Progress on Neutrino-Proton Neutral-Current Scattering in MicroBooNE

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Neutrino-proton neutral-current elastic scattering

$\nu p \rightarrow \nu p$

- Cross section determined by structure of the proton, as expressed in the electric, magnetic and axial form factors

$$G_E^p(Q^2) \quad G_M^p(Q^2) \quad G_A^p(Q^2)$$

- Electric and magnetic form factors well-determined for $Q^2 < 1$ GeV^2 by electron-nucleon elastic scattering data

- Contribution to the axial form factor from up and down quarks well-determined for $Q^2 < 1$ GeV^2 by neutrino-deuteron charged-current reaction data, and at $Q^2 = 0$ from neutron decay.

- **The dominant unknown is the strange quark contribution to the axial form factor:** $G_A^s(Q^2)$
- **A measurement at low Q^2 can determine the strange quark contribution to the proton spin:** $G_A^s(Q^2 = 0) = \Delta S$

Strange Quark Contribution to Nucleon Spin ΔS

Broad Physics Interest

- **Vital for searches for heavy dark matter particles [Ellis, Olive, & Savage, Phys Rev D 77 (2008) 065026] (see also Wick Haxton, KD.00001: Nuclear Physics of Dark Matter Detection)**

- **Lattice QCD calculates a small value:**

$\Delta S = -0.031(17)$ [M. Engelhardt, Phys. Rev. D 86 (2012) 114510];
$\Delta S = -0.024(15)$ [Babich et al., Phys. Rev. D 85 (2012) 054510];
requires experimental verification

- **Simulations of supernovae are sensitive to the value of ΔS [Melson, Janka, Bollig, Hanke, Marek, Mueller, Astro. J. Lett. 808 (2015) L42]**

- **Atomic PV experiments on hydrogen are sensitive to ΔS [Gasenzer, Nachtmann, Trappe, EPJ D (2012) 66:113]**

A Brief History of ΔS

First experimental data came from measurements of the ***inclusive*** deep-inelastic scattering of polarized muons from polarized hydrogen (EMC). ➔ $\Delta S < 0$
This has been confirmed in all subsequent ***inclusive*** measurements (SMC, SLAC, HERMES, COMPASS, JLab).
N.B. This analysis always assumes SU(3) flavor symmetry, combining the extrapolated integral of the DIS measurements with the triplet and octet axial charges determined from hyperon β-decay.

Later, it became possible to observe ***semi-inclusive*** deep-inelastic scattering, where the leading hadron (pion or kaon) served to "tag" the struck quark. ➔ $\Delta S \sim 0$
(SMC, HERMES, COMPASS).
N.B. This analysis does not use SU(3) flavor symmetry, but does rely on an understanding of quark→hadron fragmentation functions.

This dichotomy exists today: The most up-to-date analyses of leptonic DIS and polarized *pp* collision data still show a discrepancy in the determination of ΔS.

de Florian, Sassot, Stratmann, and Vogelsang [PRD 80 (2009) 034030]
Nocera, Ball, Forte, Ridolfi, and Rojo [NPB 887 (2014) 276-308]
Leader, Sidorov, and Stamenov [PRD 91 (2015) 054017]
Hirai and Kumano (AAC) [Nucl. Phys. B 813 (2009) 106]
Blumlein and Böttcher [Nucl. Phys. B 841 (2010) 205]

The Strange Quark Contribution to the Nucleon Axial Form Factor:

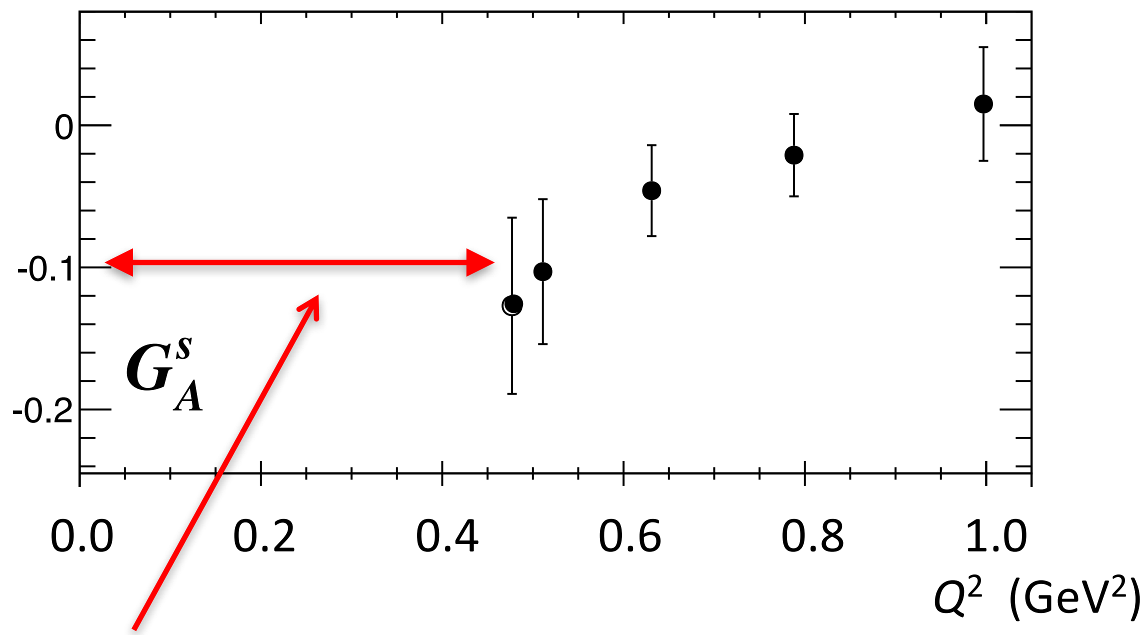
An cleaner way to determine ΔS

$$G_A^s\left(Q^2\right)$$

$$\int_0^1 \left(\Delta s(x) + \Delta\bar{s}(x)\right) dx = \Delta S = G_A^s\left(Q^2 = 0\right)$$

$G_A^s(Q^2)$ determined from a combination of **elastic** electron-nucleon and neutrino-proton scattering data.

Pate, Papavassiliou and McKee PRC 78 (2008) 015207



Big gap at low Q^2 due to complete lack of elastic neutrino-proton scattering data below 0.45 GeV^2.

Low-Q^2 neutrino-proton elastic scattering data will determine ΔS.

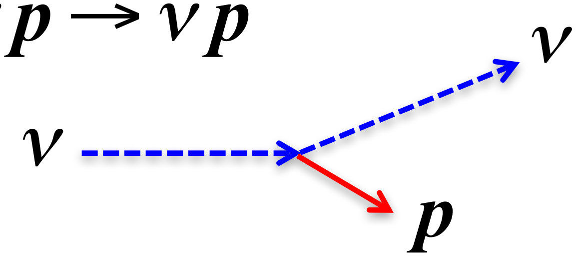
Measuring Low-Q^2 Neutrino-Proton Elastic Scattering

Not that simple, or someone would have done it already…

The observable part of the final state consists of a single isolated proton – that's all!

$$\nu p \rightarrow \nu p$$

$$T = Q^2 / 2M_p$$



For $Q^2 = 0.1$ GeV^2, this means $T \sim 50$ MeV.

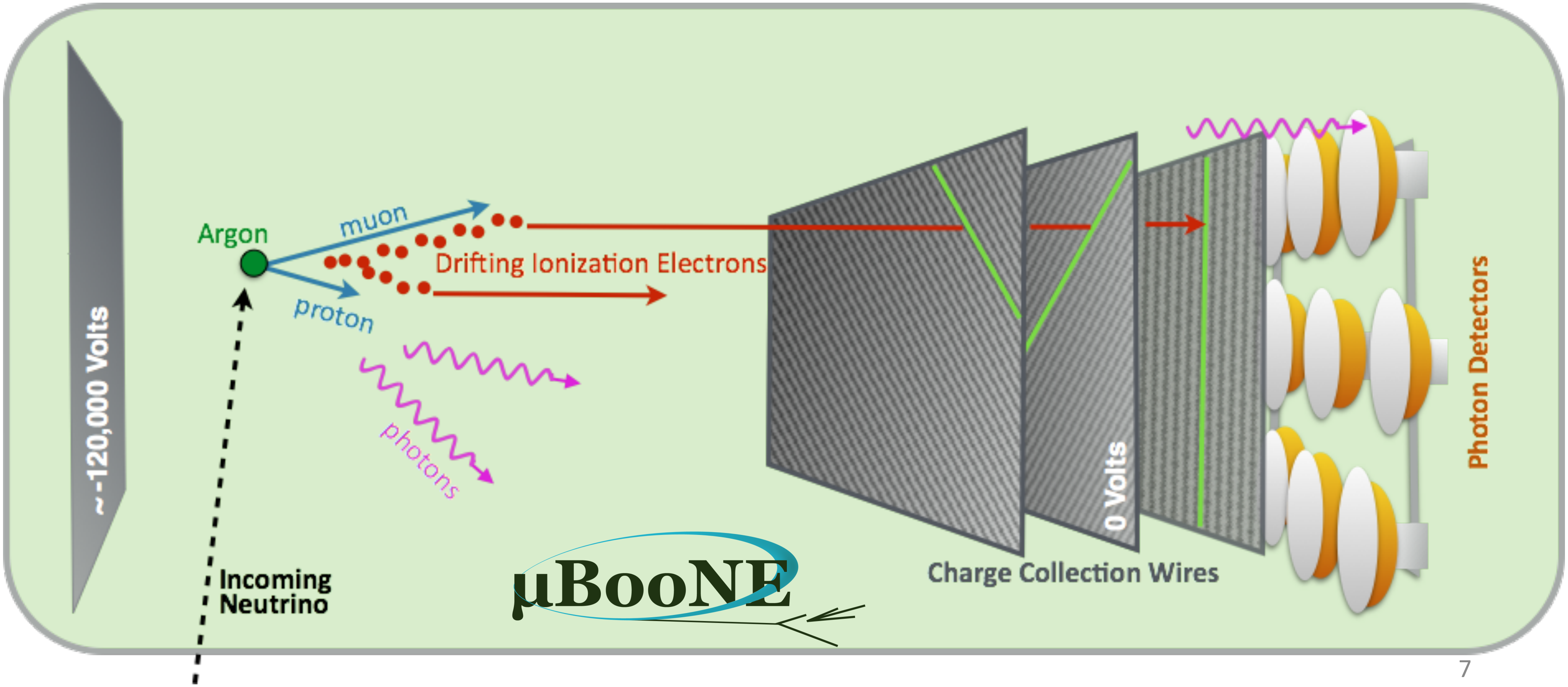
For a neutrino scattering experiment, you need a target/detector system composed of a solid or liquid material.

You will need to measure a track (direction and momentum) that will be only a few cm in length!

The solution to this problem is the liquid argon time projection chamber.

How does a Liquid Argon TPC work?

1. Neutrinos from beam interact with an argon atom.
2. Charged particles from the interaction excite/ionize surrounding LAr.
3. Scintillation light detected by photomultiplier tubes **(~few ns).**
4. Ionization electrons drifted by electric field to collect on wires **(1-2 ms).**

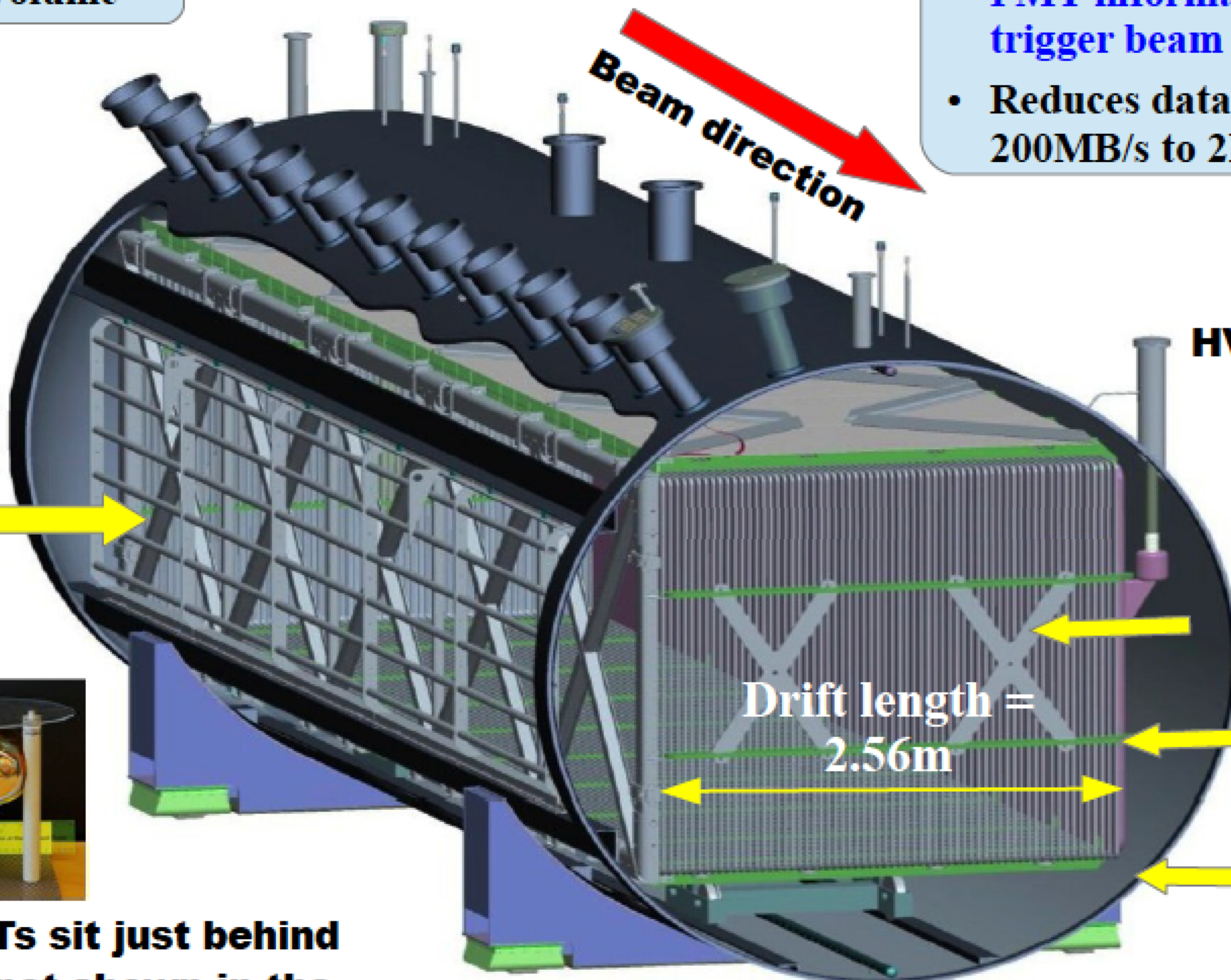


μBooNE

Fully operational with neutrino beam since Oct 15 2015.
Collected in-beam data with 3.4×10^{20} protons-on-target so far!

TPC provides ~80 tons of active volume

- PMT information used to trigger beam events
- Reduces data through-put from 200MB/s to 2MB/s



HV feed through

Anode wires (150 micron)

Field cage

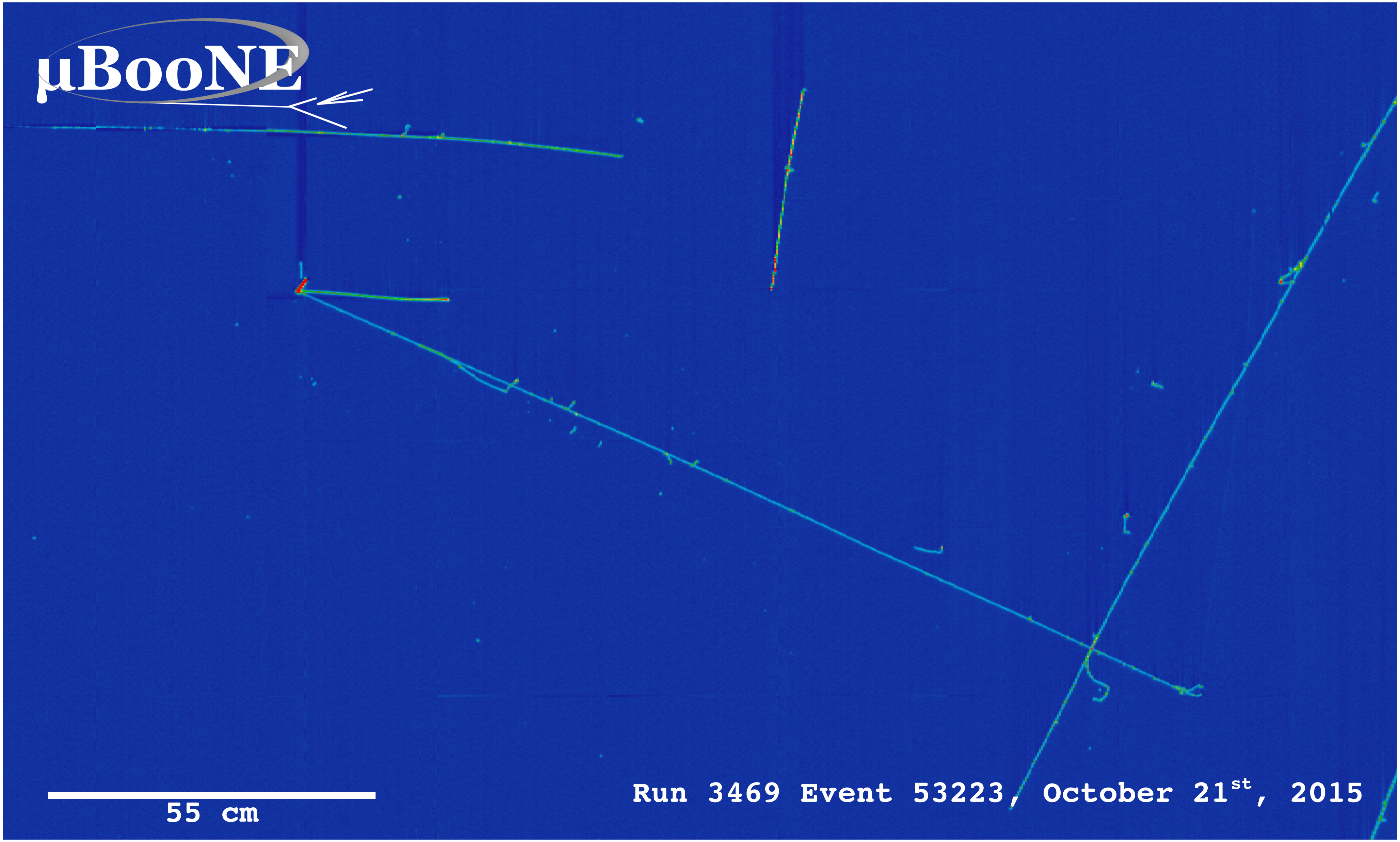
Cathode plane (~ –100 kV)

Cryostat

32 8-inch PMTs sit just behind wire planes (not shown in the picture!)

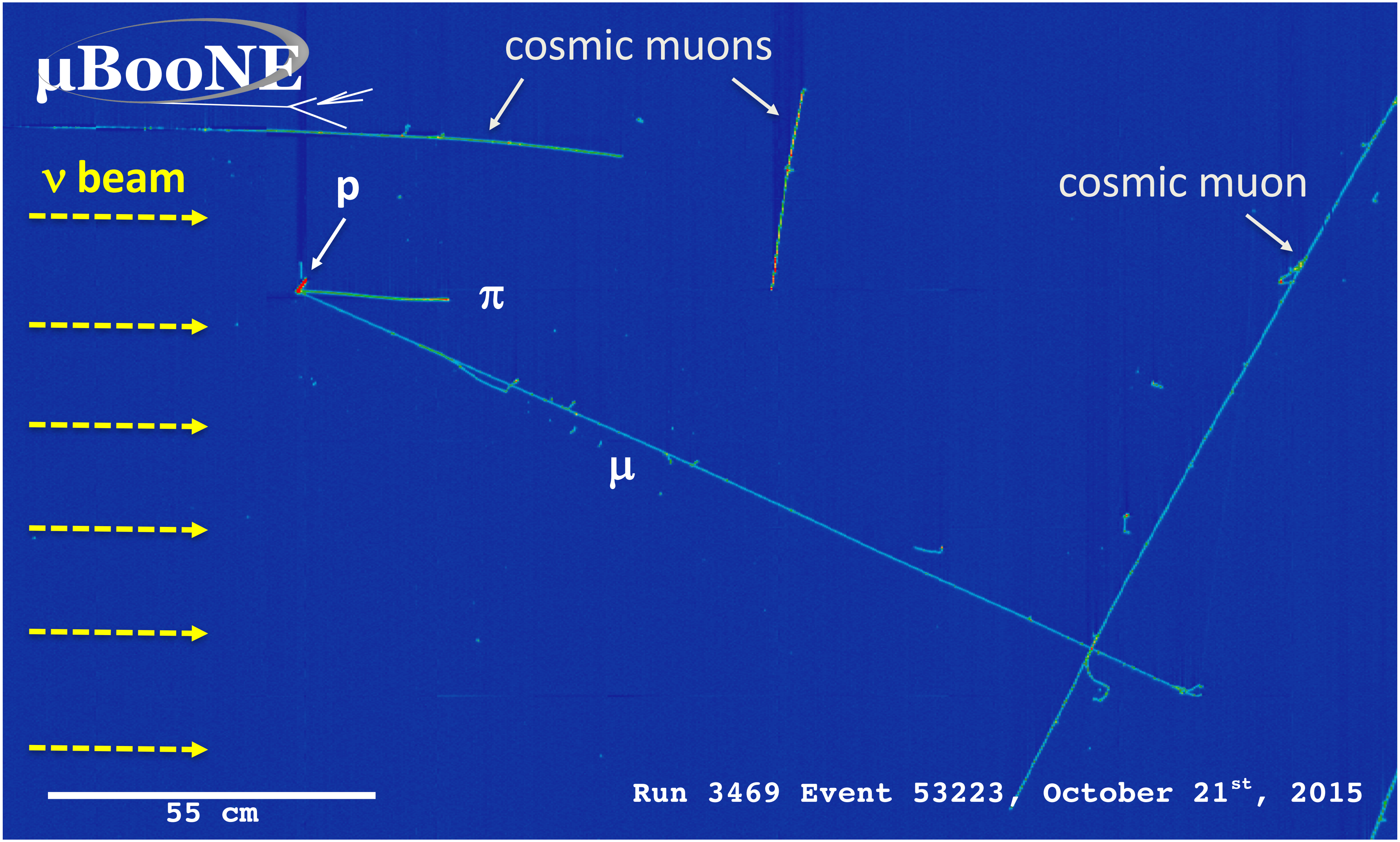
(Roughly the size of a school bus)

Event identified by automated reconstruction



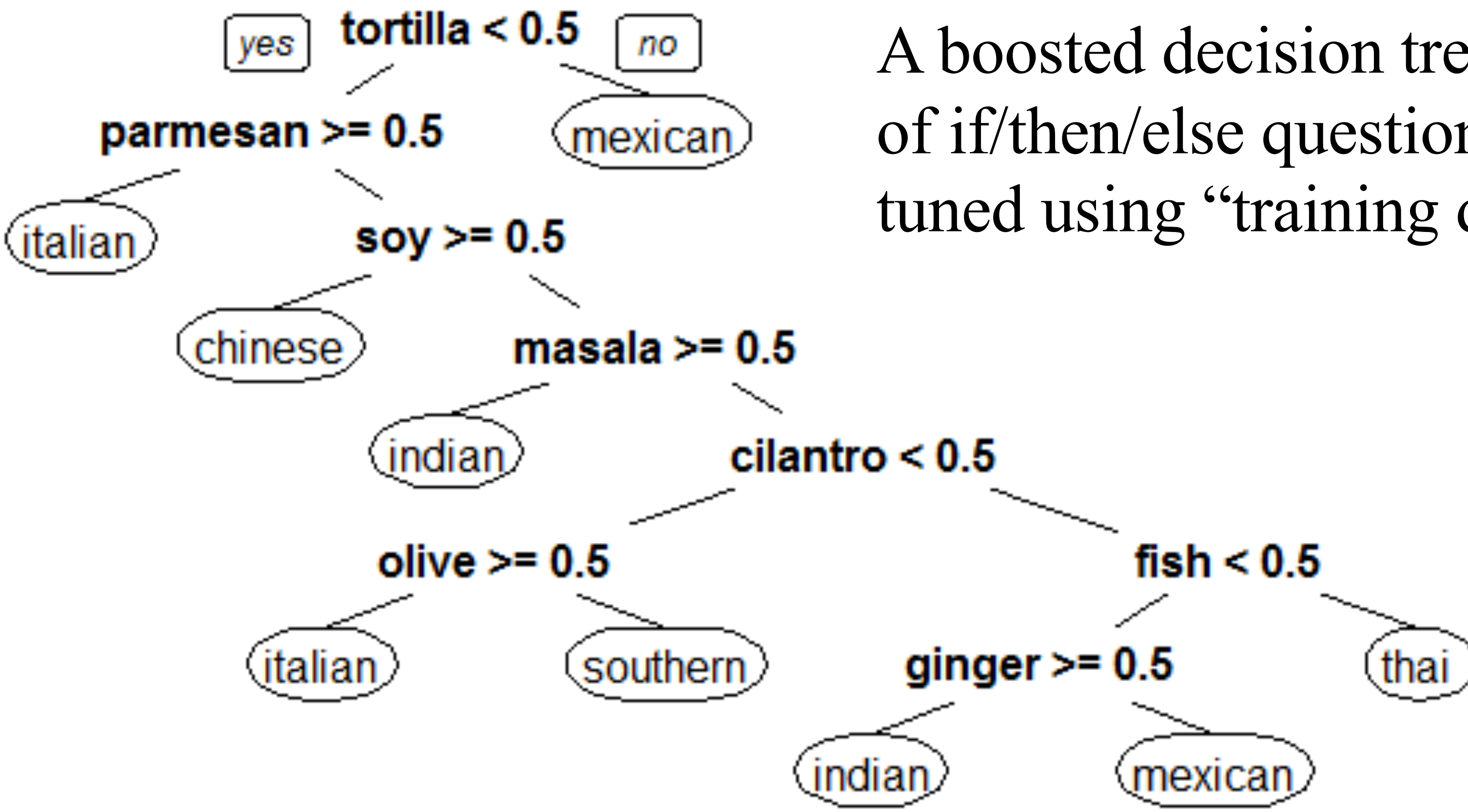
Color is proportional to ionization charge density.

Event identified by automated reconstruction



Color is proportional to ionization charge density.

Using boosted decision trees to identify neutral-current elastic events



A boosted decision tree is a series of if/then/else questions that is tuned using "training data".

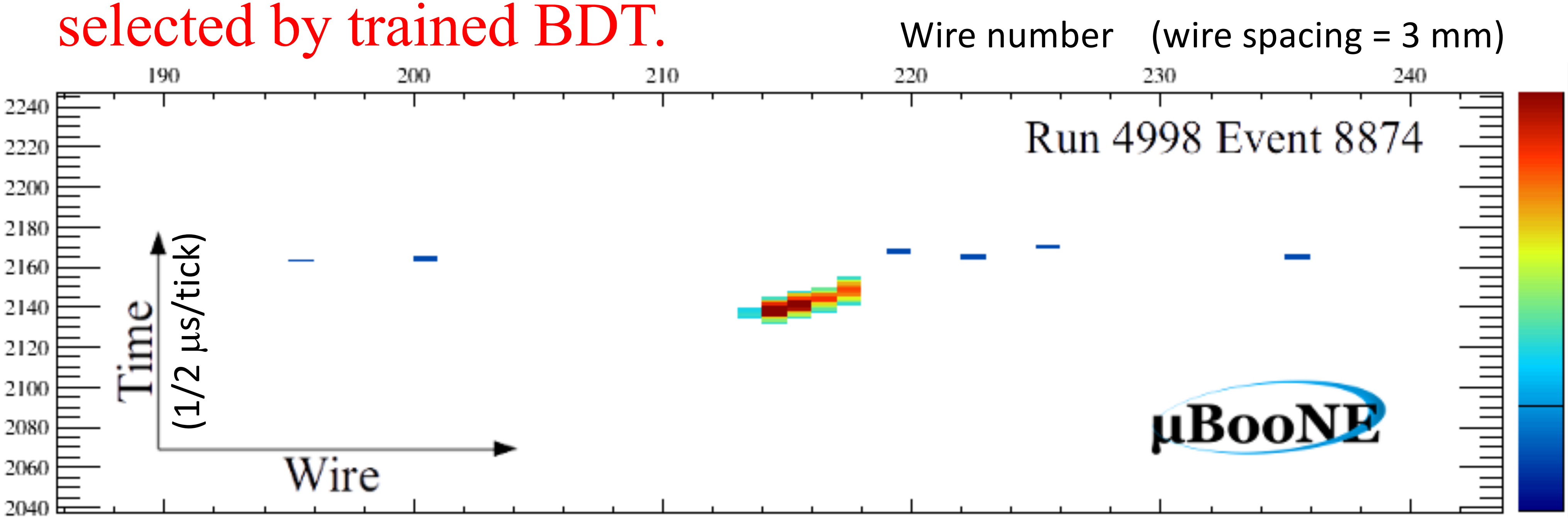
- In our case, the questions are directed at a variety of **track features**:
  - geometry (length, orientation …),
  - calorimetry (total charge …),
  - light collection (match to optical flash …).
- Each track is then assigned a **probability** to be one of five different types:
  - proton, muon, pion, electron/photon, or cosmic-generated

Using boosted decision trees to identify neutral-current elastic events

- We train using simulated events including all detector effects (true geometry, realistic noise, missing wires, etc.)
- We test using another selection of simulated events → efficiencies
- The efficiency information allows us to optimize the cut on proton probability
- Then use the BDT on real data

The effort to use BDTs to identify proton tracks is led by NMSU graduate student Katherine Woodruff.

A proton candidate track in MicroBooNE selected by trained BDT.



Color is proportional to ionization charge density.

Proton probability > 99%

A short, highly ionizing track, isolated from any other tracks.

This is a view of the track from just one wire plane. Using all three planes, the reconstructed 3-dimensional track length is 4.5 cm, corresponding to a proton kinetic energy of ~75 MeV.

If it is a neutral-current event, then $Q^2 \sim 0.15$ GeV^2.

MicroBooNE: Projected Impact on Nucleon Form Factor Measurements

(1) Start with existing 5-parameter functional fit of the strange quark contribution to the nucleon elastic electric, magnetic and axial form factors [Pate and Trujillo, arXiv:1308.5694; update to be published]

$$G_E^s = \rho_s \tau \qquad \tau = \frac{Q^2}{4M_N^2}$$

$$G_M^s = \mu_s$$

$$G_A^s = \frac{\Delta S + S_A Q^2}{\left(1 + Q^2/\Lambda_A^2\right)^2}$$

Parameter	Fit to Existing Data
ρ_s	$-0.10 \pm 0.09 \pm 0.03$
μ_s	$0.056 \pm 0.029 \pm 0.022$
ΔS	$-0.29 \pm 0.42 \pm 0.19$
Λ_A	$1.1 \pm 1.0 \pm 1.1$
S_A	$0.4 \pm 0.5 \pm 0.2$

± exp. ± theor.

These functional forms provide the minimum number of parameters required to achieve a good fit.

MicroBooNE: Projected Impact on Nucleon Form Factor Measurements

(2) Simulate MicroBooNE neutral current ($\nu p \rightarrow \nu p$) and charged current ($\nu n \rightarrow \mu^- p$) events that would be used in this analysis

- Simulated 2x10^{20} protons-on-target (1/3 of original expectation for complete dataset) with reasonable event selection cuts
- Estimated statistical uncertainty in NC/CC yield ratio

$$R_{NC/CC} = \frac{N(\nu p \rightarrow \nu p)}{N(\nu n \rightarrow \mu^- p)}$$

- Many experimental uncertainties approximately cancel in this ratio (proton detection efficiencies, target mass, neutrino flux)
- ➢ Ratio a more attractive observable than NC cross section
- Some theoretical uncertainties may also approximately cancel
- ➢ More theoretical work on argon will be helpful!
- Not the full statistics, but also does not include effect of efficiencies and backgrounds (neutrons, cosmics)

Thanks to B. Fleming, J. Spitz, and V. Papavassiliou for providing this simulation.

MicroBooNE: Projected Impact on Nucleon Form Factor Measurements

Q^2	$R_{NC/CC}$	$dR_{NC/CC}$
0.08-0.2	0.206	0.005
0.2-0.4	0.181	0.005
0.4-0.6	0.156	0.007
0.6-0.8	0.136	0.009
0.8-1.0	0.118	0.012
1.0-1.2	0.101	0.015

(3) Repeat fit using simulated MicroBooNE data; see what happens to **uncertainties**.

Parameter	Fit to Existing Data	Including μBooNE
ρ_s	± 0.09 ± 0.03	± 0.08 ± 0.02
μ_s	± 0.029 ± 0.022	± 0.023 ± 0.017
ΔS	± 0.42 ± 0.19	± 0.036 ± 0.003
Λ_A	± 1.0 ± 1.1	± 0.42 ± 0.03
S_A	± 0.5 ± 0.2	± 0.05 ± 0.02

Not much effect on vector form factors (no surprise)

BIG effect on axial form factor (expected!)

$$G_E^s = \rho_s \tau \qquad G_M^s = \mu_s \qquad G_A^s = \frac{\Delta S + S_A Q^2}{\left(1 + Q^2/\Lambda_A^2\right)^2}$$

Summary

- Observation of neutral-current elastic scattering events at low Q^2 can provide a unique measurement of the strange quark contribution to the proton spin
- The MicroBooNE experiment has collected the first year of data for this physics program; analysis is underway!

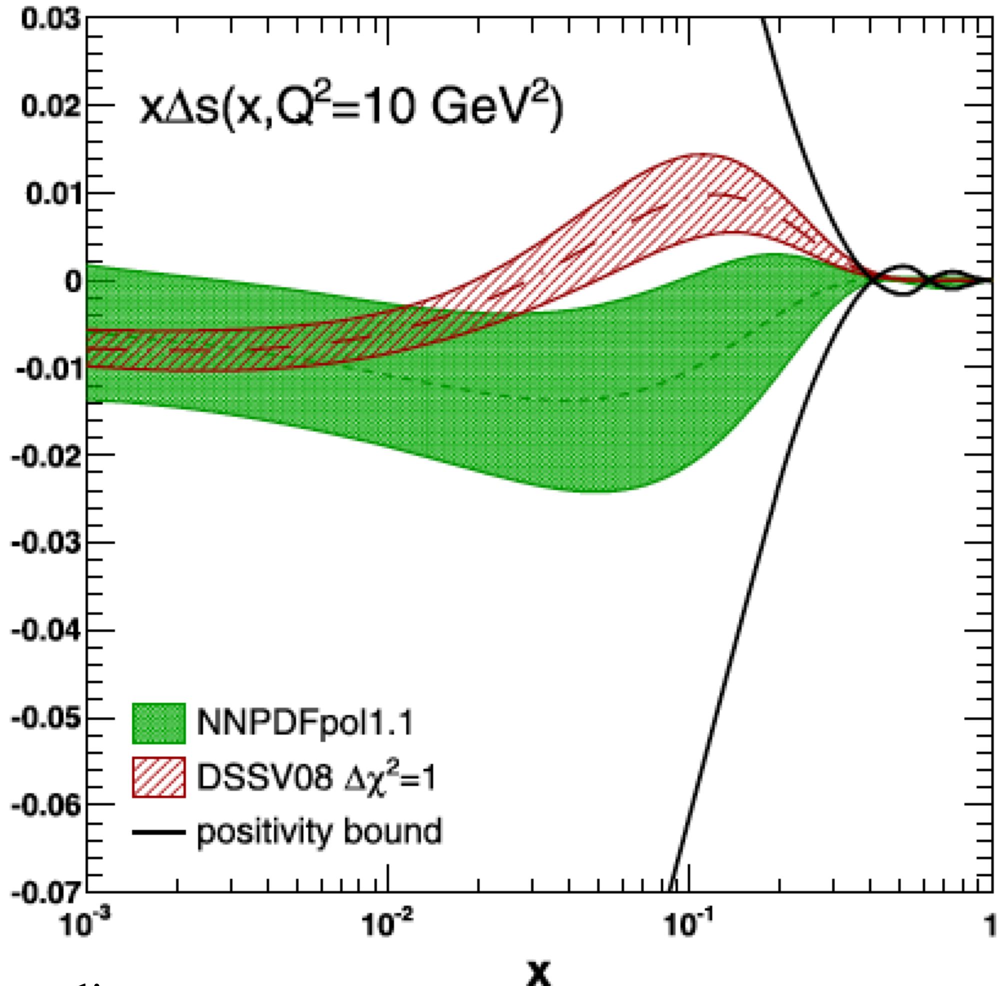
Backup

The (unknown) Strange Quark Contribution to the Nucleon Spin

One figure sums it all up!

de Florian, Sassot, Stratmann, and Vogelsang [PRD 80 (2009) 034030]
(1) Assumes flexible functional forms for the PDFs
(2) Includes Semi-Inclusive DIS data

Nocera, Ball, Forte, Ridolfi, and Rojo [NPB 887 (2014) 276-308]
(1) No functional forms
(2) Excludes light-quark SIDIS data



We don't yet know the shape, size or even the uncertainty of $\Delta s(x)$.

Other good reading:
Leader, Sidorov, and Stamenov, PRD 91 (2015) 054017
Hirai and Kumano (AAC), Nucl. Phys. B 813 (2009) 106
Blumlein and Böttcher, Nucl. Phys. B 841 (2010) 205

The strange quark contributions to the axial form factor and nucleon spin are related!

$$\int_0^1 \left(\underline{\Delta s(x) + \Delta\bar{s}(x)}\right) dx = \Delta S = \underline{G_A^s\left(Q^2 = 0\right)}$$

Polarized parton distribution functions determined in <u>inelastic</u> partonic hard-scattering processes (EMC, SMC, SLAC, HERMES, COMPASS, JLab, RHIC)
<u>As shown in earlier slide, the results are inconclusive.</u>

Axial form factor determined from electron-nucleon and neutrino-proton <u>elastic</u> scattering processes (JLab, Mainz, Bates, BNL E734, and many other elastic scattering experiments used here)

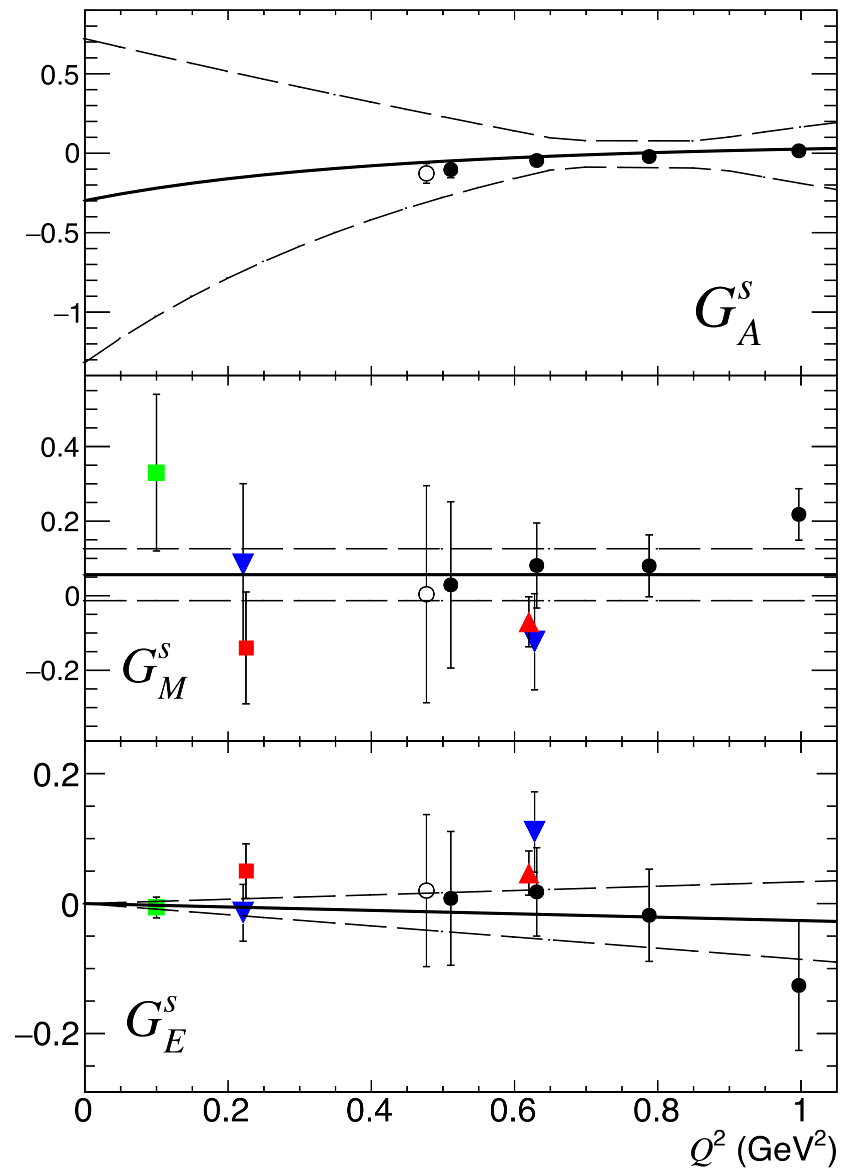
Fit Uncertainty Limit Curves

- ● G0 (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ○ HAPPEx (forward *ep*) + E734 (νp and $\bar{\nu} p$)
- ■ PVA4 (forward and backward *ep*)
- ▼ G0 (forward and backward *ep*, and backward *ed*)
- ■ HAPPEx + PVA4 + SAMPLE + G0 (0.1 GeV^2)
- ▲ HAPPEx + G0 (0.62 GeV^2)

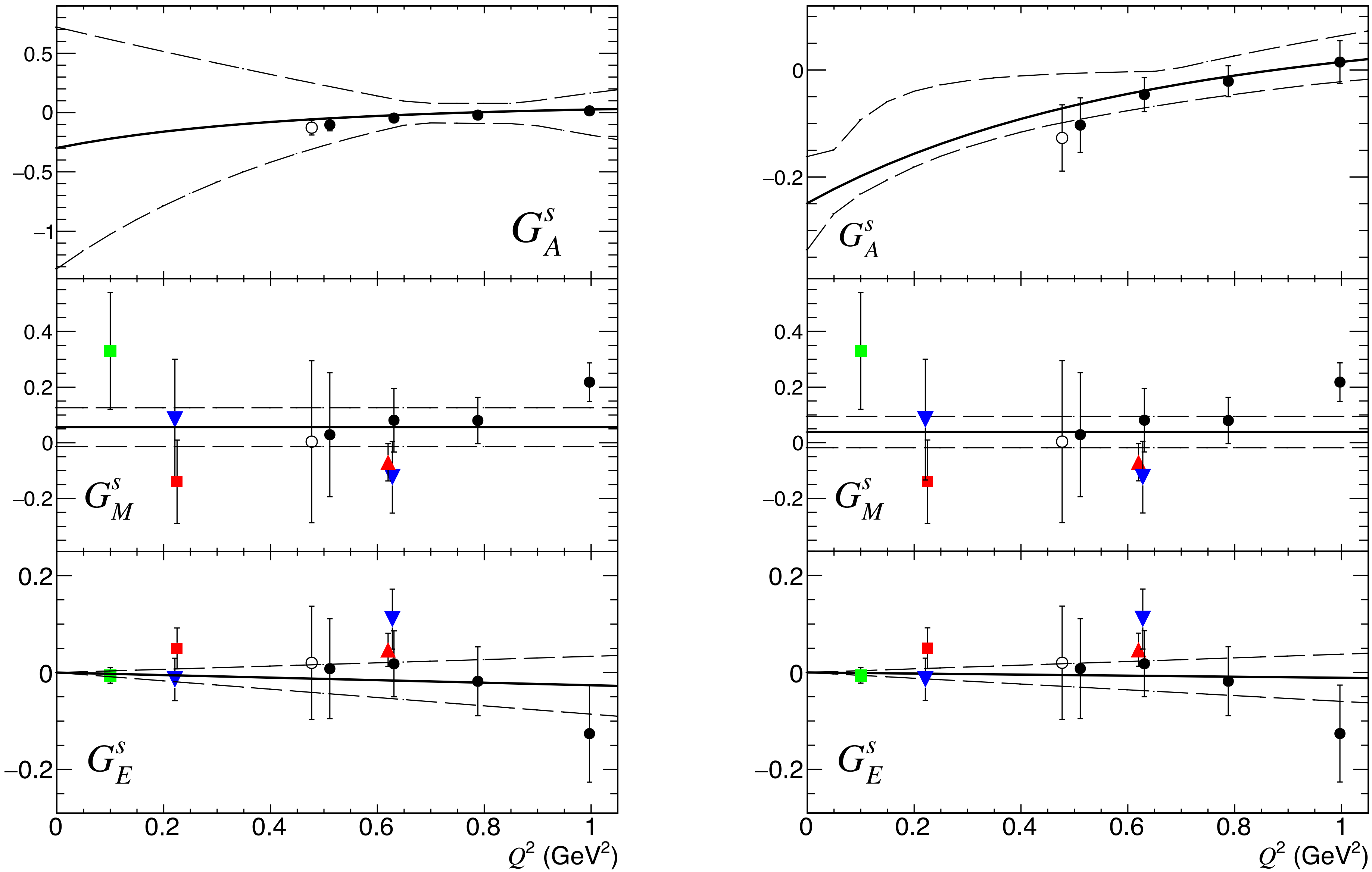
——— 5 parameter fit

– – – 70% confidence level

Parameter	Fit to Existing Data
ρ_s	$-0.10 \pm 0.09 \pm 0.03$
μ_s	$0.056 \pm 0.029 \pm 0.022$
ΔS	$-0.29 \pm 0.42 \pm 0.19$
Λ_A	$1.1 \pm 1.0 \pm 1.1$
S_A	$0.4 \pm 0.5 \pm 0.2$

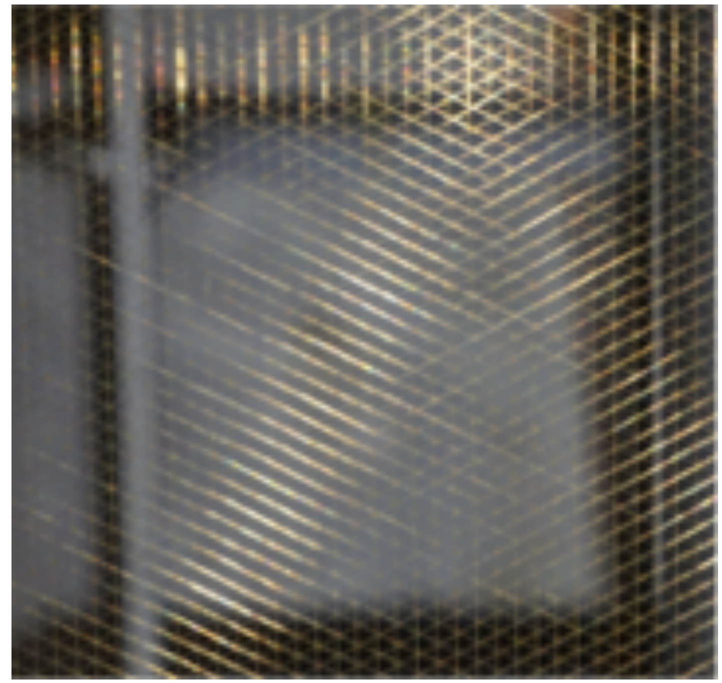


Fit Uncertainty Limit Curves Including Simulated MicroBooNE Data



fit uncertainty limits much tighter with MicroBooNE data

Construction of the Wire Frame



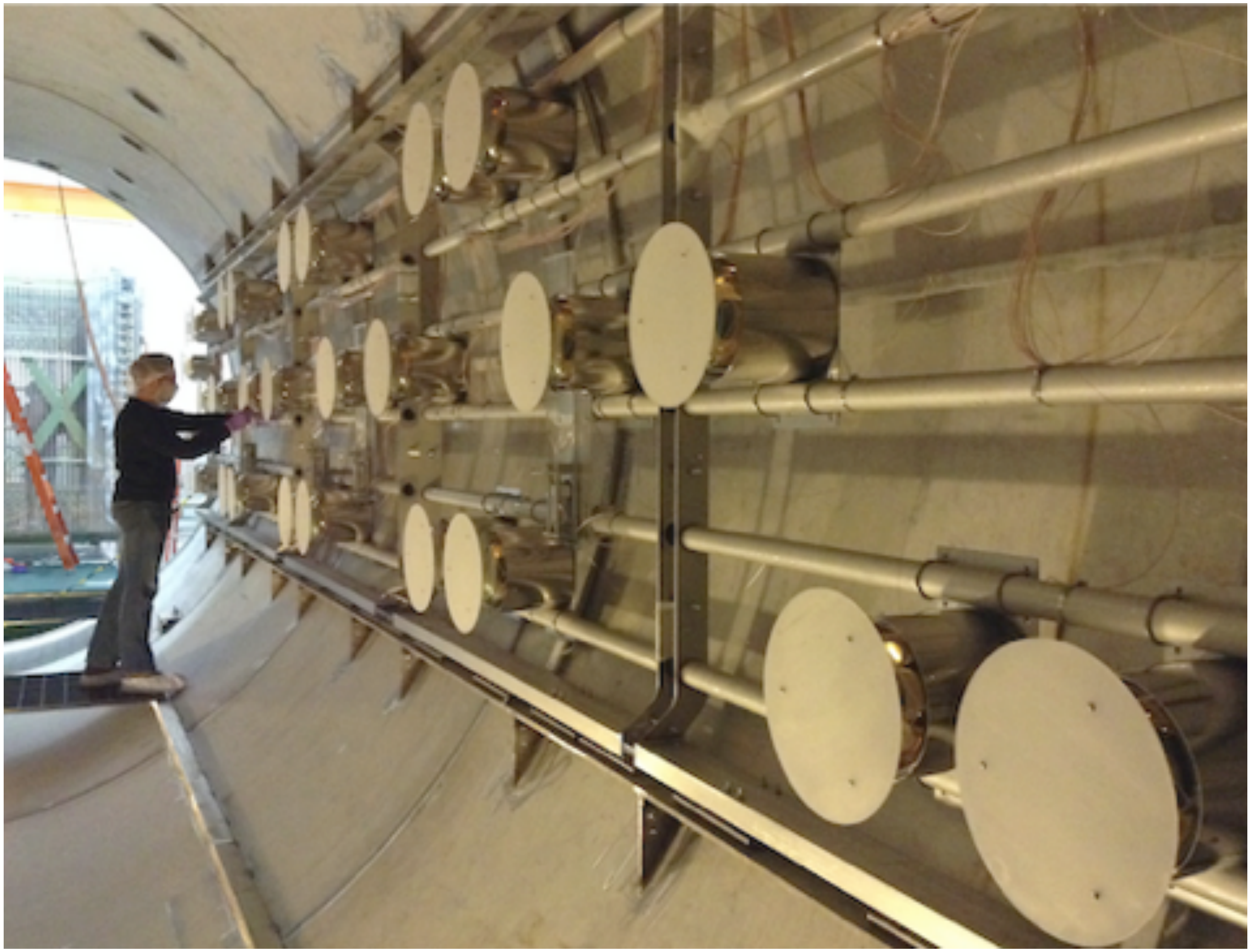
3 Planes of wires

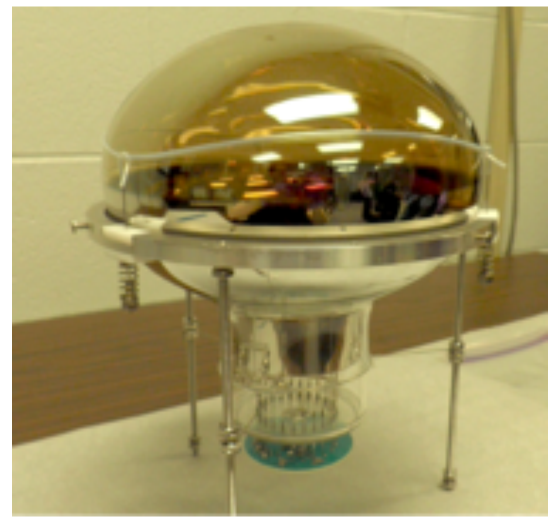
Wires are spaced by 3 mm

8256 wires total!

μBooNE

Installation of 32 Phototubes with wavelength-shifter plates



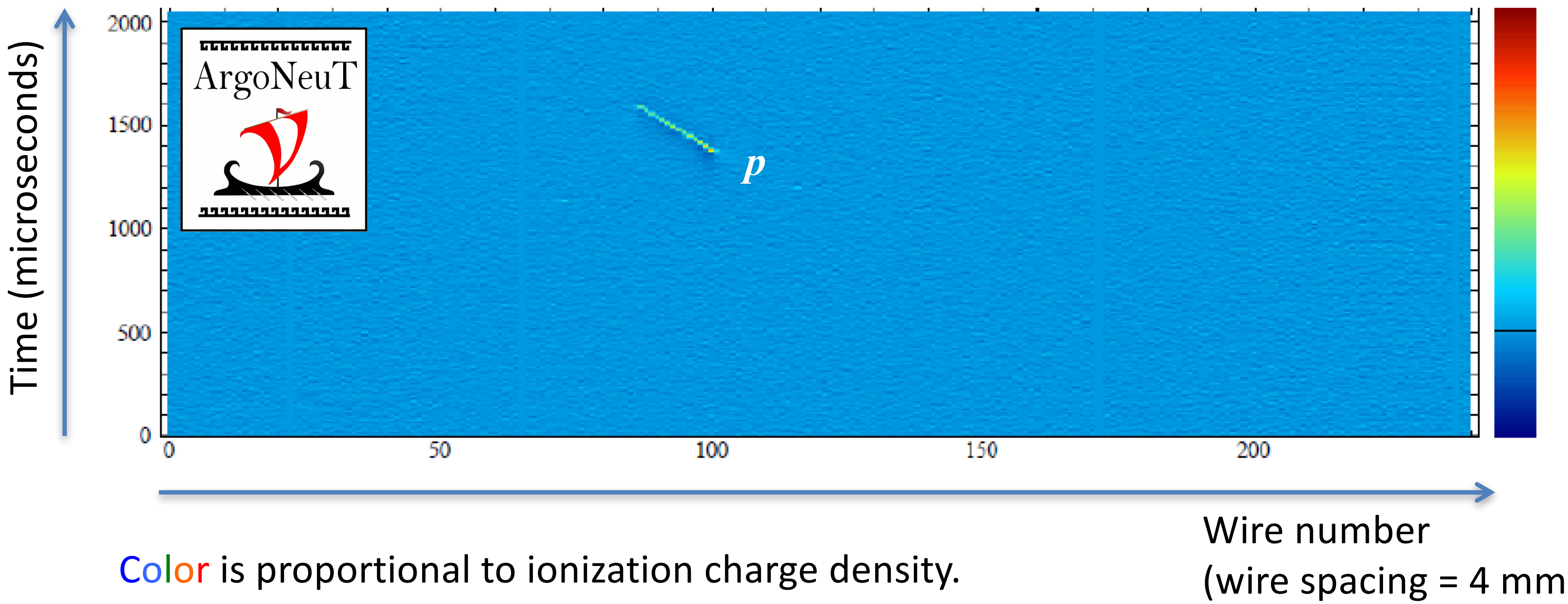


µBooNE

MicroBooNE Status:

- 170 tons of pure (< 0.1 ppb O_2) liquid argon
- Drift field operational at 70 kV over 2.5 meters
- Wire planes and phototubes operational
- Saw first neutrino beam on 15 Oct 2015
- Collected data until 29 July 2016 when summer shutdown started; 3.4×10^{20} protons on target
- **Moving forward with automated reconstruction and identification of liquid argon TPC event data – this has never been done before.**

What does a proton track look like in a Liquid Argon TPC?



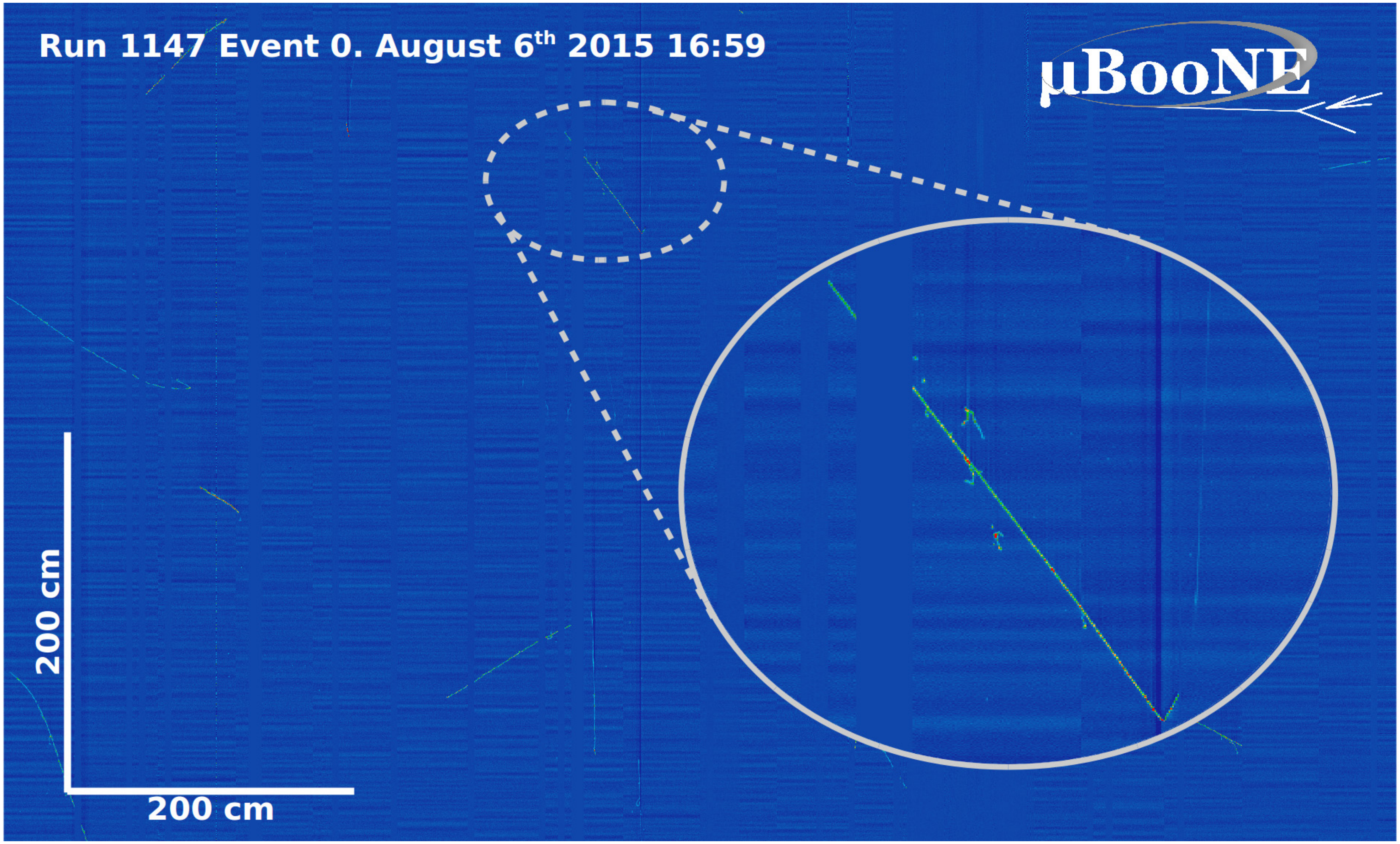
Color is proportional to ionization charge density.

Neutrino is incident from the left; it interacts with an argon nucleus.
A single proton track is seen in the TPC.
This track is 9.7 cm long. The proton kinetic energy is ~100 MeV.

ArgoNeuT was a small Liquid Argon TPC (47 x 40 x 90 cm^3) operated underground at Fermilab in 2009 and 2010. [Figure is from arXiv:1306.1712]

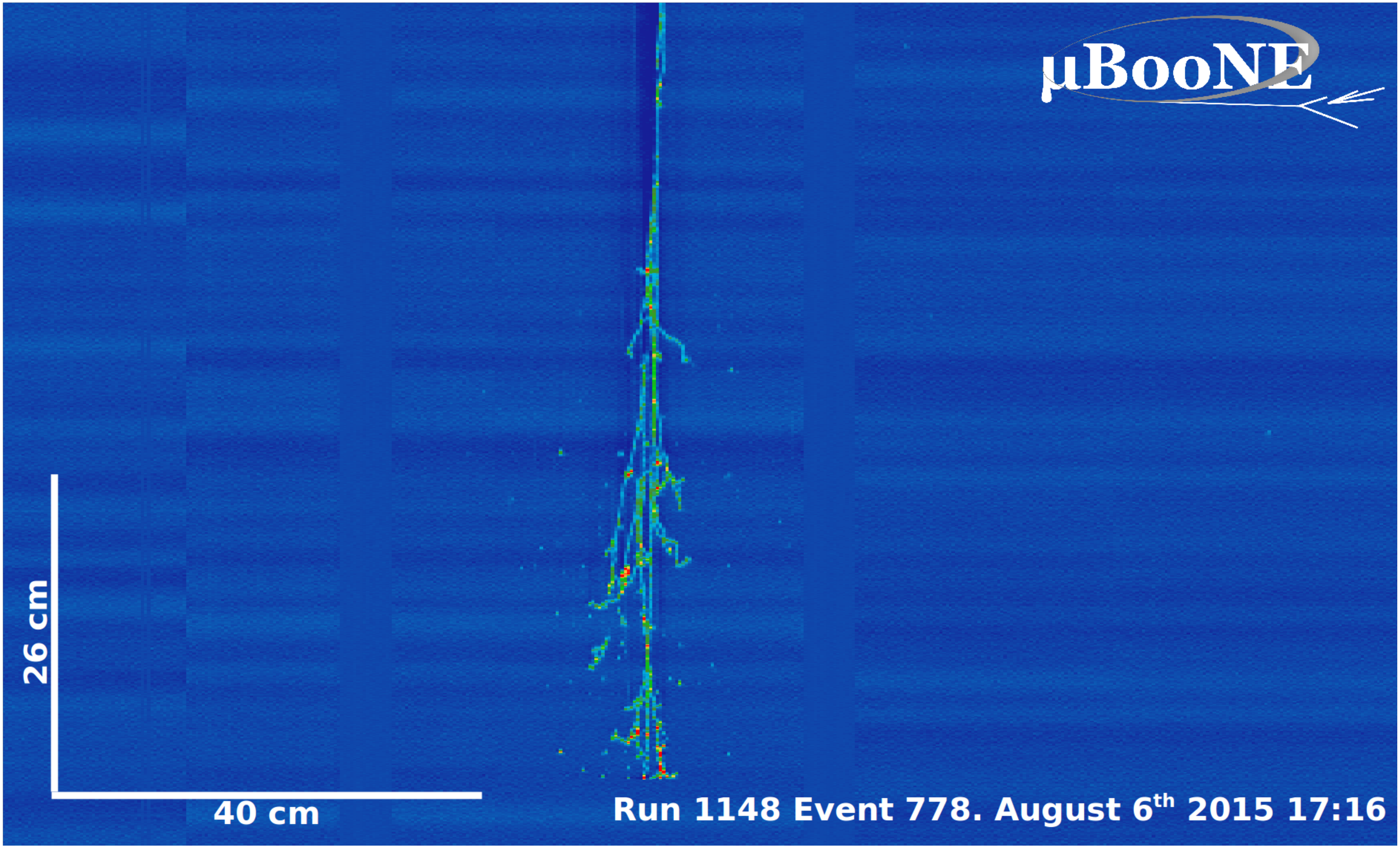
MicroBooNE is much larger: 2.5 x 2.3 x 10 m^3 ! (but at the surface)

We turned on the detector for the first time on August 6, 2015, and we saw cosmic ray tracks immediately! (No neutrino beam yet.)

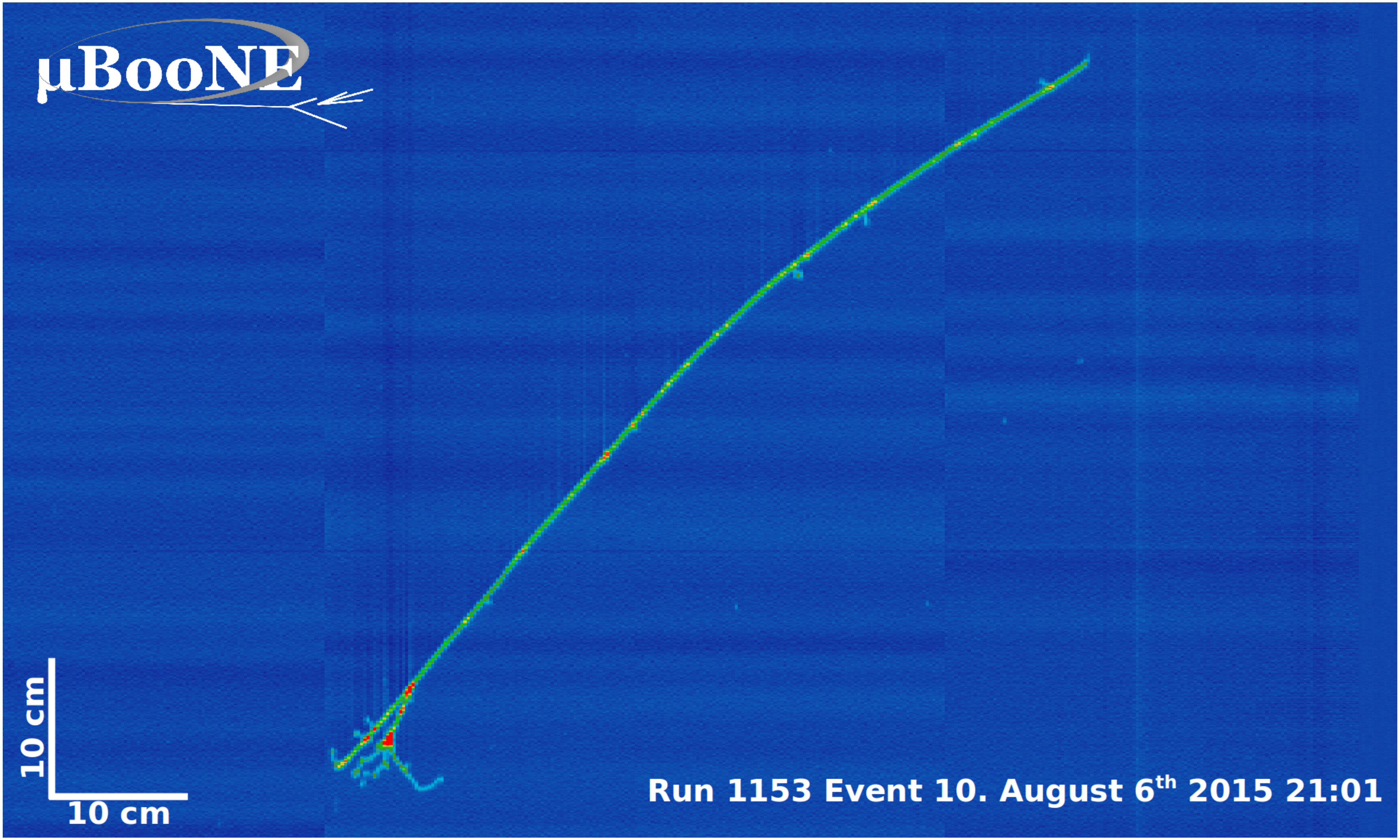


This view is using just one plane of wires.

Typical electron track with <u>large</u> amount of secondary low-energy electrons produced.



Typical muon track with small amount of secondary low-energy electrons produced..



Using <u>all 3 planes of wires combined with the drift time information</u>, you can construct a 3D view of the tracks.

This event shows ~20 cosmic ray tracks collected in 4.8 ms.