Temporary Muon Spectrometer

(SSRI: Sign-Selecting Range Instrument)

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DUNE ND Review

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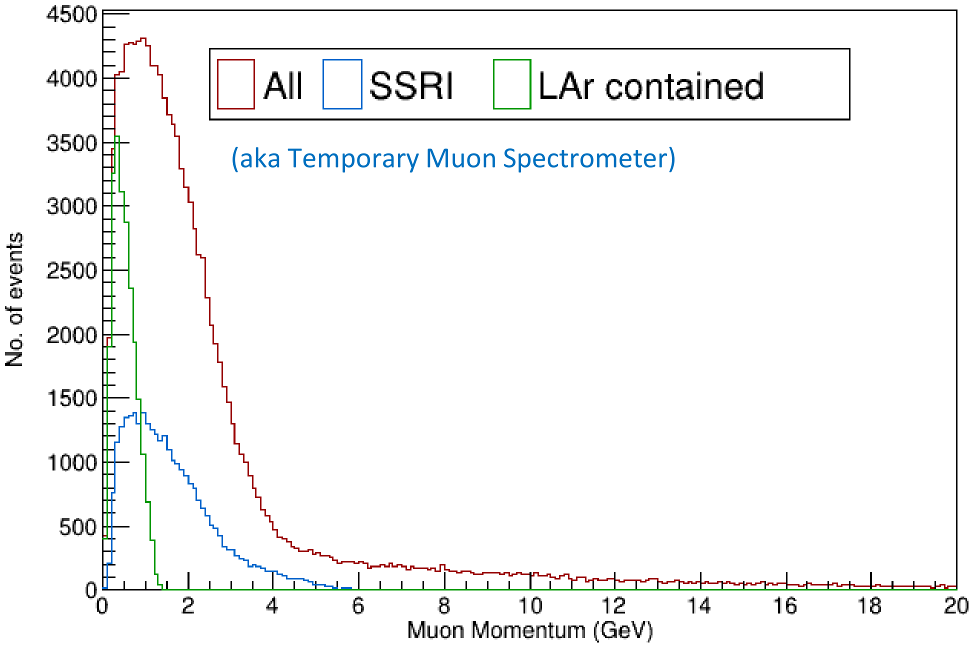
Outline

- Overview & Scope
- Requirements and Specifications
- Organization
- Subsystem descriptions
- Risks
- Milestones
- Summary

Role and Background

- Size constraints on the LArTPC cause muons not to be fully contained in the argon
- To address this, the DUNE TDR includes a Multi-purpose detector (MPD) composed of a high-pressure gas TPC (HPgTPC) and calorimeter (ECAL)
- This is foreseen to be an international contribution, but has not yet advanced to the MOU level
- To **mitigate this risk**, we have added a Temporary Muon Spectrometer
  - **Capable of supporting the first years' science**
  - Low-risk, proven technology
- We want to **make the decision** to begin construction **as late as possible**, to take advantage of any positive international developments.



The liquid argon TPC does not fully contain muons even at the oscillation maximum (muon energies 1-1.5 GeV)

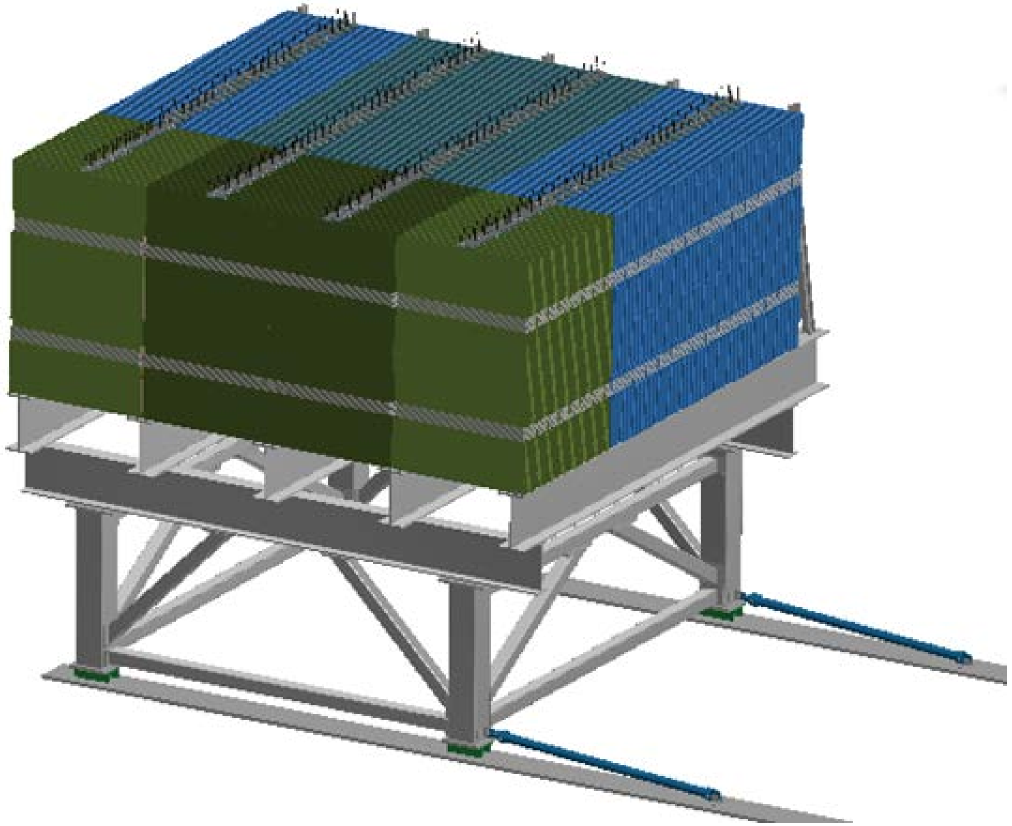
The Temporary Muon Spectrometer extends the energy range to about 5 GeV.

CHARGE QUESTION 2

Scope

In response to two October IPR recommendations

- A magnetized range stack with =100 layers
  - Face is the same size as the ND-LArTPC face
  - 192 scintillator slats (@ 3.5 cm wide) per plane
- Entirely DUNE-US scope
- Sits where the MPD will eventually go
- Intended to run until the MPD is delivered
  - Requires some flexibility on our part as the international situation evolves
  - Nevertheless, this is a device we can build for a known cost (~$6M base) and schedule (22 months) sufficient for initial physics.



7m wide x 3.2m tall x 7m deep
~700 tons

CHARGE QUESTION 2

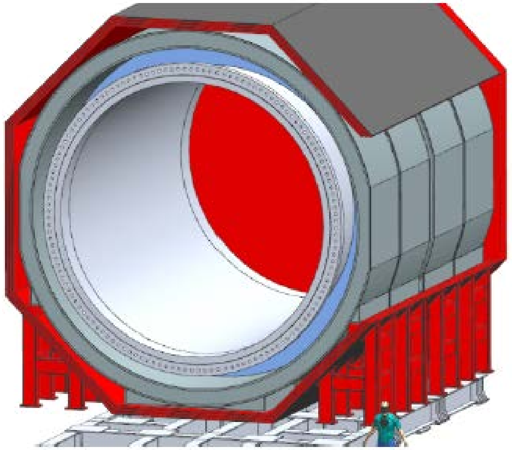
Flexibility?

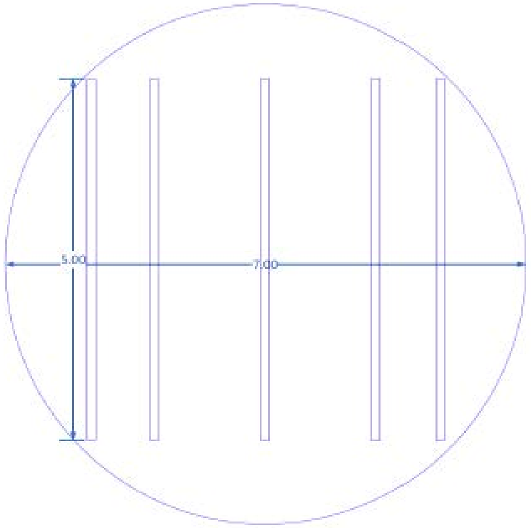
- If the MPD will arrive in time, we won’t build an iron range stack. Why would we want to?

- Things becomes more complicated if part of the MPD arrives in time – e.g. perhaps we get a magnet in time, but no detector elements
  - We would use the funding for the SSRI detector elements to build more appropriate detectors for that configuration
    - e.g. high granularity scintillator

- We need to accurately determine the time to build the muon spectrometer in order to know the latest possible decision date
  - We don’t want to lock ourselves into a less-capable design by doing this to early
  - We don’t want to have an incomplete detector by doing this too late

SPY magnet design





SPY-appropriate detector layout

CHARGE QUESTION 1

Requirements and Specifications I

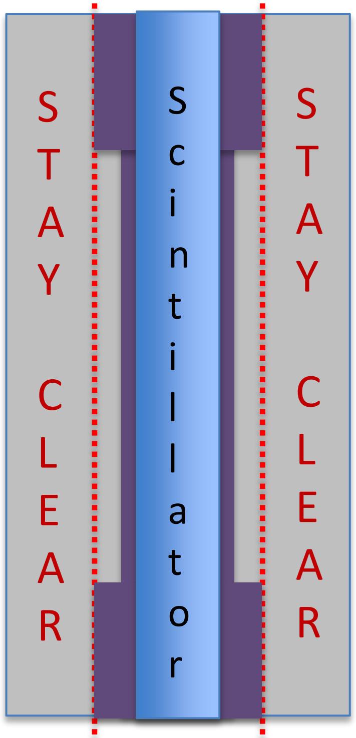
- Determine the muon (and thus neutrino) energy (ND-M1):
  - If you don’t have muon energy measurement, you don’t have neutrino energy measurement at the near site, so you don’t have an experiment
  - Goal: **do no worse than the Far Detector** (~4%).

- Determine the neutrino/antineutrino composition of the beam (ND-M5)

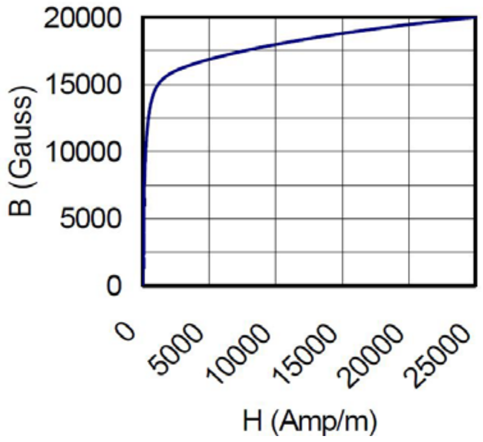
- Introduce as little bias as possible
  - Cover the full ND-LArTPC face to minimize kinematic dead spots

CHARGE QUESTION 2

Requirements and Specifications II (Flowdown)



- We need a 40 mm gap between plates
  - 1cm scintillator, 1 cm frame+light box, 0.3% flatness spec on each plane of steel
  - That limits us to ~3 m of steel, which sets our upper threshold near 5 GeV.
- We need 25 hits to do a 4% range measurement
  - That sets a 1.5cm thickness for a 500 MeV muon
  - After 40 thin planes we go to 4 cm thickness (build-to-cost)
- A high a magnetic field inside, as low outside as we can (to avoid having fringe field inside the liquid argon)
  - Drives us to “BaBar/MINOS”-type low-carbon high-silicon steel ($\mu = 700$)
  - Also drives us to an unconventional coil design (see later slides)
- In this field, track sagittae are ~7cm (approximately independent of momentum
  - We need a slat width of ~3.5 cm. Channel count should be a multiple of 16.



CHARGE QUESTION 4

Organization

- This effort has just started – we do not have a work plan in place
  - The answer to Charge Question 4 is “no”
  - We intend to use a very MINOS-like university-lab partnership model
  - At least two university sites would produce panels (and three would be better)

- QA/QC scheme
  - QA plan will be developed with LBNF/DUNE-US QA managers (J. Mateyack and K. Fahey)
  - One lab role in MINOS was ensuring that parts produced in multiple places were identical
  - Immediate concerns: steel flatness, optical coupling to SiPM

- ESH issues
  - We will follow ANL, FNAL, and local university ESH procedures
    - Coordination and review provided by the LBNF/DUNE-US ESH managers (D. Newhart and M. Andrews)
  - Specific hazards: Panel weight (about 200 pounds) and glue

Interested institutions

Argonne National Laboratory

The University of Mississippi

University of Rochester

Wichita State University

William & Mary Chartered 1693

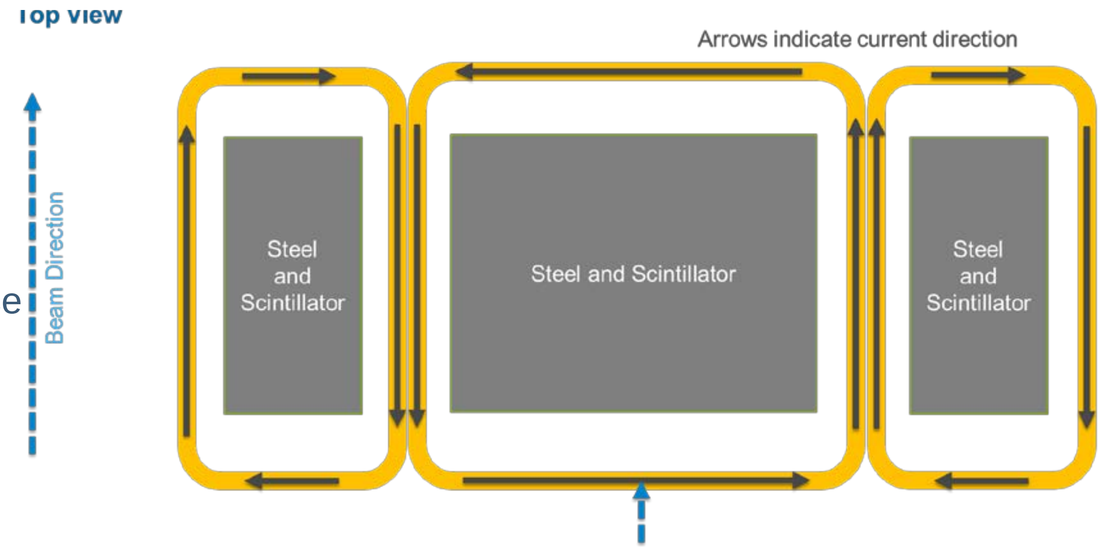
Subproject engineer is Vic Guarino (Argonne)

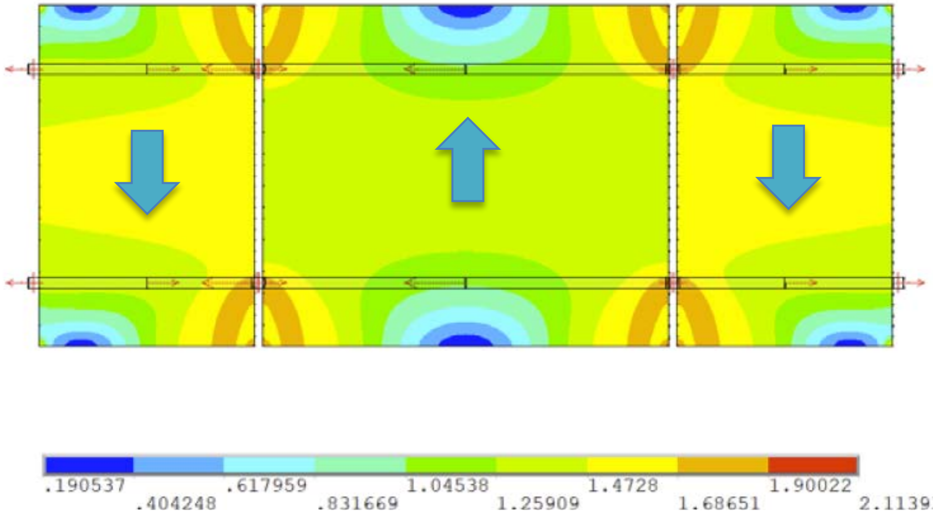
CHARGE QUESTIONS 2 & 6

Subsystems: Infrastructure, Steel and Magnets

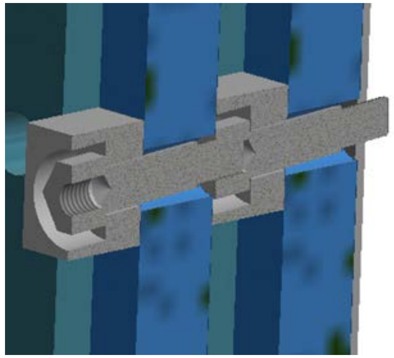
- Steel – described earlier
- Support structure is movable by PRISM
  - PRISM mechanics lets us also map the magnetic field in front of the device
- Magnet
  - Each plate sees a dipole; outside it’s a sextupole
    - 1.4-1.5 T inside, < 0.1 T at the edge of LArTPC
  - Plan on 15000 Ampere-turns to slightly oversaturate the plates
  - Can possibly be air-cooled (under study)

Coil Design

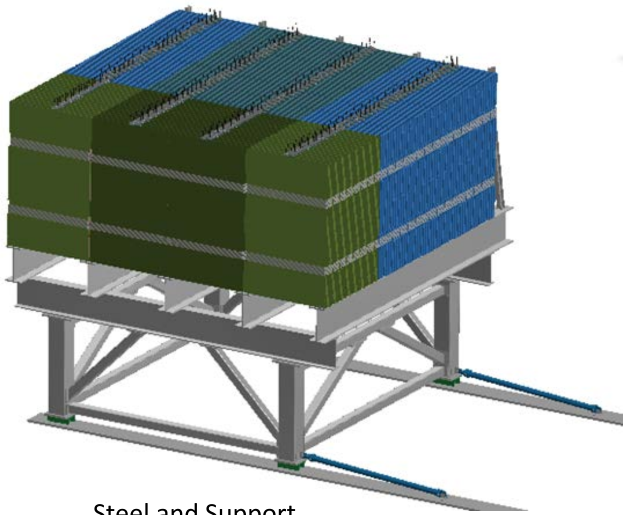




Magnetic Field at First Plate



Spacer bolts



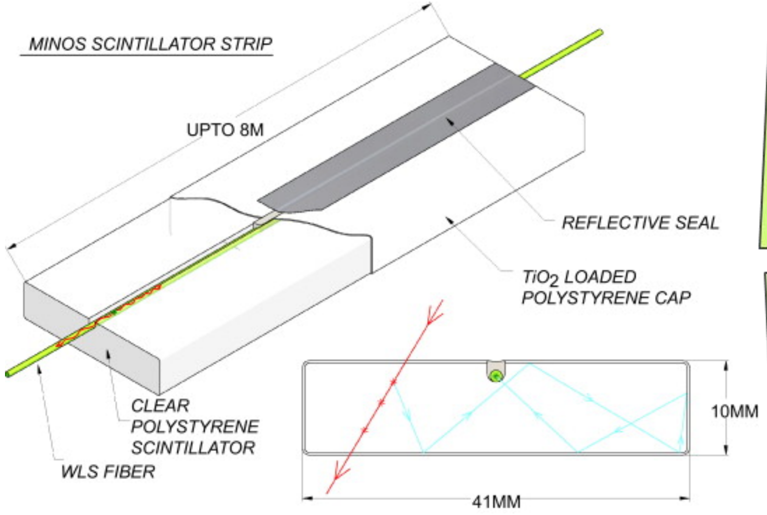
Steel and Support

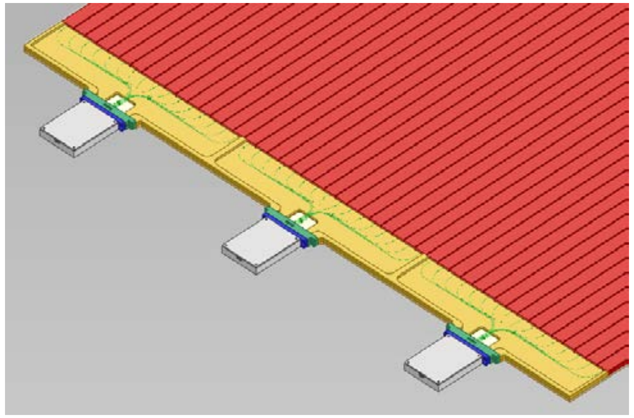
CHARGE QUESTIONS 2 & 6

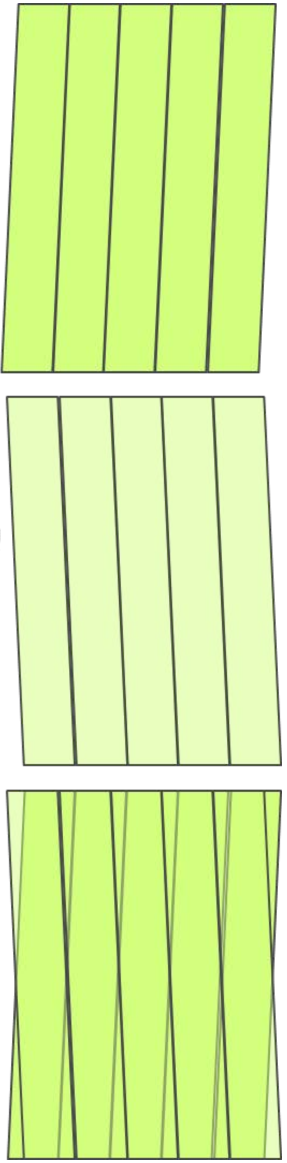
Subsystems: Scintillator Panels (Mechanical)

- Design is MINOS-like (extruded polystyrene)
- Each (of 100) plane has four panels (192 channels)
- Each panel is a self-contained box containing
  - 48 slats of scintillator 3.5 cm wide with Y11 wavelength-shifting fiber
  - SiPM, Front End-ADCs and associated electronics (discussed later)

- Panels (which are rectangular) are tilted ±3° in alternating layers
  - With stereo you win as sine but only lose as cosine
  - Gets us ~45 cm resolution in y-direction
  - An inexpensive choice – but will be subject to pileup issues at 2.4 MW.



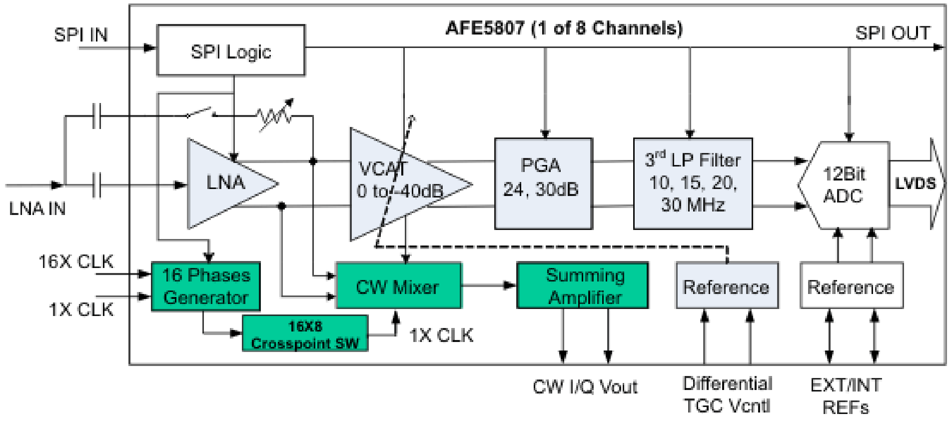




CHARGE QUESTIONS 2 & 6

Subsystems: Scintillator Readout

- On-Panel Board (OPB)
  - Has three 16-channel SiPMs and six Texas Instruments AFE5807 analog front ends
    - Output is LVDS on shielded twisted pair (96c)
  - Also does low-voltage DC-DC conversion and distribution (SiPM + 3 voltages for front-end chip)
  - In an early stage of design (contingency is 75%)
- Data Concentrators
  - Eight FPGA-based units that accept OPB output , reformat it and send it on to the DAQ
  - In a very early stage of design (contingency is 99%)



Electronics cost is **$80/channel**.

We compared costs line by line with the mu2e CR veto – this is less expensive because 48 channels share a common low voltage system.

CHARGE QUESTION 8

Summary costs

	M&S	Labor	Base	Est. uncert.	Total
Management & Infrastructure	299	359	659	42%	1063
Steel	599	162	721	45%	1170
Magnet Coil	169	164	222	88%	710
Detector Mechanical	1250	939	2189	45%	3509
Detector Readout	430	540	970	66%	1808
Transport & Assembly	30	96	126	45%	236

Units are $k

- Total cost is about $9M (TPC) including 47% estimate uncertainty
- Cost drivers are
  - Detector assembly labor
  - Detector readout
  - Both of these are in a less advanced stage than the rest of the subsystem, so estimate uncertainty is also large
- These are captured in WBS elements 131.02.03.04.01 (design) .02 (production) and .03 (testing), but this table is perhaps more reviewable
- Our next P6 update will reduce the estimate uncertainty as vendor quotes come in (e.g. steel will be 17%)

* The reason readout contingency is less than OPM and DC contingency is that it also includes the SiPMs, where we have a quote.

CHARGE QUESTION 8

Summary schedule

- As mentioned earlier, we do not yet have a detailed workplan
- Because of the interactions with the MPD, the green light to begin construction will come as late as possible
  - It is critical that we understand the schedule well enough to know when “as late as possible” is. We are working towards that.

- With today’s labor estimates,
  - and one site building modules, module assembly is on the critical path (33 months).
  - With two sites, the critical path starts with assembly and moves to installation (22 months)

- To solidify these estimates, we will begin prototyping as soon as we can get back into our labs

CHARGE QUESTION 5

Prototyping & Test plans

- Our first prototype will be “1/3 scale” and purely mechanical
  - Undoped plastic slats
  - Clear fiber
  - No electronics
  - 22” (16 channels) wide and only as long as it needs to be (probably also about two feet)
  - Time and Motion studies will inform the cost estimate
- Once we are happy, we can start scaling up
- Electrically, our top priority is to get a full design, but some open questions are:
  - Can we live without a pre-amp? (Means using only the low 8-bits of the 12-bit ADC)
  - Can we send LVDS on a 4m run near the magnet coils?

CHARGE QUESTION 8

Risks

- We are beginning to develop our risk register
- This is an established technology with low technical risk
- Things I worry about:
    - Descoping – especially deferring engineering
    - Our steel is a commodity item, but people don’t buy it for its magnetic properties: it may be more expensive or unavailable when it is time to release the purchase order
    - The Texas Instruments AFE5807 chip has gone up in price – and down again - by a factor of 4 since February, probably because of Covid-19. (Its primary market is medical instruments)

CHARGE QUESTION 3

Interfaces

- We need to keep the magnetic field low inside the liquid argon TPC.
  - Lower is always better, but $B_{xy} < 1000$ Gauss keeps magnetic bend well below multiple Coulomb scattering. Preliminary ANSYS studies suggest we are well below this.

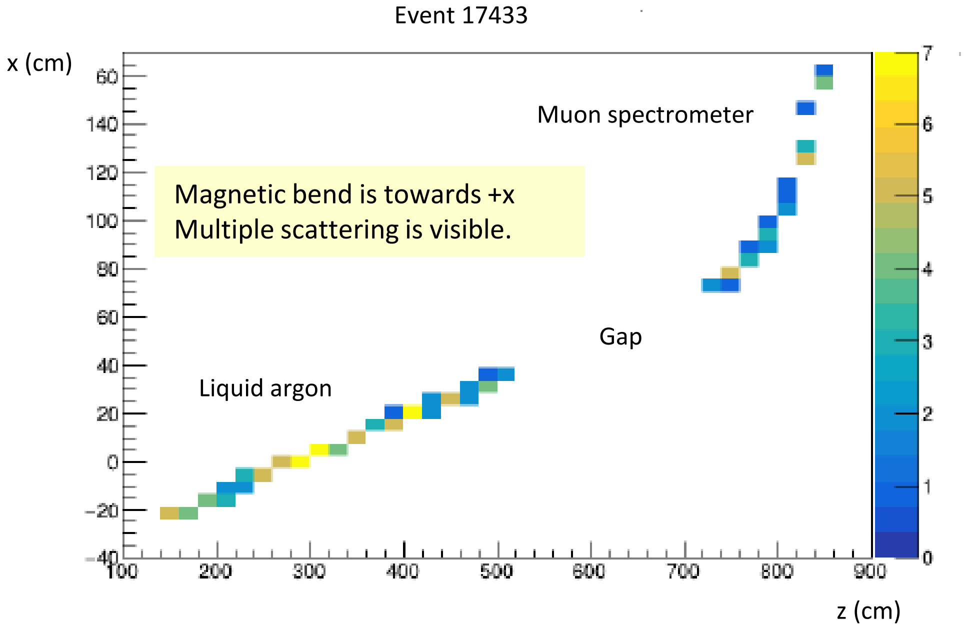
- Interface to the DAQ has just started, but the Data Concentrators' job is to take 19200 LVDS signals and format them the way the DAQ wants to see them

- Magnet power supply interfaces are settling – we hope to recycle an unused FNAL supply (and thereby gain more contingency)

- Mechanical interfaces are well understood between us and PRISM.
  - Down to the Hilman rollers
  - n.b. We cannot operate the spectrometer as it is moving

CHARGE QUESTION 2

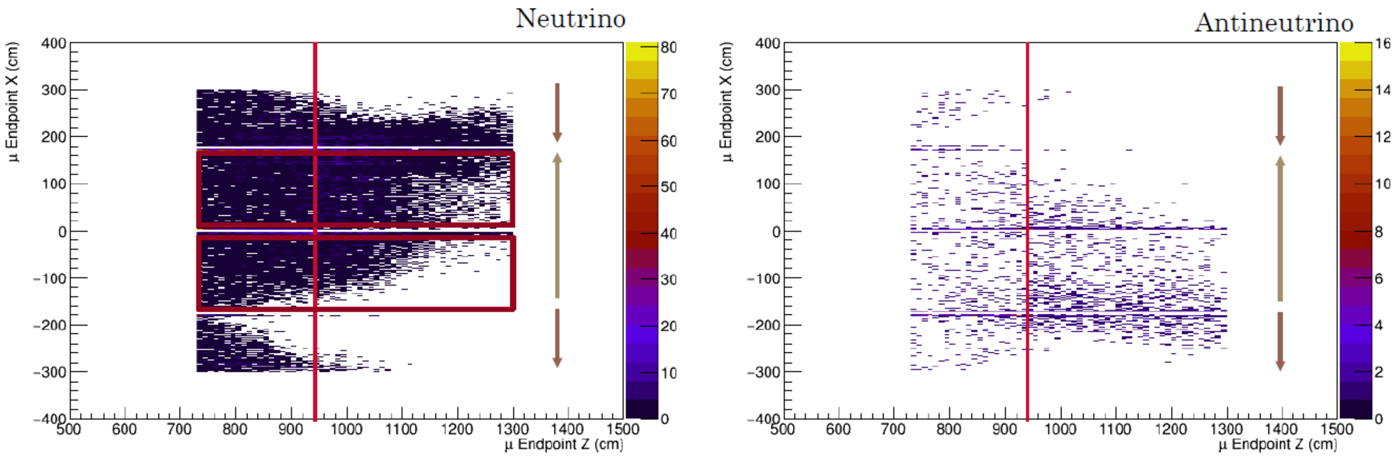
How Well Are We Doing Meeting the Goals?


Event 17433

Magnetic bend is towards +x
Multiple scattering is visible.

- Energy Resolution Goal: do no worse than the Far Detector (~4%).
- Preliminary simulations are at 6% core with a 10% RMS at oscillation maximum. (“Out of the box”)
  - This uses only the track stopping point
  - We believe 4% is achievable with a full fit + energy information. (MINOS did about this well)

- Sign-selection evident in the opposite bend between neutrinos and anti-neutrinos
- You can also see the effect of the magnetic field configuration
- This demonstrates why we want large acceptance:
  - There are regions of low occupancy, but that’s because they are populated by antineutrinos.
  - Reducing acceptance introduces complex kinematic sculpting.



Track endpoint position

Summary

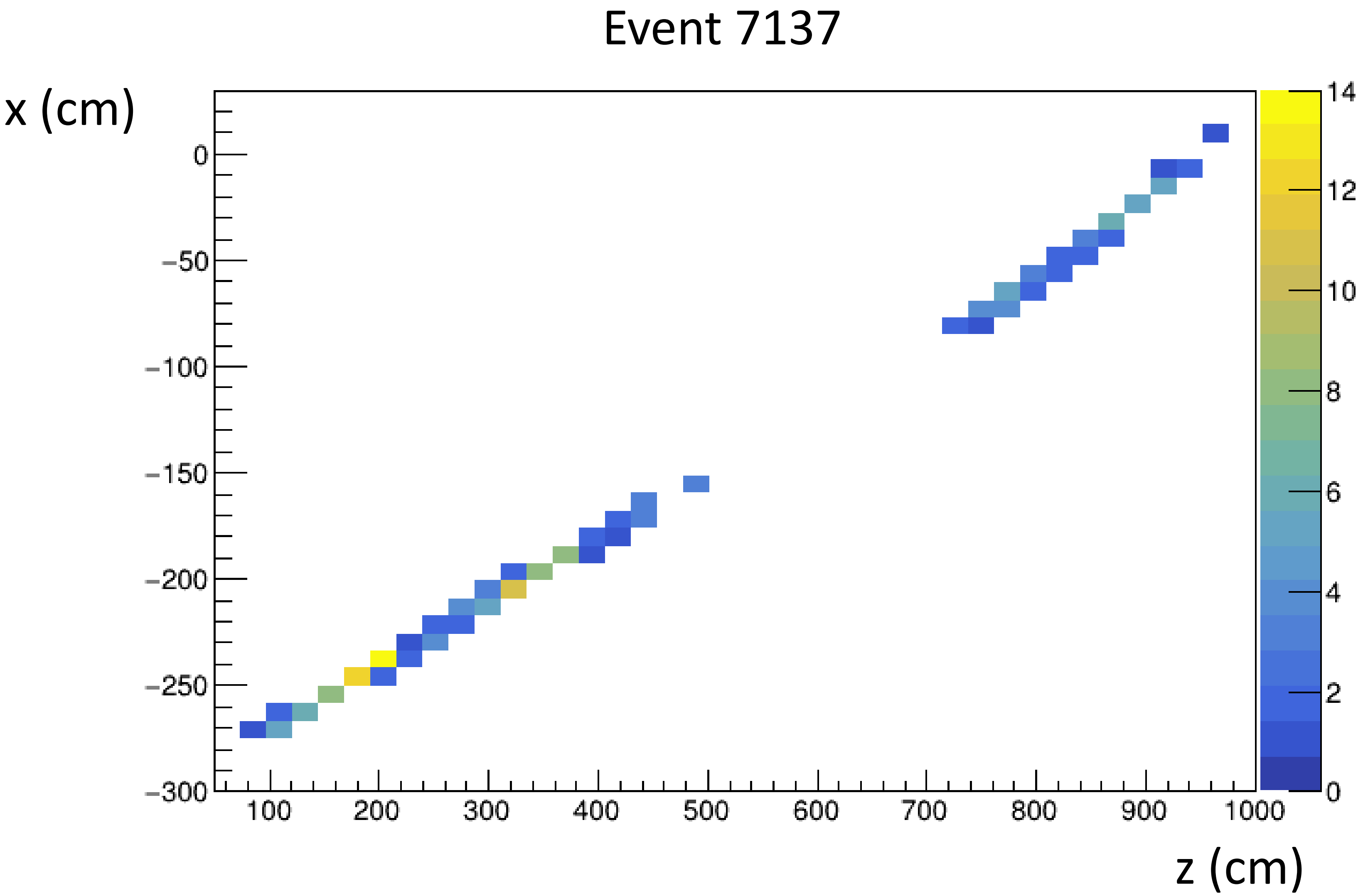
- This is a new subdetector, in response to the October IPR recommendations

- This subdetector design is not anyone's first choice. But…
    - It will do the job for the initial physics goals (see Dan Dwyer and Hiro Tanaka's talks)
    - We are prepared to build it
    - We know how much it will cost
    - We know about how long it will take – and will soon know this better.

- We're eager to get started!

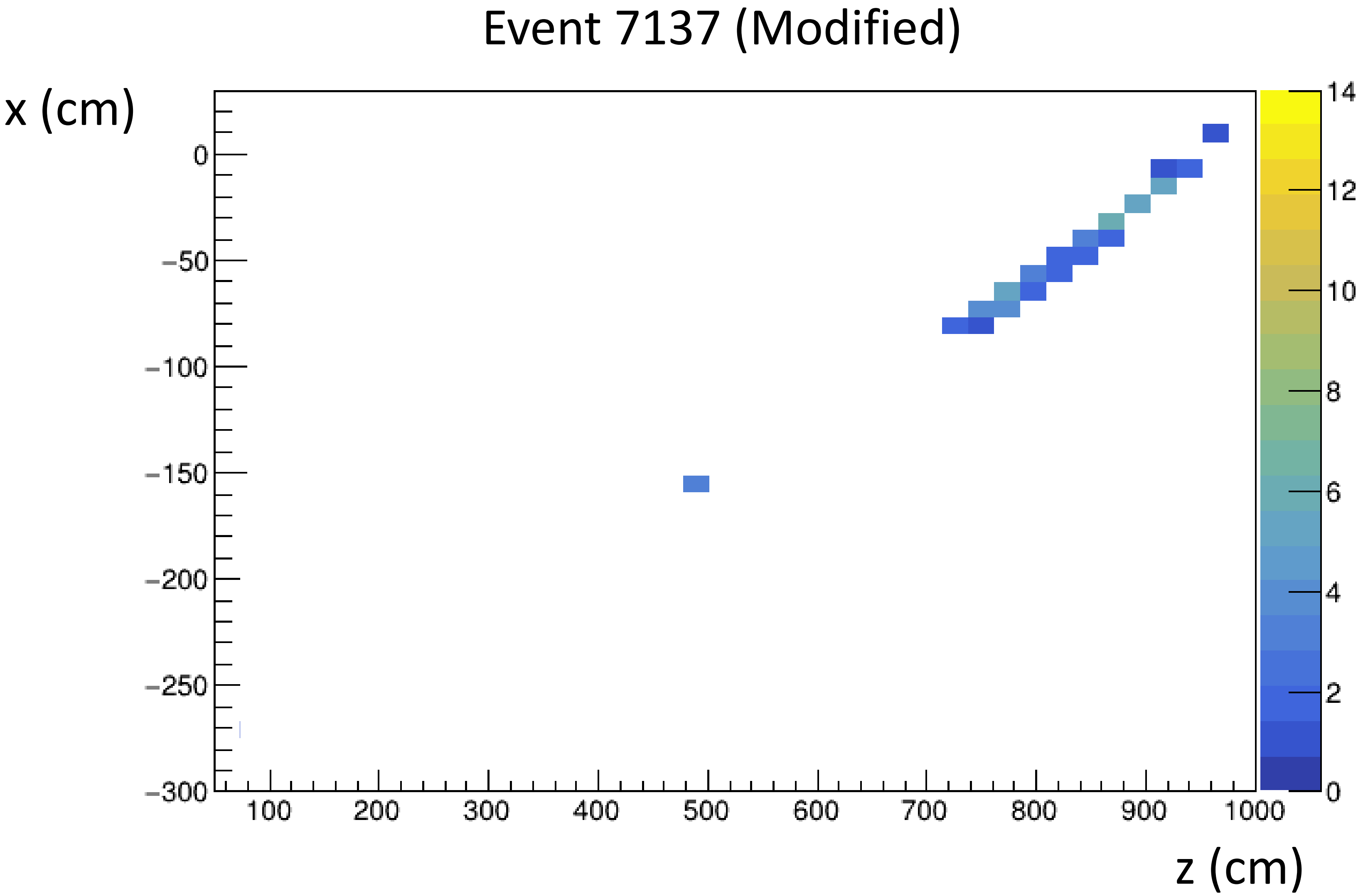
Backup

Extra Event Displays



Muon energy is 5.4 GeV

Extra Event Displays 2

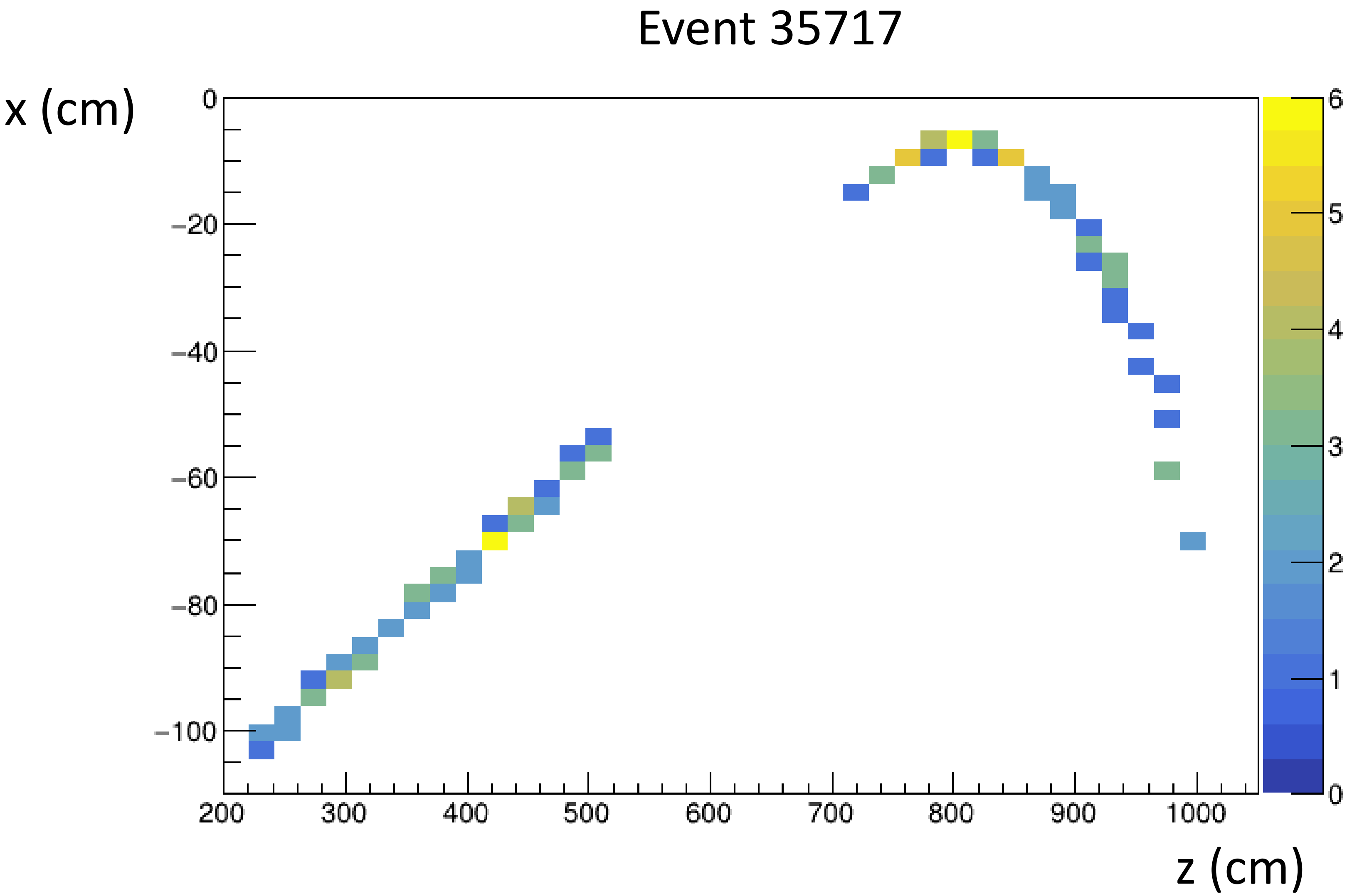


Muon energy is 5.4 GeV

The event interaction was moved to the far end of the argon.

This is the toughest case we have to deal with.

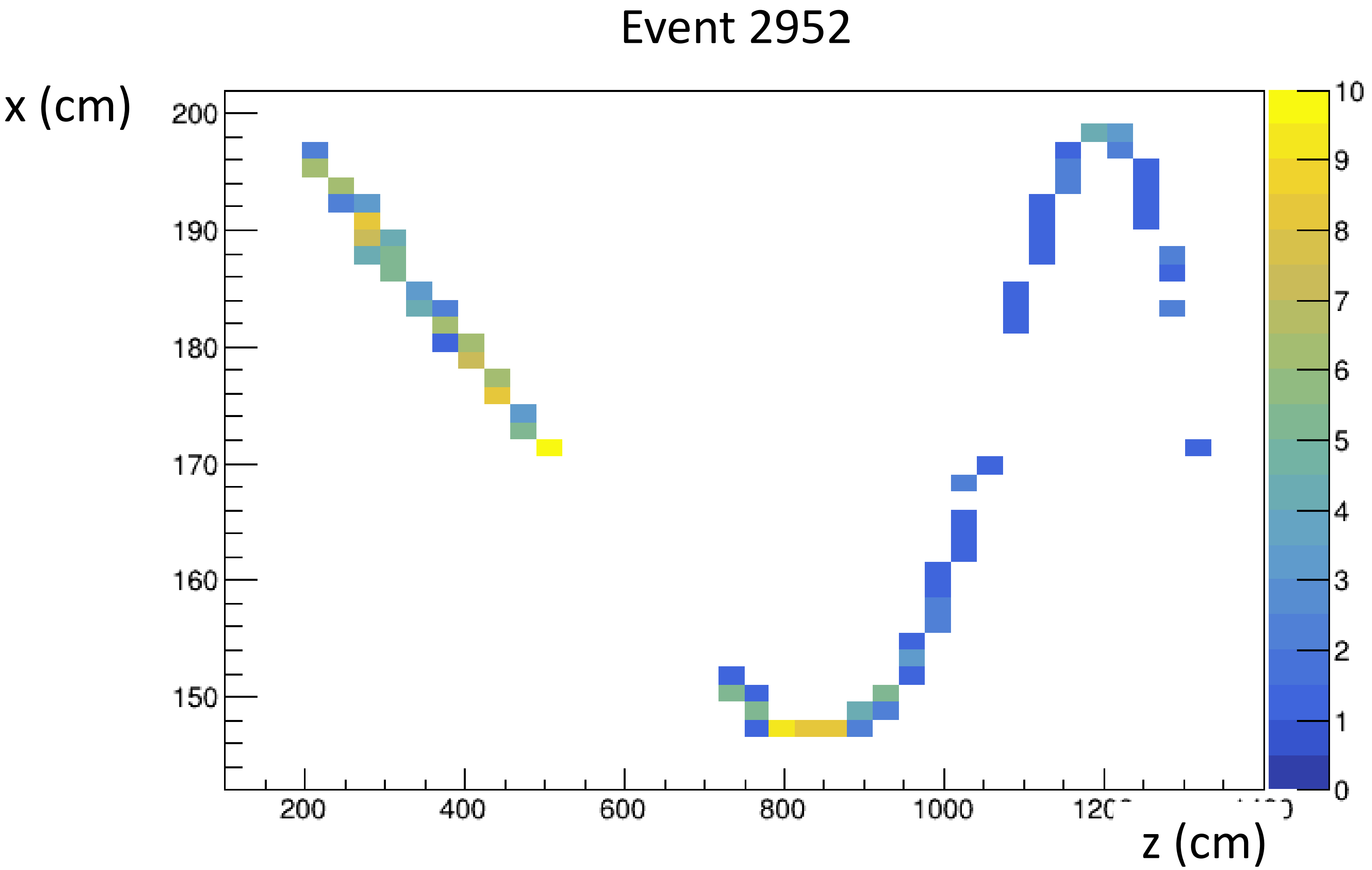
Extra Event Displays 3



Muon energy is 2 GeV

This is an anti-neutrino, so bends in the opposite direction.

Extra Event Displays 4



This is what happens when you cross a coil boundary.

Covid-19 Impacts

- Design work is still going on, but less efficiently
  - Issues that would normally take a few minutes in front of a whiteboard take longer vis Zoom
- We can’t start prototyping until we get back in our labs
- We haven’t started electronics design in part because a face-to-face kickoff is more likely to be successful than doing everything remotely

WHAT MEASUREMENTS DO WE HAVE?

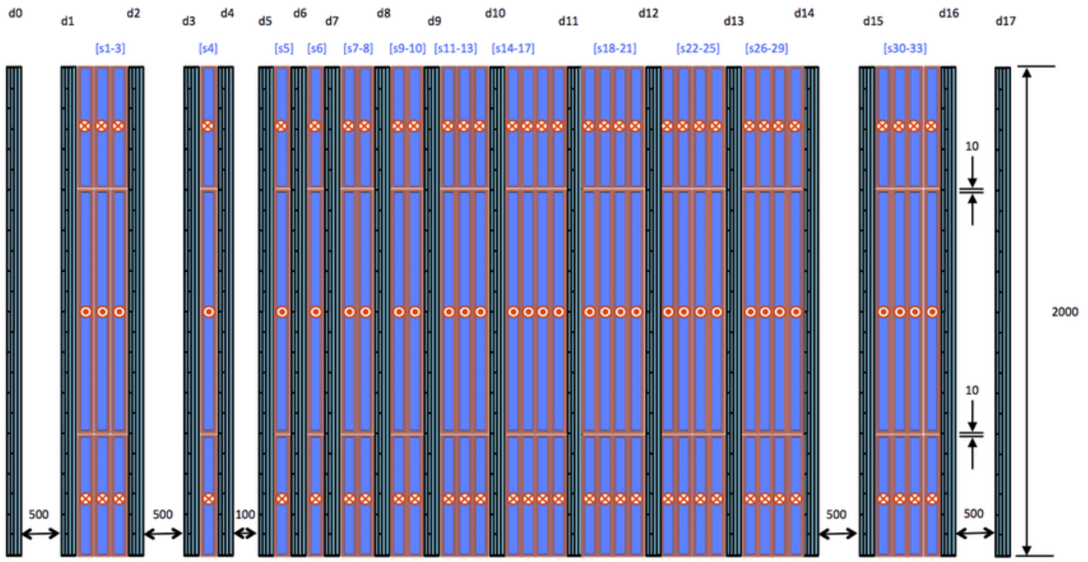
- In decreasing order of power
  - Muon range
    - Good to ~4% peak (matching far detector), 10% RMS
  - Total energy in scintillator
    - About 50% worse than range; it is hoped that this is largely anti-correlated with range (and thus can reduce tails)
  - Curvature in magnetic field
  - Relativistic rise & Bragg peak
    - Distinguishing between a muon that traverses 98 or 99 layers and one that exits the spectrometer is difficult.

- Combining these might be a good application of machine learning

- This device predominantly measures p_z.
  - Range works by energy loss, which is proportional to $1/\cos(\theta)$. $p = p_z/\cos(\theta)$.
  - The magnetic field is in the y-direction, and deflection is measured in x.
- Relativistic rise sees $|p|$

MAGNETIZED RANGE STACKS

- Alternating layers of magnetized absorber and active detector simultaneously measure a muon’s momentum and its energy.
- Each centimeter of magnetized iron provides:



An early design of Baby MIND, an example

Energy Loss

$$\frac{dE}{dx} \approx 11.4\ \text{MeV}$$

Accumulates linearly

Multiple Scattering

$$\Delta\varphi \approx \frac{1}{p} 0.59°$$

Accumulates as square root

Magnetic Bend

$$\Delta\varphi \approx \frac{qB}{p} 0.17°$$

Accumulates linearly