Beam monitoring with ECAL+STT configuration

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Main goal

Study the possibility of beam monitoring with the SAND detector in ECAL+STT configuration (interactions in MAGNET will be added)

Idea: get the neutrino beam spectrum and muon energy spectrum for nominal conditions depending on radius from the beam center and compare them with the beam with all the various systematic changes (including horns, protons, etc.) recommended by the beam working group and find the sensitivity to these changes

- fiducial volume STT: R < 190, $|X| < 159$ cm
- fiducial volume ECAL: $200 < R < 225$, $|X| < 169$, $|Y| < 200$, $Z < 0$ cm

Reference statistics - one week of data taking

EXPECTED WEEKLY RATES

- *Weekly rates (7 days) used for beam monitoring purpose: STT, ECAL, magnet.*
- *Number of events per week (7 days) in FV defined as:*
  Magnet, ECAL $\mid X \mid < 1.69$m, $\mid Y \mid < 2.0$m; LAr+STT 10cm from edges

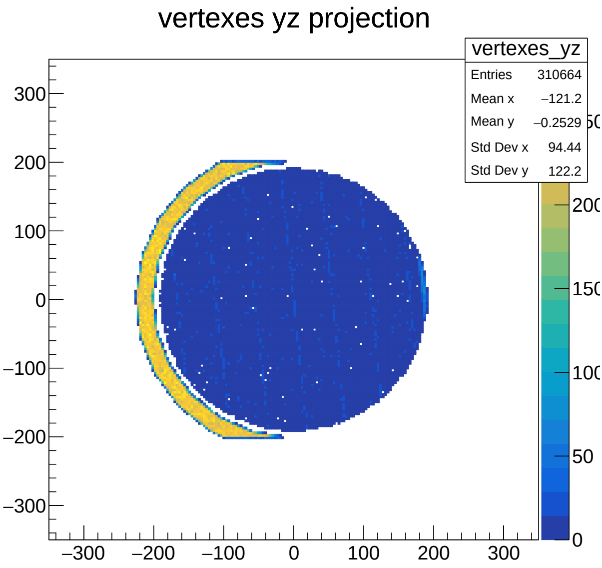
Detector	Mass	FHC		RHC	
		ν_μ CC	$\bar{\nu}_\mu$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC
Magnet front FV	45.9 t	2,150,420	105,341	344,801	821,289
ECAL front FV	19.7 t	922,945	45,212	147,986	352,492
LAr+STT FV	7.7 t	360,745	17,672	57,842	137,776
Total	73.3 t	3,434,110	168,225	550,629	1,311,560

- *Inclusive CC rates per week (7 days):*
  FHC ν_μ CC 46,850/ton, $\bar{\nu}_\mu$ CC 2,295/ton
  RHC ν_μ CC 7,512/ton, $\bar{\nu}_\mu$ CC 17,893/ton

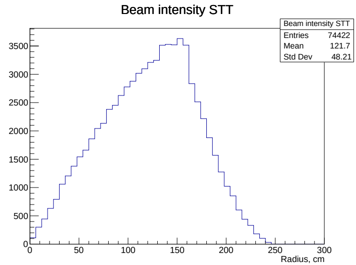
Procedure

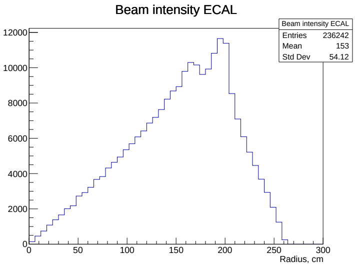
- making primary vertex distribution map
- rotate all events to the beam direction (-0.101 rad)
- making beam profile depending on radius from the detector center
- preliminary results are done for the true simulation information for the neutrino interactions in STT and ECAL
- χ^2-values for beam comparison $\nu_\mu + \bar{\nu}_\mu$ CC between nominal beam and various beam conditions
- expected weekly exposure 3.78×10^{19} p.o.t.
- events simulated with complete chain dk2nu+GENIE+GEANT4+edep-sim

Vertices distribution



Beam intensity - FHC





Radial bins used to monitor E_ν and E_μ (ν_μ CC):

- STT: 0-100, 100-150, 150-250 cm
- ECAL: 0-100, 100-150, 150-200, 200-250 cm

Whole range for $\bar{\nu}_\mu$ CC sample

χ^2 determination

Two methods of χ^2 calculation:

1. Two unweighted histograms:

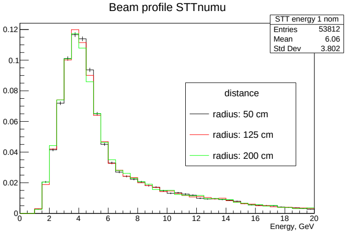
$$\chi^2 = \frac{1}{N^{nom} \cdot N^{var}} \sum_{i=1}^{k} \frac{(N^{var} \cdot n_i^{nom} - N^{nom} \cdot n_i^{var})^2}{n_i^{nom} + n_i^{var}}$$

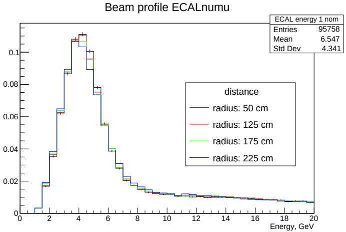
where N^{nom}, N^{var} - total number of events in histograms, k - total number of bins, n_i - number of events in i^{th} bin.

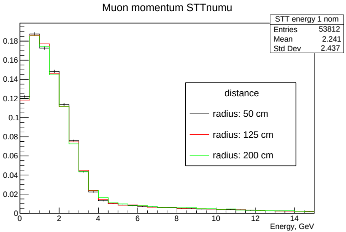
2. Histograms are weighted for the weekly number of p.o.t.

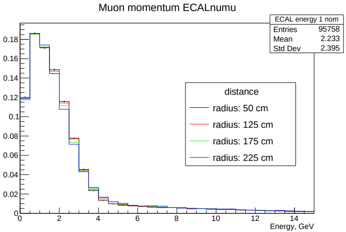
$$\chi^2 = \sum_{i=1}^{k} \frac{(n_i^{nom} - n_i^{var})^2}{\sigma_{i,nom}^2 + \sigma_{i,var}^2}$$

Beam profile - FHC









Variations of beam parameters considered

Beam parameters	Variation	Statistics ($\times 10^{19}$ p.o.t.)	Simulated events
Nominal	–	4.320	5.31×10^6
Horn 1 along X	+0.5 mm	3.986	4.90×10^6
Horn 1 along Y	+0.5 mm	4.586	5.64×10^6
Horn 2 along X	+0.5 mm	3.200	3.94×10^6
Horn 2 along Y	+0.5 mm	4.126	5.07×10^6
Proton beam X offset	+0.45 mm	4.190	5.15×10^6
Proton beam radius	+0.1 mm	4.078	5.02×10^6
Proton beam angles	$0.07\ \theta$, $1.57\ \phi$	4.084	5.02×10^6
Decay pipe radius	+0.1 m	2.658	3.27×10^6
Horn currents	+3 kA	2.694	3.31×10^6
Target density	+2%	4.230	5.20×10^6
Horn water thickness	+0.5 mm	2.778	3.42×10^6

STATISTICAL CONSIDERATIONS

✦ *Statistical consistency of weekly samples:*

$$\chi^2 \equiv \sum_{i=1}^{N} \frac{(N_i^{\rm nom} - N_i^{\rm var})^2}{\sigma_{i,{\rm tot}}^2}$$

$N_i^{\rm nom}$ *weekly statistics in i-th bin with nominal beam settings*
$N_i^{\rm var}$ *weekly statistics in i-th bin with varied beam parameters*
$\sigma_{i,{\rm tot}}$ *total uncertainty in i-th bin*

- *Relative comparison between 2 indipendent (& different) weekly samples:*
  $\sigma_{i,{\rm tot}}^2 \equiv \sigma_{i,{\rm nom}}^2 + \sigma_{i,{\rm var}}^2 \sim 2\sigma_{i,{\rm nom}}^2 = 2N_i^{\rm nom}$

  $\Longrightarrow$ *Both samples can fluctuate: $\sigma^i_{\rm Tot} \equiv \sigma^i_{\rm Nom}$ overestimates χ^2 (e.g. CDR)*

- *Comparison of single weekly sample with "model" predictions:*
  $\sigma_{i,{\rm tot}}^2 \equiv \sigma_{i,{\rm nom}}^2 + \sigma_{i,{\rm sys}}^2$ *with $\sigma_{i,{\rm sys}}$ systematic uncertainty on beam prediction*

  $\Longrightarrow$ *Typically $\sigma^i_{\rm Sys} \gg \sigma^i_{\rm Nom}$, washing away sensitivity of data to beam variations*

- *Need to simulate full expected statistics (7 days):*
  - *Scaling up smaller statistics samples makes scaled σ^i_{Tot} inconsistent with actual sample fluctuations*
    $\Longrightarrow$ *Potential overestimate of χ^2, especially in low-statistics tails*
  - *Given large expected weekly rates statistical fluctuations on original simulated samples may introduce significant biases on χ^2*
    $\Longrightarrow$ *"Fake variation" with independent nominal sample to validate results*
- *Significance cannot be calculated simply as $\sqrt{\chi^2}$ (e.g. CDR), but need to take into account number of bins N: for large N the $\chi^2 \rightarrow$ gaussian with $\mu = N$ and $\sigma = \sqrt{2N}$*
  $\Longrightarrow$ *Preferable χ^2 probability test to evaluate sensitivity to variations of beam settings*

Summary

- method for calculating difference between nominal and various beam conditions has been proposed
- results will be shown after full sample generating and making normalization to the weekly p.o.t. number
- momentum and energy smearing are under implementation