An external muon tagger for ND-LAr

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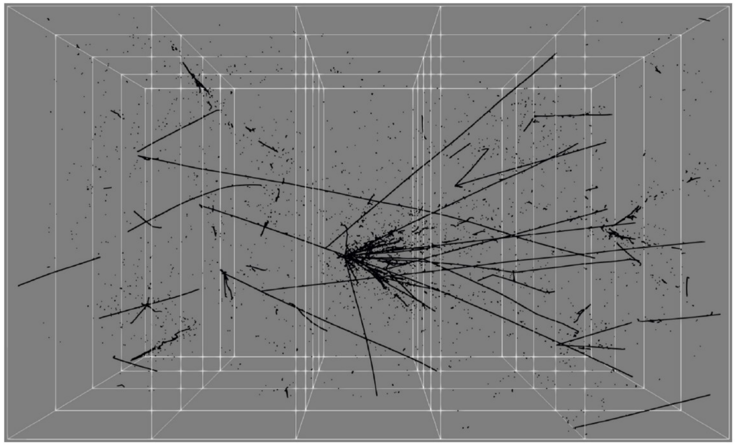
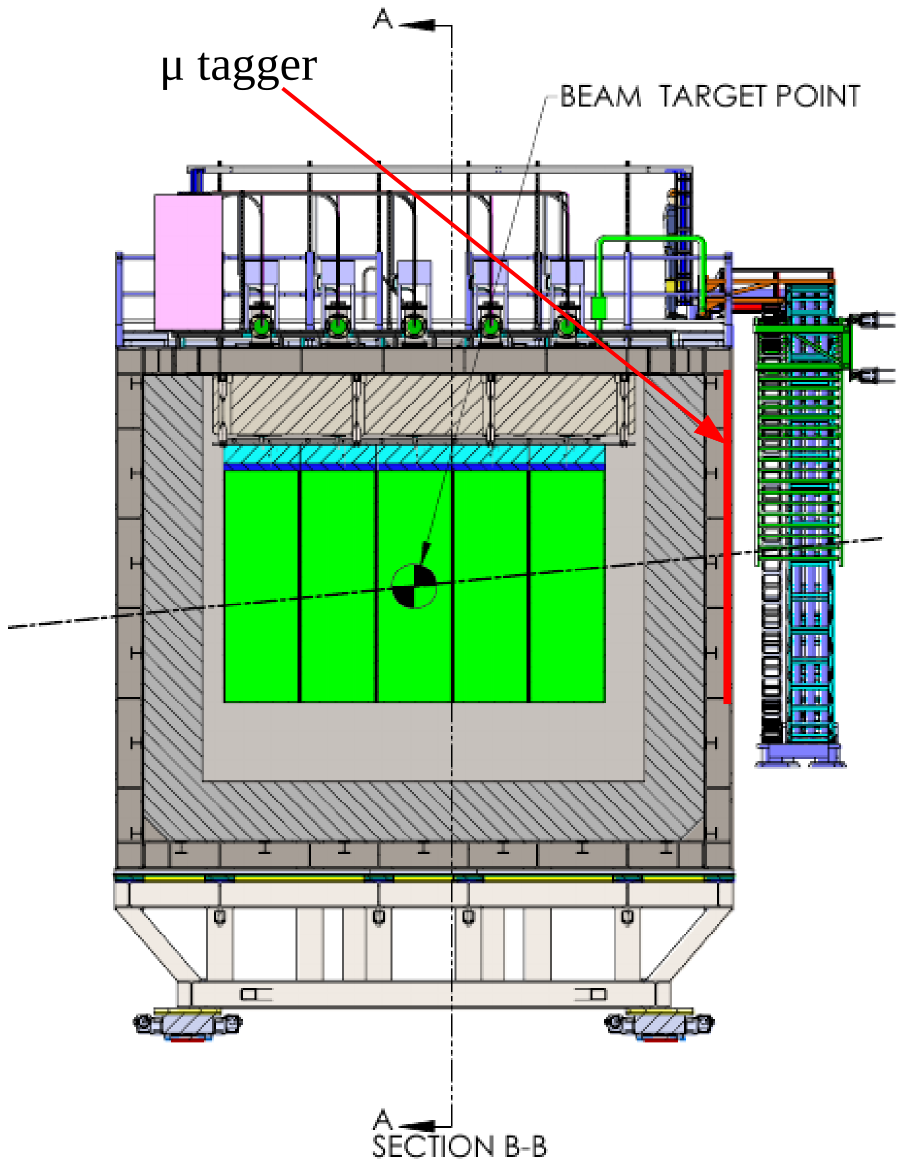
Why



- Pile-up mitigation
  - ~30 rock muons per spill at 2.4 MW
  - Will produce light signals in ND-LAr that can be easily confused with fiducial muon tracks
  - External tagger can identify rock muons so they can be excluded from analysis
- Externally-tagged calibration sample
  - Select through-going tracks for calibrating relative energy response, argon purity, alignment, etc.
  - Also measure tracking efficiency

What



- Two 1cm scintillator planes, with 3.85cm-wide strips in 90° stereo for 3D position
- Cover ~9x4.5m area on upstream face of ND-LAr
- Use TMS scintillator design, fiber extrusion, readout electronics
- Piggy-back on existing TMS design and prototyping effort to reduce new costs

How

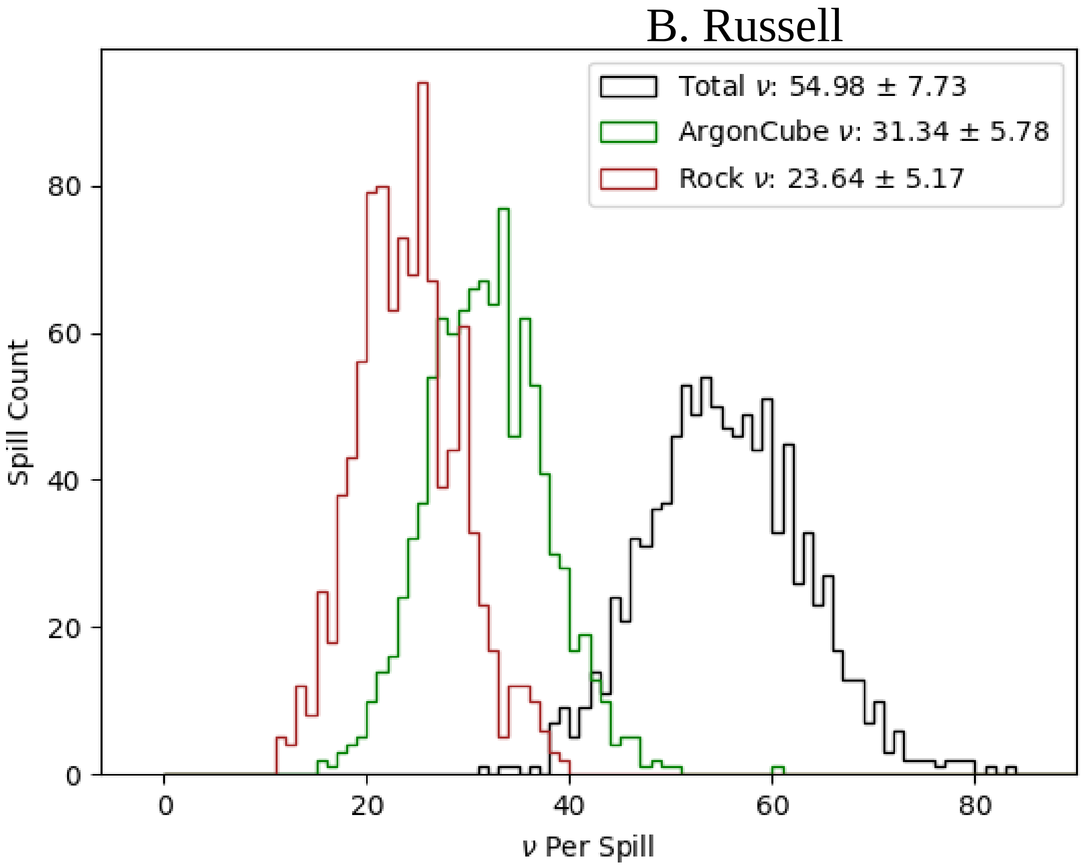
- Propose to integrate external muon tagger into the ND-LAr design, and coordinate the work through this consortium
- Close collaboration with TMS is critical
- Next steps:
  - Continue design optimization work
  - Develop a plan for integration
  - Understand DAQ requirements and plan
  - …

My talk from Thursday's ArgonCube meeting follows

Outline

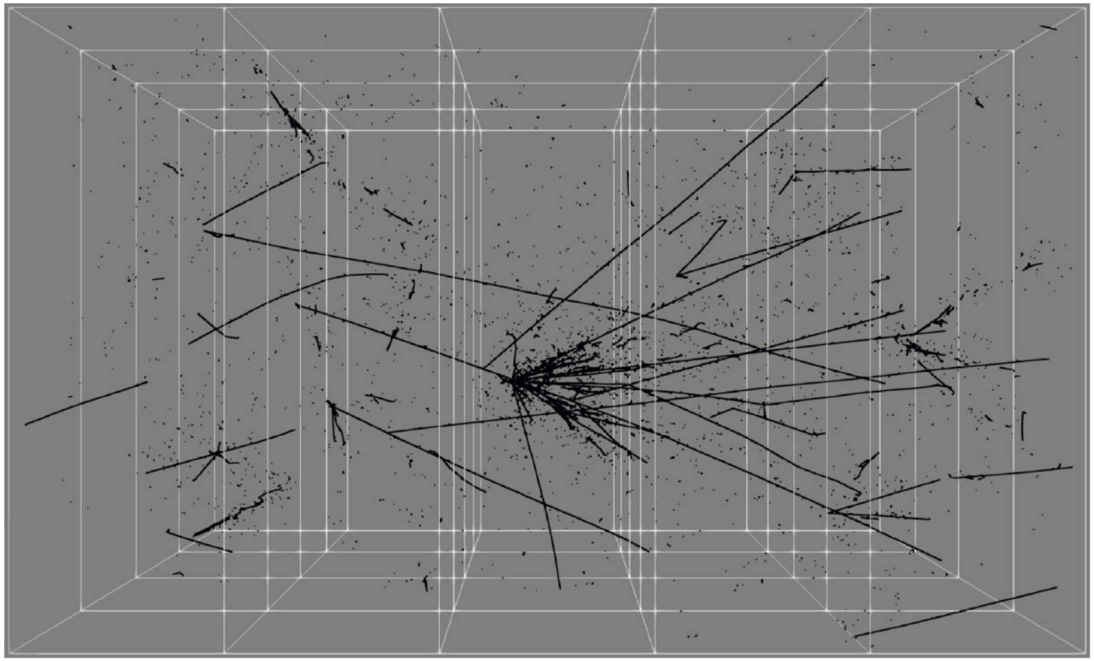
- Why we need a muon tagger
  - Charge-light ambiguity
  - Calibration sample tagging
- Can’t the photon detector double as the muon tagger?
- External tagger preliminary physics requirements
- Design concept
- To do

Pile-up is going to be challenging



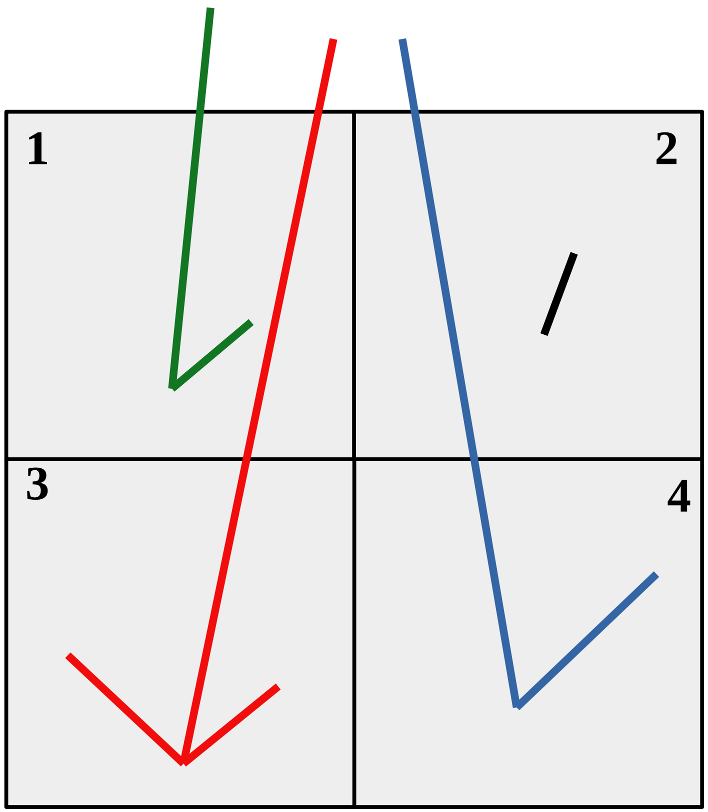
- At 1.2 MW, ~55 neutrino interactions per spill deposit energy in ND-LAr
- ~45% originate in the rock – entirely external to ND-LAr
- ~80% of rock-originating interactions that reach ND-LAr include a muon, the rest are mostly neutrons
- You should multiply this by 2 in your head – we need to be able to handle the 2.4 MW intensity – over 100 interactions per spill!

Detached energy deposits require timing information



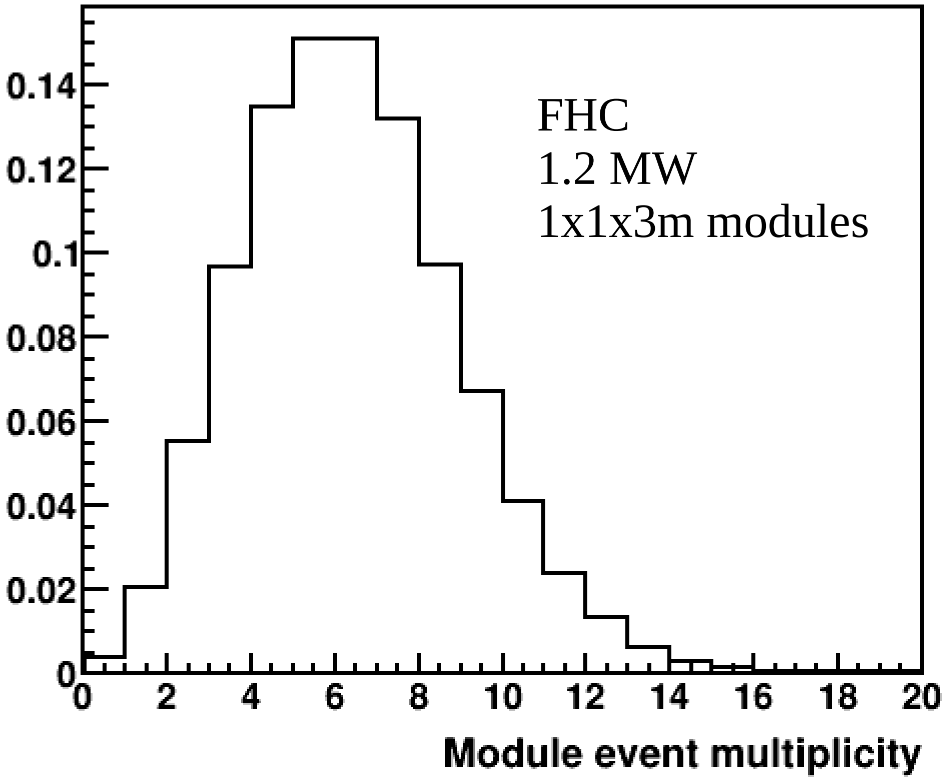
- Due to 3D charge readout, fully-connected interactions can *probably* be reconstructed without scintillation/timing information, though this has not been demonstrated
- Associating detached energy to the correct neutrino interaction is critical, and nearly impossible without timing in some cases
- This is unique to the ND, so getting it wrong will result in a ND/FD difference that will have to be corrected with models and lead directly to increased systematics in the OA

Simple cartoon example



- Thanks to 3D readout, all the tracks and vertices can be found
- But which neutrino produced the black detached energy in module 2?
- If it's red or green, then there will be two distinct scintillation signals in module 2, and you can use timing to associate the black charge signal to the right event

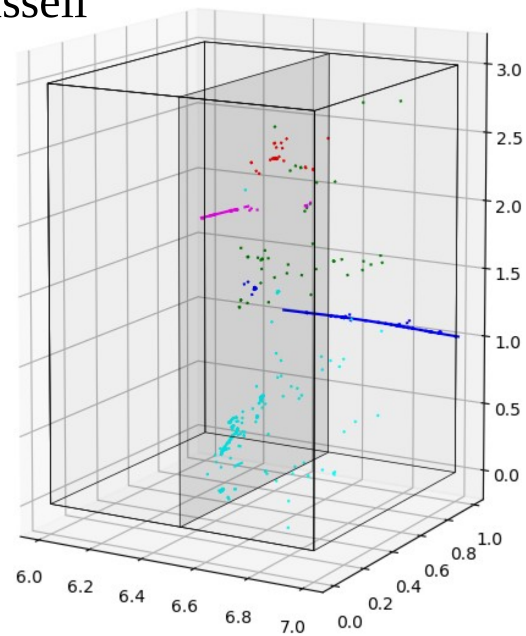
Optical modularity is critical, but it's still nontrivial

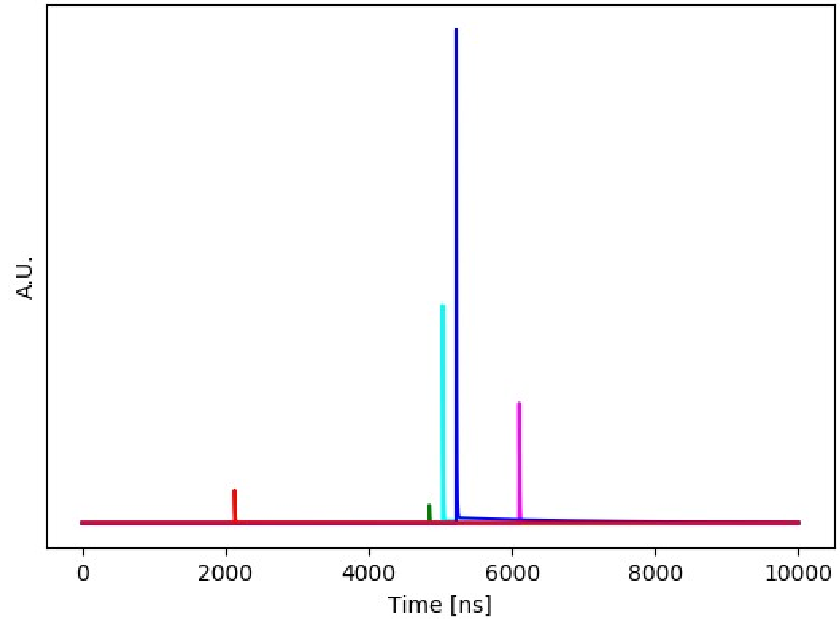


- ~55 events per spill in entire detector
- ~6 events per spill per module, with a tail out to 15
- A typical module will record ~6 charge signals and ~6 light signals in each spill

Charge-light matching creates potential ambiguities

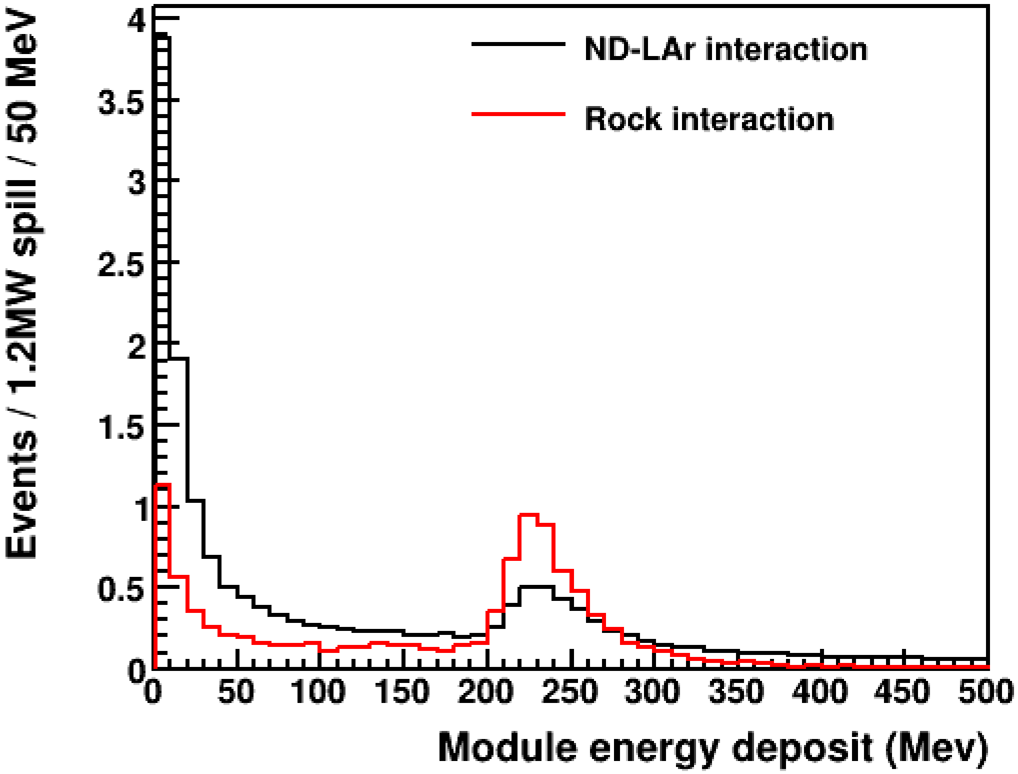
B. Russell





- Which light signal goes with which charge signal? “Flash matching” problem
- Modularity helps *a lot* – without it flash matching would be a 50-to-50 problem
- Three handles to help with matching: (1) position resolution, (2) pulse height resolution, (3) correlations between modules

Through-going MIP tracks are extremely common

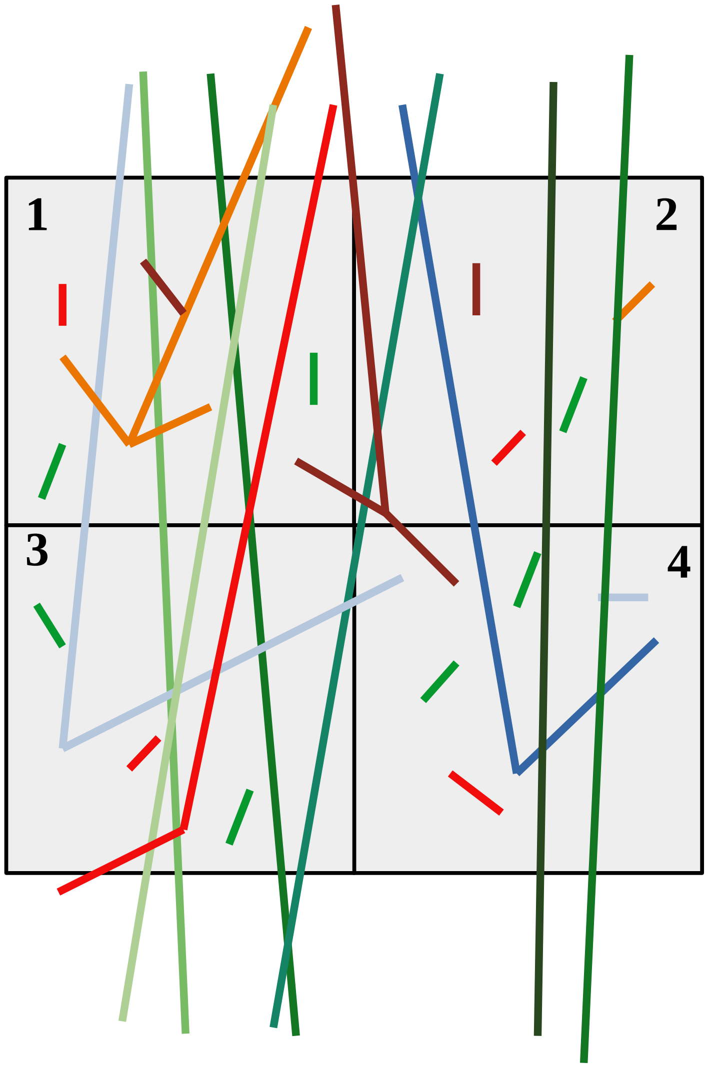


- True energy deposit per 1x1x3 module for neutrino interactions in rock, and ND-LAr (including all passive elements, cryostat, etc.)
- On average, a typical module will have ~2-3 low-energy events, which are often detached
- On average there are ~2 through-going MIP tracks per module per spill, ~1 of which is a rock muon
- Poisson fluctuations to several rock muons in one module will be common

Flash matching: summary

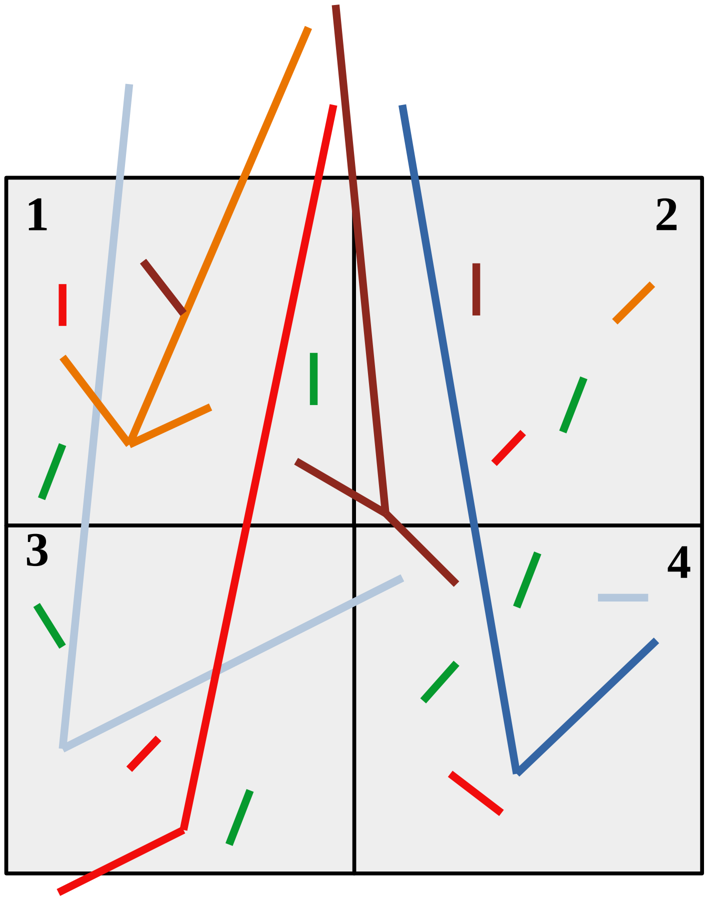
- An average 1x1x3m module in an average 2.4 MW spill will have:
  - 2-3 through-going rock muons
  - 2-3 through-going muons from ND-LAr interactions
  - 1 neutrino interaction vertex
  - 4 detached lower-energy blips/showers
- 10 time-separated prompt scintillation signals, of which 5 are essentially the exact same pulse height

Example: realistic 2.4 MW spill



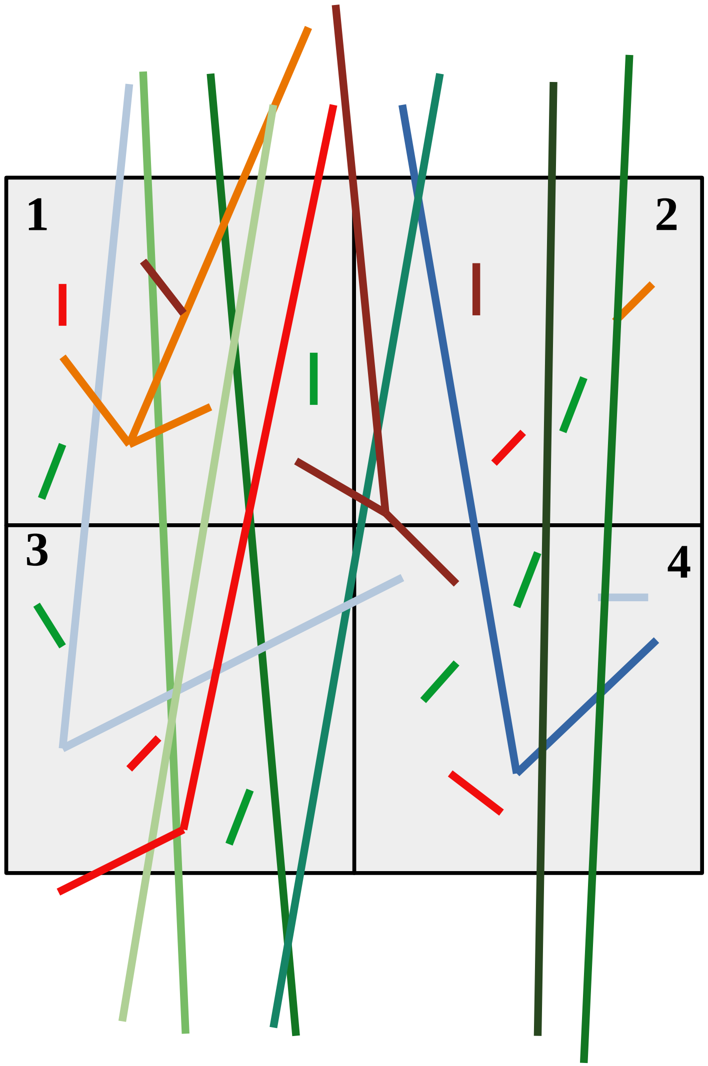
- Tracks don't actually overlap and can be reconstructed, but most detached energy requires timing
- Associating detached energy requires measuring the time of the detached deposits and the vertices
- Muon signals will look the same, position resolution is the only way to distinguish them

Example: realistic 2.4 MW spill



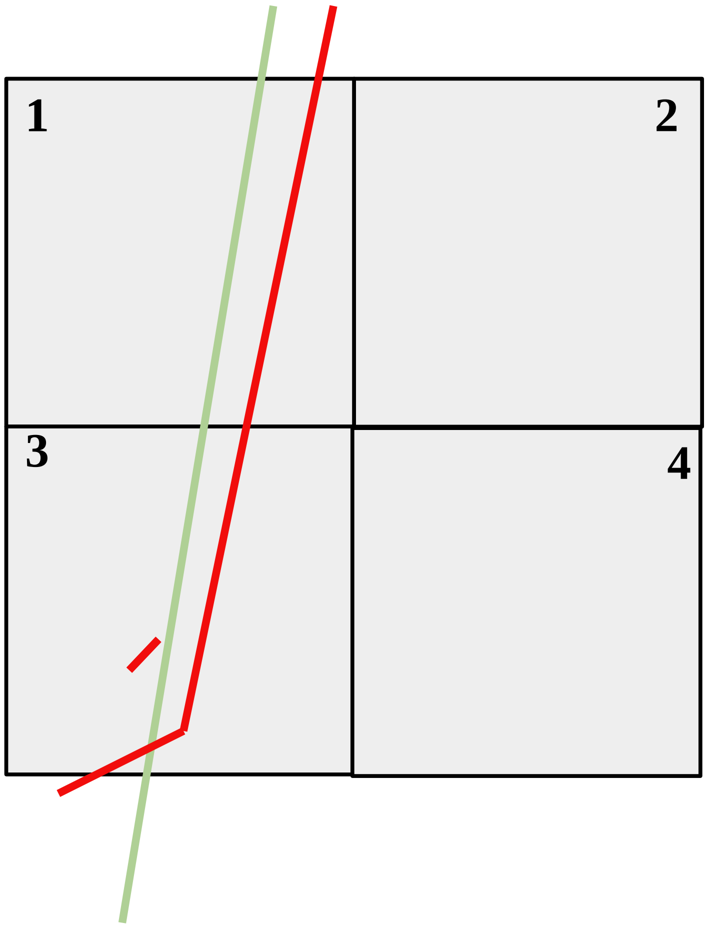
- External muon tag with ~few cm position resolution and single-bucket timing would provide external time stamps for rock muons
- The photon detector signals at these times are then known to be due to rock muons
- External tracks can just be removed from the charge-to-light matching problem
- Reduces the number of tracks by ~factor of 2

Can’t the photon detector just do this?



- If photon detector can distinguish through-going track from in-module light signal, and tiling is >> 6 per module (so that ~6 tracks ~never overlap)
- Then you still have a ~2x harder combinatorics problem at reconstruction, but it is theoretically possible

Can't the photon detector just do this?

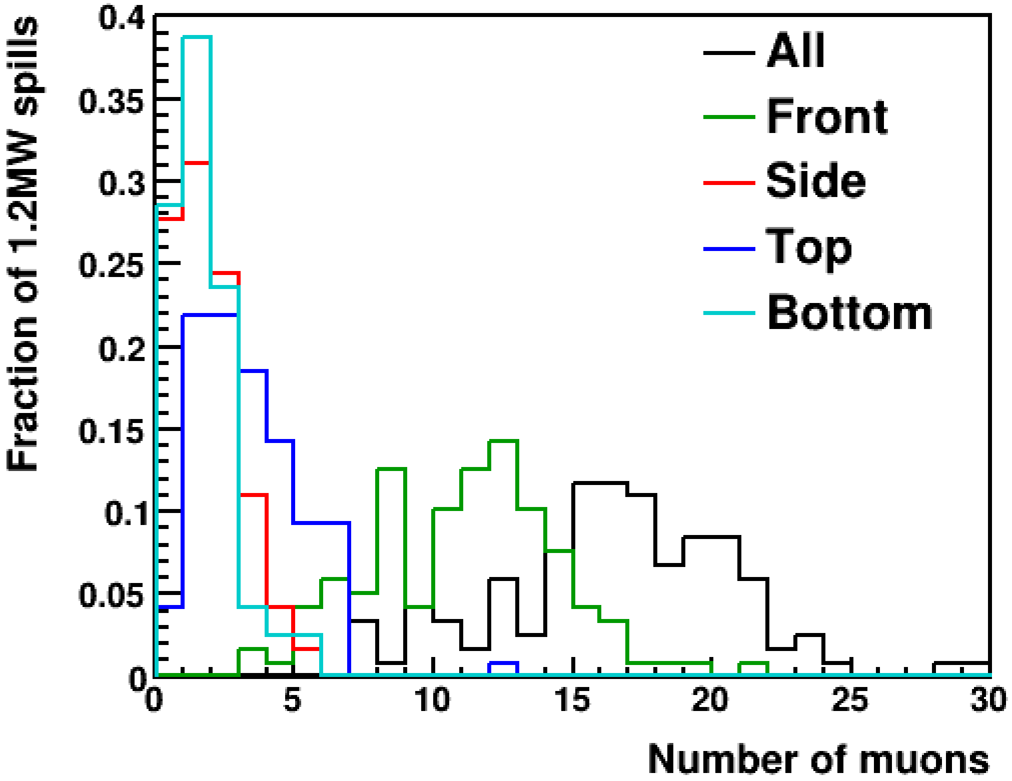


- But back-scatters could intersect light detector
- Two events like this could literally look exactly the same to the photon detector
- An external muon tag would reduce this type of ambiguity by >2x

Another benefit: externally-tagged calibration sample

- Through-going muons will populate the entire detector and are an extremely useful calibration sample:
  - Relative energy response calibration
  - Argon purity measurement
  - Module-to-module alignment
  - Tracking efficiency studies
  - Timing calibration of photon detector
  - All can be done vs. time: O(1M tracks per day)
- Matching muon tagger signal to TMS/ND-GAr reconstructed tracks gives a clean sample of through-going muons of known position and known timing that is entirely independent of any ND-LAr detector subsystem

Rock muons per 1.2 MW spill by entry location in LAr active volume



- ~10-25 total rock muons per spill at 1.2 MW
- ~5-20 enter upstream face of ND-LAr
- Top is more important than sides or bottom due to beam angle
- Double this for 2.4 MW – need to cleanly separate ~50 events in space/time

High-level physics requirements

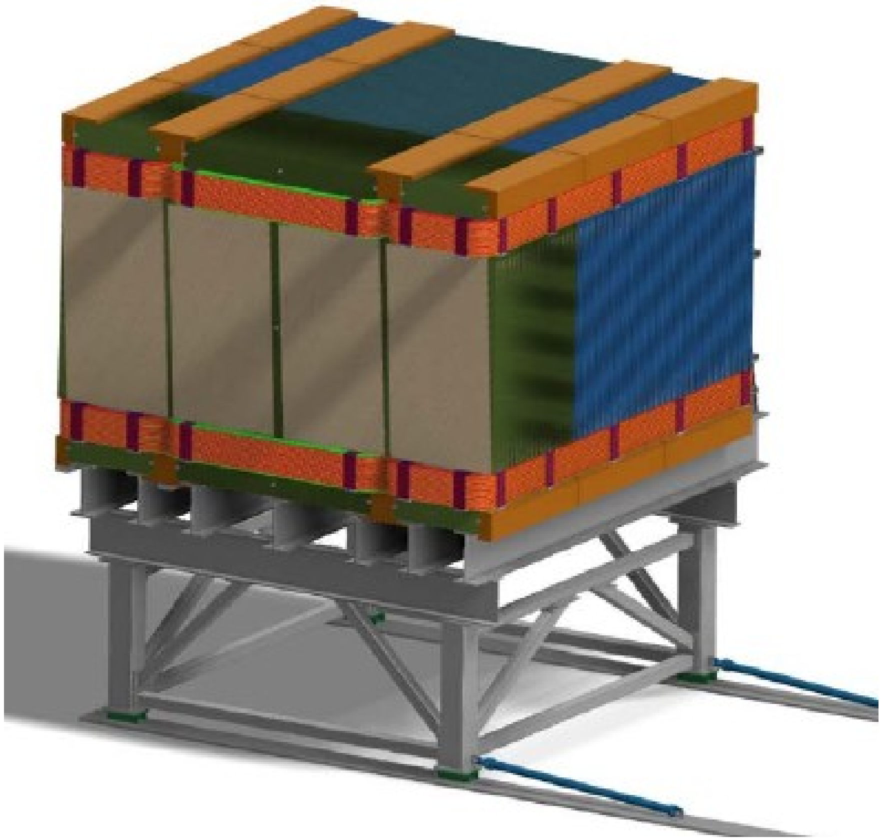
- Very high efficiency to detect MIP signals, but not necessary to measure energy precisely
- Separate ~50 tracks with sufficient position resolution to match to ND-LAr tracks, and sufficient timing resolution to match to photon detector signals
- Cover sufficient area to detect most external muon tracks

Lower-level physics requirements

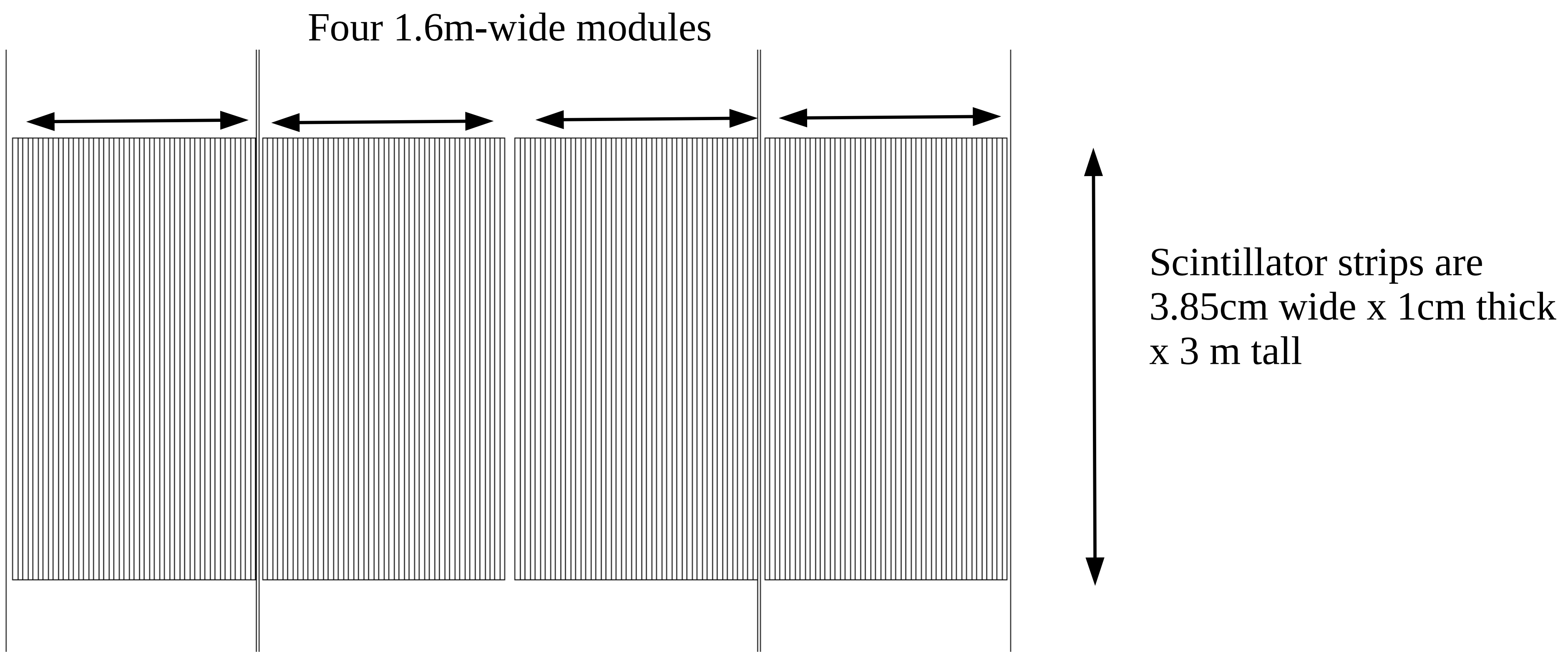
- Some further study is required, but:
  - >95% efficiency for MIP signal
  - ~5 cm position resolution in each transverse direction
  - <19 ns timing resolution
  - Cover entire front face of ND-LAr, with additional coverage above active volume
  - Move with the detector

This all sounds familiar: TMS

- Scintillator of TMS has virtually identical requirements:
  - Be roughly the size of ND-LAr
  - Measure muons efficiently
  - Resolve single bucket timing

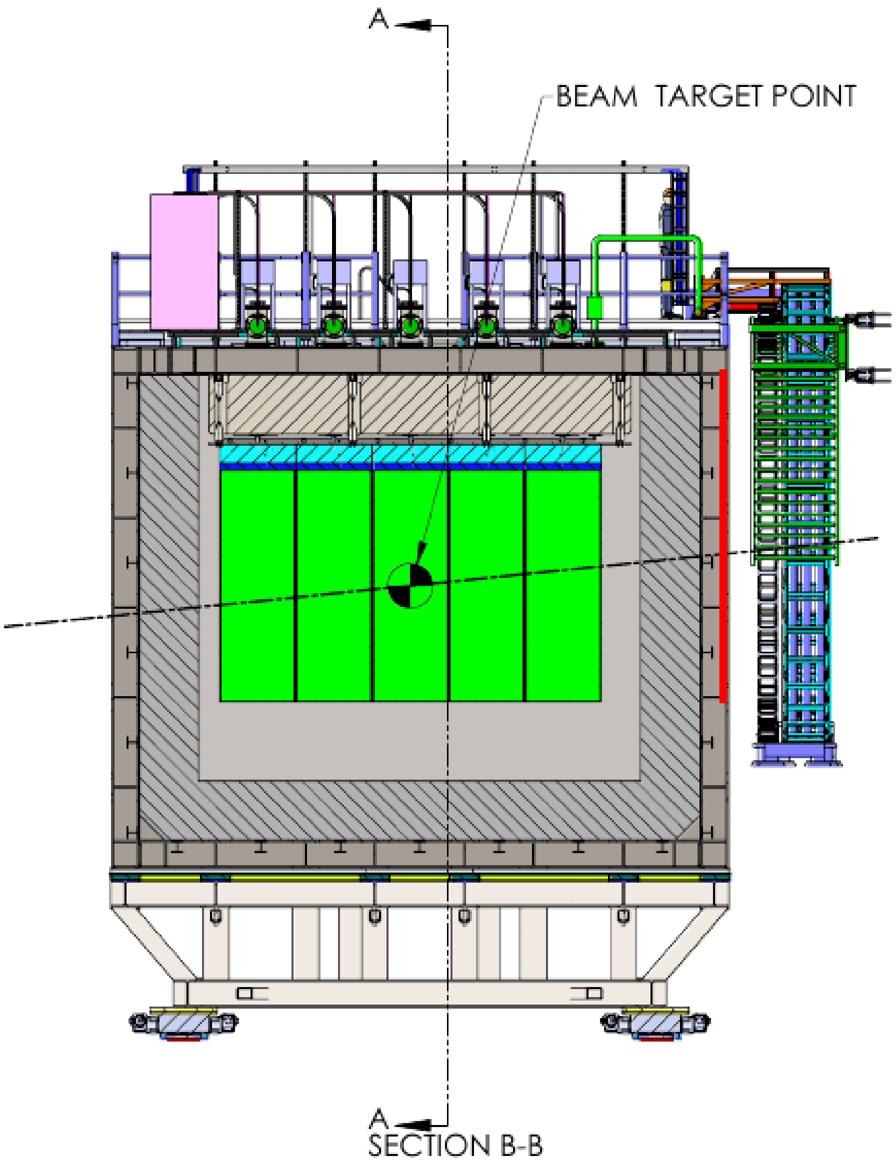


TMS scintillator geometry



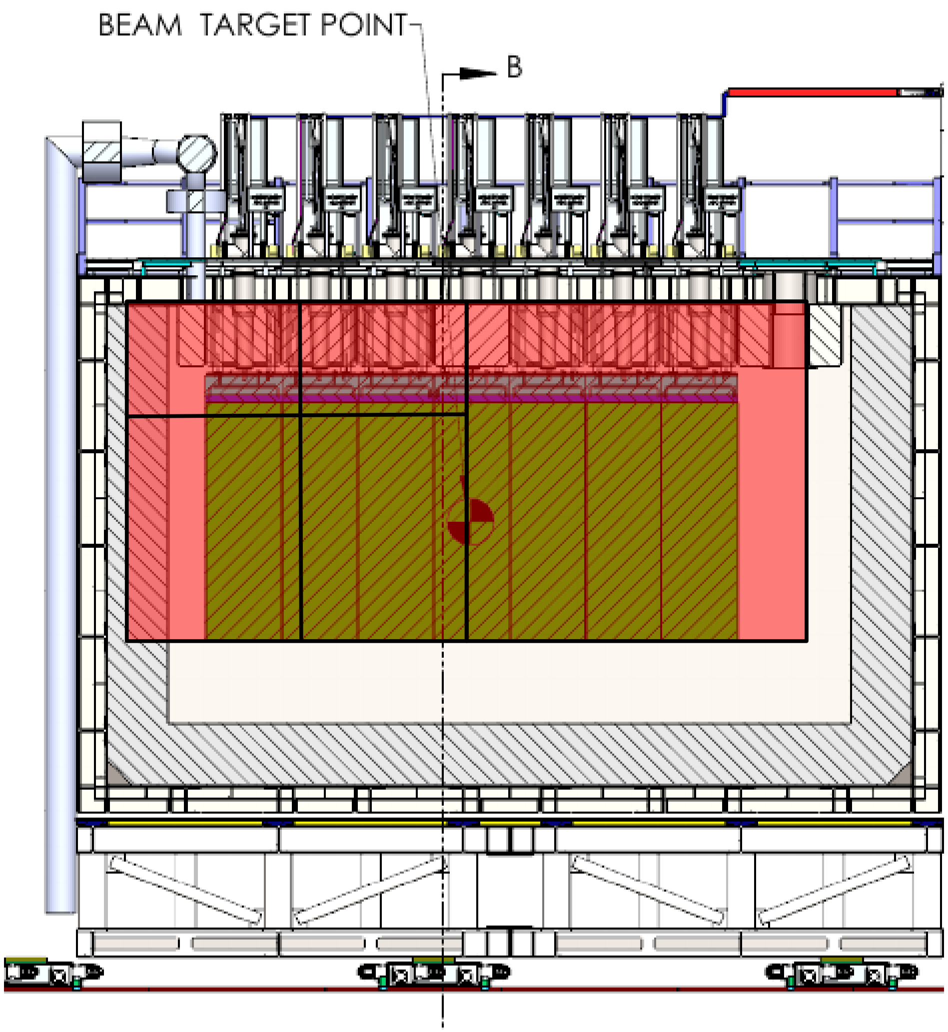
- Front/neutrino view of one plane of TMS scintillator
- Strips are very similar to MINOS

Very preliminary design concept



- Two 1cm-thick scintillator planes, using TMS strips, fibers, readout, but 90° stereo
- Mounted to the outside of the warm steel structure on the upstream face of ND-LAr
- Extends from bottom of active volume to ~1.5m above active volume – this will allow "top-entering" muons to be tagged

Very preliminary design concept



- Total coverage area shown here would be 9m x 4.5m, would give high acceptance for near-side entering tracks, and also top-entering
- Two 4.5x4.5m modules, so that maximum light propagation time is ~20 ns which is also bucket spacing
- Readout on top and sides, with mirror in the middle to avoid having 9m strips

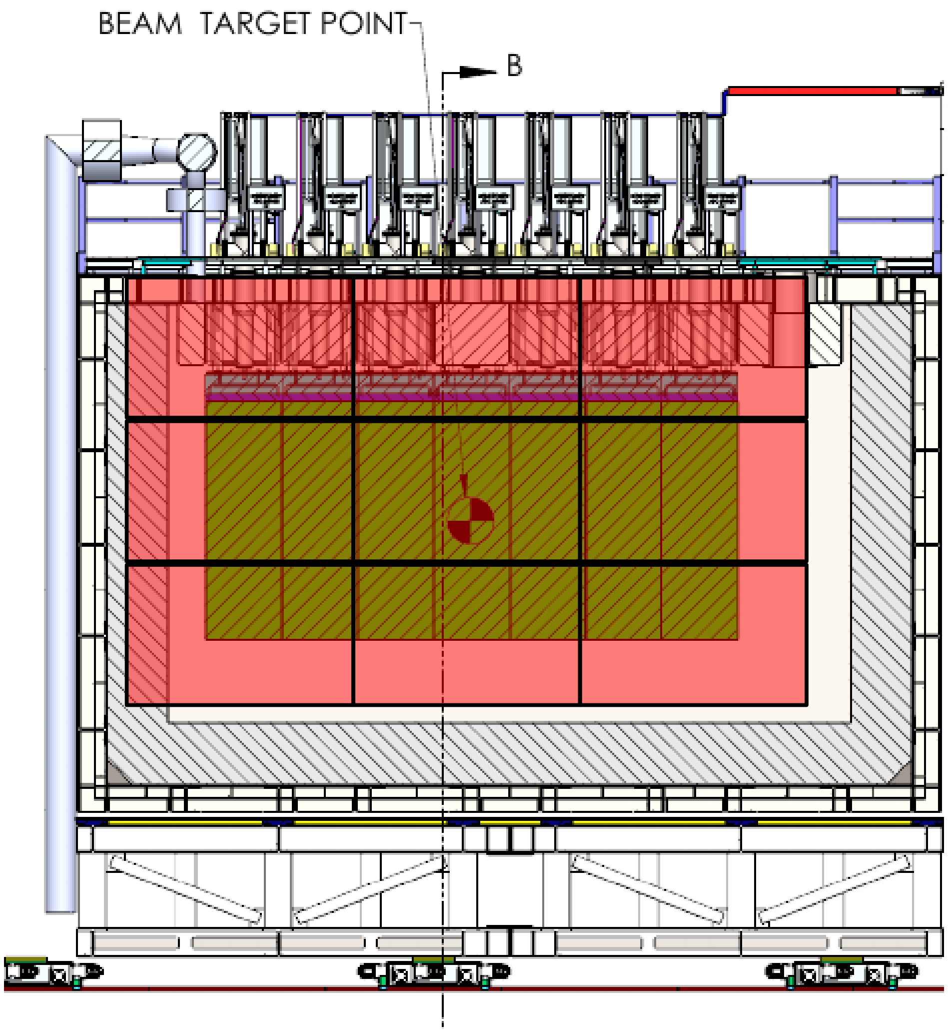
Some numbers

- This design would have 232 rectangular scintillator strips per plane 4.5m long, mirrored on one end and read out on the other
- Strip dimension 3.85cm x 1cm x 450 cm
- Read out by 464 SiPMs coupled directly to fibers
  - Compare to 19,200 strips in TMS
  - TMS is studying groove vs. hole, we would just do the same thing
- Strips could be subdivided into smaller modules for assembly
  - i.e. 4 modules of 29 strips = one 4.5m half-plane
  - This would mean 16 modules of 112 x 450 cm

TMS readout can be used for muon tagger

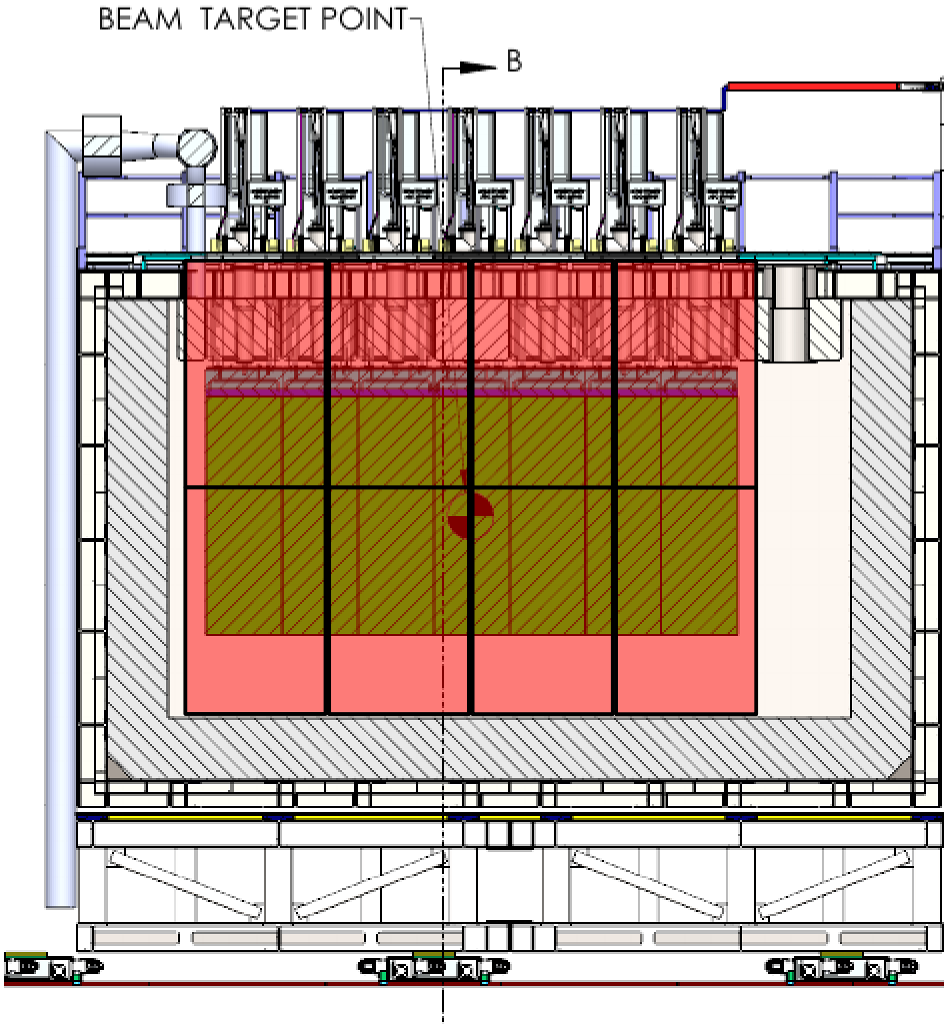
- Original TMS plan was commercial 16-channel SiPM (Hamamatsu S13361-2050AE-04), which is no longer available
- New strategy is single-channel SiPM per strip, with several options currently being considered
- Digitized by on-panel board, tentative ADC chip is 8-channel Texas Instrument AFE5807, 80 MSPS, outputs LVDS

Could we use actual TMS modules?



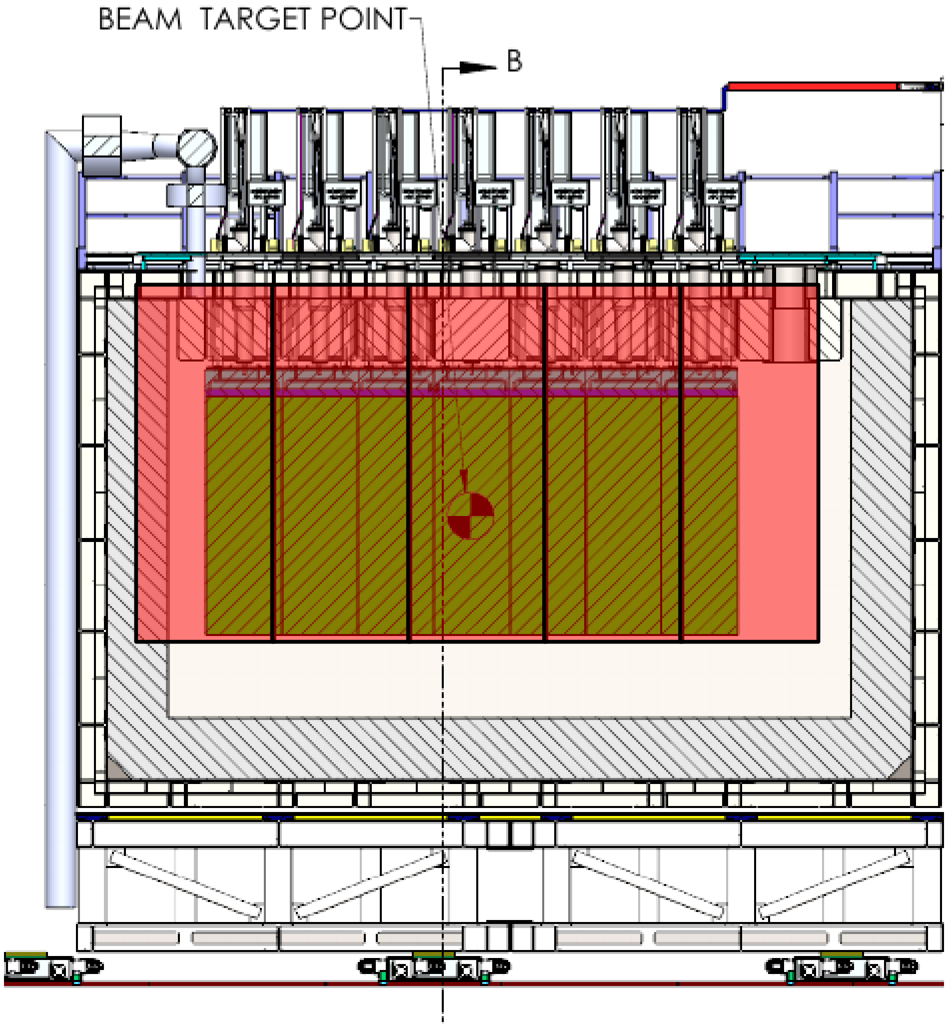
- 1 TMS module = 48 strips = 184 x 300 cm
- Pictured: 9 sideways modules (each 3m wide), 552cm instead of 450cm vertical coverage

Could we use actual TMS modules?



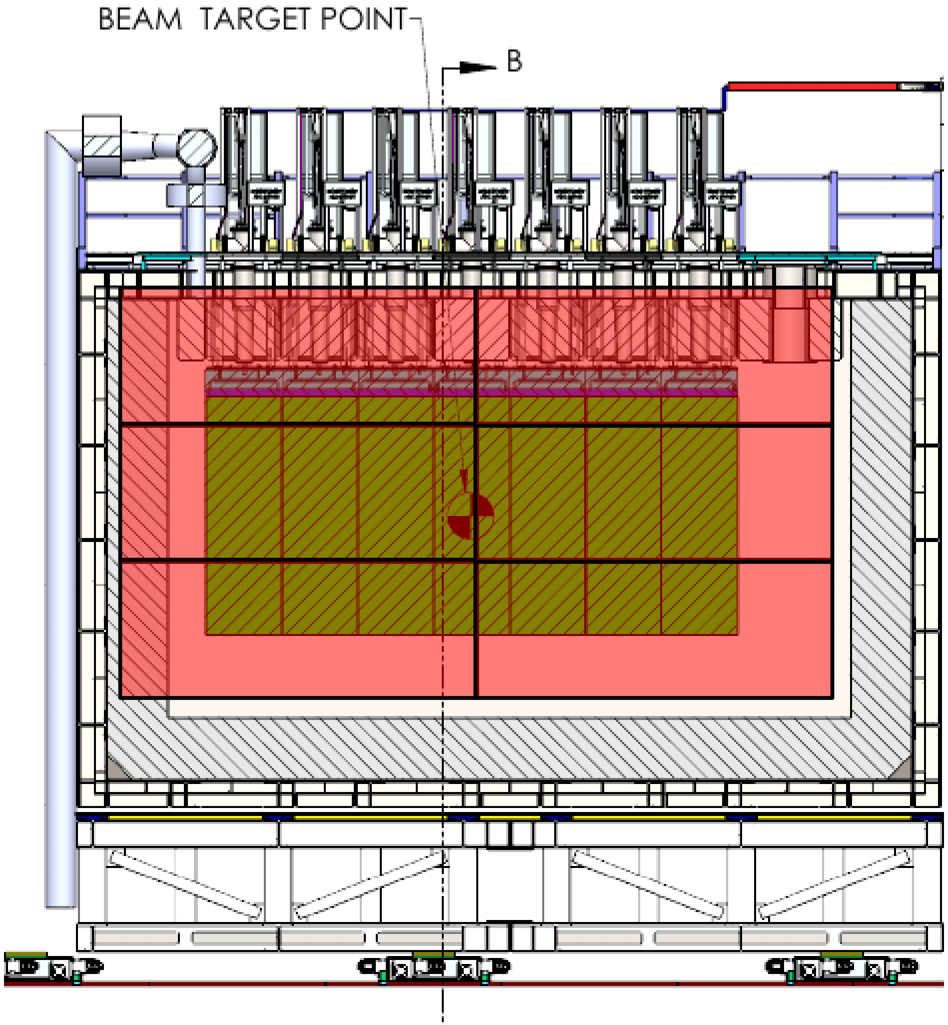
- Other view would be 2x4: 600cm tall instead of 552cm, and 736cm wide instead of 900cm
- Or 2x5: 920cm wide
- Would require readout in the middle of the plane, which would need to be worked out but is doable

Could we re-use existing system(s), like SBN CRTs?



- Top CRT modules are 4.5 x 1.8m with 16 11.2-cm strips
- 5 modules would cover the required area
- Position resolution would be worse – surface CRTs see ~10 muons per 2 ms readout window over similar area, we will see ~25 muons in 10μs

Could we re-use existing system(s), like SBN CRTs?



- Other view would be covered by 6 top CRT modules
- What SBN CRTs will be available on the timescale required for ND-LAr?

Do we need an actual CRT?

- Cosmic rate with our overburden is only ~2 Hz/m^2
- 35 m^2 for 100 μs drift → 1 in-readout-window cosmic ray every few minutes → not a problem
- We may want the ability to trigger on out-of-spill cosmic rays, but it’s not clear that a top/bottom tagger is needed

Do we need downstream muon tagger?

- I think this is worth studying
- Could simplify LAr$\rightarrow$spectrometer matching and external calibration tag
- Marginal cost may be relatively small

To do list

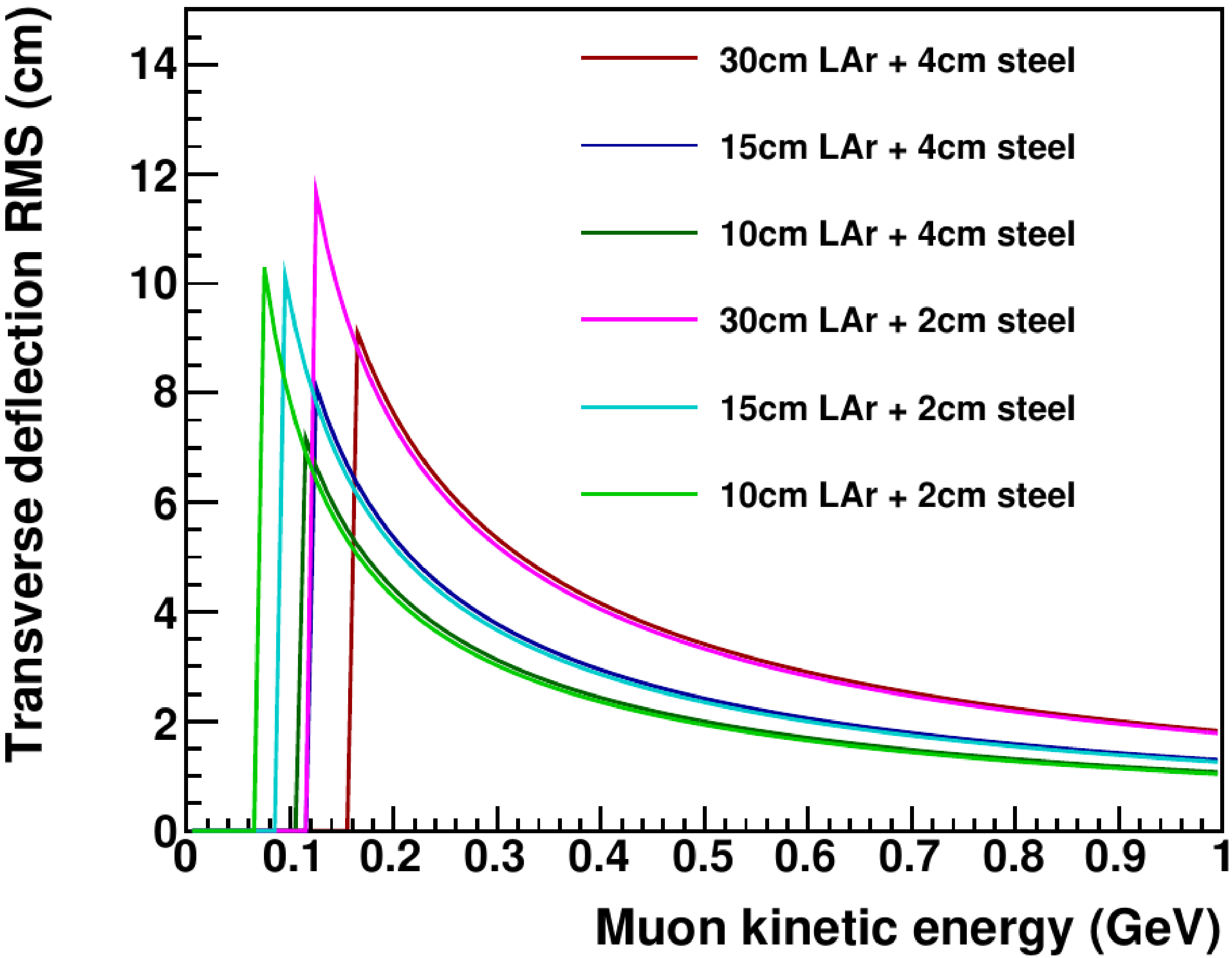
- Physics studies for design optimization
  - Update cryostat geometry, and simulate muon tagger upstream of cryostat
  - Coverage area optimization – is the current plan sufficient?
  - Impact of hadrons from near-hall rock interactions
  - View-matching
  - Estimate data rates, define DAQ requirements
  - Would SBN CRTs be sufficient?
  - Would downstream tag be useful?
- Write this up in a tech note – in progress
- Figure out what is needed to produce engineering design, cost estimates, etc.

Conclusions

- An external muon tagger would provide a crucial additional handle on pile-up, and greatly simplify the problem of charge-light matching in ND-LAr
- It is feasible to exploit synergy with muon spectrometer requirements and re-use existing TMS design elements to keep costs low
- Opinion: this is a no-brainer for ND-LAr, and we should have put this in the design a long time ago

Backups

Multiple scattering is ~ few cm in cryostat → position resolution



- Transverse deflection due to scattering in cryostat for various configurations
- All basically plateau around a few cm for the energies that are of greatest interest for the external tagger system
- Position resolution better than a few cm is pointless