

Reconstruction of Tau Neutrinos in LArTPC Detectors

NuFact 2025

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On Behalf of the DUNE Collaboration

Introduction

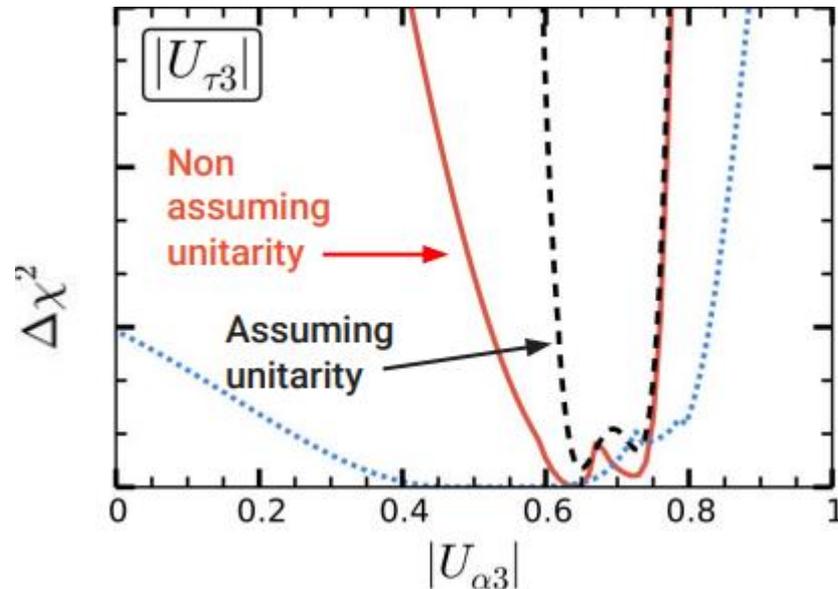
- We are interested in reconstructing/identifying tau neutrinos in the DUNE far detector (which will be a liquid argon time projection chamber).
- We have trained the NuGraph GNN on one million Monte Carlo samples which I generated.
- The network classifies the interaction as $(\nu_e \setminus \nu_\mu \setminus \nu_\tau)$ charged current or neutral current.
- Here I'll present some of our preliminary results based on this training.

Why Tau Neutrinos?

Still Many Questions!

There have only been about 30 neutrino candidates found across all of DONuT, OPERA and IceCube[1][3][6].

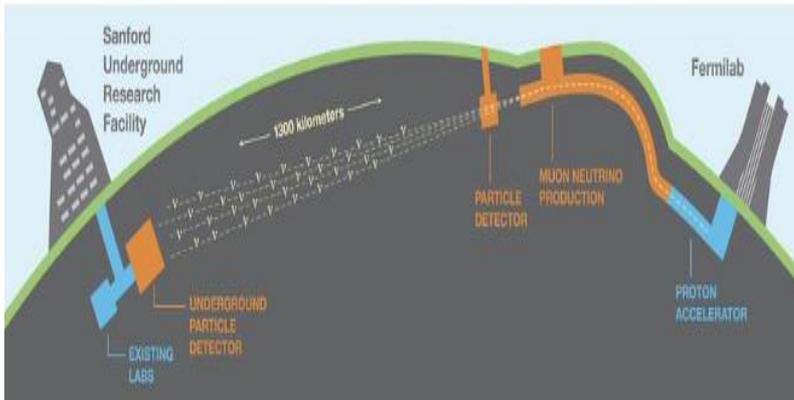
Almost all our knowledge about tau neutrino oscillations are taking from PMNS unitarity. (Unitarity of τ row in PMNS at 30% level (at 95% CL))



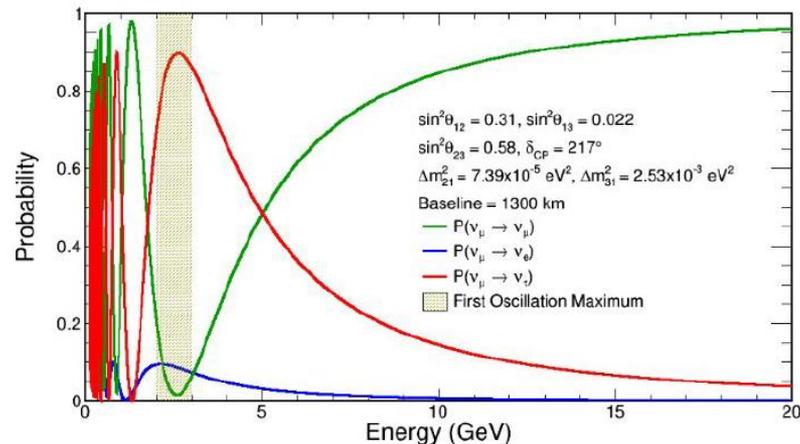
It is critical to test our assumptions!

DUNE

- The DUNE experiment gives us a unique opportunity for studying tau neutrino charged current interactions.
- The 1300km baseline and flux peaked at $\sim 2.5\text{GeV}$ is close to the $\nu_\mu \rightarrow \nu_\tau$ oscillation maximum.
- The far detector technology has $\sim 5\text{ mm}$ wire spacing which provides excellent spatial and calorimetric resolution.



[4]



[2]

Tau Difficulties

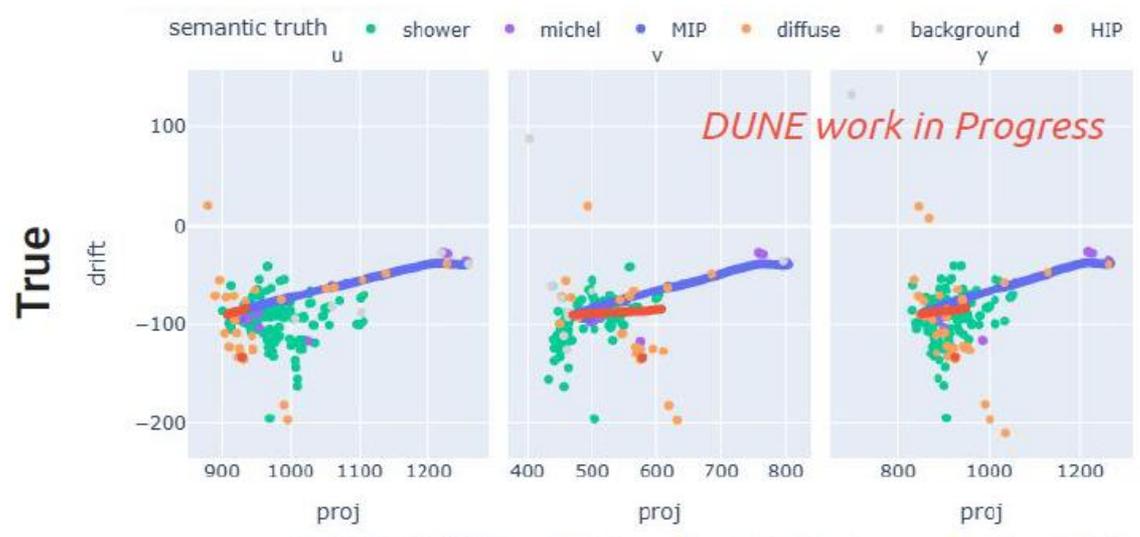
Decay mode	Branching ratio
Leptonic	35.2%
$e^- \bar{\nu}_e \nu_\tau$	17.8%
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
Hadronic	64.8%
$\pi^- \pi^0 \nu_\tau$	25.5%
$\pi^- \nu_\tau$	10.8%
$\pi^- \pi^0 \pi^0 \nu_\tau$	9.3%
$\pi^- \pi^- \pi^+ \nu_\tau$	9.0%
$\pi^- \pi^- \pi^+ \pi^0 \nu_\tau$	4.5%
other	5.7%

[7]

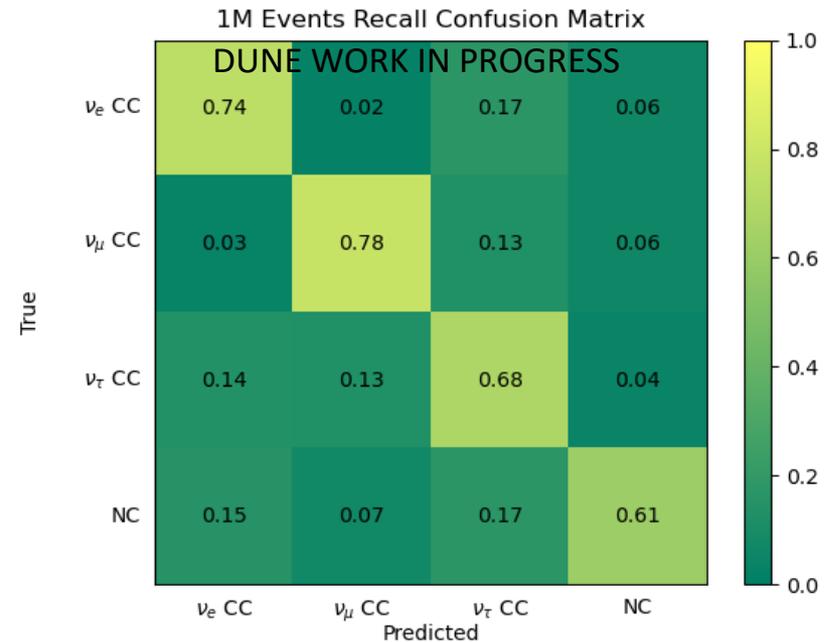
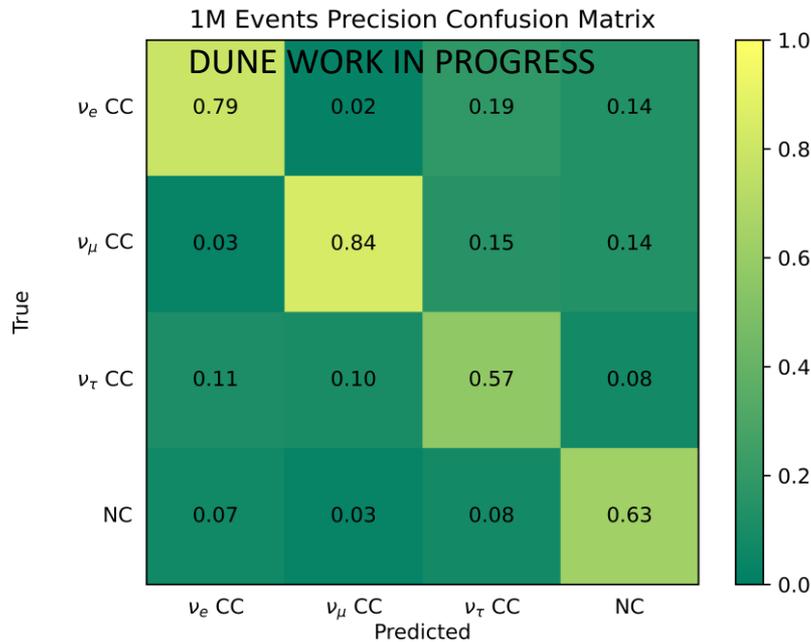
Despite the several advantages offered by DUNE detecting tau neutrinos is still difficult! *The tau lepton cannot be resolved in the detector and worse the decay products which are resolved can be confused with the other leptons.*

NuGraph

- NuGraph is a graph neural network (GNN) we use this to do interaction level classification of our events.
- The only input features are the hit positions and hit energies.
- This means the network is using very basic reconstructed quantities. Less prone to bias from reconstruction



Training Results: Confusion

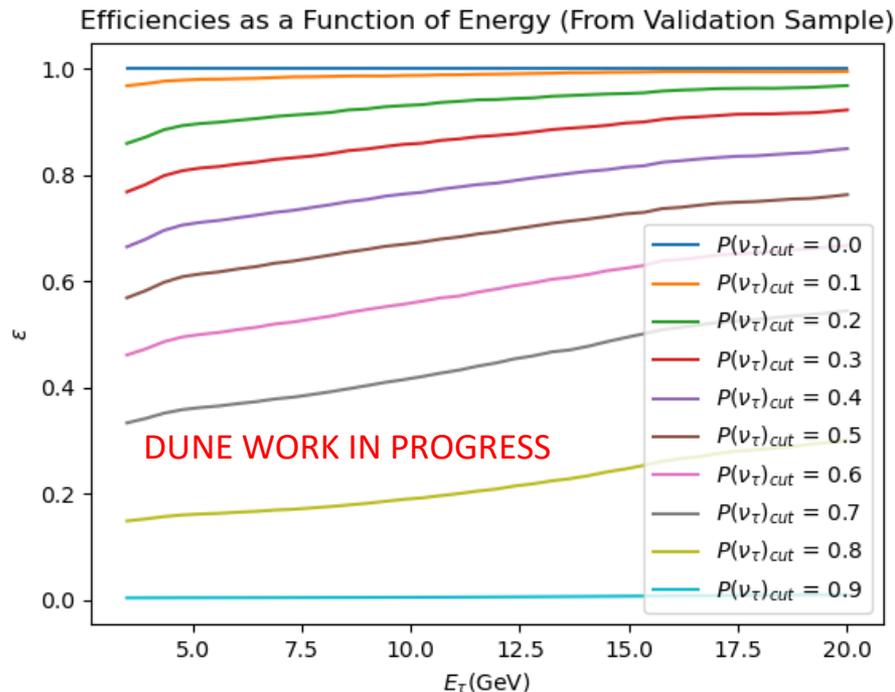


Using NuGraph For Cuts

- The output layer of the network gives a vector of the following form (after applying the SoftMax function) $(P(\nu_e), P(\nu_\mu), P(\nu_\tau), P(\nu_{NC}))$.
- We can select our signal in (at least) one of two ways.
- The first is a cut where we declare a tau neutrino whenever $P(\nu_\tau) > P(\nu_\tau)_{cut}$.
- Or we can simply declare an event to be a tau whenever $P(\nu_\tau) > P(\nu_i) \quad \forall i \in \{e, \mu, nc\}$

Efficiencies

- We compute the tau neutrino efficiency as a function of energy. This is a good base for showing the power but we have another figure of merit (next slides)



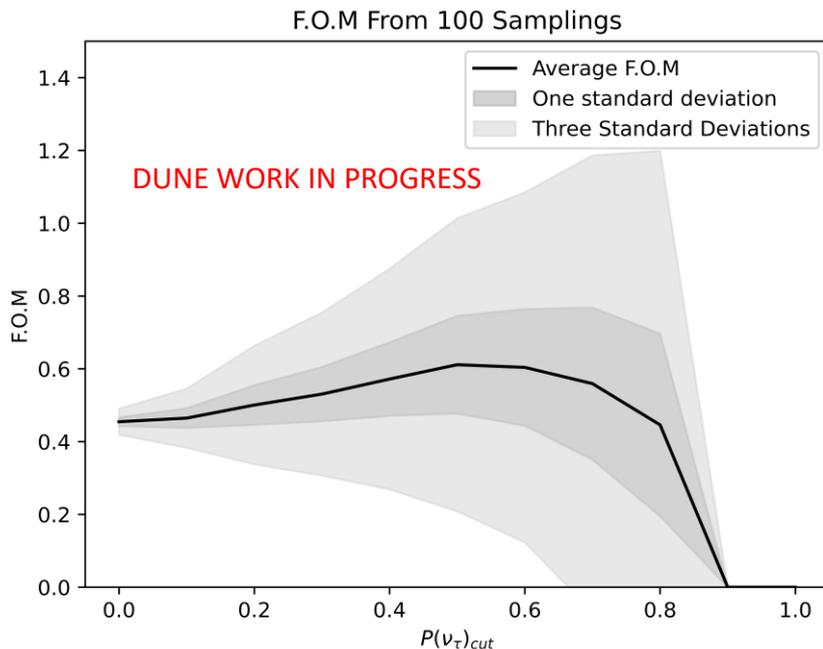
A Physics Application

- DUNE is expected to start with two far detectors each with a 10 kt fiducial mass. Thus, we can get some sensitivity numbers during the experiment's first year meaning a 20 kt-yr exposure.
- We compute the expected event assuming the following oscillation parameters. [3]

$$\theta_{12} = 0.583 \quad \theta_{23} = 0.864 \quad \theta_{13} = 0.150 \quad \delta_{CP} = -2.583$$
$$\Delta m_s = 7.42 \times 10^{-5} eV^2 \quad \Delta m_l = 2.513 \times 10^{-3} eV^2$$

- We then take the required number of events for each flavour from the validation sample and run the network to find the signal and background rates.

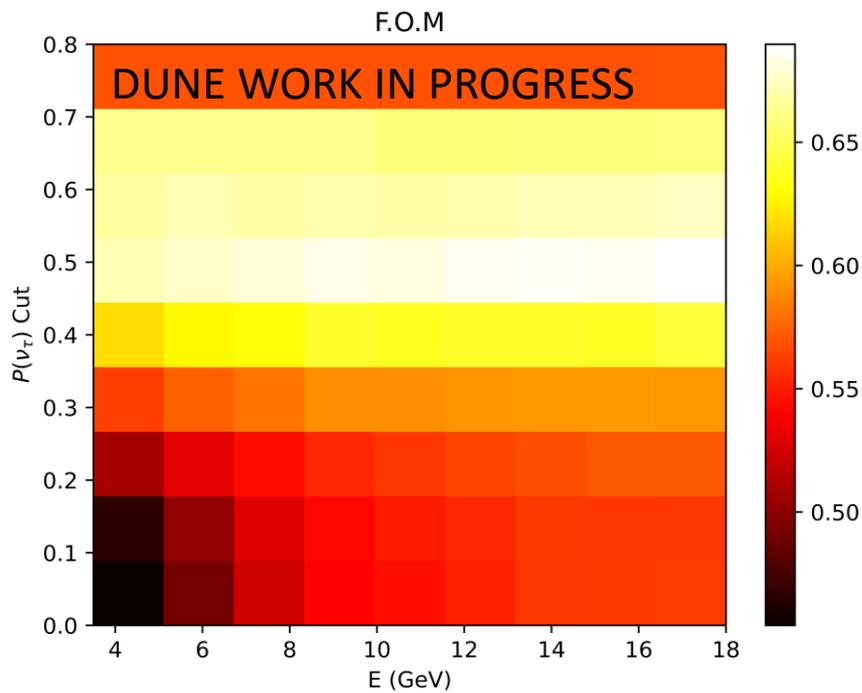
Our Figure Of Merit



We sample from our validation sample based on the rates we expect we then use $\frac{s}{\sqrt{b}}$ where s are the selected true tau cc interactions and b is the number of selected non tau CC and NC interactions.

Figure of Merit Ctd

- Here is a scan of the figure of merit across energies and cut. As expected we get the best F.O.M at moderate tau probability and energy cuts.



Conclusions

- We have shown that there is potential to get $>1\sigma$ sensitivity to tau neutrino detection after only one year of the DUNE experiment with a standard exposure.
- We have determined the ideal tau neutrino probability cuts and energy cuts from the neural networks.
- We are continuing to improve the sensitivity by training the model on a sample generated with the tau optimized flux and by the addition of a term to the loss function to try to optimize the network for tau sensitivity.

References

[1] R. Abbasi, M. Ackermann, J. Adams, S.K. Agarwalla, J.A. Aguilar, M. Ahlers, J.M. Alameddine, N.M. Amin, K. Andeen, G. Anton, C. Argüelles, Y. Ashida, S. Athanasiadou, S.N. Axani, X. Bai, V.A. Balagopal, M. Baricevic, S.W. Barwick, V. Basu, R. Bay, J.J. Beatty, J. Becker Tjus, J. Beise, C. Bellenghi, C. Benning, S. BenZvi, D. Berley, E. Bernardini, D.Z. Besson, E. Blaufuss, S. Blot, F. Bontempo, J.Y. Book, C. Bos-colo Meneguolo, S. Boser, O. Botner, J. Böttcher, E. Bourbeau, J. Braun, B. Brinson, J. Brostean-Kaiser, R.T. Burley, R.S. Busse, D. Butterfield, M.A. Campana, K. Carloni, E.G. Carnie-Bronca, S. Chattopadhyay, N. Chau, C. Chen, Z. Chen, D. Chirkin, S. Choi, B.A. Clark, L. Classen, A. Coleman, G.H. Collin, A. Con-nolly, J.M. Conrad, P. Coppin, P. Correa, D.F. Cowen, P. Dave, C. De Clercq, J.J. DeLaunay, D. Delgado, S. Deng, K. Deoskar, A. Desai, P. Desiati, K.D. de Vries, G. de Wasseige, T. DeYoung, A. Diaz, J.C. D'iaz-V'elez, M. Dittmer, A. Domi, H. Dujmovic, M.A. DuVernois, T. Ehrhardt, P. Eller, E. Ellinger, S. El Mentawi, D. Elsässer, R. Engel, H. Erpenbeck, J. Evans, P.A. Evenson, K.L. Fan, K. Fang, K. Farrag, A.R. Fazely, N. Feigl, S. Fiedlschuster, A.T. Fienberg, C. Finley, L. Fischer, D. Fox, A. Franckowiak, A. Fritz, P. Fürst, J. Gallagher, E. Ganster, A. Garcia, L. Gerhardt, A. Ghadimi, C. Glaser, T. Glauch, T. Glusenkamp, N. Goehlike, J.G. Gonzalez, S. Goswami, D. Grant, S.J. Gray, O. Gries, S. Griffin, S. Griswold, K.M. Groth, C. Günther, P. Gutjahr, C. Haack, A. Hallgren, R. Halliday, L. Halve, F. Halzen, H. Hamdaoui, M. Ha Minh, K. Hanson, J. Hardin, A.A. Harnisch, P. Hatch, A. Haungs, K. Helbing, J. Hellrung, F. Henningsen, L. Heuer-mann, N. Heyer, S. Hickford, A. Hidvegi, C. Hill, G.C. Hill, K.D. Hoffman, S. Hori, K. Hoshina, W. Hou, T. Huber, K. Hultqvist, M. Hünnefeld, R. Hussain, K. Hymon, S. In, A. Ishihara, M. Jacquart, O. Janik, M. Jansson, G.S. Japaridze, M. Jeong, M. Jin, B.J.P. Jones, D. Kang, W. Kang, X. Kang, A. Kappes, D. Kappesser, L. Kardum, T. Karg, M. Karl, A. Karle, U. Katz, M. Kauer, J.L. Kelley, A. Khatee Zathul, A. Kheirandish, J. Kiryluk, S.R. Klein, A. Kochocki, R. Koirala, H. Kolanoski, T. Kontrimas, L. Köpke, C. Kopper, D.J. Koskinen, P. Koundal, M. Kovacevich, M. Kowalski, T. Kozynets, J. Krishnamoorthi, K. Kruiswijk, E. Krupczak, A. Kumar, E. Kun, N. Kurahashi, N. Lad, C. Lagunas Gualda, M. Lam-oureux, M.J. Larson, S. Latseva, F. Lauber, J.P. Lazar, J.W. Lee, K. Leonard DeHolton, A. Leszczyńska, M. Lincetto, Q.R. Liu, M. Liubarska, E. Lohfink, C. Love, C.J. Lozano Mariscal, F. Lucarelli, W. Luszczak, Y. Lyu, J. Madsen, K.B.M. Mahn, Y. Makino, E. Manao, S. Mancina, W. Marie Sainte, I.C. Mari, S. Marka, Z. Marka, M. Marsee, I. Martinez-Soler, R. Maruyama, F. Mayhew, T. McElroy, F. McNally, J.V. Mead, K. Meagher, S. Mechal, A. Medina, M. Meier, Y. Merckx, L. Merten, J. Micallef, J. Mitchell, T. Montaruli, R.W. Moore, Y. Morii, R. Morse, M. Moulai, T. Mukherjee, R. Naab, R. Nagai, M. Nakos, U. Naumann, J. Necker, A. Negi, M. Neumann, H. Niederhausen, M.U. Nisa, A. Noell, A. Novikov, S.C. Nowicki, A. Ober-tacke Pollmann, V. O'Dell, M. Oehler, B. Oeyen, A. Olivas, R. Orsoe, J. Osborn, E. O'Sullivan, H. Pandya, D.V. Pankova, N. Park, G.K. Parker, E.N. Paudel, L. Paul, C. Pérez de los Heros, J. Peterson, S. Philip-pen, A. Pizzuto, M. Plum, A. Pont'én, Y. Popovych, M. Prado Rodriguez, B. Pries, R. Procter-Murphy, G.T. Przybylski, C. Raab, J. Rack-Helleis, K. Rawlins, Z. Rechav, A. Rehman, P. Reichherzer, G. Renzi, E. Resconi, S. Reusch, W. Rhode, B. Riedel, A. Rifaie, E.J. Roberts, S. Robertson, S. Rodan, G. Roellinghoff, M. Rongen, C. Rott, T. Ruhe, L. Ruohan, D. Ryckbosch, I. Safa, J. Saffer, D. Salazar-Gallegos, P. Sam-pathkumar, S.E. Sanchez Herrera, A. Sandrock, M. Santander, S. Sarkar, S. Sarkar, J. Savelberg, P. Savina, M. Schaufel, H. Schieler, S. Schindler, L. Schlickmann, B. Schlüter, F. Schlüter, N. Schmeisser, T. Schmidt, J. Schneider, F.G. Schröder, L. Schumacher, G. Schwefer, S. Sclafani, D. Seckel, M. Seikh, S. Seunarine, R. Shah, A. Sharma, S. Shefali, N. Shimizu, M. Silva, B. Skrzypek, B. Smithers, R. Snihur, J. Soedingrekso, A. Søgaard, D. Soldin, P. Soldin, G. Sommani, C. Spannfellner, G.M. Spiczak, M. Stamatikos, T. Stanev, T. Stezelberger, T. Stürwald, T. Stuttard, G.W. Sullivan, I. Taboada, S. Ter-Antonyan, M. Thiesmeyer, W.G. Thompson, J. Thwaites, S. Tilav, K. Tollefson, C. Tonnis, S. Toscano, D. Tosi, A. Trettin, C.F. Tung, R. Turcotte, J.P. Twagirayezu, B. Ty, M.A. Unland Elorrieta, A.K. Upadhyay, K. Upshaw, N. Valtonen-Mattila, J. Vandenbroucke, N. van Eijndhoven, D. Vannerom, J. van Santen, J. Vara, J. Veitch-Michaelis, M. Venugopal, M. Vereecken, S. Verpoest, D. Veske, A. Vijai, C. Walck, C. Weaver, P. Weigel, A. Weindl, J. Welder, A.Y. Wen, C. Wendt, J. Werthebach, M. Weyrauch, N. Whitehorn, C.H. Wiebusch, N. Willey, D.R. Williams, L. Witthaus, A. Wolf, M. Wolf, G. Wrede, X.W. Xu, J.P. Yanez, E. Yildizci, S. Yoshida, R. Young, F. Yu, S. Yu, Z. Zhang, P. Zhelnin, P. Zilberman, and M. Zimmerman. Observation of seven astrophysical tau neutrino candidates with IceCube. *Physical Review Letters*, 132(15), April 2024.

References

- [2] Roshan Mammen Abraham, Jaime Alvarez-Muñiz, Carlos A Argüelles, Akitaka Ariga, Tomoko Ariga, Adam Aurisano, Dario Autiero, Mary Bishai, Nilay Bostan, Mauricio Bustamante, Austin Cummings, Valentin Decoene, André de Gouvêa, Giovanni De Lellis, Albert De Roeck, Peter B Denton, Antonia Di Crescenzo, Milind V Diwan, Yasaman Farzan, Anatoli Fedynitch, Jonathan L Feng, Laura J Fields, Alfonso Garcia, Maria Vittoria Garzelli, Julia Gehrlein, Christian Glaser, Katarzyna Grzelak, Steffen Hallmann, Jeremy Hewes, D Indumathi, Ahmed Ismail, Sudip Jana, Yu Seon Jeong, Kevin J Kelly, Spencer R Klein, Felix Kling, Thomas Kosc, Umut Kose, D Jason Koskinen, John Krizmanic, Jeff Lazar, Yichen Li, Ivan Martinez-Soler, Irina Mocioiu, Jiwoo Nam, Valentin Niess, Nepomuk Otte, Sameer Patel, Roberto Petti, Remy L Prechelt, Steven Prohira, Miriama Rajaoalisoa, Mary Hall Reno, Ibrahim Safa, Carlos Sarasty-Segura, R Thiru Senthil, Juliana Stachurska, Oleksandr Tomalak, Sebastian Trojanowski, Roger Alexandre Wendell, Dawn Williams, Stephanie Wissel, Barbara Yaeggy, Enrique Zas, Pavel Zhelnin, and Jing-yu Zhu. Tau neutrinos in the next decade: from gev to eev. *Journal of Physics G: Nuclear and Particle Physics*, 49(11):110501, October 2022.
- [3] N. Agafonova, A. Alexandrov, A. Anokhina, S. Aoki, A. Ariga, T. Ariga, A. Bertolin, C. Bozza, R. Brugnera, A. Buonauro, S. Buontempo, M. Chernyavskiy, A. Chukanov, L. Consiglio, N. D'Ambrosio, G. De Lellis, M. De Serio, P. del Amo Sanchez, A. Di Crescenzo, D. Di Ferdinando, N. Di Marco, S. Dmitrievsky, M. Dracos, D. Duchesneau, S. Dusini, T. Dzhatdoev, J. Ebert, A. Ereditato, J. Favier, R.A. Fini, F. Fornari, T. Fukuda, G. Galati, A. Garfagnini, V. Gentile, J. Goldberg, S. Gorbunov, Y. Gornushkin, G. Grella, A.M. Guler, C. Gustavino, C. Hagner, T. Hara, T. Hayakawa, A. Hollnagel, K. Ishiguro, A. Iuliano, K. Jakovcic, C. Jollet, C. Kamiscioglu, M. Kamiscioglu, S.H. Kim, N. Kitagawa, B. Klicek, K. Kodama, M. Komatsu, U. Kose, I. Kreslo, F. Laudisio, A. Lauria, A. Ljubicic, A. Longhin, P. Loverre, M. Malenica, A. Malgin, G. Mandrioli, T. Matsuo, V. Matveev, N. Mauri, E. Medinaceli, A. Meregaglia, S. Mikado, M. Miyanishi, F. Mizutani, P. Monacelli, M.C. Montesi, K. Morishima, M.T. Muciaccia, N. Naganawa, T. Naka, M. Nakamura, T. Nakano, K. Niwa, S. Ogawa, N. Okateva, A. Olchevsky, K. Ozaki, A. Paoloni, L. Paparella, B.D. Park, L. Pasqualini, A. Pastore, L. Patrizii, H. Pessard, C. Pistillo, D. Podgrudkov, N. Polukhina, M. Pozzato, F. Pupilli, M. Roda, T. Roganova, H. Rokujo, G. Rosa, O. Ryazhskaya, A. Sadovsky, O. Sato, A. Schembri, I. Shakiryanova, T. Shchedrina, E. Shibayama, H. Shibuya, T. Shiraishi, S. Simone, C. Sirignano, G. Sirri, A. Sotnikov, M. Spinetti, L. Stanco, N. Starkov, S.M. Stellacci, M. Stipcevic, P. Strolin, S. Takahashi, M. Tenti, F. Terranova, V. Tioukov, S. Tufanli, A. Ustyuzhanin, S. Vasina, P. Vilain, E. Voevodina, L. Votano, J.L. Vuilleumier, G. Wilquet, B. Wonsak, and C.S. Yoon. Final results of the OPERA experiment on μ neutrino disappearance in the CNGS neutrino beam. *Physical Review Letters*, 120(21), May 2018.
- [4] DUNE Collaboration. The dune far detector interim design report volume 1: Physics, technology and strategies, 2018.
- [5] Ivan Esteban, M.C. Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz, and Albert Zhou. The fate of hints: updated global analysis of three-flavor neutrino oscillations. *Journal of High Energy Physics*, 2020(9), September 2020.
- [6] K. Kodama, N. Ushida, C. Andreopoulos, N. Saoulidou, G. Tzanakos, P. Yager, B. Baller, D. Boehnlein, W. Freeman, B. Lundberg, J. Morfin, R. Rameika, S. H. Chung, J. S. Song, C. S. Yoon, P. Berghaus, M. Kubantsev, N. W. Reay, R. Sidwell, N. Stanton, S. Yoshida, S. Aoki, T. Hara, J. T. Rhee, D. Ciampa, C. Erickson, M. Graham, E. Maher, K. Heller, R. Rusack, R. Schwienhorst, J. Sielaff, J. Trammell, J. Wilcox, T. Furukawa, K. Hoshino, H. Jiko, M. Komatsu, M. Nakamura, T. Nakano, K. Niwa, N. Nonaka, K. Okada, B. D. Park, O. Sato, S. Takahashi, V. Paolone, C. Rosenfeld, A. Kulik, T. Kafka, W. Oliver, T. Patzak, and J. Schneps. Final tau-neutrino results from the DONUT experiment. *Physical Review D*, 78(5), September 2008.
- [7] Pedro Machado, Holger Schulz, and Jessica Turner. Tau neutrinos at dune: New strategies, new opportunities. *Physical Review D*, 102(5), September 2020.
- [8] Stephen Parke and Mark Ross-Lonergan. Unitarity and the three flavor neutrino mixing matrix. *Physical Review D*, 93(11), June 2016.

Thank You!

Backup Slide 1 GNN Temp

- The temperature in the GNN is a parameter which is used to smooth out the output layer of the network specifically the output layer is transformed to:
- $$q_i = \frac{\exp\left(\frac{o_i}{T}\right)}{\sum_k \exp\left(\frac{o_k}{T}\right)}$$
- The temperature is a trainable parameter and in our case it became negative (it was also small) this is the plotted loss is negative.
- This is something we are trying to understand better but we think it is okay just a bit odd...
- Want to investigate why the network doesn't force $T > 0$.

Backup Slide 2 Global P and R

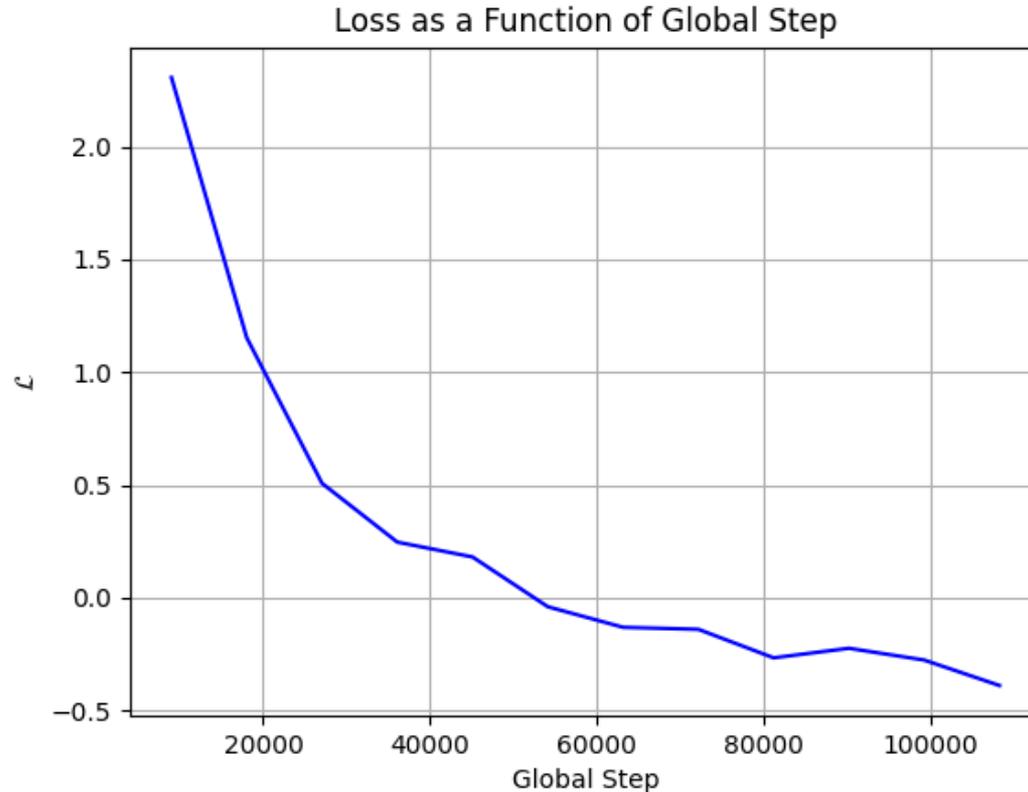
- In our plots of the precision and recall they are both the same.
- The reason for this is that here we are plotting global versions of these which are defined in the same way for both and are defined as $\frac{\#(\text{Correctly Classified Events})}{\#(\text{Correctly Classified Events}) + \#(\text{Incorrectly Classified Events})}$

Training Details

- We split our 1M events into a train/test/validation splits at rates of 90%/5%/5%.
- We use the categorical cross entropy loss here where i indexes the category and R is the recall (efficiency).
- This is called the recall loss see here ([https://arxiv.org/abs/1808.07750](#)) and is meant to compensate for slight differences in the rates of each category

$$\mathcal{L} = \sum_i (1 - R_i) \times CE_i$$

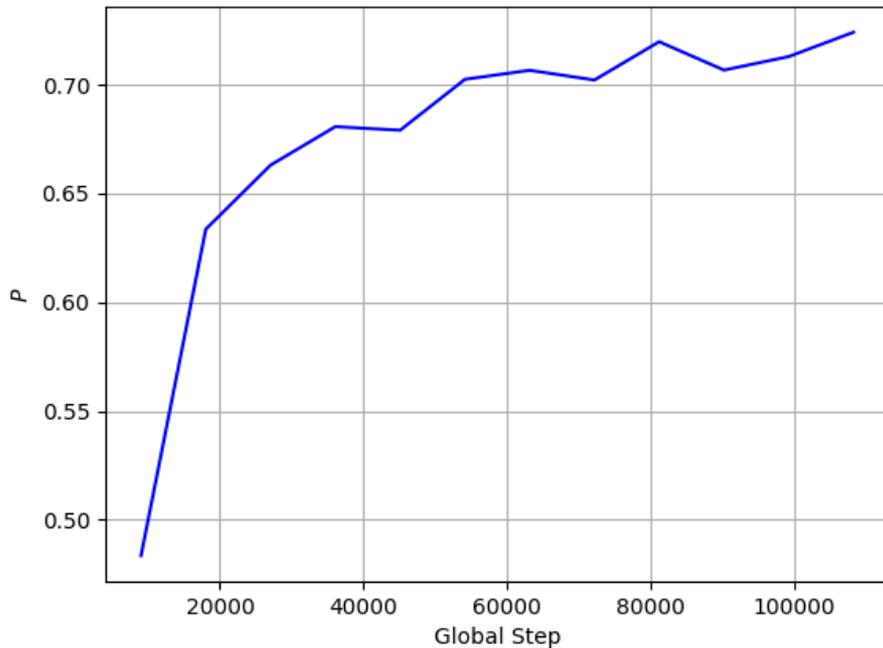
Training Results: Loss



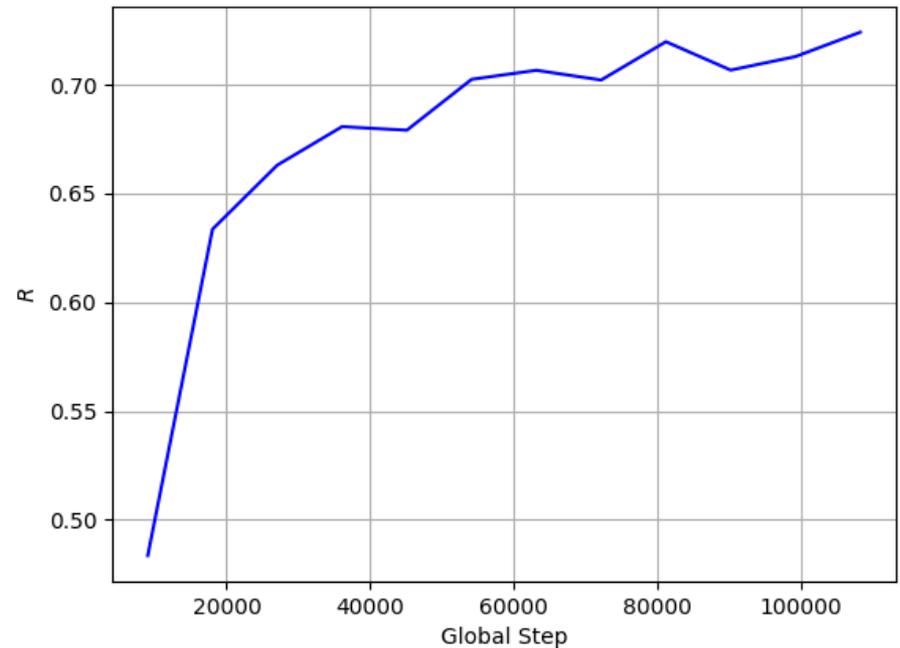
The recall loss as a function of global step. Note that the loss plotted here is actually $2e^{-T} \times \mathcal{L} + T$

Precision and Recall

Precision as a Function of Global Step



Recall as a Function of Global Step



Precision (left) and recall (right) as a function of the global step