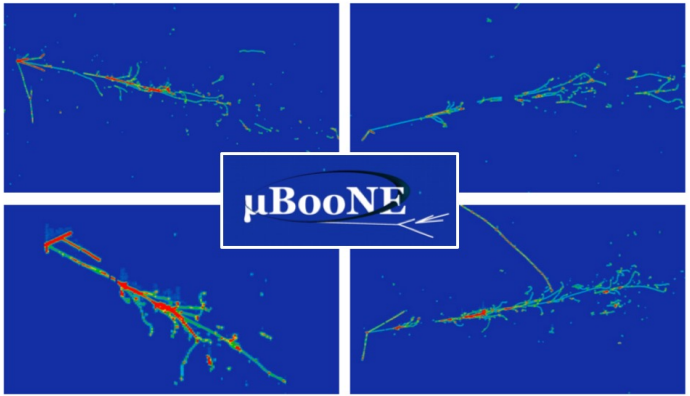
New results from MicroBooNE



Justin Evans

University of Manchester

µBooNE

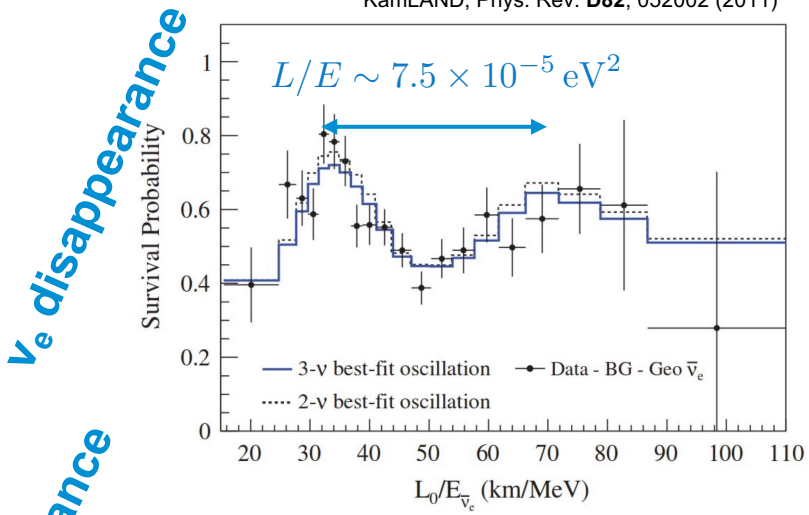
MANCHESTER 1824
The University of Manchester

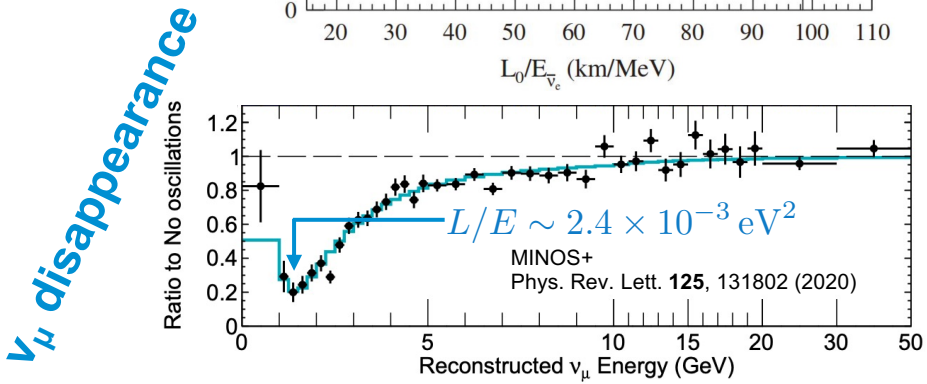
Neutrinos: the 'standard' non-standard picture

Neutrinos are beyond-Standard-Model particles

- They have mass and change flavour
- Two well-measured oscillation rates

KamLAND, Phys. Rev. **D82**, 052002 (2011)





Neutrinos: the 'standard' non-standard picture

Neutrinos are beyond-Standard-Model particles

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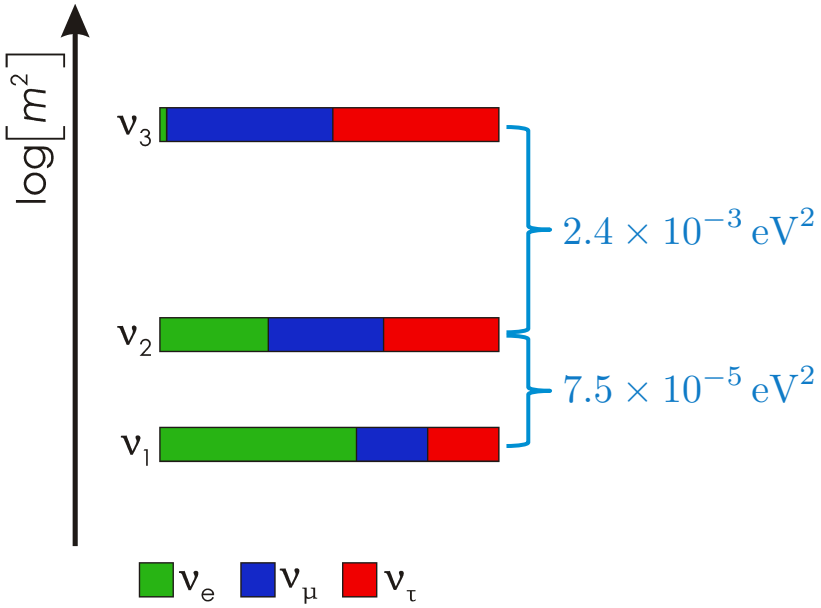
Two oscillation rates from two mass-splittings



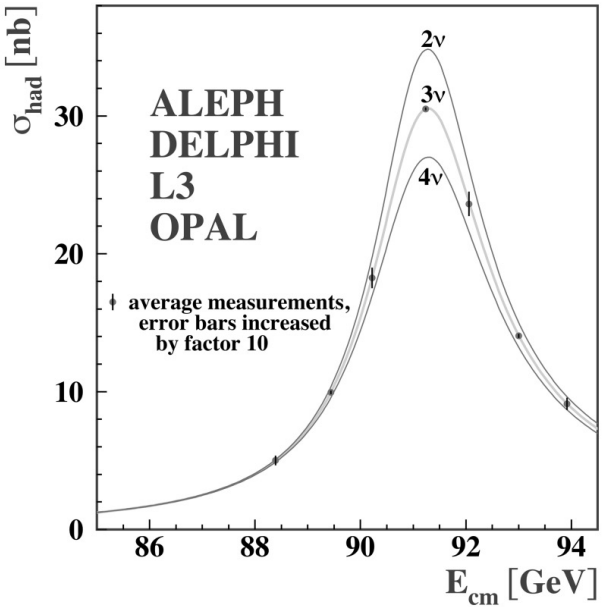
Neutrinos: the ‘standard’ non-standard picture

Neutrinos are beyond-Standard-Model particles

- They have mass and change flavour
- Two well-measured oscillation rates

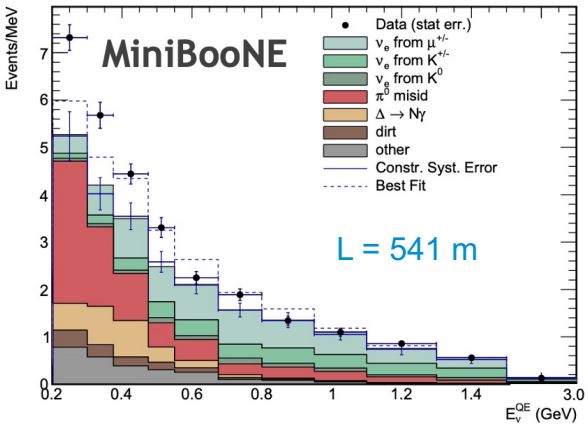
Two oscillation rates from two mass-splittings

Consistent with a three-flavour picture from Z-boson width measurements



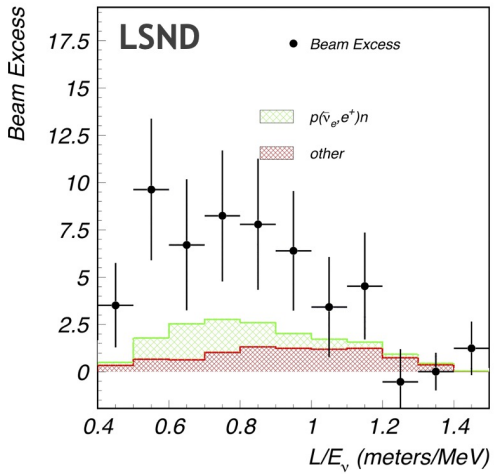
Short-baseline anomalies

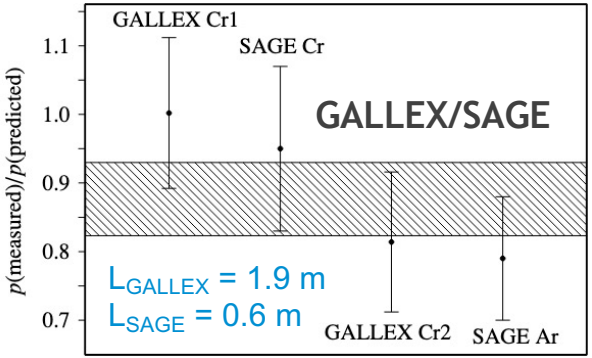
Phys. Rev. D 103, 052002 (2021)



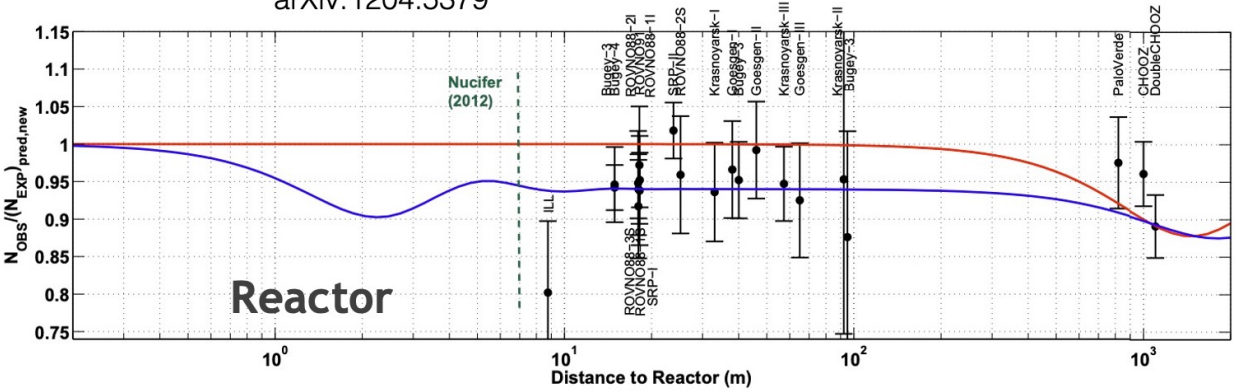
Phys. Rev. C 73, 045805 (2006)

Phys. Rev. D 64 112007, 2001





arXiv:1204.5379

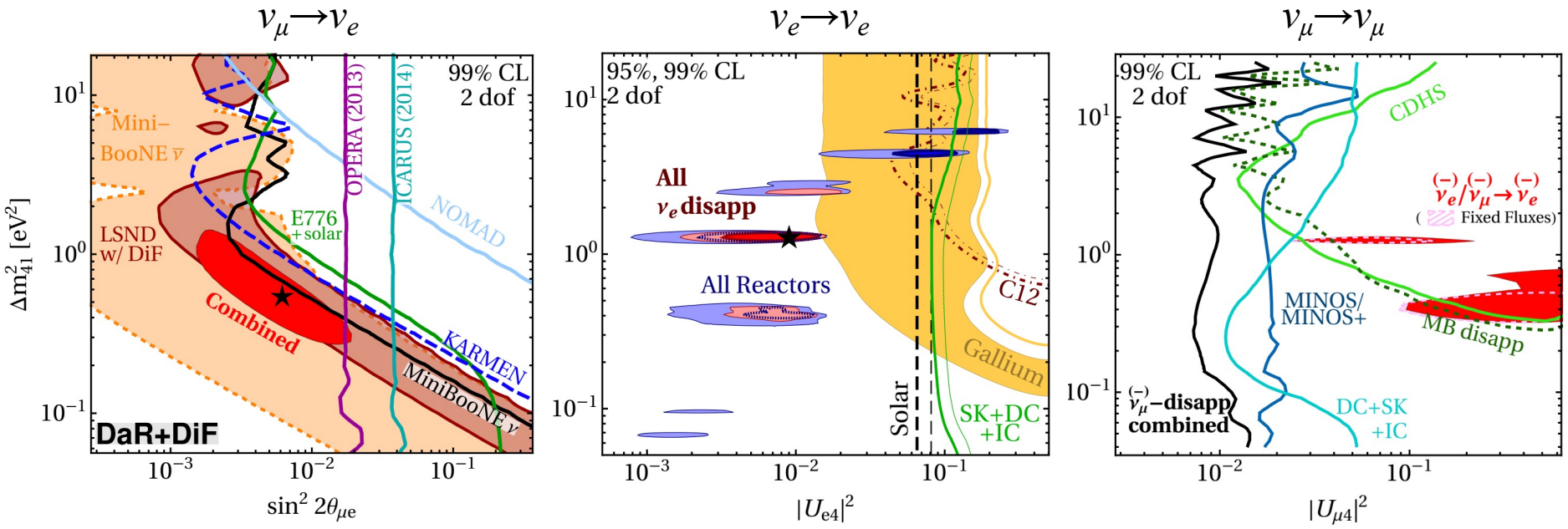


Excesses and deficits

- If caused by oscillations, not consistent with a three-flavour picture

µBooNE

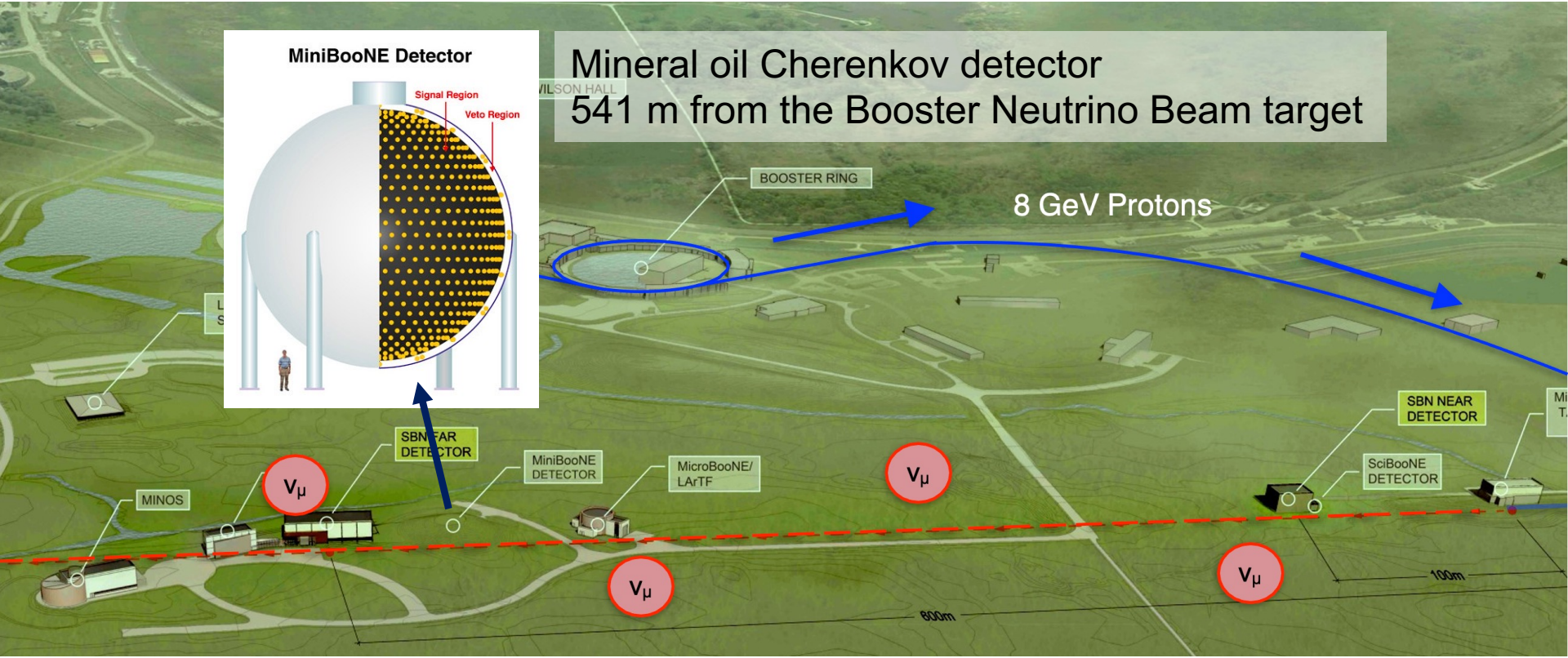
Short-baseline anomalies



- Hard to build a coherent picture

JHEP **08**, 010 (2018)

MiniBooNE


MiniBooNE Detector
Signal Region
Veto Region
Mineral oil Cherenkov detector
541 m from the Booster Neutrino Beam target
BOOSTER RING
8 GeV Protons
SBN FAR DETECTOR
MiniBooNE DETECTOR
MicroBooNE/ LArTF
MINOS
SBN NEAR DETECTOR
SciBooNE DETECTOR
ν_μ
ν_μ
ν_μ
ν_μ
100m
600m

MiniBooNE

MiniBooNE could not distinguish photons from electrons

- And had no hadronic information

Photon-like excess?

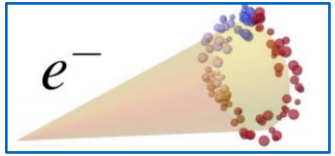
- Mismodeled background?

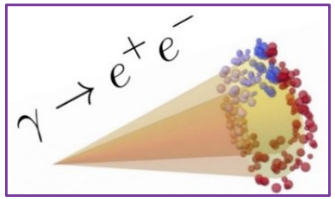
Electron-like excess?

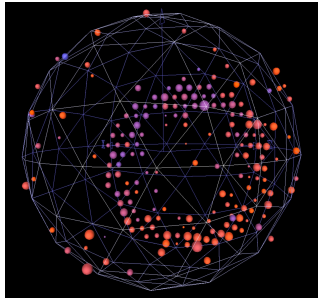
- Oscillation-driven excess? Sterile neutrino?

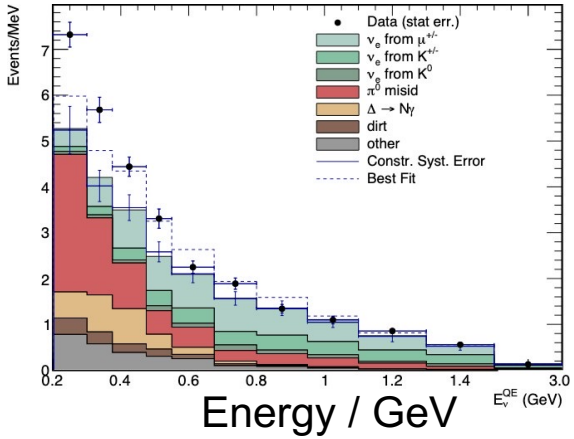
e^+e^- excess?

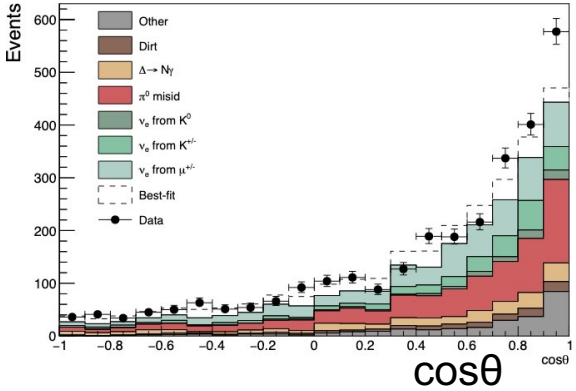
- Even more exotic new physics?



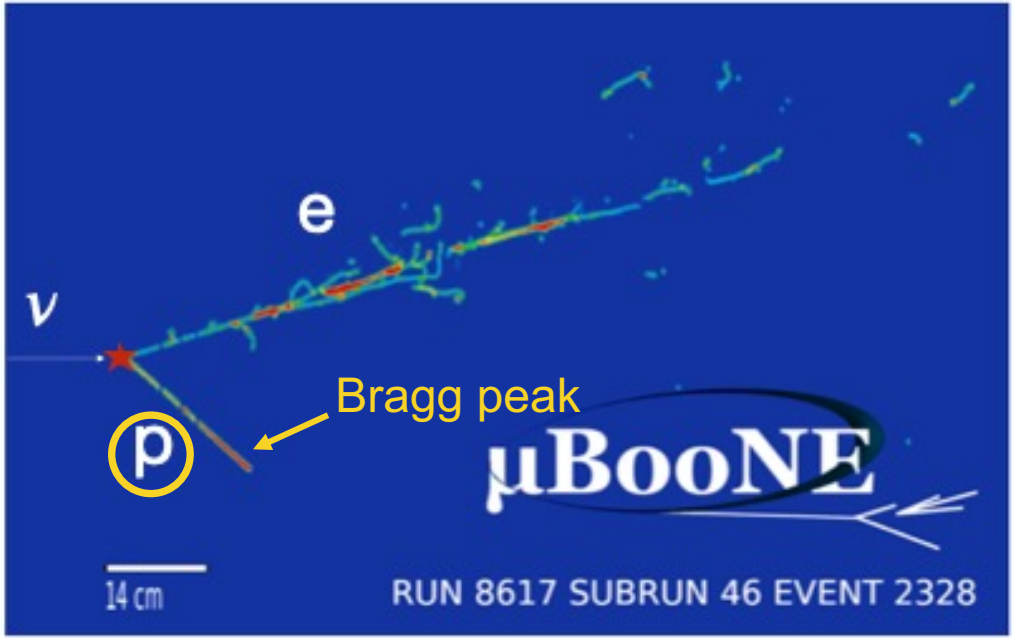


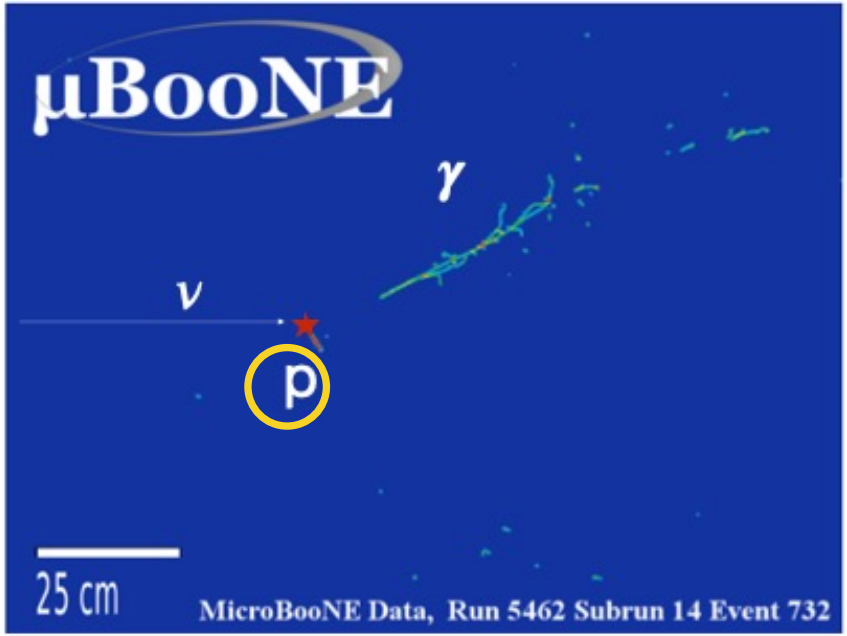






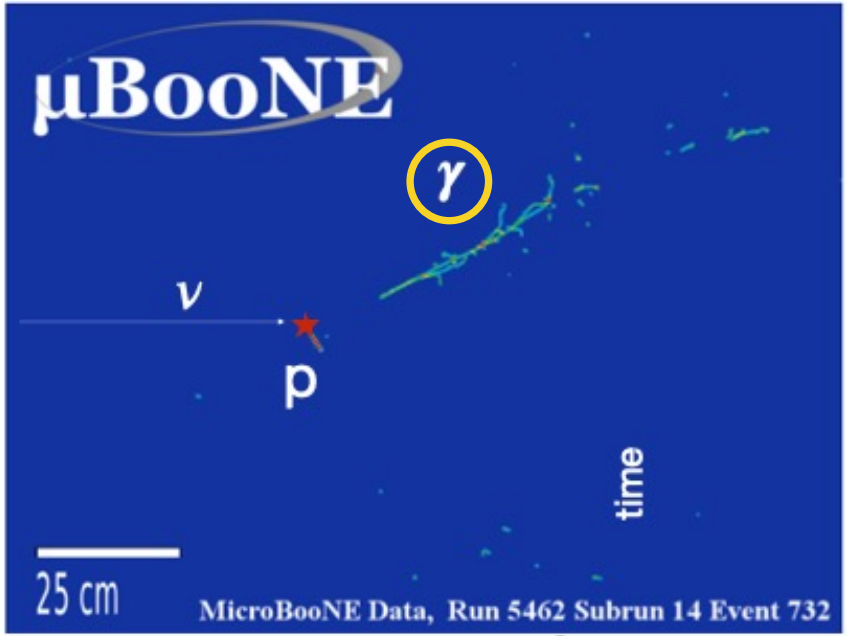
Liquid argon: MicroBooNE

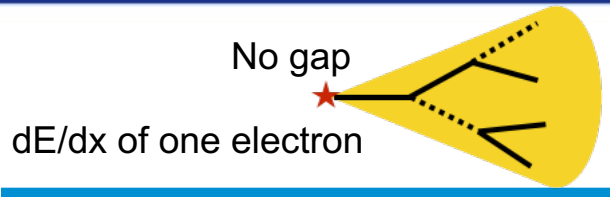


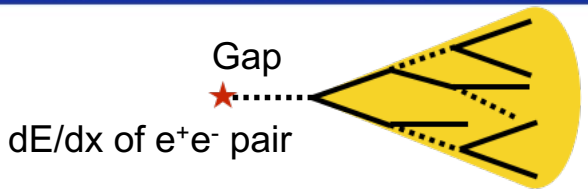


We can see the hadronic final state

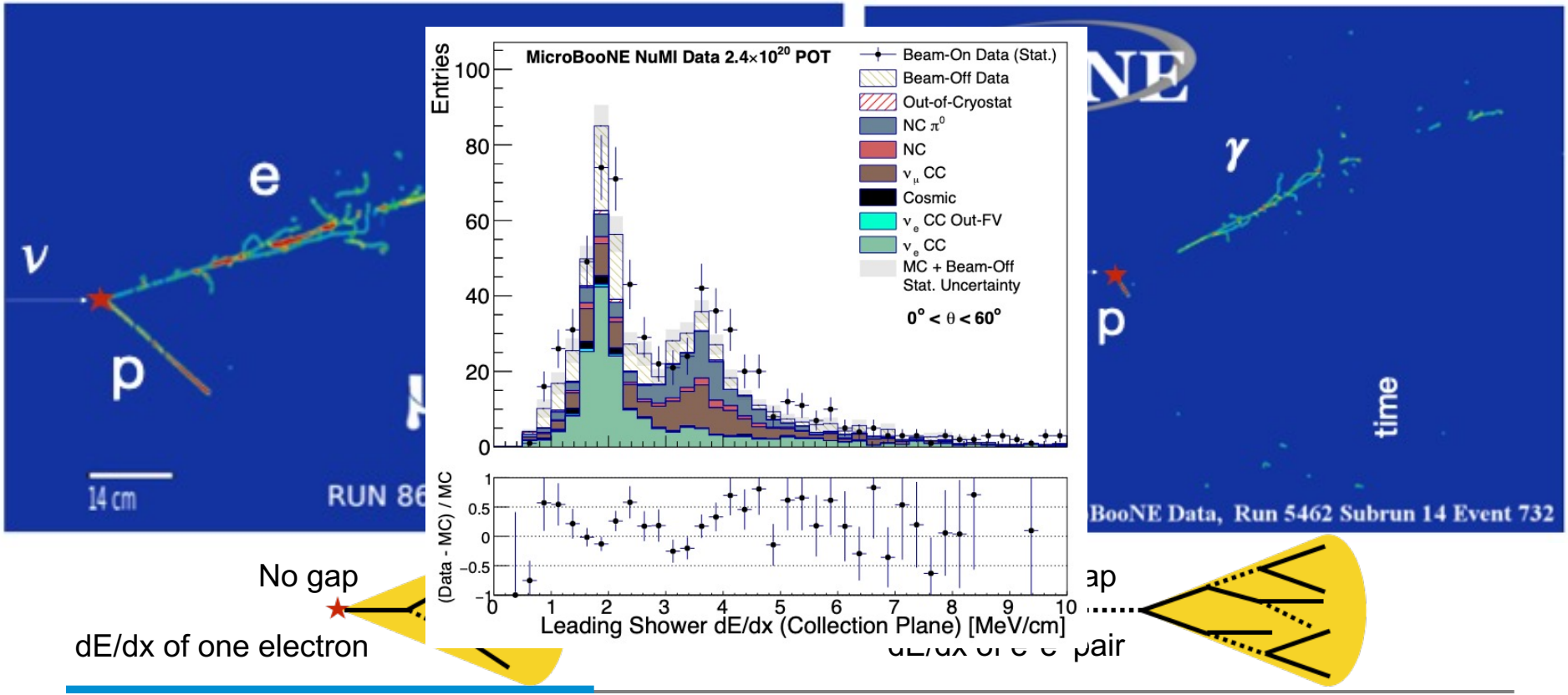
Liquid argon: MicroBooNE



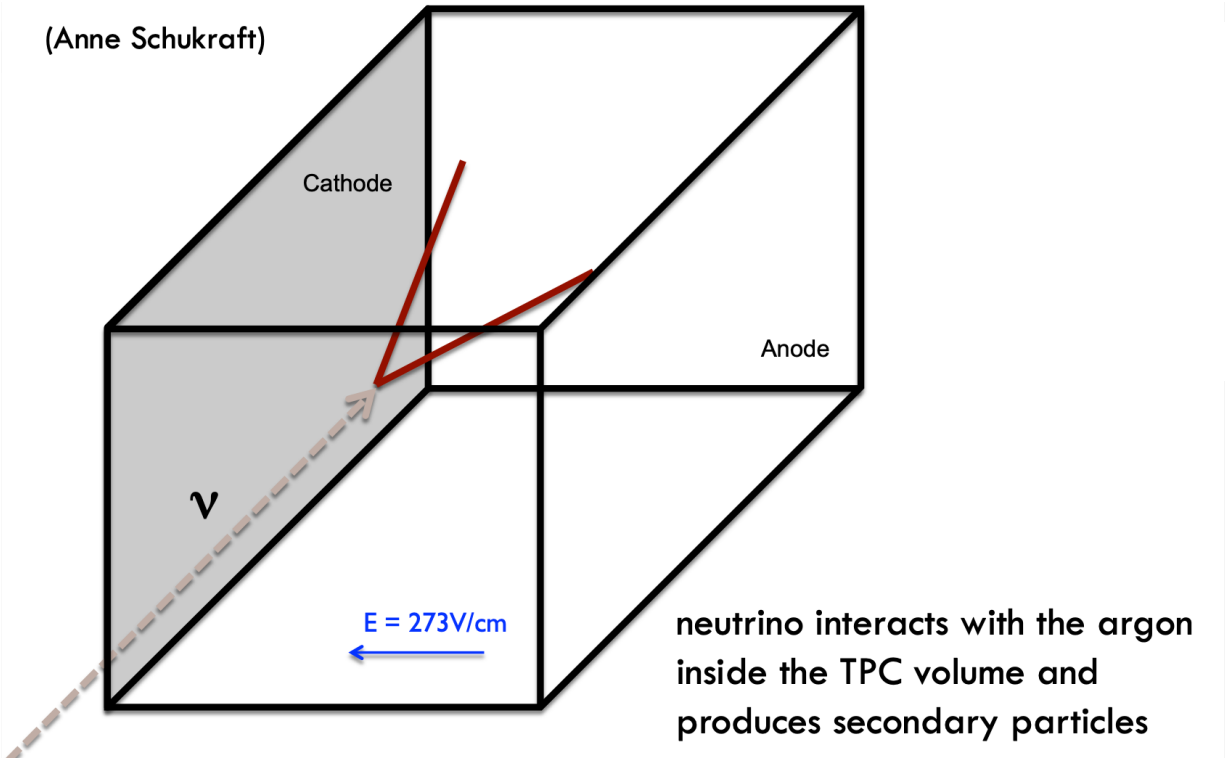




Liquid argon: MicroBooNE

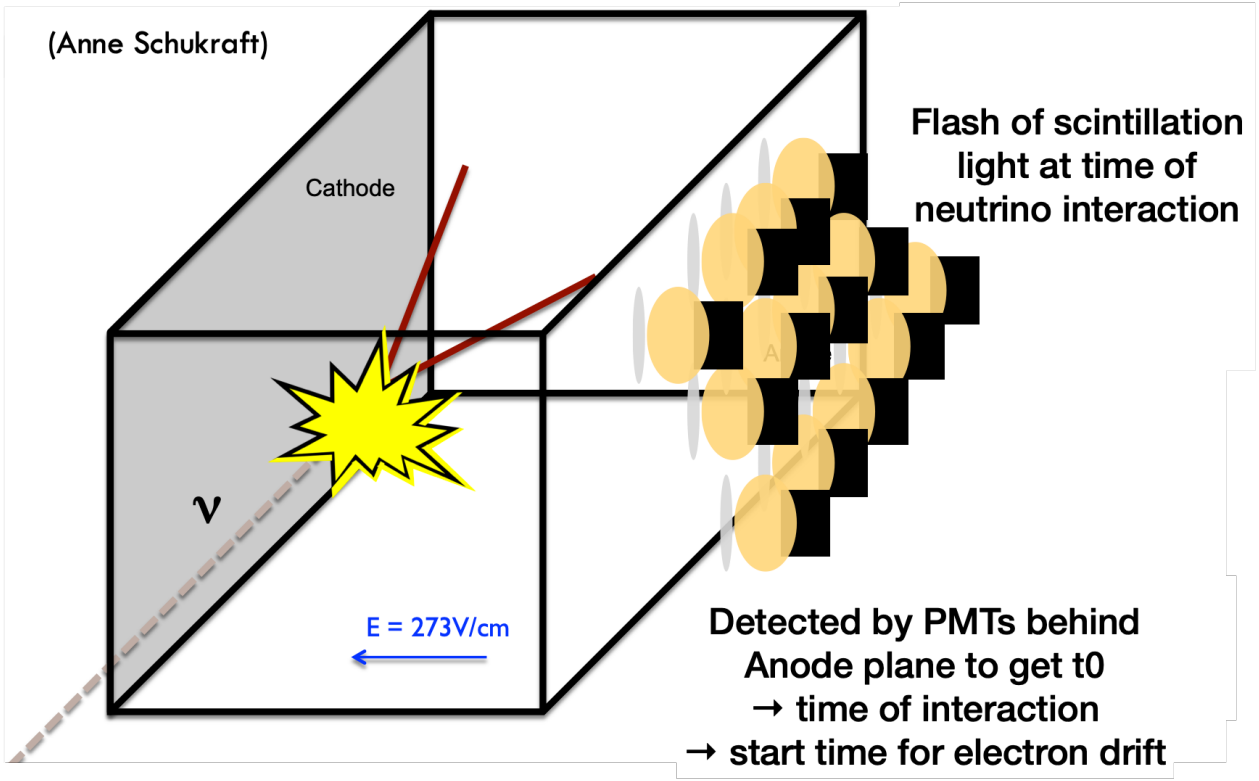


Liquid argon: MicroBooNE

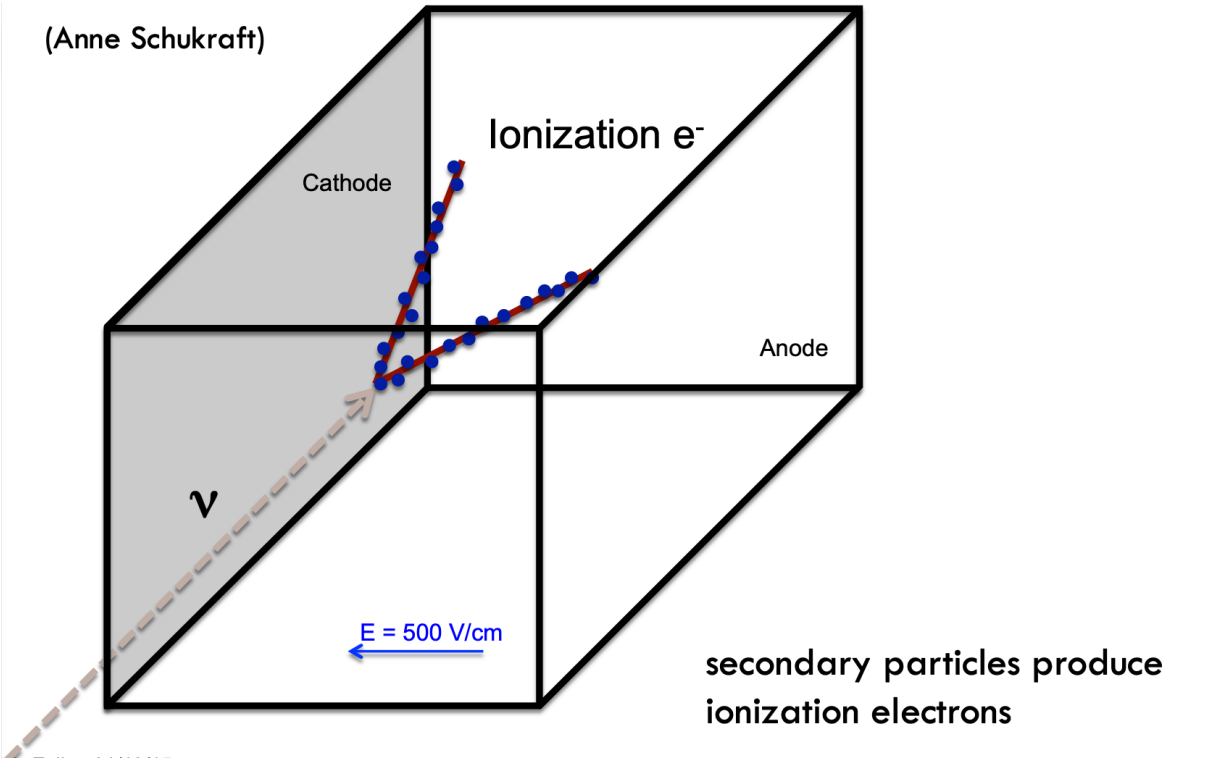


neutrino interacts with the argon inside the TPC volume and produces secondary particles

Liquid argon: MicroBooNE

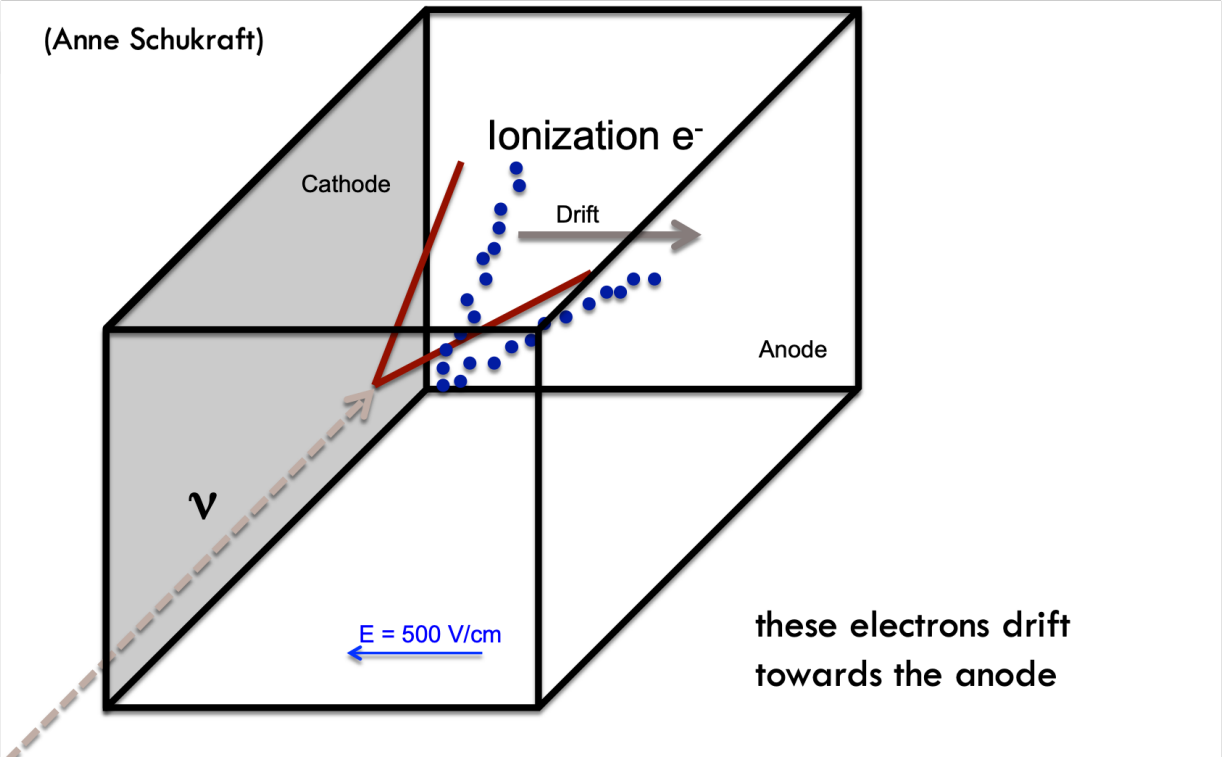


Liquid argon: MicroBooNE

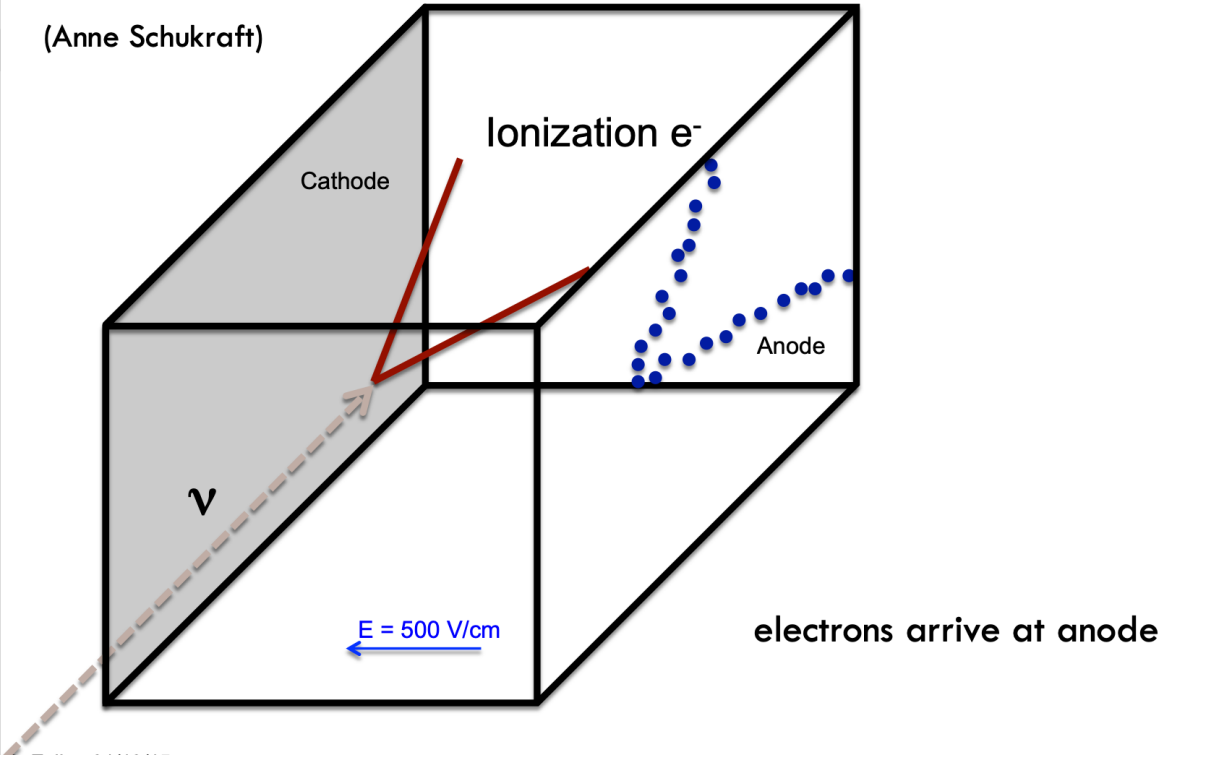


secondary particles produce ionization electrons

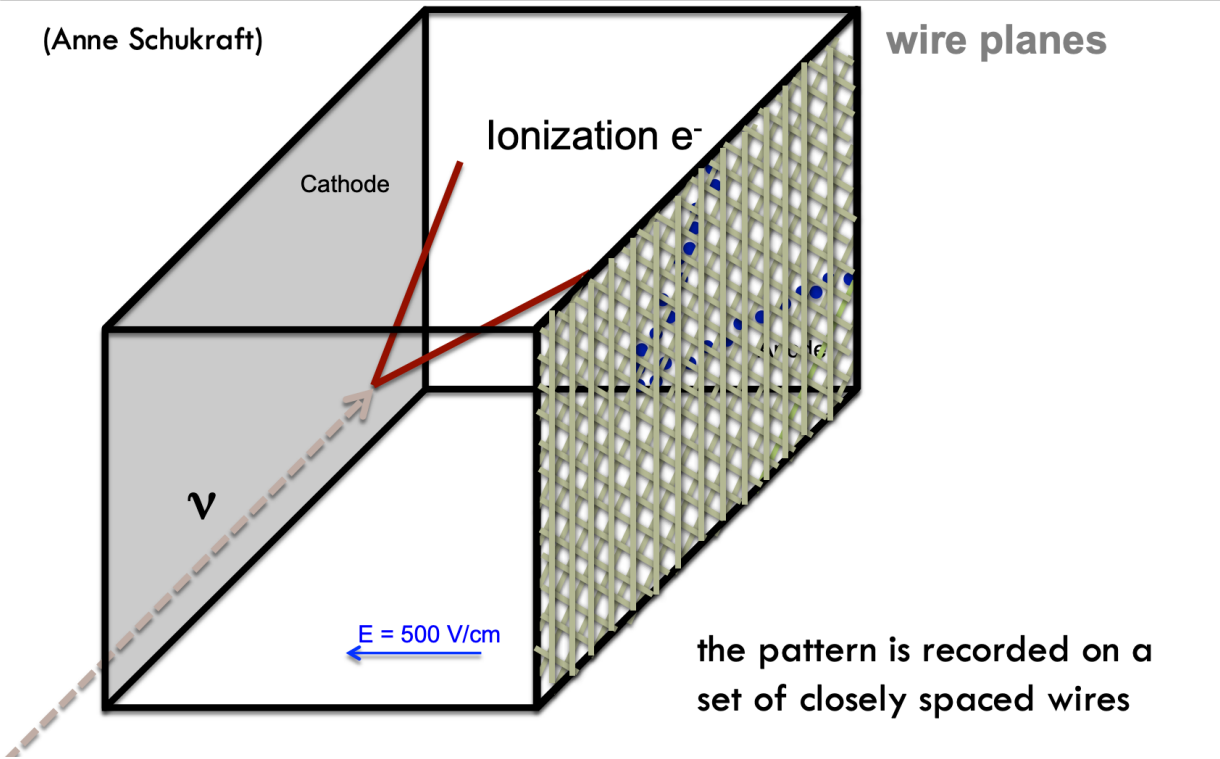
Liquid argon: MicroBooNE



Liquid argon: MicroBooNE

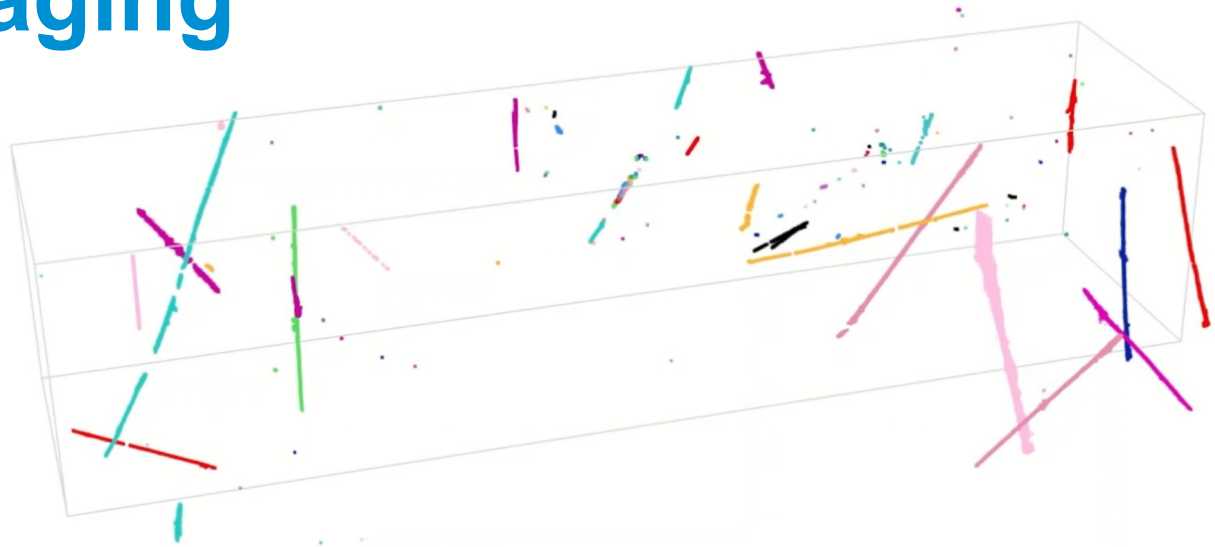


Liquid argon: MicroBooNE

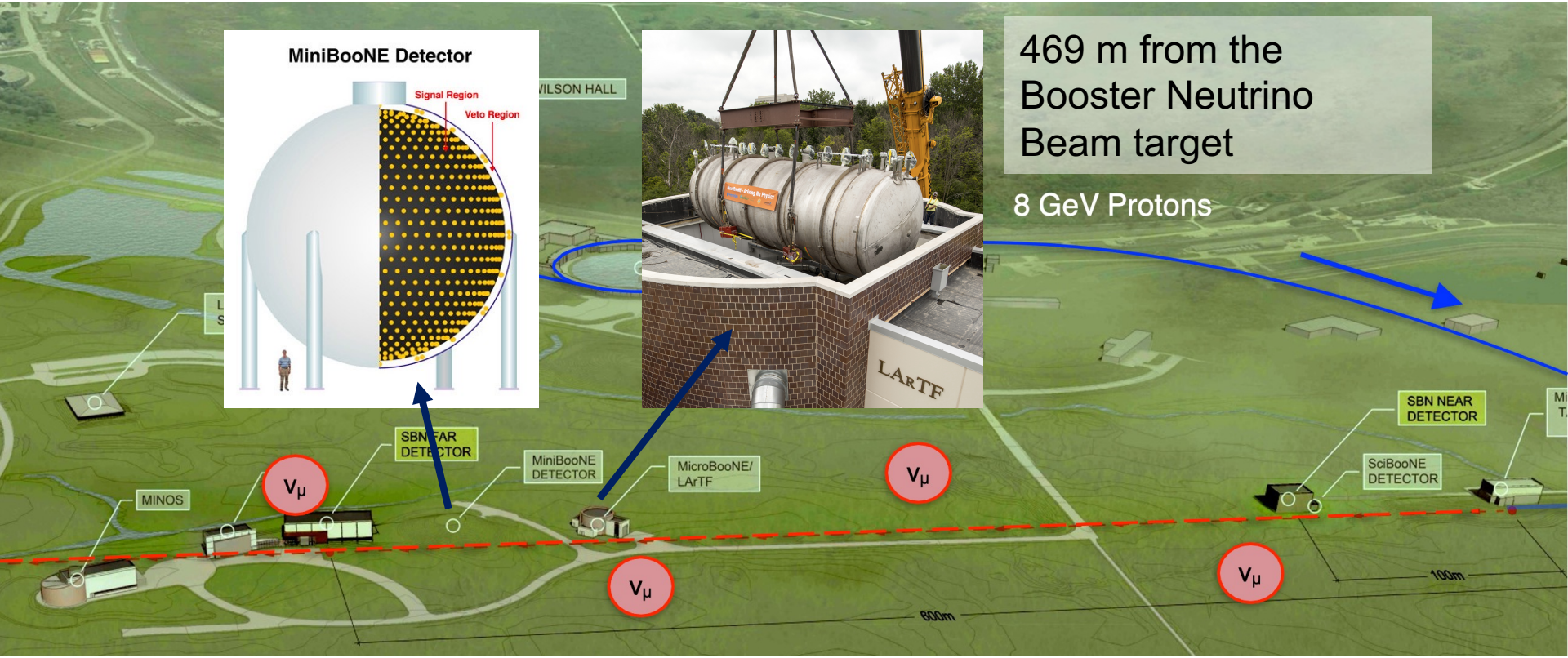


Liquid argon: MicroBooNE

3D imaging



Liquid argon: MicroBooNE



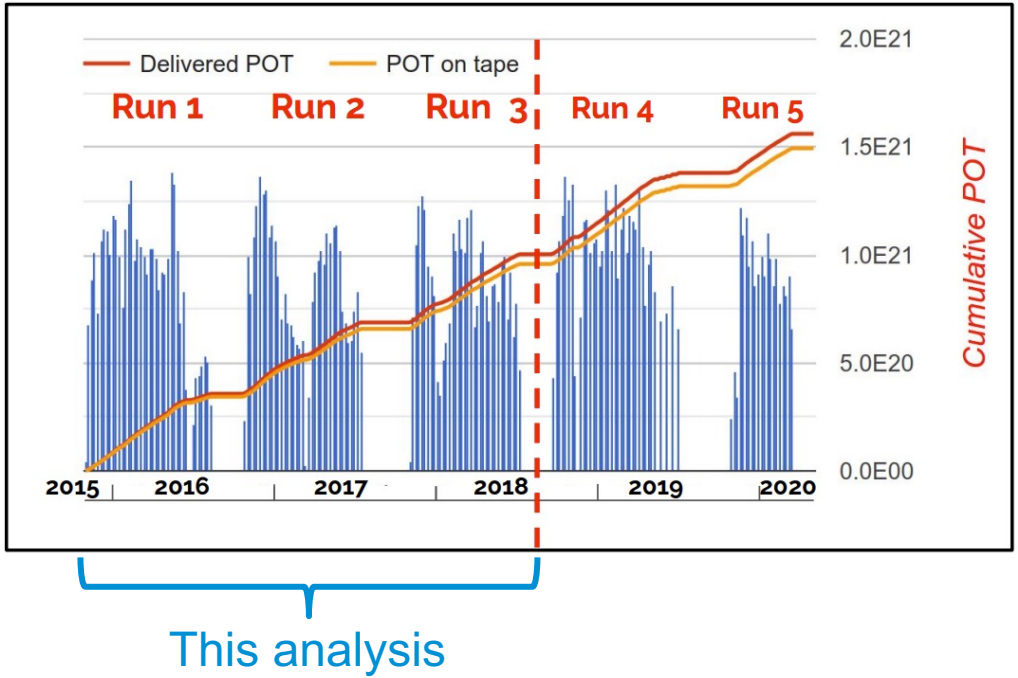
MicroBooNE

Took data from 2015 through to this year

- This analysis uses ~7×10^{20} protons on target
- ~1/2 of the full MicroBooNE data sample

MicroBooNE physics goals:

- Demonstrate the power of the LArTPC – paving the way for SBN and DUNE
- Neutrino interaction measurements
- BSM searches
- Address the MiniBooNE low-energy excess



First low-energy excess search

Four independent analyses

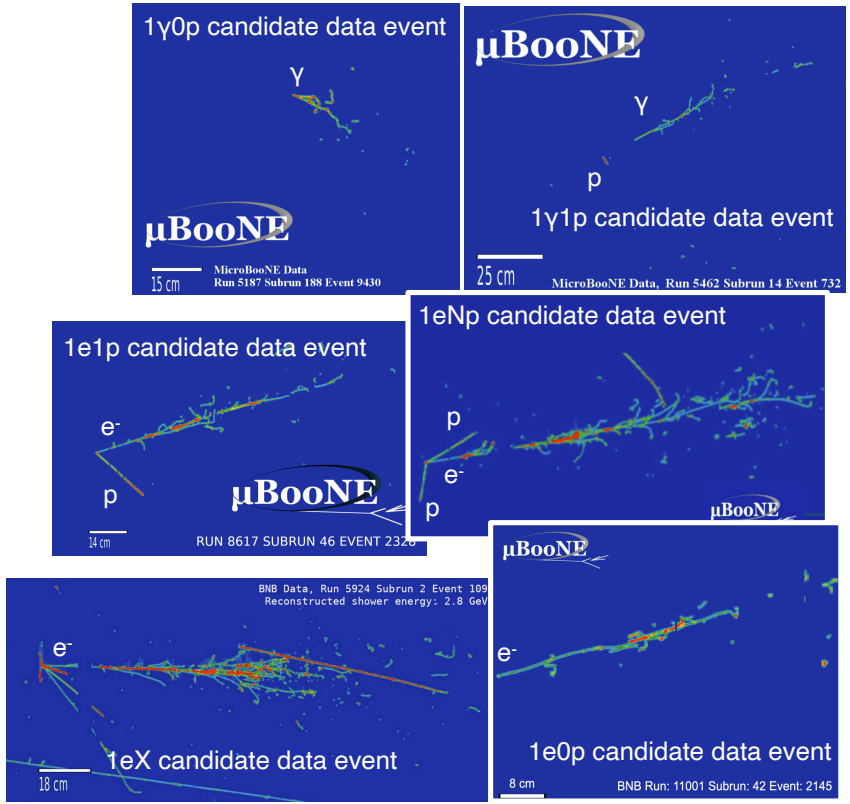
- Targeting six different final states

Single-photon analysis

- NC $\Delta \rightarrow N\gamma$ hypothesis
- $1\gamma 0p$, $1\gamma 1p$

Searches for a ν_e excess

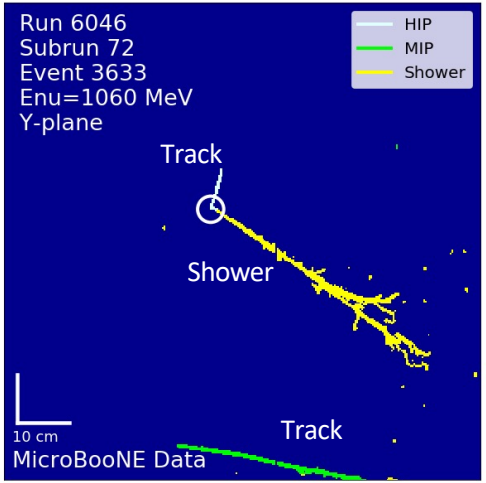
- Quasi-elastic kinematics (1e1p)
- MiniBooNE-like final states (1eNp, 1e0p)
- All ν_e final states (1eX)



Three independent reconstruction frameworks

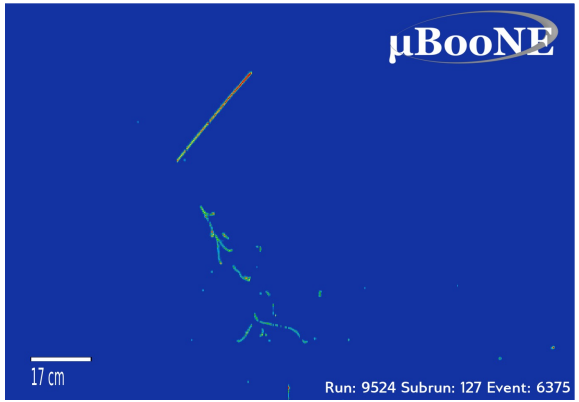
Deep-learning-based

- Semantic segmentation & CNNs
- 1e1p topology



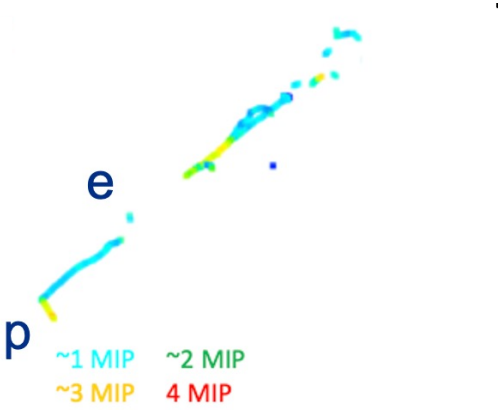
Pandora-based

- Single-photon search (1γ1p, 1γ0p)
- Pionless electron search (1eNp, 1e0p)



Wire-Cell-based

- Tomographic techniques & 3D imaging
- Fully inclusive electron search



Single photons: Δ→Nγ

Several photon sources in MiniBooNE

NC π^0 misidentification

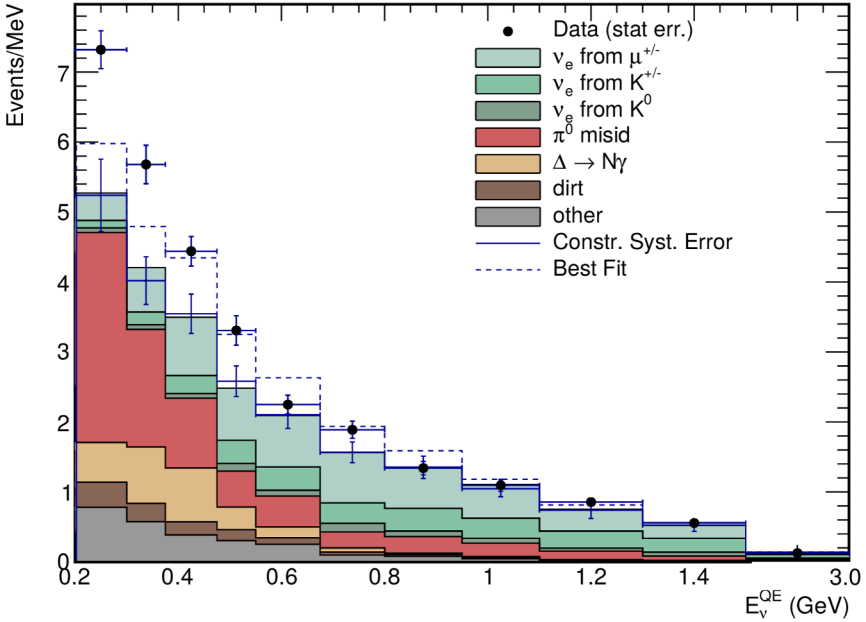
- Measured in MiniBooNE with sidebands

Interactions outside the detector

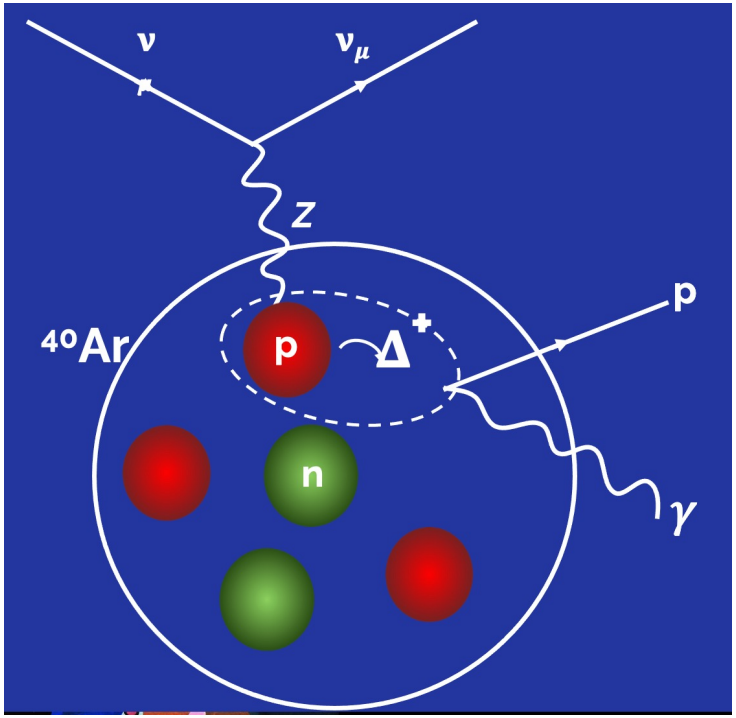
- Eliminated using beam timing and radial cuts

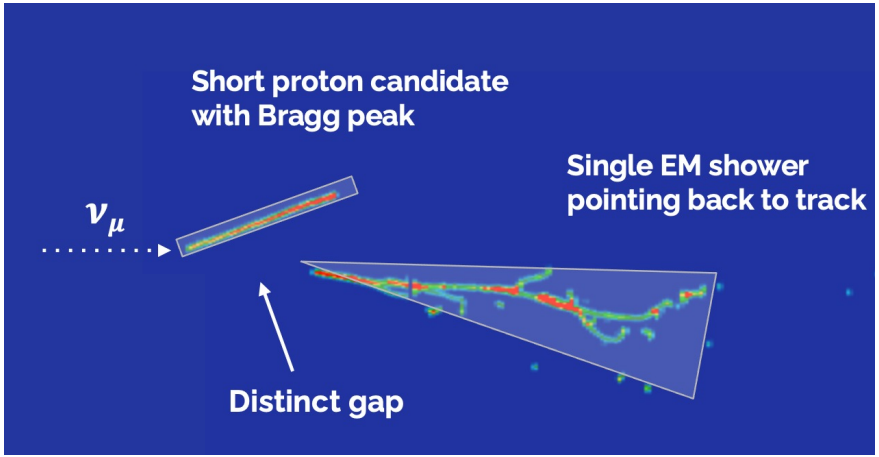
NC Δ → Nγ

- **NC delta radiative decay**
- Not constrained directly by MiniBooNE
- Used π^0 measurements and a theoretical branching ratio for the delta radiative decay

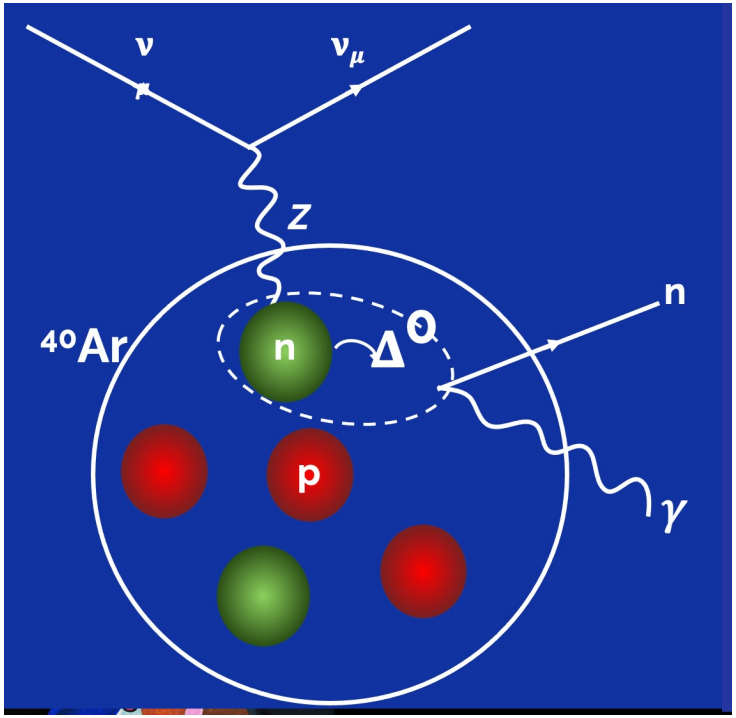


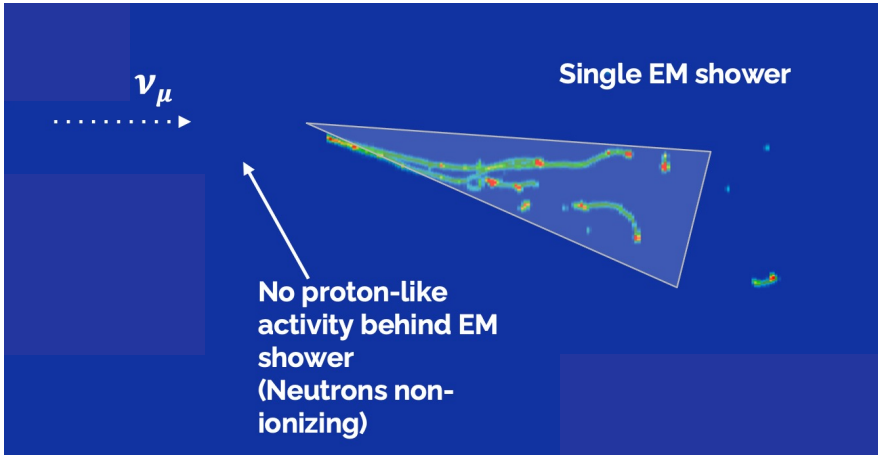
Δ→Nγ: 1γ1p topology





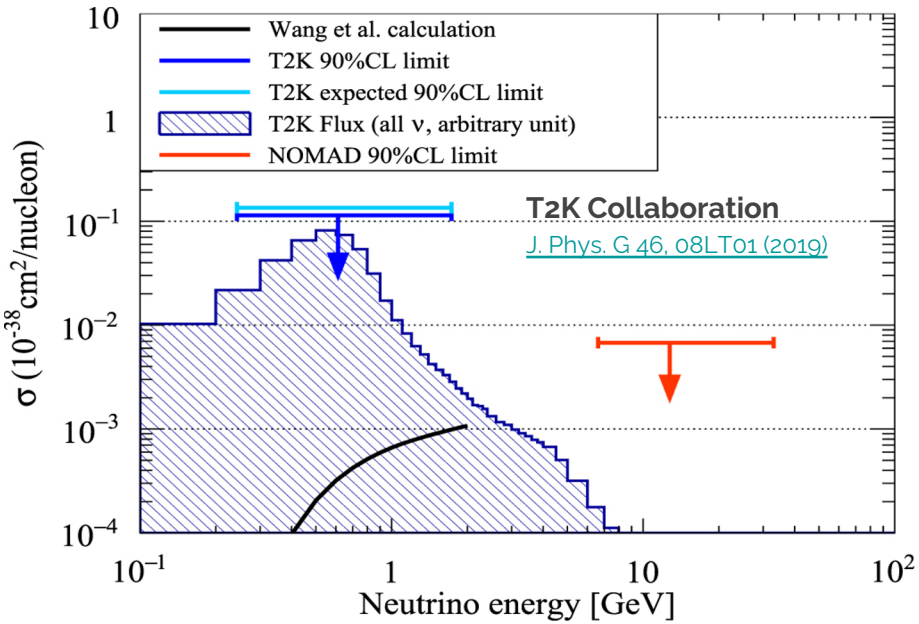
Δ→Nγ: 1γ0p topology





Current limits on NC Δ→Nγ

- Not measured directly, but inferred from pion-nucleon and photon-nucleon scattering measurements
- Best direct limit (T2K) is x100 weaker than the predicted rate (90% C.L.)



Single photons: Δ→Nγ

MiniBooNE need to scale their NC Δ → Nγ by x3.18 to best fit their excess

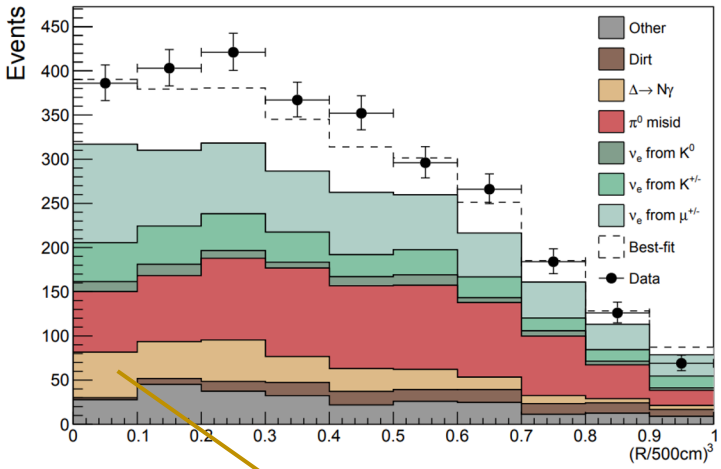
MicroBooNE therefore uses a x3.18 scaling of the nominal NC Δ → Nγ prediction as a benchmark model to test consistency with the MiniBooNE excess

Our nominal prediction comes from a custom tune of GENIE v3.0.6 (NIM **A614**, 87)

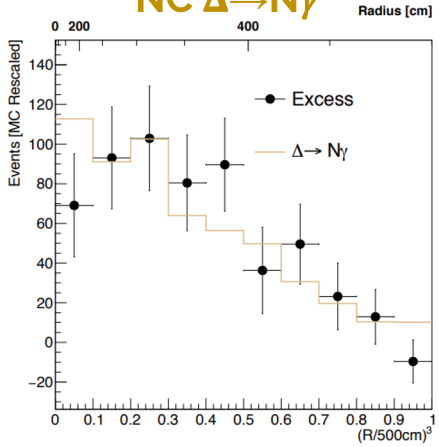
- Resonances modelled with Berger-Sehgal (PRD **76**, 113004)
- GENIE then assumes branching ratios to decay the Δ to various final states

In the three years of MicroBooNE data analysed here, 124.1 NC Δ→Nγ events are predicted

MiniBooNE Collaboration Phys. Rev. D 103, 052002 (2021)



NC Δ→Nγ



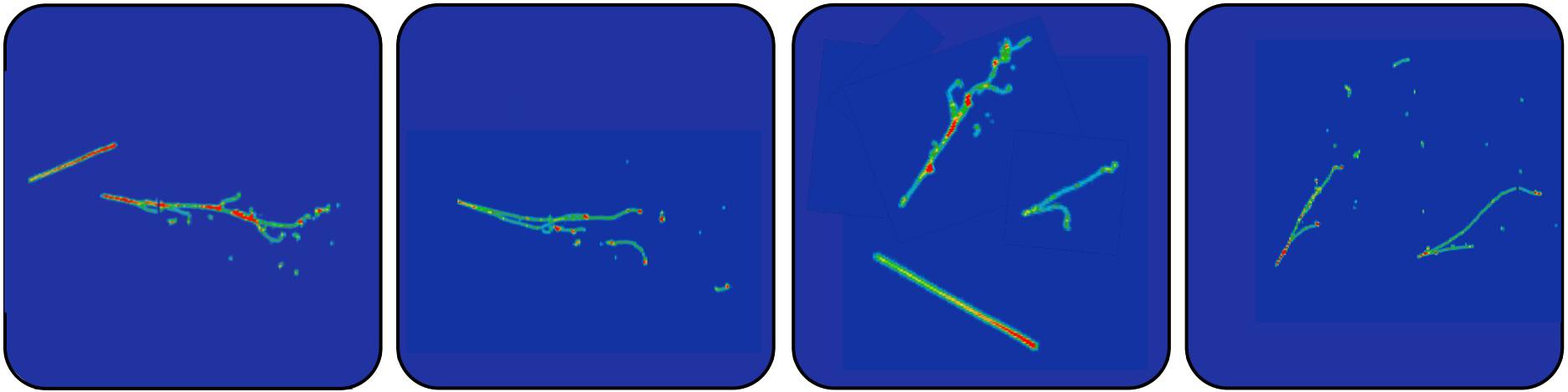
Single photon analysis

Simultaneous fit of four topologically distinct samples

Two **NC $\Delta \rightarrow N\gamma$** rich **single-photon** selections

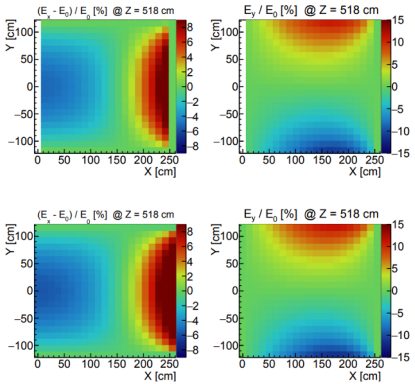
Two high-statistics **NC π^0 rich two-photon** selections to constrain backgrounds

$1\gamma 1p$ **$1\gamma 0p$** **$2\gamma 1p$** **$2\gamma 0p$**



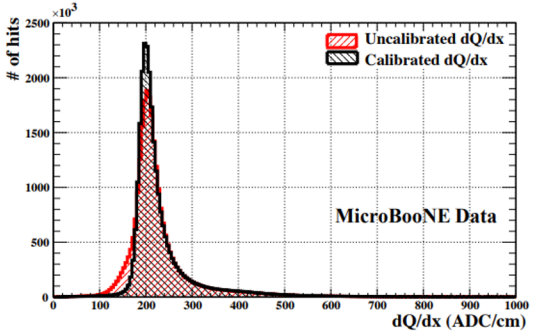
Understanding the detector

Electric field calibration with lasers and cosmic muons



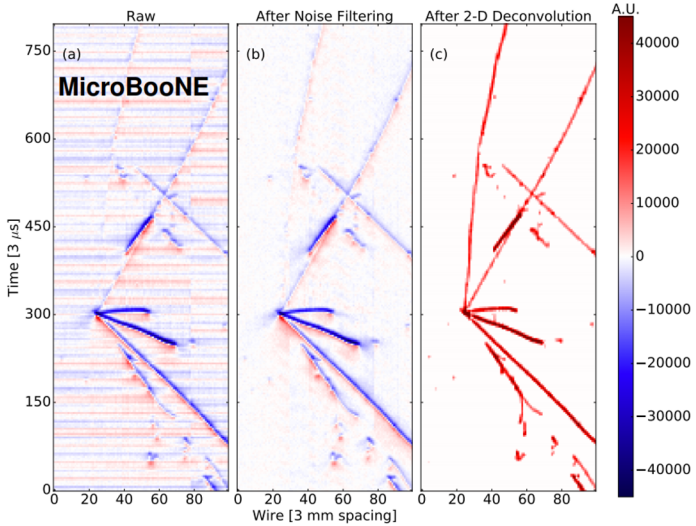
JINST 15 (2020) 07, P07010
JINST 15 (2020) P12037

Calorimetry calibration with crossing muons and π^0 samples



JINST 15 (2020) 03, P03022, *JINST* 15 (2020) 02, P02007

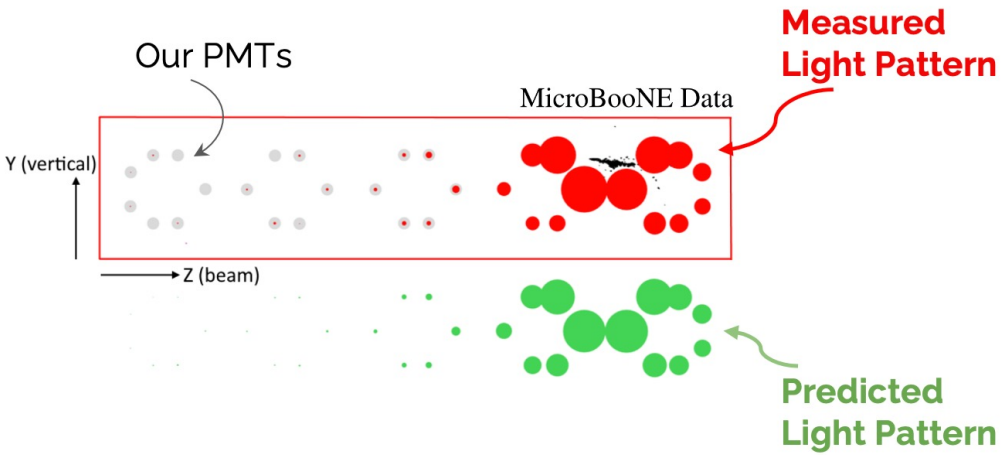
Signal Processing: From raw signals on wires to 2D reconstructed "hits"



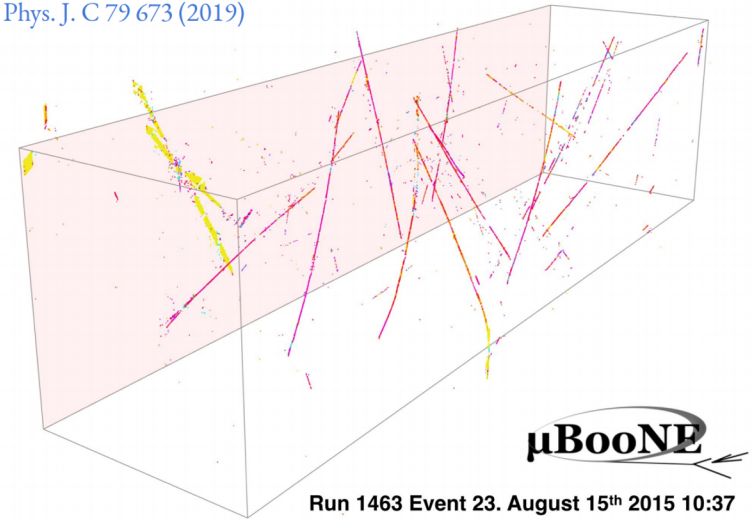
JINST 13, P07006 (2018) JINST 12 P08003 (2017)

On the surface: cosmic background

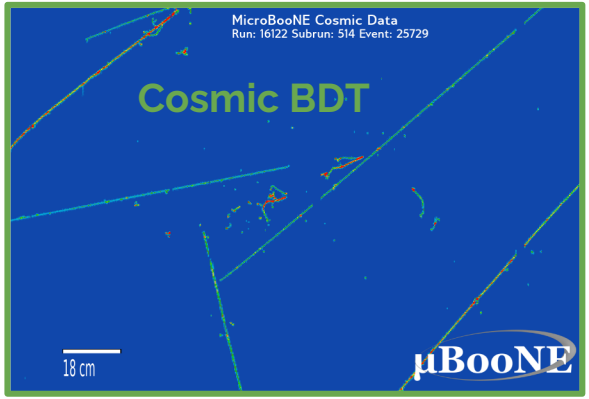
- 97% of triggered events have only cosmic activity
- Events with a neutrino typically contain 20 cosmic muons
- Matching with PMT flashes is used to identify the true beam neutrinos
- We use beam-off data to 'simulate' our cosmic overlays on simulated neutrino interactions



Eur. Phys. J. C 79 673 (2019)

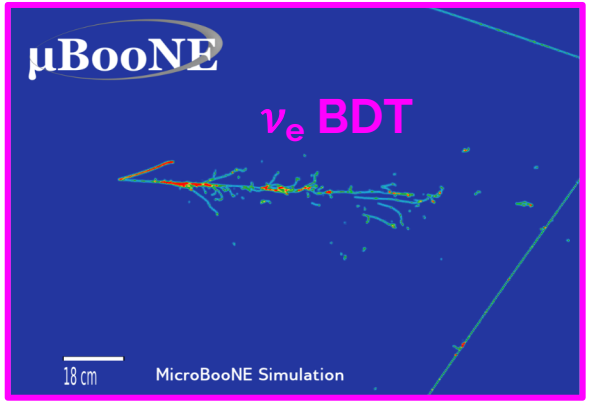


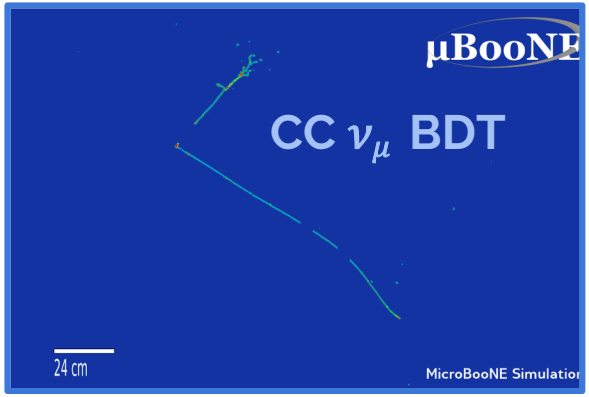
Δ→Nγ: background rejection

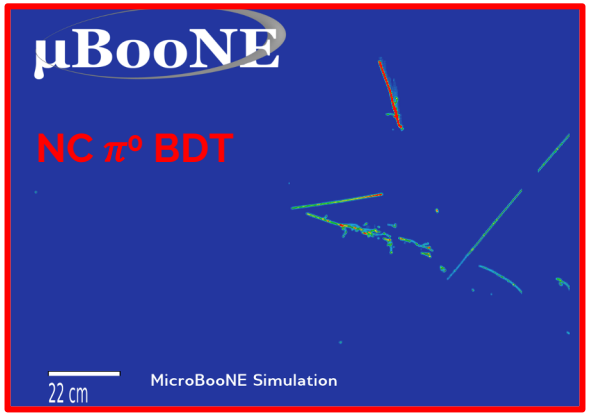


5 boosted decision trees to reject backgrounds from 1γ1p topology

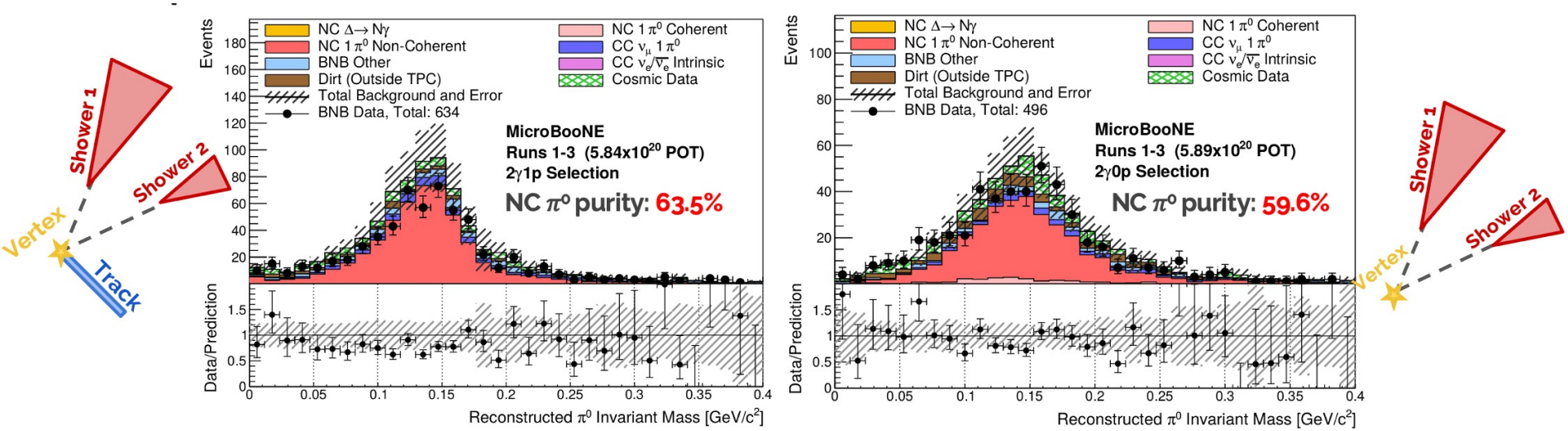
- (Similar methodology for 1γ0p topology)







1p2γ and 0p2γ samples



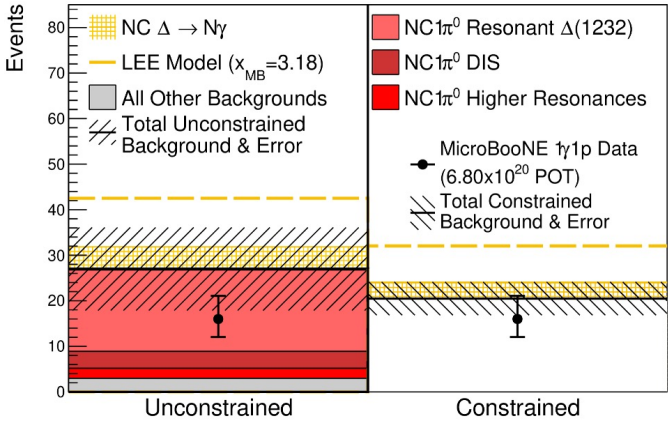
High statistics: 1130 candidate π^0 interactions

Used to constrain the π^0 backgrounds in the $\Delta \rightarrow N\gamma$ signal samples

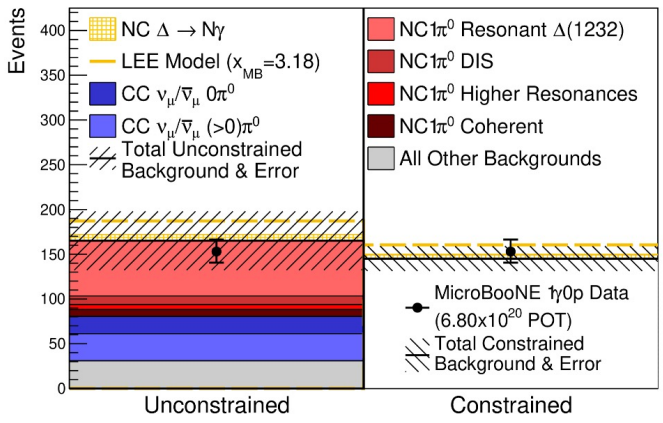
- And validate shower reconstruction and energy measurement

Single-photon results

1γ1p



1γ0p



1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	$+4.88$
LEE ($x_{\mathrm{MB}} = 3.18$)	$+15.5$

16 Data Events Observed

1γ0p

Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	$+6.55$
LEE ($x_{\mathrm{MB}} = 3.18$)	$+20.1$

153 Data Events Observed

Single-photon results

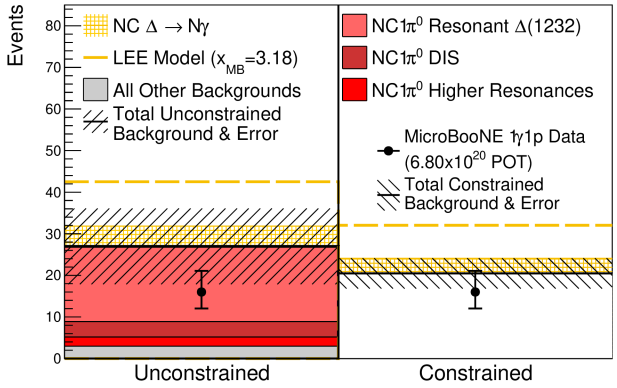
No evidence for an enhanced rate of single photons from NC Δ→Nγ decay above nominal GENIE expectations

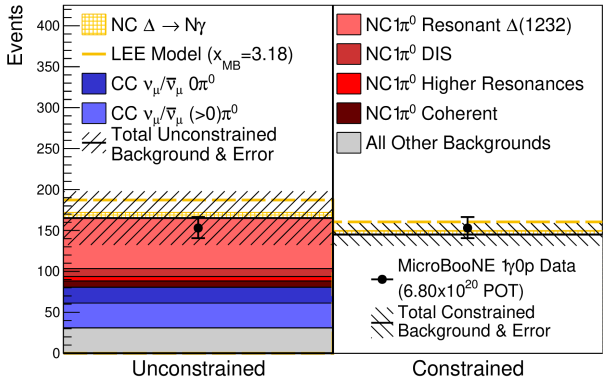
- x3.18 scaling disfavoured at 94.8% C.L.

One-sided bound on the normalisation of NC Δ→Nγ events of $x_\Delta < 2.3$ (90% C.L.)

$$\mathcal{B}_{\text{eff}}(\Delta \to N\gamma) < 1.38\% \quad \text{(90\% C.L.)}$$

More than 50 times better than the world's previous limit





Electron search

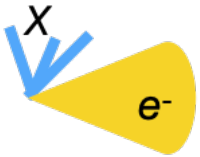
Three independent searches across multiple final states

Two-body CC quasi-elastic: 1e1p

CC νe interactions without final-state pions: 1eNp0π & 1e0p0π

- Matches the topology of MiniBooNE events

Fully inclusive charged-current ν_e: 1eX



Start with muon neutrinos

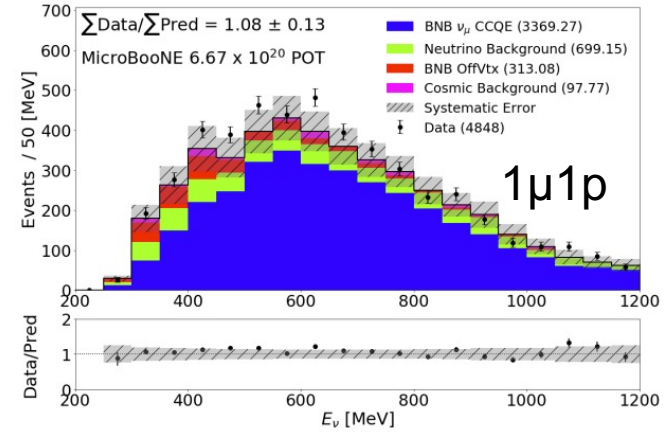
High-statistics CC ν_μ samples

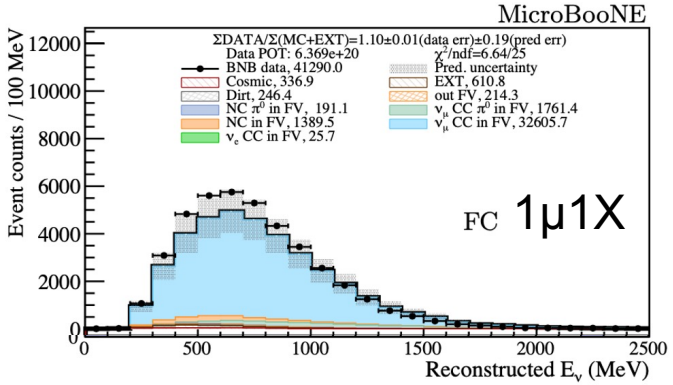
Leverage ν_μ and ν_e correlations

- Common flux parentage
- Lepton universality

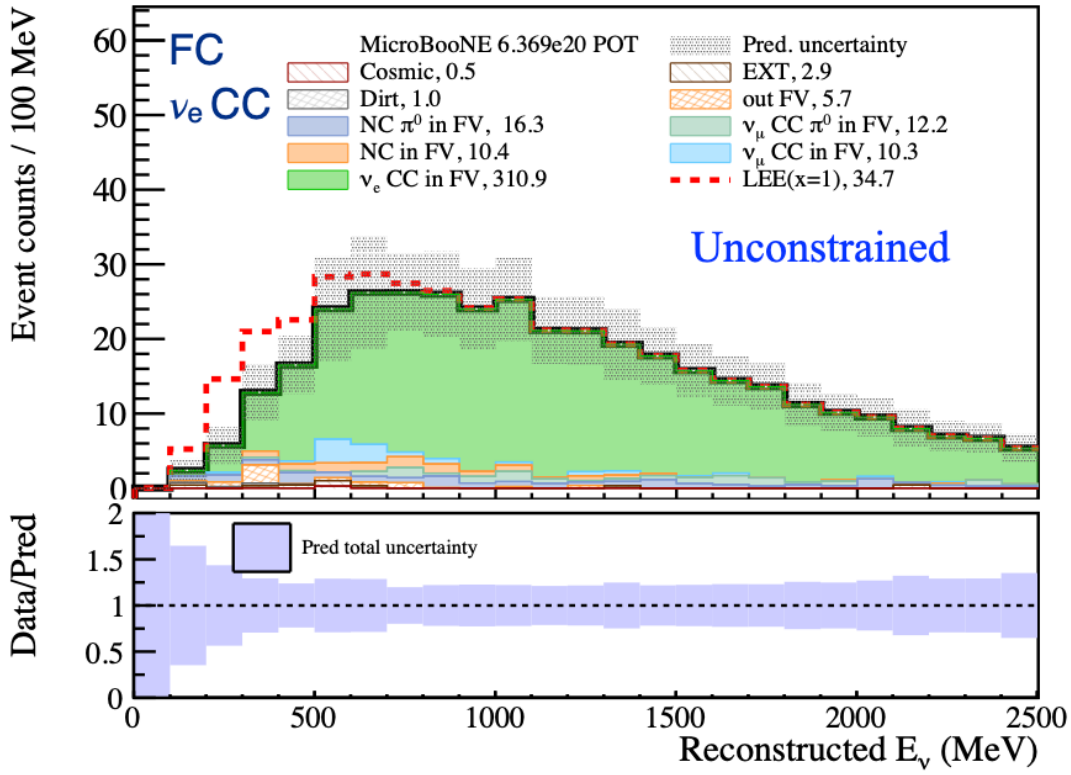
Use our ν_μ sample to create a data-driven ν_e prediction

- Systematic uncertainties incorporated through a covariance matrix
- This process reduces the uncertainty on the ν_e prediction

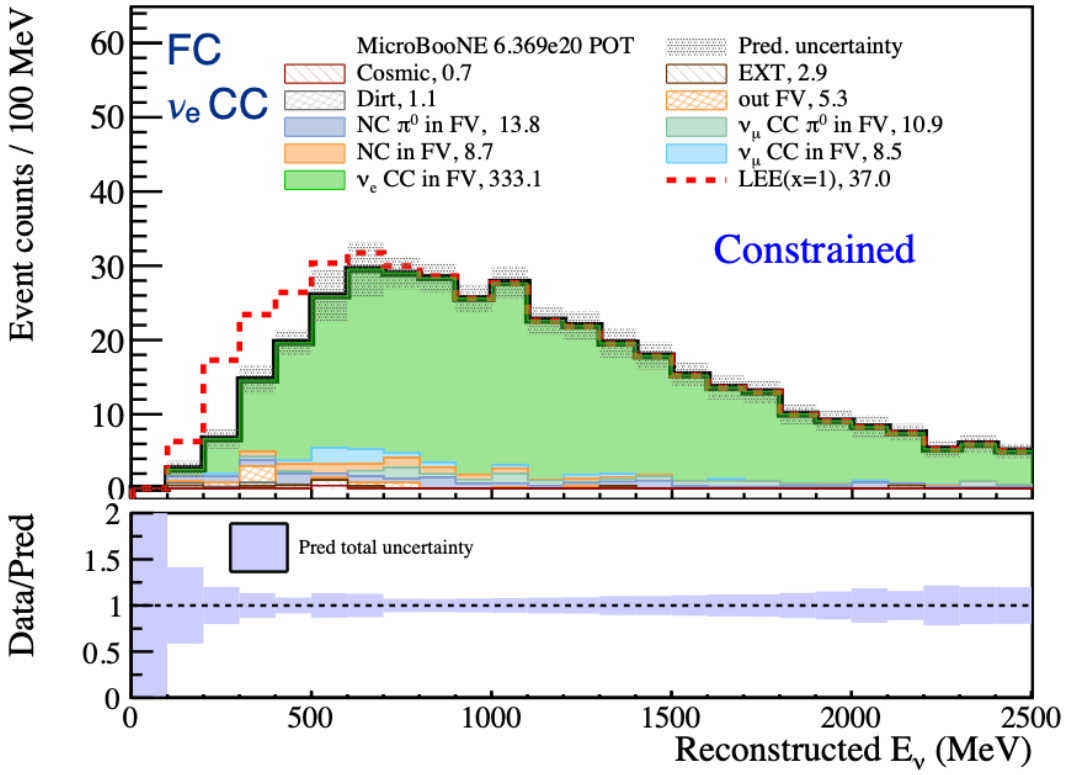




1eX prediction before constraint

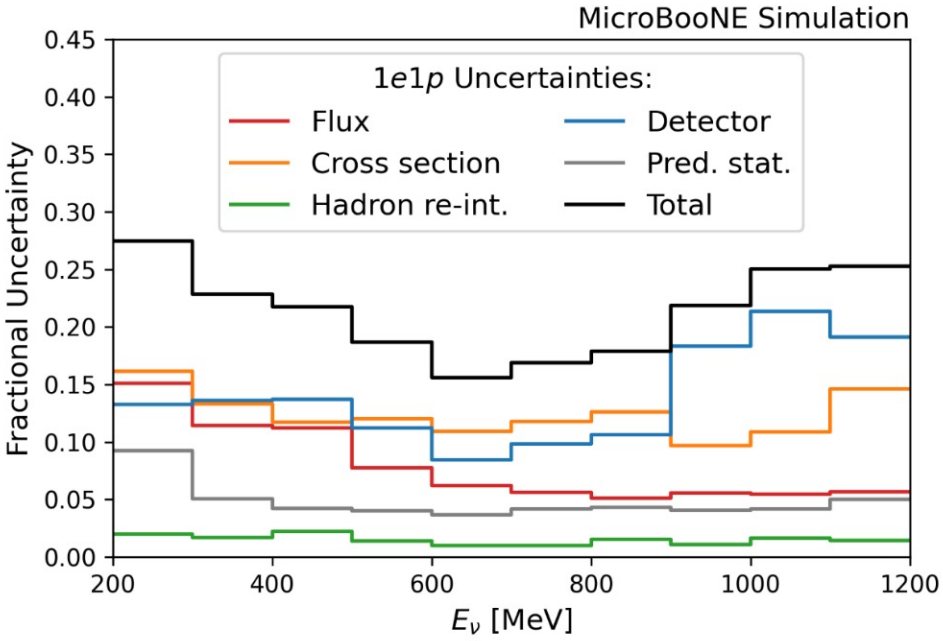


1eX prediction after constraint



Systematic uncertainties

1e1p sample, systematics before constraint



Neutrino interaction modeling

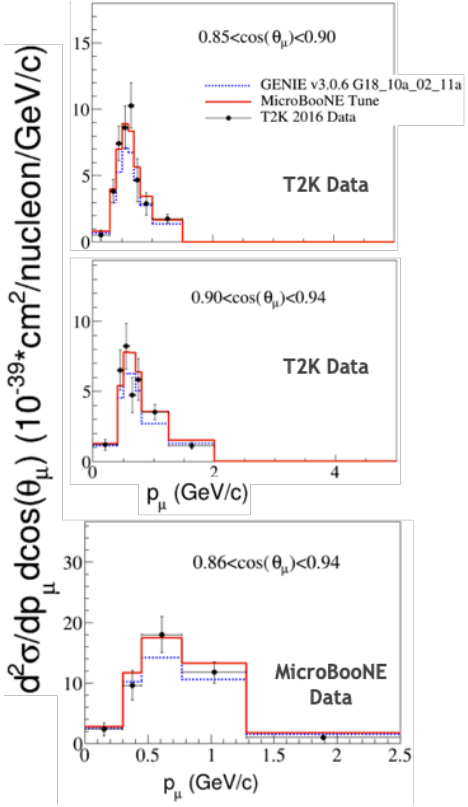
MicroBooNE drove the development of GENIE v3

Developed our own 'MicroBooNE GENIE tune'

- Fit to 2016 T2K ν_μ CC0π data taken at similar energies
- Tune CCQE and CC2p2h models
- **Varying >50 parameters to assess interaction uncertainties**

We are the first to examine neutrino scattering in argon at these energies and with such high statistics

arXiv:2110.14028

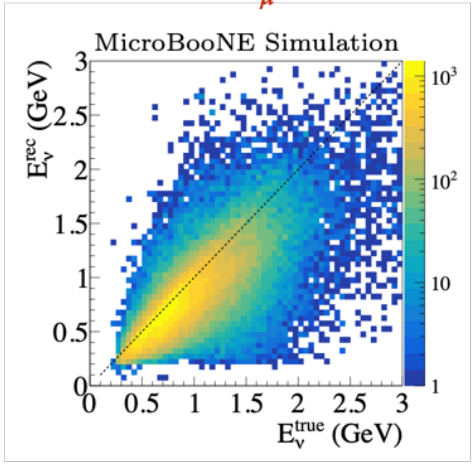


Event reconstruction performance

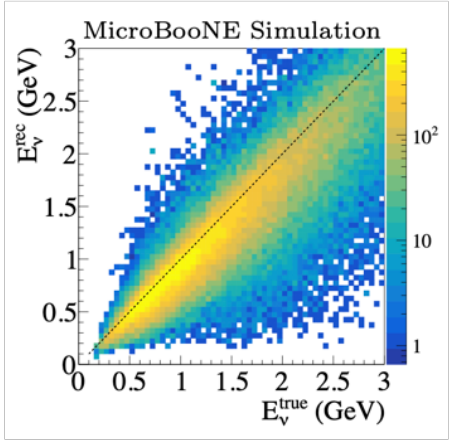
Neutrino energy reconstruction based on calorimetry with particle ID information

- 15-20% resolution for fully-contained ν_μ CC
- 10-15% resolution for fully-contained ν_e CC

FC* ν_μ CC



FC* ν_e CC



*FC "fully contained": events with reconstructed activity entirely within fiducial volume

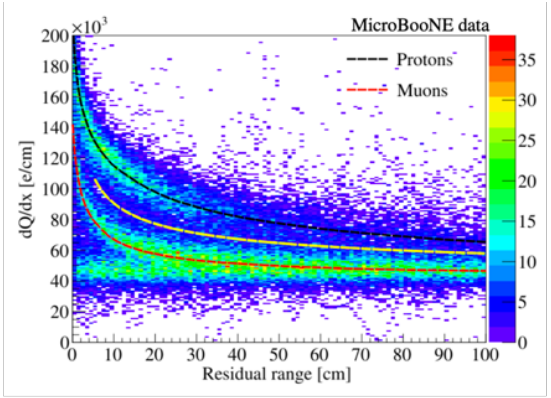
Event reconstruction performance

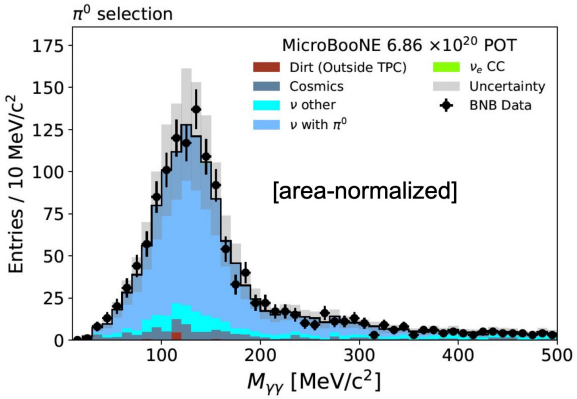
Neutrino energy reconstruction based on calorimetry with particle ID information

- 15–20% resolution for fully-contained ν_μ CC
- 10–15% resolution for fully-contained ν_e CC

Track energy calibrated with muons and protons

Shower energy calibrated with π^0 invariant mass





Detector uncertainties

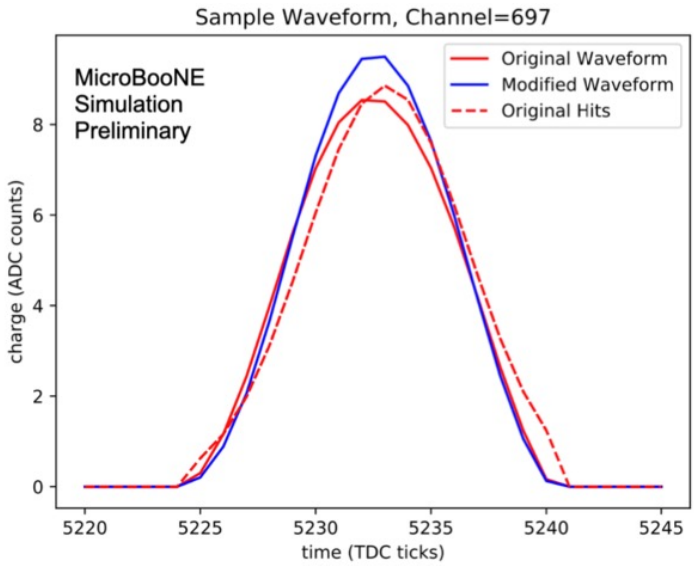
We have made the first complete assessment of systematic uncertainties in a LArTPC

Many sources of uncertainty evaluated

- Space charge, recombination, optical model, GEANT4 uncertainties

Novel data-driven technique using wire responses

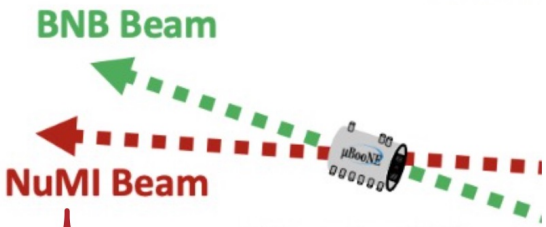
- **arXiv:2111.03556**

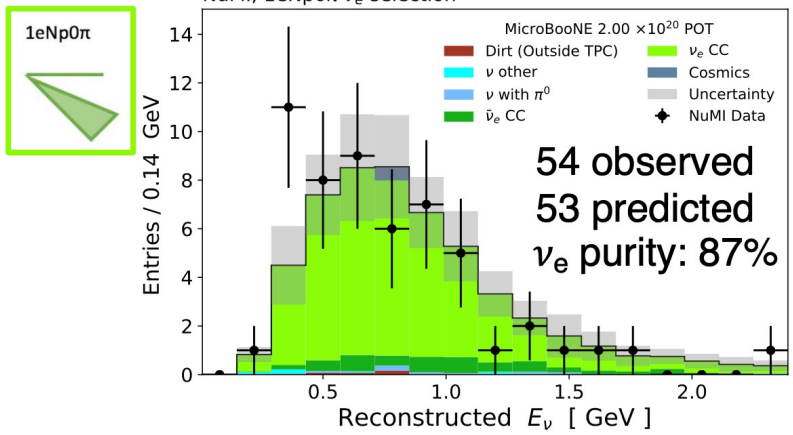


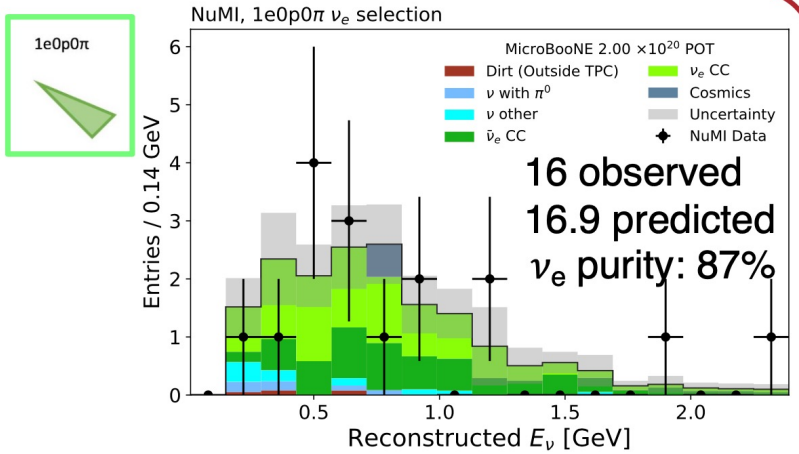
ν_e reconstruction validation with NuMI

NuMI beam data

- High intrinsic νe component relative to BNB
- Selections not tuned on NuMI data: applied after freezing BNB analysis, but before looking at BNB data







Simple MiniBooNE excess model

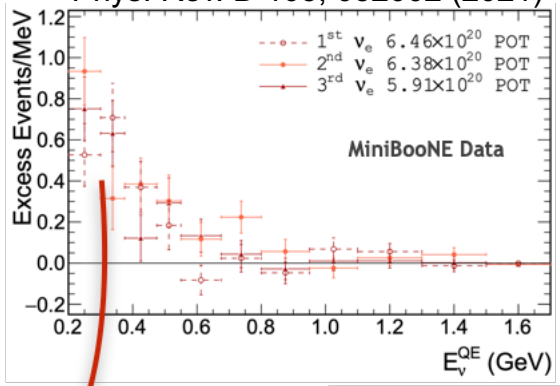
Unfold the 2018 MiniBooNE excess under a ν_e hypothesis

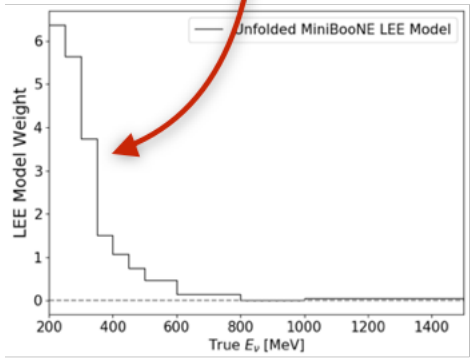
- Considering only E_ν-dependence

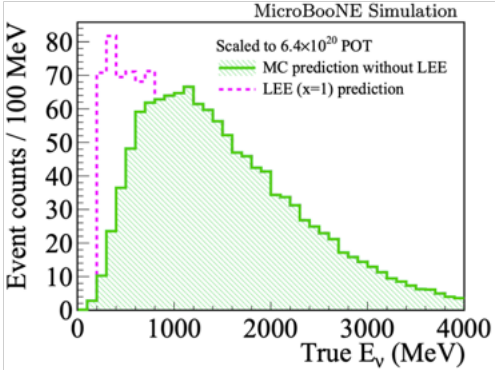
Apply to MicroBooNE as a scaling to the intrinsic ν_e component

Allow only the normalisation of the excess to vary when we make statistical statements

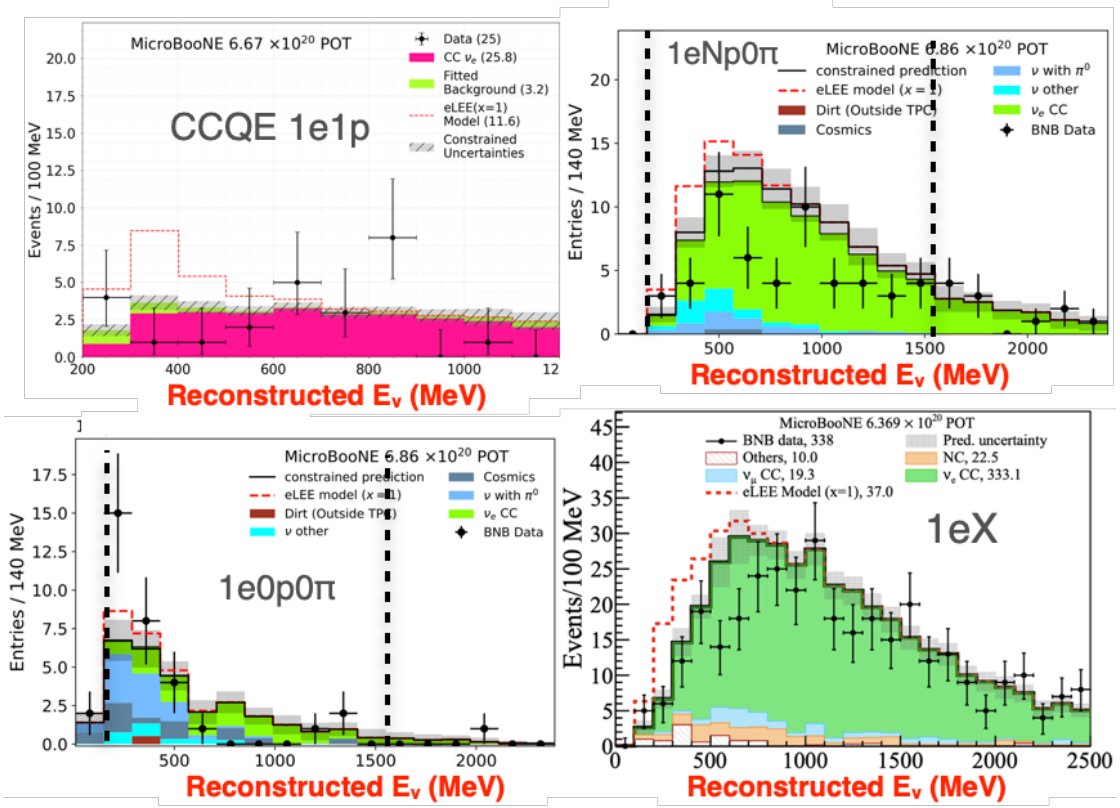
Phys. Rev. D 103, 052002 (2021)



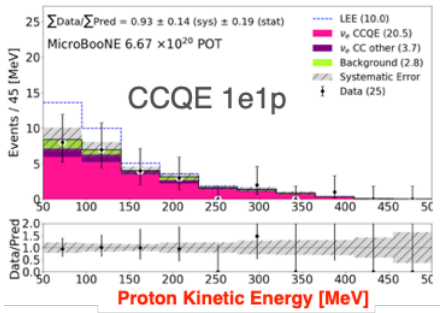


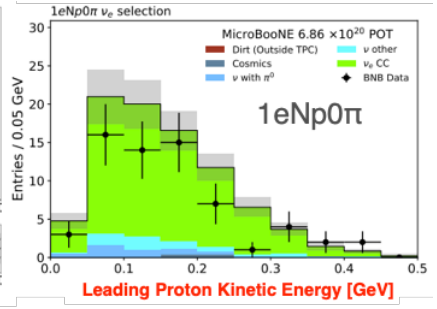


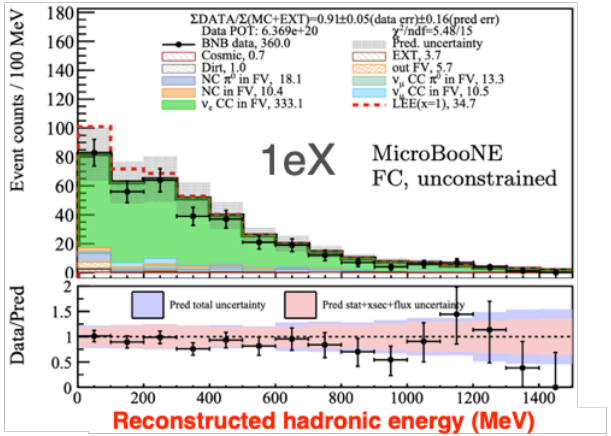
Electron results



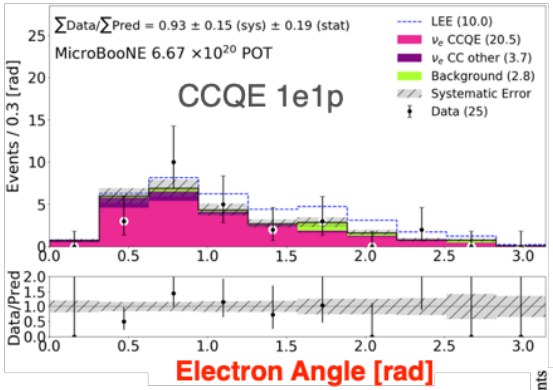
Electron results – hadronic energy

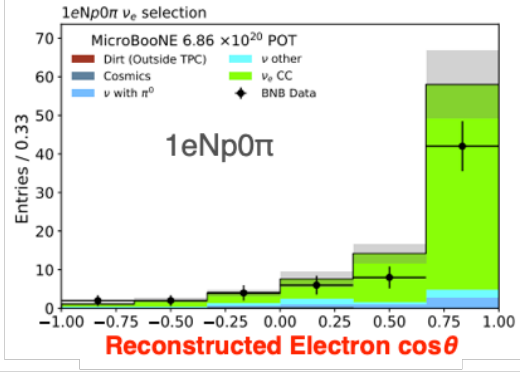


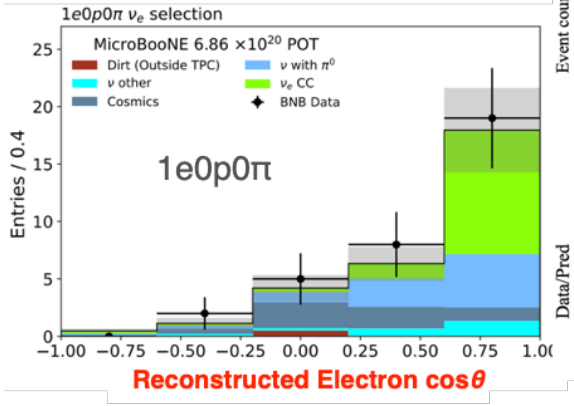


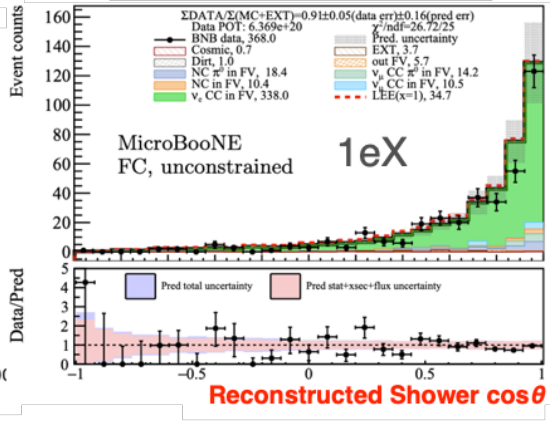


Electron results: lepton angle



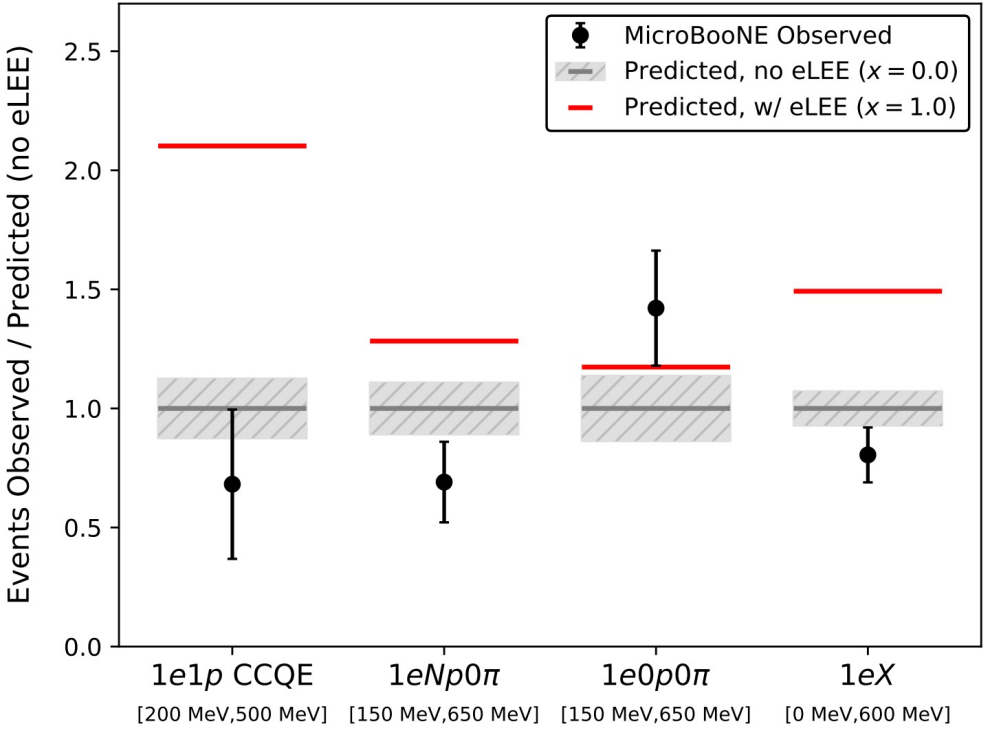






Electron results

- Observe ν_e candidate event rates in agreement with, or below, the predicted rates
- Reject the hypothesis that ν_e CC interactions are fully responsible for the MiniBooNE excess at >97% C.L. in all analyses
- Inclusive analysis rejects our median MiniBooNE electron-excess model at 3.75σ



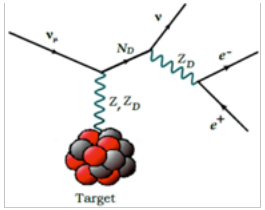
What next? Evolving theory landscape…

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces true electrons

Produces true photons

Produces e^+e^- pairs



PRL 121, 241801 (2018)

- Many of these models predict more complex final states (e^+e^-) and/or differing levels of hadronic activity

→ *The hadronic state is becoming increasingly more important as a model discriminator*

- We are fortunate that LArTPCs are sensitive to these possibilities

What next? Evolving theory landscape…

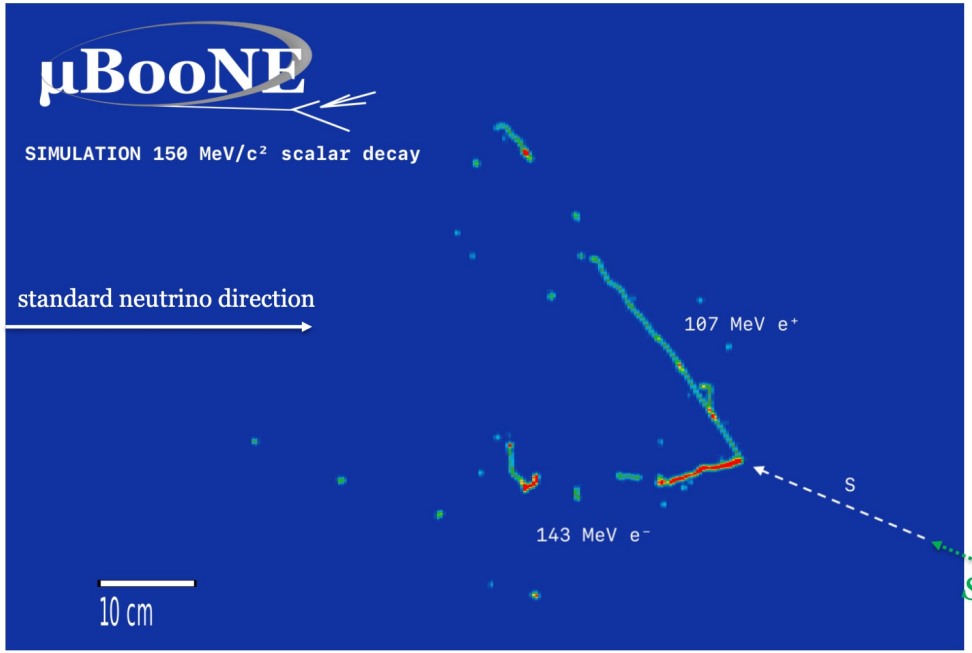
Already started probing with first LEE results

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [2,3]	✔ [2,3]	✔ [1,2,3]	✔ [1,2,3]	✔ [1,2,3]
More complex higgs *					✔ [10]	✔ [10]	✔ [6,10]	✔ [6,10]	✔ [6,10]
Axion-like particle *					✔ [8]		✔ [8]		
Res matter effects	✔ [5]	✔ [5]	✔ [5]	✔ [5]					
SM γ production							✔	✔	✔

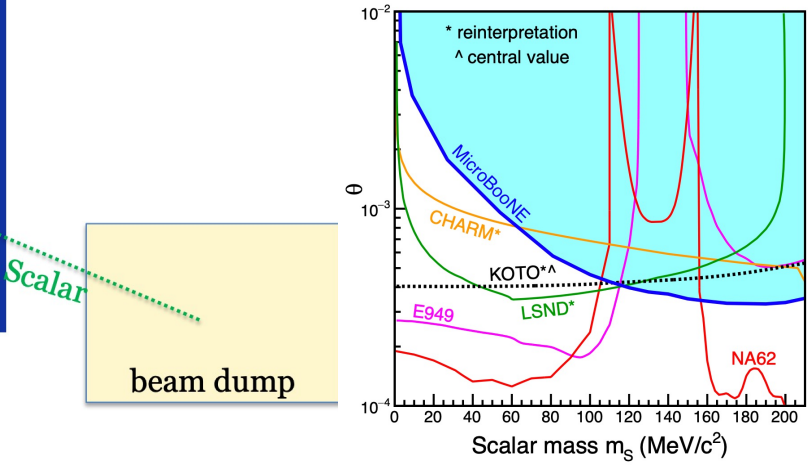
*Requires heavy sterile/other new particles also

µBooNE

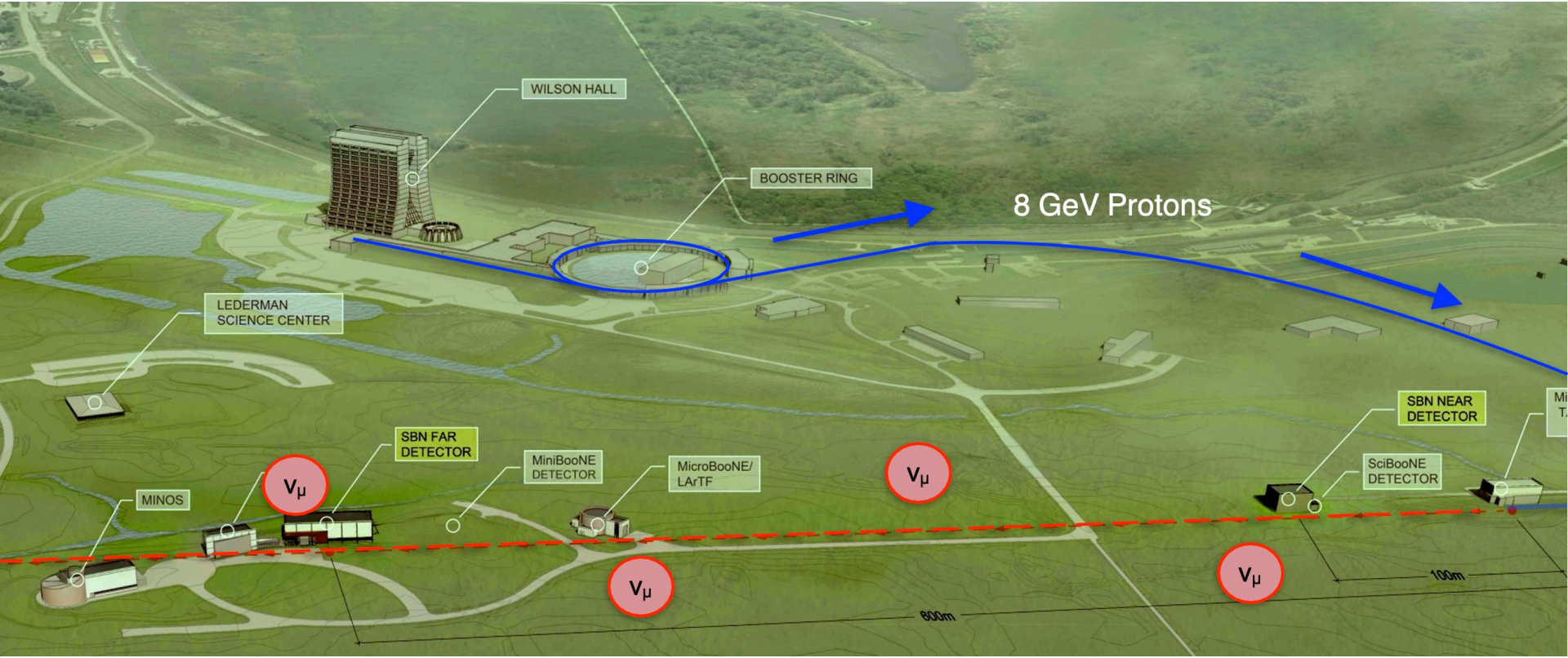
Higgs-portal scalar boson search



- Published in Phys. Rev. Lett.
- **Liquid argon is becoming a BSM search factory**



Onwards to the SBN programme…



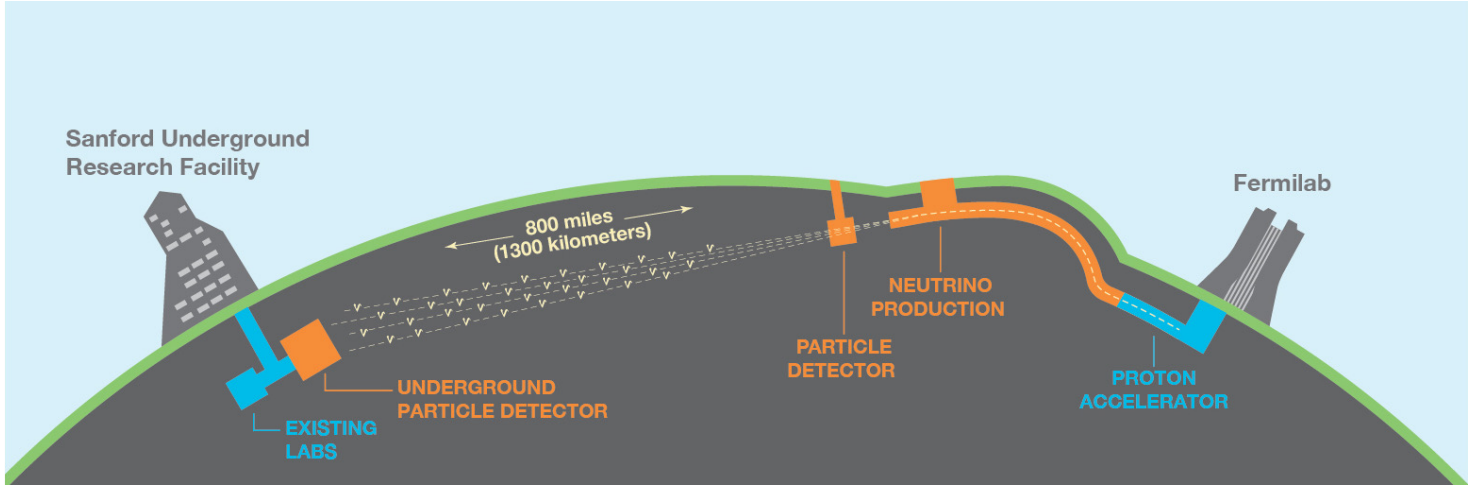
…and to DUNE

MicroBooNE has shown that liquid argon is the technology of choice for precision neutrino analyses

- We have performed end-to-end excess searches, cross-section measurements, BSM searches…

This confirms that there is an exciting future with DUNE

- CP violation, mass hierarchy, proton decay, supernovae…



Summary

Our first searches for low-energy excesses are now released

- No evidence for excesses of ν_e or NC $\Delta \rightarrow N\gamma$
- But we don't know what the MiniBooNE excess was!

We have shown that liquid argon can perform precision neutrino physics analyses

- Multiple channels and topologies
- Multiple reconstruction methods
- Reconstruction down to ~100 MeV
- Sidebands, systematics, detector response models, reconstruction algorithms…

MicroBooNE has a bright future as a BSM factory

- More data to analyse, and many more channels to investigate