LXXV International Conference «NUCLEUS – 2025. Nuclear physics, elementary particle physics and nuclear technologies»

Monte-Carlo simulation study of Straw Tracker occupancies for ion-ion and proton-proton collisions at the SPD Detector at NICA

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SPD Experiment

- **Spin Physics Detector (SPD)** is an experiment at the NICA facility designed to study the spin structure of the proton and deuteron using polarized beams, as well as other spin-related phenomena. It is being developed as a universal 4π detector equipped with tracking, particle identification systems, and high luminosity (up to $10^{32} cm^{-2} s^{-1}$)
- Expected energies for **Phase 1 is** $\sqrt{s} = 10\ GeV$ and for **Phase 2 is** $\sqrt{s} = 27\ GeV$
- **Straw Tracker (ST)** is a subsystem responsible for charged track reconstruction and their momentum determination. It plays a critical role in ion-ion collisions with high particle multiplicity, where signal overlap is likely. It is susceptible to occupancy issues, as the front-end electronics require time to process events, which may reduce accuracy under high load conditions. The Straw Tracker is planned to be used throughout all stages of the SPD experiment

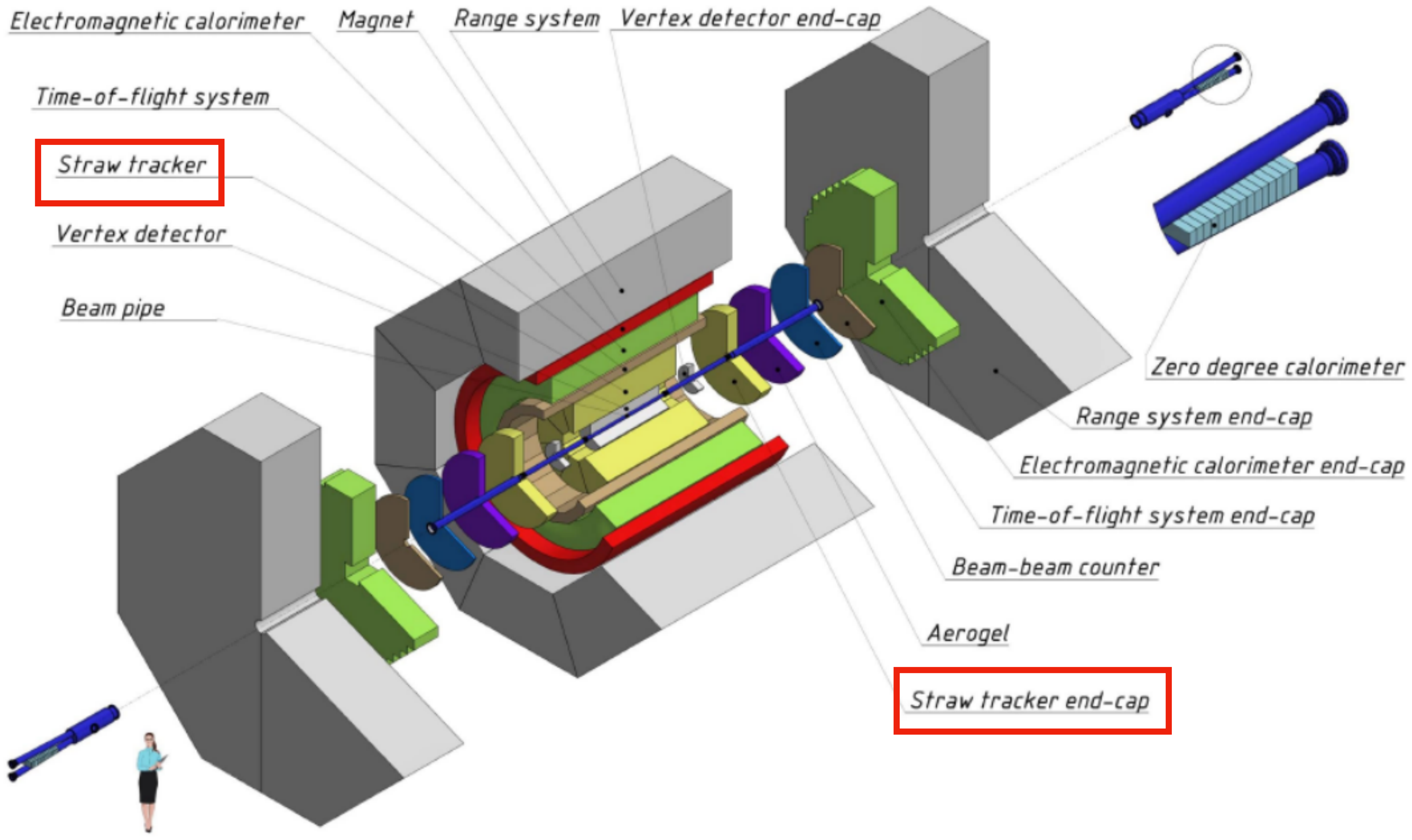


Fig. 1 - SPD Experiment

SPD Experiment

- Why an ion program?

Will provide an extraction of 'nuclear PDF' from ion-ion collisions data;

Study of quark-gluon matter properties in small systems (p+p, d+d, O+O, Ar+Ar, Xe+Xe):

1. Influence of the initial state on system dynamics
2. Final-state dynamics and effects, transport coefficients
3. Vortical structure (accessible via decays of various particles — hyperons, meson resonances, J/ψ — in a wide acceptance range; energy dependence of the vortical structure)

Heavy quark production:

1. Dissociation and recombination, quark-level energy loss
2. Access to J/ψ and other charmonia through dielectron and dimuon decay channels

- Why SPD?

• High trigger rate and small spatial resolution
• Wide pseudorapidity coverage
• Complements the MPD detector, while offering unique physics capabilities

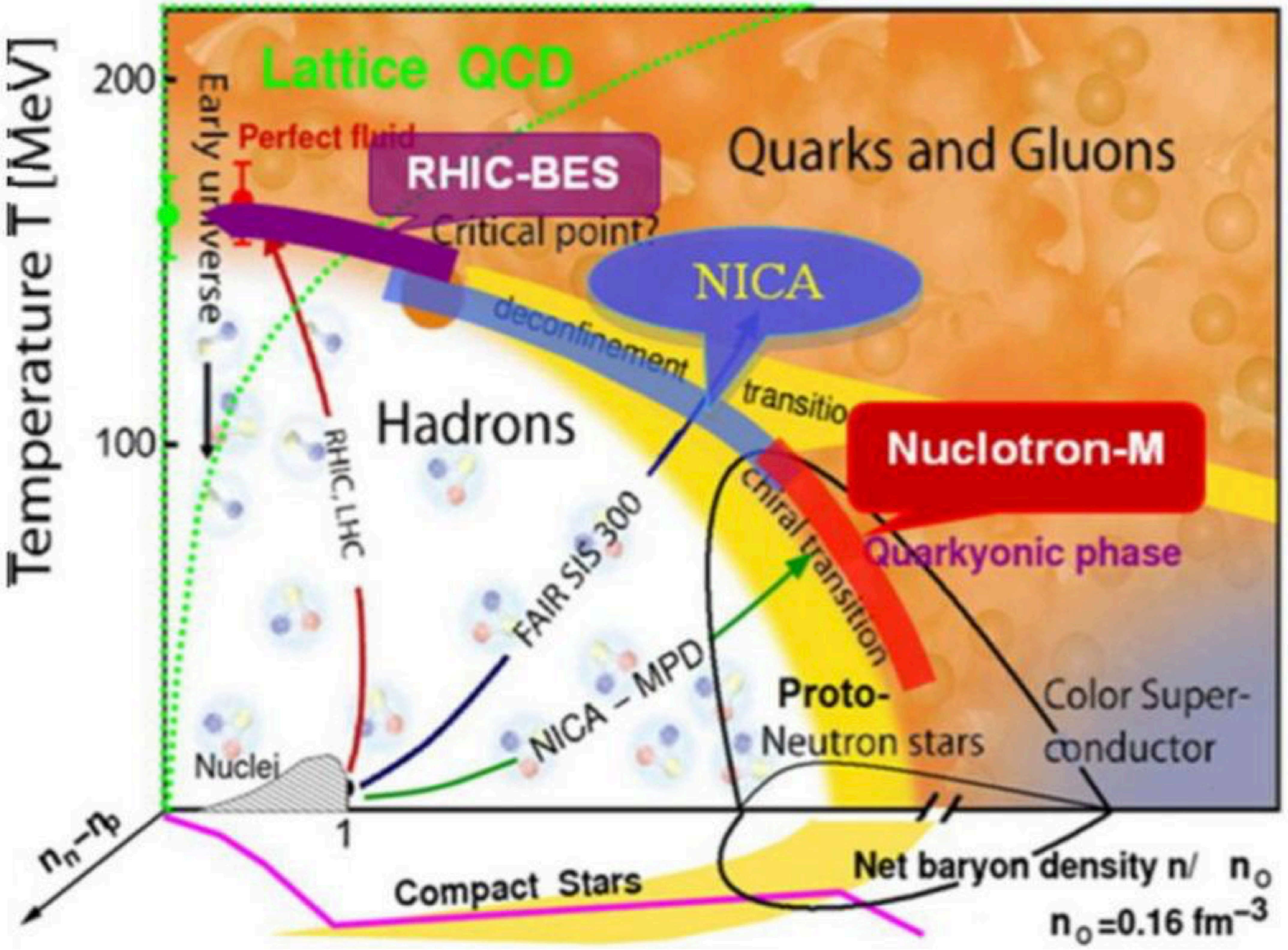


Fig. 2 - NICA position in fundamental physics

Straw Tracker (TS)

- **Purpose:**
  To reconstruct charged particle tracks, measure their momenta based on trajectory curvature in a magnetic field, and perform particle identification via energy loss (dE/dx)

- **Design:**
  The detector consists of a barrel section (for tracking) and two end-caps (primarily for tracking and for identification)

1. **Barrel:** Comprises 8 modules, each containing approximately 3,300 straw tubes (both straight and inclined), totaling around 26,000 tubes
2. **End-caps:** Each contains 8 coordinate planes (disks) utilizing straw tubes with various orientations and lengths

- **Operating Principle:**
  Charged particles ionize the gas (argon) inside the straw tubes, producing electrons that drift toward the anode.
  The signal is amplified (gas amplification) and registered at the anode wire.
  The transverse coordinates (x, y) are determined by the tube number, while the longitudinal coordinate (z) is inferred from the electron drift time.
  The resulting set of space points allows for the reconstruction of the particle's track and precise determination of its transverse momentum

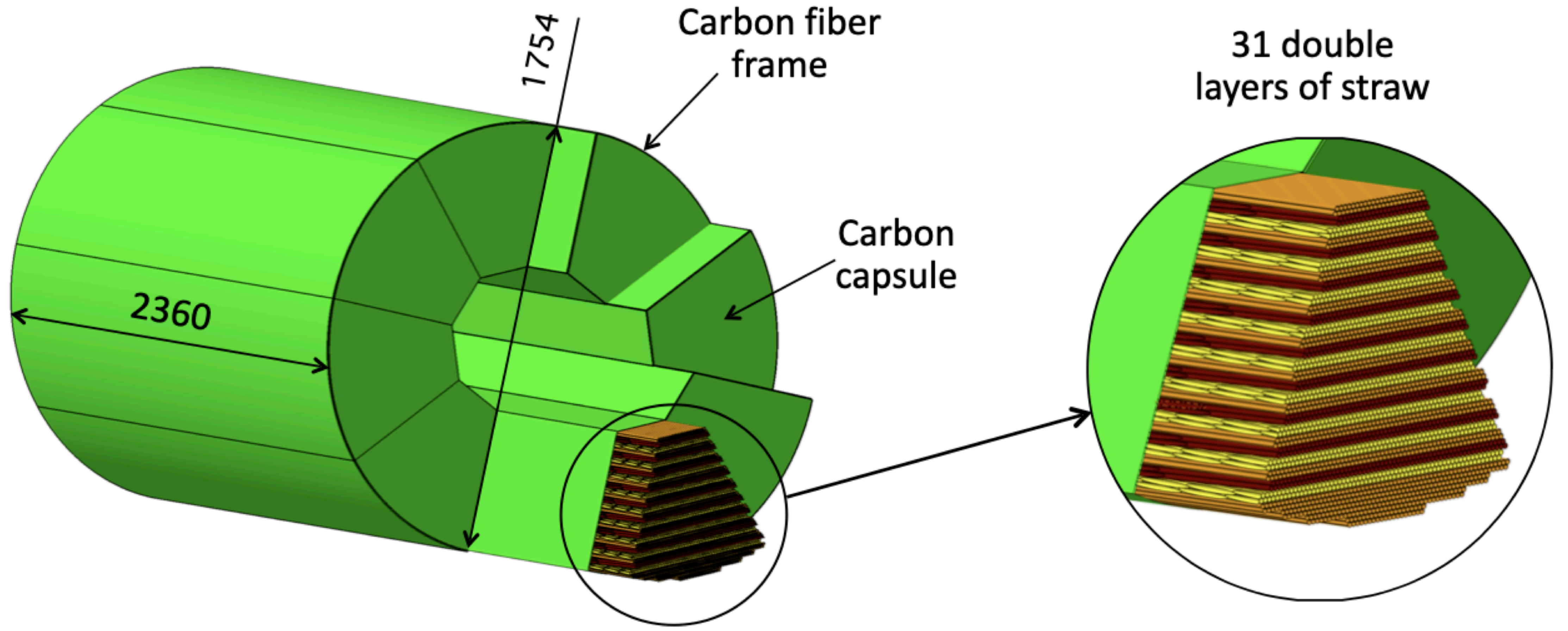


Fig. 3 - Straw Tracker (barrel)

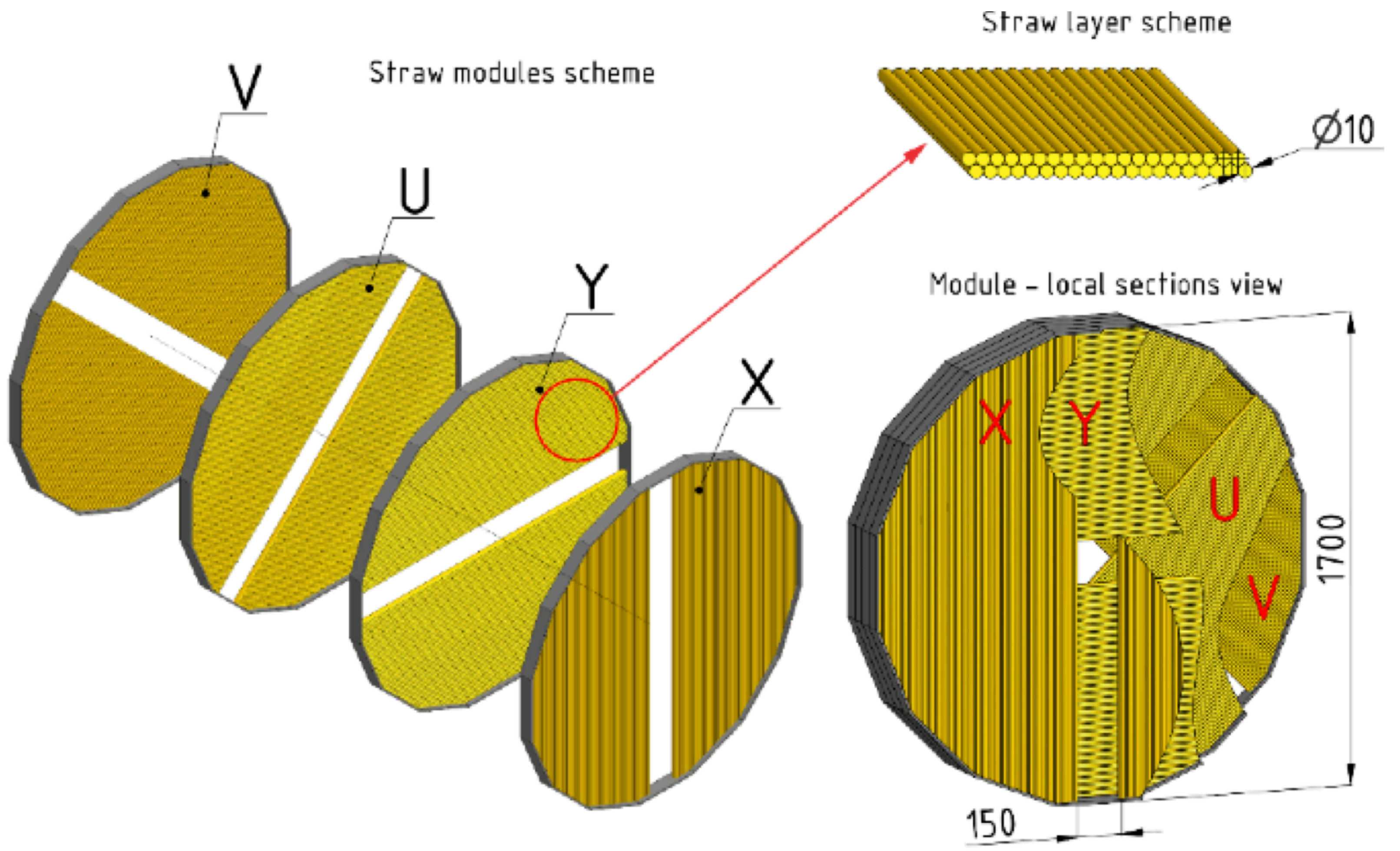


Fig. 4 - Straw Tracker (end-cap)

TS full hit rate and straw occupancy in p-p collisions

Fig. 5 - TS full hit rate (barrel и end-caps parts) in p-p collisions

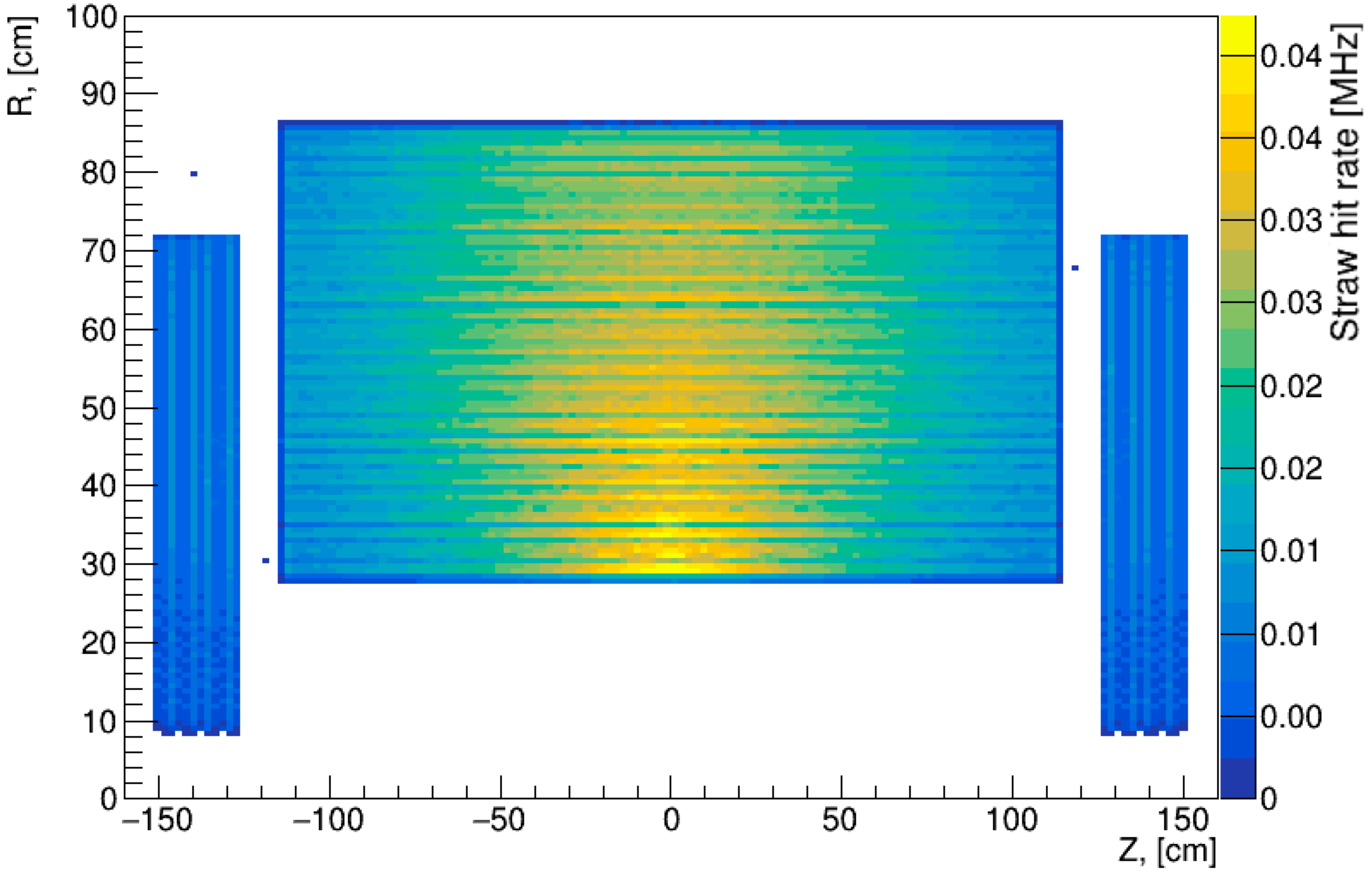
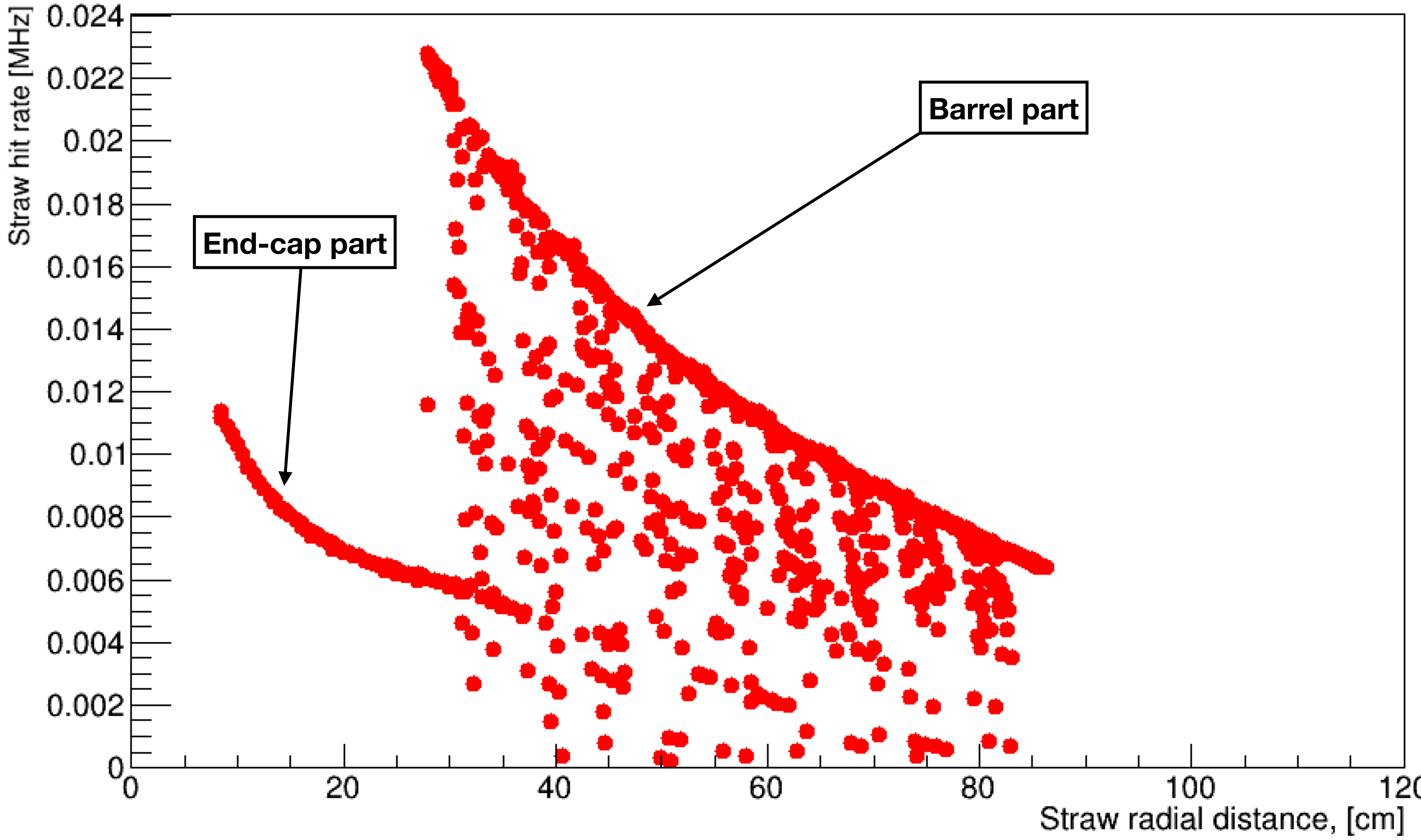


Fig. 6 - Average number of hits per straw in the TS in p-p collisions



Simulation parameters:

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 100 000 p-p collisions
- Minimum bias
- Interaction rate (for colored Z-axis) = 0.4 MHz

The relative fraction of active straws (straws with at least 1 hit): 1.8%

Interaction rates are obtained from SPD TDR: https://arxiv.org/pdf/2404.08317

Momentum resolution of the Straw Tracker in p-p collisions

A region of particular interest for event reconstruction in the Straw Tracker is that of mid-range pseudorapidity ($-1.1 < \eta < 1.1$), where the highest particle registration accuracy is expected. Figure 7 presents a total occupancy map of the entire Straw Tracker in this pseudorapidity region. To evaluate the momentum resolution, distributions of the relative momentum reconstruction accuracy $(Pt_{reco} - Pt_{truth})/Pt_{truth}$ were obtained for different MC Pt intervals. These distributions were then fitted with Gaussian functions, and the standard deviations of the fits were taken as the measure of momentum resolution.

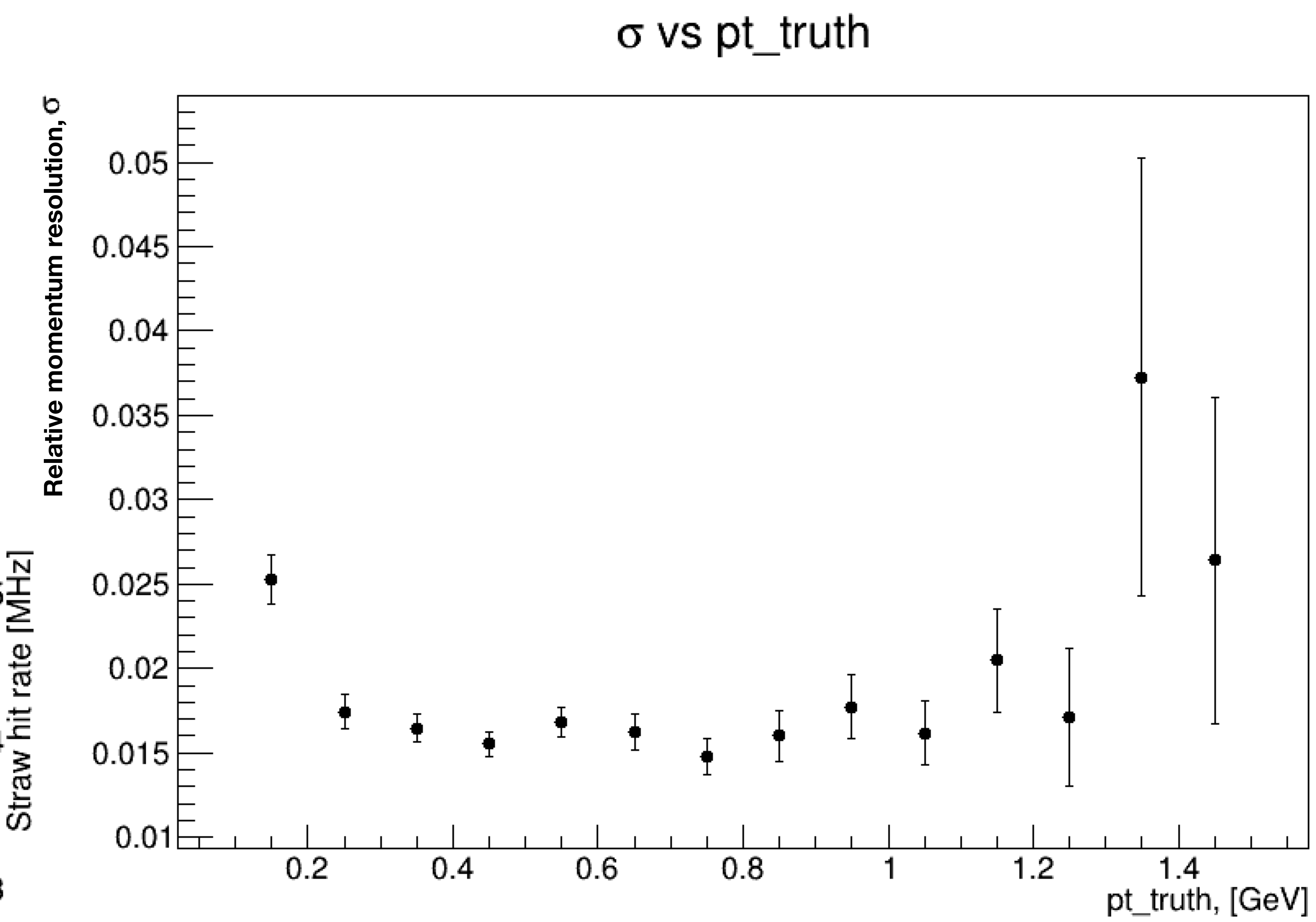


Fig. 8 - Momentum resolution of the Straw Tracker for MC Pt within the central pseudorapidity interval

<u>Simulation parameters:</u>

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 5 000 p-p collisions
- Minimum bias
- Interaction rate (for colored Z-axis) = 0.4 MHz

Interaction rates are obtained from SPD TDR: https://arxiv.org/pdf/2404.08317

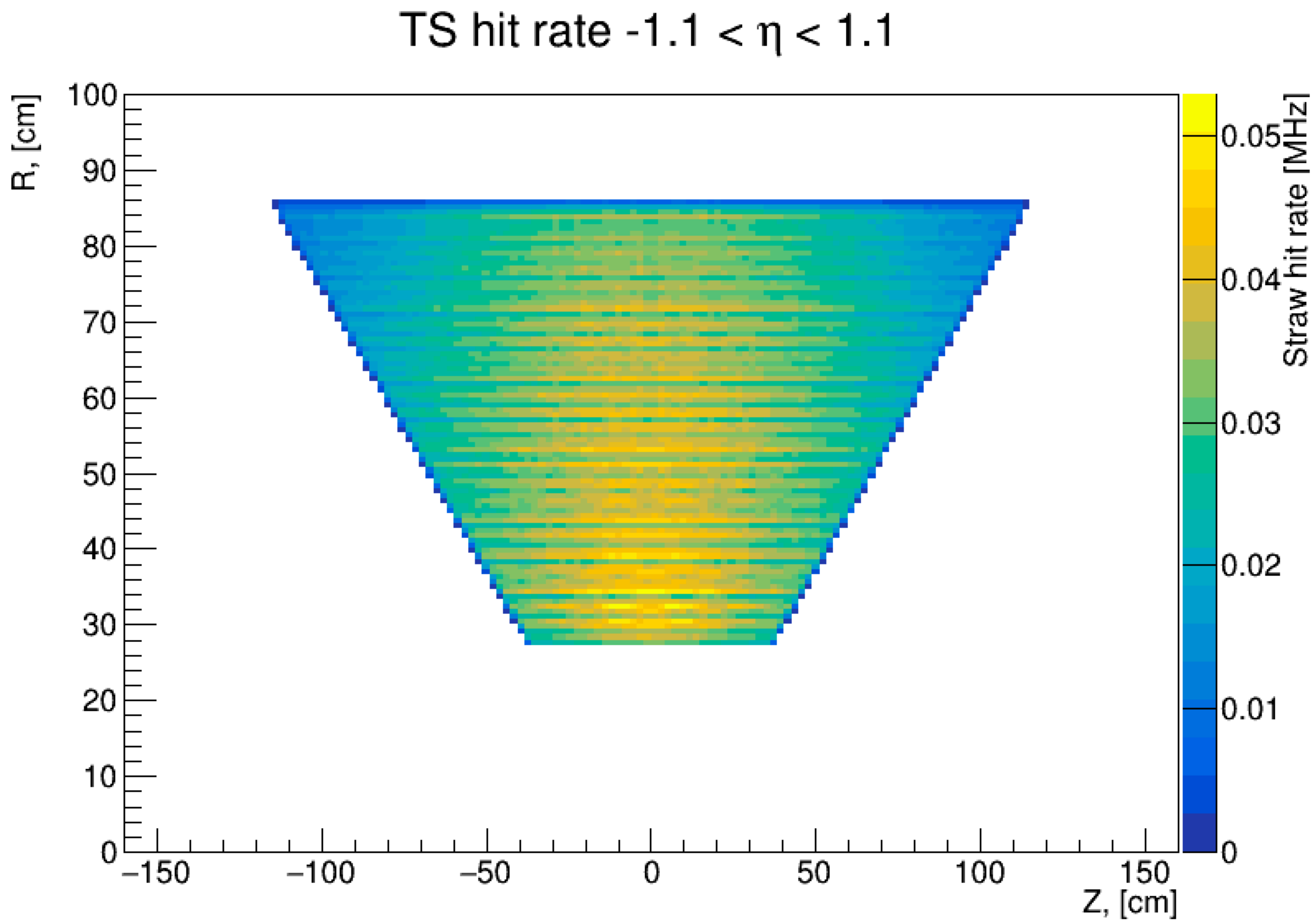


Fig. 7 - TS full hit rate in the central pseudorapidity region

TS full hit rate and straw occupancy in O-O collisions

Fig. 9 - TS full hit rate (barrel и end-caps parts) in O-O collisions

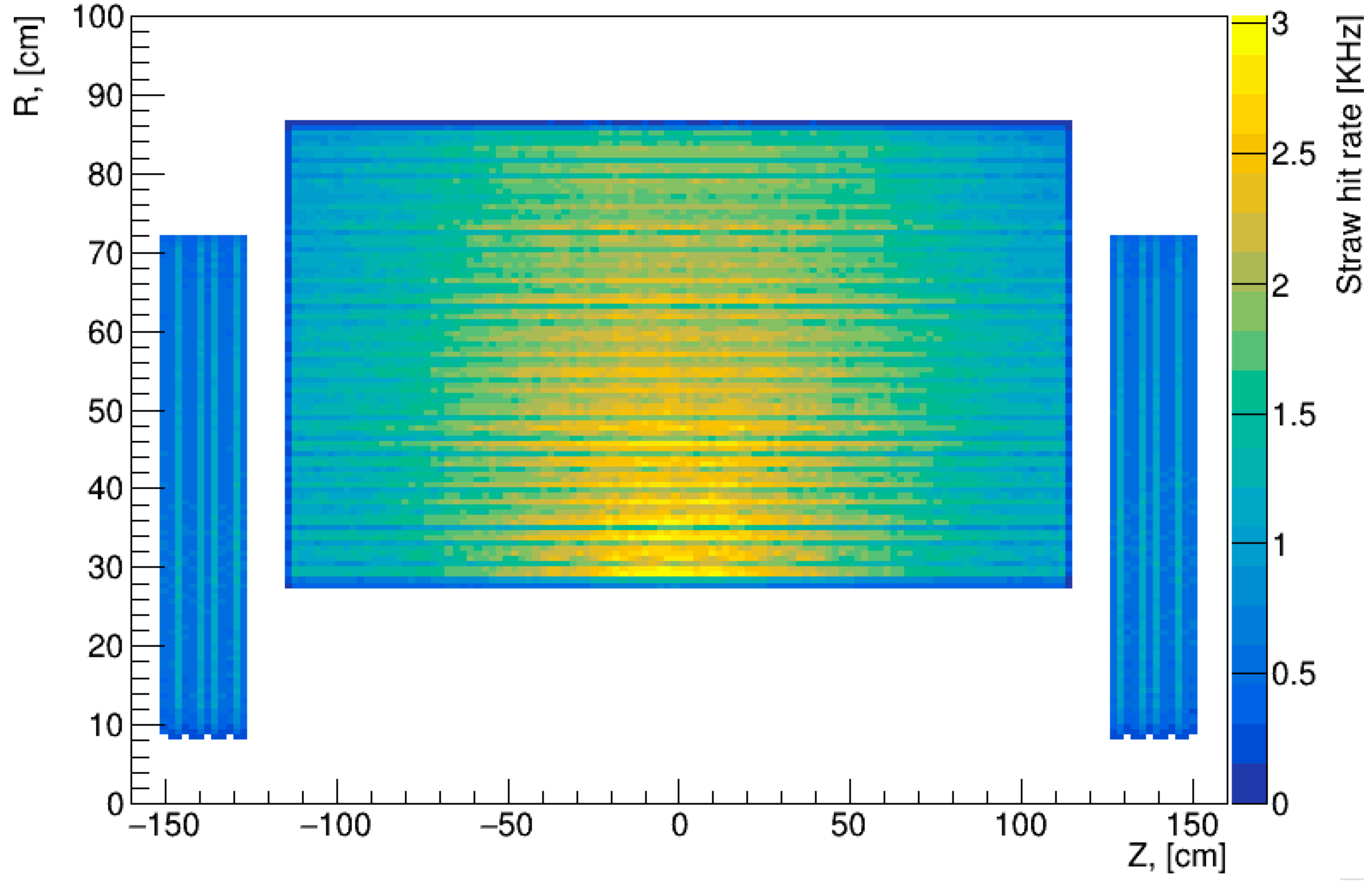
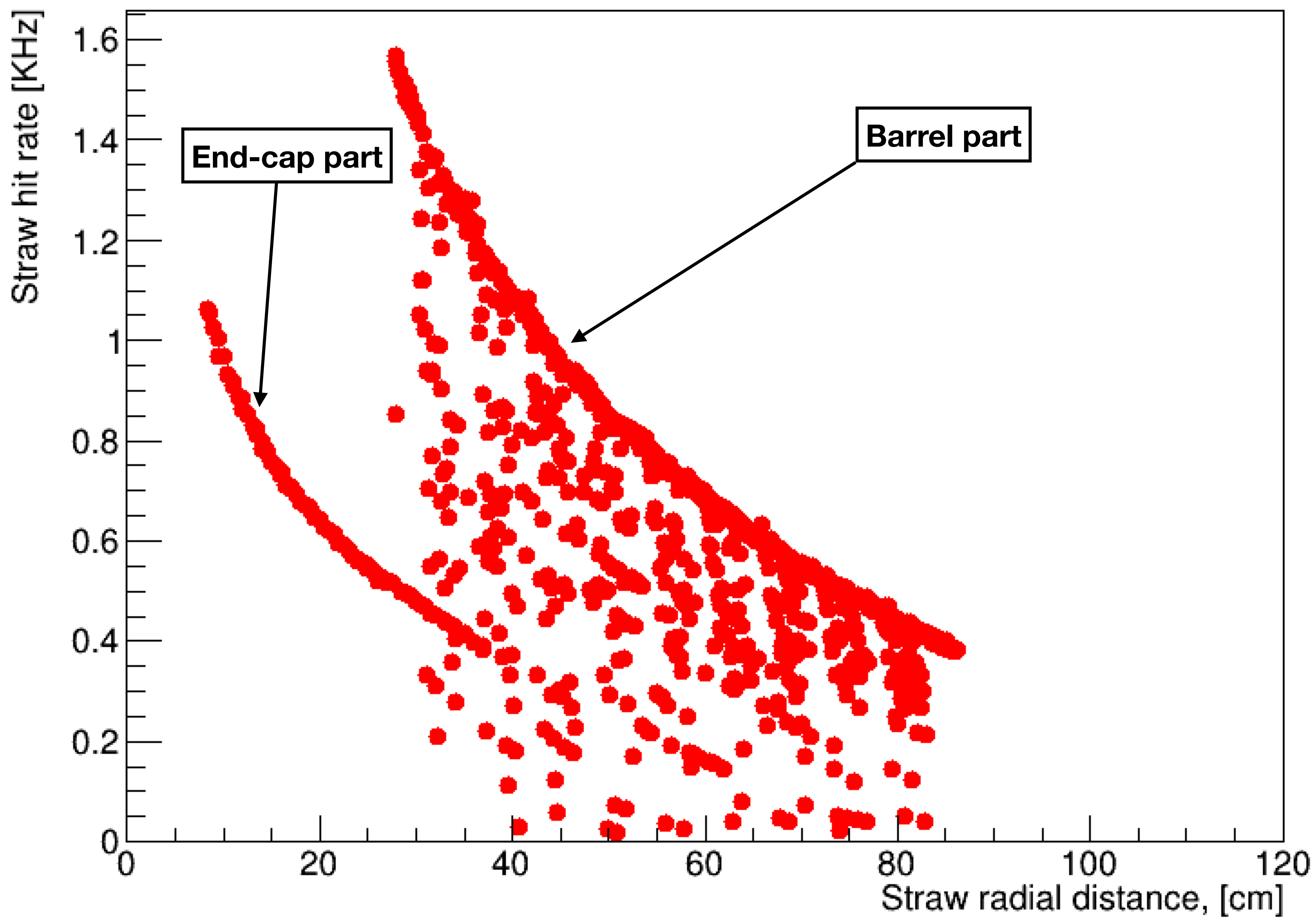


Fig. 10- Average number of hits per straw in the TS in O-O collisions



Simulation parameters:

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 O-O collisions (O_8^{16})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

The relative fraction of active straws (straws with at least 1 hit): 6.2%

Interaction rates are obtained from MPD CDR: https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

Momentum resolution of the Straw Tracker in O-O collisions

The momentum resolution was similarly evaluated for ion-ion collisions.
In particular, Figure 11 presents the total occupancy map of the entire Straw Tracker in the central pseudorapidity region ($-1.1 < \eta < 1.1$) for oxygen-oxygen (O–O) collisions.
Figure 12 shows the momentum resolution (Pt) across the full momentum spectrum for O–O collisions in the same central pseudorapidity region.

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 1 000 O-O collisions (O_8^{16})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

Interaction rates are obtained from MPD CDR:
https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

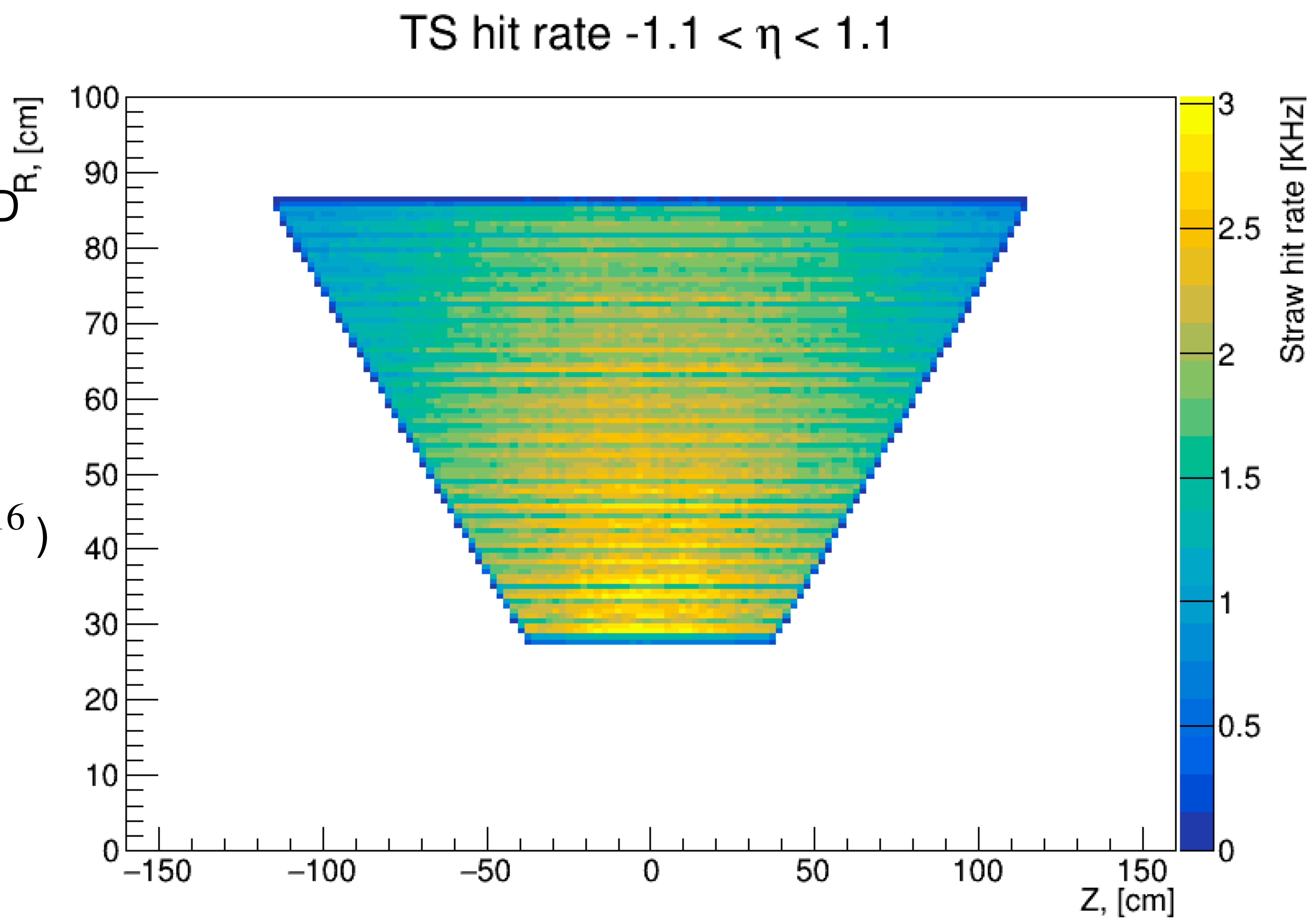


Fig. 11 - TS full hit rate in the central pseudorapidity region for the O-O collisions

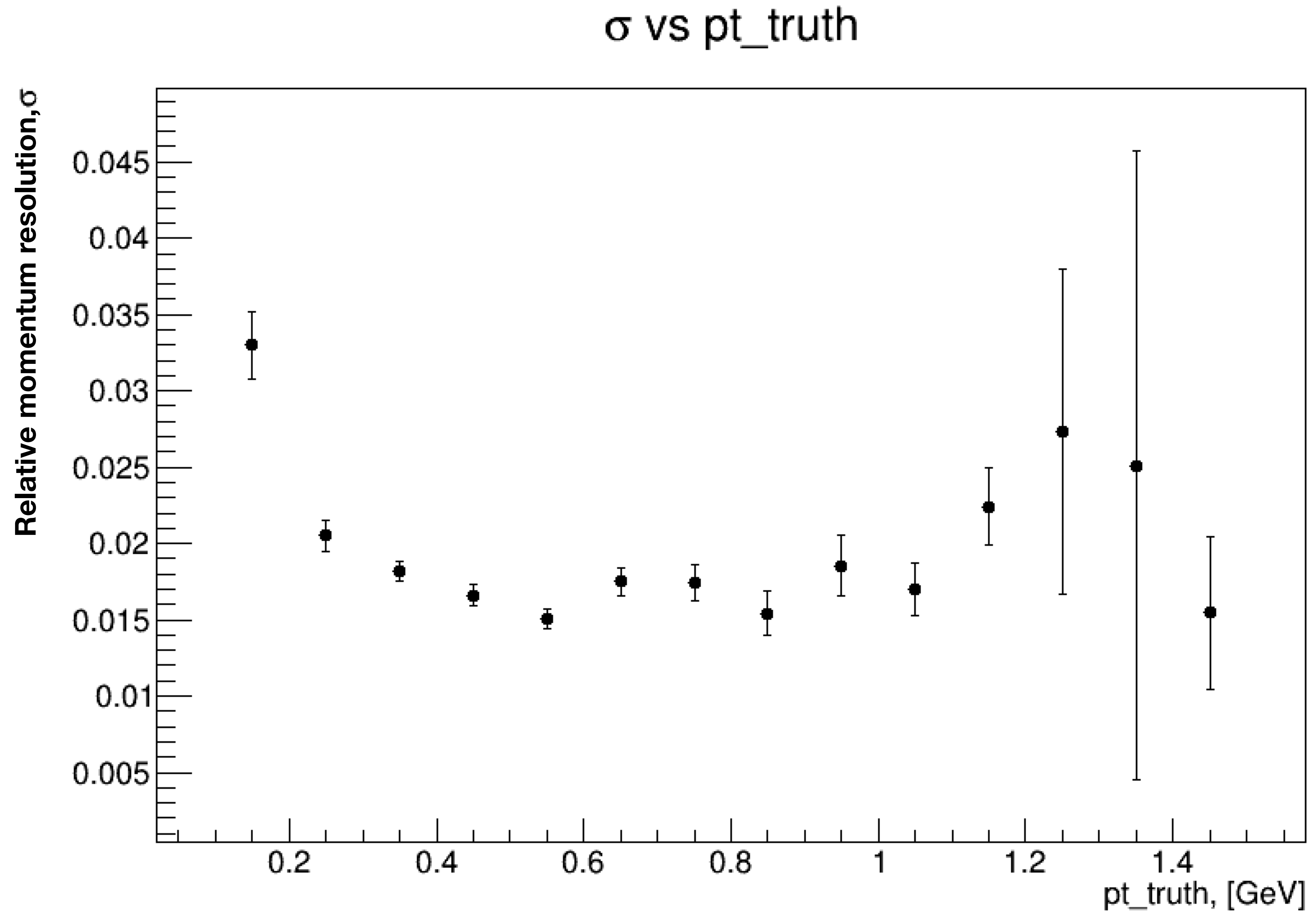


Fig. 12 - Momentum resolution of the Straw Tracker for MC Pt within the central pseudorapidity interval for the O-O collisions

TS full hit rate and straw occupancy in Kr-Kr collisions

Fig. 13 - TS full hit rate (barrel и end-caps parts) in Kr-Kr collisions

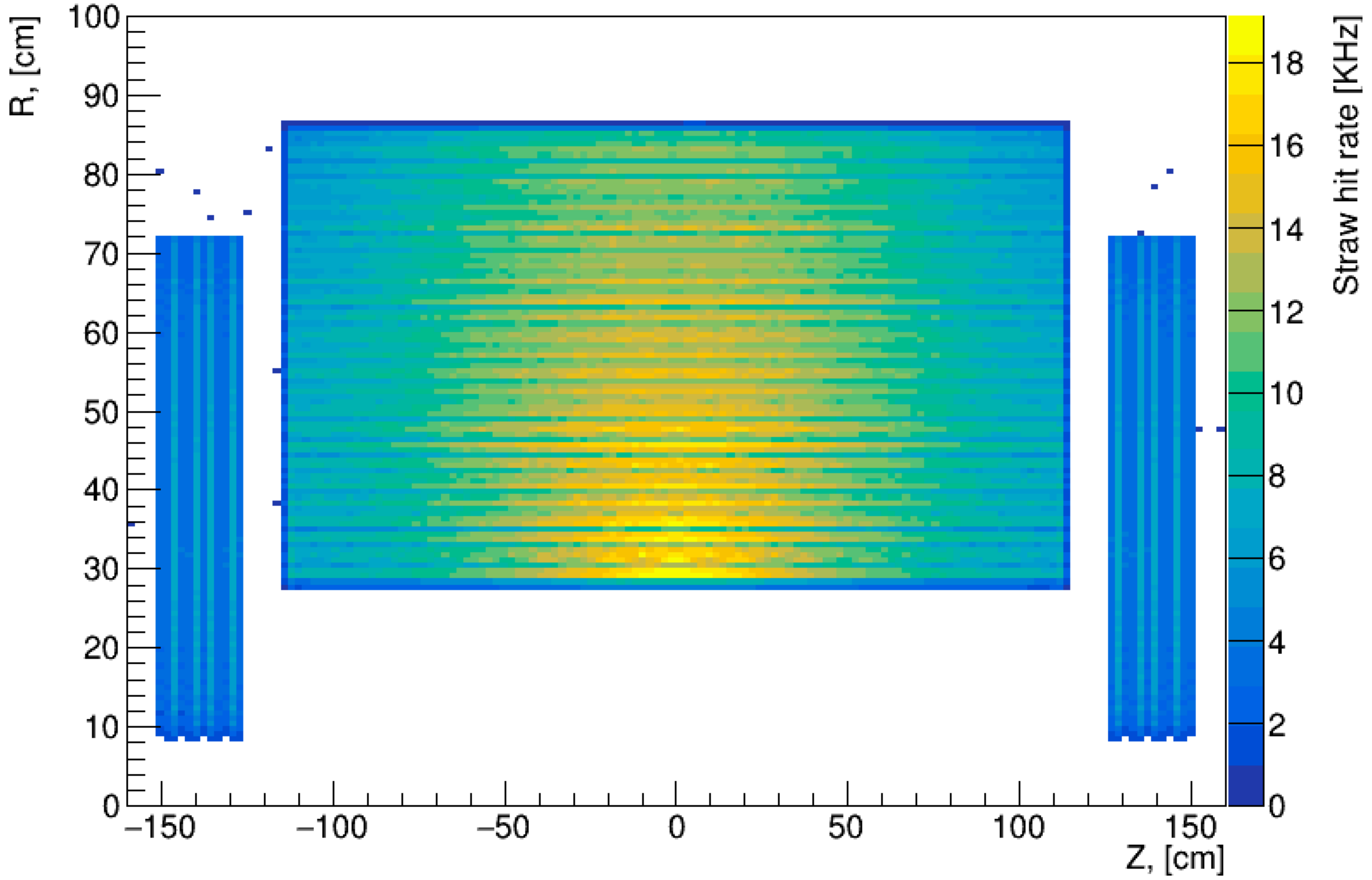
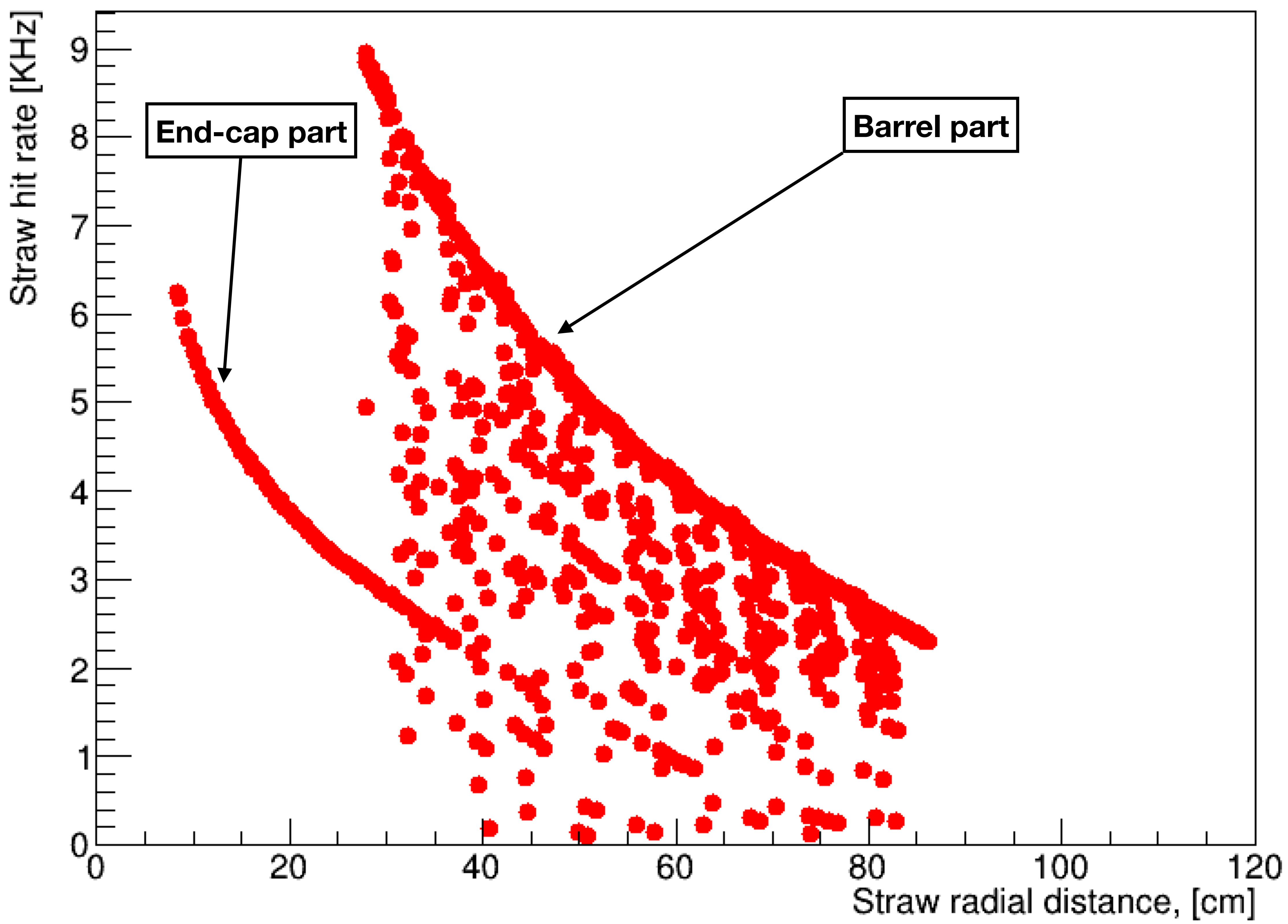


Fig. 14 - Average number of hits per straw in the TS in Kr-Kr collisions



The relative fraction of active straws (straws with at least 1 hit): 26.2%

Simulation parameters:

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Kr-Kr collisions (Kr^{84}_{36})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

Interaction rates are obtained from MPD CDR: https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

Momentum resolution of the Straw Tracker in Kr-Kr collisions

The momentum resolution was similarly evaluated for ion-ion collisions.
In particular, Figure 15 presents the total occupancy map of the entire Straw Tracker in the central pseudorapidity region ($-1.1 < \eta < 1.1$) for oxygen-oxygen Kr-Kr) collisions.
Figure 16 shows the momentum resolution (Pt) across the full momentum spectrum for Kr-Kr collisions in the same central pseudorapidity region.

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 1 000 Kr-Kr collisions (Kr^{84}_{36})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

Interaction rates are obtained from MPD CDR:
https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

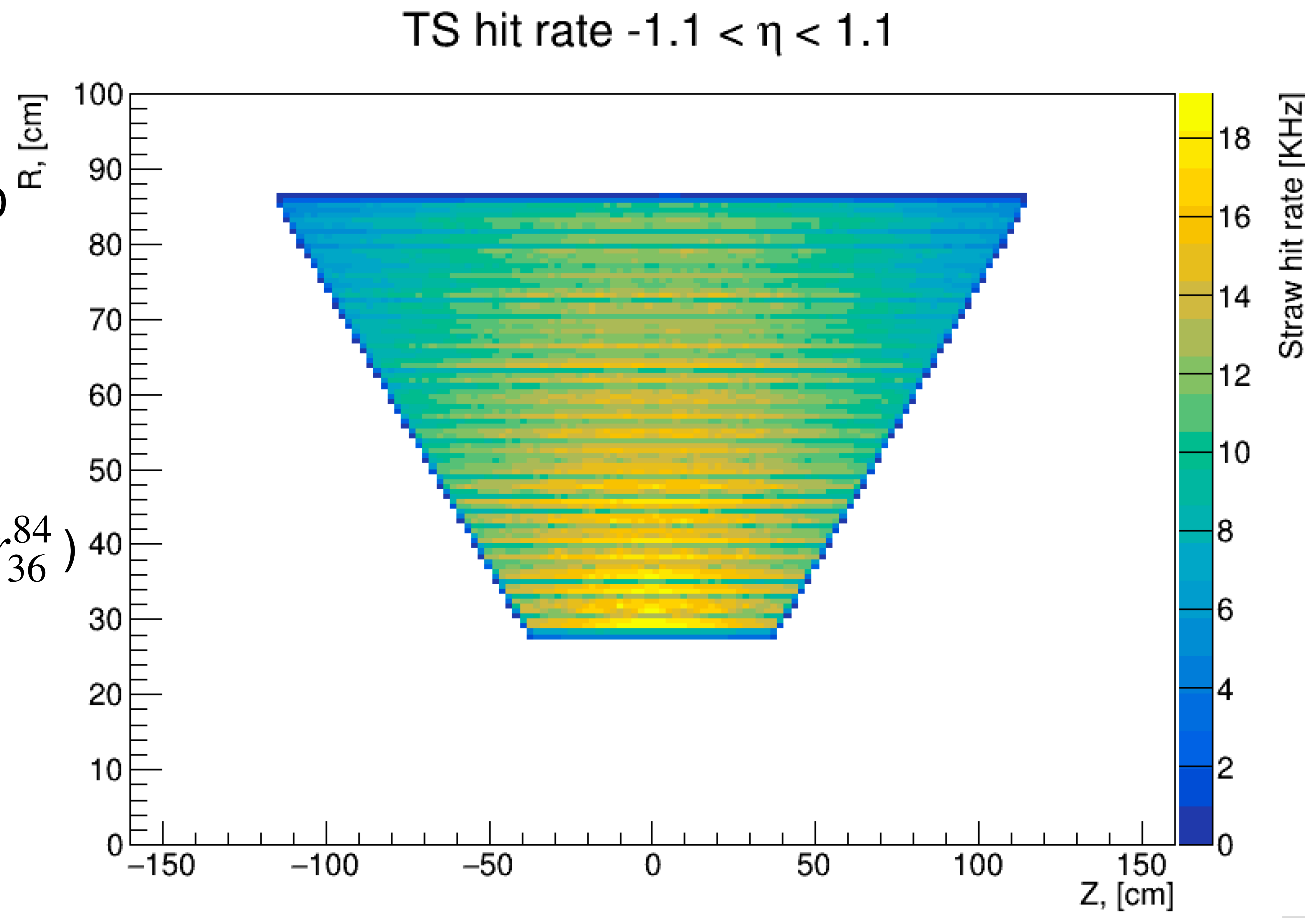


Fig. 15 - TS full hit rate in the central pseudorapidity region for the Kr-Kr collisions

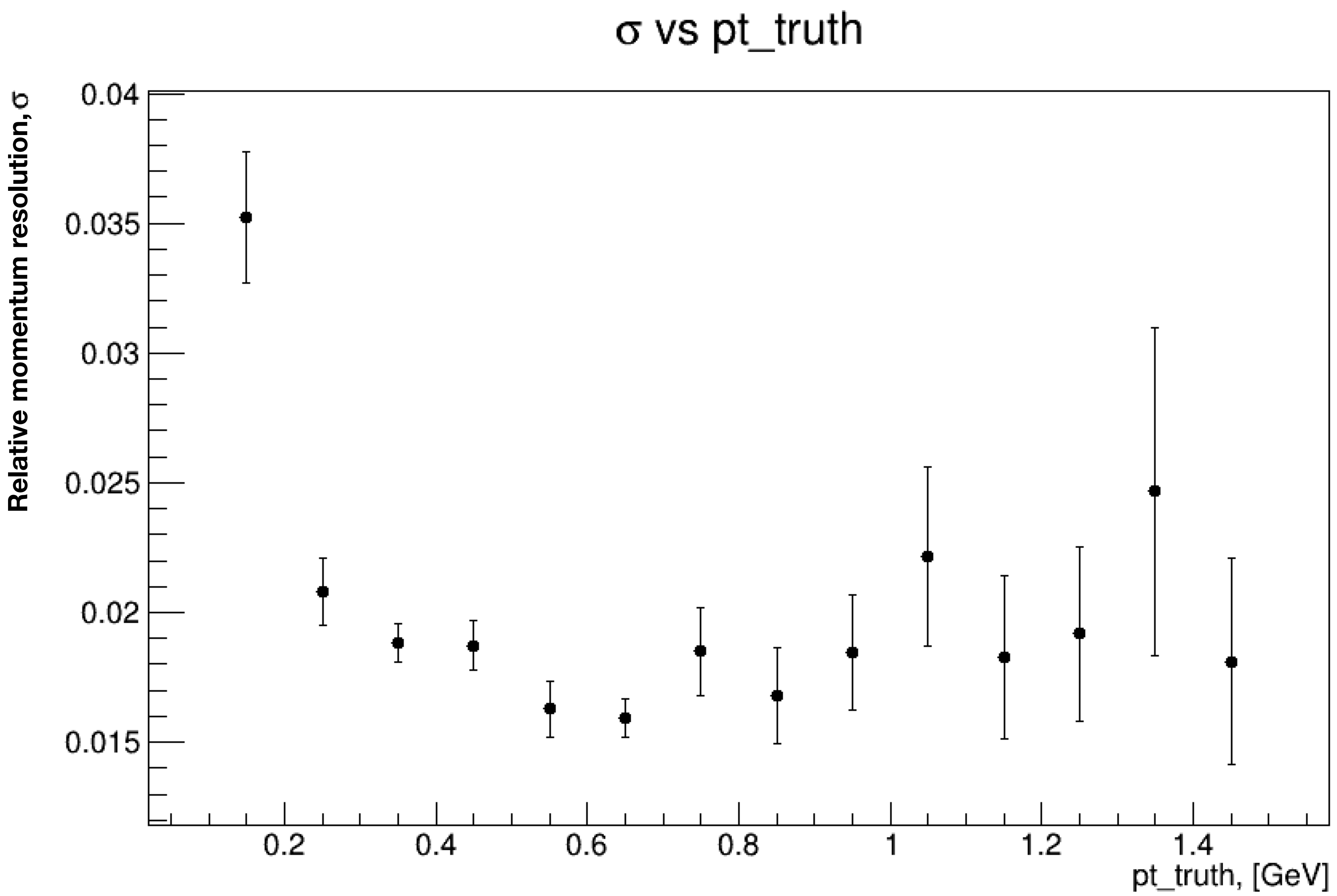


Fig. 16 - Momentum resolution of the Straw Tracker for MC Pt within the central pseudorapidity interval for the Kr-Kr collisions

TS full hit rate and straw occupancy in Xe-Xe collisions

Fig. 17 - TS full hit rate (barrel и end-caps parts) in Xe-Xe collisions

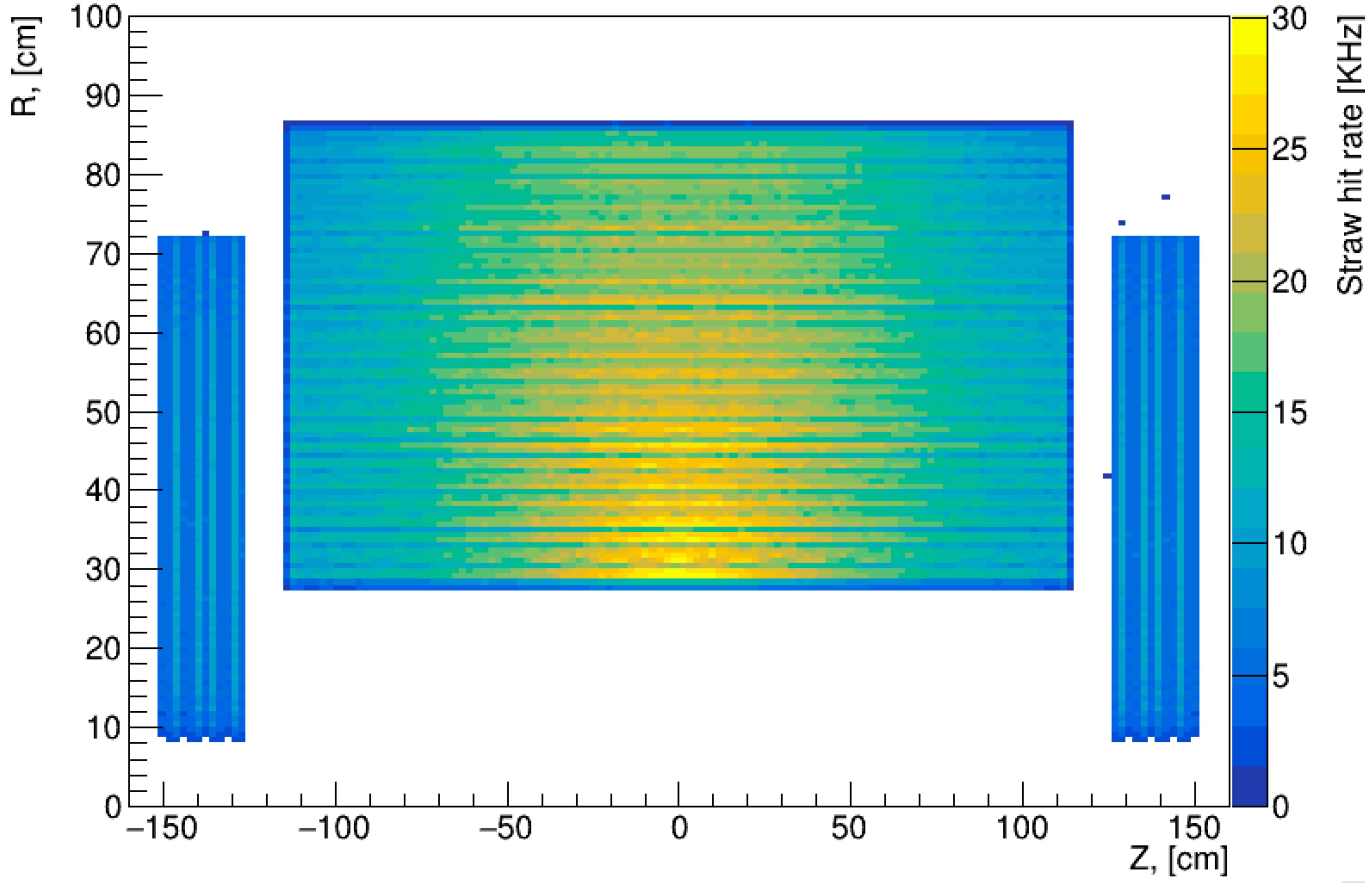
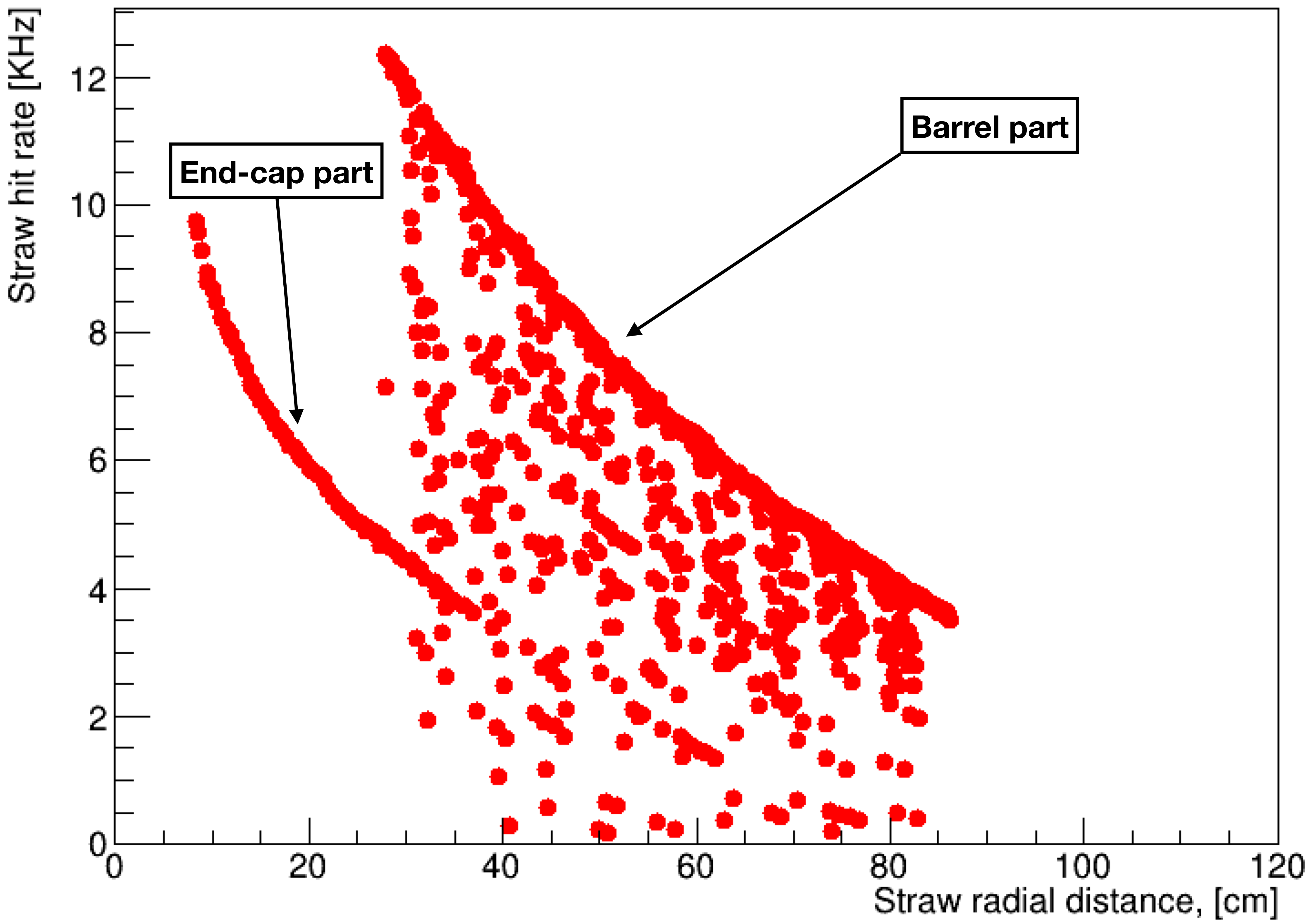


Fig. 18 - Average number of hits per straw in the TS in Xe-Xe collisions



Simulation parameters:

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Xe-Xe collisions (Xe^{131}_{54})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

The relative fraction of active straws (straws with at least 1 hit): 33.6%

Interaction rates are obtained from MPD CDR: https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

Momentum resolution of the Straw Tracker in Xe-Xe collisions

The momentum resolution was similarly evaluated for ion-ion collisions.
In particular, Figure 19 presents the total occupancy map of the entire Straw Tracker in the central pseudorapidity region ($-1.1 < \eta < 1.1$) for oxygen-oxygen Xe-Xe) collisions.
Figure 20 shows the momentum resolution (Pt) across the full momentum spectrum for Xe-Xe collisions in the same central pseudorapidity region.

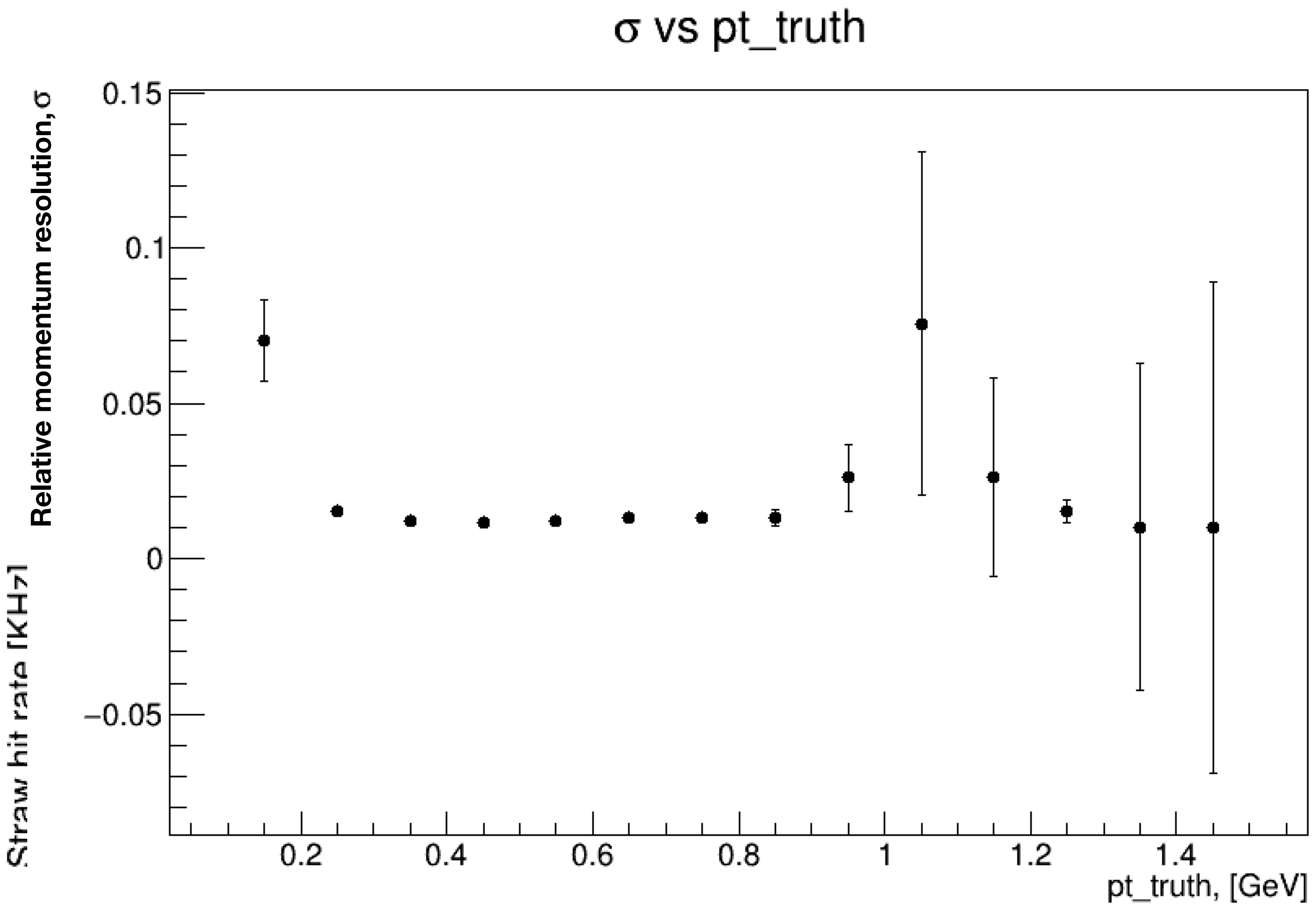


Fig. 20 - Momentum resolution of the Straw Tracker for MC Pt within the central pseudorapidity interval for the Xe-Xe collisions

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 1 000 Xe-Xe collisions (Xe_{54}^{131})
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

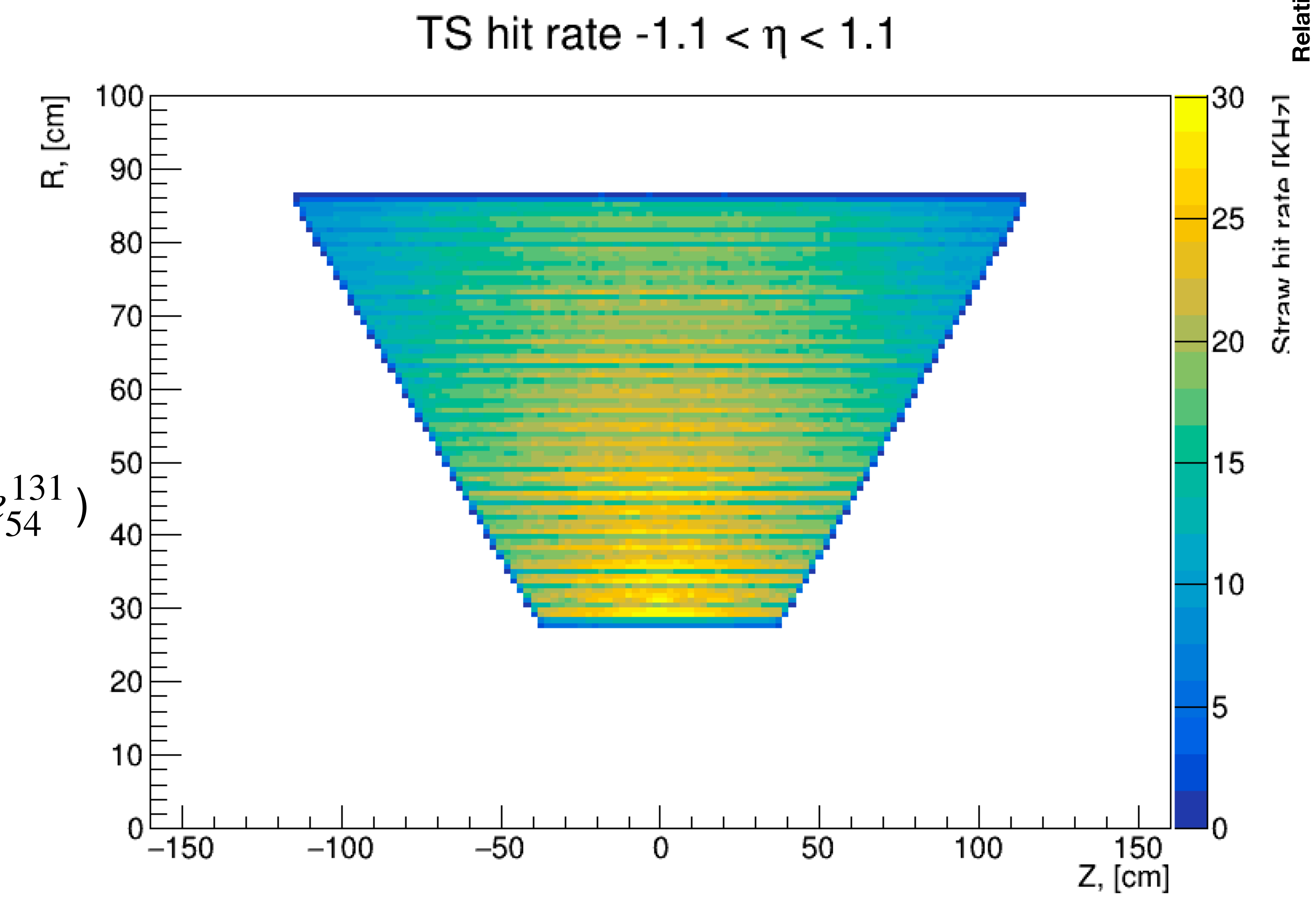


Fig. 19 - TS full hit rate in the central pseudorapidity region for the Xe-Xe collisions

Interaction rates are obtained from MPD CDR:
https://mpd.jinr.ru/wp-content/uploads/2023/11/MPD_CDR_en.pdf

Comparison of momentum resolution in the Straw Tracker in p-p and ion-ion collisions

By comparing the momentum resolution distributions between proton-proton and various ion-ion collision systems, a combined distribution was obtained.

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 p-p and 1000 ion-ion collisions
- Minimum bias

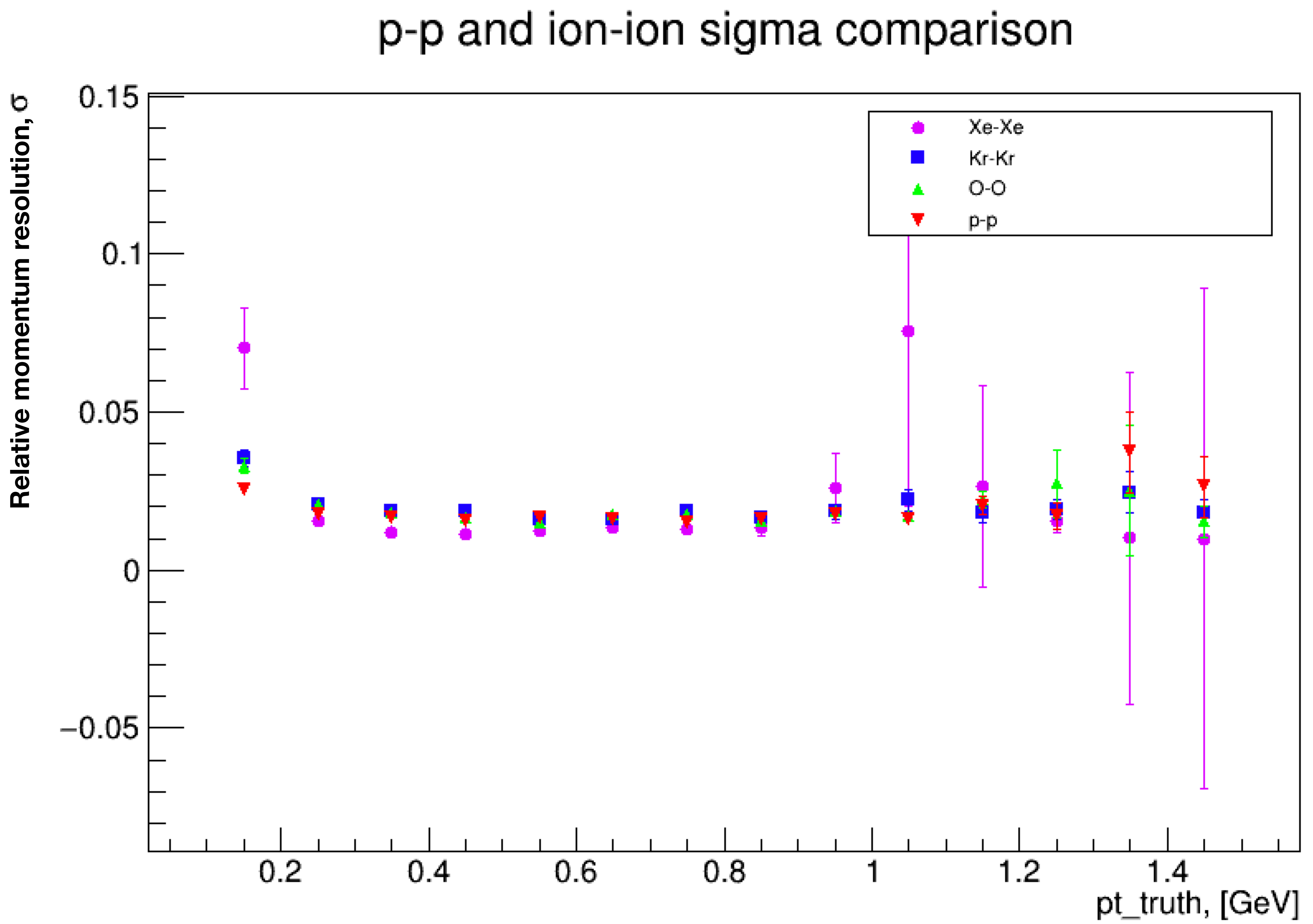


Fig. 21 - Comparison of momentum resolution in the Straw Tracker in p-p and ion-ion collisions

Compared relative fraction of active straws in the TS

Fig. 22 shows the relative fraction of active straws in the TS, compared between p-p, O-O, Kr-Kr and Xe-Xe collisions

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 100 000 p-p and 10 000 ion-ion collisions
- Minimum bias

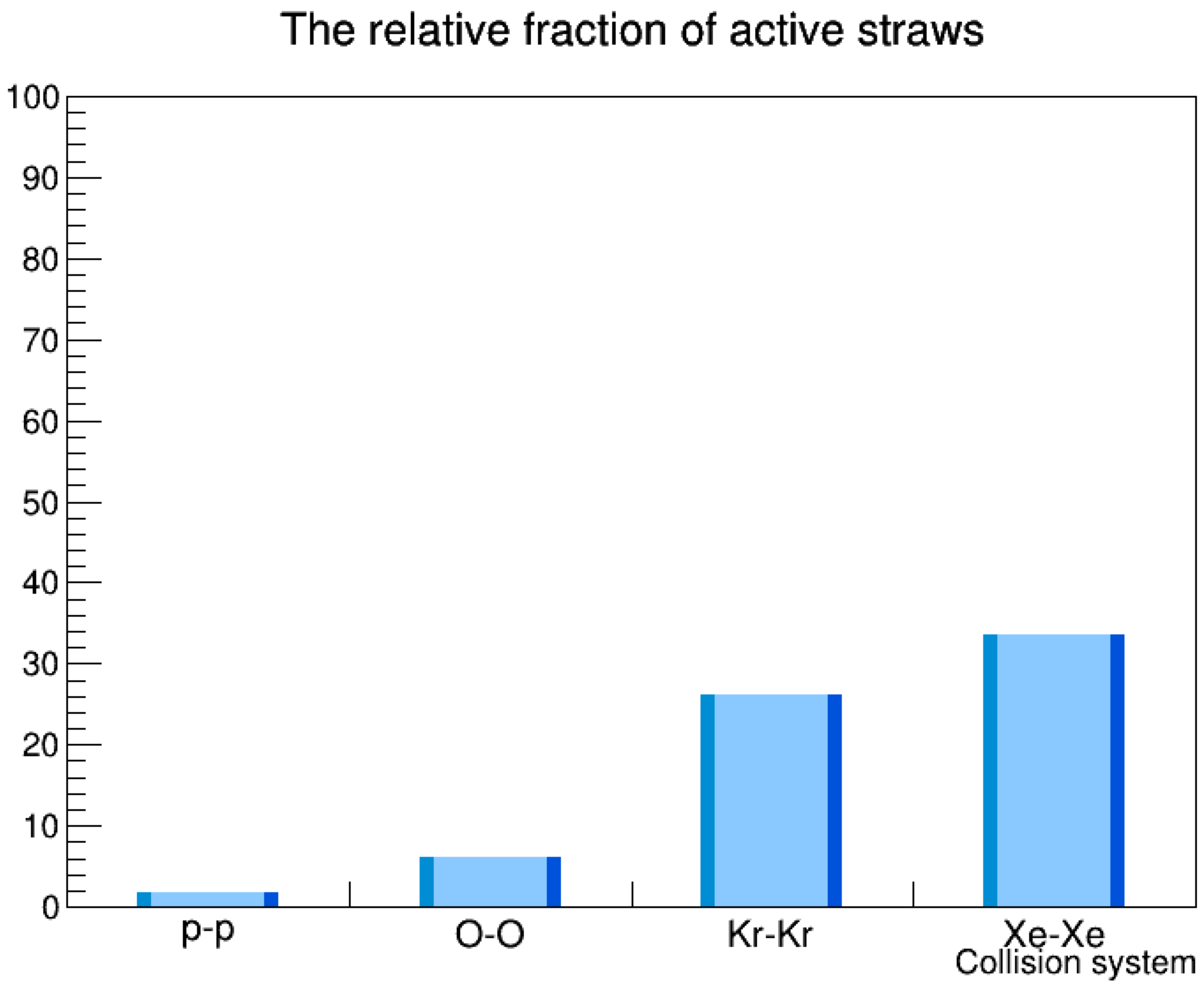


Fig. 22 - Compared relative fraction of active straws in the TS

Summary

- Total occupancy maps of the Straw Tracker were obtained for both proton-proton and different ion-ion collisions

- Momentum resolution distributions were evaluated in the central pseudorapidity region for both p–p and ion-ion collisions. **The relative fraction of active straws increased with increasing atomic number of the colliding nuclei**

- According to the average straw occupancies and hit rates maps we can make a conclusion that **light ion collisions like O can be studied with high accuracies** but it **seems unlikely to study heavier ions like Xe** at the SPD because it would be rather difficult to separate different tracks via one ion collision

Thank you for your attention!

TS module hit rate in p-p collisions

Additionally, analogous hit rate maps were obtained for each module of the Straw Tracker in p-p collisions.

<u>Simulation parameters:</u>

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 100 000 p-p collisions
- Module number - 5
- Minimum bias
- Interaction rate (for colored Z-axis) = 0.4 MHz

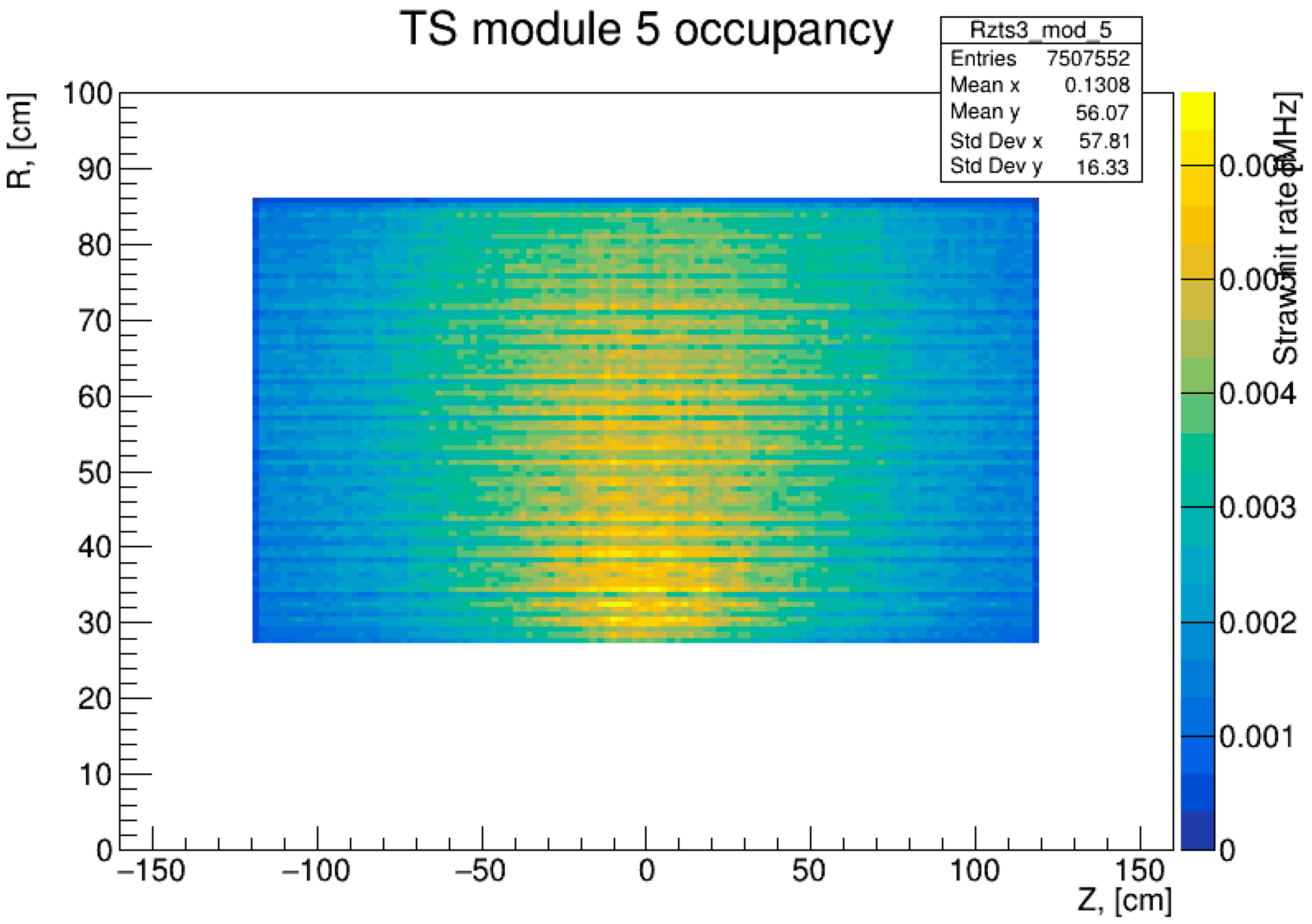


Fig. 23 - TS hit rate colormap of the 5th barrel module in proton-proton collisions

TS layer hit rate in p-p collisions

TS hit rate of the 5th barrel module in p-p collisions

Simulation parameters:

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 100 000 p-p collisions
- Layer number - 15
- Minimum bias
- Interaction rate (for colored Z-axis) = 0.4 MHz

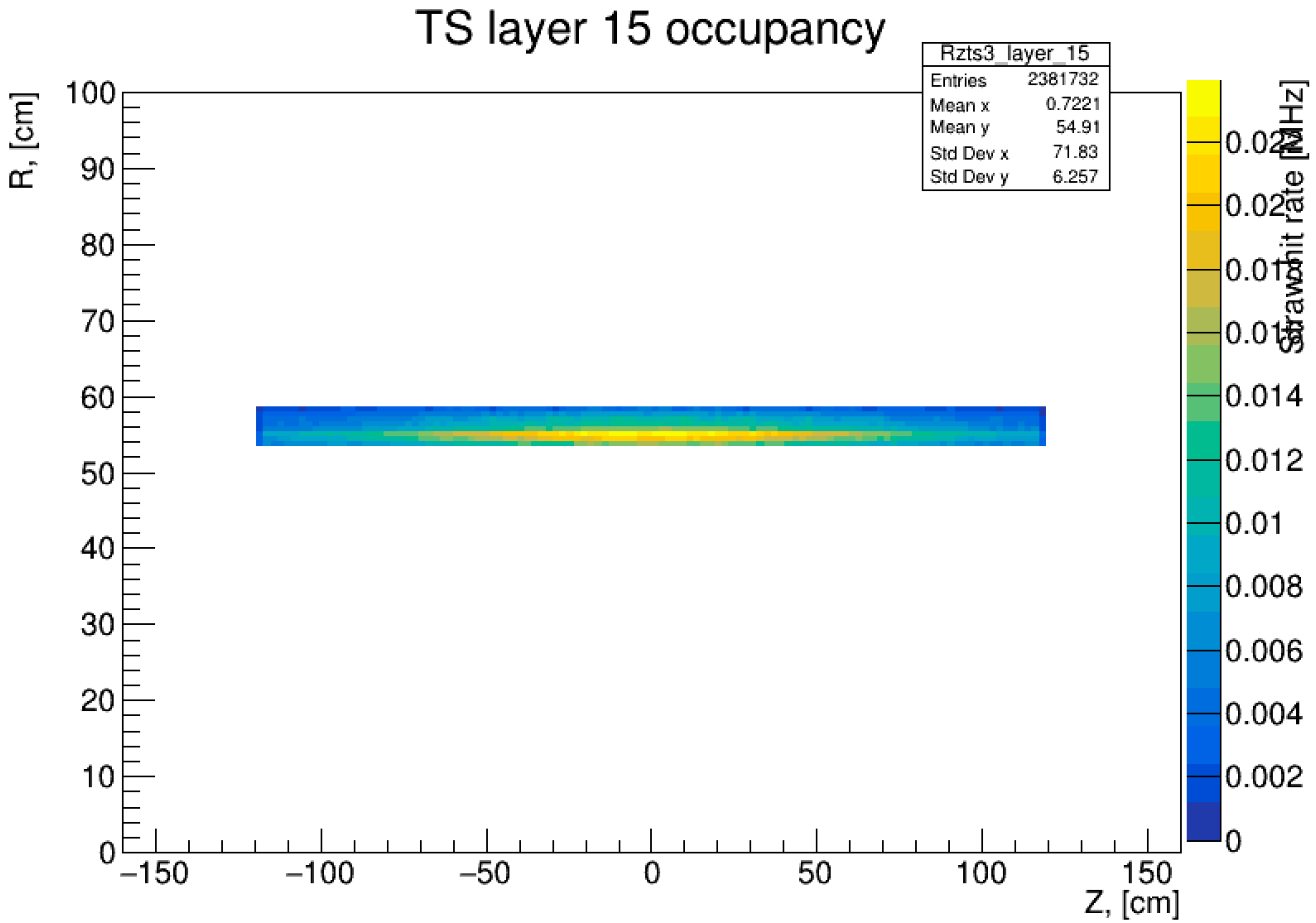


Fig. 24 - TS hit rate colormap of the 15th layer in p-p collisions

TS module hit rate in ion-ion collisions (O-O)

Additionally, analogous hit rate maps were obtained for each module of the Straw Tracker in ion-ion (O-O) collisions.

Simulation parameters:

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 O-O collisions (O_{8}^{16})
- Module number - 5
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

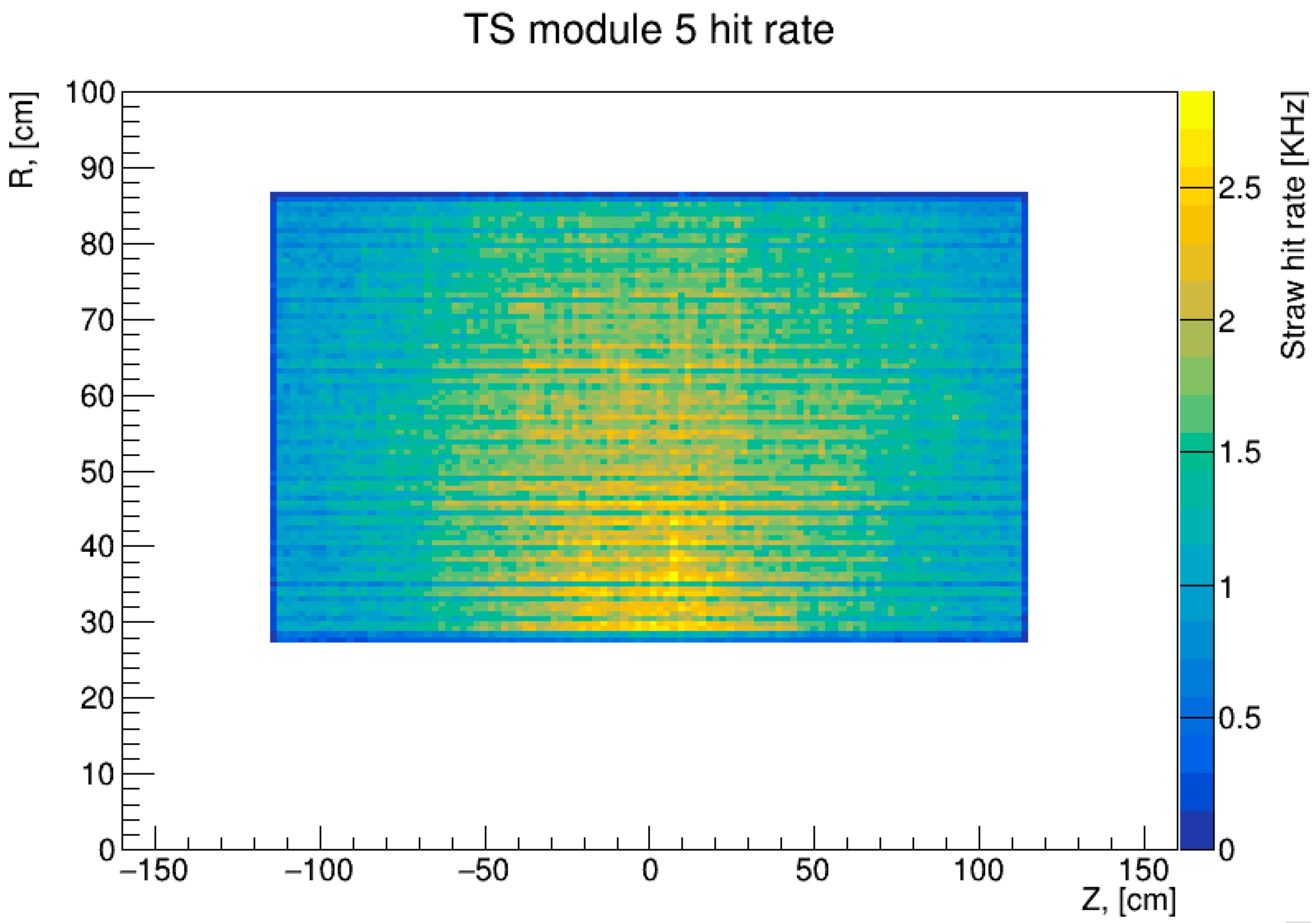


Fig. 25 - TS hit rate colormap of the 5th barrel module in O-O collisions

TS layer hit rate in ion-ion collisions (O-O)

Occupancy of the 5th barrel module in ion-ion (O-O) collisions

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 O-O collisions (O_8^{16})
- Module number - 15
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

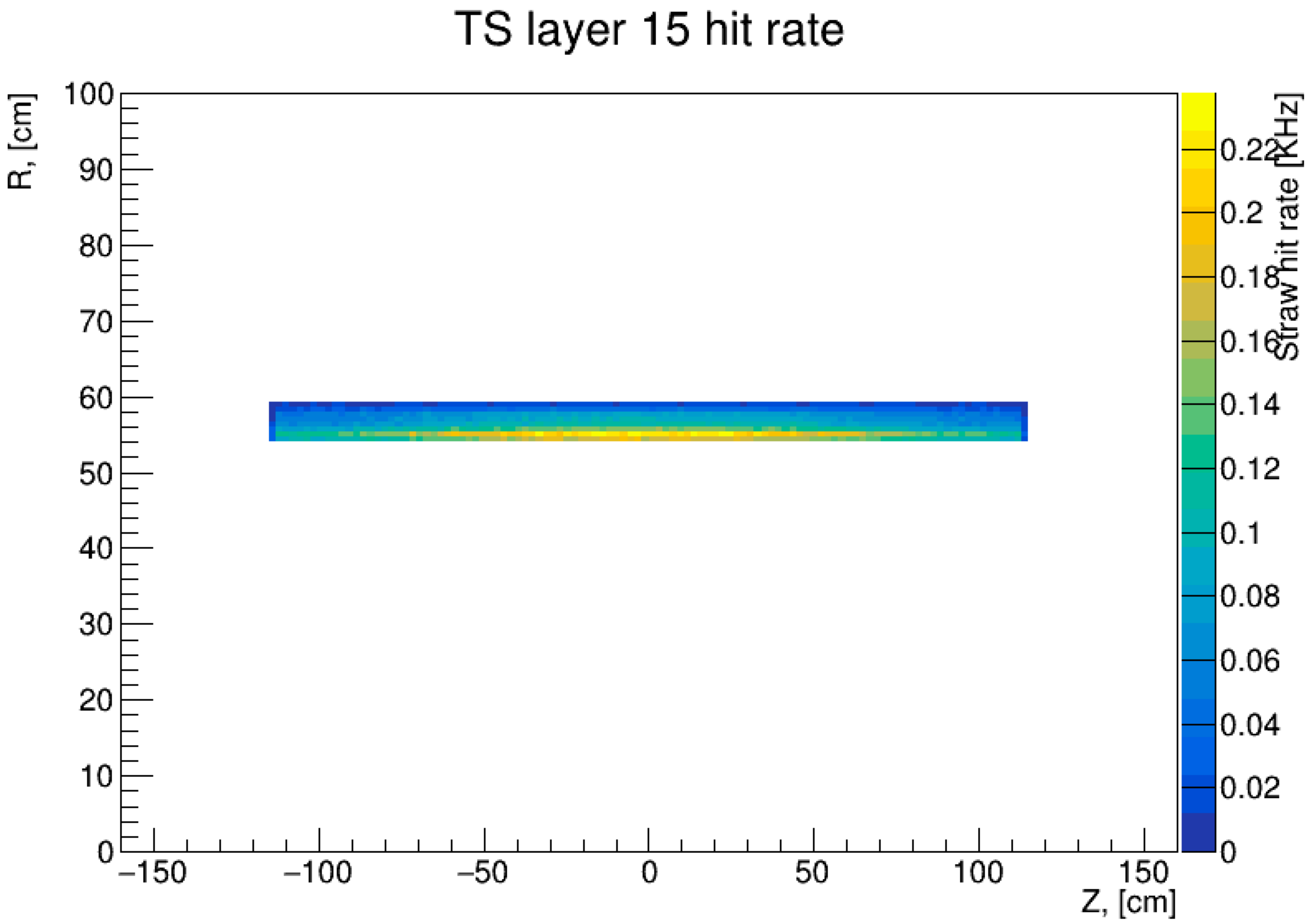


Fig. 26 - TS hit rate colormap of the 15th layer in O-O collisions

TS module hit rate in ion-ion collisions (Kr-Kr)

Additionally, analogous hit rate colormaps were obtained for each module of the Straw Tracker in ion-ion (Kr-Kr) collisions.

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Kr-Kr collisions (Kr^{84}_{36})
- Module number - 5
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz
- Kr^{84}_{36} is used for simulations

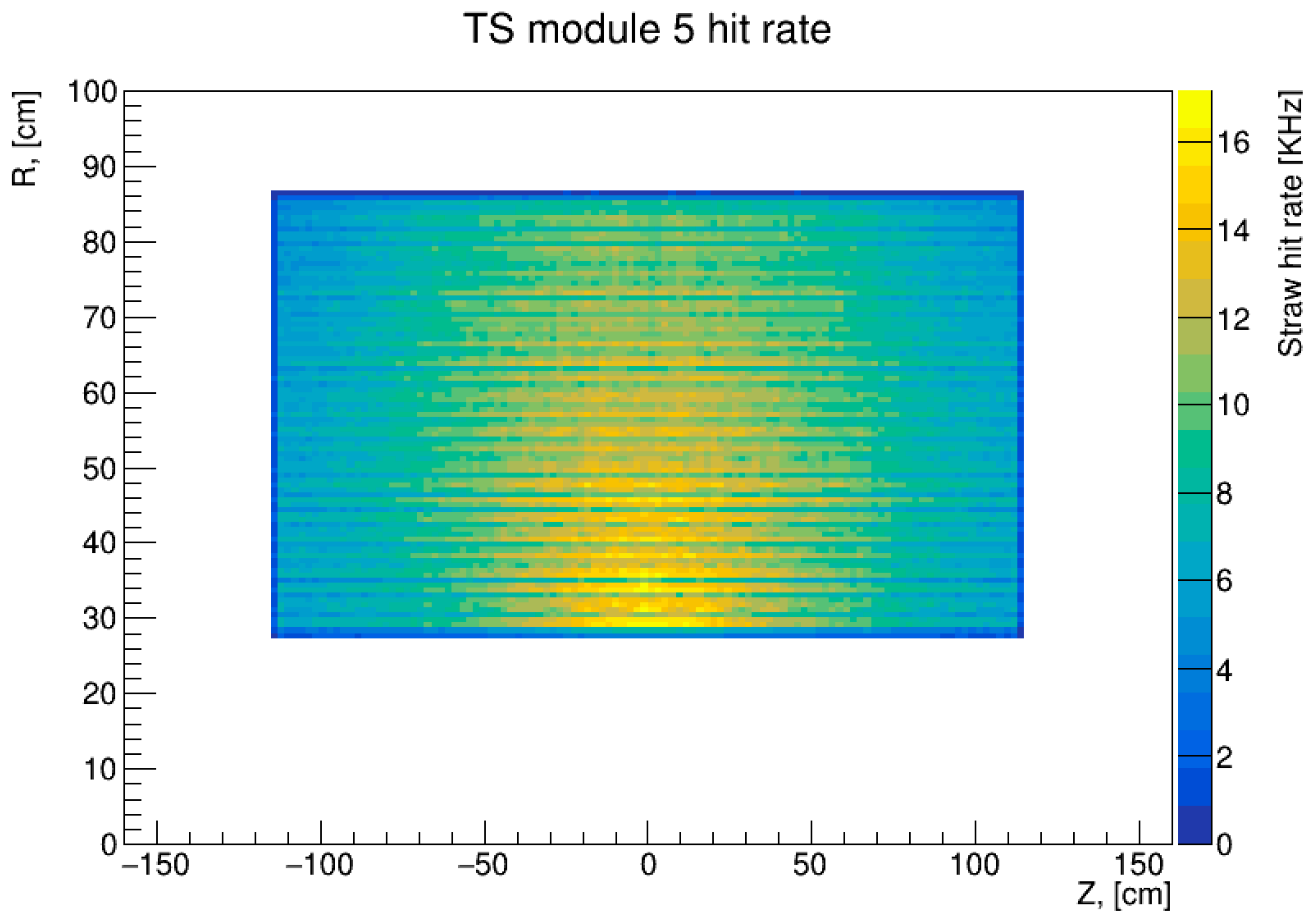


Fig. 27 - TS module hit rate colormap of the 5th barrel module in Kr-Kr collisions

TS layer hit rate in ion-ion collisions (Kr-Kr)

Fig. 28 shows the Hit rate colormap of the 5th barrel module in ion-ion (Kr-Kr) collisions

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Kr-Kr collisions (Kr_{36}^{84})
- Module number - 15
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz
- Kr_{36}^{84} is used for simulations

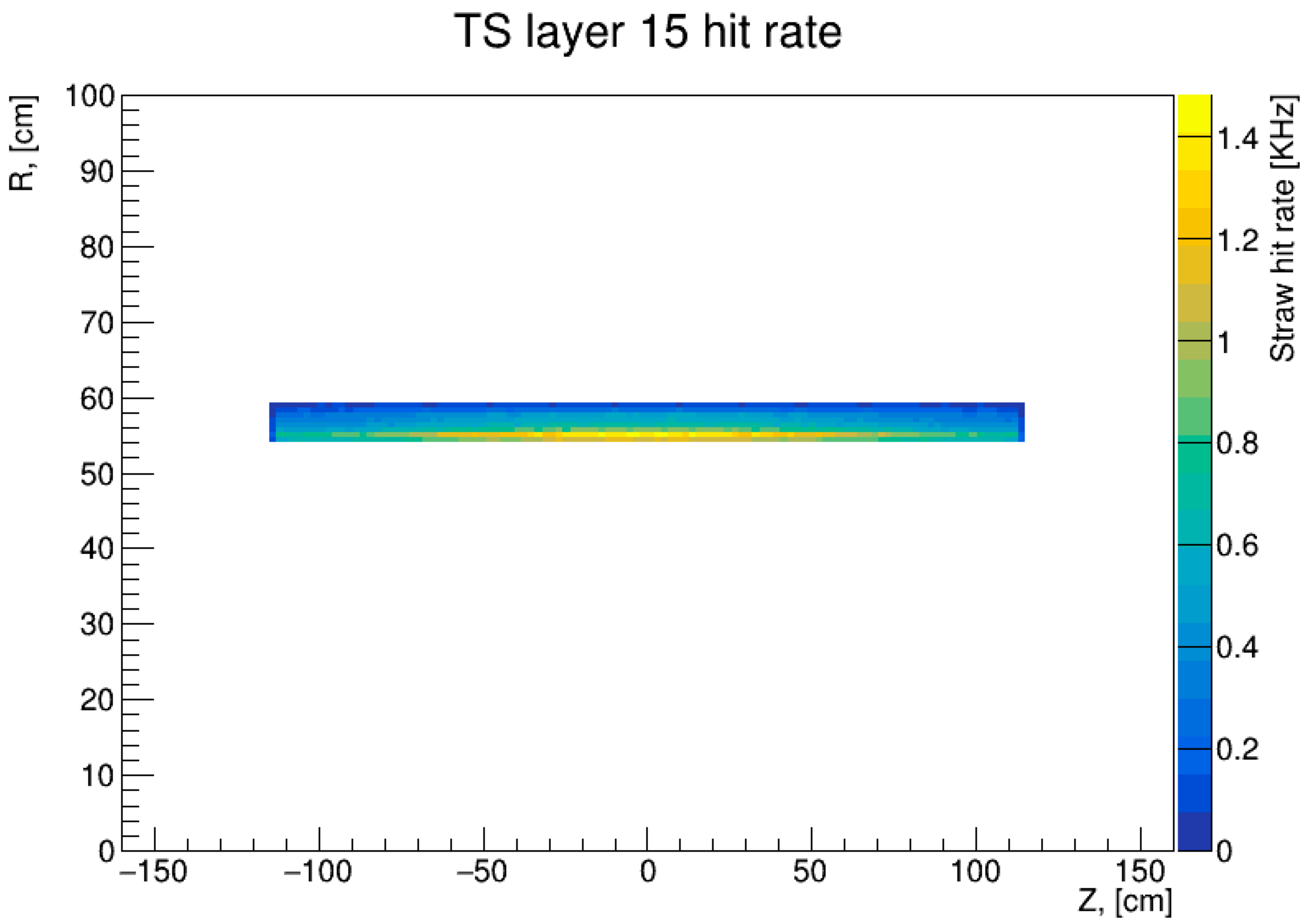


Fig. 28 - TS hit rate colormap of the 15th layer in Kr-Kr collisions

TS module hit rate in ion-ion collisions (Xe-Xe)

Additionally, analogous hit rate colormaps were obtained for each module of the Straw Tracker in ion-ion (Xe-Xe) collisions.

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Xe-Xe collisions (Xe_{54}^{131})
- Module number - 5
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

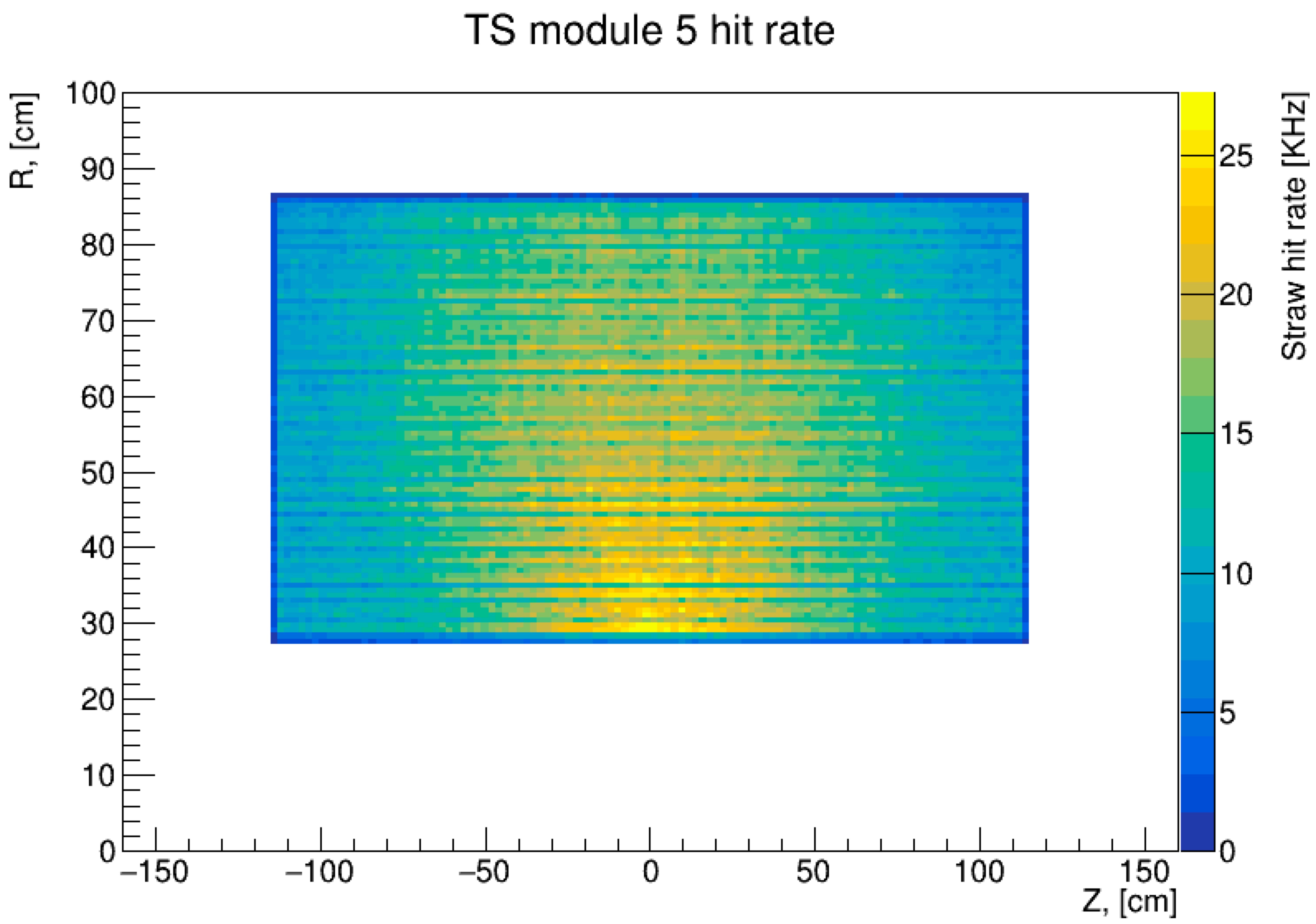


Fig. 29 - TS module hit rate colormap of the 5th barrel module in Xe-Xe collisions

TS layer hit rate in ion-ion collisions (Xe-Xe)

Fig. 30 shows the Hit rate colormap of the 5th barrel module in ion-ion (Xe-Xe) collisions

Simulation parameters:

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 10 000 Xe-Xe collisions (Xe_{54}^{131})
- Module number - 15
- Minimum bias
- Interaction rate (for colored Z-axis) = 7 kHz

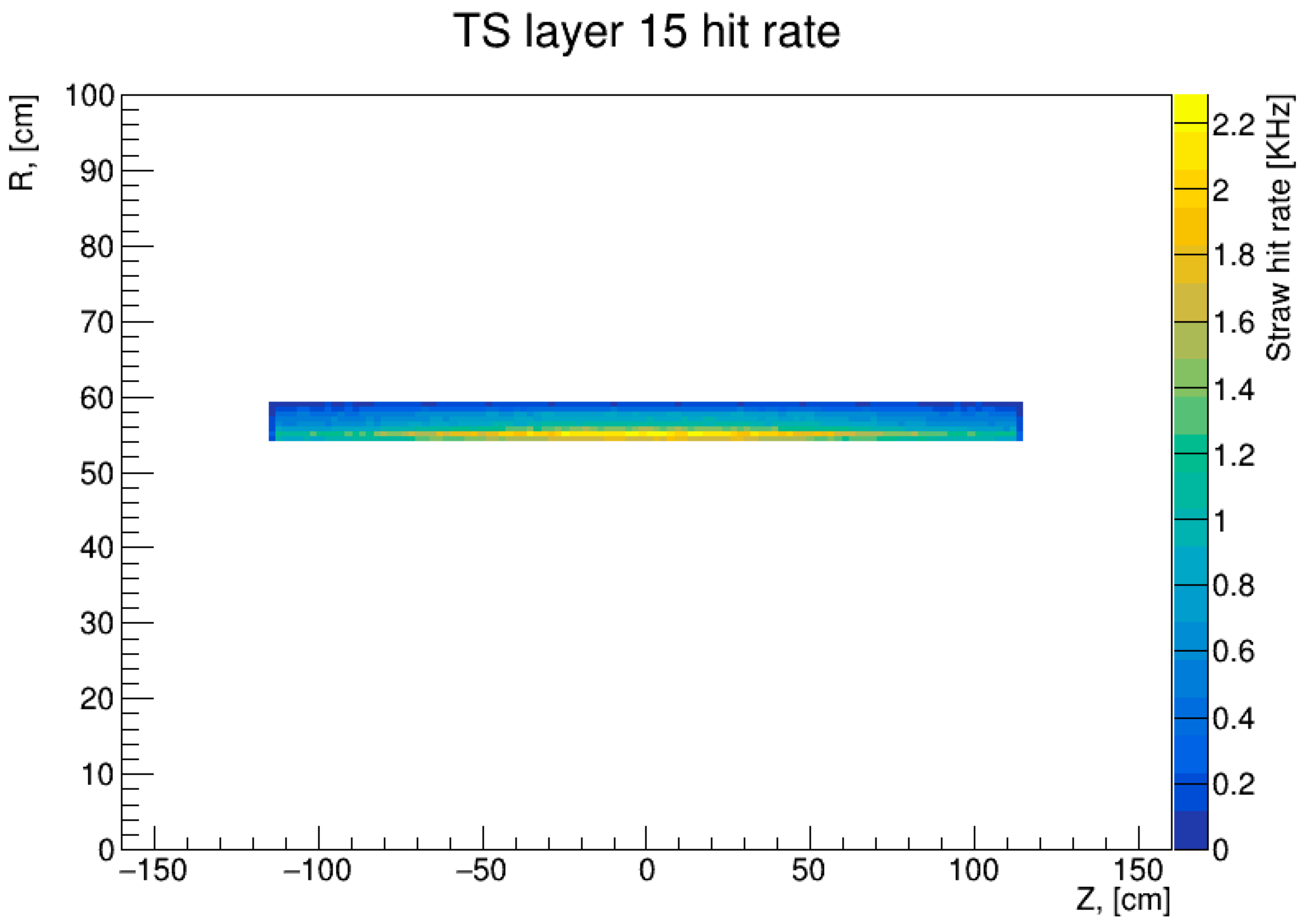


Fig. 30 - TS hit rate colormap of the 15th layer in Xe-Xe collisions

Average number of hits per straw in the TS in p-p collisions (alternative view)

Simulation parameters:

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 1000 p-p collisions
- Minimum bias

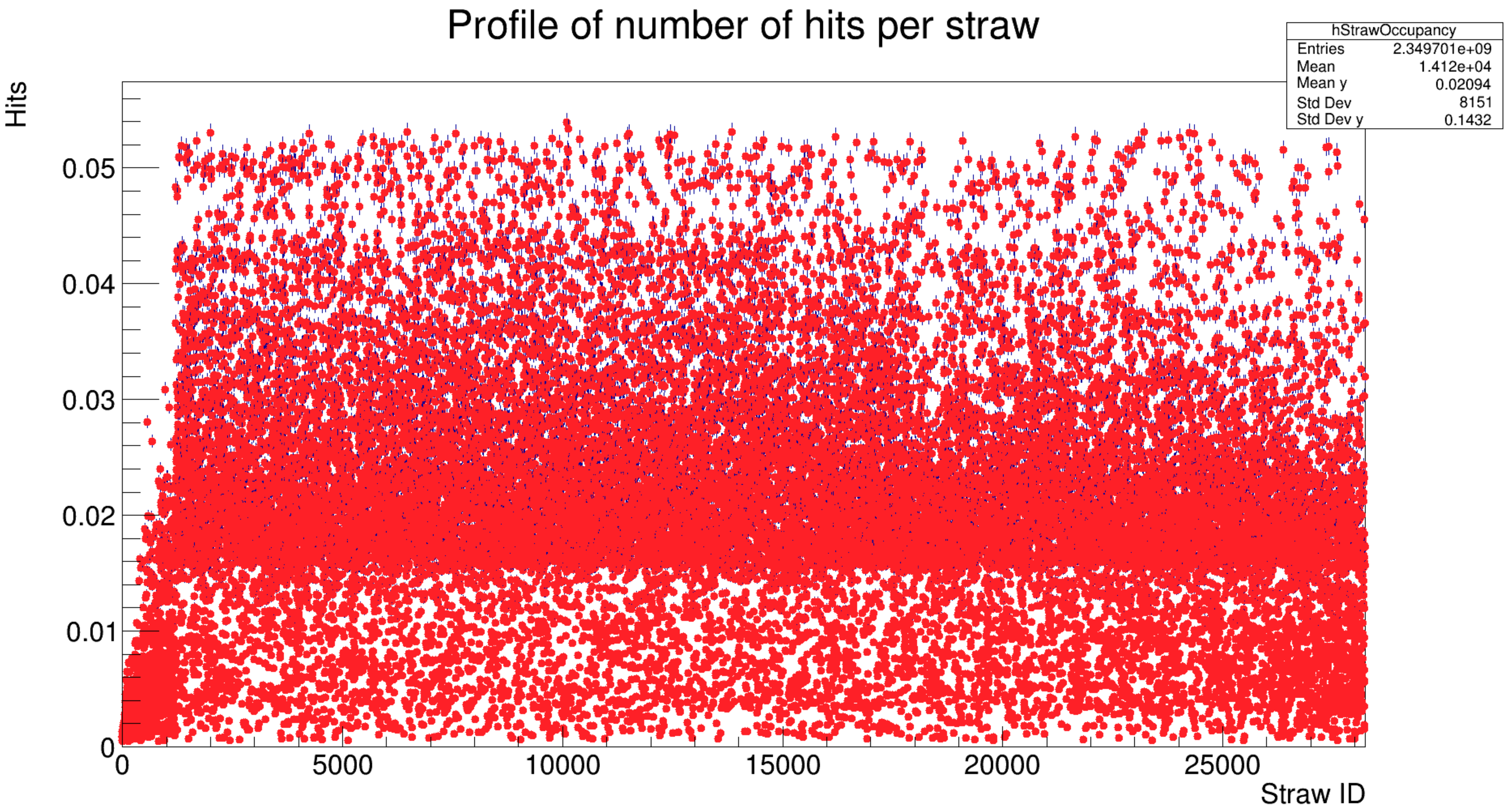


Fig. 31 - Average number of hits per straw in the TS in p-p collisions

Average number of hits per straw in the TS in O-O collisions (alternative view)

<u>Simulation parameters:</u>

- Event Generator: URQMD
- $\sqrt{s} = 10\ GeV$
- 1000 O-O collisions (O_8^{16})
- Minimum bias

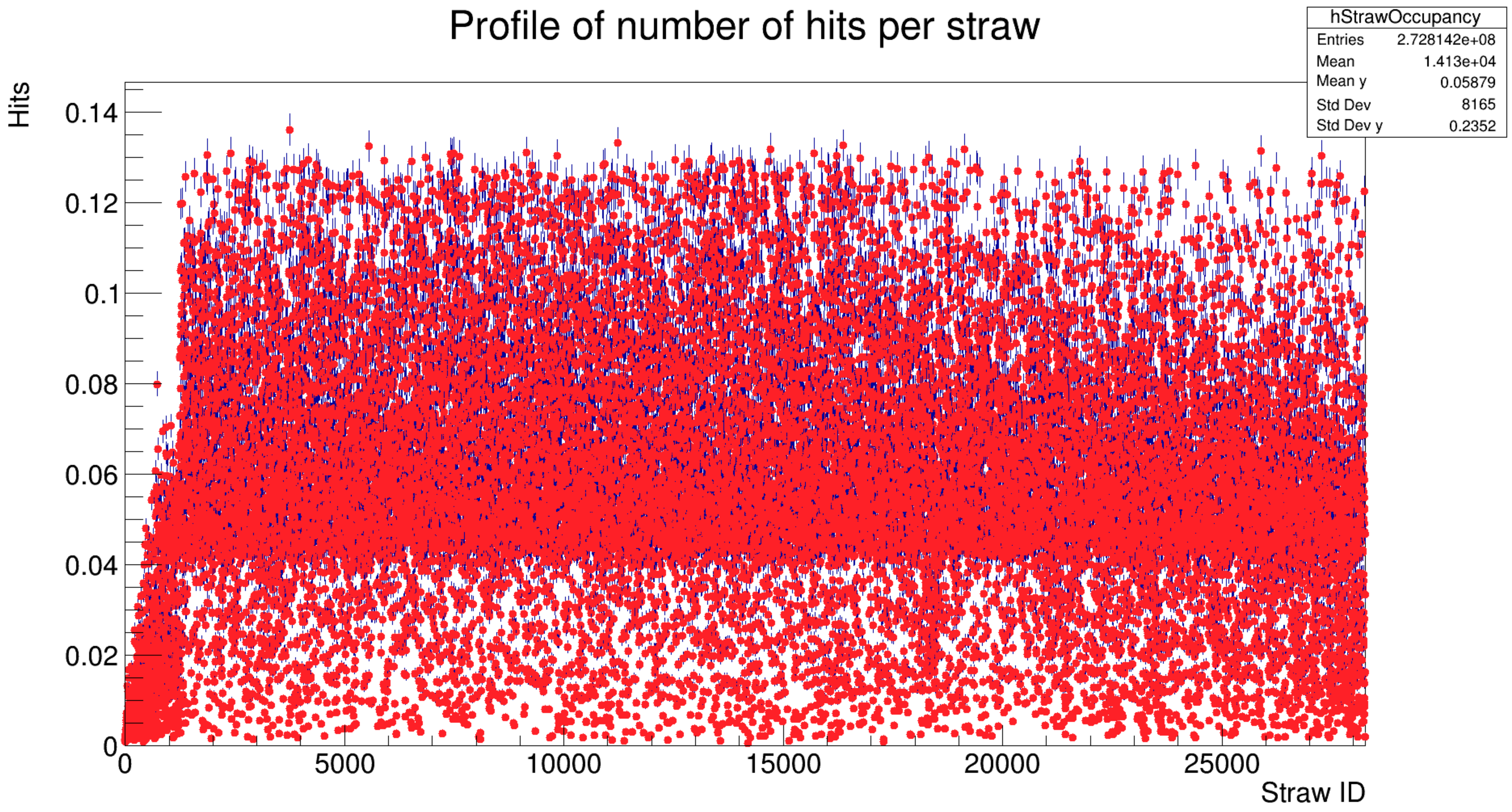


Fig. 32 - Average number of hits per straw in the TS in O-O collisions (alternative view)

Momentum reconstruction accuracy

How accuracy reconstruction was calculated

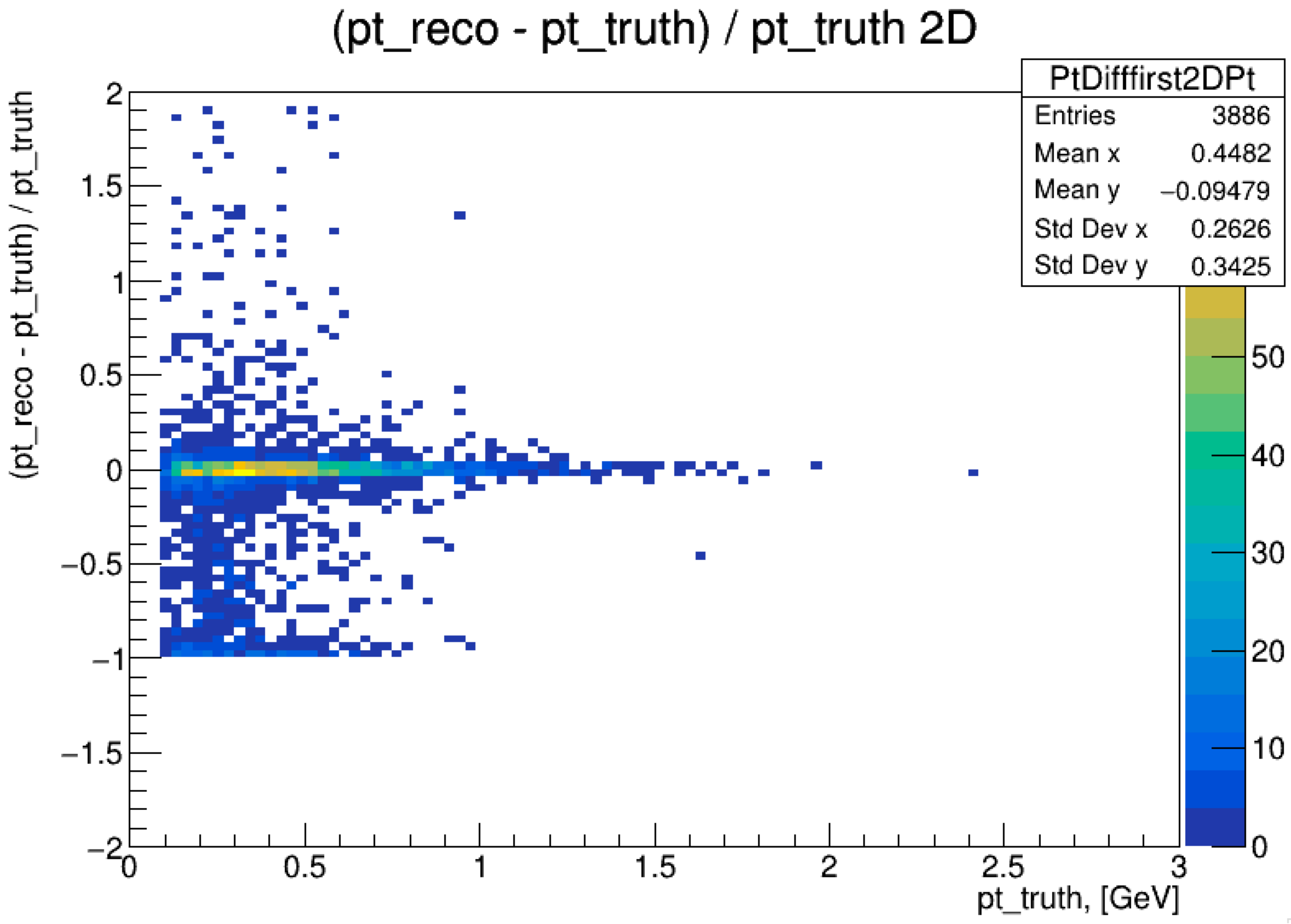


Fig. 33 - Occupancy of the 15th layer in Kr-Kr collisions

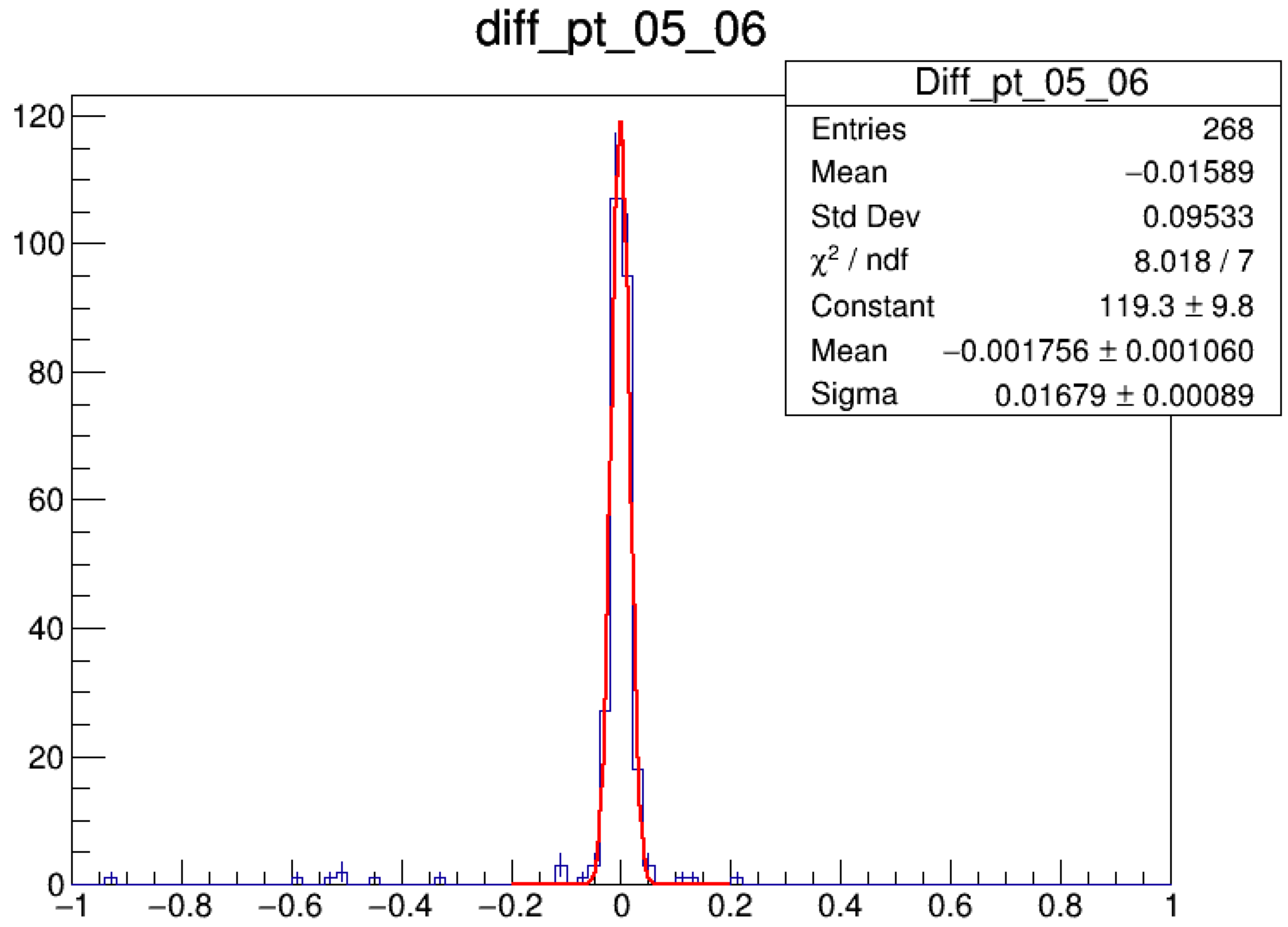
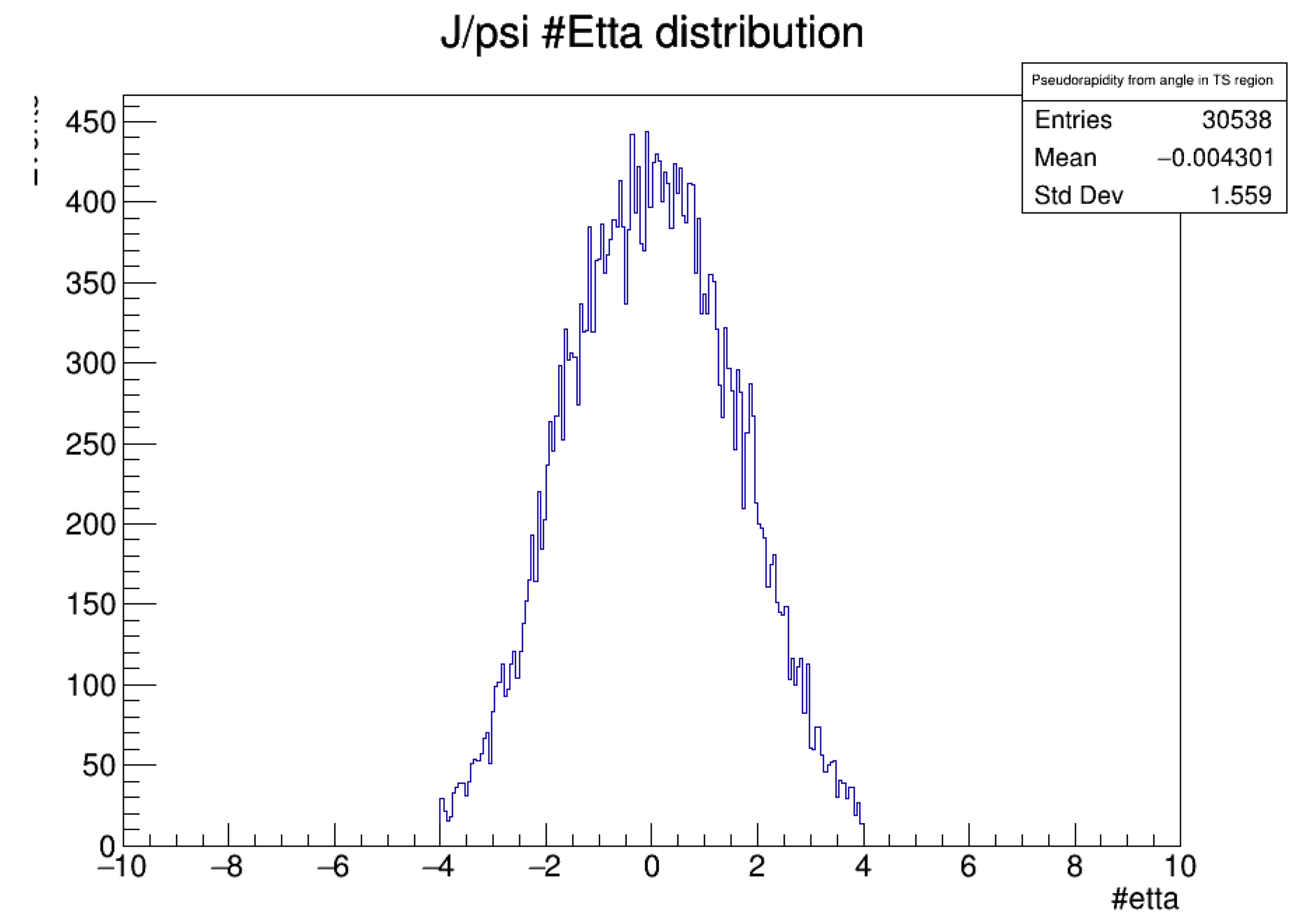


Fig. 34 - Fit results for momentum reconstruction accuracy calculations

Particles parameters from the generator



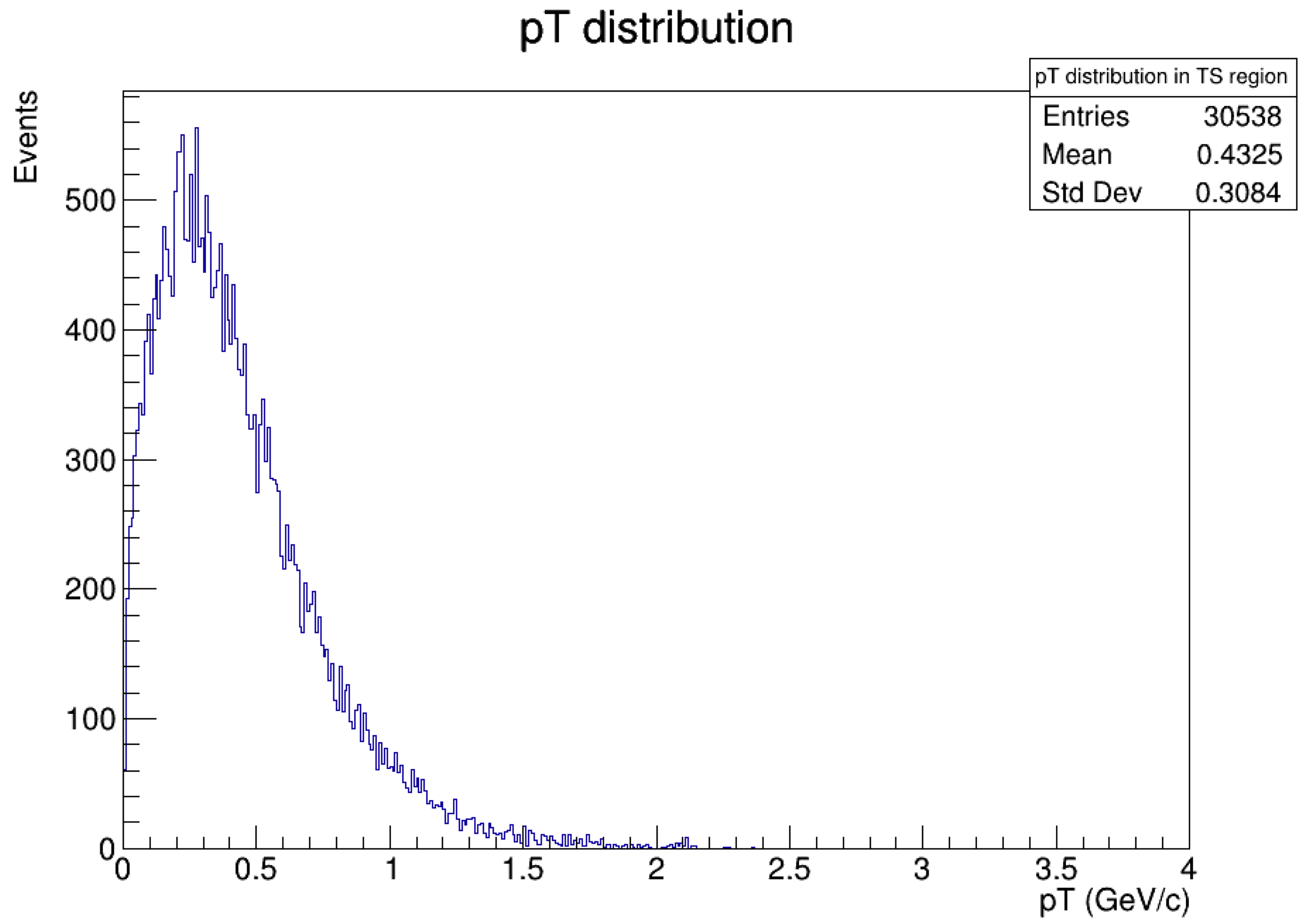
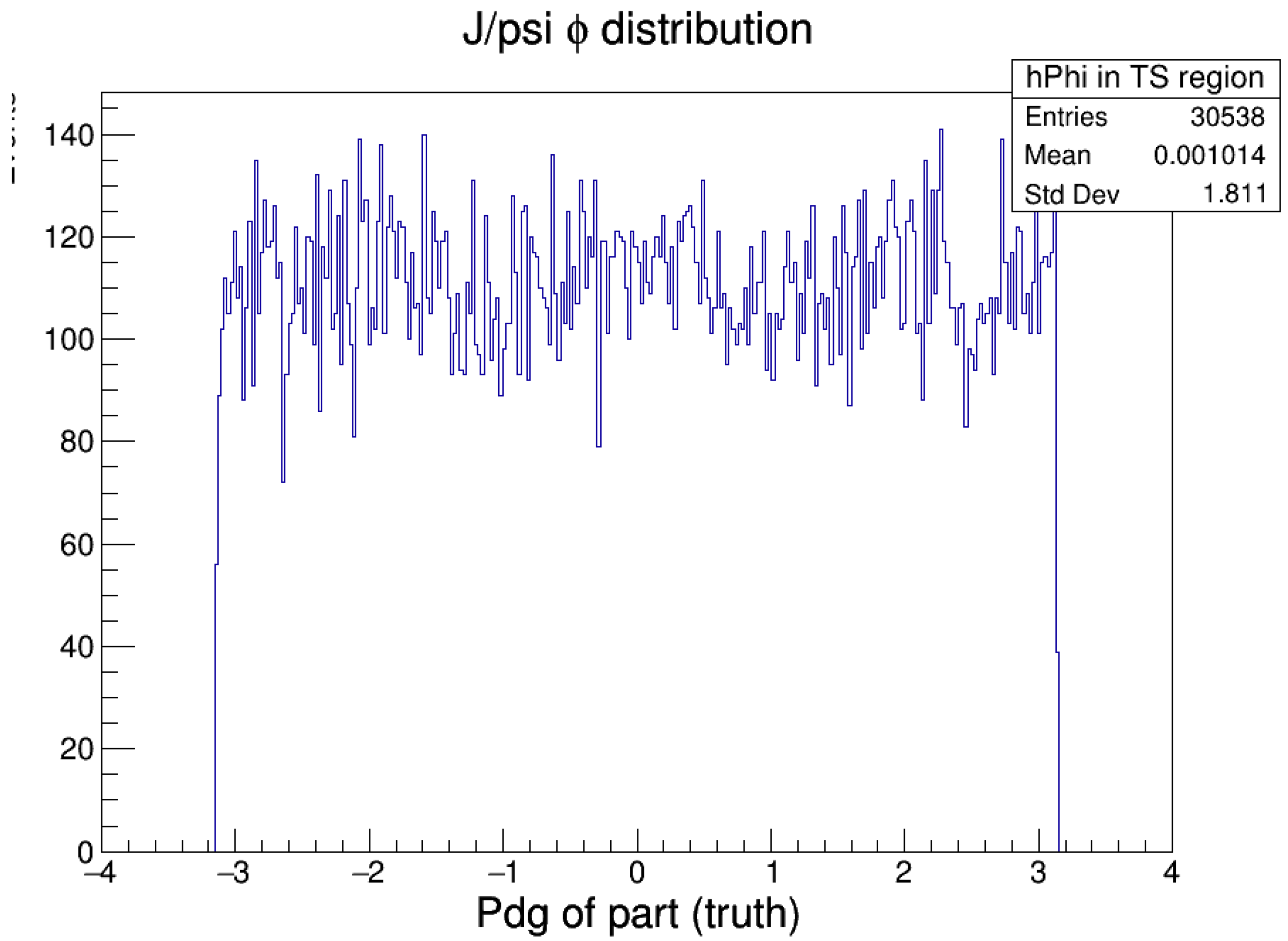
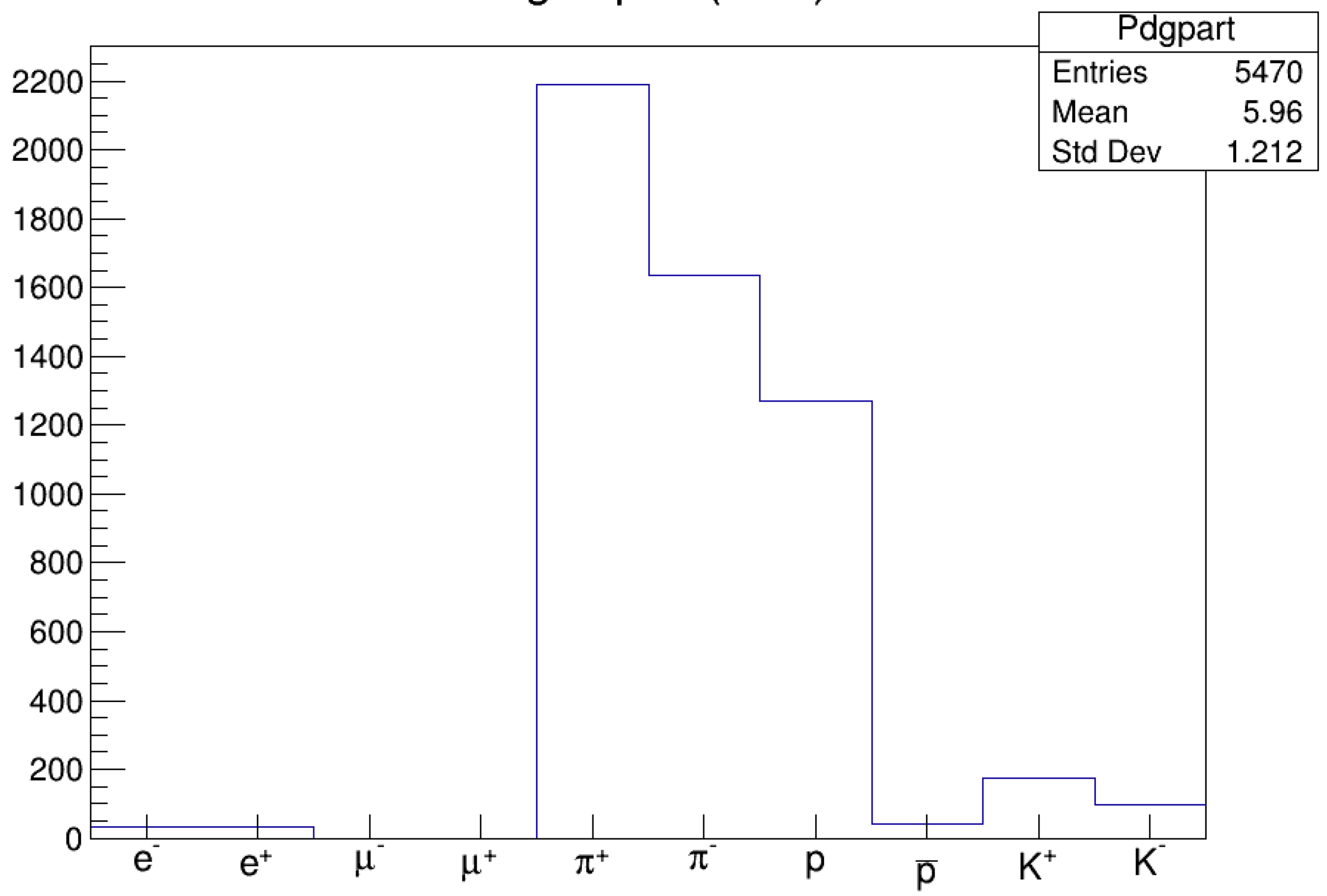
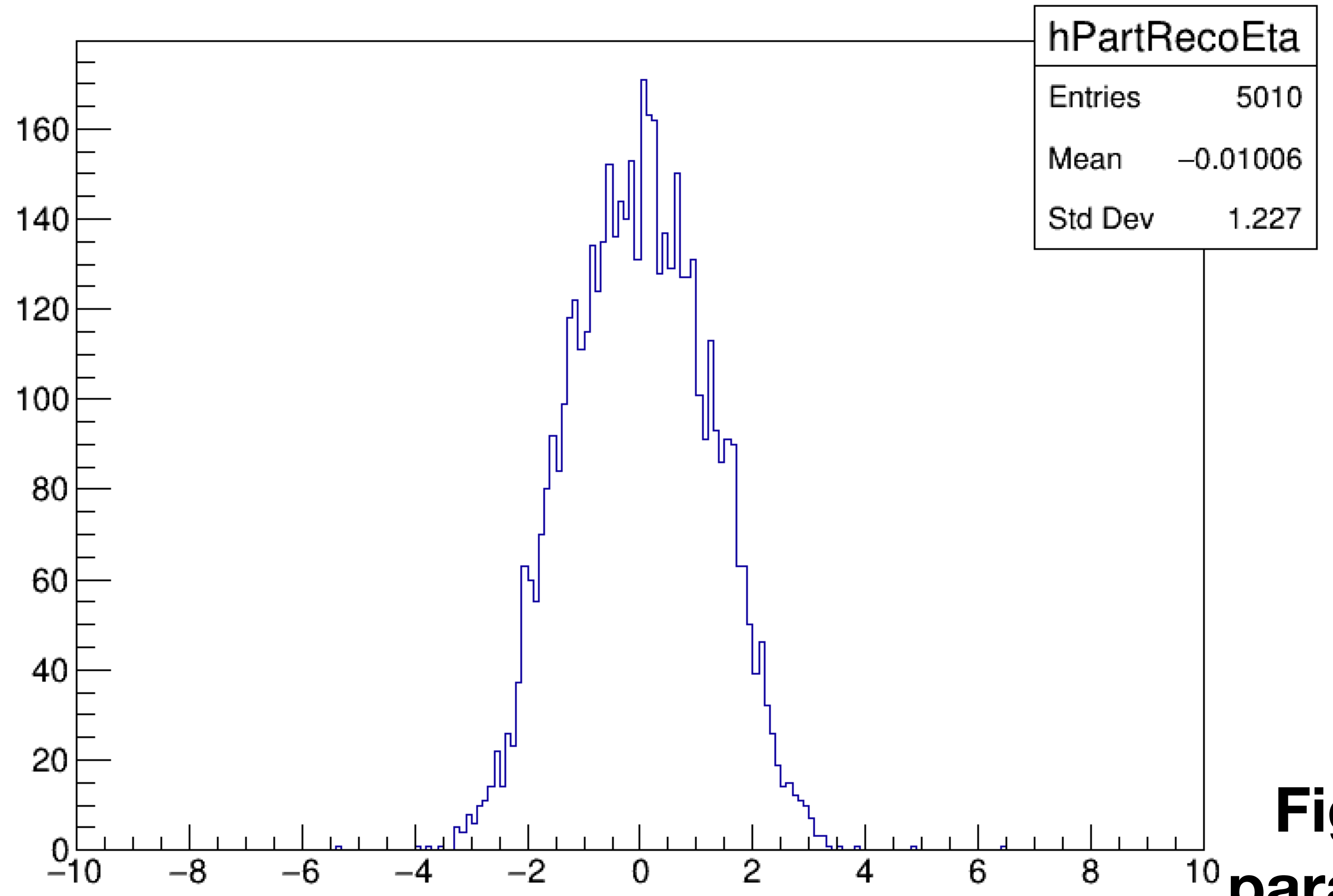


Fig. 35 - Particles parameters from the generator





Particles parameters from the reconstruction



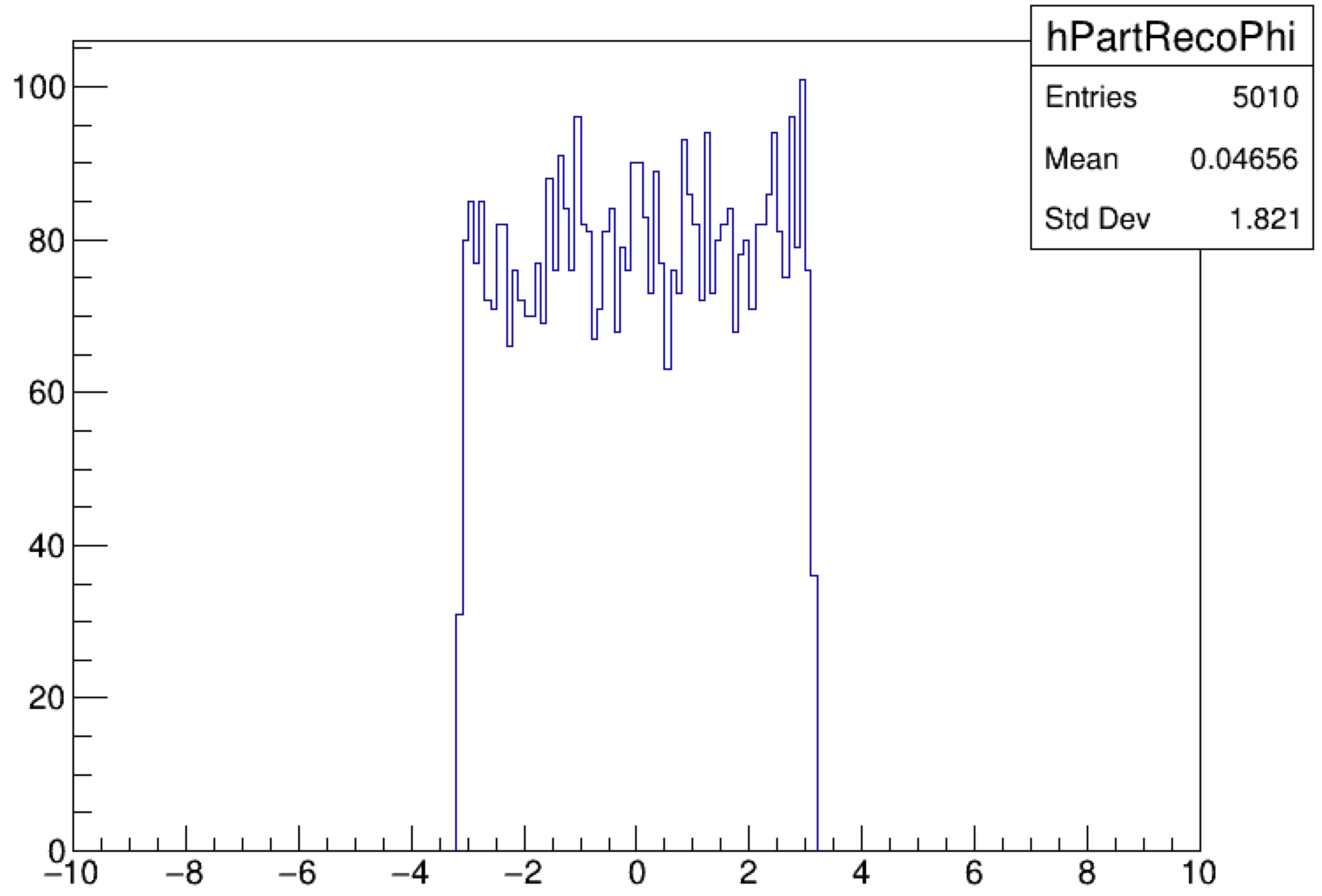
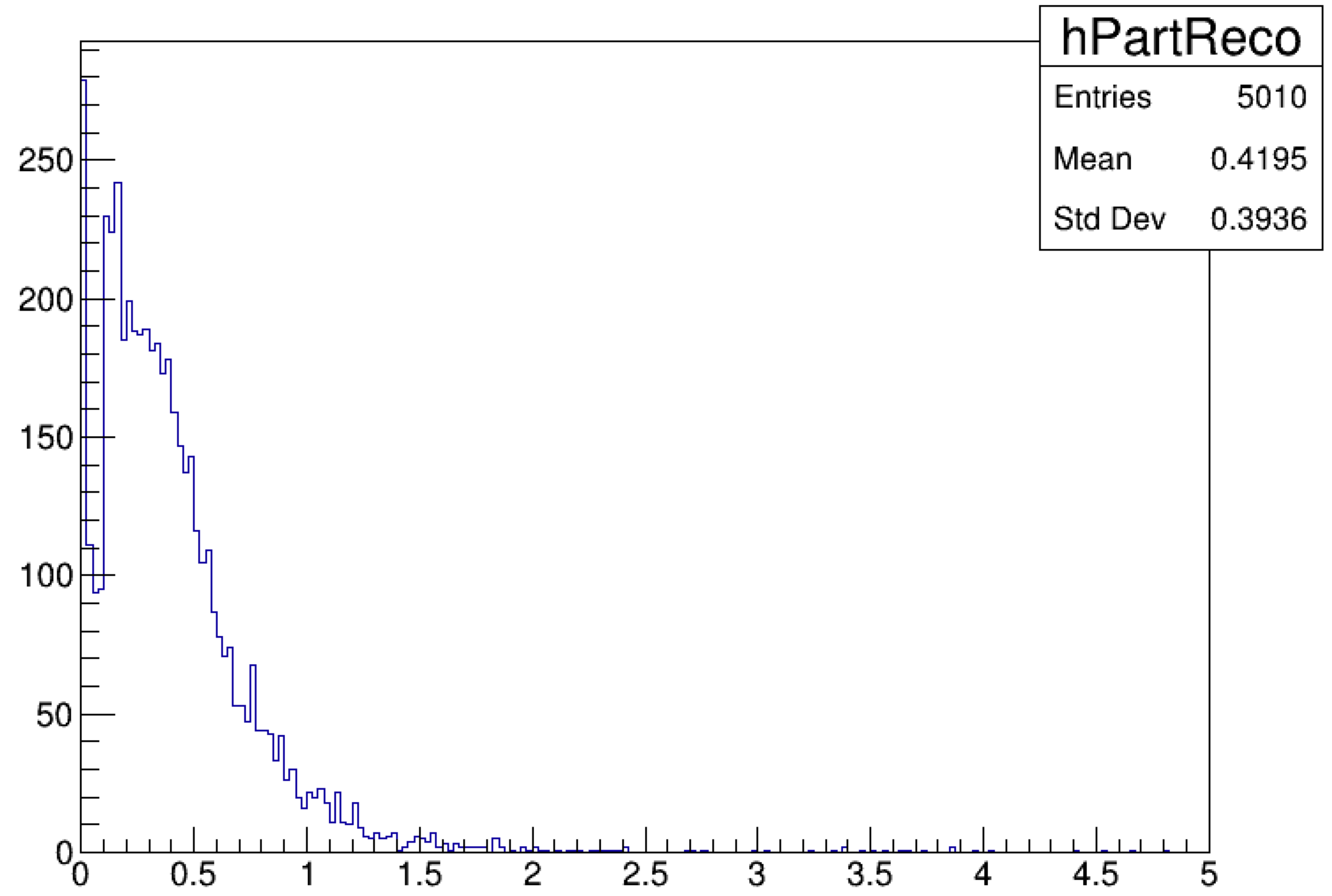
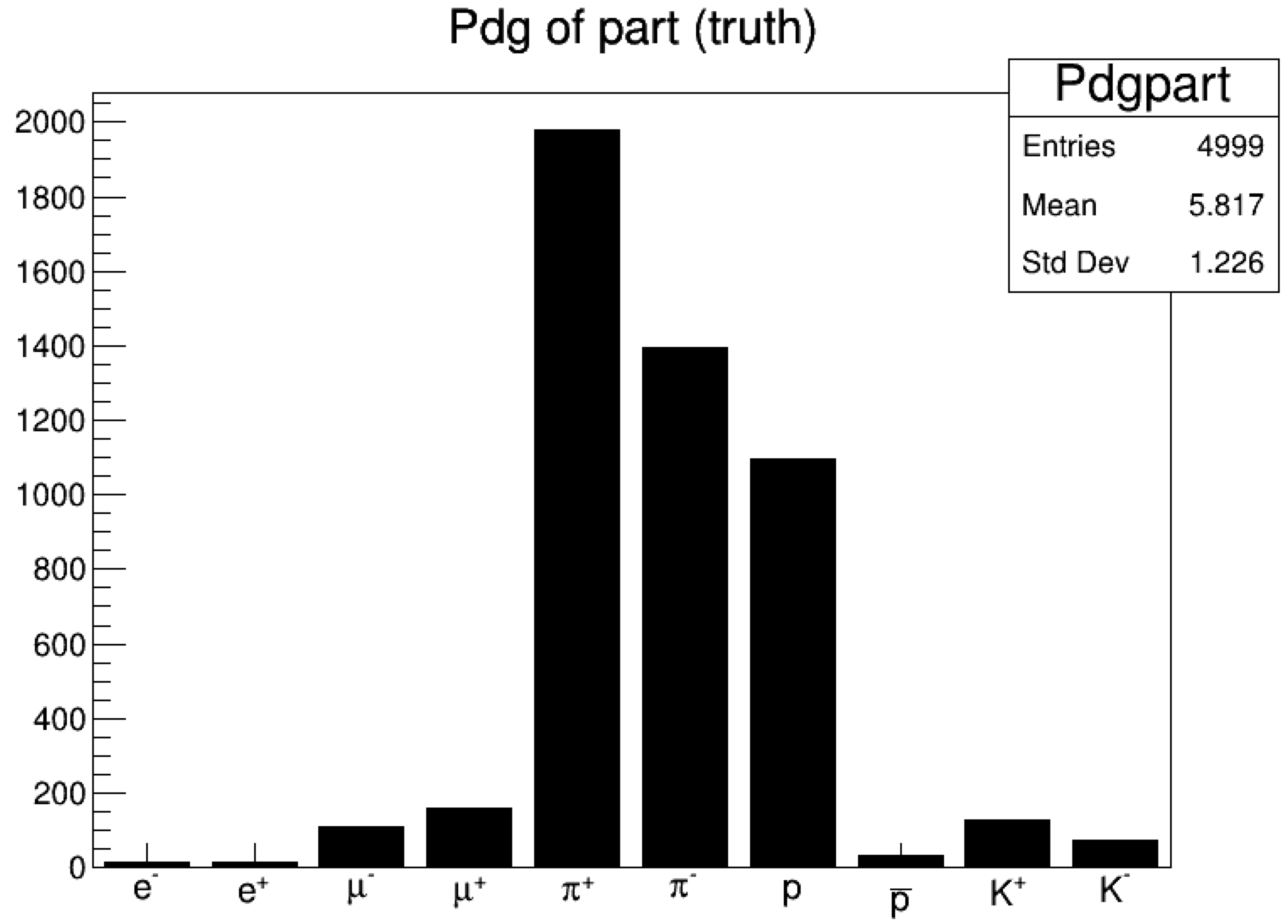


Fig. 36 - Particles parameters from the reconstruction





Different hit rate colormaps (p-p)

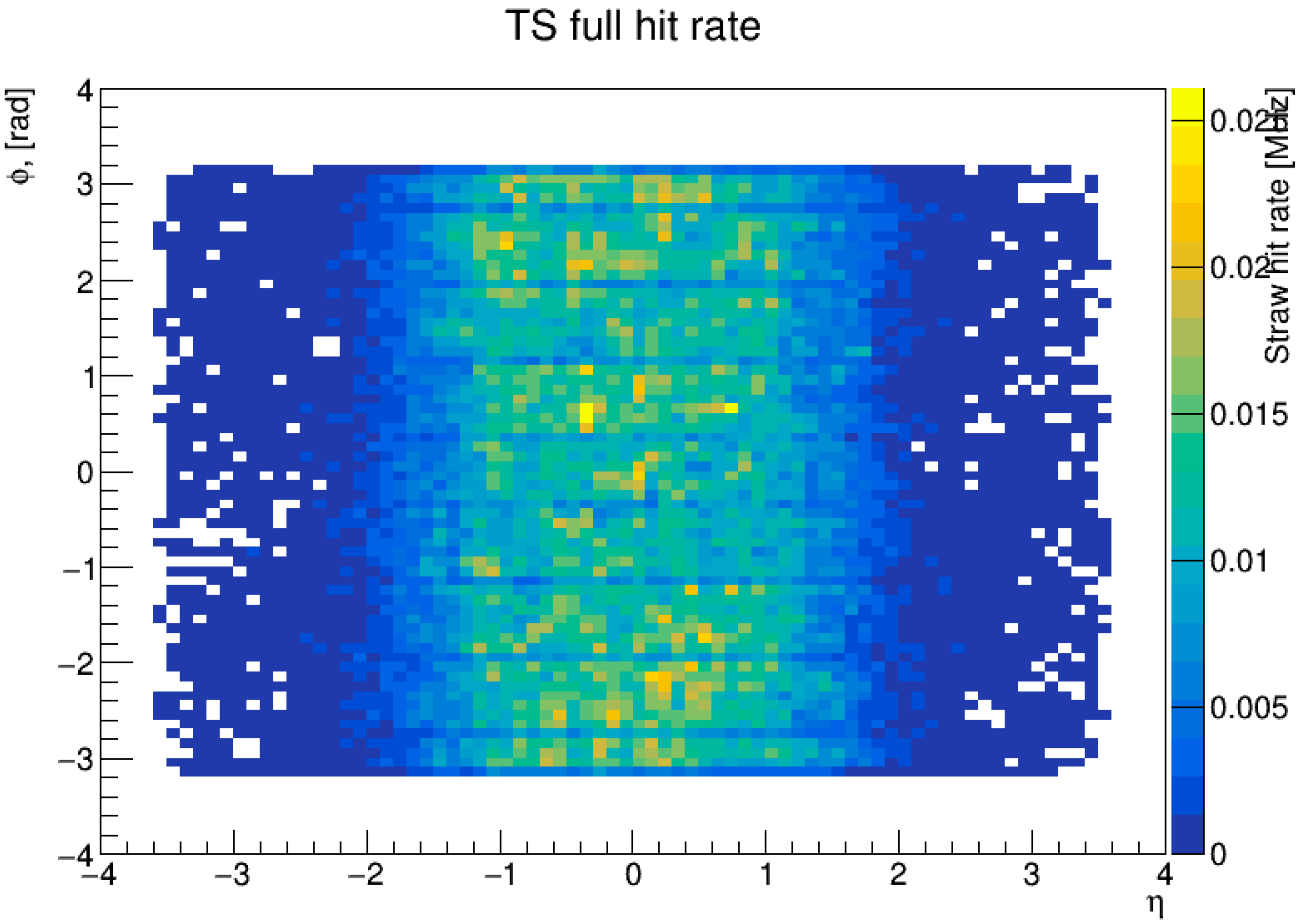


Fig. 37 - Different hit rate colormaps (p-p)

Different hit rate colormaps (O-O)

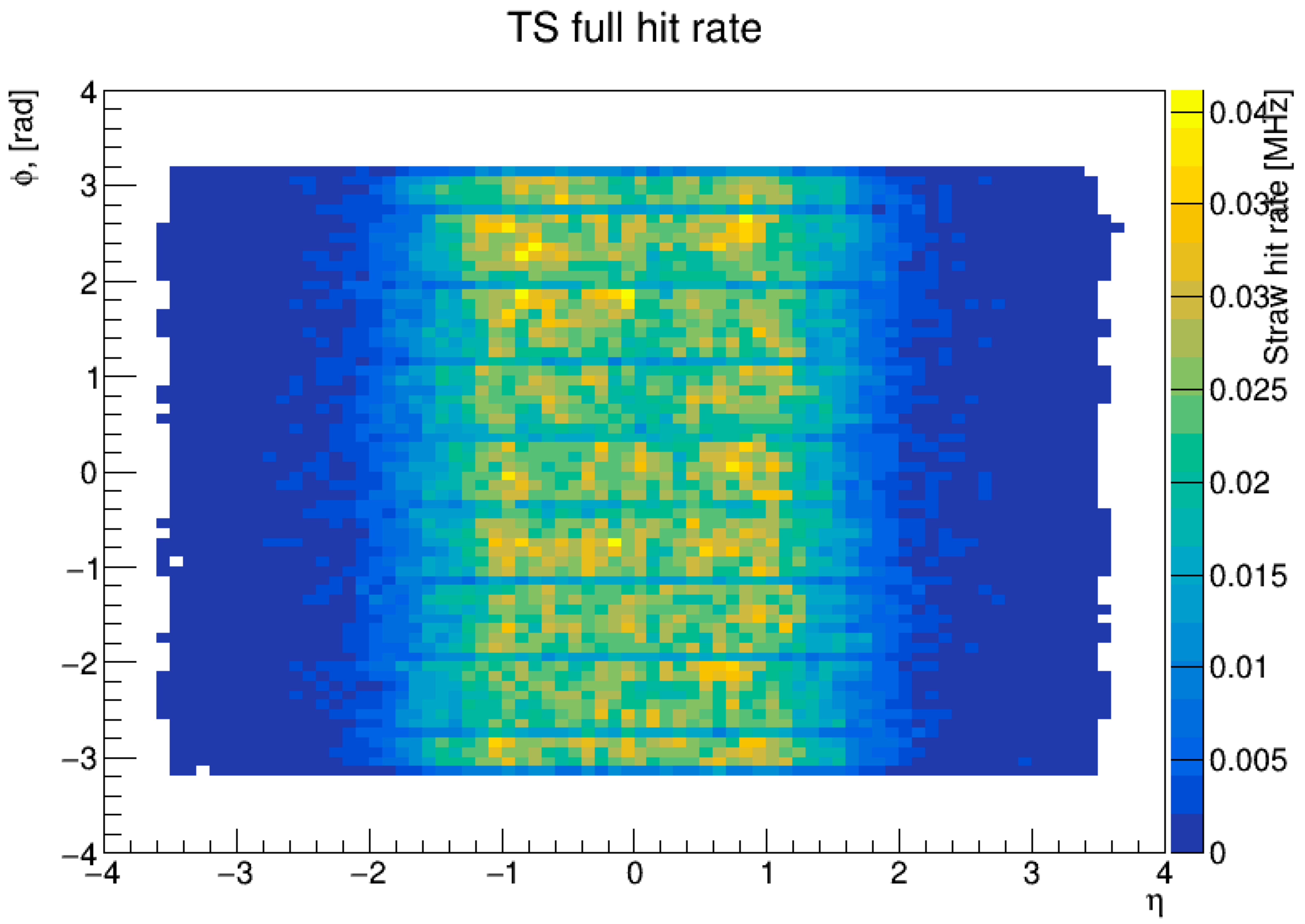


Fig. 38 - Different hit rate colormaps (O-O)

Different hit rate colormaps (Kr-Kr)

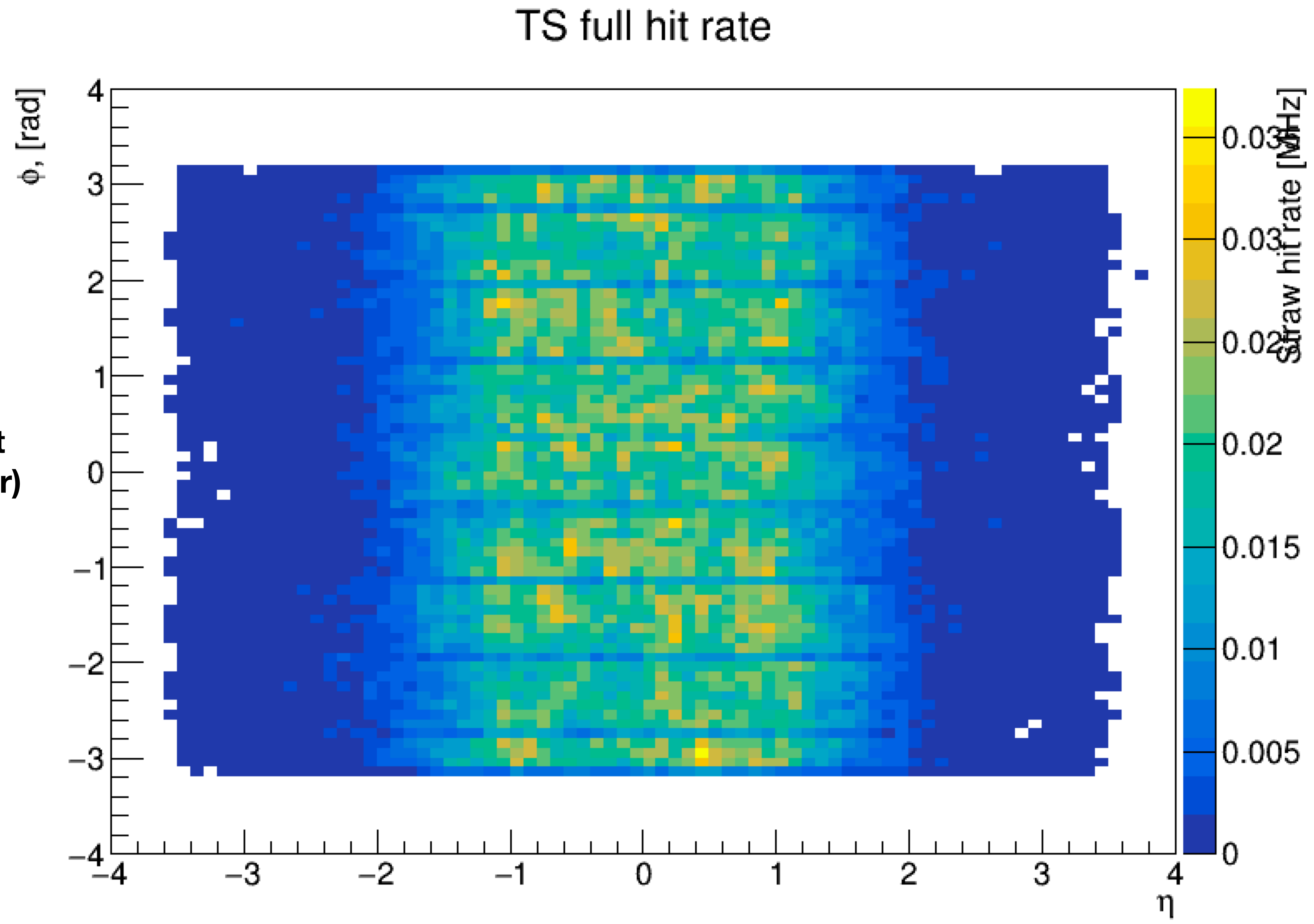


Fig. 39 - Different hit rate colormaps (Kr-Kr)

Different hit rate colormaps (Xe-Xe)

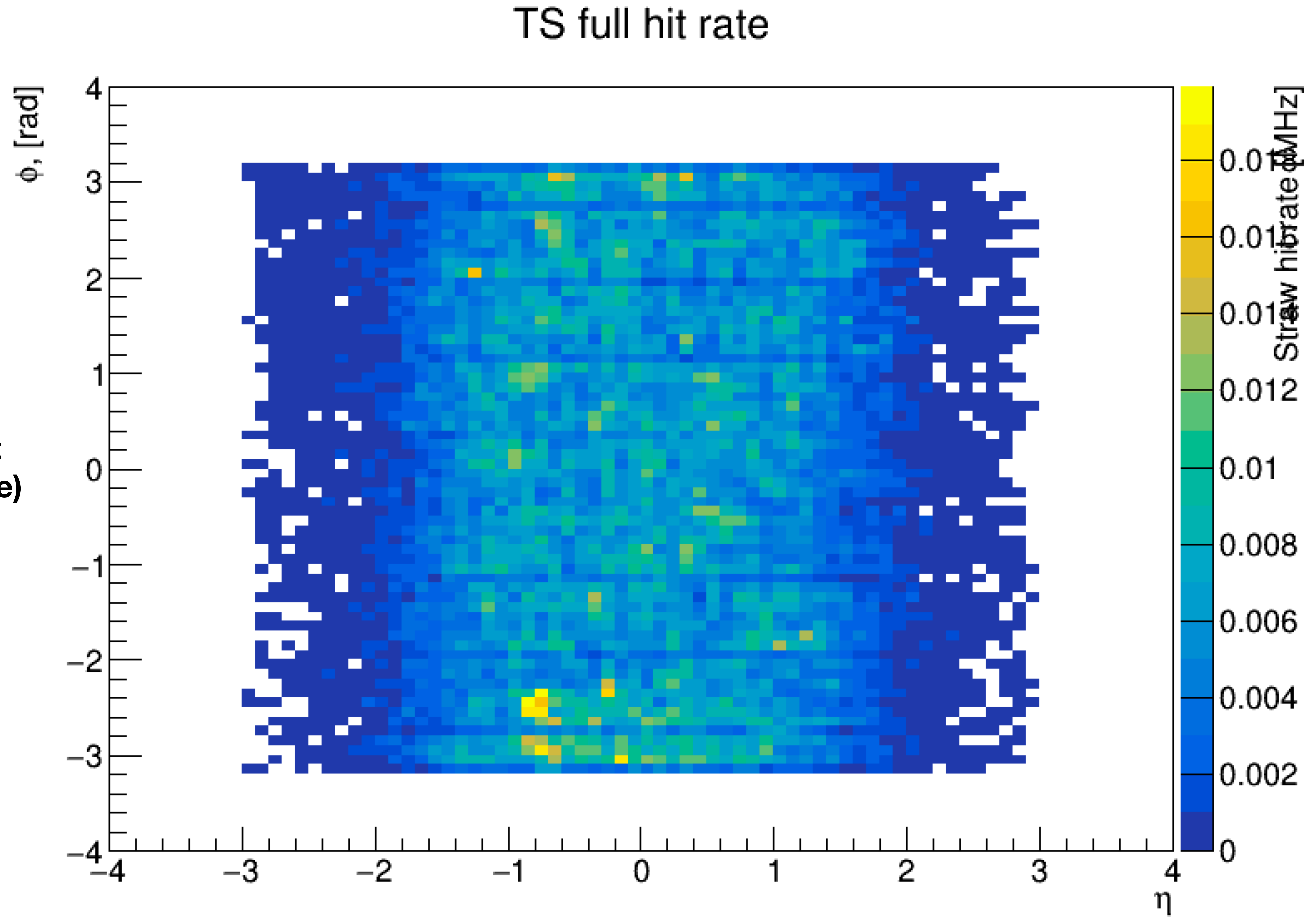


Fig. 40 - Different hit rate colormaps (Xe-Xe)