Energy Reconstruction for Theia

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Dec. 8th 2023

Fast energy reconstruction - Methodology

Muon can be measured with Cherenkov ring.

- **Energy excluding muon ~ Total scintillation light - muon energy equivalent scintillation light**

In addition, pions may be measured with Cherenkov ring if above Ch. threshold.

- **Energy excluding muon and pions ~ Total scintillation - muon energy scintillation - pion energy scintillation**

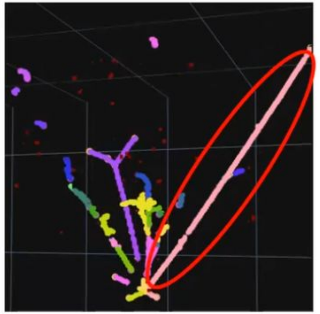
All remaining energy may be measured calorimetrically.

Neutrino and antineutrino interaction with DUNE spectra with 5% WbLS target
-> focus on FHC for today

Energy reconstruction

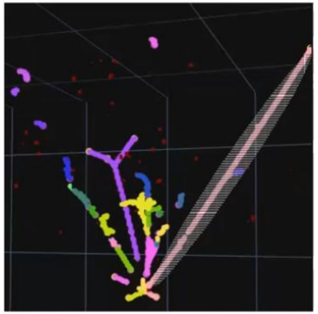
How DUNE LAr works

$$E_\nu(\nu_\mu) =$$

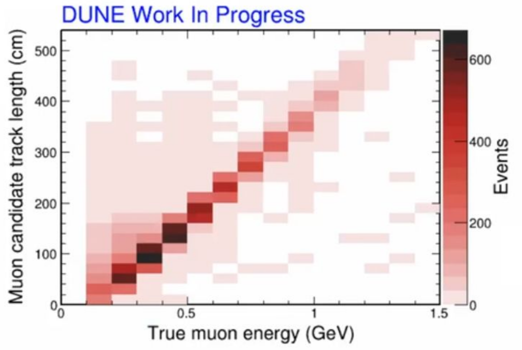


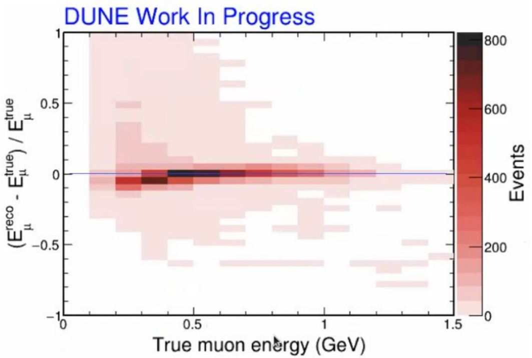
muon energy (range)

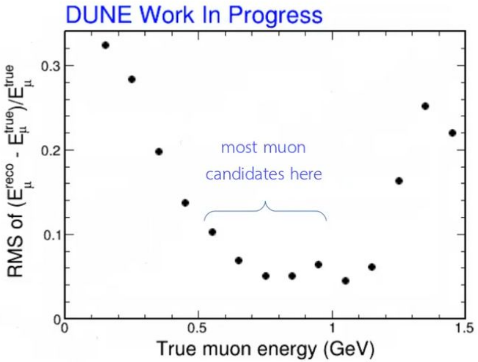
+



everything else (calorimetric)

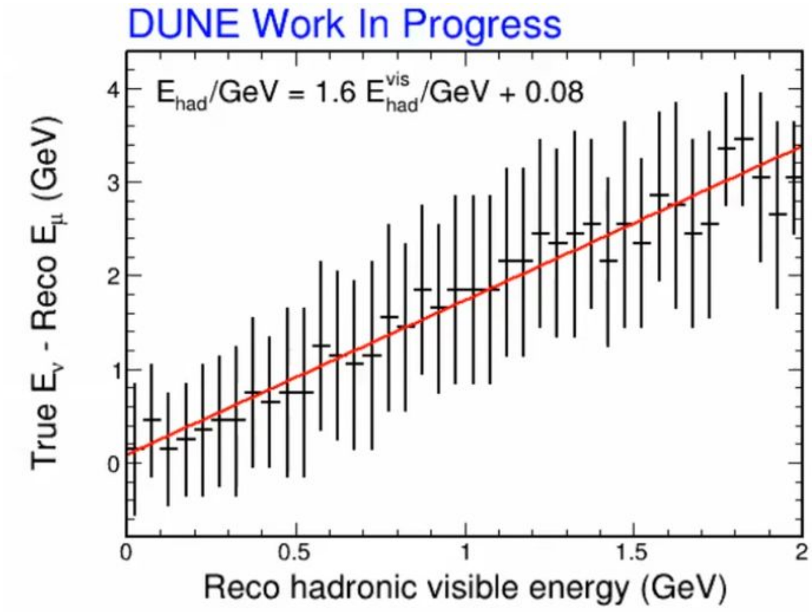


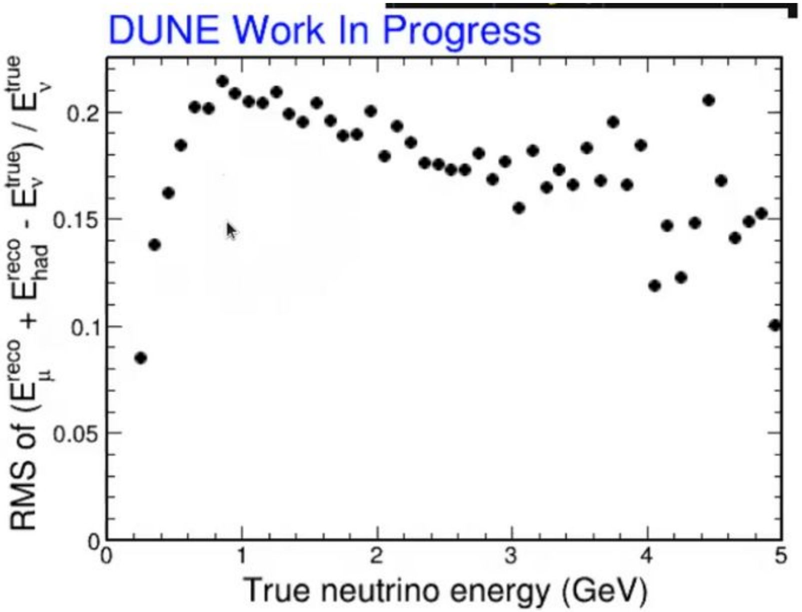




Energy reconstruction

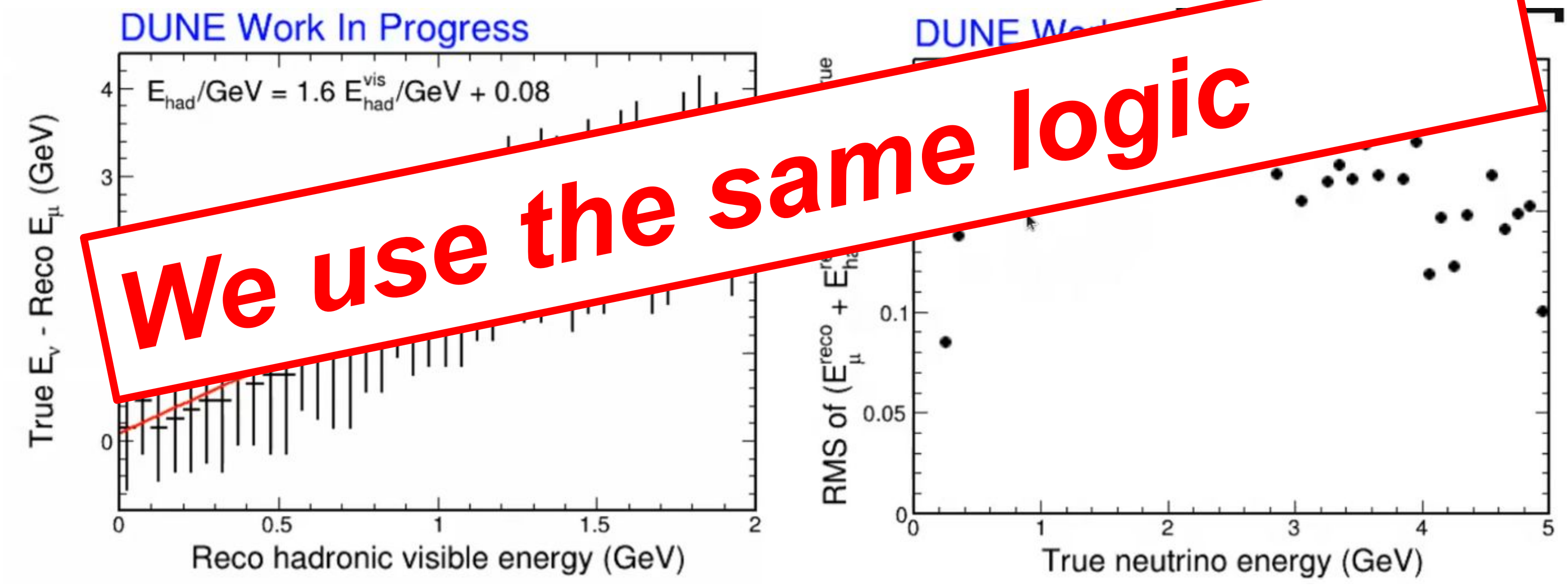
DUNE hadronic energy



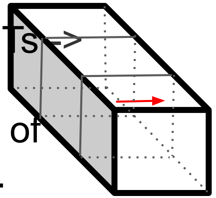


Energy reconstruction

DUNE hadronic energy



Simulation with ratpac



Geometry

- Considering a 25-kt Theia, 40% coverage results in >46,000 20-inch PMTs → too heavy for simulation.
- Instead, having 14 big sensitive regions and look at the detailed location of each hit, with quantum efficiency from Hamamatsu R14688 without TTS.

Physics model

- Various GENIE versions (2_12 for today) are ready for the neutrino interaction.
- Various G4 models are ready for the particle propagation, default QGSP_BERT.

WbLS Optical model

- Scintillation code in RAT is based on GLG4Sim with model parameter inputs.
- Light yield from measurement: here.
- Rayleigh scattering from BNL measurement.
- *Absorption length from combination of BNL LABPPO measurement and Pope+Smith for water.*
- Refractive index, scintillation rise time and spectrum are from measurements.

Output information

- Ratpac output root with true PE location and time.
- PMT Transit time spread, charge can be added, but not at the moment.

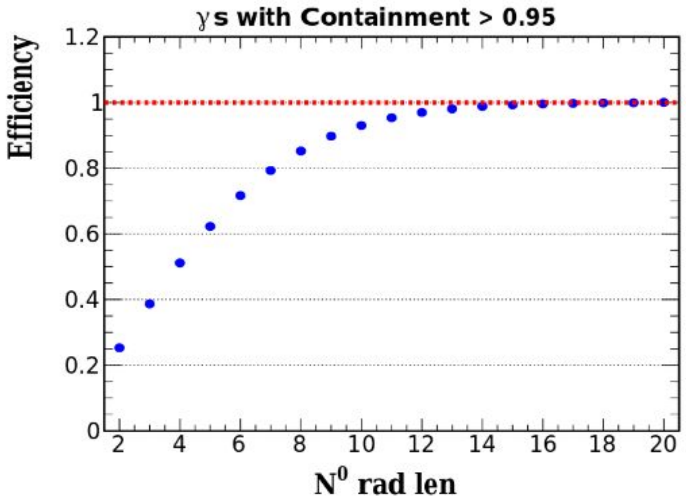
Event containment

Water radiation length is about 36 cm-> given 10 radiation length, we will contain almost all gammas.

Requirement of 10 radiation length on the downstream face and four side faces makes our fiducial mass ~ 11 kton.

- This number can/should be optimized.

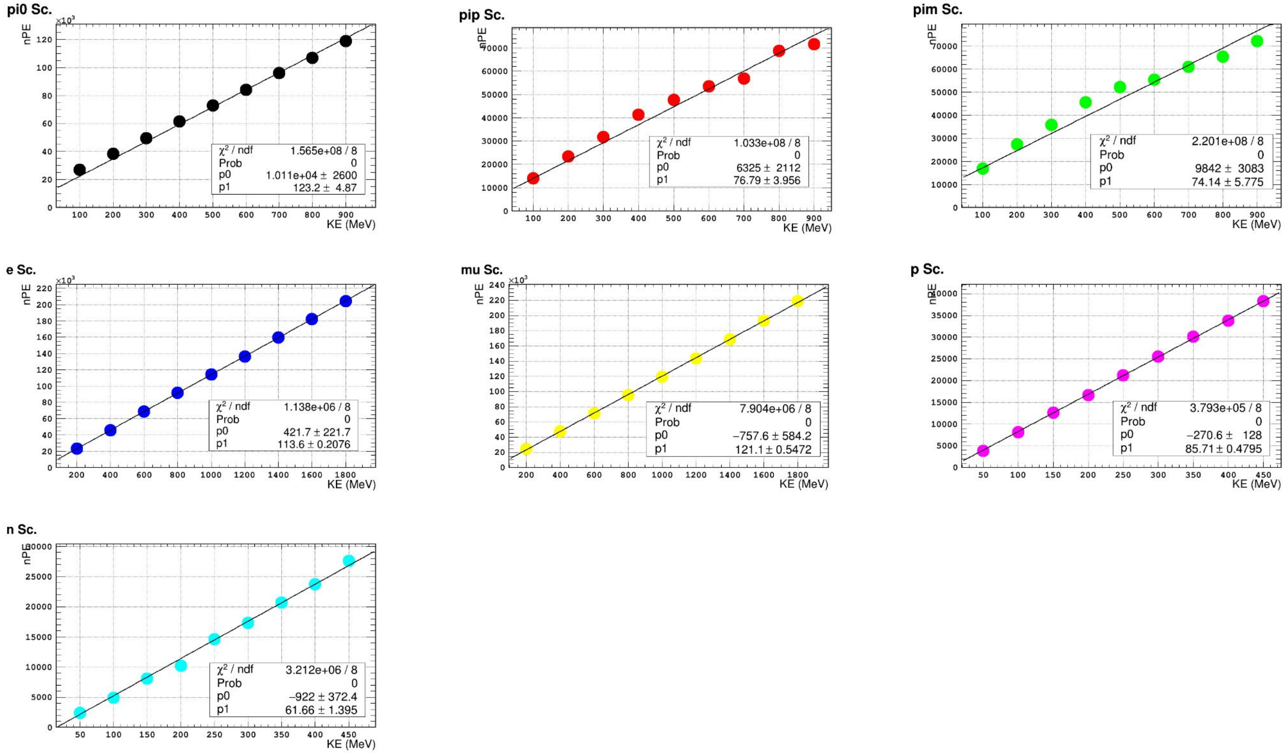
The events were simulated within a small box Region (2m x 2m x 2m), but should be extendable to 11kton.



Energy response in the WbLS (5%)

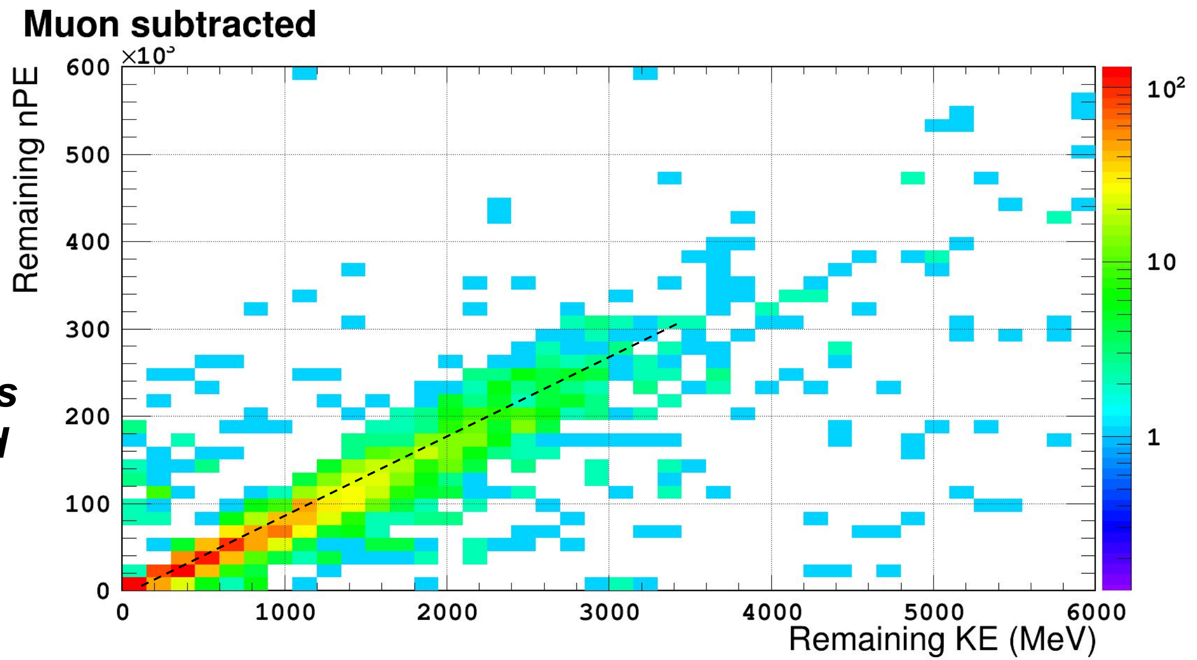
Scintillation light

Very linear!



Reconstructing energy with PE vs. KE relation

Muon KE subtracted energy vs. Muon PE subtracted nPE



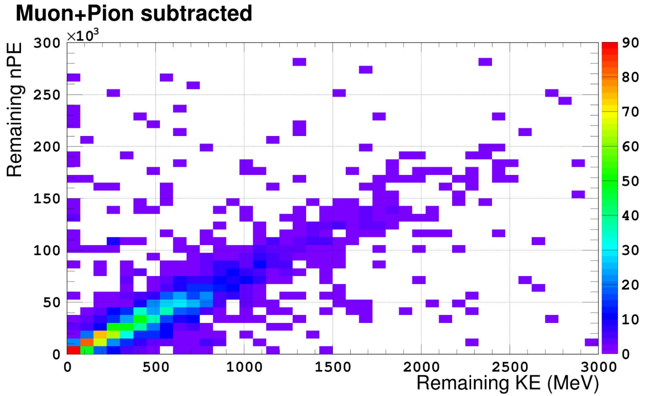
Scintillation light -> all particles KE below Cherenkov threshold

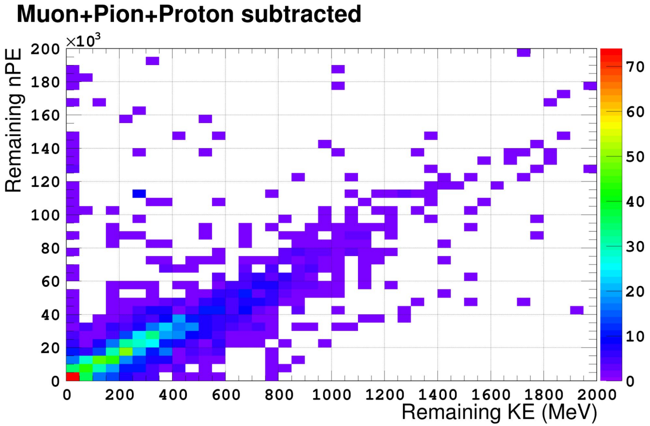
Pion and proton above the Cherenkov threshold

The pion above the Cherenkov threshold can be reconstructed with the Cherenkov ring, assuming the same momentum resolution as the muon.

The remaining energy is reconstructed with the scintillation light.

The same thing can be done for the proton as well.

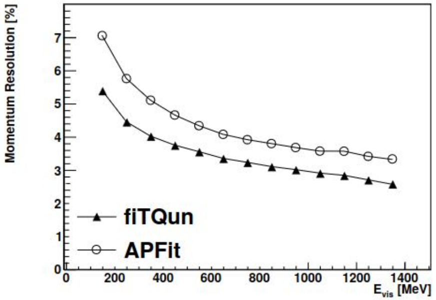




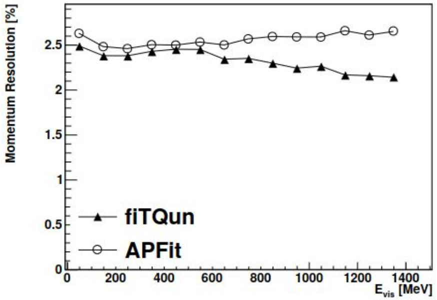
Adding particle smearing

FiTQun performance ==>

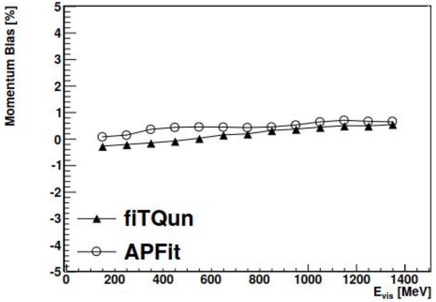
I used these momentum resolutions as functions of energy for muon and charged pion if it is above the Cherenkov threshold.



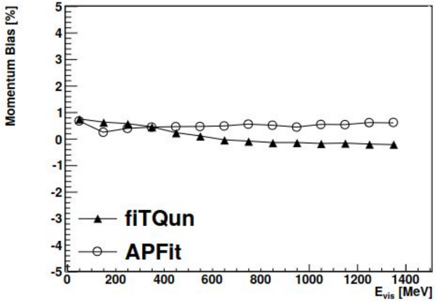
(a) Momentum resolution of true single-electron events.



(b) Momentum resolution of true single-muon events.



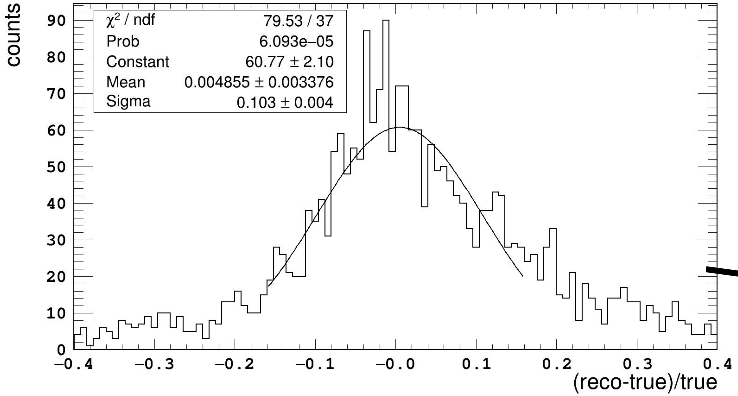
(c) Momentum bias of true single-electron events.



(d) Momentum bias of true single-muon events

Resolution with smearing

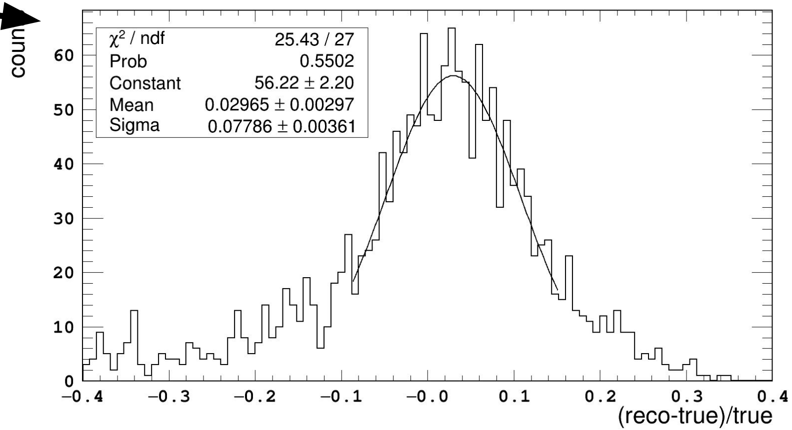
Muon subtracted Pi with smearing



Identify pion perfectly

with Ch. light

Muon+Pion subtracted with smearing



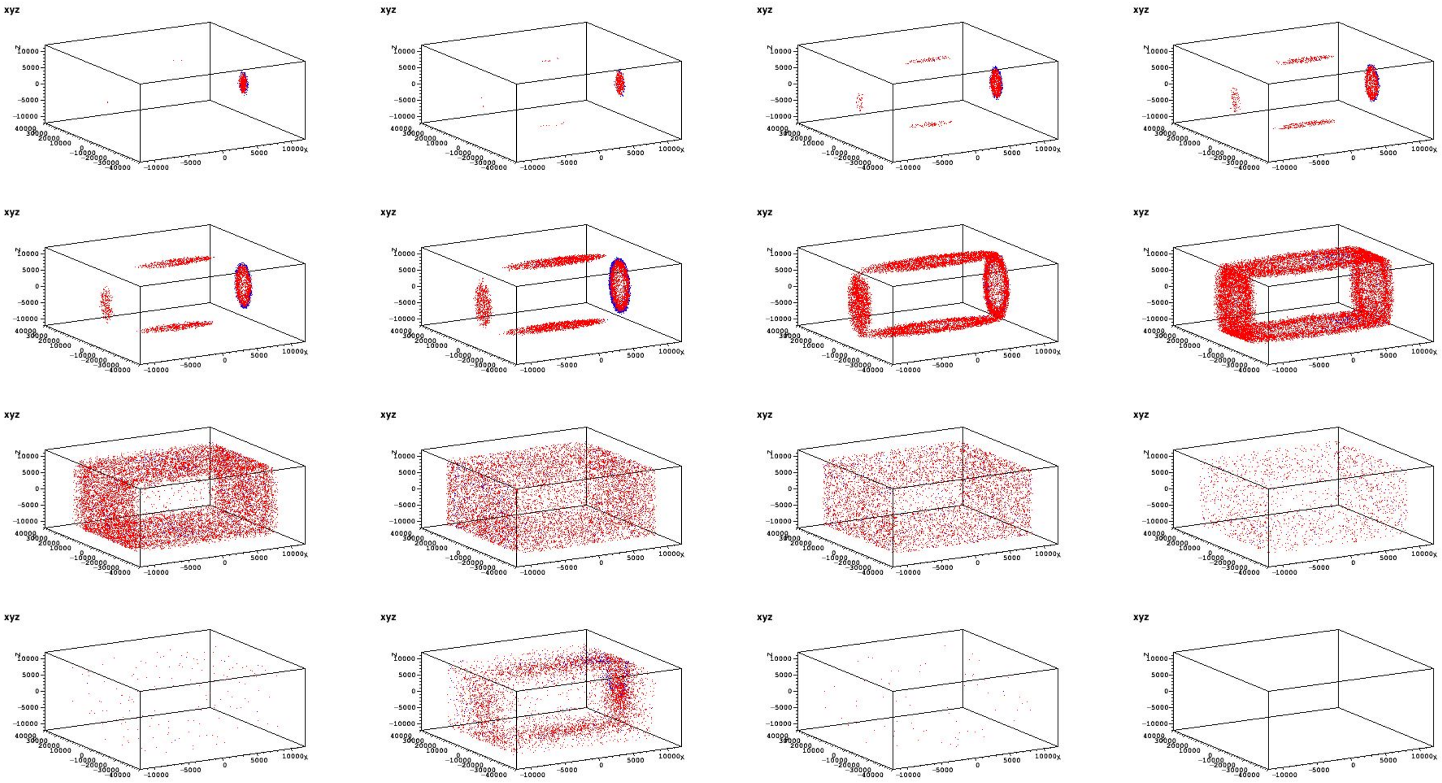
Muon ring contaminated by the scintillation light

To be more realistic, the resolution can be estimated by the uncertainty of the light inside the Cherenkov cone induced by both Cherenkov and scintillation light.

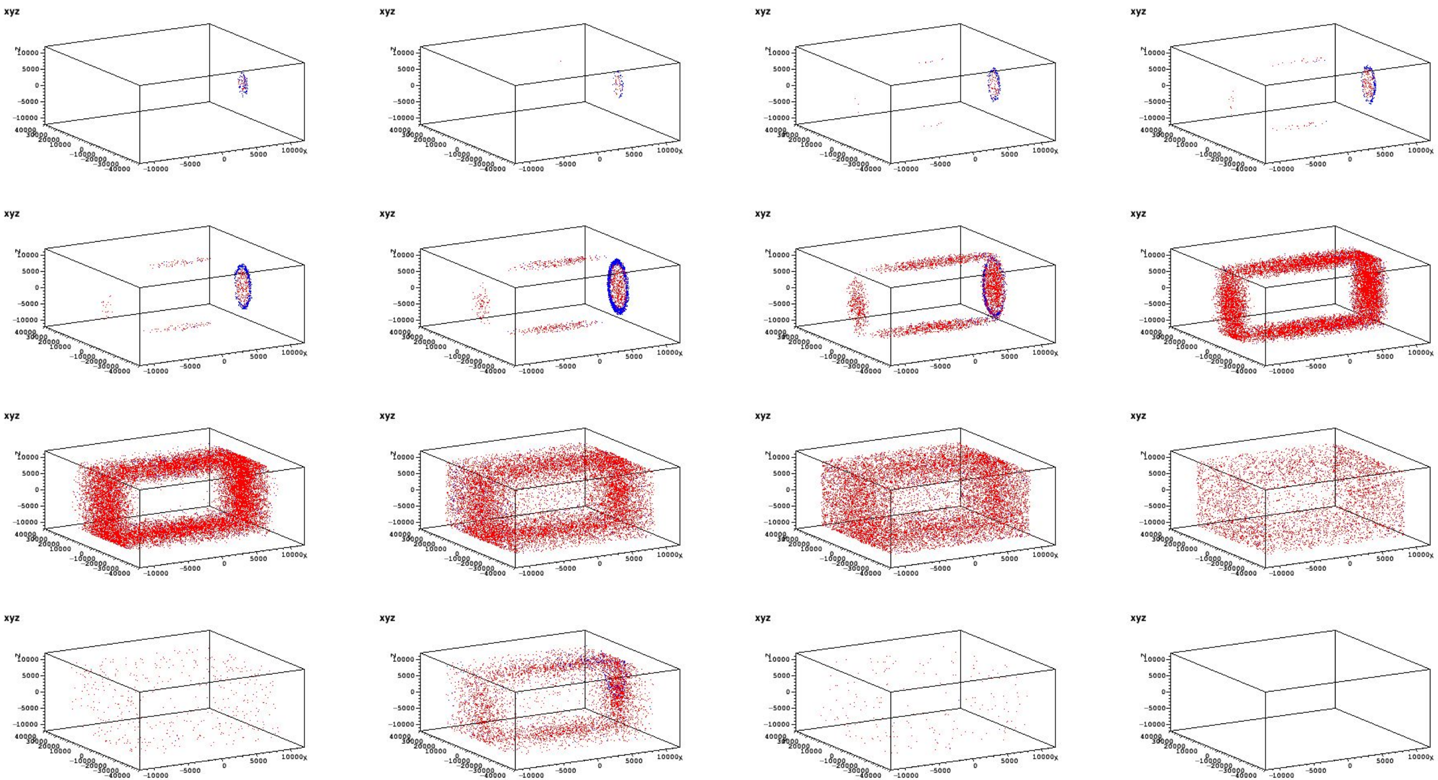
The decay time may have impact on the energy resolution estimate.

- More scintillation light at early time present more fluctuations in the Cherenkov cone.

600 MeV muon with 2ns scintillator decay time



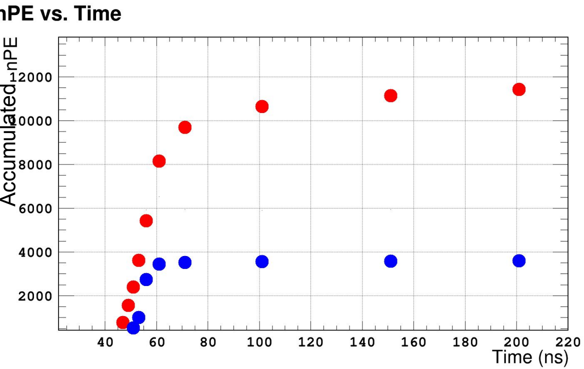
600 MeV muon with 45ns scintillator decay time



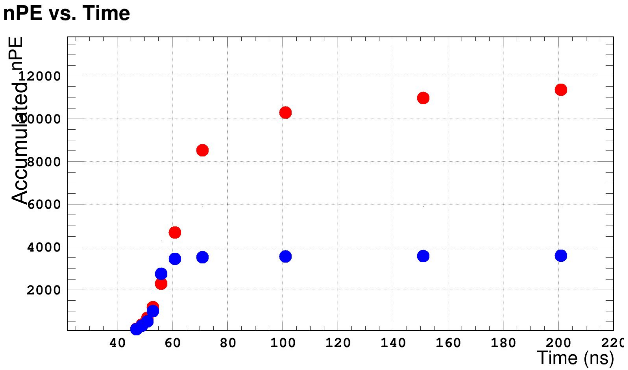
Accumulated light over time

600 MeV muons

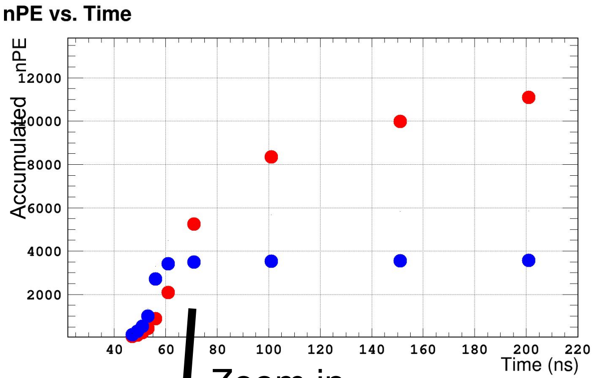
2 ns decay time



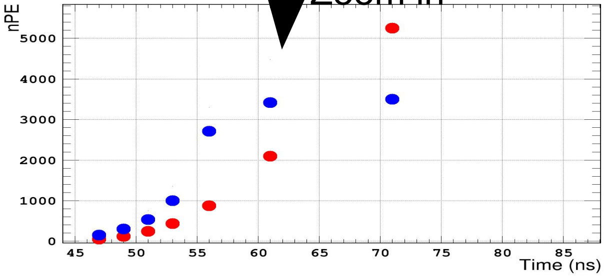
15 ns decay time



45 ns decay time

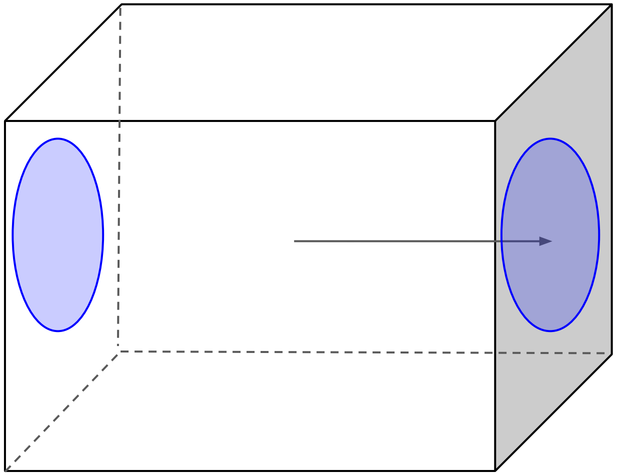


Zoom in



Red:Scint. in Cherenkov cone
Blue:Cher. in Cherenkov cone

Direct scintillation light subtraction



Define ring clarity as:

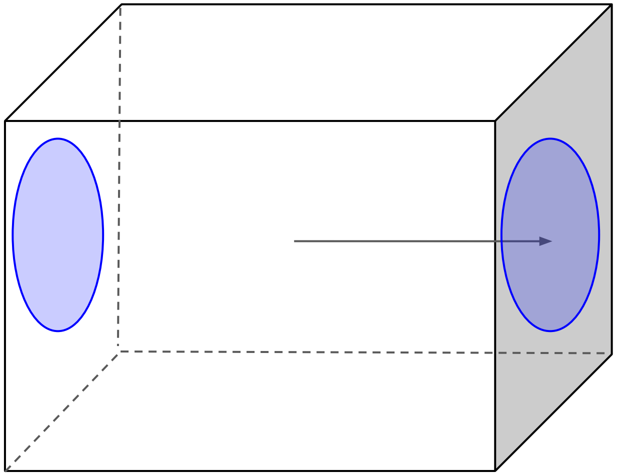
Total light in ring - light in opposite face with same solid angle

In-ring light will be Cherenkov + Scint.

Far region will be primarily Scint.

The subtraction should yield the net Cherenkov signal.

Correction to the forward/backward asymmetry



Particle travel may induce a forward/backward asymmetry in the scintillation light estimate.

Forward/backward asymmetry is estimated with a sample ***without*** Cherenkov light in simulation.

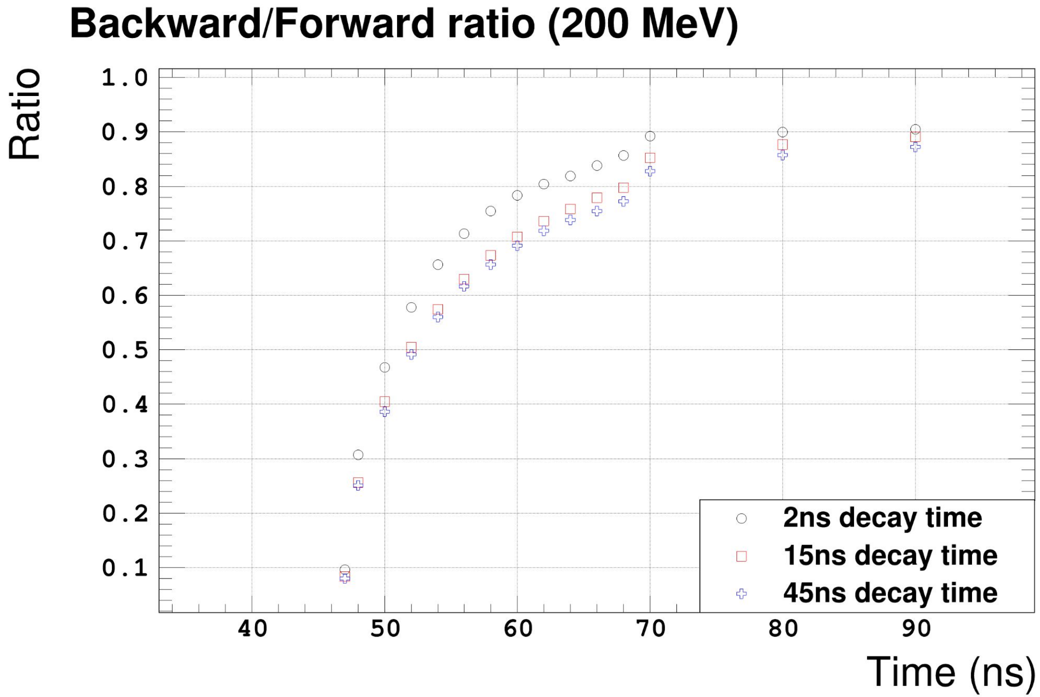
Same solid angle was selected.

The backward/forward ratio is obtained for each energy for muons.

Backward/forward ratio

This ratio as a function of time was obtained for different energy.

Particle pointing direction has more light for longer decay time at early time.

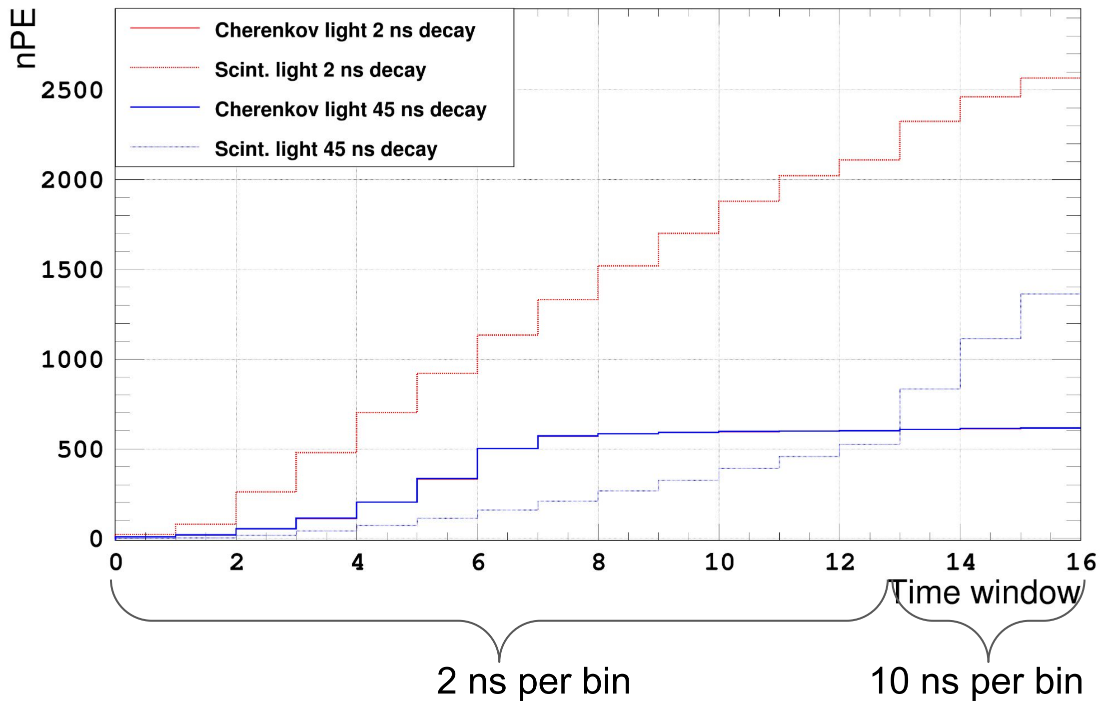


Scint. and Cherenkov light with different decay time

Cherenkov lights are very similar for different scintillation decay time.

Scintillation decay time push the scintillation light happen very late.

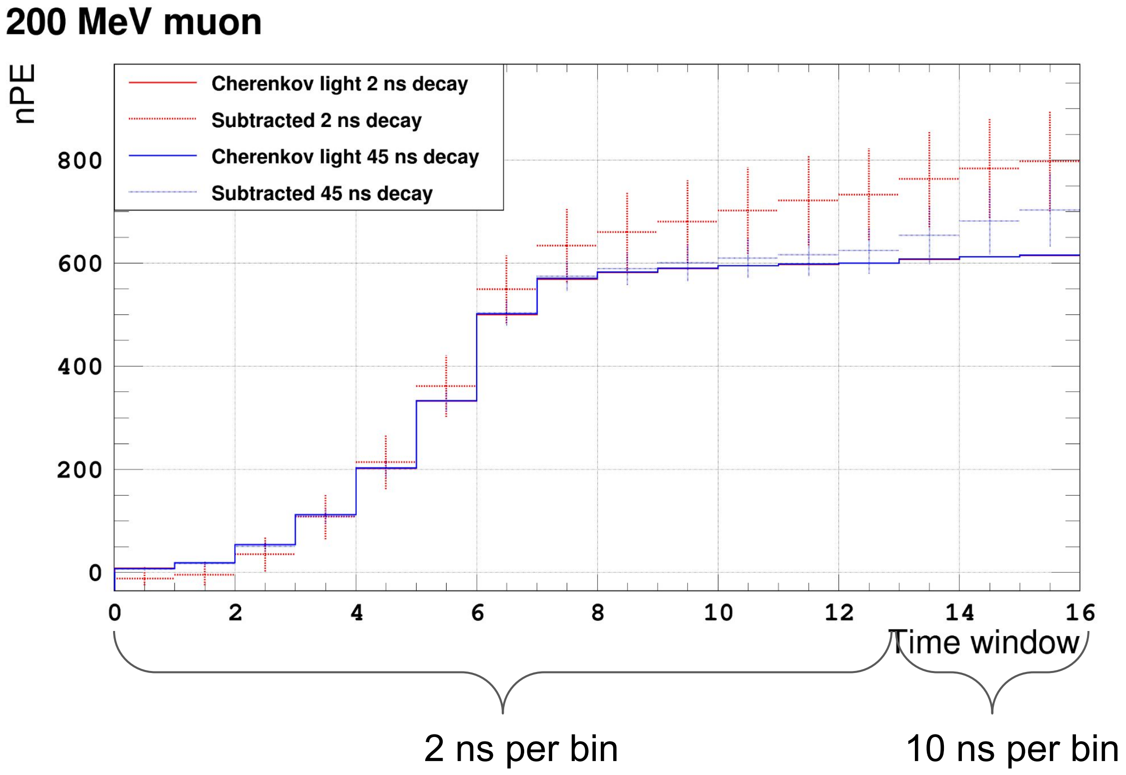
200 MeV muon



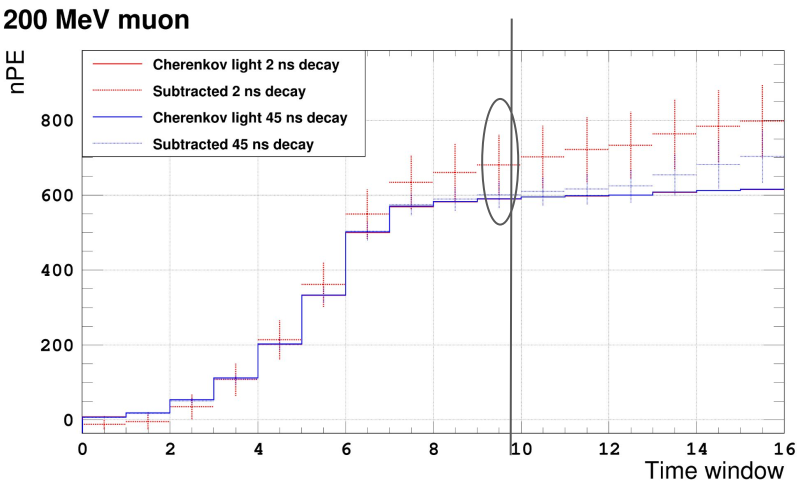
Scintillation light subtraction

For a given energy bin, take the event number on the opposite face with a Cherenkov solid angle, use the backward/forward ratio to get the expected forward scintillation light.

Errors were obtained with the spread from 100 events, proportional to the stat. Unc. of the predicted scintillation light.



Propagate to the neutrino energy resolution



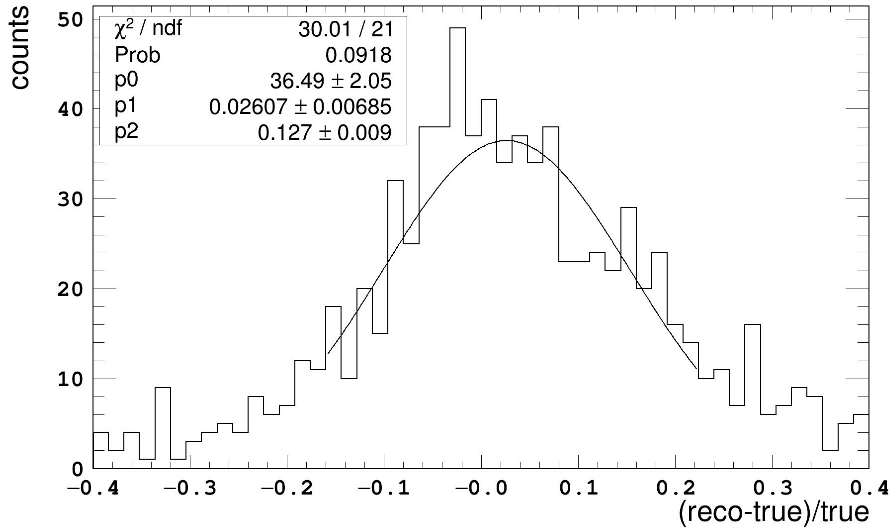
For each muon in the neutrino interaction, cut on the first 10 time bins (20 ns window).

Randomly vary the muon induced subtracted nPE based on the error bars.

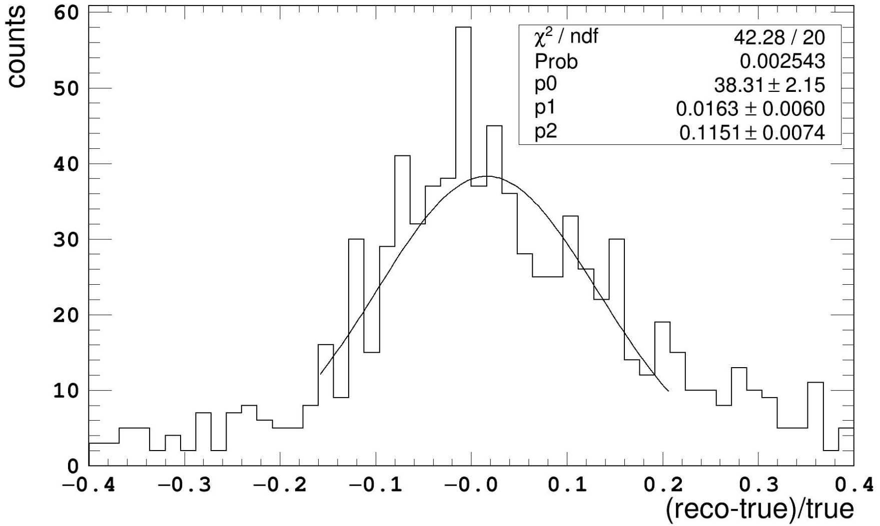
Assuming the nPE is proportional to the reconstructed muon energy. Input the reconstructed muon energy to the final neutrino energy reconstruction.

Comparing two decay times

Muon subtracted with smearing 2 ns decay time



Muon subtracted with smearing 45 ns decay time



Brookhaven National Laboratory

Energy resolution summary table

Energy resolution			
Decay time	μ-only using Cherenkov	μ and π using Cherenkov	μ, π and p using Cherenkov
2 ns	12.7%	9.209%	9.112%
15 ns	12.4%	8.989%	9.10%
45 ns	11.51%	7.844%	8.301%

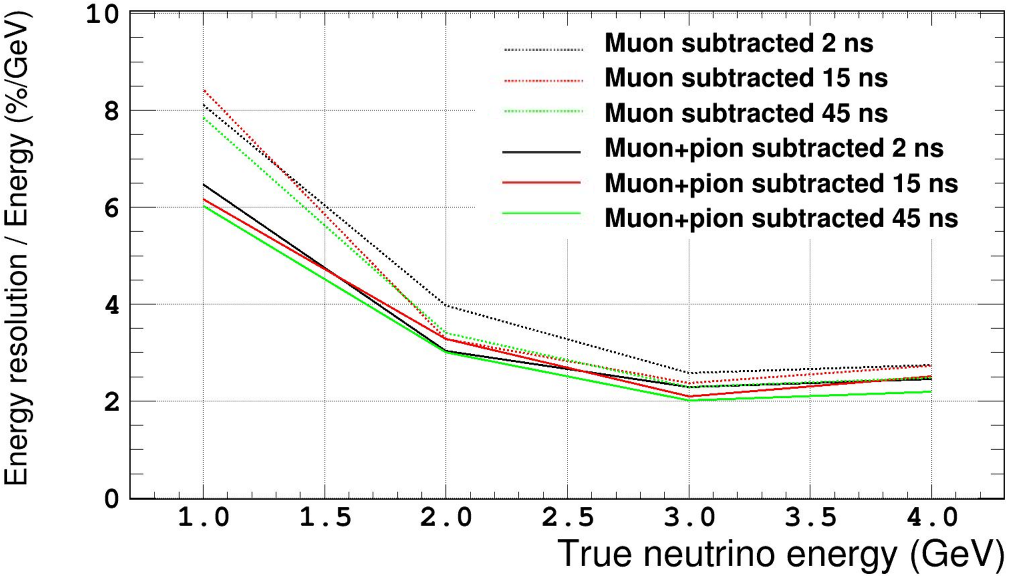
The result is slightly worse than the result using FiTQun muon momentum resolution directly

Individual neutrino energy

The exactly same thing was completed for 1,2,3,4 GeV neutrino, instead of the integrated DUNE flux.

For each energy, the muon-only or muon+pion momentum resolution was estimated with the aforementioned Cherenkov light variation, and the remaining energy was reconstructed with the KE-PE map for each individual energy.

We may expect better resolution for each energy due to dedicated KE-PE map.



A first comparison with LAr

Conclusion

We have implemented a complete first version of neutrino energy reconstruction in the DUNE far detector. This reconstruction is done by making separate estimates of the lepton and hadronic energies in CC events. We achieve overall energy resolutions of 20% for ν_μ CC and 13% for ν_e CC events.

Reference

Very preliminary

Theia numu CC

muon with Ch.; all others with Sc.: below 13%

Summary

Steven and I have completed a first pass of the sample generation, all the way from ratpac to caf.
However, many more events are needed.

The caf file is independent from OA fitters. Steven will tell you about our plan for the OA fitter effort.

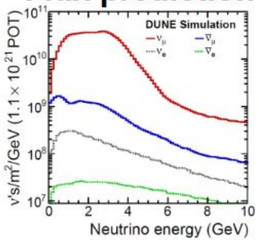
Backups

Toward the DUNE LBL analysis

Callum Aug. 2022

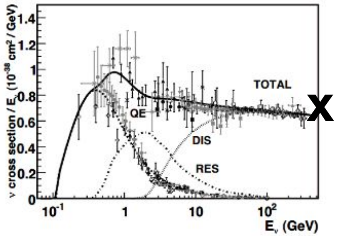
Detected event Rate for each Energy bin =

Flux prediction



X

Interaction model



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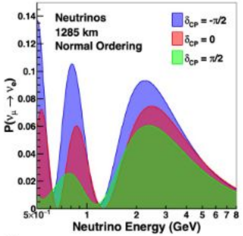
Oscillations

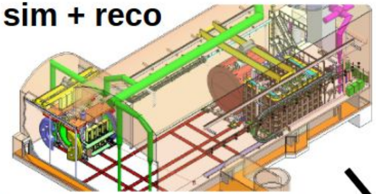


X

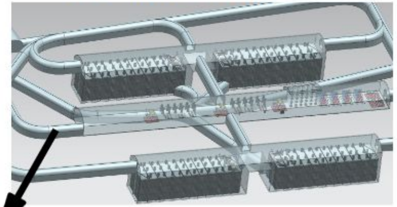
Detector non-perfection (energy resolution, efficiency etc.)

SAND and PRISM Not immediate
ND constrains the flux and nu-Ar interaction syst.

ND sim + reco



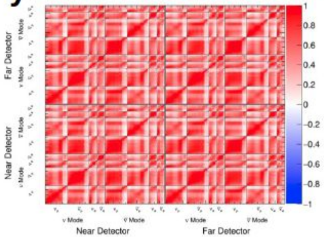
FD sim + reco



FD takes the constrained flux and interaction syst. with its own detector syst. (energy + efficiency)

Correlated syst. as floating parameters

Systematic uncertainties



Fitting framework

$$\chi^2(\vec{\vartheta},\vec{x}) = 2\sum_{i}^{N_{\text{bins}}}\left[M_i(\vec{\vartheta},\vec{x}) - D_i + D_i \ln\left(\frac{D_i}{M_i(\vec{\vartheta},\vec{x})}\right)\right] + \sum_{j}^{N_{\text{systs}}}\left[\frac{\Delta x_j}{\sigma_j}\right]^2$$

Toward the DUNE LBL analysis

What's in-hand with a WbLS detector?

- **Flux is the same.**
- **We have the estimated energy resolution for each energy range.**
- **We could (not yet) have the detection efficiency with a box-shaped detector.**

What we don't have for a WbLS detector?

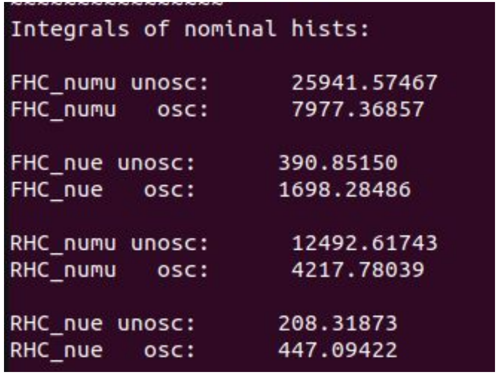
- **nu-H2O interaction systematics (with or without a H2O ND)**
- **Correlation between the H2O and Ar interaction parameters**

Toward the DUNE LBL analysis

- **DUNE LBL analysis is moving from Cafana (NOvA framework) to Mach3 (T2K framework). We need to stick to the latest one.**
- **The first step could be implementing our energy resolution with all existing systematics in DUNE LBL framework-> not realistic, but a ramp-up work.**
    - **the study would show "assuming the same level of constraints on the flux and interaction obtained for the H2O target with some near detectors, the WbLS far detector can lead to a sensitivity of X."**
- **Modifying the systematics in the framework will be a longer-term work. It requires:**
    - **Knowledge of the near detector**
    - **If combing with Ar in any way: Implementing the correlation between Ar and H/C/O**
    - **If independent near-far WbLS target: T2K-style implementation**

Toward the DUNE LBL analysis

- Started conversation with Callum Wilkinson and Patrick Dunne - conveners of LBL group and MaCh3 group
- Started conversation with Ed and Asher - major force in MaCh3
- Started conversation with Liban - major force in MaCh3_DUNE
- Started conversation with Dominic - FD simulation convener
- Able to go through the chain of GENIE-> Ratpac-> Fast energy handling -> CAF format conversion (CAF is required by DUNE OA)
- Compiled and run MaCh3 successfully to obtain event rate and systematic variations



```
Integrals of nominal hists:

FHC_numu unosc:      25941.57467
FHC_numu   osc:      7977.36857

FHC_nue unosc:       390.85150
FHC_nue   osc:       1698.28486

RHC_numu unosc:      12492.61743
RHC_numu   osc:      4217.78039

RHC_nue unosc:       208.31873
RHC_nue   osc:       447.09422
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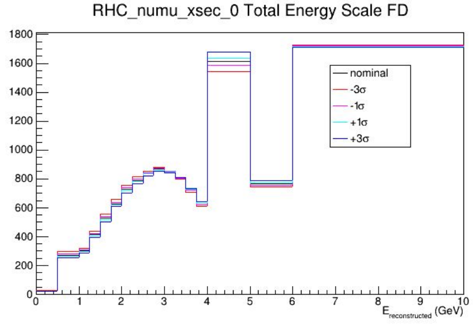
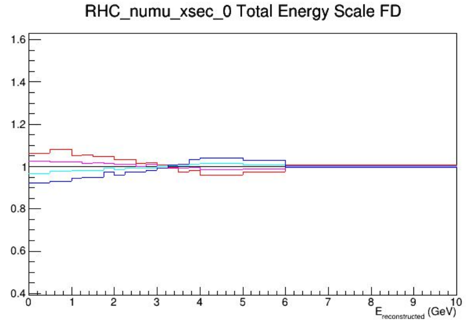




Neutrino sample format

In MaCh3, the samples look like “fHC_nua_x_nub” with f horn current, and a and b two flavors.
Steven and I had multiple redirections and figured out that: nua_x_nub means that with the flux of nua, change the nua events to nub events. For example, numu_x_nue means nue events with numu flux.
The a loops through mu and e; the b loops through mu, e and tau.

Neutrino sample requirement

Currently MaCh3 is taking flavor x to flavor y sample with the selection of flavor z. Here x and z loop over numu and nue; y loops over numu, nue, nutau. Same thing for antineutrinos and do it for both FHC and RHC -> 48 samples in total (2x2x3x2x2). However, we can simplify this:

- Let's worry about the selection at a later stage
- Wrong-sign generated with the right-sign
- Two swapped samples can be generated at once

The resulting sample number is 6 at least:

- FHC unoscillated
- FHC numu->nue, nue->nutau, same for antinu
- FHC numu->nutau, nue->numu, same for antinu
- RHC unoscillated
- RHC numubar->nuebar, nuebar->nutaubar, same for nu
- RHC numubar->nutaubar, nuebar->numubar, same for nu

Three steps

1. What is the intrinsic energy resolution in a WbLS detector?
   - Due to the binding energy, nuclear final state interaction
2. What is the energy response of Cherenkov and Scintillation light to each particle?
   - In particular, we need the scintillation light response to pi0, pi+, pi-, e, mu, proton, neutron.
3. In the context of neutrino interaction, what is the resolution we can get?
   - Test with different muon momentum reconstruction resolutions with different scintillation decay times.

Toward the DUNE LBL analysis

Had a few conversations with the DUNE LBL convener

- **DUNE LBL analysis is moving from Cafana (NOvA framework) to Mach3 (T2K framework).**
- **The first step could be implementing our energy resolution with all existing systematics in DUNE LBL framework.**
- **Modifying the systematics in the framework will be a long-term run. It requires:**
    - **Knowledge of the near detector**
    - **If combing with Ar in any ways: Implementing the correlation between Ar and H/C/O**
    - **If independent near-far WbLS target: T2K-style implementation**
    - **Good side: flux is shared.**

Intrinsic energy reconstruction

GENIE 2.12.10 with xsec DefaultPlusValenciaMEC

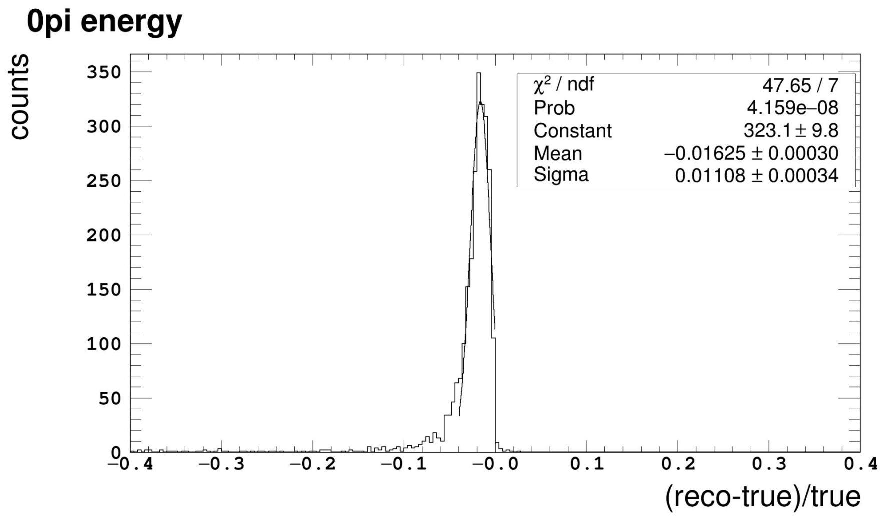
Reconstructed energy = all final state particle kinetic energy + muon mass if needed + pion mass if needed + baryon mass difference between target and outgoing

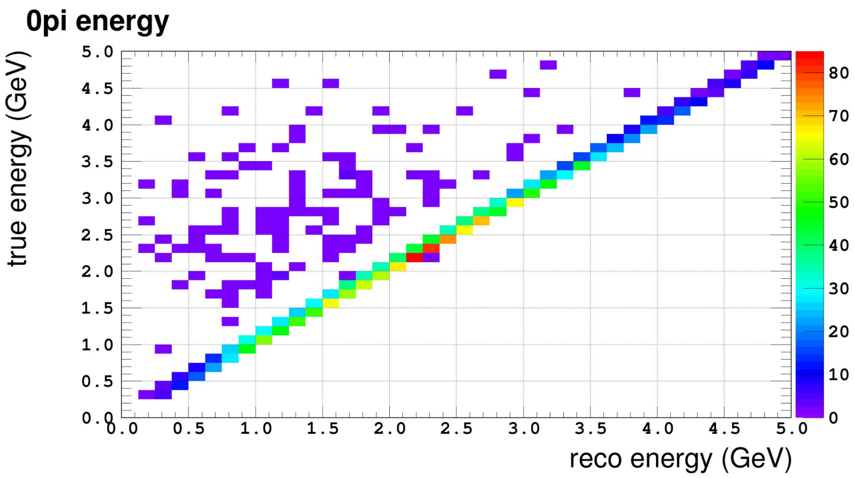
True energy = original neutrino energy

I separate out the three cases: 0 pion in the final state outgoing particle list, 1 pion (no matter pi0 or pi+-) in the final state outgoing particle list, and > 1 pion (nPi0 + nPi+ + nPi-) in the final state outgoing particle list.

Intrinsic energy reconstruction

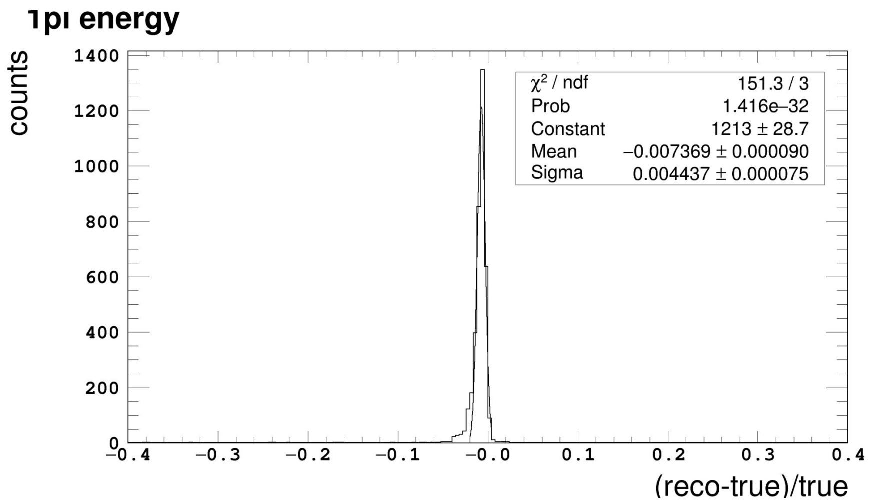
GENIE 2.12.10 with xsec DefaultPlusValenciaMEC

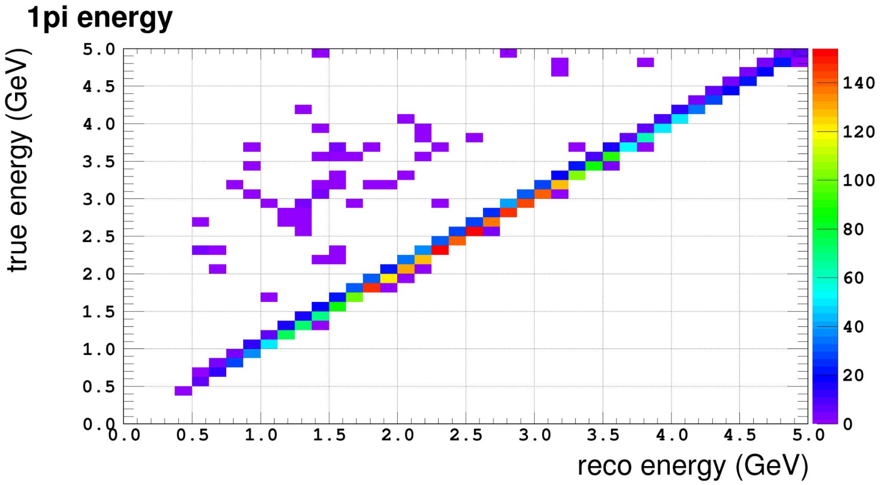




Intrinsic energy reconstruction

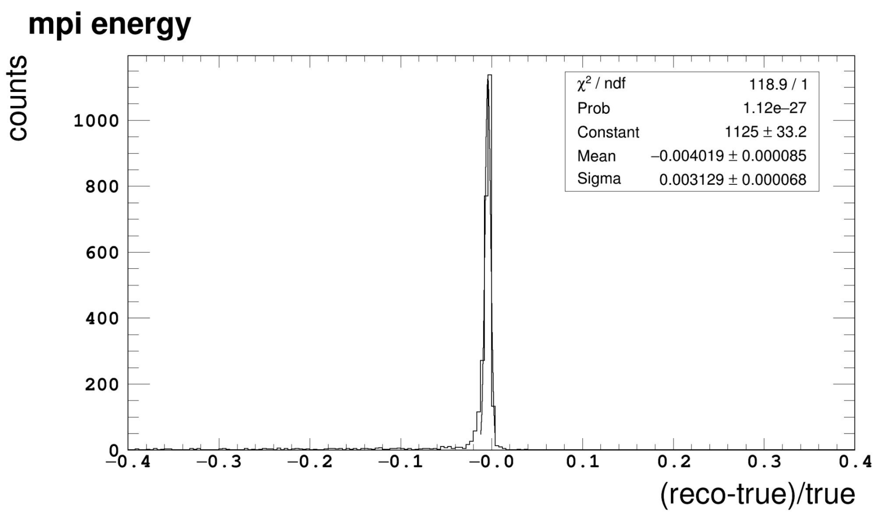
GENIE 2.12.10 with xsec DefaultPlusValenciaMEC

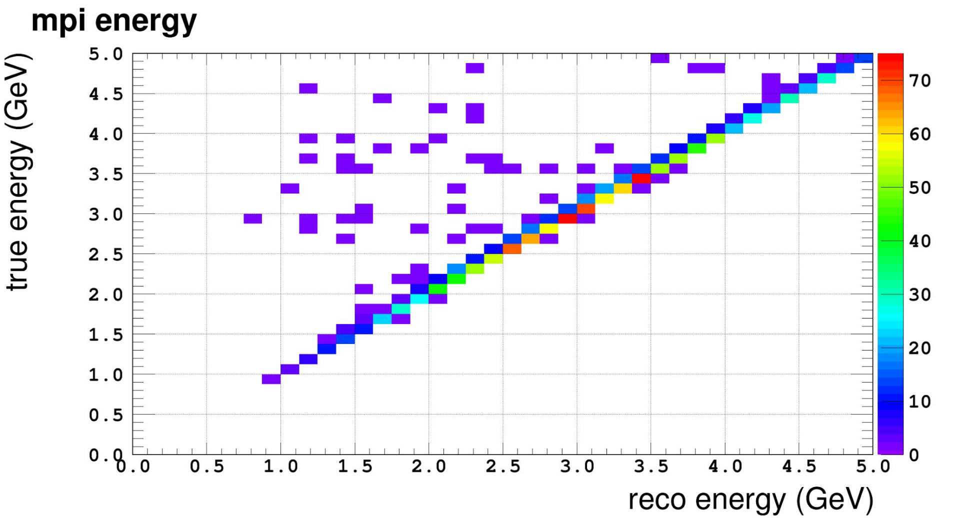




Intrinsic energy reconstruction

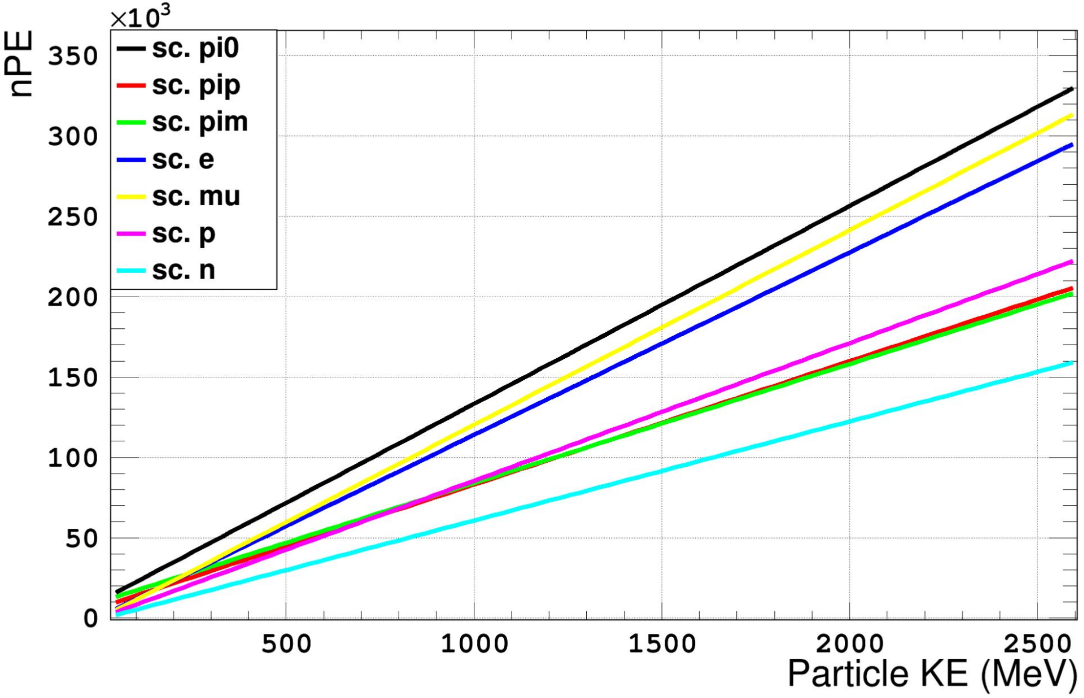
GENIE 2.12.10 with xsec DefaultPlusValenciaMEC





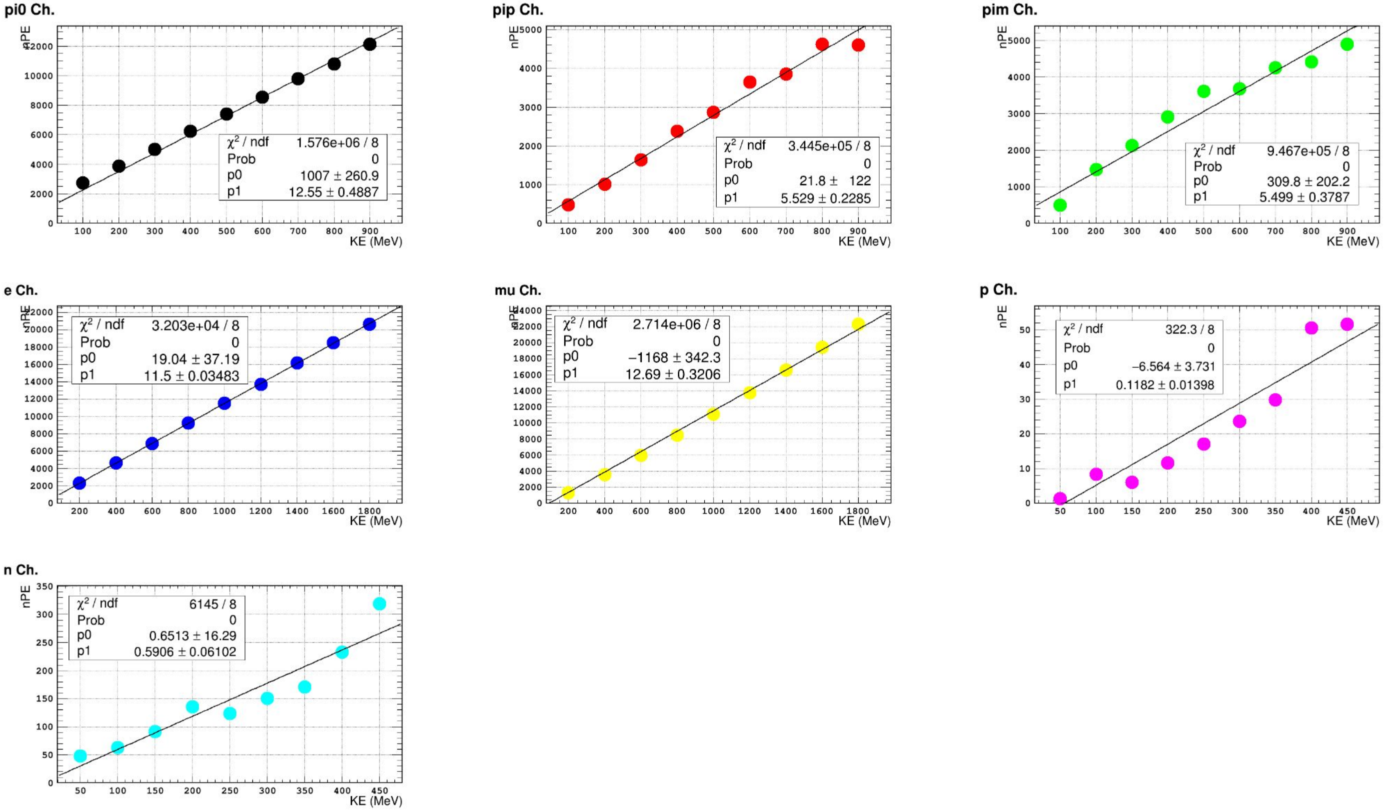
Energy response in the WbLS (5%)

Scintillation light vs. nPE fitting lines



Energy response in the WbLS (5%)

Cherenkov light

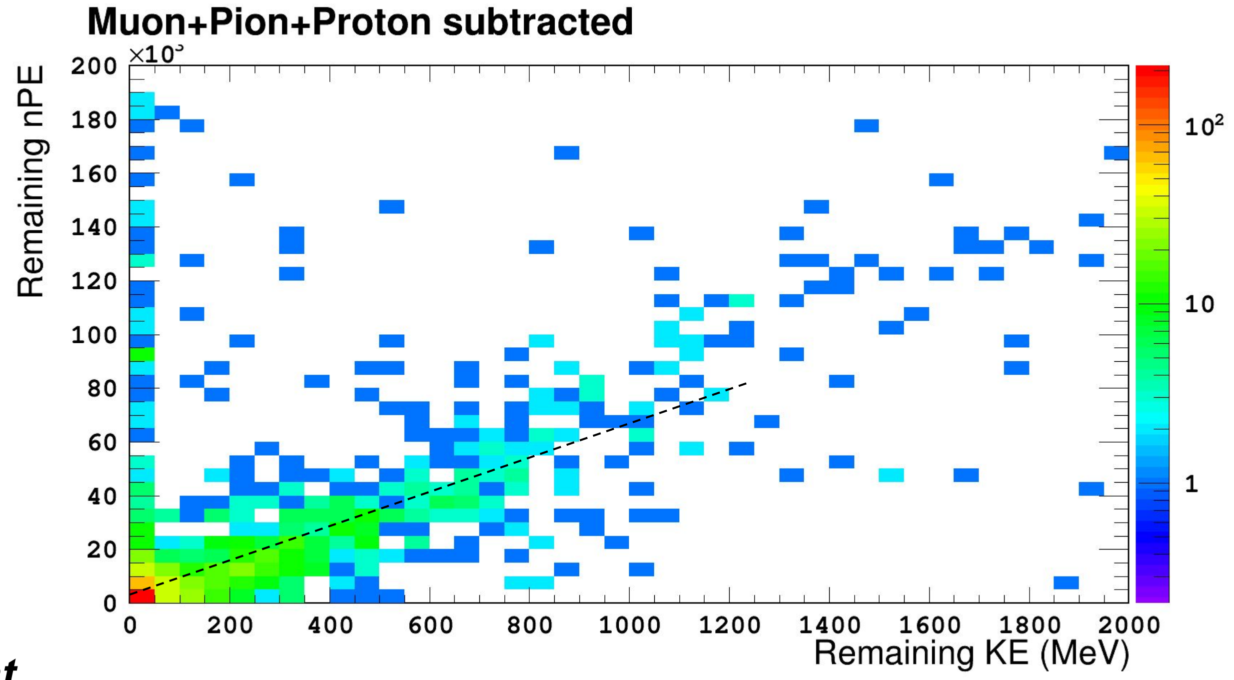


Reconstructing energy with PE vs. KE relation

Muon+Pion+Proton KE subtracted energy vs. Muon+Pion+Proton PE subtracted nPE

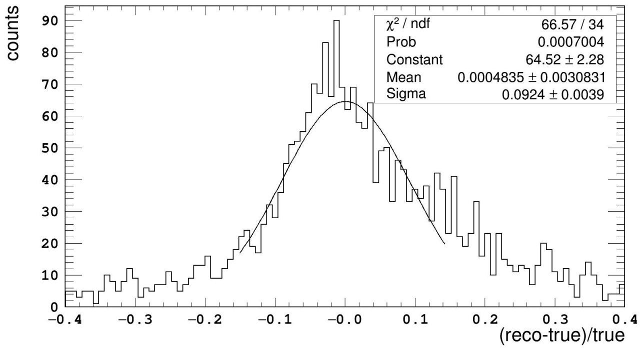
Assuming perfect ability to identify pion and proton-> even less realistic

Target: with scintillation light



Resolution with all those cases above

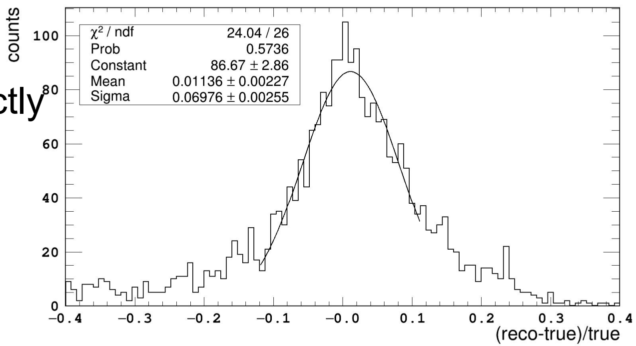
Muon subtracted



Identify pion perfectly

with Ch. light

Muon+Pion subtracted



Identify proton perfectly
With Ch. light

Muon+Pion+Proton subtracted