Taming ν-Ar scattering

Raquel Castillo Fernández
NuWro Workshop
3rd December 2017

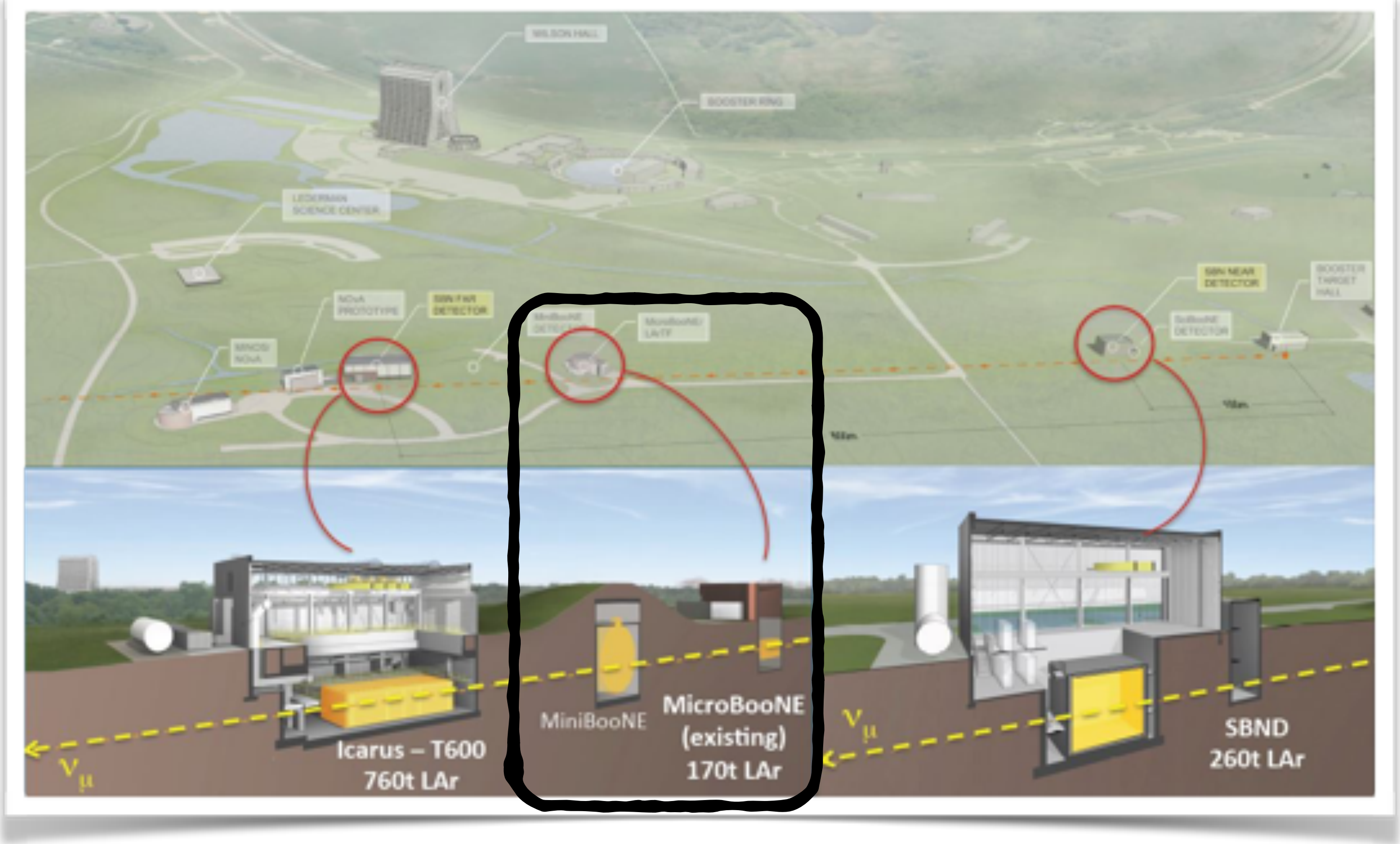
Warning: most of the talk includes very personal opinions

Outline

- **The SBN Program**
    - LArTPC in one slide
    - Reconstruction capabilities in LArTPC
- ν Reactions vs Topologies in MicroBooNE
    - What 2p2h means in Argon?
    - FSI and the cascade model
- Considerations on external data, ν & hadron
    - LArIAT
- Uncertainties from an oscillation point of view
    - Different approaches to understand the unexpected

The SBN Program

SBN (Short Baseline Neutrino) aims to search for non-standard ν oscillations by ν_e appearance and ν_μ disappearance with unprecedented precision in BNB.



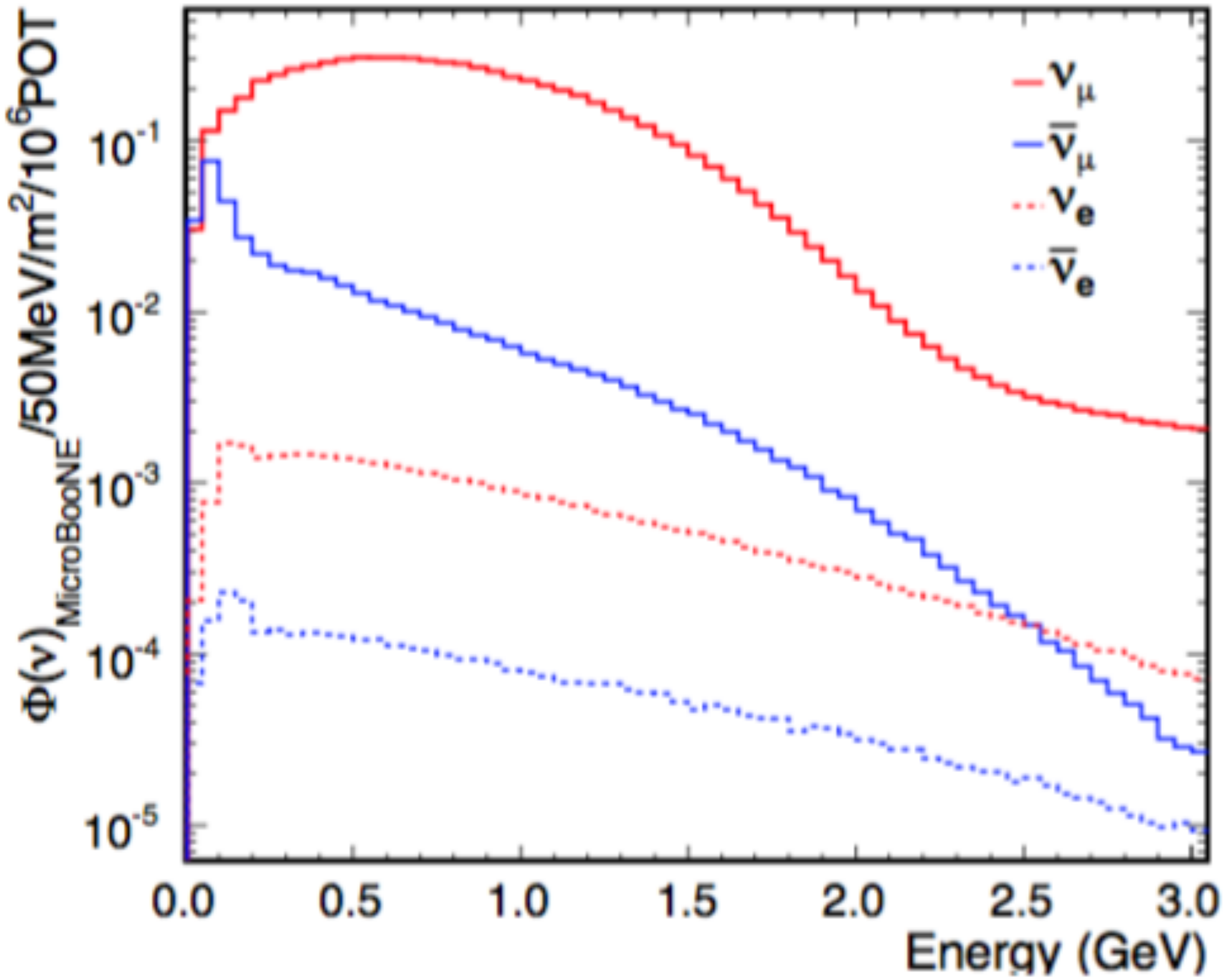
Main MicroBooNE physics goals:

- Investigate MiniBooNE low- energy un-predicted data (ν_e CC events?)
- Measure first high statistics ~1GeV ν-Ar cross sections
- R&D for Deep Underground Neutrino Experiment (DUNE)
- Joint oscillation analysis within the SBN program

+ Exotic physics capability studies (proton decay, heavy sterile ν, SN).

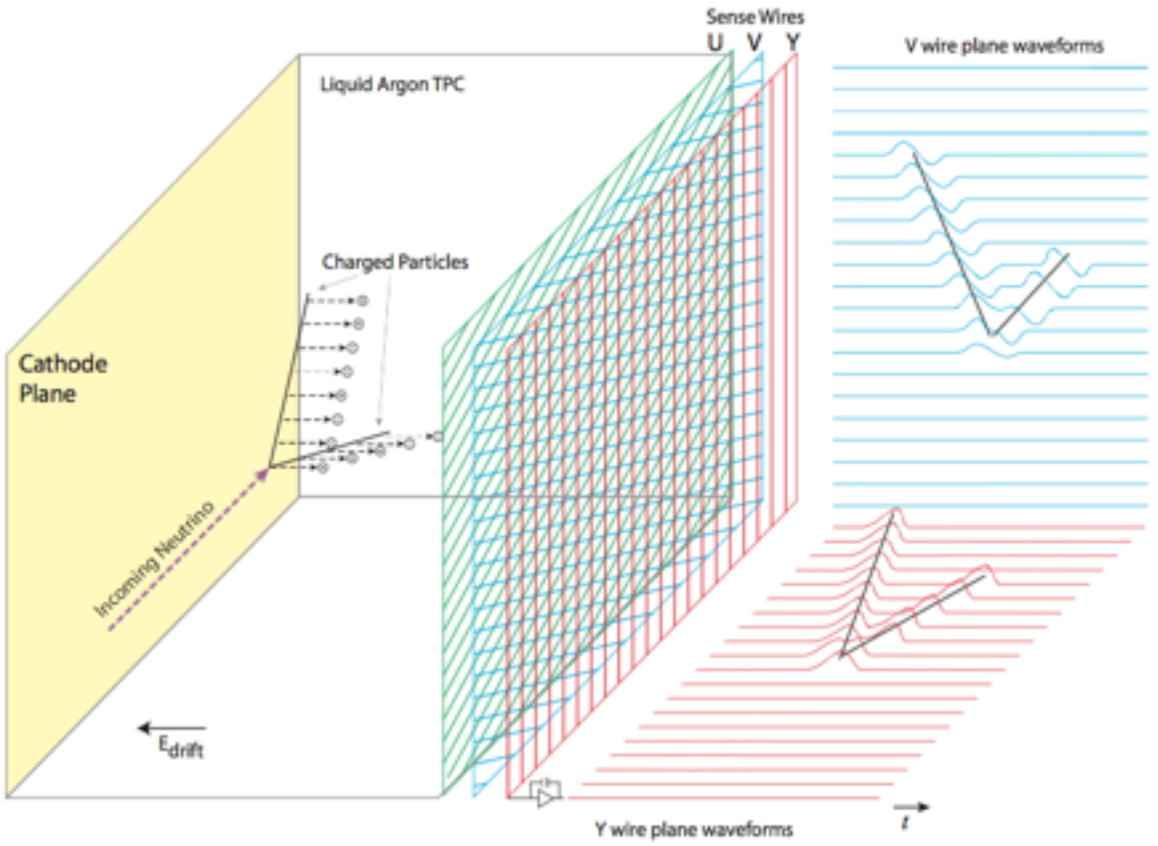
ν Flux @ SBND, MicroBooNE and ICARUS

8 GeV Protons from BNB
Almost pure ν_μ beam (0.5% intrinsic ν_e contamination at uB)



Same ν beam at different detection locations: different spectrum
Same detector technology: very similar detection thresholds, resolutions and detector uncertainties
Sharing simulation, reconstruction and analysis techniques

LArTPC in one slide



- Charge particle detection by collection of **ionization** charge.
- 3D event reconstruction by combining signals from all planes (2 required)
- **Scintillation** light can be used for triggering on events but also can be used for calorimetry.

MicroBooNE:

- 170 tons of liquid argon : 86 tons of active mass
- Two induction planes (U, V) and one collection plane (Y), 3 mm pitch, 3mm separation between wires
- Near-surface operation: adding cosmic rays into the game!

Huge efforts on simulation, reconstruction and calibration: several public technical notes and papers produced during the first 2 years of data taking.

Sharing efforts with the other SBN detectors and LArIAT (our main test-beam experiment which also includes important physics goals for the program).

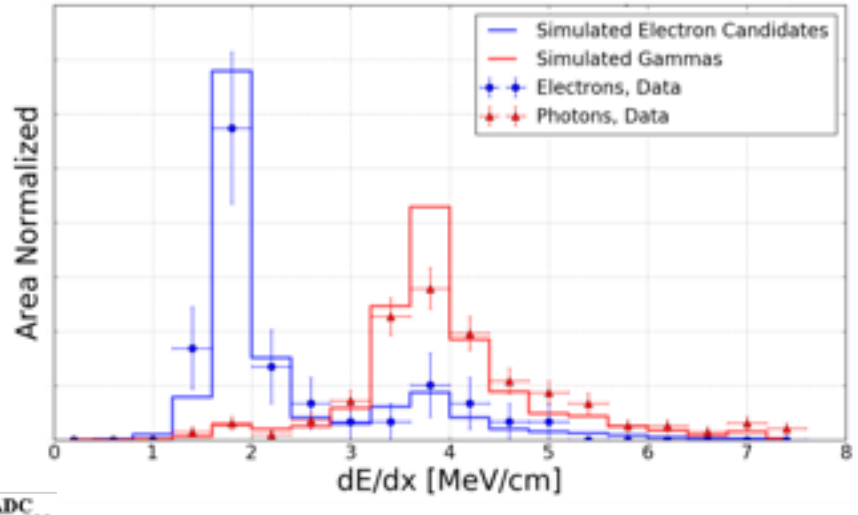
Our main neutrino event generator is GENIE, detector simulation uses Geant4.

arXiv:1609.06169 [physics.ins-det]

Reconstruction capabilities in LArTPC

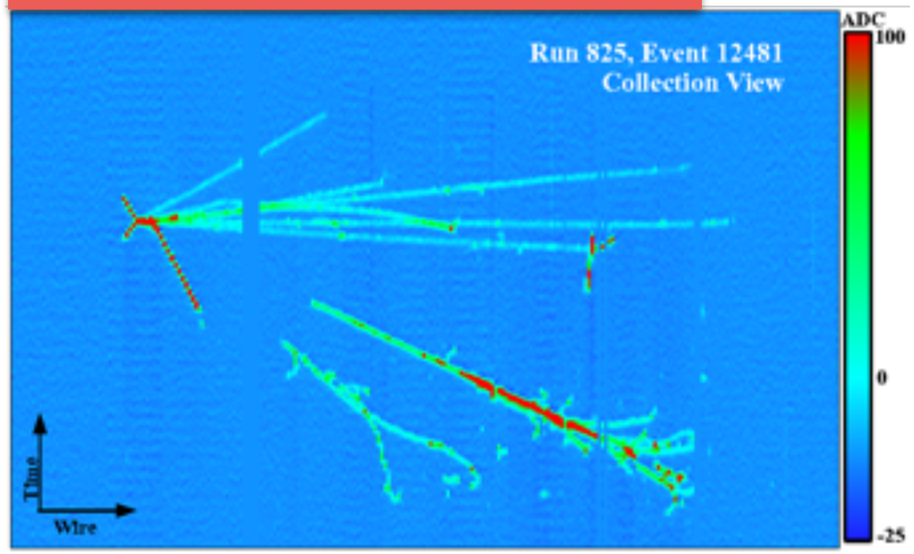
Momentum reconstruction:

- For contained particles in the detector can be achieved by using momentum-by-range or calorimetry (not presented yet).
- For particles leaving the detector it is performed using Coulomb scattering (decreased resolutions with respect to contained tracks).
- Continuously working on improving reconstruction and achieve lower energy thresholds, particularly important for protons.
- Improving shower reconstruction resolution, **e/γ separation** capabilities
- 4π acceptance

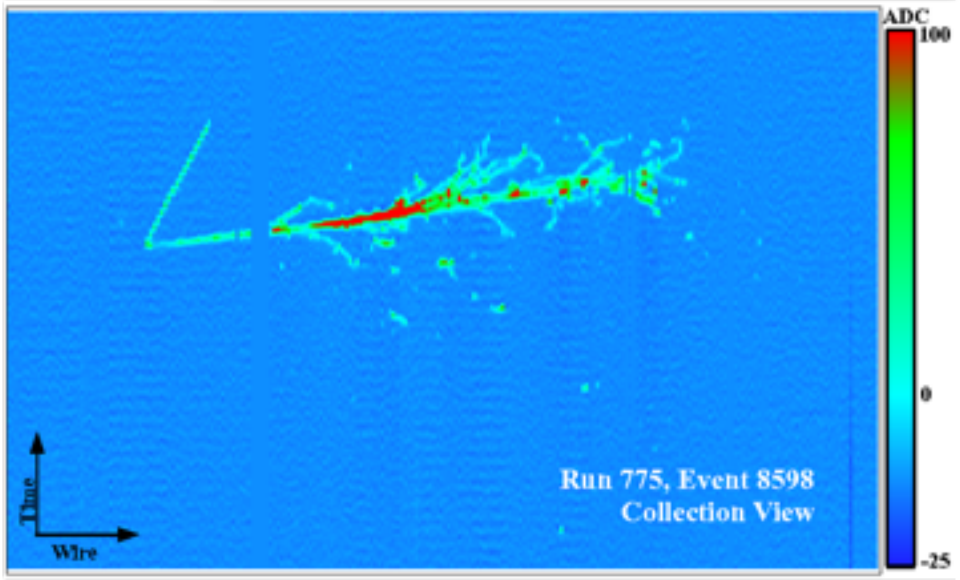


Phys.Rev.D arXiv:1610.04102

2 γ candidates @ ArgoNeuT



ν_e CC candidate @ ArgoNeuT



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ν Reactions vs Topologies in MicroBooNE

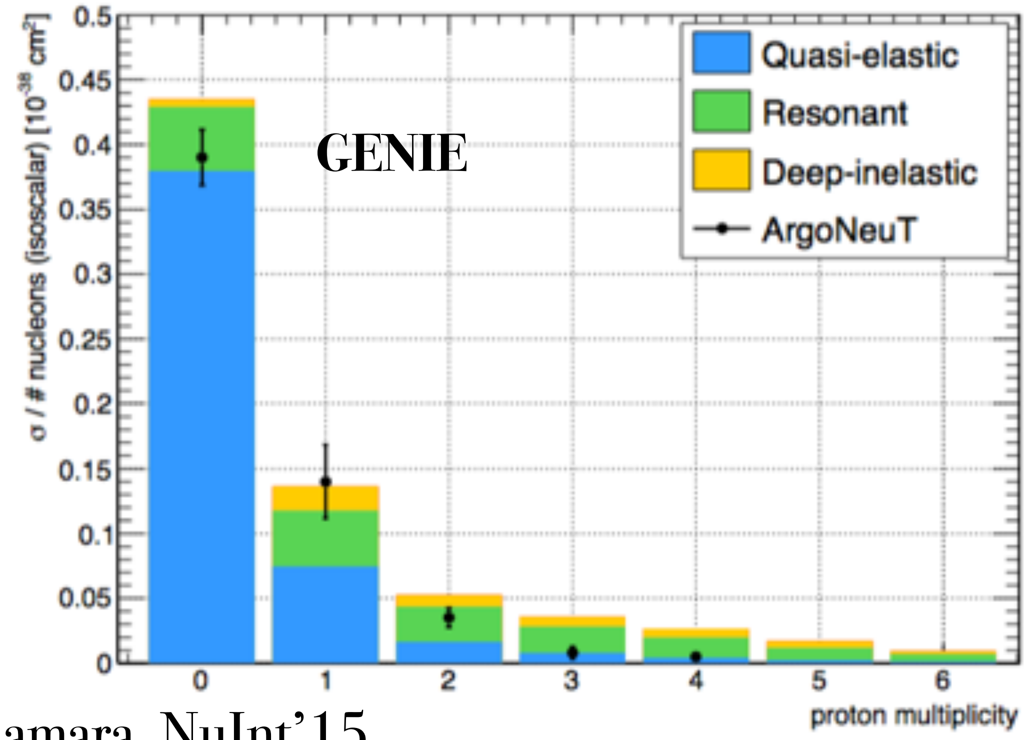
As argon is a heavy nucleus (in terms of ν scattering detection) it is fundamentally important to distinguish reaction vs topology.
Any extrapolation from our data to the reaction type is highly model dependent and not proved to be correct.

René Magritte

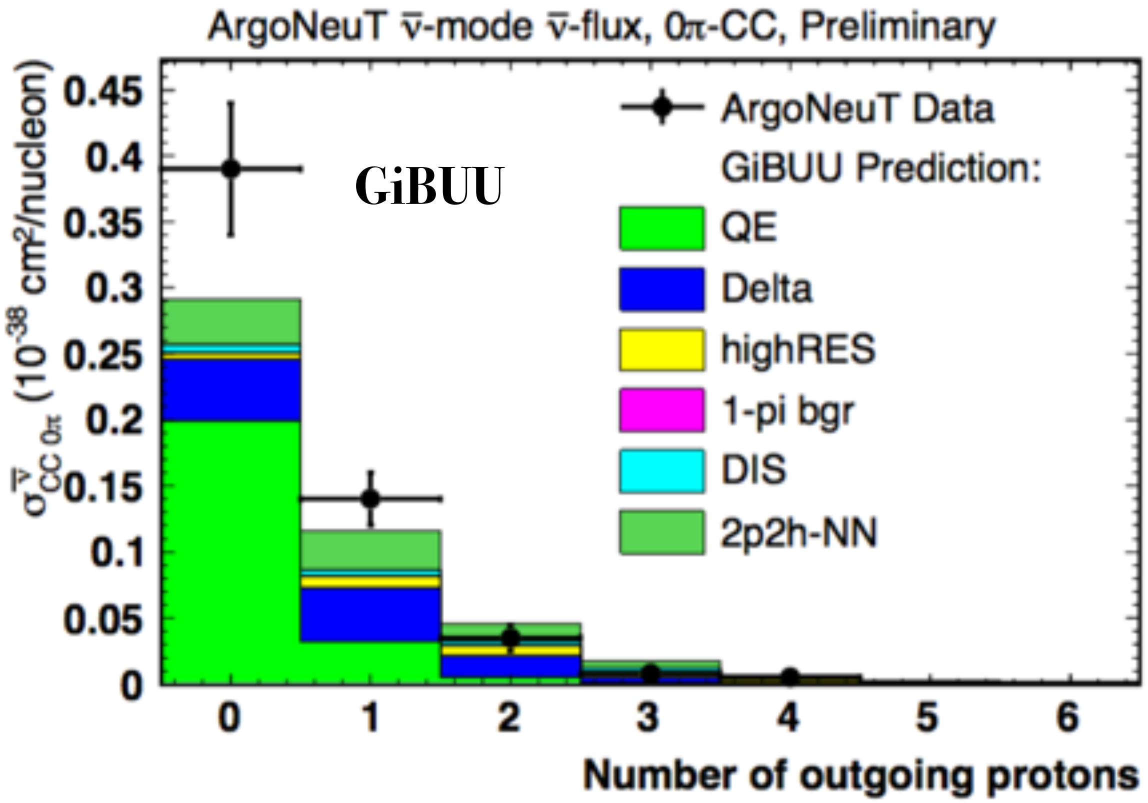
Next slides will show NuWRO description of the neutrino interactions at MicroBooNE, other MC simulations are shown in comparison with **ArgoNEUT** measurements (as available).
But only data is the *pipe*.

ν Reactions vs Topologies in MicroBooNE

Precedent/ongoing experiments proved an un-accuracy in current MCs.
Most of the cases it has been treated as isolated problems due to specific channels (MEC, CCQE,..) or combination of them. Consequently, the way to treat these un-accuracies were performed by re-weighting these channels using exclusive data topologies.
However, it is **not possible from non-light nuclei to factorize the problem of the neutrino-nucleus scattering wrt FSI which involves hadron-(deep-core)nucleus** (highest binding energy, SRC,.., than hadron-nucleus experiments) scattering.



O. Palamara, NuInt'15



Already with this simple exercise is easy to observe that the association of final state particle to specific reaction is more than delicate.

ν Reactions vs Topologies in MicroBooNE

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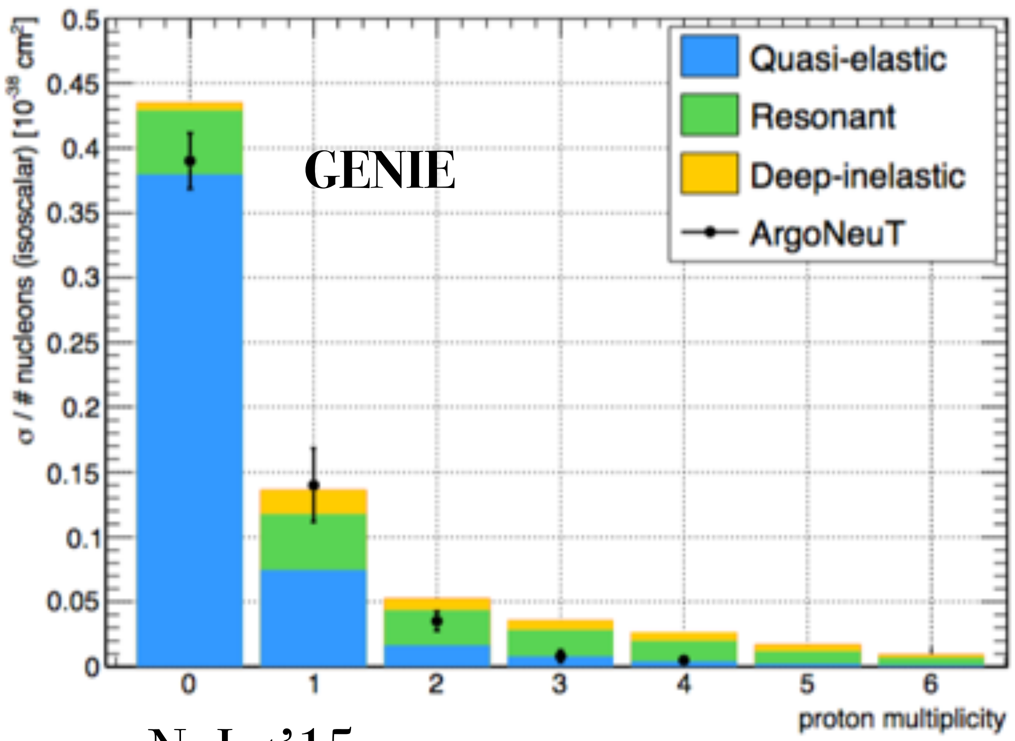
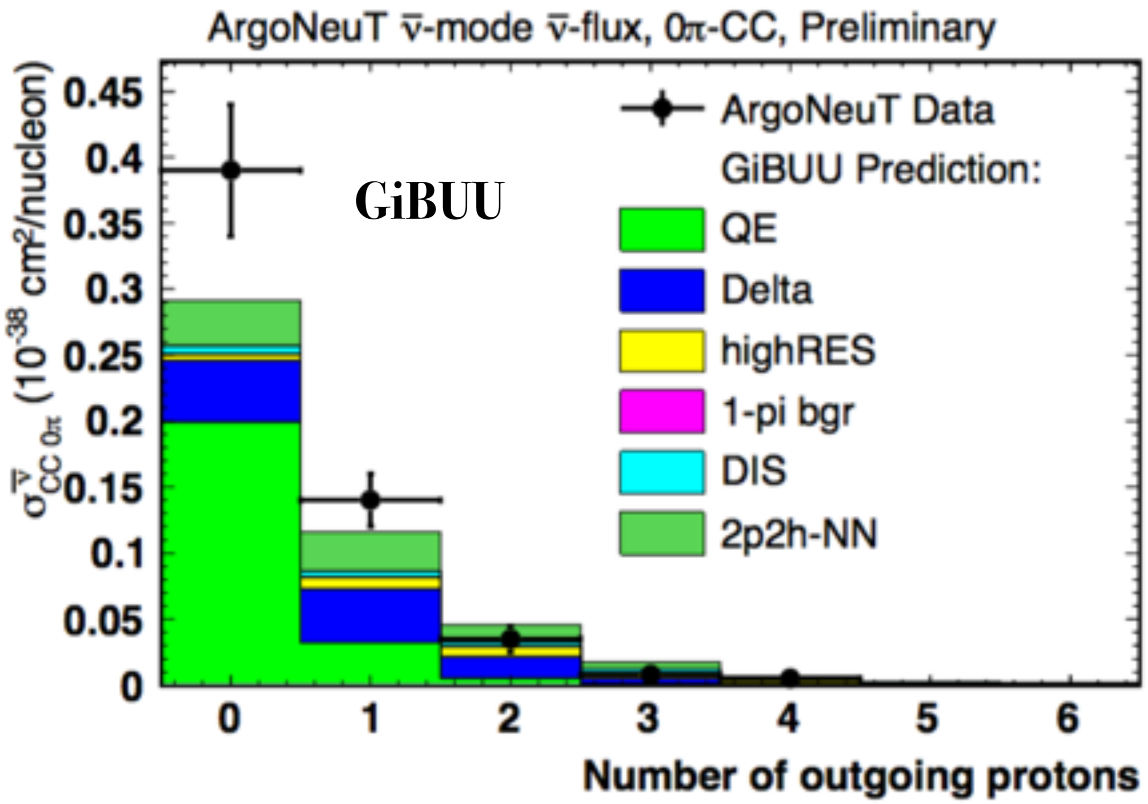




O. Palamara, NuInt'15

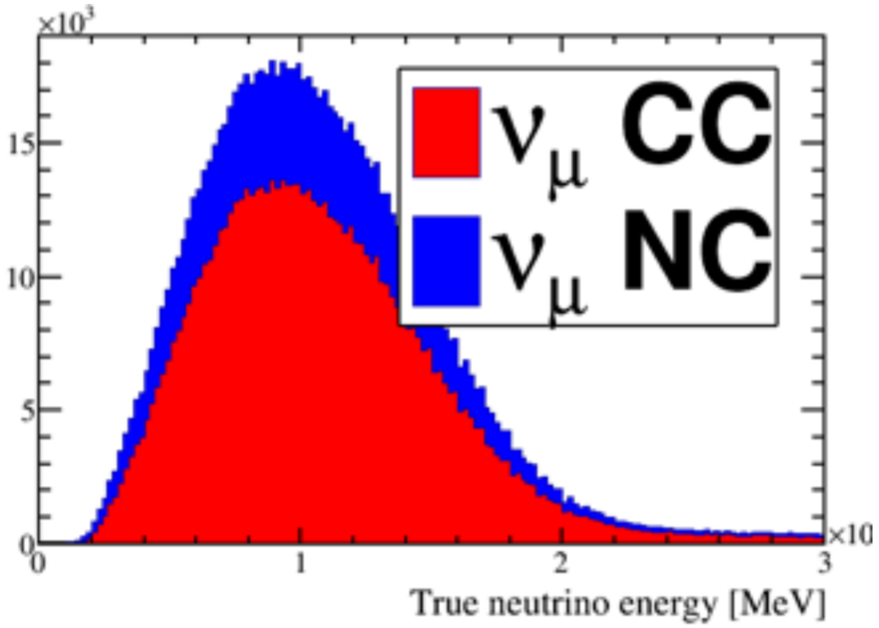
Two main problems:

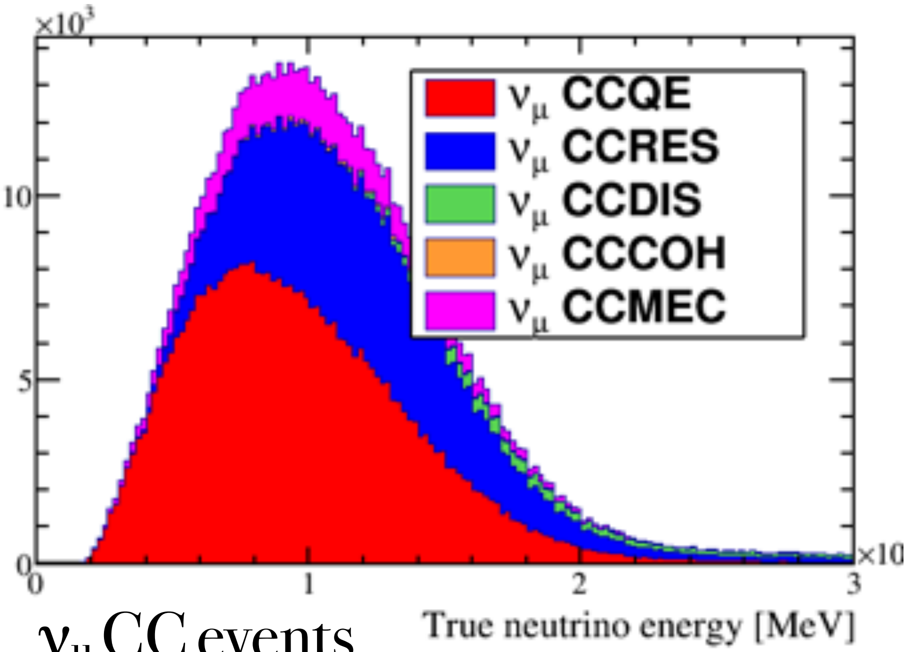
- we don't predict the final number of particles
- we are not sure of the original reaction that originates the particle.

To me, both problems are associated to each other and solution may come together, not a question of normalization.

ν Reactions vs Topologies in MicroBooNE

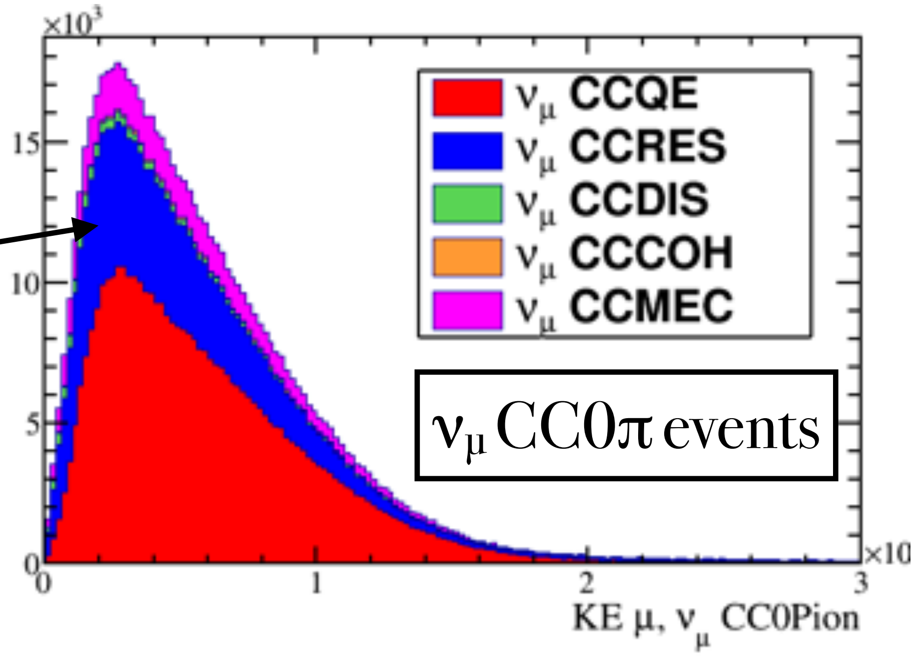
Our beam provide us mostly ν_μ. The highest statistics is in the ν_μ CC channels.
The composition of this CC events, according to NuWRO (and other MCs as GENIE) predicts a highest percentage of ν_μ CCQE. But still makes me difficult to claim that this channel is really *dominant* in its full expression of the term.





ν_μ CC events

Predicted pion absorption already makes a huge impact on how we should interpret our data

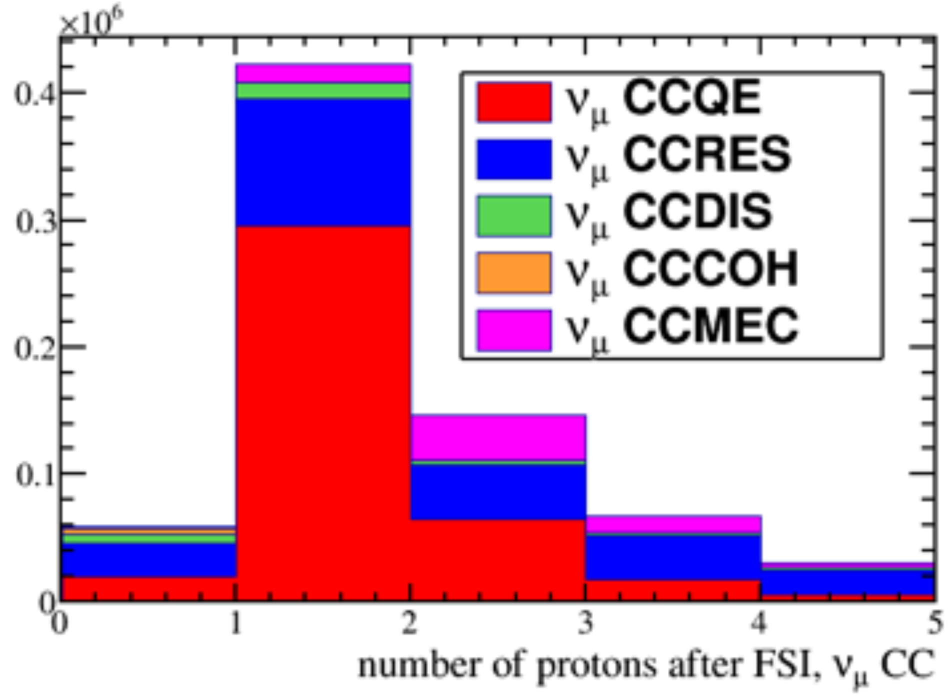


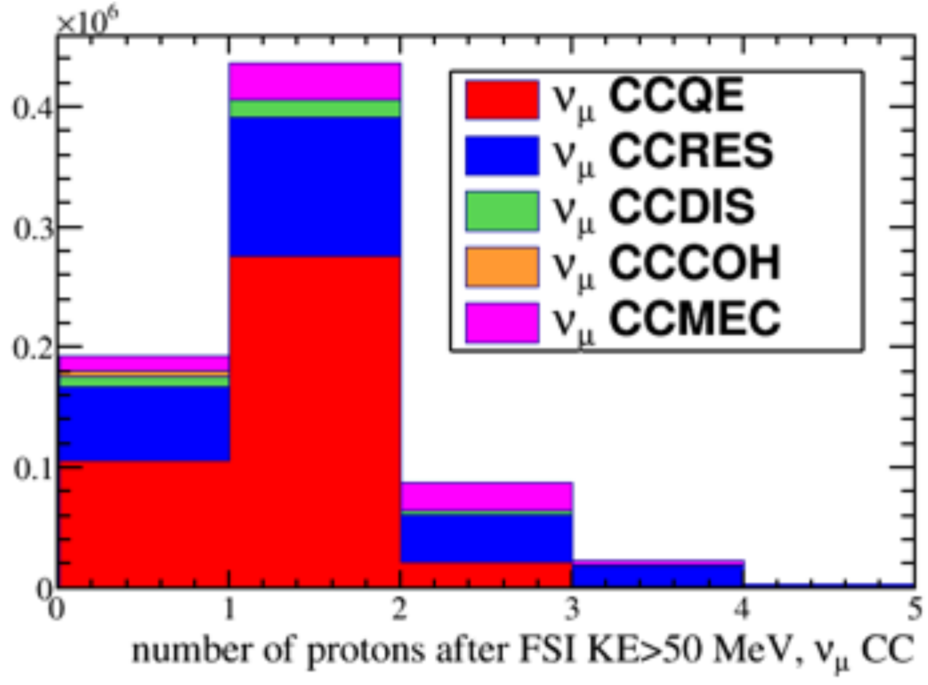
ν_μ CC0π events

NuWRO simulation at uB

What 2p2h means in Argon?

Note:
I always referred to **2p2h** processes the ones on which 2 nucleons are produced (not necessarily leaving the nucleus) via MEC or SRC. I believe most of the MCs uses same terminology.
Recently I learn (during the NuSTEC school 2017) that theorists refer to 2p2h to any process that emits 2 nucleons in the final state leaving 2 holes in the nucleus.
This leave us with processes as:
CCQE on which the original nucleon re-interacts again in the nucleus and 2 nucleons leaves the nucleus.
MEC and **SRC** on which 2 nucleons leaves the nucleus.
Resonant pion production on which the **pion is absorbed**.
But not all CCQE, MEC, SRC or pion absorption will be a 2p2h if 2 nucleons don't appear in FSI.





Not adding here neutrons, but LArTPC has neutron reconstruction capabilities.

NuWRO simulation at uB

FSI and the cascade model

FSI corresponds to the most sophisticated piece of the puzzle . Its importance has been historically underestimated within ν-nucleus data analyzers.

Argon experiments put us into the place on which FSI processes are a mandatory question.

Same final topology can be explained by different reactions types, the most famous one:

1 muon & 2 protons can be:

- CCQE with **nucleon re-interaction**
- MEC or SRC effects
- **Pion absorption** (from a previous pion production)

Some of these reactions are generated at different phase-spaces, consequently can be produced by different ν energies.

FSI and the cascade model

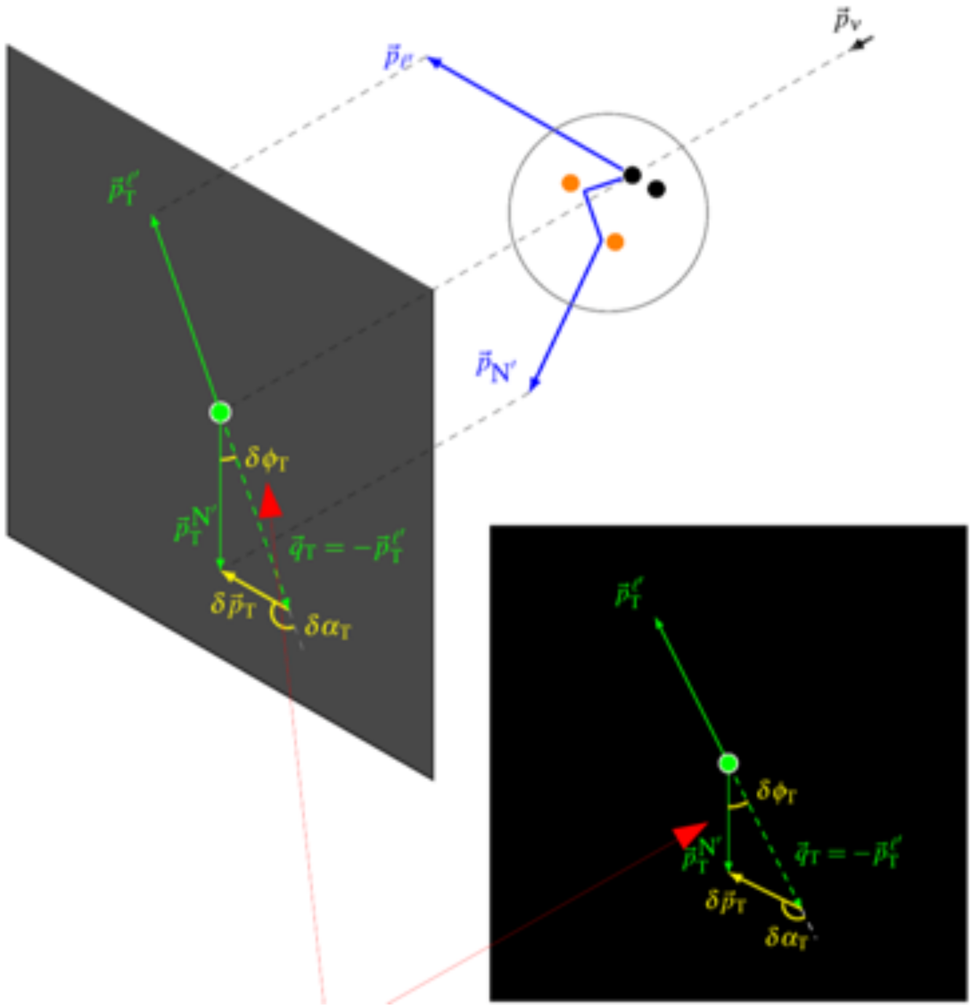


Diagram stolen from Xianguo Lu, PINS2017

Additional problem, the phase-space of the interaction:

Several attempts have been done by different experiments/groups to propose a way to *get rid off* nuclear effects.

Some of these attempts includes the investigation of the so-called transversal variables (**p_T, p_L**) of detected protons.

This approach has several inconveniences:

- The final state (detected) proton is not necessarily the one produced by the ν interaction.
- Other effects within the nucleus (e.g. **Coulomb potential**) modify outgoing particle energy, then affects the interpretation of these studies.
- **Neutrons** traditionally are not taken into account in our data (LArTPC should have capabilities for interacting/captured neutrons reconstruction).

FSI and the cascade model

MC approaches:

All the different MCs uses different approaches to determine FSI. In some cases these options are quasi-different.

Transport model:

- Used only by **GiBUU** within the neutrino MC community.
- We don't have any estimation on how different is wrt to other solutions since the original ν interaction is predicted in a different approach.
- Does not include correlations. However, the extensive external data used in the modeling already has it included.

Cascade model:

- **NuWRO**:
  - It propagates the cascade with several steps modifying the cross section of the process (absorption, CHEX,..) by step so in this way it follows a Woods-Saxon approximation (I understood that from T. Golan). To be clear, a W-S is actually how we expect a nucleus would respond.
- **GENIE** :
  - In practice it only applies one step in its propagation (I understood that from G. Perdue & T. Golan). I believe that in this way you can only apply an effective value of the different FSI cross section processes.
  - Oset model is already validated to be used (not in default), we are in the way of checking differences wrt previous one.

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Considerations on external data, ν & hadron

External data has been extensively used by both **MC builders** (to parametrize models) and **data analyzers** (when trying to get their uncertainties). Sometimes (usually) the MC builders and the data analyzers use the **same data sets**.

Commonly used data:

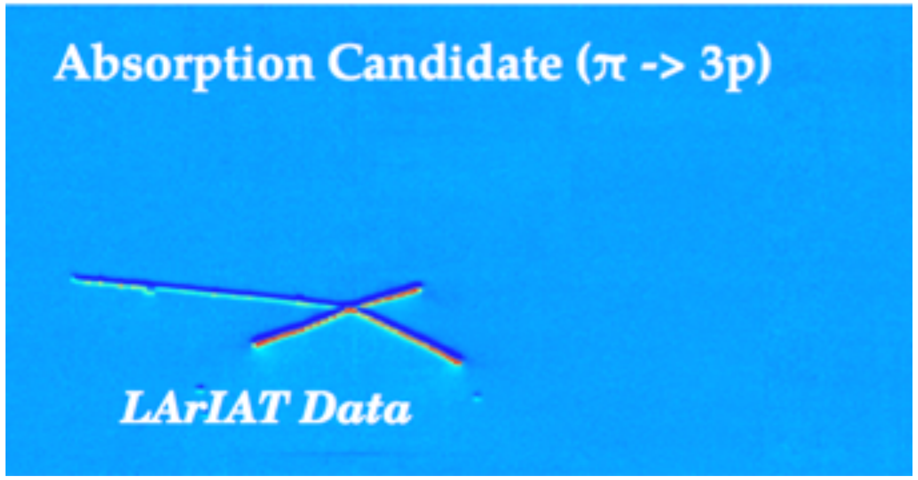
- **ν-nucleus** (deuterium and higher)
- **electron-nucleus** (I think also very light nuclei, at least in NuWRO)

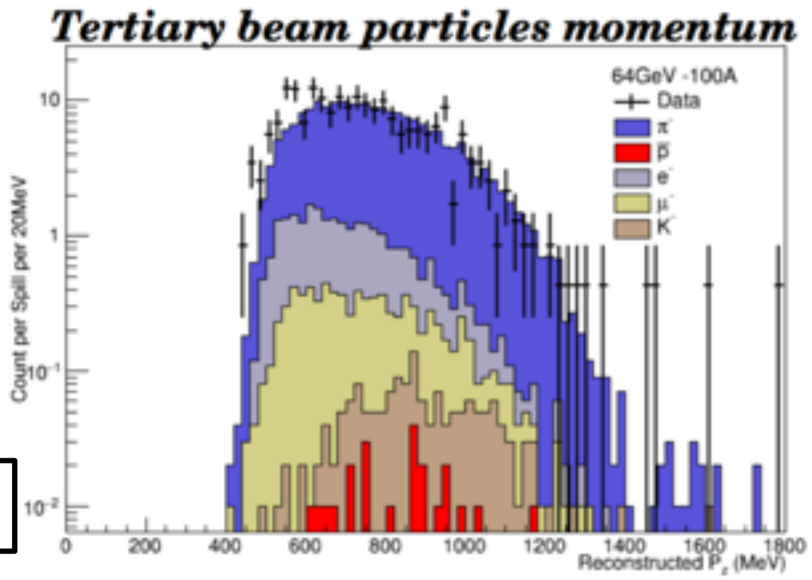
I think, MC builders should use only light nuclei for parametrization of the initial reaction (exception here for MEC, LRC and SRC) while data analyzers should go into higher nuclei to check the uncertainties of these MCs.

However, it is still uncertain to me the methodology to test the FSI approach.

Should we move into global uncertainties instead of factorizing the initial interaction and FSI?

LArIAT: Liquid Argon In A Test beam

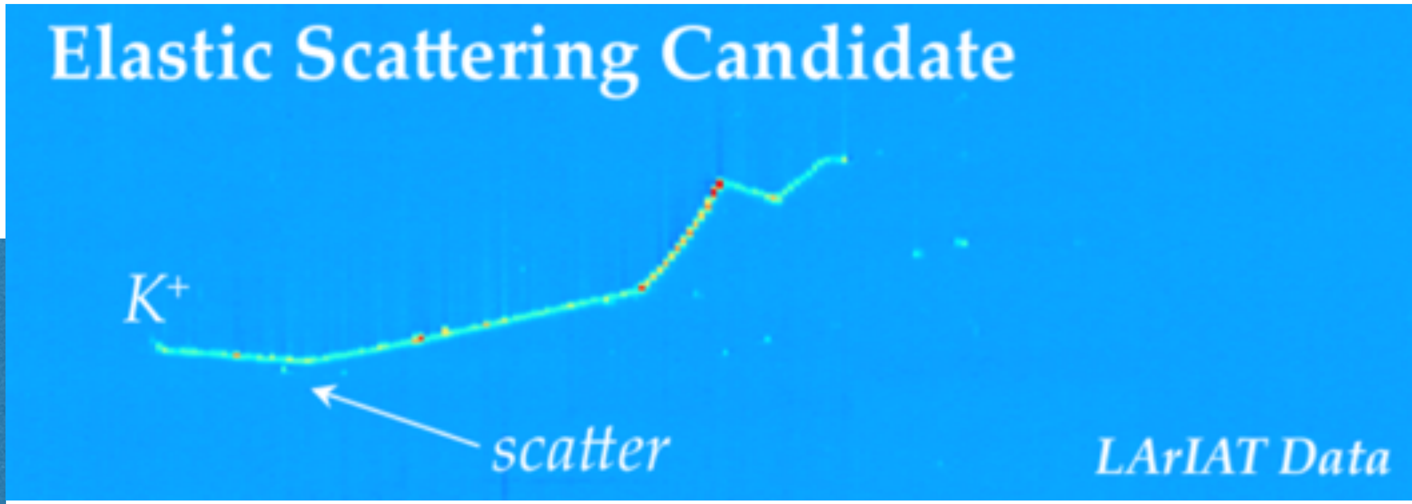


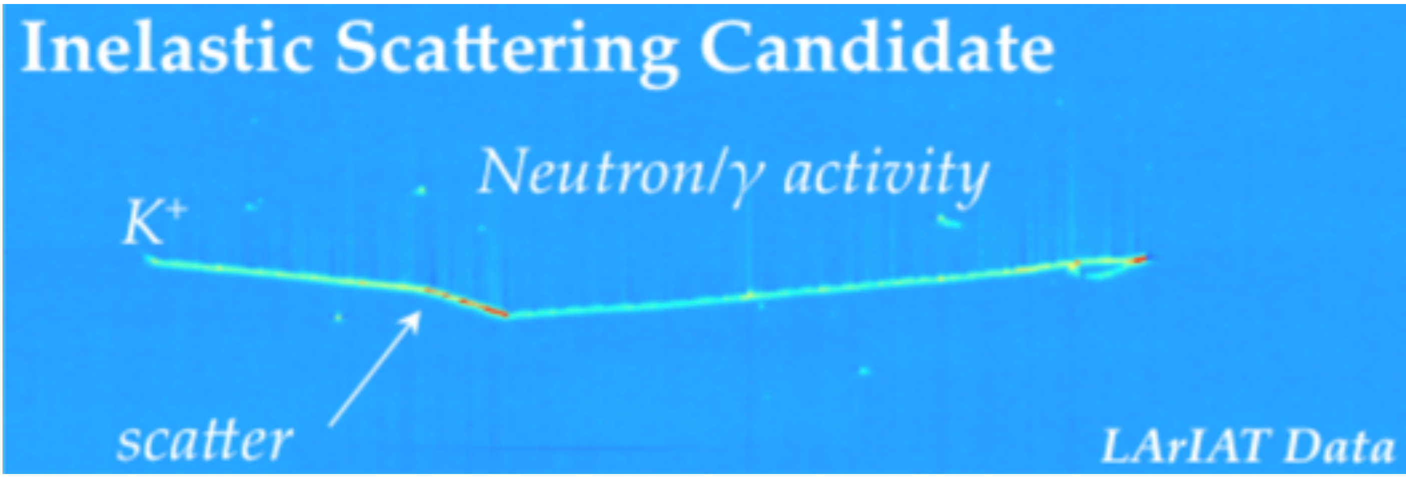


J. Assadi, NuINT'17

Experiments such as **LArIAT** provide a wealth of data with direct applications for studying **secondary interaction** processes.

As well can be used for **FSI estimations**, only if the FSI model adopted distinguishes if that the FSI interaction has different cross section depending of the shell structure and assuming that this external data only constraints the last shell values.





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Uncertainties from an oscillation point of view

Now, let's complicate the problem.
To measure neutrino oscillations **we need to measure the neutrino energy**.
The usual options: **calorimetry** or **model approach** (CCQE formula using an exclusive dataset,..).

Both options are model dependent, at different levels.

- Using **calorimetry** you assume you can reconstruct (accurately) every particle leaving the nucleus. You also assume that these particles contains all the energy information of the original neutrino.
- Using **CCQE** (or CC1Pion, depends how your exclusive channel is determined) formula you don't rely as much on how well you reconstruct the final state particles. However, you assume you have under control your background (any other exclusive channel) and any hadron absorption, nucleon multiplicity in the final state,…

Applied solution to this (till now) is to produce the so-called **migration matrix** (reconstructed vs truth energy) and cross fingers that the MC does a good job on **moving from reaction into topology**.
Which is the best (or less worst) solution will depend on the detector characteristics (and beam conditions).

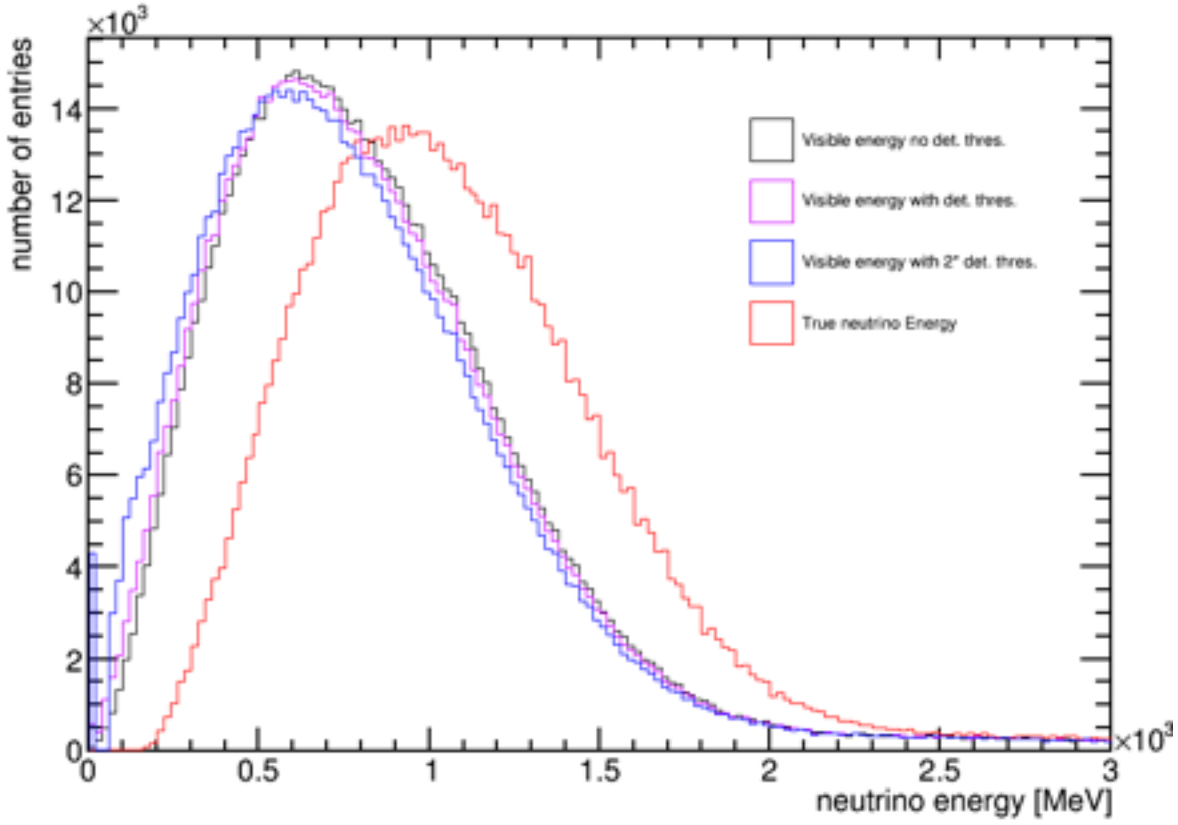
Uncertainties from an oscillation point of view

As naif example of **calorimetry approach**, let's compare **truth ν energy** vs **visible energy** vs **visible energy considering detector acceptance** vs **visible energy with half of assumed acceptance**.

Detector acceptance here is assumed to be the same as the one used within the DUNE Fast MC:

- **KE muon =30 MeV**
- **KE proton = 50 MeV**
- **KE Pion $^{+/-}$ = 100 MeV**
- **KE $e^{+/-}$= 30 MeV**
- **neutrons not considered at any threshold**

Red: true neutrino energy
Black: Visible energy without detector threshold (neutrons not included)
Violet: visible energy with detector thresholds (neutrons not included)
Blue: visible energy with double detector thresholds (neutrons not included)



NuWRO simulation at uB

Uncertainties from an oscillation point of view

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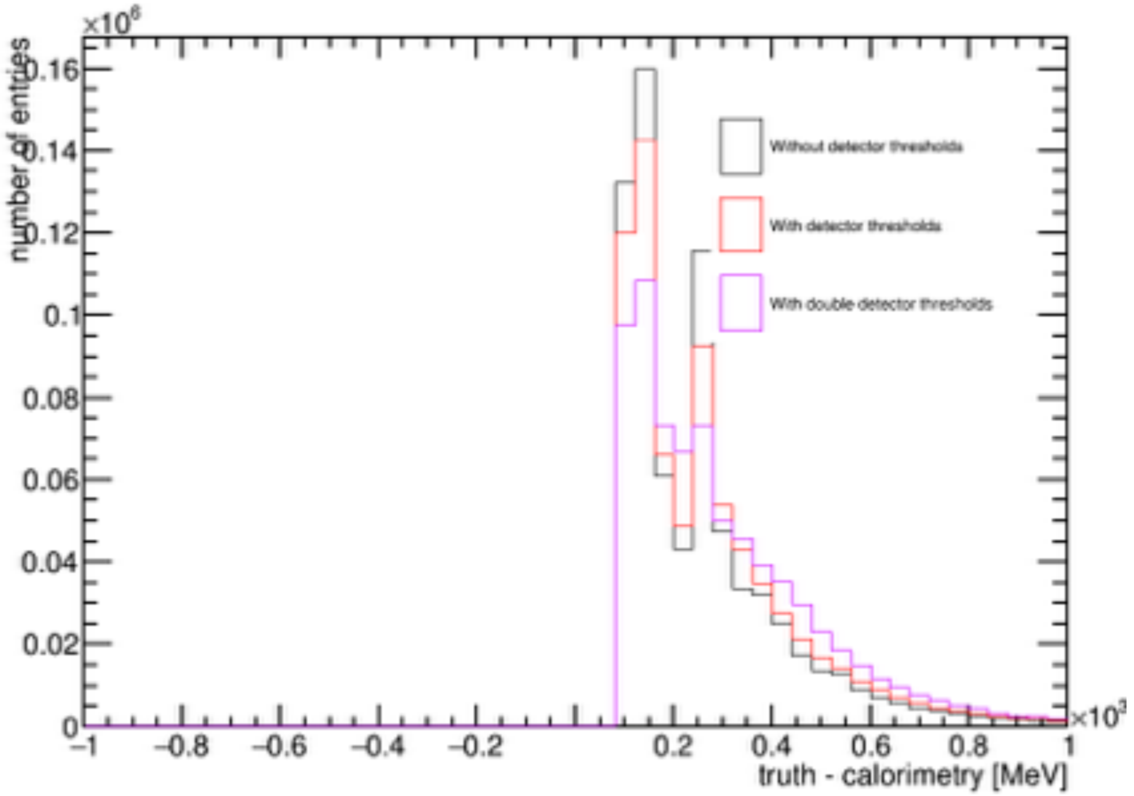
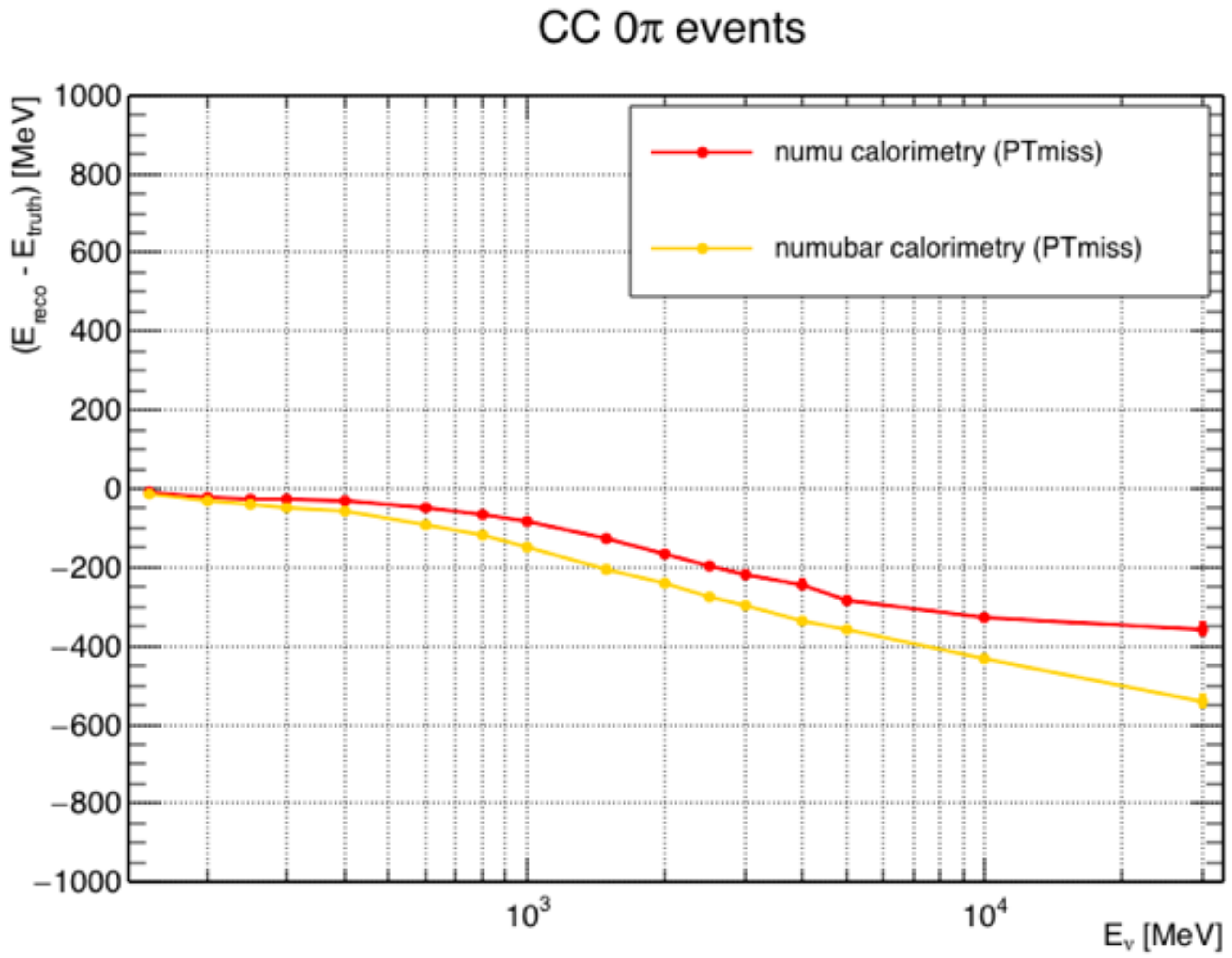


NuWRO simulation at uB

Uncertainties from an oscillation point of view

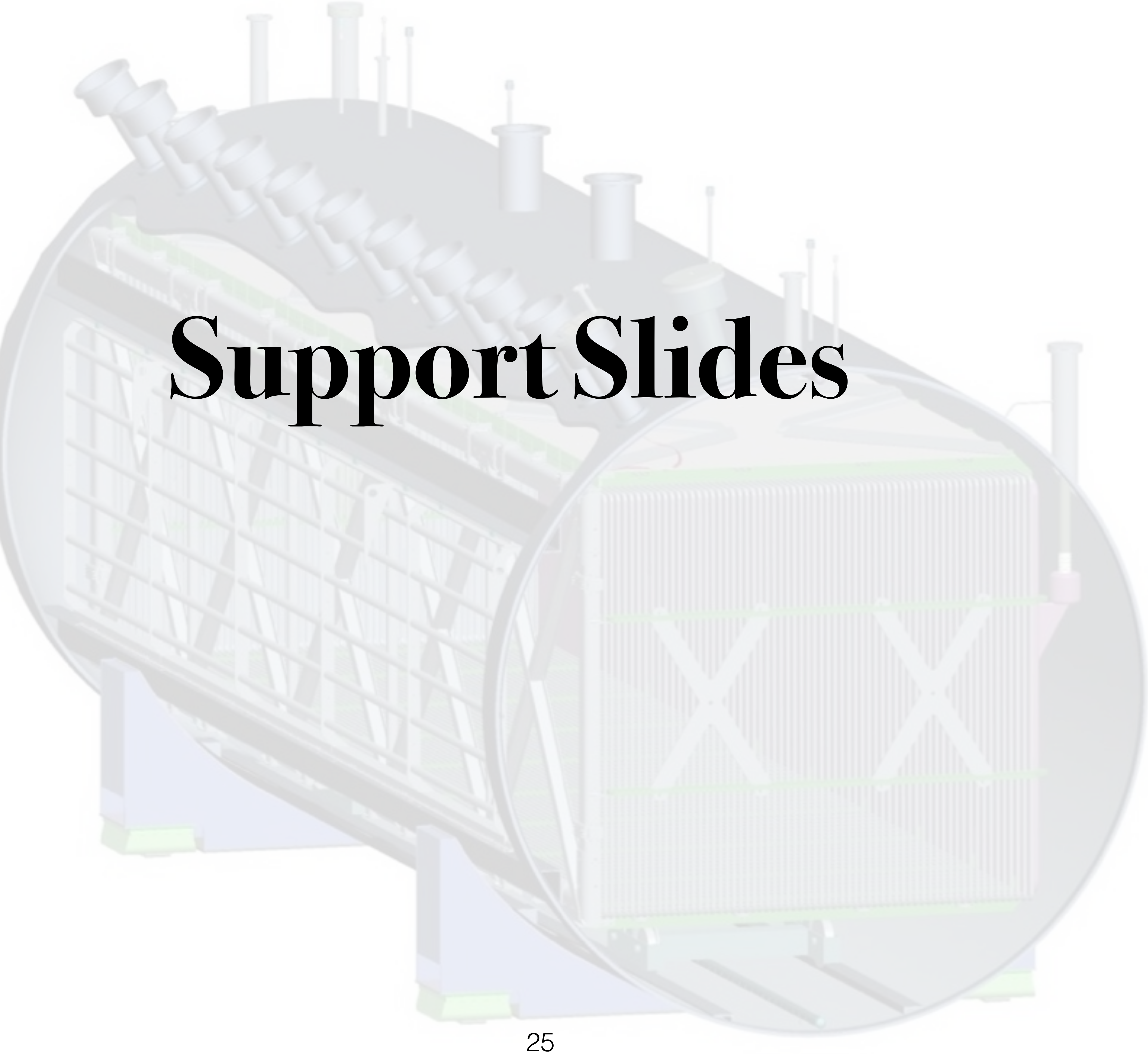
A different solution to the problem, which uses calorimetry approach but correcting nucleus response with kinematic transversal variables, showed better results for ArgoNEUT. This may allow for not using MC migration matrix for correcting on neutrino energy.



O. Palamara, NuINT'15
(ArgoNEUT simulation using GENIE,
with detector threshold)

Summary (!= conclusions)

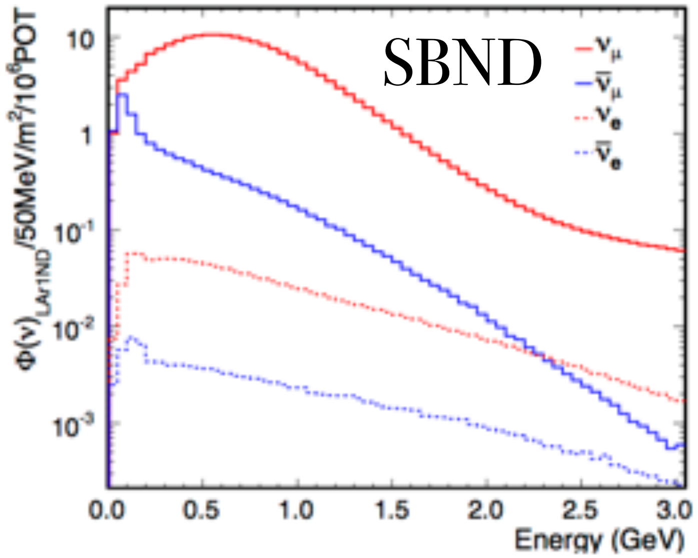
- We are in the position that we need to understand **together ν scattering and FSI**. It <u>may be possible that we cannot distinguish anymore these processes when approaching its uncertainties</u>.
- We have to find a better **strategy to estimate uncertainties from FSI modeling**.
  - **FSI uncertainties should be not the same as the ones obtained from hadron-nucleus scattering.**
  - <u>Reweighing methods should be carefully examined before to apply. Datasets for modeling should be different that the ones used for validation/uncertainty measurements</u>.
  - I believe MC builders should **not use neutrino-(heavy)nucleus to tune specific reactions.**
- We need to understand better the **limitations of calorimetry and reaction type** approach for **neutrino energy estimation**.
- **SBND will provide the highest data statistics ever achieved in neutrino physics** and will allow for **triple, and even some quadruple differential measurements**. This can allow us to <u>re-connect the initial interaction with the calorimetry response</u> in high accuracy.
- We are on the need of help/collaboration from/with the **theory** and **MC builders** to offer support in the <u>description of these processes</u> but as well to estimate <u>its uncertainties</u>.

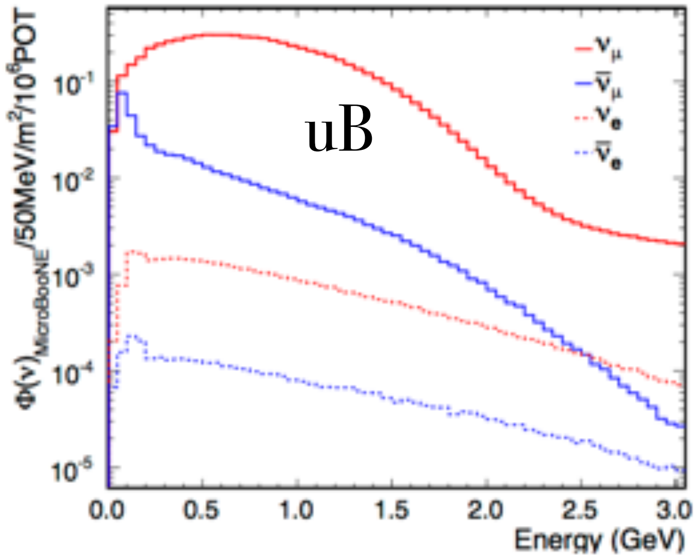


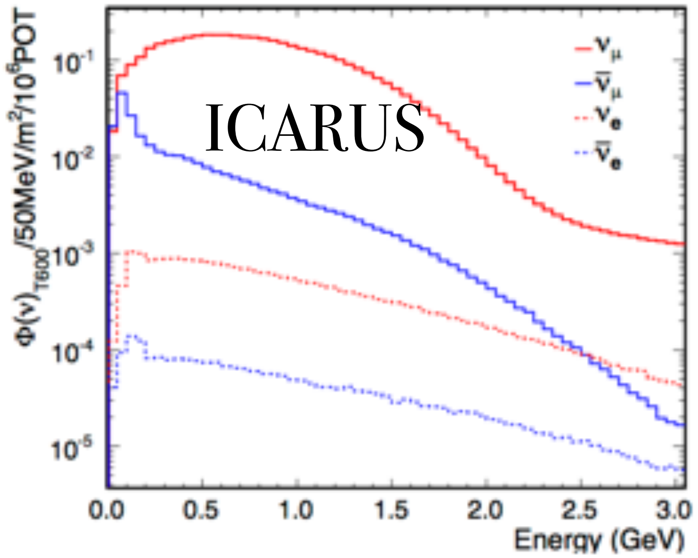
Support Slides

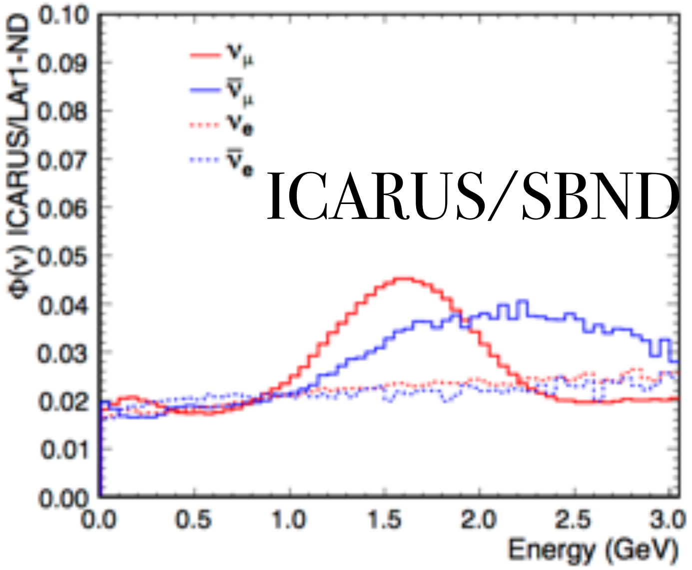
ν Flux @ SBND, MicroBooNE and ICARUS

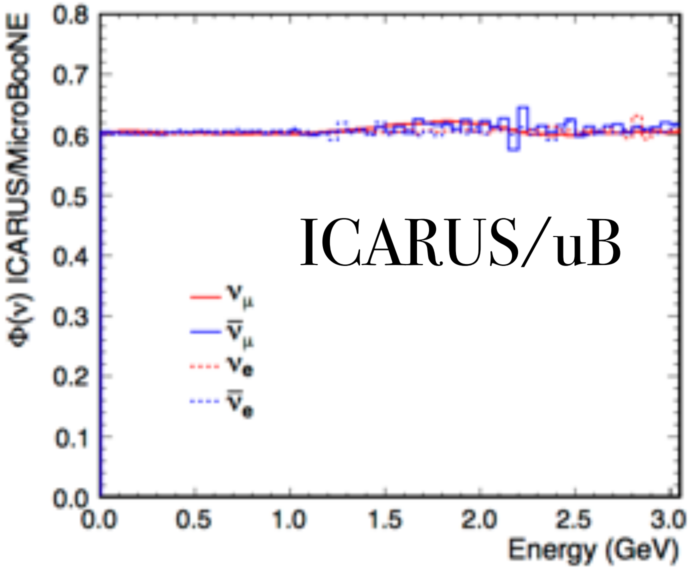
8 GeV Protons from BNB
Almost pure ν_μ beam (0.5% intrinsic ν_e contamination at uB)







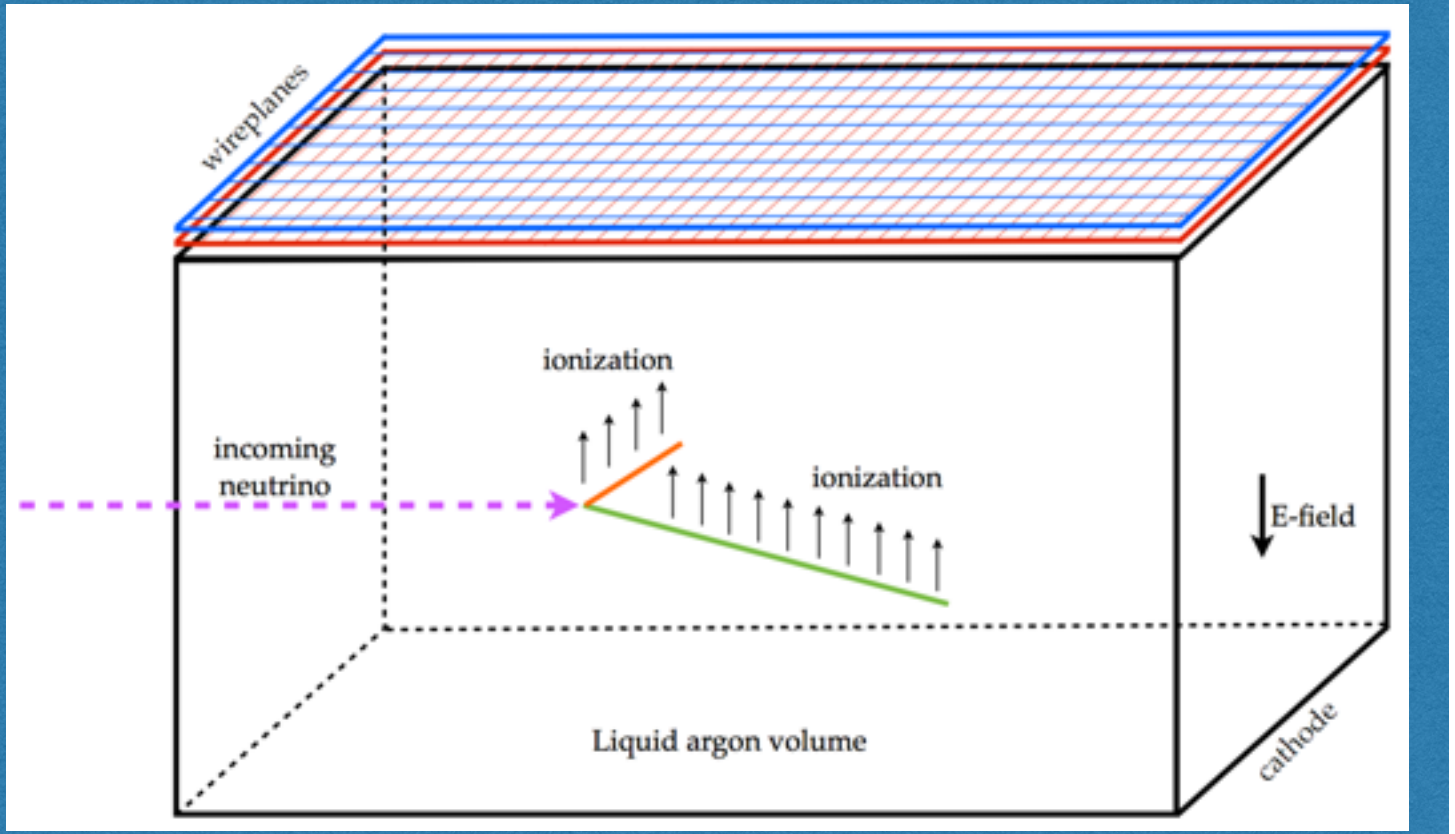




Same ν beam at different detection locations: different spectrum
Same detector technology: very similar detection thresholds, resolutions and detector uncertainties
Sharing simulation, reconstruction and analysis techniques

Precision era: Liquid Argon TPC

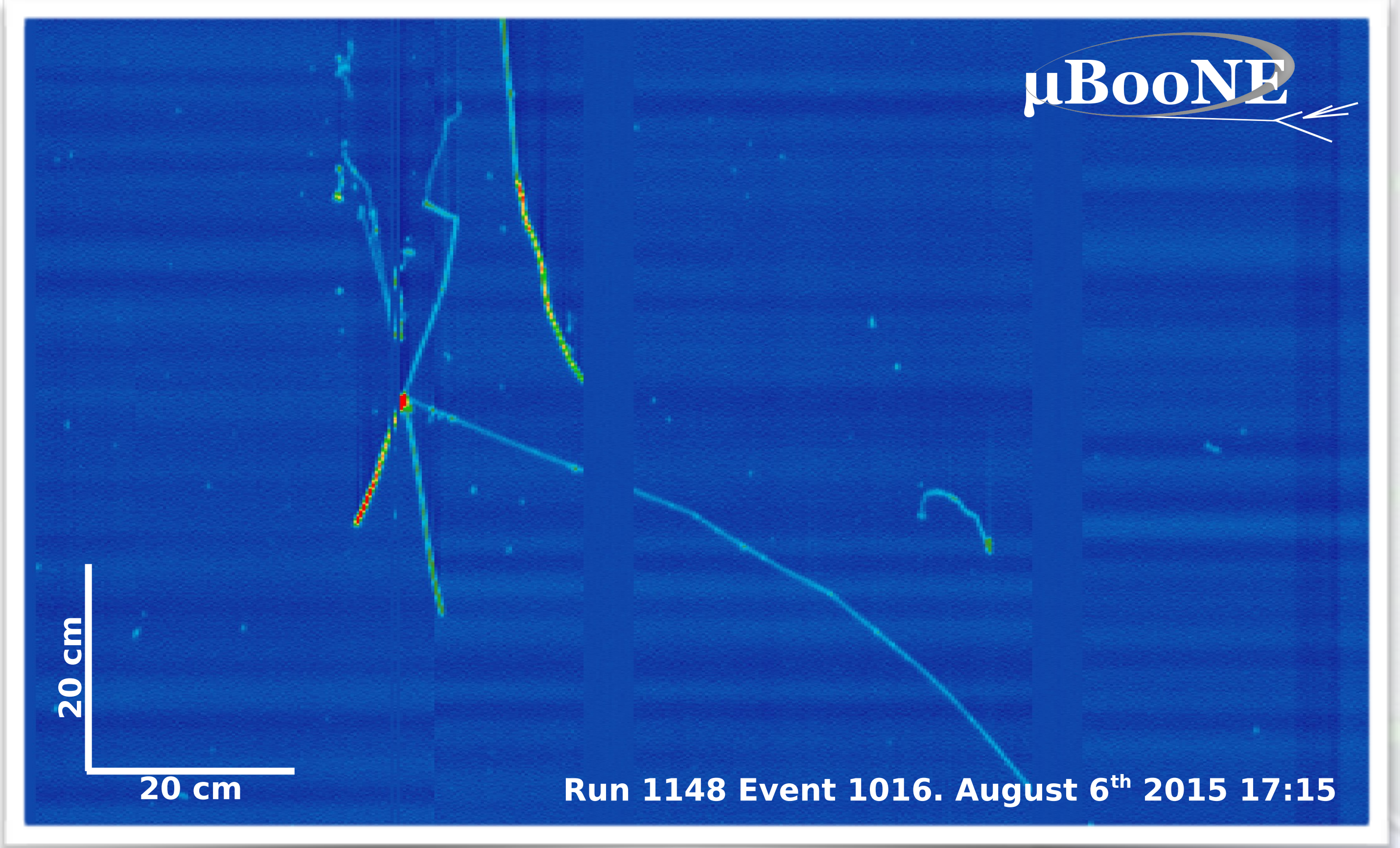
- Ionization from traversing charged particles is drifted along E-field to the segmented wire planes.
  - argon ionizes easily, ~70 ke/cm (@500 V/cm)
- Wire pulse timing information is combined with known drift speed to determine drift-direction coordinate.
- Calorimetry information is extracted from wire pulse characteristics.
- Abundant **scintillation light**, which LAr is transparent to, also available for collection and triggering.
  - **40k γ/MeV @null E-field**
- Argon is **40%** more dense than water.
- **1%** abundance in the atmosphere.



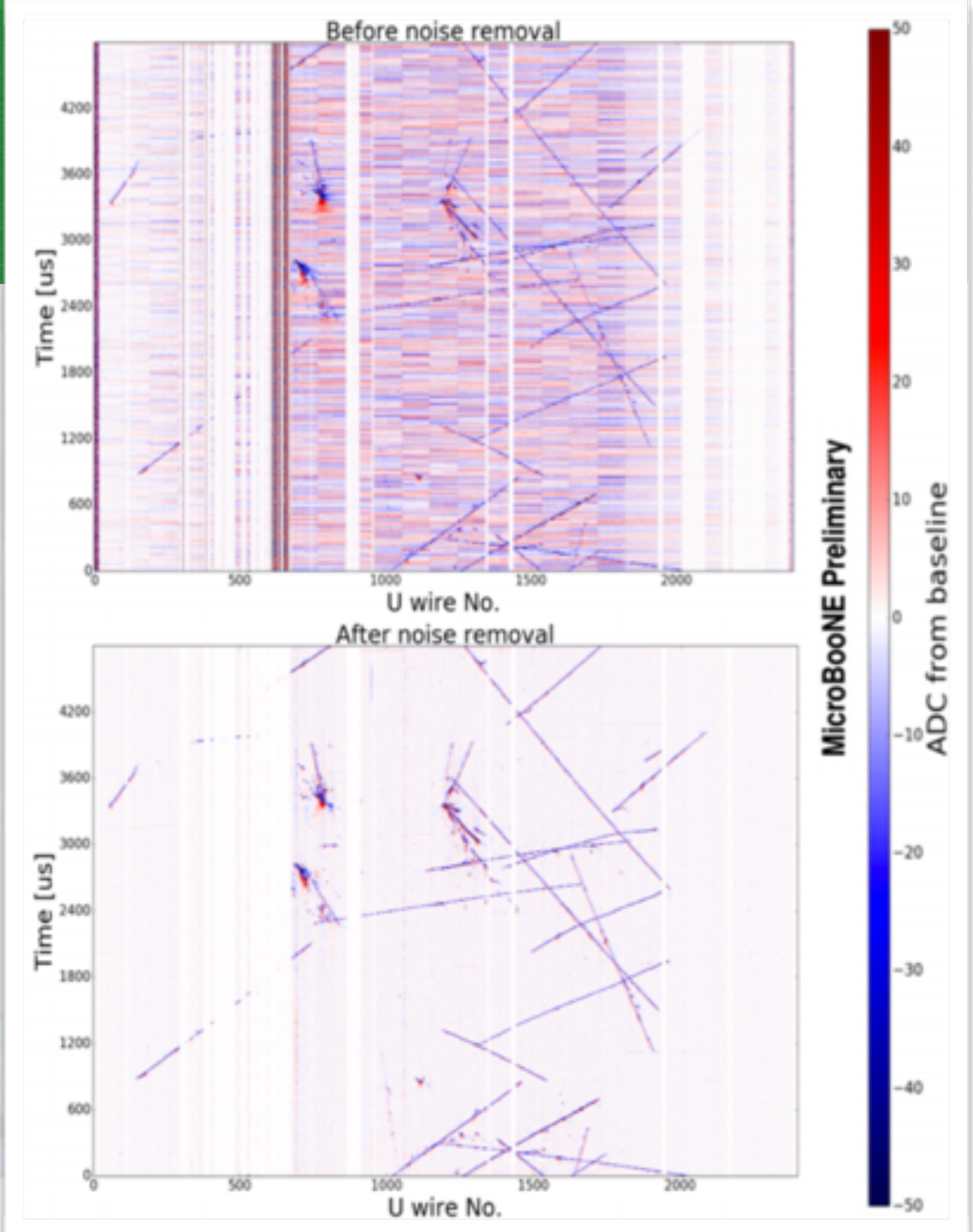
MicroBooNE TPC

MICROBOONE-NOTE-1016-PUB

- Coherent noise over group of channels
  - This noise is associated to a voltage regulator on a warm service board
  - With software filtering we are able to improve signal-to-noise by factor of 2
- Signal-to-noise ratio after software noise filtering
- U plane 15.8 : 1
- V plane 12.9 : 1
- Y plane 45.3 : 1

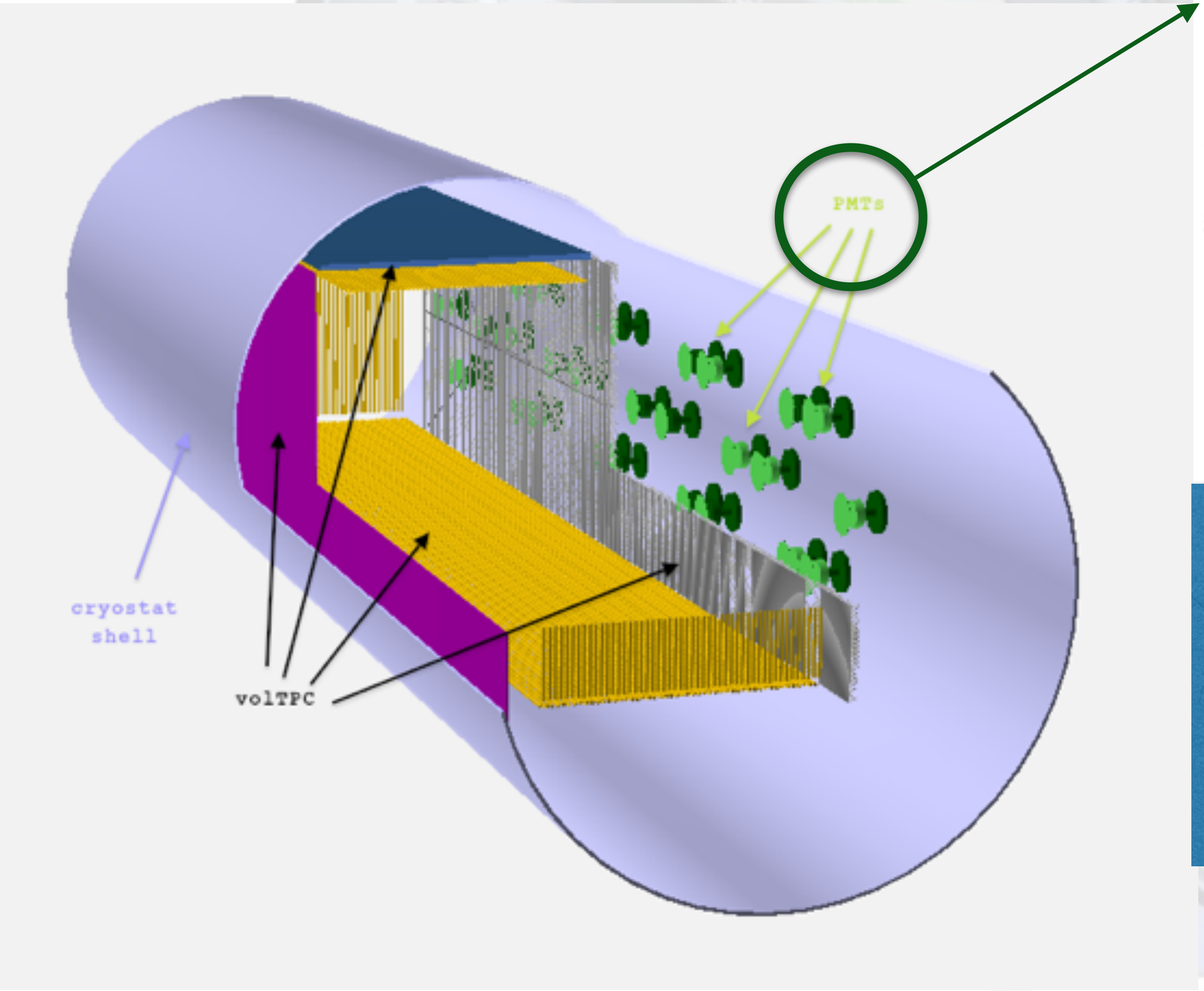


Run 1148 Event 1016. August 6th 2015 17:15

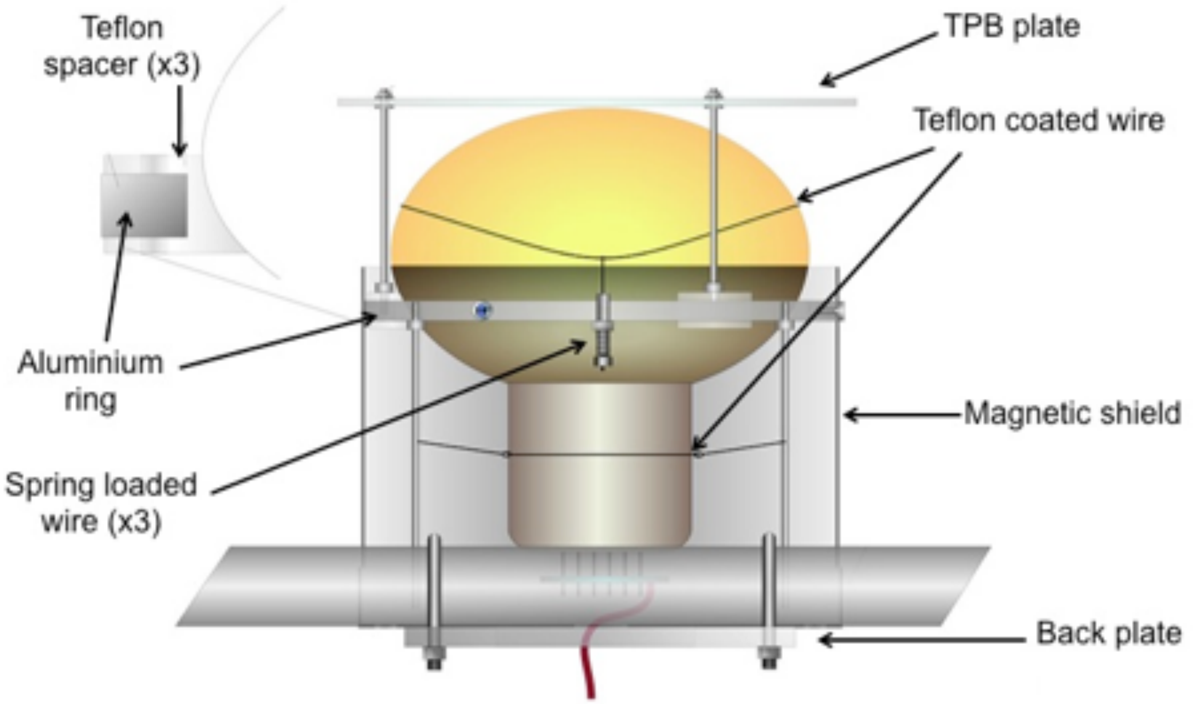


MicroBooNE Photon Detectors

32 PMTs + 4 light guide paddles

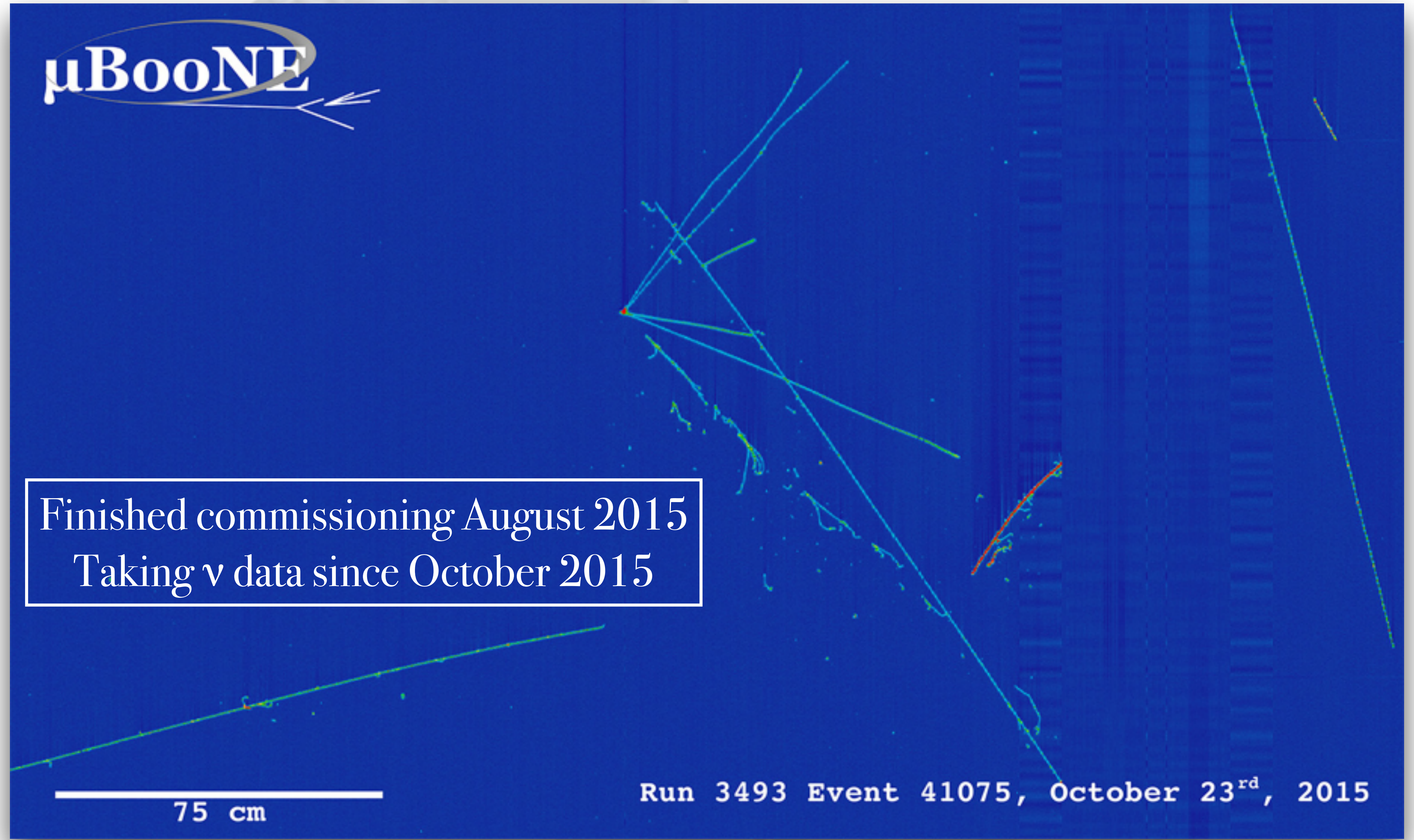


PMT mount with a PMT



A wire ring is pulled down by 3 spring loaded wires to an aluminium ring.
Direct contact of the PMT to the aluminium ring is avoided by Teflon blocks.
The magnetic shield and the TPB plate are fixed on to the PMT mount.

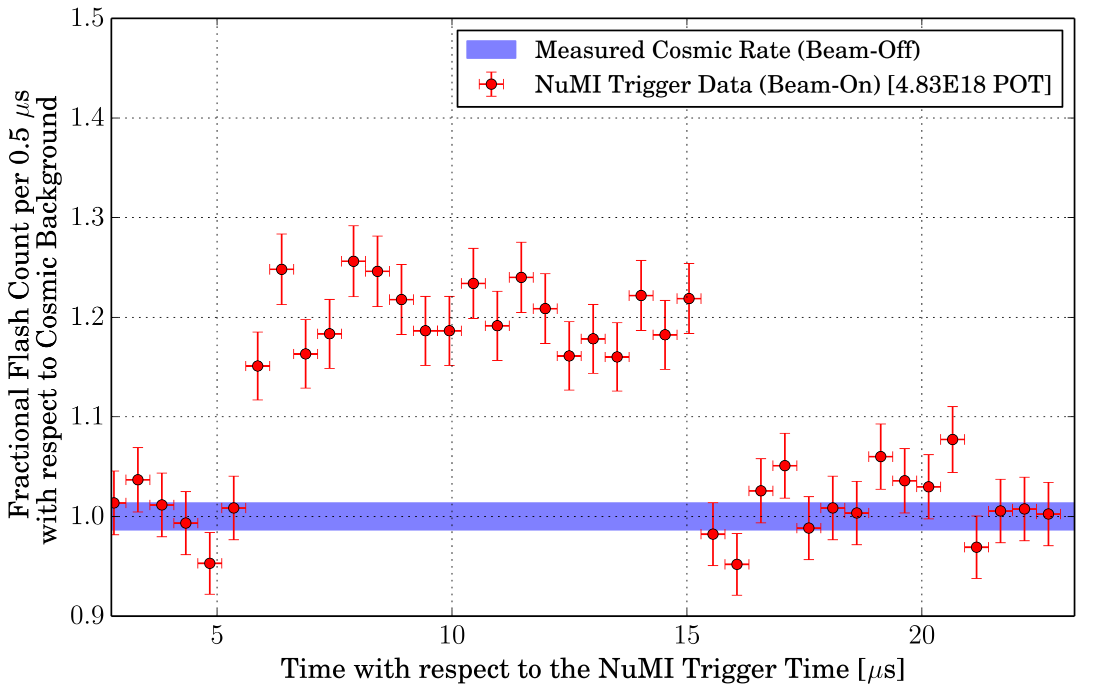
MicroBooNE Physics



Finished commissioning August 2015
Taking ν data since October 2015

MicroBooNE ν Physics

NuMI: On the way to constrain ν-Argon interactions



MicroBooNE receives 2 different neutrino beams: BNB but also NuMI
NuMI arrives off-axis ~6 degrees wrt z

Double the beam, double the fun!