Needs from NDK/Atmospheric Physics point of view

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On behalf of the DUNE NDK/Atmospheric/Cosmogenic Physics WGs

ProtoDUNEs Science Workshop

28-30 June 2016, CERN

Workshop goals

From the Indico page

The workshop goals are to:

- provide well-defined parameters of the beam (particle types, rates, momentum resolution, PID) to execute a successful measurement programme
- identify a prioritized list of measurements and analyses and a plan to develop the required tools and analysis algorithms
- define and discuss benchmark measurements to evaluate the detector performance

- This talk aims to contribute to these goals, from the perspective of Nucleon Decay and Atmospheric Neutrino Physics at DUNE

ProtoDUNEs measurements for Nucleon Decay Physics

NDK searches: where do pDUNEs measurements enter?

$$\tau/B = n_{p/n} \cdot \varepsilon \cdot Mt \,/\, (N_{obs} - N_{bgr})$$

- **$n_{p/n}$**: number of p or n per unit mass [1 / kton]
- **ε**: signal detection efficiency [1]
- **Mt**: detector exposure [kton·yr]
- **N_{obs}-N_{bgr}**: (upper limit on) number of signal events [1]
- **τ/B**: (lower limit on) partial lifetime sensitivity [yr]

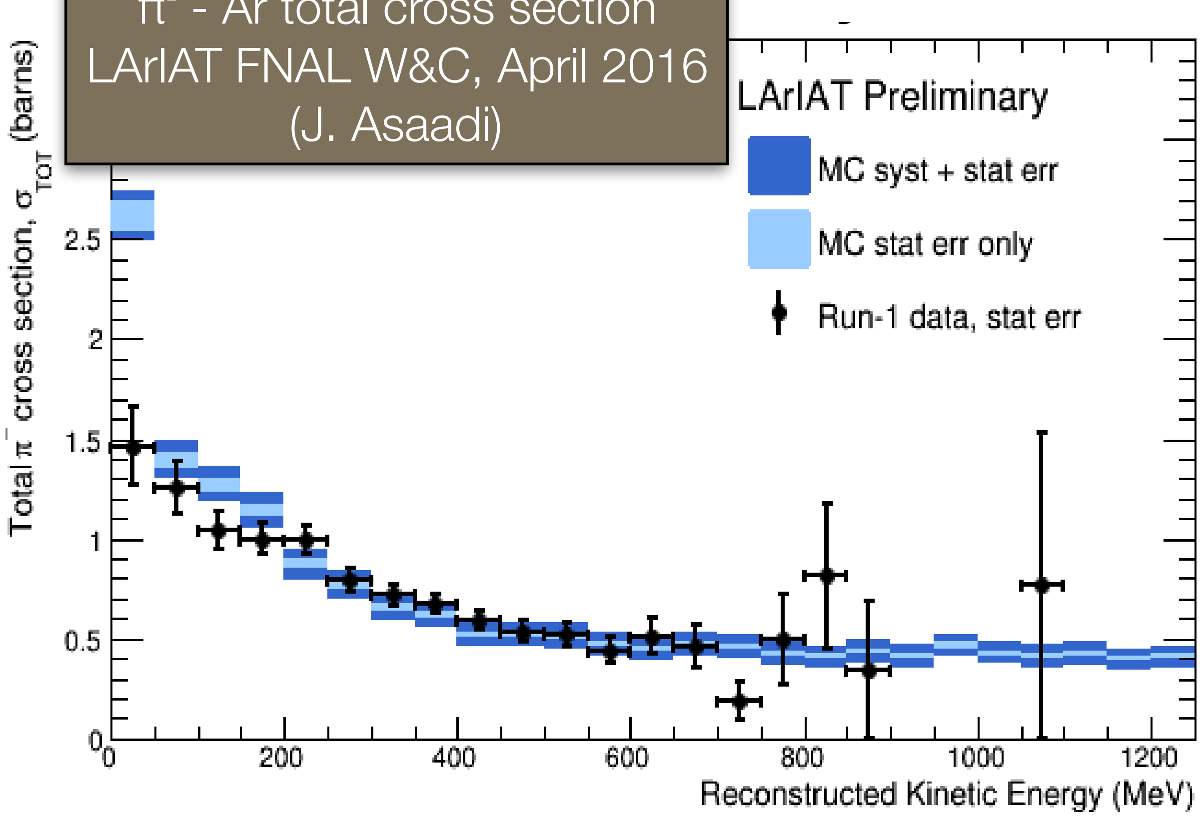
- ProtoDUNE measurements will affect ε, N_{bgr} estimates through:
  - π-Ar and K-Ar cross section measurements
  - Track/shower reconstruction performance
  - Particle ID performance

- ProtoDUNE data may also permit to refine NDK event selection in a LAr-TPC

$K^{\pm}$-Ar and $\pi^{\pm}$-Ar cross section measurements

- Tune hadron-nucleus interaction models in NDK generator (**GENIE**) and detector simulation (**Geant4**)
  - Understand irreducible signal efficiency losses, affect background rates
- Not just total cross sections, but **exclusive** measurements needed
  - absorption, charge exchange, inelastic, elastic
- Particularly interested in **0.1-0.5 GeV/c** incident meson momenta
  - **Caveat**: LArIAT is a better match in momentum for this

π^- - Ar total cross section
LArIAT FNAL W&C, April 2016
(J. Asaadi)



pDUNEs: need measurement of low-momentum $K^{\pm}$-Ar and $\pi^{\pm}$-Ar cross sections. Cross-check LArIAT

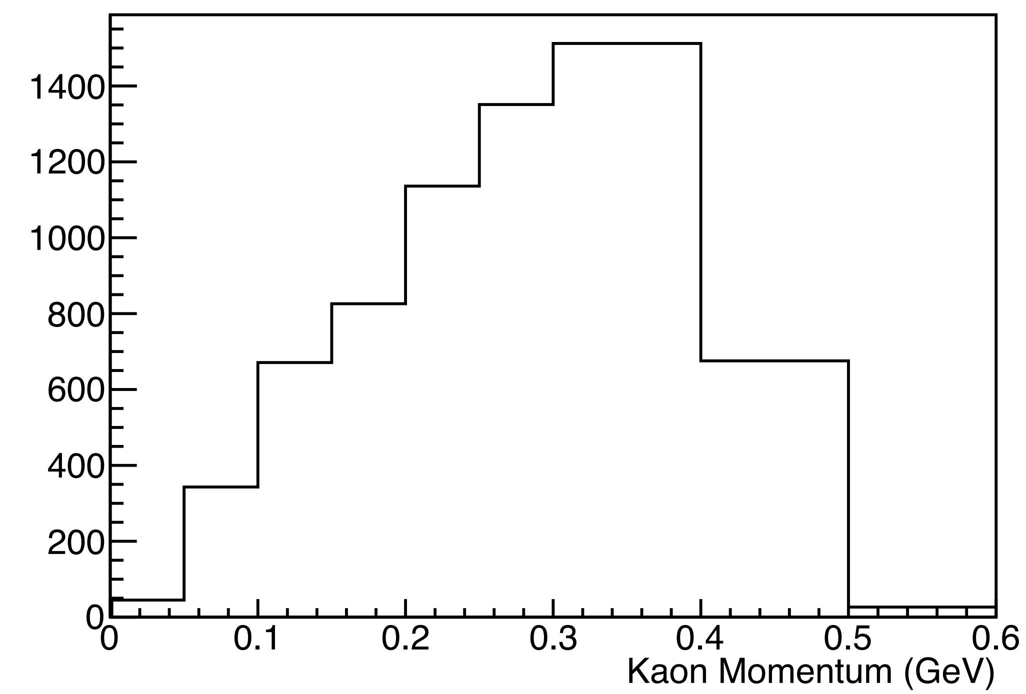
Track/shower reconstruction performance

Single-particle reconstruction efficiencies, resolutions

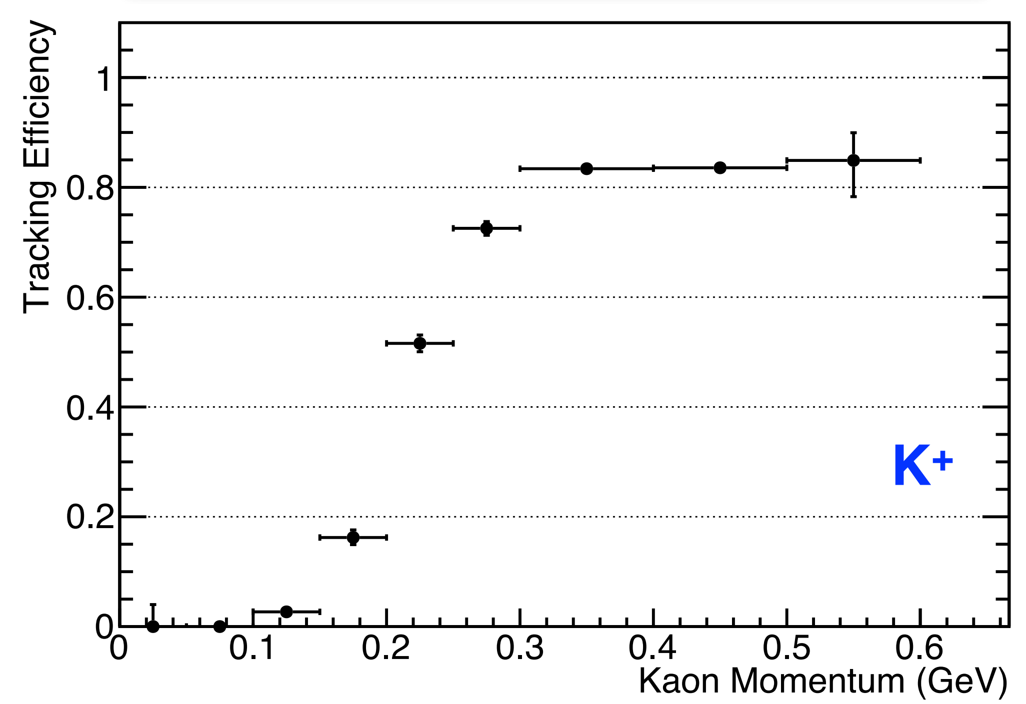
- Single-particle momentum/angular resolutions not so important, considering nuclear Fermi motion

- Single-track **efficiencies** very useful to validate

pDUNEs: measure single-particle reconstruction efficiencies in LAr-TPC as similar as possible to DUNE FD



K⁺ momentum distribution and tracking efficiency in p → $\bar{\nu}$ K⁺ MC (A. Higuera)



Track/shower reconstruction performance

"Multi-particle" reconstruction for NDK signal

- **"Multi-particle reco"**: reconstruction of observables involving multiple particles
  - **Examples**: invariant mass of 2-body system, decay vertex position

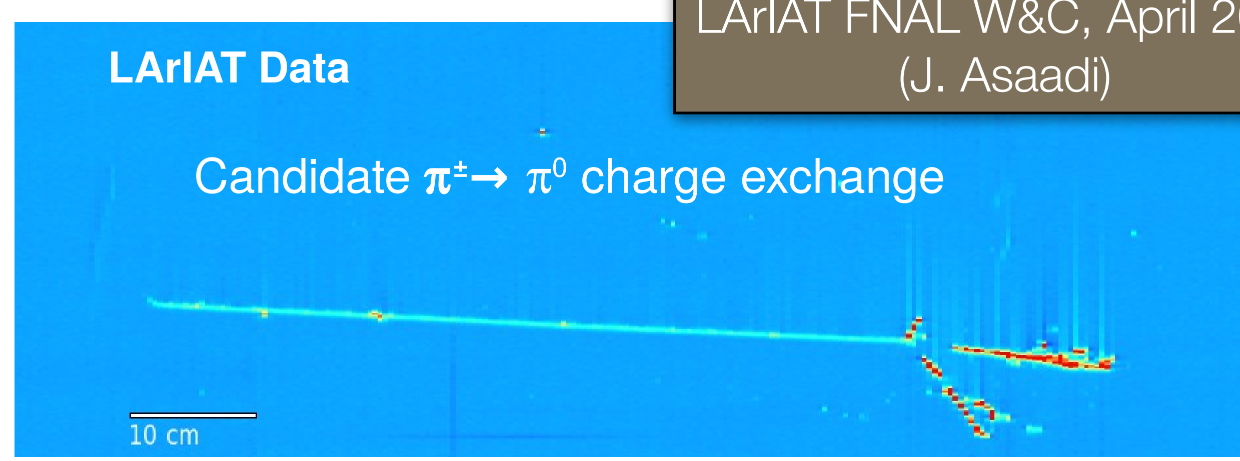
- **Invariant mass** and **vertex** reconstruction important, since many NDK searches involve reconstructing decays of neutral particles

- **Vertex/position** resolution also needed to quantify signal efficiency due to fiducial requirement

Examples:

- $K^0_S \rightarrow \pi^+\pi^-$ in $p \rightarrow \mu^+ K^0$
- $\pi^0 \rightarrow \gamma\gamma$ in $p \rightarrow e^+ \pi^0$
- $\eta \rightarrow \gamma\gamma$, $3\pi^0$ in $p \rightarrow e^+ \eta$

pDUNEs: use pion charge exchange events to understand invariant mass and vertex reconstruction?

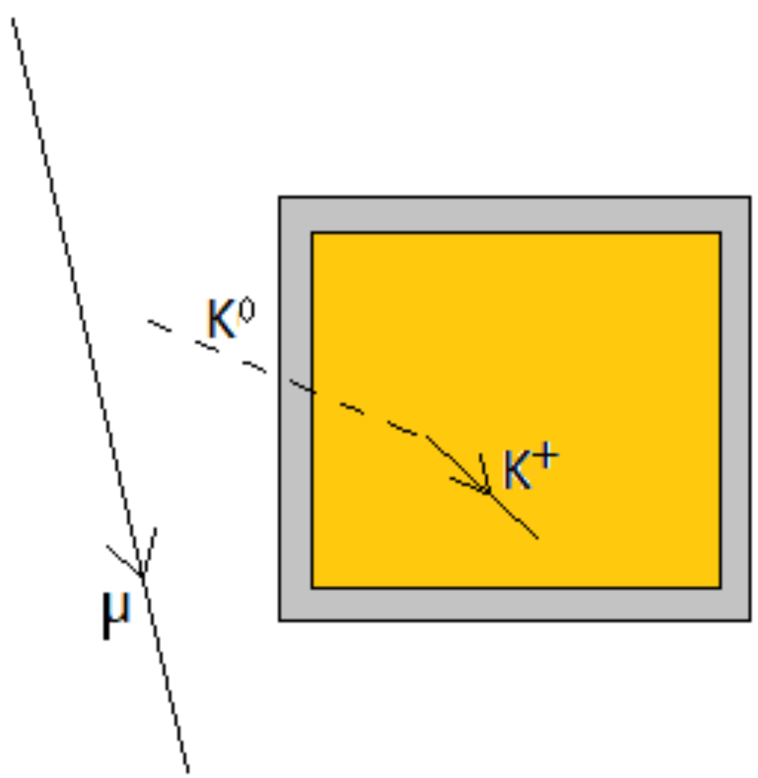


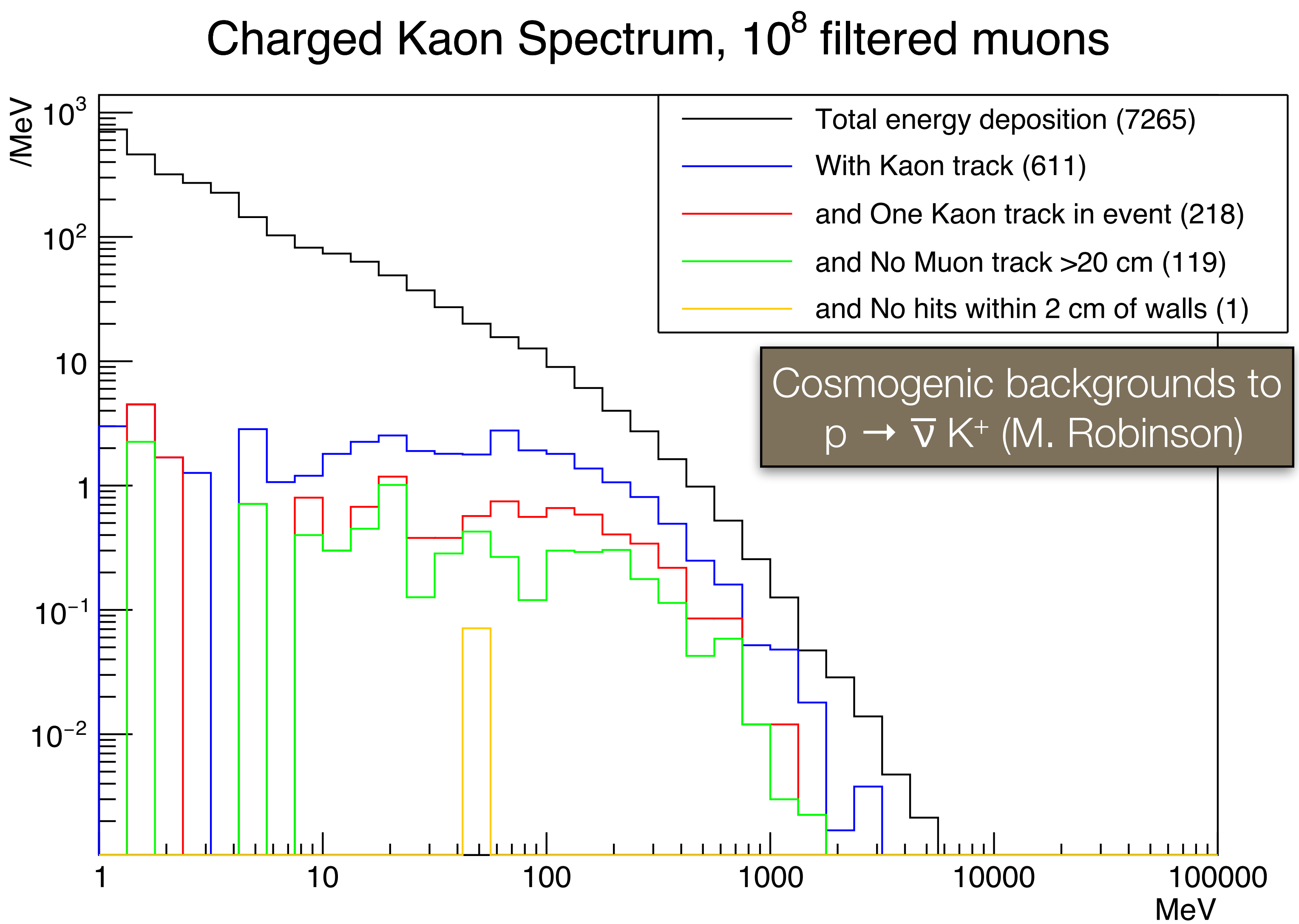
LArIAT FNAL W&C, April 2016 (J. Asaadi)

Track/shower reconstruction performance

Cosmogenic background to NDK

- Understanding position resolution also important to suppress cosmogenic backgrounds



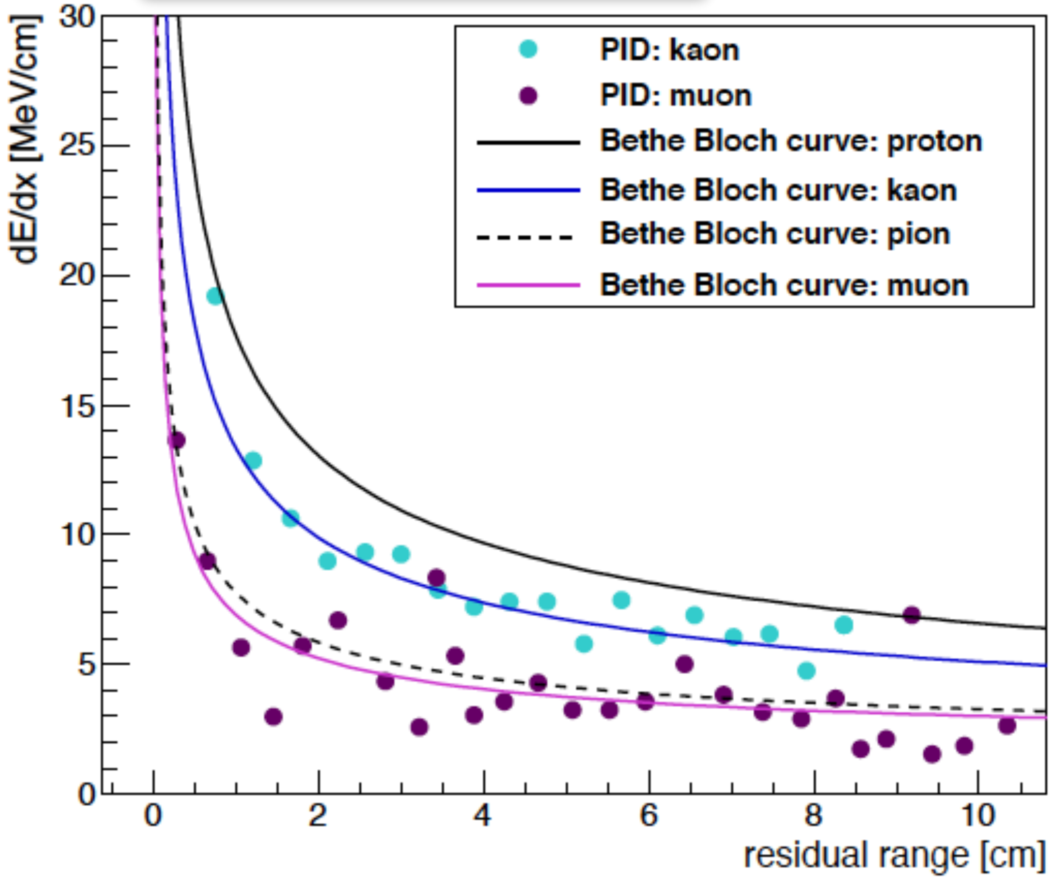


Particle ID performance

dE/dx of stopping particles

- Understand **PID** performance (ID efficiencies, mis-ID rates) based on **dE/dx of stopping particles**
  - Several separations needed: e/μ/π/K/p
  - What mis-ID rates can we tolerate?
  - Need better understanding of NDK backgrounds from mis-reconstruction via full MC study within NDK WG (6 months away?)

K/μ separation in ICARUS

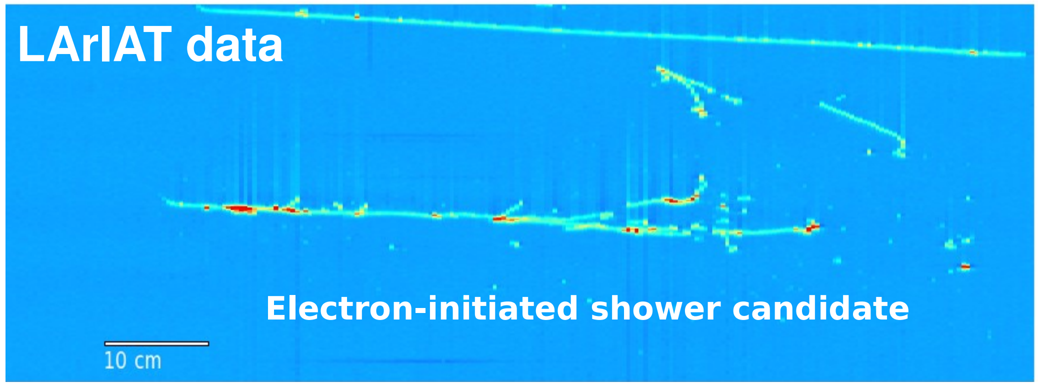


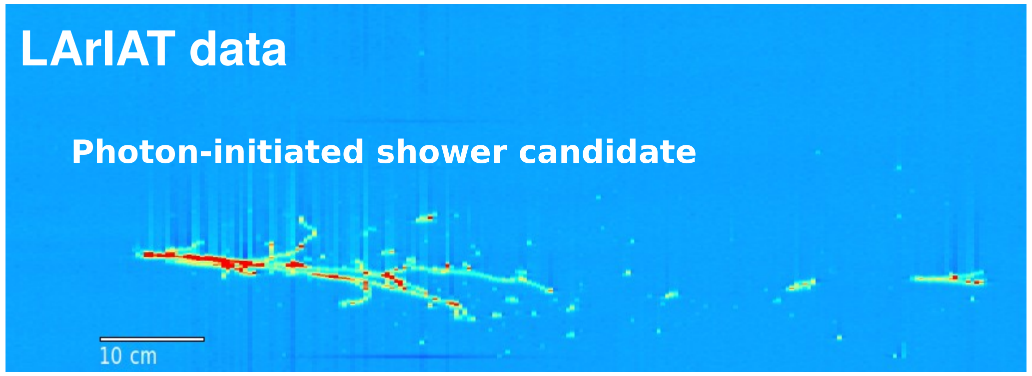
pDUNEs: characterise dE/dx vs range in LAr-TPC as similar as possible to DUNE FD

Particle ID performance

e/γ separation

- **e/γ separation** also important, since many NDK searches involve electrons and gammas simultaneously
  - **Example**: p→e^+ η, η→γγ
- Possible from dE/dx at shower beginning (first few cm): single vs double ionisation





pDUNEs: measure e/γ separation performance. Photon-initiated showers from electron bremsstrahlung events?

Prioritized list of pDUNEs measurements for NDK physics

For discussion

1. Particle ID performance

- PID from dE/dx of stopping particles. Full e/μ/π/K/p separation
- e/γ separation
- Muon charge sign

2. Track/shower reconstruction performance

- Single-particle reconstruction efficiency
- Decay vertex reconstruction
- Invariant mass in neutral particles’ decays

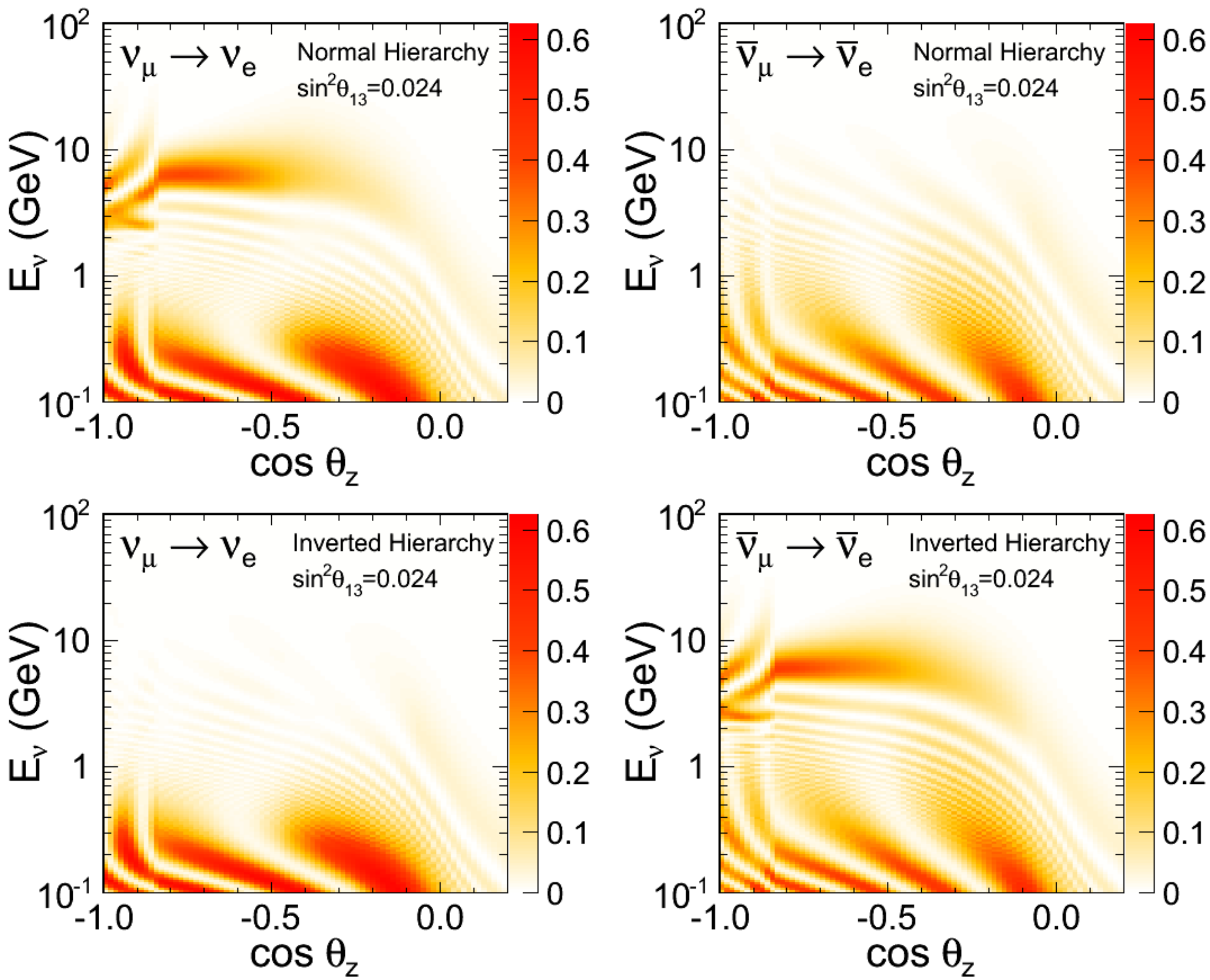
3. $\pi^{\pm}$-Ar and $K^{\pm}$-Ar cross section measurements

- Few 100 MeV kinetic energies

Increasing importance

ProtoDUNEs measurements for Atmospheric Neutrino Physics

Atmospheric measurements: $\nu_\mu \rightarrow \nu_e$ channel



Goal: measurement of MH and other oscillation parameters

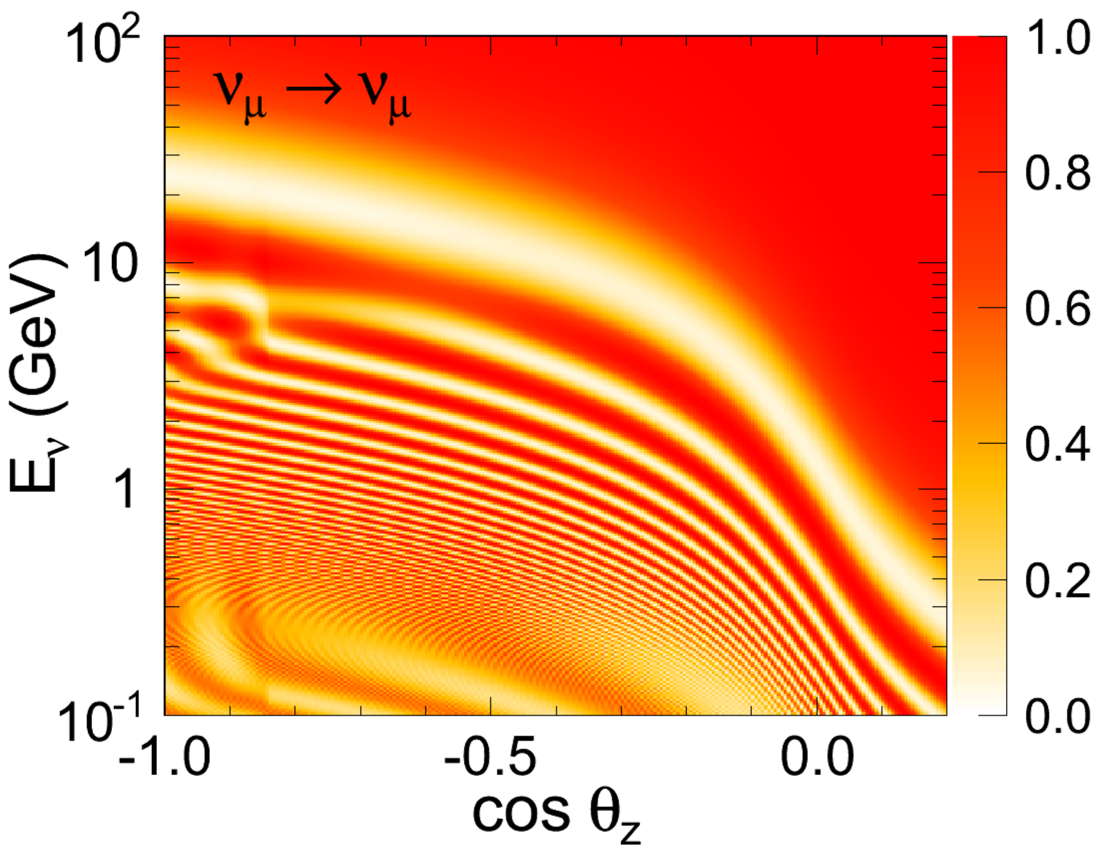
Neutrino is reconstructed as lepton plus hadronic system as a whole

Need to measure at least:

- lepton flavor = e
- energy (e + h)
- direction (e + h)

Atmospheric measurements: $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\tau$ channels

ν_μ disappearance

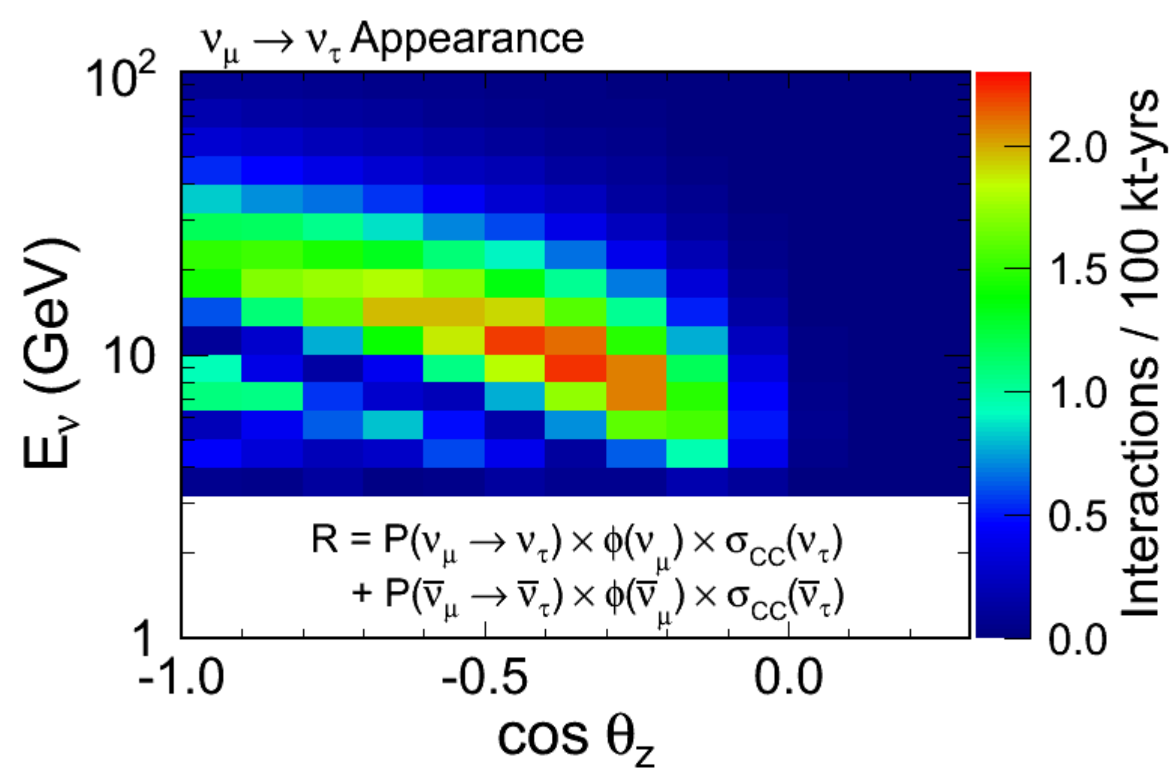


Goal: measurement of MH and other oscillation parameters, test of flux models

Need to measure at least:

- lepton flavor = μ
- energy (μ + h)
- direction (μ + h)

ν_τ appearance



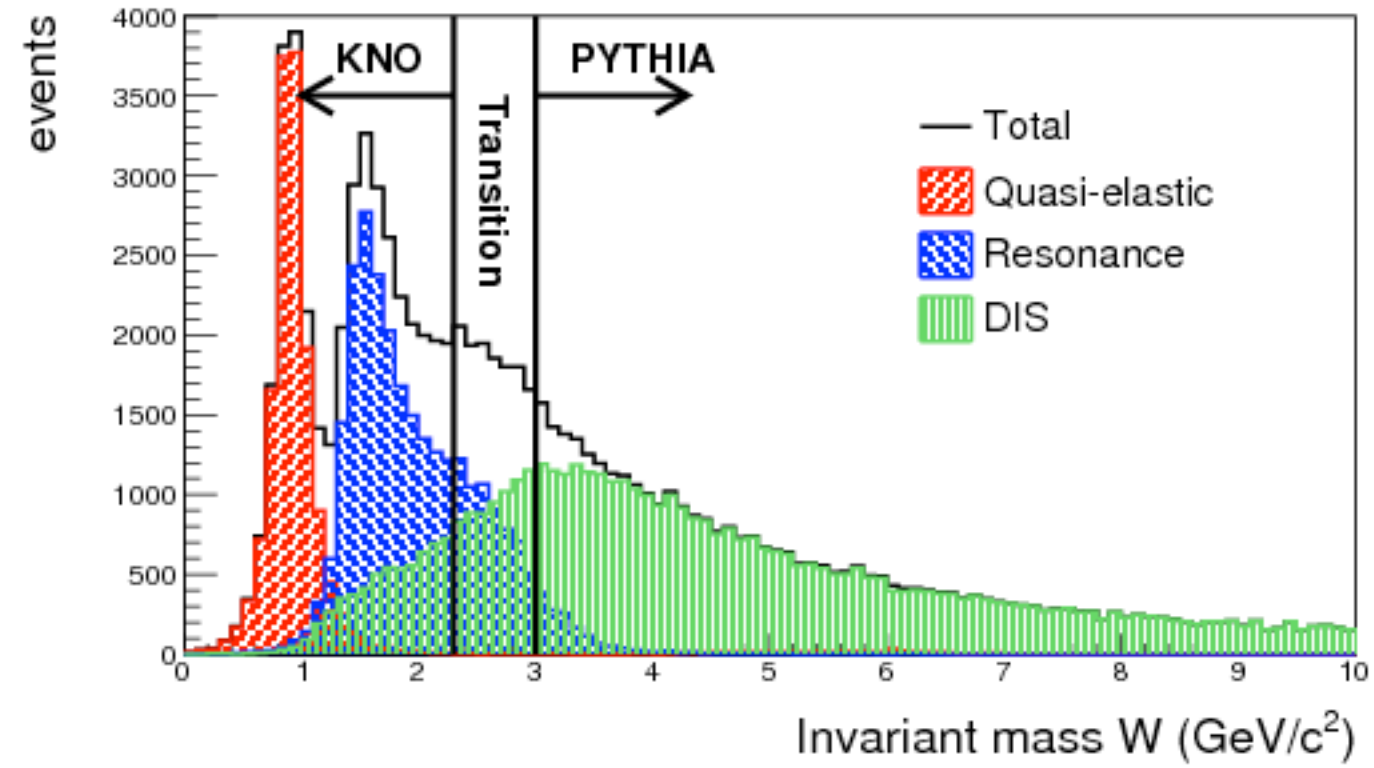
Goal: unitarity tests

Need to measure at least (focus on inclusive hadronic channels):

- $\pi^{\pm}$ ID
- energy
- direction

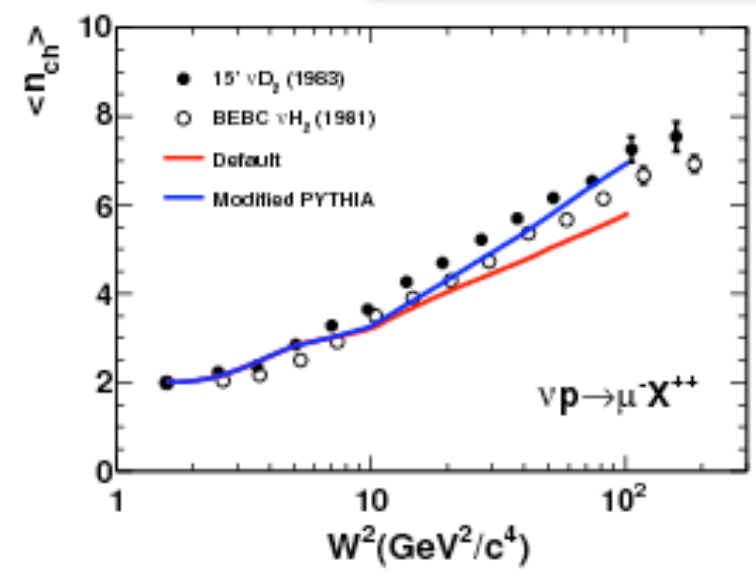
Hadron multiplicities in atmospheric neutrinos

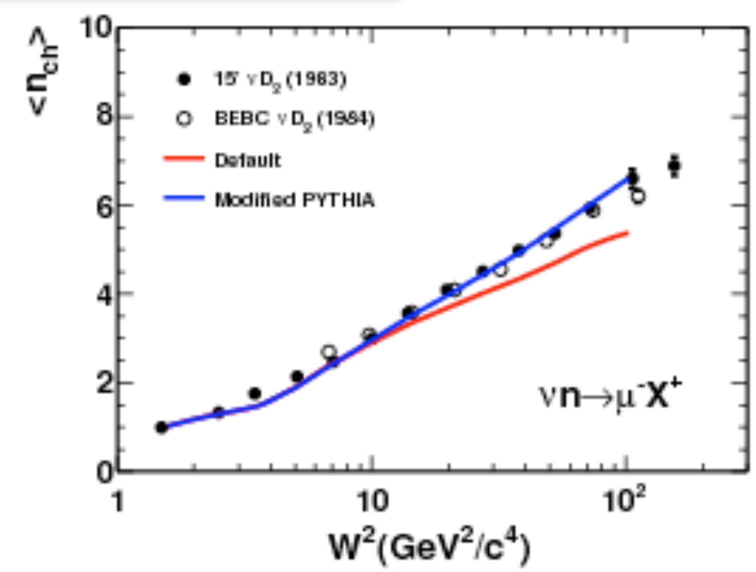
- Invariant mass distribution from atmospheric neutrino flux



T. Katori, S. Mandalia, arXiv:1412.4301

- 1-5 hadrons in final state typically expected





Detector performance assumptions

From lbne-doc-7184

Angular Resolution	Electron	1 deg
	Muon	1 deg
	Hadronic System	10 deg
Energy resolution	Stopping muon	3%
	Exiting muon	15%
	Electron	$1\%/\sqrt{E} + 1\%$
	Hadronic system	$30\%/\sqrt{E}$
Signal Acceptance	Electrons	90%
	Muons	100%
Background rejection	e-like (π^0, γ)	95%
	μ-like (π^+, π^-)	99%

MH sensitivity versus detector performance

From lbne-doc-7039

DPA	Nominal	Better Angular Resolutions	Better Energy Resolutions	Improved FCE	Improved FCMU	Improved PCMU	Improved Hadrons
Nu/Nubar separation	None	None	None	None	None	None	None
Muon Energy	15% exiting 3% contained	15% exiting 3%contained	7.5% exiting 1.5% containd	15% exiting 1.5% containd	15% exiting 1.5% containd	7.5%exiting 3% contained	15% exiting 3% contained
EM shower energy	$1\%\oplus1\%/\mathrm{sqrt(E)}$	$1\%\oplus1\%/\mathrm{sqrt(E)}$	$.5\%\oplus.5\%/\mathrm{sqrt(E)}$	$.5\%\oplus/.5\%/\mathrm{sqrt(E)}$	$1\%\oplus1\%/\mathrm{sqrt(E)}$	$1\%\oplus1\%/\mathrm{sqrt(E)}$	$1\%\oplus1\%/\mathrm{sqrt(E)}$
Hadronic resolution	30%/sqrt(E)	30%/sqrt(E)	15%/sqrt(E)	30%/sqrt(E)	30%/sqrt(E)	30%/sqrt(E)	15%/sqrt(E)
Lep angular resolution	2^o	1^o	2^o	2^o	1^o	1^o	2^o
Had angular resolution	10^o	5^o	10^o	10^o	10^o	10^o	5^o
MH Sensitivity (σ) δ_{CP}=0	**1.983 (beam ~4.2)**	**1.987**	**2.314**	**2**	**1.981**	**2.107**	**2.382**

Impact of hadrons on atmospheric neutrino physics

- Since hadrons are the most difficult part of the event to measure, they dominate our resolution in neutrino energy and angle
- For the MH measurement, we are talking about hadronic systems with **few 100 MeV - few GeV**
- **Caveat**: neutrino-induced hadronic showers will be different from those produced by single particle test beams
  - *However, the same nuclear models to simulate the former can be applied to the latter (ie, run GENIE in hadron-scattering mode)*
  - *Understanding the level of agreement in test beam data will be crucial for validating at least part of the models*

pDUNEs: need measurement of energy and direction resolutions for hadrons. Study of multi-hadron final states important

Bonus: neutrino/antineutrino separation in atmospherics

Separating neutrinos from antineutrinos would greatly enhance DUNE's sensitivity to MH

- Full separation could be achieved with B-field. In non-magnetised detector as DUNE, statistical discrimination still possible with **proton tag** or **decay electron tag**

[Fechner and Walter, JHEP 0911 (2009) 040]

neutrino: $\nu_\mu + n \rightarrow \mu^- + p$

75% ↳ capture

25% ↳ $e^- + \bar{\nu}_e + \nu_\mu$

antineutrino: $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

100% ↳ $e^+ + \nu_e + \bar{\nu}_\mu$

Tag	Efficiency
Proton	100% if p KE > 50 MeV
Decay electron	25% μ^-, 100% μ^+

pDUNEs: need measurement of p and decay e tagging efficiencies

Atmospherics and interaction models

From Y. Hayato's talk at ANW'16

pDUNEs: need measurement of $\pi^{\pm}$-Ar and p-Ar cross sections

Summary ~ what has to be understood

- Neutrino – nucleus interactions
  - Major sources of the systematic errors
    - Axial coupling
    - Treatment of `bound' nucleon
    - ➡ Hadron multiplicities
    - Re-interaction of hadrons in nucleus
      - ➡ pion interactions
      - ➡ re-scattering of nucleon etc..
    - Nuclear parton distribution function
- Actual systematic uncertainties in the neutrino experiments
  - Neutrino – nucleus interactions
  - Hadron interactions in nucleus
    - ➡ pion interactions in the detector
    - ➡ nucleon interactions
      - high energy nucleon ~ particle production

- http://indico.universe-cluster.de/indico/conferenceDisplay.py?ovw=True&confId=3533

Prioritized list of pDUNEs measurements for atmospherics physics

For discussion

1. Track/shower reconstruction performance

- Energy and direction resolution for single hadrons
- Energy and direction resolution for multi-particle hadronic system
- Reconstruction efficiency
- Vertex resolution
- Lepton track sense (up/down)

2. Particle ID performance

- Efficiencies and contamination for e / μ, e / γ, μ / π separation
- Particle / anti-particle ID via decay electron and proton tagging efficiencies

3. $\pi^{\pm}$-Ar and $K^{\pm}$-Ar cross section measurements

- Few 100 MeV - few GeV kinetic energies

Increasing importance

pDUNEs measurements for NDK/Atmospherics

Summary of priorities (tentative)

Physics topic	h-Ar xsecs	Track/shower reco	Particle ID
NDK	√	√ √	√ √ √
Atmospherics	√	√ √ √	√ √

ProtoDUNEs datasets and non-TPC instrumentation

ProtoDUNEs test beam requests

From SP proposal, DP TDR

pDUNE-SP
(DUNE-doc-186)

Particle	Momenta (GeV/c)	Sample Size	Purpose
π^+	0.2, 0.3, 0.4, 0.5, 0.7, 1, 2, 3, 5, 7	10k	hadronic cal, π^0 content
π^-	0.2, 0.3, 0.4, 0.5, 0.7, 1	10k	hadronic cal, π^0 content
π^+	2	600k	π^o/γ sample
proton	0.7, 1, 2, 3	10k	response, PID
proton	1	1M	mis-ID, PD, recombination
e^+ or e^-	0.2, 0.3, 0.4, 0.5, 1, 2, 3, 5, 7	10k	e-γ separation/EM shower
μ^-	(0.2), 0.5, 1, 2	10k	E_μ, charge sign
μ^+	(0.2), 0.5, 1, 2	10k	E_μ, Michel el.,charge sign
μ^- or μ^+	3, 5, 7	5k	E_μ MCS
anti-proton	low-energy tune	(100)	anti-proton stars
K^+	1	(13k)	response, PID, PD
K^+	0.5, 0.7	(5k)	response, PID, PD
μ, e, proton	1 (vary angle $\times$5)	10k	reconstruction

pDUNE-DP
(arXiv:1409.4405)

Type	**Momentum [GeV/c]**	**Rate [kHz]**	**Total**	**Time est. [hrs]**
Muon tracks				
$\mu^{+/-}$	0.8, 1.0, 1.5, 2.0, 5.0, 10.0, 20.0	0.1	$5 \times 10^6 \times 14$	200
Shower reconstruction				
$\pi^{+/-}$	0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0	0.1	$5 \times 10^6 \times 14$	200
e	0.5, 0.7, 1.0, 2.0, 5.0, 10., 20.0	0.1	$5 \times 10^6 \times 7$	100

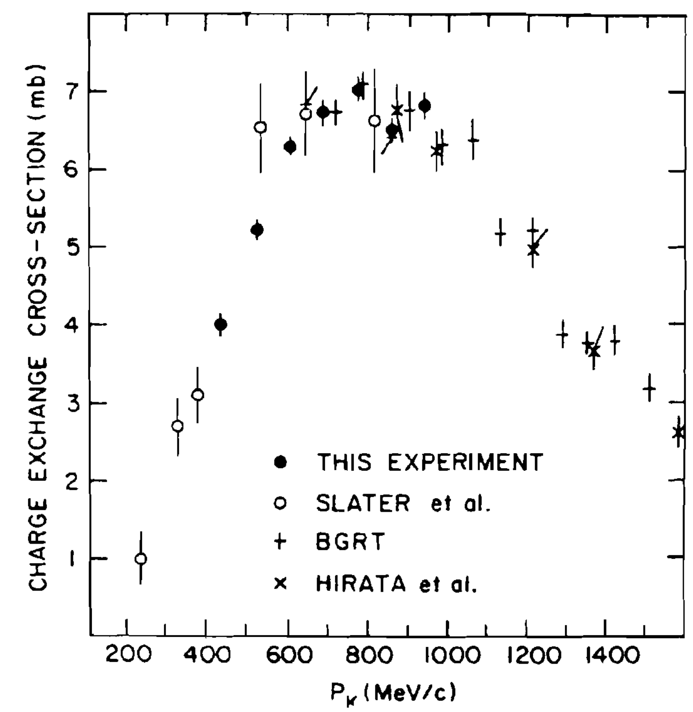
Beam datasets

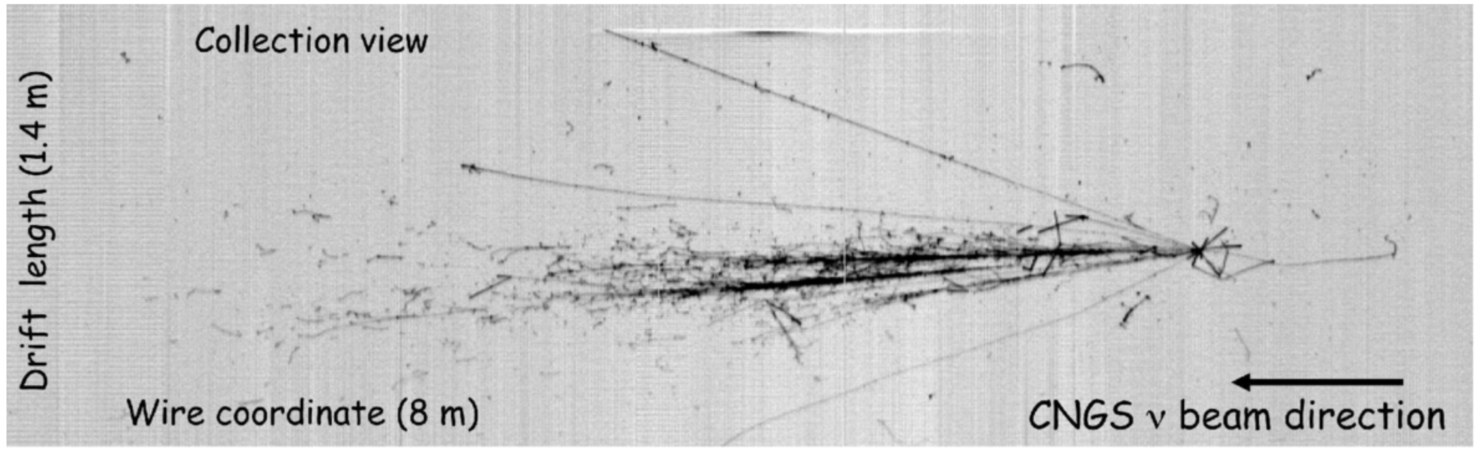
Particle types and momenta

Overall, initial test beam request from pDUNEs is a good match to NDK/Atmospherics physics goals

- Specific comments:
  - **K^+ beams** would be valuable. Not just **K^+** non-interacting events. Also K^+ charge-exchange events to study **K^0_S** decay topologies
  - **μ^+ vs μ^- beams** to study decay electron tag efficiency
  - **$\pi^\pm$ beam** data sets over **extended** momentum range valuable, covering from **single track topologies** to **hadronic showers**

$K^+n \rightarrow K^0p$ charge exchange





~10 GeV ν_μ CC interaction in ICARUS

Beamline instrumentation

Momentum resolution

Ideally, beamline instrumentation should provide **better** momentum and PID selection/measurement compared to the ones we wish to perform in pDUNEs

- Current pDUNEs goal to measure **momentum** of incoming particles with **1-5% accuracy** should be **sufficient** for NDK/Atmospherics purposes

Beamline instrumentation

PID

Ideally, beamline instrumentation should provide **better** momentum and PID selection/measurement compared to the ones we wish to perform in pDUNEs

- **PID** requirements for NDK/Atmospherics still to be quantified. Preliminary numbers:
  - (e+μ+π) / K / p separation with **>99% purity** (and >99% efficiency) via dE/dx from Bueno et al. (arXiv:0701101) assumptions for NDK searches

Current pDUNEs goal to provide **>3σ** *π/K separation over full momentum range should be maintained, even if for only a subset of events*

  - LBNE atmospherics studies assume **99%** $\pi^{\pm}$ suppression in μ-like sample

Possible to limit muon contamination in $\pi^{\pm}$ *datasets to* **1%** *at most?*

  - Also need "good" (tbd) e / μ / π separation

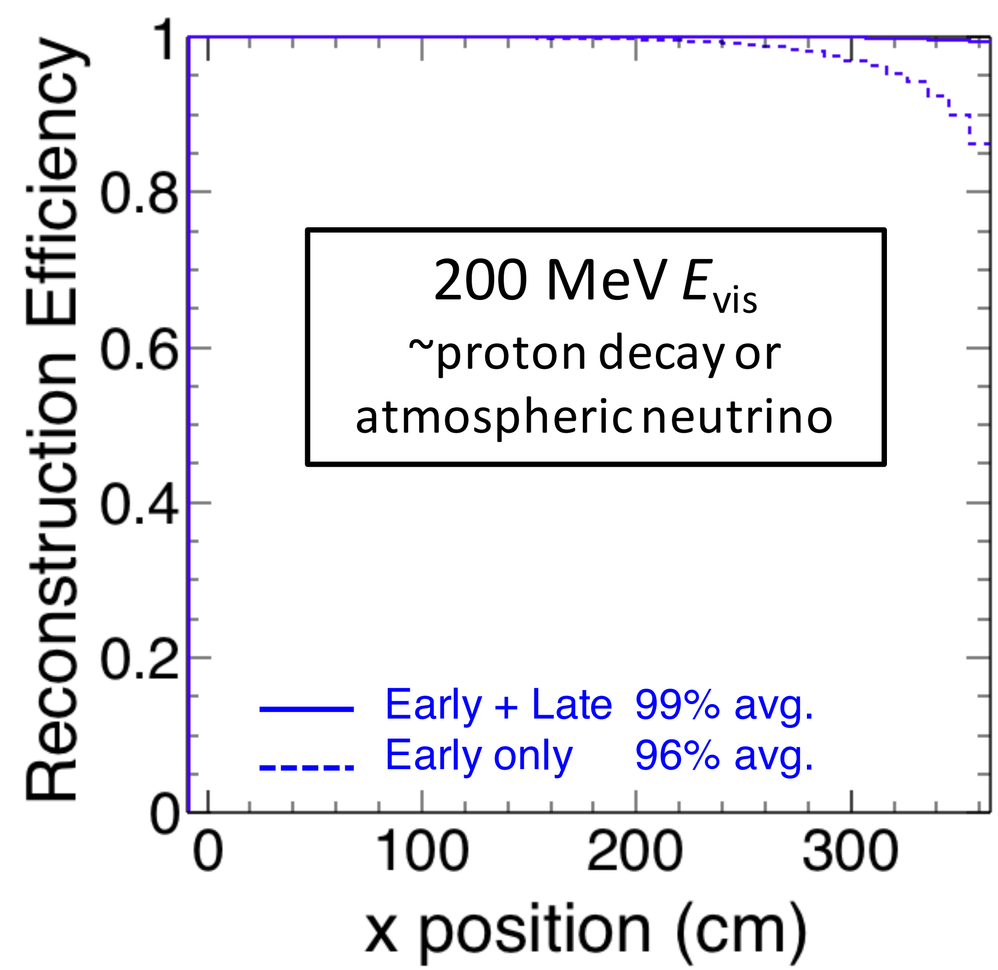
Photon detector system

- Slide from Alex Himmel for DUNE FD

pDUNEs: validate MC expectations for PDS light yields

How much light do we need?

- Assume 0.32% detector efficiency, 5 PE threshold summed across all PDs.
- Look at proton decay or atm. neutrino-like energy depositions.
- Good efficiency (>99%) across the whole detector.
  - Seeing ~80 photons from the far side of the detector.
- Note: basically a calculation, not a full event simulation and reconstruction!



Cosmic-ray sample

And related instrumentation

- Instrumentation enabling cosmic ray muon sample very useful for pDUNEs **calibration**
- May also provide information for NDK/Atmospherics/Cosmogenic **physics** that is **complementary** to beam data samples
  - Photon detector system trigger efficiency vs deposited energy, position
  - Neutrons?

Summary

Summary

- Have tried to provide a prioritized list of pDUNEs measurements of particular relevance for Nucleon Decay / Atmospheric Neutrino Physics
- Started to think about pDUNEs beam requirements from NDK/ Atmospherics point of view. To be made more quantitative
- Natural for people involved in NDK/Atmospherics/Cosmogenic Physics WGs to also be involved in related pDUNEs analyses
    - *TPC PID performance, hadron track/shower reco, charge sign discrimination, photon detector light yields, etc.*