Exploring Golden Channel Proton Decay in DUNE

INT Workshop on
Baryon Number Violation
From Nuclear Matrix Elements to BSM Physics

by J. L. Barrow
The University of Minnesota
with key inputs from T. Stokes
Louisiana State University ⟹ Yale University

On Behalf of the DUNE Collaboration

January 13th, 2025

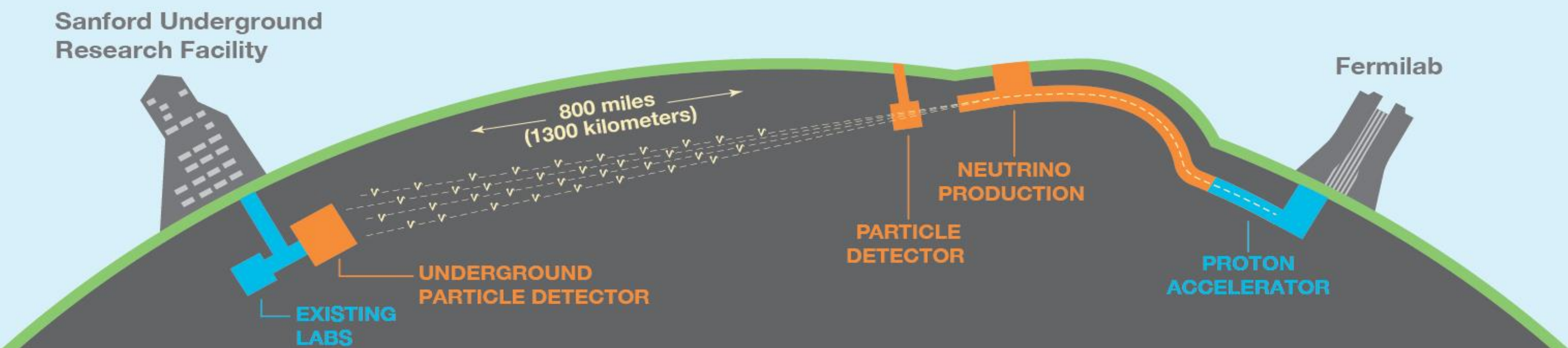
The DUNE Collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- **1400+ collaborators**
- 200+ institutions across 30+ countries
- **30+ peer-reviewed publications**
  - **Many more in preparation!**

Design of DUNE

- Broad-band neutrino beam at Fermilab
- $1.2\ \mathrm{MW}$—upgradeable to $> 2.0\ \mathrm{MW}$
- $1300\ \mathrm{km}$ baseline
- **Near detectors**: suite of technologies, off-axis capabilities
- **Far detectors:** Liquid Argon Time Projection Chambers
  - Total mass: $\mathbf{4 \times 17,000}$ **tons**



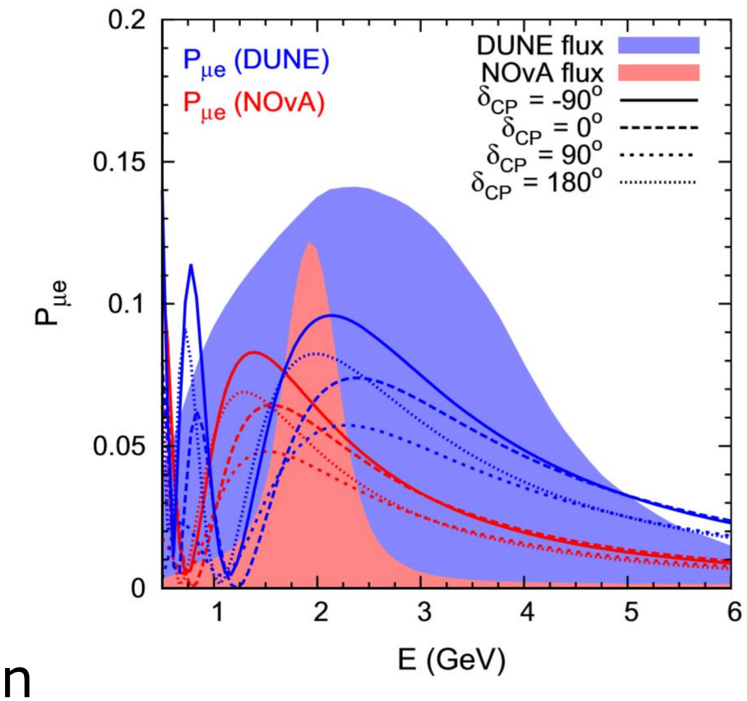
Adapted from T. Stokes

Adapted from UKRI PPD: DUNE

What is DUNE?

Goals of DUNE

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



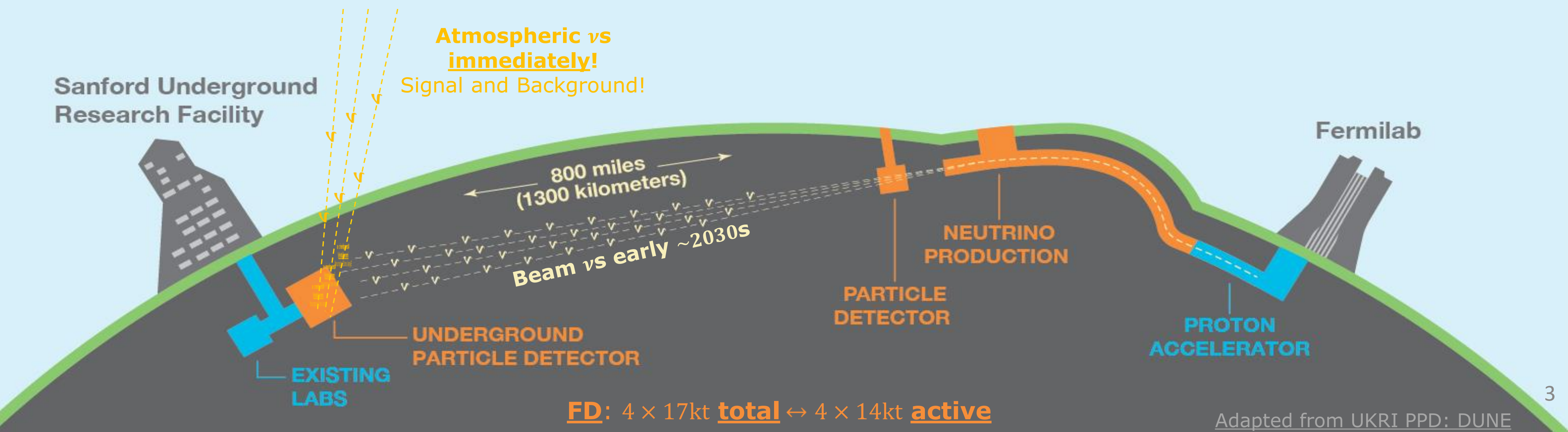
Ghosh *et al*. Eur. Phys. J. C (2016)76

Implications of DUNE

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

Features and Challenges

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



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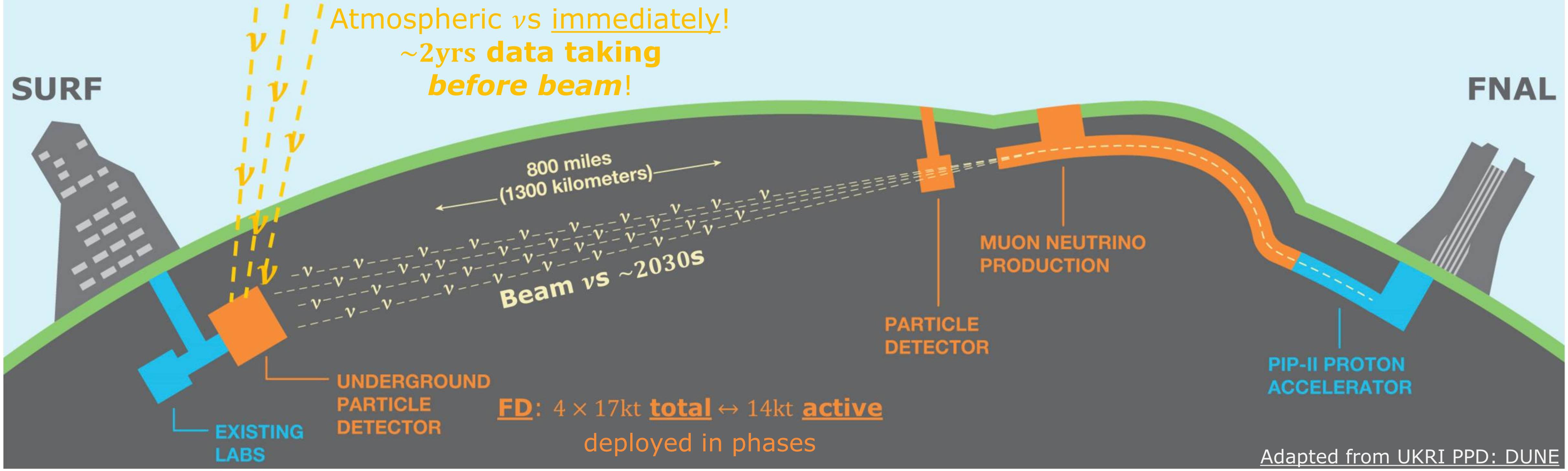


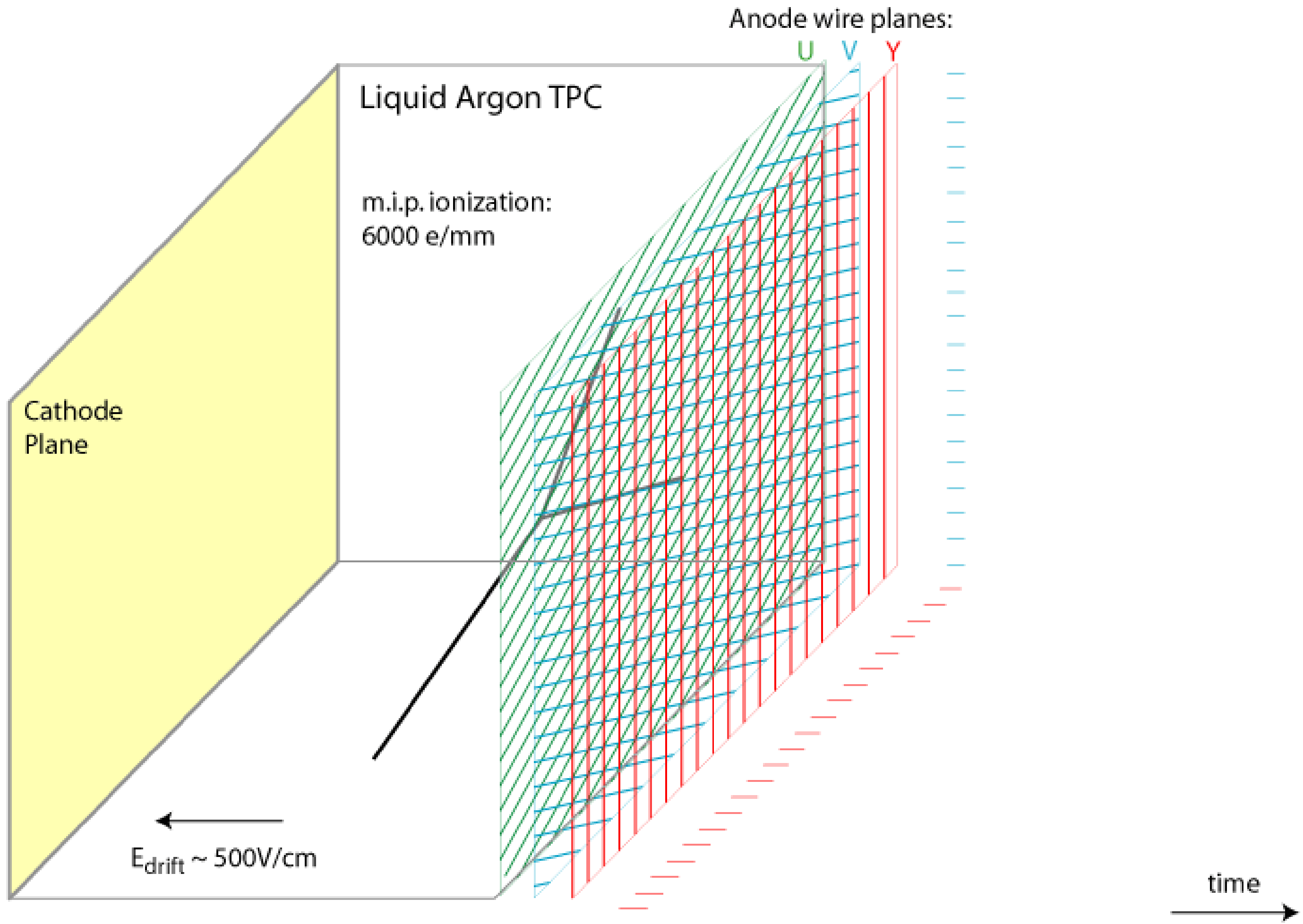
Far Detectors located on $4910'$ level at SURF

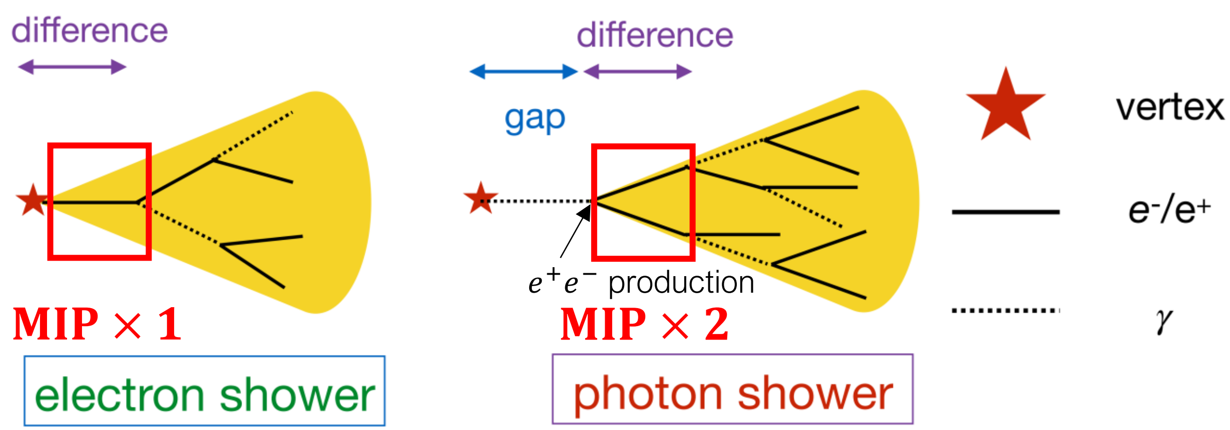
- Excellent shielding to cosmogenic events—quiet!
  - ~ 1000 cosmics/**day** in single FD module
  - Compare to ~ 1000 cosmics/**s** in MicroBooNE!

Atmospheric νs: first $\gtrsim 2$ yrs DUNE ν data!

Liquid Argon Time Projection Chambers

- γ/e discrimination
  - Tracks and gaps
- Low KE hadron thresholds
  - **Directly reconstruct $K^{\pm}$**
- DUNE's technology
  - ICARUS, MicroBooNE, SBND
  - **ProtoDUNE operational!**
    - $\sim$1kt prototype at CERN
    - First HE K^{+} cross section
- ^{40}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
  - $dQ/dx \sim dE/dx$ for calorimetry





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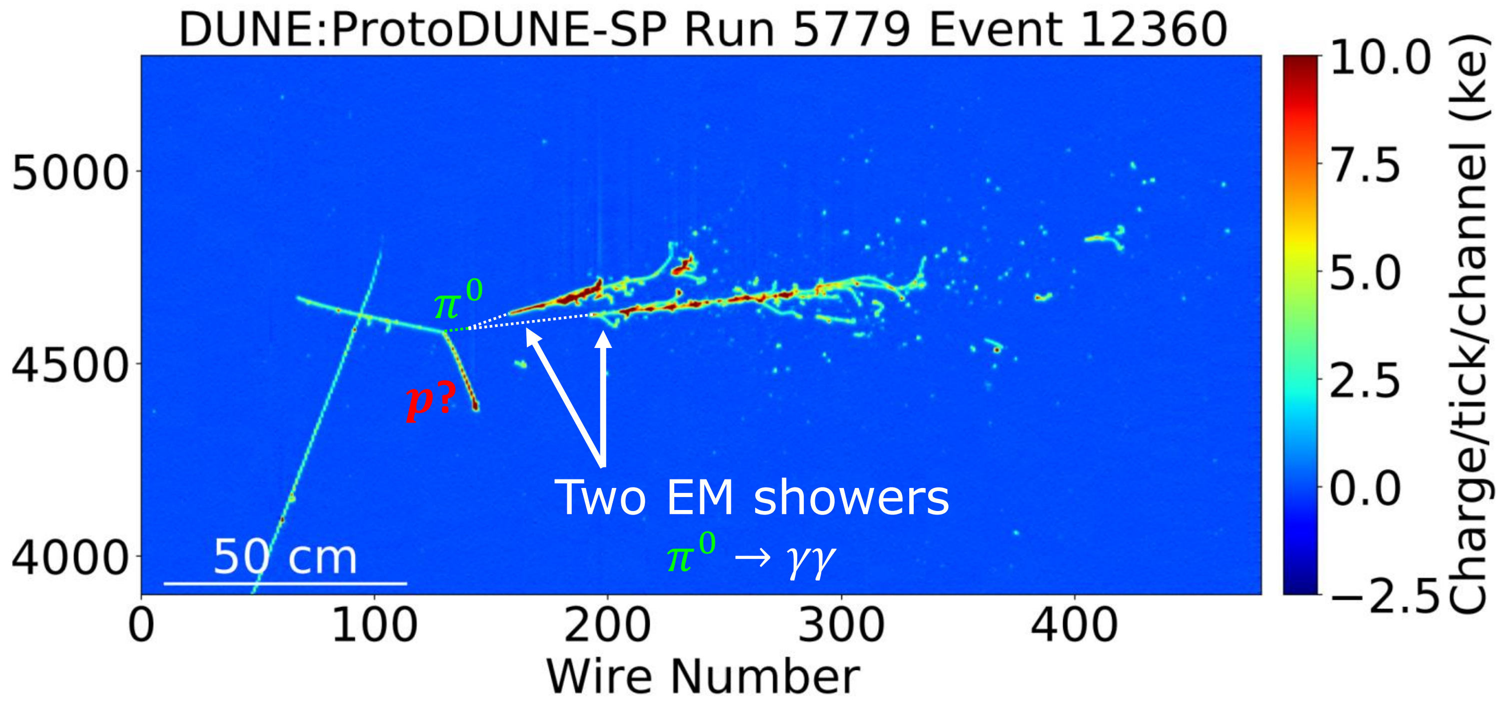

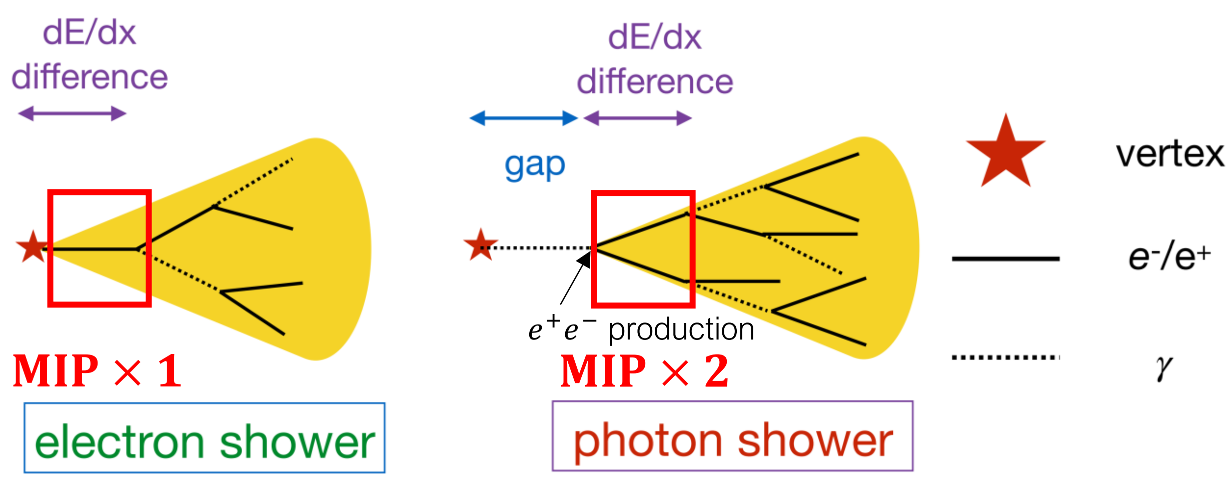

Adapted from B. Yu, H. Wei, and J. H. Jo   V. Meddage APS April 2019

Liquid Argon Time Projection Chambers

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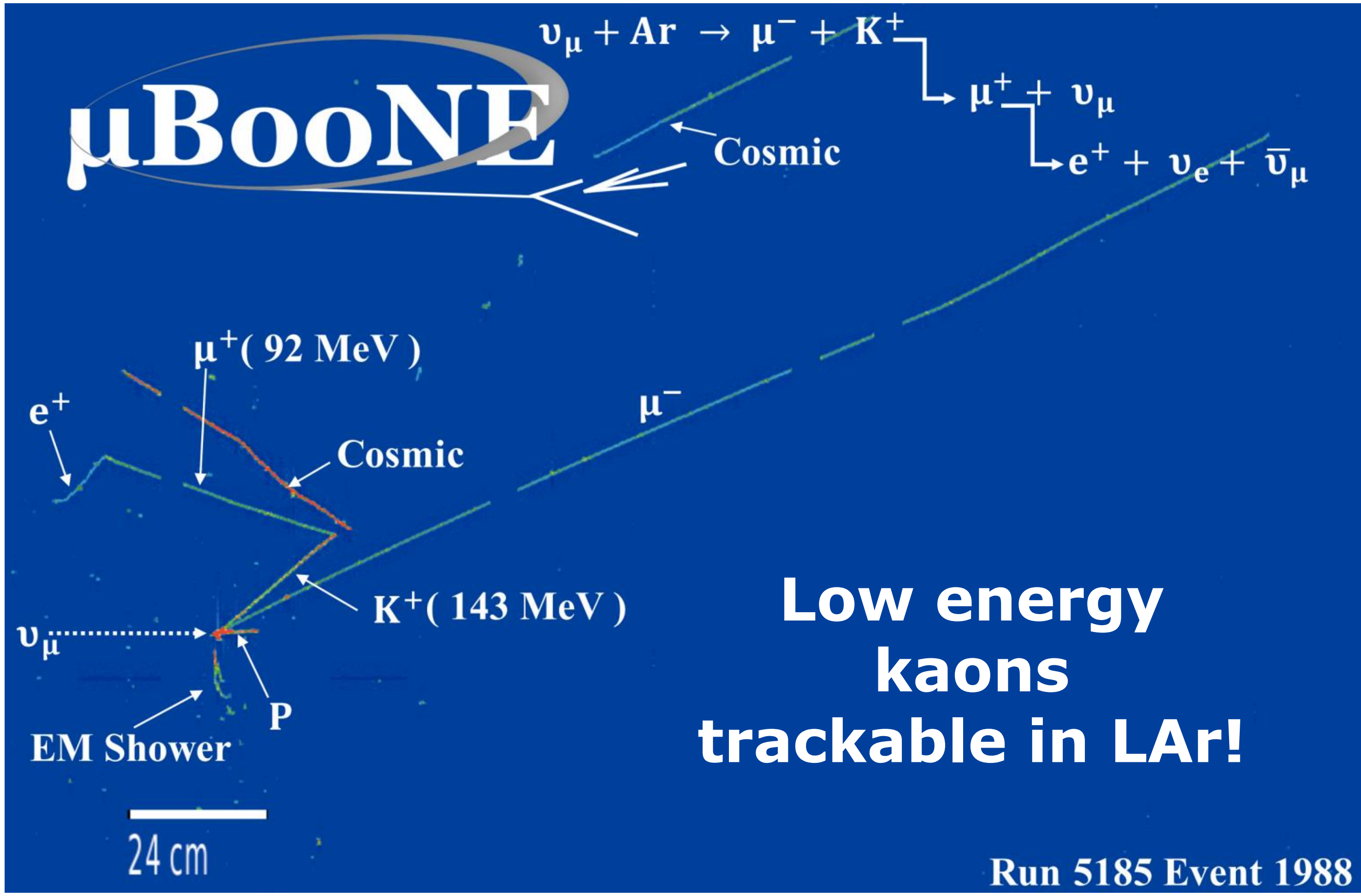
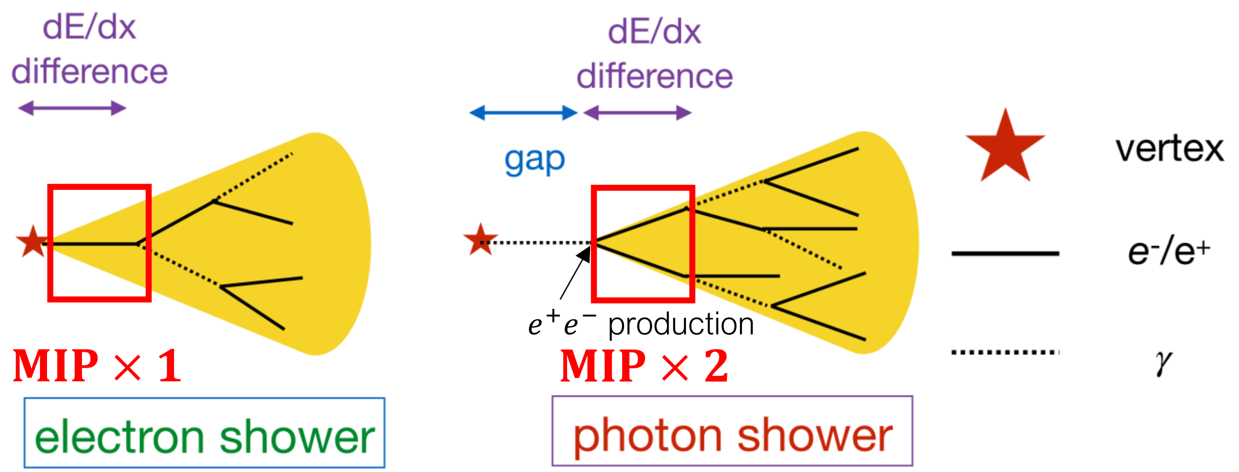




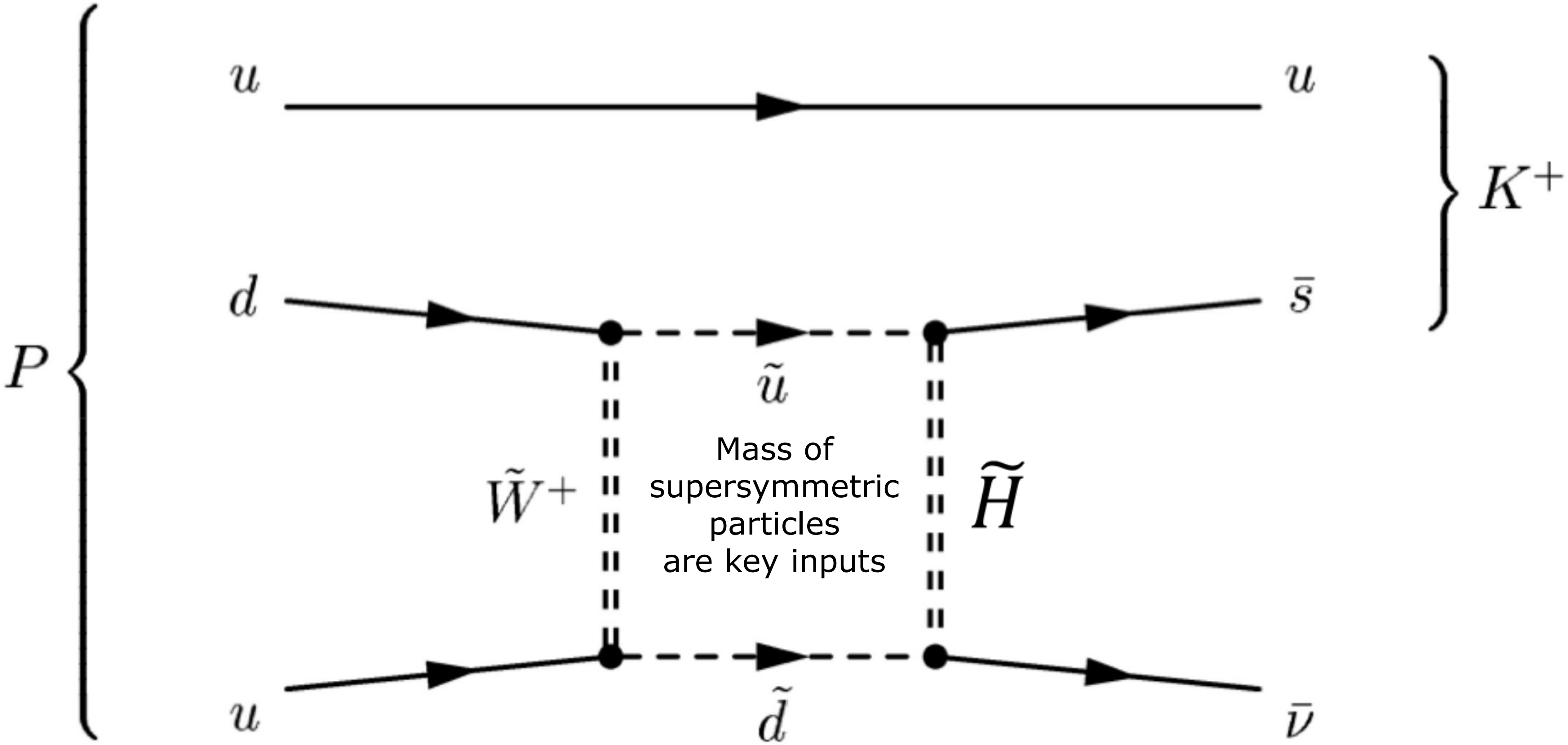
Adapted from B. Yu, H. Wei, and J. H. Jo

G. Santucci Thesis

Adapted from T. Stokes

"Golden Channel"

Supersymmetric Particles Can Lower Mass Scales for Observable PDK



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

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

Unification of Forces

Possibility for quark to lepton transitions

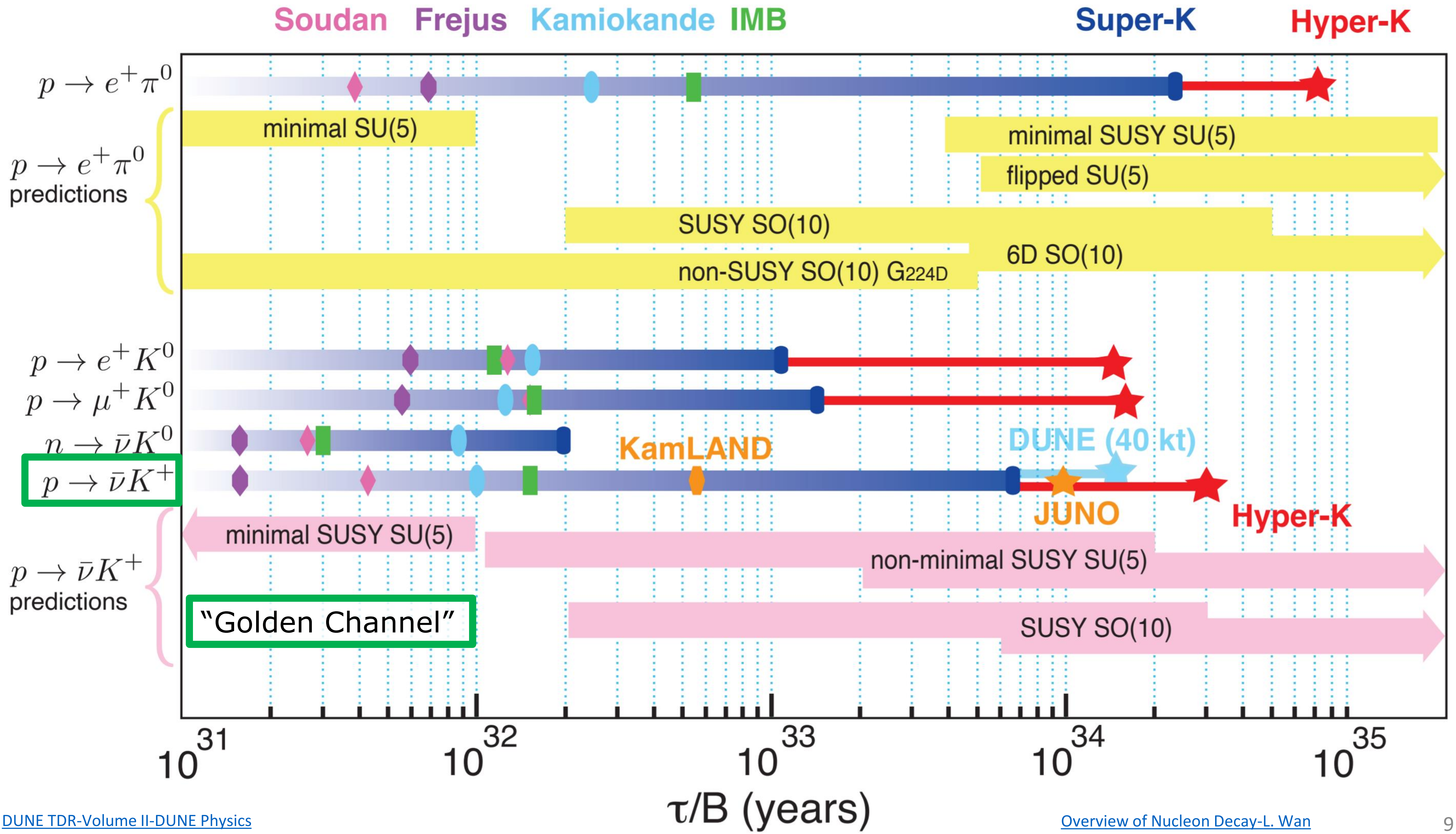
Baryon Number Violation

$\Longrightarrow$Proton Decay

Courtesy of E. Kearns

Expected PDK Lifetimes

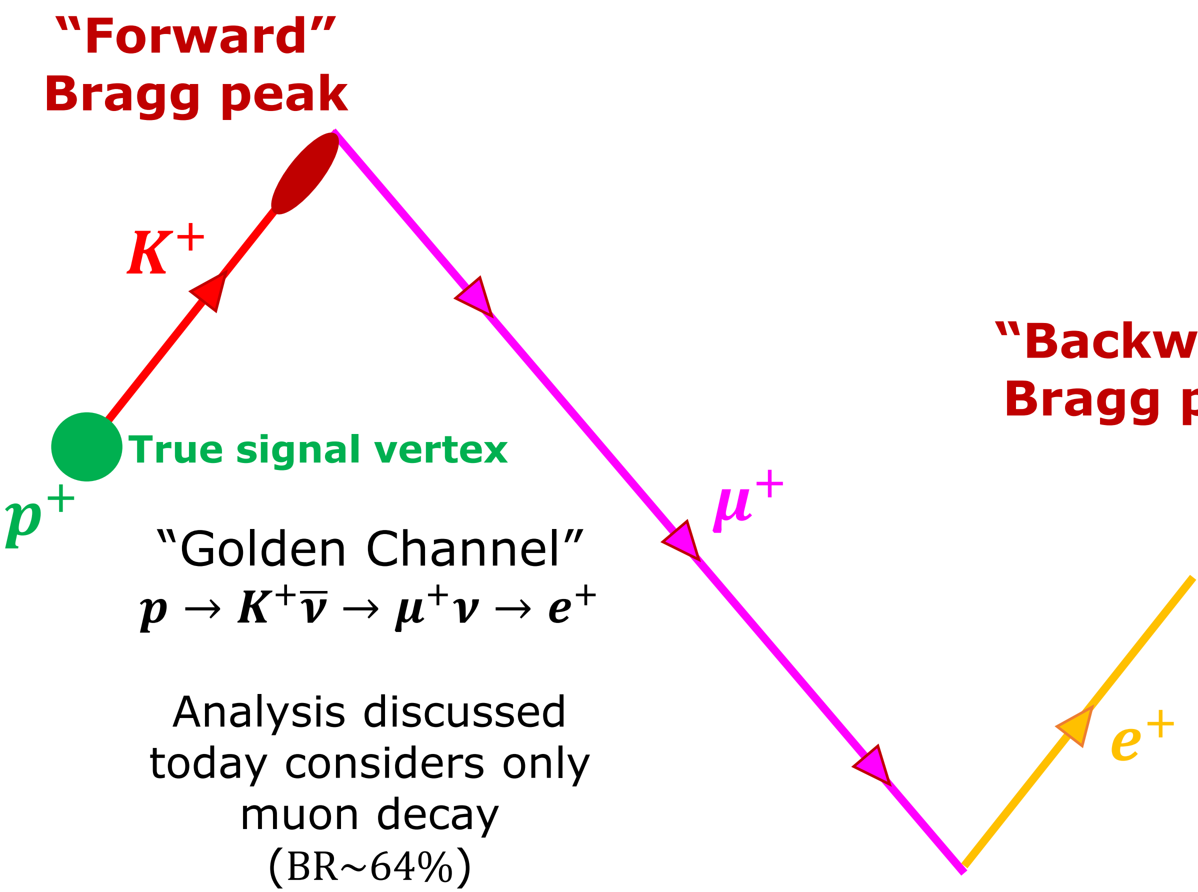
From GUTs and Supersymmetric GUTs



Considered $p \to K^+\bar{\nu}$ Event Topologies

Opens Doors to Deep Learning Techniques

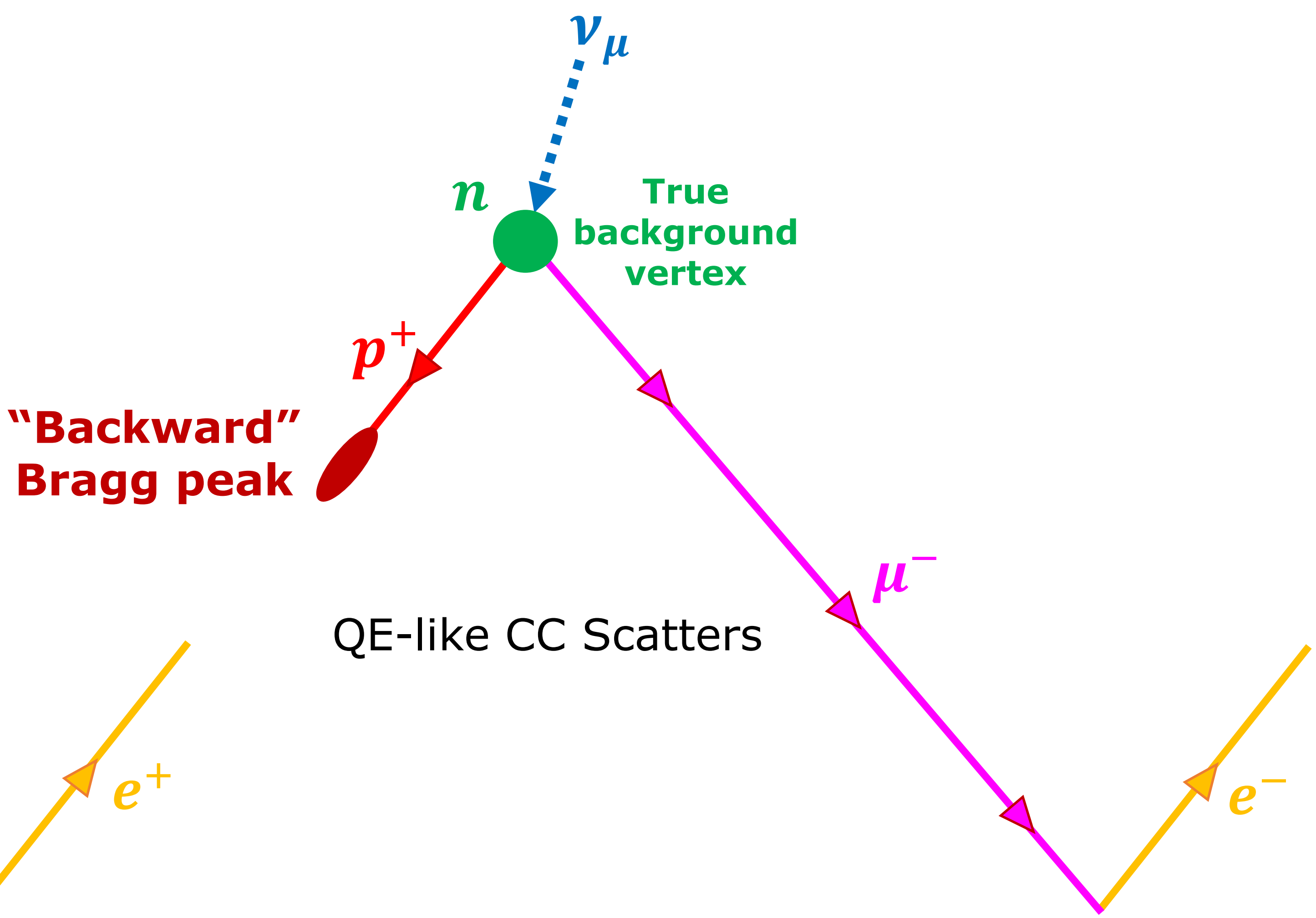
Signal



"Golden Channel"
$p \to K^+\bar{\nu} \to \mu^+\nu \to e^+$

Analysis discussed today considers only muon decay (BR~64%)

Background



QE-like CC Scatters

Considered $p \to K^+\bar{\nu}$ Event Topologies

Opens Doors to Deep Learning Techniques

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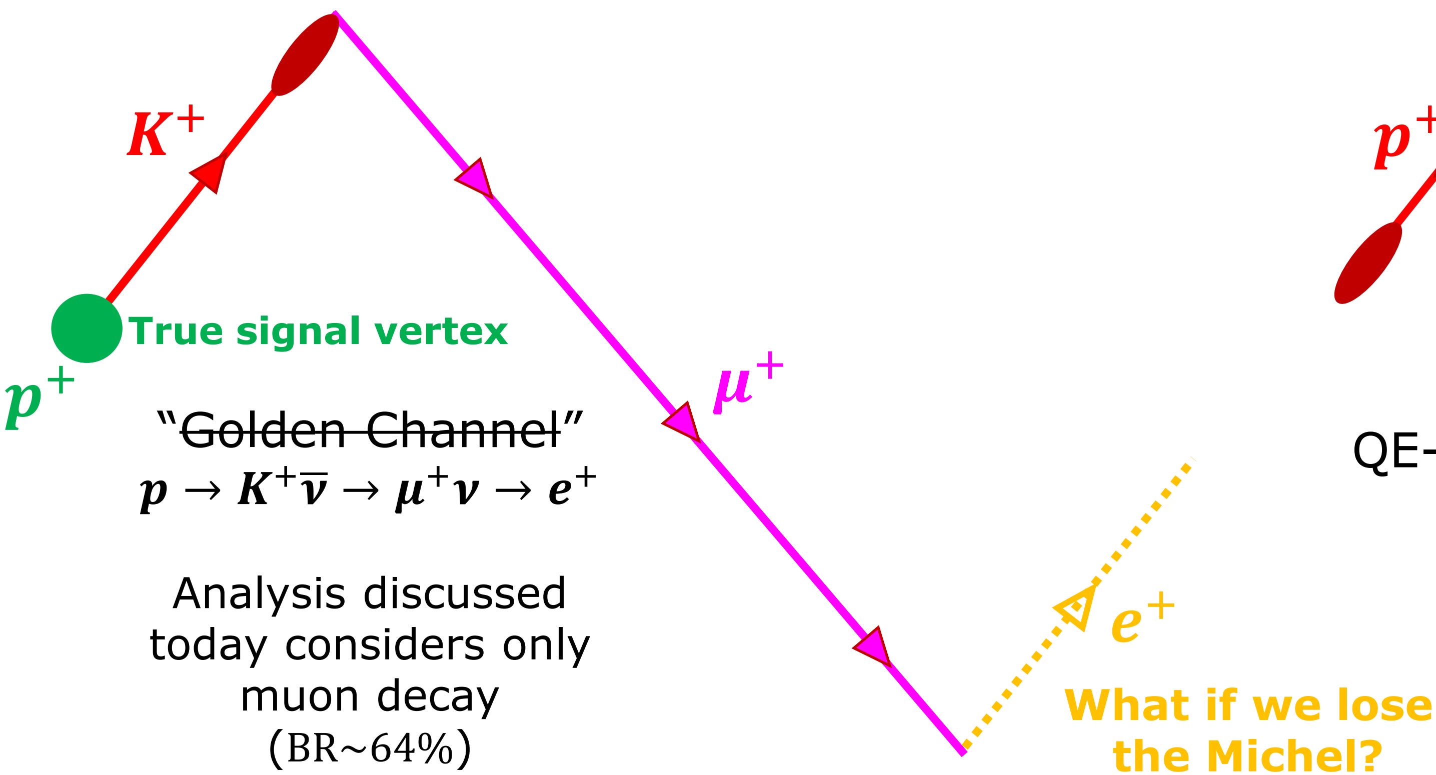

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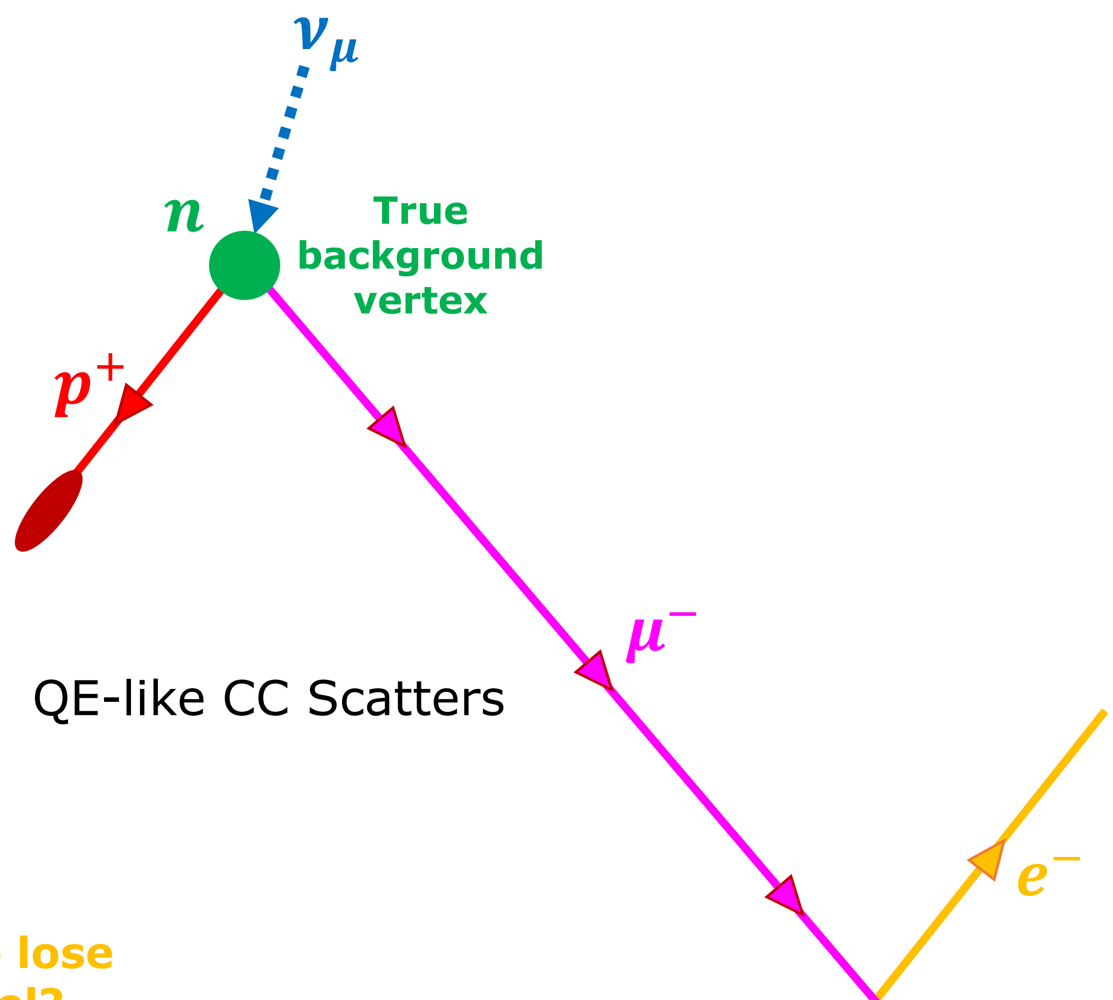

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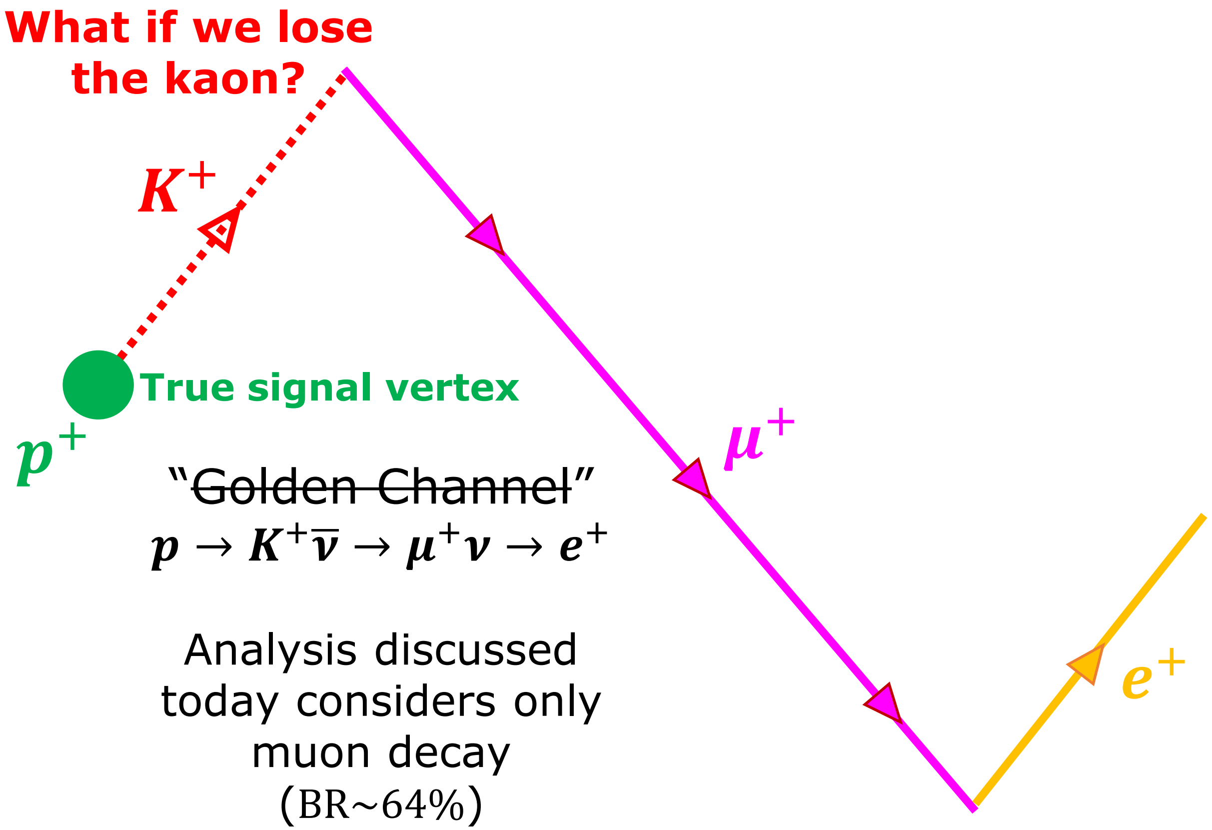

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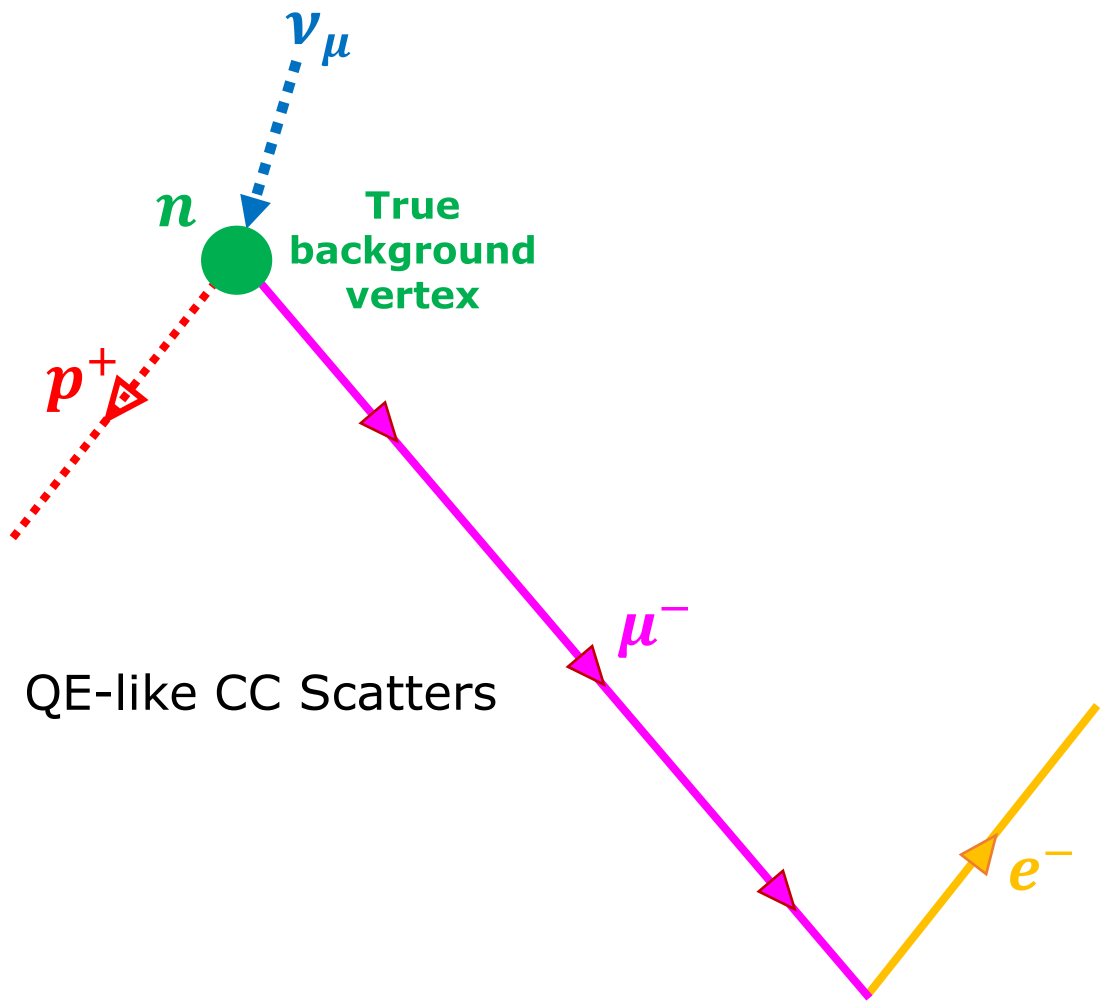


QE-like CC Scatters

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

Adapted from T. Stokes

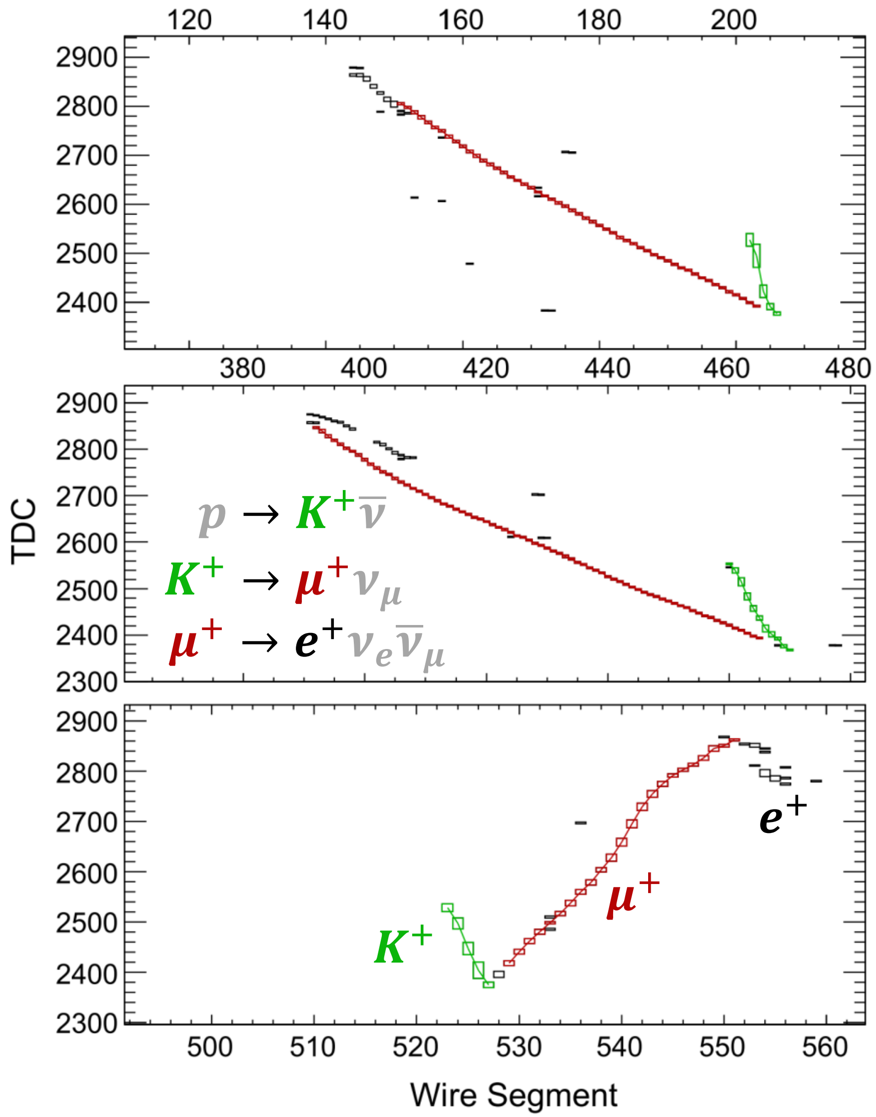
PDK Event Displays

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

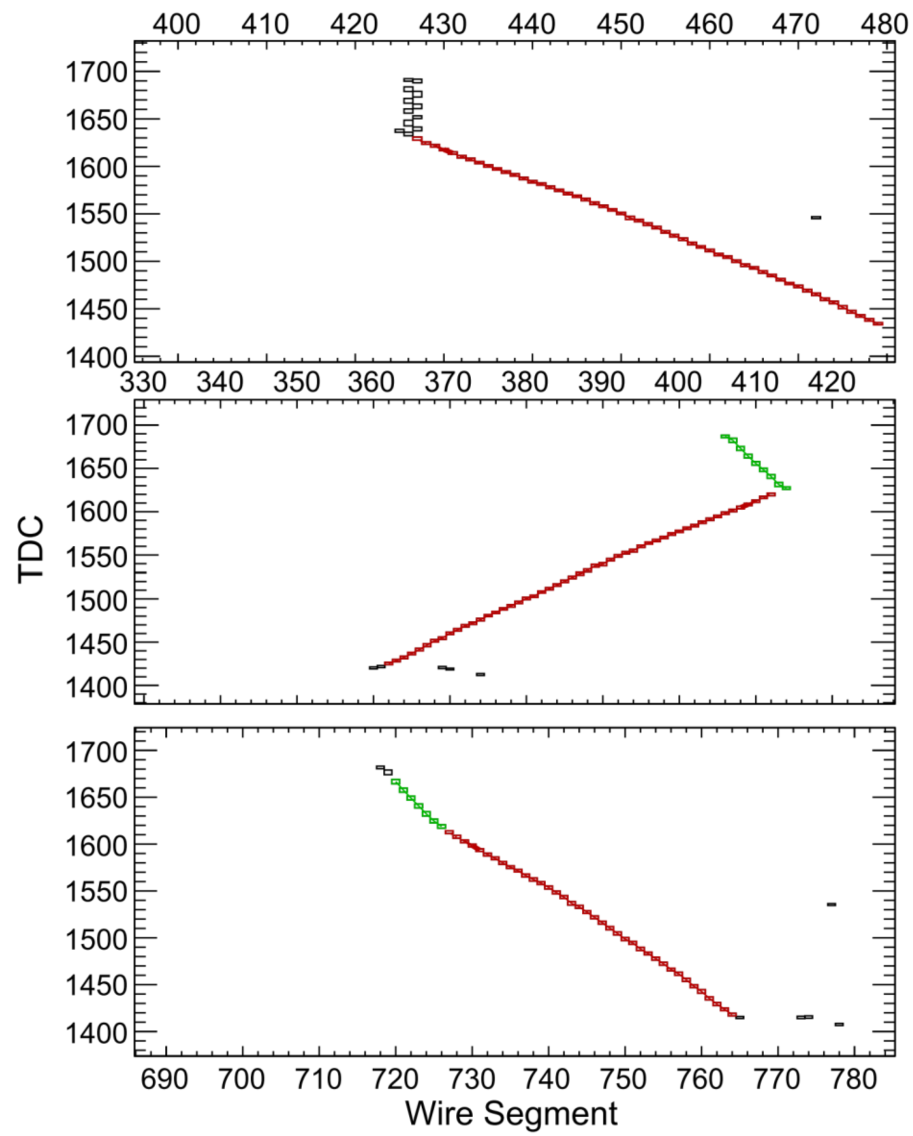
Collection

Induction 2

Induction 1



Signal-like True Atmospheric ν



Collection

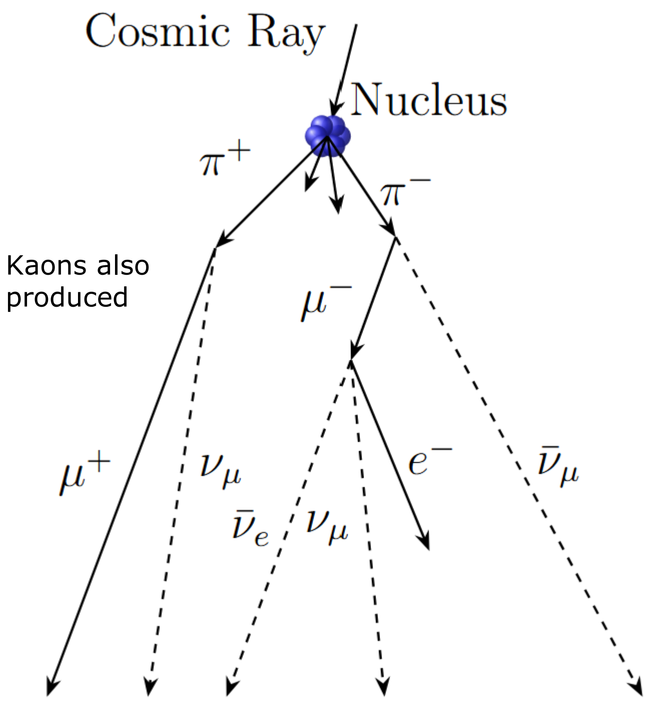
Induction 2

Induction 1

Atmospheric Neutrinos Analysis Progress

Atmospheric Neutrino Physics

A Most Brief Overview



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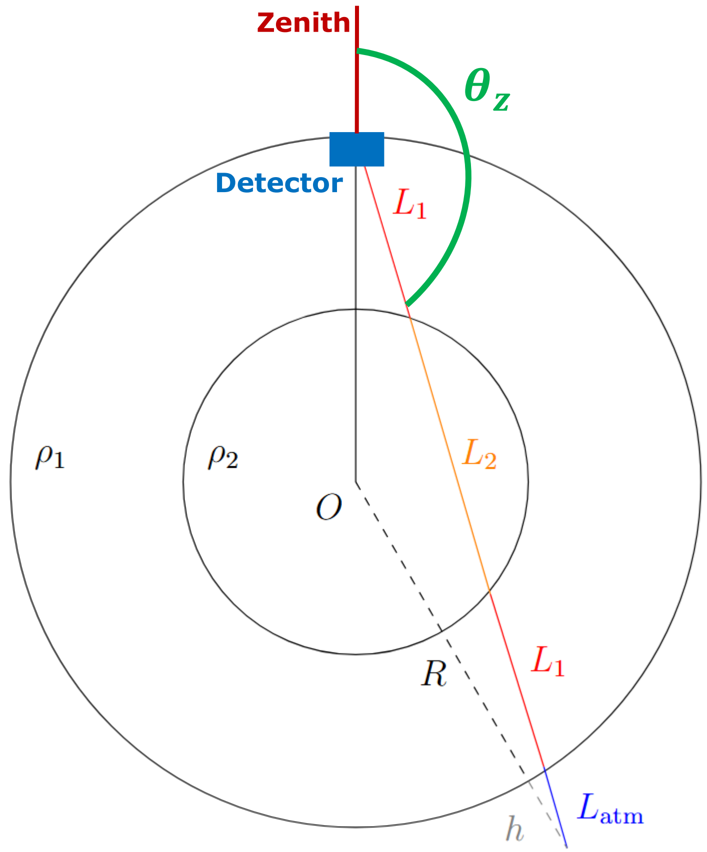
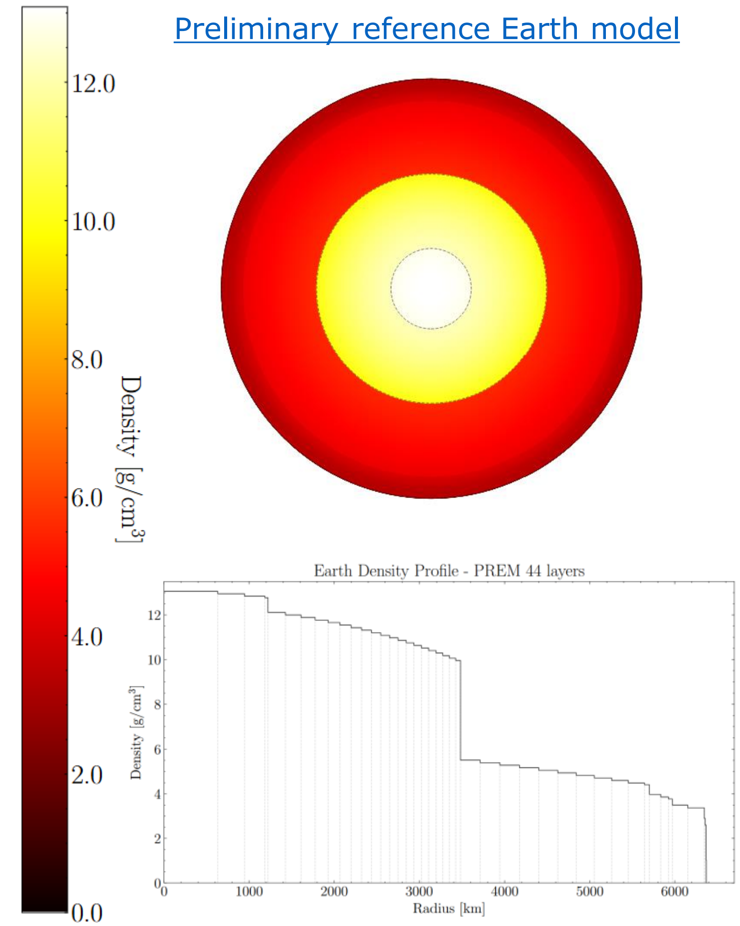


$$L_{tot} = \sqrt{(R+h)^2 - R^2 \sin^2(\pi - \theta_z)} + R\cos(\pi - \theta_z)$$

Preliminary reference Earth model



E_ν

PMNS: δ_{CP}	PMNS: θ_{23} Mass Ordering	Sterile ν Oscillations	…astrophysics…

0.1 GeV — **1 GeV** — $\lesssim$ **10 GeV** — **100 GeV** — *… and beyond*

Figures adapted from M. Oliveira-Ismerio, physics scale visualization adapted from P. Granger

Atmospheric Neutrino Physics

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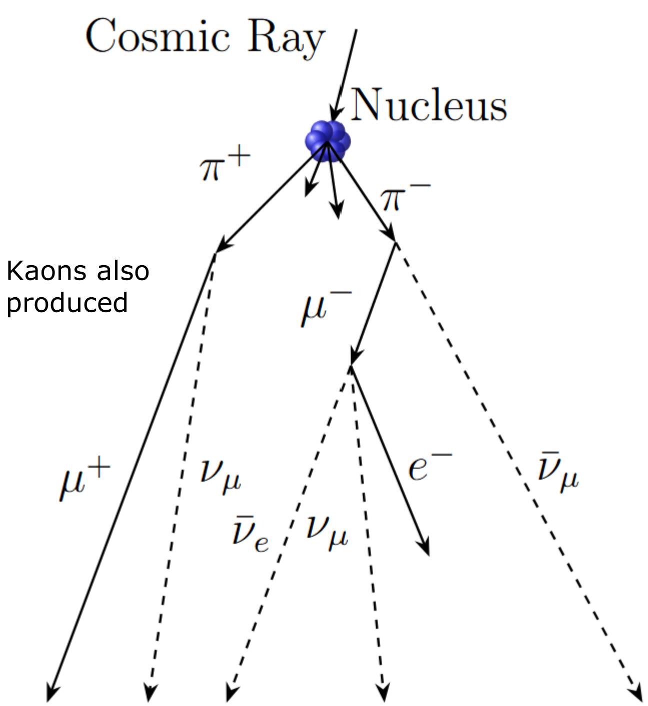

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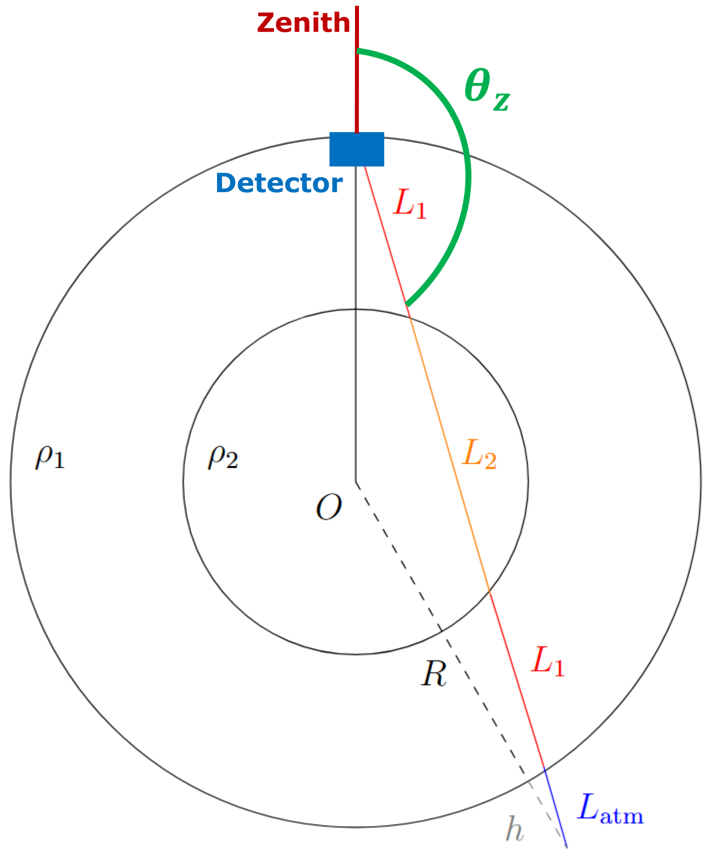

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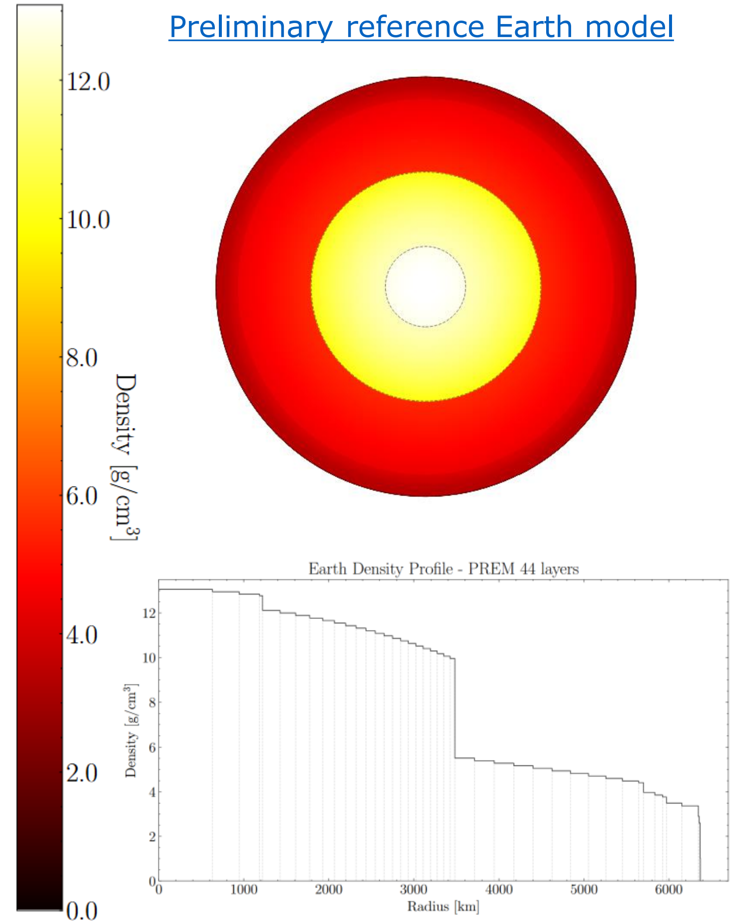

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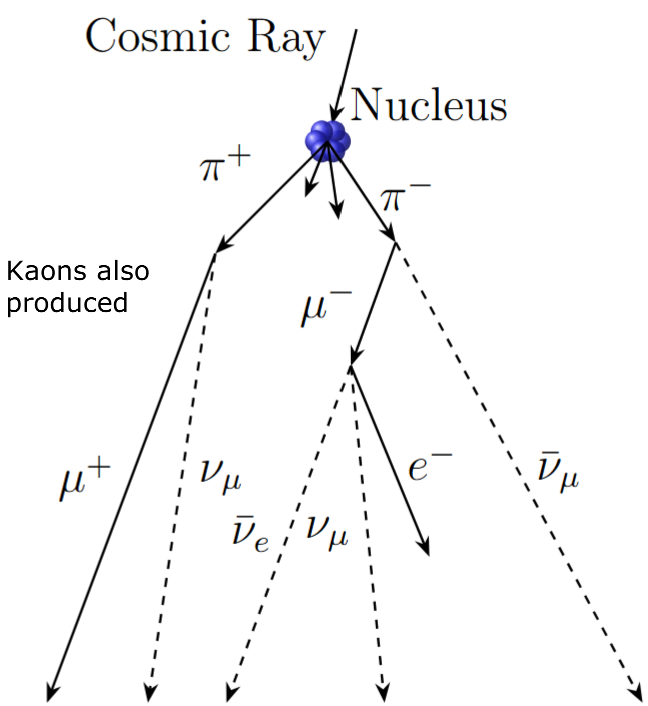

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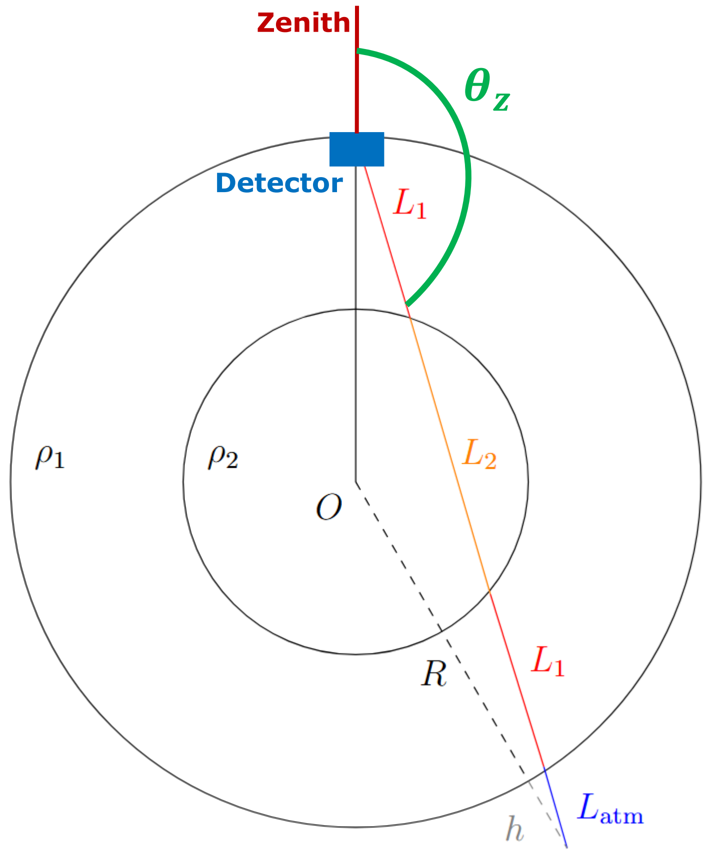

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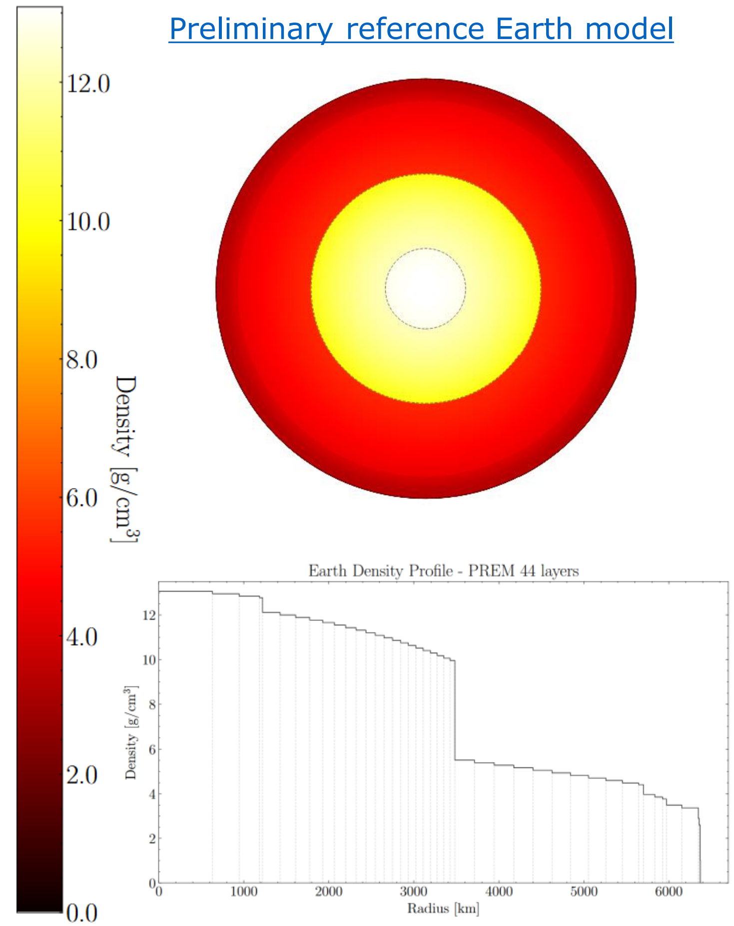

E_ν

0.1 GeV – 1 GeV	1 GeV – $\lesssim$ 10 GeV	$\lesssim$ 10 GeV – 100 GeV	100 GeV – … and beyond
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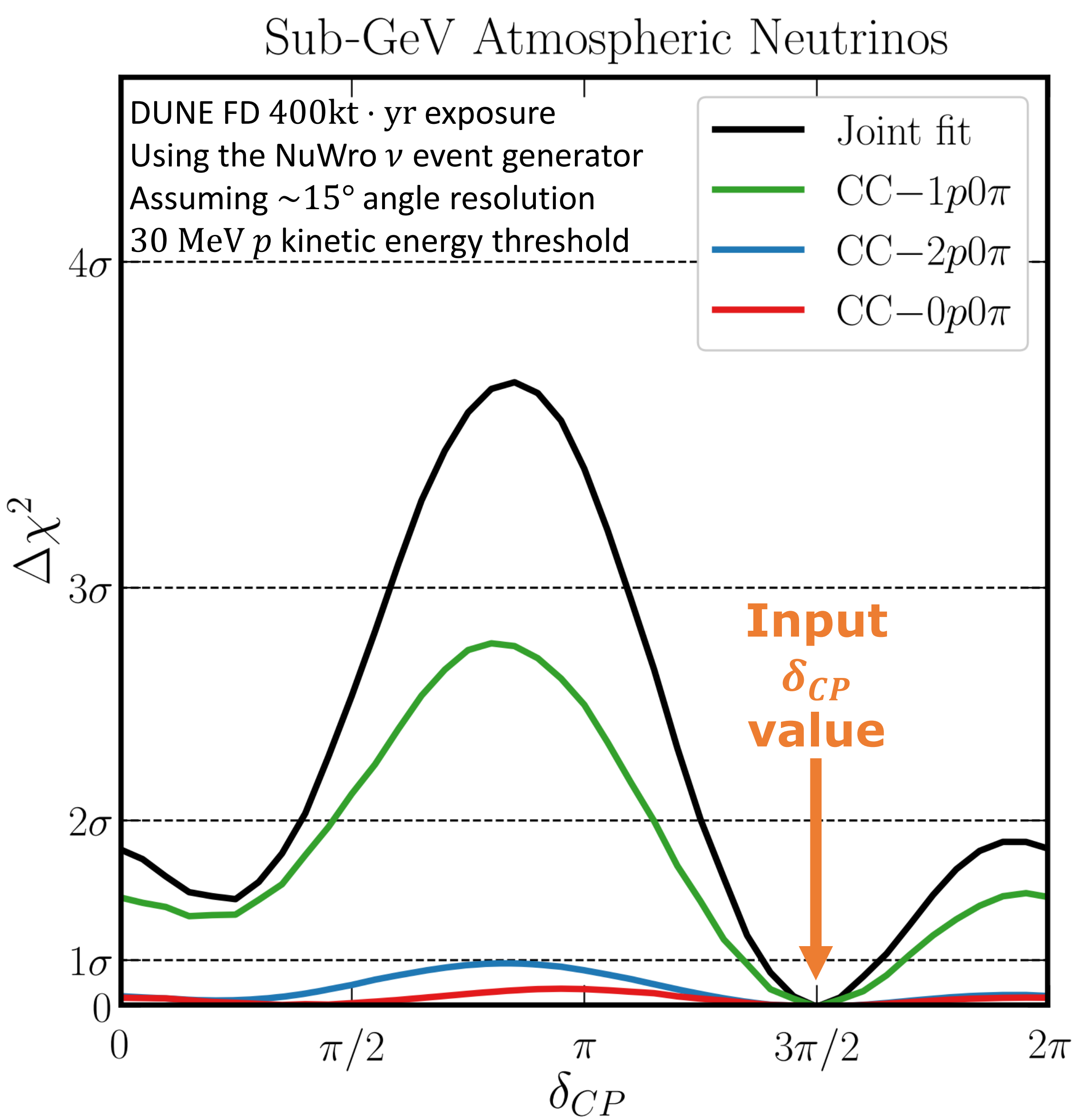
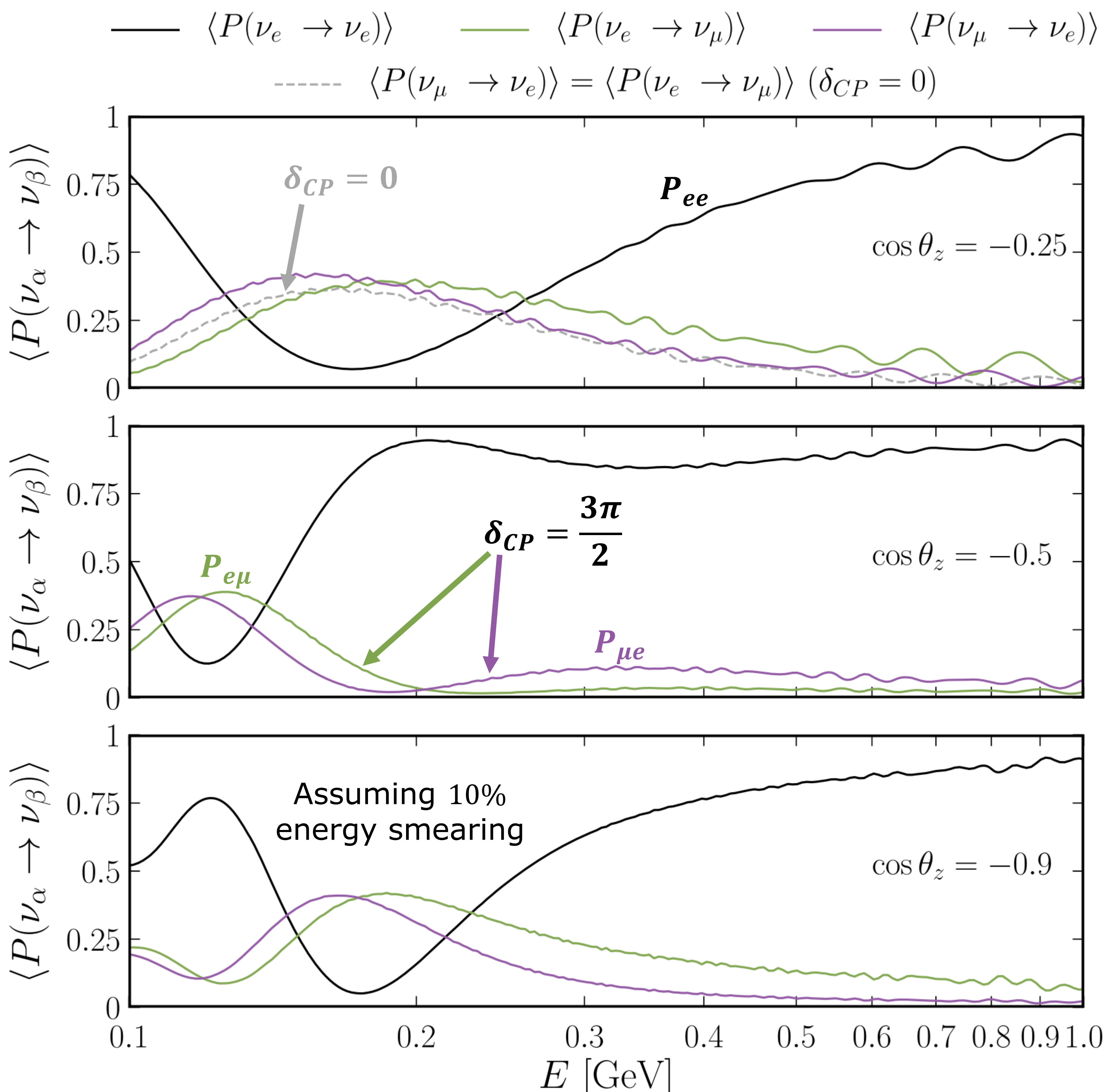
Atmospheric ν Oscillation Promise



- Atmospheric νs are both…
  - **Primary Rare Processes' background**
  - Valuable ν oscillation physics signal
    - Many baselines, many energies
    - DUNE capable in $< 1\text{GeV}$ reconstruction
- 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 A&EWG members
    - Could improve ν_{atm} and even ν_{beam} reconstruction

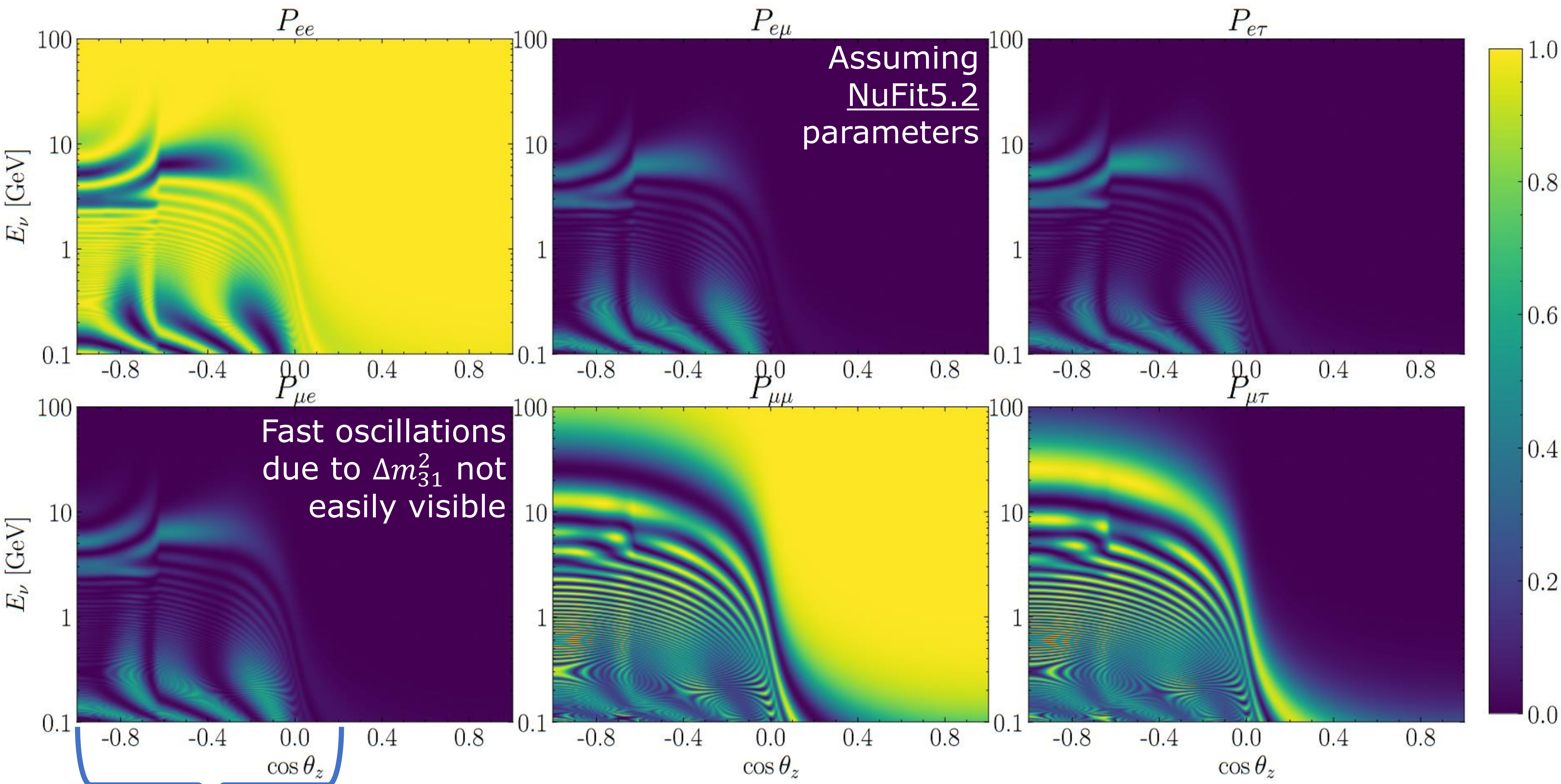
Sub-GeV Atmospheric Neutrinos and CP Violation in DUNE



Sub-GeV Atmospheric Neutrinos and CP Violation in DUNE

Accessing low energy ν_{atm} events with hadron-rich final states gives more importance to low energy ν_{atm} flux predictions

⇒ Large systematic uncertainties



Improving angular resolution is a must for sub-GeV oscillation sensitivity

Figure from M. Oliveira-Ismerio, physics scale visualization adapted from P. Granger

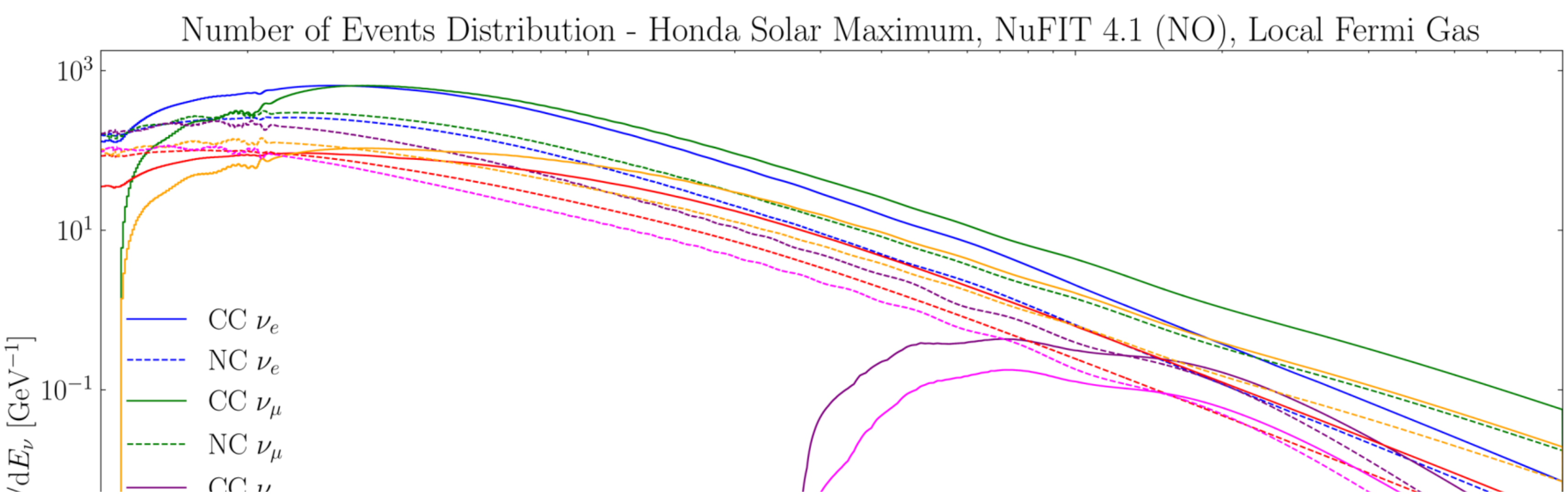
Atmospheric Spectra at Homestake

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 $\nu_\tau/\bar{\nu}_\tau$ expectations

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

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



Totals per 10 kt · yr

	Solar Maximum, NuFIT 4.1 (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		
	CC	NC	Total	CC	NC	Total	CC	NC	Total	CC	NC	Total
ν_e	387.5	144.4	532.0	219.5	69.6	289.1	13.63	4.3	17.9	620.7	218.3	839.0
ν_μ	393.5	173.2	566.7	318.3	103.4	421.7	41.35	13.0	54.4	753.2	289.6	1042.8
ν_τ	0.0	95.4	95.4	2.4	36.7	39.1	4.23	3.3	7.5	6.6	135.4	142.0
$\bar{\nu}_e$	60.9	46.5	107.4	57.3	24.1	81.4	4.46	1.7	6.2	122.7	72.3	194.9
$\bar{\nu}_\mu$	74.3	67.1	141.4	102.5	44.1	146.6	14.93	5.7	20.7	191.7	116.9	308.7
$\bar{\nu}_\tau$	0.0	39.2	39.2	0.9	16.0	16.9	1.54	1.4	3.0	2.4	56.7	59.1
Total	916.2	565.9	1482.1	700.9	293.8	994.8	80.1	29.4	109.58	1697.3	889.2	2586.5

Rates already being used in current BNV studies

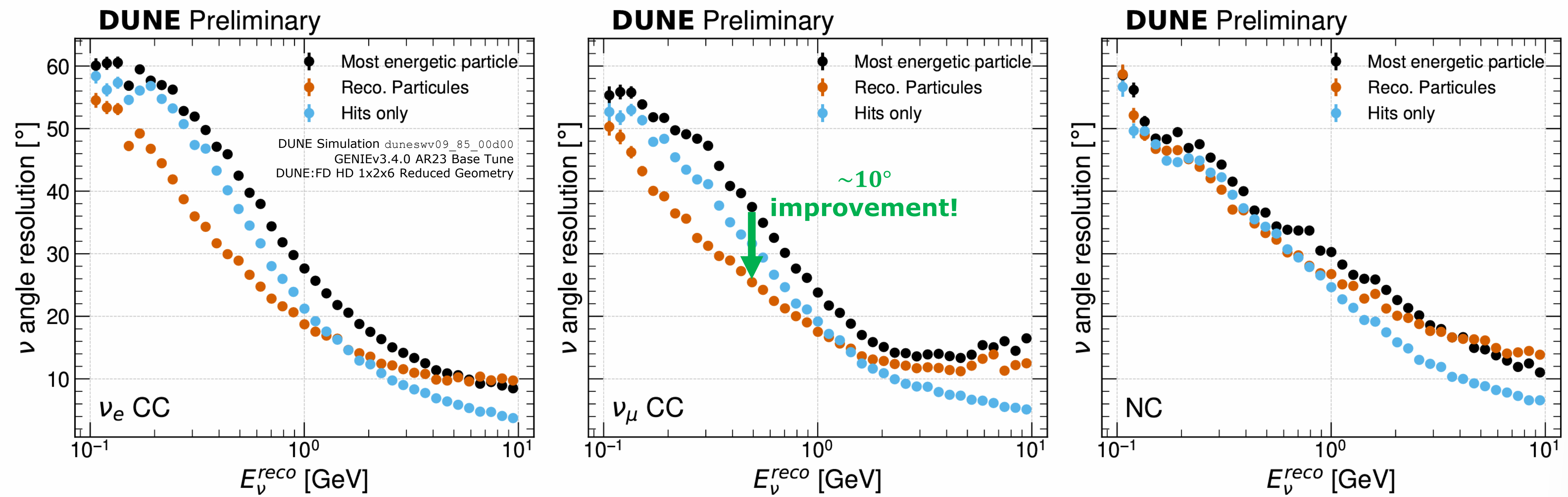
M. Oliveira-Ismerio

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 complete (15M)
  - Lead by P. Granger (CERN) and S. Farrell (Rice) *et al.*
- Reconstruction techniques across energies—**under review!**
  - Lead by APC & CERN groups (kinematics), Rice (process identification)
  - Optimizing tools will inform first publication's energy range and analysis target
  - Improved angular reconstruction $< 1\text{GeV}$ can greatly empower δ_{CP} sensitivity
  - Near future: ML-powered energy and angle estimation for oscillations
- MaCh3 atmospheric ν oscillation framework ready to go (Oxford, Imperial, APC)
  - Lead by D. Barrow (Oxford) *et al.*
  - Systematics inputs under development for full analysis—cross section systematics needed!
  - Updated FLUKA (P. Sala *et al.*) simulation in process!



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

Understanding Nuclear Modeling Systematics in Rare Processes

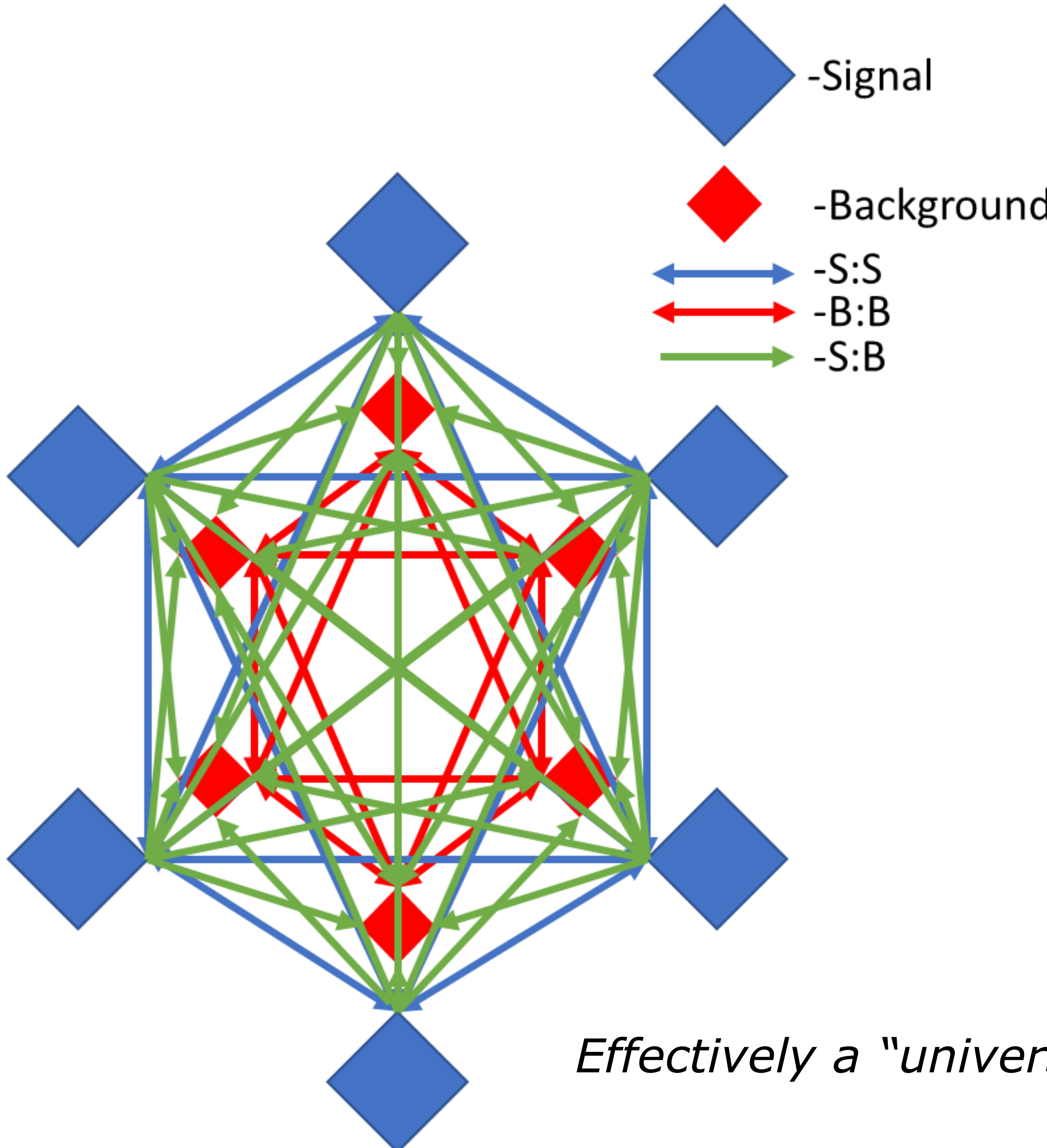
Nuclear Model Configuration Comparative Flows

Signal & Background Sample Comparisons to Better Determine Modeling Systematics

S:S	hA_BR	hA_LFG	hA_E SF	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_E SF	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" style approach

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

Final State Interactions

Two main GENIE intranuclear cascades:

1. **hA2018** (single *effective* interaction simulation)
   - Table based method
     - Hadron+nucleus data→final state prediction
   - **Reweightable**, conserves total cross section
     - Useful for systematics studies
   - No full step-by-step interaction modeling

2. **hN2018** (full intranuclear cascade simulation)
   - Models **stochastic** intranuclear interactions
   - Full stepped sequence of hadronic interactions

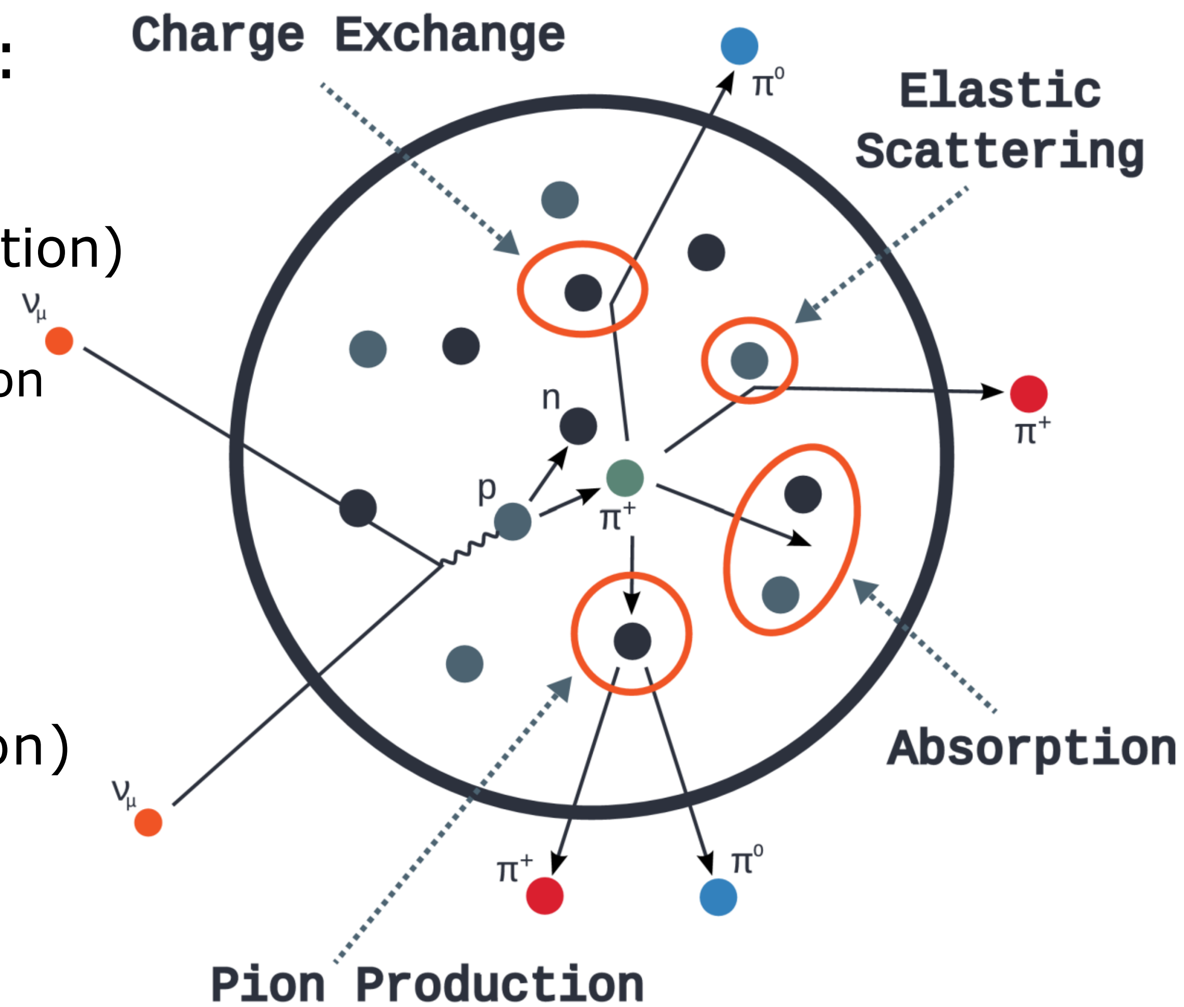
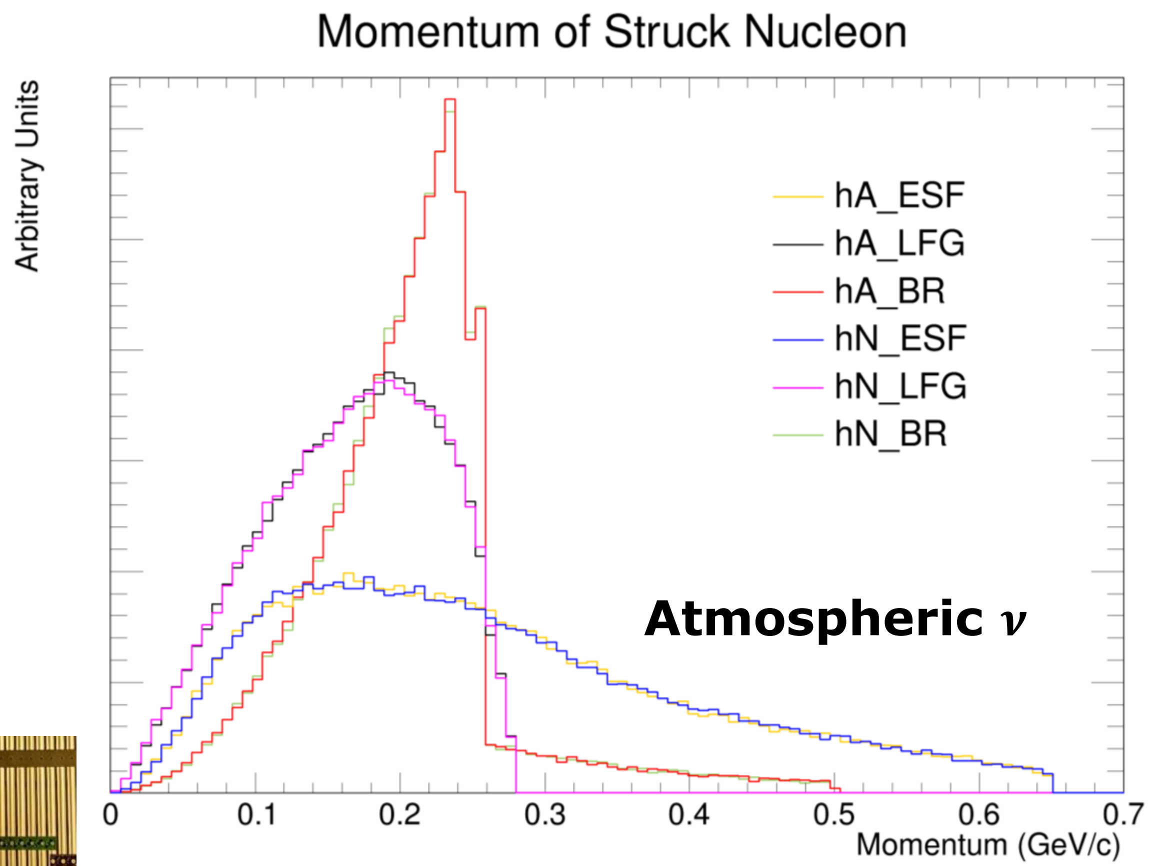
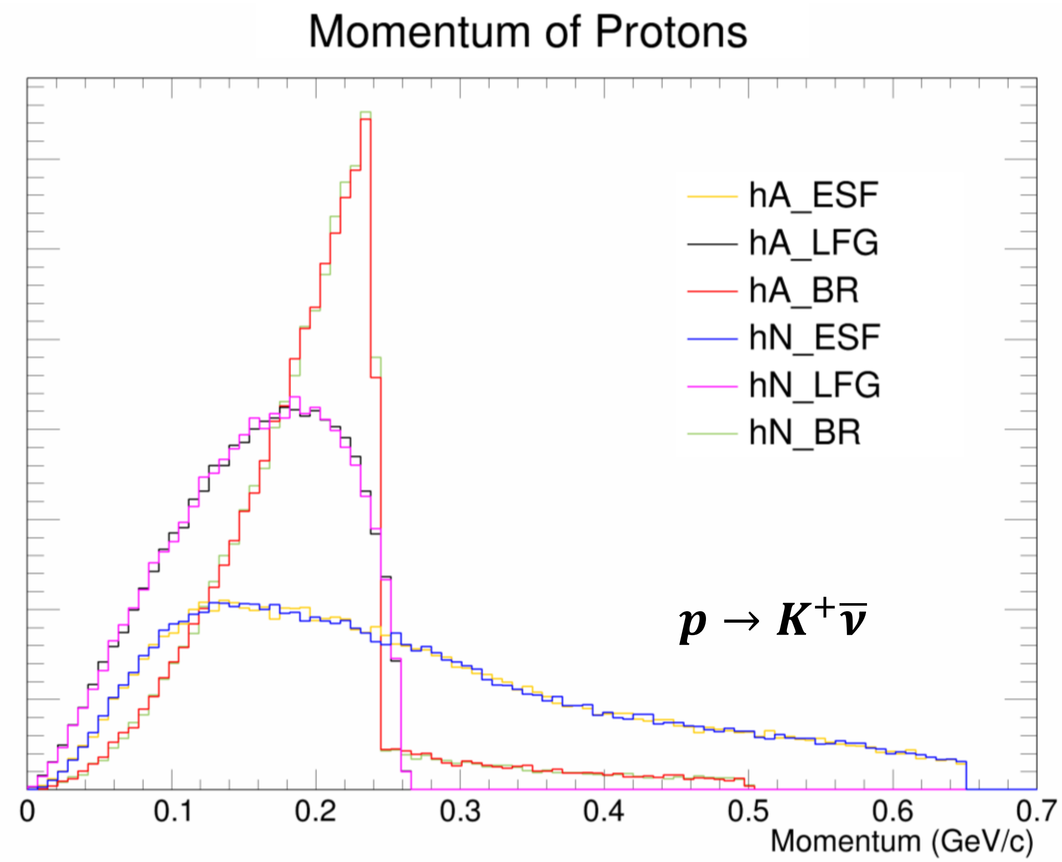


Figure courtesy of T. Golan

Initial Nucleon Momentum Distributions

Initial State Preparation for Atmospherics and $p \to K^+\overline{\nu}$ in GENIEv3.0.6





T. Stokes

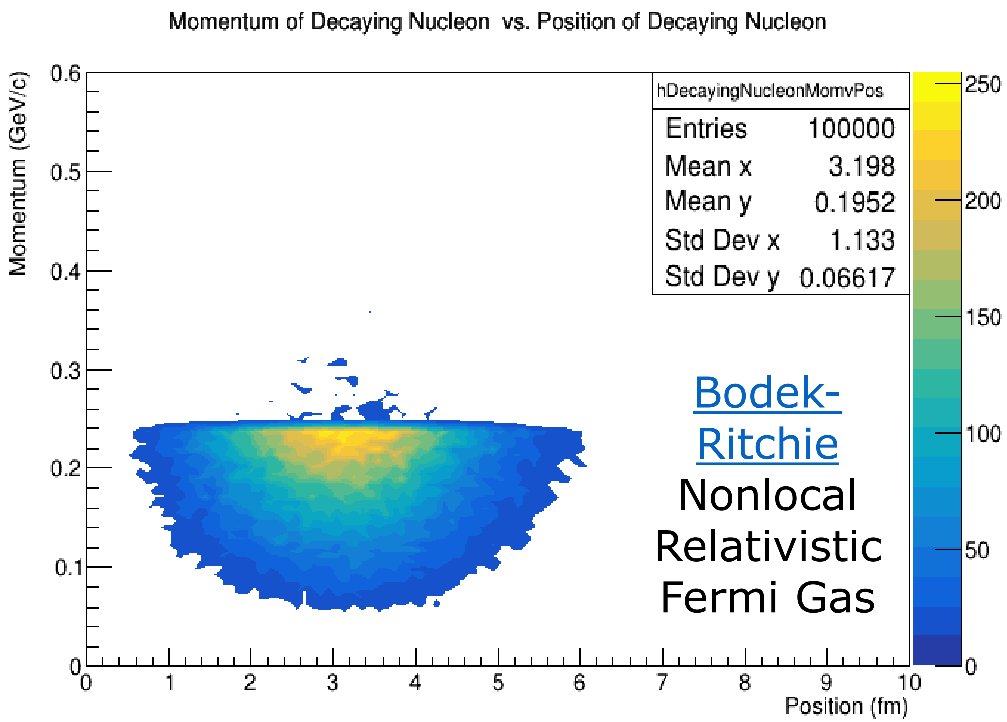
Bodek-Ritchie Nonlocal Relativistic Fermi Gas (red & green)

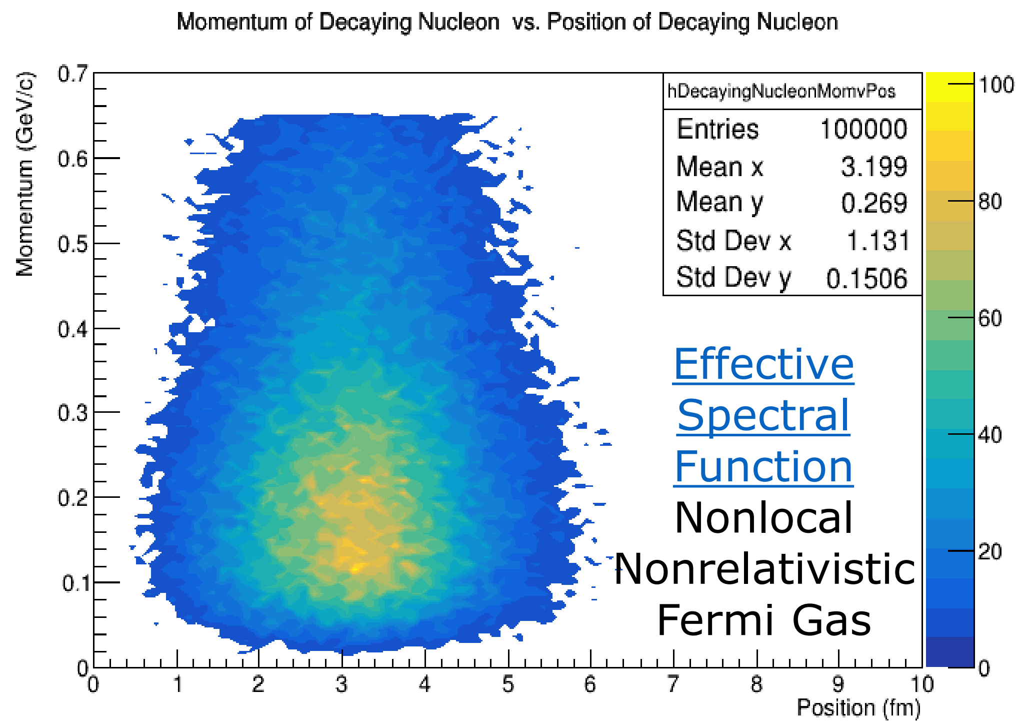
Effective Spectral Function Nonlocal Nonrelativistic Fermi Gas (blue & yellow)

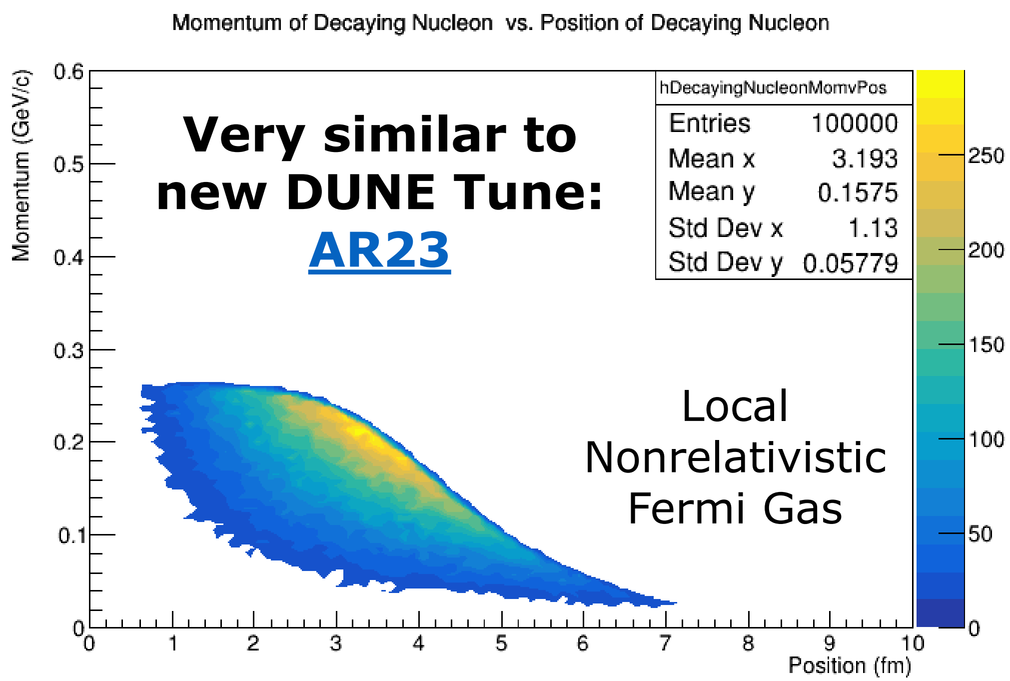
Local Nonrelativistic Fermi Gas (pink & black)

Initial Nucleon Momentum Distributions

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







Vastly different initial states can lead to different final states

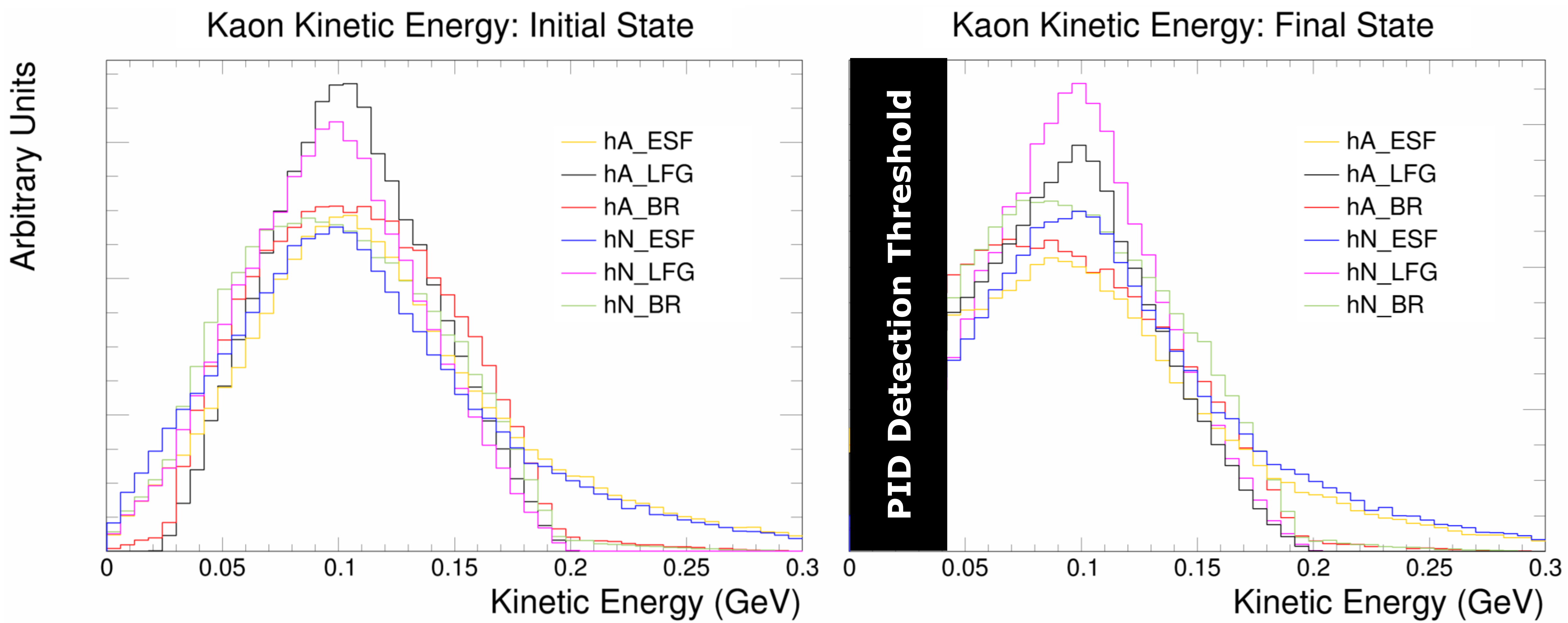
Different nuclear model assumptions can lead to softer FSI

→Better signal efficiency

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



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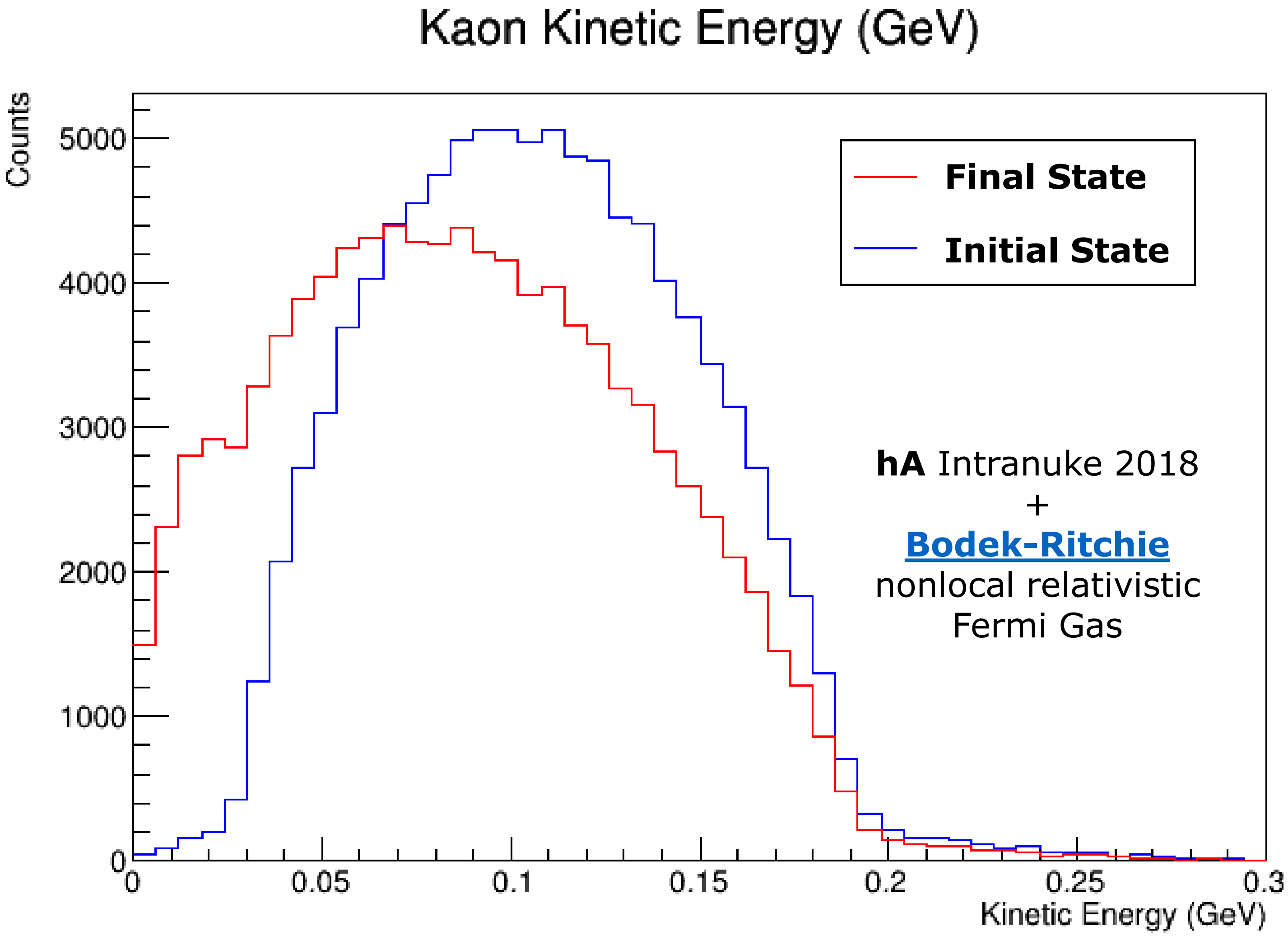

Lower final state K^+ momentum can adversely affect signal efficiencies

Must understand modeling systematics!

T. Stokes

Nuclear Modeling Effects on Kaon Energy

- K^+ generated directly from decaying p in nucleus
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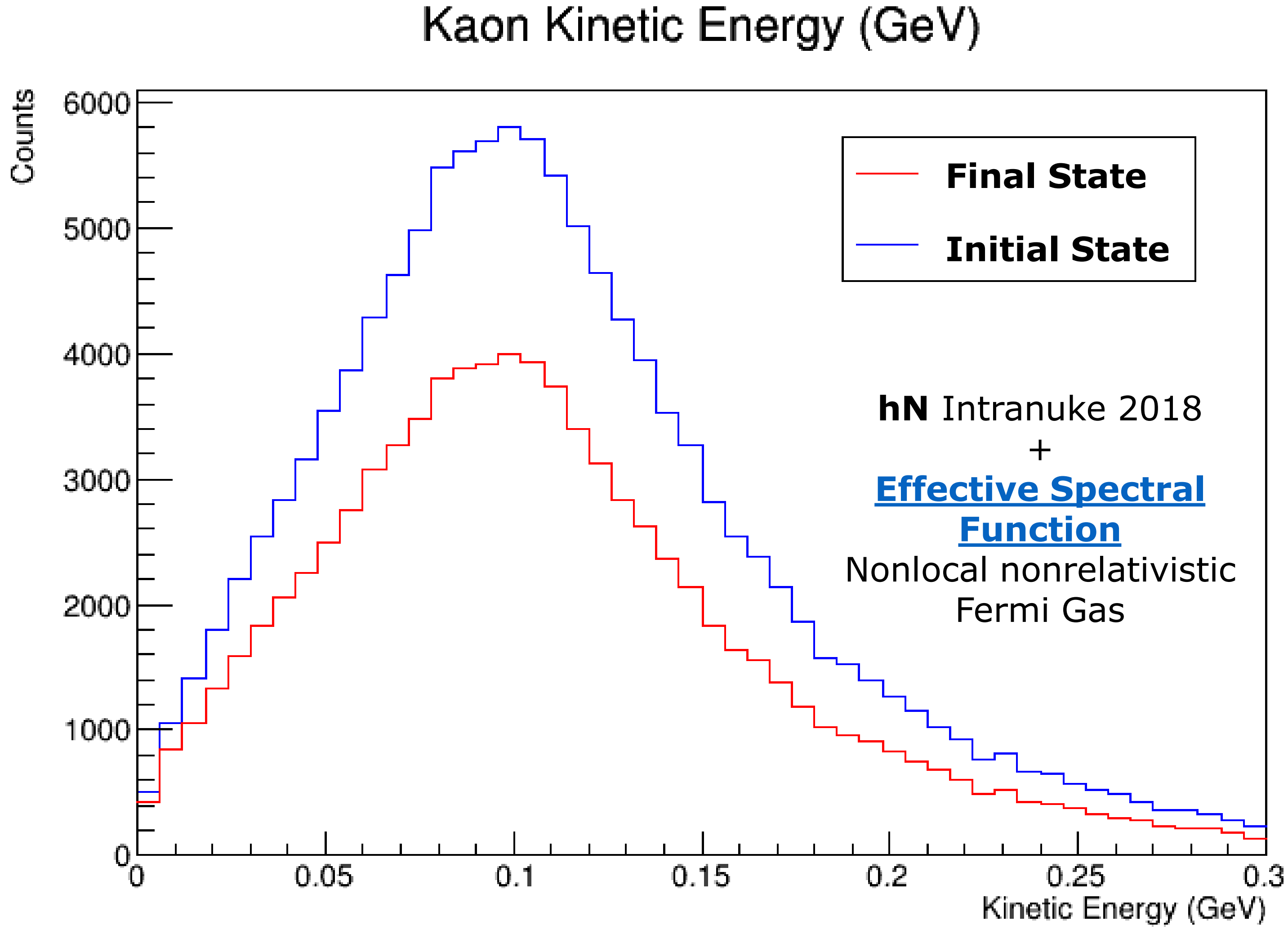
T. Stokes



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

Must understand modeling systematics!

Current $p \to K^+\overline{\nu}$ Analysis

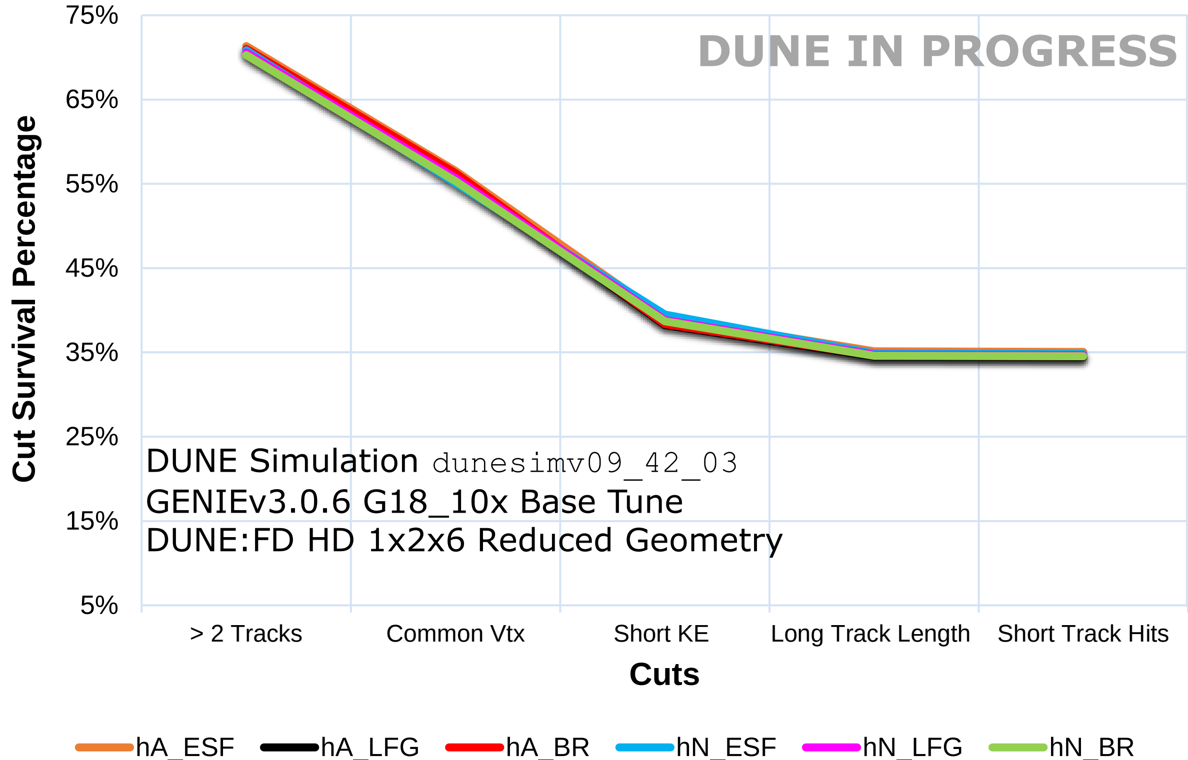
Preselection Cuts Before BDT Input

Improving PDK Signal Quality and Reducing Backgrounds

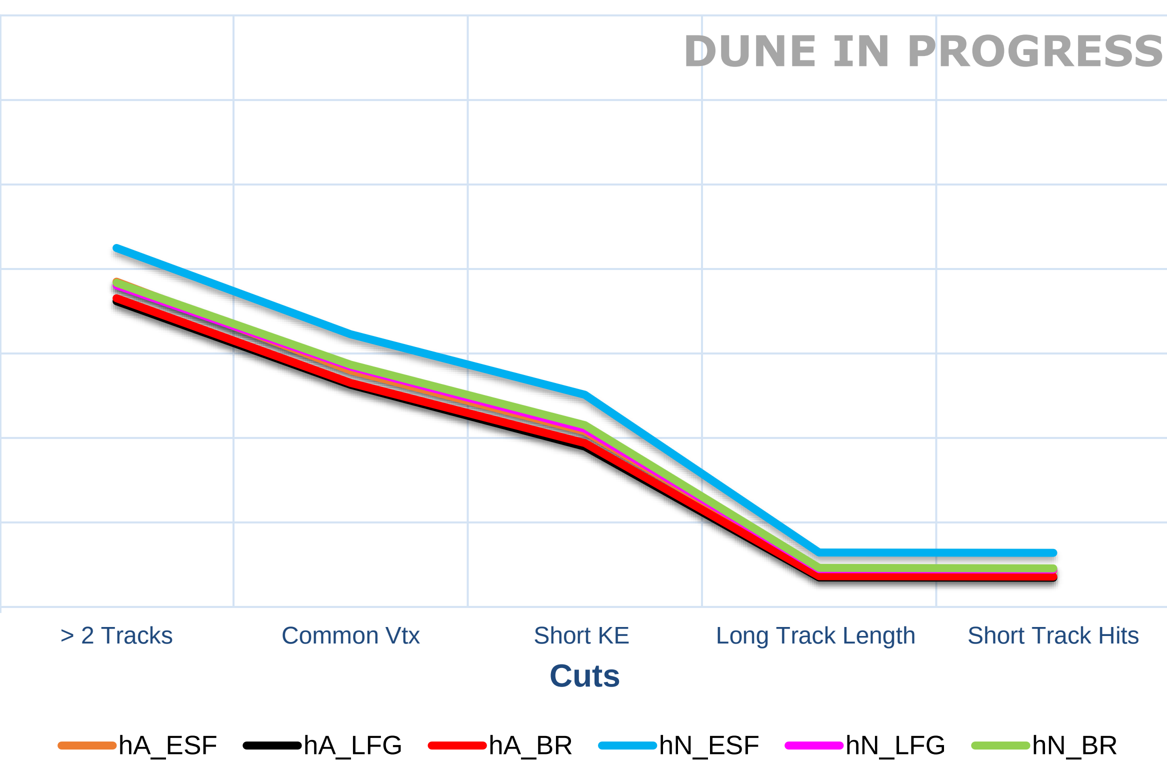
1. Minimum of two tracks per event
2. A common vertex between tracks, each within 5cm
3. Short track kinetic energy requirement, improves purity
4. Long track length of requirement, reduces backgrounds
5. Short track must contain min. numb. hits, improve dE/dx

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

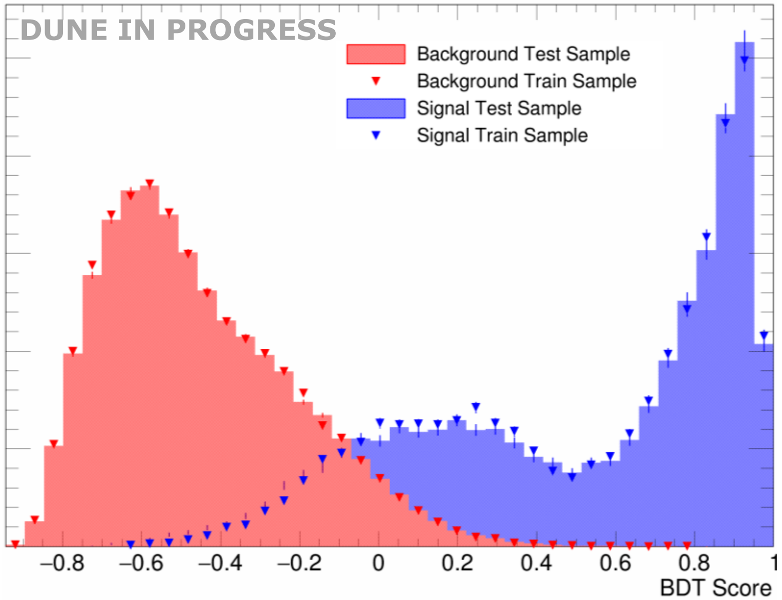
What you get:

- 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

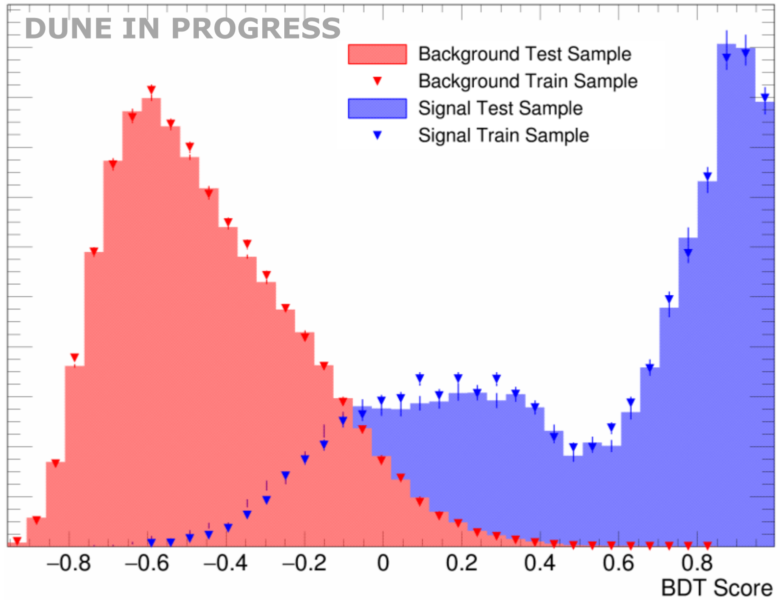
DUNE Simulation `dunesimv09_42_03`
GENIEv3.0.6 G18_10x Base Tune
DUNE:FD HD 1x2x6 Reduced Geometry

T. Stokes

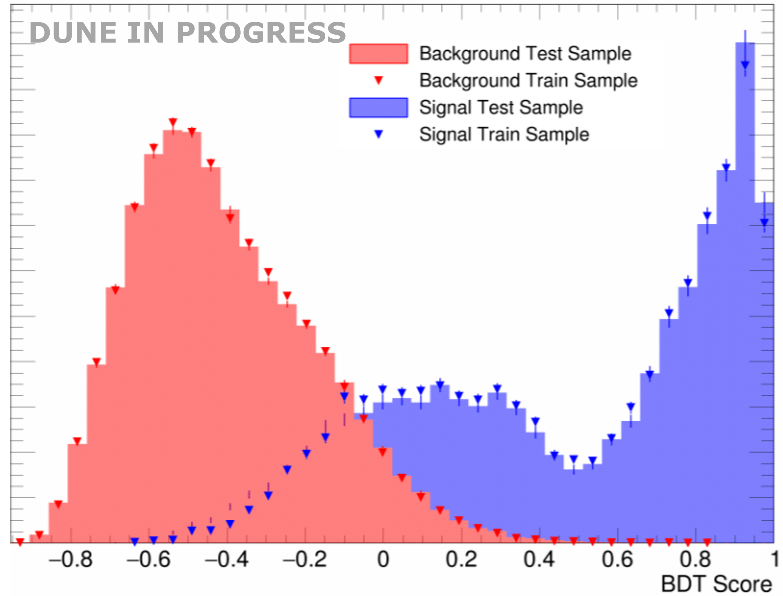
BDT Scoring: hA_LFG



BDT Scoring: hA_BR

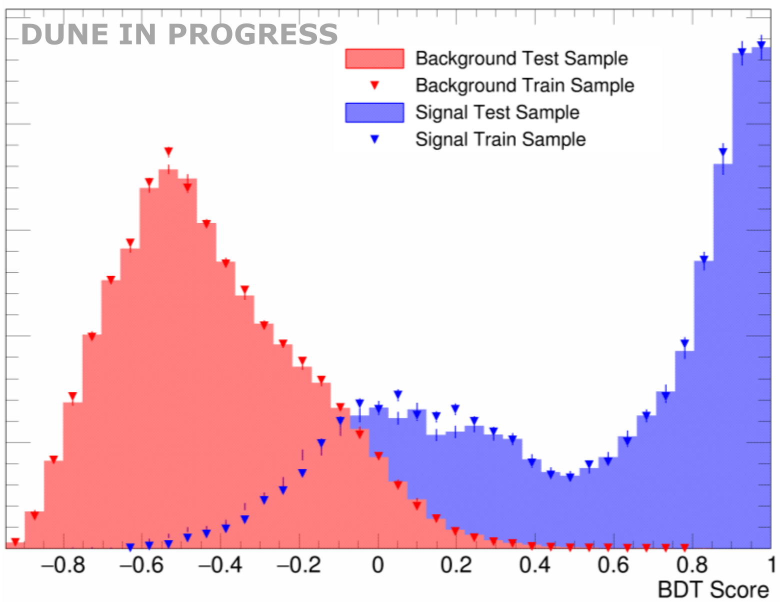


BDT Scoring: hA_ESF

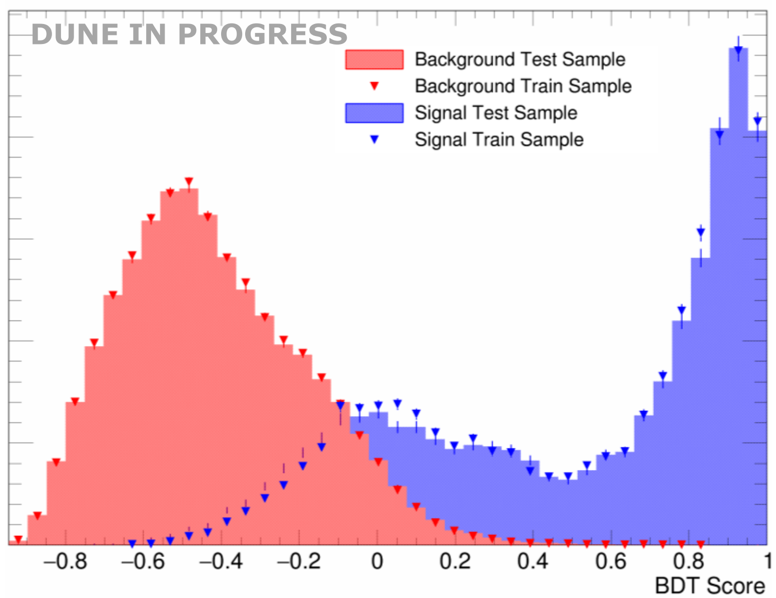


Good signal and background discrimination capabilities!

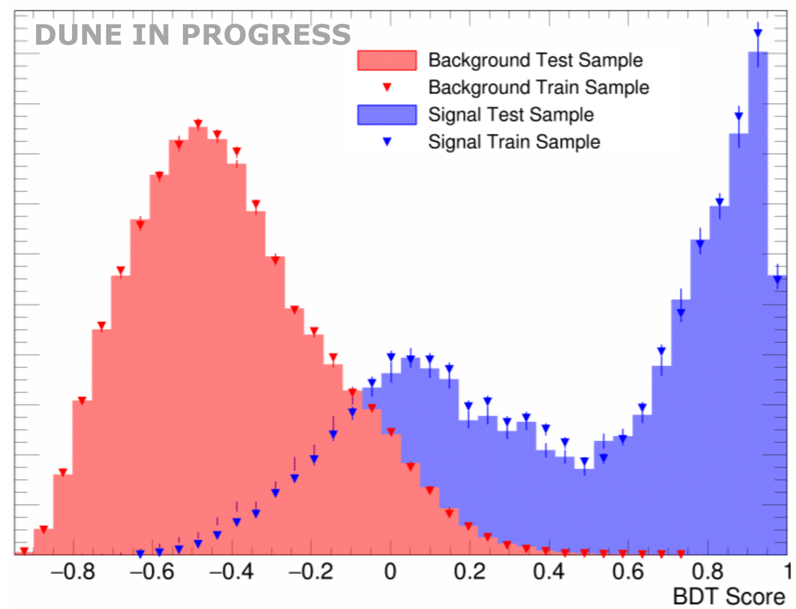
BDT Scoring: hN_BR



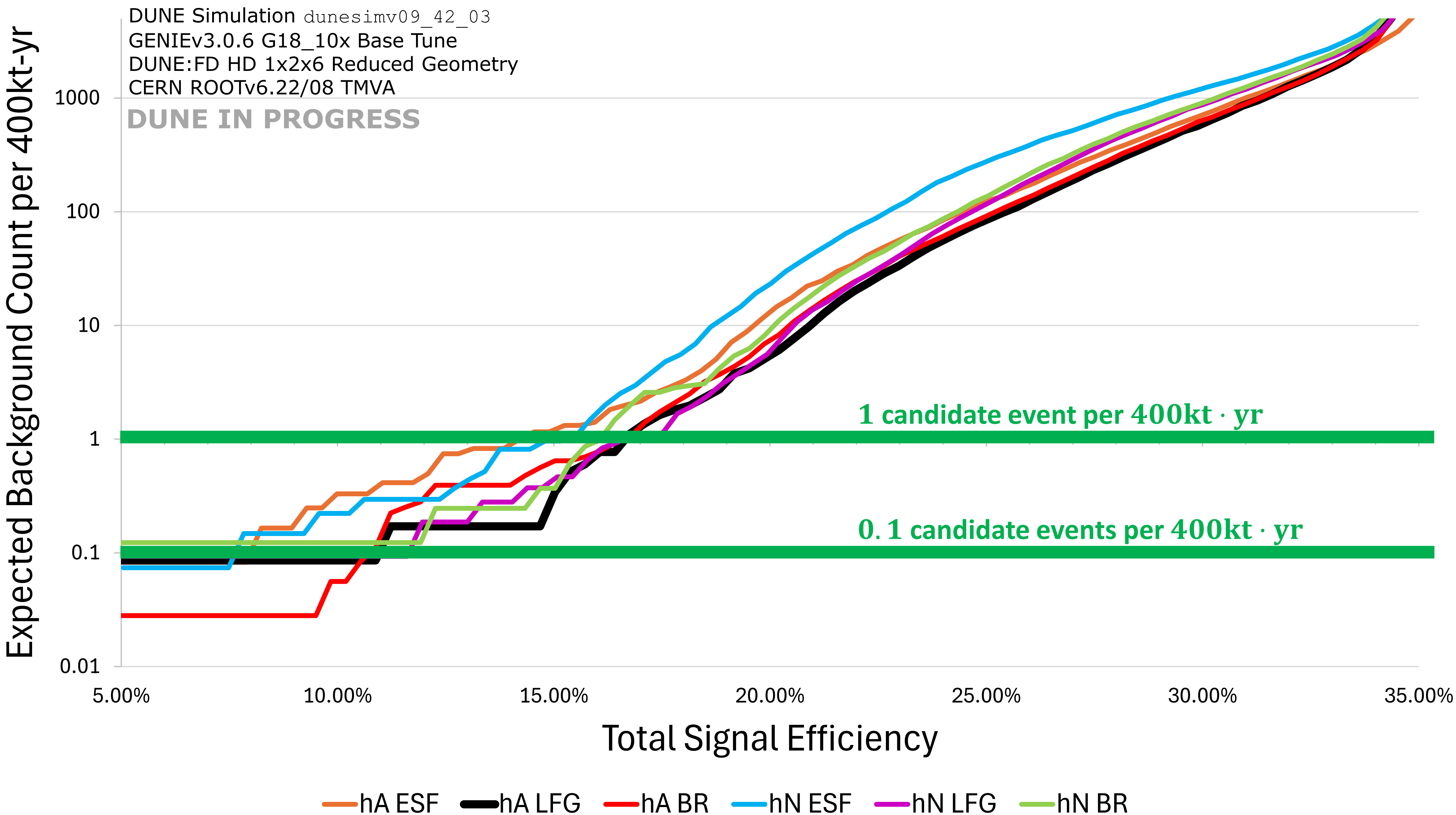
BDT Scoring: hN_LFG



BDT Scoring: hN_ESF



BDT ROC Curves from Testing Samples
Signal Efficiency vs. Expected Background Count
hA LFG BDT Parameter Optimized

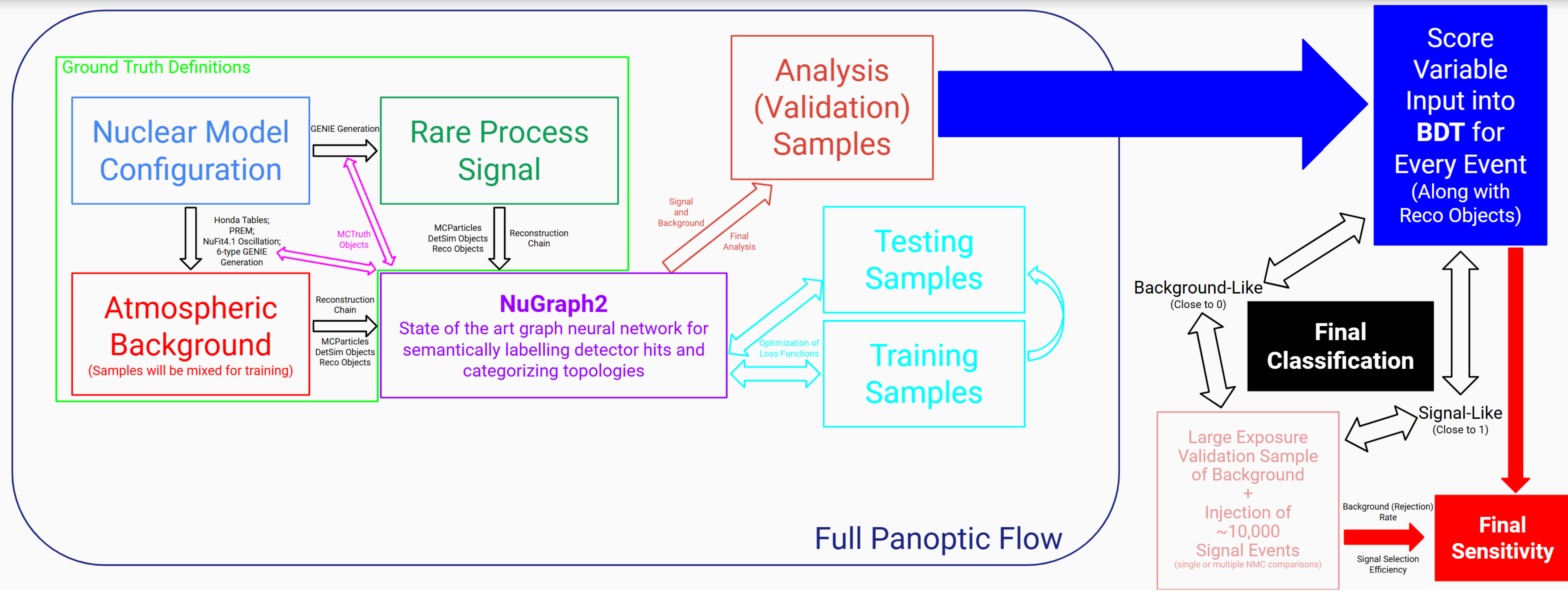


T. Stokes

Graphical Neural Network Methods for Baryon Number Violation

Analysis Flow
Using Automated Learning Techniques For Event-Level Classification

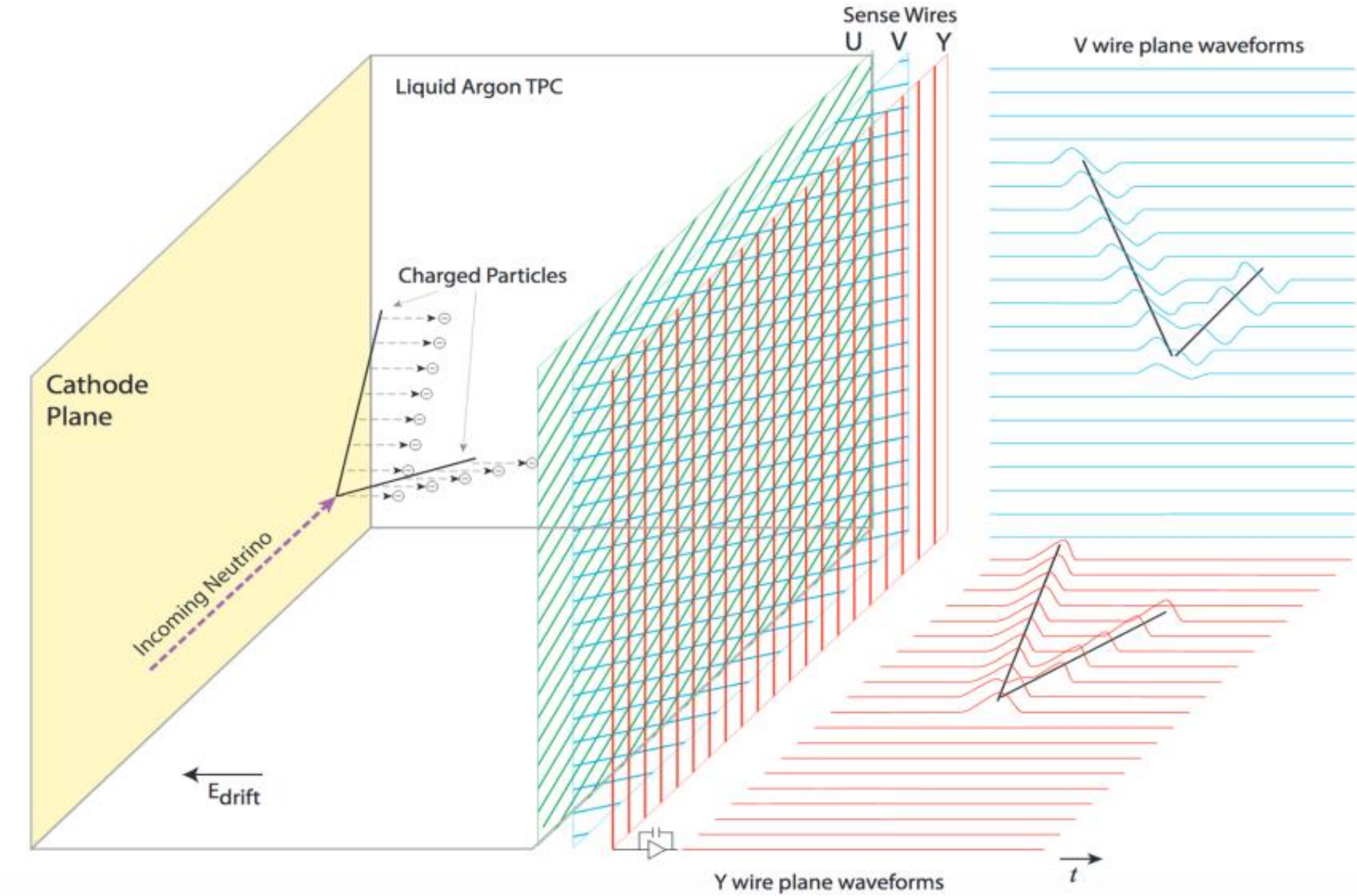
NuGraph, V Hewes *et al.*



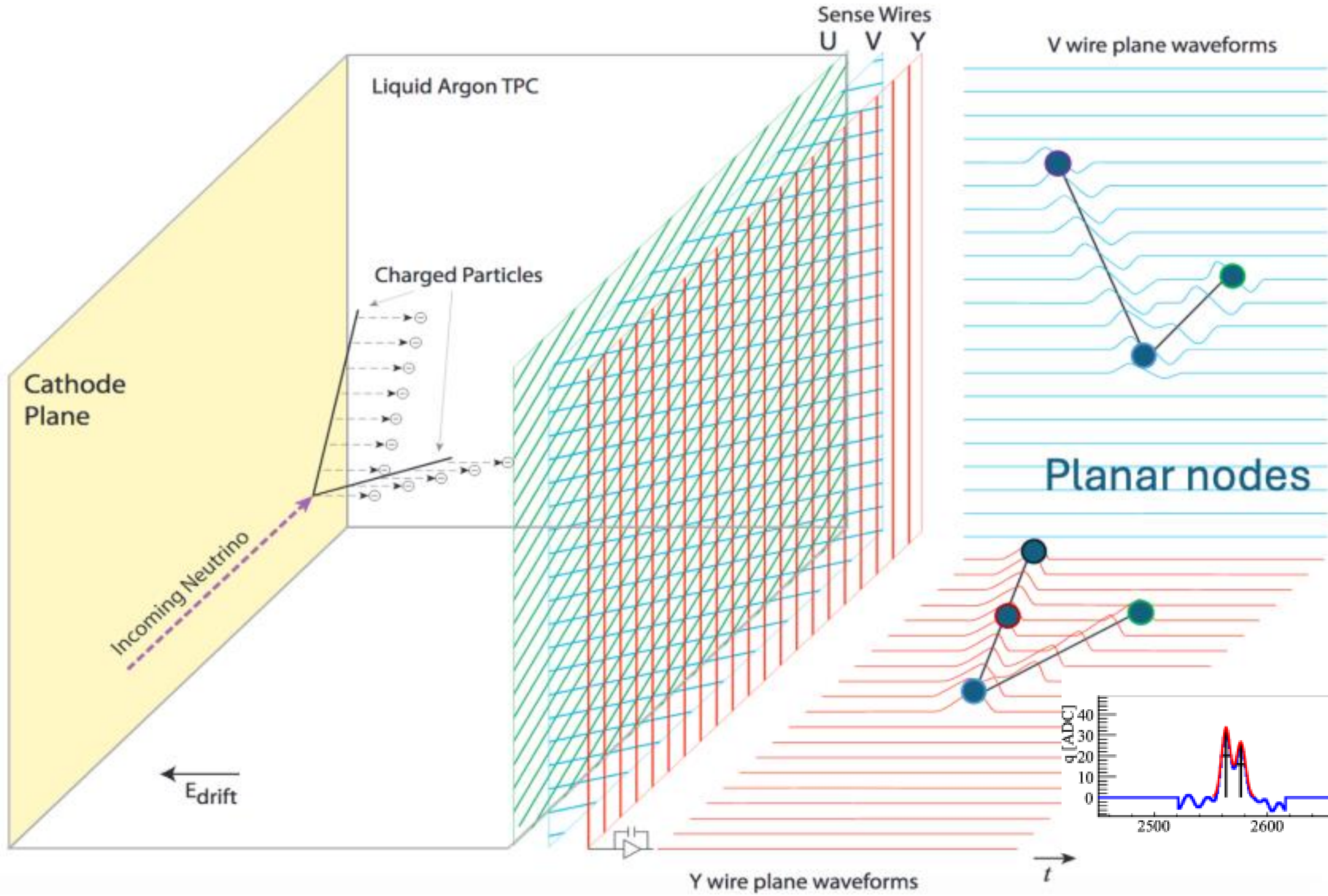
Developed with T. Stokes, V Hewes, Y-J. Jwa, & C. Sarasty

NuGraph Operation

Adapted from T. Stokes & G. Cerati



NuGraph Operation



1) Hits as GNN inputs

- Gaussian fits to waveforms
- Features:
  - Wire number
  - ADC peak time tick
  - ADC integral
  - RMS

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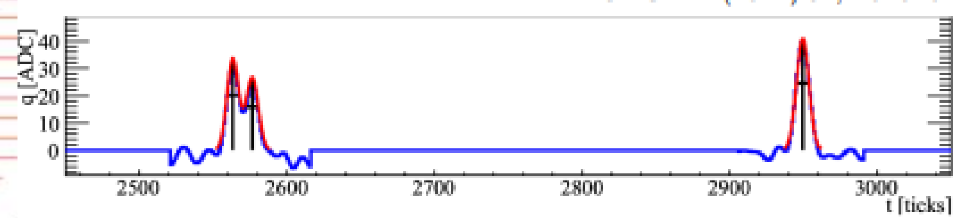

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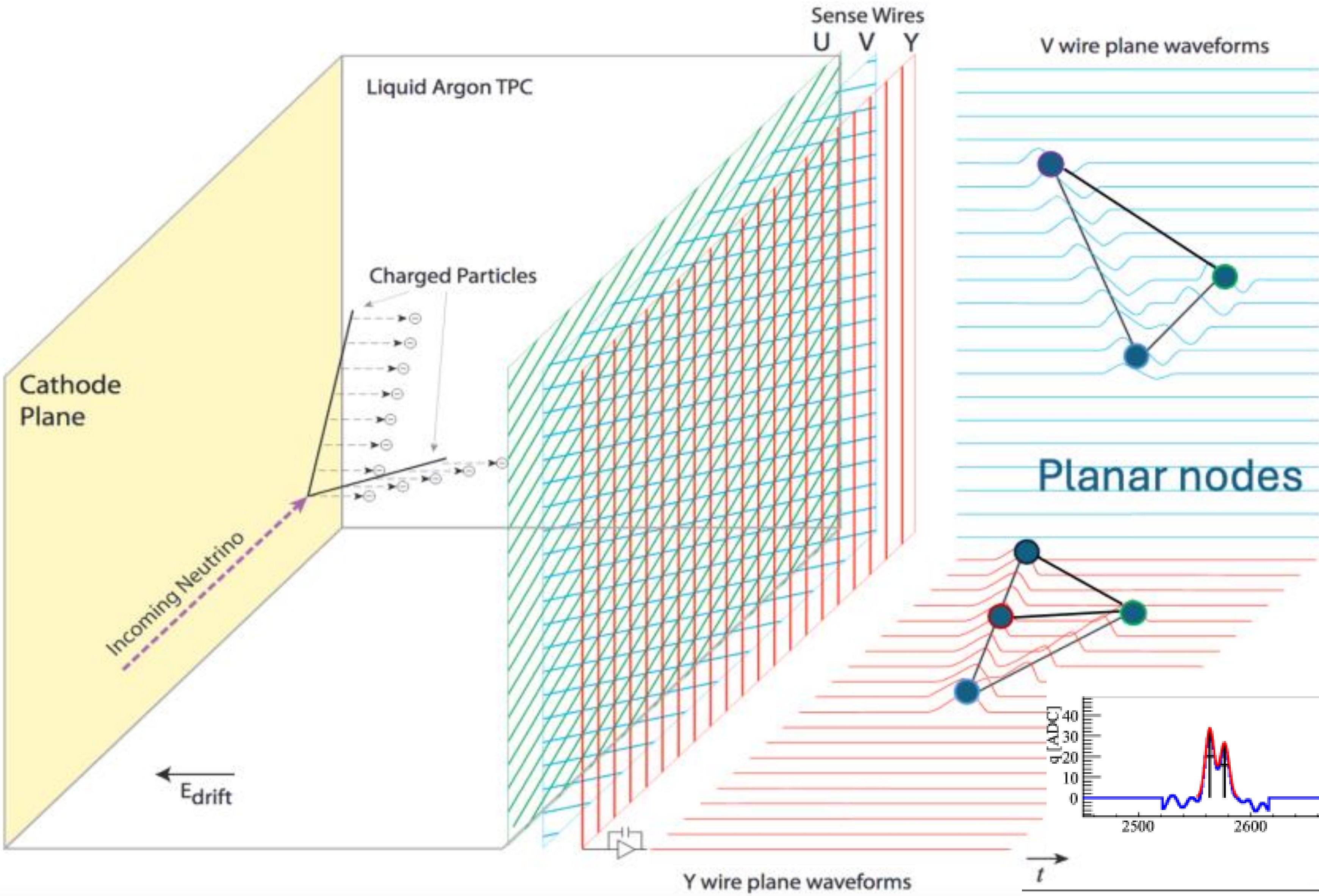

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- Features:
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  - RMS

2) Hit connections made

- Effective within each plane
- Utilizes Delaunay triangulation
  - Produces connected graph
  - Long & short connections made
  - Can connect across dead regions

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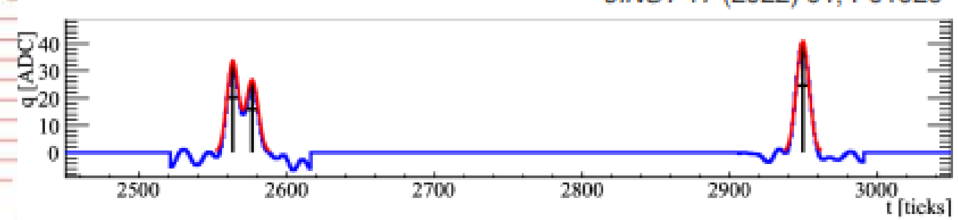

2023 J. Phys.: Conf. Ser. 2438 012091

Edge Type	Data Type	Labeling Scheme	Accuracy
Delaunay	**2D**	**Full**	**81.97%**
Window	2D	Full	74.64%
kNN	2D	Full	78.52%
Radius	2D	Full	76.02%

ExaTrkx Phase II Kickoff: Cerati PhysRevD.110.032008 Neutrino ML 2024: Cerati

NuGraph Operation

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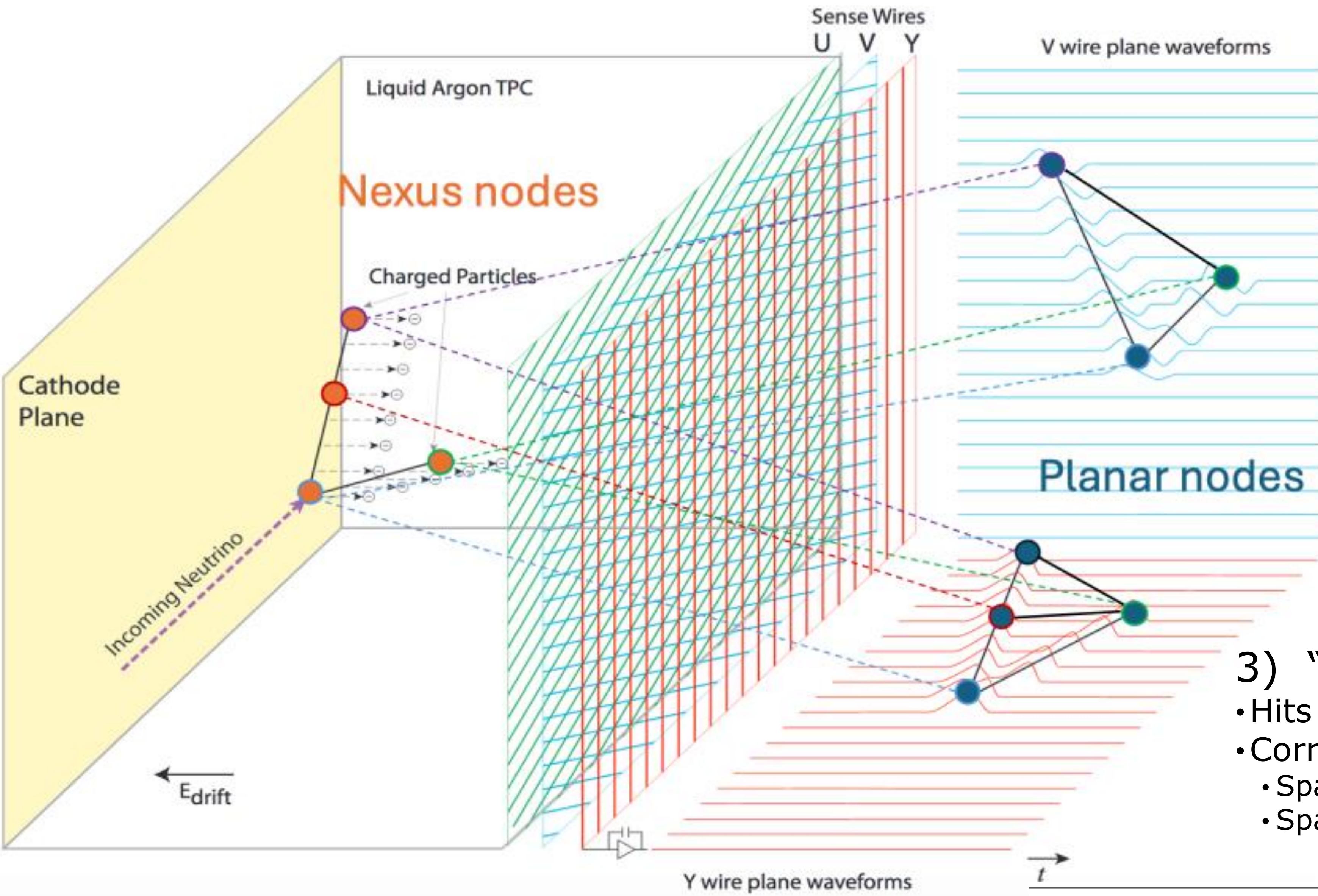

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- Utilizes Delaunay triangulation
  - Produces connected graph
  - Long & short connections made
  - Can connect across dead regions

3) "Nexus" connections made

- Hits associated with 3D SpacePoints
- Corroborated across planes
  - SpacePoints unconnected among selves
  - SpacePoints' features not used in GNN

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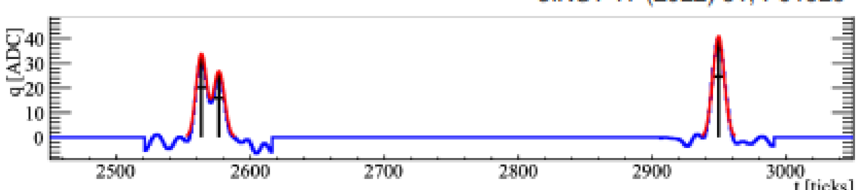

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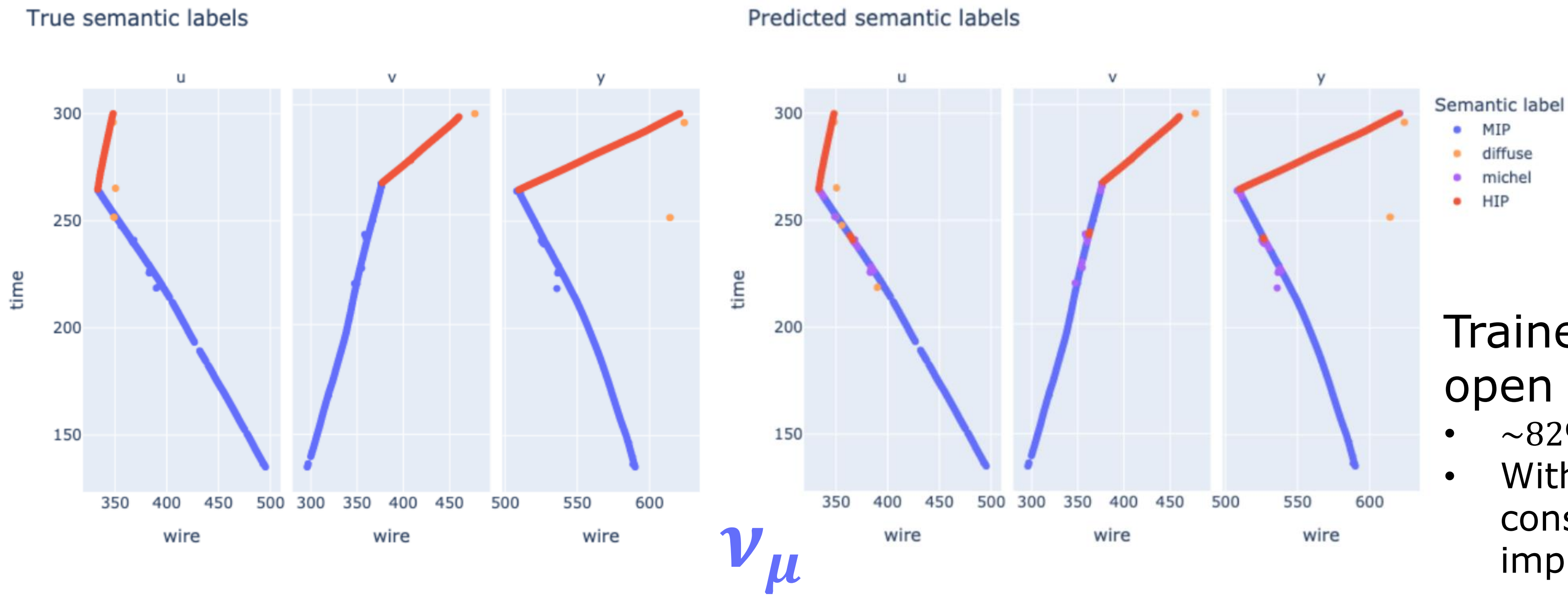
NuGraph Capabilities

Semantic Labeling Performance in Example ν_μ Interaction

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

- **NuGraph 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

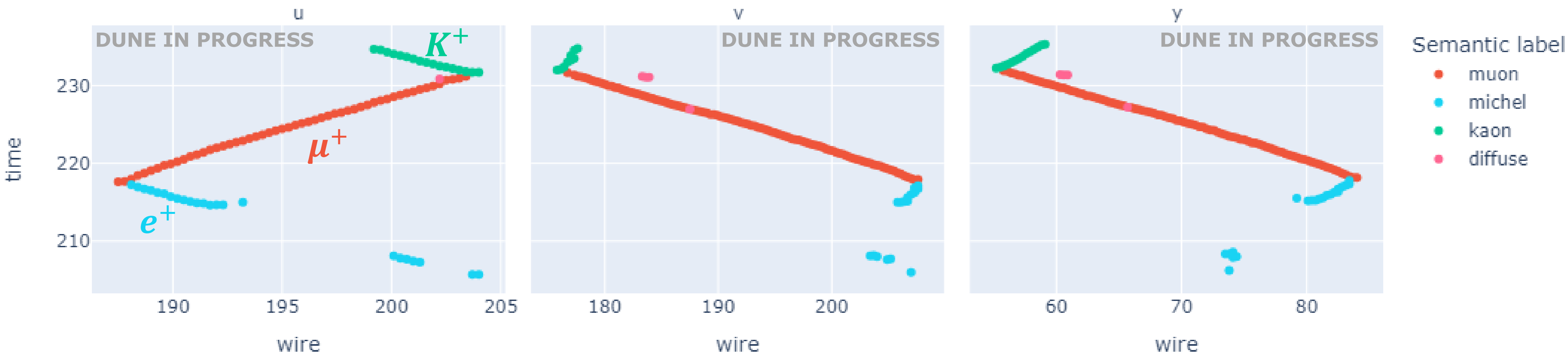
- $\sim 82\%$ hit PID accuracy
- With 3D connections, consistency between views improved: $\sim \mathbf{67}\% \Rightarrow \mathbf{94}\%$

V Hewes CHEP 2023

2023 J. Phys.: Conf. Ser. 2438 012091

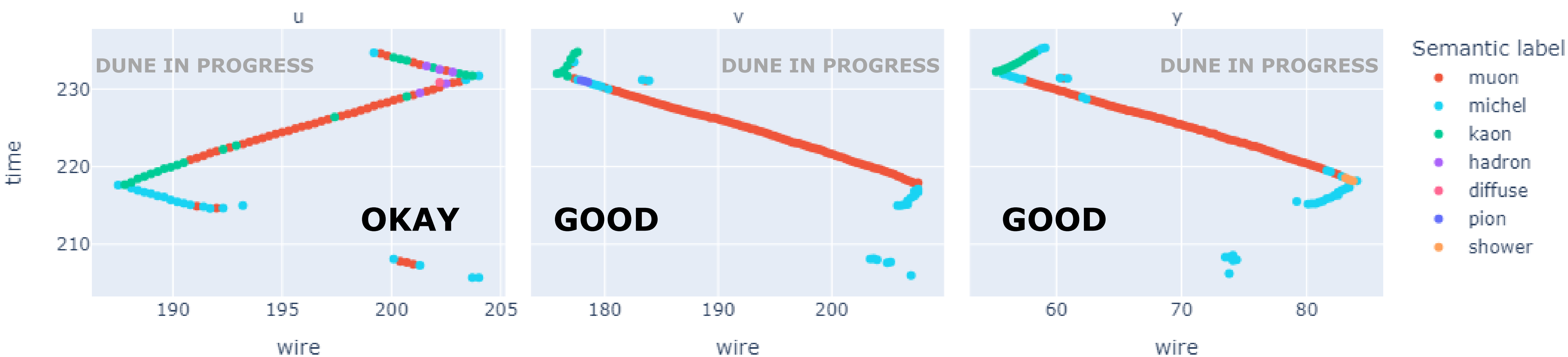
True Positive

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
NuGraph Training on hA LFG Sig:Bckgr 40k:40k

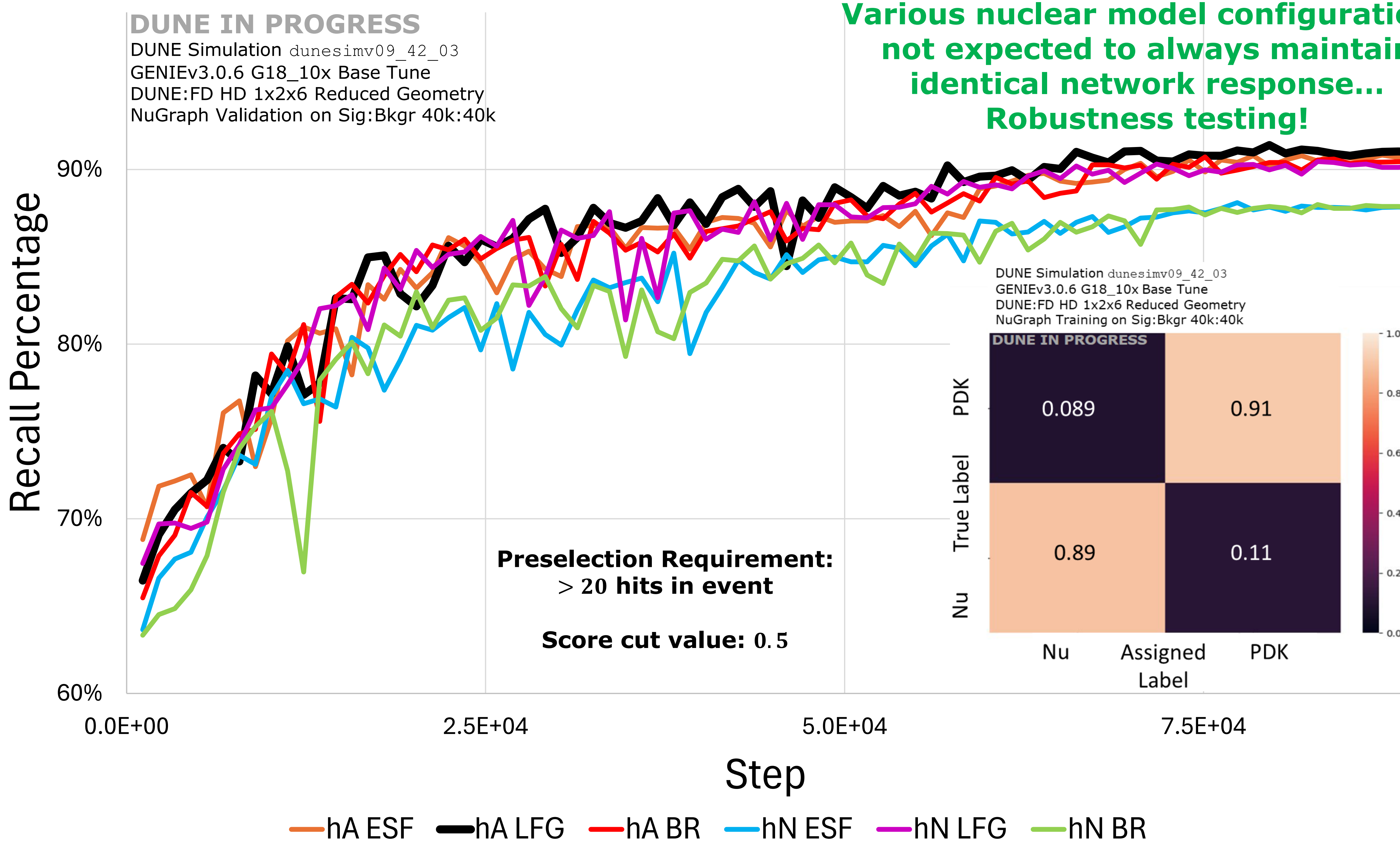
Predicted semantic labels for signal-like true $p \rightarrow K^{+}\bar{\nu}$ signal



Corroboration between planes increases hit-by-hit PID and binary classification capabilities—<u>Nexus nodes!</u>

T. Stokes

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



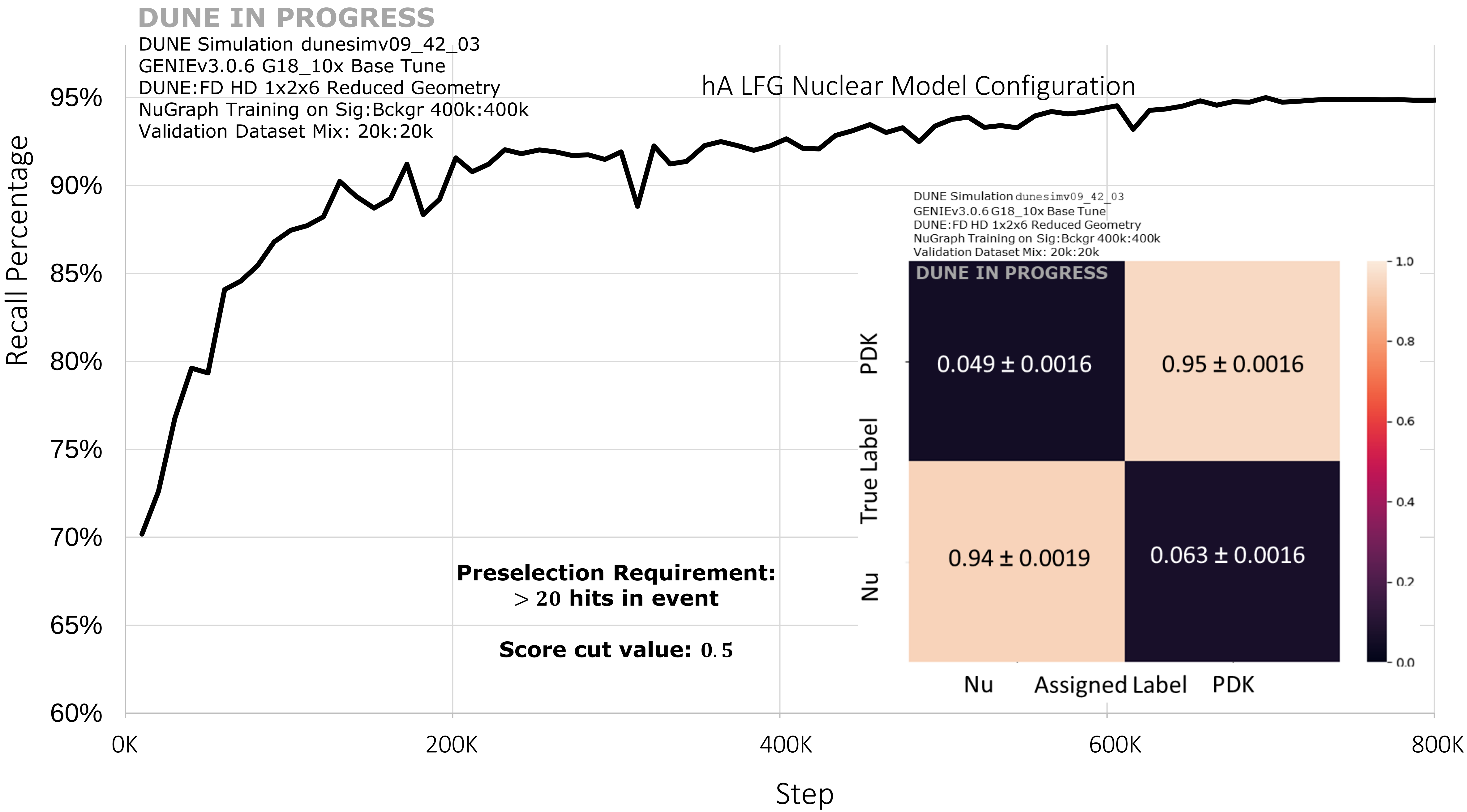
Various nuclear model configurations not expected to always maintain identical network response… Robustness testing!

Preselection Requirement:
> 20 hits in event

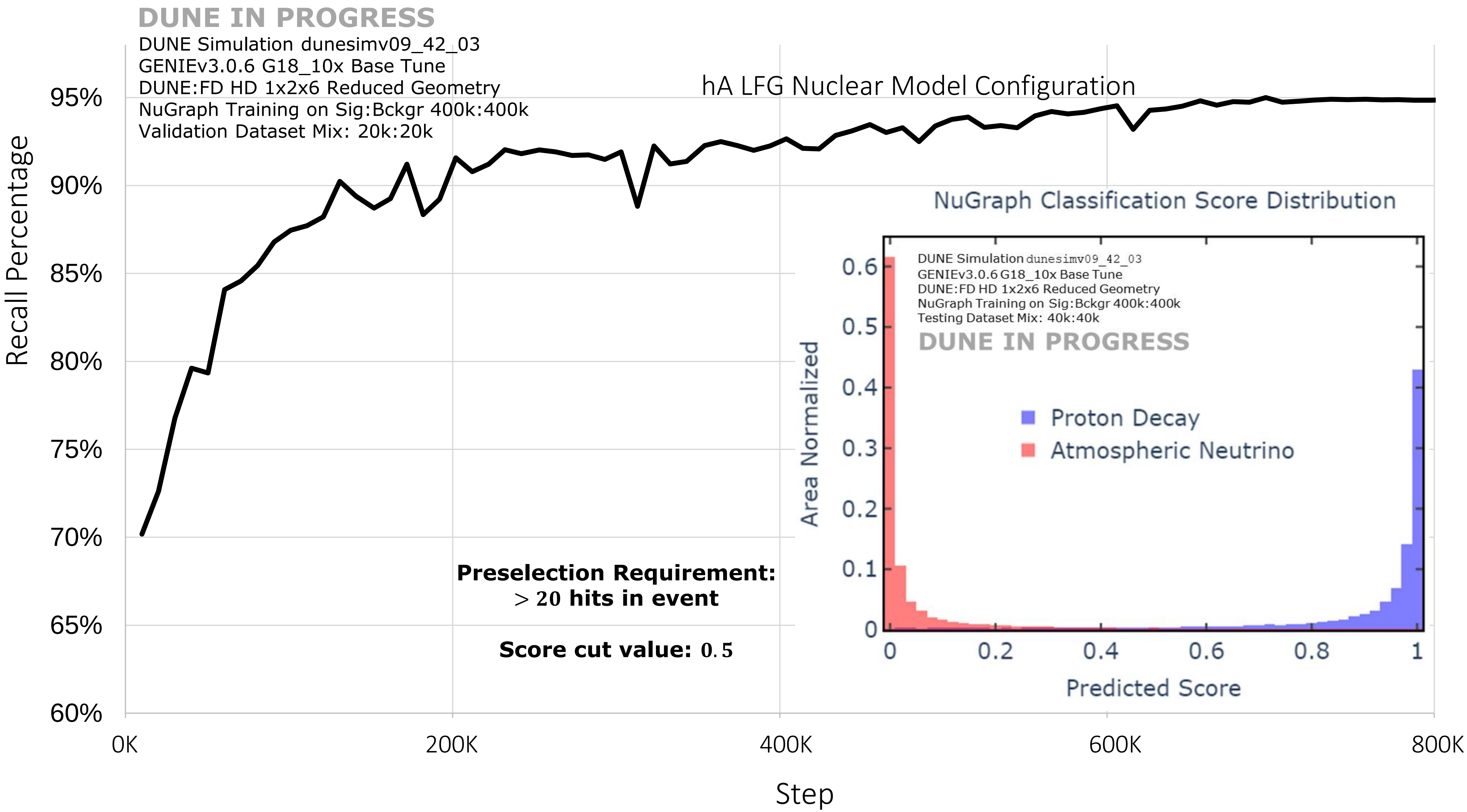
Score cut value: 0.5

T. Stokes

NuGraph Event Classification: Larger Dataset
Training on 400k:400k Signal:Background Events



NuGraph Event Classification: Larger Dataset
Training on 400k:400k Signal:Background Events



NuGraph Event Classification: Larger Dataset
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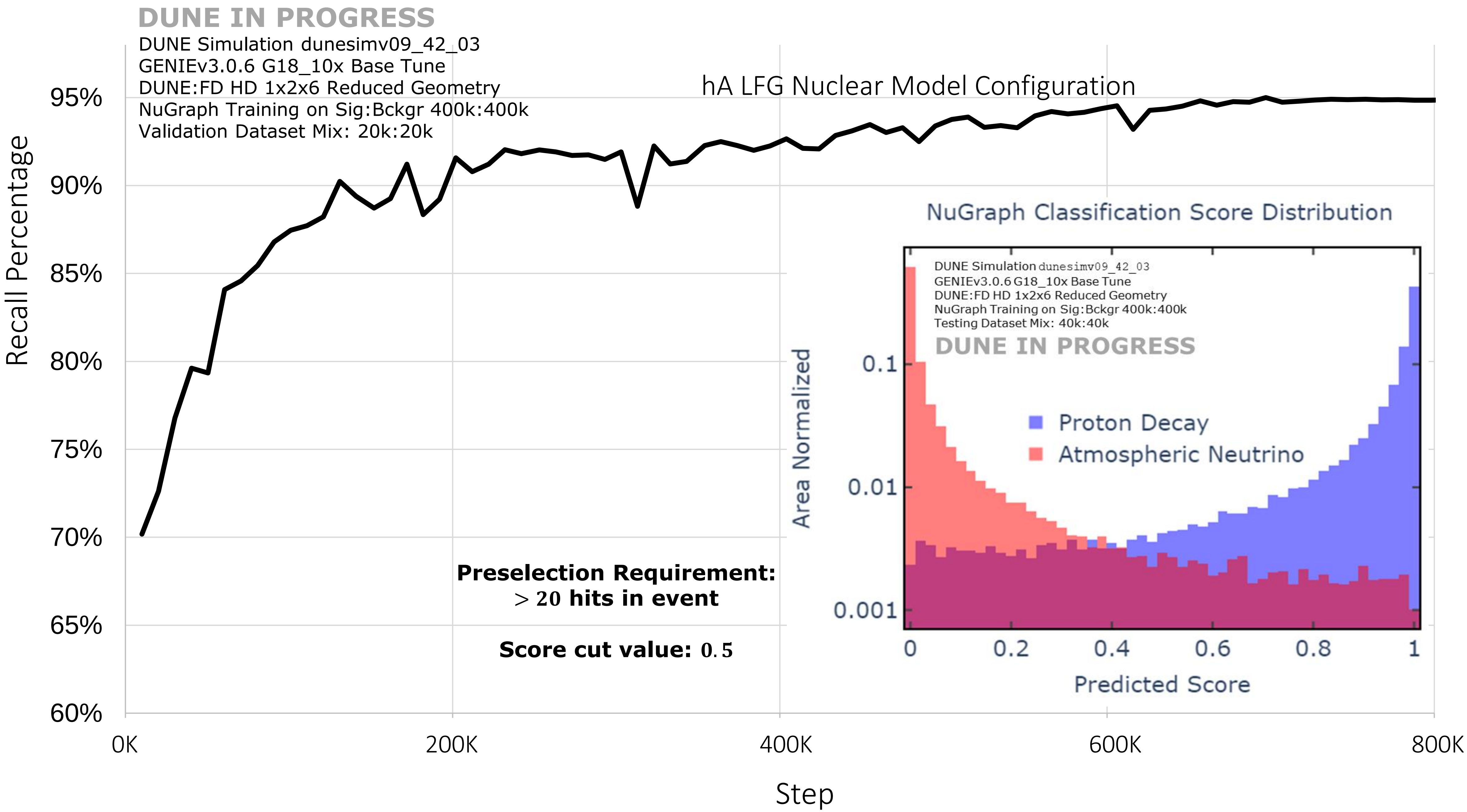
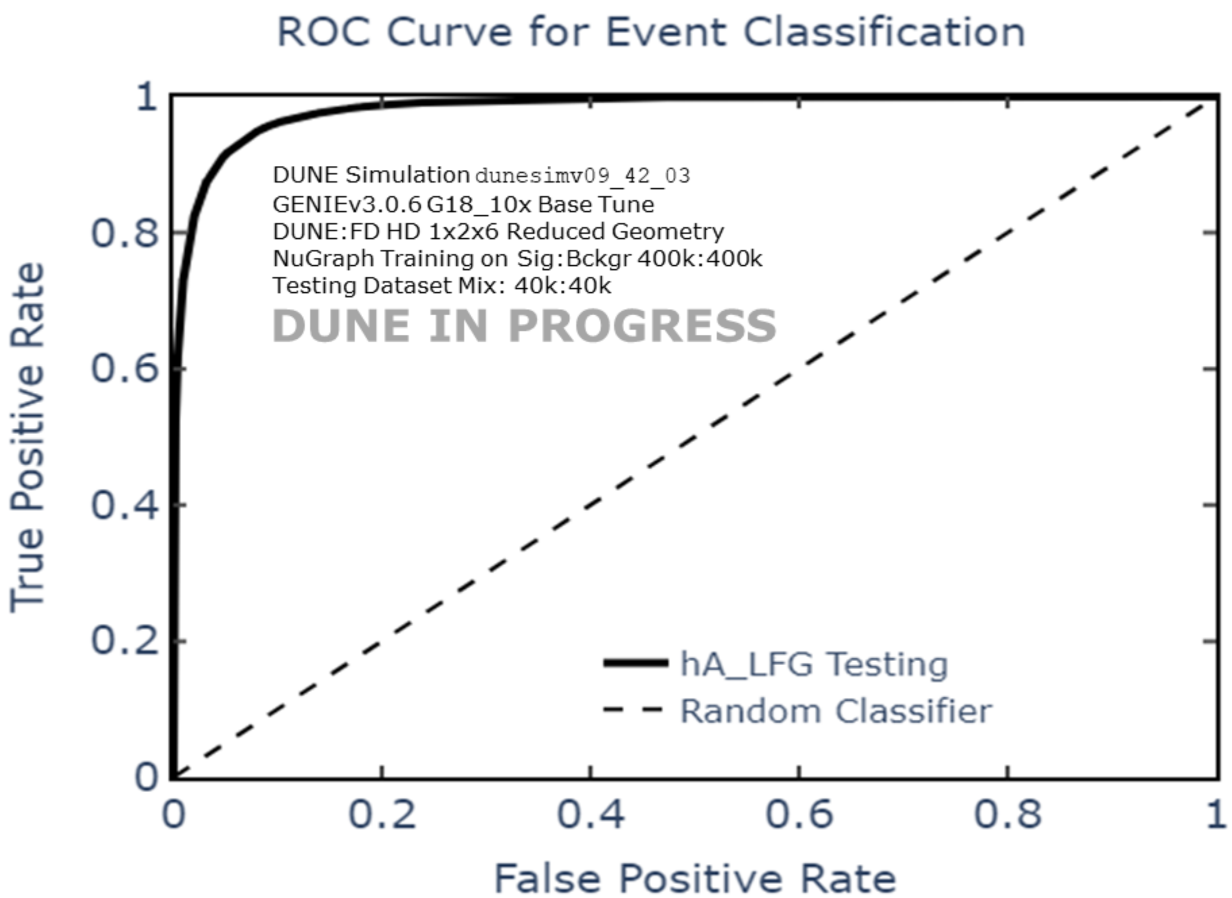
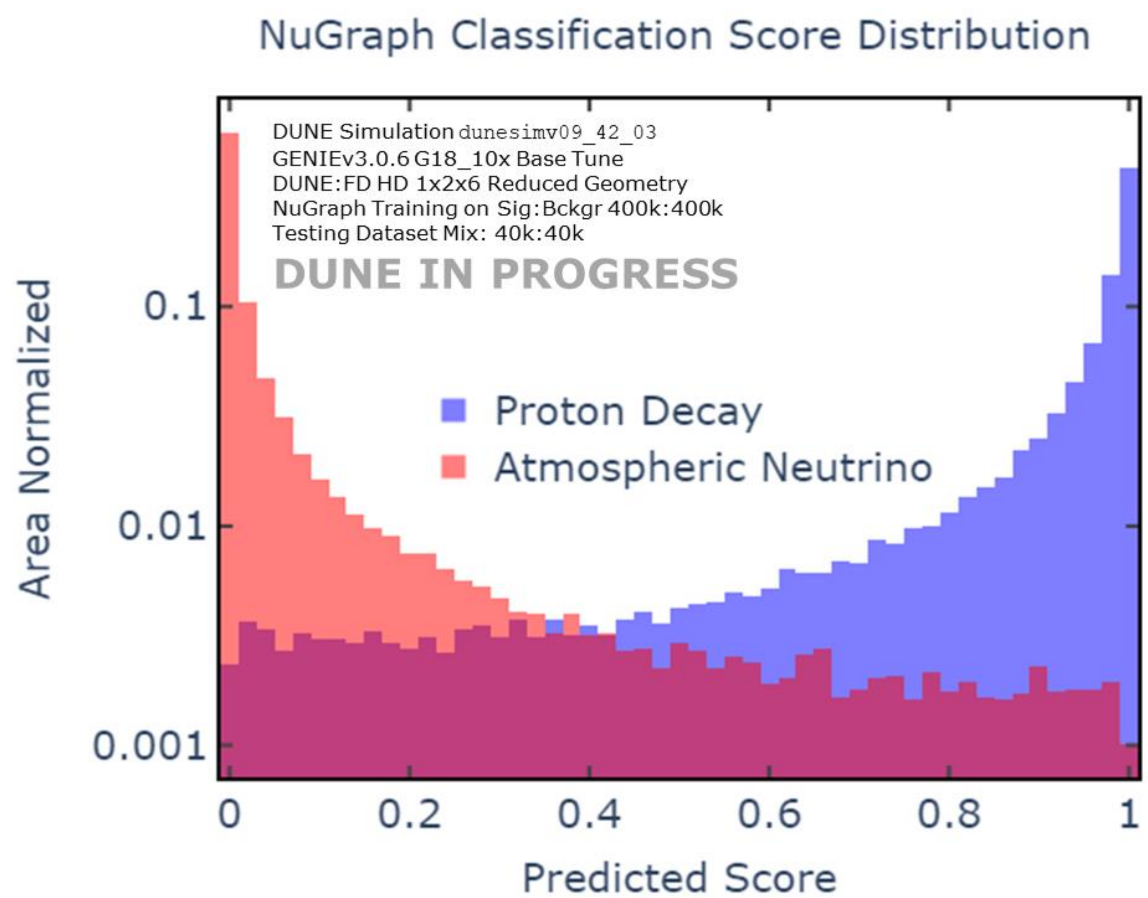


NuGraph Performance: Larger Dataset Training

400k hA_LFG PDK & 400k hA_LFG Atmospheric Neutrinos





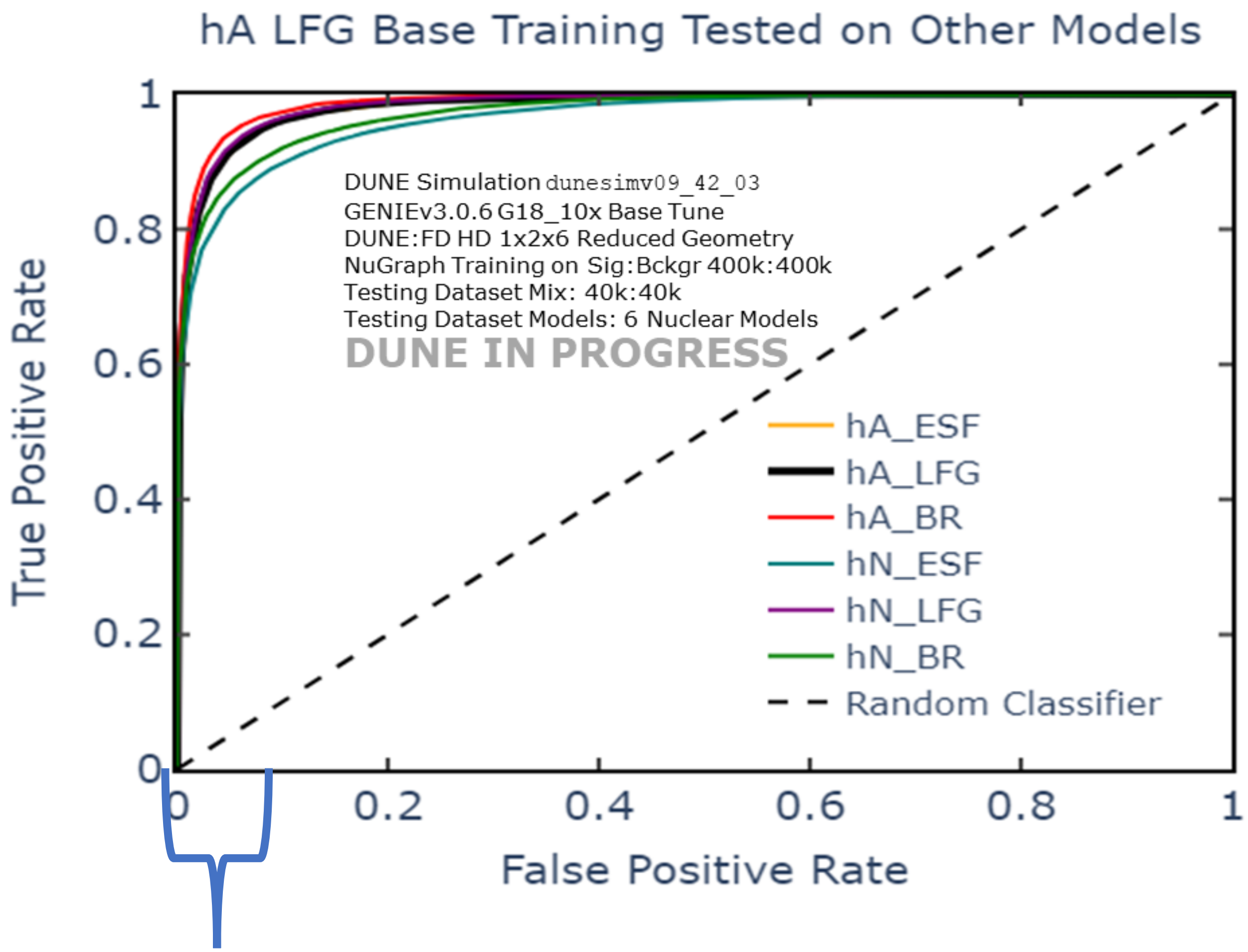
Preselection Requirement:
> 20 hits in event

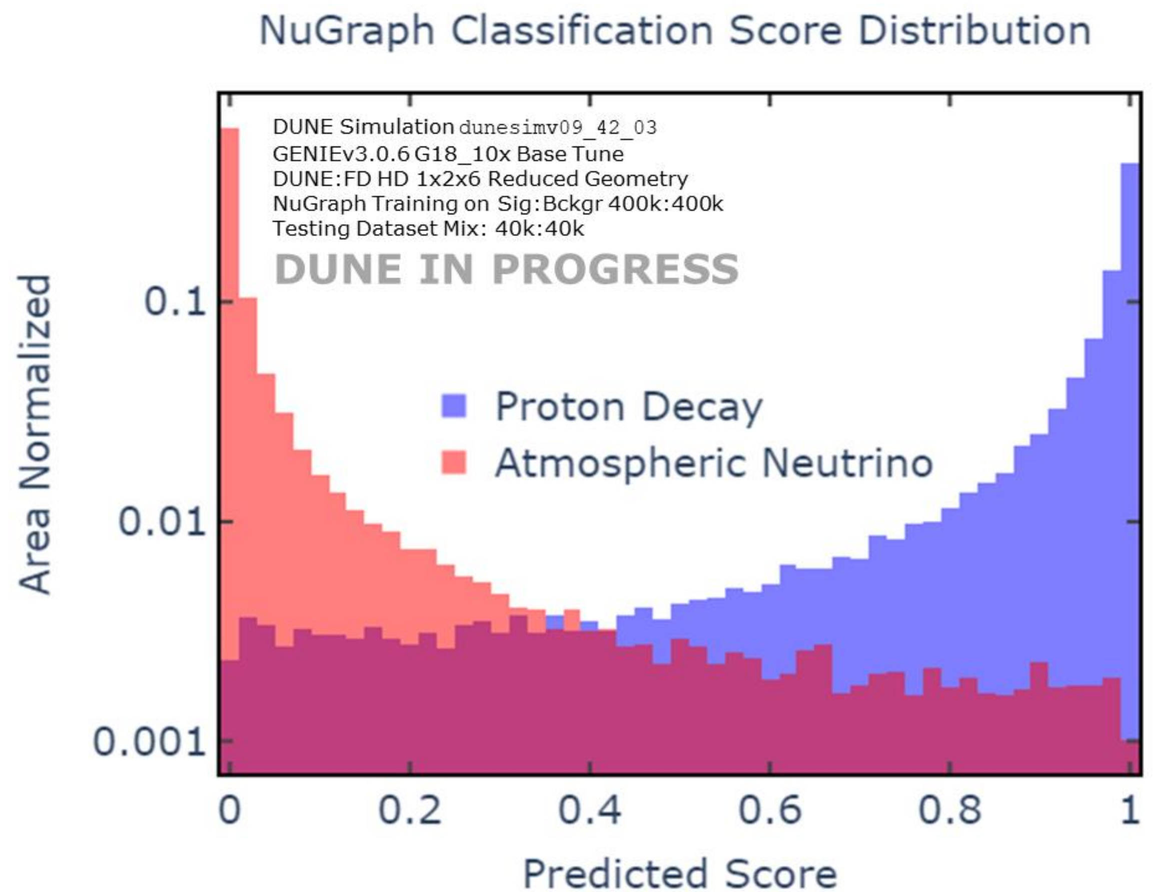
Variable score cut to produce ROC curve

NuGraph Performance: Larger Dataset Training

400k hA_LFG PDK & 400k hA_LFG Atmospheric Neutrinos

Trained Model Applied to Other Nuclear Model Configurations





All the real action is here…

Studying low background regions for nuclear model configuration robustness tests

Preselection Requirement:
> 20 hits in event

Variable score cut to produce ROC curve

Summary & Conclusions

- DUNE's first neutrino physics results will come from atmospheric neutrino oscillation measurements
  - A&EWG 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 reconstruction techniques study near complete
    - Will eventually be a key input for precision BNV background studies

- BNV analyses ongoing: public 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**
    - **Need improvements in reconstruction to increase efficiency**
  - **NuGraph performance incredibly encouraging**
    - Powers of semantic classification and **binary classifier**!
    - **BDT(GNN) combined analysis underway**—similar to MicroBooNE $n \to \bar{n}$
    - Will include pionic K^+ decay modes soon—step towards inclusive BNV search?
  - New $n \to \bar{n}$ analysis in development, new BRs now in GENIE