Beam monitoring with the SAND reference design

Guang Yang (Stony Brook)

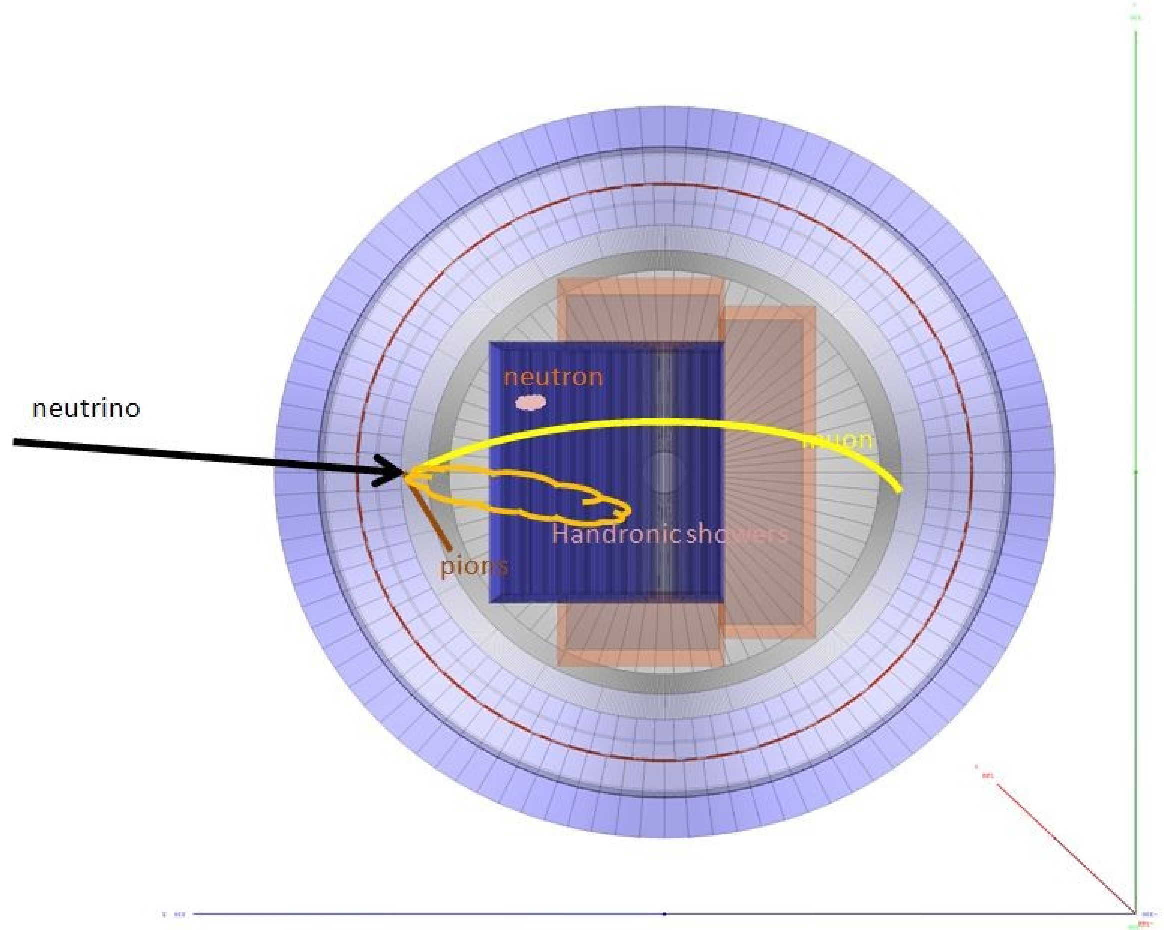
Introduction

- Reference design : KLOE magnet and ECAL + 3DST + low-density tracker (TPC here)
- Two independent samples can be obtained with the reference design
  - ECAL events
  - 3DST events
- Beam monitoring sensitivity is a sum of those two independent samples

Main updates

- Event selection
- Event rate
- Flux window dependence

Geometry

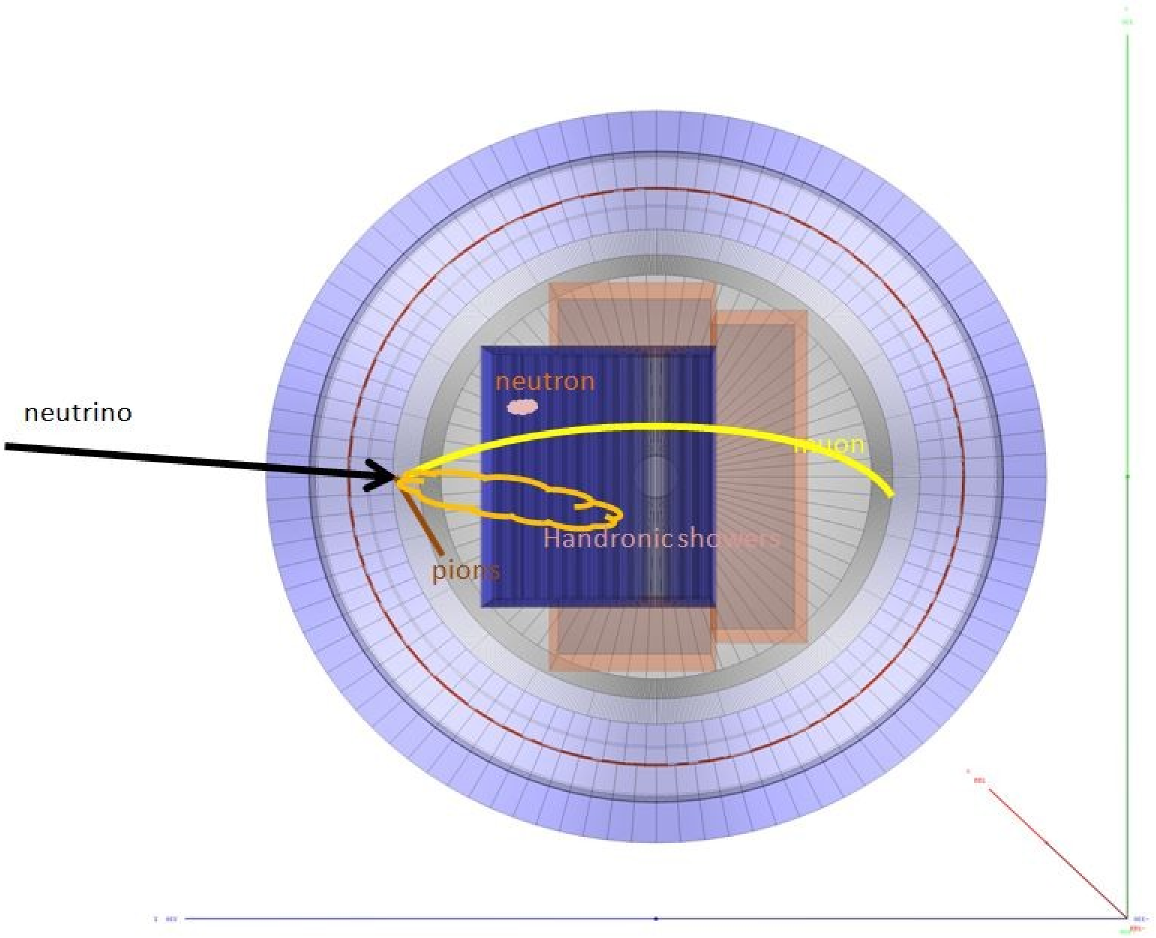


3DST 2.4 x 2.4 x 2 m^3

TPC covering downstream, top and bottom

Sensitive volumes are all ECAL region and 3DST.

Selected events



- Energy resolution in ECAL, calorimetrically

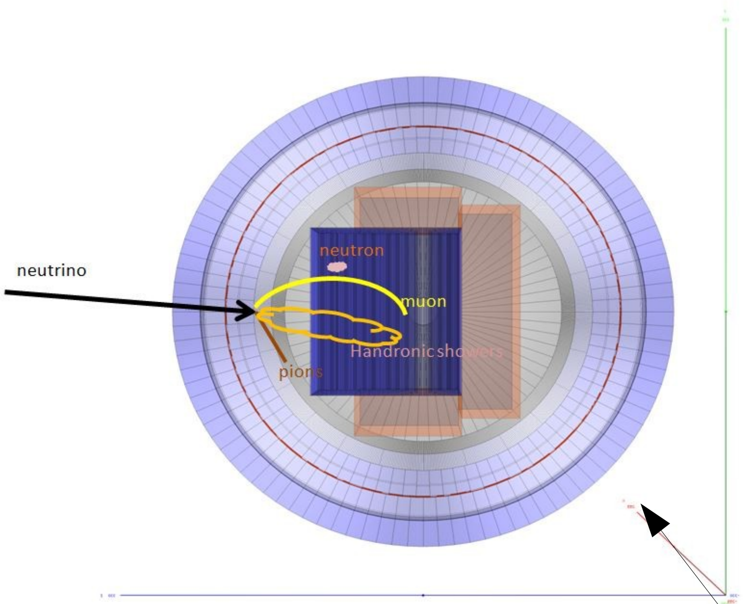
$$\sigma_E = 5.7\,\% \;/\; \sqrt{E_{dep}(GeV)}$$

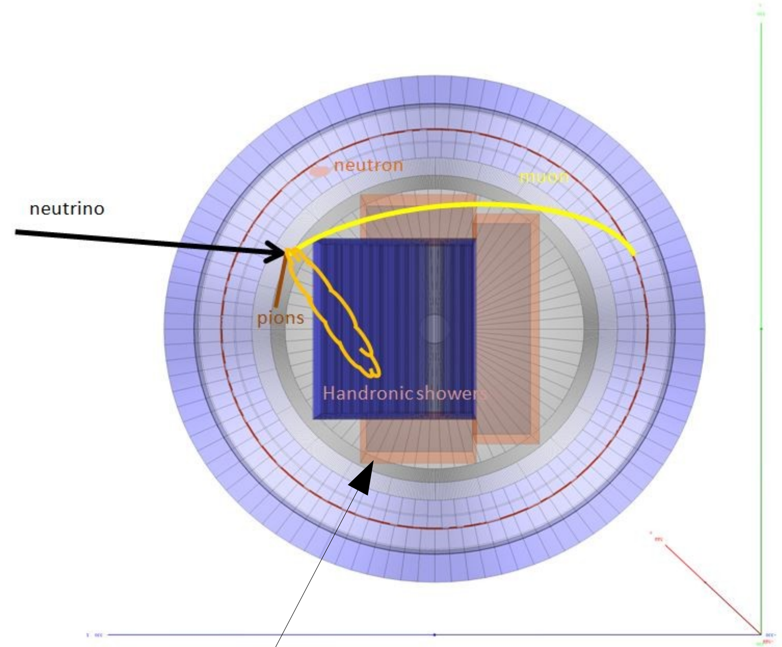
- Muon in 3DST, calorimetrically 1%
- Muon in TPC, mom. Res.

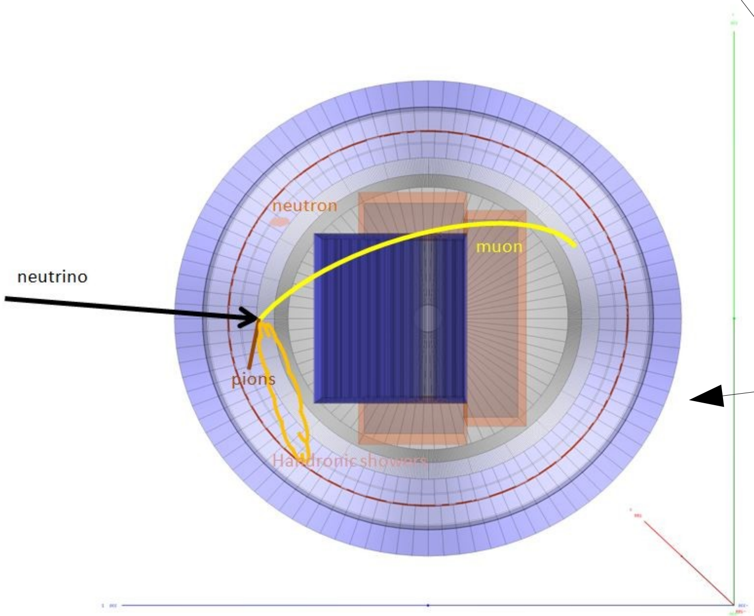
$$\frac{\delta p_T}{p_T} \sim 10\% \frac{p_T(\mathrm{GeV})}{6}$$

- Hadron in 3DST: cumulating deposit energy in sensitive volumes (i.e. ECAL,TPC 3DST).
- Neutrino energy = muon energy + hadronic energy deposit.

Selected events



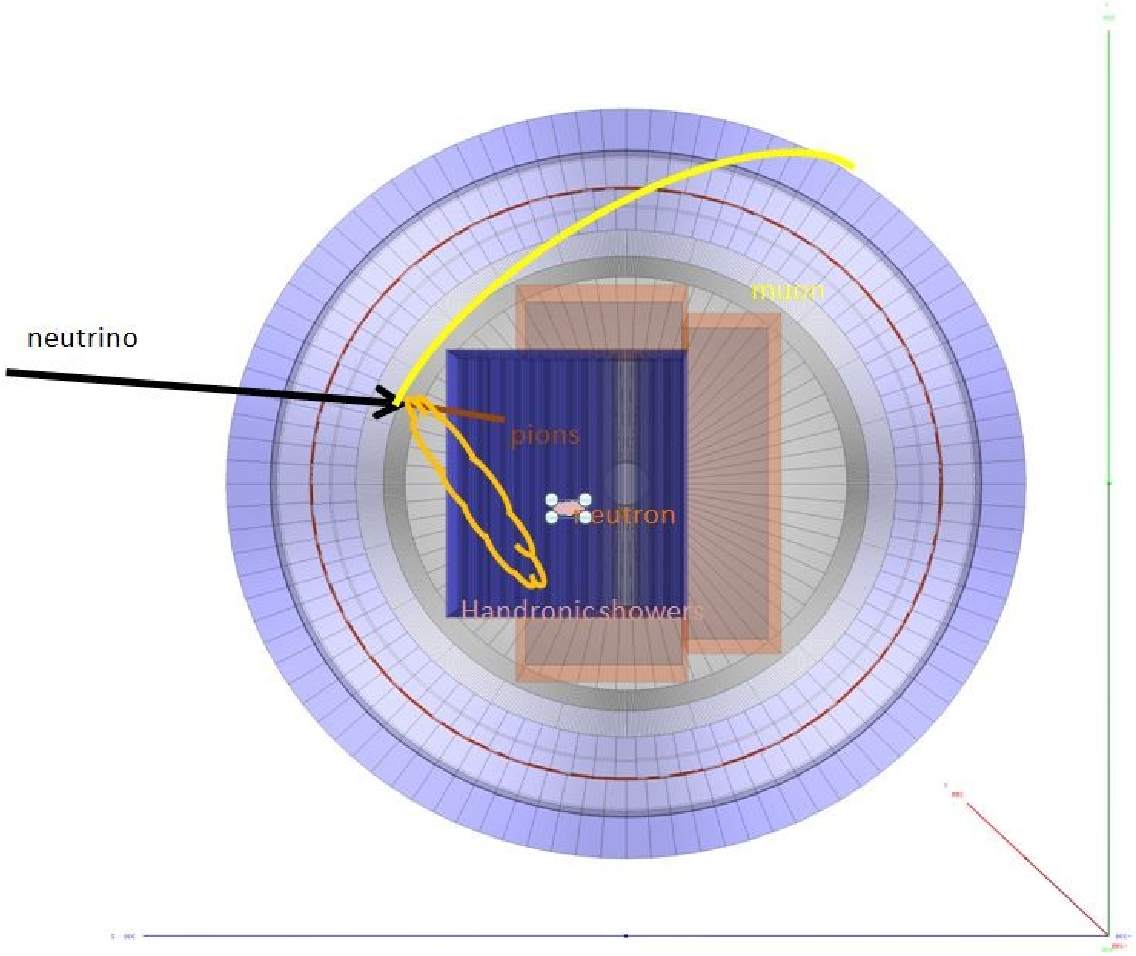




Muons:

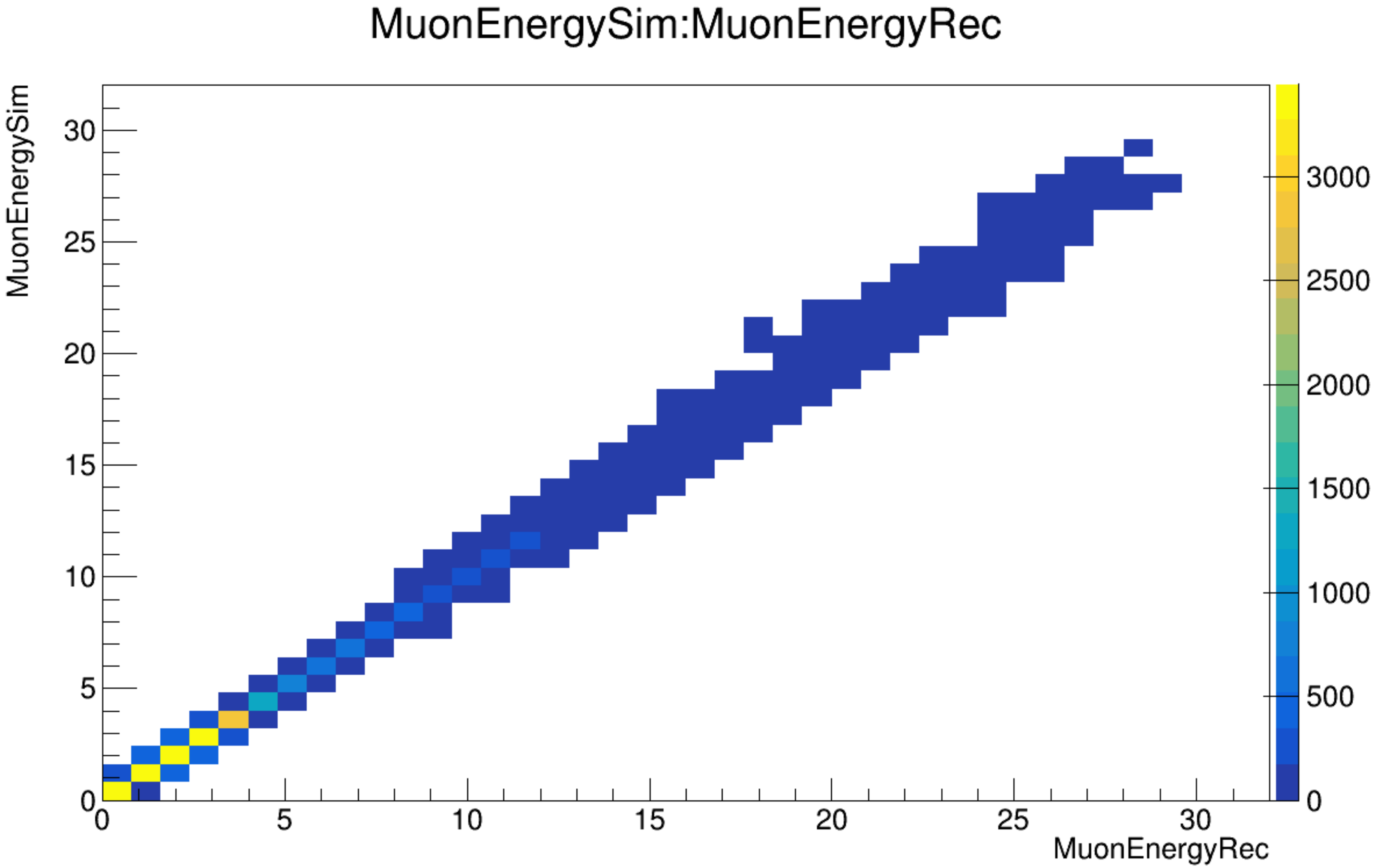
- Contained (calorimetrically) or
- > 20 cm in TPC $\frac{\delta p_T}{p_T} \sim 10\% \frac{p_T(\mathrm{GeV})}{6}$ or
- > 20 cm in 3DST (if 3DST+TPC, combination of above, if 3DST-only (tiny amount), 15% tracking)

Rejected events



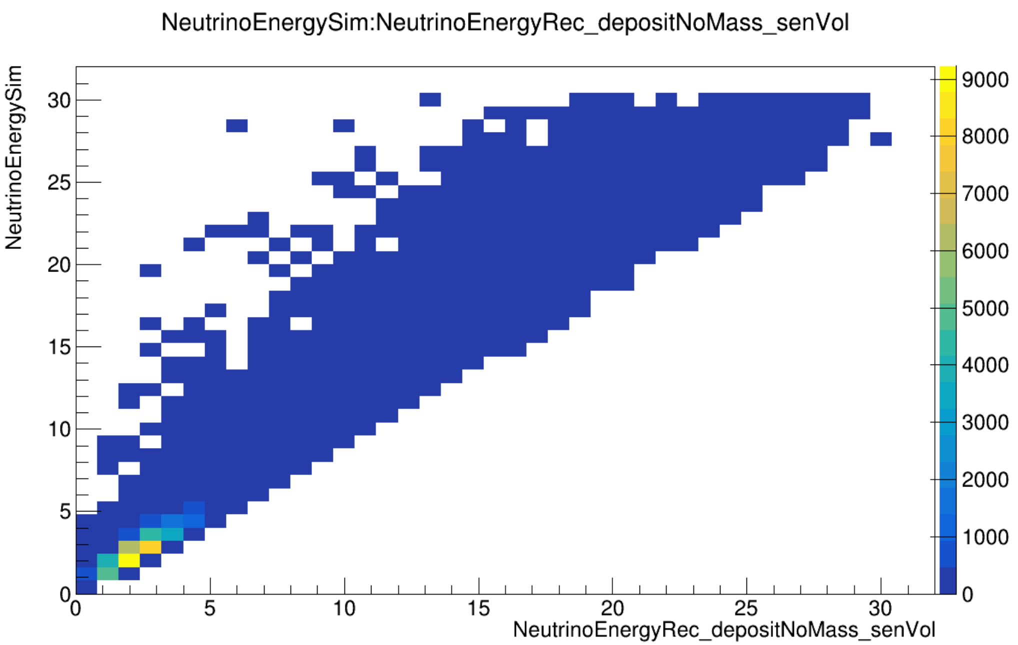
- If muon was not going through either 3DST or TPC, regardless hadron, it is rejected.

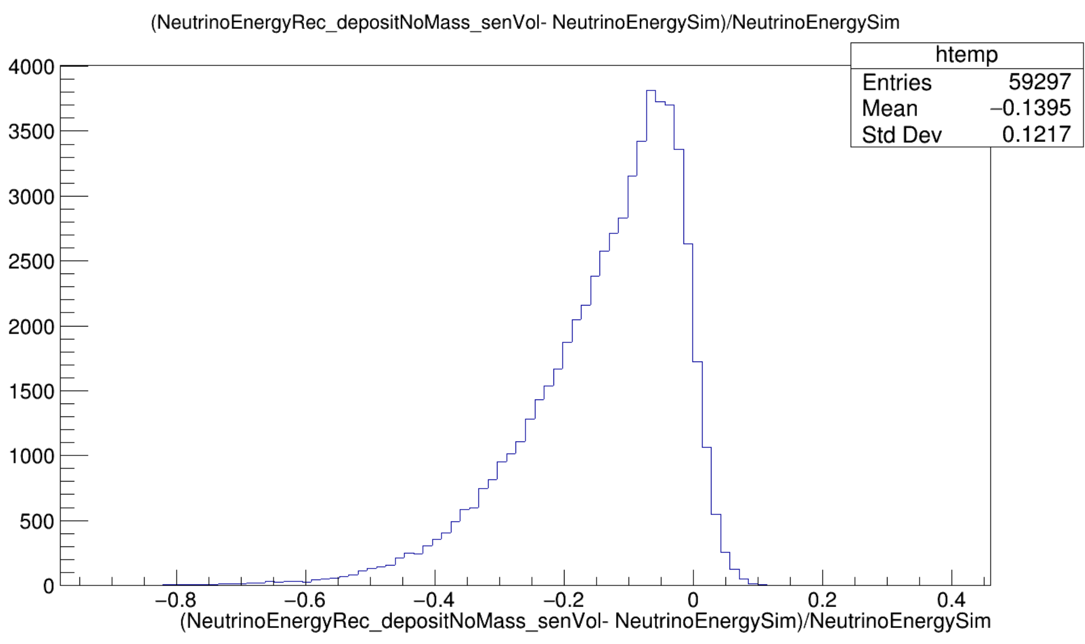
Muon energy reco.



Neutrino energy reco.

- Hadronic energy purely based on energy deposits in the sensitive volumes (without pion masses)
- Asymmetric shape due to nuclear effect, missing particles like neutron, energy leaking etc.





Event rate

- One week full pot : ~45 k per ton per week
- Efficiency table (out of all ECAL CC events)

Overall efficiency (whole ECAL)	23%
With |x| < 150 cm	20%
Upstream half + With |x| < 150 cm	19%
Downstream half + With |x| < 150 cm	< 1%
With |x| < 100 cm	14%
3DST interaction (10 ton FV)	> 90%

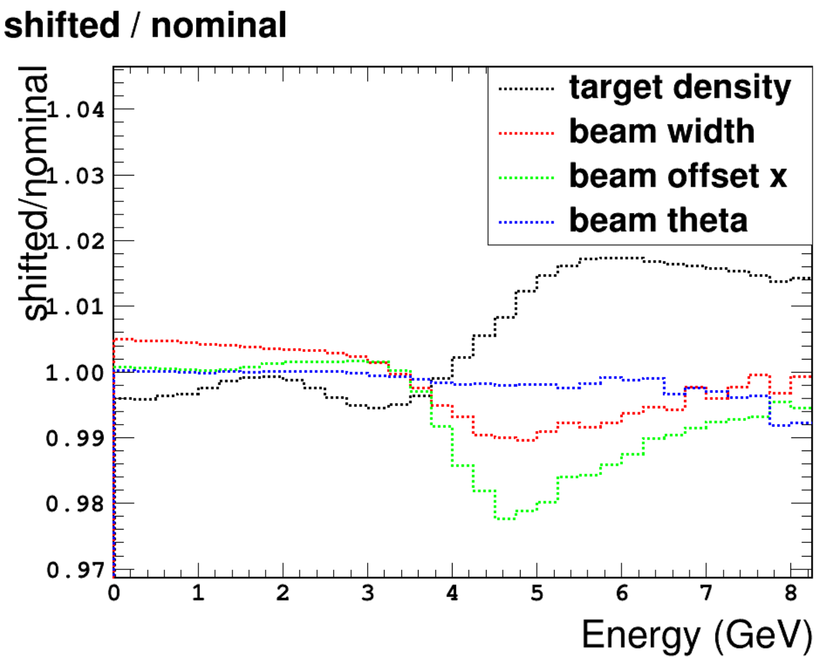
- An additional 80% efficiency due to outer layer as veto
- Without ECAL end-caps, It turns out ~660k events for ECAL and ~400k events for 3DST per week
- Beam sensitivity calculation is the same way as before using flux reweighting.

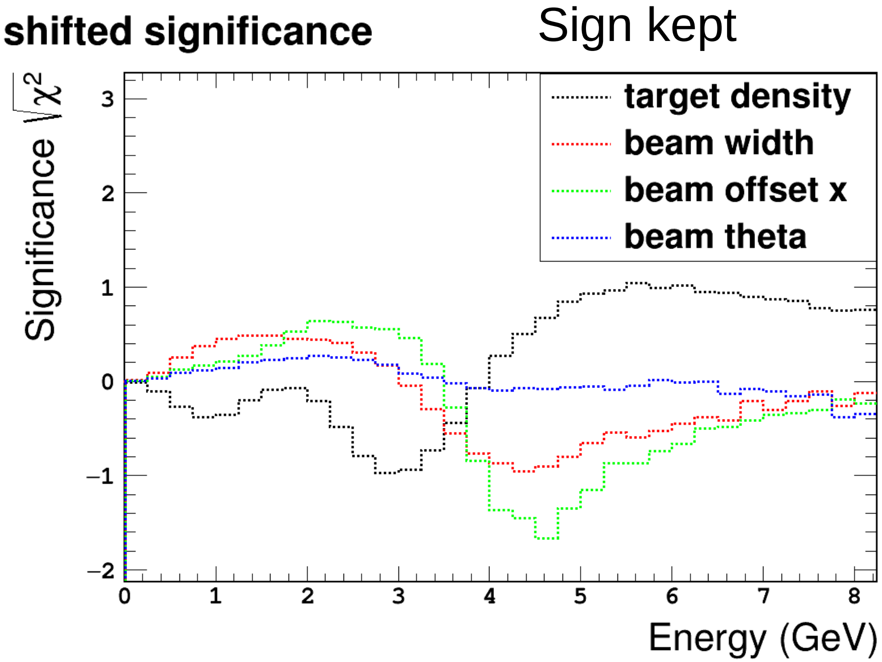
Sensitivity calculation

- 2% systematic rate uncertainty included:

$$\chi^2 = \sum_i \left(\frac{N_i^{nom}(\alpha) - N_i^{shift}}{\sigma_{stat}}\right)^2 + \left(\frac{(\alpha-1)}{2\%}\right)^2$$

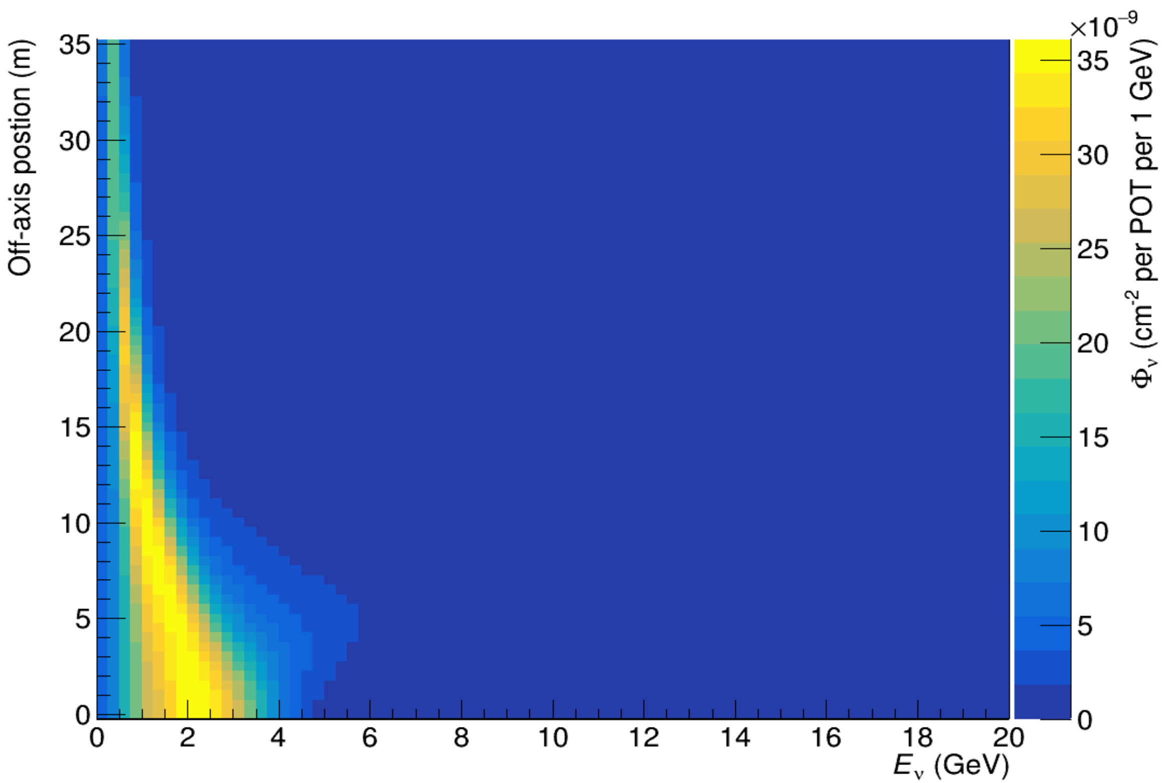
- Significance (sqrt(chi2)) in each bin defined as (nominal – shift)/ error for each bin
- Total sqrt(dchi2) is the square root of squared sum of all bins





A quick update : flux window

- Some concerns raised by people that the flux reweight may depend on the flux window, which may be non-uniformity on the transverse plane
- Added the X dependence.



- Flux window along Y : +-2 m
- Flux window along X :

  - before : not considered, just used center

  - Now: with a resolution of 0.5 along X
- Carry-out point:

  - It does not change results significantly

Spectral Results (with 2% rate uncertainty)

- Most energy ranged up to 10 GeV

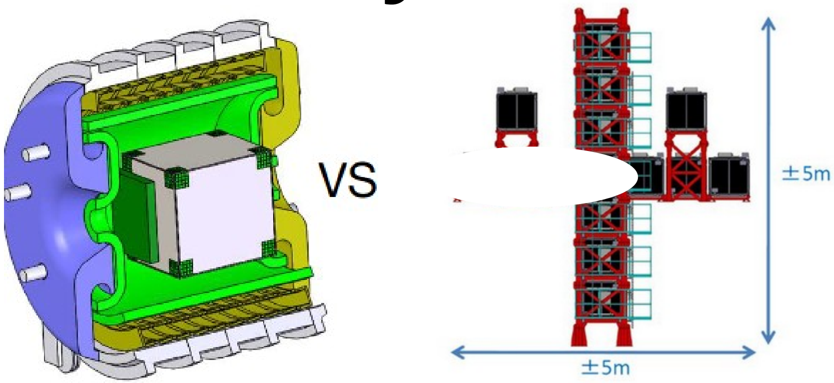
sqrt(dchi2)	Horn 1X	Horn 1Y	Horn 2X	Horn 2Y
ECAL 7 days	3.7	2.8	0.7	0.7
3DST 7 days	2.7	2.2	0.5	0.4
Total 7 days	4.6	3.6	0.9	0.8

sqrt(dchi2)	Target density	P Beam width	P Beam offset	P Beam theta
ECAL 7 days	4.4	2.8	3.6	0.4
3DST 7 days	3.4	2.3	2.4	0.3
Total 7 days	5.6	3.6	4.3	0.5

sqrt(dchi2)	P Beam tilt	Horn current	Water layer	Decay pipe radius
ECAL 7 days	0.9	9.2	3.2	5.3
3DST 7 days	0.5	7.6	2.7	4.5
Total 7 days	1.0	11.9	4.2	7.0

Ingrid-like 28 ton Rate results (with 2% rate uncertainty)

- Spectral monitoring is needed obviously



sqrt(dchi2)	Horn 1X	Horn 1Y	Horn 2X	Horn 2Y
INGRID 7 days	0.5	0.1	0.02	0.00
SAND 7 days	4.6	3.6	0.9	0.8

sqrt(dchi2)	Target density	P beam width	P beam offset	P beam theta
INGRID 7 days	0.02	0.02	0.09	0.03
SAND 7 days	5.6	3.6	4.3	0.5

sqrt(dchi2)	P beam tilt	Horn current	Water layer	Decay pipe radius
INGRID 7 days	0.00	0.2	0.5	0.5
SAND 7 days	1.0	11.9	4.2	7.0

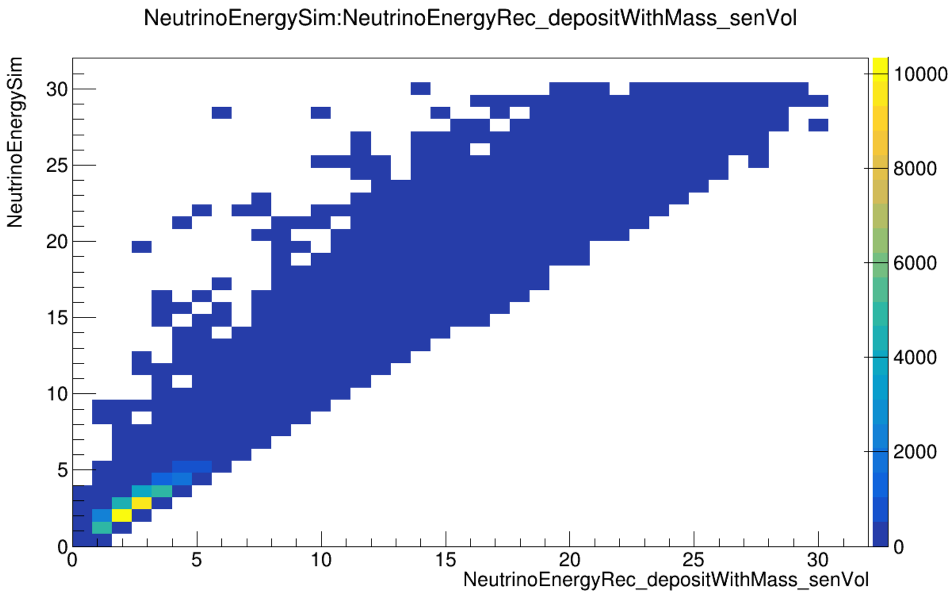
Summary

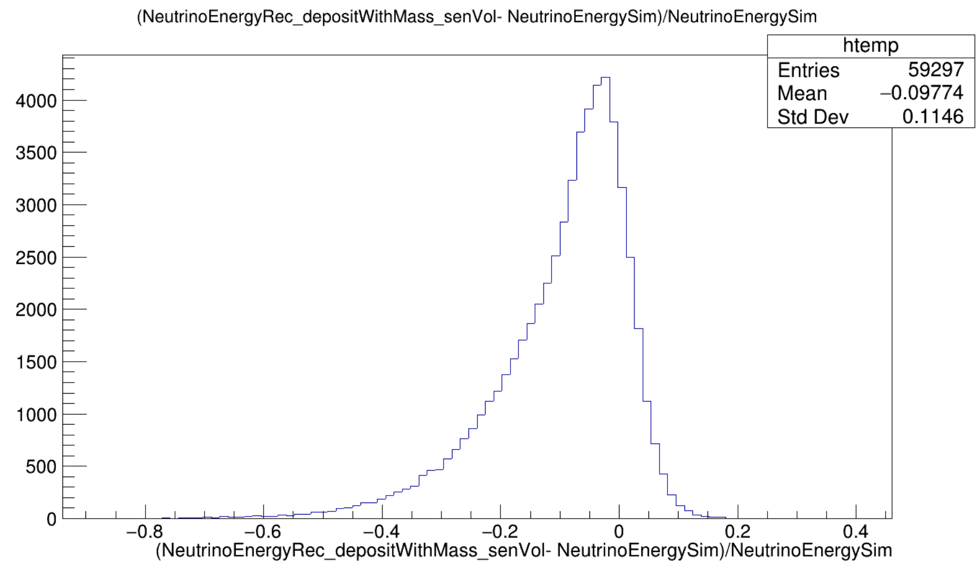
- Many beam variation effects can be seen above 3 sigma in SAND with reference design's one week of data.
- A detector like INGRID can't monitor beam variation effectively :SAND is needed for the spectral monitoring.
- ECAL increases the statistics thus enhances the beam monitoring capability of SAND significantly.
- There are free space along X, which can potentially make 3DST extendable to 3 m (shown last time, sensitivity improvement can be otained by a mass scaling to the first order).

Backups

Neutrino energy reco.

- Hadronic energy purely based on deposits in the sensitive volumes (with pion masses)





POT systematics

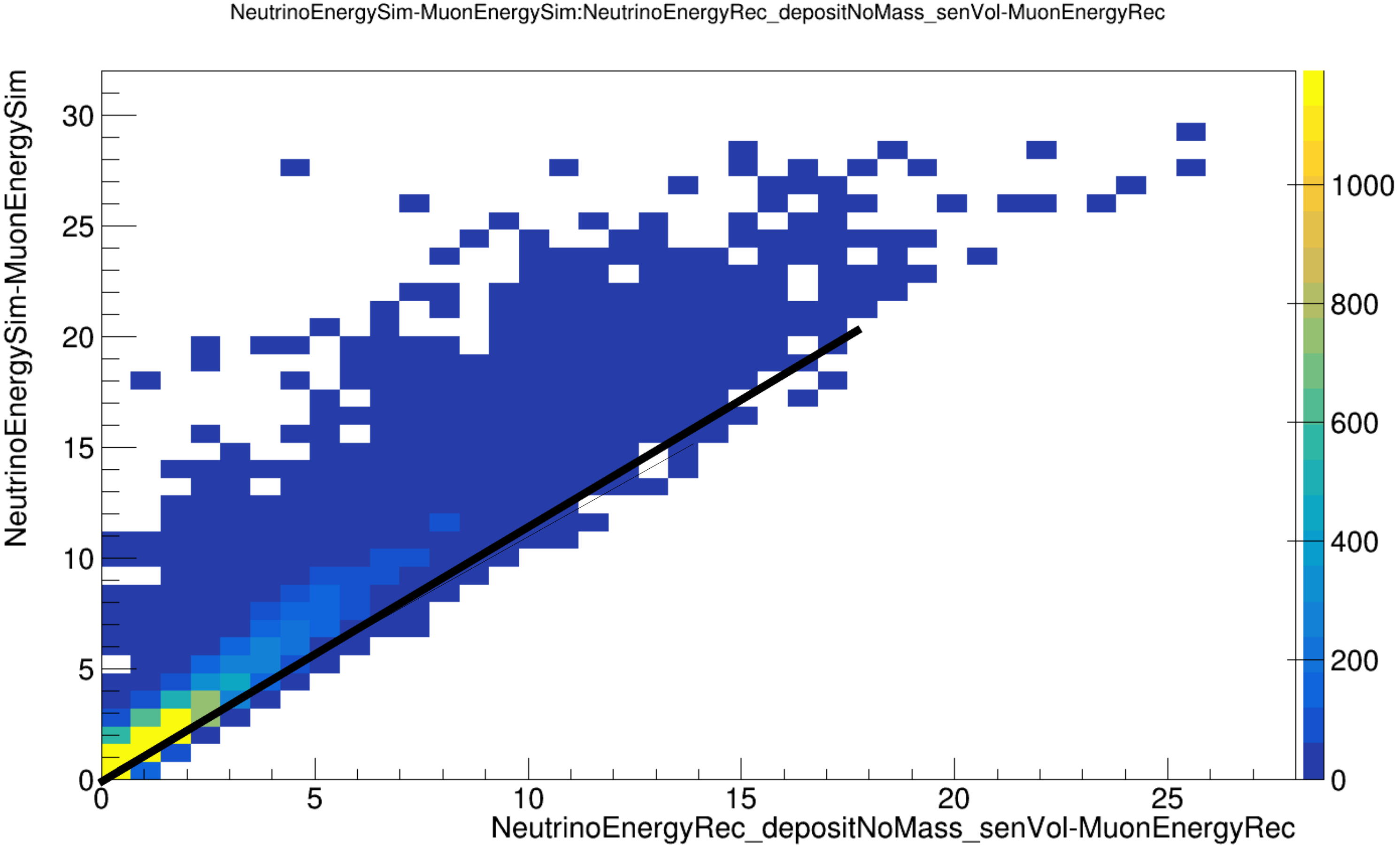
- Zarko: “ The systematic that you care about here is how precise can we measure the POT. We typically assign 2% to this number. It includes several effects, like toroid precision but also if there is some beam in the tail that doesn't go through whole target or if the beam wanders a bit and again some protons at the edge don't go through the whole target. The power of monitoring with on-axis spectrum is coming from the shape, but I don't think you should drop the normalization. I'd include it and have a 2% uncertainty to begin with.”
- Reference talk: https://indico.fnal.gov/event/20144/session/5/contribution/149/material/slides/1.pdf

Designed tolerance of the target parameter at LBNF

Parameter	Tolerance
Target Position (each end)	0.5 mm
Horn A Position (each end)	0.5 mm
Horn B Position (each end)	0.5 mm
Horn C Position (each end)	0.5 mm
Decay Pipe Radius	0.1 m
Horn Current	3 kA
Horn water layer thickness	0.5 mm
Beam radius at target	0.1 mm
Baffle Scraping	0.25%
Beam position at target	0.45 mm
Beam angle at target	70 microradians
Target Density	2%
Protons on Target	2%

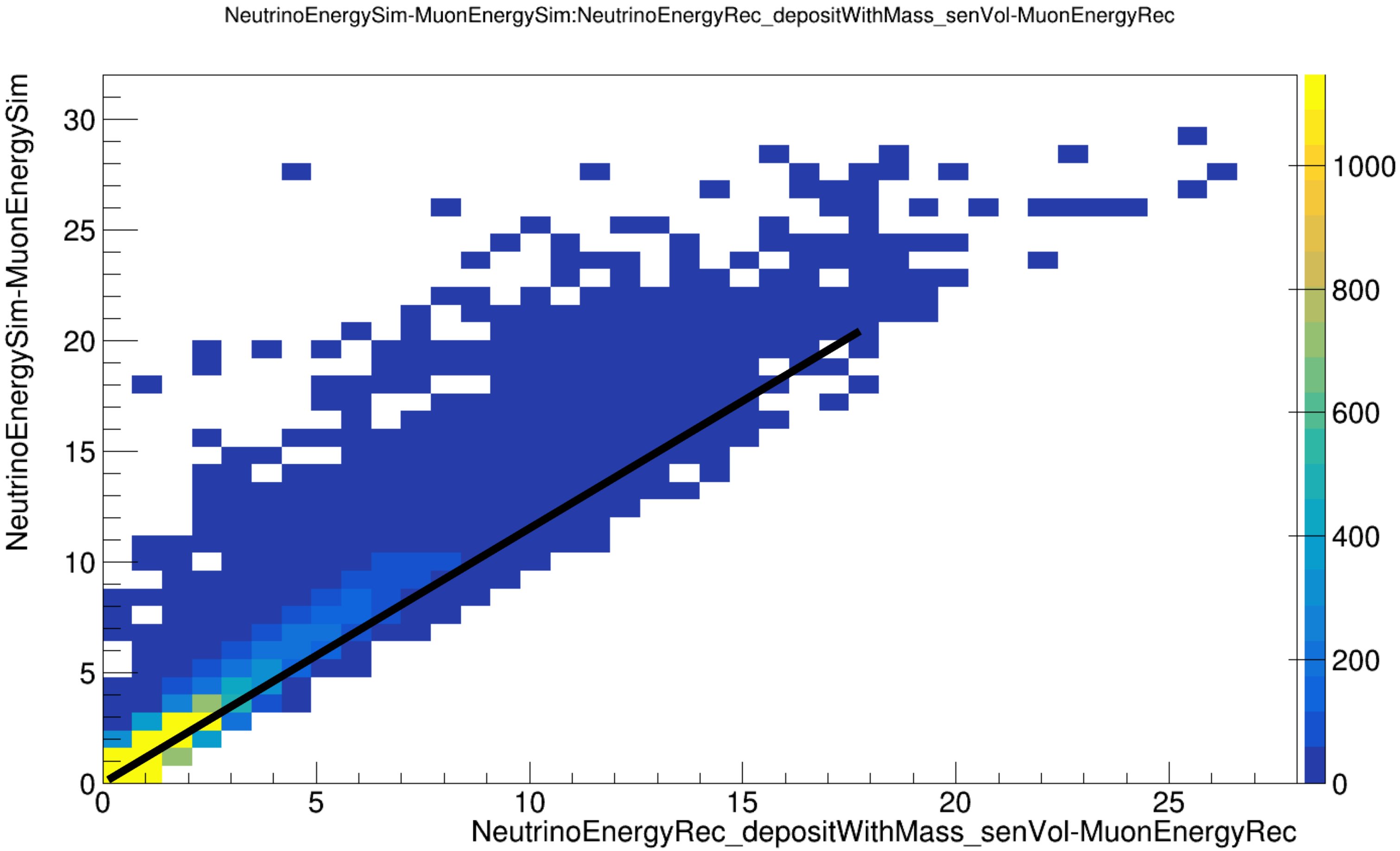
Hadron energy

- Without pion masses



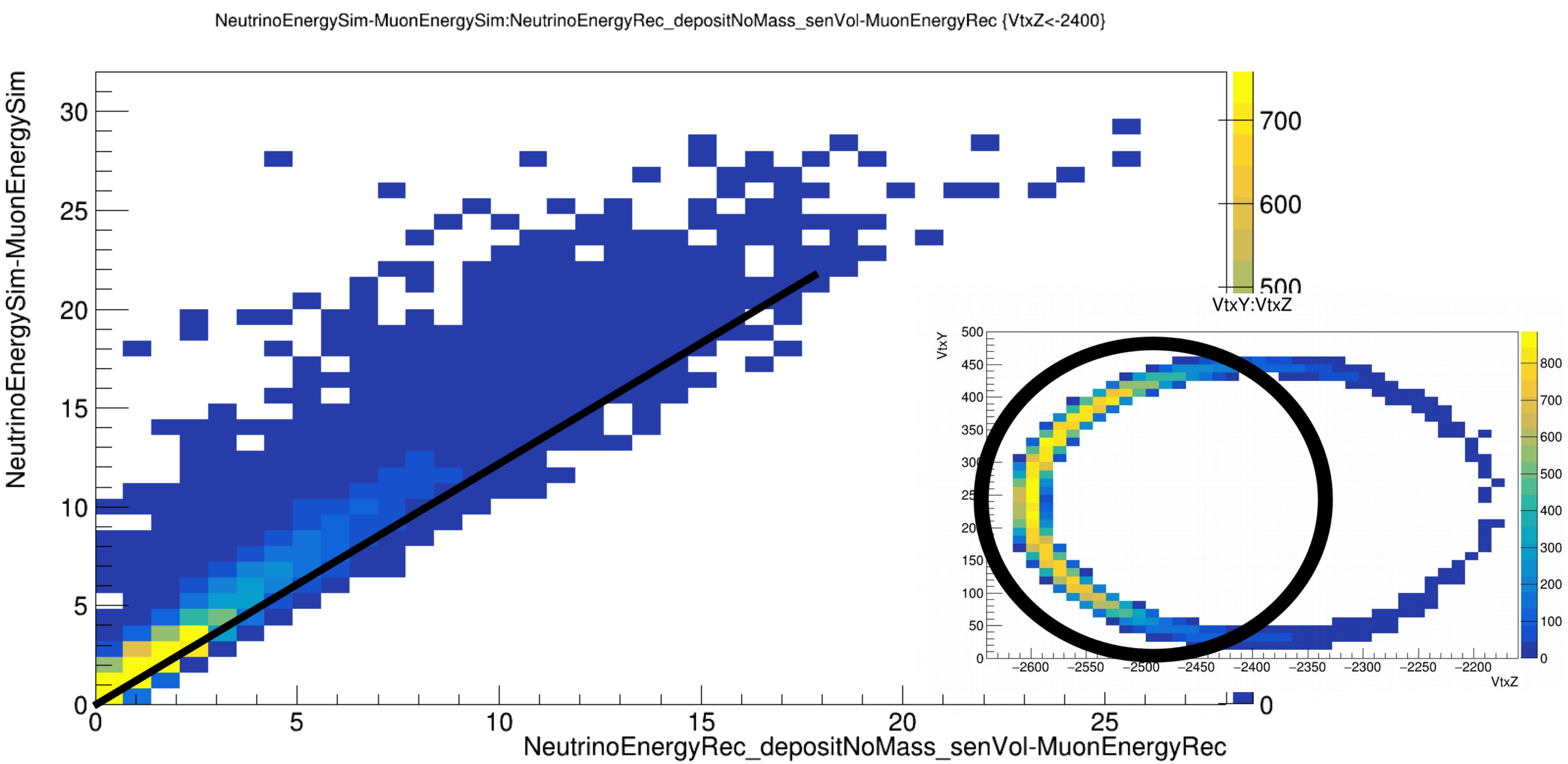
Hadron energy

- With pion masses



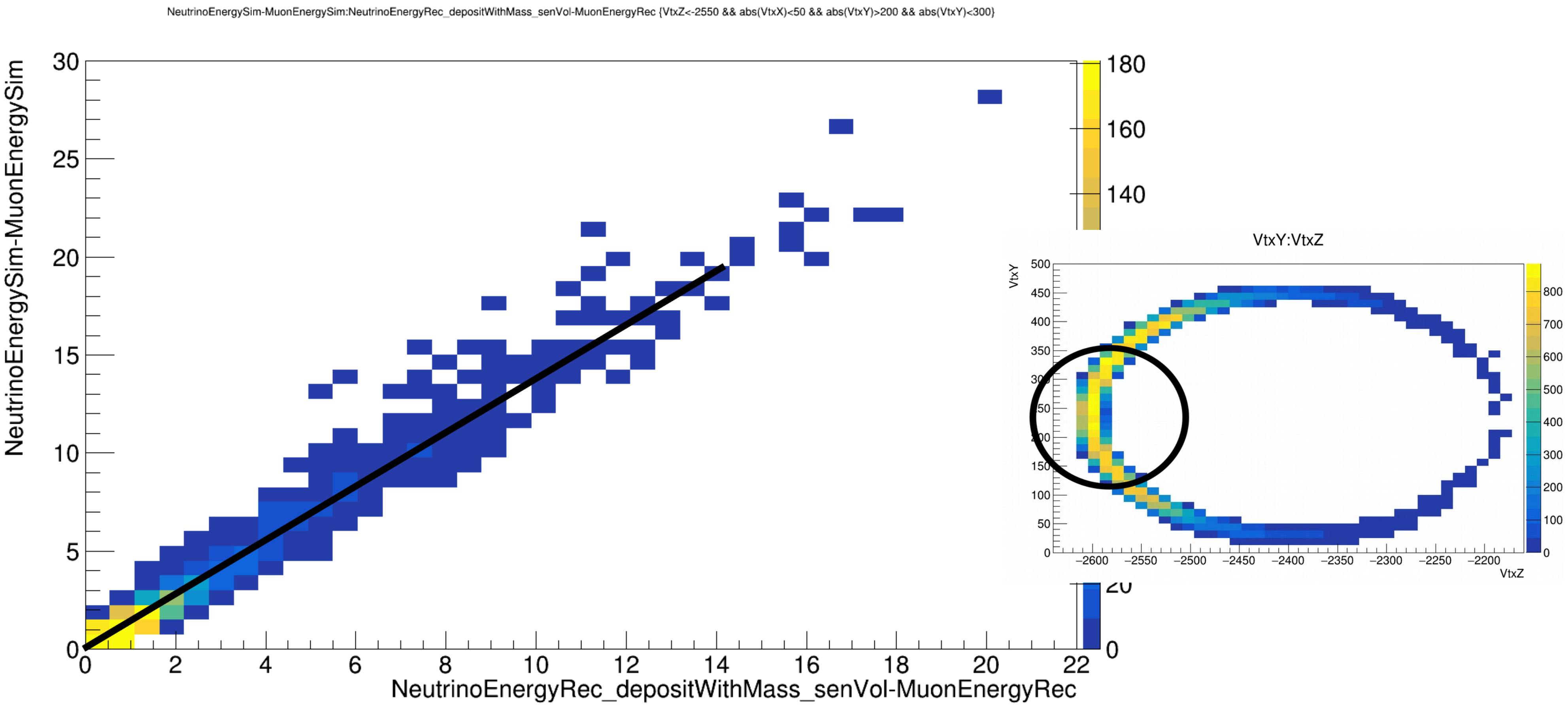
Hadron Energy

- With pion mass upstream half of the detector



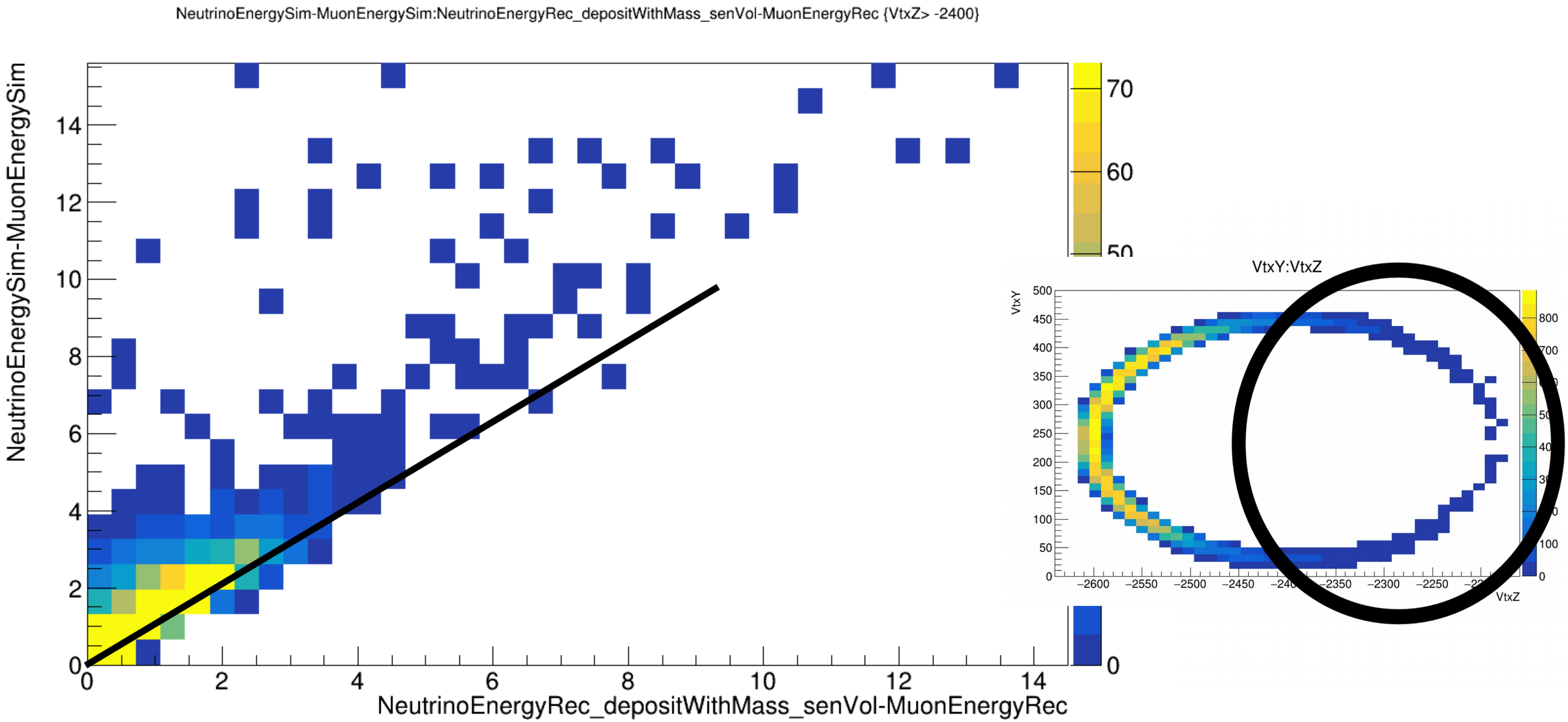
Hadron Energy

- With pion mass very upstream middle part of the detector

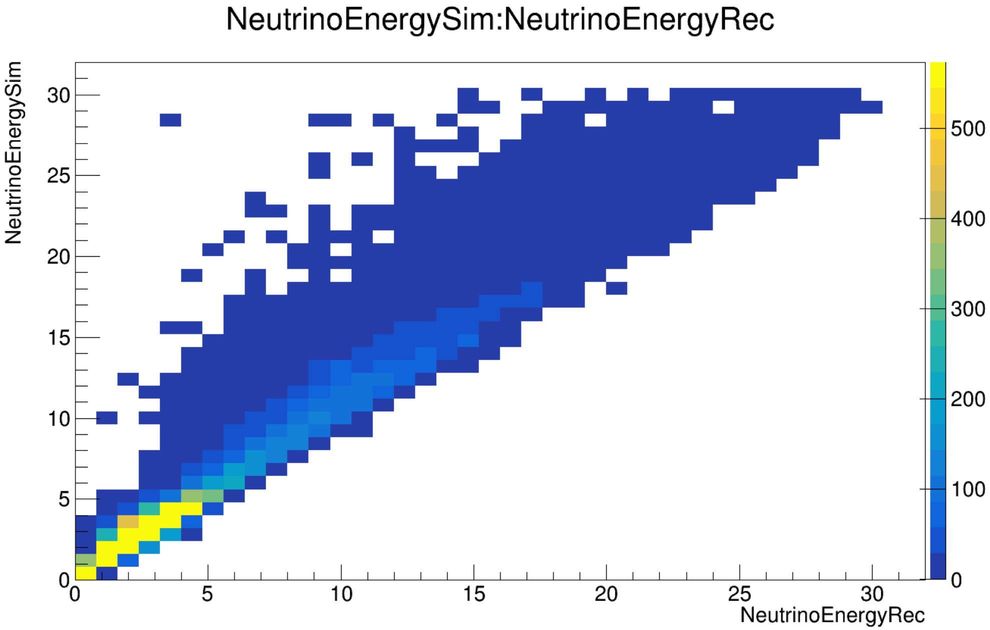


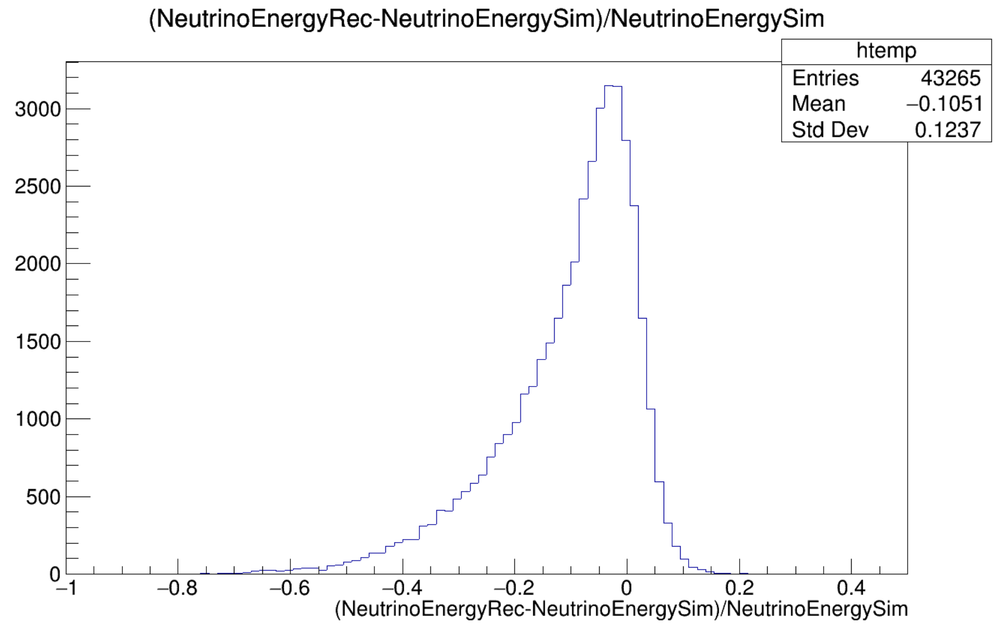
Hadron energy

- Downstream part of the ECAL

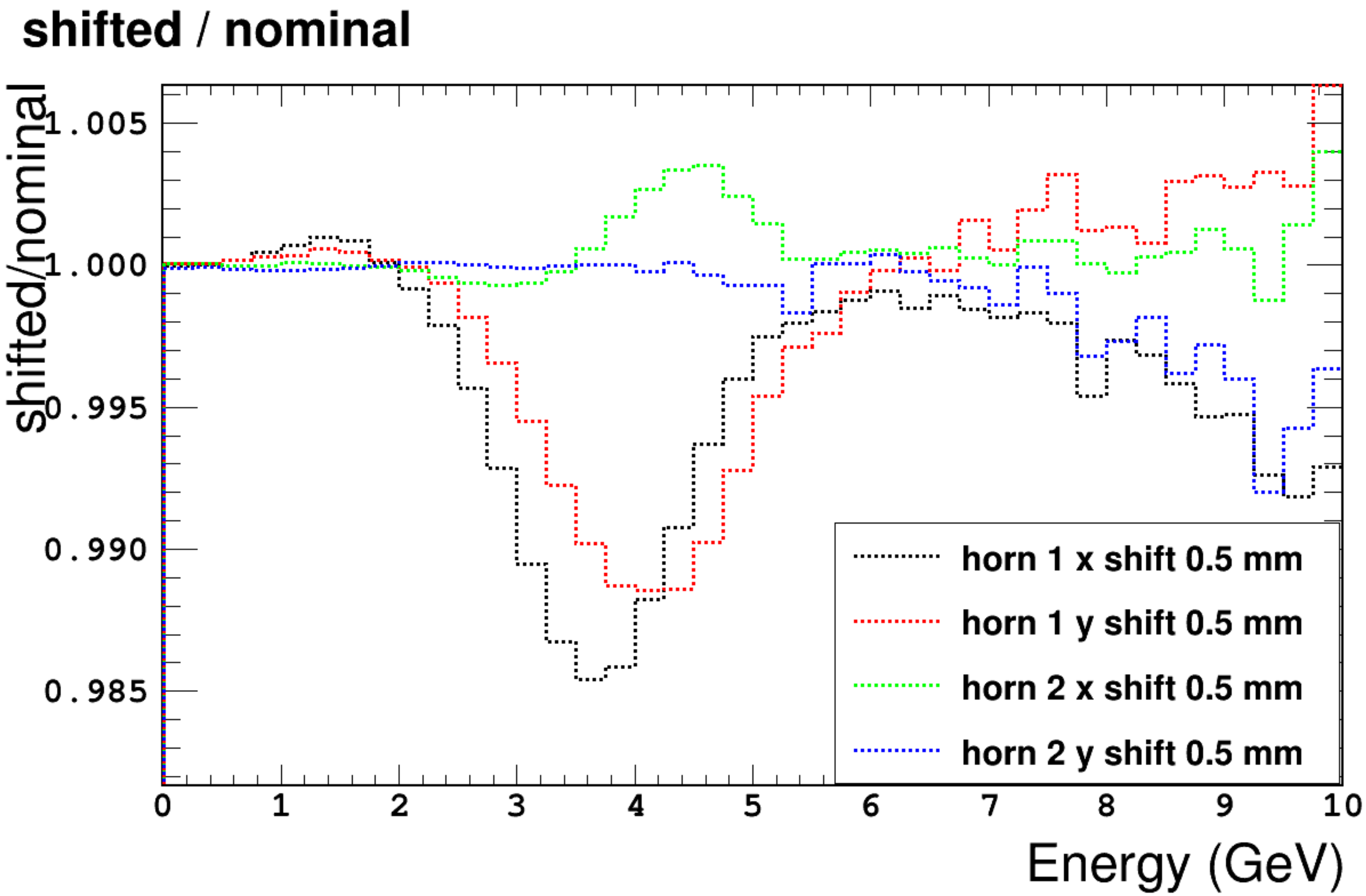


3DST energy with 10 ton FV



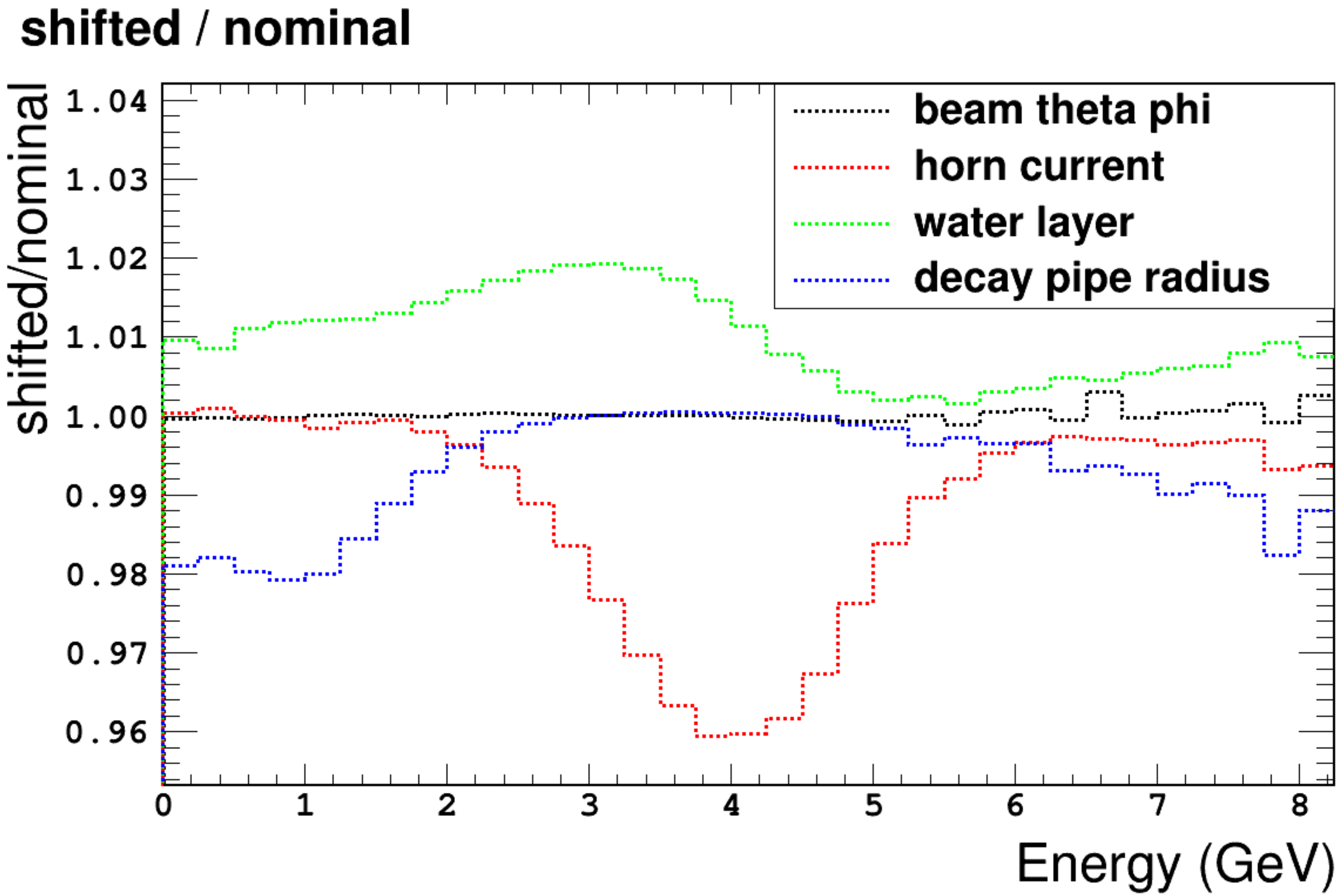


ECAL



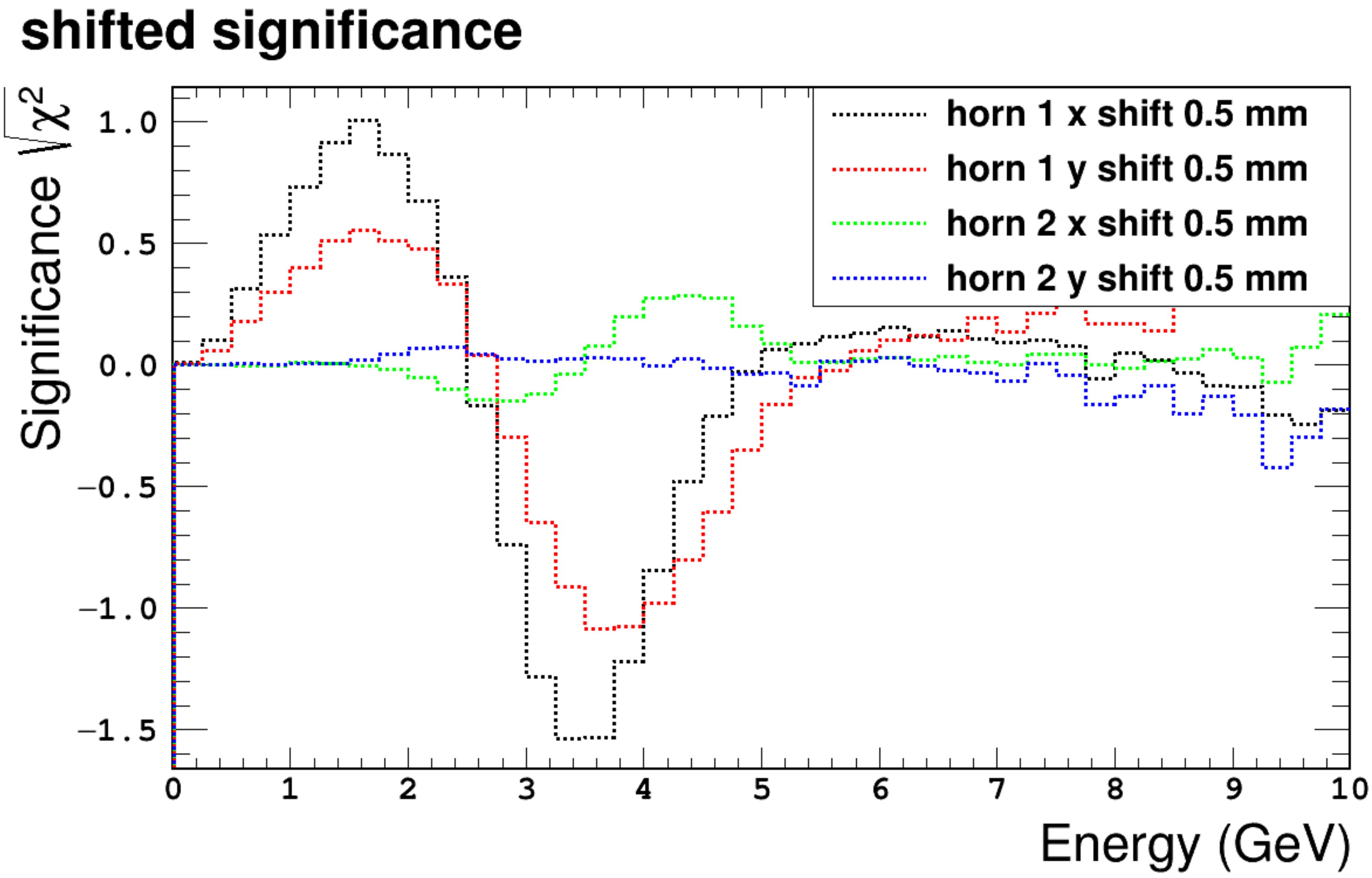
shifted / nominal
shifted/nominal
1.005
1.000
0.995
0.990
0.985
0
1
2
3
4
5
6
7
8
9
10
Energy (GeV)
horn 1 x shift 0.5 mm
horn 1 y shift 0.5 mm
horn 2 x shift 0.5 mm
horn 2 y shift 0.5 mm

ECAL

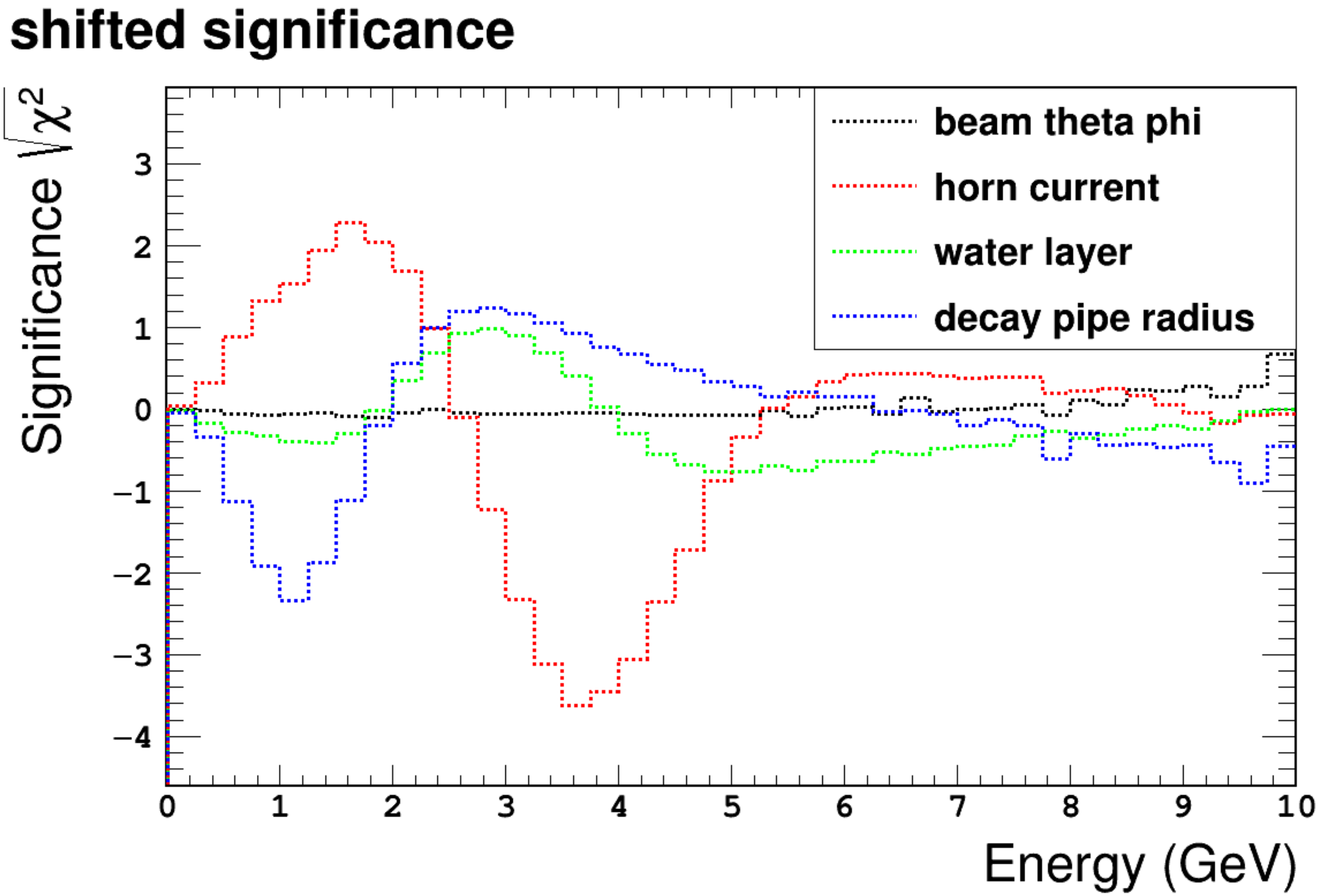


shifted / nominal
shifted/nominal
1.04
1.03
1.02
1.01
1.00
0.99
0.98
0.97
0.96
0
1
2
3
4
5
6
7
8
Energy (GeV)
beam theta phi
horn current
water layer
decay pipe radius

ECAL


shifted significance
Significance $\sqrt{\chi^2}$
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
1
2
3
4
5
6
7
8
9
10
Energy (GeV)
horn 1 x shift 0.5 mm
horn 1 y shift 0.5 mm
horn 2 x shift 0.5 mm
horn 2 y shift 0.5 mm

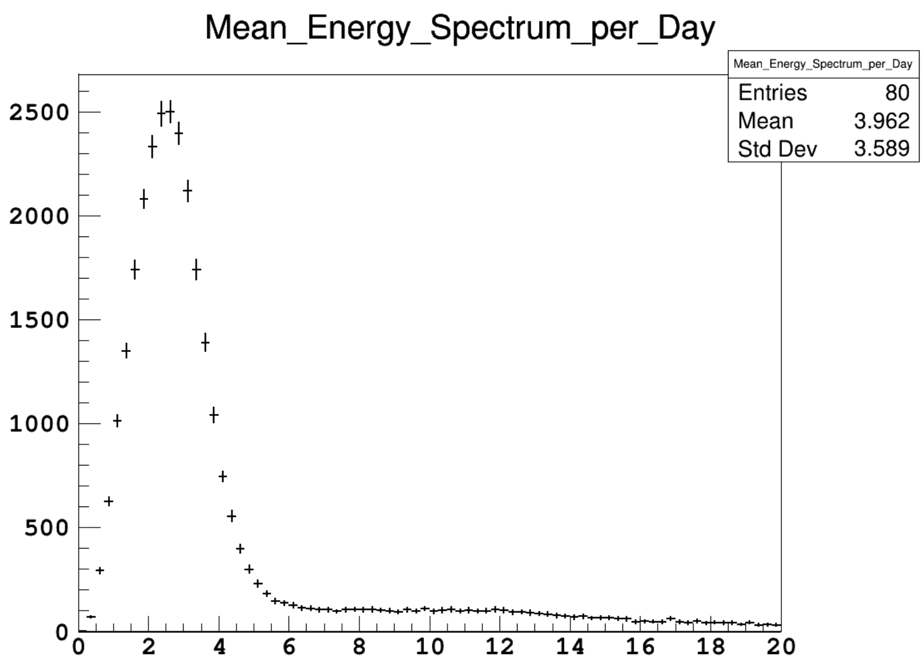
ECAL



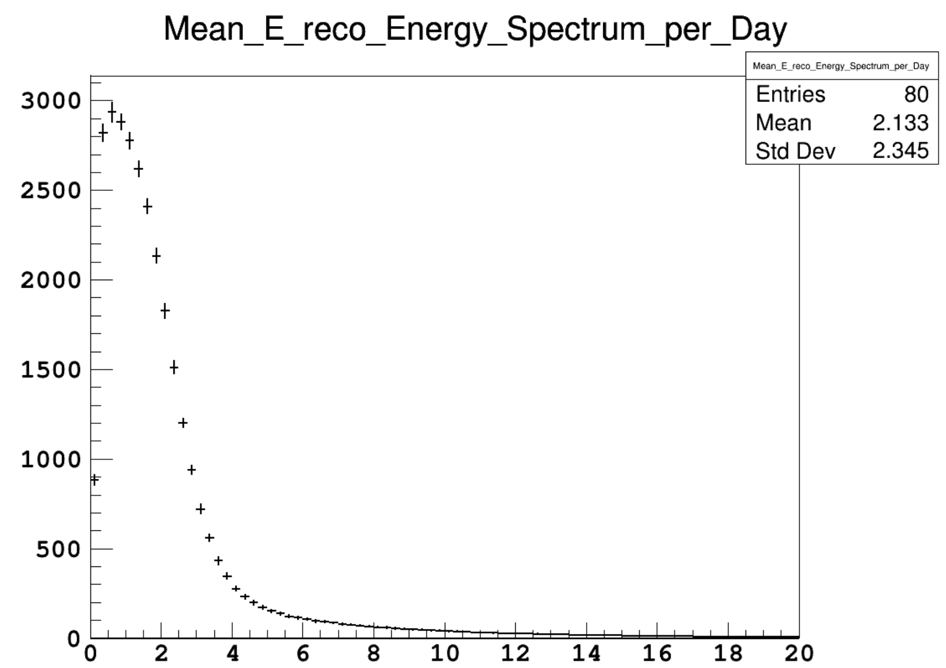
shifted significance
Significance $\sqrt{\chi^2}$
3
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
7
8
9
10
Energy (GeV)
beam theta phi
horn current
water layer
decay pipe radius

How the work was done? - step 1

- Averaged one-day spectra are generated with nominal flux based on a year of sample. These spectra can be scaled to whatever desired stat.



One day neutrino energy w/ smearing

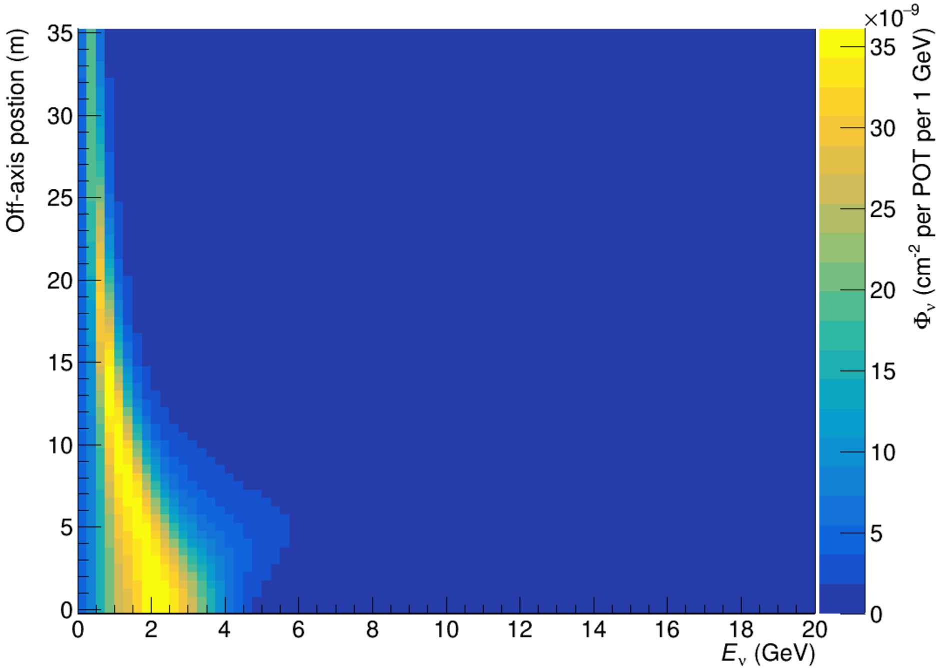


One day muon energy w/ smearing

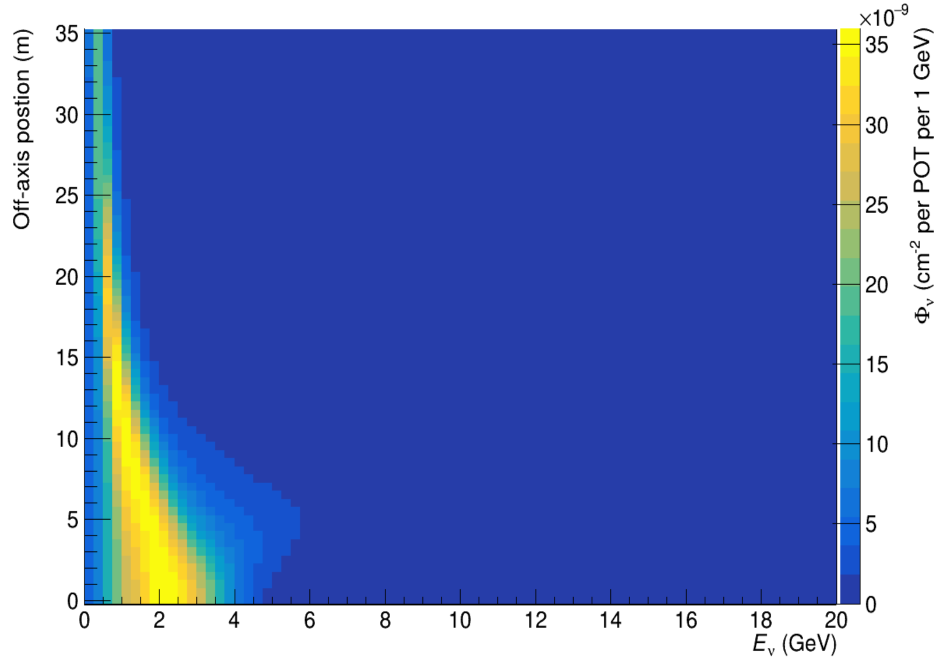
How the work was done? - step 2

- Nominal and variations have been generated (2017 engineered optimized flux)

Nominal flux

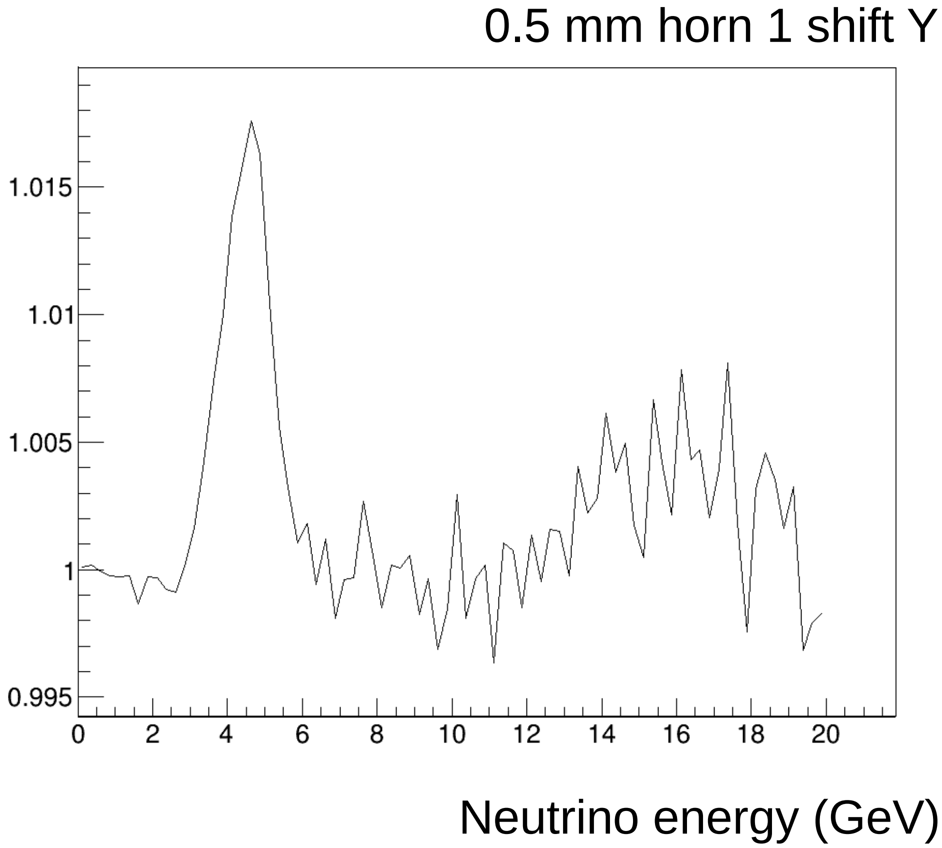


0.5 mm horn 1 shift Y



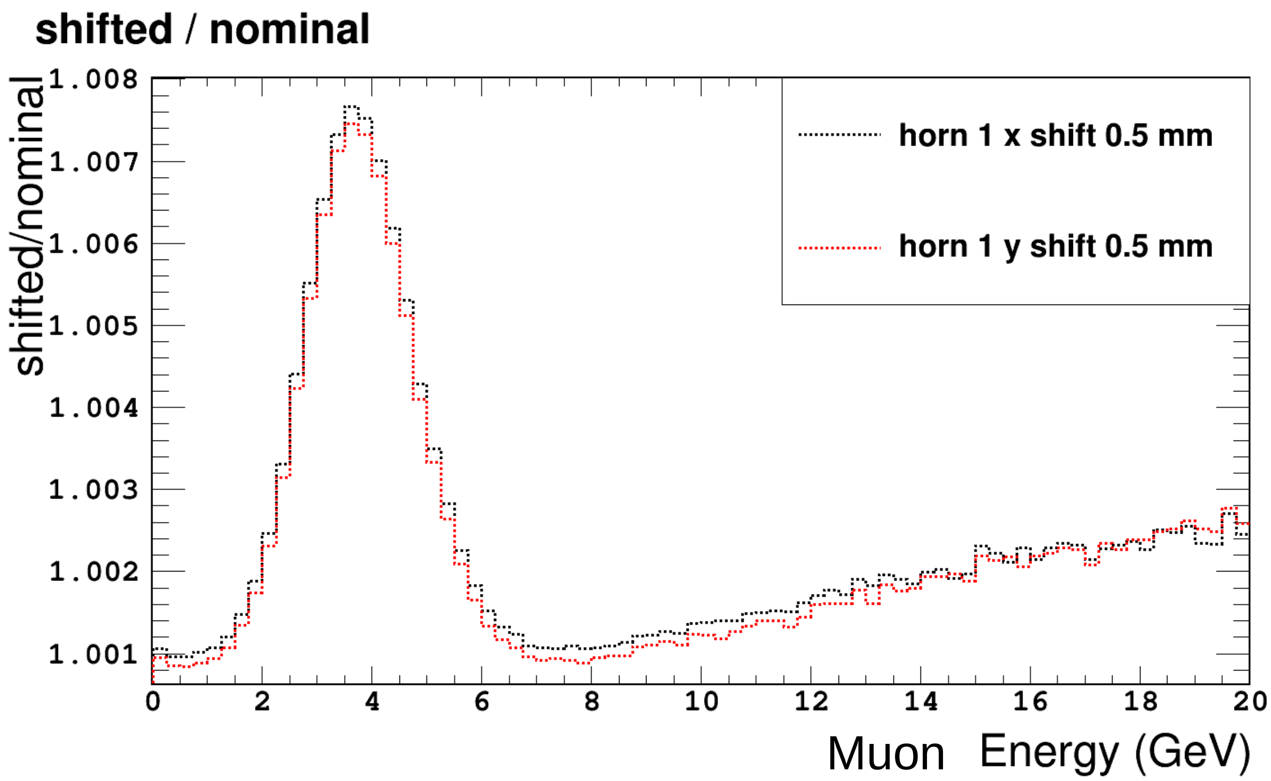
How the work was done? - step 3

- Flux reweight has been generated based on nominal flux and varied flux



How the work was done? - step 4

- Reweight has been applied to the nominal spectrum based on energy and neutrino species



Likelihood ratio

- The Pearson (standard) chi2 between A (nominal) and B (data) is our test statistics: (obs-exp)^2/exp (only stat)
- Likelihood ratio w/ Asimov :

  - chi2(A) – chi2(B) = chi2 (A/B)

  - A could be nominal while B shifted
- We are showing the sensitivity to the beam change, not the real weekly monitoring.