$\nu_\mu + Ar \rightarrow \mu^- + p$ channel selection in SAND

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DUNE Italia Collaboration Meeting – LNF

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Purpose

- Assess the contributions SAND (with GRAIN) could provide in understanding the physics of $\nu_\mu + Ar$ interaction including FSI

- Here we exploit GRAIN as homogeneous calorimeter
  - Study the effect of the spill structure on the calorimetric capabilities of GRAIN

- Performaces of SAND in terms of selecting and reconstructing exclusive $\mu^- + p$ channel are studied

Caveat and References

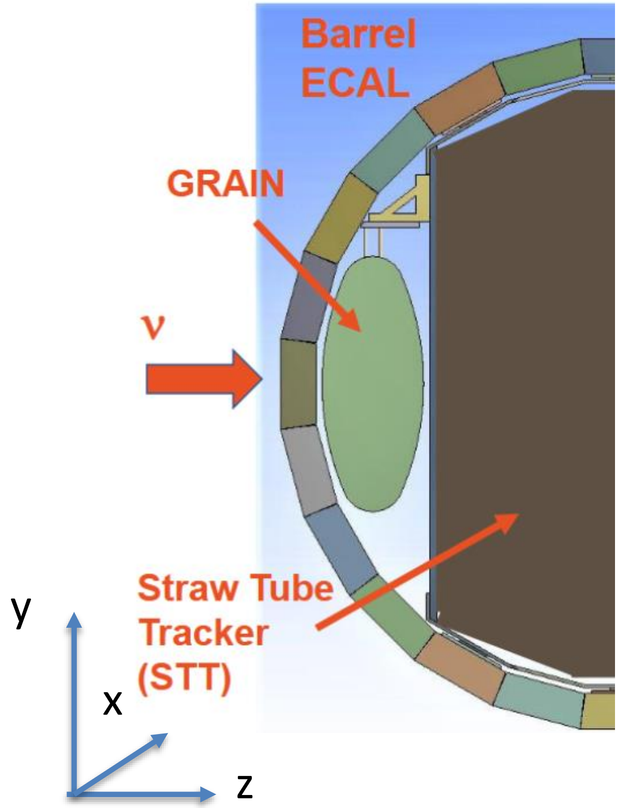
- Work in progress
- Final results are preliminary
- Repositories:
  - baltig.infn.it/dune/analyses/grain-physics-case
  - baltig.infn.it/dune/sand-optical/opticalmeniscus

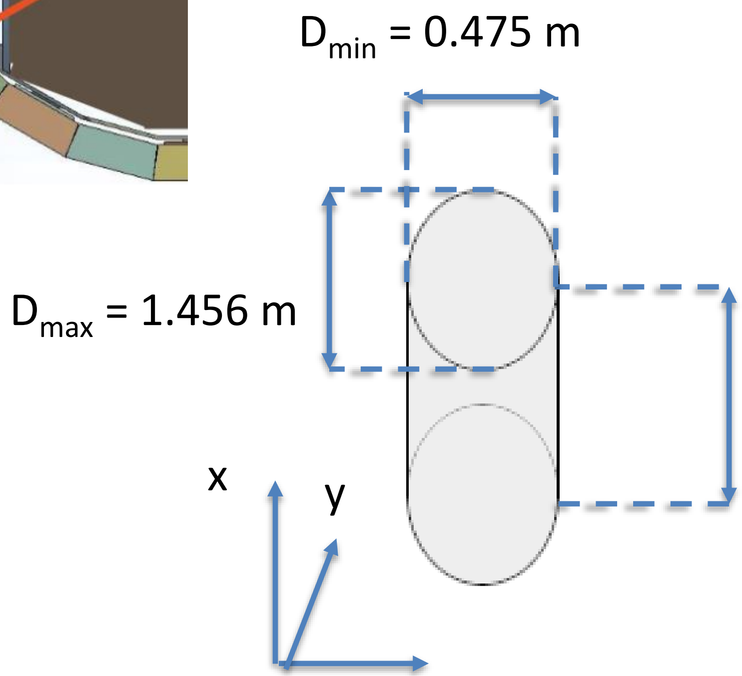
MC Sample

- 8.2M $\nu_\mu - Ar^{40}$ (CC+NC) interactions generated by GENIE 2.12.10
- Muon neutrino energy spectrum: FHC
- Beam direction: along z
- Neutrino interactions are uniformely distributed in LAr volume inside GRAIN
- Particles are propagated with edep-sim

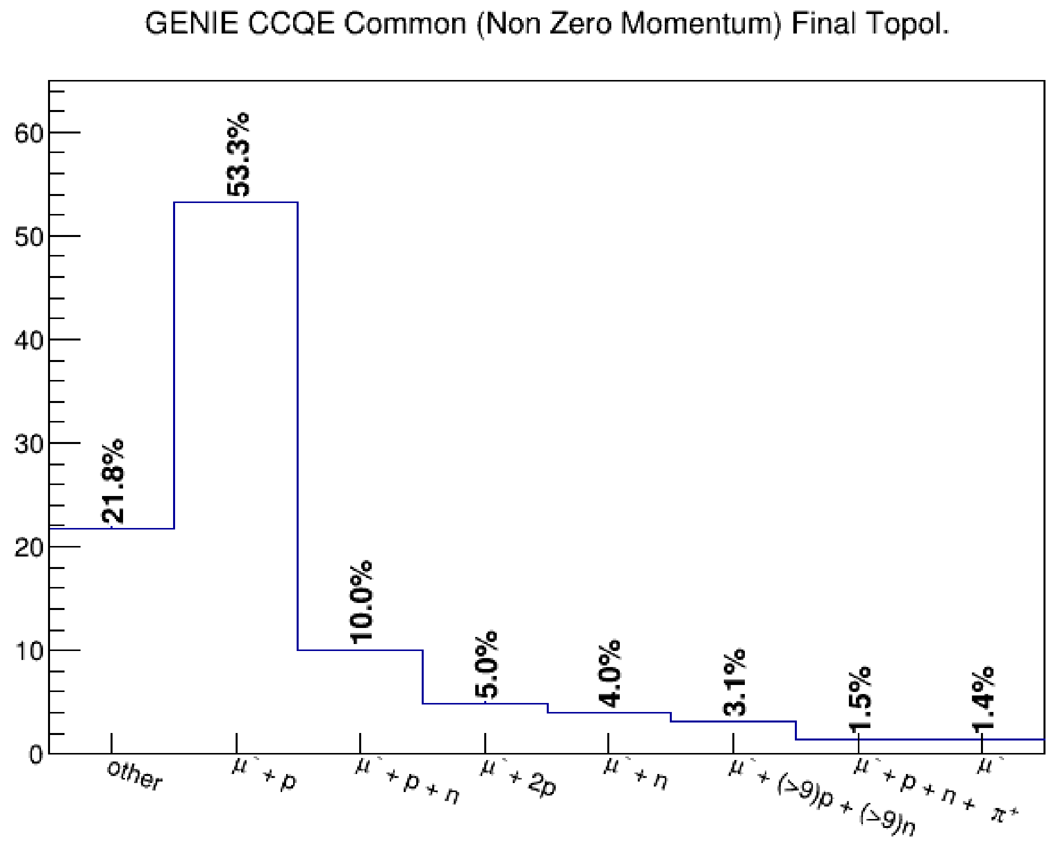
Reconstruction

- SAND detector is composed by:
  Magnet, ECAL, GRAIN and STT
- STT tracks reconstructed by [FastReco]
- ECAL clusters reconstructed by [sand-reco]
- GRAIN as calorimeter with 10% energy resolution
- Particle ID is assumed

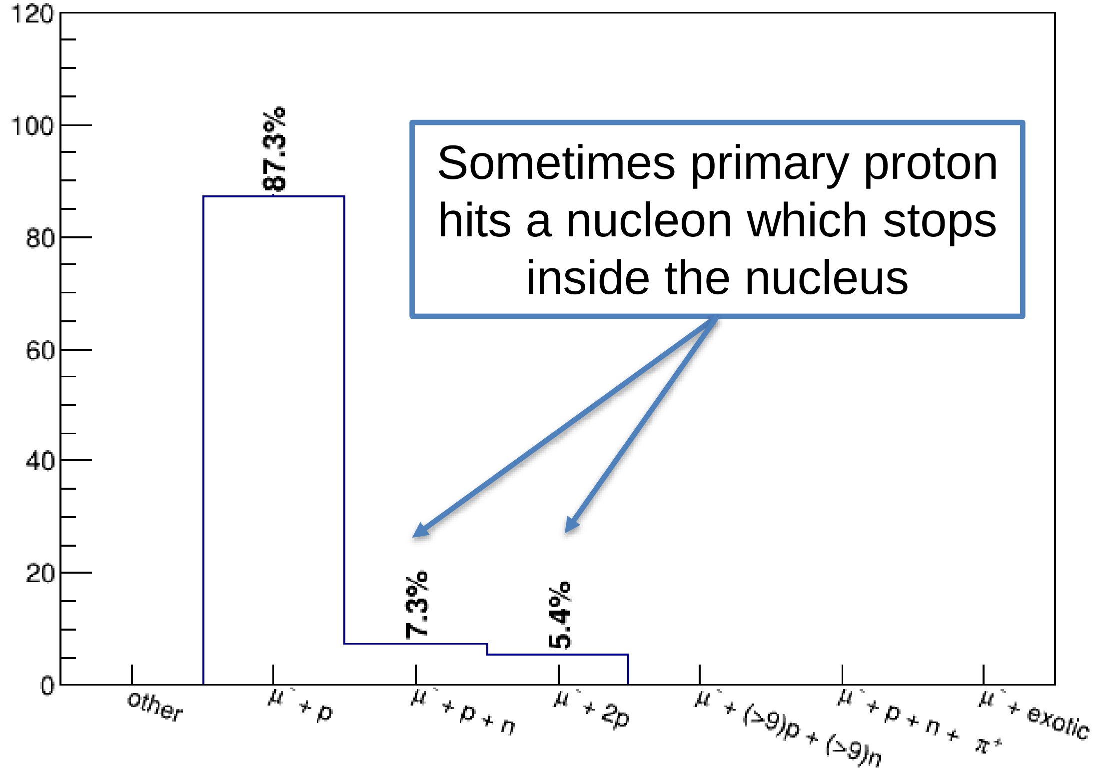




Common Final Topologies (CCQE)



$\mu^- + p$ channel



CCQElike Selection

1. Only 1 muon and 1 proton tracks reconstructed by STT

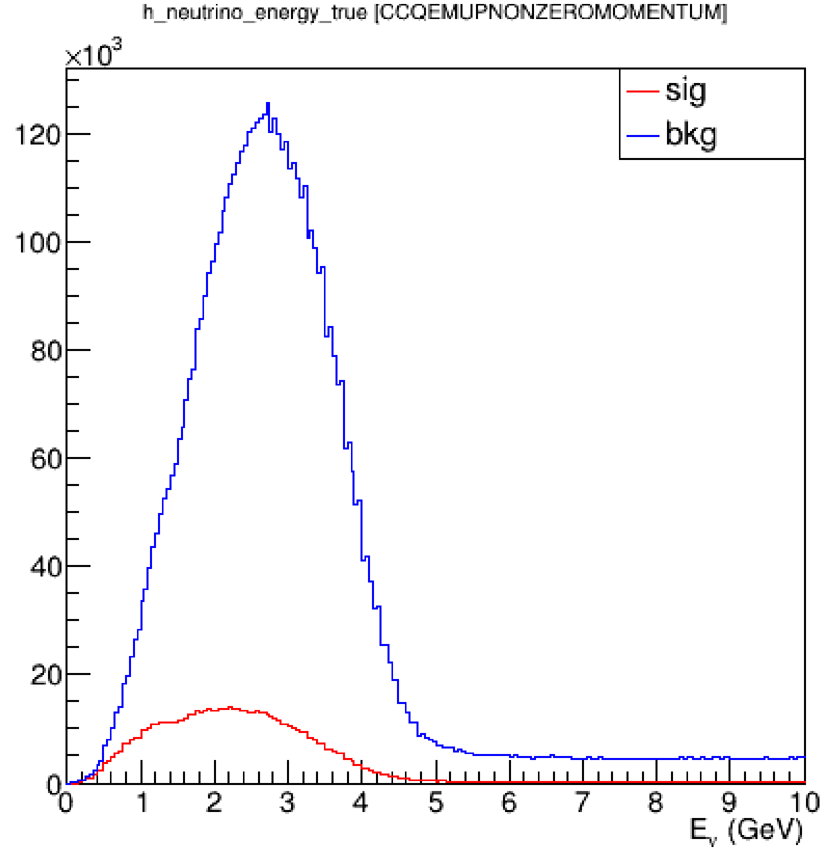
2. Reconstructed energy in GRAIN compatible with energy release expected by 2 mip.
   - [vtx position in GRAIN reconstructed using STT tracks]

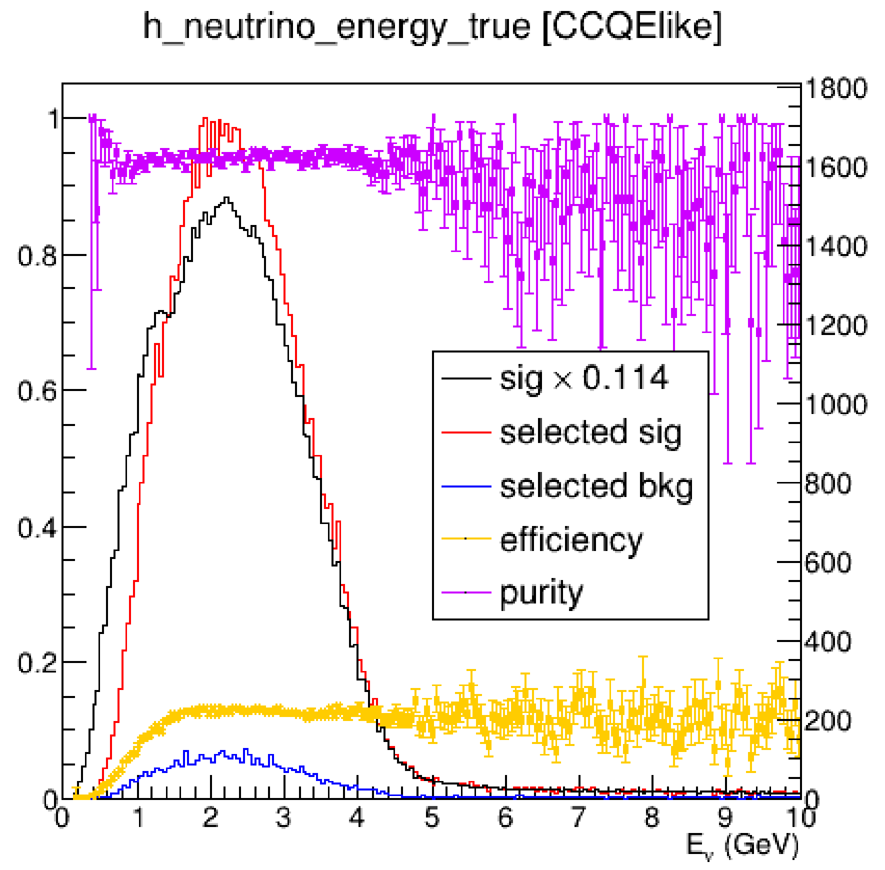
3. No unmatched clusters in ECAL

CCQElike Efficiency

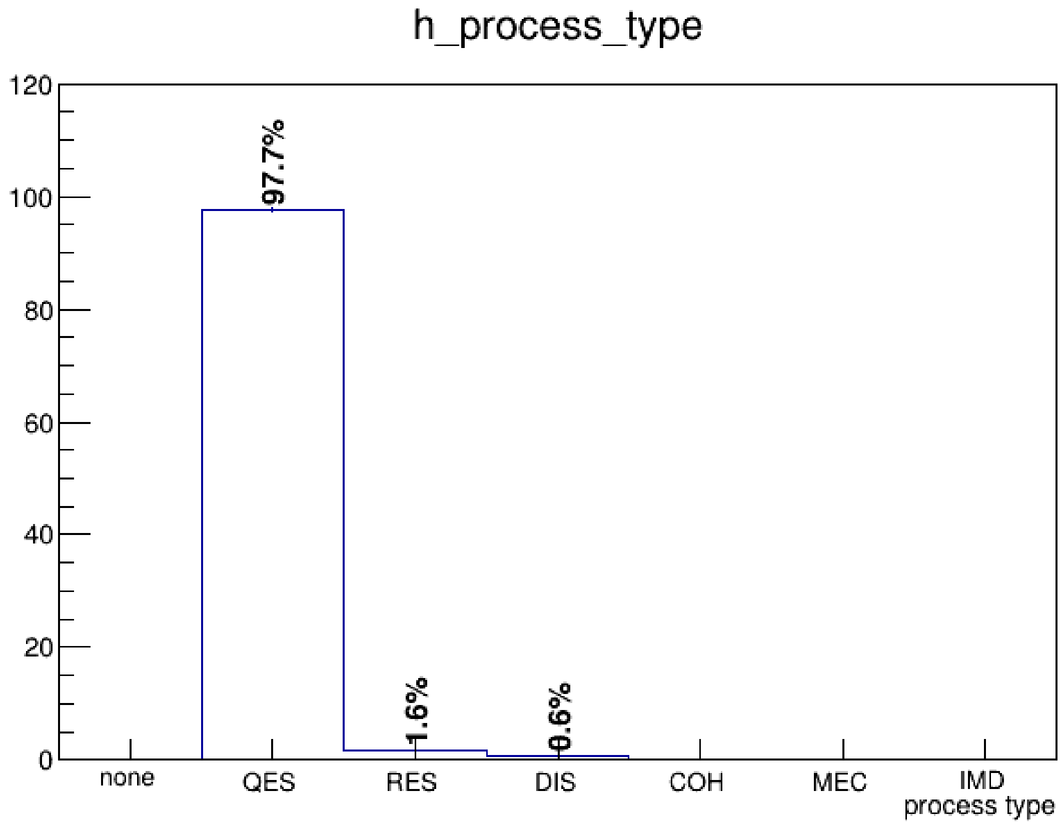
```
ALL                  : 8200000
SIGNAL               : 764398
SELECTED             : 93226
SELECTED SIGNAL      : 87358
SELECTED BACKGROUND  : 5868
SELECTION EFFICIENCY : 11.4%
SELECTION PURITY     : 93.7%
```

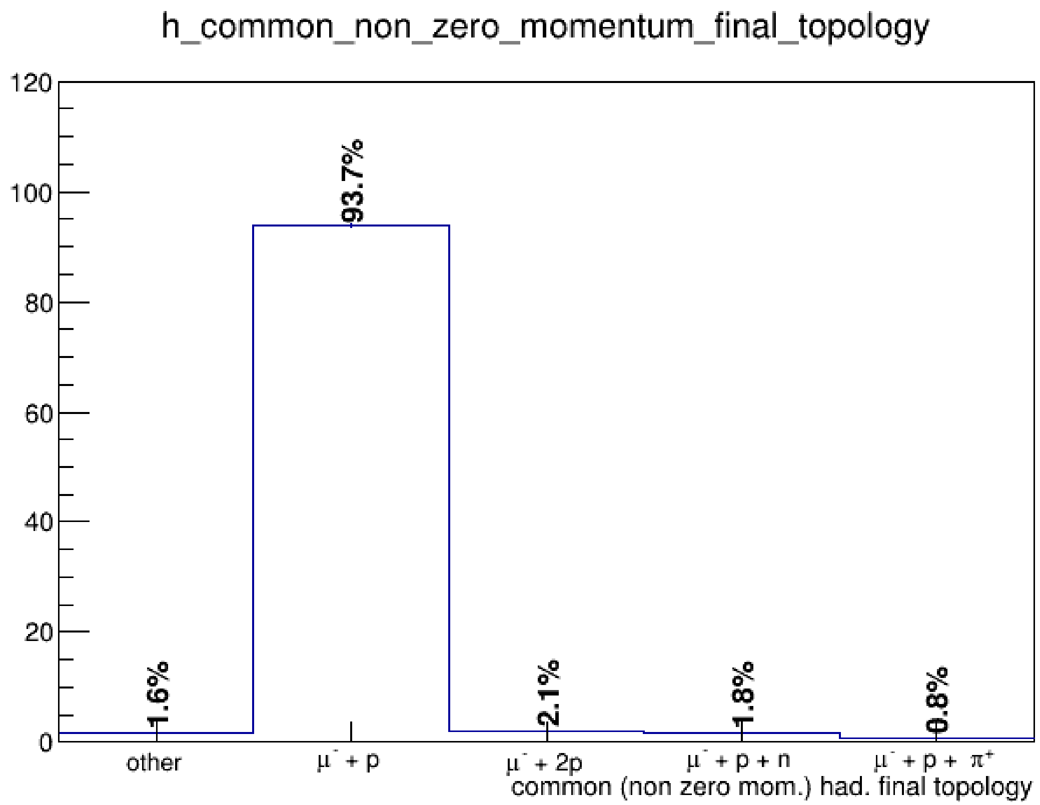
Signal: $\mu^- + p$ channel
Selection: CCQElike



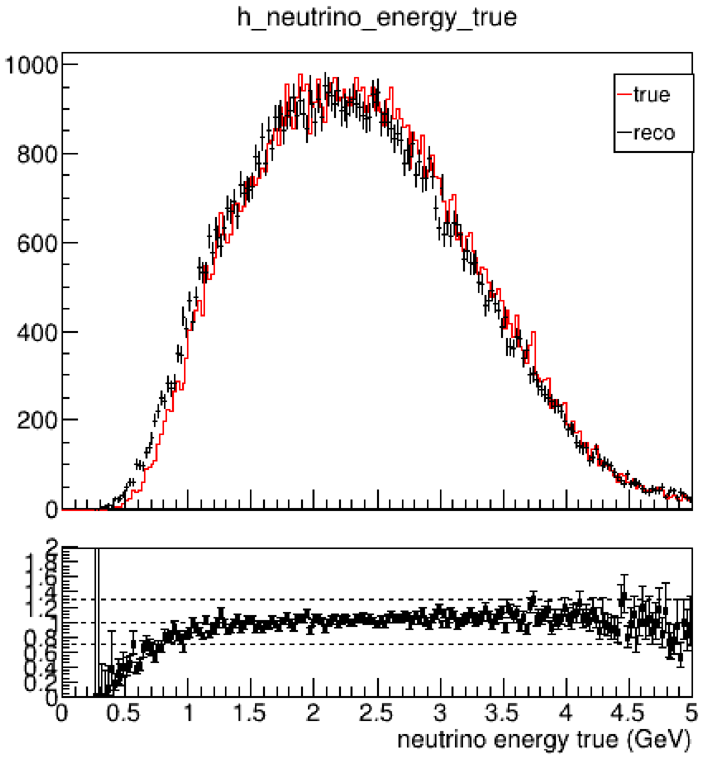


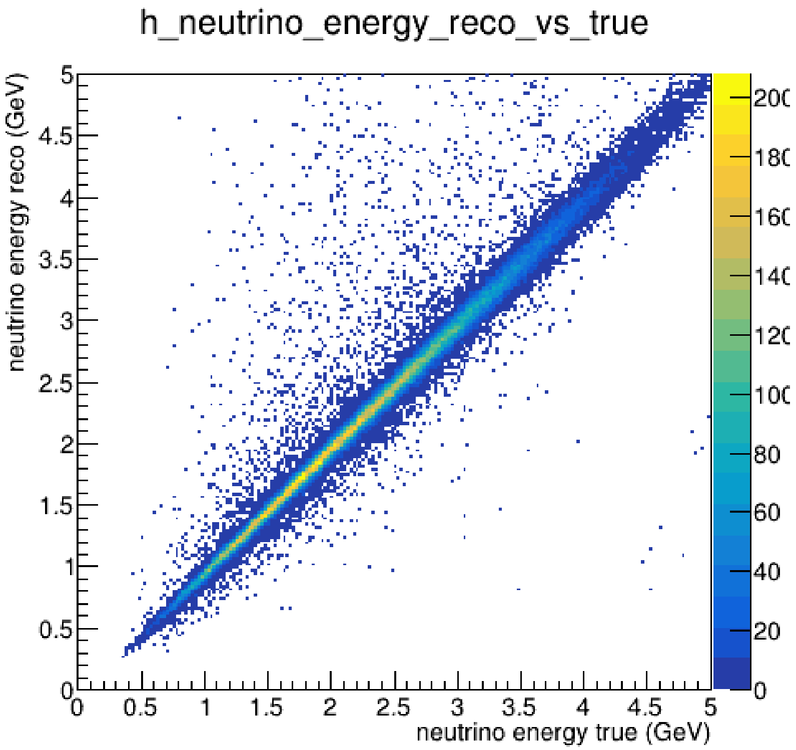
CCQElike Sample

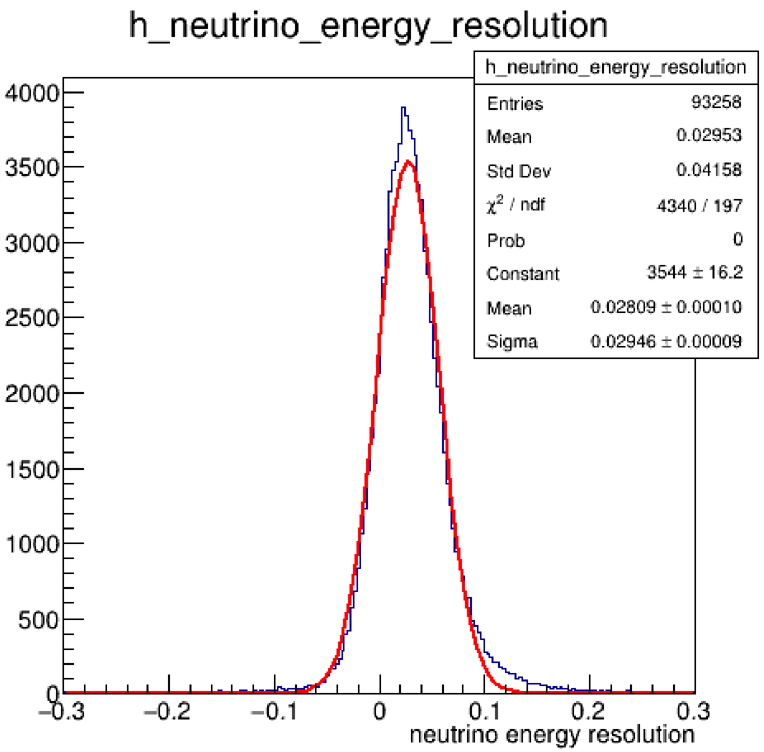




Neutrino Energy Reconstruction in CCQElike

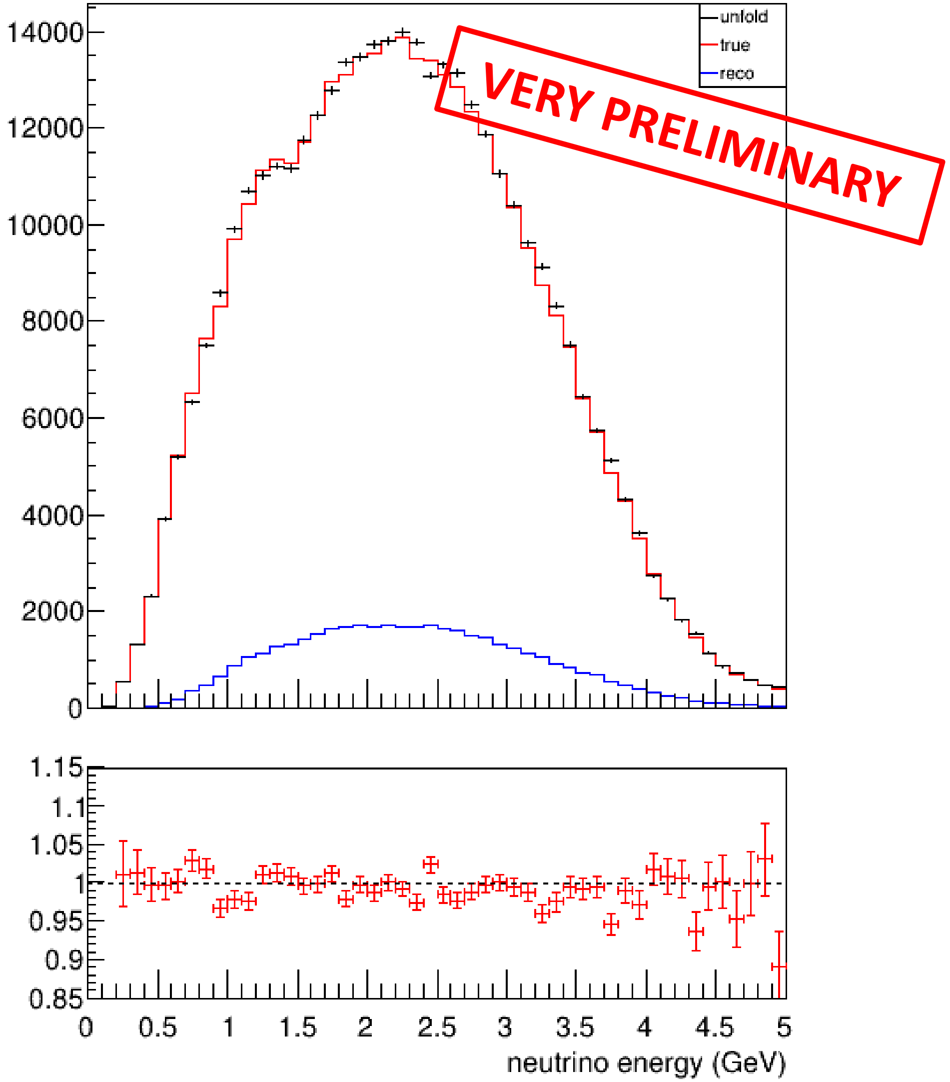






Unfolding

- Attempt to unfold the reconstructed variables
- RooUnfold package
- Method: **S**ingular **V**alue **D**ecomposition
- [Unfolded/True – 1]< 5% …**but overregularisation?**
- Checks in progress



Purpose (2)

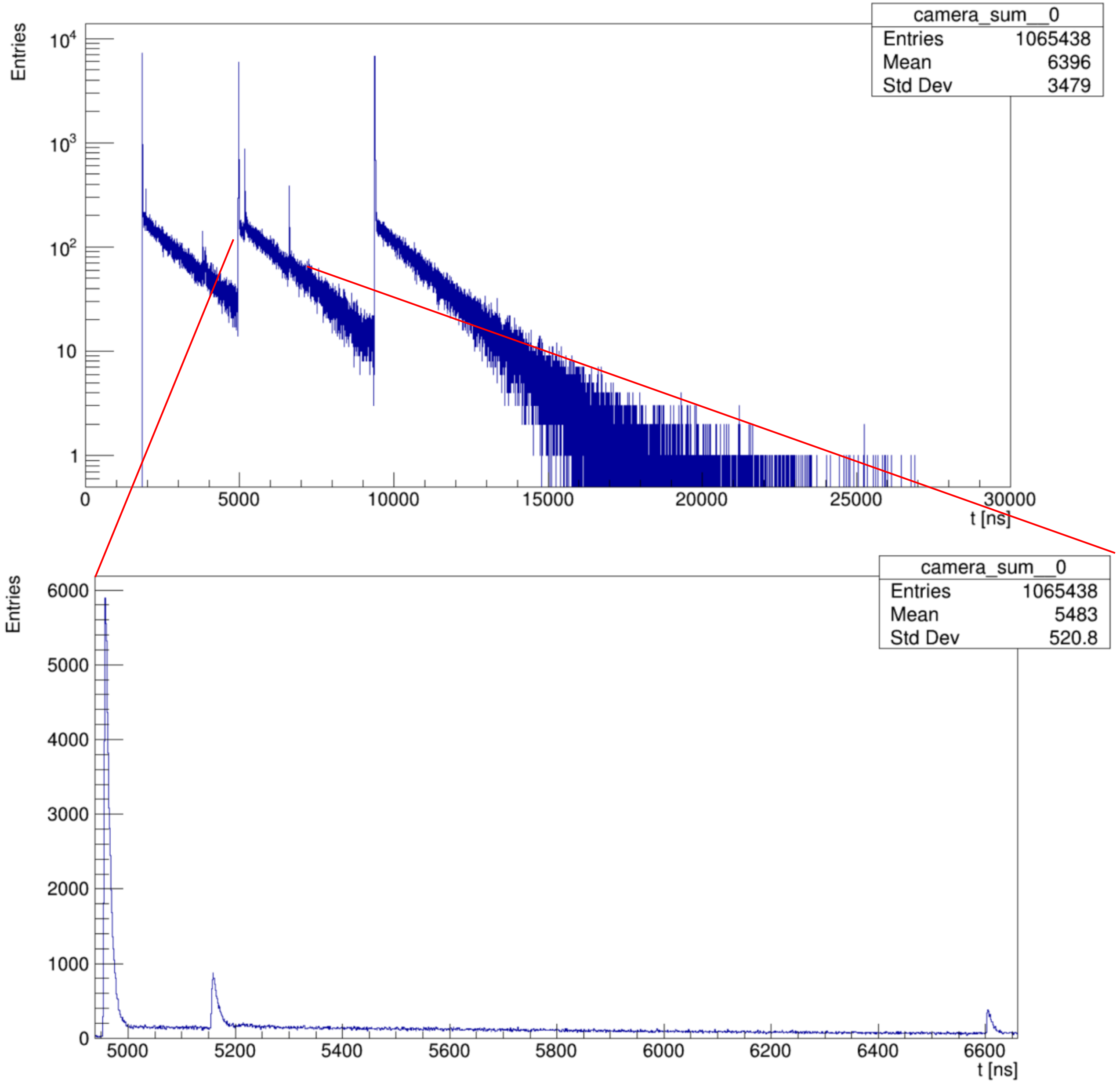
- Here we exploit GRAIN as homogeneous calorimeter
  - Study the effect of the spill structure on the calorimetric capabilities of GRAIN

- Isolate the contribution of each event from the background of the previous events

- Reconstruct the deposited energy in GRAIN from the total number of detected photons by means of a calibration lookup table (more in Valentina's presentation tomorrow)

Spill simulation

- Spill simulated in GENIE
- Argon scintillation by OptMen
- 25% QE, 7% crosstalk applied as multipliers to the total number of detected photons

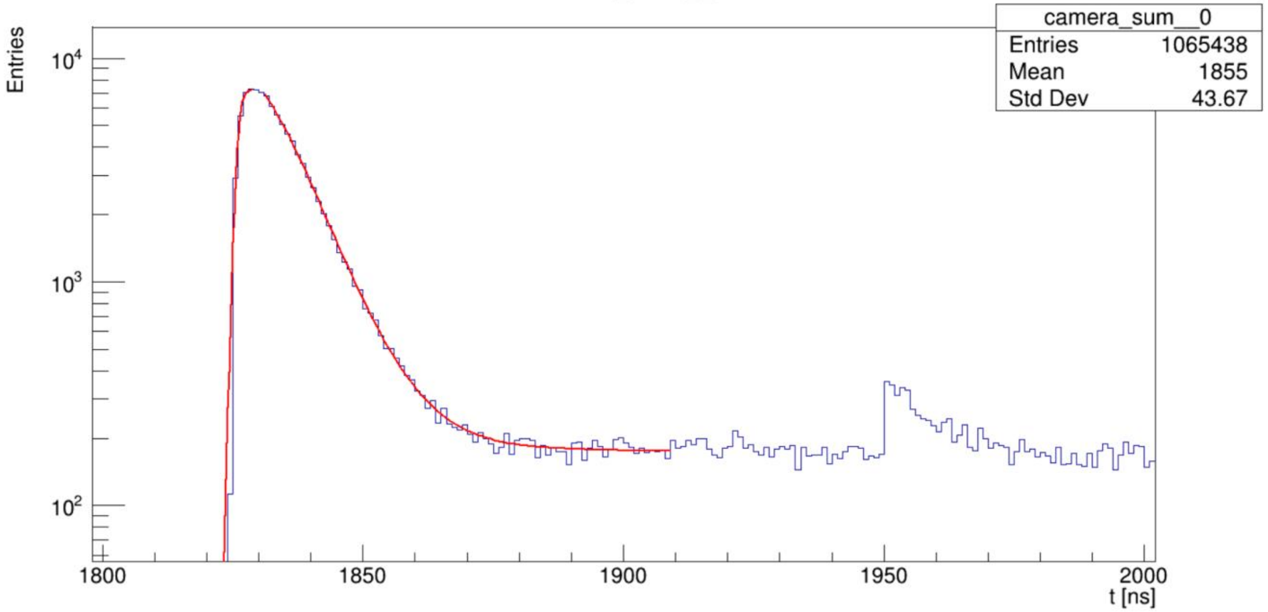


Peaks fit

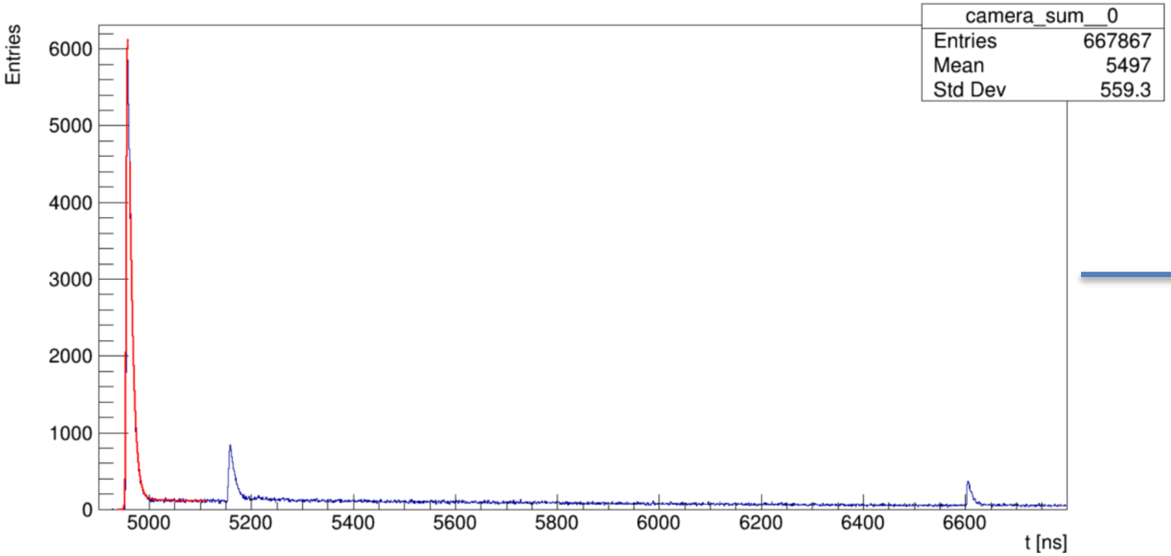
- Rising edge and tails fitted separately

- Tails: $f(t) = \sum_{j=f,s} \frac{A_j}{2\tau_j} \exp\left[\frac{1}{2}\left(\frac{\sigma}{\tau_j}\right)^2 - \left(\frac{t-t_m}{\tau_j}\right)\right]\left[1 - \text{erf}\left(\frac{1}{\sqrt{2}}\left(\frac{\sigma}{\tau_j} - \frac{(t-t_m)}{\sigma}\right)\right)\right]$

- Rising edge: $P(t) = \frac{1}{1+e^{-t}}$



Peaks fit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Entries 667867
Mean 5497
Std Dev 559.3
Entries
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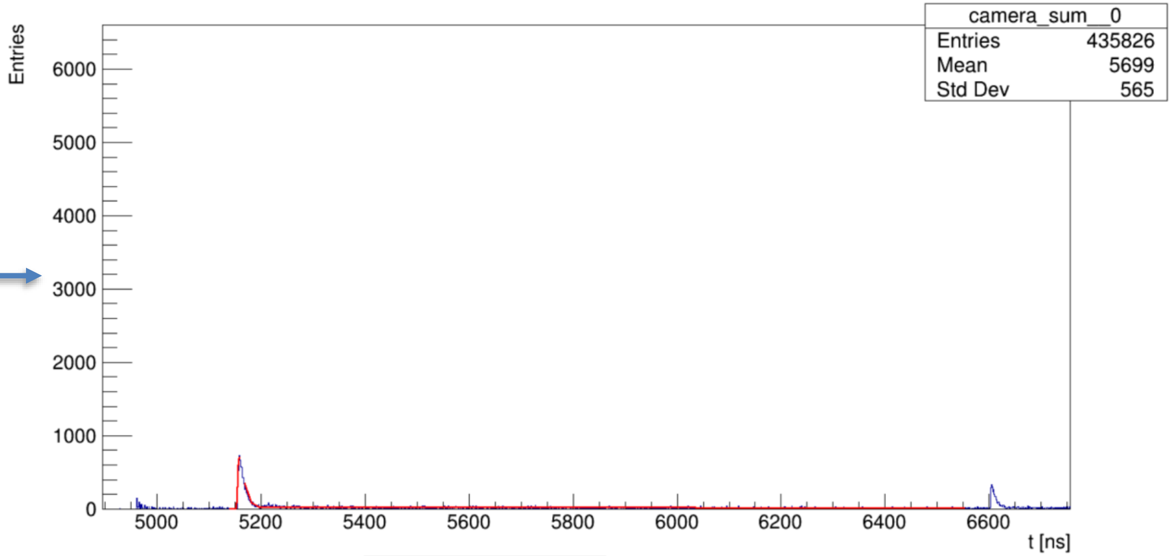
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Mean 5699
Std Dev 565
Entries
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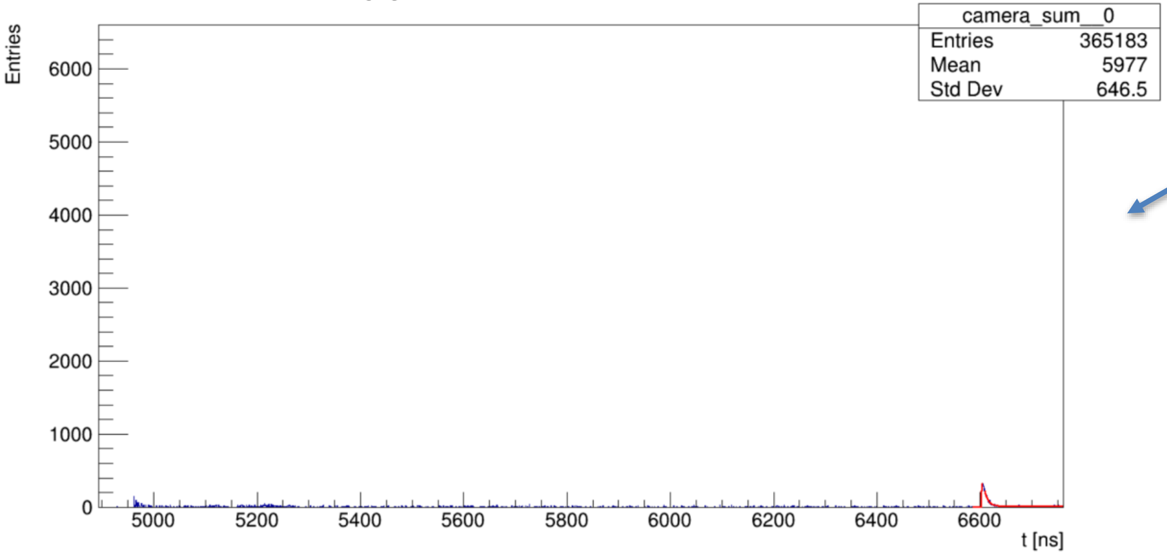
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Mean 5977
Std Dev 646.5
Entries
t [ns]
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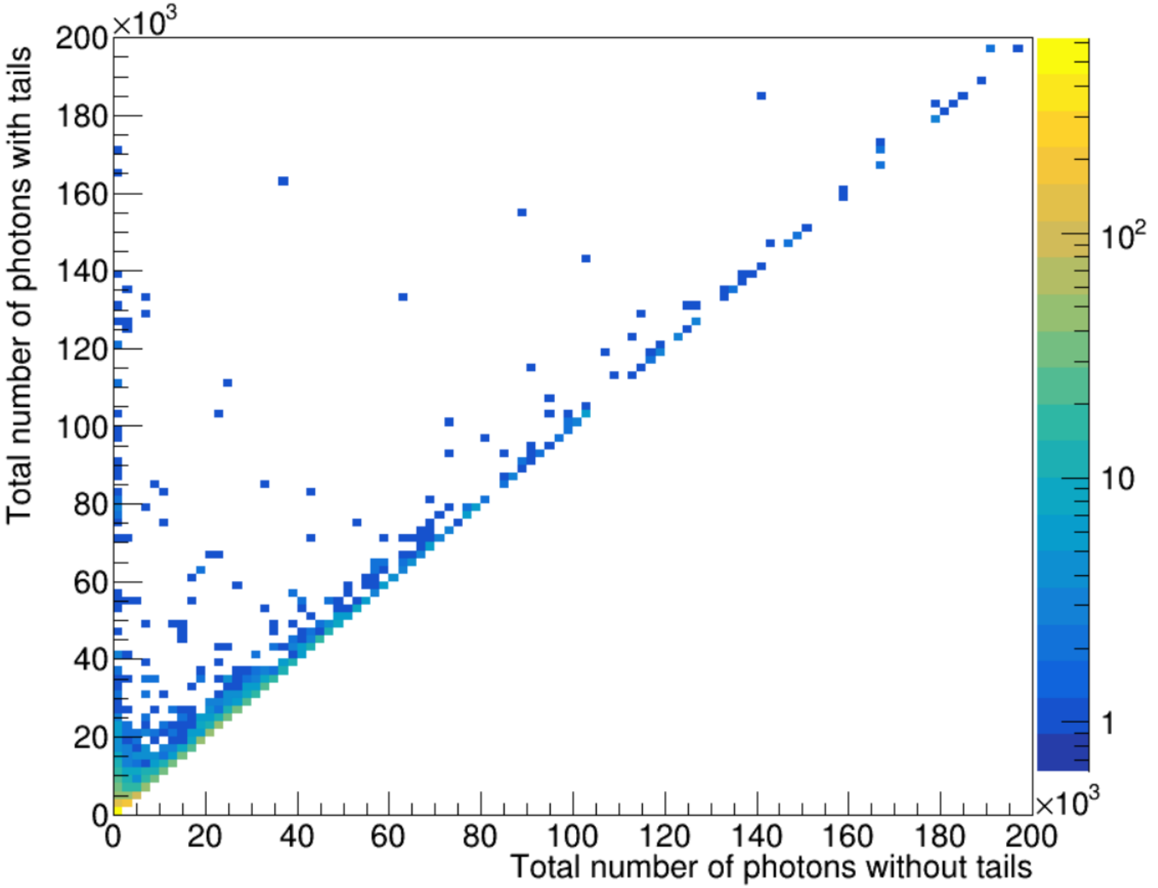
Total number of photons

- After the background removal it is possible to compute the number of photons detected for each peak.

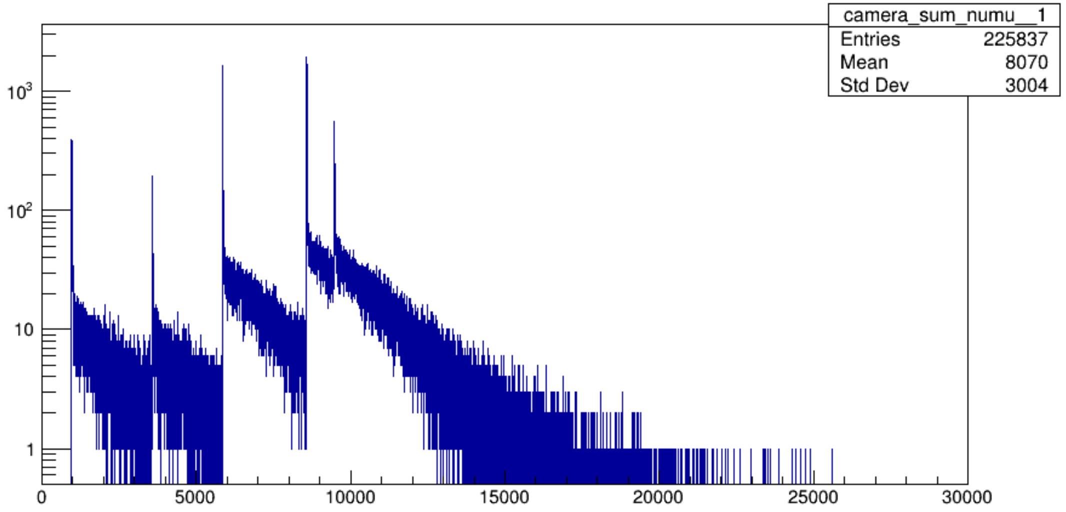


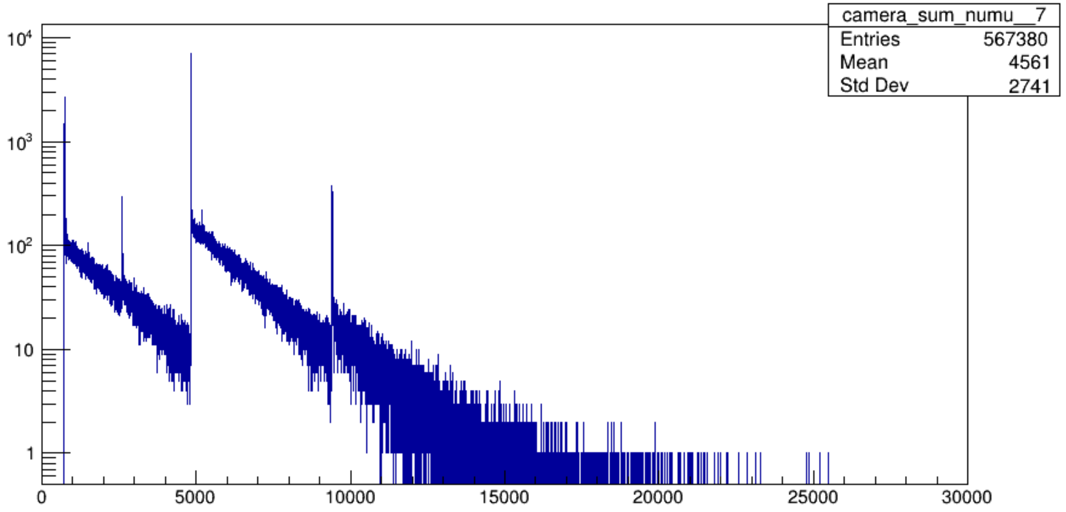
Ad-hoc spills

- 8.2M $\nu_\mu - Ar^{40}$ (CC+NC) interactions generated by GENIE 2.12.10

- 1M $\nu_\mu - SAND$ (CC+NC) interactions generated by GENIE 2.12.10

- Build one spill per $\nu_\mu - Ar^{40}$ interaction extracting random backround event from the $\nu_\mu - SAND$ sample





Next steps

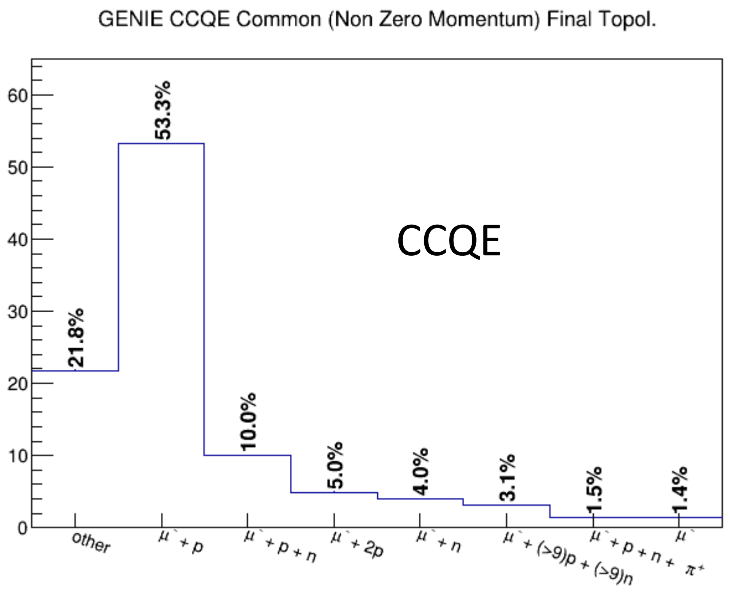
- Simulate the spills for each $\nu_\mu - Ar^{40}$ event and fit the peaks
- Timing match between first STT hit and peaks of the spill to identify the neutrino interaction
- Reconstruct the position of the interaction inside GRAIN
  - from STT or 3D reco
- Reconstruct the deposited energy in GRAIN from the total number of detected photons

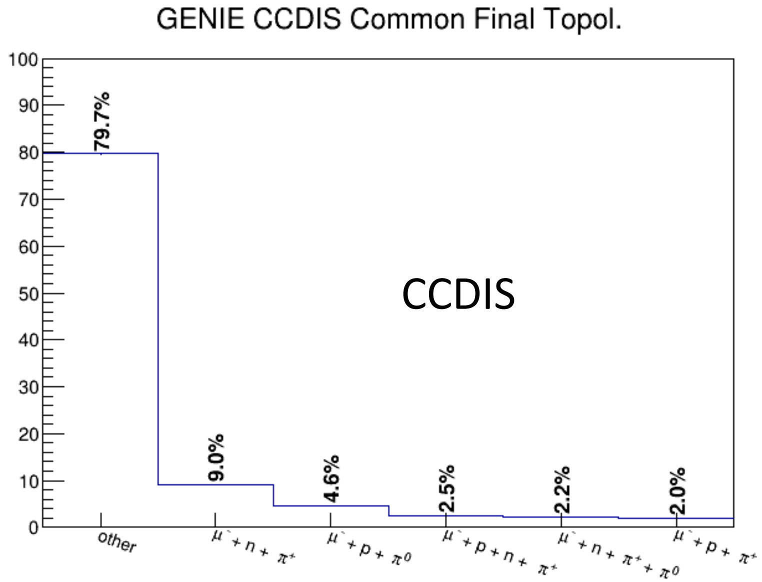
Conclusions

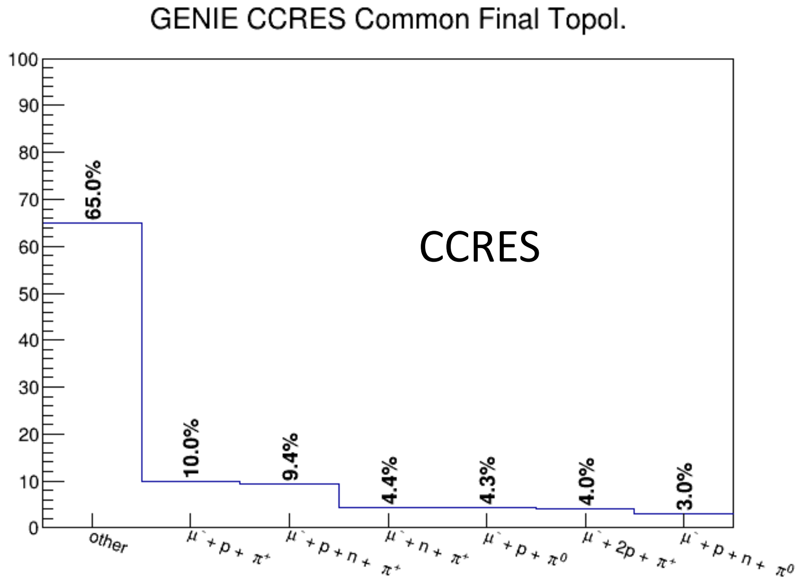
- GRAIN physics case has been addressed studying the performance of SAND (w/ GRAIN) in selecting and reconstructing $\mu^- + p$ channel
- 8.2M $\nu_\mu + Ar$ events have been simulated
- GRAIN exploited as homogeneous calorimeter
- CCQElike selection has been defined:
  - Efficiency > 10% and Purity > 90%
- Events have been reconstructed and Unfolding procedure has been applied to retrieve true variable distributions
- Checks on unfolding procedure is in progress
- Studies on the effect of the spill structure and on the calorimetry capabilities of GRAIN are in progress

Backup

Common Final Topologies



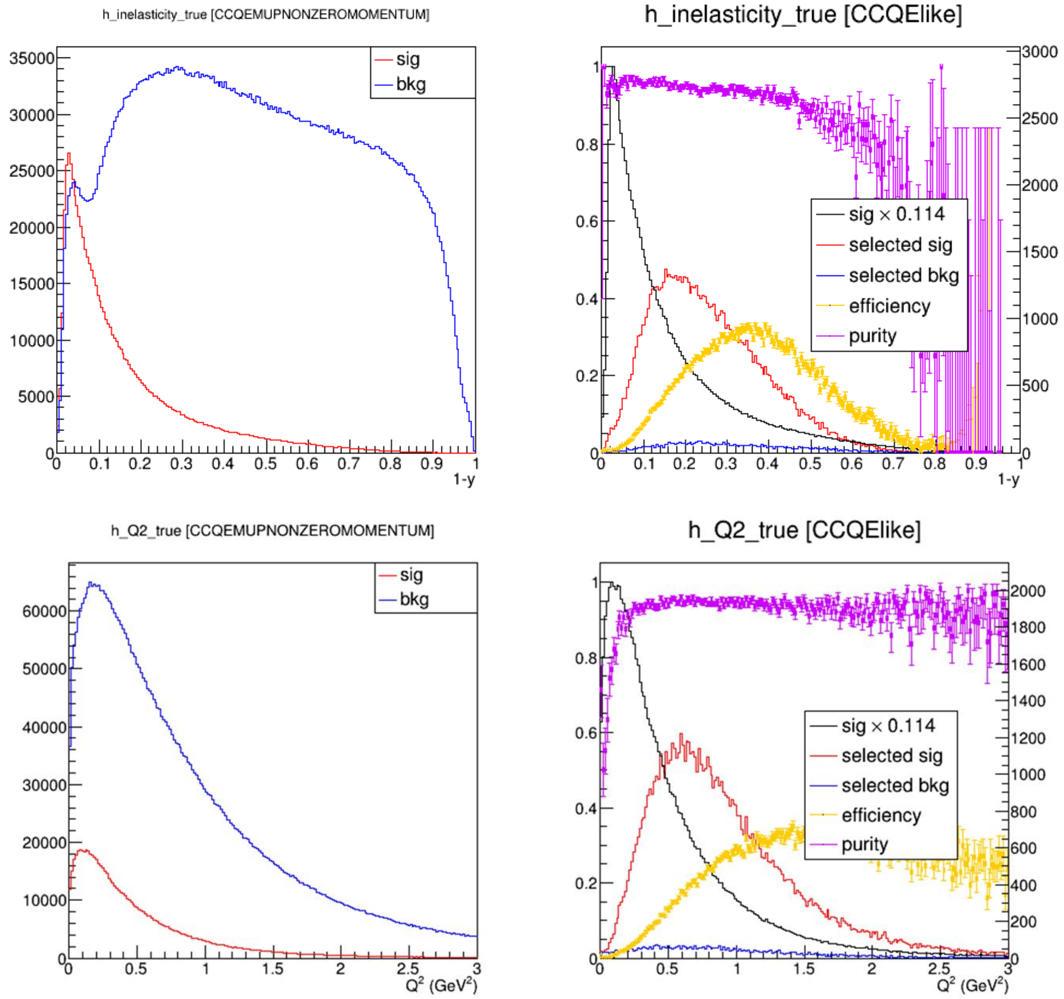




Efficiency VS …

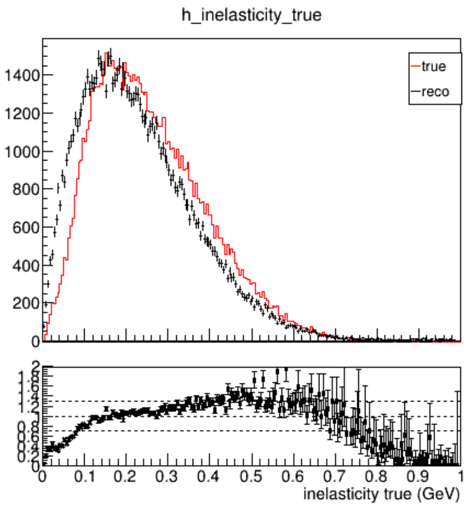
Inelasticity

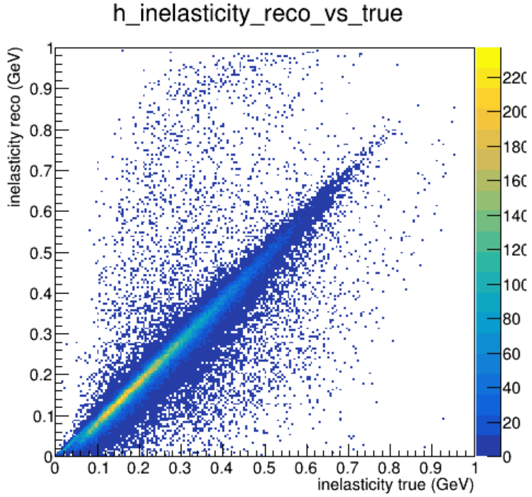
Q^2

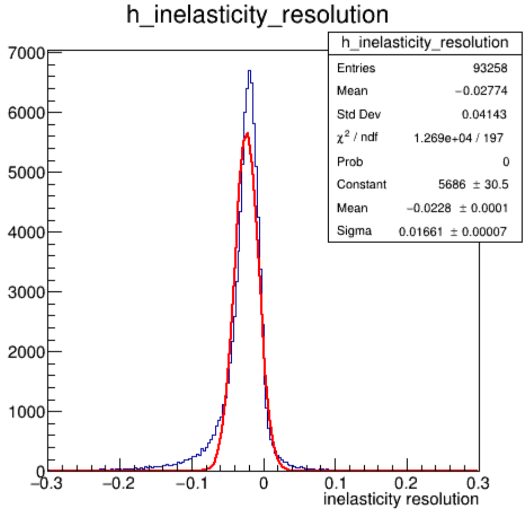


Inelasticity and Q^2 Reconstruction in CCQElike

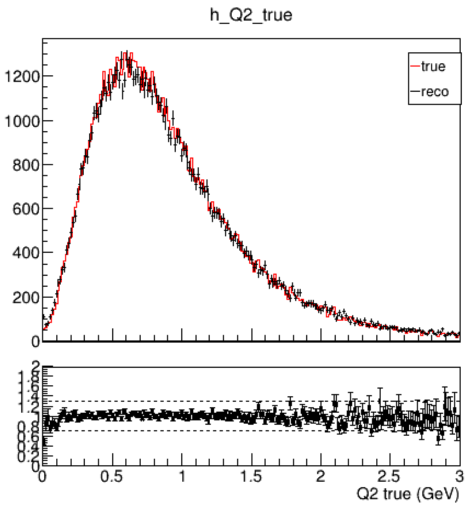
Inelasticity

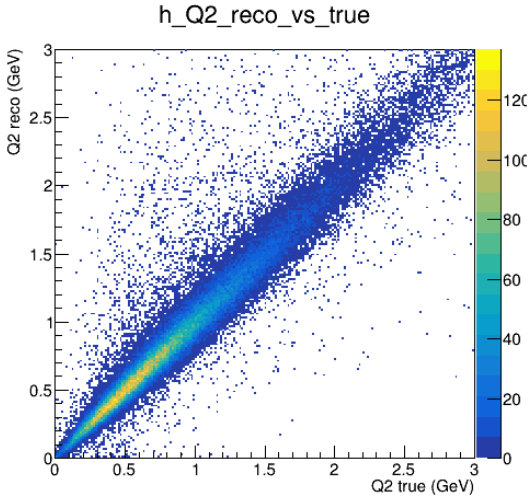


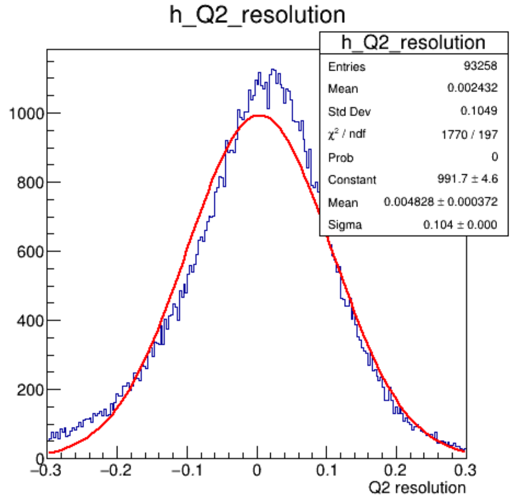




Q^2

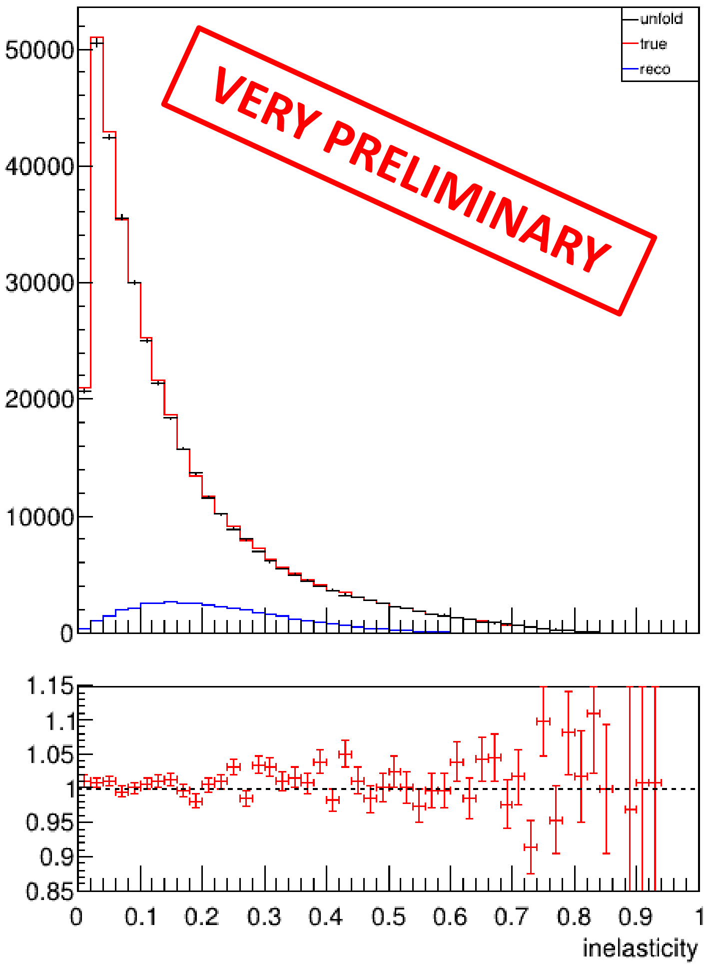




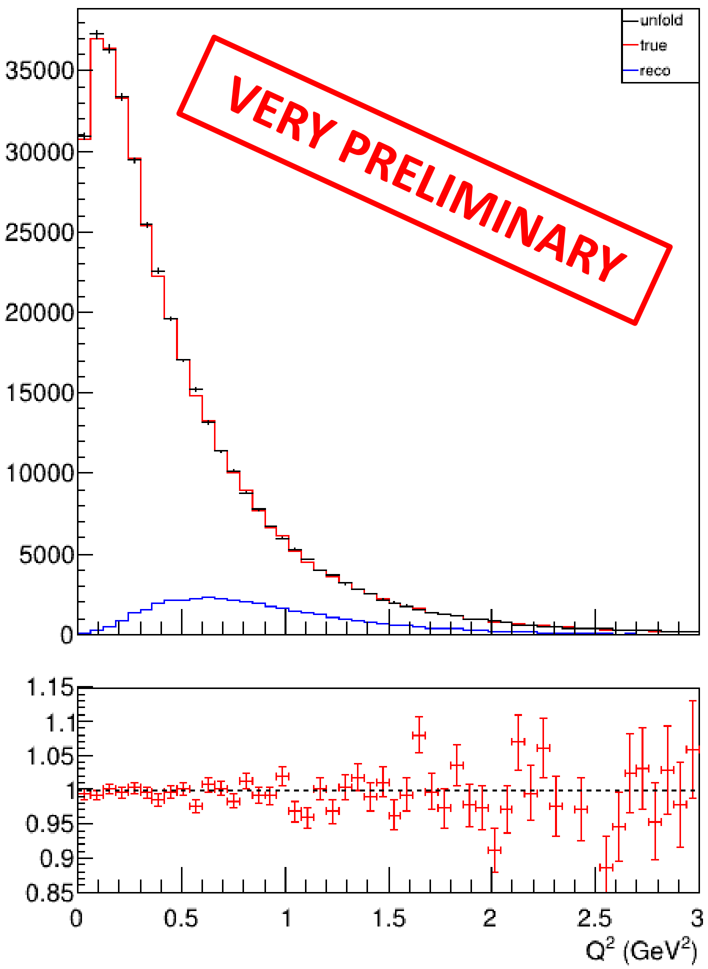


Unfolding

Inelastcity

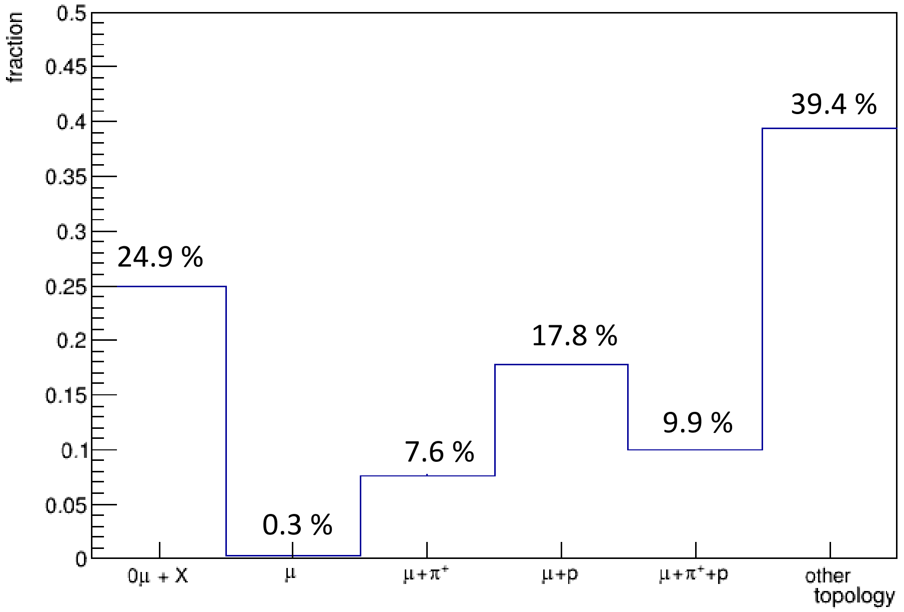


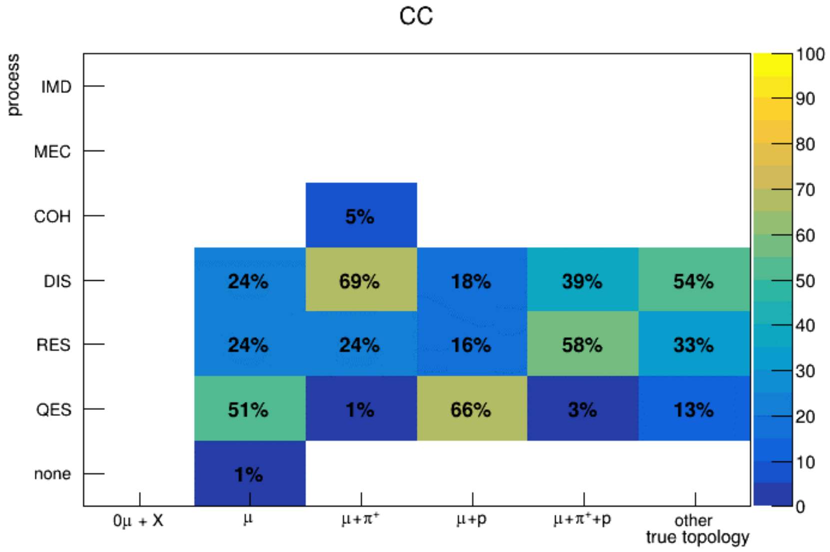
Q^2

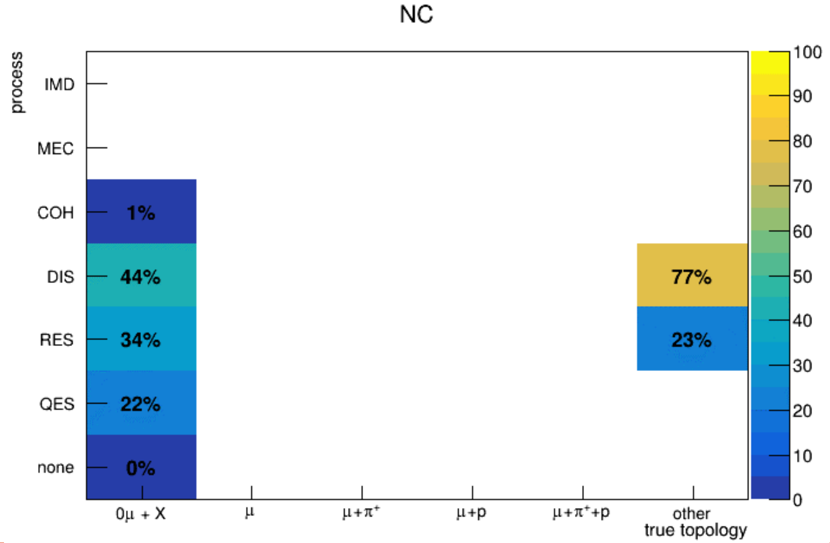


Simple Charged Topology

- Stable final particles
  `GHepStatus == kIstStableFinalState`
- Simple exclusive charged topology:
  $\mu + \pi^+, \mu + p, \mu + \pi^+ + p$

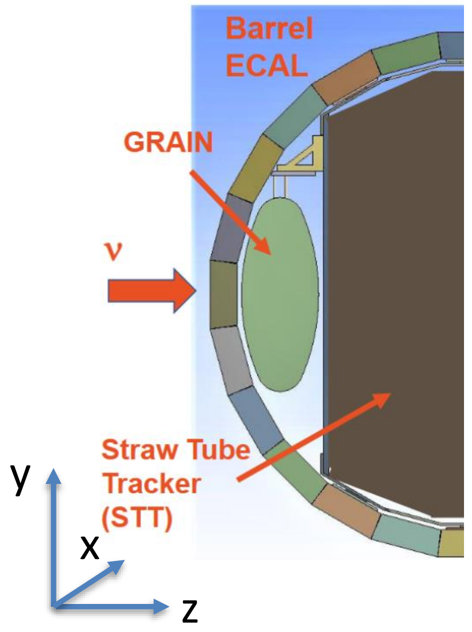


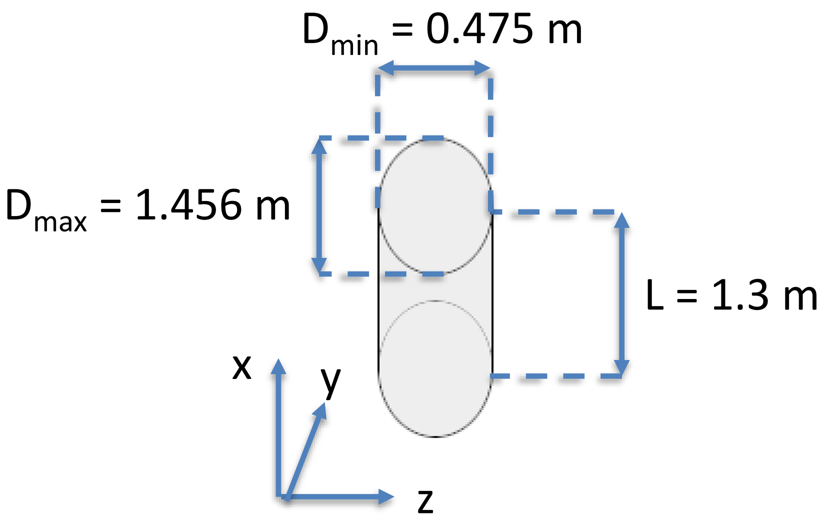




Detector simulation

- Official geometry: https://github.com/DUNE/dunendggd
- Interactions are placed in GRAIN
- LAr volume: elliptical cylinder
- LAr mass: 988.6 kg
- Particles propagated with *edep-sim*

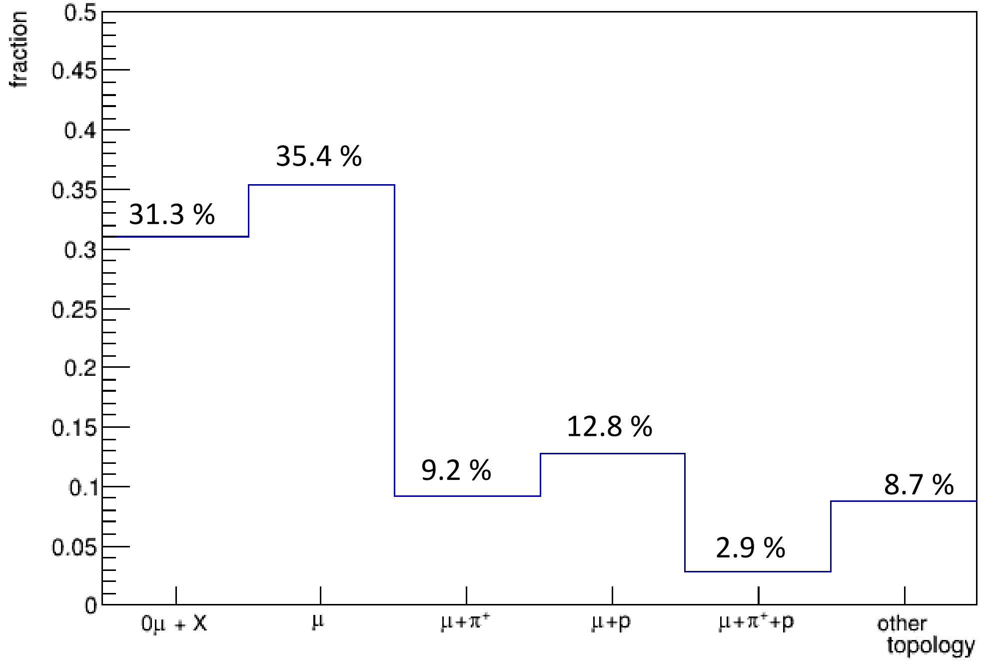




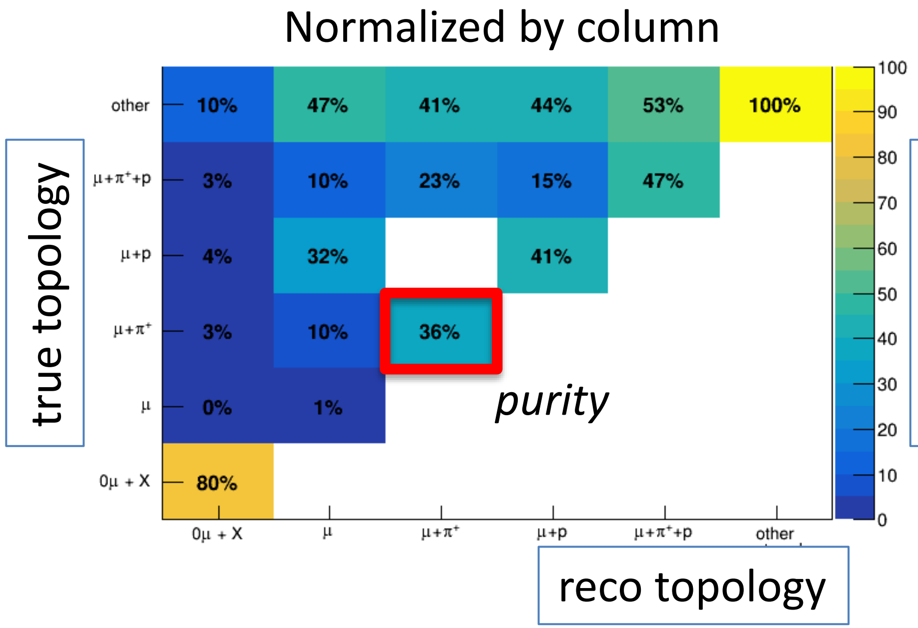
STT track Reconstruction

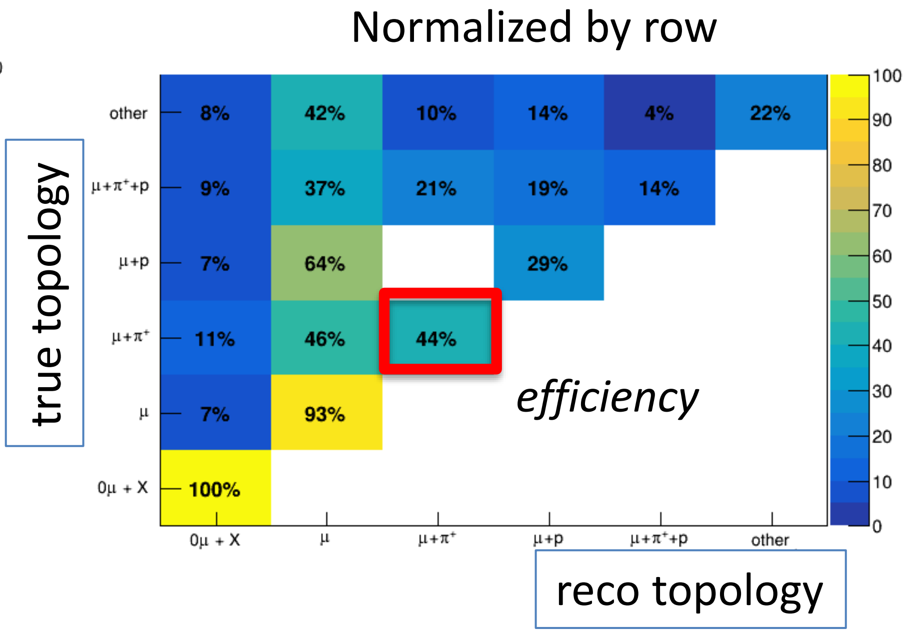
- STT track reconstruction with FastReco:
  https://baltig.infn.it/dune/FastReco

- FastReco in a nutshell:
  - STT Track are reconstructed if number of STT hits in YZ view >= 4
  - Reconstructed momentum from Gluckstern formula
  - Particle ID is assumed



Topology Migration



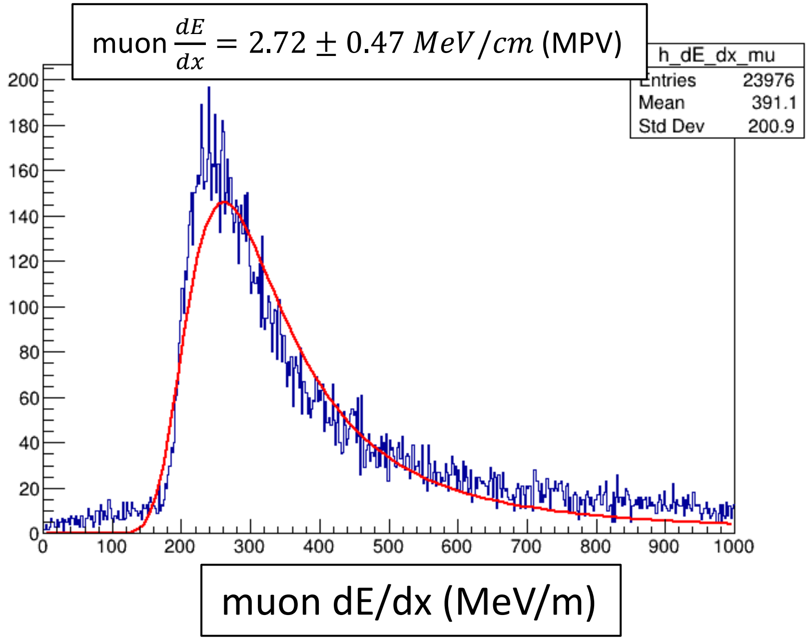


GRAIN as calorimeter

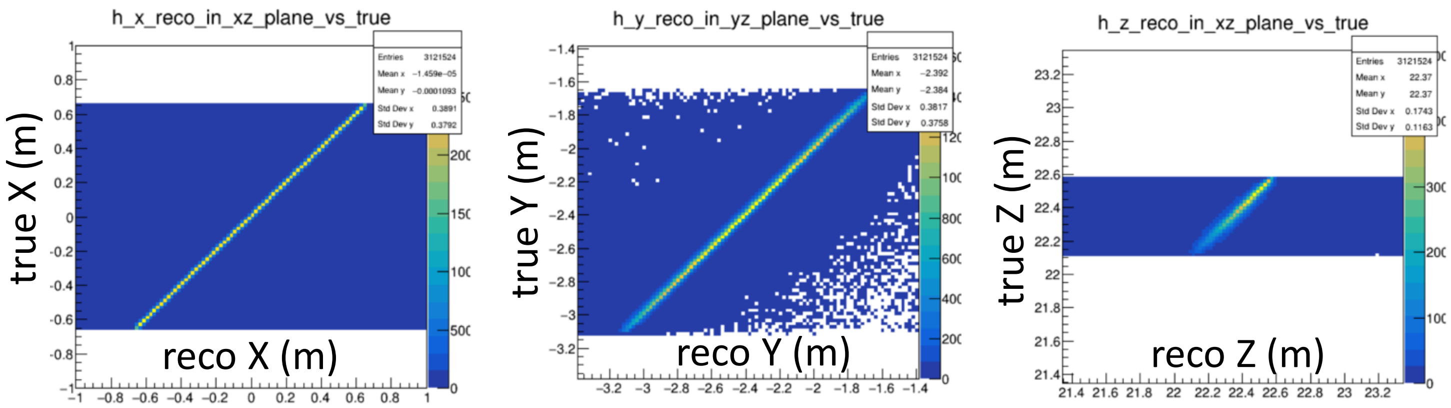
- Use calorimetric info from GRAIN
- Preliminary studies suggest a 10% resolution on the energy deposit can be achieved
- Define *grain_reco_energy* as 10% gaussian smeared *grain_true_energy_deposit*
- Define *grain_extra_energy* as *grain_reco_energy* subtracted by the energy deposits in GRAIN expected from particles reconstructed in STT
- If *true_topology == reco_topology*, then *grain_extra_energy* ~ 0

Expected energy deposit in GRAIN

- The expected energy deposit in GRAIN is given by:
  (energy loss rate) X (path length in LAr)
- Energy loss rate is assumed that of muons
- Path length in Lar is evaluated analytically from vertex position

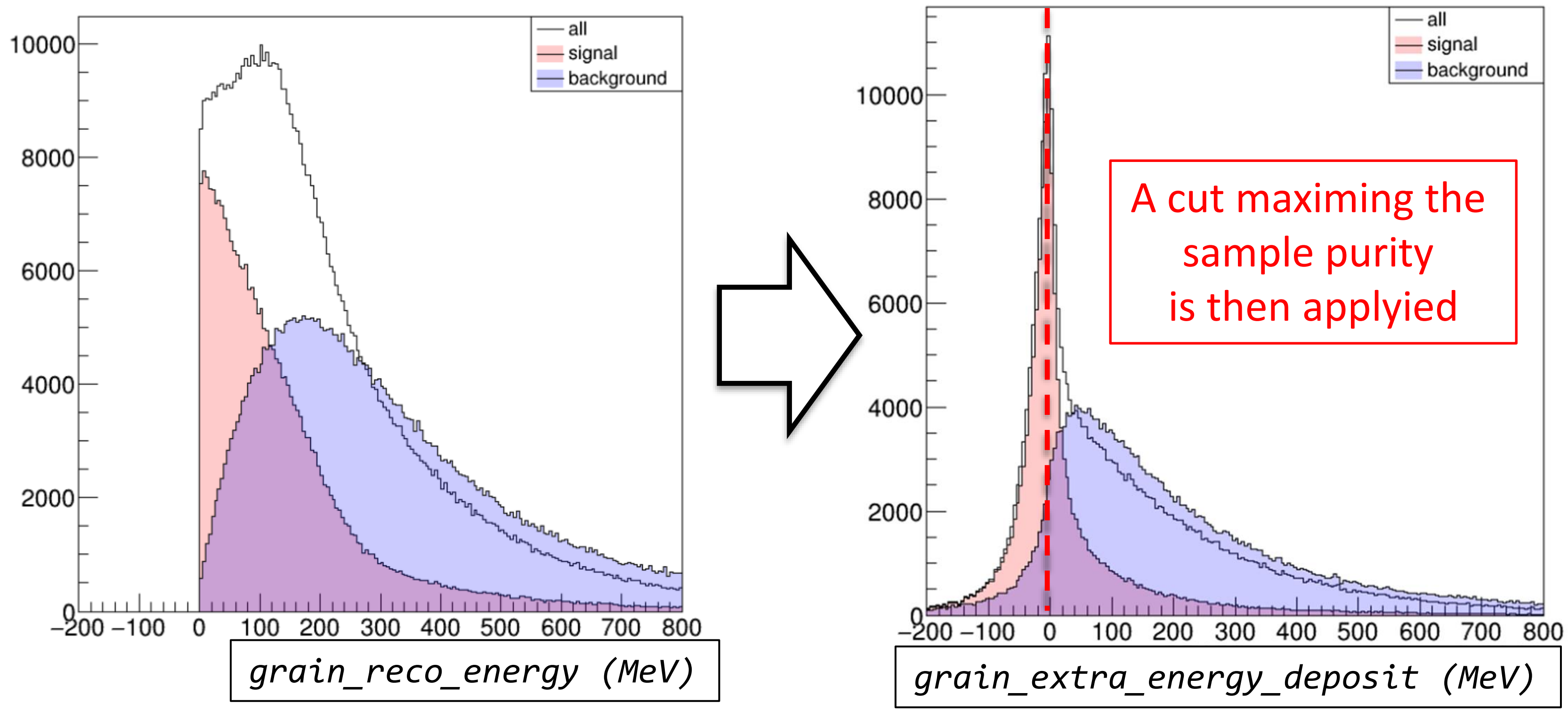


- Vertex position is reconstructed using the two highest momentum (if more than two) tracks



grain_extra_energy

all: $true\_topology == \mu + \pi^+$
signal: $(true\_topology == \mu + \pi^+)$ && $(reco\_topology == \mu + \pi^+)$
background: $(true\_topology\ != \mu + \pi^+)$ && $(reco\_topology == \mu + \pi^+)$

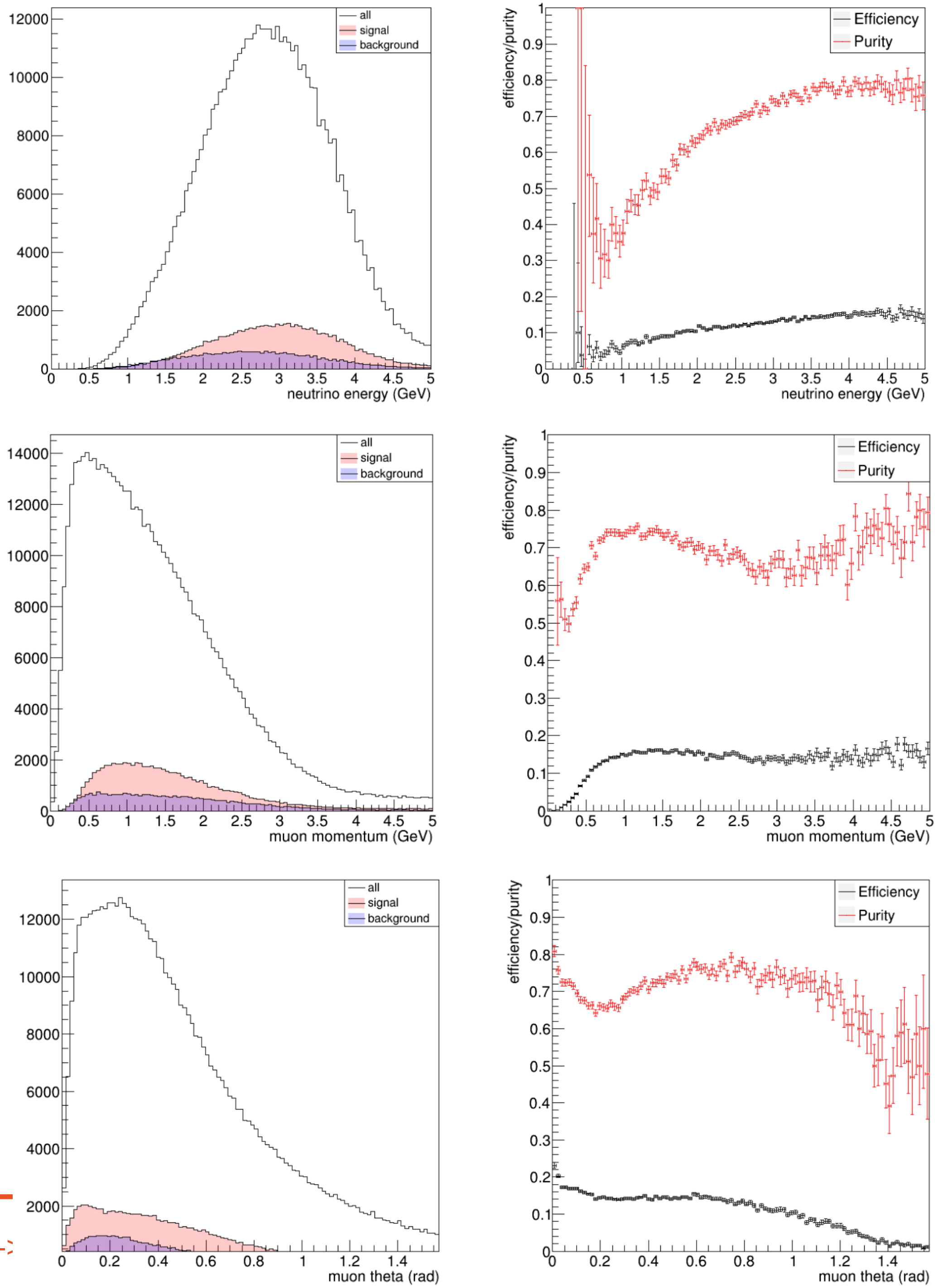


Preliminary Results

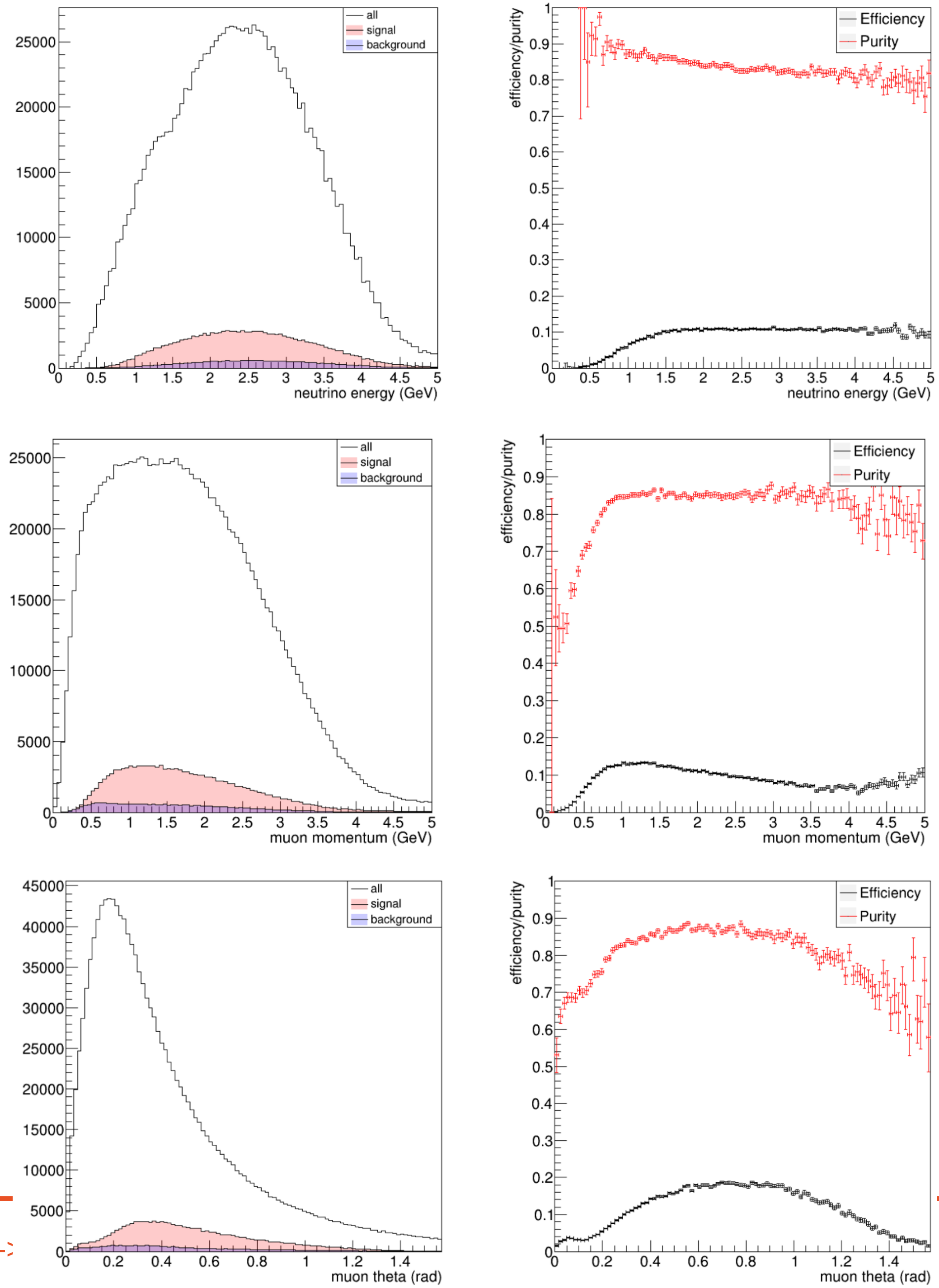
```
Assuming:
- LAr fiducial mass: 1 t
- spill per second: 0.83
- events per spill per ton: 0.14
- days per year: 200
- years: 5
```

	Selection	Efficiency	Purity	n. of events in 5y (S+B)
$\mu + \pi^+$	None	100%	8%	~ 10M
$\mu + \pi^+$	reco_topology	44%	36%	935k
$\mu + \pi^+$	reco_topology && ΔE_extra < -2.5 MeV	13%	71%	140k
$\mu + p$	None	100%	18%	~ 10M
$\mu + p$	reco_topology	29%	41%	1.26M
$\mu + p$	reco_topology && ΔE_extra < 2.5 MeV	10%	83%	215k
$\mu + p + \pi^+$	None	100%	10%	~ 10M
$\mu + p + \pi^+$	reco_topology	14%	47%	316k
$\mu + p + \pi^+$	reco_topology && ΔE_extra < 2.5 MeV	5%	82%	65k

$\mu + \pi^+$

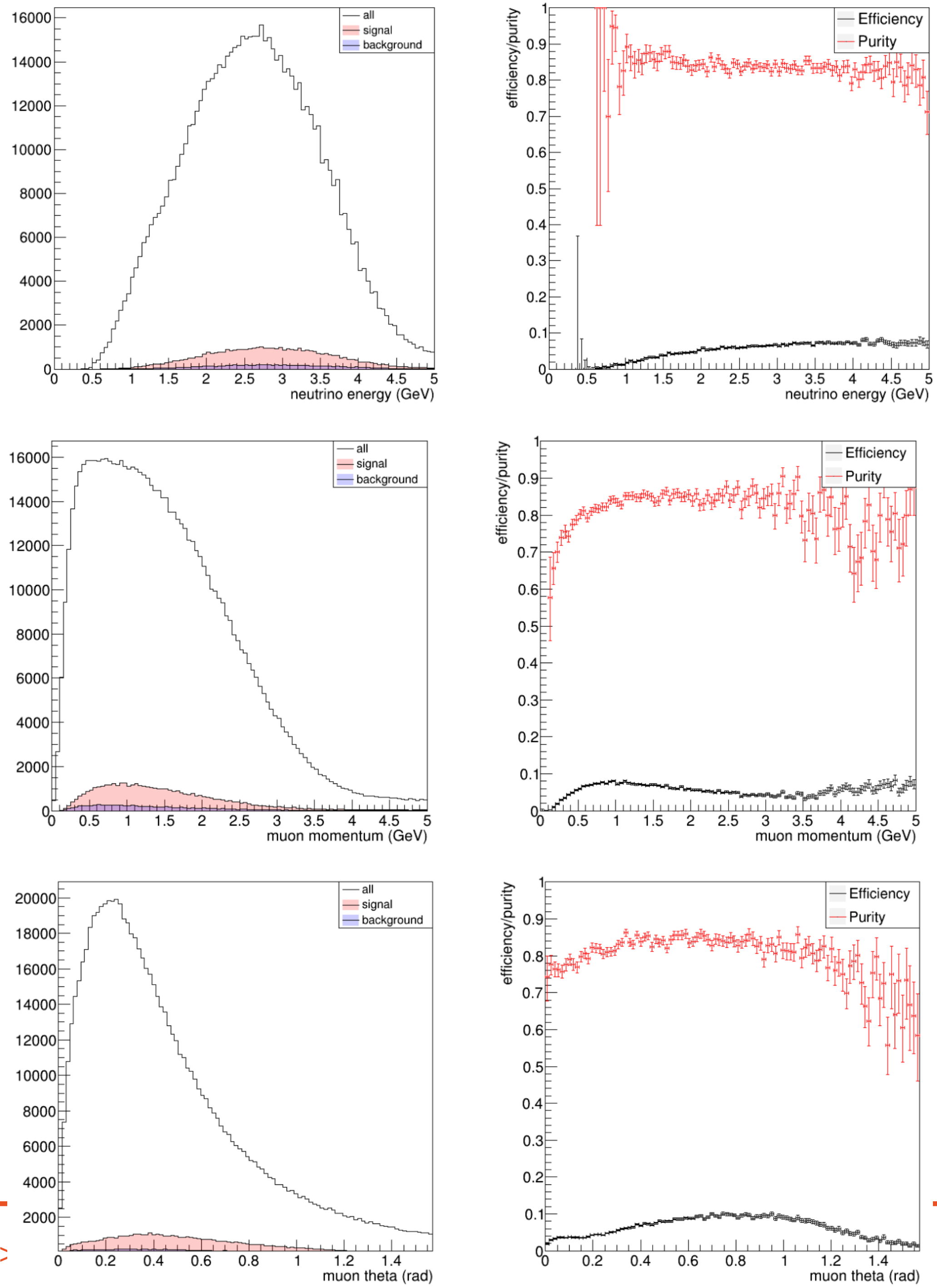

all
signal
background
neutrino energy (GeV)
Efficiency
Purity
efficiency/purity
muon momentum (GeV)
muon theta (rad)

$\mu + p$



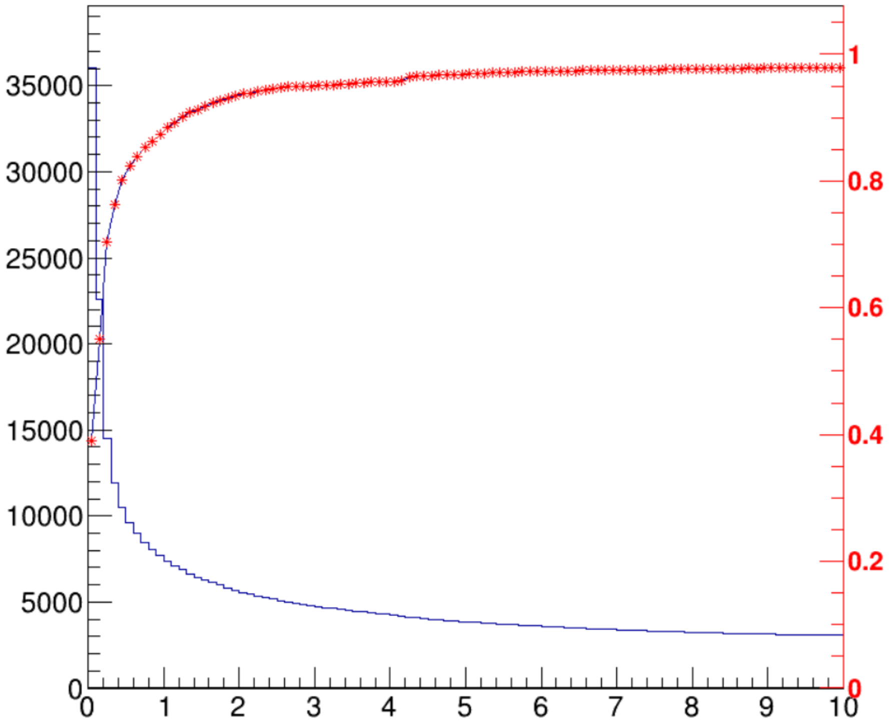
all
signal
background
neutrino energy (GeV)
Efficiency
Purity
efficiency/purity
muon momentum (GeV)
muon theta (rad)

$\mu + p + \pi^+$



all
signal
background
neutrino energy (GeV)
Efficiency
Purity
efficiency/purity
neutrino energy (GeV)
all
signal
background
muon momentum (GeV)
Efficiency
Purity
efficiency/purity
muon momentum (GeV)
all
signal
background
muon theta (rad)
Efficiency
Purity
efficiency/purity
muon theta (rad)

Errors


35000
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25000
20000
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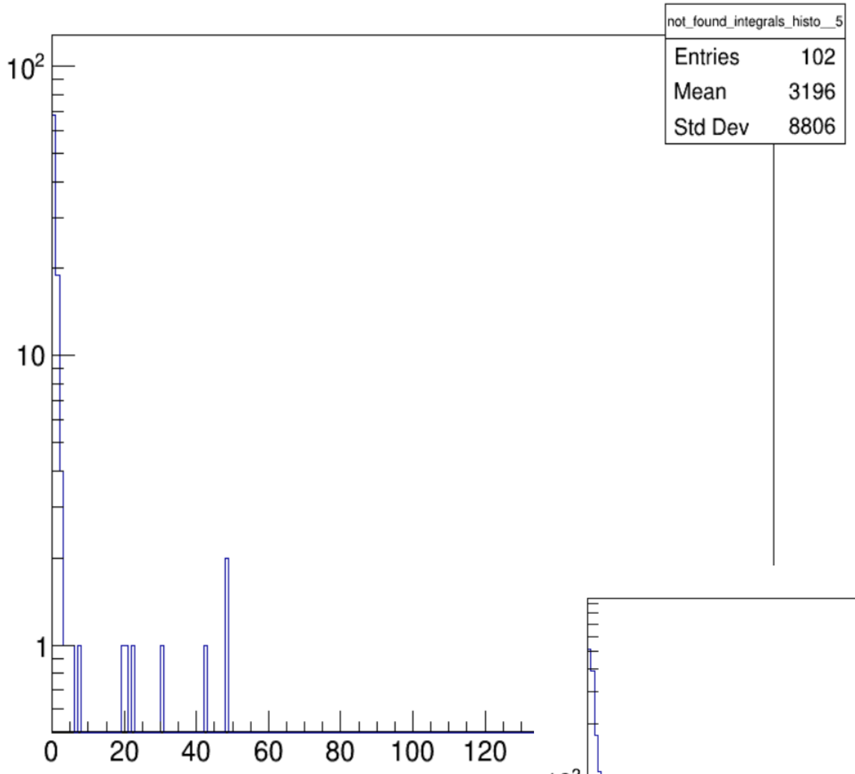
0.4
0.2
0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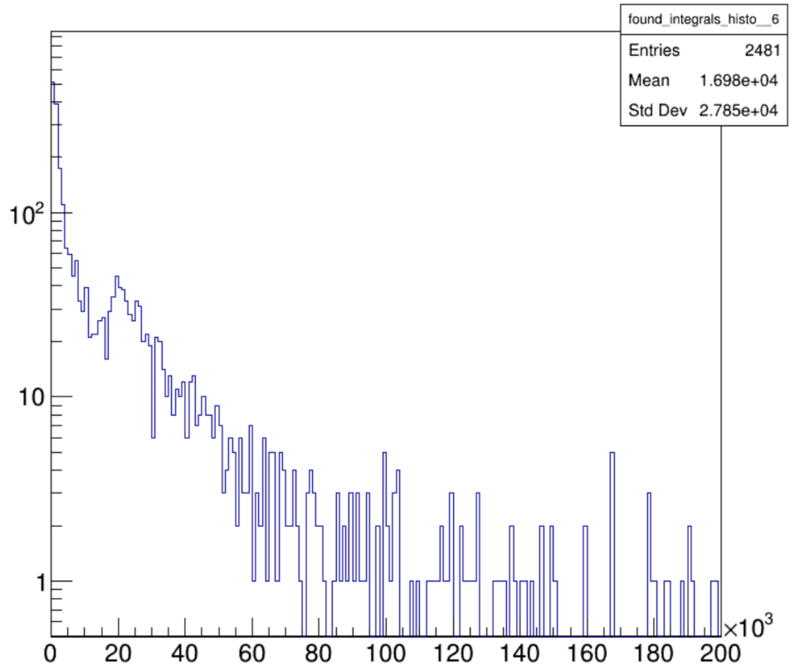
Std Dev 8806
10^2
10
1
0 20 40 60 80 100 120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Entries 2481
Mean 1.698e+04
Std Dev 2.785e+04
10^2
10
1
0 20 40 60 80 100 120 140 160 180 200
$\times 10^3$