MPD answers to (pink and red) LBNC comments

Broad categories of questions

1. **Justify higher pressure → answer is statistics, so really this question is "justify why you need a high-statistics sample of interactions in the MPD"**
   1. **Tied to this: request for quantitative studies about how this sample will affect the LBL analysis (we can't really provide this yet — best bet seems to be fake data studies for the CDR)**
   2. **Also related: questions about how we can use the MPD sample (particularly pi0s and events without secondary interactions) to actually constrain the far detector**
2. **Backgrounds/occupancy:**
   1. **Will we be able to select neutrino interactions? Will we be overwhelmed by entering background (interactions in ECal/magnet/LAr)?**
   2. **Need to consider for both the numu analysis (general questions) and the nue analysis (specific questions about entering photon background)**
3. **Neutron measurement**
4. **ECal design (our answers should link to background/occupancy topics)**

What needs to be done?

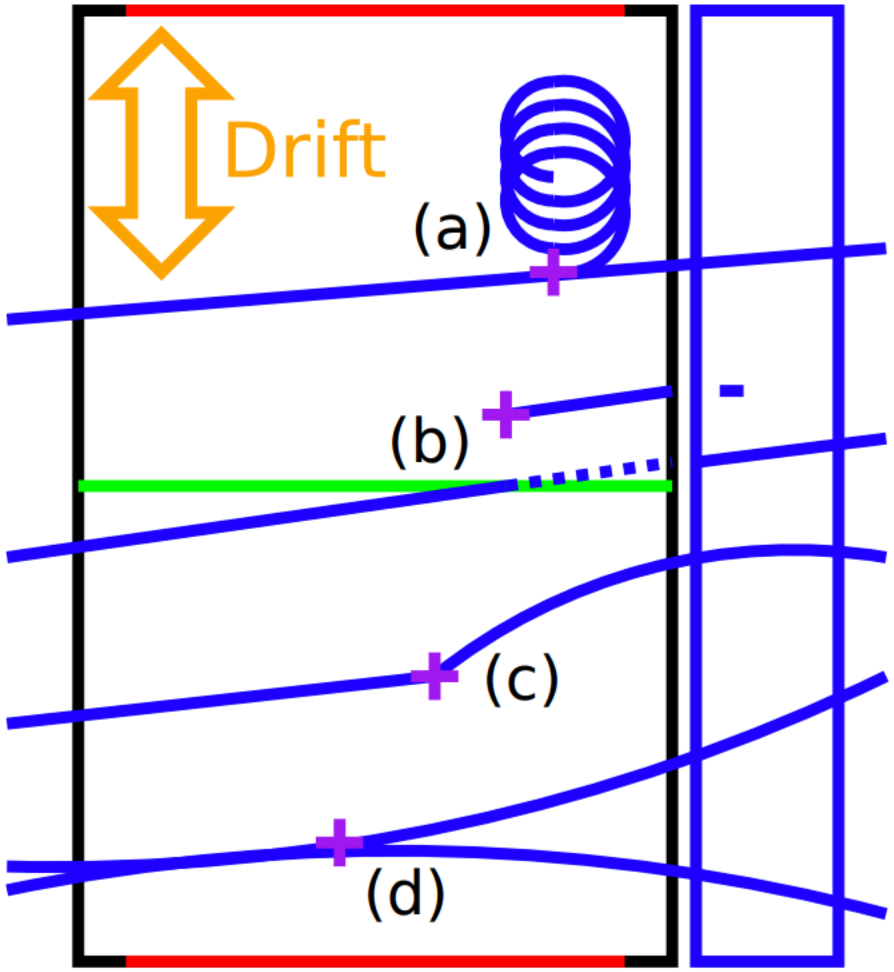
- We have answered a lot of the LBNC's questions in these slides
  - Some questions have action items that need clearing up before they are finalized
  - Some questions have not yet been answered ("yellow" questions that Steve Manly thought would be quicker to answer)
- To do: turn these answers into a document!
- My suggestion: group questions into categories (as on previous slide) and give one detailed answer per category with a blurb saying "this is intended to address reviewer questions A B C D". That way we can avoid a lot of repetition, and make sure we answer every question fully
- Obviously there is some work still to be done putting together full answers - action items (where applicable) are marked on these slides in a red box.
- I'm not going to be here for the rest of this week (taking my long weekend Weds-Fri) so I've tried to give as much information as possible here!

General response to comments about occupancy

A lot of the reviewer comments show concerns about occupancy and the number of tracks in the HPgTPC per spill. This concern may be informed by the T2K analysis described in https://t2k.org/docs/thesis/100/final-version, which is the only existing analysis (that we know of) that has attempted to select numuCC interactions in a gaseous TPC. The analysis had a purity of only 26%, and found that the selected background events from non-signal interactions inside the fiducial volume is very small, but the overwhelming majority of background events are interactions that happened outside the fiducial volume (OOFV).

Below, we examine the categories of OOFV background events identified in the T2K analysis, and explain why we believe that the analysis on this detector will not be hampered by the same issues. The T2K analysis identified four dominant categories of OOFV background events, illustrated in the accompanying cartoon from https://t2k.org/docs/thesis/100/final-version:

- **(a) Delta-ray induced:** A delta-ray emitted from a through-going particle is misidentified as a vertex with two outgoing tracks
- **(b) Timing related:** (A part of) a track is matched with a wrong hit for the T0 assignment, and therefore the track is shifted along the TPC drift direction
- **(c) Particle decay/stop:** A particle decaying in the TPC looks like a 2-track vertex
- **(d) Coincident particles:** Multiple particles close together in the TPC confuse the reconstruction and cause fake vertices



General response to comments about occupancy

- **(a) Delta-ray induced:** A delta-ray emitted from a through-going particle is misidentified as a vertex with two outgoing tracks
  - 22.56% of events in the T2K selection
  - The MPD will have a much longer lever-arm for determining the direction of through-going tracks than the T2K TPCs. We expect the average crossing track to traverse a distance on order of the radius, 250cm. In that case the timing difference between ECal hits when the track enters and exits the HPgTPC is expected to be ~8.3ns. With O(ns) timing on the ECal we expect to be able to use timing to distinguish a throughgoing track that emits a delta-ray from an interaction in the HPgTPC that has two outgoing tracks.
  - The larger size of the MPD (and larger lever arm) than the T2K TPCs will also give us an advantage compared to T2K in identifying the topology of two back-to-back tracks with a delta-ray emitted at the "vertex"
- **(b) Timing related:** (A part of) a track is matched with a wrong hit for the T0 assignment, and therefore the track is shifted along the TPC drift direction
  - 3.95% of events in the T2K selection
  - This background is related to the number of interactions in the ECal relative to the number of interactions in the HPgTPC. We expect 60 ECal interactions per spill, and around 300x more interactions in the ECal than in the HPgTPC (see answers to SSC 28 and 38). By comparison, T2K has a factor of 1000x more interactions in the solid detectors of ND280 than in the gas of the TPC. Even in this case, these backgrounds only form ~4% of the selected events.
  - The fact that we have a tile ECal (at least: tiles on 10% of layers closest to the HPgTPC) is also expected to greatly reduce the HPgTPC-ECal mismatching over T2K's TPC-ECal matching efficiency. This background will be an important input to ECal optimization studies. For these reasons, we do not expect this background class to be a significant issue for the MPD analysis.

General response to comments about occupancy

- **(c) Particle decay/stop:** A particle decaying in the TPC looks like a 2-track vertex
  - 13.02% of events in the T2K selection
  - Following the argument above, we expect that the MPD will be able to distinguish a throughgoing track that emits a delta-ray from an interaction in the HPgTPC that has two outgoing tracks because of the larger distances and longer lever-arm for the timing information.
  - Assuming this, we expect that we can reject events in which the particle decays in the TPC and the decay product still reaches the ECal (as in the cartoon)
  - In this case, the remaining background is from particles that enter the TPC and stop, or decay products do not exit the TPC. Because low-momentum particles will still travel a long distance in the low-density tracker (and therefore the proportion of decay products that do not reach the ECal is expected to be very small), we expect this background to be small.
- **(d) Coincident particles:** Multiple particles close together in the TPC confuse the reconstruction and cause fake vertices
  - 13.87% of events in the T2K selection
  - This background depends critically on the efficiency of the reconstruction, which is still under evaluation and development. One of the active studies is assessing multi-spill events in a realistic MC, which will be used to assess effects on the analysis due to this background
  - We will continue to evaluate the reconstruction in the context of this and other background classes, and optimize the size of the ECal in light of that information.

SSC 2

1-6 12: There are a number of trade-offs for high pressure vs. atmospheric pressure TPC. Only a few arguments are made in favor of high pressure (statistics), some weak (PID and momentum resolution), and a mention later that cost of vessel is not a driver. The downsides like more inactive material for out of fiducial volume events and conversions/scattering, routing for services, implications for ECAL are not mentioned. Would be good to have a solid set of arguments why high pressure is essential for the device to serve its purpose.

- Statistics is the strongest argument, which hinges on having a separate set of independent interactions on Argon, with different energy reconstruction, different detector systematics, and lower thresholds.
- In particular, if we plan to do any kind of exclusive final state analysis using a sample of interactions on Argon gas in the MPD, we will need large statistics to do these studies effectively.
- PID is better at high pressure and momentum resolution is worse. We think we made this argument in the document but it is secondary to having a sample of interactions in the gas - as the comment points out, this is a weak argument for high pressure.
- Should make it clear that the new design for pressure vessel doesn't introduce a lot of extra material. If we can get pressure vessel thickness below 1 radiation length and put ECal outside, we're still ok. Current design for pressure vessel with aluminium is ~0.3 radiation lengths.
- If more statistics is better, why limit to 10atm? Practicality - we know 10atm is reasonable and achievable. PEP-4 was designed and tested at 10atm (although operated at 8.5atm in the end). Dark Matter experiments operate TPCs at ~20-30 bar (although these examples were for electroluminescent TPCs and therefore not identical to this case). 10atm is our initial starting point, which we know is safe, but final pressure is still under consideration for optimisation.

SSC 23

1-31, line 25-26: What about gammas from interactions elsewhere entering and converting? What is the radiation length in cm in the MPD? If T2K is any indication, you will be swamped by gammas produced outside of the detector, and even if the fraction that converts is very low, the total # of events from external gammas converting in the gas may be significant. I actually give a calculation later that suggests the conversion probability could be in the tens of percent. (See Comment 58 below.)

Comment 58:

Across a 500cm long MPD, that's a 33% interaction rate! It seems to me like photons have a significant chance of interacting in the gas, and that there needs to be serious consideration given to background produced by gammas or other neutral particles entering the FV.

- We don't yet have a simulation of a spill in the entire ND complex, which we would need to properly estimate the entering background from external gammas. We would also like to try to write a selection for neutrino events, and see how well we can do at rejecting entering photons. Not possible to do in the next week.
- In the meantime, we offer some numbers as an estimate:
  - ND task force saw up to ~5 tracks per spill in HPgTPC from outside interactions. Significant overestimate in our case because used the old design featuring an 800 ton magnet (current design has ~100 ton magnet), and around 80% of entering tracks came from magnet. Note: this is anything that deposits energy in the HPgTPC, majority very short tracks.
  - That's just for interactions in the MPD. Considering LAr tracks entering into MPD: have to add ~2 more tracks per spill (including muons - 77% of the time it's muons).
- Show event display showing photon conversions. Pairs of spirals - quite easy to identify.
- See also answer to general comment 8b - this is quite related

SSC 23

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- We note that T2K saw ... more interactions in their entering gamma sideband sample than predicted by MC. Even scaling up our

Magnet interactions might invalidate 5 tracks per spill from outside interactions. The ECAL not the magnet is the primary source of outside interactions and BTW external photons will not get through the ECAL.

Q: What is the relationship between tracks and photons here? A: That was just jargon. It means charged particles in the TPC. For photons, that means converted photons.

We do in fact have the ECAL in the simulation; and it is the thicker version with 20 tons. It is of uniform thickness all around the octagon.

The 5 tracks must not count the rock muons? We think there are about 10 rock muons per spill. Q was about the origin of that number.

Rock muons will come through the LAr--- implication? Chris M says between rocks & interactions in LAr there will be 20 tracks per spill in the GAr

Conclusion is that we need to agree what is the multiplicity of tracks in the detector; but there is also some importance to the number of photons entering the GArTPC... we need that number as well

Discussion of how to compute the rate of photon conversion into the TPC. BTW, I have an MC sample that might be usefull for this problem.

What ECAL is in the simulation? 300 ton ECAL in the simulation -> Chris says that is 40 interactions per spill in the ECAL.

Q: What is the effort level on rejecting photons? Discussion - convertions should be easy to kil

Gusto says 15-20 interactions in the "old" ECAL. 0.2 interactions per ton per spill is a number given by Alan. Does that vary with the optimized/old beam?

Existing MC is generated as individual events so there is no overlay simulated.

Stephan is asked to get "A proper number" - Tom is not sure we can get this on a short time frame. Alphonse says we need number of photons that convert, and also an estimate of rejection rate for converted pairs. Tom to make some MC with overlay.

Stephan asks how much does this depend on the asymmetry of the ECAL? Answer is not much because the converted photons are all from the inner layer of the ECAL. It all has to be from the innermost Xo.

Comment - we can't say to the LBNC that we don't know the rejection rate... we need a number to give confidence that the LBNC that we know roughly the scale of it.

Action item (Tom): get number of photons from external interactions that convert in the tracker from MC. Use truth information. Also include spectrum of photon energies so we can say something about how likely we are to be able to find/reject pairs?

Action item (everyone): refine argument based on these notes

SSC 28 and 38

1-33 20, I think this needs a discussion of the TOF resolution to aid in understanding

1-50 8: Using ECAL to tag neutrons associated with a HPgTPC event. Could other neutrino interactions in ECAL mimic a neutron signal (ie. pileup).

- Expect neutron energy resolution ~20-30% assuming 250ps time resolution in ECal (excluding backgrounds)
  - 1ns achievable for tiles with electronics we have now
  - Current studies assume 250ps, which will require some advancement.
  - How realistic is that advance? Tile-based ECal time resolution depends mostly on electronics. Strip-based ECal will have other effects.
- ND task force estimated that in a 10ns window 5% of neutrino interactions generate Ecal activity coincident in time with another interaction
- Current ECal design is ~300 (metric) tons total. Assuming 0.2 interactions/ton → 60 interactions in the ECal per spill. TPC has 1 ton of gas, so expect 300 interactions in the ECal for each one in the gas.

Action item (**who?**): get numbers, even if back-of-the-envelope, by the end of the week.
(Comment from Kirsty: not clear on exactly which numbers we need for this. May not be able to give anything for neutrons, but can talk about pileup more specifically, at least with event displays)
Does 10ns number apply to neutrons? Not long enough for TOF.
Action item (Justo and Alan?): make a table showing differences between ND task force study and current design

General 8a

What gas mixture will the MPC TPC use? The physics TDR says 90% Ar/10% CO_2, but this executive summary doesn't specify the mixture. If it will contain any components besides argon (which we believe it must), how will you subtract out the non-argon contribution when attempting to use gas interactions to understand nu interactions on argon? Does this undermine the argument that you can use interactions in the gas to understand neutrino interactions in argon?

- Probably a typo in the physics TDR, which should be fixed. Official correct mixture should be Ar+CH_4
- For 90%/10% mixture (10% is by partial pressure, not by weight), 97% of neutrino interactions are on an argon nucleus - only need correction for 3%
- Current uncertainty on neutrino-Carbon cross-section (and therefore the correction we would need to do) is around 25%. 25% uncertainty on a 3% correction = ~0.75% uncertainty in total

Action item (**Andy F?**): find something like a plot to justify 25% uncertainty on carbon xsec

General 8b

Can you specify the occupancy you expect in the high pressure TPC? Is occupancy a problem at all?

- We expect an average of 60 neutrino interactions in the MPD per spill, of which almost all will occur on the ECal (see answers to other questions for calculations).
- In addition, we expect ~20 tracks to enter the HPgTPC due to rock muons and muons from neutrino interactions in the LAr
- Have event displays (which we should show) of 10 neutrino interactions in the MPD in the same spill. Easy by eye to tell tracks apart and match to ECal. Automatic reconstruction has found all of the tracks
- Overall, we expect occupancy of 1e-4 per voxel, and the ALICE TPC was built to (and has demonstrated) operate at occupancy ~3-4% per voxel. Given this, and illustrated by event displays, we do not expect occupancy to be a problem.

Action item (Tom): provide event displays showing multiple neutrino interactions

General 8c

In many ways you argue for the MPD convincingly. However the arguments are mostly qualitative, not quantitative. Can you supply some concrete numbers which illustrate the gain from having this detector, with these particular capabilities?

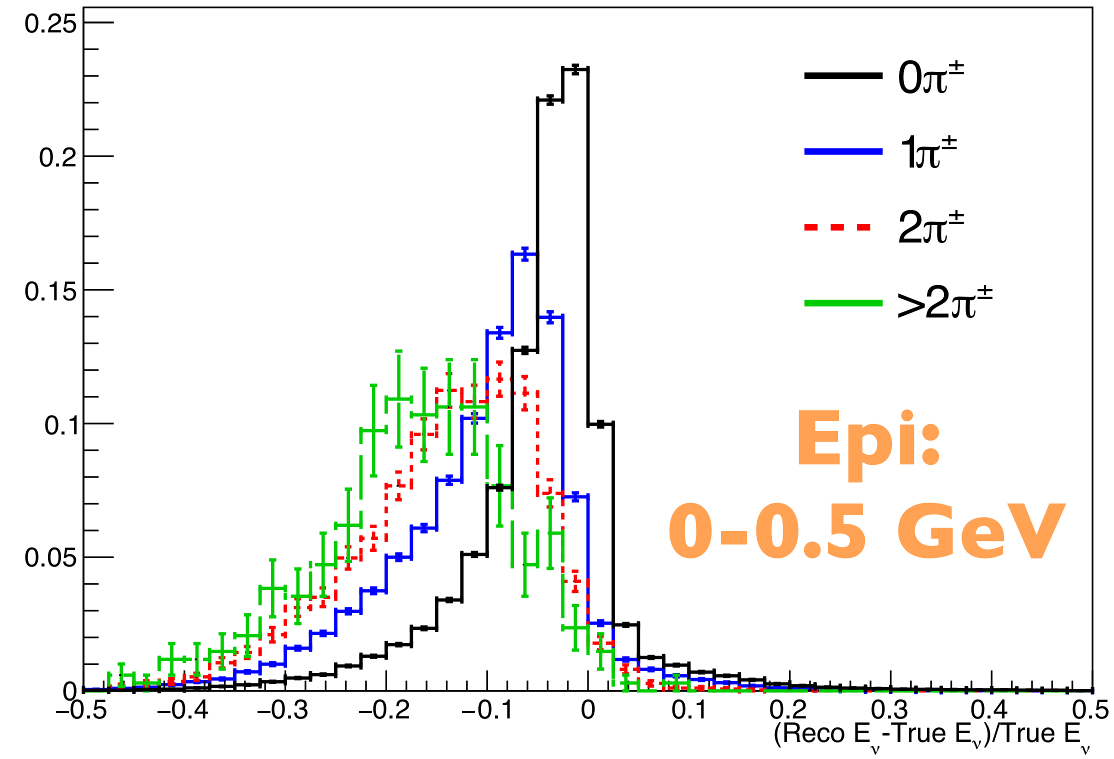
- We plan to address this for the CDR/TDR by performing some mock data LBL analysis studies showing the effect of systematic effects for which the MPD has complimentary abilities to the LAr. Examples of such systematic effects that we are considering are:
  - Pion multiplicity and energy resolution: we expect high-energy pions to produce showers in the LAr. Uncertain amounts of energy could be lost as neutral particles or missed due to reconstruction. It is also not certain how often pion showers might be close together, even in 3D. Information about this will come from ProtoDUNE, but the MPD will provide complimentary information with lower thresholds, different reconstruction (pions will produce curved tracks, not showers, in the HPgTPC), and significantly fewer secondary interactions. Comparing data from the MPD to the LAr will inform us about potential biases
  - Low-energy protons and pions: low-energy particles will be easier to identify in the MPD than in the LAr because of its lower threshold. If, for example, a pion is not selected or mis-identified in the LAr it will cause us to mis-reconstruct the neutrino energy by an amount equal to the pion mass (assuming calorimetric energy reconstruction). This could produce an energy scale uncertainty that would directly affect the measurement of oscillation parameters.

Action item (Leo): plot of Edep-Etrue for interactions with low-E particles in Lar?

General 8c

In many ways you argue for the MPD convincingly. However the arguments are mostly qualitative, not quantitative. Can you supply some concrete numbers which illustrate the gain from having this detector, with these particular capabilities?

- To be more specific about the proposed fake-data study with low-energy pions: this plot shows the relationship between true and reconstructed energy in the LAr for different charged pion multiplicities, when the total energy of all pions in the event is small (<0.5 GeV)
- The reco-true energy relationship depends strongly on the number of charged pions, especially when the pions are low energy.
- We also see that the dependence on pion multiplicity reduces for higher pion energies
- This could be because the reconstructed energy calculation does not include a correction for pion mass (it only considers energy deposited in the detector). In the far detector we will have to make such a correction, which will have an uncertainty due to pion multiplicity



- The MPD can measure pion multiplicity at lower pion energies than the LAr due to the lower thresholds, lower density of tracking material, and magnetic field, and inform the far detector correction

General 8d

Along the same lines, can you give some indication on the linking efficiency between the TPC and the ECAL?

- We expect the inefficiency to be primarily driven by coverage gaps in the ECal. As the ECal design is immature, we can't give a reliable estimate at this point. However, based on the experience of other experiments we expect the linking efficiency to be very high.
- To justify this estimate, we have considered matching efficiencies achieved by T2K. Note: T2K basket is large and contains a lot of mass, our pressure vessel is small (0.3 rad lengths). Therefore T2K TPC-FGD matching efficiency may be more appropriate for comparison than the T2K TPC-ECal matching efficiency. Both are provided here to inform our estimates.
  - T2K TPC-FGD basic matching efficiency (for matching any TPC track to a hit in the upstream FGD) was found to be 100%
  - T2K TPC-ECal matching efficiency for particles with track momentum > 200 MeV
    - e-like particles in DS ECal: a little over 70%
    - e-like particles in barrel ECal: a little over 60%
    - mu-like particles in DS ECal: >96%
    - mu-like particles in barrel ECal: 80-85%

General 8e

You give one number for the neutron efficiency in the document, of 60%, if I am not mistaken, but do not specify for which momentum range or acceptance. This makes it hard to judge whether or not this number is good or "bad".

- The full answer to this question has a number of parts, because neutron efficiency is not the full story: it is also important to consider the resolution and bias on the neutron energy measurement. The efficiency and energy resolution and bias all depend on how the neutron is detected in the ECal (whether the energy deposition is caused by the first neutron interaction, by a neutron that has already previously scattered, or by a prompt de-excitation photon)
- Caveat: This study does not include backgrounds, which are expected to be ~30-50% depending on the exact design, but can be measured directly in data and possibly reduced with a veto on ECal activity

Fermilab

General 8e

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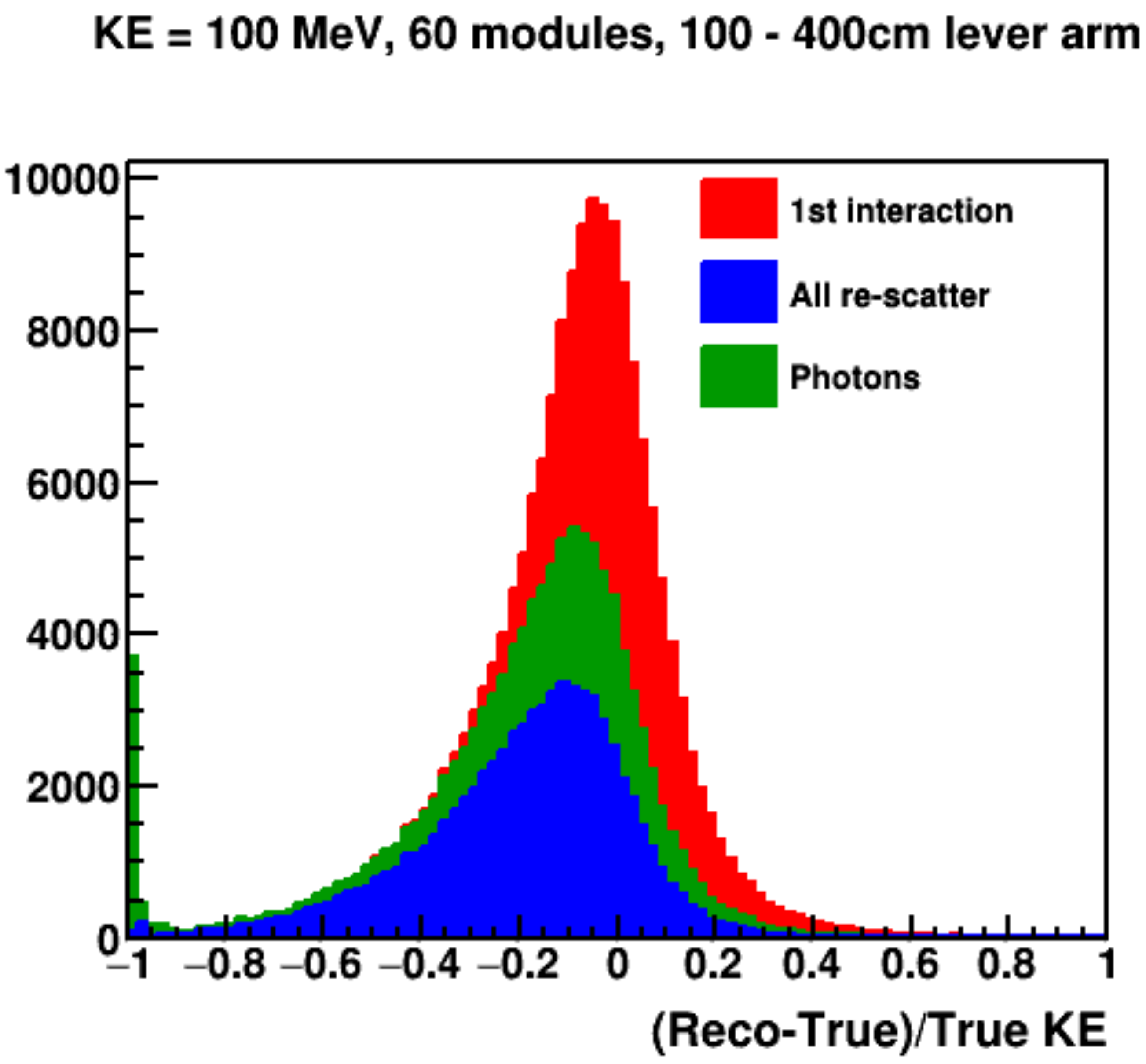
- The full answer to this question has a number of parts, because neutron efficiency is not the full story: it is also important to consider the resolution and bias on the neutron energy measurement. The efficiency and energy resolution and bias all depend on how the neutron is detected in the ECal (whether the energy deposition is caused by the first neutron interaction photon)
- Caveat: This s on the exac on ECal ac

Longer version of this caveat text for document: These studies are based on simulations of single neutrons, and do not account for backgrounds. The largest background is due to neutrons produced by other neutrino interactions outside the gas TPC, and is expected to be significant. A study performed with an out-of-date ECal and magnet design showed a ~30-50% background (50-70% purity) for neutron kinetic energies between 50-500 MeV. This background can be measured in data by selecting neutron candidates in the outermost region of the ECal, which is dominated by pile-up background. This background could also be reduced by implementing a veto on other activity in the ECal, which could reject these backgrounds with a ~10-20% loss of efficiency. These studies should be repeated now that more detailed ECal and magnet designs are available.

General 8e

You give one number for the neutron efficiency in the document, of 60%, if I am not mistaken, but do not specify for which momentum range or acceptance. This makes it hard to judge whether or not this number is good or "bad".

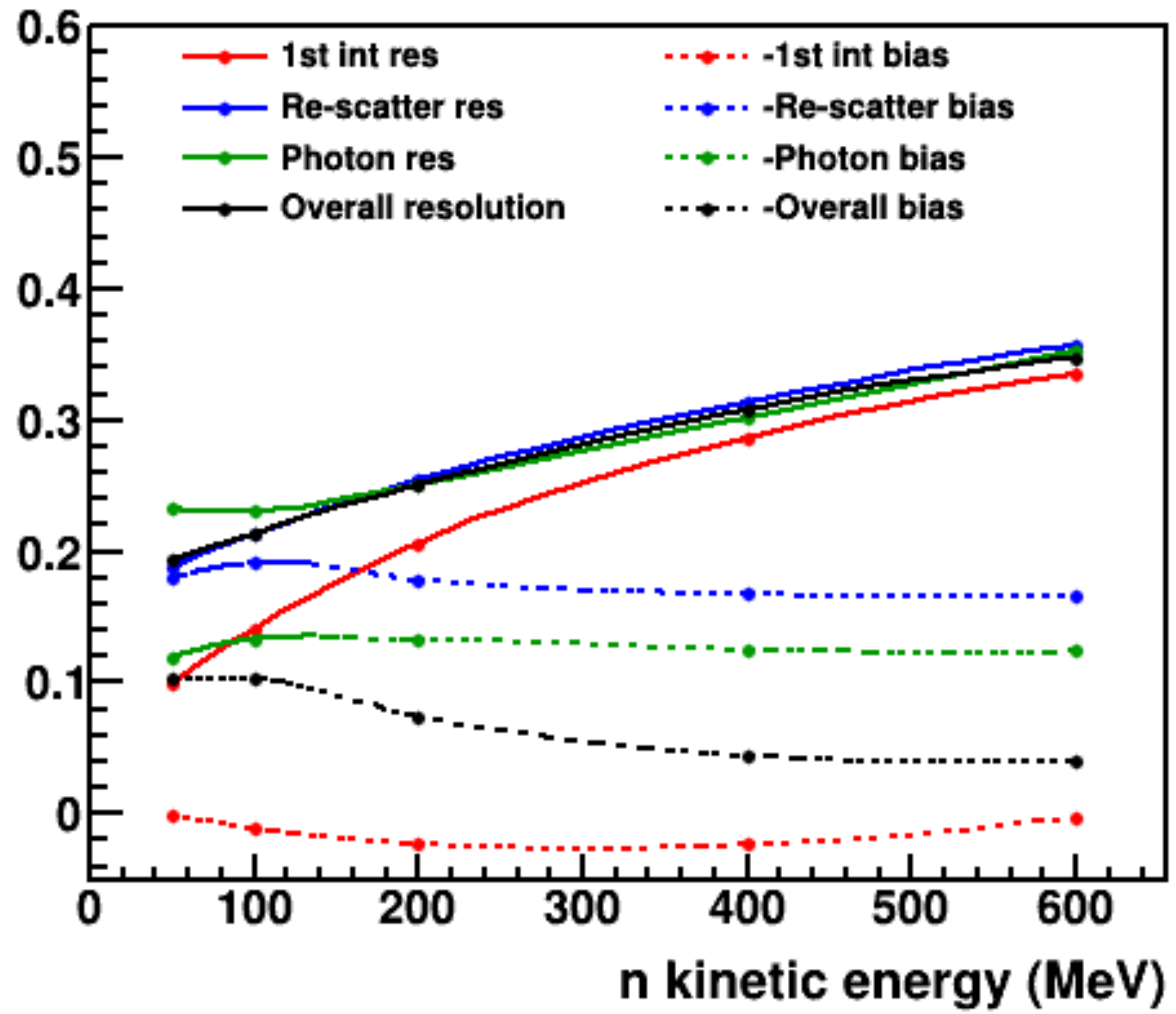
- This plot shows the relationship between reconstructed and true neutron energy for the three categories laid out above.
- Neutrons that are detected on their first interaction have almost no bias in the reconstructed energy
- When including neutrons that are detected after a re-scatter and by de-excitation photons, there is a ~10% bias in the reconstructed neutron energy.



General 8e

You give one number for the neutron efficiency in the document, of 60%, if I am not mistaken, but do not specify for which momentum range or acceptance. This makes it hard to judge whether or not this number is good or "bad".

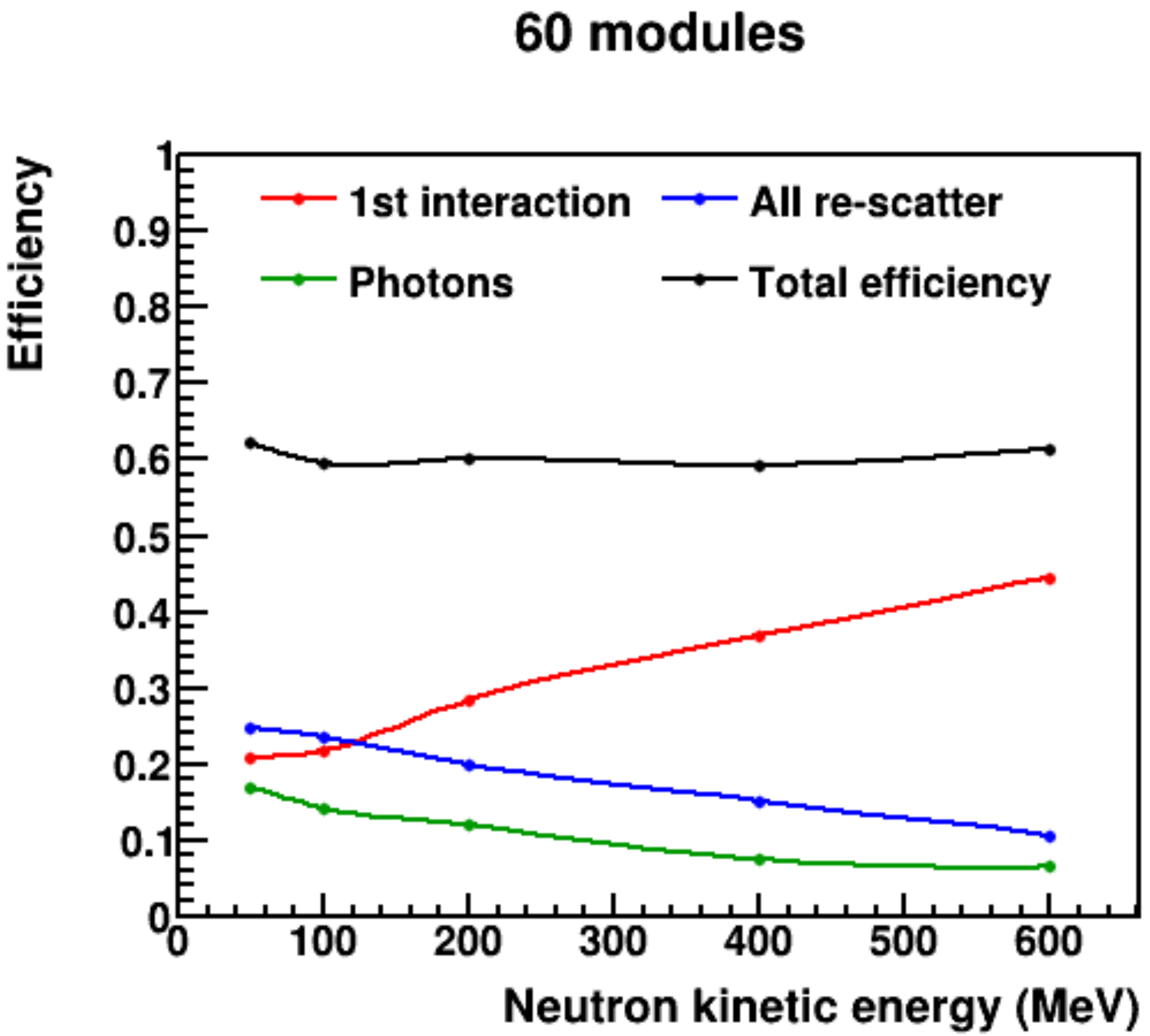
- This plot shows similar information: the energy resolution and bias on the reconstructed neutron energy for the three different categories, and over all predicted neutrons
- Neutrons that are detected on their first interaction have almost no bias in the reconstructed energy, and a resolution of 10-30% depending on neutron energy
- When including neutrons that are detected after a re-scatter and by de-excitation photons, there is a ~10% bias in the reconstructed neutron energy and resolution of 20-35%



General 8e

You give one number for the neutron efficiency in the document, of 60%, if I am not mistaken, but do not specify for which momentum range or acceptance. This makes it hard to judge whether or not this number is good or "bad"

- This plot shows the neutron efficiency as a function of energy for each of the categories described above
- The efficiency for detecting neutrons on their first interaction (i.e. with no reconstructed energy bias and good resolution) is ~20-40% depending on neutron energy
- The total efficiency for detecting all neutrons is ~60%, but that includes neutrons for which the reconstructed energy will have significant biases.



- Despite these caveats, this shows a huge increase in neutron reconstruction capability compared to other neutrino experiments (which largely do not have the capability to reconstruct neutrons)

SSC 3

1-7, Table 1.2: Can you please estimate the additional rate contributions from "rock muons" and other neutrino interactions occurring outside of these detectors? Please discuss the extent to which these are backgrounds or analysis problems for each of the ND components.

- Partial answer about other interactions occuring outside the TPC: see answers to General Comment 8b and SSC 23
- We don't have a current simulation of rock muons, but ND task force studies (with the normal caveats that the studies used the CDR beam and out-of-date geometry) estimate ~10 rock muons in the MPD per spill, which we do not anticipate to be a problem for this detector.

SSC 5 and SSC 13

1-7: Table 1.2 – It will be good to see some statistics for few off-axis positions for HPgTPC & LArTPC

1-23 Statistics: we have already had discussions about moving off axis and the changes resulting, however these statements here about statistics make no mention of configuration... I think that should be clarified. Are all these numbers "on-axis" if so, how relevant are they? These stats need to refer to a particular location. For on-axis, will there be an inefficiency due to discarding of pileup events?

- We should clarify in the document - all the numbers we have given are on-axis
- DUNE-PRISM group have generated off-axis statistics for HPgTPC, so they will be added in that section.

Action item (DUNE-PRISM): add numbers for off-axis HPgTPC

SSC 25

1-31: Is there a plot to show the energy carried by fast and slow neutrons? How much really MPD ECAL will help in recovering this missing energy. This is an important information and a little more explanation will help.

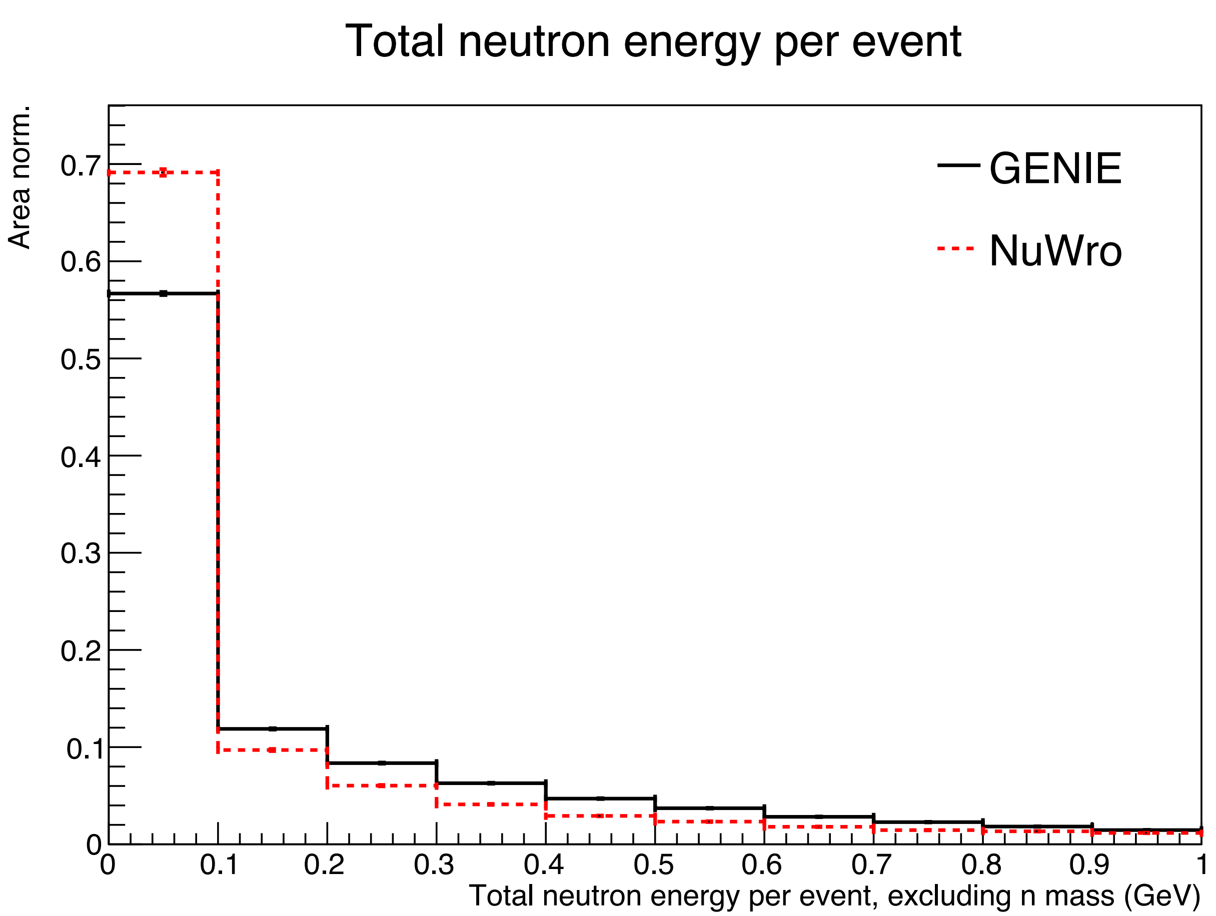
- Eldwan is working on getting the plot to show energy carried by fast and slow neutrons this week. TODO: Add Eldwan's plot
- Want to show expected neutron energy spectrum - that will tell us how we should focus ECal capabilities. Is most of the lost neutrino energy lost in the form of many low-E neutrons ("slow" - 50 MeV) or a few high-E neutrons ("fast" - 100 MeV)

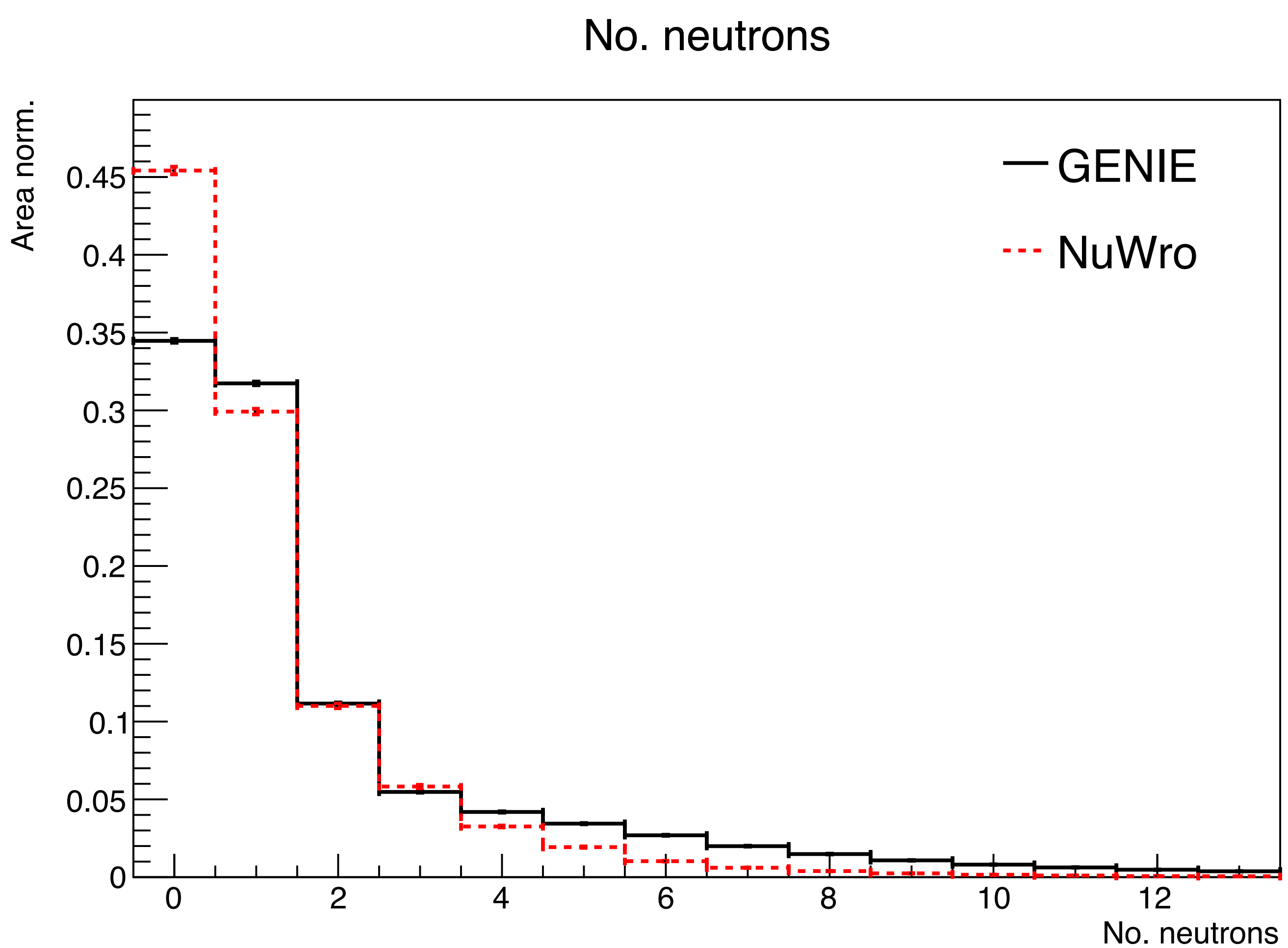
Action item (Eldwan): plot

SSC 25

1-31: Is there a plot to show the energy carried by fast and slow neutrons? How much really MPD ECAL will help in recovering this missing energy. This is an important information and a little more explanation will help.

- In addition to the information shown on the previous slide, it should be noted that predictions of neutrons produced in neutrino interactions can differ significantly between generators, because there is very little data to inform them.
- Demonstrated in these plots: total number of neutrons and total neutron energy predicted per neutrino interaction from NuWro and GENIE.





SSC 25

1-31: Is there a plot to show the energy carried by fast and slow neutrons? How much really MPD ECAL will help in recovering this missing energy. This is an important information and a little more explanation will help.

- The only direct measurement (that I am aware of - KD) of neutrons produced by neutrino interactions on Argon is from the Argoneut experiment: https://arxiv.org/pdf/1810.06502.pdf
- Say something about Argoneut! I need to think about the paper a little, but I don't think they even attempt to associate neutrons with neutrino interactions event-by-event, let alone use it to correct neutrino energy.
- Because of the difficulties involved in measuring neutrons and the large uncertainties in the predictions, this is a place where the MPD can significantly contribute to the oscillation analysis. Uncertainty on the amount of energy "lost" to neutrons in the far detector will form an energy scale uncertainty for the oscillation analyis: if we can measure neutrons from interactions in the MPD, we will be able to derive a data-driven correction to the neutrino energy in the FD.

SSC 31

1-38, line 1-9: This ECAL provides lots of mass for nu interactions. What kinds of backgrounds will it produce inside the TPC?

- Answer about other interactions occurring outside the TPC: see answers to General Comment 8b and SSC 23. Almost all interactions that we have considered in the answers to those comments are, in fact, interactions in the ECal.
- In general we estimate ~300x the rate of interactions in the ECal to interactions in the gas, because the ECal has mass of 300 tons, compared to 1 ton of gas.
- At a rate of ~0.2 interactions per ton per spill, we expect ~60 neutrino interactions in the ECal per spill, compared to 0.2 per spill in the gas.
- While the ECal does provide a large amount of mass for neutrino interactions, it is an active target so can be used to veto some interactions in the ECal.

SSC 31

Also, the channel count for the ECAL is scary large! Do you really need that many channels? Could you build something almost as good from long bars oriented in perpendicular directions, or do something like the 3D FGD here, to reduce the channel count? This is orders of magnitude more than the channel count in ND280's ECAL. Do you have any cost estimate? Keeping in mind that it is a neutrino experiment, is such a high granularity ECAL is necessary? Please justify the granularity and channel count.

- Given the size, we are not proposing to have tiles over the full detector. In the current design, 10% of layers have tiles, but account for 90% of channels. The remaining 90% of layers are made of bars in the current design
- We recognise the need to optimize the design, and understand trade-off between tiles and bars in terms of angular resolution. The ECal design is still evolving and will optimize with respect to cost and detector performance.
- We now understand how the costs will scale depending on the choices we make with regard to granularity and channel count, so this optimization can be done when the physics implications are understood.

Action item (Eldwan/Frank): come up with a nice picture of the ECal to show to the LBNC in order to explain the current design

SSC 40 and 58

1-50, line 19-21: I am worried about particles entering from the outside. I do not believe that the probability of gammas converting in the gas is as small as you think. More on this later (See Comment 58 below.)

- About particles entering from the outside: see answers to General Comment 8b and SSC 23. Almost all interactions that we have considered in the answers to those comments are, in fact, interactions in the ECal.
- The Pi0 study we did showed that ~10% of gammas in neutrino events convert in the HPgTPC, but is still consistent with the calculation in comment 58 because in this study Pi0s were generated uniformly inside the detector.
- The calculation in comment 58 used a larger distance than will be typical of traversing photons (we expect a typical traversal length to be O(radius of the detector), which is ~250 cm, since we calculate that the average of all possible chords traversing the detector is roughly equal to the radius)
- Based on this, we estimate that 10% of photons generated in neutrino interactions inside the detector will convert, and ~20% of photons generated outside the detector.
- We agree, we need to revisit the text on p.71, line 24 to reflect the above.
- The problematic background will be photons that convert in a location and direction consistent with coming from a neutrino interaction such that it confuses the selection, which will be significantly smaller than 20%

Action item (Tom): update with newer numbers

SSC 59

1-71: Energy carried by neutrons? To what extent ND components will be able to measure it. It and has been stated that for 20% and 40% of nu and nubar hadronic energy are carried by neutrons. To what extent the current Near Detector components will be able to measure it and with what error ?

- Same answer as to question SSC 25 — combine answers?

SSC 22

1-30 29 It's not clear to me how the magnet distinguishes pions and muons of the same momentum??

- In the document we wrote "At higher momenta, the magnet makes it possible to easily distinguish π^+ from μ^- (or π^- from μ^+), as has been done in T2K near-detector fits for oscillation analyses."
- T2K uses curvature to select the muon candidate as the highest-momentum negative track, and require it is the highest-momentum track in the event, but the comment is right — this does nothing to distinguish pions and muons of the same charge and momentum
- At low momenta (<500 MeV/c) a high-pressure gas TPC can distinguish pions from muons by dE/dx
- At higher momenta, we will need to use the ECal for this information. Optimization clearly needs to be done — may need to include muon system or expand the design of the ECal (e.g. putting a large absorber layer before the outer-most layer).
- The first step of the optimization will be to understand kinematics and typical particle distributions in our events and the needs (and allowable uncertainty on particle ID) for the oscillation analysis. The potential contamination in the LBL from pion mis-ID as muons and potential for identifying based on ECal information will be an important input to the ECal optimization.
- Update sentence in document to reflect that the full MPD suite is needed (including ECal) for this.

What about staging?

All these arguments don't address why (or whether) the MPD should be in place from day 1, or whether we should be staging it. Some comments about staging:

- Argument against is that it's a waste of money: need to pay for some kind of muon catcher to sit behind LAr for a short amount of time
- Whether or not staging saves money depends on flavour of money - may not save money if there is money for the MPD from e.g. international contributors that would not be available for something else instead
- Being honest, this is a candidate for staging as long as the infrastructure (including magnet) is built such that we can put in this detector later
- With staging: prioritize magnet. Build the magnet first that will allow you to put MPD in later (similar argument to building the hall full size from the start). Allows complex to be upgraded later (don't build a small and rubbish magnet that then needs to be upgraded because it's just a waste of money)
- ECal has to come with tracker. May determine timeline if e.g. international money has a timeline for ECal then it may dictate timeline of tracker.
  - Could stage parts of ECal: put downstream in before upstream
- Staging pressure of TPC doesn't buy us anything - doesn't drive cost of pressure vessel. Running at atmospheric pressure would require different gas system etc. If we ever want something more than 1atm, need to go straight to high pressure.
- Need to consider whether shape/size of hall dictates the order that you can put detectors in with staging (can you physically install one detector around another?). Seems like that has been considered - may be complicated by possible in any configuration (is that true?)

All the reasons we want a sample of interactions in the gas

This is the most important part of the argument for the HPgTPC: we need to justify why a sample of neutrino interactions in the gas is vital for the oscillation analysis. Otherwise we can't justify this detector over a more basic spectrometer. Need to put together ~1-3 main arguments with simple plots, where the rest of this forms examples

- Focus on nue and nuebar. Put in table from white paper. **This is the only detector** (in all of DUNE? 3DST may also be able to but will be harder than in HPgTPC) that can measure electrons and positrons with ~no background (and measure charge). Statistics scale with pressure. Note background from entering gammas!
- Also enhances signal/background when considering interactions outside the TPC FV. Signal statistics scales with pressure, and background is always the same (since it depends on ECal mass and surrounding material)
- This detector gives us the only chance to have a momentum scale pinned to real physics via Ks and Lambda decays. Statistics are expected to be reasonable, but only at high pressure (copy numbers from response to Spokes' questions). Expect around 20x statistics in ECal than in gas - can we use those too? Being able to calibrate momentum scale to percent level is very difficult, and significant if we can do it.
- HPgTPC acceptance mimics the FD (i.e. is essentially flat), whereas LArND with HPgTPC tracking doesn't. HPgTPC acceptance is flat but lower (~30% as opposed to FD more like 50-60%) so need statistics to enable us to make measurements and fill in areas where LArND+tracker has not-flat acceptance and validate comparisons to FD. (We have plots for this)
- Select events with given muon angle/momentum in gas and measure hadronic energy (at least: charged pions, protons, maybe pi0s). Then select same events in the liquid — that gives us a data-driven way to correct the hadronic energy in the liquid (up to missing neutrons). Very important for reducing model-dependence in ML event identification and energy reconstruction. Essentially gives us a calibration source (and a debug tool) for the FD liquid argon.
- ND complex (and particularly LAr) is basically a control on the FD. For the precision we want, need a control on the LAr (that is the gas TPC)

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- Integrate plot showing lower threshold - "we can see this much more energy in gas than LAr"
- How much do you get the energy wrong by missing low-momentum protons? 0.5% or 5%?
- GENIE/NuWro/NEUT different predictions for proton multiplicity at low energy. Why do we care?
- Pion multiplicity (we have plots). What happens if we don't make these measurements? Notice differences between GENIE and NuWro. If you find something that is wrong, want to have better capability in your ND to correct real physics in FD. Current LBL analysis shows how well we can do IF our xsec problem is constraining parameters within a model that we know is right. If we don't have the right model we end up in the Fake Data NuWro situation. This detector can tell you if your model is right (or rather: if it's very wrong). Having this very capable detector gives you the chance to figure out WHAT is wrong rather than just attempting to do some data-driven correction that might just be good enough for the FD (but might not)
- Losing pion masses!
- MPD acceptance
- Energy scale - complimentary to DUNE-PRISM

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- Neutral current events - will need to be corrected for in DUNE-PRISM
  - Show raw event rates, kinematic plots before cuts
  - Care about understanding angular and momentum distributions - want to distinguish between models at ~10% level
  - Quantitave idea: plot showing NC events under different interaction models. Directly forms uncertainty on extrapolation to far detector.
- Pion spectrum for different models - MPD can measure low-E pions more effectively
- True vs reco energy for hadrons.
- For CDR (maybe): 20% of proton energy into neutrons (but actual neutrons, don't just scale energy). Can we see it in MPD
- Friedland/Li fig. 14 - if we can measure low threshold and understand recombination, has a direct effect on oscillation analysis https://arxiv.org/pdf/1811.06159.pdf
- Explicitly highlights it in the CDR. Issues of secondary interactions in that. MPD gives cleanly defined samples of initial interactions. Run them through the detector response, and compare directly to the data. Powerful constraint, decoupling the interaction mechanism and detector response.

All the reasons we want a sample of interactions in the gas

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- Energy scale: potential constraint on the energy scale using Ks and lambda decays. At last week's meeting, Chris Marshall showed the now infamous systematic error plot where energy scale appears in black, and dominates the error budget over much of the CP range. The only in-situ way of obtaining an E_mu, and charged E_had energy scale of 1% or less is via those strange decays. In the executive summary, near the end, we argue how to use that energy scale to calibrate the LAr detector, and maybe even the FD. We should make the usefulness of the strange decays clear, and make sure that we demonstrate the loss of capability if we end up having to run at 1 atm.

All the reasons we want a sample of interactions in the gas

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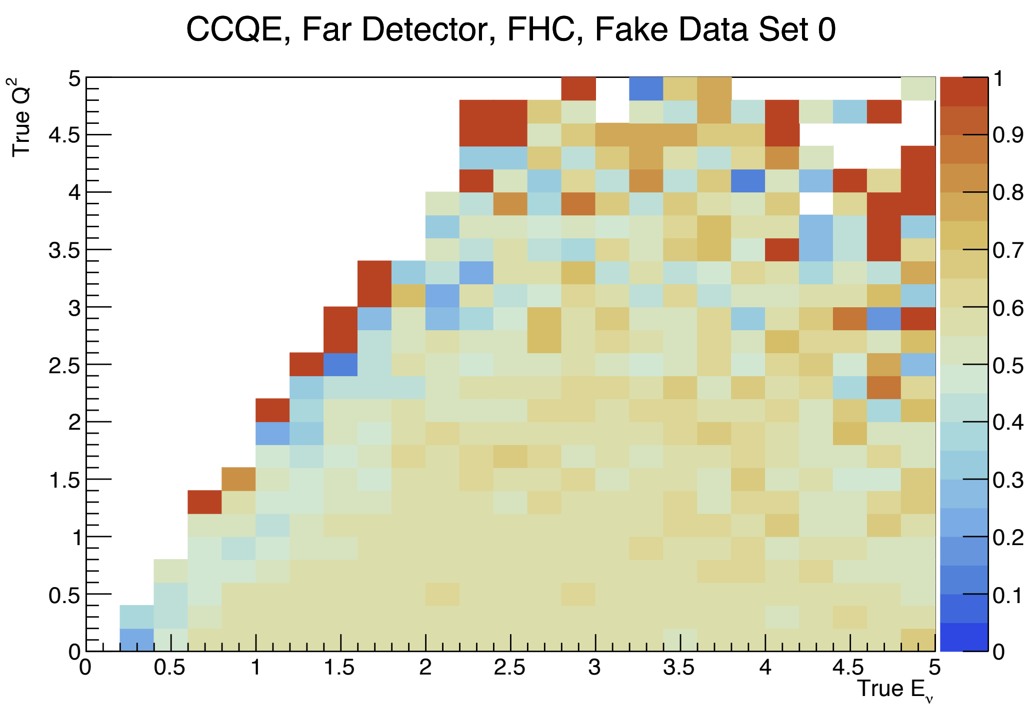
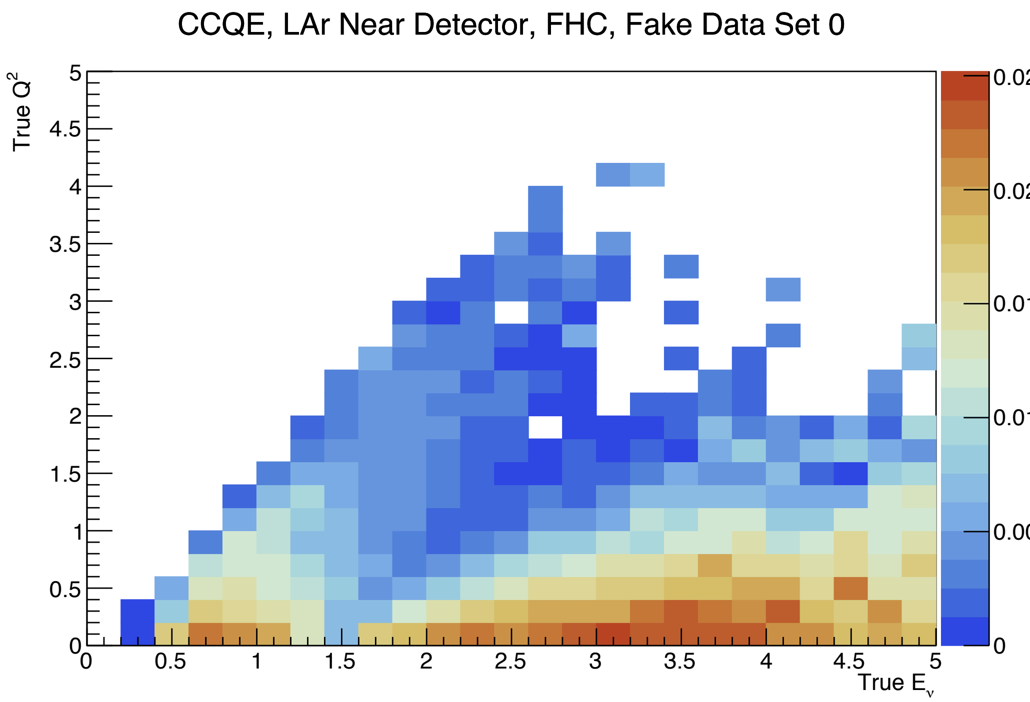
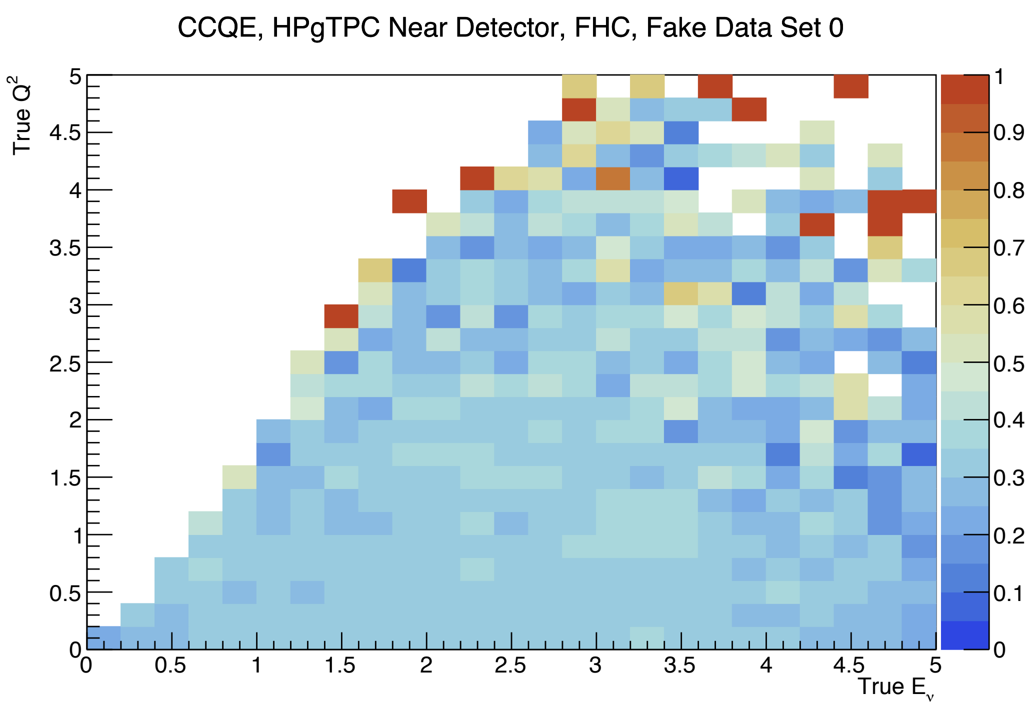
- Are these arguments helped by plots showing acceptance?







All the reasons we want a sample of interactions in the gas

This is the most important part of the argument for the HPgTPC: we need to justify why a sample of neutrino interactions in the gas is vital for the oscillation analysis. Otherwise we can't justify this detector over a more basic spectrometer

First attempt at ~1-3 main arguments with simple plots, where the rest of this forms examples — input needed!

- nue/nuebars
- detector response in LAr. Illustrate with aceptance plots? demonstration of being able to measure e.g. multiplicity better in Gar than LAr (like T2K vs uB)?
- missing energy, recombination correction etc. Tie to Friedland/Li plot
- Energy scale (possibly our strongest argument?)

SSC 21

1-30, line 17-19: The FD has secondary interactions. Can you use ArgoCube and MPD to disentangle secondary interactions, or are there plans to measure the secondary interactions independently? I'm wondering how you would apply measurements in the MPD gas to make predictions for the FD.

SSC 24

1-31, line 31: Sure, you may be able to measure the misID rate in the ND, but is the pi0 misID rate measured in the ND relevant to the FD? I'm not convinced you've measured anything relevant to the FD here. What fraction of pi-zeros are misidentified as electrons in the LArTPC and in the MPD?

SSC 29

1-35 7. Reusing the ALICE readout: the electronics need to be designed to handle very large dynamic range, if there is interest in tracking low momentum protons. (This has been a problem with T2K's TPC readout).

SSC 30

1-36, line 9-10: Given what you say here, why even consider steel for the MPD pressure vessel?

- Good question - at the time of writing this report, the pressure vessel design was not fixed.
- Our primary option now is Aluminium, with a width of 0.3 radiation lengths

SSC 32

1-38: Electromagnet vs. superconducting magnet? Same arguments in terms of cost/running cost against electromagnet are applicable for the 3DST magnet. Also background coming from the iron. Since we continue to hear noise about the KLOE magnet being used, you may want to comment on the need to reduce the magnet's mass.

- Discussed in Alan's slides about magnet questions

SSC 33

1-41, Table 1.3, and p. 1-45 line 19: Perhaps I don't understand what is being shown, but I am surprised that the table indicates that momentum resolution improves at higher momentum. That's the opposite of what I would expect for curvature in a TPC. And is the 4.2% number given on p. 1-45 consistent with this table?

SSC 34

1-44 the discussion of different gases in the TPCs tends to confuse. I understand why, but suddenly, having been convinced that Argon is mandatory, given the FD, we get this discussion.

- I

SSC 35

1-49 choice of absorber. Surely over the past thirty years this has been discussed in so many places that making the choice should be more like a "trade study"??

- Good point — the sentence in the CDR needs to be reformulated. This is definitely a trade study guided by physics requirements that have not quite been finalized
- Copper is better for angular resolution and in terms of mechanical engineering
- Lead is better for electromagnetic resolution but more difficult in terms of engineering
- Questions to consider in this trade study (and in general for ECal design optimization):
  - What level of angular resolution is required? Driven by pi0 mis-ID for energetic photons that could mimic an electron?
  - How much should we optimize for neutrons? Can we sacrifice EM resolution for better neutron detection?
- We are planning a fake data study to help answer some of the above questions, by quantifying the impact of detecting 10-20% of the neutron energy in neutrino interactions on the oscillation analysis. However, this is not possible for the 4th June (on the timescale of the CDR)

SSC 36

1-49, line 11: "Converted photons are rejected based on Monte-Carlo information." I'm not sure exactly what you mean, but it sounds like you are using the MC truth information to cheat in your reconstruction. Shouldn't this bother me?

- This is a work in progress - the reconstruction has not yet been tuned to detect photon conversions in the gas.

SSC 37

1-49, line 22: ”The mean of the Gaussian is taken as the angular resolution and the error as its variance..“ I don't understand. Maybe showing a plot of what you're fitting would help.

- Eldwan has a plot to add

SSC 39

1-50 11,12, 13 at these energies, use of TOF seems obvious??

- Correct. Perhaps we need to clarify? This had not been investigated at the time the document was submitted.

SSC 47

Page 1-54: “3DST-s can measure neutrons on an event by event basis” – This should be the case for MPD-ECAL also as the event rate in the MPD per spill is low. (Less than one). Why MPD ECAL will not be sensitive to low energy neutrons?

- Somewhat touched upon in responses to other questions
- Current studies indicate that the MPD will be able to detect neutrons, but a background study is required to understand the efficiency on an event-by-event basis.