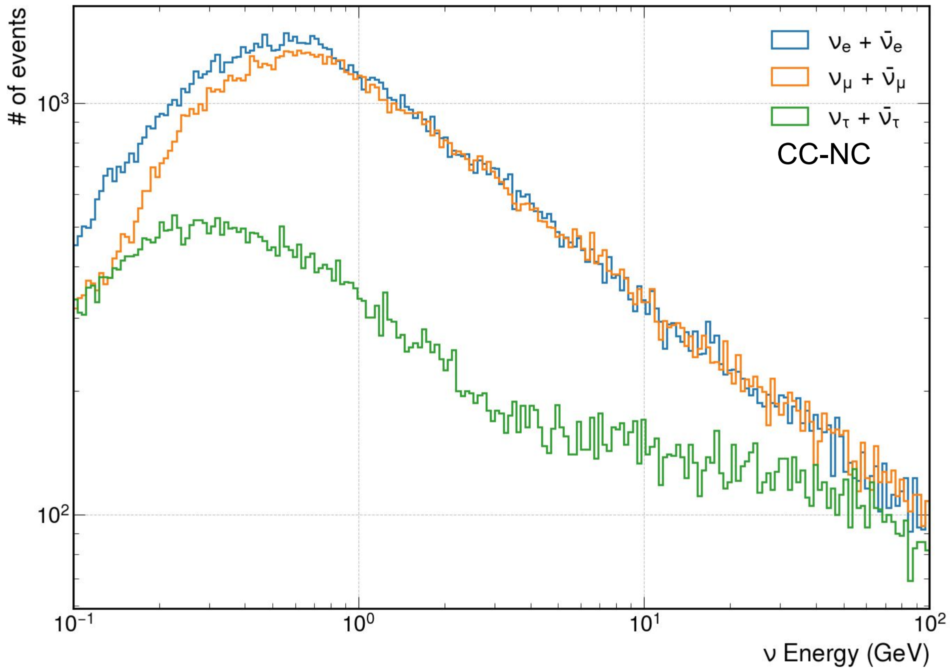


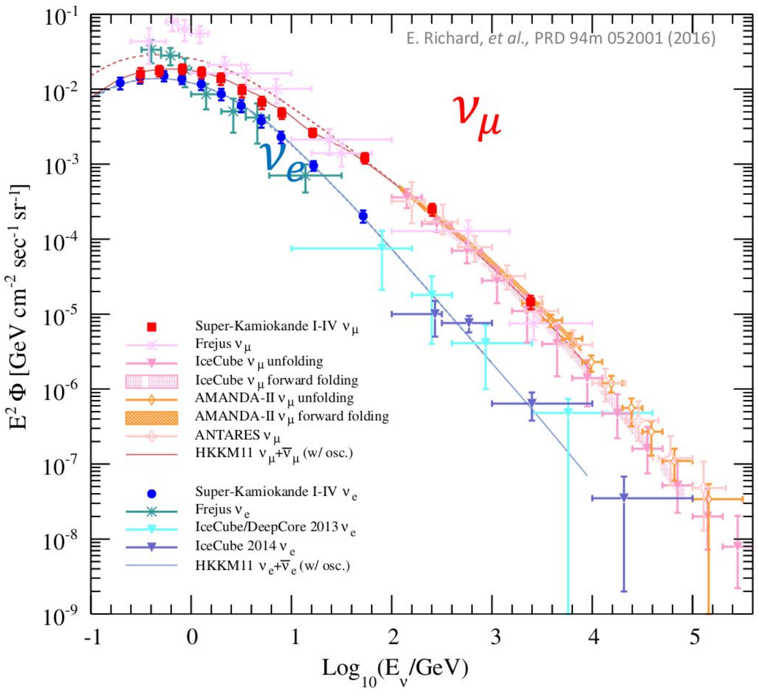


- Angle reconstruction is not implemented in current workflow, as neutrinos always arrive in the 'z' (beam) direction
  - We need to implement angle reconstruction algorithms to verify DUNE capability for atmospheric neutrinos.

Reconstruction of atmospheric neutrinos

- Sample generated with ~300k events on HD 1x2x6
- Energy from 0.1 to 100 GeV
- Flux slightly changed to have more statistics in higher energies
- DUNESW v9_75_03d00





Outline:

- Energy reconstruction
- Angle reconstruction

Energy reconstruction - Current state

- Currently, energy reconstruction done using three different methods:

Method 1 (ν_μ):
Energy of longest track
+ Hadronic energy

Method 2 (ν_e):
Energy of shower with the most charge deposited
+ Hadronic energy

Method 3:
In case everything else fails, add all deposited charges

(Method 1 and 2 are always computed, the decision is given later with CVN score)

NOTE:

- Hadronic energy is computed by adding the total deposited charge (corrected by lifetime), but removing the hits associated with the lepton (longest track or most charged shower)
- Method 2 and Method 3 are equivalent, with the difference of adding the electron mass.

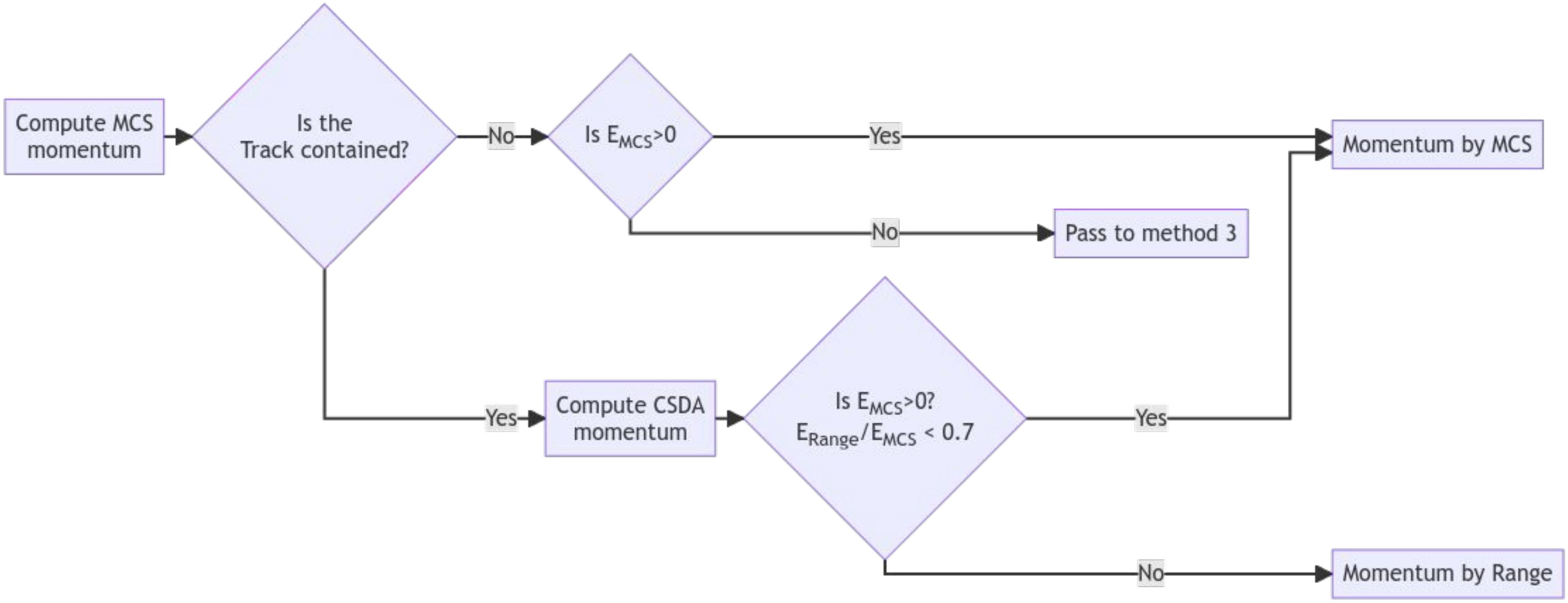
Energy reconstruction - Method 1

Method 1 (ν_μ):

Energy of longest track

+ Hadronic energy

- Multi Coulomb Scattering (MCS):
  Computes momentum by angle of scattering
- Constant slow down approximation (CSDA):
  Uses particle range to estimate momentum



Energy reconstruction - Method 1

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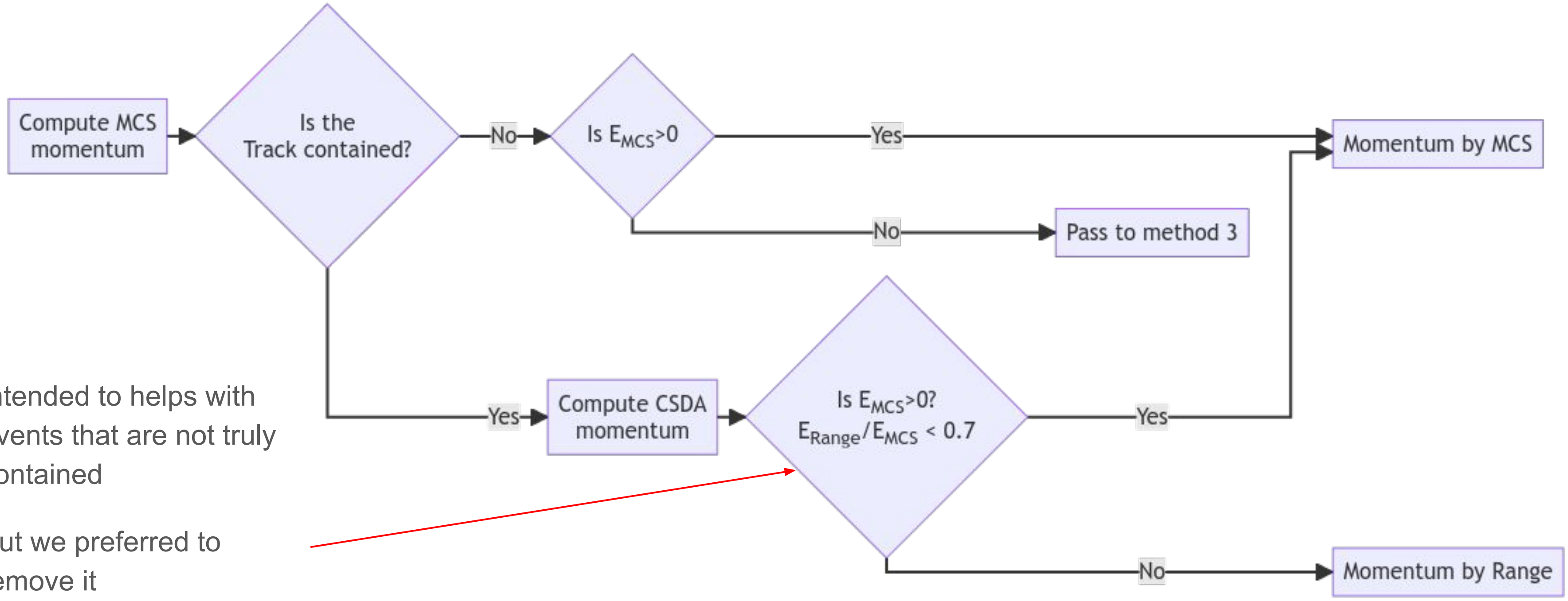
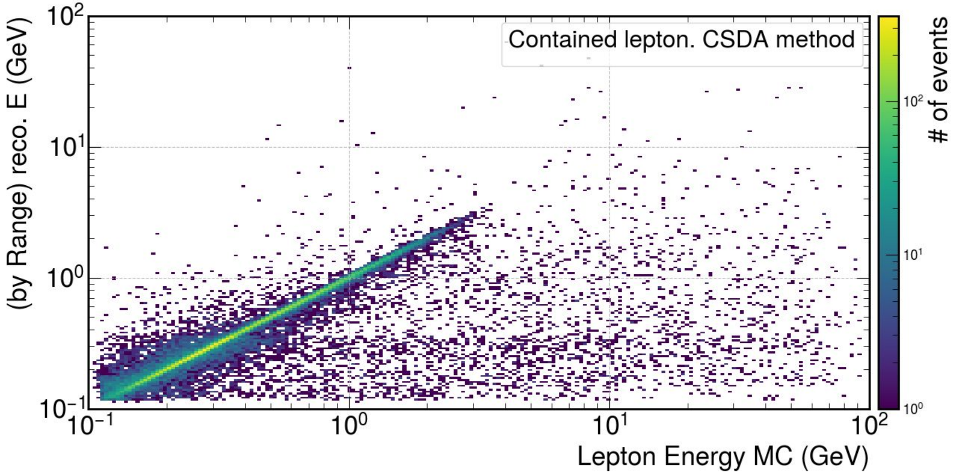
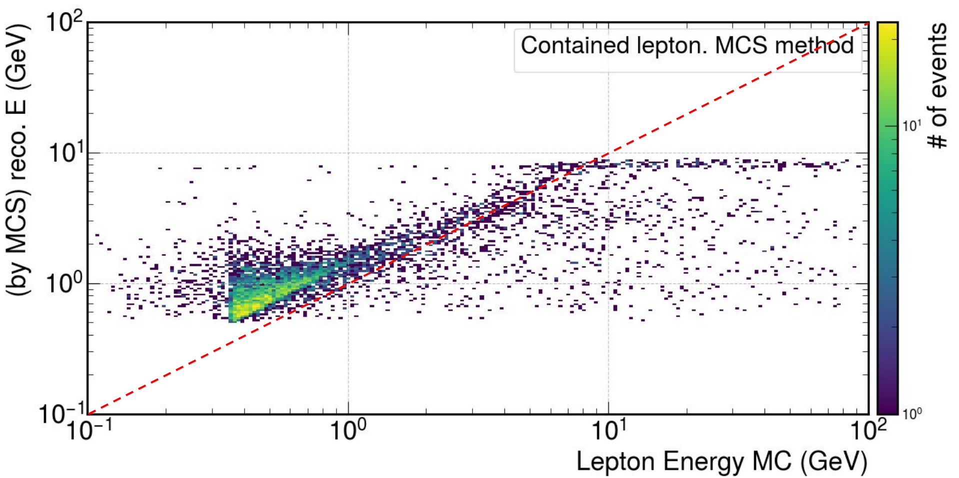


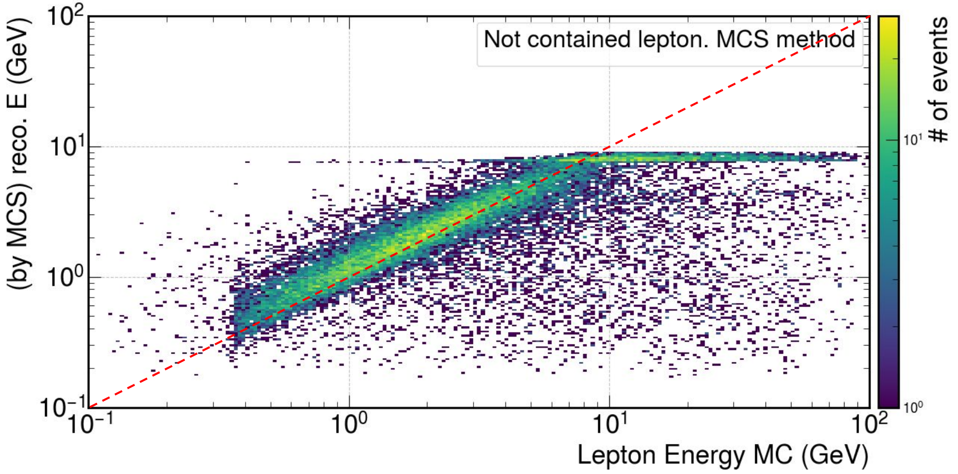
Intended to helps with events that are not truly contained

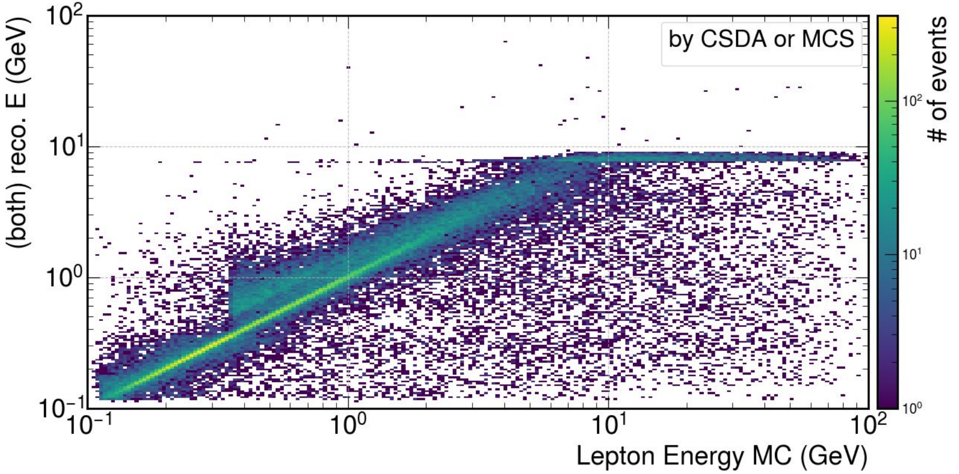
But we preferred to remove it

Energy reconstruction - Lepton E. reconstruction

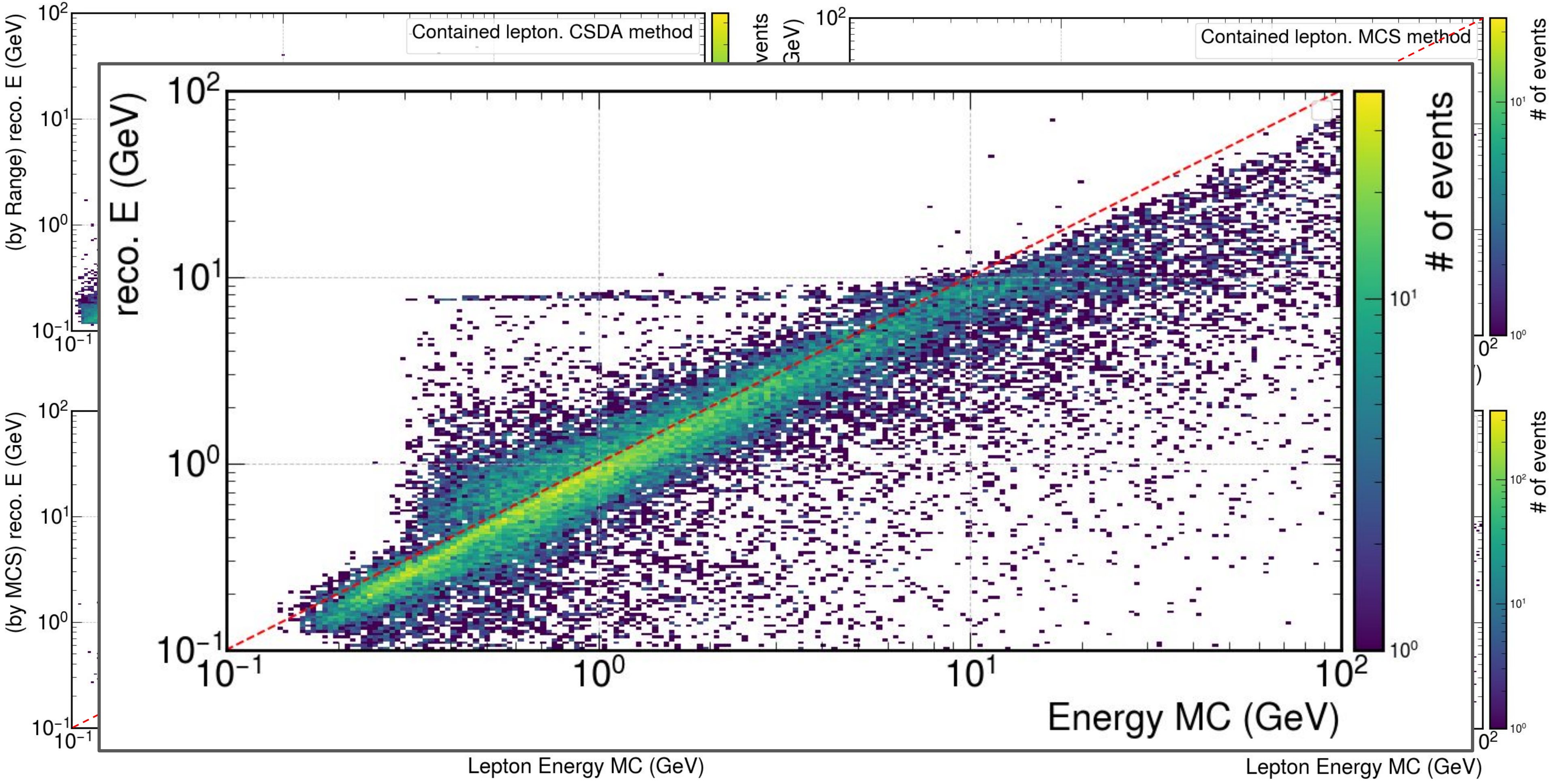




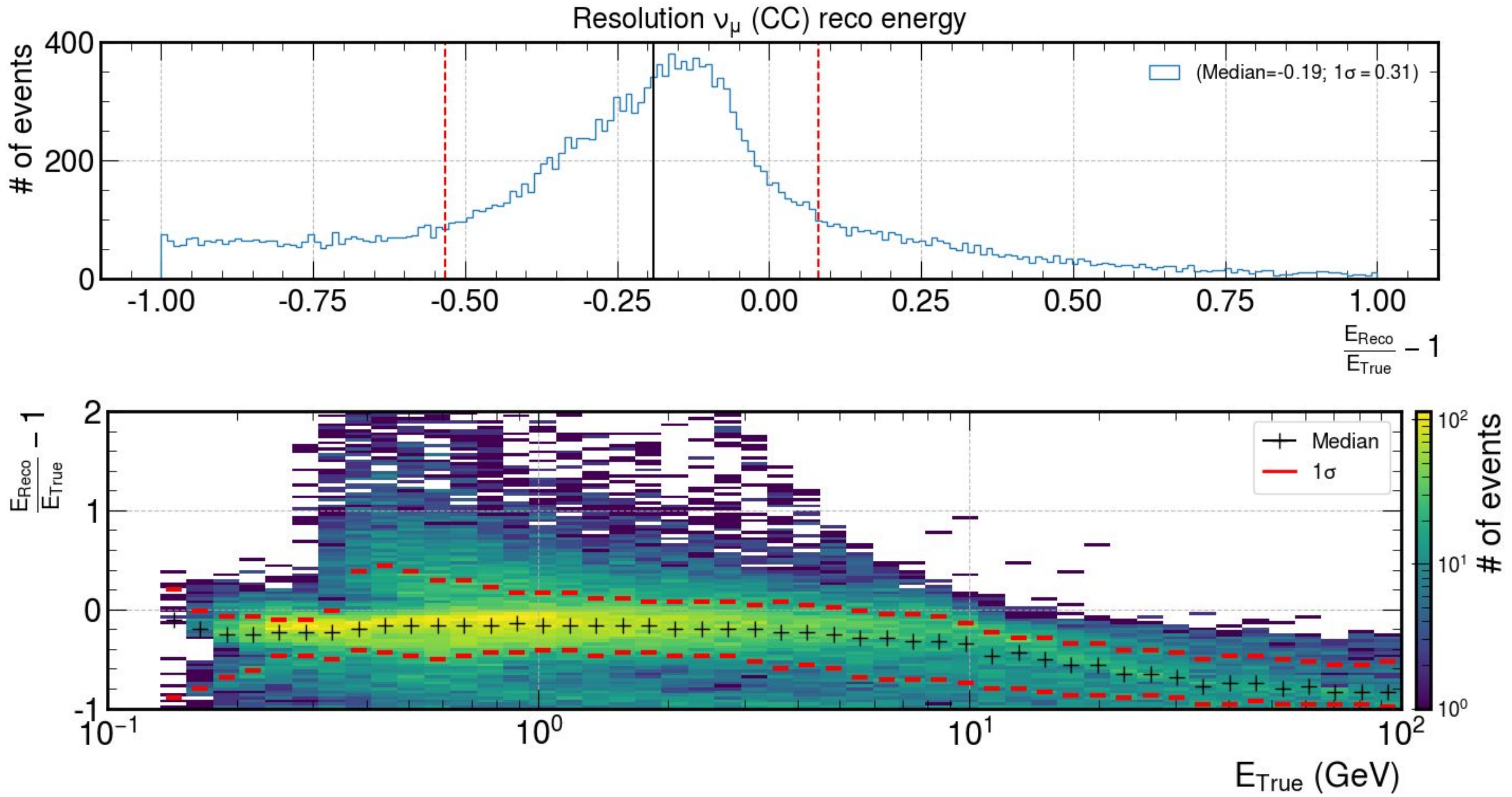




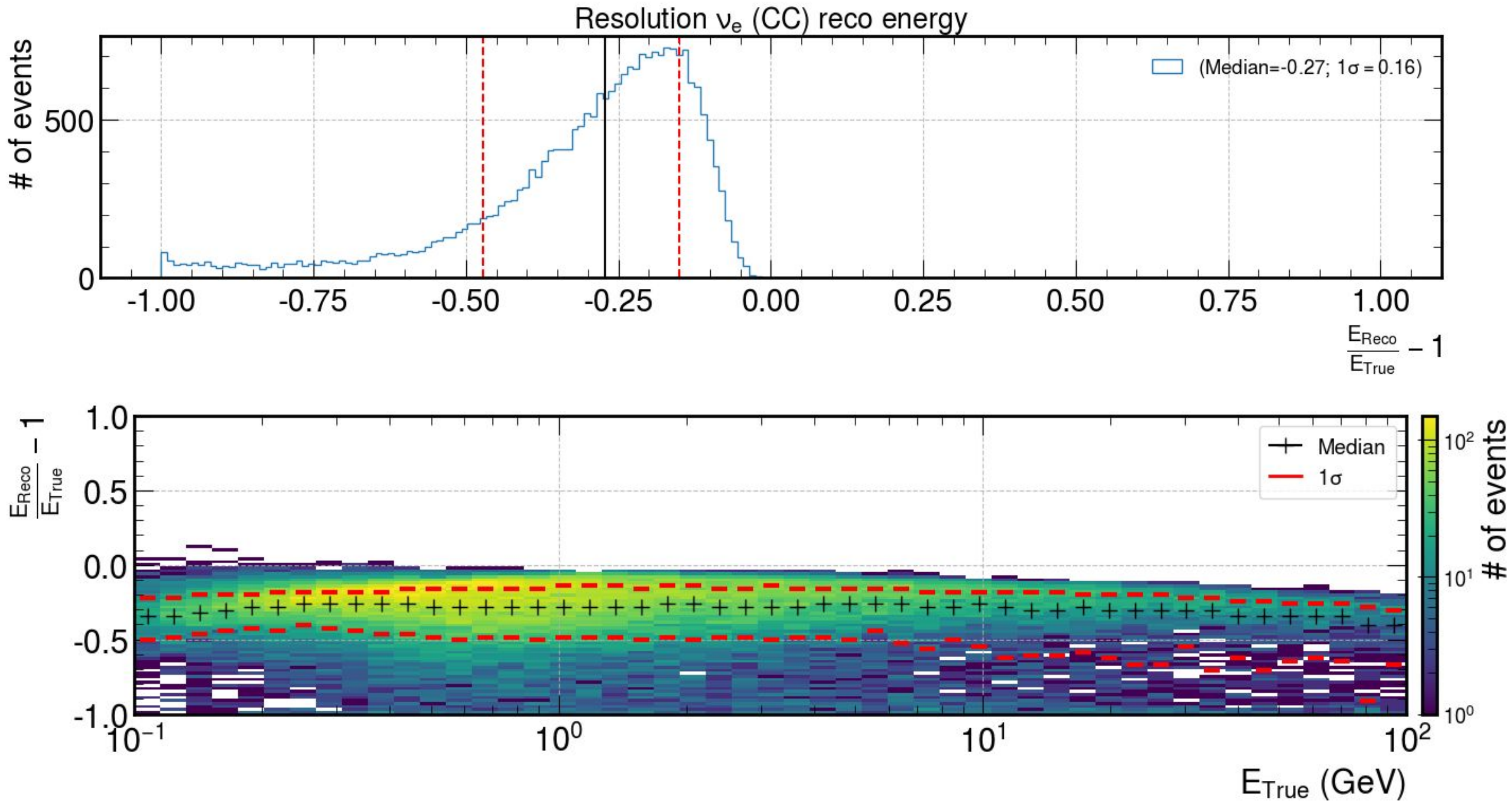
Energy reconstruction - Lepton E. reconstruction



Energy reconstruction - Numu energy reconstruction



Energy reconstruction - Nue energy reconstruction



Energy reconstruction

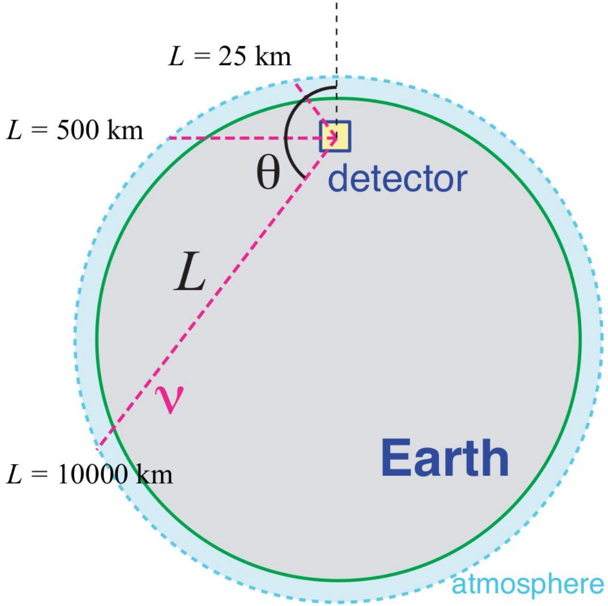
- Running energy reconstruction:
  - Producer: EnergyReco_module
  - Example of how to use from CAFMaker:

```
# Define and configure some modules to do work on each event.
# First modules are defined; they are scheduled later.
# Modules are grouped by type.
physics:
{

 producers:{
   mvaselectnue:   @local::dunefd_mvaselect
   mvaselectnumu:  @local::dunefd_mvaselect
   energyreconue:  @local::dunefd_nuenergyreco_pandora_nue
   energyreconumu: @local::dunefd_nuenergyreco_pandora_numu
   energyreconc: @local::dunefd_nuenergyreco_pandora_nc
   cvnmap: @local::standard_cvnmapper
   cvneval: @local::standard_cvnevaluator
   regcnnmap:      @local::standard_regcnnmapper
   regcnneval:     @local::standard_regcnnevaluator
 }

 analyzers:
{
 cafmaker:           @local::dunefd_cafmaker
}

 #define the output stream, there could be more than one if using filters
 stream1:  [ out1 ]

 #define the producer and filter modules for this path, order matters,
 #filters reject all following items.  see lines starting physics.producers below
 prod: [mvaselectnue, energyreconue, mvaselectnumu, energyreconumu, energyreconc, cvnmap, cvneval, regcnnmap, regcnneval]
 caf:  [ cafmaker]
 trigger_paths: [prod]

 #end_paths is a keyword and contains the paths that do not modify the art::Event,
 #ie analyzers and output streams.  these all run simultaneously
 end_paths:     [stream1, caf]
# end_paths:     [stream1]

}
```

- Output:
  - Example in CAFMaker
- I currently implemented it into anatree (pull request soon)

Angular reconstruction - ν_μ

- For the angular reconstruction performance, we first used Geant4 information to help us to decide what to do with reconstruction. We tried three scenarios:
    1. Using only μ angle as ν_μ angle
    2. Using all particles except neutrons
    3. Using all particles



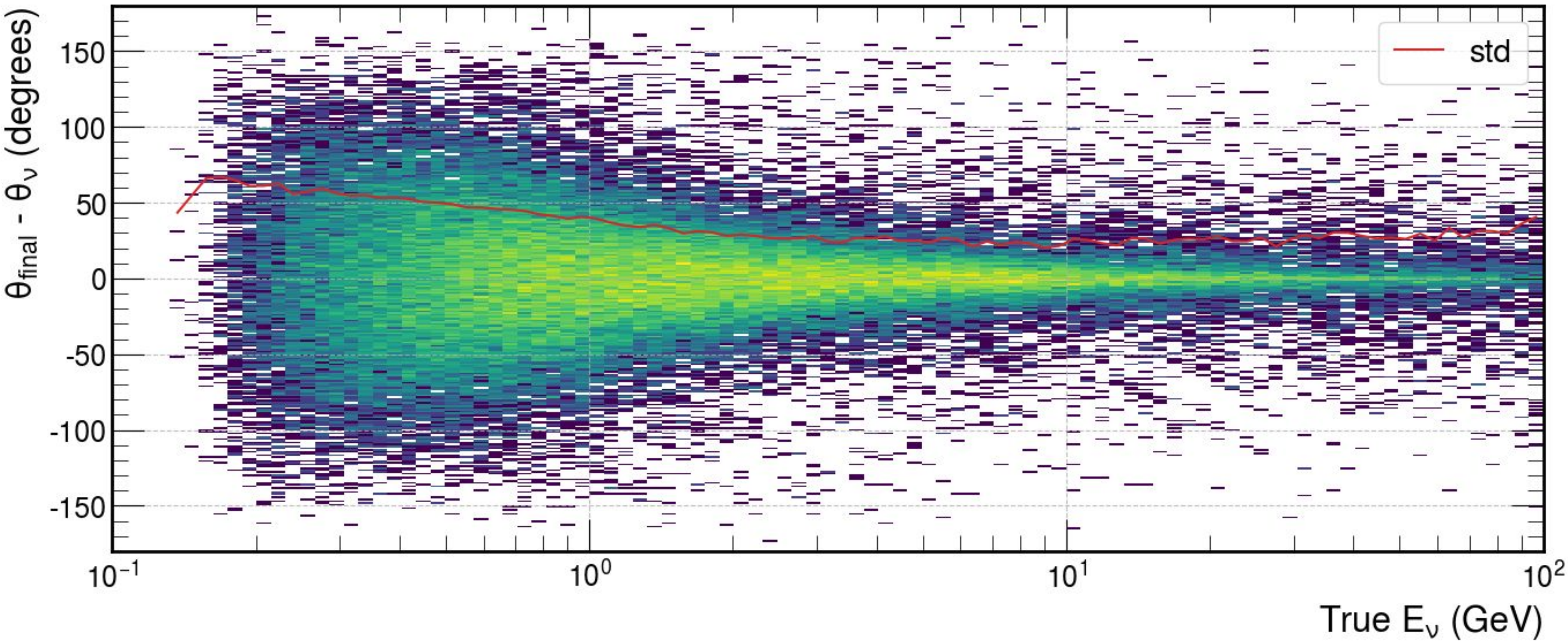
- Selection of muon (anti)neutrino in (CC) interactions

- "θ_{FINAL}" is the zenith angle using one of the three methods

NOTE: angular resolution without projection on the zenith is in the backup slides

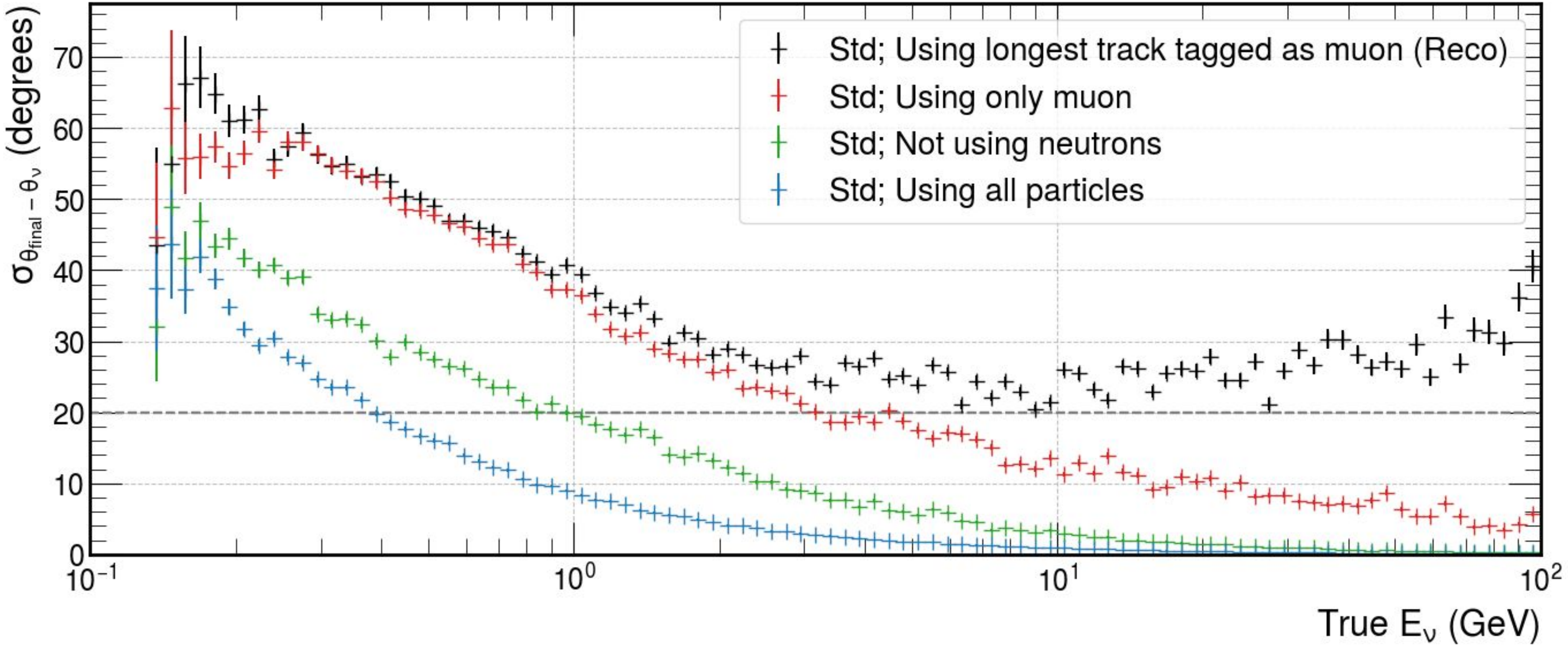
Angular reconstruction - numu (CC) using only muons

- This is the angular resolution by using only the longest track



Angular reconstruction - numu (CC) using only muons

- Comparison between the three methods:
  - Fermi motion has great impact for low energies
  - Reconstruction needs to be improved for higher energies



Angle reconstruction

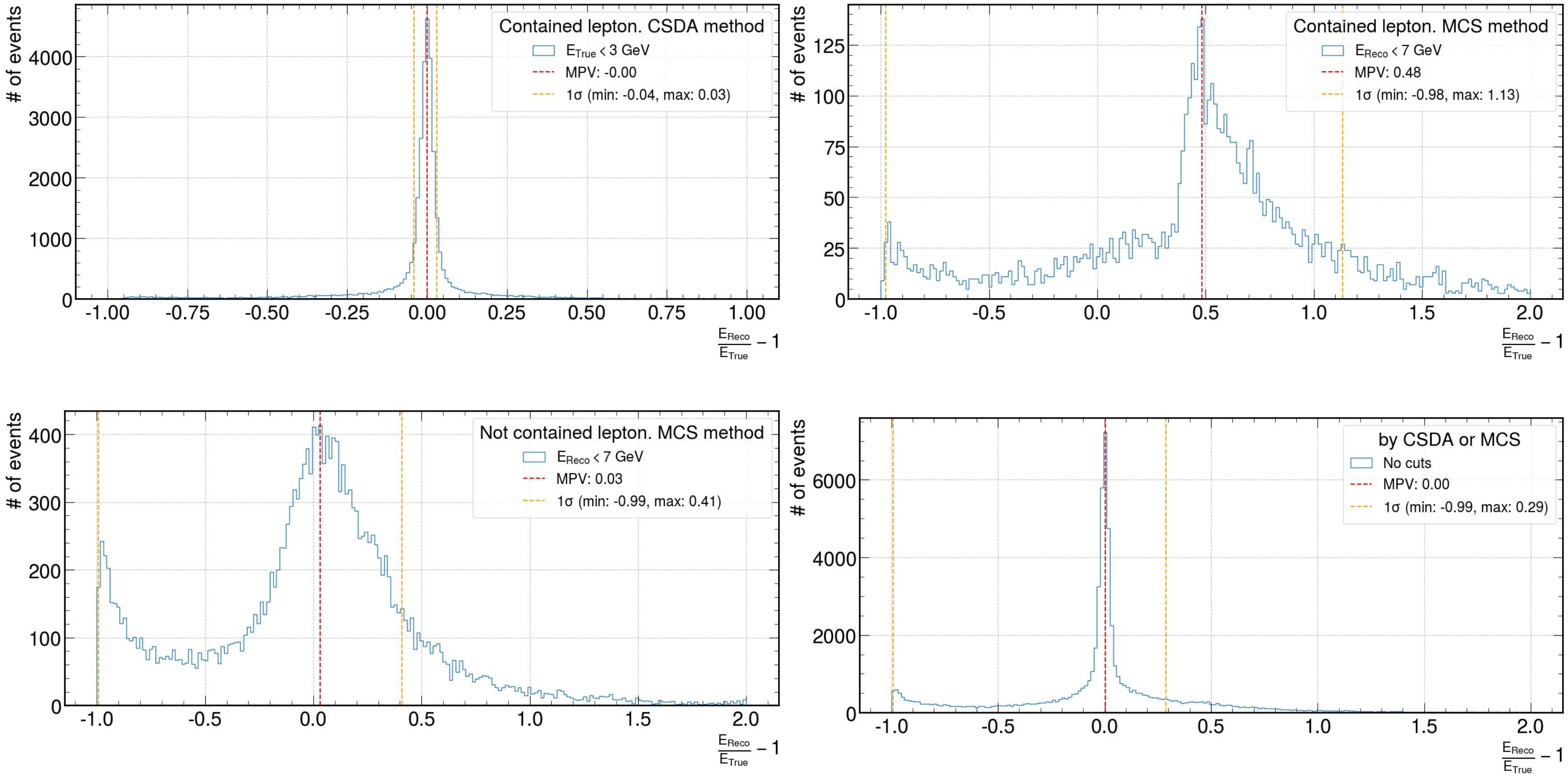
- **First (very basic) version of angle reconstruction has been implemented**
  - The producer can be run for nue or numu reconstruction
  - For numu:
    - it reconstructs the momentum of the neutrino using the direction of the longest track
  - For nue:
    - it uses the direction of the shower with the highest charge deposition
  - Output: is the normalized reconstruction directions

Future steps

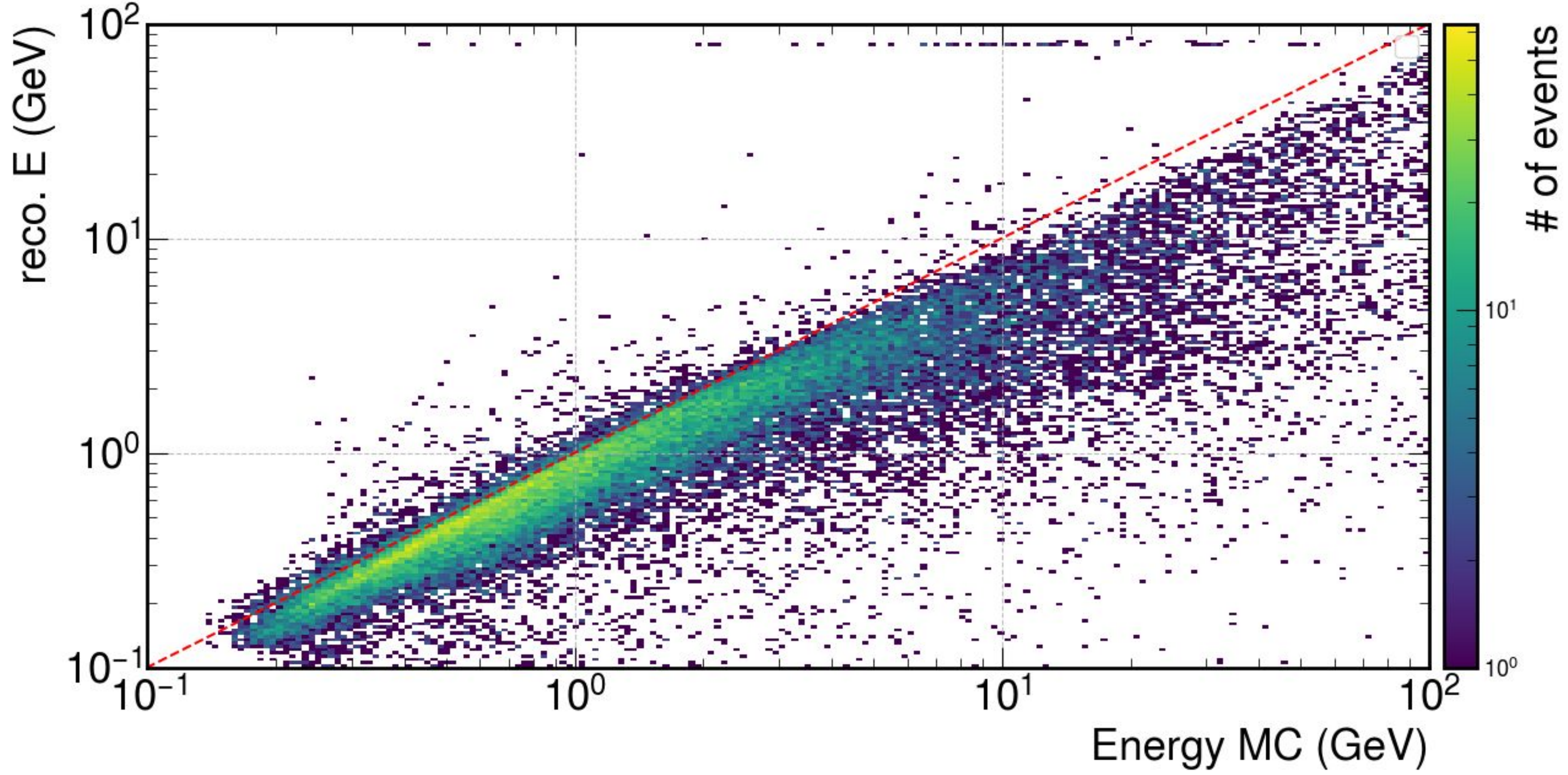
- **Energy reconstruction**
  - Try different Multi-Coulomb Scattering algorithms to improve escaping muons energy resolution
    - We have recently “re-implemented” the log-likelihood method and we are evaluating between this and chi2 method. See this slides presented in Sim/Reco meeting.
  - Check where reconstruction can be improved
  - Estimate energy resolution
- **Angular reconstruction**
  - Adding more than the longest track
    - Compute PID for protons and pions (and muons)
  - Add other tracks and showers based on how good reconstruction is and which impact we expect from Geant4

Backup

Energy reconstruction - Lepton E. reconstruction

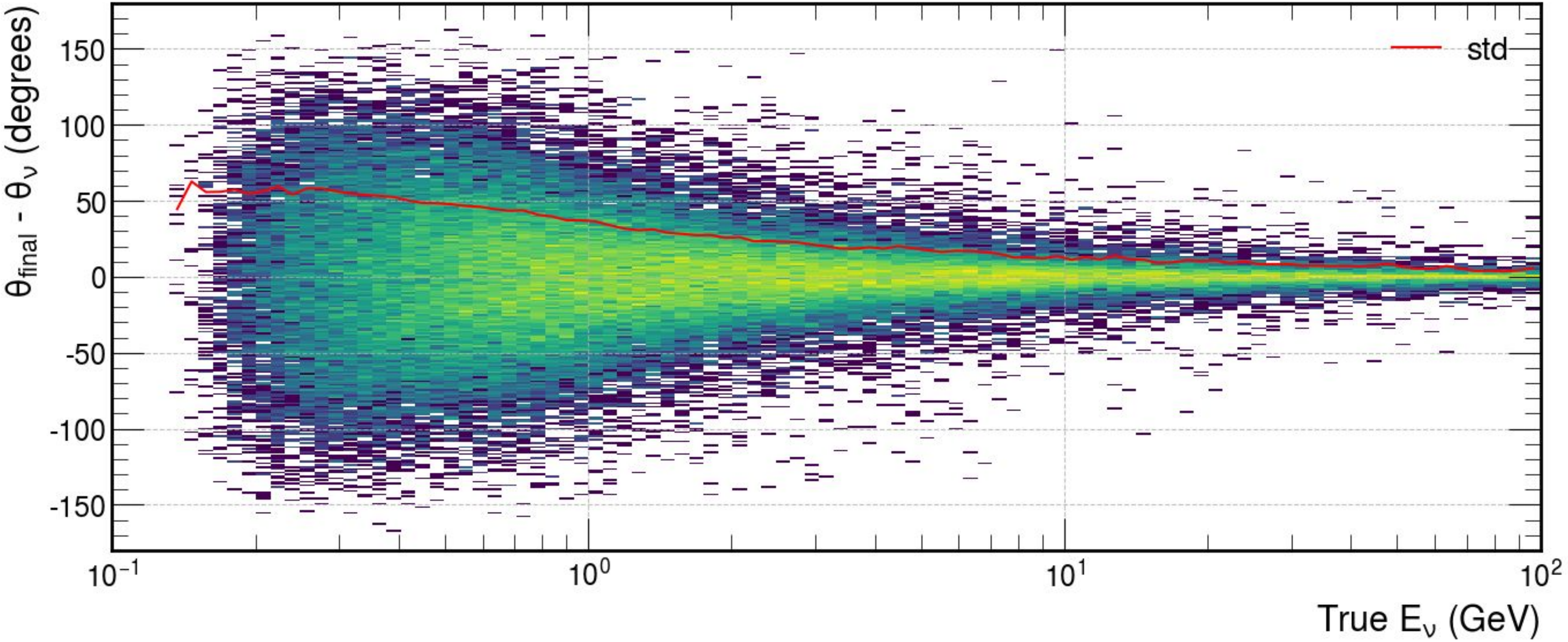


Energy reconstruction - numu reco



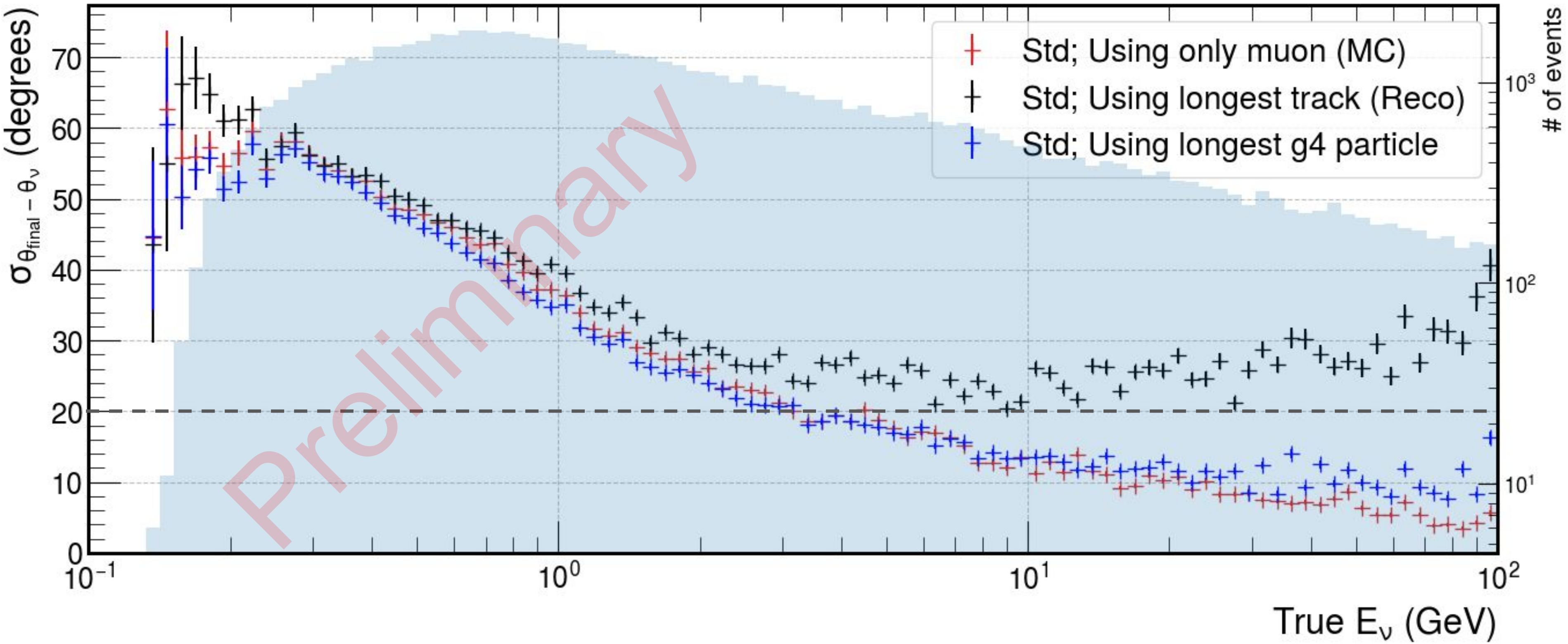
Angular reconstruction - numu (CC) using only muons

- This is the angular resolution "as good as it gets" by using only the muon
  - Assumption of perfect angle reconstruction on the lepton



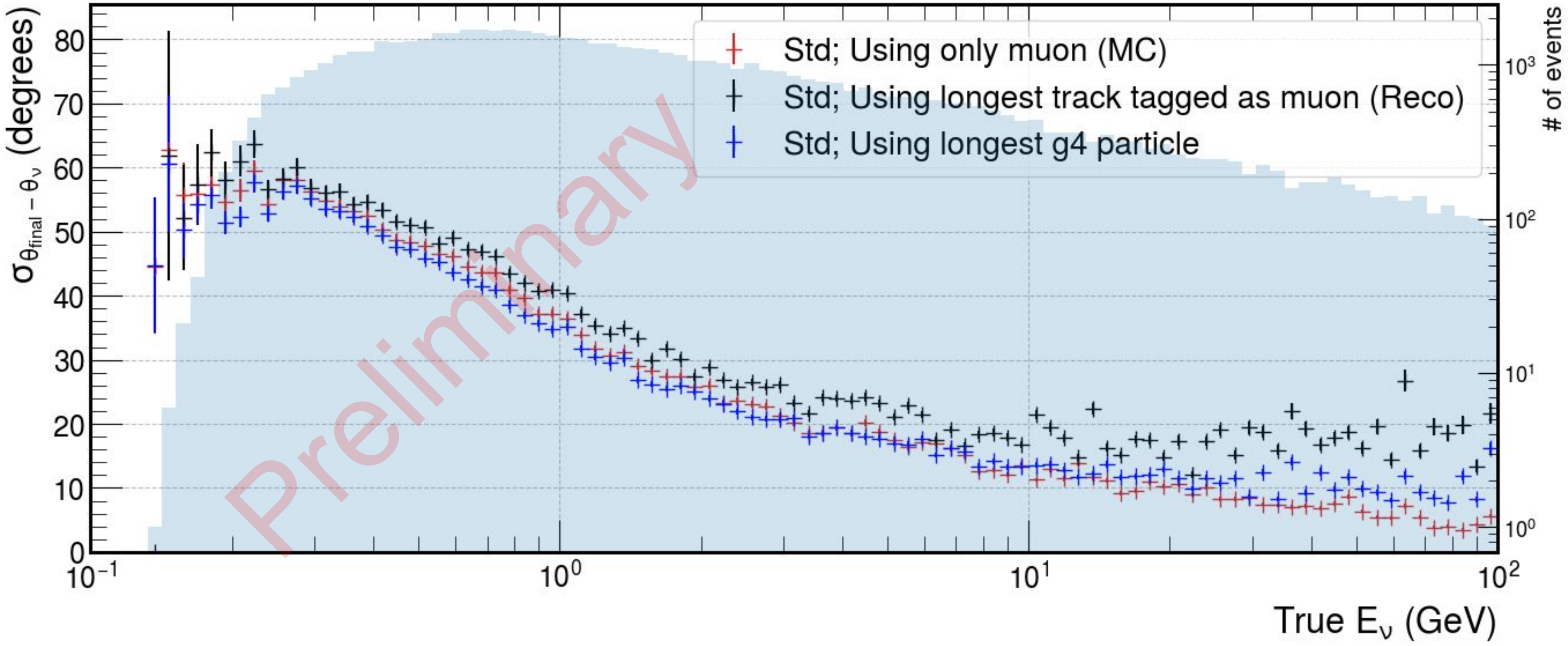
Angular reconstruction - numu (CC) reconstruction

- Using the longest track reconstructed, result is in agreement up to ~3 GeV
  - For higher energies reconstruction needs to be improved



Angular reconstruction - numu (CC) reconstruction

- Using the longest track reconstructed, result is in agreement up to ~3 GeV
  - For higher energies, gammas, pi, pr are the main issue



Angular reconstruction

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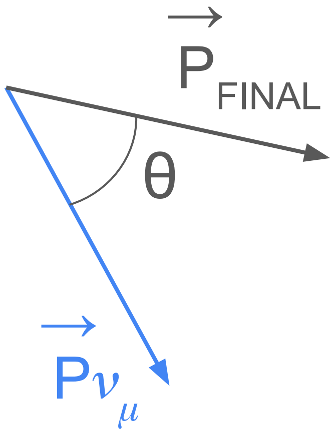
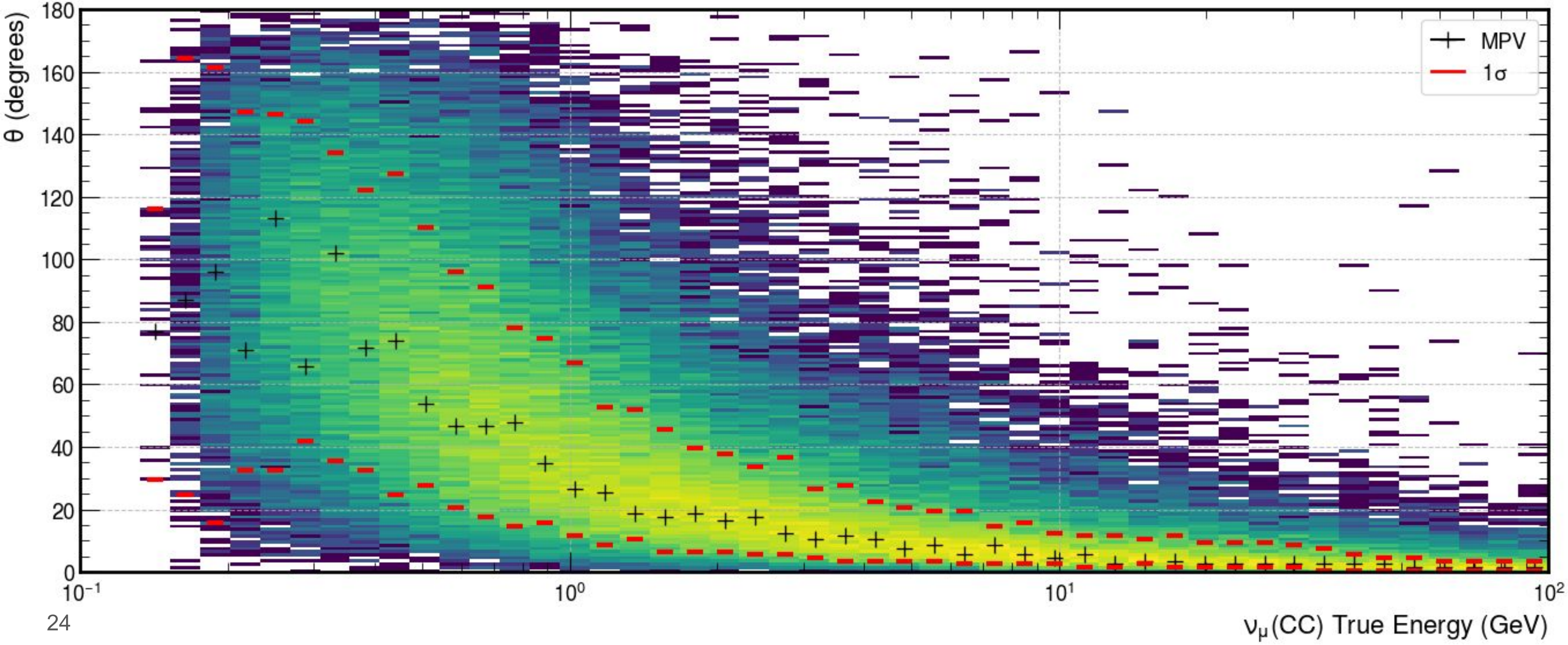


$$\theta(\text{degrees}) \equiv \cos^{-1}[\vec{p}_{final} \cdot \vec{p}_{\nu_\mu} / (|\vec{p}_{final}||\vec{p}_{\nu_\mu}|)]$$

- "P_{FINAL}" is the momentum of the final state using one of the three methods
- Selection of muon (anti)neutrino in (CC) interactions
- In the atmospheric analysis, we are interest in the zenith angle reconstruction. Projections will be done later

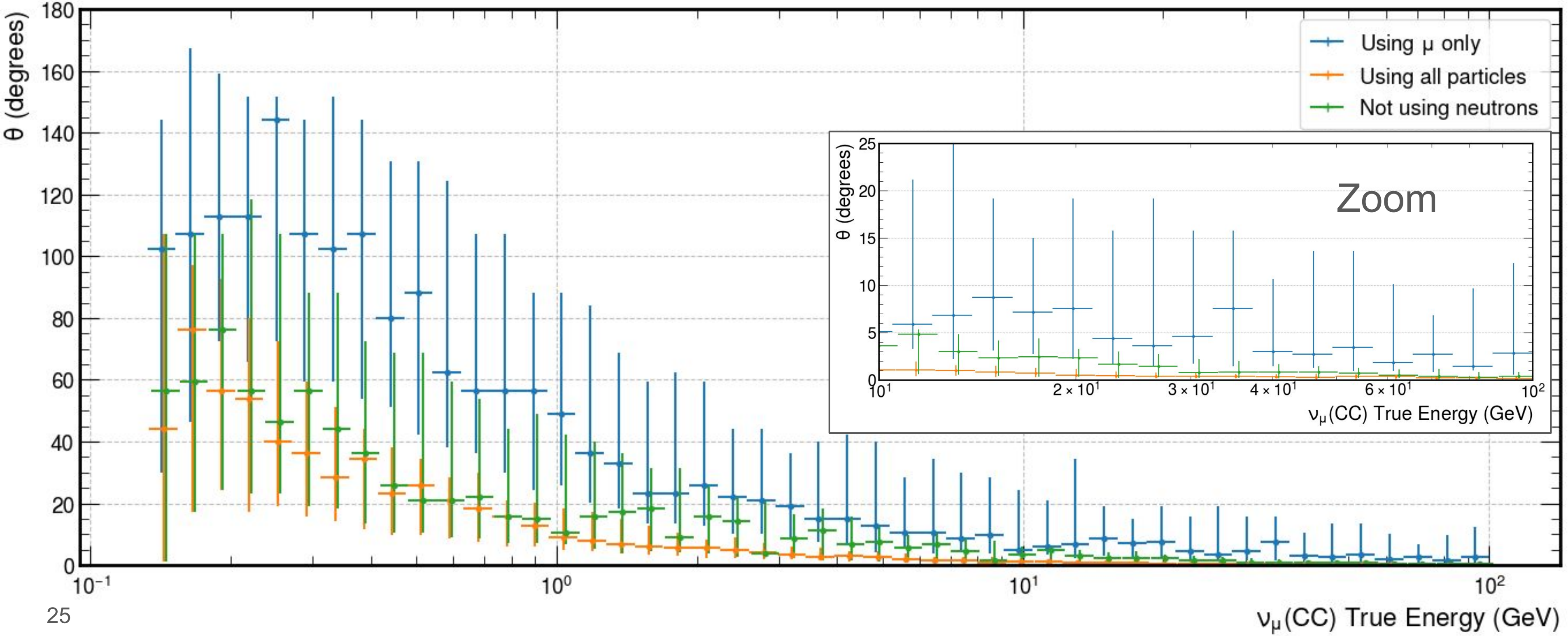
Angular reconstruction - numu (CC) only muons

- This is the angular resolution “as good as it gets” by using only the muon
  - Assumption of perfect angle reconstruction on the lepton



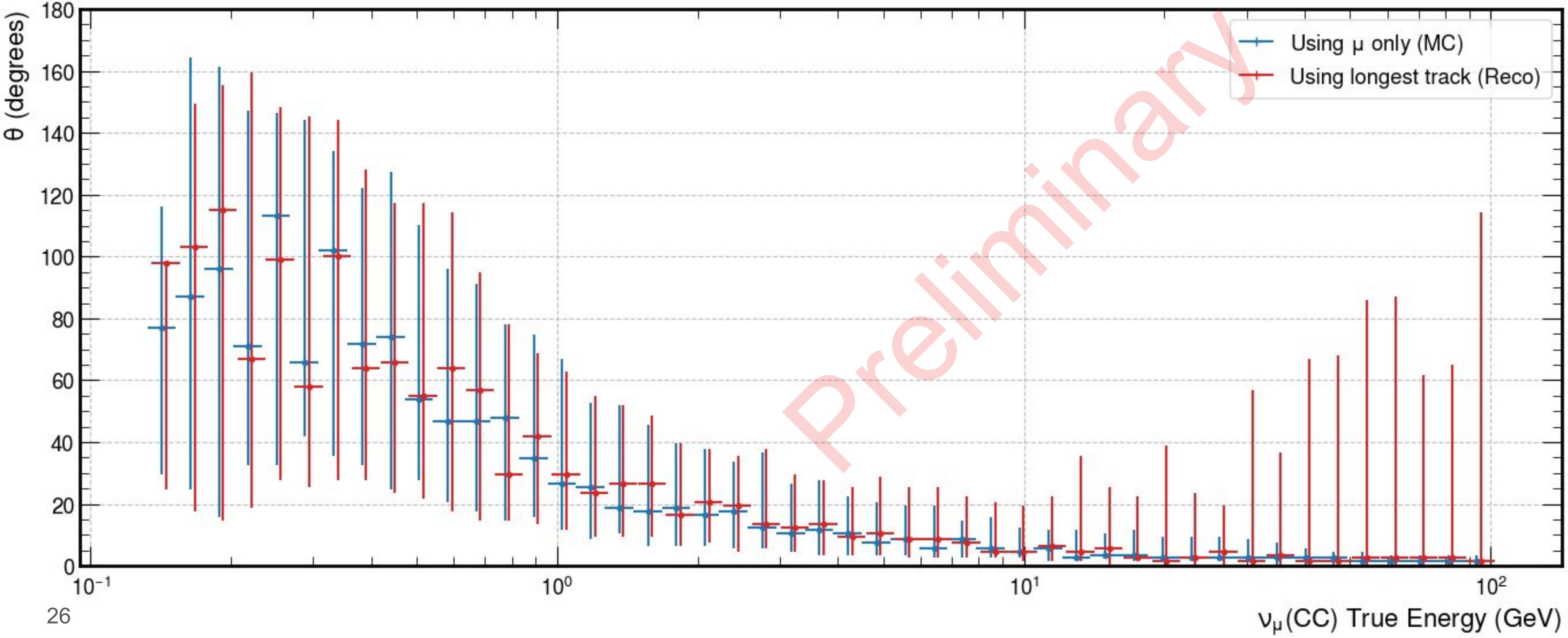
Angular reconstruction - MC information only

- Comparison between the three methods:
  - Fermi motion has great impact for low energies

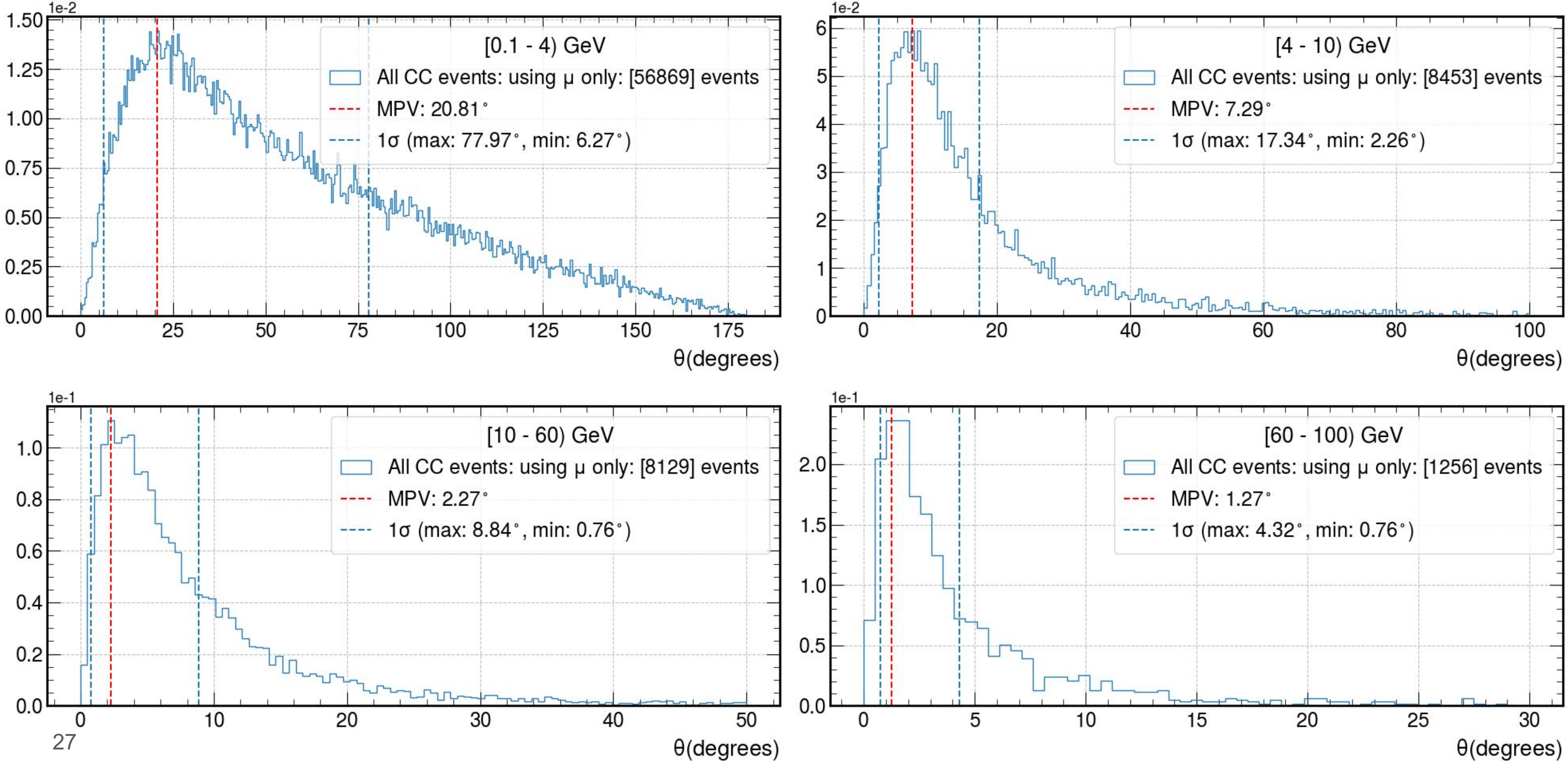


Angular reconstruction - numu (CC) reconstruction

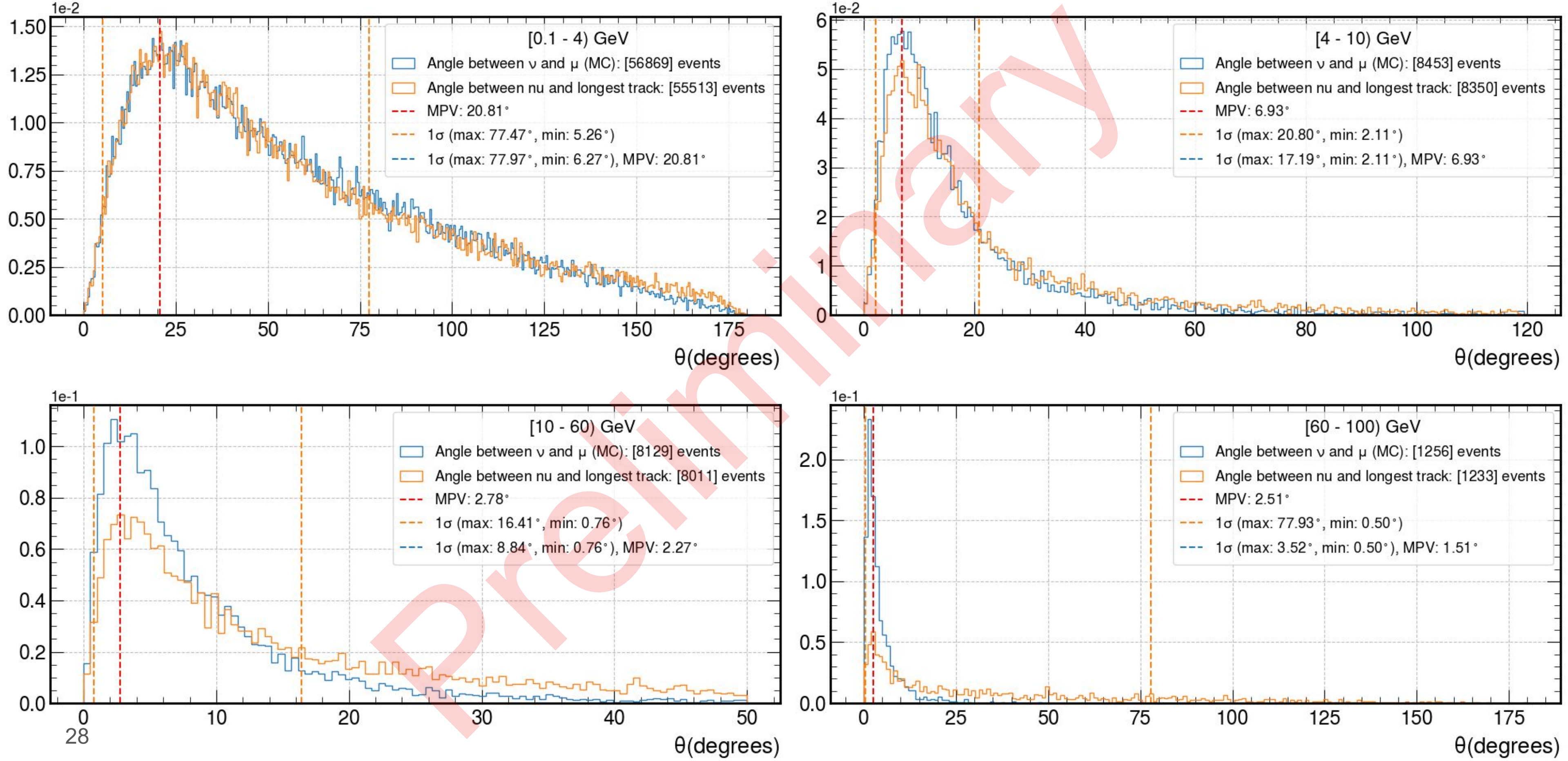
- Using the longest track reconstructed, result is in agreement up to ~10 GeV
  - The higher deviation is caused by break in the assumption that the longest track is the muon



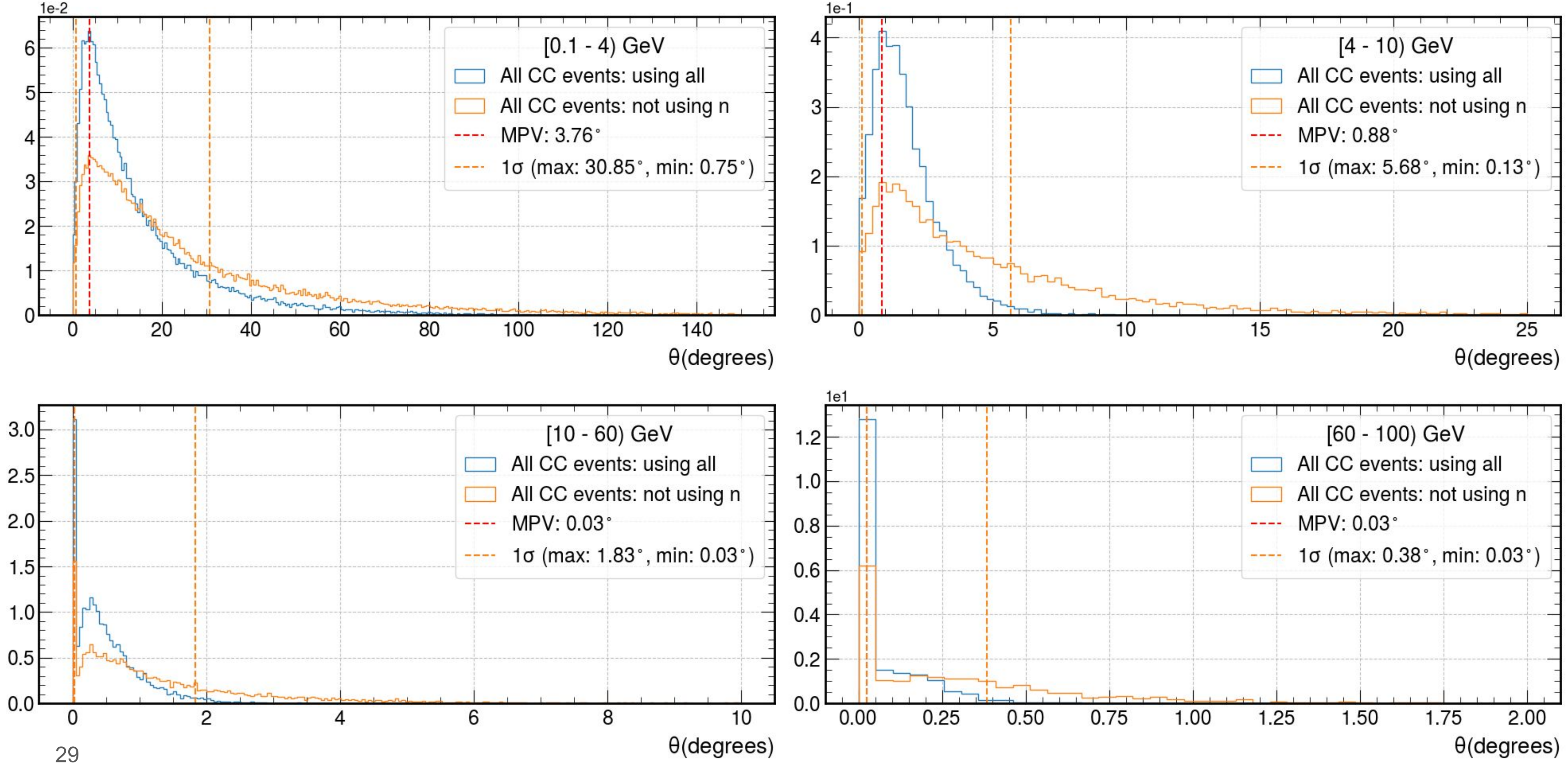
Angular reconstruction - numu (CC) only muons



Angular reconstruction: using longest track

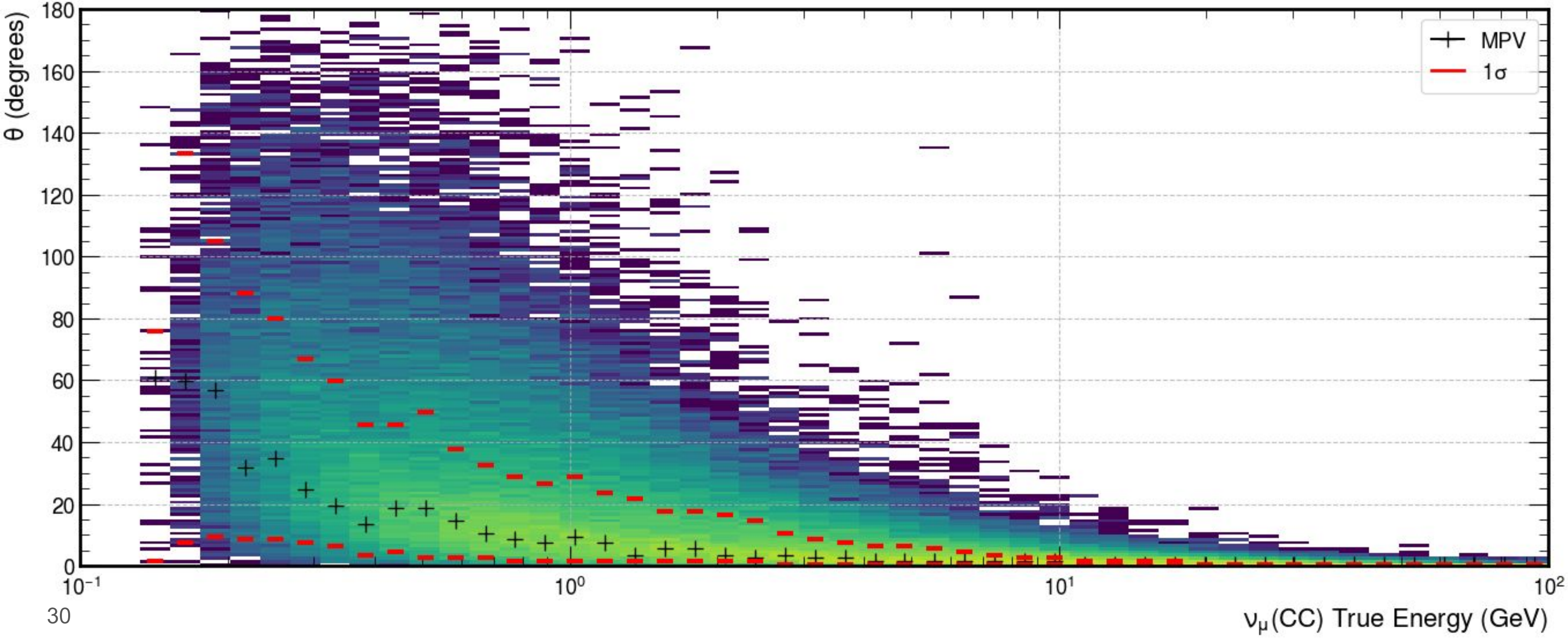


Angular reconstruction: using all particle (and minus n)

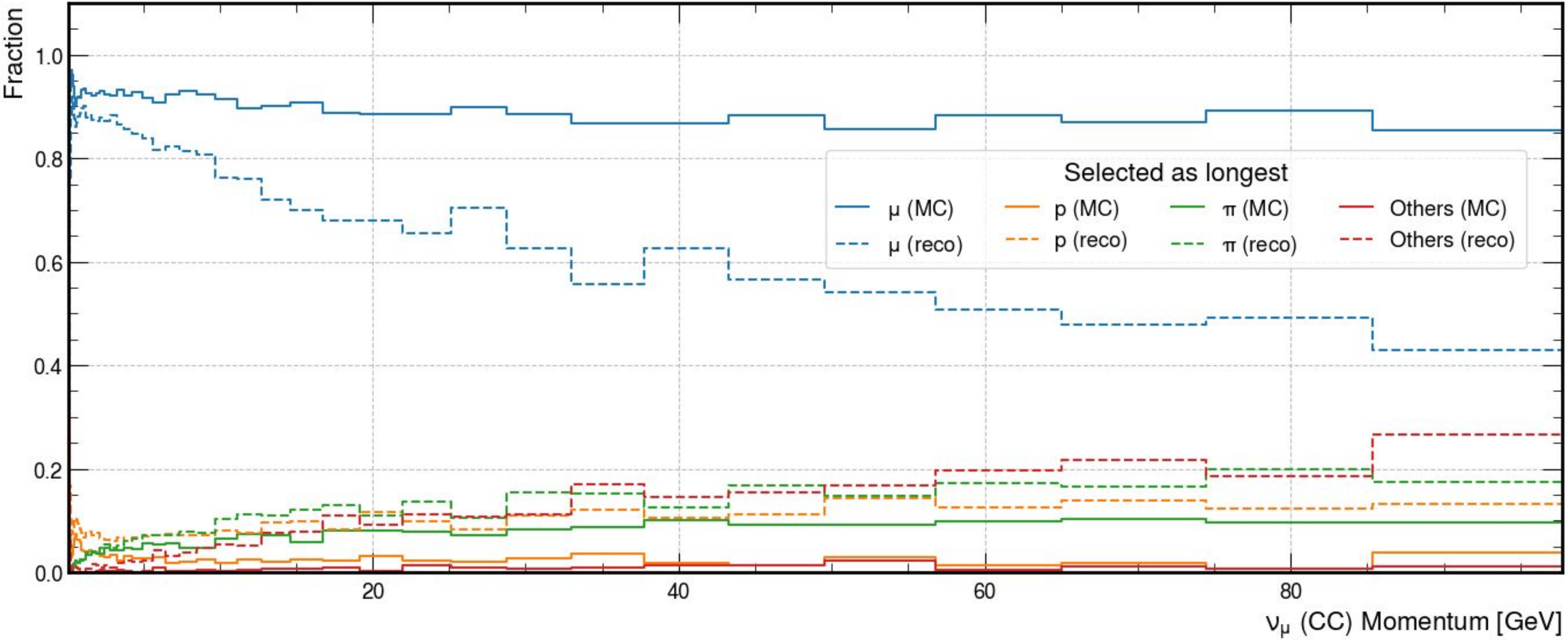


Angular reconstruction - Not using neutron

- This is the best possible angular reconstruction we can have.
  - Fermi motion has a great impact. 1σ < 20º for E ≳ 2 GeV



“PID” of longest track



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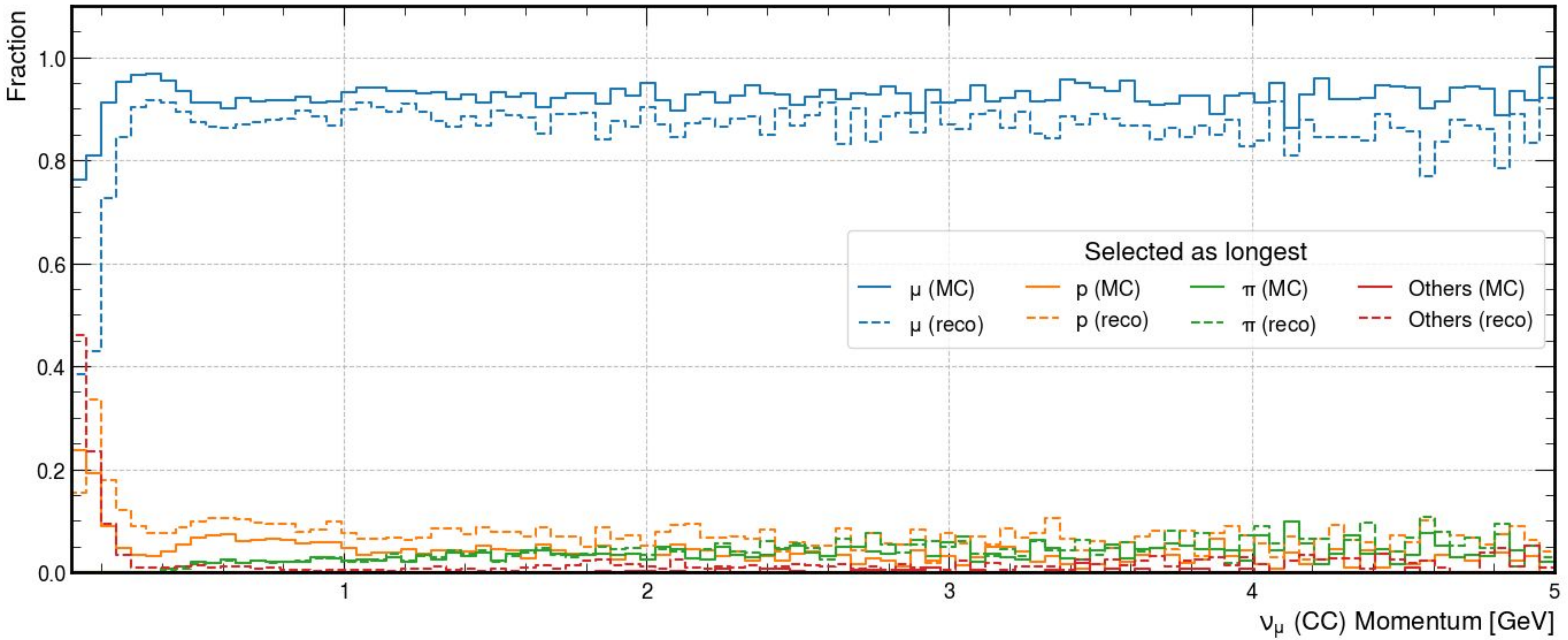
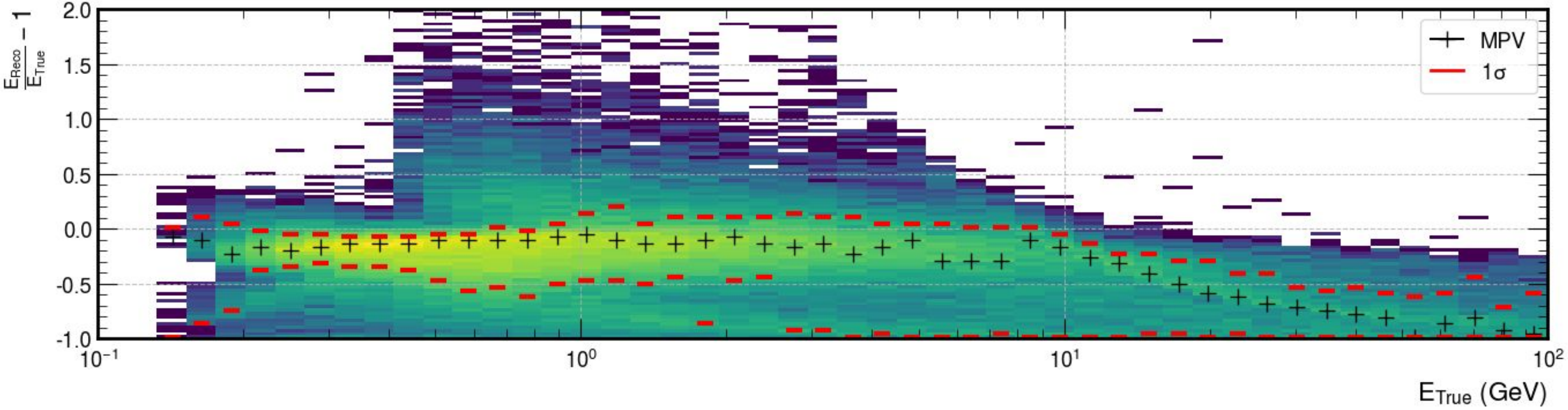


Energy reconstruction - Summary

- **Lepton energy**:
  - **MCS reaches a plateau @ E ~ 7.5 GeV**
    - Hardcoded maximum energy: fixed in dunereco v09_81_00d01
  - **MCS fails quite often (~34%)** when longest tracks not contained. Different methods to be tested
- ***ν* energy**:
  - Linear corrections on lepton energy must be applied for different methods



Angular reconstruction - Summary

- Started angular reconstruction with longest track assumed to be a muon
- **Fermi motion** impacts angular reconstruction for low energy neutrinos (drives the limit of reconstruction):
  - Using all particles minus neutrons: $1\sigma \sim 20^{\circ}$ @ $E_\nu \sim 1$ GeV
  - Using lepton: $1\sigma \sim 20^{\circ}$ @ $E_\nu \sim 3$ GeV
- **Next steps:**
  - Add other tracks and showers based on how good reconstruction is and which impact we expect from Geant4
  - First attempt of Particle Identification (PID) w/ anatree (Chi2PIDAlg.h):
    - PID for muons suggested by Dominic (PandizzleAlg.h): to be tested