L2G :
CONTAINED AND CROSSING MUONS AND MULTIPLE MUON EVENTS

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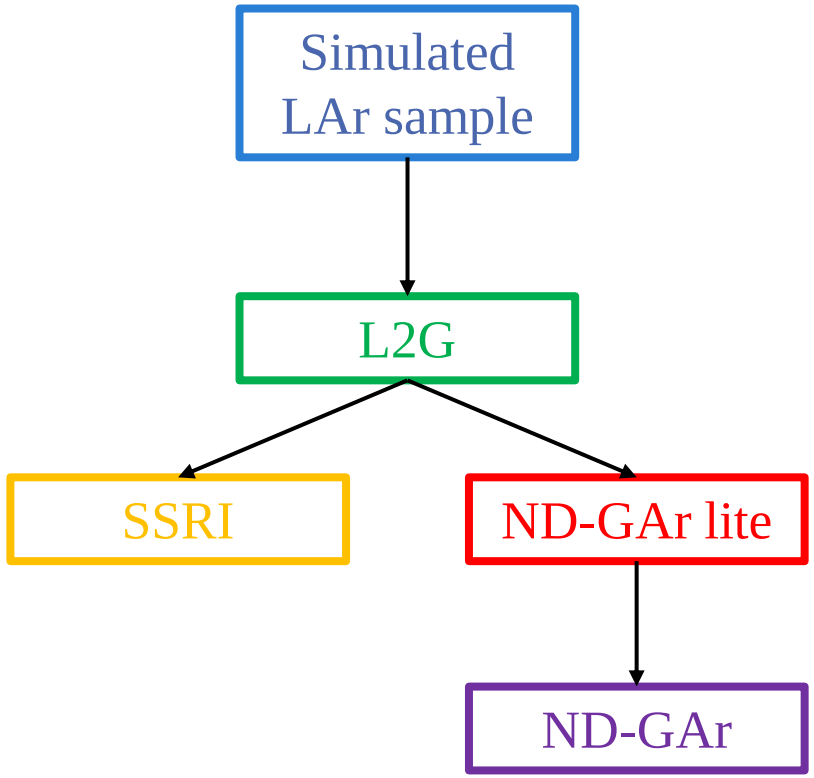
LAR TO GAR SAMPLE: L2G

- L2G: interface that takes outgoing LAr particles and feeds them to edep-sim with any TMS detector could simplify the sample simulation/reconstruction and standardize the procedure between detector designs (ND-GAr/TMS).

- Progressed in our analysis of the LAr interacting sample produced by Eldwan, focusing on differences between the muons contained in the Liquid Argon and the ones produced in LAr that reach ND GAr.

- We also started analysing events where multiple muons traversing the Liquid Argon are produced

- To see previous analysis results see: https://indico.fnal.gov/event/47020/contributions/204949/attachments/138880/174374/l2g_Presentation_Gen13_2021.pdf



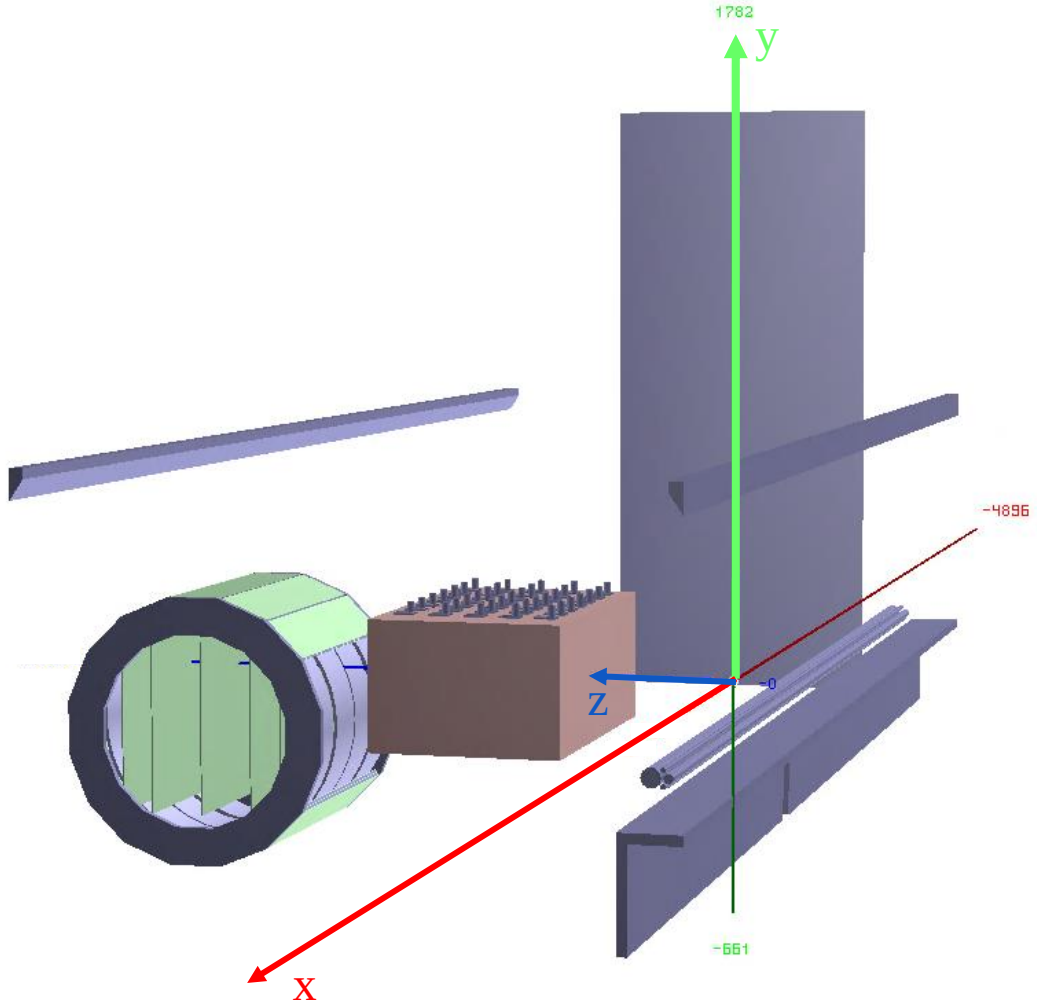
https://indico.fnal.gov/event/44562/contributions/200915/attachments/136745/170170/DUNE_ND_Meeting_28.10.20.pdf

GENERATED SAMPLE: NEUTRINO INTERACTIONS IN LAR

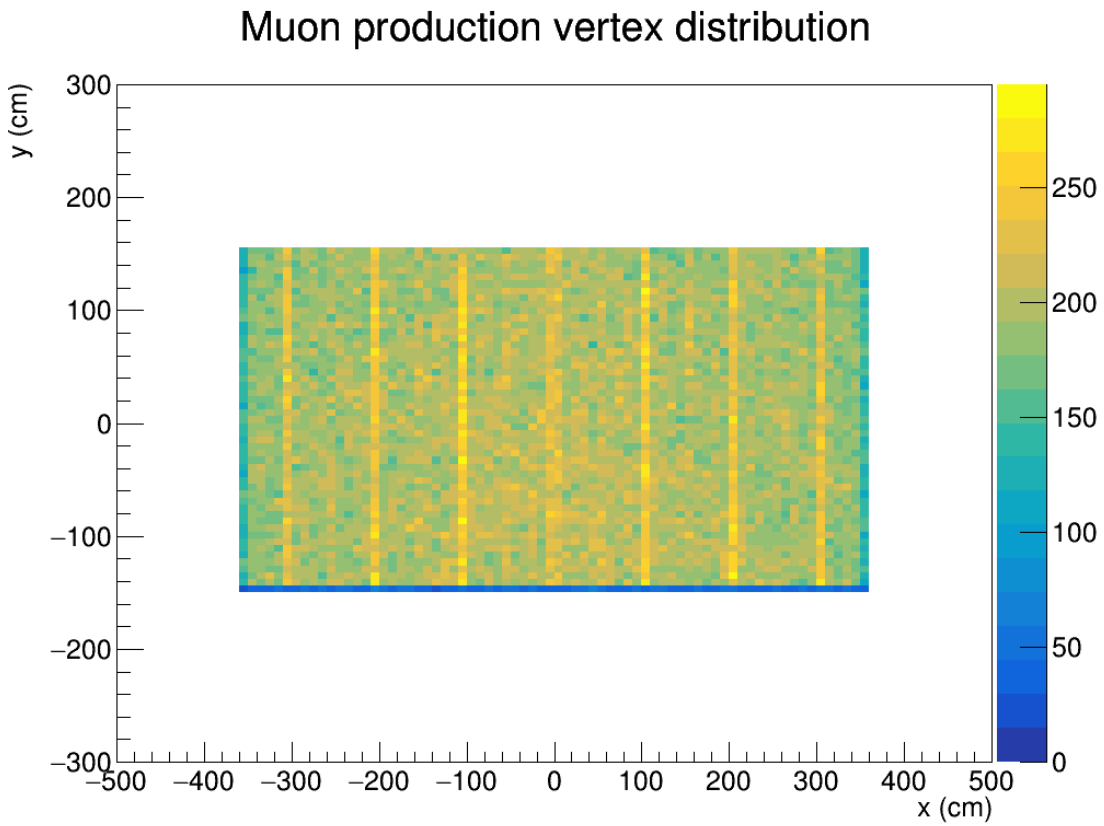
- Sample generated with GENIE v2
  - Gsimple flux in ND-Hall (from Tanaz)
  - 1M single interaction events in ND-LAr (volArgonCubeActive)

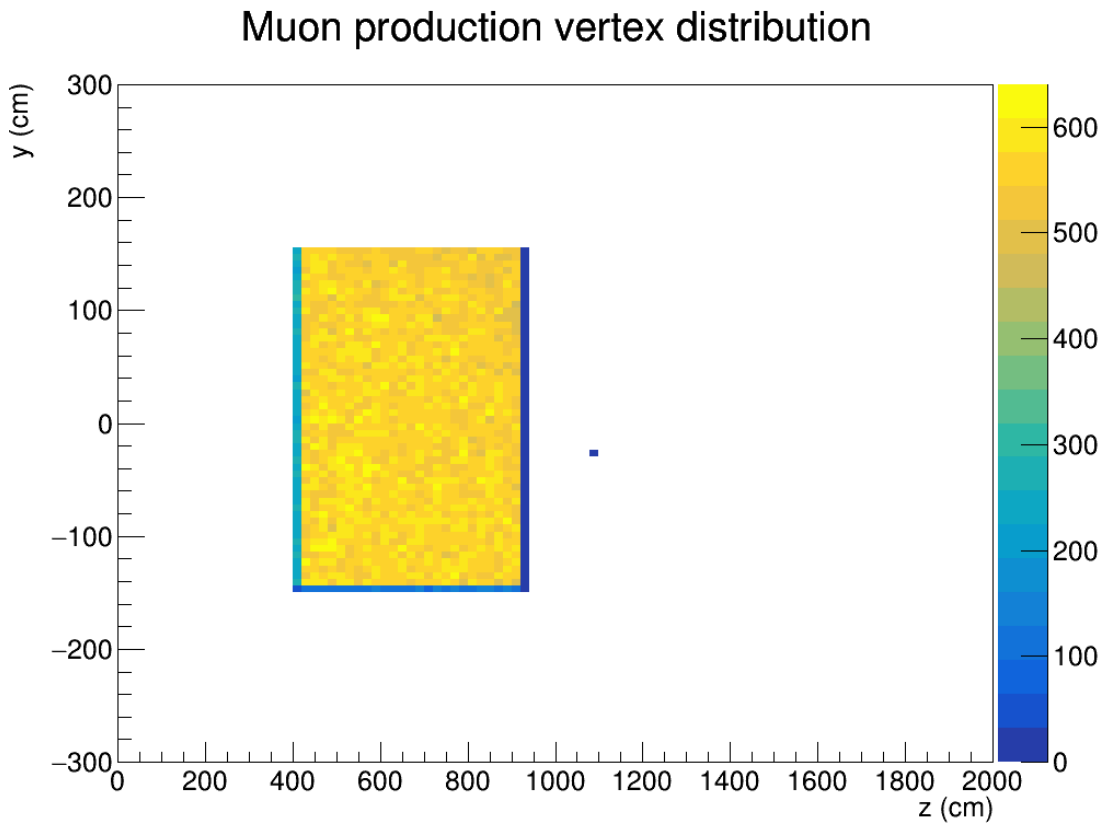
- Geometry used:
  - Baseline ND-LAr from dunendggd (apparently some updates are needed but not pushed yet...)
  - ND-GAr-Lite detector with SPY magnet (not the latest one acting as PV)
    - 5 Scintillator planes (Minerva-like) of 6mx5mx4cm at (-240, -150, 0, 150, 240) //Not Optimized yet!
    - Segmented with triangular shapes strips in X/Y (2 cm triangle base)
    - Includes a muon detector (3 planes of Sc of 2 cm around the magnet yoke of the ND-GAr) with 2x7.5cm iron for mu/pi separation over 500 MeV/c

- Coordinate sytem: z roughly the flux direction, y is the vertical direction and x is the drift direction (i.e. the magnetic field direction)



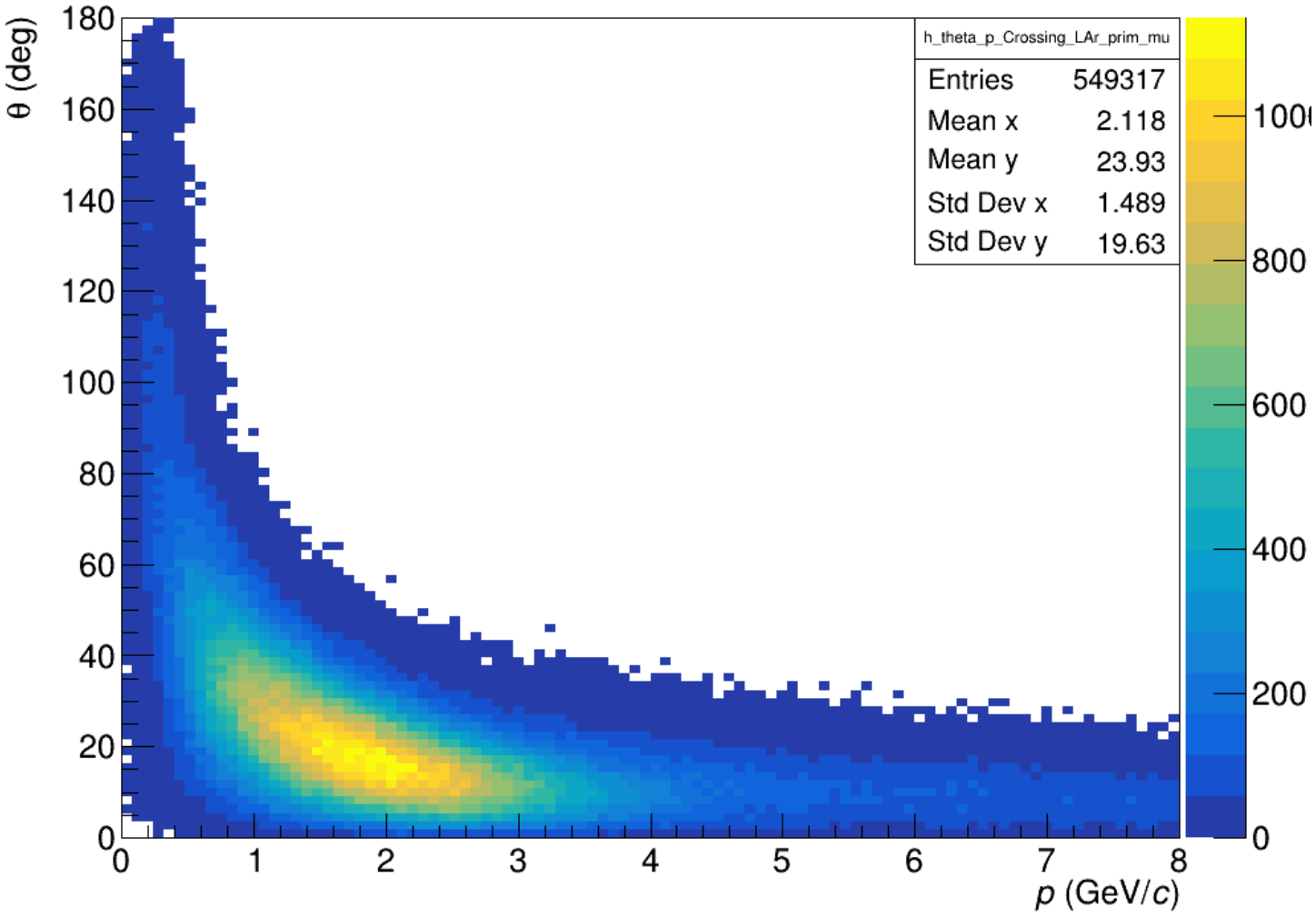
LAR FIDUCIAL VOLUME





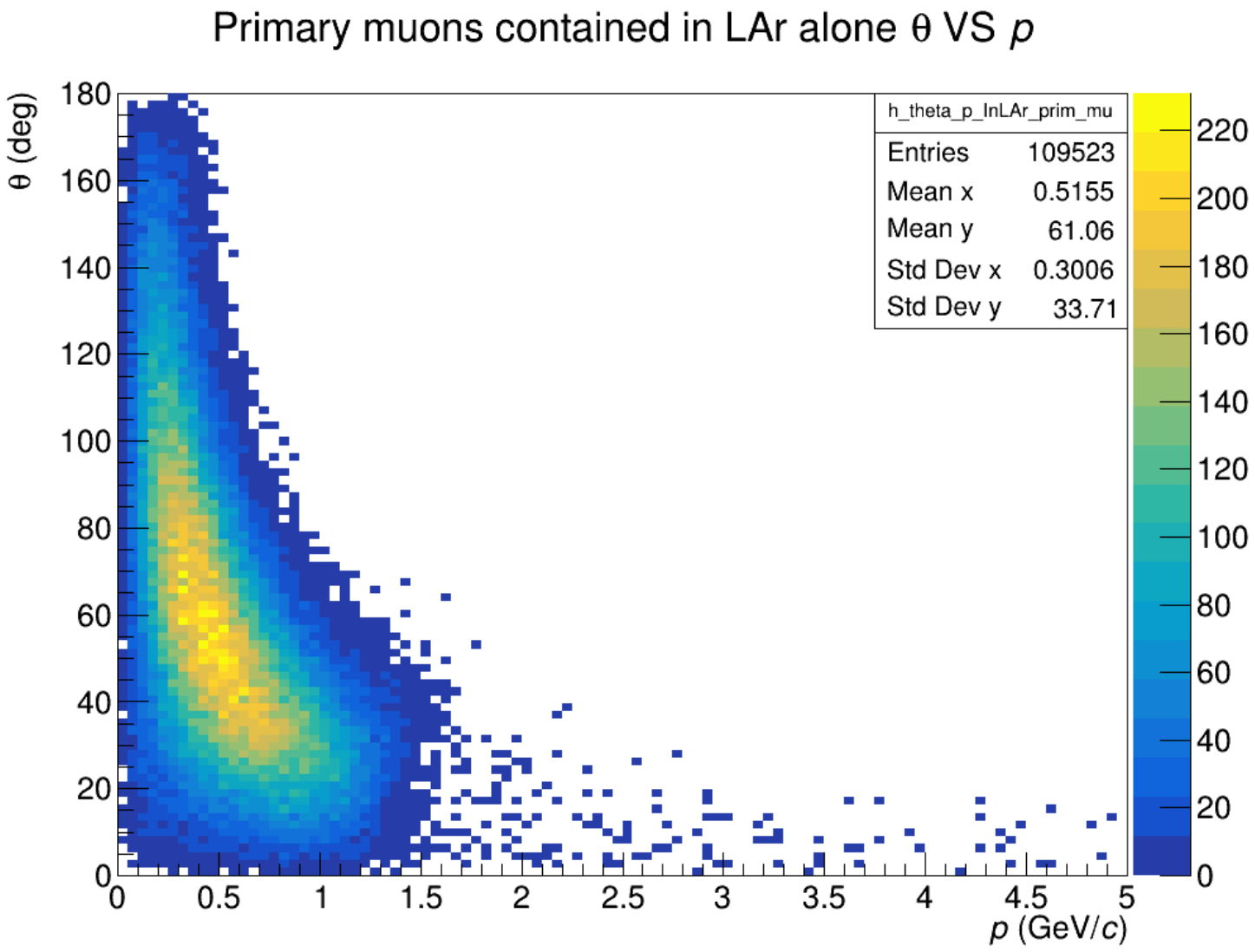
- Here we plot all the primary muon production vertexes which are all contained in the Active LAr fiducial volume: $(-357.35 < x < 357.35)$ cm $(-127.275 < y < 127.275)$ cm $(411.5 < z < 920.5)$ cm

ALL PRIMARY MUONS AT GENERATOR LEVEL



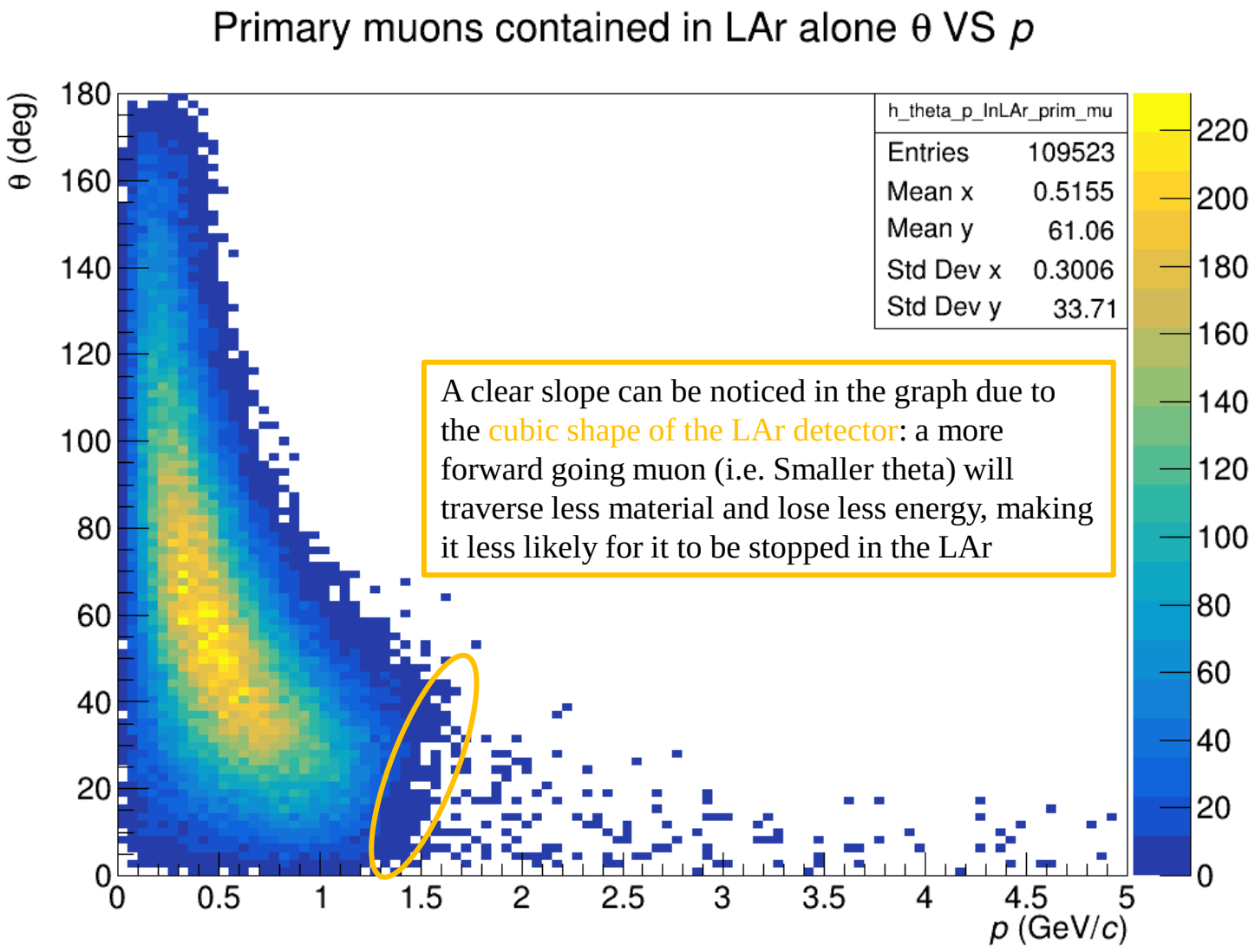
- Theoretical truth: Sample of all primary muons at generator level
- We plot the initial muon angle at primary vertex with the z axis θ [deg] VS the muon momentum module p [GeV/c]

LAR ALONE MUONS P VS THETA



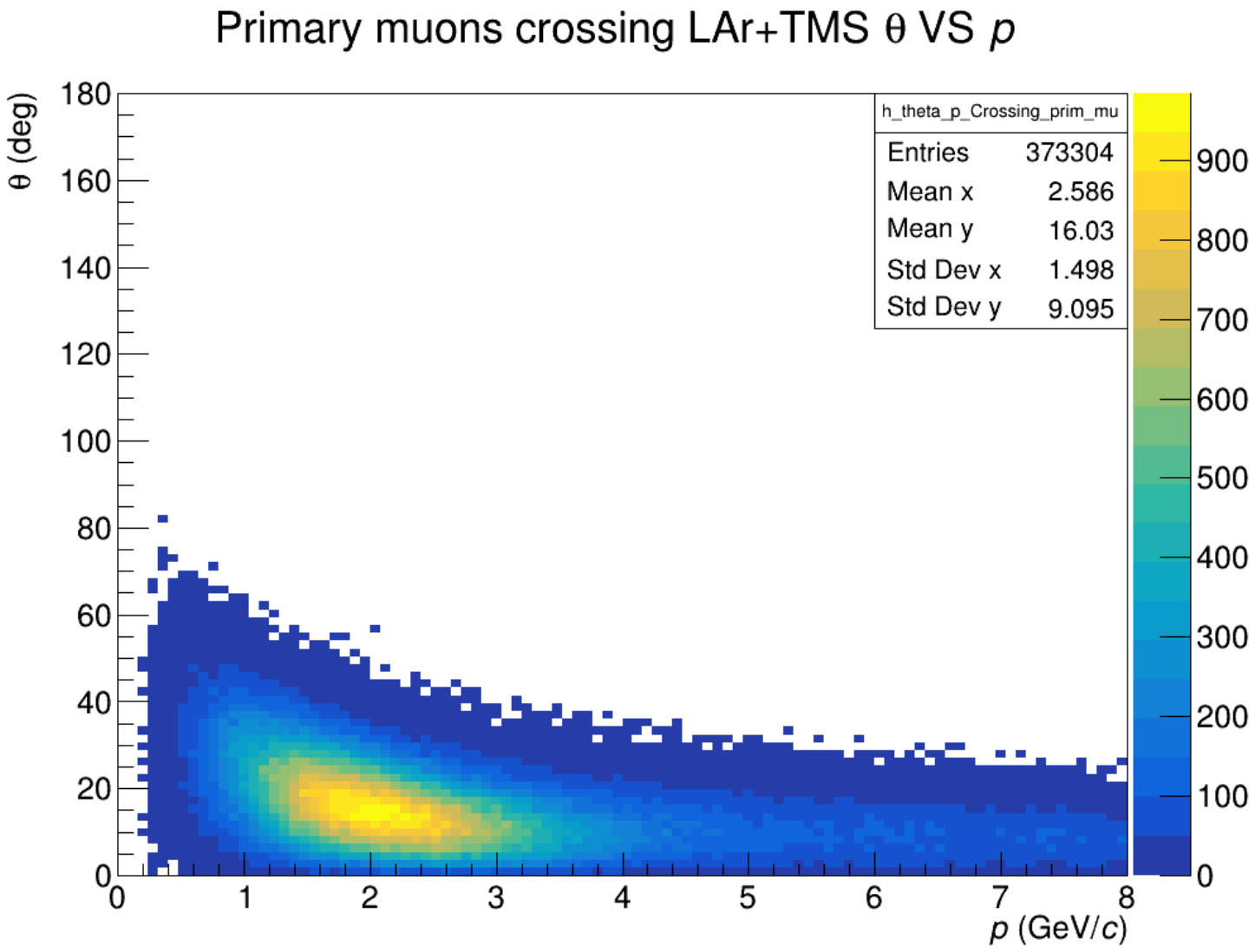
- LAr alone muons: sample of primary muons that are produced in interactions in the LAr, that are fully contained in ArgonCube's active volume
- The momentum spectrum is quite limited, having very few contained muons with $p > 1.5\mathrm{GeV}/c$ while the θ's are relatively high peaking between 25° and 100°
- Note that this sample represents roughly 20% of all the primaries

LAR ALONE MUONS P VS THETA



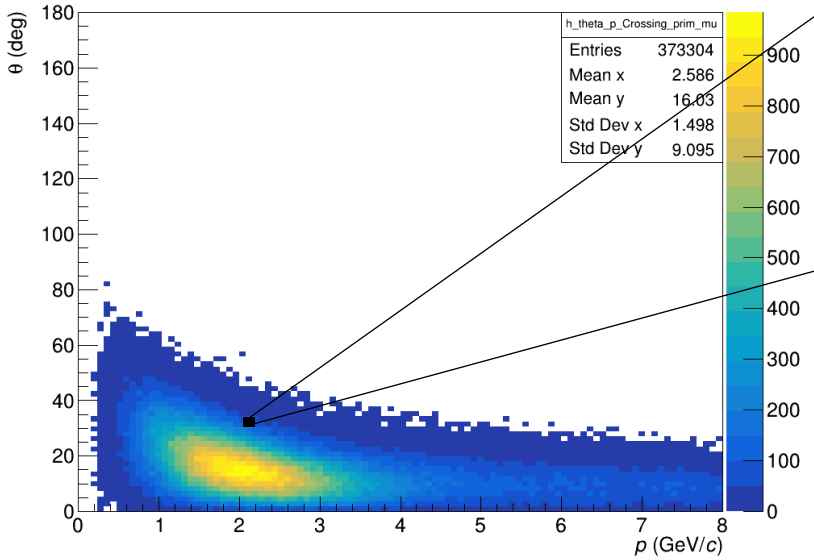
- LAr alone muons: sample of primary muons that are produced in interactions in the LAr, that are fully contained in ArgonCube's active volume
- The momentum spectrum is quite limited, having very few contained muons with $p > 1\text{GeV}/c$ while the θ's are relatively high peaking between 60° and 100°
- Note that this sample is represents roughly 20% of all the primaries

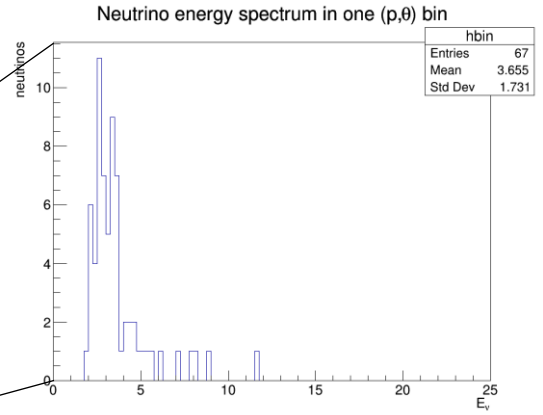
LAR+TMS MUONS P VS THETA



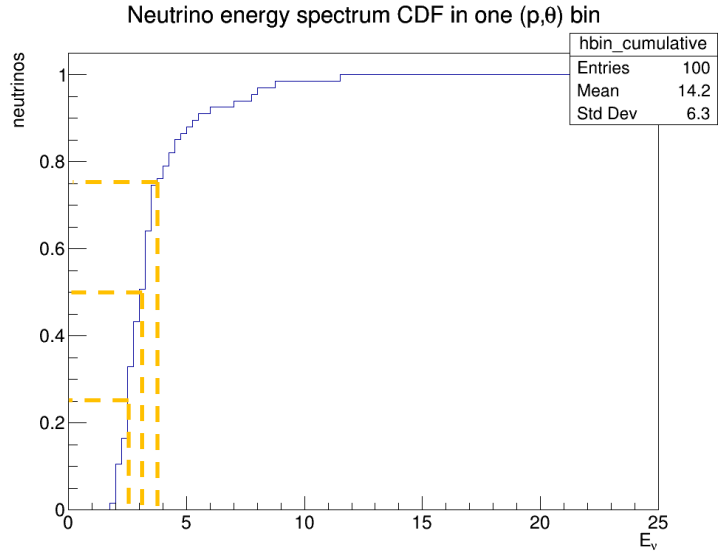
- LAR+TMS muons: sample of primary muons whose trajectories have at least one point in the LAr active volume, one outside the two detectors and one in ND-GAr's
- Most muons in the sample are forward oriented (i.e. low θ) and have relatively high momenta peaking between 1GeV/c and 3GeV/c

NEUTRINO ENERGY DISTRIBUTION QUANTILES

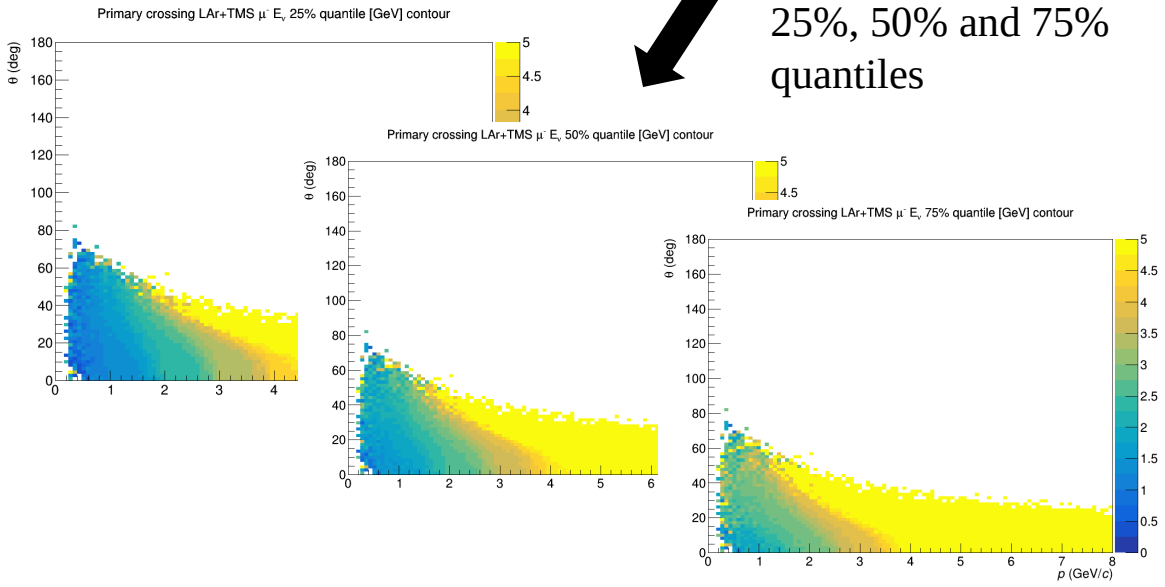




CDF

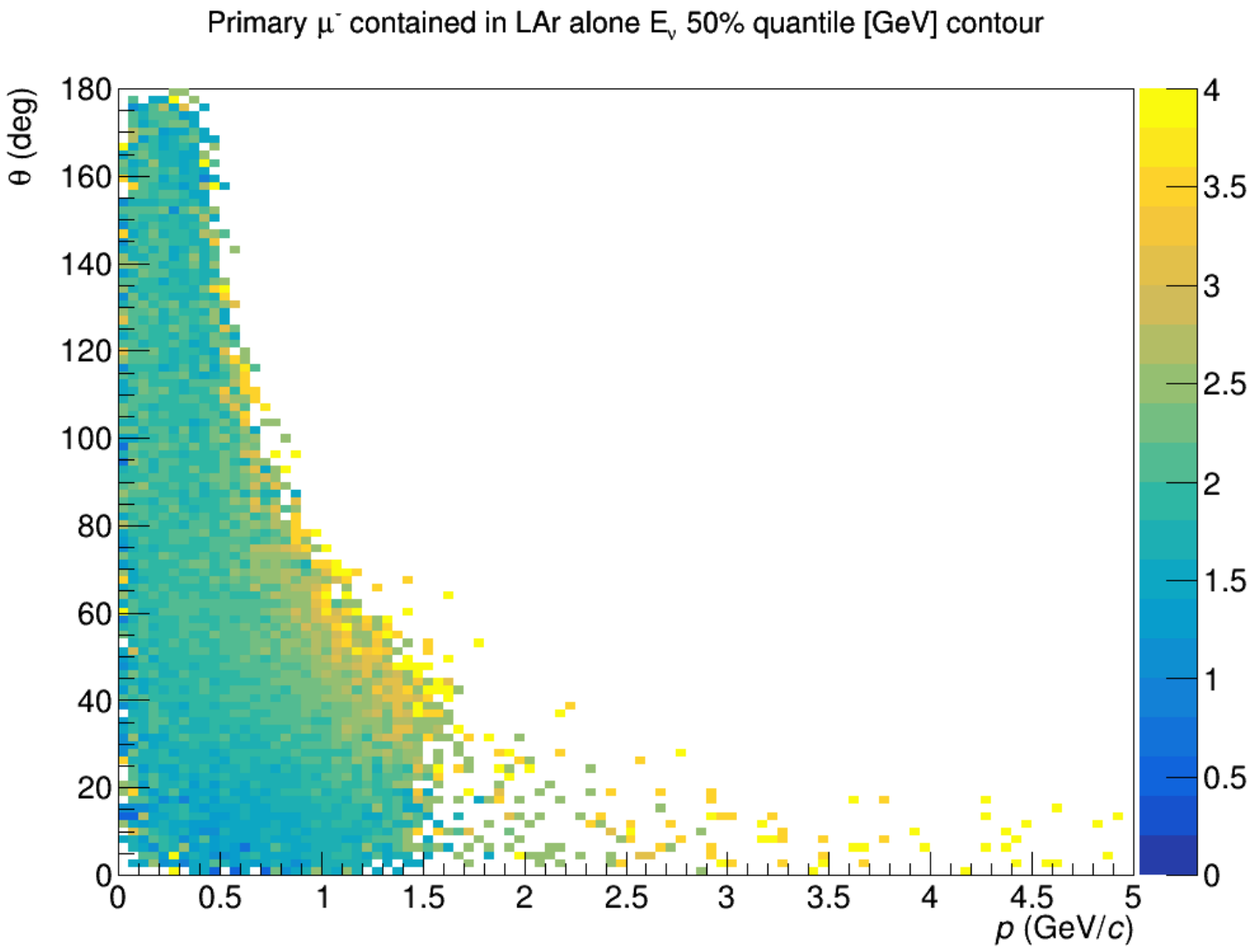


25%, 50% and 75% quantiles



Select bin by bin and look at the energy spectrum of the neutrinos producing the primary muons

LAR ALONE MUONS P VS THETA 50% QUANTILE

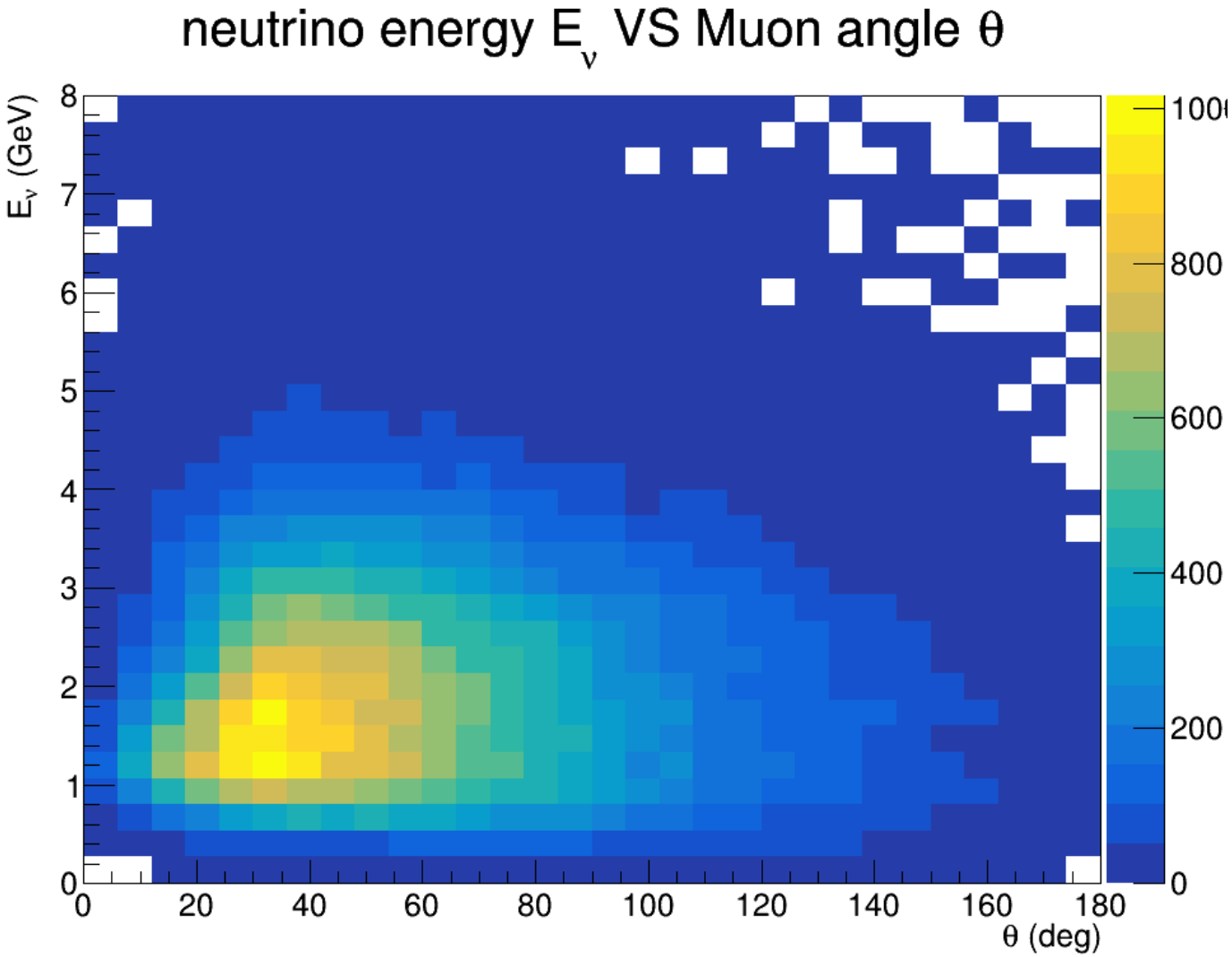


- LAr alone muons: sample of primary muons that are produced in interactions in the LAr, that are fully contained in ArgonCube's active volume
- E_ν axis is taken at 50% quantile of all neutrino parent energies contained in the bin
- Two very interesting features:
  - The average neutrino energy seems to be homogeneous no matter the angle
  - The neutrinos in the energy range of the first oscillation peak seem to dominate the sample overall despite the small muon momentum $E_\nu \sim 2.5$ GeV VS $p_\mu < 1\text{GeV}/c$ (the energy transfer is > 1.5 GeV)

LAR ALONE NEUTRINO SPECTRUM

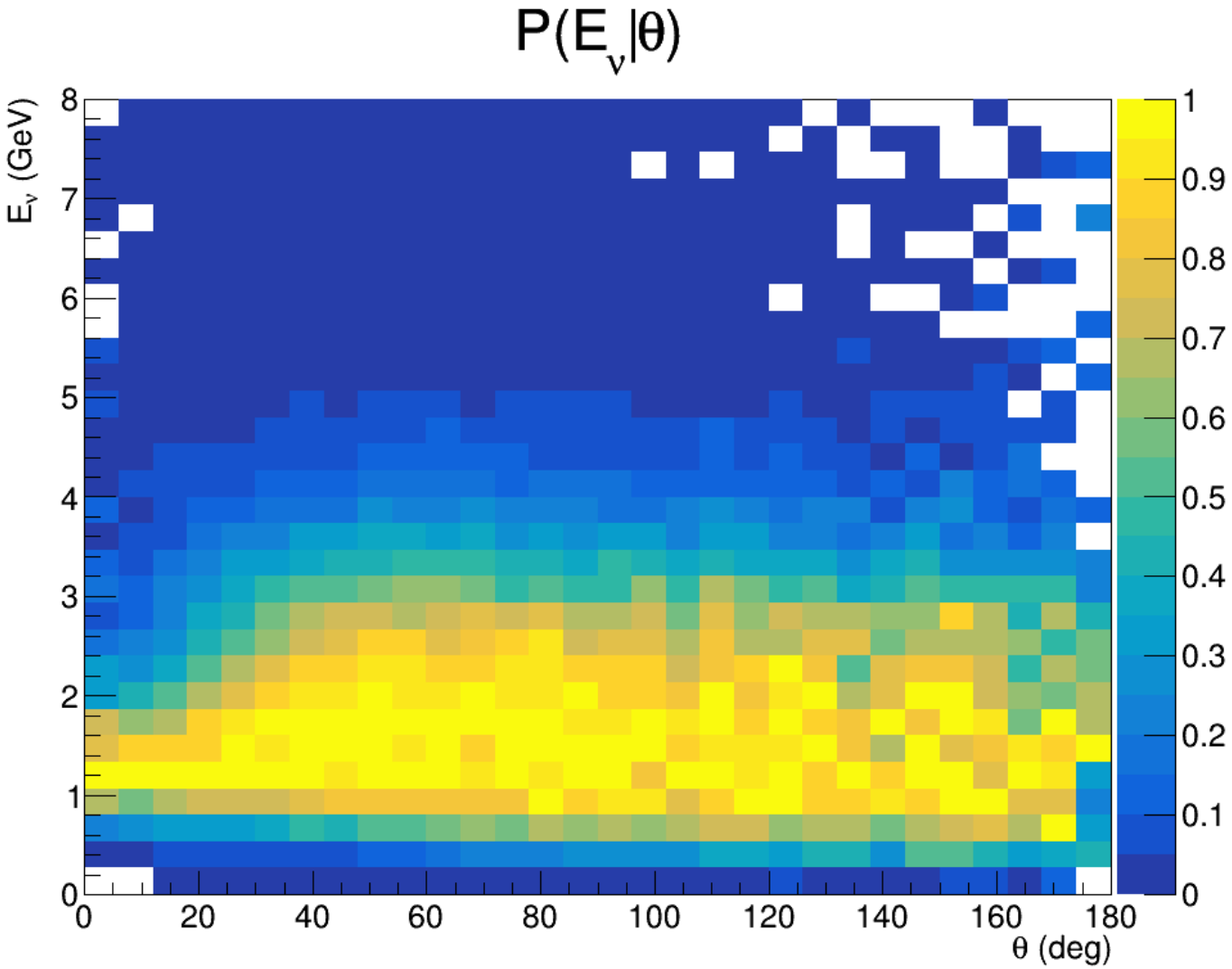
- As a reference we plot the neutrino flux energy spectrum $E_\nu\ [GeV]$ spectrum VS the muon angle with the z axis $\theta[deg]$ for neutrinos producing muons contained only in LAr

- The vast majority of neutrinos in the sample fall between $E_\nu \sim 0.5 GeV$ and $E_\nu \sim 4 GeV$ with angles over the entire spectrum

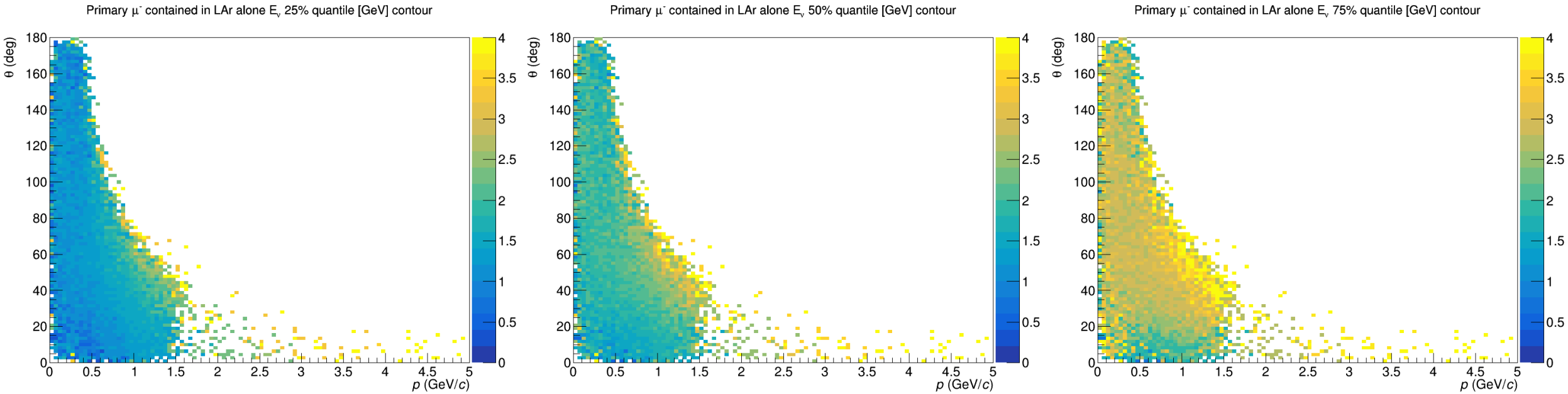


LAR ALONE NEUTRINO SPECTRUM

- Here we plot the conditional probability $P(E_\nu|\theta)$ as a function of $E_\nu\ [GeV]$ VS $\theta[deg]$ for neutrinos producing muons contained only in Lar
- The z axis is normalized such that the maxima for each column have 1 at their maxima (i.e. These are not proper PDF's normalized to 1)
- The conditional probabilities are very uniform throughout except at very forward angles

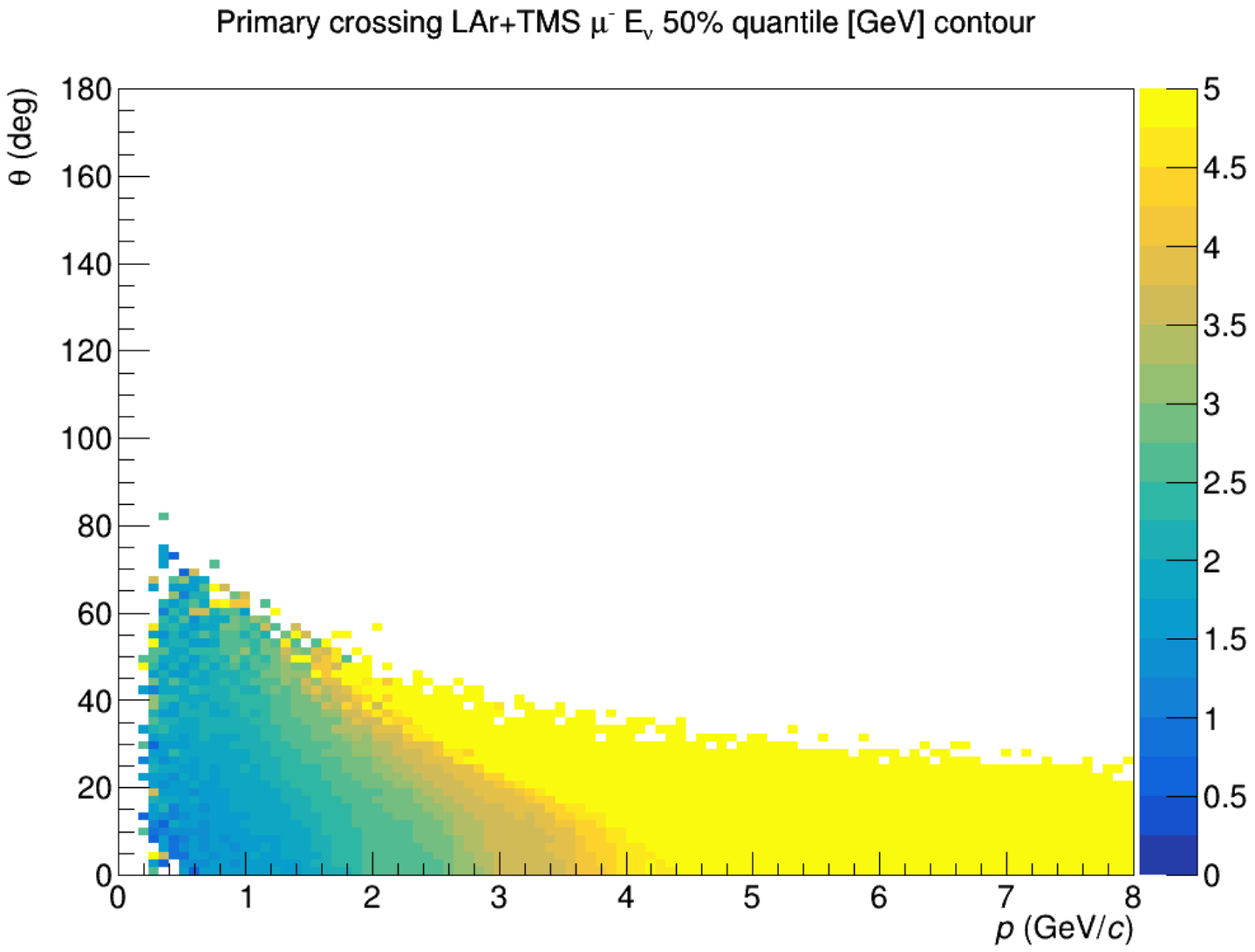


LAR ALONE MUONS NEUTRINO ENERGIES QUANTILES



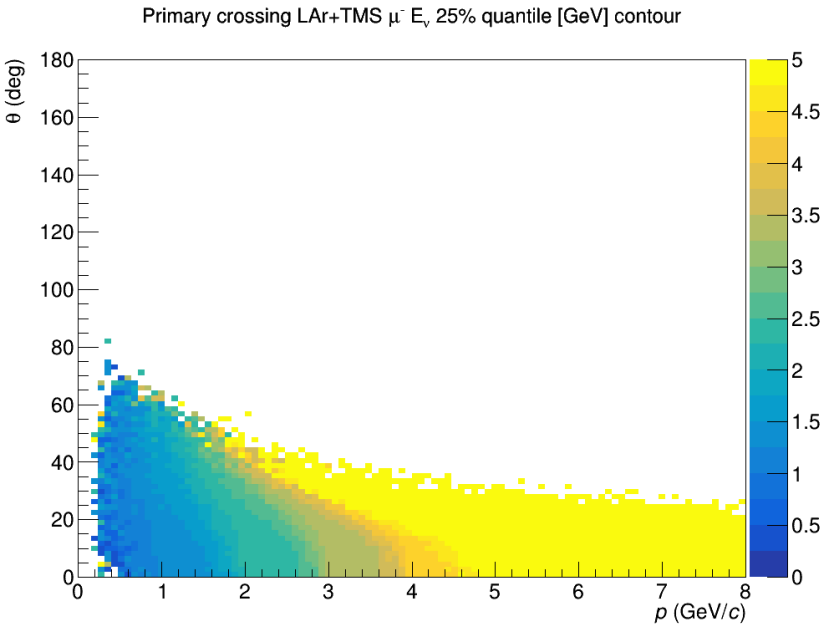
- LAr alone: 25%, 50% and 75% parent neutrino energy E_ν quantiles plotted as a function of muon initial momentum p [GeV/c] and θ [deg] angle with the z axis.
- This gives an idea of the spread of the parent neutrino energy distribution in the phase space
- As expected from the probability $P(E_\nu|\theta)$ the neutrino energy quantiles are uniform in the (θ, p) phase space for all the quantiles
- It is also noticable that that neutrino energy spreads right around the first oscillation peak region $(1.5 < E_\nu < 3.5)$ GeV

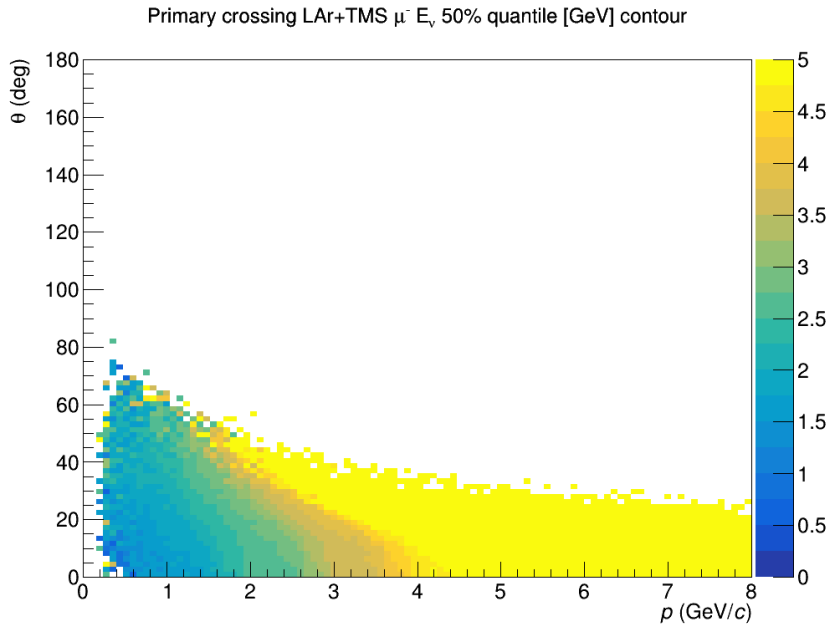
LAR+TMS MUONS P VS THETA 50% QUANTILE

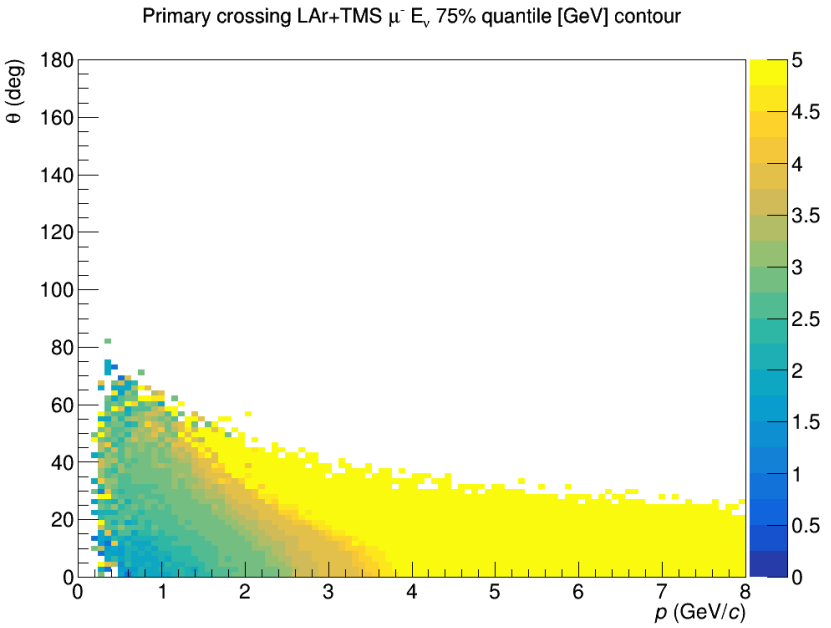


- LAr+TMS: sample of primary muons whose trajectories have at least one point in the LAr active volume, one outside the two detectors and one in ND-Gar's
- E_ν axis is taken at 50% quantile of all neutrino parent energies contained in the bin (note the slightly different z scale)
- The phase space region where most neutrinos at first oscillation peak ($E_\nu \sim 2.4$ GeV) lie is at higher momenta $(0.6 < p < 3)$GeV/c with low energy transfer and $(0 < \theta < 60)$ deg angles,
- Complementary phase space to LAr alone in terms of interaction energy transfer

LAR+TMS MUONS NEUTRINO ENERGY QUANTILES

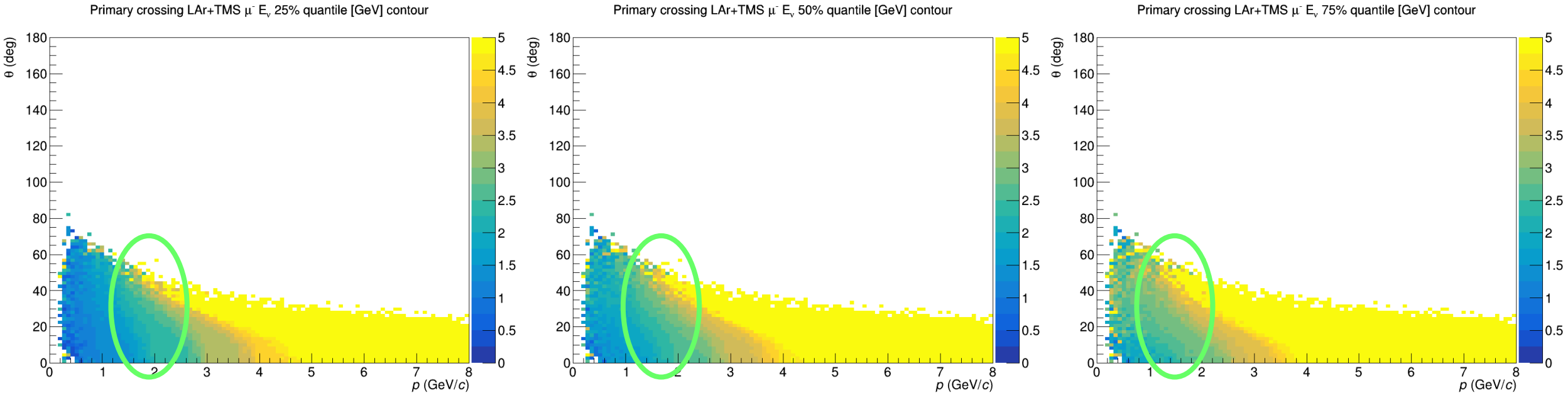






- LAr+TMS: 25%, 50% and 75% parent neutrino energy E_ν quantiles plotted as a function of muon initial momentum p [GeV/c] and θ [deg] angle with the z axis.
- This gives an idea of the spread of the parent neutrino energy distribution in the phase space

LAR+TMS MUONS NEUTRINO ENERGY QUANTILES

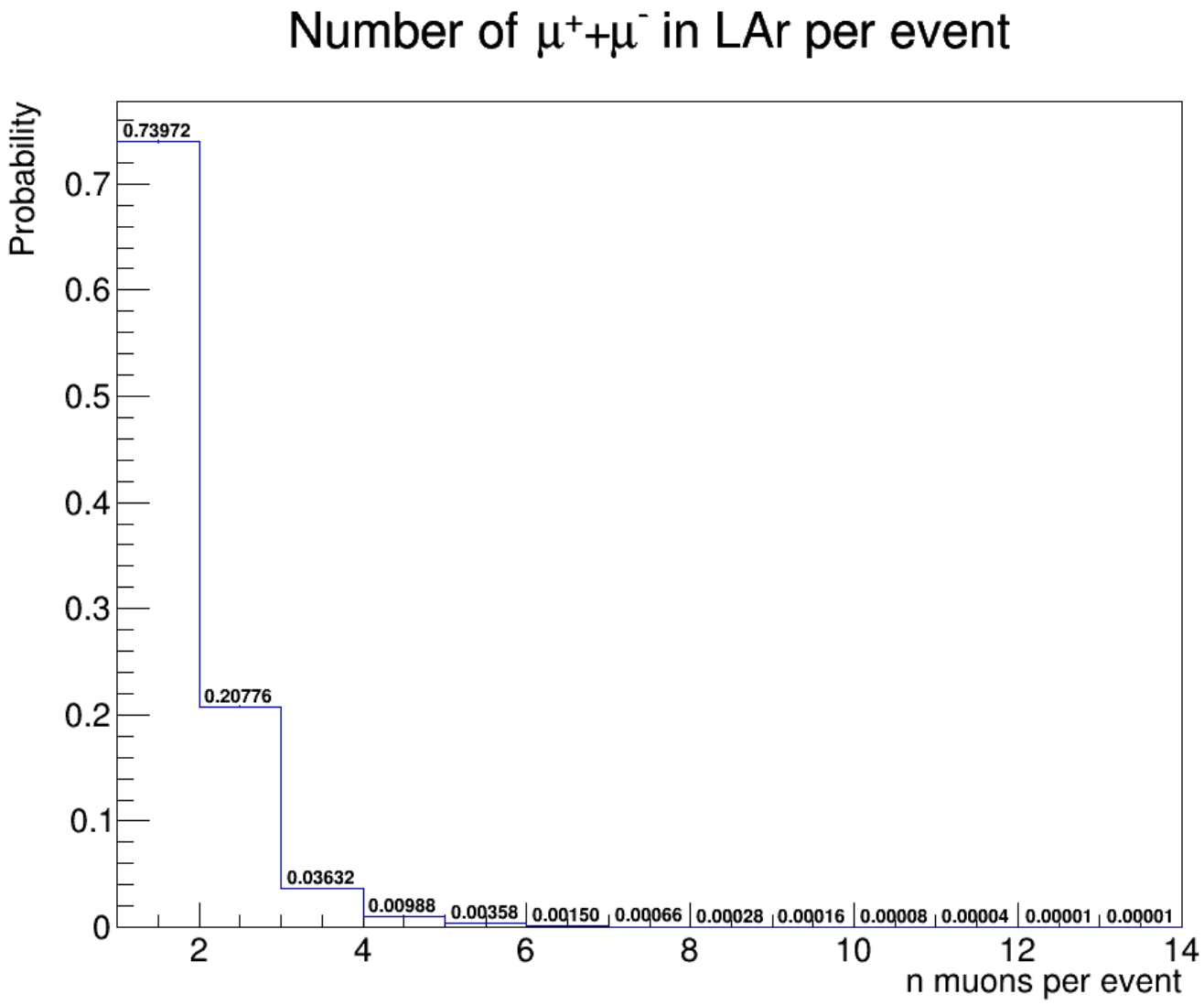


- LAr+TMS: 25%, 50% and 75% parent neutrino energy E_ν quantiles plotted as a function of muon initial momentum p [GeV/c] and θ [deg] angle with the z axis.
- This gives an idea of the spread of the parent neutrino energy distribution in the phase space
- The first oscillation peak energy region spreads roughly between $(0.5 < p < 2.5)$ GeV/c and $(0 < \theta < 70)$ deg

EVENTS WITH MULTIPLE MUONS IN LAR

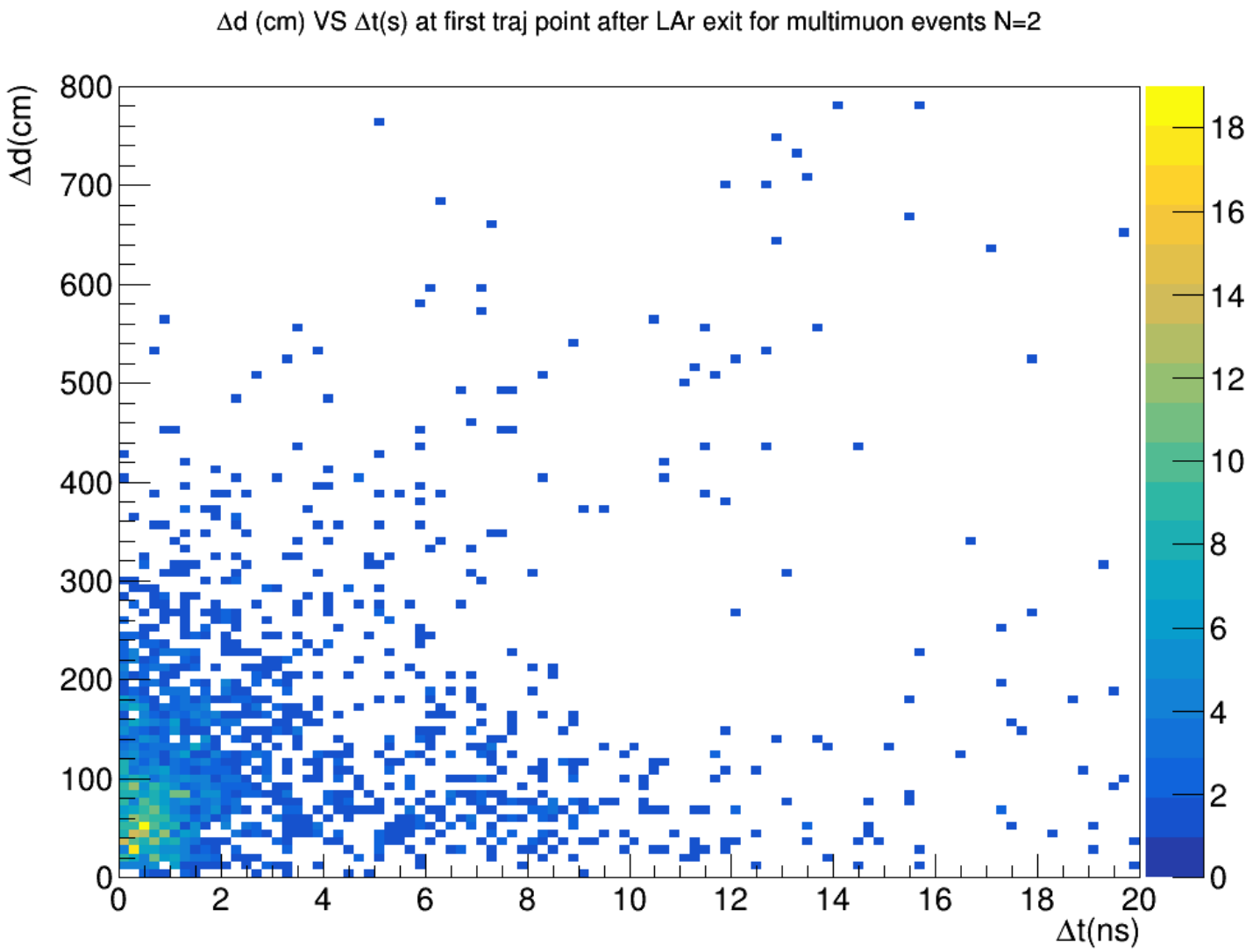
- Events producing multiple muons in the LAr chamber could cause problems in the reconstruction, especially in cases where the trajectories are very close together
- To study this topology we use MC truth data and we consider all events producing one or more muon or anti-muon tracks in the LAr irresgardless if they stop in it or not.
- To set a baseline for this events sample we start by analyzing a single-interaction simulation (i.e. the same one used for the previous analysis) and we than repeat out analysis for a single-spill sample

SINGLE INTERACTION: NUMBER OF MUONS IN LAR FIDUCIAL VOLUME



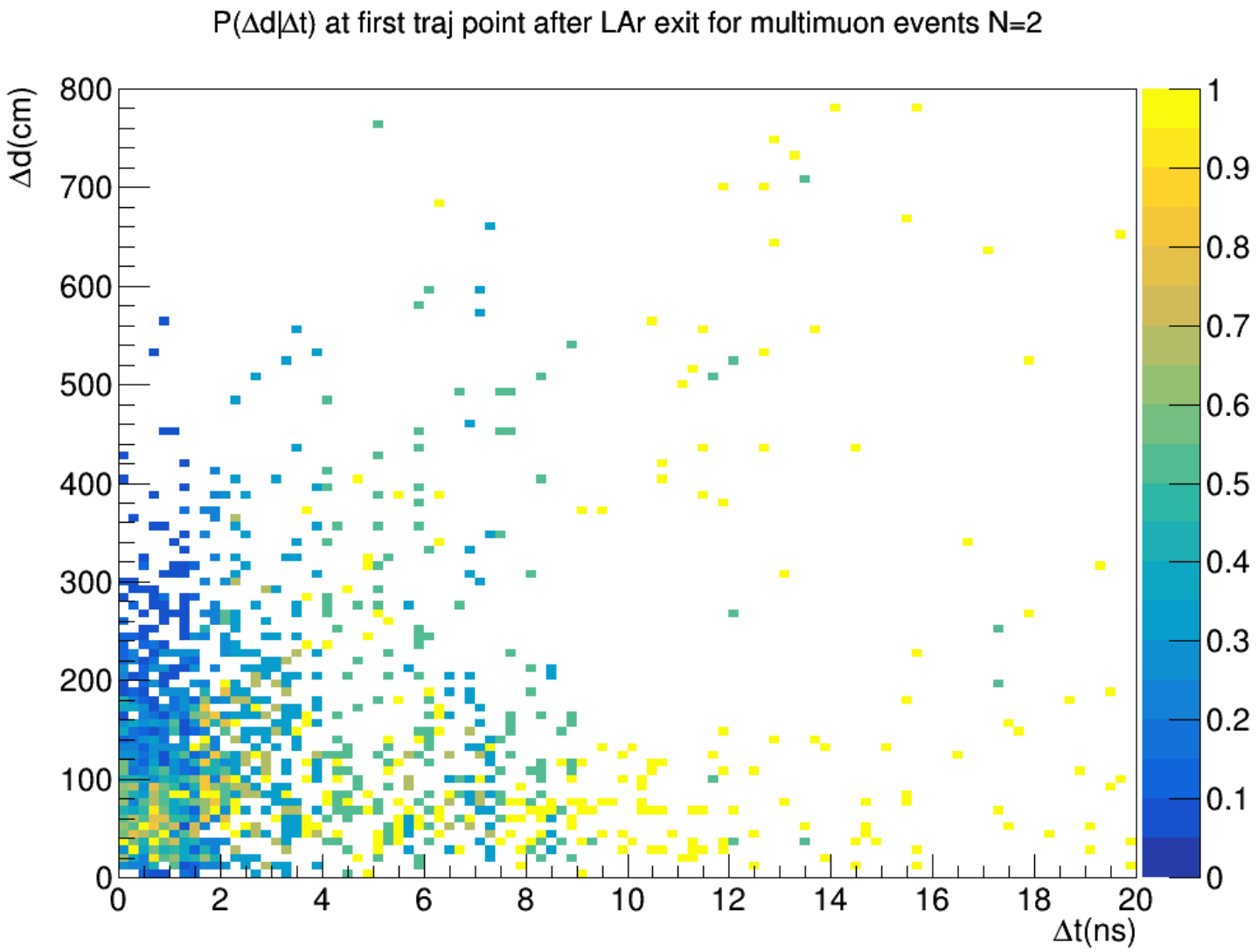
- Number of negative and positive muons having at least one MC trajectory point inside the LAr volume per muon producing event (The histogram is normalized to 1)
- Active LAr fiducial volume:
  $(-357.35 < x < 357.35)$ cm
  $(-127.275 < y < 127.275)$ cm
  $(-411.5 < z < 920.5)$ cm
- We can see that while the vast majority of the events produce a single muon trajectory in the LAr roughly 25% of the events produce two or more

SINGLE INTERACTION: TIME-SPACE SPREAD



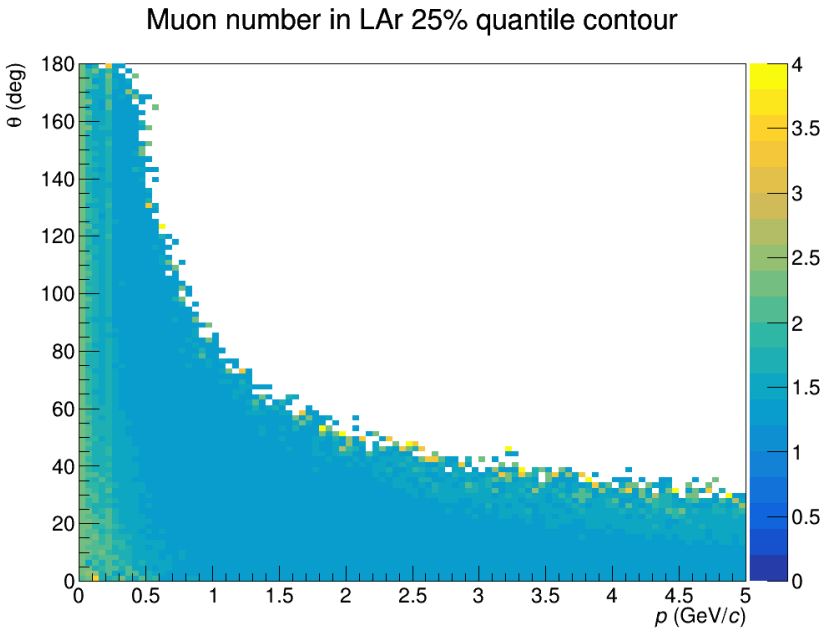
- Distance spread in time $\Delta t\ [s]$ and space $\Delta d = \sqrt{\Delta x^2 + \Delta y^2}\ [cm]$ (calculated in the XY plane) between muons from double muon events (N=2) at the exiting point of the LAr active volume $z = 920.5$ cm
- We plot the values assigned to the first MC trajectory point for the muon after $z = 920.5$ cm

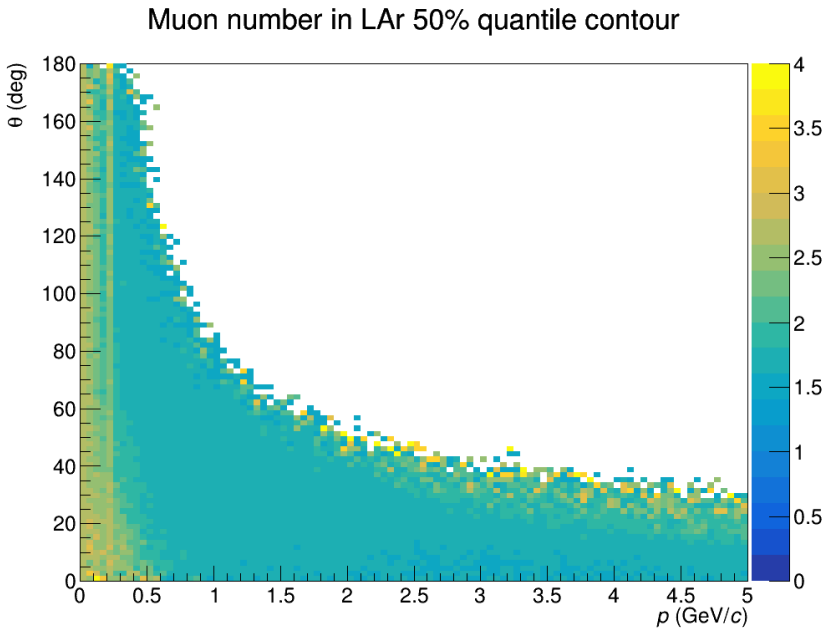
SINGLE INTERACTION: TIME-SPACE SPREAD

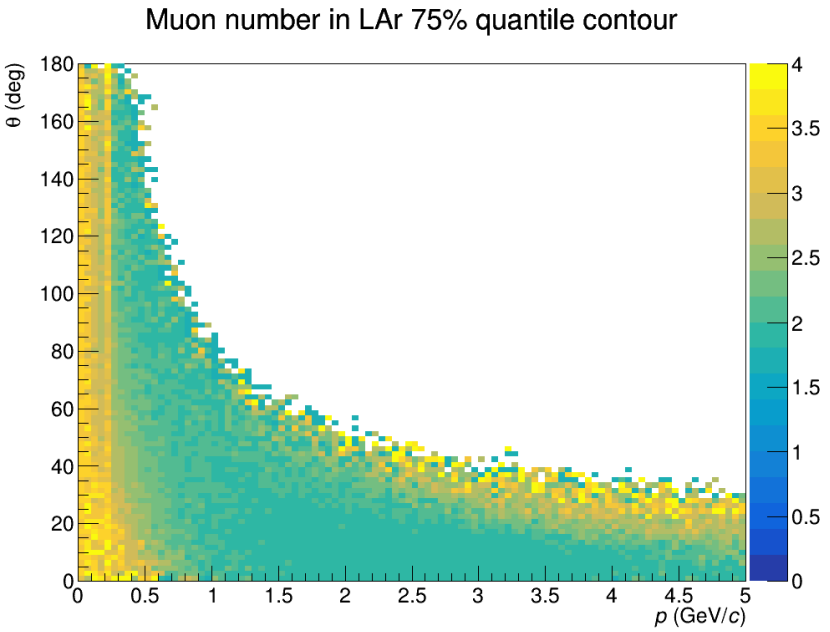


- Conditional probability $P(\Delta d|\Delta t)$ for muons from double muon events (N=2) at the exiting point of the LAr active volume $z = 920.5$ cm
- The z axis is normalized such that the maxima for each column have 1 at their maxima (i.e. These are not proper PDF's normalized to 1)
- We plot the values assigned to the first MC trajectory point for the muon after $z = 920.5$ cm

SINGLE INTERACTION: NUMBER OF MUONS IN LAR QUANTILES

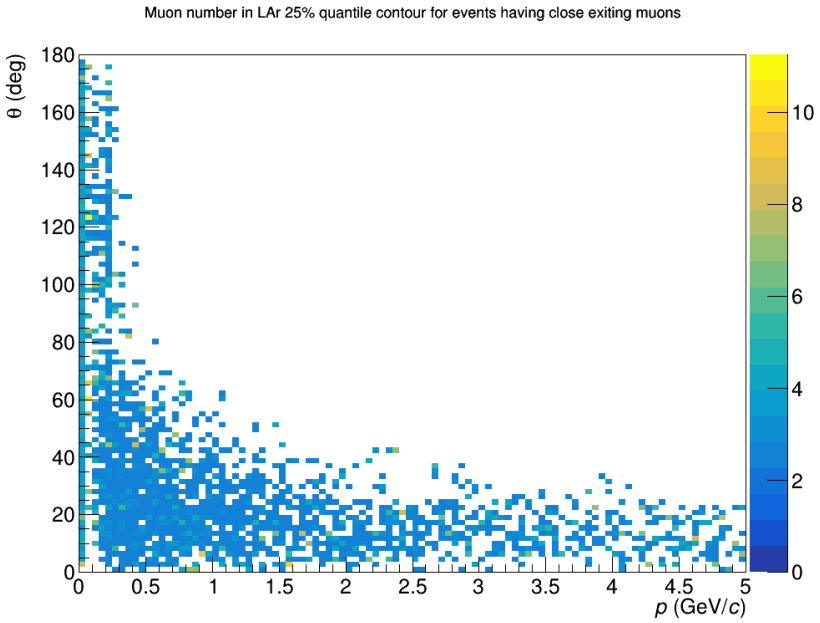


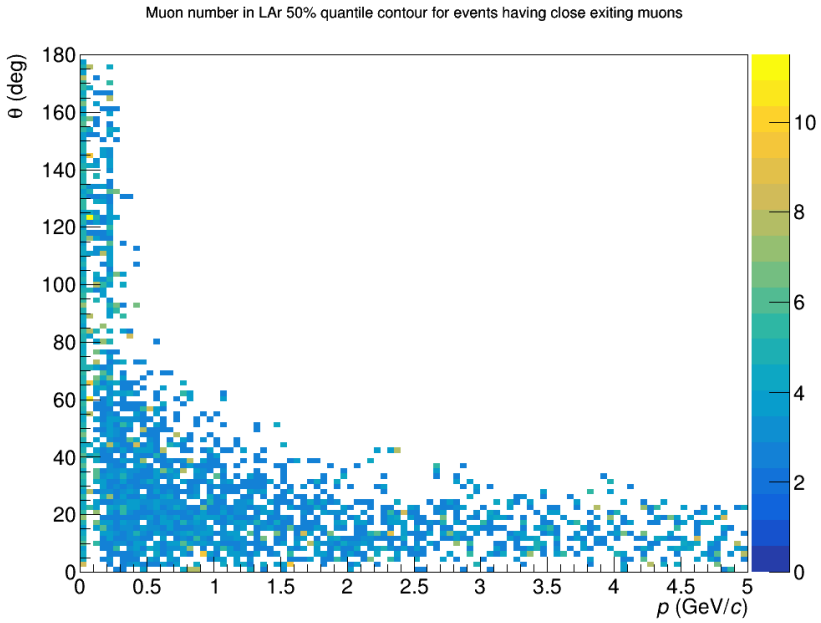


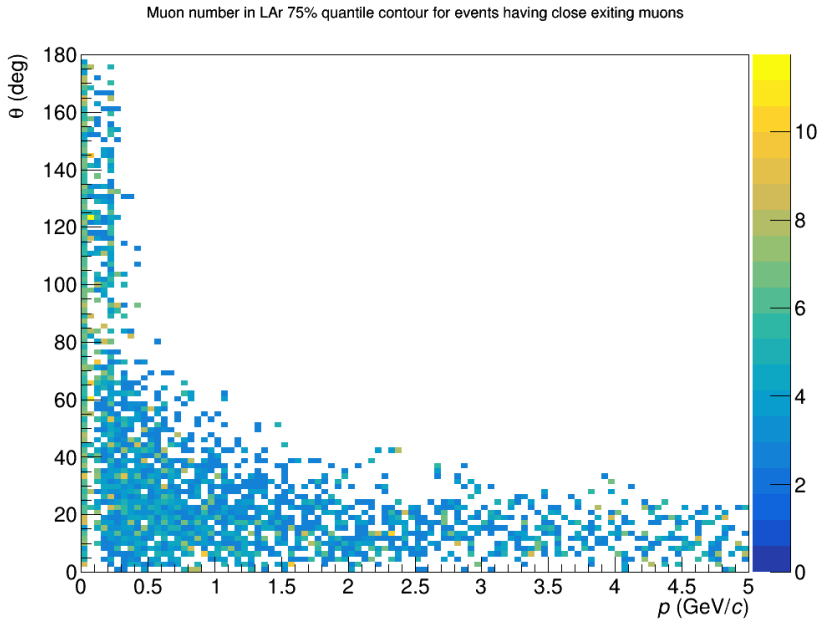


- Here we plot the 25%, 50 % and 75% quantiles for the number of muons having a trajectory point in LAr in the phase space of muon momentum and angle (θ, p) at vertex (note that the procedure with which these plots have been made is is analogous to the one in slide 8 for E_ν quantile)
- The number of muons distribution seem to be overall very uniform in the phase space, slight increases in the edge regions

SINGLE INTERACTION: N OF MUONS IN LAR QUANTILES; CLOSE MUONS

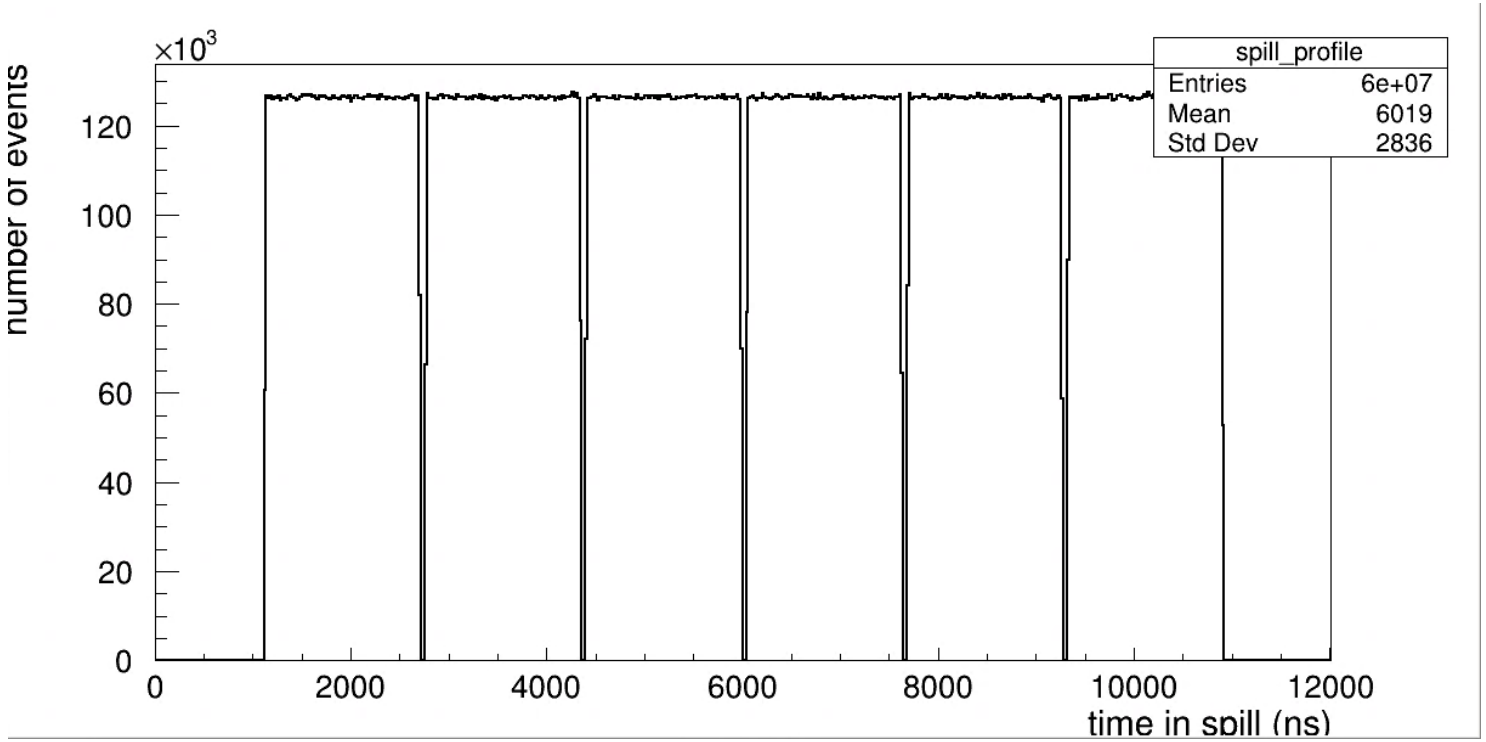






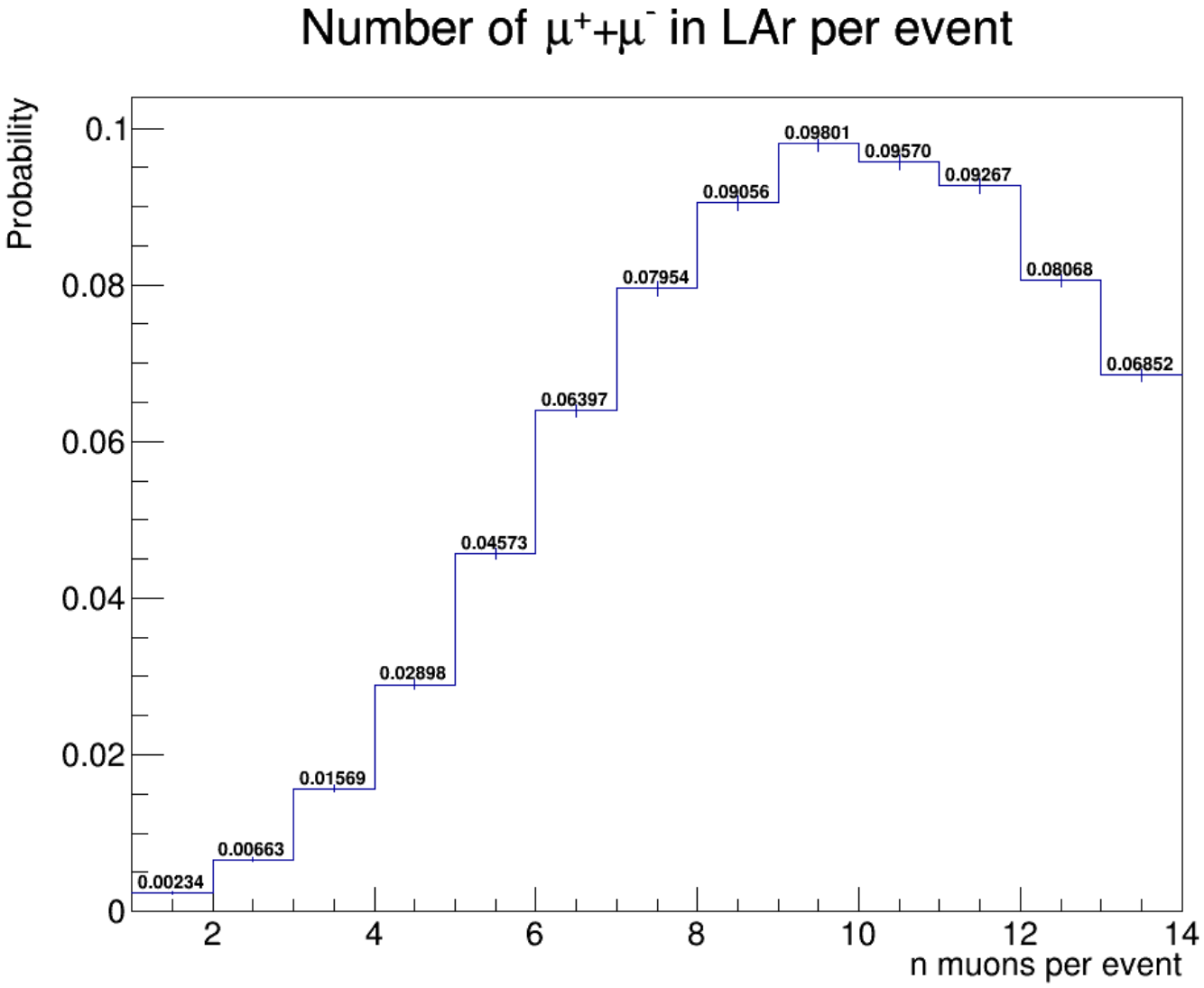
- Here we plot the 25%, 50 % and 75% quantiles for all those events which have at least a couple of close exiting muons defined as $\Delta t < 5ns$ and Δd <100cm
- Here we see that a big number of events do not pass the selection

SINGLE SPILL SIMULATION



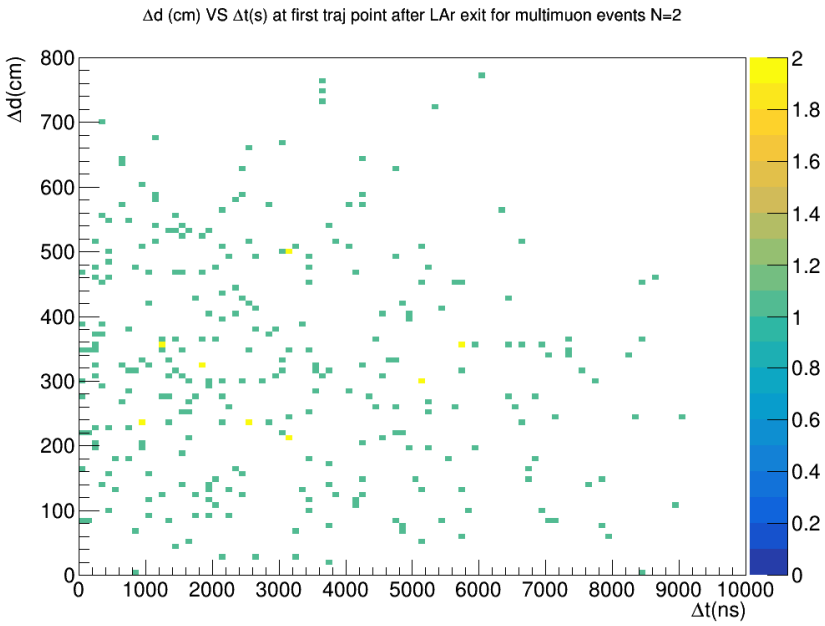
- For the single spill analysis we use a sample containing MC truth for 10^5 single spills produced by Eldwan
- Spills are generated simply by using the OverlayGENIE package with the parameters: Poisson distribution around 10 events/spill, 10 μs spill using single GENIE events

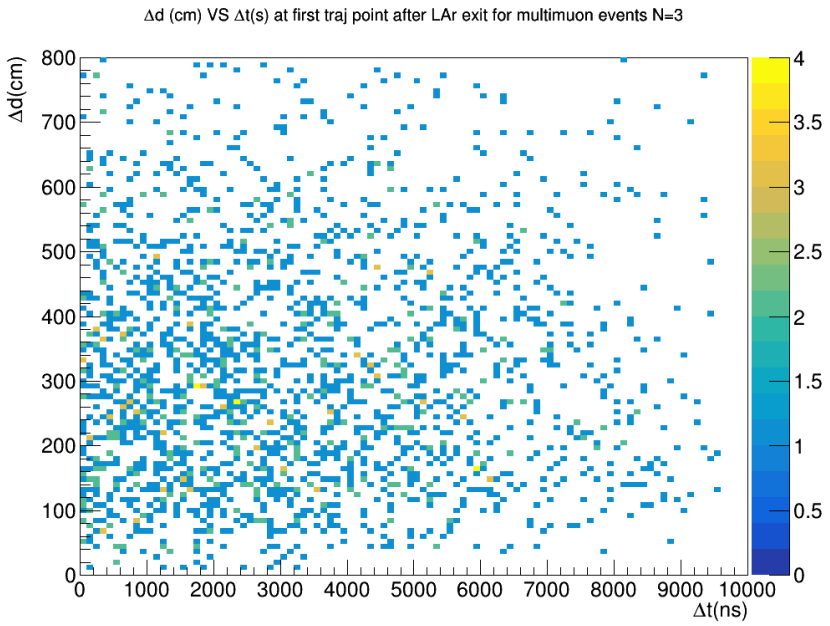
SINGLE SPILL: NUMBER OF MUONS IN LAR FIDUCIAL VOLUME

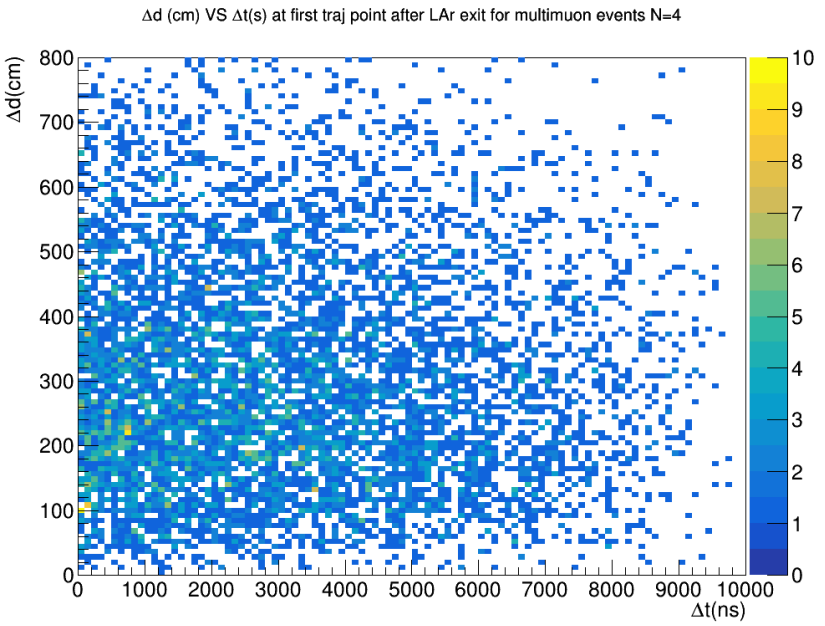


- Number of negative and positive muons having at least one MC trajectory point inside the LAr volume per muon producing event (The histogram is normalized to 1)
- Active LAr fiducial volume:
  $(-357.35 < x < 357.35)$ cm
  $(-127.275 < y < 127.275)$ cm
  $(411.5 < z < 920.5)$ cm
- The multiplicity is now much higher with the vast majority of events producing two or more muons in the LAr

SINGLE SPILL: TIME-SPACE SPREAD

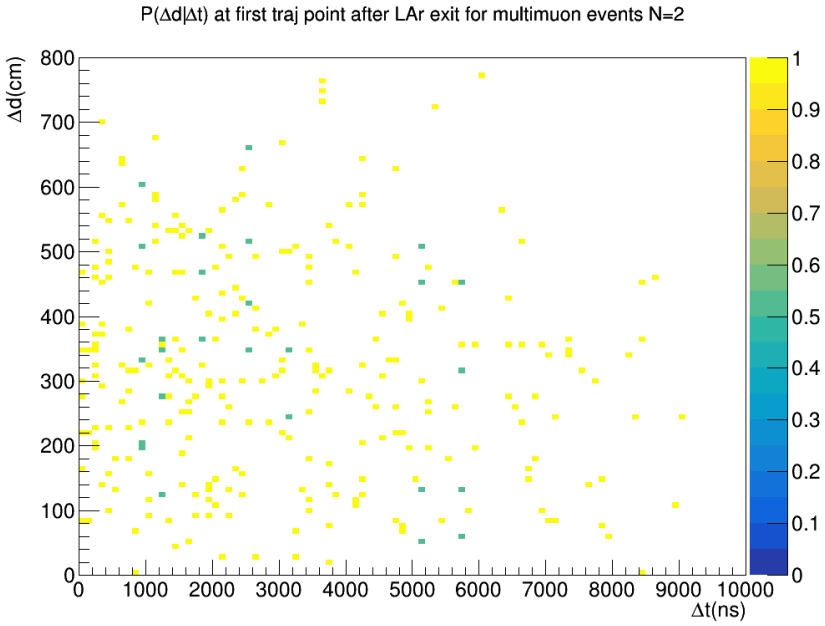


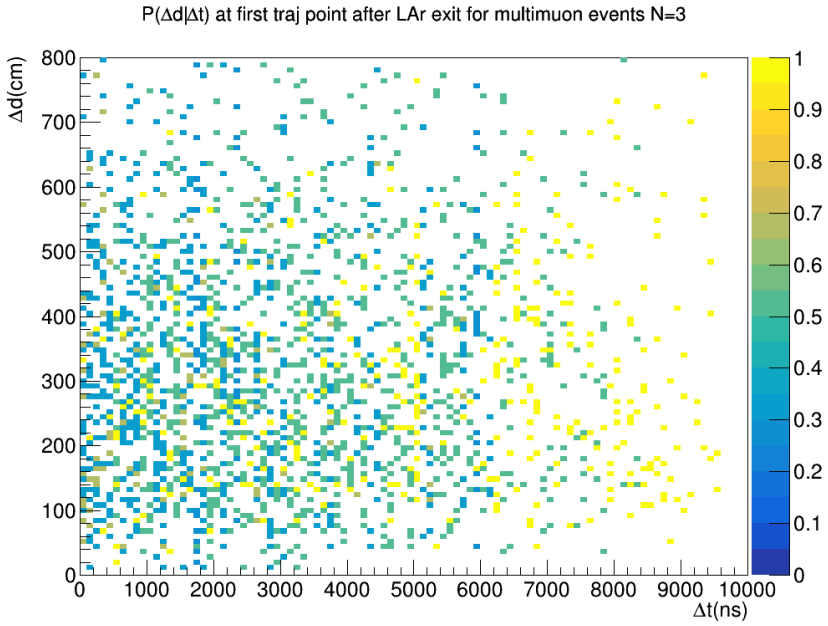


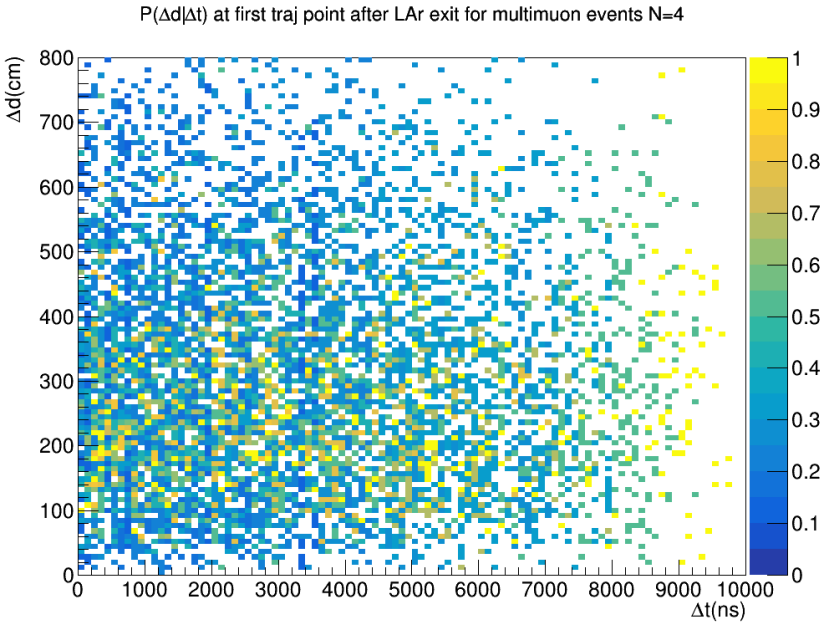


- Distance spread in time $\Delta t\ [s]$ and space $\Delta d = \sqrt{\Delta x^2 + \Delta y^2}\ [cm]$ (calculated in the XY plane) between muons from multiple muon events (N=2,3,4 chosen as a starting point) at the exiting point of the LAr active volume $z = 920.5$ cm. All dinstance combinations are plotted.
- We plot the values assigned to the first MC trajectory point for the muon after $z = 920.5$ cm

SINGLE SPILL: TIME-SPACE SPREAD

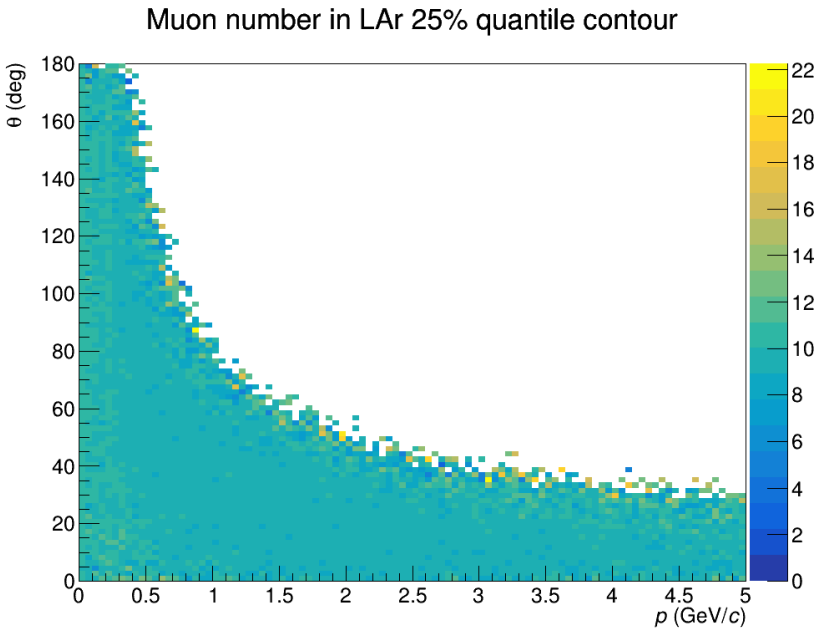


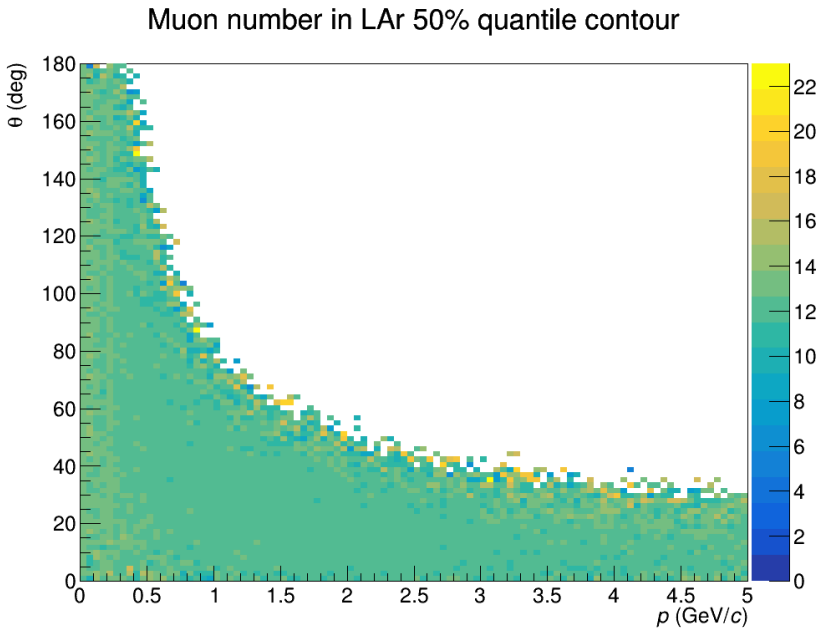


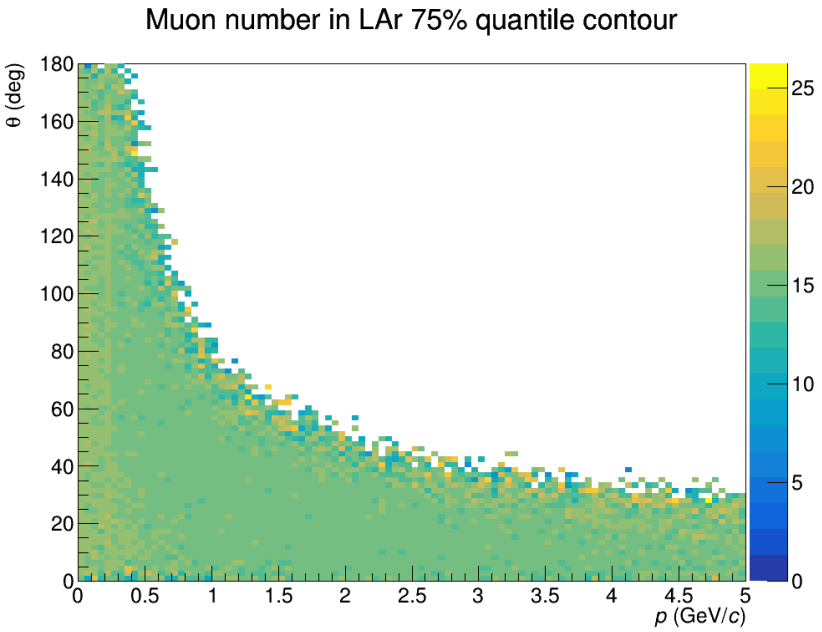


- Conditional probability $P(\Delta d|\Delta t)$ for muons from multiple muon events (N=2,3,4) at the exiting point of the LAr active volume $z = 920.5$ cm. All dinstance combinations are plotted.
- The z axis is normalized such that the maxima for each column have 1 at their maxima (i.e. These are not proper PDF's normalized to 1)
- We plot the values assigned to the first MC trajectory point for the muon after $z = 920.5$ cm

SINGLE SPILL: NUMBER OF MUONS IN LAR QUANTILES

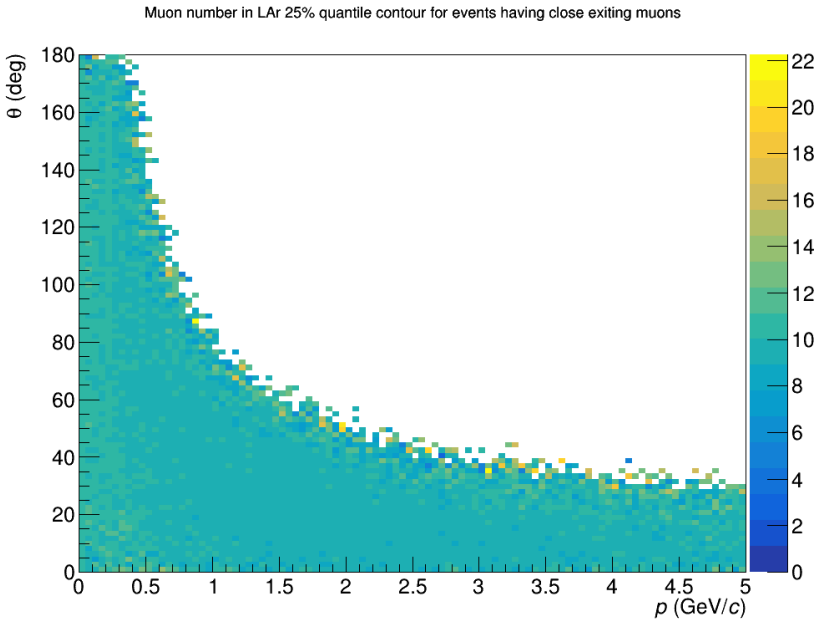


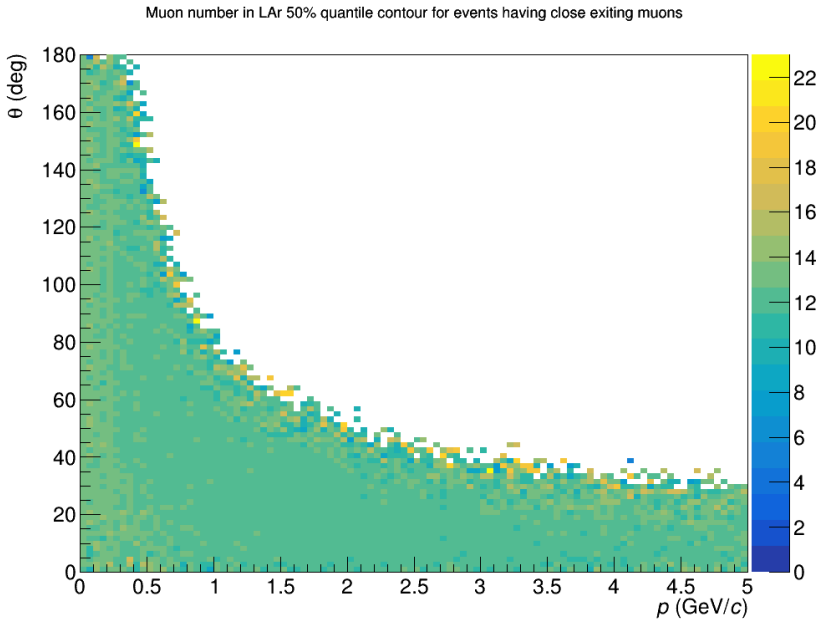


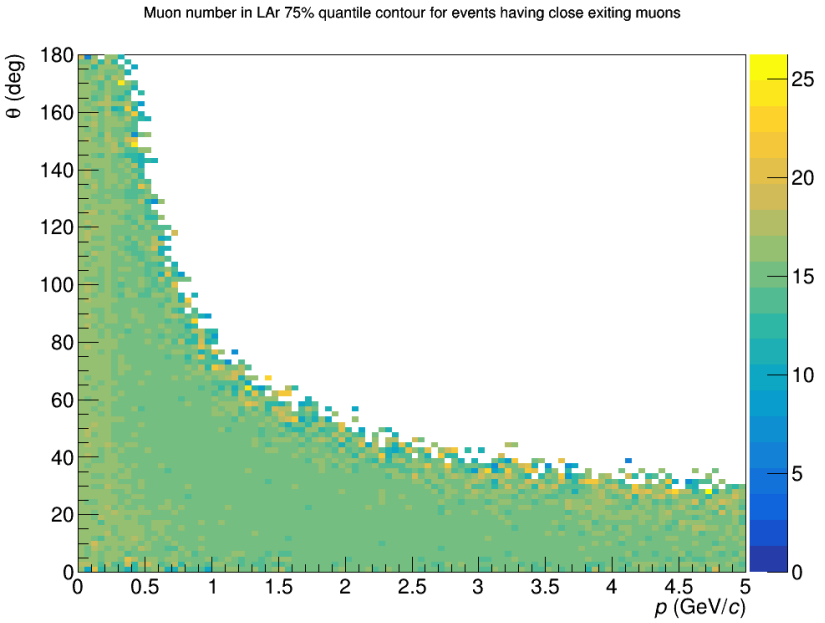


- Here we plot the 25%, 50 % and 75% quantiles for the number of muons having a trajectory point in Lar in the phase space of muon momentum and angle (θ, p) at vertex (note that the procedure with which these plots have been made is is analogous to the one in slide 8 for E_ν quantile)
- The number of muons distribution seem to be even more uniform in the single-spill sample, but with higher multiplicities, as it is expected
- Note that on average we have on average 10 events/spill across all phase space

SINGLE SPILL: N OF MUONS IN LAR QUANTILES; EVENTS WITH CLOSE MUONS







- Here we plot the 25%, 50 % and 75% quantiles for all those events which have at least a couple of close exiting muons defined as $\Delta t < 5000ns$ and $\Delta d < 500$cm
- The cut $\Delta t < 5000ns$ is chosen somewhat arbitrarily at the moment but should depend on the timing precision of LAr and TMS: we might need to check different scenarios after this talk.
- Here we see that most events do have at least a couple of close muons

SUMMARY AND FUTURE STEPS

- We analyzed the LAr+GAr and LAr alone muon samples' (p, θ) distribution and relative parent E_ν spread and found that:
  - LAr+GAr muons have larger initial momenta and smaller angles with average parent E_ν that grows with p and θ; the first oscillation peak energy region ($E_\nu \sim 2.5\text{GeV}$) spreads roughly between $(0.5 < p < 2.5)$ GeV/c and $(0 < \theta < 70)$ deg
  - LAr alone have smaller initial momenta and larger angles, with neutrinos in the first oscillation peak region dominating the sample overall

- We then looked at events producing muon trajectories in the Liquid Argon in terms of muon multiplicity, space-time distance spread for exiting muons and number of muons quantiles both for the all sample and specifically for events producing close exiting muons.
- This analysis has been performed first over a single interaction sample, to set a baseline and then on a more realistic single spill sample

- Immidiate next steps:
  - Study detector reconstruction performances (so far only considered MC truth)
  - Reconstruction seem to be very slow in single spill samples, around 24 s/ev, which might indicate difficulties with multimuon events: need to investigate
  - Check $E_\nu$and N_μ at DUNE-PRISM off-axis angles