Baryon Number Violation Searches Using the DUNE Far Detector

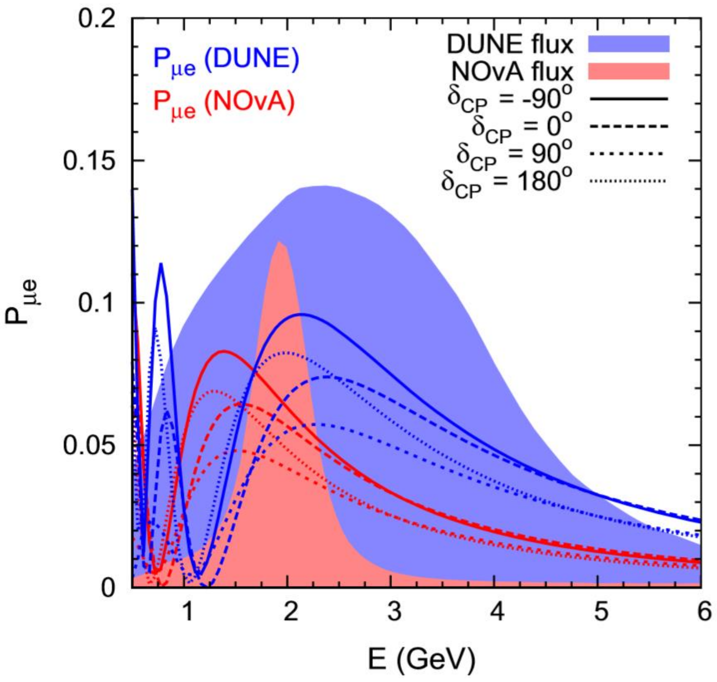
Conference on Science at the Sanford Underground Research Facility

by J. L. Barrow
On Behalf of the DUNE Collaboration
For the High-Energy Physics Working Group
The University of Minnesota
May 15th, 2024

What is DUNE?

Goals of DUNE

- Extract ν oscillation parameters, especially δ_{CP}
  - **<u>First</u> measurements will be rendered using atmospheric νs**
- **Search for BSM physics (baryon number violation)**



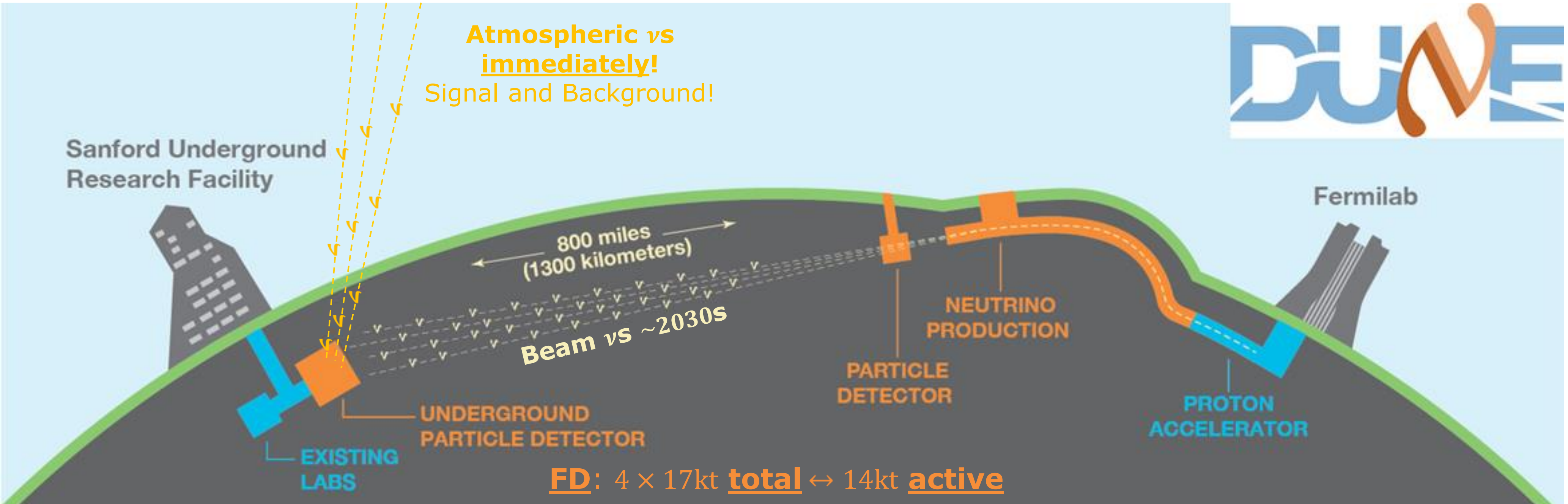
Ghosh *et al*. Eur. Phys. J. C (2016)76

Implications of DUNE

- Precision U_{PMNS}, lepton universality, τ production, BSM/NSI constraints, calibrations, cross sections (ND)

Features and Challenges

- $\boldsymbol{\nu}_{\mathbf{beam}}$: timing, broadband (~1-5GeV) energy, known direction
- $\boldsymbol{\nu}_{\mathbf{atm}}$: no timing, even broader energies, ~unknown direction
  - **Backgrounds** for rare processes: $\boldsymbol{p \to K^+\bar{\nu}}$ **and** $\boldsymbol{n \to \bar{n}}$



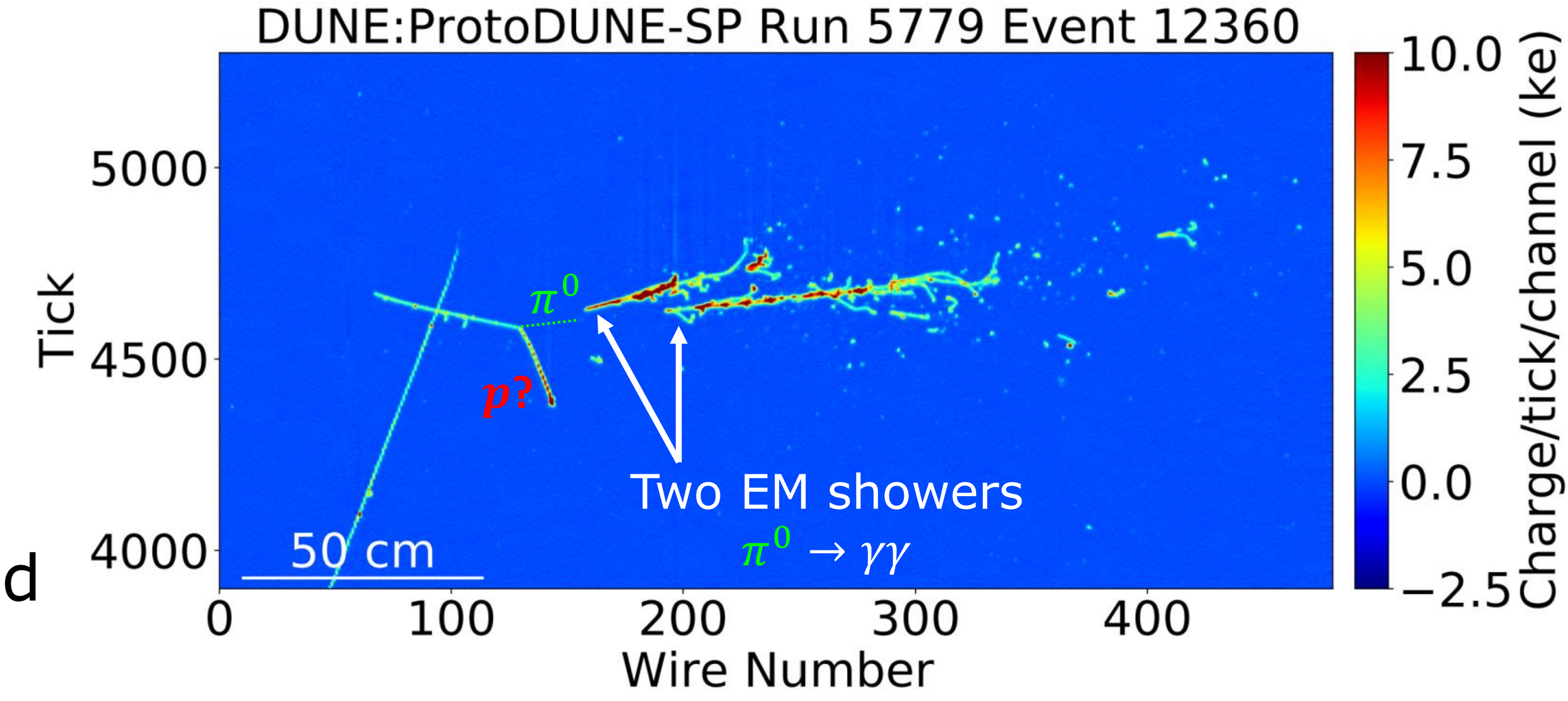
Atmospheric νs
<u>immediately</u>!
Signal and Background!

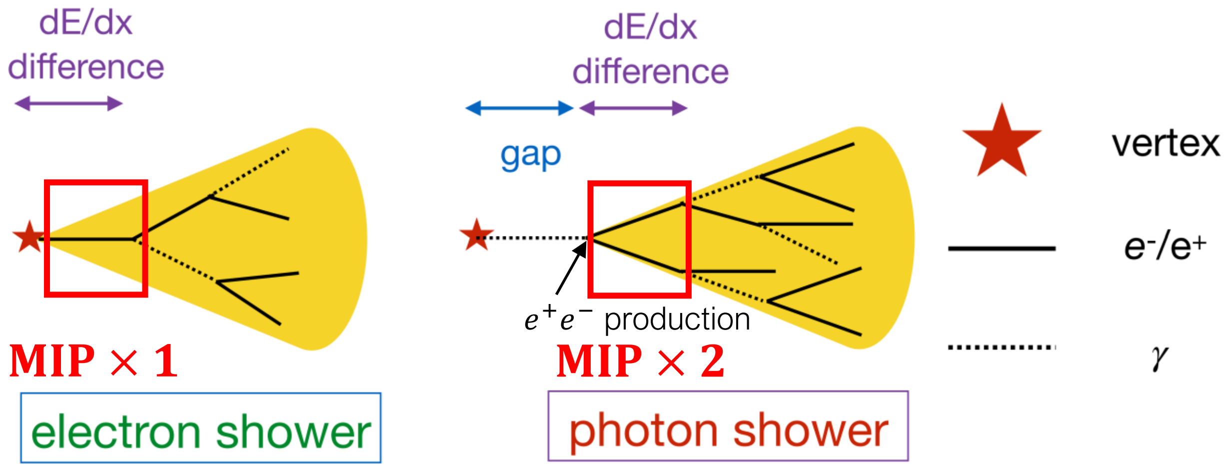
Beam νs ~2030s

<u>FD</u>: 4×17kt **<u>total</u>** ↔ 14kt **<u>active</u>**

Liquid Argon Time Projection Chambers

- γ/e discrimination
  - Tracks and gaps
- Access to low KE hadron thresholds
- DUNE’s technology
- $^{40}\mathrm{Ar}$ as nuclear target and detector medium
- Ionization of LAr for track and shower reconstruction
  - Charge drifts via high $\vec{E}$ field
  - mm-scale resolution
  - $dQ/ds \sim dE/ds$ for calorimetry





Adapted from H. Wei and J. H. Jo

V. Meddage APS April 2019

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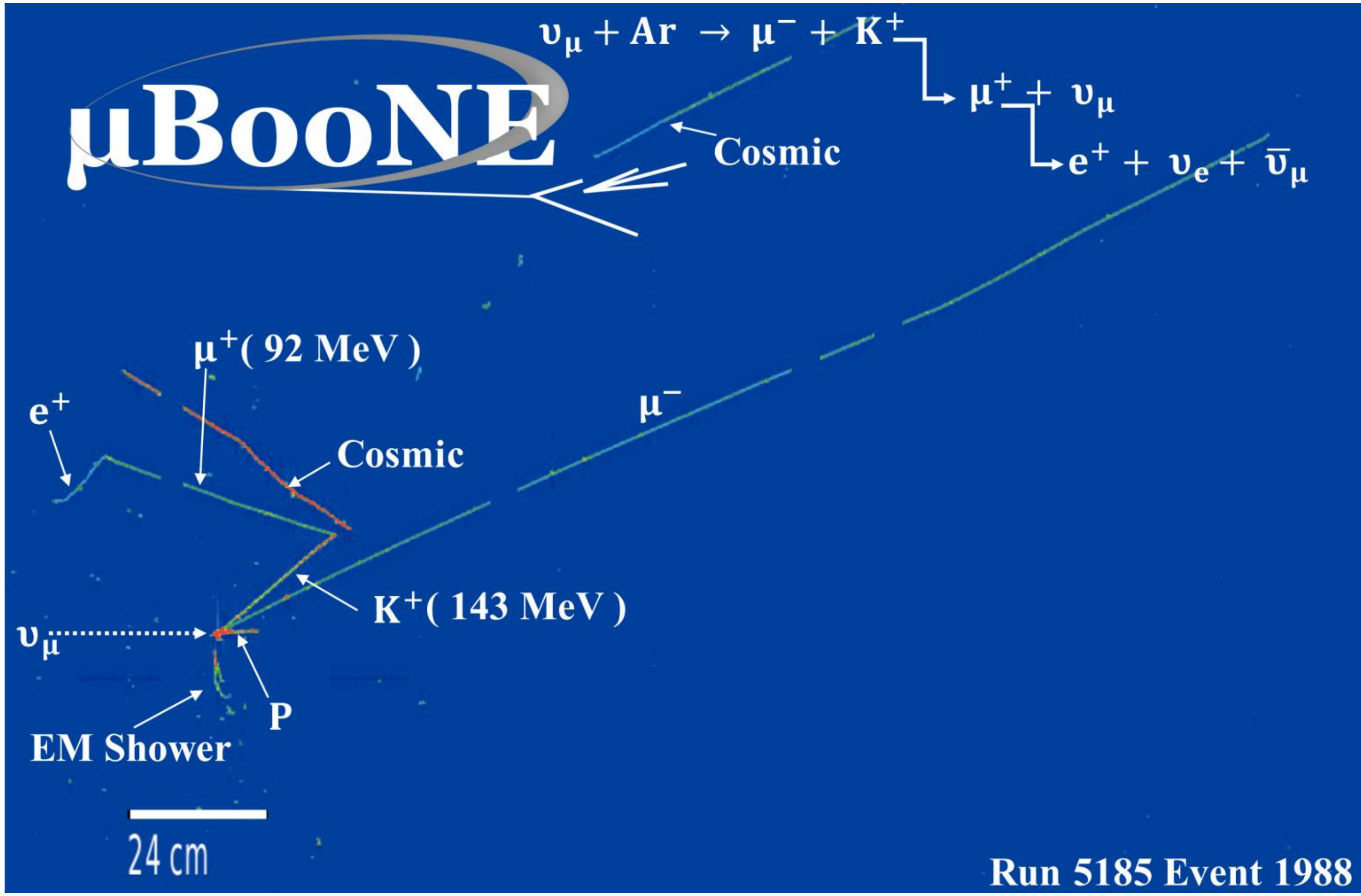

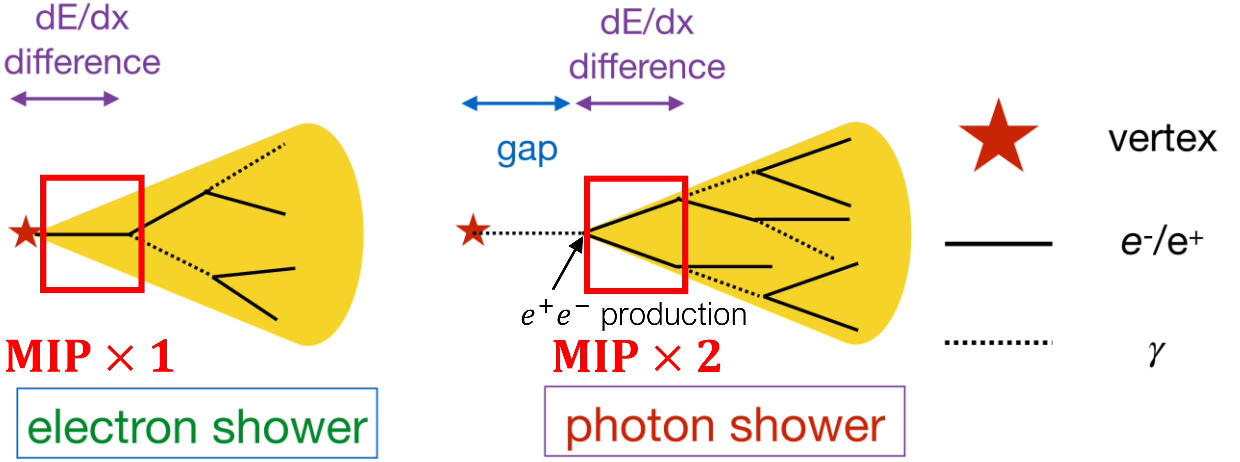

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The Baryon Asymmetry of the Universe

Implies BNV is a Necessary Part of Sakharov Conditions

- Protons outnumber antiprotons in cosmic rays $10^4:1$

- Cosmic microwave background (CMB) yields magnitude

$$\beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx \frac{n_B - 0}{n_\gamma} \approx 10^{-10}$$

- Expectation: effectively no leftover B or $\bar{B}$
  - Due to mutual annihilation occurring down to roughly 1 GeV ("freeze" out)
  - Gives rise to an ***expected relic baryon abundance***

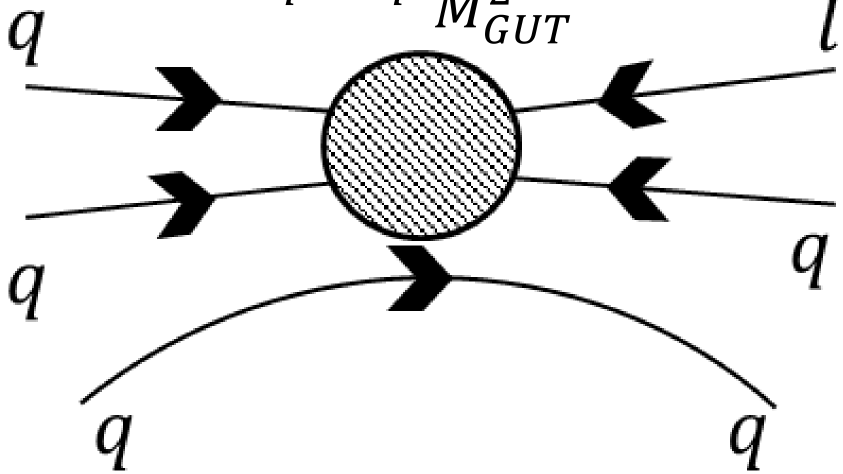
$$n_B = n_{\bar{B}} \approx \frac{n_\gamma}{\sigma_{ann} m_B m_{Pl}} \approx 10^{-19} n_\gamma$$

- Comparison between these: $\sim 10^{-9}$…*that's Bill Gate's lunch*

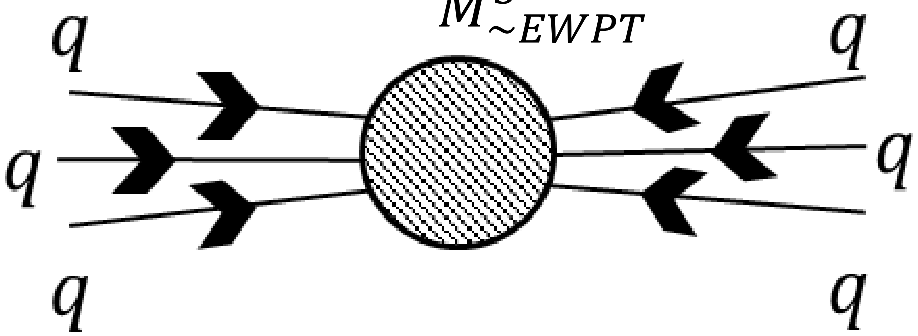
A. D. Dolgov, *Baryogenesis, 30 Years Later*

Going Beyond the Standard Model

$$\mathcal{O}_p^6 \sim \lambda_p \frac{qq\bar{q}l}{M_{GUT}^2}$$



$$\mathcal{O}_{2\mathrm{N}}^9 \sim \lambda \frac{qqq\bar{q}\bar{q}\bar{q}}{M_{\sim EWPT}^5}$$

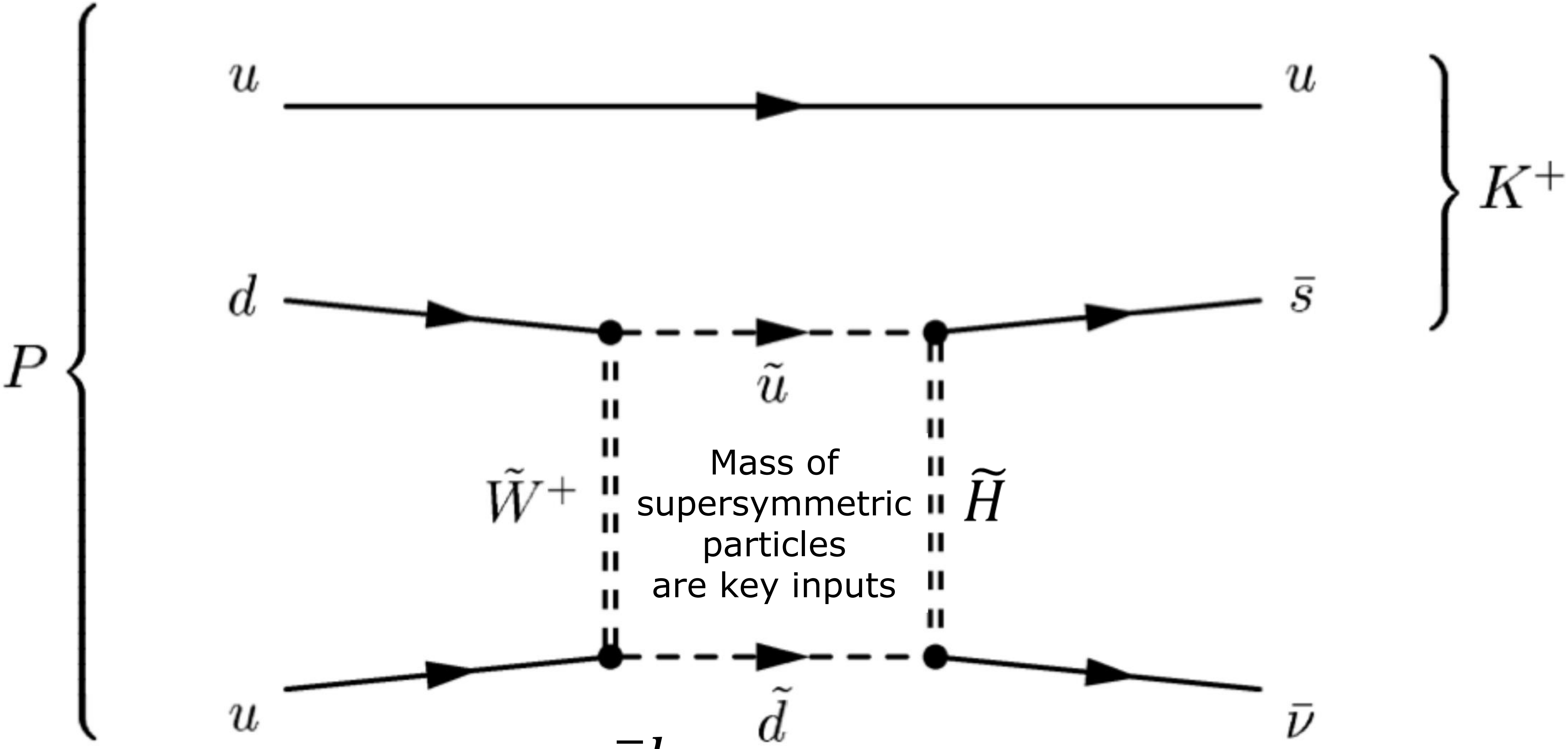


What else do we need to add?

- Proton decay?
  - PDK∝ $qqql \Longrightarrow B - L$ conserved
  - Key to BSM GUT & SUSY theories
- Other $\Delta B \neq 0$ or $\Delta L \neq 0$?
  - $\boldsymbol{\Delta B = 2}$ operators?

“Golden Channel”

Supersymmetric Particles Can Lower Mass Scales for Observable PDK



Mass of supersymmetric particles are key inputs

$$\mathcal{O}_p^6 \sim \lambda_p \frac{qq\bar{q}l}{M_{GUT}^2} \propto ud\bar{s}\bar{\nu} \Longrightarrow \boldsymbol{p \to K^+\bar{\nu}}$$

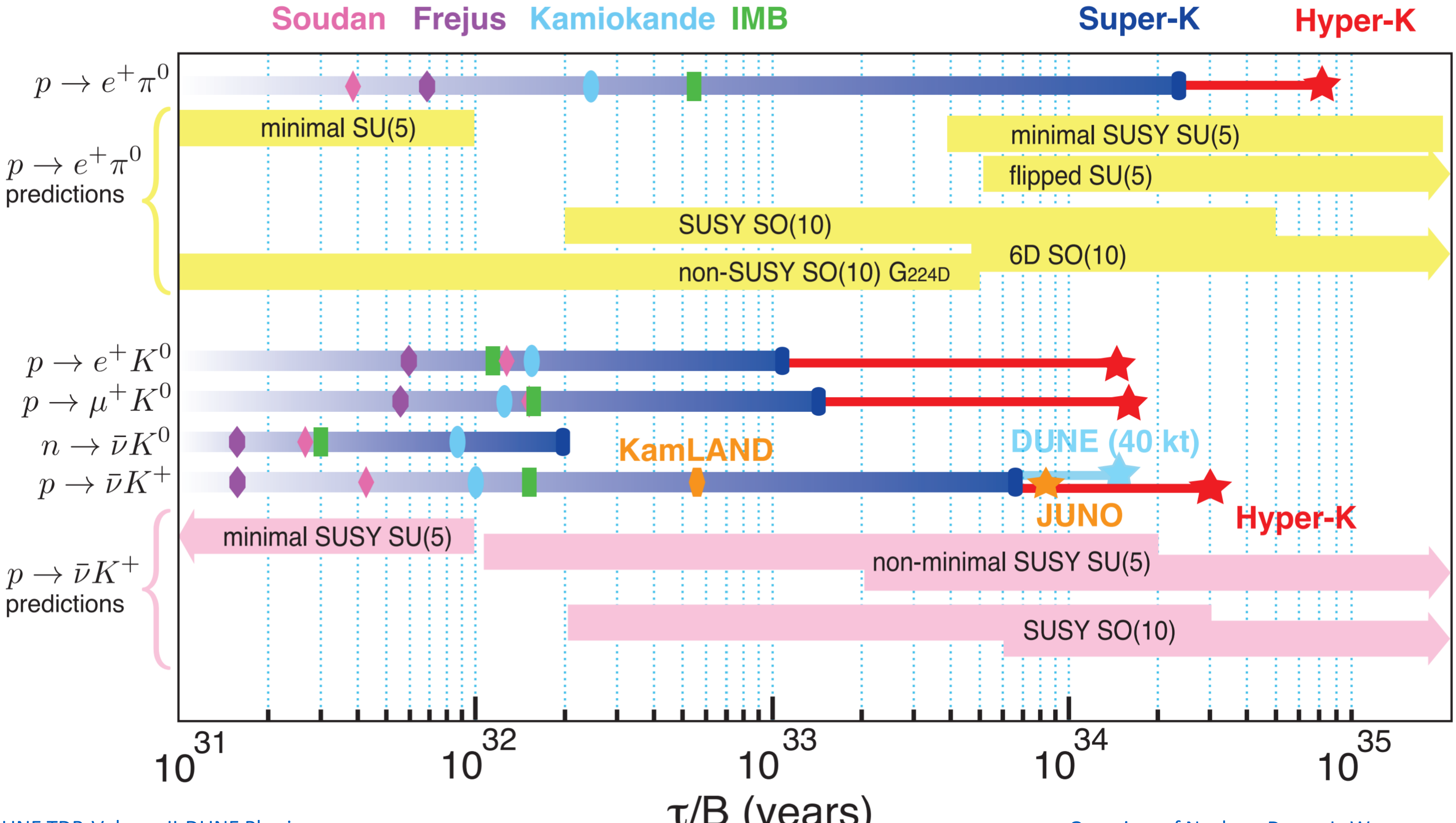
Can **be faster than $p \to e^+\pi^0$**

G. Santucci Thesis

Courtesy of E. Kearns

Expected PDK Lifetimes

From GUTs and Supersymmetric GUTs



DUNE TDR-Volume II-DUNE Physics

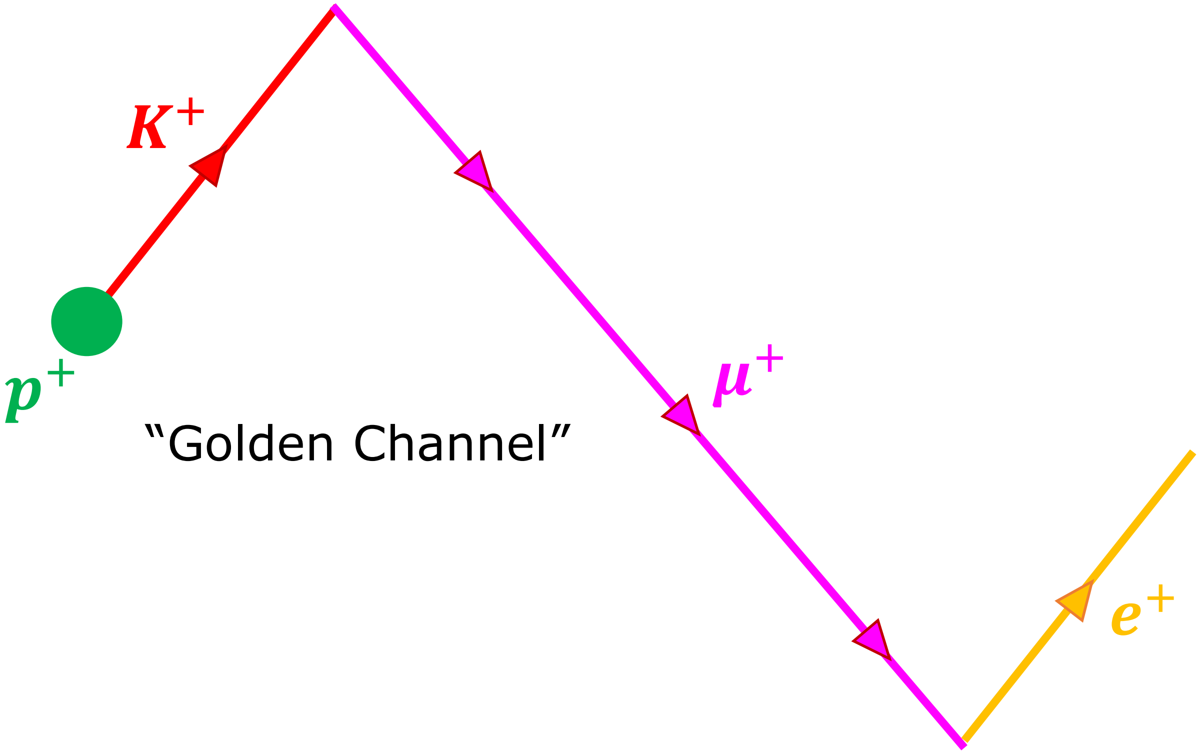
G. Santucci Thesis

Adapted from T. Stokes

$p \rightarrow K^{+}\bar{\nu}$ Expected Event Topologies

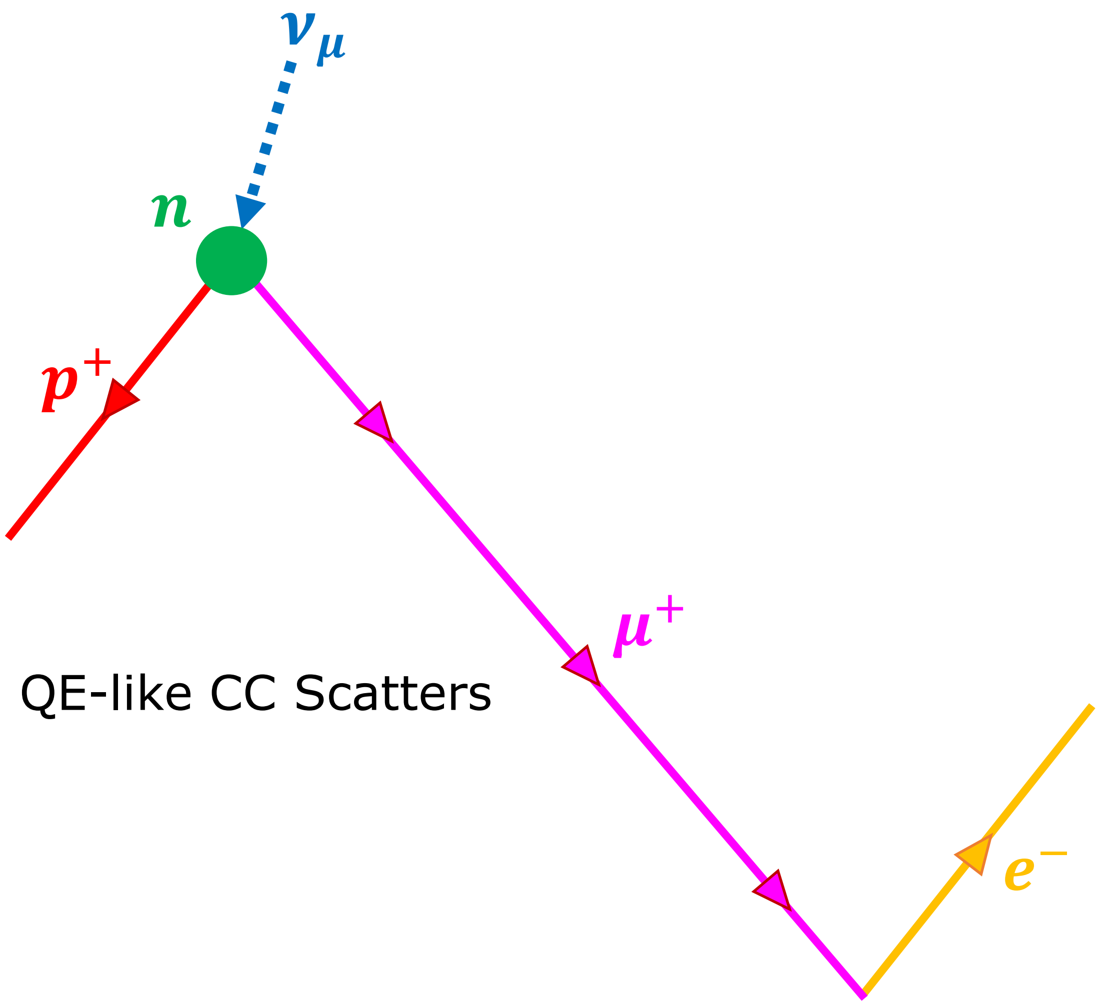
Opens Doors to Deep Learning Techniques

Signal



"Golden Channel"

Background



QE-like CC Scatters

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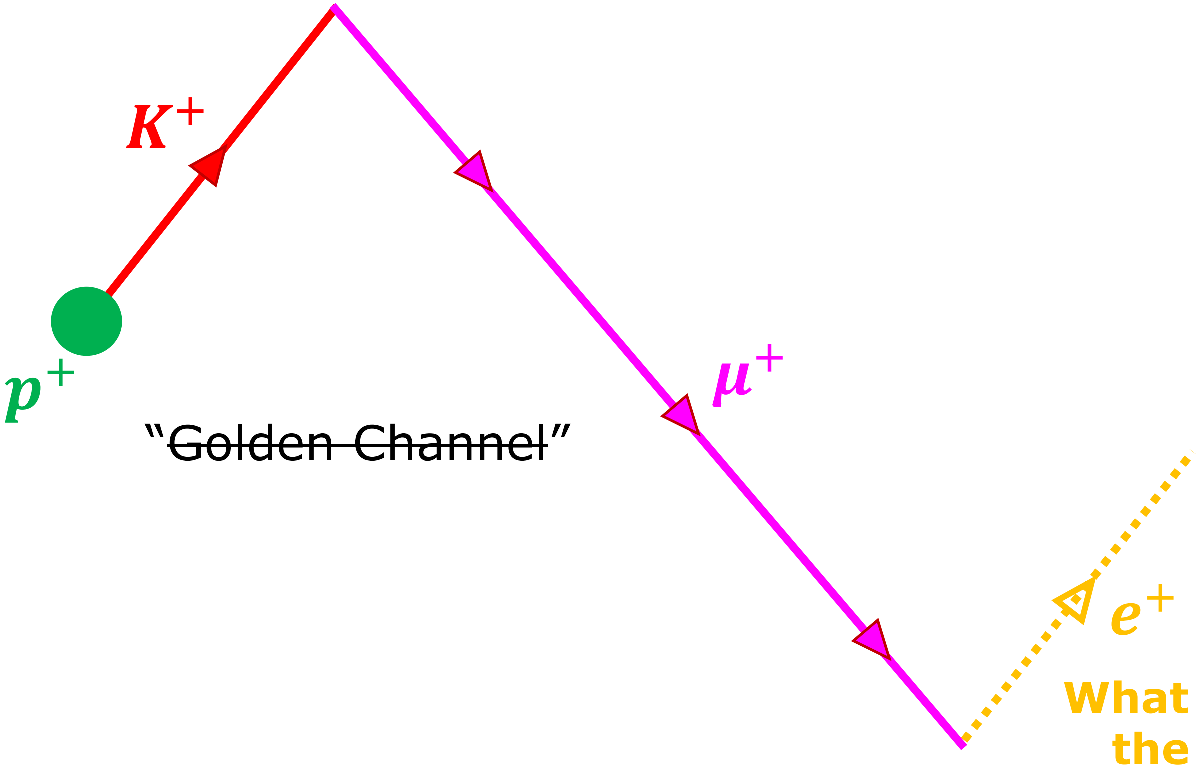
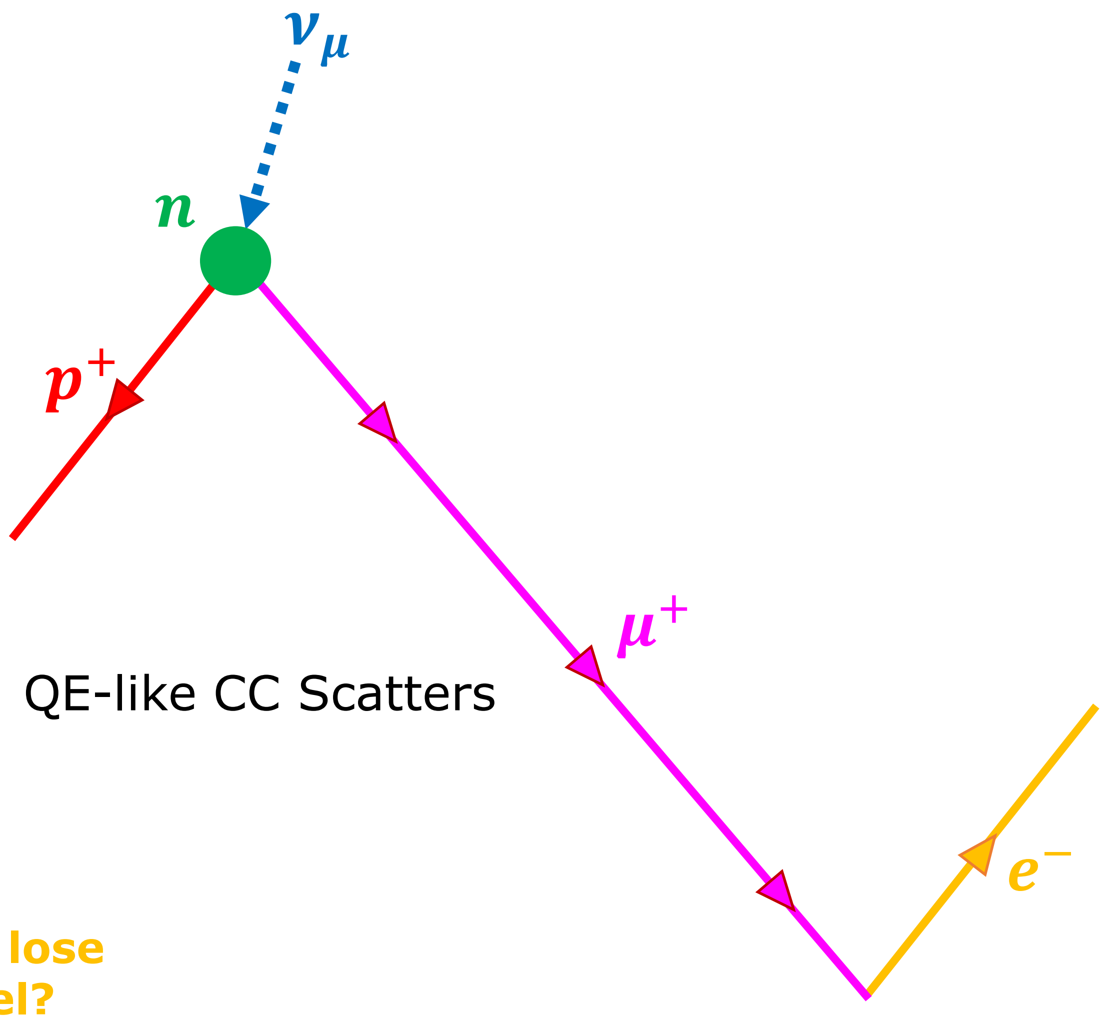


“~~Golden Channel~~”

What if we lose the Michel?

Background



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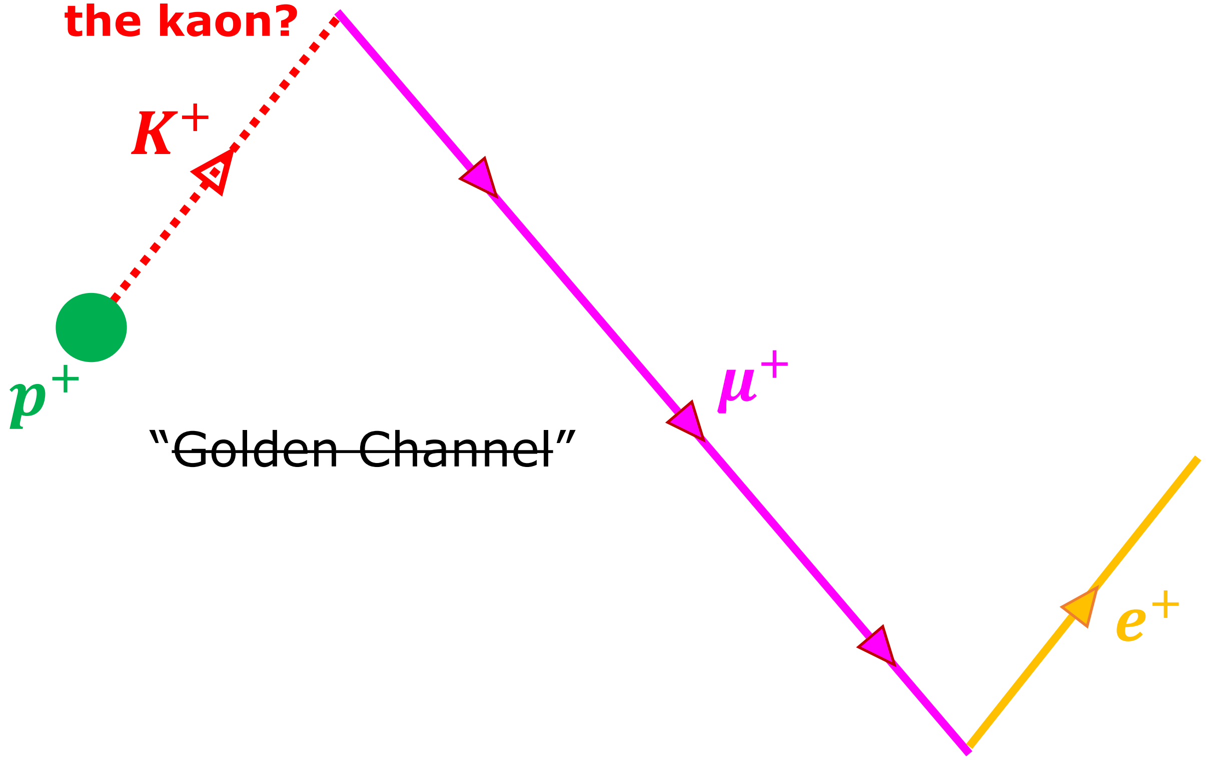
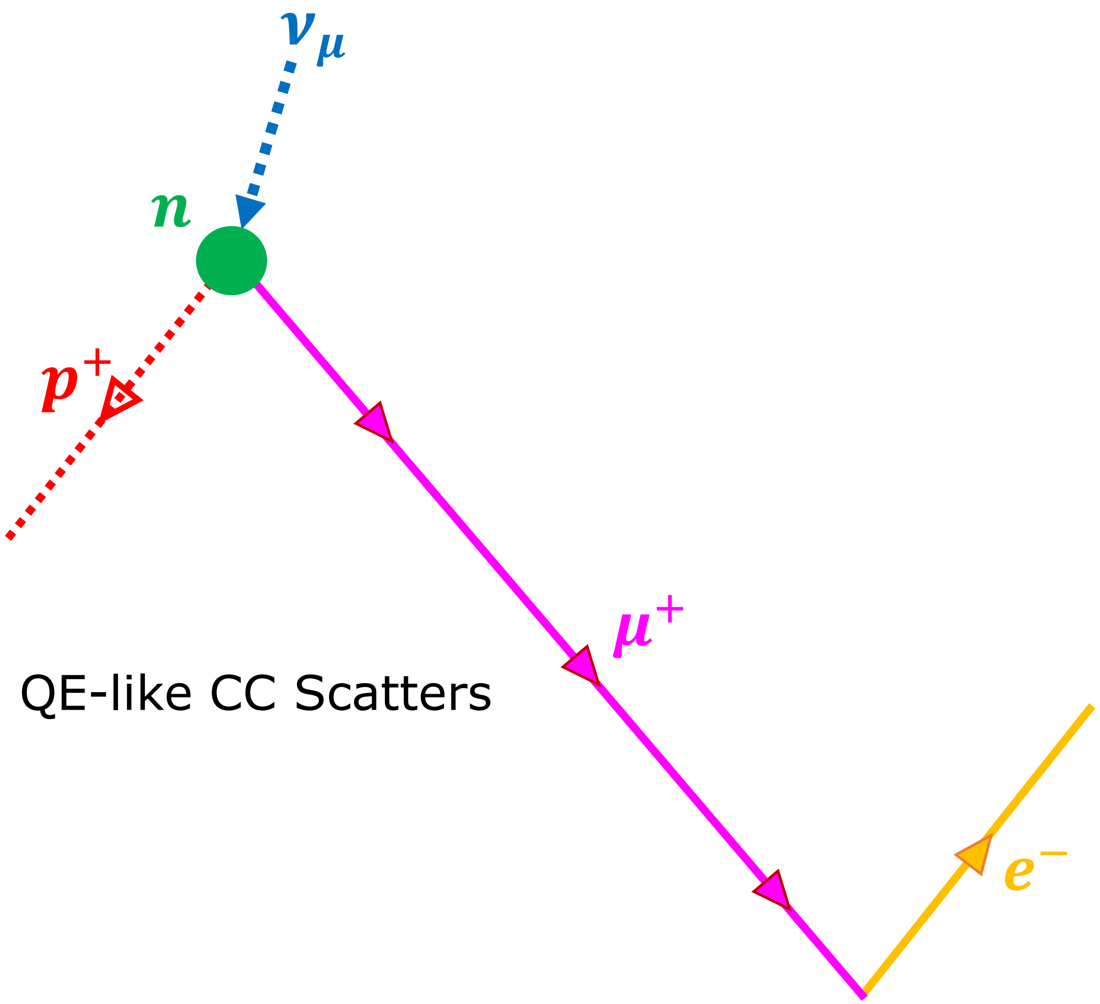


What if we lose the kaon?

“~~Golden Channel~~”

Background



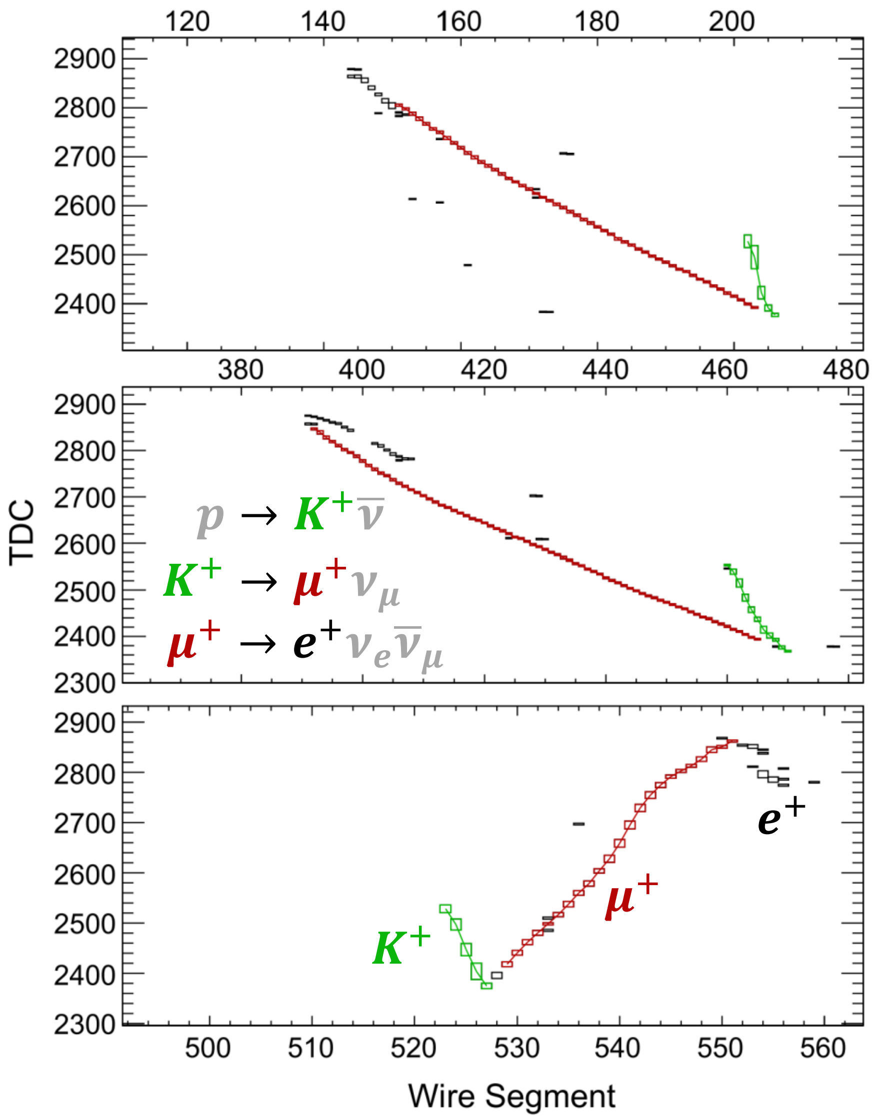
QE-like CC Scatters

Work completed with V. Pec, Y-J. Jwa, & J. Barrow

Slide adapted from T. Stokes

PDK Event Displays

Signal-like True $p \rightarrow K^+\overline{\nu}$

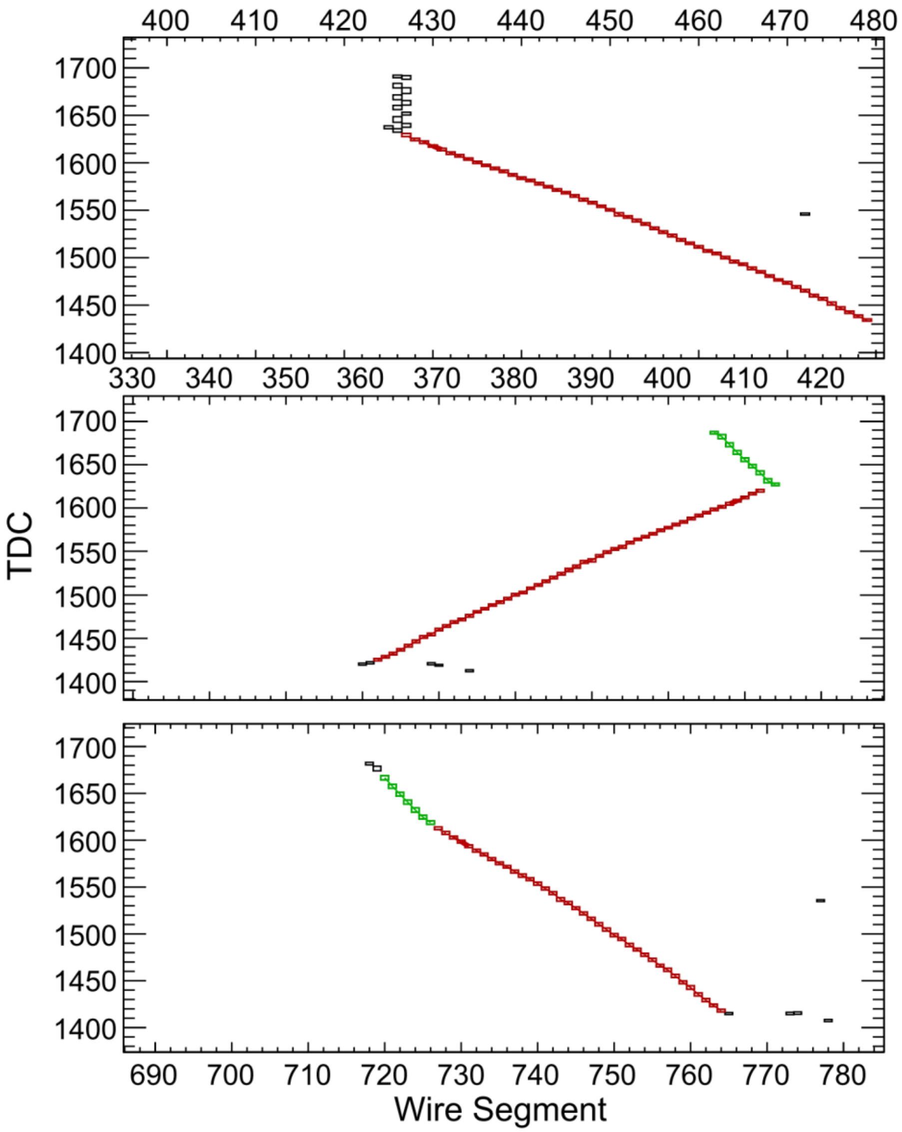


Collection

Induction 2

Induction 1

Signal-like True Atmospheric ν



Collection

Induction 2

Induction 1

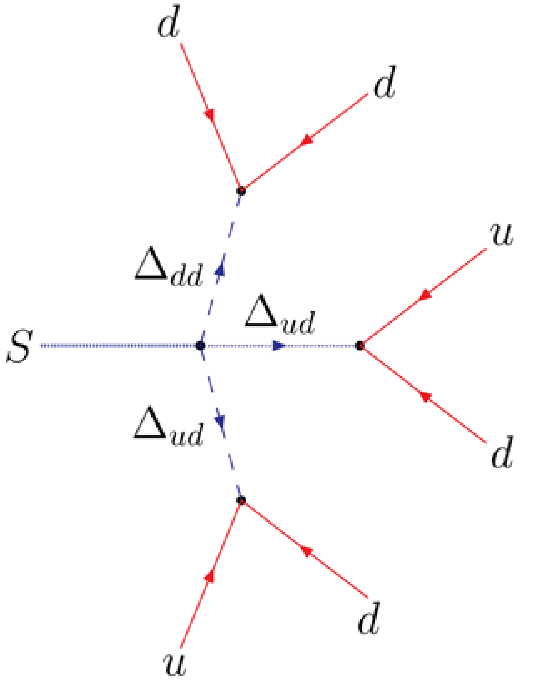
Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment

Neutron-Antineutron Transformation ($n \to \bar{n}$)

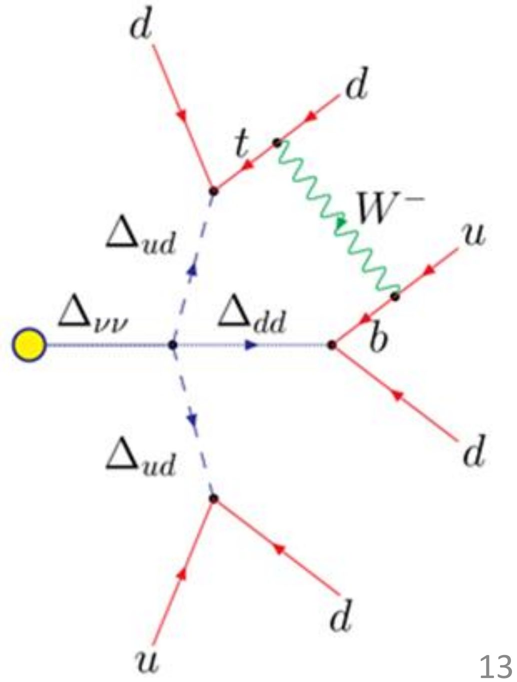
Testable $|\Delta \mathrm{B}| = 2$ Process with Direct Baryon Abundance Predictability

- $\Psi = \binom{n}{\bar{n}}$ evolves according to the Hamiltonian:

$$\mathcal{H}_{n\to\bar{n}} = \begin{pmatrix} m_n - \overrightarrow{\mu_n} \cdot \vec{B} - \frac{i\lambda}{2} & \delta m \\ \delta m & m_n + \overrightarrow{\mu_n} \cdot \vec{B} - \frac{i\lambda}{2} \end{pmatrix} \Longrightarrow P_{n\to\bar{n}}(t) \cong \left(\frac{\delta m}{\overrightarrow{\mu_n} \cdot \vec{B}}\right)^2 \left(\overrightarrow{\mu_n} \cdot \vec{B} t\right)^2 = \left(\frac{t}{\tau_{n\to\bar{n}}}\right)^2$$



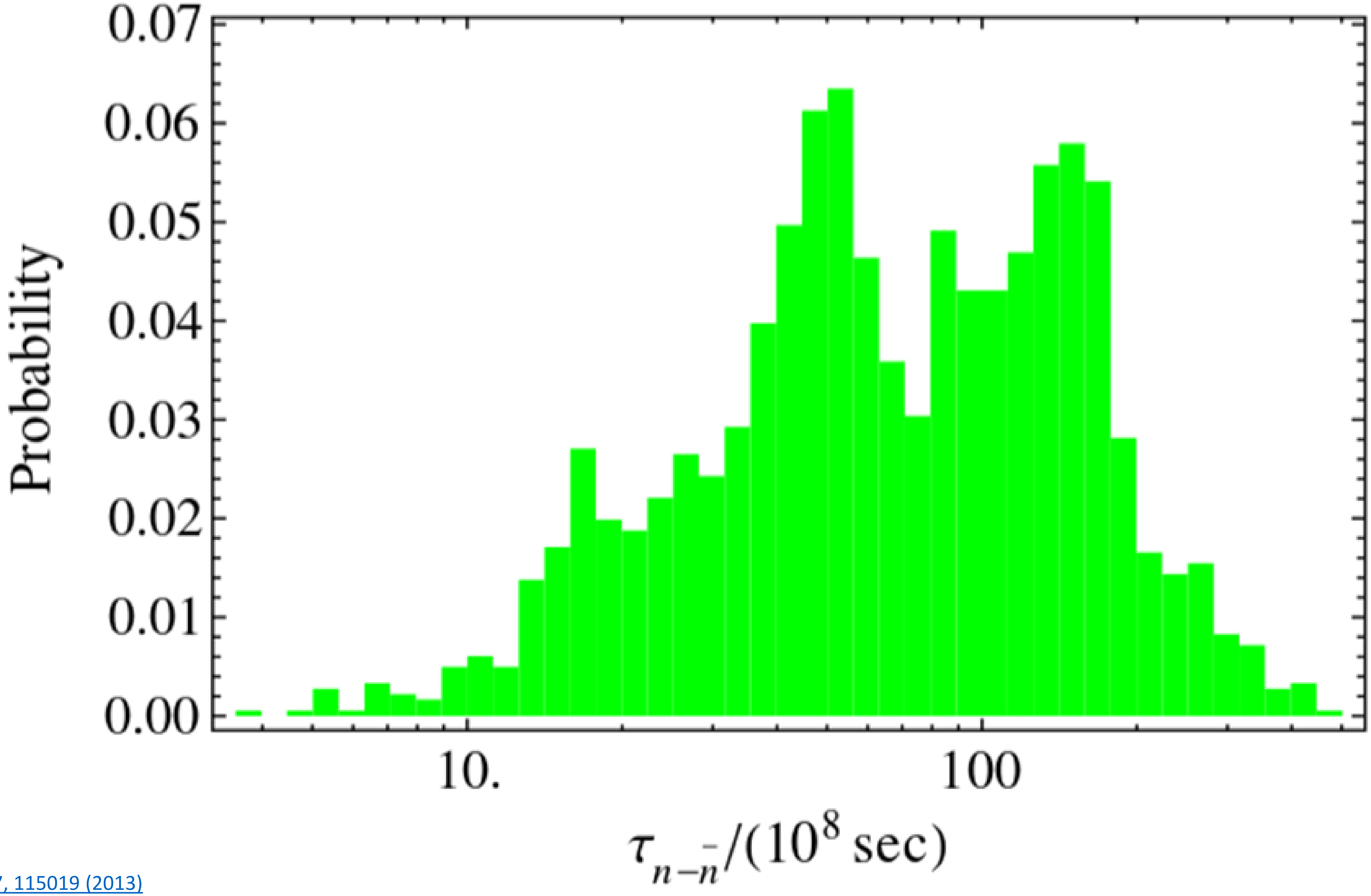
- QFT perspective
  - Post-Sphaleron Baryogenesis
    - Mohapatra et al 2006, 2013
    - Heavy ($\sim$100 TeV) Higgs-like scalar S decays to (di)quarks



- Under proper laboratory conditions
  - Matter spontaneously becomes antimatter
  - Free neutron beams
  - **Within nuclei**

Expected $n \rightarrow \bar{n}$ Lifetimes

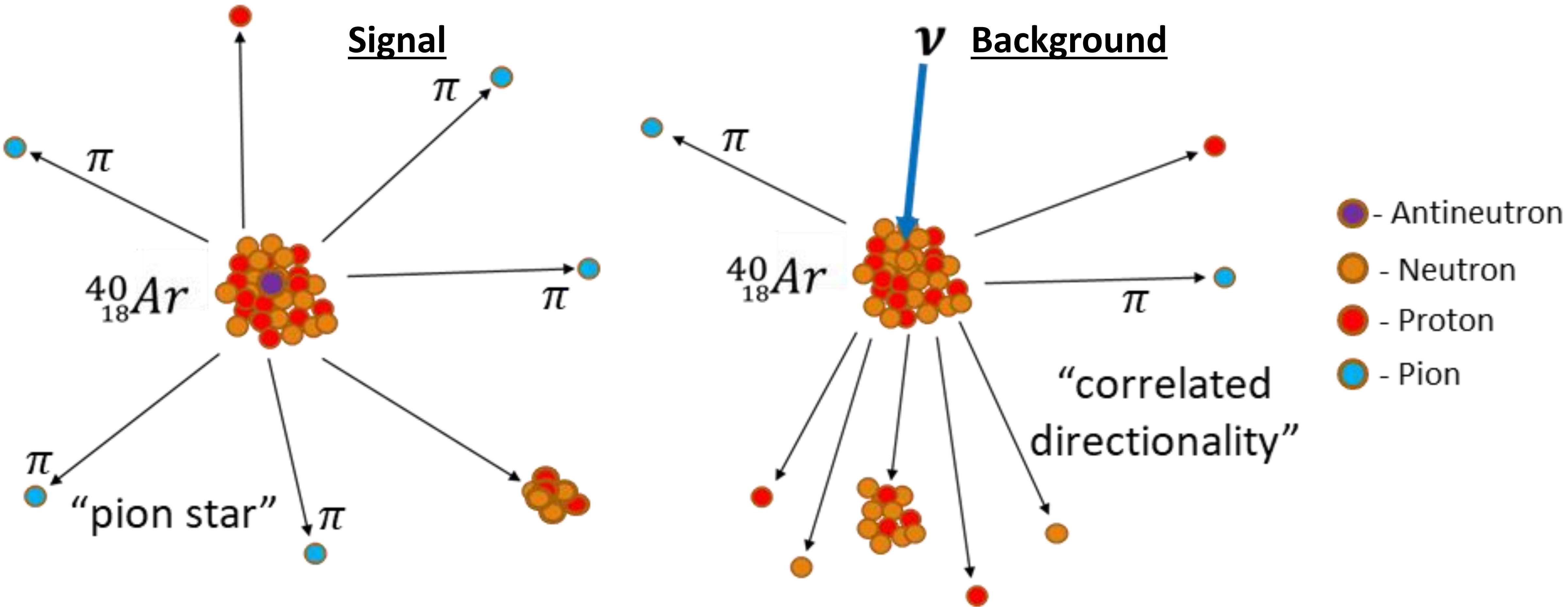
From Post-Sphaleron Baryogenesis



Phys. Rev. D 87, 115019 (2013)

$n \rightarrow \bar{n}$ Expected Event Topologies

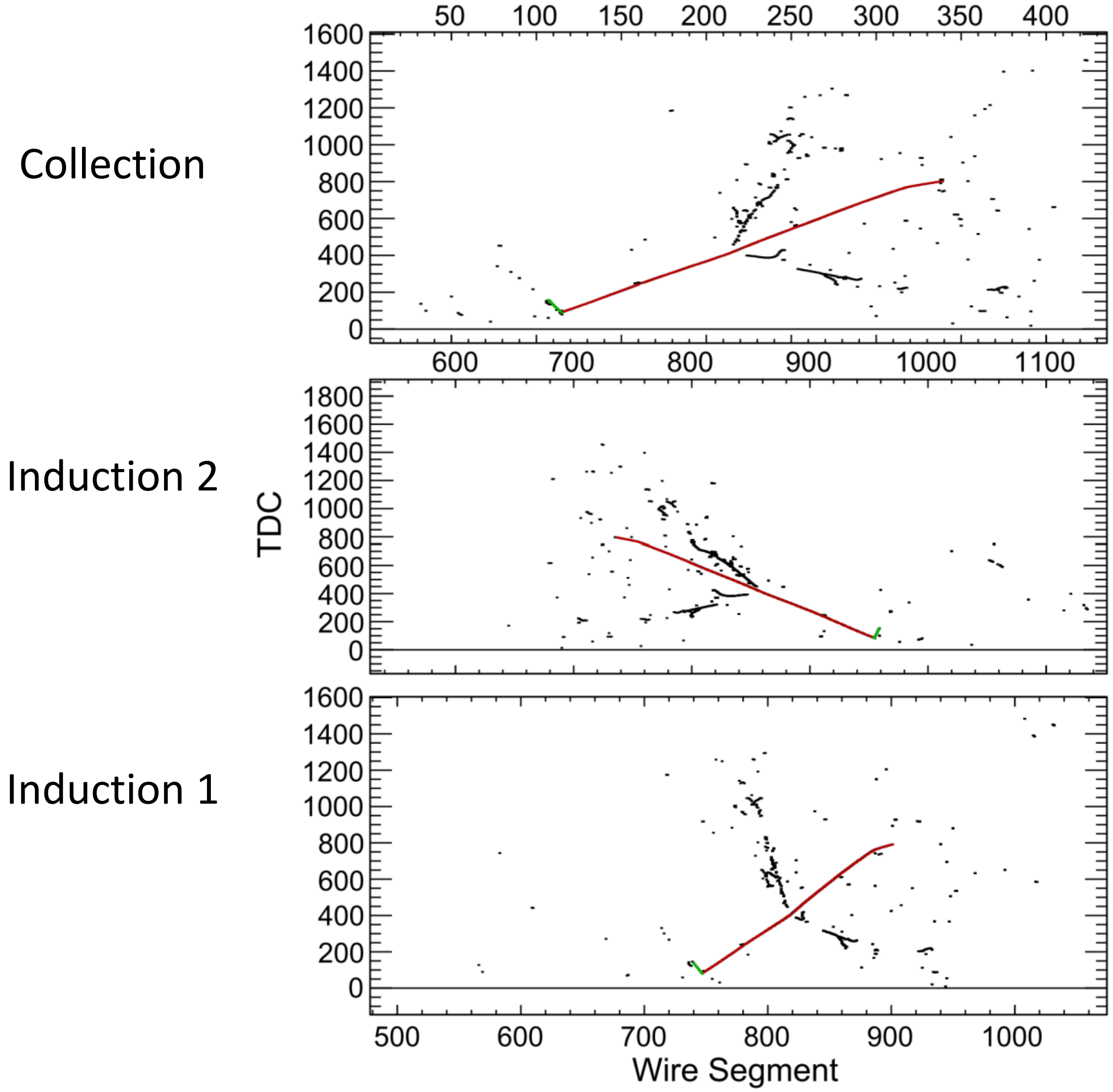
Opens Doors to Deep learning techniques



$n \rightarrow \bar{n}$ Event Displays

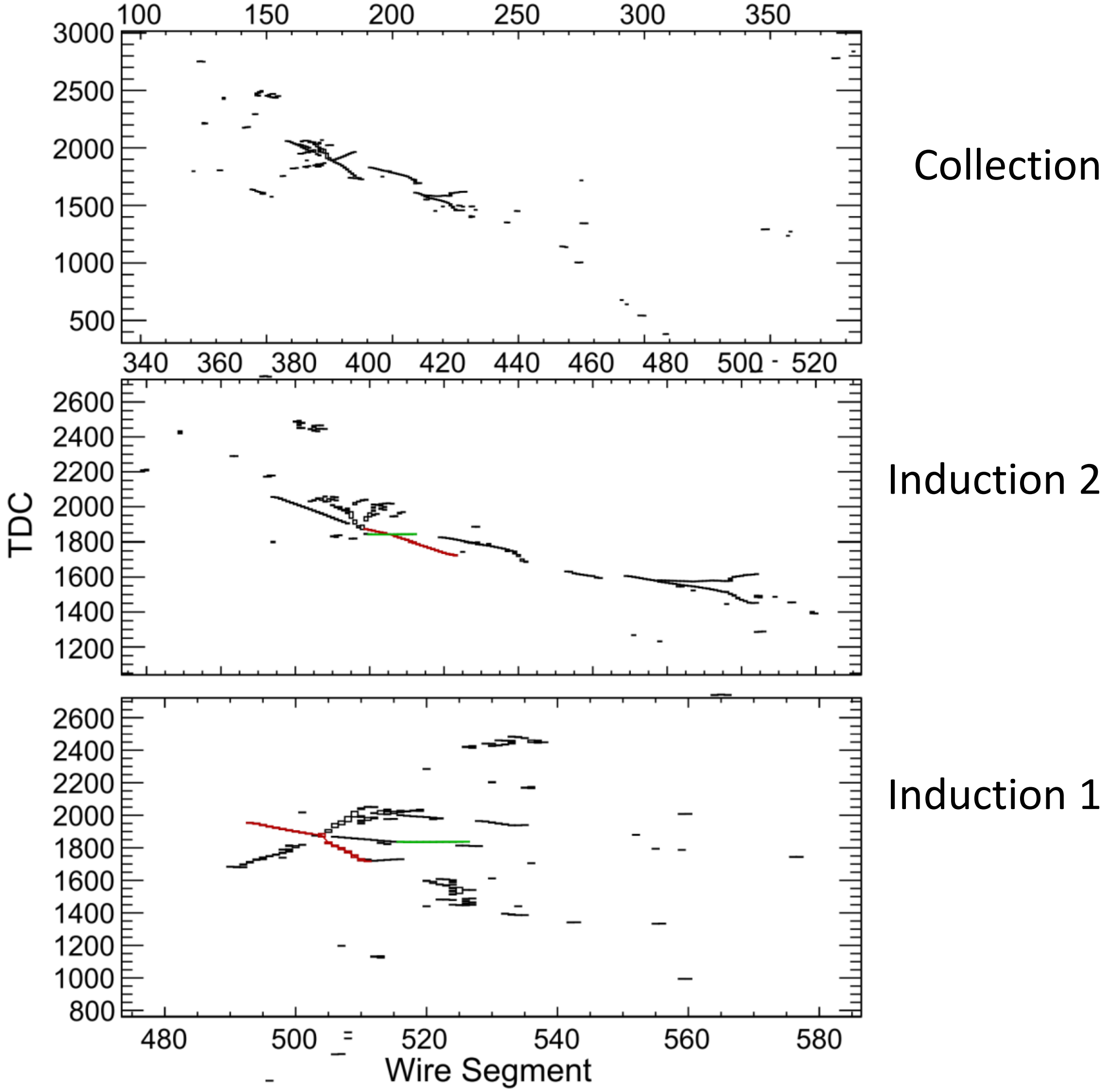
Signal-like True $n \rightarrow \bar{n}$

$n\bar{n} \rightarrow n\pi^0\pi^0\pi^+\pi^-$

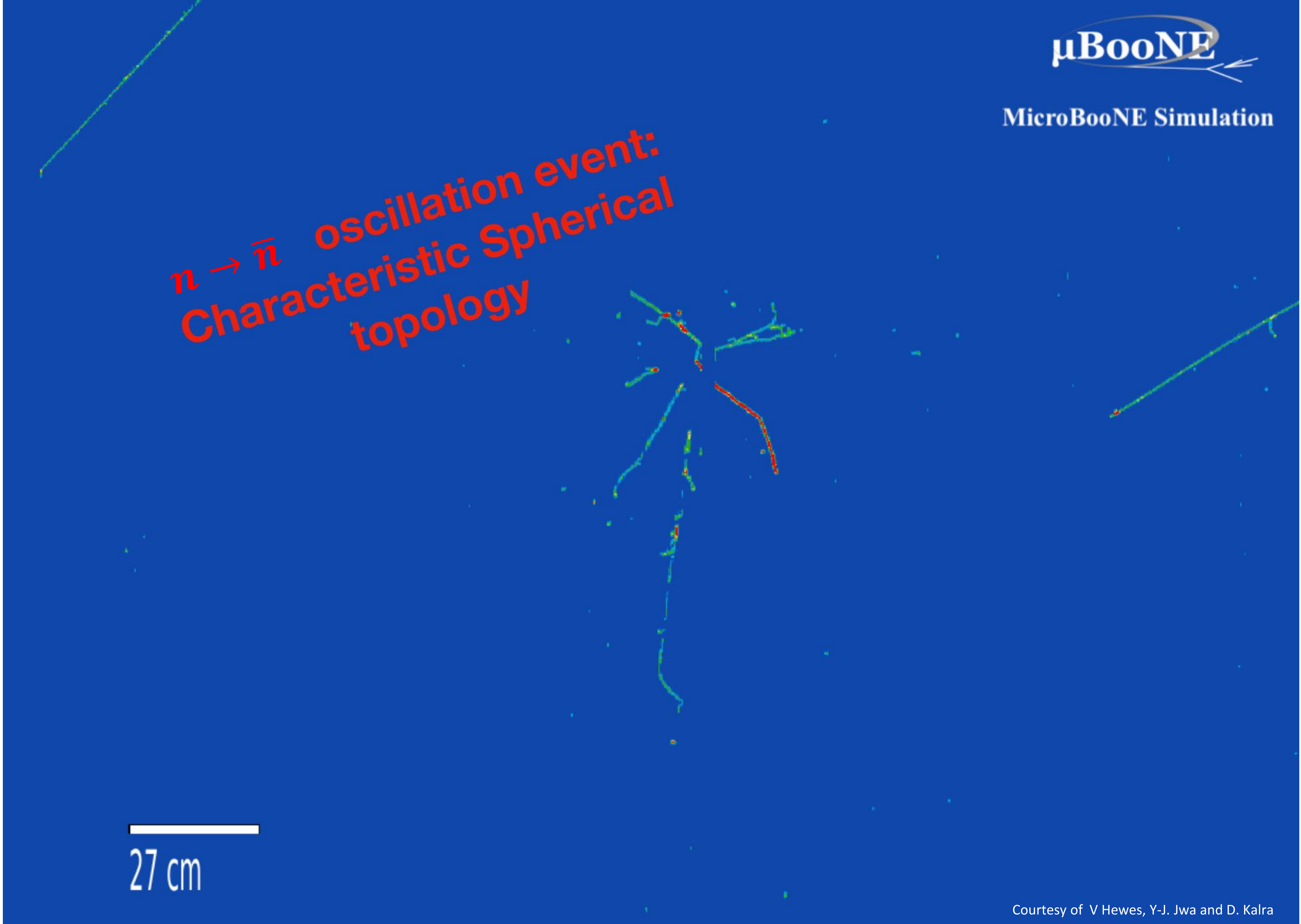


Signal-like True Atmospheric

High Multiplicity, Showers



[Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment](#)

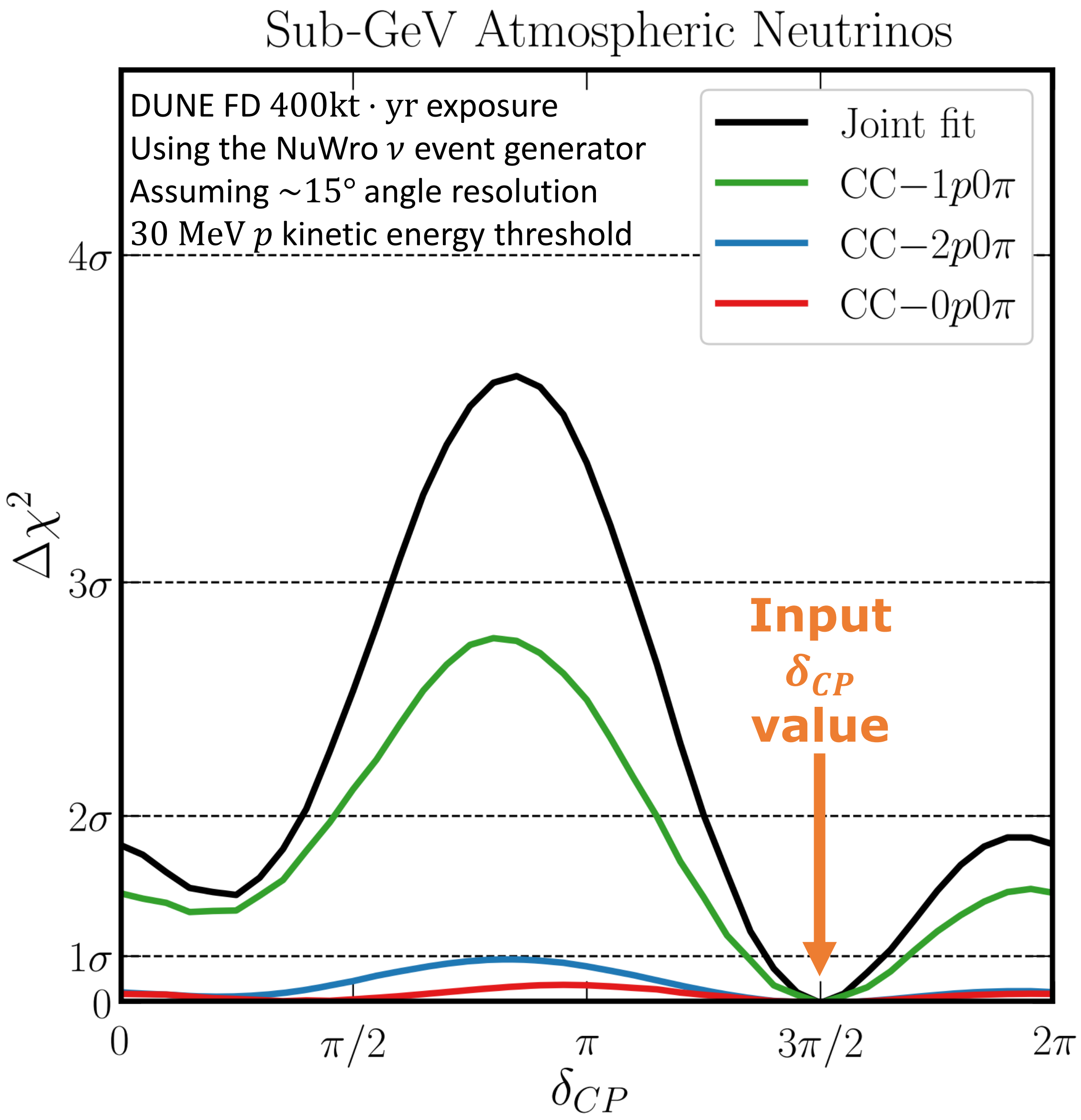


$n \rightarrow \bar{n}$ oscillation event: Characteristic Spherical topology

Courtesy of V Hewes, Y-J. Jwa and D. Kalra

Atmospheric Neutrinos Analysis Progress

Atmospheric ν Oscillation Promise



- Atmospheric νs are both…
  - **Primary Rare Processes' background**
  - Valuable ν oscillation physics signal
    - Many baselines, many energies
- ν_{atm} sample adds to ν_{beam} sample
  - Increases overall DUNE sensitivities
    - Different systematic uncertainties
  - Improvements to angle resolution very important at low energies
    - Difficult due to Fermi motion
  - New ML methods in development by DUNE HEPWG members
    - Could improve ν_{atm} and even ν_{beam} reconstruction

Sub-GeV Atmospheric Neutrinos and CP Violation in DUNE

Atmospheric Spectra at Homestake

Expected ν_{atm} Count Rates via Integration a Key Input for BNV Backgrounds

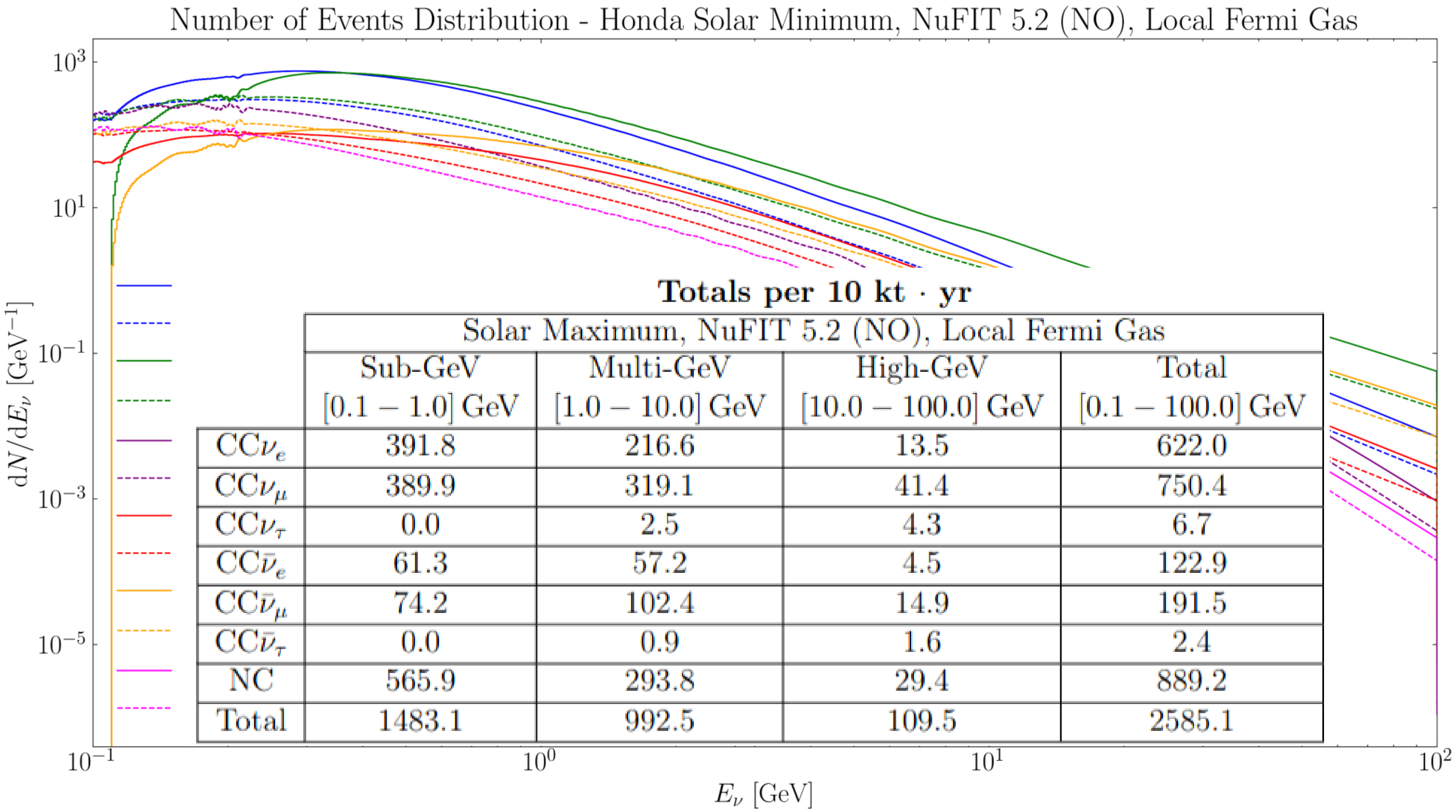
Improvements from past analysis
- Interpolation scheme
- Move to NuFitv5.2 w/OscProb
- CC $\nu_\tau/\overline{\nu}_\tau$ expectations

Ongoing work directly targets systematic uncertainties
- Cross section dependencies
- Solar minimum/maximum
- PREM layering constraints
- Normal/Inverted ordering
- Production height
- Will serve as key inputs to forthcoming MaCh3 osc. analysis

Rates already being used in current BNV studies

M. Oliveira-Ismerio

$$\phi(E) = 10^{\log_{10}\phi(E_1) + \frac{\log_{10}\phi(E_2) - \log_{10}\phi(E_1)}{\log_{10}E_2 - \log_{10}E_1}(\log_{10}E - \log_{10}E_1)}$$



Totals per 10 kt · yr

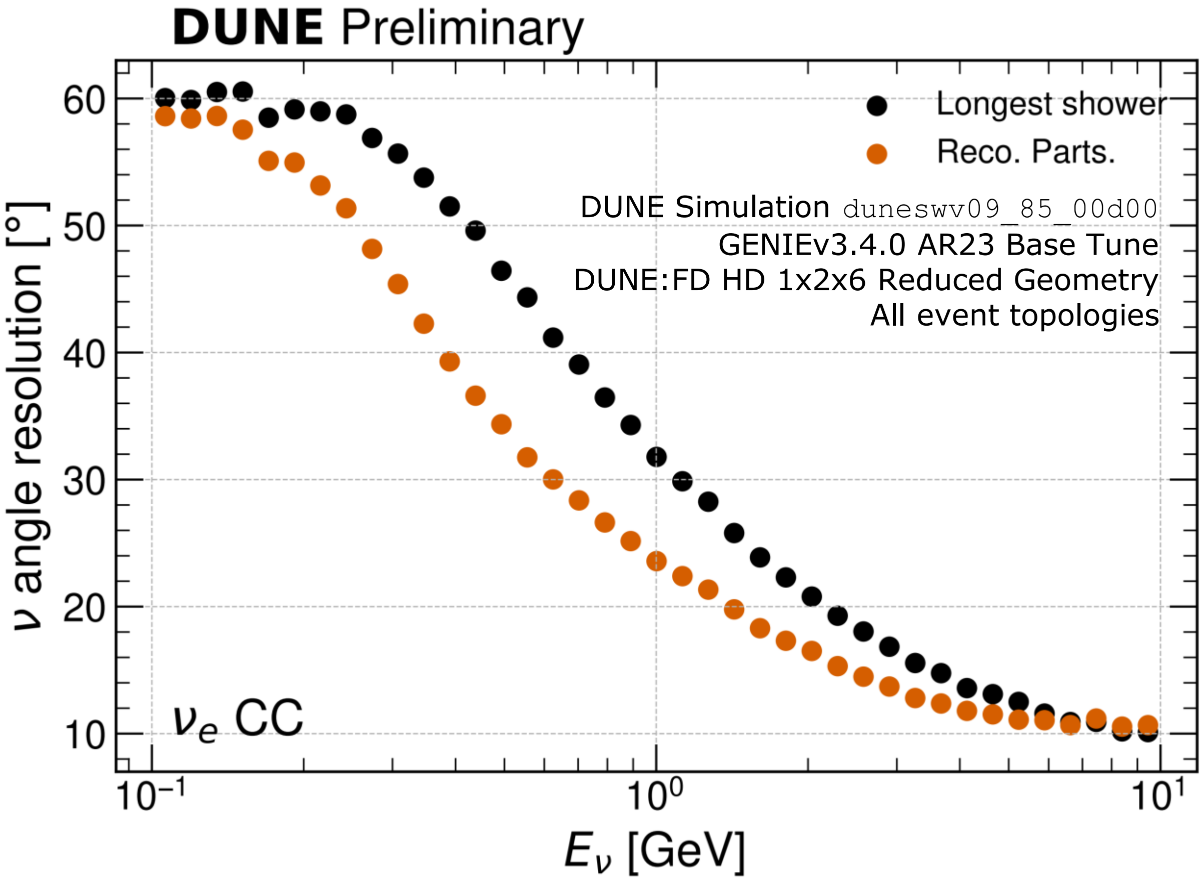
	Solar Maximum, NuFIT 5.2 (NO), Local Fermi Gas			
	Sub-GeV [0.1 – 1.0] GeV	Multi-GeV [1.0 – 10.0] GeV	High-GeV [10.0 – 100.0] GeV	Total [0.1 – 100.0] GeV
CCν_e	391.8	216.6	13.5	622.0
CCν_μ	389.9	319.1	41.4	750.4
CCν_τ	0.0	2.5	4.3	6.7
CC$\bar{\nu}_e$	61.3	57.2	4.5	122.9
CC$\bar{\nu}_\mu$	74.2	102.4	14.9	191.5
CC$\bar{\nu}_\tau$	0.0	0.9	1.6	2.4
NC	565.9	293.8	29.4	889.2
Total	1483.1	992.5	109.5	2585.1

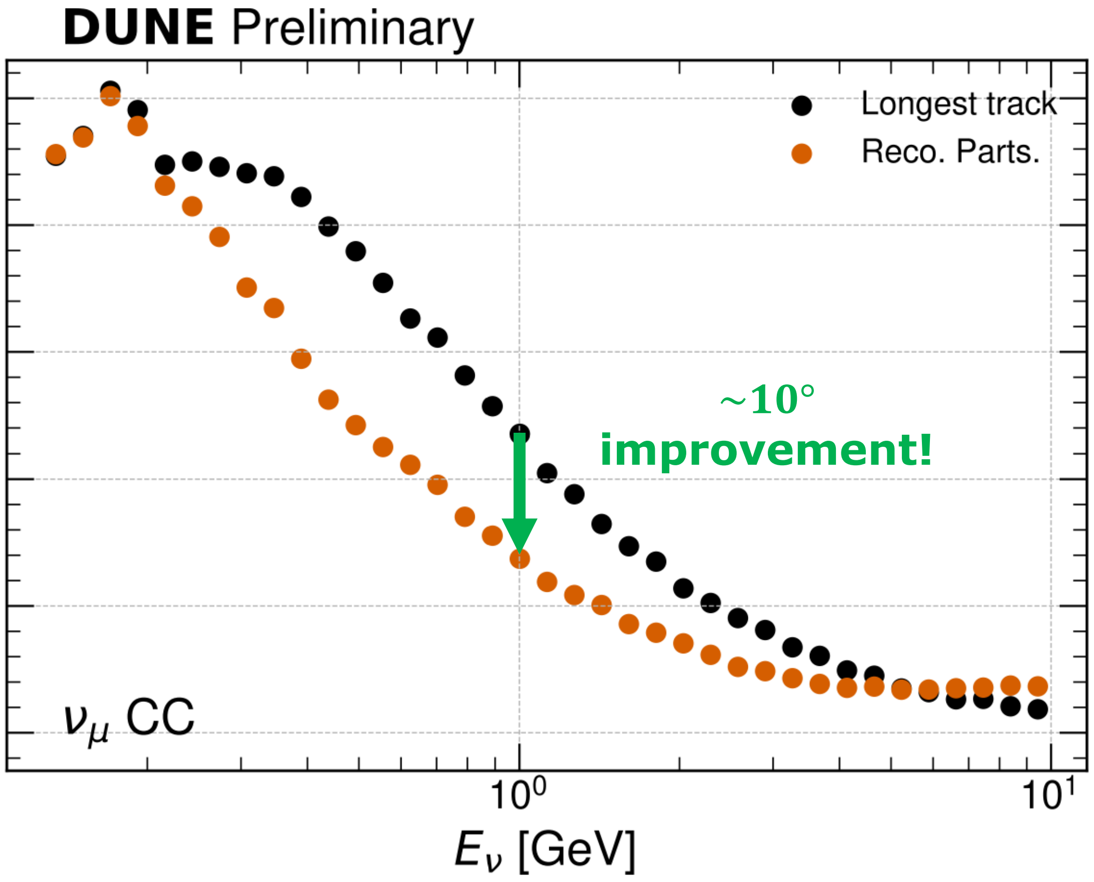
ν_τ are also of interest to our group: B. Yaeggy APS April 2024

Atmospheric Angular Reconstruction

Improved Resolution Driven by LArTPCs’ Hadronic Reconstruction Capabilities

- Final part of atmospheric production underway (15M)
  - Lead by P. Granger (APC) and S. Farrell (Rice)
- Reconstruction techniques across many energies under development
  - Lead by APC group (kinematics), Rice (process identification)
  - Optimizing tools will inform first publication’s energy range and analysis target
  - Improved reconstruction $< 1\mathrm{GeV}$ can empower δ_{CP} sensitivity
  - Near future: ML-powered energy and angle estimation for oscillations
- MaCh3 ν oscillation framework for atmospherics nearly ready to go (APC & Imperial groups)
  - Systematics inputs under development for full analysis





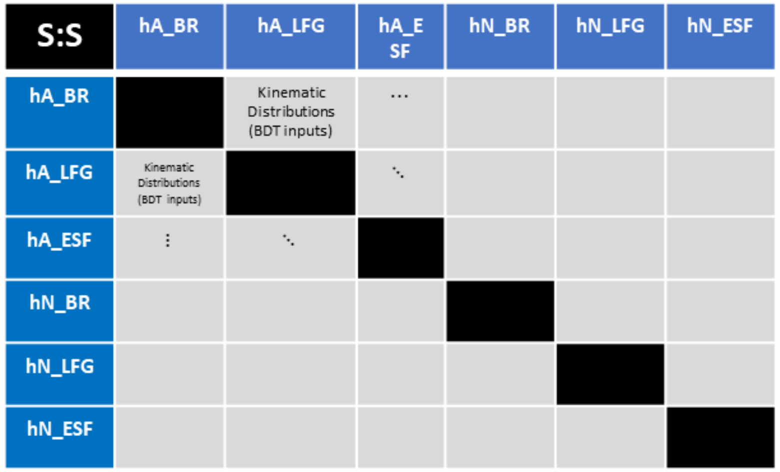
$\sim 10°$ improvement!

P. Granger, H. Souza, C. Sironneau, C. Mironov

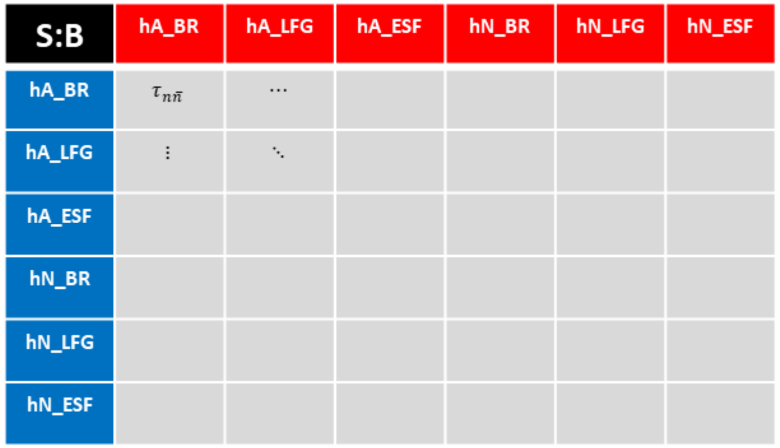
Understanding Nuclear Modeling Systematics in Rare Processes

Nuclear Model Configuration Comparative Flows

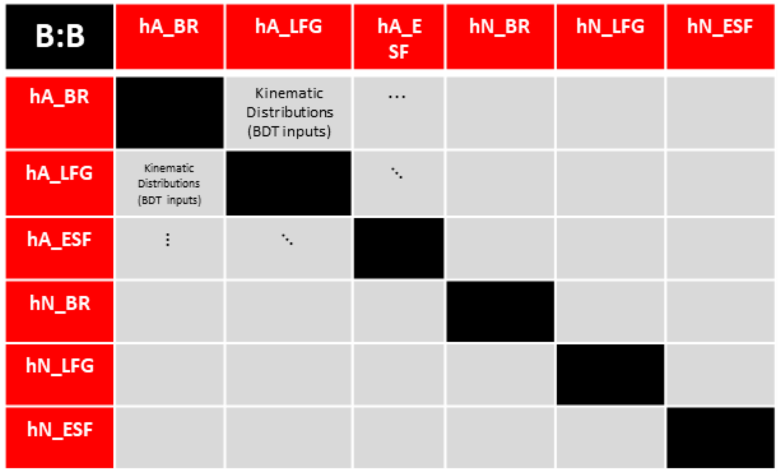
Signal & Background Sample Comparisons to Better Determine Modeling Systematics



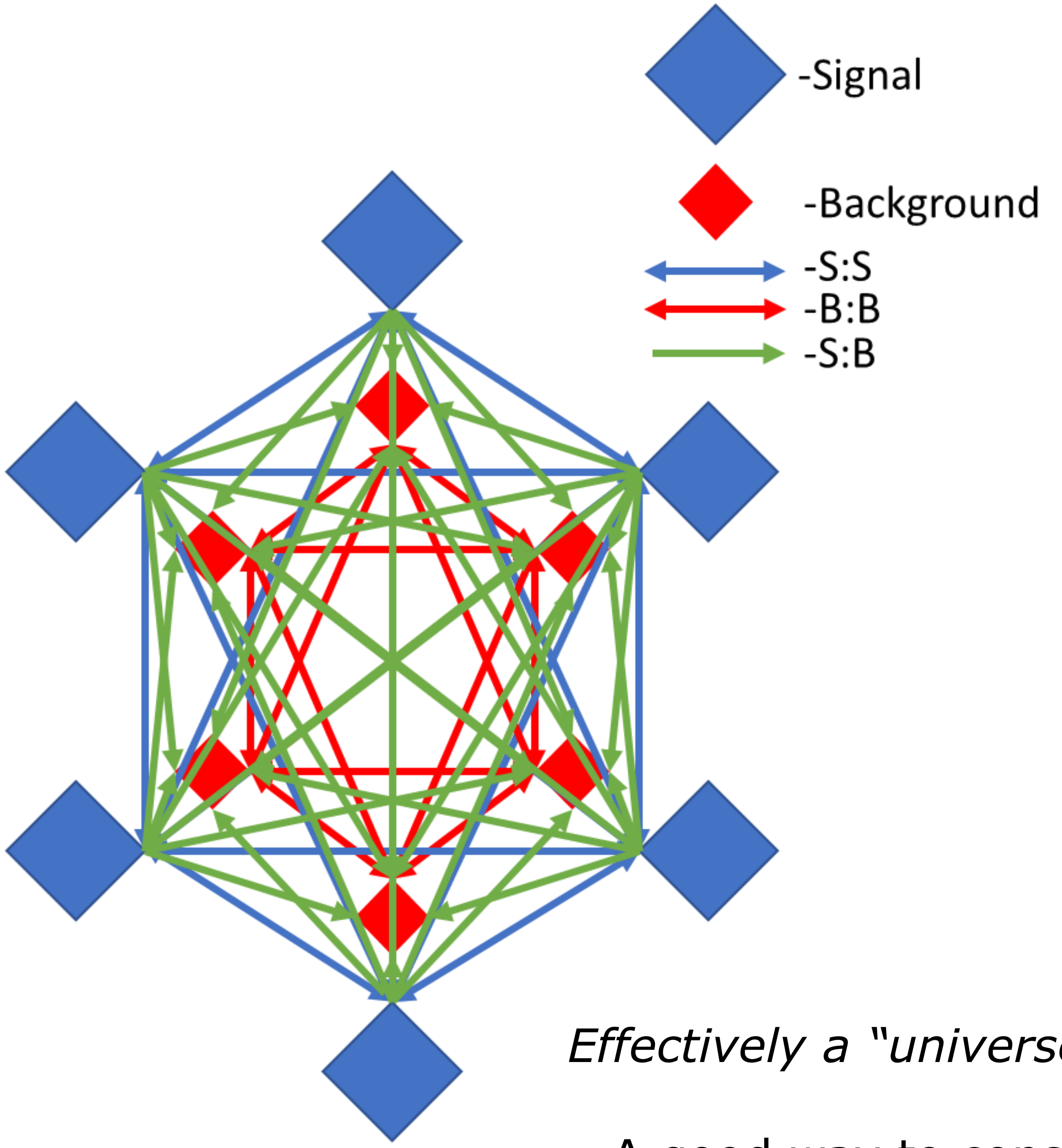
S:S	hA_BR	hA_LFG	hA_ESF	hN_BR	hN_LFG	hN_ESF
hA_BR	■	Kinematic Distributions (BDT inputs)	⋯			
hA_LFG	Kinematic Distributions (BDT inputs)	■	⋱			
hA_ESF	⋮	⋱	■			
hN_BR				■		
hN_LFG					■	
hN_ESF						■



S:B	hA_BR	hA_LFG	hA_ESF	hN_BR	hN_LFG	hN_ESF
hA_BR	$\tau_{n\bar{n}}$	⋯				
hA_LFG	⋮	⋱				
hA_ESF						
hN_BR						
hN_LFG						
hN_ESF						



B:B	hA_BR	hA_LFG	hA_ESF	hN_BR	hN_LFG	hN_ESF
hA_BR	■	Kinematic Distributions (BDT inputs)	⋯			
hA_LFG	Kinematic Distributions (BDT inputs)	■	⋱			
hA_ESF	⋮	⋱	■			
hN_BR				■		
hN_LFG					■	
hN_ESF						■



Mixing signal and background models to understand ranges of expected background rates and signal efficiencies

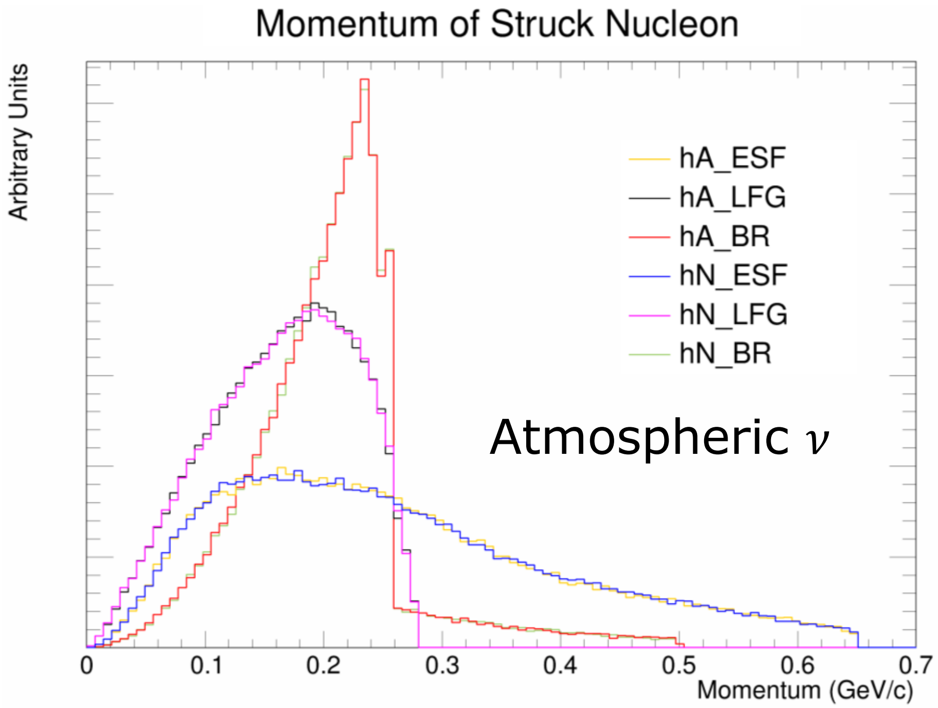
Mixing of available nuclear models and final state interaction models

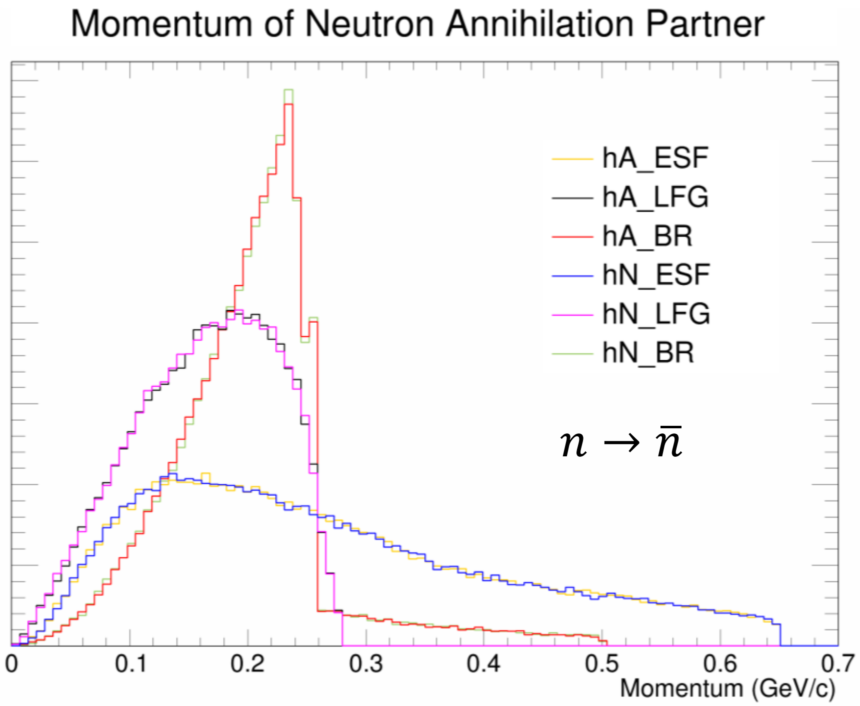
Effectively a "universe" approach

A good way to conservatively understand modeling systematics for an unknown process is to iterate!

Initial Nucleon Momentum Distributions

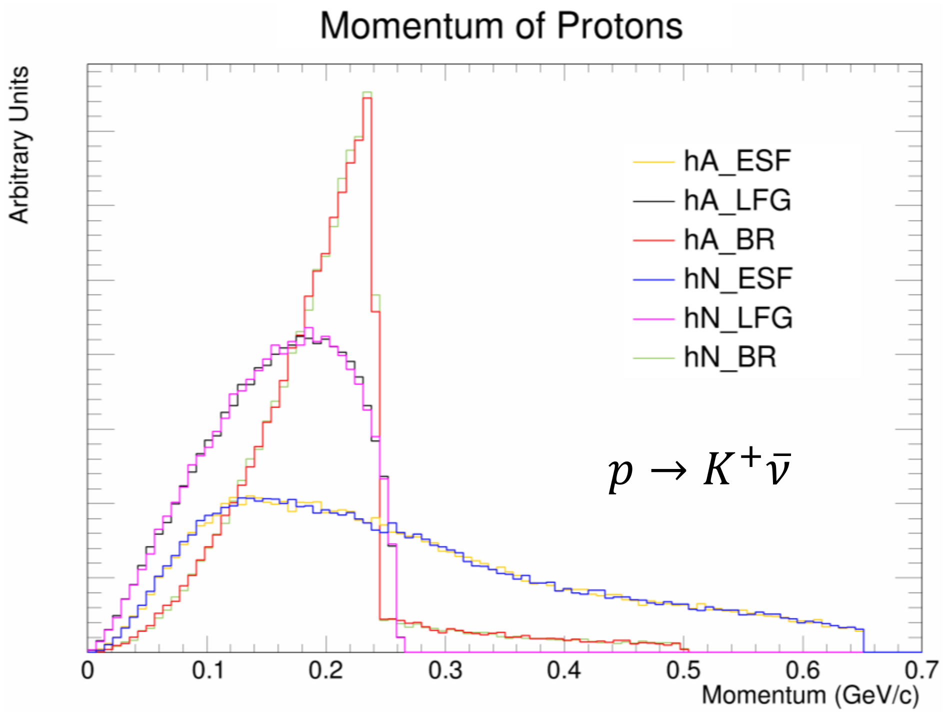
Initial State Preparation for Atmospherics, $p \to K^+\bar{\nu}$, & $n \to \bar{n}$ in `GENIEv3.0.6`





Bodek-
Ritchie
Nonlocal
Relativistic
Fermi Gas

Effective
Spectral
Function
Nonlocal
Nonrelativistic
Fermi Gas

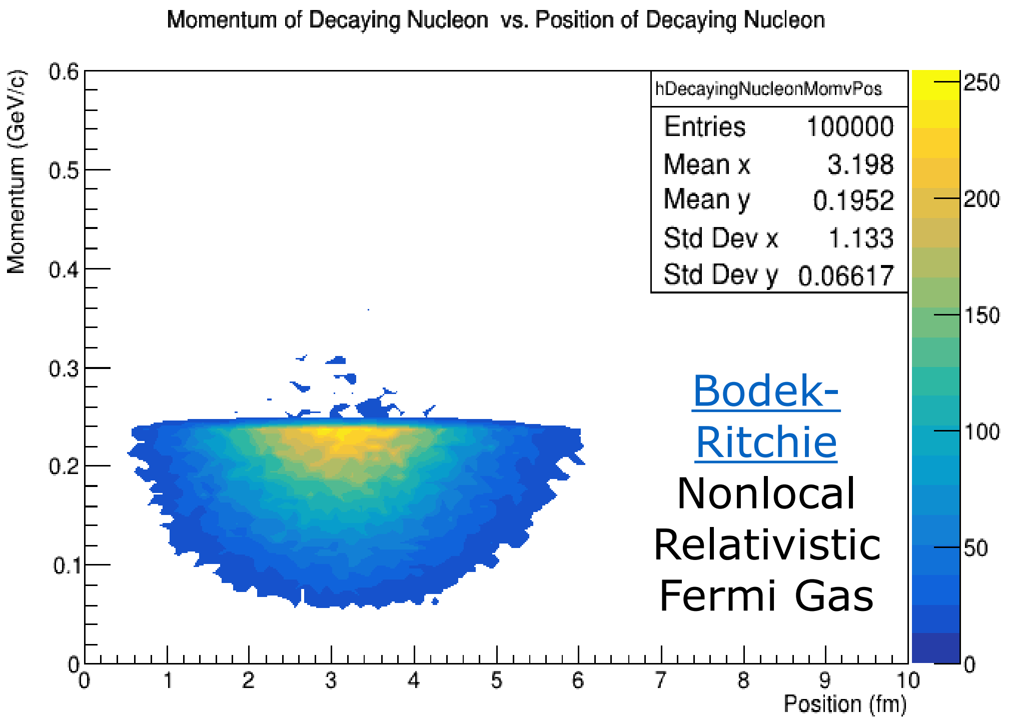


Local
Nonrelativistic
Fermi Gas

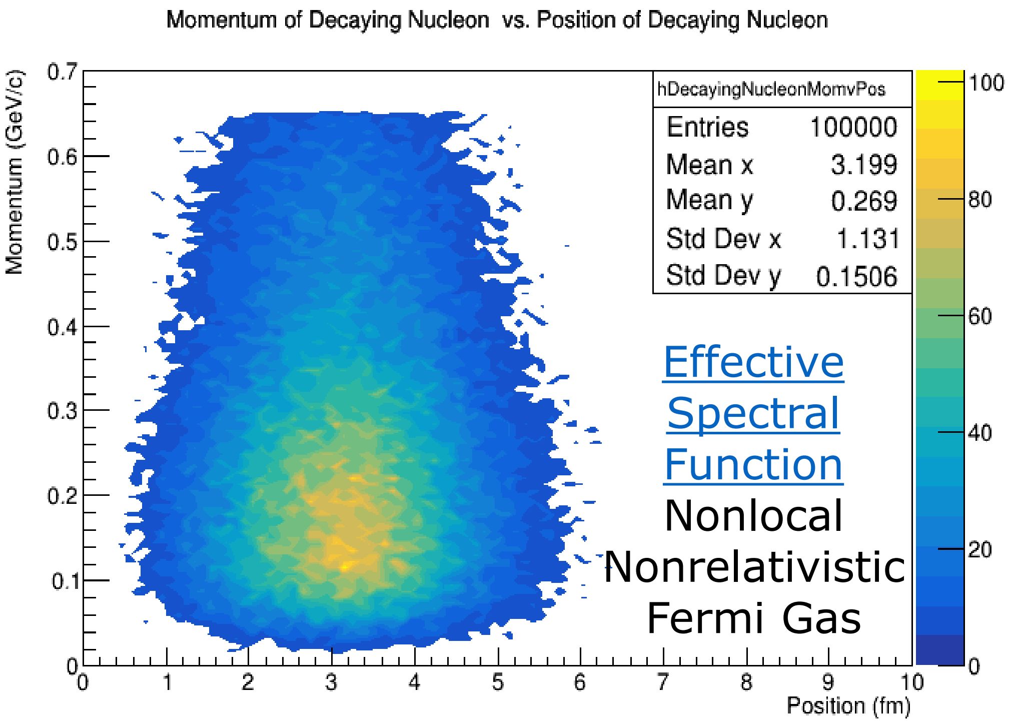
T. Stokes

Initial Nucleon Momentum Distributions

$p \to K^+\bar{\nu}$ Initial State in `GENIEv3.0.6`



Bodek-Ritchie
Nonlocal
Relativistic
Fermi Gas



Effective
Spectral
Function
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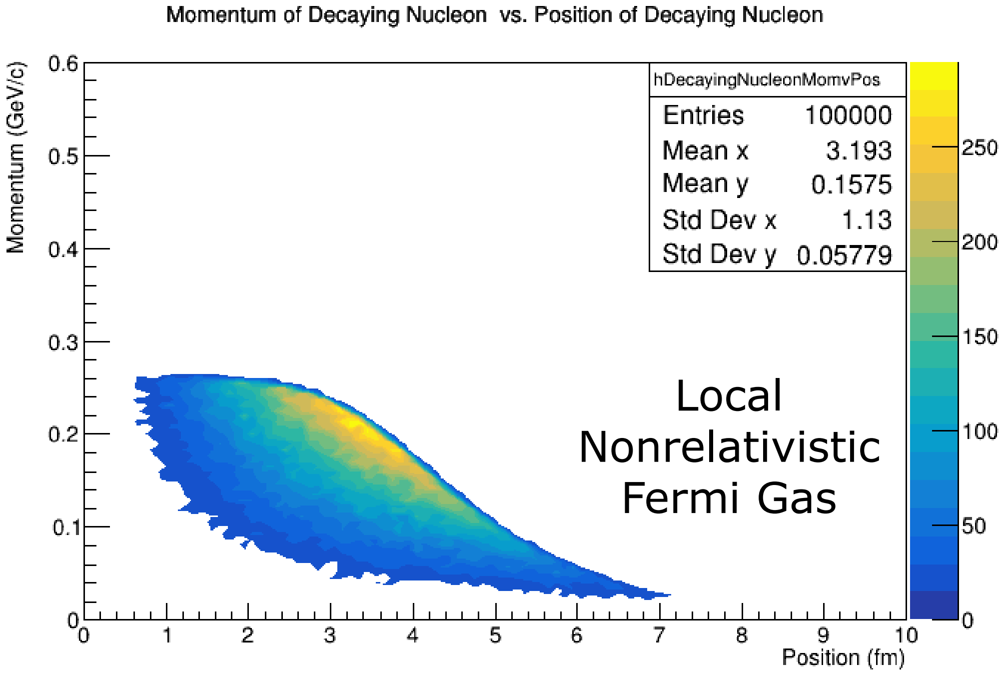
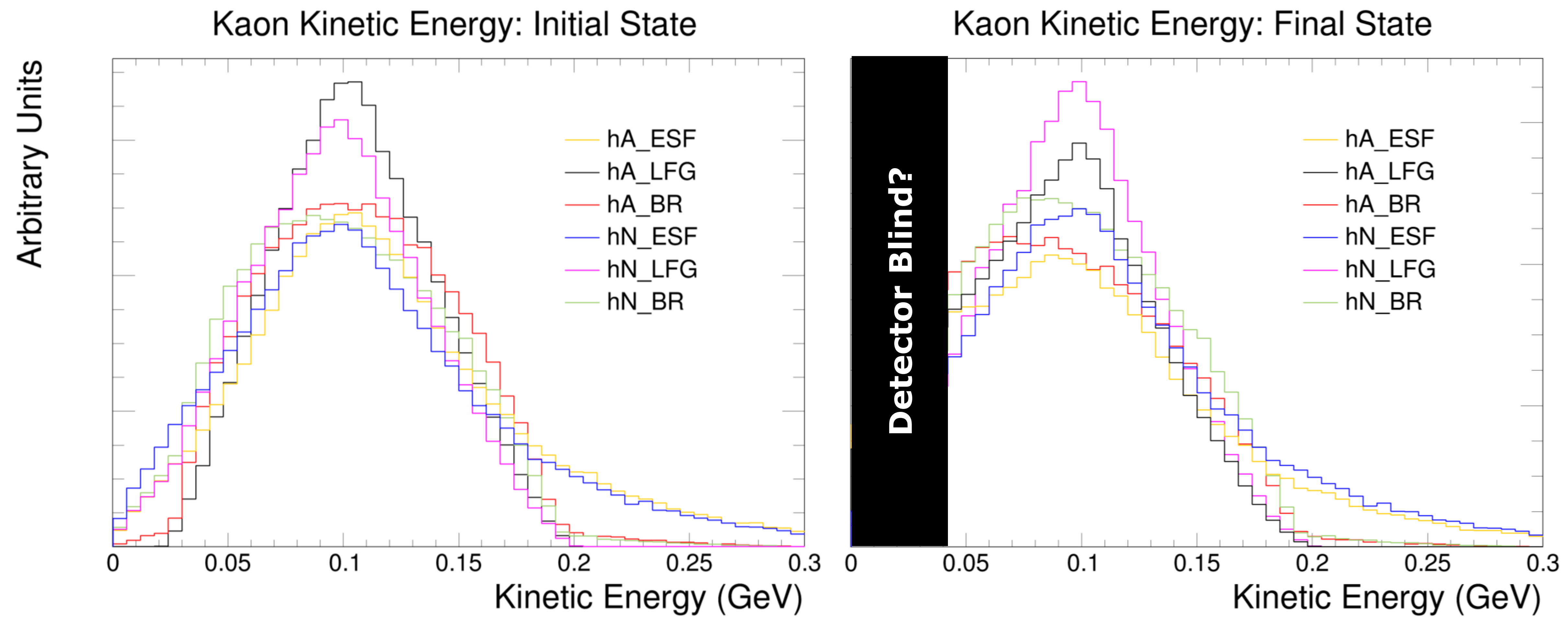
T. Stokes



Local
Nonrelativistic
Fermi Gas

Nuclear Modeling Effects on Kaon Energy

- K^+ generated directly from decaying p in nucleus
  - Initial momentum from Fermi motion and rest mass
  - FSI effects of hA or hN Intranuke 2018 show differences
    - hA has distinct shift toward lower energies upon exiting envelope



T. Stokes

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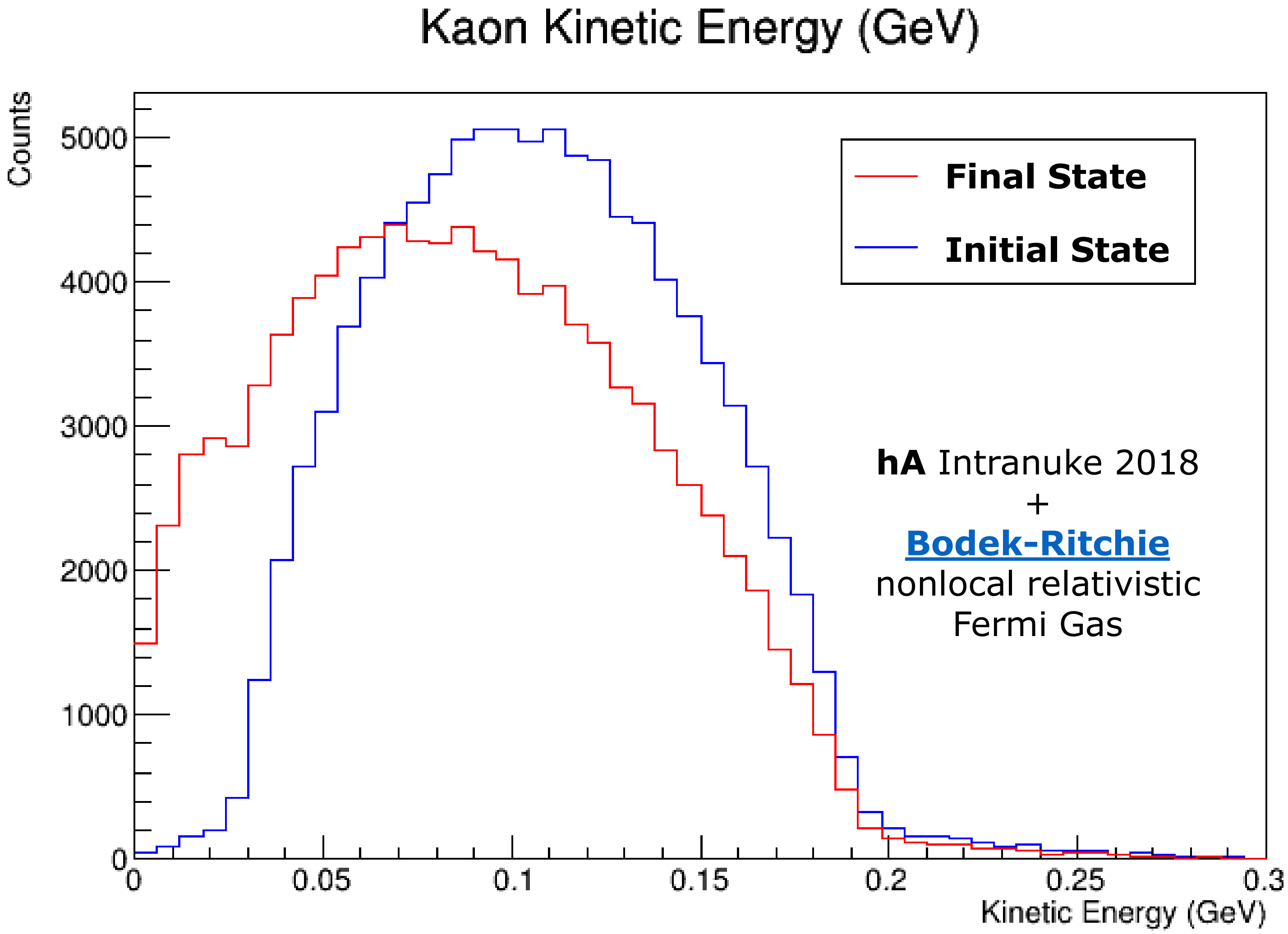


hA Intranuke 2018
+
[**Bodek-Ritchie**]
nonlocal relativistic
Fermi Gas

Lower final state K^+ momentum can adversely affect signal efficiencies

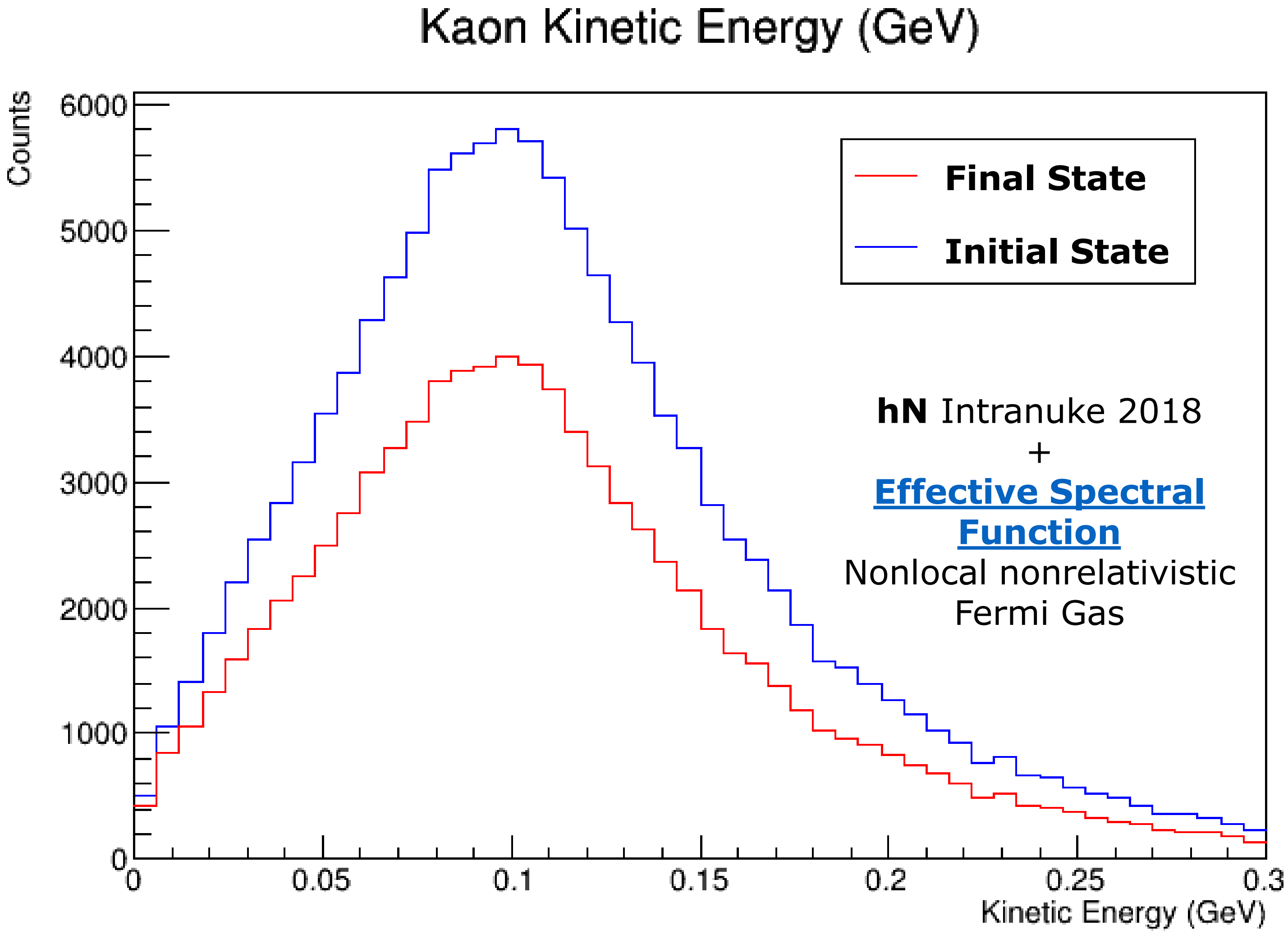
Must understand modeling systematics!

T. Stokes

Nuclear Modeling Effects on Kaon Energy

- K^+ generated directly from decaying p in nucleus
  - Initial momentum from Fermi motion and rest mass
  - FSI effects of hA or hN Intranuke 2018 show differences
    - hA has distinct shift toward lower energies upon exiting envelope

T. Stokes



hN Intranuke 2018
+
Effective Spectral Function
Nonlocal nonrelativistic Fermi Gas

Lower final state K^+ momentum can adversely affect signal efficiencies

Must understand modeling systematics!

Ongoing $p \to K^+\bar{\nu}$ Analysis

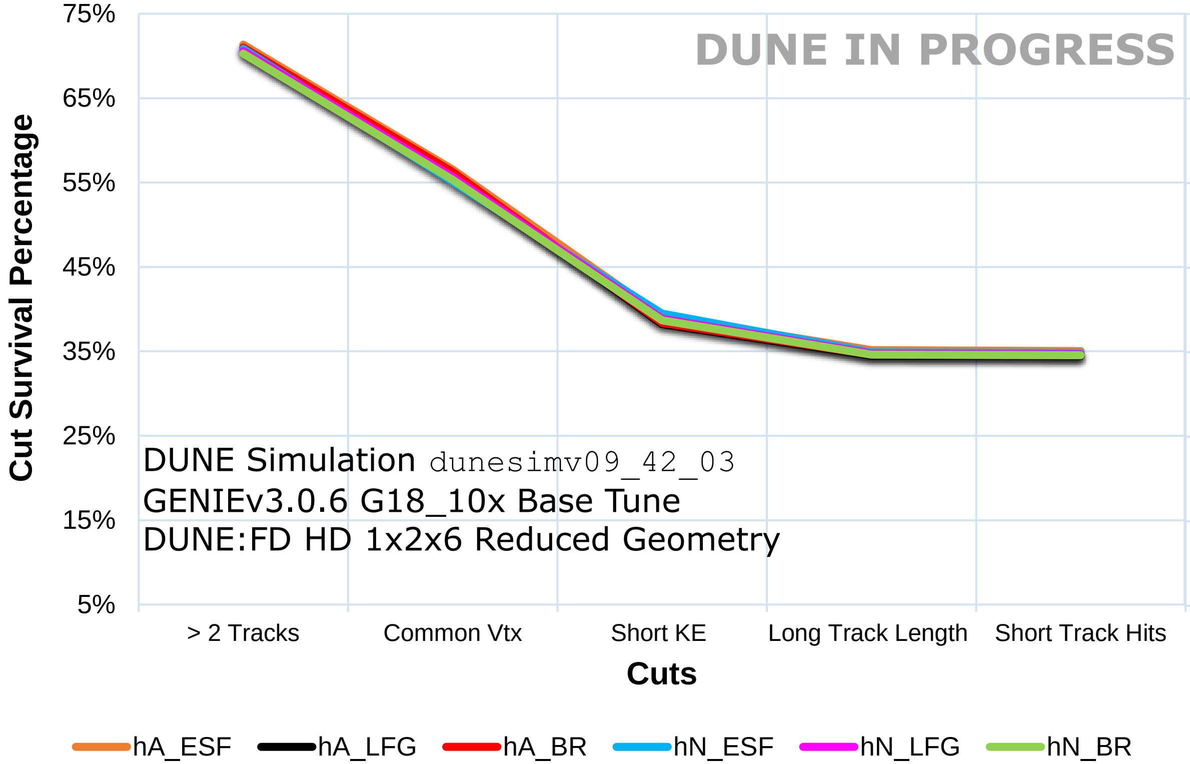
Preselection Cuts Before BDT Input

Improving PDK Signal Quality and Reducing Backgrounds

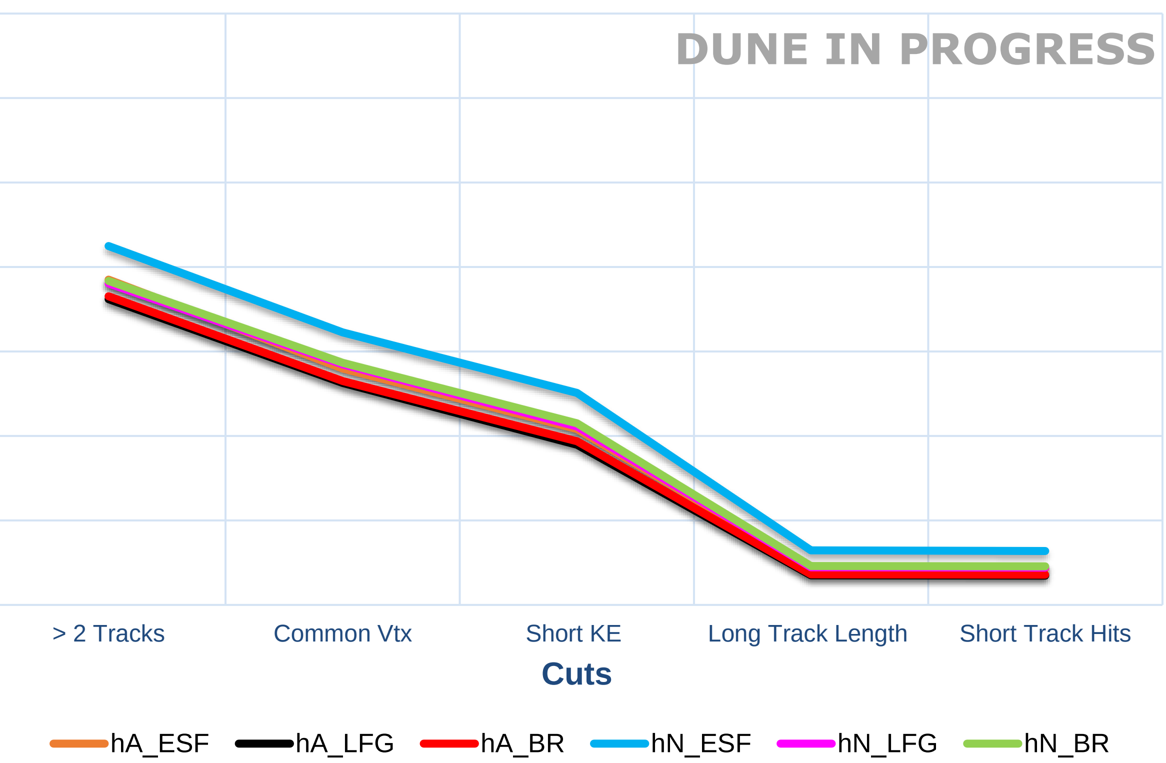
1. >Two tracks per event
2. A common vertex between tracks, each within 5cm
3. Short track kinetic energy requirement, improves purity
4. Long track length of requirement, reduces backgrounds
5. Short track must contain min. numb. Hits, improve dE/ds

T. Stokes

Sample Surviving vs Cuts: Signal



Sample Surviving vs Cuts: Background



Boosted Decision Tree Implementation

Strategy:

1. Select a nominal nuclear model configuration (hA LFG)
    - Note that hA predicts markedly lower K^+ FS kinetic energy—conservative
2. Tune BDT parameters to this base model
3. Obtain a classification
    - Use base nuclear model configuration BDT parameters, run over all others

What you get:

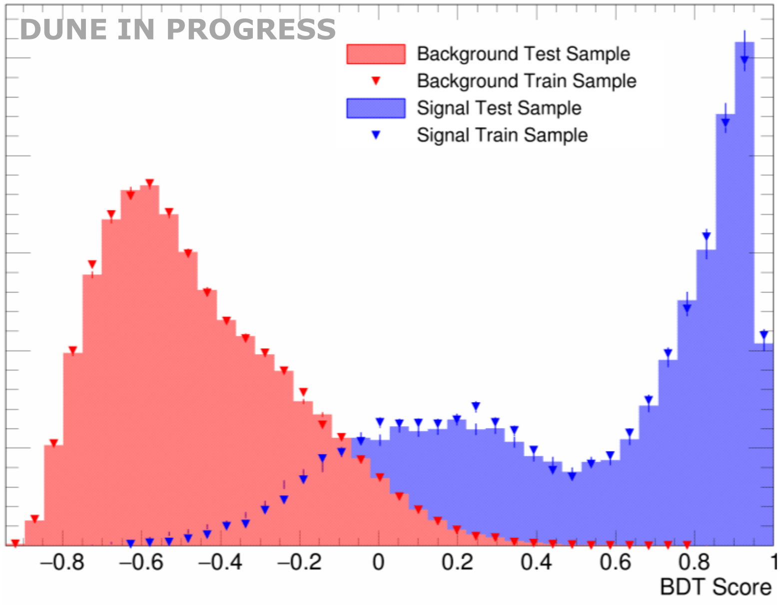
- A spread of signal efficiencies and background rates
    - Expected due to different responses to FSs from each configuration
- Representation of how changing model affects classification
    - Can be used to conservatively estimate nuclear modeling uncertainties
    - Large component of the systematics will come from this source

Still need to show consistency of performance with very high statistics

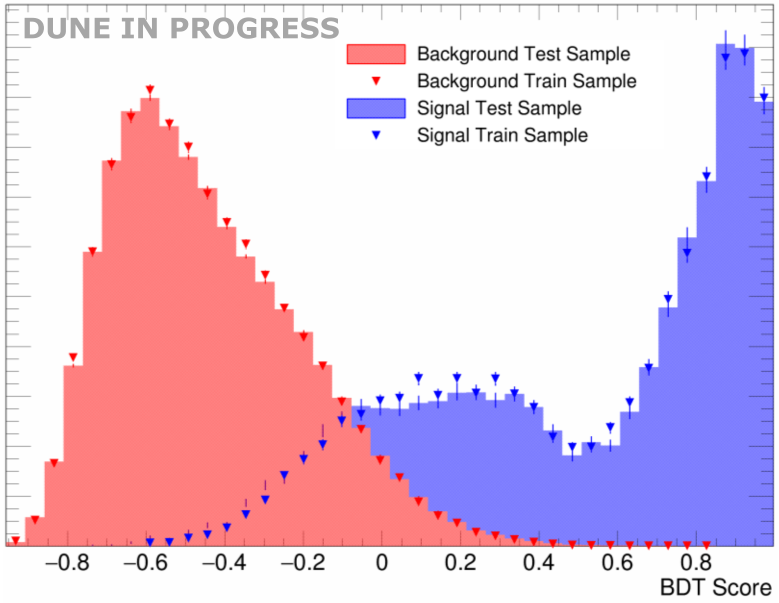
DUNE Simulation `dunesimv09_42_03`
GENIEv3.0.6 G18_10x Base Tune
DUNE:FD HD 1x2x6 Reduced Geometry

T. Stokes

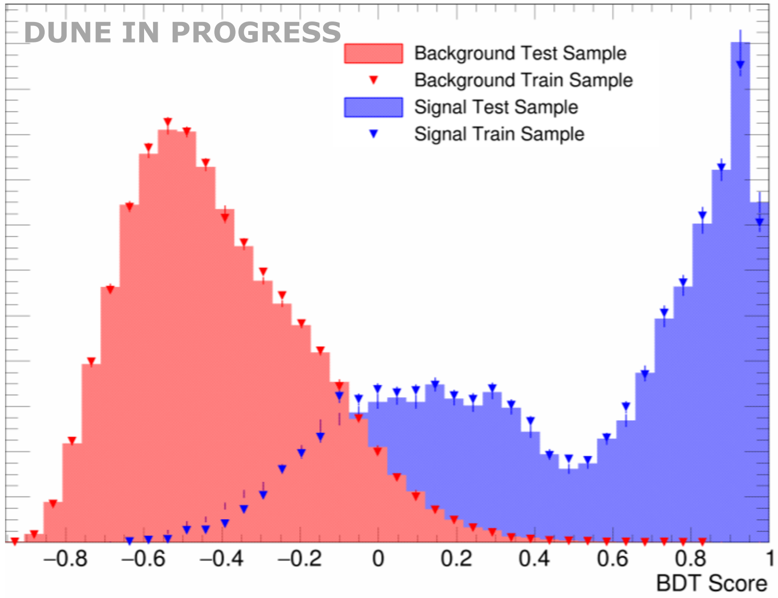
BDT Scoring: hA_LFG



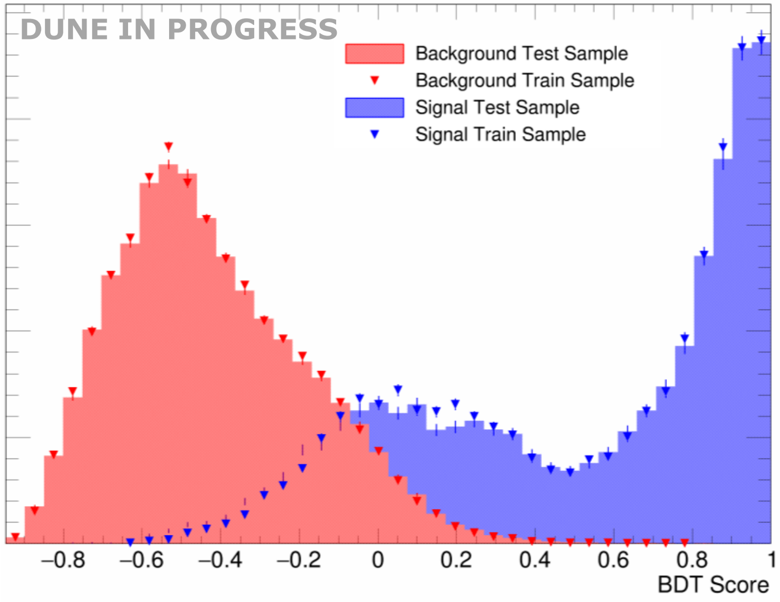
BDT Scoring: hA_BR



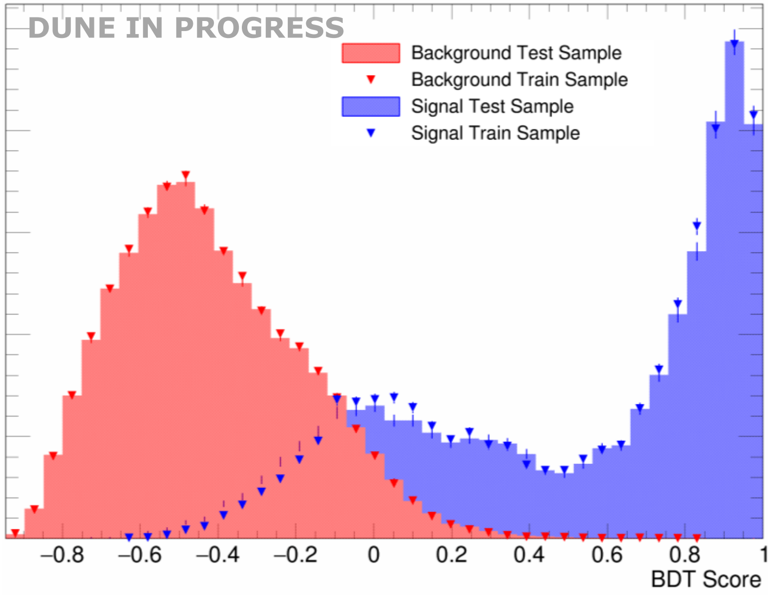
BDT Scoring: hA_ESF



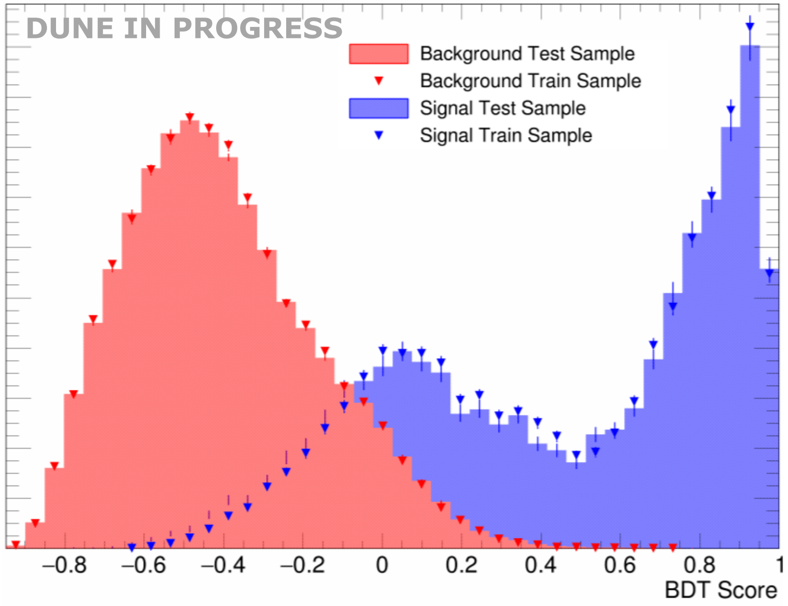
BDT Scoring: hN_BR



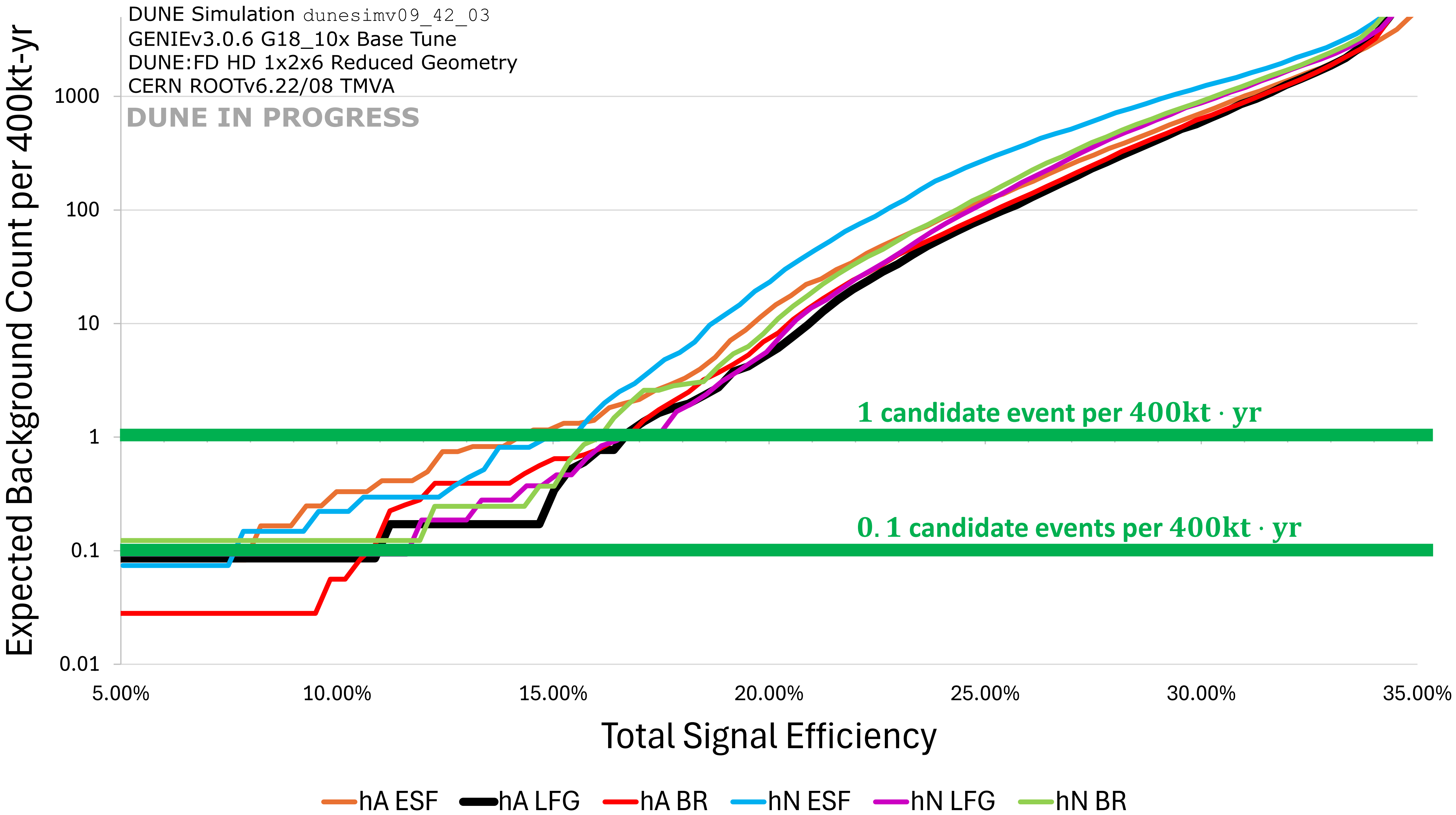
BDT Scoring: hN_LFG



BDT Scoring: hN_ESF



BDT ROC Curves from Testing Samples
Signal Efficiency vs. Expected Background Count
hA LFG Base Training

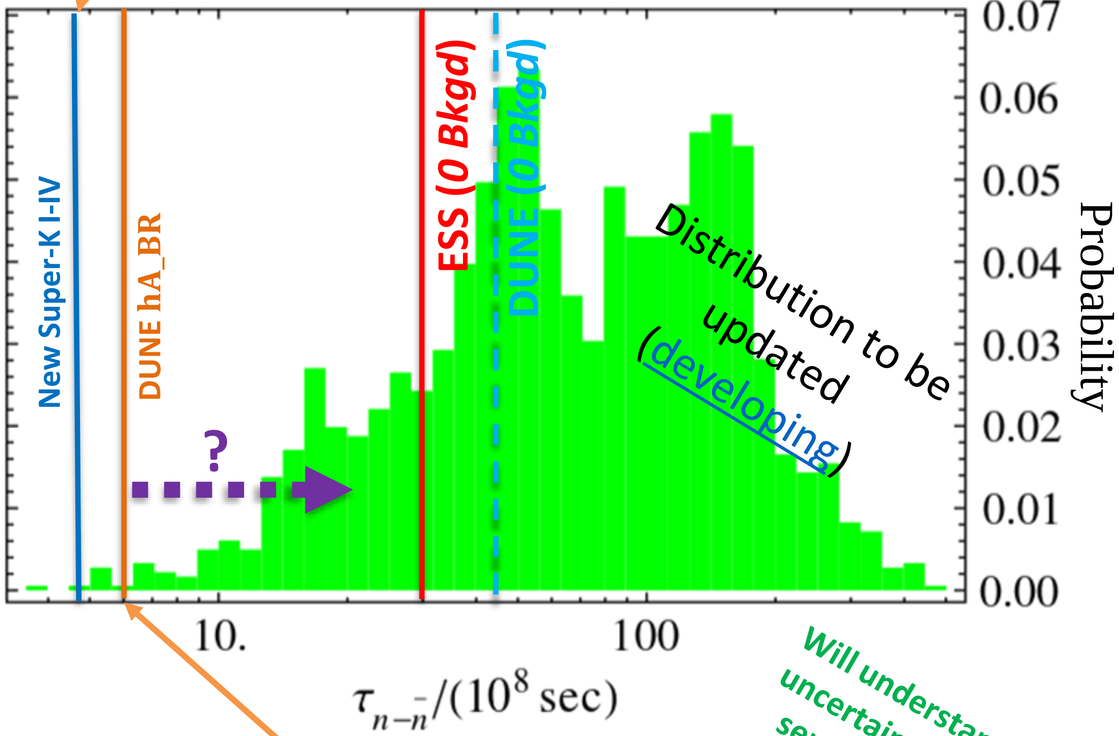


Theoretically Important Parameter Space of $\tau_{n\to\bar{n}}$

Post-sphaleron baryogenesis predicts the free $n \to \bar{n}$ transformation time

- **Dark blue** shows the new Super-K result
- **Orange** shows the DUNE TDR analysis using the $\mathrm{hA\_BR}$ model configuration with the new R_{Ar}
- **Blue dashed** shows converted limit from intranuclear transformation time
  - DUNE@$400\mathrm{kt}\cdot\mathrm{yr}{\sim}13{,}500$ ×ILL sensitivity
  - **Assumes 25% efficiency**
  - **Assumes backgroundless search**
- **Red** line shows free neutron transformation time
  - ESS, 3-year *goal:* $1000\mathrm{x}$ ILL sensitivity
  - Assuming ILL-like *zero background*
    - Ongoing work to show this definitively
  - Potential for increase by 10^4?

$$\tau_M = R \cdot \tau^2_{n\to\bar{n}}$$



Super-K I-IV
$11: 4.1\%$

DUNE TDR BDT(CNN) hA_BR
$\sim 16: 8\%$

Super-K I
$24: 12\%$

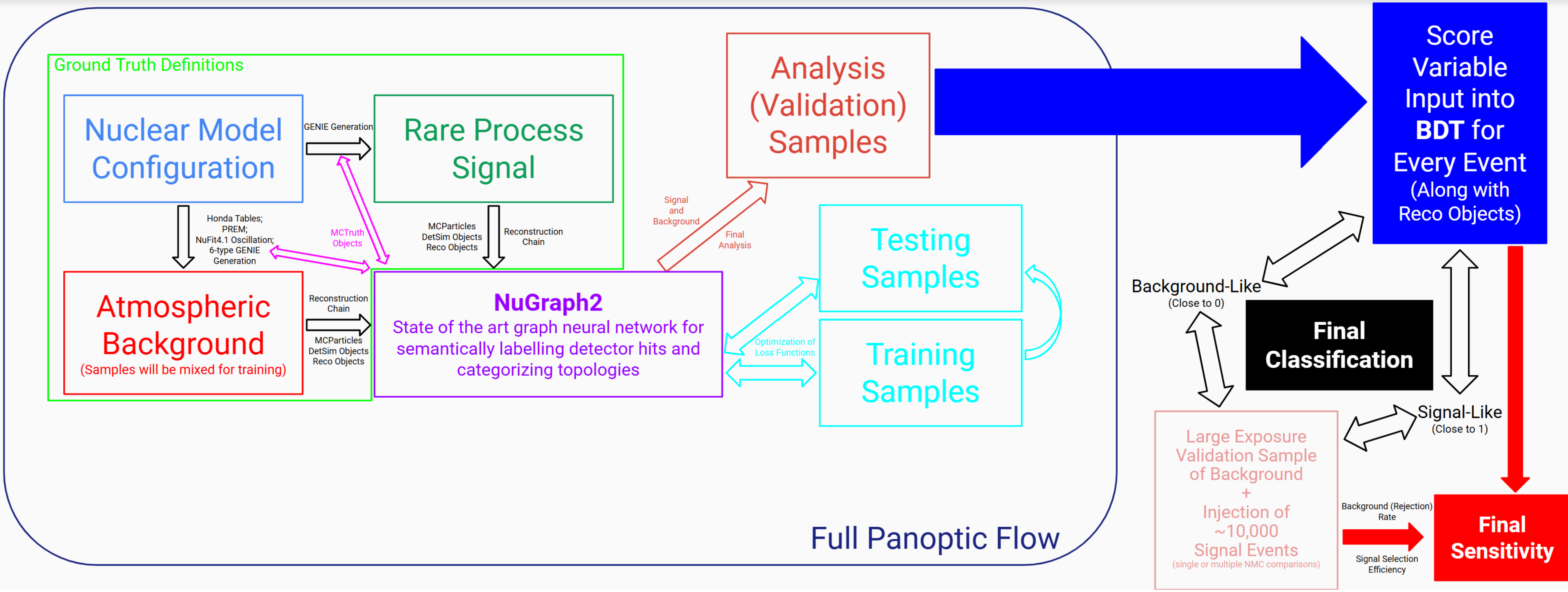
Will understand full uncertainties in $\tau_{n\bar{n}}$ sensitivities with more model comparisons

Phys. Rev. D 87, 115019 (2013)

Future Directions
for
Baryon Number Violation

Analysis Flow
Using Automated Learning Techniques For Event-Level Classification

NuGraph2, V Hewes



Ground Truth Definitions

Nuclear Model Configuration

GENIE Generation

Rare Process Signal

Honda Tables;
PREM;
NuFit4.1 Oscillation;
6-type GENIE Generation

MCTruth Objects

MCParticles
DetSim Objects
Reco Objects

Reconstruction Chain

Atmospheric Background
(Samples will be mixed for training)

Reconstruction Chain

MCParticles
DetSim Objects
Reco Objects

NuGraph2
State of the art graph neural network for semantically labelling detector hits and categorizing topologies

Signal and Background

Final Analysis

Analysis (Validation) Samples

Testing Samples

Optimization of Loss Functions

Training Samples

Full Panoptic Flow

Score Variable Input into **BDT** for Every Event (Along with Reco Objects)

Background-Like
(Close to 0)

Final Classification

Signal-Like
(Close to 1)

Large Exposure Validation Sample of Background
+
Injection of ~10,000 Signal Events
(single or multiple NMC comparisons)

Background (Rejection) Rate

Signal Selection Efficiency

Final Sensitivity

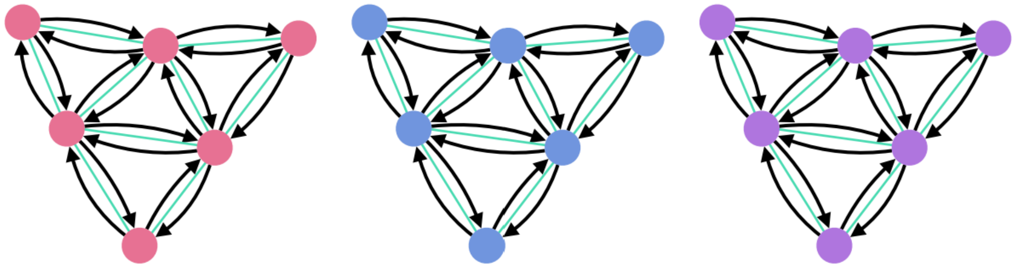
Slide adapted from V Hewes & T. Stokes

NuGraph2

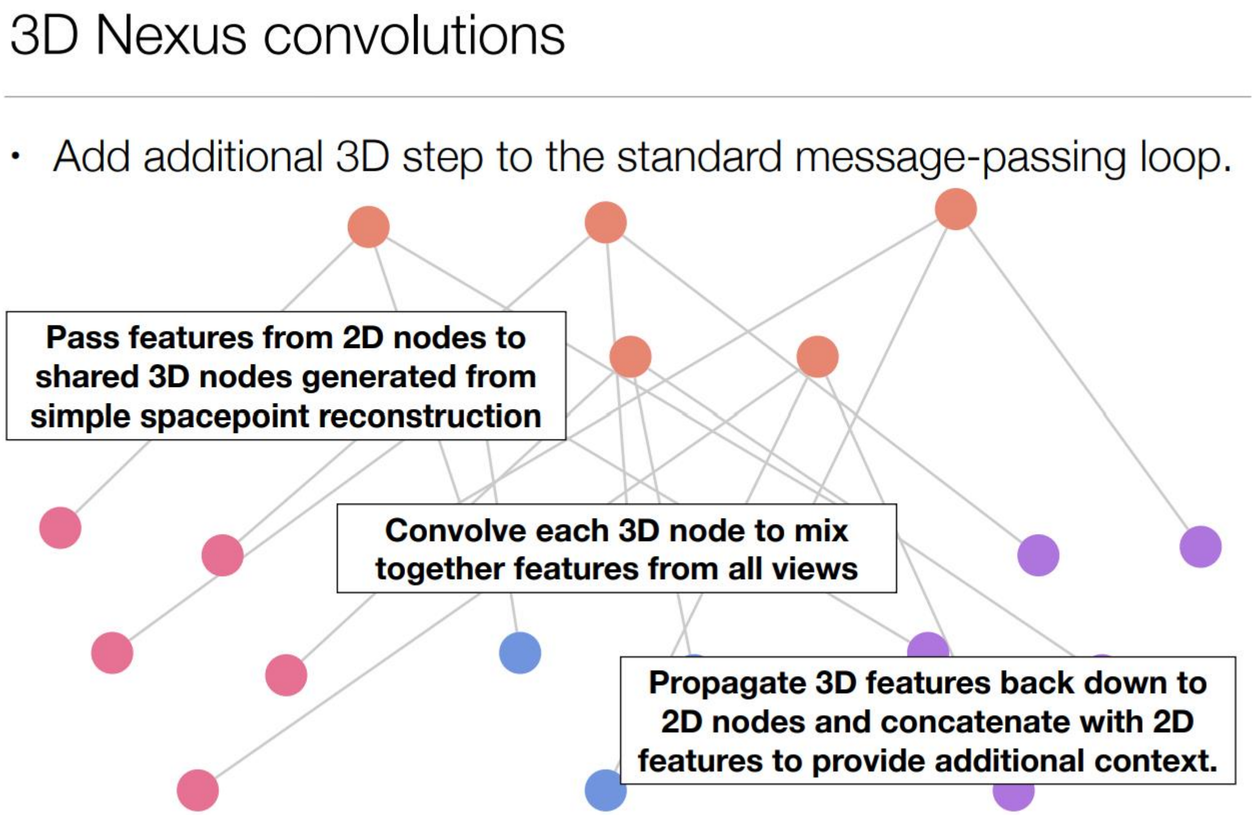
Using MicroBooNE Open Data Release

- A state-of-the-art graph neural network for semantically labelling detector hits in neutrino physics experiments
- Works natively on detector hits without modifying structure
- Utilizes a nexus convolution block
  - Combines information from all planes and injects it back into each plan at specific intervals

3D graph nodes/convolutions perform
message-passing independently
in each detector view



3D graph nodes/convolutions add
additional 3D steps to the standard
message passing loop



3D Nexus convolutions

- Add additional 3D step to the standard message-passing loop.

Pass features from 2D nodes to shared 3D nodes generated from simple spacepoint reconstruction

Convolve each 3D node to mix together features from all views

Propagate 3D features back down to 2D nodes and concatenate with 2D features to provide additional context.

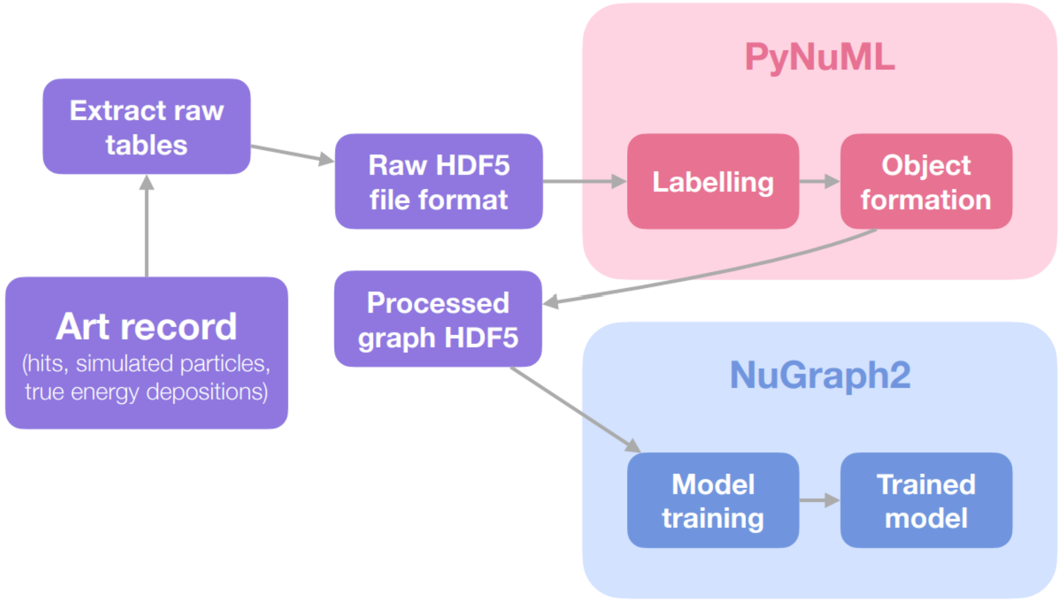
V Hewes CHEP 2023

How Does NuGraph Work?

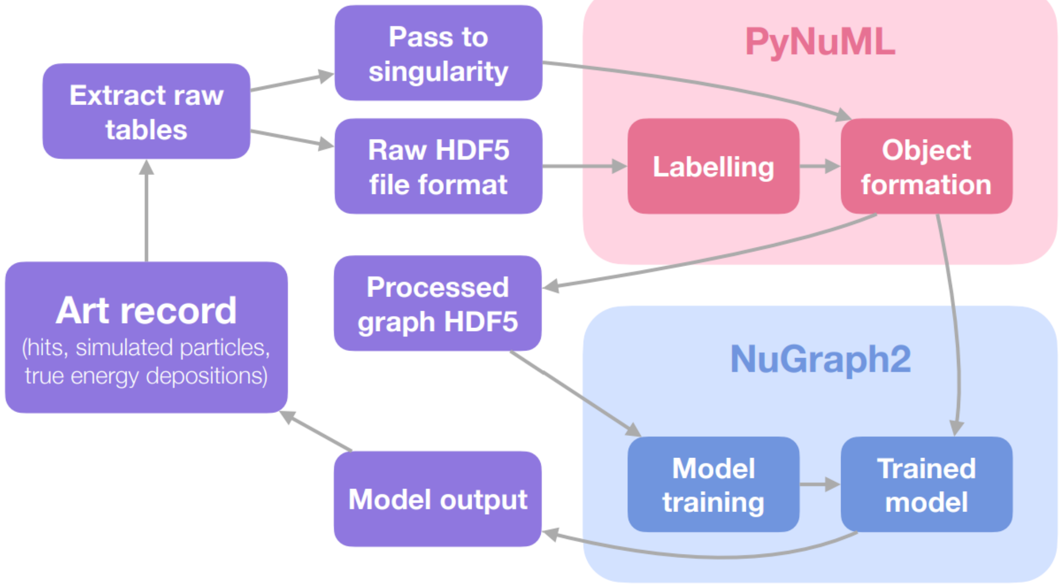
- NuML: ROOT files converted to HDF5
  - Holds low level information
    - Simulated particle labels, hits, true energy deposition, etc.
  - GitHub: https://github.com/vhewes/numl

- PyNuML: Provides efficient, flexible solution for tasks leveraging ML in particle physics
  - Defines ground truth labels
  - Arranges detector hits in ML objects (graphs)
  - Makes pixel maps, etc.
  - GitHub: https://github.com/vhewes/pynuml

Producing Graphs for Model Training



Inference in Production



V Hewes CHEP 2023

Slide adapted from V Hewes & T. Stokes

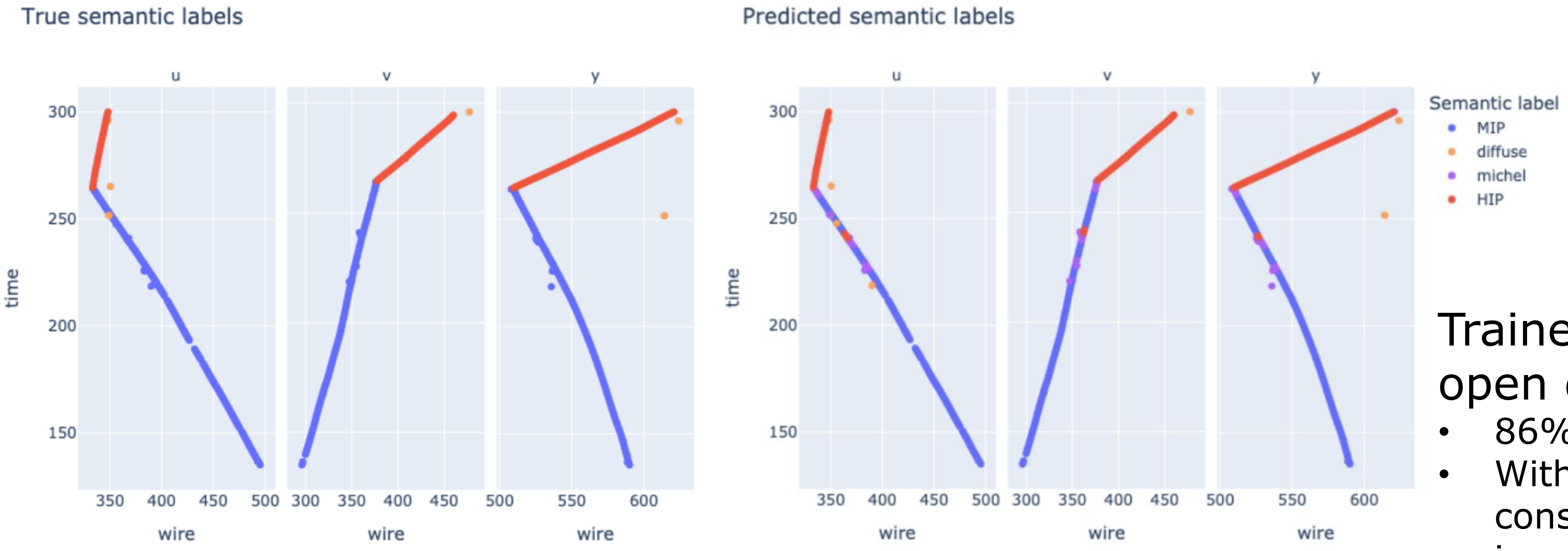
Slide adapted from V Hewes & T. Stokes

NuGraph2

Semantic Labeling Performance in Example ν_μ Interaction

- NuGraph2 can semantically label detector hits well
  - Particle identification & topology is critical
    - Central in separating $p \rightarrow K^+\bar{\nu}$ signal from atmospheric ν background

- **NuGraph2 can operate after training to yield binary classifier**
  - **Direct access to signal-like or background-like discriminator**
  - **Can semantically label K^+ classes in signal and background**
  - Plan: Utilize this binary classification as an input into the BDT analysis



Trained on MicroBooNE open datasets

- 86% overall hit efficiency
- With 3D connections, consistency between views improved from 70% to 98%

V Hewes CHEP 2023

Slide adapted from V Hewes & T. Stokes

NuGraph2

Semantic Labeling Performance in Example ν_e Interaction

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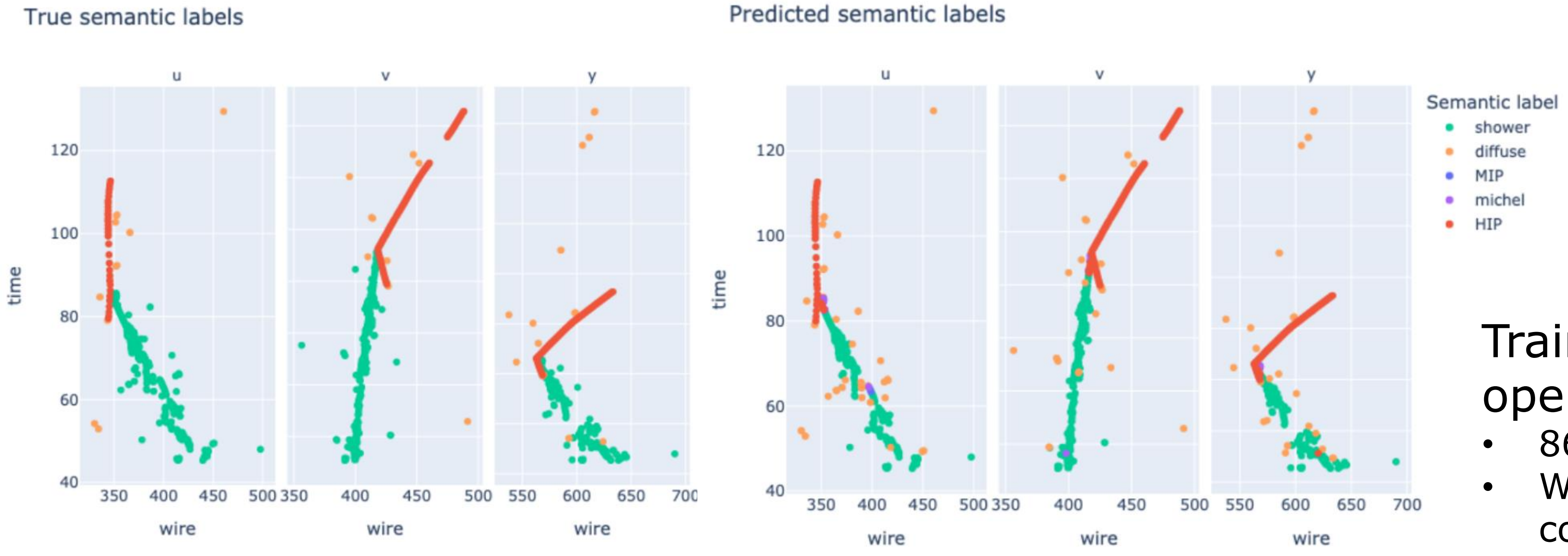

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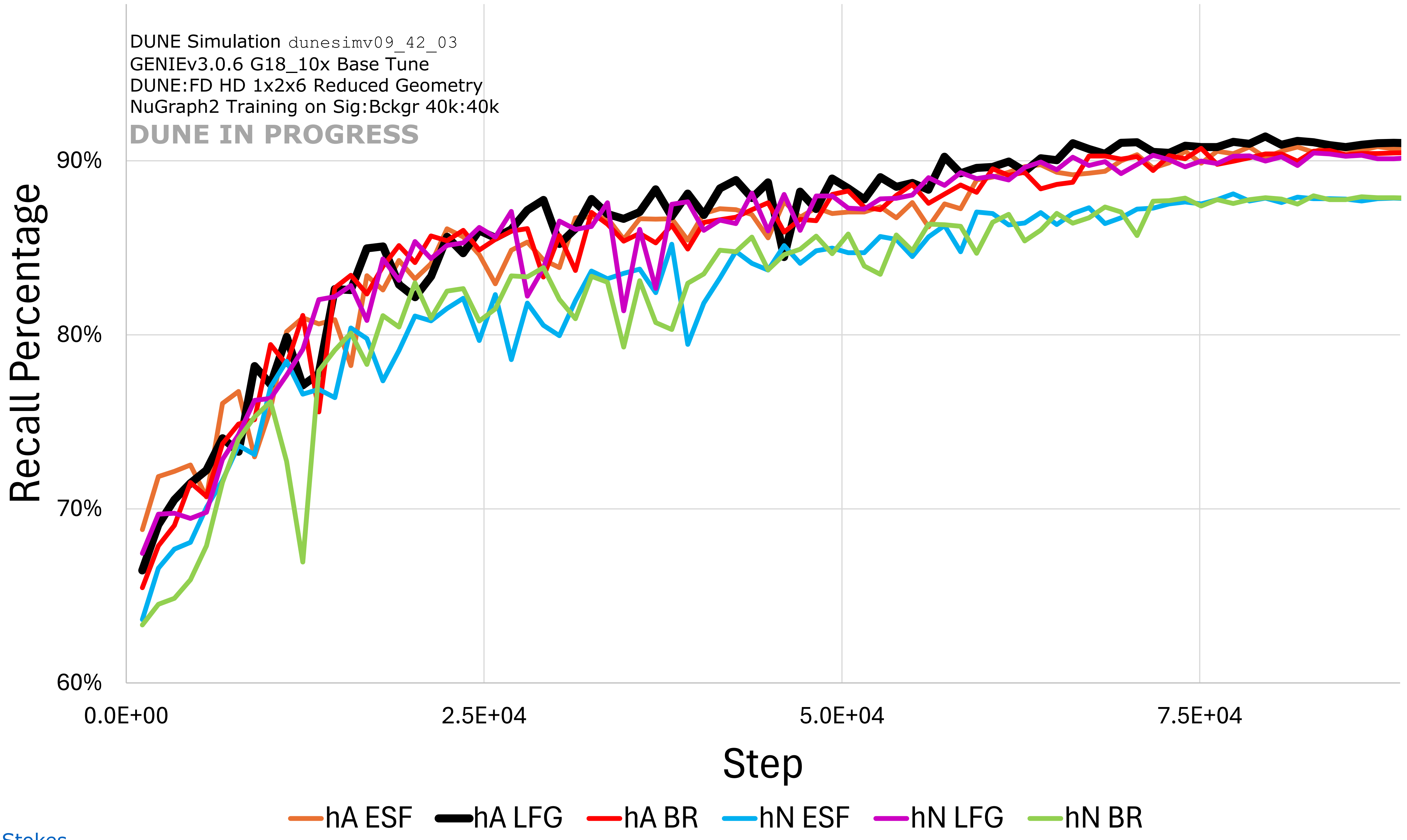
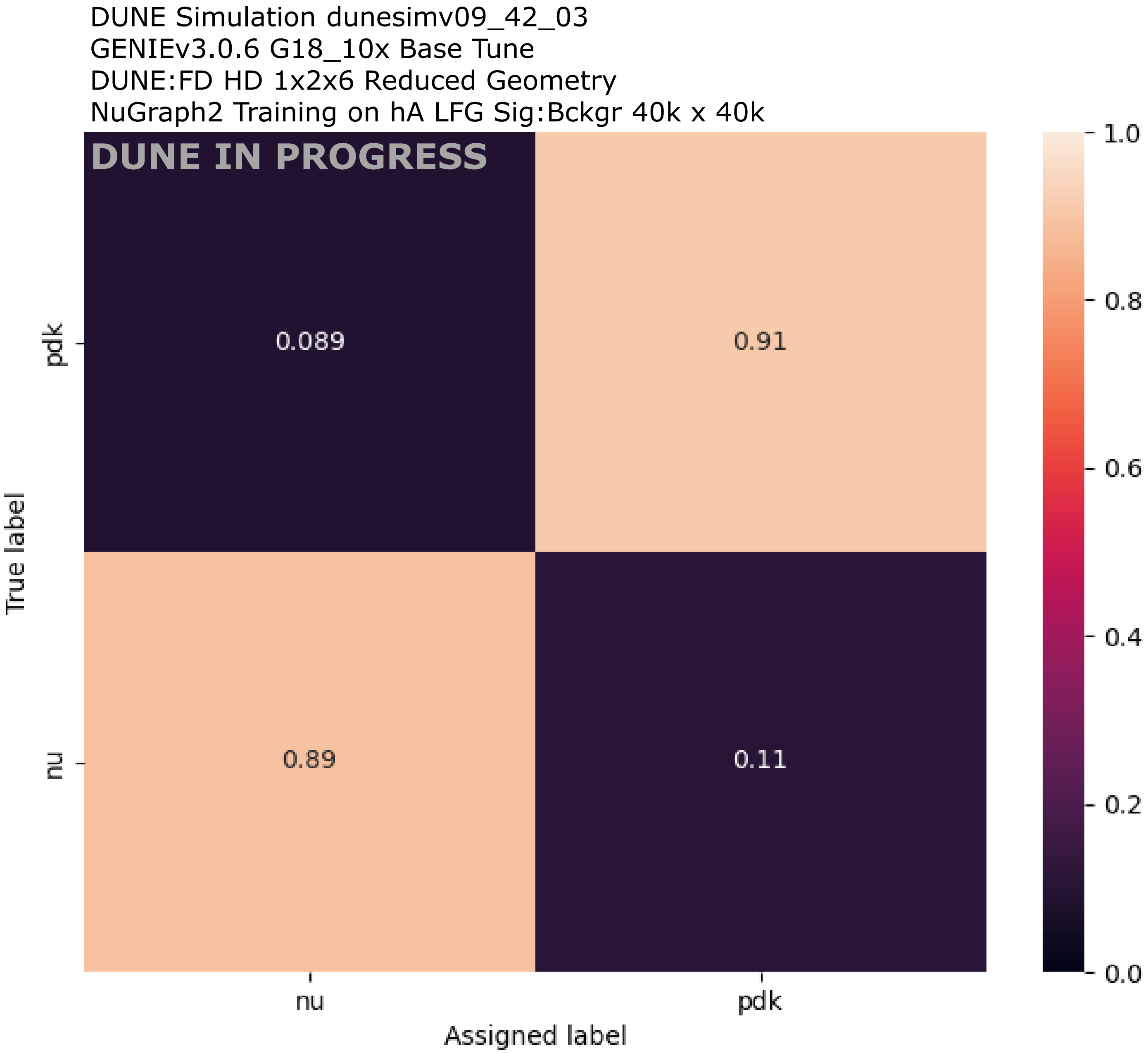
V Hewes CHEP 2023

NuGraph2 Event Classification
Training on 40k:40k Signal:Background Events



NuGraph2

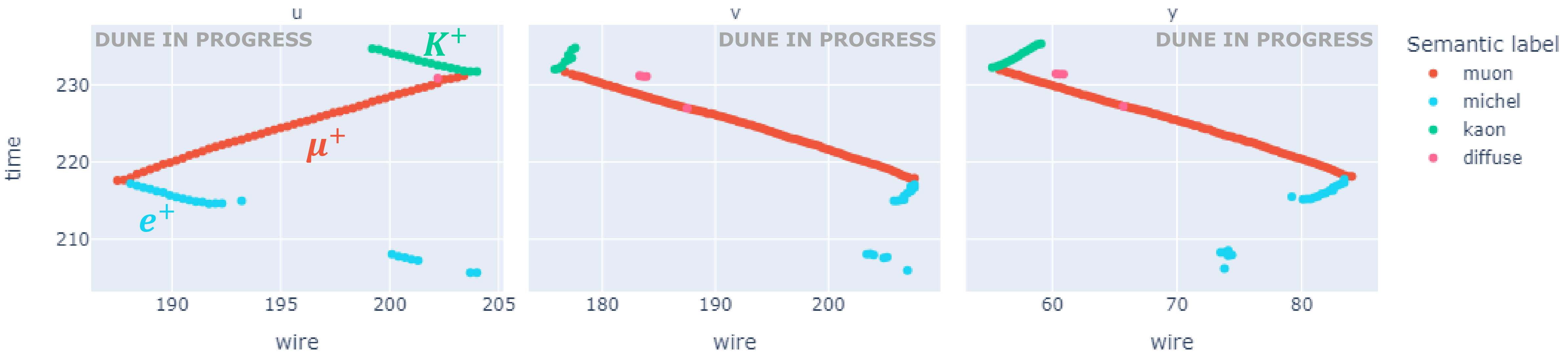
Binary Classifier for $p \rightarrow K^{+}\bar{\nu}$ and Atmospheric ν


DUNE Simulation dunesimv09_42_03
GENIEv3.0.6 G18_10x Base Tune
DUNE:FD HD 1x2x6 Reduced Geometry
NuGraph2 Training on hA LFG Sig:Bckgr 40k x 40k

T. Stokes

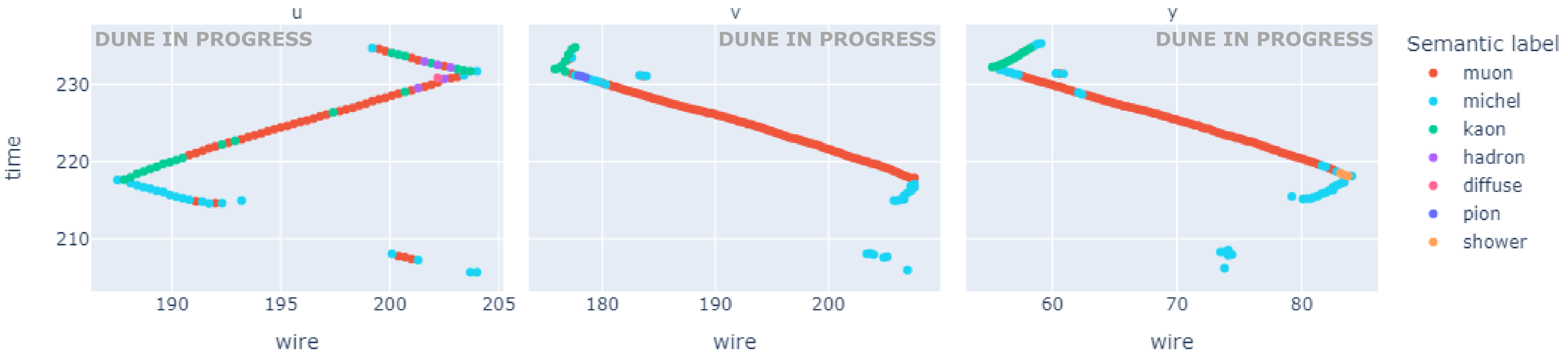
True Positive

True semantic labels for signal-like true $p \rightarrow K^{+}\bar{\nu}$ signal



DUNE Simulation `dunesimv09_42_03`
GENIEv3.0.6 G18_10x Base Tune
DUNE:FD HD 1x2x6 Reduced Geometry
NuGraph2 Training on hA LFG Sig:Bckgr 40k:40k

Predicted semantic labels for signal-like true $p \rightarrow K^{+}\bar{\nu}$ signal



T. Stokes

Summary & Conclusions

- DUNE’s first neutrino physics results will come from atmospheric neutrino oscillation measurements
  - HEPWG taking lead here, working toward first publication
    - Rate predictions, flux uncertainties, ang. reco. improvements ongoing
      - Exploiting LArTPC powers for hadronic info critical to improvements
    - MaCh3 Oscillation framework ready for analyses
    - Large first analysis near complete
    - Will eventually be a key input for precision BNV background studies

- BNV analyses ongoing, new PDK sensitivities soon
  - Understanding nuclear mod. syst. uncertainties critical
    - Iteration over nonreweightable nuc. mod. configs. as conservative estimator of selection effects in automated methods (BDT, NuGraph)
    - Will directly assess signal eff. & background rate uncertainties
  - Current BDT framework shows good performance
  - NuGraph performance incredibly encouraging for future
  - New $n \rightarrow \bar{n}$ analysis in development, new BRs now in `GENIE`