Neutrino energy reconstruction study in LArTPC

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Motivation

❑Understand the limiting factors that affect neutrino energy resolution

❑Simulation setup

- Neutrino interaction generator: Genie (**for** $\boldsymbol{\nu_\mu + Ar}$ **&** $\boldsymbol{\nu_e + Ar}$)
- Detector simulation: edep-sim (wrapper of Geant4)
- Detector geometry: LArBath (a very large volume of argon)
- 1000 events per 0.5 GeV in energy range of 0.5-5GeV

❑Previous study in these slides. Update in **this work:**

➢ Convert deposit energy to charge and light;

➢ Apply threshold;

➢ Simple reconstruction study from charge;

➢ Simple reconstruction study include light;

Energy deposition mechanism

- Energy deposition is shared between
  - N_{ex}: excitation quanta (exciton, de-excite by scintillation or heat)
  - N_i: ionization quanta (electron-ion pairs)
  - $\alpha = N_{ex}/N_i = 0.21$
  - $W_{ph} = 19.5$ eV
  - $W_{ion} = 23.6 \text{ eV} = (1+\alpha) W_{ph}$

$$N_{ex} + N_i = \frac{\Delta E}{W_{ph}}, \qquad N_i = \frac{\Delta E}{W_{ion}}$$

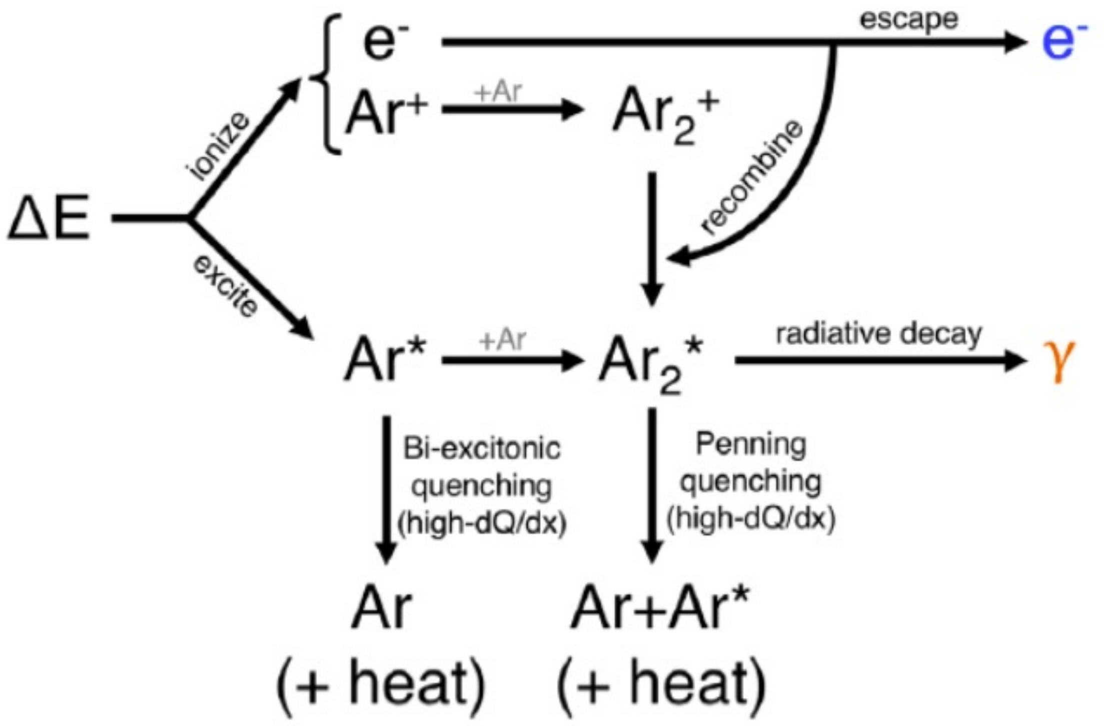
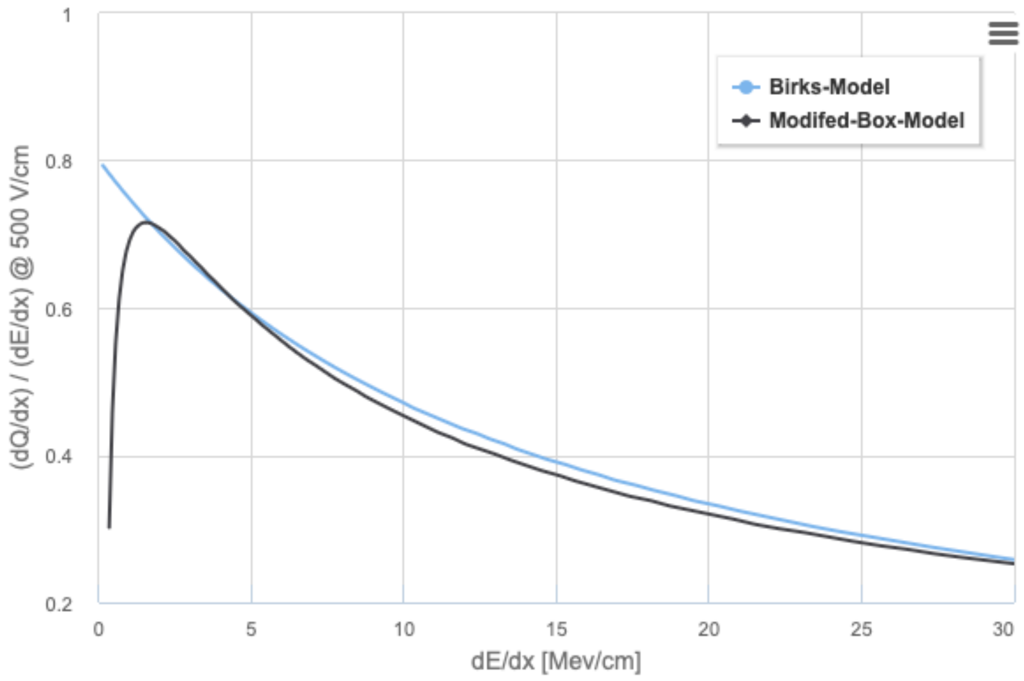


FIG. 1. Schematic diagram illustrating the production of free ionization electrons (e^-) and scintillation photons (γ) from energy deposited in liquid argon.

From deposit energy to charge ; Add threshold

- ❑ Convert deposit energy (dE/dx) to charge (dQ/dx)
  - e- recombination model: Birks model
- ❑ Recombination factor
  - For MIP (mu, e, …), r=0.7 @ dE/dx = 2 MeV/cm
  - For heavily ionizing particle (p, n, …), and at the end of the track, smaller r (much higher dE/dx)



Recombination factor:

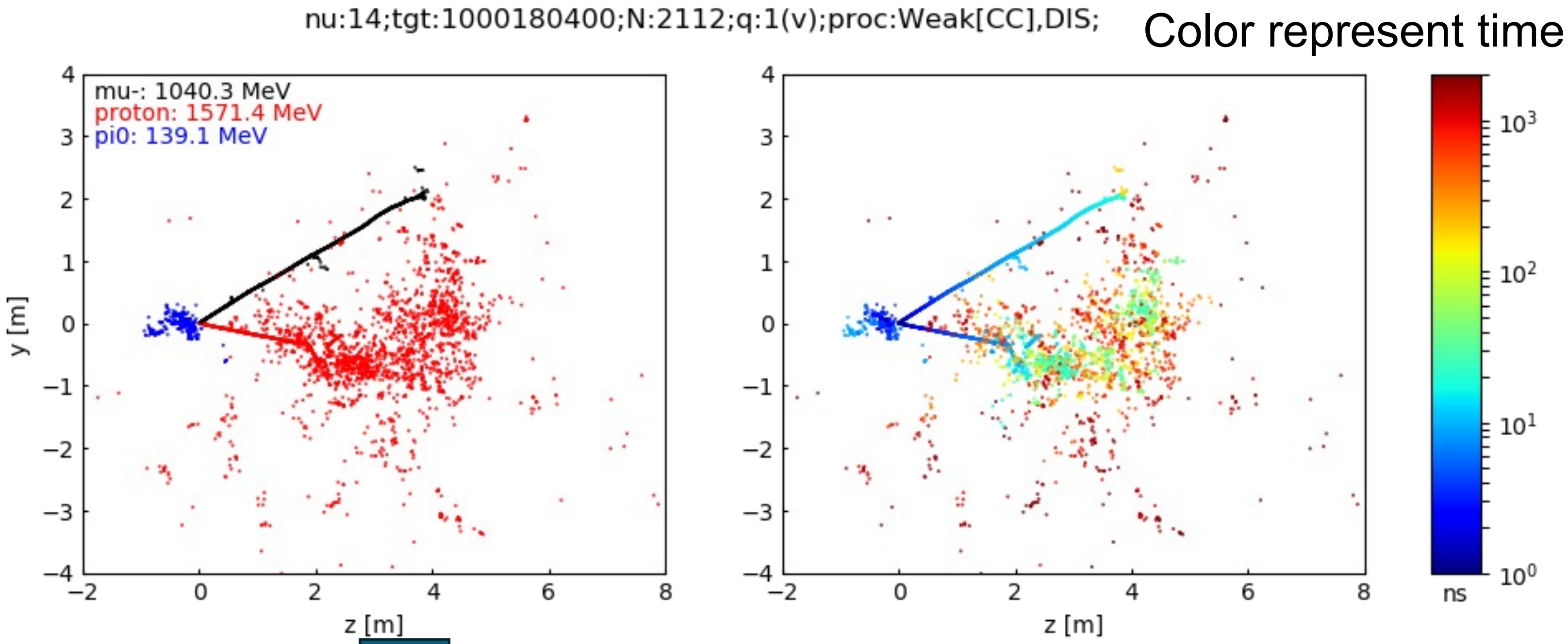
$$R_c = \frac{dQ/dx}{dE/dx} = \frac{A_{3t}}{1 + k_{3t}/\varepsilon \times dE/dx}$$

Where $A_{3t} = 0.8$,
$k_{3t} = 0.0486 (g/MeV\,cm^2)(kV/cm)$,
$\varepsilon = 0.5\ kV/cm$.

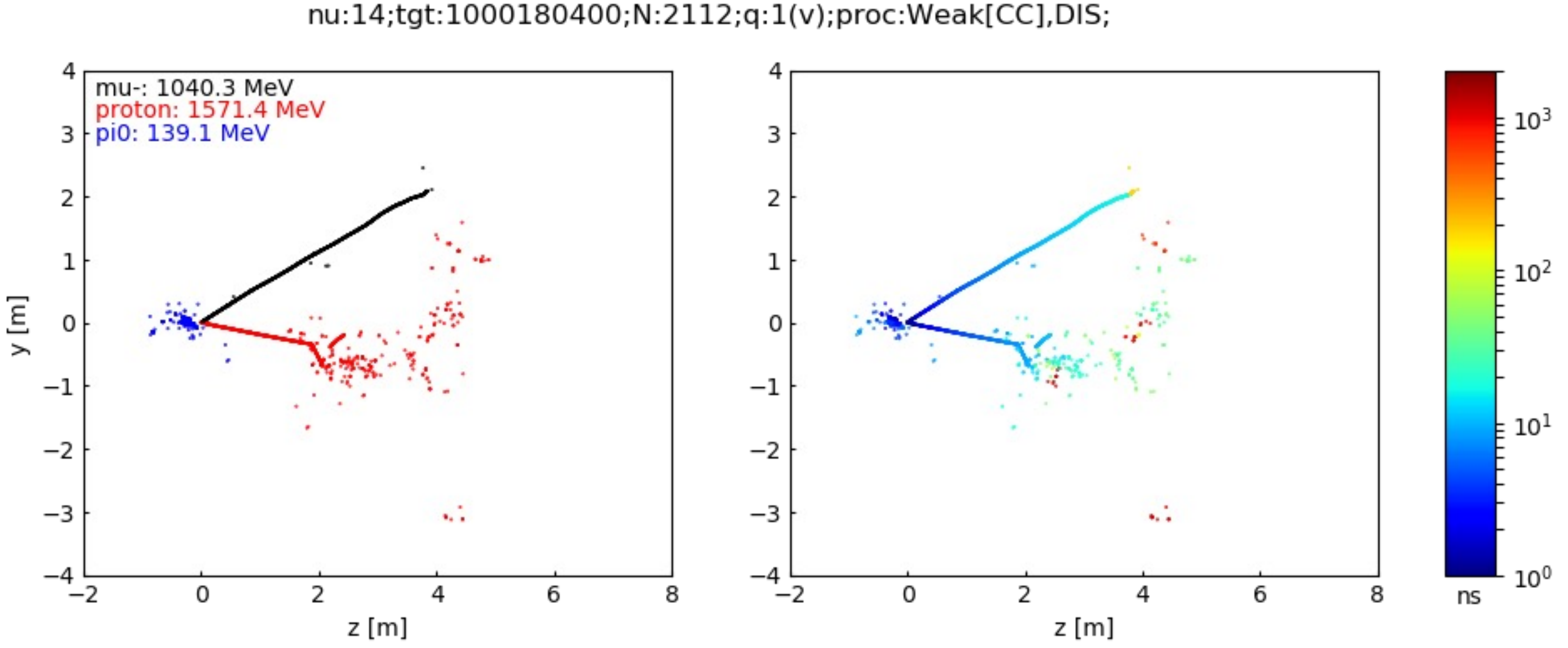
- ❑ Threshold on dQ: 0.075MeV
  In arXiv:2006.14675, a blip energy >75keV is used as threshold

- ➢ Many spray dots don't pass the threshold.
  - But total energy loss is small
- ➢ Time information can be used to separate particles.
- ➢ Long tracks can be identified; energy deposition can be reconstructed by Birk's model.
  - We assume spray dots are too short to reconstruct dQ/dx.

Color represent time



Add threshold: dQ>0.075MeV



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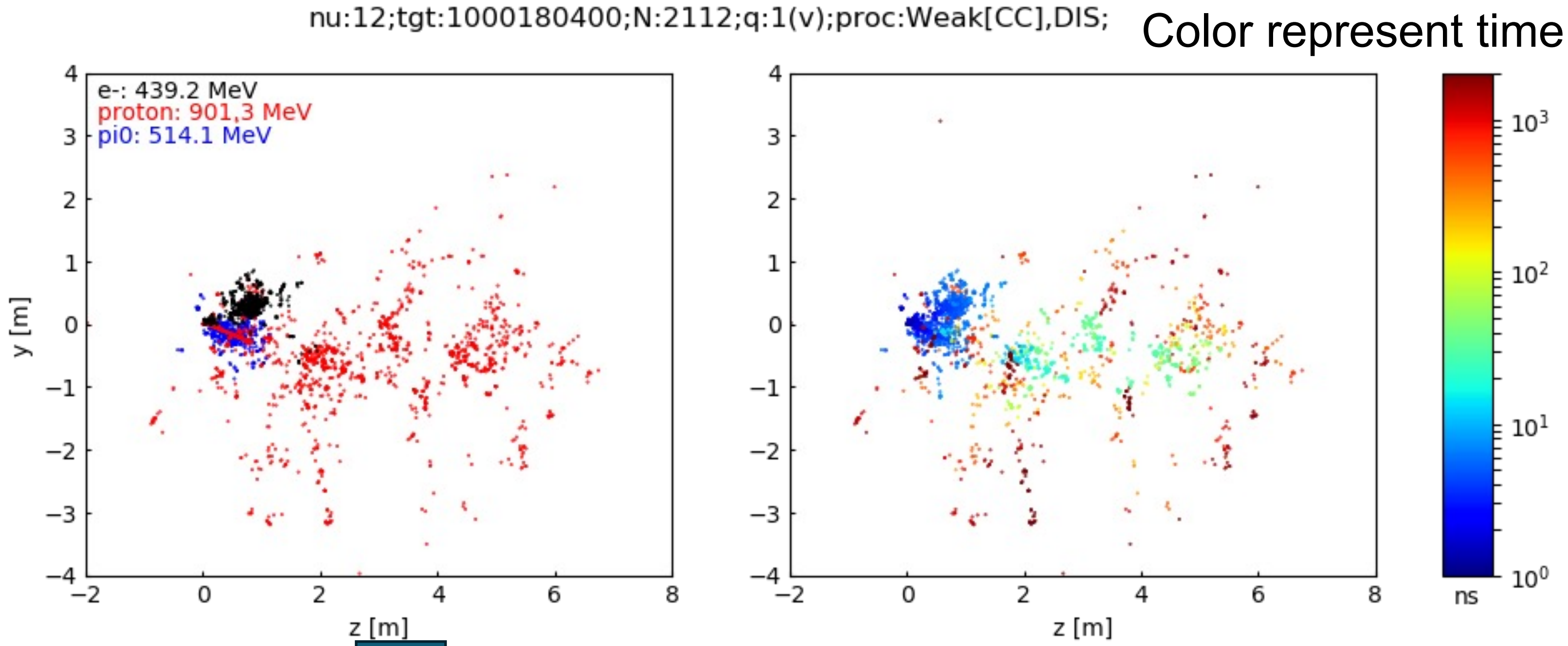

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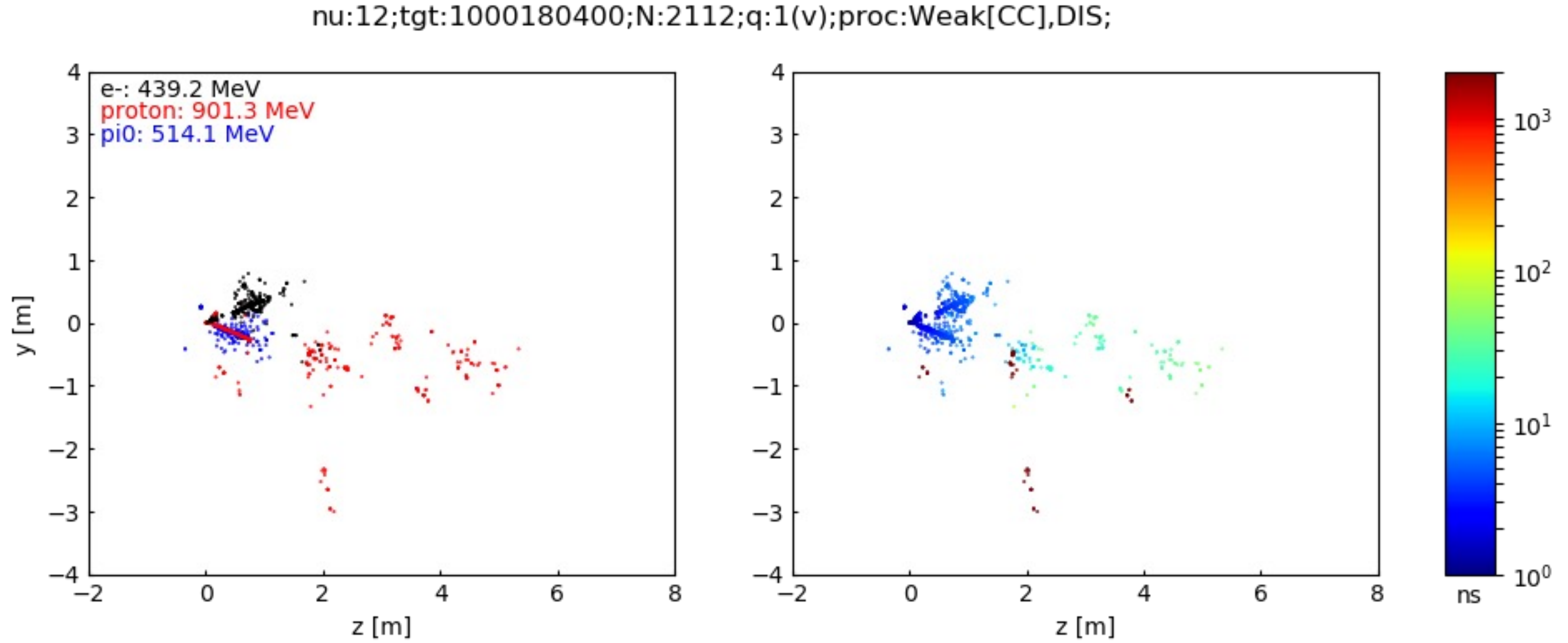
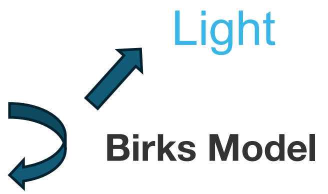


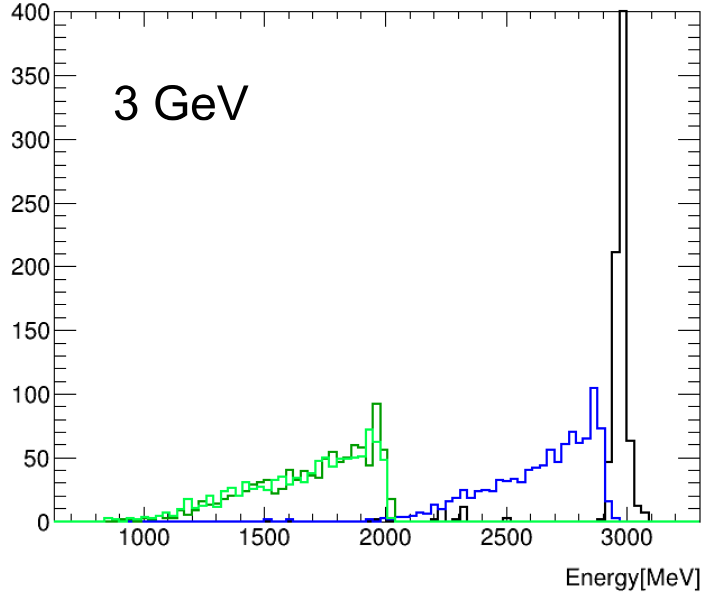
Energy smearing at each step

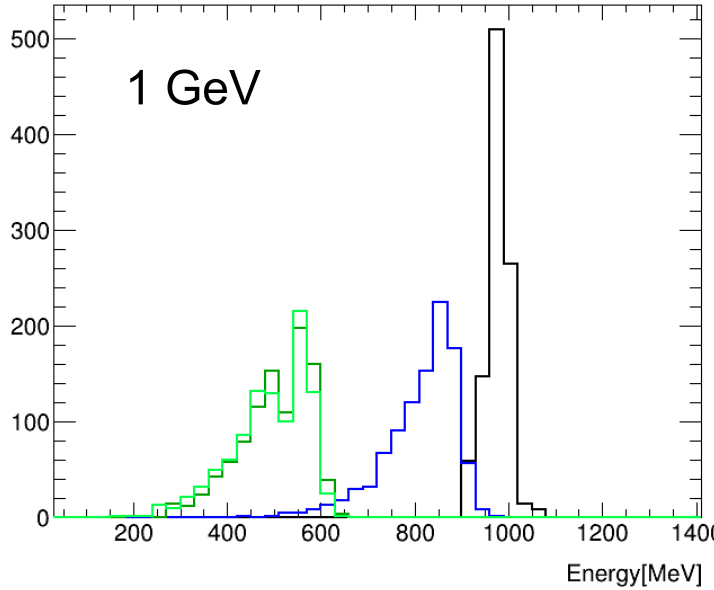
$(\nu_\mu + Ar)$

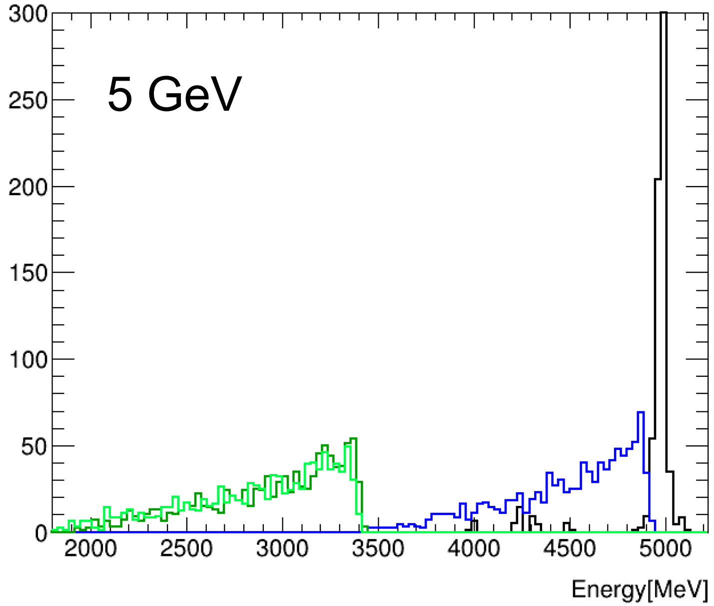
- Available energy (E_{avail})
- Deposit energy E (E_{depo})
- Deposit Charge Q (Q_{depo})
- Deposit Charge with threshold(Q_{depo_thre}):
  - dQ>0.075MeV



- Reconstruction start from Q_{depo_thre}







Reconstruction with charge

- We tried **4** different reconstruction methods from easiest to hardest:

1. No track/PID information, only charge calorimetry:
   - scale dQ by 1/0.7 (r for MIP)

2. Separate energy deposit from lepton or hadron; then scale them according to simulation:

$$E_v = (Q_{lep} + Q_{\pi_0})/a + (Q_{had})/b$$

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3. Separate tracks and dots:
   1. Correct Birks model for tracks (assuming dQ/dx can be reconstructed);
   2. correct muon decay product (if any)
   3. scale the dots of leptons and hadrons (separately)

$$E_v = E_{track} + E_\mu + (Q_{lep\_dots} + Q_{\pi_0\_dots})/c + (Q_{had\_dots})/d$$

4. + Further scale other energy loss for individual particles:
   Neutron; Pion

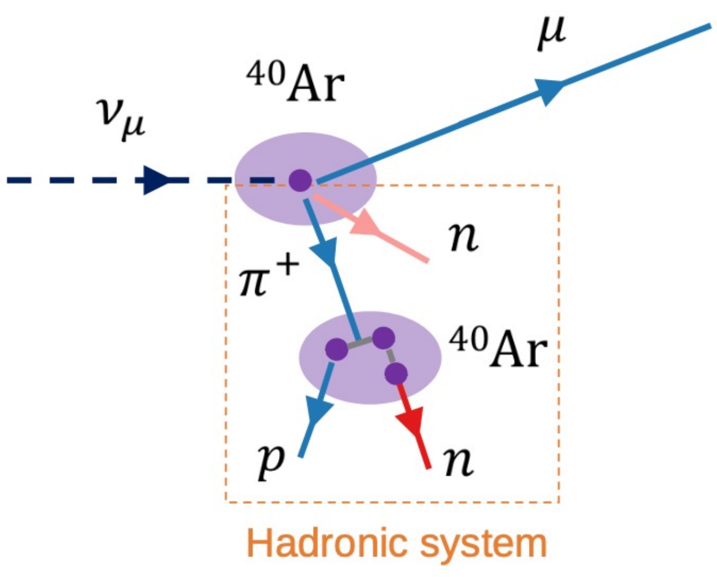
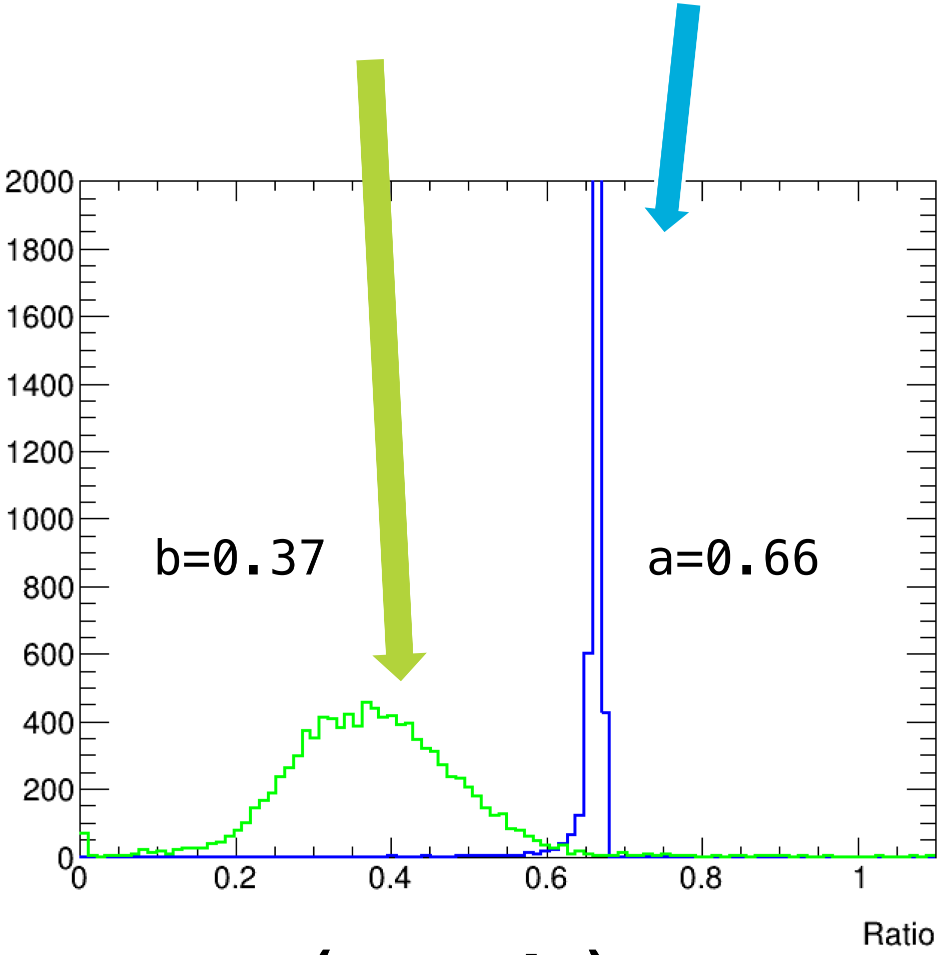


FIG. 1. A neutrino event at DUNE: a conceptual illustration.

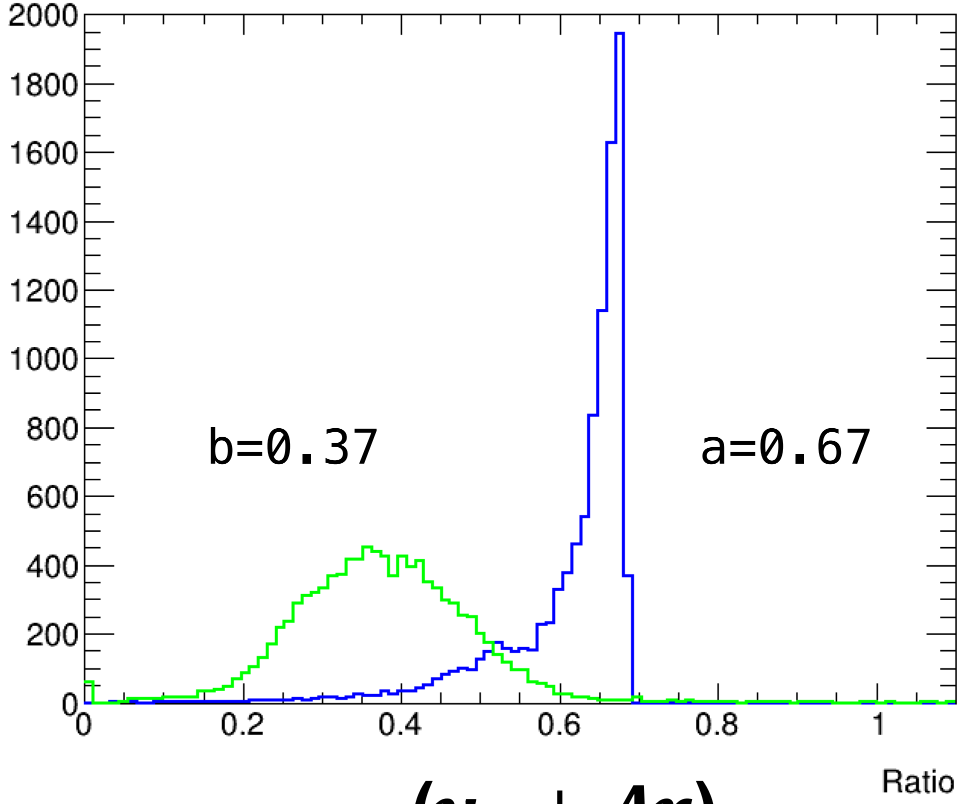
(From 1811.06159)

Method 2: Separate lepton and hardon

- Separate energy deposit from lepton or hardron; then correct them accordingly
  - $E_v = (Q_{lep} + Q_{\pi_0})/a + (Q_{had})/b$



$(\nu_e + Ar)$



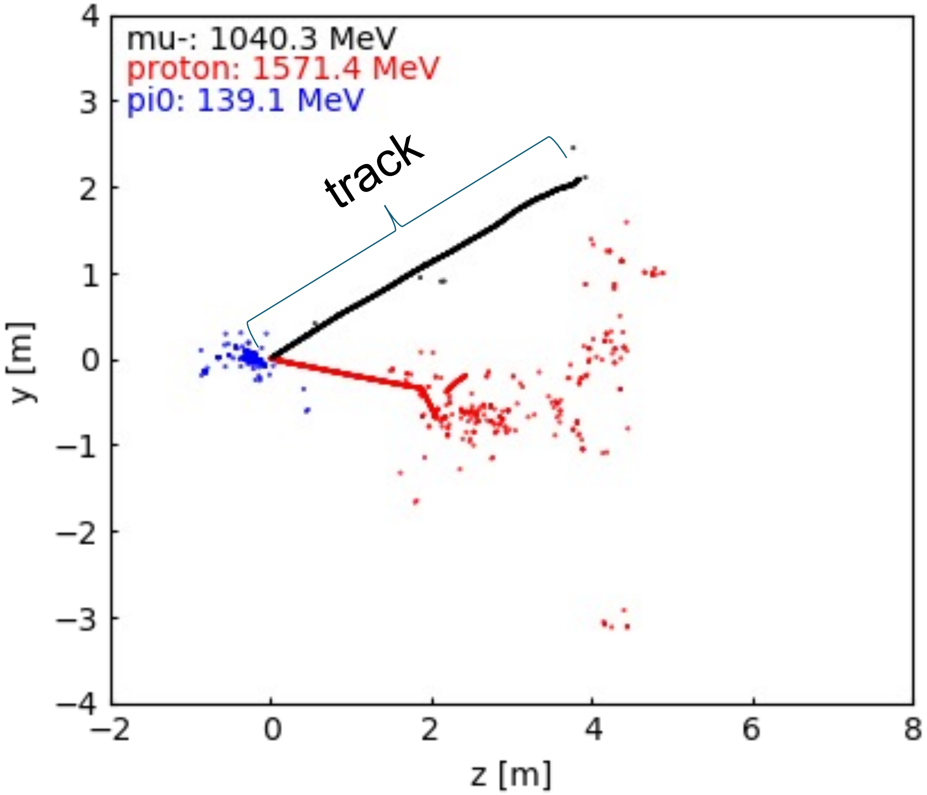
$(\nu_\mu + Ar)$

X axis: $Ratio = Q_{(lep;\pi_0\ or\ had)}/E_{avail}$

Method 3: Separate tracks and dots

$(\nu_\mu + Ar)$

- We find a track according to its track ID in the simulation
- If the length of the track is larger than **2cm (~4 pitch)**, we assume we can
  - reconstruct the track trajectory
  - Measure dQ/dx along the track
  - Correct to dE/dx according to the Birks model;

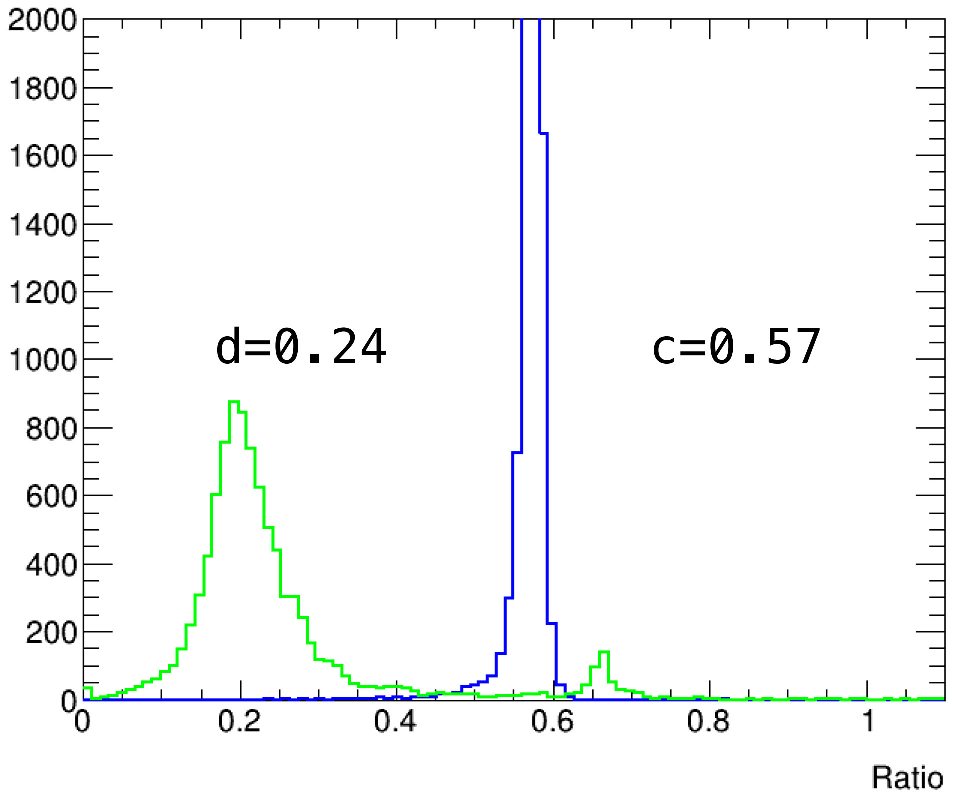


Method 3: Separate tracks and dots

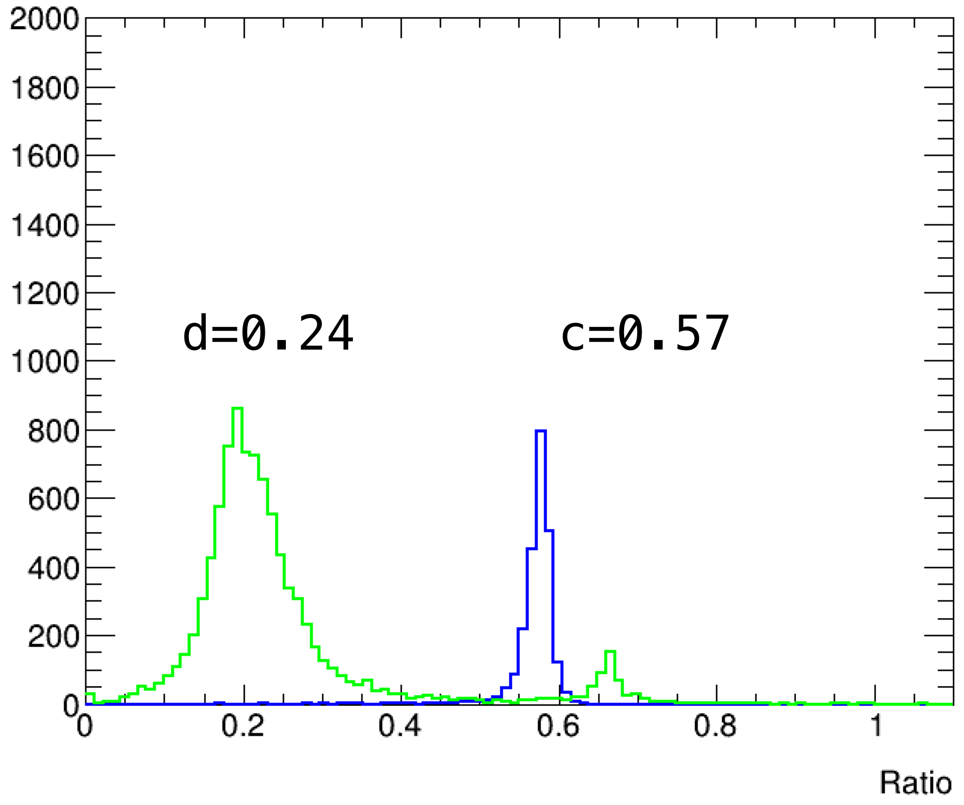
- ❑ **Rescale lepton and hardon dots; correct muon energy**

$$E_{\upsilon} = E_{track} + E_{\mu} + (Q_{lep\_dots} + Q_{\pi_0\_dots})/c + (Q_{had\_dots})/d$$

X axis: $Ratio = Q_{dots}/(E_{avail} - E_{track} - E_{\mu})$



$(\nu_e + Ar)$



$(\nu_\mu + Ar)$

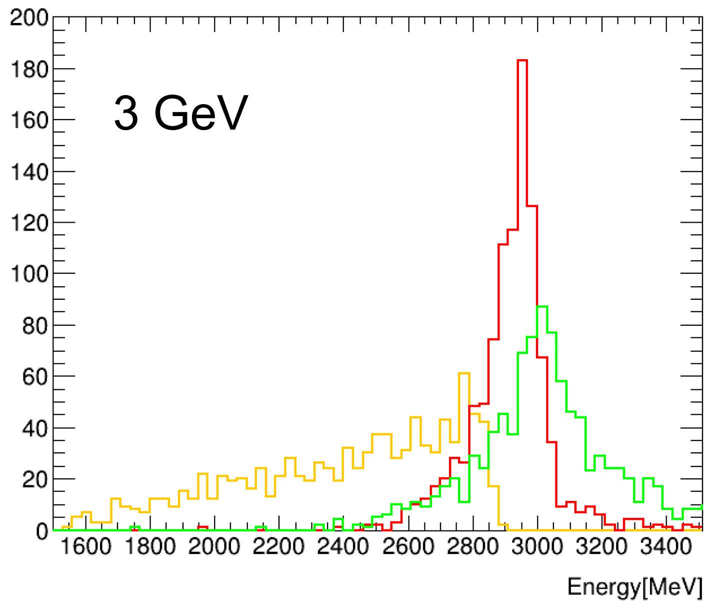
Compare the 3 Energy reconstruction $(\nu_\mu + Ar)$

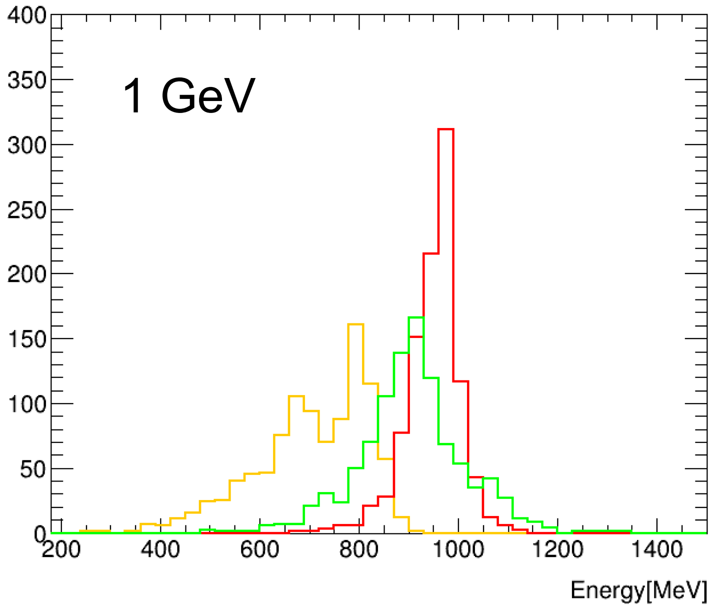
1. Charge calorimetry, r=0.7
2. Separate lepton/hadron :

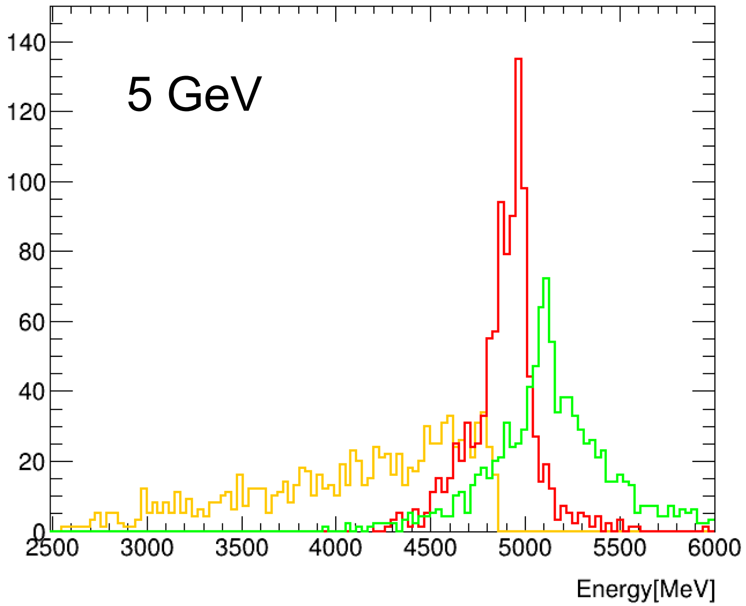
$$E_{rec\_2} = (Q_{lep} + Q_{\pi_0})/0.66 + (Q_{had})/0.37$$

3. Separate tracks/dots

$$E_{rec\_3} = E_{track} + E_\mu + (Q_{lep\_dots} + Q_{\pi_0\_dots})/0.24 + (Q_{had\_dots})/0.57$$





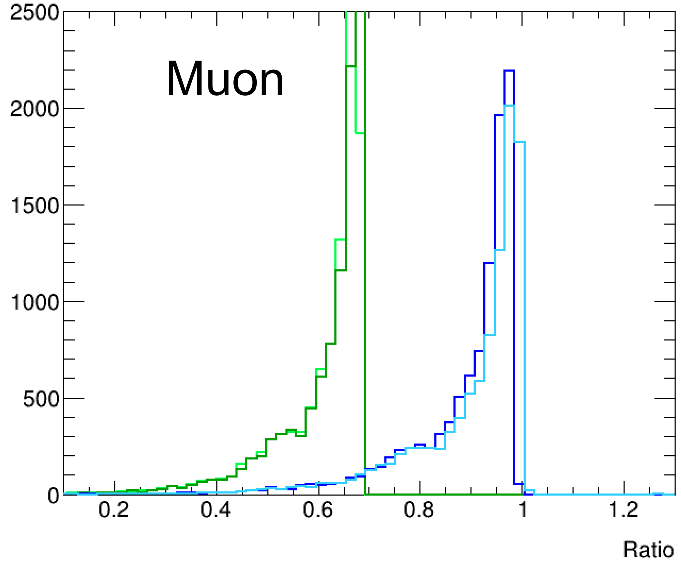


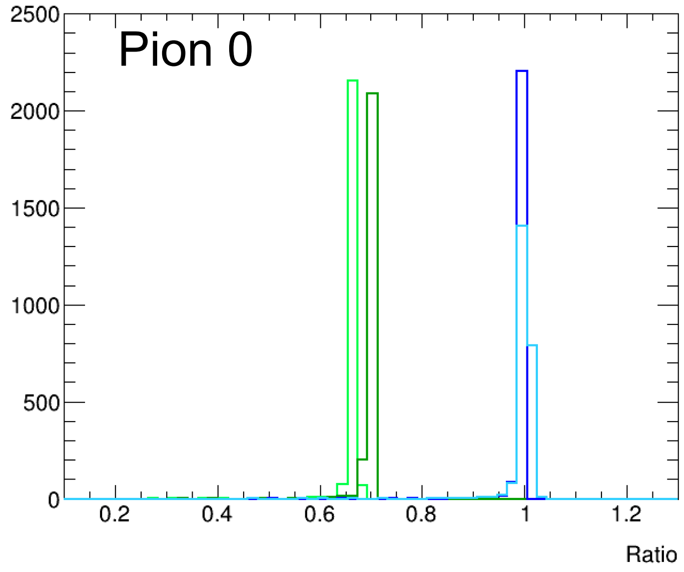
Method 4: Individual PID

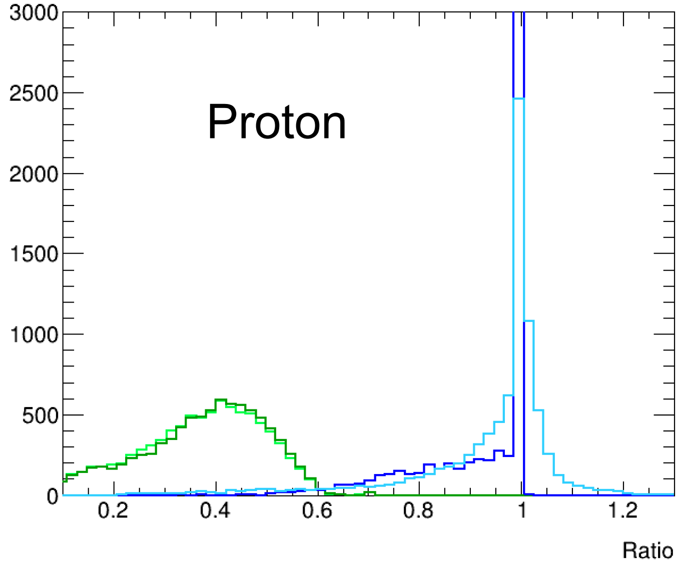
$(\nu_\mu + Ar)$

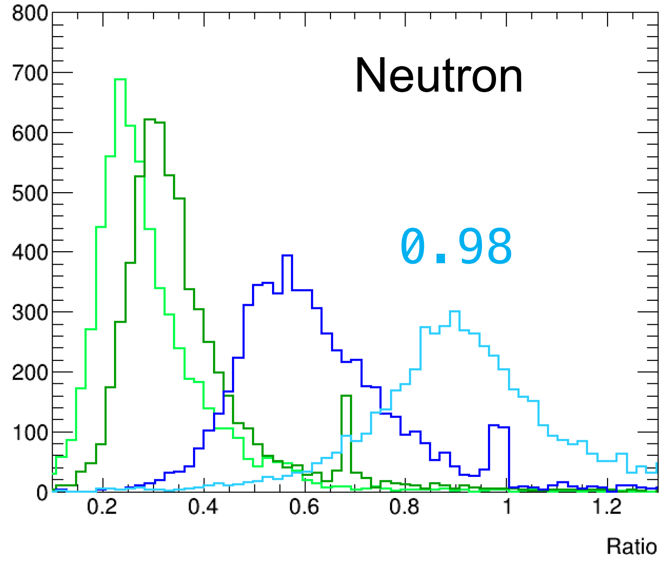
- $E_{depo}/\ E_{avail}$
- $Q_{depo}/\ E_{avail}$
- $Q_{depo\_thre}/\ E_{avail}$
- $E_{rec\_3}/\ E_{avail}$

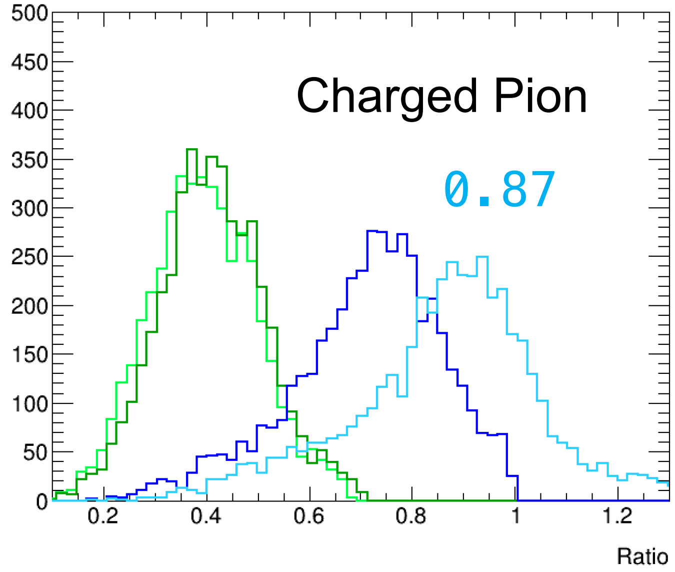
➢ Scale the mean value of neutron and the charged pion if we know the PID











Compare the 4 Energy reconstruction $(\nu_\mu + Ar)$

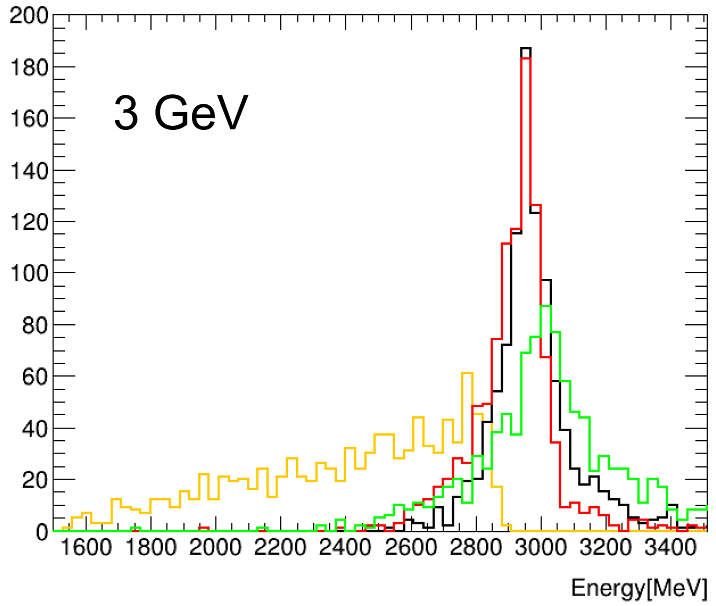
1. Charge calorimetry, r=0.7
2. Separate lepton/hadron :

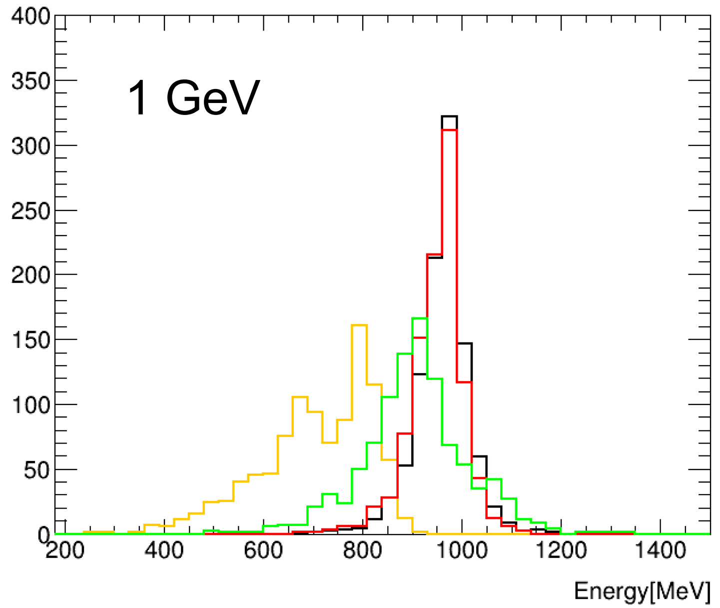
$$E_v = (Q_{lep} + Q_{\pi_0})/0.66 + (Q_{had})/0.37$$

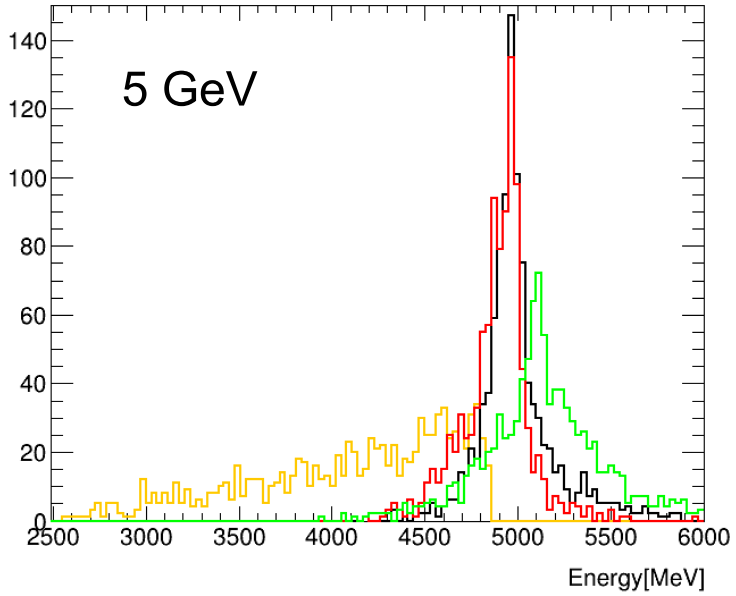
3. Separate tracks/dots

$$E_v = E_{track} + E_\mu + (Q_{lep\_dots} + Q_{\pi_0\_dots})/0.24 + (Q_{had\_dots})/0.57$$

4. **+ Individual PID;**
   neutron, charged pion







Simplified light simulation

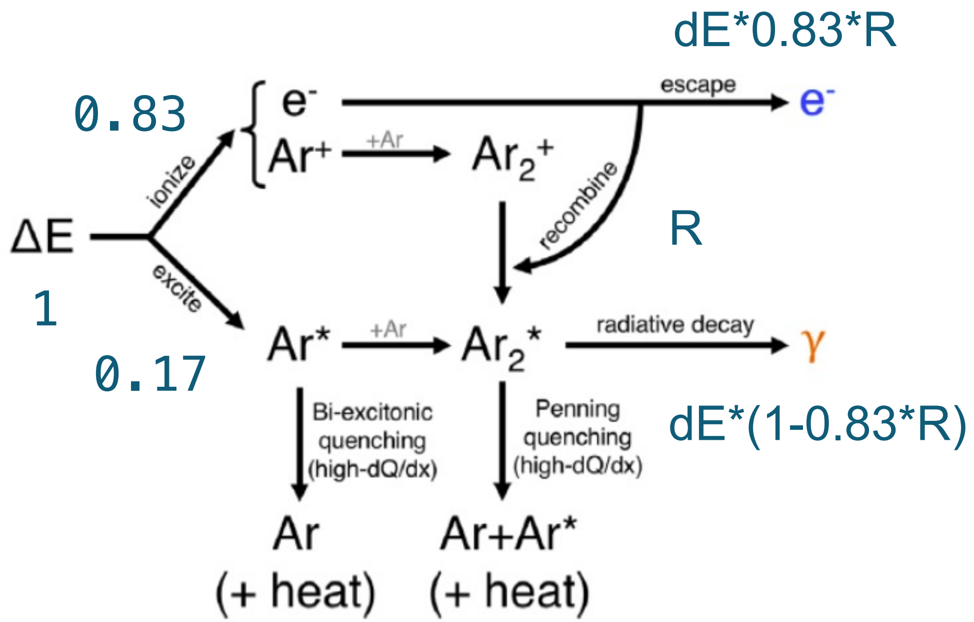


FIG. 1. Schematic diagram illustrating the production of free ionization electrons (e^-) and scintillation photons (γ) from energy deposited in liquid argon.

$\alpha = N_{ex}/N_i = 0.21$

- How we convert deposit energy to light:

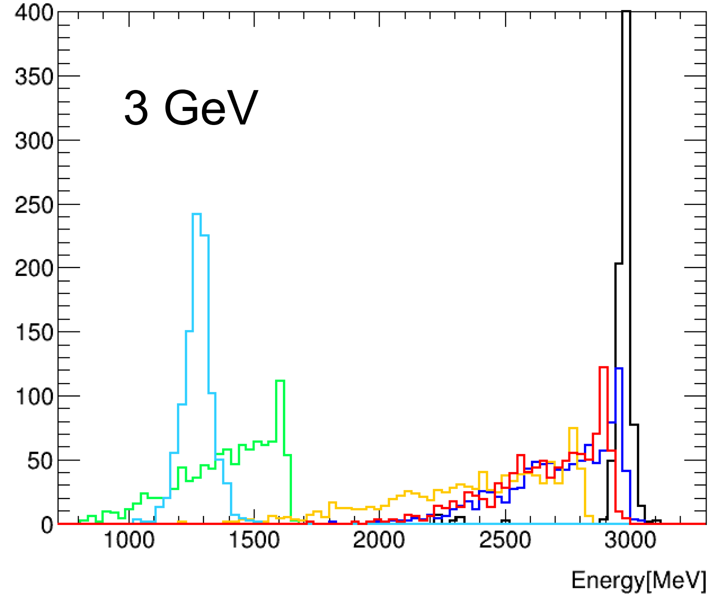
If we ignore heat loss, for deposit energy dE[MeV];

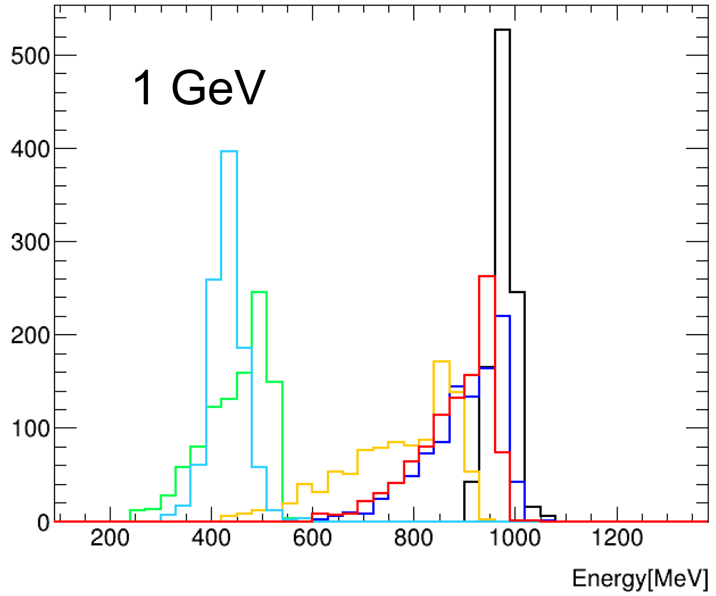
- Part of it goes to charge:
  dQ = dE*R*0.83;
- Rest of it will become light:
  dL = dE - dQ
- Apply the light yield: 180PE/MeV, the number of PE for an event would be:
  N_{PE} = L*180
- Apply the fluctuation, the detected photon number would be:
  N_{PE_rand} = Gaussian(N_{PE},$\sqrt{N_{PE}}$)
- The detected energy in light:
  $L_{detected}$ = N_{PE_rand} *180(PE/MeV)
- Combined with charge energy, the detected energy in total:
  E_{LQ} = $L_{detected}$ + Q

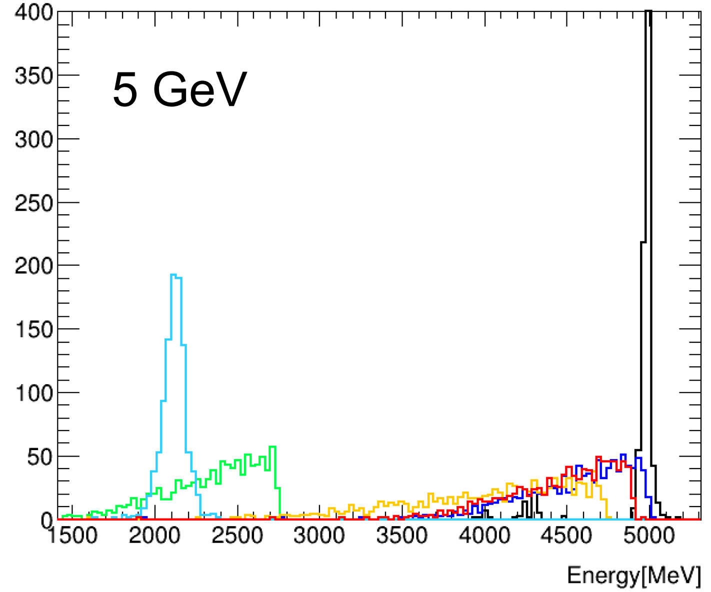
Reconstruction with charge and light

- Available energy (E_{avail})
- Deposit energy (E_{depo})
- Detected energy from charge (Q_{depo_thre})
- Detected energy from light ($L_{detected}$)
- Charge calorimetry; r=0.7
- Calorimetry from charge + light

➢ For pure calorimetry, the best we can do is reproducing the deposit energy.
➢ In this simple simulation, the light-only energy seems have better resolution than charge-only







Compare the 5 Energy reconstruction $(\nu_\mu + Ar)$

1. Charge calorimetry, r=0.7
2. Separate lepton/hadron :

$$E_v = (Q_{lep} + Q_{\pi_0})/0.66 + (Q_{had})/0.37$$

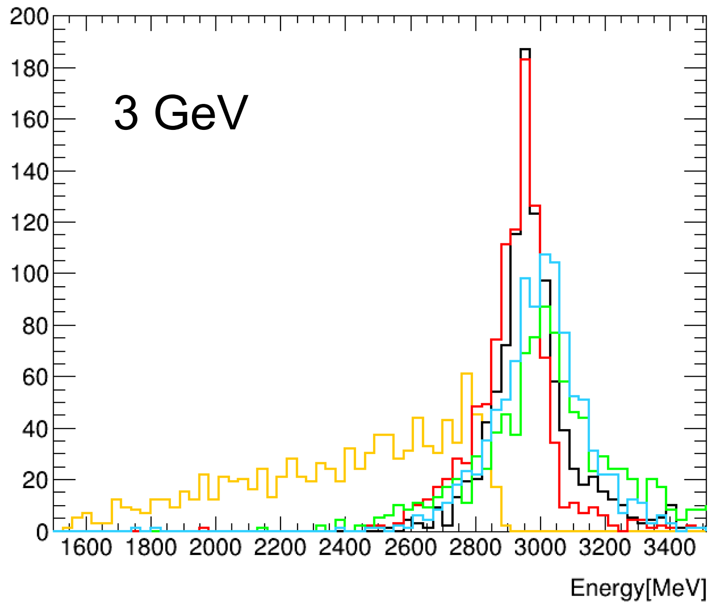
3. Separate tracks/dots

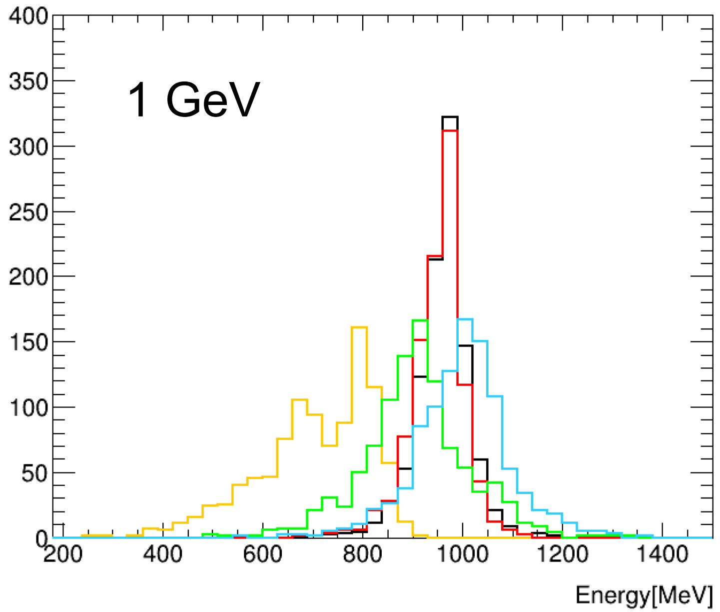
$$E_v = E_{track} + E_\mu + (Q_{lep\_dots} + Q_{\pi_0\_dots})/0.24 + (Q_{had\_dots})/0.57$$

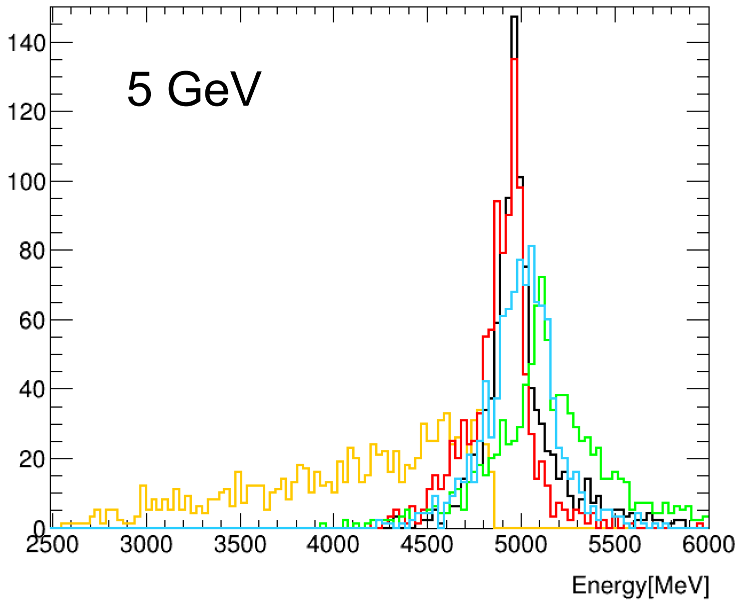
4. + Individual PID;

   neutron, charged pion

5. **Light**





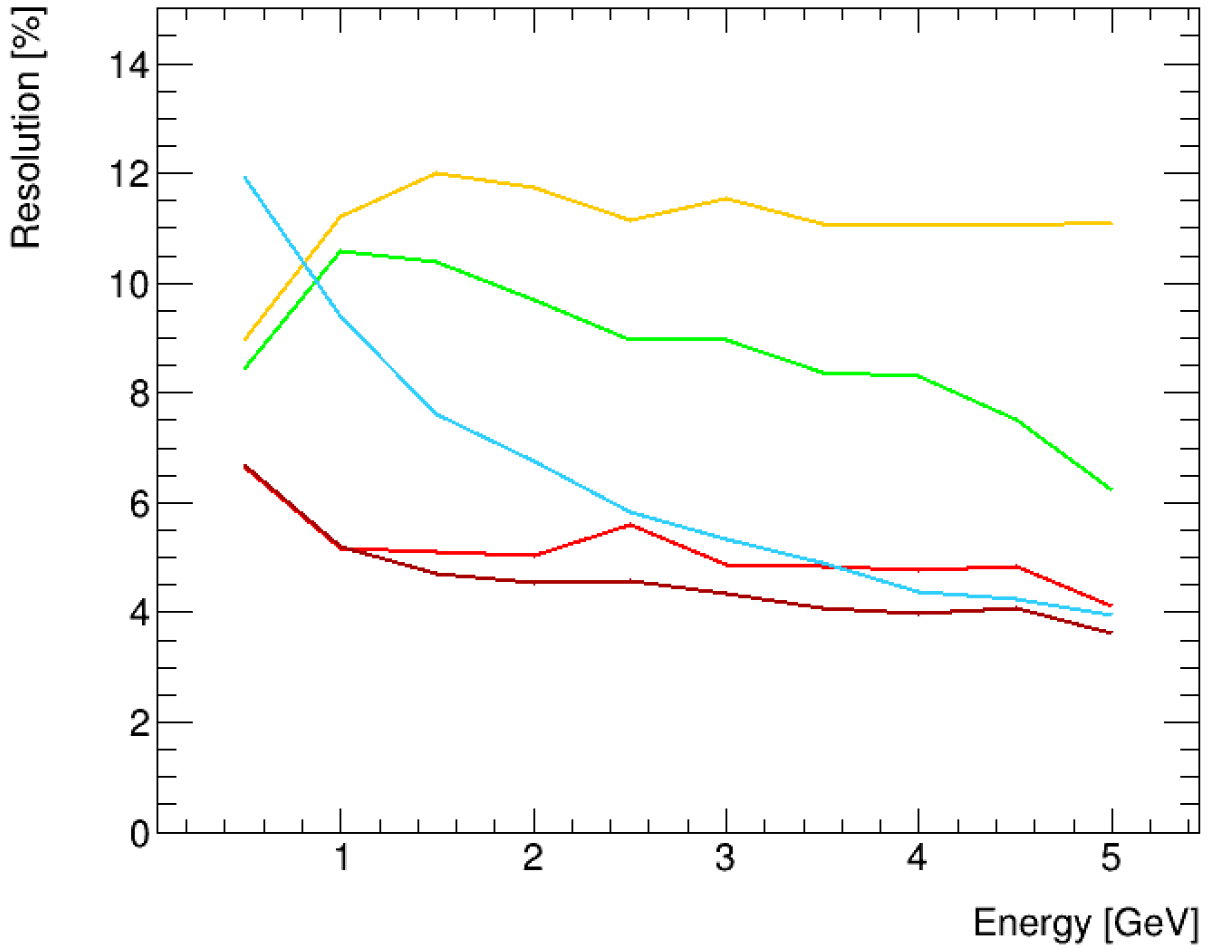


Energy resolution

$(\nu_\mu + Ar)$

- Resolution is sigma/E ;

1. Charge calorimetry : 11.2% @1GeV
2. Separate lepton/hadron : 10.5% @1GeV
3. Separate tracks/dots : 5.2% @1GeV
4. Individual PID : 5.2% @1GeV
5. Light: 9.4% @1GeV

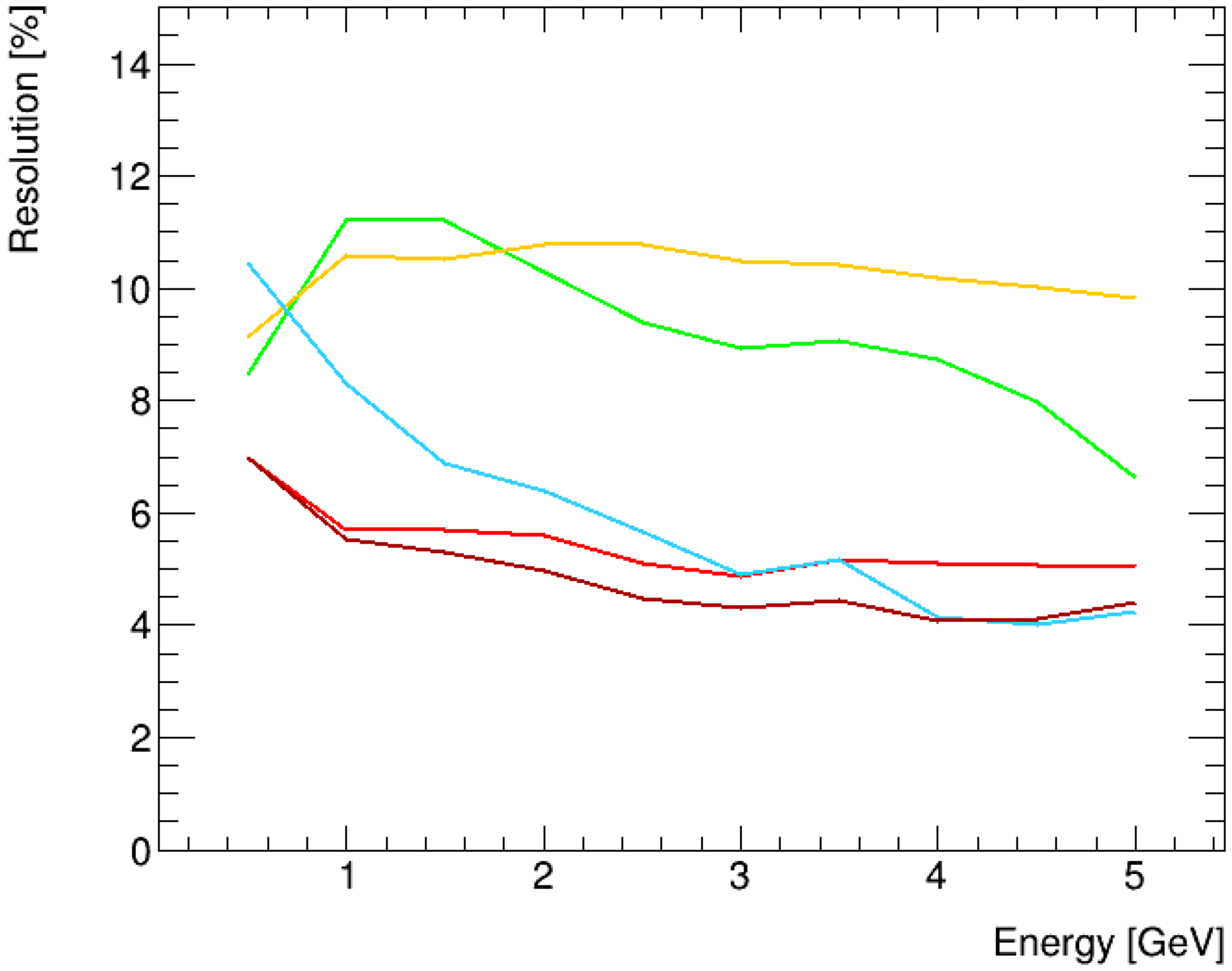


Energy resolution

$(\nu_e + Ar)$

- **Resolution is sigma/E ;**

1. **Charge calorimetry: 10.5% @1GeV**
2. **Separate lepton/hadron: 11.2% @1GeV**
3. **Separate tracks/dots: 5.7% @1GeV**
4. **Individual PID: 5.5% @1GeV**
5. **Light: 8.2% @1GeV**



Summary

- Charge-based neutrino energy reconstruction
  - Calorimetry with lepton/hadron separation: ~10% @1 GeV, agree with current experiments' best performance such as MicroBooNE
  - Adding track/dots separation: ~6% @1GeV
  - Adding further PID separation improve slightly
- Light for energy reconstruction
  - Light-only calorimetry @180PE/MeV: ~9% @1GeV
    - Comparable performance to charge-based reconstruction
    - Does not have a tailed shape like charge, which is helpful to reduce bias
    - more detailed simulation is needed (heat loss, position dependent light yield,…)
  - Light information can help PID in event reconstruction (timing, position, dL/dx, etc.)
  - Further adding light calorimetry to charge does not improve the resolution by a lot, because the resolution is dominated by PID

- Factors that affect energy resolution
  - Generator level energy loss: negligible
  - Detector threshold: small (@75keV)
  - Particle-dependent energy loss:
    - Energy loss to nuclei: large, particularly for neutrons
    - Decay/capture: moderate for muons, pions (easier to correct for muons)
  - Charge recombination: large, but can be corrected for tracks