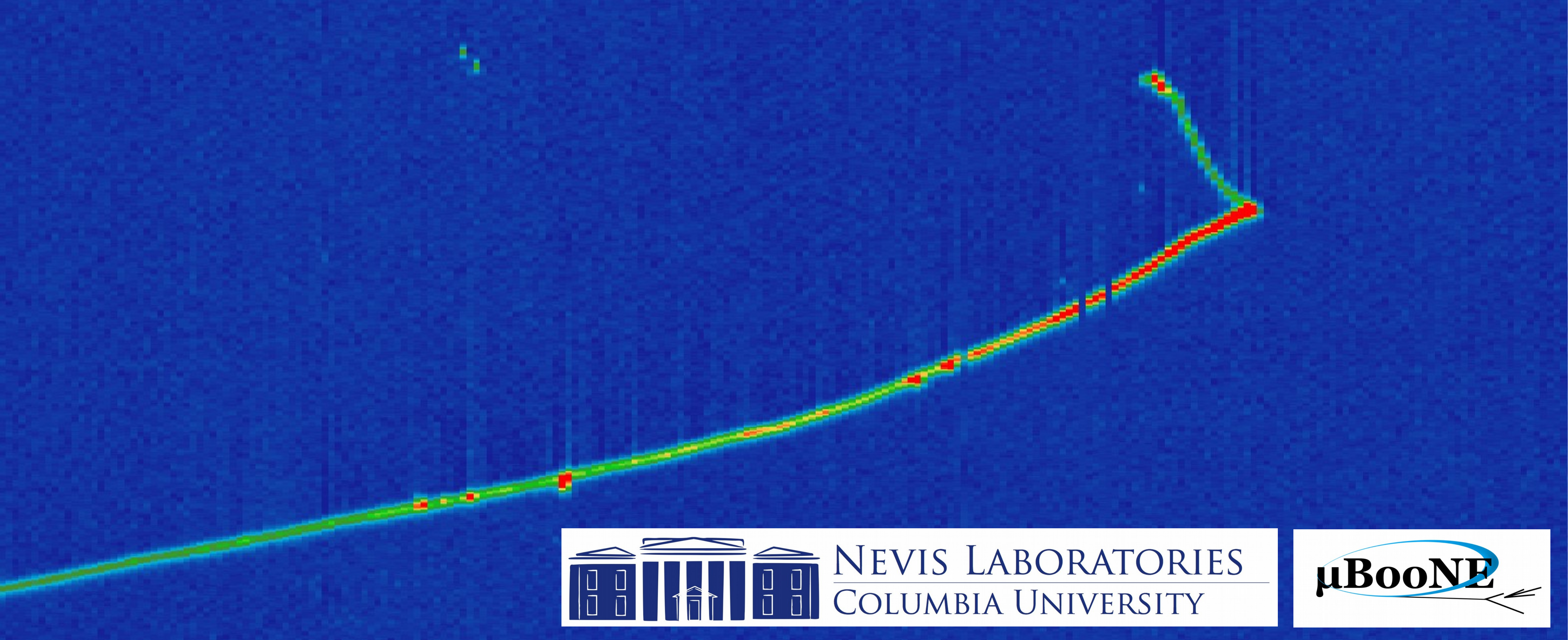
Michel Electrons in MicroBooNE

May 15th 2017, DUNE/SBN Meeting : Lessons Learned

David Caratelli

Nevis Labs @ Columbia University



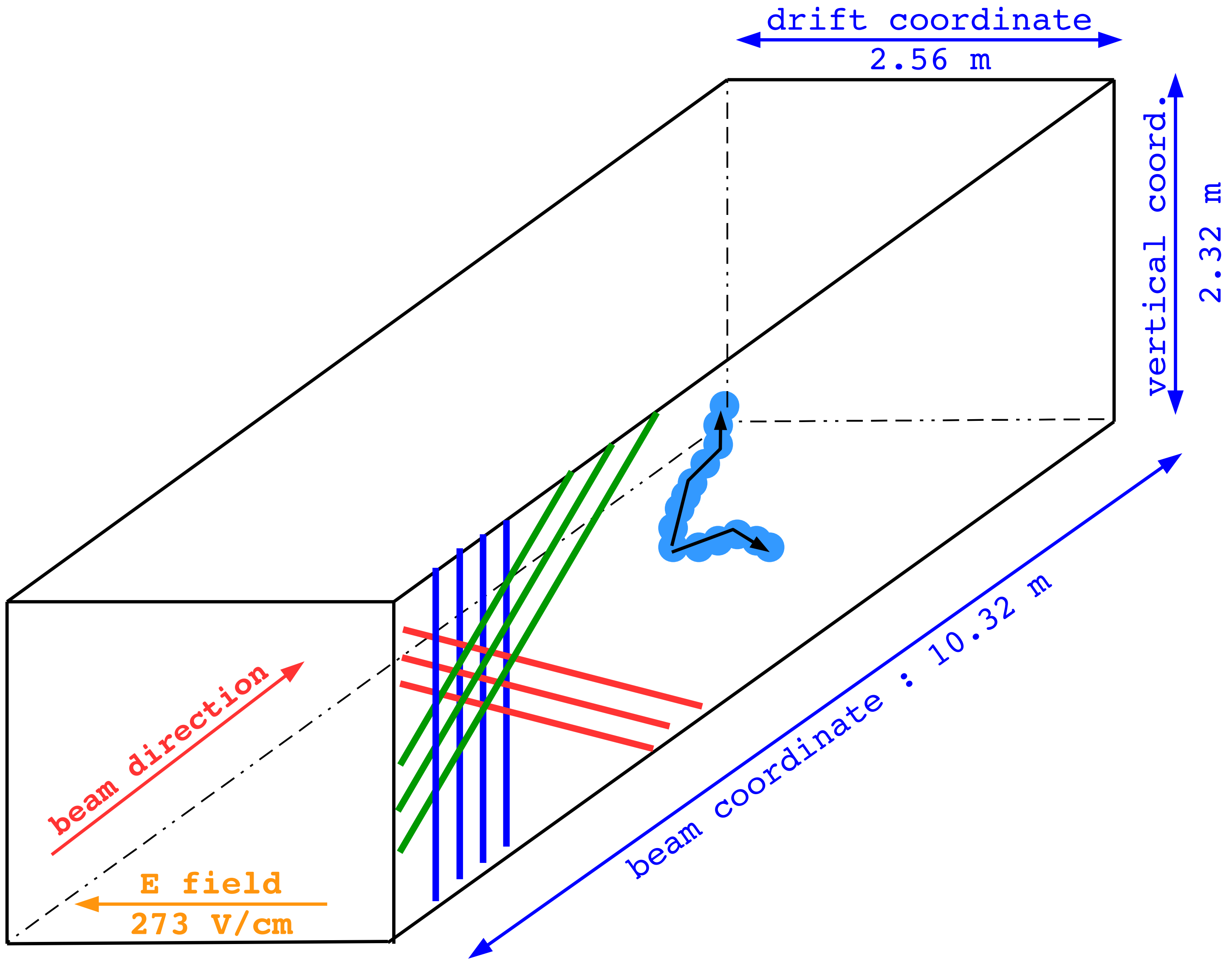
Nevis Laboratories
Columbia University

μBooNE

Outline

- Characteristics of electromagnetic energy deposition in LAr.
- How reconstruction of low-energy EM activity impacts DUNE & SBN programs.
- Reconstructing Michel electrons in MicroBooNE: results and “lessons learned”.
- Brief note on muon momentum determination via multiple Coulomb scattering.

MicroBooNE by the numbers.



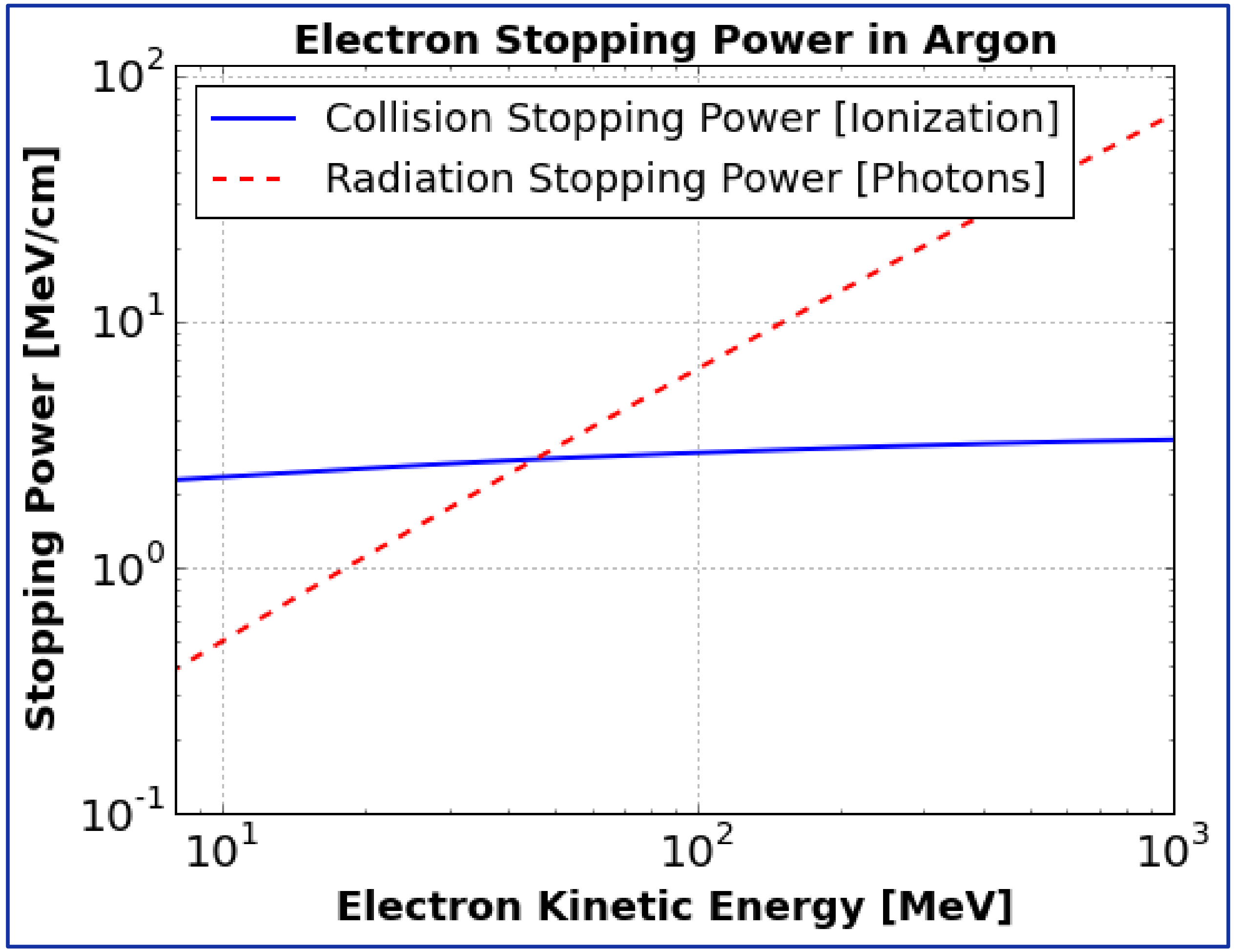
Single-phase TPC:
90 Ton active volume, on BNB @ FNAL.

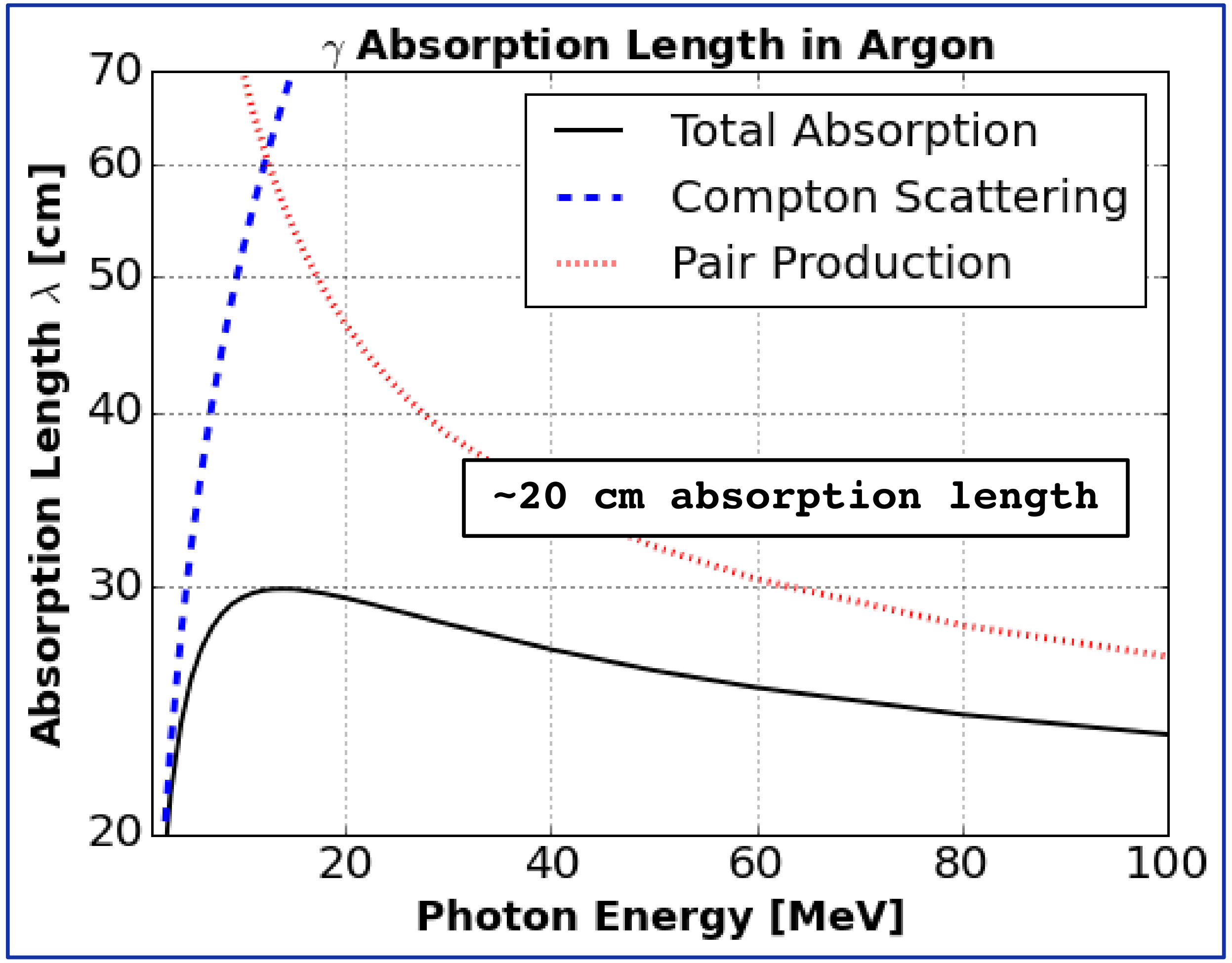
Triggered readout:
4.8 ms RO window [two drift-windows].

Drift field:
273 V/cm → 0.11 cm / μs drift velocity.

Surface detector:
5 kHz cosmic rate → ~20 cosmic muons / event.

EM activity in LAr : a summary





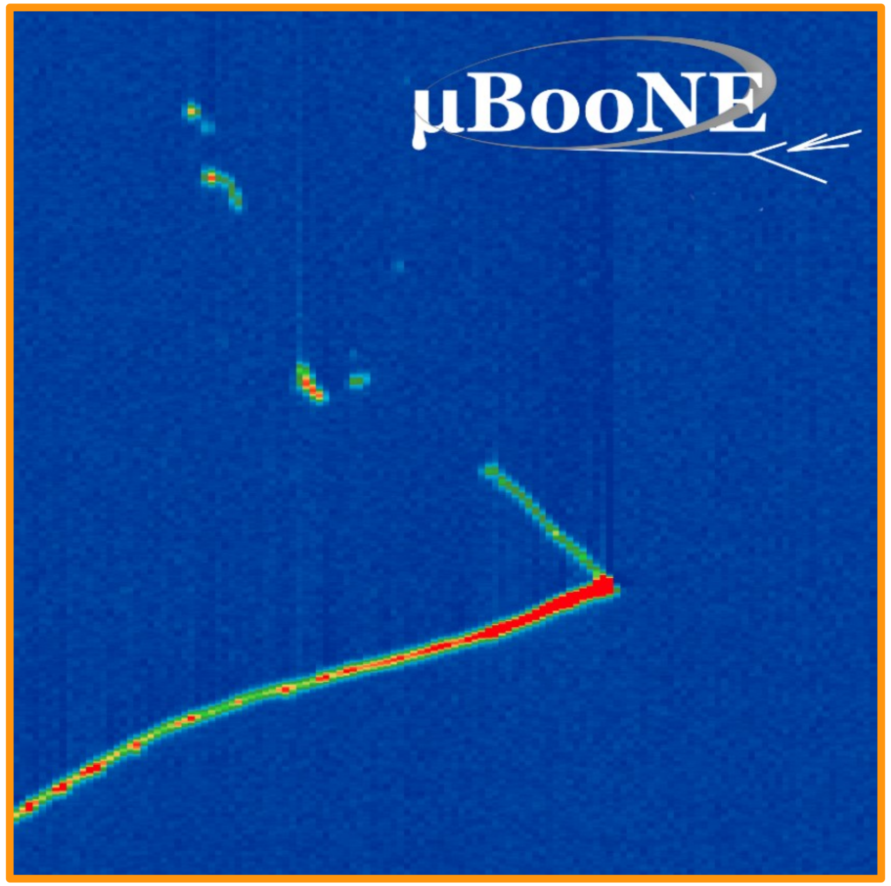
Two things to note:

1) Energy loss process depends significantly on energy. At lower energies (<100 MeV) significant contribution from primary ionization. Electron/photon not very “shower-like”.

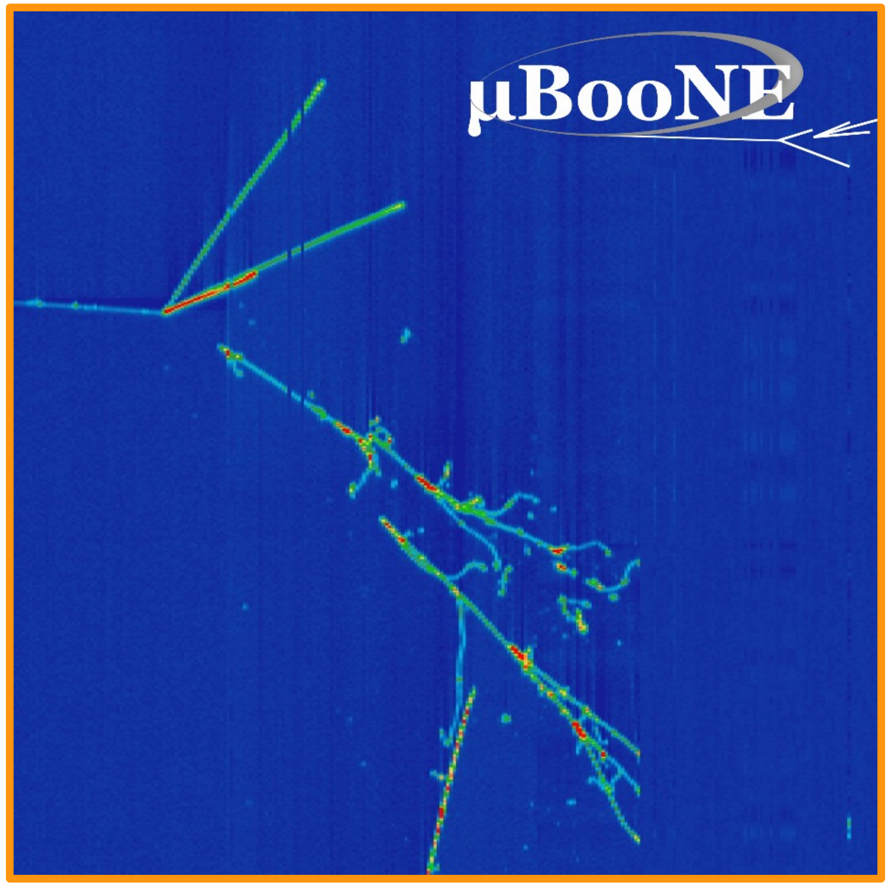
2) Radiative photons travel tens of cm before depositing their energy in TPC.

EM activity in LAr : a summary

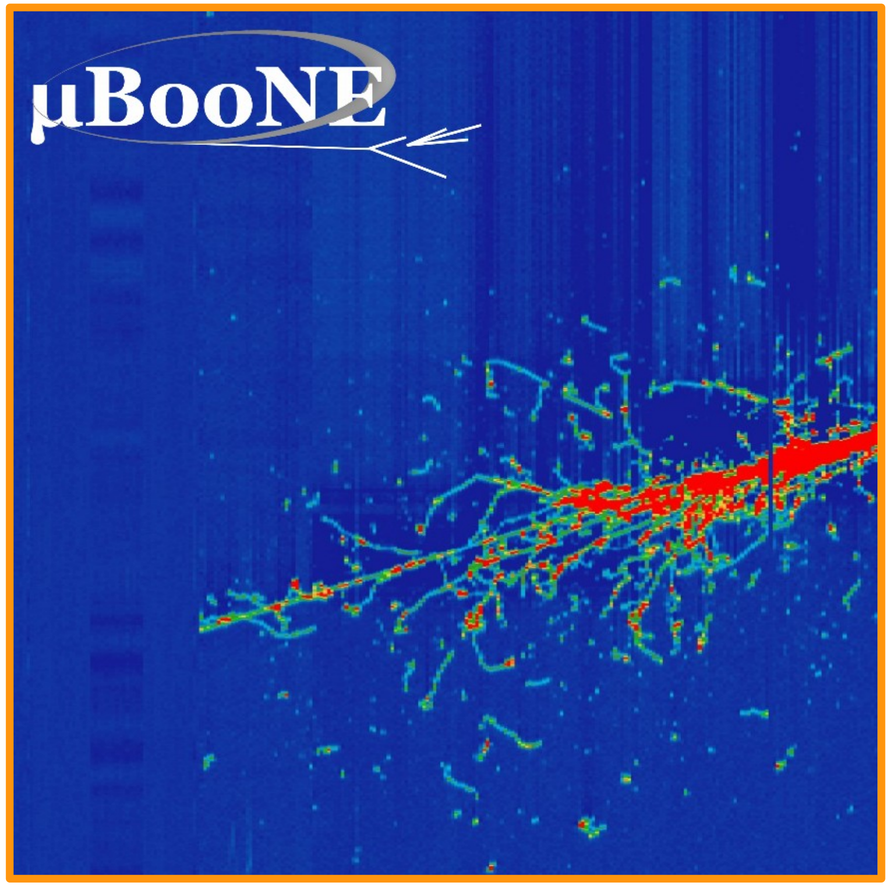
1) EM shower topology depends significantly on energy



Michel electrons [0-55 MeV]



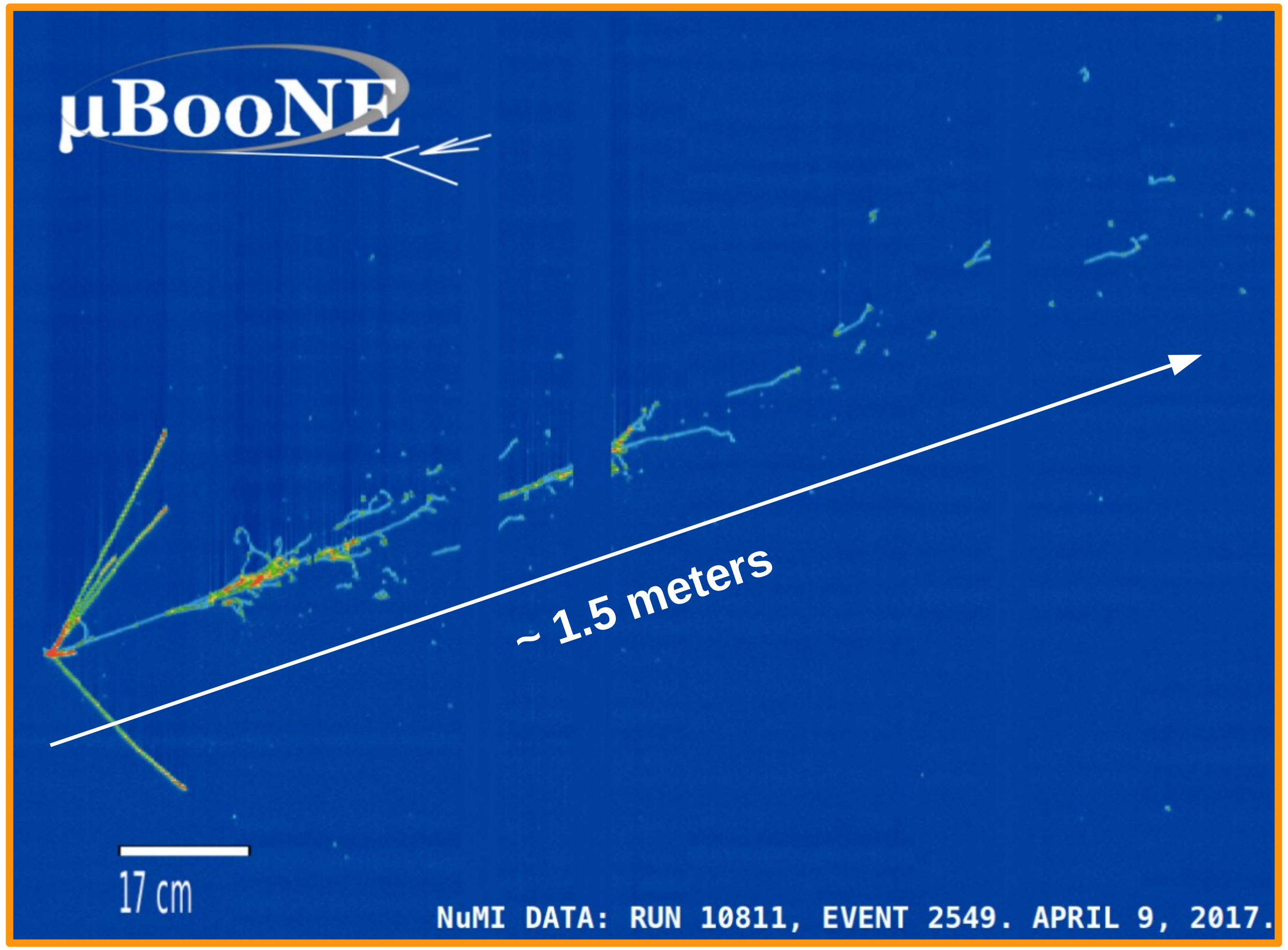
Beam π^0 [tens-hundreds MeV]

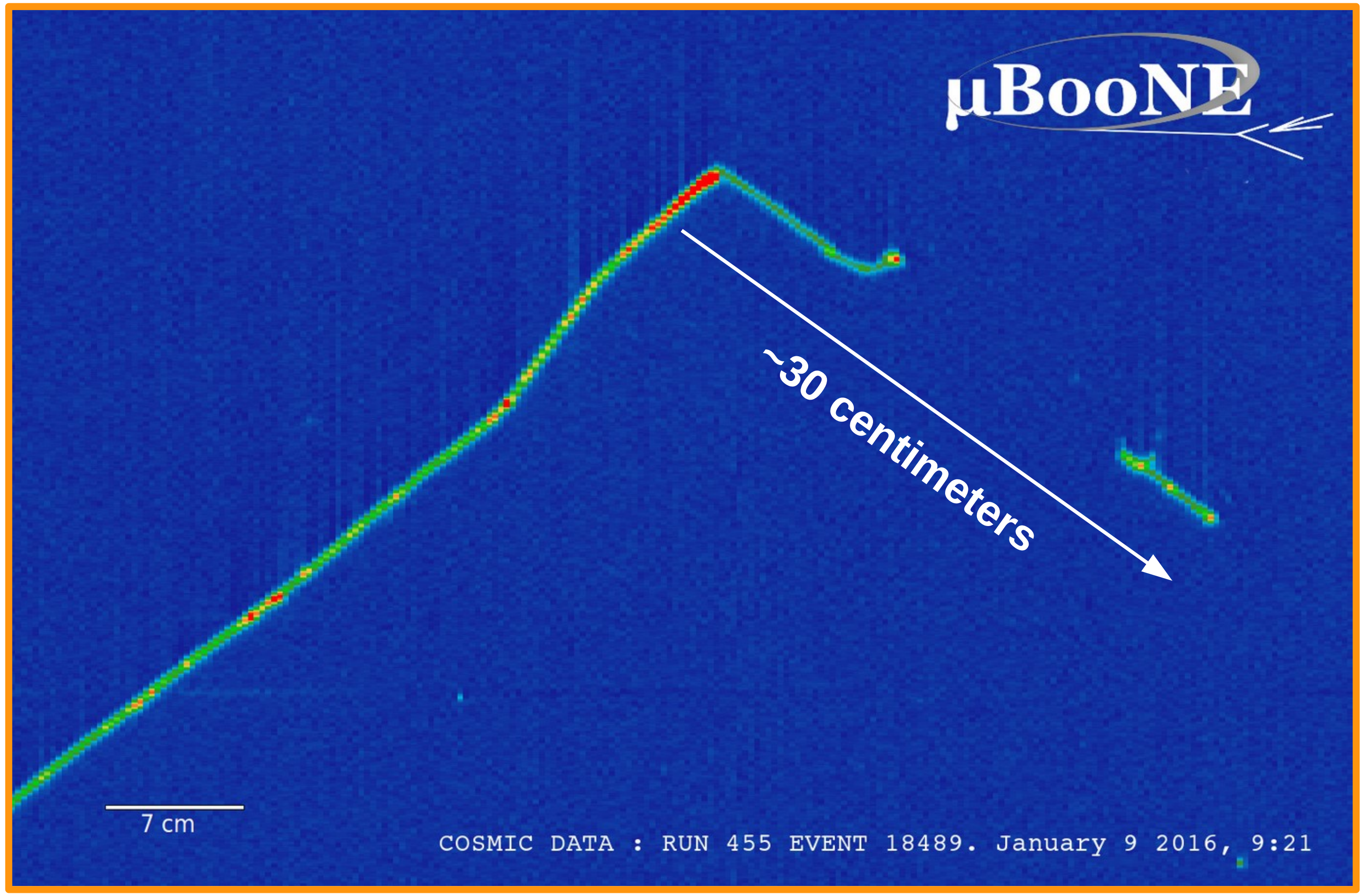


cosmic EM activity

EM activity in LAr : a summary

2) Radiative photons travel tens of cm before depositing their energy in TPC.





“Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC”

arXiv:1704.02927

Impact on DUNE/SBN Physics Programs

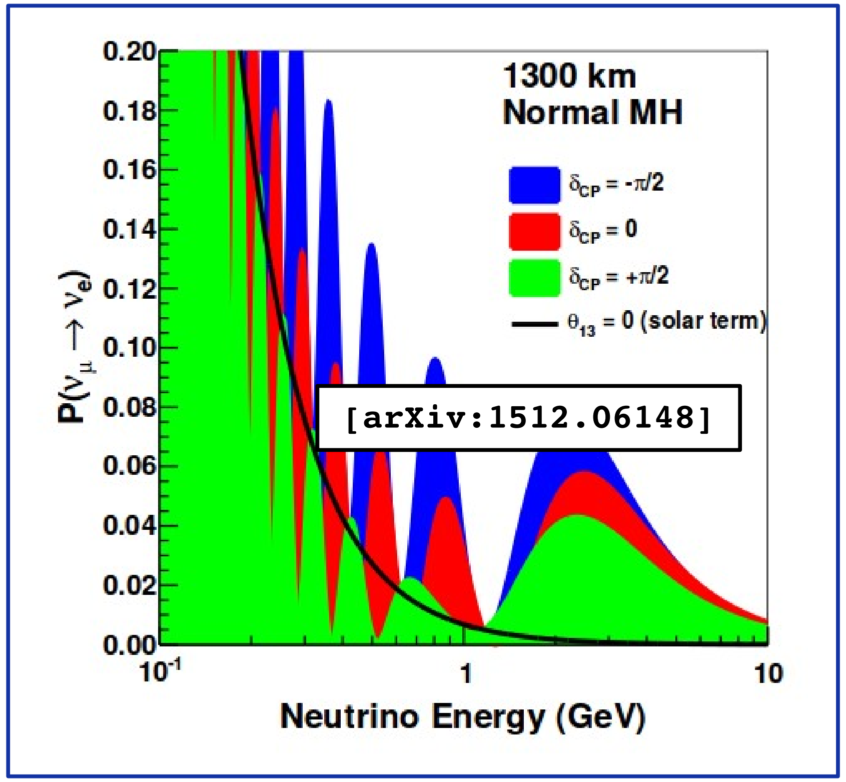
How does low-energy EM activity impact DUNE / SBN ?

1) π^0 background rejection at all ν energies.

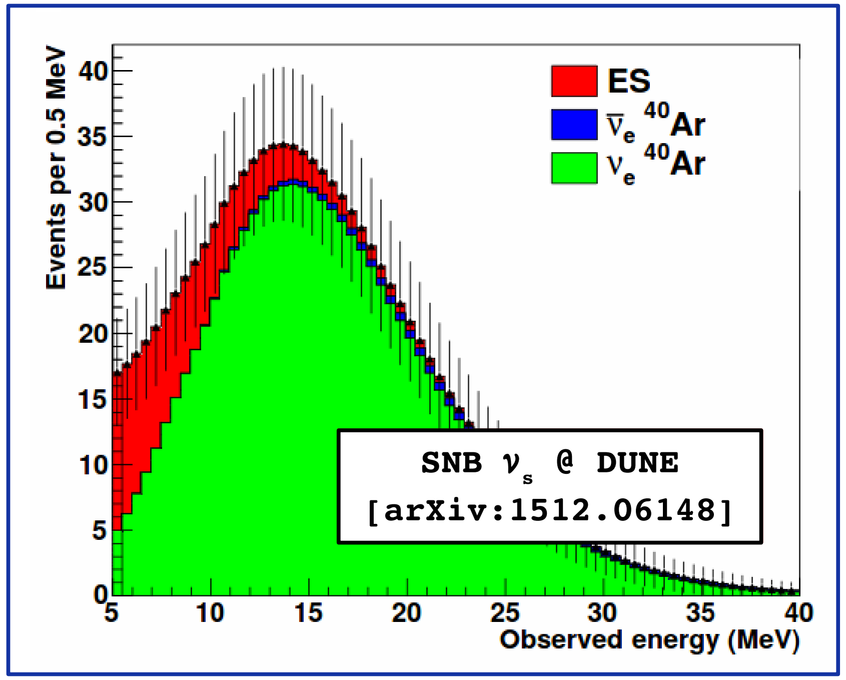
2) precise ν energy reconstruction depends on well-reconstructed lepton kinematics.

3) DUNE's 2nd oscillation peak → O(100) MeV lepton energy.

4) Impact on supernova physics.



[arXiv:1512.06148]



SNB ν_s @ DUNE
[arXiv:1512.06148]

Michel Electrons

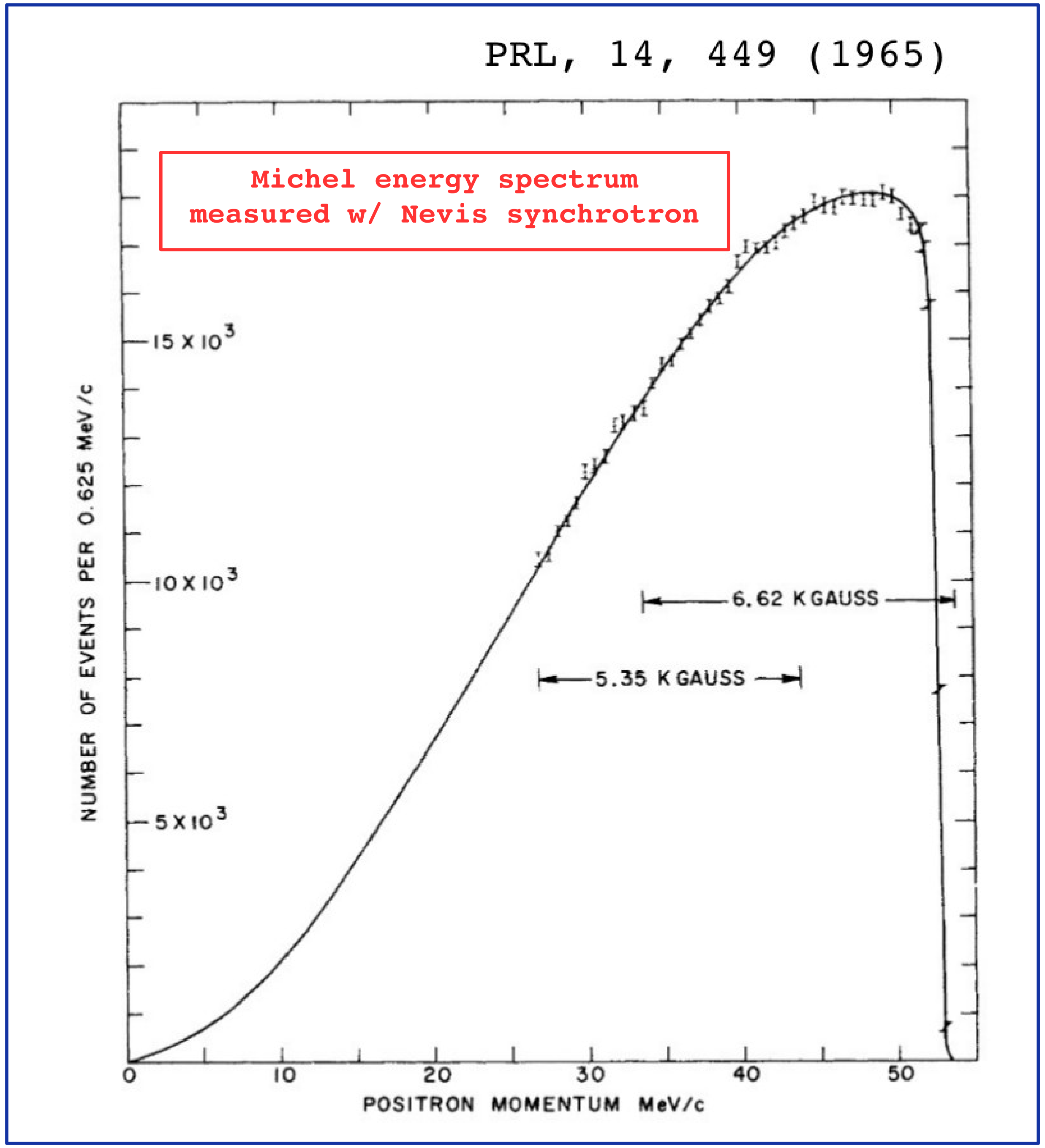
$$\mu^- \rightarrow \bar{\nu}_e \quad \nu_\mu \quad e^-$$

Michel electrons produced by decay-at-rest muons.

Take advantage of large cosmic flux : beam-external events used for this analysis.

Powerful tool to study energy response < 60 MeV.

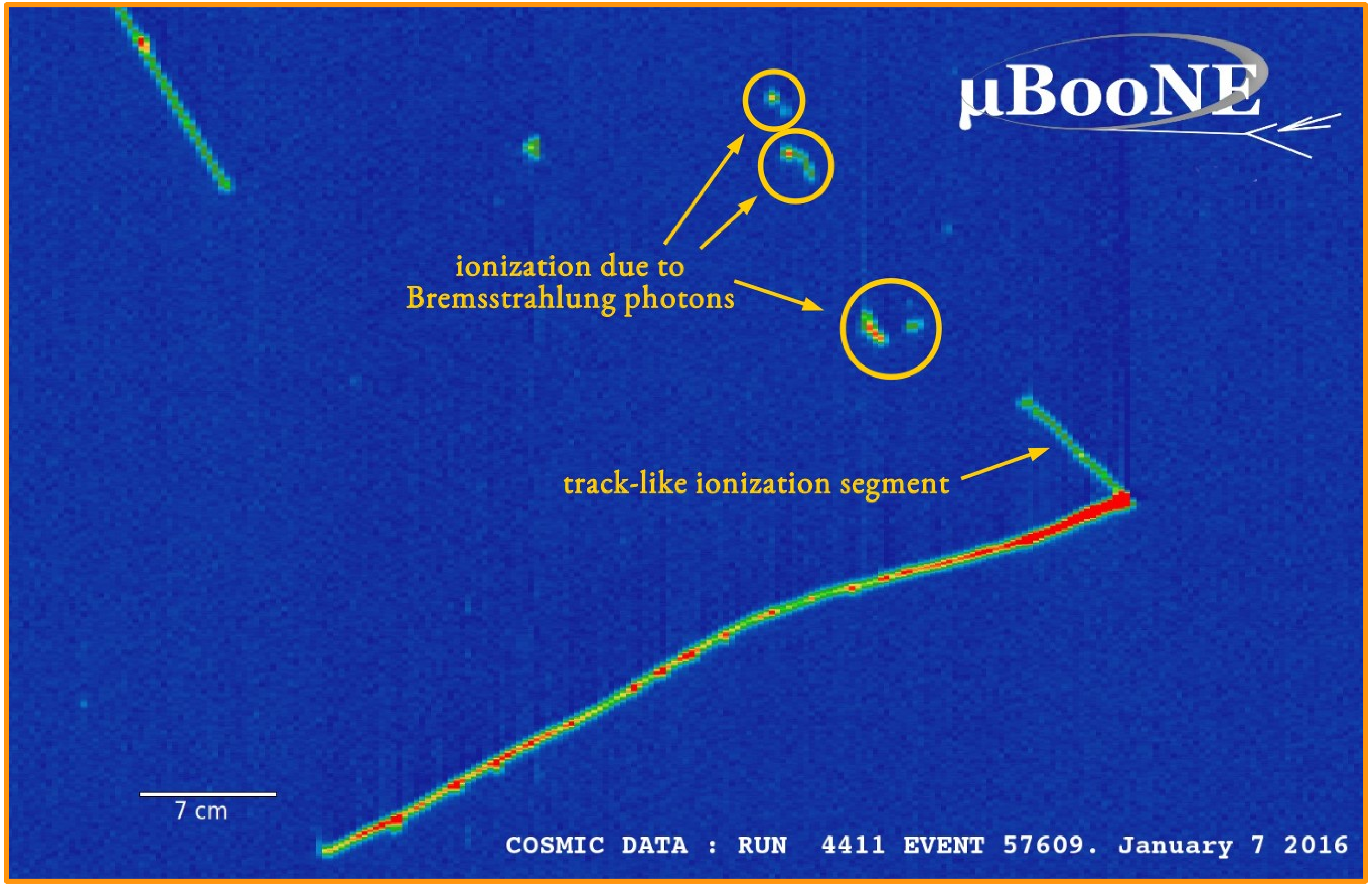
At energies < 100 MeV challenges in $e^{+/-}$ reconstruction due to topological features.



PRL, 14, 449 (1965)

Michel energy spectrum measured w/ Nevis synchrotron

What do Michel electrons look like?



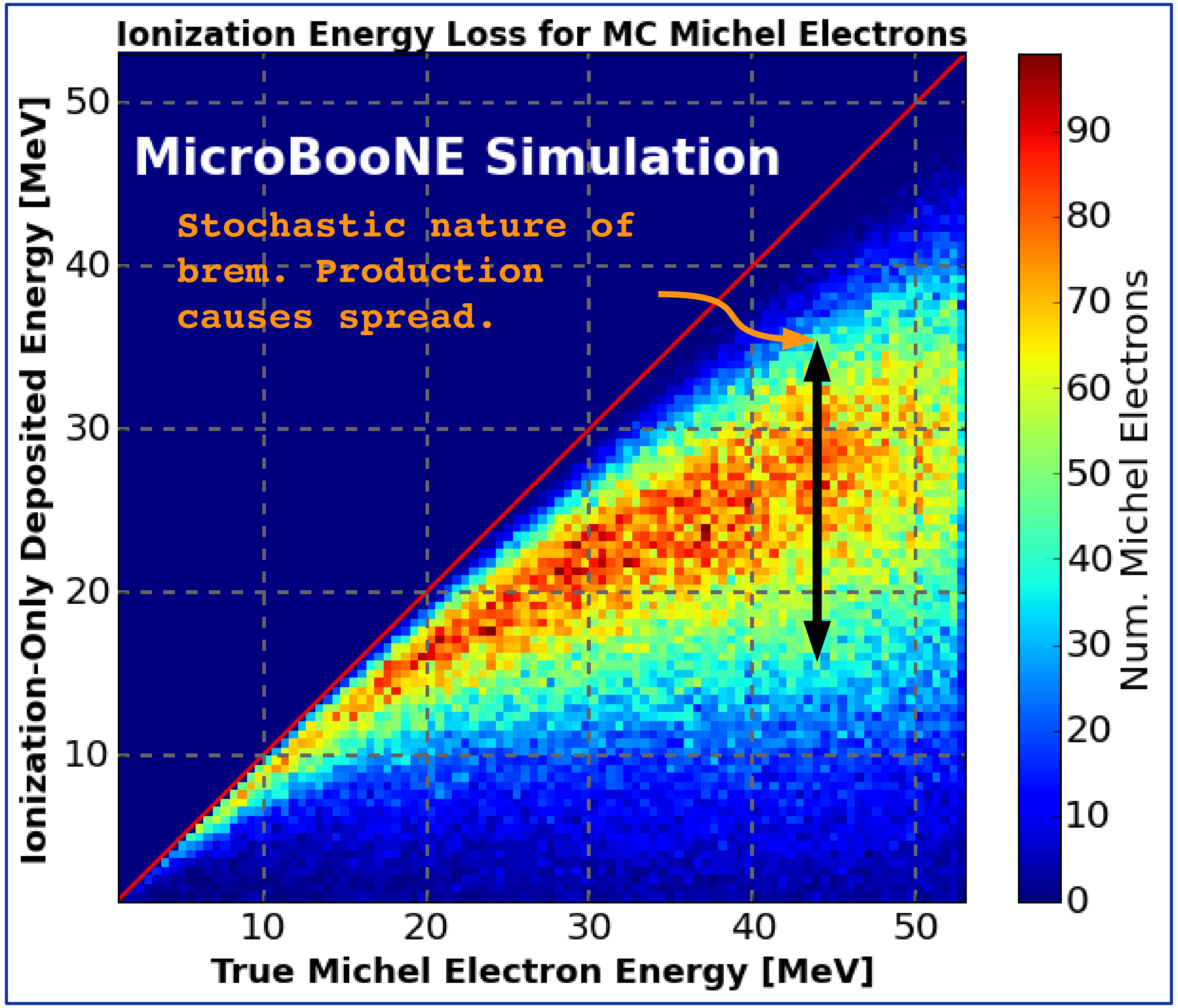
Michel electrons : impact of radiative energy loss

Similar contributions to energy loss from bremsstrahlung photons and ionization.

→ Complex topology.

Stochastic nature of bremsstrahlung photon production:

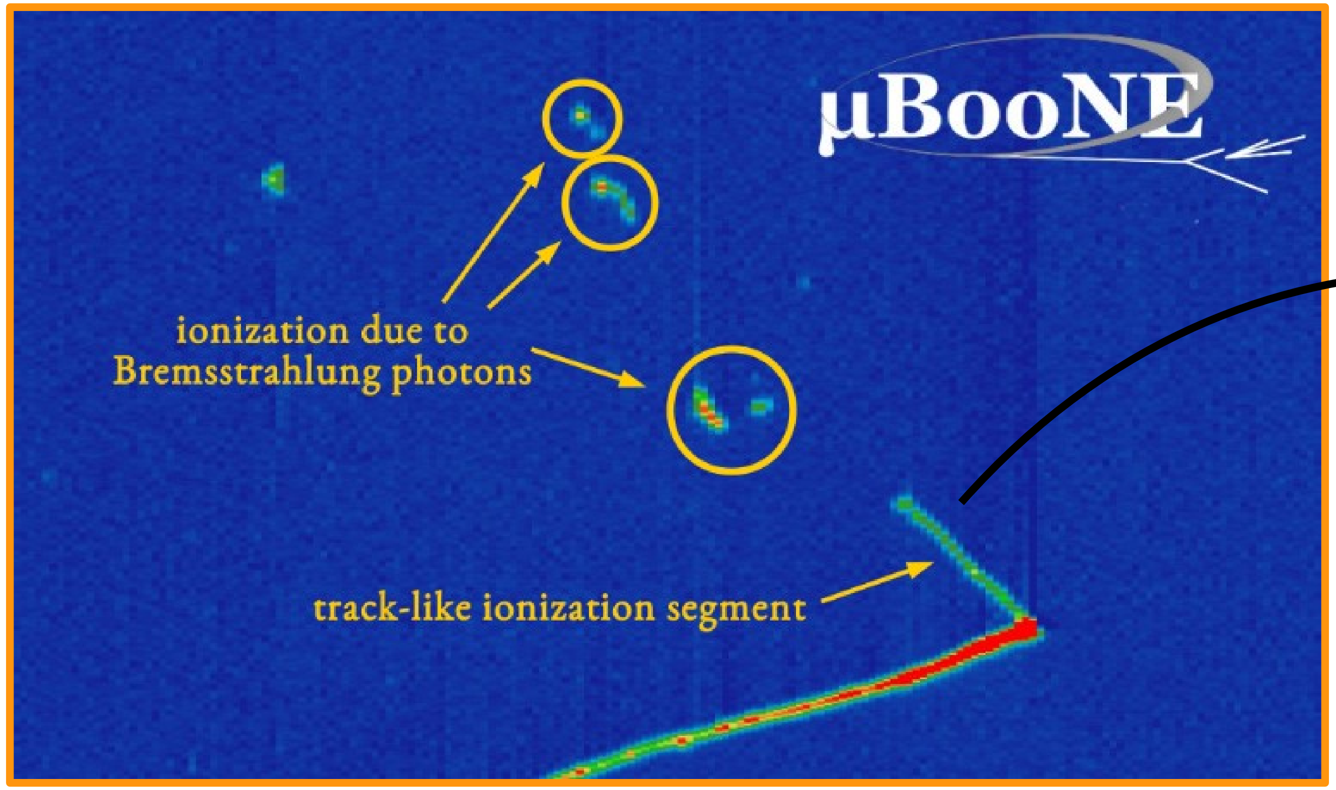
→ “Ionization-only” energy not sufficient for good energy resolution.

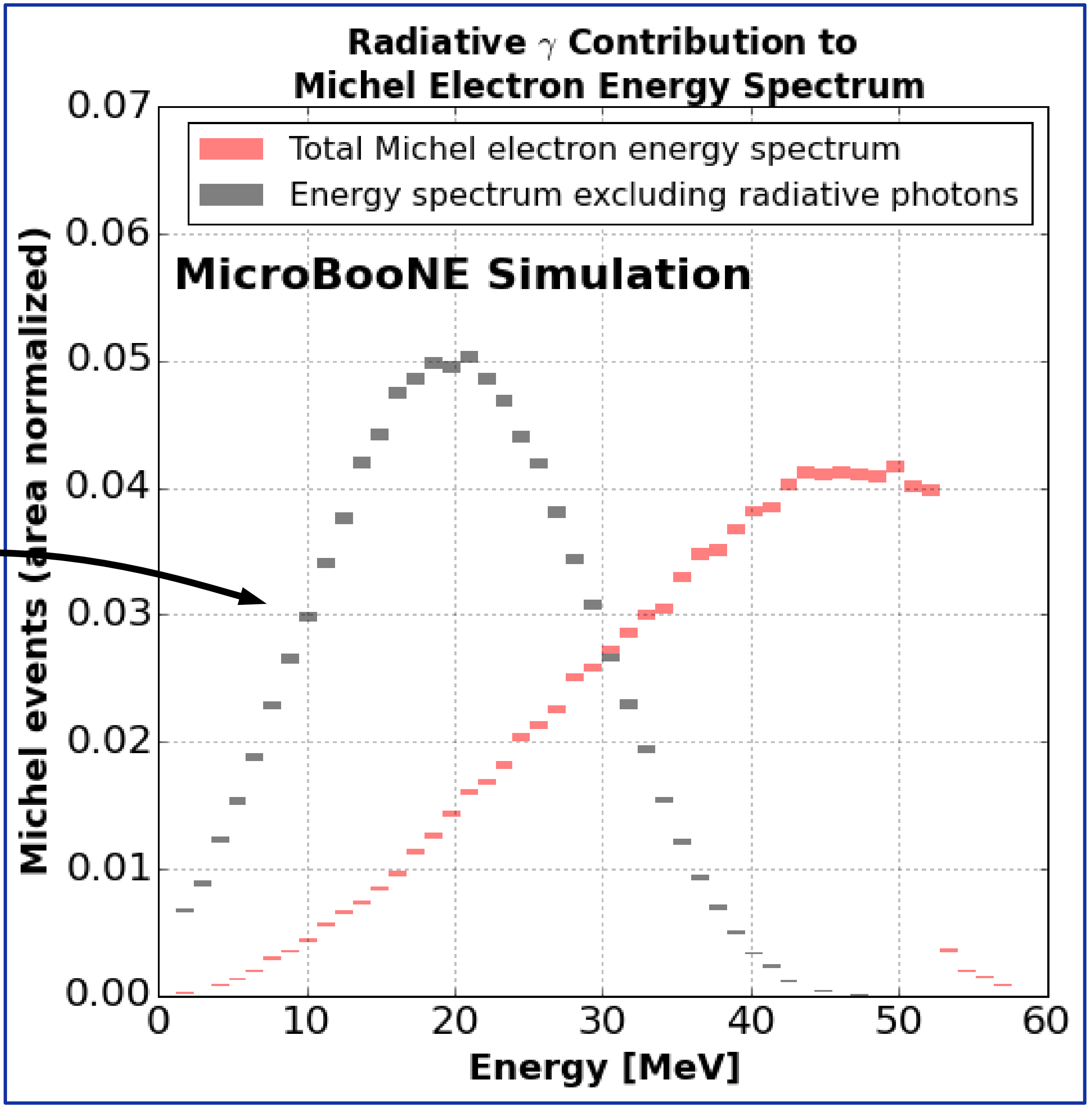


Michel electrons : impact of radiative energy loss

David Caratelli @ Columbia University

Missing energy from radiative photons has a significant impact on the Michel energy spectrum.



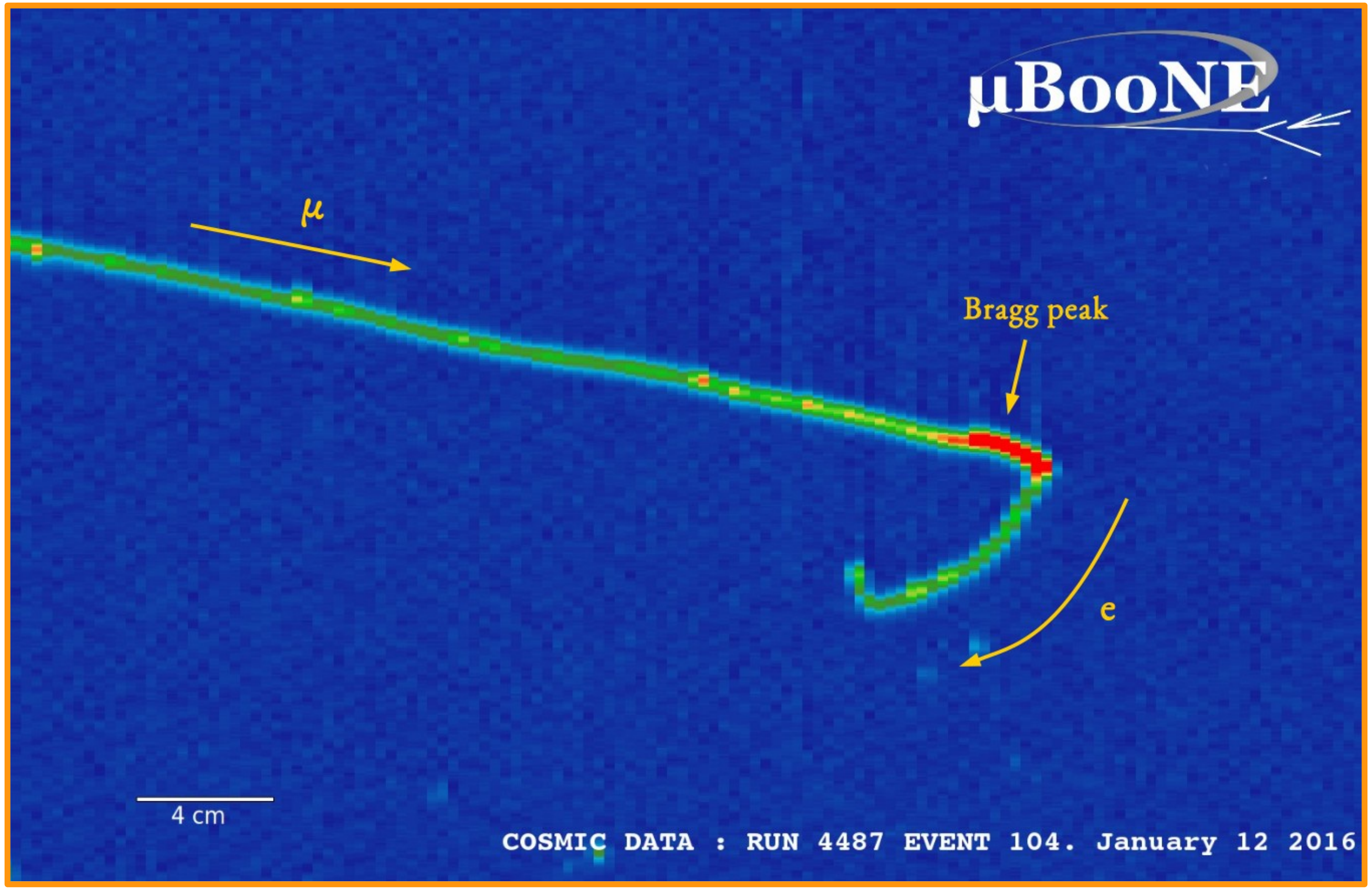


Michel electrons : what do they look like in MicroBooNE?

Characteristic topology:

- Bragg peak.
- Outgoing Michel electron at an angle with incoming muon.

Rely on calorimetric + spatial info. to identify & reconstruct.



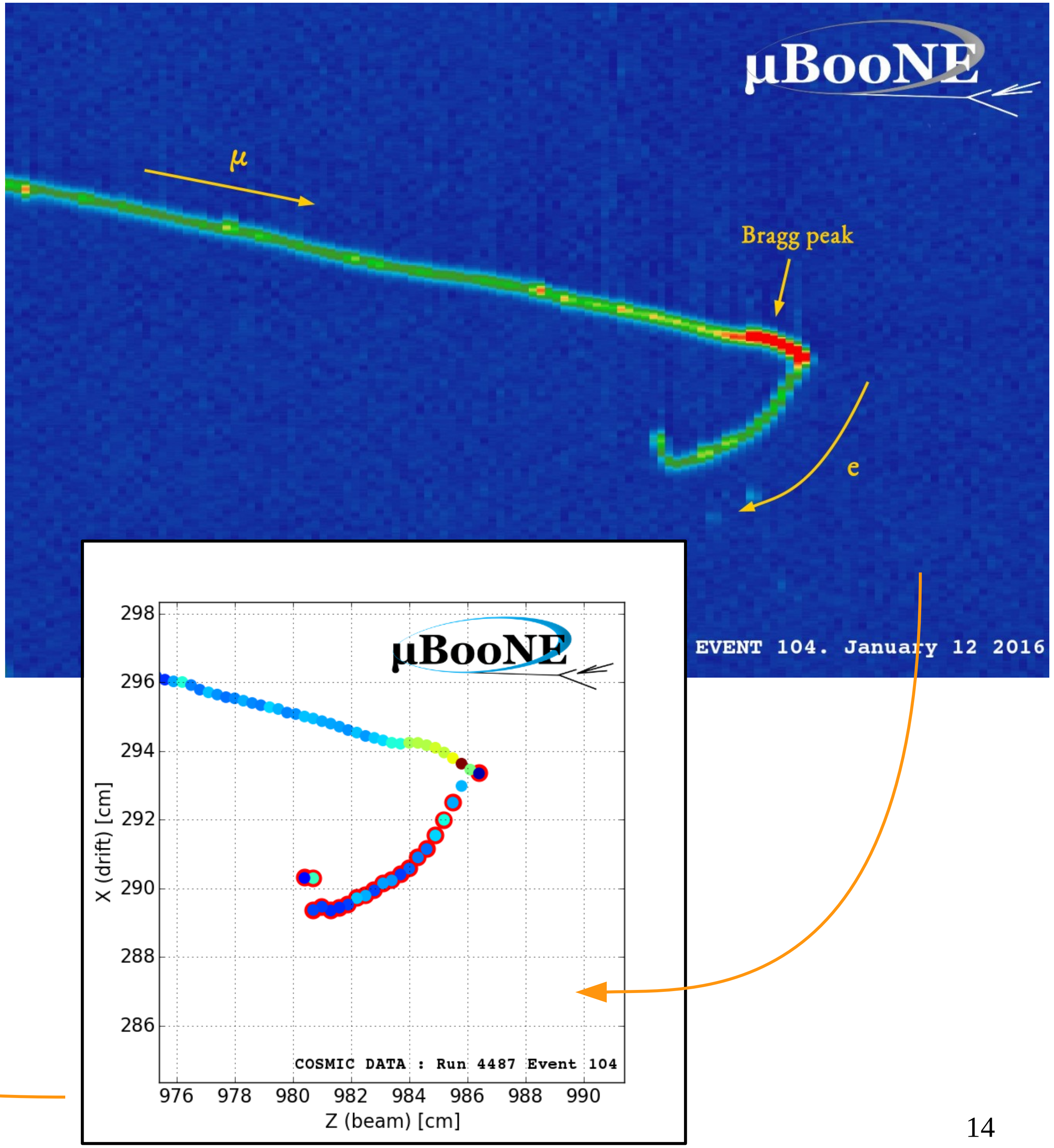
Michel electrons : reconstruction

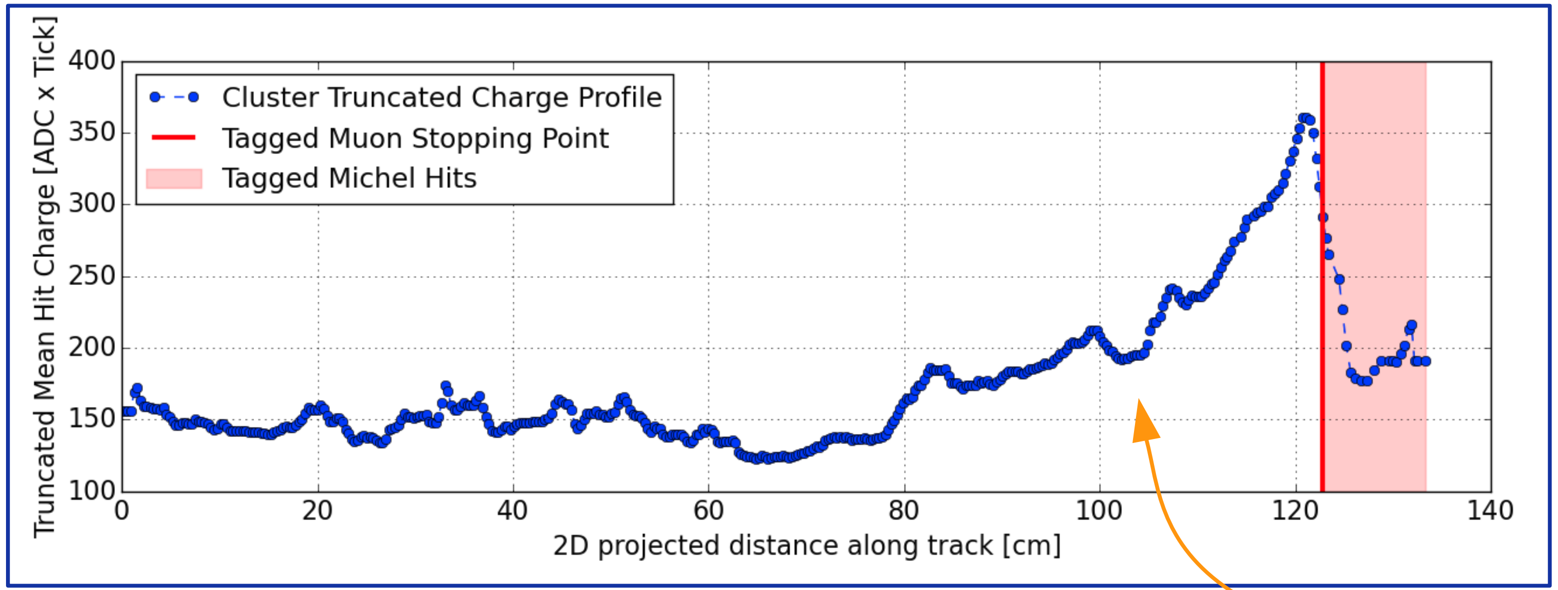
2D “collection-plane” reconstruction technique:

1) Signal processing and 2D “hit” reconstruction to identify energy deposition points on the collection-plane.

2) generic pattern-recognition clustering to group together hits from each cosmic interaction.

3) Tailored set of algorithms to identify Michel topology and obtain pure sample.

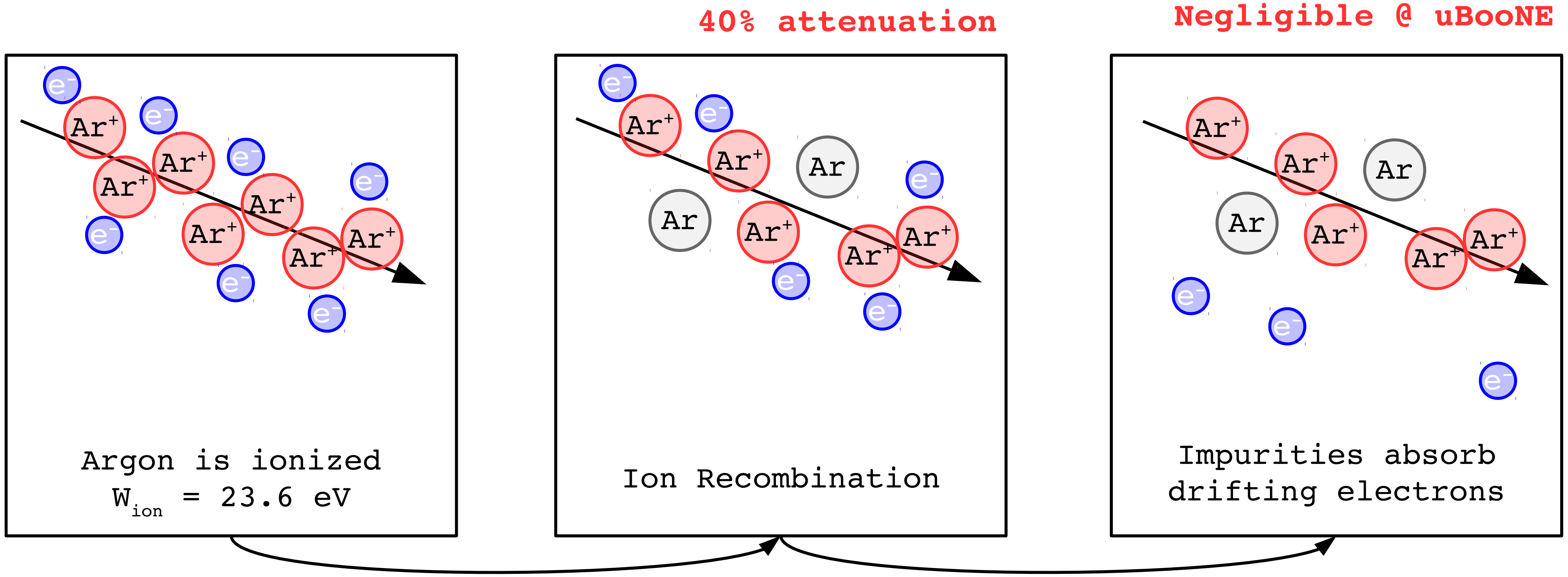




Calorimetric Energy Reconstruction

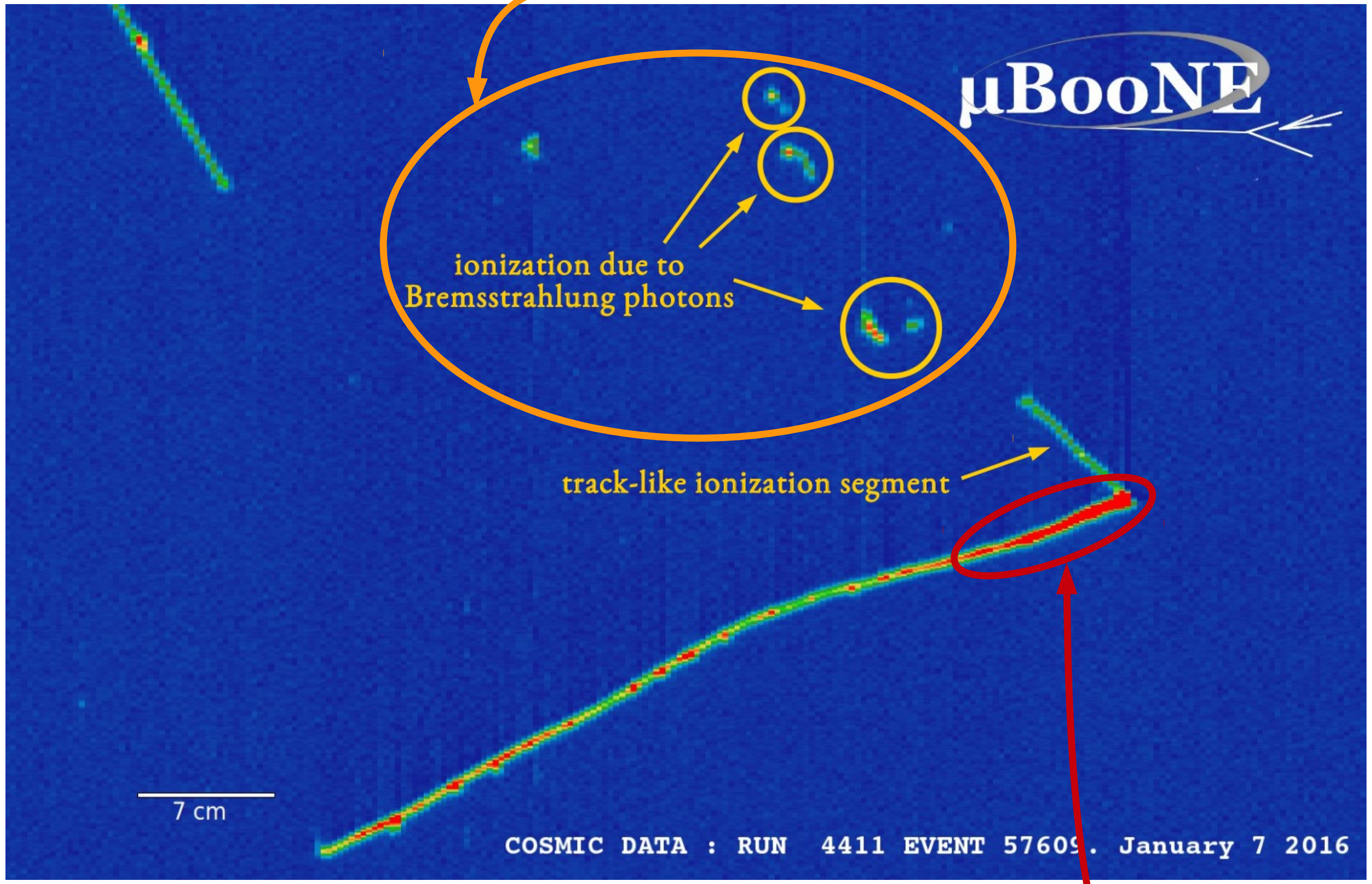
1) Integrate charge associated to tagged Michel electron hits.

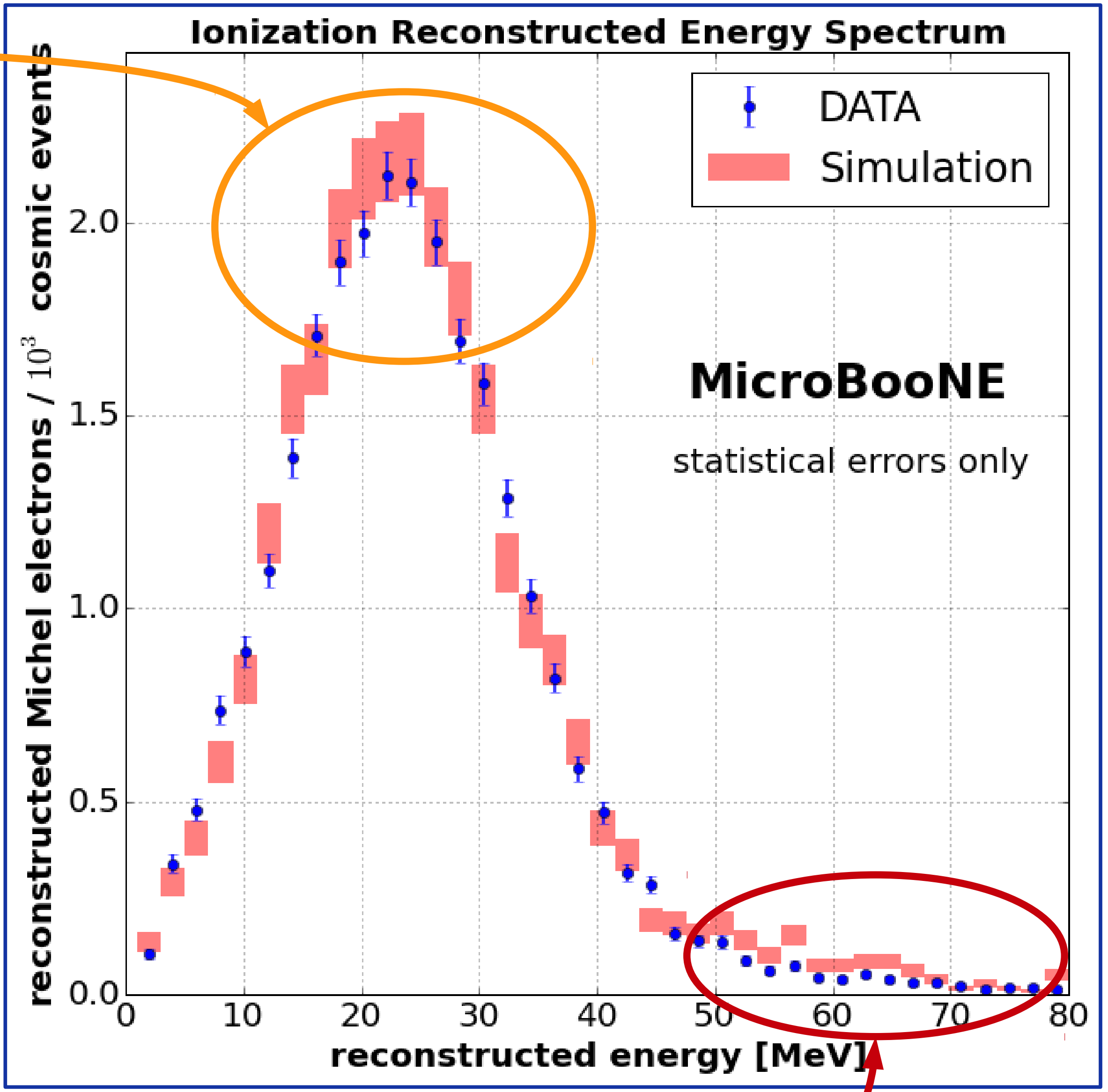
2) Account for processes affecting energy loss and signal formation in MicroBooNE's TPC:



Michel electrons : Energy Reconstruction

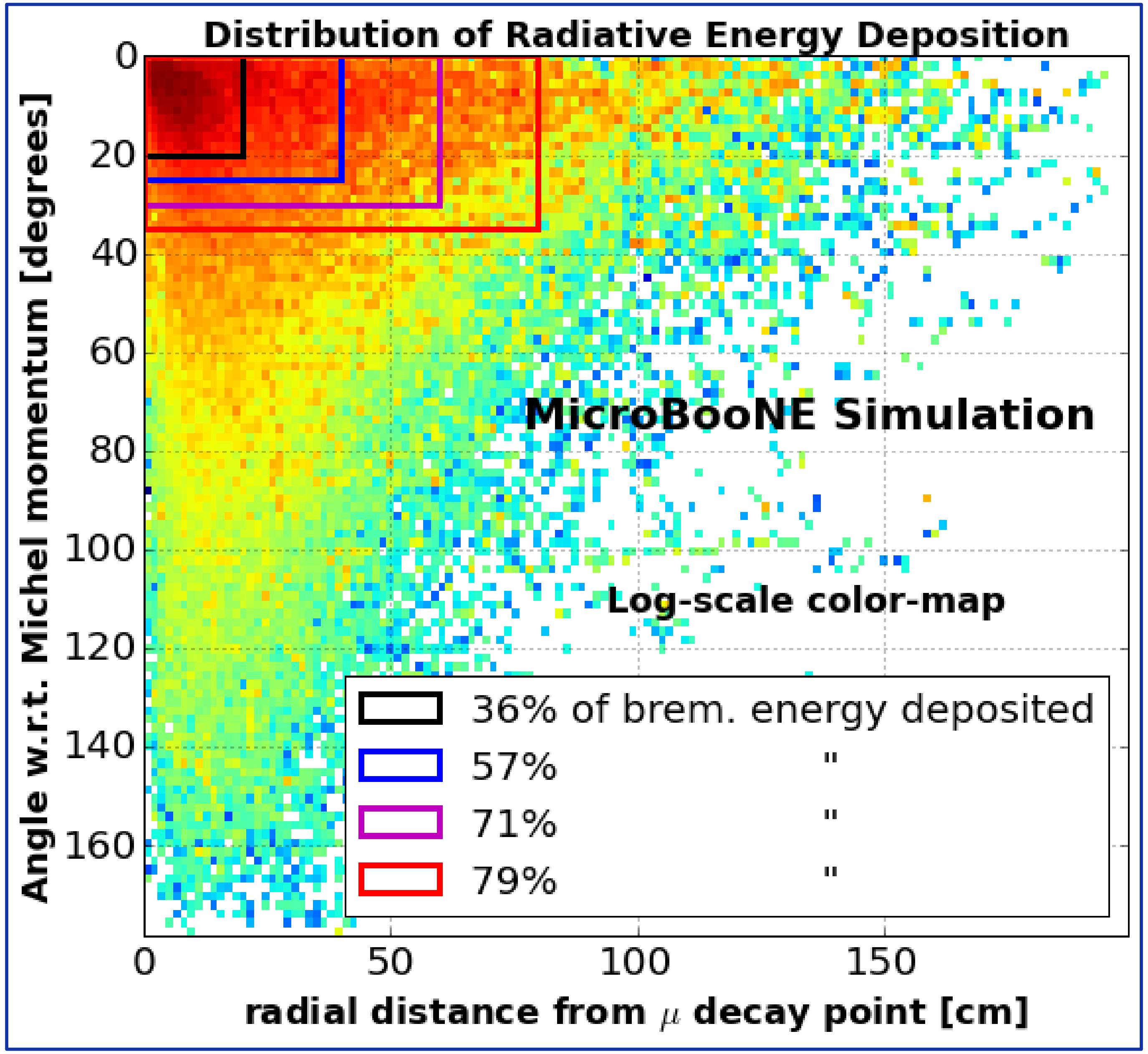
Exclusion of radiative photons causes shift in spectrum.





Muon Bragg peak can contaminate clustered Michel energy

Michel electrons : tagging radiative photons



To recover radiative photons need to extend the search for charge tens of cm away from muon stopping point.

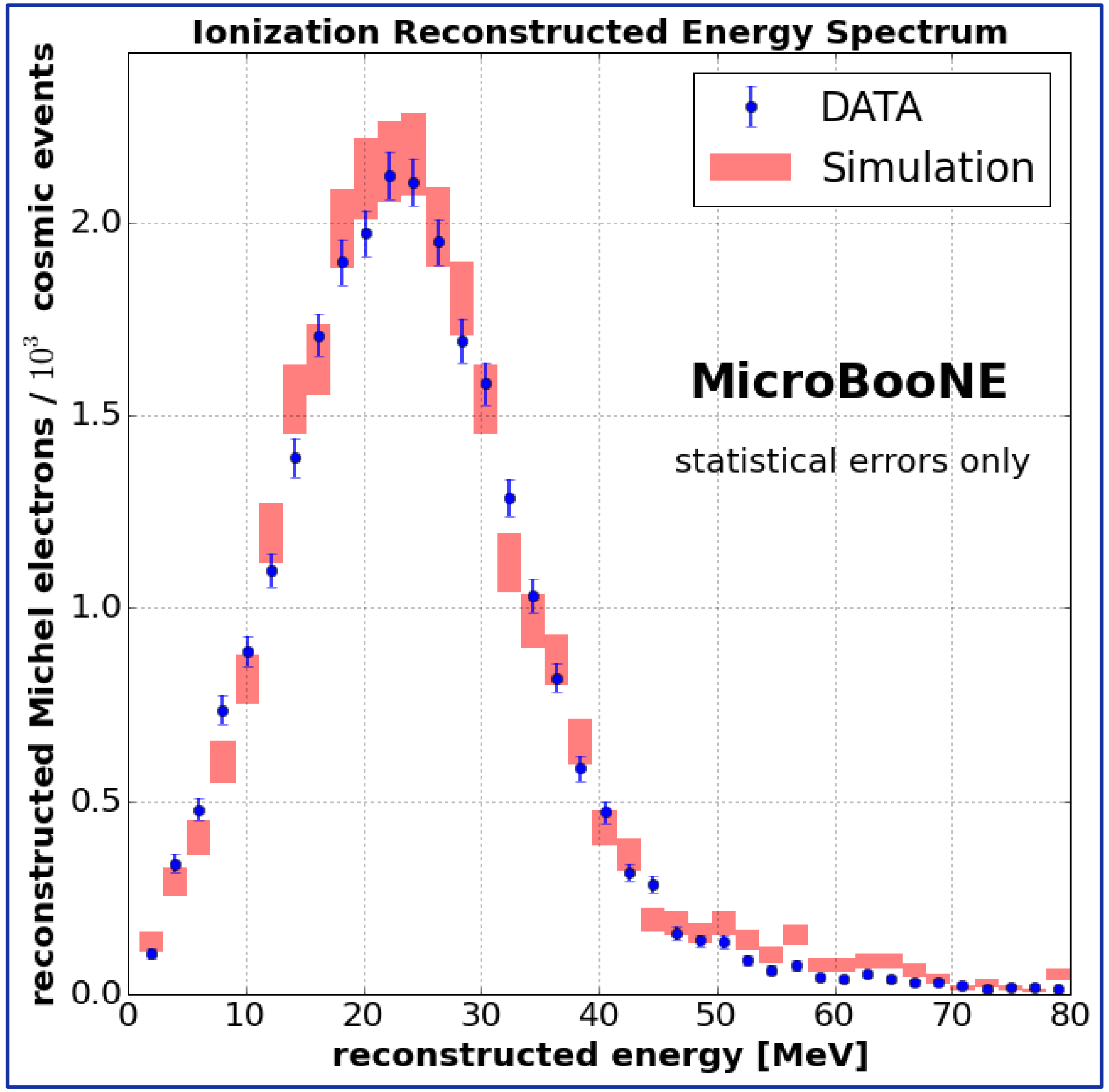
This presents challenges, especially for a surface detector with “dense” accidental cosmic activity.

Cuts used: 80 cm & 25 degrees in 2D.

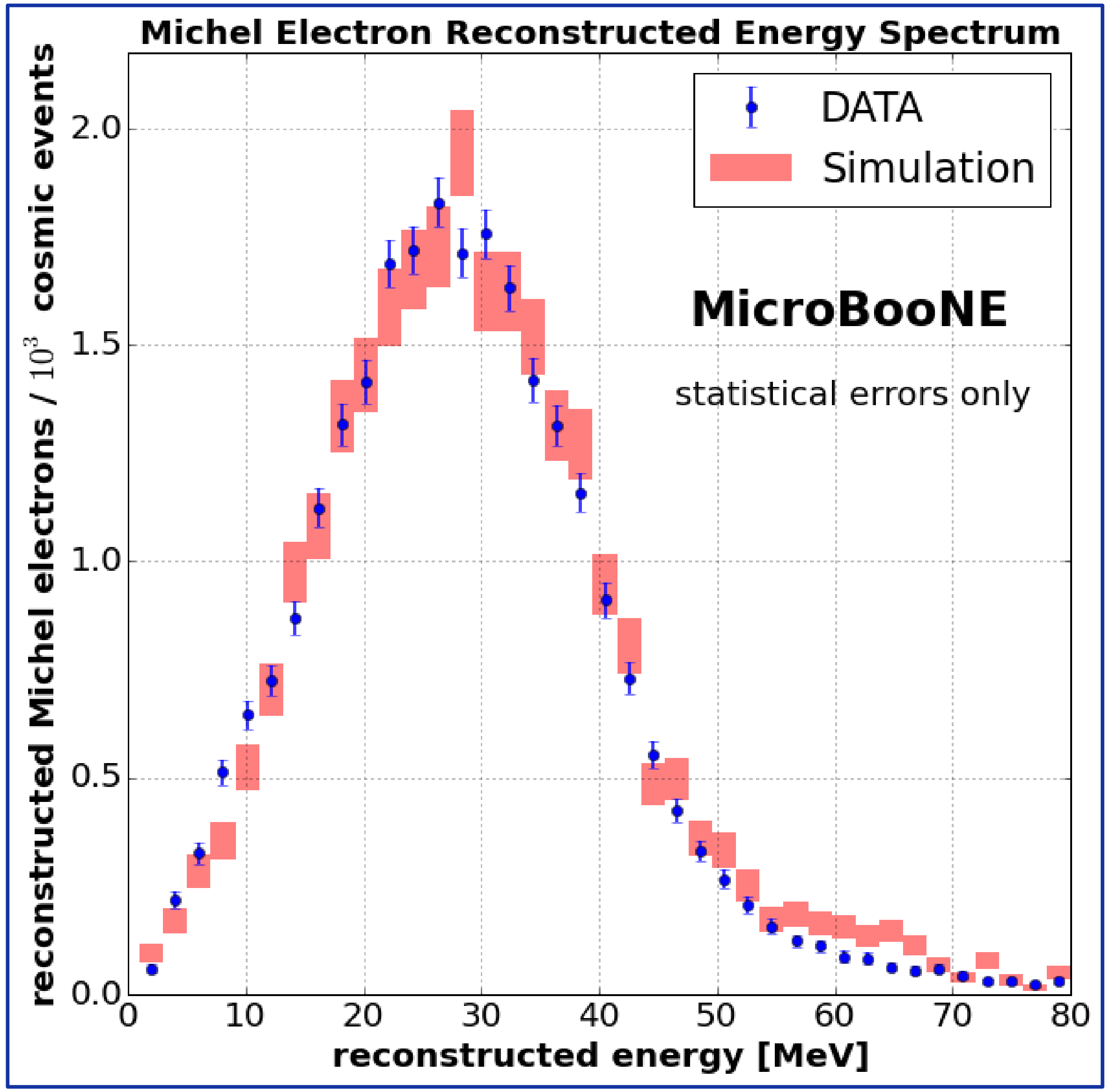
Michel electrons : Energy Reconstruction

David Caratelli @ Columbia University

`ionization only`



`photon tagging cut:`
`80 cm & 25 degrees`

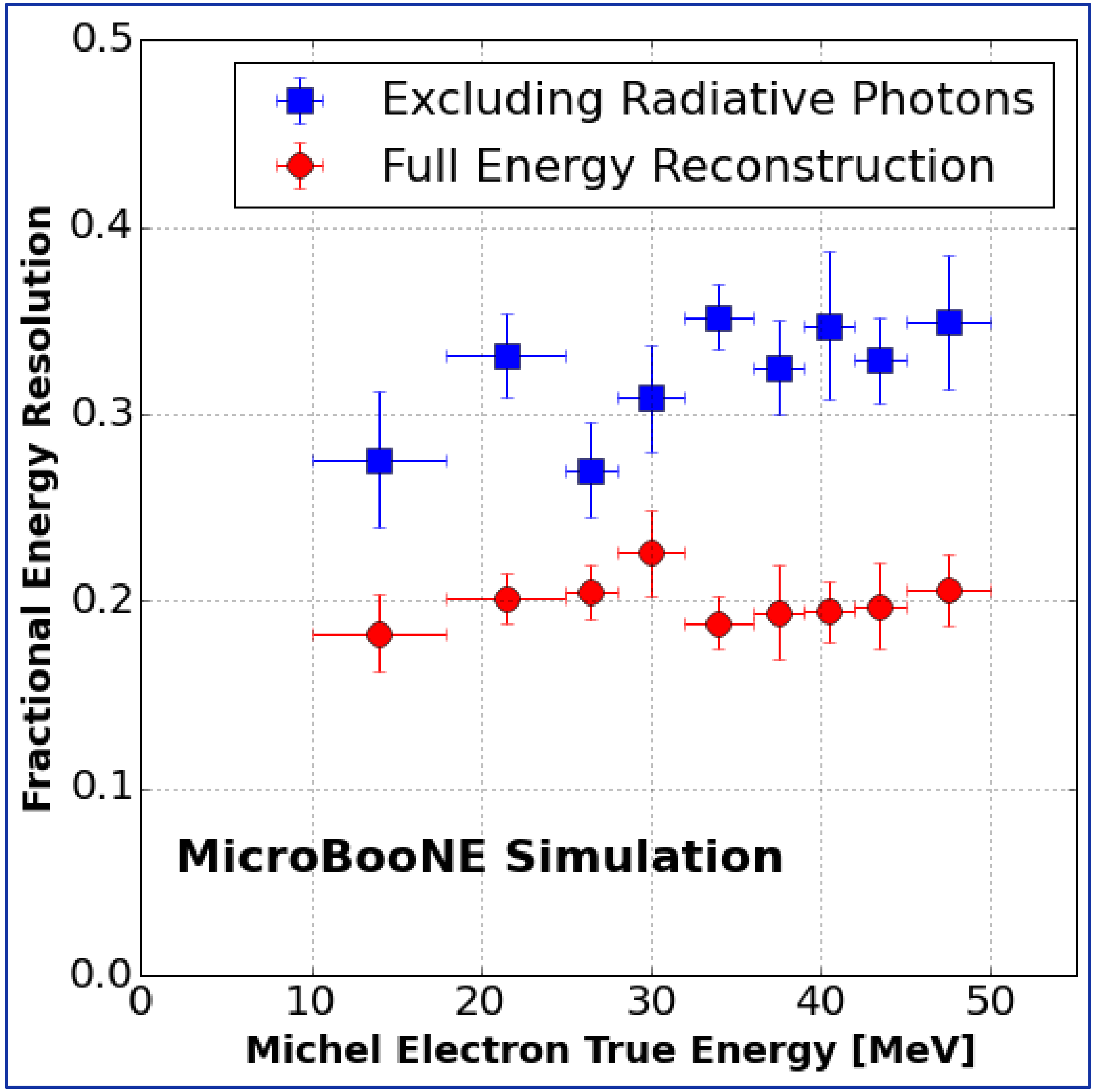


Where is the remaining charge?
- inefficiency in clustering.
- charge under hit-threshold.

Michel electrons : MC resolution study

Tagging radiative photons reduces energy bias and improves energy resolution.

Energy Definition	Energy Bias	Energy Resolution
Ionization only	-40%	> 30%
+ tagged photons	-25%	20%



MicroBooNE : moving forward

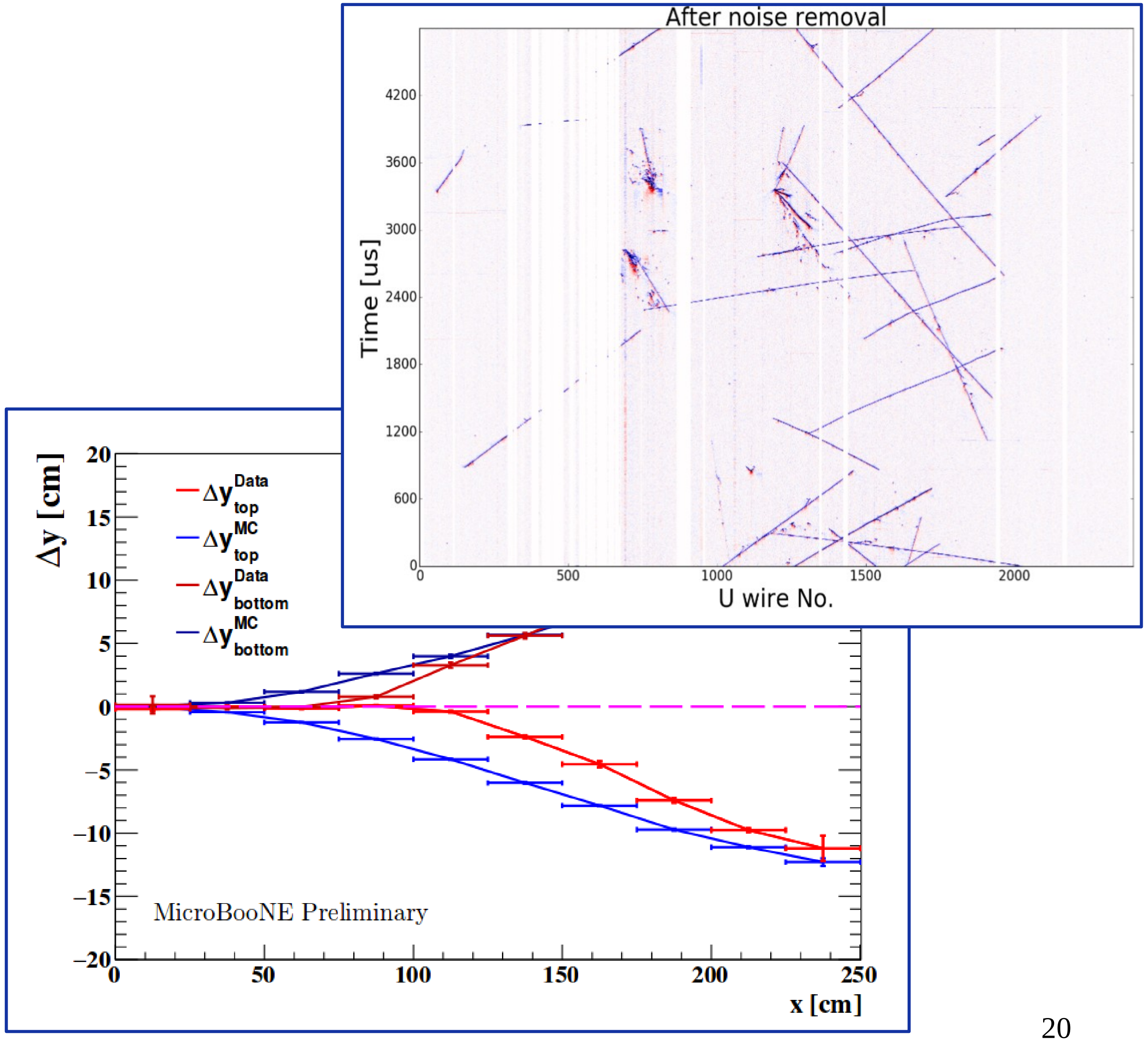
Ongoing efforts:

1) Effective signal-processing and hit-reconstruction to keep detection thresholds low.

2) Careful detector calibration to account for non-uniformities in calorimetry.

3) Use of more sophisticated 3D reconstruction techniques: CNNs / Wire-Cell / Pandora.

All play a role in improving our performance moving forward.



Lessons Learned

Stochastic nature of Brem. Production means tagging radiative photons is essential to obtain good energy resolution.

Complicated due to: a) large absorption length. b) low-energy photons.

No “one-solution-fits-all” reconstruction approach for EM activity at different energies.

How can a light collection system complement energy reconstruction for low-energy electrons?

There is always more to learn…

EM showers from π^0s:

Higher energy range [few hundred MeV]

Many of the same challenges remain:

- **Sparse energy deposition.**
- **Track-like ionization deposition.**

Watch for future results from MicroBooNE

Thesis work by David Kaleko @ Columbia University

"Determination of muon momentum in the MicroBooNE *LArTPC*
using an improved model of multiple Coulomb scattering"

arXiv:1703.06187

Multiple Coulomb Scattering: what and why?

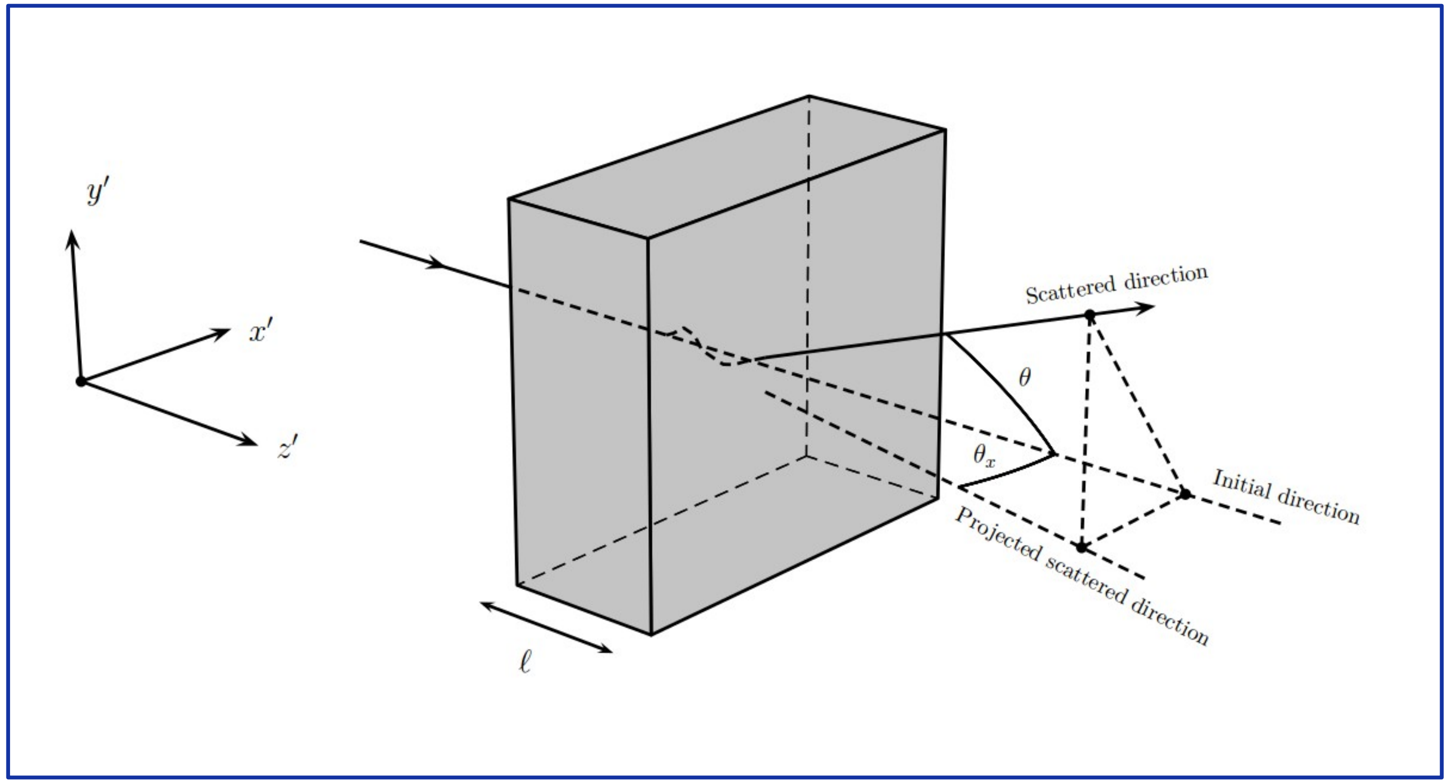
Charged particles traversing a medium scatter. Angular deflection correlated with momentum.

Method allows momentum reconstruction when track not fully contained in detector volume.

- [50% BNB ν_μ CC muons not contained]

Scattering angle distribution described by Highland formula:

$$\sigma_o^{\mathrm{HL}} = \frac{S_2}{p\beta c} z \sqrt{\frac{\ell}{X_0}} \left[1 + \epsilon \times \ln\left(\frac{\ell}{X_0}\right)\right]$$



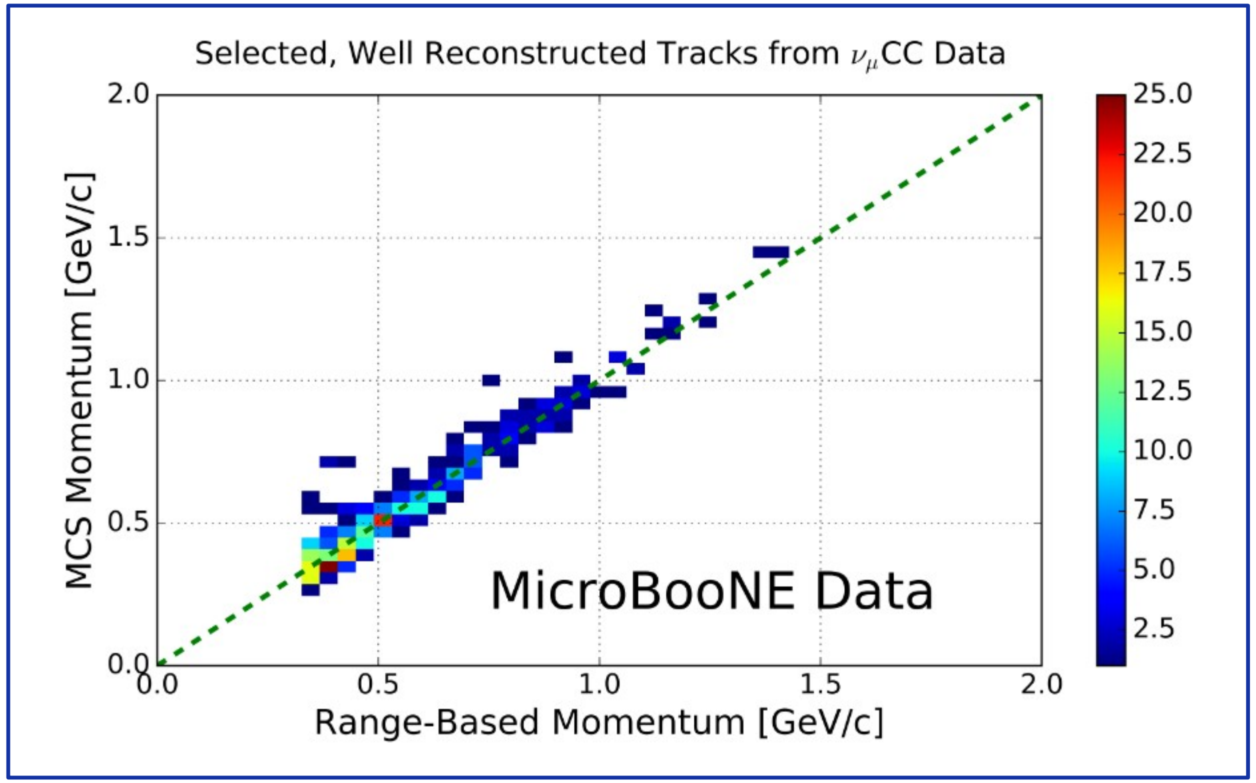
MicroBooNE approach to MCS momentum determination:

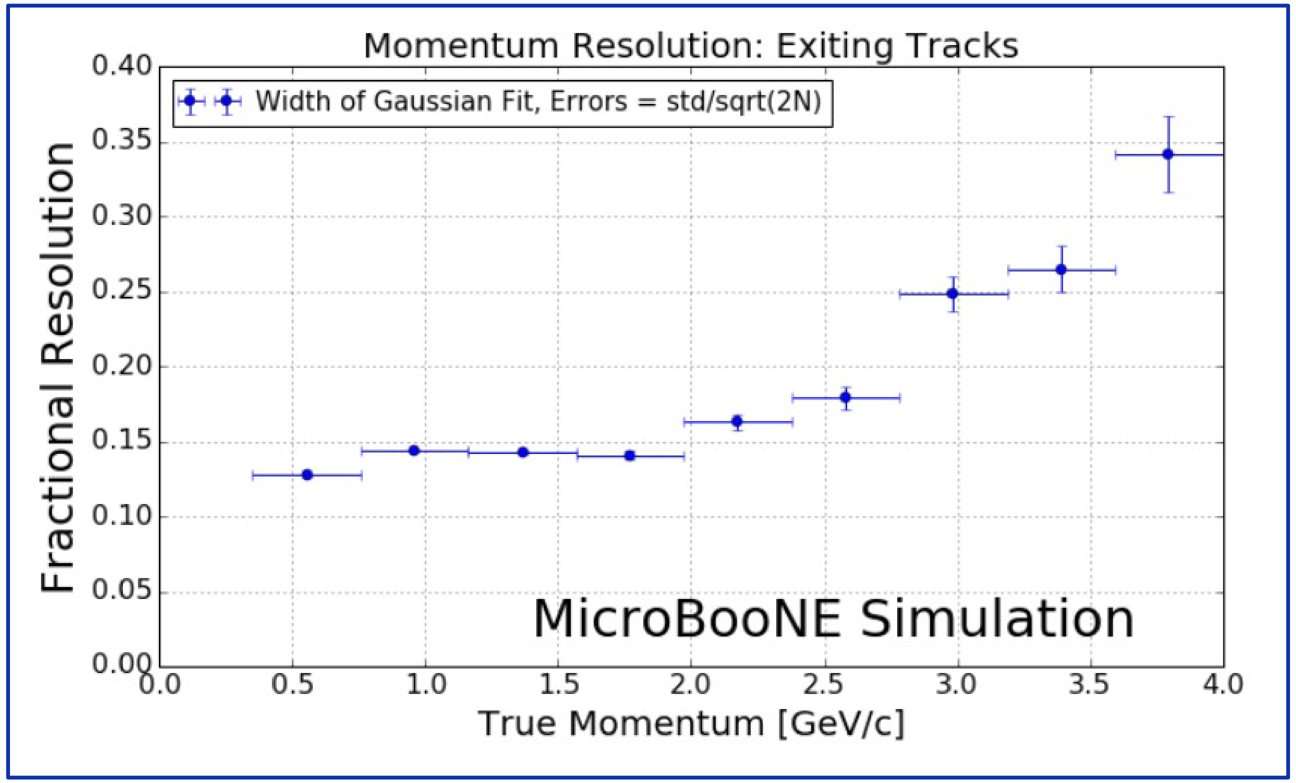
- Account for detector angular resolution.
- Study and account for S_2 momentum-dependence in Ar.
- Maximum-likelihood $\overline{p}$ determination.

Multiple Coulomb Scattering: results

Paper performs several studies:

- Comparison of MCS vs. range-based momentum estimation on contained muons from BNB ν_μ CC interactions.
- Simulation studies of momentum determination bias and resolution for contained / exiting muon tracks.





Multiple Coulomb Scattering momentum-estimation is an important technique which will allow MicroBooNE to extend its physics reach in studying neutrino interactions at O(1 GeV) neutrino energies.

Thank you

Imaging
Cosmic
And
Rare
Underground
Signals

Downstream

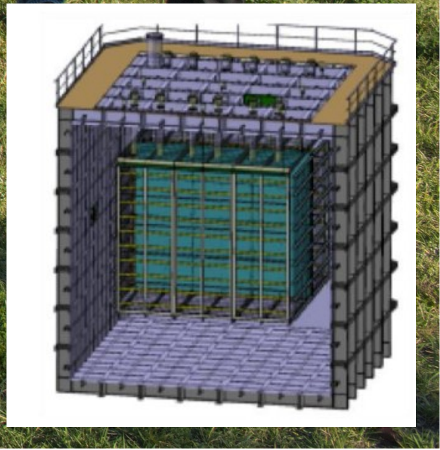
Upstream

SHORT-BASELINE
SBND
NEAR DETECTOR

DUNE

LBNF @ SD

CERN @ CH



Backup

Motivation for EM activity response studies

Precise energy reconstruction is essential for near and long-term precision neutrino oscillation experiments.

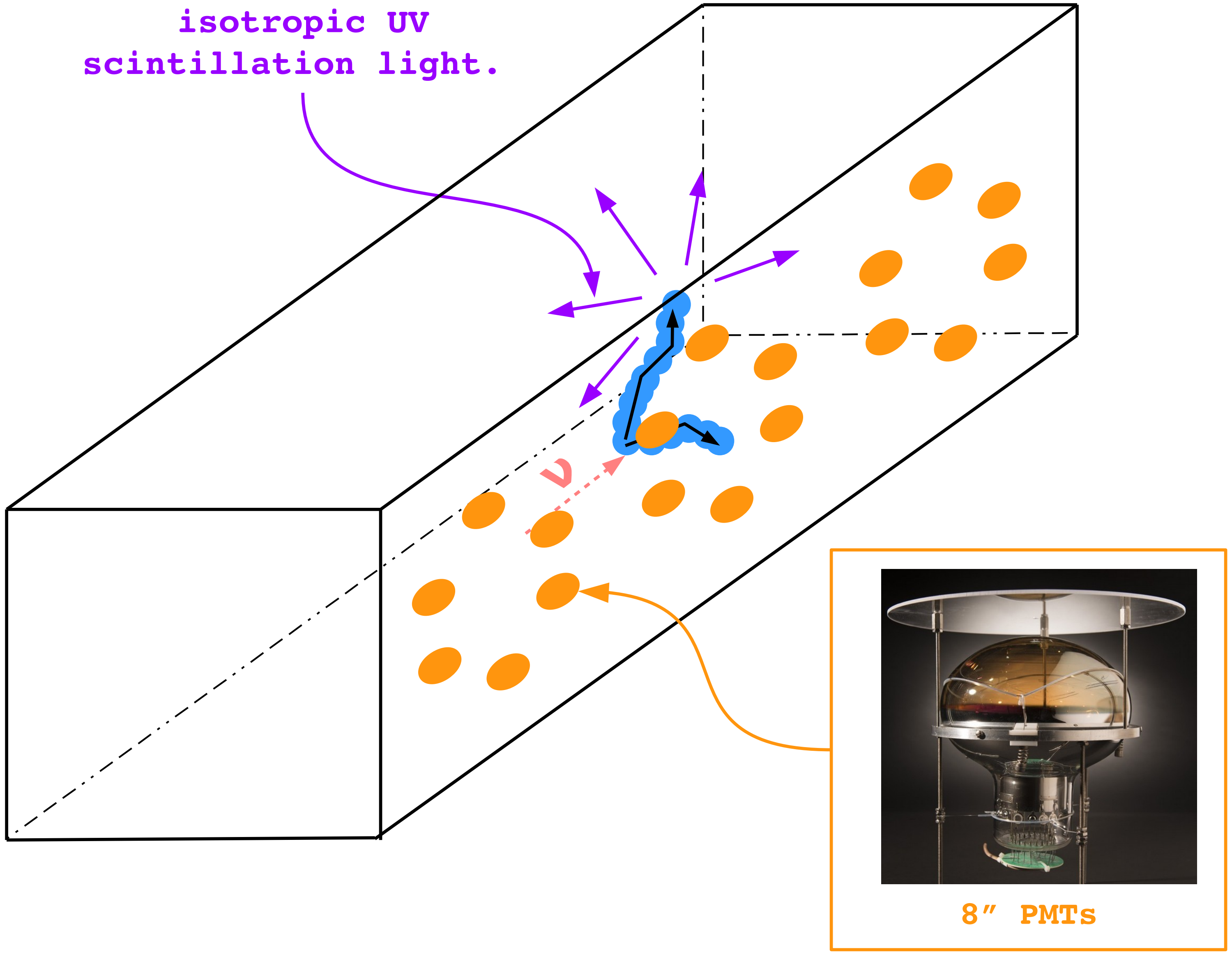
Electron/photon energy reconstruction key to a variety of measurements:

Experiment	Measurement	$e^{+/-}$ energy resolution	Relevant energy Range
DUNE	CP-violation / mass-hierarchy	2% ⊕ 15% / (E [GeV] ½) [1]	100 MeV – 10 GeV
SBN	non-standard oscillations	15% / (E [GeV] ½) [2]	0.1 – 1 GeV
MicroBooNE	MiniBooNE Low Energy Excess	15% / (E [GeV] ½) [2]	100-400 MeV

Limited experimental validation to-date of LArTPC's calorimetric energy reconstruction of EM showers.

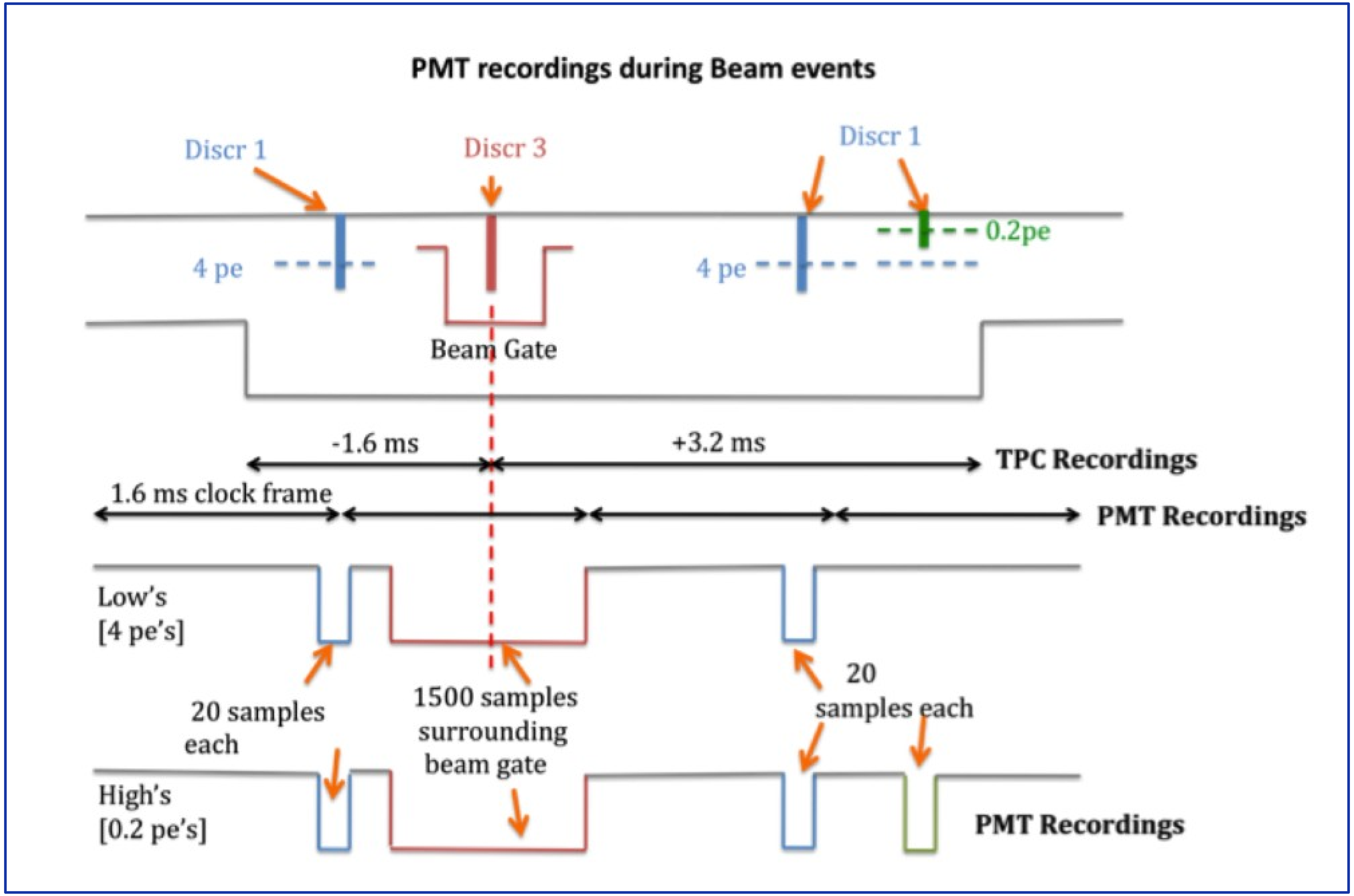
[1]: DUNE CDR: physics arXiv:1512.06148. **[2]**: SBN Proposal arXiv:1503.01520v1.

LArTPC Working Principle : MicroBooNE



Looking inside cryostat, before TPC inserted

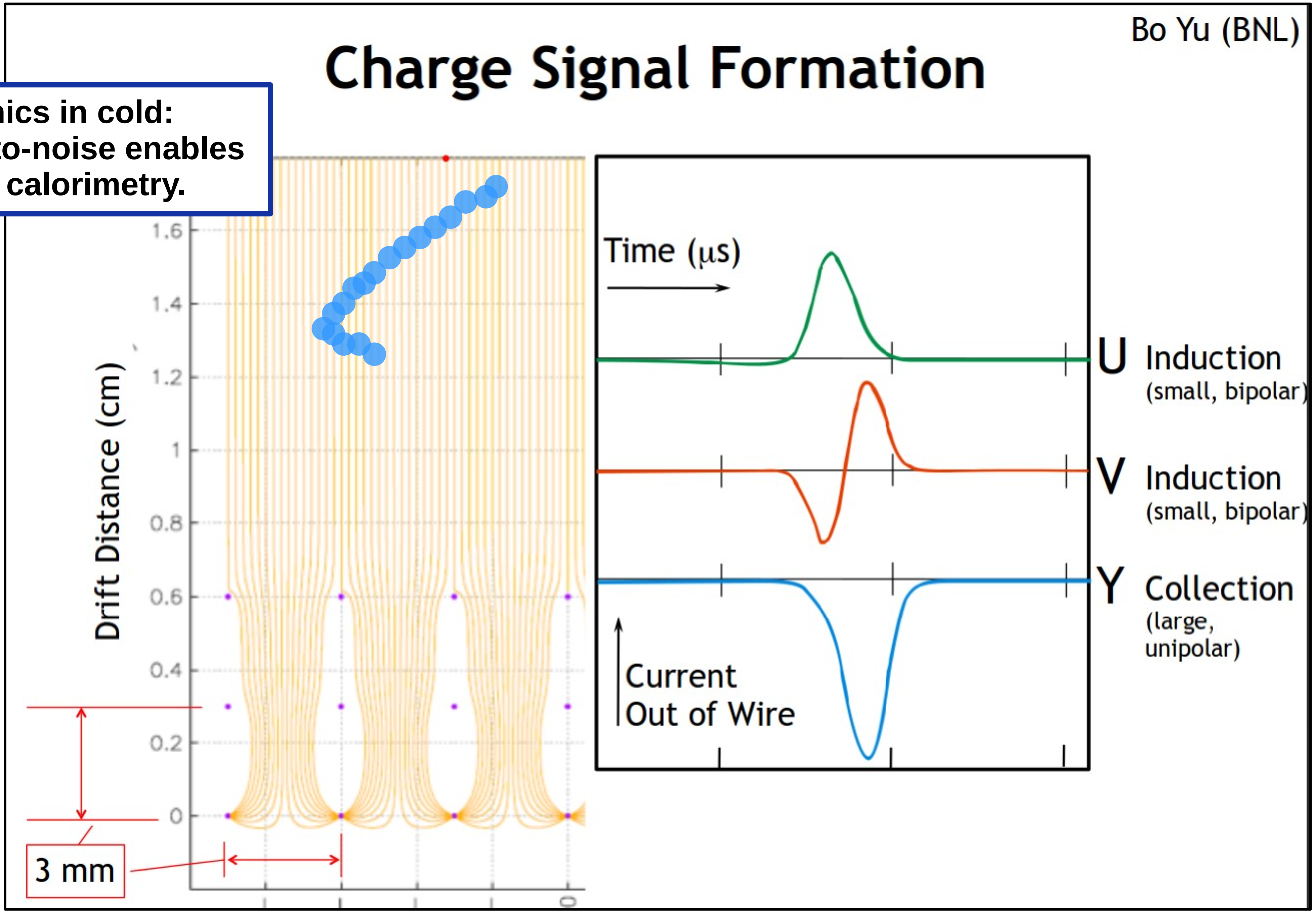
MicroBooNE Readout Electronics “timeline”



ArXiv:1308.3446v1 — D. Kaleko @ Columbia

LArTPC Working Principle : MicroBooNE

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



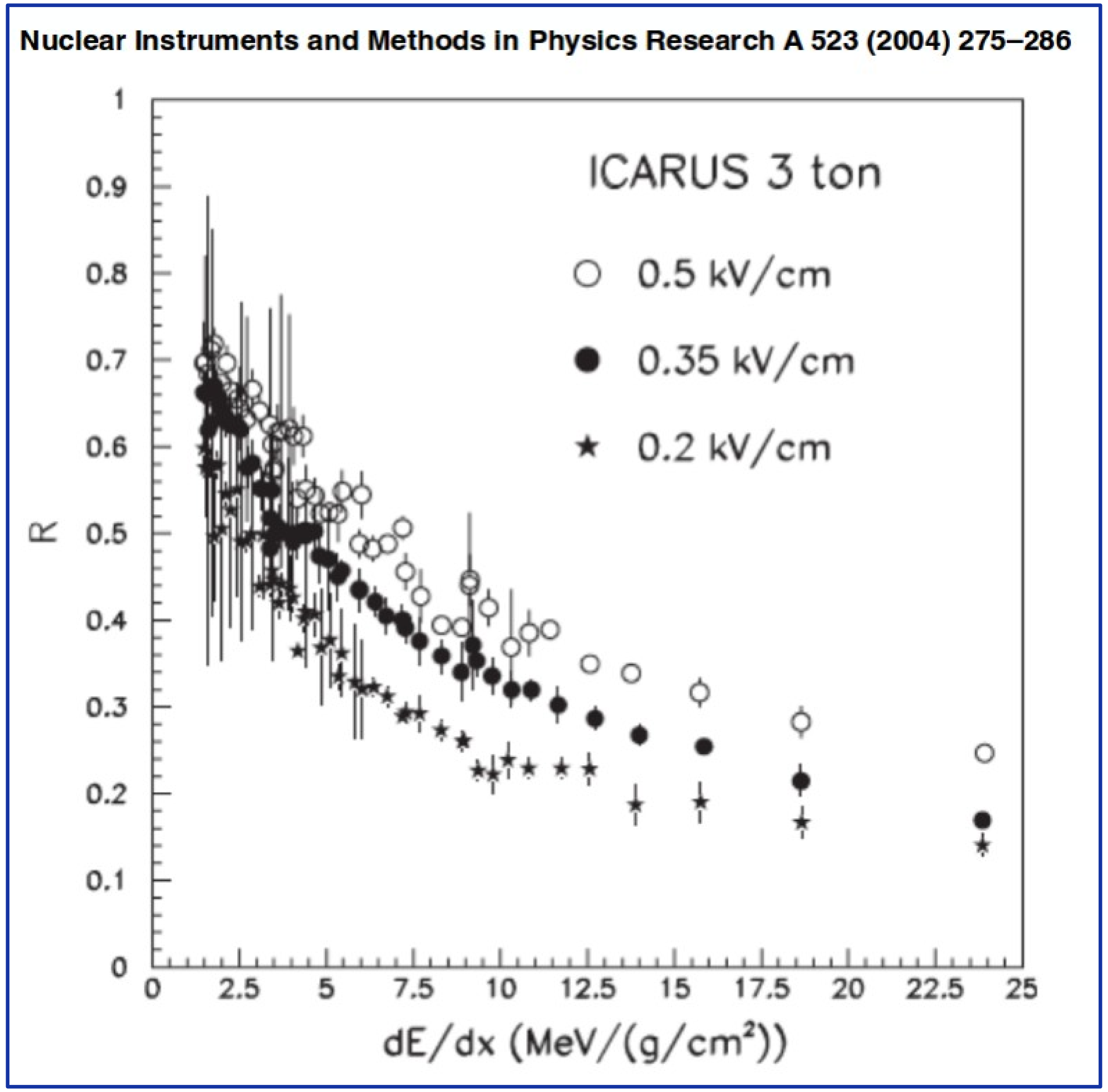
Recombination

$$\mathscr{R}_{\mathrm{ICARUS}} = \frac{A_B}{1 + k_B \cdot (dE/dx)/\mathscr{E}}$$

Birks model

Box model

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}.$$



Recombination depends on density of Ar^+ and e^-.

Affected by:

- dE/dx (more energy deposition per unit distance → larger ion density → more recombination)
- E-field strength: determined timescale at which Ar^+ / e^- drift away from each other.

For electrons / photons much smaller variation in dE/dx vs. energy compared to muons/protons/pions.

→ significant effect, but ~constant.

Space Charge

Positive ions in LAr drift at 10^{-3} the speed of electrons.

→ “space-charge” buildup in TPC.

Effect leads to distortions in electric field.

Local variations in E field In turn affect:

- Local drift speed → spatial “wiggles”
- Field magnitude → recomb. Effect.

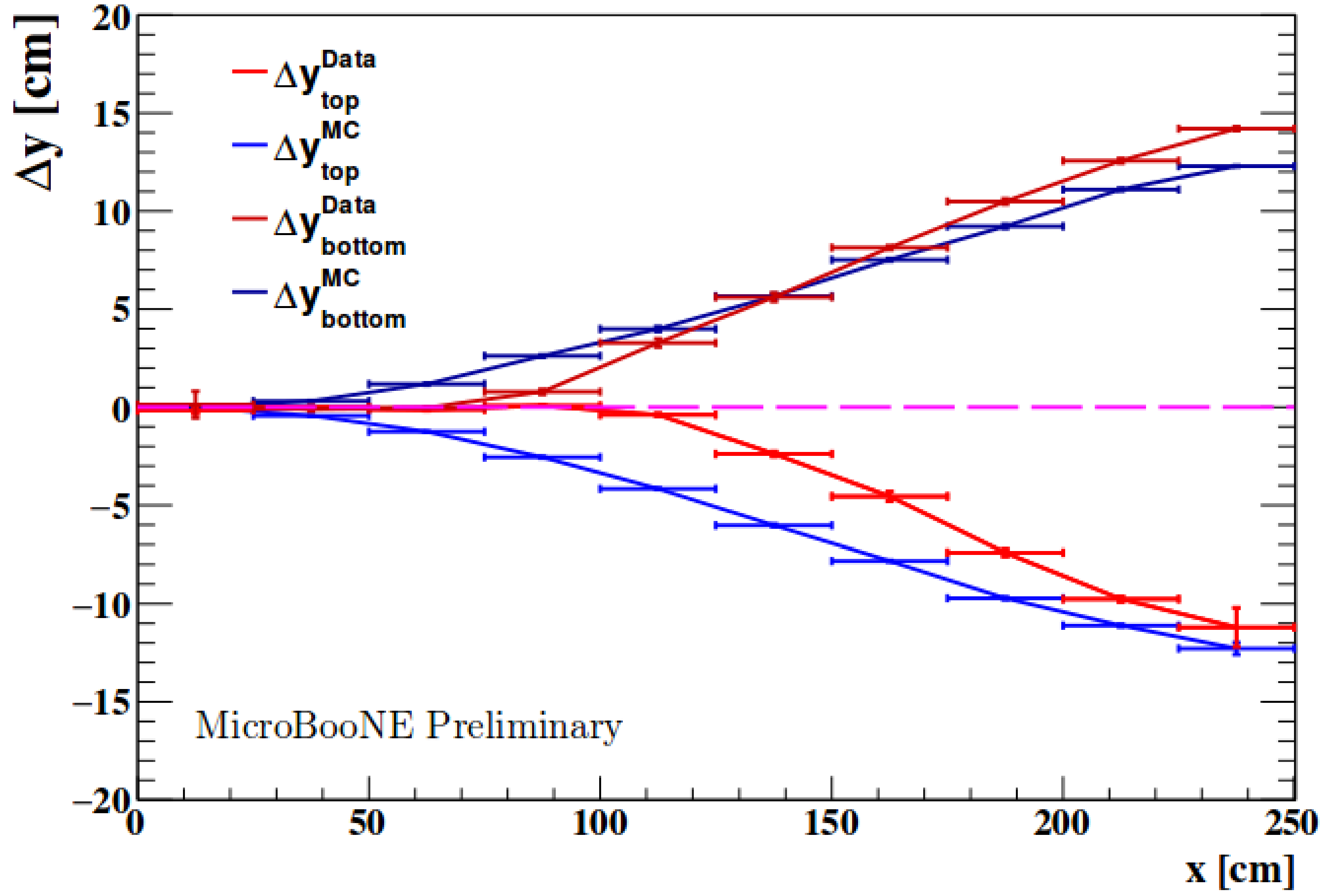
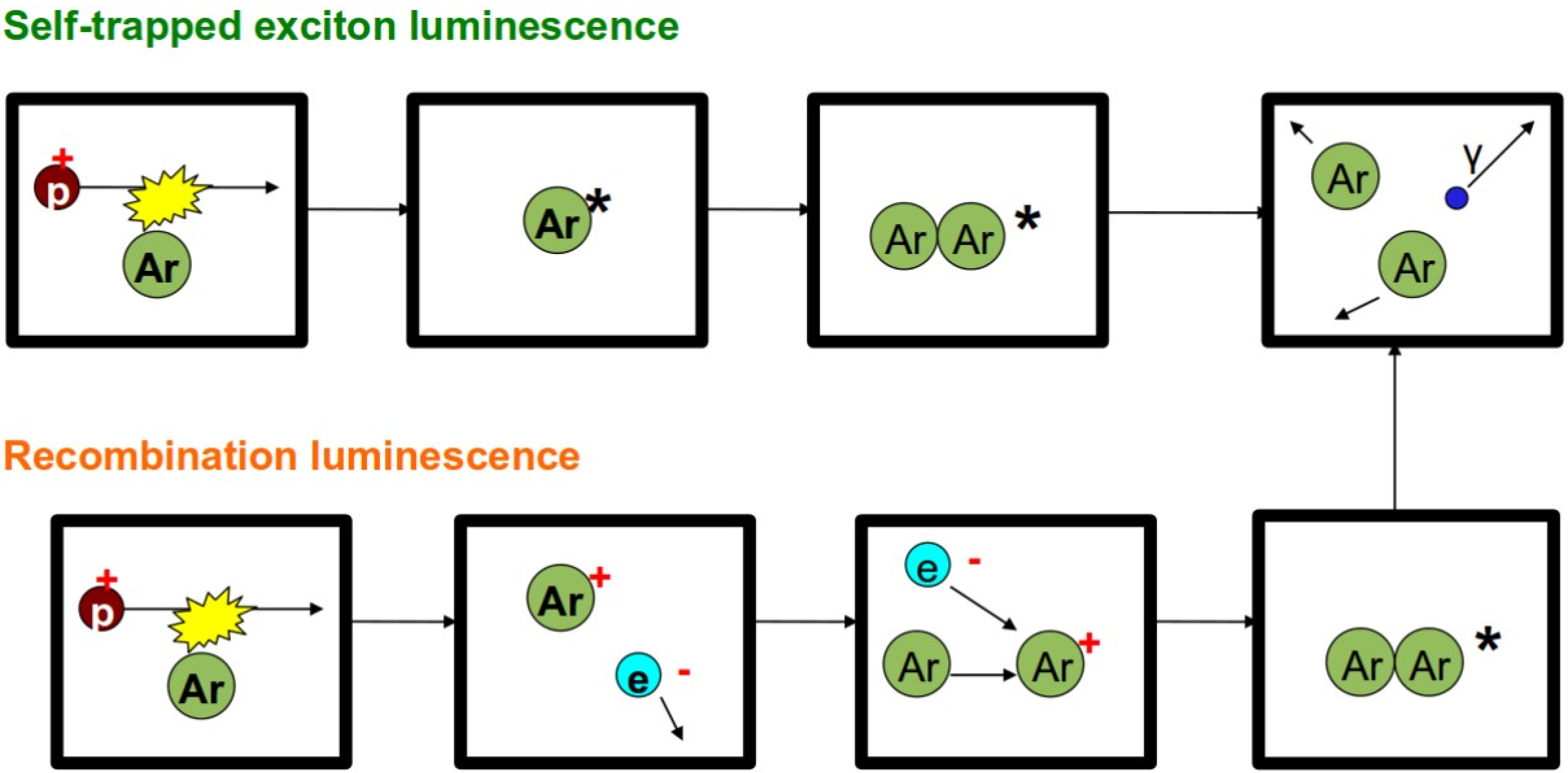


Figure 9: Predicted/measured SCE distortions as a function of the drift coordinate at both the top and bottom of the TPC, comparing data to MC. The magenta dashed line represents the offsets expected if there were no SCE in the detector.

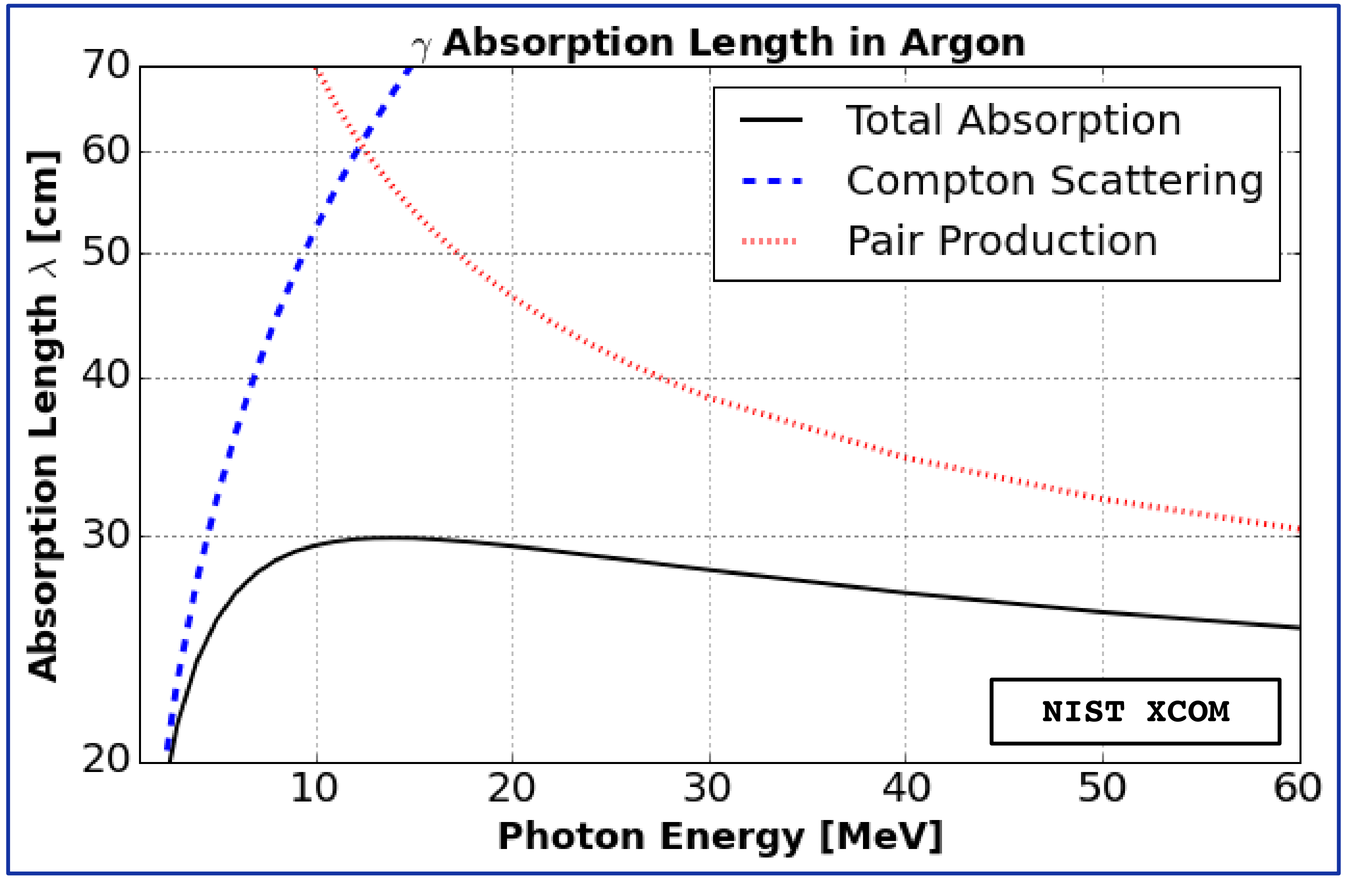
Source: Study of Space Charge Effects in MicroBooNE:
http://www-microboone.fnal.gov/publications/publicnotes/MICROBOONE-NOTE-1018-PUB.pdf

Scintillation Light


Self-trapped exciton luminescence

Recombination luminescence

Michel electrons : Radiative Photons



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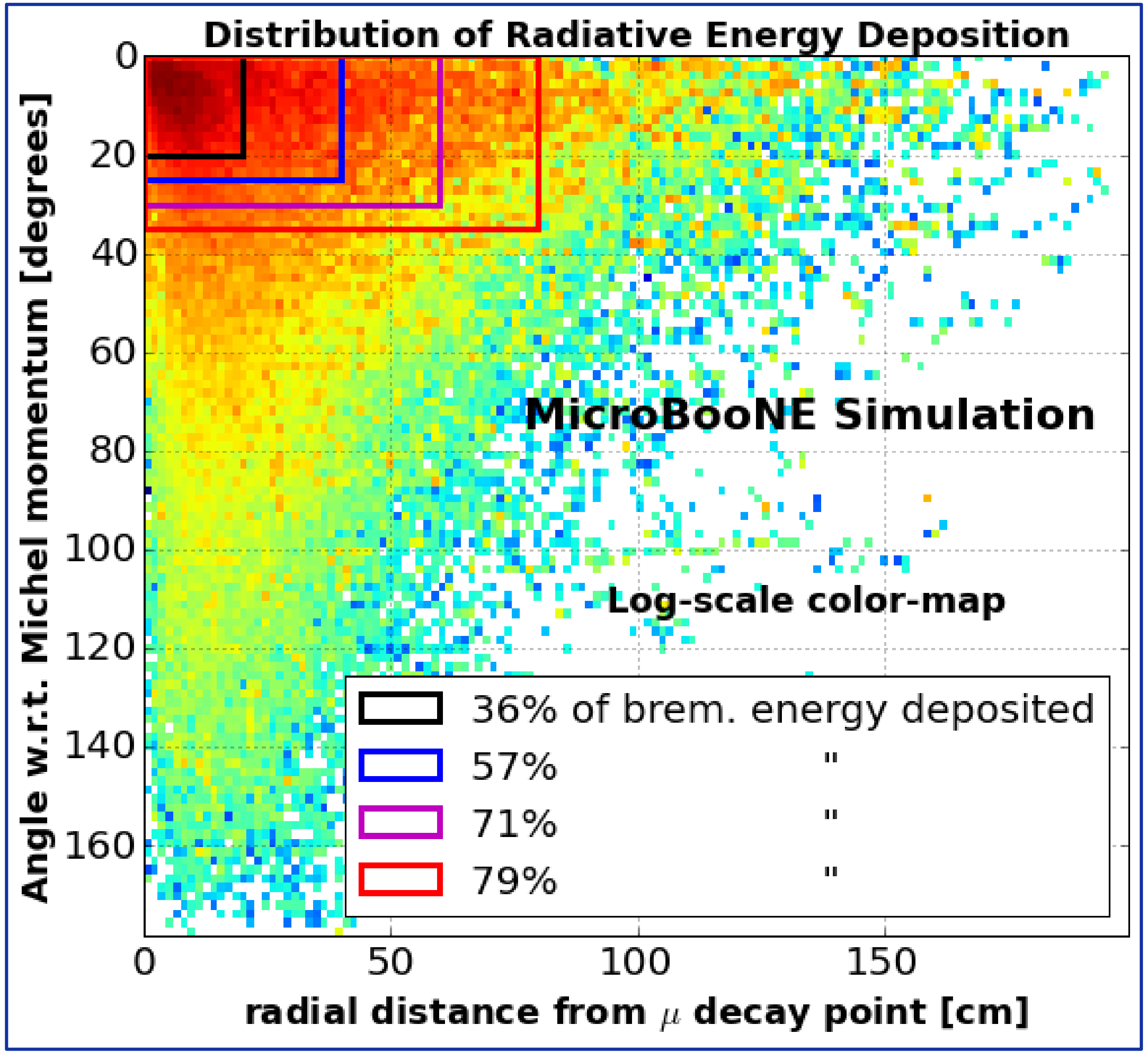
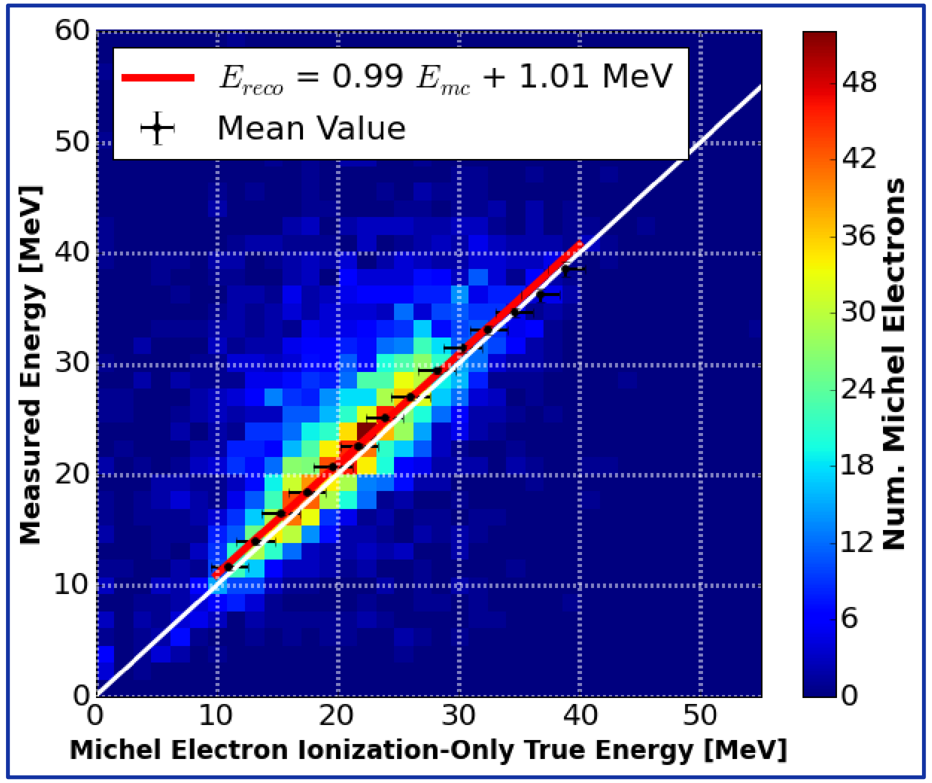
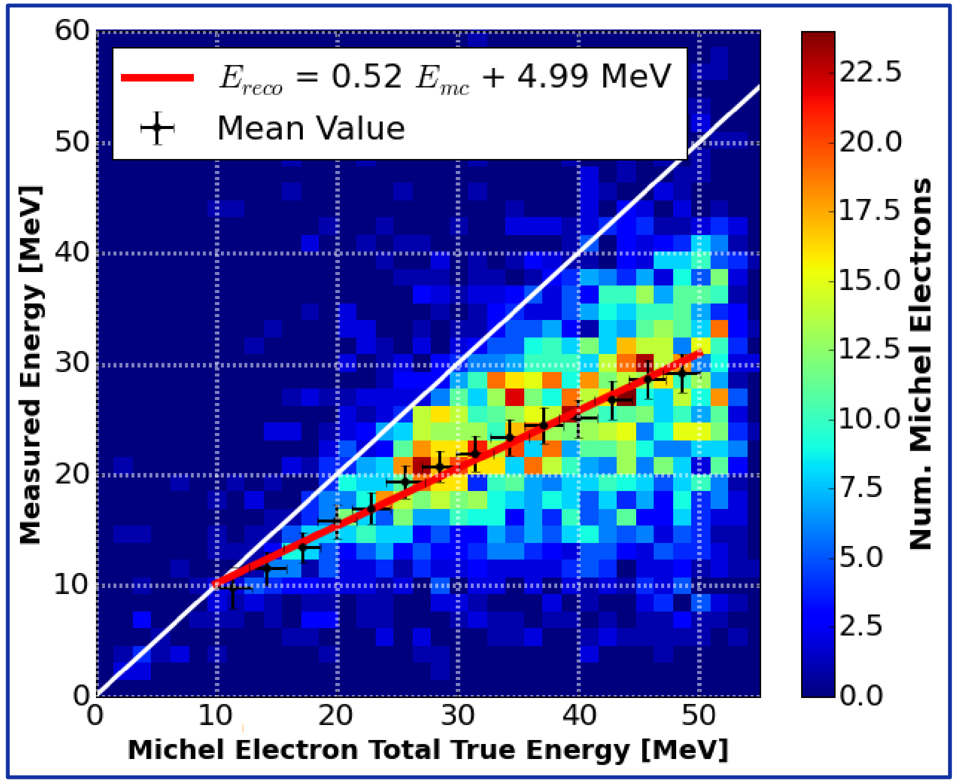
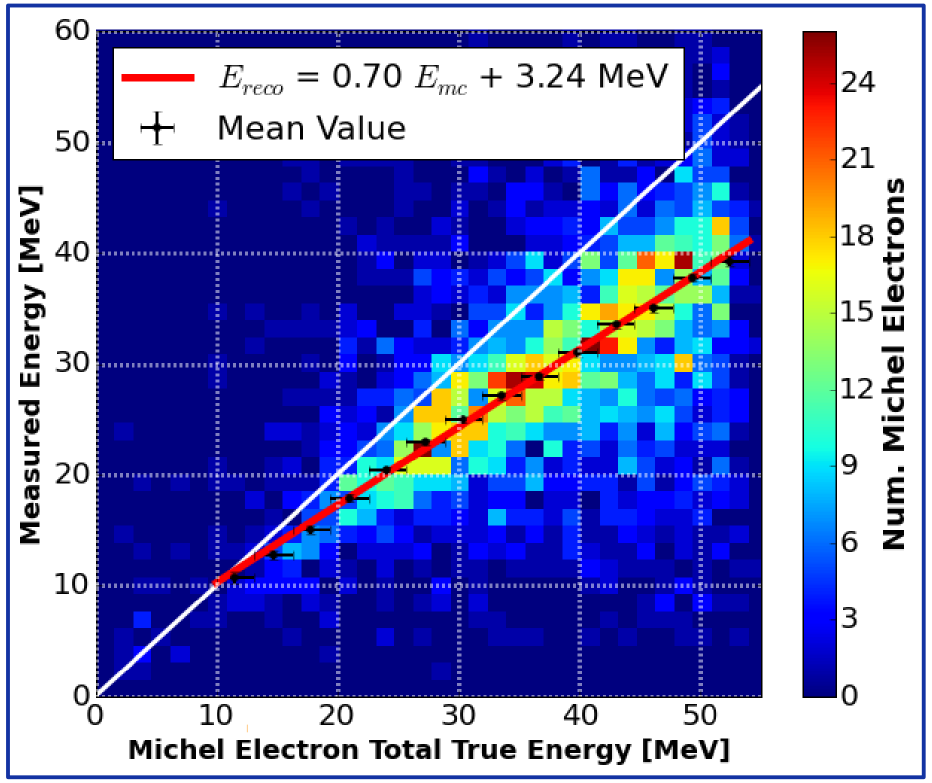
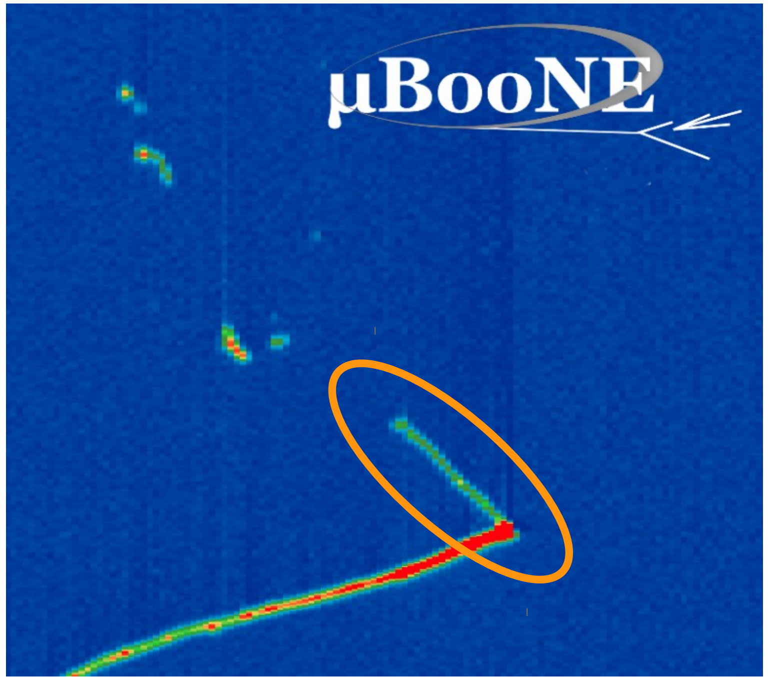


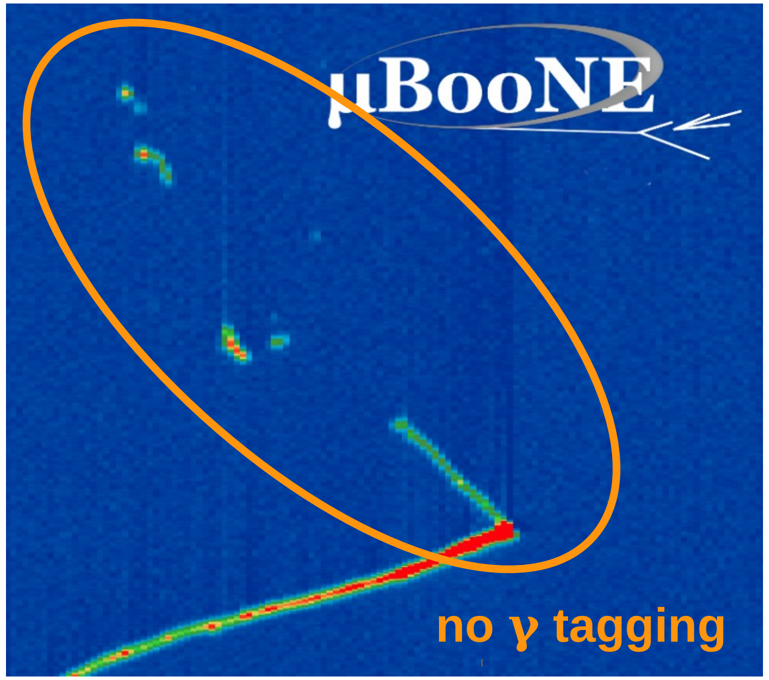
Michel electrons : Monte Carlo energy resolution studies.

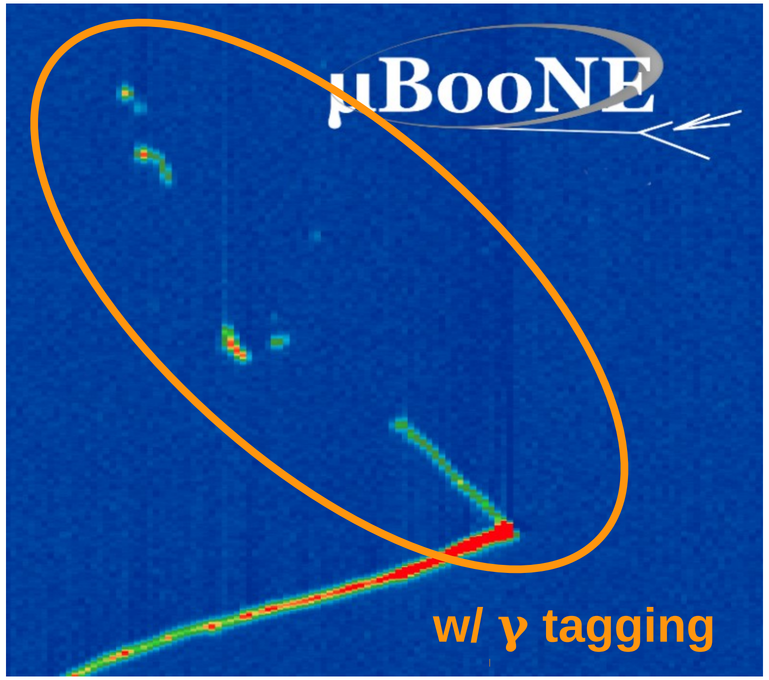




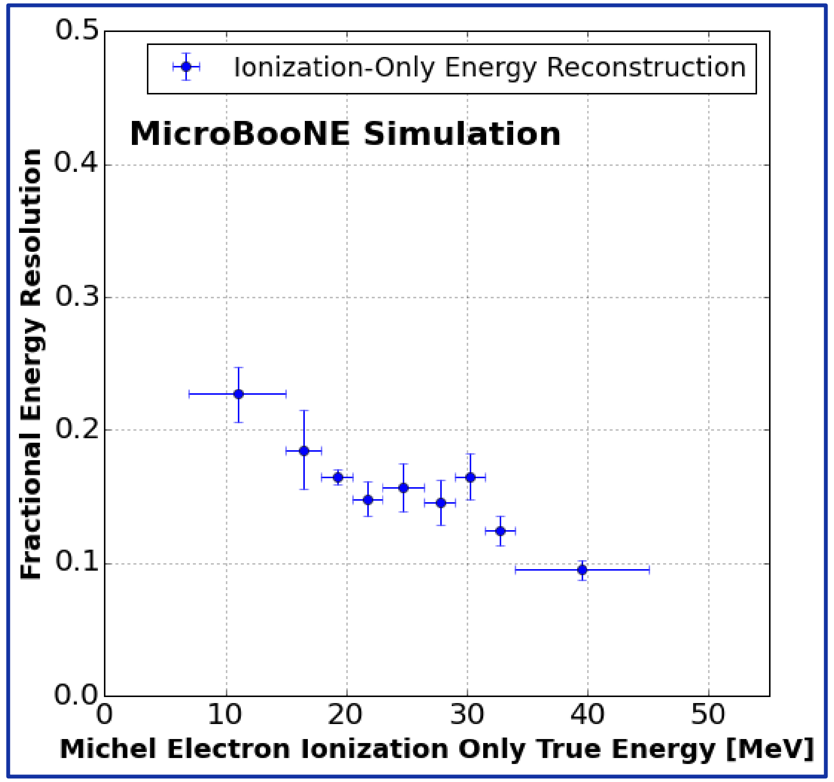


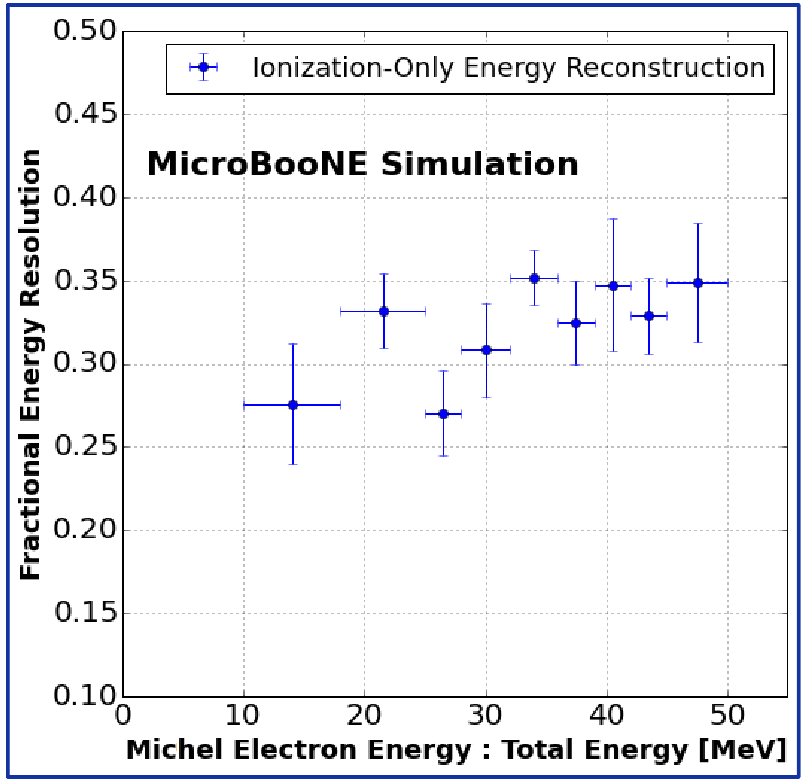


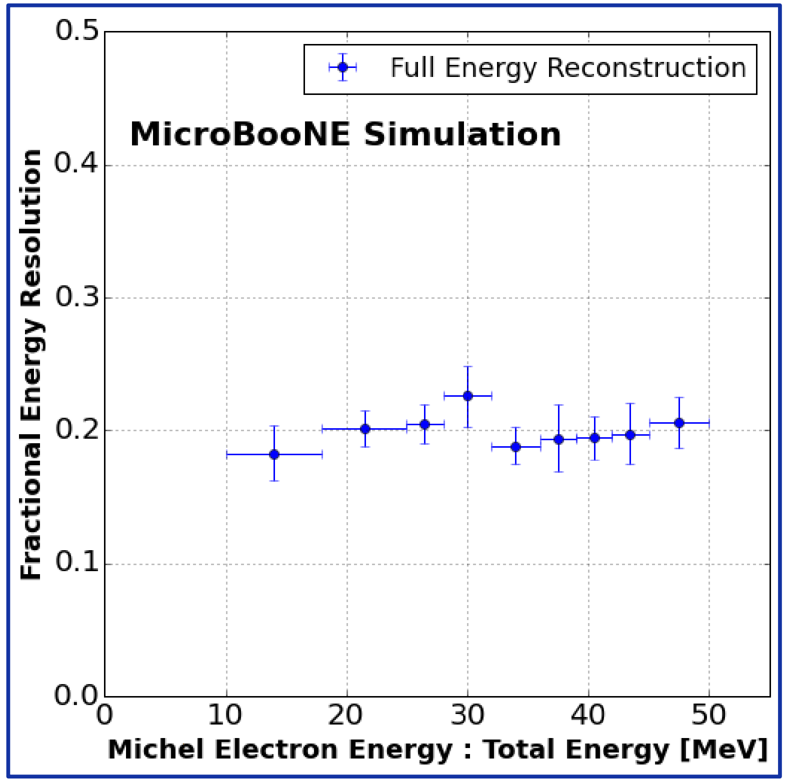


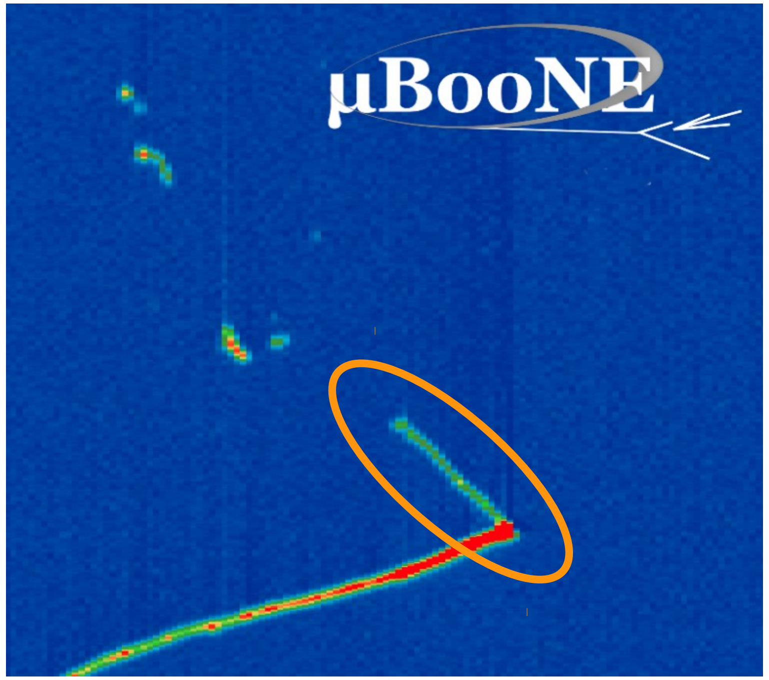


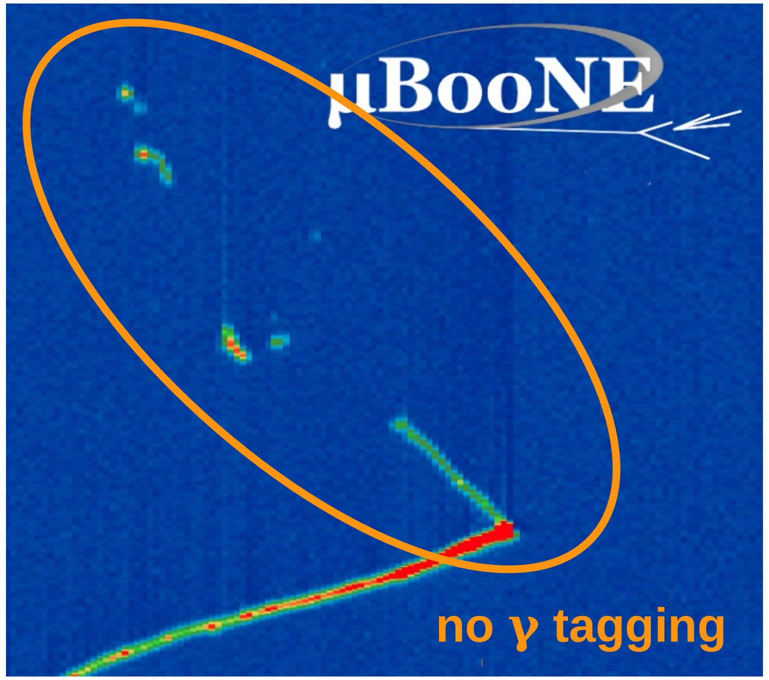
Michel electrons : Monte Carlo energy resolution studies.

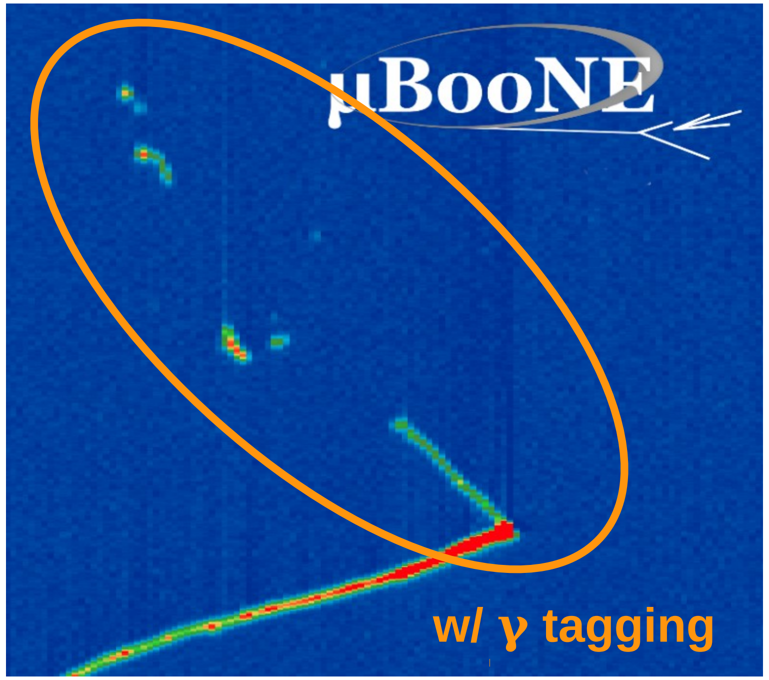












Michel Electrons : Purity and Resolution