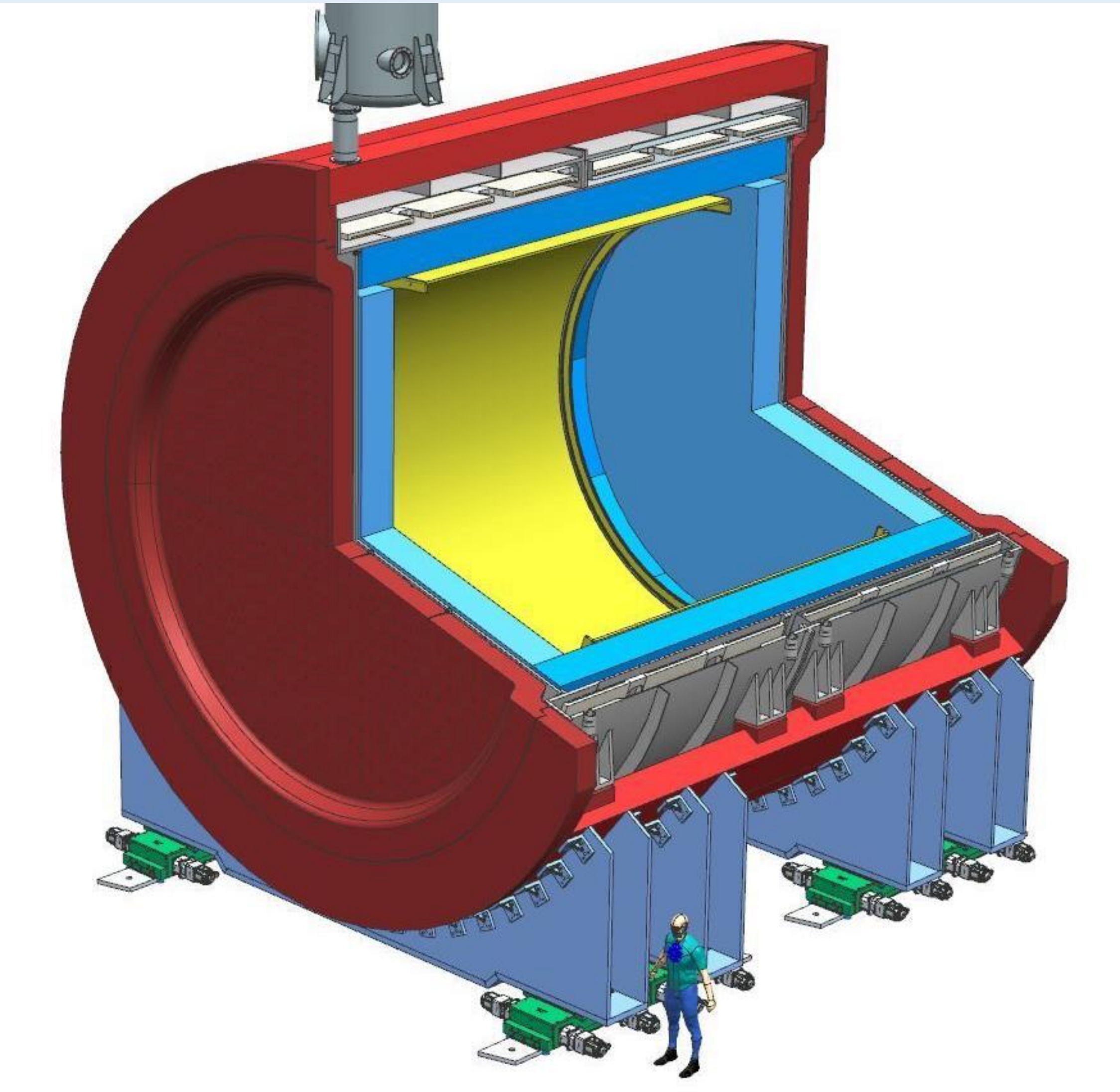
ND-GAr Update

Patrick Dunne & Tanaz Mohayai

On behalf of the ND-GAr WG

ND-GAr reminder and WG current goals

- ND-GAr is a magnetised gas TPC surrounded by an ECal that will replace TMS in DUNE Phase II
- We had a design for ND-GAr as a day-one detector, but we are re-evaluating all the choices from that design
- Working group is currently focusing on setting requirements so we can do this in a physics driven way
- In parallel, we have various hardware R&D ongoing that we will evaluate against these requirements



ND-GAr reasons to exist

- Highlights for LBL analysis:
  - Gas detectors have very low thresholds
    - Will image low energy hadrons from neutrino interactions better than ND-LAr providing test of assumptions made in reconstructing energy from below threshold particles
  - They have 4π angular acceptance
    - Will give interaction measurements with no acceptance correction required
- Highlights for BSM analysis:
  - Long-lived particle search signal rates are proportional to detector volume
  - Background rates are proportional to detector density
  - Gas detectors are ideal
- For more, see the Phase II white paper

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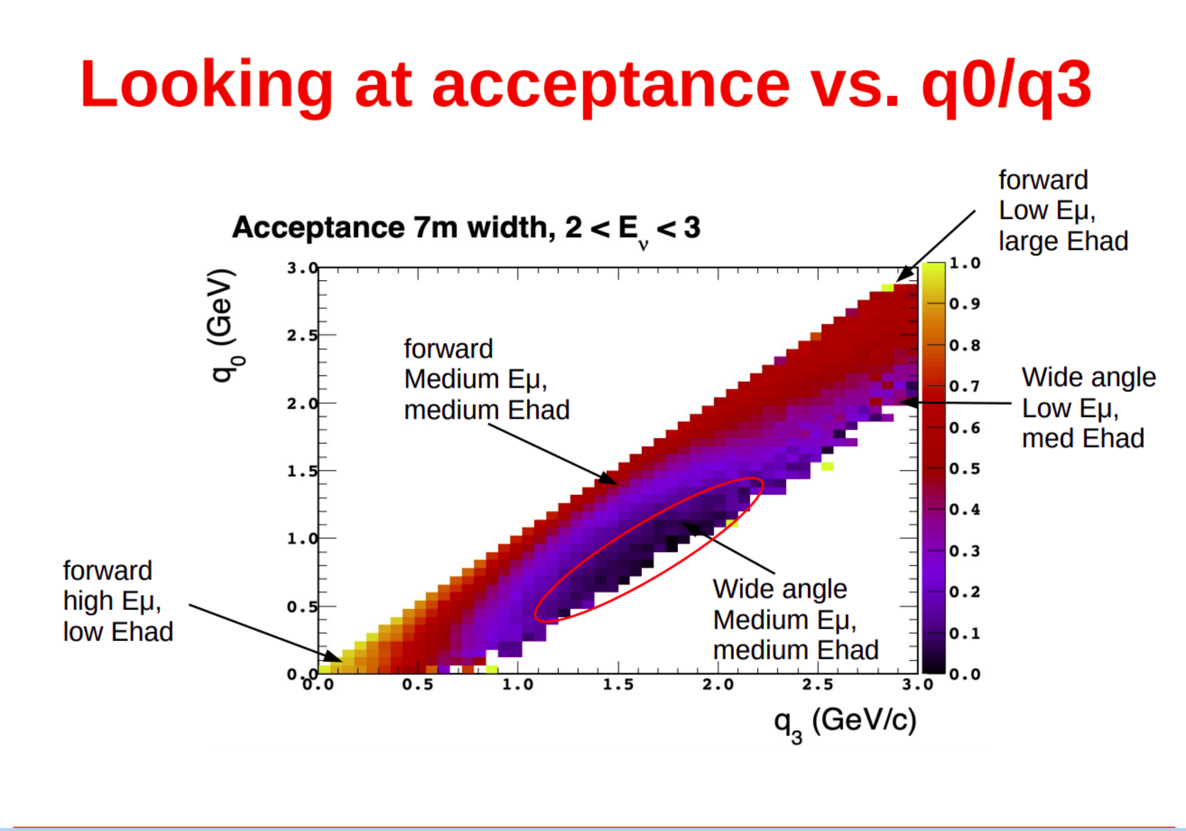
- For more, see the Phase II white paper

Motivation

- Study by KY Jung presented by Chris M at CM
  - Uses full G4 Sim of ND-LAr+TMS
  - Region in Q3 vs Q0 phase space that has very low acceptance
    - This is a "blind spot" for the ND that will need acceptance correction uncertainty
  - Not a problem in Phase I as the uncertainty will be smaller than stat error
  - However, in Phase II, this will become a dominant uncertainty
- **ND-GAr will have full 4π coverage so should be able to mitigate this**



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ND-GAr acceptance

- ND-LAr study assumes any particle contained in ND-LAr or passing through TMS is accepted. Target momentum resolution for contained particles is 5% resolution
    - Neutrons are ignored
- **Naseem Khan** producing comparable study for ND-GAr (most work shown today is hers)
- For ND-GAr, define acceptance as all final state particles are either:
    - Contained inside the TPC instrumented volume
    - Charged and have better momentum resolution than 5% from TPC measurement
    - Neutral hadron or photons, which we assume will be well reco'd in the ECAL
    - Not considering neutrons (as ND-LAr study has ignored these)
    - Not accounting for any mis-reconstruction, at the moment
- Use 100k events simulated with same G18 model as ND-LAr study

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Momentum Resolution Calculation

- For particles that do not stop in the fiducial volume, we get momentum from track curvature
- Track must be long enough and curved enough to measure momentum with a 5% uncertainty
- Assume a helix with fixed radius of curvature
- Use Gluckstern formula plus multiple interaction term for momentum transverse to drift direction:

$$\frac{\sigma_{p_{T_G}}}{p_T} \approx \sqrt{\frac{720}{N+4}} \left(\frac{\sigma_y p_T}{0.3BL^2} \right) \sqrt{1 - \frac{1}{21} \left(\frac{L}{R} \right)^2}$$

$$\frac{\sigma_{p_{T_{ms}}}}{p_T} = \frac{0.016}{0.3BL_{tot}\cos(\lambda)\beta} \sqrt{\frac{L_{tot}}{X_0}}$$

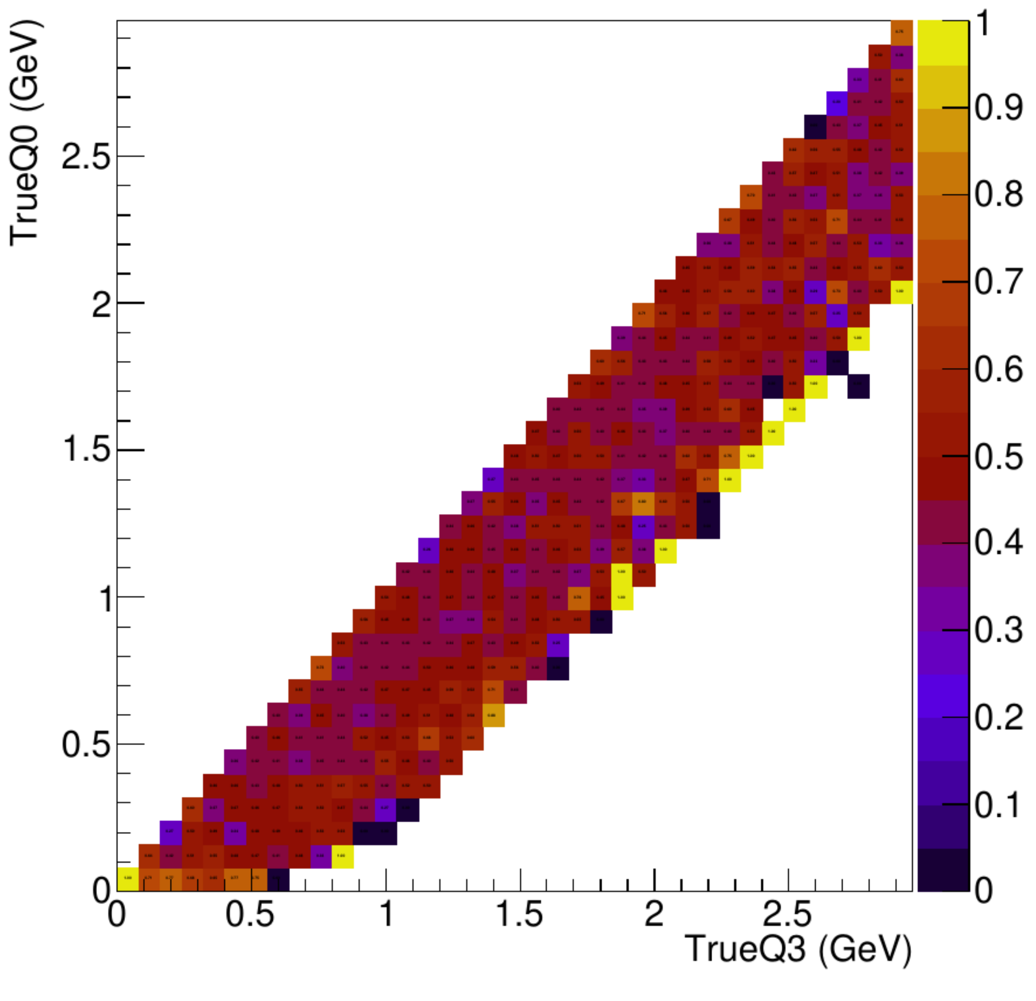
- Resolution in drift direction given by electronics sampling frequency

$$\sigma_\lambda = \cos^2(\lambda) \left(\frac{pitch}{2\pi R} \right) \sqrt{\left(\frac{\sigma_x}{L_x} \right)^2 + \left(\frac{\sigma_{p_T}}{p_T} \right)^2}$$

- For studies presented today use B=0.5T, X0 for 10 bar argon, 2.5mm spatial resolution in transverse direction, 1.5 mm in drift direction

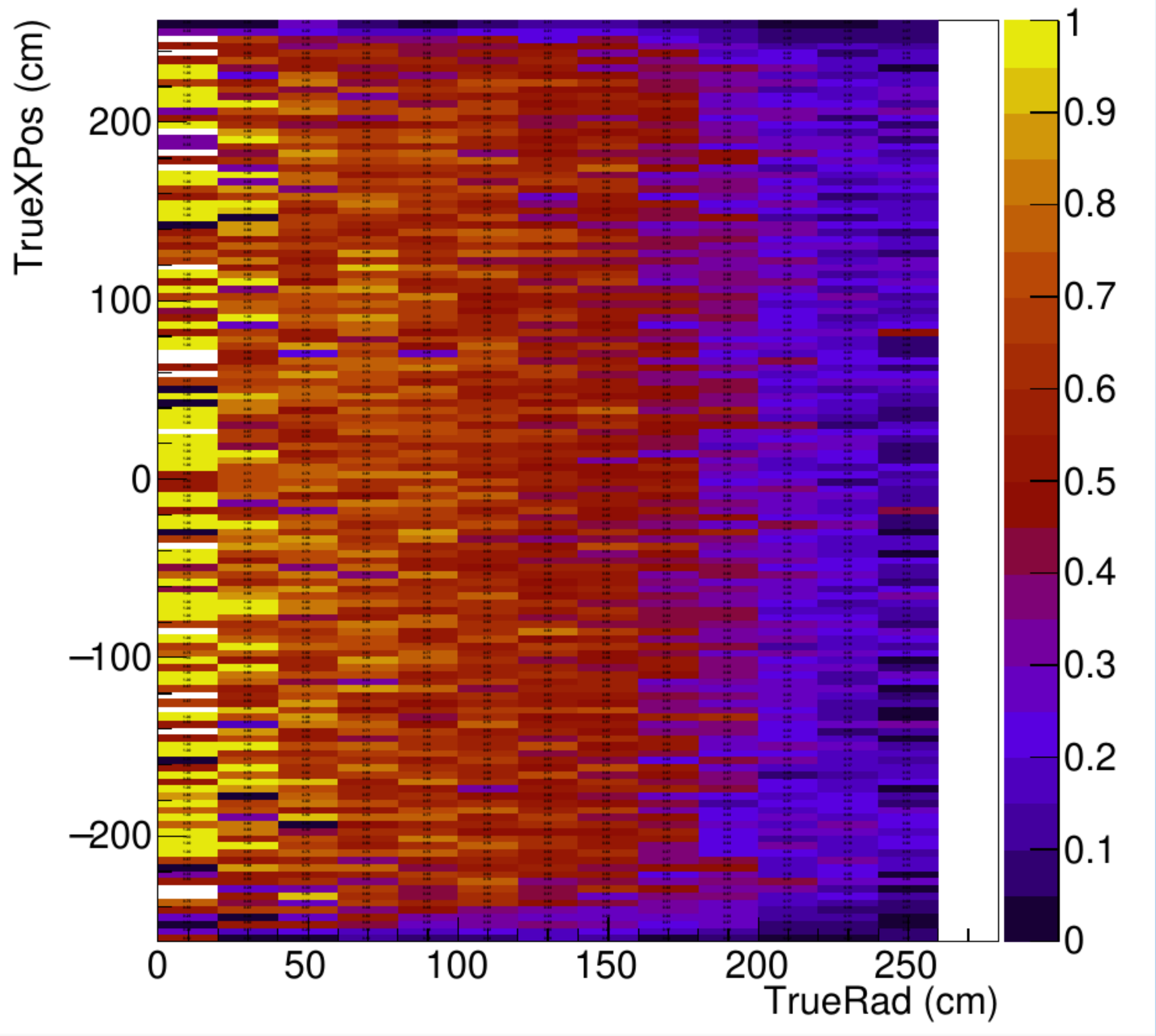
First Results

- This is including every CC event within the fiducial volume **(227 cm rad, 209 cm length)**
  - No other cuts placed on this sample
- **Multiple scattering dominates for very low momenta** particles which leave the TPC's instrumented region
- No restriction on Ev here, so there are some **very high momenta particles** rejected as the curvature becomes too small to measure
  - ND-LAr study was for 2-3 GeV Ev



Fiducial Volume Cuts

- Can see that the acceptance depends a lot on where the fiducial volume cut is placed
- **Very poor acceptance near the edges of the TPC**
- The current fiducial volume used in GArSoft is **209.0 cm in Length and 227.02 cm in radius**
- While we may want this larger FV for some studies eg maximising BSM rates, we could select a smaller region for ND-LAr acceptance correction analysis



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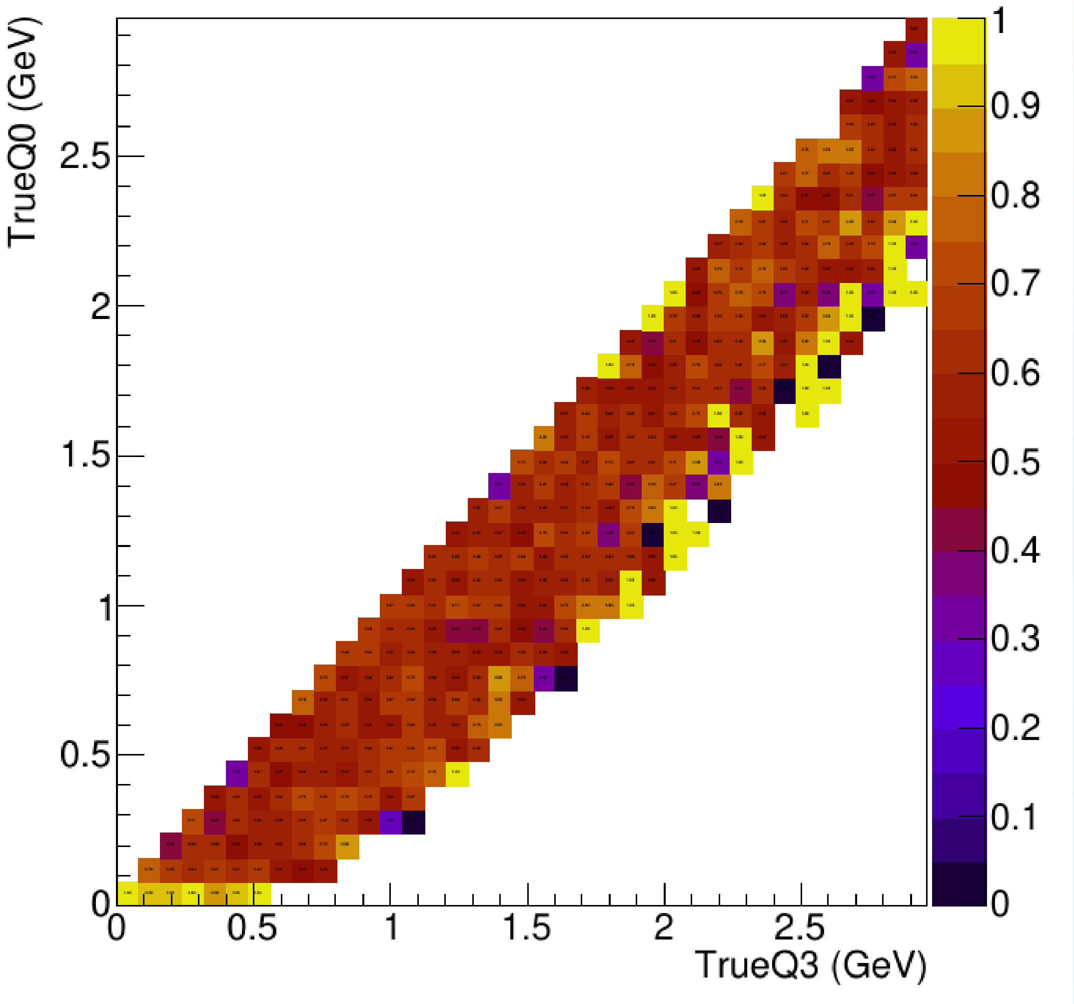
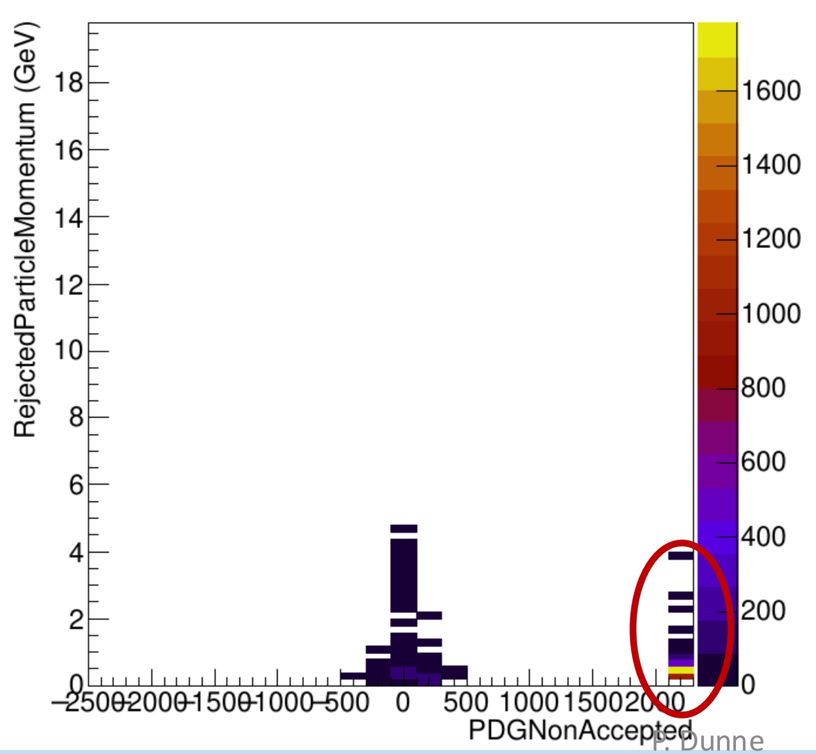
Restricted Ev range and Fiducial Volume

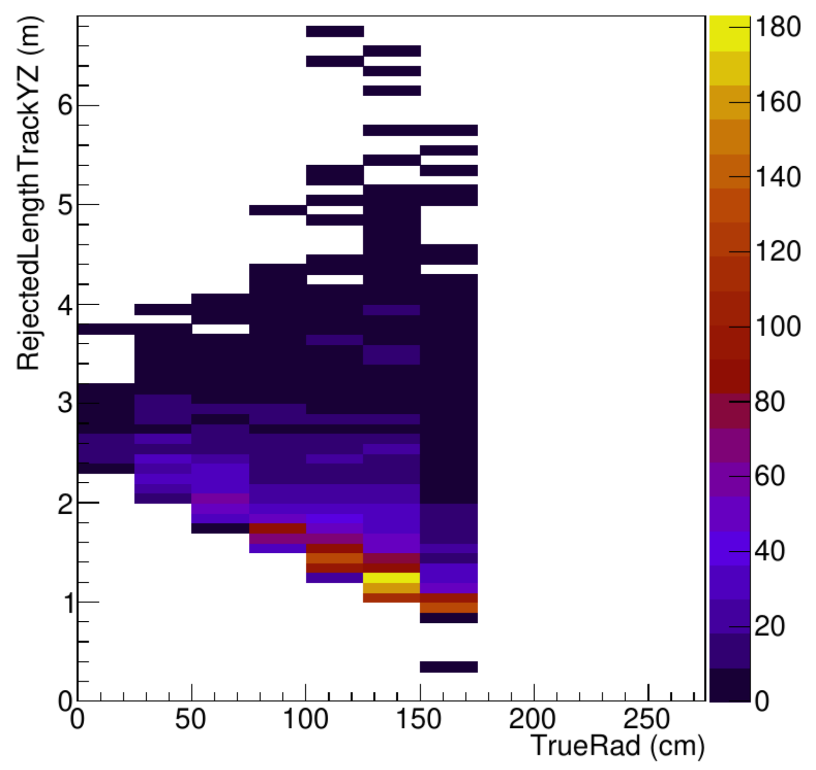
- **Require 1GeV<Ev<5GeV**
  - Ideally would want to cut between 2 to 3 GeV as this is what the ND-LAr+TMS study has done
    - Not enough stats in our 100k event sample
    - Generating more events
- **Fiducial radius cut of 160 cm and length 209 cm**



What is getting rejected?

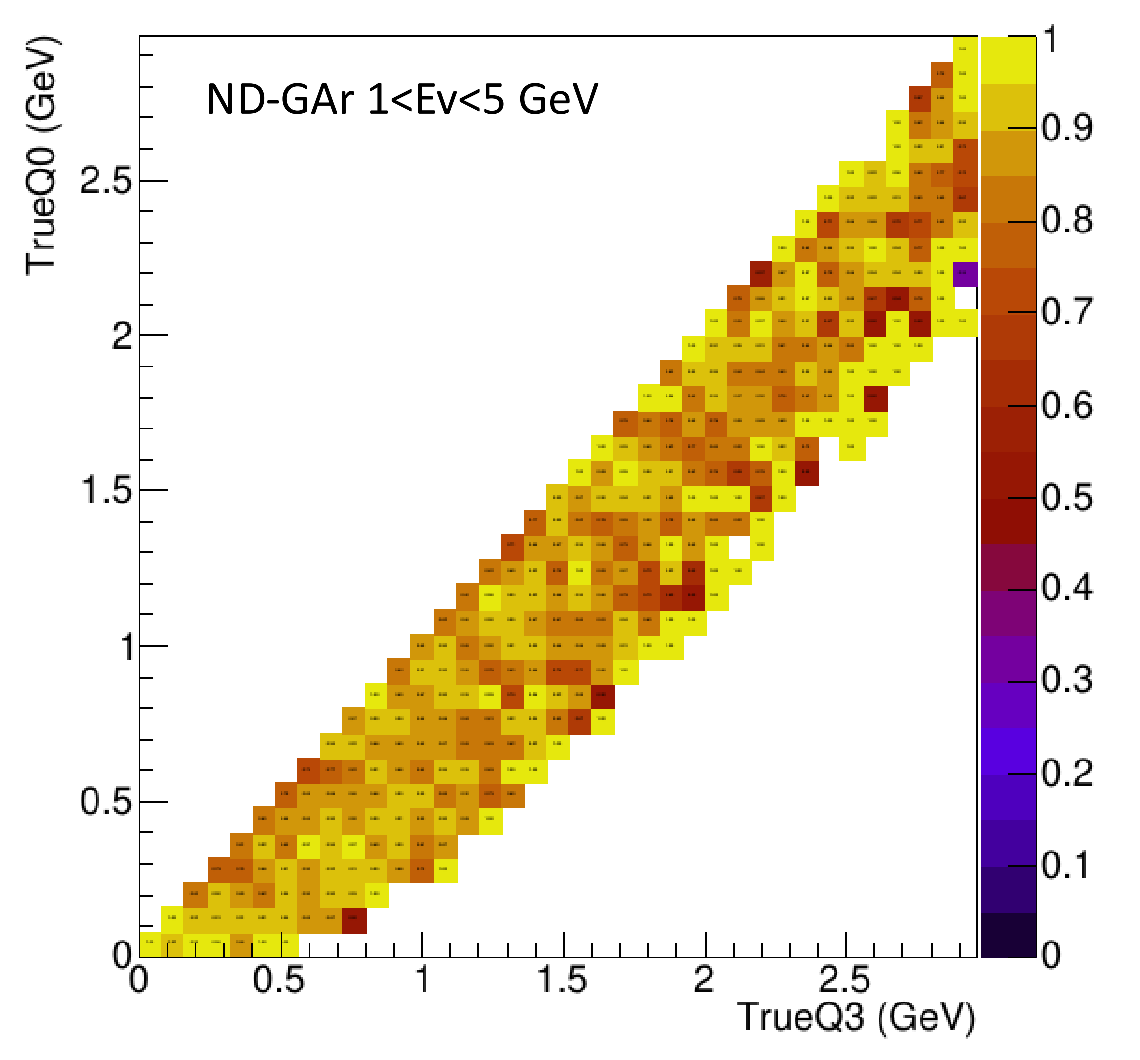
- Mostly low momentum protons (see small yellow dot in left plot)
  - Protons have higher mass ie lower velocity and get more scattering
- They are mostly tracks originating near the edge of the FV of less than ~1.5m
  - Same events starting in the middle of the FV are not getting rejected





What about the ECal?

- If our problem is mostly low energy protons exiting the TPC what about the ECal?!
- So far, study assumed ECal only sees neutral hadrons but the ECal also gives energy deposition information on charged particles
- Add effect on charged particles
  - If a particle track ends in the ECAL, assume it can be momentum resolved at at least 5%
- **Fiducial radius cut of 160 cm and length 209 cm**
- **1GeV<E_nu<5GeV**



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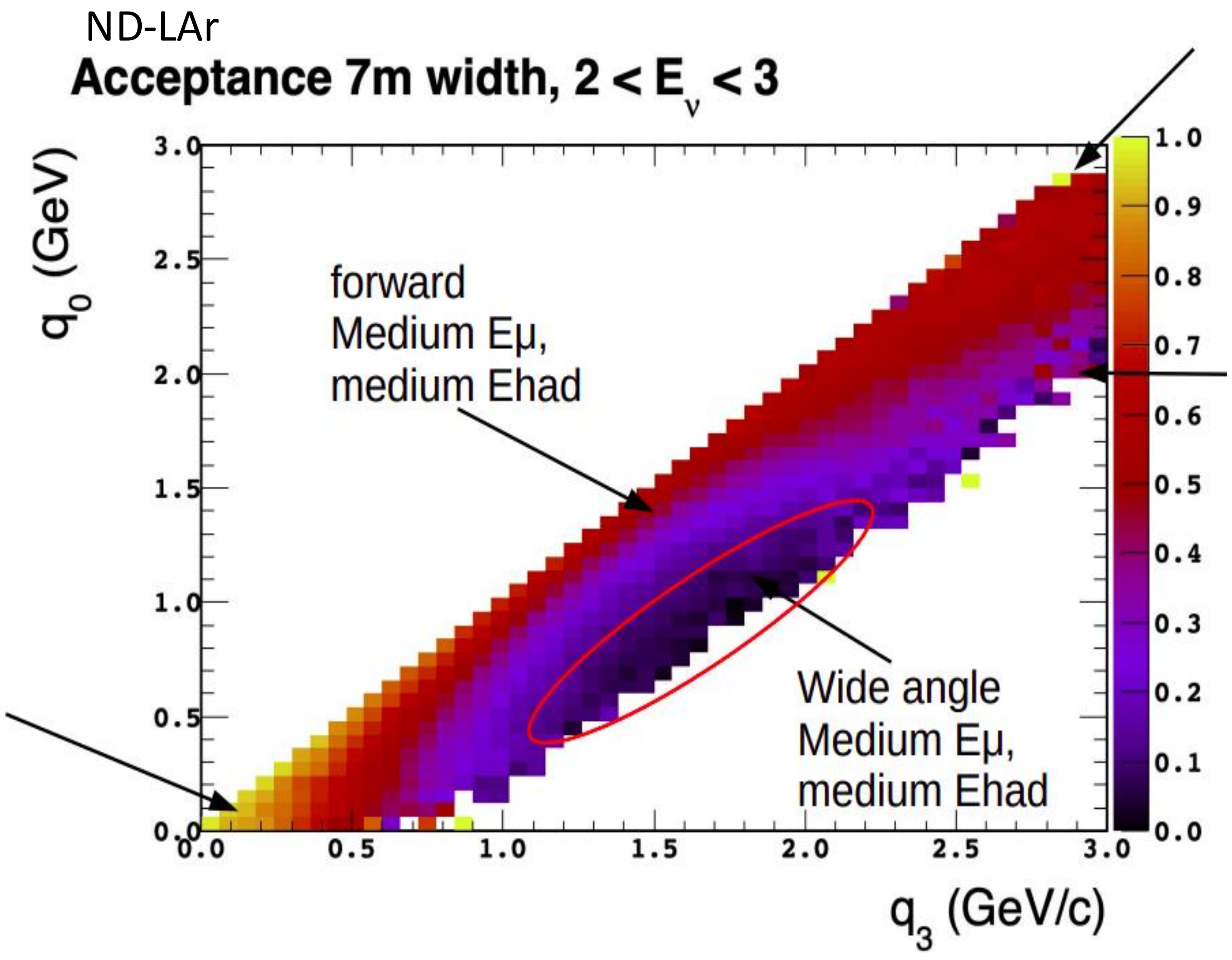
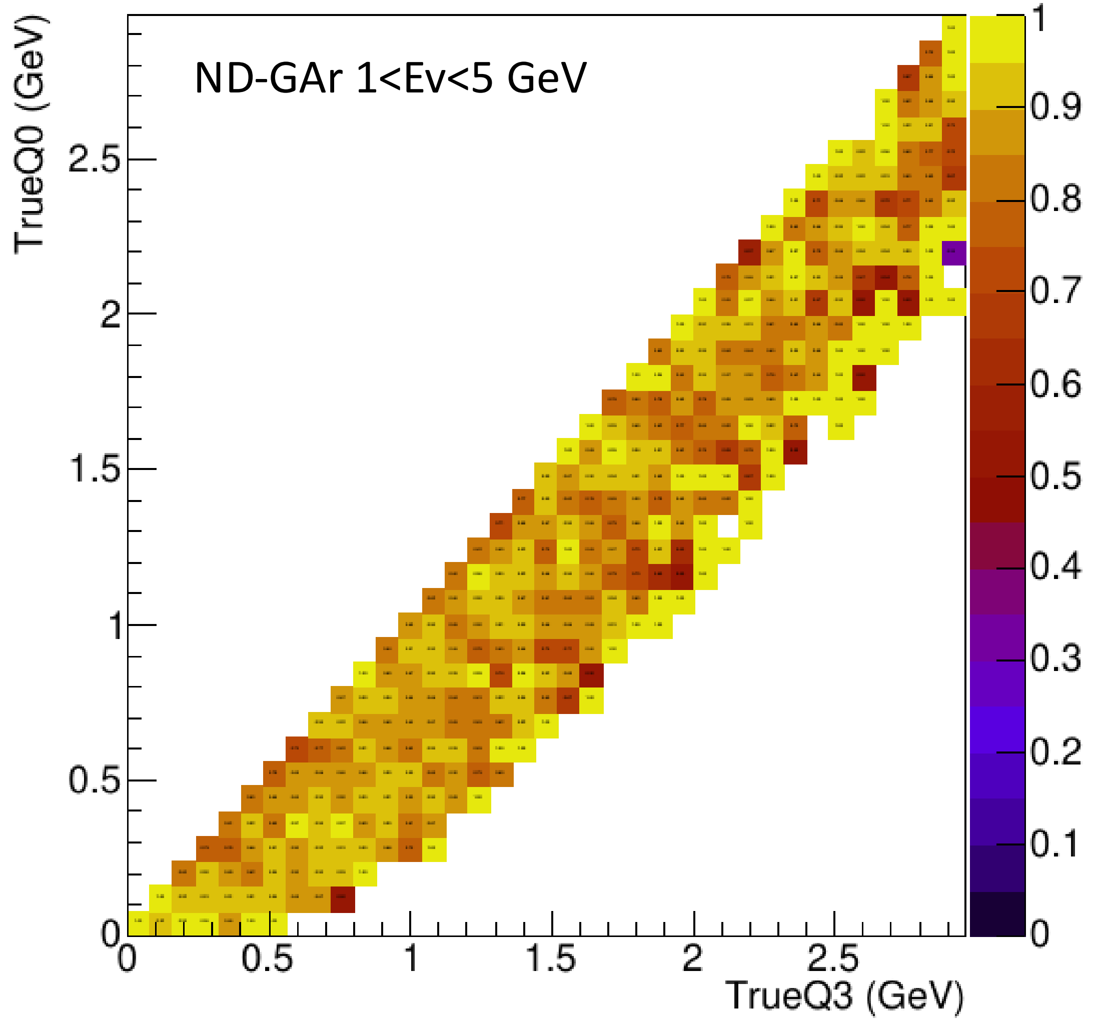
What about the ECal?





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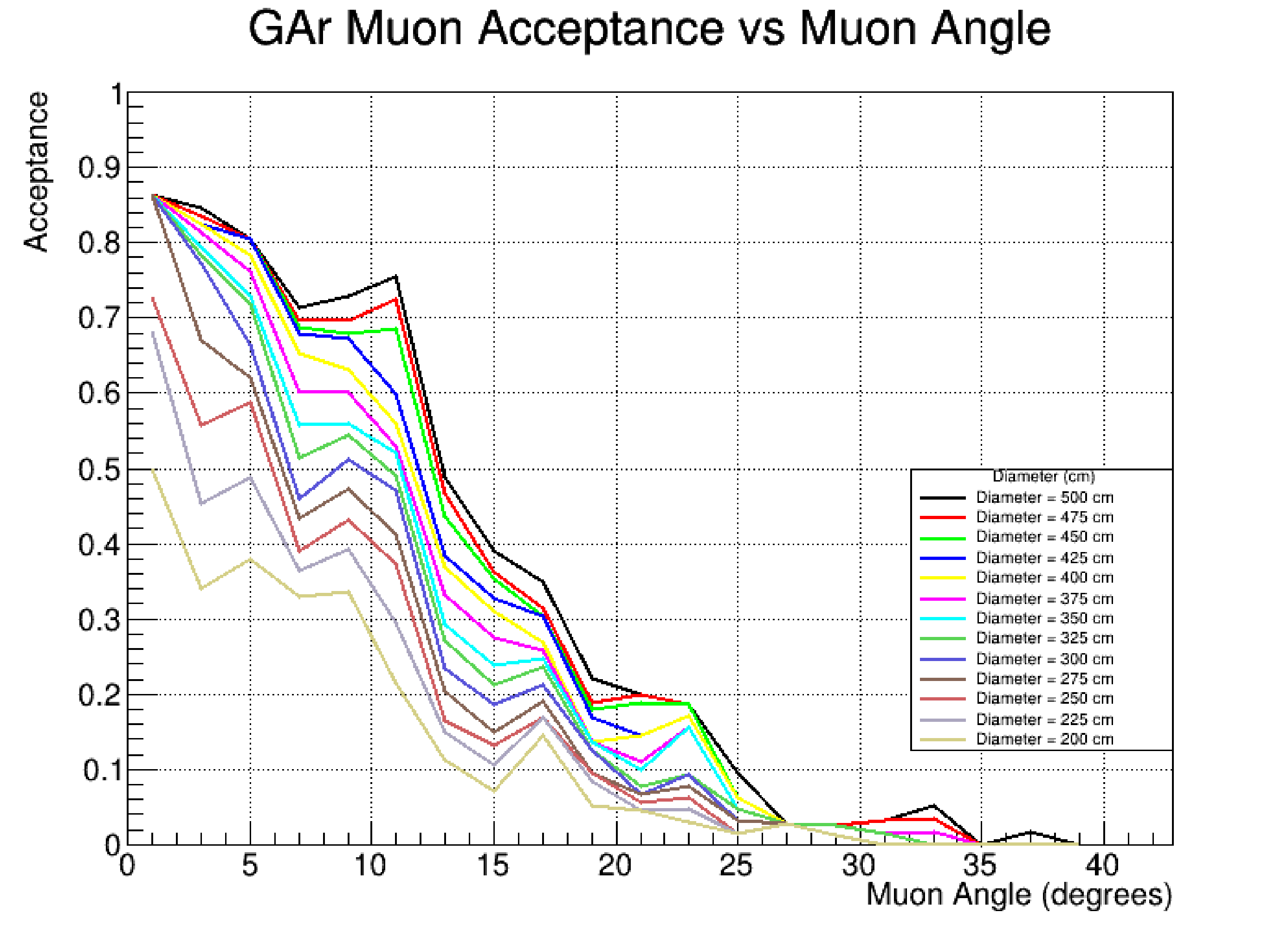
Next steps

- Vary detector parameters and see what the minimum requirement we can get away with is to retain this good performance
  - B field, position resolution, detector size can all be changed easily
- Get these results approved
- ECal has been assumed 100% efficient for Pi0/gamma
  - Daniel Xing will start to study this in the same way as a function of detector eg number of layers, absorber type, position resolution

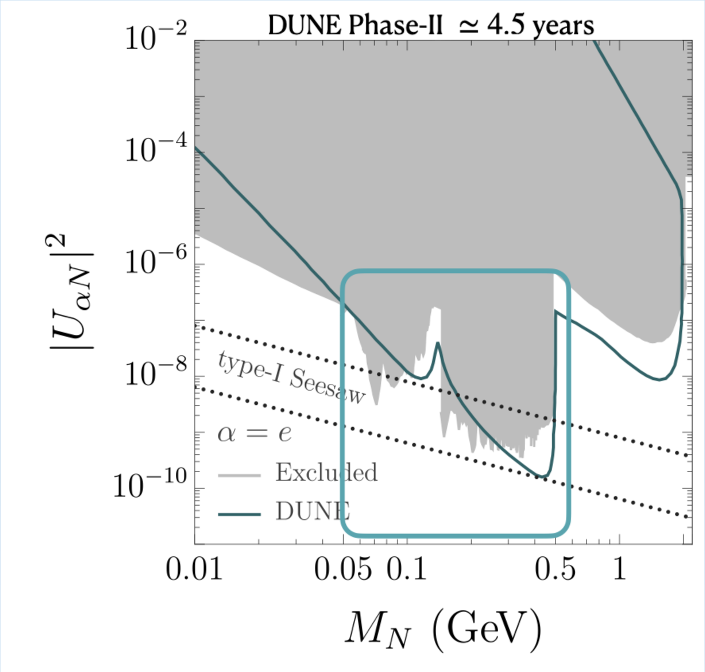
ND-GAr as ND-LAr’s spectrometer (Daniel Xing)

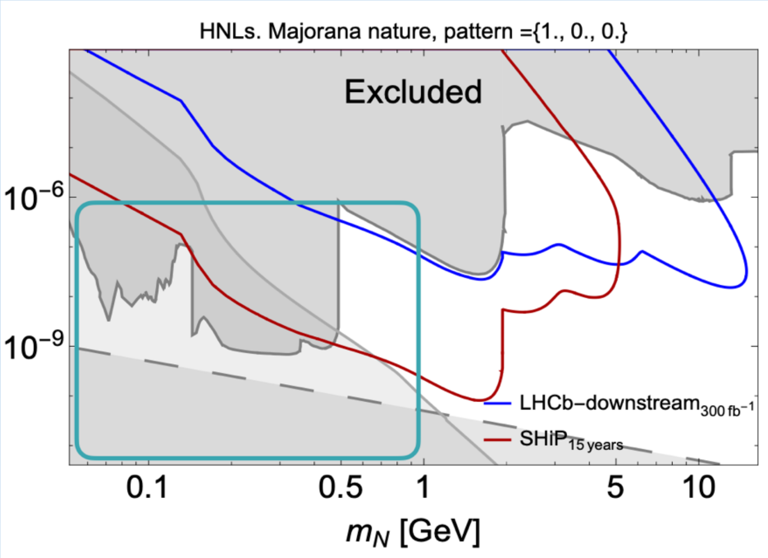
- Another key role for ND-GAr is spectrometer for ND-LAr
- Must be at least as good as TMS
- Study fraction of ND-LAr muons tracked well by ND-GAr for various detector fiducial volume diameters
- This is an example where we wouldn’t place such stringent FV cuts as for acceptance correction



Other items since last CM

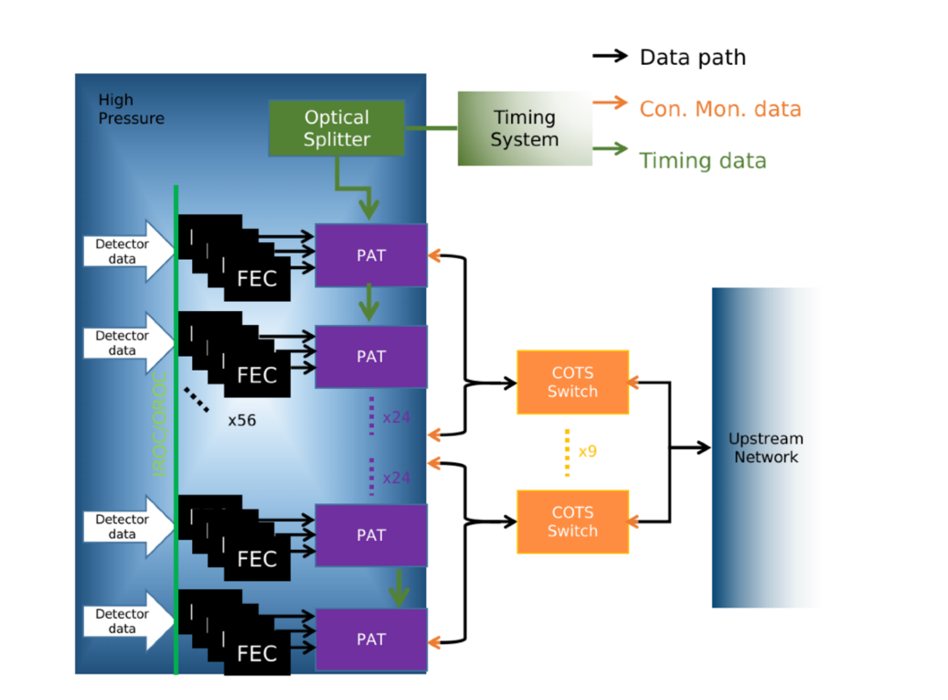
- BSM performance comparisons to SHIP were shown by Josu Hernandez Garcia in one of the ND-GAr meetings
  - ND-GAr performance is world-leading in low mass region for HNLs (see 2 plots below)
  - ALPs we are less competitive
  - Some discussions underway about being able to adjust the detector design parameters (e.g., energy threshold) to test the impact on low-mass HNLs
  - Will require creating new BSM-specific samples in GArSoft

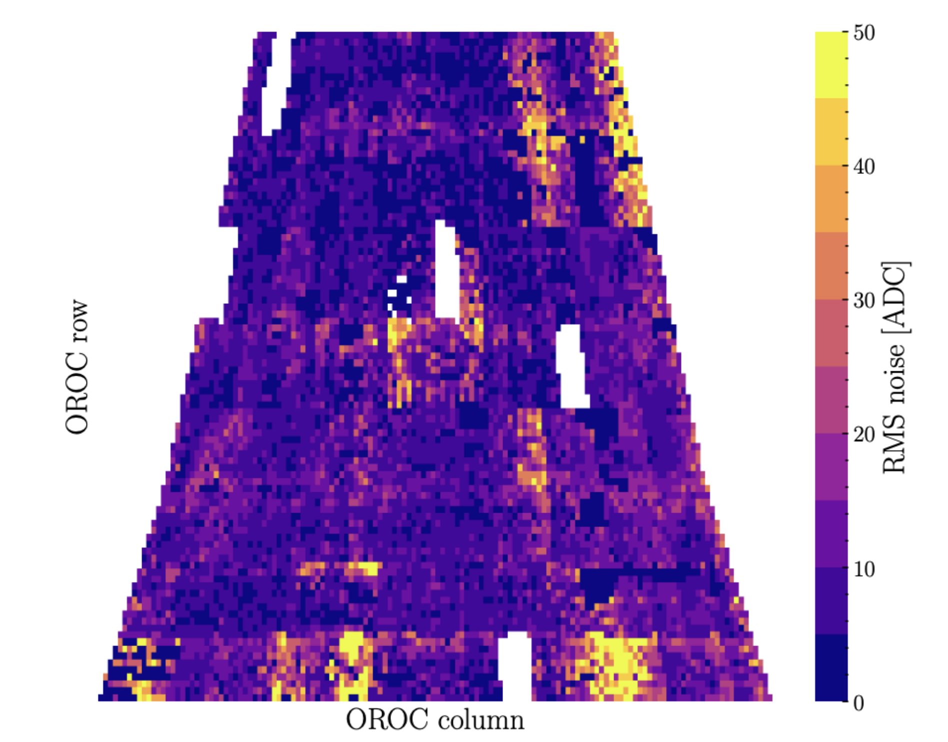




R&D Efforts

- TOAD high pressure TPC test stand operating over the last couple of years at FNAL, demonstrated operation of electronics that would cost ~£2M for 700k channels, not O($200M)
  - This is being written up in a short author list technical paper

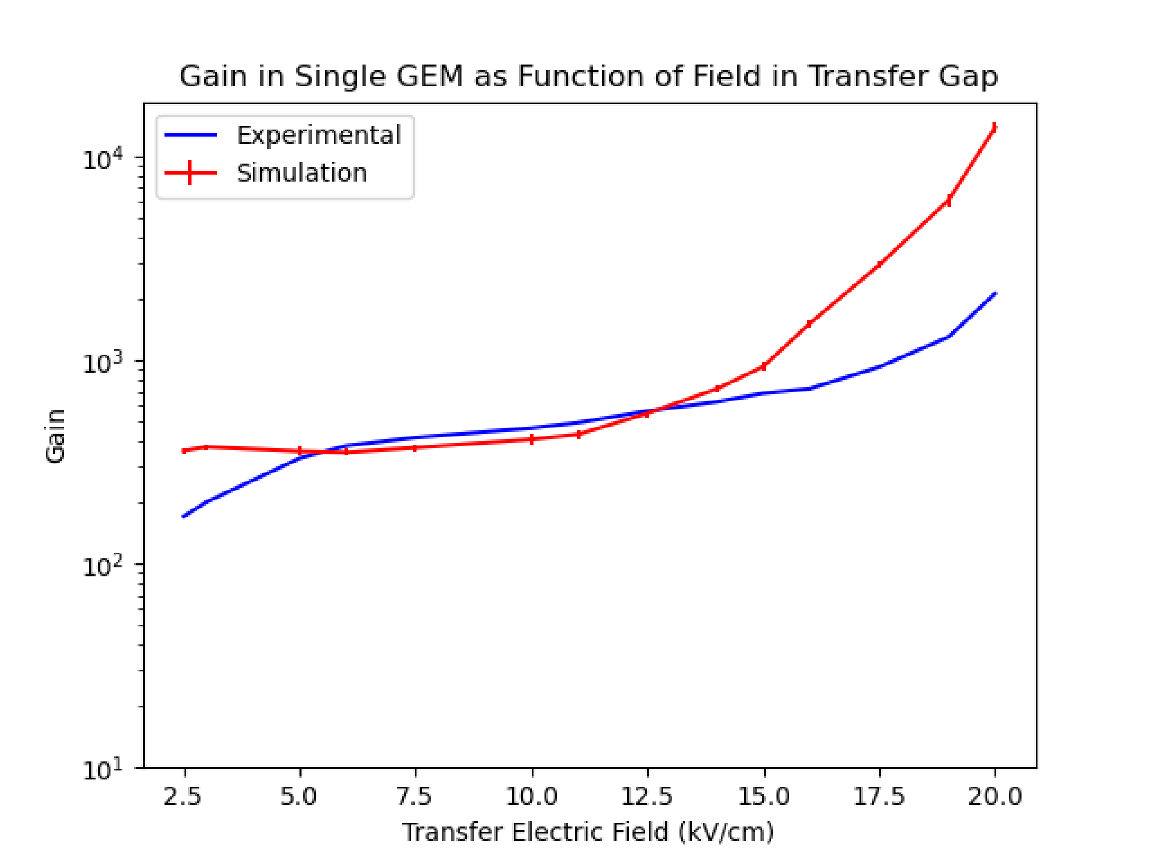




R&D Efforts

Blue is from a paper by Sauli: [J. Benlloch et al, NIMA 419(1998)410](#)
And red is Brenna's simulation

- Brenna McConnell is presenting her GEM performance studies at CPAD
  - Focus is on generic detector R&D & the novelty of optimizing GEM parameters to maximize gain in high-pressure gaseous argon environments
  - Adjustments to the transfer gap/field & gas mixtures being implemented in simulation to evaluate their impact on gain
  - Both adjustments—reducing the gaps and incorporating small percentages of CH_4 as quenchers—show promise and are straightforward to implement experimentally as benchmarks in GORG



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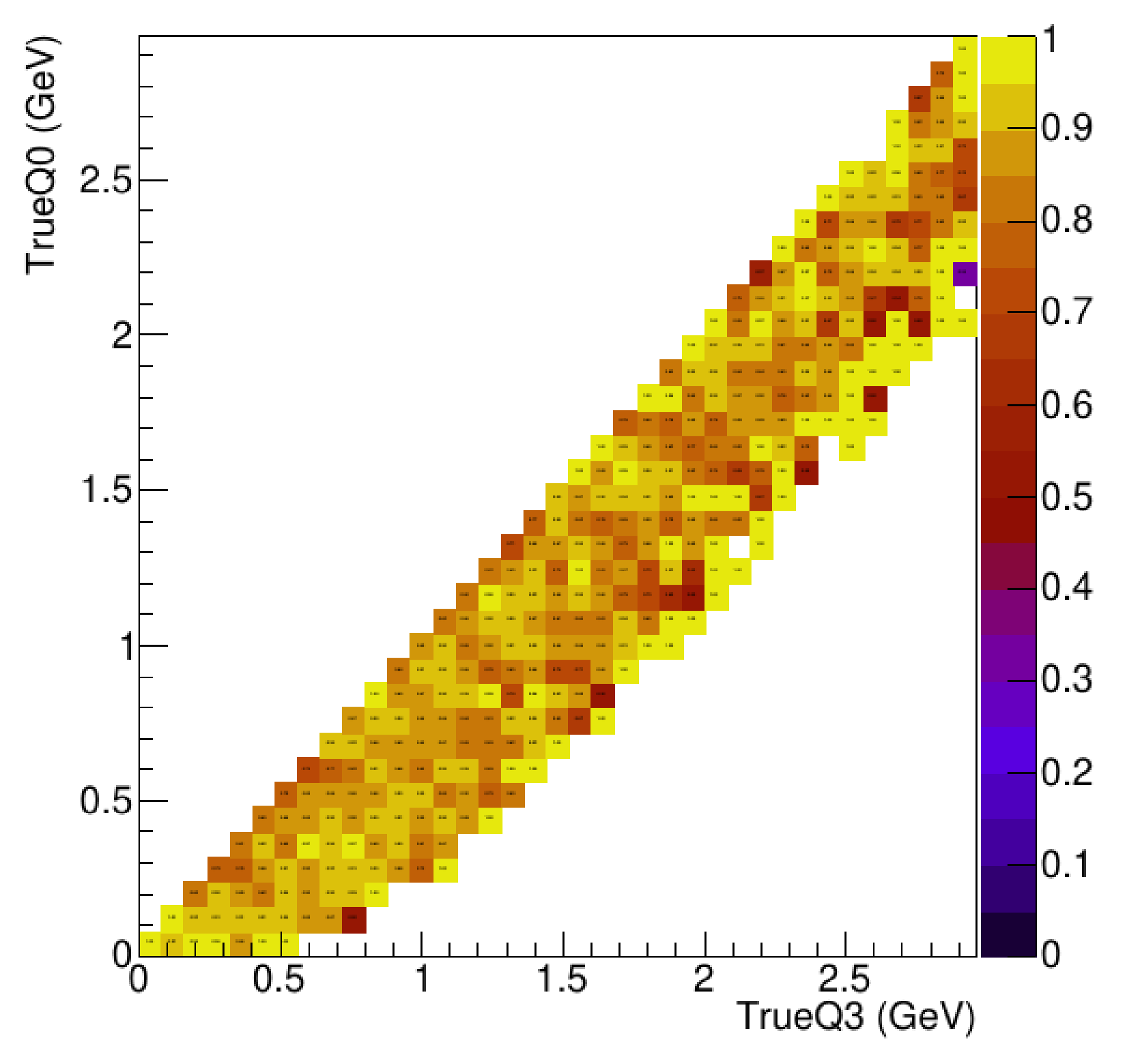
Summary

- ND-GAr working group focused on setting physics driven requirements for our detector
- We are in parallel doing hardware R&D and will benchmark that against the physics requirements
- Look out for papers and talks from our group coming soon



Backup

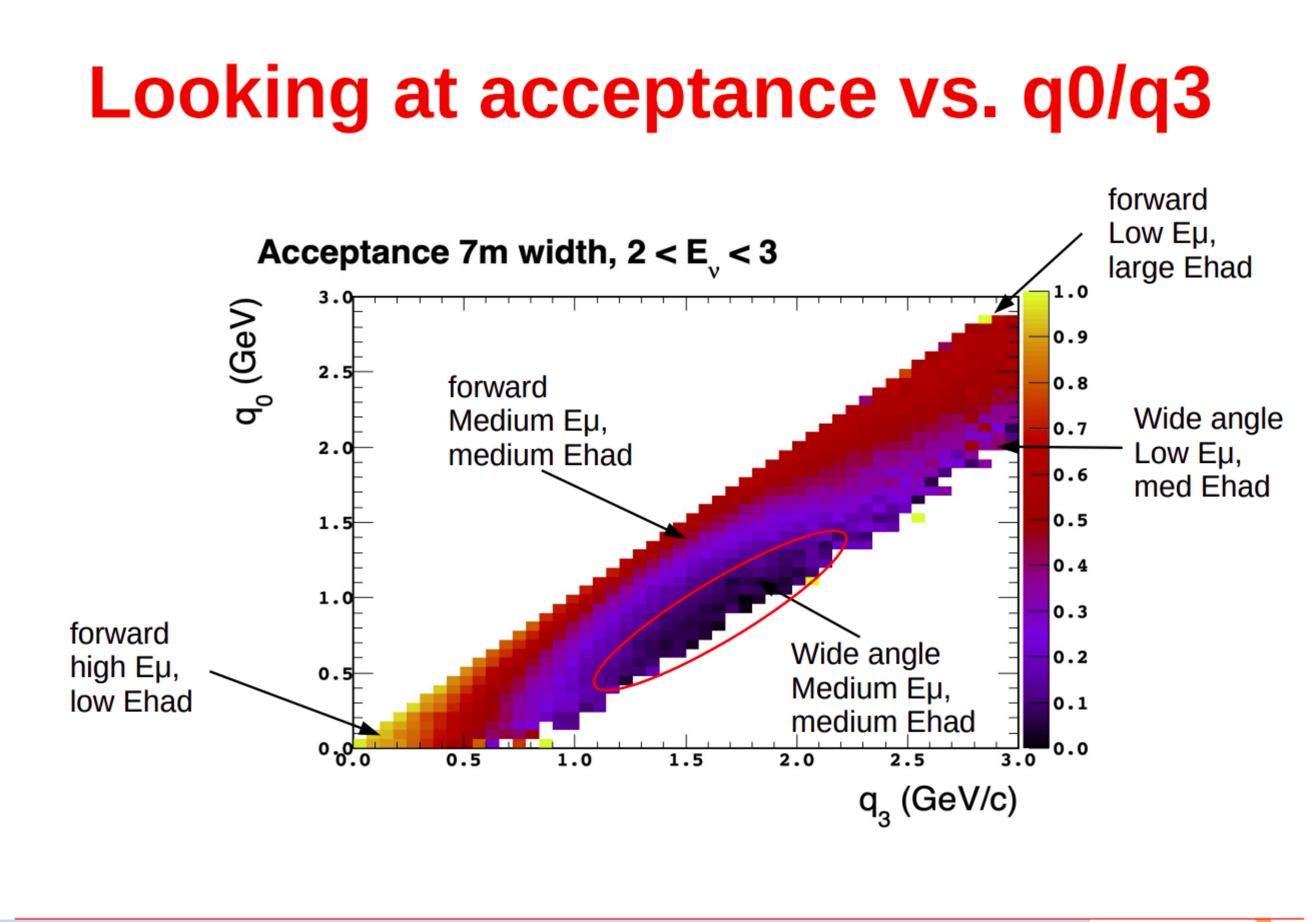
Naseem’s talk at Sim/Reco

Motivation

- Chris Marshall's talk
  - FD has 4π acceptance, so ND needs to measure neutrino interactions over the full 4π to match the FD
  - Need to ensure the full phase space has good acceptance so that a reliable correction can be applied
  - However, some regions have very small, or zero, acceptance with ND-LAr + TMS.
  - Events are classed as "accepted" in ND-LAr+TMS if:
    - Hadrons are contained in ND-LAr
    - Muon stops in ND-LAr active volume or TMS instrumented region
  - Some events will be accepted if the vertex is in some region of ND-LAr but the same event can be rejected if it happens elsewhere
  - However, some events are not accepted no matter where the vertex is

Motivation

- [Chris Marshall's talk]
- Study by KiYoung Jung
  - Uses a full Geant4 Simulation of ND-LAr+TMS
  - Region in Q3 vs Q0 phase space that has very low acceptance
    - This is a "blind spot" for the ND
    - Not a problem in Phase I as the uncertainty on this will be much smaller than the stat error
    - However, in Phase II this will become a dominant uncertainty



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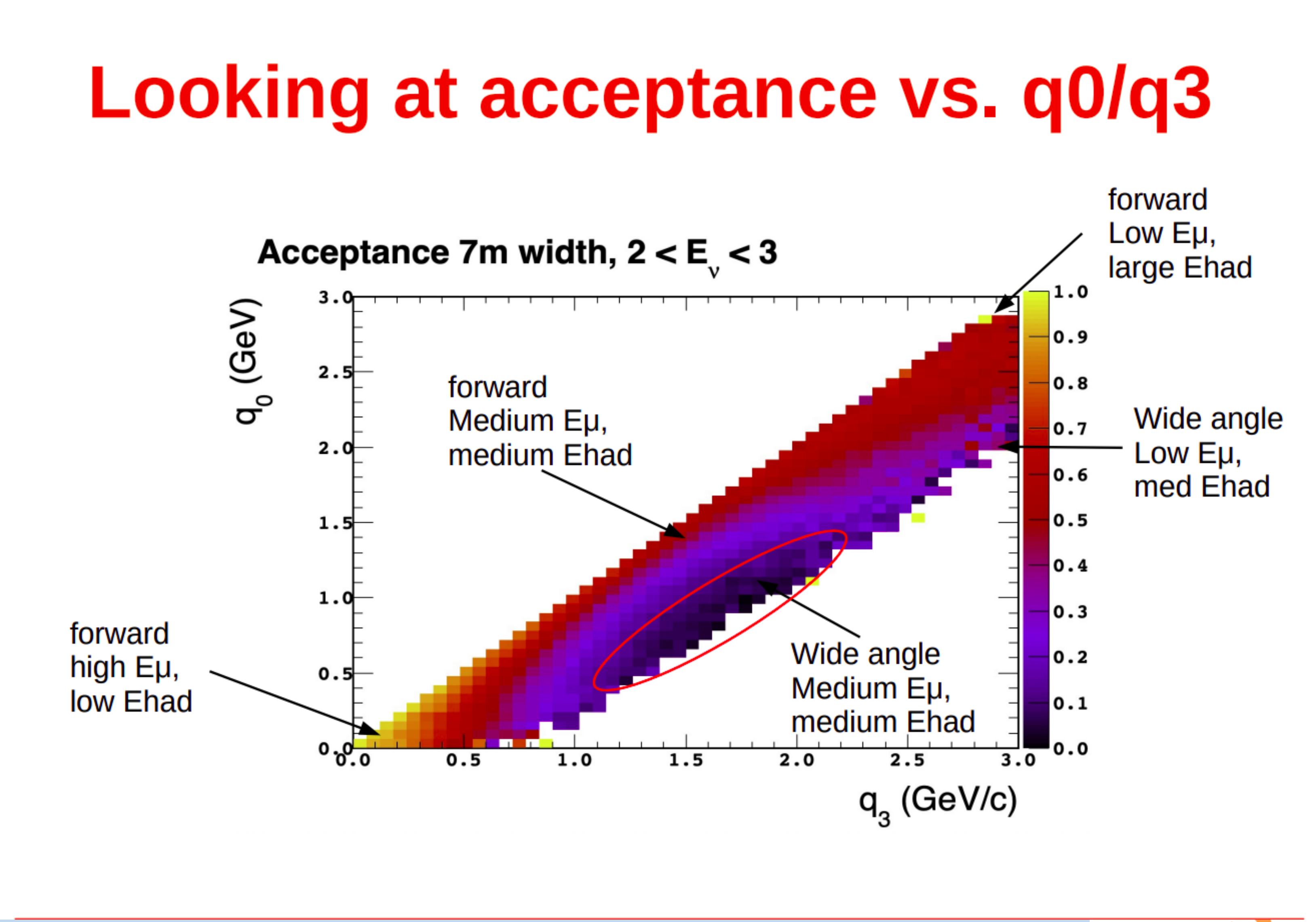
    - Not a problem in Phase I as the uncertainty on this will be much smaller than the stat error
    - However, in Phase II this will become a dominant uncertainty
- **ND-GAr will have full 4π coverage**



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ND-GAr Acceptance Studies

- We want to know what requirements we can put on the design of ND-GAr in order to have a good acceptance in this region that ND-LAr will miss
- We will use the same assumptions as ND-LAr+TMS studies so it is a fair comparison
  - Use the Geant4 Simulation of ND-GAr with GENIE events
  - Using the 100k event sample
  - Using the G18 tune of GENIE

ND-GAr Acceptance Studies

- Define Acceptance as all tracks are either:
  - Contained
  - Better momentum resolution than 5% for any charged particles leaving the TPC
  - Assume Neutral Pions/Photons will be well reco'd in the ECAL
  - Ignore neutrons (as ND-LAr study has ignored these)
- Not accounting for any misreconstruction at the moment

Momentum Resolution Calculation

- For particles that do not stop in the fiducial volume, we can determine their momentum from track curvature
- Track must be long enough and curved enough to measure momentum with a 5% uncertainty
- Assuming a helix with fixed radius of curvature

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_T}}{p_T}\right)^2 + (\tan(\lambda)\sigma_\lambda)^2$$

R. Kogler

- p is Total Momentum
- pT is Transverse Momentum
- λ is the dip angle of the helix

Momentum Resolution Calculation

- Transverse momentum resolution estimated from the **Gluckstern Formula**

$$\frac{\sigma_{p_{T_G}}}{p_T} \approx \sqrt{\frac{720}{N+4}} \left(\frac{\sigma_y p_T}{0.3BL^2}\right) \sqrt{1 - \frac{1}{21}\left(\frac{L}{R}\right)^2}$$

A. Karimaki

- N is the number of pixels a track goes through.
  - This is estimated using a pixel grid of **6mm x 6mm** pixels.
- B is the magnetic field.
  - Set to **0.5 T**, but will be varied and studied
- L is the length of the **chord** of the track in the transverse plane
  - Estimate the track as a circle in the transverse plane and find where the track intersects with the detector edge (intersection of two circles, with the point of intersection that comes first in the track trajectory taken)
- σy is the **spatial resolution** in the transverse plane (estimated from resolution achieved by ALICE with MWPCs and GEMs)

Momentum Resolution Calculation

- **Multiple Scattering contribution to momentum resolution**
  - Dominates **low momenta** particles due to β factor

$$\frac{\sigma_{p_{T_{ms}}}}{p_T} = \frac{0.016}{0.3BL_{tot}\cos(\lambda)\beta}\sqrt{\frac{L_{tot}}{X_0}}$$

P. A. Zyla et al.

- L_{tot} is the **total track length** in the transverse plane of the helix in the TPC
- X0 is the **radiation length** of Argon at 10 bar = **1193 cm**
- The total momentum resolution in the transverse plane then becomes

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_{T_G}}}{p_T}\right)^2 + \left(\frac{\sigma_{p_{T_{ms}}}}{p_T}\right)^2}$$

Momentum Resolution Calculation

- **Dip Angle Resolution Estimation**

$$\tan(\lambda) = \frac{L_x}{L_T}$$

$$L_T = \frac{L_x}{pitch} 2\pi R$$

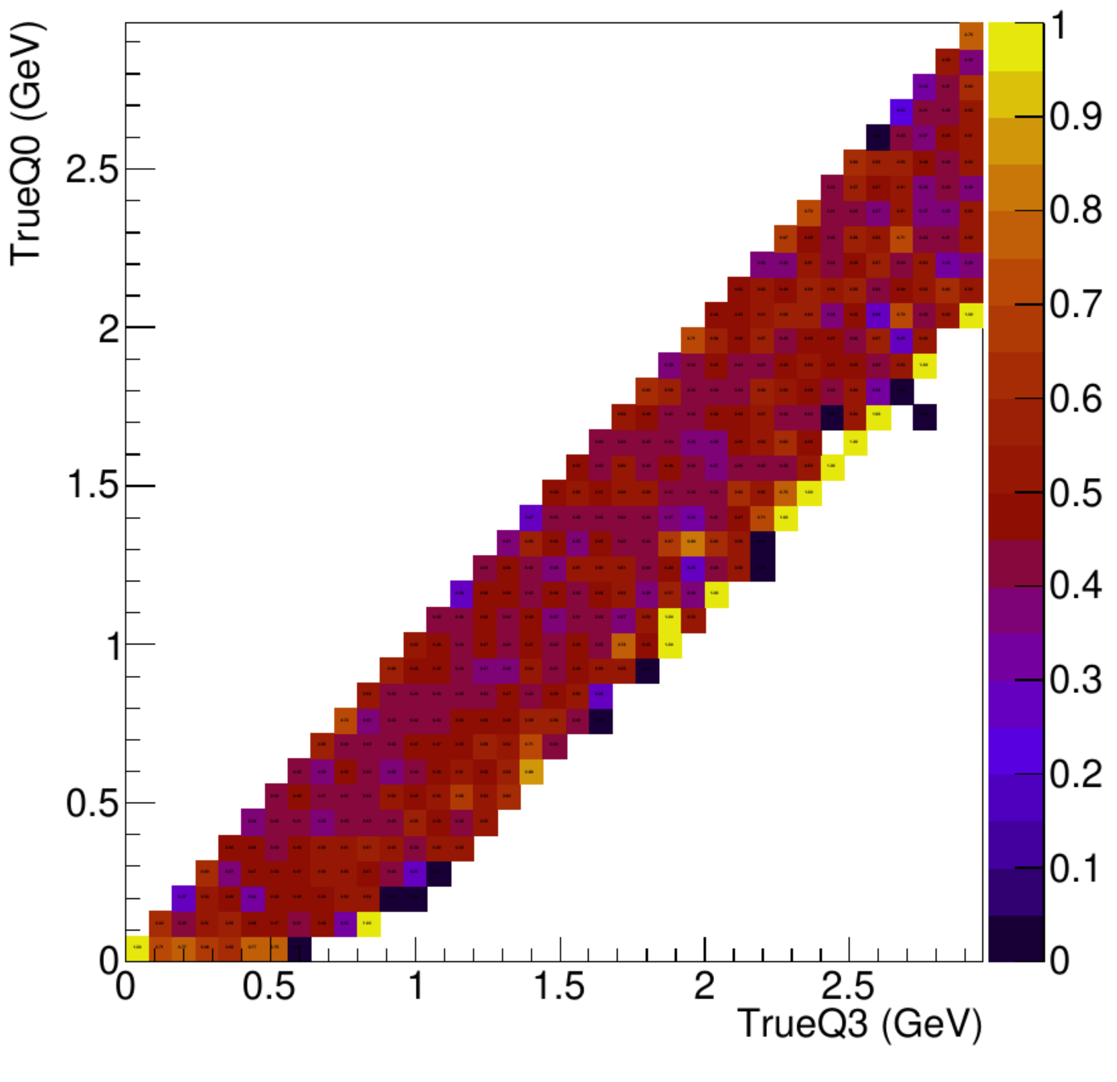
- Lx is the track length in the X-direction (direction of the B-field)
- This gives:

$$\sigma_\lambda = \cos^2(\lambda) \left(\frac{pitch}{2\pi R}\right) \sqrt{\left(\frac{\sigma_x}{L_x}\right)^2 + \left(\frac{\sigma_{p_T}}{p_T}\right)^2}$$

- We take σx to be the spatial resolution in the x-direction (assuming a drift velocity of ~**3.011 cm/μs** and a Sampling frequency of **20 MHz**, which gives a $\boldsymbol{\sigma_x}$ **= 1.5 mm**)

First Results

- This is including every CC event within the fiducial volume **(227 cm rad, 209 cm length)**
  - This is the only selection cut placed on this sample



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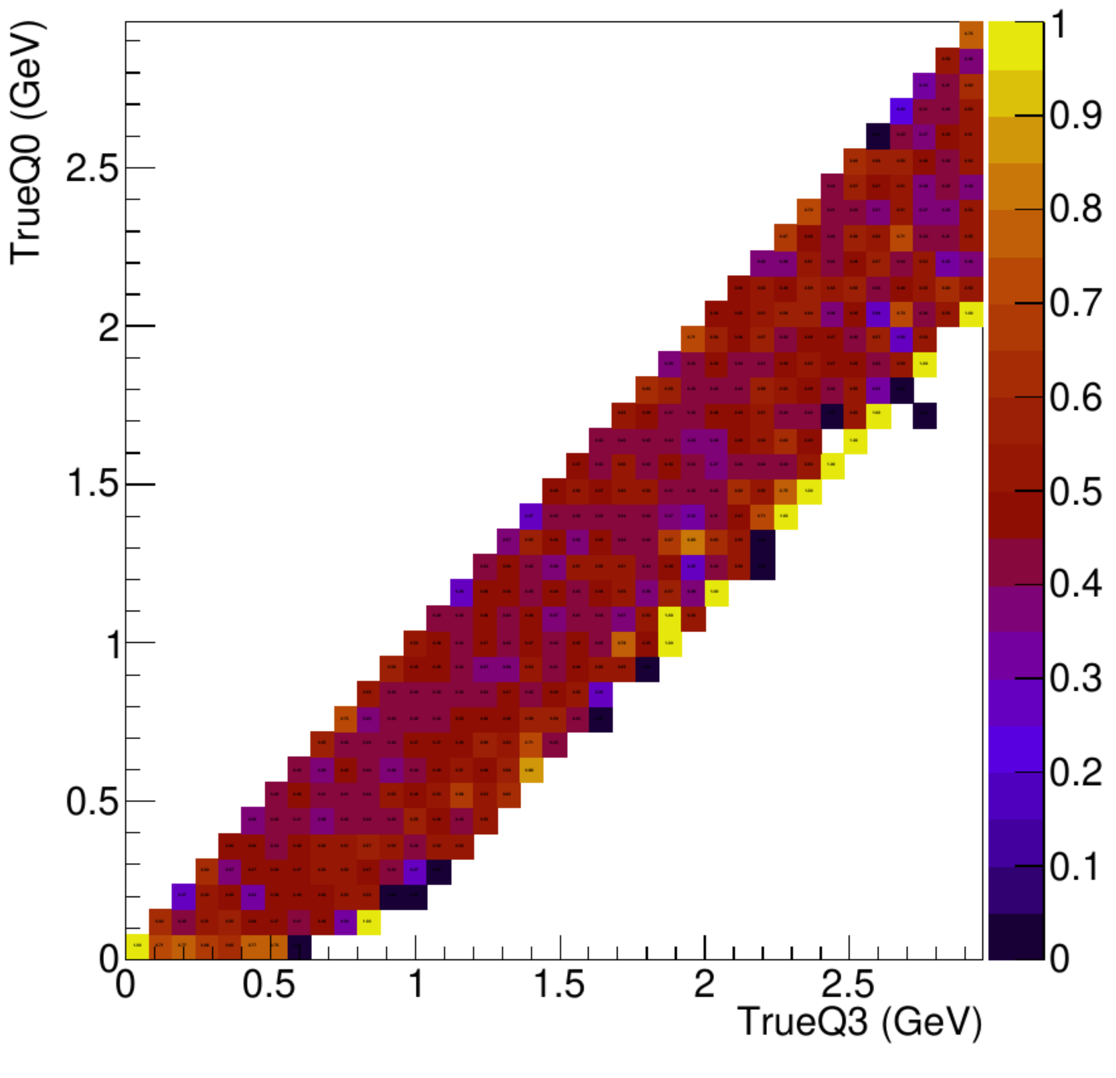
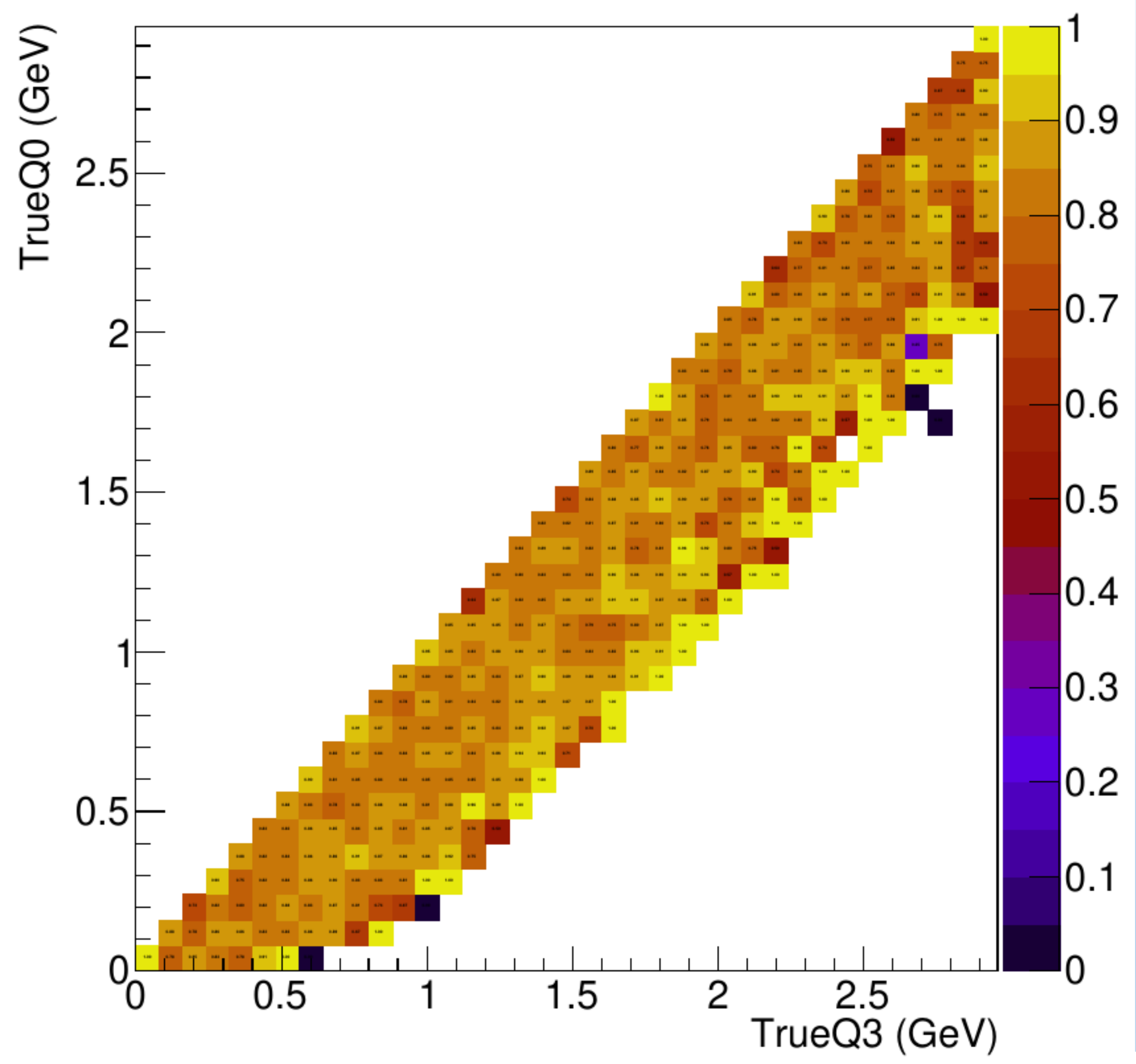
First Results

- This is including every CC event within the fiducial volume **(227 cm rad, 209 cm length)**
  - This is the only selection cut placed on this sample
- This assumes a **2.5 mm** spatial resolution with MWPCs
- **Multiple scattering dominates for very low momenta** particles which leave the TPC instrumented region
- We need to find a good cut for the fiducial volume which optimises this acceptance
- We haven't yet restricted the energy range – **very high momenta particles** will also be rejected as the Gluckstern formula dominates and the curvature becomes too small to measure



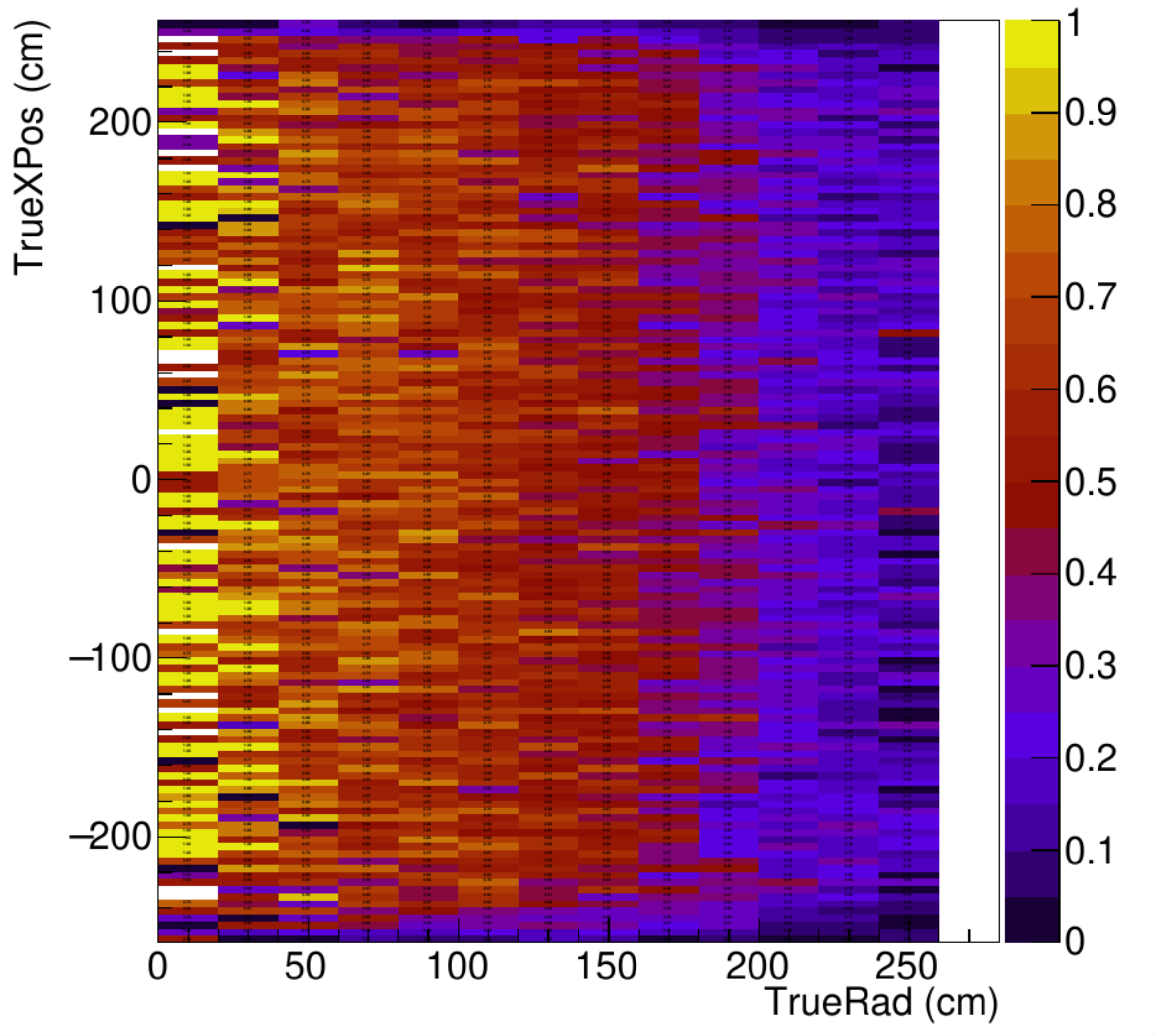
Without Multiple Scattering Effects?

- This is including every event within the fiducial volume (227 cm rad, 209 cm length)
- **Ignores multiple scattering** contribution to the momentum resolution calculation
  - Can see that multiple scattering is the biggest cause for a reduced acceptance



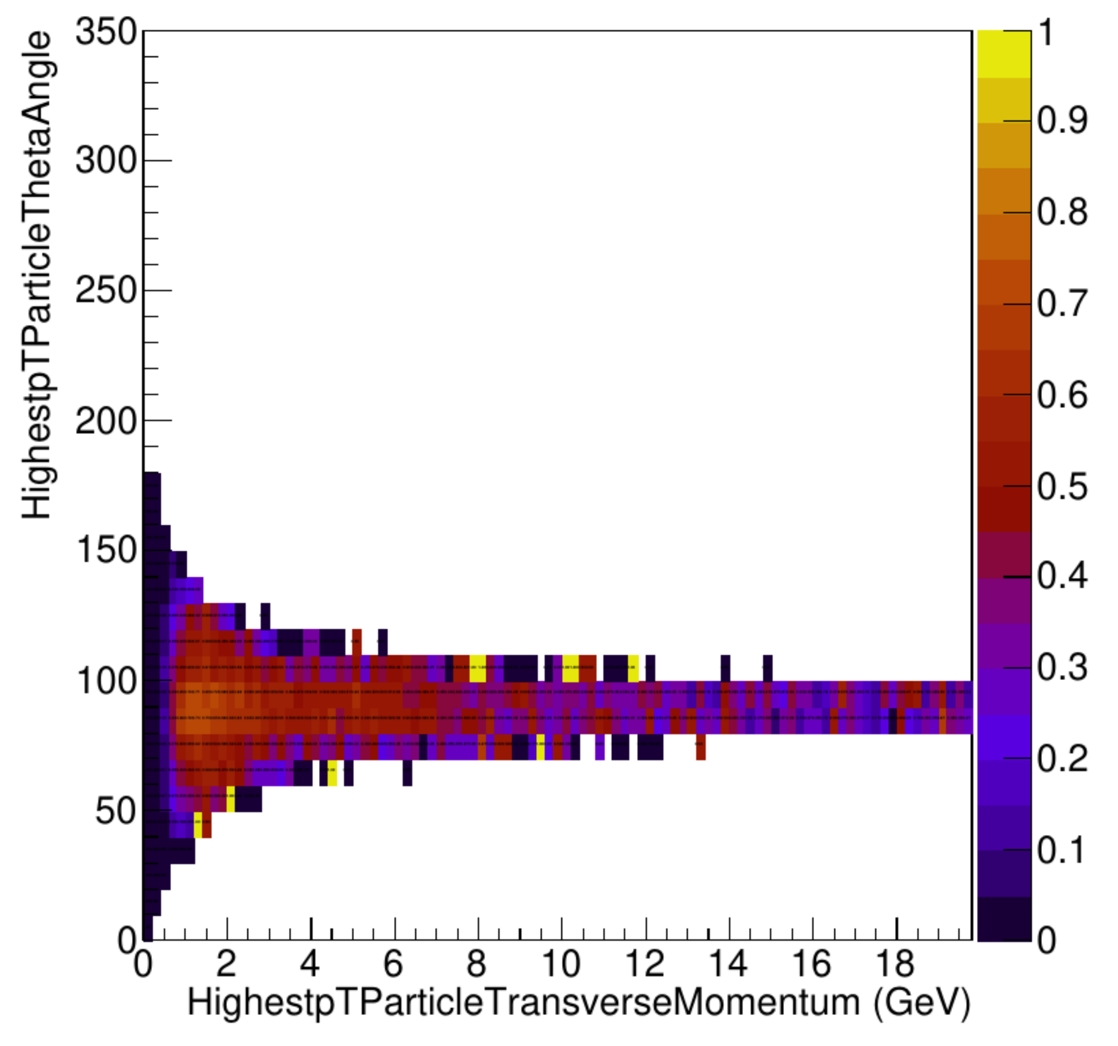
Fiducial Volume Cuts

- Have **added multiple scattering contribution back in**
- Can see that the acceptance depends a lot on where the fiducial volume cut is placed
- **Very poor acceptance near the edges of the TPC**
- The current fiducial volume used in GArSoft is **209.0 cm in Length and 227.02 cm in radius**
  - This should probably be smaller in radius
- The number of events in our fiducial volume **~ r^2 L**
  - This means with the cuts shown here we have **~42%** of the total events in the TPC instrumented region (34% of the events in the full TPC volume)
  - If we shift the fiducial radius to 160 cm then we reduce the number of events to 33% of the total events in the TPC instrumented region



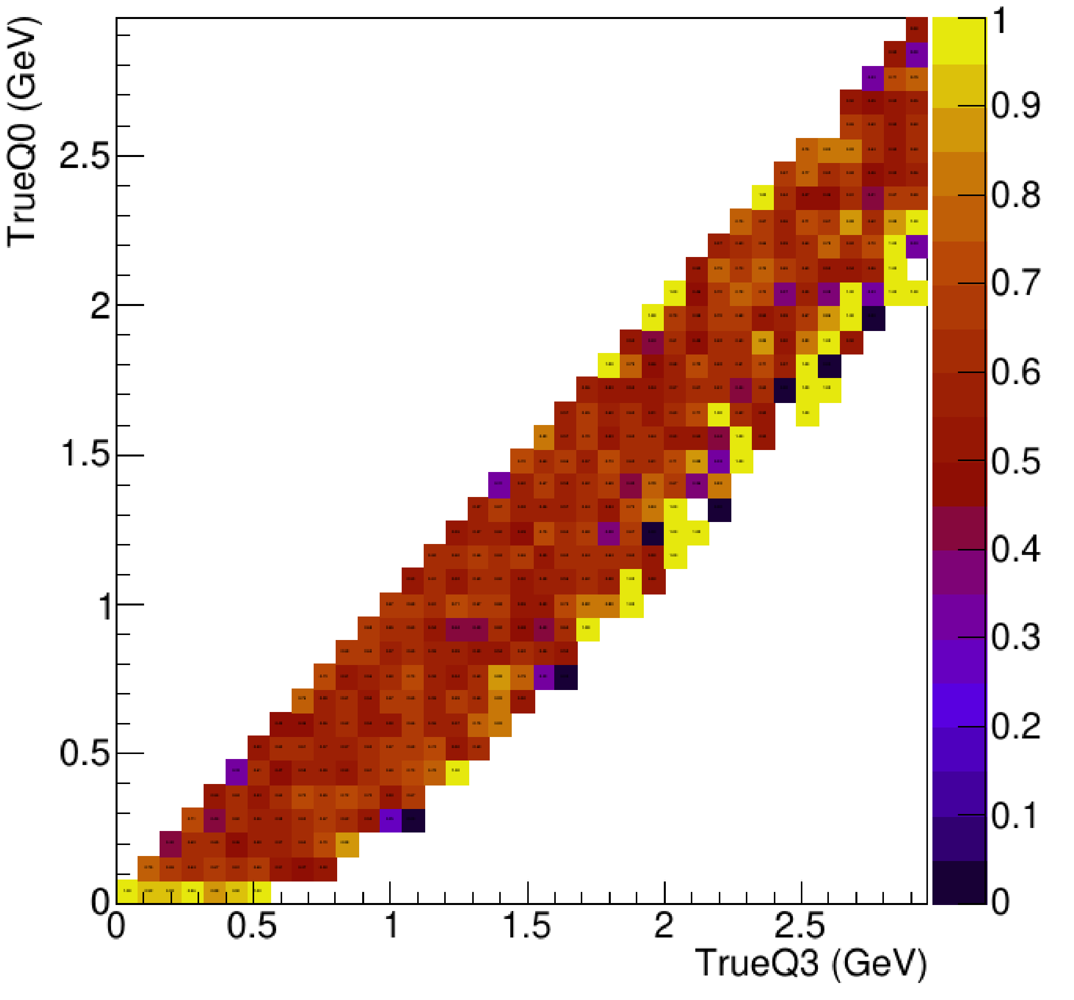
Neutrino Energy Range

- Low momenta particles have very low acceptance
  - Can't improve that by adding an energy range cut as these will exist in most interactions
- However, high momenta particles also have worse acceptance and those will go away when we place a cut on true neutrino energy
- This is plot has no cuts on fiducial volume
- Here the angle is the angle between the B-field and Track
- This is expected as no dE/dX information or calorimetric information has been used
  - We plan to add this information in to recover performance here



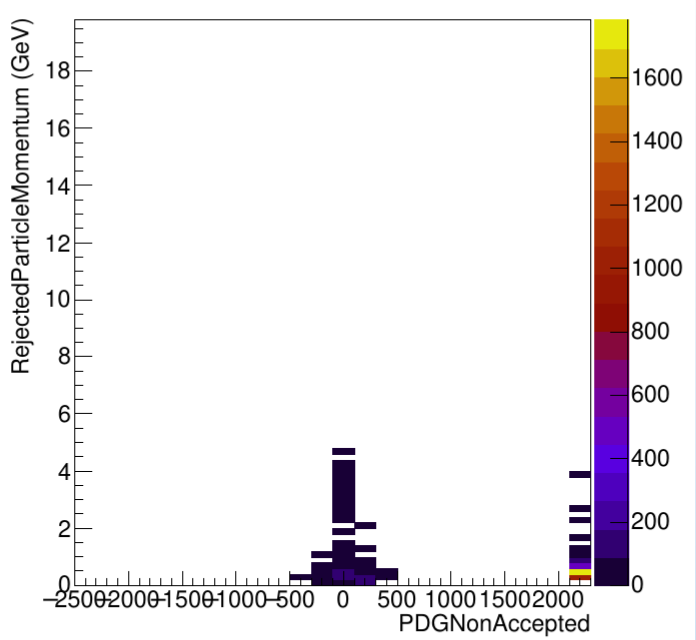
Cut on Fiducial Volume and E_nu

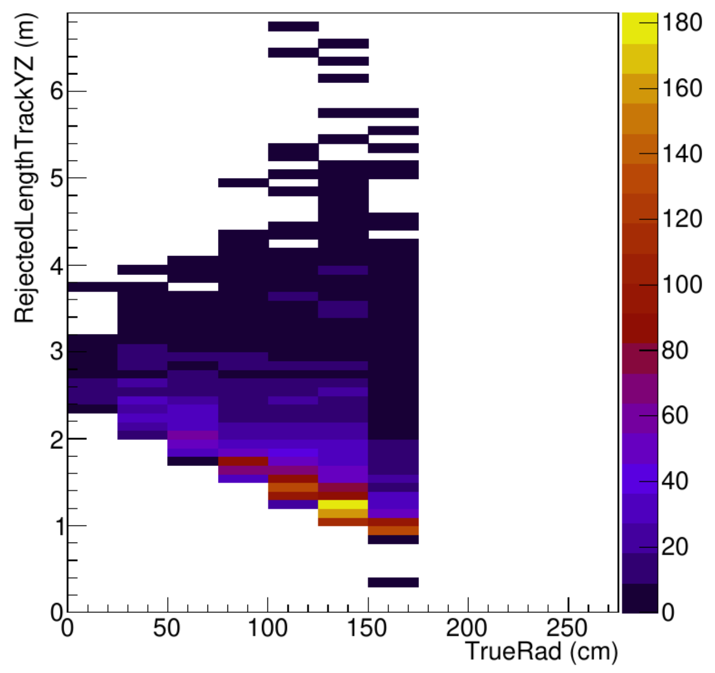
- **1GeV<E_nu<5GeV**
  - Ideally would want to cut between 2 to 3 GeV as this is what the ND-LAr+TMS study has done
    - Not enough stats for that at the moment
- **Fiducial radius cut of 160 cm and length 209 cm**

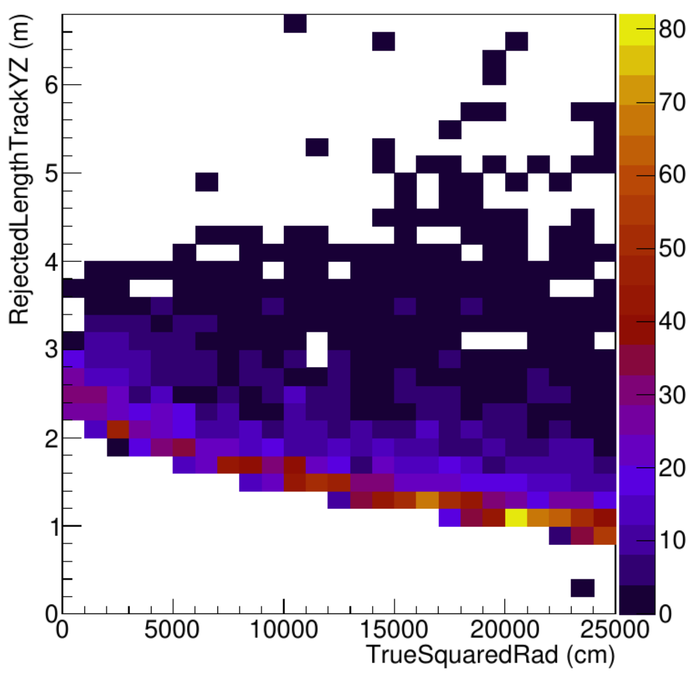


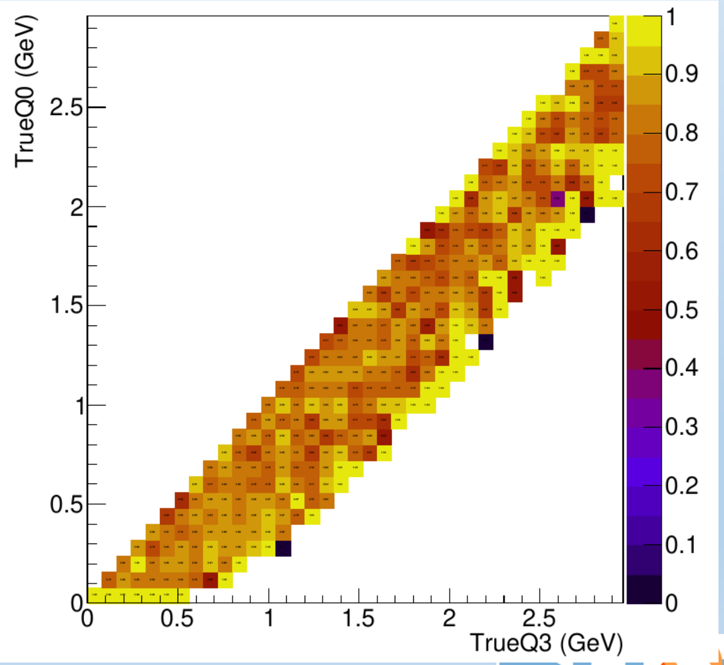
What is getting rejected?

- We can see that **low momenta protons** are mostly getting rejected (top right)
  - This is because protons have higher mass, the β value is lower at the same momentum compared to pions and the protons will scatter more
  - Setting the **momentum resolution threshold to 8%** (bottom right) improves the acceptance significantly
  - Looking just at protons (Rad vs Track length) can see most are **near the edge of the FDV**









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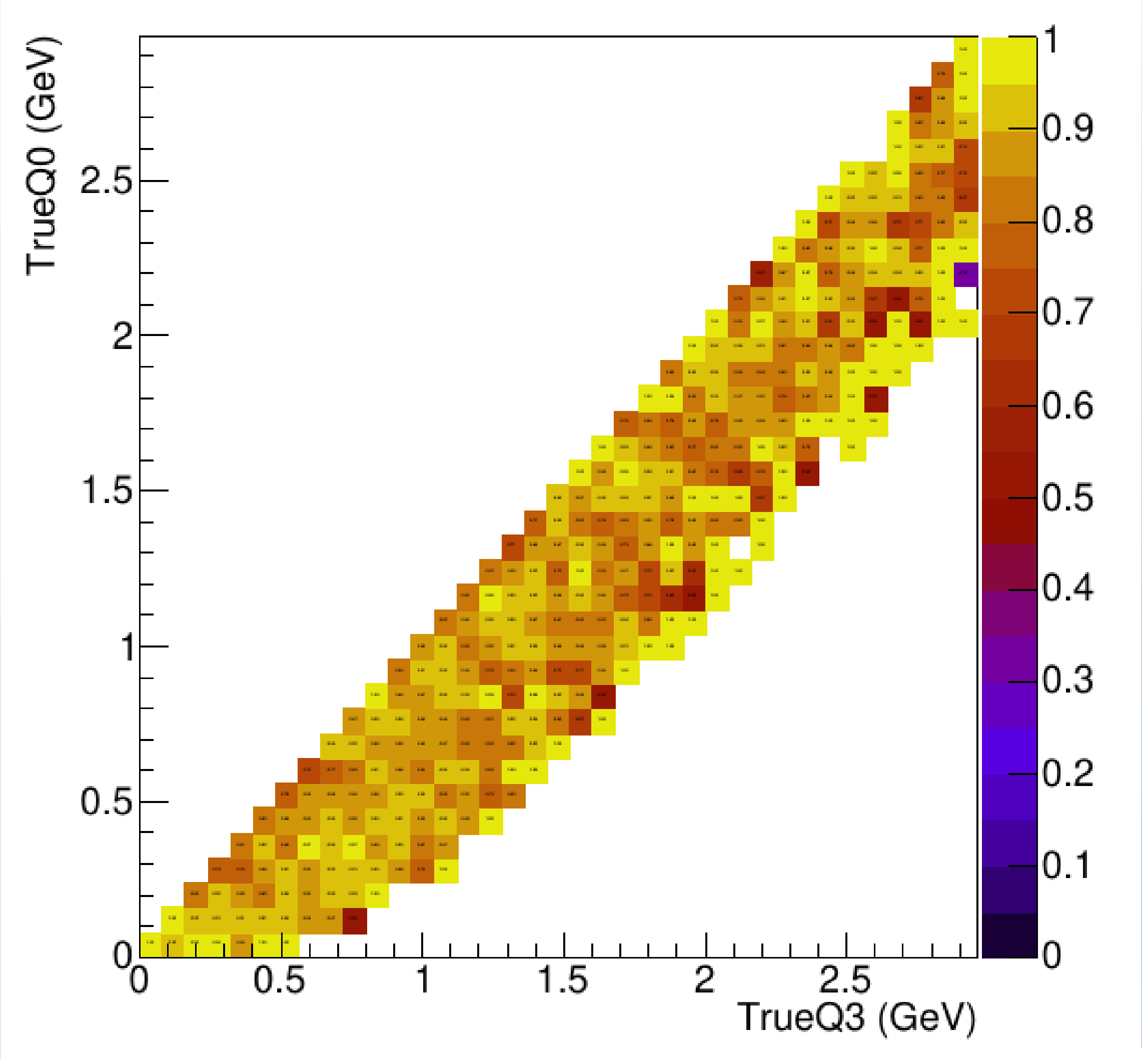
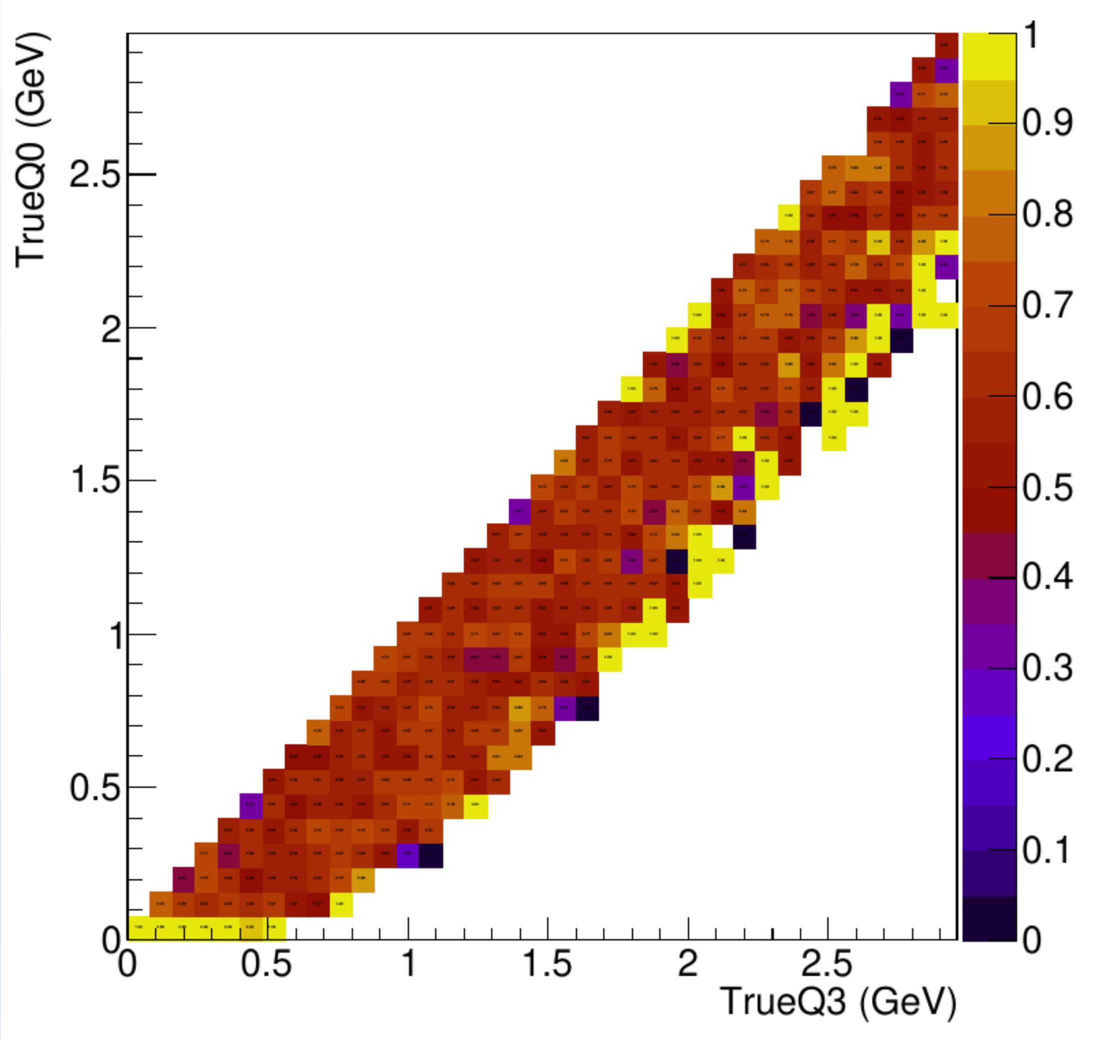
Adding ECAL assumptions

- If a particle track ends in the ECAL, assume it can be momentum resolved
  - The ECAL will provide energy deposition information
  - This is a rough estimate to show the potential impact of the ECAL
- **Fiducial radius cut of 160 cm and length 209 cm**
- **1GeV<E_nu<5GeV**



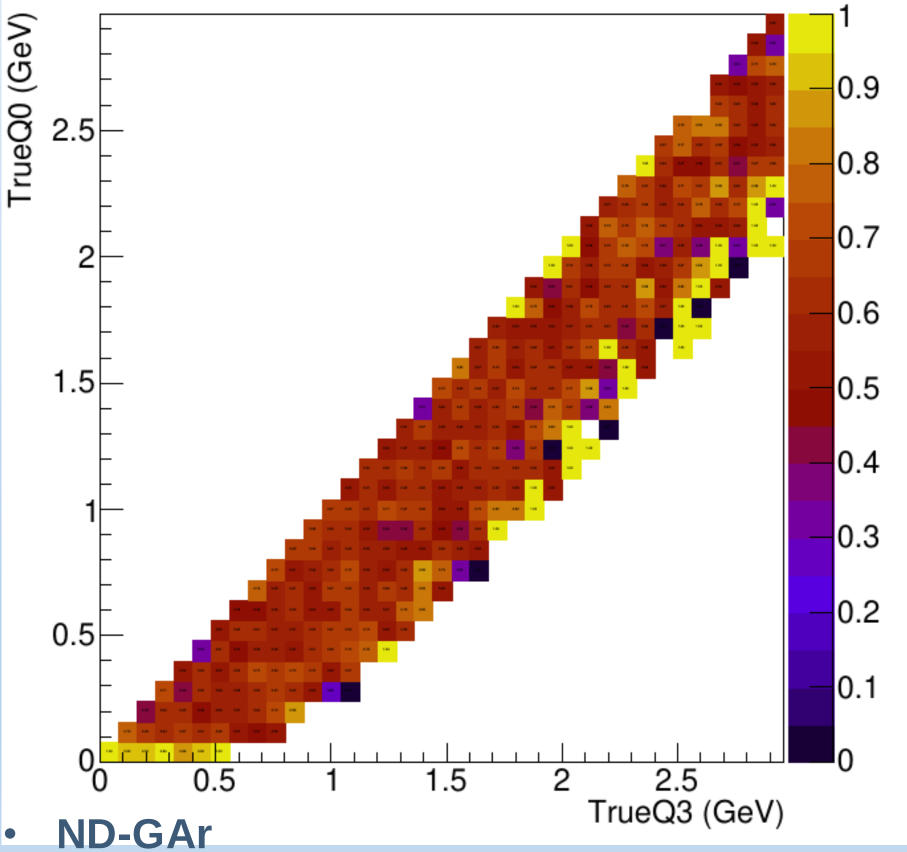
Using Spatial Resolution of GEMs

- Setting the spatial resolution in the transverse plane to **1mm** resolution (if we move to GEM readout), using the same pad spacing of 6mm x 6mm
- Impact reduced as does not improve the contribution from multiple scattering on the momentum resolution. Using dE/dx information could improve this
- No ECAL Assumption

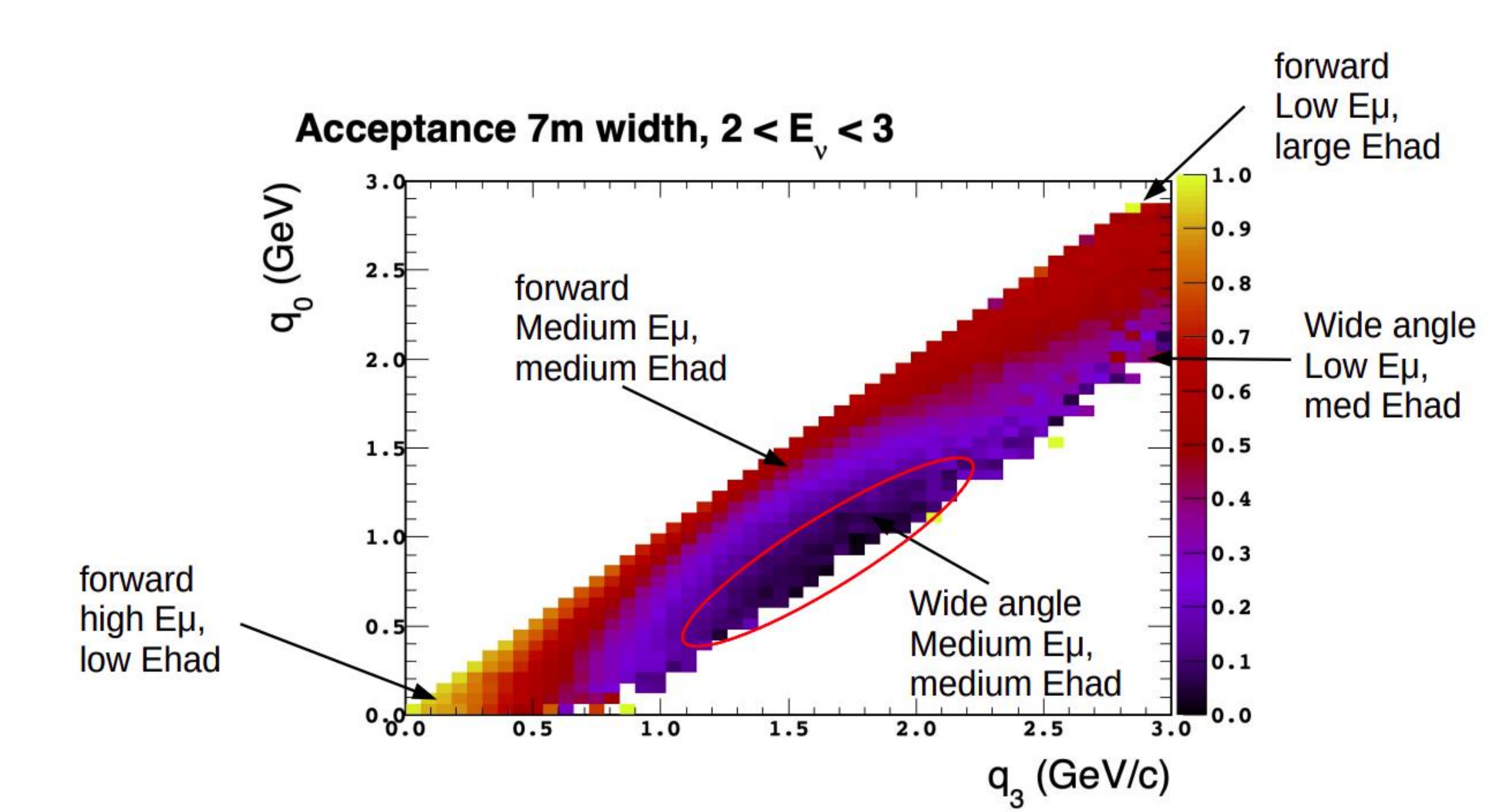


Current Results - Acceptance

- ND-GAr plot (left) made using **1GeV < E_{nu} < 5GeV , Fiducial Radius = 160 cm, Fiducial Length = 209 cm**
- Total number of events with these cuts = 11582, Accepted Events = 7150, giving **~62% overall acceptance -** good acceptance across the **entire phase space**



- **ND-GAr**



ND-LAr+TMS