Study of Muonless Events at the INO ICAL Detector

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Introduction:

- ⋆ Events in ICAL@INO can be classified as those with muon tracks and those without.
- ⋆ The $\mu^{\pm}$ tracks reconstructed by standard algorithms, hence ν energy and direction reconstructed.
- ⋆ Events with no such tracks have shower-like pattern of hits and are referred to as "muonless" events.
- ⋆ "Muonless" events = ν_e**CC** + [others(all NCs & ν_τCC) + ν_μCC(Low energy or Horizontal)].
- ⋆ Different/New approach required to know the energy and direction of such neutrinos.

Objective:

1. *Energy* and *Direction* estimation of the incident neutrinos in the muonless events.
2. Obtaining an events sample rich in atmospheric ν_eCC interactions.

Physics Motivation:

Energy and direction are the primary kinematical properties of the neutrinos, and hence are required for several purposes like,

- Study neutrino NC interactions
- Study the GeV ordered ν_eCC interactions and their extent of contributing to neutrino mass hierarchy determination (insignificant).
- Understand the characteristics of the incident neutrinos in such muon-trackless (*muonless*) events.

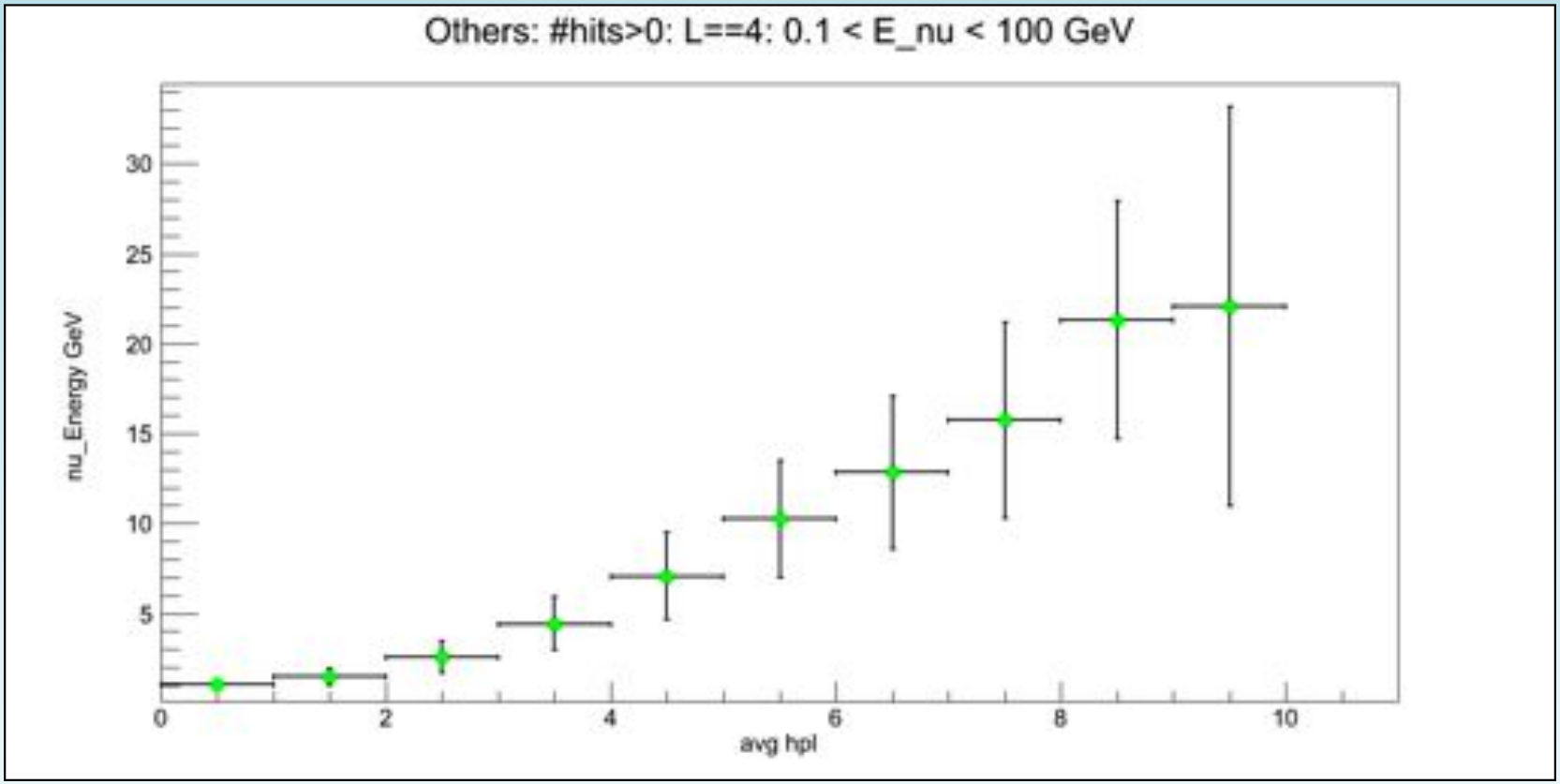
Energy of the *muonless* events at ICAL

- E_ν is vaguely dependent on hits/layer, but not significant enough.
- Direct correlation is realizable, when looked at particular number of layers hit in an event.

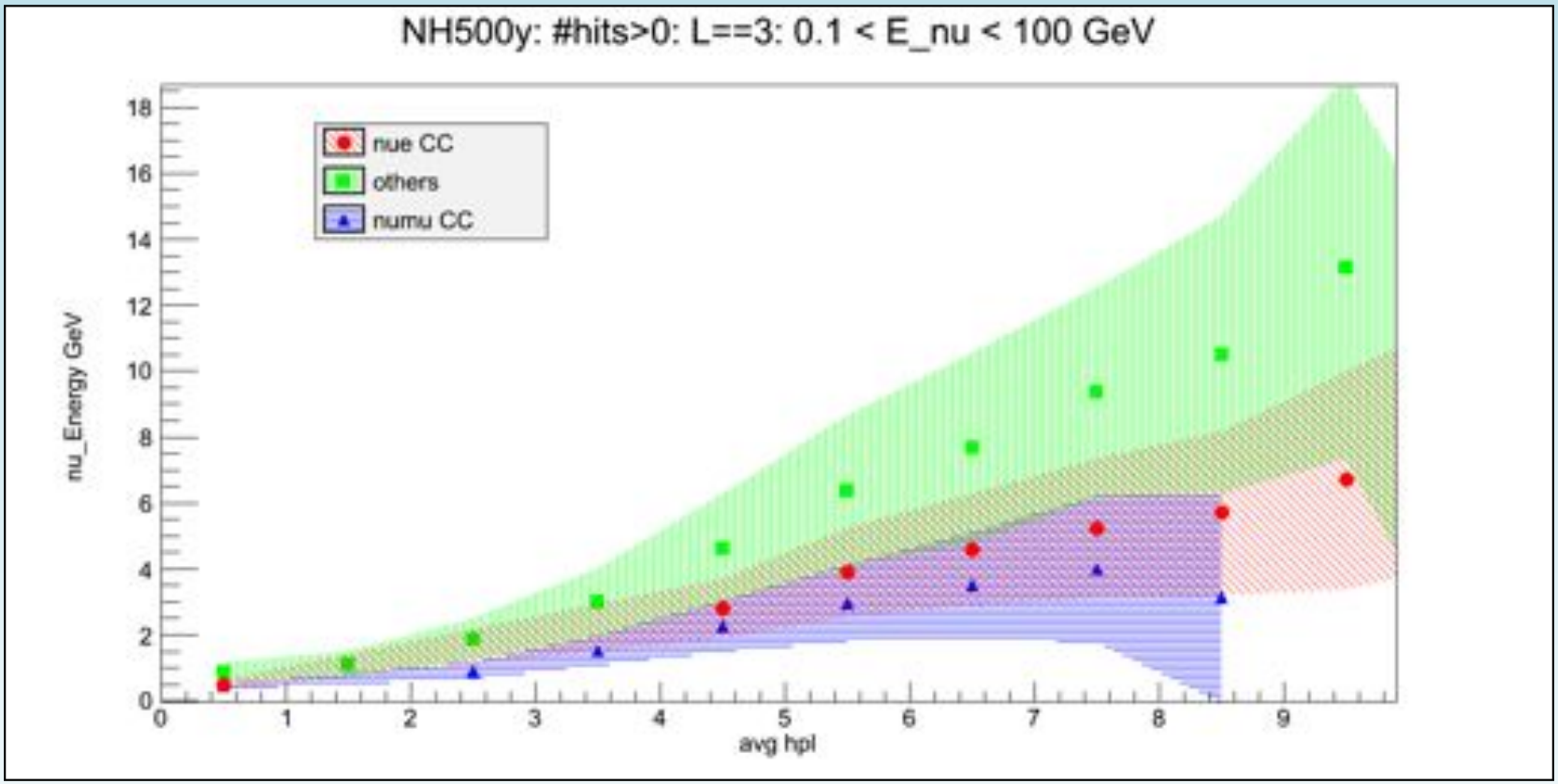
Extraction of the energy information:

- Observe the Energy distribution in small bins of hits per layer, for every individual "no. of layers hit".
- Gradual shift in energy plot in the various bins.
- Fit the distribution with a function: Landau. here
- Recognize a parameter to represent the identity of the distributions in every such bin:
  - ✓ Landau: Most Probable value & σ_L

Calibration of neutrino Energy:

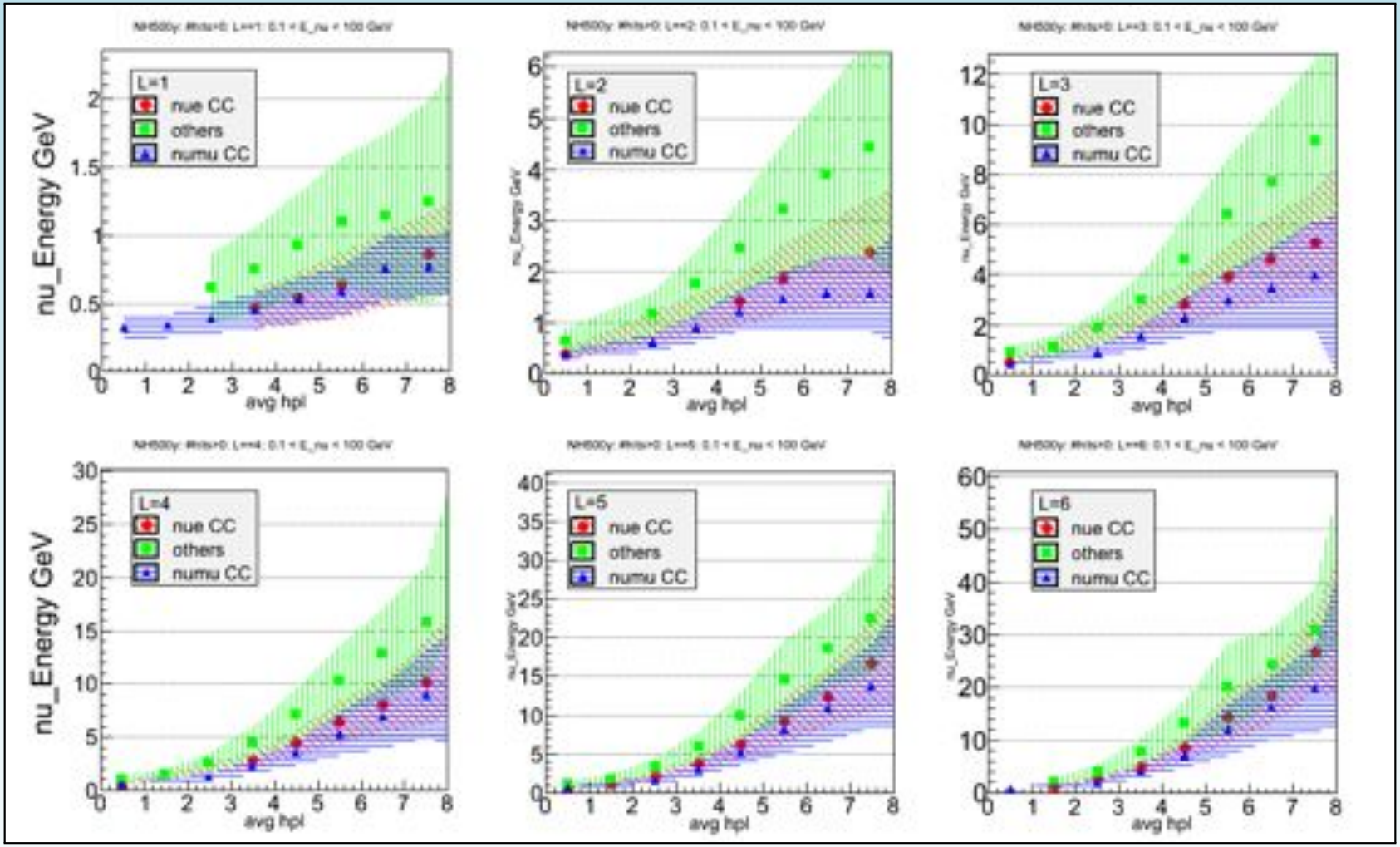


Calibration of ν-Energy vs. Average hits per layer (hpl) for L=4, for the NC ($+\nu_\tau$ CC) events. (Points representation.) The points are given by the Landau peak positions and the 'error bars' by Landau σ in vertical scale (the horizontal bars cover the hpl bin-width).



Calibration of ν-Energy vs. Average hits per layer for L=3, in a shaded representation.

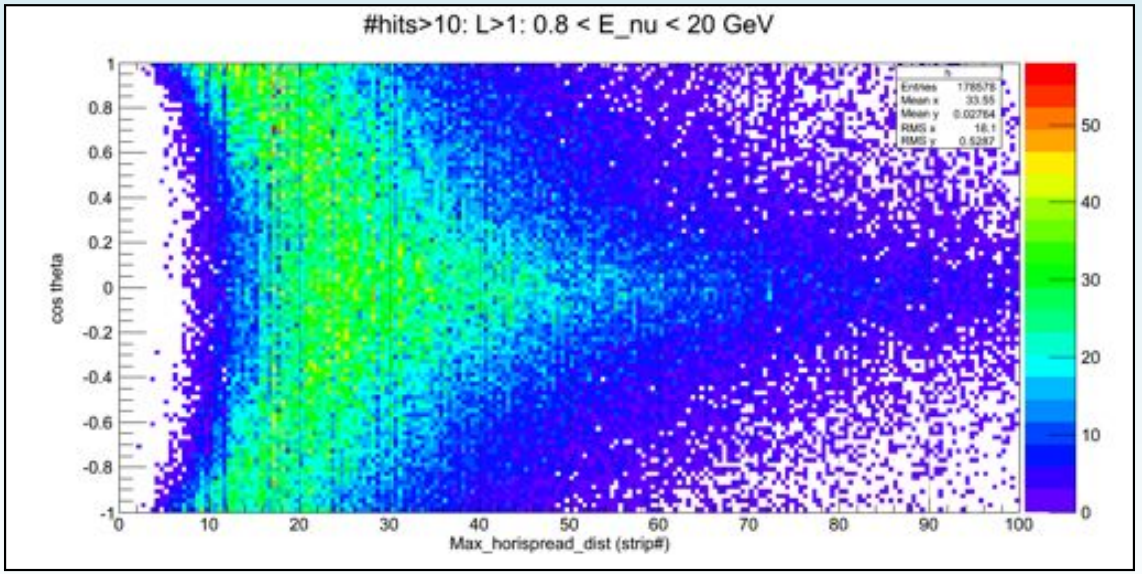
The E_ν Calibration Chart:



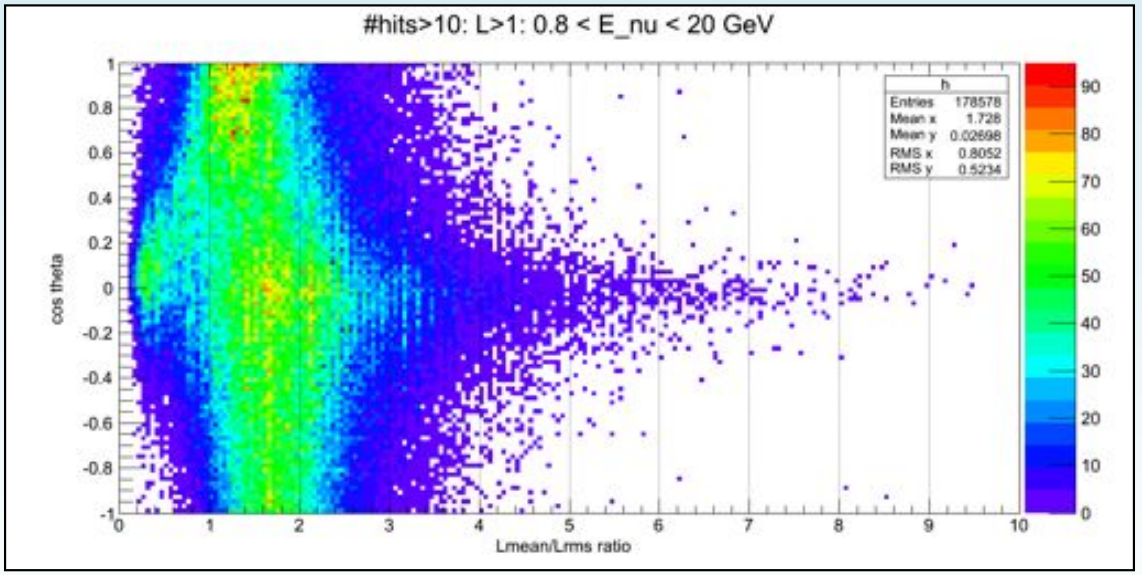
Calibration of ν-Energy vs. Average hits per layer for L={1,6} in order from top-left.

Incident Direction of the neutrinos

1. Resolving Horizontal or Vertical Direction:
   - The vertical or near vertical events have shorter average horizontal spread than the horizontal or near horizontal events.
   - The *horizontal spread* can also be interpreted as the projected length of the largest diagonal between two hits in the event.
   - The maximum value of this distance in an event serves as our selection parameter.



2. Resolving Upward or Downward Direction:
   - The hits in different layers of the ν_e CC events are non-uniform.
   - The ν_μ CC gives a broader distribution than the ν_e CC / NC.
   - Consider the Mean or RMS value of the layerwise hits distribution of each event. here
   - This value of the ratio of Mean to RMS shows some characteristic difference for the up-going and the down-going νs.



- The ratio of layer-hits mean to rms ("MRratio") attempts to pick between the upgoing and the downgoing neutrino events.
- The maximum spread ("mxdist") attempts to select vertical events from the horizontal events.
- 2-D histograms of these two variables show gradual shifts in the peak positions of such distributions, in varying bins of neutrino direction. here

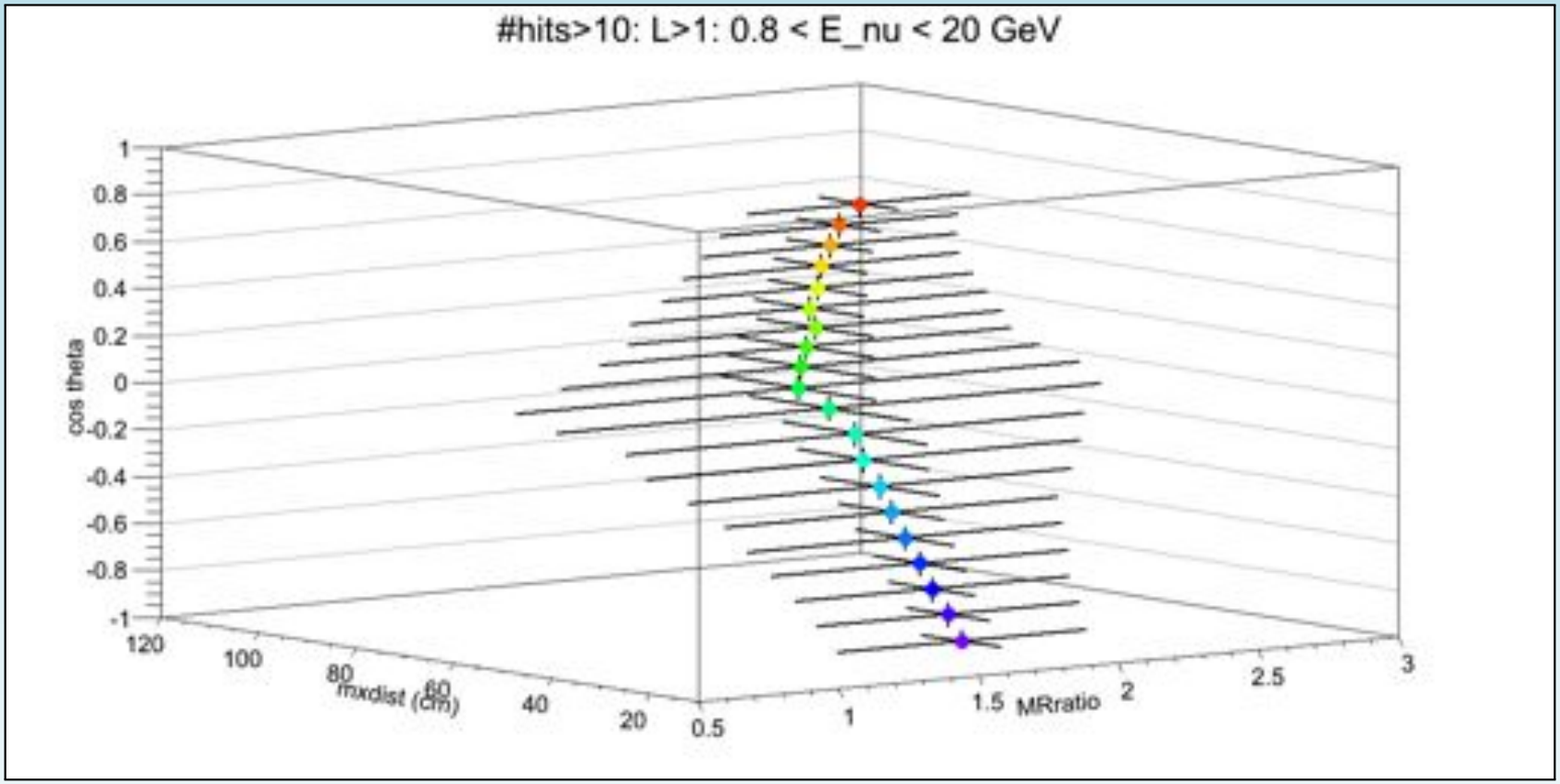
Estimation of the neutrino cos θ:

- An angular estimation may be attempted in terms of a 3D-calibration plot of

  MRratio along X-axis,
  mxdist along Y-axis and,
  costheta along Z-axis.

- X-axis contains the Gaussian mean of the MRratio with $\pm$ Gaussian σ as the standard deviation, in that cosθ bin.
- Y-axis contains the Landau peak position of the maximum spread with $\pm$ Landau sigma as the standard deviation.
- cosθ is along Z-axis with binwidth=0.05.

3D-Calibration Plot of the neutrino $\cos\theta$:



"The Skewed-Hair-pin Structure": Calibration of cos theta with respect to the plane spanned by the layer-hits mean to rms ratio and maximum spread, for the 500years NH data (here ν_e shown). E_ν={0.8,20}GeV. XZ-plane YZ-plane

Selection criteria for ν_eCC majority

- Cuts are based mostly on the # hits and #layers hit.
- Various cuts have been devised, the significant ones mentioned here.
- Selection Cuts and Sample-size optimizations:

$$53\%(68\%)\ \textit{purity with}\ 300(15)\ \textit{events/yr.}$$

- Purity of ν_e CC in the total sample decreases with increasing sample size.

Selection Criteria	Best Ratio of $\#\nu_e$ CC to total #events	Sample size for 500 years
Maximum Hits diff.	53%	156k
Comparison: hits in layers	60%	43k
Overall Pattern: hits in layers	62%(58%)	26k(88k)
Single layer hits	68%	6.5k

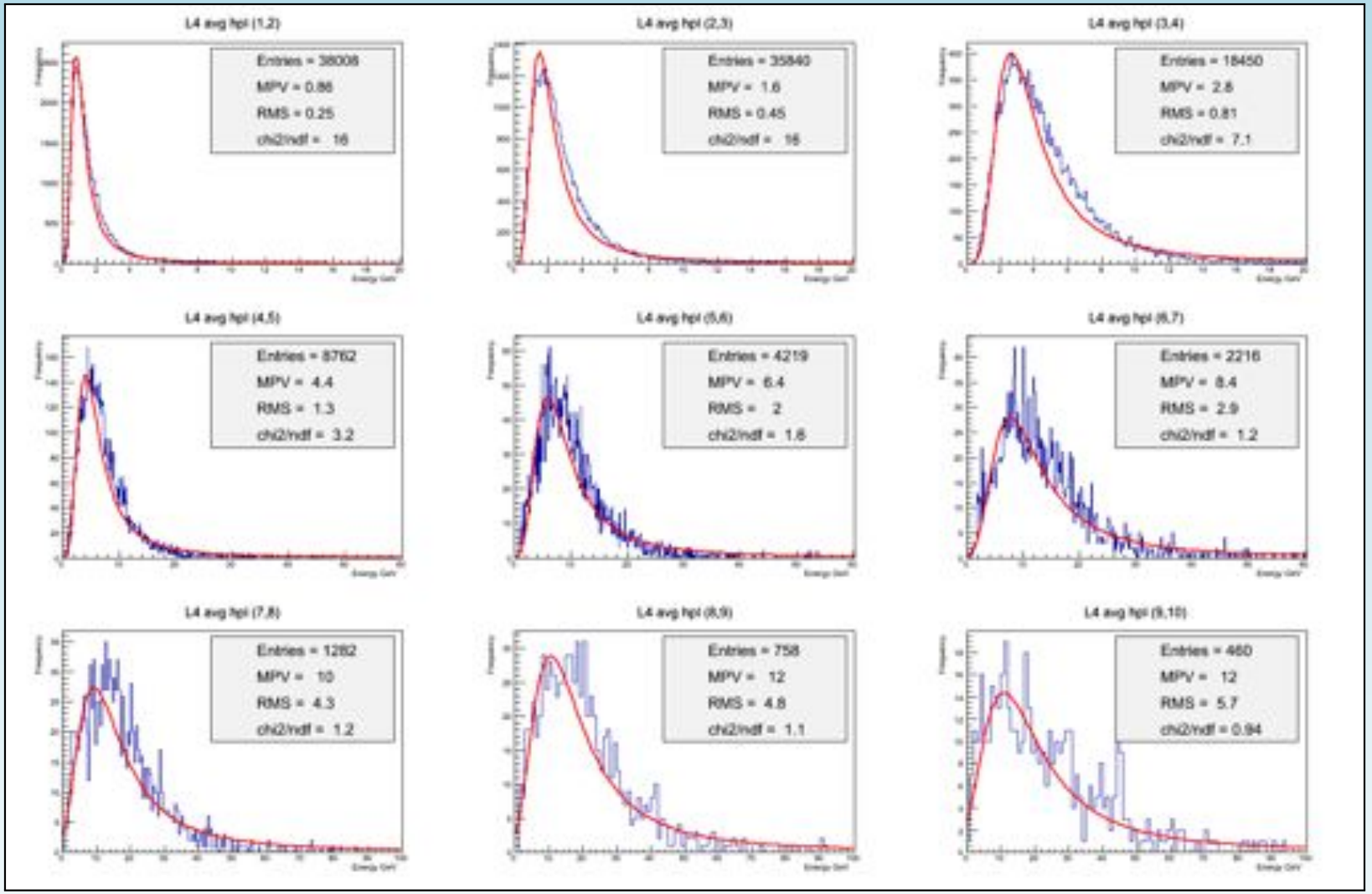
Conclusion:

- An approximate **Calibration of the E_ν** obtained, for *muonless* events. [Energy resolution still to be finalised.]
- A muonless sample rich in any one of the three types of ν-events (ν_e CC, NC/ν_τCC or ν_μ CC (low energy or horizontal)) has better energy resolution.
- Muonless samples rich in up-going ν's can be obtained to $\sim$70% purity.
- Muonless samples rich in vertical ($\lesssim 65^o$) ν's can be obtained to above 80% purity.
- An approximate **Estimation of the neutrino direction** obtained, for *muonless* events.
- A significantly **rich event-sample of atmospheric ν_eCC** can be obtained with $\lesssim$40% background.

Acknowledgement: *We extend our sincere thanks and regards to Prof. Gobinda Majumder, Prof. Indumathi and Prof. Amol Dighe for their invaluable suggestions. We also thank Tarak Thakore for the worthy discussions, and all the Collaboration members for their encouragement and unfailing cooperation.*

Thank you !

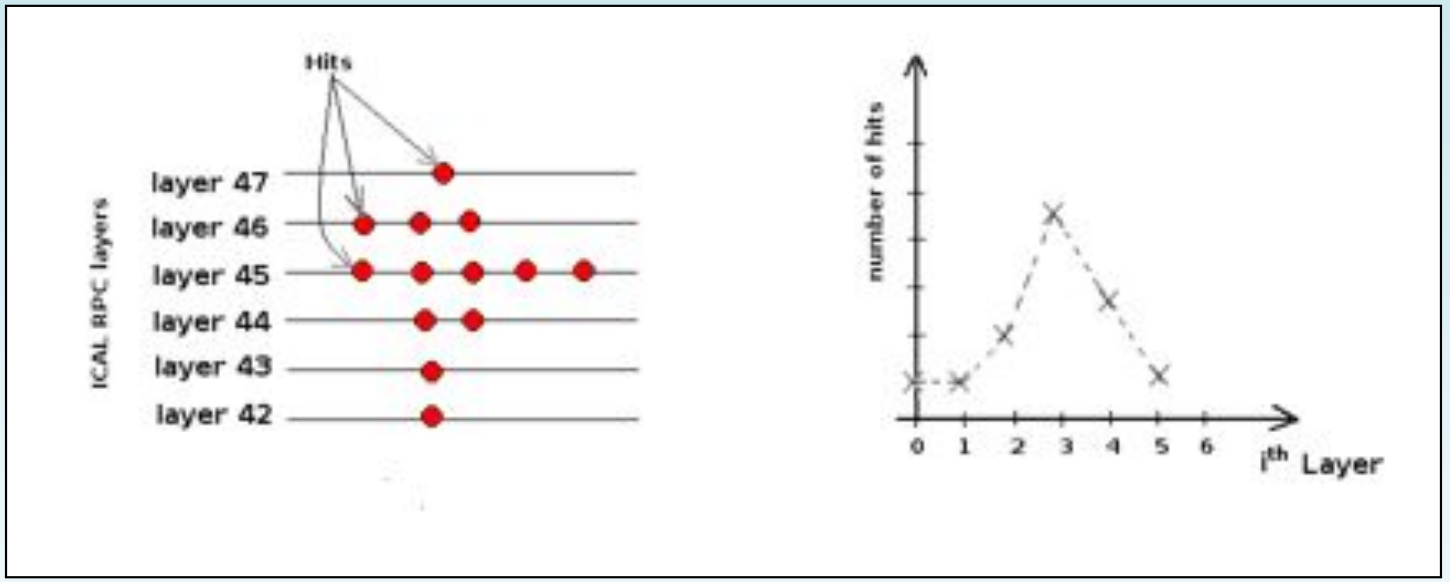
Back ups !



Distribution of E_ν in different bins of avg hits per layer but in a particular layer only, here L=4. They are fitted with Landau distribution function. The bins as from top left are hits/layer= (1,2), (2,3), (3,4), ... , (9,10) at the bottom right. back

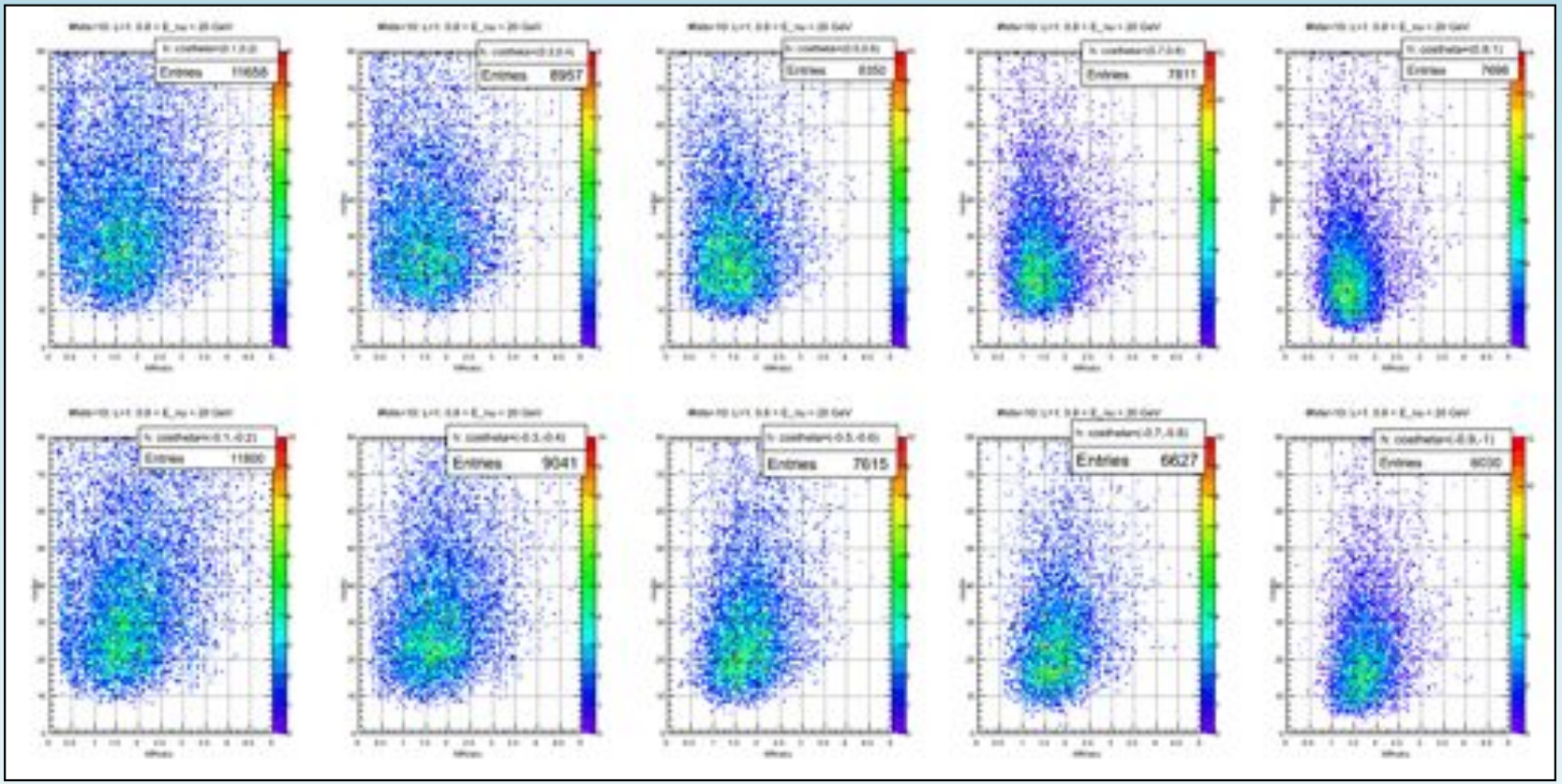
Resolving Upward or Downward Direction: The Final Algorithm:

- in the right panel, the lowest layer hit is labelled to be **0**, the next layer is **1** and so on.
- the ν_μ CC gives a broader distribution than the ν_e CC / NC.



Schematic Diagram of hits in the RPC layers: the hit pattern among various layers in an event (left panel) and the number of hits vs layer number (right panel) back

Up (Horiz.) → **Up (Vert.)**



Down (Horiz.) → **Down (Vert.)**

Correlation of the layer-hits mean to rms ratio (MRratio) and the maximumum total distance (mxdist), in a neutrino event (here ν_e shown) in bins of cos theta (here only six of them are shown)for the 500years NH data. E_ν={0.8,20}GeV. back

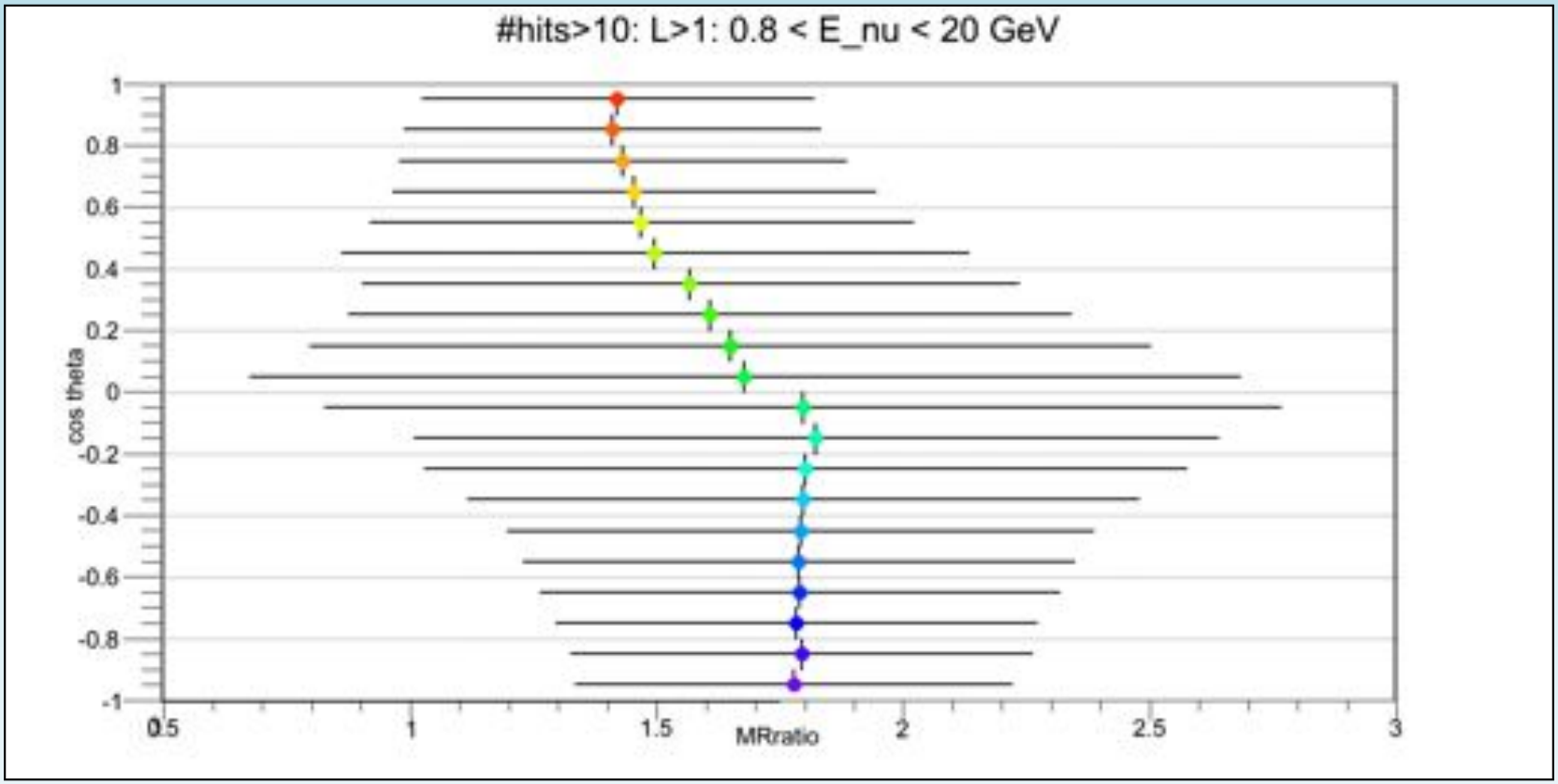


Figure 1: The X-Z projection of the 3D plot, i.e. gaussian fitting of the distribution.

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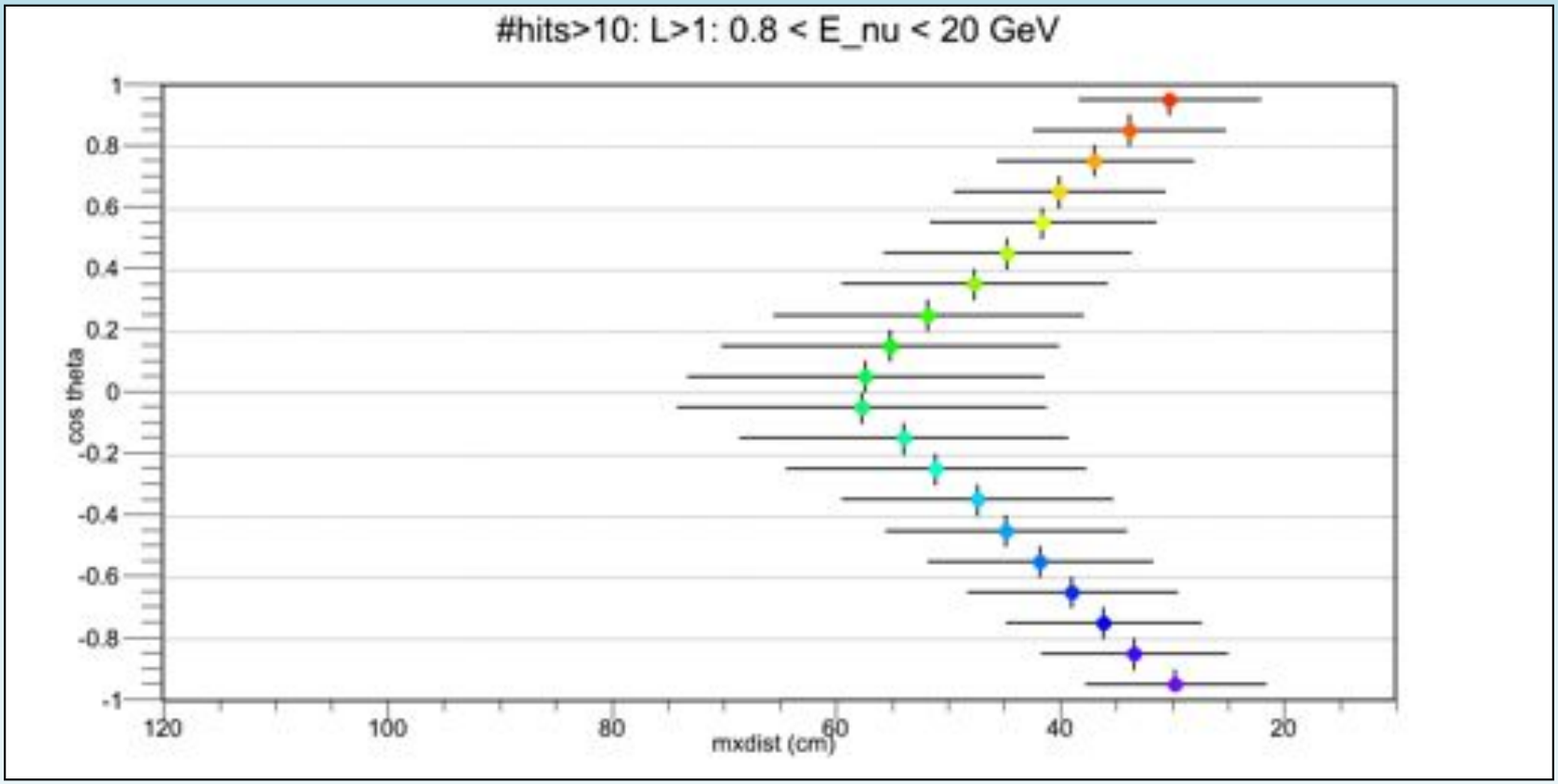

Figure 2: The Y-Z projection of the 3D plot, i.e. Landau fitting of the distribution.

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