Enforcing Self-Consistent Kinematic Constraints in Neutrino Energy Estimators

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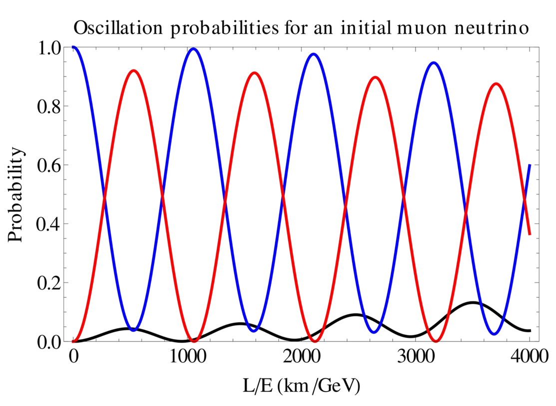
Neutrino Oscillations & Interactions

Neutrinos oscillate their flavor

- Dependent on $\{\mathbf{E}_\nu, \boldsymbol{L}\,(\boldsymbol{\theta}_\nu)\}$

Most neutrino beams begin with ν_μ flavor

- Created from meson decays following spallation
- Oscillate into ν_τ principally and some ν_e



Measure ν interaction counts in our detectors…
Must use an interaction model to deconvolute the ν flux

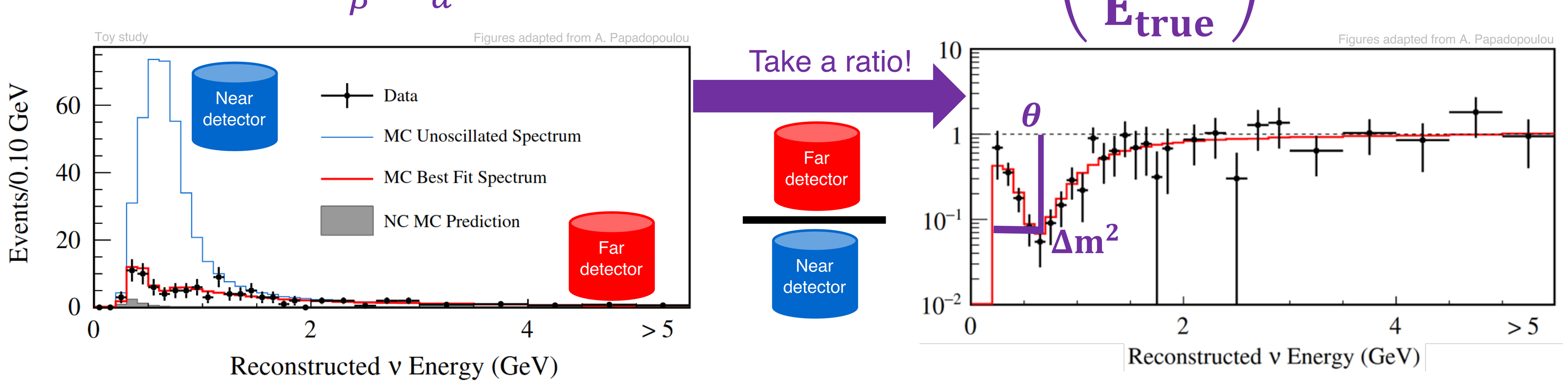
$$N_\alpha(E_{rec}, L) = \sum_{i=\text{Nucleus Type}}^{I} \sum_{j=1}^{\text{Nuclei}} \int \boxed{\Phi_\alpha(\mathbf{E_{true}}, L)}\, \sigma_{\alpha_i}(\mathbf{E_{true}}) R_{\sigma_{\alpha_i}}(\mathbf{E_{true}}, E_{rec})\, d\mathbf{E_{true}}$$

Measured in Far Detector — Required! ν flux — Interaction Model—*i.e.* GENIE

$$\Phi_\alpha(\mathbf{E_{true}}, L) \propto \left[1 - P_{\nu_\beta \to \nu_\alpha}(\mathbf{E_{true}}, L)\right] \Phi_\alpha(\mathbf{E_{true}}, \sim 0)$$

$\propto$ Oscillation parameters! — Near detector constraint

$$P_{\nu_\beta \to \nu_\alpha}(\mathbf{E_{true}}, L) \approx \sin^2(2\boldsymbol{\theta}) \sin^2\left(\frac{\boldsymbol{\Delta m^2} L}{\mathbf{E_{true}}}\right)$$



A ratio of Far to Near Detector event spectra shows dependencies on…

- Flavor mixing angle θ (not ν direction!) & mass state splitting Δm^2

Event spectra are in E_ν^{reco}, but we calculate oscillations given E_ν^{true}!

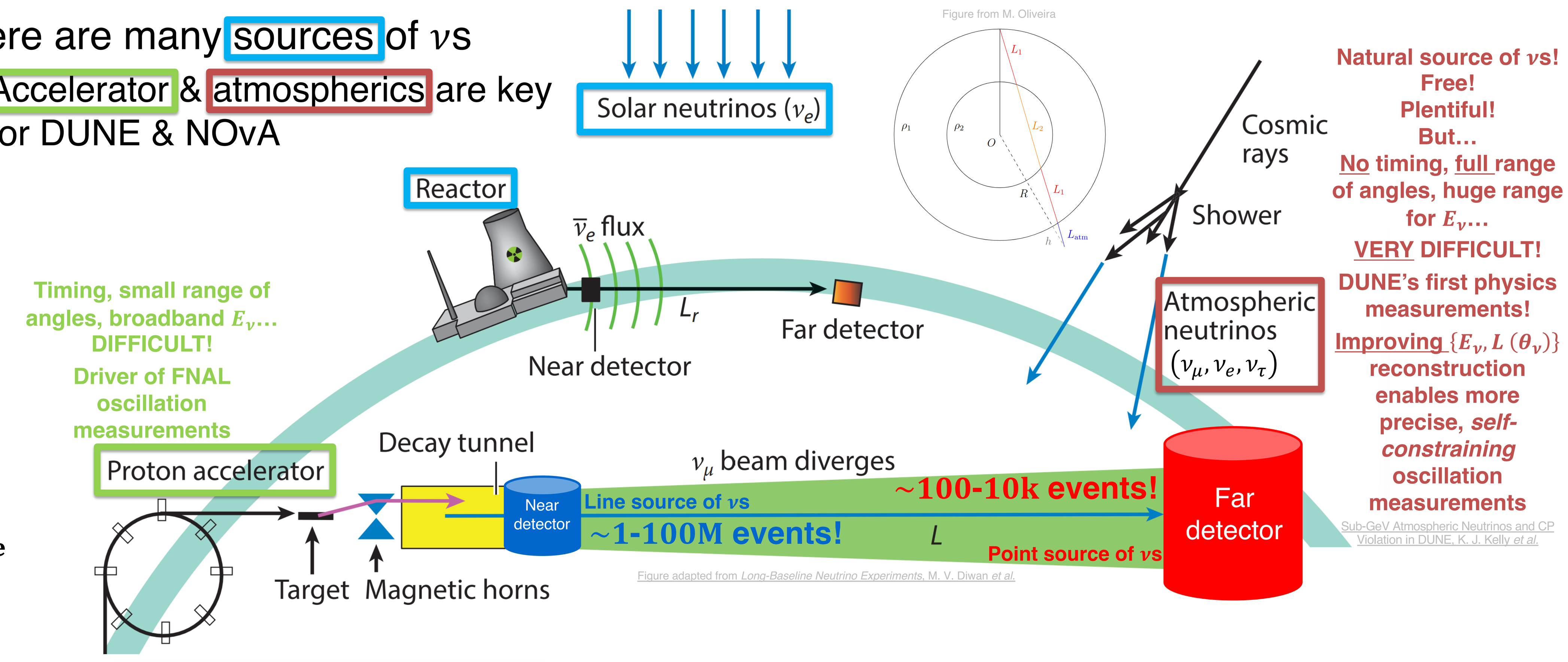
- Understand mapping between these with ν event generators, reconstruction software

Machine learning ν energy estimators can perform this reconstruction

- **Improvements possible in ML algorithms with physics motivations at heart!**

There are many sources of νs

- Accelerator & atmospherics are key for DUNE & NOvA

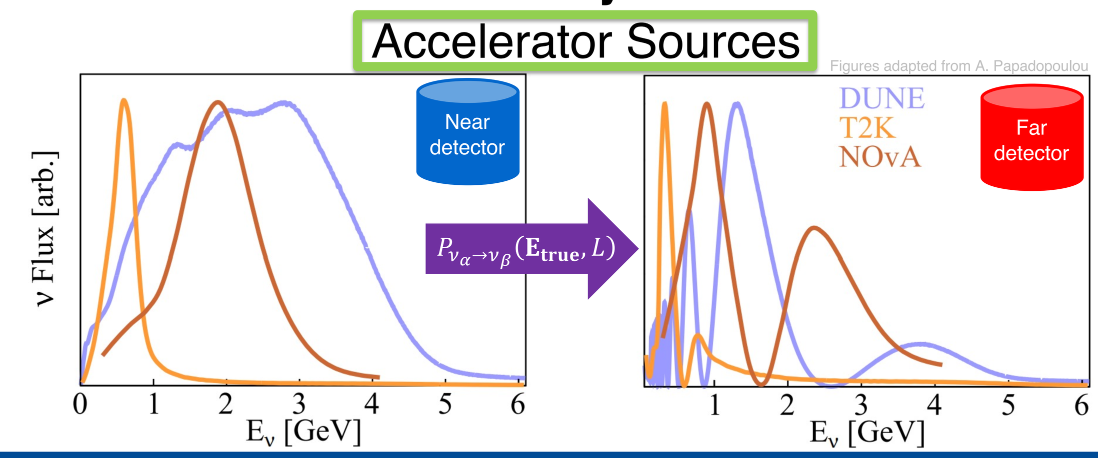


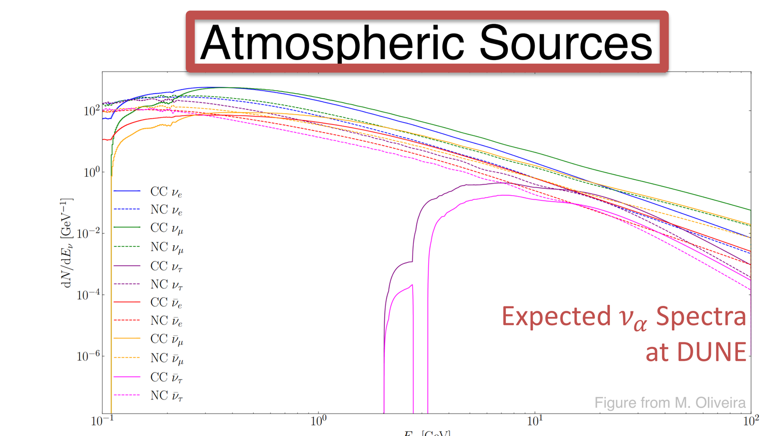
Accelerator sources usually have small range of energy: $\sim\{0.1, 10\}\text{GeV}$

- ν beam energies are tuned to oscillation maxima given chosen baseline
  - Many possible interactions: CC/NC, quasielastic, resonant production…
- **Well-known incoming direction** from geometrically diverging beam
  - No *historic* need to reconstruct θ_ν, only E_ν
- Timing from proton beam pulse helps eliminate backgrounds

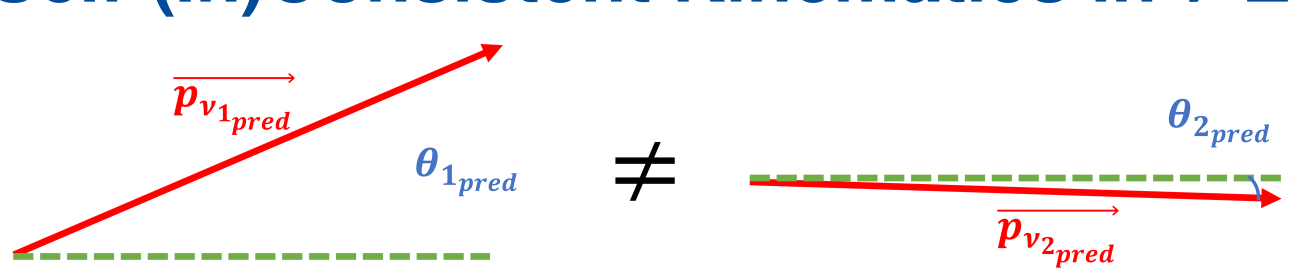
Atmospherics have *huge* range of energy: $\sim\{0.1, 1000\}\text{GeV}$

- Even more high energy processes possible! Containment issues abound…and τs!
- **Many baselines** from all around the globe! Like having many accelerators all over!
- Many baselines from **many incoming angles**! Not just one…
- No timing info to quell backgrounds—detectors deep underground to avoid cosmic μs
  - These νs become **very hard to reconstruct** because of these factors…





Self-(In)Consistent Kinematics in ν Energy Estimators



$$\boldsymbol{E}_{\nu_{1pred}} = \boldsymbol{E}_{\nu_{2pred}}$$
$$\overrightarrow{\boldsymbol{p}_{\nu_{1pred}}} \neq \overrightarrow{\boldsymbol{p}_{\nu_{2pred}}}$$
$$\boldsymbol{\theta}_{1pred} \neq \boldsymbol{\theta}_{2pred}$$

Most ν energy estimators do not consider the full kinematics of the ν

- Optimize a single loss function of a single variable, s_ν:

$$L\left(s_\nu^{\text{true}}, s_\nu^{\text{pred}}\right) = \cdots = L\left(E_\nu^{\text{true}}, E_\nu^{\text{pred}}\right)$$

- ν should be defined by more than simply their E_ν…need *momenta* info!

$$\left(E_\nu, p_{x_\nu}, p_{y_\nu}, p_{z_\nu}\right) \propto (E_\nu, \theta_\nu) \propto (E_\nu, L(\theta_\nu))$$

- Should continue training until four-vector components are kinematically consistent!
- **Must include <u>new inputs to loss function</u>!**
- **Otherwise:** $\boldsymbol{E}_\nu \approx \left|\boldsymbol{p}_{\nu_{1pred}}\right| \approx \left|\boldsymbol{p}_{\nu_{2pred}}\right|$ **while** $\boldsymbol{\theta}_\nu \not\approx \boldsymbol{\theta}_{1pred} \not\approx \boldsymbol{\theta}_{1pred}$
- There is no automatic guarantee that angular correlations are respected in a kinematically consistent way without a loss function which penalizes such behavior

Composite Loss Functions for Kinematic Estimators

Seek to encourage faster, accurate, kinematically consistent learning

- **Instead: make the loss composite and multivariate**
- Utilize possibly many kinematic variables *simultaneously*: $\{s_\nu, x_\nu, \ldots\}$

$$\mathcal{L}\left(\left\{s_\nu^{\text{true}}, s_\nu^{\text{pred}}\right\}, \left\{x_\nu^{\text{true}}, x_\nu^{\text{pred}}\right\}, \ldots\right) = \alpha L_s\left(s_\nu^{\text{true}}, s_\nu^{\text{pred}}\right) + \beta L_x\left(x_\nu^{\text{true}}, x_\nu^{\text{pred}}\right) + \cdots$$

- Can use this to imbue more physics into the loss function!
- "Physics motivated loss functions", "Physics informed machine learning" (PIML)
- Individual loss functions $\{L_s, L_x, \ldots\}$ create a composite $\mathcal{L}$ with
  - Composite loss $\mathcal{L}$ optimized

Initial loss variable combinations to be considered during trainings

- "Target" variables for *predictions* which enter losses against *truth* values

$$\left(E_\nu, p_{x_\nu}, p_{y_\nu}, p_{z_\nu}\right), \left(p_{x_\nu}, p_{y_\nu}, p_{z_\nu}\right), (E_\nu, \cos\theta_\nu), (E_\nu, \theta_\nu)$$

- Can calculate angular values from predicted/true momenta
- Will compare to single variable trainings: $E_\nu, \cos\theta_\nu, \theta_\nu$

Training Sample Preparation w/GENIE Simulation

Large, truth level samples of ν interactions available

- GENIE used by ν experiments to predicted final state particles from initial state neutrino interactions on nuclei
- Can simulate beam and atmospheric neutrinos across many energies

Initial challenge of this project: improve atmospheric ν reconstruction

- Utilize Inclusive, CC, NC, NpNπ, $1p0\pi$, $Np0\pi$…. selections for topologies
  - Make realistic selections on final state particles only above kinematic thresholds
- All done at truth-level—will utilize reconstructed values w/experiments!

Transformer Training Variables

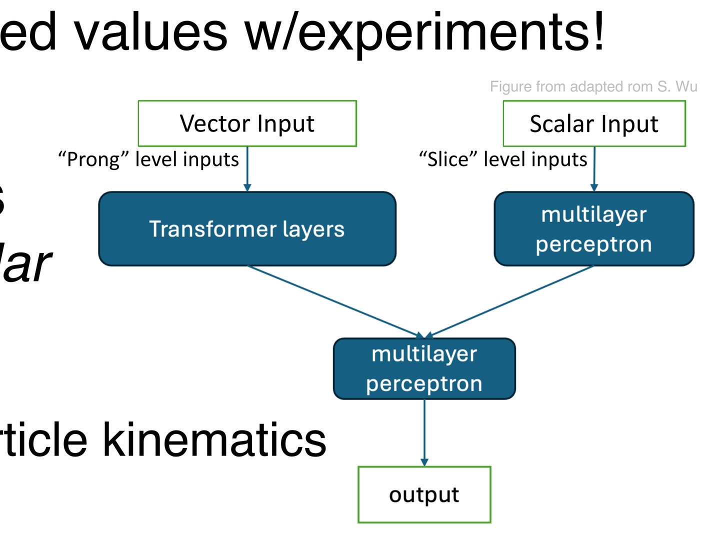
Transformer network used for initial studies

- Training variables organized as *vector* & *scalar*
  - Scalar: whole, event-level kinematic variables

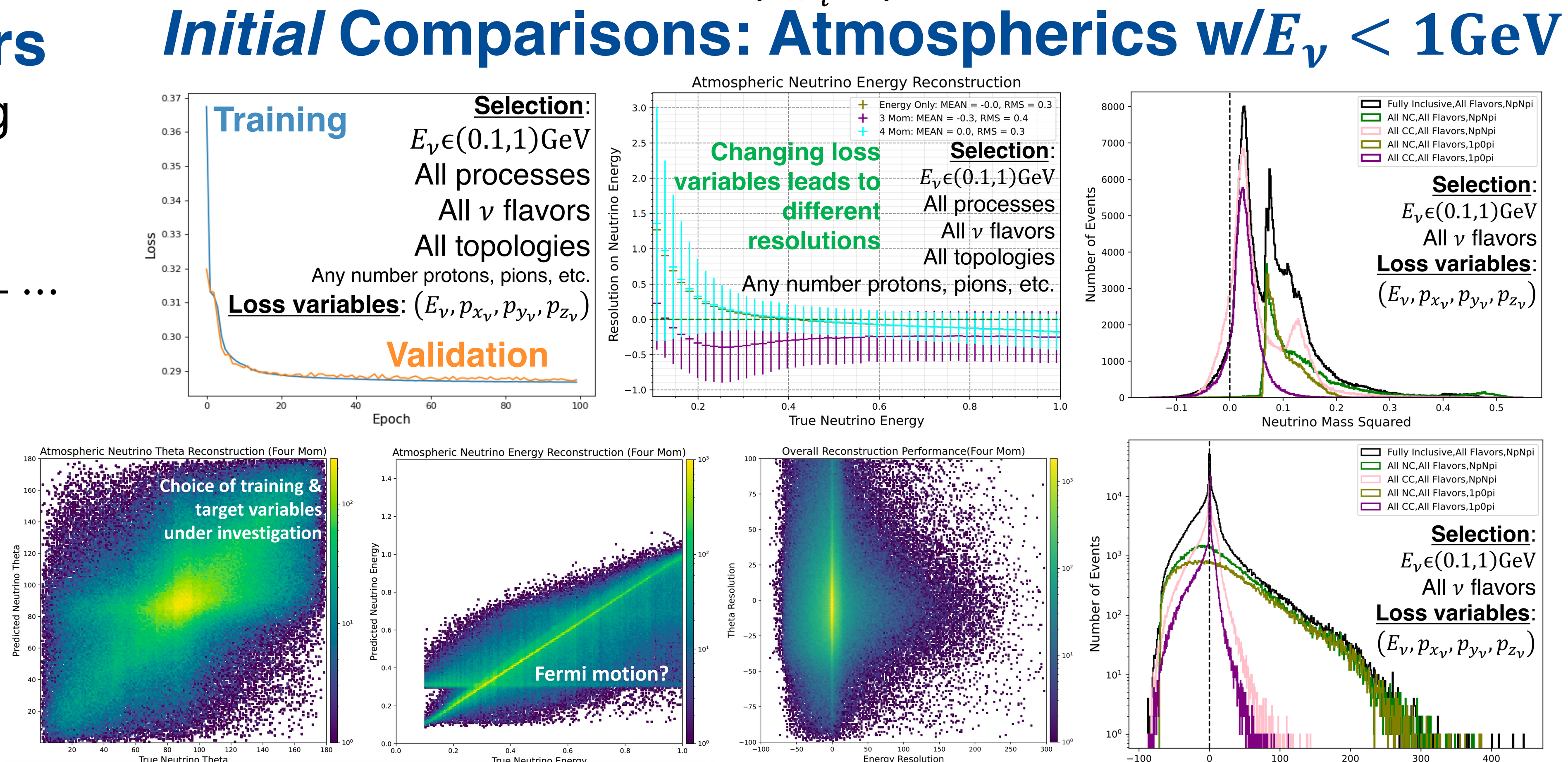
$$P_{\text{Tot}}, KE_{\text{Tot}}, P_{\text{Miss}}$$

- Vector: "visible" (*above threshold*) final state particle kinematics

$$\text{PDG}_i, \text{Mass}_i, KE_i, P_{x_i}, P_{y_i}, P_{z_i}, \cos\theta_i, \theta_i$$



Initial Comparisons: Atmospherics w/$E_\nu < 1\text{GeV}$



Low-E_ν reconstruction difficult…work needed on θ!

- Fermi motion, Intranuclear cascade, many incoming θ_ν^{atmo}

Targeting GENIE-oriented publication *first*

- Both atmospheric & beam comparisons
- DUNE-&-NOvA-oriented publications to follow w/fully reconstructed inputs

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