TMS Workshop Open Issues

Tom LeCompte
SLAC

Outline

- TMS Scintillator Thickness
  - Mechanical and Cost Issues
  - Michel Electrons
  - Stopping Muons and the Bragg Peak
  - Other Uses of Deposited Energy

- Scintillator Orientation
  - Resolution
  - Acceptance
  - Charge ID

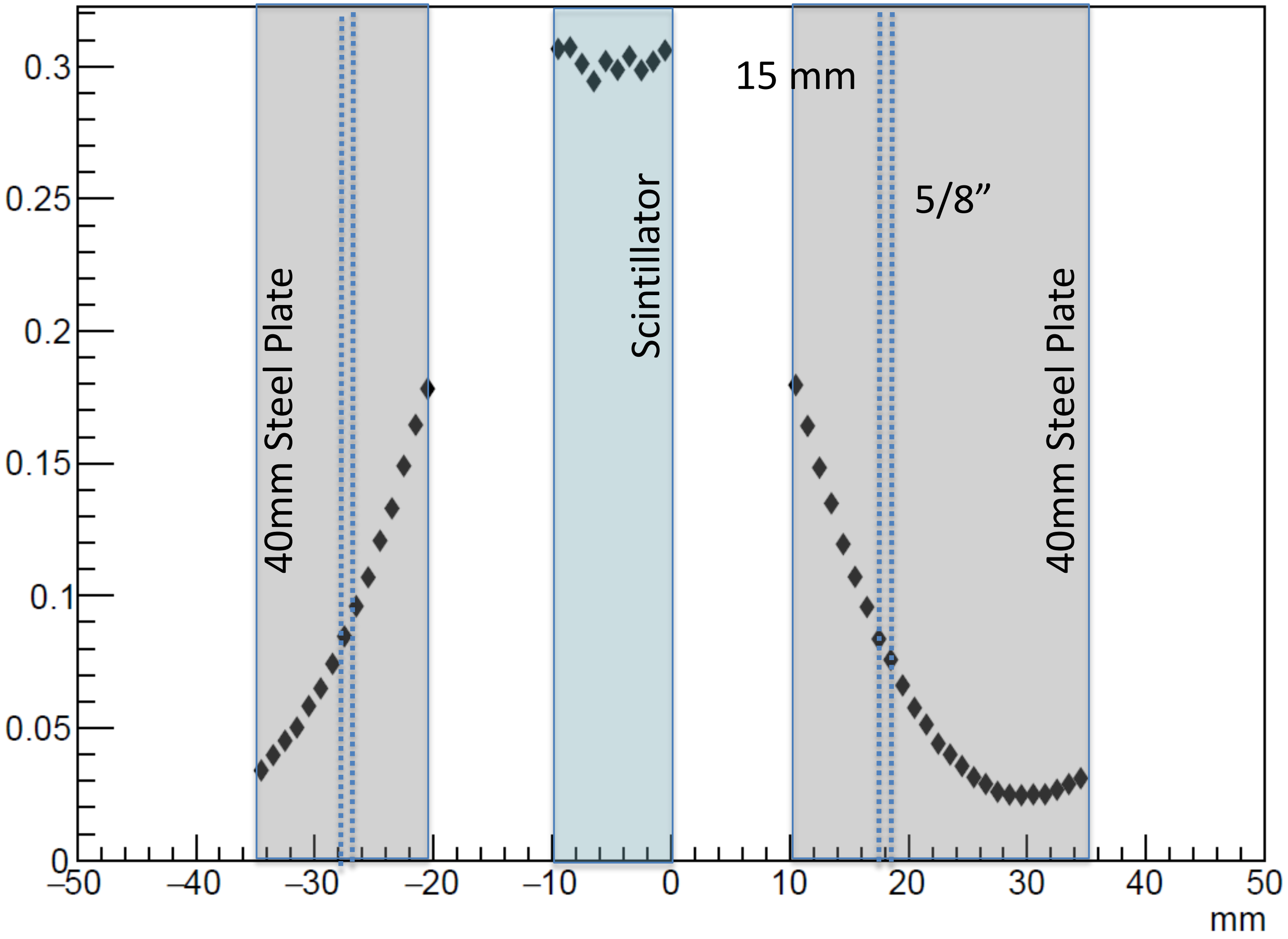
Why Thicker Counters?

- We nay need more stiffness
  - Stiffness goes as the cube of the thickness
- Thicker scintillator means more light - and who wouldn’rt want more light?
  - “More is better” is not a useful basis for a spec
  - Later slides discuss whether there is a threshold on light for some use cases.
- Scintillator cost scales 50—50 (maybe 60-40) with number of pieces and total volume:
  - We are spending just under $1M overall,
- Aluminum covers cost $250K
  - More than I wanted to pay, and I hope we can bring this down. But…

If we need to stiifen the panels, it makes more sense to do it with scintillator than aluminum. Further, the increased cost is not that much more.

If there is space to do it given the expected steel flatness remaind an open issue.

Michel Efficiency vs. stopping z



- “Efficiency” means “at least 2.0 mips anywhere in the active region”.
- Efficiency peaks at ~30% for muons that stop in the scintillator
- Efficiency bottoms out in the middle of the steel (where else?)
- Steel thickness matters
  - This is one of the few places where 5/8” vs. 15 mm steel plate thickness makes a difference. Even this difference is small.

Micnel Event Rates

	15 mm Plate Region	40 mm Plate Region
Stopping Muons	40,000,000	10,000,000
E > 0	18,000,000	2,600,000
E > 2.0 mips	8,400,000	800,000
Decay time window	6,000,000	600,000

Per 50 million events

50M events is a few weeks running for muons that exit the argon and a few days for muons in the steel or rock. (A sample that may have less utility)

- 2.0 mips means "anywhere in the active region." Most of these are in a single counter, rarely two.
- The decay time window is a few microseconds after the spill ends.
  - Too short, and soft interactions in the steel can be a problem
  - Too long and SiPM noise can fake a Michel
  - This will depend on the Front-end chip and whether it has deadtime

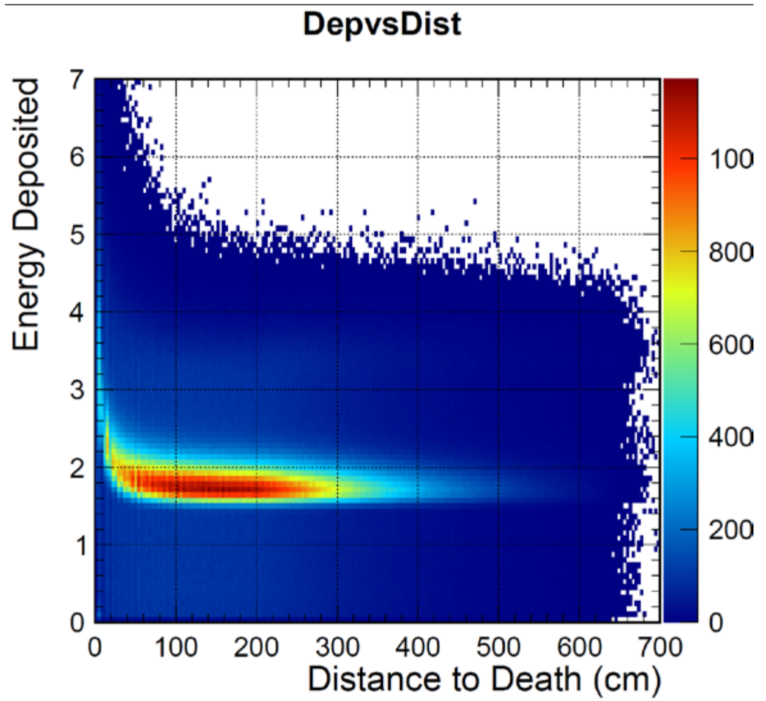
Double the scintillator thickness and rates increase by 1.5-2.0x.

A real analysis with real cuts will have different numbers, but this shows the scale.

Bragg Peak

- In principle, we can see where a muon stops by looking for the Bragg Peak – the increase in ionization as the muon slows and stops. (dE/dx ~ $1/\beta^2$)

- In practice, this is not so easy
  - Photostatistics can limit this (why I am showing this)
  - The end of the track is usually in the steel
    - Wide variation in energy of the last scintillator hit
    - Happens more often in the thick steel, which also has a greater distance to the 2nd-to-last hitg
  - The track scatters a lot as it stops and the last hit may not be near the rest of the track

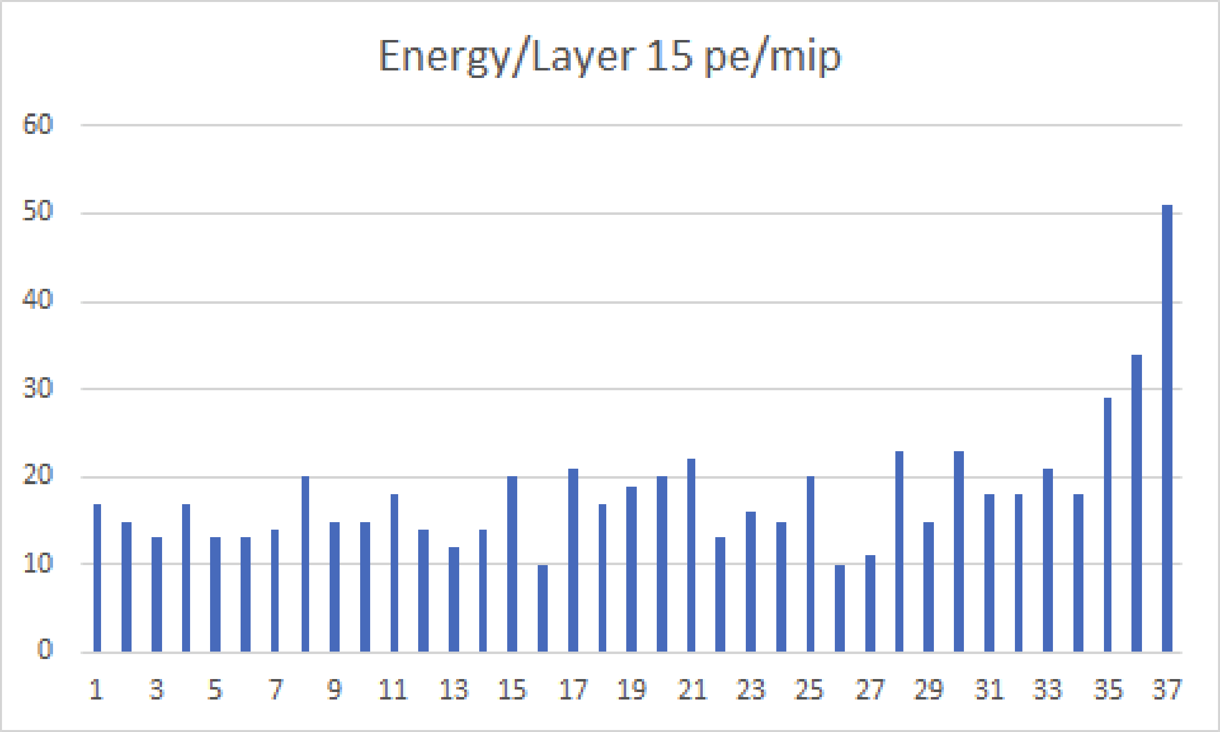


C. Wret

These are Excel-leve studies – Geant will do a lot better.

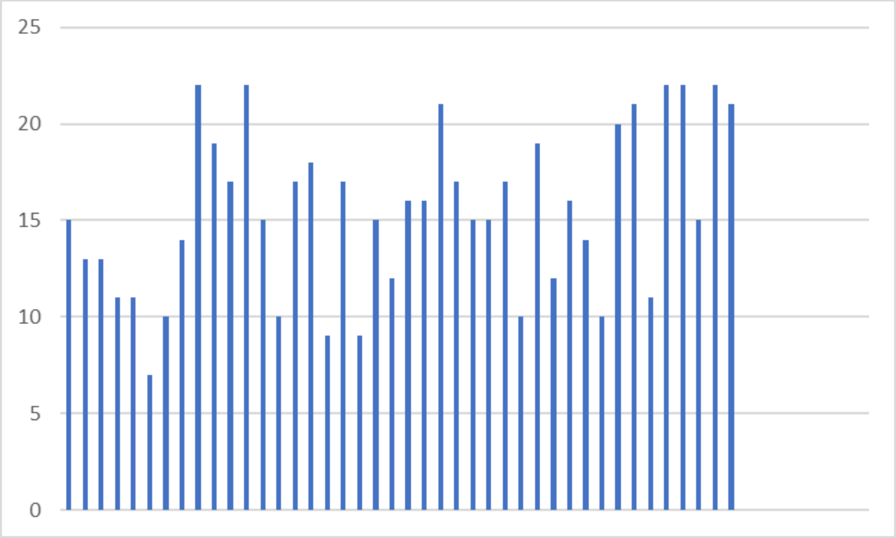
This will tell us something unsurprisiung: we're looking foa 50% effect, and its easier to tell 60 from 40 (photoelectrons) t thatn 22 from 15.

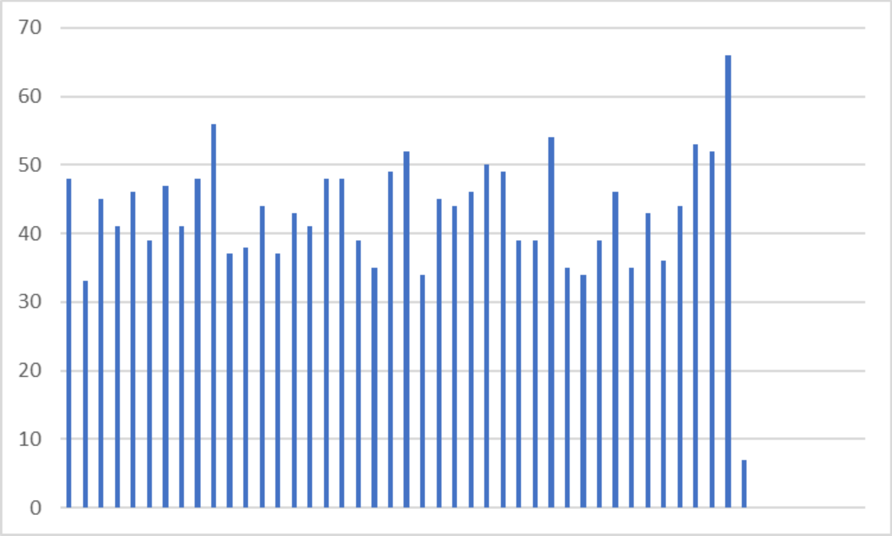
Bragg Peak – Thin Plates



- 15 photoelectrons does reasonably well event-by-event in the thin plates

Bragg Peak – Thick Plates



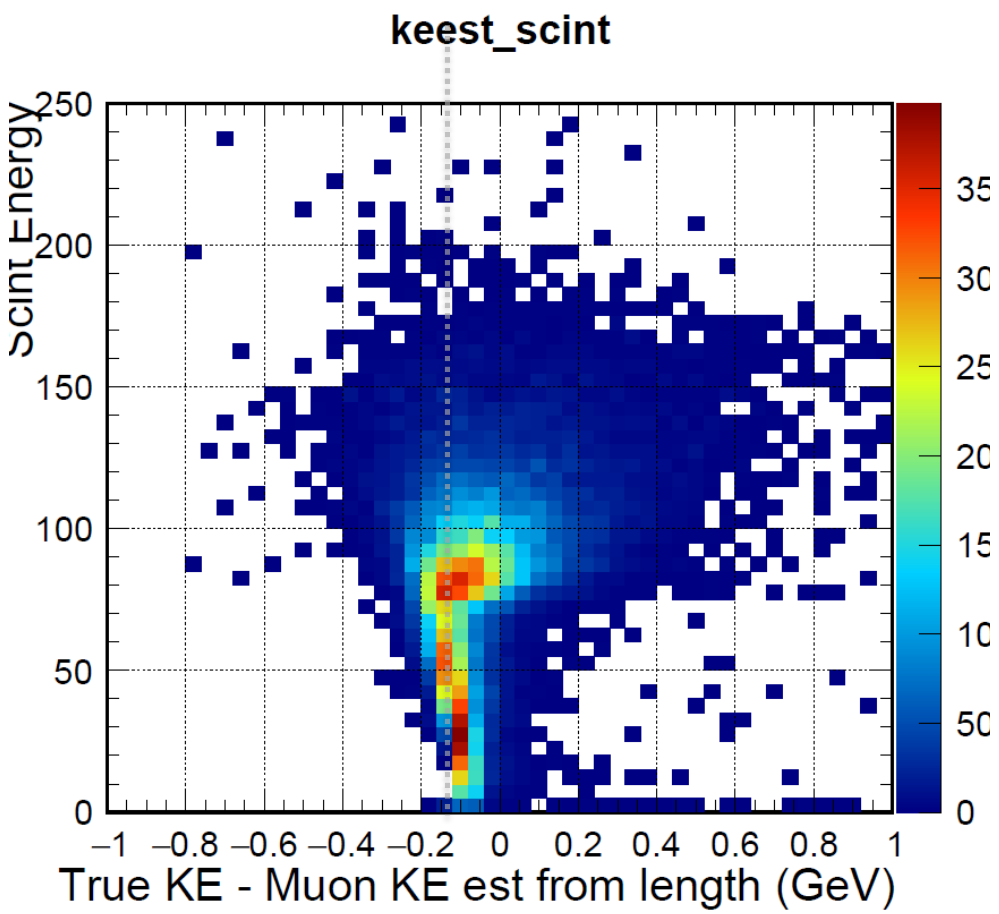


- 15 photoelectrons is difficult (event by event)
- 40 looks a lot better
- A few percent of the time we do really well
  - The muon goes 99% of the way through the last plane of scintiollator and stops.

This is an area where more progress requires Geant

Other Uses of Energy

- Correcting Tracks?
  - Plot at right (from Clarence Wret) shows this is not simple. For both high and low light levels we tend to underestimate (!) the muon energy.
  - It might be helpful in identifying problematic tracks. This would take a study, and probably would not finish anytime soon.
- Energy by calorimetry?
  - For a 1 GeV muon (or electron) the resolution will be 10-15%. It is not dominated by photostatistics so more light is only marginally helpful/



Changing Gears - Stereo

Channel Geometry

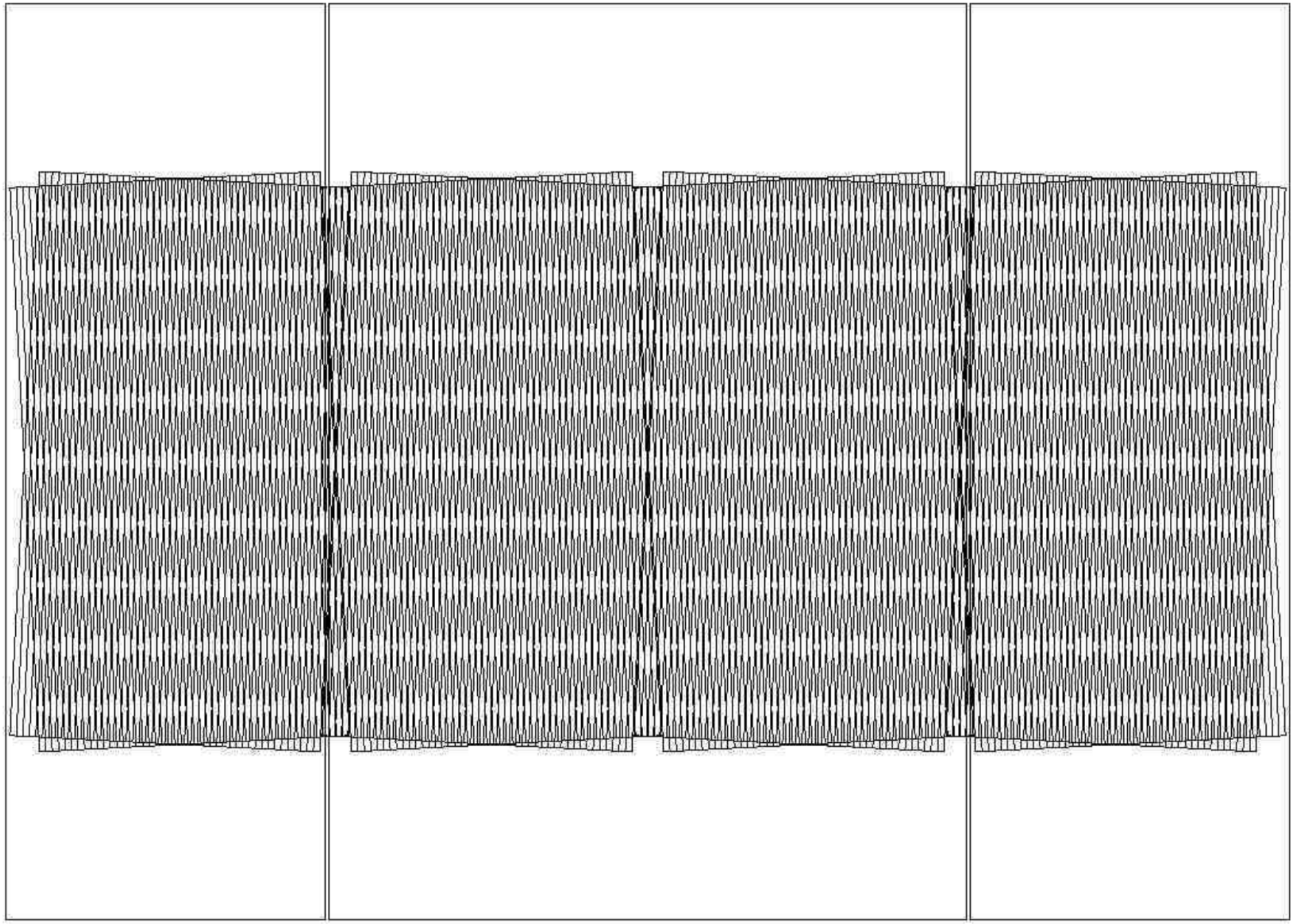
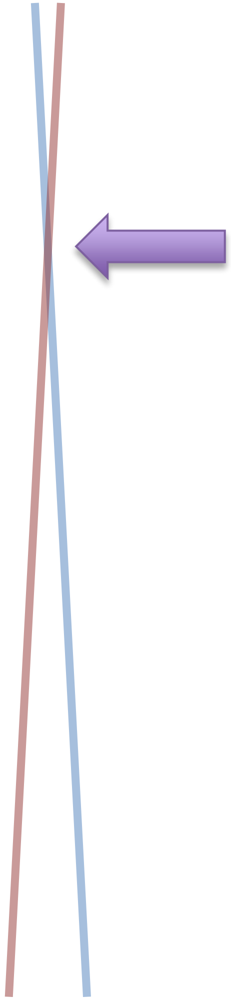


Figure by Palash Roy, Wichita State



Stereo tracking localizes a muon about this well.

TMS has the single-track localization of a ~100,000 channel detector with only 19,200 channels.

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

How These Studies Were Done

- Start with a sanple of muons from CC interactions provided by Chris Marshall in the pre-TMS days
  - I believe it is Genie, but contains μ and ν MC truth kinematics
- Loose requirments (enter TMS from the east, obvious error events removed)
- For pattern recognition studes, project to the front face of TMS
- For range studes use the average dE/dx to determine where the muon ranges out
- In either case, apply counter granularity to position in space.

There is no Geant and (usually) no smearing. This is telling us mostly just about geometry

Confusion at the TMS Front Face (i.e. Pattern Recognition”)

- Extrapolate tracks from ND-LAr to the TMS front face
- See how often there is potential for confusion
- For three models
  - CDR Stereo (“Good”)
  - Orthogonal (“Better”)
  - Perfect position resolution (“Best”), but still track scattering

Results

	Perfect (Best)	Orthogonal (Better)	Baseline (Good)
Potentially confused pairs	16	44	330
Accuracy	99.98%	99.96%	99.7%

Reminder: 105,394 muons

- Important question – are these the same muons?
  - The inclusive sample has an average momentum (at TMS face) of 1.71 GeV.
  - "Good" (potentiall confused) is 1.71 GeV, "Better" is 1.66 GeV and "Best" is 1.61 MeV.
  - So maybe: as fewer events fail, they may show more commonalities, like low p.
    - But the effect is not large (if it is even real).

Interpretation

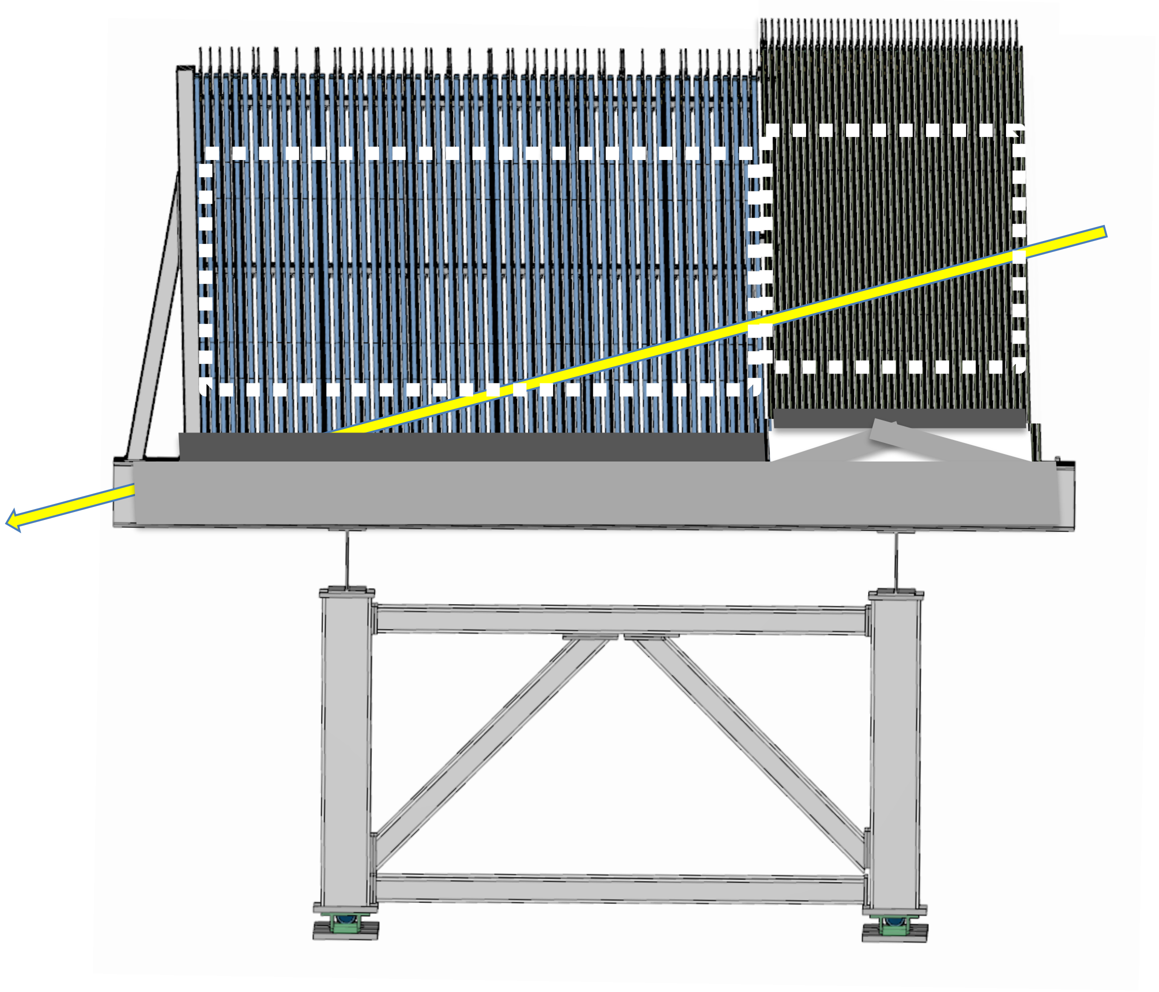
- The denominator is where you already have two tracks in the same time window.

- If ND-LAr can localize a track to one bucket 99.7% → 99.98% (at 1.2 MW)

- If the ND-LAr light system doesn't work *at all*, the is the wrong design
  - Stereo has at least one cpmfusable pair ¾ of the time
  - Orthogonal has at least one cpmfusable pair ¼ of the time
  - Even perfect position resolution fails 5% of the time
  - Better than ¾ μs resolution and confusion is <1%

The Main Problem With Stereo

- The good news with stereo is it measures x better than y
- The bad news with stereo is that it measures y worse than x
- Did the particle exit or was it stopped?
  - Top and bottom are worse than sides (they're bigger)
  - Bottom is worse than top (beam point down)



So How Often Does This Happen?

- I started with the 100K TMS muon sample Chris Marshall gave me at the start of TMS design
  - Required them to exit the west face of ND-Lar, enter the east face of TMS, and have sane energies
  - See how often they exist assuming average energy loss and no side-to-side multiple scattering (on average the same number scatter up as scatter down)

- 3.5% of muons exit before stopping
  - This is predominately at high momentum – at and below oscillation max it's 1.7%
  - That sets the scale for the size of error we might make

How Much Error Does This Introduce?

- There is an upper bound – the size of the effect
  - If we assume nothing ever exited, we would underestimate the energy of 3.5% of our muons by some non-zero amount. (But its small, as this is a steeply falling function of p)
- We have more information
  - We have the y-slope from ND-LAr
  - We have (at least statistical) information on slowing tracks from the Bragg peak
  - We have the location of Michel electrons
  - We have the energy spectrum (problem is worse at high p)
- I believe we are looking at ~20% of the magnitude of the effect or better
  - Double it to determine what might exit, and take 10% of that.
  - That's 0.7% overall, and 0.4% at oscillation max – comparable to confusion because two muons end up in the same strip

One General Comment

- If you are worried about a sub-percent error in acceptance, get involved in the strip extrusion process: this corresponds to about 140 microns in the scintillator active width.
  - Just a little bigger than the thickness of a sheet of paper.

That will take work.

Track Direction Ionization Correction

	Correction	Additional p Uncertainty
Only use z-Information	4.71%	4.11%
Add Perfect x-Direction	2.01%	2.96%
Add Stereo y-Direction (worst case)	0.05%	2.07%
Better stereo direction (more realistic?)	0.02%	1.54%
Orthogonal Estimate*	0%	1%
Perfect Detector	0%	0%

* Actually √2 of 1D in y and perfect x

- Take a muon. Move it to the center of the "virtual counter" and look at the mean and standard deviation of the path length change
- "Worst case" → measure to 30 cm in y (one hit pair)
- "Better stereo" → measure to 15 cm in y (to try and mock up multiple hit pais

Track Direction Interpretation

- These are stand-alone muons. ND-LAr tarcks will greatly improve on this, with either orientation
- These need to be added in quadrature with the resolution due to range and straggling
  - Assume it is 5%
  - Orthogonal would be 5.1% total (standalone)
  - Stereo would be 5.3-5.35% total (standalone)

Comment On Geometry

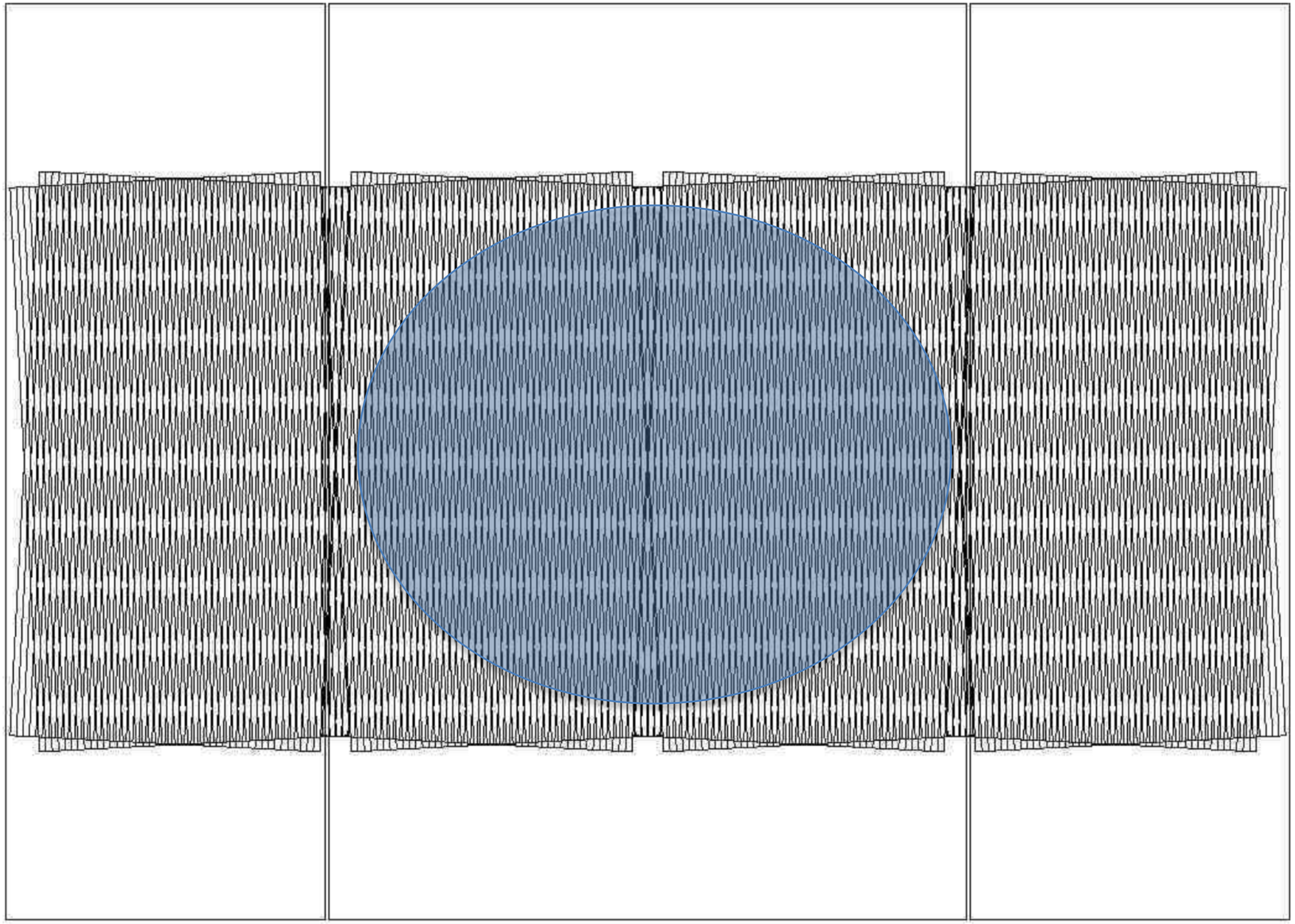


Figure by Palash Roy, Wichita State

- The same kinematics for muons near the top and bottom of the circle are well-measured by the muons on the sides.
  - Physics requires this ϕ– symmetry
    - Neutrinos are 100% longitudinal and ^{40}Ar is spin-0 (as is ^{38}Ar)
  - I will discuss beam asymmetries in a few slides

A Slide from Chris Marshall (ftom 1/24/23)

Scintillator orientation/stereo ”orthogonal counters”

- Current design is 3° rotation → better resolution in bend direction, but quite bad (~30 cm) resolution in vertical dimension
- Three possible physics issues:
  - LAr-TMS matching
  - Selecting stopping TMS tracks (confusion with bottom-exiting)
  - Momentum reconstruction (vertical component of track length, and possibly tracking muons through passive material)
- Existing tracking algorithm is essentially 2D – doesn’t use the two views separately, and can’t really address this
- Proper timing simulation may also be required

4 UNIVERSITY of ROCHESTER DUNE

Now We Have Answers

Scintillator orientation/stereo ”orthogonal counters”

- Current design is 3° rotation → better resolution in bend direction, but quite bad (~30 cm) resolution in vertical dimension
- Three possible physics issues:
  - LAr-TMS matching
  - Selecting stopping TMS tracks (confusion with bottom-exiting)
  - Momentum reconstruction (vertical component of track length, and possibly tracking muons through passive material)
- Existing tracking algorithm is essentially 2D – doesn’t use the two views separately, and can’t really address this
- Proper timing simulation may also be required

- Below 1%
- Below 1%
- Below 1%

Charge Identification

- We start getting good charge ID (several percent misidentification) above about 8 hits

- With 30 hits we expect 20σ separation, assuming errors are Gaussian
  - They aren't – at that level they are driven by large angle scatters and catastrophic energy loss
  - We should see sub-percent errors at oscillation max, even with fewer counters in the bend view

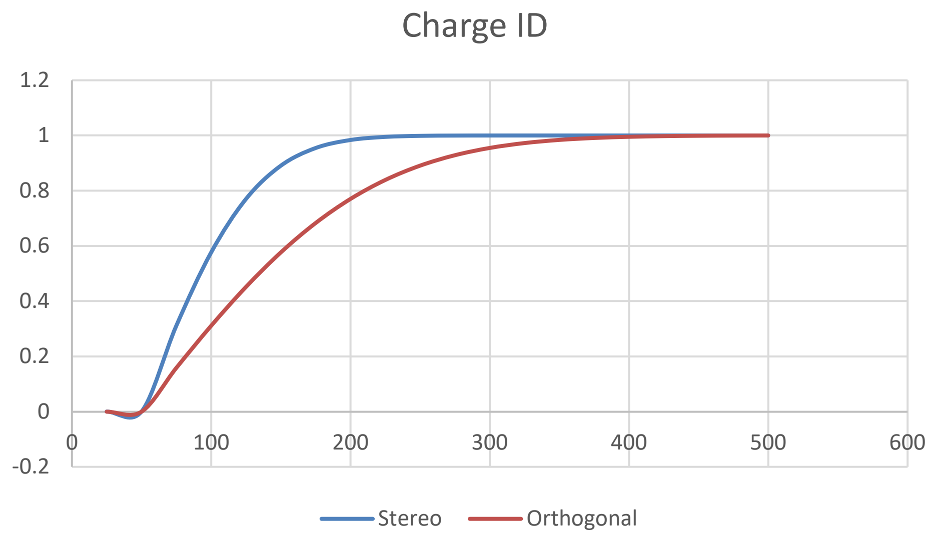
- What about the second oscillation max?
  - These muons barely make it into the TMS (if they do at all). I don't trust this level of study.
  - But the point is well-taken: the problems with charge identification will present itself for muons in the few hundred MeV range.

Stereo vs Orthogonal: Charge ID

- We need about 8 hits to do reasonably well on charge identification

- Stereo was designed to do this better than orthogonal
  - Stereo TMS muon charge identification starst at ~100 MeV (+600-1200 in LAr)
  - Orthognal TMS muon charge identification starst at ~200 MeV (+600-1200 in LAr)
  - Difference is a little smaller than one would expect from naïve hit counting (about 120 MeV)

- Reminder: off-axis the p spectrum falls dramatically



- Caveats:
  - The Chris Marshall sample doesn't go this low.
  - These curves are purely analytic
  - They assume Gaussian errors
  - In real life, things will be worse and dominated by non-Gaussian tails.
- "The line is there to guide your eye".

Comment On Beam Monitoring

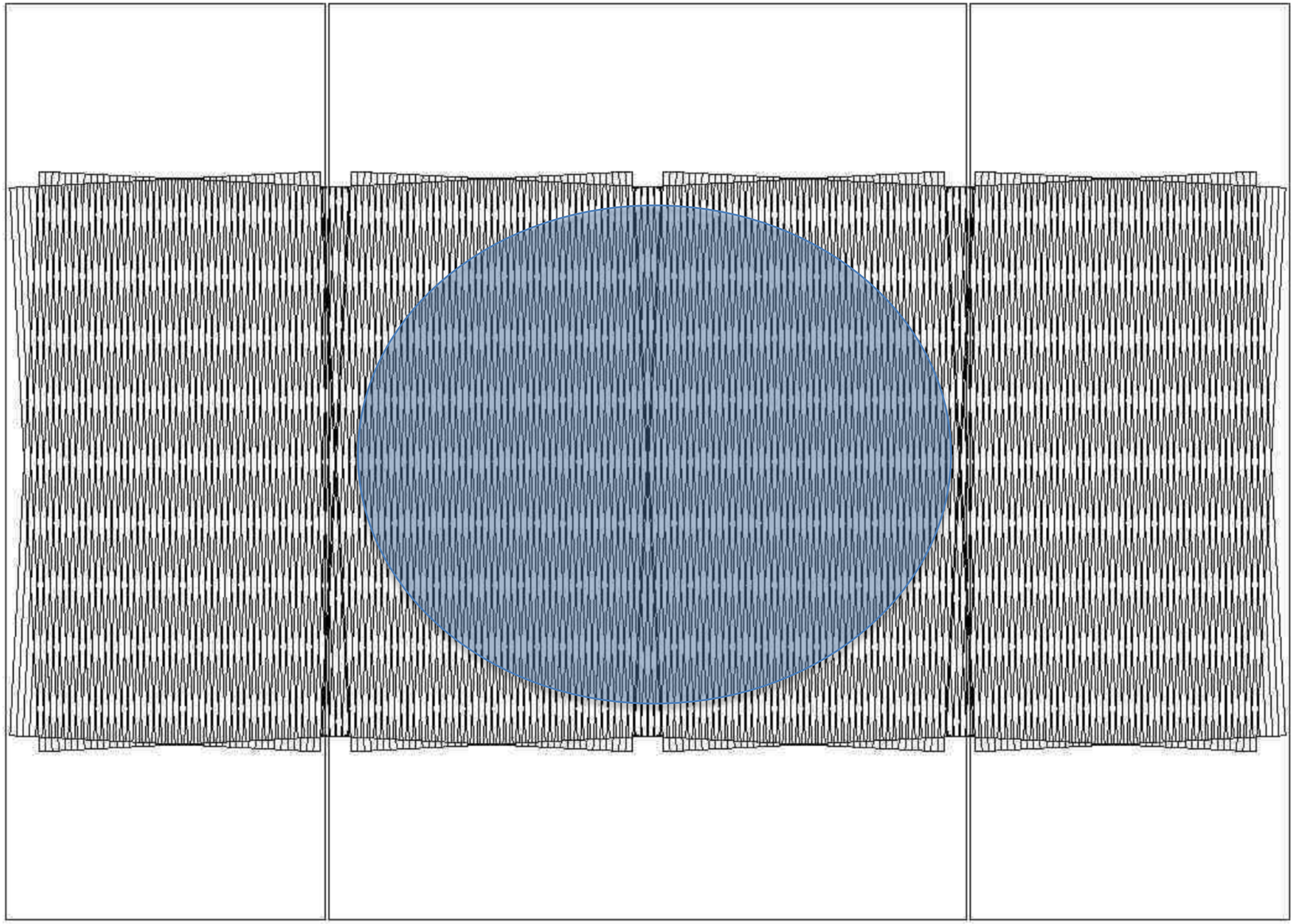


Figure by Palash Roy, Wichita State

- Clarence Wret showed that in most cases beam issues manifest earlier as a energy change than a position change.,
  - Even a horn tilt – the reason is that this effectively moves TMS off-axis

- An issue with a primary proton beam is substantially diluted by the time you get to the quaternary muons.

LBNF/DUNE

“One Good Hit”

- There was a lot of positive support for a high resolution first layer
  - Measure after the muon has scattered in the window…
  - …but before it has scattered in the steel

- A good idea – but I recommend we hold off on this for now
  - We don’t know the financial situation near the end of the Project
  - We don’t have a good handle on the optimal parameters
  - We have plenty of studies to do with the existing design
  - The “cassette” lets install it later
    - Technology might or might not be scintillator (but remember the rate is 25 Hz/cm^2)

Conclusions

- Scintillator thickness is a critical issue – nobody is getting any scintillator First Items for prototyping until this is settled. (We need to tell them what to make!)
- This is coupled to the question of steel flatness amd the stay clear: everybody feels the space between the plates is bigger than it needs to be, but we have no evidence yet.
- Chris Marshall's concerns with stereo are quantified – they are all sub-percent level
- The decision on whether to switch to orthogonal will not be made based on studies with smaller uncertainties. It's a physics issue: would you rather have charge ID at low p (above 300 MeV and the effect is gone) or reduce these sub-% errors at higher p?
  - We can do better with some muons at the cost of doing worse on others.
  - It is difficult to make more progress without an advocate and a specific design

Backup

How Did We Get Here?

We had been thinking about y-direction measurements from the very beginning.

- The very first TMS designs had a vertical magnetic field bend
  - The “MPD” – what became ND-GAr – had a horizontal field
  - Scintillator strips were horizontal, to measure the vertical bend.
- This design was mechanically unstable
  - The steel wouldn’t support its own weight and would end up in a pile on the floor. This is less than ideal.
- We switched to a horizontal bend
  - This is better anyway – you want the bend in the long dimension not the short dimension
- With small angle stereo, you win as sin(ϕ) or ϕ, but only lose as cos(ϕ) or ϕ^2.
  - Why stop at 3^o? The larger than angle, the wider the plates get, and the wider they get, they heavier they get → we’re coming up against PRISM/Hilman limits, steel cost is an issue, interferences are an issue, etc.

Stereo Comments

- Stereo is intended to do better with charge identification at low p
- Orthogonal benefirtts are usually more diffuse – smaller and in more places
- Wbich is better depends on what physics you consider more important.
  - Can we decide soon? What will we know in six months we don’t know today?

- Cost is hard to gauge
  - Two kinds of counters is more expensive
  - Orthogonal has slightly lower channel count and higer occupalncy → less expsive
  - Both are small effects, and it’s not clear which one will dominate

Some Unimportant Details

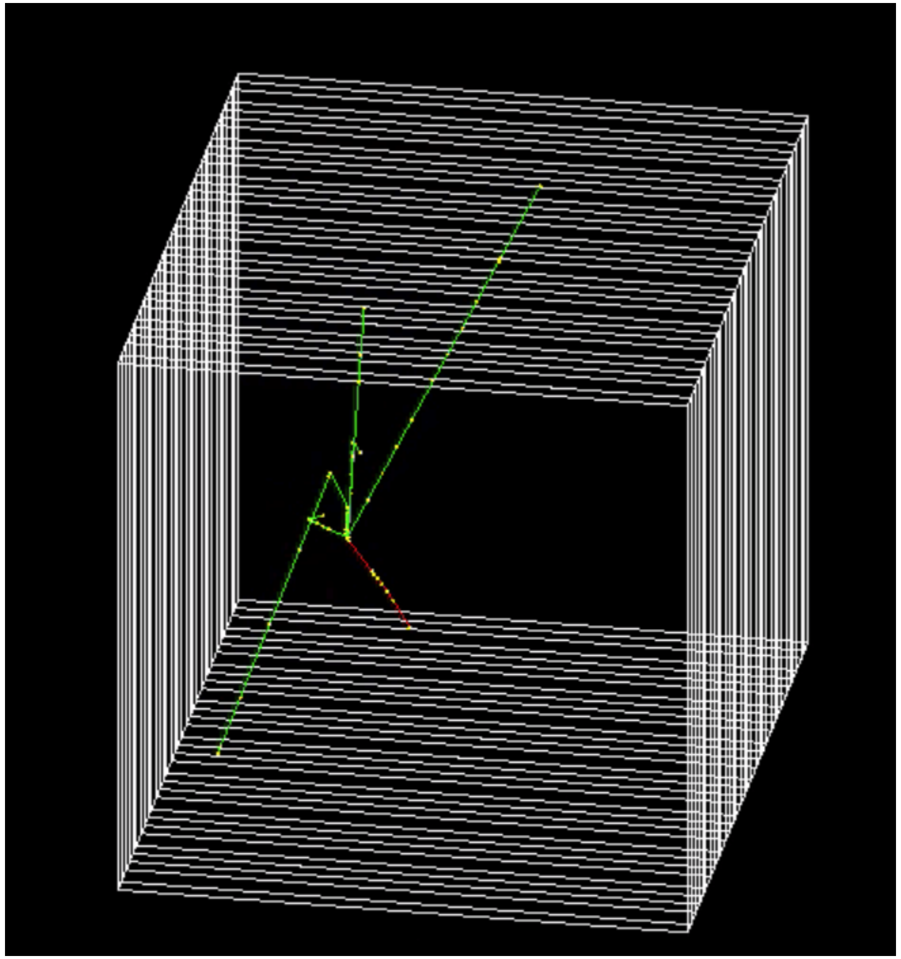
- These are all negative muons
  - Positive muons have ~1½% more visible energy from the positron annihilation
  - There are no atomic effects for captured muons – particularly no Decay-In-Orbit events
- The magnetic field is there, but makes no real difference
  - I thought it might constrain electrons, but the energy loss in iron does that pretty well already
- The rate calculation is for muons produced in the liquid argon. If you are interested in Michels produced from parent neutrino interactions in the steel, that's about a factor of 1.8 more. (2.8x total)
- The definition of "MIP energy" is from Geant4 for muons at normal incidence. Typical muons average 14^{o} incidence (6^{o} of which is from the beam direction)

Meet Mini-TMS

- A stand-alone Geant4 TMS model
  - 8 layers (steel, scintillator, stay clear, no aluminum box)
  - 30 x 30 cm in x and y
  - No digitization – just energy deposits
  - 1 T magnetyic field in the steel plates

- Intended to answer two questions
  - Is this even feasible? i.e. do we get enough Michels to use?
  - What dynamic range do we need? Is the simple calculation correct? (53 MeV → 25 mips → 5 bits)

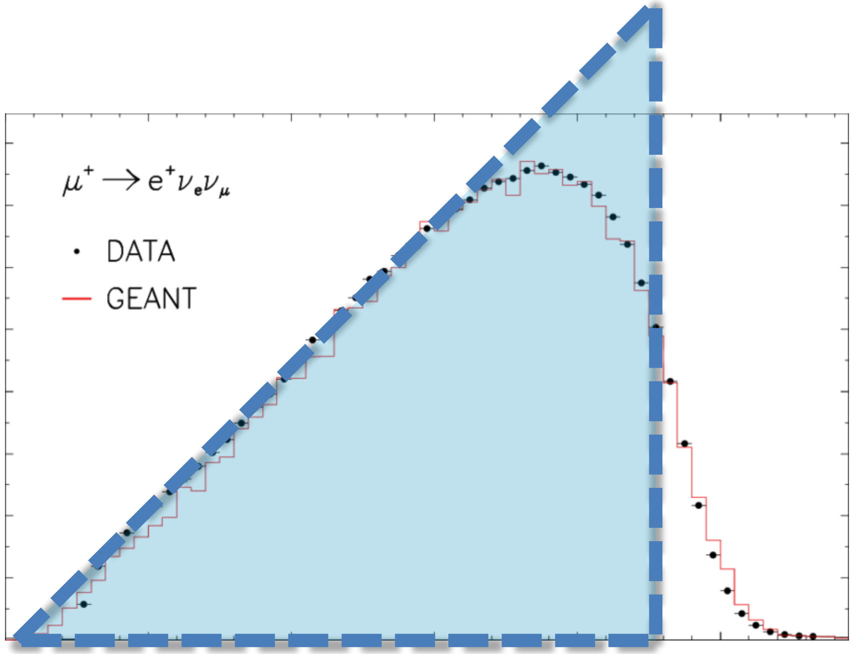
This is not intended to be an analysis-level study.

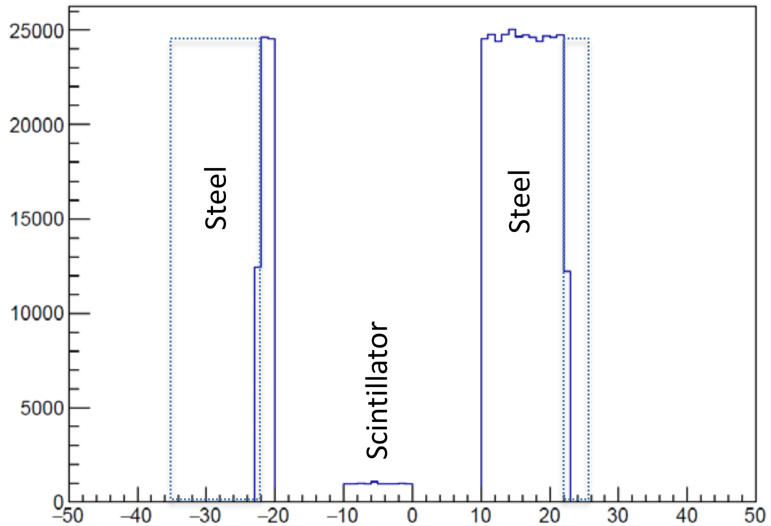


A $\mu \rightarrow e\nu\nu$ decay in miniTMS.

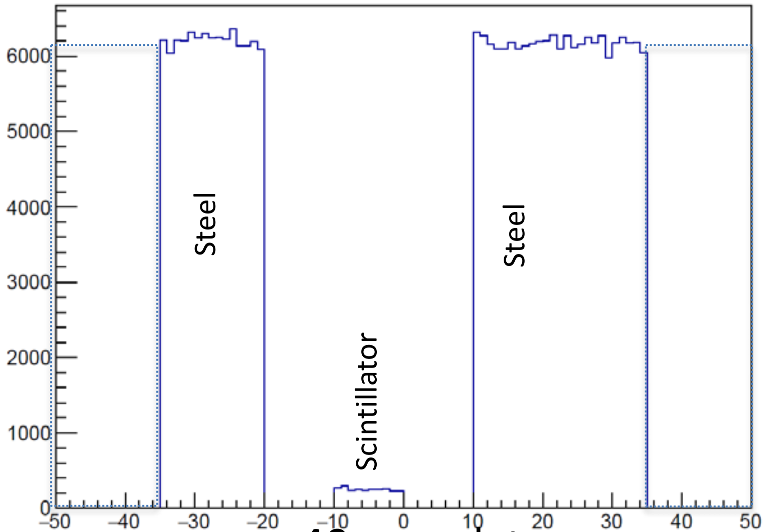
Modeling Muon Decays

- The true energy spectrum has been replaced by a triangular distribution.
- Where the muons stop is proportional to the radiation length.
  - Questionable for very low energy – below the Bethe-Bloch region
  - The model is, for technical reasons, not centered on the scintillator. My bad.





15 mm plates

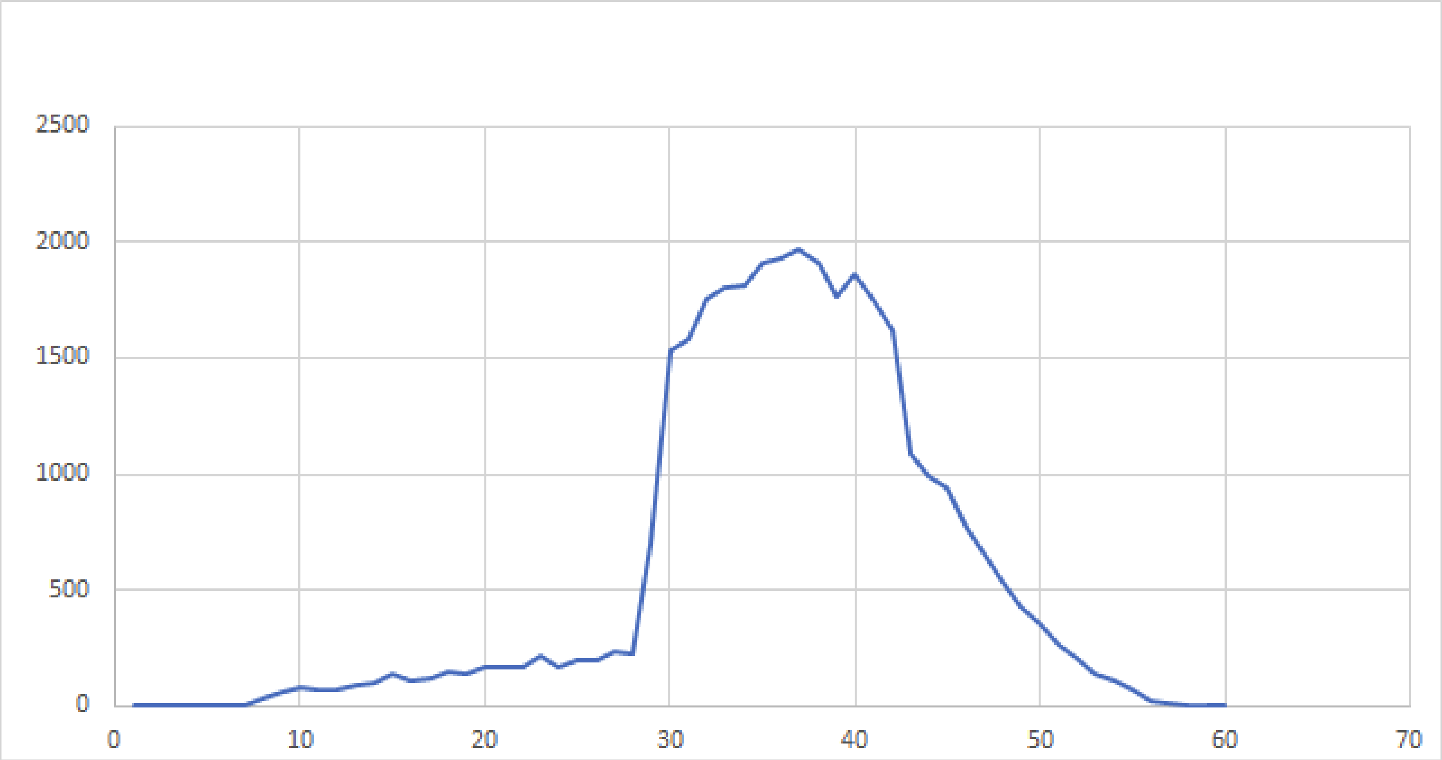


40 mm plates

LBNF/DUNE

Where Do Muons Stop?

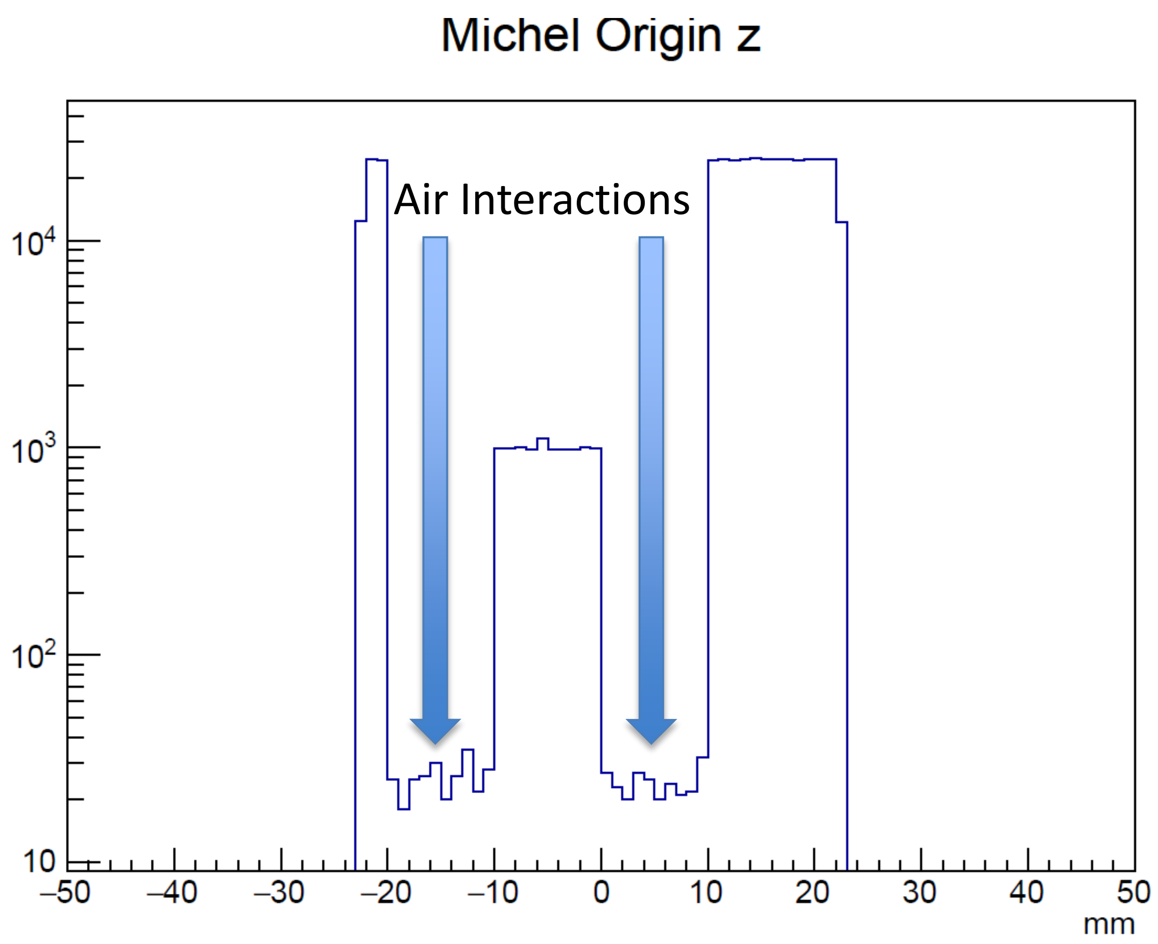
- From the same sample and look at where muons stop if the parent neutrino is within 20% of oscillation max.



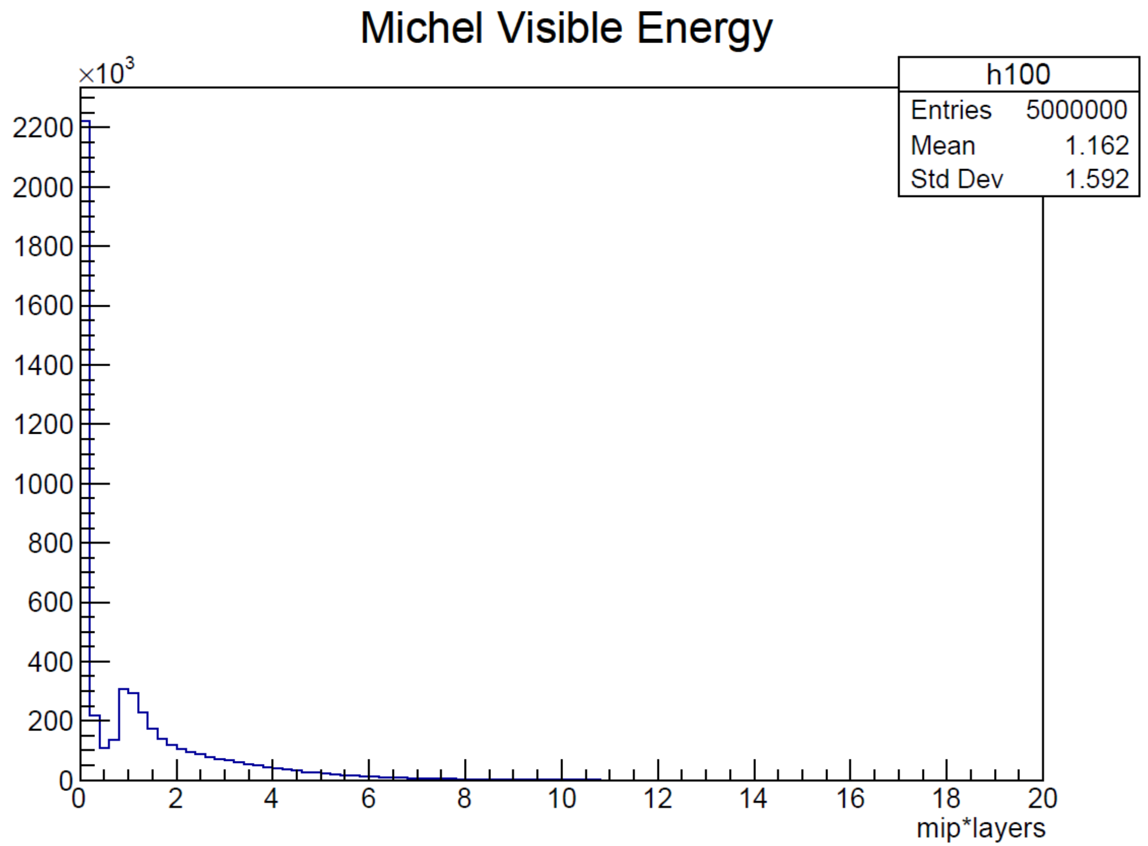
LBNF/DUNE

Some Fun With Log Plots

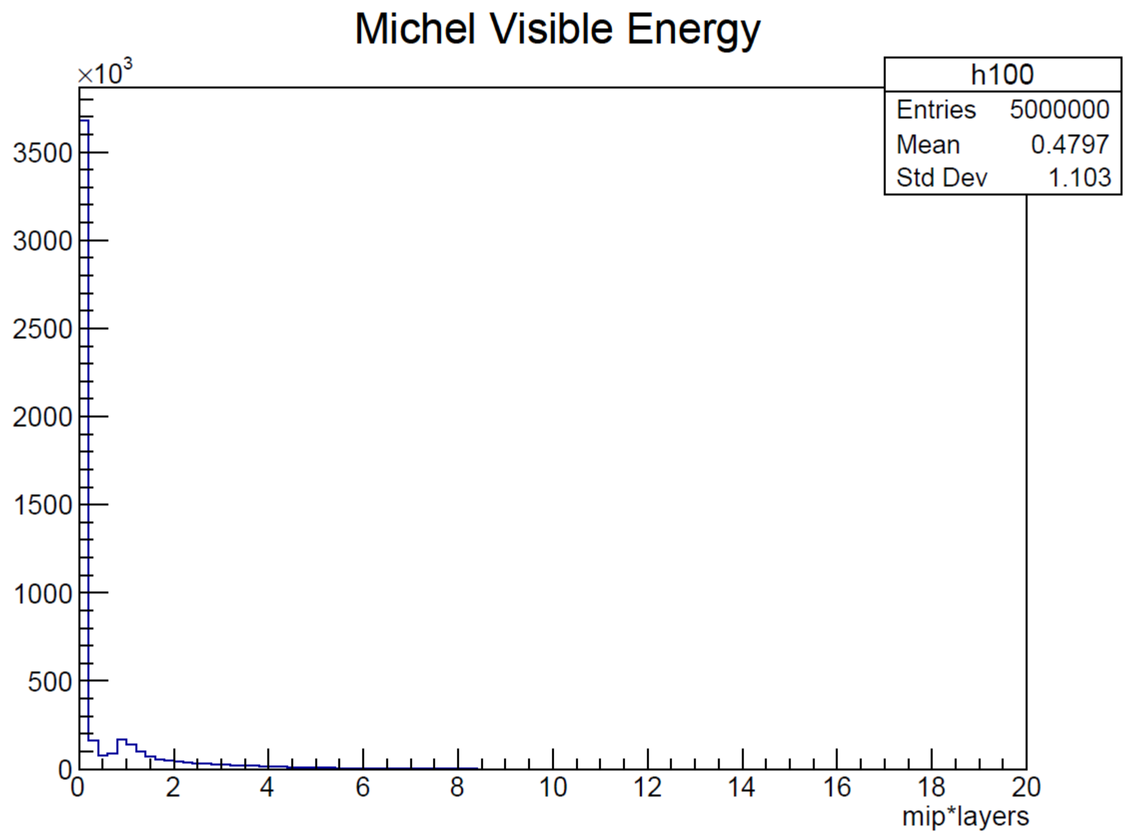
- On a log plot one can spot the air gaps
- We will have muons stopping in air
  - Of order 10^{-3} muons stop in the air
  - Of order 10^{-2} of those stop in the argon
- We expect a few events per day on gaseous argon (!)
- I don't see any way to identify, much less use these events. But they will be there.



Michel Visible Energy



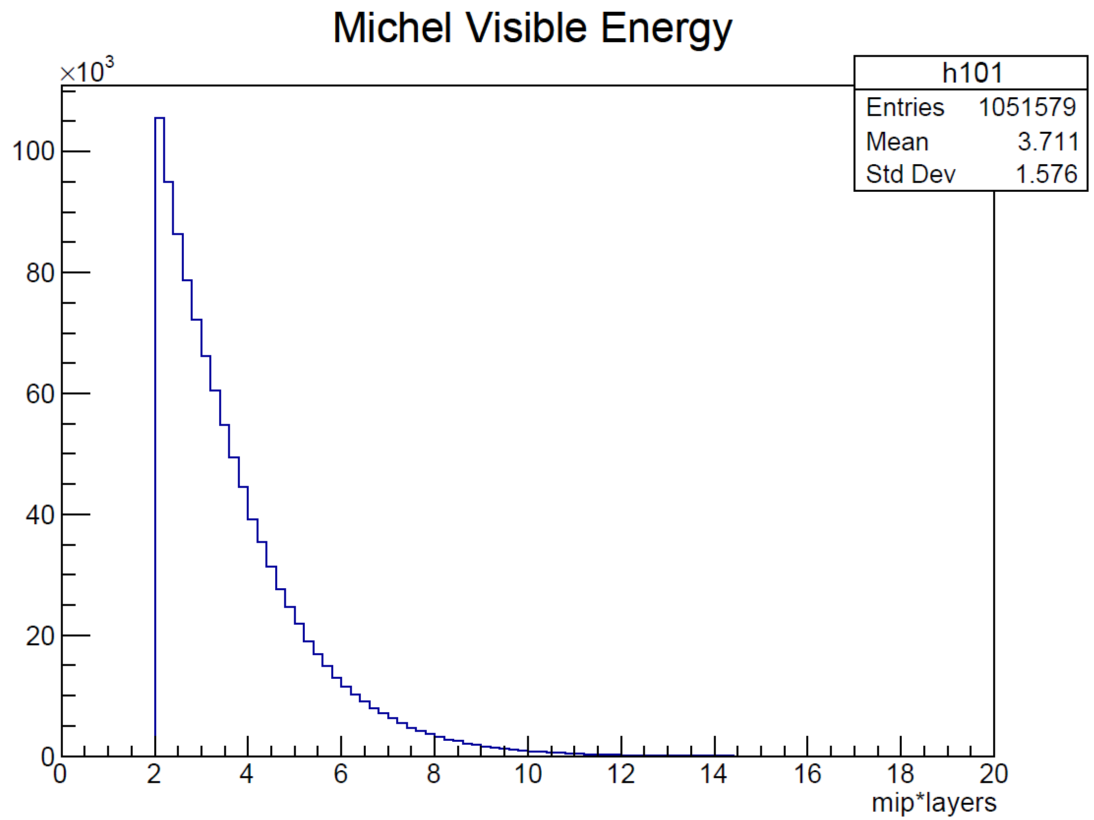
15mm Plates



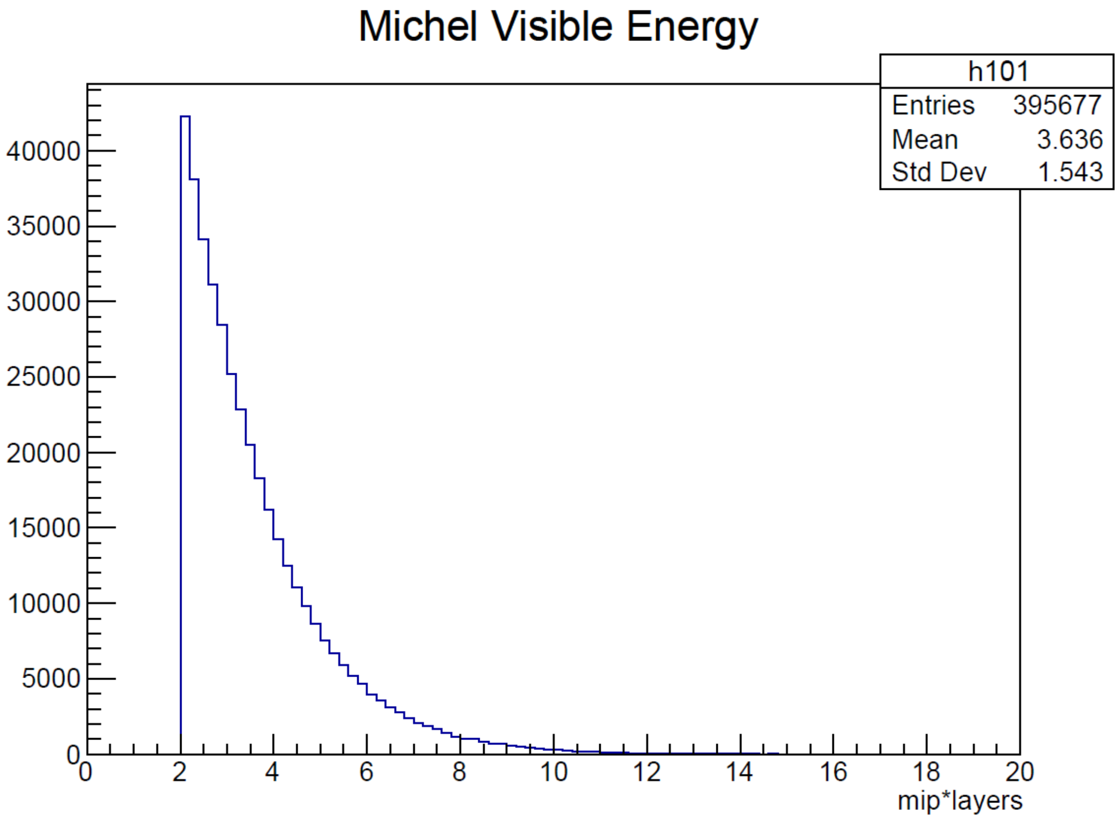
40 mm Plates

n.b. it says “mips*layers” but multilayer events are rare.

Michel Visible Energy (> 2.0 mip Equivalent)

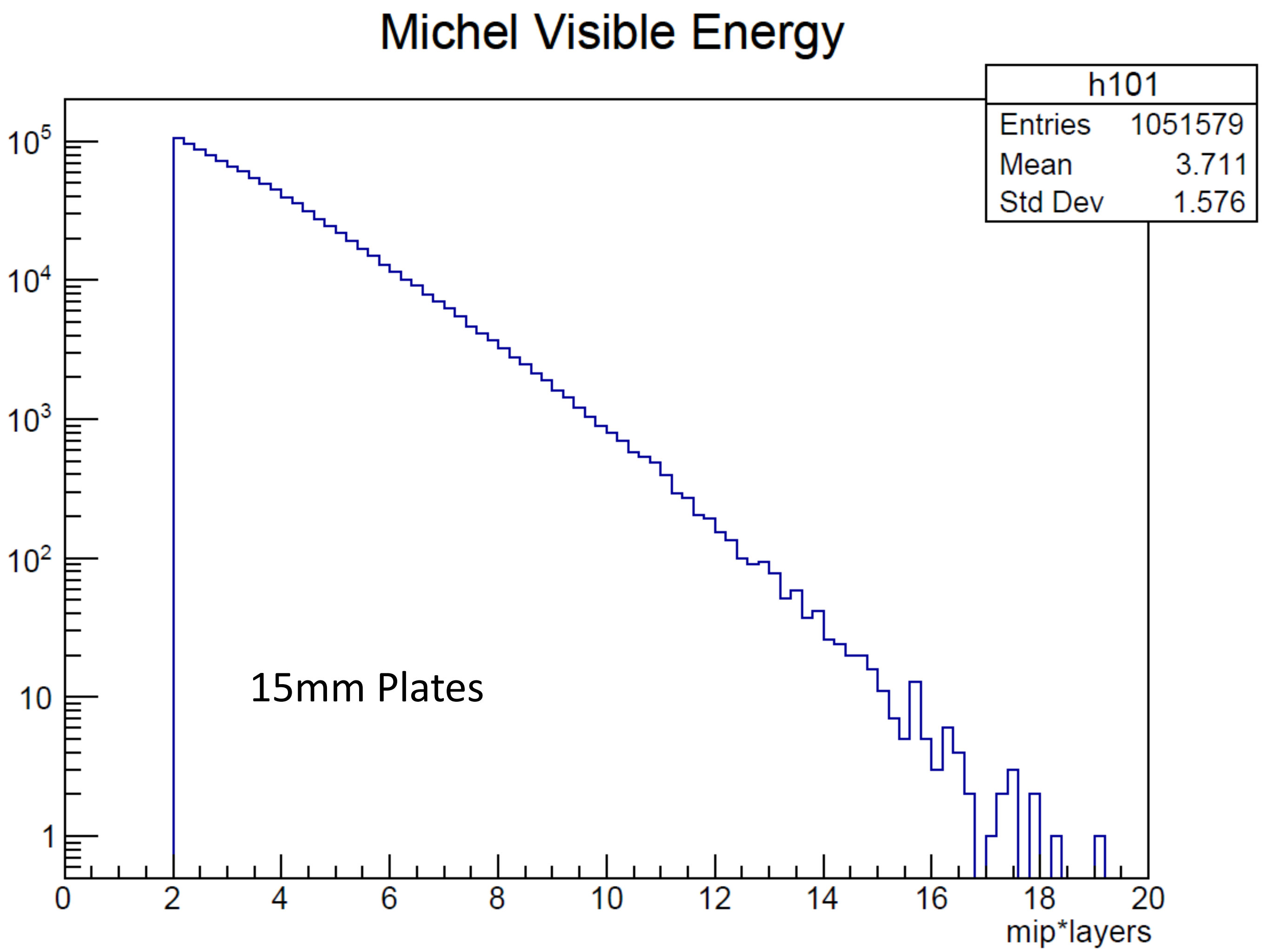


15mm Plates



40 mm Plates

More on Michel Visible Energy



- We see events almost out to the kinematic maximum.
- These events, however, are rare
  - The geometry has to be exactly right: stop in the scintillator, and decay so the electron is in the x-y plane.
- The 2.0 mip cut may well be too high
  - This is a question of background, as the Michels are often single hits. Of course we don't know that yet.