µBooNE

Analysis and Systematic Uncertainty Experience From MicroBooNE

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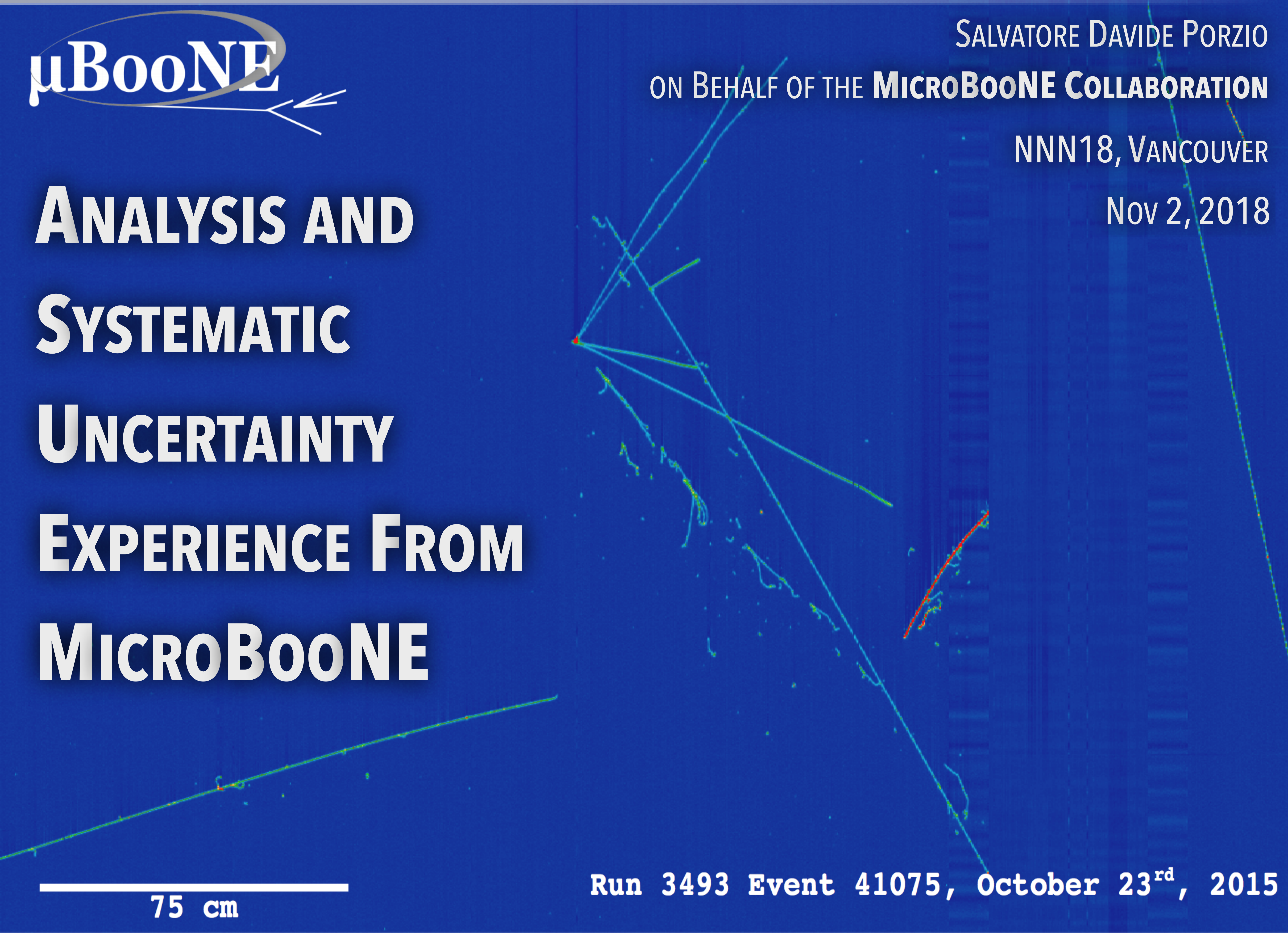
on Behalf of the MicroBooNE Collaboration

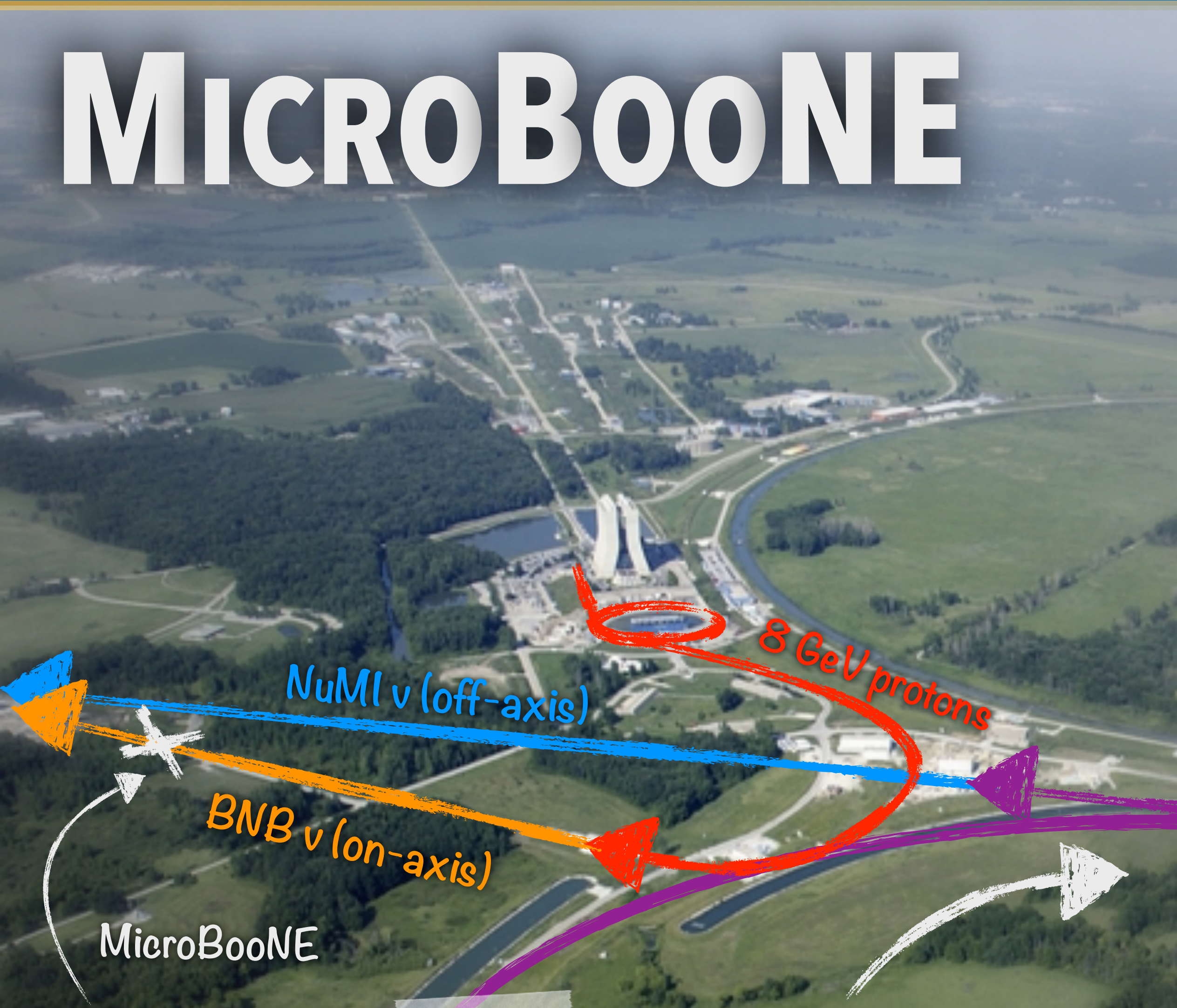
NNN18, Vancouver

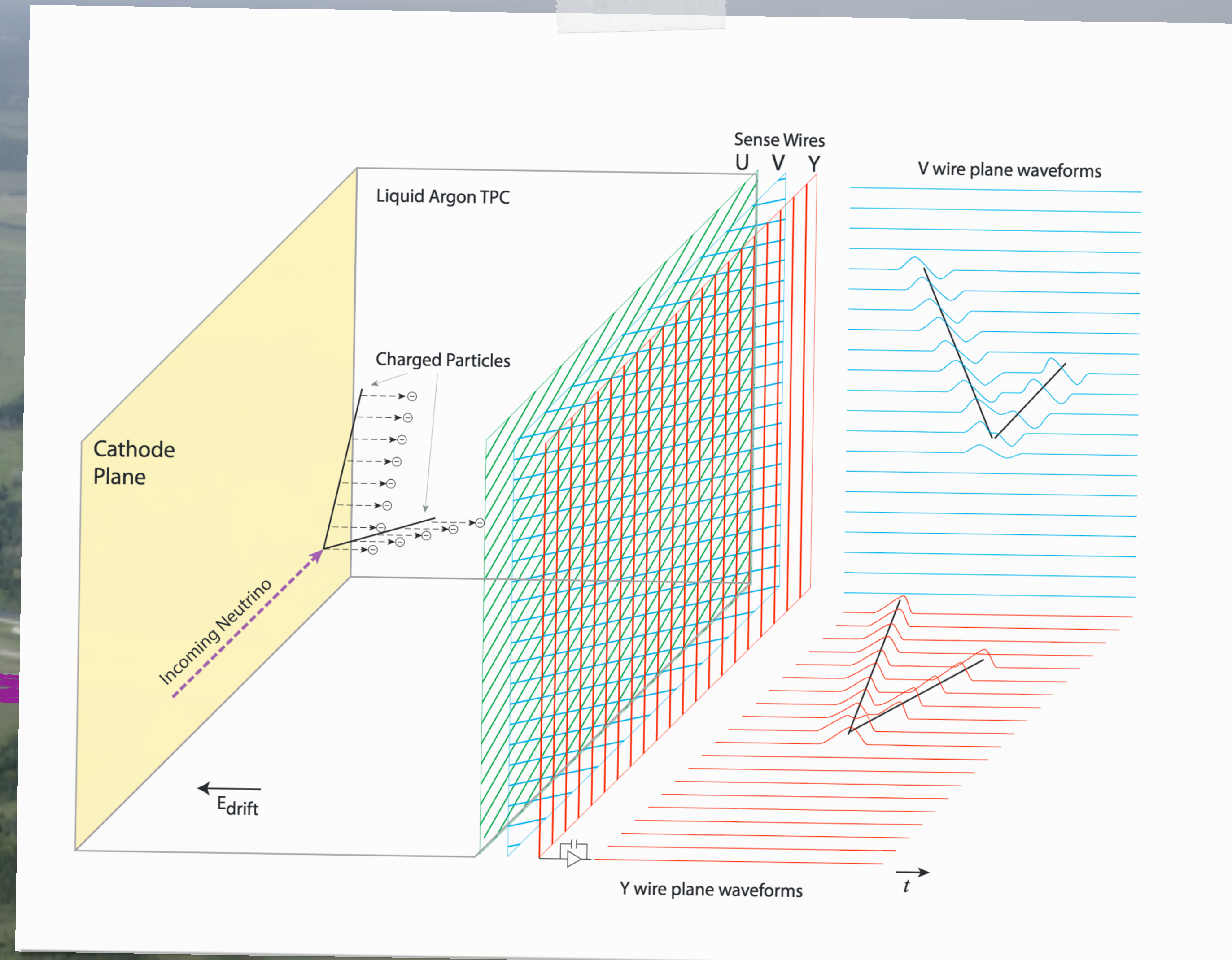
Nov 2, 2018

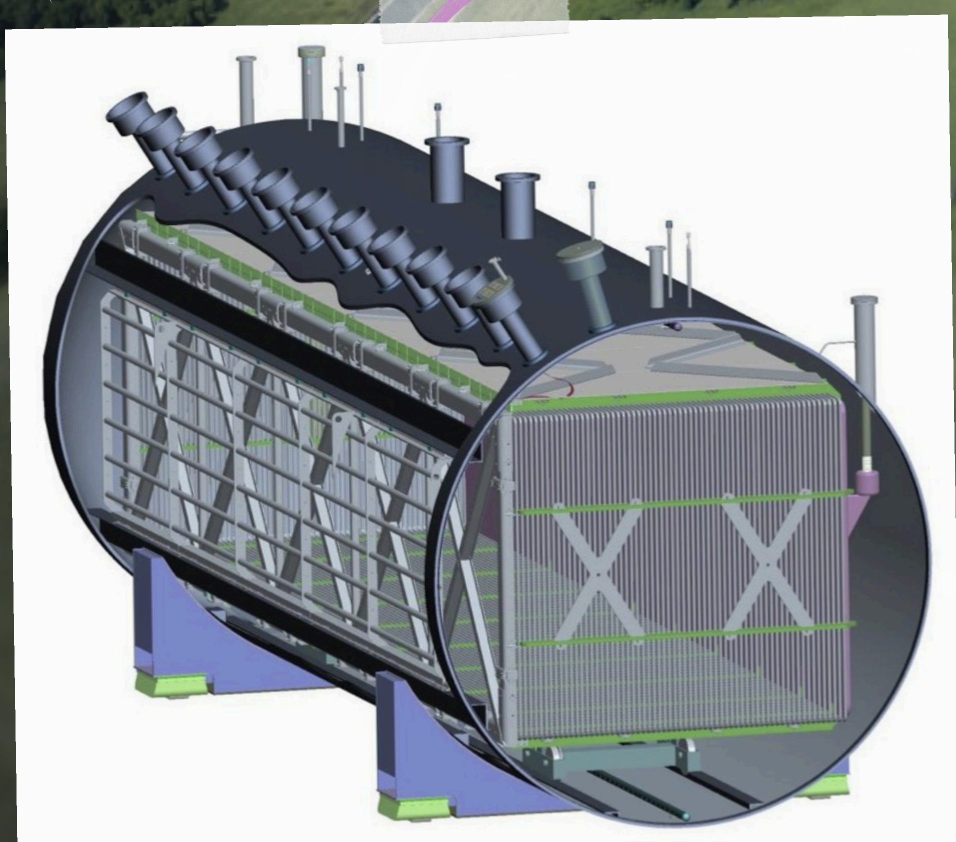


1) Fermilab's short baseline program: arXiv:1503.01520 [hep-ex]

MicroBooNE







- Liquid Argon Time Projection Chamber
- Short-Baseline Oscillation[1] Experiment (470 m baseline), along with SBND and ICARUS
- Downstream of BNB and NuMI

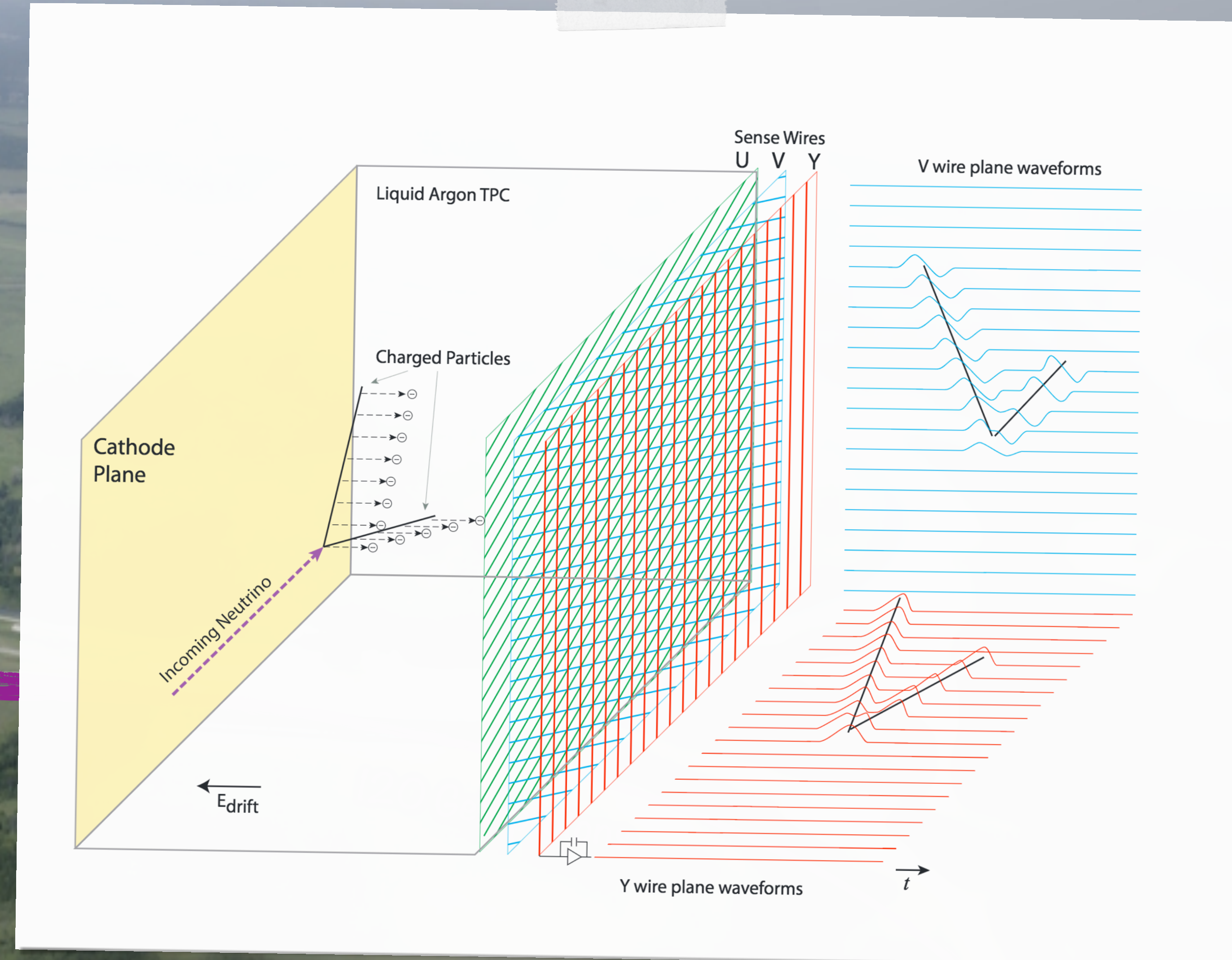
- 87-ton active volume LAr
- Drift chamber with E-field at 273 V/cm
- Three wire planes (8192 wires):
  - 2 induction, 1 collection
  - 3 mm wire pitch
  - 3 mm plane spacing
- 32 8″ Cryogenic PMTs

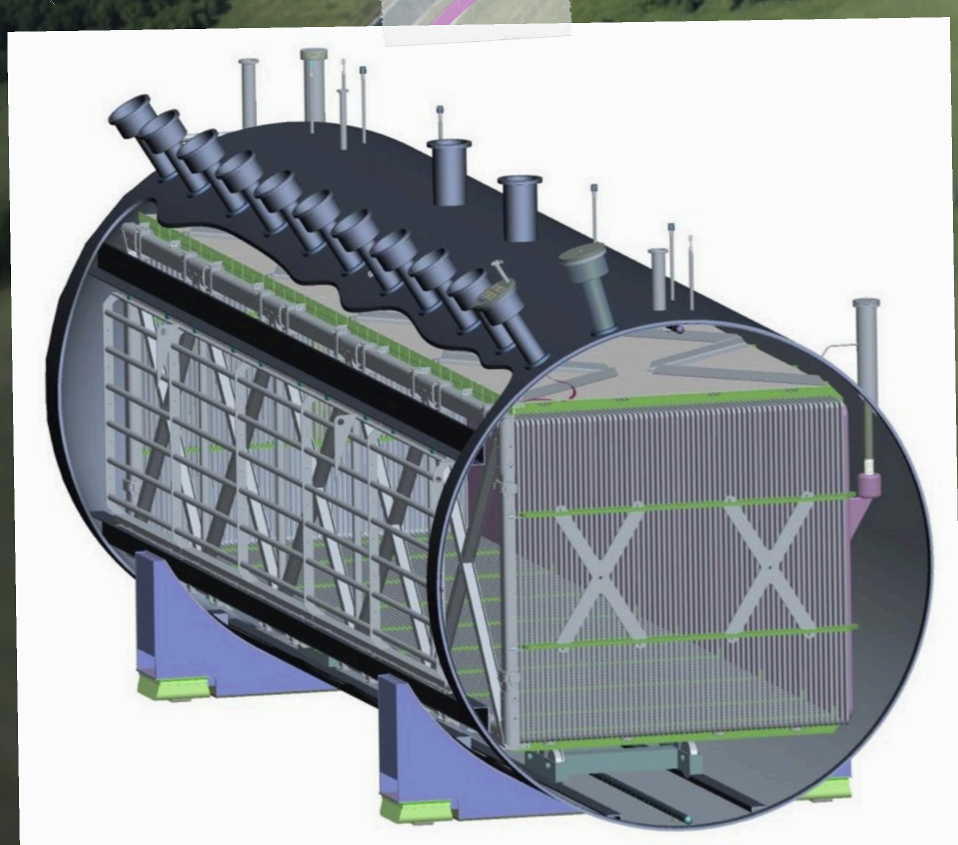
1) Fermilab's short baseline program: [arXiv:1503.01520 [hep-ex]]

MicroBooNE

See Brooke Russell talk tomorrow morning:

Short Baseline Neutrino Experiments





- **Liquid Argon Time Projection Chamber**
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MicroBooNE

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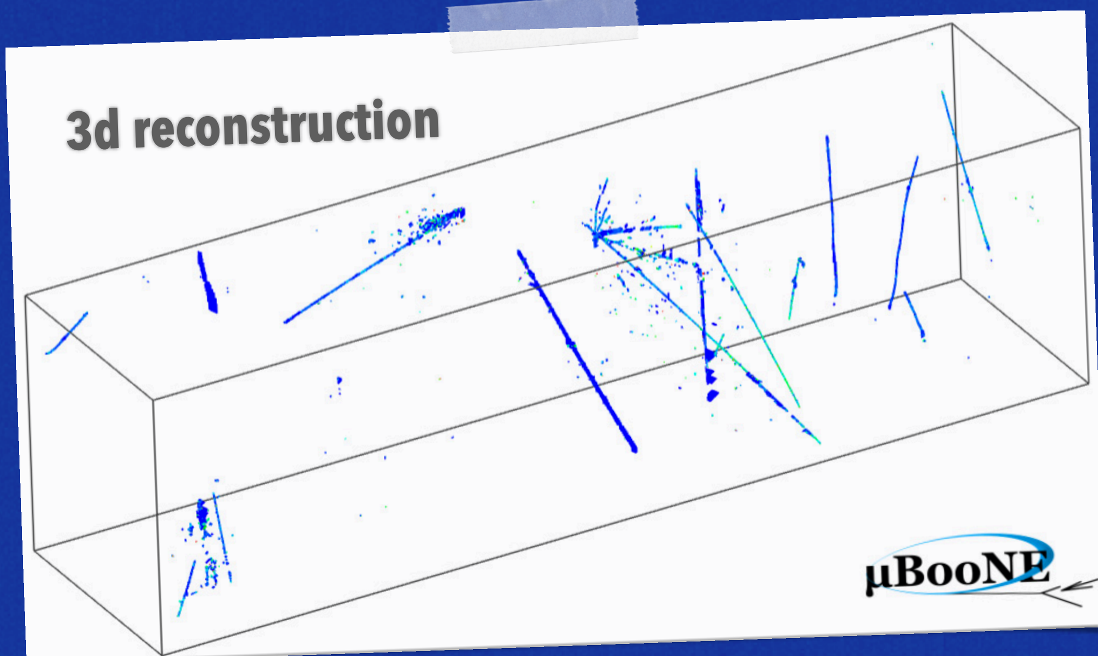


Science goals:

- Resolve MiniBooNE low energy excess
- Study ν-argon cross-sections
- LArTPC R&D
- Astrophysics and Exotica Physics

Bubble chamber quality images
+ calorimetry and automated reconstruction!

Excellent resolution (~3mm)

75 cm

Run 3493 Event 41075, October 23rd, 2015

Experience From Physics Analysis

Also providing great input to:

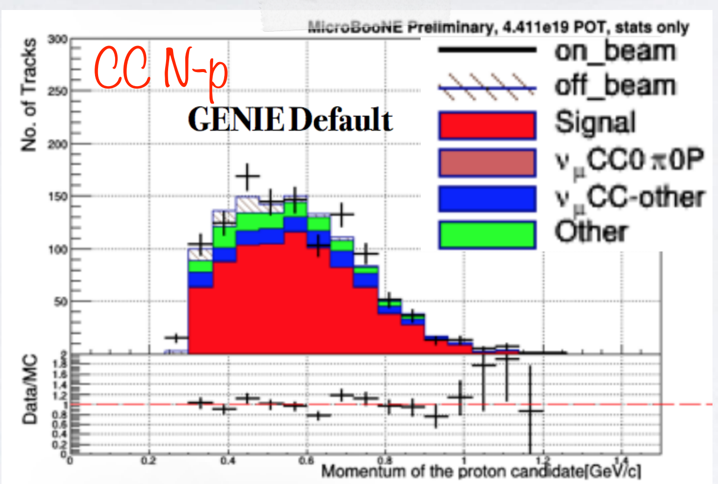
- **Oscillation analysis**
- **Physics R&D**

Invaluable experience towards understanding of LArTPC systematics!

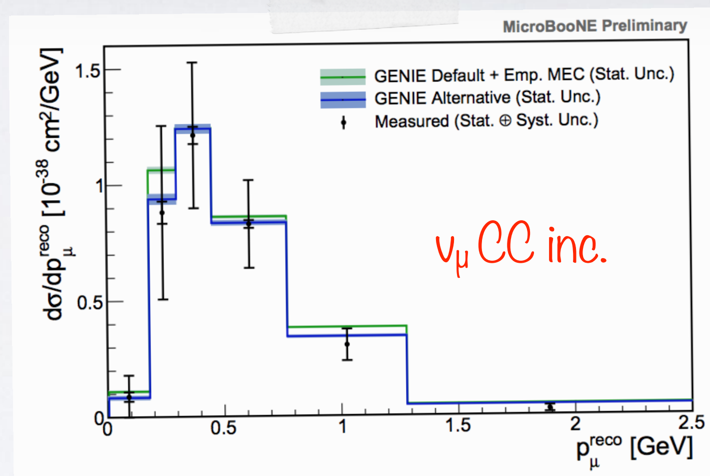
Building up momentum thanks to our first **interaction** and **cross sections measurements**:

- Charged Particle Multiplicity
- ν_μ CC inclusive
- CC π^0
- CC N-p
- NuMI CC ν_e

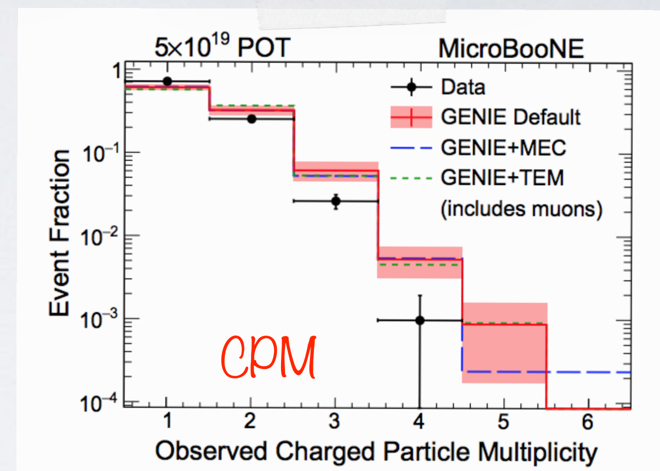
CC N-p **NuInt18 talk**: https://indico.cern.ch/event/703880/contributions/3159004/attachments/1735013/2805892/Raquel_NuINT.pdf



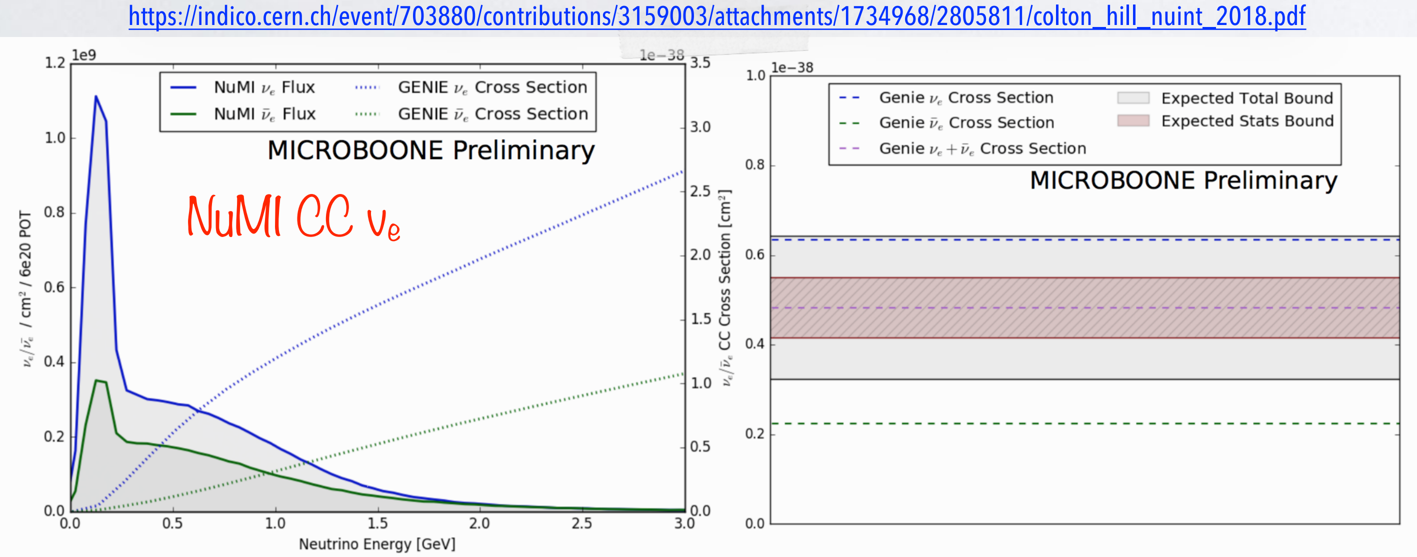
ν_μ CC Inclusive Cross Section **MICROBOONE-NOTE-1045-PUB**: http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1045-PUB.pdf



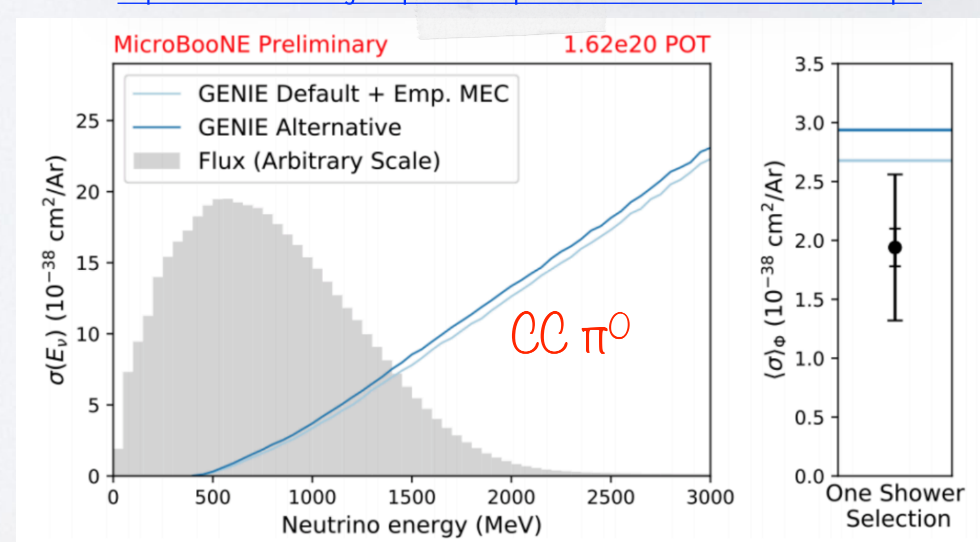
ν-Ar Multiplicity Distribution comparison to GENIE: https://arxiv.org/abs/1805.06887



NuMI CC νe **NuInt18 talk**: https://indico.cern.ch/event/703880/contributions/3159003/attachments/1734968/2805811/colton_hill_nuint_2018.pdf



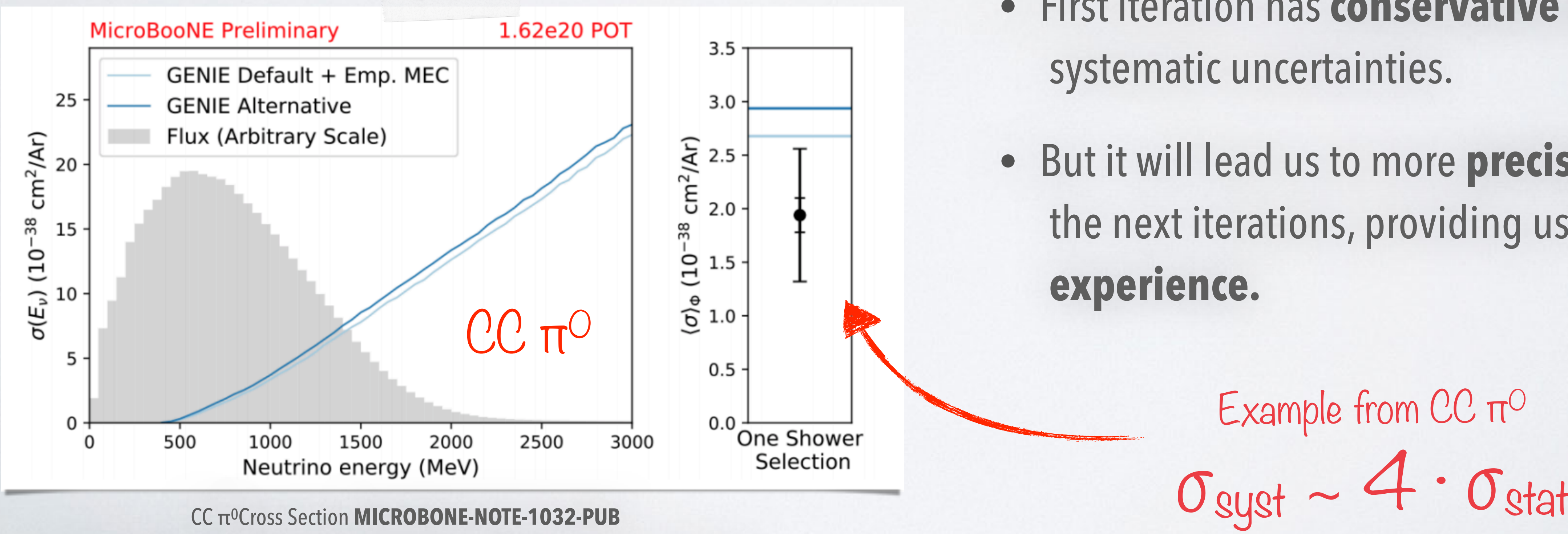
CC π^0 Cross Section **MICROBONE-NOTE-1032-PUB**: http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1032-PUB.pdf



APPROACH TO SYSTEMATICS

- Approach based on:
  - **Simulating / re-weighting** parameters
  - **Propagating effects** through the full chain

- Use 1σ variations from central value, **constrained by data** when available or using an **alternative underlying model**.
- Many parameters have not been fully constrained yet by **internal or external measurements**.
- Very **high statistics**, need better understanding of systematics than previously ever needed.
- First iteration has **conservative estimates** on systematic uncertainties.
- But it will lead us to more **precise constraints** for the next iterations, providing us with **invaluable experience.**

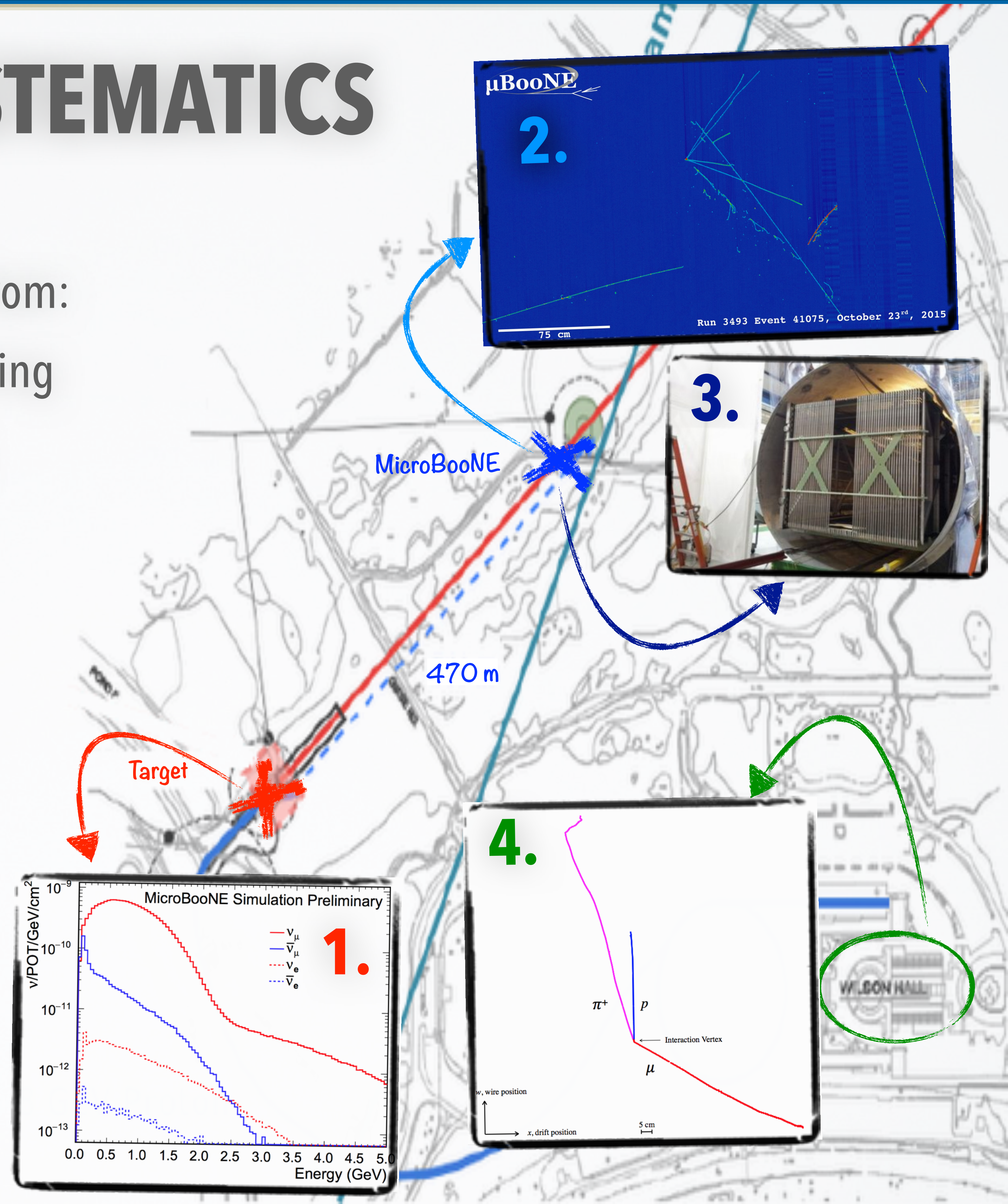


CC π^0 Cross Section **MICROBONE-NOTE-1032-PUB**
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1032-PUB.pdf

SOURCE OF SYSTEMATICS

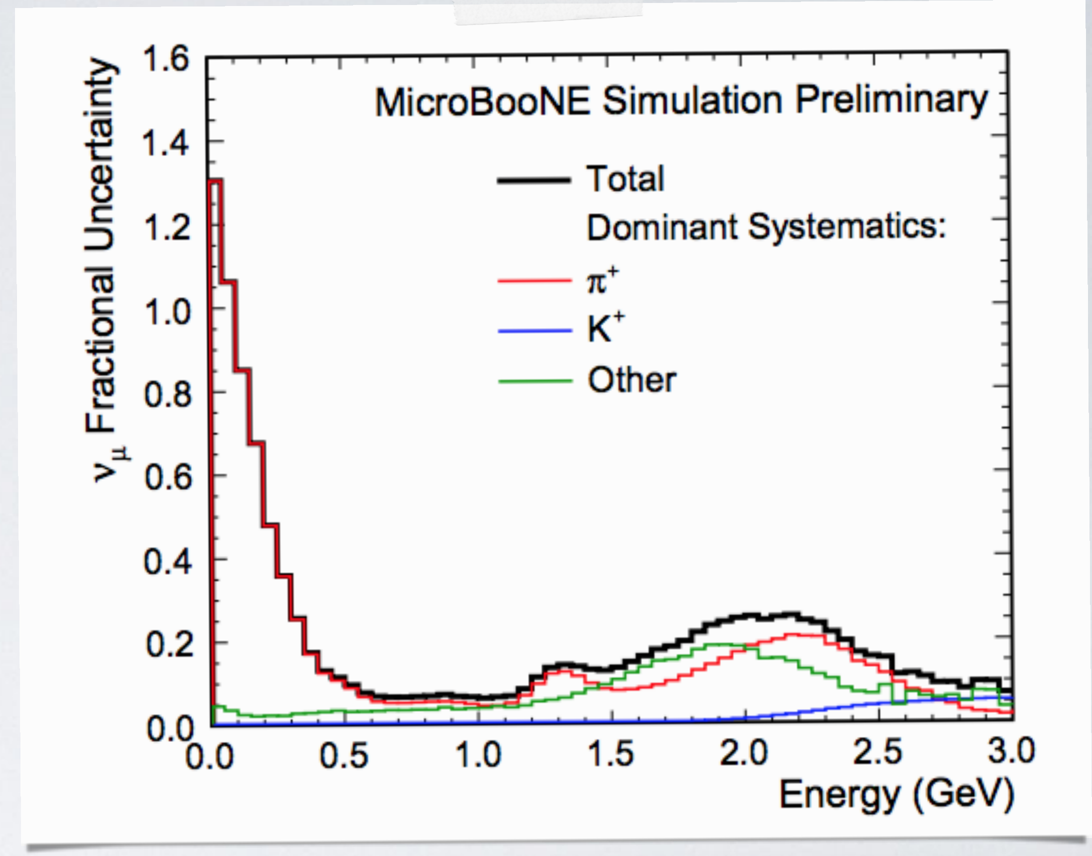
Main sources of **uncertainties** from:

1. Beam flux and POT counting
2. Cross section modelling
3. Detector response
4. Reconstruction



1. Beam Flux

- **BNB:** Using **MiniBooNE / SciBooNE techniques**
  - **>15 years of experience** running neutrino experiments in BNB.



BNB Flux Prediction Public Note **MICROBOONE-NOTE-1031-PUB**: http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1031-PUB.pdf

Hadron production uncertainties

- Uncertainties in the production of secondary particles after proton collision
  - $\pi^+, \pi^-, K^+, K^-, K^0_L$
  - Based on fits to HARP data and Feynman scaling for cross-section measurements at different energies

Non-Hadron production uncertainties

- Mismodelling of horn current distribution
- Horn current miscalibration
- Pion and nucleon scattering cross sections on Be and Al

Systematic	ν_μ/%	$\bar{\nu}_\mu$/%	ν_e/%	$\bar{\nu}_e$/%
Proton delivery	2.0	2.0	2.0	2.0
π^+	11.7	1.0	10.7	0.03
π^-	0.0	11.6	0.0	3.0
K^+	0.2	0.1	2.0	0.1
K^-	0.0	0.4	0.0	3.0
K^0_L	0.0	0.3	2.3	21.4
Other	3.9	6.6	3.2	5.3
Total	12.5	13.5	11.7	22.6

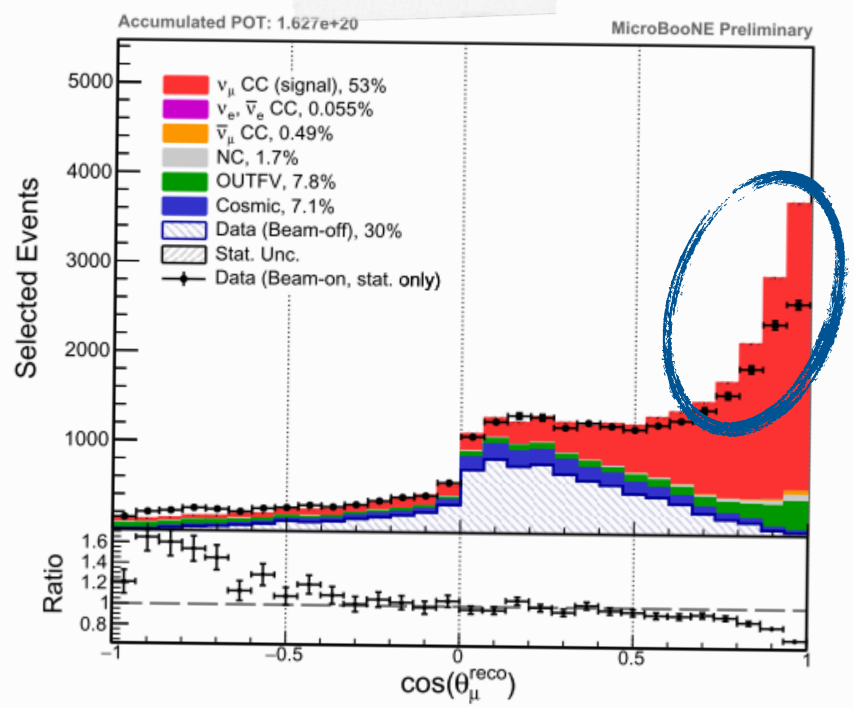
Strategy: CORRELATED UNIVERSES SIMULATION via reweighting

- **NuMI:** Similar approach as BNB but taking care of off-axis angle. Following MINERVA and NOVA techniques.

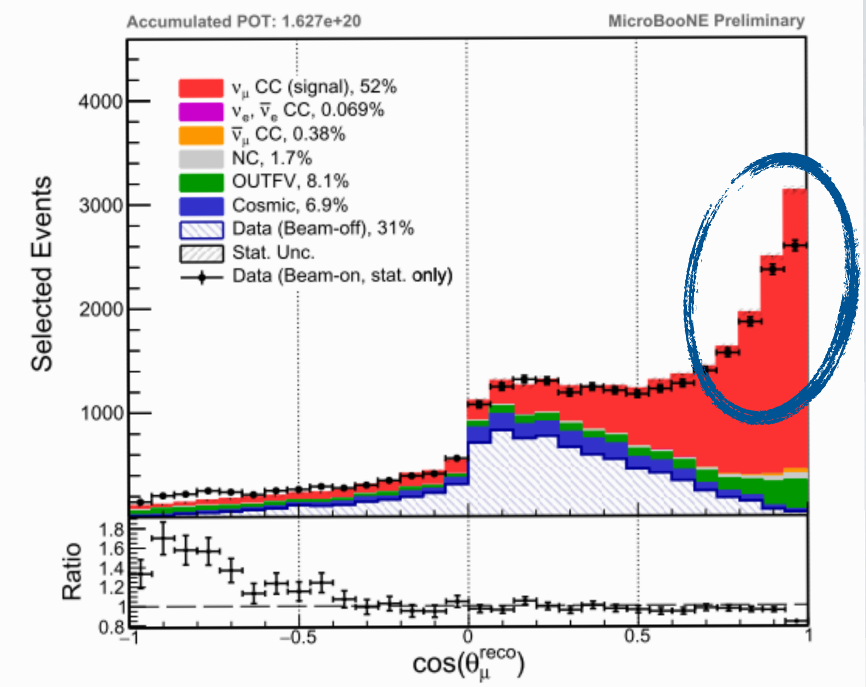
- Additional uncertainty on **normalization** from **proton delivery**, measured independently by two toroids.

2. Cross Section Modelling

- ν-Ar Cross-sections difficult to predict.
    - Large nucleus, complicated nuclear effects
- First generation analyses using default **GENIE v2** with **empirical MEC**,
    - Using also **alternative tune** with Valencia QE/MEC.
- Recent results from ν_μ CC have shown **better agreement** with alternative tune.



(c) Default GENIE + Emp. MEC.



(d) GENIE Alternative.

Model element	Default GENIE + Emp. MEC	GENIE Alternative
Nuclear Model	Bodek-Ritchie Fermi Gas	Local Fermi Gas
Quasi-Elastic	Llewellyn-Smith	Nieves
Meson-exchange Currents	Empirical	Nieves
Resonant	Rein-Seghal	Berger-Seghal
Coherent	Rein-Seghal	Berger-Seghal
FSI	hA	hA2014

MEC: Meson Exchange Current (*interaction with correlated nucleon states populating multi-nucleon final states*)

2. Cross Section Modelling

- For the future planning transition to **GENIE v3** using either:
  - **G18_10a**
    - Theory-driven comprehensive model
  - **G18_10i**
    - Like G18_10a
    - Using z expansion in place of the dipole model for the QE axial form factor.
- **State of the art** generators.
- Expected to lead to **further reduction** in uncertainties

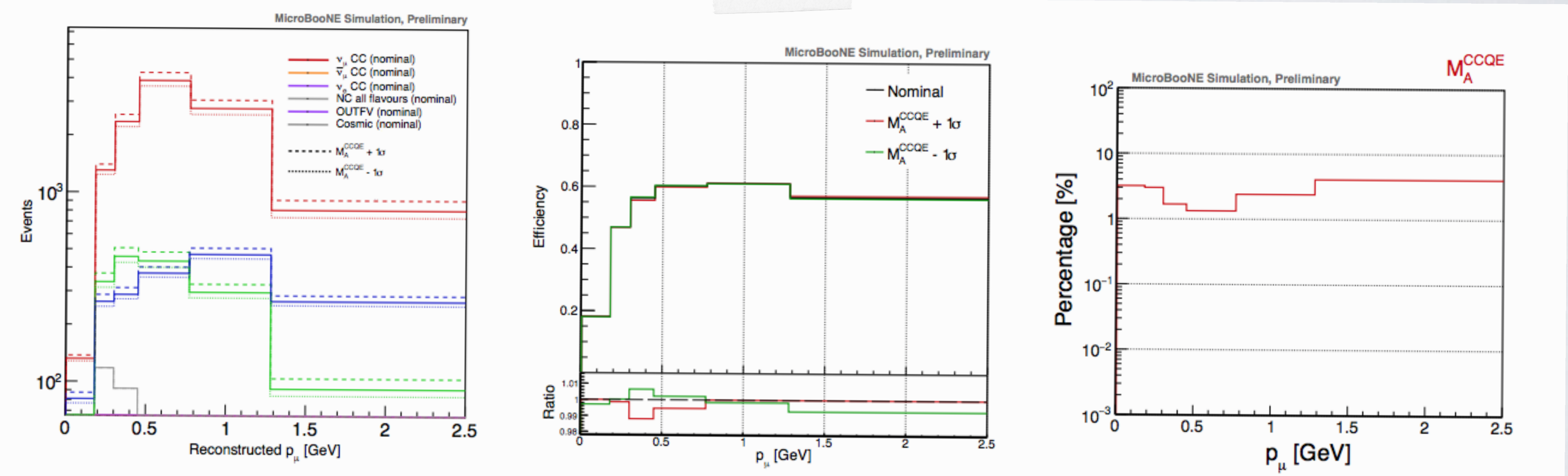
Model Element	G18_10a
Nuclear Model	Local Fermi Gas
Quasi-Elastic (CC)	Nieves
Quasi-Elastic (NC)	Empirical
Meson-exchange Currents	Nieves
Resonant	Berger-Sehgal
Coherent	Berger-Sehgal
FSI	hA2018

Strategy: CORRELATED UNIVERSES SIMULATION via reweighting

2. Cross Section Modelling

- Initial estimates varying parameters within standard 1σ estimates from GENIE manual.
- Developing in addition a re-weighting strategy for **QE (RPA)** and **MEC** based on differences between **GENIE default** and **Valencia QE/MEC** models.
  - Planning on importing **MINERνA/NOνA** RPA/MEC uncertainties treatment in next-generation analyses.

Example of the impact of the variation of M_a^{CCQE} axial mass parameter on ν_μ CC inclusive

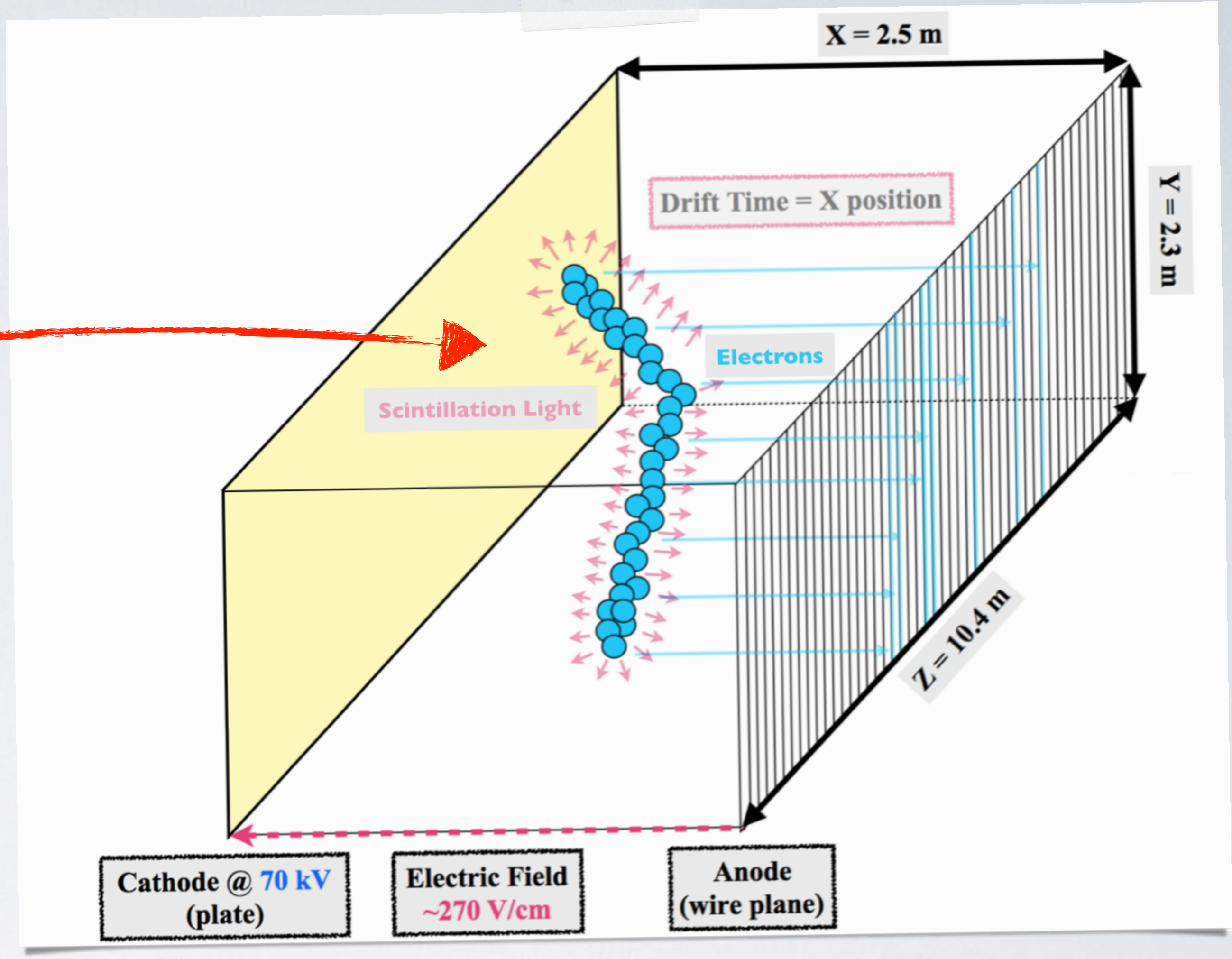


(a) Number of events (b) Selection efficiency (c) Cross section percental difference

- Progress in the implementation of GEANT4 uncertainty on **hadron reinteraction** with bulk Argon.

RPA: Random Phase Approximation (*screening effect due to W polarization leading to cross-section suppression at low q^0*)
MEC: Meson Exchange Current (*interaction with correlated nucleon states populating multi-nucleon final states*)

3. Detector Response



- Two main sub-**categories**:
  A. **Propagation** of scintillation **light** and **electrons** through the detector and towards PMTs and wire plane
  B. **Readout response** from *PMTs* and *wires*

Analysis / Uncertainties	Inclusive	ccPi0
Cross section model uncertainties	3.63%	16%
Flux	11.93%	17%
Detector	18.90%	21%

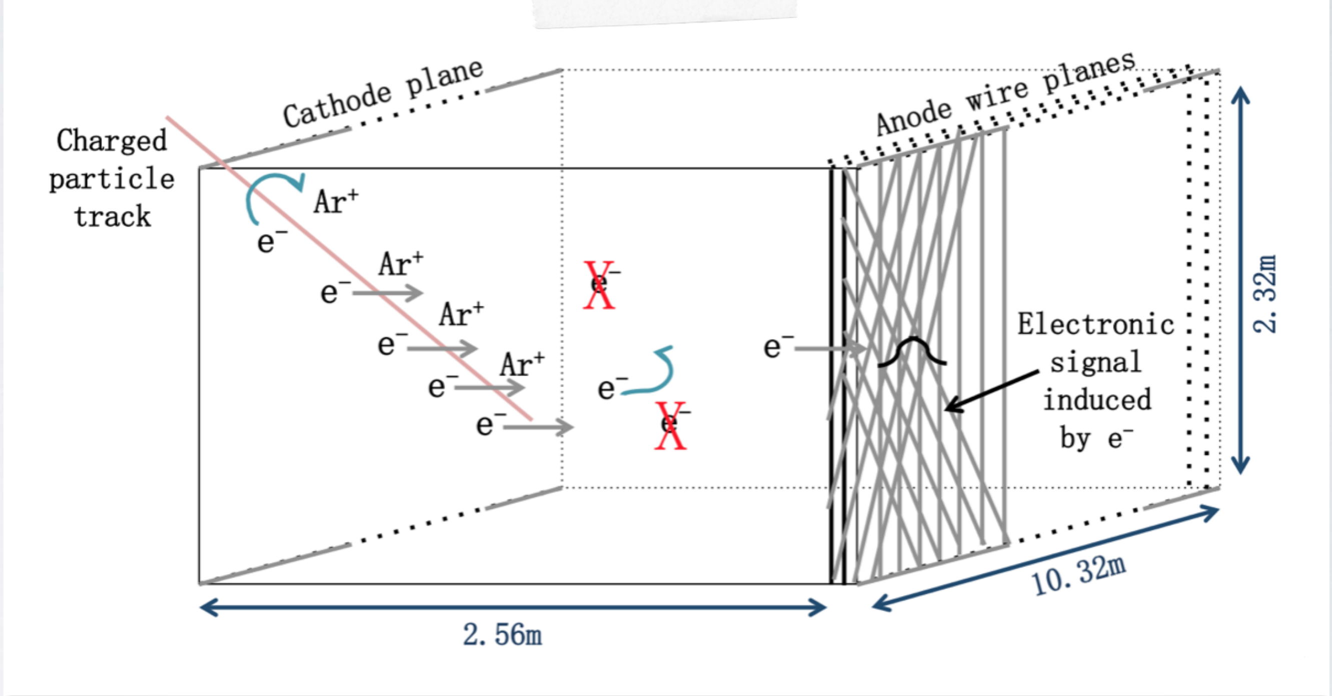
- **Largest contribution** so far to total uncertainty.

Uncertainty strategy: UNCORRELATED UNIVERSES SIMULATION* via whole resimulation

*all data samples use identical generated interactions

3a. Light and Electron Propagation

- Assuming a constant field, when propagating toward the wire plane, ionization electrons go through **multiple effects**.



$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

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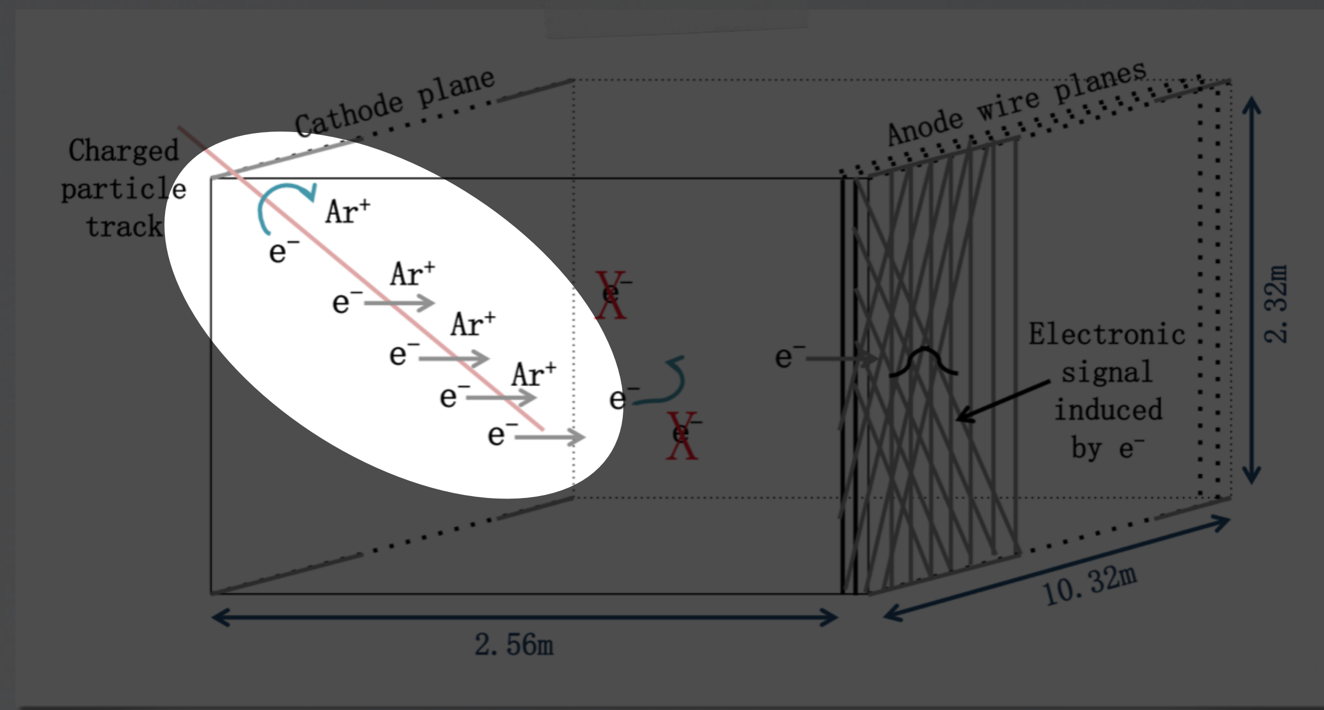

Energy lost by charged particle through ionization

Recombination

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

Energy needed to free an e^-

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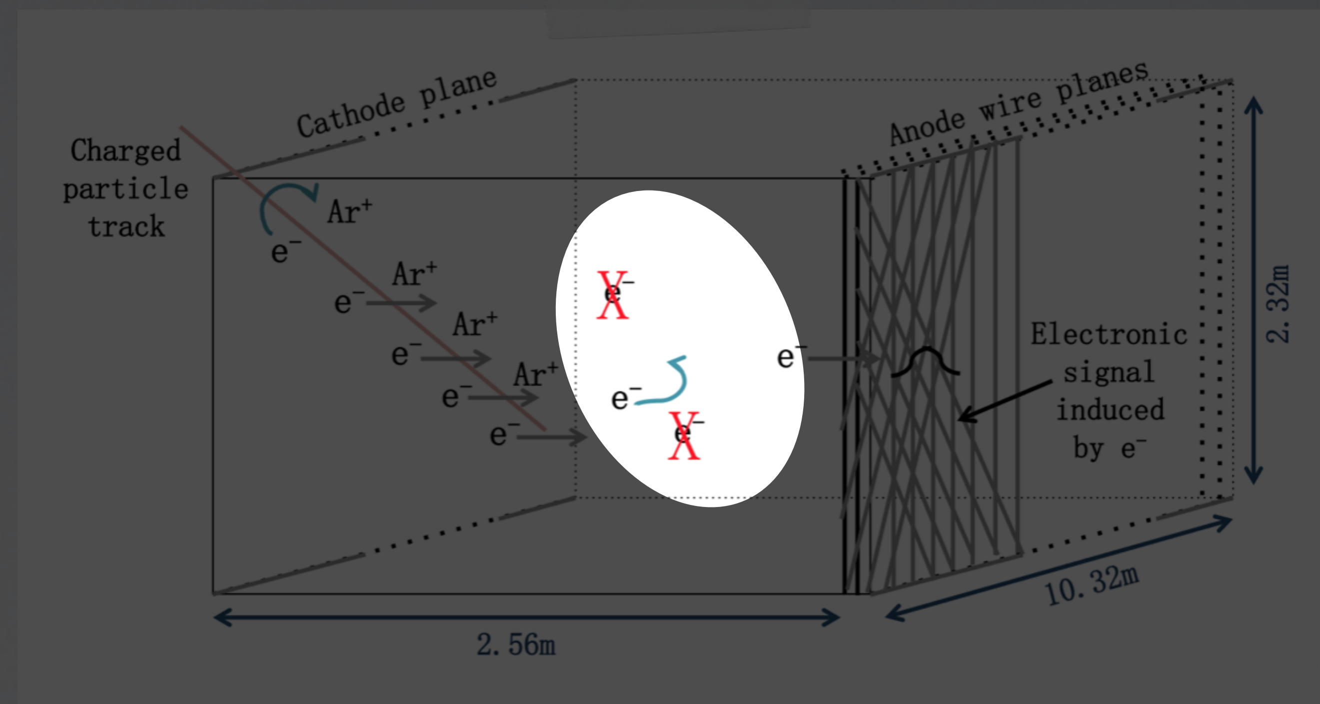


Energy lost by charged particle through ionization

Recombination

Diffusion

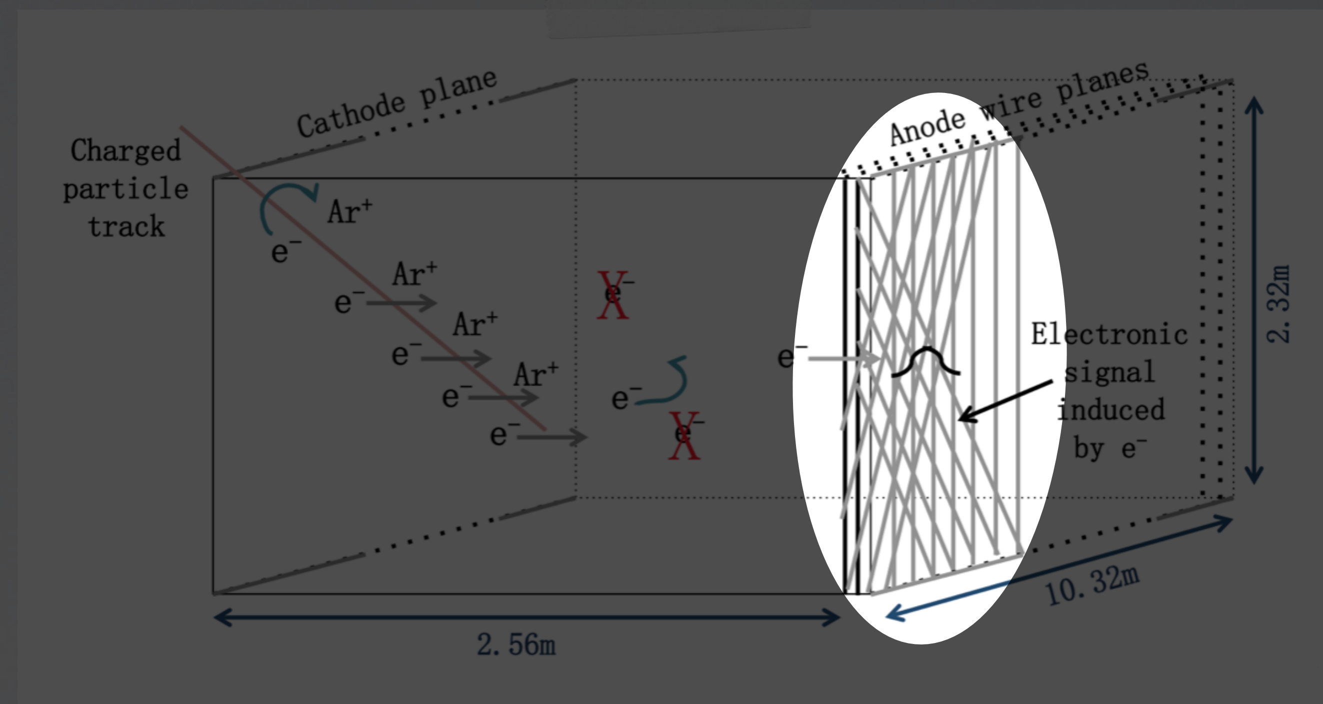
$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

Energy needed to free an e−

Attenuation

3a. Light and Electron Propagation

- Assuming a constant field, when propagating toward the wire plane, ionization electrons go through **multiple effects**.



Energy lost by charged particle through ionization

Recombination

Diffusion

Calibrated signal on the anode

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

Energy needed to free an e⁻

Attenuation

Calibration of electronic signal

3A. Light and Electron Propagation

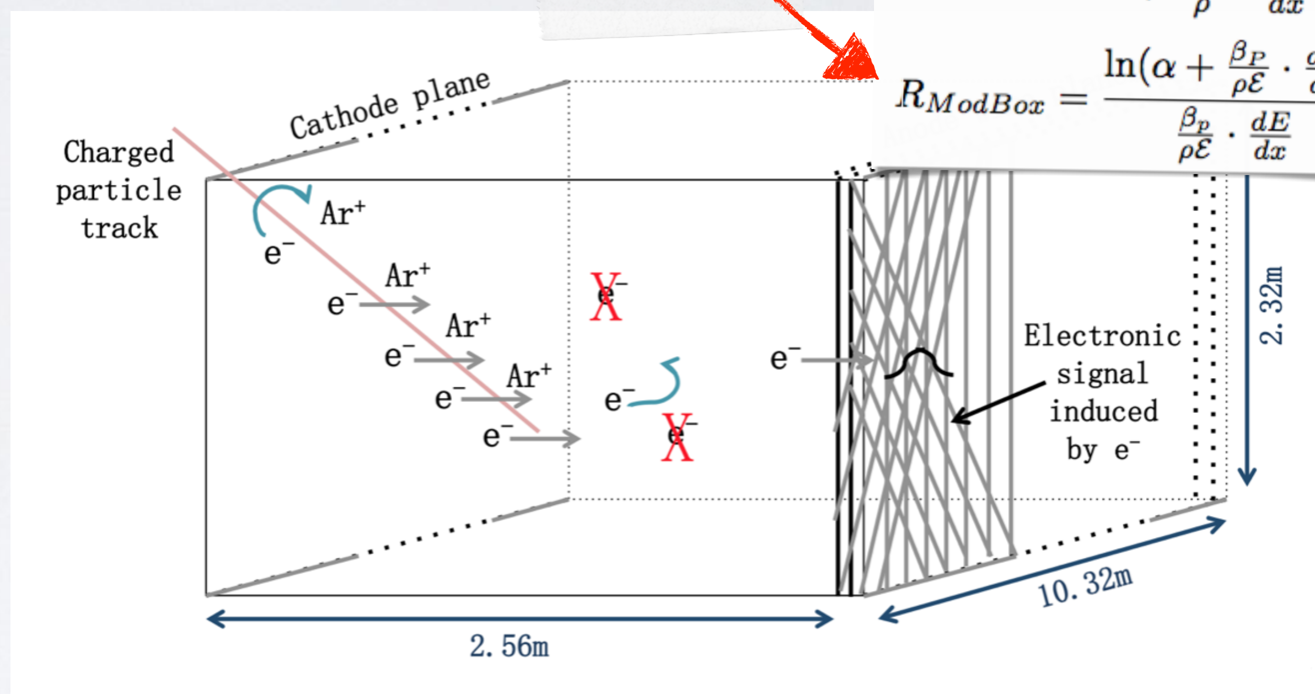
Recombination

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

$$R_{Birk's} = \frac{A_B}{1 + \frac{k_B}{\rho} \cdot \frac{dE}{dx} \cdot \frac{1}{\mathcal{E}}}$$

$$R_{ModBox} = \frac{\ln(\alpha + \frac{\beta_P}{\rho \mathcal{E}} \cdot \frac{dE}{dx})}{\frac{\beta_p}{\rho \mathcal{E}} \cdot \frac{dE}{dx}}$$

- Before transport, the electron can **recombine** with the **Ar^+ ions**.
- Effect depends on **density of Ar^+** and **e^-**.
  - Affected by dE/dX and E-field strength.
- Using
  - Modified **box model** with parameters fit to **ArgoNeuT** data
  - **Birks model** fitted to **ICARUS** data for the systematic variations.



Current implementation:

Using alternative model externally constrained with other argon detectors measurements

Future implementation:

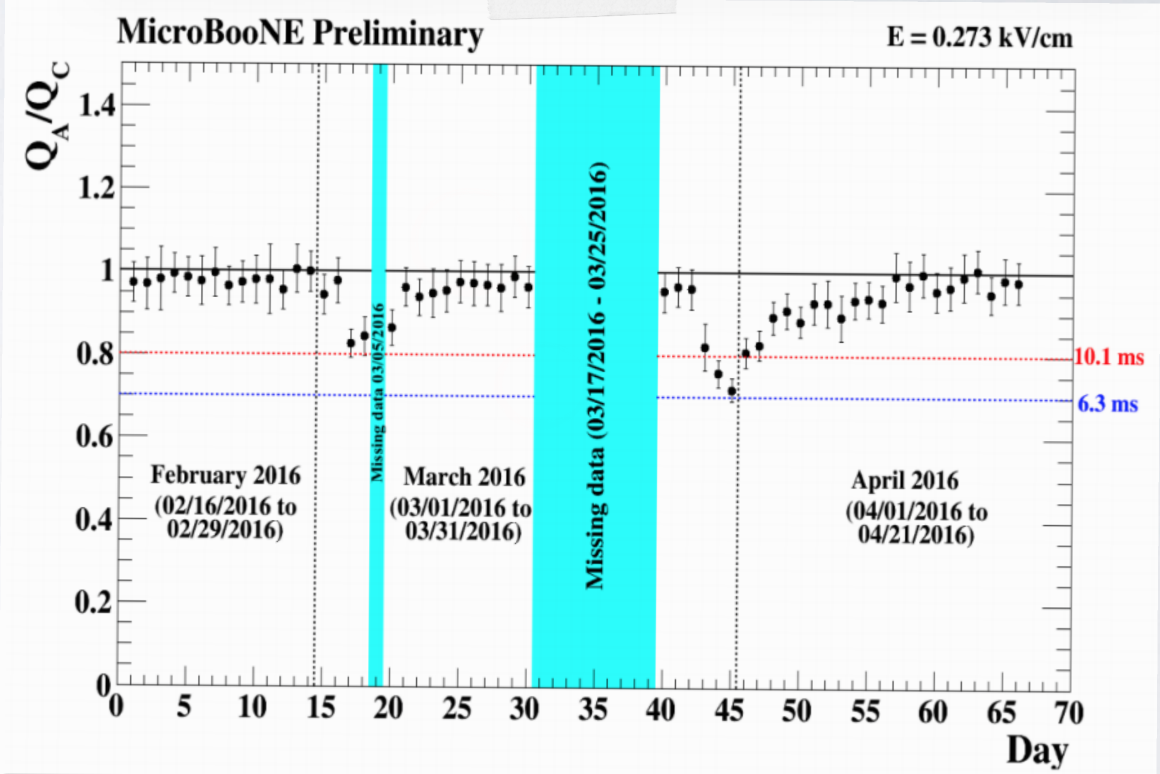
Internal constraints from ongoing MicroBooNE calibration measurements

3a. Light and Electron Propagation

Electron Attenuation

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

MicroBooNE Attenuation measurements Public Note **MICROBOONE-NOTE-1026-PUB**: http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1026-PUB.pdf



- **Contaminants** in the liquid argon, such as **oxygen** and **water** can **capture** the drifting electron.
    - Causing a drift-distance dependent **reduction** of the size of the **signal**.
- Using **electron drift lifetime** to characterize attenuation.
- MicroBooNE design electron lifetime: **3ms**
- We're currently well **above 10ms**.
- Simulating most **extreme value** allowed by run quality selection (10 ms, only ~10% of data at this purity) for systematic variations.

Current implementation:

Infinite lifetime for default

"Extreme case" simulation (10 ms) for uncertainty

Future implementation:

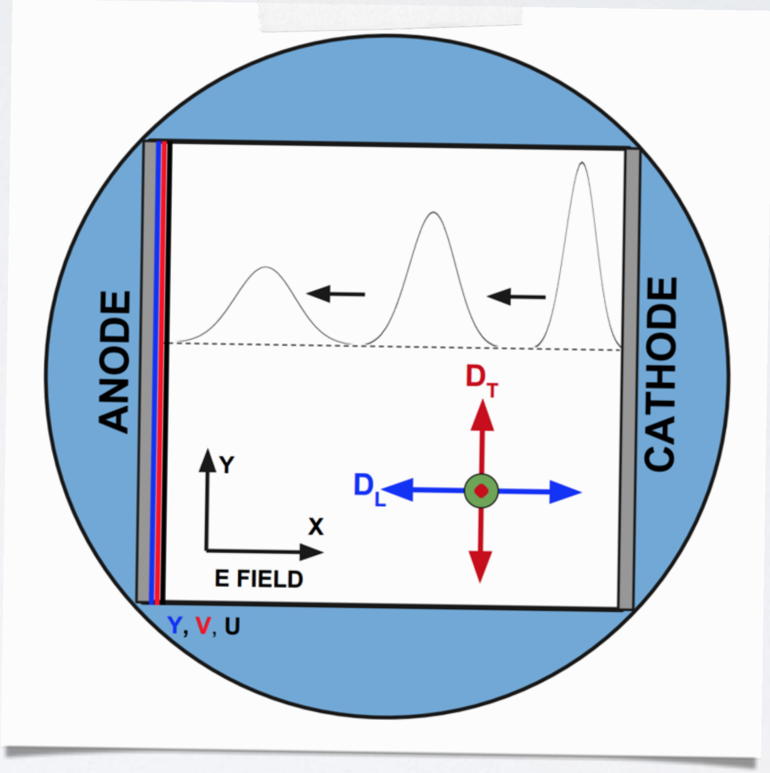
- Ongoing MicroBooNE calibration measurements to disentangle it from other effects.

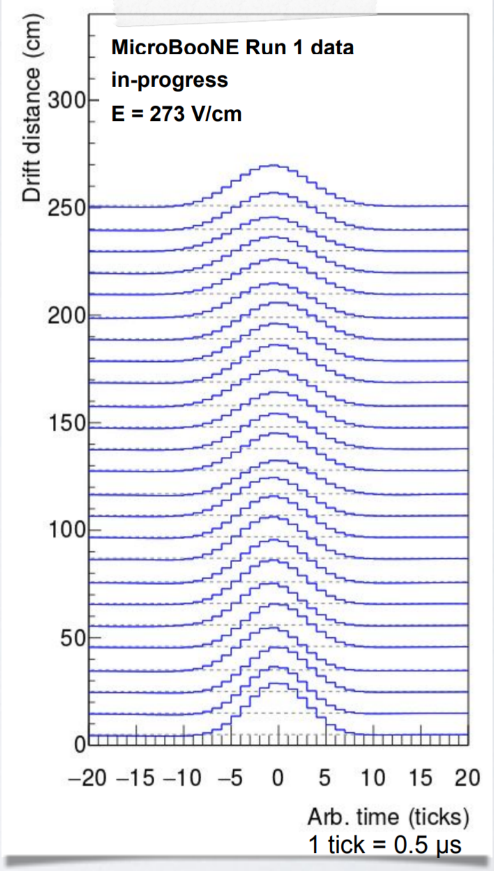
3A. Light and Electron Propagation

Longitudinal & Transverse Diffusion

$$\frac{dE}{dX} \times \frac{1}{W} \times R \times L \times D \times C = \frac{dQ}{dX}$$

- Ionisation electrons travel due to electric field.
- During transport, the **shape** of the electron cloud is **smeared**.
  - Depending on **distance** to wire plane.
  - Separated in:
    - **Longitudinal** component *(parallel to travel direction)*
    - **Transverse** component *(perpendicular to travel direction)*





Current implementation: 1σ

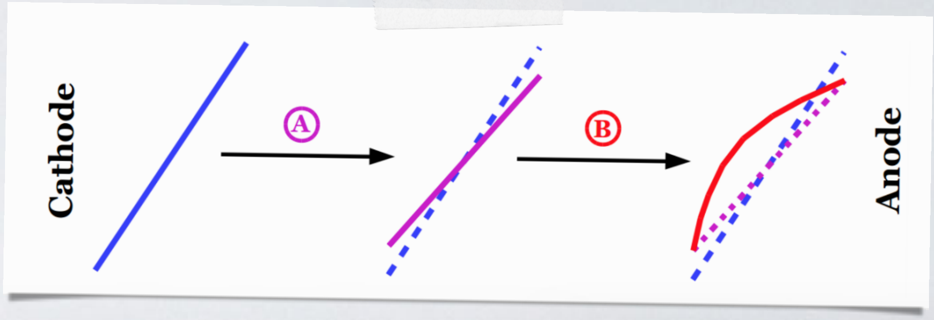
- External constraints on argon for L
- T less studied in literature, using external measurements and theoretical extrapolation to MicroBooNE field strength

Possible future implementation:

- Internal constraints from ongoing MicroBooNE calibration measurements
- ^{39}Ar to disentangle L/T components

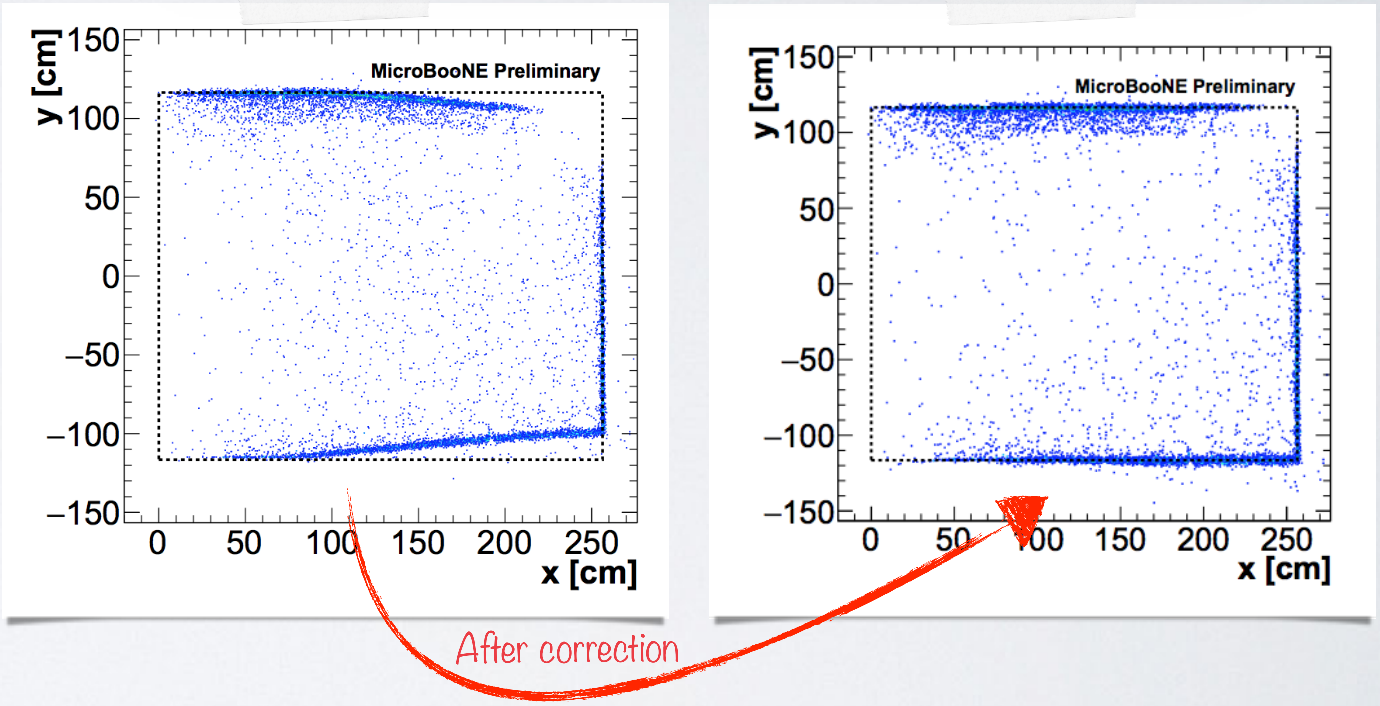
3A. LIGHT AND ELECTRON PROPAGATION

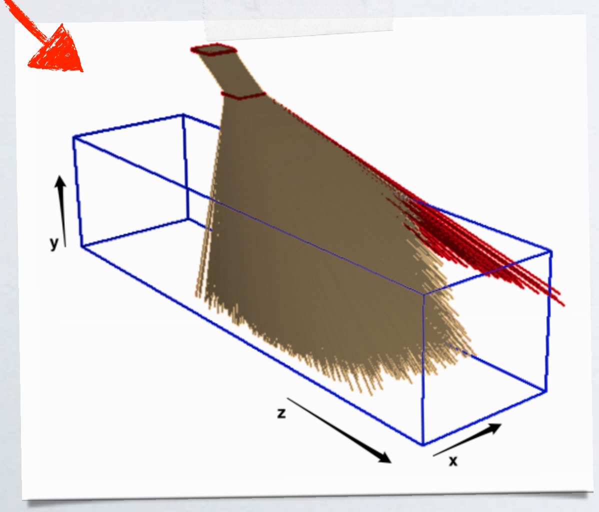
SPACE CHARGE



MicroBooNE Space-Charge Effects Public Note **MICROBOONE-NOTE-1018-PUB**: http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1018-PUB.pdf

- Positive ions drift **105 times** slower than e⁻ in LAr
- **Build-up of** Ar⁺ **ions** in steady-state configuration due to ionization **from cosmic rays** (3kHz).
- Leads to a **distortion of the electric field** within the detector.
  - **Displacement** in the reconstructed position of signal ionization electrons in LArTPC detectors (spatial distortion)
  - Variation in E-field strength (calorimetry distortion)
- Using a **data-driven correction** determined with **through-going cosmic muons** measured with an **external muon telescope** (MuCS).
- We built a map of **electric field** and obtain variations accordingly





Current implementation:

MicroBooNE data-driven calibration

Calibration varied by 70% for systematic treatment

Possible future implementation:

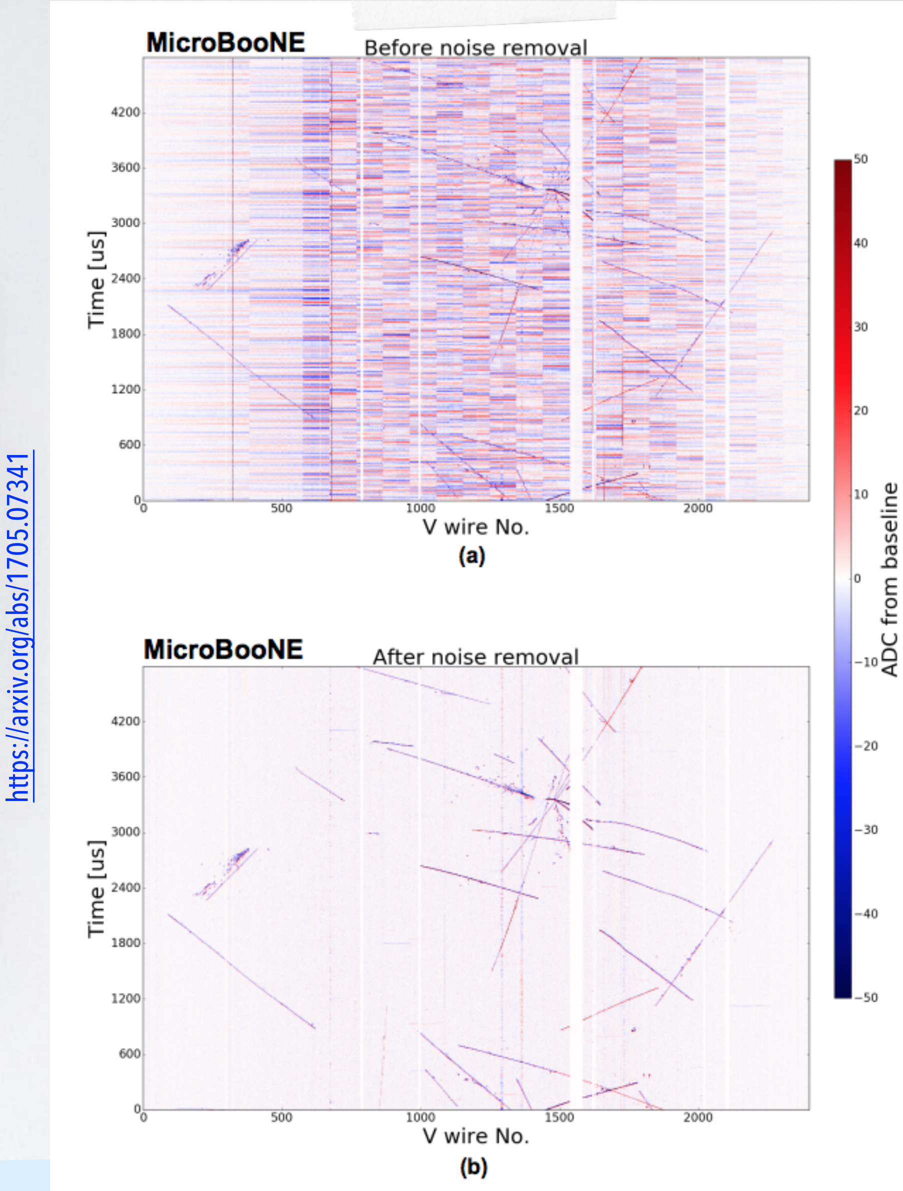
Improving mapping by combining laser induced tracks + cosmic measurement

3b. Readout Response

Noise, Response Function and Saturated/Misconfigured Channels

- Using MicroBooNE measured **noise spectrum in data**.
- Determined list of channels associated with:
  - Cold ASICs circuits that have a **different gain** and **shaping time** than desired. (*misconfigured channels*).
  - Prone to have cold **ASIC's circuits saturated** as charge builds up on capacitors due to wire motion. (*saturated channels*)
- Determined uncertainty on **response functions** from MicroBooNE data via *narrower/ wider* response function motivated by data measurements.

MicroBooNE noise characterization and filtering **arXiv:1705.07341**
https://arxiv.org/abs/1705.07341



Current implementation:

- "Extreme case" simulation for saturated/ misconfigured channels, turning off channel list.
- 1σ constrained by MicroBooNE data measurements for PMT/Wire noise and response functions.

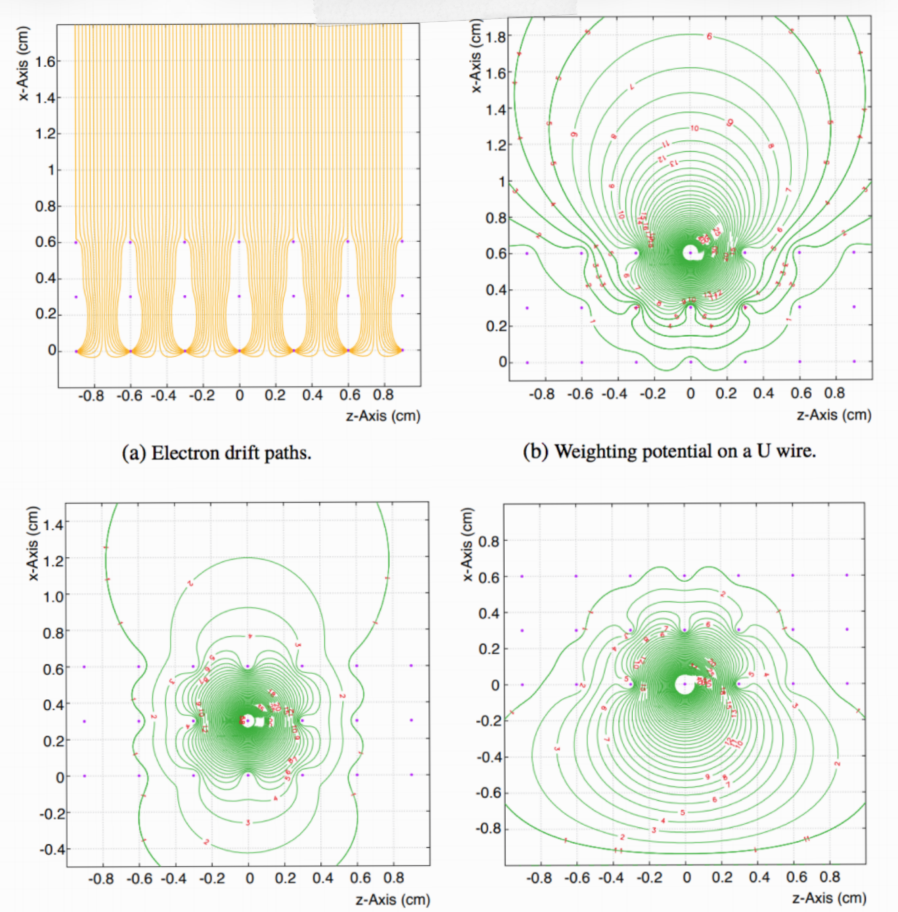
Future implementation:

- Ongoing MicroBooNE calibration measurements to improve constraints and capture an overall uncertainty
- Use of background data cosmics instead of CORSIKA simulated samples in next-generation analyses, is expected to reduce the impact of these uncertainties

3B. Readout Response

Dynamic Induced Charge

- **Electrons** collected by wire **induce charge** also on **neighbouring wires.**
- Effect **observed in data**, but not currently modelled in default simulation.
    - Effect strongest for **tracks** travelling **towards the wire plane**.
- Simulation of dynamic induced charge (DIC) **improves data/MC agreement**.
- Determining the impact of switching DIC on/off and use as exaggerated effect for systematic variation.
- So far **largest contributor** to systematic uncertainty.



(a) Electron drift paths. (b) Weighting potential on a U wire. (c) Weighting potential on a V wire. (d) Weighting potential on a Y wire.

First LArTPC experiment to take this effect into account

MicroBooNE Signal processing:
arXiv:1802.08709
arXiv:1804.02583
https://arxiv.org/abs/1802.08709
https://arxiv.org/abs/1804.02583

	ν_μ CC incl.	ν_μ CC π^0
Total systematic uncertainty	25%	31%
Detector response uncertainty	19%	21%
Dynamic induced charge uncertainty	15%	≈15%

Current implementation:

Updated vs. current simulation

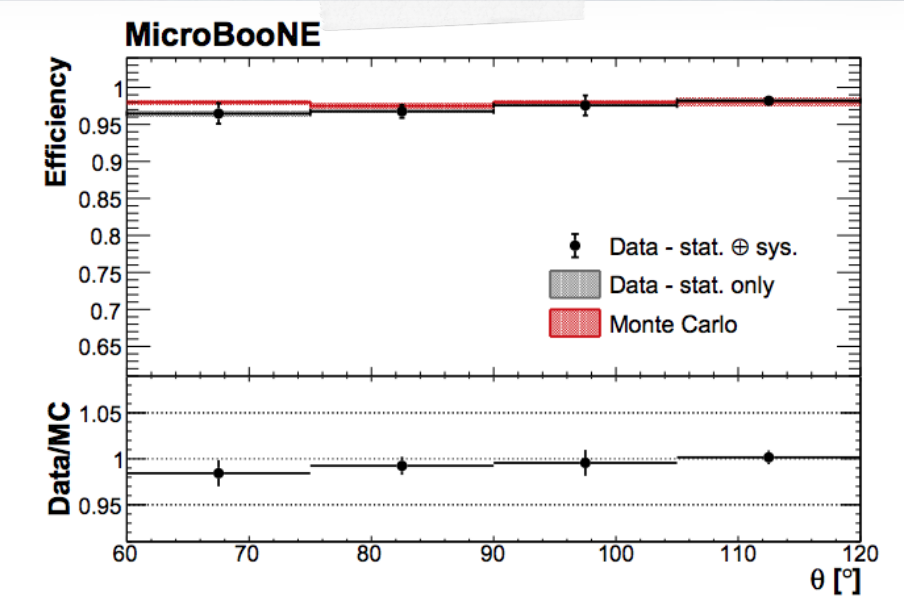
Future implementation:

New simulation and reconstruction handling dynamic induced charge effects becomes default

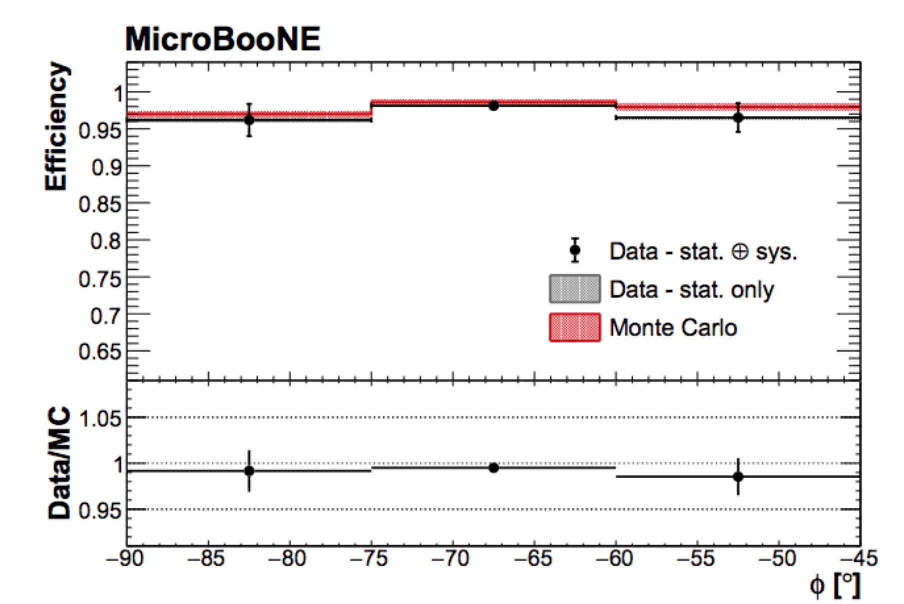
4. Reconstruction

Data-Driven Reconstruction Efficiencies

MicroBooNE reconstruction performance studies **MICROBOONE-NOTE-1049-PUB:** http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1049-PUB.pdf

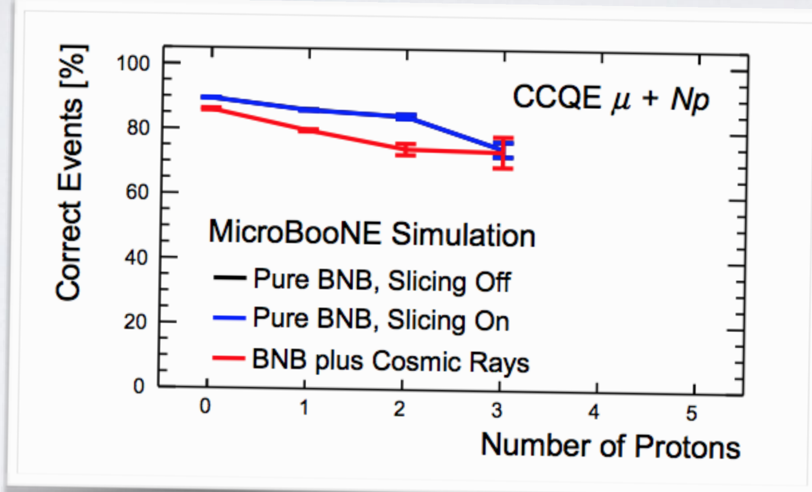


(a) θ

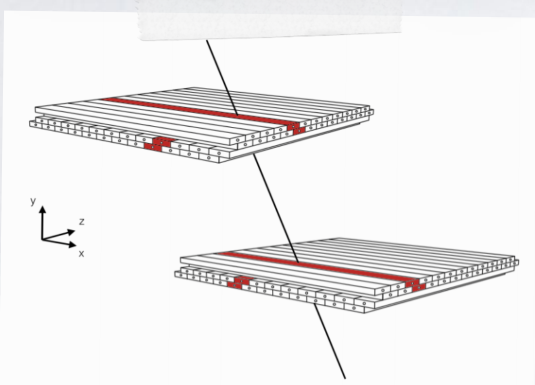


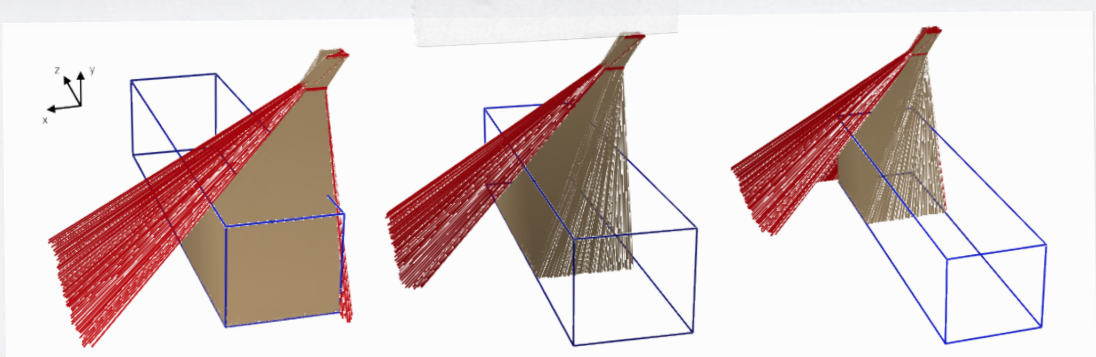
MicroBooNE Pandora approach to pattern recognition
Eur. Phys. J. C78 (2018) no.1, 82: https://arxiv.org/abs/1708.03135

- Using **Pandora** pattern recognition toolkit including multiple algorithms
- Good **reconstruction efficiency** in the presence of cosmics.



- Using an external movable **cosmic-ray telescope** to measure **data-driven efficiency** of **track reconstruction** algorithm with cosmics.





(a) Upstream (b) Center (c) Downstream

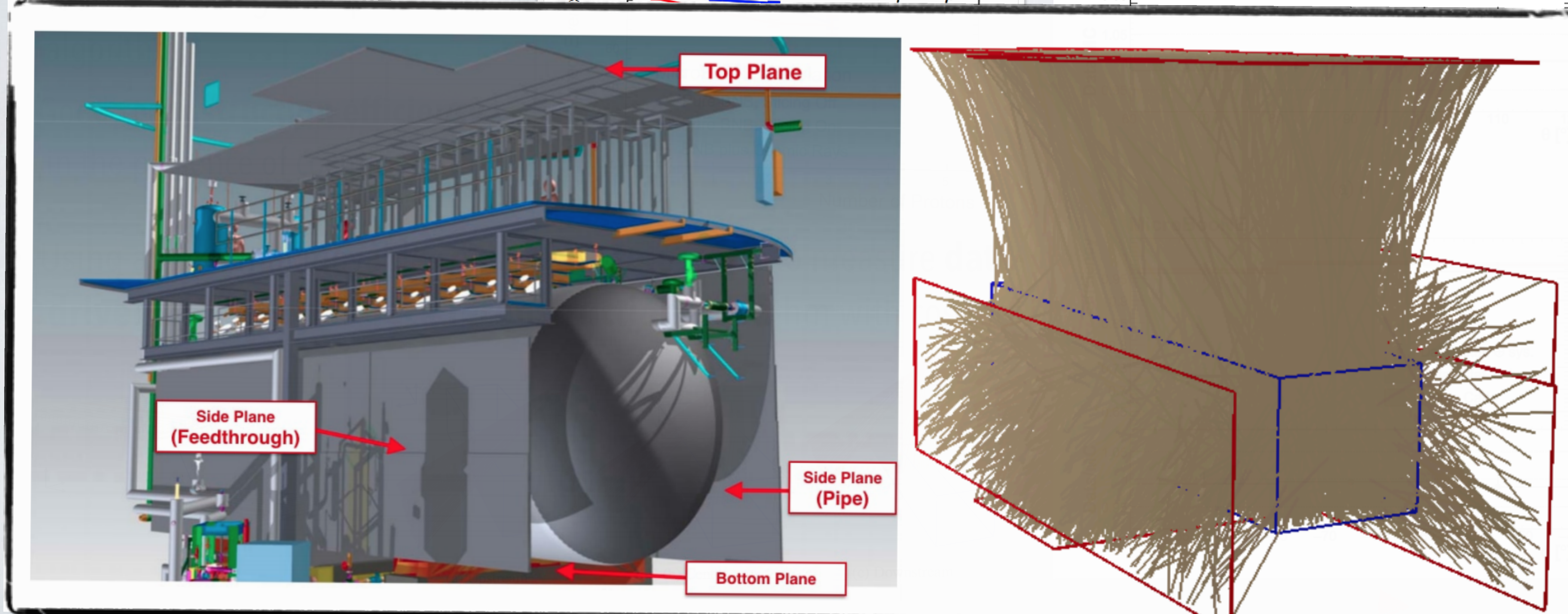
- Overall **high reconstruction** efficiency: (97.1 ± 0.1 (stat) ± 1.4 (sys)) %
- Measured reconstruction efficiency from **data agrees with the predicted efficiency** in the simulation
    - **Confirmation** of our **simulation** and **reconstruction** chain.

COSMIC RAY TAGGER

85% through-going muon coverage

OONE-NOTE-1049-PUB:
ONE-NOTE-1049-PUB.pdf

- Using
  toolkit including multiple



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- Measured reconstruction efficiency from **data agrees with the predicted efficiency** in the simulation
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The Path Forward

- MicroBooNE is the first stage LArTPC **exposed by high intensity neutrino beam**:
    - **Large statistics**, allowing us to measure **ν-Ar cross-sections precisely**.
- First LArTPC on **surface**.
    - **Many cosmic rays**, measurements more challenging.
    - But also useful tools to **calibrate** and **understand** our TPC

- **Many other analyses** currently in progress:
    - Neutral-Current elastic scattering, charged-current 0π, 1μ+1p channel
    - Charged pion production, CC and NC neutral pion production, Coherent pion production
    - Kaon production
    - Exotic physics: Heavy Sterile Neutrinos & SuperNova ν
- Many **calibration analyses** are maturing.
    - Allowing us to set better **data-driven constraints** on our **systematics**.
    - Getting ready for the **next generation of analysis**.

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  -
  -
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Thank you for your attention

Backup

3. Detector Response

	Uncertainty source	Present implementation
Electron-Light propagation	Space charge	Modified MicroBooNE model
	Longitudinal/Transverse diffusion	1σ (external constraints)
	Recombination	Alternative external models
	Electron attenuation	"Extreme case" simulation
	Outside-TPC light visibility	Conservative estimate
	Light production yield	Updated vs. current simulation
Readout response	Dynamic Induced Charge	Updated vs. current simulation
	Saturating channels	"Extreme case" simulation
	Misconfigured channels	"Extreme case" simulation
	Wire response function	1σ (internal constraints from data)
	Wire noise	1σ (internal constraints from data)
	PMT PE noise	1σ (internal constraints from data)

Space charge through Outside-TPC light visibility: Ongoing MicroBooNE calibration measurements will constraint these uncertainties further

Light production yield and Dynamic Induced Charge: New simulation becomes default simulation

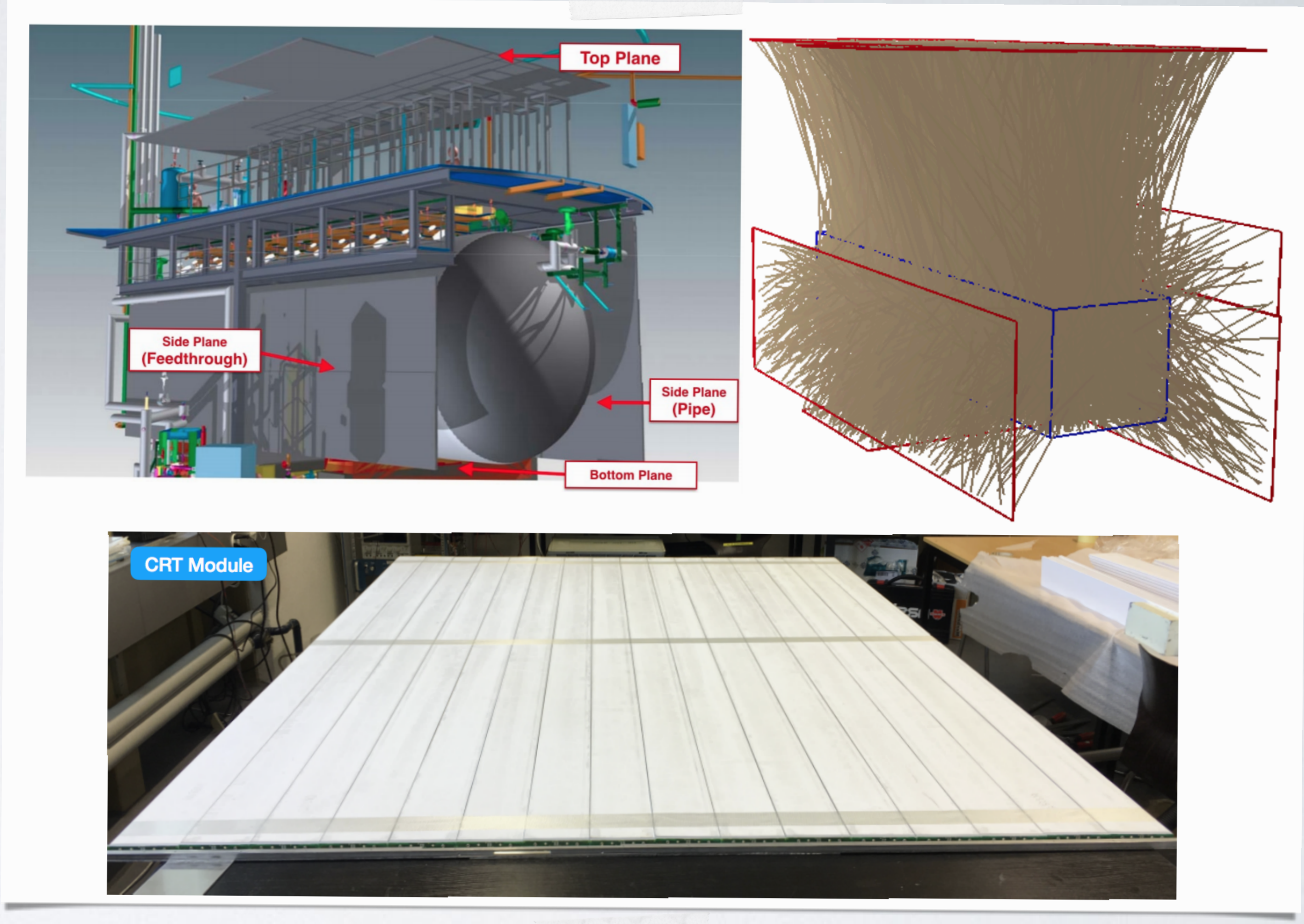
Saturating channels and Misconfigured channels: Ongoing work on more realistic treatment

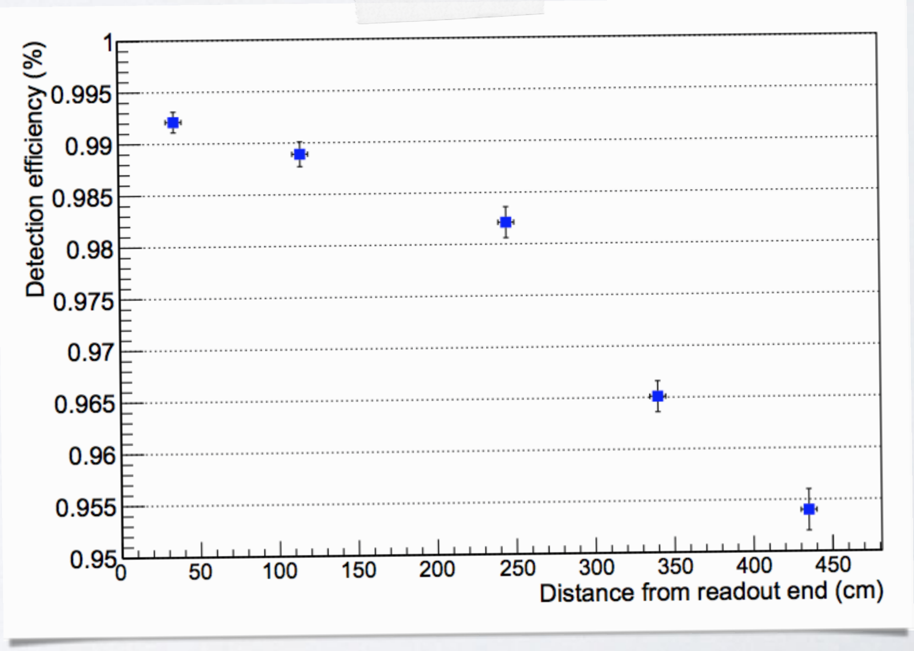
Wire response function, Wire noise and PMT PE noise: Improvement in noise filtering and signal processing and using cosmic data as background (overlay) expected to reduce impacts of these effects

4. Reconstruction

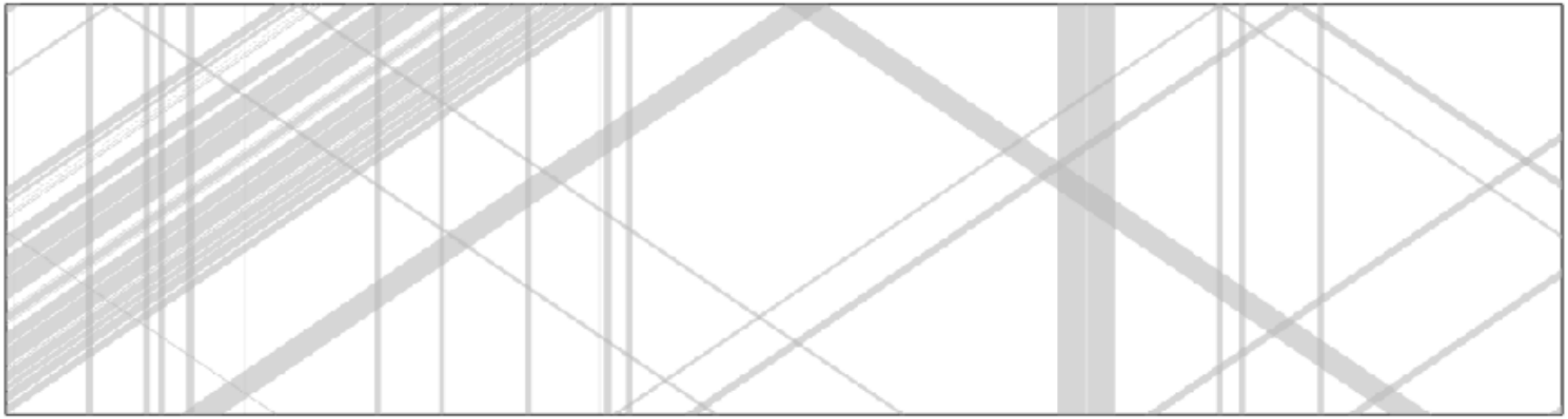
Data-Driven Reconstruction Efficiencies

- The cosmic-ray telescope has been replace by a **novel Cosmic Ray Tagger** (CRT) system.
- Based on **plastic scintillator modules** and **SiPMs readout**.
- **85% coverage** for through-going muons and **excellent detection efficiency**.
- Will allow to **expand** on the **reconstruction studies** and improve on them.





MicroBooNE Cosmic Ray Tagger
Instruments 1, no. 1 (2017): 2: https://arxiv.org/abs/1612.04614

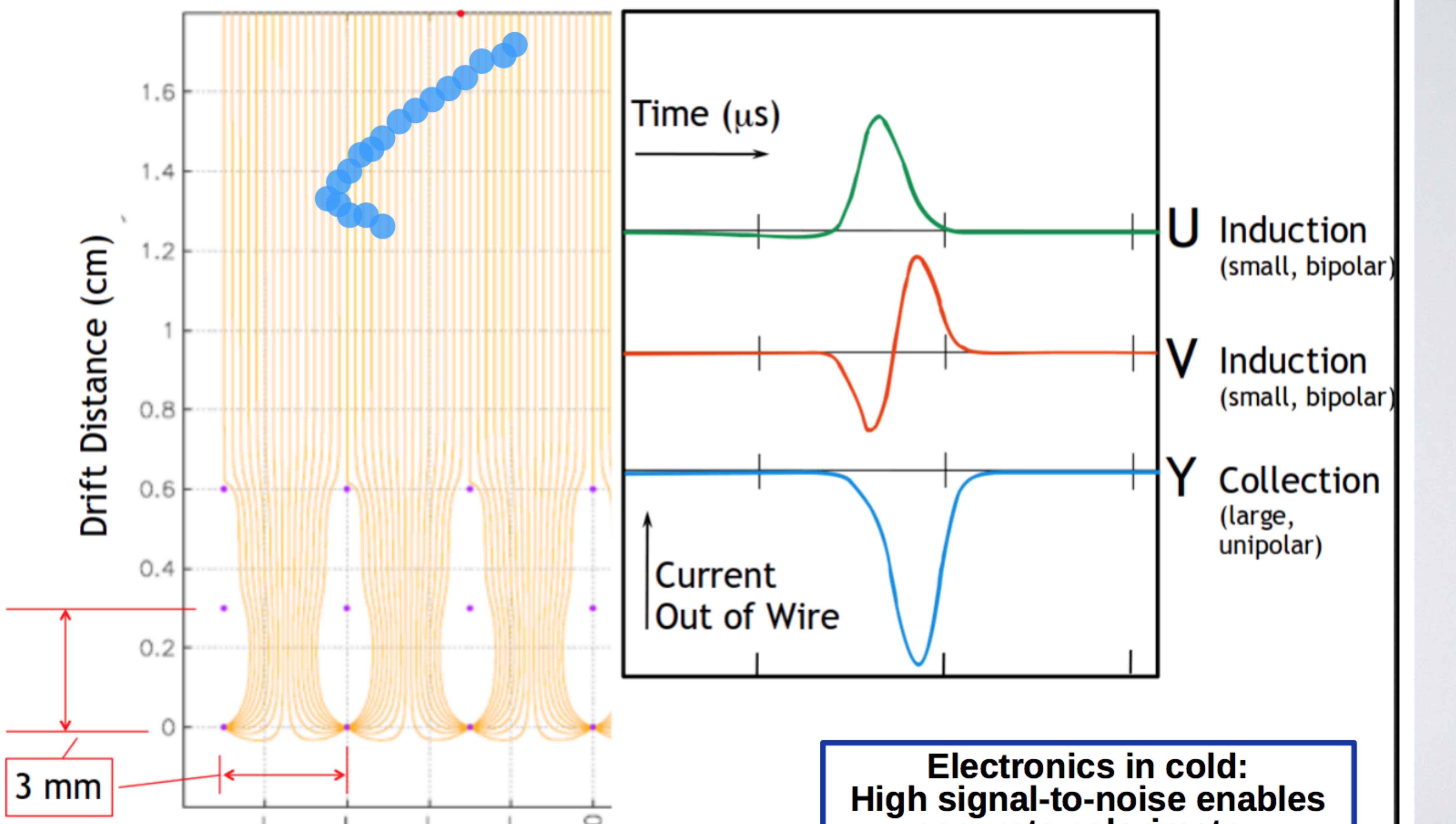


All unresponsive wires on all three planes (~10%)

All unresponsive wires with no redundancy (~3%)

Bo Yu (BNL)

Charge Signal Formation



Electronics in cold:
High signal-to-noise enables accurate calorimetry.

CPM Uncertainties

- GENIE (short-track)

Observed multiplicity	$\frac{\Delta P_n}{P_n}$ Default	$\frac{\Delta P_n}{P_n}$ MEC	$\frac{\Delta P_n}{P_n}$ TEM
1	+7%	+7%	+8%
2	−11%	−12%	−12%
3	−25%	−25%	−25%
4	−33%	−36%	−39%
5	−44%	−48%	–

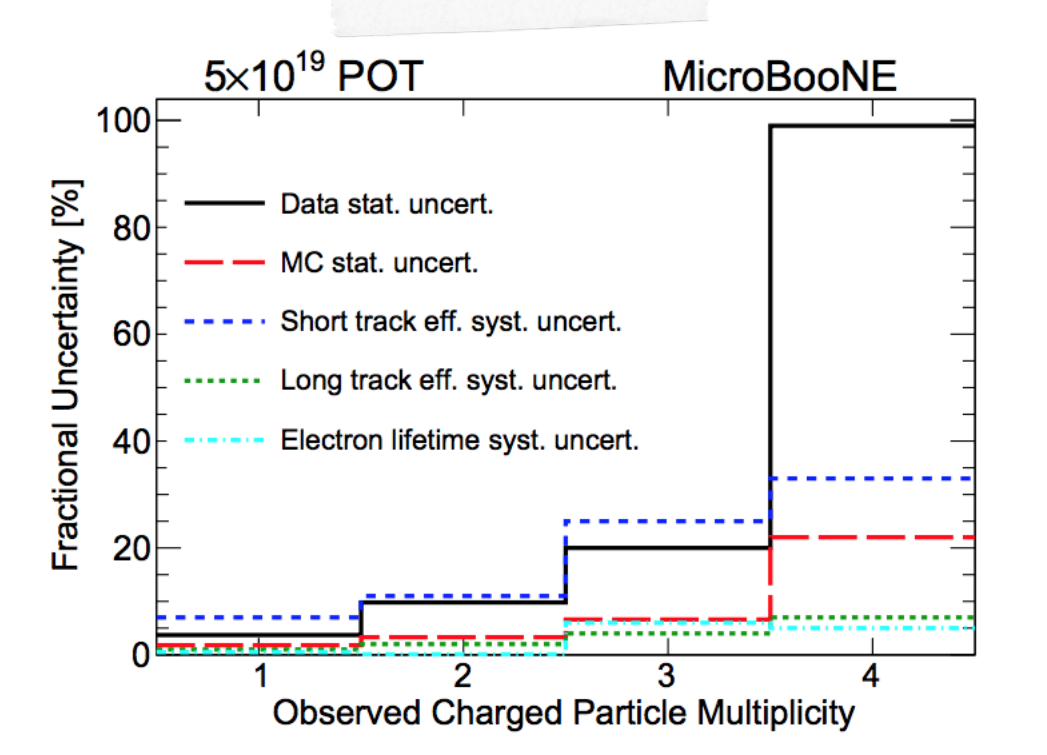
- GENIE (long-track)

Observed multiplicity	$\frac{\Delta P_n}{P_n}$ Default	$\frac{\Delta P_n}{P_n}$ MEC	$\frac{\Delta P_n}{P_n}$ TEM
1	−1%	−1%	−1%
2	+2%	+2%	+2%
3	+4%	+4%	+2%
4	+7%	+7%	+7%
5	+9%	+9%	–

- Total

	Uncertainty Estimates			
Uncertainty Sources	mult=1	mult=2	mult=3	mult=4
Data statistics	4%	10%	20%	99%
MC statistics	2%	3%	7%	22%
Short track efficiency	7%	11%	25%	33%
Long track efficiency	1%	2%	4%	7%
Background model systematics	2%	2%	0%	0%
Flux shape systematics	0%	0.4%	0.2%	0.5%
Electron lifetime systematics	0.5%	0.1%	6%	5%

- Total (histogram)



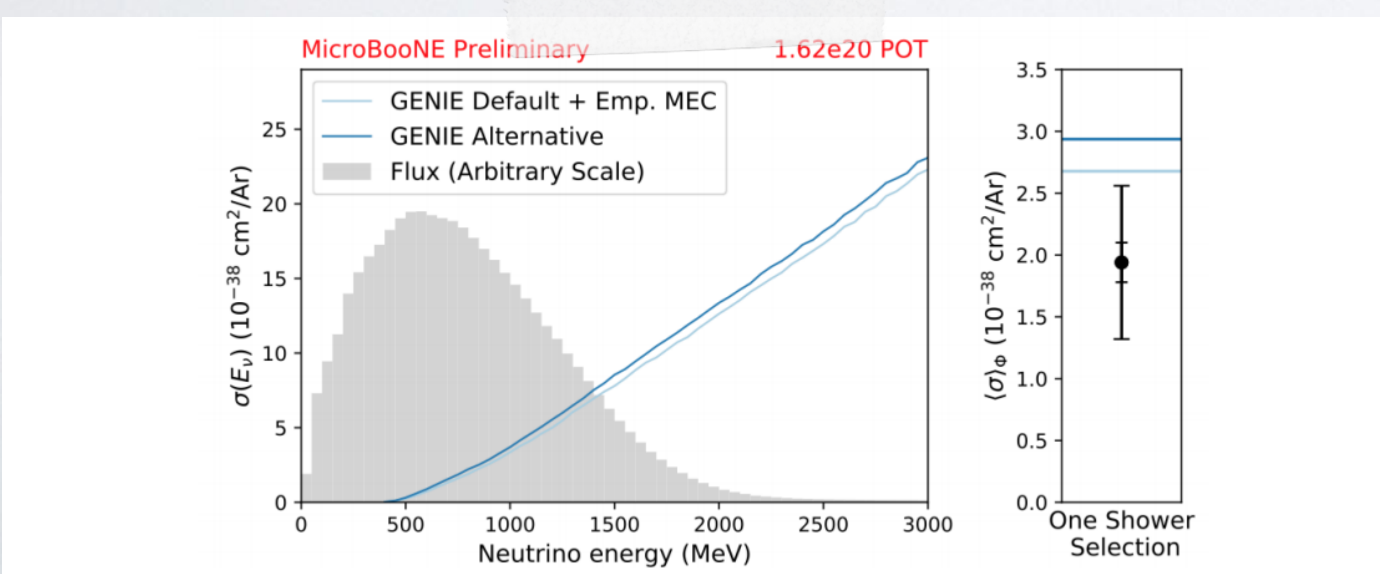
CC π^0 Uncertainties

- Flux
- Cross-sections
- Detector

Variation	1σ Uncertainty
p+Be→ π^+	11.5%
Beamline	10.2%
p+Be→ K^+	1.4%
p+Be→ K^-	0.4%
p+Be→ K^0	0.4%
p+Be→ π^-	0.3%
Total Uncertainty	15.5%

Variation	1σ Uncertainty
Cross Section Parameterization	11.5%
Final State Interactions	10.2%
Hadronization	1.4%
Deep Inelastic Scattering	0.0%
Total Uncertainty	17.2%

Variation	1σ Uncertainty
Micro-physics	12.9%
Detector Response	12.5%
Cosmic Simulation	11.0%
Total Uncertainty	21.1%



CC Inclusive Uncertainties

- Flux

Parameter	Description	Total Cross Section Relative Uncertainty
Non-Hadron	Non-Hadron	5.34%
K^- Production	K^- production cross section	0.50%
K^+ Production	K^+ production cross section	0.55%
K^0 Production	K^0 production cross section	0.51%
π^- Production	π^- production cross section	0.73%
π^+ Production	π^+ production cross section	9.69%
Total	Combined uncertainty	11.93%

- Total (+ cross-section)

Error Source	Method	Estimated Relative Uncertainty
Beam Flux	Estimated with multisim variations	12%
Cross Section Modeling	Estimated with multisim variations	4%
Detector Response	Estimated with unisim variations	19%
POT Counting	Toroids Resolution	2%
Cosmics (in-time)	Estimated from data-driven cosmic model	7%
Cosmics (out-of-time)	Estimated from off-beam statistics	1%
Beam Timing Jitter	Estimated from on- minus off-beam flashes	4%

- Detector

Detector Systematic Sample	Description	Type	Total Cross Section Relative Uncertainty [%]
Space Charge	A simple data-driven calibration is applied to the space charge simulation to make it better match measured space charge effects [29].	Modified Model	2.7
Induced Charge	Charge induction is simulated on a longer spatial range than in the default MC, so that more distant wires see the effect of drifting charge.	Alternate Model	15
Light Yield	An improved light production simulation model is used.	Alternate Model	3.7
Remove Channels Prone to Saturating	Turning off channels that frequently become saturated as charge builds up on capacitors in the ASIC circuits, resulting in deadtime.	Alternate Model	2.1
Remove Misconfigured Channels	Turning off the misconfigured channels associated with ASICs that have a different gain and shaping time than desired	Modified Model	2.1
Wire Response Function	The wire response functions used during deconvolution are stretched by 20% based on MicroBooNE data.	$\pm 1\sigma$	1.4
Longitudinal Diffusion	The amplitude of longitudinal diffusion is varied based on world data [32, 33].	$\pm 1\sigma$	1.4
Transverse Diffusion	The amplitude of transverse diffusion is varied based on world data [34, 35, 36].	$\pm 1\sigma$	2.1
Wire Noise	The amplitude of the wire noise model varied.	$\pm 1\sigma$	6.4
PE Noise	The single-PE noise of the PMTs is varied.	$\pm 1\sigma$	2.1
TPC Visibility	The light yield in the cryostat but outside the TPC is increased by 50%.	Alternate Model	4.3
Lifetime	The electron lifetime is reduced to 10 ms. (This condition affects only about ~10% of data taken with lower purity).	Alternate Model	1.2
Recombination	The Birks recombination model, with parameters derived from ICARUS, is used instead of the default modified box model, with parameters derived from Argoneut.	Alternate Model	1.3
Total combined relative uncertainty			18.7