WE START WITH YES.

# MUON SPECTROMETER

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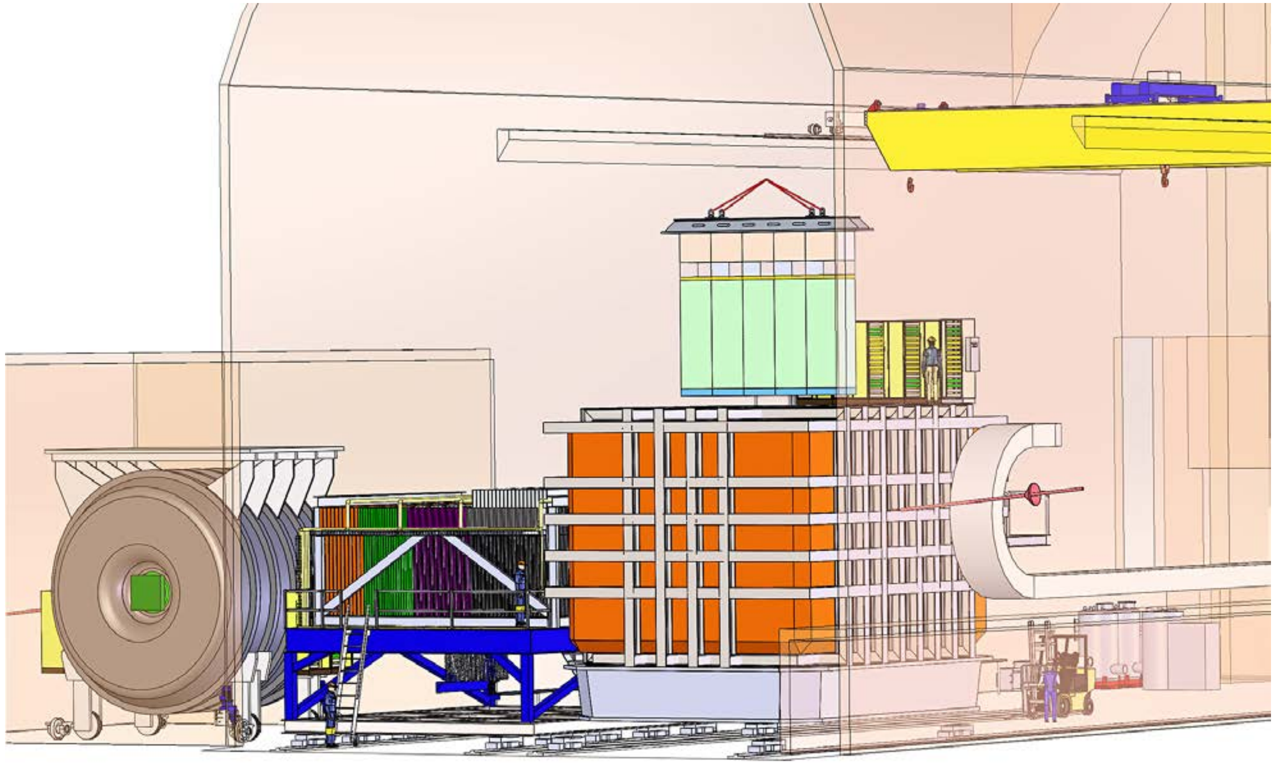
# WHO AM I?


- Current roles:
  - I am not presently a DUNE collaborator
  - This work has been done helping Vic Guarino engineer a device that will meet DUNE's physics requirements

- Experience Includes
  - FNAL E-705 (@Proton West), CDF, STAR (BNL), ATLAS (CERN) and CTEQ
  - Physics Coordinator of ATLAS (first with beam) and STAR
  - CDF Run II Upgrade Project Level 2 for muons
  - (Re-) Designed STAR's EM Calorimeter
  - Two years at DOE in the Washington DC area

# WHAT IS THIS MUON SPECTROMETER ANYWAY?

- It is a magnetized steel range stack between ArgonCube and SAND
  - Face is the same size as ArgonCube, depth is 7m
  - Detector is 100 planes of 192 scintillator strips each
- It’s job is to measure the momentum of muons that exit ArgonCube
  - With a precision comparable to the Far Detector (taken to be 4%)
  - In the kinematically relevant region, ~1 to ~5 GeV
- It needs to be inexpensive
  - The hope is that it will be replaced by the MPD after a short time



An early design by M. Leitner

# THIS TALK

## What it is and what it isn’t

- This is a description of the instrument

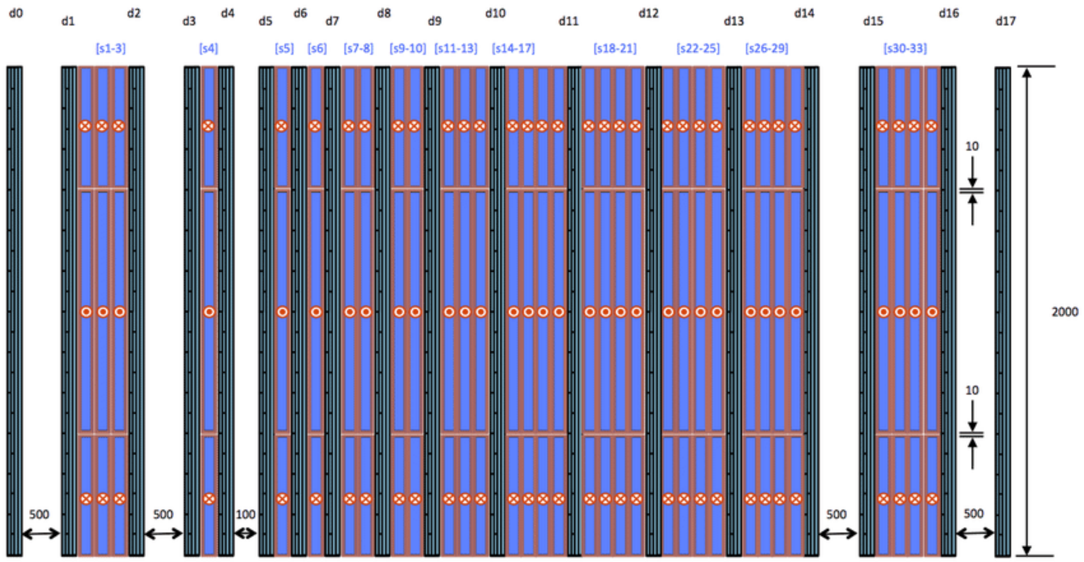
- Performance numbers are intended to show that it meets the targets, not to be the final word

- There is work going on now on simulation
  - Tim Bolton, Gavin Davies, Zelimir Djurcic, Dan Dwyer, Vic Guarino, Mike Kordosky, TJL, Chris Marshall, Mat Muether (contact), Holger Meyer, Roberto Petti, Palash Roy
  - This would be a good topic for a future meeting (but I won’t speak on this today)

- Cost is $5.7M (base) and $9M (w/contingency)
  - This meeting is not a WBS scrubbing
  - The original question was “how much does it cost to build a minimal instrument?”.
  - There is some room (and time!) for optimization, subject to the above cost envelope.

# 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 | Multiple Scattering | Magnetic Bend |
|---|---|---|
| $\frac{dE}{dx} \approx 11.4\ \text{MeV}$ | $\Delta\varphi \approx \frac{1}{p} 0.59°$ | $\Delta\varphi \approx \frac{qB}{p} 0.17°$ |
| Accumulates linearly | Accumulates as square root | Accumulates linearly |

# HOW MOMENTUM & CHARGE ID WORKS

- Momentum resolution is a contest between magnetic bend and multiple scattering, and a race against energy loss

- Example: a 1.5 GeV muon in steel with a 1.5 T field
  - Will range out in ~130 cm
  - In that space it will bend by 22 degrees*
  - In that space it will scatter by on average 5 degrees*
  - It will have a sagitta of about 7 cm
    - A resolution of ~2 cm here is well-matched to the multiple scattering
    - That corresponds to ~3.5 cm slats
  - With an average 1 inch steel and 1 cm scintillator, ~10% of the muon's energy is deposited in the scintillator

* Actually somewhat more than this because the muon slows as it traverses the detector

# 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 $|p|$

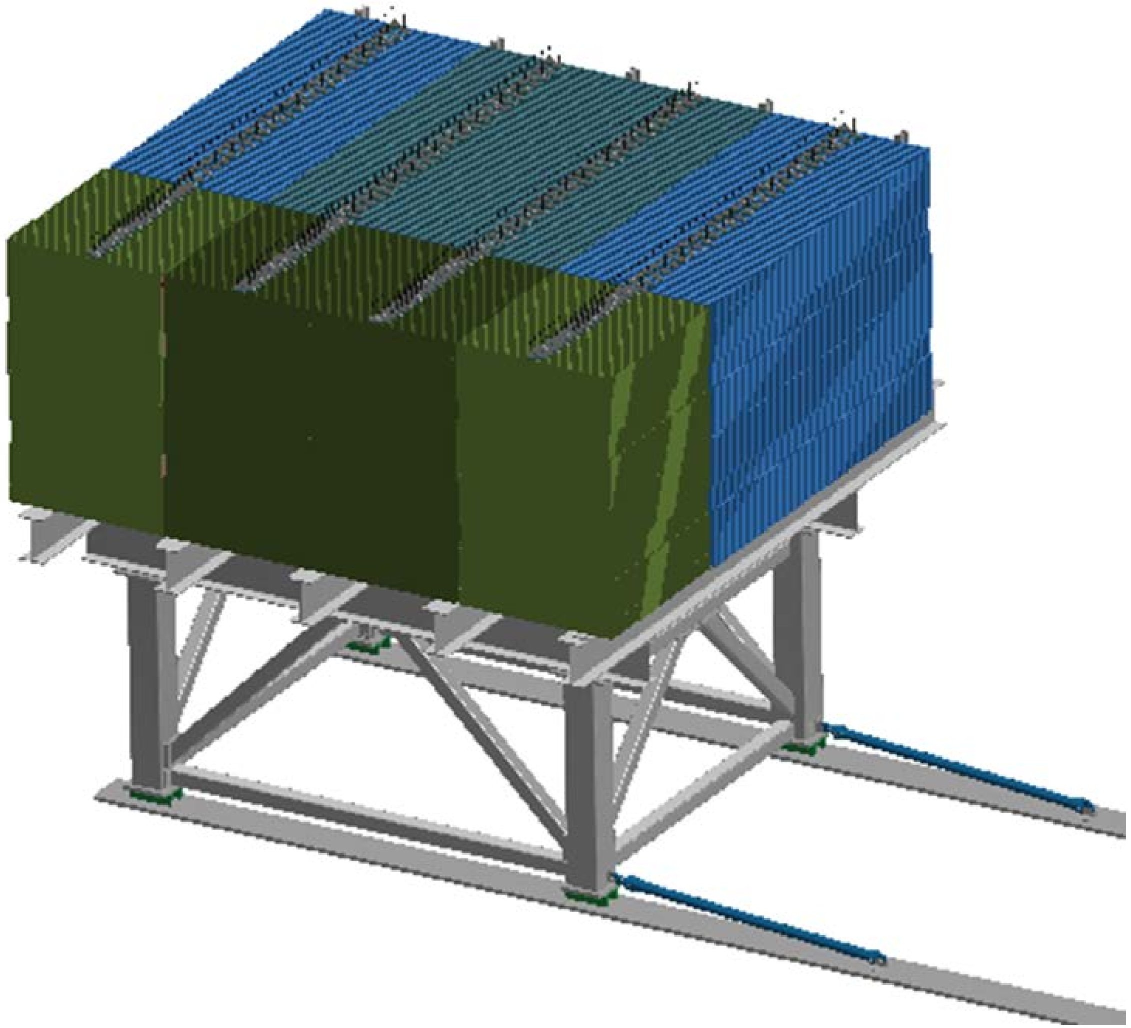
# MUON SPECTROMETER DESIGN

- 100 layers of alternating steel and scintillator
  - 80 plates 175 cm  x 300 cm x 1.5 cm
  - 40 plates 350 cm x 300 cm x 1.5 cm
  - 120 plates 175 cm x 300 cm x 4 cm
  - 60 plates 350 cm x 300 cm x 4 cm
  - 40 mm gap between layers

- Each layer has four panels, each containing 48 MINOS-like scintillator slats, 3.5 cm wide

- The entire stack is surrounded by two belts of coils (shown later) providing a 1.5T vertical field
  - The center 2/4 is in one direction
  - The outer 2/4 are in the opposite direction

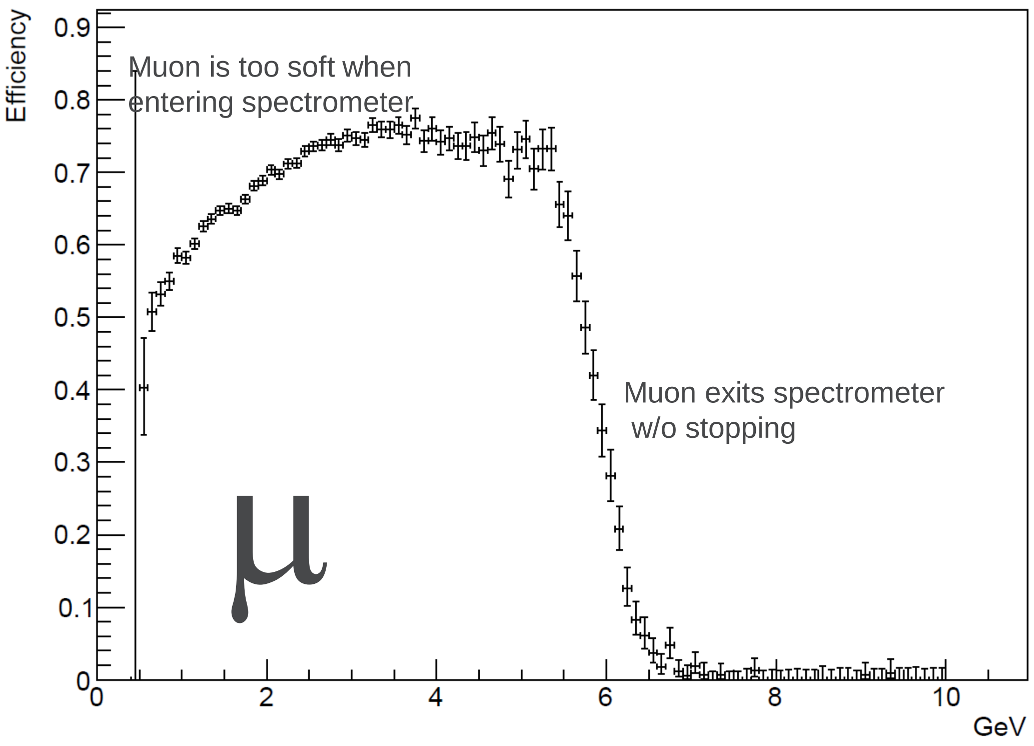
- It can move in the x-direction (PRISM)

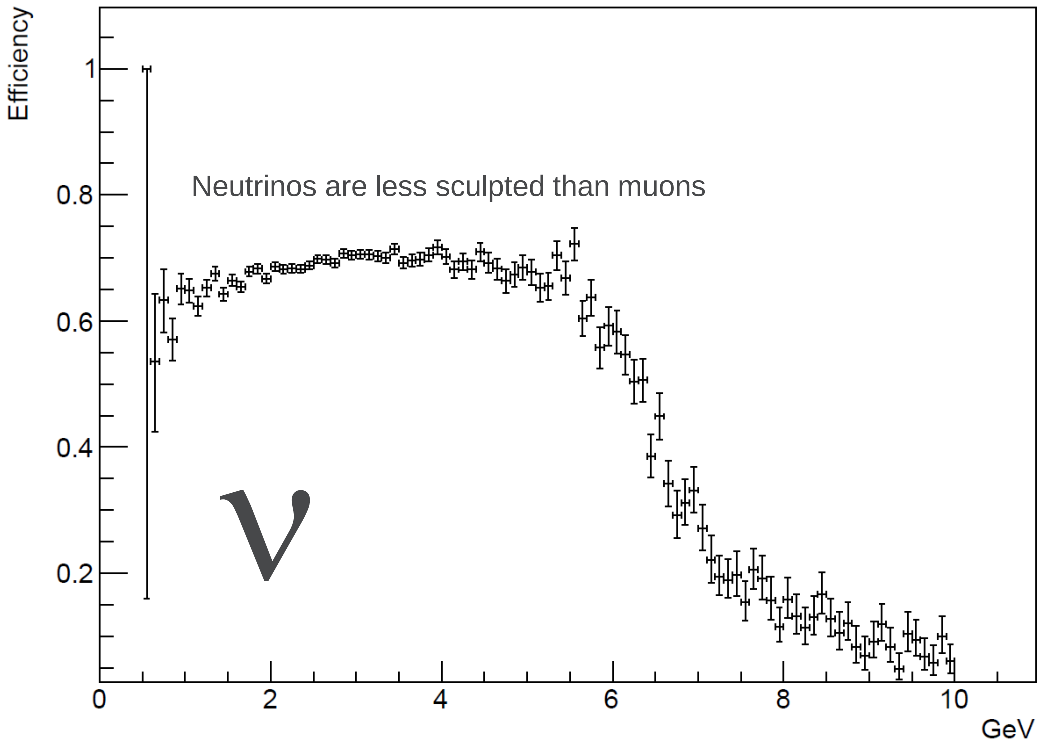


# ACCEPTANCE

## This is not GEANT

- This is an *unsmeared* reflection of the spectrometer acceptance (for muons that stop inside it) into the muon or neutrino kinematics at the primary vertex.

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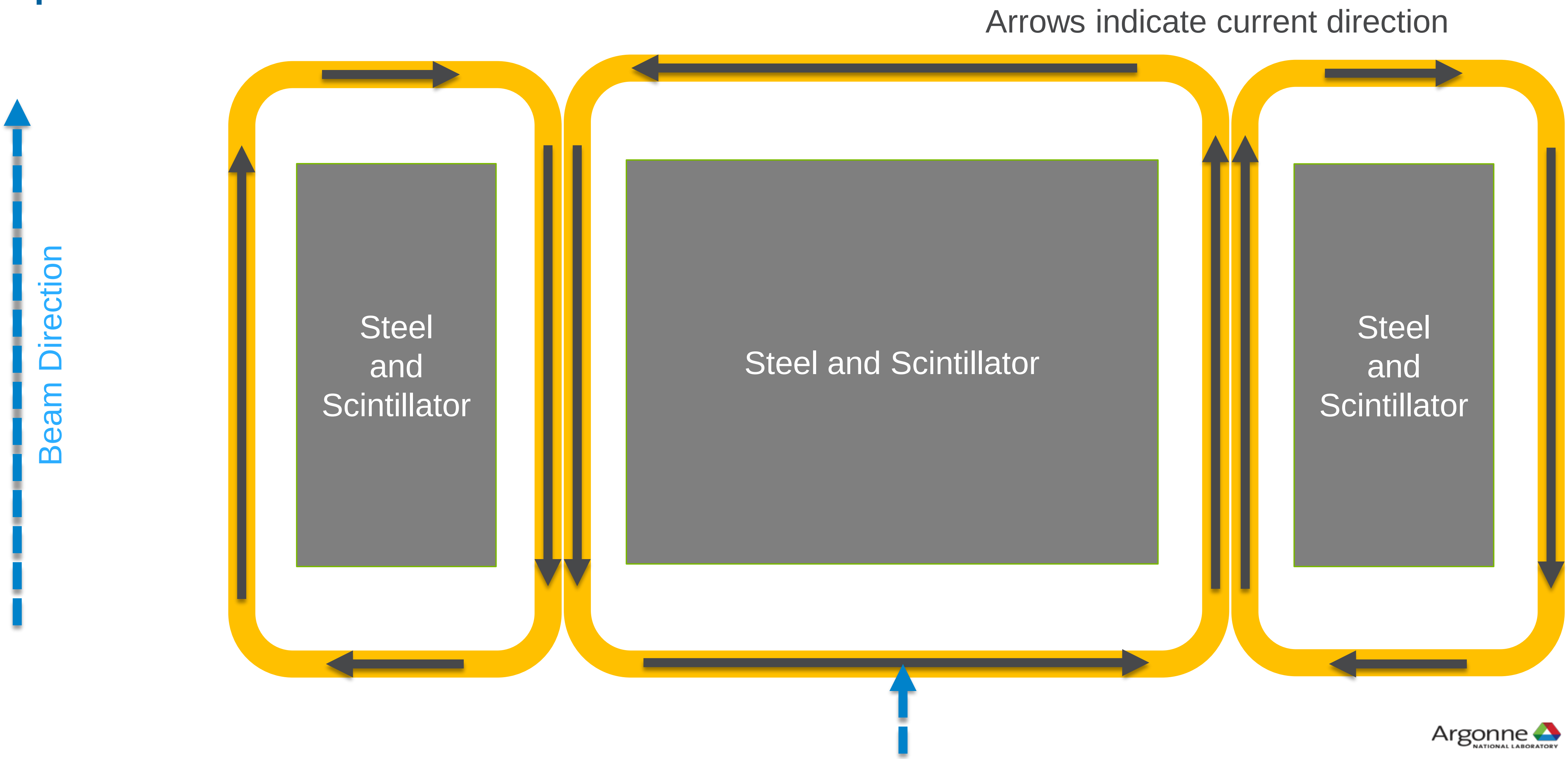
# COIL DESIGN

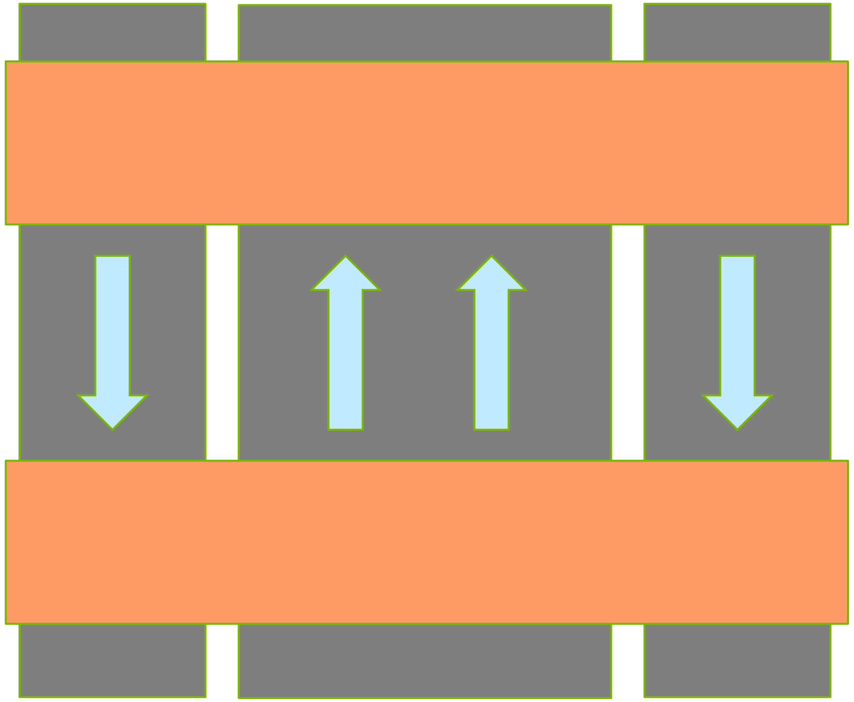
## Top View



# MAGNETIC FIELD

## Beam’s Eye View

- Two “belts” of coils in a “Helmholtzy” configuration.
  - Gives reasonably uniform field, especially between the coils
  - Coils cost us a bit less than 1% in acceptance
- The steel is the same as MINOS/BaBar
  - High silicon, low-carbon $\mu \approx 700$
  - Electrical steel is 5x better magnetically, but 5x as expensive
- The magnetic field configuration is a dipole inside the coils, and a sextupole outside the coils
  - A sextupole has its dipole cancelled and its quadrupole partially canceled: field goes as $1/r^4$
  - The intent is to get the field inside as large as possible, but keep the field outside (especially the liquid argon) as small as possible – goals are somewhat in tension



Arrows indicate the direction of the magnetic field

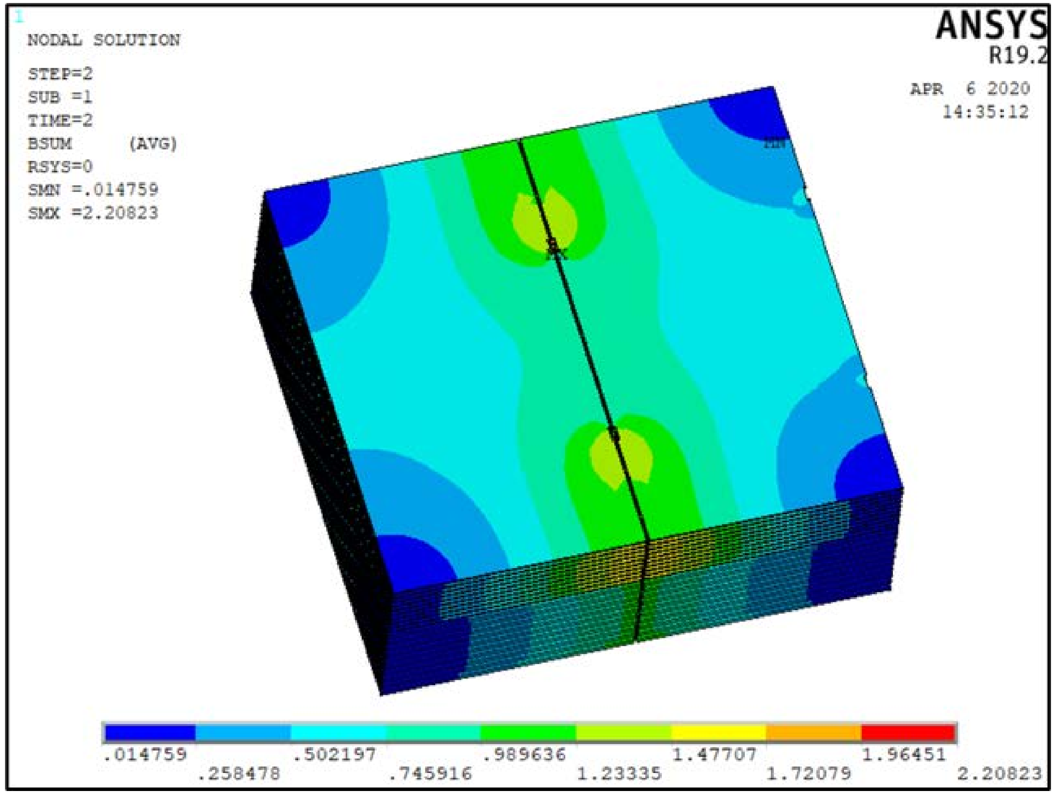
# MAGNETIC ANALYSIS

## Numerical Solutions of Maxwell's Equations with ANSYS

- We have a 5000 Ampere-turn model
  - Field quality is good
  - Most of the steel does not saturate.
    - Saturation is at ~ 1.5 T
    - Most of the plates are between 0.5 and 0.75 T

- We are planning for 15,000 Ampere-turns
  - This will slightly over-saturate the plate
  - The ANSYS model has some features we don't understand and are still investigating

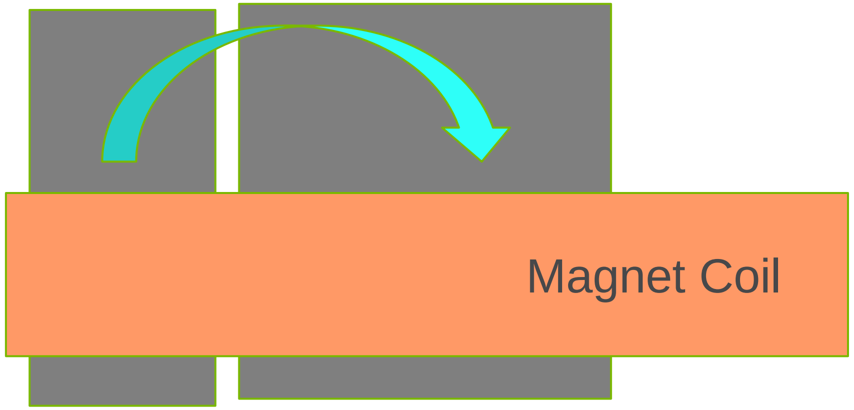
- Ultimately this model will tell us what the field is inside the liquid argon
  - Our target: a 1 GeV muon will experience less than ½ a pixel deflection from the fringe magnetic field



# WHY OVERSATURATE?

If the steel just barely saturates between the coils, it will not saturate – i.e. contain the field – in the upper and lower sections.

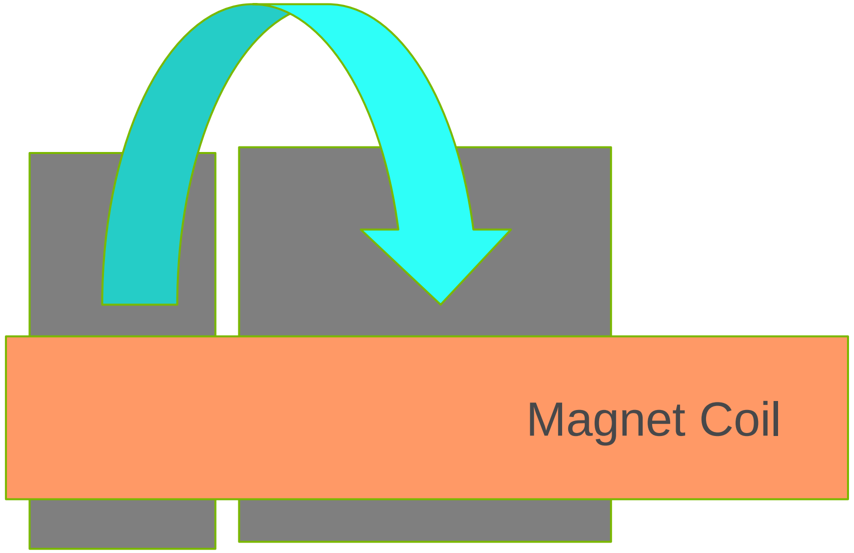
This reduces the bend in the bend view and induces a bend in the non-bend view.




By oversaturating, you get better field quality (i.e. more vertical) in the upper and lower sections.

You also get a little more bend everywhere.

The cost is that the fringe field gets larger everywhere, even though most of it is in the y-direction. We want to avoid fringe field in z.

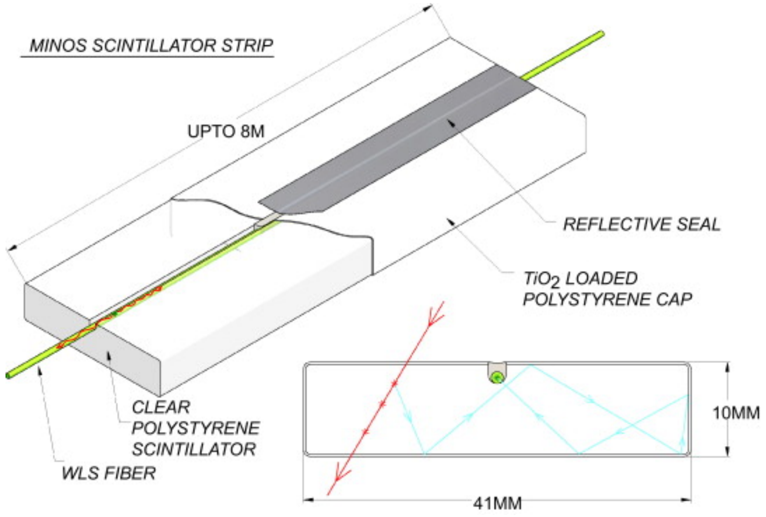


# A 40MM GAP?


- 40 mm might sound excessive for a 1 cm scintillator
- There's more to a scintillator panel than the scintillator
  - Titanium dioxide-loaded polystyrene cap
  - Aluminum cover
  - Aluminum frame
- This all adds up to about another centimeter
- This requires a flatness tolerance of slightly less than 0.3%
  - 0.3 - 0.5% is easy to find commercially
- 100 layers means 4 meters of gap –implying only ~3 meters of steel
  - We have 7.1 meters of space

- If we could get flatter steel, how could we put it to use?
  - We could thicken the scintillator to get more light
  - We could thicken the steel to get a higher upper momentum
    - At a cost of resolution
  - We could optimize the location in z of the gaps

# SCINTILLATOR DESIGN

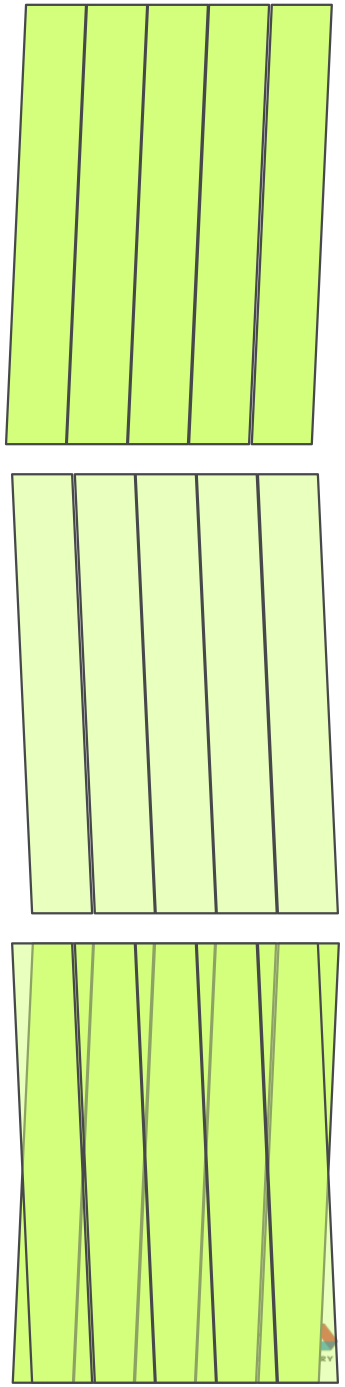



- Design is MINOS-like (extruded polystyrene)

- Spectrometer has 100 planes

- Each 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, ADC and associated electronics (discussed later)

- Panels (which are rectangular) are tilted ±3$^{o}$ in alternating layers
  – With stereo you win as sine but only lose as cosine
  – Gets us ~45 cm resolution in y-direction



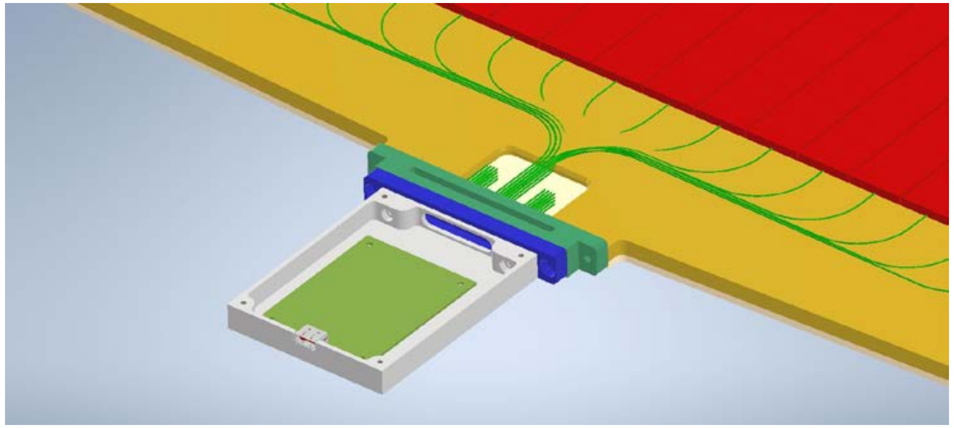
# SCINTILLATOR READOUT

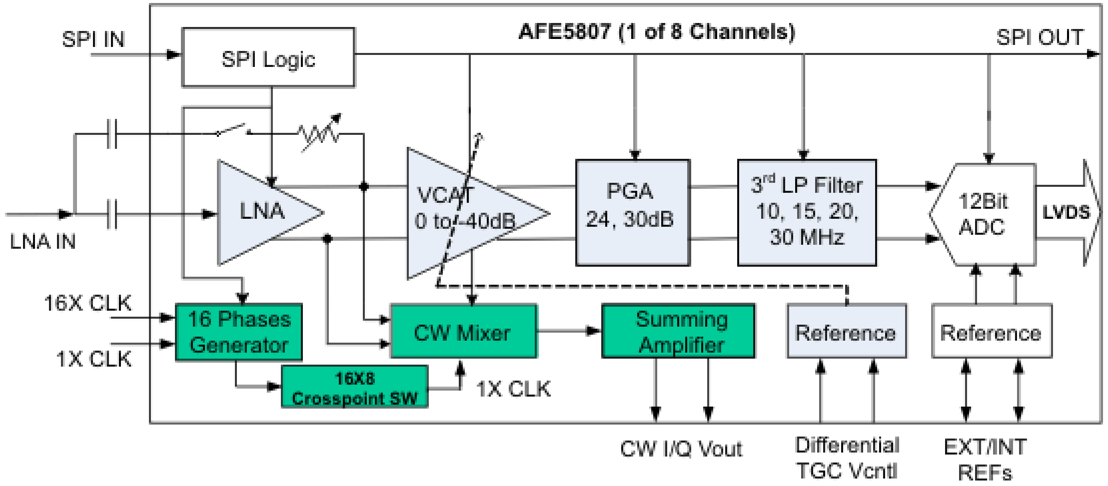
- Each panel has three 16-channel Hamamatsu SiPMs
  - $8/channel (quote)

- Each panel has six 8-channel Texas Instruments AFE-5807 analog  front ends/12-bit ADCs (intended market is ultrasound)
  - $6/channel MSRP (we have a quote (qty. 1000) at less than $4 per channel)
  - Up to 80 MHz (Main Injector is 53 MHz)
  - LVDS output
  - Variations on this chip (e.g. lower power) exist

- Digital signals are combined and reformatted off-detector
  - And then on to the DAQ

- Events have single bucket (19 ns) resolution



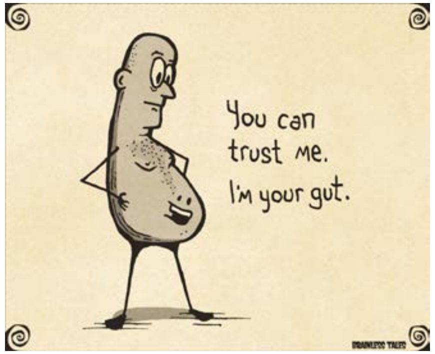



Cost drivers are engineering and support circuitry (e.g. power)

# PILEUP AND MULTIPLE MUONS

- Pileup as we usually think of it is not an issue. The Main Injector harmonic number is 588 and we have single RF bucket resolution
  - Could probably do better, but what would be the point?
- However, here are events with multiple muons
  - Charm events in ArgonCube
  - Neutrino interactions in the steel: the steel weighs ~10x the ArgonCube fiducial
    - Typically traverse half or less of the steel
    - This could be the first measurement cross-section on iron relative to argon
  - Have not considered rock muons that don’t range out
- Pileup from multiple interactions in the steel may cause difficulty for a small number of events per year
  - We will get some events with ~8 muons: could have ~4 muons per panel in the same bucket
  - This becomes problematic at 2.4 MW.
  - This assumes Poisson statistics. If we see any double-bucketing, it will make this worse.

# TRACKING & CHARGE IDENTIFICATION




## All my instincts about tracking were wrong

- 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
- There are more measurement points at higher momentum
  - More measurements are good in general…
  - …but are particularly important here because multiple scattering must be overcome
    - It takes of order a dozen points before the bend exceeds scattering

- Sign identification is poor at low p (too few hits), improves with p until the muon exits the stack, and then falls off as $p^2$. (This is just tracking $BL^2$)

# CHARGE IDENTIFICATION

## Or…Why 95% isn't good enough

- The sagitta is 7 cm, the slats are 3.5 cm wide, so we should have 95% correct charge identification

- If we had a beam that was a 50-50 mix of neutrinos and antineutrinos, this would be perfectly fine. But…
  - With a true antineutrino fraction of 5%, though, this would mean that real antineutrinos make up only half of the identified antineutrino sample
  - With a true antineutrino fraction of 2.5%, this would mean that real antineutrinos make up only a third of the identified antineutrino sample
  - We would really like 99% or better

- MINOS' solution (which we can adopt) – use only well-measured tracks
  - This means "know your biases", which implies a high acceptance is better
  - I recommend a $\chi^2$ ratio under the $\mu^+$ and $\mu^-$ hypotheses (distributed as an F distribution)
    - I do not recommend a likelihood ratio (the Neyman-Pearson Lemma is not appropriate here)

# SUMMARY

## The Muon spectrometer will allow DUNE to reach its goals – but is far from overdesigned

- The intent is to do two things, both of which we think this device can do
  - Measure the momentum of muons to a resolution comparable to the far detector for most momenta
  - Measure the neutrino/antineutrino content of the beam via sign-selection

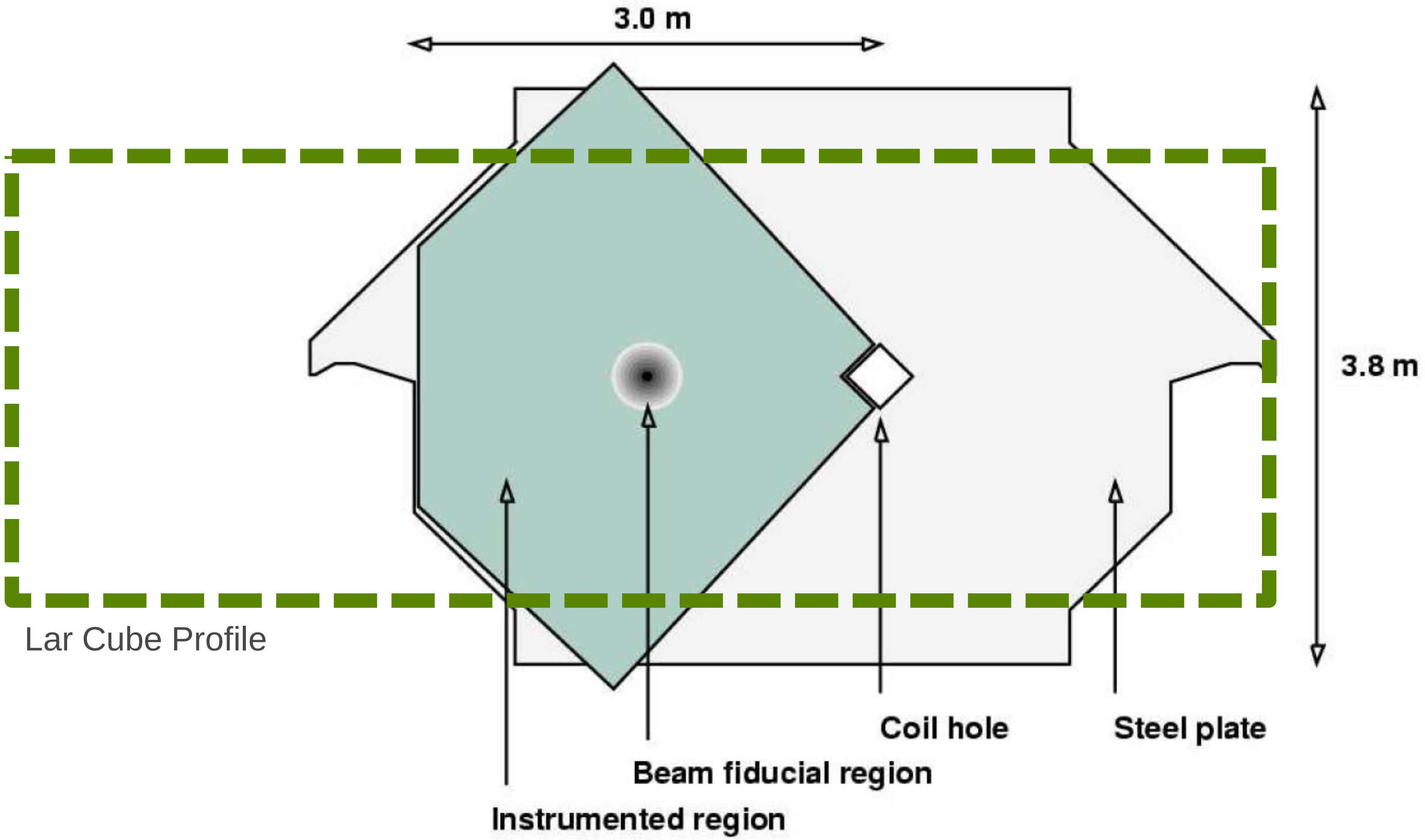
- We have a baseline design, but there is some room for optimization (subject to space and financial constraints).
  - This baseline will struggle at 2.4 MW

- We need a name. The current favorite is SSRI
  - Sign-selecting Range Instrument
  - Pronounced “surrey” because the fringe is on top

# BACKUP

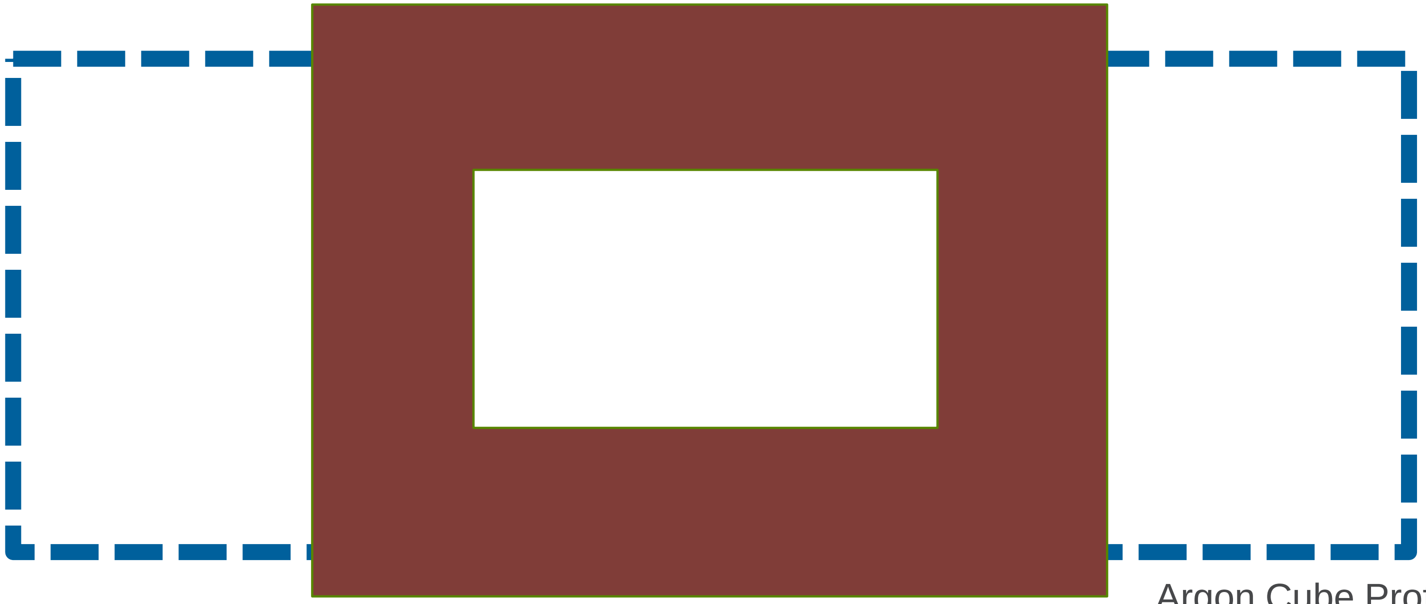
# WHY NOT USE THE MINOS NEAR DETECTOR?

- It's too small
  - It covers 20-30% of the area behind ArgonCube
- It's also too big
  - It's 16.6 m long – we only have 8m
- It's too dense
  - MINOS beam is ~3x as energetic as LBNF



# WHY NOT USE AN EXISTING MAGNET?

- They are all too small
  - The largest picture-frame dipole I am aware of at FNAL is the KTeV magnet
  - It covers ~20% of the area behind ArgonCube
  - It has a max $p_T$ kick of 600 MeV
    - 400 MeV is more reasonable; a field map exists



Argon Cube Profile

# PURE CALORIMETRY

- Why not use a mini-NOvA instead?
- No muon sign measurement – can’t measure nubar contamination
- 8 meters is too short
  - dE/dx = 1.9 MeV/cm for mineral oil
  - Muons with p > 1.5 GeV will not range out
  - Minimum density is 3.5-4 $g/cm^3$: no organic scintillator will do that