Analysis Note

Report on the QA and run-by-run systematics in the Xe+Cs(I) run8

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The Xe+Cs(I) event set for an energy of 3.8 GeV lasted several weeks. During such a long period of time, the characteristics of various detector subsystems may change. This may be due to changes in operating conditions and active areas of the detectors, changes in noise levels, failure of individual electronic components, etc. The task of analyzing the quality of experimental data is to select the part of the data that is characterized by the same characteristics of the detector subsystems used in the physical analysis. The entire volume of BM@N experimental data within a single Nuclotron accelerator cycle is divided into separate segments (runs), which can be selected using a special identifier (RunId). Within a single run, the characteristics of the BM@N detector subsystems remain unchanged. A QA (quality assurance) selection procedure was performed to select runs suitable for the analysis. This note describes the software used for the QA procedure and the results of its operation.

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Contents

1 Quality Assurance (QA) study

The collection of events for a collision energy is done over several discrete time spans. Each of these time spans where the detector was continuously recording events is called a "run" and it can be selected by RunId. Each run consists of event and track information of the heavy-ion collisions recorded by the BM@N detector. We perform quality assurance (QA) checks for the selection of good runs. Averaged QA observables like: N_{ch} (charged particle multiplicity in FSD GEM system), E_{tot} (total energy of spectator fragments in the FHCal), N_{vtx} (number of tracks in the vertex reconstruction), etc., are calculated for each run. Then, the mean (μ) and standard deviation (σ) are calculated for the distribution of selected observables Y as a function of RunId:

$$\mu_j = \frac{1}{N_j} \sum_{i=1}^{N_j} Y_i \tag{1}$$

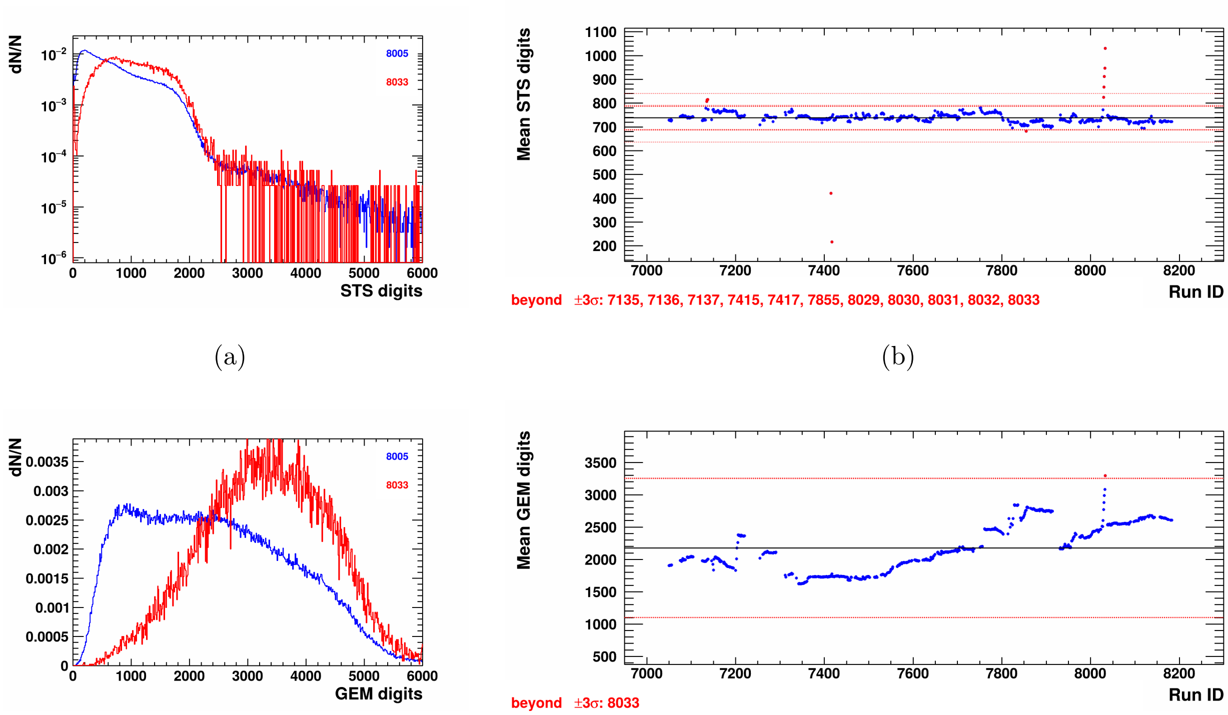
$$\sigma_j = \sqrt{\frac{1}{N_j} \sum_{i=1}^{N_j} (Y_i - \mu)^2}, \tag{2}$$

where i - RunId number and N - total numbers of RunId, j - iteration number. We reject RanId beyond $3\sigma_j$ and then perform a similar procedure for the remaining runs until $|\mu_j - \mu_{j+1}| > 0.01\mu_j$. Typically, 2 or 3 iterations are required. Details on selecting “bad” RunId are presented in the sections 1.1-1.12. The runs for which the averaged QA observables lie beyond $\pm 3\sigma$ away from their global means are identified as bad runs, and all the events from that run are removed from the analysis.

The preliminary list of bad runs based on QA study [18M events] RunId: 6968, 6970, 6972, 6973, 6975, 6976, 6977, 6978, 6979, 6980, 6981, 6982, 6983, 6984, 7313, 7326, 7415, 7417, 7435, 7517, 7520, 7537, 7538, 7542, 7543, 7545, 7546, 7547, 7573, 7575, 7657, 7659, 7679, 7681, 7843, 7847, 7848, 7850, 7851, 7852, 7853, 7855, 7856, 7857, 7858, 7859, 7865, 7868, 7869, 7907, 7932, 7933, 7935, 7937, 7954, 7955, 8018, 8031, 8032, 8033, 8115, 8121, 8167, 8201, 8204, 8205, 8208, 8209, 8210, 8211, 8212, 8213, 8215, 8289.

1.1 Number of digits in the detectors

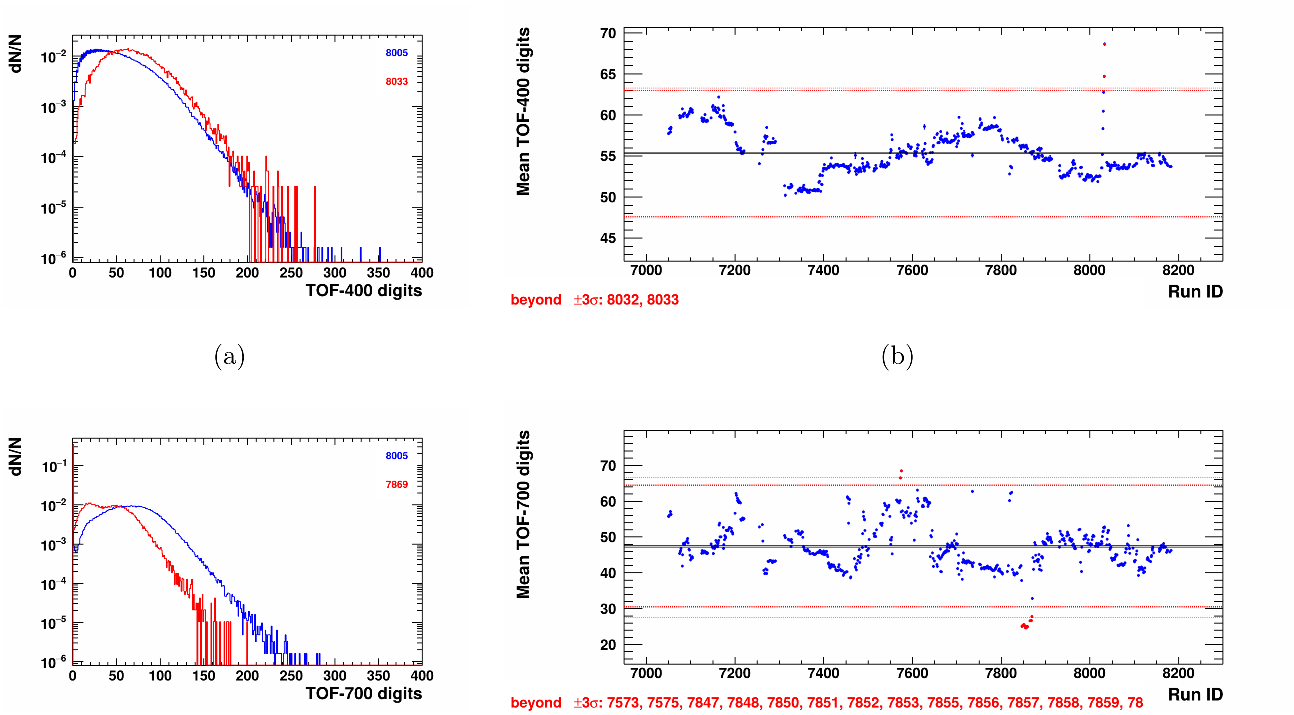
Figures 1- 2 show the RunId dependence of the mean number of FSD, GEM, TOF400 and TOF700 digits. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.



(a) (b)

(c) (d)

Figure 1: Distribution of the number of digits in the FSD (a) and GEM (c) detector. The red marker corresponds to the distribution from the "outlier" RunId. Mean FSD digits (b) and GEM digits (d) as a function RunID (right panel). Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.



(a) (b)

(c) (d)

Figure 2: Distribution of the number of digits in the TOF400 (a) and TOF700 (c) detector. The red marker corresponds to the distribution from the "outlier" RunId. Mean TOF400 digits (b) and TOF700 digits (d) as a function RunID (right panel). Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.2 Vertex position

Figure 3- 4 shows the RunId dependence of the mean number of tracks used in the vertex reconstruction and χ^2/NDF. Figure 5 shows the RunId dependence of the mean x, y and z positions of the reconstructed vertex.

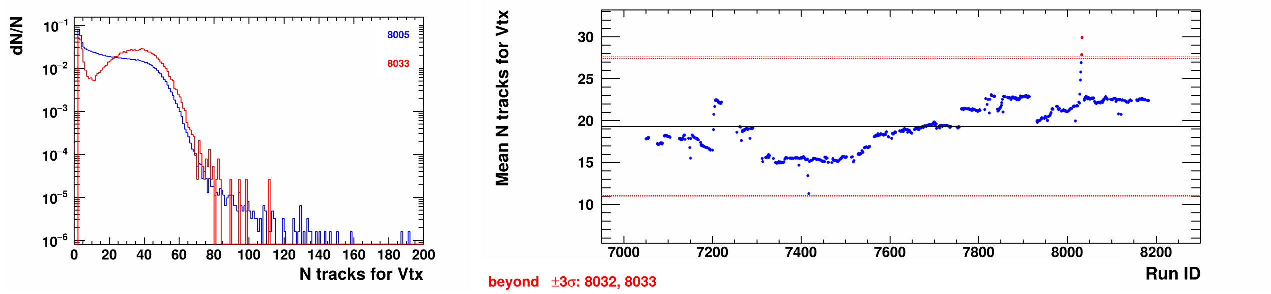


Figure 3: Left panel: distribution of the number of track in vertex reconstruction. The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean the number of track in vertex reconstruction as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

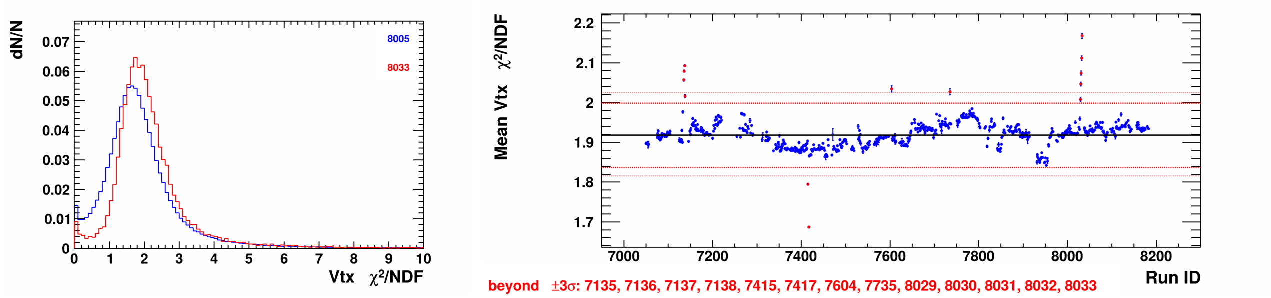


Figure 4: Left panel: distribution of χ^2/NDF for vertex reconstruction. The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean χ^2/NDF for vertex reconstruction as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

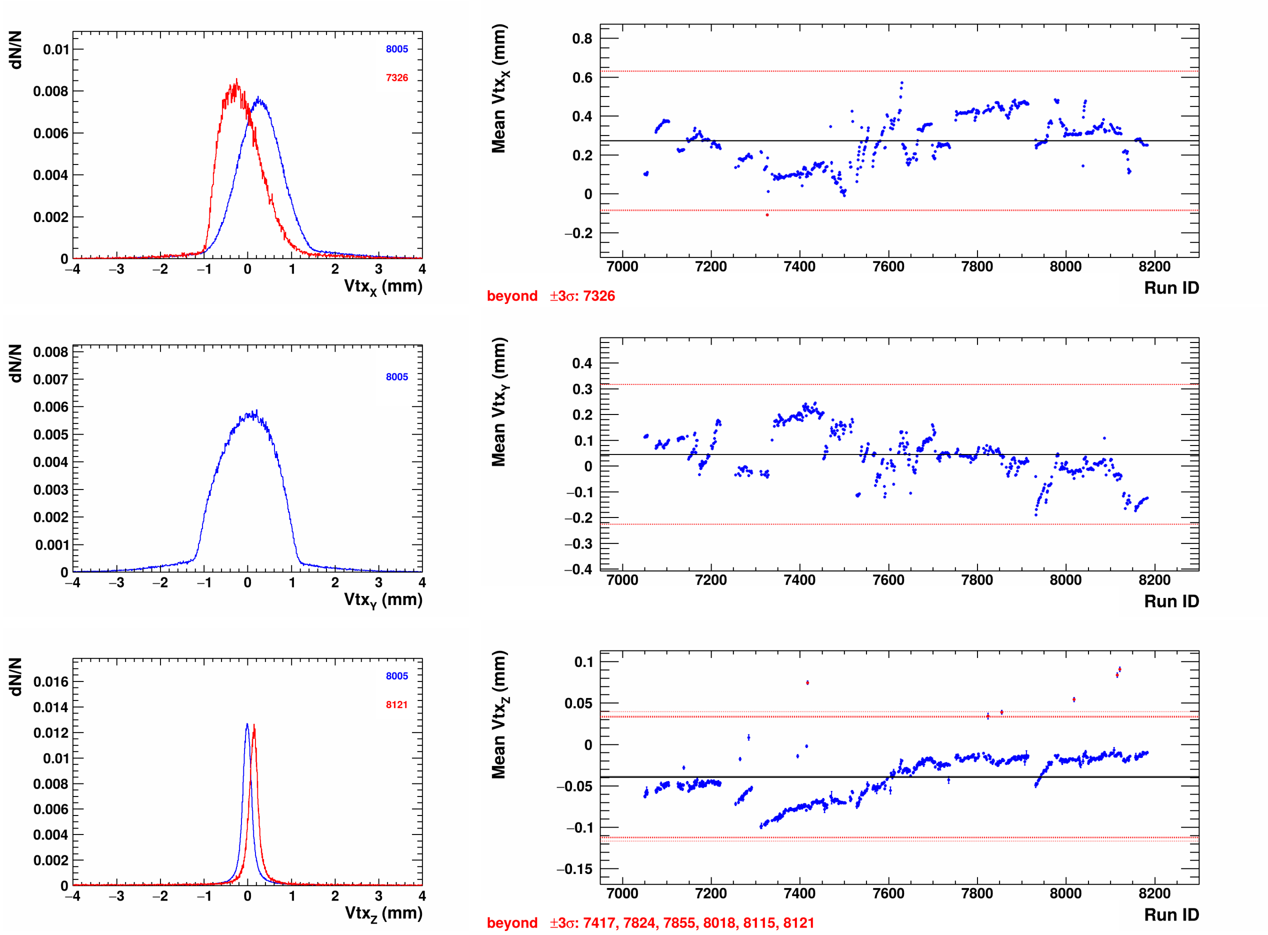


Figure 5: Left panels: distribution of the x,y and z positions of vertex. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean of the x,y and z positions of vertex as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.3 Multiplicity

Figure 6 shows the RunId dependence of the mean multiplicity of charged particles in the tracking system (FSD + GEM).

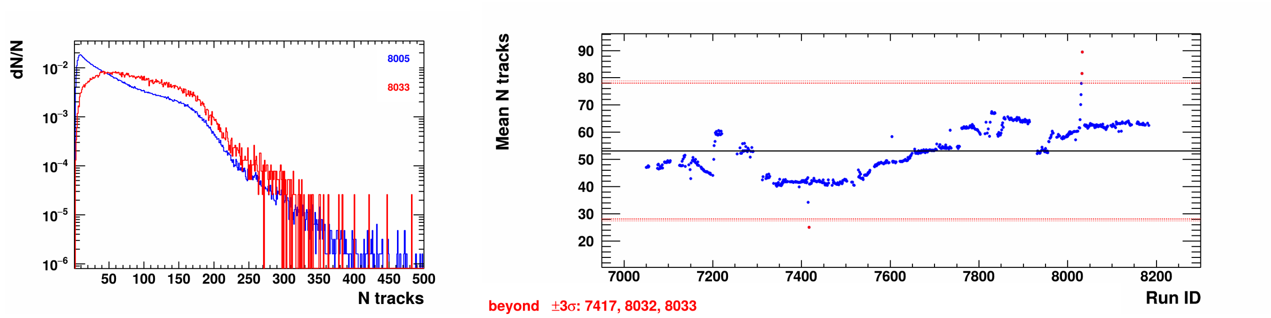


Figure 6: Left panel: distribution of the number of charged particle in the tracking system (FSD + GEM). The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean multiplicity as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.4 Beam scintillation counters (BC)

Figure 7 shows the RunId dependence of the mean amplitude and integral of the summed signal in the beam scintillation counters (BC1). Figure 8 shows a similar distribution for BC2 (in progress).

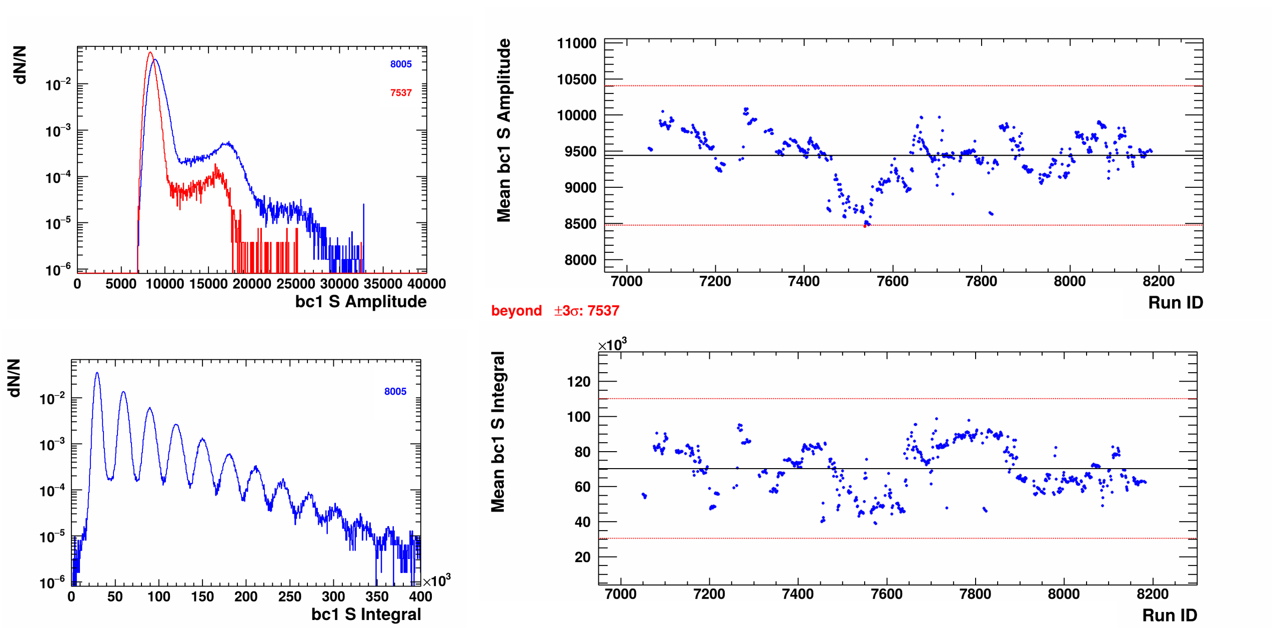


Figure 7: Left panels: Distribution of the amplitude and integral of the summed signal in the BC1. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean amplitude and integral as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

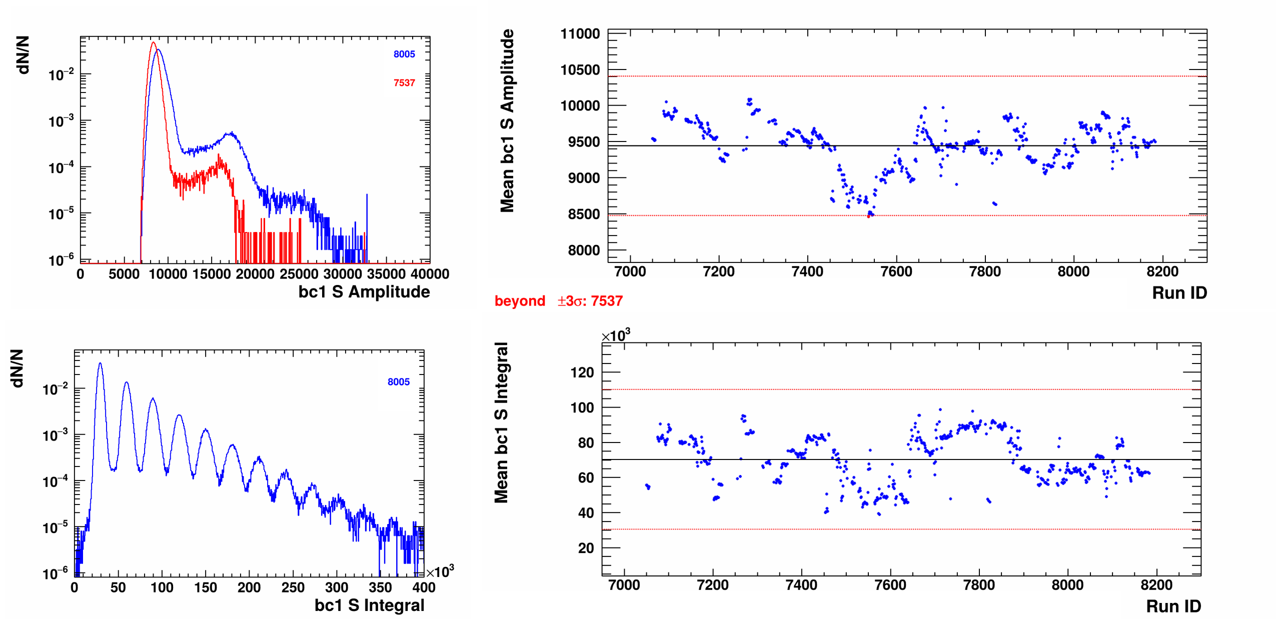


Figure 8: Left panels: Distribution of the amplitude and integral of the summed signal in the BC2. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean amplitude and integral as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.5 Scintillation Veto counter (VC)

Figure 9 shows he RunId dependence of the mean amplitude and integral of the summed signal in the scintillation Veto counter (VC).

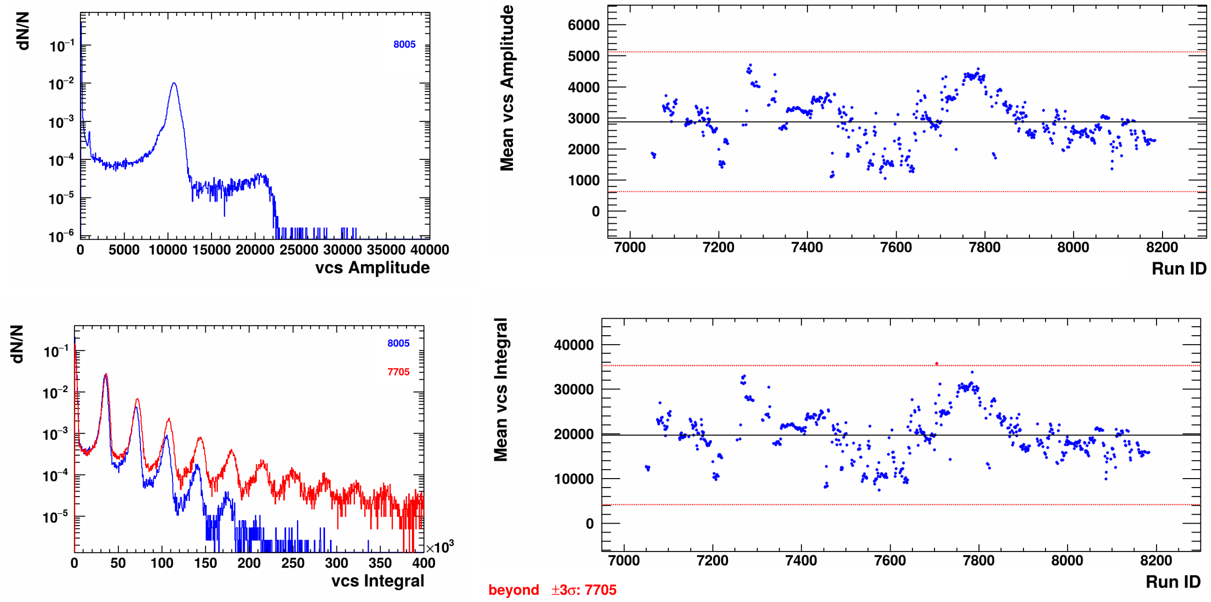


Figure 9: Left panels: Distribution of the amplitude and integral of the summed signal in the VC. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean amplitude and integral as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.6 Fragment Detector (FD)

Figure 10 shows he RunId dependence of the mean amplitude and integral of signal in the fragment detector (FD). Figure 11 shows correlation between the integral of signal from FD and BC1. The figure 11 shows the correlation between the integral of the signal from FD and the integral of the summed signal from BC1.

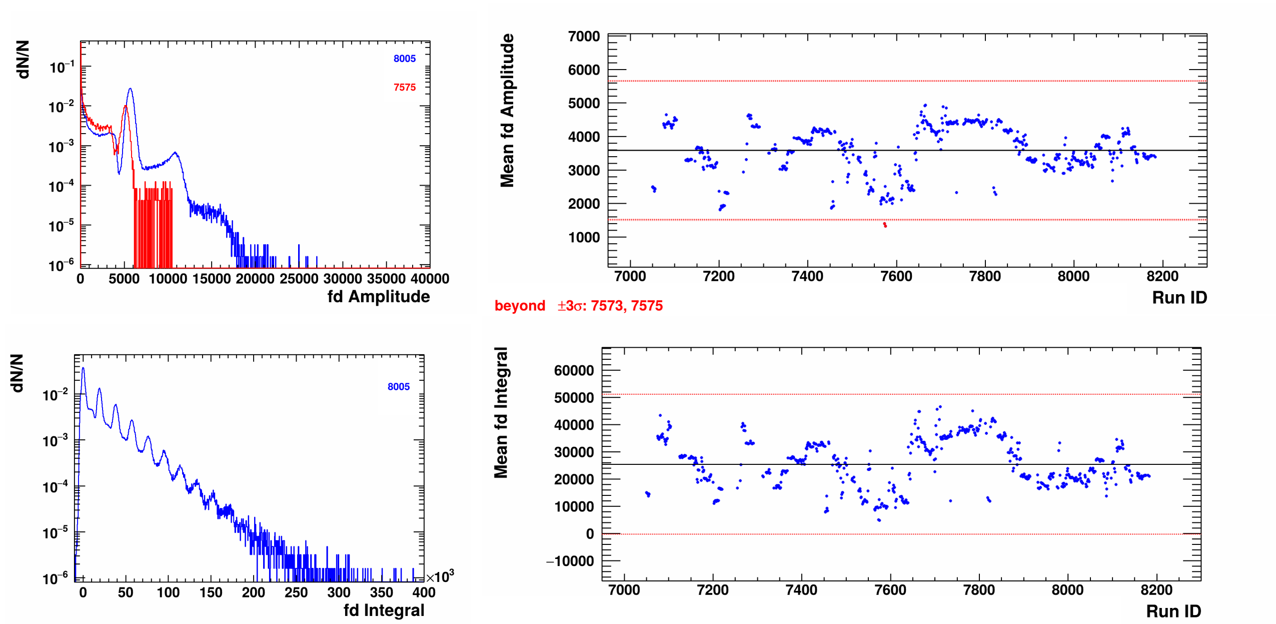


Figure 10: Left panels: Distribution of the amplitude and integral of signal in the FD. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean amplitude and integral as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

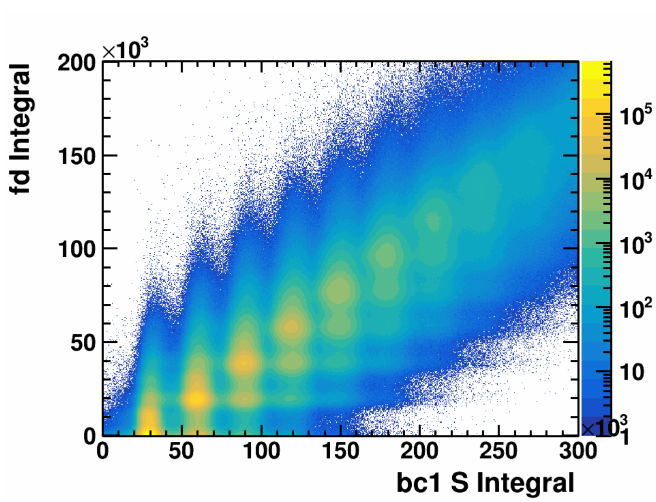


Figure 11: Correlation between the integral of the signal from the FD, and integral of the summed signal from the BC1.

1.7 Forward Hadron Calorimeter (FHCal)

Figures 12,13,14 shows the RunId dependence of the mean of the total energy E_{tot} of spectator fragments in the FHCal and mean of the charge (Q^2) of spectator fragments in the forward quartz hodoscope (FQH) and scintillation wall (ScWall). Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

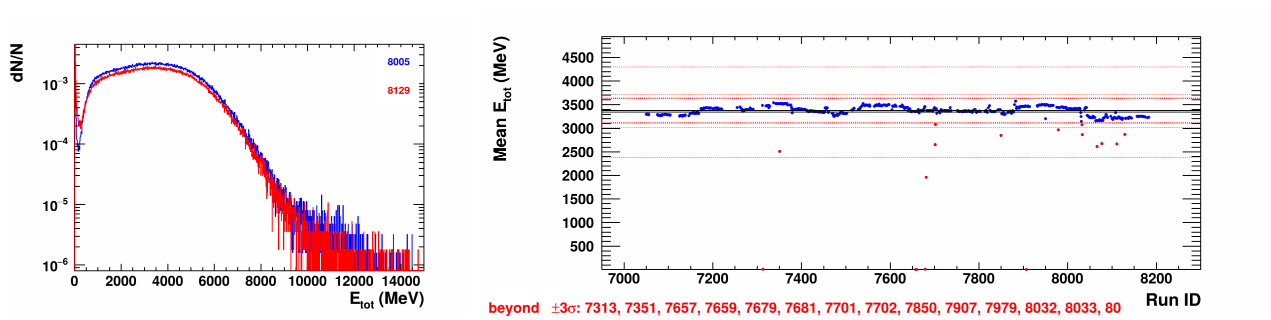


Figure 12: Left panel: distribution of the total energy E_{tot} of spectator fragments in the FHCal. The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean E_{tot} as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

1.8 Forward Quartz Hodoscope (FQH)

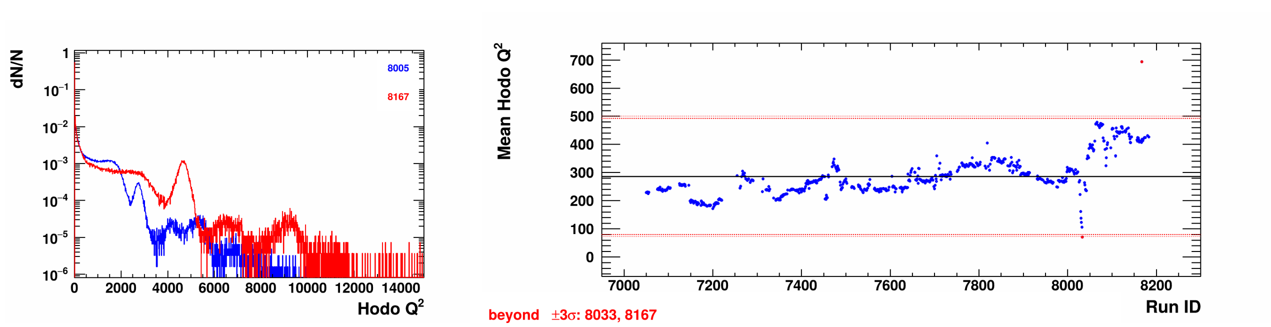


Figure 13: Left panel: distribution of the charge (Q^2) of spectator fragments in the forward quartz hodoscope (FQH). The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean Q^2 as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

1.9 Scintillation Wall (ScWall)

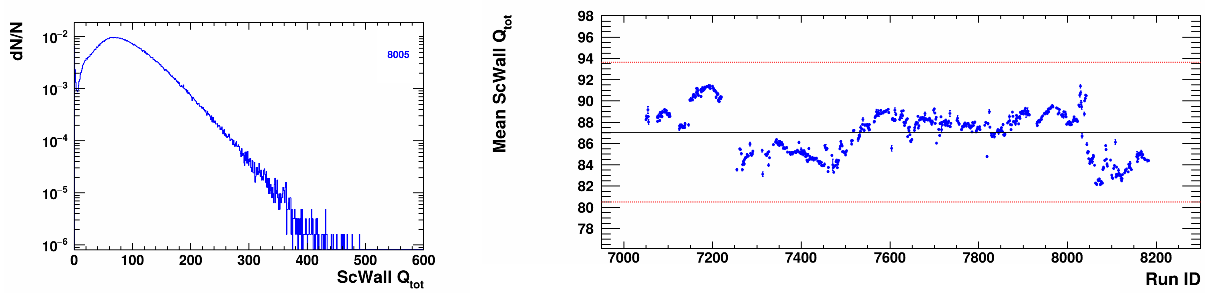


Figure 14: Left panel: distribution of the charge (Q^2) of spectator fragments in the ScWall. The red marker corresponds to the distribution from the "outlier" RunId. Right panel: Mean Q^2 as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.10 Silicon Beam Tracker (SiBT)

Figure 15 shows hits position in silicon beam tracker (SiBT) for three stations. The lower panels of the figure are obtained from the upper ones by rotation by 0, 30 and 60 degrees. Figures 16-17 show the RunId dependence of the mean x and y hit positions for the three SiBT stations after rotation. Figure 18 show the RunId dependence the mean x and y of beam position in SiBT.

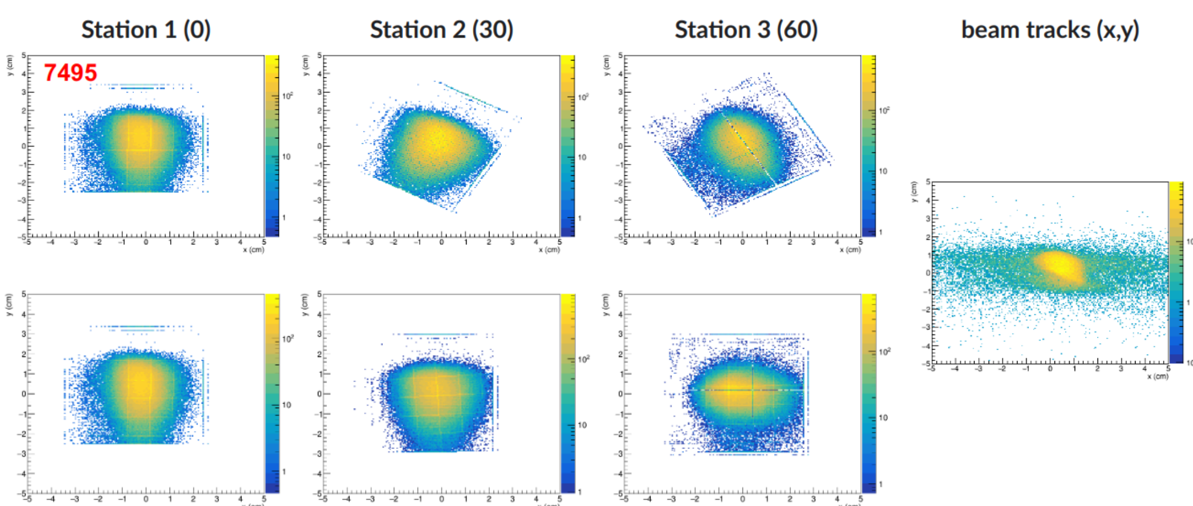


Figure 15: Beam hits in three SiBT stations and reconstructed beam position

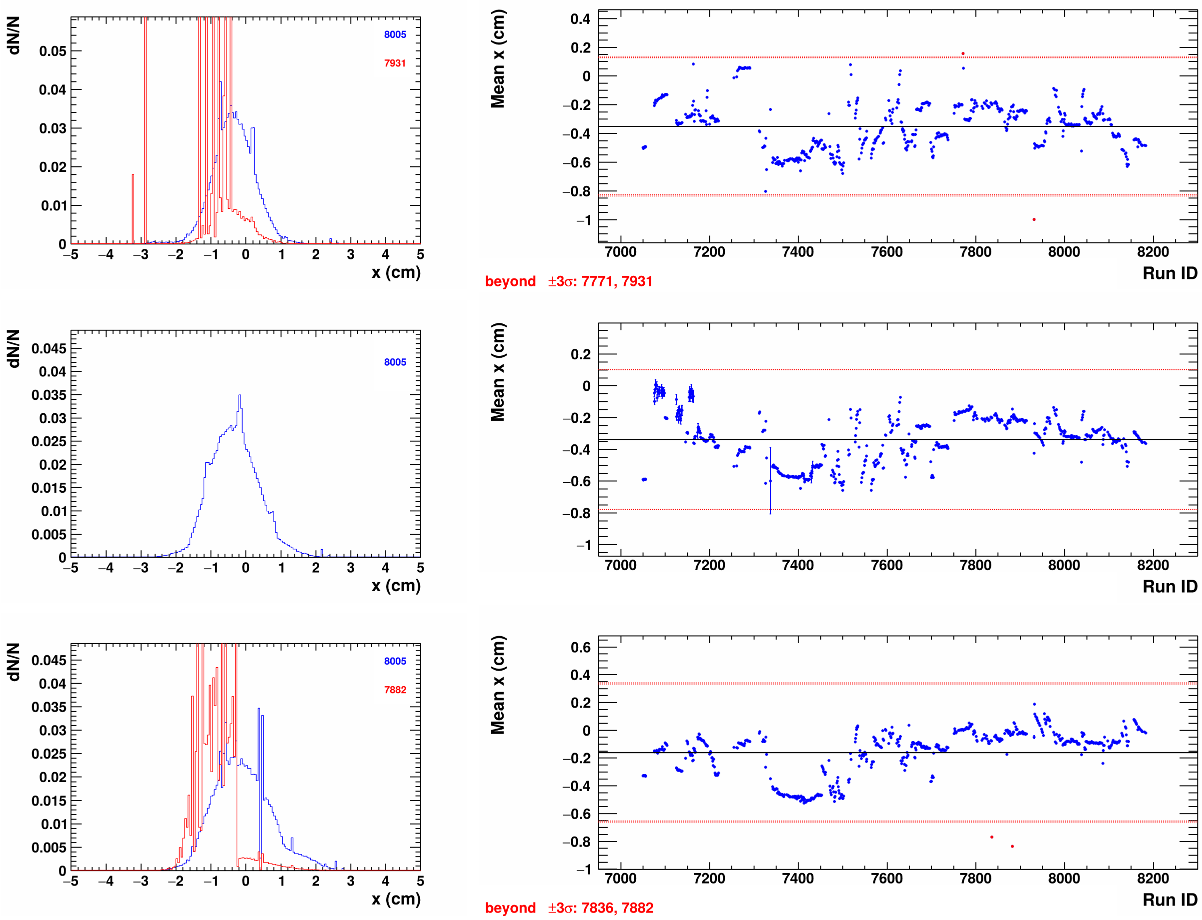


Figure 16: Left panels: distribution of the x of hit beam position in 1,2 and 3 (from top to bottom respectively) SiBT stations. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean of the x of beam hit as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

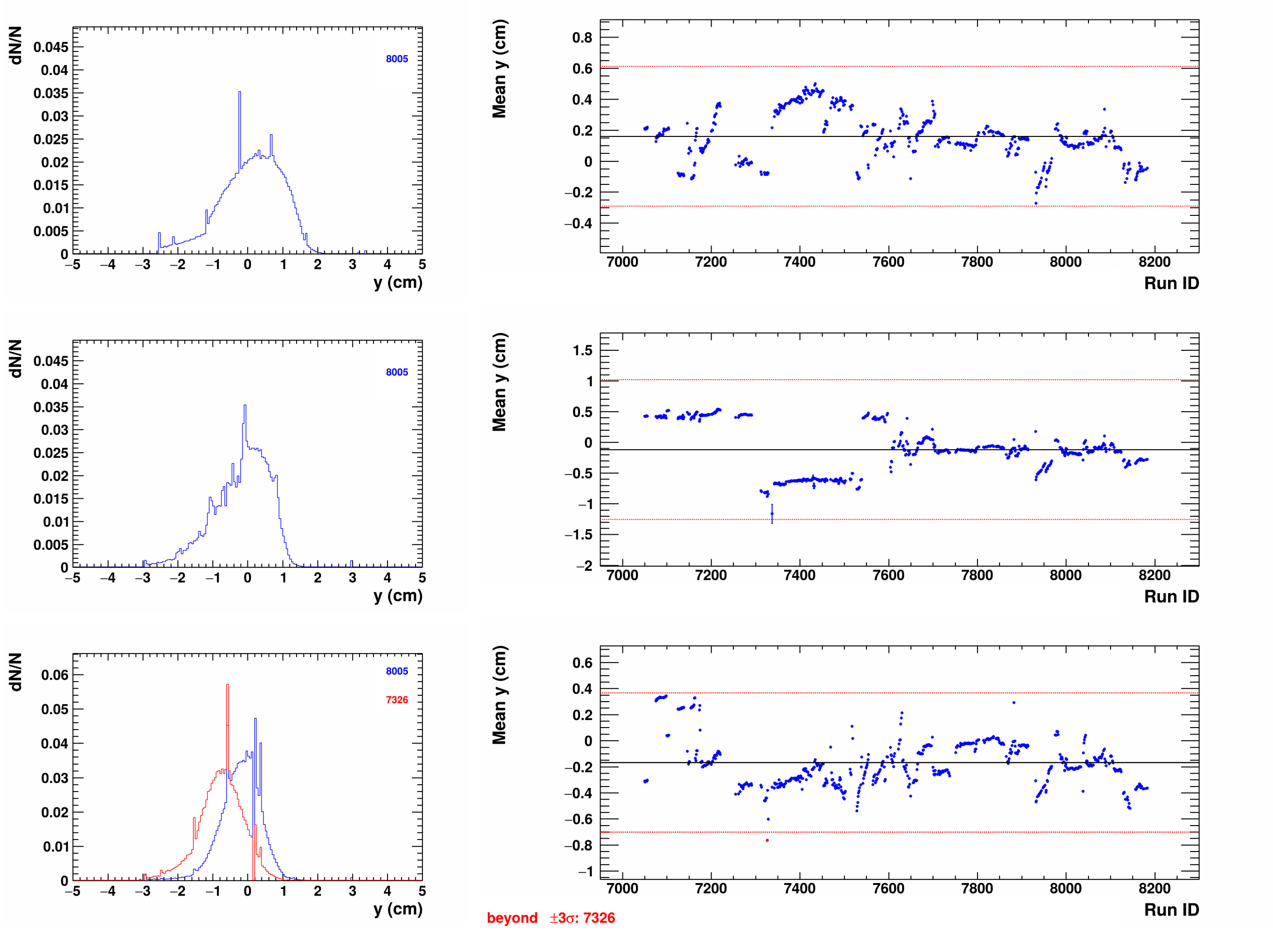


Figure 17: Left panels: distribution of the y of hit beam position in 1,2 and 3 (from top to bottom respectively) SiBT stations. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean of the y of beam hit as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

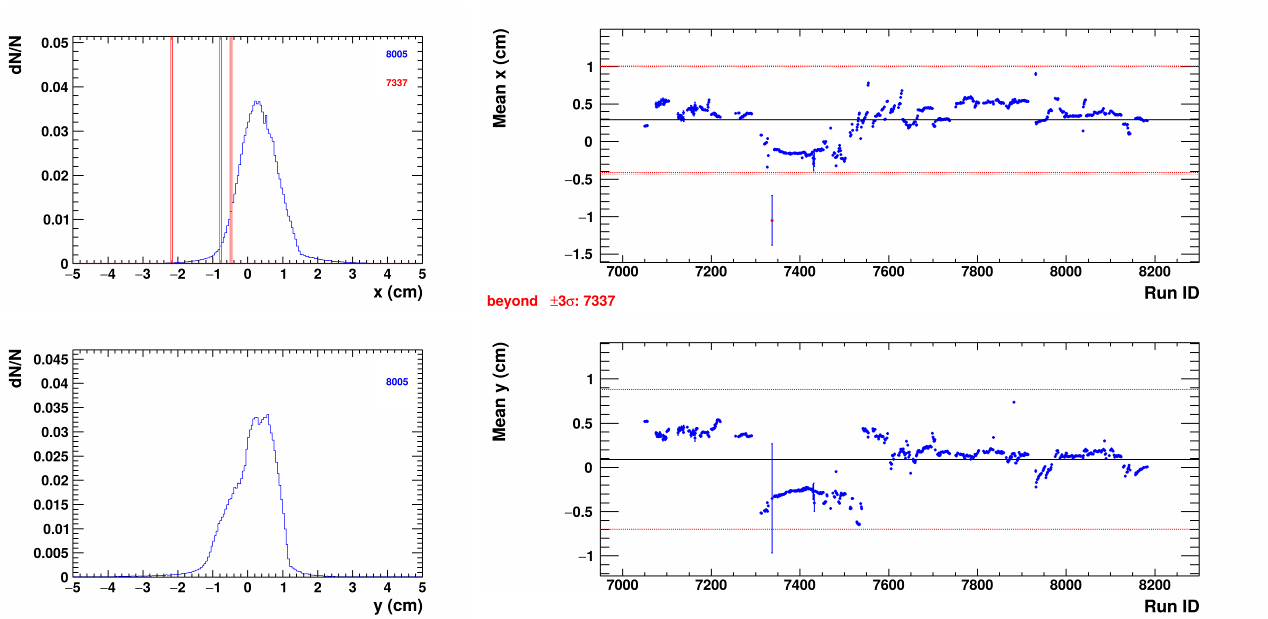


Figure 18: Left panels: distribution of the x and y of beam position in SiBT. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean of the x,y of beam position in SiBT as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.11 Global tracks

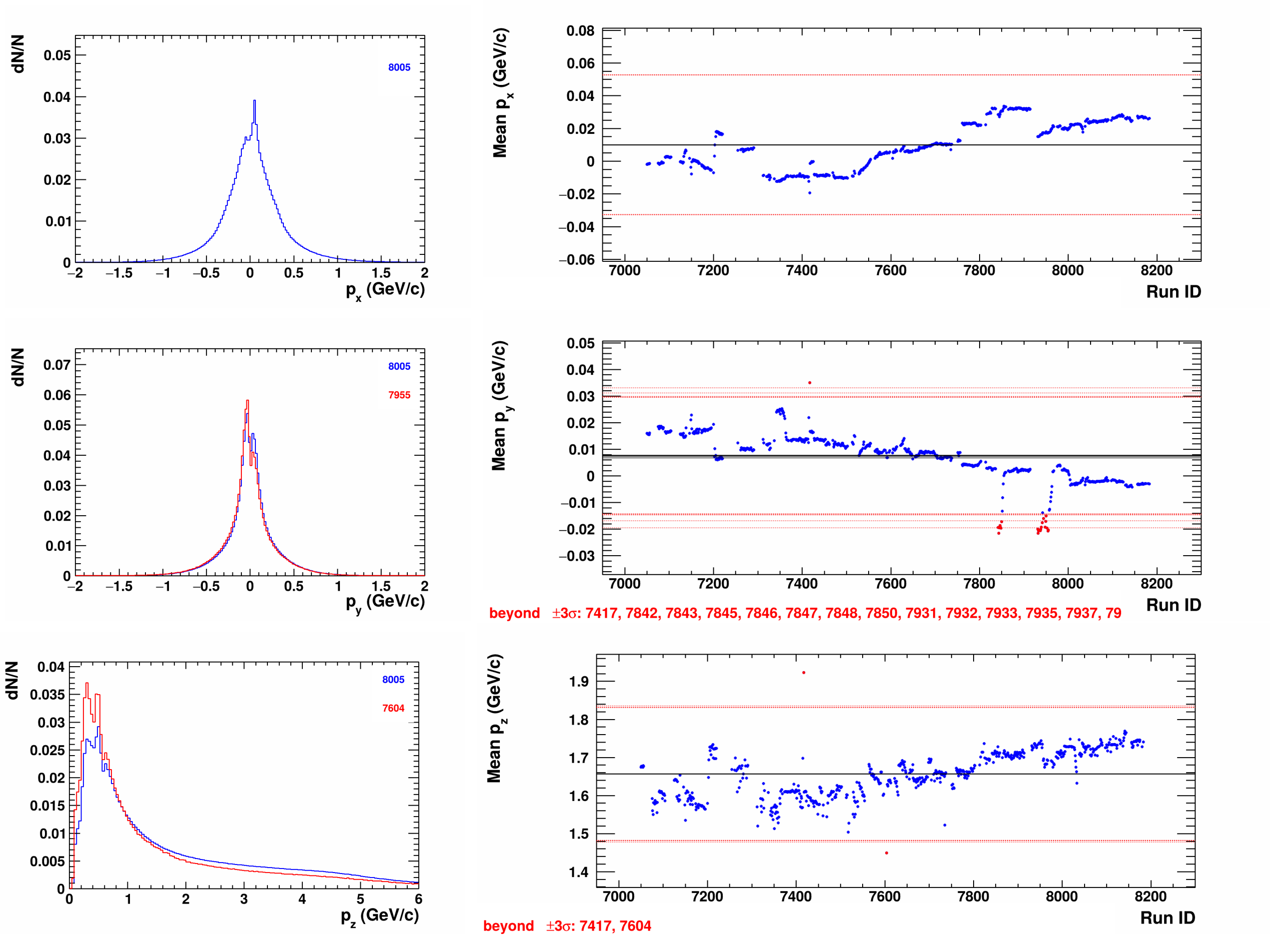


Figure 19: Left panels: Distribution of the x,y and z component of momentum of charged particles. The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean x,y and z component of momentum as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

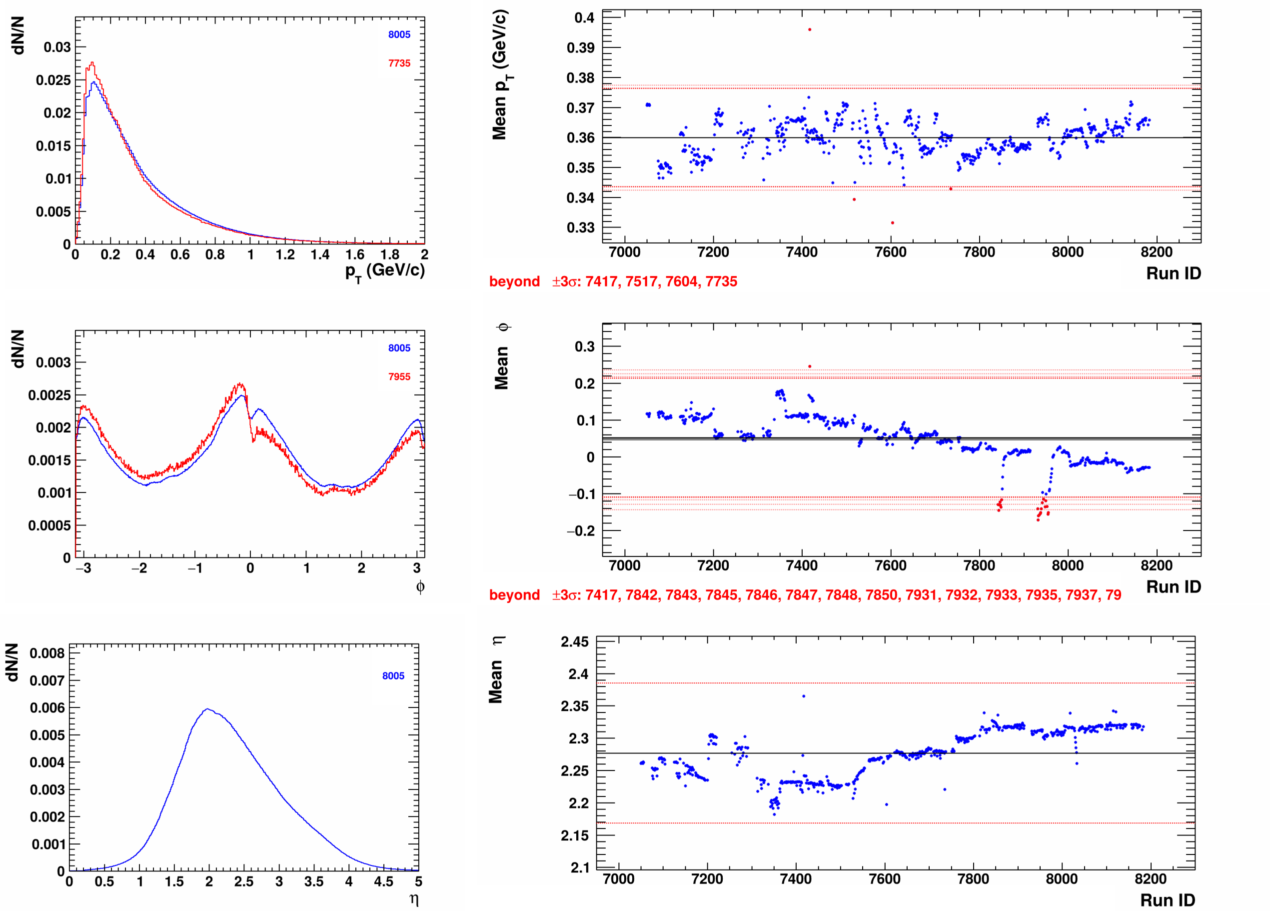


Figure 20: Upper panels: Distribution of the transverse momentum (upper), azimuthal angle (center) and rapidity (bottom) of charged particles. The red marker corresponds to the distribution from the "outlier" RunId. Bottom panels: Mean p_T, ϕ and η as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

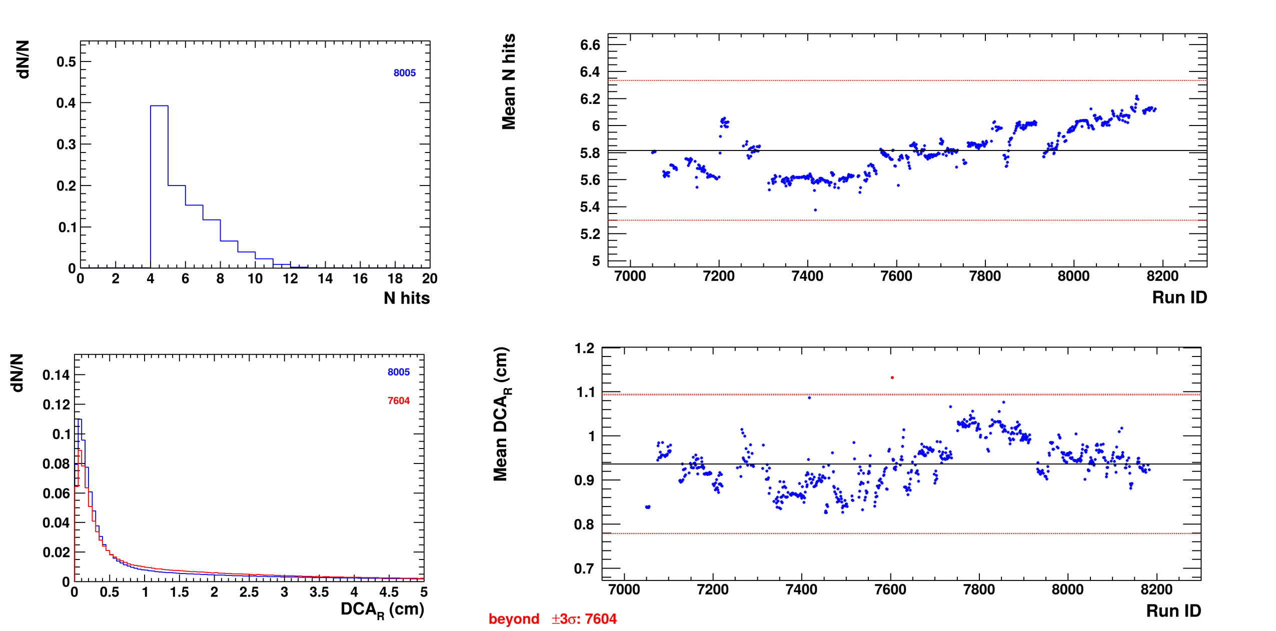


Figure 21: Left panels: Distribution of the number of fit points in to accurate track momentum reconstruction (upper) and the distance of closest approach DCA_R (bottom). The red marker corresponds to the distribution from the "outlier" RunId. Right panels: Mean nHits and DCA_R as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm3\sigma$, respectively.

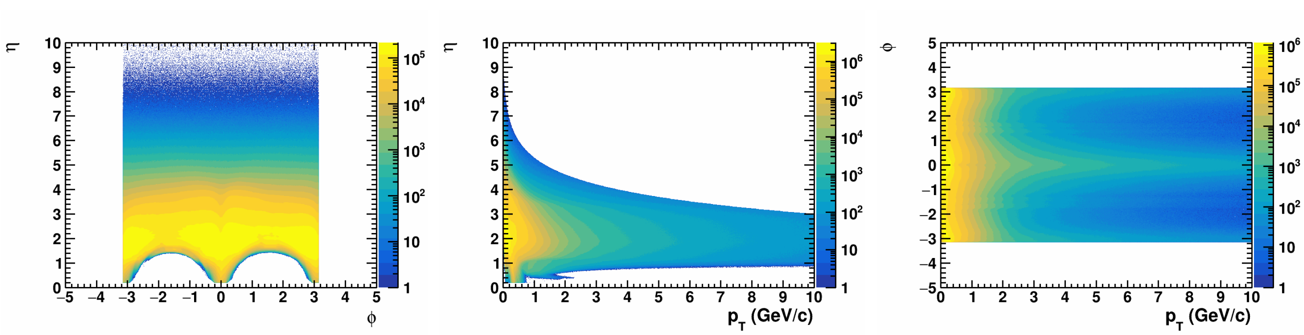


Figure 22: Correlation between the η and the ϕ (left), η and p_T (center), ϕ and p_T (right).

1.12 Mass squared distribution

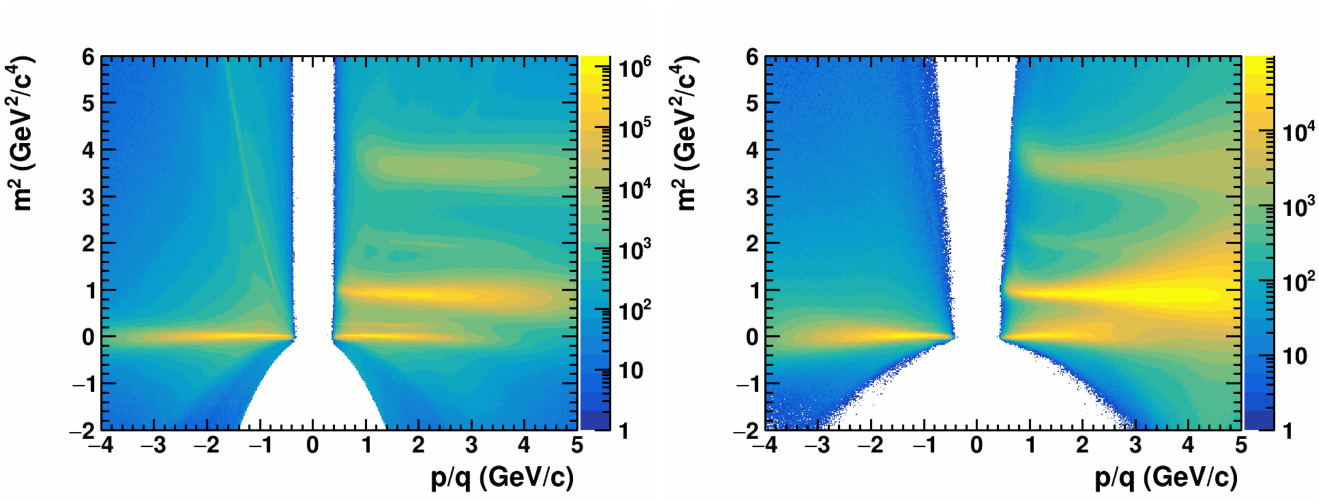


Figure 23: Correlation between the mass squared (m^2) and rigidity (p/q) in the TOF-400 (left panel) and TOF-700 (right panel) detectors.

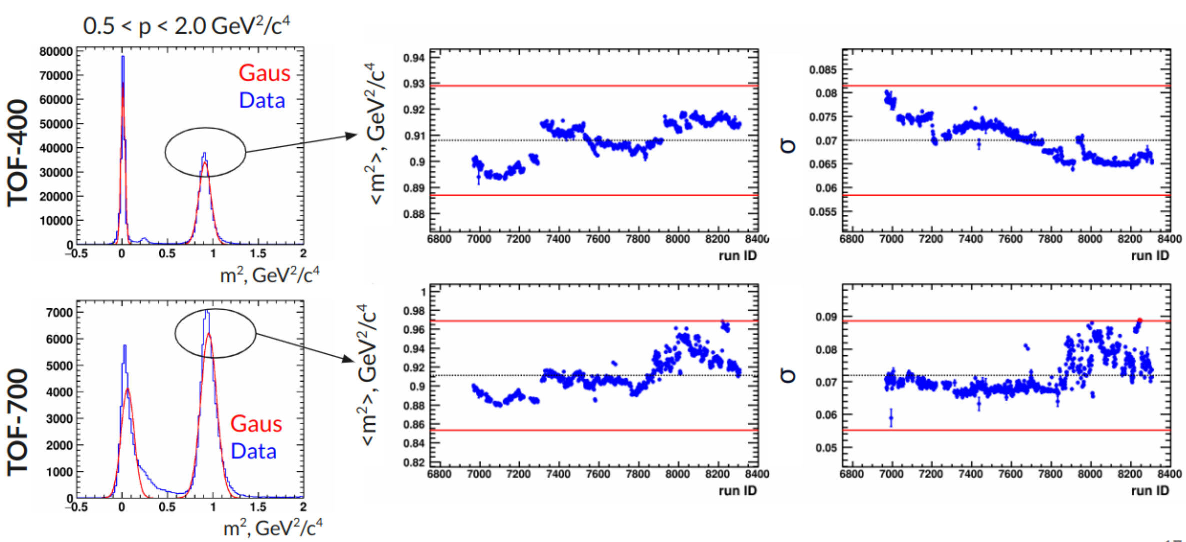


Figure 24: Distribution of the mass squared (m^2) and Gaussian fit of the proton peak in the TOF-400 (upper panels) and TOF-700 (bottom panels) detectors. Center and right panels: mean of the mass squared of proton and σ_p as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

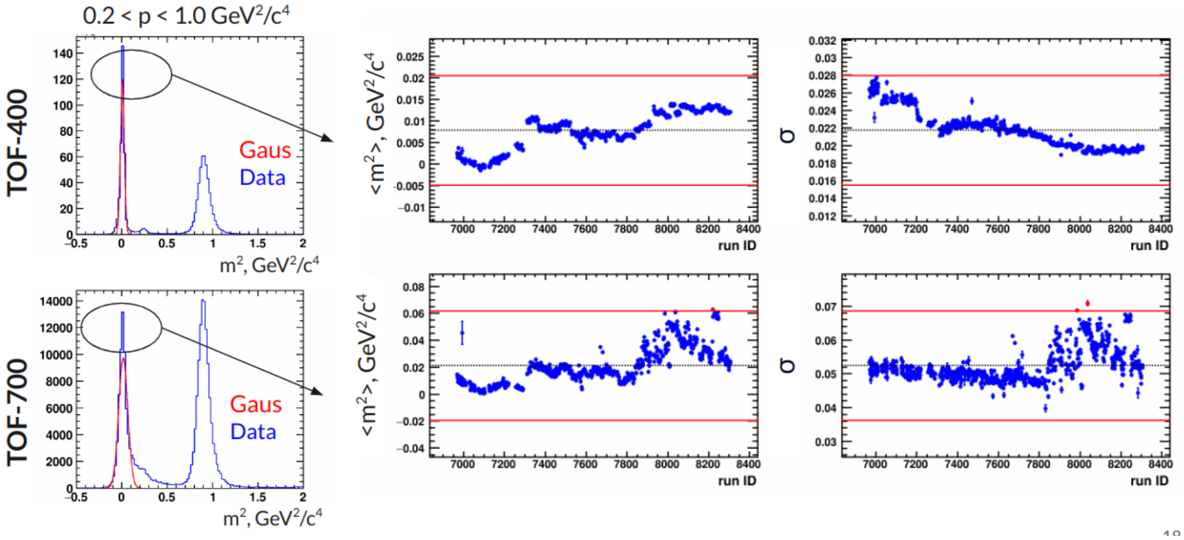


Figure 25: Distribution of the mass squared (m^2) and Gaussian fit of the π^+ peak in the TOF-400 (upper panels) and TOF-700 (bottom panels) detectors. Center and right panels: the mass squared of π^+ and σ as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

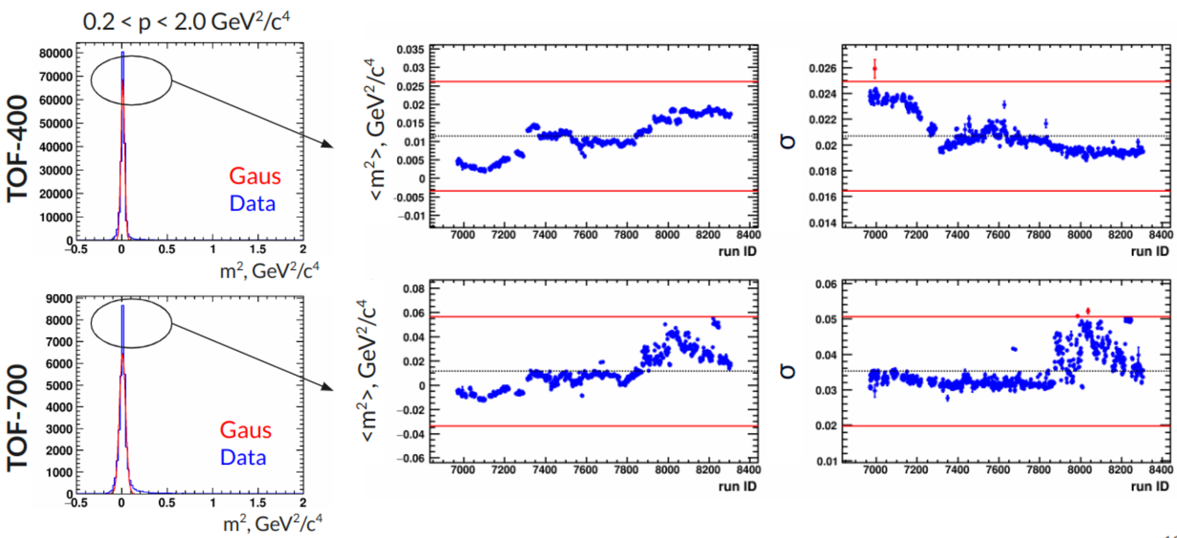


Figure 26: Distribution of the mass squared (m^2) and Gaussian fit of the π^- peak in the TOF-400 (upper panels) and TOF-700 (bottom panels) detectors. Center and right panels: the mass squared of π^- and σ as a function RunID. Black dotted horizontal line and red horizontal lines represent μ and $\pm 3\sigma$, respectively.

1.13 Event selection

In total approximately 500 million events of Xe+Cs(I) collisions at the beam energy of 3.8A GeV were collected by the BM@N experiment in the January of 2023.

1. We don't consider runs below RunId=6924 due to unstable operation of the GEM and FSD detectors (BM@N Electronic Logbook).

2. We removed 74 runs [18M events] based on QA study, see section 1.1-1.12.

3. We used events from Physical runs and CCT2 trigger.

4. at least 2 tracks in vertex reconstruction

5. The pileup events were rejected based on the $\pm 3\sigma$ cut on the correlation between the number of FSD digits and the number of charged particles in the tracking system (FSD + GEM), see the left and center panels of the Figure 1.13.

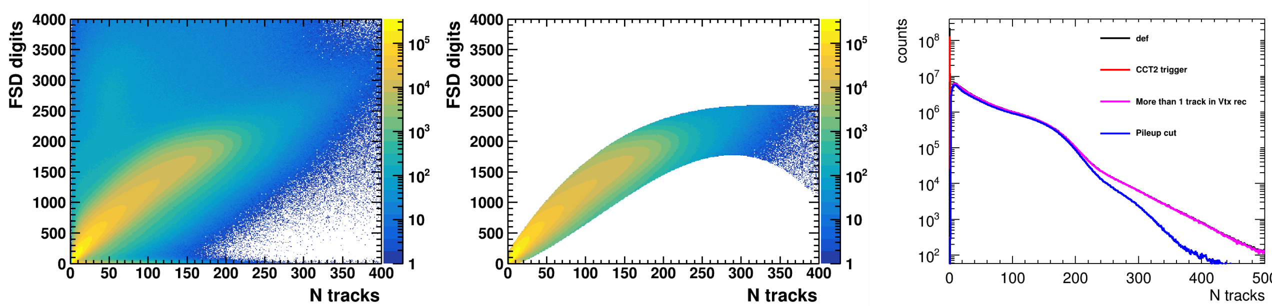


Figure 27: Left and center panels: Dependence of STS (FSD) digits hit on tracks multiplicity before and after applying pileup cut. Right panel: tracks multiplicity distribution before and after applying event and pileup cuts.

Table 1: Statistics after applying selection criteria

Cuts	no. of events	%
def.	530 M	100%
CCT2 trigger	437 M	82%
More than 1 track in vertex reconstruction	315 M	59%
Pileup cuts	285 M	53%

2 Framework

This section provides instructions for using the analysis framework. The framework includes the following macros:

- `../convert_macro/convertBmn_run8.C` and `../convert_macro/run8_convert.sh`: These files are conversion macros used to convert files from the .dst format to a ROOT tree (.tree.root).
- `../QA_macro/run8_qa_new.C`:This is the main macro for the QA (Quality Assurance) stage. It defines the variables for analysis and sets up the corresponding histograms. `../QA_macro/run8.sh`: This script is used to run the `../run8_qa_new.C` macro on the NICA cluster.
- `../QA_macro/GoldRuns_script.C`: This macro is used for drawing figures and run-by-run QA analysis.
- `../QA_macro/Get_VtxXYZ_corrRunId.C`: This macro is used for run-by-run correction of the x, y and z positions of the reconstructed vertex.
- `../QA_macro/Get_GraphiCuts_cuts.C`: This macro defines a graphical cut to reduce the impact of pileup events based on the number of FSD and GEM digits and multiplicity.
- `../QA_macro/Get_BC1_FD_cuts.C`: This macro defines a graphical cut to reduce the impact of pileup events based on signal data from the BC1 and FD detectors.
- `../QA_macro/refMult_corr.C`: This macro is used for run-by-run correction of the multiplicity of charged particles.

Detailed instructions will be provided for each macro below.

2.1 convertBmn_run8.C macro

`convert_macro/convertBmn_run8.C` - This macro converts files from the .dst and .digi formats into a single simple format: a ROOT tree. The input files are .dst and

.digi files from EOS, as well as .hitInfo.root files. The latter contain the results of the pileup event analysis conducted by Oleg Golosov. To start on a cluster, use the `convert_macro/run8_convert.sh` script. Example of running a script: sbatch `run8_convert.sh` `path_to_lists/name_list.list` `out_dir`, where one `name_list.list` contains the names of 999 files. From now on we will work only with the our .tree.root format using the ROOT's RDataFrame.

2.2 run8_qa_new.C macro

`../QA_macro/run8_qa_new.C` - This macro is used to read the .tree format and create histograms. Additionally, you can add your own variables and their corresponding histograms. `../QA_macro/run8.sh`: This script is used to run the `../run8_qa_new.C` macro on the NICA cluster. The input parameters:

- str_in_list - list of .tree.root files
- str_in_list_plp - list of files containing pileup corrections.
- out_file_name - output file name
- in_fit_file - this file containing corrections for the vertex and multiplicity. This file is specified during the second run of the `../QA_macro/run8_qa_new.C`. The correction file is obtained after running the `refMult_corr.C` and `Get_VtxXYZ_corrRunId.C` macros.

The output is a file containing a set of histograms.

2.3 GoldRuns_script.C macro

`../QA_macro/GoldRuns_script.C`: This macro is used for drawing figures and run-by-run QA analysis. The input parameters:

- _inFileName - input file name
- _outFileName - output file name

After the macro runs, a set of specified plots and a list of bad runs will be generated.

2.4 Get_VtxXYZ_corrRunId.C macro

`../QA_macro/Get_VtxXYZ_corrRunId.C`: This macro is used for run-by-run correction of the x, y and z positions of the reconstructed vertex. The input parameters:

- _file_inFile - input file name
- _file_outFile - output file name

The result of running the macro will be a file containing 2D histograms. The x-axis represents the run number, and the y-axis represents the value by which the reconstructed vertex needs to be corrected.

2.5 Get_GraphiCuts_cuts.C macro

`../QA_macro/Get_GraphiCuts_cuts.C`: This macro defines a graphical cut to reduce the impact of pileup events based on the number of FSD and GEM digits and multiplicity.

- _file_inFile - input file name
- _file_outFile - output file name

After the macro runs, we obtain the parameters for a graphical cut that reduces the contribution of pileup events. The result of this macro needs to be manually recorded in `../QA_macro/run8_qa_new.C` in functions $stsNdigitsMultCut$

2.6 Get_BC1_FD_cuts.C macro

`../QA_macro/Get_BC1_FD_cuts.C` - macro defines a graphical cut run-by-run to reduce the impact of pileup events based on signal data from the BC1 and FD detectors.

- _file_inFile - input file name
- _file_outFile - output file name

After the macro runs, graphs for run-by-run corrections of signals from the BC1 and FD detectors will be written to the output file. These corrections are used when macro `../QA_macro/run8_qa_new.C` is run again.

2.7 refMult_corr.C macro

`../QA_macro/refMult_corr.C`: This macro is used for run-by-run correction of the multiplicity of charged particles.

- _file_inFile - input file name
- _file_outFile - output file name
- Specify the region of stable runs to which the multiplicity from other runs will be fitted.

After the macro runs, graphs for run-by-run corrections for multiplicity will be written to the output file. These corrections are used when macro `../QA_macro/run8_qa_new.C` is run again.

The procedure for multiplicity corrections consists of the following steps:

- We used events from Physical runs and CCT2 trigger.
- remove "bad" runs
- remove events with pileup
- apply event selection criteria: at least 2 tracks in vertex reconstruction
- Extract the high-end point of refMult distribution in each RunId via fitting the refMult tail by the function:

$$f(refMult) = A * Erf(-\sigma(refMult - H)) + A \tag{3}$$

- refMult can then be corrected by:

$$refMult_{corr} = refMult * H_{ref}/H(RunId), \tag{4}$$

where H_{ref} - high-end point of refMult distribution from stable runs.

3 Format .tree.root

The format is a simple root tree. The tree includes the following branches:

- RunId
- BmnTrigInfo
  - triggerMapBR - trigger masks (before reduction)
  - triggerMapAR - trigger masks (after reduction)
- BD
  - bdMult - multiplicity
  - bdModId - module id
  - bdModAmp
- bc1 s(t,b)
  - bc1sNSamples
  - bc1sIntegral - signal integral (BC)
  - bc1sAmplitude - signal amplitude (BC)
  - bc1sTdcValues
  - bc1sTdcTimes - time
- VC s(t,b)
  - vcsNSamples
  - vcsIntegral - signal integral (VC)
  - vcsAmplitude - signal amplitude (VC)
  - vcsTdcValues
  - vcsTdcTimes - time
- FD

  - fdNSamples
  - fdIntegral - signal integral (FD)
  - fdAmplitude - signal amplitude (FD)
  - fdTdcValues
  - fdTdcTimes - time

- PrimaryVertex

  - vtxX - x position of the reconstructed vertex
  - vtxY - y position of the reconstructed vertex
  - vtxZ - z position of the reconstructed vertex
  - vtxChi2 - χ^2
  - vtxNdf - NDF

- BmnGlobalTrack

  - trMom (Pt,Eta,Phi)
  - trNhits - the number of fit points in to accurate track momentum reconstruction
  - trNdf - NDF
  - trChi2 - χ^2
  - trP - momentum
  - trChi2vtx (BmnGlobalTrack.fChi2InVertex)
  - trLength (BmnGlobalTrack.fLength) - track length
  - trCharge - track charge
  - trDca (from BmnGlobalTrack and PrimaryVertex) - the distance of closest approach
  - trTof400hit ("BmnGlobalTrack.fTof1Hit") - number of fit points
  - trBetaTof400 ("BmnGlobalTrack.fBeta400") - β from TOF-400

  - trTof701hit ("BmnGlobalTrack.fTof2Hit") - number of fit points
  - trBetaTof701 ("BmnGlobalTrack.fBeta701") - β from TOF-700
  - trPosLast (recPosLast,"BmnGlobalTrack") - ?
  - trPos450 (recPos450,"BmnGlobalTrack") - ?
  - trM2Tof400 (from trMom and trBetaTof400) - m^2 from TOF-400
  - trM2Tof700 (from trMom and trBetaTof700) - m^2 from TOF-700

- gemDigits - the number of GEM digits
- stsDigits (implies FSD digit) - the number of FSD digits
- trParamFirst - vector containing information about the global track: $x, y, z, T_x = p_x/p_z, T_y = p_y/p_z, Qp$.
- trParamLast - vector containing information about the global track: $x, y, z, T_x = p_x/p_z, T_y = p_y/p_z, Qp$.
- from BmnGlobalTrack and StsVector
  - stsTrackCovMatrix - covariance matrix for tracks
  - stsTrackMagField - magnetic field vector
  - stsTrackParameters - vector containing information about the global track: $x, y, z, T_x = p_x/p_z, T_y = p_y/p_z, Qp$.
  - globalTrackParameters - duplicates trParamFirst
  - globalTrackCovMatrix - covariance matrix for tracks
  - stsTrackMomentum - momentum
  - stsTrackChi2Ndf - χ^2/NDF
  - stsTrackNdf - NDF
  - stsTrackNhits - the number of fit points in to accurate track momentum reconstruction
- TOF-700

  - tof700Digits - the number of TOF-700 digits
  - tof700Plane - plane number
  - tof700Strip - strip number
  - tof700hitPos - x,y,z hit pozition
  - tof700hitT - time of flight
  - tof700hitL - track length
  - tof700hitResX - distance from hit to global track on x axis
  - tof700hitResY - distance from hit to global track on y axis
  - tof700hitRefIndex - global track index of this hit
  - tof700hitResCalc - distance from hit to global track extrapolated by straight line

- TOF-400
  - tof400Digits - the number of TOF-400 digits
  - tof400Plane - plane number
  - tof400Strip - strip number
  - tof400hitPos - x,y,z hit pozition
  - tof400hitT - time of flight
  - tof400hitL - track length
  - tof400hitResX - distance from hit to global track on x axis
  - tof400hitResY - distance from hit to global track on y axis
  - tof400hitRefIndex - global track index of this hit
  - tof400hitResCalc - distance from hit to global track extrapolated by straight line

- scwallModPos - x and y position of cells (ScWall)
- scwallModId - cells numbers in ScWall

- scwallModQ - cells charges (ScWall)
- hodoModPos - x and y position of strips (FQH)
- hodoModId - strips number (FQH)
- hodoModQ - strips charge (FQH)
- fhcalModPos - x and y position of module (FHCal)
- fhcalModId - module number (FHCal)
- fhcalModE - module energy (FHCal)
- fhcalSecE - section energy (FHCal)