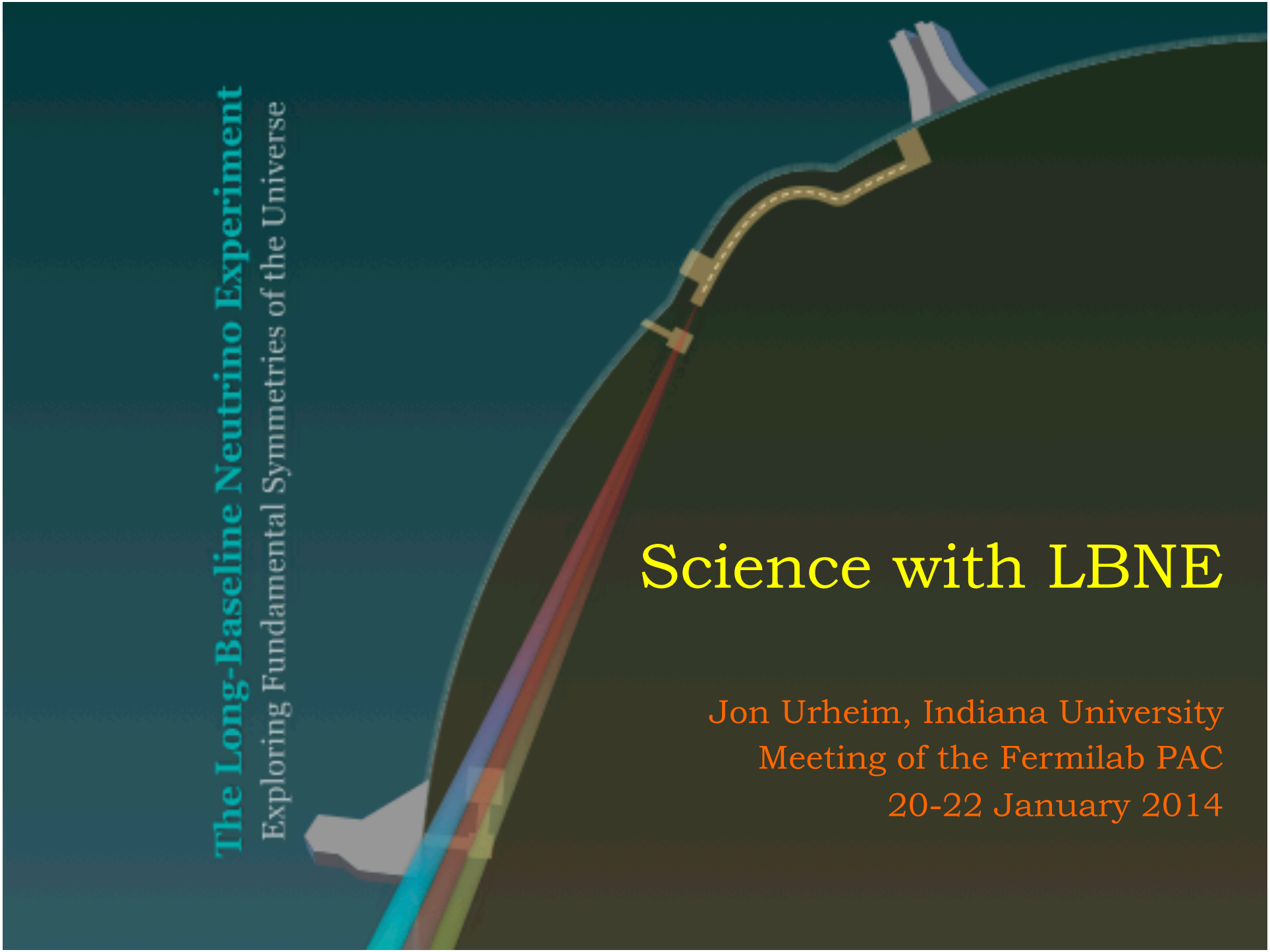


Science with LBNE

Jon Urheim, Indiana University

Meeting of the Fermilab PAC

20-22 January 2014

Outline

Updates on Long-Baseline Physics Sensitivity

- Impact of PIP-II
- Status of Systematic Error Studies

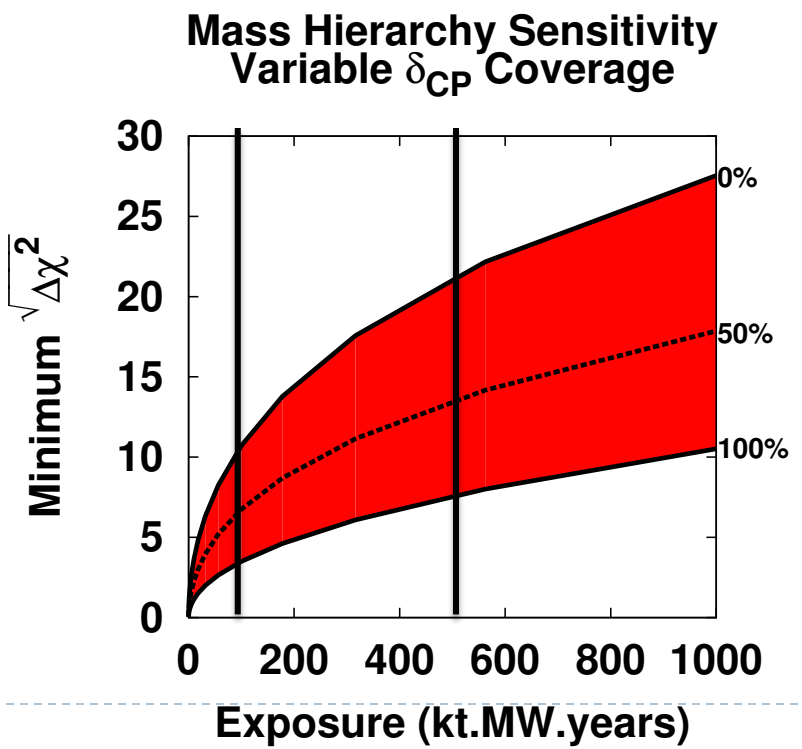
Summary of Capabilities for Underground Physics

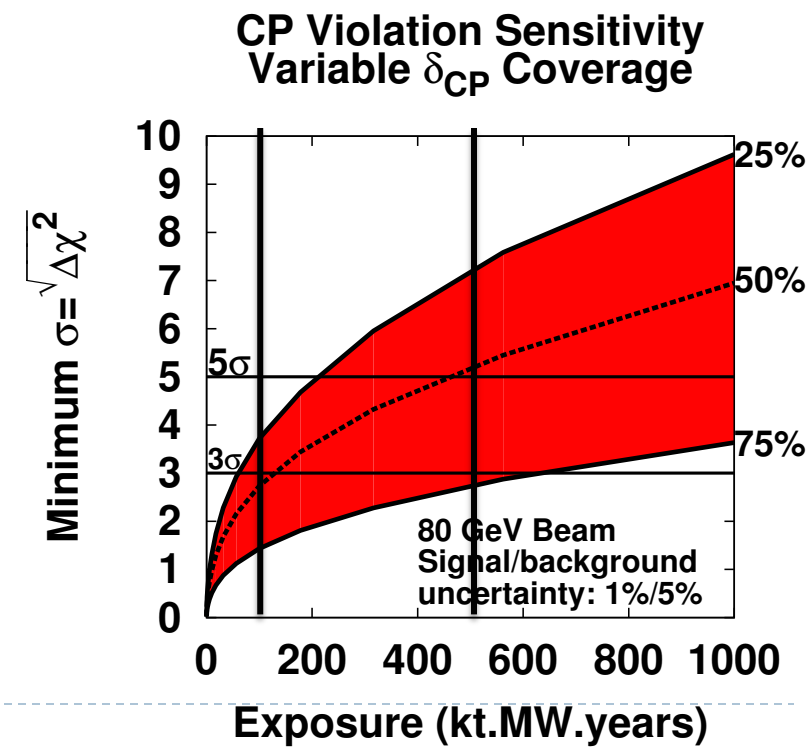
- Precision Physics with Atmospheric Neutrino Samples
- Nucleon Decay ($p \rightarrow K^+ \nu$)
- Supernova Neutrino Burst Detection

- Note: will indicate where work being done to "further the understanding of LBNE science capabilities" will provide additional input in the "immediate future".

Long-Baseline Physics – PIP-II Impact

- Now assume 700kW → 1.2MW at LBNE Phase-I start (~2025)
- Imagine following scenario:
  - Start w/ 15-kt LArTPC & 1.2 MW in 2025 → 90 kt-MW-yr exp by 2030
  - Add 20-kt in 2030; upgrades to 2.3 MW → ~500 kt-MW-yr net by 2035





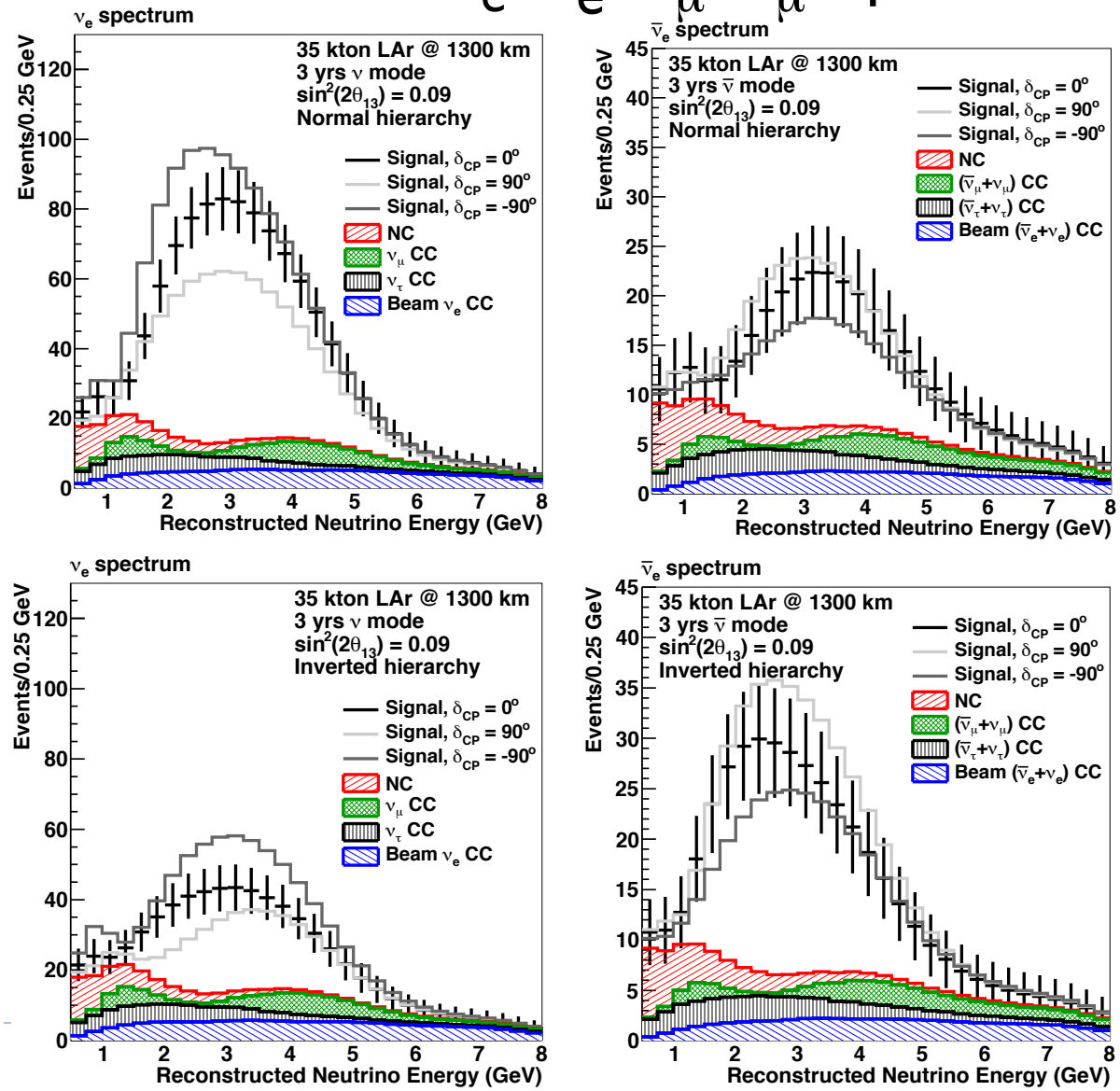
Long-Baseline Physics – Systematics

- Analysis involves simultaneous fit to ν_e/ $\bar{\nu}_e$/ ν_μ/ $\bar{\nu}_\mu$ spectra

<u>Left Plots:</u>

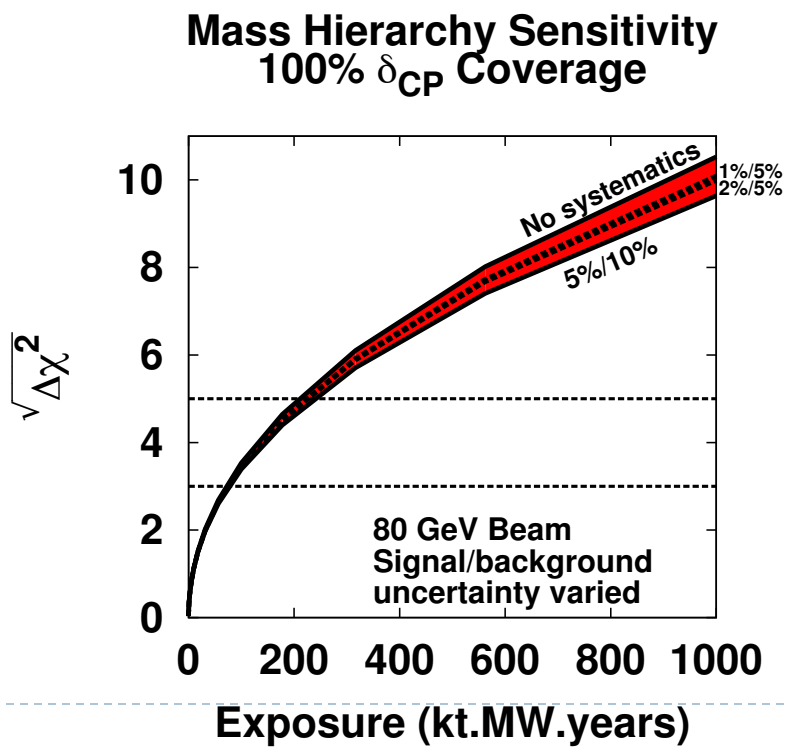
ν_e energy spectra for:
NH (top)
IH (bottom)
For 35-kt LArTPC @ 1.2 MW for 3 years (125 kt-MW-yr)

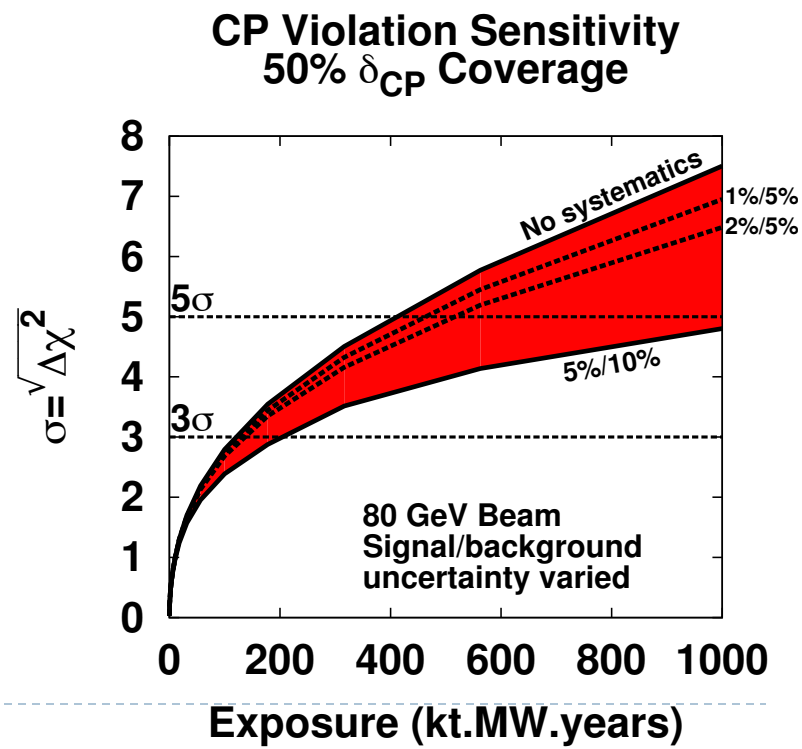
<u>Right Plots:</u>
Corresponding spectra for 3 years of anti-nu running for net exposure (nu + anti-nu) of 250 kt-MW-yr



Long-Baseline Physics – Systematics

- Renewed studies of systematic errors under way
- Benefitting from interactions with LBNO colleagues
- Below, show impact of changes to 2 simple inputs:
  - 1) Uncorrelated ν_e Signal Normalization unct'y (nominally 1%)
  - 2) ν_e Background rate uncertainty (nominally 5%)





Long-Baseline Physics – Systematics

- Consider initial event yields.

Event yields for 10-kt @ 1.2 MW, for 3 (nu) + 3 (anti-nu) years → 72 kt-MW-yr

	Signal Events	Background Events				
	ν_e	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC	Total
Neutrino Normal Hierarchy	222	19	24	42	14	99
Neutrino Inverted Hierarchy	98	19	23	44	15	100
Antineutrino Normal Hierarchy	54	11	11	23	9	54
Antineutrino Inverted Hierarchy	80	11	11	23	9	54

- Can tolerate larger systematic errors for low-exposure expt (e.g., "LBNE Phase-I")
  - Reconfiguration Process carefully assessed capability of 10-kt LArTPC
    - 1) located on the surface
    - 2) with no near neutrino detector
    - Much documentation !!

Projected 5%/10% (signal/bg) syst error, based on:
1) LBNE beam similar to NuMI
2) Anticipated μ flux detection at near site
3) Anticipated results from hadron production expts (NA61/SHINE + MIPP)
4) Experience of previous ν_e appearance expts

Long-Baseline Physics – Systematics

Experiment	Year	NC/CC (π^0) Events	ν_e-like Events	Background Syst.Error	Comment
BNL E734 [115]	1985	235	418	20%	No ND
BNL E776(89)(NBB) [116]		10	9	20%	No ND
BNL E776 (WBB)	1992	95	40	14%	No ND
NOMAD [117]	2003	<300	5500	< 5%	No ND
MiniBooNE [118]	2008	460	380	9%	No ND
MiniBooNE [119,120]	2013	100	312	6%	No ND
MINOS [103]	2013	111	36	4%	ND–FD
T2K [121]	2013	1.1	26	9%	ND–FD

- General considerations for larger exposure LBNE
  - Now assume a fully equipped Near Neutrino Detector
    - see MINOS entry above for Background systematics achieved
    - corresponding near site measurements can be done with LBNE
    - similarly, precise neutrino flux determination possible (next slide)
  - Recognize that full suite of measurements from MINERvA, MicroBooNE & NOvA Near Detector will also provide input.

Long-Baseline Physics – Systematics

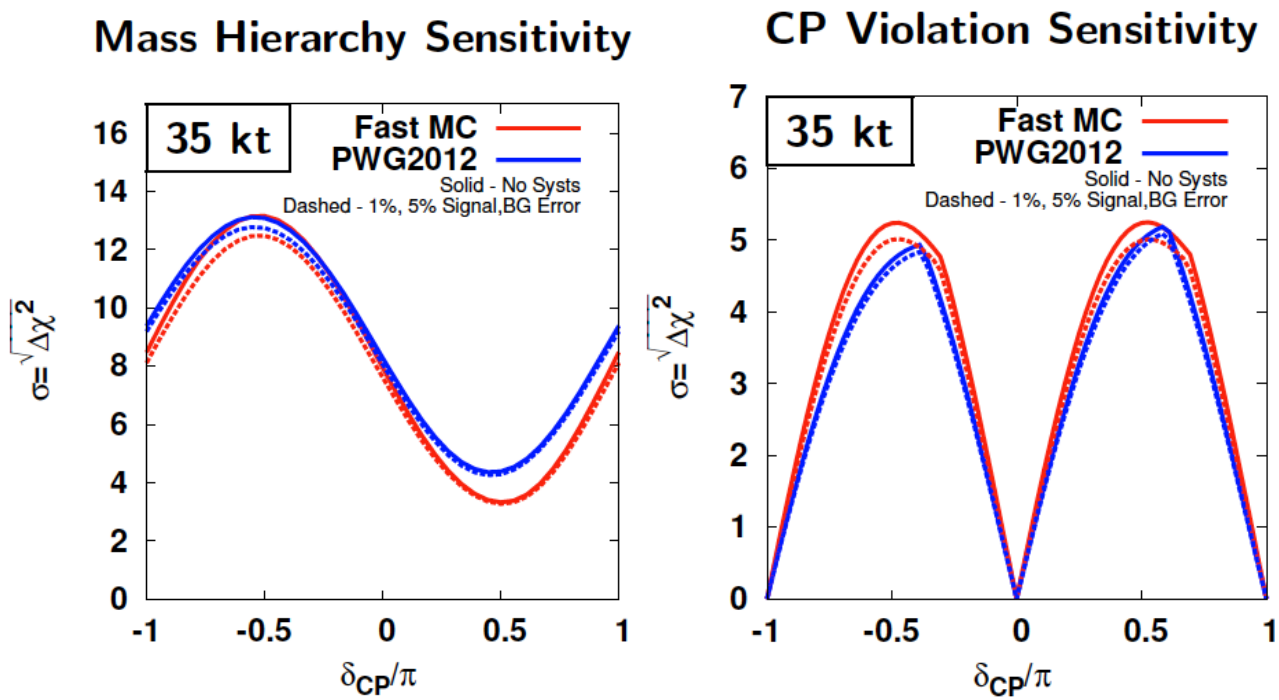
- Signal Normalization Calibration w/ LBNE Near Detector
  - Several methods used successfully in MINOS & NOMAD
  - Note some specific capabilities of LBNE Near Detector:

Flavor	Technique	Relative abundance	Absolute normalization	Relative flux $\Phi(E_\nu)$	Detector requirements
ν_μ	$\nu_\mu e^- \to \nu_\mu e^-$	1.00	2.5%	$\sim 5\%$	e ID θ_e Resolution e^-/e^+ Separation
ν_μ	$\nu_\mu e^- \to \mu^- \nu_e$	1.00	3%		μ ID θ_μ Resolution 2-Track (μ+X) Resolution μ energy scale
ν_μ	$\nu_\mu n \to \mu^- p$ $Q^2 \to 0$	1.00	$3-5\%$	$5-10\%$	D target p Angular & Energy resolution Back-Subtraction
$\bar{\nu}_\mu$	$\bar{\nu}_\mu p \to \mu^+ n$ $Q^2 \to 0$	0.70	5%	10%	H target Back-Subtraction
ν_μ	Low-ν_0	1.00		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\bar{\nu}_\mu$	Low-ν_0	0.70		2.0%	μ^- vs μ^+ E_μ-Scale Low-E_{Had} Resolution
$\nu_e/\bar{\nu}_e$	Low-ν_0	0.01	1-3%	2.0%	e^-/e^+ Separation (K_L^0)

Long-Baseline Physics – Systematics

- Status of LBNE-specific efforts
  - More detailed understanding of sources of error with more detailed parameterization → "FastMC"

Examples of comparisons of "FastMC" based sensitivity with GLoBES-based approach (D. Cherdack, M. Bass)



  - Parallel efforts toward full simulation+reconstruction making good progress as well (next two slides + back-up)

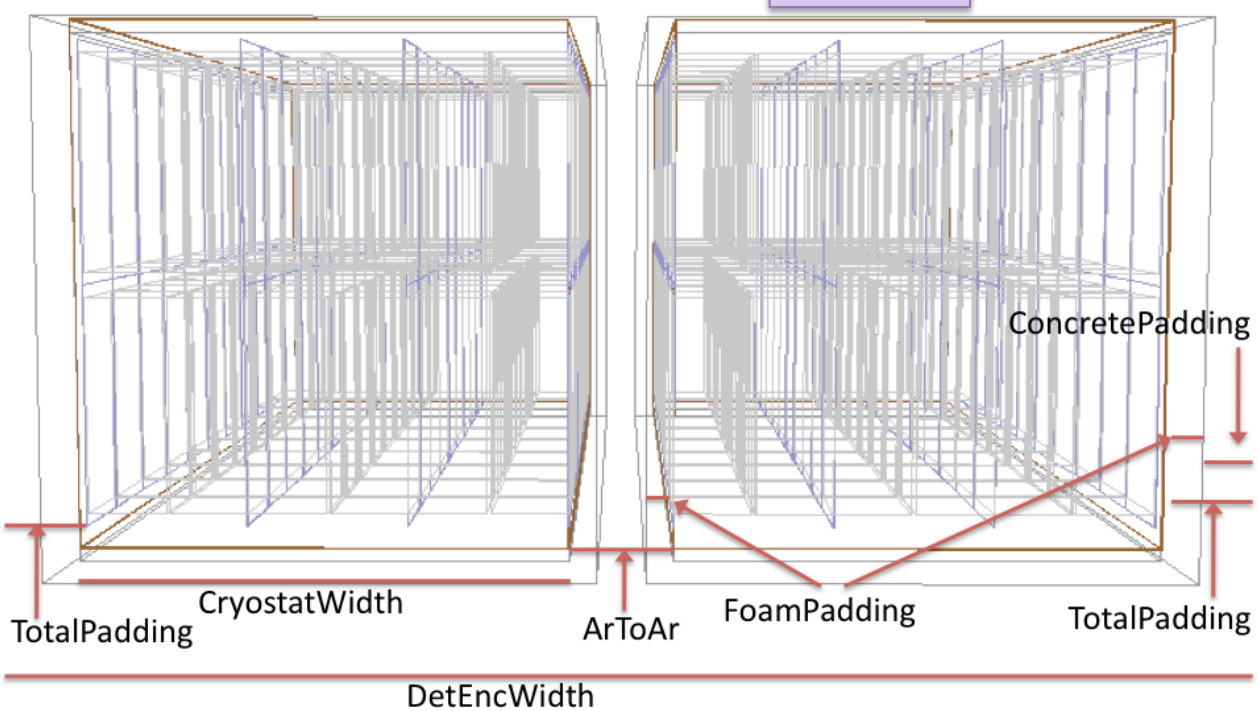
Far Detector Simulation Status

Geometries included in GEANT4-based LArSoft simulation:

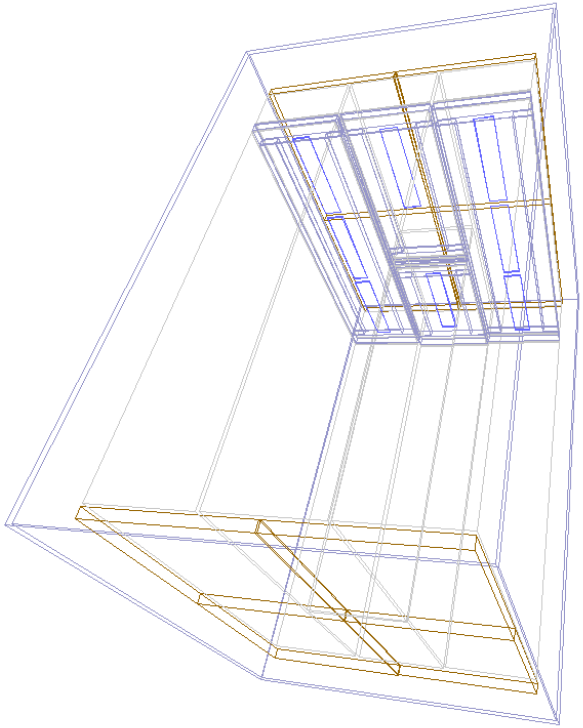
- 10 kt FD (with 45° and 36° wires)
- 34 kt FD
- "reduced" 4-APA Far detector – for computational efficiency (also 45° and 36° versions)
- 4-APA 35t Phase II prototype detector
- Simplified ICARUS Detector

MicroBooNE and ArgoNeuT geometries also available

10 kt FD



35t Phase II



Tyler Alion, Jae Kim, Sanjib Mishra,
Kevin Wood, Xinchun Tian,
Mike Kirby, Brian Rebel, Tom Junk

Ongoing Reconstruction and Simulation Studies

- Hit-finding efficiency, charge resolution, and two-hit separation power
- Disambiguation efficiency and purity
- Impact of disambiguation performance on energy resolution of showers
- Calorimetric energy resolution for low-energy electrons
- dE/dx vs. residual range
- Tracking efficiency
- e-gamma separation
- straight-track reconstruction in 35t
- stopping muon identification in 35t
- Energy resolution vs. zero-suppression threshold
- incorporation of NEST electron/photon production model
- Refinement of radiological simulation
- Cosmogenics background simulation for surface and underground options
- Adaptation of PANDORA reconstruction (clustering, track and shower identification, vertex finding) to the LBNE FD
- Acceptance and containment as a function of detector orientation with respect to the beam axis

Long-Baseline Physics – Summary

- **PIP-II strengthens early program of LBNE physics**
  - We continually work to enhance early sensitivity of LBNE
  - Every 5 and 10% improvement counts!
  - PIP-II is a 70% improvement on its own!

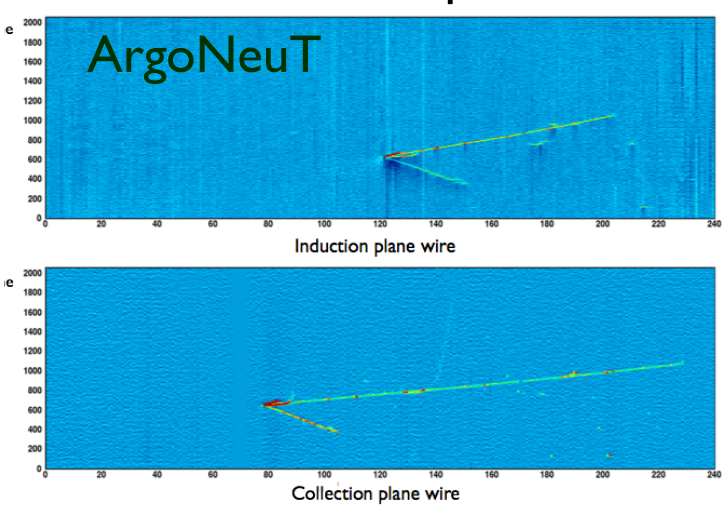
- **Anticipated LBNE systematic errors becoming better established**
  - Already making use of much work from the community
  - Will benefit from experiments now running / soon to run
  - Impact of systematic errors on early LBNE physics is minimal
  - Ambitious design for LBNE Near Detector & subsequent analysis
  - Simulation & Analysis tools at a stage of rapid development: (comprehensive review of LBNE computing & software planned for May)
  - Summary of systematic error issues in LBNE SciOpp Document (LBNE-docdb-8087, arXiv:1307.7335), updated version to be released imminently.
  - A dedicated standalone document on systematic errors is in preparation; pulls together knowledge on the full span of sources of error for LBNE. This document will be completed on timescale of weeks, not months.

LBNE Underground Physics

- Reviews of LBNE capabilities have been carried out
  - Much Documentation:
    - Physics Working Group 2010 Interim Report (arXiv:1110.6249)
    - LAr Case Study Document (LBNE-docdb-3600)
    - LBNE Conceptual Design Report
    - LBNE Science Opportunities Document (docdb-8087, arXiv:1307.7335)
  - LBNE Project reviews, (inter)national studies, etc., *plus (for example)*:
    - DOE Office of Science Independent Review of Options for Underground Science (Marx Committee), April 2011.
    - LBNE Science Capabilities Review, November 2011.
    - LBNE Reconfiguration Review, Spring 2012.
  - Reviews have tended to focus on the long-baseline physics
- So, now focus on Underground Physics for rest of talk
  - Please consult Science Opportunities Document for more detail
  - Start with Atmospheric Neutrinos…

Atmospheric Neutrinos – Introduction

- Well-studied by many experiments, most notably SuperK
- Exquisite capabilities of LArTPC give LBNE potential for new discoveries in an arena that has already yielded surprises
  - detailed imaging of interaction
  - → **exclusive reconstruction, ν energy & direction resolution**
- Recent Parameterized MC & Analysis Studies for LBNE.
  - Just a brief summary here: see LBNE SciOpp Document for details
  - Key feature: precise neutrino direction (& hence baseline) determination
  - Assumed performance parameters (based partly on ICARUS):

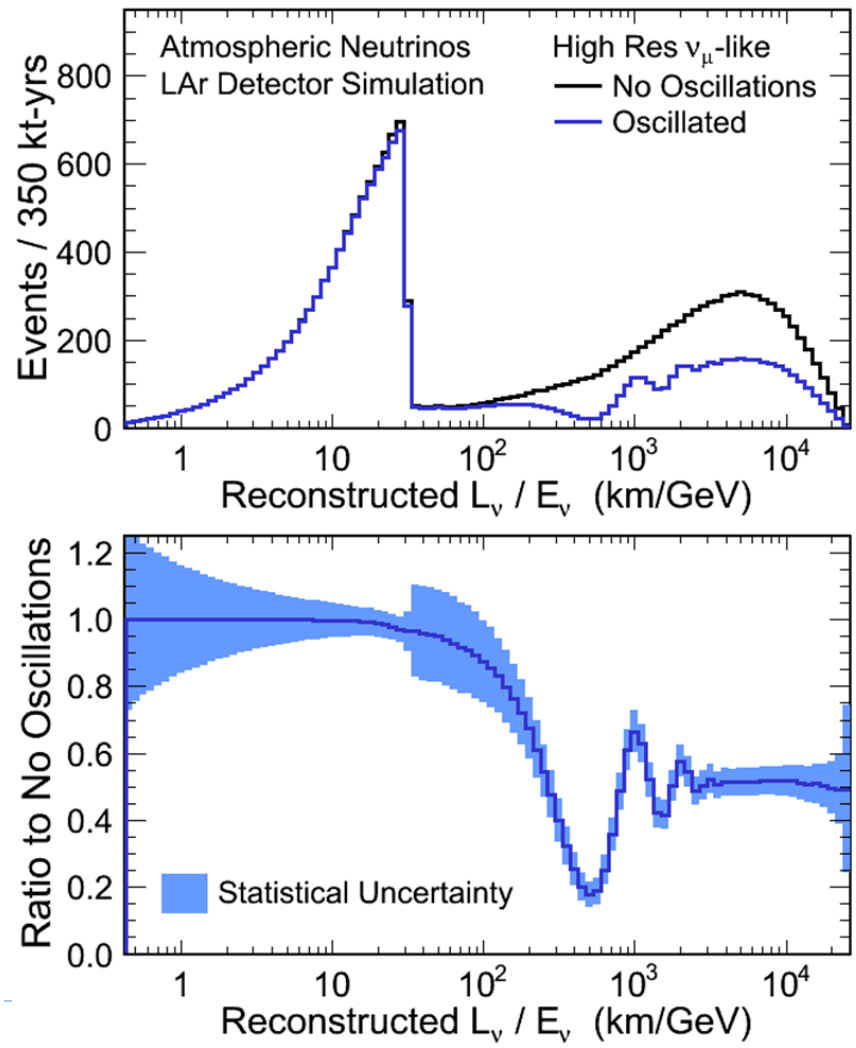


Angular Resolutions	Electron	$1°$
	Muon	$1°$
	Hadronic System	$10°$
Energy Resolutions	Stopping Muon	3%
	Exiting Muon	15%
	Electron	$1\%/\sqrt{E(GeV)} \oplus 1\%$
	Hadronic System	$30\%/\sqrt{E(GeV)}$

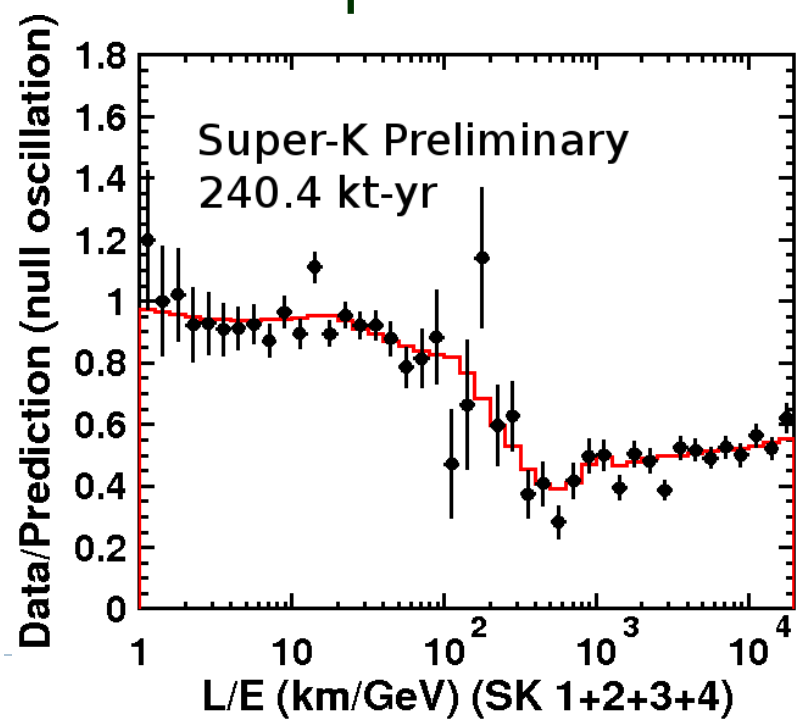
Atmospheric Neutrinos – L/E

LBNE 350 ky-yr exposure

MC w/ Parameterized Response

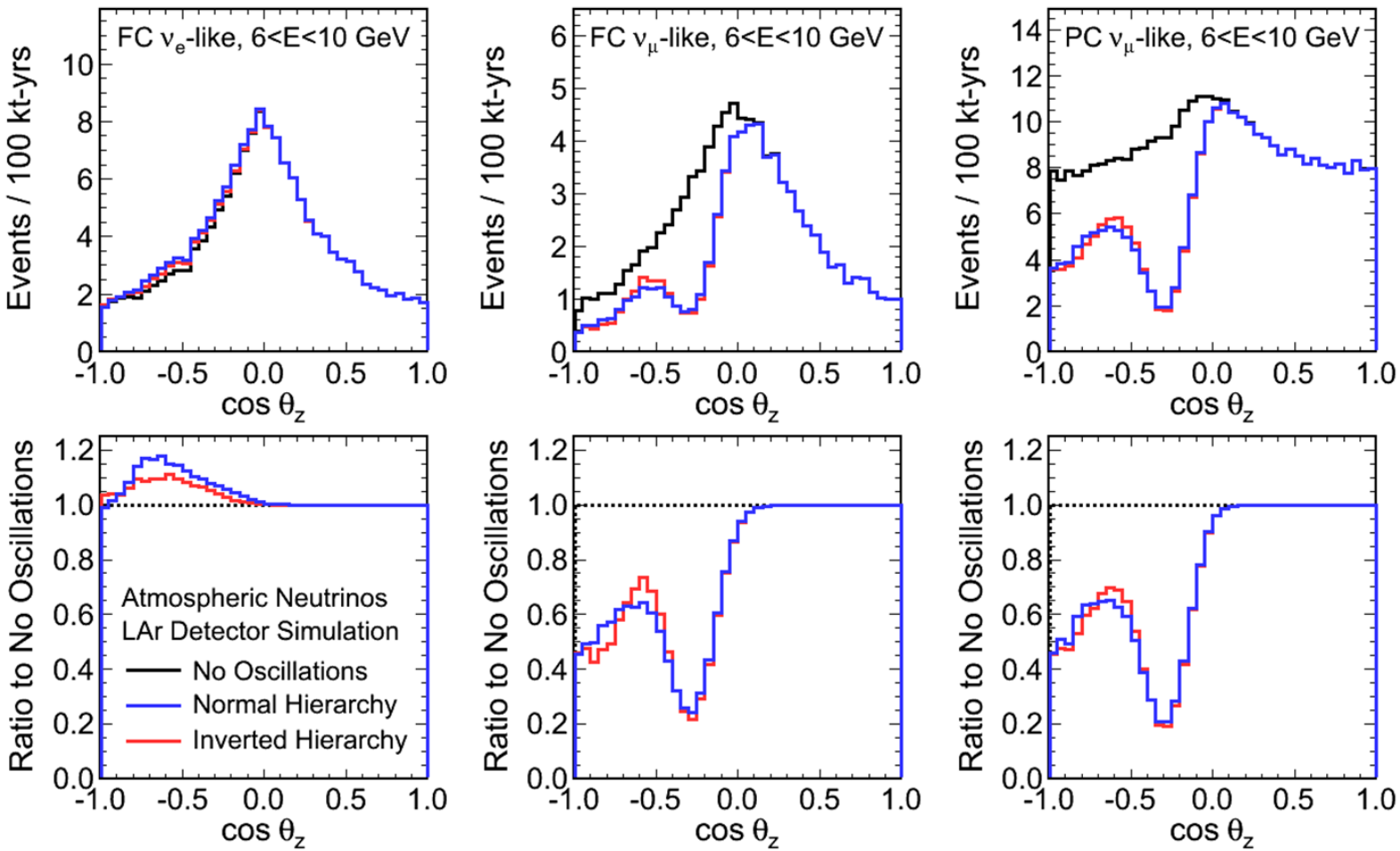


SuperK Data



Atmospheric Neutrinos – MH sensitivity

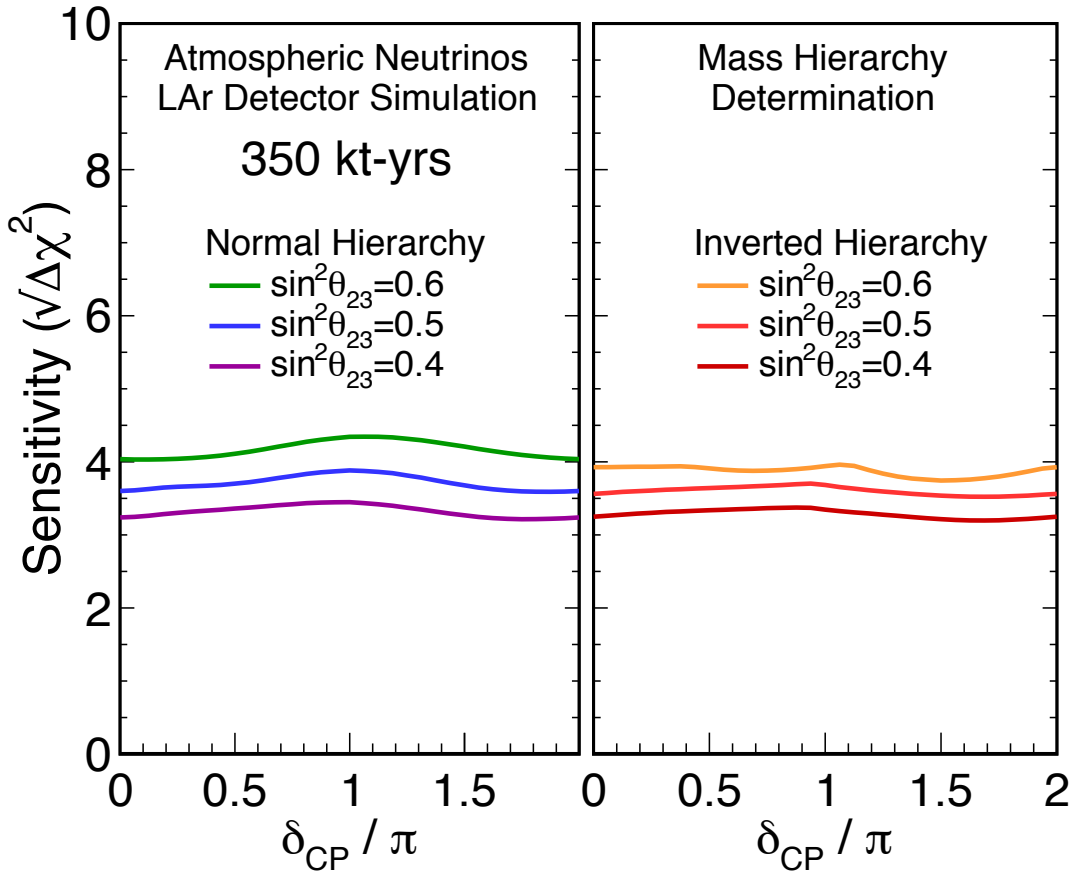
Zenith angle distributions for events w/ E = 6-10 GeV
Comparison of Normal vs Inverted MH



Atmospheric Neutrinos – MH results

Sensitivity to Mass Hierarchy

- see combination with beam-based determination in backup slides
- see also sensitivities to CP violation & θ_{23} Octant determination



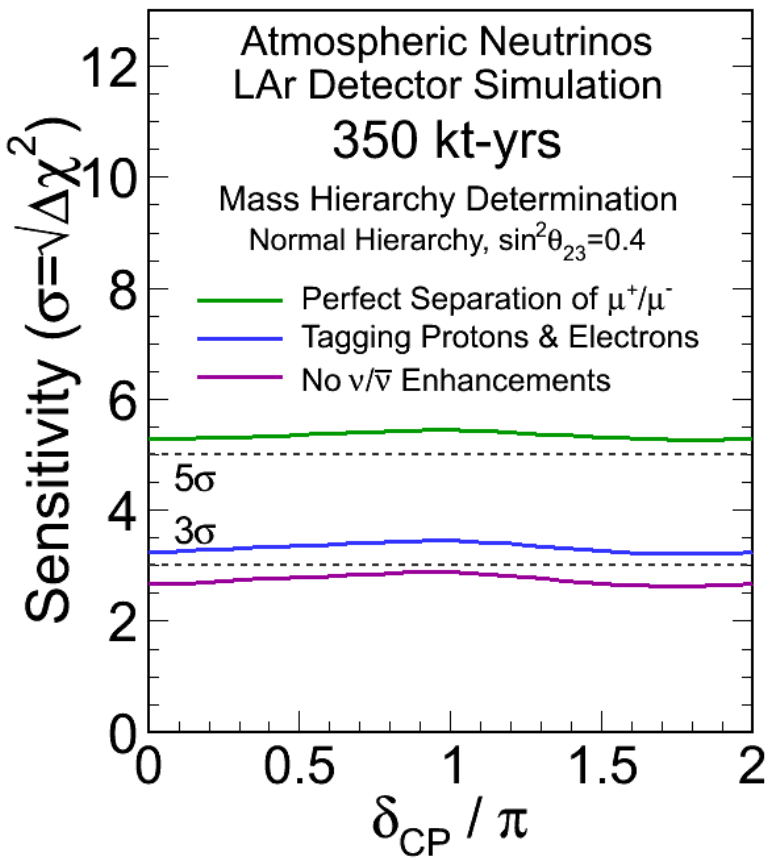
Atmospheric Neutrinos: $\nu/\bar{\nu}$

- Sensitivity to MH is enhanced if nu's & anti-nu's can be separated…
  - First studies of impacts of possible tagging strategies:
    - Tag proton for neutrino CC events :

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

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

    - Absence of Michel electron tags muon capture (μ^- only)



Atmospheric Neutrinos – Summary

- **LBNE LArTPC provides unique opportunity to explore atmospheric neutrinos in an entirely new way.**
  - Reconstruct both neutrino energy & direction w/ good resolution
  - Excellent discrimination of ν_e CC, ν_μ CC, and NC interaction
  - Possibility of (limited) nu/anti-nu discrimination

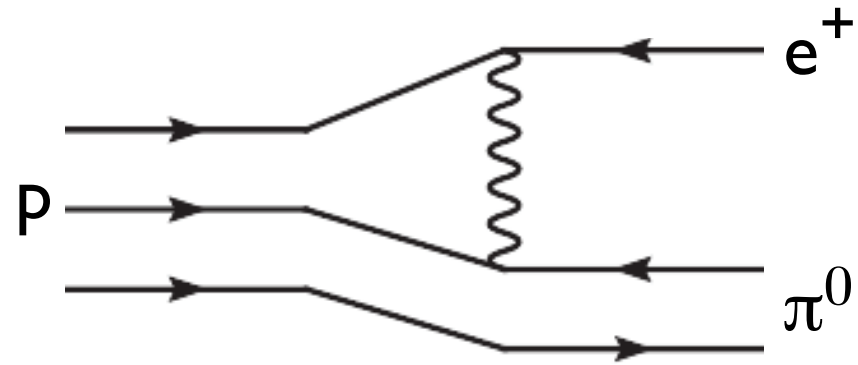
- **Demonstration of capabilities for oscillation physics with parameterized MC and independent (non-GLoBES based) multivariate oscillation parameter fitting codes, building on experience with MINOS**
  - See LBNE SciOpp Document for detailed description
  - See also: A. Blake, presentation at ISOUPS, May 2012.

- **Now have first round of fully simulated (LBNE Geometry) atmospheric neutrino events.**
  - Studies with real event reconstruction will take some time
  - First attempts with promising Pandora package will be soon (backup)

Nucleon Decay – Benchmark Channels

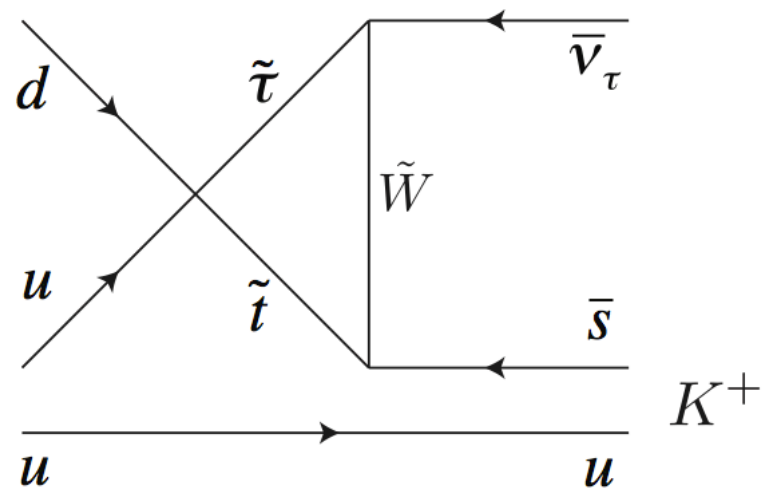
- $p \rightarrow e^+ \pi^0$
  - Gauge mediated mode from GUTs; Non-observation ruled out minimal SU(5)
  - SUSY would raise GUT scale, making mode a favorite for same reasons as before
  - Current limit: **1.3 x 10^{34} yr** (90%CL), from **SK1–4, 206 kt-yr**. (PRD 85.112001)

    No candidates, bckgrnd est. at **2 / Mt-yr**

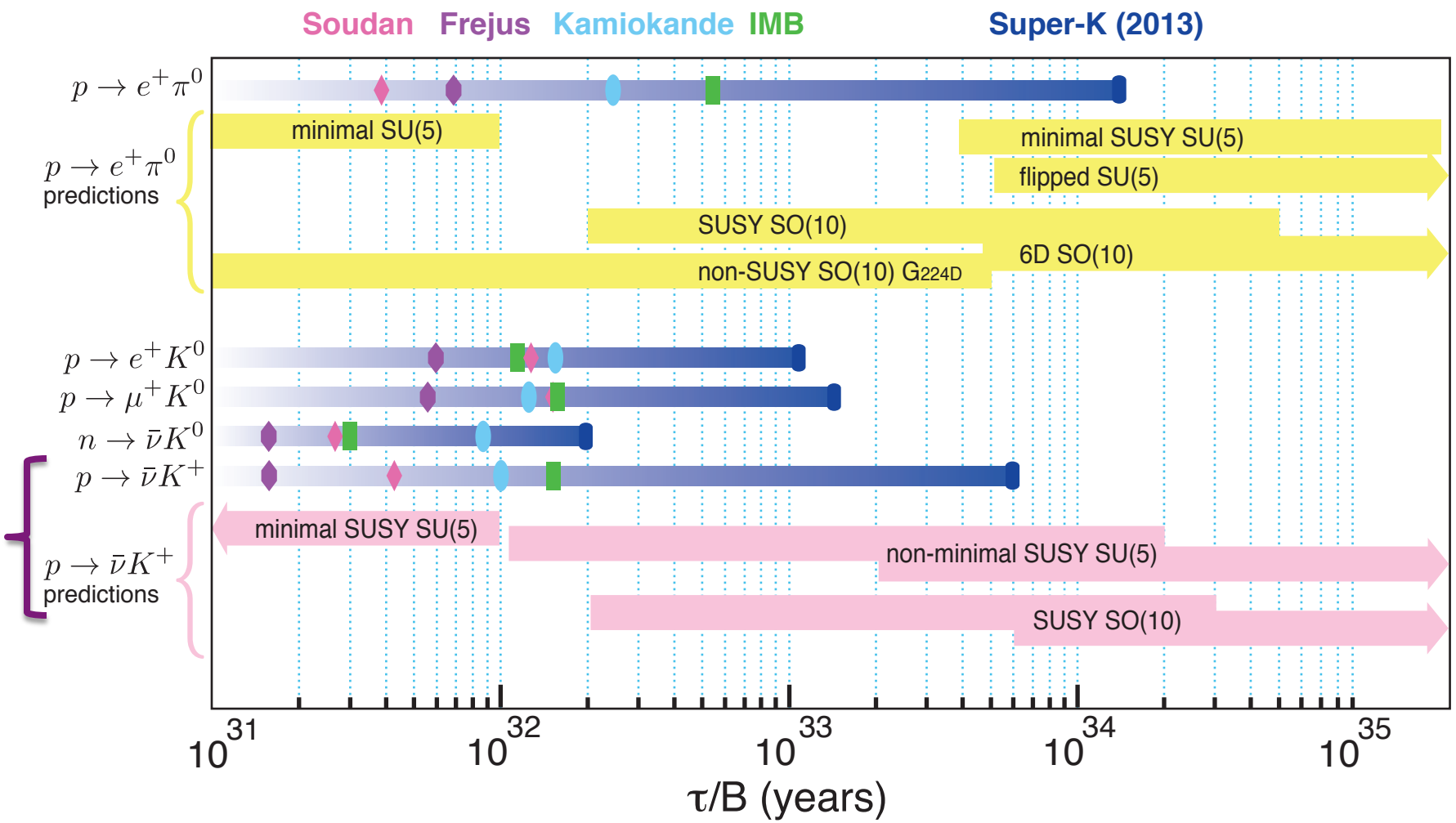


- $p \rightarrow K^+ \nu$
  - A favored mode for SUSY
  - Current limit: **0.6 x 10^{34} yr** (90%CL), from **SK1–4, 206 kt-yr**. (preliminary)

    No candidates observed in 19%-effcy K id signature, bg estimated at **~4 / Mt-yr.**
  - LBNE LArTPC has discovery potential !

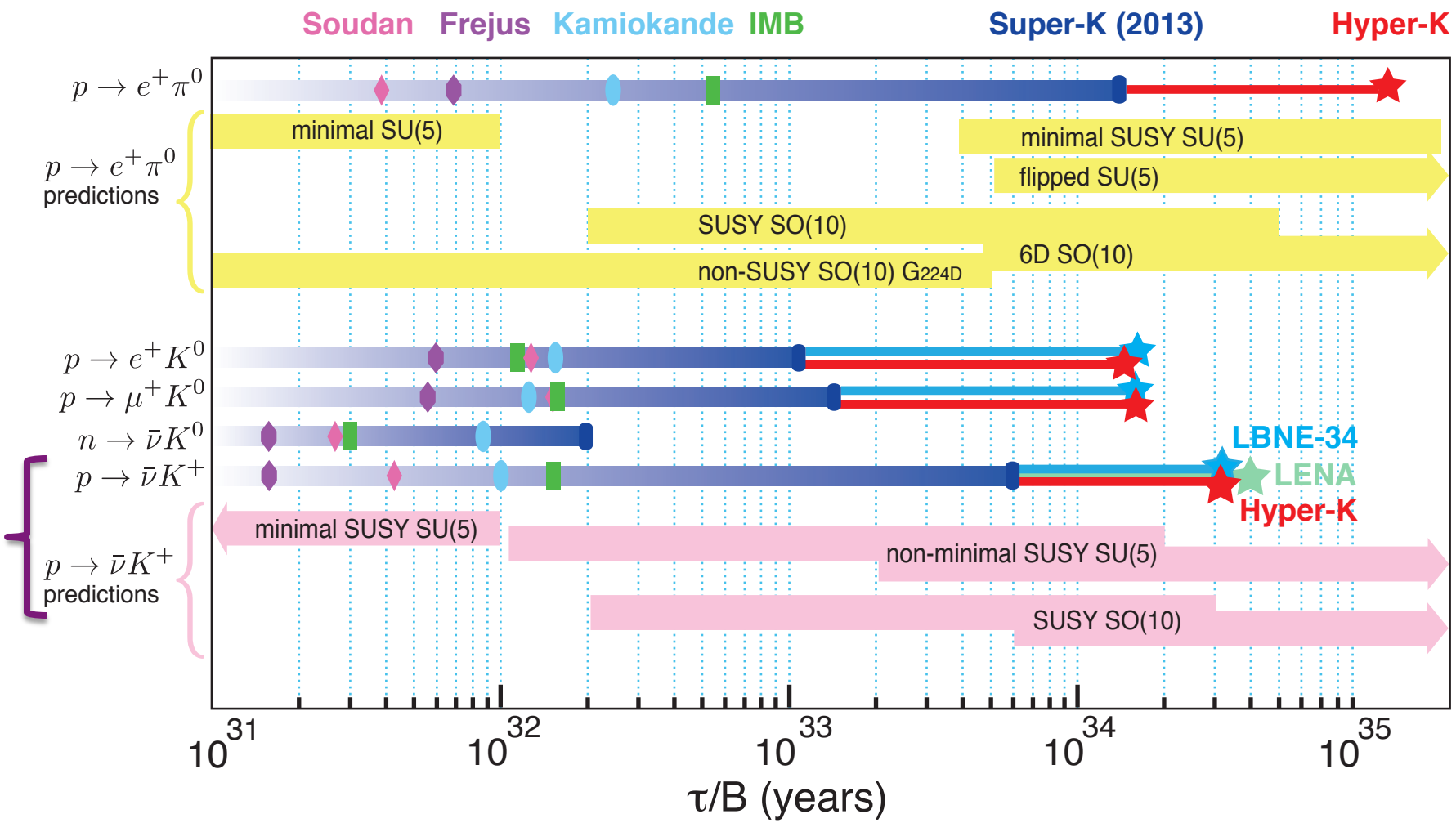


Theoretical Context & Current Experimental Limits



E. Kearns

Theoretical Context & Current Experimental Limits



E. Kearns

p → K^+ ν Signatures – I

- Two-body decay: for free protons, K^+ momentum 340 MeV,
  - But nuclear effects in Ar: (1) proton Fermi momentum (2) rescattering of K
  - Simulations in Geant4 show considerable smearing:

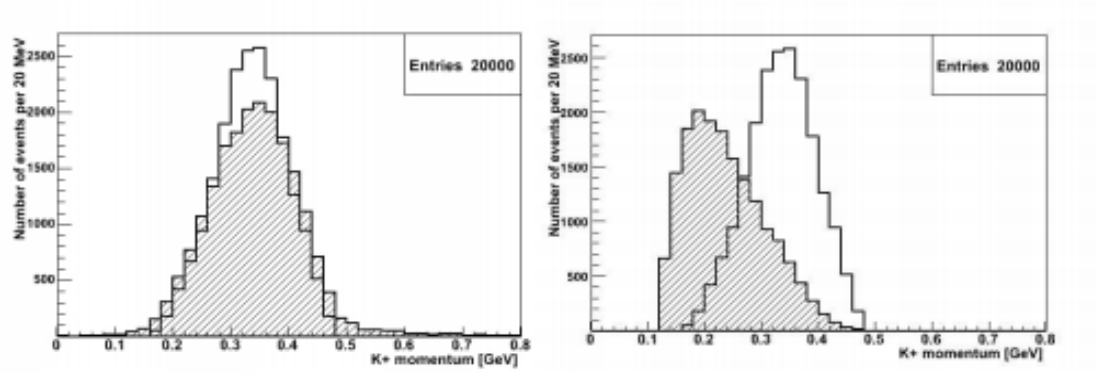


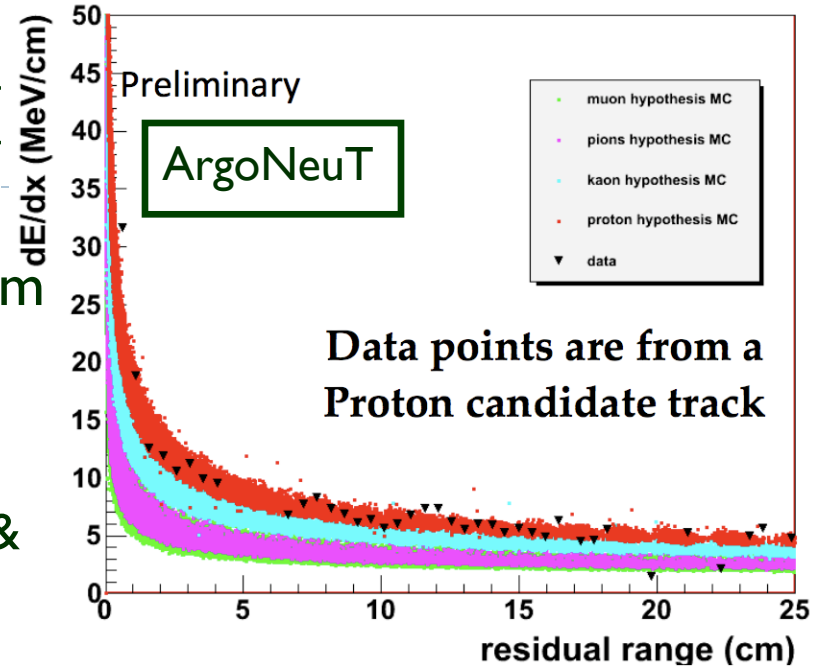
Fig. 1. Momentum distribution of kaons produced in the $p \to \bar{\nu}K^+$ decay inside the argon nucleus predicted by different approaches. Left: Calculations for the spectral function of argon (hatched) compared to the local Fermi gas model from GEANT4 without the intranuclear cascade (plain histogram). Right: GEANT4 with (hatched) and without (plain histogram) the cascade.

from Stefan & Ankowski, ArXiv:0811.1892 [nucl-th], 2009

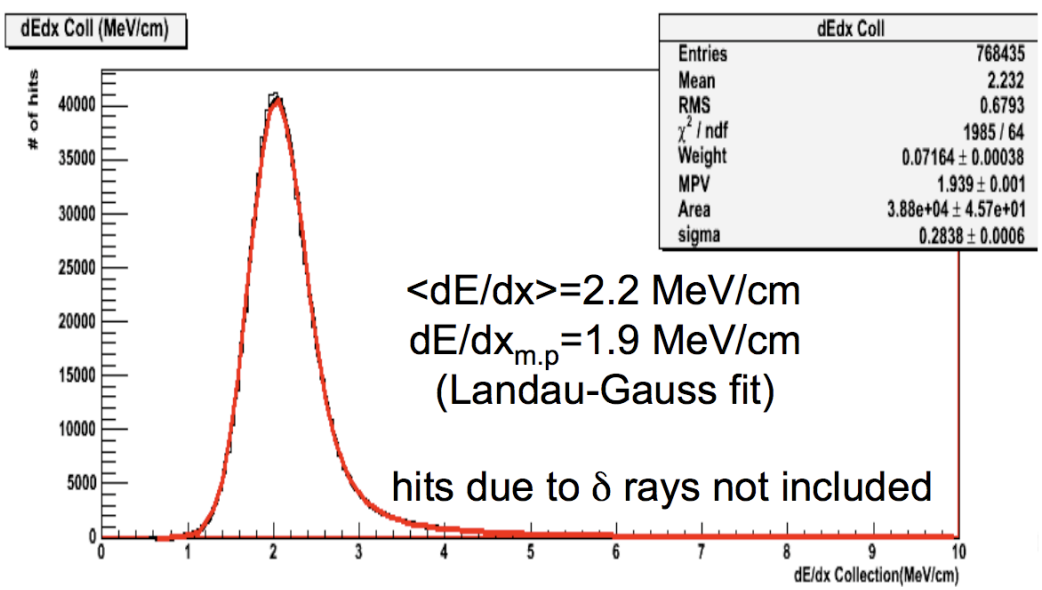
  - But note: below inelastic collision threshold → no absorption of K^+ within Argon nucleus → K^+ emerges intact in ~97% of p → $K^+\nu$ decays.

p → K^+ ν Signatures – II

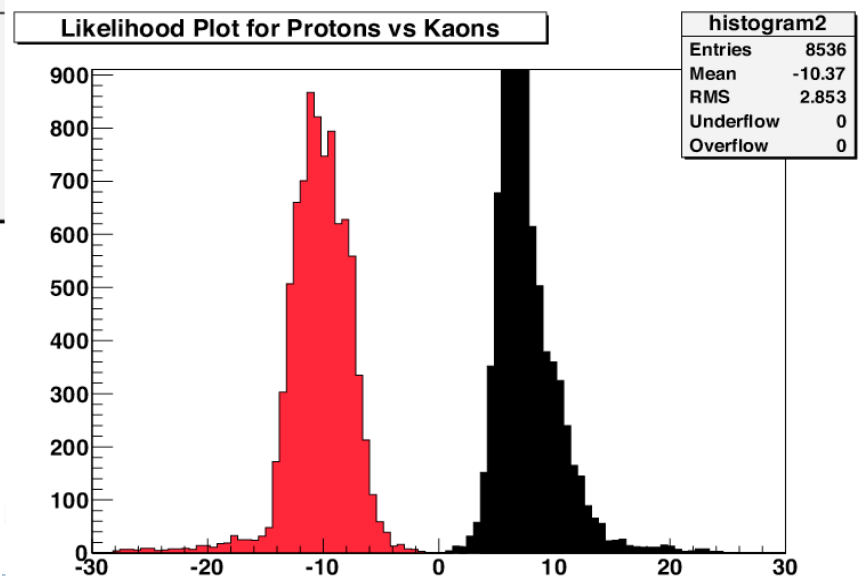
- K^+ momentum 340 MeV → range ~14cm
  - distinctive dE/dx signature already seen in ICARUS and ArgoNeuT
  - Will also be studied in detail with LArIAT & MicroBooNE



dE/dx for muons in ArgoNeuT Data

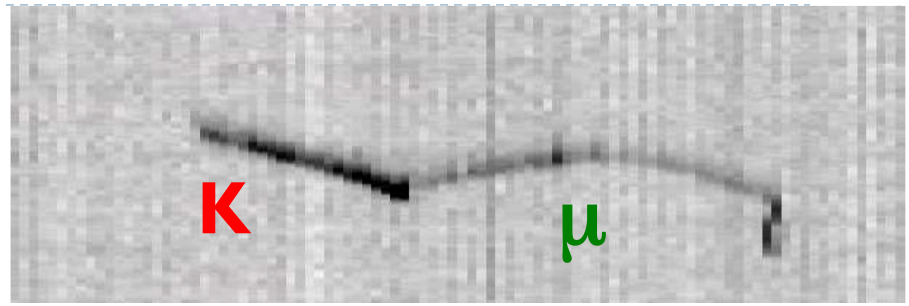


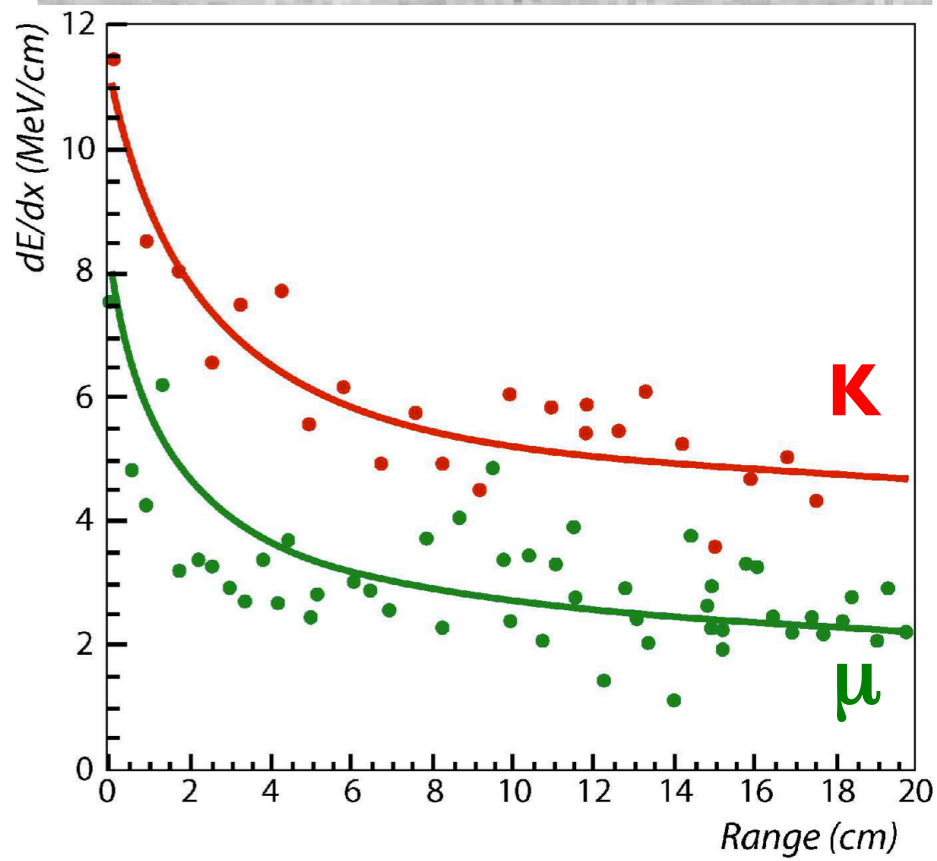
From LArSoft Simulation: K/p separation



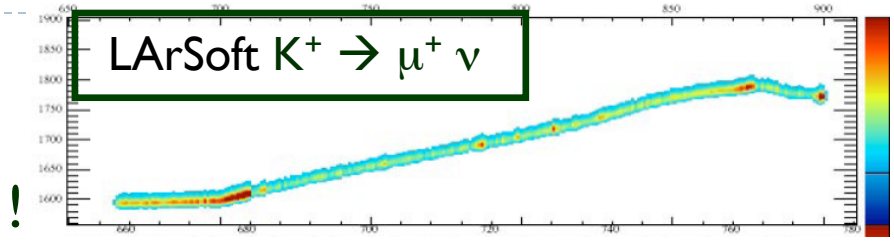
p → K^+ ν Signatures – II (cont'd)

- ICARUS, Pavia 2001, CR data
  - K → μ → e decay chain
  - Kaon is below Cherenkov threshold in water detectors
  - But dE/dx signature of Kaon is distinctive in LArTPC !!



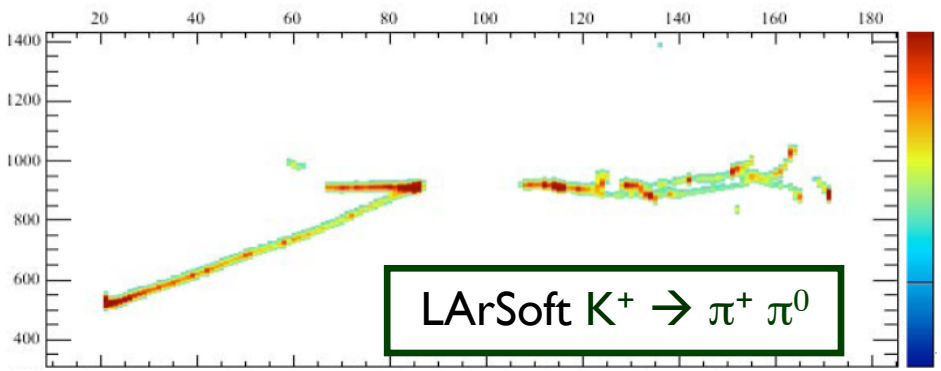


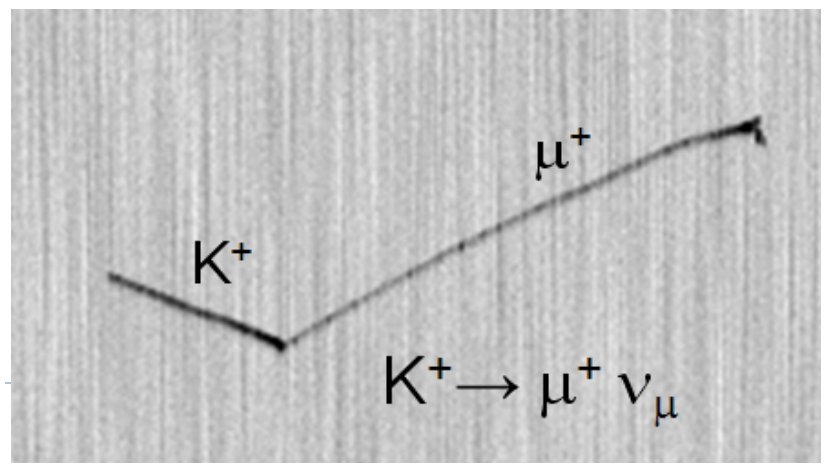
$p \rightarrow K^+ \nu$ Signatures - III



- K^+ decay at rest: Simple topologies !
  - $\mu + \nu$ (63.6% BR): monochromatic μ: p_μ = 236 MeV
    - Minimum-ionizing track, momentum by range/multiple scattering/energy deposition
      - Note: muon from π+ decay-at-rest has p_μ = 30 MeV
    - Followed by decay electron.
  - $\pi + \pi^0$ (20.7% BR): fully reconstructable final state
  - 3π (7.4% BR): fully reconstructable final states
  - $\pi^0 l^+ \nu$ (8.3% BR): kinematically constrained final states

ICARUS T300 data from 2001 surface run @ Pavia





$p \rightarrow K^+ \nu$: Background Issues

Just Two Sources

- Cosmic ray muon induced backgrounds:
  - CR Rate at 4850L is ~0.1 Hz in 34-kt LBNE LArTPC
  - **10 yr run → ~3 x 10^7 muons. Rejection needed is "only" at 10^{-7} level !!**
  - Easily met, since muons in detector volume are tracked with ~100% efficiency!

- Atmospheric Neutrinos:
  - Again consider: interaction rate in 34-kt detector only at level of few x 10^5 per Mt-yr
  - **So rejection needed is 'only' at the10^{-6} level !!**

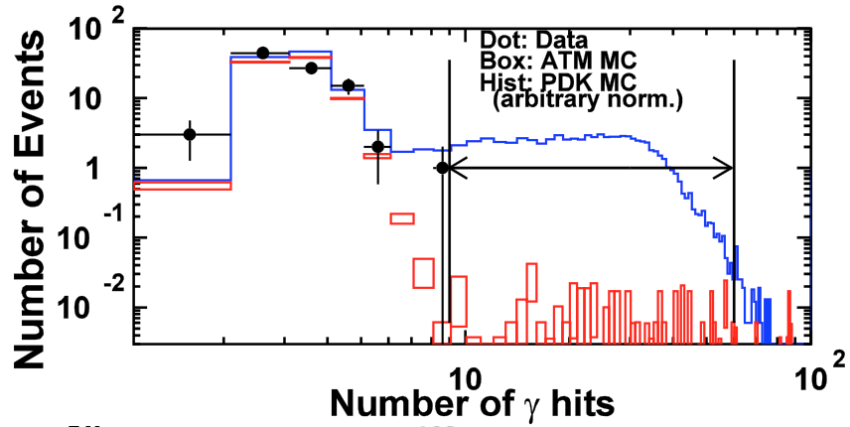
$p \rightarrow K^+ \nu$: SuperK & Background

As a start, we believe LBNE can be background-free because:

<u>SuperK has already carried out background-free searches!</u>

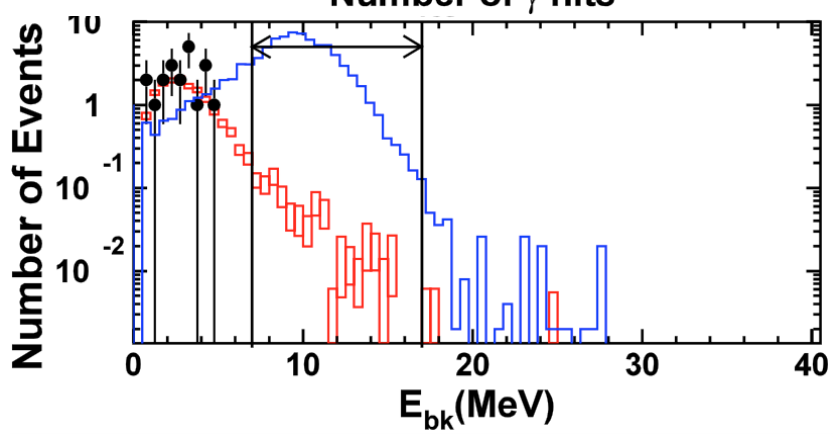
- $K \rightarrow \mu\nu$, w/ prompt γ tag (de-excitation of ^{15}N):

  Plot from Miura, NNN10



- $K \rightarrow \pi^+ \pi^0$:

  Again, plot from Miura, NNN10



<u>Main point: atmospheric neutrinos are now exceptionally well-modeled !!</u>

Background to p → K^+ ν in LAr: Bueno et al., JHEP 04 (2007), 041

"Nucleon decay searches with large liquid Argon TPC detectors at shallow depths: atmospheric neutrinos and cosmogenic backgrounds"

Comprehensive study based on well tested event generators & parametrized detector response

Projected LBNE capabilities currently based on these results

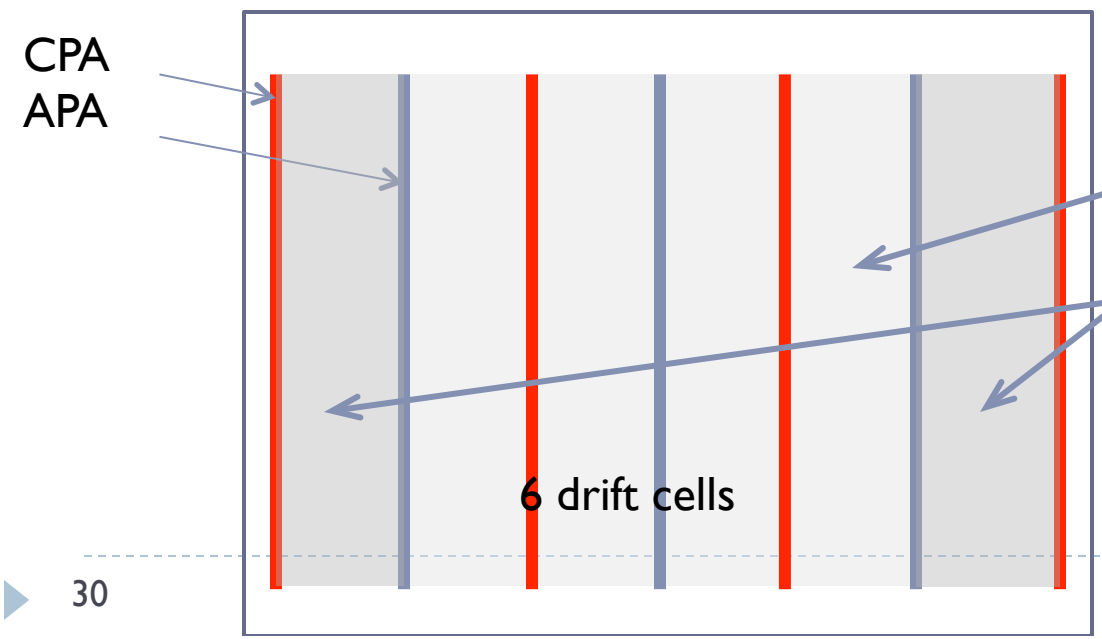
Decay mode	This paper (LAr TPC) Efficiency (%)	Atmospheric ν background 100 kton×year	Super-Kamiokande results [5, 10] Efficiency (%)	Atmospheric ν background 92 kton×year	Published limit 90% C.L.
(p1) $p \to e^+ \pi^0$	45.3	0.1	40	0.2	1.6×10^{33}
(p2) $p \to \pi^+ \bar{\nu}$	41.9	78.2			
(p3) $p \to K^+ \bar{\nu}$	96.8	0.1	8.6 (prompt-γ)	0.7	2.3×10^{33}
			6.0 ($K^+ \to \pi^+\pi^0$)	0.6	
(p4) $p \to \mu^+ \pi^0$	44.8	0.8	32	0.2	
(p5) $p \to \mu^+ K^0$	46.7	< 0.2	5.4 ($K^0_S \to \pi^0\pi^0$)	0.4	
			7.0 ($K^0_S \to \pi^+\pi^-$ method 1)	3.2	1.3×10^{33}
			2.8 ($K^0_S \to \pi^+\pi^-$ method 2)	0.3	
(p6) $p \to e^+ K^0$	47.0	< 0.2	9.2 ($K^0_S \to \pi^0\pi^0$)	1.1	1.0×10^{33}
			7.9 ($K^0_S \to \pi^+\pi^-$ method 1)	3.6	
			1.3 ($K^0_S \to \pi^+\pi^-$ method 2)	0.04	
(p7) $p \to e^+ \gamma$	98.0	< 0.2	73	0.1	
(p8) $p \to \mu^+ \gamma$	98.0	< 0.2	51	0.2	
(p9) $p \to \mu^- \pi^+ K^+$	97.6	0.1			
(p10) $p \to e^+ \pi^+ \pi^-$	18.6	2.5			
(n1) $n \to \pi^0 \bar{\nu}$	45.1	47.4			
(n2) $n \to e^- K^+$	96.0	< 0.2			
(n3) $n \to e^+ \pi^-$	44.4	0.8			
(n4) $n \to \mu^- \pi^+$	44.8	2.6			

$p \rightarrow K^+ \nu$: CR muon Backgrounds

- CR Rate at 4850L is ~0.1 Hz in 34-kt LBNE LArTPC
  - **10 yr run → ~3 x 10^7 muons. Rejection needed is "only" at 10^{-7} level !!**
  - Easily met, since muons in detector volume are tracked with ~100% efficiency!
  - Rejection of 2ms drift period around μ track → fractional dead time ~ 2 x 10^{-4}.
- Consider some specific pathologies

1) CR muon induced K+ production outside active volume:

- Require K+ originates well within active volume (t-zero from photon detection helps)



Fiducial mass fraction loss if no t-zero

0 % loss for interior cells

50% loss for 2/6 cells
(only cut inward-going K^+ candidates)

worst case:17% w/o photon detection

$p \rightarrow K^+ \nu$: more on CR Backgrounds

2) Another pernicious CR muon background:

- HE cosmic ray interacting outside detector generates K^0_L that enters & charge-exchanges; looks like isolated charged kaon.
- Such backgrounds are usually accompanied by other particles entering the active detector volume
- Geant4-based simulations of CR interactions found no candidate events passing simple cuts; upper bound on background at 2 events / Mt-yr.
- Again can reject such backgrounds by restricting fiducial volume

3) Study of Bueno et al (2007)

- Found CR backgrounds could be suppressed below atmospheric nu backgrounds, even at shallow depths (employed active veto system outside detector volume).

$p \rightarrow K^+ \nu$: Background Sources

- Atmospheric Neutrinos:
  - Again consider: interaction rate in 34-kt detector only at level of few x 10^5 per Mt-yr
    - **So rejection needed is 'only' at the 10^{-6} level !!**
  - Final state consisting of / mimicking single kaon very low probability
  - Atmospheric neutrino MC's well validated (i.e., by SK proton-decay searches)
  - Analysis by Bueno et al., JHEP 0704, 041 (2007) [arXiv:hep-ph/0701101] → 0.3 evts / 10 yrs, for 34-kt detector, based on a single simulated NC interaction passing nominal cuts.
  - Definitely needing more investigation
  - Note: considerable theoretical/phenomenological effort ongoing, toward improving simulation of exclusive neutrino interaction processes, including those with strange quark production.

Nucleon Decay Summary

- The LBNE LAr Far Detector has superb capabilities for nucleon decay searches.
  - Well identifiable final state signatures
  - Multiple measurements (i.e., dE/dx, range, kinematic reconstruction) to confirm a given signature
  - Simple topologies well suited for automated reconstruction
  - High efficiency detection (limited mainly by acceptance cuts)
  - Backgrounds expected to be intrinsically low relative to other detector technologies.

- LBNE has significant discovery potential for modes like $K^+\nu$
  - A single candidate event could provide convincing evidence!
  - If $\tau/B = 1 \times 10^{34}$ yr (just beyond SK), a 34-kt detector would see 9 events in a 10-year run, with less than 1 event of background.
  - Work in progress on candidate event reconstruction

Neutrino Bursts from Supernova

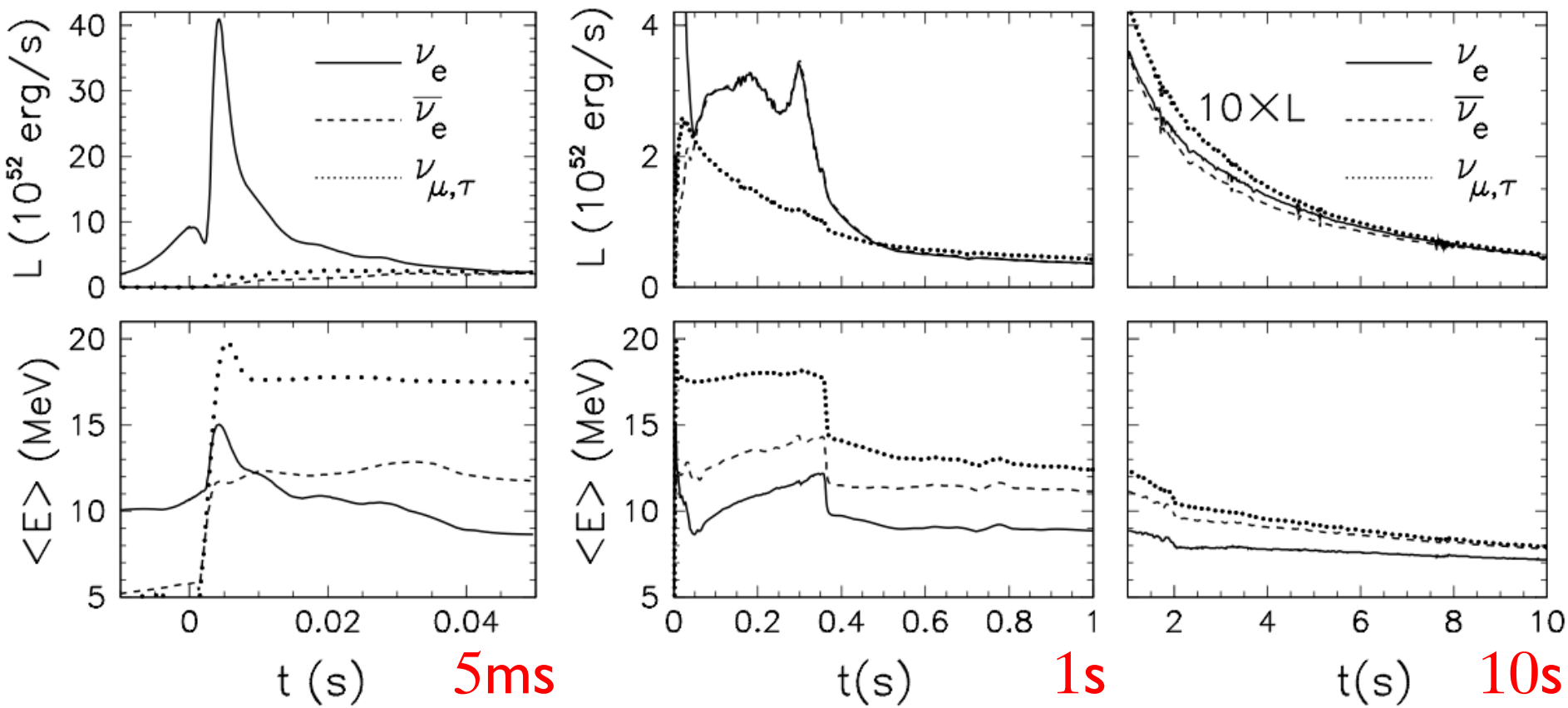
- SN physics – a multifaceted topic, challenging to cover in short time!
  - Neutrino signal in LBNE from galactic SN would be a treasure trove.
  - Identifiable features in flavor-specific ν energy spectrum (**spanning 10's of MeV**)
  - …and in corresponding time dependence (**from ~ms to 10's of seconds**)
  - Most dramatic feature: sharp cutoff in flux at black hole formation time
  - May also learn about neutrinos – (e.g., Mass Hierarchy sensitivity)

Main Questions:

- Are SN neutrino signals detectable / reconstructable and with sufficient resolution? – YES !!
- Are the backgrounds tolerable? – YES !!
- Is there enough mass to do the physics ? – YES !!
- Does LBNE LArTPC bring new capability (e.g., beyond H_20)? – YES !!

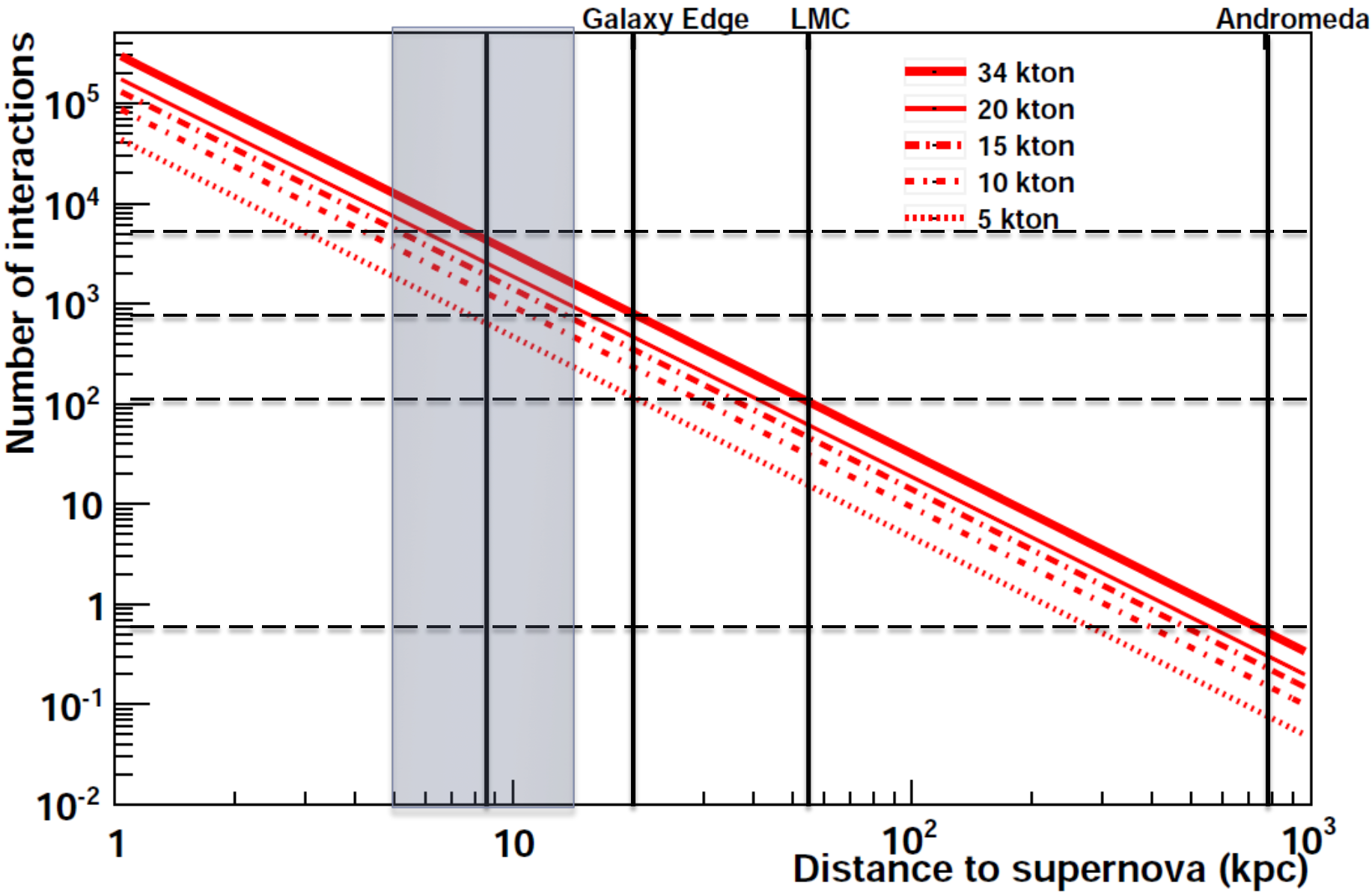
Features of SN Neutrino Spectra

- In LAr, dominant process is: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
  - In water / liquid scintillator, signal dominated by interactions of $\overline{\nu_e}$
  - Note distinct features for flavor-separated fluxes & energy spectra !



Basel Model, plot from LENA Collab., arXiv:1104.5620

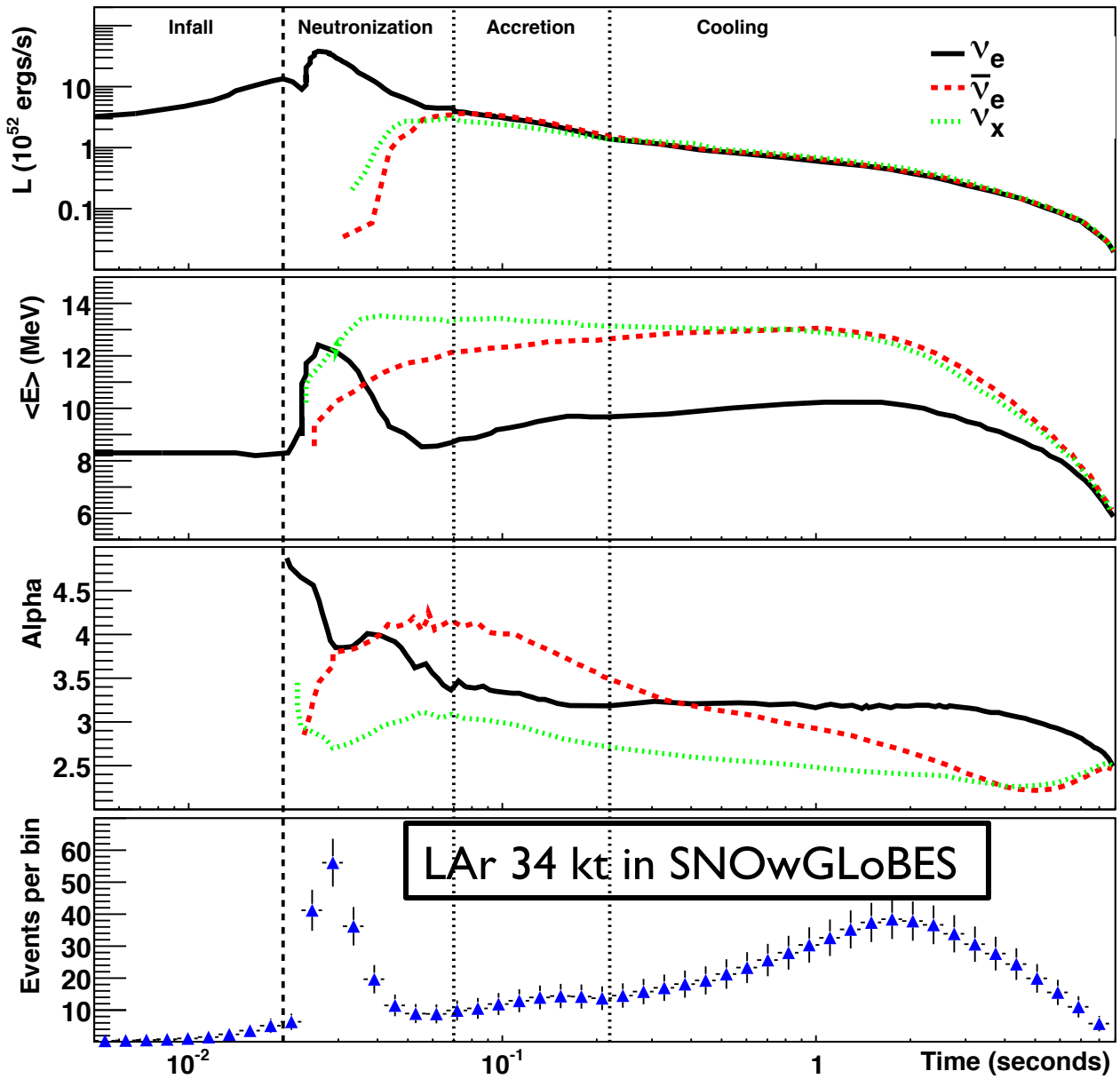
SN Neutrino Rates in LAr



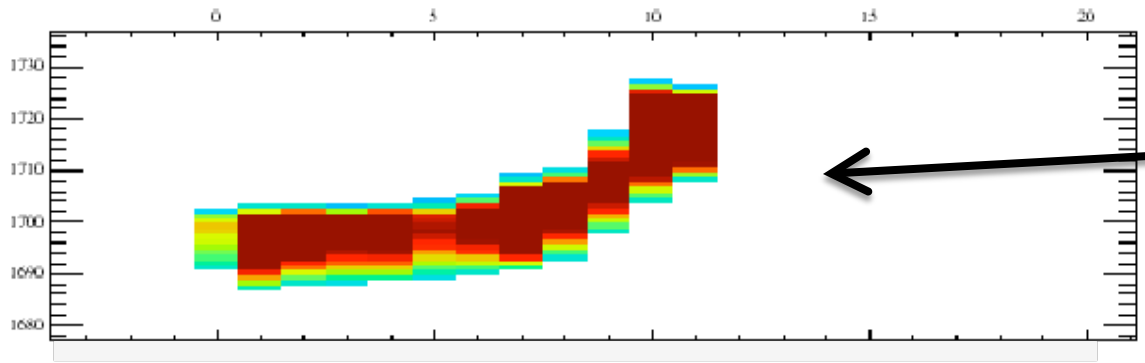
Signal for SN@10kpc (34kt LAr)

Blue histogram at bottom shows expected event yield in 34-kt LArTPC versus time for the SN model (Garching) characterized in the top three plots.

Note the neutronization peak at ~30 ms. Uniquely among neutrino observatories, large LAr detectors provide a direct probe of this stage of the Supernova process



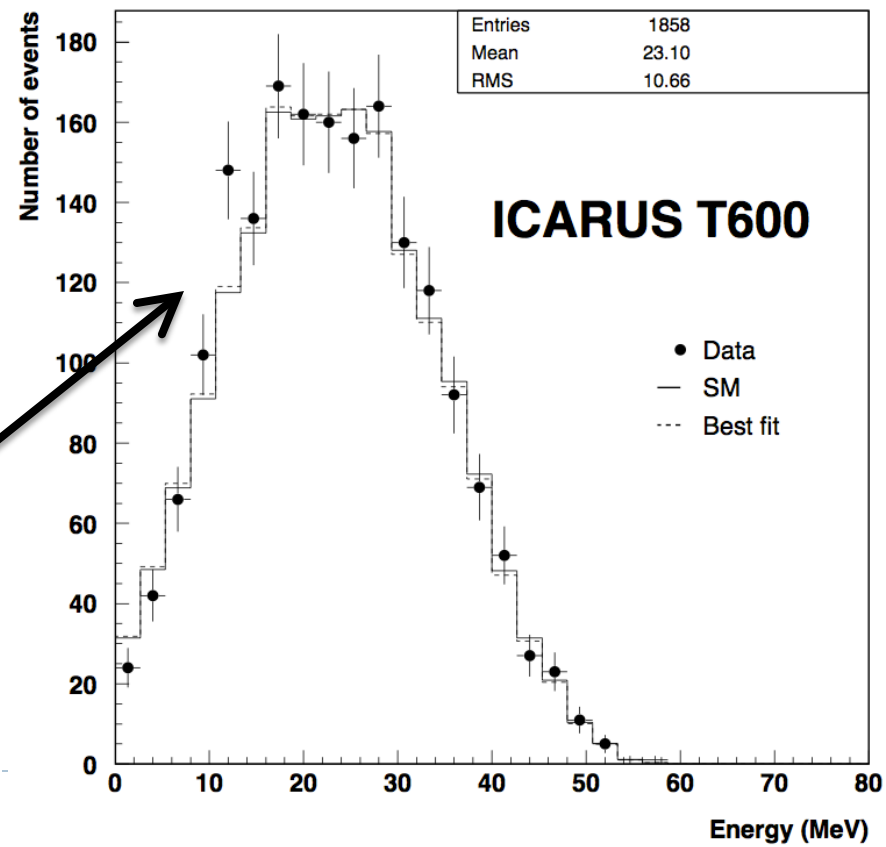
Can SN ν_e's be Reconstructed?



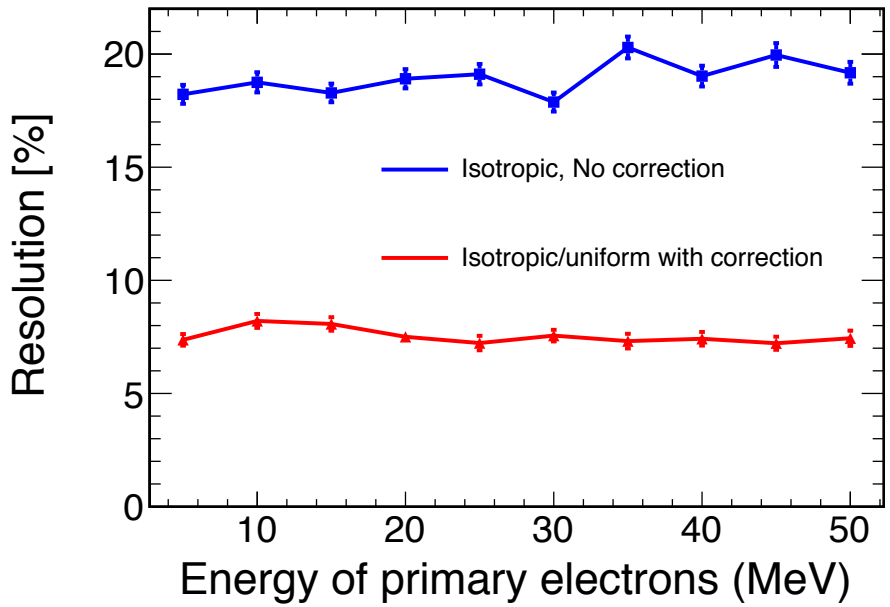
20 MeV electron (LArSoft/LBNE geom)

- ICARUS 2003, Pavia CR Test
  - Michel electron energy spectrum
  - Note: sub-10 MeV threshold
  - Found resolution consistent with:

$$\frac{\sigma_E}{E} = \frac{11\%}{\sqrt{E[\mathrm{MeV}]}} + 2\%$$



Ongoing Reconstruction Studies



LEFT: Assessing importance of T-zero determination for electron energy resolution, assuming drift electron lifetime ~ 3 ms (note: > 6 ms possible):

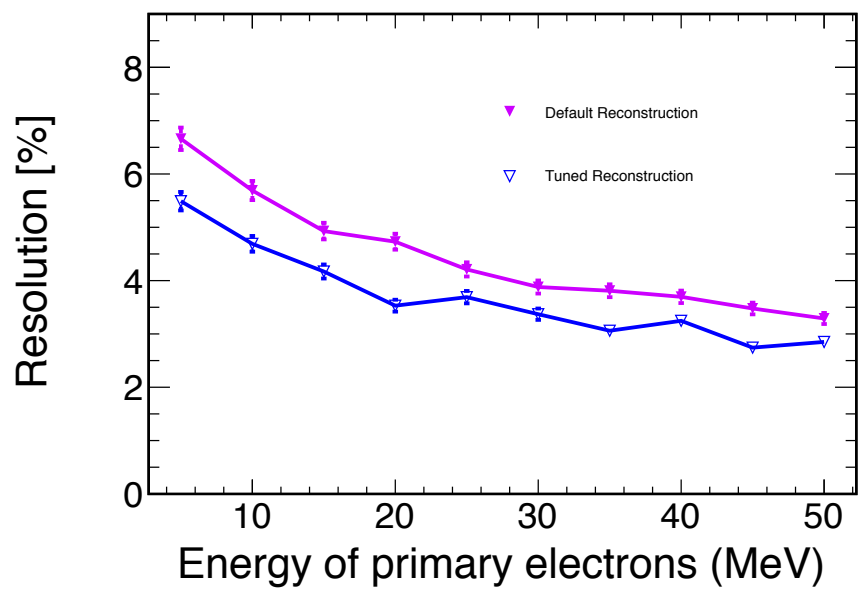
Blue: no drift dist. correction

Red: with correction

RIGHT: Initial steps in tuning hit & track finding algorithms (within LArSoft)

Purple: default reconstruction

Blue: tuned reconstruction



Modeling De-excitation gammas

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

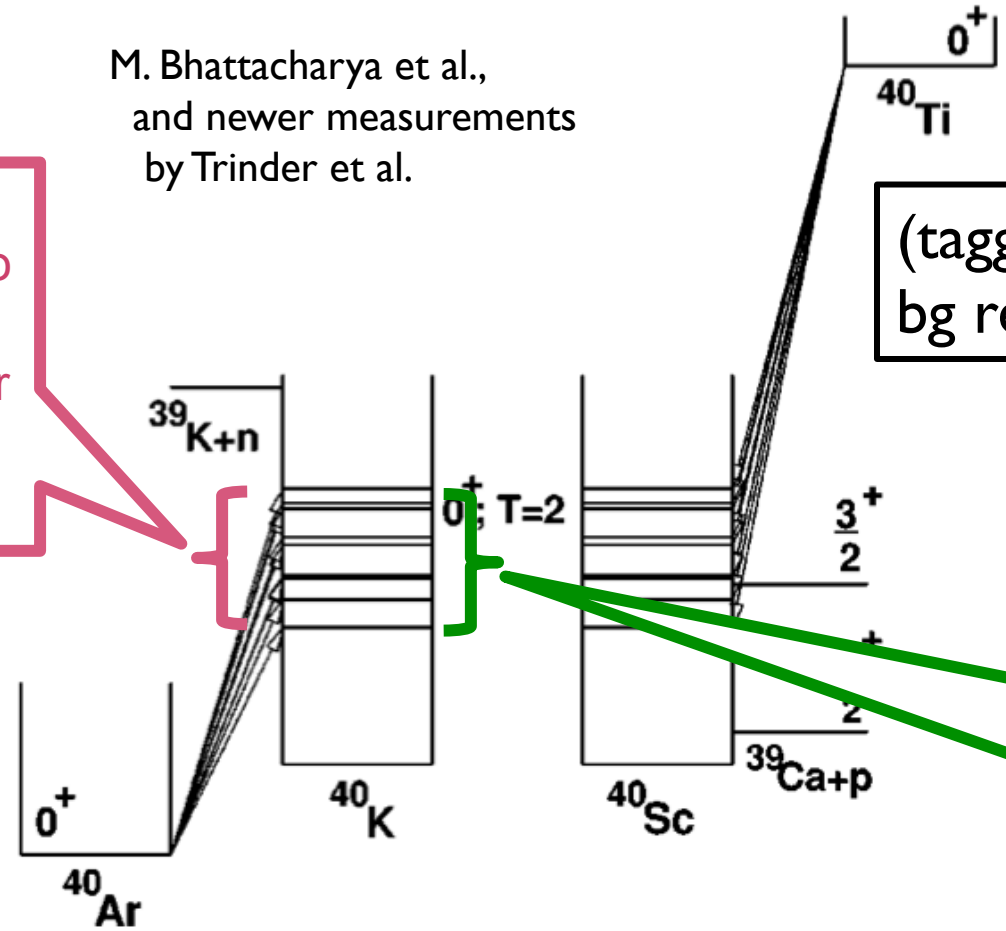
PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

Neutrino absorption efficiency of an ^{40}Ar detector from the β decay of ^{40}Ti

M. Bhattacharya et al.,
and newer measurements
by Trinder et al.

use measured ^{40}Ti strengths to determine relative xscn for ending up in each level

(tagging w/ γ's helps in bg rejection & CC id



then use Table of Isotopes γ database to decay the nucleus

Slide courtesy K. Scholberg

Backgrounds from Radionuclides

^{39}Ar/^{85}Kr rate (β's) in LBNE:

→ 62 kHz per drift cell (7m x 2.5m x (3.7mx2)), out of 216

Est. U/Th rate (γ's):

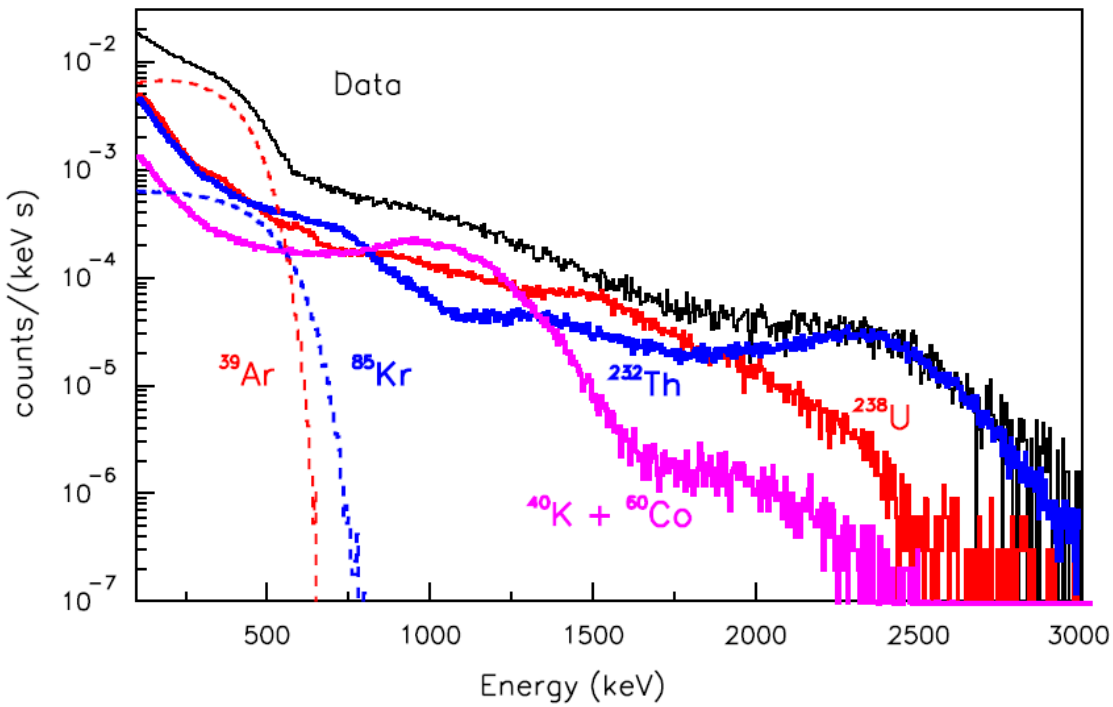
→ ~1 kHz per drift cell

Impacts under study, not yet incorporated fully into LBNE simulations

Main impacts:

1) Threshold energy to reject background events

2) "Dark noise" can impact reconstruction / resolution

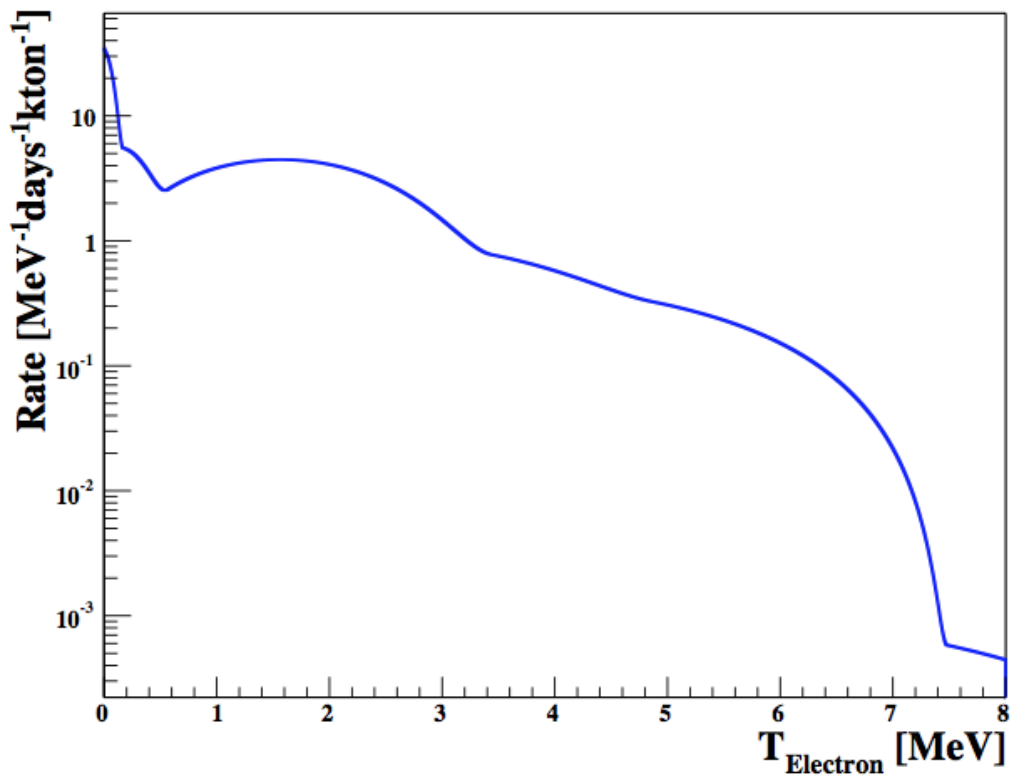


P. Benetti et al. (WARP), NIM A 574 (2007) 83

LBNE Radiological Model

Work in progress, showing here preliminary β spectrum due to activation of ^{40}Ar, out to 8 MeV based on known cross sections
(V. Gehman, K. Oliver-Mallory, R. Kadel)

This is an ongoing vigorous effort – LBNE low energy program will depend on knowing radiological backgrounds well !!



R&D for Low Energy Neutrino Physics

- Spallation product production and light yield will be measured in the LANSCE neutron beam at the end of this year in a 5 ton detector.

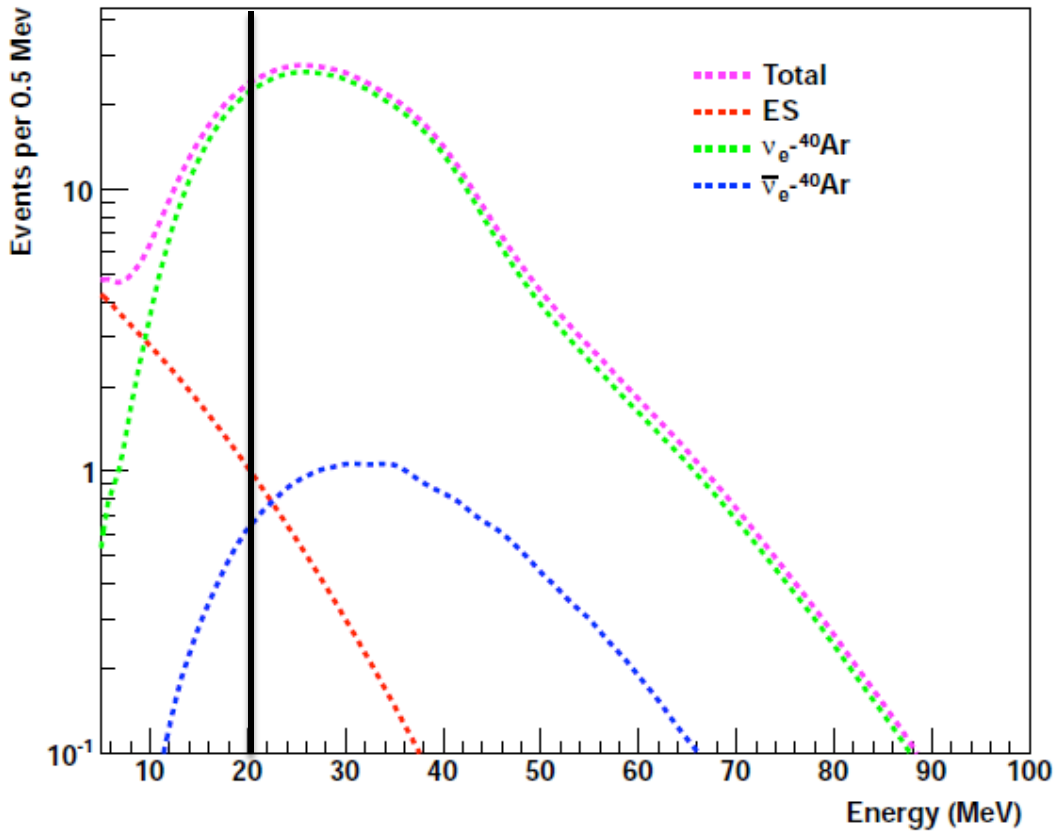
- Plans to run a small detector at BNB target hall in 2015-16. Will use these to validate the inclusive cross-section calculations and develop a practical SN trigger for LBNE.

Crocker Nuclear Lab (CNL)
5-68 MeV neutron beam

- A major background will be $^{40}Ar(n,p)^{40}Cl$. Cross-section measured only up to 15 MeV. We will measure up to 68 MeV at CNL by end of this summer

Expected Supernova Neutrino Energy Spectrum (resolution smearing included)

Channel	Events, "Livermore" model	Events, "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	1154	1424
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	97	67
$\nu_x + e^- \rightarrow \nu_x + e^-$	148	89
Total	1397	1580



Expected rates in an LBNE 17-kt LArTPC module for SN@10kpc

Would like to have low threshold, esp., for elastic scattering evts, which give directional information.

But, even with a 20-MeV threshold LBNE would do great physics!

Underground Physics – Summary

- **Atmospheric Neutrinos**
  - The large LBNE LArTPC provides a new way of looking at this physics
  - Results will complement/enhance/cross-check the beam-based analysis.
  - Much recent progress – promising ideas to pursue w/ full simulations & reconstrct'n

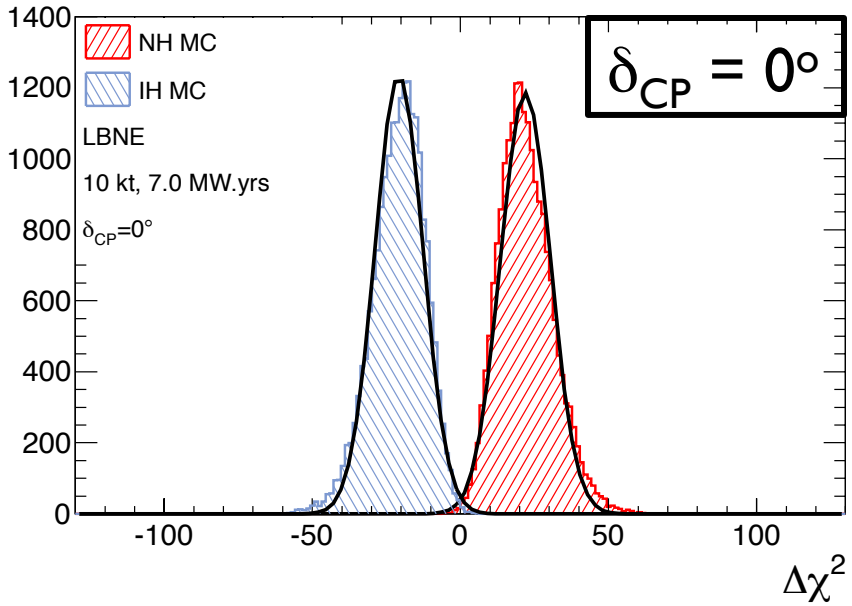
- **Nucleon Decay**
  - Striking signatures for many channels, esp. modes w/ charged kaons
  - Existing LArTPC data (ICARUS, ArgoNeuT) demonstrate capabilities
  - Backgrounds are modest, reasonably well understood, and controllable
  - Simulation & analysis tools development will allow further identification of strategies

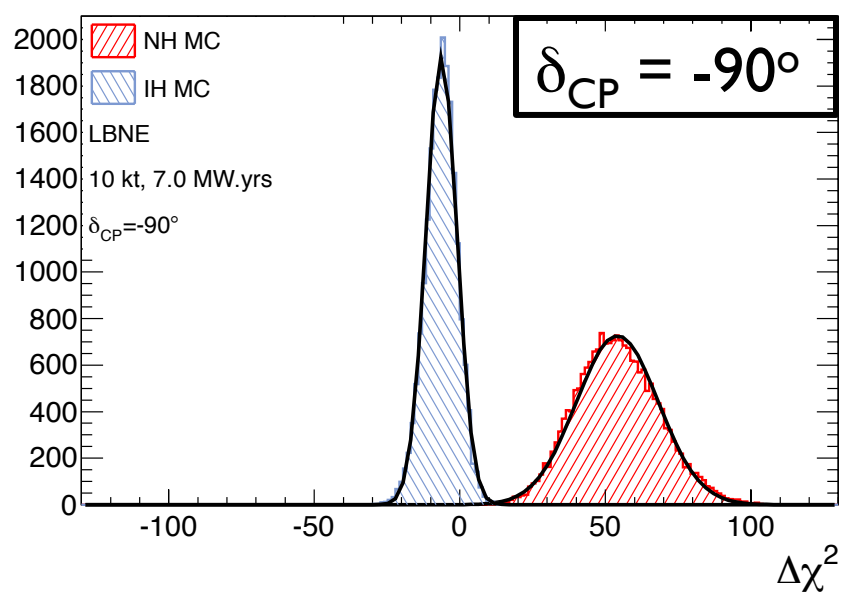
- **Galactic Supernova Neutrino Burst Detection**
  - Physics opportunity very compelling
  - Ability to detect ν_e component of flux is unique to LAr → only LBNE can probe neutronization !!
  - Much recent effort ongoing on reconstruction of low-energy ν_e signatures; no show-stoppers, but will take time for mature analysis. Backgrounds are not severe.

Additional Slides

Long-Baseline Physics – MH statistics

- Special feature: experiment is a test of two discrete hypotheses:
  - Has been noted that the 'T = $\Delta\chi^2$' test metric employed does not follow a χ^2 distribution for one dof, as it would more typically.
  - Rather, approximately Gaussian, with mean & width = ($\underline{\underline{T}}$) & $2(\underline{\underline{T}})^{1/2}$.





Showing toy MC for 10-kt detector @ 1.2 MW for 6-years w/ δ_{CP} = 0°, -90°, to give feel for rejection power of ensemble of experiments.

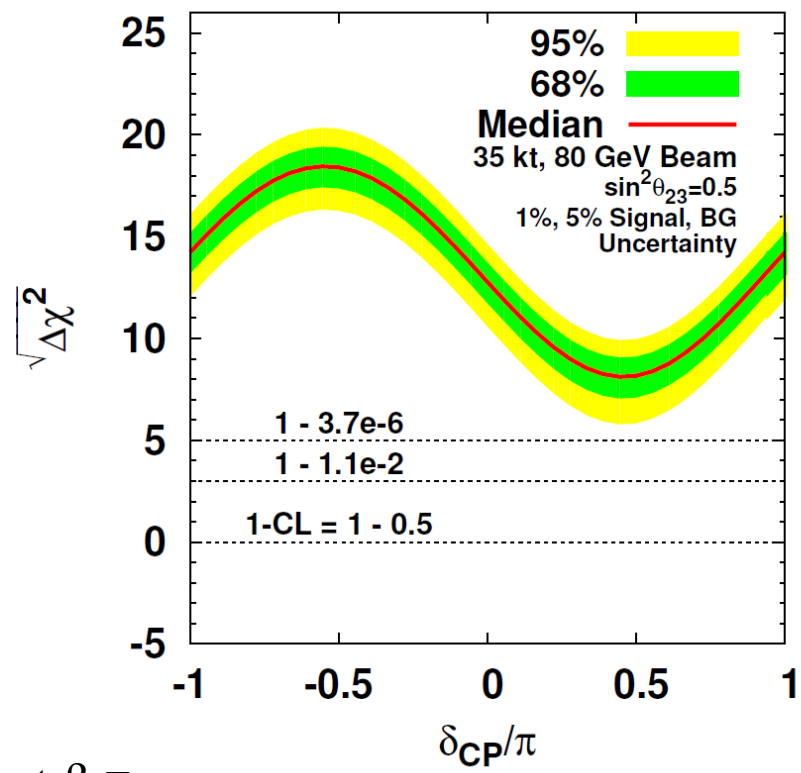
Long-Baseline Physics – MH statistics

In addition to showing δ_{CP} dependence of square root of most likely value for $\Delta\chi^2$ (red), we also show 68% (green) & 95% (yellow) intervals in its probability density

[Note: if LBNE measures a value of $\Delta\chi^2$ that lies on the red curve, then Sqrt($\Delta\chi^2$) approximates the # of standard deviations of significance, for δ_{CP} values (0,π) where P($\Delta\chi^2$|NH) ~ P(-$\Delta\chi^2$|IH).]

In statistical language of hypothesis testing, significance of red curve corresponds to Type-I error rate 'α' (prob of rejecting the true mass ordering) for a Type-II error rate (prob of failing to reject false mass ordering) of 'β' = 0.5

MH Sensitivity
(True Ordering = Normal)

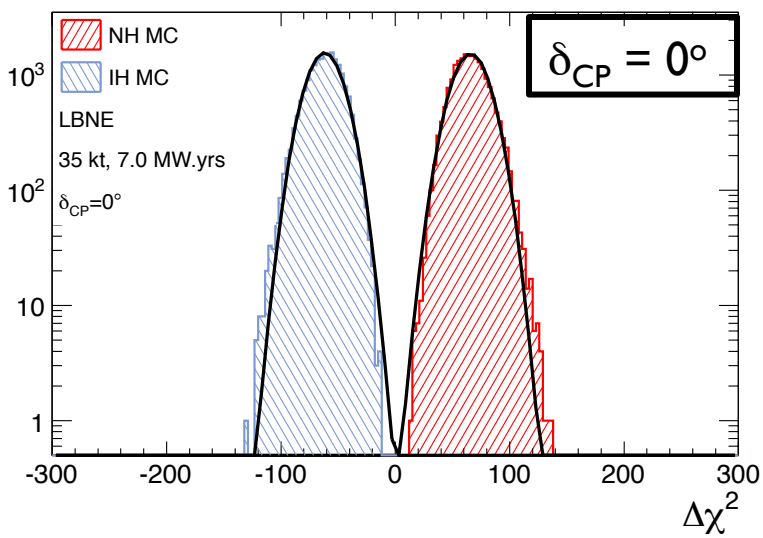


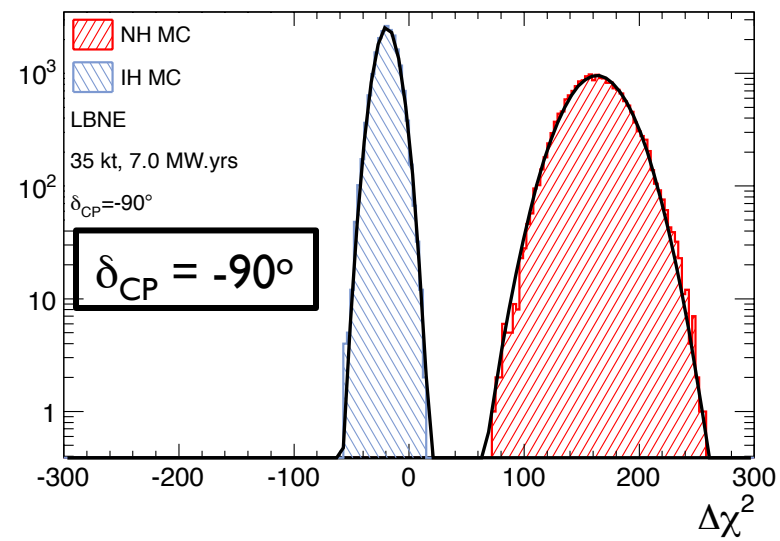
May wish to report sensitivity as value for α such that $\beta = \alpha$.
For this, a useful benchmark is: Sqrt($\Delta\chi^2$) = 6 corresponds to $\beta = \alpha = 0.0013$

Qian et al., PRD 86, (2012) 113011, arXiv:1210.3651, Ciuffoli et al, arXiv:1305:5150, Blennow et al, arXiv:1311.1822, Cousins et al, JHEP 0511, (2005) 046.

Long-Baseline Physics – MH statistics

- Special feature: experiment is a test of two discrete hypotheses:
  - Has been noted that the 'T = $\Delta\chi^2$' test metric employed does not follow a χ^2 distribution for one dof, as it would more typically.
  - Rather, approximately Gaussian, with mean & width = ($\underline{\underline{T}}$) & $2(\underline{\underline{T}})^{1/2}$.

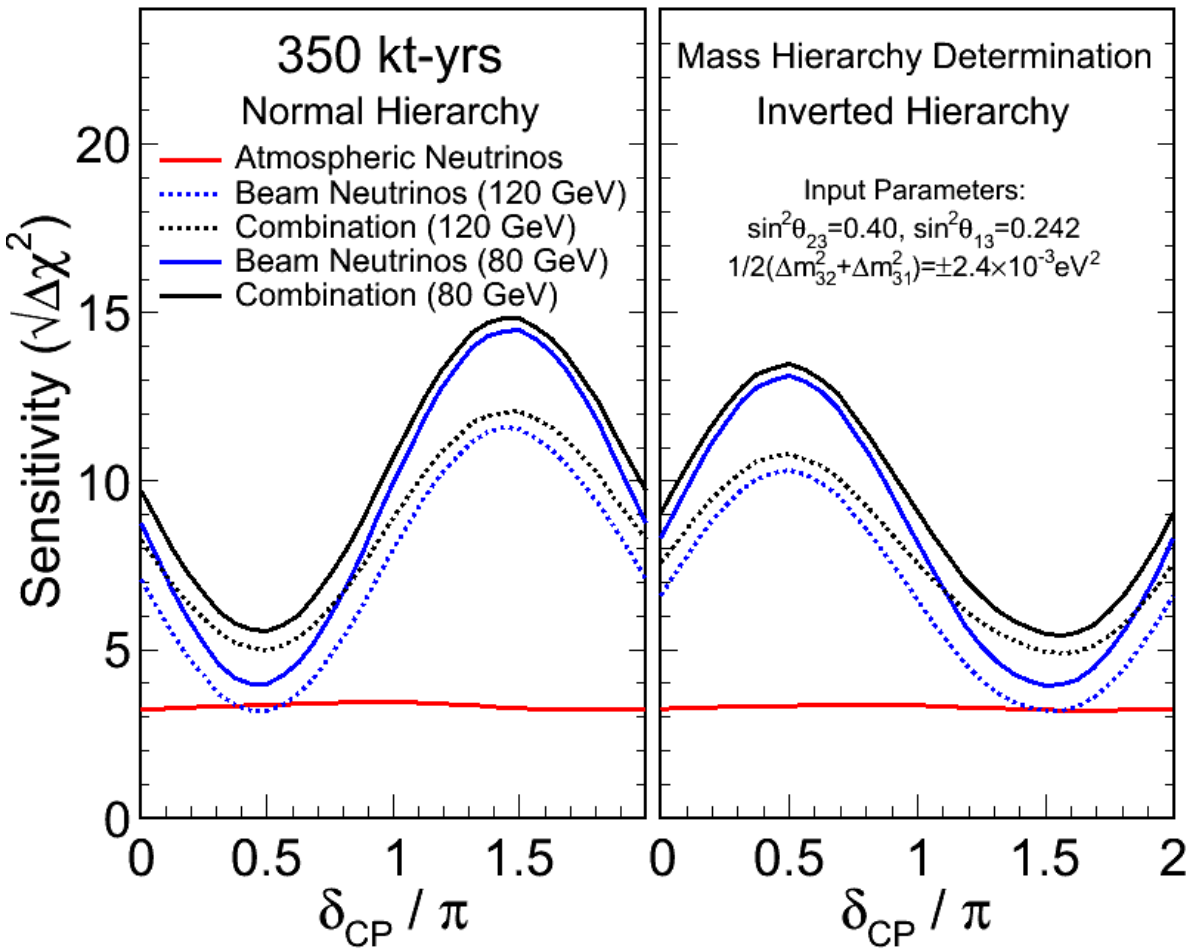




Showing toy MC for 34-kt detector @ 1.2 MW for 6-years w/ δ_{CP} = 0°, -90°, to give feel for rejection power of ensemble of experiments.

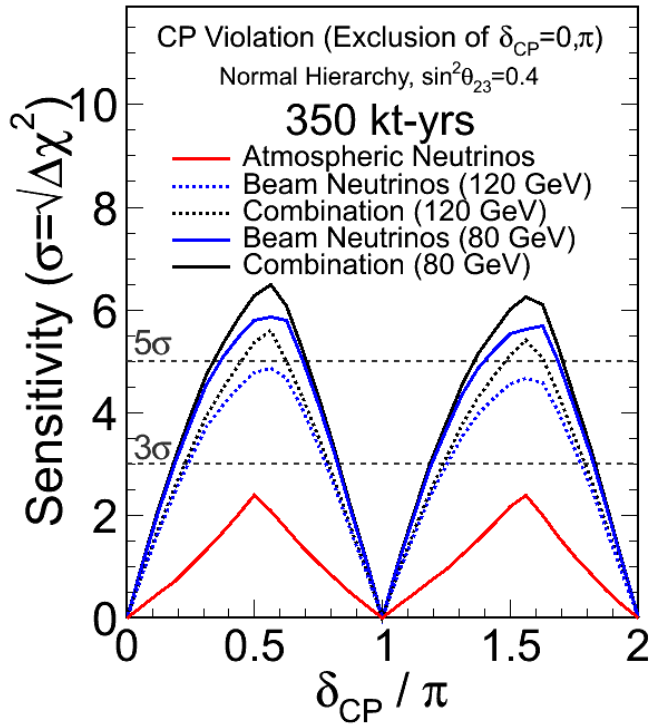
Atmospheric Neutrinos

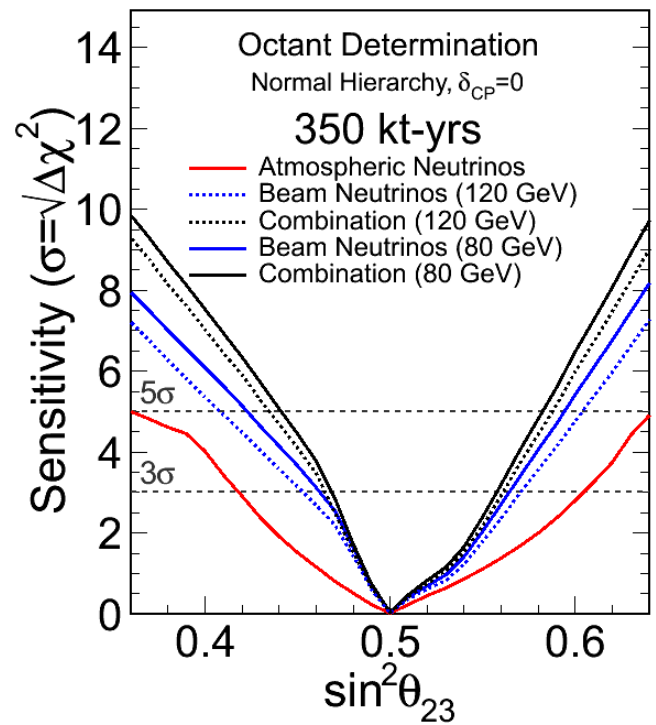
- Combining beam and atmospheric MH sensitivities
  - Plotting sensitivity as sqrt($\Delta\chi^2$) for typical expt
  - Note: independent (i.e., not GLoBES) analysis framework employed here..
  - Also note: plots here pre-date PIP-II; show 35kt detector running for 10 years at 700 kW.



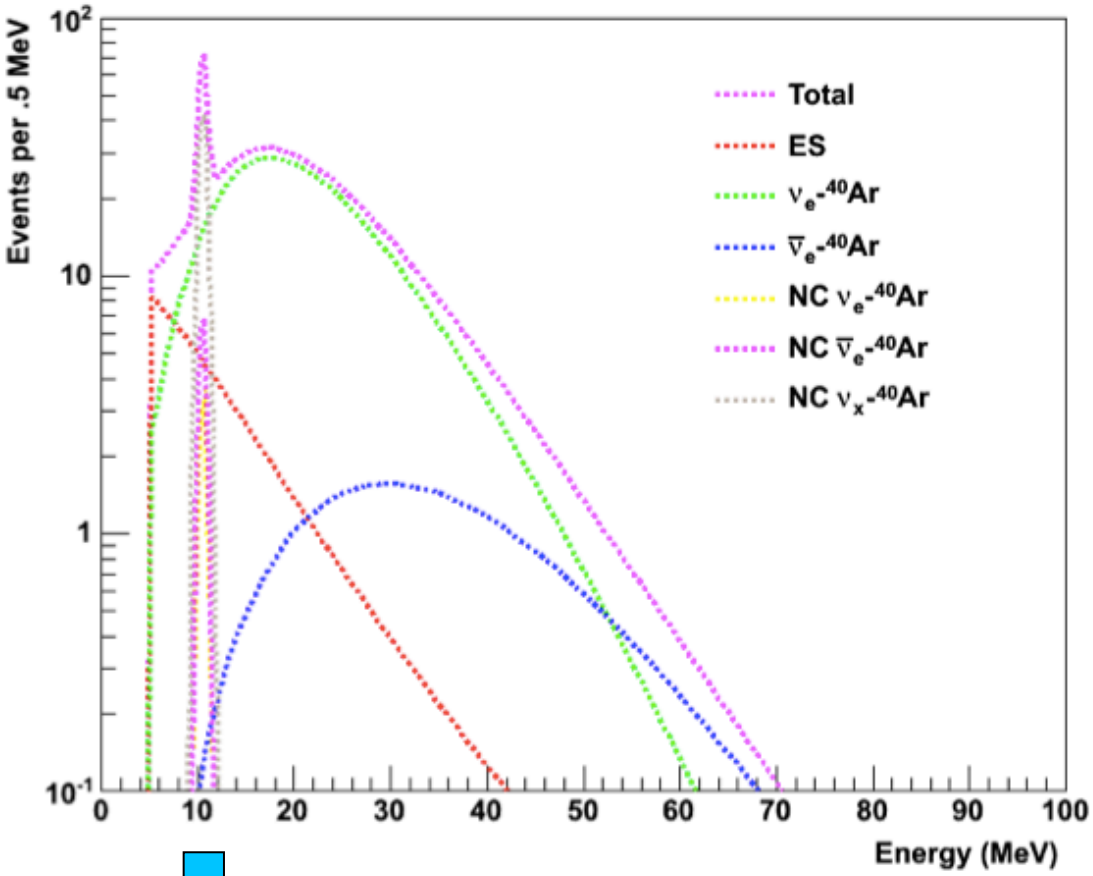
Atmospheric Neutrinos

- Combining beam and atmospheric CPV & θ_{23} octant sensitivities
  - Plotting sensitivity as sqrt($\Delta\chi^2$) for typical expt
  - Note: independent (i.e., not GLoBES) analysis framework employed here..
  - Also note: plots here pre-date PIP-II; show 35kt detector running for 10 years at 700 kW.





New NC x-scn from A. Hayes (LANL),
for excitation to 10 MeV level in ^{40}Ar, implemented by Ben Suh



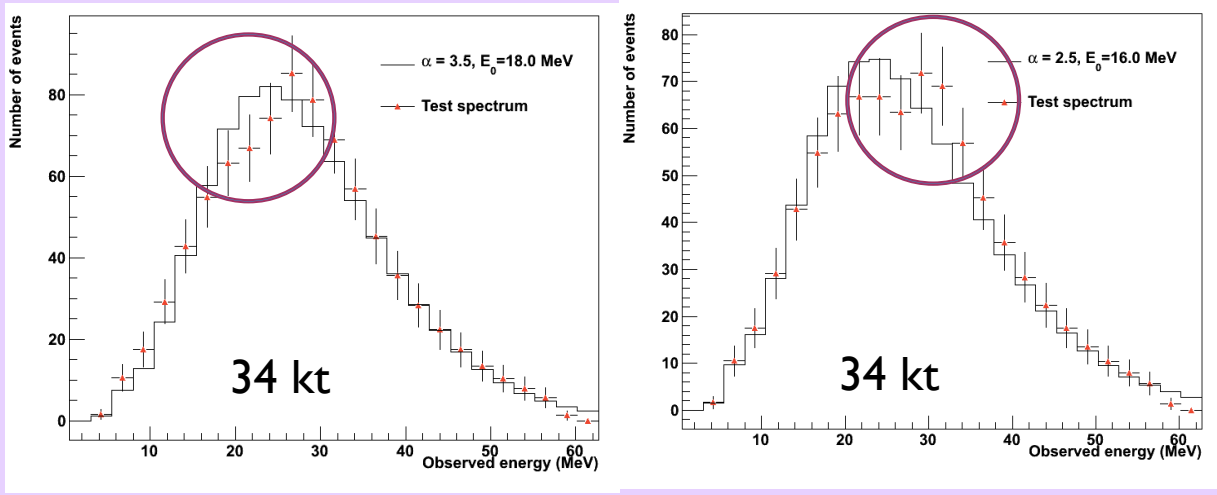
promising NC spike! (➔full flux measurement)
However this is assuming the full 9.8 MeV γ-ray energy is collected,
with standard SNOwGLoBES resolution
(from Icarus paper)

Slide courtesy K. Scholberg

Preliminary work featured in Snowmass white paper

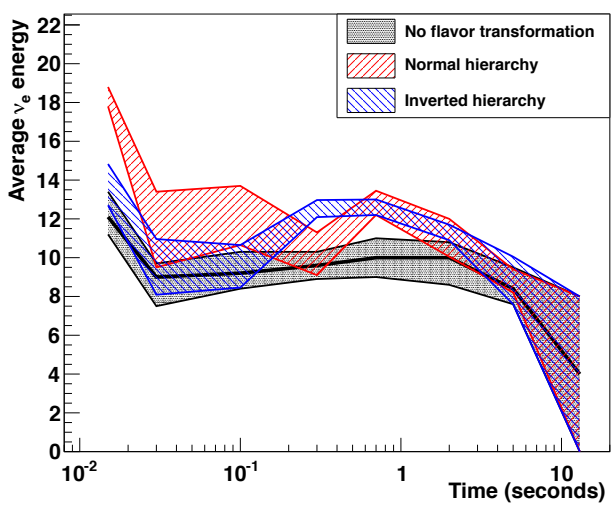
(A. Friedland, J.J. Cherry, H. Duan, K. Scholberg)

Hierarchy-dependent time-evolving shock feature



For NMH (*not* for IMH), "non-thermal" features clearly visible, and change as shock moves through the SN

Measuring SN ν_e temperature vs time



<u>More work to be done</u>

- checking
- explore more SN model space/examples
- better quantification of sensitivity
- study vs resolution assumptions

Slide courtesy K. Scholberg

Photon Detector Simulation in LArSoft

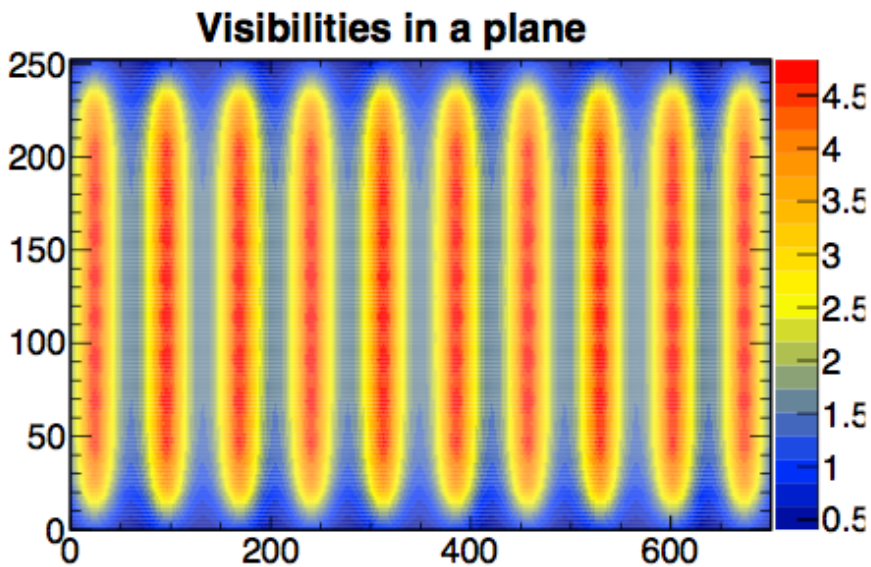
- Full simulation using GEANT4 to propagate scintillation photons
  -- very slow!

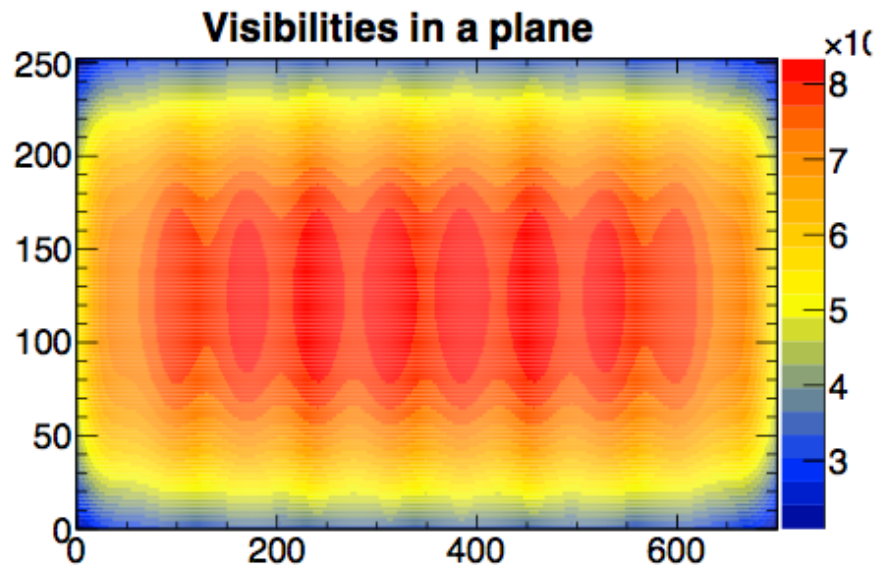
- MicroBooNE-style photon propagation lookup library
  -- Does not scale to the 10 kt FD; too much CPU and memory needed. But appropriate for the 35t Phase II prototype

- Analytic parameterization based on full simulation
  -- fast, compact, but approximate.

- Looking into hybrid methods – library for photons that don't propagate too far, analytic parameterization for far light.

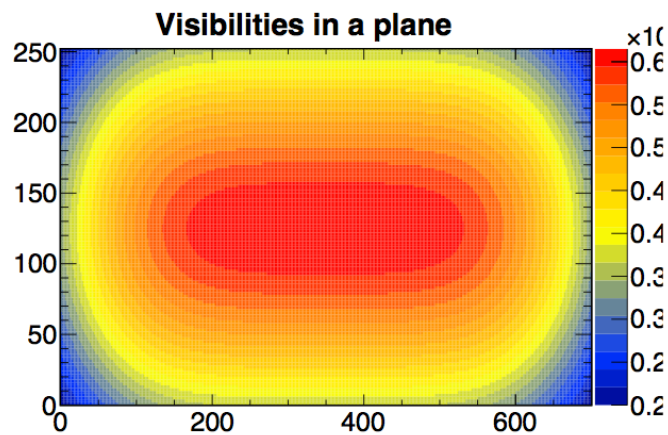
Parameterized Photon Simulation – 10 kt





Just visibilities to the bars, no attenuation function in the bars on this page.

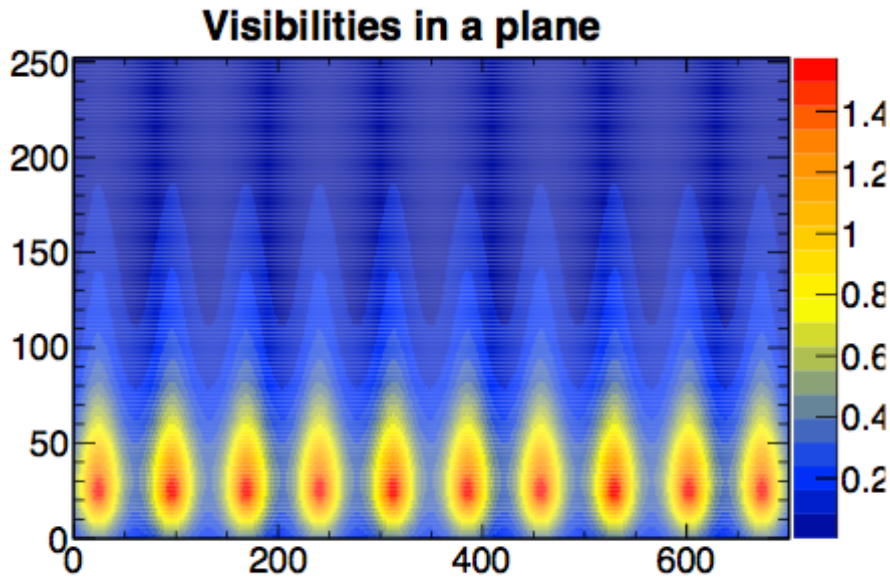
200 cm from APA

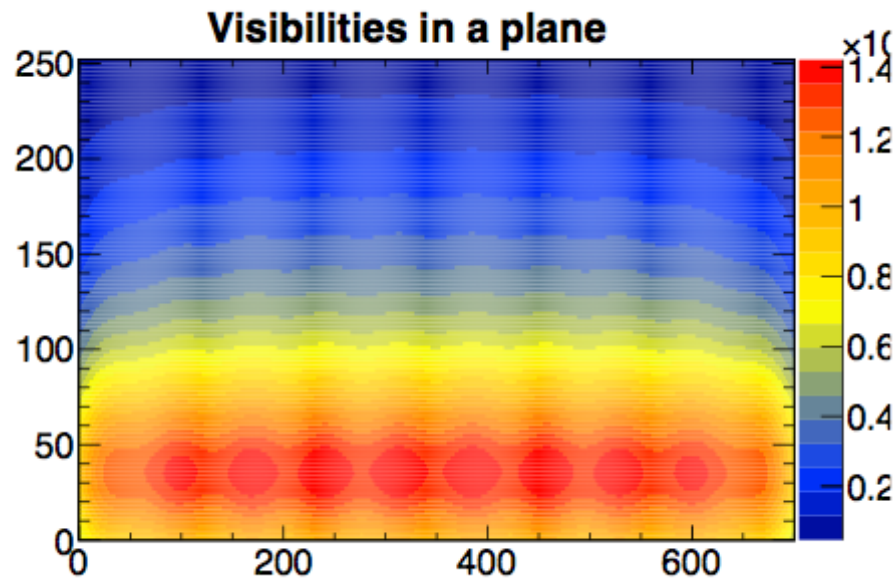


Visibilities within an APA. Pattern continues for many APA's and fills in edges.

Zepeng Li

Parameterized Photon Simulation – 10 kt

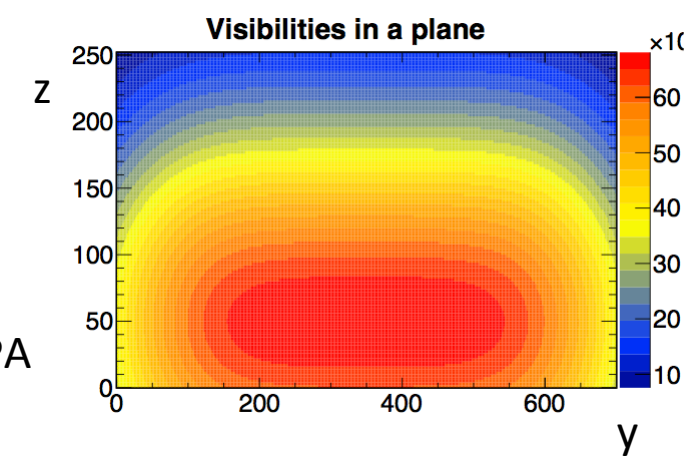




Including effects of attenuation in the acrylic bars

35t Photon simulation library with new geometry in progress

200 cm from APA



Need measured efficiencies and attenuation functions. These are placeholders.

Zepeng Li

Available Far Detector Simulated Samples

Fully simulated samples available for 10 kt FD, 4-APA FD, and 35t Phase II:

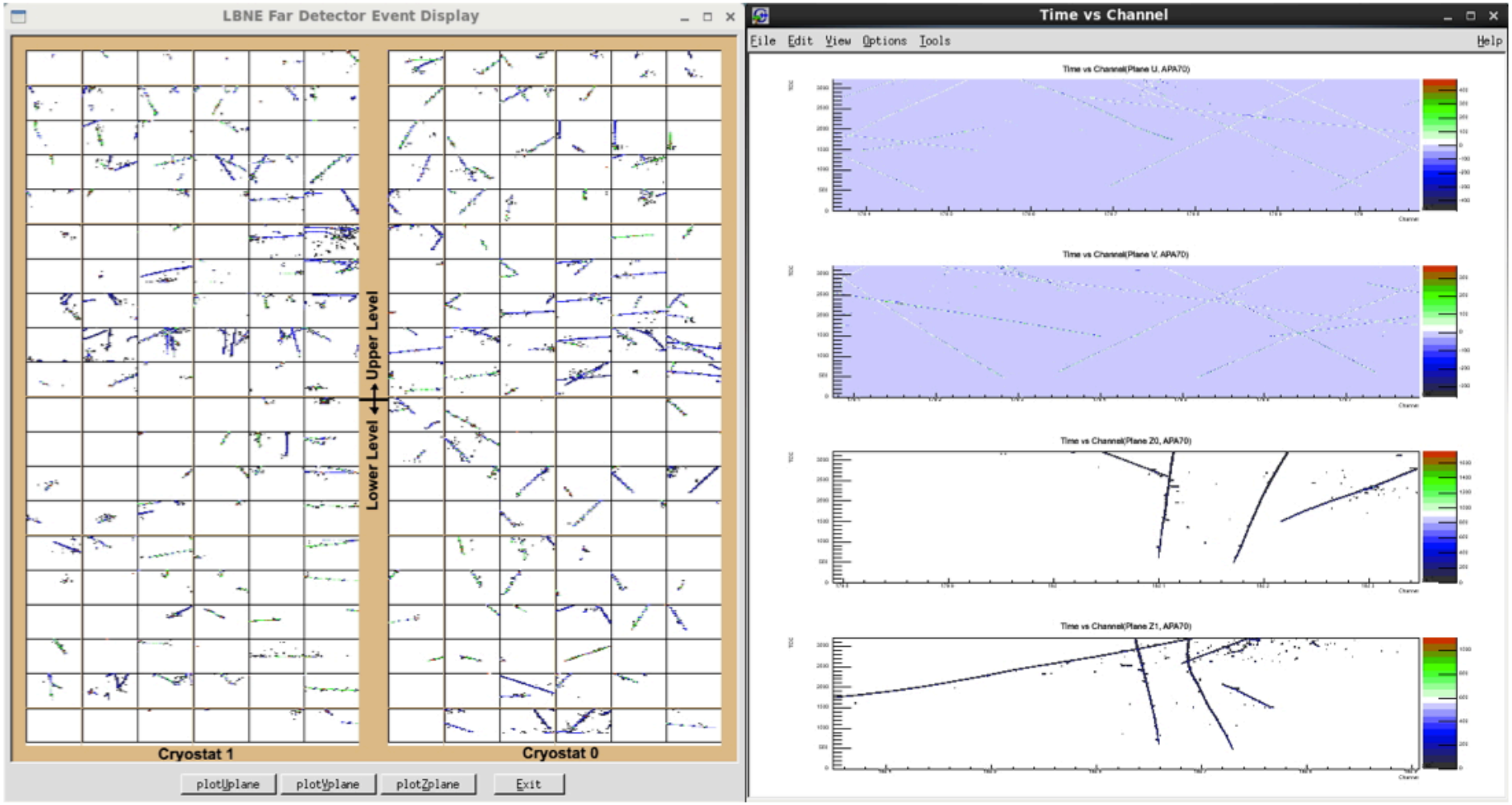
- Single particles: e, μ, p, $\pi^{\pm}$, π^{0}
- CC ν_{μ} , CC ν_{e} and NC interactions simulated with GENIE
- Cosmic-ray samples and neutrino scatters with cosmic-ray overlay
- Atmospheric neutrino interactions simulated with GENIE
- Samples re-simulated with same particles in 45° and 36° geometries
- Not all processes available yet in all geometries.

Electronic noise and crude ^{39}Ar decay model available but not used in these samples.

10 kt Far Detector Thumbnail Event Display

240 TPC's to hand-scan! click on a thumbnail to get a full view.

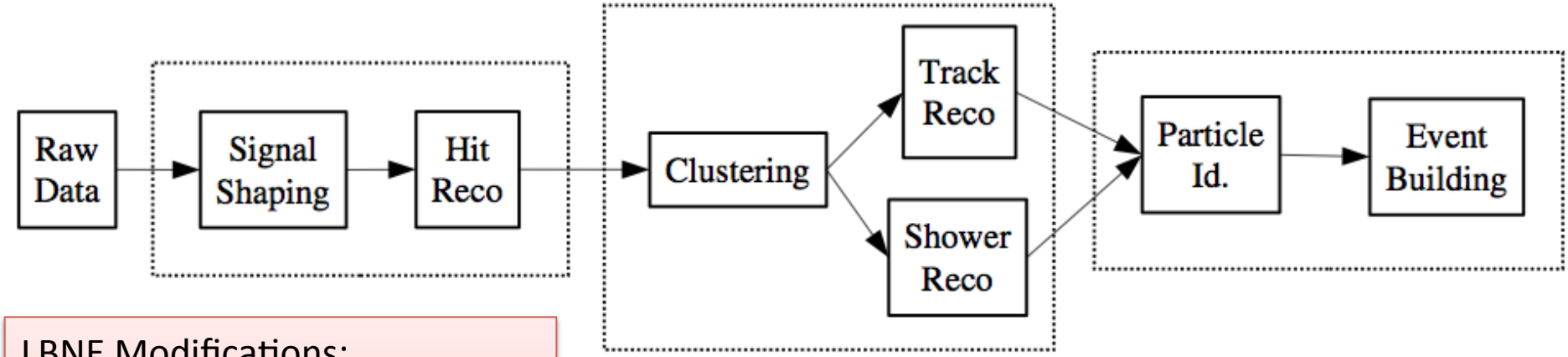
Simulated surface FD event with cosmic rays + a neutrino scatter



Seongtae Park

LArSoft FD Reconstruction Chain

As used by ArgoNeuT and MicroBooNE



LBNE Modifications:
Raw Data are zero-suppressed, and likely other compression algorithms applied. Cannot unpack
it all at once.

One wire at a time, and apply deconvolution and hit reco on blocks of nonzero data

Need a fast version for software triggering

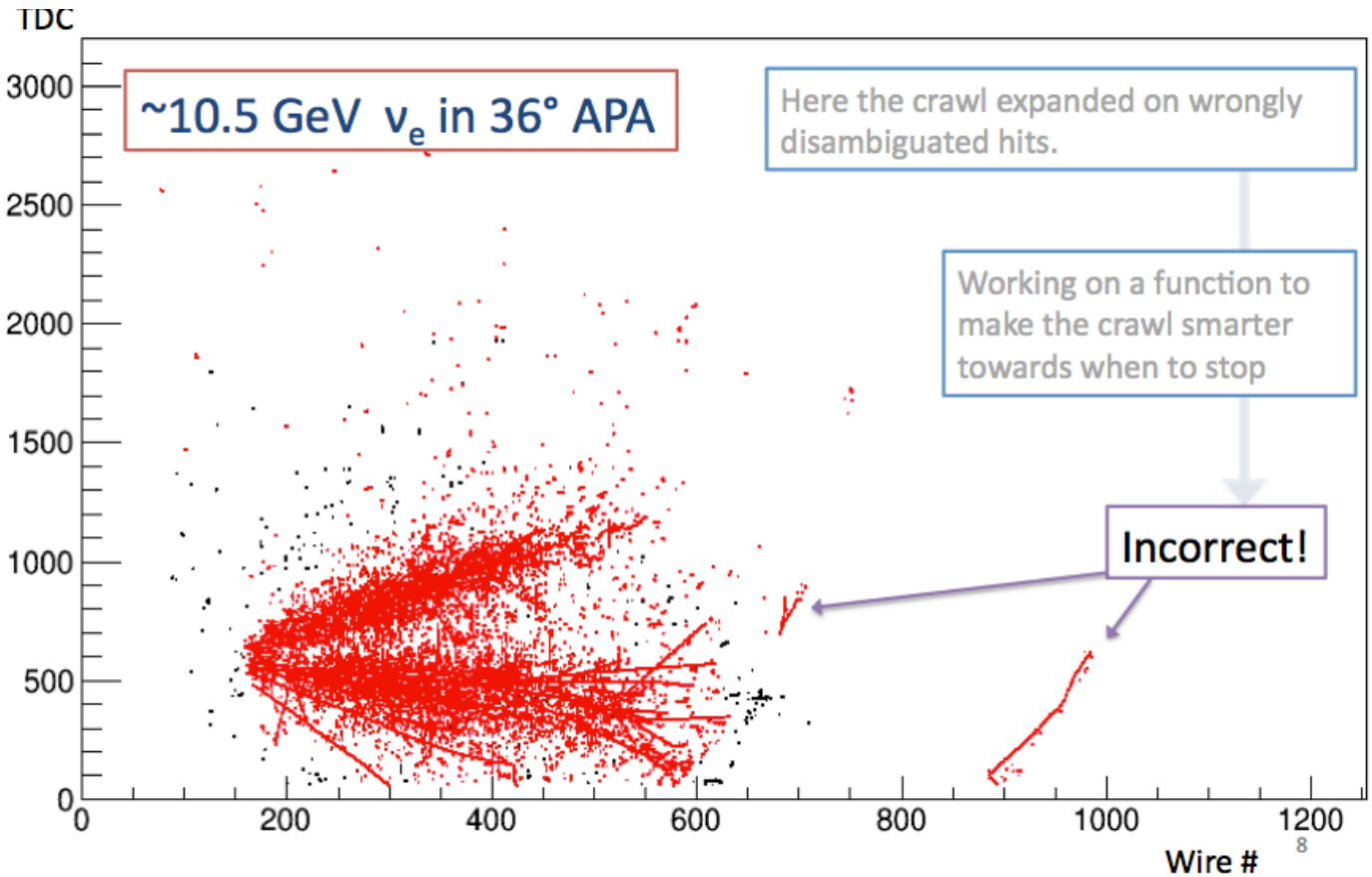
LBNE Modifications:
Ambiguity breaking for induction-plant hits: “disambiguation”

Reconstruct one APA at a time vs. global tracking and shower finding.

Cosmic-ray rejection may be done at a faster, more approximate level and events selected for further processing

Disambiguation algorithm example:

Associate hits by time between views: U, V, Z. Start with the easy, unambiguous combinations and "crawl" to grow clusters of nearby hits, propagating ambiguity choices
It's a pattern-recognition step which is needed to pick which wire segment a hit belongs to.



Once induction-hit ambiguities are broken, one can run MicroBooNE and ArgoNeuT-style tracking and calorimetry algorithms.

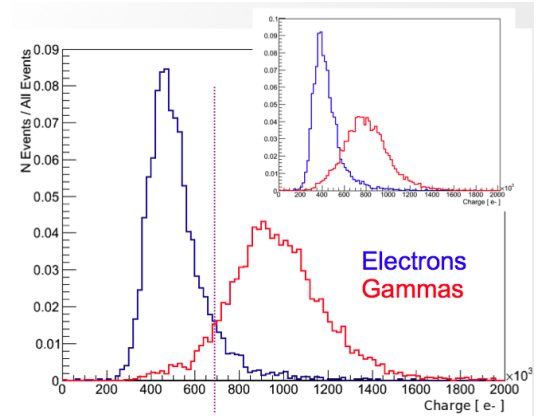
Tyler Alion, Jae Kim

e/γ Separation

M. Szydagis, D. Coelho

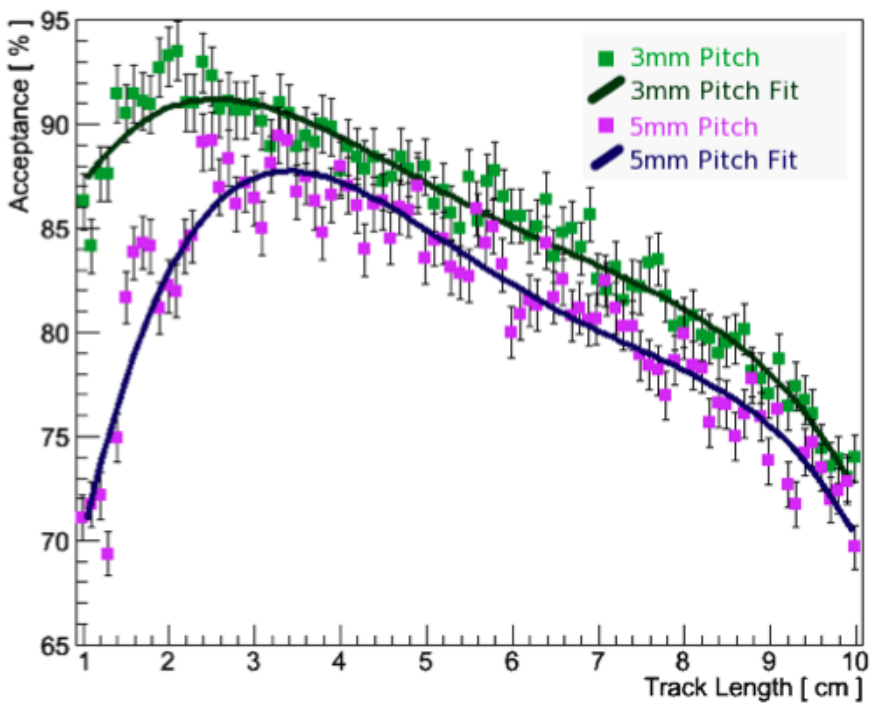
Measured charge in the first part of an EM shower used to tell one MIP from two

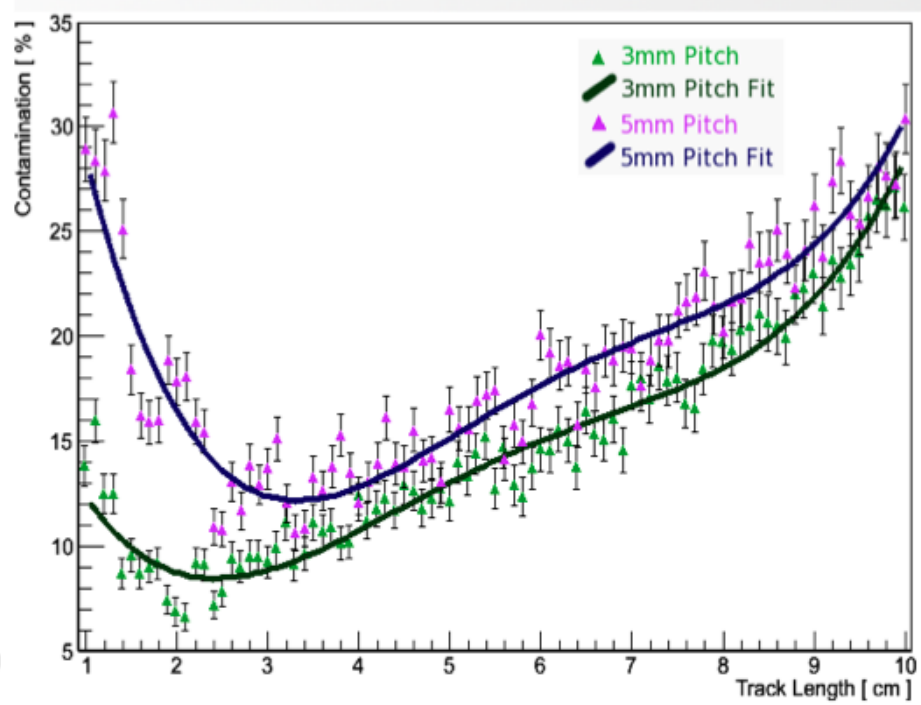
Consulting with ICARUS colleagues to optimize performance



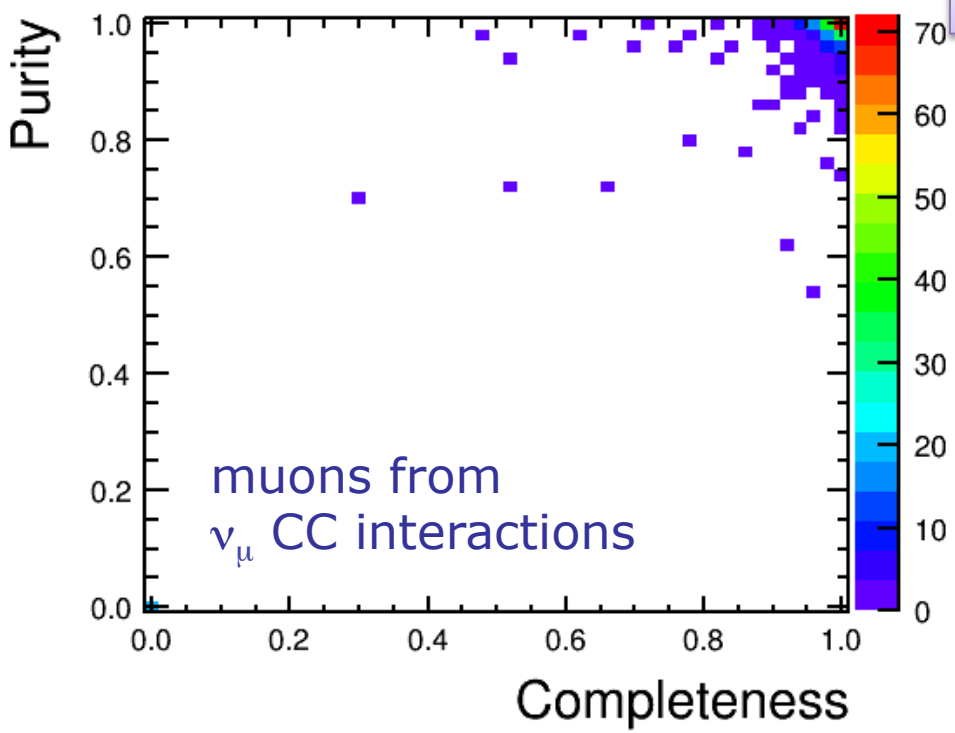
Acceptance for selecting electrons

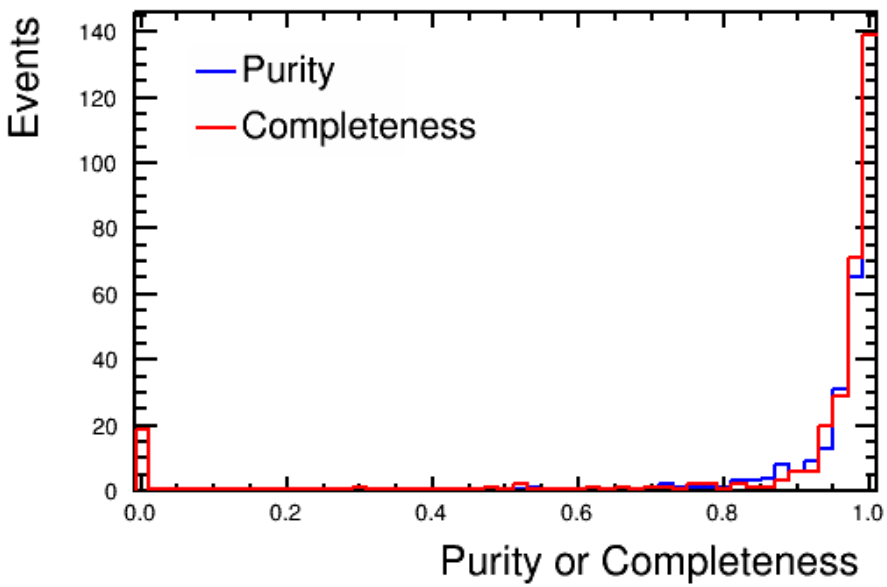
Fraction of selected events that are misID photons (assuming equal e and photon parent





PANDORA Performance





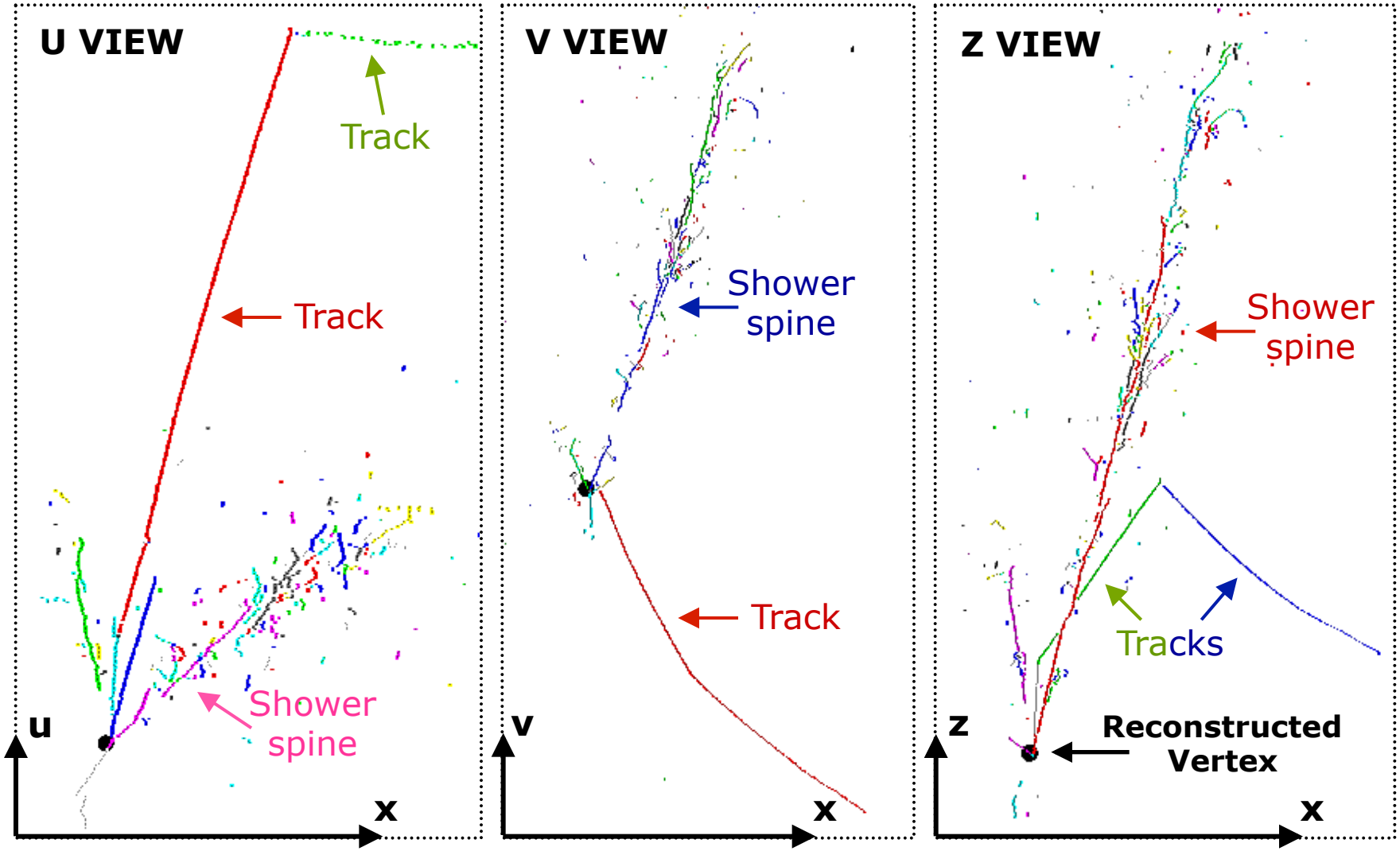
- **First performance metrics:**
  - For true ν_μ CC interactions, compare the true muon with its nearest reconstructed 3D particle.
  - Define:
    - ◇ 'True hits' in the true muon.
    - ◇ 'Reco hits' in the reco particle.
    - ◇ 'Matched hits' that are in both true muon and reco particle.
  - Calculate two metrics:

$$\textbf{Completeness} = \frac{\textbf{Matched hits}}{\textbf{True hits}}$$

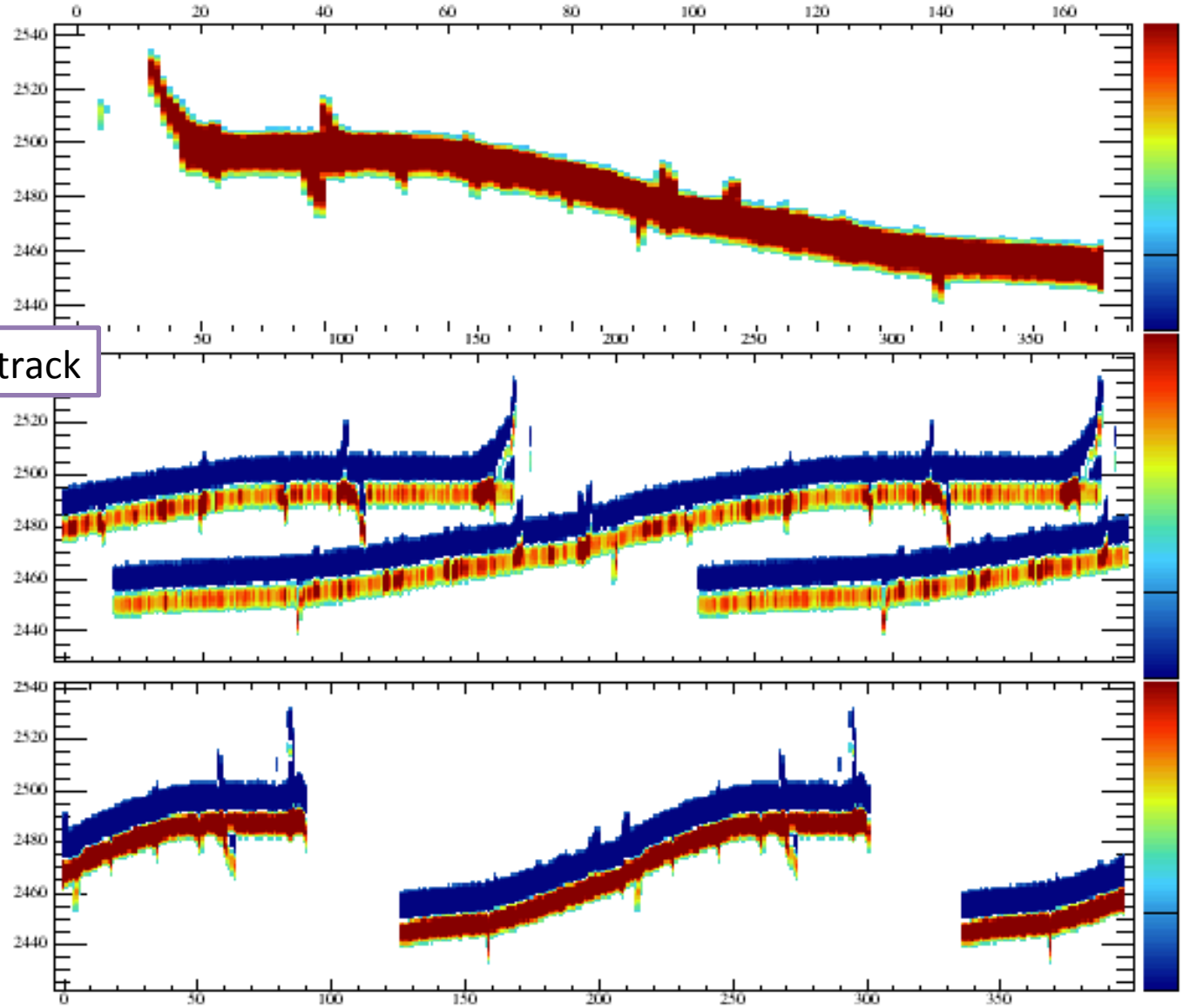
$$\textbf{Purity} = \frac{\textbf{Matched hits}}{\textbf{Reco hits}}$$

- **2D scatter, and 1D profiles, are shown left.**
  - Most events have >90% purity and completeness.

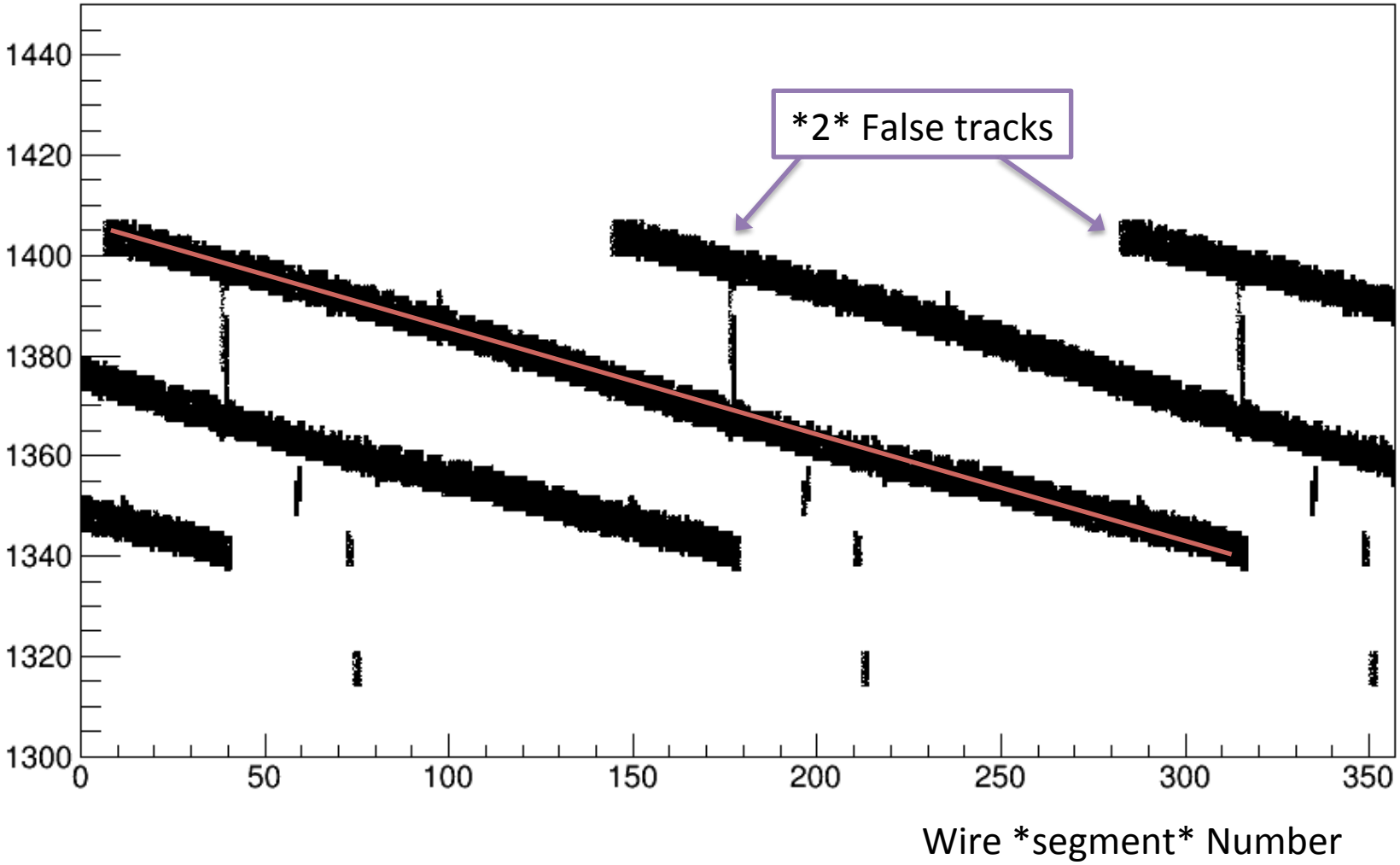
PANDORA: 2D Clusters & 3D Vertex



Cosmic in FD APA



1 False track

Cosmic in tallest 35t APA

More wrapping of the induction-plane wires due to the narrower aspect ratio of the 35t APA's