Reconstruction of atmospheric neutrino events at JUNO

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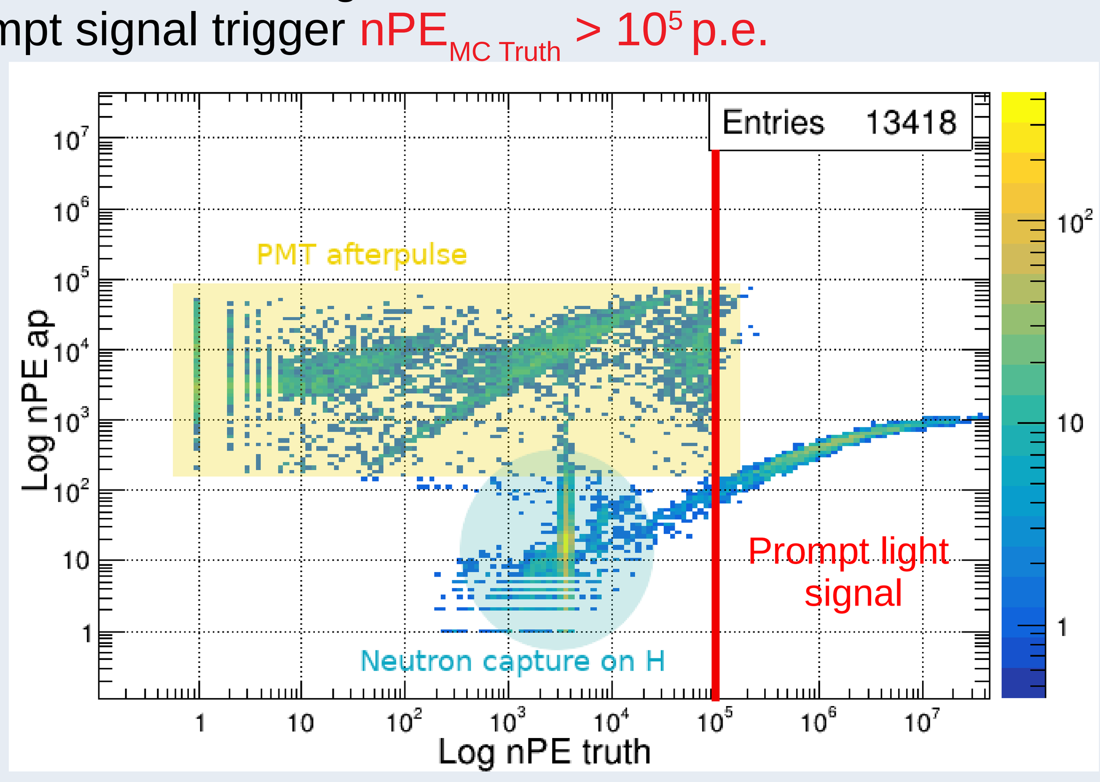
Motivation: Use atmospheric neutrinos to enhance JUNOs sensitivity for the neutrino mass ordering (NMO).

Atmospheric Neutrino Data

Idea: Optimize readout window for atmospheric neutrino events to improve charge to energy ratio.

- Using simulated atmospheric neutrino events
- Fully contained charged current events
- Prompt signal trigger $nPE_{MC\ Truth} > 10^5$ p.e.

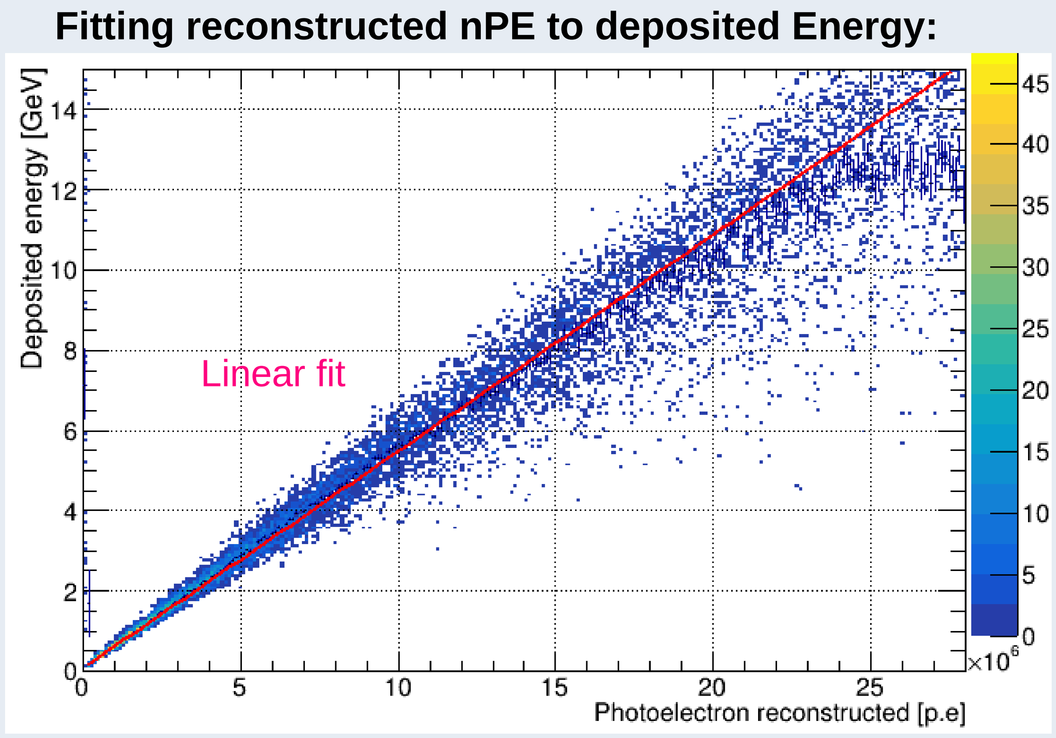


Energy reconstruction with linear fit

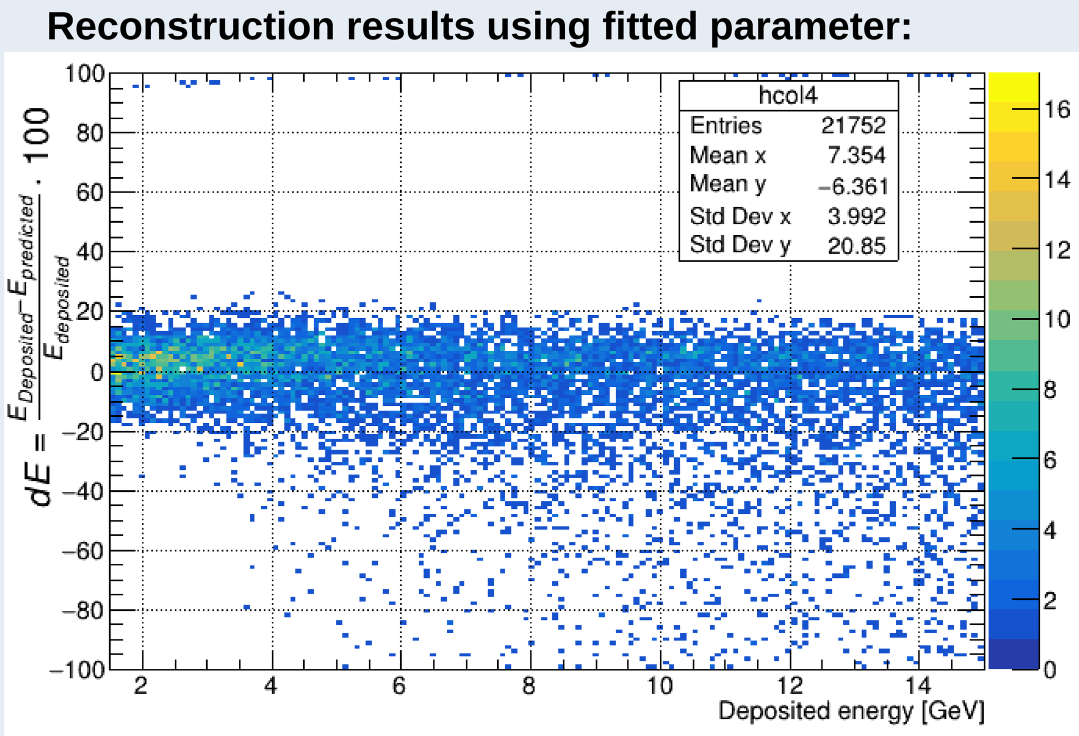
Idea: Reconstruct the deposited energy by using a linear fit to the reconstructed number of photo electrons (nPE).

Using fully contained events with readout window selection.

Fitting reconstructed nPE to deposited Energy:



Reconstruction results using fitted parameter:



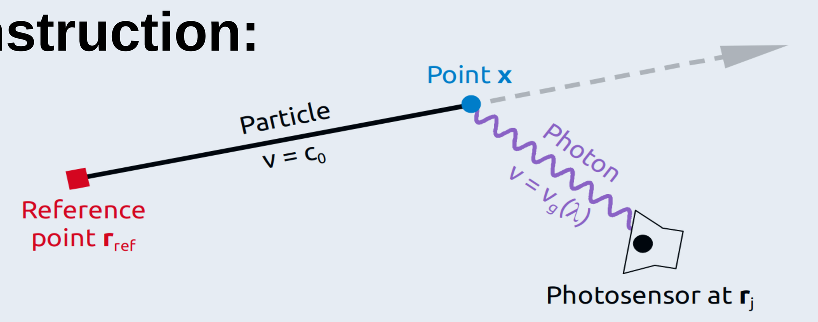
resulting energy resolution of ~ 20 %

Reconstruction of neutrino direction

Idea: Use the PMT detection probability to infer the reconstructed light emission topology, based on topological track reconstruction[1].

Approach - Topological Track Reconstruction:

$$\hat{t}(x) = t_{ref} \pm \underbrace{\frac{|\hat{x} - \hat{r}_{ref}|}{c_0}}_{t_{particle}} + \underbrace{\frac{|\hat{r}_j - \hat{x}|}{v_g}}_{t_{photon}}$$

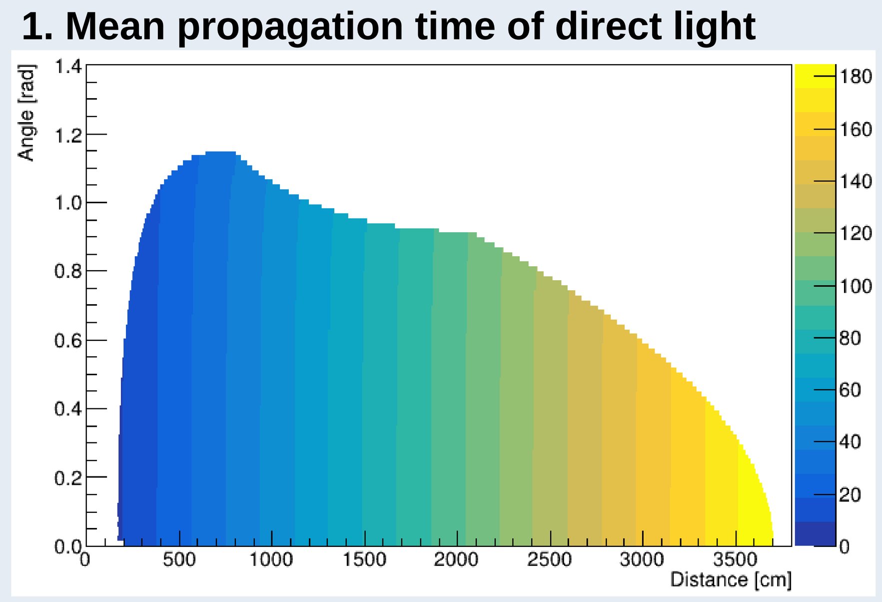


r_{ref}: Reference point, any point along track

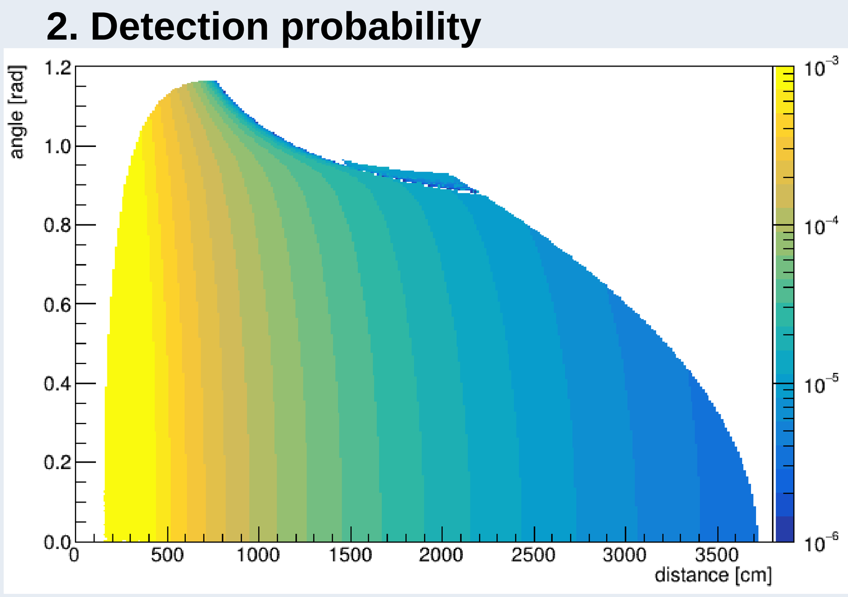
[1] H. Rebber *et al* 2021 *JINST* **16** P01016

Analytical probability density functions:
based on the scintillation average wavelength (436 nm), total reflection and re-emitted light removed

1. Mean propagation time of direct light



2. Detection probability



Application on neutrino direction:

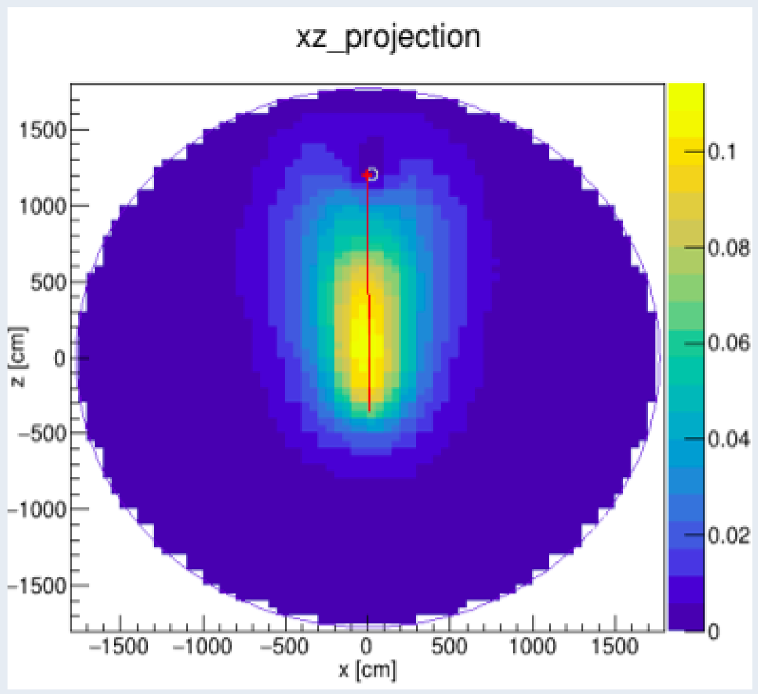
Data:
- Charge and hit time per PMT
  - → considering 17612 LPMTs
  - → 400 ns event window
- Reference point from MC Truth smeared with 25 cm uncertainty and PMT time resolution

Results:

→ of 6 iterations with different mash sizes
- For Muon
- For CC ν_μ

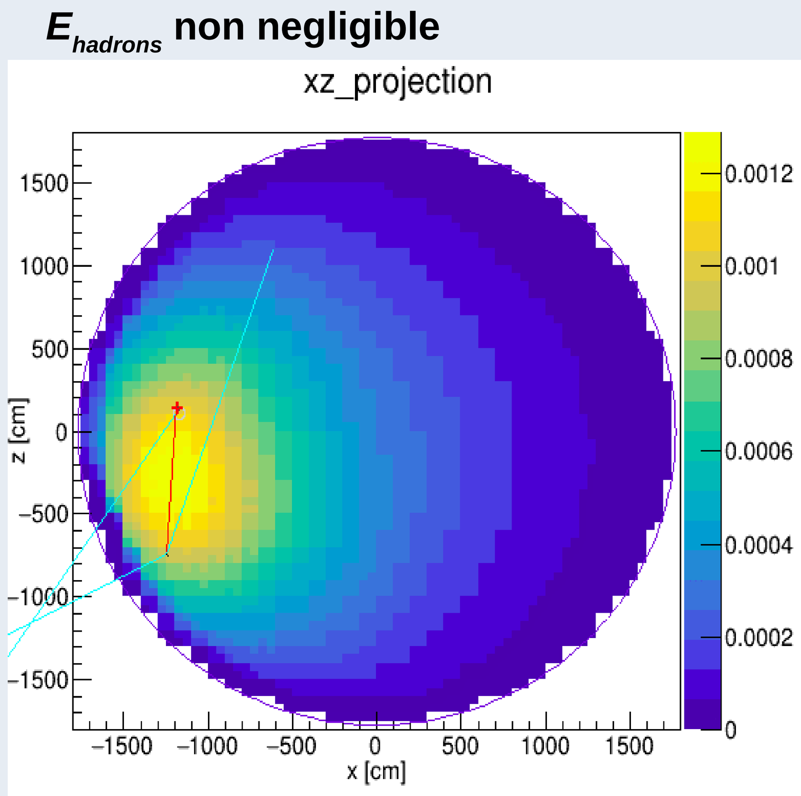
Legend:
- primary tracks (Monte Carlo)
- neutrino tracks

Muon with E = 3 GeV

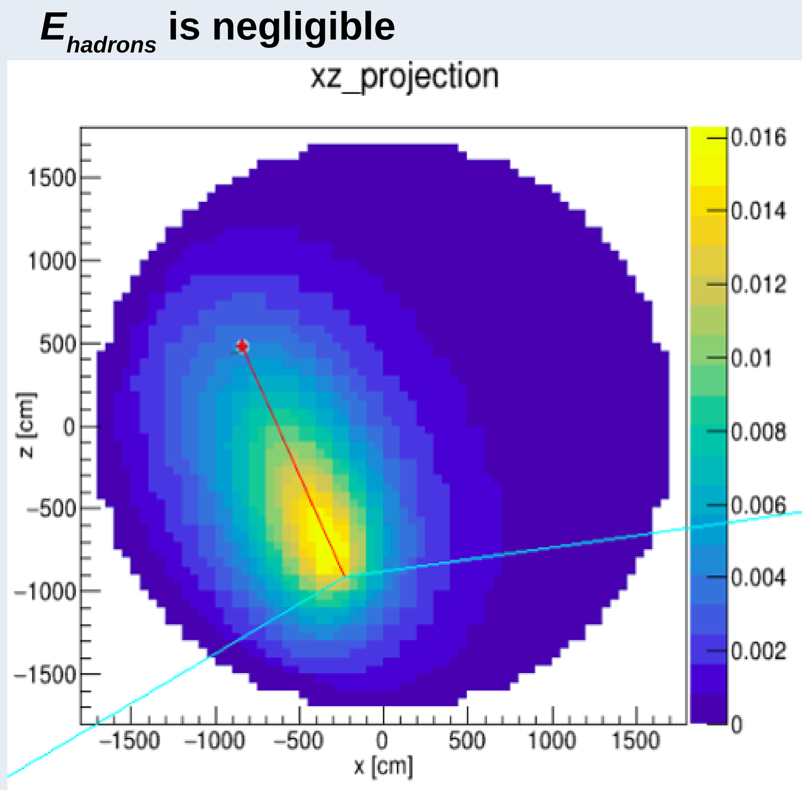


Charged Current ν_μ with E = 3 GeV

$E_{hadrons}$ non negligible



$E_{hadrons}$ is negligible



Energy reconstruction using Graph Convolution

Idea: Use convolution on charge detected by PMTs on detector surface to reconstruct the energy of FC and CC atmospheric neutrino events.

Graph Convolution:

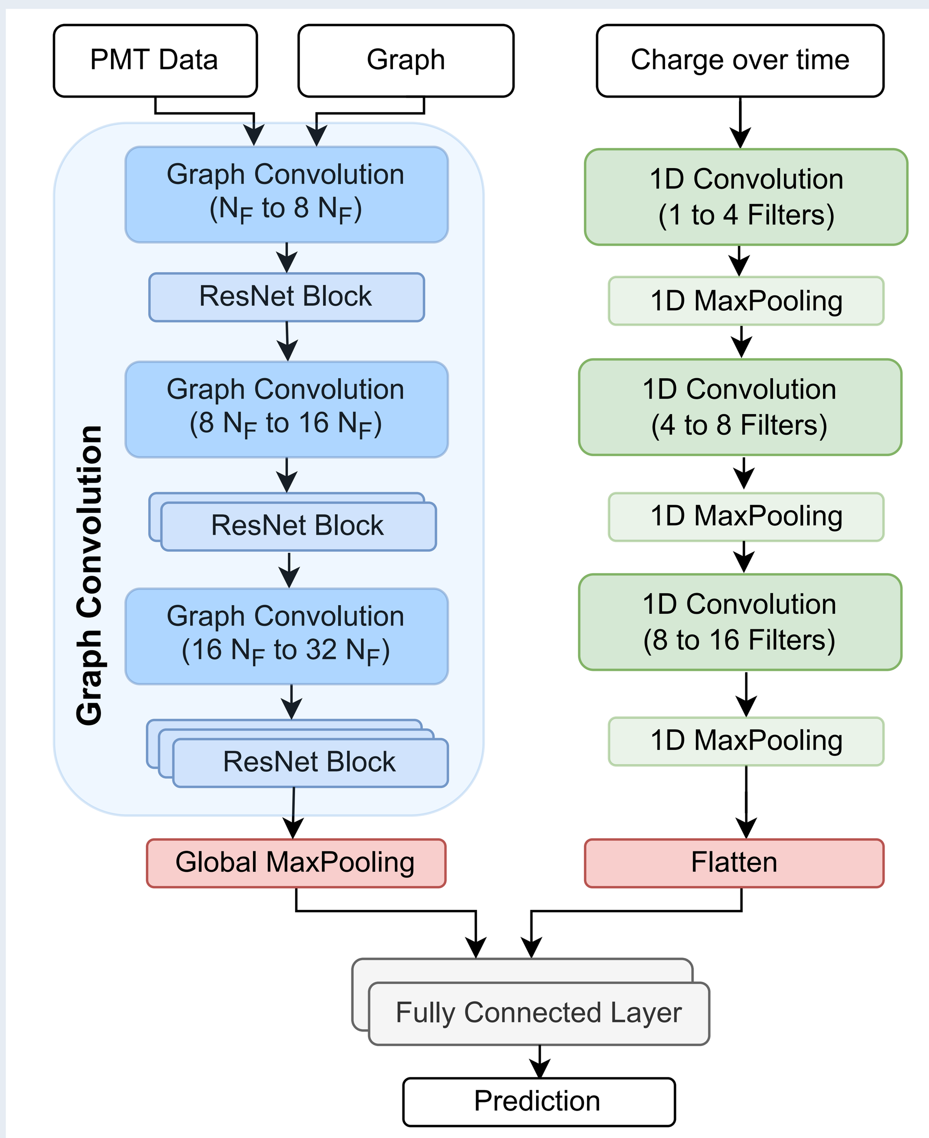
- Graph consists of nodes and edges
- Nodes represent PMTs of central detector
- Each Node connected to the four closest neighbors in space
- Using 5000 LPMTs
- Convolution based on Kipf and Welling[2]:

$$h_i^{(l+1)} = \sigma\left(b^{(l)} + \sum_{j \in N(i)} \frac{1}{c_{ij}} h_j^{(l)} W^{(l)}\right)$$

$h_i^{(l+1)}$: features of node i in layer, σ : activation function, $W^{(l)}$: weights for layer l, $N(i)$: set of neighbors of node i, normalization $c_{ij} = \sqrt{|N(i)|}\sqrt{|N(j)|}$, $b^{(l)}$: bias for layer l

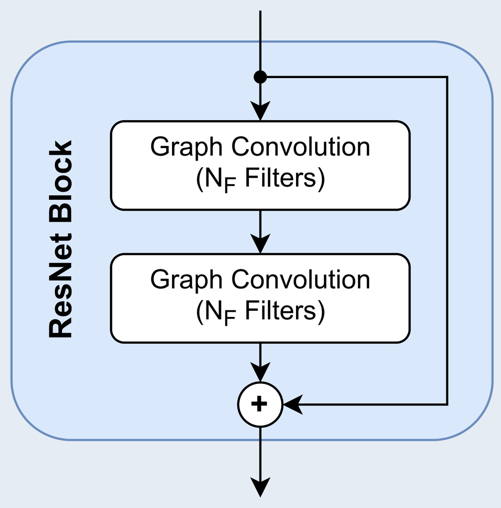
[2] Kipf and Welling, arXiv:1609.02907

→ Graph represents detector geometry.



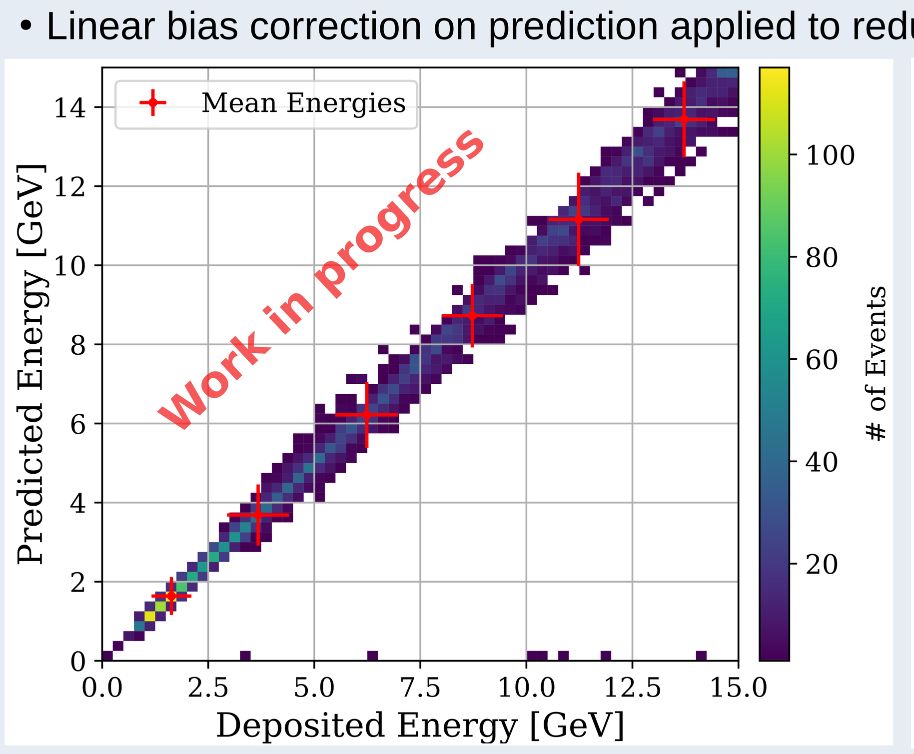
Architecture:

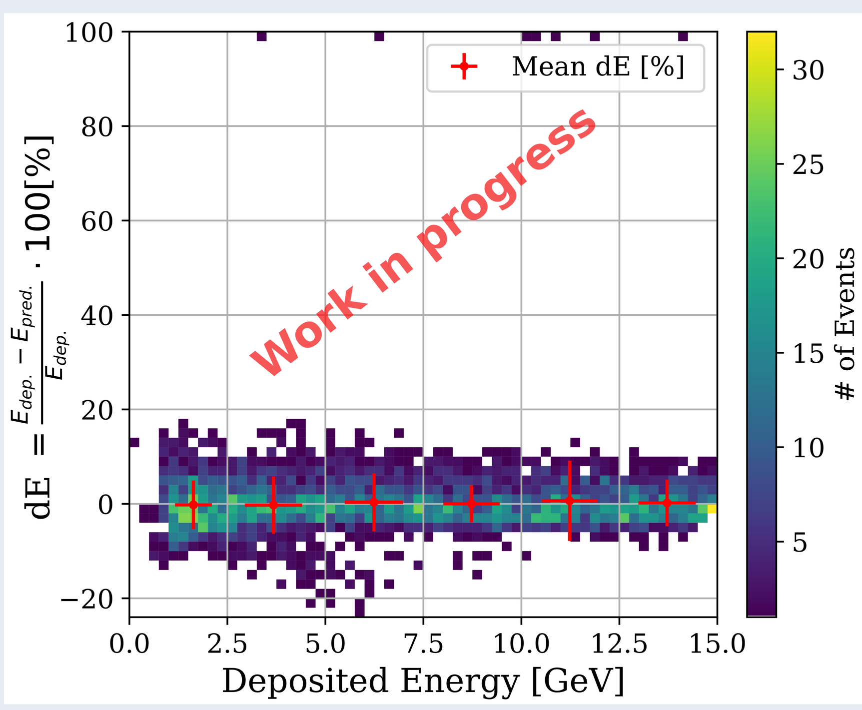
- Inputs: First hit time, charge per PMT + charge over time distribution
- Charge summed over readout window selection
- Graph Convolution with ResNet Blocks
- 1D convolution on Charge over time
- Combination of both convolution outputs
- Fully Connected Layers
- Activation function: SELU



Results:

- Using fully contained charged current events
- Reconstruction of the deposited energy in NMO range
- Linear bias correction on prediction applied to reduce offset





resulting energy resolution of ~ 6 %, after bias correction

Conclusion: Energy and directional reconstruction for atmospheric neutrinos feasible on JUNO data.