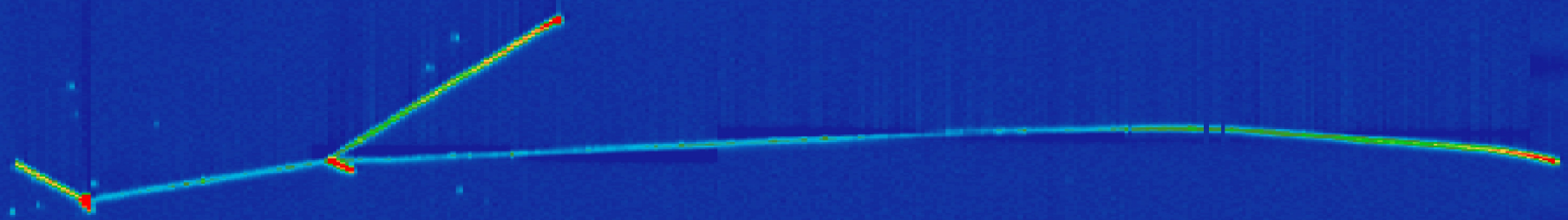
Neutrino-nucleus interactions with LArTPCs



Sowjanya Gollapinni
KSU to UTK

Neutrinos in Nuclear Physics Workshop @ ns2016, Knoxville, TN, July 30, 2016

Era of Precision Measurements

Oscillation as a probe to understand many open questions in υ Physics

Long baseline (~1000 km) Oscillations: Neutrino mass hierarchy, CP Violation
(NovA, MINOS, T2K, DUNE and Hyper-K)

Short baseline (~ 1km) Oscillations: Sterile neutrinos, New physics
(MiniBooNE, MicroBooNE, SBND, ICARUS)

Most of these can be answered by $\upsilon_\mu \rightarrow \upsilon_e$ oscillations

υ_e Appearance experiments

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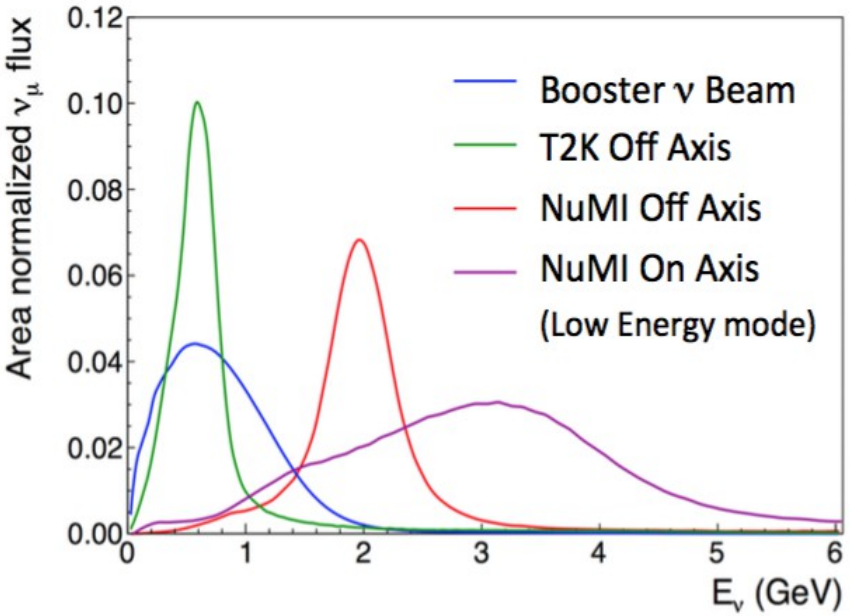
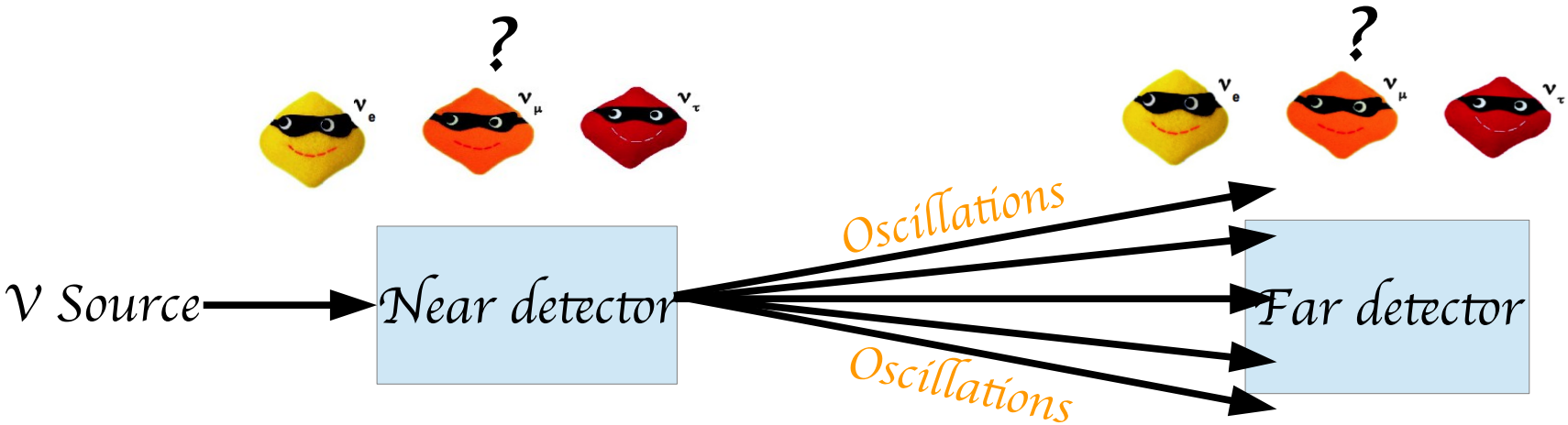
υ_e Appearance experiments

- All of the above experiments focus in the few GeV range and use dense targets
- Reliable cross section models for heavier targets in the few GeV region are critical for the success of precision measurement of oscillations at Short and long baseline experiments



Why do we care about Cross sections?

Probing Oscillations: current global scheme

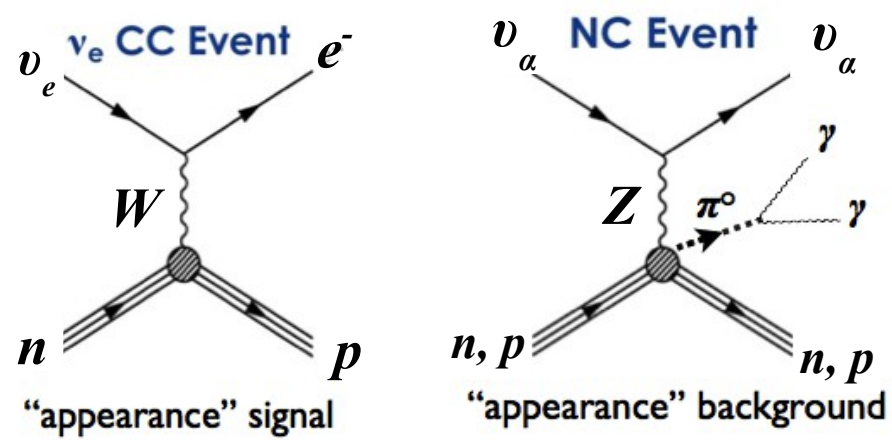


- Count interaction types (by counting leptons) at near and far detectors

$N_\upsilon(E) = \Phi_\upsilon(E) \times \sigma_\upsilon(E) \times N_T$

FLUX (neutrino source)	Neutrino Cross-section On target	No. of nuclear targets in the detector

- Use ND data to constrain Oscillations in the FD

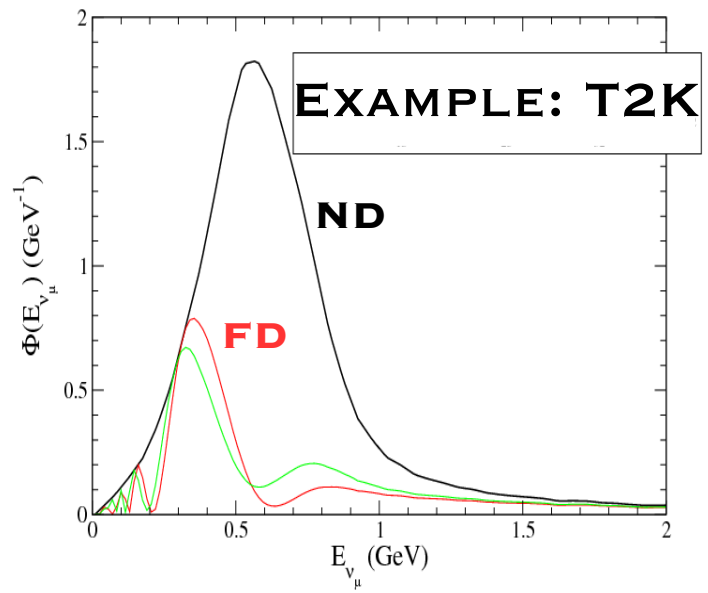


But, Near to Far extrapolation is tricky, many effects convoluted!

Why do we care about Cross sections?

Problem 1: Having Near and Far detector doesn't eliminate the need to know cross-sections even if they use same detector technology and target:

- Near & Far fluxes are different due to Oscillations resulting in different energy and flavor spectra at both locations
- different technologies and targets make things even worse



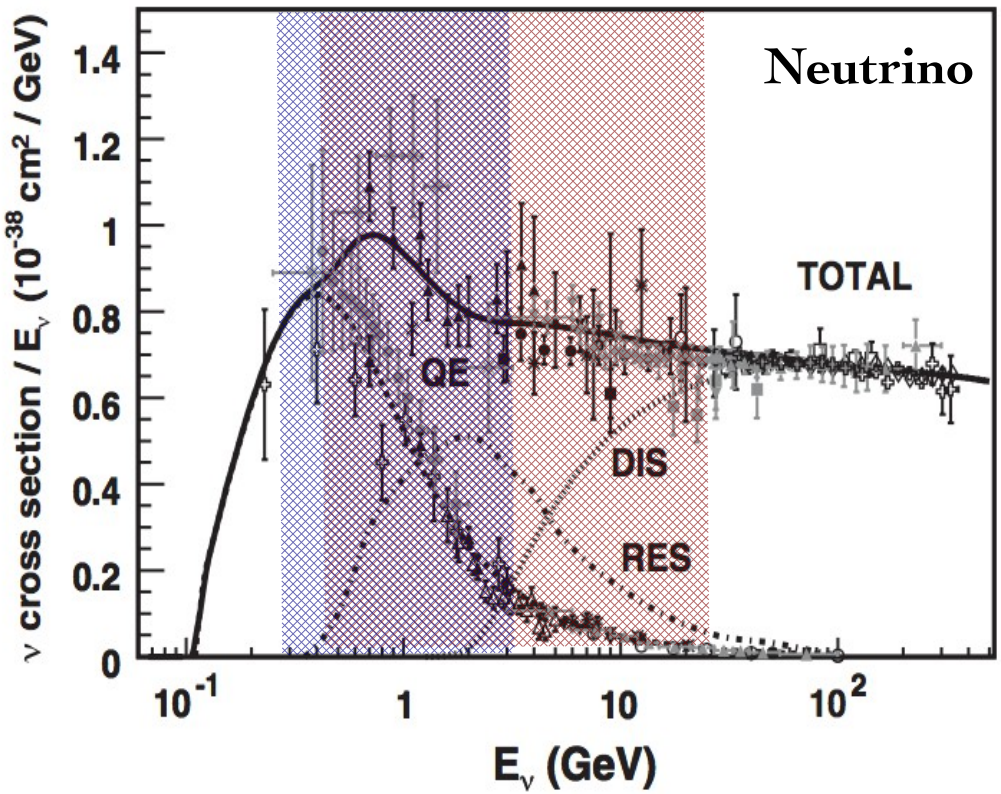
Problem 2: The measured energy and flavor spectra at the near detector doesn't necessarily represent the initial neutrino state due to cross sections being convoluted with effects from using denser targets

Talk by Jorge Morfin tomorrow on "neutrino-nucleus interactions"

We rely on cross-section models to relate the detected state to initial state and also do proper near to far comparison

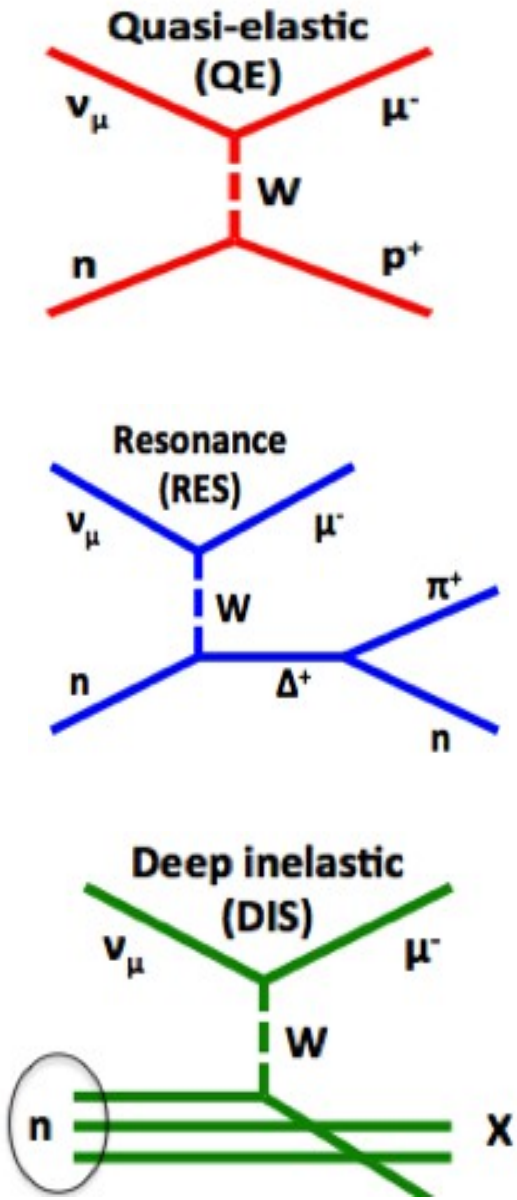
The few GeV energy for neutrinos is a mess!

- Region full of Reaction thresholds, Sparse data and large errors => cross section knowledge is weak
- Data comes from bubble chambers 30 years ago...



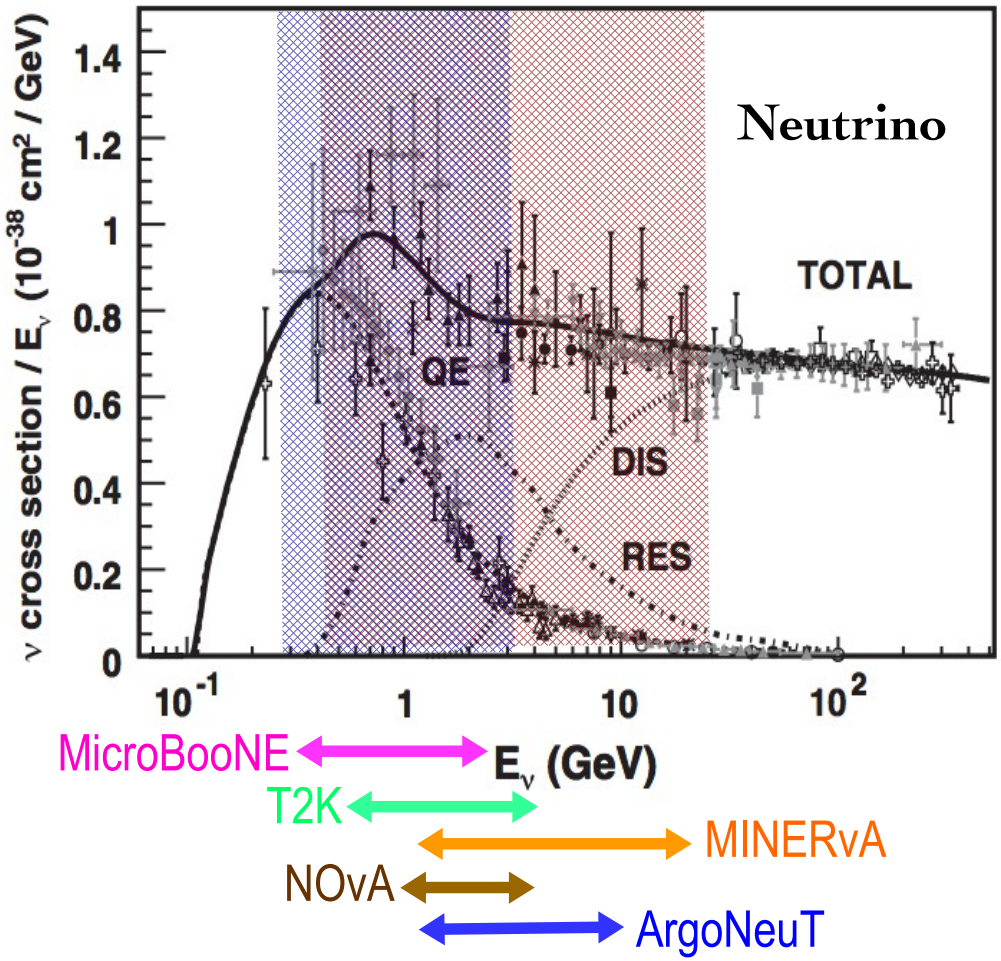
SBL (MicroBooNE, SBN) LBL (T2K, NovA, DUNE, MINOS)

(Current oscillation experiments focus in this region)



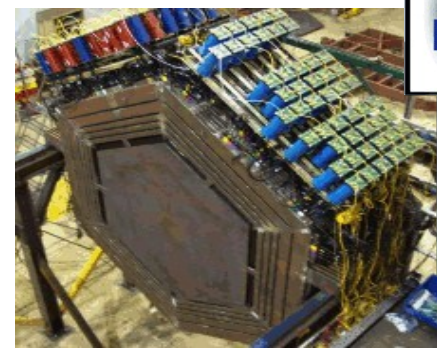
Neutrino Scattering experiments to the rescue...

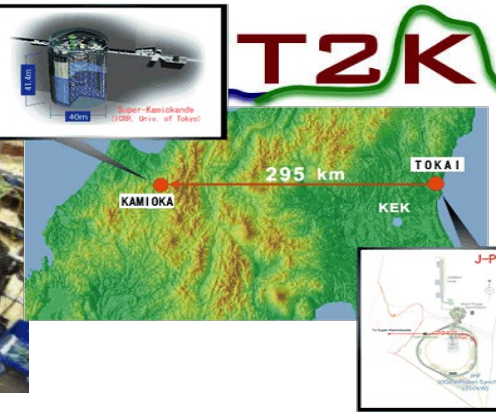
SBL (MicroBooNE, SBN) LBL (T2K, NovA, DUNE, MINOS)



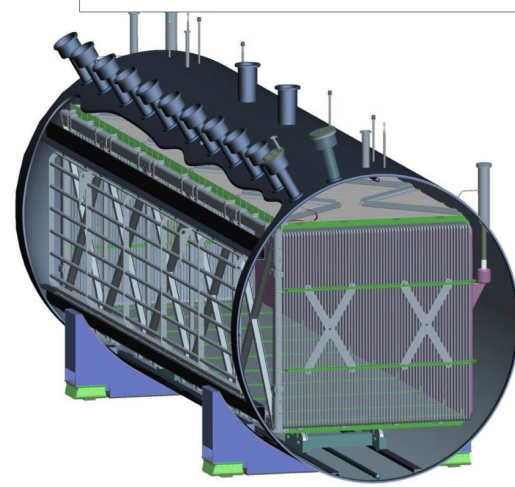
- Also LArIAT (in a non-neutrino beam)
- **Future:** SBND, CAPTAIN – Minerva, ANNIE, NuPRISM, WAGASCI, TITUS, Pion/Kaon decay experiments (e.g. at JPARC, ...)

MINERvA





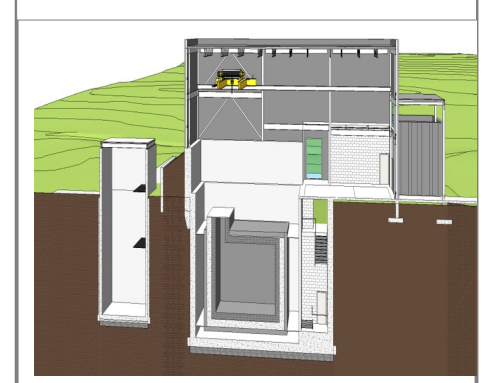
MicroBooNE



ArgoNeuT

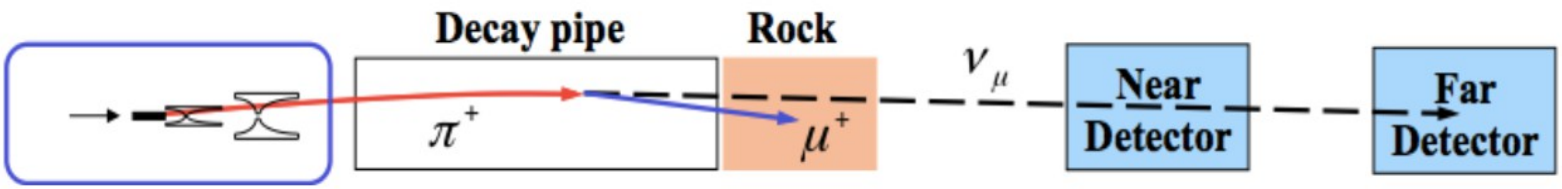
CAPTAIN Minerva

SBND



Neutrino cross section measurement challenges

- Beam flux uncertainties are dominant (around 15%) due to poor knowledge of hadron production data in accelerator neutrinos



Neutrino cross section measurement challenges

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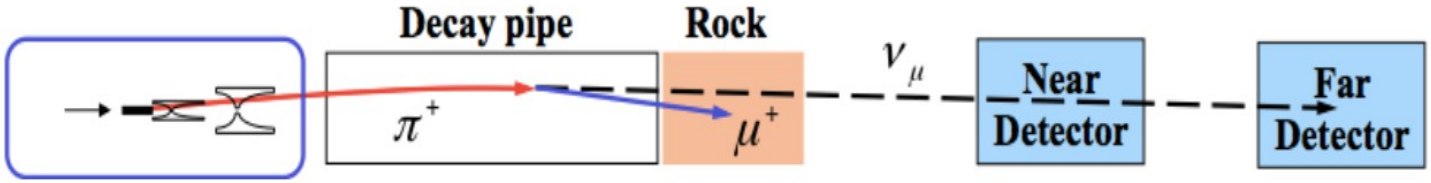
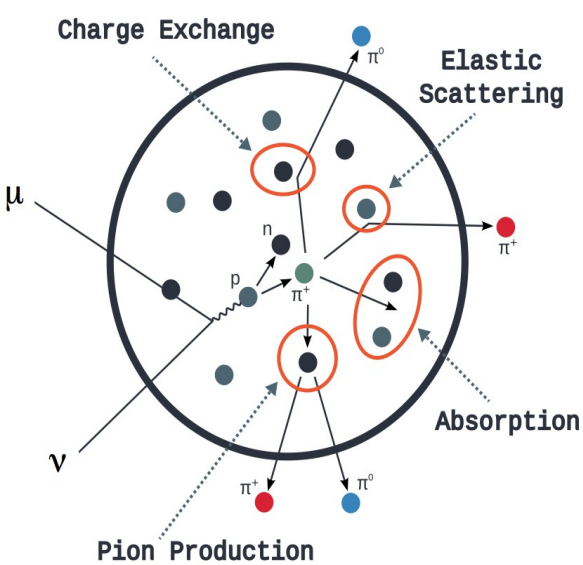


- Neutrino energy reconstruction is challenging due to non-monochromatic beams. Need to extract it from final state interactions

$$P = \sin^2 2\theta \sin^2\left(1.27\frac{L}{E_\nu}\Delta m^2\right)$$

- Modern experiments use dense targets for higher statistics
  - Dense targets introduce nuclear effects and final state interactions

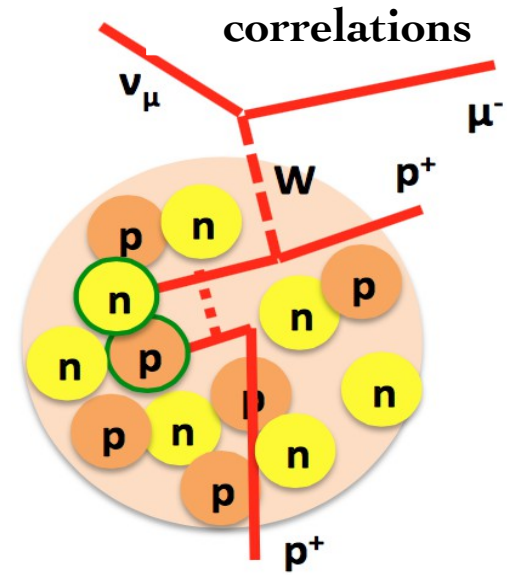
Final state Interactions



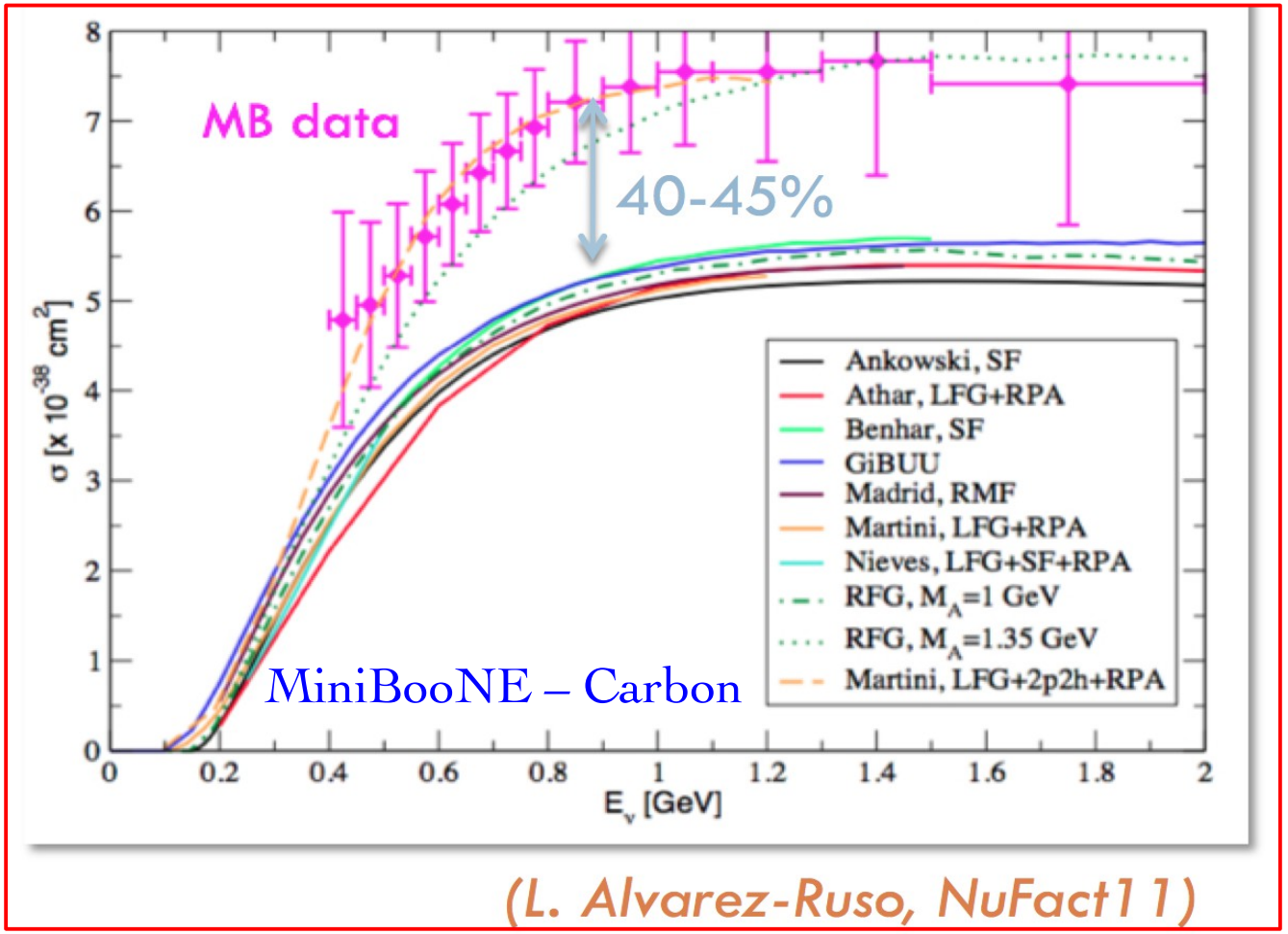
MiniBooNE – Carbon
T2K – Carbon, water
Minerva – C, He, Fe, Pb
MicroBooNE, SBND, ICARUS, DUNE: Ar

Hadron kinematics come into play!
Detector technology is critical here!!

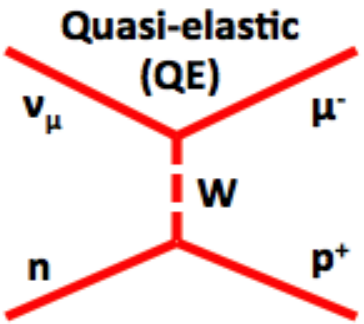
Nucleon-nucleon correlations



Tension between data and models



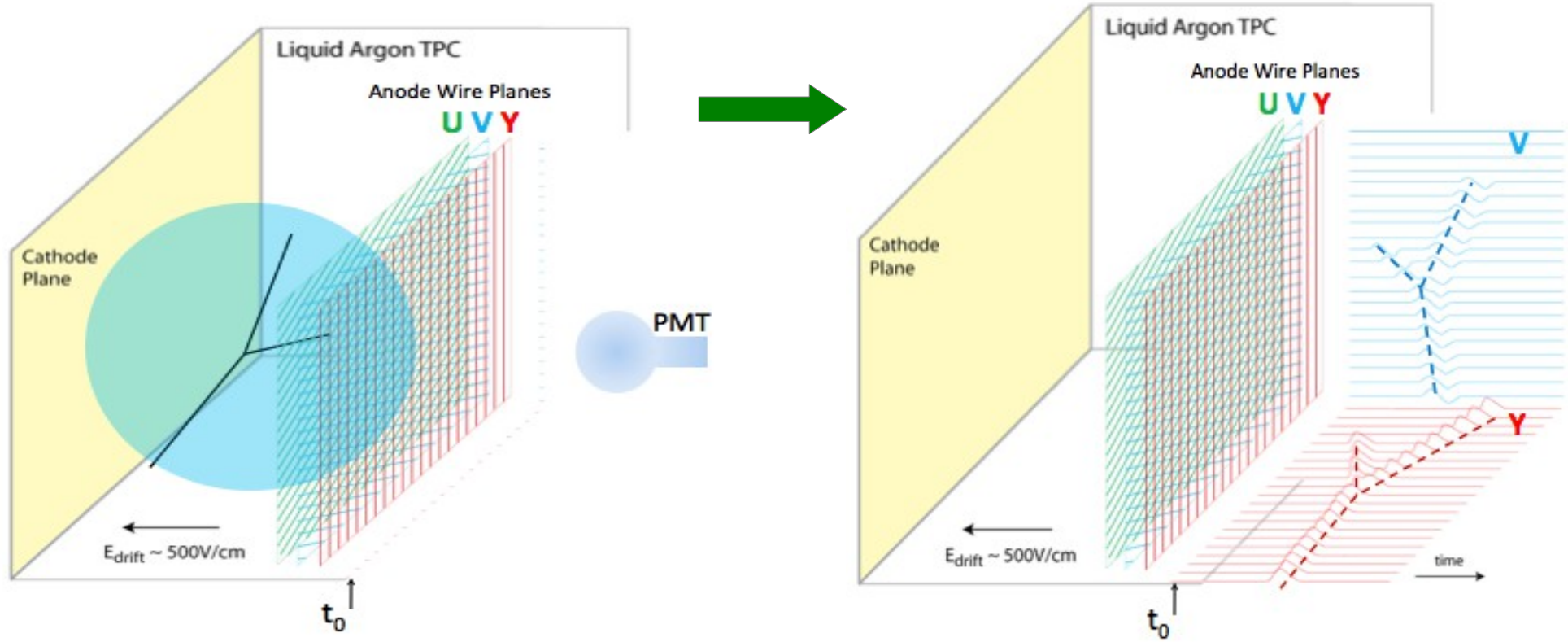
(L. Alvarez-Ruso, NuFact11)



- Existing models do not accurately represent modern data resulting in large systematics (5% – 8%)
- These systematics continue to dominate our current & future long and short baseline neutrino physics program – need to get it down to 1%

Liquid Argon Time Projection Chambers for Neutrinos

NIM 120 (1974), no. 2, 221-236



Desirable features:

- Finely segmented anode wires ⟶ excellent granularity
- Allows for scalability, don't need to instrument the entire volume
- Liquid Argon makes an excellent target (dense, abundant, etc.)
- Presents neutrino interactions with unprecedented amount of detail

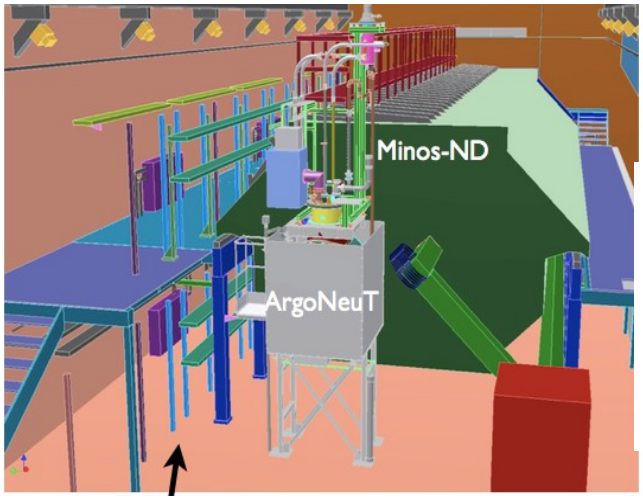
Imaging detectors
Digitized Bubble chambers
With Calorimetry

Neutrino target = Argon

The ArgoNeuT Experiment

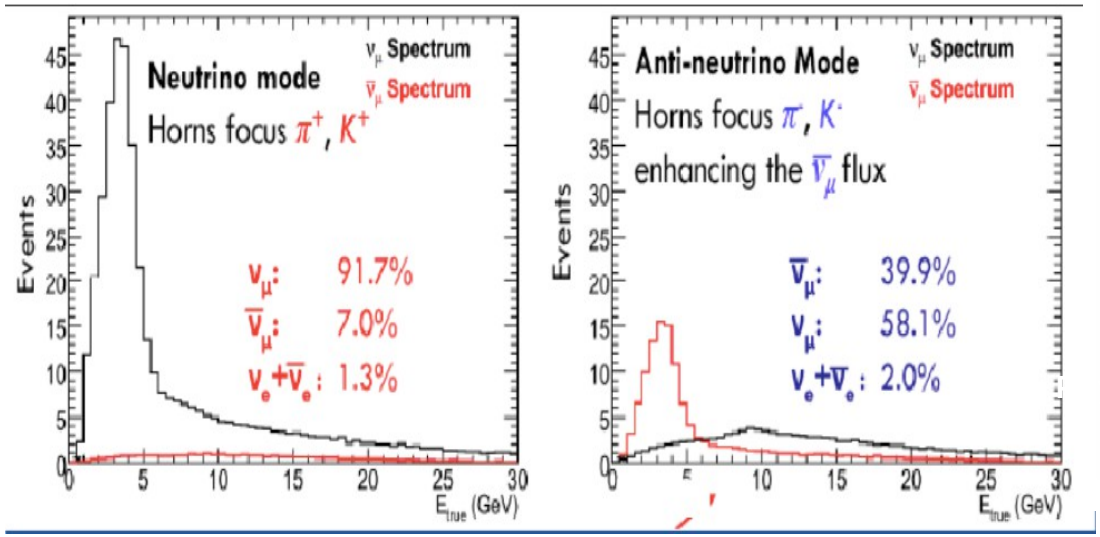
- Produced first ν-Ar cross-section data in the medium-energy region
  - CC inclusive, CC coherent pion, NC Pi0, CC 0-pion etc.
  - Ongoing analyses: υ_e CC, CC 1-pion

Around 7000 total CC events

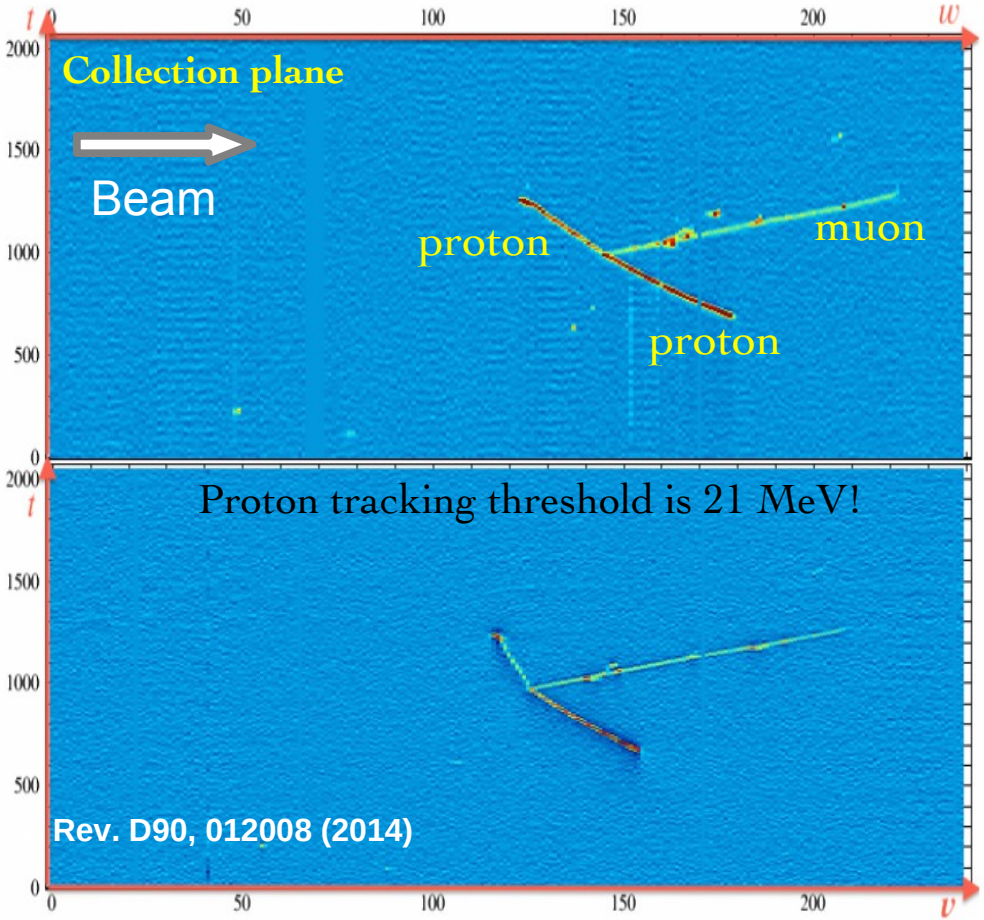


2009 to 2010

NuMI LE beam
ν−mode (2 weeks): 8.5×10^{18} POT
$\bar{\nu}$−mode (5 months): 1.20×10^{20} POT

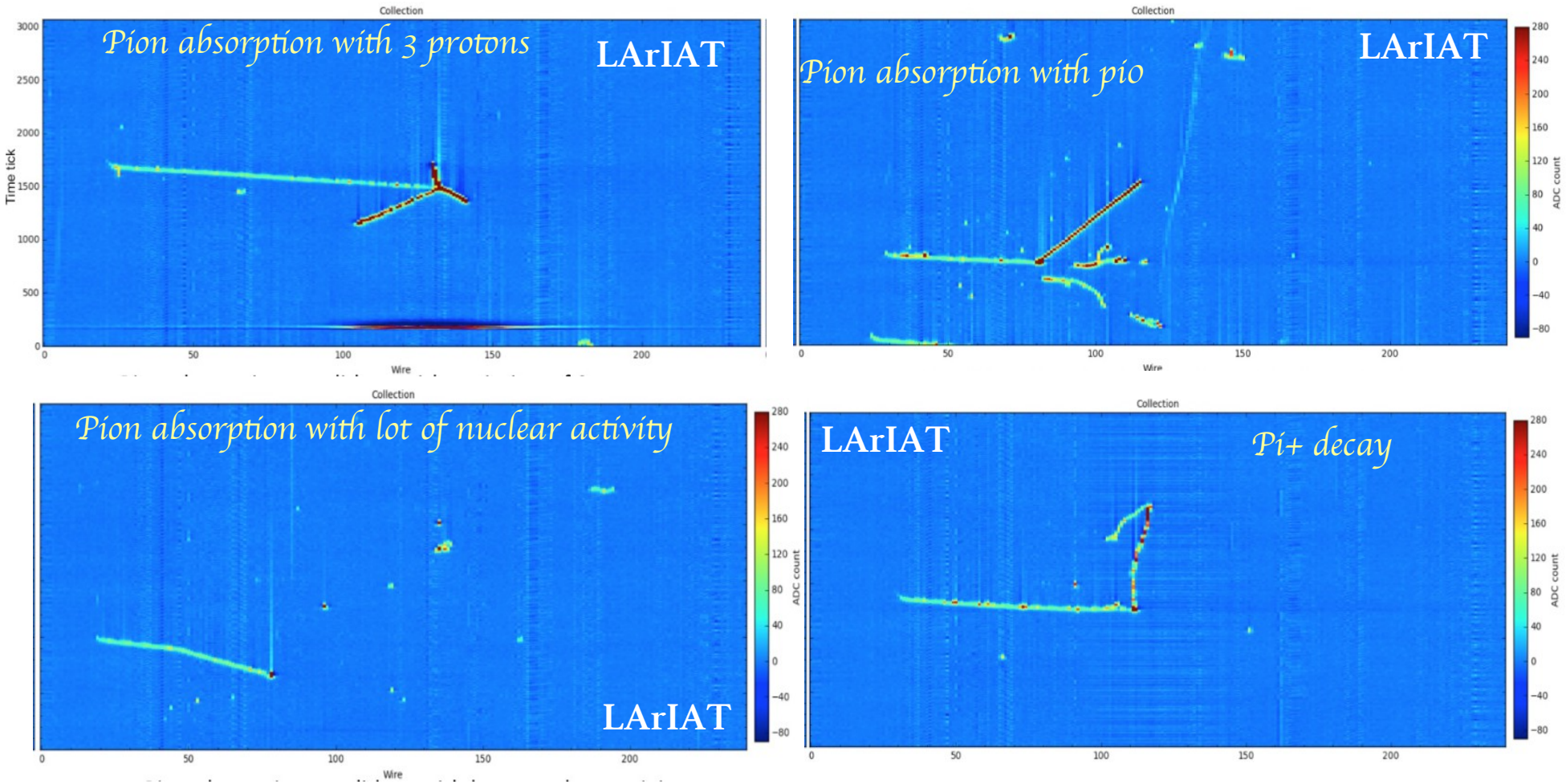


first direct investigation of nuclear effects

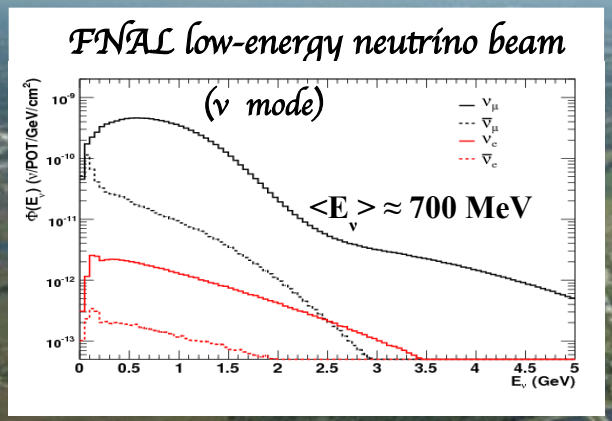


Argon data in a non-neutrino beam – LArIAT

- Pion absorption dominant effect for CC-0 pion cross-section
- LArIAT a test beam experiment at Fermilab will study
  - pion interaction cross-sections in Argon (not studied before)
- Charged particle tertiary beam (mostly pions), 200 MeV – 1.5 GeV
  - great source for studying pion absorption, charge exchange, also Kaon and pion production



Next big avenue for Cross-section data on Ar – MicroBooNE!



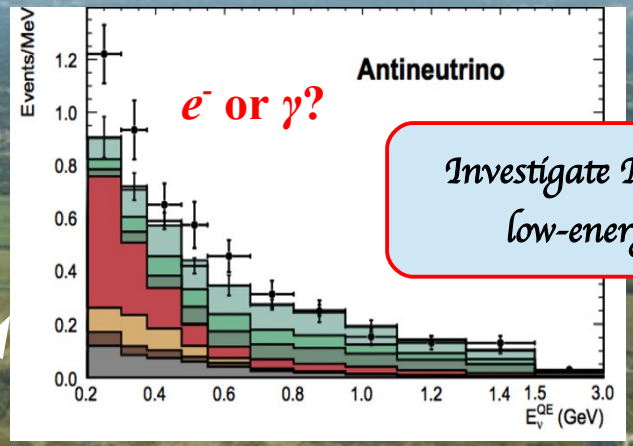
Booster (BNB)
Proton Energy: 8 GeV

Neutrinos

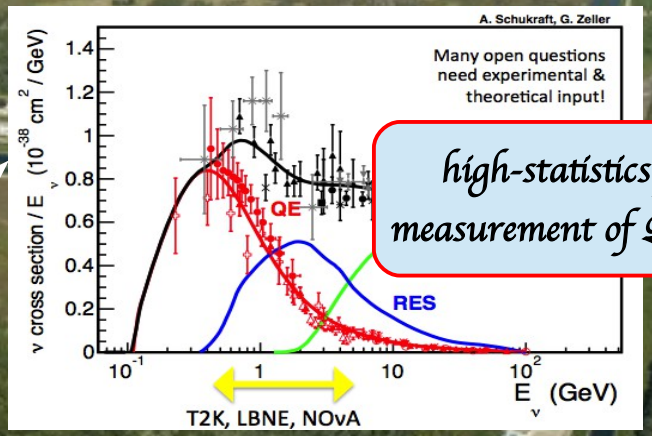
Protons

MiniBooNE
541m baseline

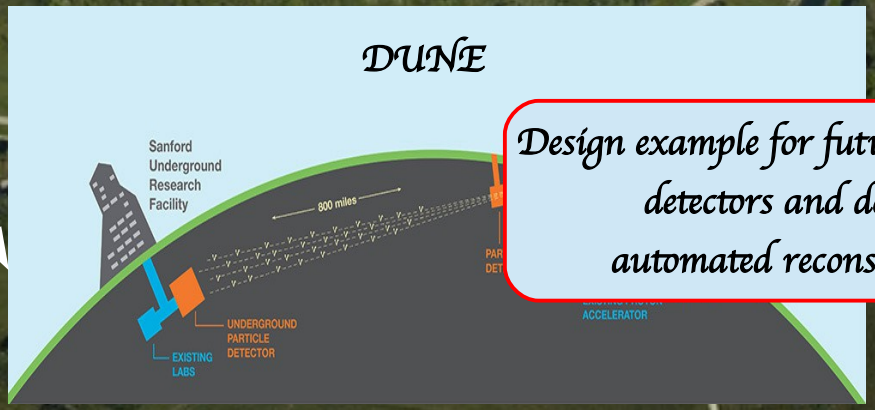
MicroBooNE
470m baseline



Investigate MiniBooNE low-energy excess

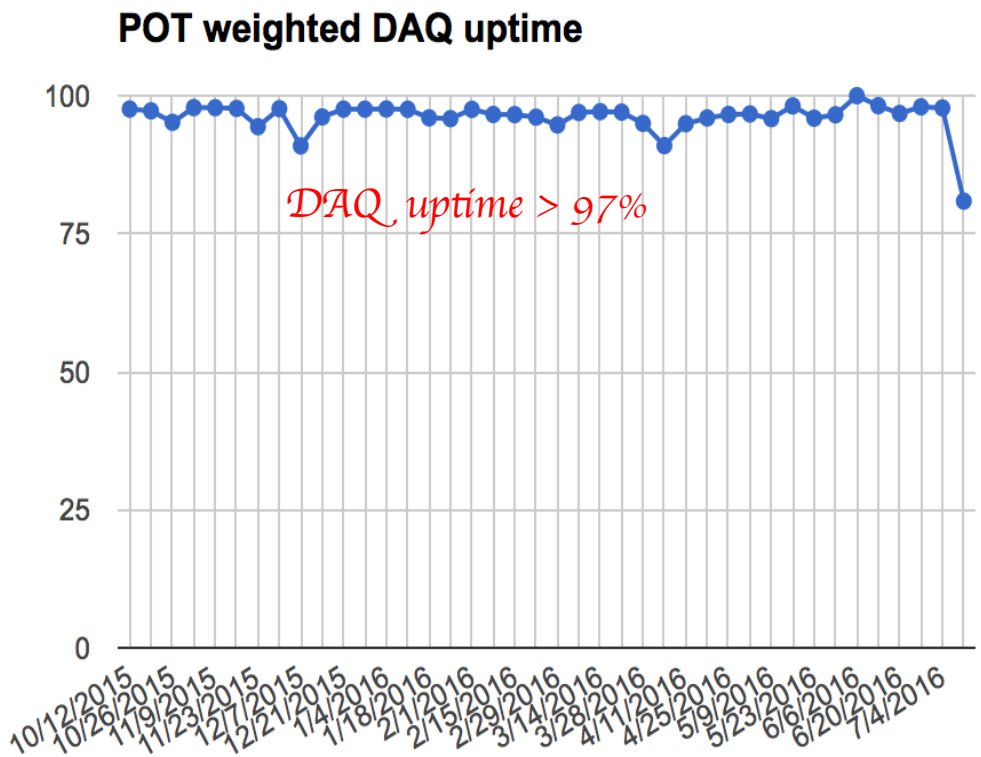


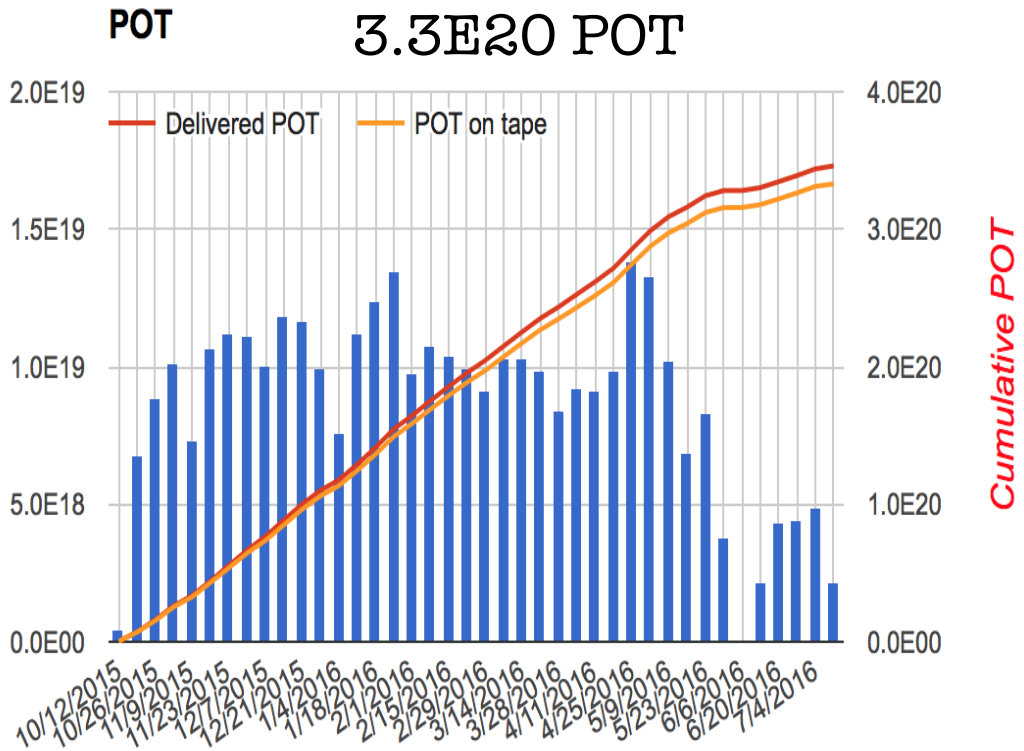
high-statistics precision measurement of LAr in 1 GeV



Design example for future multi-kton detectors and develop automated reconstruction

MicroBooNE is taking data now

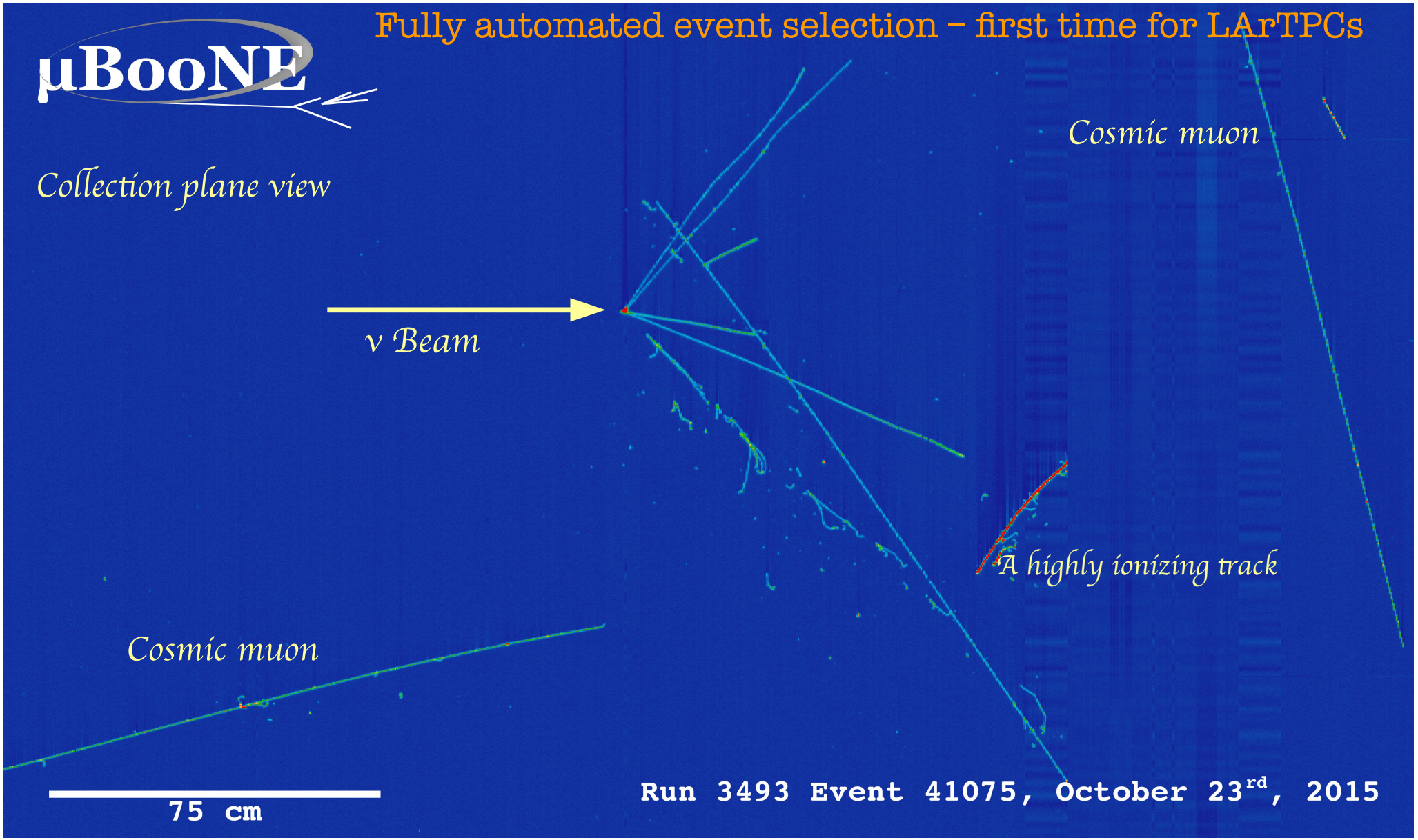




BNB performing incredibly well, continuous beam!

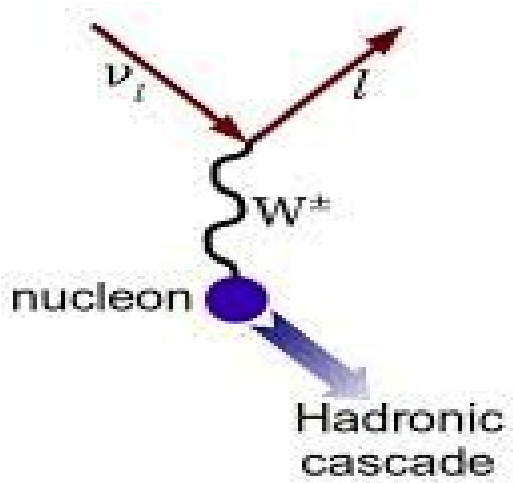
We collected 50%
of our data already!
(since Fall 2015)

A neutrino event in MicroBooNE
(Surface detector, cosmics pose a challenge)



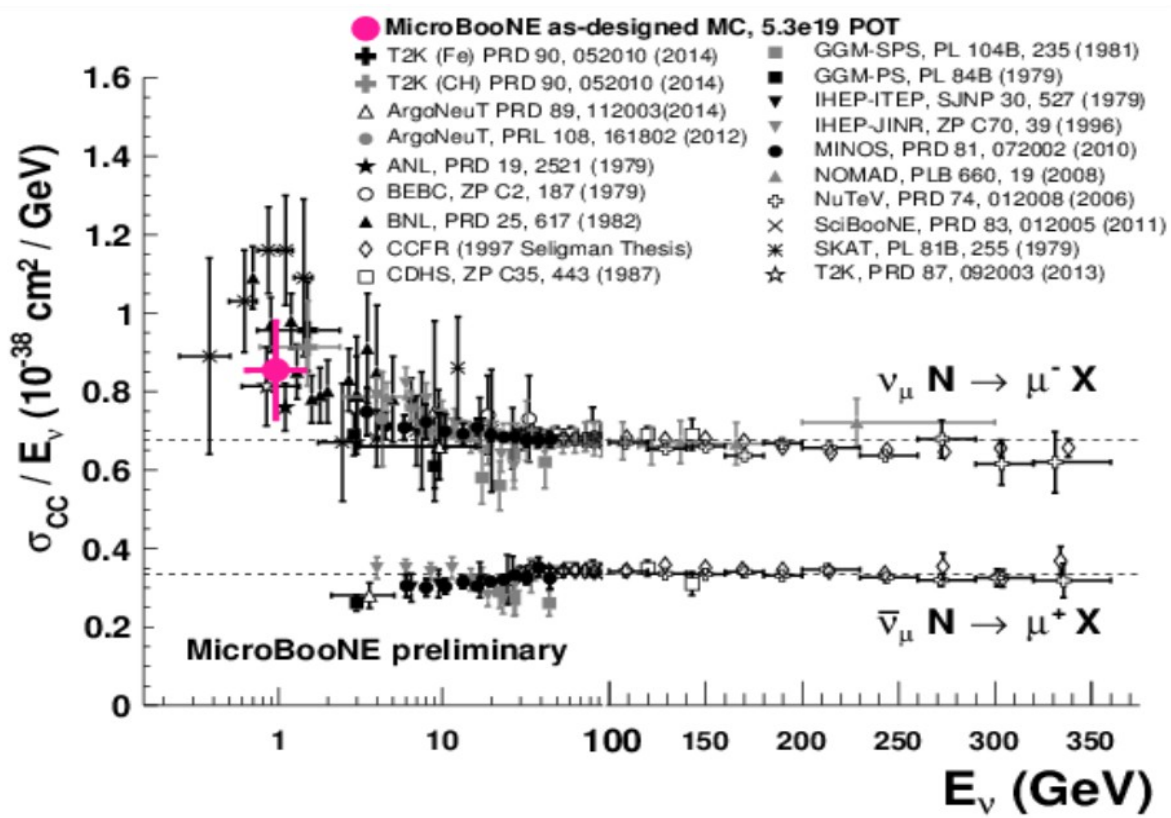
See more neutrino tracks here: http://www-microboone.fnal.gov/first-neutrinos/index.html

First neutrino analysis: Charged Curren ν_μ inclusive



Signature: Look for a muon (plus anything) in the final state with an associated neutrino vertex

CC inclusive world data plot



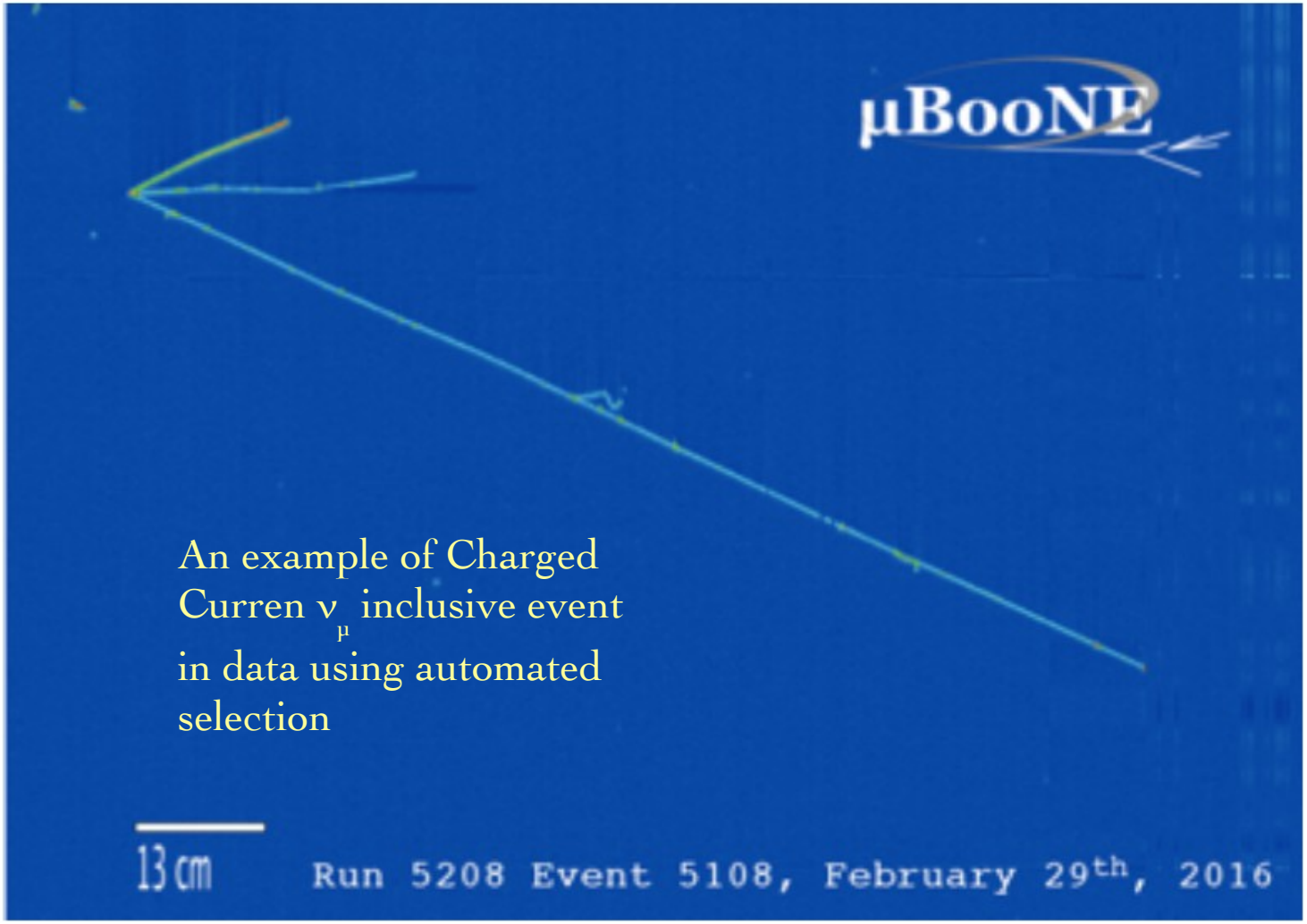
Importance:

1. First step towards a cross section measurement

2. Will develop the reconstruction and systematics tools needed for final state topologies

3. Lets you compare data between various experiments

First neutrino analysis: Charged Curren ν_μ inclusive



An example of Charged Curren ν_μ inclusive event in data using automated selection

Importa

1. First
section

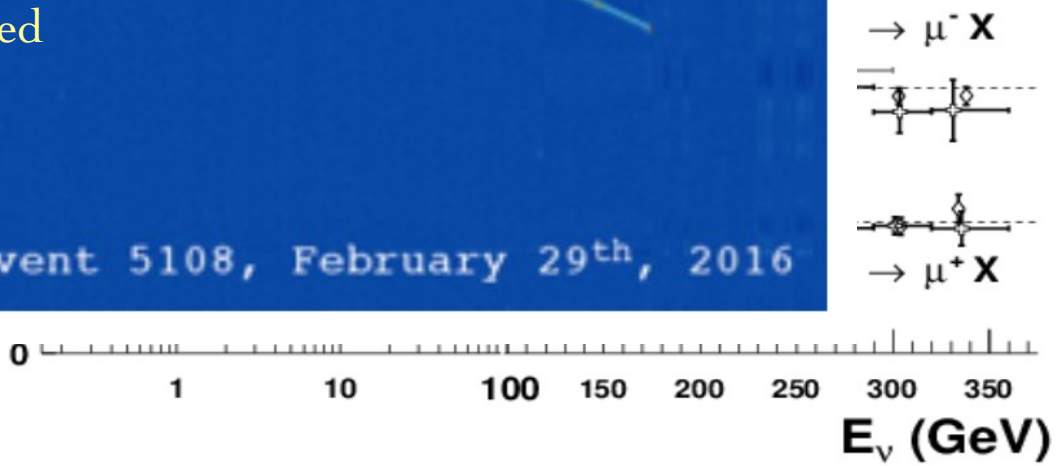
2. Will c
reconst
systema
final sta

3. Lets
between various experiments

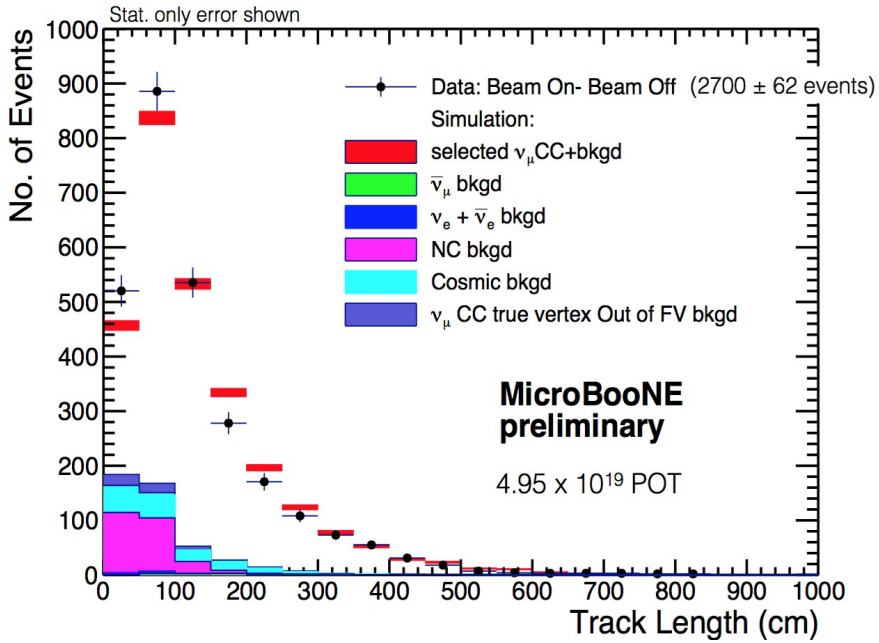
an

plot

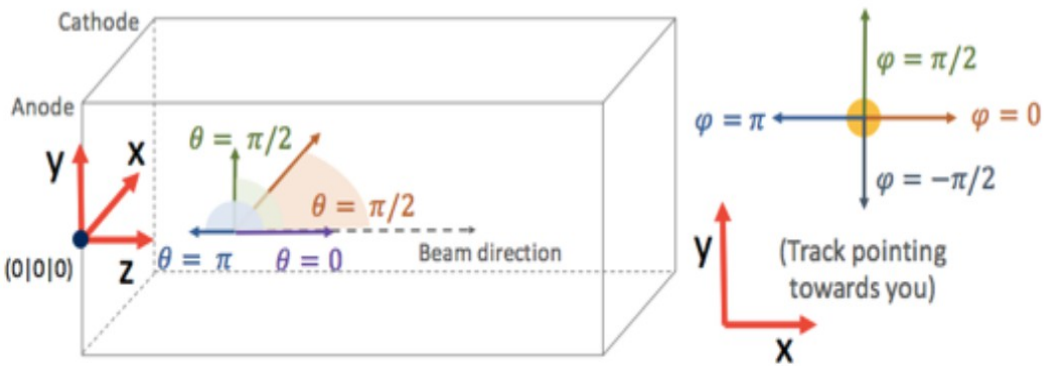
. 104B, 235 (1981)
34B (1979)
INP 30, 527 (1979)
C70, 39 (1996)
31, 072002 (2010)
660, 19 (2008)
'4, 012008 (2006)
D 83, 012005 (2011)
, 255 (1979)
092003 (2013)

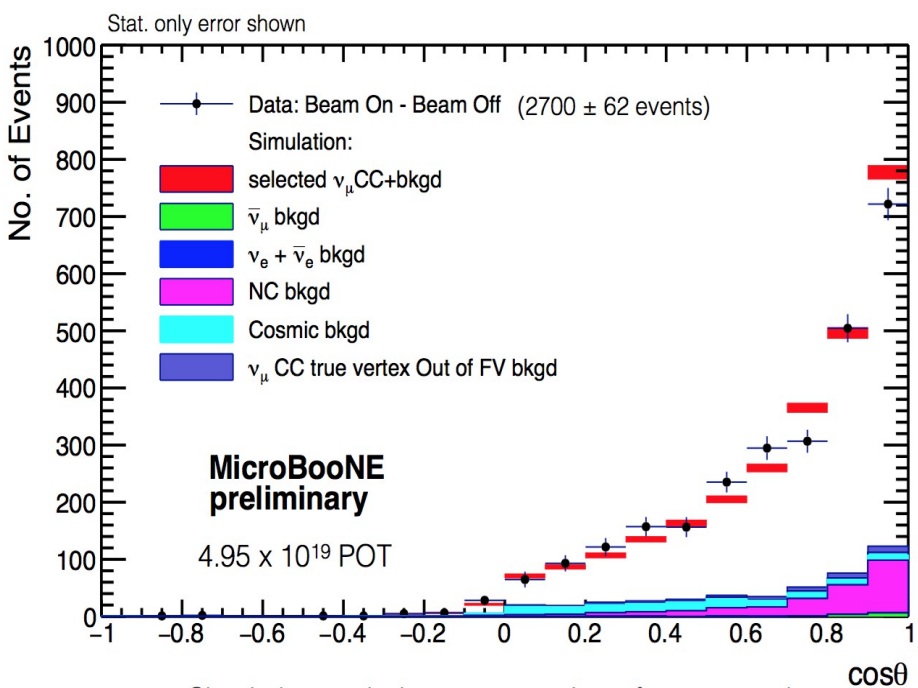


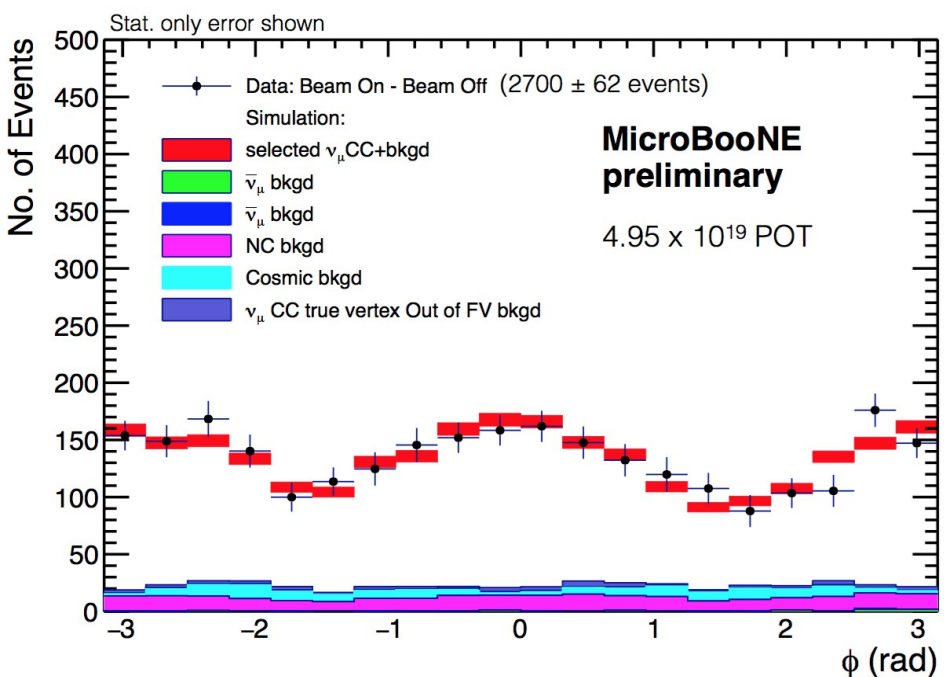
Charged Current ν_μ inclusive event distributions



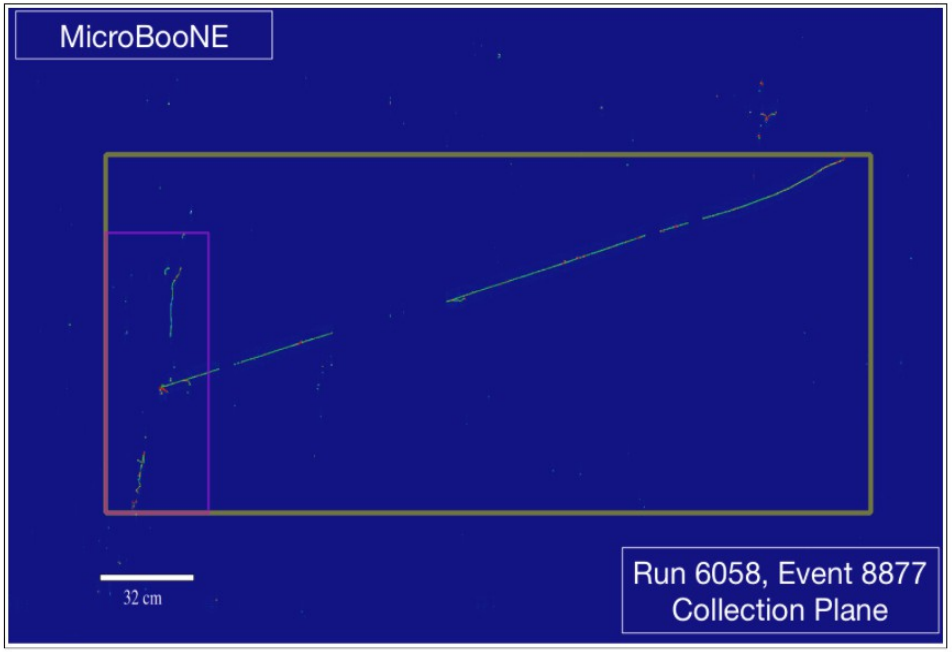
MicroBooNE coordinate system

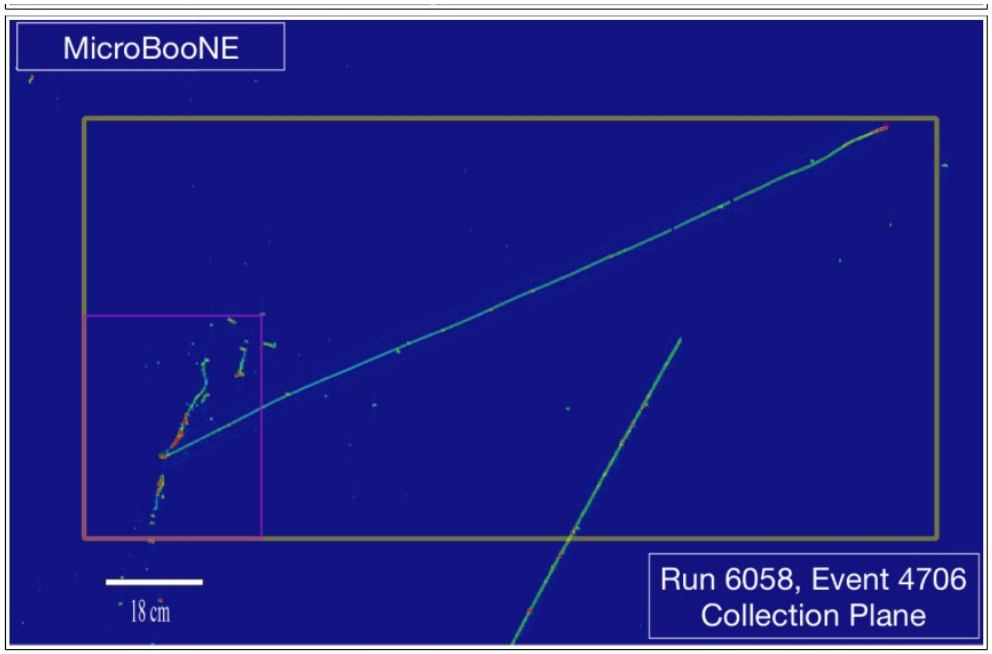




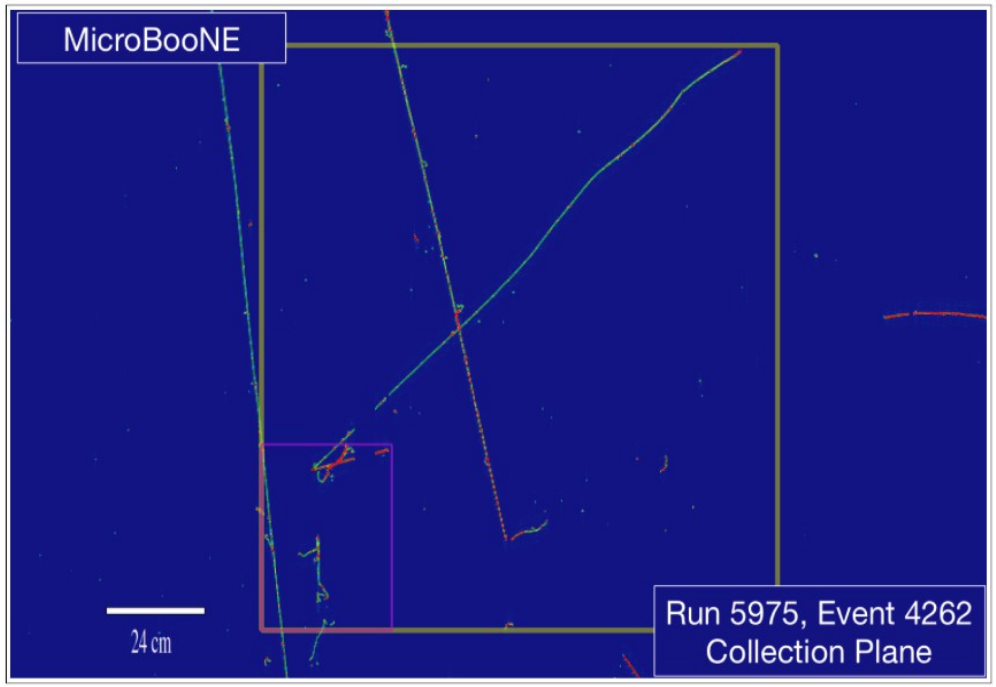


Building on CC inclusive: CC π^0 analysis



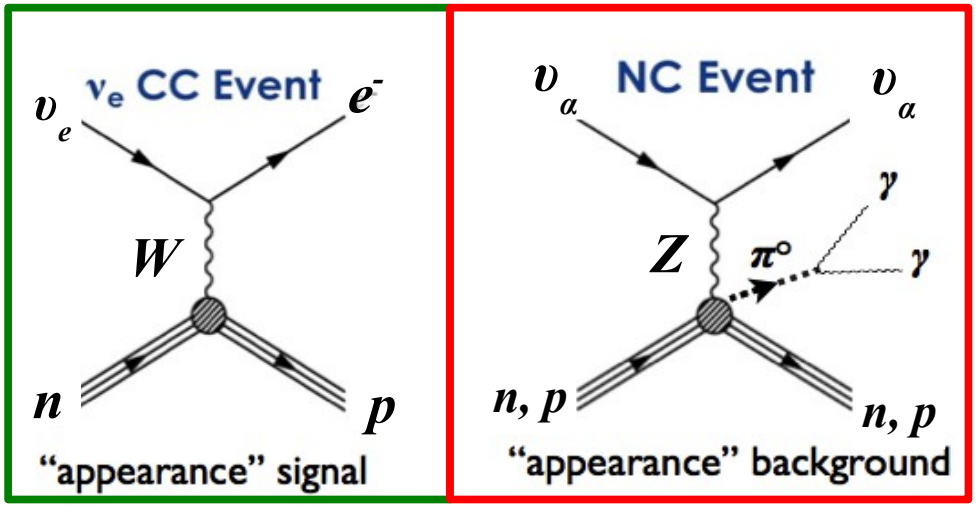


- First step towards the low energy excess analysis
- Demonstration of the Shower reconstruction algorithms



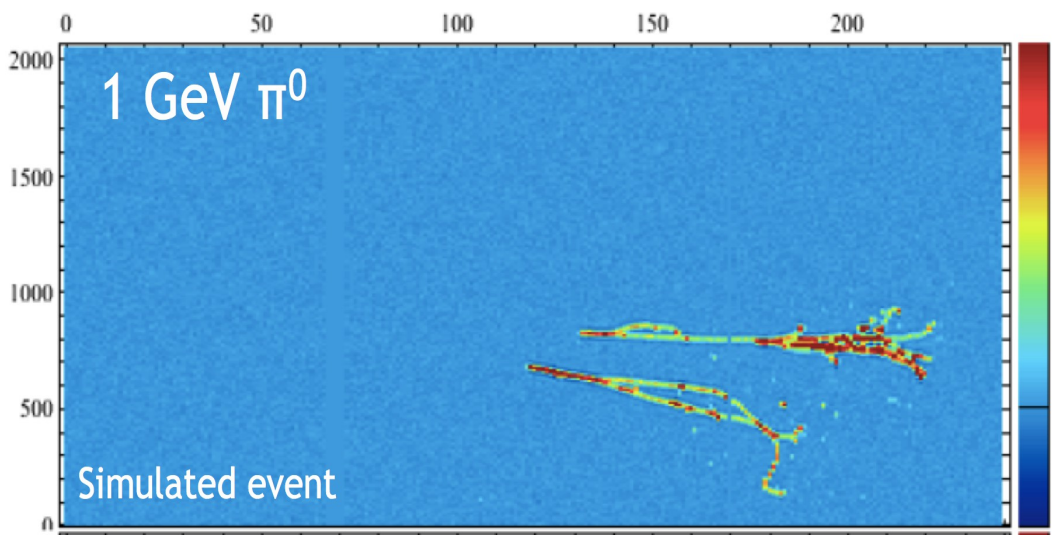
NC π^0: An important background for ν_e Appearance searches

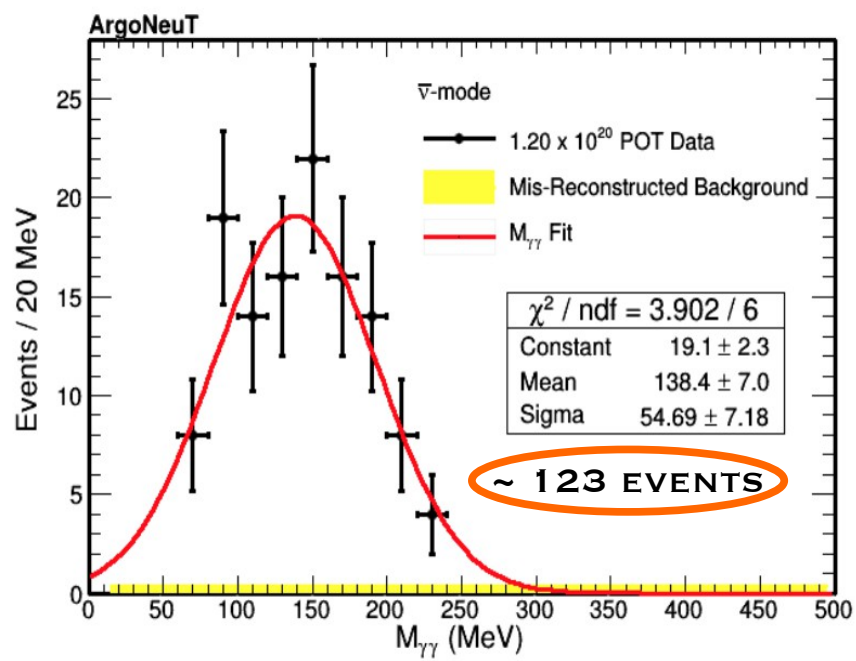
- *Calibration source for the detector*
- *Study Pion absorption on Ar*
- *Shower reconstruction is critical*



MicroBooNE projections

	NC single π^0
≈ 3 months	886
≈ 6 months	1771
≈ 3 years	11688

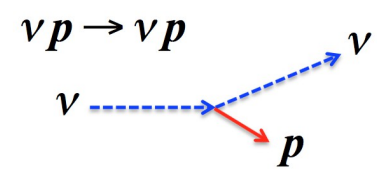




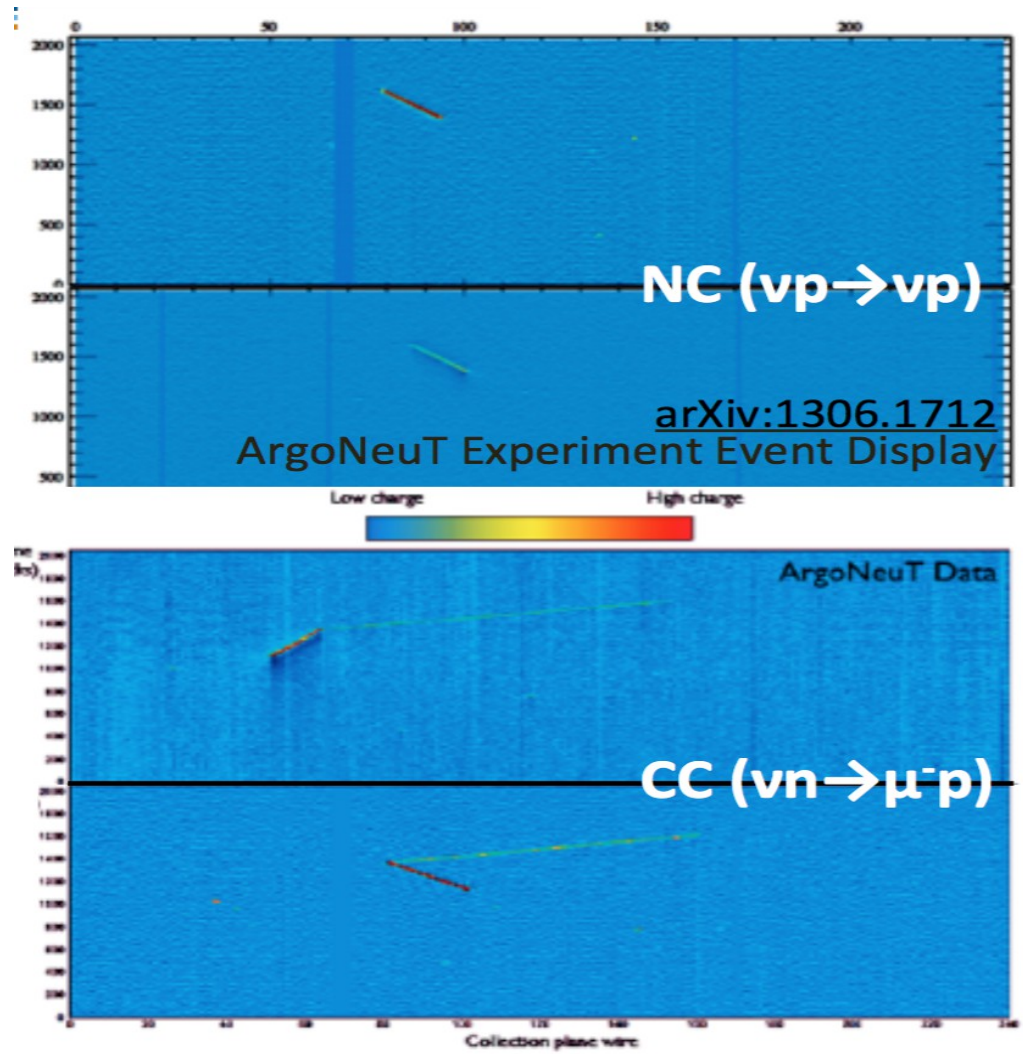
ArXiv: 1511:00941 [hep-ex]

MicroBooNE as a strange spin detector

- Strange quark contribution to the axial form factor of the nucleon or to the nucleon spin are still open questions.
- Low-Q^2 neutrino-proton elastic scattering data will determine ΔS



- Final state signature is just a single isolated proton track of few cm
  – requires a powerful detector that can probe low Q^2 with improved particle ID.



- LArTPCs provide the best opportunity for this (remember ArgoNeuT proton tracking was 21 MeV)

- Ratio of Neutral current to Charged Current cross sections is sensitive to Δs

$$R_{NC/CC} = \frac{N(\nu p \rightarrow \nu p)}{N(\nu n \rightarrow \mu^- p)}$$

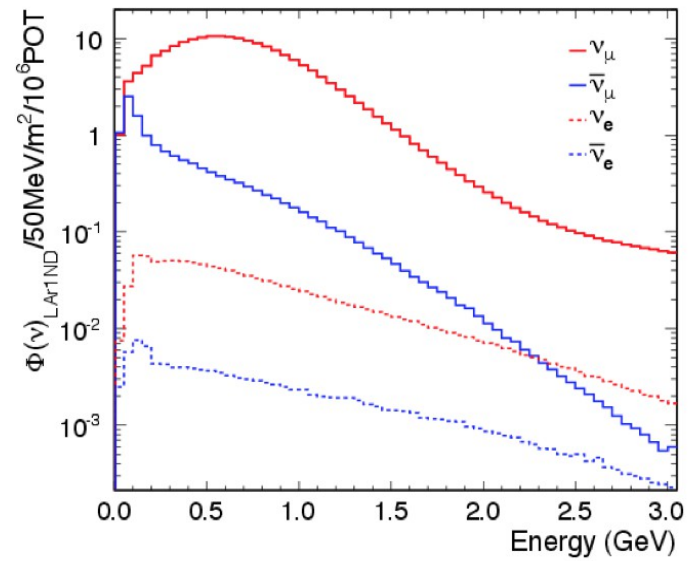
- Taking the ratio cancels a lot of experimental uncertainties such as flux, efficiencies etc.

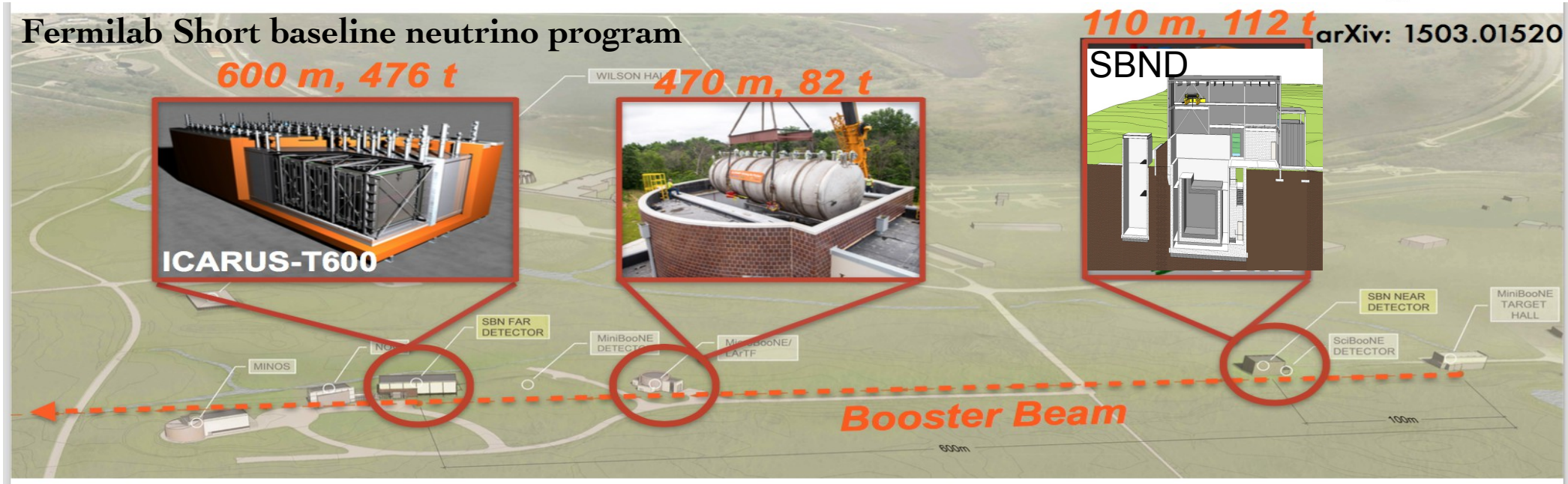
Short-Baseline Near Detector (SBND)

- Near detector (110m on BNB) in the Fermilab SBN program; currently under construction
- Sitting close to the beam, will collect around 1 million muon-neutrino events/year
  - "physics test bed" for GeV scale ν-Ar cross sections!
- SBND flux is 30 times larger than MicroBooNE

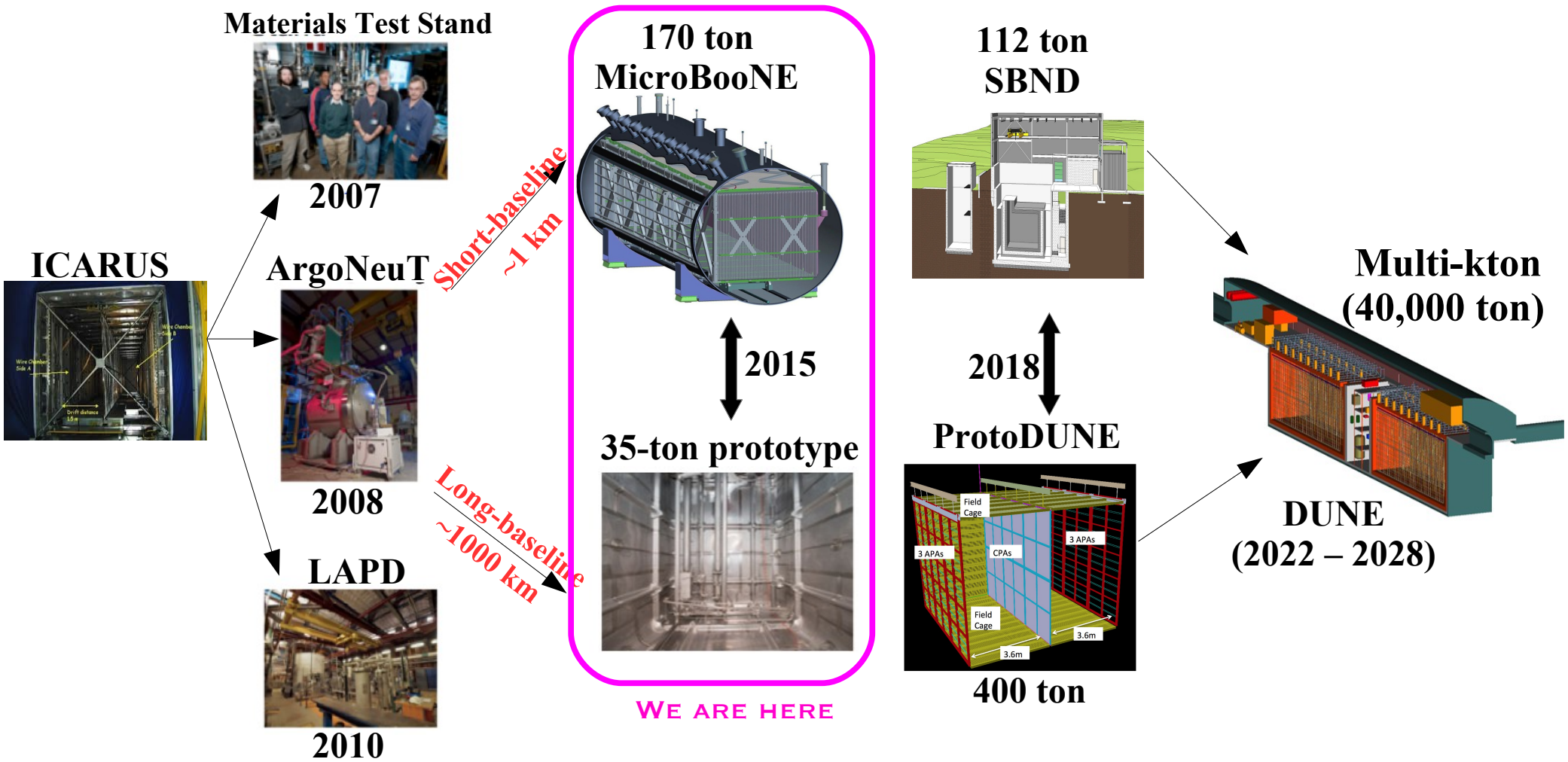
Charged Current Zero Pion Expectations (GENIE estimate, rounded)

Final State Topology	1 Month	1 Year	3 Years
CC + Np	97,000	1,170,00	3,500,000
CC + 0p	22,000	260,000	790,000
CC + 1p	56,000	667,000	2,000,000
CC + 2p	10,000	120,000	360,000
CC + >3p	10,000	120,000	370,000

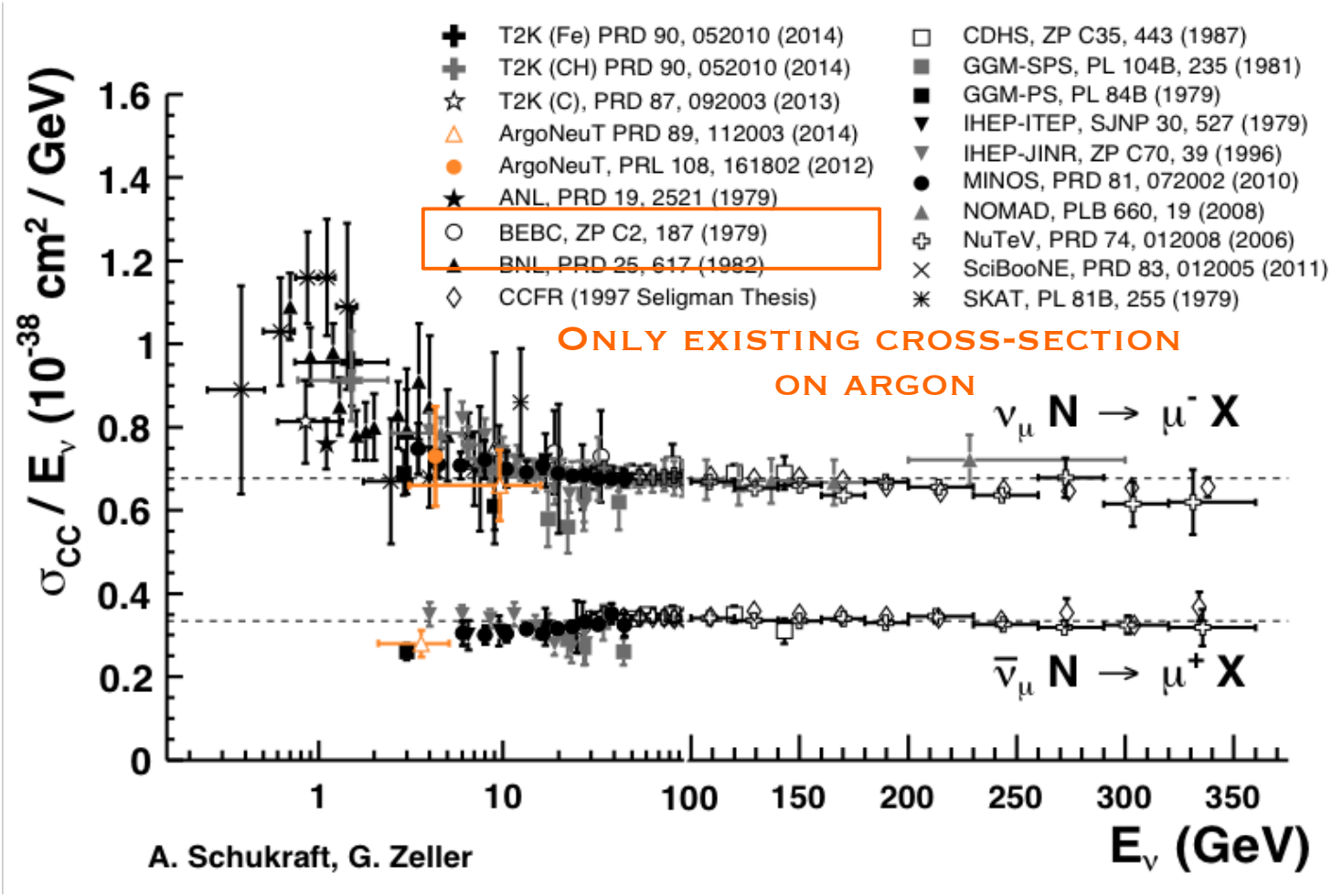




The Short and Long baseline LArTPC Neutrino Program



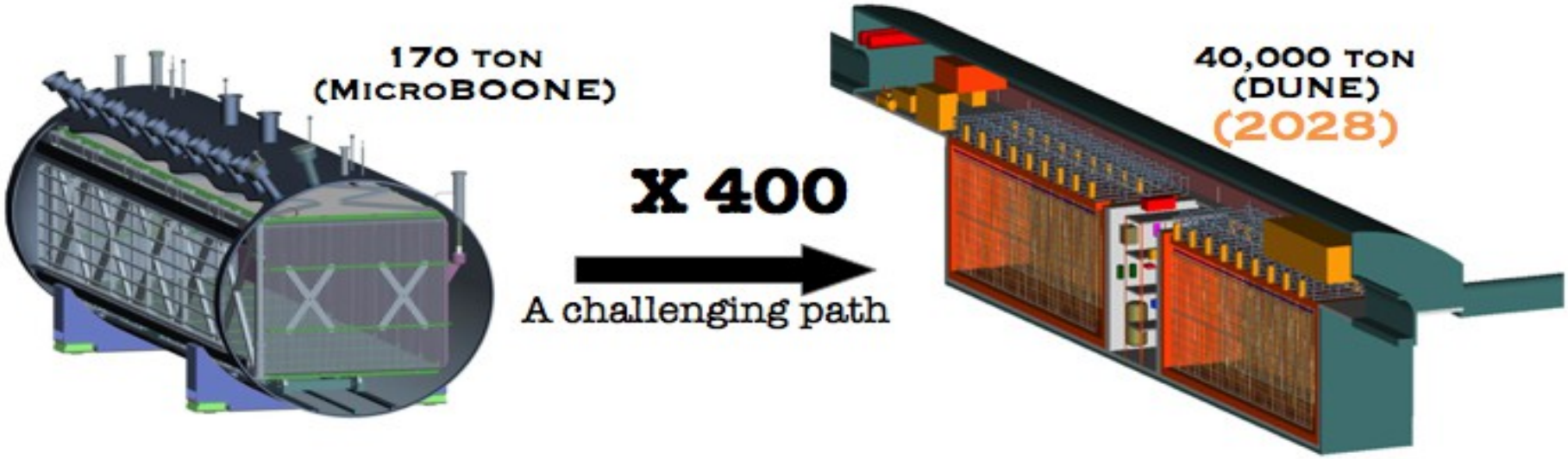
Neutrino Cross-Section on Argon: what is our current knowledge?



The multi-kiloton LArTPC program critically depends on how much ν-Ar cross-section knowledge we gain in the next few years

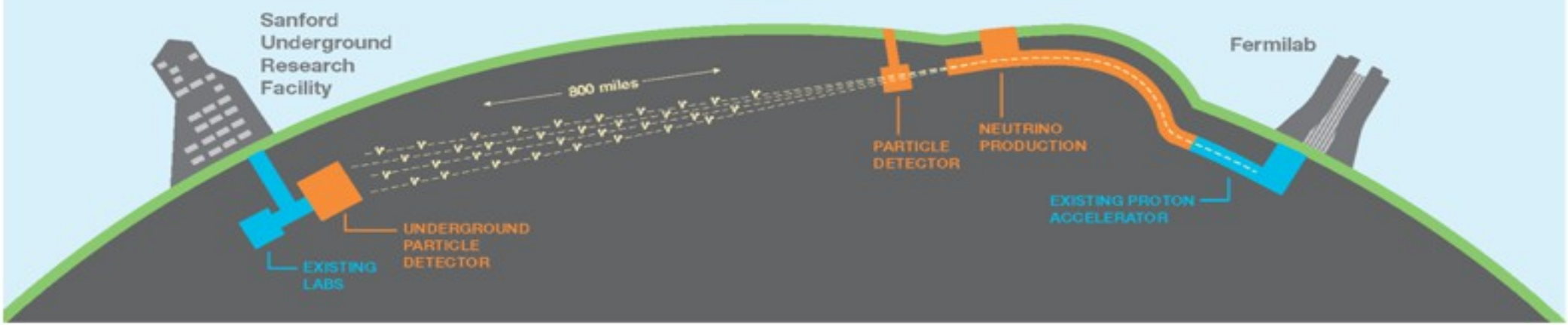
A long way to go...

Trying to build something that is 400 times bigger than what we have

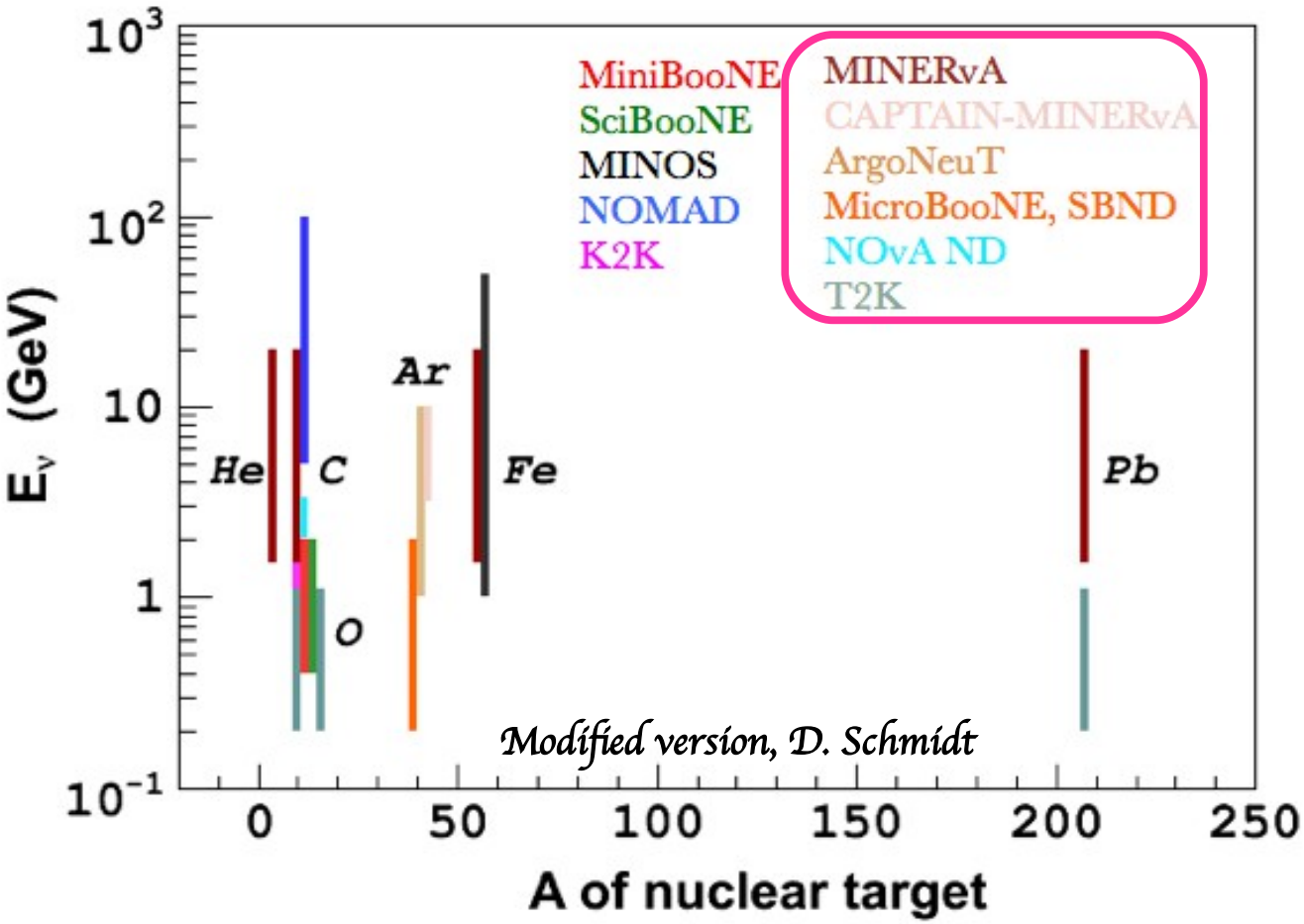


Goals: Supernovae physics, nucleon decay, CP violation, neutrino mass ordering and mixing etc.

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



The next few years are going to be really exciting for Neutrino Cross-sections



There is a lot more exciting physics one can do with LArTPCs:

1. Supernovae physics
2. Proton decay background

etc.

3.Captain Minerva can do cross section ratios such as Ar to CH

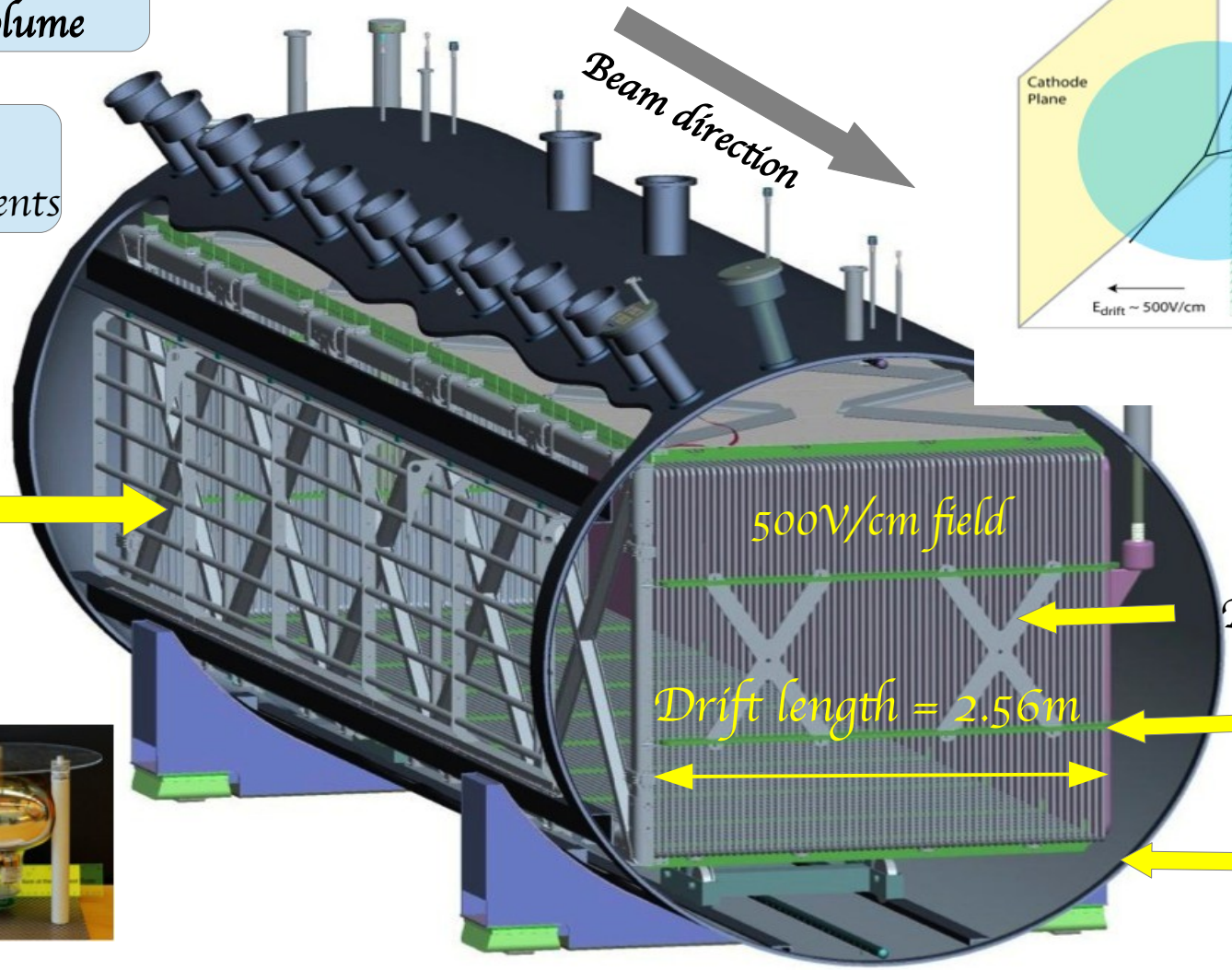
(probably covered in the CAPTAIN talk later today)

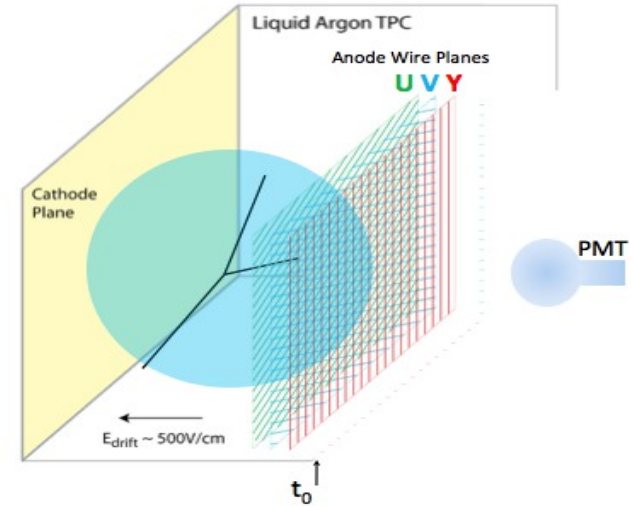
Spares

The not-so-micro MicroBooNE

TPC provides ~80 tons of active volume

PMTs used to trigger beam events



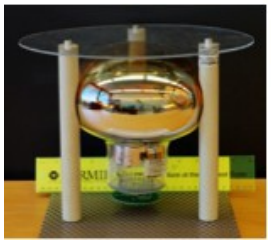


Anode wires (150 micron)

Field cage

Cathode plane (-70kV)

Cryostat



32 8-inch PMTs sit just behind wire planes (not shown in the picture!)

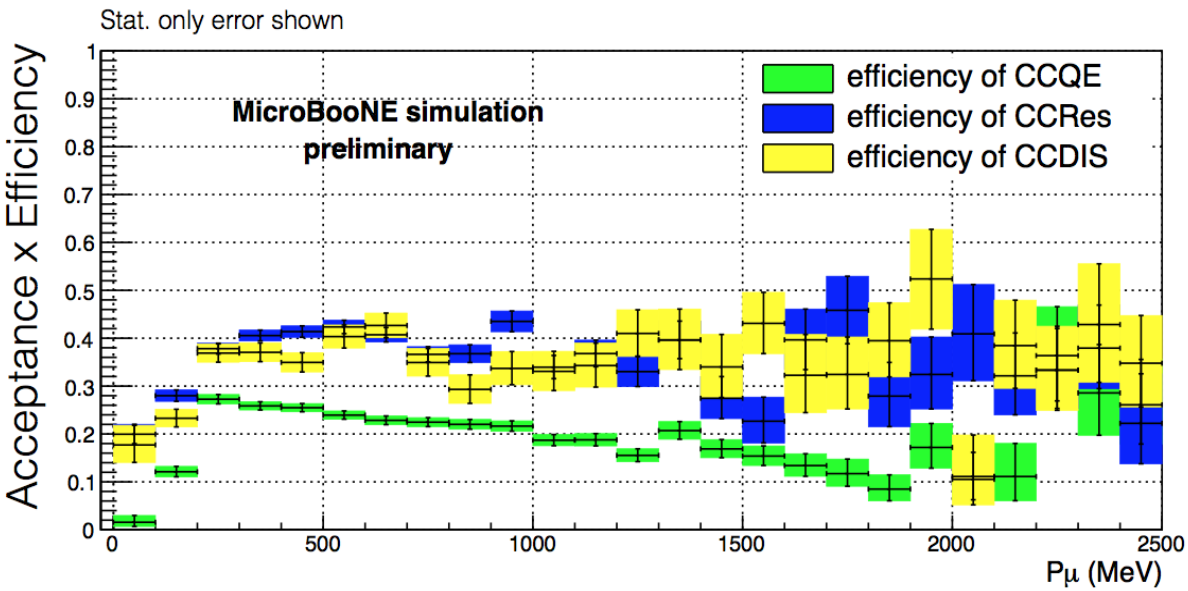
(Roughly the size of a school bus)

Charged Curren ν_μ inclusive: event selection

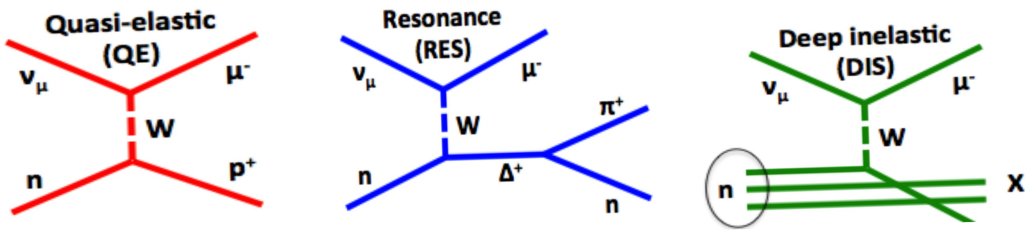
- Fully automated reconstruction and event selection:
  - A fully contained (1 track) + partially contained track selection (>=2 tracks) with an associated reconstructed vertex
  - Look for muon candidates inside the TPC fiducial volume and light in coincidence with the beam
  - Containment and minimum length cut for the 1 track sample

- Metrics:
  Purity: 60%
  Acceptance x efficiency: 30%

	Before Selection	After Selection
CCQE	60%	43%
RES	30%	42%
DIS	10%	14%



- Cosmic backgrounds challenging



CAPTAIN – MINERvA

(proposed, Stage-1 approval)

Mike Kordosky, NuInt 2015

- *Medium energy NuMI program, integrate CAPTAIN detector with MINERvA*
- *Second medium energy program in LAr after ArgoNeuT, (20 times more FV compared to ArgoNeuT)*
- *Can measure Cross-section ratios (for eg., Ar to C)*
- *Focus on neutrons for neutrino energy reconstruction*
- *Prototype Mini-CAPTAIN already operational*

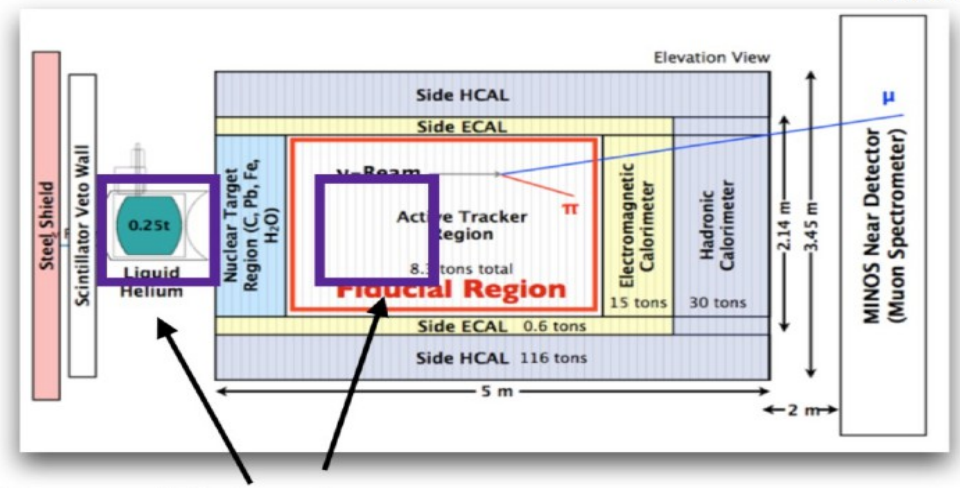
ν-mode, 6.6E20 POT, GENIE

interaction channel	Events w/ reco μ track (MINOS/MINERvA)	Events w/ reco μ track and charge (MINOS)
CCQE-like	460k	390k
CC1π±	980k	480k
CC1π0	780k	300k

Acceptance of 64%

MINOS/MINERvA Hall

unscaled

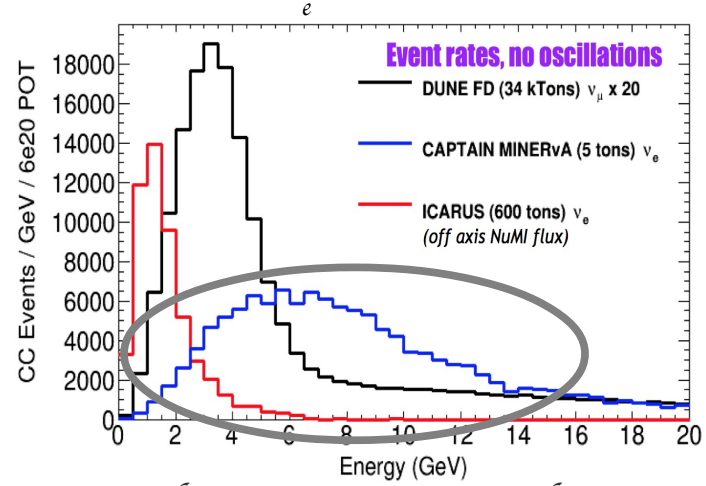


Two posible locations

a) at the position of the He target

b) at the module 30 (removing half of the tracker)

ν_e event rates



Broad energy coverage complements MicroBooNE & ICARUS

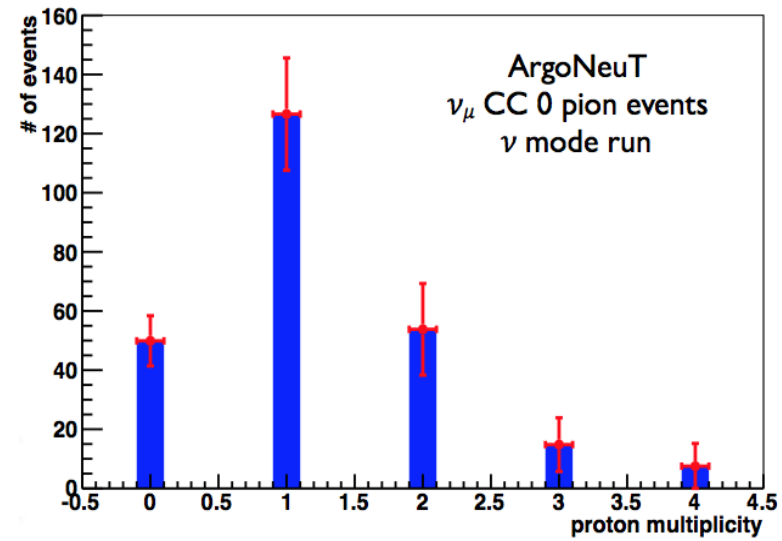
Cross section Prospects at SBND

C. Adams, NuINT 15

Final State Topology

Charged Current Zero Pion Expectations (GENIE estimate, rounded)

	1 Month	1 Year	3 Years
CC + Np	97,000	1,170,00	3,500,000
CC + 0p	22,000	260,000	790,000
CC + 1p	56,000	667,000	2,000,000
CC + 2p	10,000	120,000	360,000
CC + >3p	10,000	120,000	370,000



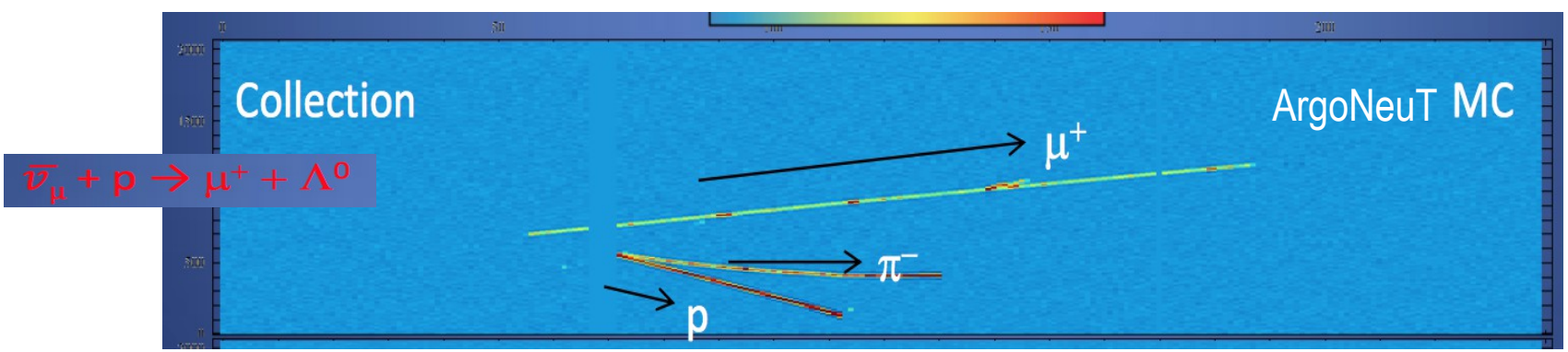
High statistics for rare neutrino interactions

Hyperon Production Expectations (CC + NC) (GENIE Expectations)

	1 Month	1 Year	3 Years
Λ^0 Production	200	2,600	8,000
Σ^+ Production	125	1,500	4,500

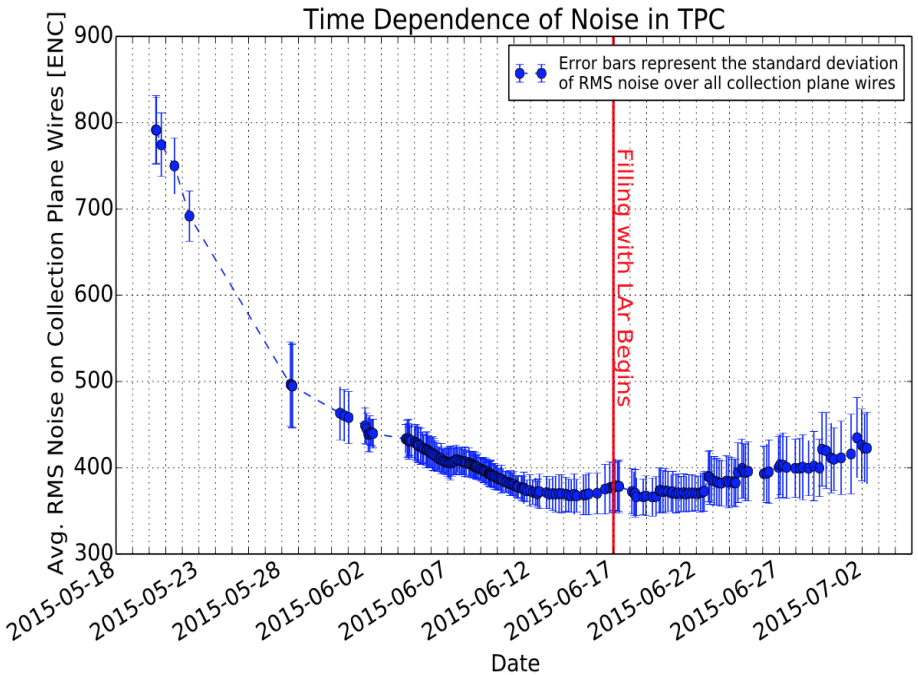
High Statistics electron-neutrino sample (benefits SBN/DUNE programs)

	1 Month	1 Year	3 Years
CC ν_e	1,000	12,000	37,000

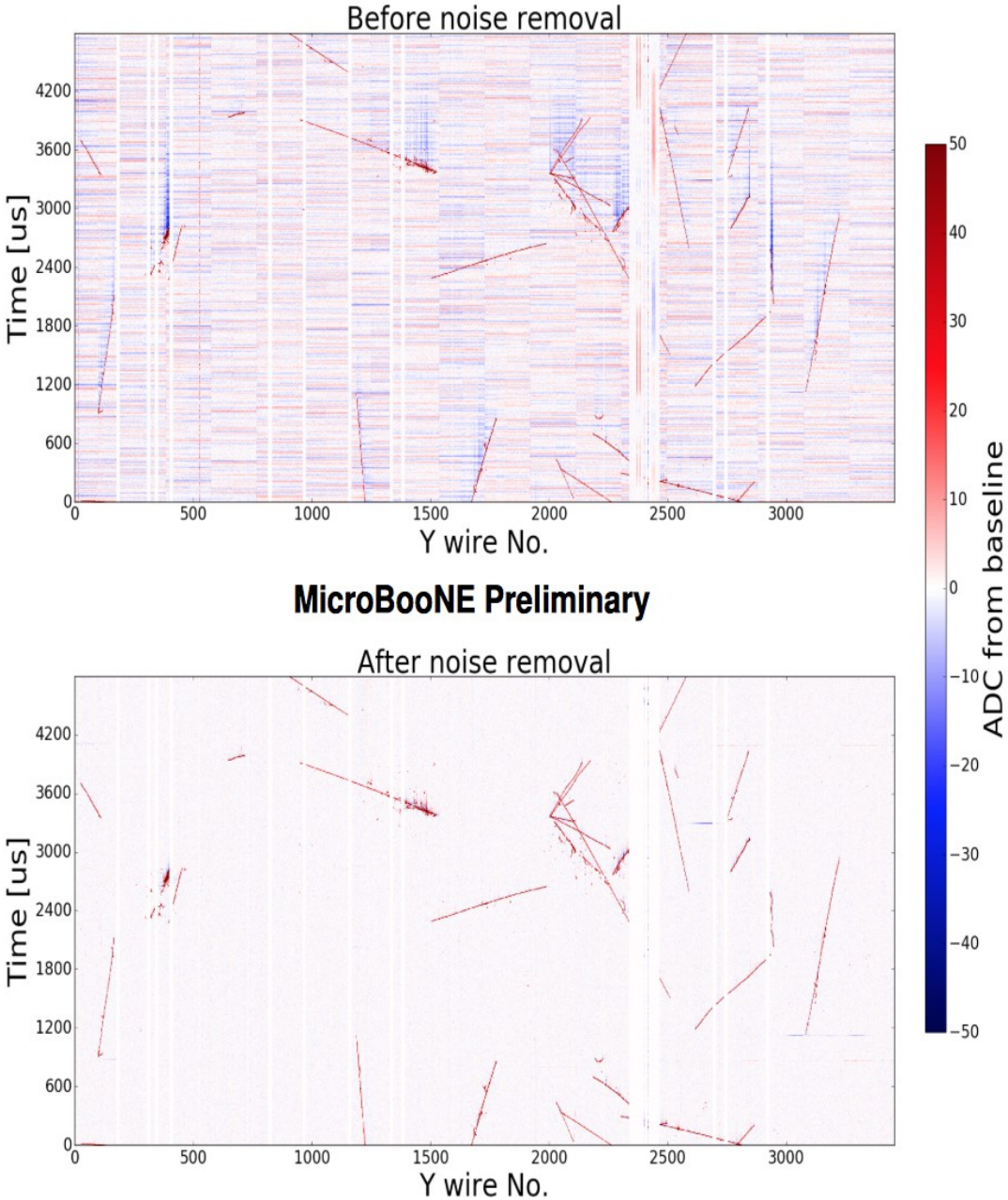


TPC Noise Filtering

MICROBOONE-NOTE-1001-TECH



MICROBOONE-NOTE-1016-PUB



- Noise in TPC depends on
  1. Temperature
  2. LAr fill level
  3. other sources: power supplies, cathode HV, wire motion etc.

- A software filter applied to remove noise.

- Peak signal to noise ratio after filtering:
  > 10:1 (induction planes)
  > 40:1 (collection planes)

Proton decay background

Some GUT models explicitly break the baryon number symmetry predicting proton decay

MicroBooNE is not big enough to study proton decay itself

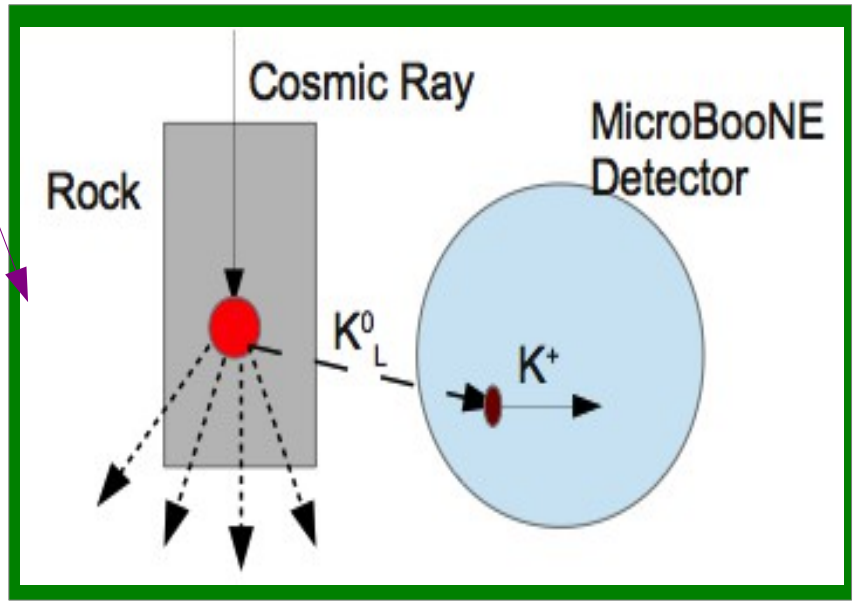
– *But, MicroBooNE can study proton decay backgrounds for future experiments!*

Proton decay background

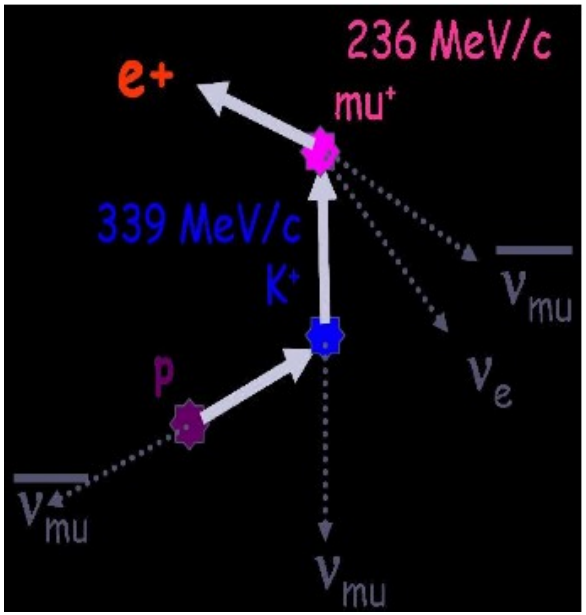
A cosmic muon interacts in a rock near the detector, produces a K^0_L which then charge exchanges, $K^0_L p \rightarrow K^+ n$ = looks like a K^+ from proton decay if right energy (339 MeV/c).

Decay mode of interest to MicroBooNE: $p \rightarrow K^+ \nu;\ K^+ \rightarrow \mu^+ \nu_\mu;\ \mu^+ \rightarrow e^+ \nu_e$ *(anti-*ν_μ*)*

– the distinct dE/dx pattern enables study of this 3-fold decay mode

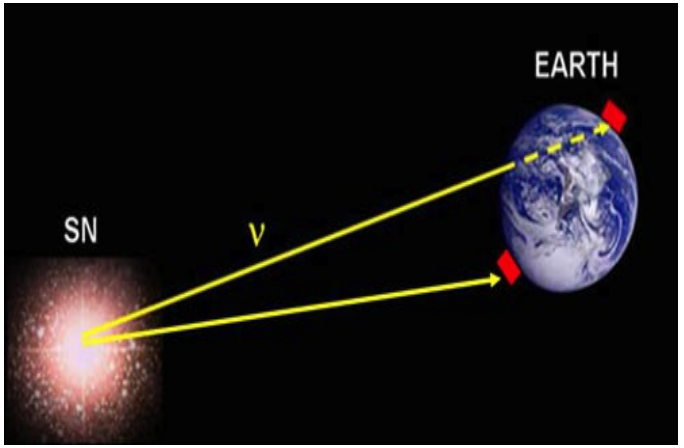


From J. Esquivel



Supernovae neutrinos

A core-collapse supernova **(SN)** produces **a burst of neutrinos of all flavors (in few-tens-of-MeV range)**
→ physics of oscillations of SN neutrinos holds key astronomical phenomena



Water and liquid scintillator neutrino detectors,
→ **primarily sensitive to electron anti-neutrinos**
***anti-*$\nu_e + p \rightarrow n + e^+$** *(inverse beta decay on free protons)*

LArTPCs posses unique capability to detect SN *electron neutrinos*

1. CCν_e capture of SN neutrinos on Ar

$$\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$$

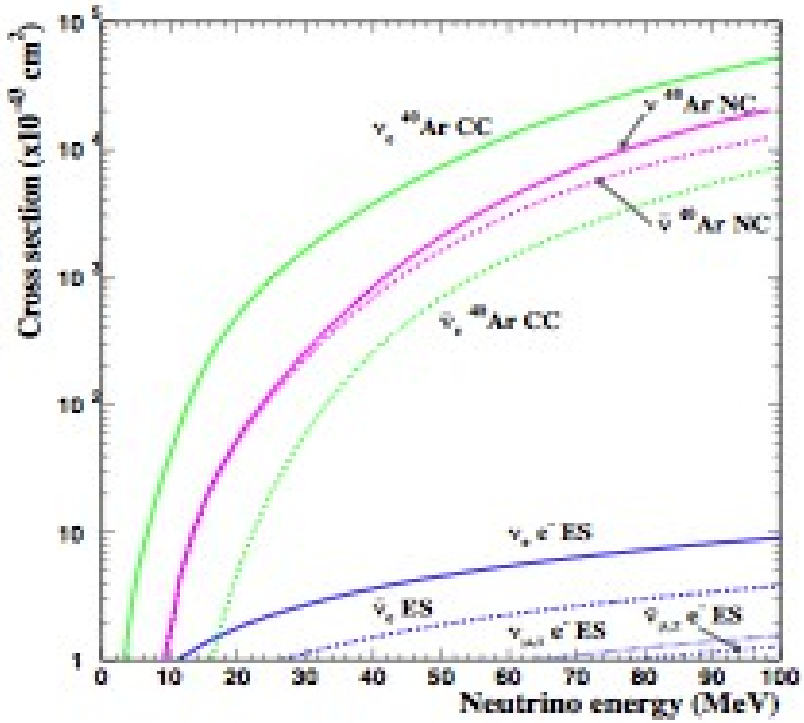
Other processes:

2. Neutral current excitation of Ar^{40}

$$\nu_{e,\mu,\tau} + Ar^{40}(18) \rightarrow Ar^{*40}(18) + \nu_{e,\mu,\tau}$$

3. Elastic scattering off electron

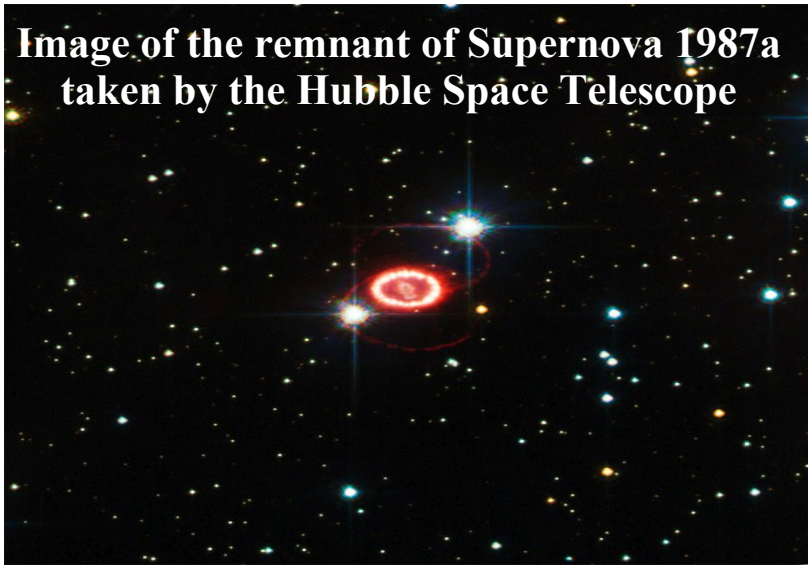
$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-$$



Supernovae neutrinos

Detection requires sensitivity to low-energy gammas (<50 MeV) and electrons

- CCν_e capture on Ar can be tagged via
  the coincidence of emitted electron and accompanying de-excitation gamma cascade



Due to small size of MicroBooNE,

- will only see about *10-20 SN neutrinos in a duration of about 20 seconds*
- A multi-kiloton detector (like LBNE) will be able to see a few hundred SN events!

Triggering on Supernovae events,

- MicroBooNE sits just below surface,
  too much cosmic traffic to have its own trigger!
- MicroBooNE will subscribe to SNEWS!

Supernova Early Warning System