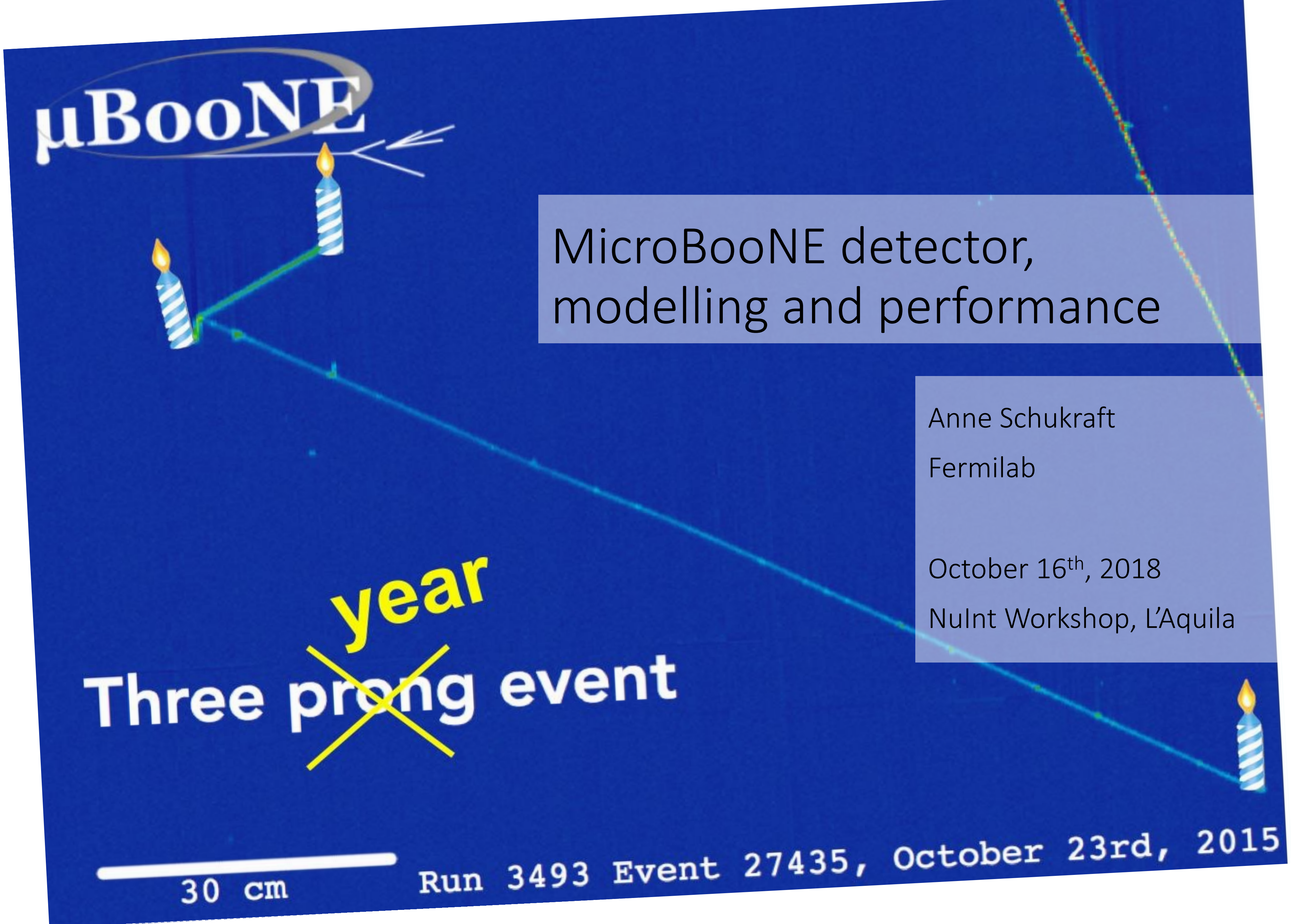
MicroBooNE detector, modelling and performance

Anne Schukraft

Fermilab

October 16th, 2018

NuInt Workshop, L'Aquila

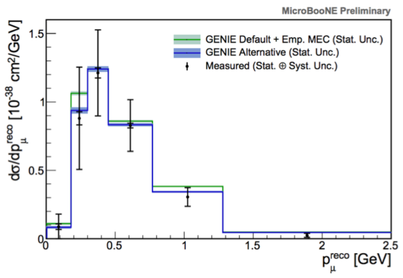


Outline

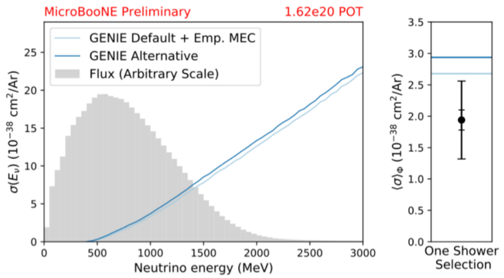
This talk will introduce the MicroBooNE experiment and discuss tools and approaches common to all cross section analyses presented today:

- Experiment introduction
- Data samples
- Cosmic rejection
- Reconstruction performance
- Systematics evaluation

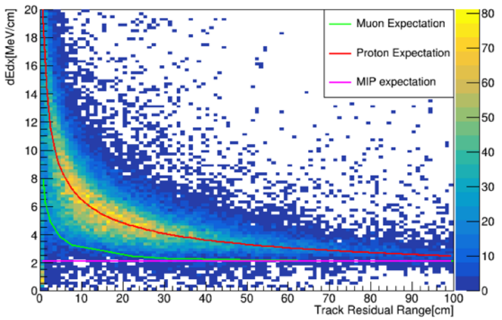
MicroBooNE analyses presented at NuInt2018:



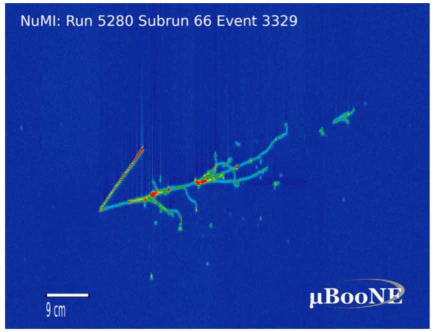
ν_μ CC inclusive
Marco Del Tutto



CC π^0
Joel Mousseau



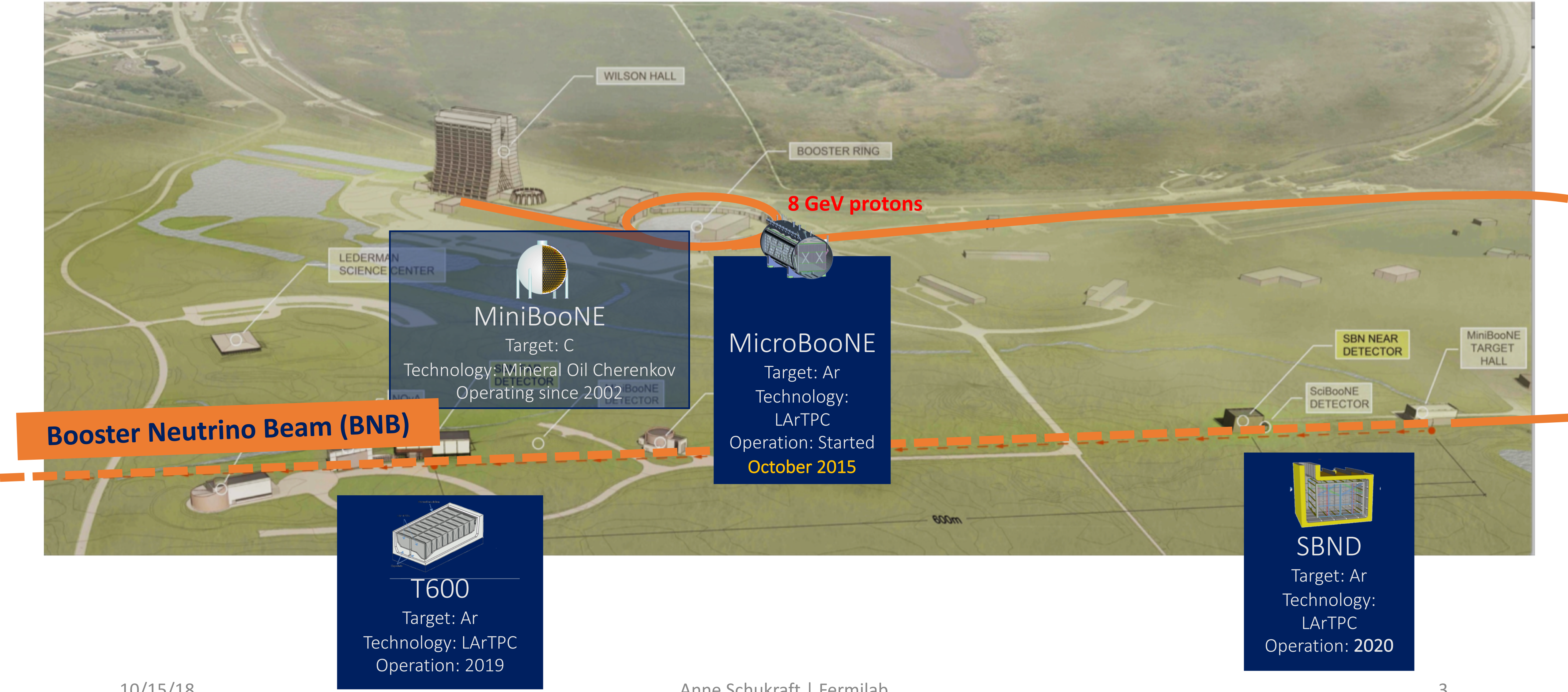
CC 1μ Np & CC 1μ 2p
Raquel Castillo Fernandez



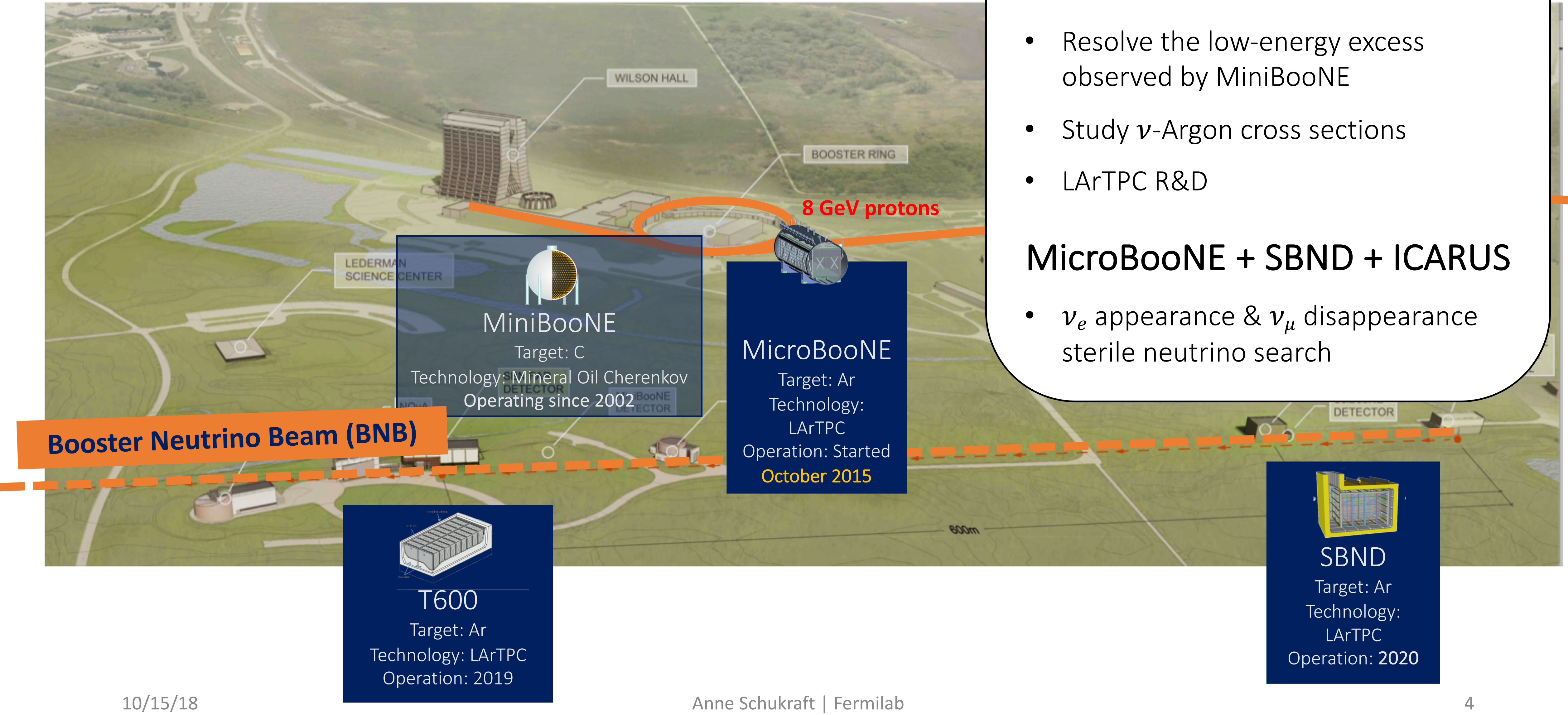
ν_e CC (NuMI)
Colton Hill

The MicroBooNE experiment

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



The MicroBooNE experiment



Science goals

MicroBooNE

- Resolve the low-energy excess observed by MiniBooNE
- Study ν-Argon cross sections
- LArTPC R&D

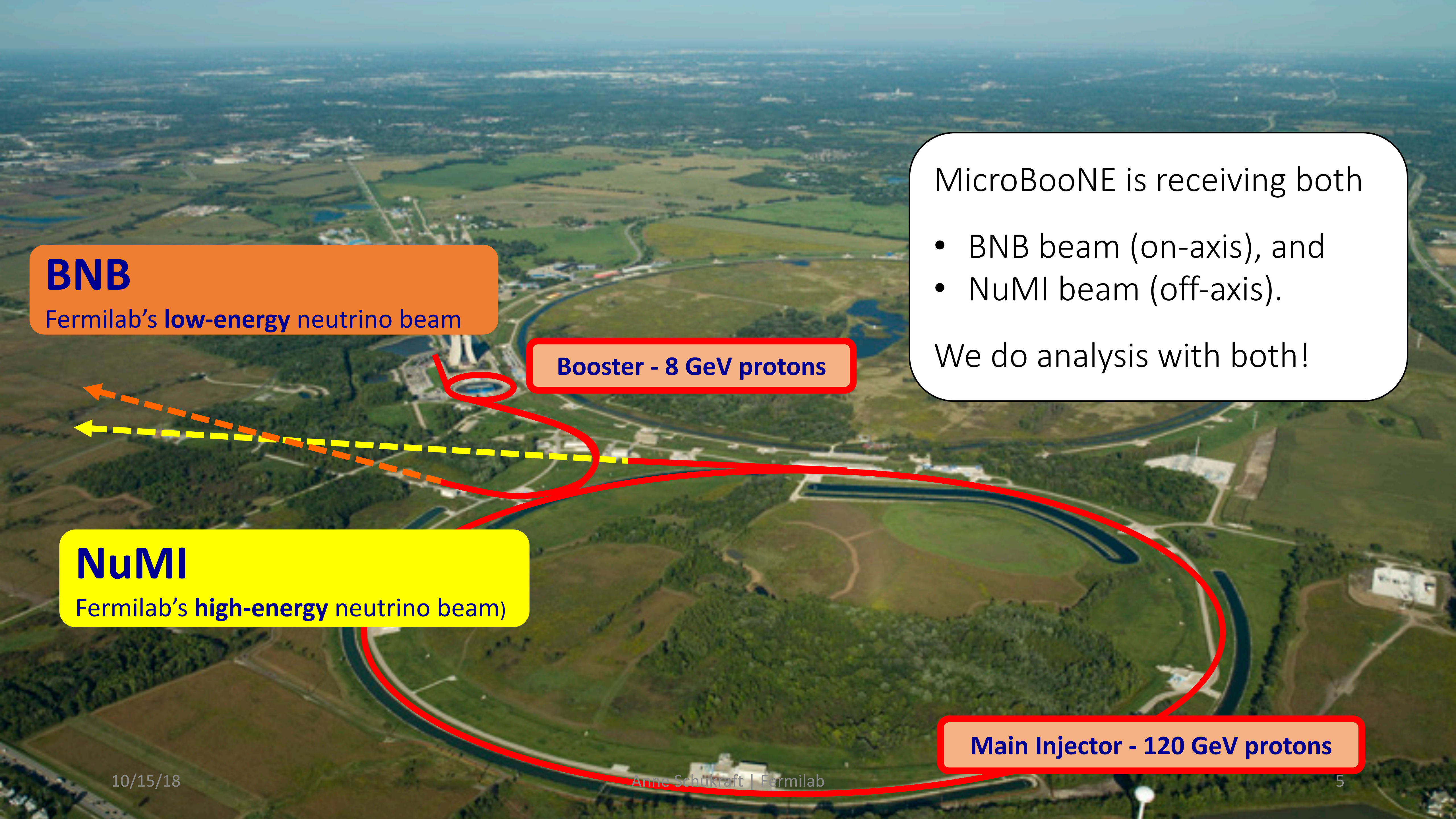
MicroBooNE + SBND + ICARUS

- ν_e appearance & ν_μ disappearance sterile neutrino search

MicroBooNE is receiving both

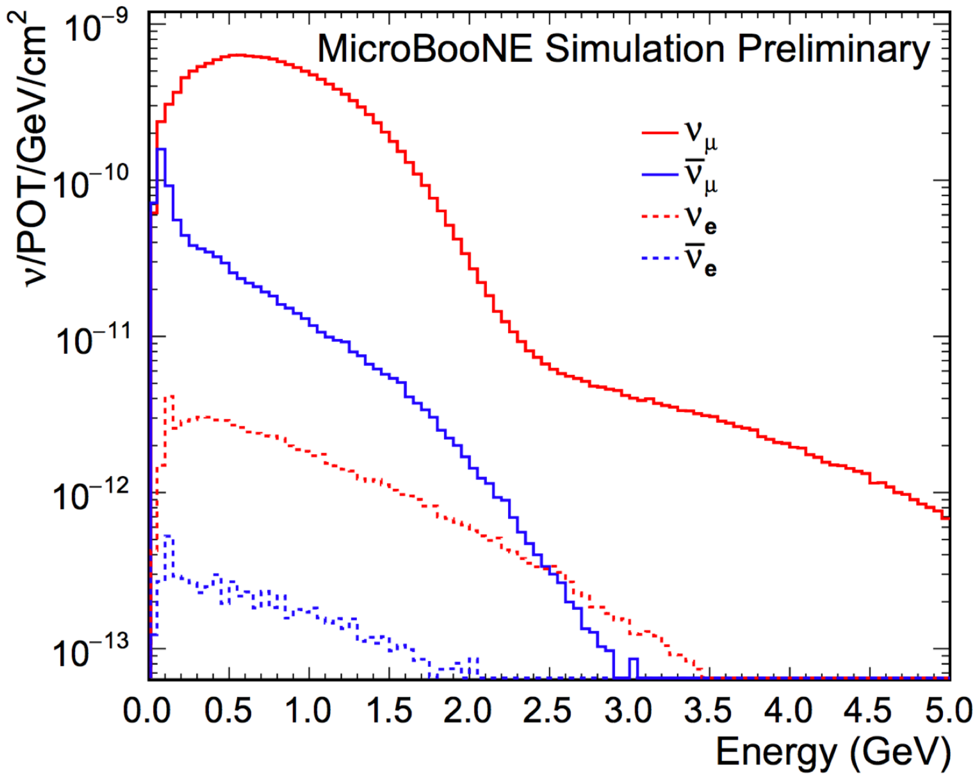
- BNB beam (on-axis), and
- NuMI beam (off-axis).

We do analysis with both!

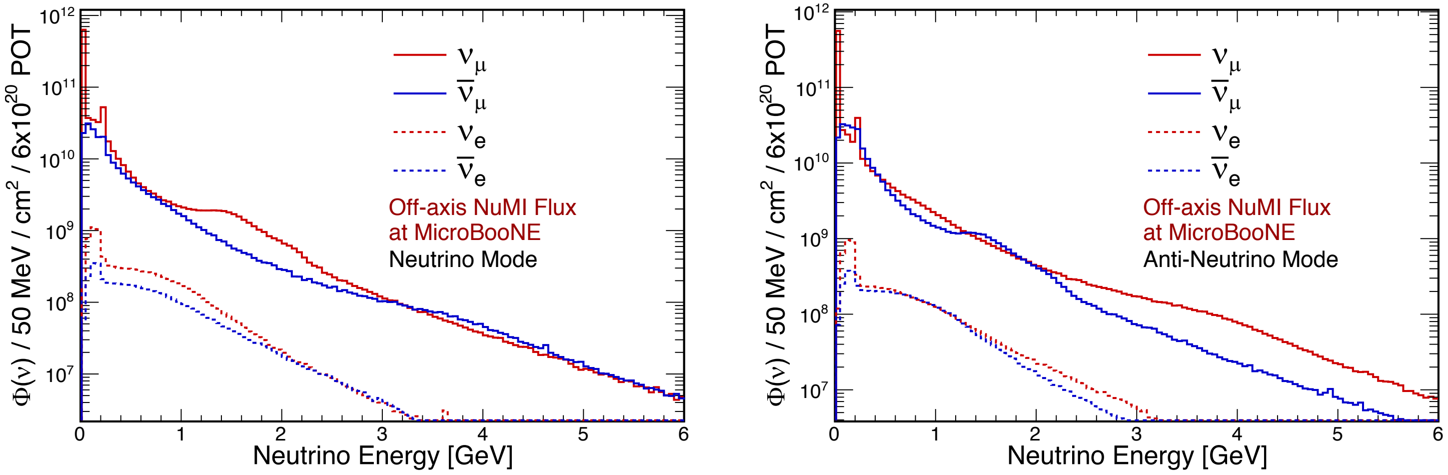


BNB and NuMI fluxes @ MicroBooNE

BNB



NuMI

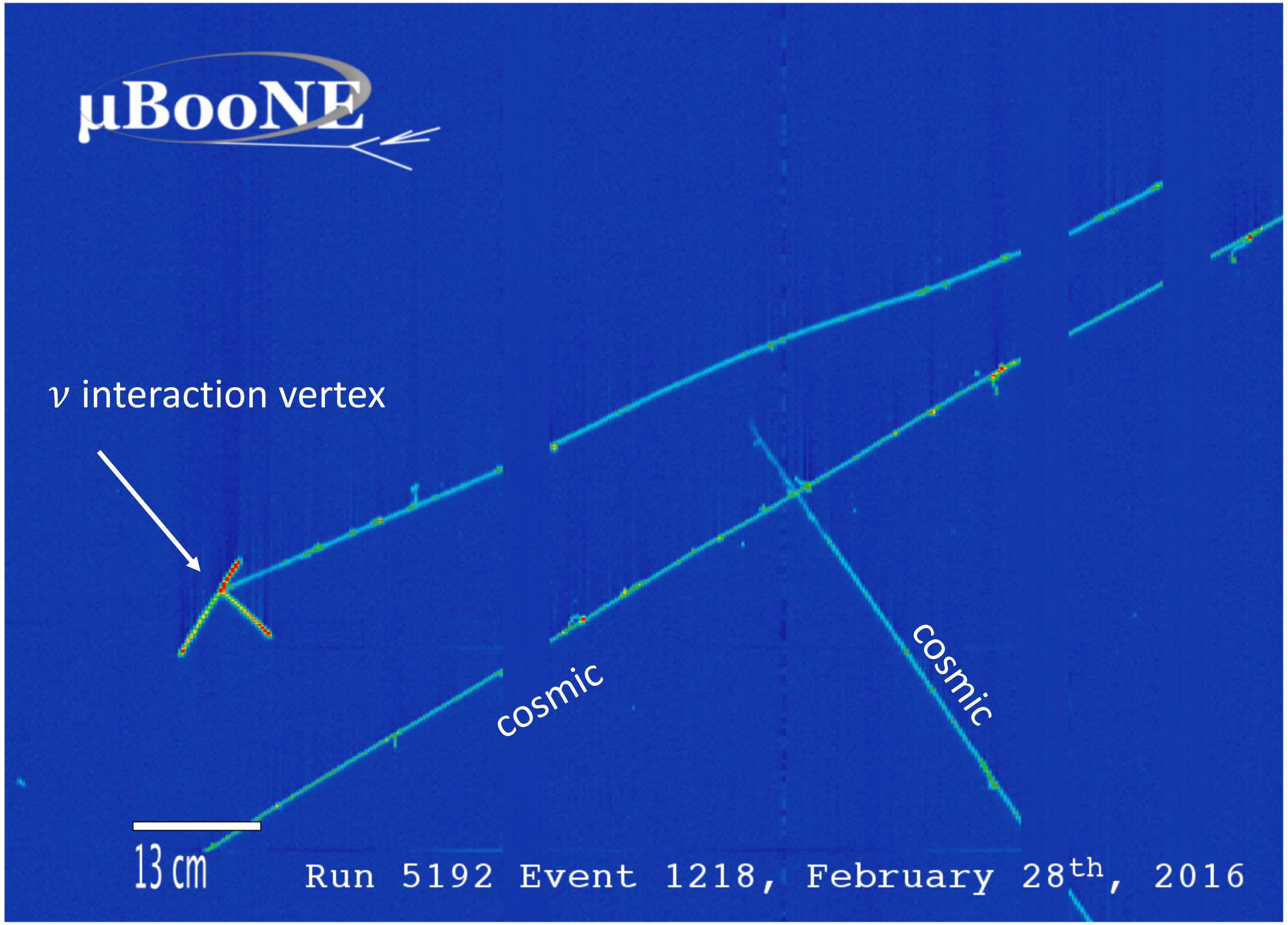


- MicroBooNE is ~ 8 degrees off-axis in the NuMI beam.
  Note that therefore the neutrino energy spectrum MicroBooNE sees is very different from other NuMI experiments (MINERvA, MINOS, NOvA)

- The ν_e contribution to the flux is large (~ 5% compared to ~ 0.5% in BNB).
  This makes for some interesting ν_e measurements!

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

LArTPC technology



Strengths

- mm-scale resolution
- Protons visible down to energies of few 10s of MeV
- Calorimetric information
- 4π angular coverage

Challenges

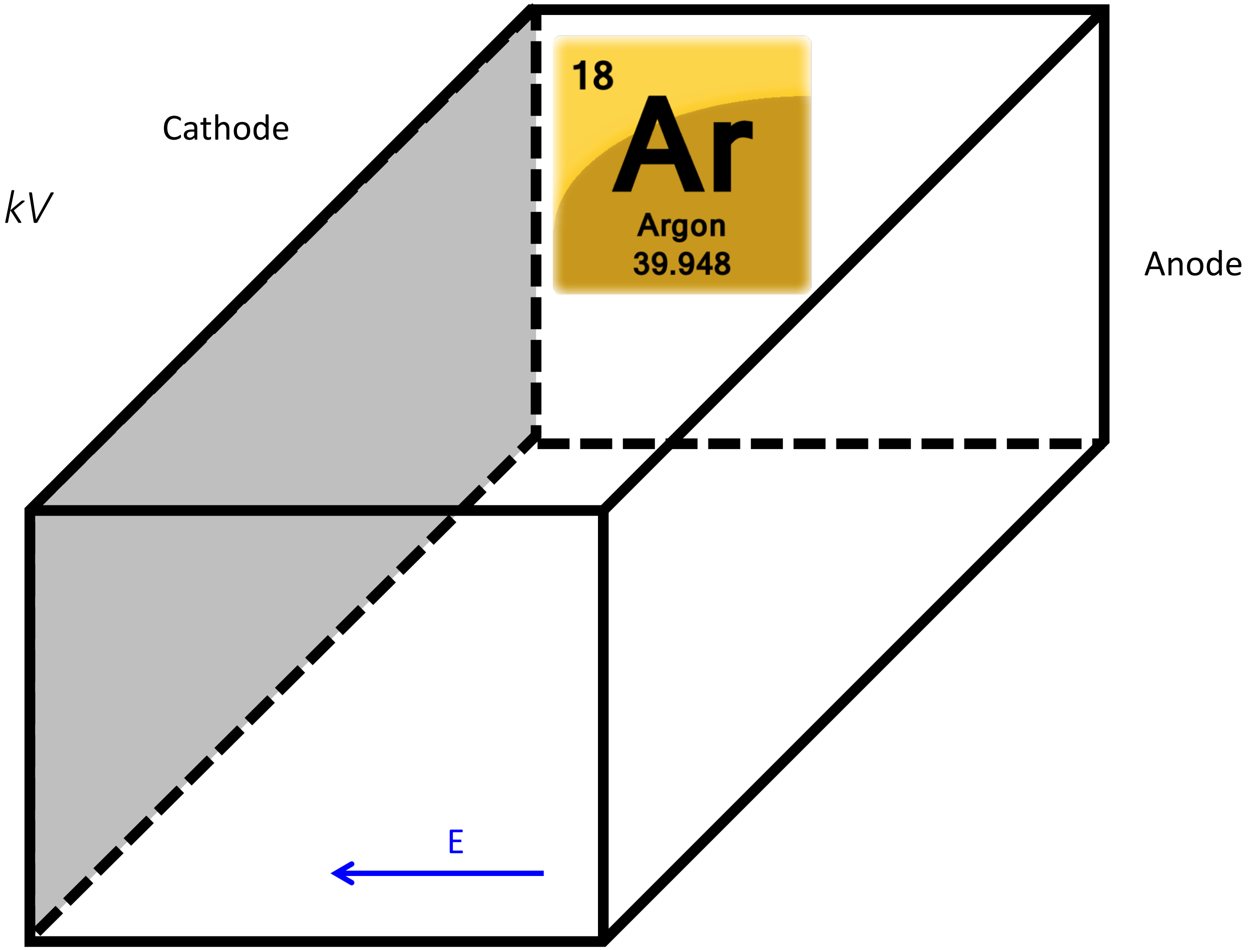
- Operations: purity and HV
- Cosmic backgrounds
- Heavy nuclear target
- Same as for other detectors: neutrons

The principle of a LArTPC

- *87 tons active LAr volume*
- *170 tons total LAr volume*
- *Operated at 87 K*
- *Operated at 1.24 atms*

Operating at 70 kV

E = 273 V/cm

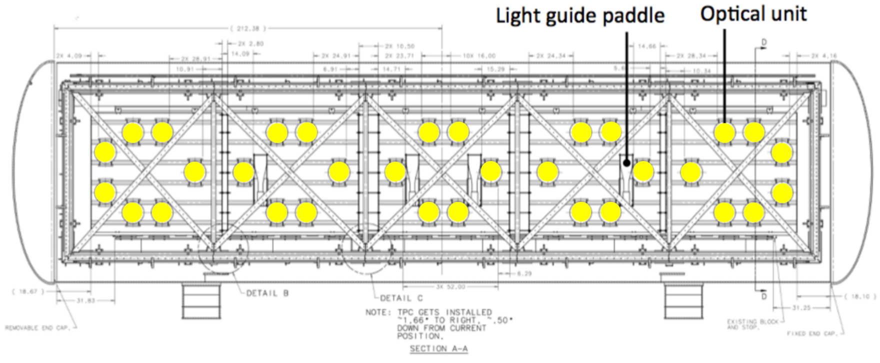


- Large volume filled with liquid-argon
- Strong electric field

JINST 12 (2017) no.02, P02017
https://arxiv.org/abs/1612.05824

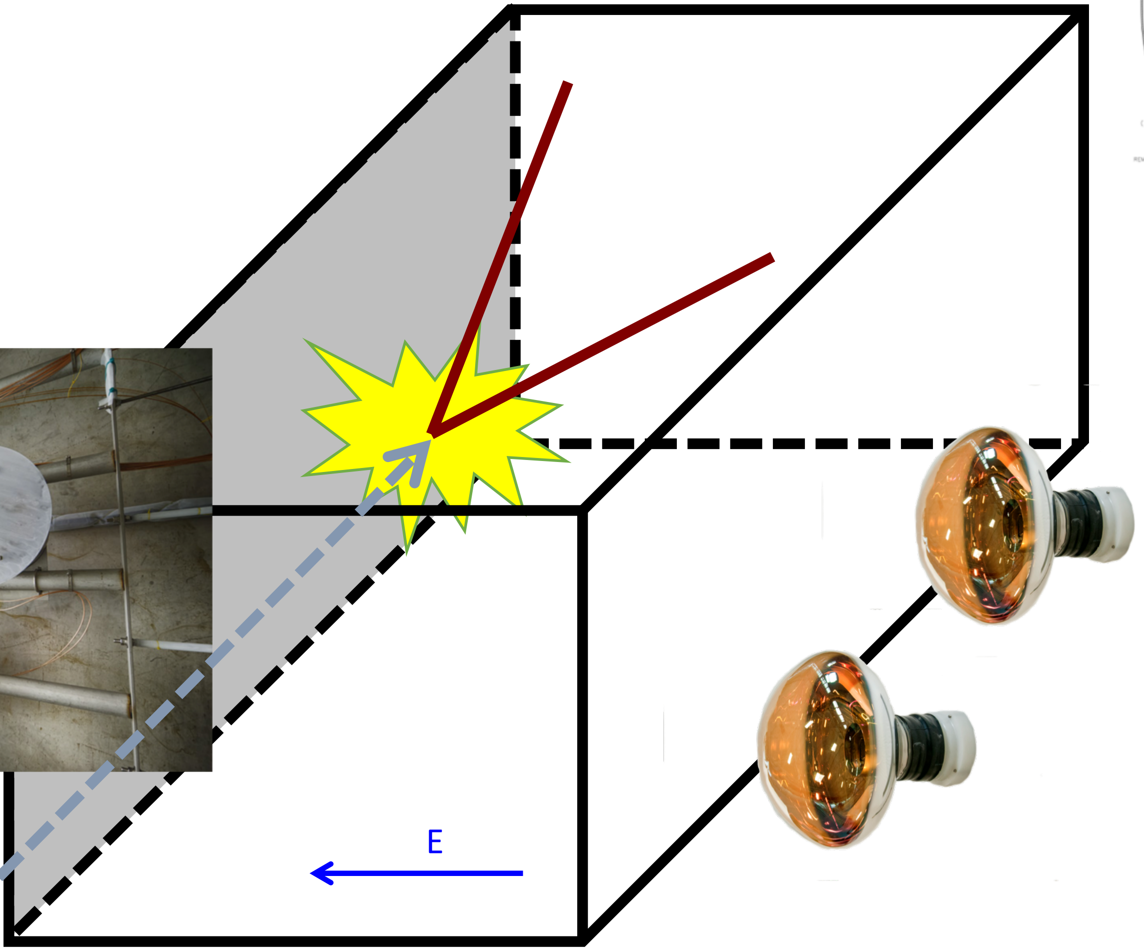
The principle of a LArTPC

μBooNE



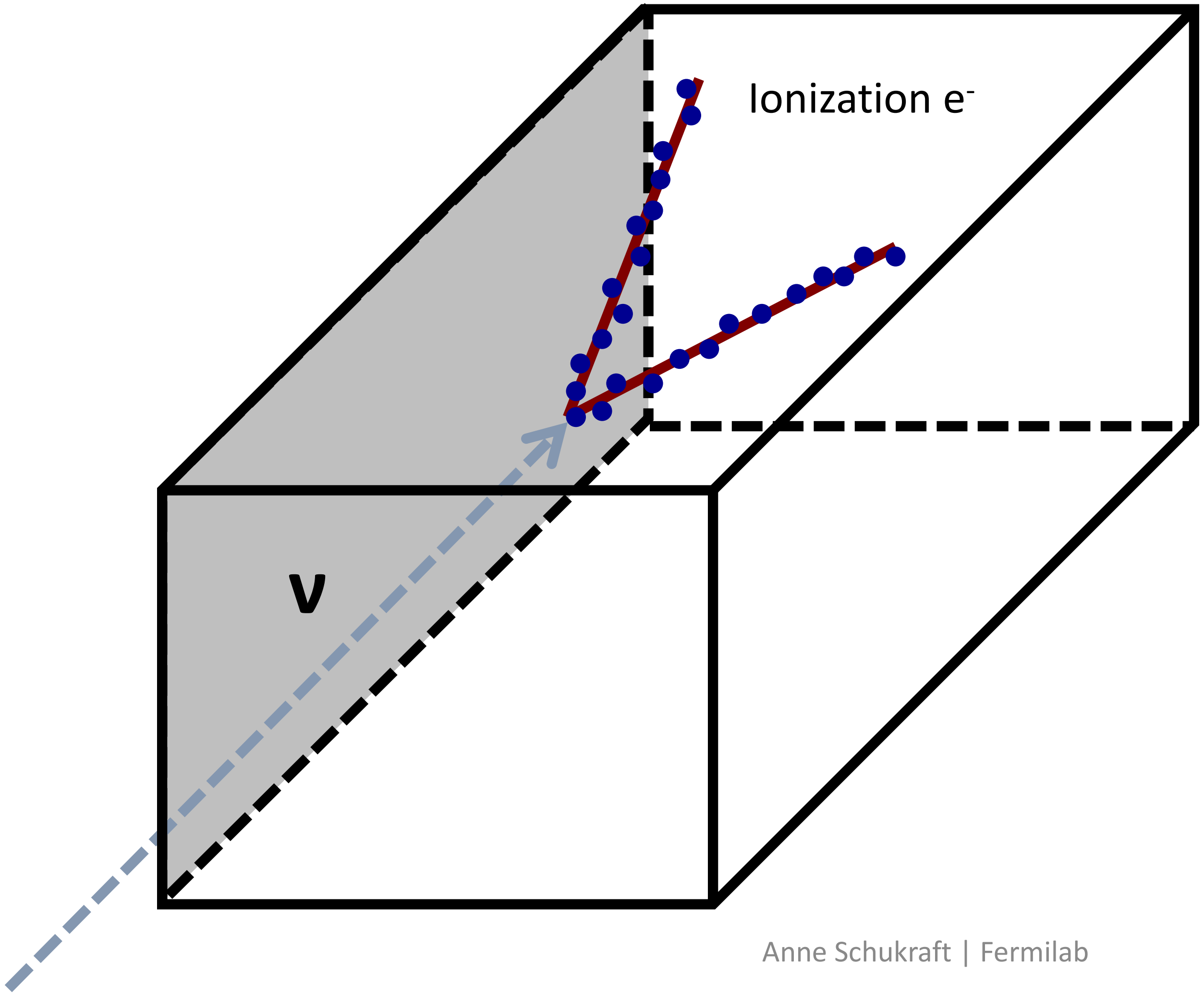
μBooNE *32 8-inch PMTs*

μBooNE



- Light system behind wire plane for scintillation light detection
- Prompt scintillation light signal is important for rejecting cosmic backgrounds

The principle of a LArTPC

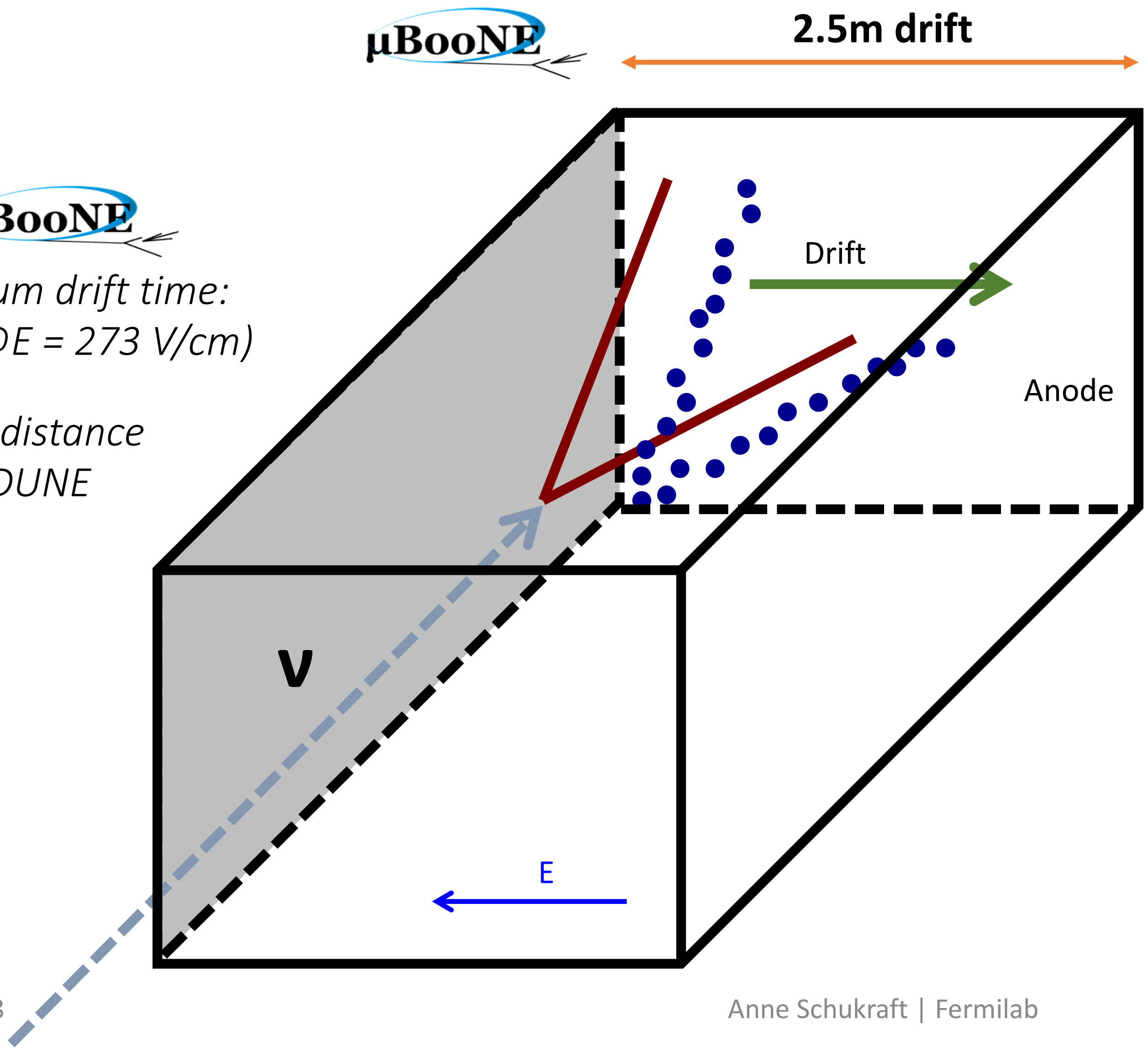


- Secondary charged particles produce ionization electrons

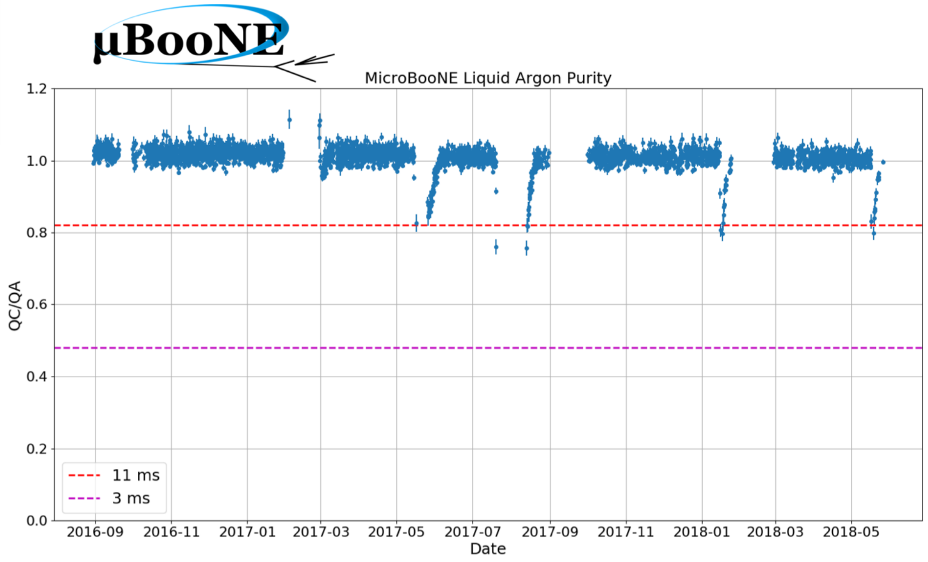
The principle of a LArTPC

Maximum drift time:
2.3ms (@E = 273 V/cm)

Longest drift distance before ProtoDUNE



- Electrons drift towards anode plane
- Argon purity is important to reduce electron attenuation

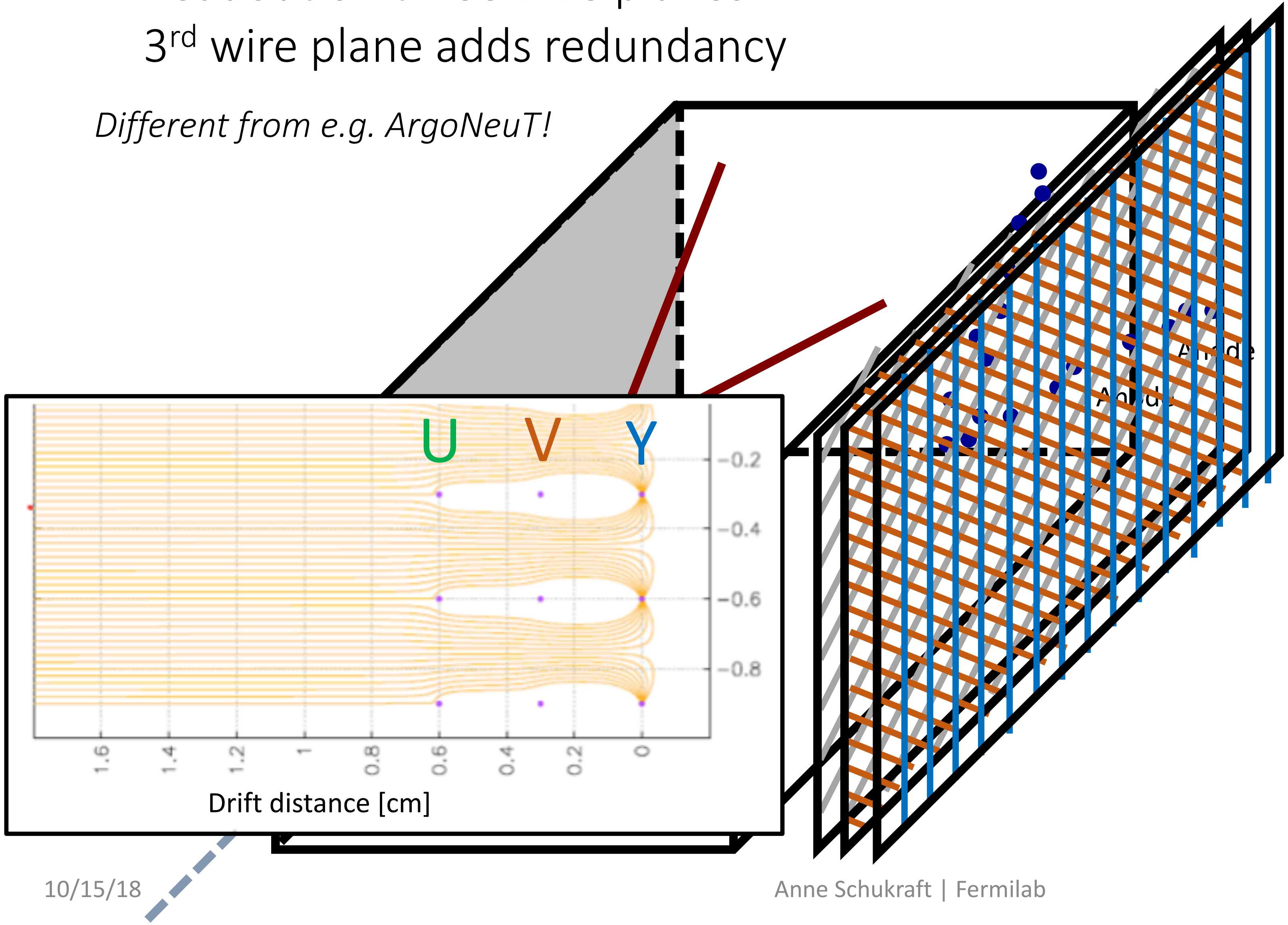


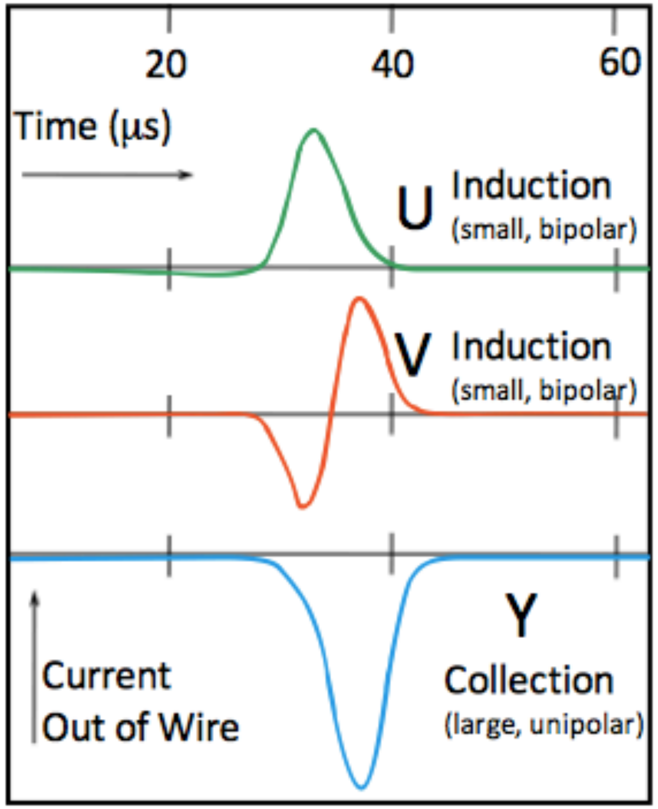
Purity exceeds design requirements!

The principle of a LArTPC

- Readout on three wire planes
  3rd wire plane adds redundancy

Different from e.g. ArgoNeuT!





The principle of a LArTPC

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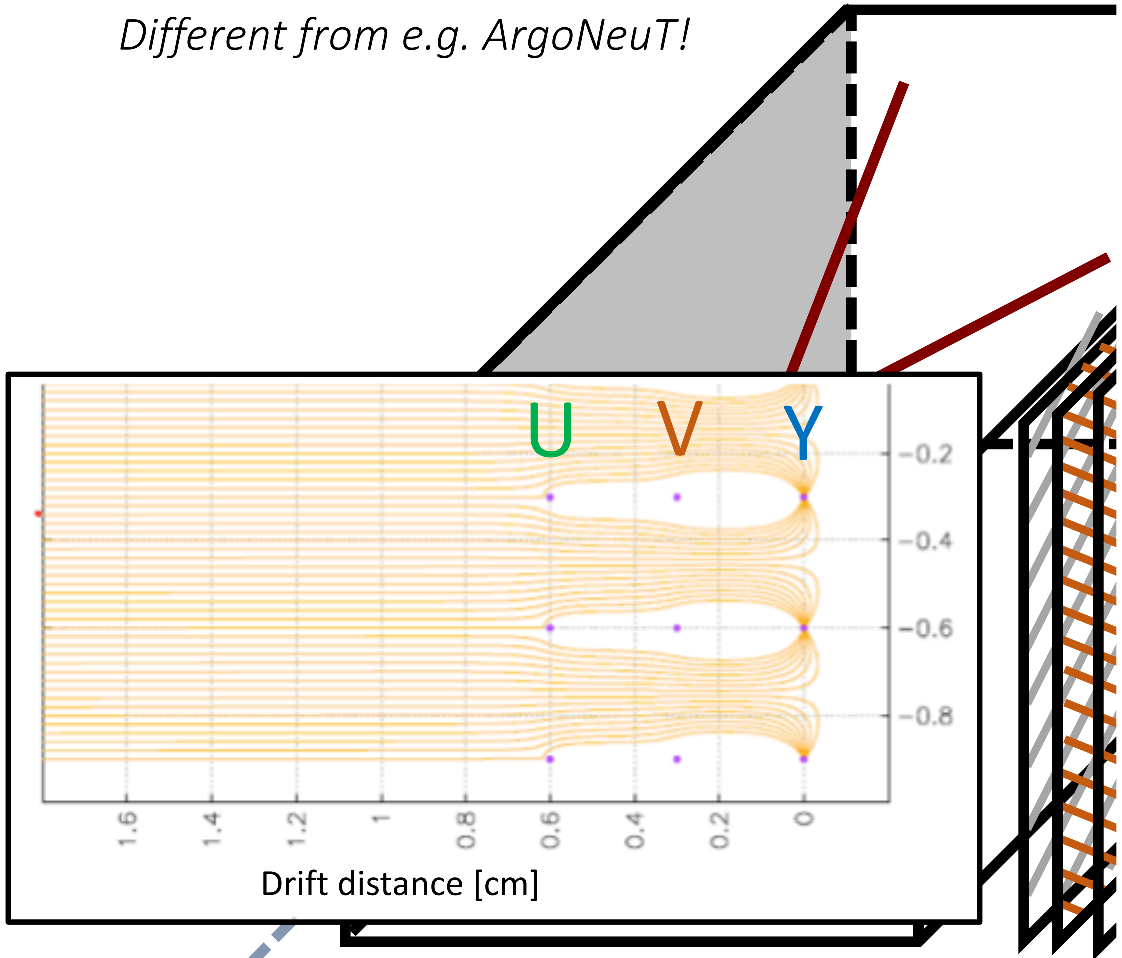
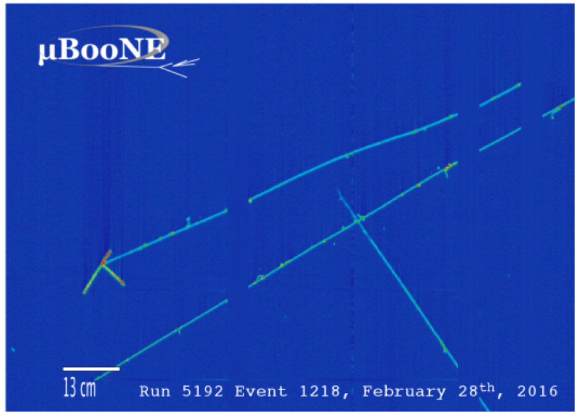
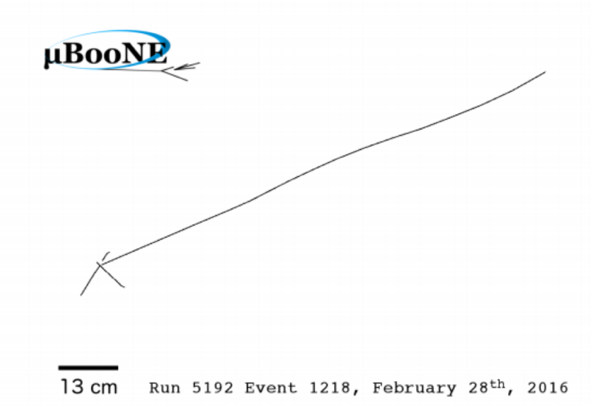
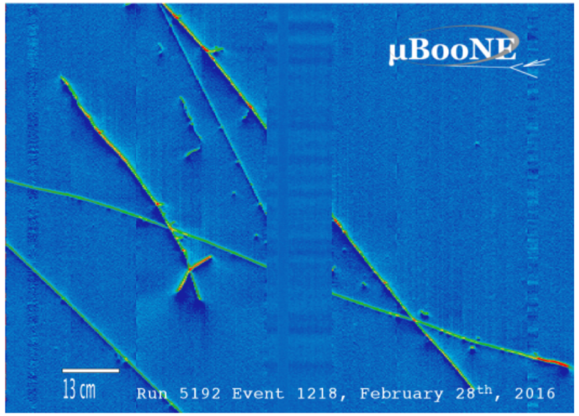




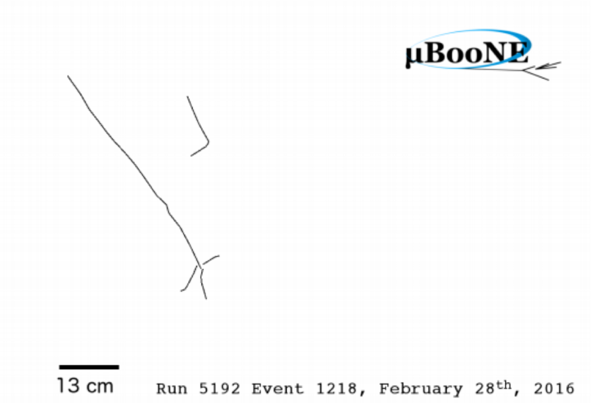
(a) Collection plane (Y)



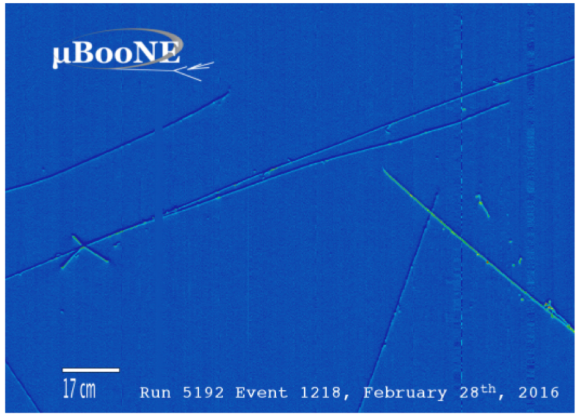
(b) Reconstructed 3D image (Y plane projection)



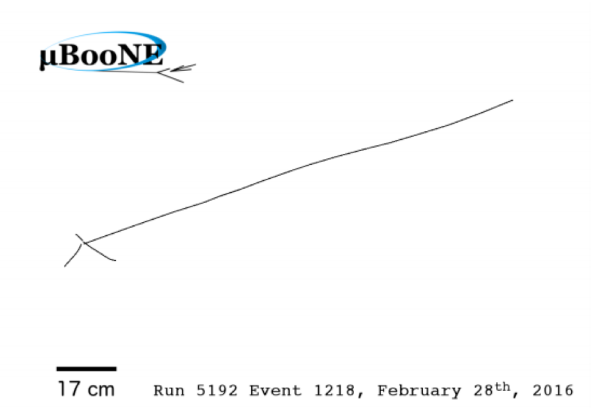
(c) Induction plane (U)



(d) Reconstructed 3D image (U plane projection)

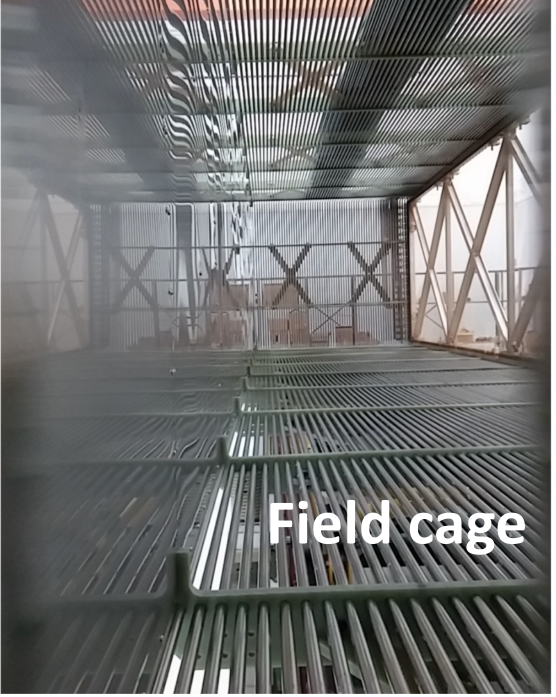


(e) Induction plane (V)

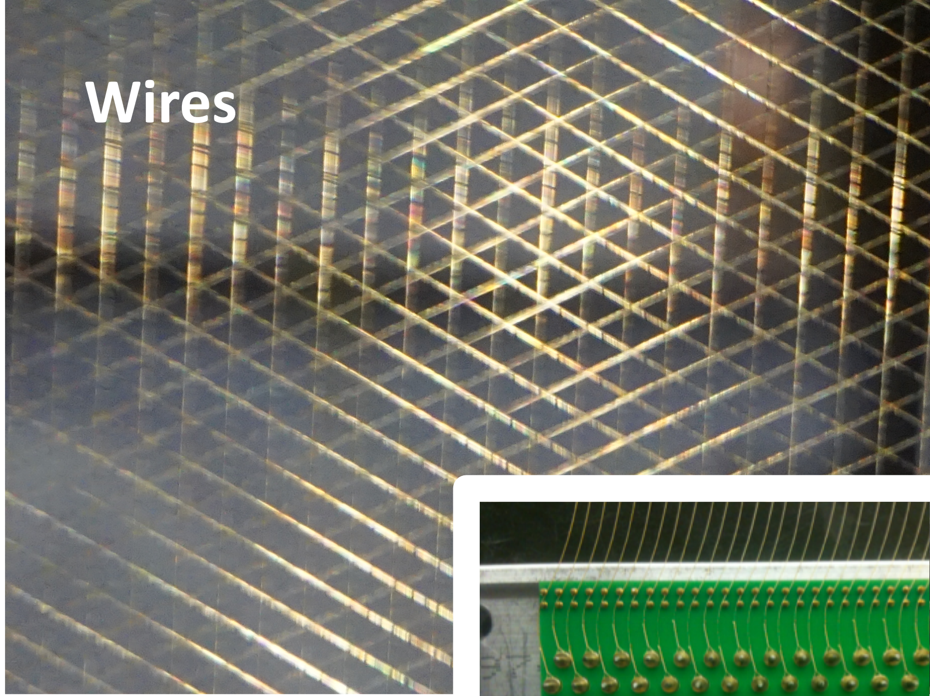


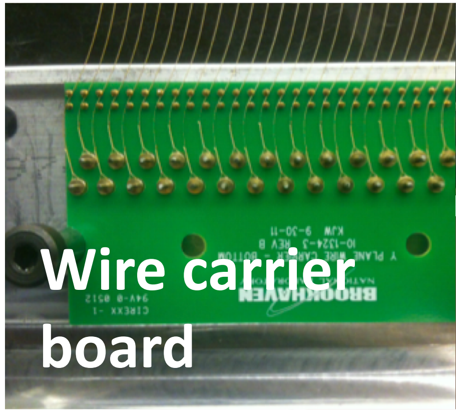
(f) Reconstructed 3D image (V plane projection)

Public Note **MICROBOONE-NOTE-1010-PUB**
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1010-PUB.pdf


Field cage


Cryostat


Wires

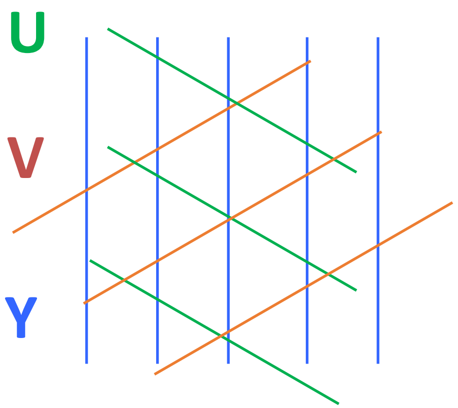

Wire carrier
board


TPC

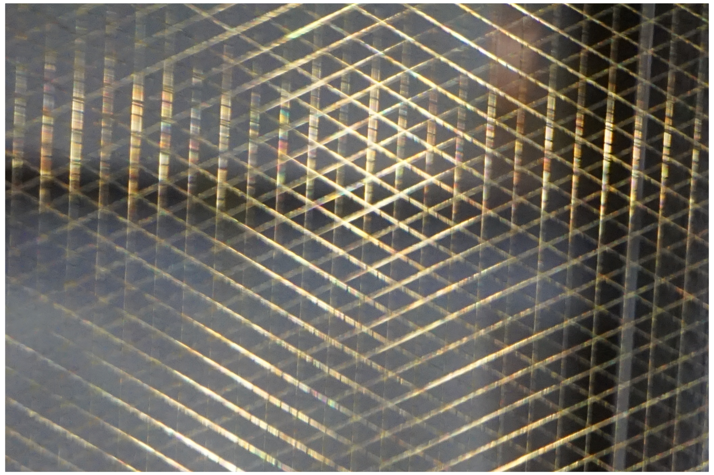

HV feedthrough


Anode plane

LArTPC thresholds

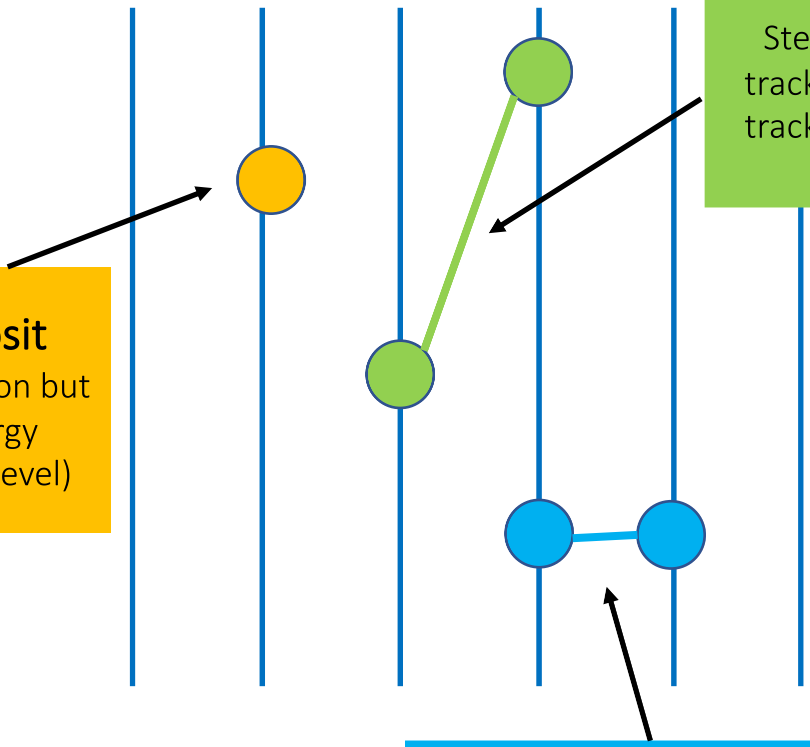


3 mm wire spacing
60° angles between wires



3 wire planes
8192 wires total

Wire spacing ultimately determines LArTPC resolution and detection thresholds

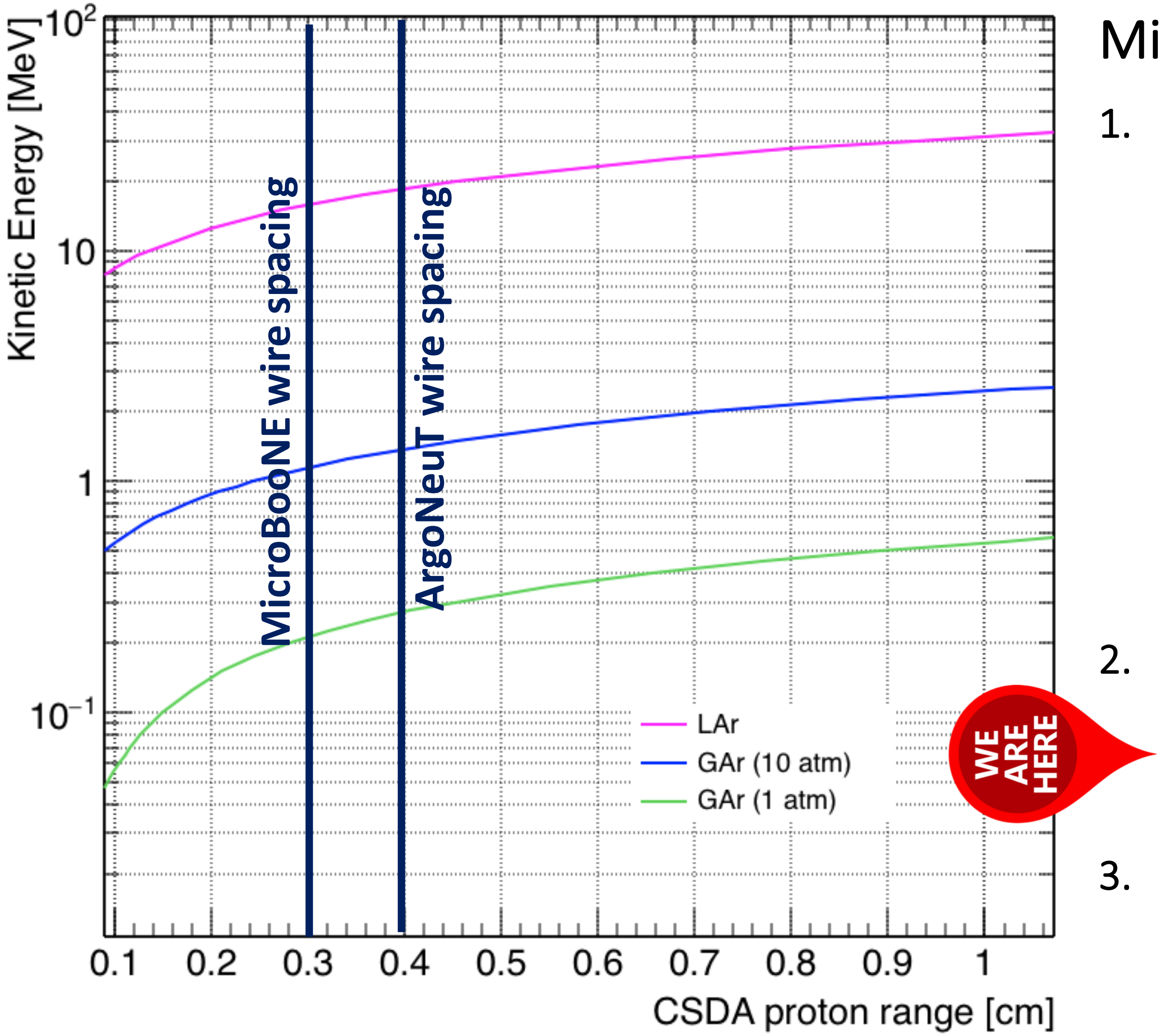


Single wire deposit
No angular reconstruction but reconstructable energy deposit (caveat: noise level)

>= 2 wire deposit
Steep angles require longer track lengths (thresholds), but track is more perpendicular in other plane

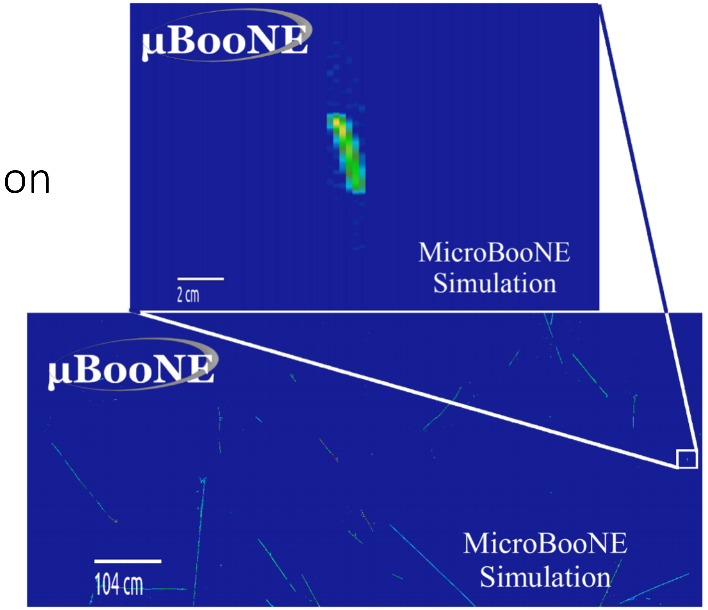
>= 2 wire deposit
Lowest possible threshold for track reconstruction for tracks perpendicular to wires

LArTPC thresholds



ArgoNeuT: Threshold reached using manual reconstruction

MicroBooNE Status:



1. Proof of principle
   Automatic reconstruction and identification of protons successfully demonstrated

   Public Note
   MICROBOONE-NOTE-1025-PUB
   http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1025-PUB.pdf

2. Reliable proton ID and calorimetric reconstruction

   See talk by Raquel Castillo Fernandez at this conference

   CC 1μ Np & CC 1μ 2p

3. Lowering proton threshold & increasing efficiency at low-energy

   Work on-going. Improvements will go into our next round of analyses

Experiment introduction

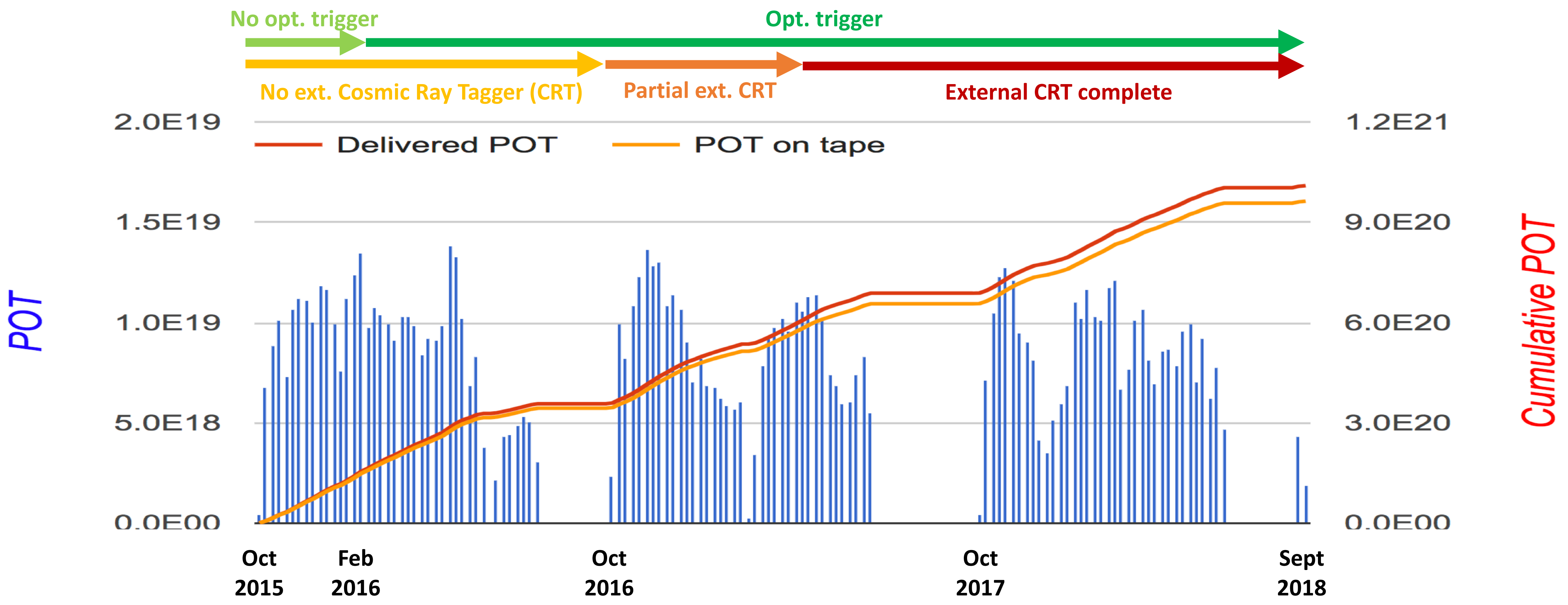
Data samples

Cosmic rejection

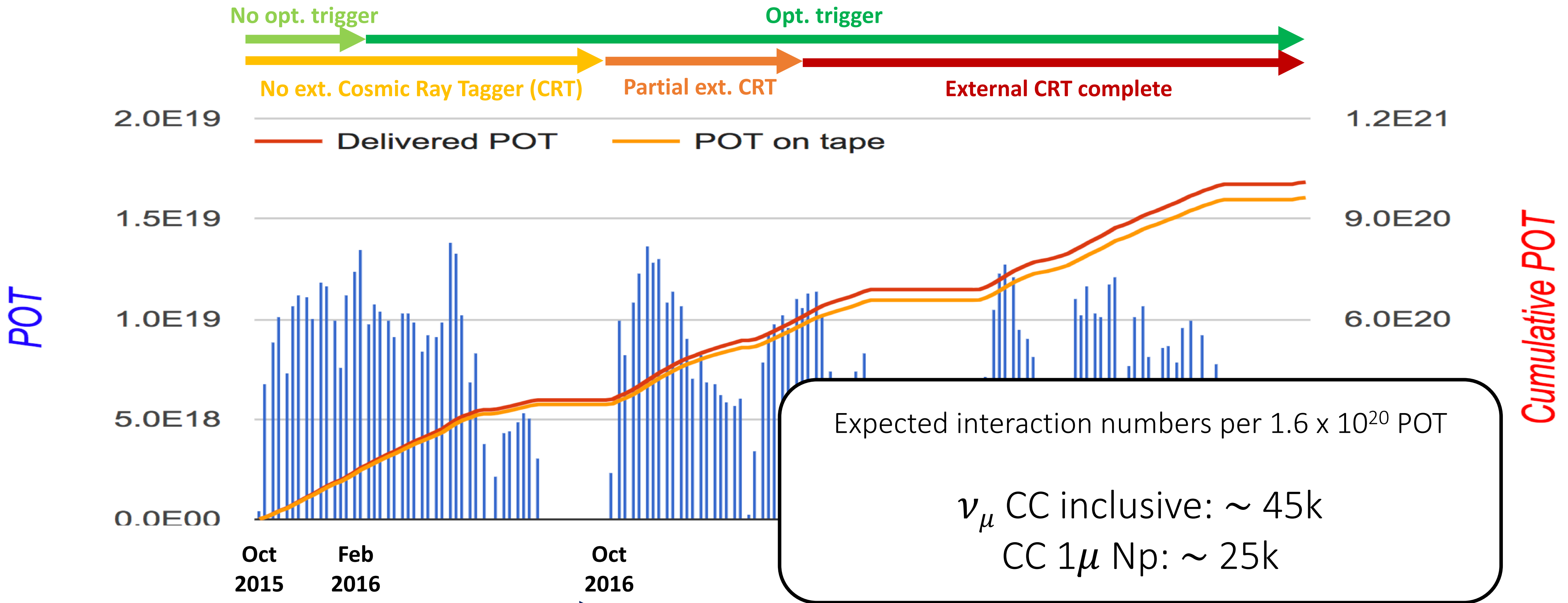
Reconstruction performance

Systematics evaluation

BNB data taking



BNB data taking



Expected interaction numbers per 1.6×10^{20} POT

ν_μ CC inclusive: ~ 45k
CC 1μ Np: ~ 25k

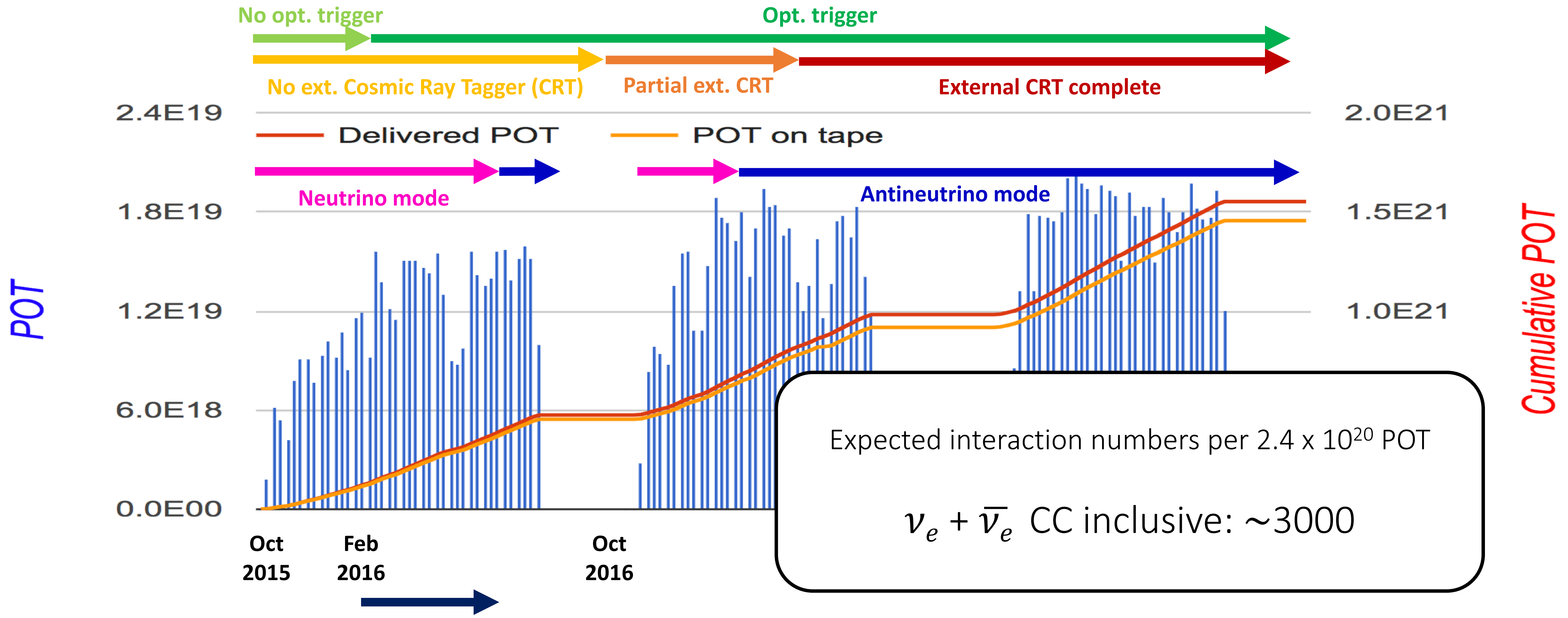
5×10^{19} POT unblind data sample

Run I analyses: 1.6×10^{20} POT

CC 1μ Np & CC 1μ 2p | ν_μ CC inclusive | CC π^0

All analyses presented today are pre-external Cosmic Tagger era

NuMI data taking



Expected interaction numbers per 2.4 x 10^{20} POT

$\nu_e + \overline{\nu}_e$ CC inclusive: ~3000

Run I neutrino mode analyses: 2.4 x 10^{20} POT

ν_e CC (NuMI)

All analyses presented today are pre-external Cosmic Tagger era

Experiment introduction

Data samples

Cosmic rejection

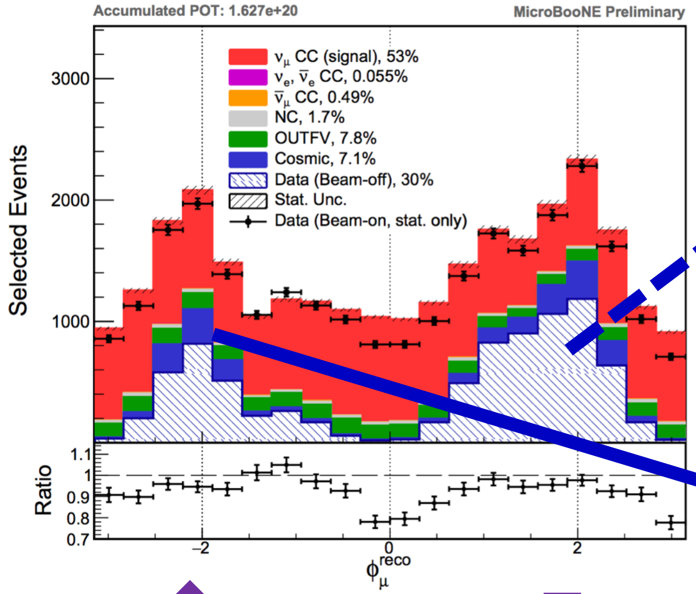
Reconstruction performance

Systematics evaluation

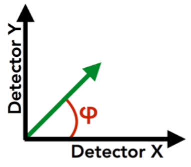
Cosmic backgrounds

Example

ν_μ CC inclusive analysis selection



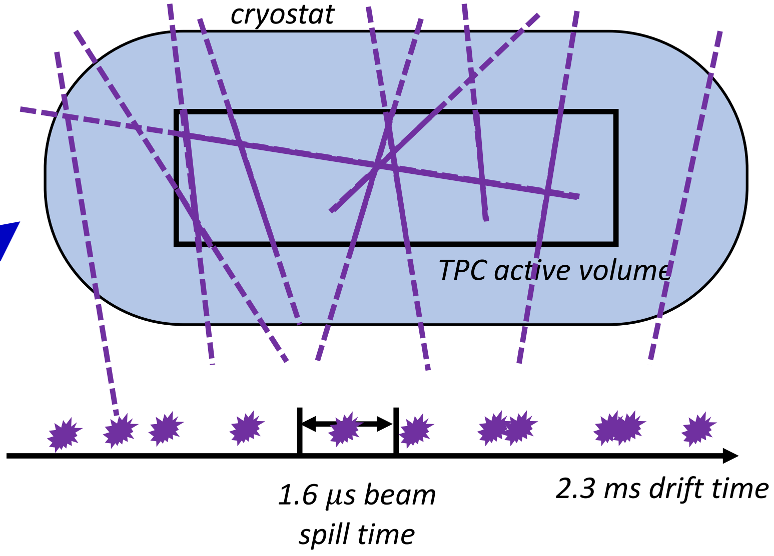
Cosmics typically mis-reconstructed as upwards going



Downward going

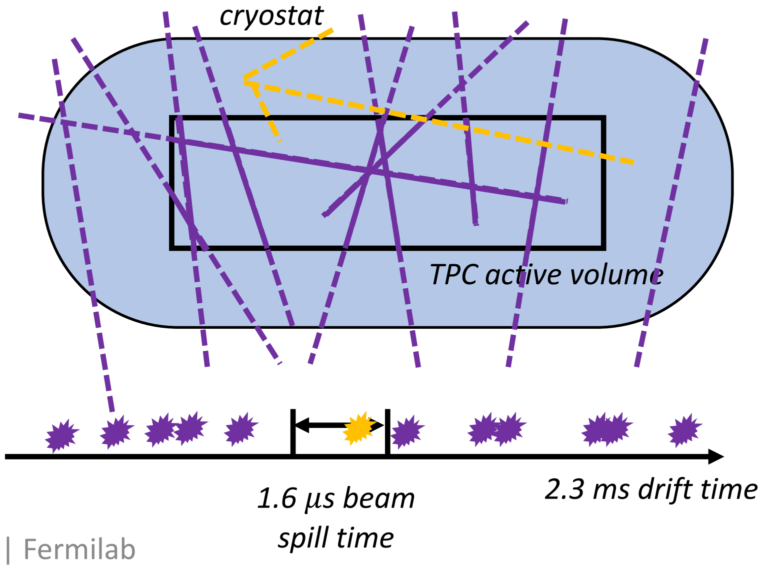
φ: angle around the beam

"Cosmics only"



- No neutrino in the event
- Perfect measurement during beam-off time

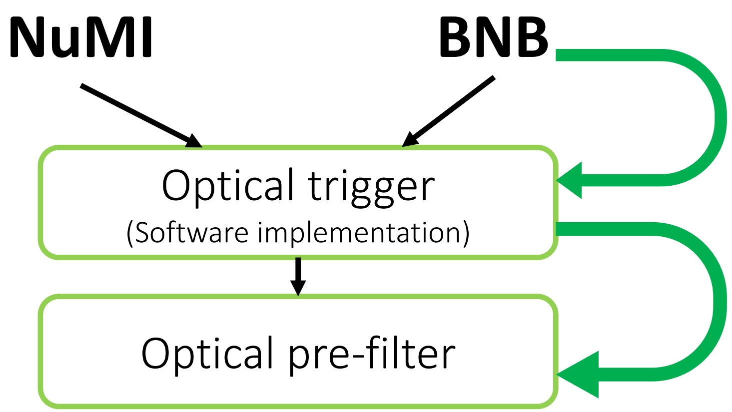
"Neutrinos + cosmics"



- Optical signal from neutrino interaction triggers
- Cosmic induced TPC track picked up by selection

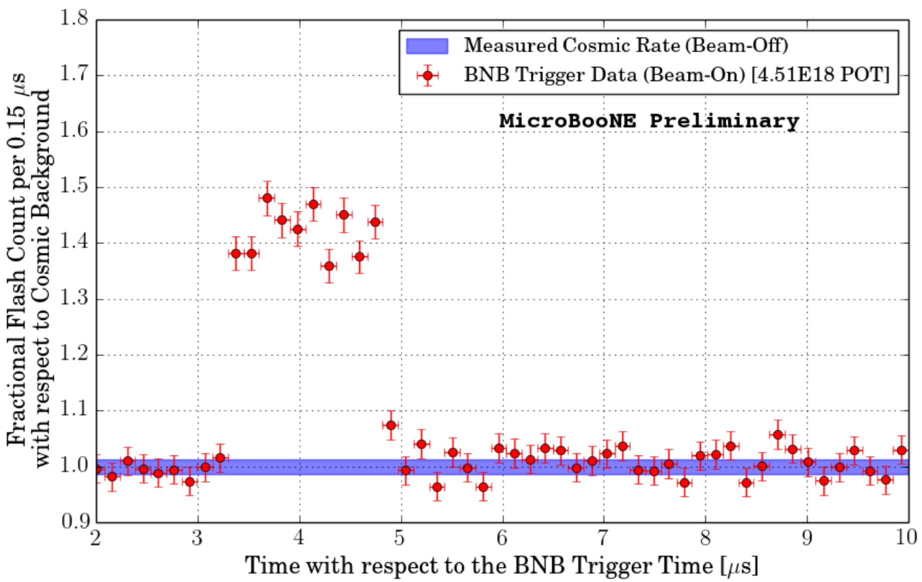
Cosmic rejection flow

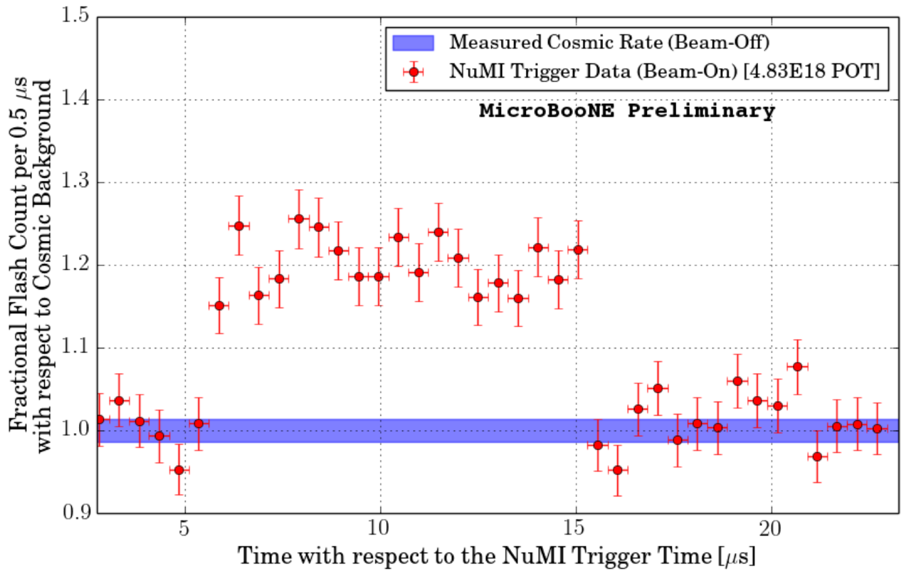
Step 1: Optical



Rejecting
95%
cosmic events*

Rejecting
67%
cosmic events*





Public Note
MICROBOONE-NOTE-1002-PUB
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1002-PUB.pdf

- Total drift time is 2.3 ms
- Beam spill arrival time window is much shorter for both BNB and NuMI

* “cosmic events” = cosmics – no neutrino. Measured with off-beam data

Cosmic rejection flow

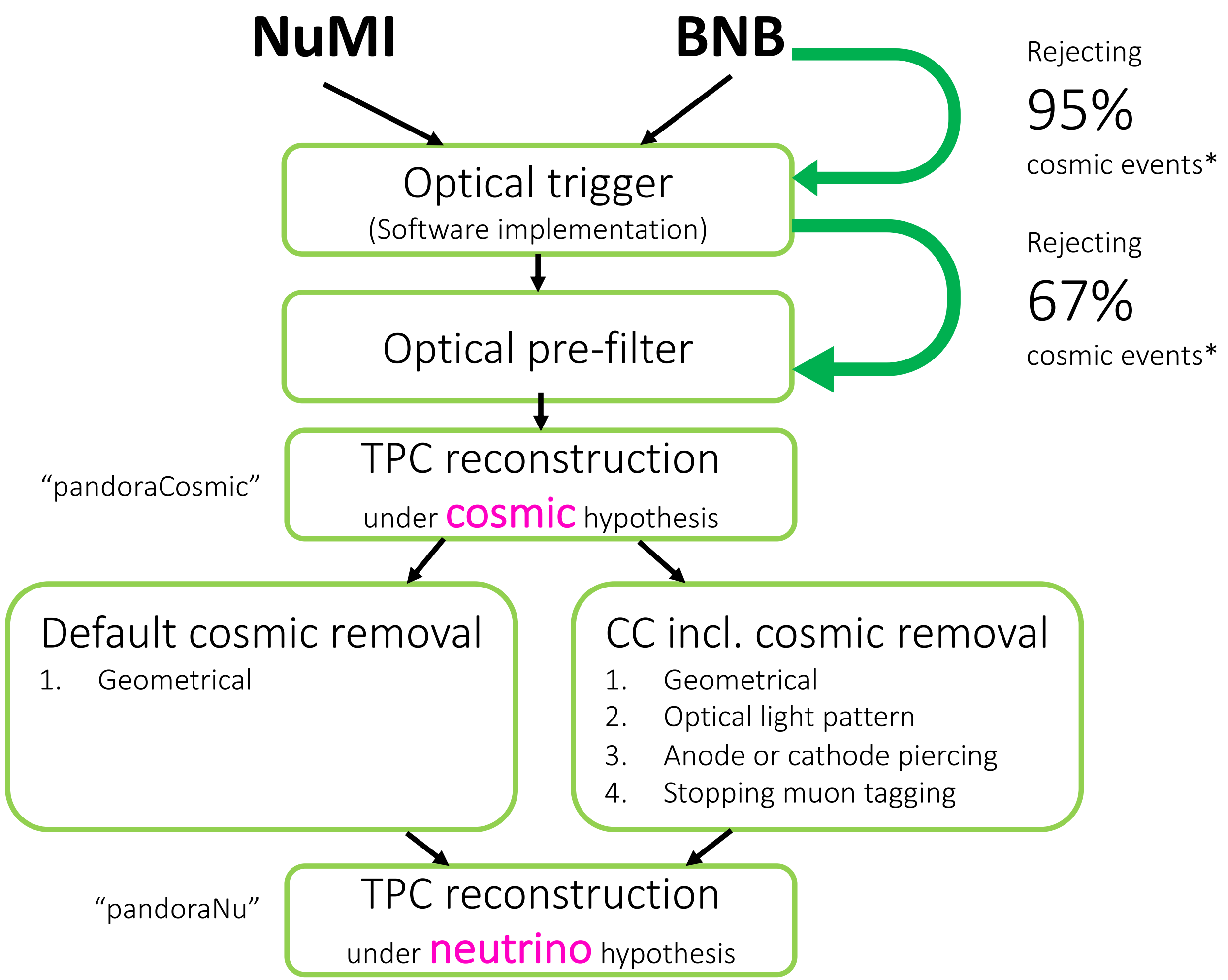
Step 2:

TPC reco chain

Note:
All analyses presented today use this Pandora chain.

Eur. Phys. J. C78 (2018) no.1, 82
https://arxiv.org/abs/1708.03135

Other approaches e.g. machine learning techniques are also being developed in MicroBooNE



Public Note **MICROBOONE-NOTE-1045-PUB**
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1045-PUB.pdf

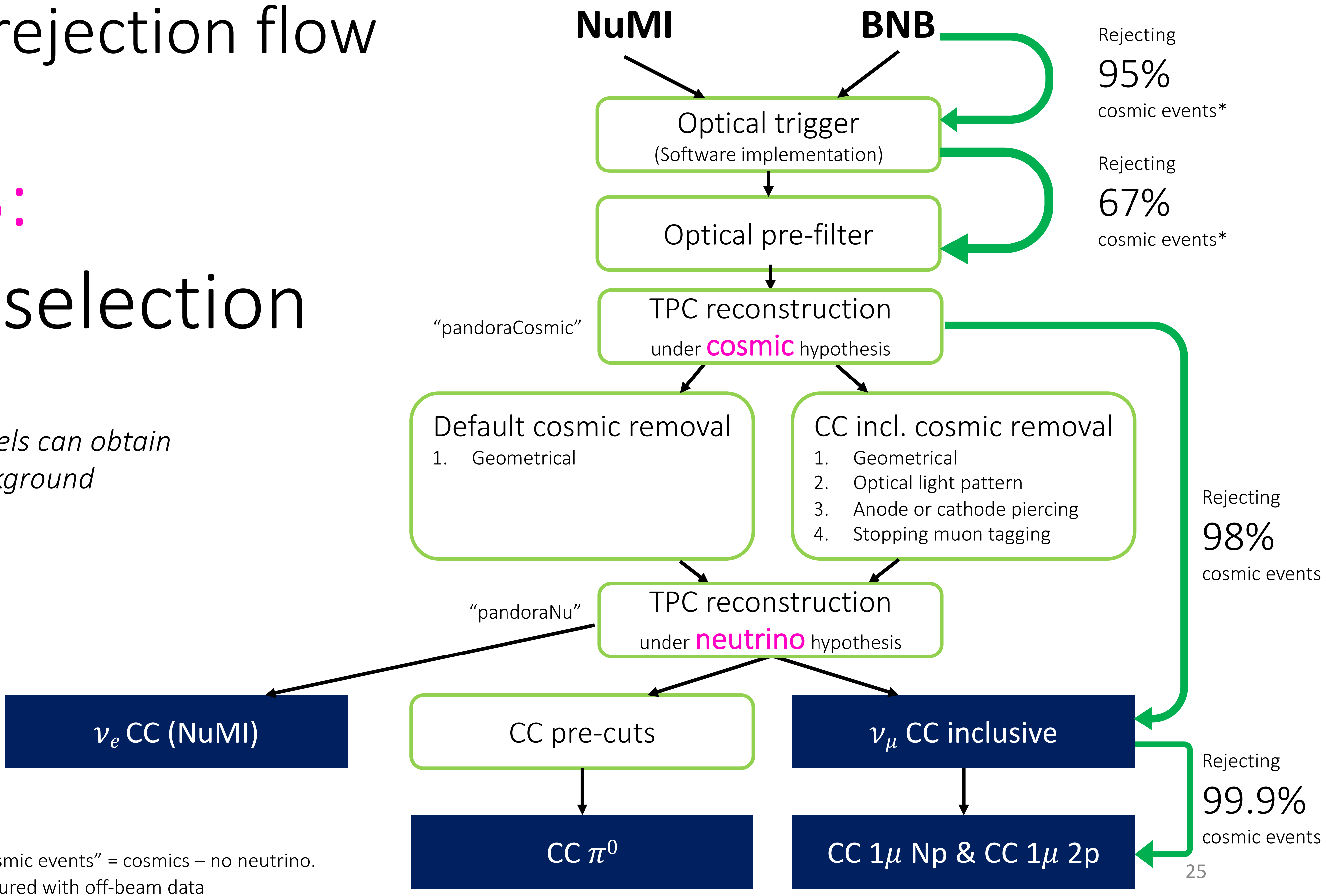
* "cosmic events" = cosmics – no neutrino.
Measured with off-beam data

Cosmic rejection flow

Step 3:

Event selection

Exclusive channels can obtain low cosmic background



* "cosmic events" = cosmics – no neutrino. Measured with off-beam data

Experiment introduction

Data samples

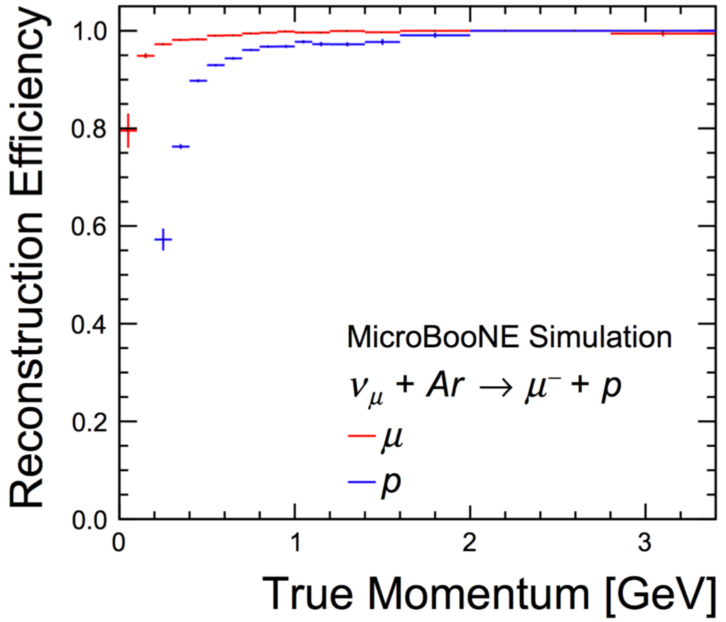
Cosmic rejection

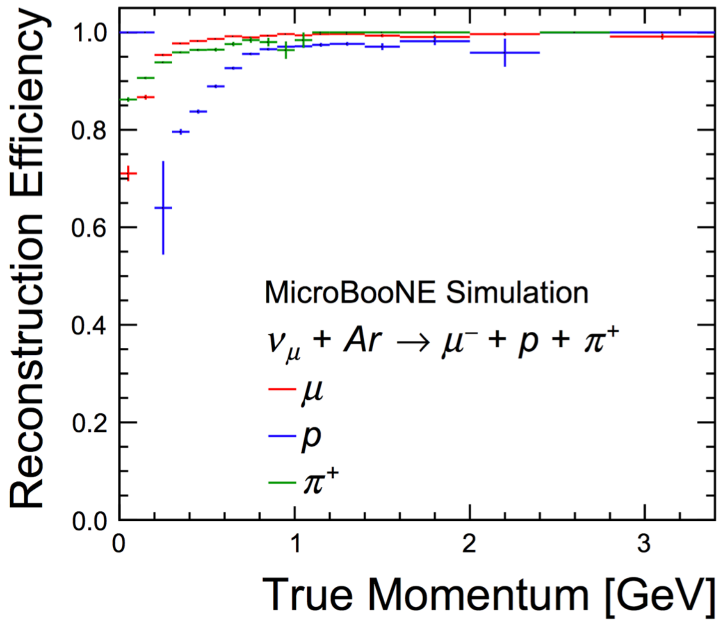
Reconstruction performance

Systematics evaluation

Simulation-based reconstruction efficiencies

Reconstruction efficiencies for different interaction channels for the Pandora algorithm suite for pure neutrino events (no cosmics simulated, no cosmic tagging algorithms applied)





#Matched Particles	0	1	2	3+
μ	1.3%	95.8%	2.9%	0.1%
p	8.9%	87.3%	3.6%	0.2%

#Matched Particles	0	1	2	3+
μ	3.5%	95.1%	1.4%	0.0%
p	9.0%	86.8%	4.0%	0.3%
π^+	6.9%	80.9%	11.4%	0.8%

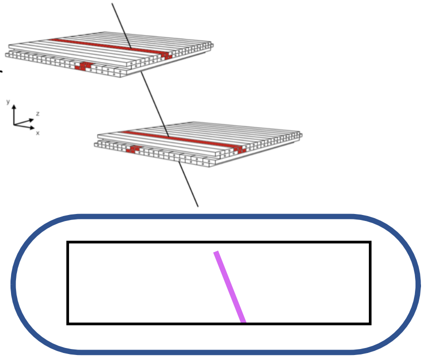
Eur. Phys. J. C78 (2018) no.1, 82
https://arxiv.org/abs/1708.03135

Tables include overall numbers folded with BNB energy spectrum.

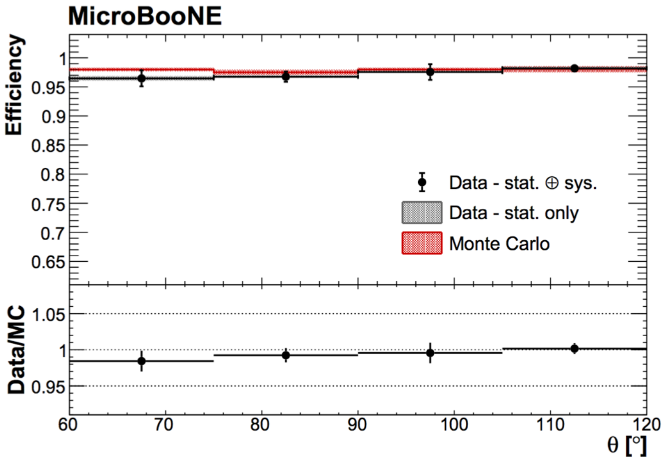
Data-driven performance measurements

1. Efficiency

2 X-Y scintillator modules

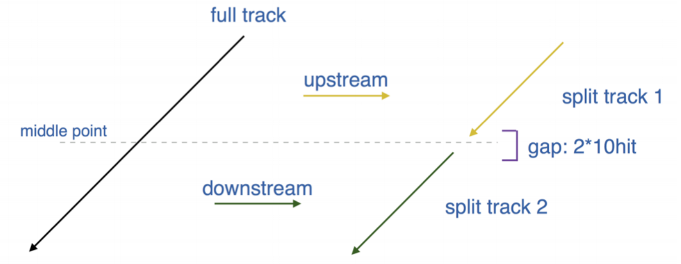


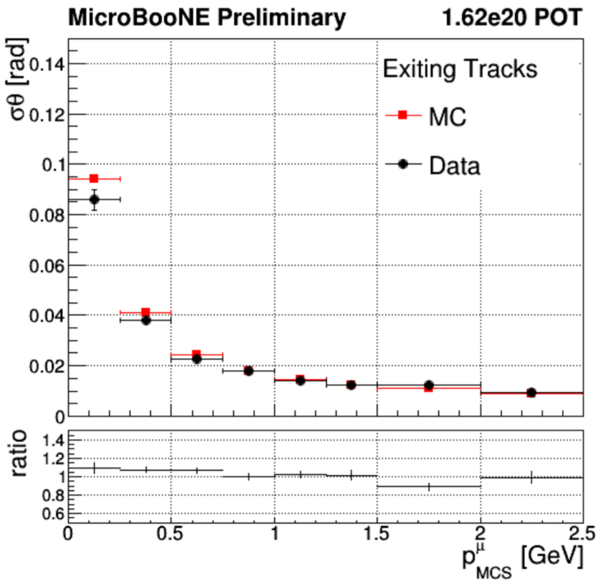
TPC reconstruction efficiency measurement:



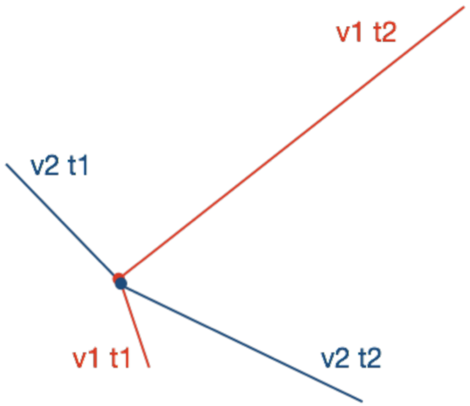
JINST 12 (2017) no.12, P12030
https://arxiv.org/abs/1707.09903

2. Track resolution





3. Vertex resolution

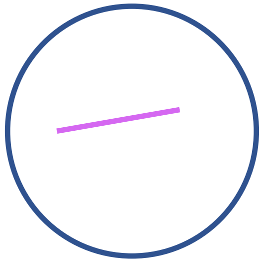
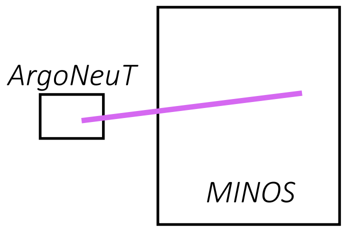
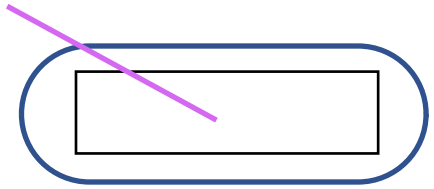


Resolution	Data	MC
x	0.15 ± 0.02 cm	0.133 ± 0.005 cm
y	0.24 ± 0.05 cm	0.182 ± 0.006 cm
z	0.18 ± 0.02 cm	0.209 ± 0.009 cm

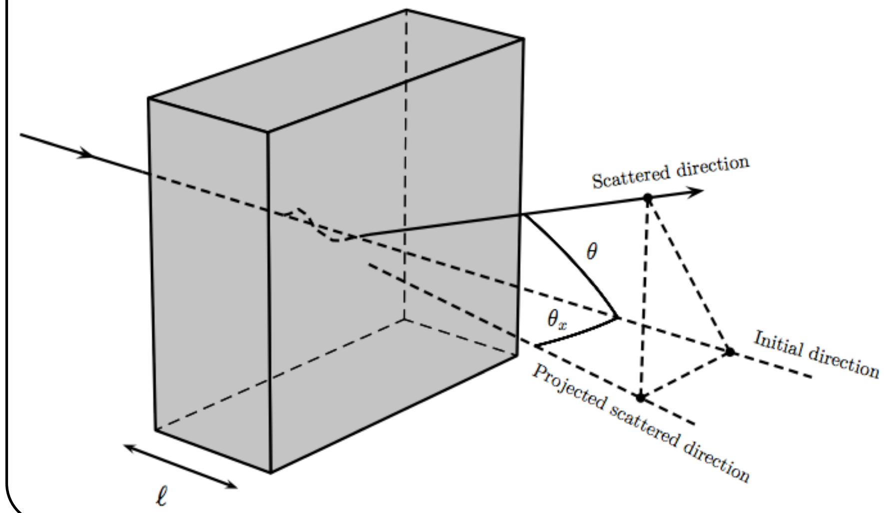
Public Note **MICROBOONE-NOTE-1049-PUB**
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1049-PUB.pdf

Good data-MC agreement in reconstruction performance measurements

Momentum reconstruction

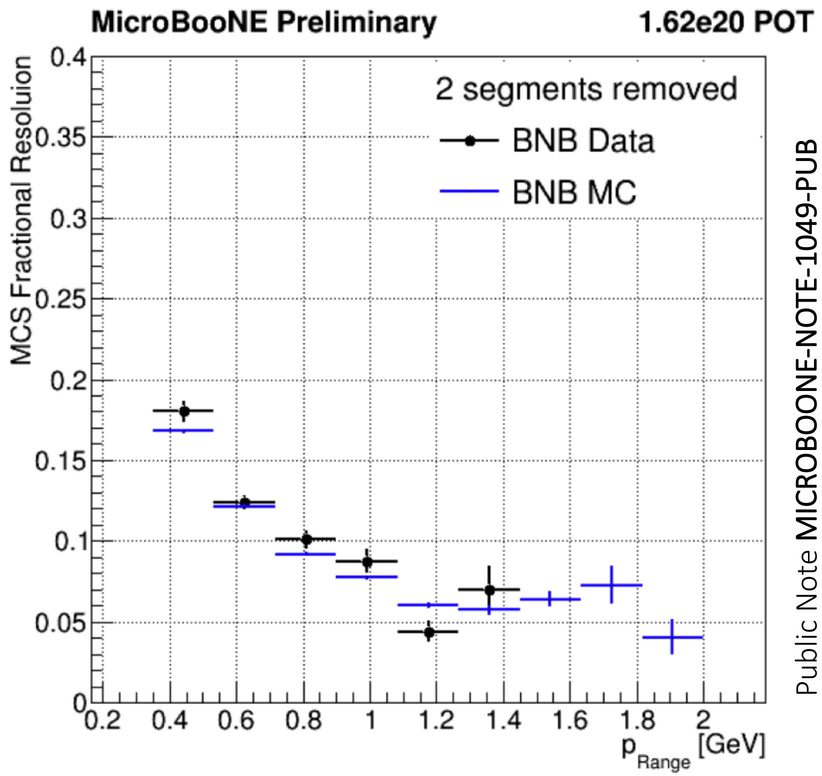
MiniBooNE	ArgoNeuT	MicroBooNE
		
Only contained tracks	Only forward going tracks	Contained & exiting, Any direction!

Technique: Multiple Coulomb Scattering (MCS)



The spread of deflection angles along a track depends on the particle's momentum

JINST 12 (2017) no.10, P10010
https://arxiv.org/abs/1703.06187



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http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1049-PUB.pdf

- MicroBooNE adding to the parameter space of ArgoNeuT and MiniBooNE
- Technique has been demonstrated to work well. Good data – MC agreement for momentum estimation
- Other usage for MCS: track directionality and track reconstruction quality measure

Experiment introduction

Data samples

Cosmic rejection

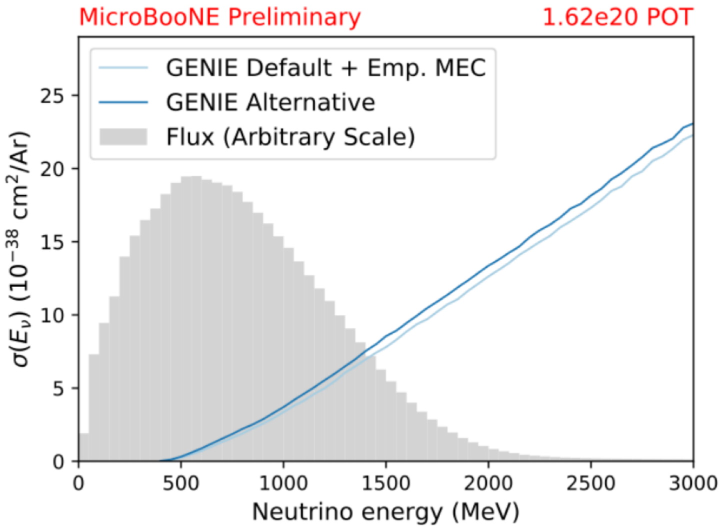
Reconstruction performance

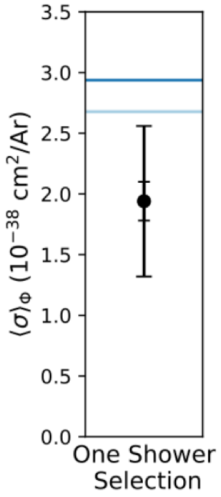
Systematics evaluation

Systematic uncertainty estimation in MicroBooNE

- First generation of analyses evaluating systematics by simulating or re-weighting parameters and propagating the effects through all the chain
- Many parameters not yet well constraint through internal or external measurements.

$\Longrightarrow$ Systematic uncertainties you'll see today are very conservatively estimated





Example:
ν_μ CC π^0 error budget

$\sigma_{sys} \sim 4 * \sigma_{stat}$

We are working on improved constraints for next generation analyses

Categories of systematic uncertainties in MicroBooNE

Example: ν_μ CC inclusive error budget

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%

Discussion on following slides (Beam Flux, Cross Section Modeling, Detector Response)

Future iterations are tuning our beam window for triggering to decrease this uncertainty (Beam Timing Jitter)

Measured from off-beam data taking. More data (e.g. shutdown data!) decreases the uncertainty (Cosmics (out-of-time))

Our very conservative estimate of CORSIKA cosmics simulation. We are switching to using cosmic data for this, which will decrease the uncertainty (Cosmics (in-time))

Beam Flux

BNB

- Evaluation of flux uncertainties is based on the MiniBooNE/SciBooNE techniques and > 15 years of experience running neutrino experiments in the BNB

- Hadron production uncertainties
  - $\pi+, \pi-,\ K^{+}, K^{-}$, and $K^0{}_L$
- Non-hadron production uncertainties:
  - Mismodeling of horn current distribution
  - Horn current miscalibration
  - Pion and nucleon scattering cross sections on beryllium and aluminum

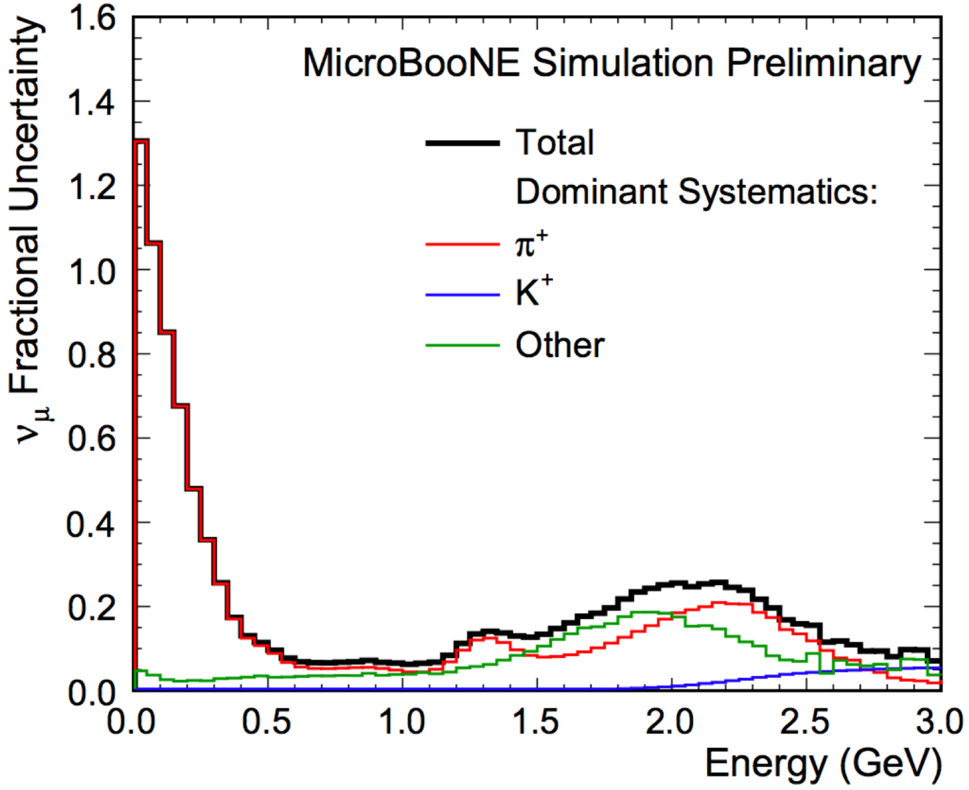
- We use a **multisim strategy**, creating a set of universes with different variations of all parameters

- Work ongoing to confirm with updated beamline simulation

NUMI

- Currently estimating NuMI uncertainties using PPFX software following MINERvA and NOvA techniques

BNB



Systematic	$\nu_\mu/\%$	$\bar{\nu}_\mu/\%$	$\nu_e/\%$	$\bar{\nu}_e/\%$
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

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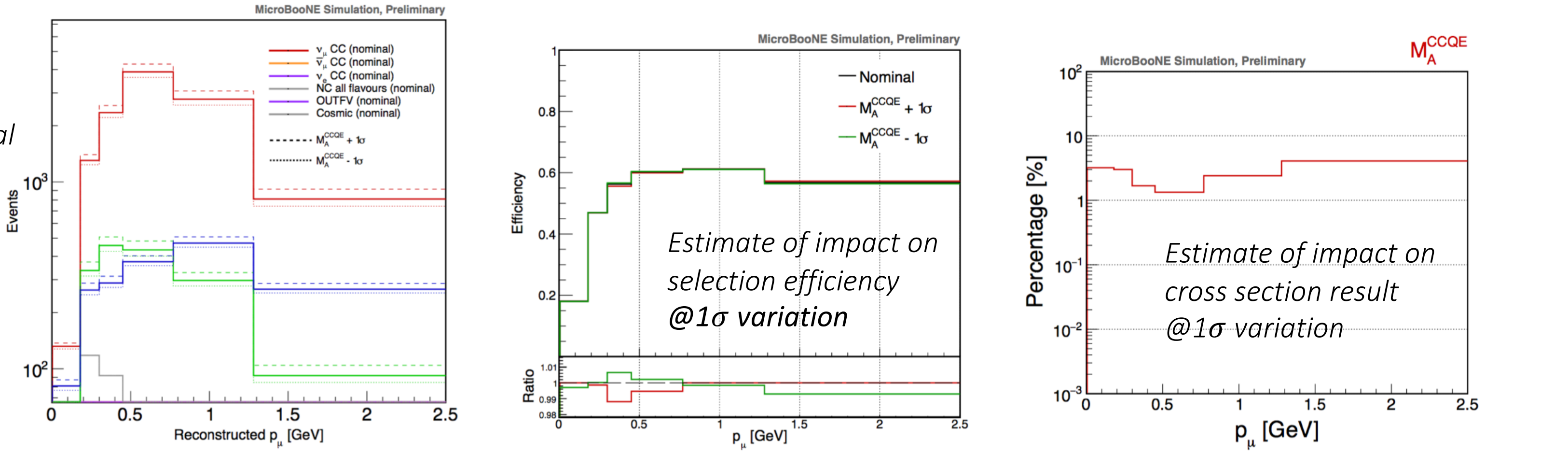
Cross section model uncertainties

- Default: GENIE **v2_12_2** + empirical MEC model
- All parameters are varied within the 1σ estimates given in the GENIE manual
- We use a **multisim strategy**, creating a set of universes with different variations of all parameters
- Our cross section uncertainty modeling is based on the experience from T2K and MINERvA

Illustration of the impact of a parameter variation on the ν_μ CC inclusive: M_A^{CCQE}

Propagation of uncertainties on signal und GENIE simulated backgrounds

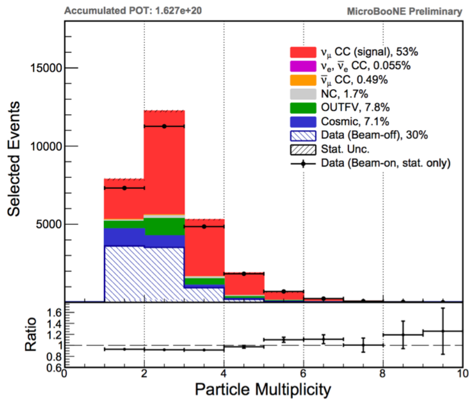


(a) Number of events (b) Selection efficiency (c) Cross section percental difference

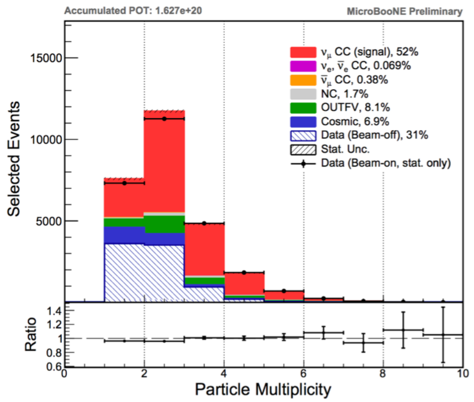
- Currently developing a re-weighting strategy for MEC uncertainties based on differences between the GENIE empirical and Valencia QE&MEC models. Will be included in publication of the CC incl.

Comparison to different model sets

Starting to compare our results with different models and generators by propagating through our simulation chain



(i) Default GENIE + Emp. MEC.



(j) GENIE Alternative.

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

Also used for comparison in *T2K, MINERvA* *T2K*

Detector response uncertainties

Largest contributor to systematic error budget:

	ν_μ CC incl.	ν_μ CC π^0
Total systematic uncertainty	25%	31%
Detector response uncertainty	19%	21%

Technique:

Unisim simulation

Generate a data sample for each uncertainty that is varied.

Note: all data samples use identical generated interactions

Different effects contained in "detector response uncertainties"

Group into two categories:

- Electron and light propagation
- Readout response

Electron and light propagation uncertainties

Electron and light propagation	Present implementation	Future implementation
Electron lifetime	"Extreme case" simulation	*Ongoing MicroBooNE calibration measurements will constrain these uncertainties further*
Recombination	External models	
Longitudinal Diffusion & Transverse Diffusion	External constraints	
Space charge	Alternative MicroBooNE model	
Outside-TPC light visibility	Conservative estimate	
Light production yield	Updated vs. current simulation	New light yield simulation becomes new default simulation

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Readout response uncertainties

Readout response	Present implementation	Future implementation
Dynamic induced charge	Updated vs. current simulation	New dynamic induced charge simulation becomes default simulation
Saturating channels	“Extreme case” simulation	*Working on more realistic treatment*
Misconfigured channels	“Extreme case” simulation	
Wire response function	Constraints from first MicroBooNE data	*Improvements in noise filtering and signal processing, and usage of cosmic data as background expected to reduce impact of these effects*
Wire noise	Constraints from first MicroBooNE data	
PMT PE noise	Constraints from first MicroBooNE data	

JINST 12 (2017) no.08, P08003
https://arxiv.org/abs/1705.07341

JINST 13 (2018) no.07, P07006 & P07006
https://arxiv.org/abs/1802.08709 & https://arxiv.org/abs/1804.02583

Readout response uncertainties

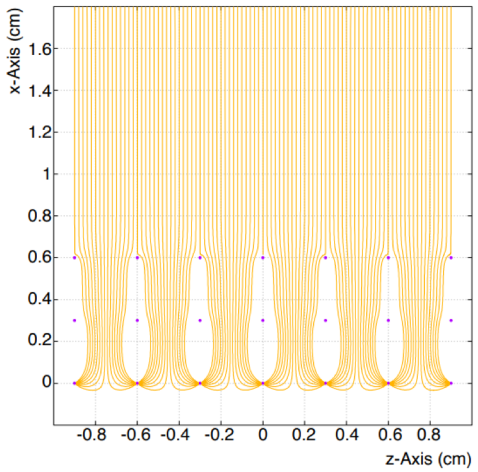
Readout response	Present implementation
Dynamic induced charge	Updated vs. current simulation
Saturating channels	
Misconfigured channels	
Wire response function	
Wire noise	
PMT PE noise	

	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%

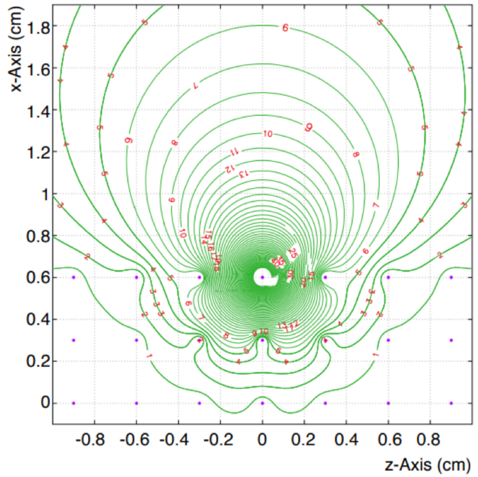
- Most parameters contribute on the 1-2% level
- Dynamic induced charge is by far the largest contributor to the detector response uncertainty

Dynamic induced charge effect

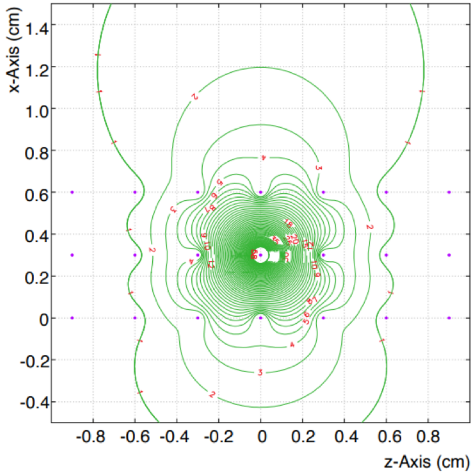
JINST 13 (2018) no.07, P07006 & P07006
https://arxiv.org/abs/1802.08709
https://arxiv.org/abs/1804.02583



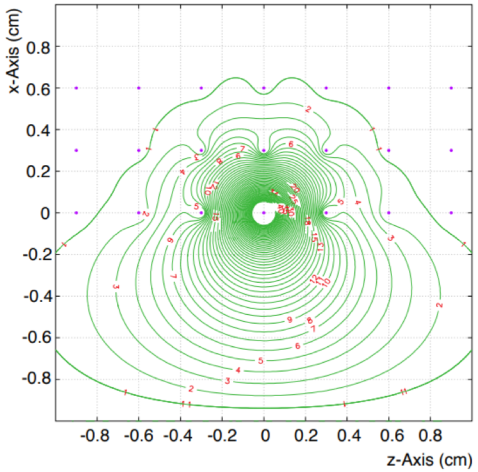
(a) Electron drift paths.



(b) Weighting potential on a U wire.



(c) Weighting potential on a V wire.



(d) Weighting potential on a Y wire.

- Drifting electrons induce charge not only on the central wire but also on neighboring wires
- This effect is observed in data, but not modeled in our default simulation
- The impact on our reconstruction and analyses is strongest for tracks traveling towards the wire plane
  ☑ we have verified that we can see this in several analyses. Simulation of dynamic induced charge improves our data/MC agreement
- Comparing the impact of "dynamic induced charge on/off" and use as systematics is exaggerating the effect
- Future simulation will include simulation of dynamic induced charge as default
- MicroBooNE is the first LAr TPC experiment to take this into account

Today's presentations

MicroBooNE has a lot of new work to show since last NuInt!

MicroBooNE detector, modelling and performance	*Anne Schukraft*
Gran Sasso Science Institute (GSSI)	16:30 - 17:00
MicroBooNE charged-current inclusive cross section measurement	*Marco Del Tutto*
Gran Sasso Science Institute (GSSI)	17:00 - 17:25
MicroBooNE charged-current neutral pion cross section measurement	*Joel Musseau*
Gran Sasso Science Institute (GSSI)	17:25 - 17:50
MicroBooNE electron neutrino inclusive cross section	*Colton Hill*
Gran Sasso Science Institute (GSSI)	17:50 - 18:15
MicroBooNE charged-current analyses with final state protons	*Raquel Castillo Fernandez*
Gran Sasso Science Institute (GSSI)	18:15 - 18:40

MicroBooNE's first single differential cross sections (Paper in preparation)

- Developing tools for cosmic rejection
- pre-selection for majority of current analyses

First ν_μ CC π^0 production on Argon (Paper under collaboration review)

- first time exercising shower reconstruction
- π^0 are in important background to constrain in LEE searches

MicroBooNE's first NuMI analysis

- Exercising NuMI analysis flow
- Exercising ν_e reconstruction and identification

MicroBooNE's first proton analysis

- Exercising calorimetric reconstruction
- Exercising proton identification

MicroBooNE cross sections beyond NuInt

Ongoing work towards improved performance

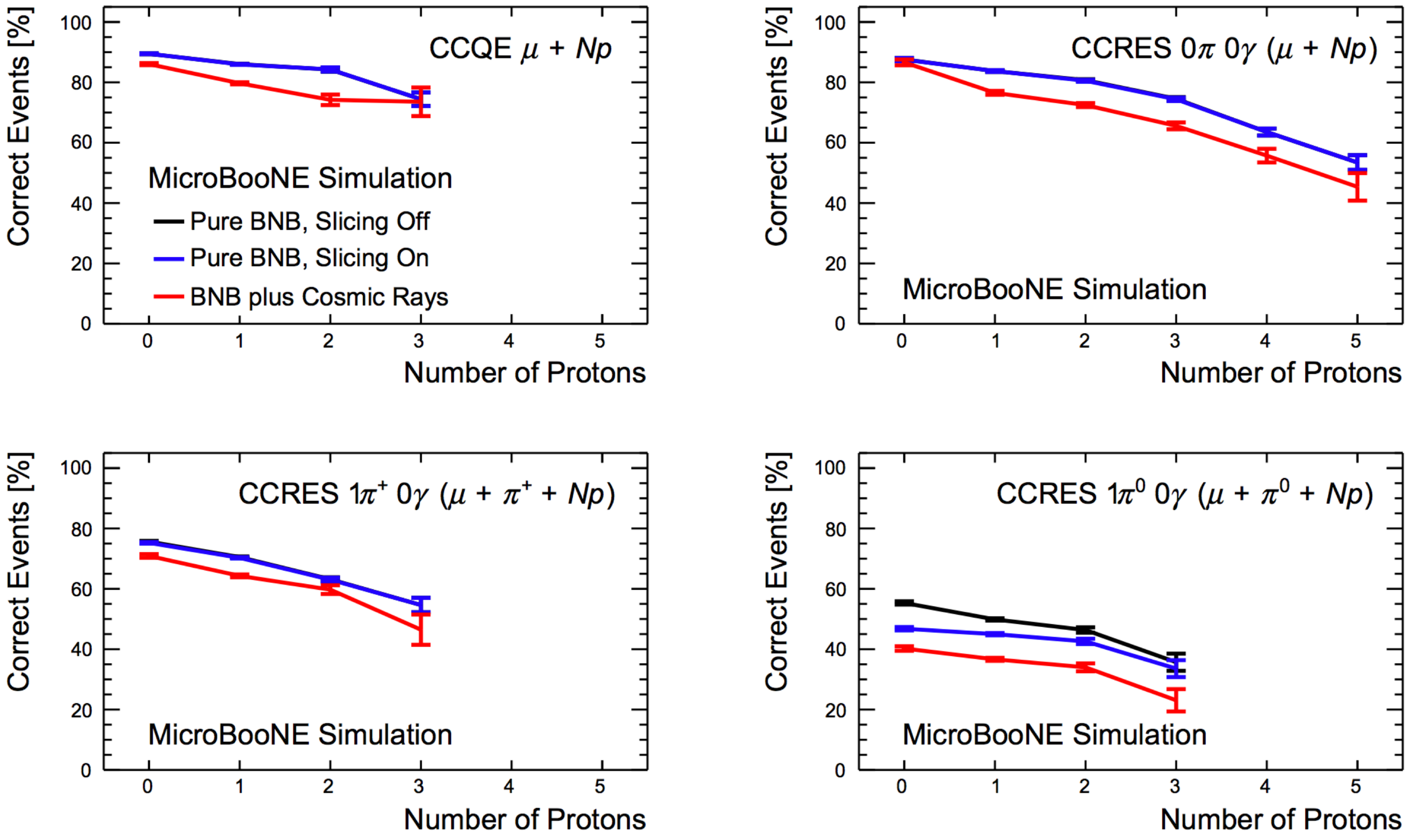
- Detector physics measurements
  to improve systematics constraints
- Integration of cosmic tagger system
  into analysis flow for better cosmic rejection
- Development of alternative reconstruction chains
  (e.g. machine learning) in particular for better
  shower reconstruction
- Improvements to particle ID and detection thresholds

Other analyses in progress

- Neutral-Current elastic scattering, charged-current 0π, $1\mu + 1p$ channel
- charged pion production, CC and NC neutral pion production, Coherent pion production
- Kaon production

Backup

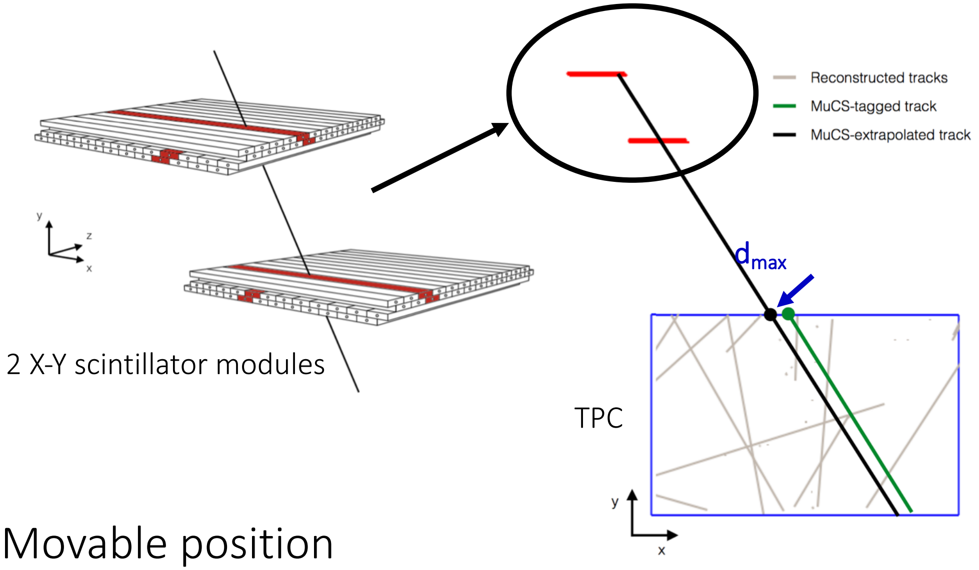
Pandora reconstruction performance in the presence of cosmics



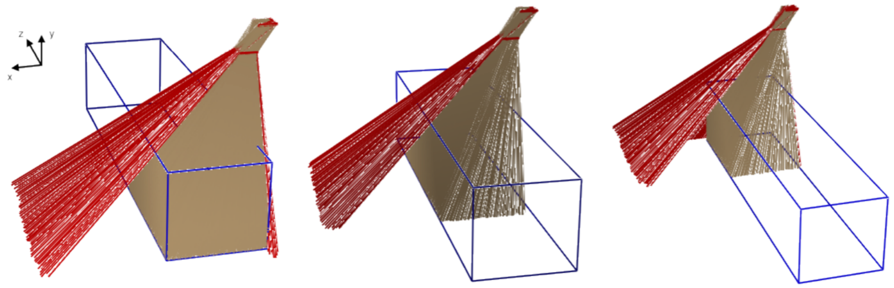
Eur. Phys. J. C78 (2018) no.1, 82
https://arxiv.org/abs/1708.03135

Data-driven tracking efficiency estimation

External muon telescope to measure the efficiency of our track reconstruction with cosmics

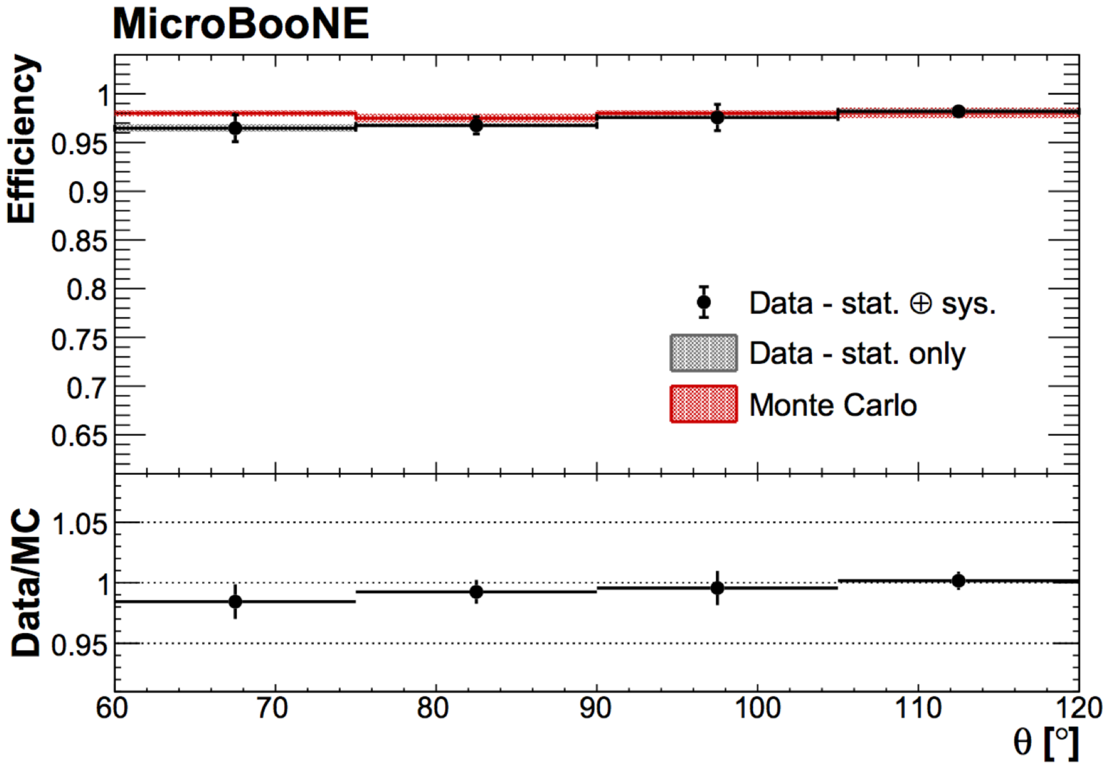


Movable position
–> test different angles and locations in TPC



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

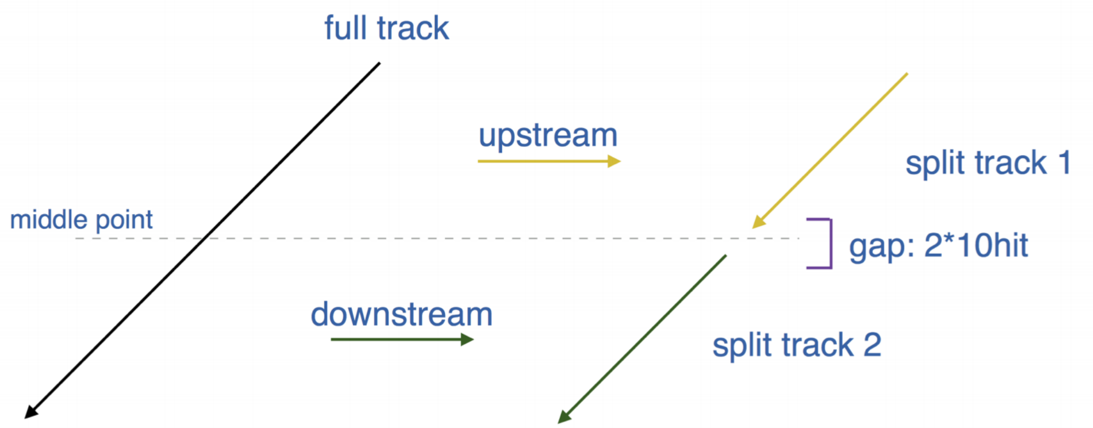
JINST 12 (2017) no.12, P12030
https://arxiv.org/abs/1707.09903



- Overall reconstruction efficiency is high:
  (97.1 ± 0.1 (stat) ± 1.4 (sys)) %

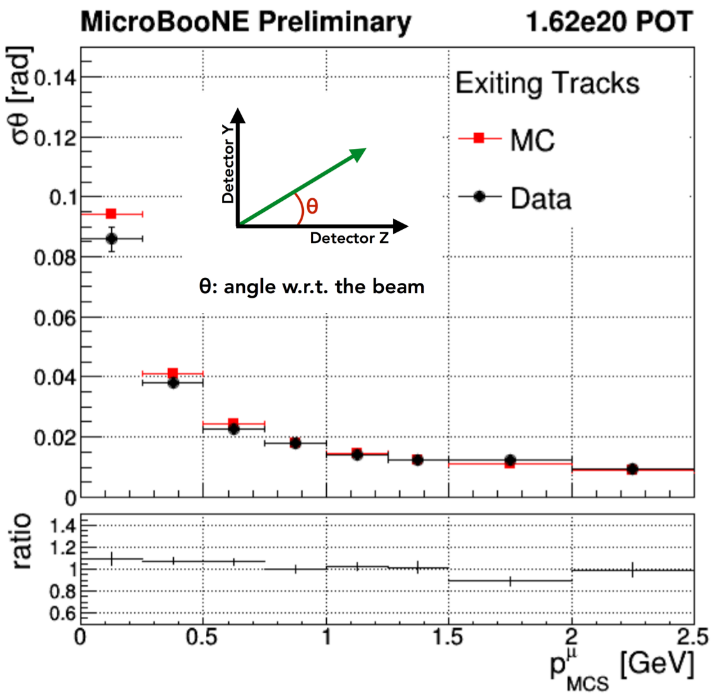
- Measured reconstruction efficiency from data agrees with the predicted efficiency in the simulation
  -> confirmation of our simulation and reconstruction chain

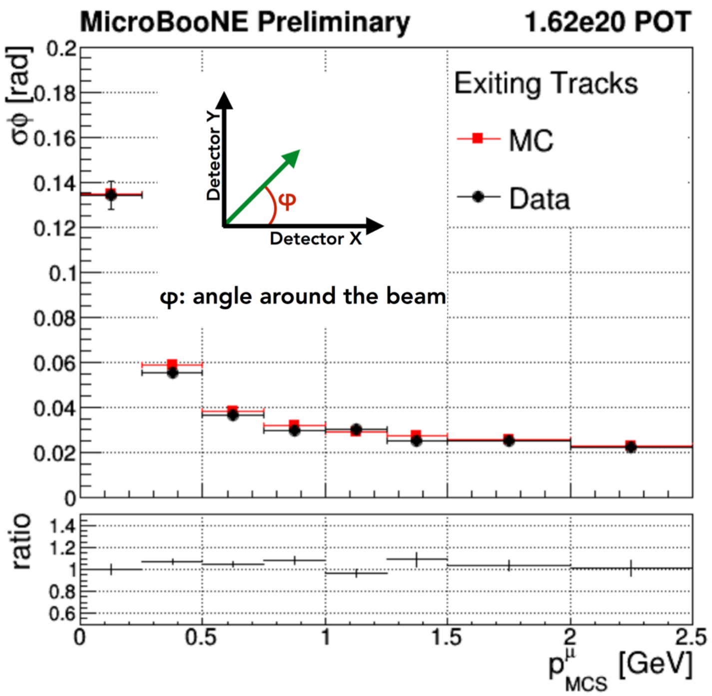
Data-driven Track resolution

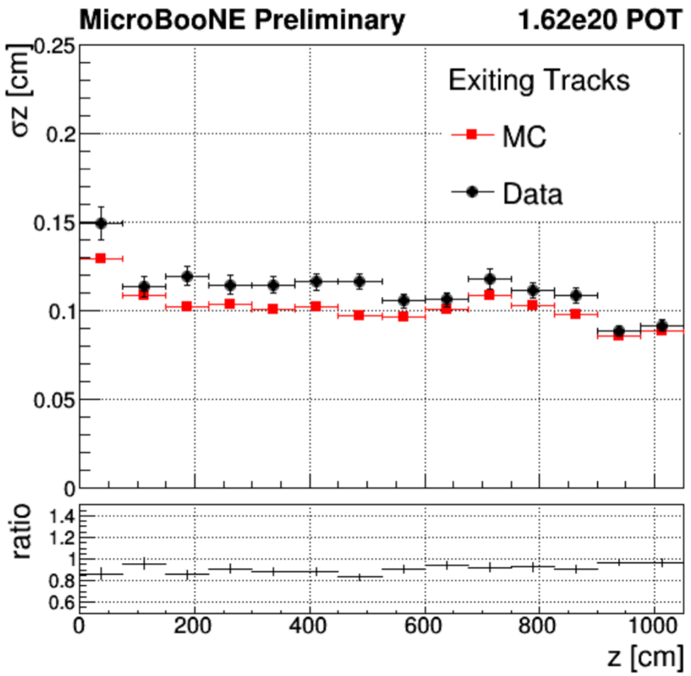


Developed more data-driven methods to build trust into our simulation based reconstruction performance estimates

- Here: split track in the middle, reconstruct each half, compare the reconstructed directions
- Most important take away: Performance estimates in data and MC are very similar







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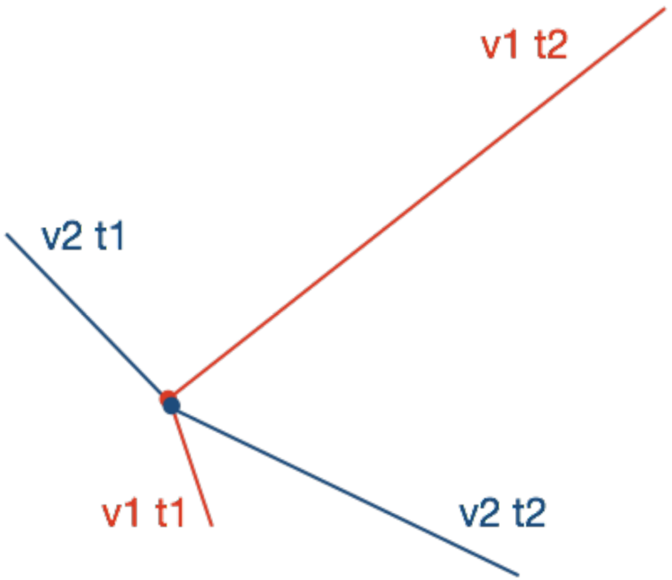
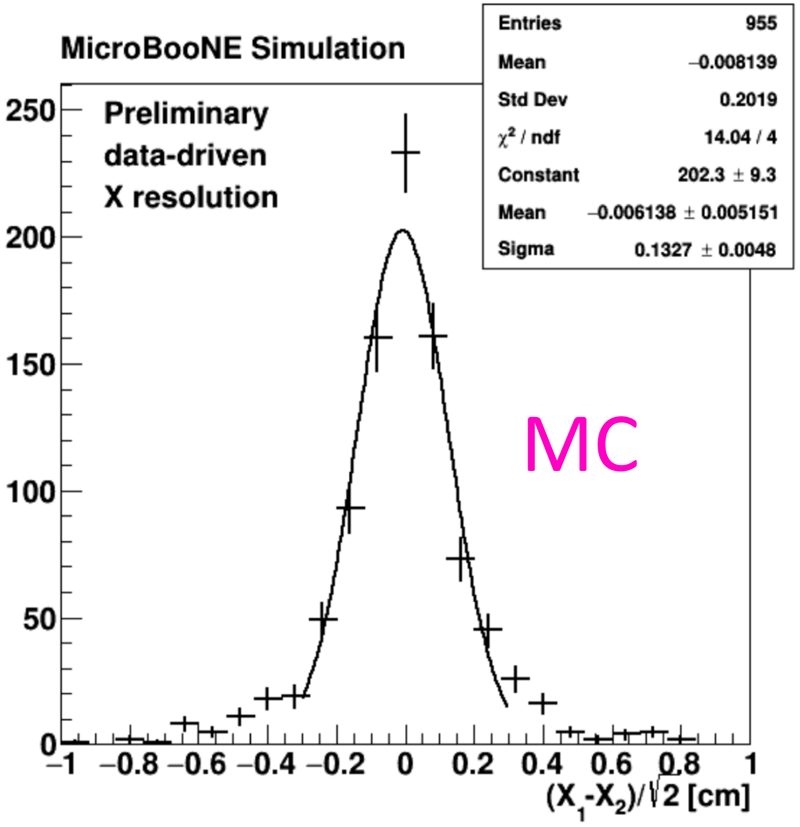
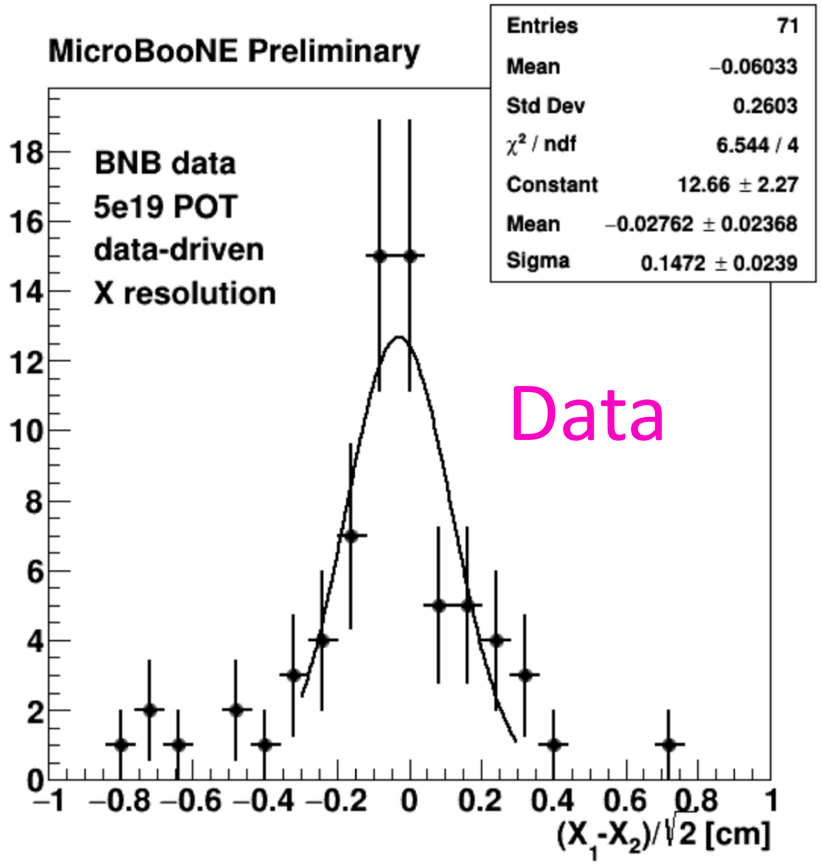
Data-driven vertex resolution

- Here: split 4-track events into pairs of 2-tracks. Reconstruct the vertex position in both cases and compare vertex positions







Resolution	Data	MC
x	0.15±0.02 cm	0.133±0.005 cm
y	0.24±0.05 cm	0.182±0.006 cm
z	0.18±0.02 cm	0.209±0.009 cm

- Performance estimates in data and MC are similar in general.

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Momentum reconstruction

Methods of momentum reconstruction in MicroBooNE

For contained muons:

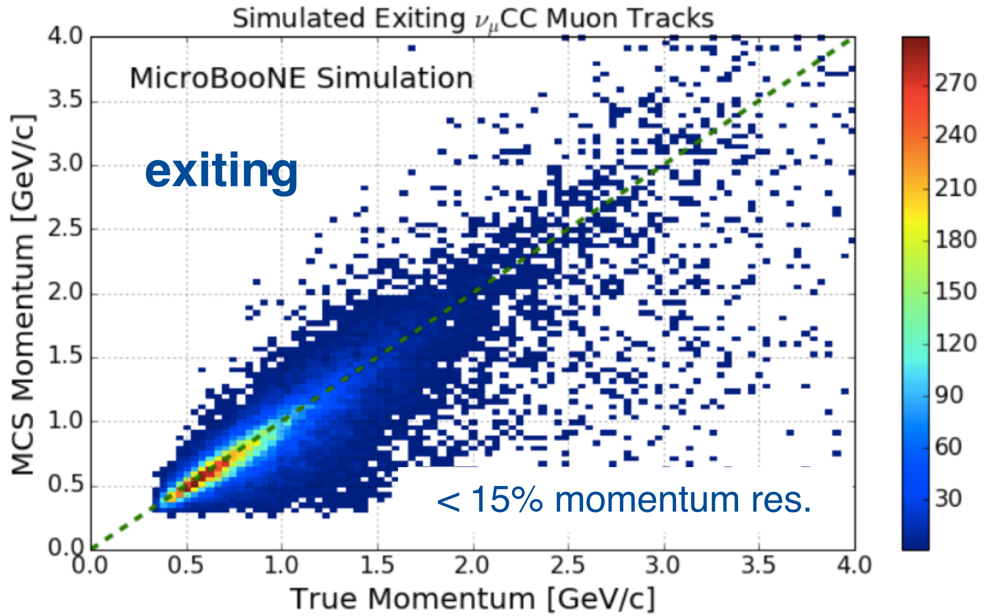
- Range-based
- Calorimetric

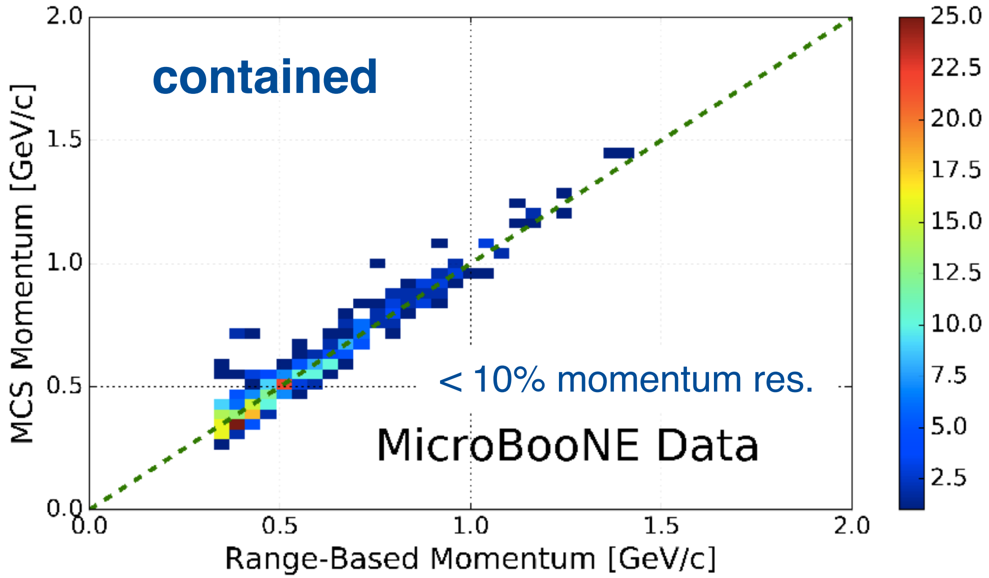
JINST 12 (2017) no.10, P10010
https://arxiv.org/abs/1703.06187

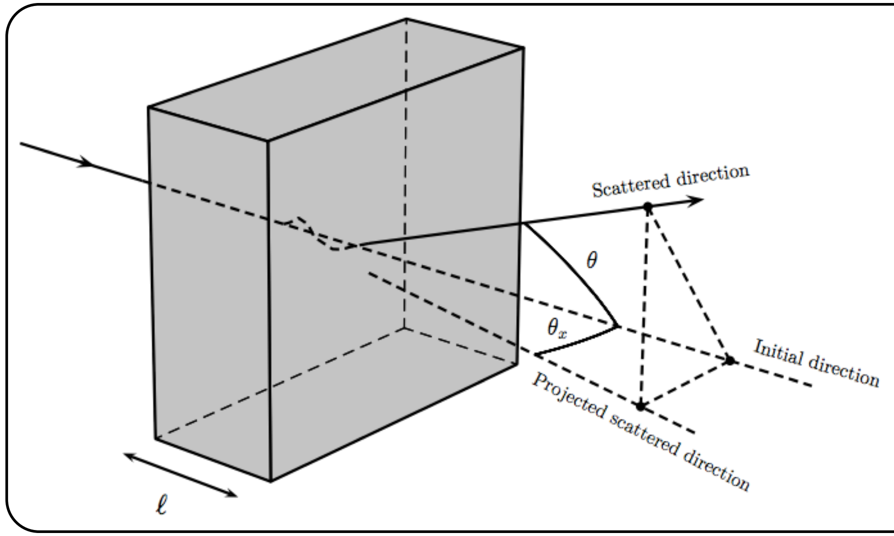
For contained and exiting muons

- Multiple Coulomb scattering

The majority of BNB muons in MicroBooNE is exiting!





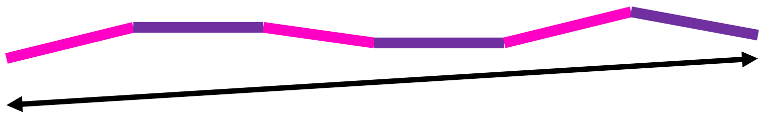


The spread of deflection angles along a track depends on the particle's momentum

Momentum reconstruction performance

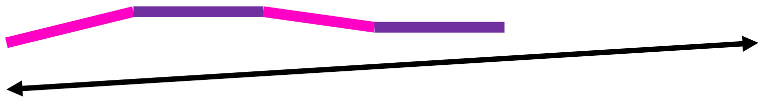
Data driven method to test the performance of MCS for exiting tracks:

Contained data track
Split in 14cm segments for MCS measurement

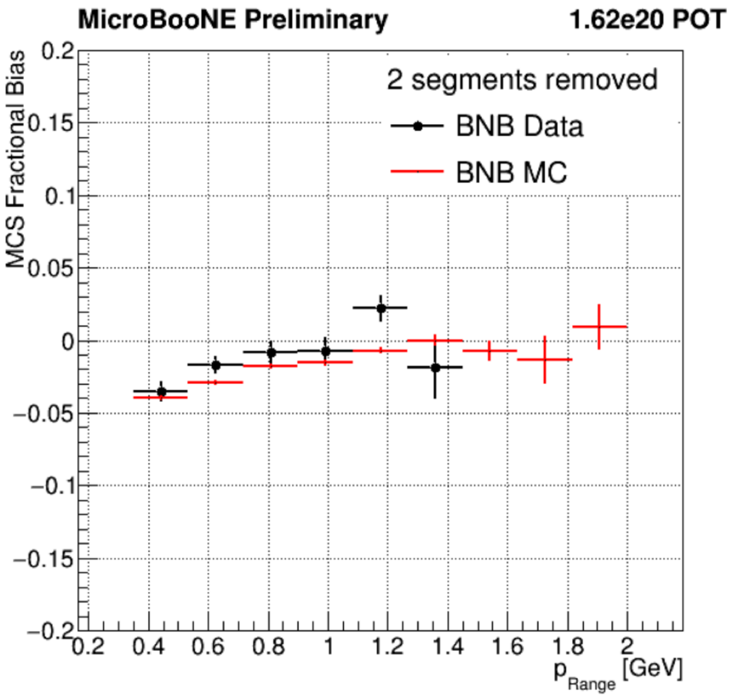


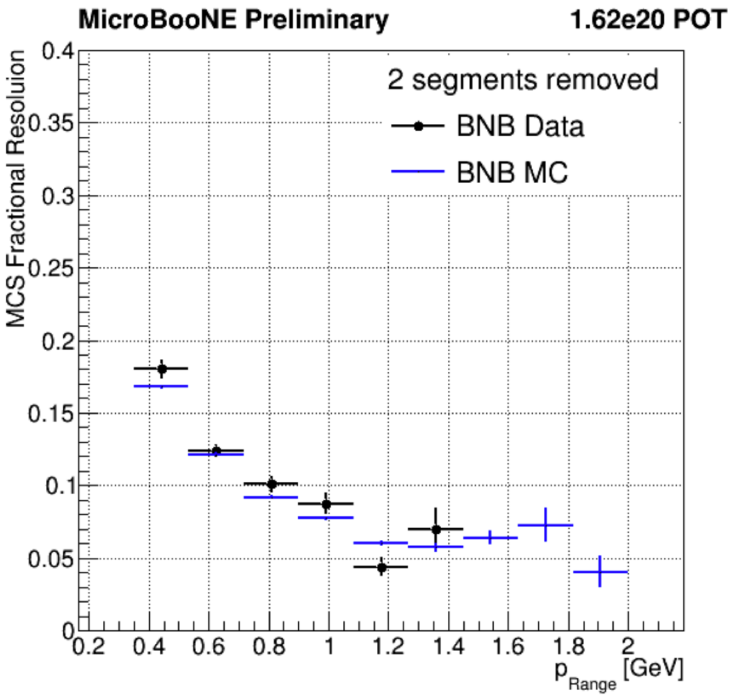
p_{range} Know momentum from range measurement

Turn into
Pseudo-exiting data track
by removing track segments at the end



p_{range} Still know momentum from range measurement





- Bias < 5%
- Resolution < 20%, improving with momentum
- Good agreement between data and MC for this method!

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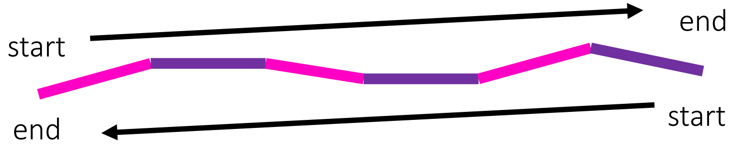
http://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1049-PUB.pdf

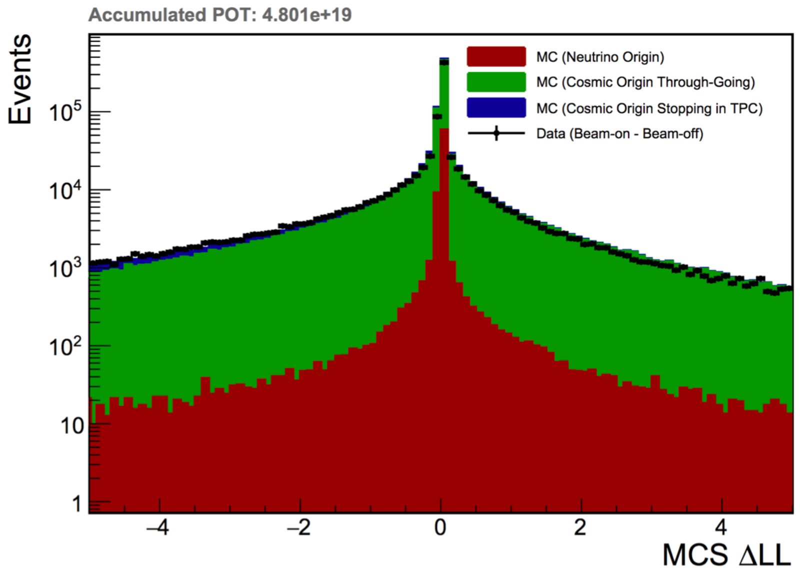
Other uses of Multiple Coulomb Scattering

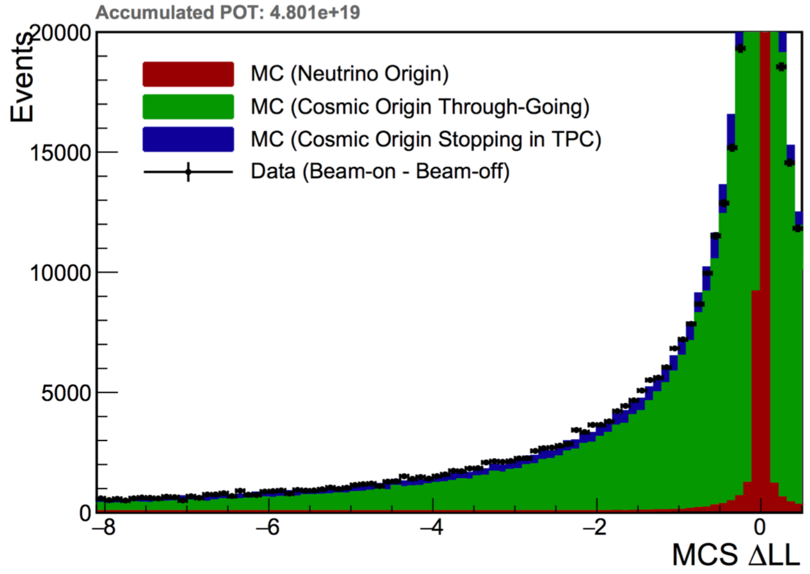
Identification of stopping muons

- The MCS fit to a track can be performed in both directions. The difference of the Log-likelihood helps determine the true track direction



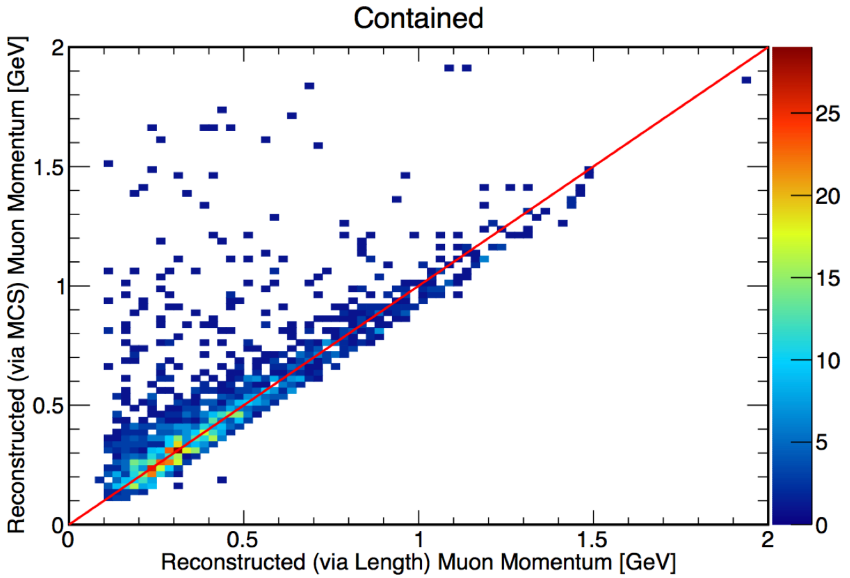
- This is used to identify entering cosmics

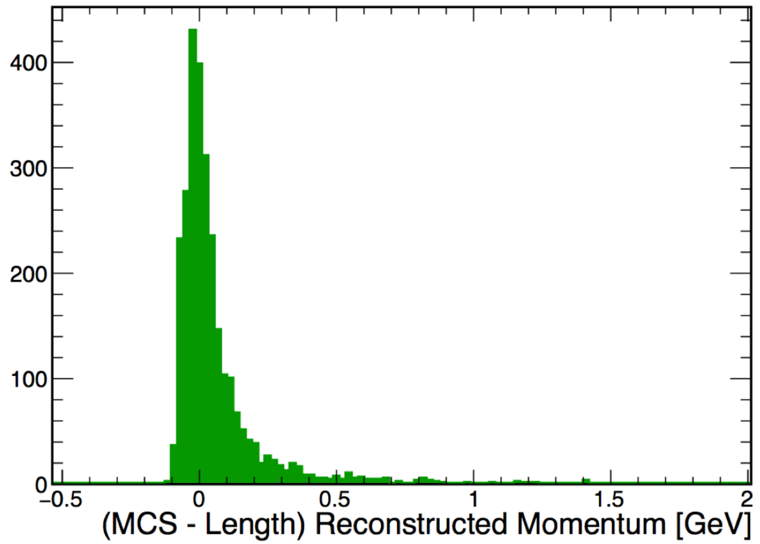




Identification of mis-reconstructed tracks

- A comparison of the MCS and range-based reconstructed momentum for contained tracks helps identify mis-reconstructed tracks





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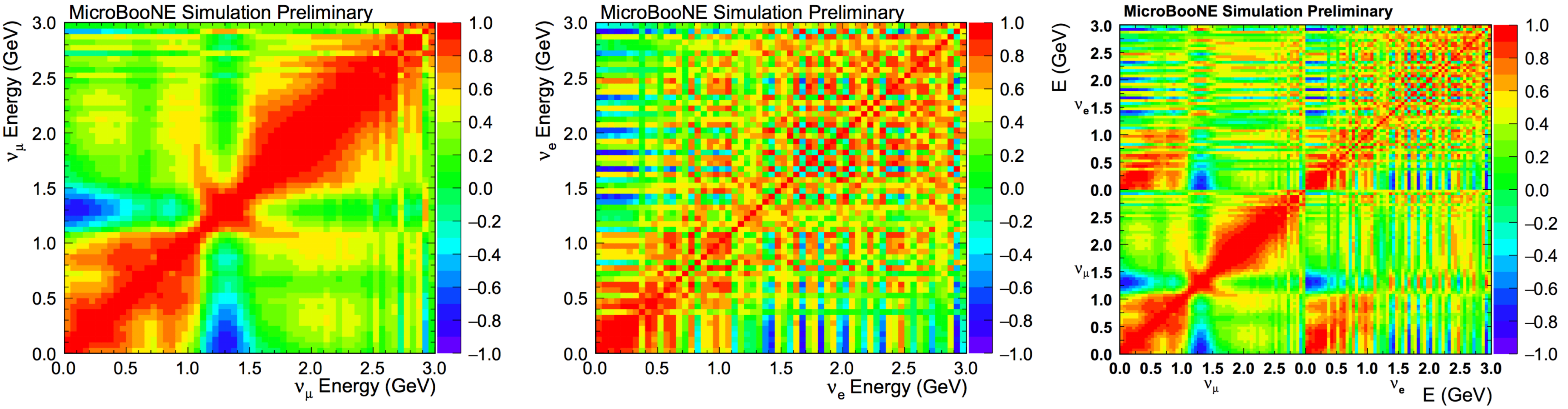
Beam flux correlation matrices (BNB)



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Beam flux uncertainties: all flavors

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