Simulation study of the SPD Straw Tracker performance limits for ion–ion collisions at NICA

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SPD Experiment

1st Phase of SPD:

- Subsystems: Magnet, ST, BBC, MVD, ZDC
- Expected energies: up to $\sqrt{s} = 10\ GeV$ for p and up to $\sqrt{s_{NN}} = 10\ GeV$ for ions
- Expected luminosity: up to $L = 10^{31} cm^{-2} s^{-1}$
- **Possible to request ion-ion collisions**

Straw Tracker under high-load conditions:

- Key detector for track reconstruction in ion–ion collisions
- High particle multiplicity may cause signal overlap
- Front-end electronics have finite signal processing time
- High detector load may affect reconstruction performance
- Planned for use at all stages of the SPD experiment

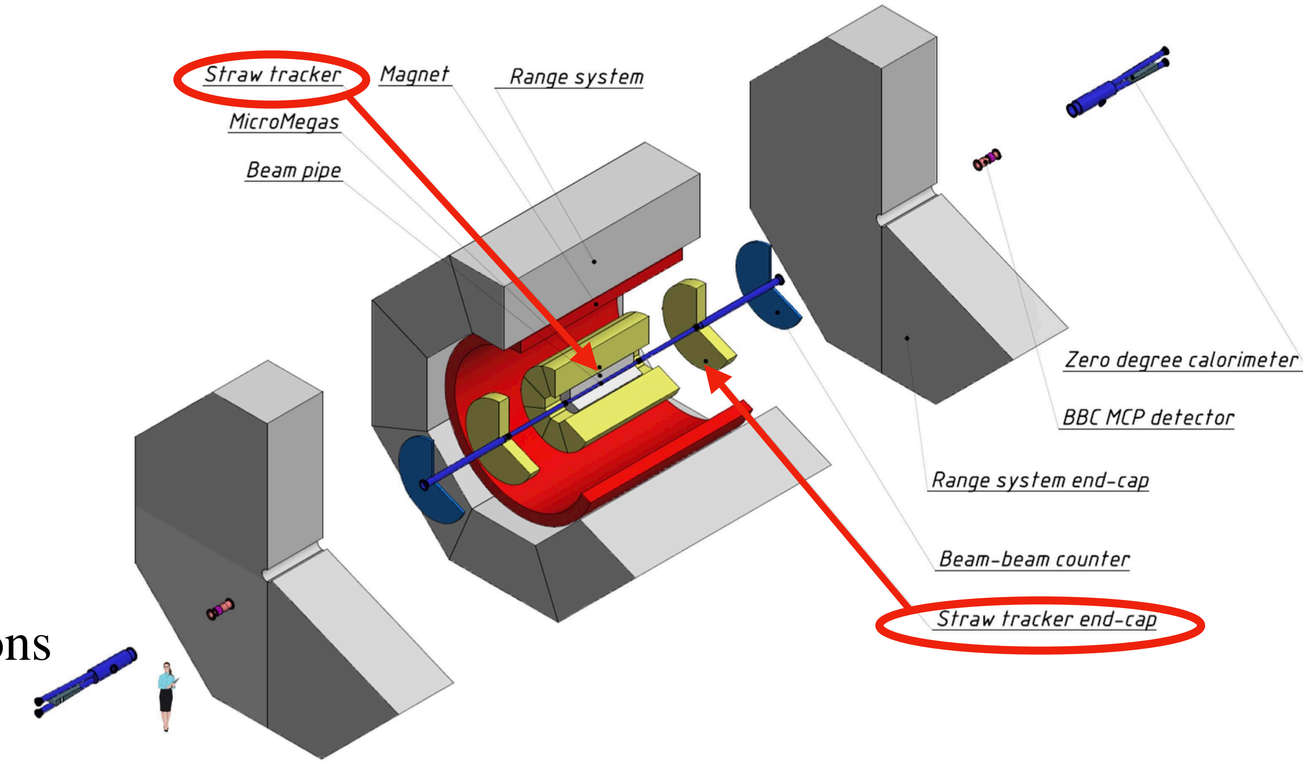


Fig. 1 - SPD Experiment (1st Phase)

Ion-ion program at SPD

Why an ion program?

- Provide an extraction of ‘nuclear PDF’ from ion-ion collisions data
- Study of quark-gluon matter properties in small systems
- Heavy quark production

Why SPD?

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

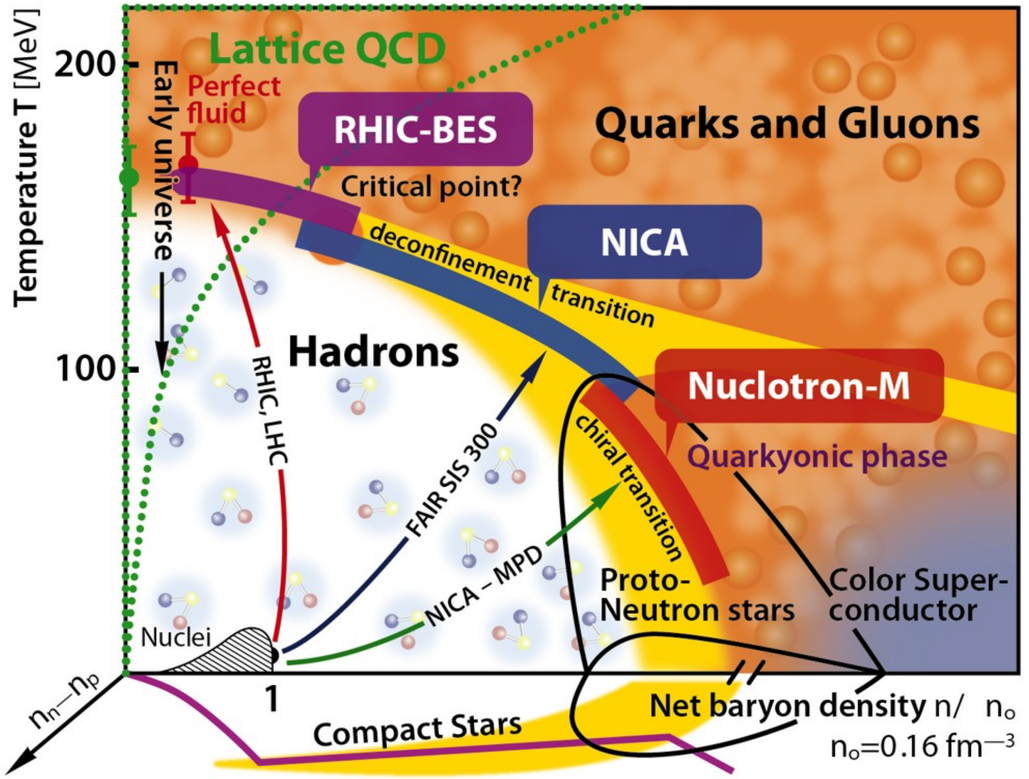


Fig. 2 - NICA region in the QCD phase diagram

Straw Tracker (ST) & purpose of the study

Design:

1. **Barrel:** Comprises 6 modules, each containing approximately 3,860 straw tubes (both straight and inclined, d=10mm), totalling around 23,160 tubes, supposed for tracking
2. **End-caps:** Each contains 8 coordinate planes (disks) utilizing straw tubes (d=10mm) with various orientations and lengths (16 in total), supposed for tracking & identification

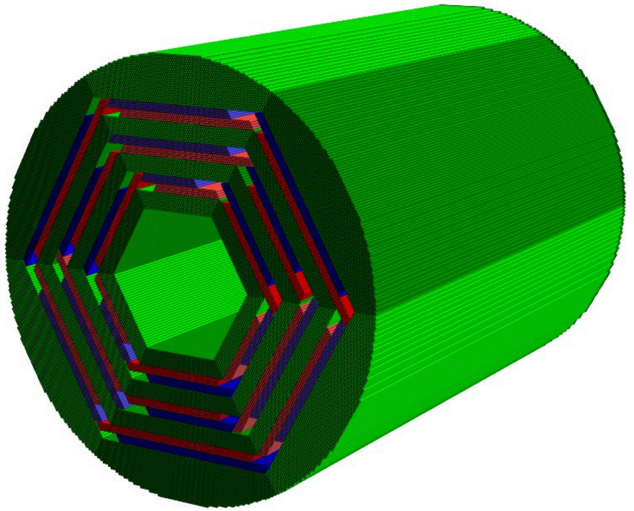


Fig. 3 - Straw Tracker (barrel)

Purpose of the study:

- Evaluation of the SPD tracking efficiency and momentum resolution under different NICA collision conditions to determine the accuracy and kinematic limits of physics measurements.

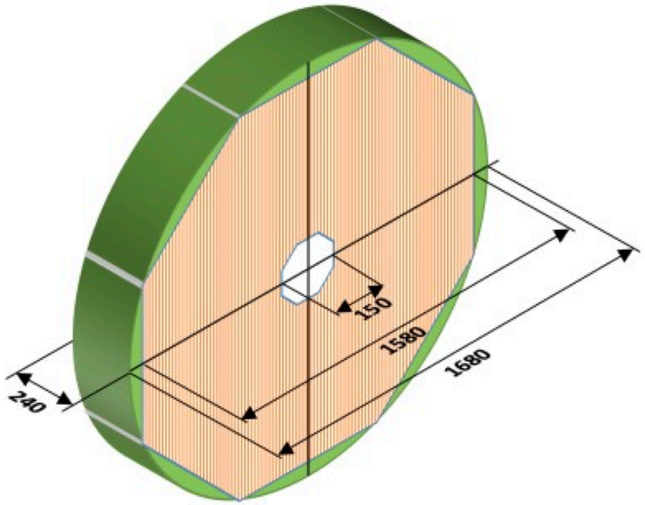


Fig. 4 - Straw Tracker (end-cap)

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

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

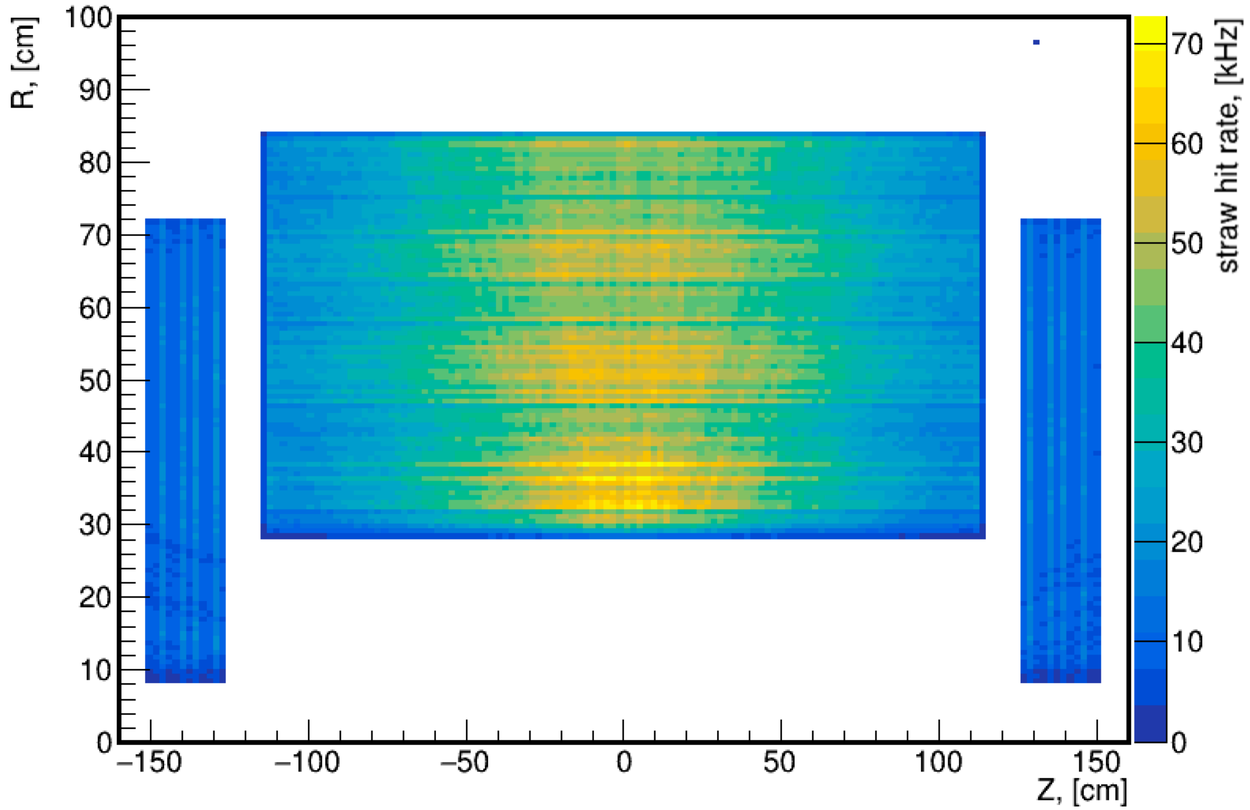
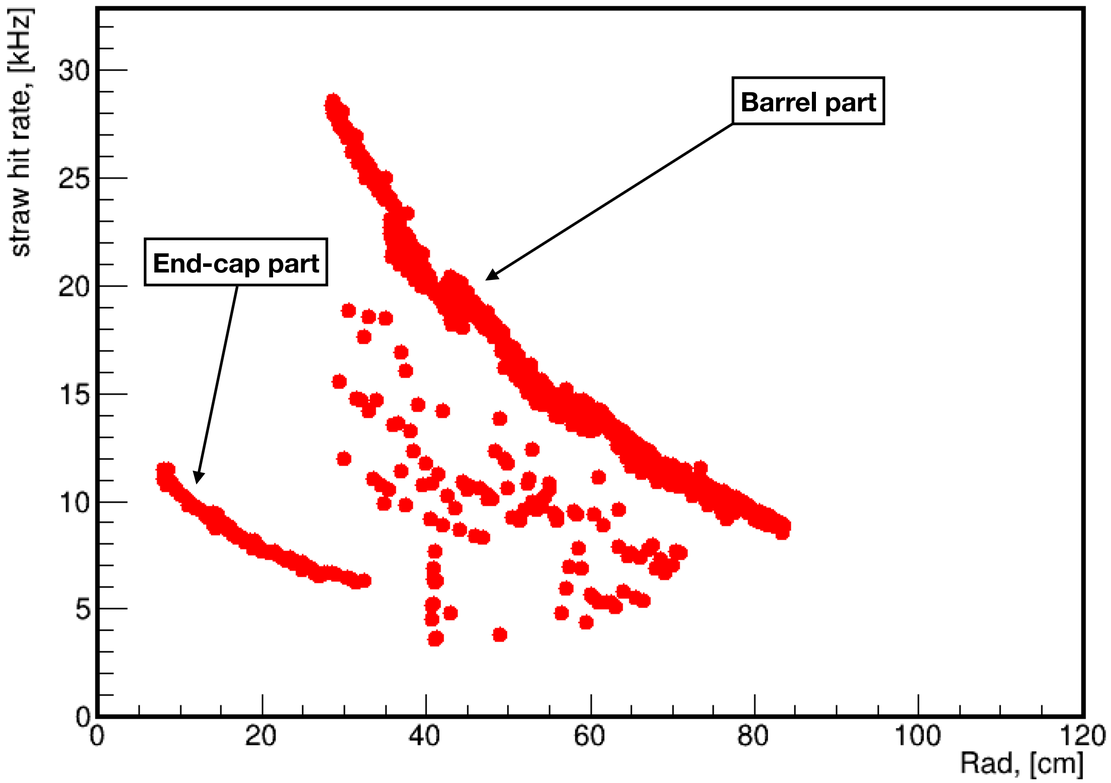


Fig. 6 - Average number of hits per straw in the ST in p-p collisions



<u>Simulation parameters:</u>

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 48 000 p-p collisions
- Minimum bias
- Interaction rate (for colored Z-axis) = 400 kHz

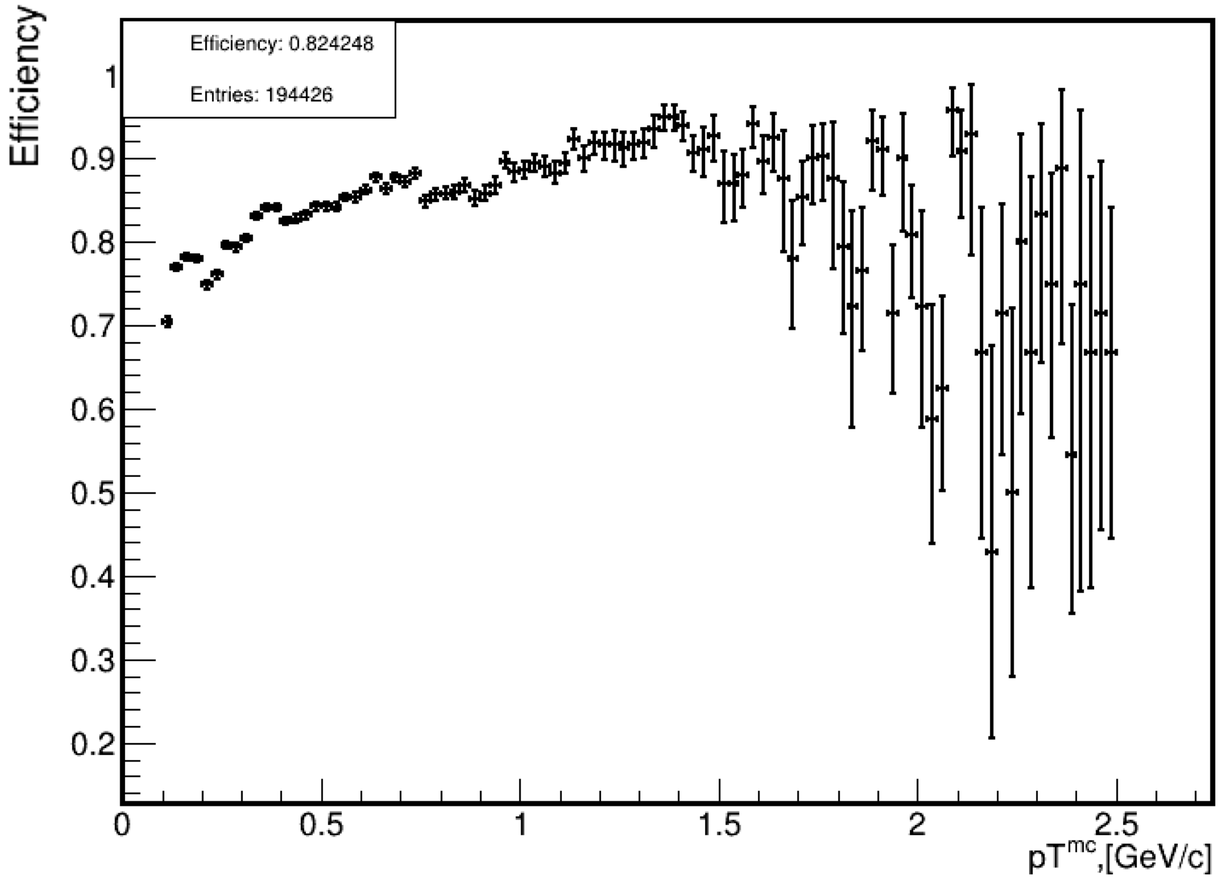
The isolated points are binning artifacts; the chosen binning provides a clearer visualization of the detector geometry.

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

Reconstruction efficiency in p-p collisions

Here and below, the reconstruction efficiency refers specifically to the performance of the **track reconstruction algorithm**. A reconstructed track is considered successfully matched to an MC track if more than a half of its hits correspond to the same MC track. Thus, this definition does not include effects such as the efficiency of the subsequent track fitting procedure.

Fig. 7 - Efficiency vs pT^{MC}



Efficiency (p-p) ~ 82.4%

Simulation parameters:

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- 48 000 p-p collisions
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

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

Fig. 8 - ST full hit rate (barrel и end-caps parts) in O-O collisions

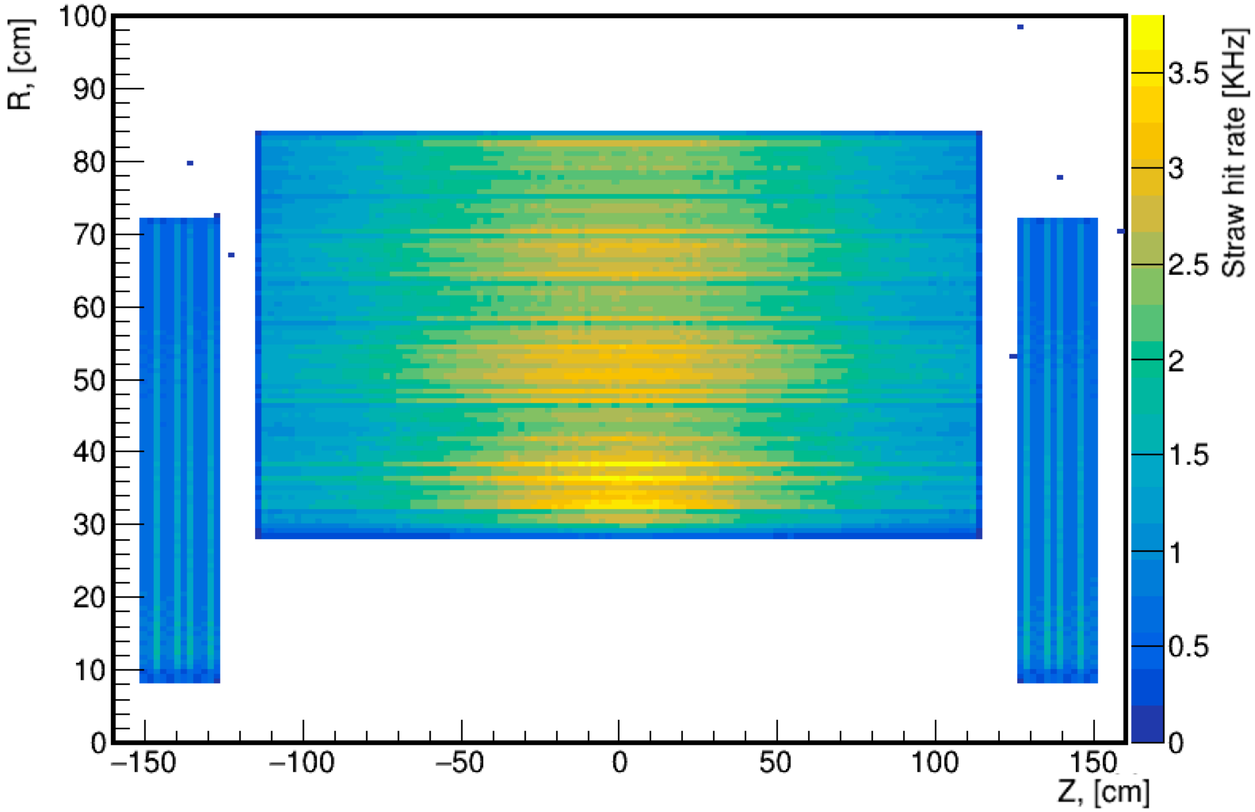
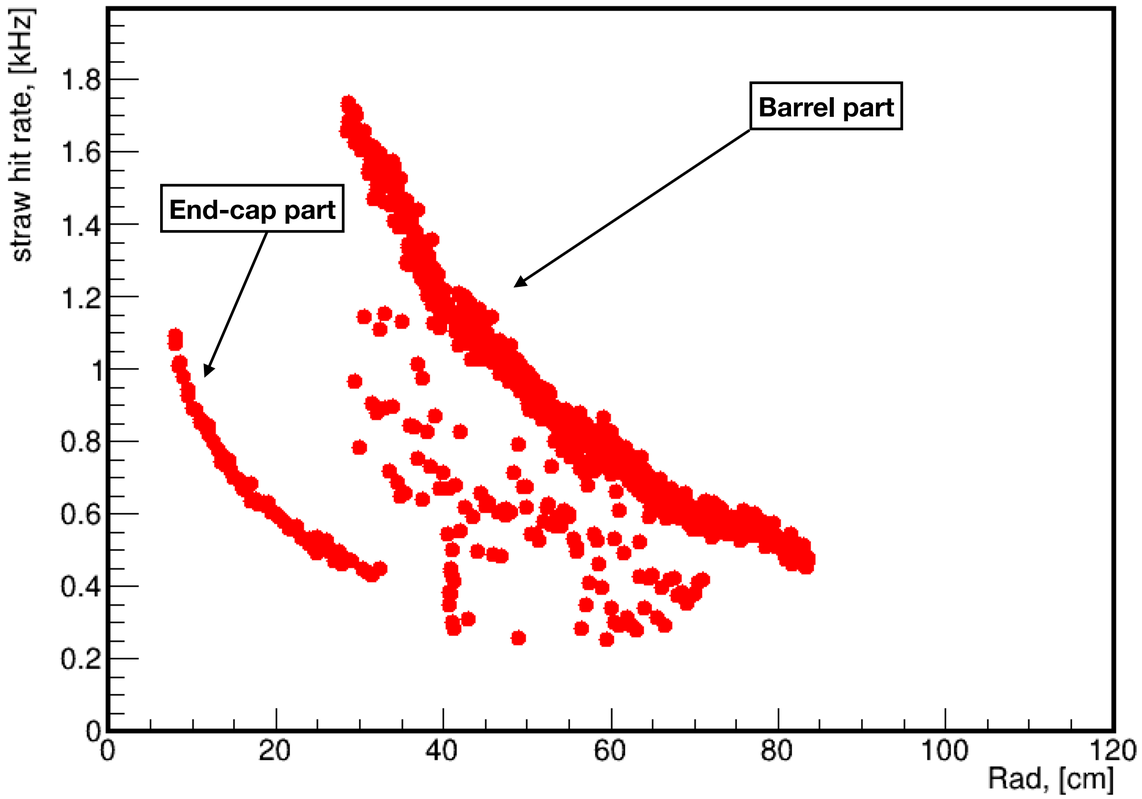


Fig. 9 - Average number of hits per straw in the ST in O-O collisions



The isolated points are binning artifacts; the chosen binning provides a clearer visualization of the detector geometry.

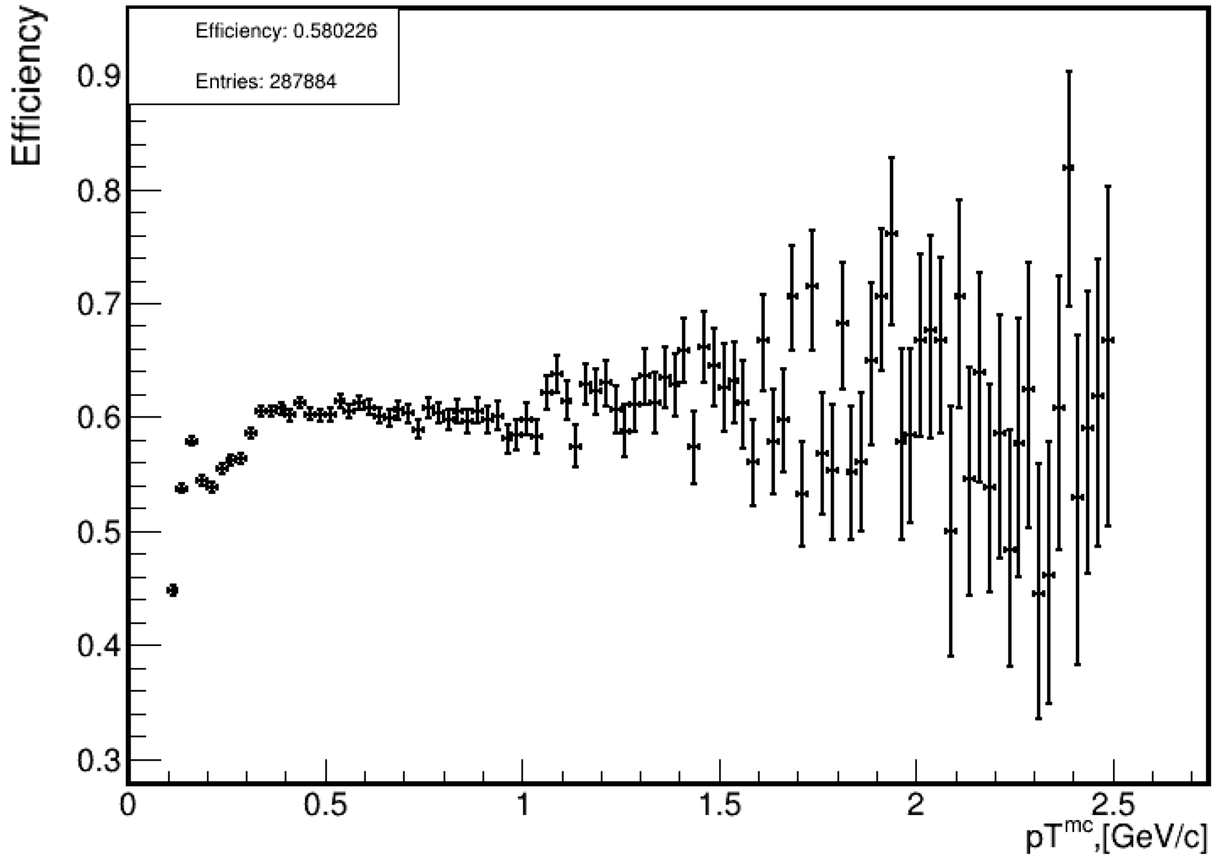
Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 25 000 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

Reconstruction efficiency in O-O collisions

Fig. 10 - Efficiency vs pT^{MC}



Efficiency (O-O) ~ 58.0%

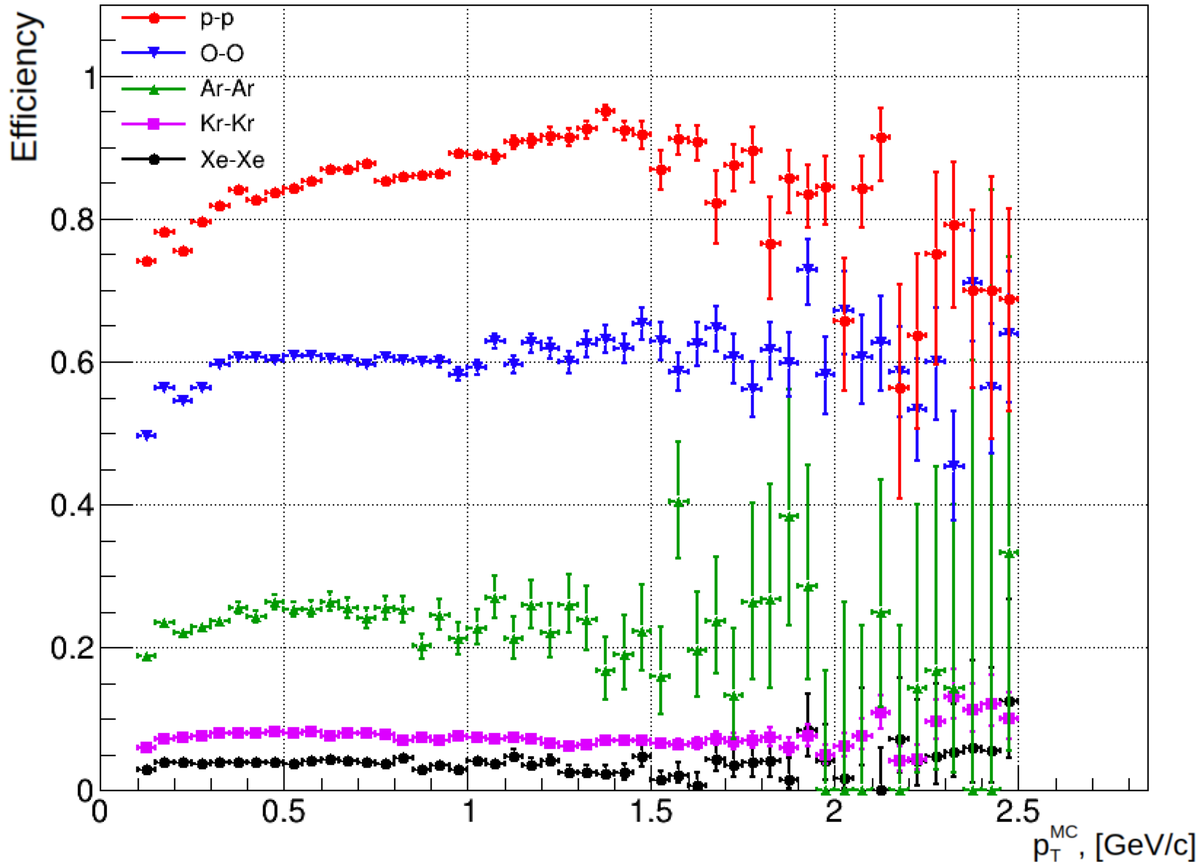
Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 25 000 O-O collisions (O_8^{16})
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Reconstruction efficiencies comparison

Fig. 11 - Reconstruction efficiencies comparison



The reconstruction efficiency decreases with increasing collision-system size (from p–p to heavier ion collisions)

Collision system	Number of events	Efficiency
p-p	48k	82.4%
O-O	75k	58.0%
Ar-Ar	40k	23.6%
Kr-Kr	10k	7.5%
Xe-Xe	10k	3.8%

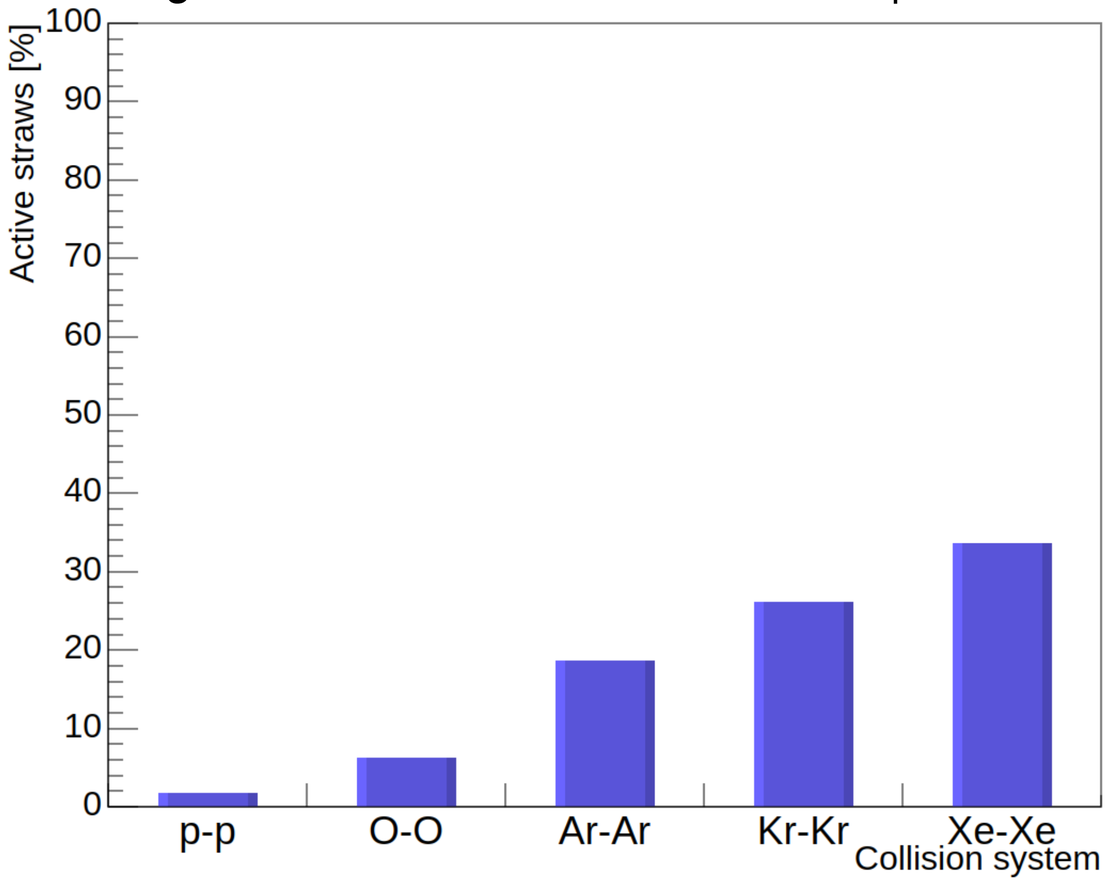
Simulation parameters:

- Event Generators: Pythia8 & UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- p-p, O-O, Ar-Ar, Kr-Kr and Xe-Xe collisions
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Fraction of fired straw tubes comparison

Fig. 12 - Fraction of fired straw tubes comparison



The fraction of fired straw tubes increases with increasing collision-system size

Collision system	Number of events	Fraction of fired straws
p-p	48k	1.8%
O-O	75k	5.8%
Ar-Ar	40k	18.1%
Kr-Kr	10k	24.6%
Xe-Xe	10k	33.7%

Simulation parameters:

- Event Generators: Pythia8 & UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- p-p, O-O, Ar-Ar, Kr-Kr and Xe-Xe collisions
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Momentum resolution of the Straw Tracker in p-p collisions

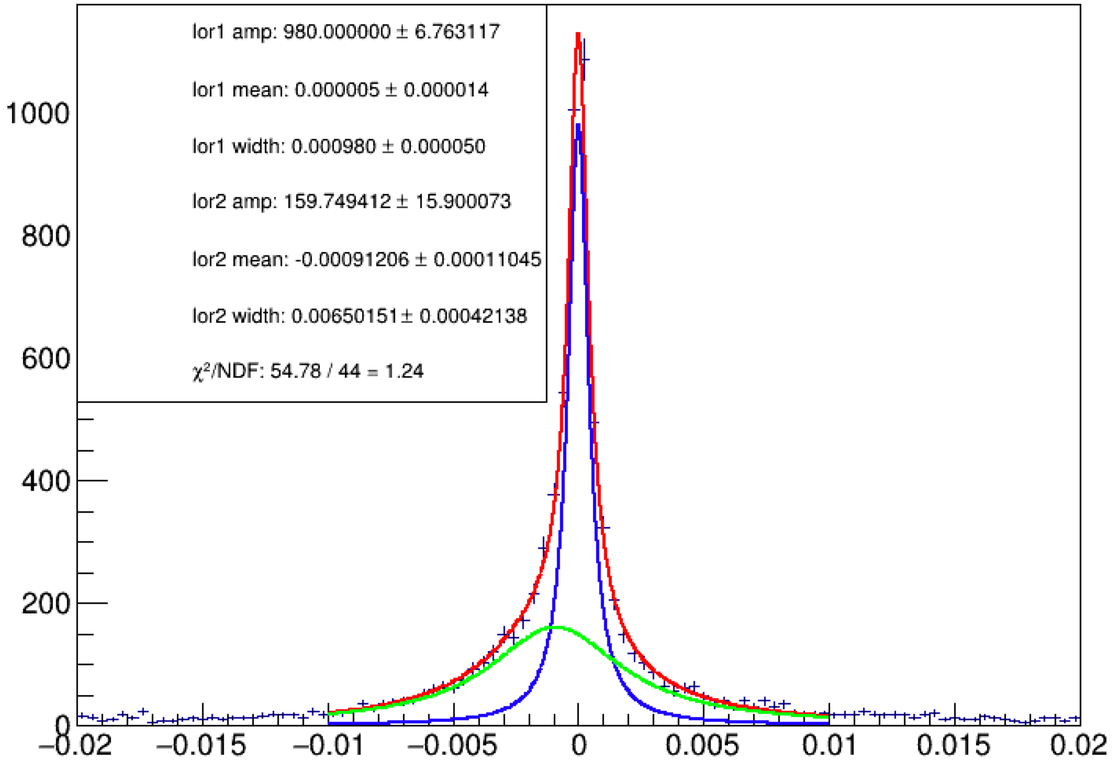


Fig. 13 - Fitting example of one of the pT regions

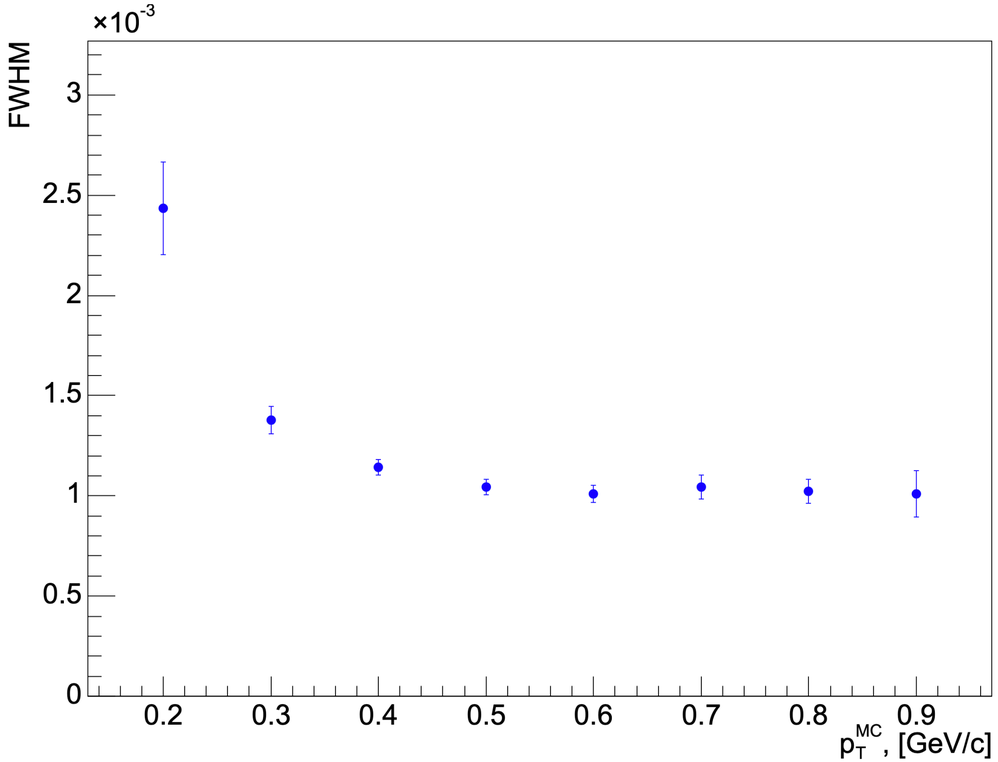


Fig. 14 - FWHM distribution of fits

- A region of particular interest for event reconstruction in the Straw Tracker is $-2 < \eta < 2$
- It is proposed to evaluate the relative momentum resolution from the $(pT_{reco} - pT_{MC})/pT_{MC}$ distributions
- These distributions were fitted with **Lorentz+Lorentz** functions, and the **FWHM** of the fits were taken as the measure of momentum resolution.

The simulation parameters are the same as it stated at the slide 8

Momentum resolution of the Straw Tracker in O-O collisions

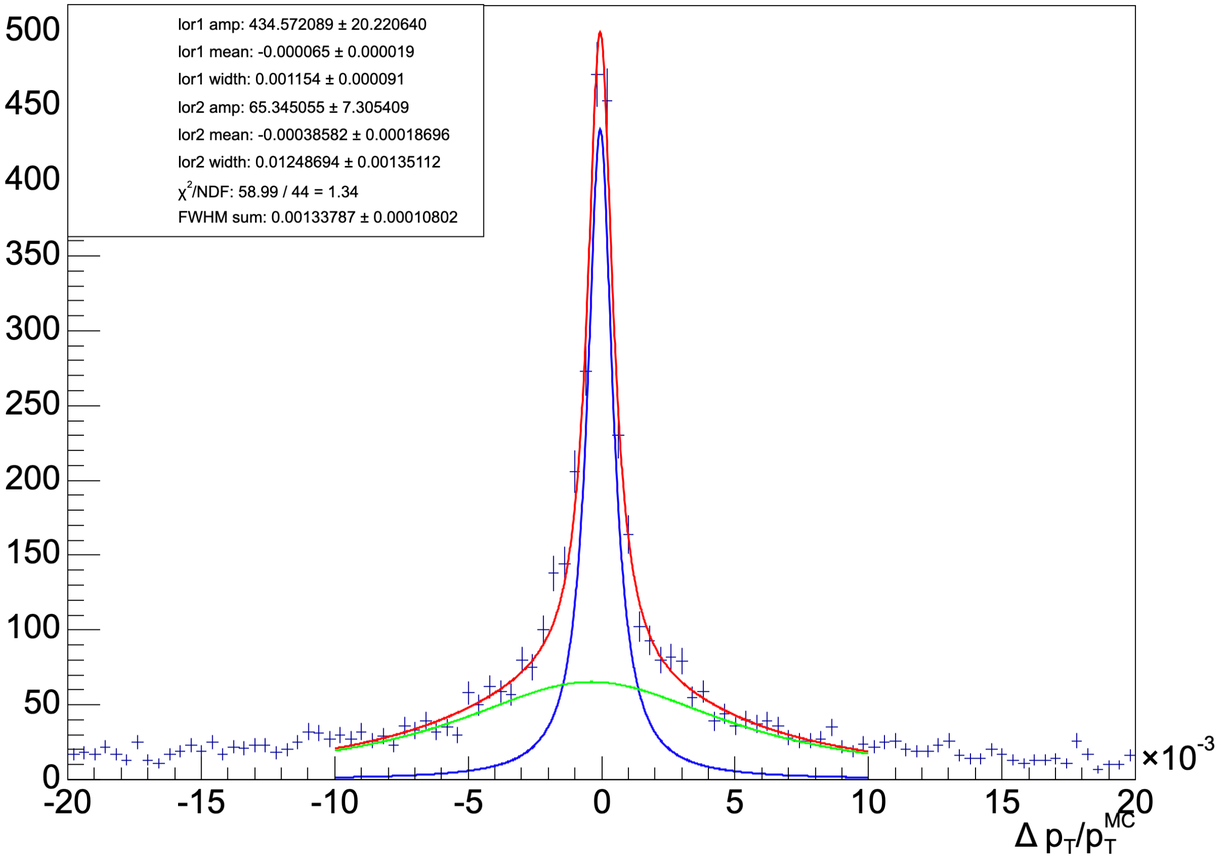


Fig. 15 - Fitting example of one of the pT regions

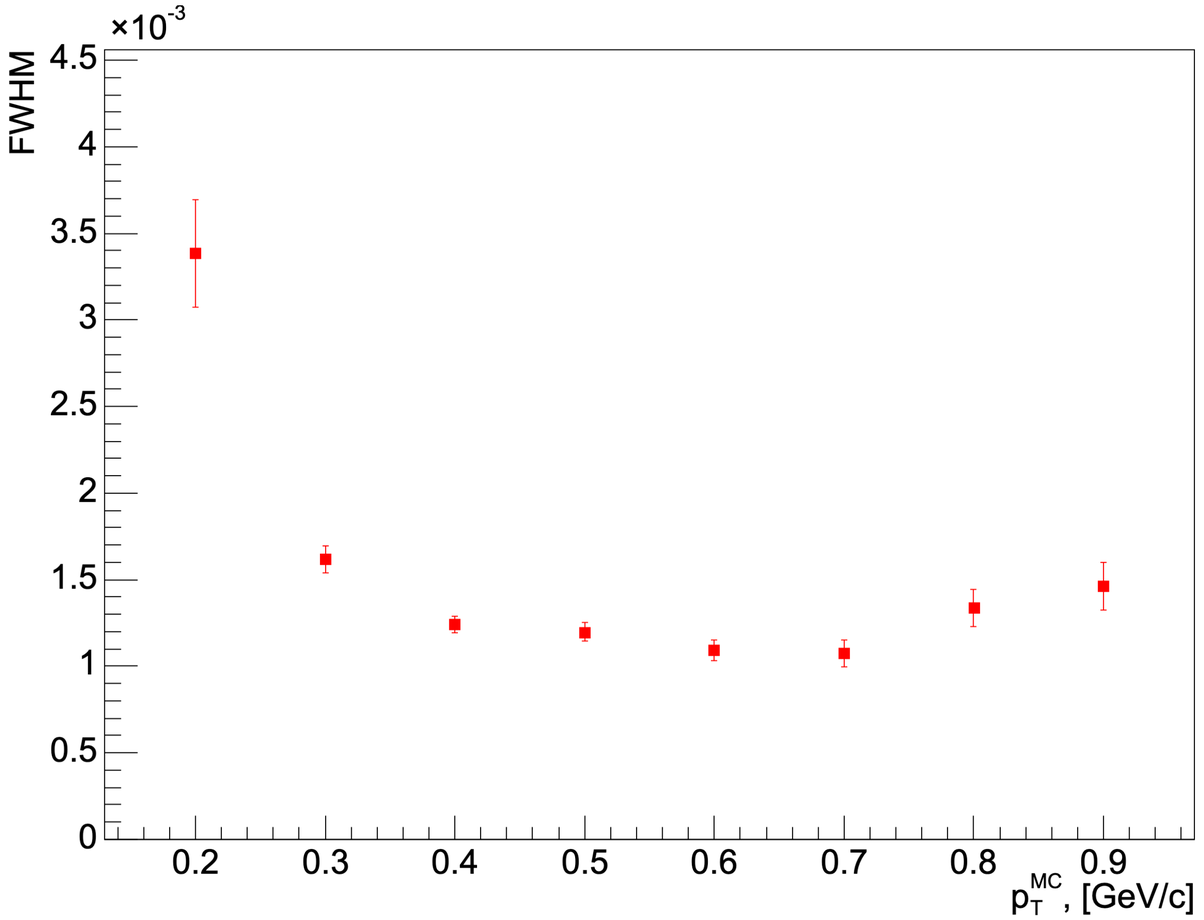


Fig. 16 - FWHM distribution of fits

The simulation parameters are the same as it stated at the slide 8 and 11

Momentum resolution of the Straw Tracker comparison

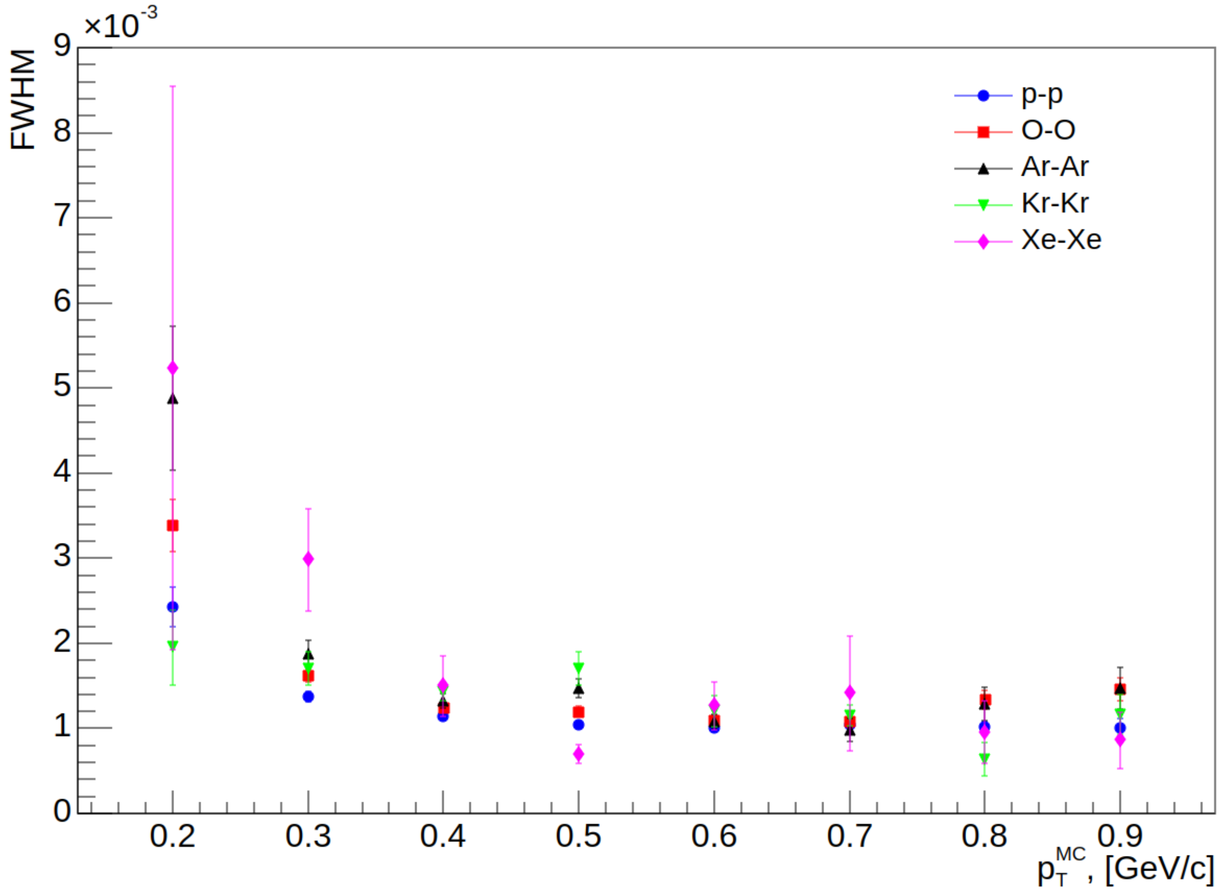


Fig. 17 - Momentum resolution of the Straw Tracker comparison

Collision system	Number of events
p-p	48k
O-O	75k
Ar-Ar	40k
Kr-Kr	10k
Xe-Xe	10k

The momentum resolution remains approximately the same for all collision systems, with only minor variations.

The simulation parameters are the same as it stated at the slide 8

Implications for hyperon polarization studies

$$\Lambda \rightarrow p + \pi^{-}$$
$$\bar{\Lambda} \rightarrow \bar{p} + \pi^{+} \quad \textbf{(1)}$$

The reconstruction of hyperon decays, such as stated above, relies on efficient reconstruction of charged daughter tracks.

Increasing detector occupancy in heavy-ion collisions may reduce tracking efficiency and increase the complexity of secondary-vertex reconstruction.

Further studies are needed to evaluate hyperon reconstruction efficiency and the feasibility of polarization measurements.

Conclusions

- Total occupancy maps of the Straw Tracker and average number of fired straws were obtained for both proton-proton and different ion-ion collisions (O-O, Ar-Ar, Kr-Kr, Xe-Xe) with new updated simulation parameters (**6-module ST geometry, UrQMD 4.0, new reconstruction algorithms, multiple detector subsystems enabled**)

- **Reconstructions efficiencies** were studied for different colliding systems, **showing degradation** with increasing atomic number of the colliding nuclei

- The obtained performance results will be used to assess the feasibility and sensitivity of physics studies at SPD, including hyperon production and other relevant processes in different collision systems.

Thank you for your attention!

BACK-UP SLIDES

ST full hit rate and straw occupancy in Ar-Ar collisions

Fig. 18 - ST full hit rate (barrel и end-caps parts) in Ar-Ar collisions

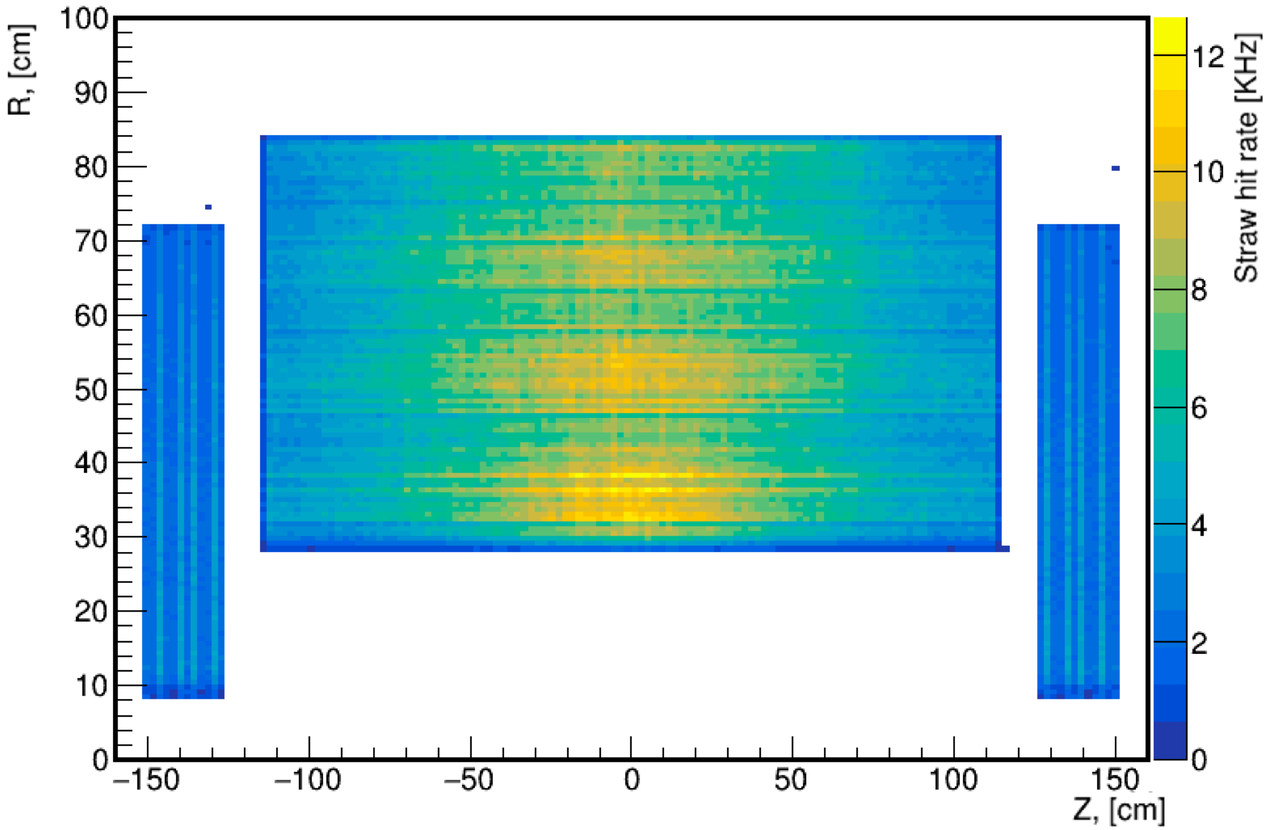
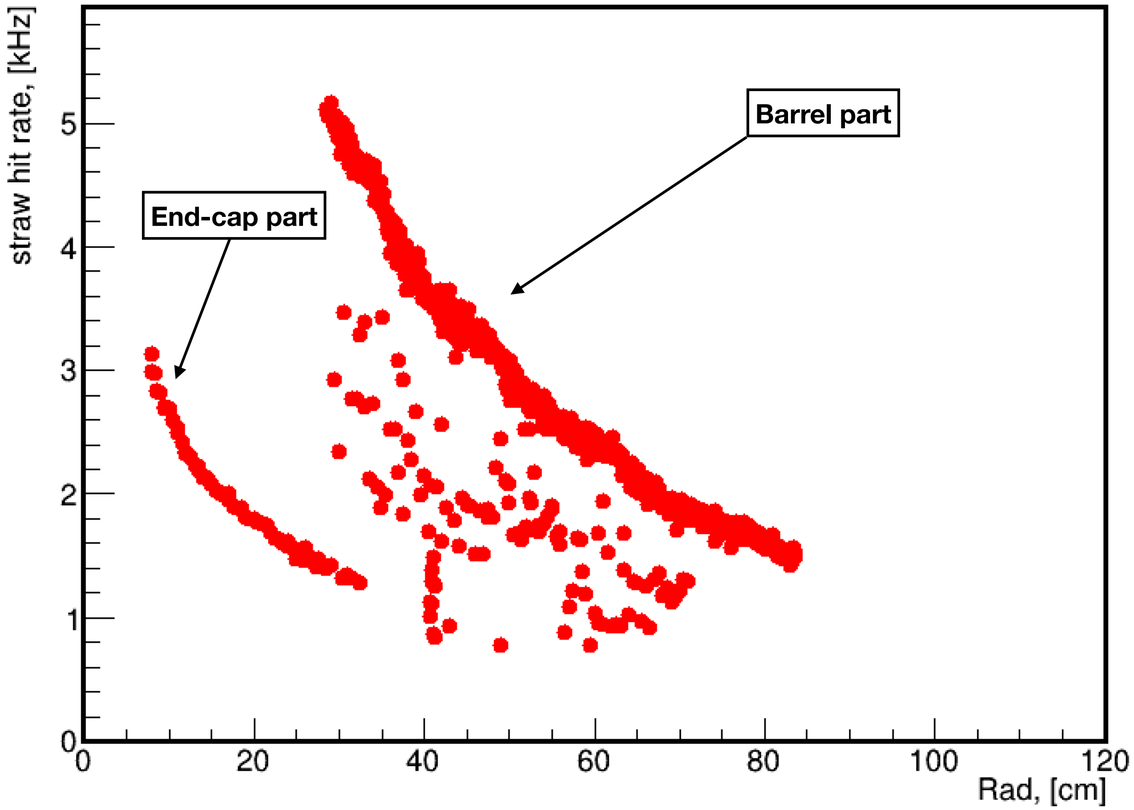


Fig. 19 - Average number of hits per straw in the ST in Ar-Ar collisions



The isolated points are binning artifacts; the chosen binning provides a clearer visualization of the detector geometry.

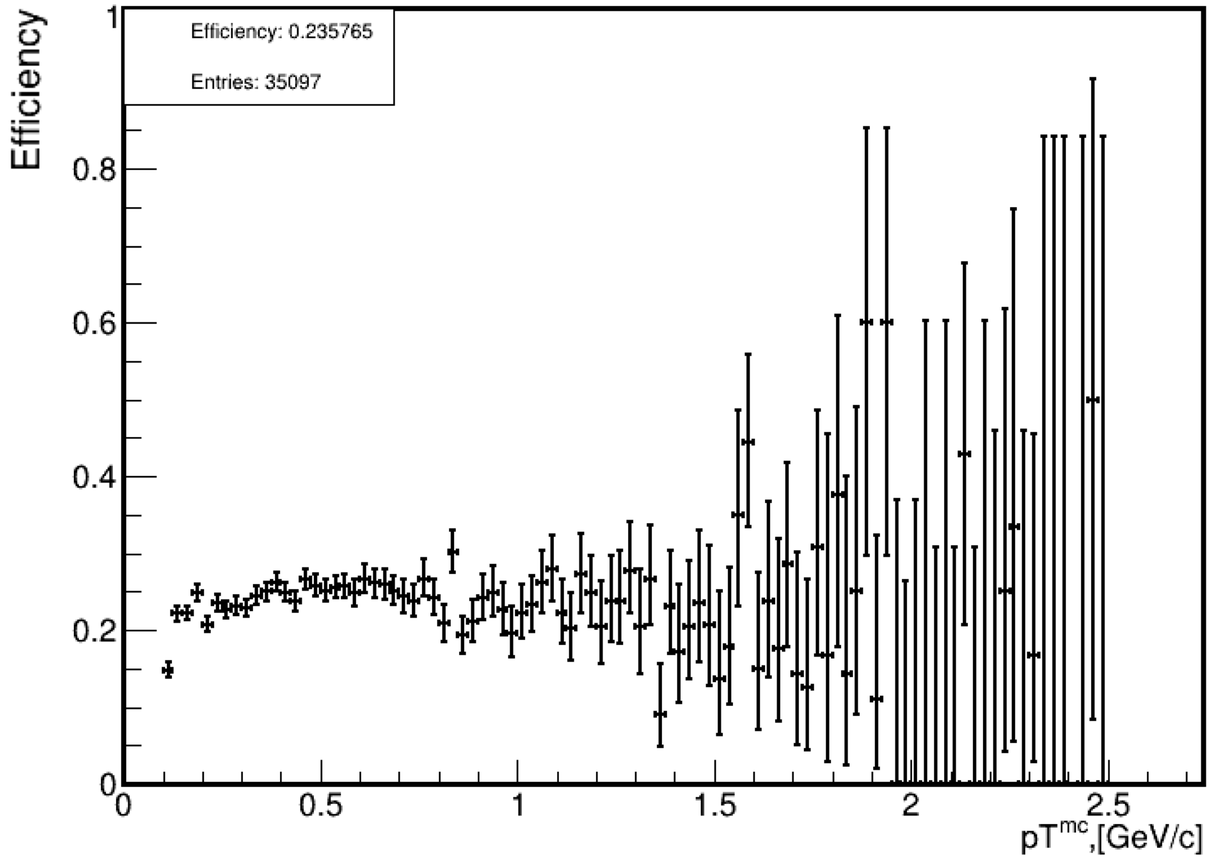
<u>Simulation parameters:</u>

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 40 000 Ar-Ar collisions (Ar^{40}_{18})
- 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

Reconstruction efficiency in Ar-Ar collisions

Fig. 20 - Efficiency vs pT^{MC}



Efficiency (Ar-Ar) ~ 23.6%

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 40 000 Ar-Ar collisions (Ar_{18}^{40})
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

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

Fig. 21 - ST full hit rate (barrel + end-caps parts) in Kr-Kr collisions

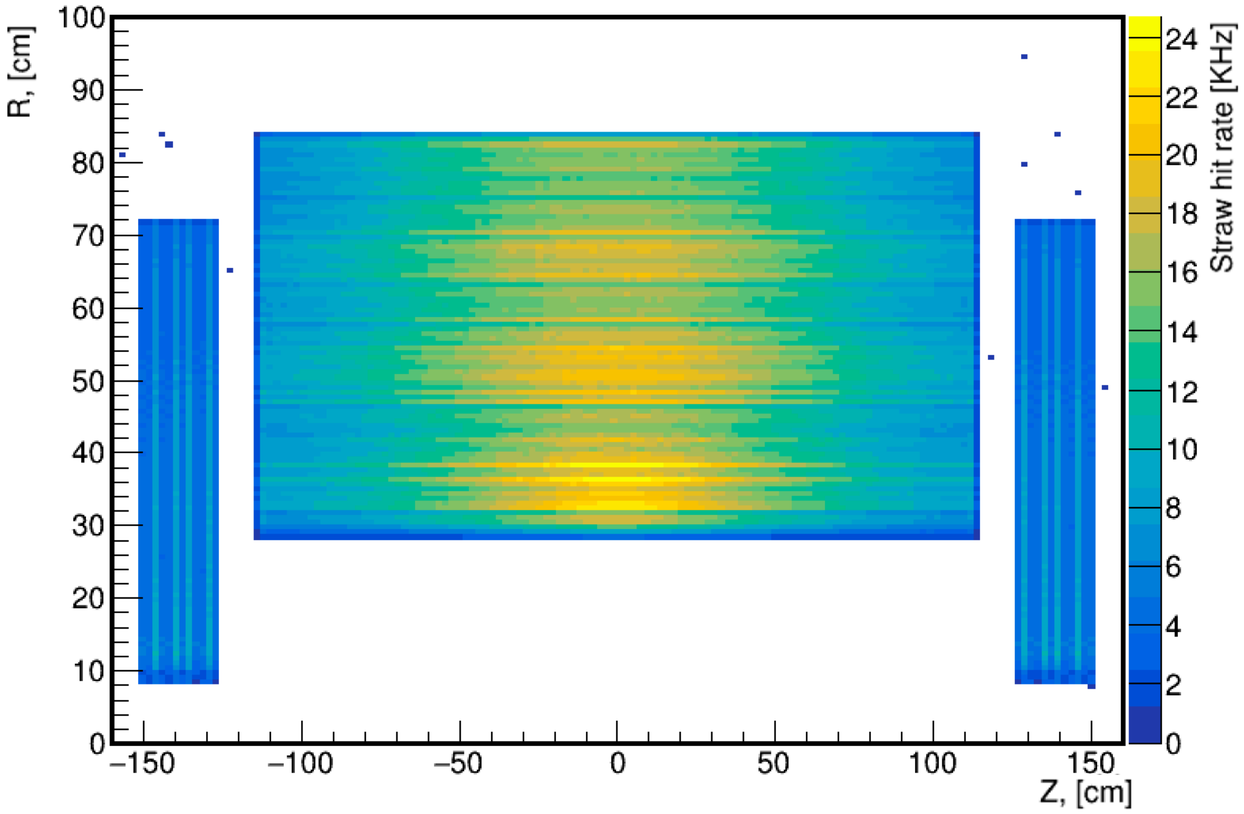
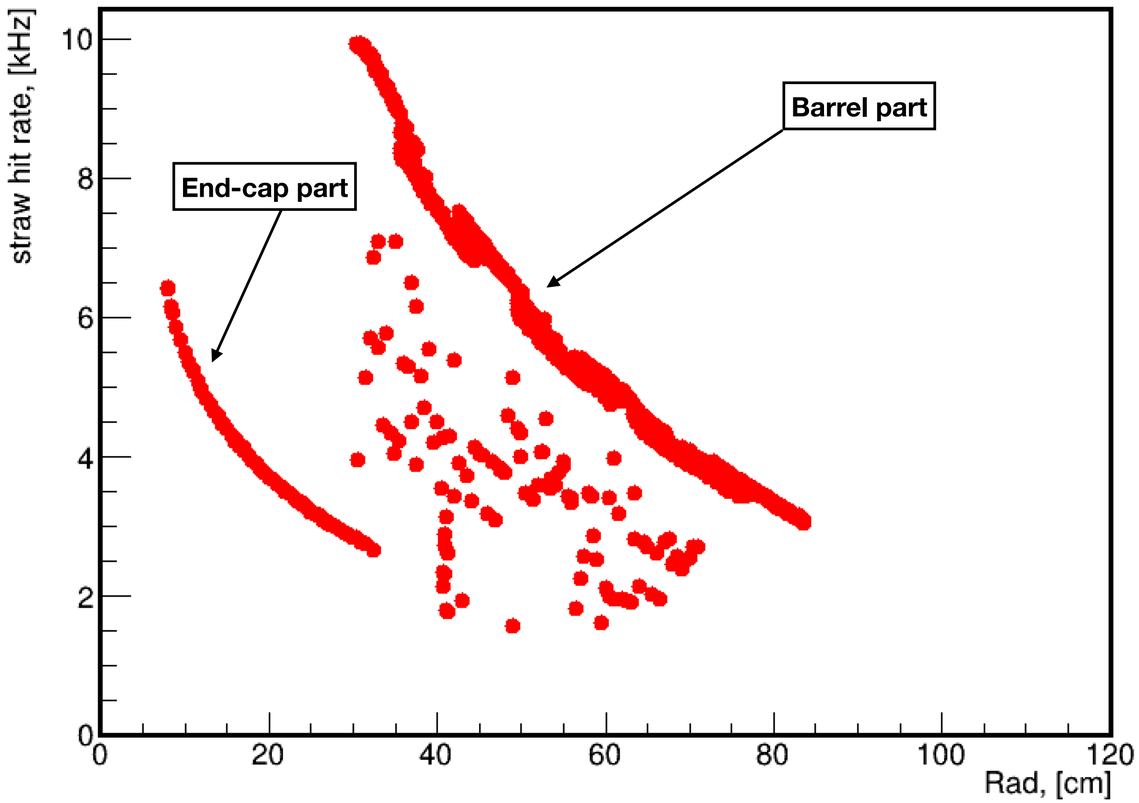


Fig. 22 - Average number of hits per straw in the ST in Kr-Kr collisions



The isolated points are binning artifacts; the chosen binning provides a clearer visualization of the detector geometry.

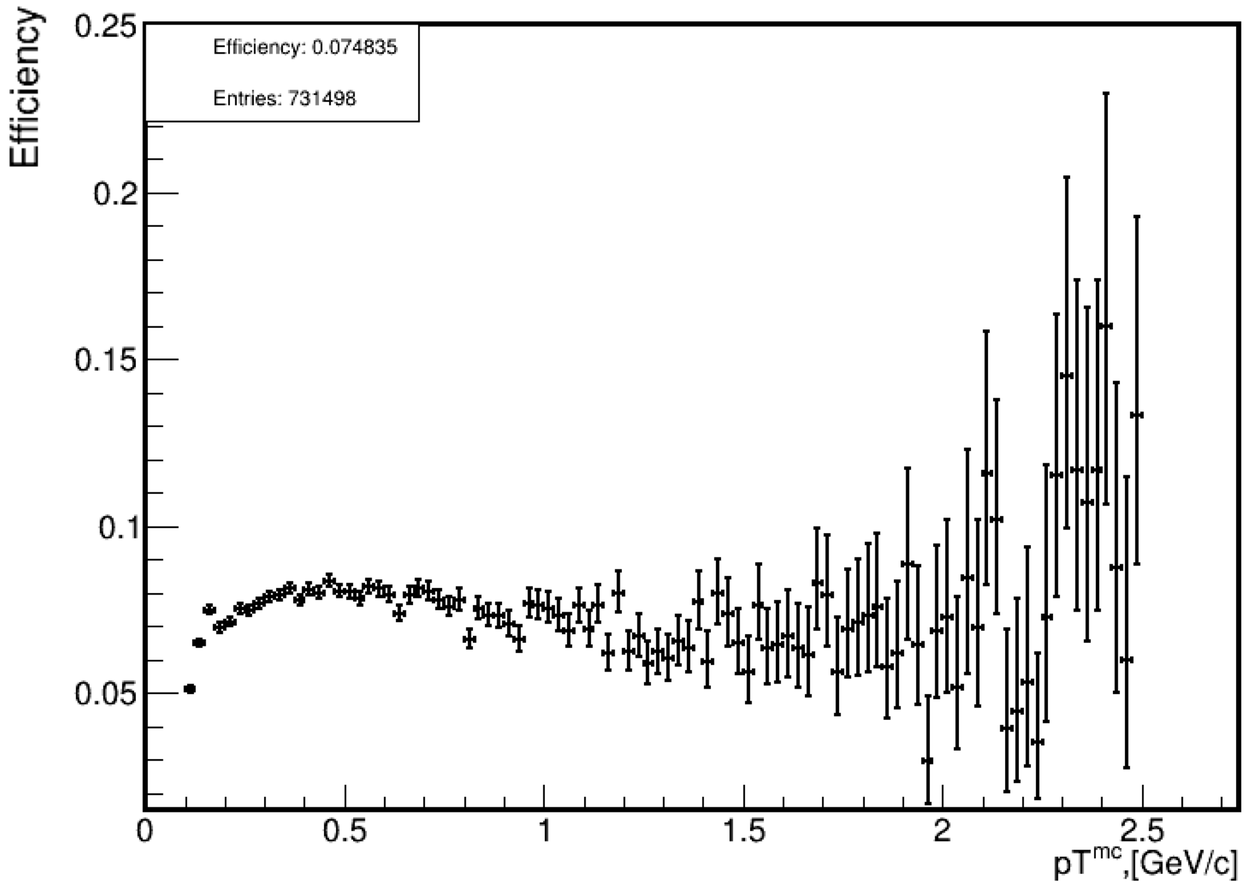
<u>Simulation parameters:</u>

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 10 000 Kr-Kr collisions (Kr_{36}^{84})
- 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

Reconstruction efficiency in Kr-Kr collisions

Fig. 23 - Efficiency vs pT^{MC}



Efficiency (Kr-Kr) ~ 7.5%

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 10 000 Kr-Kr collisions (Kr_{36}^{84})
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

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

Fig. 24 - ST full hit rate (barrel и end-caps parts) in Xe-Xe collisions

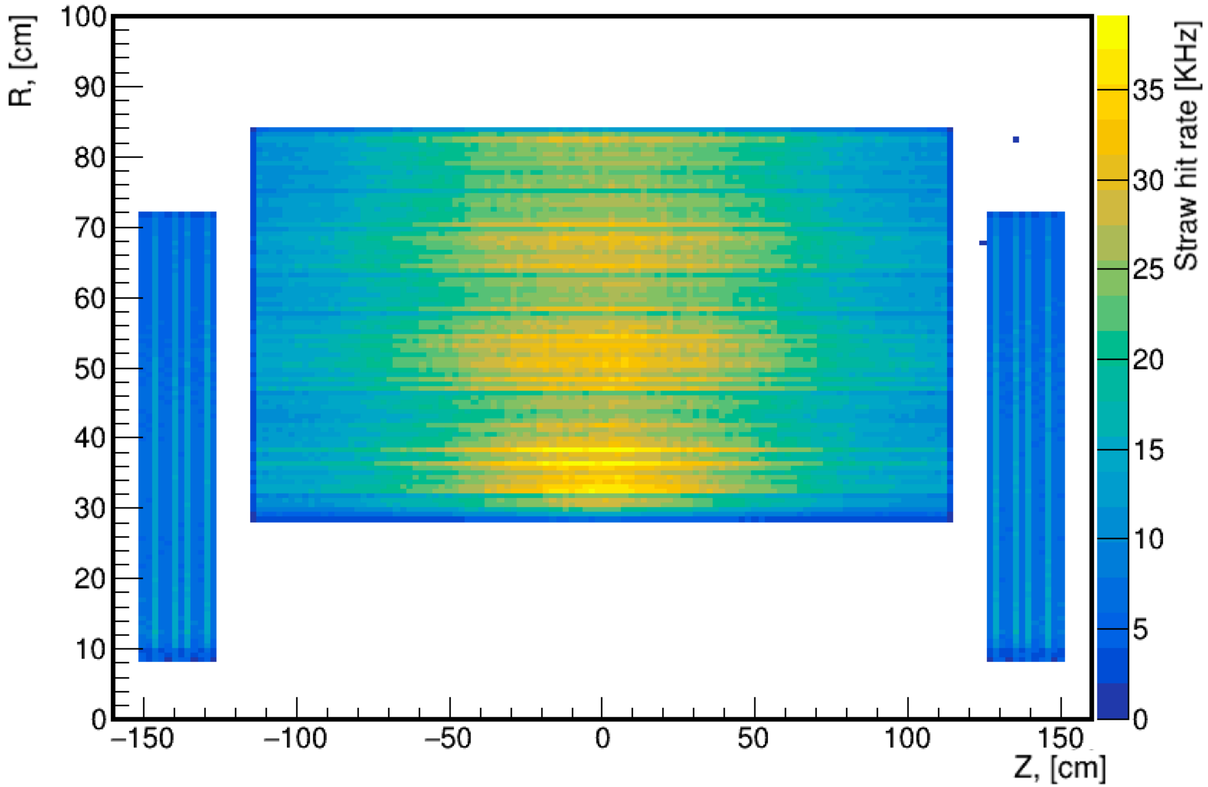
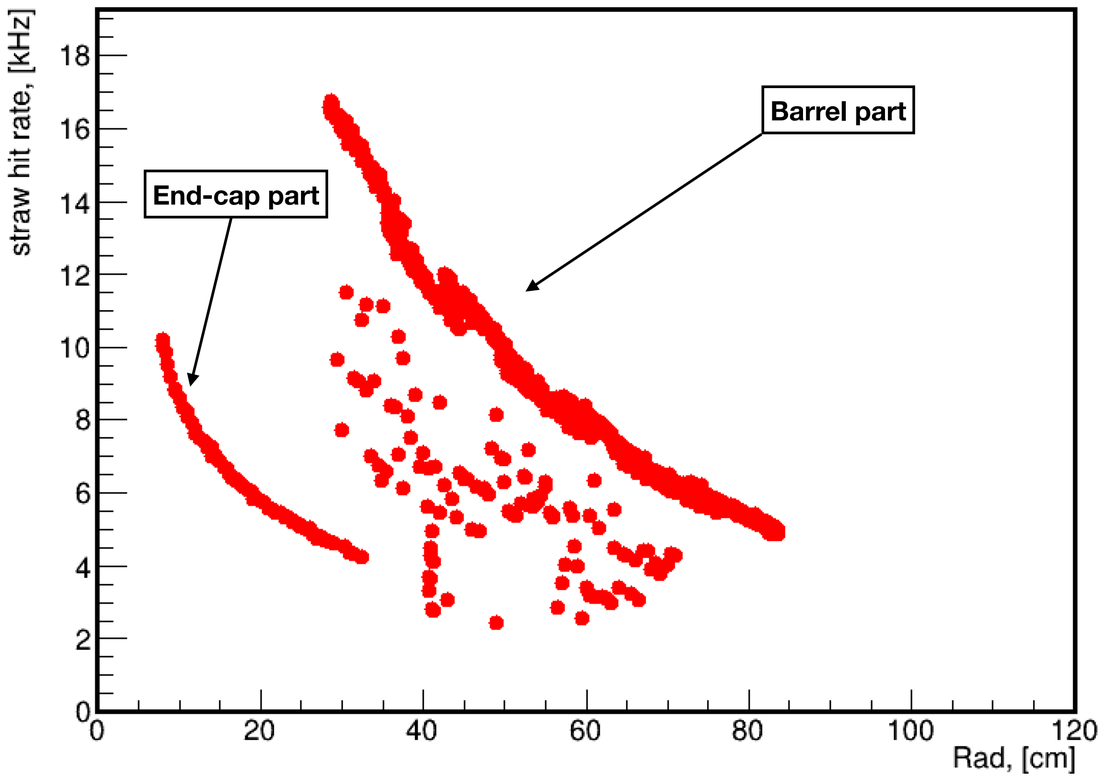


Fig. 25 - Average number of hits per straw in the ST in Xe-Xe collisions



The isolated points are binning artifacts; the chosen binning provides a clearer visualization of the detector geometry.

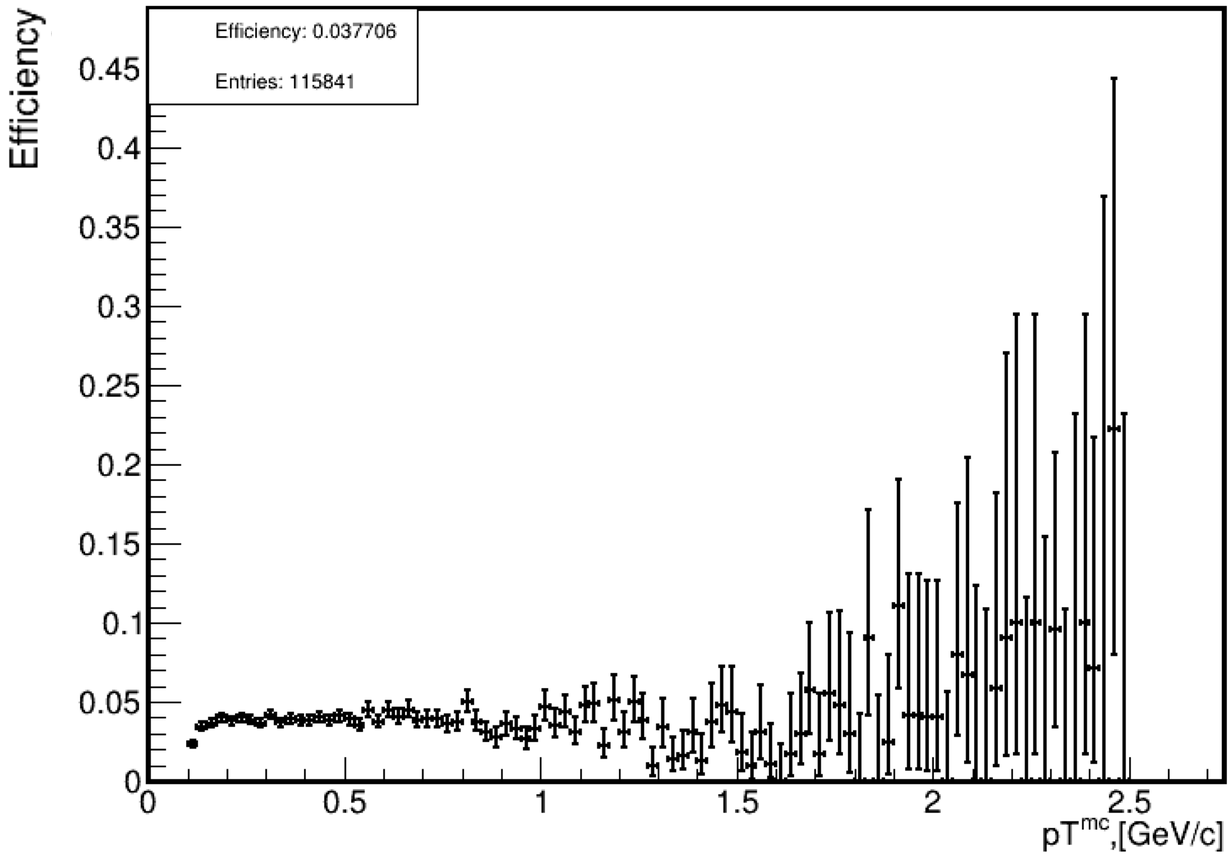
Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 1 000 Xe-Xe collisions (Xe_{54}^{131})
- 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

Reconstruction efficiency in Xe-Xe collisions

Fig. 26 - Efficiency vs pT^{MC}



Efficiency (Xe-Xe) ~ 3.8%

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- 1 000 Xe-Xe collisions (Xe_{54}^{131})
- Minimum bias
- $-2 < \eta < 2$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Momentum resolution of the Straw Tracker in Ar-Ar collisions

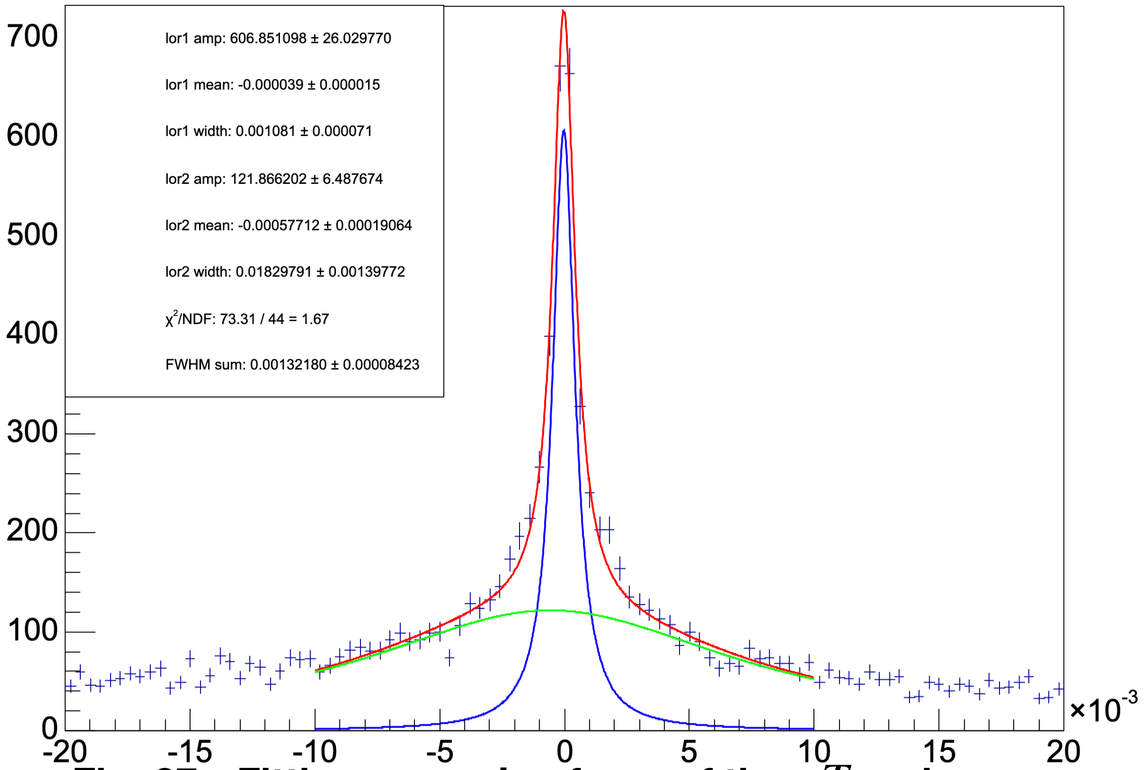


Fig. 27 - Fitting example of one of the pT regions

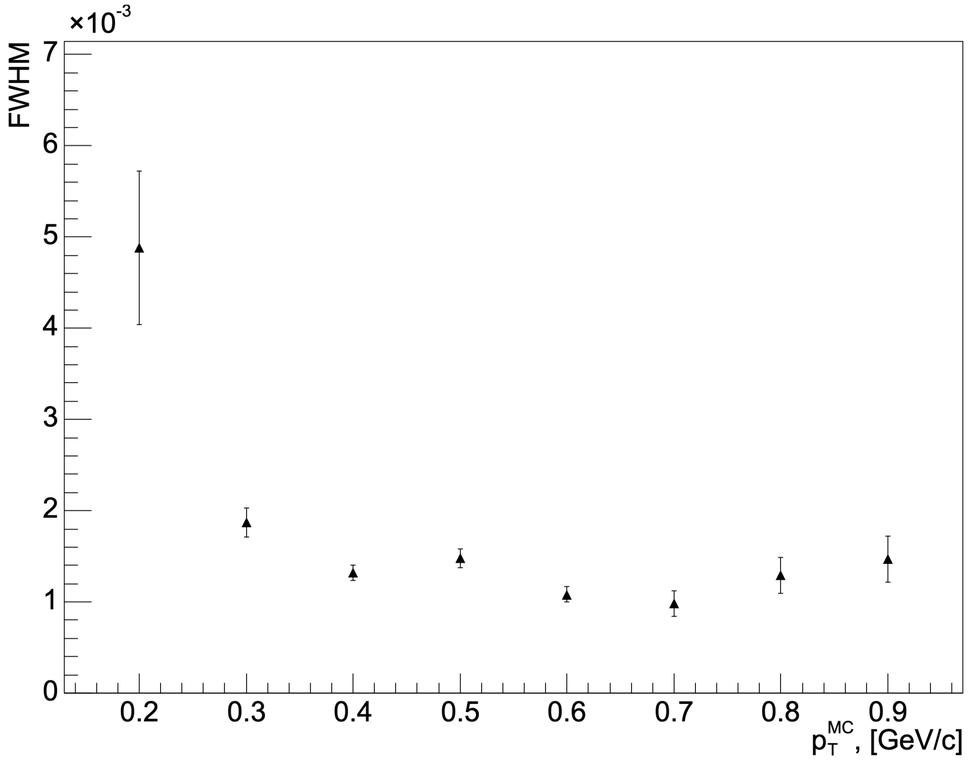


Fig. 28 - FWHM distribution of fits

- A region of particular interest for event reconstruction in the Straw Tracker is $-2 < \eta < 2$
- It is proposed to evaluate the relative momentum resolution from the $(pT_{reco} - pT_{MC})/pT_{MC}$ distributions
- These distributions were fitted with **Lorentz+Lorentz** functions, and the **FWHM** of the fits were taken as the measure of momentum resolution.

The simulation parameters are the same as it stated at the slide 7

Momentum resolution of the Straw Tracker in Kr-Kr collisions

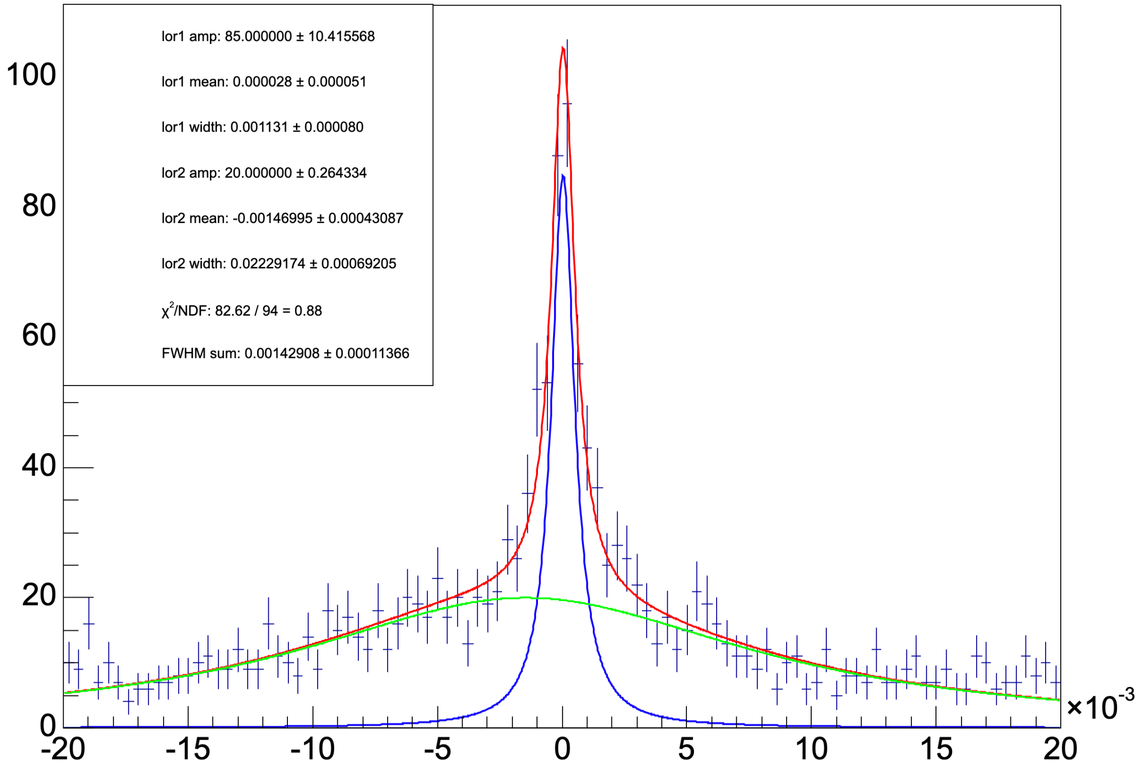


Fig. 29 - Fitting example of one of the pT regions

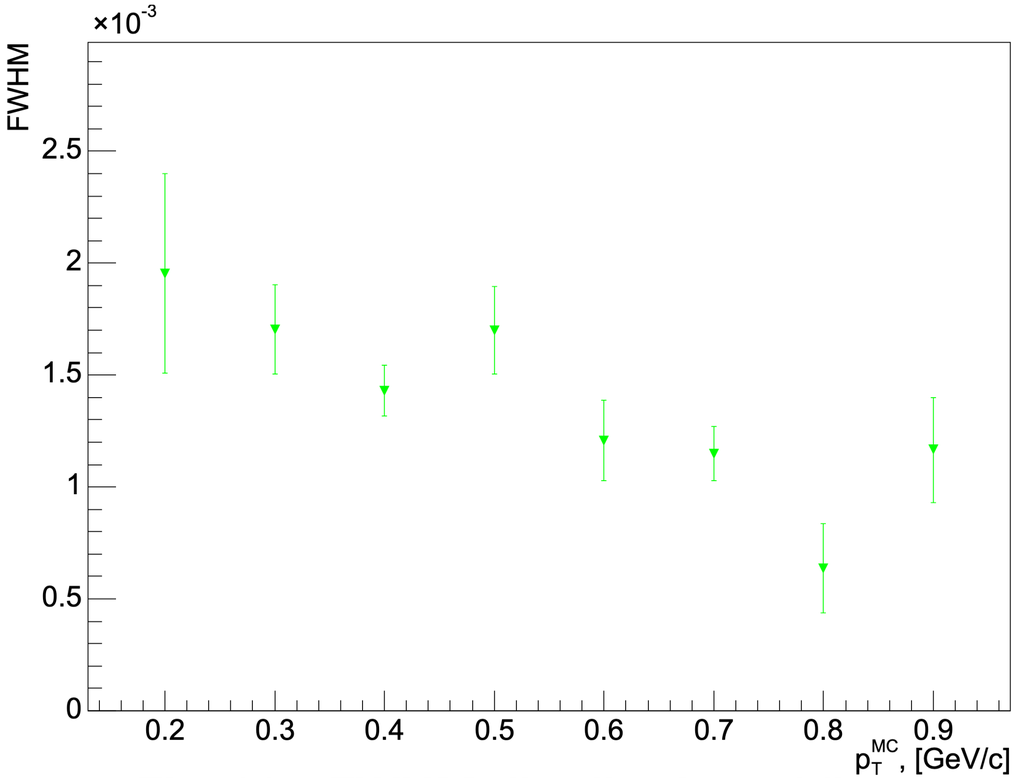


Fig. 30 - FWHM distribution of fits

- A region of particular interest for event reconstruction in the Straw Tracker is $-2 < \eta < 2$
- It is proposed to evaluate the relative momentum resolution from the $(pT_{reco} - pT_{MC})/pT_{MC}$ distributions
- These distributions were fitted with **Lorentz+Lorentz** functions, and the **FWHM** of the fits were taken as the measure of momentum resolution.

The simulation parameters are the same as it stated at the slide 7

Momentum resolution of the Straw Tracker in Xe-Xe collisions

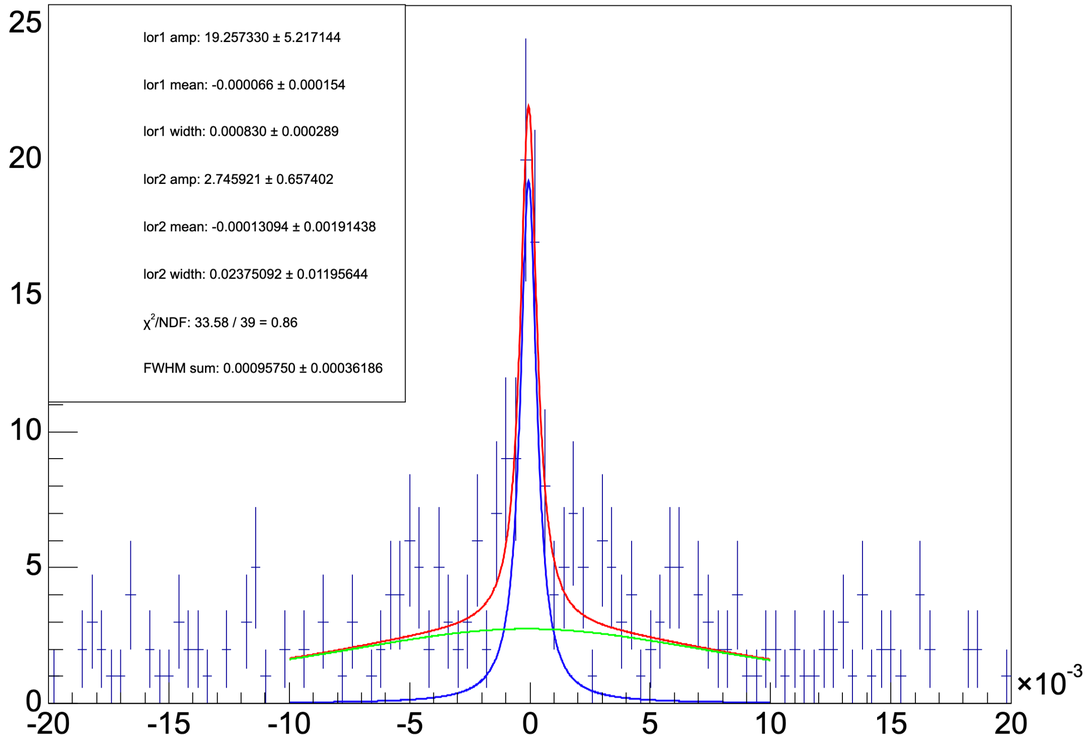


Fig. 31 - Fitting example of one of the pT regions

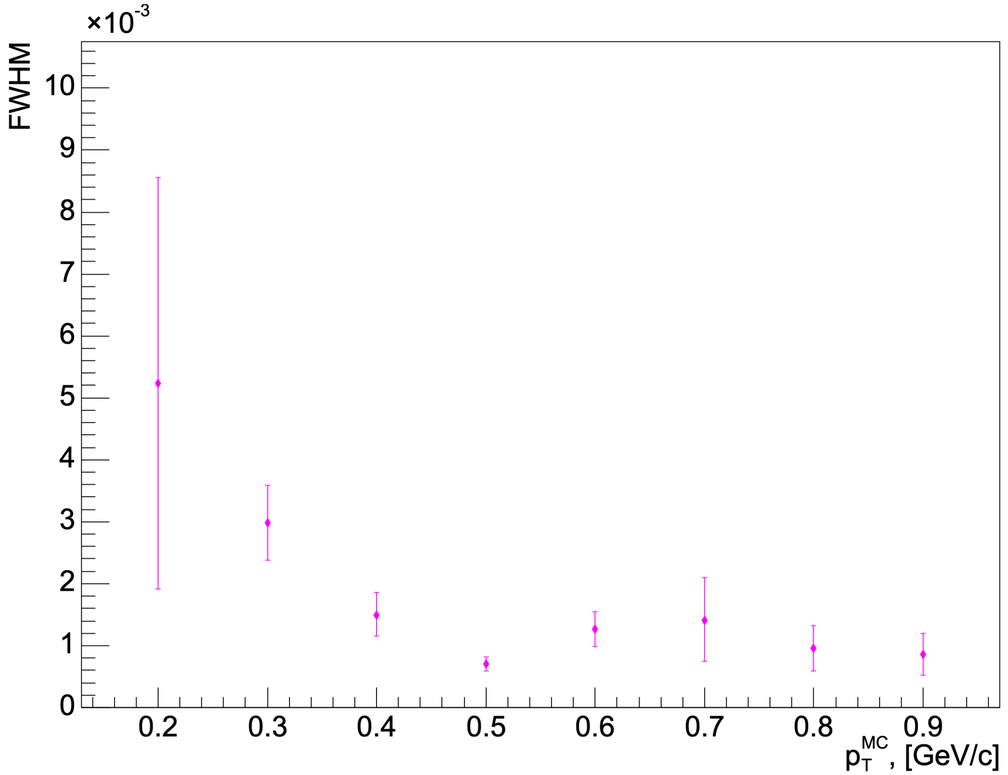


Fig. 32 - FWHM distribution of fits

- A region of particular interest for event reconstruction in the Straw Tracker is $-2 < \eta < 2$
- It is proposed to evaluate the relative momentum resolution from the $(pT_{reco} - pT_{MC})/pT_{MC}$ distributions
- These distributions were fitted with **Lorentz+Lorentz** functions, and the **FWHM** of the fits were taken as the measure of momentum resolution.

The simulation parameters are the same as it stated at the slide 7

Pseudorapidity of the MC particles (p-p)

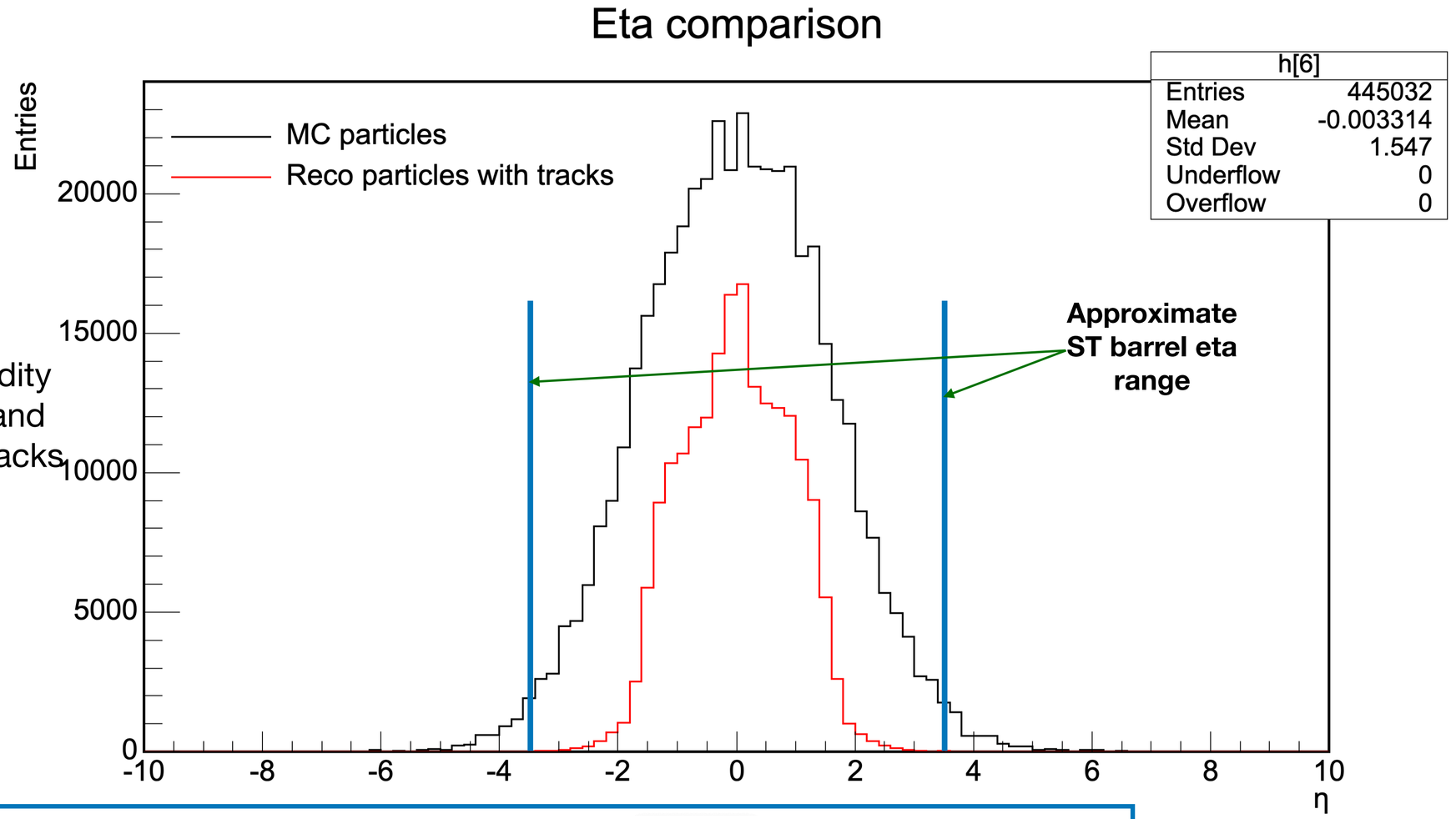


Fig. 33 - Pseudorapidity of the MC particles and Reco particles with tracks

Simulation parameters:

- Event Generator: Pythia8
- $\sqrt{s} = 10\ GeV$
- Nevents = 48k
- p-p collisions
- Minimum bias
- Approx. ST barrel eta range $-3.5 < \eta < 3.5$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Pseudorapidity of the MC particles (O-O)

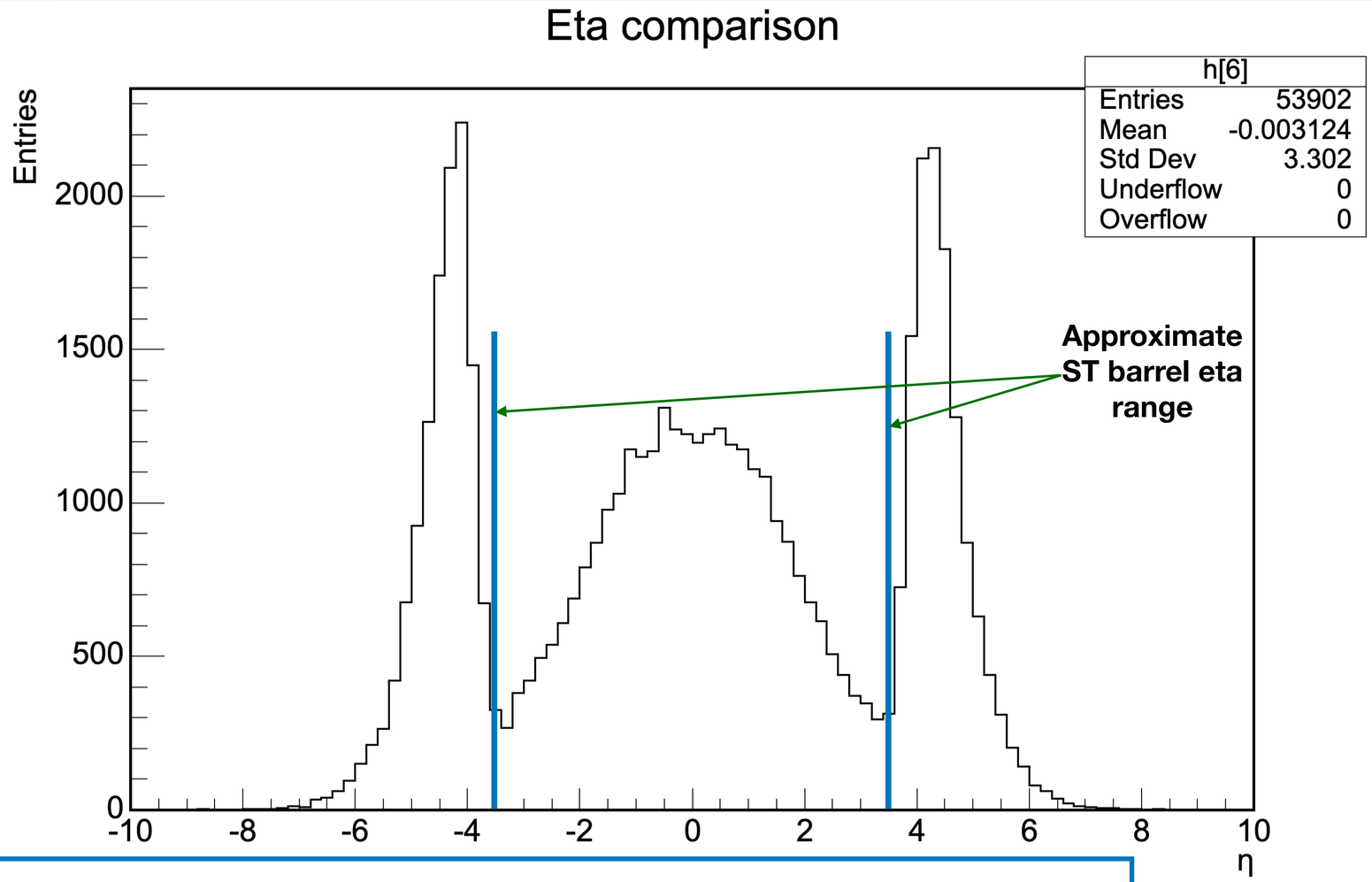


Fig. 34 - Pseudorapidity comparison

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- Nevents = 1k
- O-O collisions
- Minimum bias
- Approx. ST barrel eta range $-3.5 < \eta < 3.5$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Pseudorapidity of the MC particles (Ar-Ar)

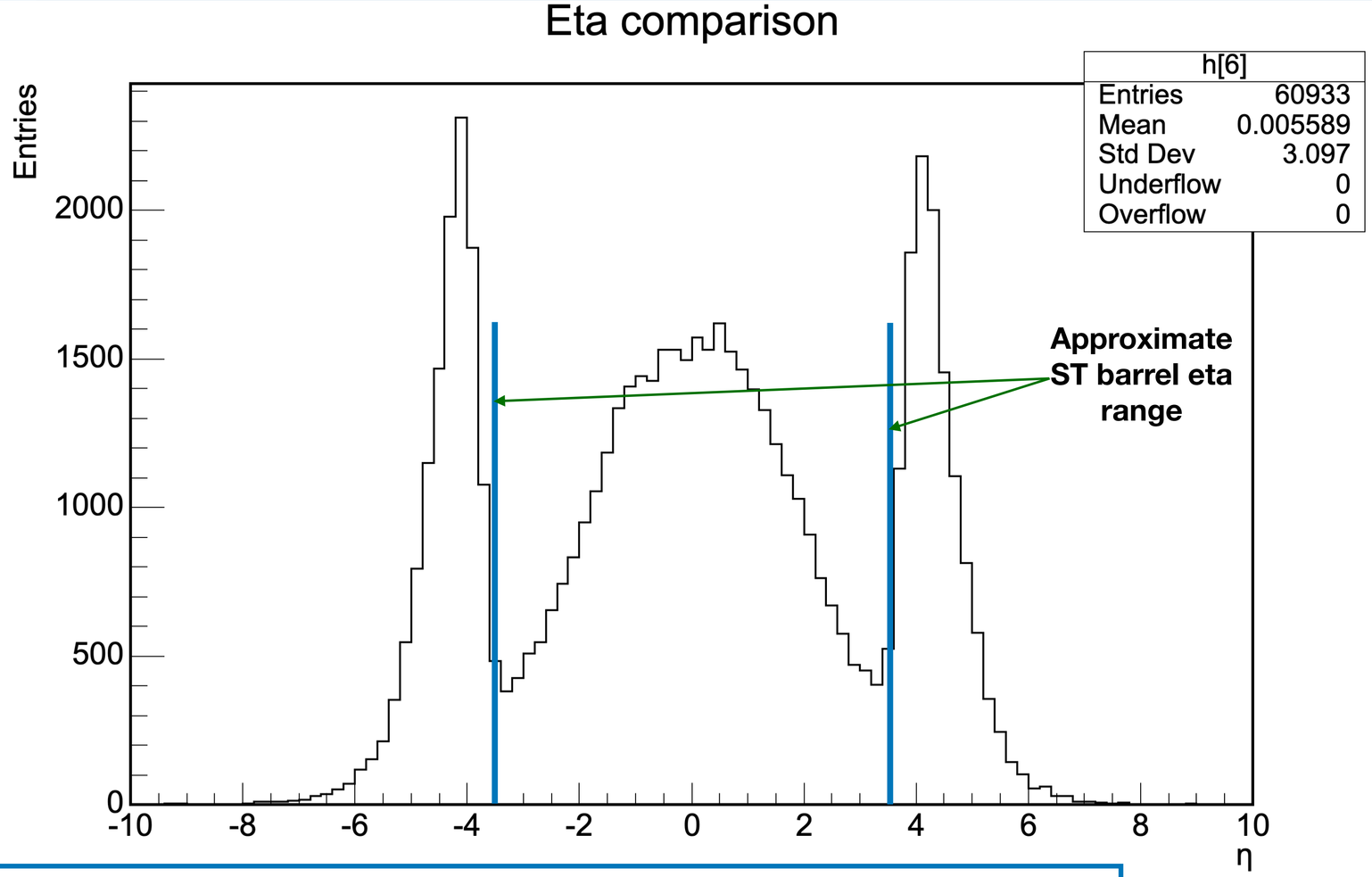


Fig. 35 - Pseudorapidity of the MC particles

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- Nevents = 1k
- Ar-Ar collisions
- Minimum bias
- Approx. ST barrel eta range $-3.5 < \eta < 3.5$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Pseudorapidity of the MC particles (Kr-Kr)

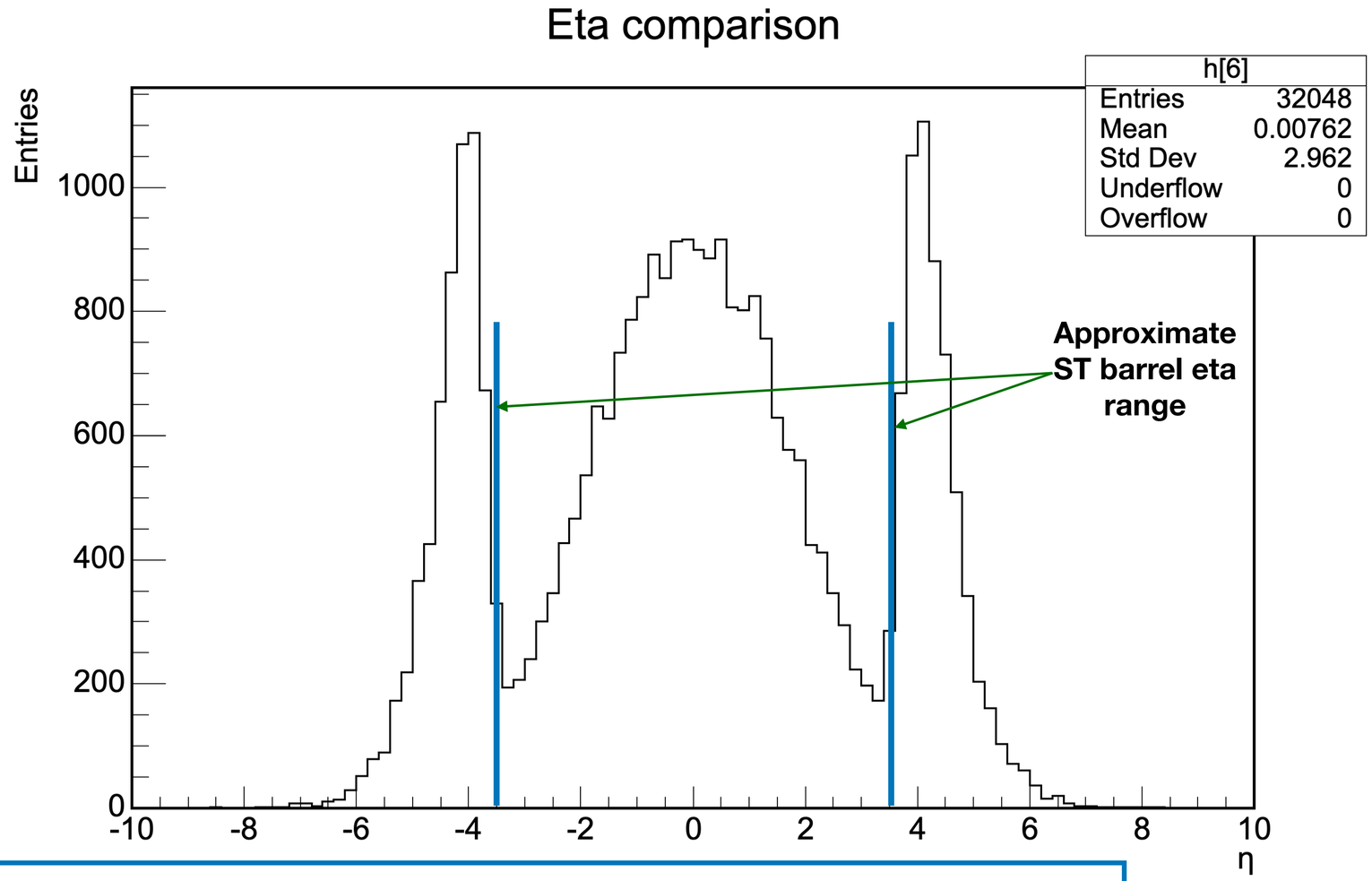


Fig. 36 - Pseudorapidity of the MC particles

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- Nevents = 1k
- Kr-Kr collisions
- Minimum bias
- Approx. ST barrel eta range $-3.5 < \eta < 3.5$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks

Pseudorapidity of the MC particles (Xe-Xe)

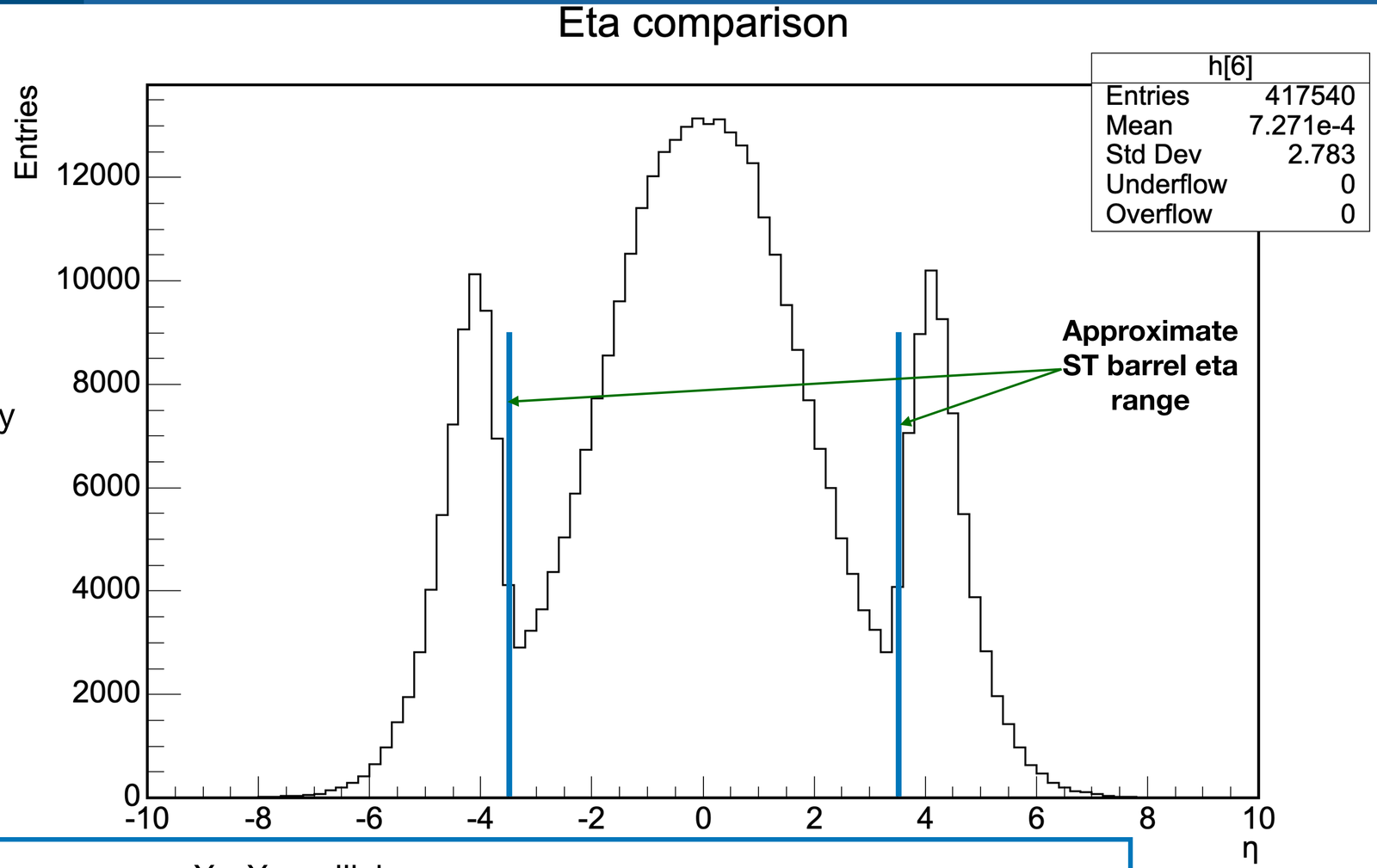


Fig. 37 - Pseudorapidity of the MC particles

Simulation parameters:

- Event Generator: UrQMD 4.0
- $\sqrt{s} = 10\ GeV$
- Nevents = 1k
- Xe-Xe collisions
- Minimum bias
- Approx. ST barrel eta range $-3.5 < \eta < 3.5$
- $pT \geq 0.1\ GeV$
- **MC tracks and reco tracks share more than a half common hits**

This criteria provides exclusion of «false» reco tracks