Temporary Muon Spectrometer

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Conclusions (on Slide 1!)

- If all you are interested in is muon measurements from ν interactions, ND-GAr, ND-GAr(Lite) and TMS all perform similarly. (And now you can read your email instead of listening to this talk)
  - Momentum resolution in the few percent range
  - Similar acceptance (~20 m^2 scale)

- If your analysis is sensitive to these, you need to run the full MC to understand the impact – a 20 minute talk is not going to be enough.

- Of course, the reason we want ND-GAr is not superior muon measurement
  - It's the enhanced physics reach, especially at low energy
- The argument for ND-GAr(Lite) is not superior muon measurement either
  - It's the better path to full ND-GAr. (Among other reasons, you don't have a thousand tons of iron in your way)
- The argument for TMS is to start the physics program at the earliest possible time, and to convince the funding agencies that we have the resources in hand to do this.

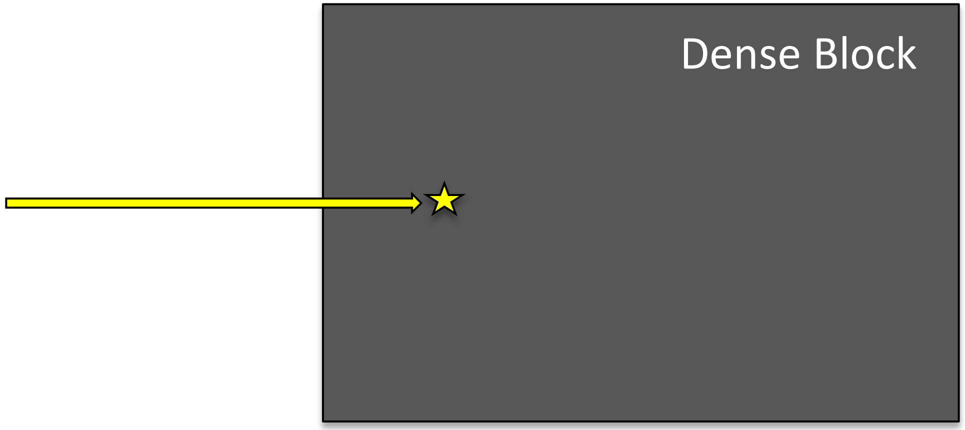
Temporary muon spectrometer (lower case) requirements

- Inexpensive and quick to build
  - Allows delaying go/no-go decision to take advantage of favorable ND-GAr developments
- Large area
  - Match ND-LAr, which is sized for event containment (not event rate)
- Inexpensive and quick to build
- Resolution comparable to the Far Detector
  - We don't want to be the limiting systematic (the point of the ND is to *reduce* systematics)
  - Doing a lot better does not substantially improve the Long Baseline program
- Inexpensive and quick to build
- Operate in the ND environment
- Inexpensive and quick to build
- Able to tell μ+ from μ-
  - Some will say we don't need this for FHC, because antineutrino contamination is so small. I don't want to argue this today, other than to point out that this is "trust the beam Monte Carlo" applied to flavor rather than momentum.
- Oh, and Inexpensive and quick to build

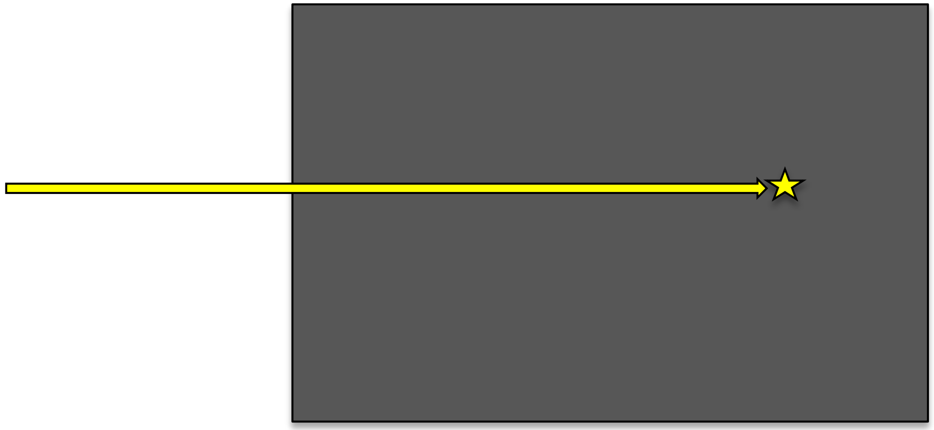
You might detect a theme here.

Measuring A Muon’s Momentum Without A Spectrometer

See how far it takes to stop:

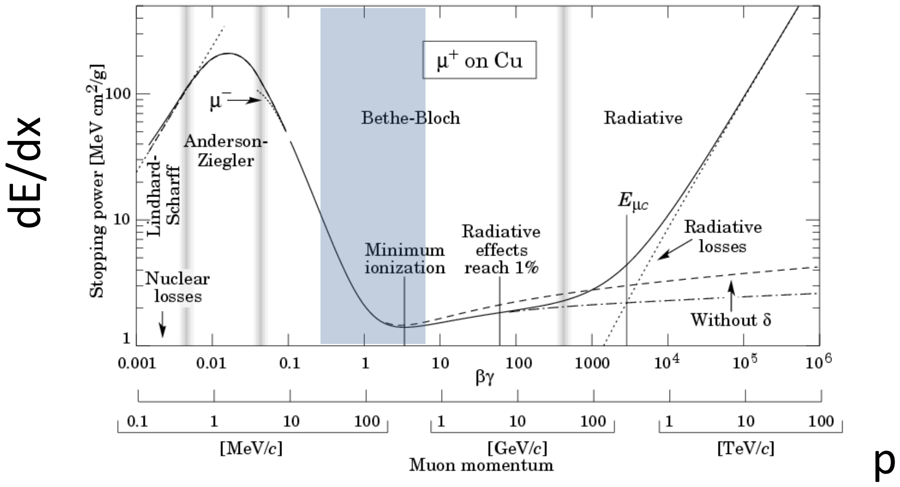


Low Momentum



High Momentum

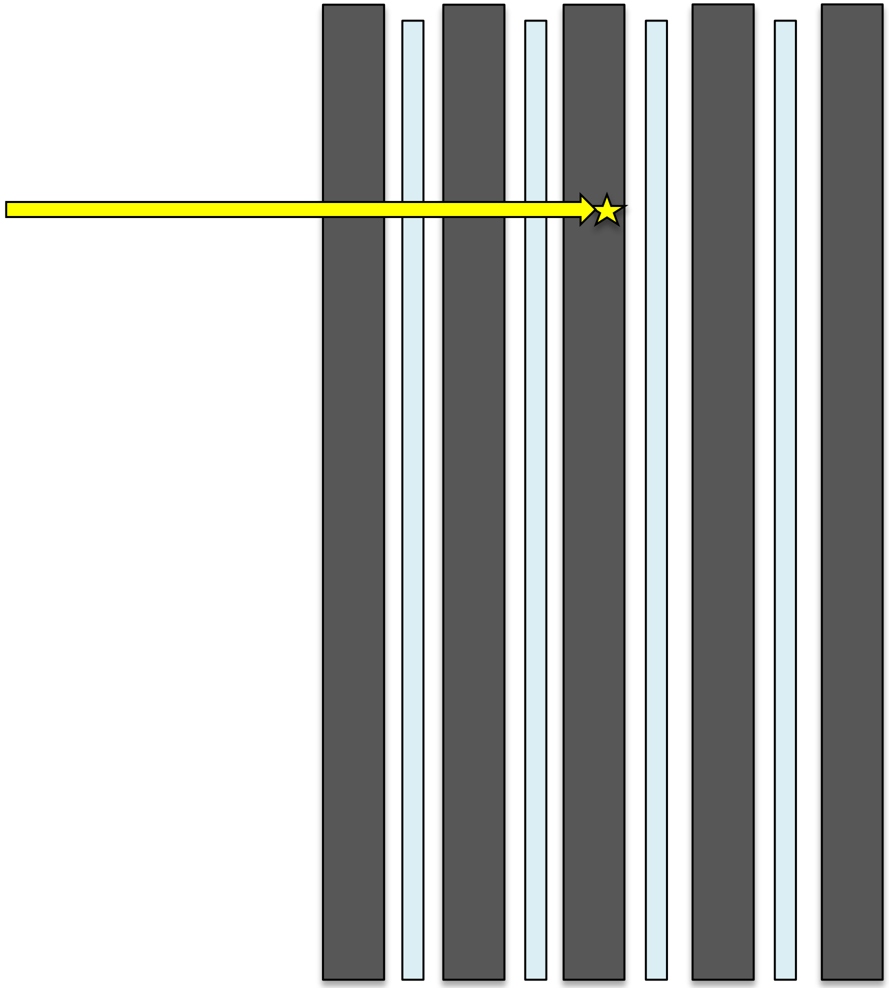
- The larger the momentum, the farther the muon goes.
  - This is monotonic, and almost linear:



DUNE operates mostly in the blue

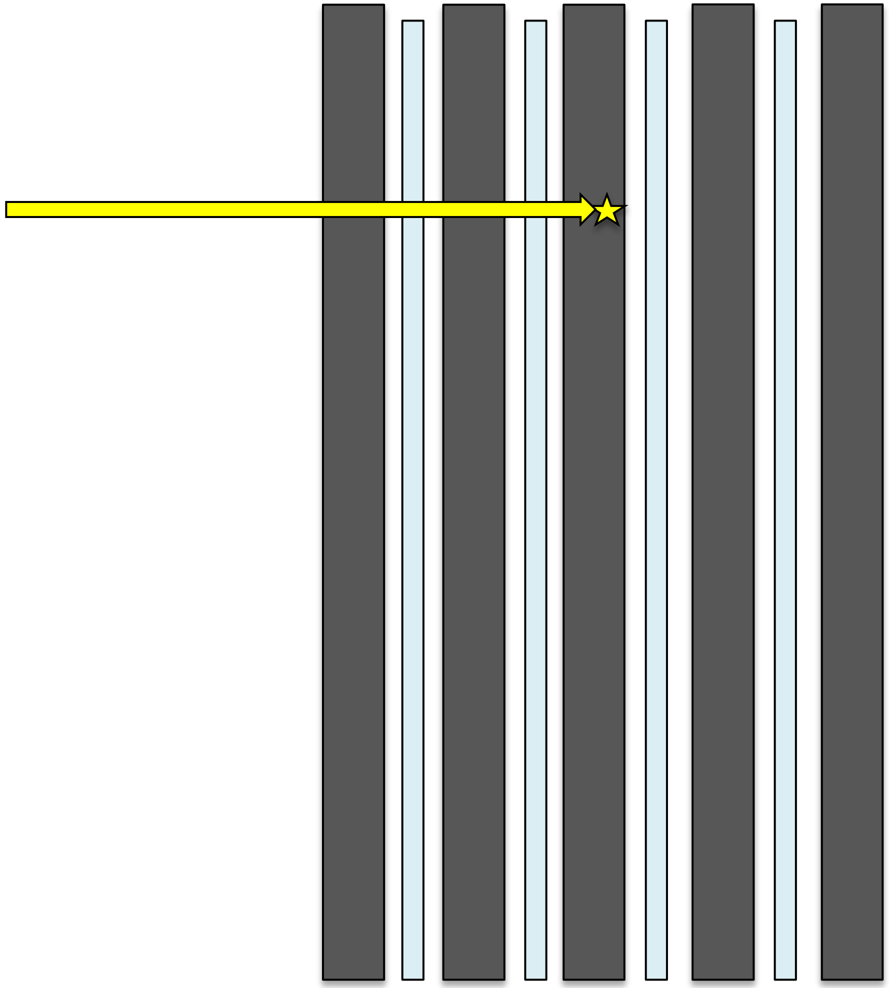
- Resolution is a few percent at these energies
  - Worked out by R.R. Wilson. (Yes, *that* Wilson)

Where Exactly Does It Stop?

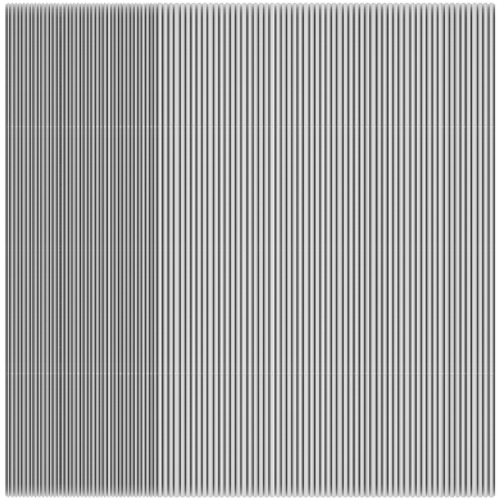


- One giant block is not very helpful.
- Slice it into planes, and put detectors between each plane
  - See where the track ends
  - Resolution depends on the plane thickness – thinner is better (but that affects channel count and mechanics)
  - Upper energy range depends on plate thickness – thicker is better (more dense material)
- A 10 mm thick scintillator requires a 40 mm gap
  - 10 mm for the scintillator
  - 10 mm for the box to put it in (greatest extent)
  - 10 mm on each side as a stay-clear for steel tolerances.

Longitudinal Geometry



- We want ~4% momentum resolution – requires a “typical” muon to penetrate 25 layers.
  - We would like this to be at ~600 MeV (after the muon leaves the argon)
- We would like to go out to momenta of ~5 GeV
  - This implies 3 m of steel. We have 7 m of space. Arithmetic gives 100 layers.
- The only way to do both of these things is to vary the steel thickness with depth
  - First 40 (42) layers are 15 mm (5/8”) thick
  - Last 60 (58) layers are 40 mm thick
  - This is the aspect ratio of a 3x5 index card



Transverse Geometry

- Conventional trackers measure curvature (1/p). This is not a conventional tracker.
  - At each layer, a particle gets a magnetic bend proportional to 1/p
  - The number of such bends before the muon ranges out is proportional to p (well, E)
  - The deflection is therefore **independent of muon momentum**

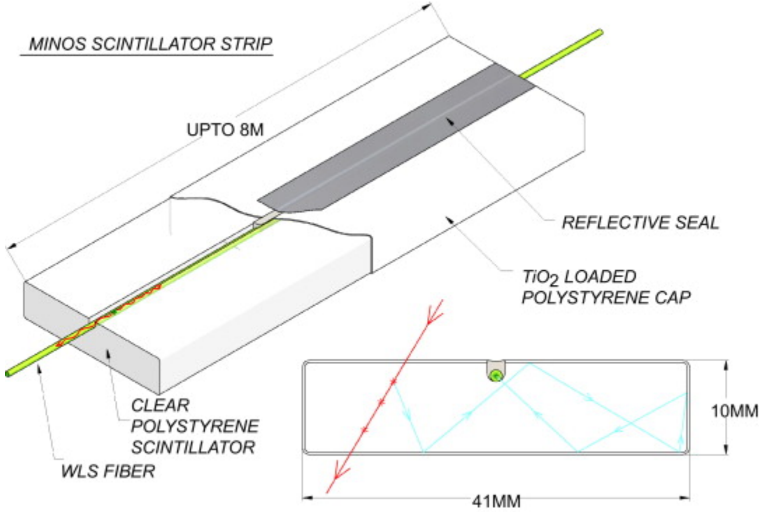
- For high momentum muons the point of maximum deflection occurs later in the stack

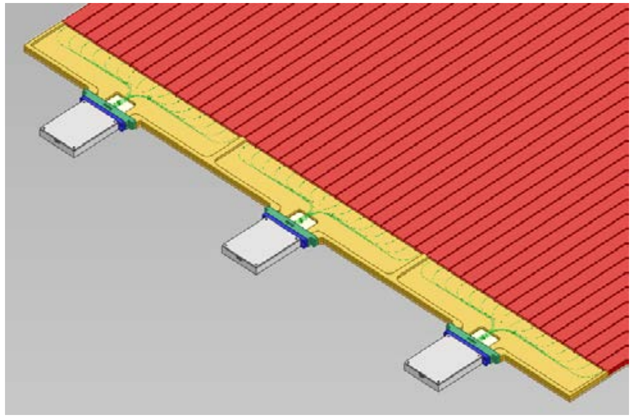
- Sagitta is ~7 cm for a 1 Tesla field (independent of momentum)
  - Therefore we want a granularity of 3.5 cm or less in the magnetic bend view
  - Because maximum deflection can occur anywhere in the stack, we need this granularity for every layer.

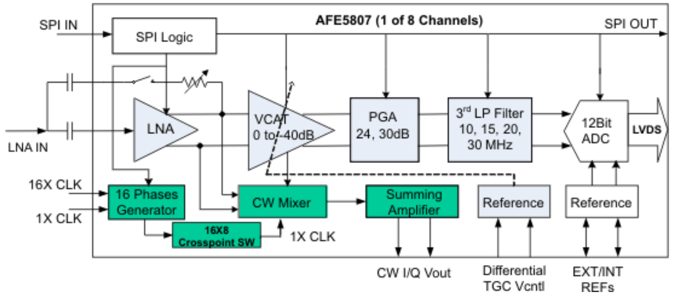
Detector Design Overview

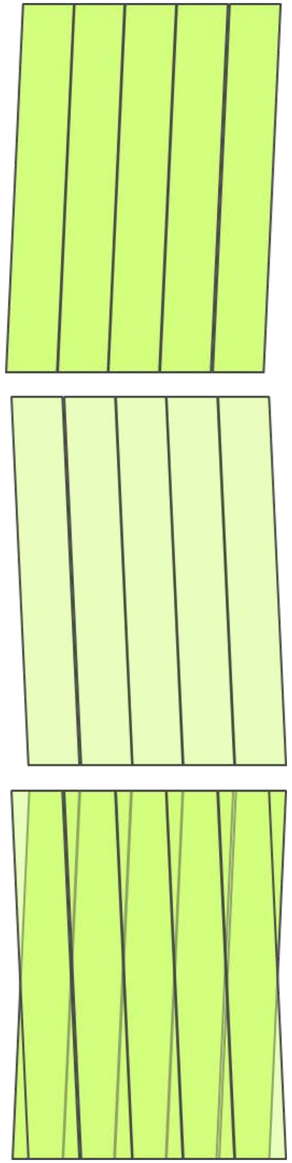
- Design is MINOS/mu2e-like (co-extruded polystyrene)
- Each plane (of 100) has four panels (192 channels)
- Each panel is a self-contained box containing
  - 48 slats of scintillator 3.54 cm wide with Y11 wavelength-shifting fiber
  - SiPMs, Front End-ADCs (based on Texas Instruments AFE5807 chip) and associated electronics

- Panels (which are rectangular) are tilted ±3^{o} in alternating layers
  - Gets us ~45 cm resolution in y-direction
  - Single bucket (under 19 ns) time resolution

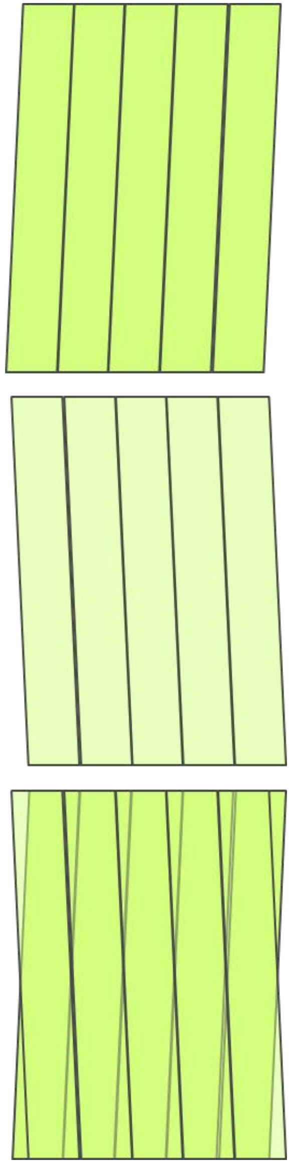








Stereo Implications



- Stereo is a cheap way to get non-bend information

- The ±3° angle is as big as we can make it – even that is pushing it
  - Order of magnitude worse resolution in the non-bend view

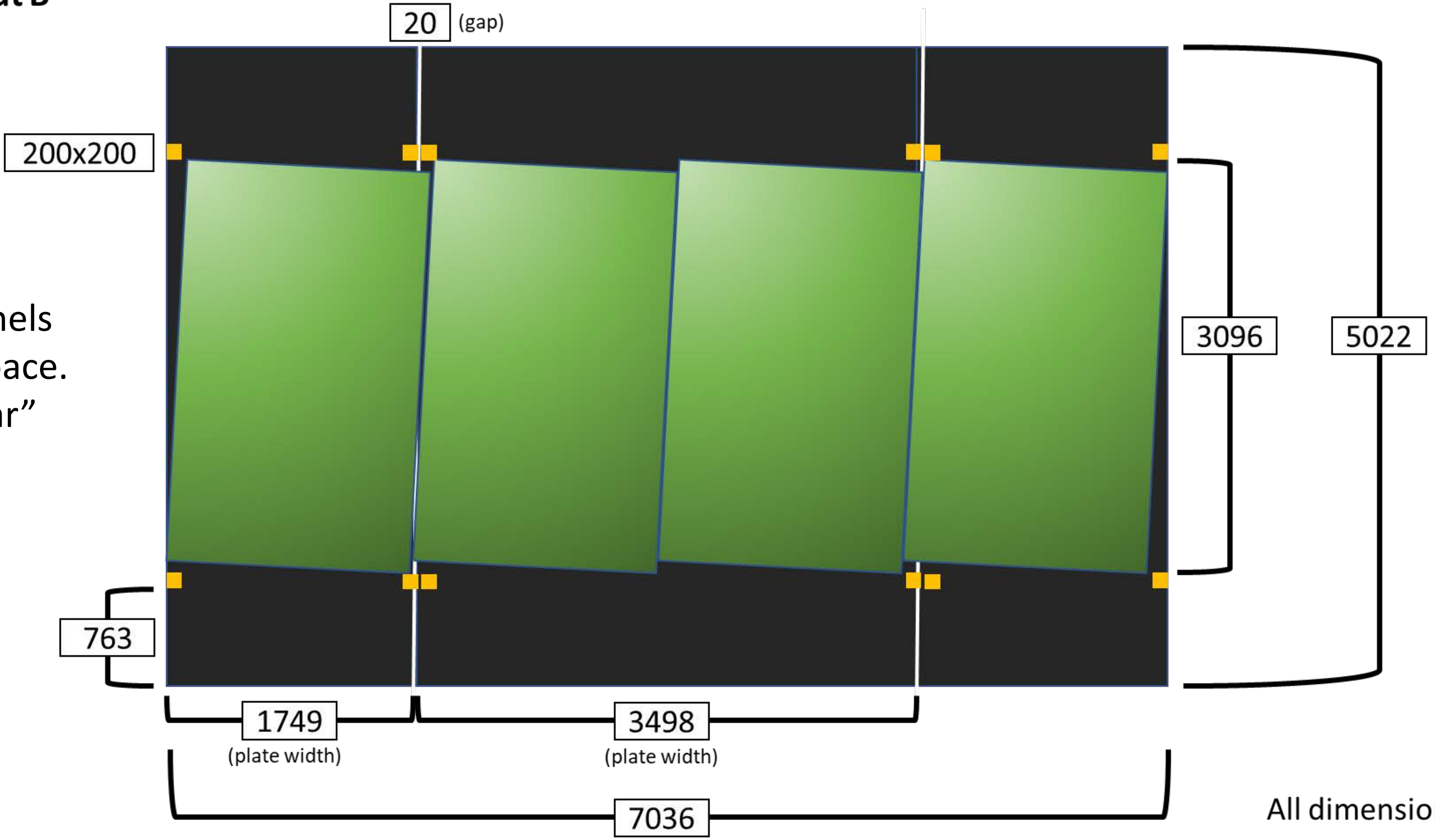
- Alternating orthogonal views would have better pattern recognition, but worse sign determination.

- This is designed for single muons – multi-muons have to contend with this geometry
  - The best way to improve this is increasing the channel count. That costs money.

Detector Plane + Detector Panel Geometry

Layout B

There is a 40 mm gap between plates. The panels occupy 20 mm of this space. The remaining “stay clear” accommodates steel flatness tolerances.



All dimensions in mm

Counter boxes are 1710 x 3010

Channel Geometry

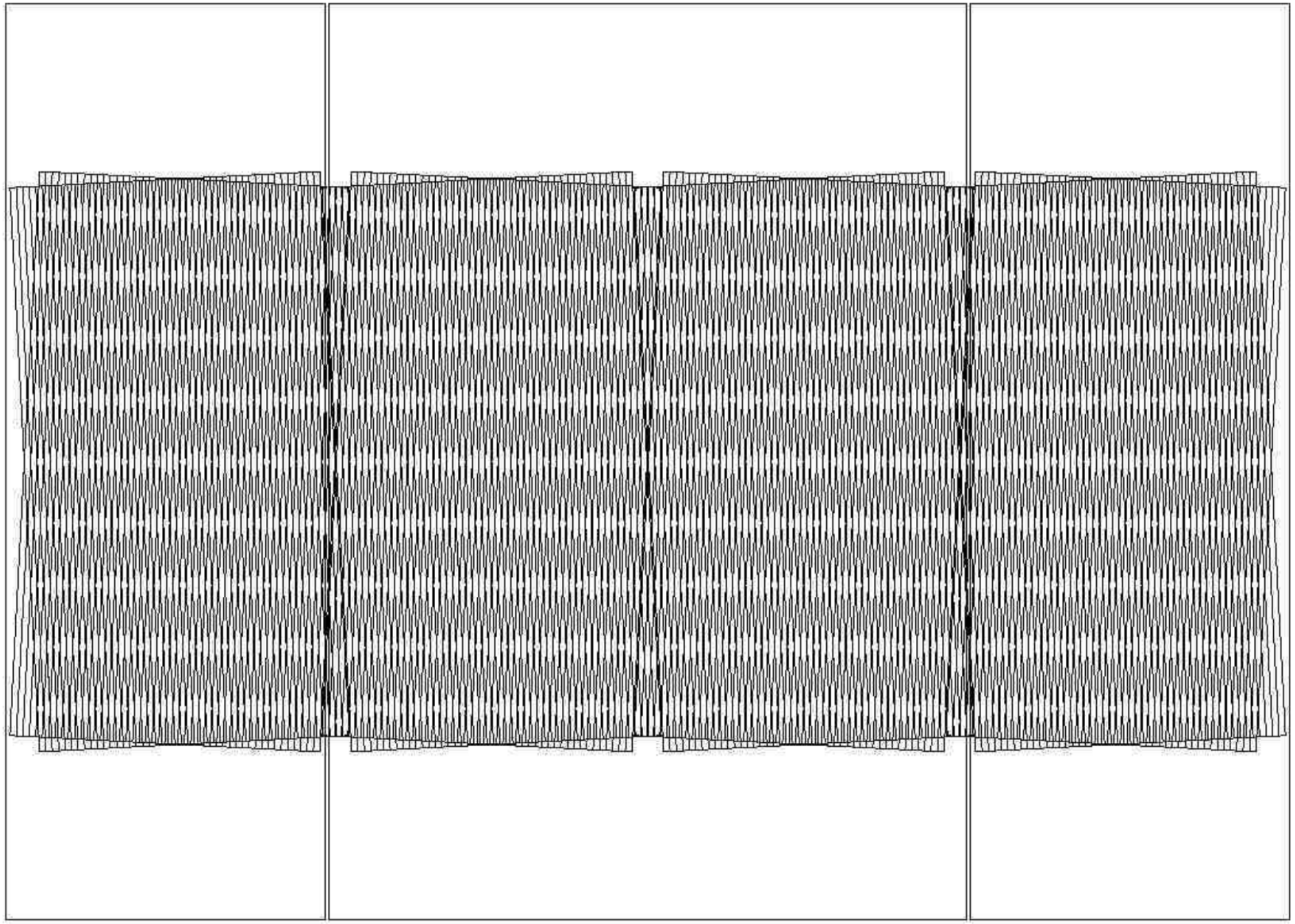
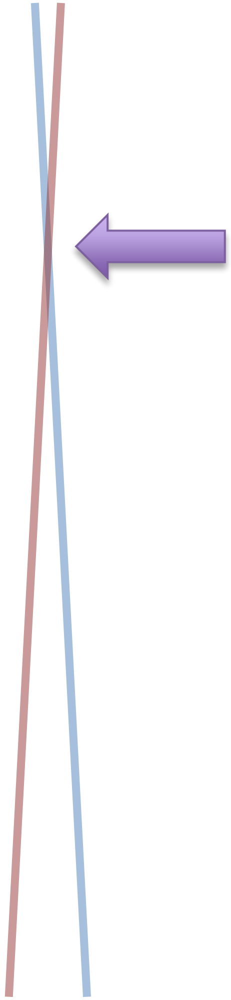


Figure by Palash Roy, Wichita State



Stereo tracking localizes a muon about this well.

TMS has the single-track localization of a ~300,000 channel detector with only 19,200 channels.

But it still has the pattern recognition of a 19,200 channel detector.

Measuring three muons is easy. Measuring three *nearby* muons is going to be tough.

Magnetic Field

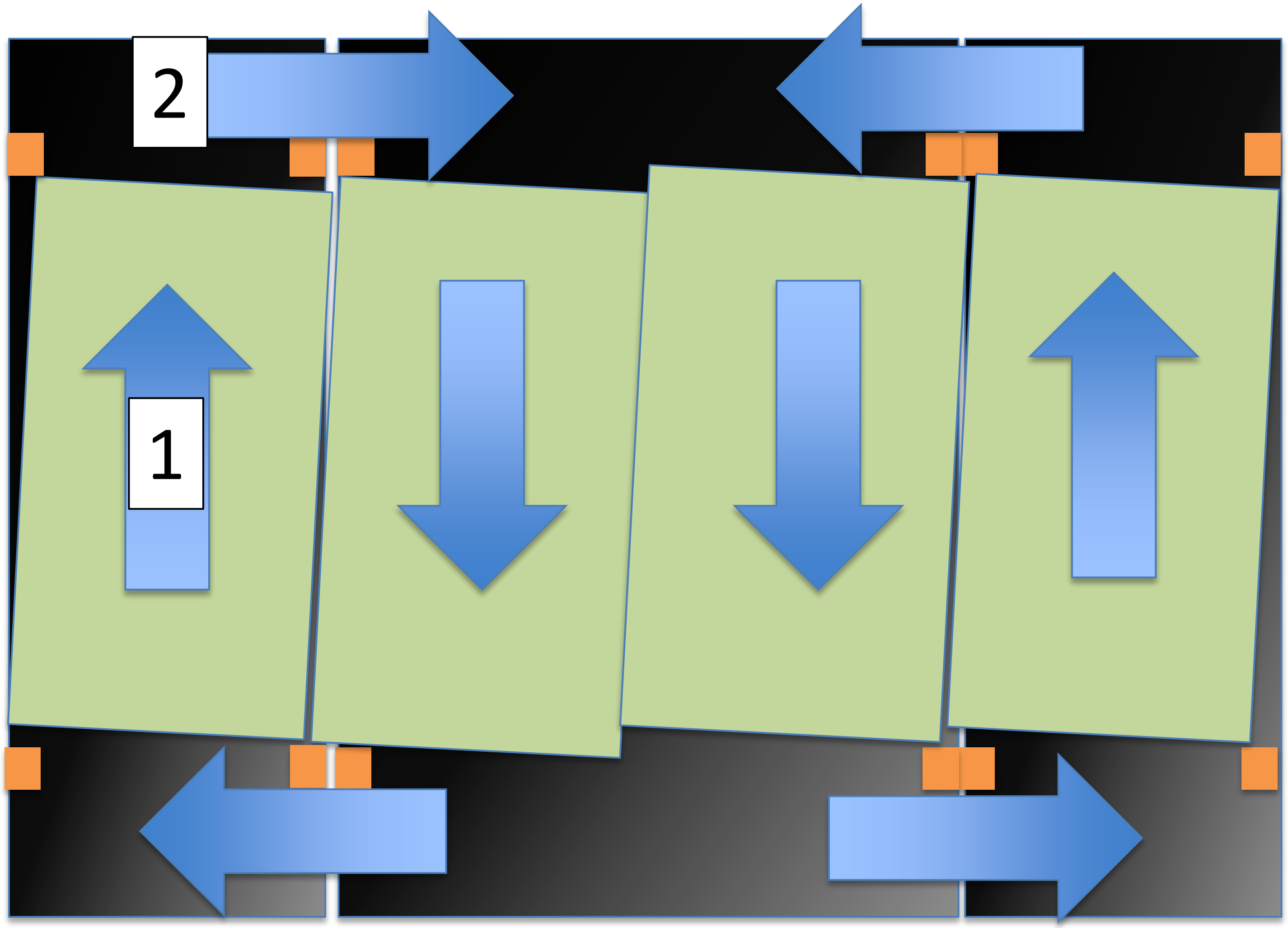
- There is a relationship between the field and the geometry of regions 1 & 2:

$$B_1 = \frac{h_2}{w_1} B_2$$

$$(\nabla \cdot B = 0)$$

- Saturating the iron in Region 2 gives a magnetic field of 1.0-1.1 T in Region 1 (where we measure muons)
  - Region 2 is about as big as we can make it in both cost and weight

We use AISI 1006 steel (i.e. “Minos steel”) $\mu = 700$



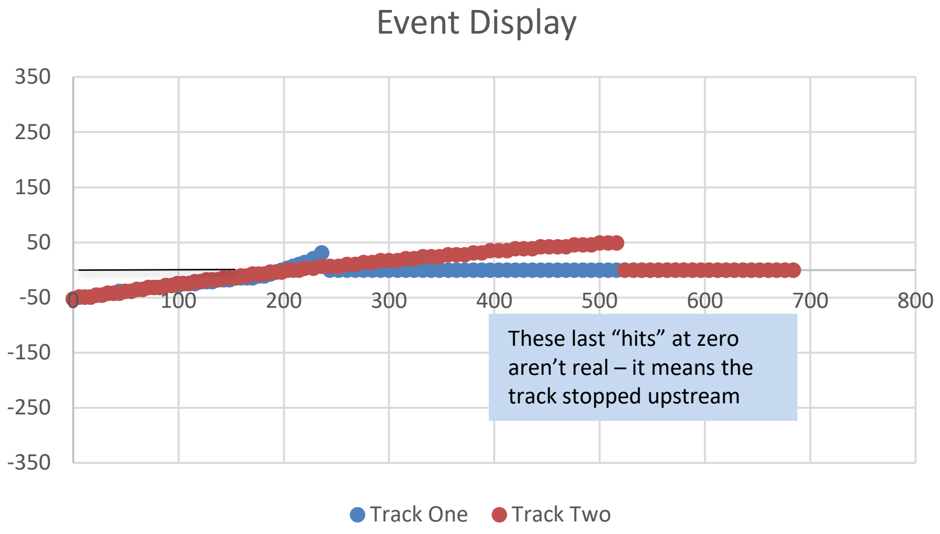
How Well Are We Doing? Some TMS “Event Displays”

- These are Excel-level “Monte Carlo” that includes magnetic bend, multiple scattering, Landau-like energy loss, and counter quantization.
  - We have a real simulation as well – this is just more convenient for me, especially for finding “oddball” events
  - Measurements are vertical only – no stereo

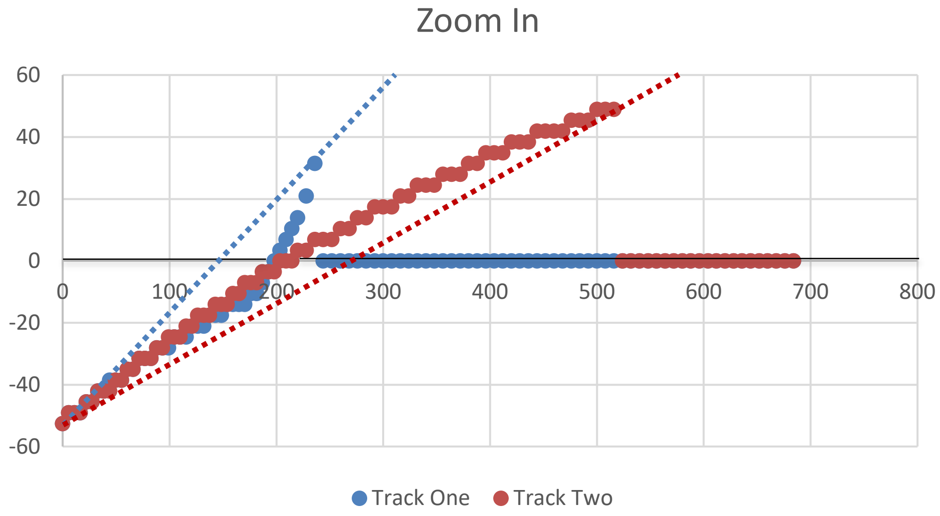
- **Blue** is a 1 GeV μ^+, **Red** is a 3 GeV μ^-.

- Range is visibly different
  - A factor 3 in material, which is not a factor of 3 in distance (steel is thicker in back)

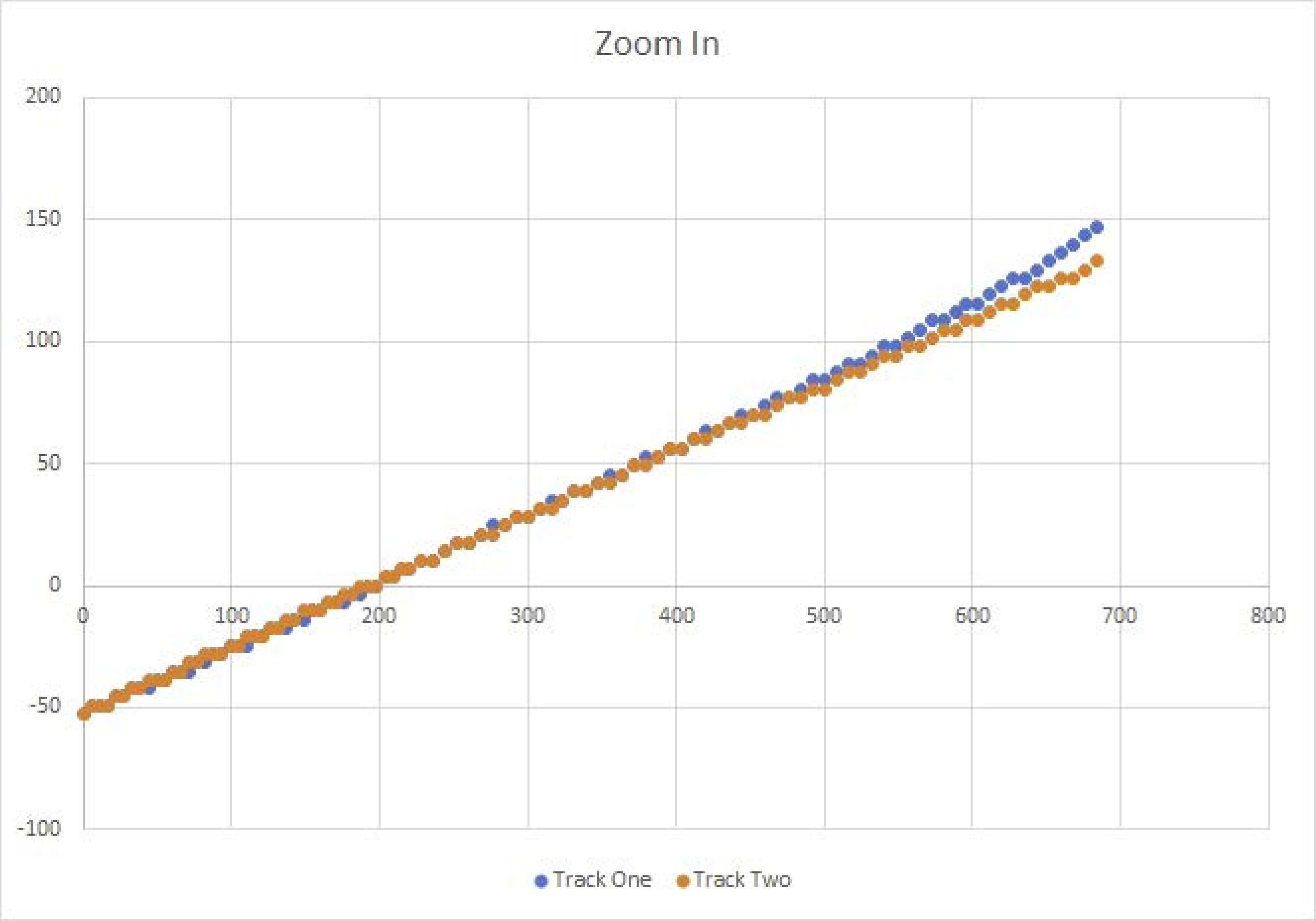
- Sagittae are in opposite directions (good)
  - Their magnitude is almost constant - not proportional to 1/p (as expected)



These last “hits” at zero aren’t real – it means the track stopped upstream



TMS At High Momentum



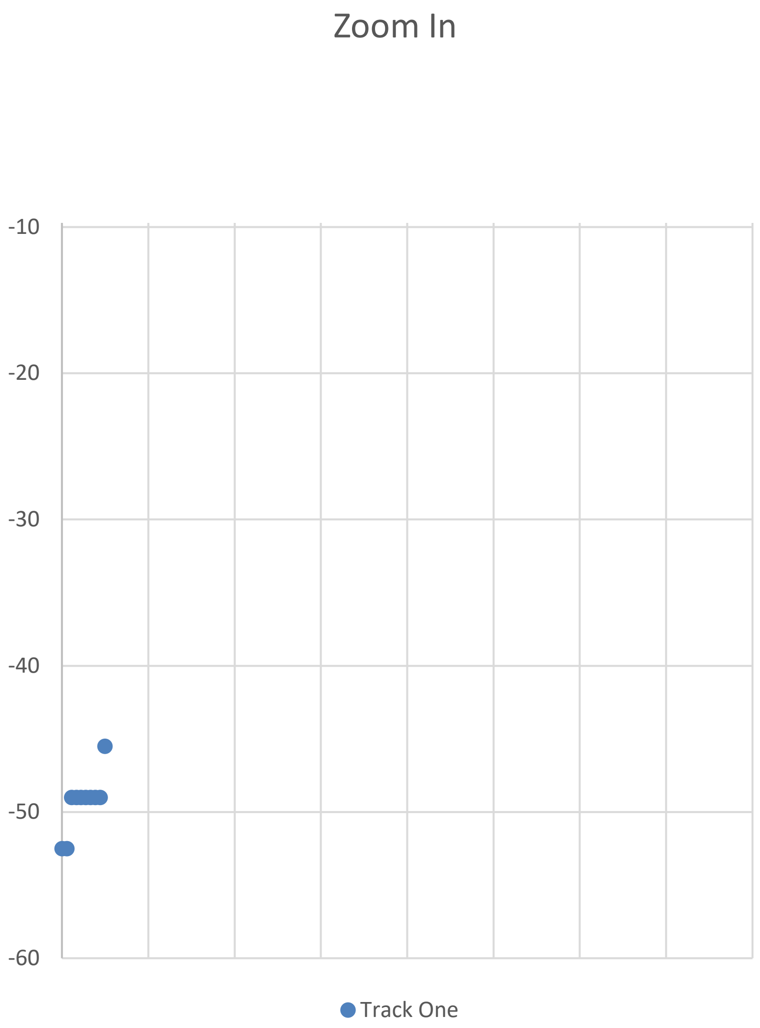
- **Blue** is a 5 GeV μ^+, **Orange** is a very high momentum μ.

- At 5 GeV, we have pretty good charge ID.

- The track starts curving late – once p < 1 GeV or so.
  - One could say TMS measures the charge of ~1 GeV muons. The more energetic the muon is initially, the deeper in the stack this happens

- We can distinguish 5 GeV from infinity. We probably can't distinguish 6 GeV from infinity.

TMS At Low Momentum

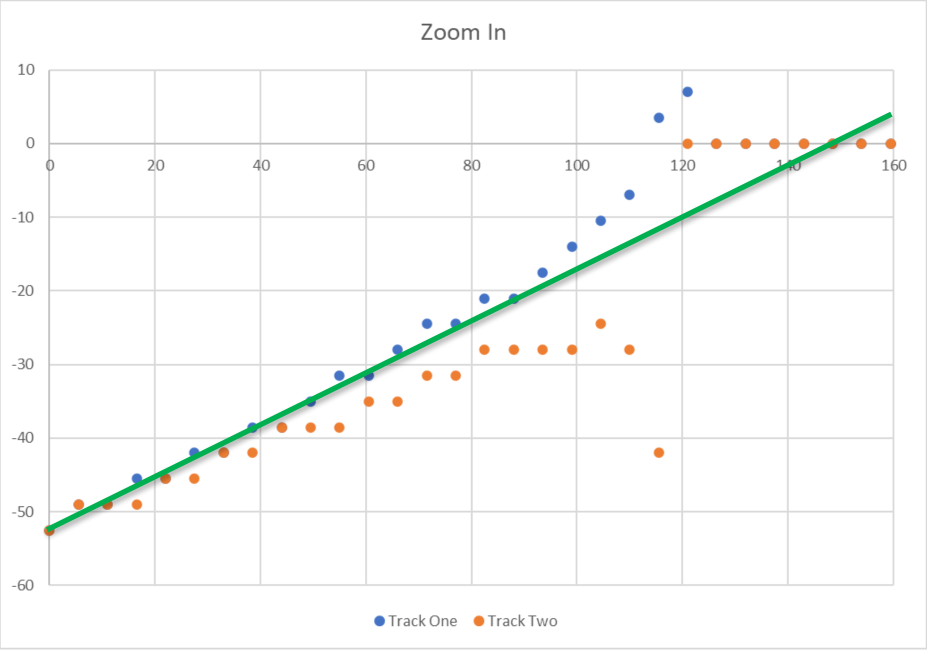


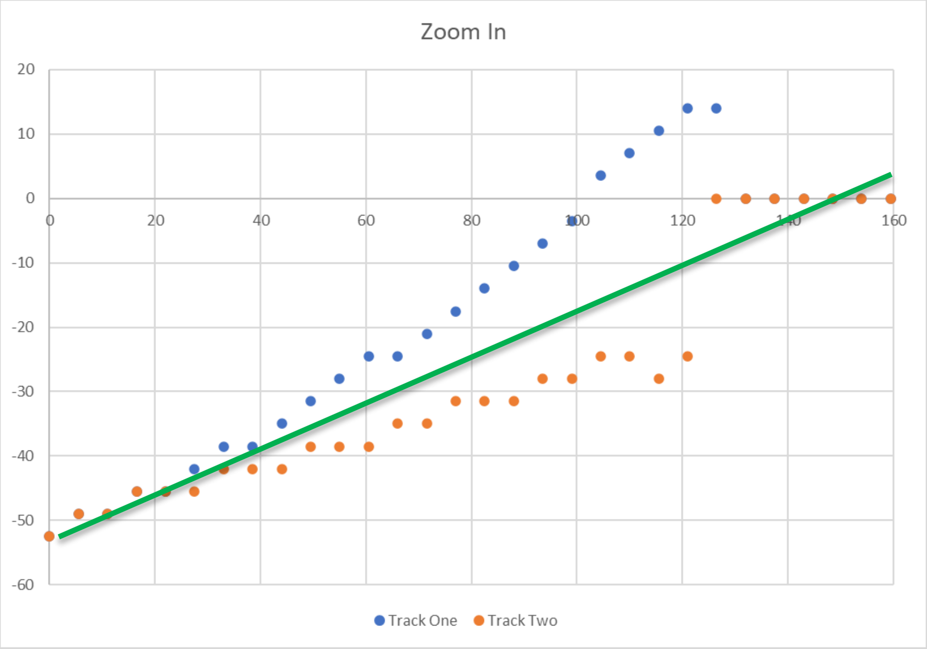
- This is a 200 MeV muon.
  - This is after 0-1.2 GeV energy loss in the LAr depending on where the interaction occurred
  - The energy resolution here is at its worst (fewest hits)
  - The energy resolution here is at its least important (most energy is lost in the liquid argon)
- Its charge is not discernable. (But sometimes you can – see later slides)
- Our charge ID actually gets better at high p, unlike a conventional tracker
  - We have more hits (major reason)
  - We have less multiple scattering (minor reason)

Some Typical Muons

- Muons are 500 MeV of each charge entering the same place in the detector at the same angle (green line), presumably well known from ND-LAr.
  - These are typical at oscillation max

- The vast majority of events (>90%) look like this.
  - Oddballs in backup.





Energy Measurement

- Based on similar detectors, we expect around 15 photoelectrons/mip per hit

- While we wouldn’t necessarily pay extra for it, the front-end chip provides a 12-bit ADC “for free”
  - This is presently the Texas Instrument AFE5807 chip (ultrasound and fishing sonar)
    - My hope is a 106 MHz version will be out when we need it –allows two time samples per signal
    - mu2e also uses a variant of this chip

- The SiPM provides at most 9.2 bits of dynamic range
  - It’s not decided where in the 12 bits we put the 9.2

- As a calorimeter, it’s not too bad – the biggest issue will be uniformity

Data Rates, Thresholds & Cosmic Rays

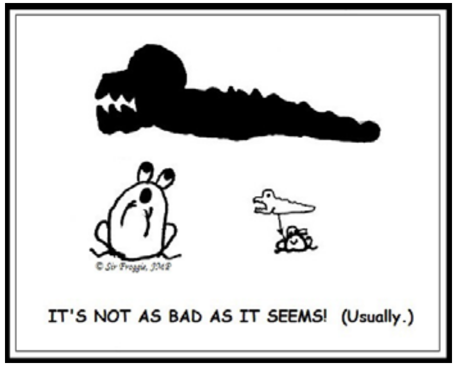
- The spill structure is: (in terms of 19 ns RF buckets)
  - ~530 buckets with beam (588 MI harmonic number less ~50 for extraction gap)
  - 53,000,000 buckets with only cosmic rays while the MI ramps
  - Then ~530 buckets with beam…etc.

- The data rates are dominated by SiPM noise
  - Takes 30x the duration of the spill to read out everything (but that’s OK, because the electrons in the liquid argon are still drifting)

- We cannot read out the entire detector with zero threshold over the full cycle
  - 98% of the cosmic period will require at least ½ mip total energy in non-overlapping groups of 5 panels to trigger a full-readout
  - The other 2% will be read out like in-spill data

- We don’t have to go to cosmic mode immediately after the spill ends (for late-arriving particles search)

Data Rates and ν–Fe

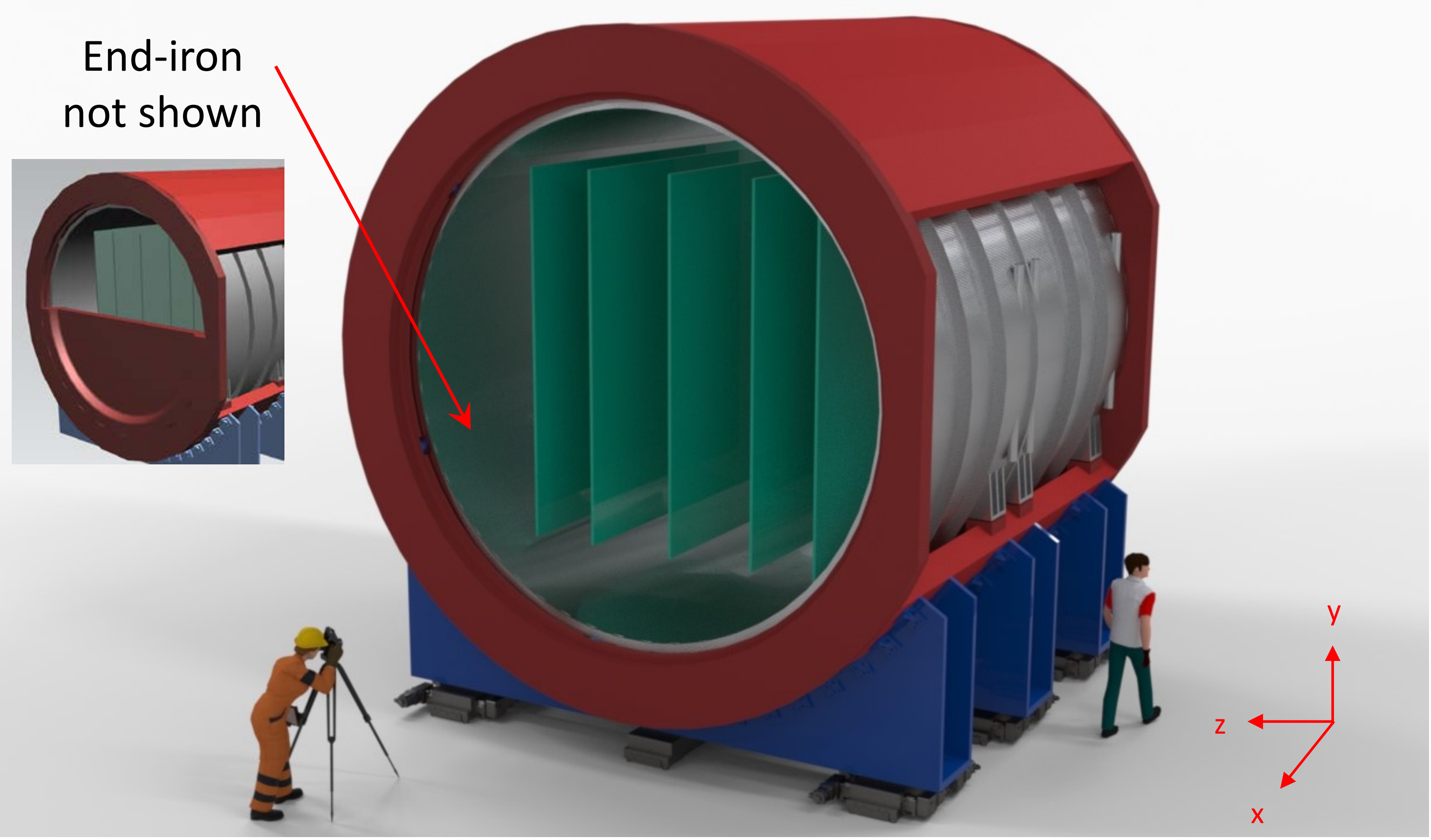


- 1000 tons of iron makes a swell neutrino target
  - We estimate ~200 CC events per spill from neutrino-iron interactions

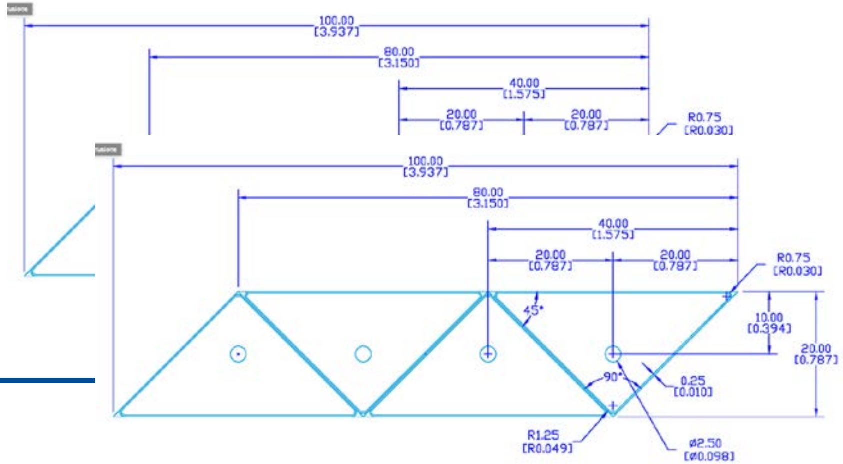
- This is not as bad as it looks
  - Most of these are in the back, where the steel is – unlike muons from the Lar
  - Each plane has 48 channels per panel, and ¾ of the time the 2nd neutrino isn't even in the same panel

- However, Poisson is Poisson
  - 40% means there will be a handful of events every year with 7 or 8 muons in TMS
  - That may set an ultimate limit on multimuons

One Slide on ND-GAr(Lite)



- Full magnet system
  - Coil(s)
  - Return iron
- Scintillator tracker (still under design)
  - Minerva-like scintillator planes
    - Triangle: 4 cm base, 2 cm height
    - 5 planes: 6 m long X 5 m tall
      - Spacing to be optimized
    - X-Y readout



Conclusions

- If all you are interested in is muon measurements from ν interactions, ND-GAr, ND-GAr(Lite) and TMS all perform similarly.
  - Momentum resolution in the few percent range
  - Similar acceptance (~20 m^2 scale)

- If your analysis is sensitive to these, you need to run the full MC to understand the impact – a 20 minute talk is not going to be enough. *Take your numbers from the MC Geometry, not this talk!*

- Of course, the reason we want ND-GAr is not superior muon measurement
  - It's the enhanced physics reach, especially at low energy
- The argument for ND-GAr(Lite) is not superior muon measurement either
  - It's the better path to full ND-GAr. (Among other reasons, you don't have a thousand tons of iron in your way)
- The argument for TMS is to start the physics program at the earliest possible time, and to convince the funding agencies that we have the resources in hand to do this.

Backup

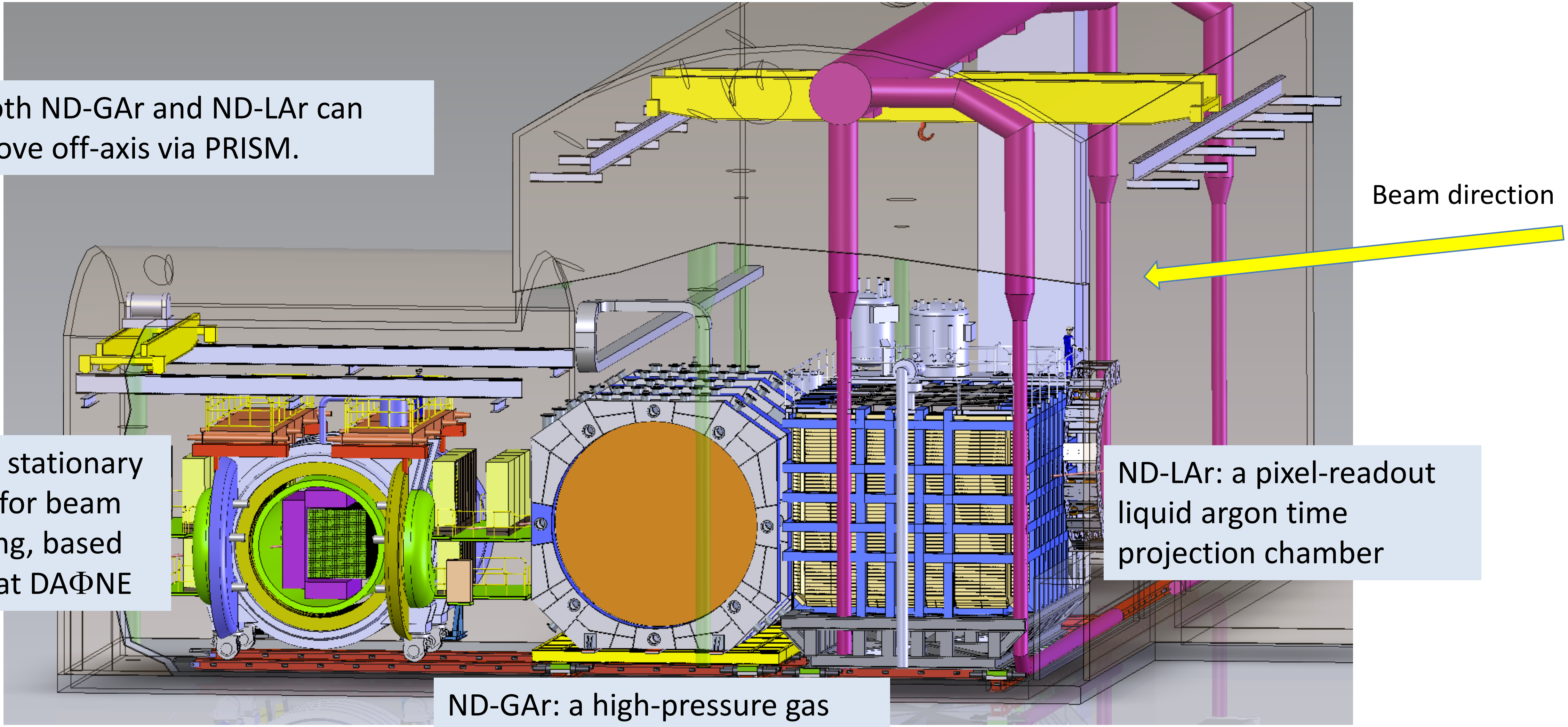

LiUNA!
TEXT BRIDGE TO 69866
DUCT TAPE YOUR
Dangerous Bridge Ahead
Emergency Road Repair Team

The Perfect Near Detector

- Do we even need one? Can’t we just use beam modeling?
  - Beam modeling is likely only good to about 15%
  - This would dominate the systematics.
  - If it’s wrong, how could we tell?
  - We need a near detector

- Ideally, we would use a clone of a Far Detector module to cancel systematics
  - To handle the rates, it needs to be ~5 miles out from Fermilab (just northwest of Mooseheart)
  - Because the Earth is round, the beam goes down by 6^{o}.
    - The detector needs to be ~2000 feet underground.
    - There’s no nearby mine – this would be prohibitively expensive

A More Practical Near Detector



Both ND-GAr and ND-LAr can move off-axis via PRISM.

Beam direction

SAND – a stationary detector for beam monitoring, based on KLOE at DAΦNE

ND-LAr: a pixel-readout liquid argon time projection chamber

ND-GAr: a high-pressure gas time projection chamber

ND-GAr Costs and Schedule

- ALICE TPC was 17 MCHF “Core costs”
  - $29M in today’s dollars,
    - Plus Labor
    - Minus recycling

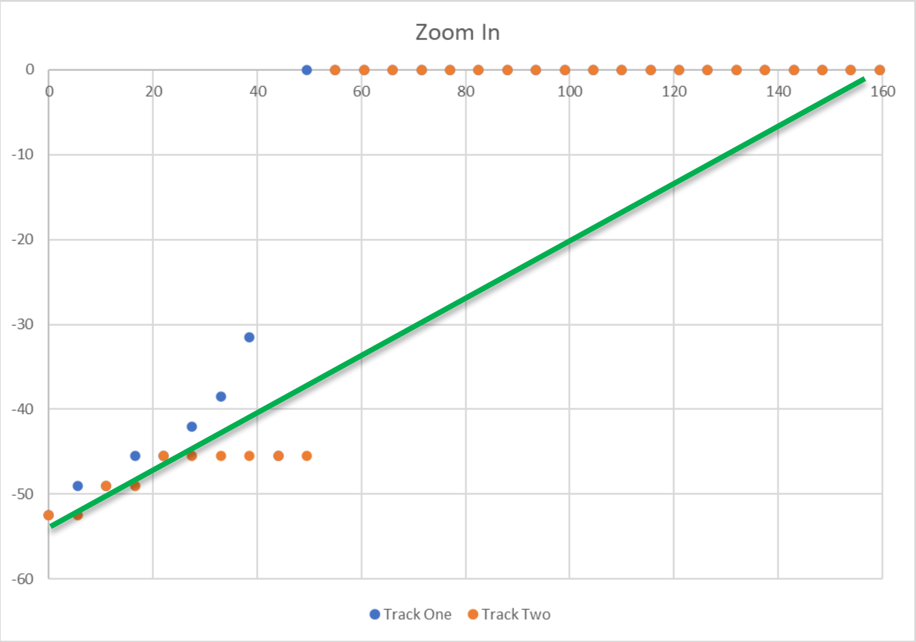
- Plugging ALICE Magnet parameters through the equations of Green and Strauss gives a 2008 cost of $20M

- The ND-GAr cost is several tens of millions – needs to be a non-US contribution
  - Putting a consortium to do this is ongoing, but nothing is yet guaranteed for Day One
  - More expensive → arrives later

What could you do for 10% of the cost & be ready on Day One?

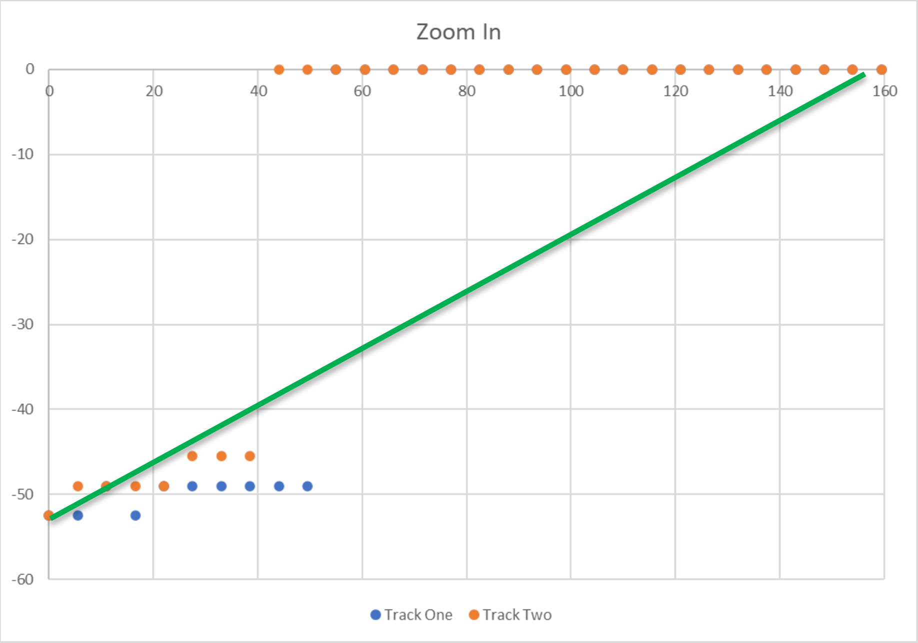
More on Lower Momentum (200 GeV)

- Some events are just fine (top)



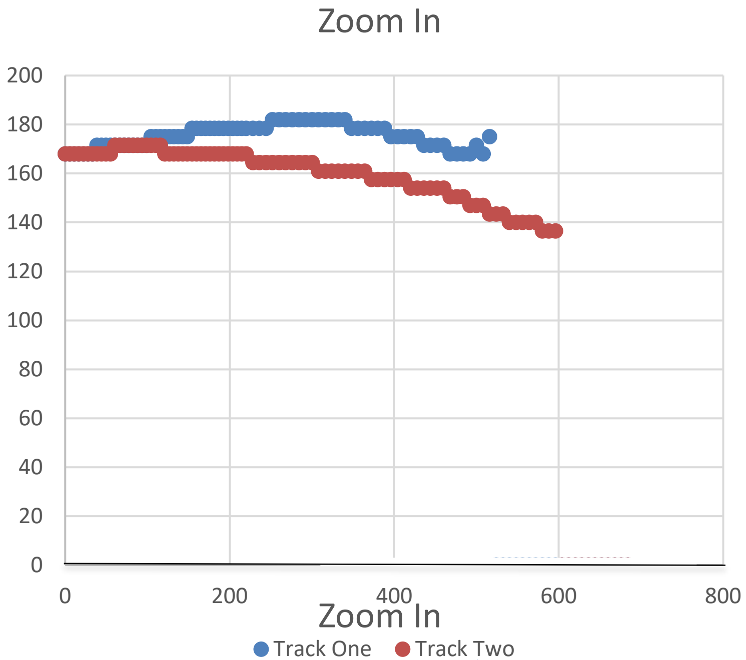
- Some are just a mess (bottom)

- You can see the variation in stopping layers
  - 6-10 layers

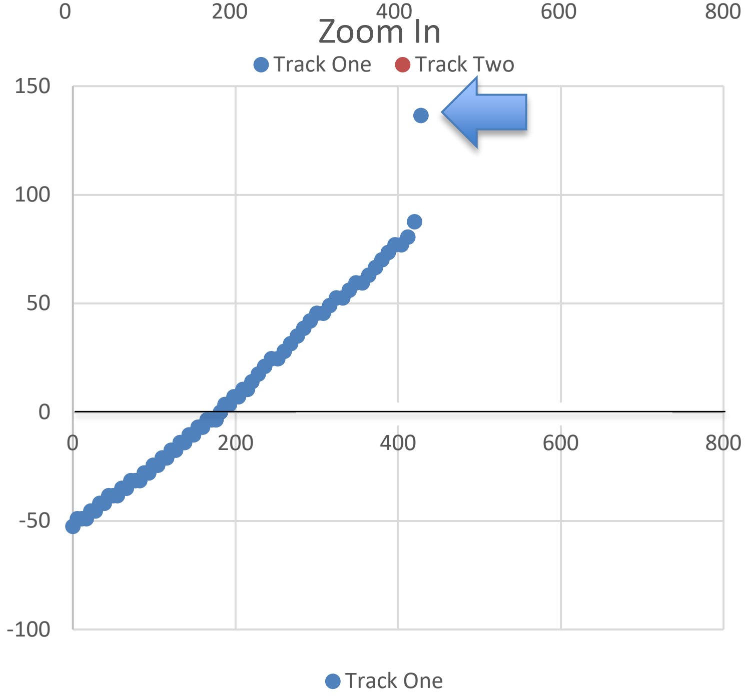


Some Oddball Events

- The blue track is a “swimmer”. It crosses the field reversal boundary (twice) which reverses its bend.
- The charge is still distinguishable from the oppositely charged red track, which has the wrong charge to swim.

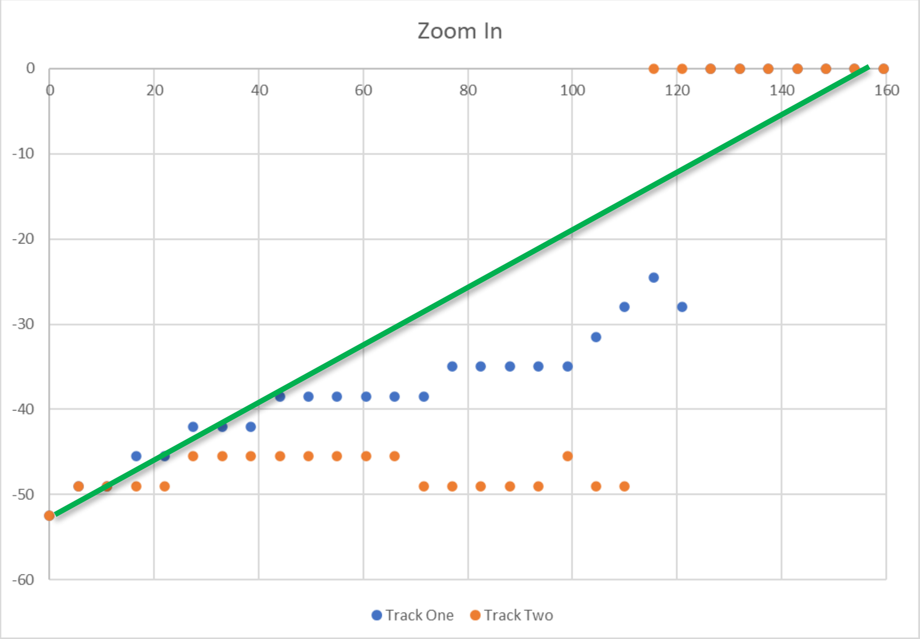


- The last hit is significantly displaced from the rest of the track.
  - Almost certainly happens more in the model than in real life, but at the end of the track the muon has low energy and we all know low energy particles do weird things.

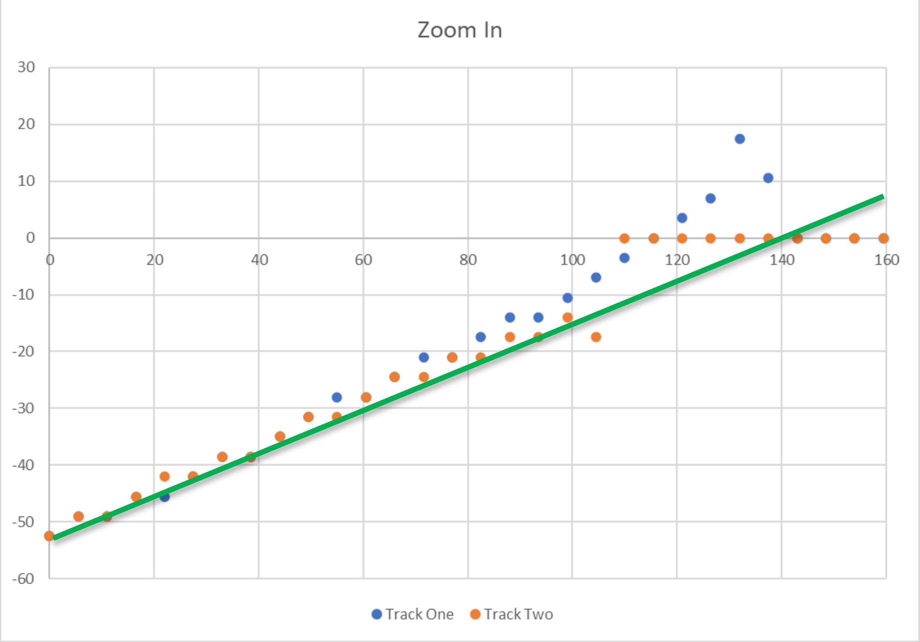


More Oddballs

Positive track has an initial wide-angle scatter.
Negative track multiple scatters and looks straight.
Neither will have a good χ^2.

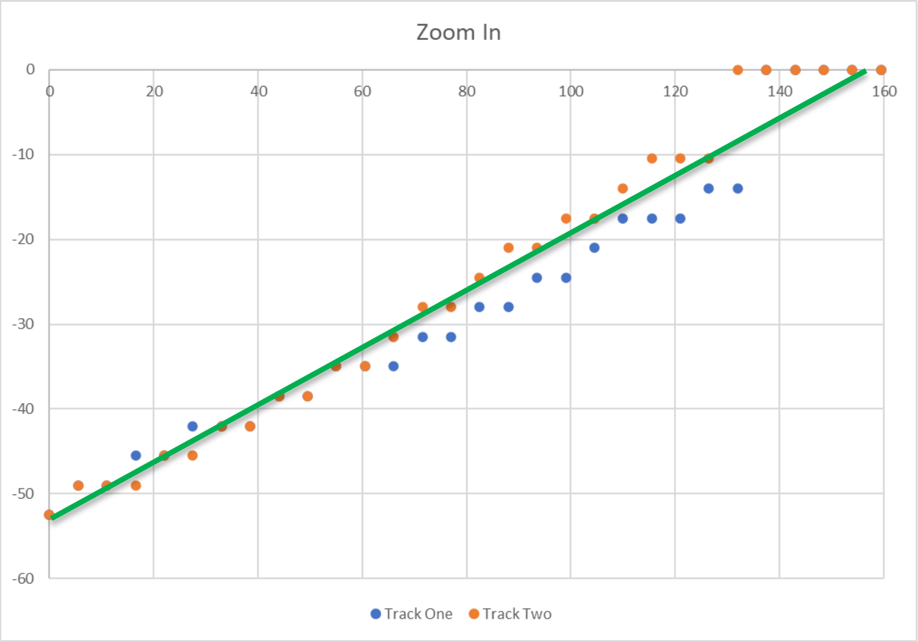


Both tracks have less curvature than average (a lot less). While the hit positions don’t have a lot of separation power, the tracks are oppositely curved.

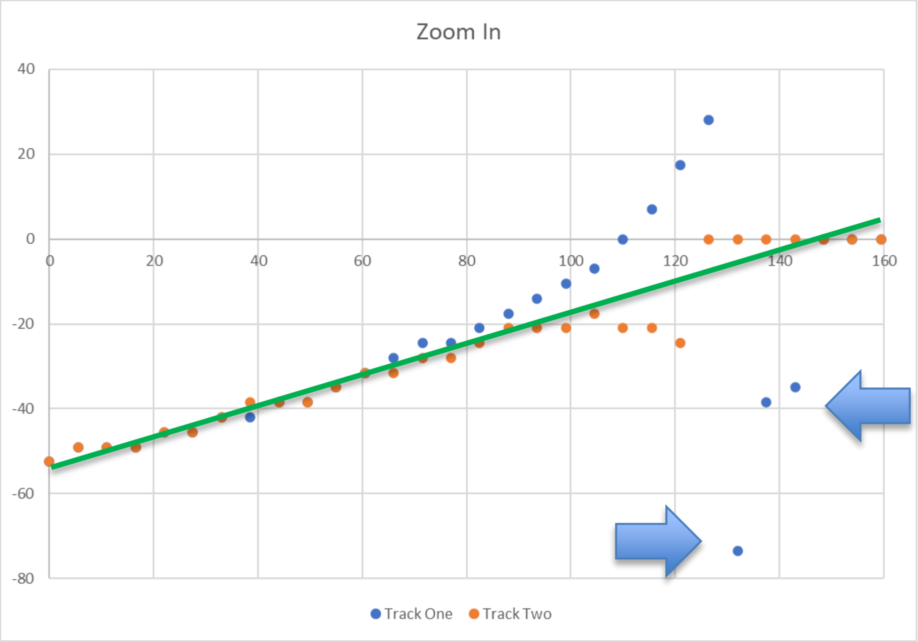


Even More Oddballs

Some events are just bad news

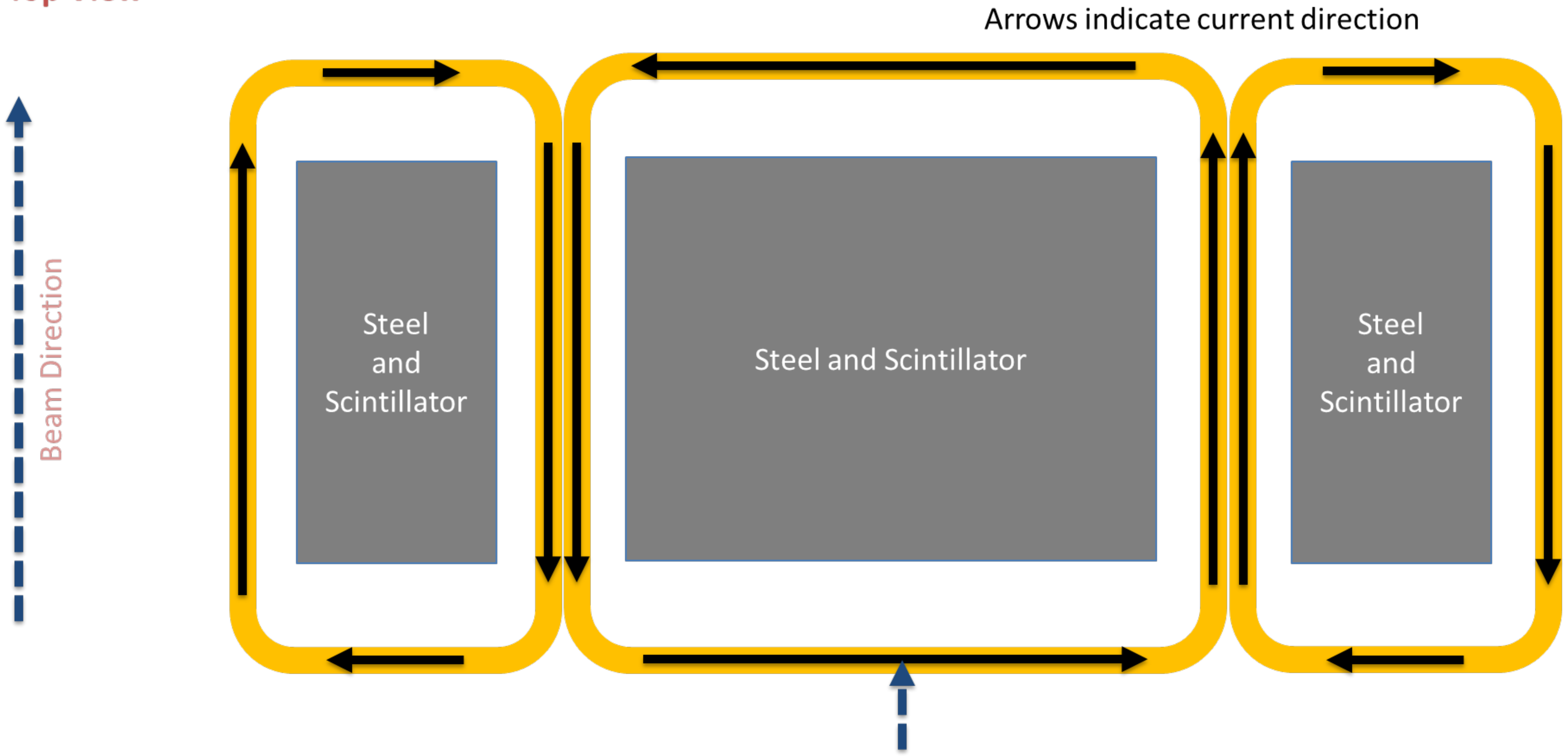


Sometimes the last hit(s) can be quite far from the track



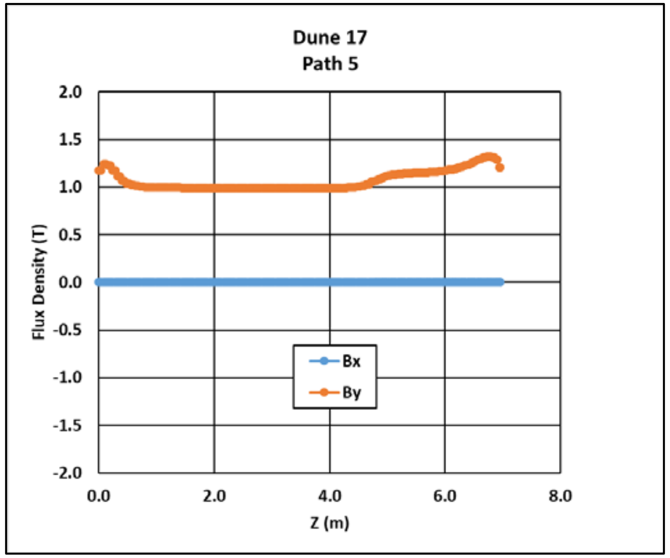
Coil Design

Top View

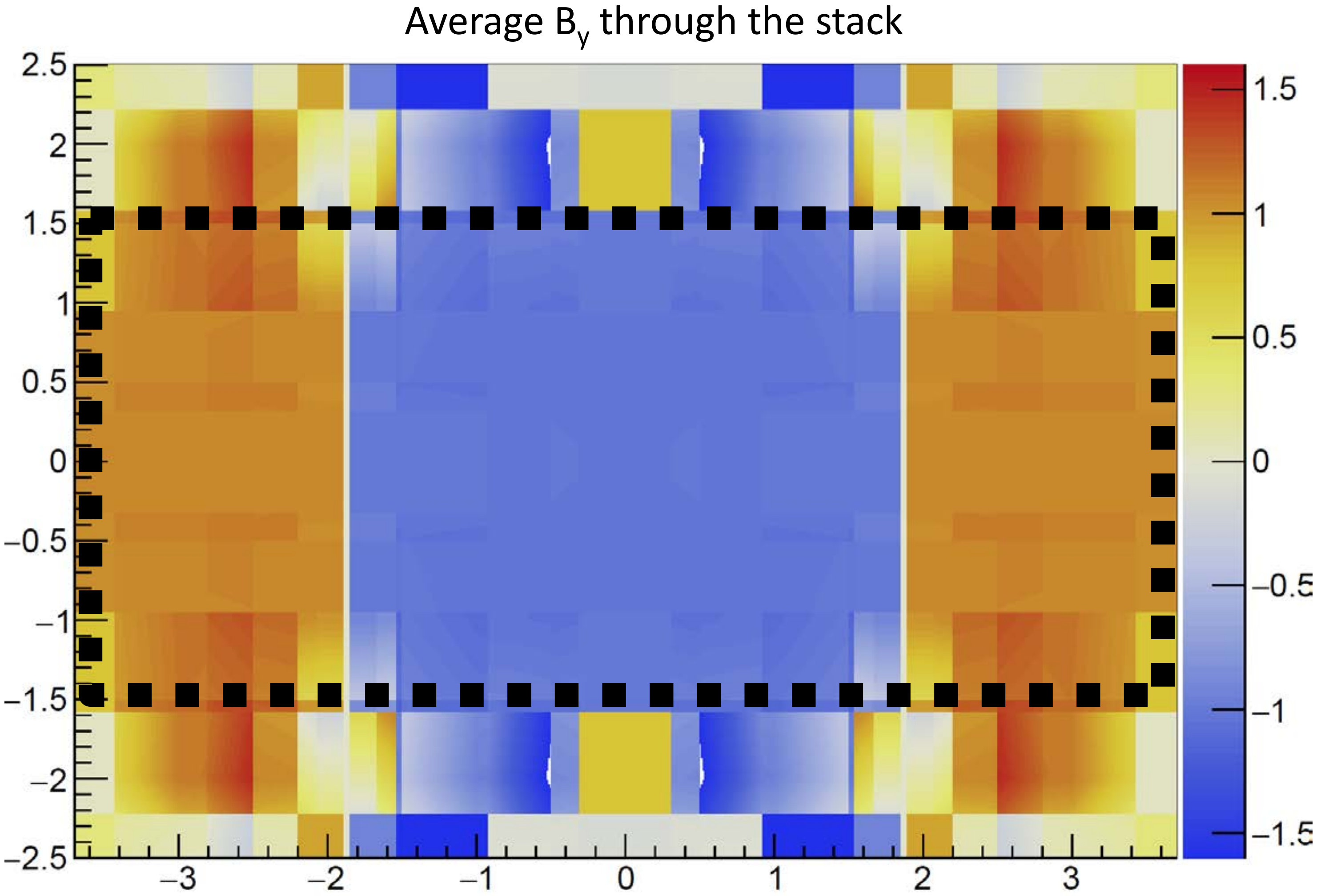


Magnetic Field

- This steel geometry produces a fairly uniform field where the detectors are.
  - Standard deviation of By in the x-y direction is 6%



B vs. z from ANSYS at single (x,y)



x-y (front) view

Black dashed line indicates active area

Field in ND-LAr is negligible (15 gauss)