Status of the MiniBooNE and MicroBooNE experiments

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MIT
August 27 2019

μBooNE

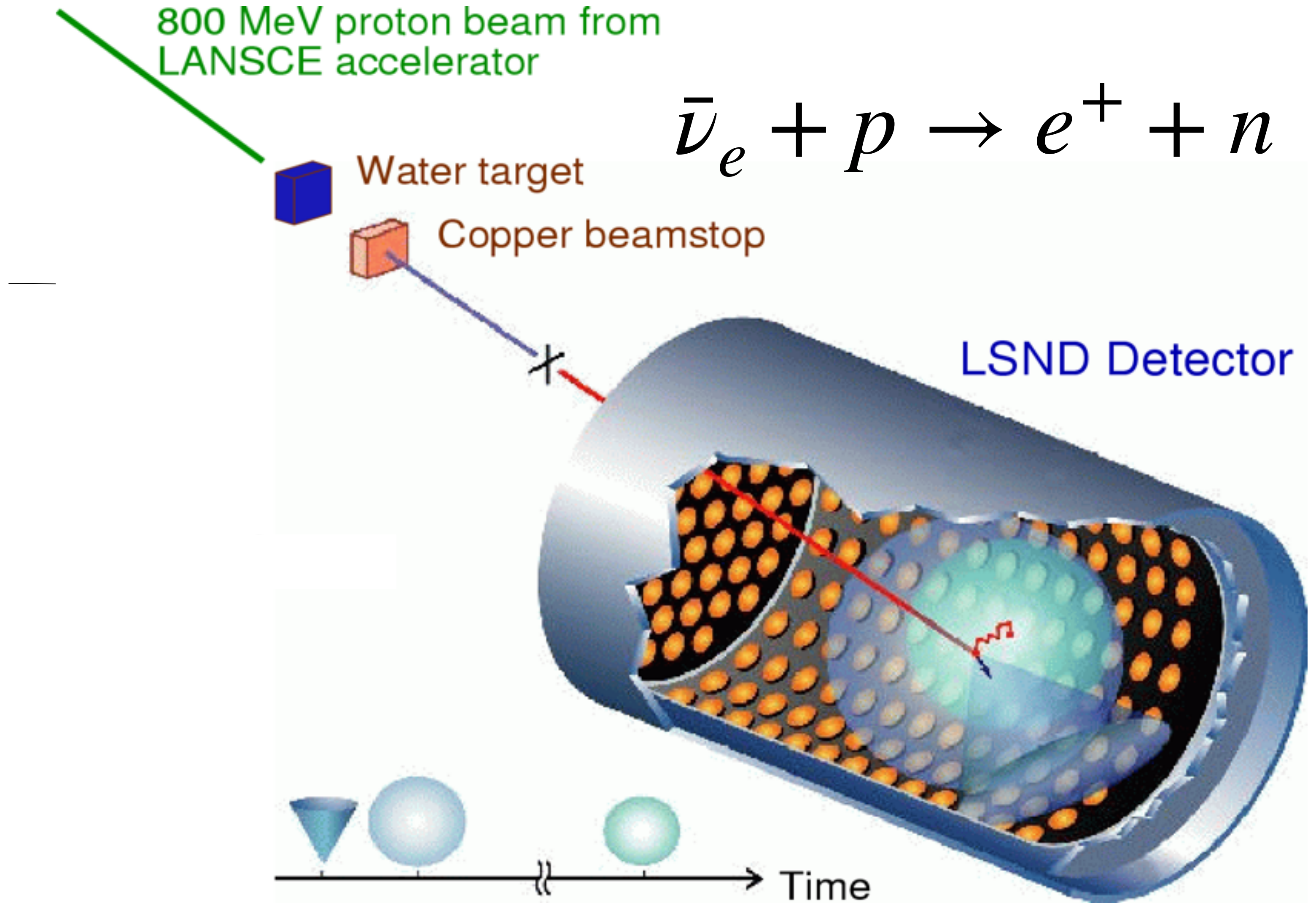
NuFact 2019

Before MiniBooNE : The LSND Anomaly

- Stopped π beam

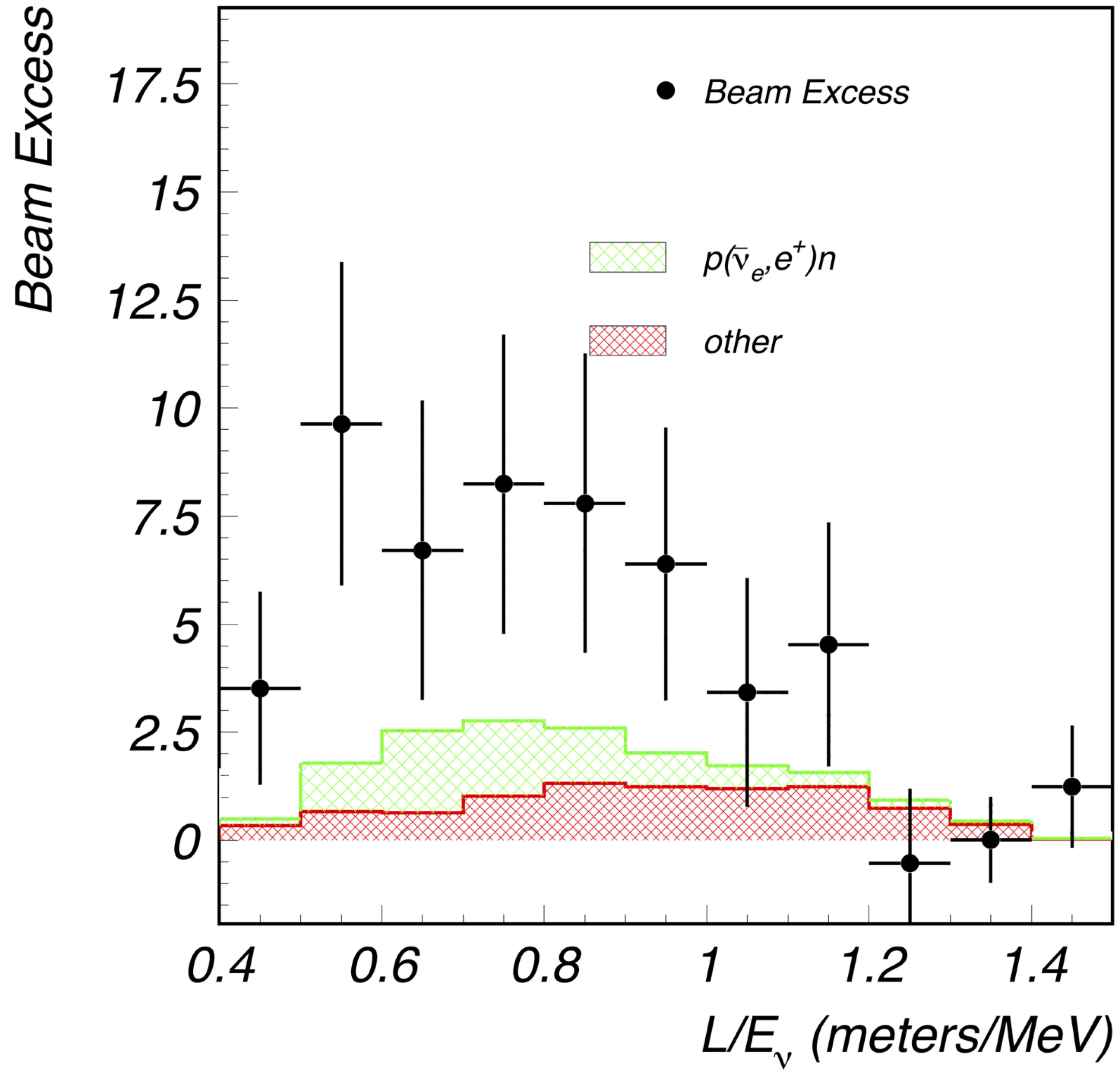
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature : Cherenkov light from e^+ with delayed n-capture
- Excess = 87.9 ± 22.4 ± 6 (3.8σ)



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Phys.Rev.D 64.112007



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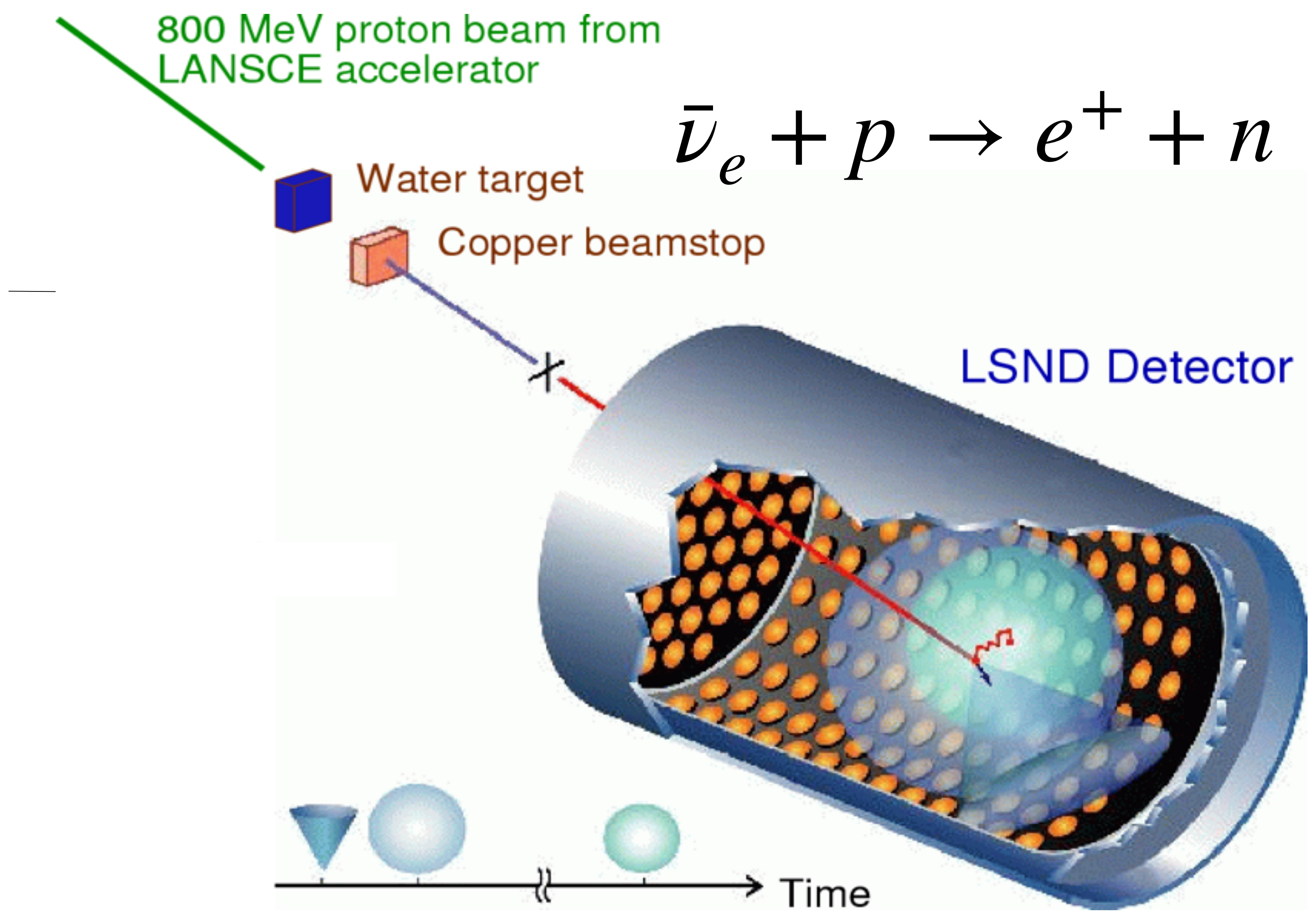

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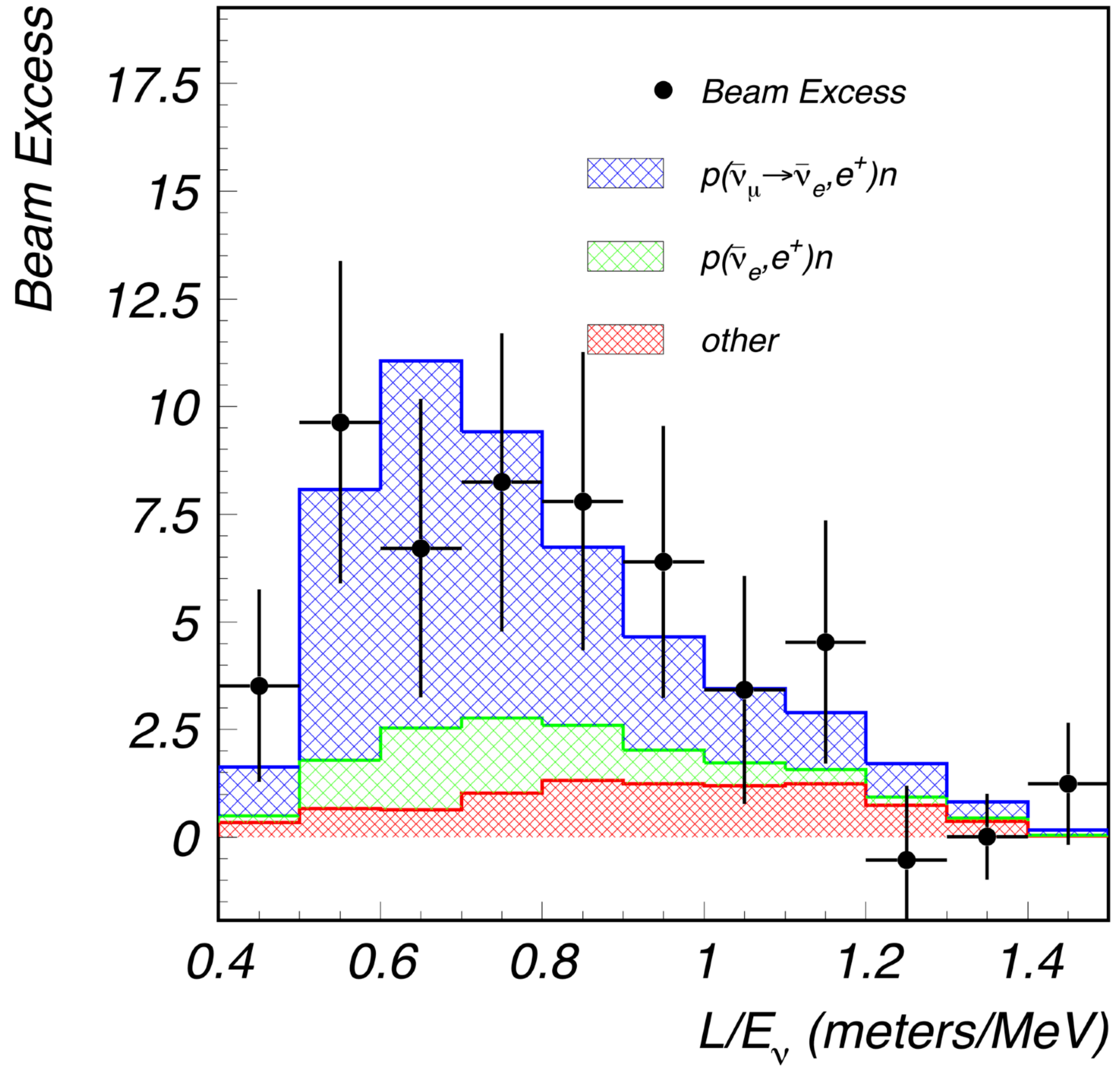
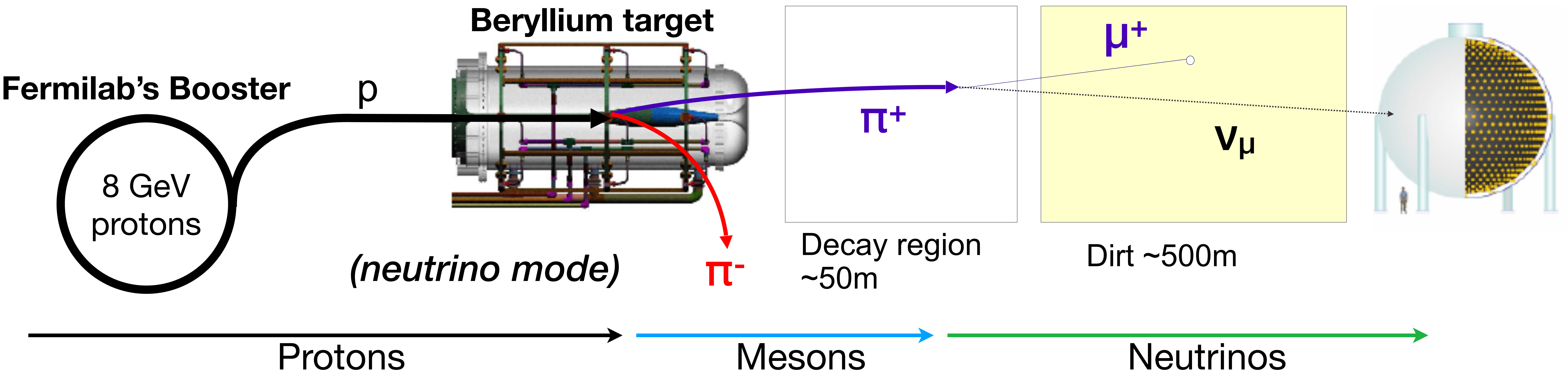
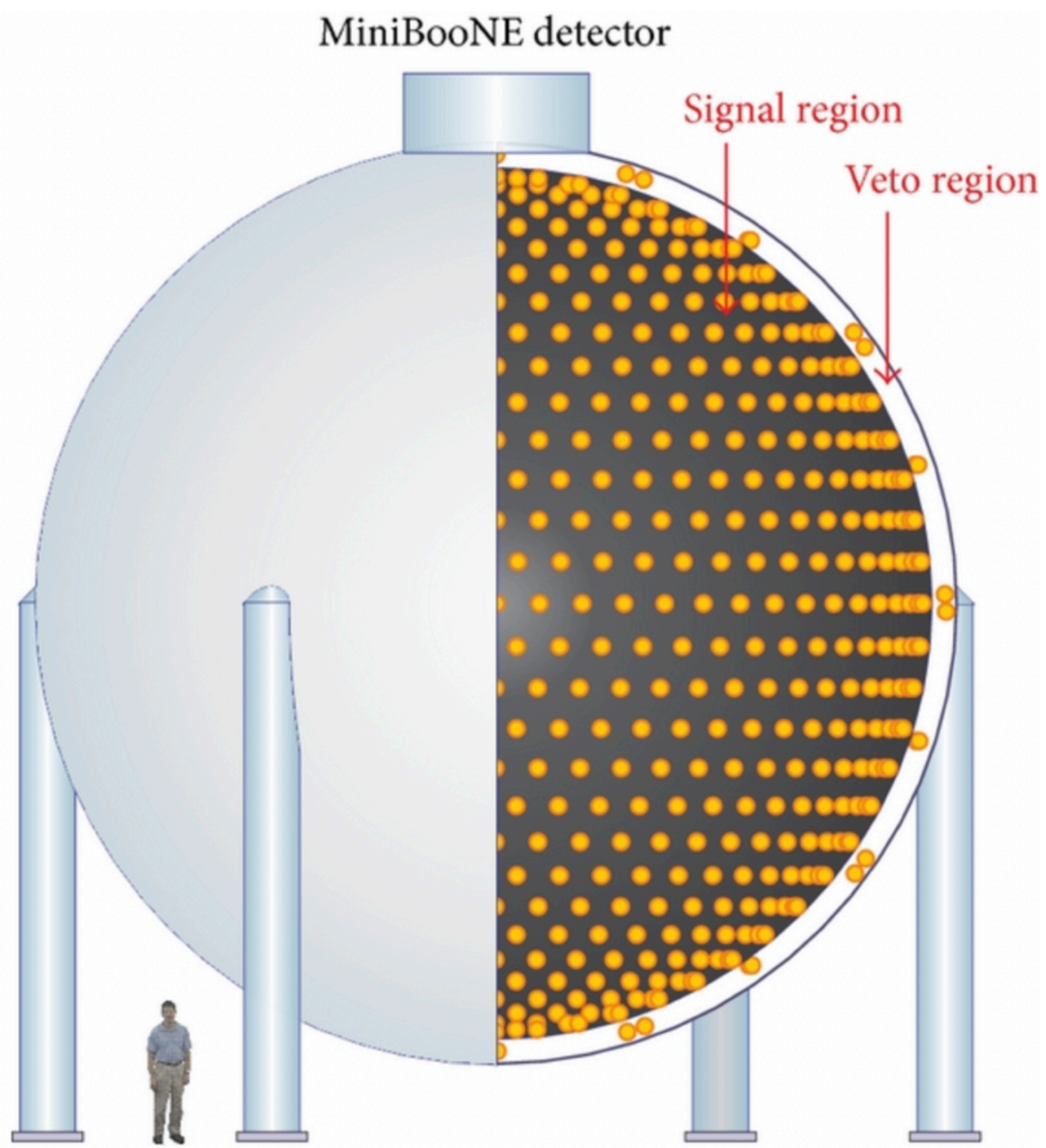


The MiniBooNE Experiment

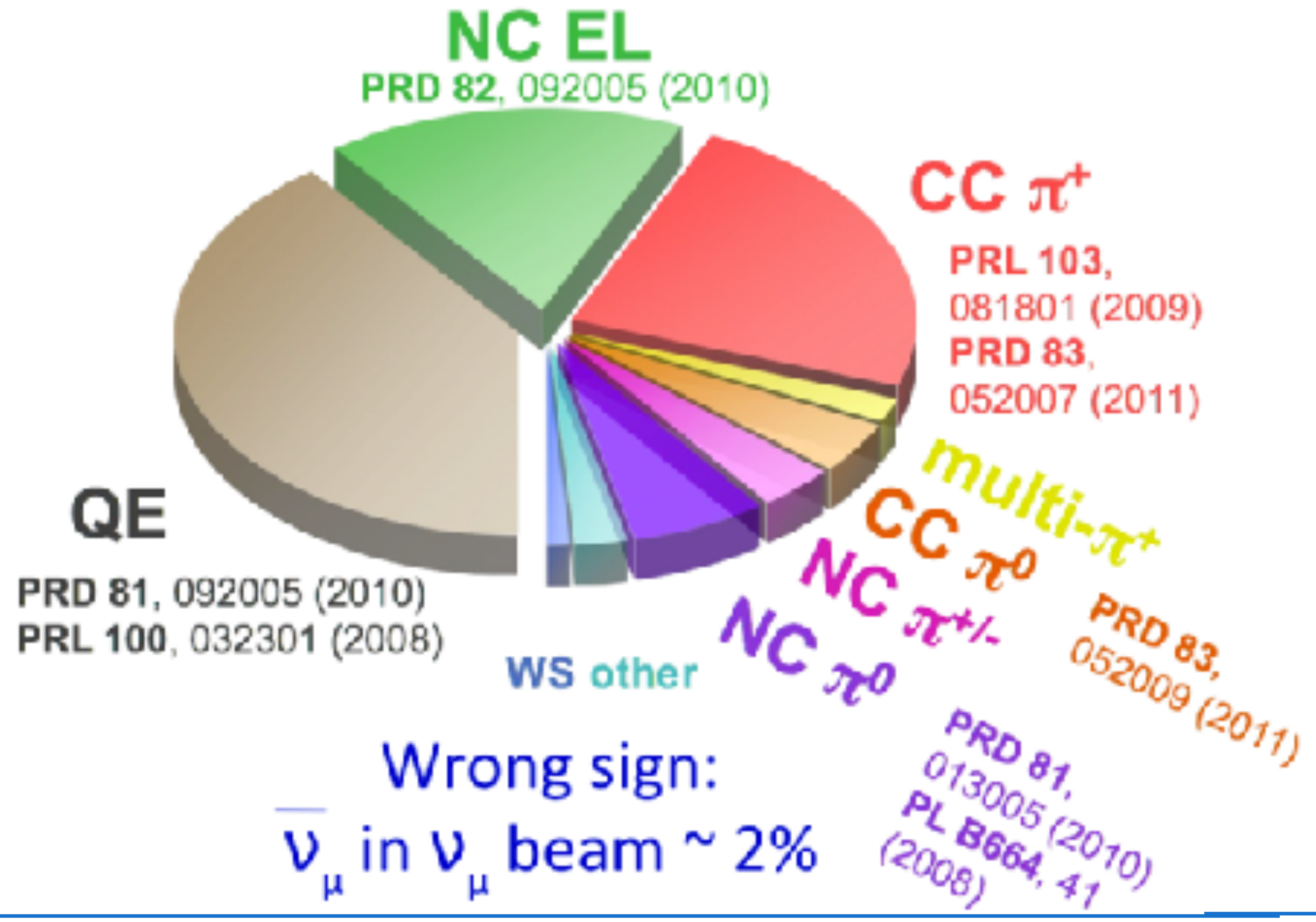


- Proposed to investigate the LSND anomaly, in search for sterile neutrinos
- Located on the Booster Neutrino Beam at Fermilab
- Single horn focused neutrino beam : Selection of neutrino/antineutrino modes
- Similar L/E as LSND :
  - MiniBooNE ~500 m / ~500 MeV
  - LSND ~30 m / ~ 30 MeV
- Different systematics due to different fluxes, event signatures and backgrounds

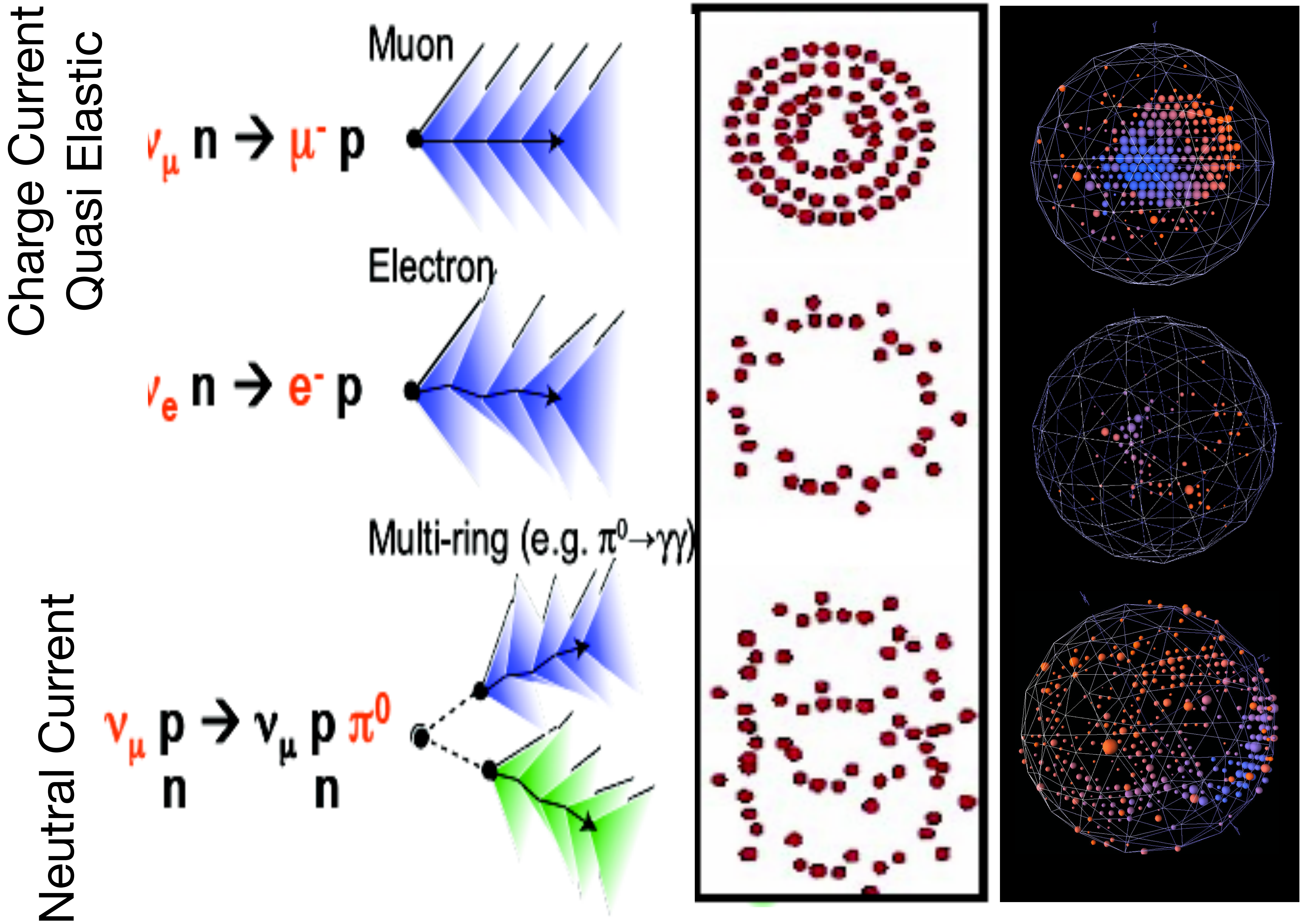
The MiniBooNE Detector



- ⌀12.2 m sphere, ⌀10m fiducial volume
- 800 tons of mineral oil, 450 tons fiducial mass
- 2 optically isolated volumes
- 1280 inner PMTs, 240 veto PMTs
- Very well understood detector
  - 2% change of the energy scale over 15 years of running
  - Measurements of cross sections for most of the neutrino and anti-neutrino processes



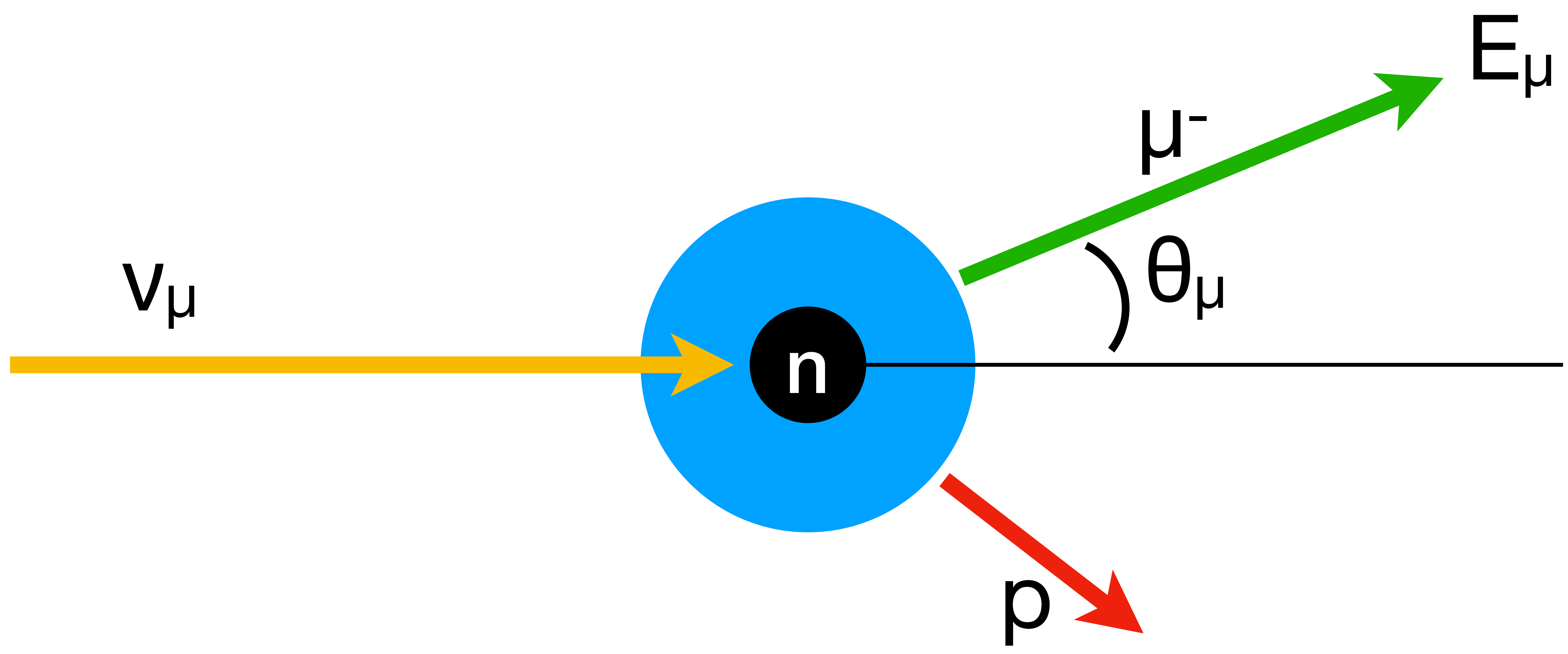
Events in MiniBooNE



- Background reduction using beam timing and hit topology
- Use primarily Cherenkov light
- ID based on ratio of fit likelihoods under different particle hypotheses
- Only sensitive to particles above the Cherenkov threshold
  => no proton detection
- Cannot distinguish single photon from single electron

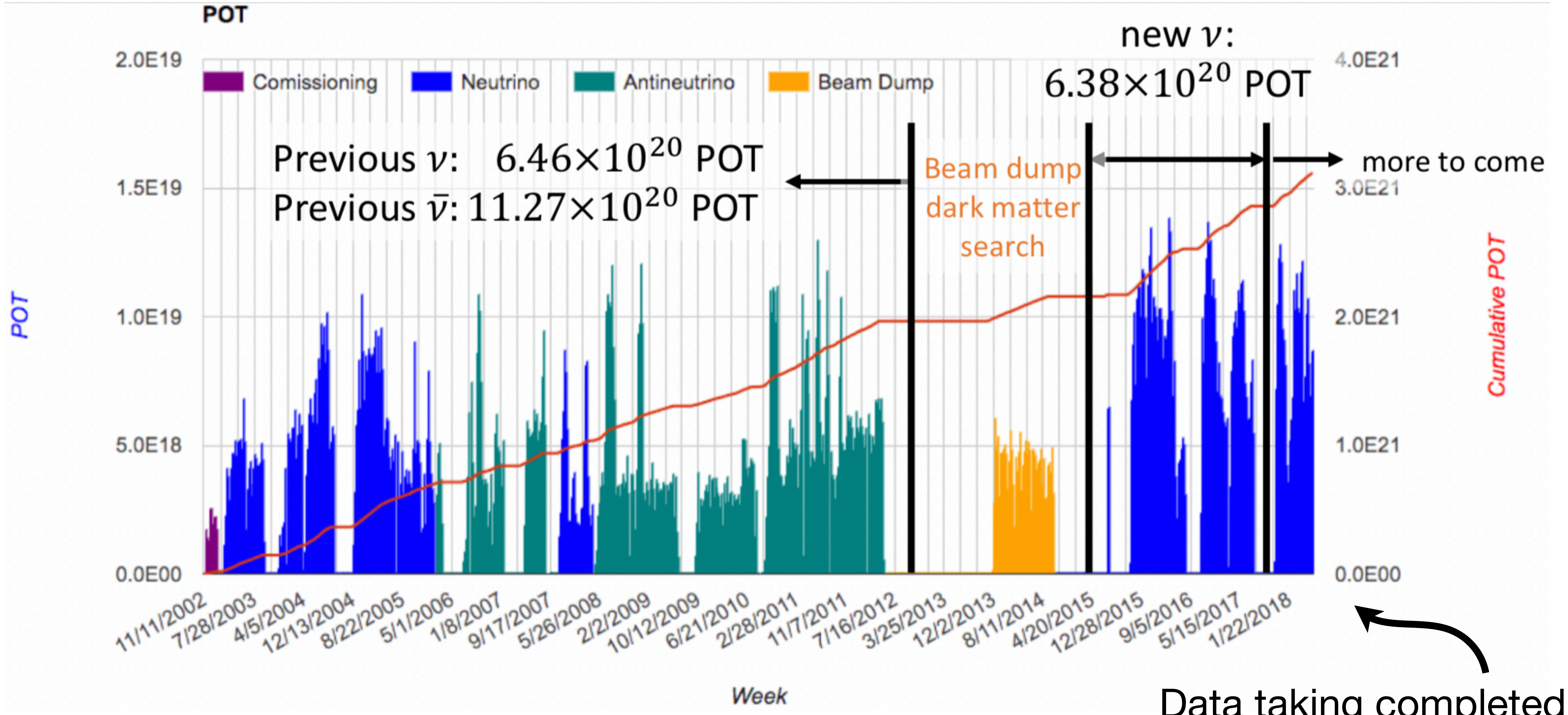
Energy Reconstruction

- Energy reconstructed using only the lepton kinematics derived from the Cherenkov cone
- Energy is reconstructed under the CCQE assumption
- Assumes CCQE interaction on a nucleon at rest, accounts for nuclear binding energy



$$E_\nu^{QE} = \frac{2(M_n - E_B)E_\ell - ((M_n - E_B)^2 + M_\ell^2 - M_p^2)}{2((M_n - E_B) - E_\ell + p_\ell \cos\theta_\ell)}$$

Data Taking

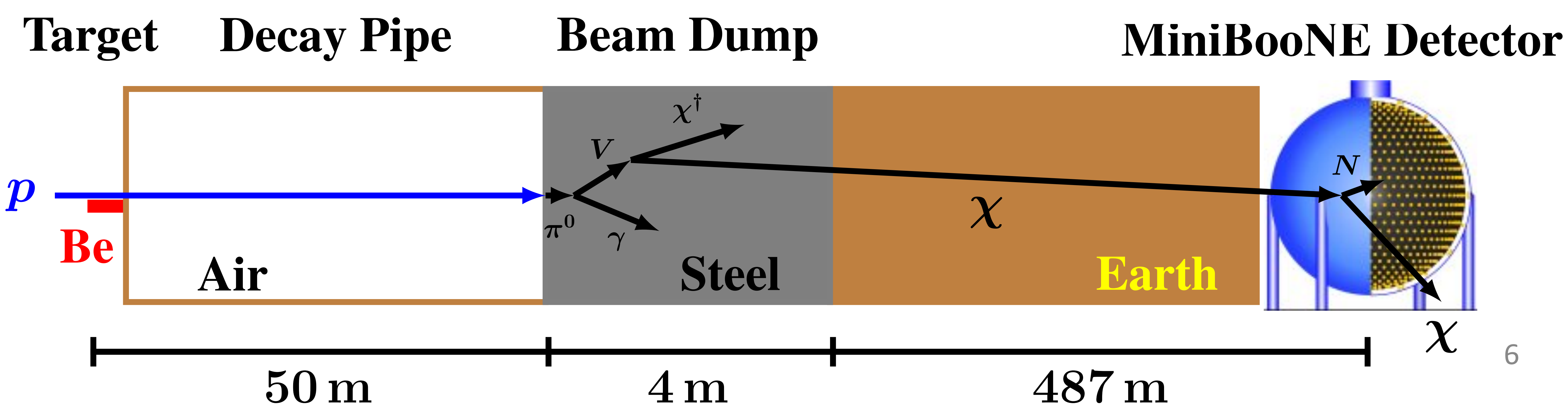


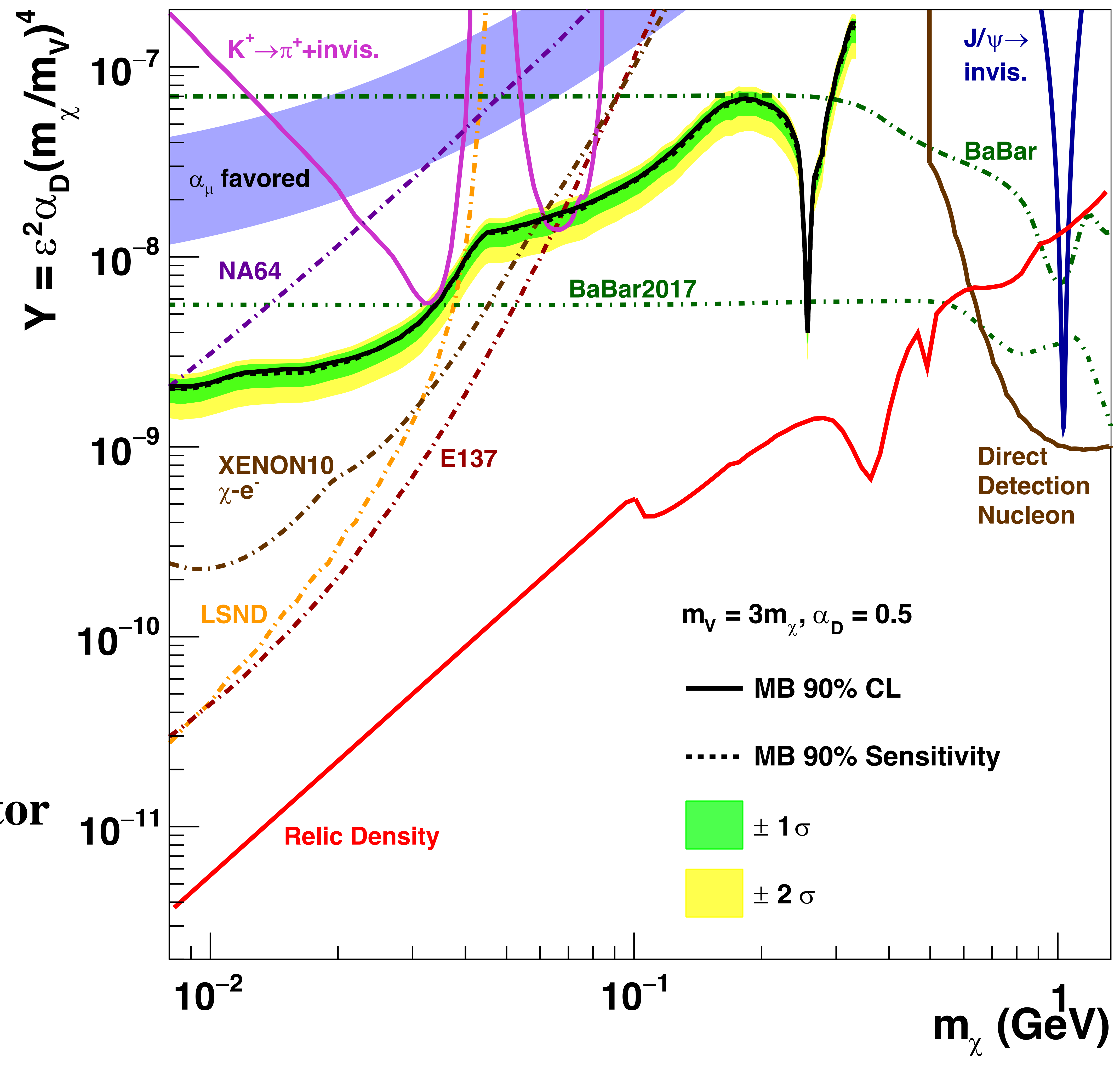
Data taking completed in June 2019
Another ~6x10^{20} POT not yet analyzed

- 15+ years of data taking with a very stable and robust detector
- New result published in 2018 doubles the statistics in neutrino mode (PRL 121,221801 (2018))
- Improved data-driven background constraints

Other analyses : DM search in beam dump mode

- First dedicated search for direct detection of accelerator-produced dark matter in a proton beamline
- Beam-dump mode reduced the ν flux by ~50
- The goal was to test vector portal model interpretation of g-2 (ruled out)
- At time of publication : set world leading limits in the vector portal dark matter model with a dark matter mass between 0.01 and 0.3 GeV





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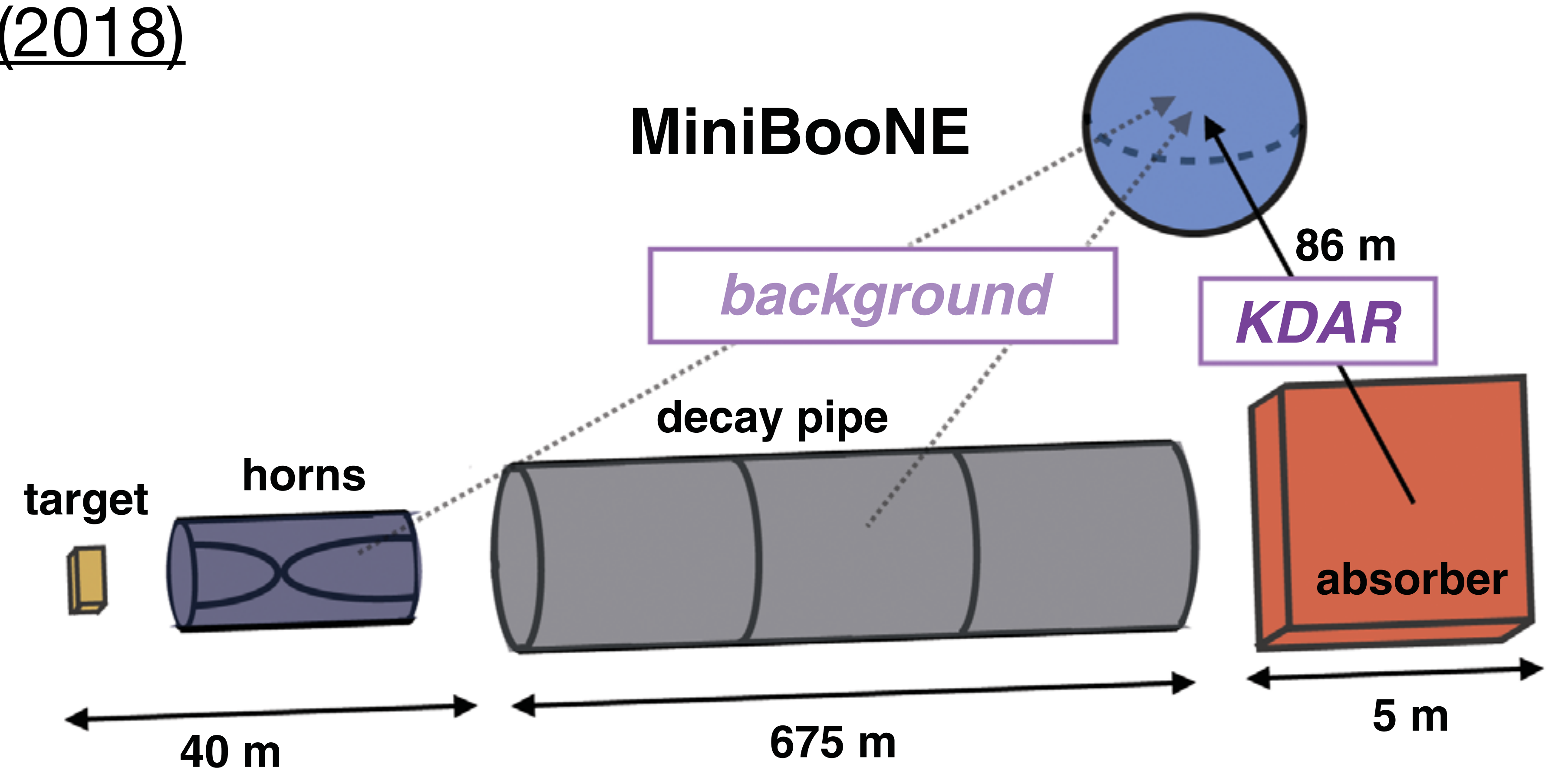
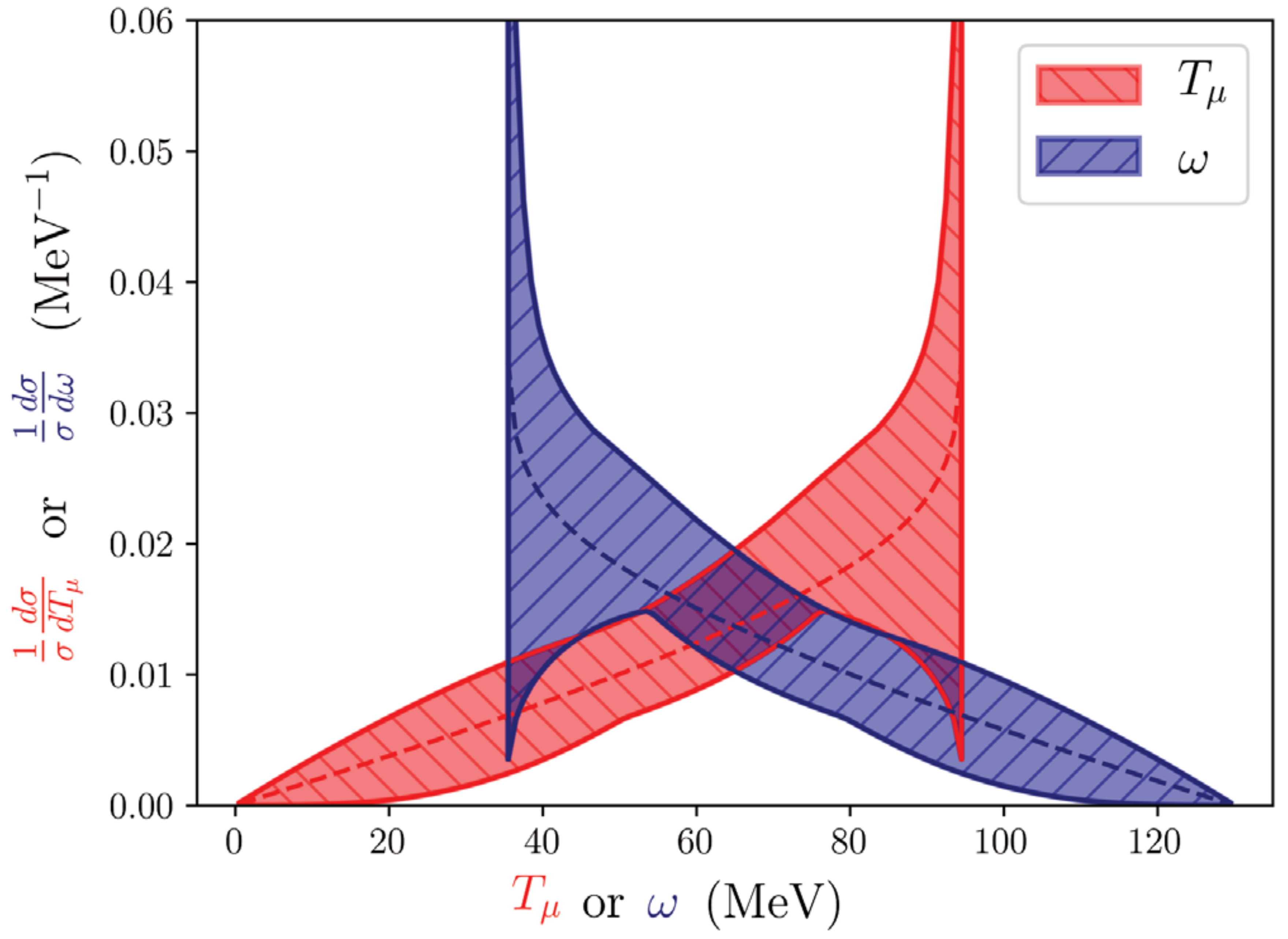
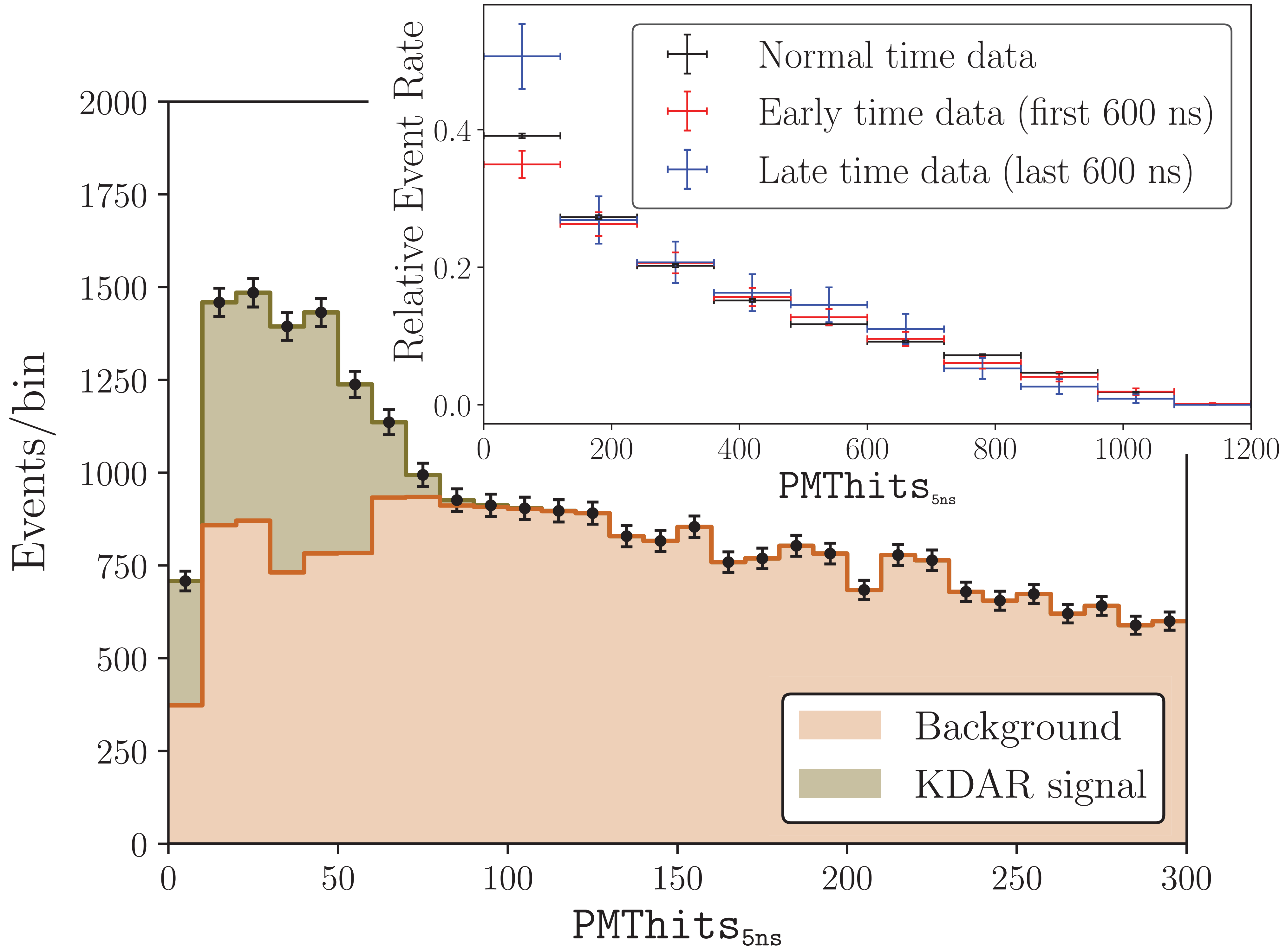
Other analyses : KDAR

PRL 120, 141802 (2018)

- Kaon Decay At Rest
- KDAR neutrinos from the NuMI beam line absorber have been identified based on energy reconstruction and timing
- First measurement of ω (energy transfer to the nucleus) with a known energy, weak interaction-only, nuclear probe
- Results provide a standard candle for understanding ν_μ CC events at a known energy (236 MeV)

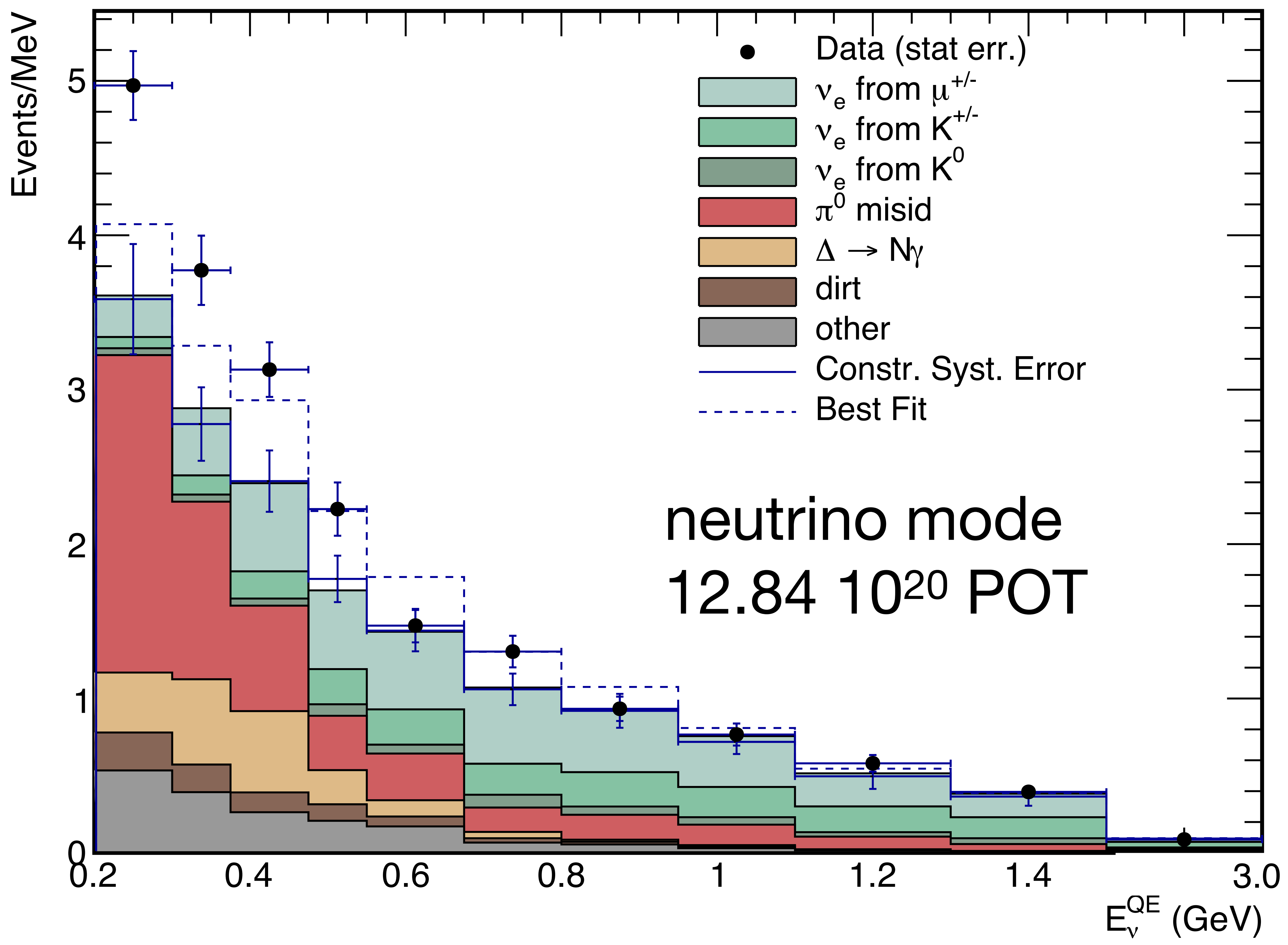






ν_e-Like Excess

PRL 121,221801 (2018)



- Old+new dataset in neutrino mode
- Neutrino mode ν_e excess of 4.5σ
- Main backgrounds are related to separating γ and e^-

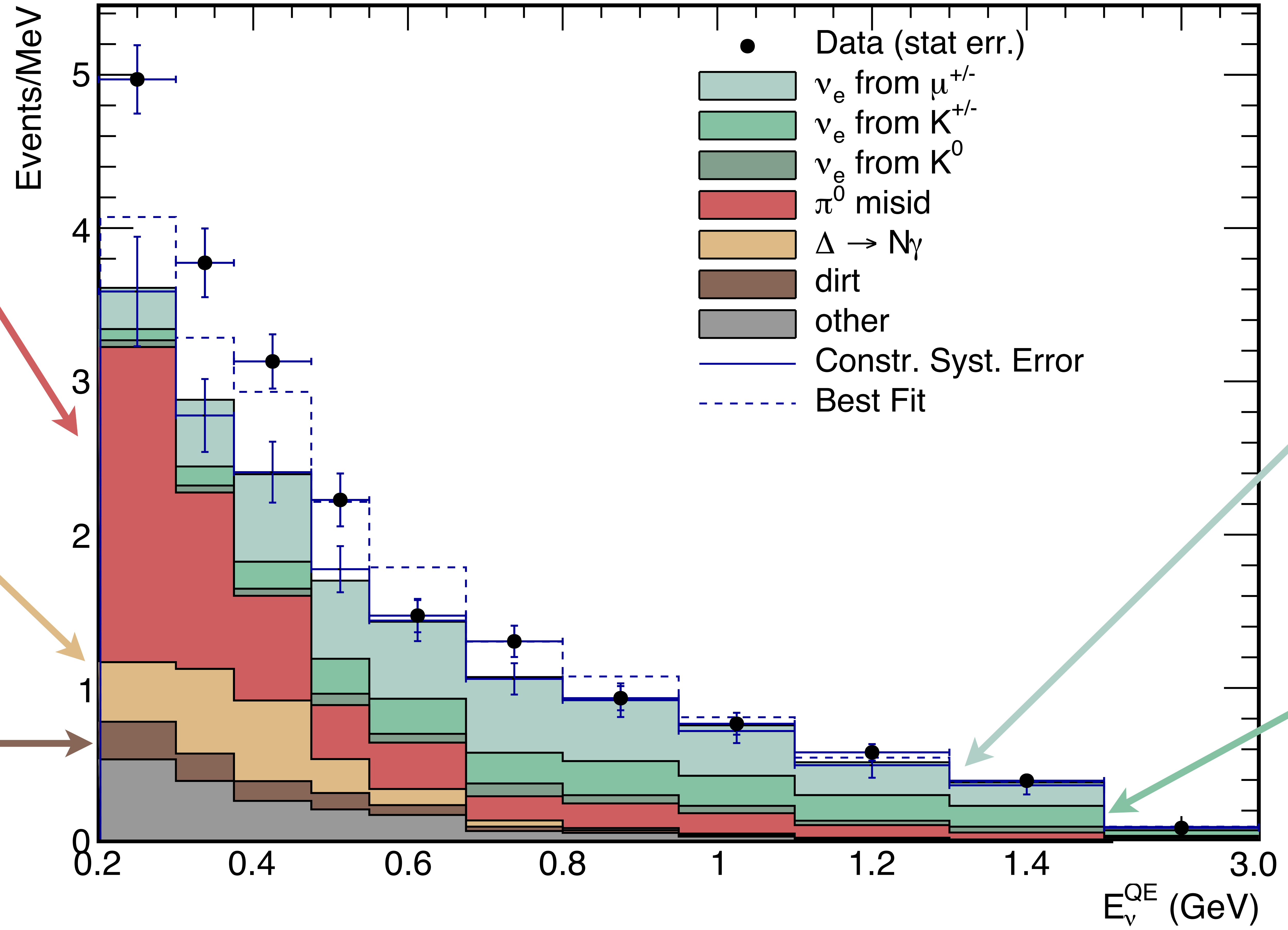
Constraining Backgrounds

π^0 MisID
constrained from *in situ* measurement of NC π^0 rate

Δ-> Nγ resonance
constrained from *in situ* measured NCπ^0 rate and theoretical prediction

Dirt
constrained from *in situ* dirt data sample

PRL 121,221801 (2018)

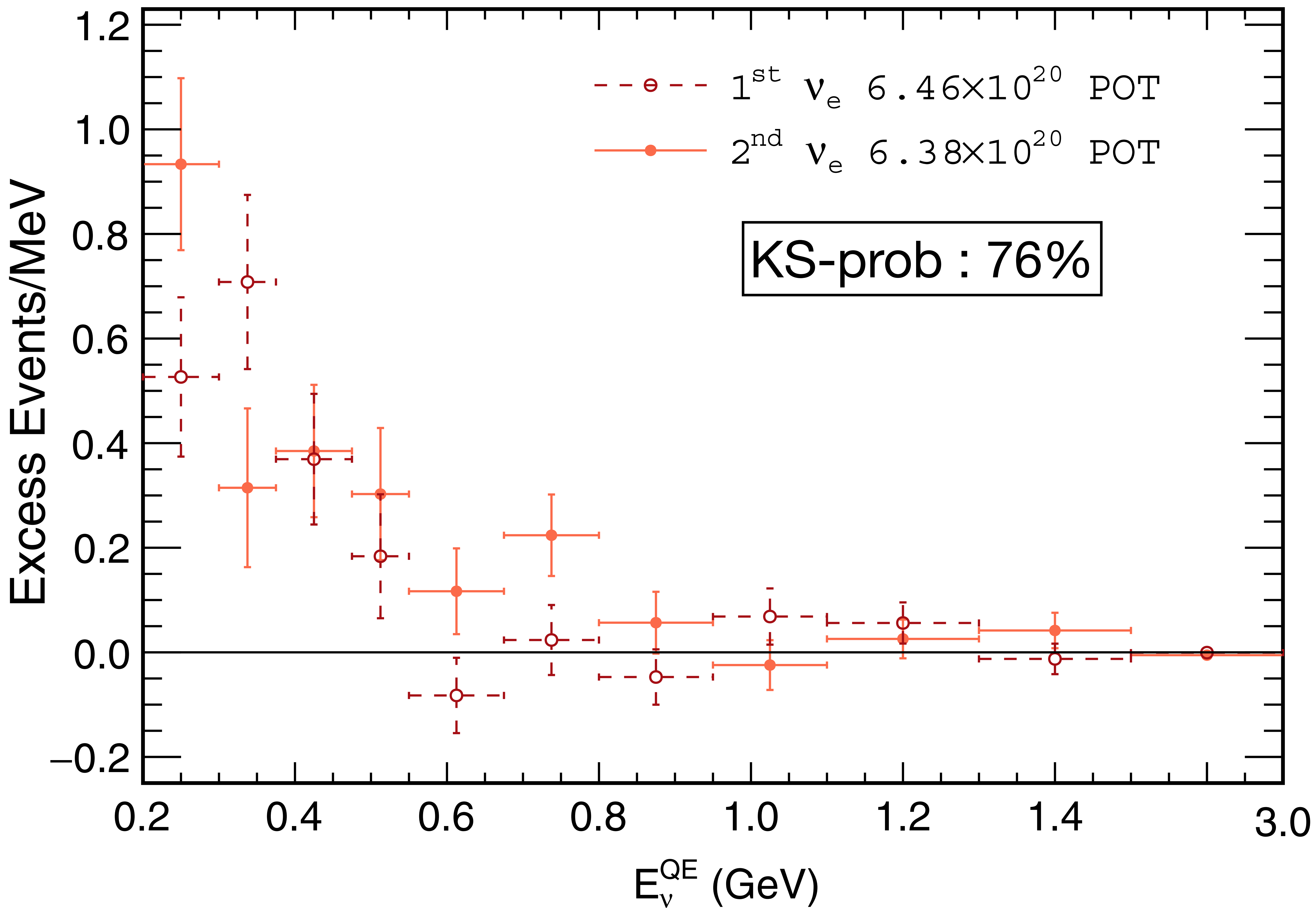


ν_e from μ decay
is constrained by *in situ* ν_μ CCQE measurement

ν_e from K decay
constrained from *in situ* high energy events + SciBooNE high energy ν_μ event rate

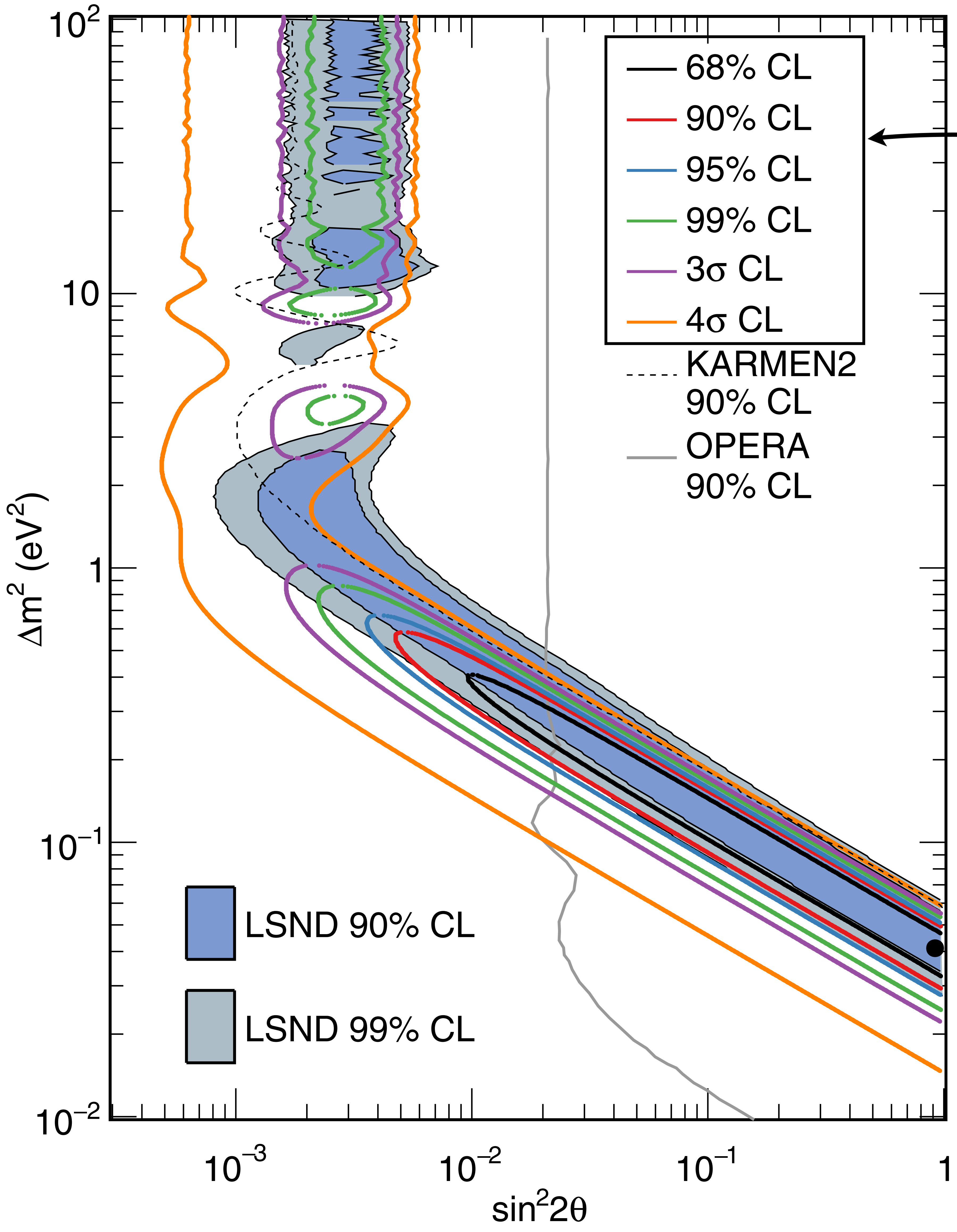
ν_e-Like Excess consistency

PRL 121,221801 (2018)



- Comparing the data-prediction excess for two data sets in neutrino mode
- Comparable statistics between:
  - 2009 data release in neutrino mode
  - 2018 data release in neutrino mode
- The observed excess remains well compatible between the two data sets

Preferred regions in a (3+1)ν interpretation

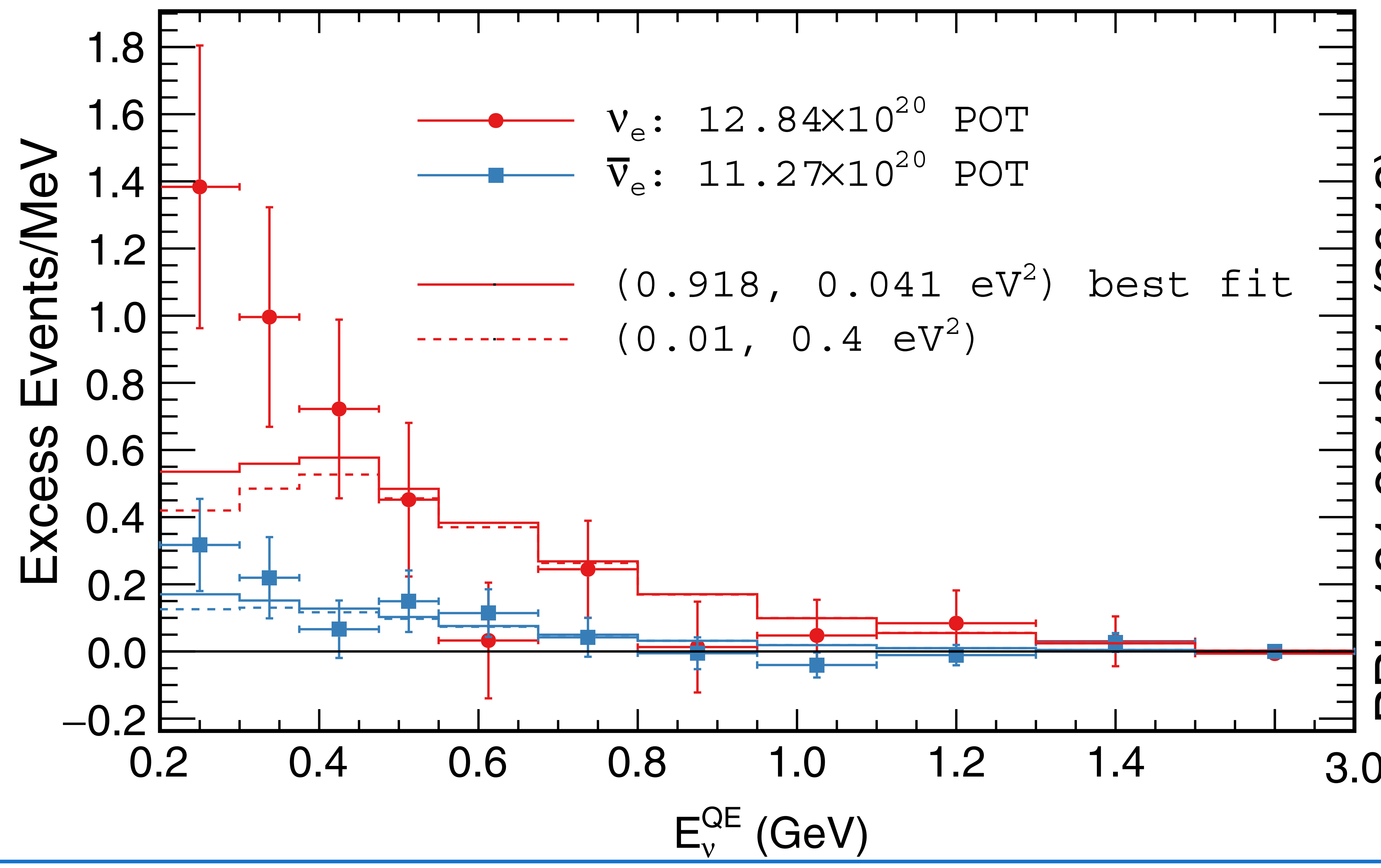


MiniBooNE's lines

Neutrino + Anti-Neutrino Mode

$$(\Delta m^2, \sin^2 2\theta) = (0.041\ \text{eV}^2,\ 0.918)$$
$$\chi^2/ndf = 19.4/15.6\ (\text{prob} = 21.1\%)$$

- Neutrino mode excess 4.5σ,
- Neutrino+Anti-neutrino modes excess 4.8σ
- Combined LSND and MiniBooNE significance of 6.1σ
- Similar agreement of neutrino and anti-neutrino data to (3+1)ν fit



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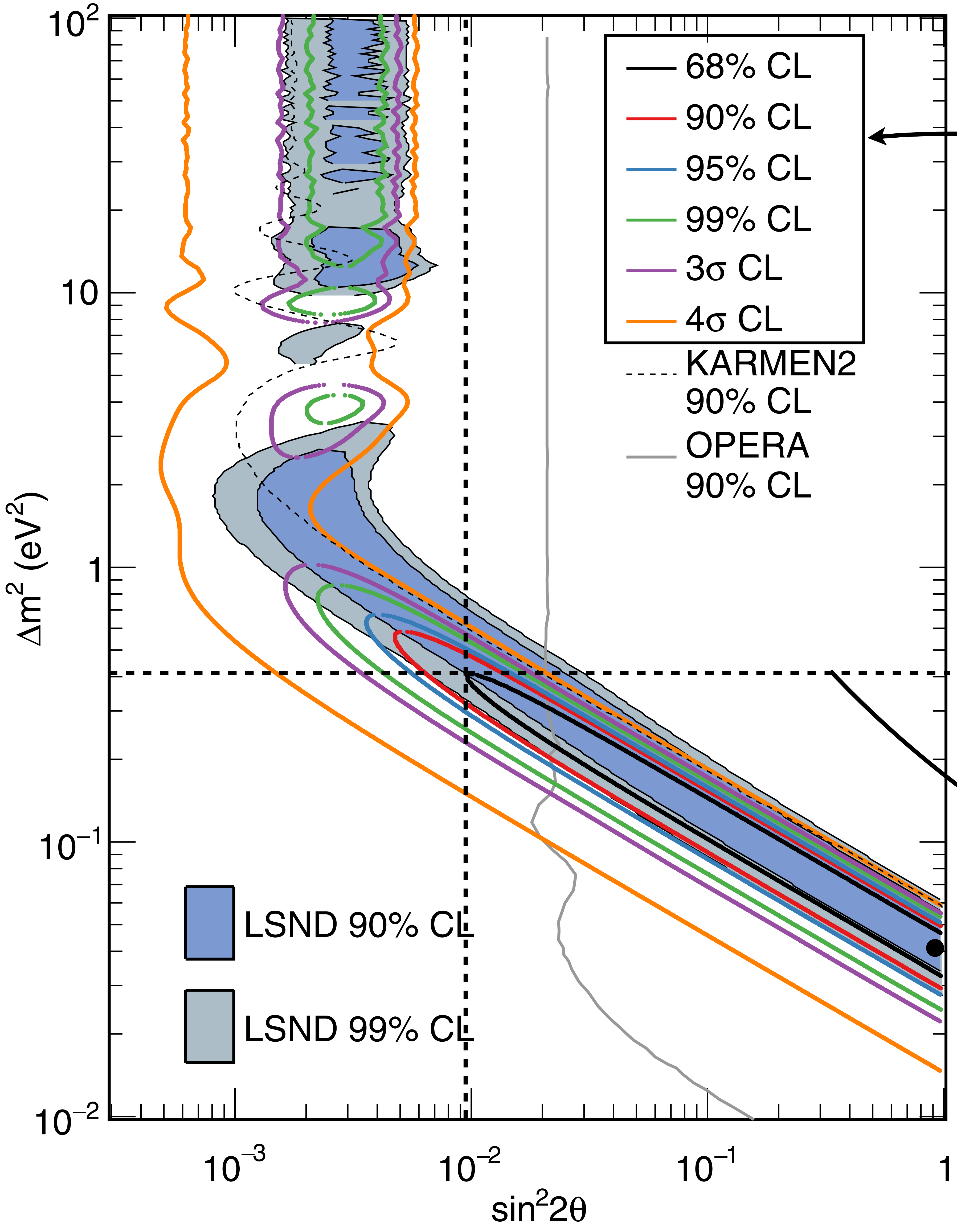

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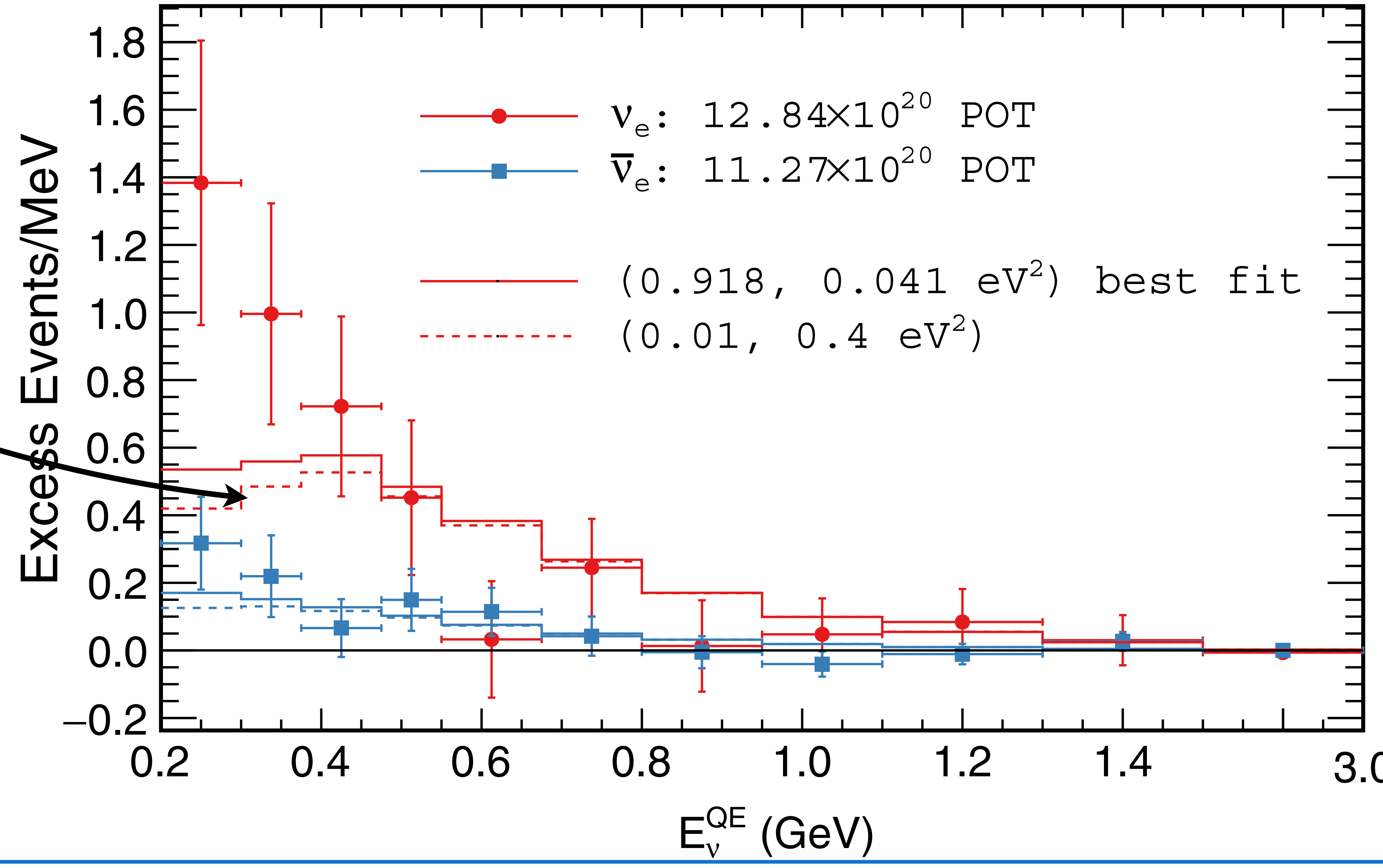


PRL 121,221801 (2018)

MiniBooNE : take away

- MiniBooNE observes a low energy ν_e-like excess with a significance of 4.8σ, compatible with the LSND excess

- Combines MiniBooNE+LSND significance of 6.1σ
- Not a perfect fit to a (3+1)ν model (large best fit value of $\sin^2 2\theta$ seems unphysical)
- Very stable detector over 15 years, well constrained backgrounds, from *in situ* measurements

- Excess seems real, needs a satisfactory explanation

MiniBooNE in the global picture

ν_e appearance, ν_e disappearance, and ν_μ disappearance are interlinked by these three probabilities :

$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$ ✓

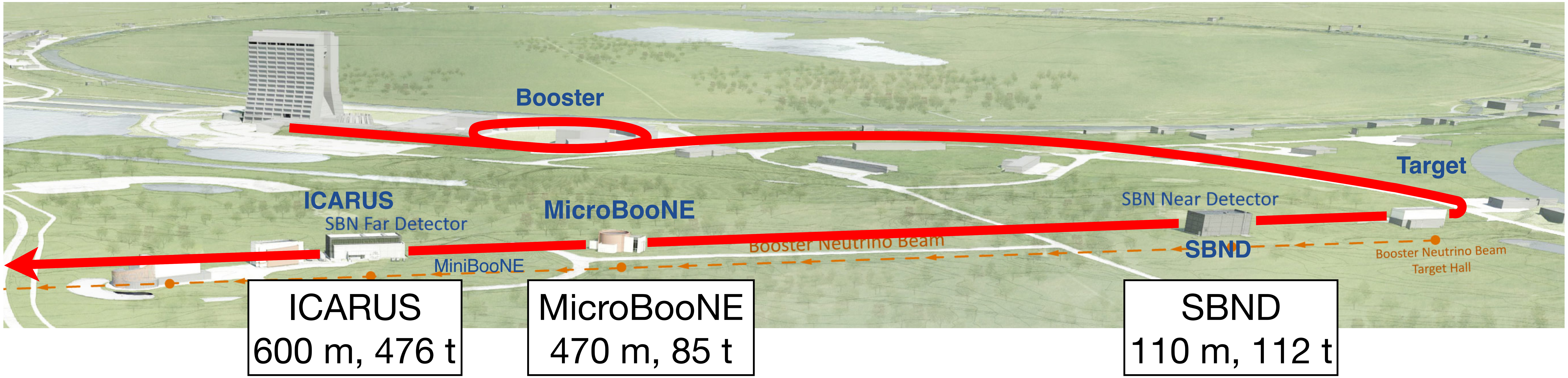
$$P_{\nu_\mu \to \nu_e} = 4|U_{\mu 4}|^2 |U_{e4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$ ✓

$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2(1.27\Delta m_{41}^2 L/E)$$ ✗

- We see signals in the ν_e appearance and disappearance, somewhat compatible, but not in the ν_μ disappearance
- The (3+1) model implies that we also see a signal in the ν_μ disappearance mode
- The (3+1) model alone seems insufficient
- Does MiniBooNE have a sterile signal + a systematics that could lead to a mis-estimation of the appearance excess?
- Are all appearance signals from backgrounds?

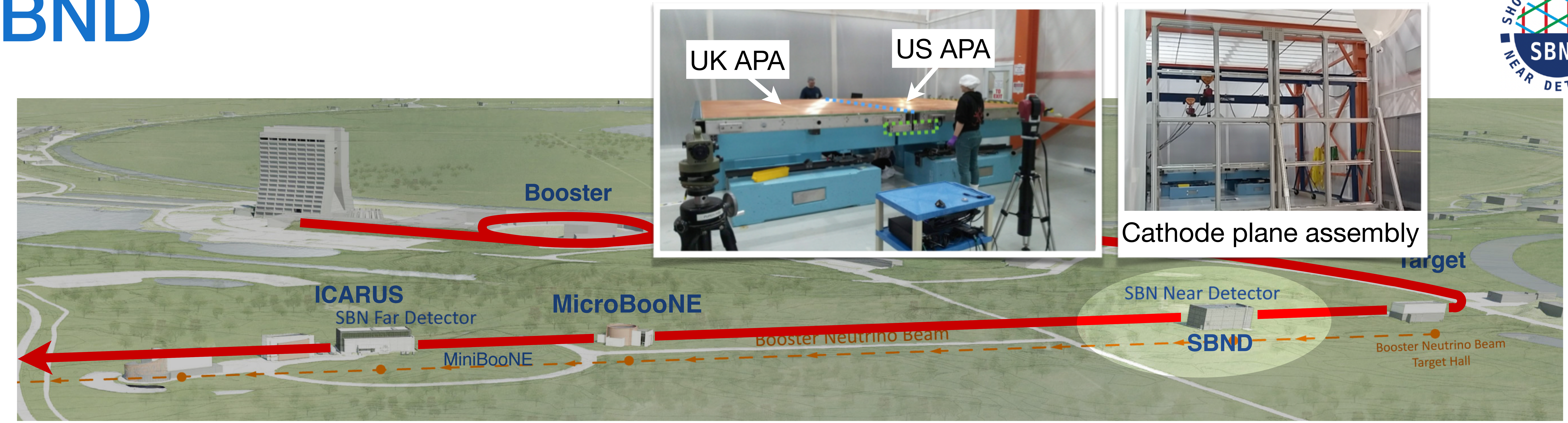
see arXiv:1906.00045 [hep-ex] for more details

SBN program



- Same beam line as MiniBooNE
- Three detectors on axis
- Same technology : Liquid Argon Time Projection Chamber (LArTPC)
  => Flux and cross-section systematics constraint, some detector systematics.
- High precision flux measurement
- High precision oscillation measurement

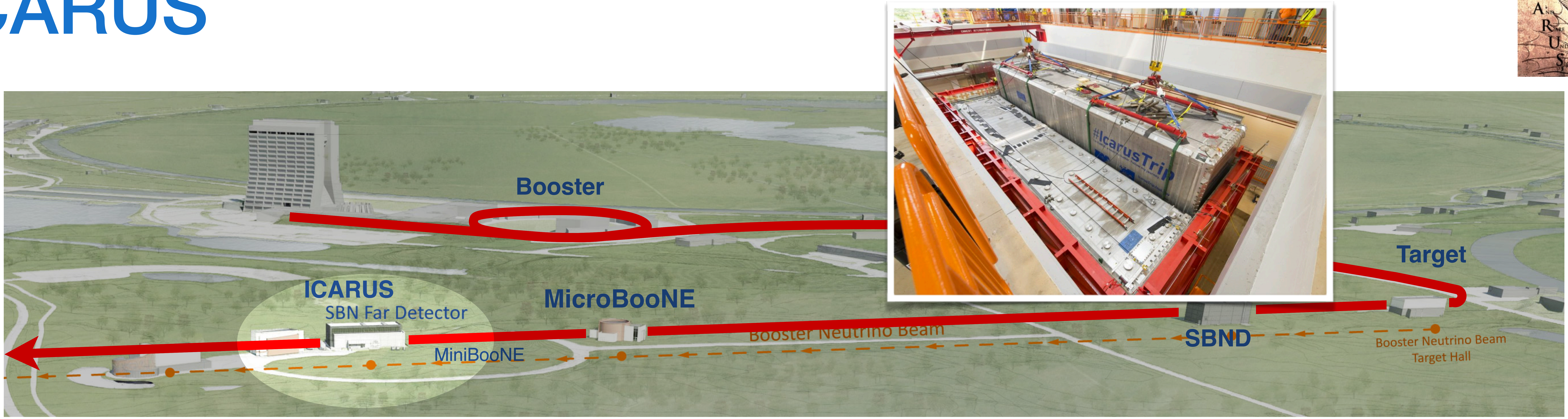
SBND



- Production of TPC components in UK and US complete
- Successful alignment, coupling, and QC of first two anode planes
- TPC assembly transport plane under construction at FNAL
- Cryogenics platform, valve box, and proximity cryogenics installation completing this month
- Warm cryostat construction at CERN underway

See the talk from Stephen Robert Dennis on Friday

ICARUS



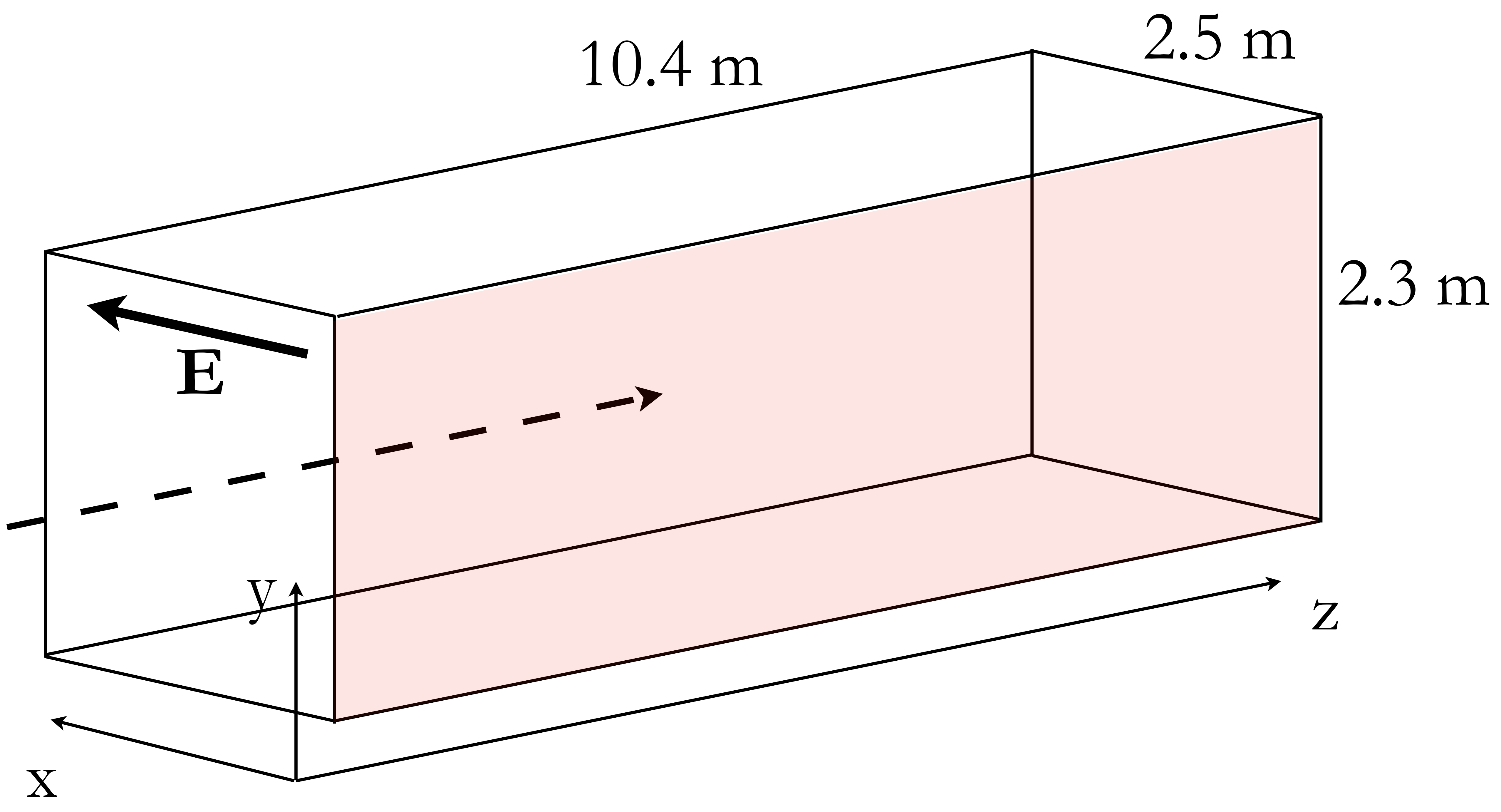
- Previously at Gran Sasso, shown feasibility of large scale LArTPC
- Significant upgrades and refurbishment at CERN in 2015-2017
- New Cosmic Ray Tagger
- Transported to FNAL, arrived in August 2017, installation ongoing
- Commissioning will start this fall and expect first neutrino data within a year

See the talk from Jaehoon Yu on Friday

MicroBooNE

- Designed to investigate the e-like excess of MiniBooNE and LSND
- LArTPC technology:
  - γ/e- separation
  - Position and topology
  - low detection threshold
- Data taking since October 2015 : longest running LArTPC
- Smooth operation with 96% detector & DAQ uptime
- 13.4 10^{20} POT on tape to date
- Surface operation : Cosmic Ray Tagger used to understand/reduce cosmic background (1/2 of data-taking period)

LArTPC Working Principle



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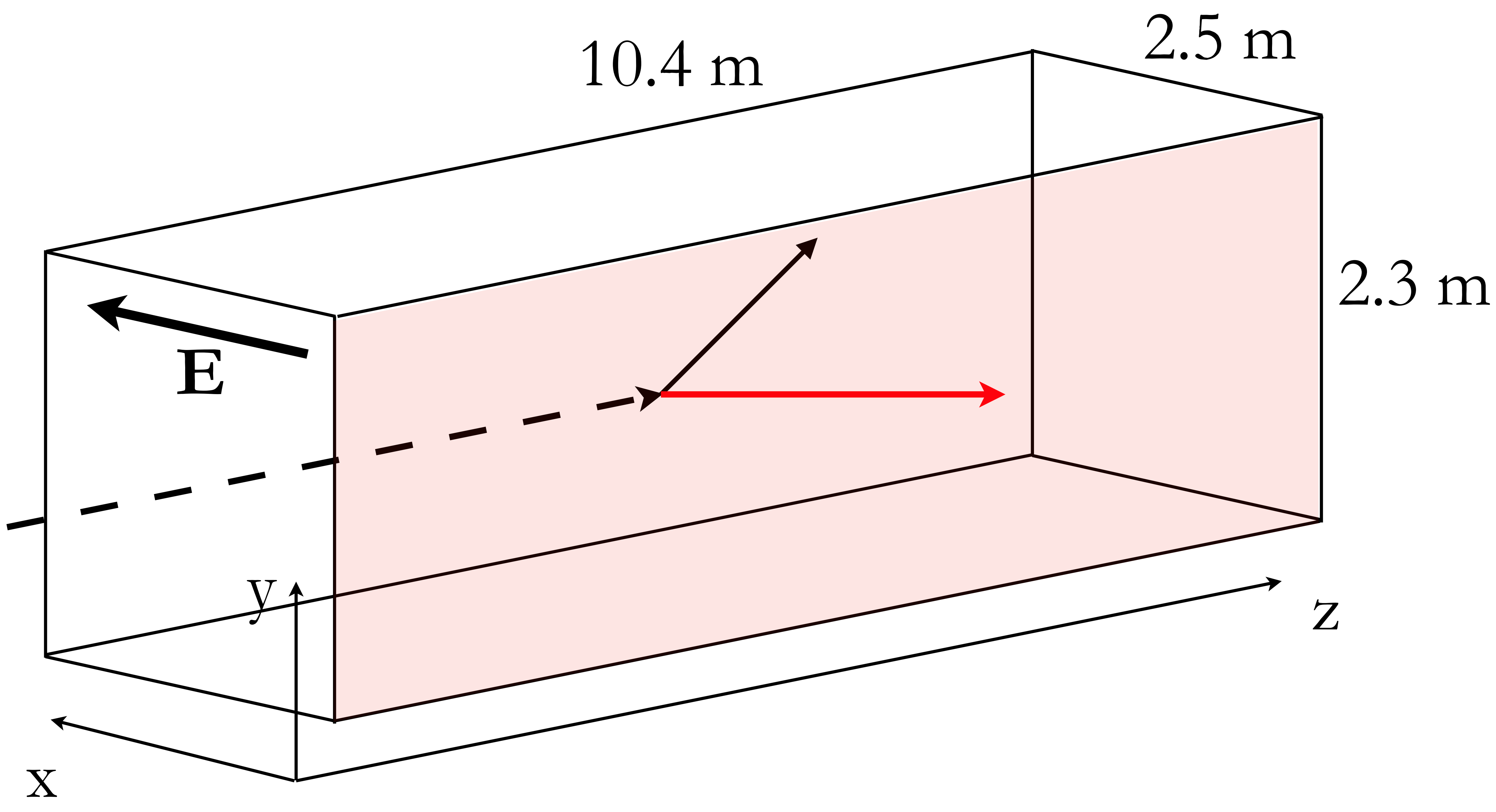

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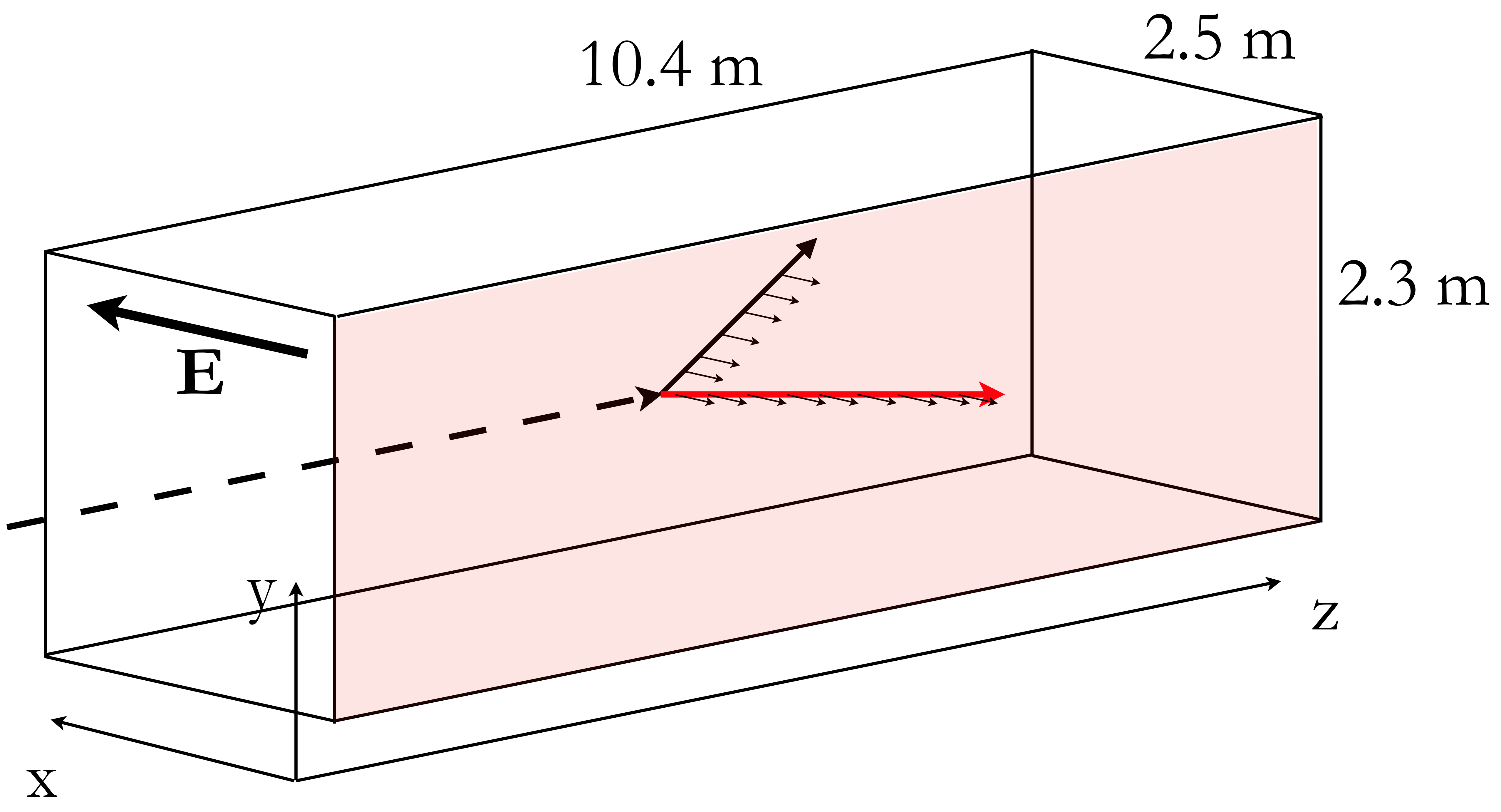

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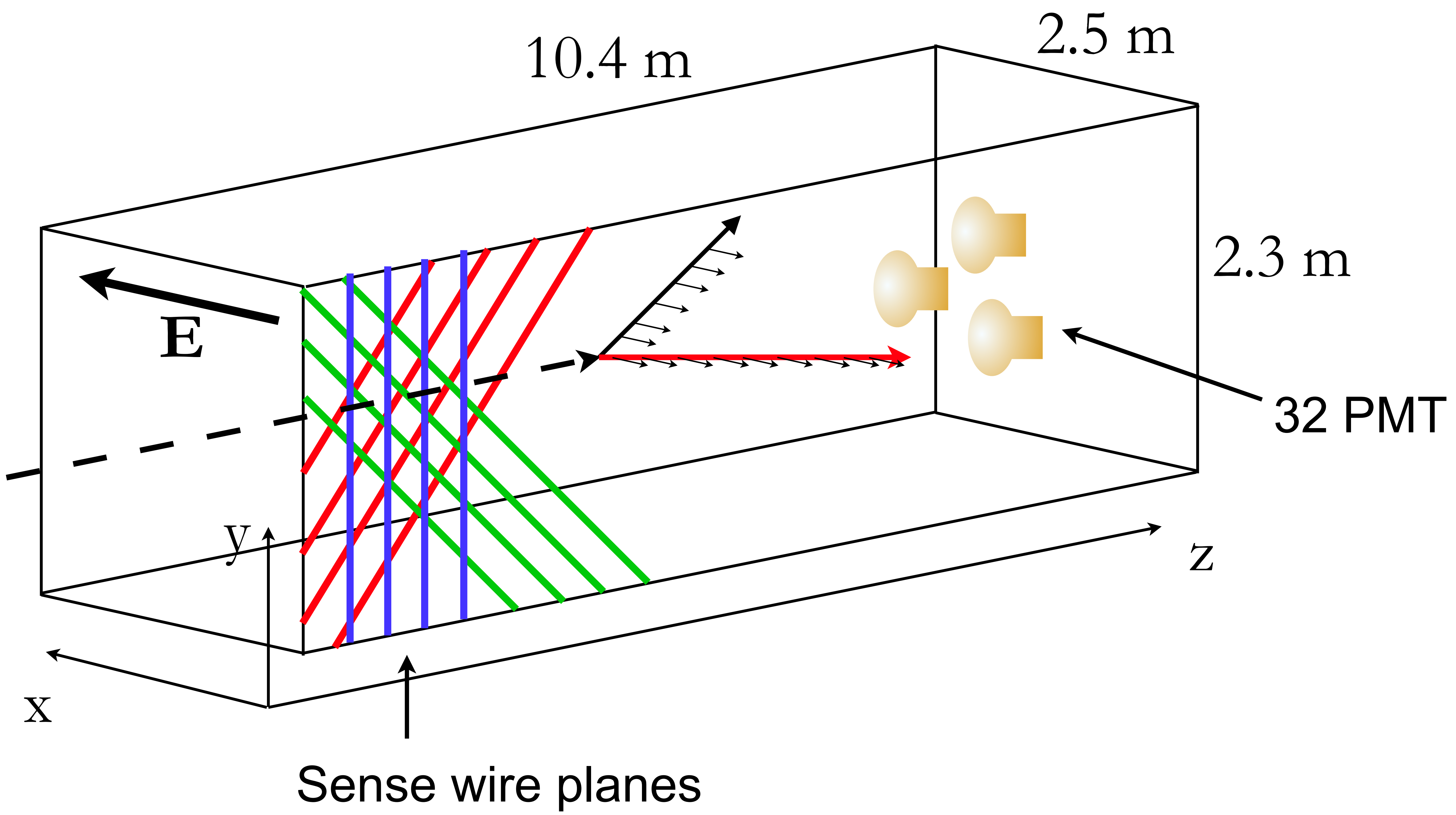

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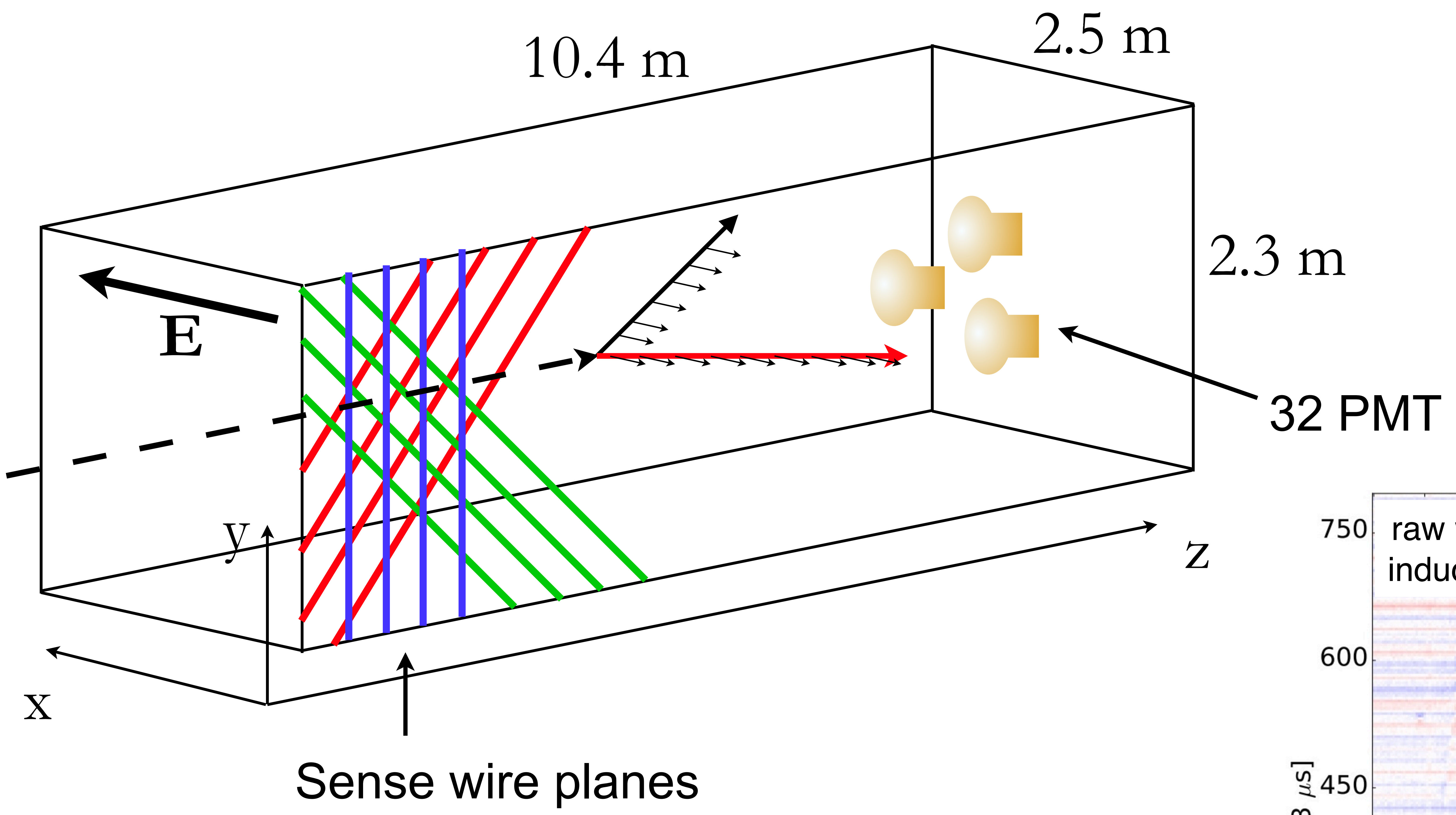

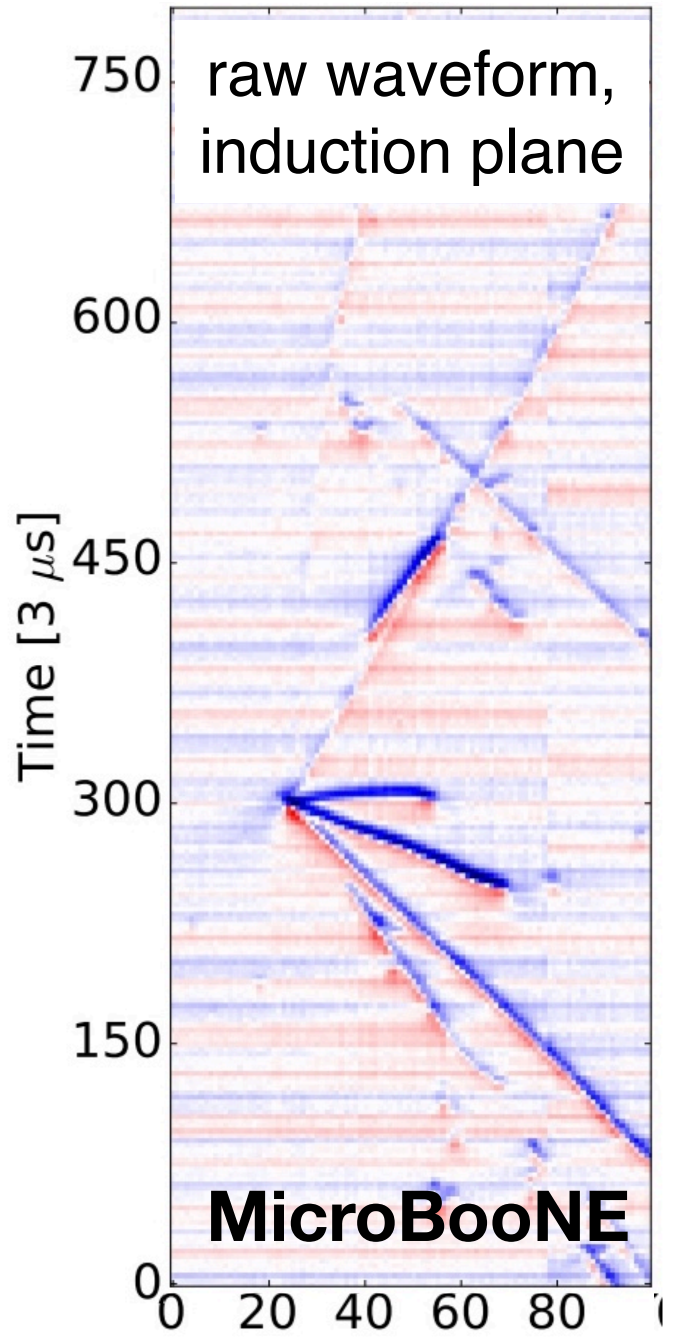

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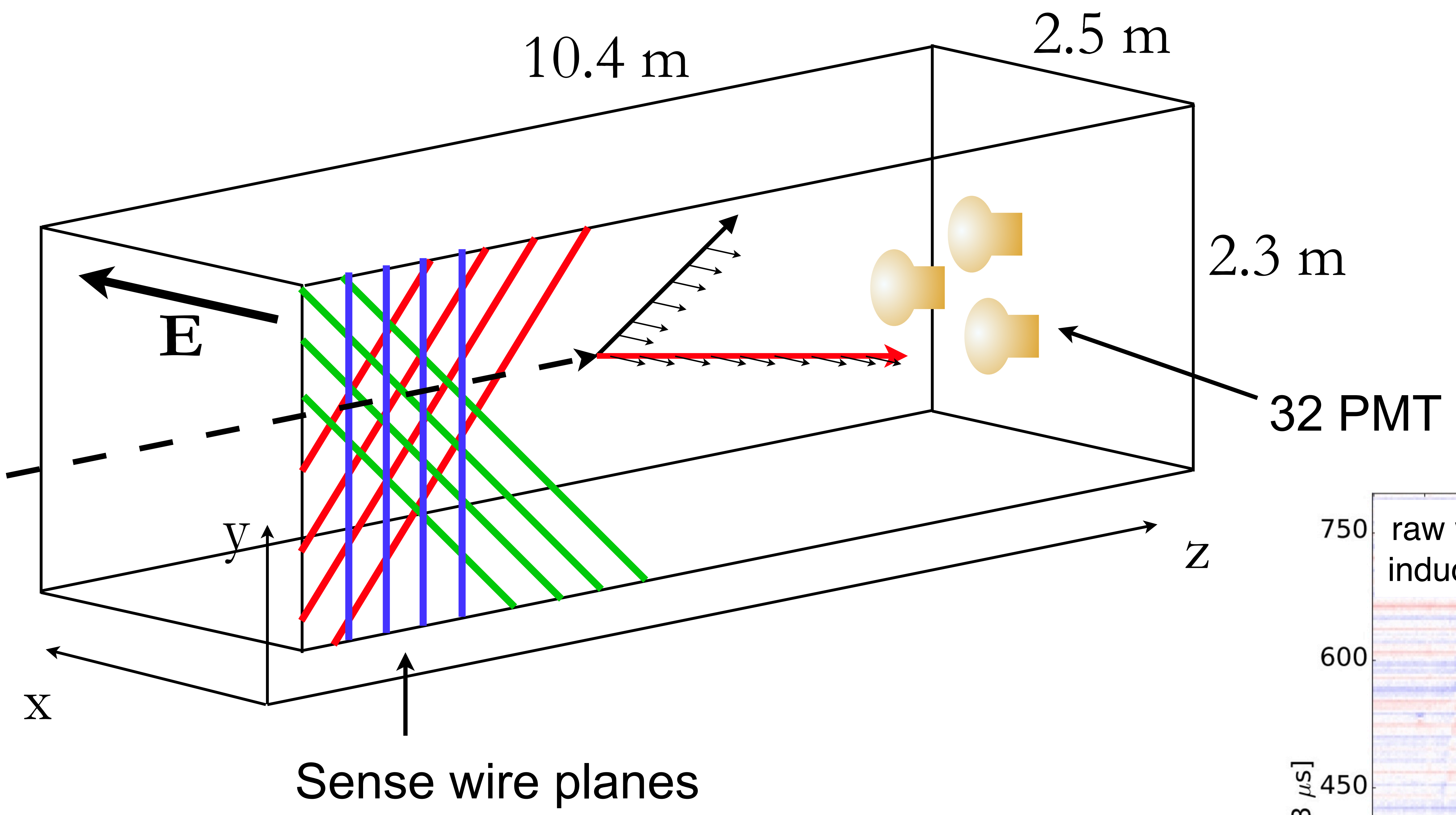

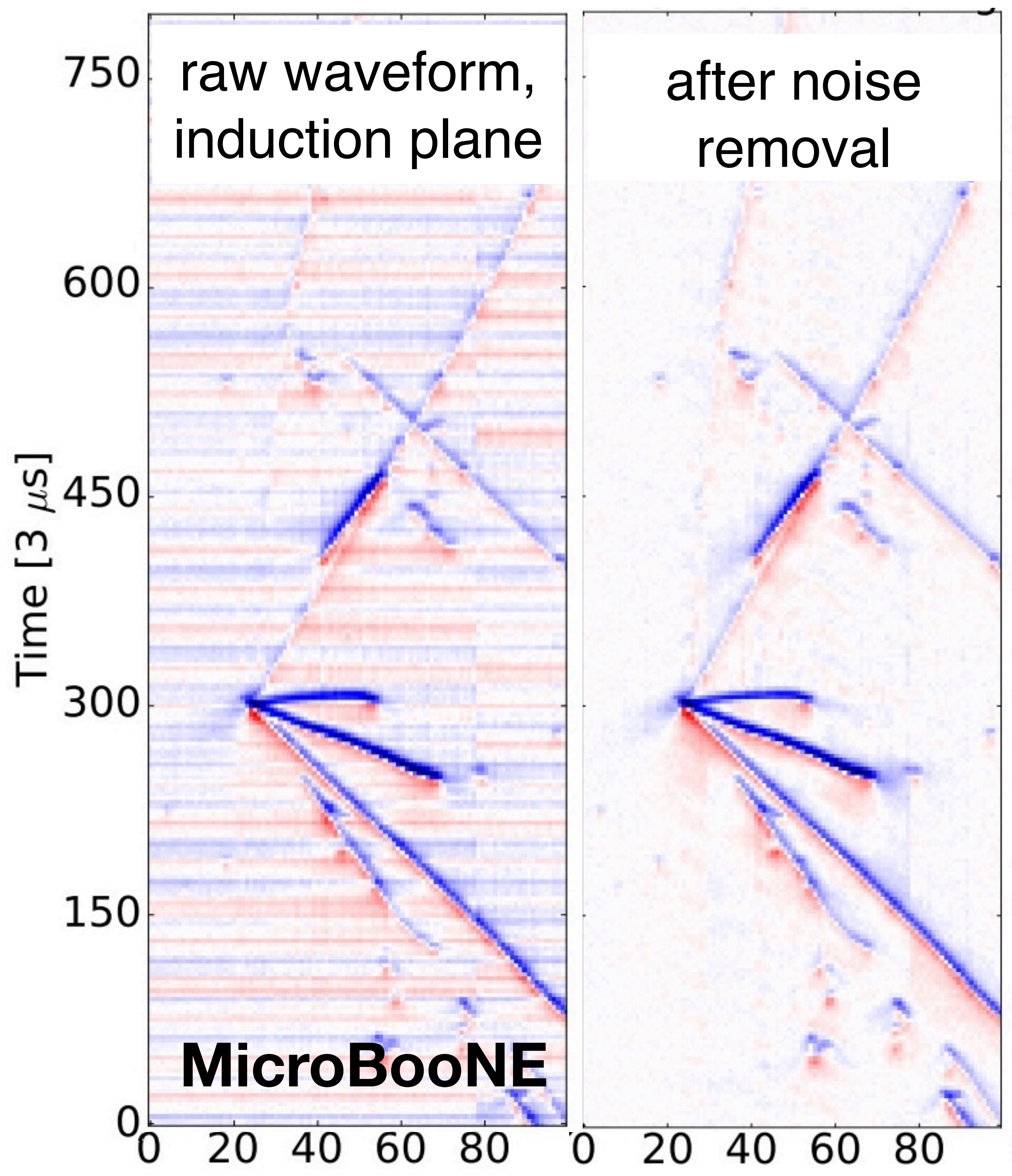

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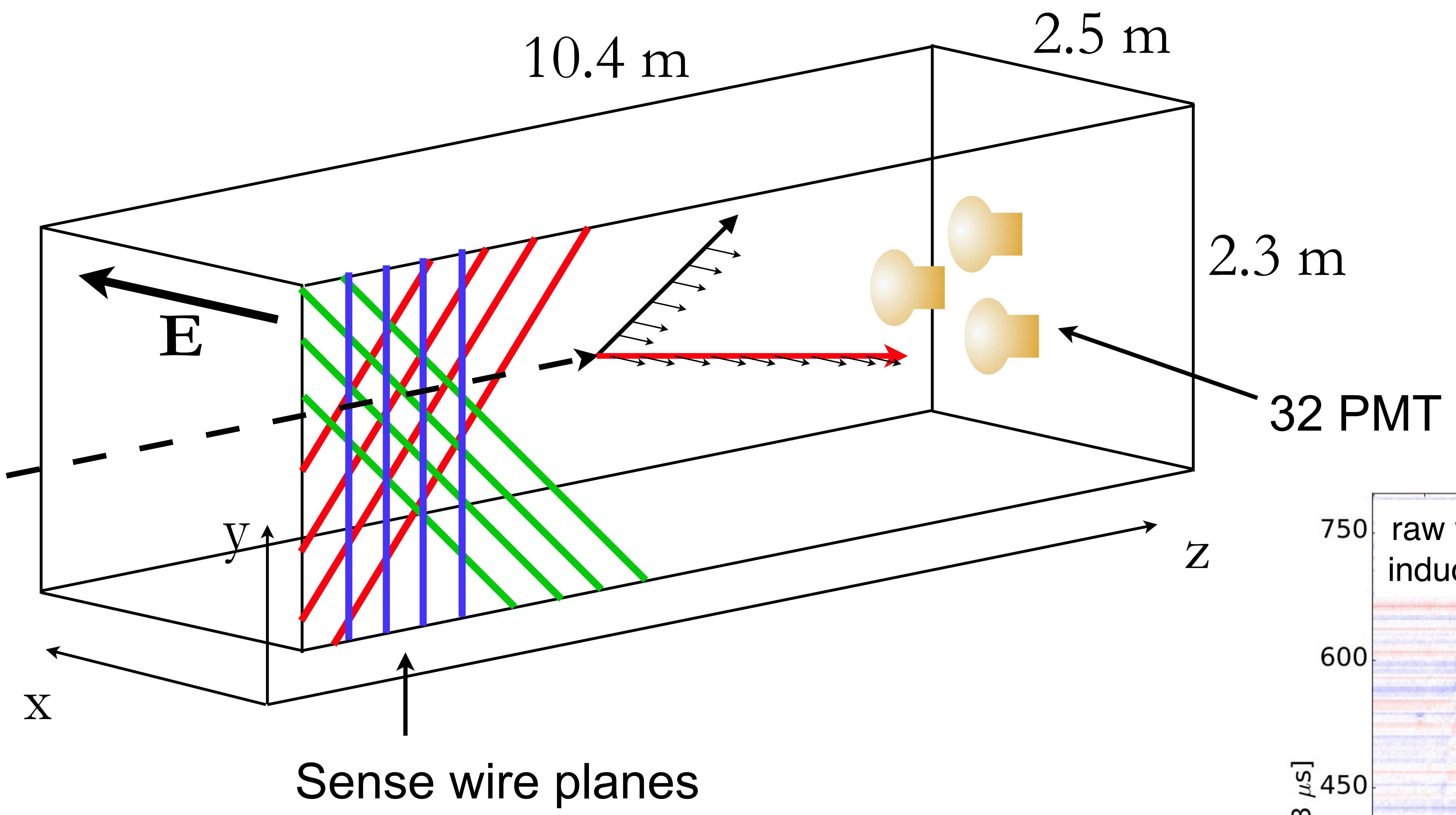

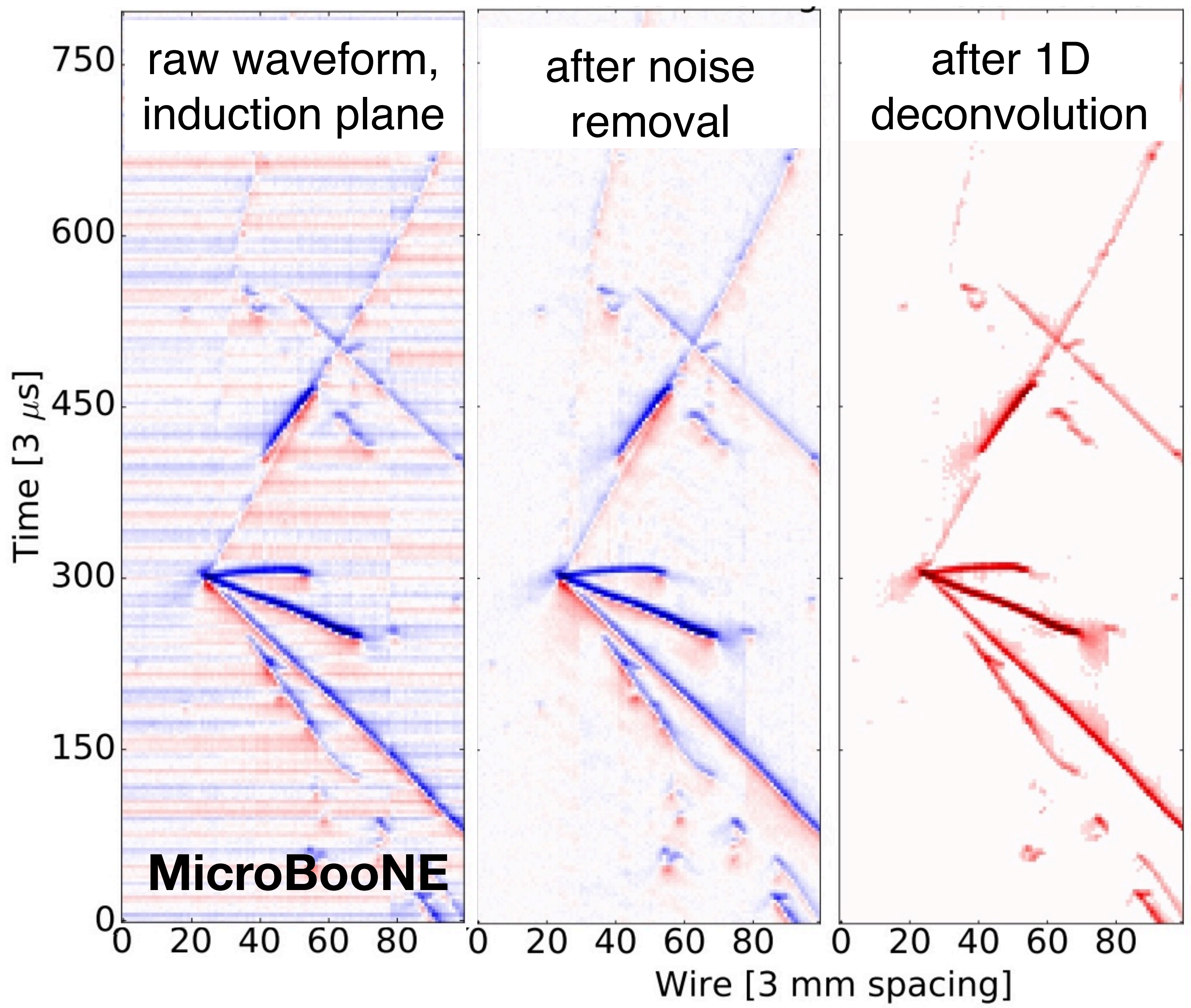

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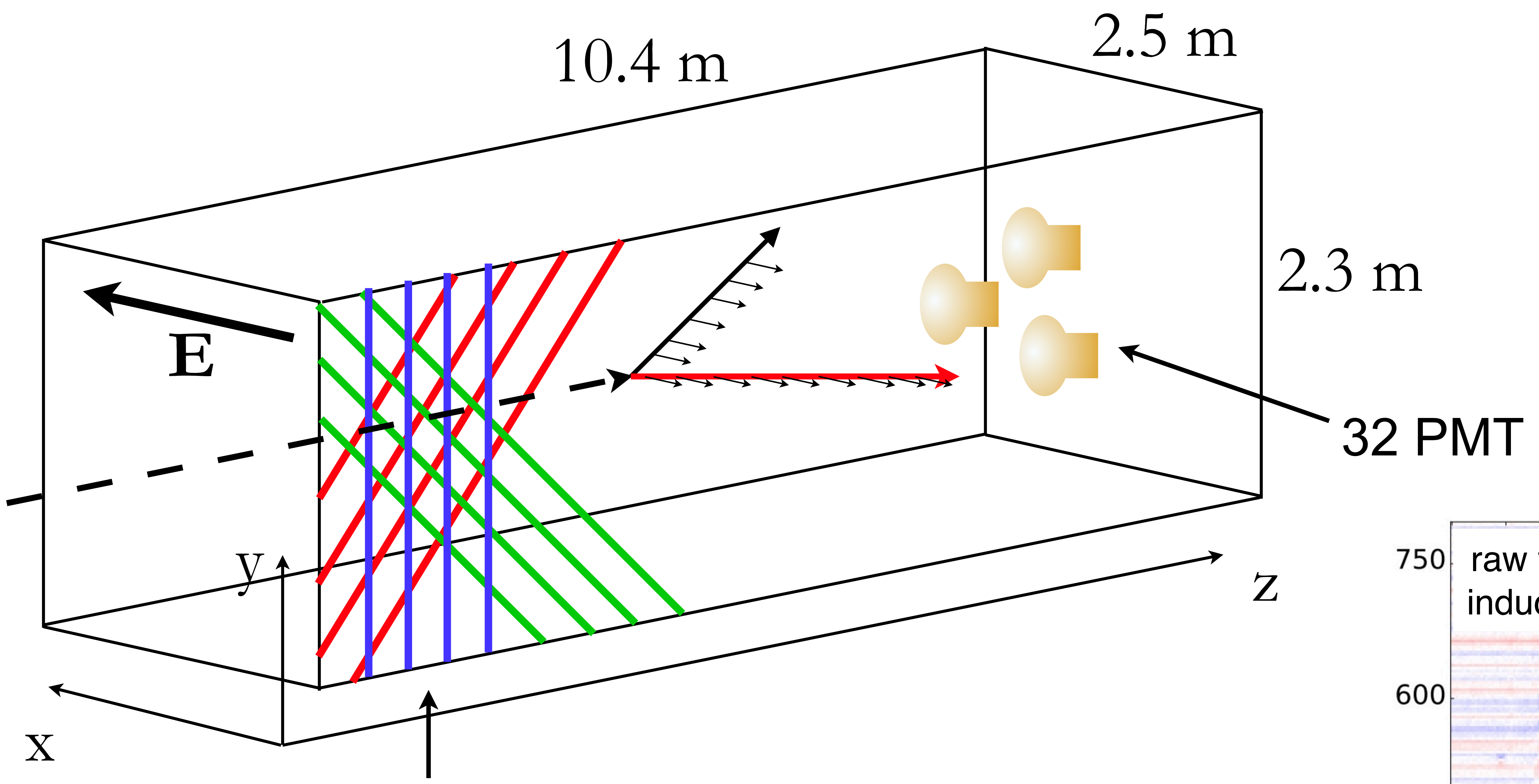
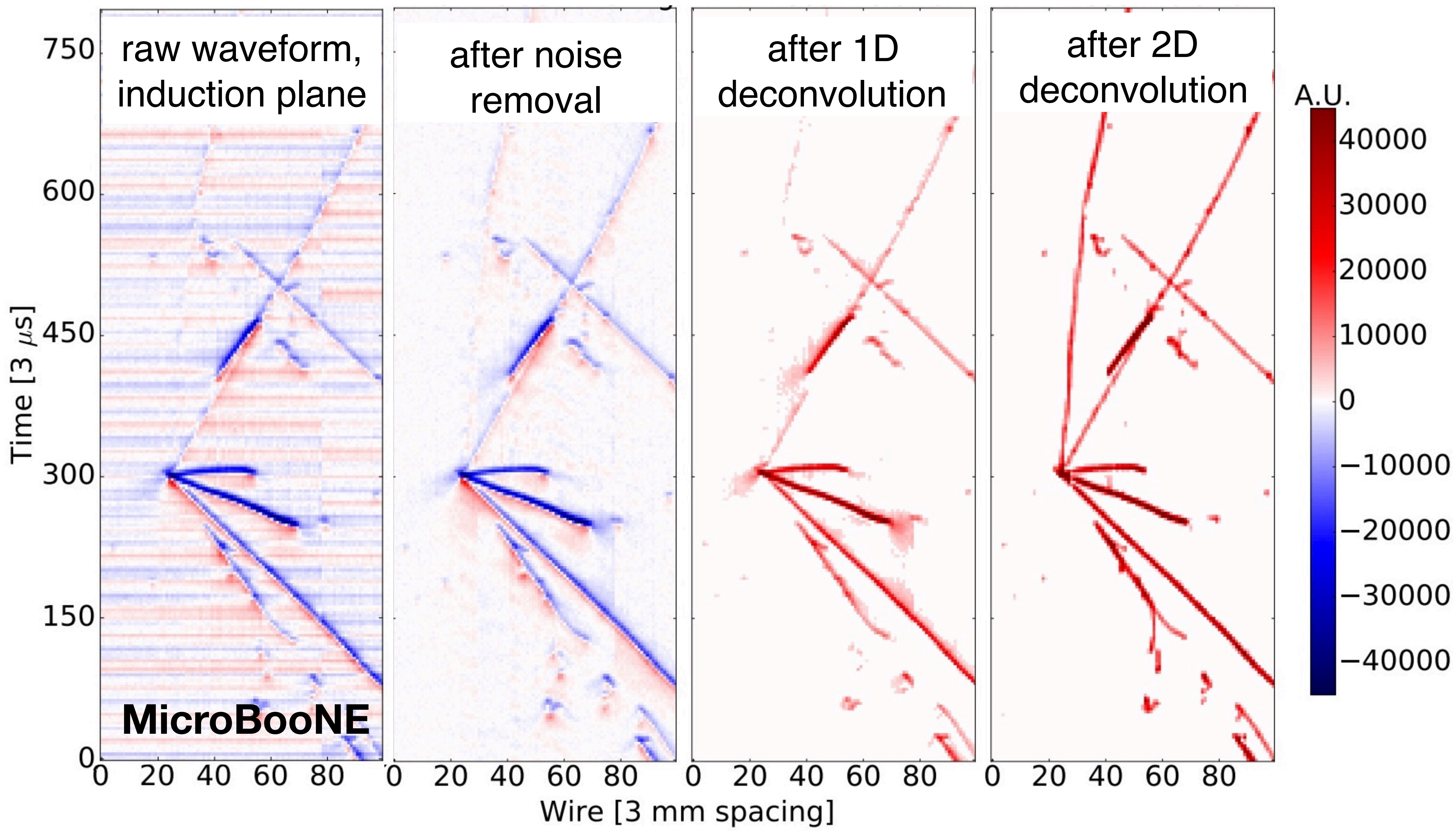


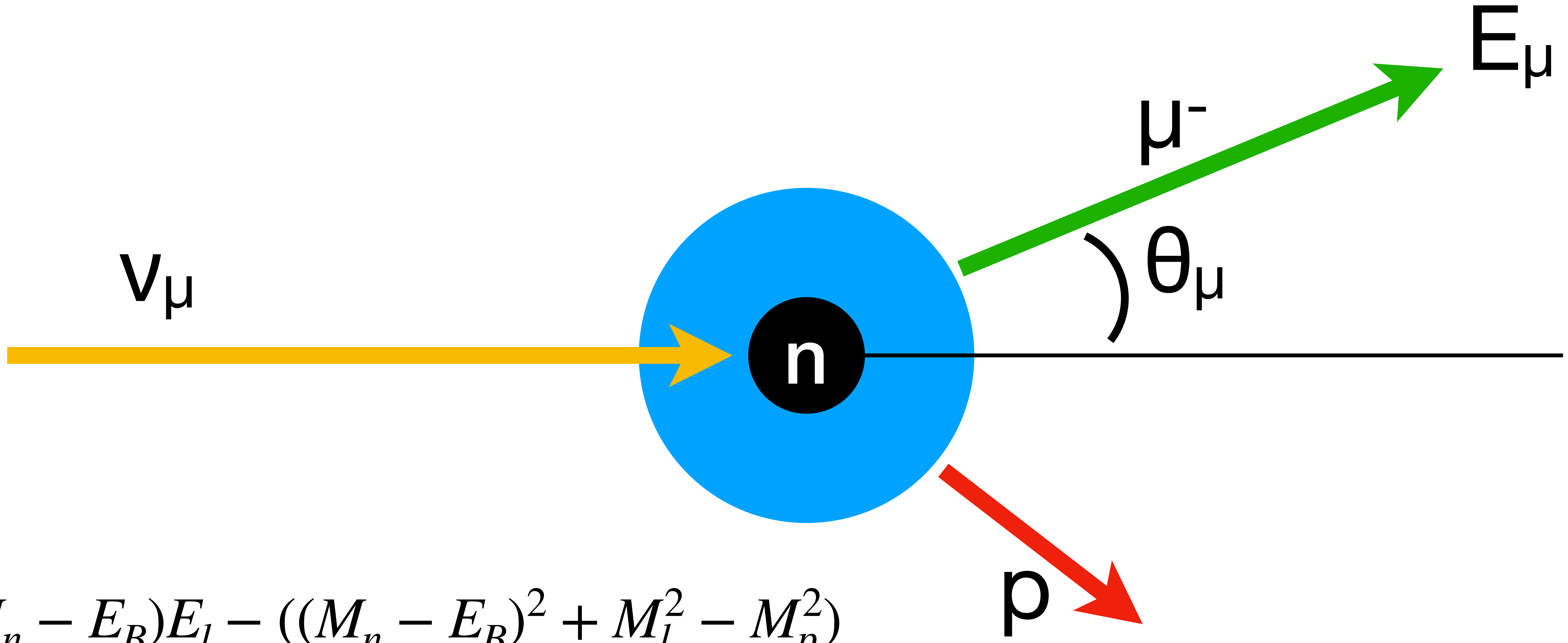


"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", JINST 12, P08003 (2017)

"Ionization Electron Signal Processing in Single Phase LArTPCs" Parts I & II, JINST 13, P07006 (2018) & JINST 13, P07007 (2018)

LArTPC Energy Reconstruction

- Calorimetric reconstruction => charge clustered in each track
- Access kinematics of all the particles above O(10 MeV)
- Assumes CCQE interaction on a nucleon at rest, accounts for nuclear binding energy



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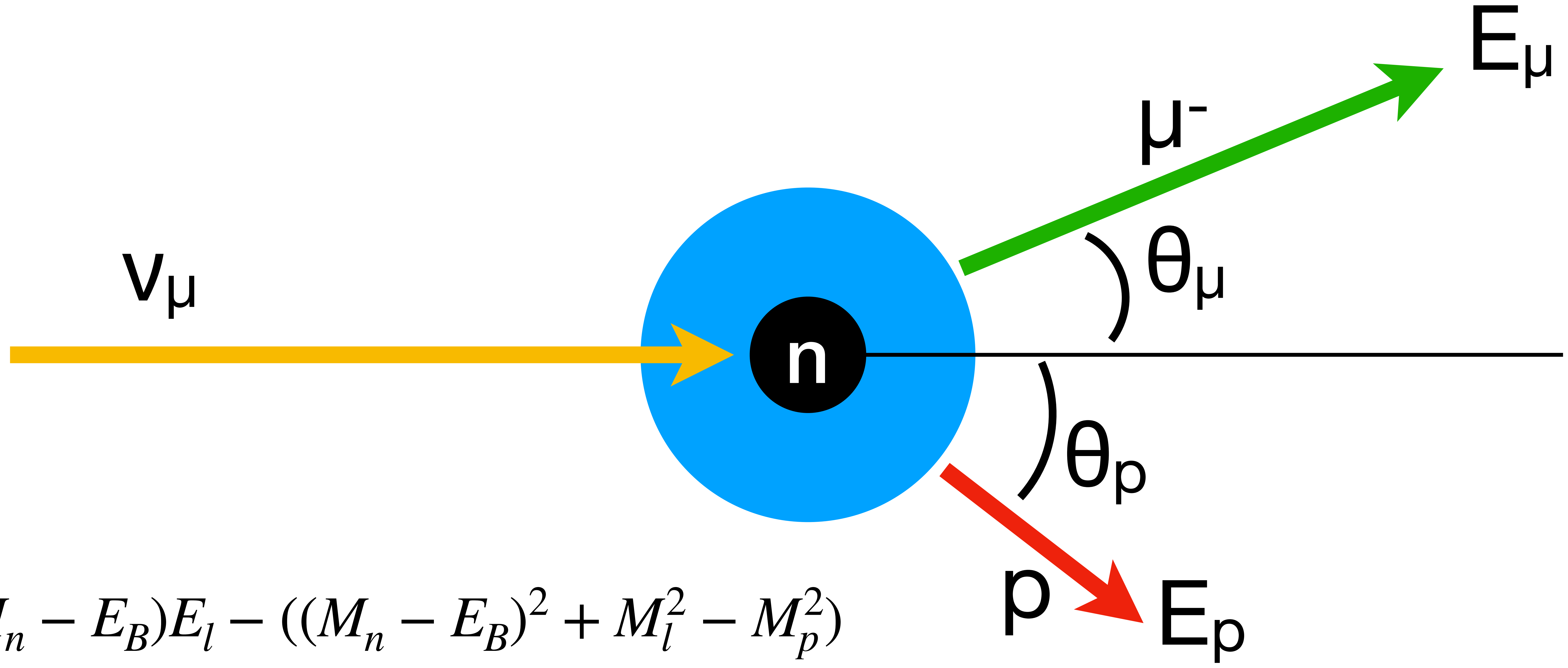

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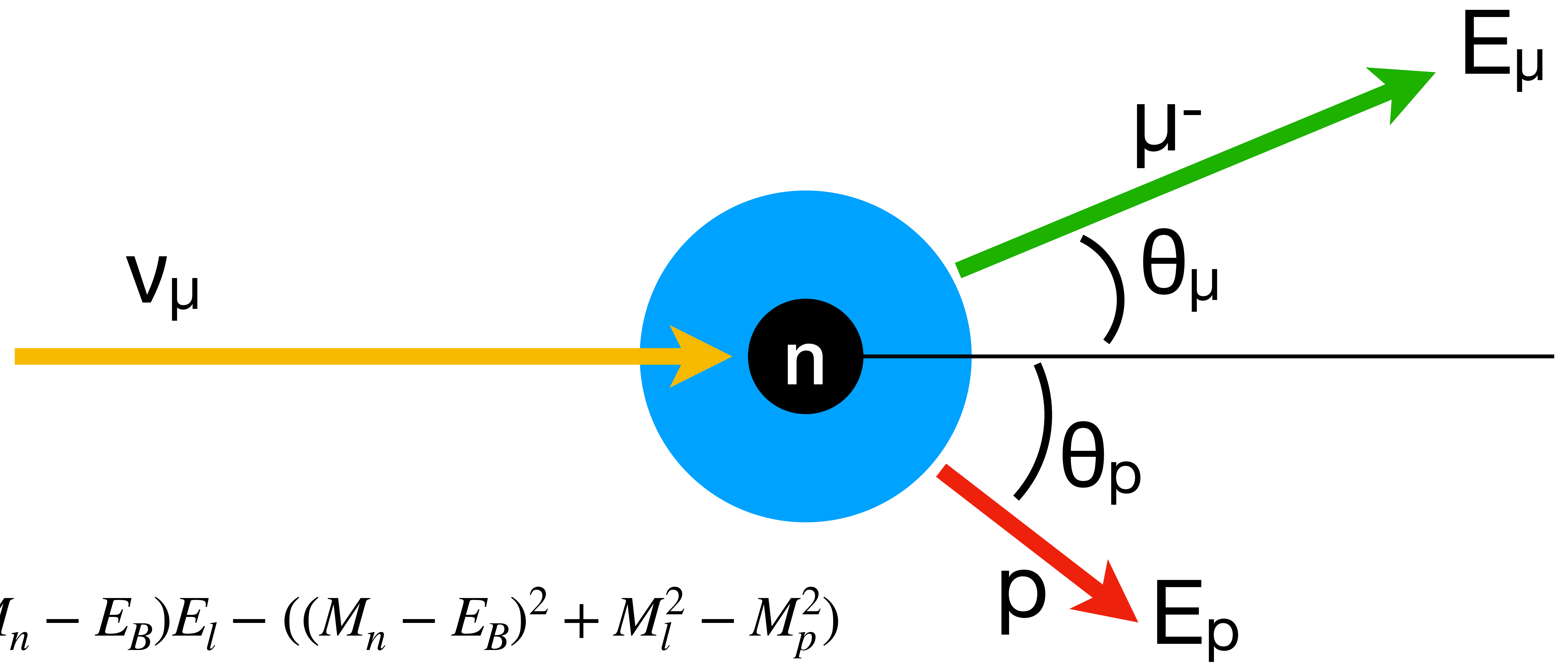

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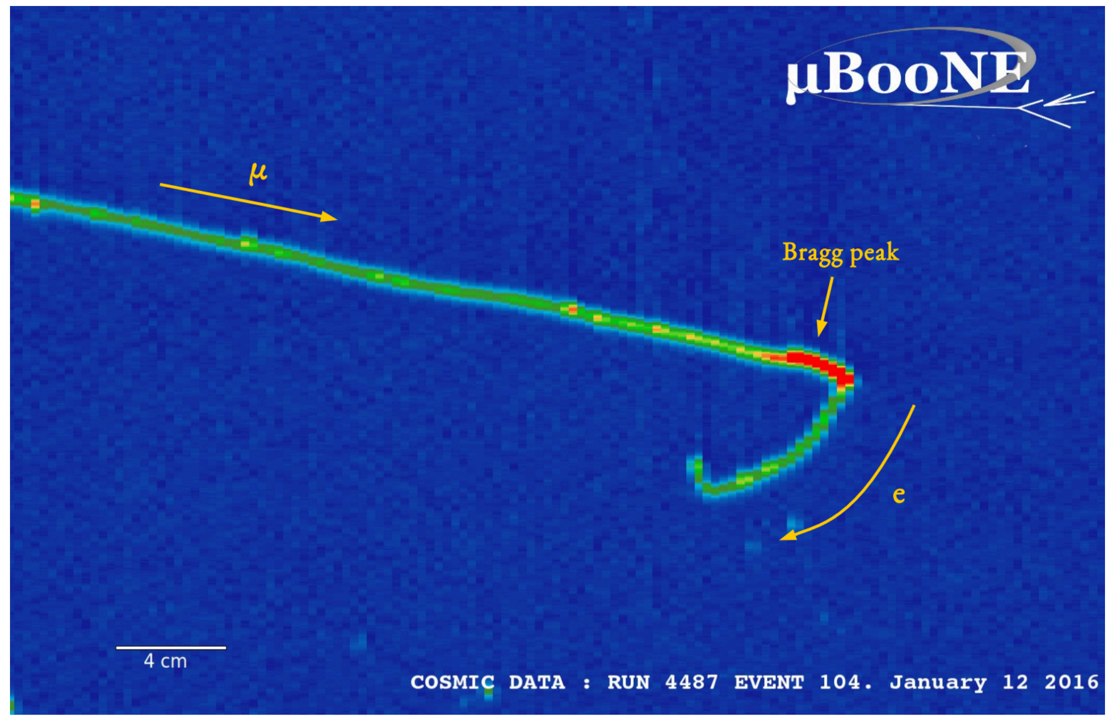
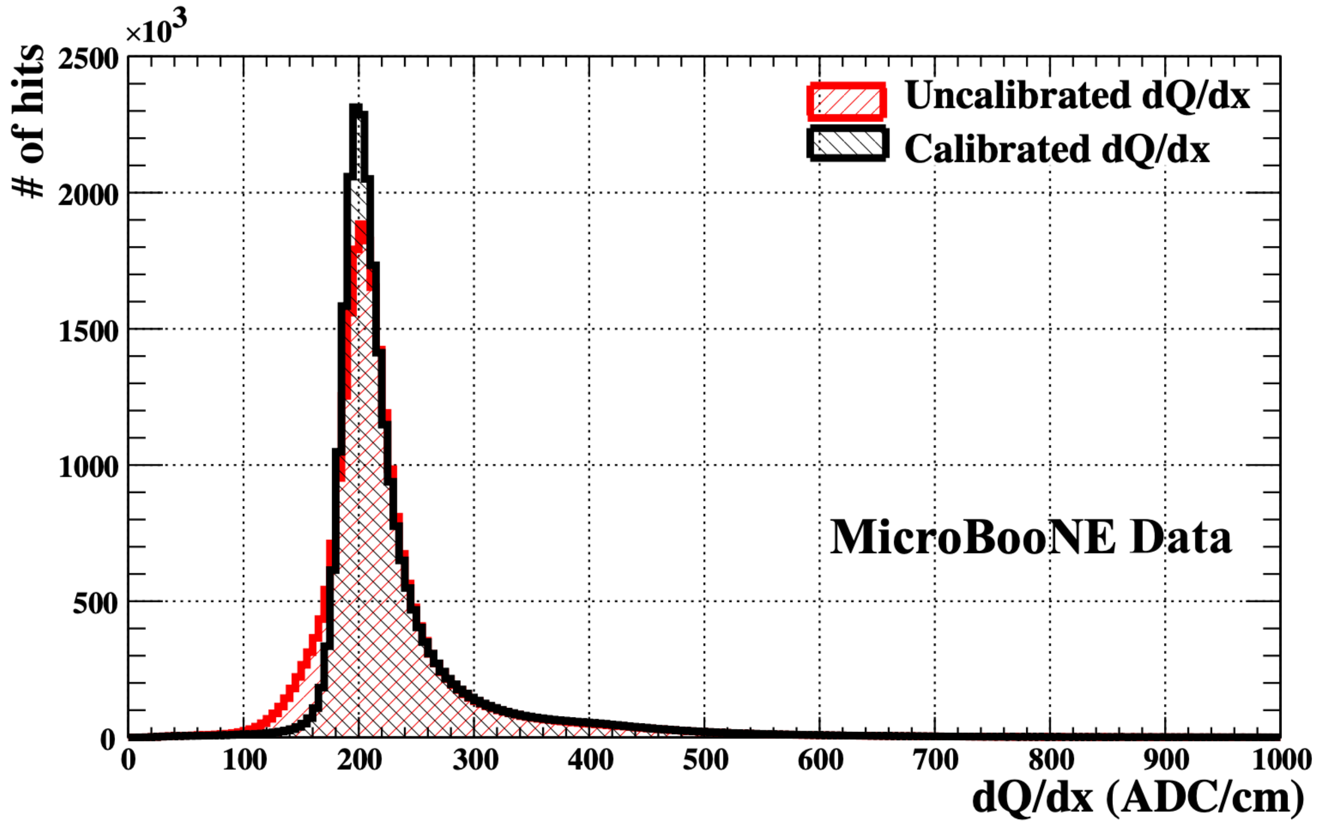
$$E_\nu = KE_l + KE_p + M_l + M_p - M_n + B$$

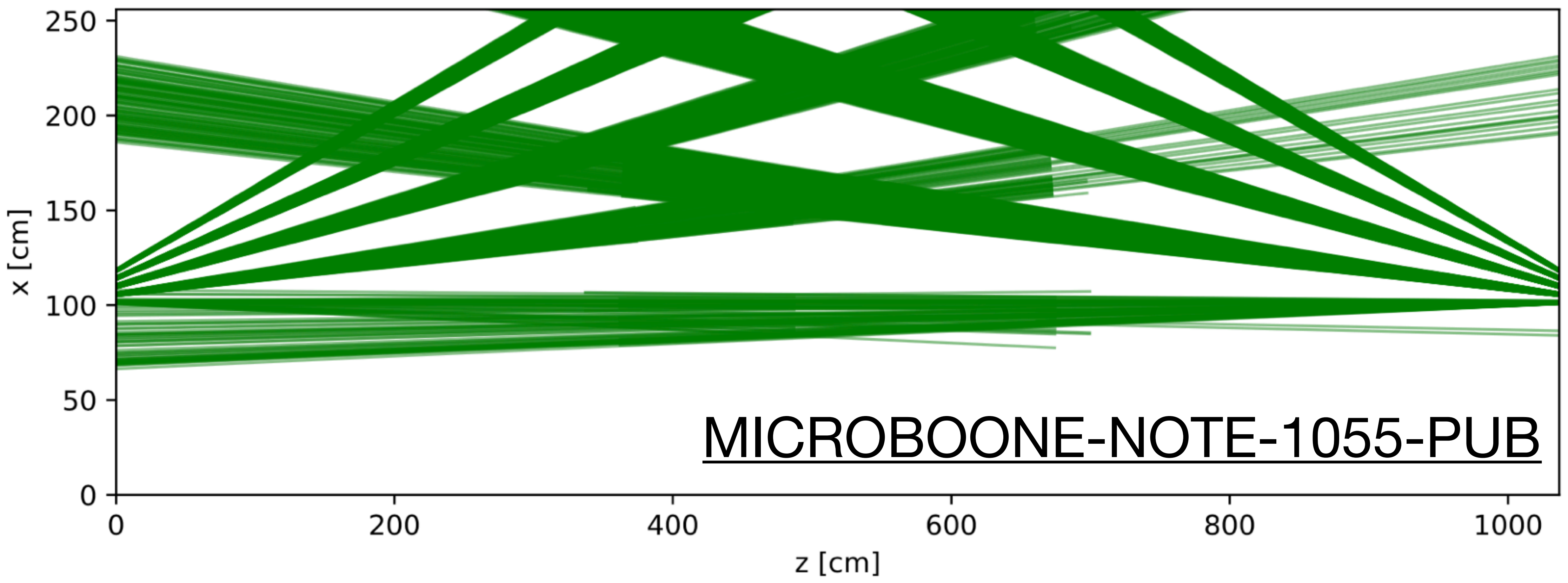
Studying Detector Physics

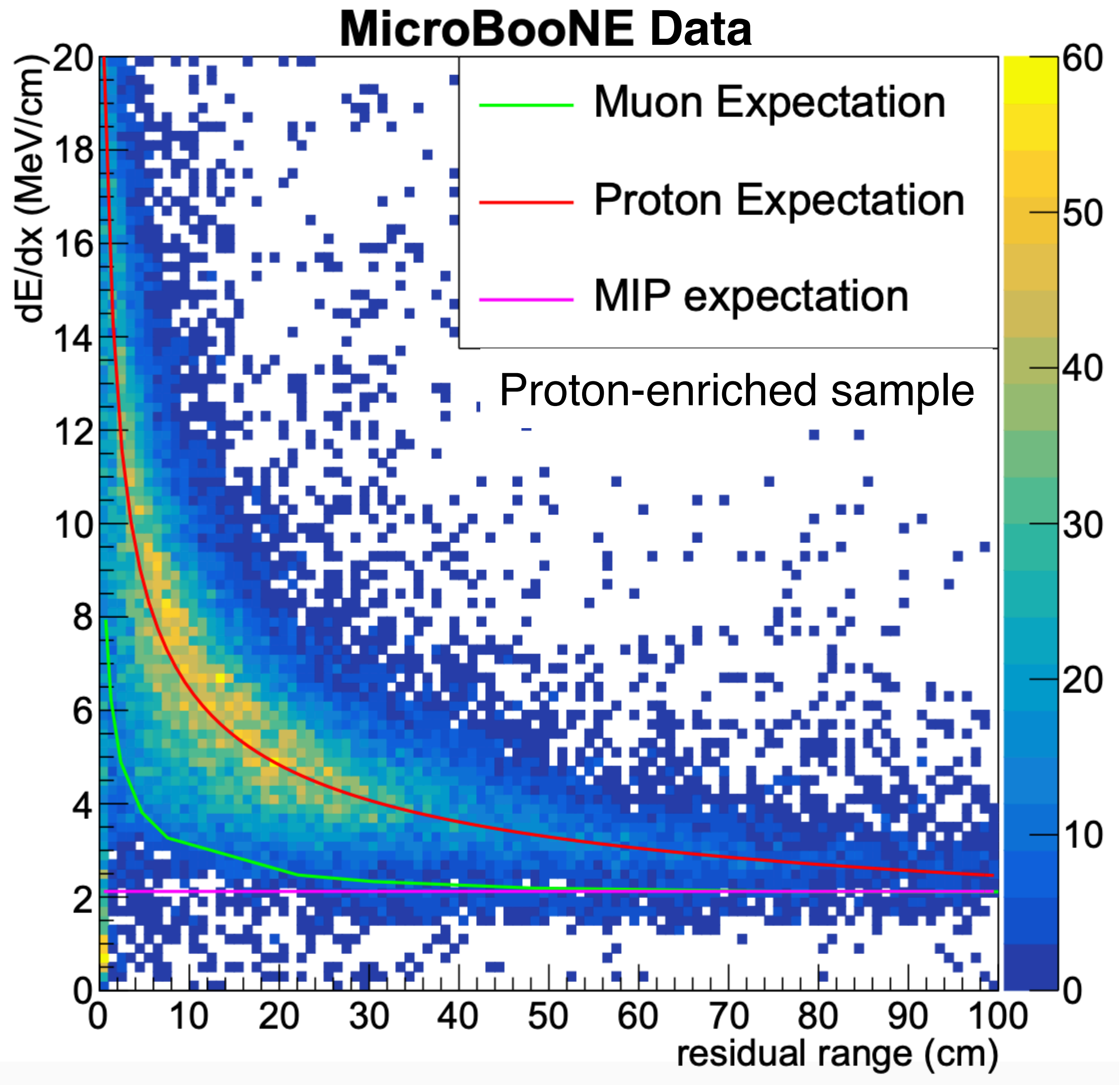
arXiv:1907.11736 [physics.ins-det]

- Major calibration campaign completed
- Use through-going muons and stopping muons as standard candles
  - uniformity in position and time
  - ADC to e-/cm calibration
  - E field distortions due to charge accumulation
- Use protons to correct for recombination
  - e-/cm to MeV/cm calibration
- Use UV-laser runs
  - E field distortions due to charge accumulation









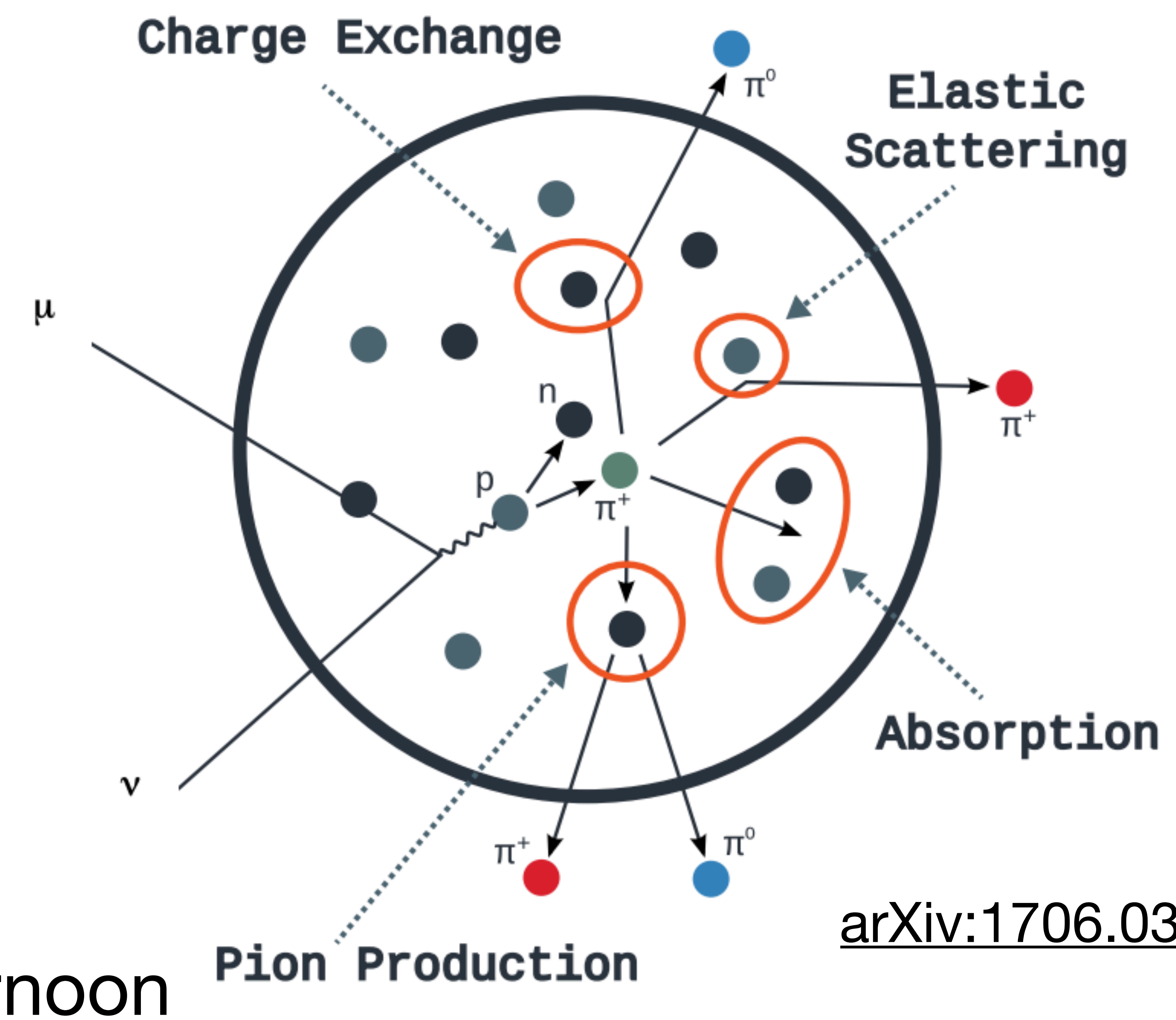
Studying Neutrino Interactions

BNB:

- ν_μ CC inclusive
  arXiv:1905.09694[hep-ex], accepted to PRL
- ν_μ CC π^0
  PRD 99,091102(R) (2019)
- Track multiplicity
  Eur. Phys. J. C (2019) 79: 248
- ν_μ CCQE
  arXiv:1812.05679 [physics.ins-det], accepted to EPJC
- NC elastic
  MICROBOONE-NOTE-1053-PUB
- ν_μ CC Np, 2p
  MICROBOONE-NOTE-1056-PUB
- CC $1\pi^+$
- CC coherent π
- CC $K^\pm$
- NC π^0
- … and more

NuMI:

- ν_e CC inclusive
  MICROBOONE-NOTE-1054-PUB
- ν_e CC 0π
- Kaon decay at rest (KDAR)



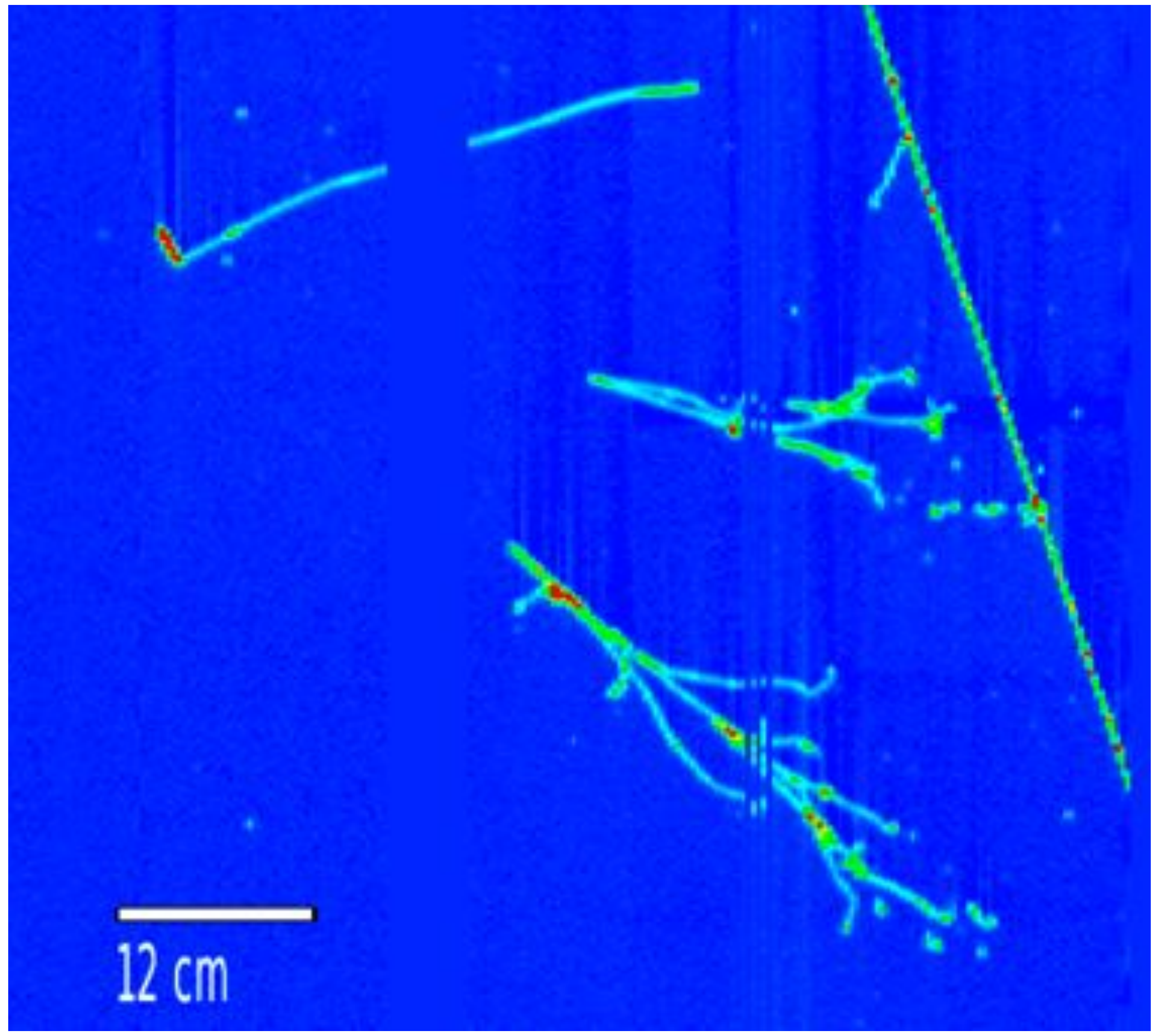
arXiv:1706.03621 [hep-ph]

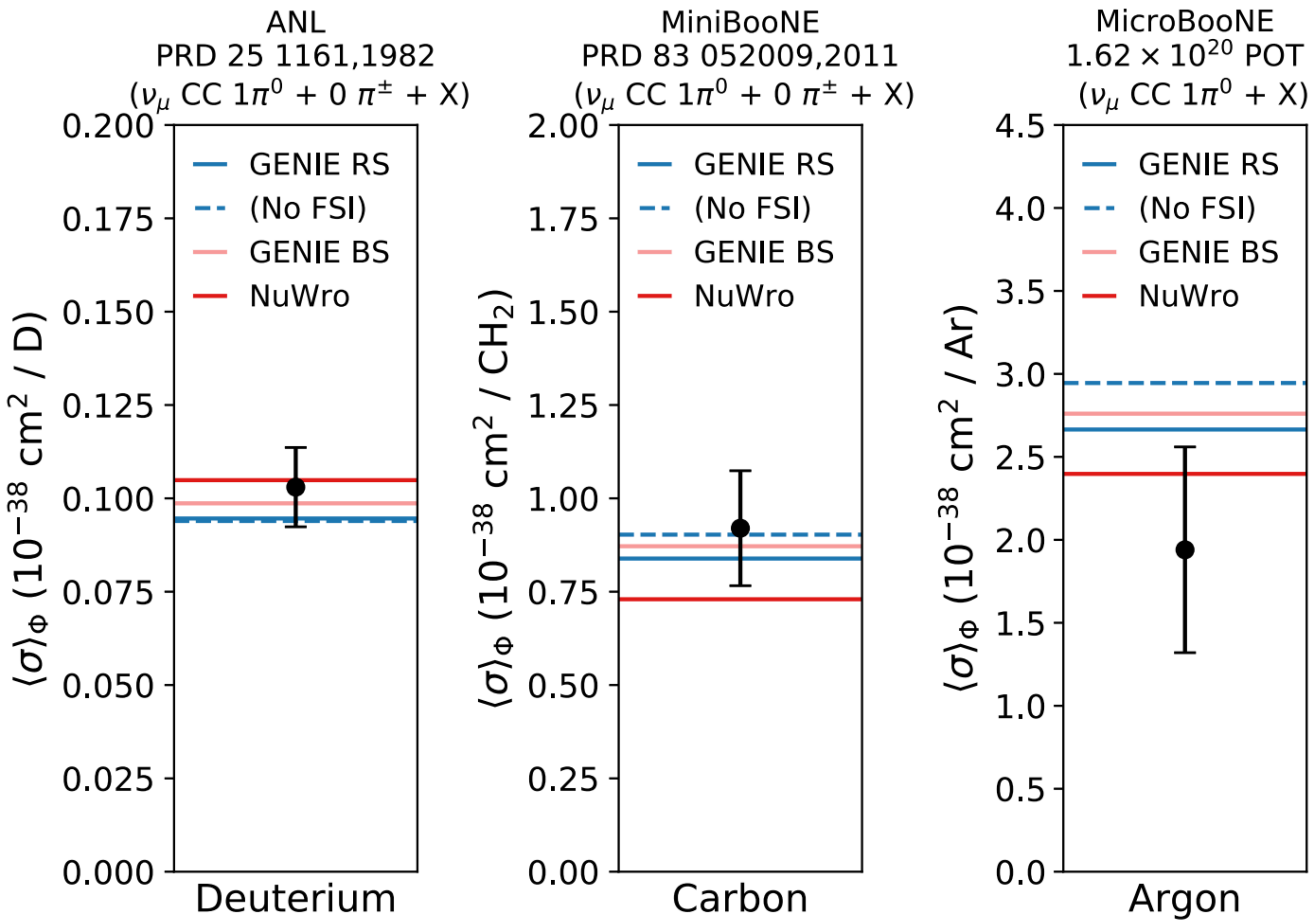
See Pip Hamilton's talk this afternoon

Studying Neutrino Interactions : ν_μ CCπ^0

- Exclusive measurements like this one allow us to study final state interactions
- Can compare to past measurements on deuterium and carbon
- Can evaluate accuracy of generators assuming different nuclear models
- First implementation of fully automated shower reconstruction to analyze LArTPC data

$$\langle\sigma(\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + 1\,\pi^0 + X)\rangle_\Phi = 1.9 \pm 0.2\ (\mathrm{stat.}) \pm 0.6\ (\mathrm{syst.}) \times 10^{-38}\ \mathrm{cm}^2/\,\mathrm{Ar}$$





PRD 99, 091102(R) (2019)

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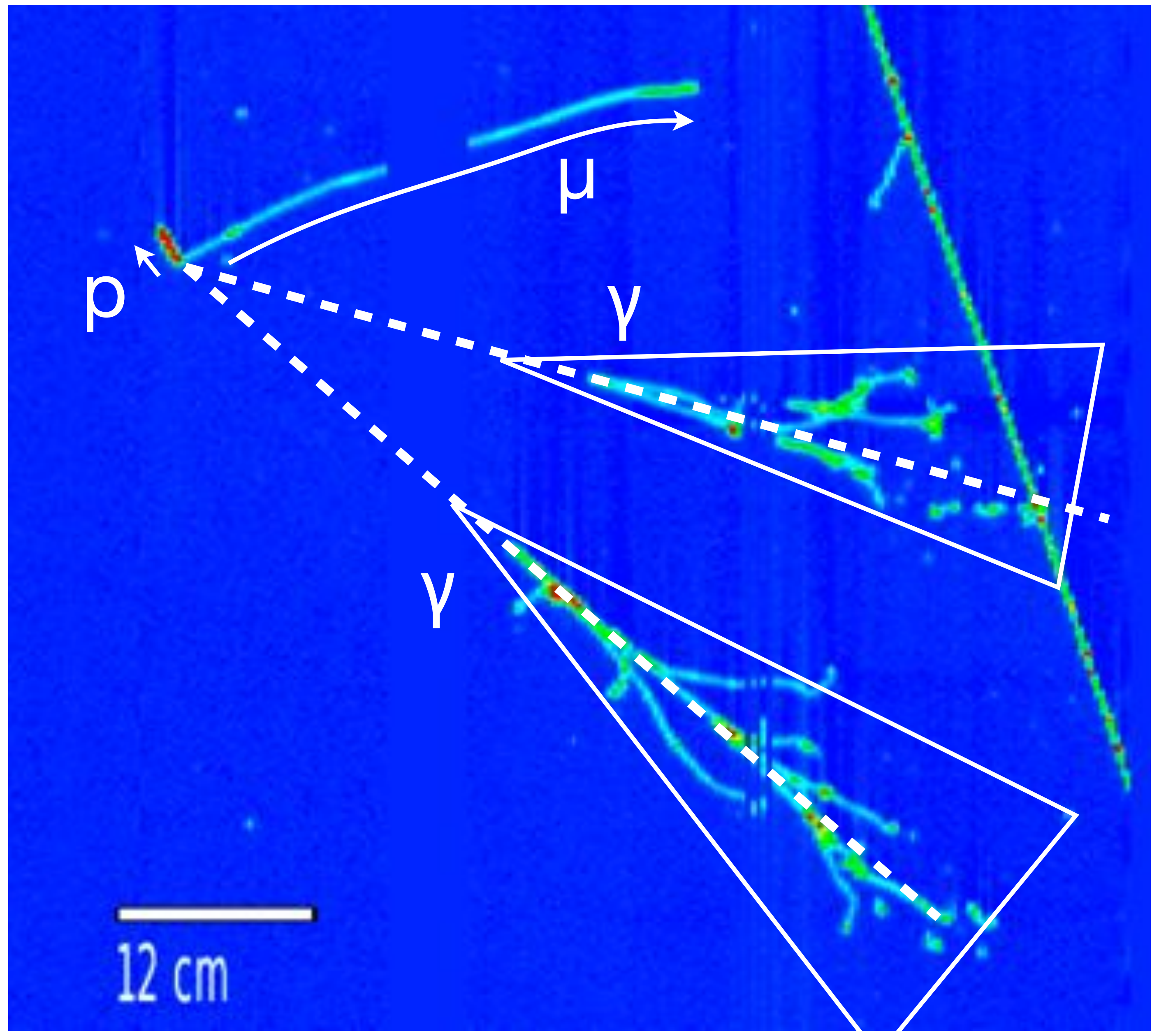
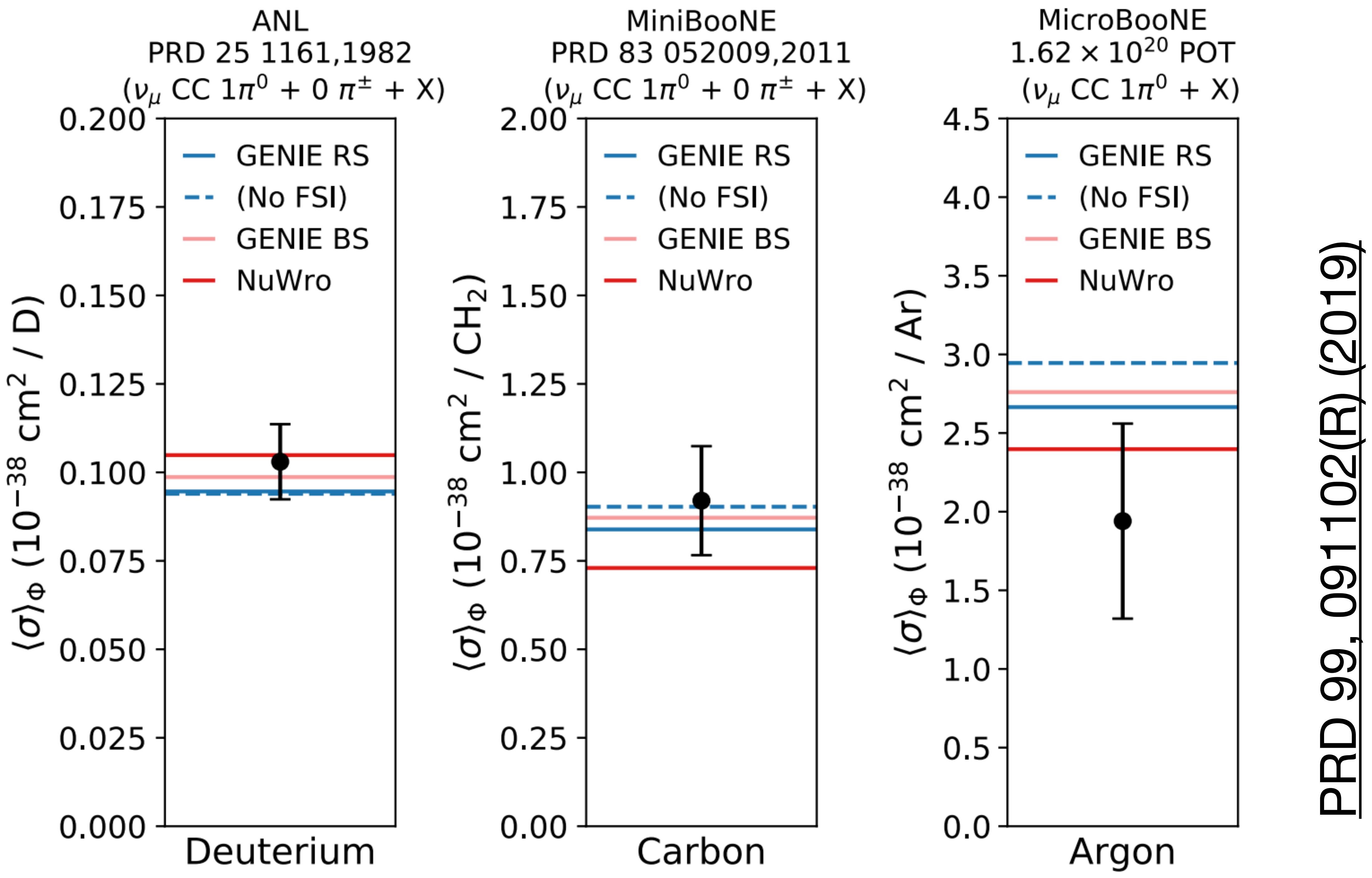
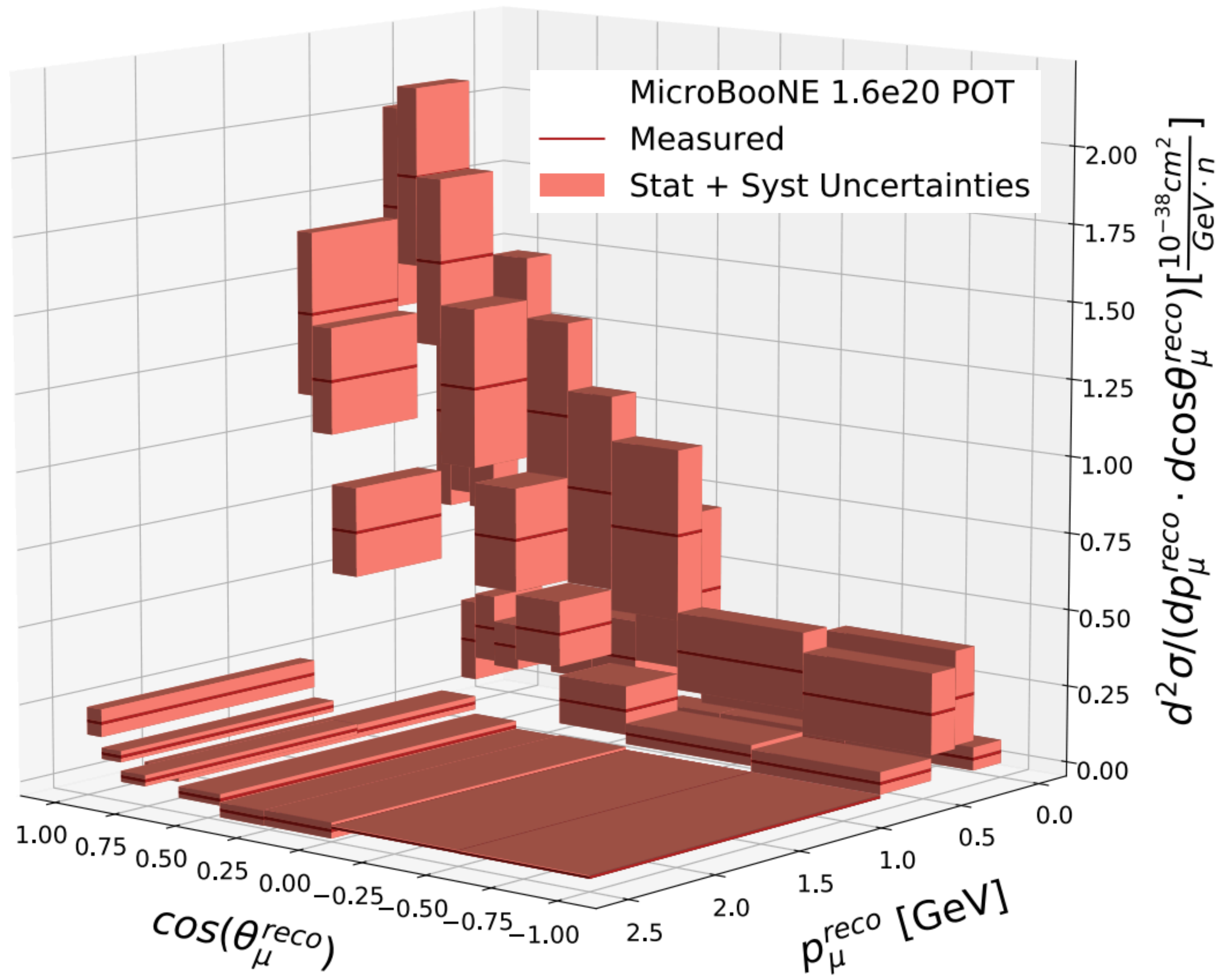


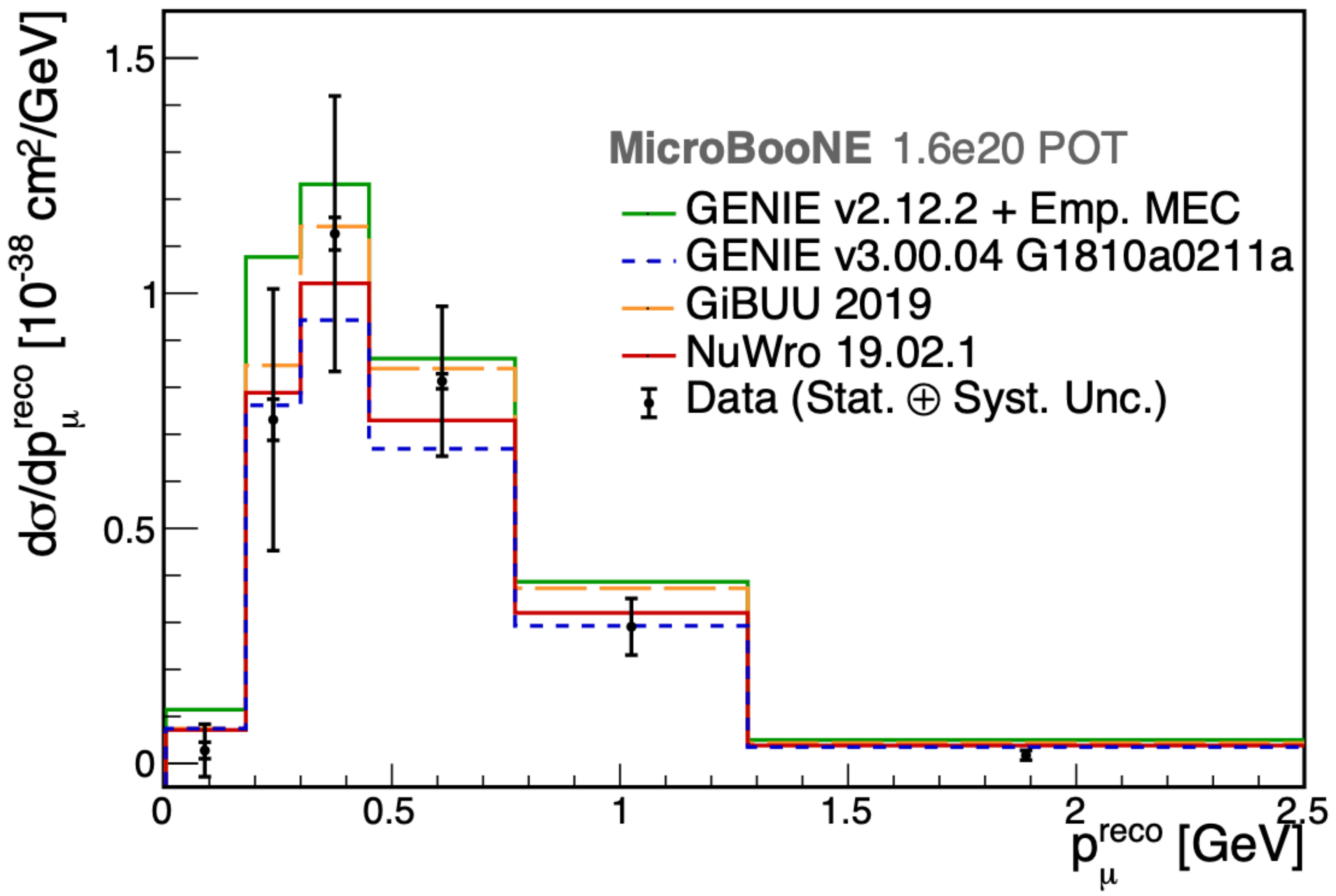


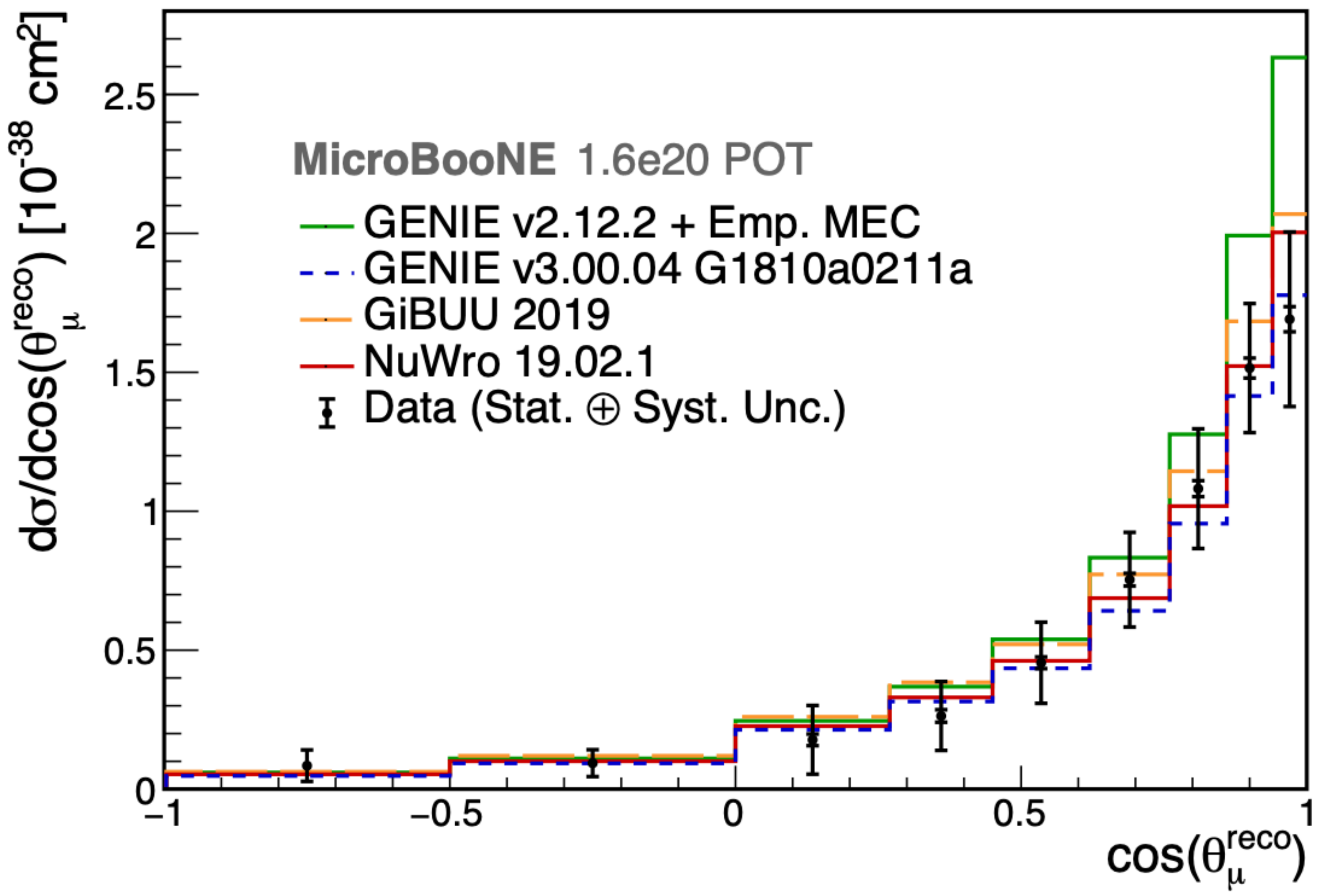
See Pip Hamilton's talk this afternoon

Studying Neutrino Interactions : ν_μ CC inclusive

- Single and double differential cross sections are measured as a function of p_μ and θ_μ
- Use multiple coulomb scattering for measuring muon momentum **=> not only contained particles!**



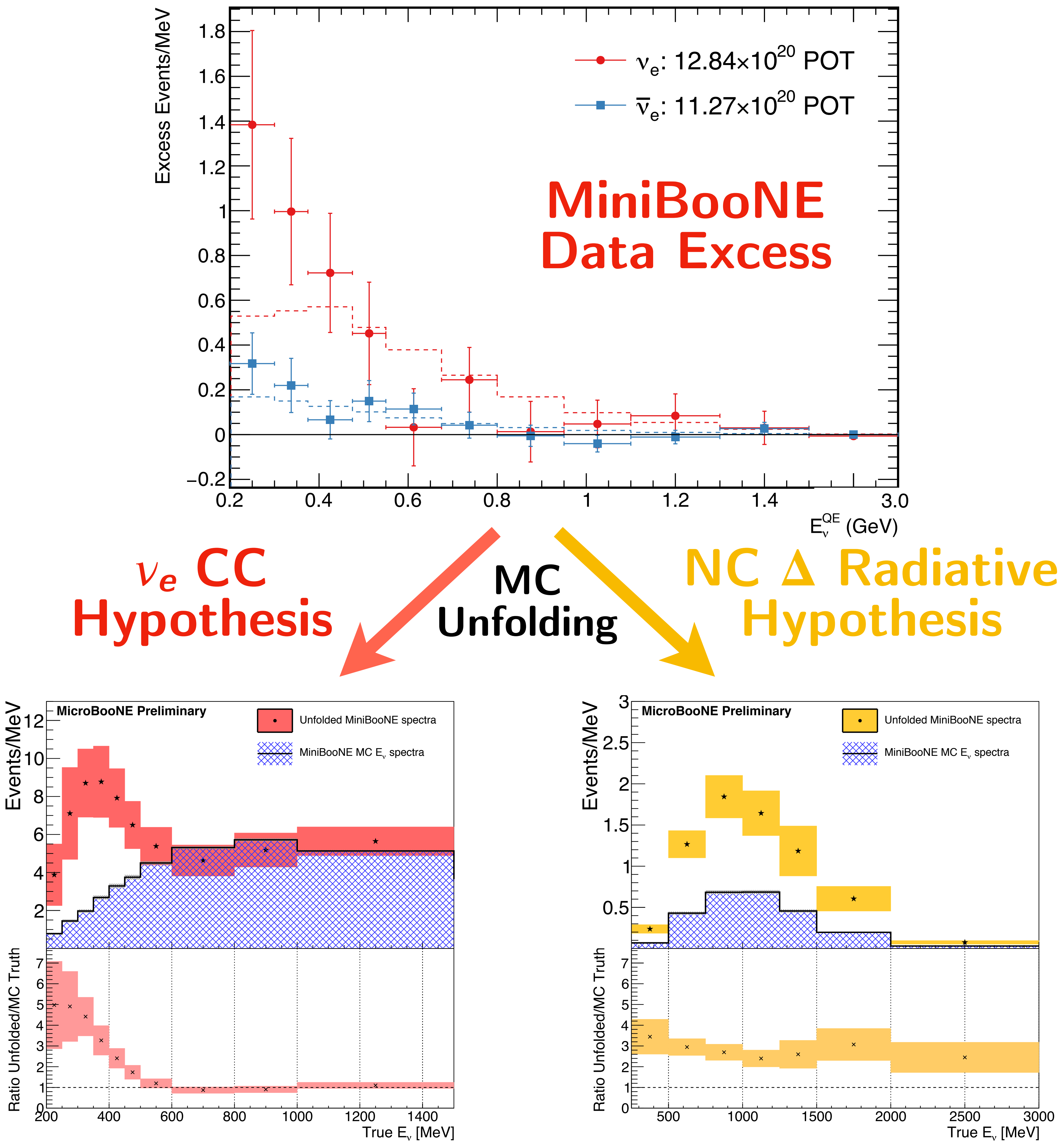




arXiv:1905.09694 [hep-ex], accepted to PRL

See Pip Hamilton's talk this afternoon

Low Energy Excess Models for MicroBooNE



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- What does a MiniBooNE-like LEE signal look like in MicroBooNE?
- 2 hypotheses :
  - ν_e-like excess
  - γ-like excess (NC Δ radiative decay resonance)
- Deconvolve MiniBooNE's detector effects
- Convolve MicroBooNE's detector effects
- ν_e-like excess mostly at low energy => electron shower topology different at low energy

Low Energy Studies

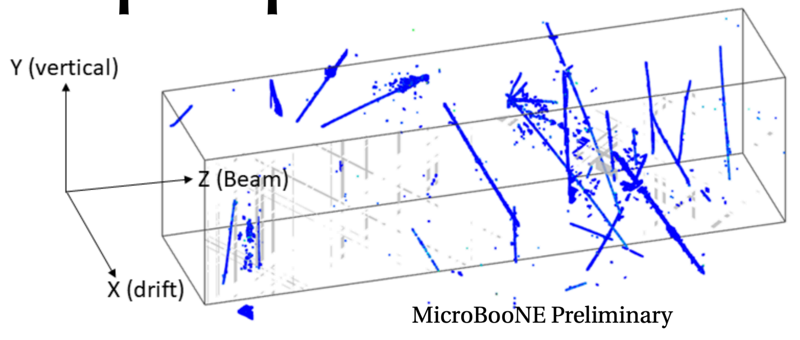
- Multiple, independent blind analyses
- Multiple reconstruction packages
- Multiple target event topologies

- Electron-like :
  - WireCell reconstruction
  - Deep Learning reconstruction
  - Pandora multi-algorithm reconstruction
- Photon-like :
  - Pandora multi-algorithm reconstruction

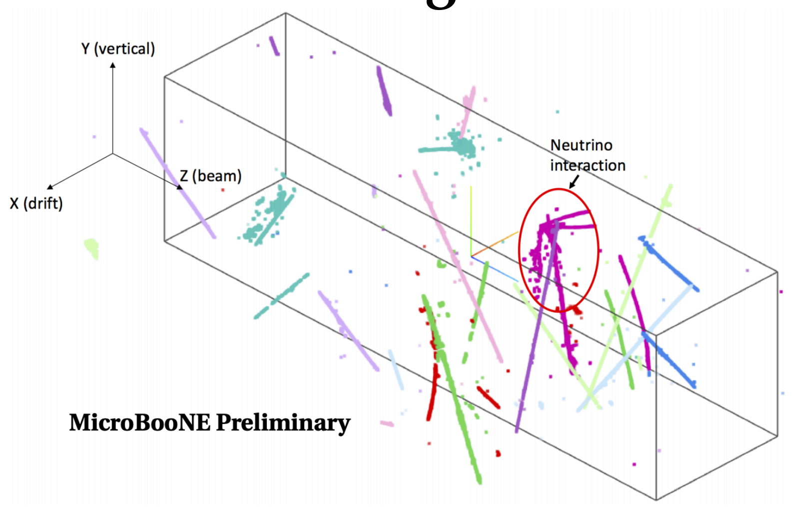
WireCell Reconstruction

Tomographic reco. Creates 3D space points and clusters in 3D

Space point creation



3D clustering

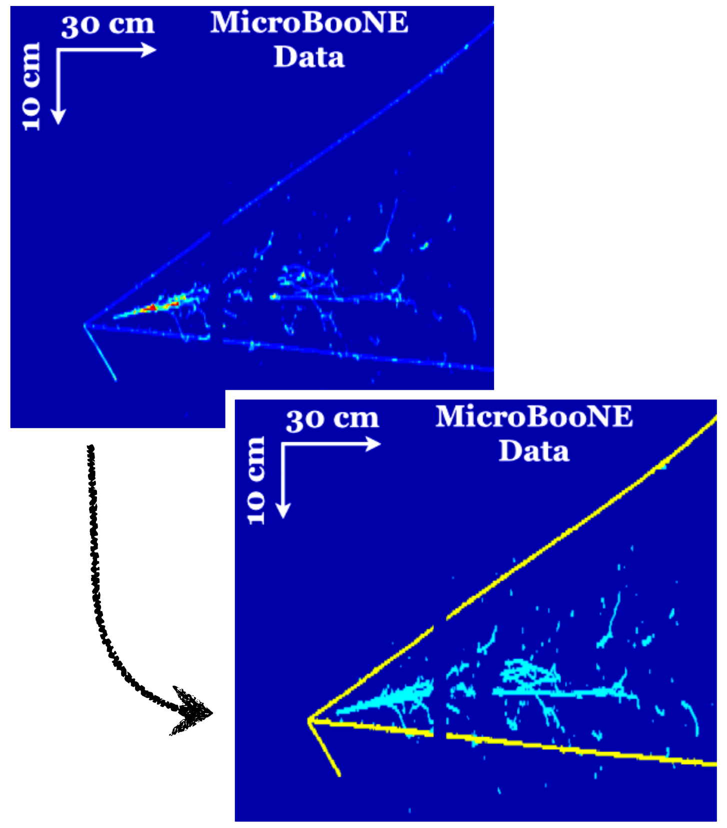


MICROBOONE-NOTE-1040-PUB

Deep Learning Reconstruction

Uses CNNs for PID and track/shower pixel labels

Pixel labeling example on a ν_μ CC π^0 event



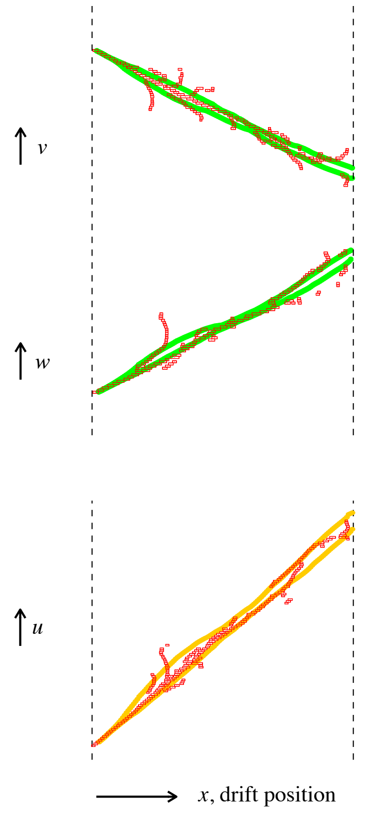
JINST 12, P03011 (2017)

PRD 99, 092001 (2019)

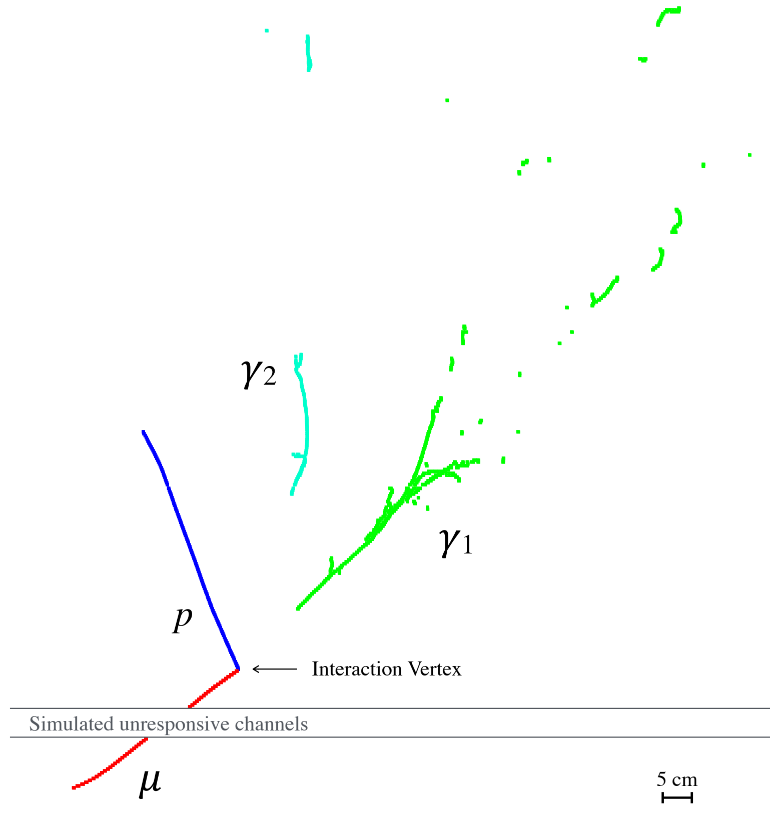
Pandora Multi-Algorithm Reconstruction Toolkit

Clusters in 2D independently on each plane before matching across planes to form 3D reconstructed tracks and showers

Matching a shower across three planes



Reconstruction of a ν_μ CC π^0 event



Eur.Phys.J. C78 (2018) no.1, 82

See the talk from Mark Ross-Lonergan on Friday

Selecting e-Like Events

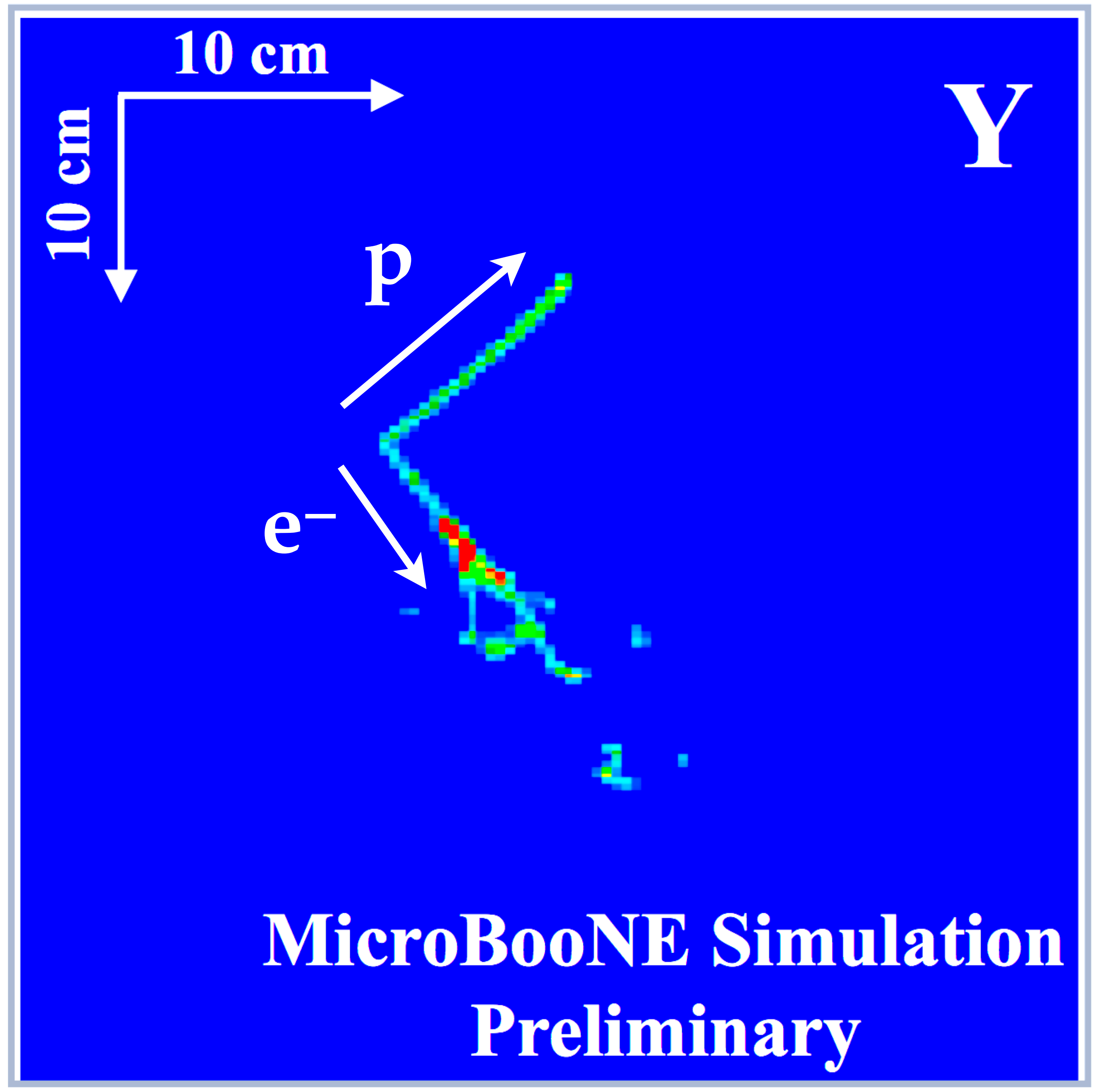
Multiple complimentary searches:

- High purity, exclusive 1e1p with Deep Learning
- High efficiency, more inclusive 1e0πNp with Pandora
- Fully inclusive with Pandora+WireCell

Major challenges

- reconstructing low energy electrons that do not shower
- rejecting non-ν_e backgrounds

1e1p Topology



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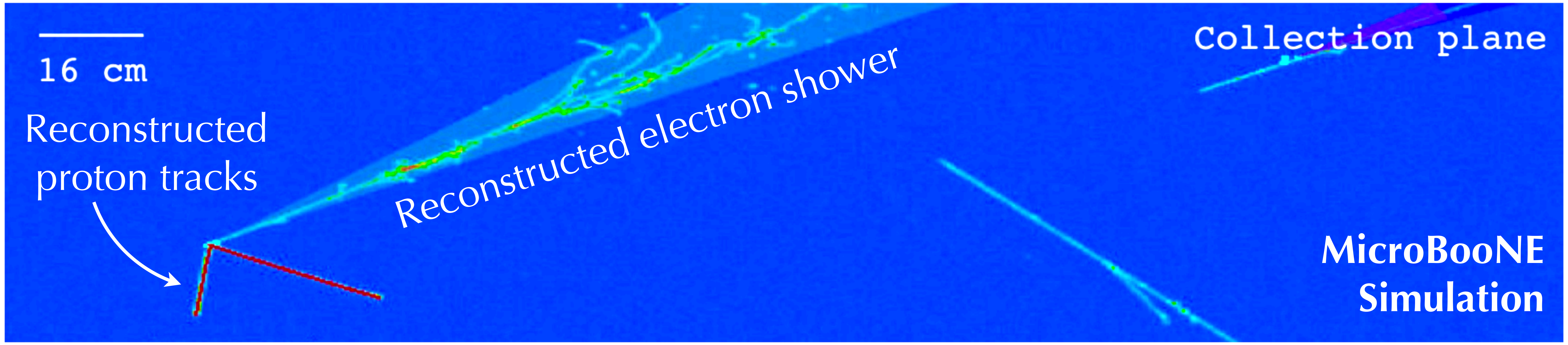
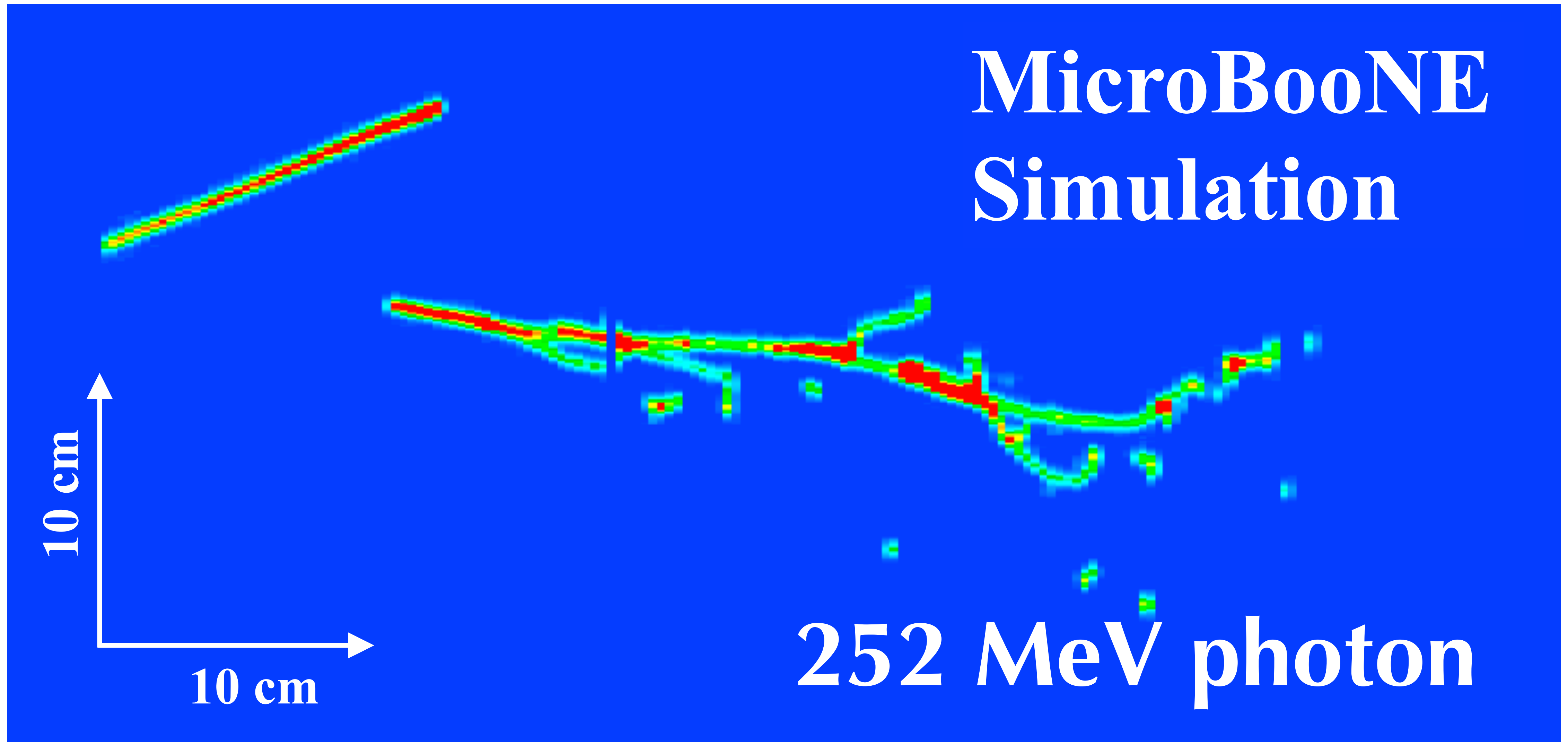
1e0πNp Topology MICROBOONE-NOTE-1038-PUB



Selecting γ-Like Events

- NC Δ radiative search in investigating both 1γ1p and 1γ0p to maximize signal statistics, and is using Pandora reconstruction
- Major challenge is understanding and rejecting NCπ^0 backgrounds. Topology for these is 2γ1p or 2γ0p, but second shower can be difficult/impossible to reconstruct
- First analysis of the NC Δ ⟶ p+γ interaction by a neutrino experiment!

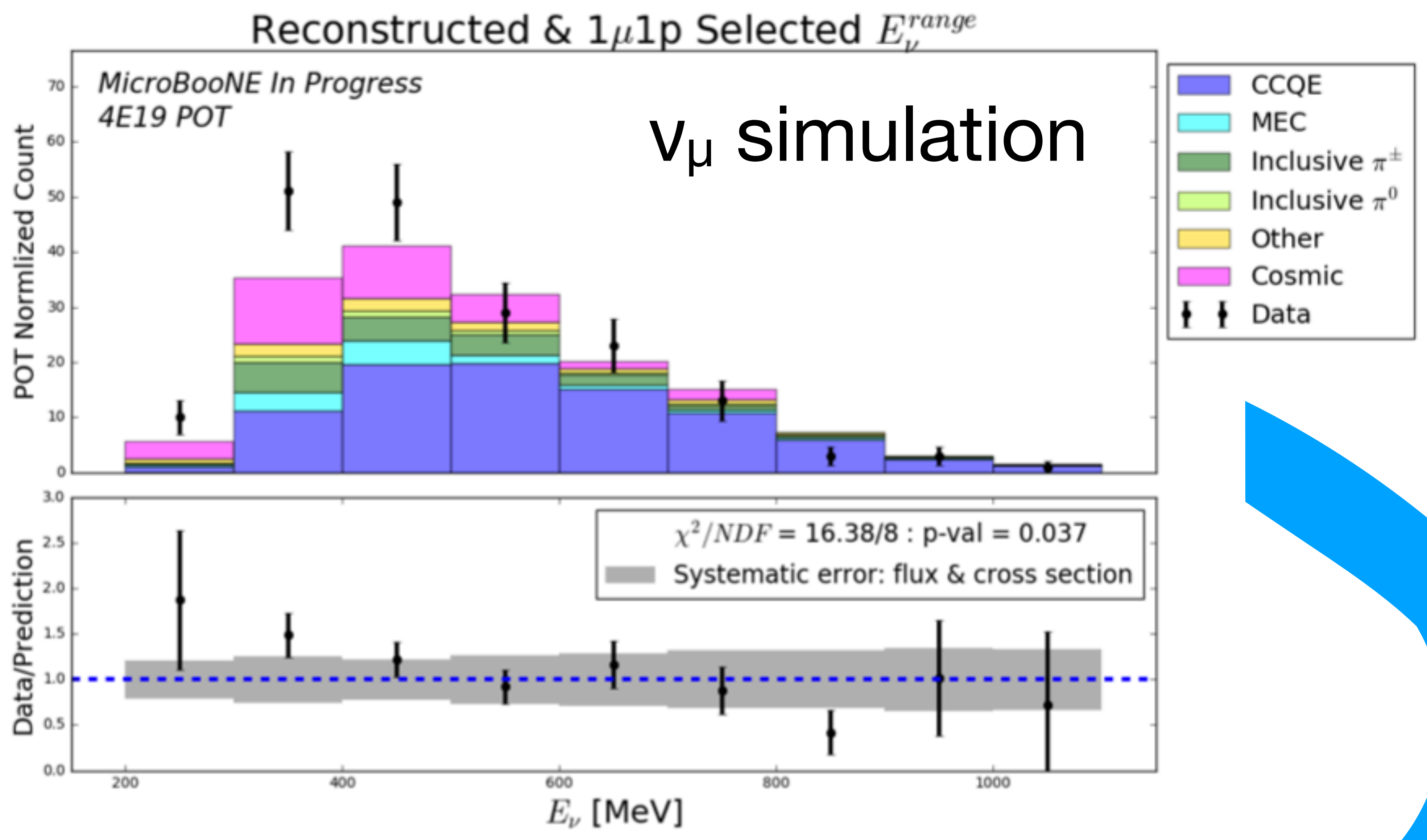
MICROBOONE-NOTE-1041-PUB

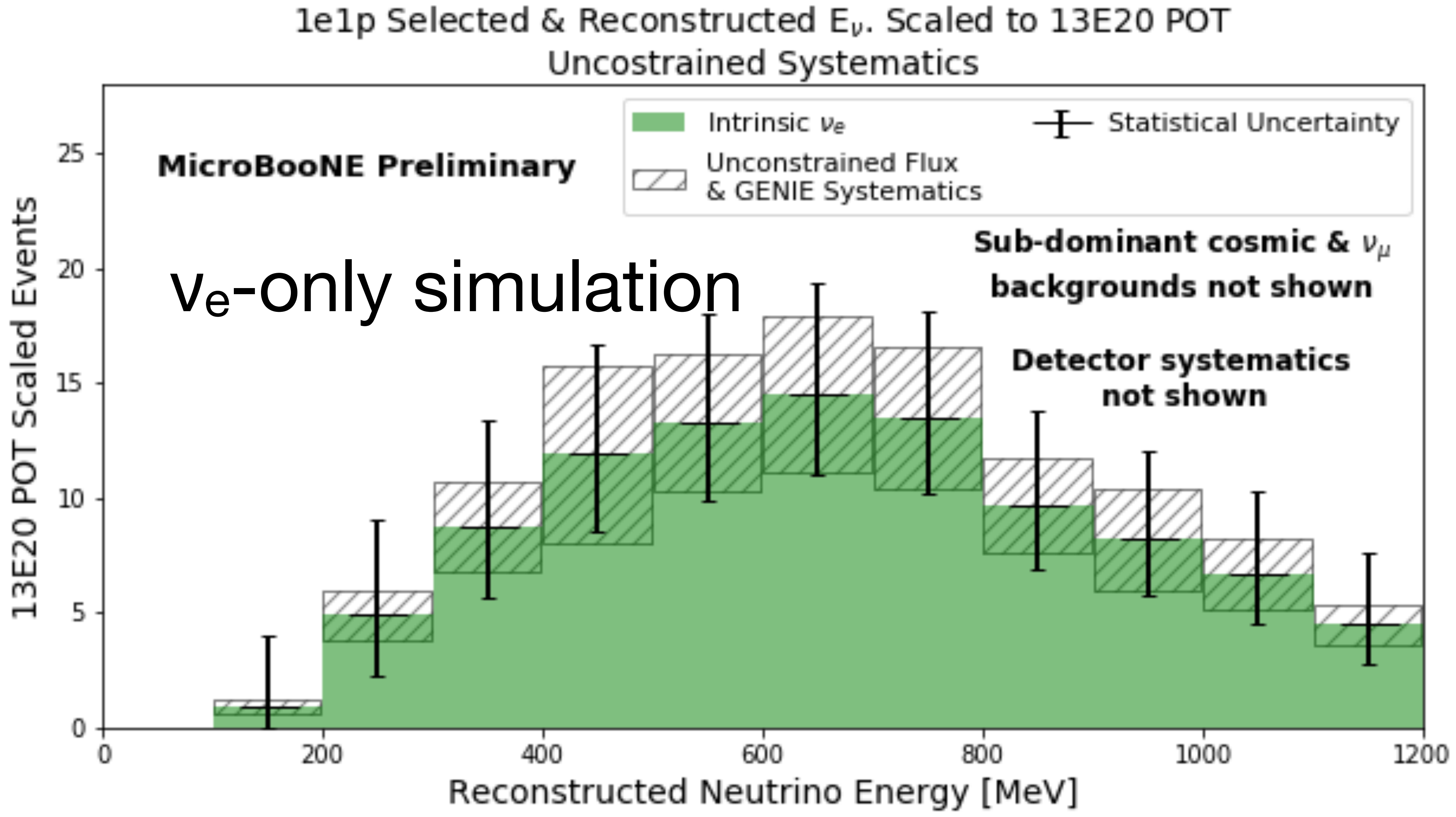


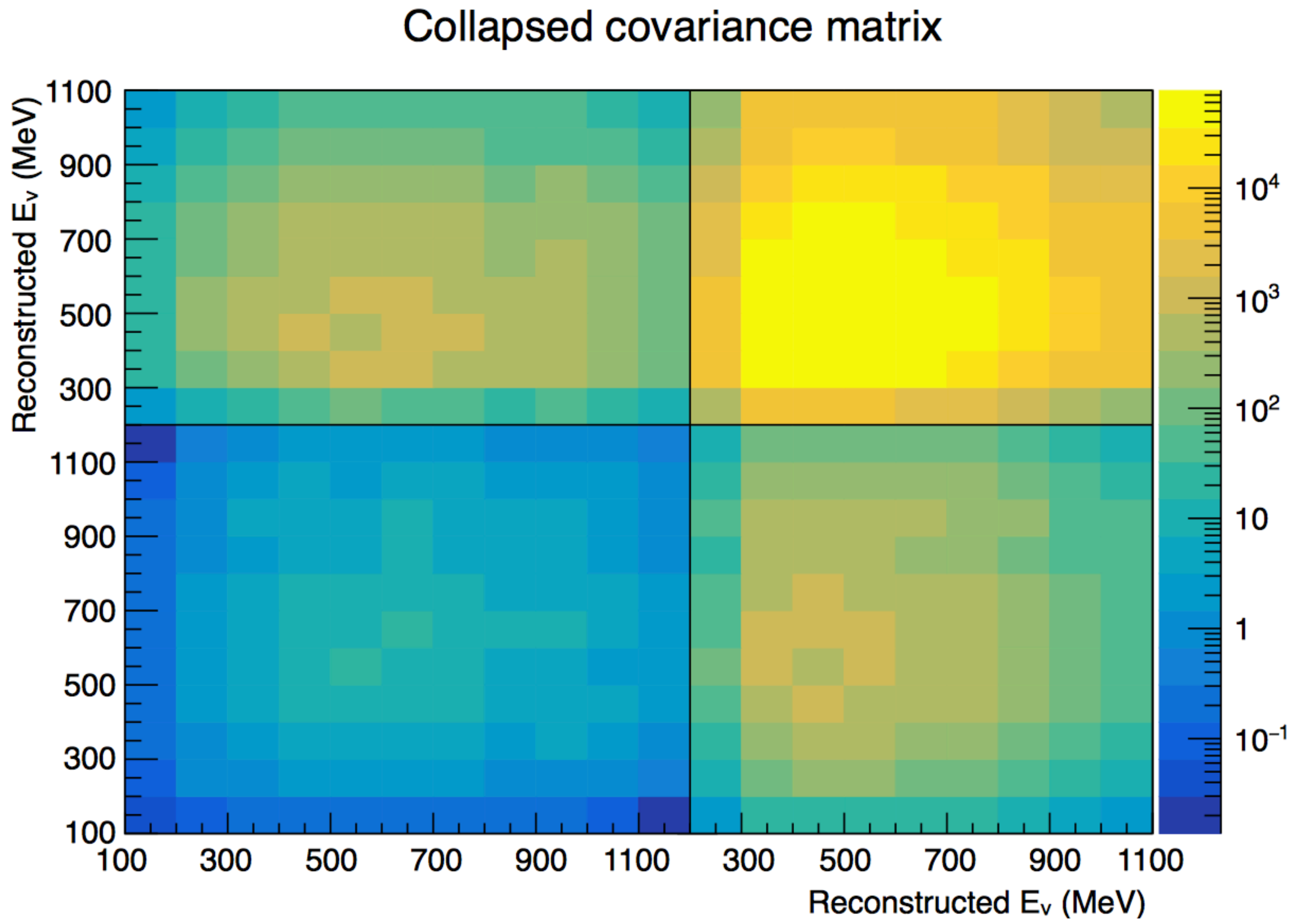
Constraining Systematics

- Want to constrain systematics on intrinsic ν_e backgrounds
  - unconstrained flux and cross section uncertainties are 20-30%
  - constraints should significantly improve our sensitivity to an excess
- Also want to constrain other beam-related backgrounds
- Without near detector, we plan to use measurements of ν_μ events to constrain our uncertainties

Constraining systematics

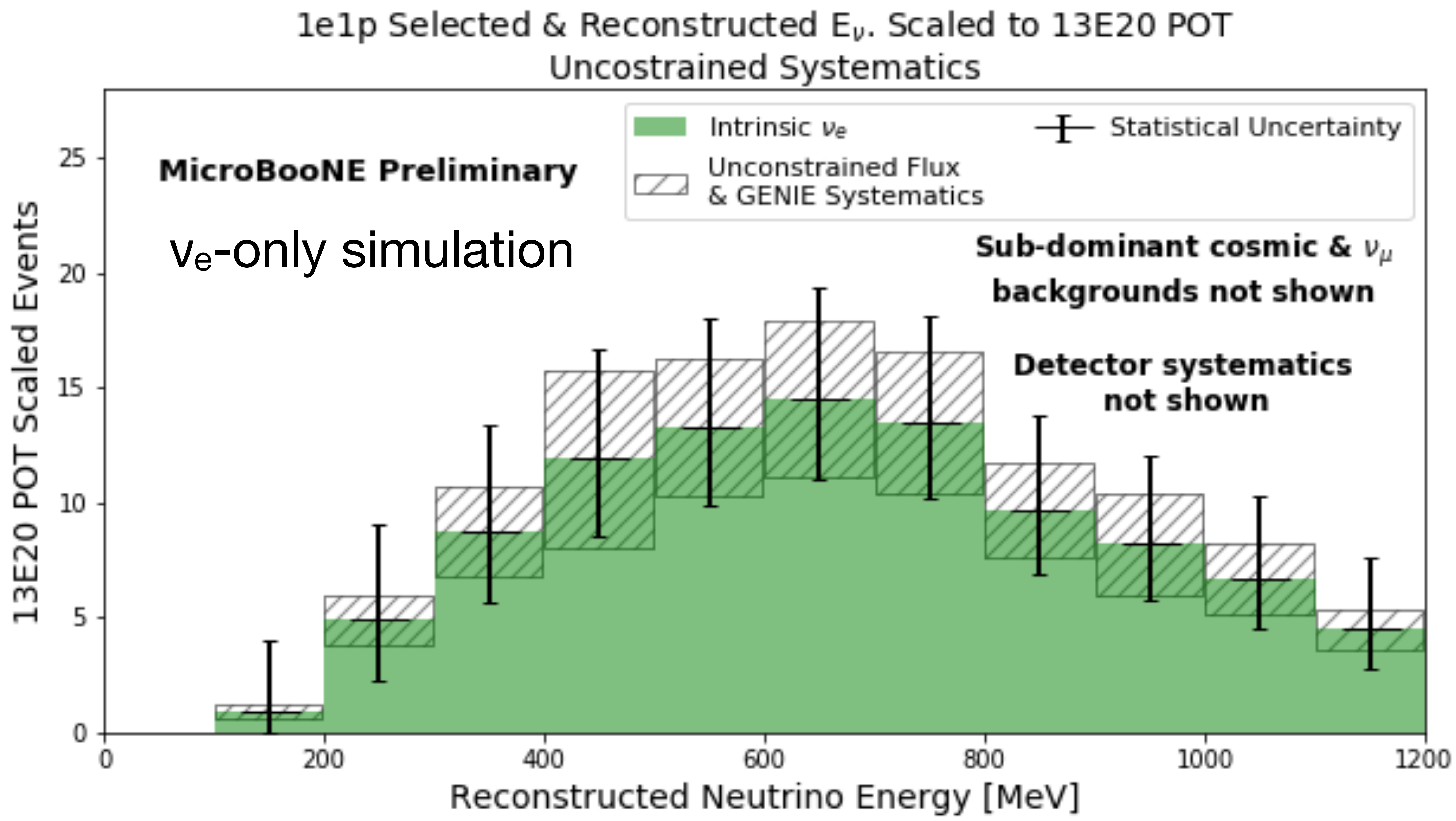






- Deep Learning based reconstruction and selection MICROBOONE-NOTE-1039-PUB
- Re-weight events to account for neutrino generator systematic uncertainties (flux & cross section)
- Generate uni-simulations to account for detection and selection systematic uncertainties

Constraining Systematics



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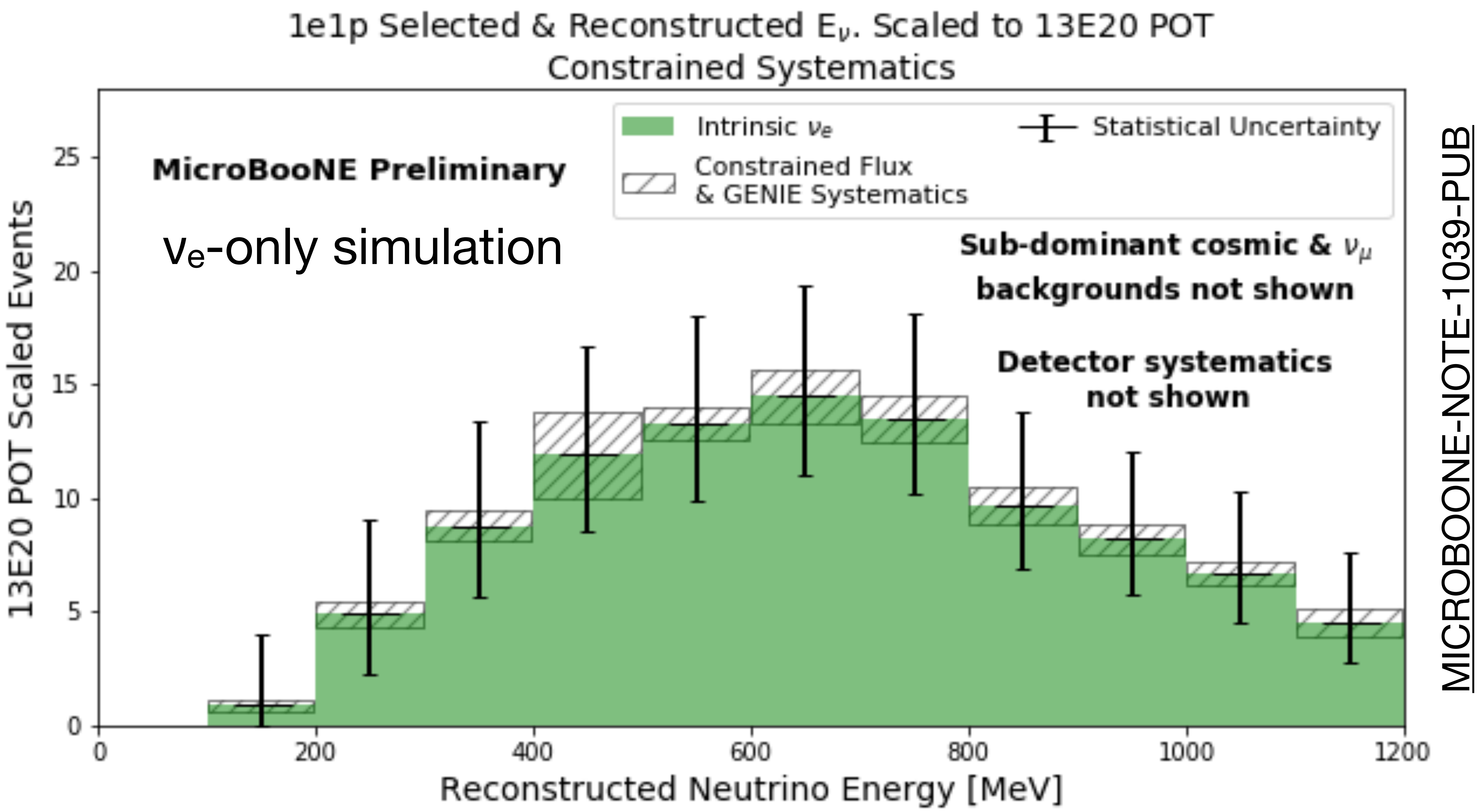
Constraining Systematics



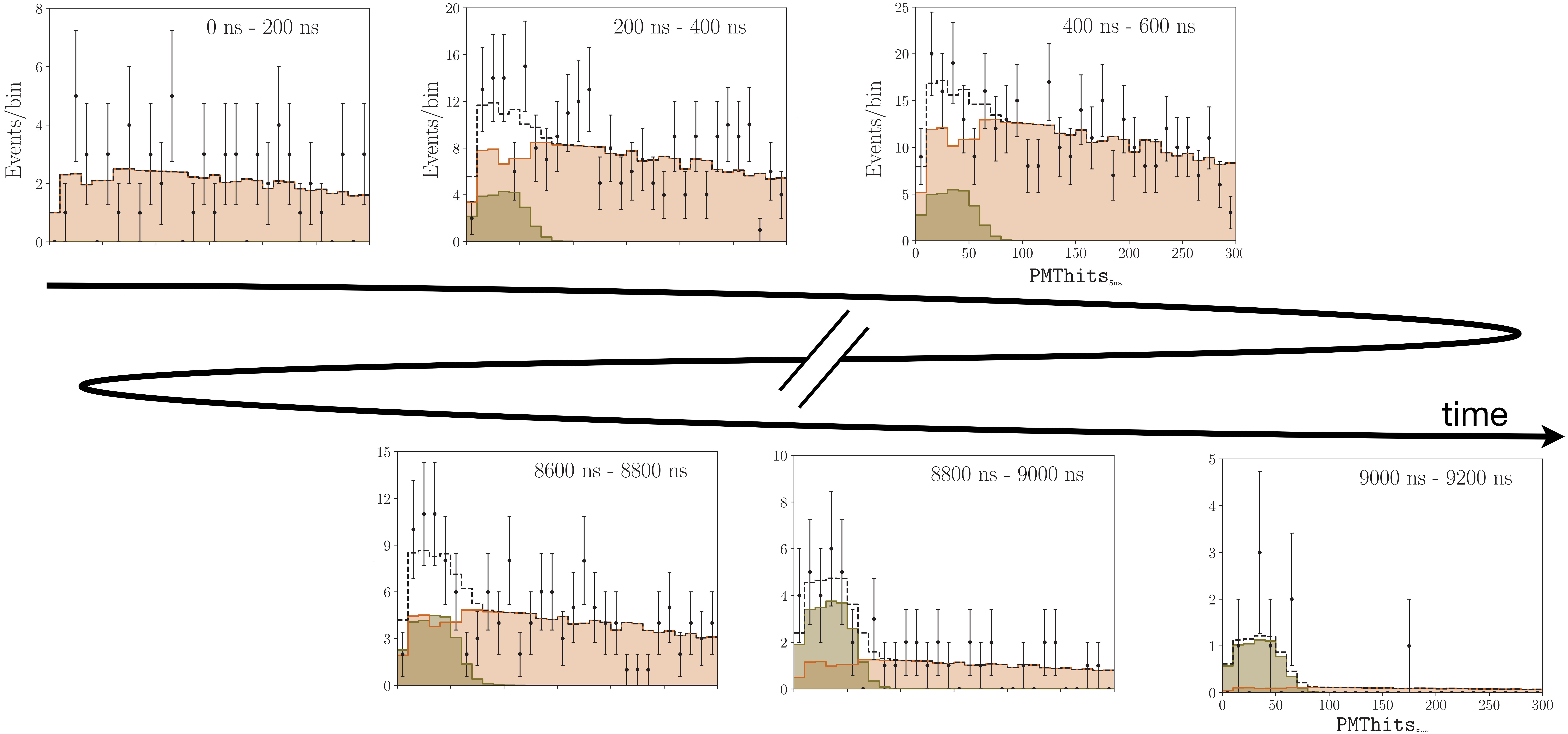
Summary

- **MiniBooNE** has presented an updated measurement of a low energy excess with twice the statistics in neutrino mode in 2018
  - Very stable and well understood detector
  - In Situ measurement of the backgrounds and different ν-C cross sections
  - Combined LSND+MiniBooNE excess has a 6.1σ significance

- **MicroBooNE** has made significant progress towards analyses that will test both possible interpretations of the MiniBooNE excess
  - Signal processing, calibration and detector physics
  - ν-Ar cross section measurements
  - Independent analyses, exploring different hypotheses for the excess, different final states and different reconstructions
  - Constraining systematics by using *in situ* measurement of ν_μ


Thank You!

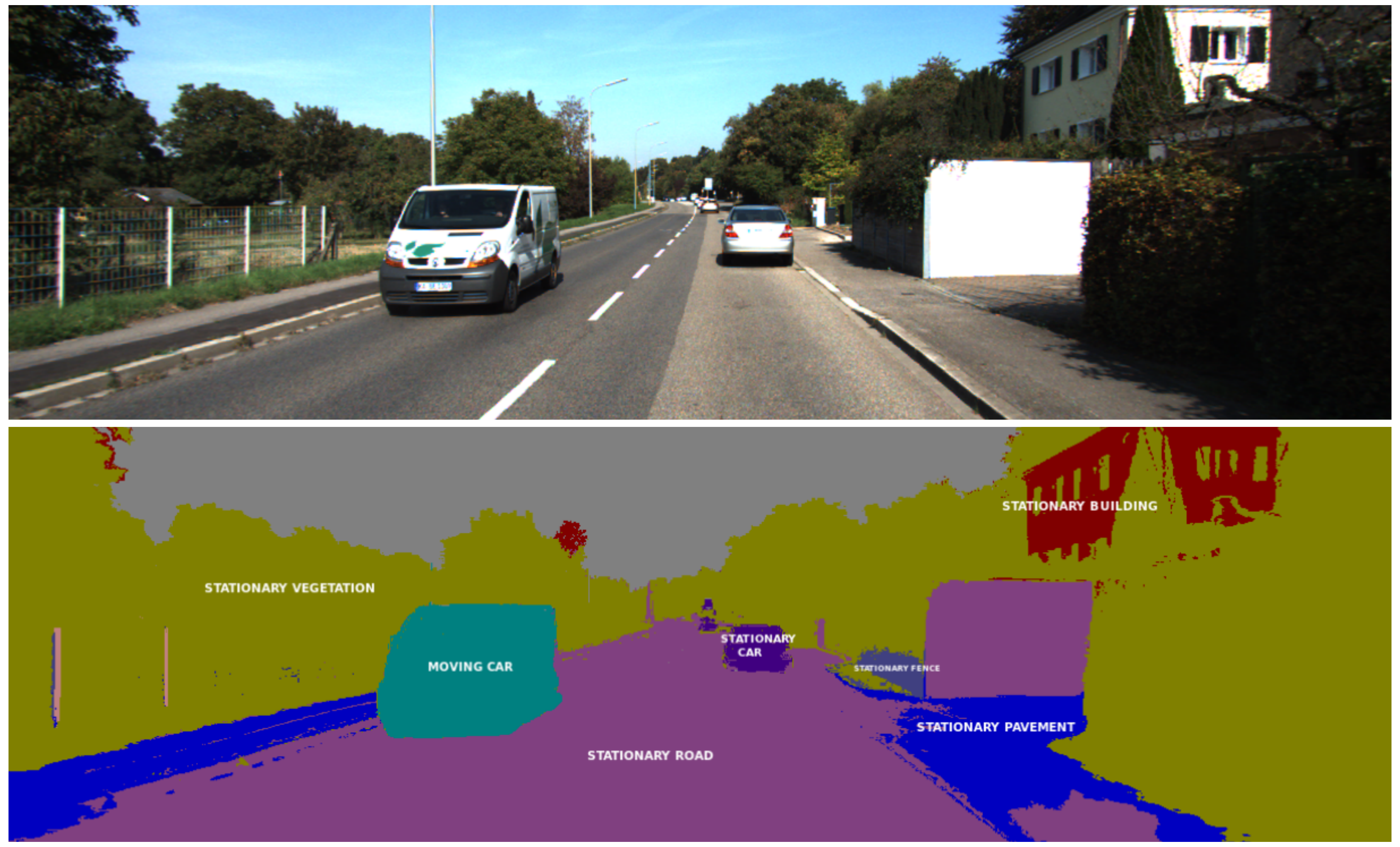
MiniBooNE KDAR

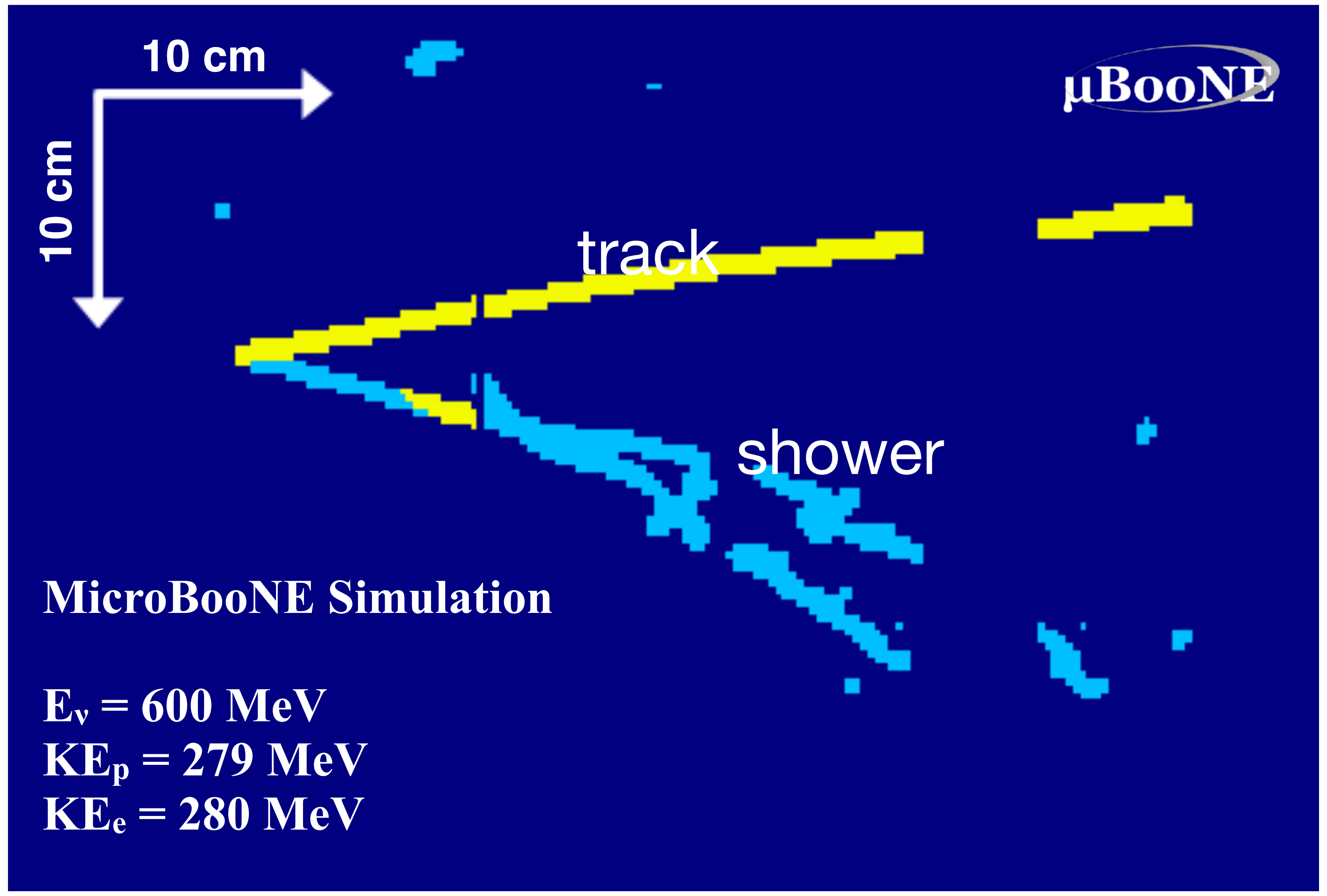


appearance of a low energy component as a function of time after a NuMI trigger

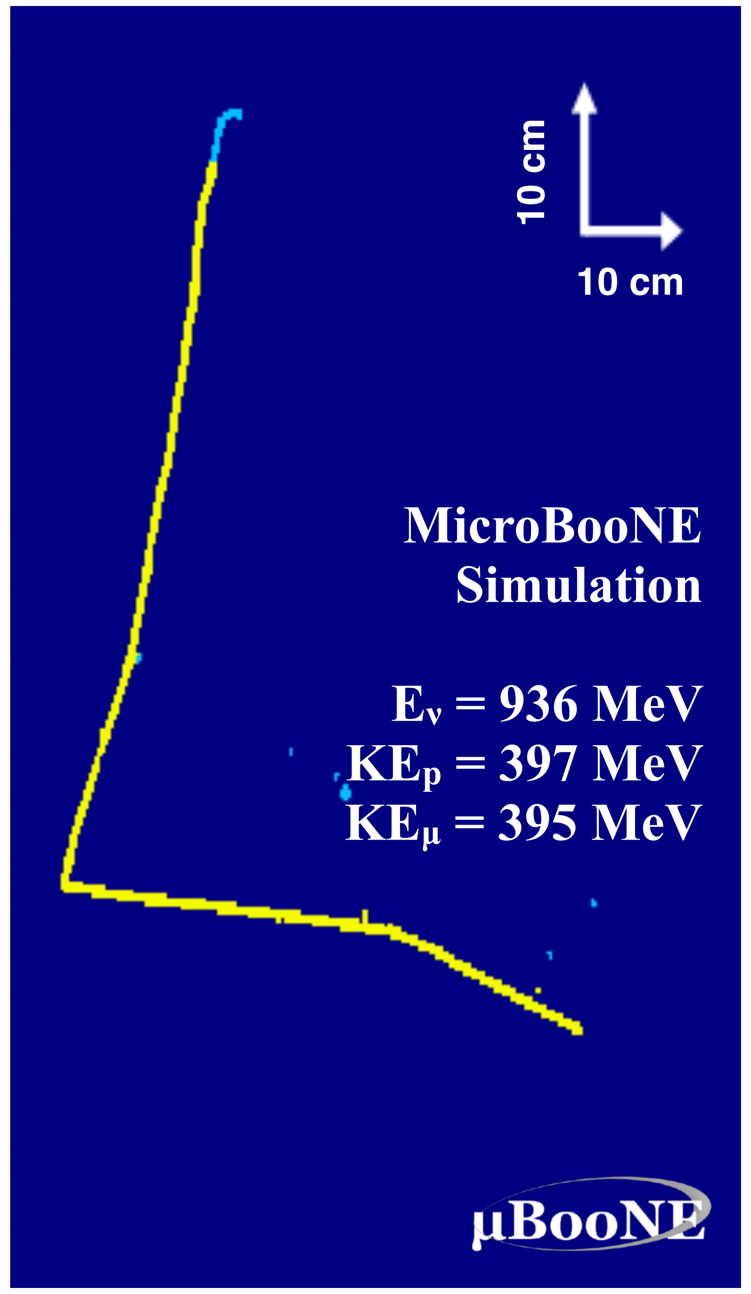
Semantic Segmentation Networks

- SSNets identify the content of an image, and work the convolution chain back to the location of the identified objects
- Pixel-level identification
- Trained to recognize tracks to shower
- Track/shower boundaries can be potential vertex!
- How to validate such network?
    - use manual pixel labeling from trained physicist
    - network -human agreement to within 2.5%





MICROBOONE-NOTE-1042-PUB



MICROBOONE-NOTE-1042-PUB

JINST 12, P03011 (2017)

PRD 99, 092001 (2019)