Ultra-Forward High Energy Muons with Small Showers

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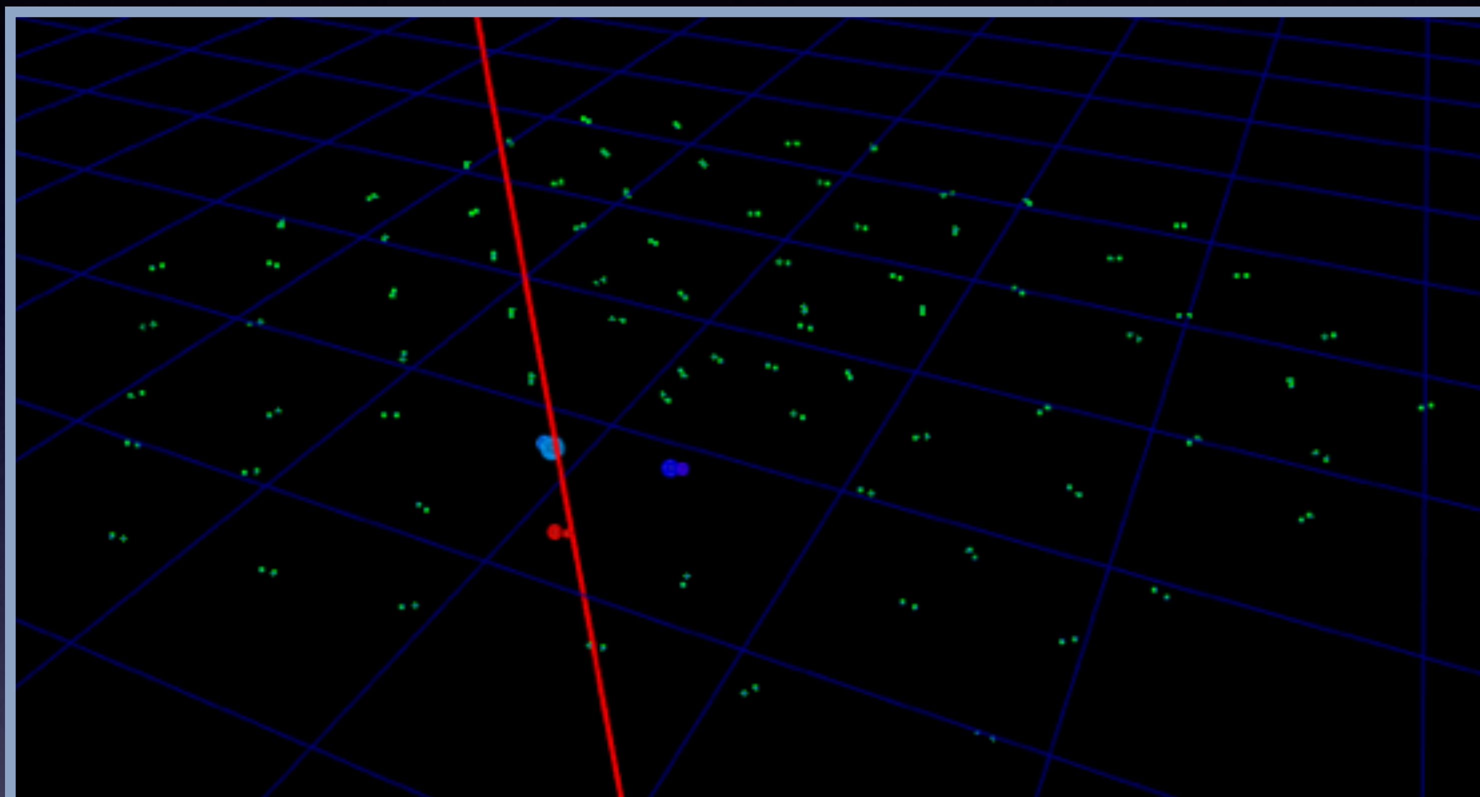
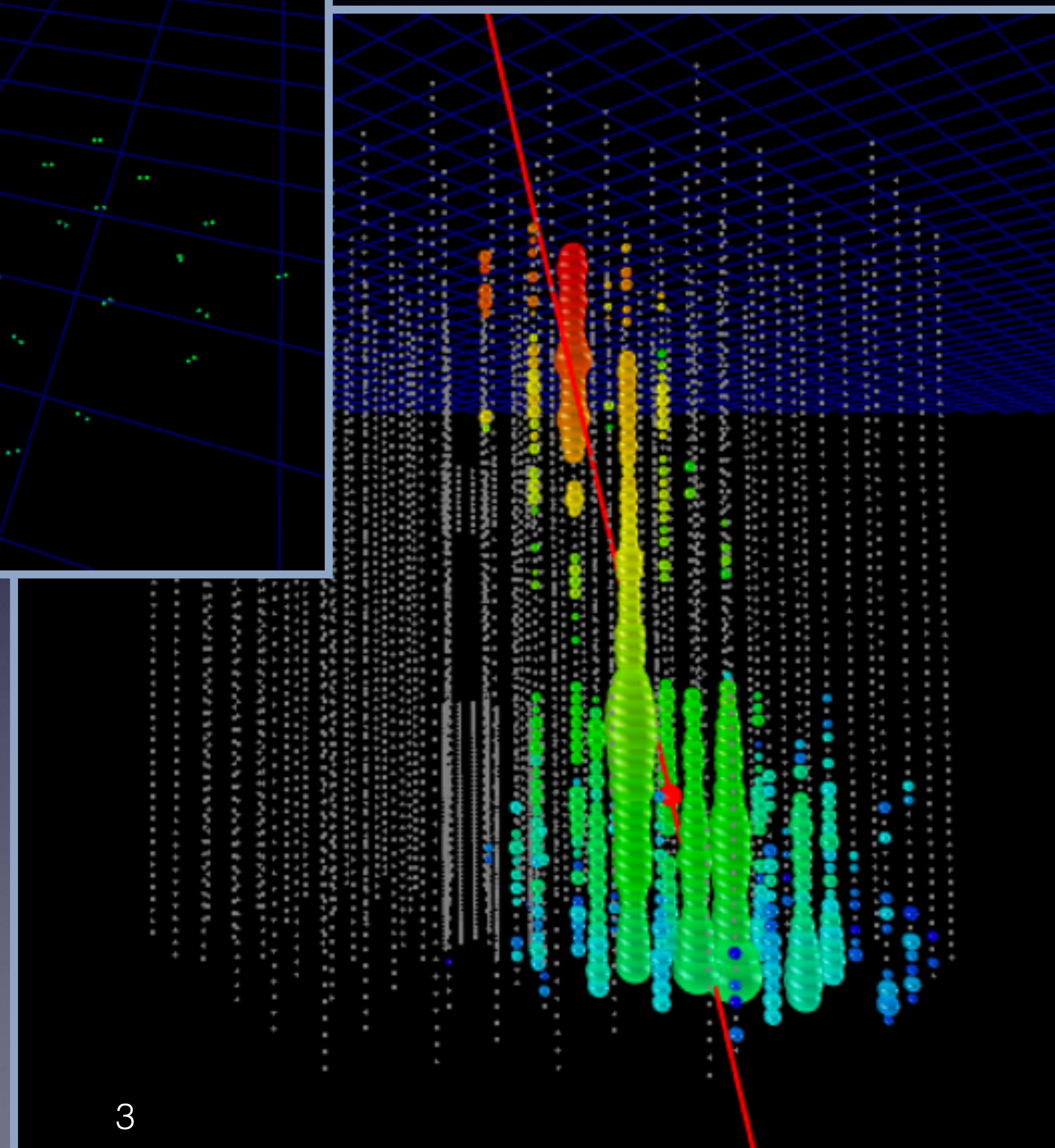
What are Ultra-Forward Muons?

- Highly energetic in-ice muon events with small coincident IT showers.
  - Most likely due to CR (protons) interaction where most energy given to a single muon.
    - Direct probe to start of CR showers.
    - Prompt muon production.
    - Background for neutrino searches.

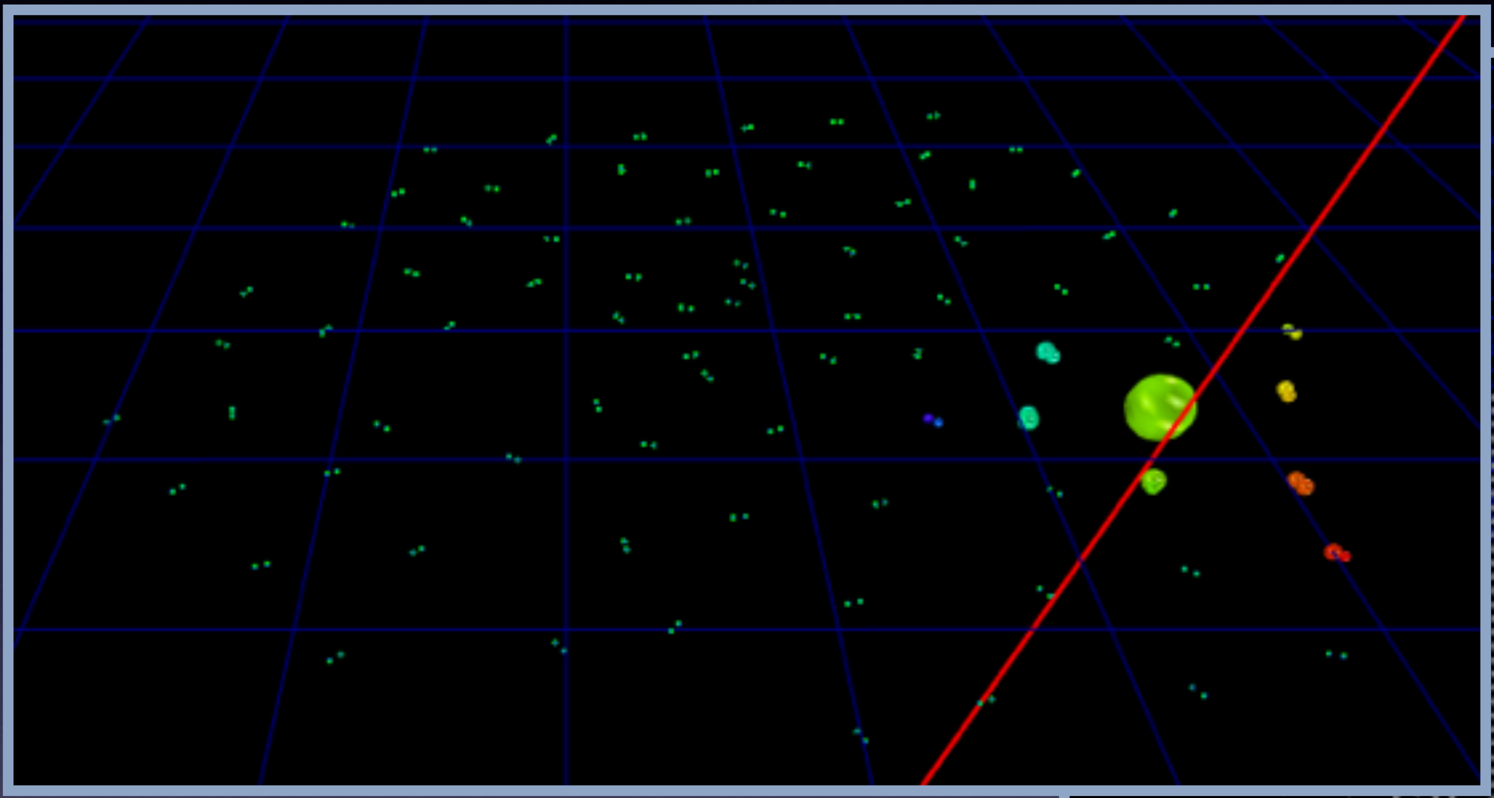
Real Event #1

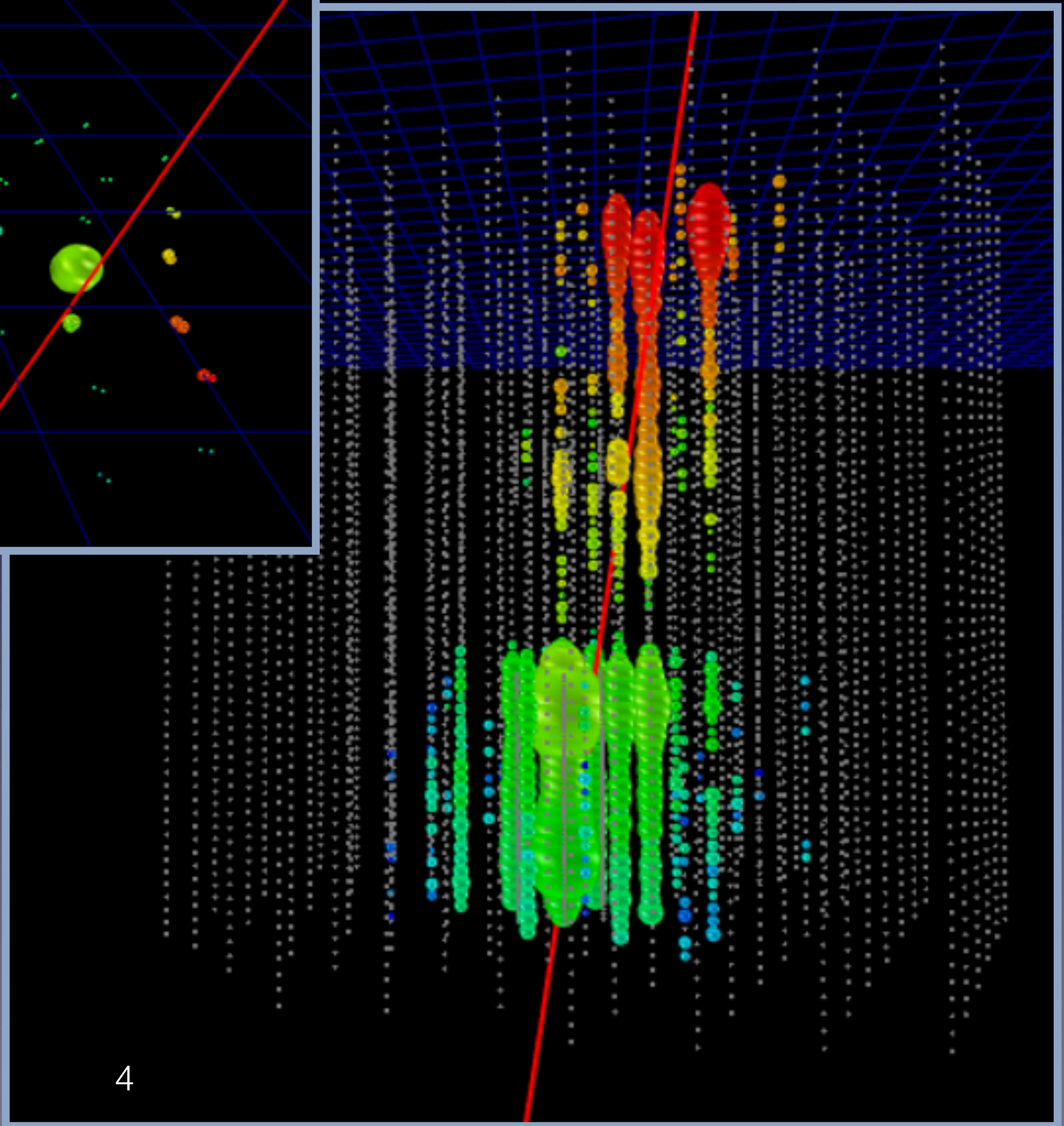




Event	119110-48804723
N_InIce_HLC	419 DOMs
Q_InIce	6,256 PEs
E_muon_BINS	**461 TeV**
N_IceTop_HLC	**6 tanks**
E_surface	**55.7 TeV**
r_IceTop	315 m
b	0.042
chi^2	3.75

Real Event #2





Event	122270-71288137
N_InIce_HLC	506 DOMs
Q_InIce	13,425 PEs
E_muon_BINS	**1,489 TeV**
N_IceTop_HLC	**18 tanks**
E_surface	**1,372 TeV**
r_IceTop	364 m
b	0.077
chi^2	5.04

Event Selection

- Start with IC data
  - Select events with Q > 5000 P.E.
  - Reconstruct Event Track (SPEFit4)
    - Must pass through IT.
- Applied to four years of burn sample (IC79, IC86-1/2/3)

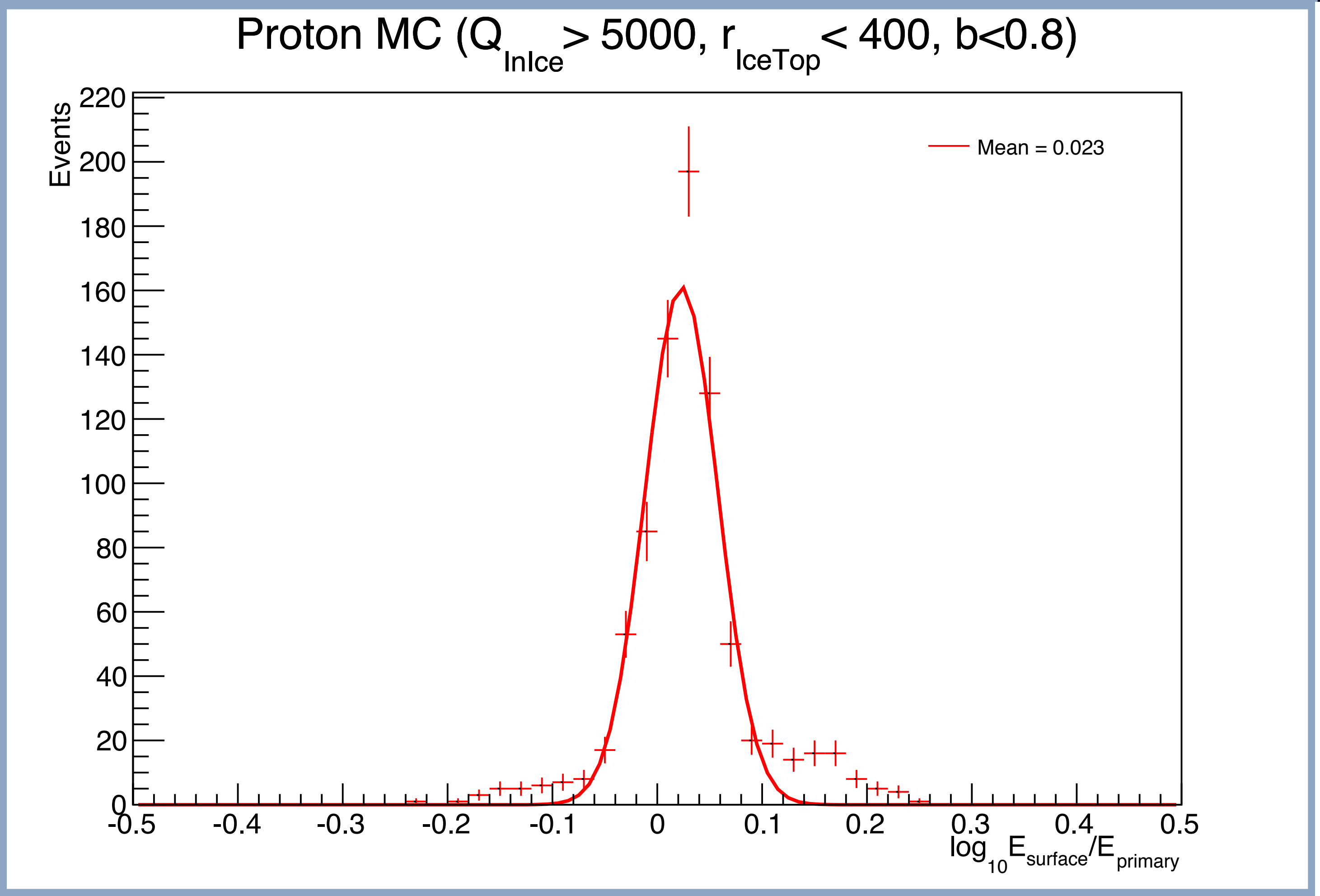
CORSIKA Simulations

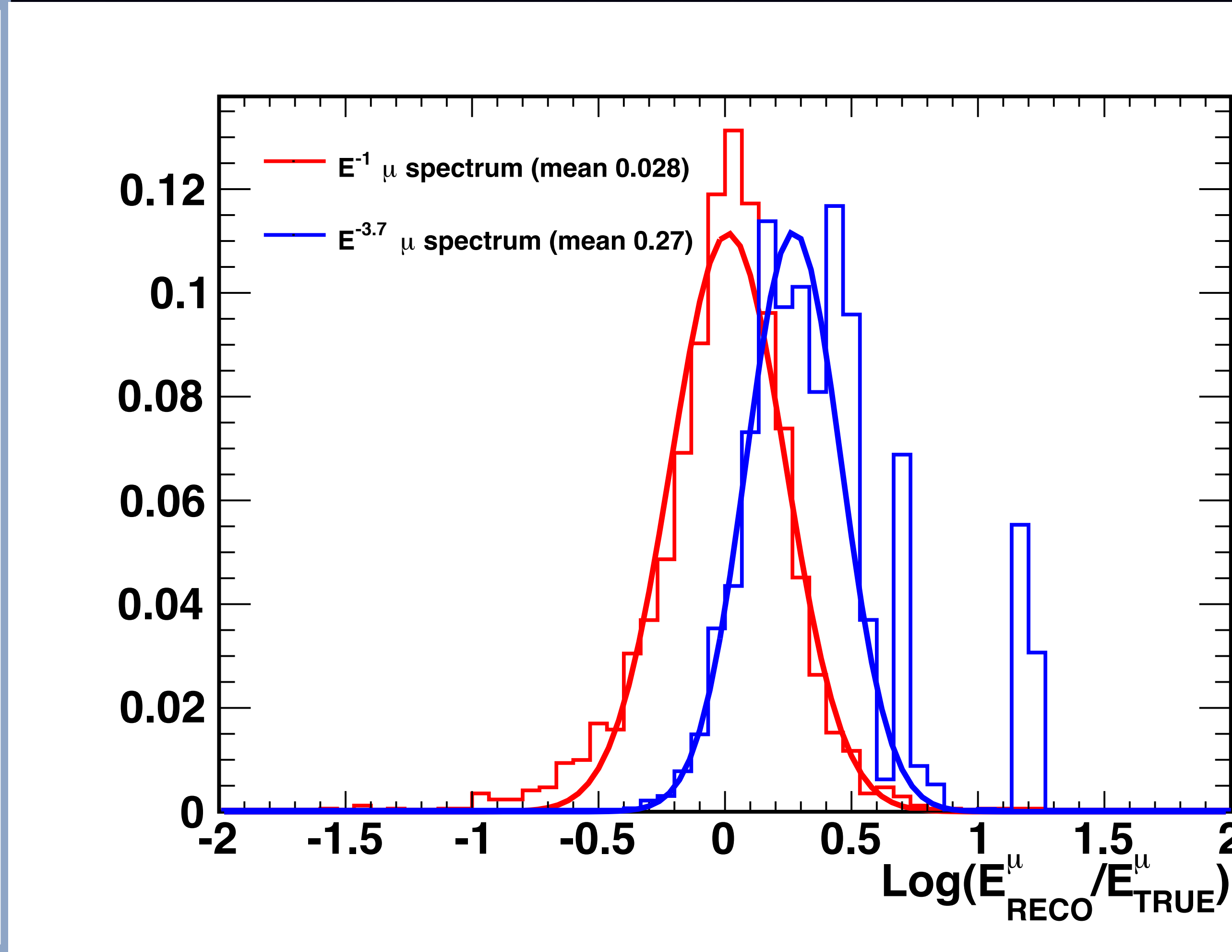
- Proton and Iron Showers
  - 6000000 Showers each (oversampling each shower 100 times)
  - Energy: 100TeV to 100PeV
  - Zenith Angle: 0 to 10 deg
  - E^{-1} spectrum used for generation, reweighted for $E^{-2.7}$
  - SIBYLL 2.1
- Muon Showers
  - 200000 showers (oversampling each shower 100)
  - Energy: 1TeV to 100PeV
  - Zenith Angle 0 to 45 deg
  - E^{-1} spectrum used for generation

Cut Variables of Interest

- IC Total Charge: $Q > 5000$ P.E.
  - Truncated mean used for energy reco.
- Balloon Parameter: $b < 0.8$
  - Highest DOM Q / Total Q of Event
- IT Radius: $r < 400$m
  - Reconstructed track's distance from center of IT.

Energy Reconstruction Distributions

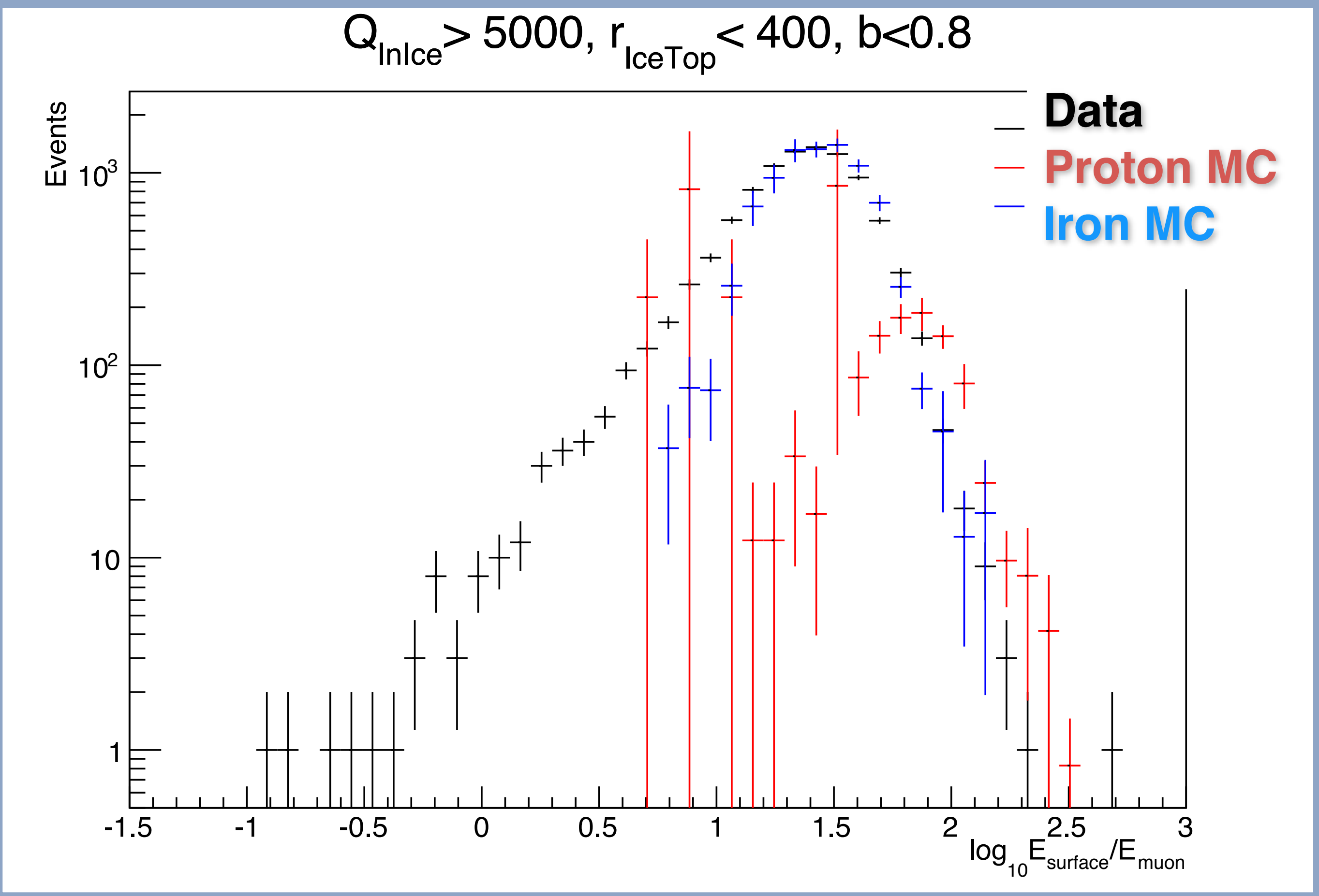


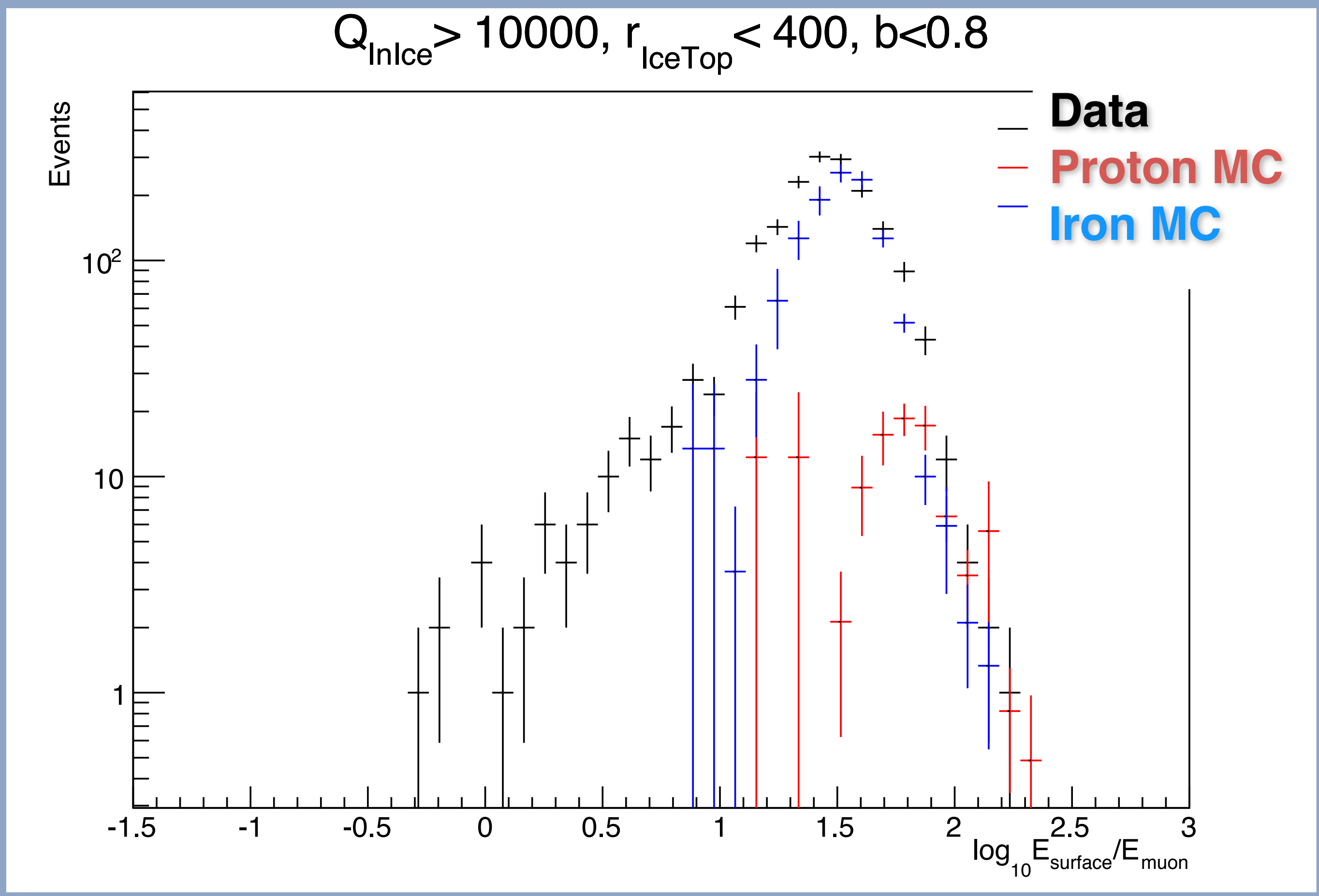


- Ratio of reconstructed surface energy to true primary energy.
- S125 used for Laputop, S80 may be better for the smaller showers.

- Factor of 2 shift going from E^{-1} to $E^{-3.7}$ muon spectrum.

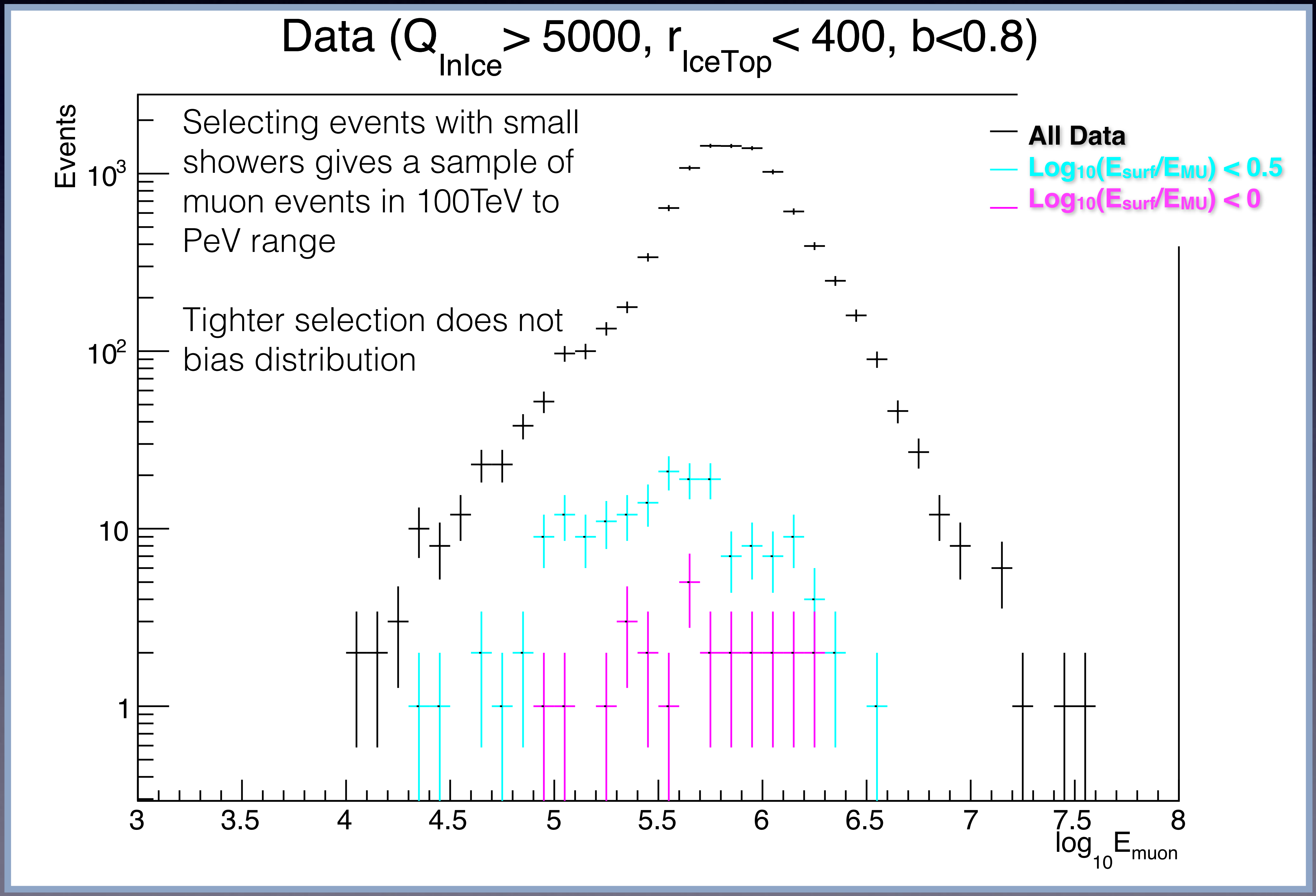
Surface / Muon Energy



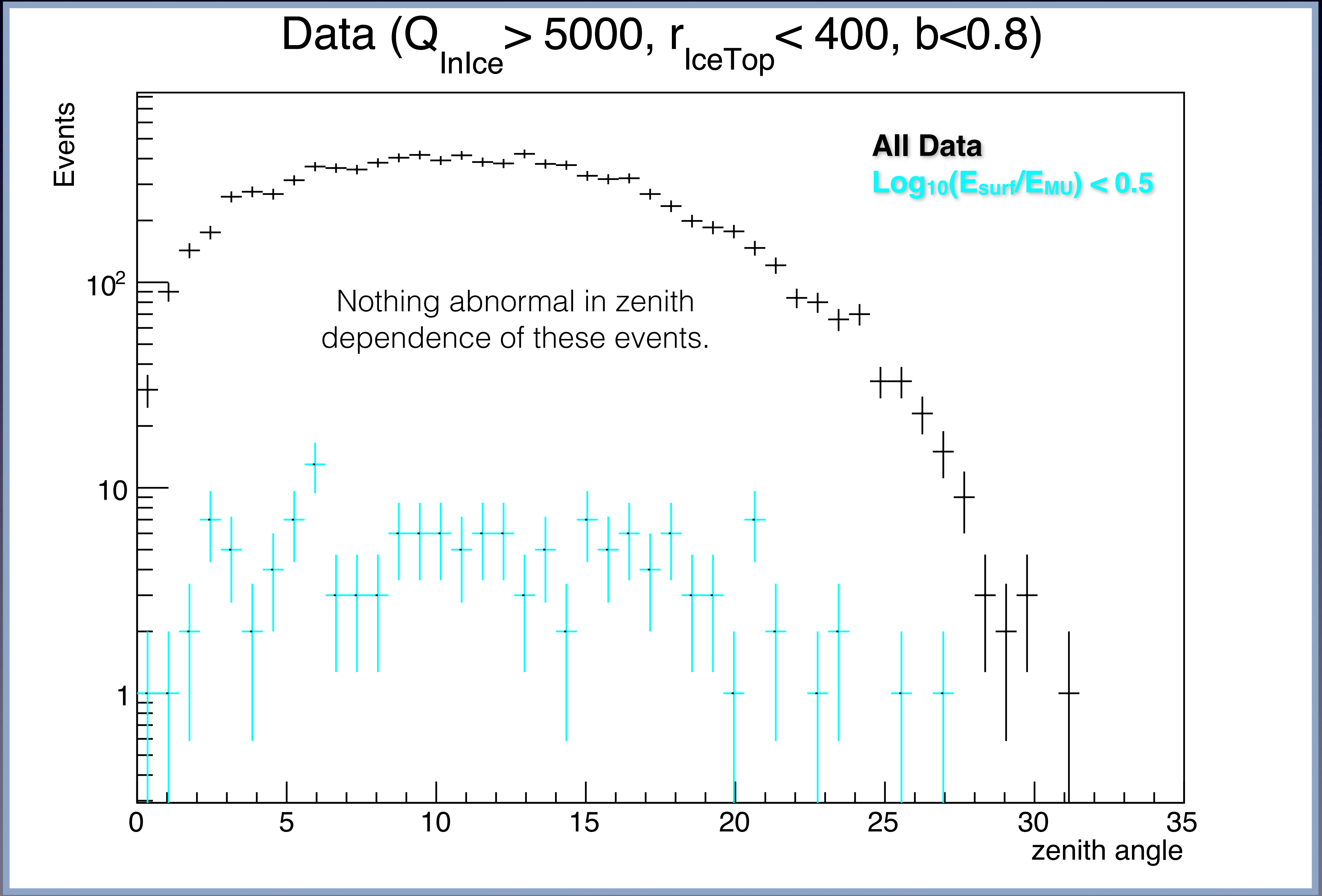


- Peaks at the right place.
- Extended tail at small surface to muon energy.
- Overall distributions look as expected.
- Need more MC

Data: Muon Energy



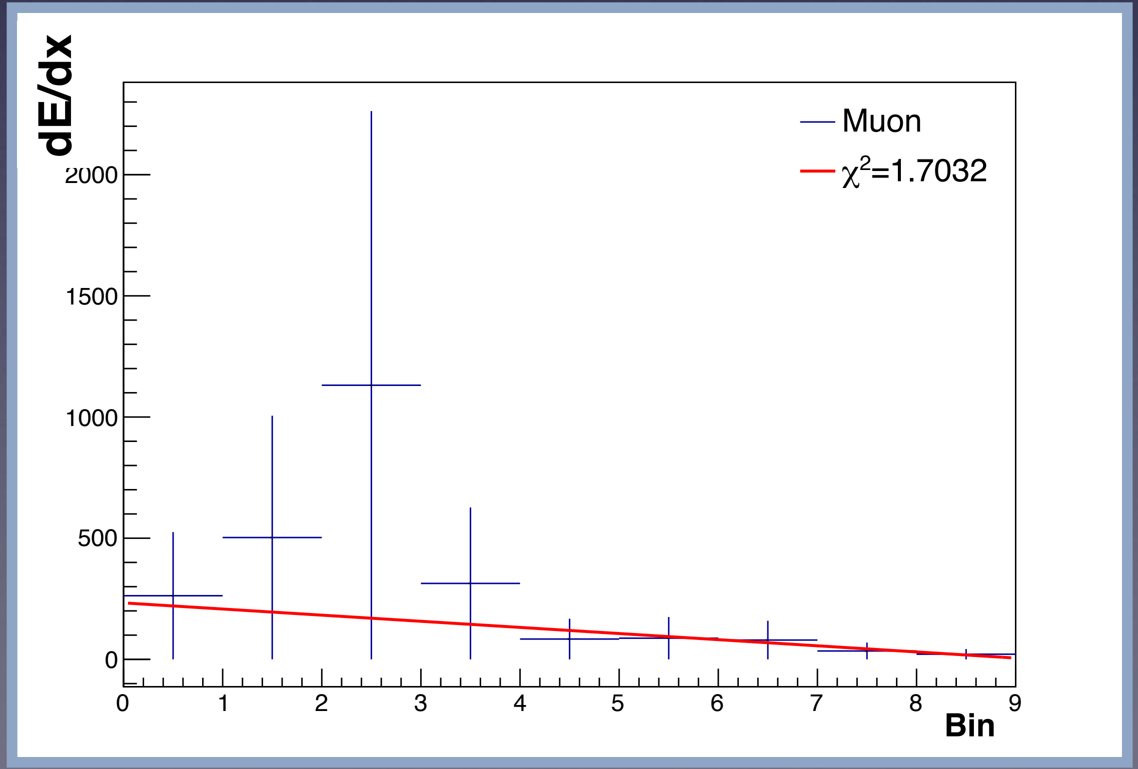
Data: Zenith Angle Distribution



χ^2 Variable

- Muon track binned in 120m width bins
  - >= 6 bins required (720m tracks)
- dE/dx calculated for each bin
- Linearly fit dE/dx

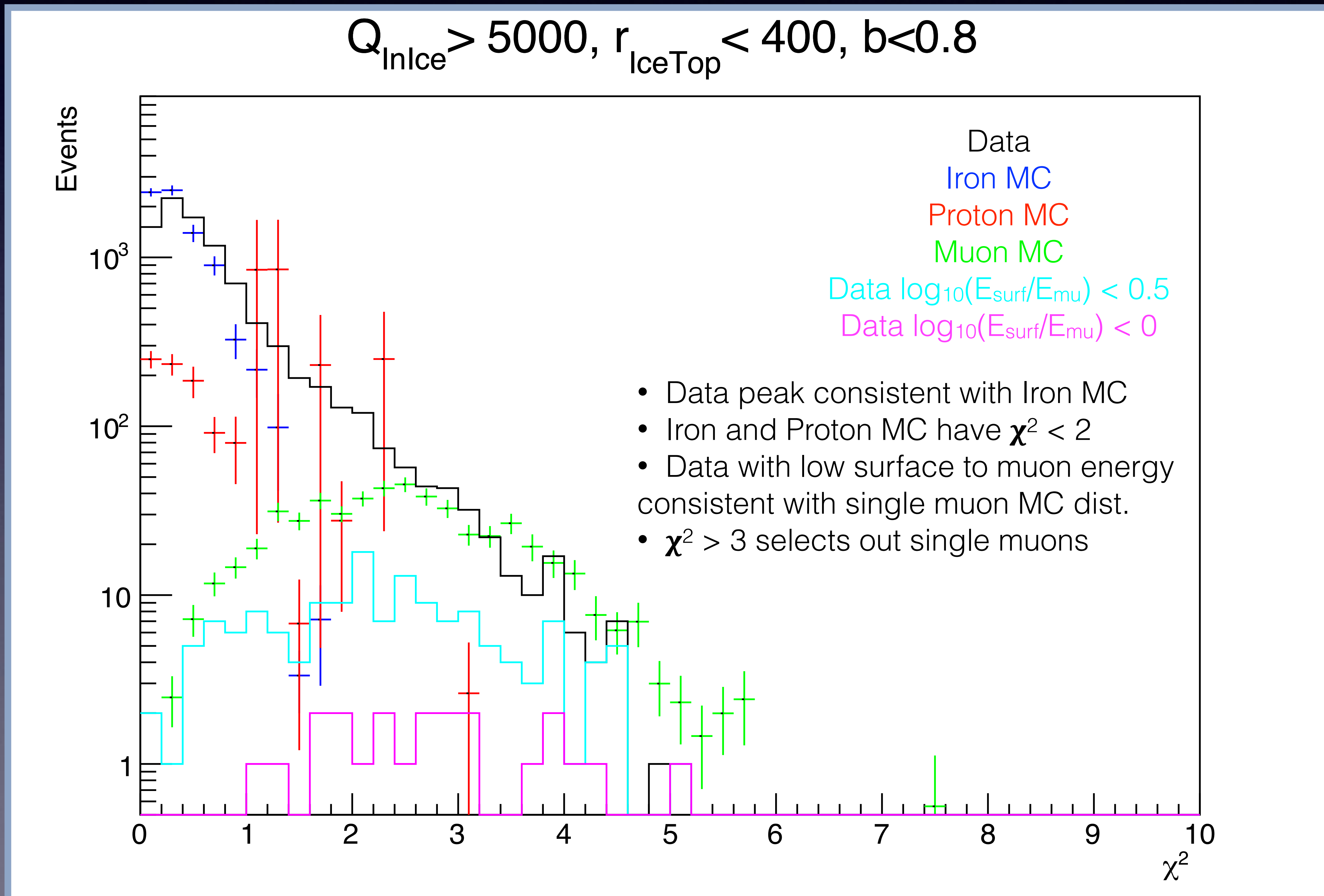
$$\chi^2 = \sum_{i=1}^{N_{bins}} \frac{(\frac{dE}{dx}_i - f(i))^2}{\sigma_i^2}$$



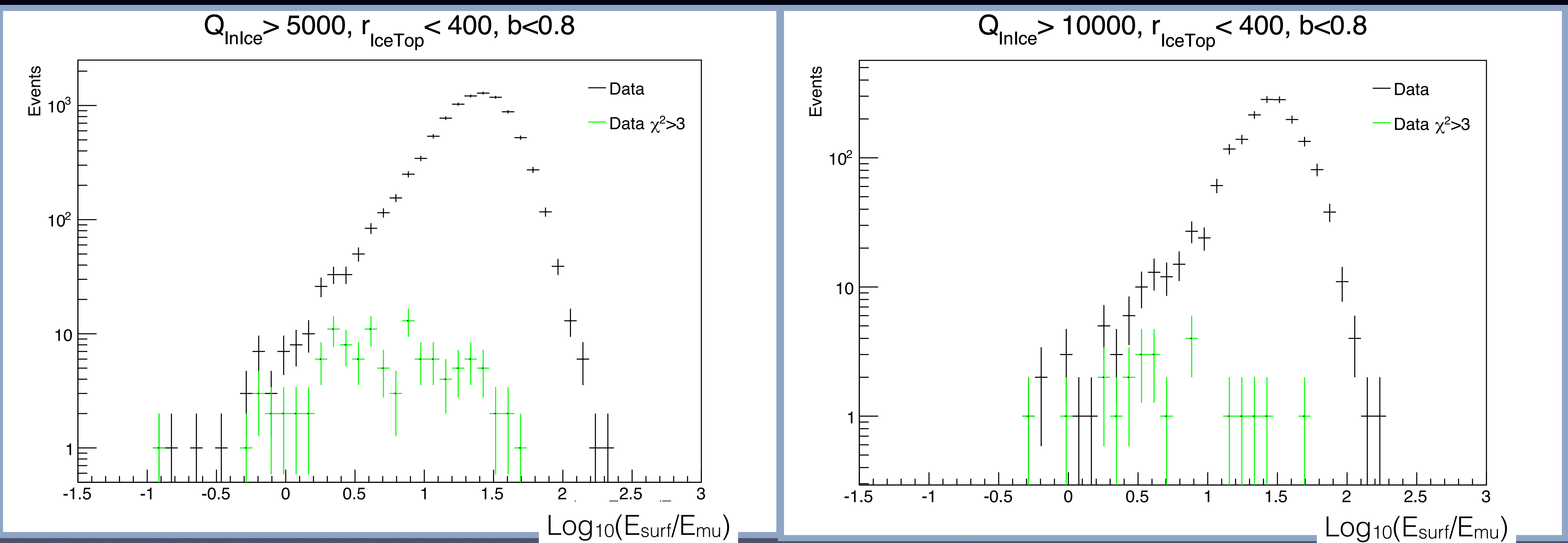
χ^2 for Single Muon vs Bundle

- Single muons exhibit much more dE/dx variation than bundles due to their stochastic losses.
    - High $\chi^2 \rightarrow$ single muon
    - Low $\chi^2 \rightarrow$ muon bundle

χ^2 Distributions

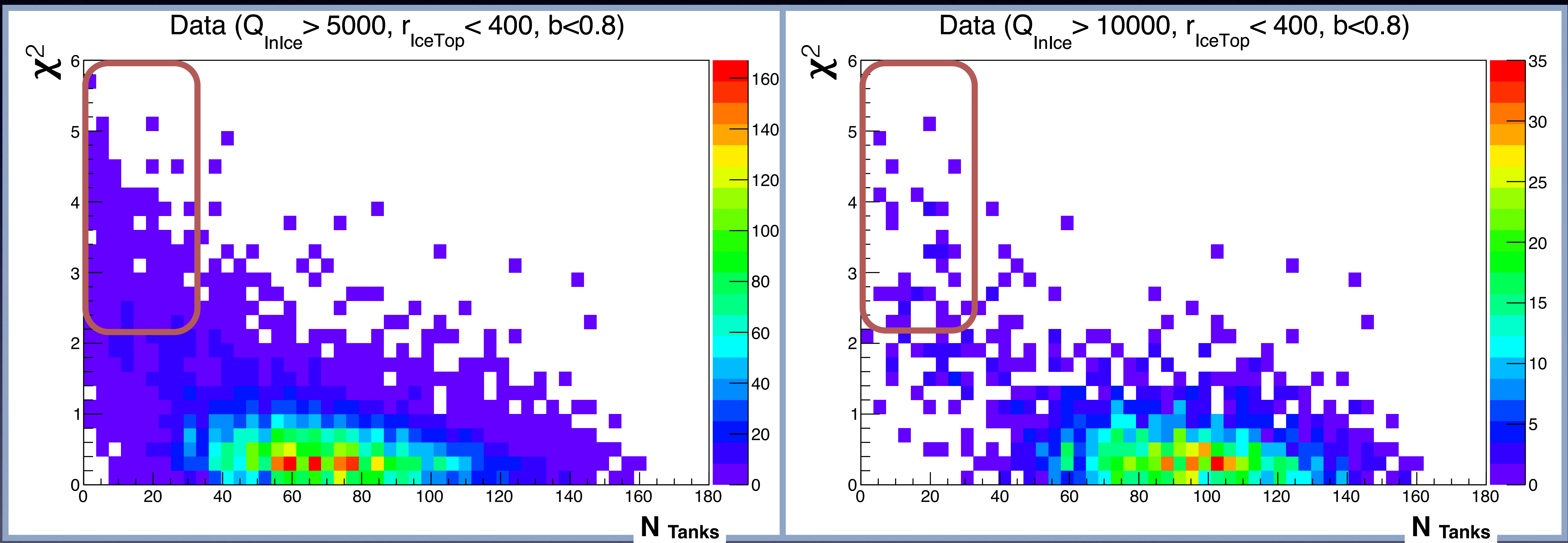


χ^2 > 3 Cut



- χ^2 > 3 cut selects events with low surface to muon energy
- Gives an idea of expected rate of these single muon events

χ^2 vs Number IT Tanks



Events with high χ^2 have small number of IT tank hits.
Events with low number of IT tanks hit ⟶ low surface energy
High χ^2 ⟶ single muons

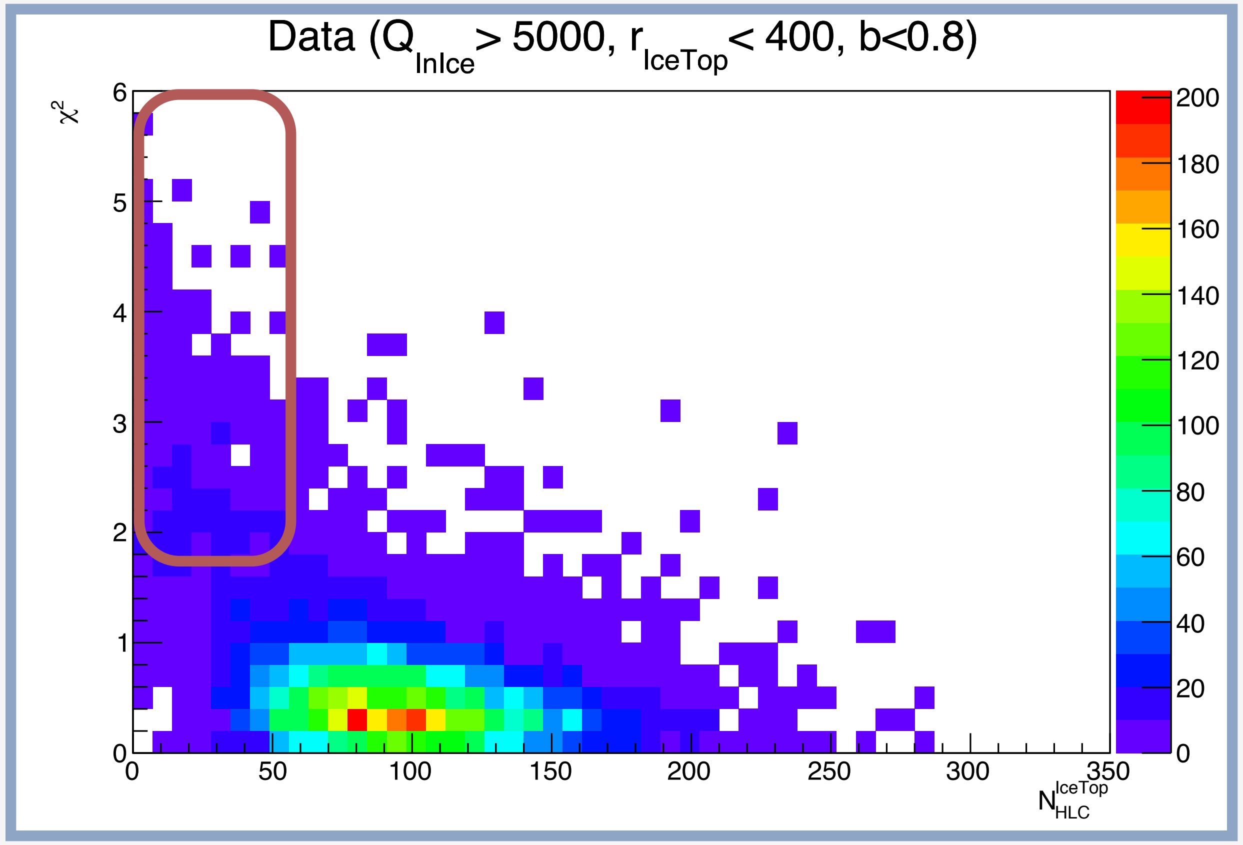
100TeV to PeV single muons with low accompanying EM showers

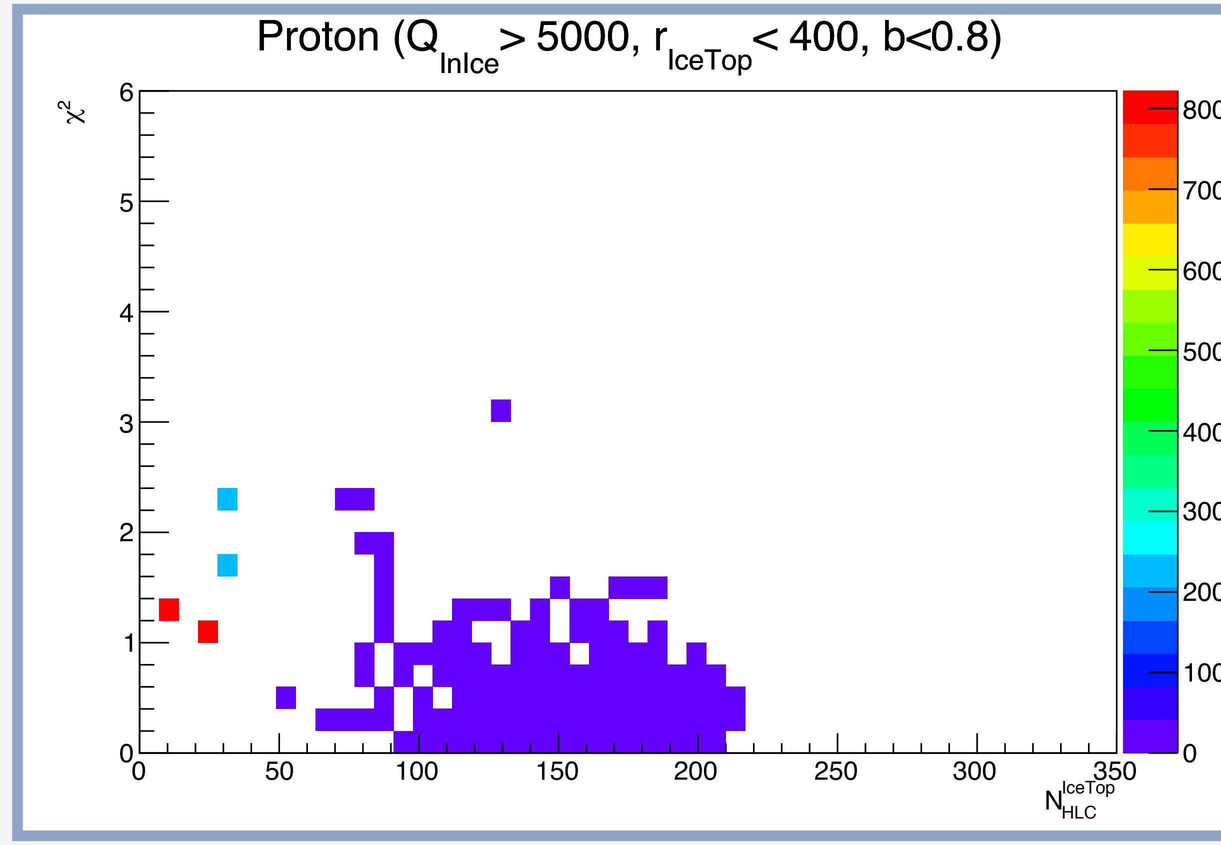
Conclusions

- Small surface to in-ice muon energy suggests these muons are produced at high Feynman-x.
- The events observed are consistent with single muons because of their high stochasticity.
- The energy of these muons suggests they may be prompt.
- Better targeted simulations are coming very soon and will be followed by an unblinding request.

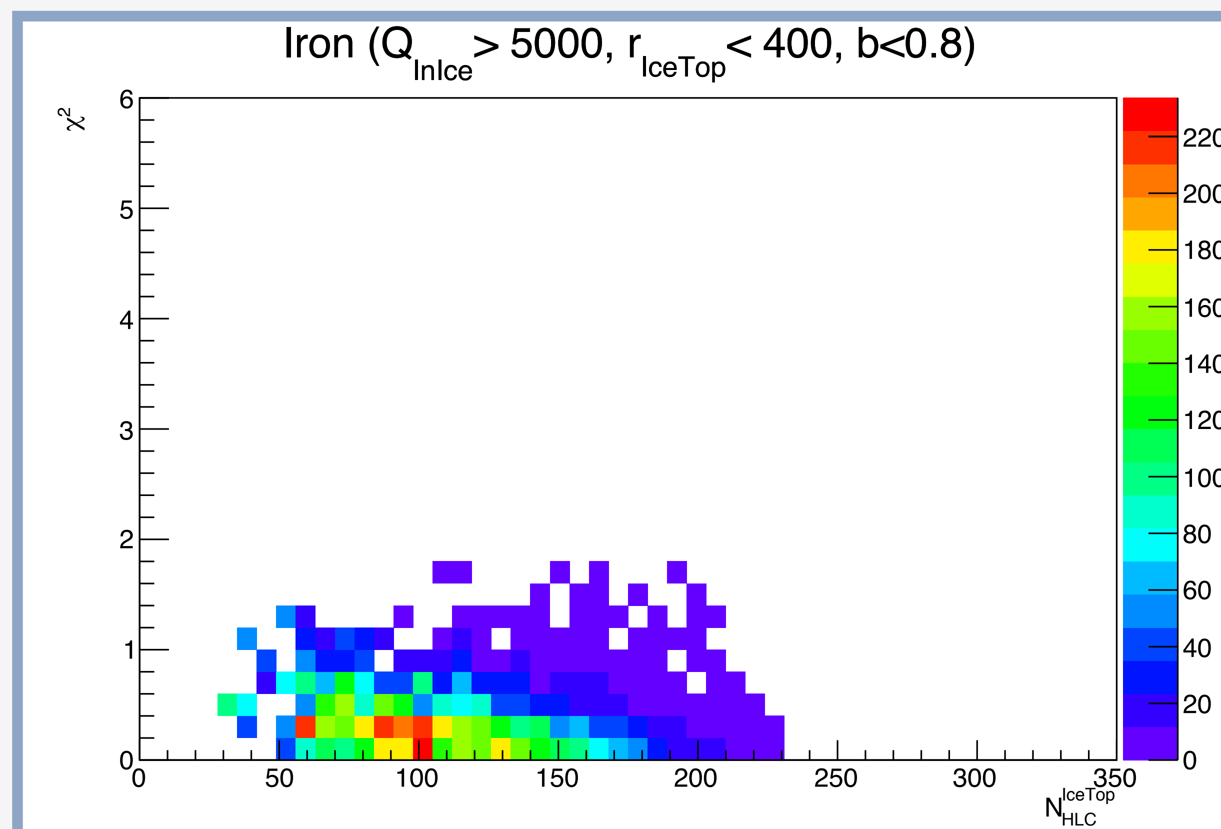
Thank you for your attention.

N_IceTop_HLC vs chi^2

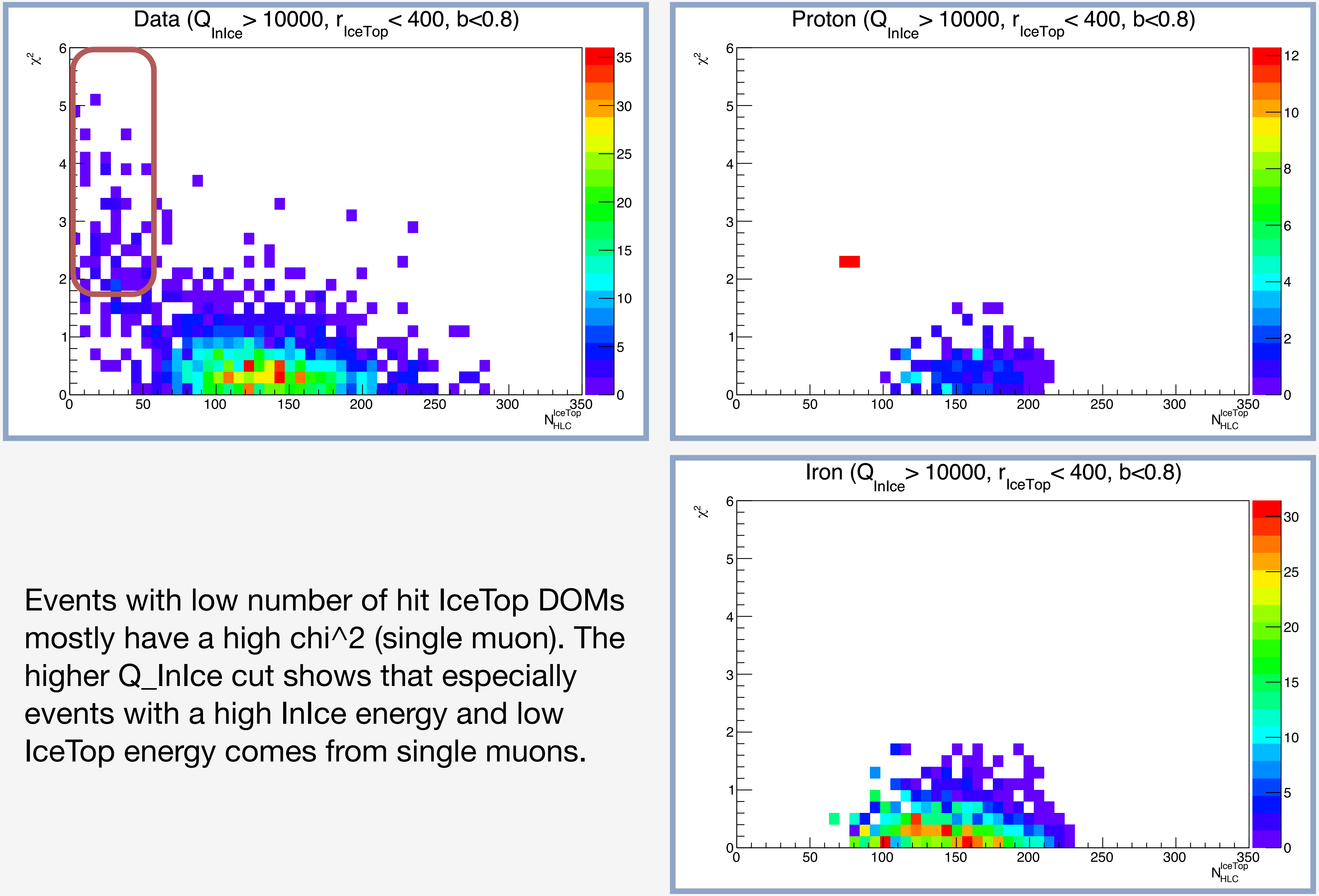




Events with low number of hit IceTop DOMs mostly have a high chi^2 (single muon). Note that IceTop energy threshold plays a role.

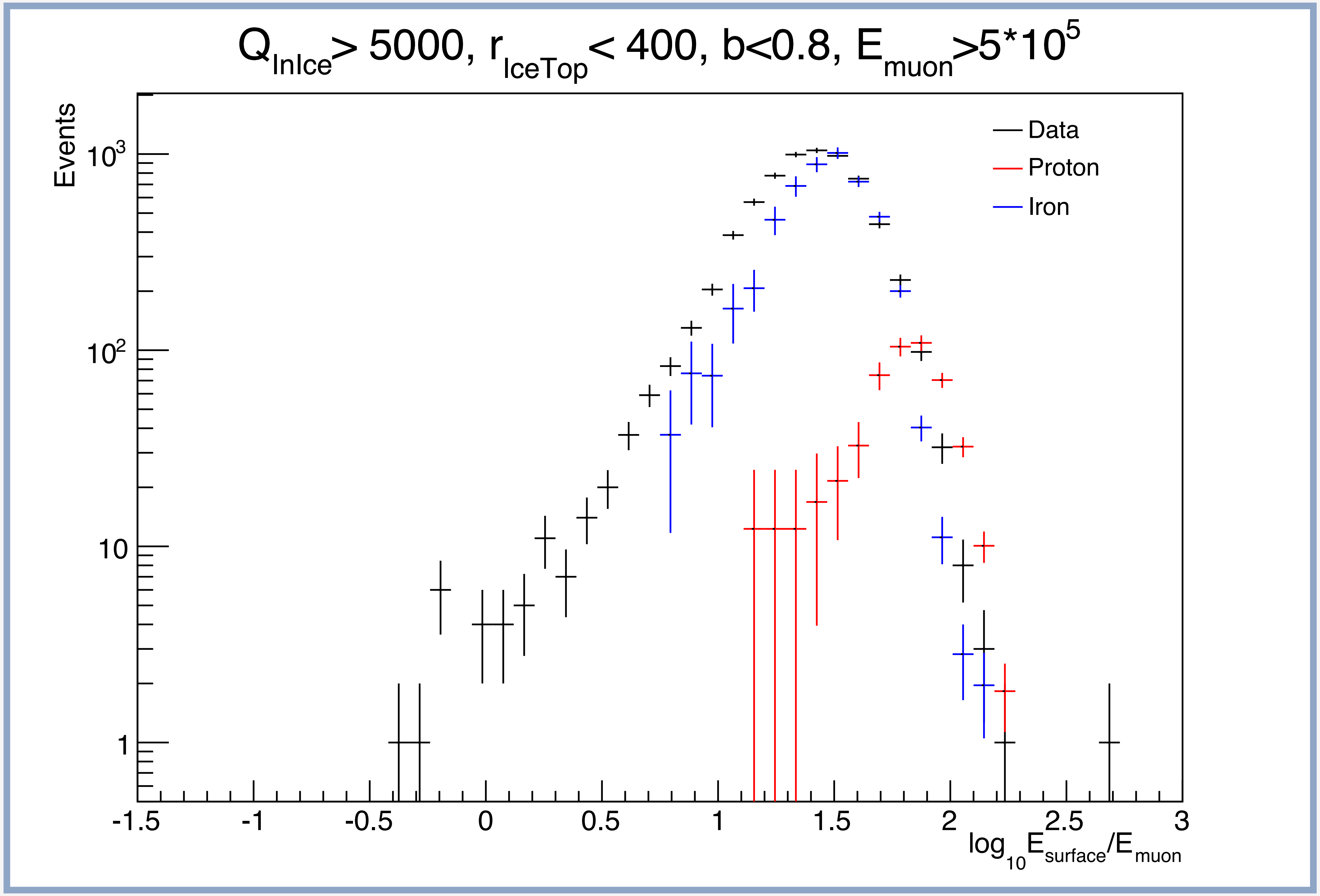


N_IceTop_HLC vs chi^2

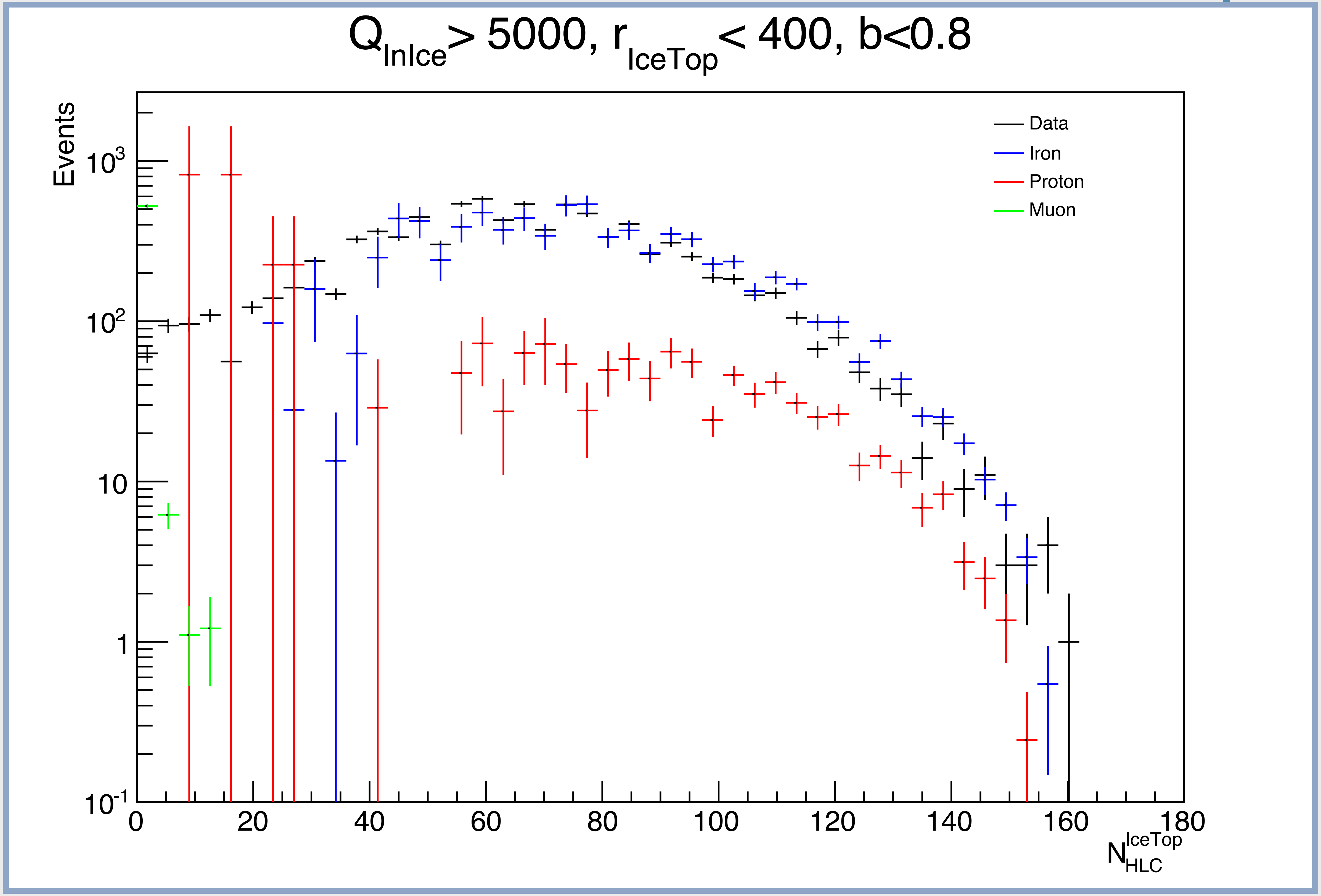


Events with low number of hit IceTop DOMs mostly have a high chi^2 (single muon). The higher Q_InIce cut shows that especially events with a high InIce energy and low IceTop energy comes from single muons.

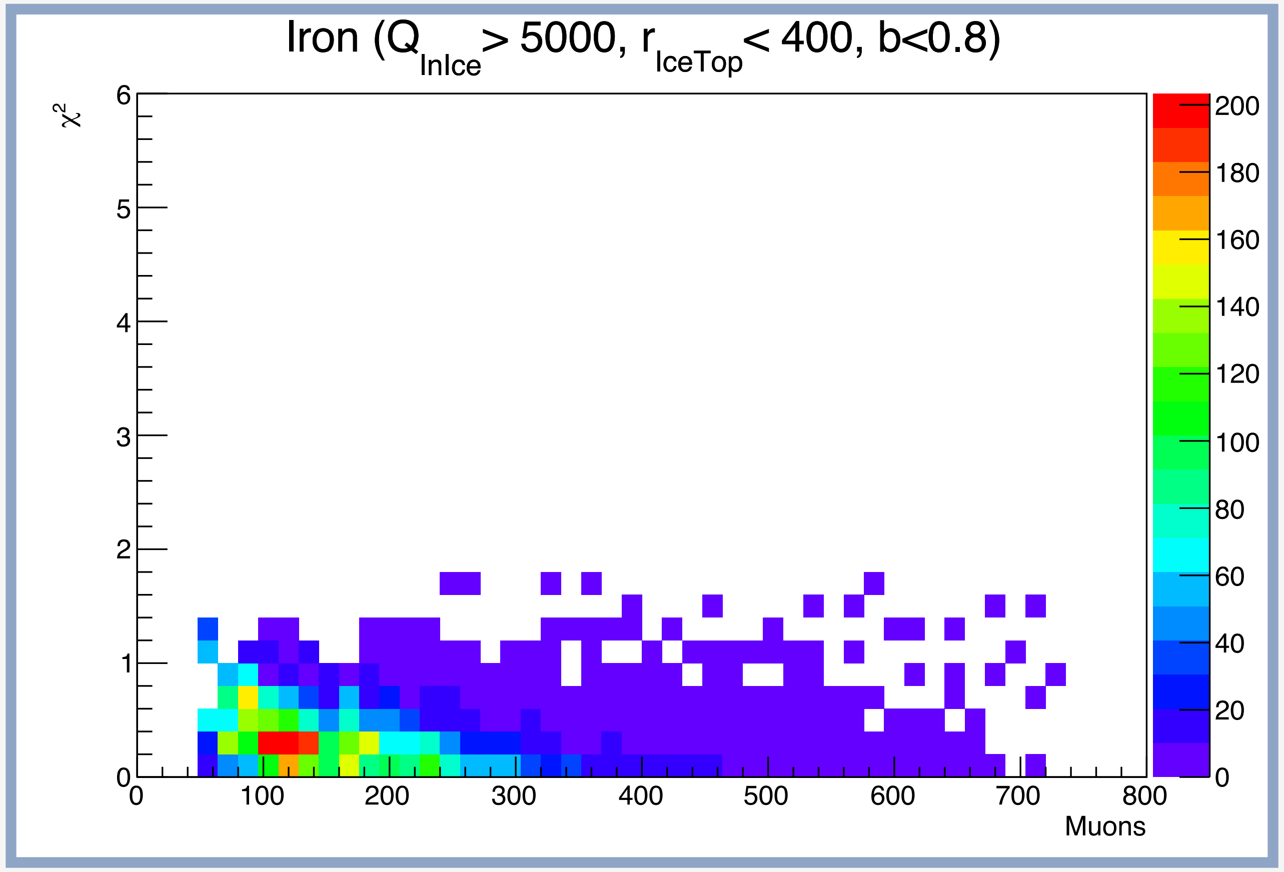
Ratio of surface and muon energy

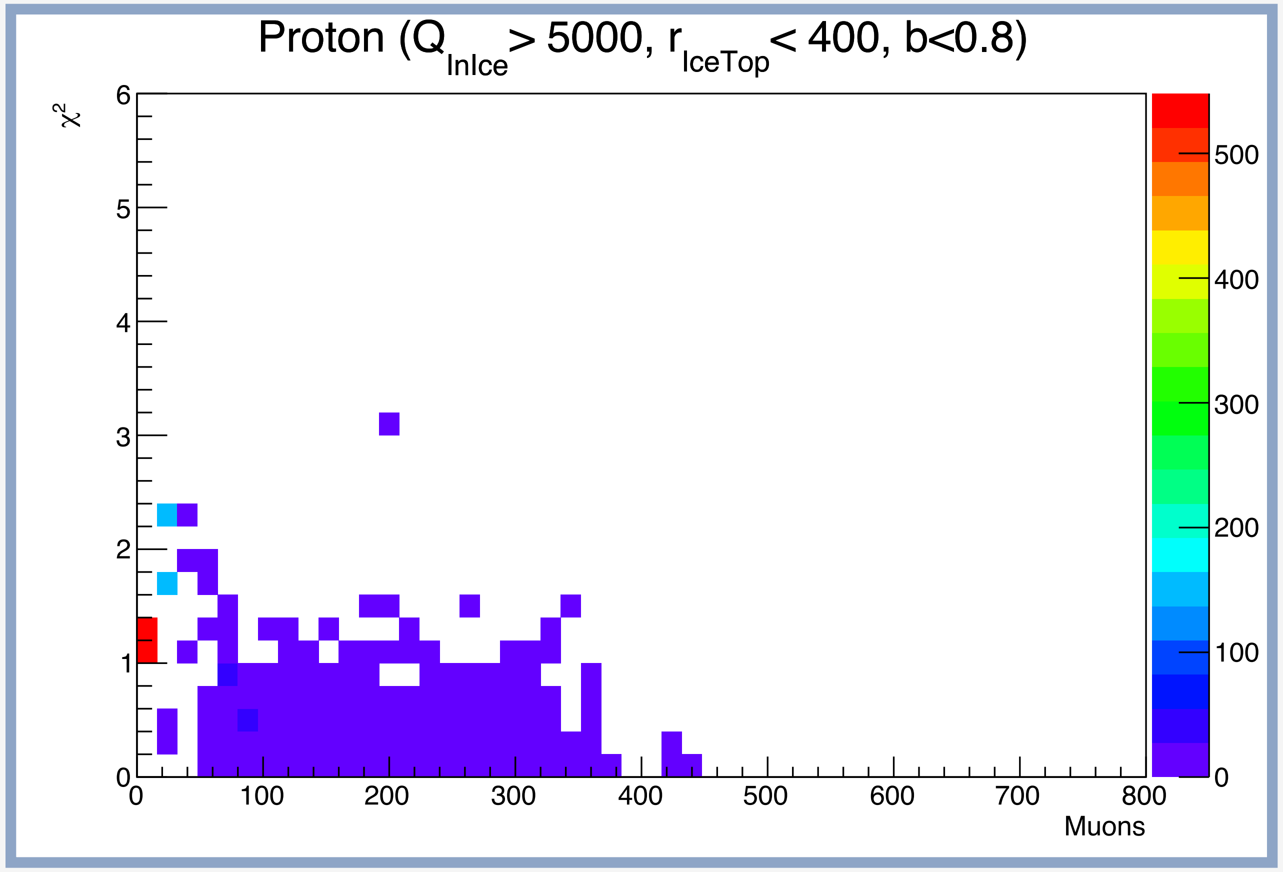


Number of hit TANKS in IceTop



Muons vs chi^2





N_IceTop_HLC vs chi^2 - Q>15000