Misalignment influence on track reconstruction in the time projection camera of the MPD detector

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Simulation
Results

Introduction

Many scientific results of modern high-energy physics are obtained by comparing simulated theoretical predictions with experimental data.

Tracking detectors provide basic information about charged particles observed in the experiment.

High-precision knowledge of the locations of the sensors in a detector's global coordinate system is the basis for its high resolution and for obtaining unbiased physical results. Partially, such knowledge can be achieved by optical survey, for example, by laser systems that are used to determine the actual position of the sensors.

However, it turns out that the most accurate alignment can be obtained from experimental data by fitting tracks from millions of events and analyzing the track reconstruction.

Introduction in the theory

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To find the detector alignment we minimize the amount of their average deviation over all measured track points from the track model:

$$\chi 2 = \overline{\left(\frac{h_i - T_i}{\sigma_i}\right)^2} \quad (1)$$

where vector h_i is the position of *i-th* track hit, T_i is the point of the expected track trajectory to the closest hit, σ_i is the measurement error.
By minimizing the sum (1) for a single track, its best trajectory is found assuming the detector perfect alignment. After finding the parameters of each track, the minimum of Equation (1) for a set of events can be searched for using the detector alignment settings as variables.
Let Hx be the real coordinate of the sensor of the experimental setup along some axis, and Tx is the corresponding coordinate of the track point closest to the sensor. Since the track points are distributed evenly in space around the sensor, the average deviation ($Hx-Tx$)=*0.* Let us introduce the distortion d in Hx and calculate the difference between values (1) in case of wrong and real alignments:

$$\overline{(\boldsymbol{H}_x + d - \boldsymbol{T}_x)^2} - \overline{(\boldsymbol{H}_x - \boldsymbol{T}_x)^2} = 2d(\overline{\boldsymbol{H}_x - \boldsymbol{T}_x}) + d^2 = d^2 > 0,$$

Correct sensor alignment provides a minimum of expression (1) for a large number of tracks and real values of the alignment parameters

MPD TPC

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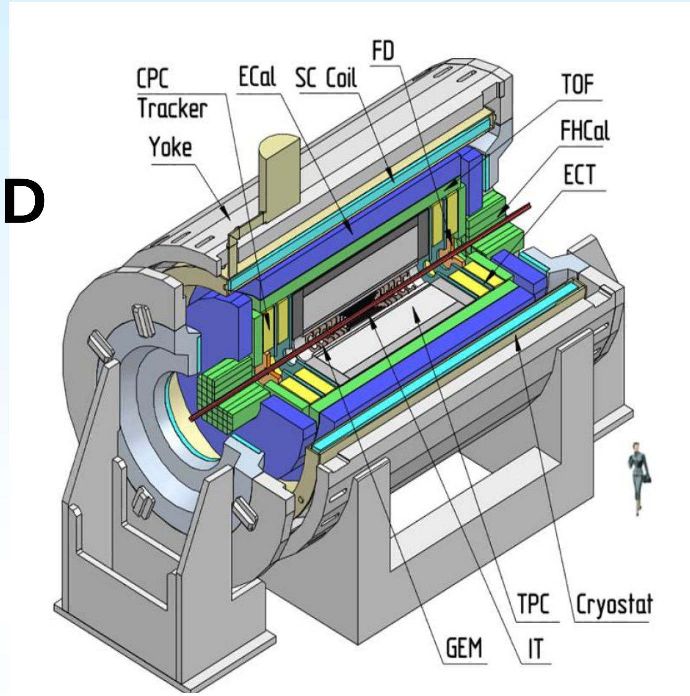
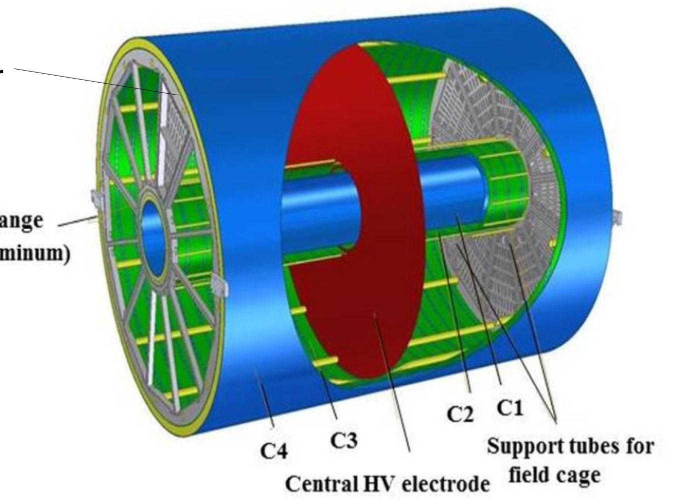
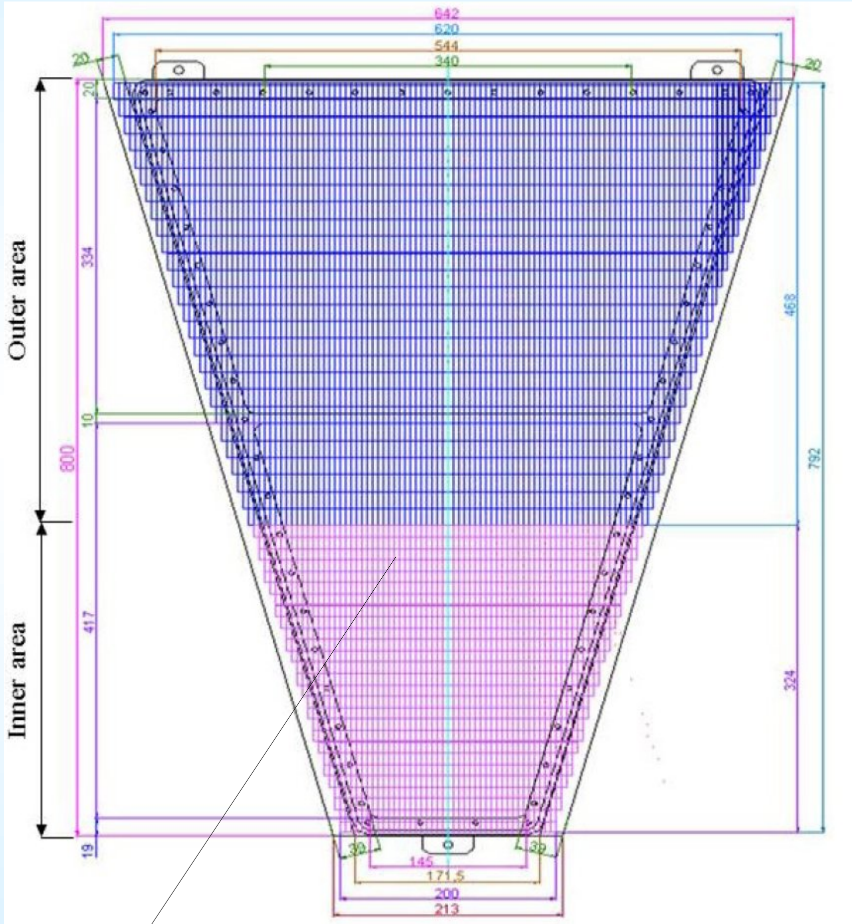
MPD



TPC



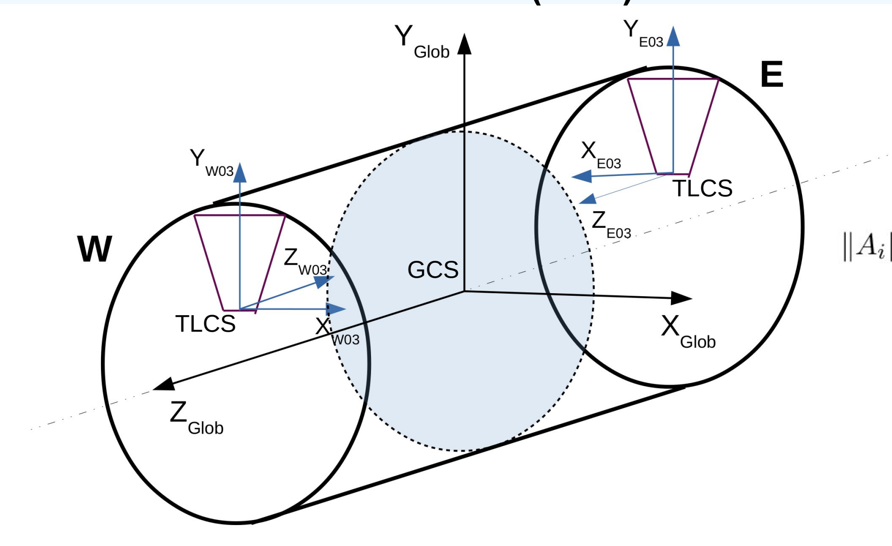
TPC sector



4074 sensitive elements that fix the projection of the track on the sector

TPC alignment parameters

Global Coordinate System of the TPC (GCS), Theoretical Local Coordinate System of the sector (TLCS) and Local Coordinate System of the sector (LCS)



$$\boldsymbol{X_g} = \boldsymbol{S_i^{tl}} + \left\|T_i^{-1}\right\| \boldsymbol{X_{tl}}$$ TLCS → GCS

$$\boldsymbol{X_{tl}} = \boldsymbol{S_i^{A}} + \left\|A_i^{-1}\right\| \boldsymbol{X_{l}}$$ LCS → TLCS

S^{tl}, T – constants, $S^A(x_0,y_0,z_0)$, $A(\alpha,\beta,\gamma)$

$$\|A_i\| = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\gamma_i) & \sin(\gamma_i) \\ 0 & -\sin(\gamma_i) & \cos(\gamma_i) \end{pmatrix} \times \begin{pmatrix} \cos(\beta_i) & 0 & -\sin(\beta_i) \\ 0 & 1 & 0 \\ \sin(\beta_i) & 0 & \cos(\beta_i) \end{pmatrix} \times \begin{pmatrix} \cos(\alpha_i) & \sin(\alpha_i) & 0 \\ -\sin(\alpha_i) & \cos(\alpha_i) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\left\|R_i^{-1}\right\| = \left\|T_i^{-1}\right\| \left\|A_i^{-1}\right\|$$ LCS → GCS

The position of sector *i* is determined by the 6 parameters x_{0i}, y_{0i}, z_{0i}, α_i, β_i, γ_i, which in the alignment problem are called global, and they need to be found for each sector.

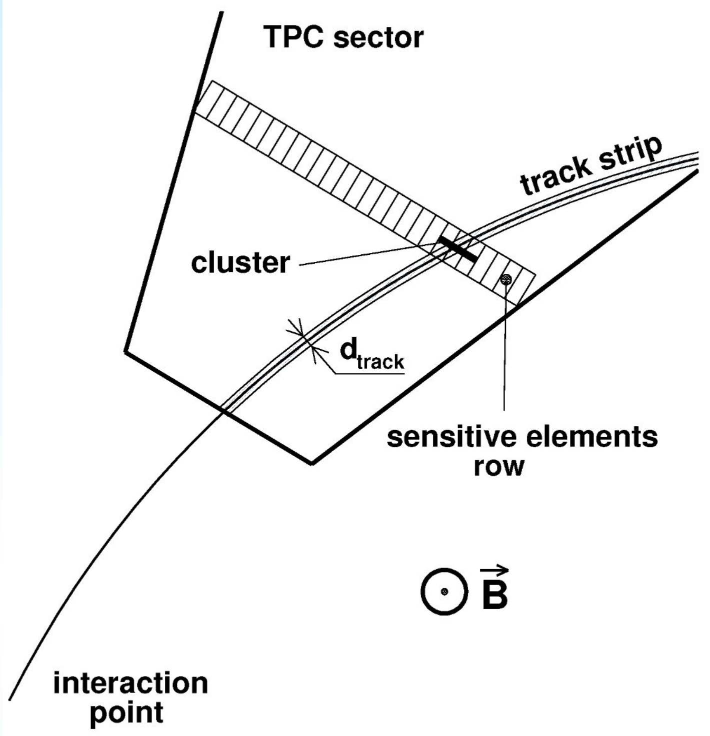
Simplified TPC Simulation

- To study the effect of detector alignment on the accuracy of experimental data, it is necessary to simulate the process of detecting and reconstructing tracks in the detector.
- Modeling needs to be done for a variety of alignment sets of the detector.
- The process of minimizing the function to find the alignment parameters is interactive, which multiplies the amount of calculations.
- Full simulation of the detector is a rather time-consuming computational operation.

The above factors can be the reason for the practical absence in the literature of works on the influence of the magnitude of incorrect alignment of track detectors on the accuracy of the track reconstruction.

To solve this problem, a simplified simulation of the reaction of TPC to charged particles is needed, followed by a reconstruction of the tracks.

Simplified TPC Simulation



1. A charged particle leaves a trace of width d_{track} (~8mm*) on the surface of the sector.
2. The center of the strip is the projection of the track along the electric field onto the plane of the sector sensors.
3.The amplitude of the pad signal is proportional to the area of pad coverage by the band and the final value is smeared according to the Gaussian function.
4. The distance along the electric field from the particle to the pad plane (signal time delay) is smeared according to the Gaussian function.
5. Adjacent pads of the same row with a signal above the threshold form a cluster. The local coordinates of the cluster are determined as the weighted sum of the coordinates of individual pads. Using these coordinates, the coordinates of the hit are calculated in the GCS of the detector.
6. The global hits are fitted by the mathematical model of the track (line or helix).
7. According to the results of the track fit, χ^2 and its derivatives are calculated to find the minimum of χ^2 and the alignment.

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* V. Kolesnikov a , A. Mudrokh a , V. Vasendina and A. Zinchenko, «*Towards a Realistic Monte Carlo Simulation of the MPD Detector at NICA*», Physics of Particles and Nuclei Letters, 2019, Vol. 16, No. 1, pp. 6–15.

Simplified TPC Simulation

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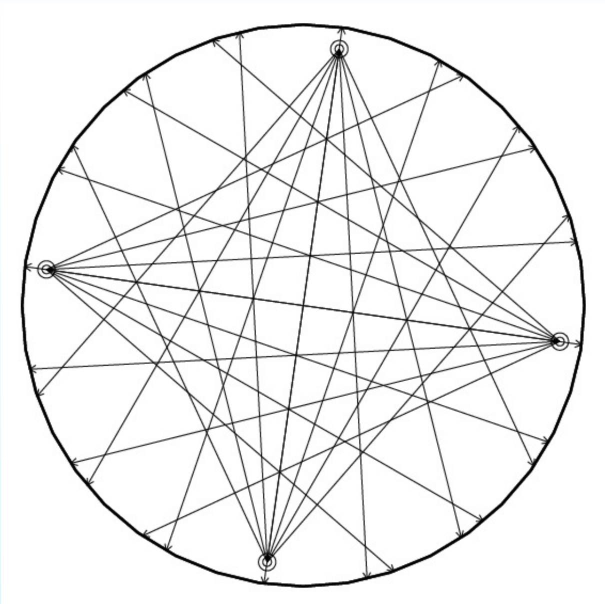
The following types of the tracks were modeled:

1. Cosmic muons without a magnetic field in the detector.
2. Single muons are born in the interaction point at the detector magnetic field.
3. Tracks initiated by the TPC laser system.

In each TPC half, there are four planes perpendicular to the longitudinal axis of the detector, into which laser radiation capable of ionizing the TPC gas is injected. In each plane, four sources emit seven rays each.

The laser beam diagram



The simulation is described in
V.Kuzmin "MPD TPC Alignment"
Physics 2023, 5(2), 508-516;
https://doi.org/10.3390/physics5020036

Main results:

- The TPC laser system, designed exclusively for monitoring the properties of the gas in the detector can also be used to monitor the MPD TPC alignment.
- The accuracy of the MPD TPC alignment finding has been investigated. In the case of cosmic and laser rays, the accuracy is obtained to be about 1mm for the shift in the sector position and 7 arc minutes for Euler angles.
  If muons born in the collisions between nuclei are used, the accuracy becomes several times worse.

Misalignment in and its measure

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What happens in practice?

- Usually, in a large experiment, an entire team works on the alignment problem and tries to minimize χ2 of tracks using experimental data to find the positions of the detector parts.
- Next, all experimental data are reconstructed again using a new alignment, after which the physical distributions before and after are compared.
- Based on the form of these distributions, it is concluded that the results have improved.

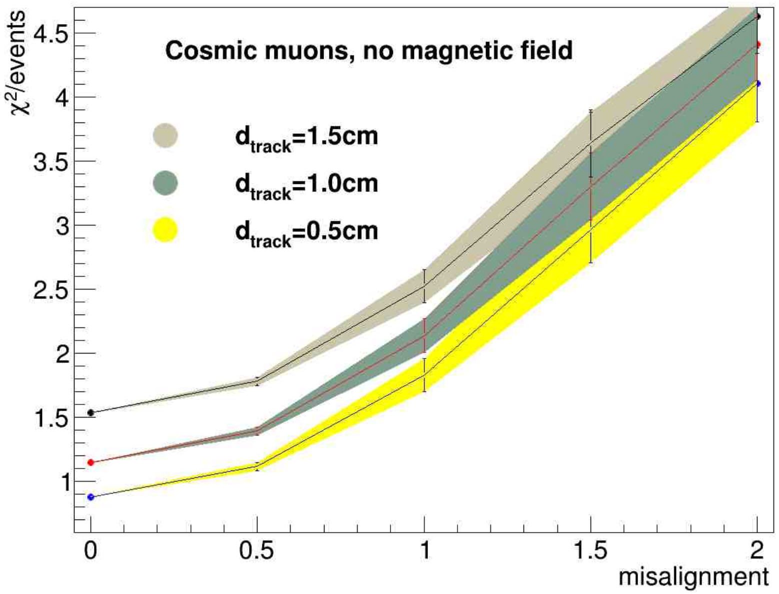
The issue of alignment accuracy has been resolved for the MPD TPC, but remains open for other detectors and there is an interest in terms of possible error of the final result, as well as the mechanical condition of the detector, displacements/deflections of its supporting structures. For example, finding the correct position of each laser ray in the MPD TPC which is important to monitor gas properties.

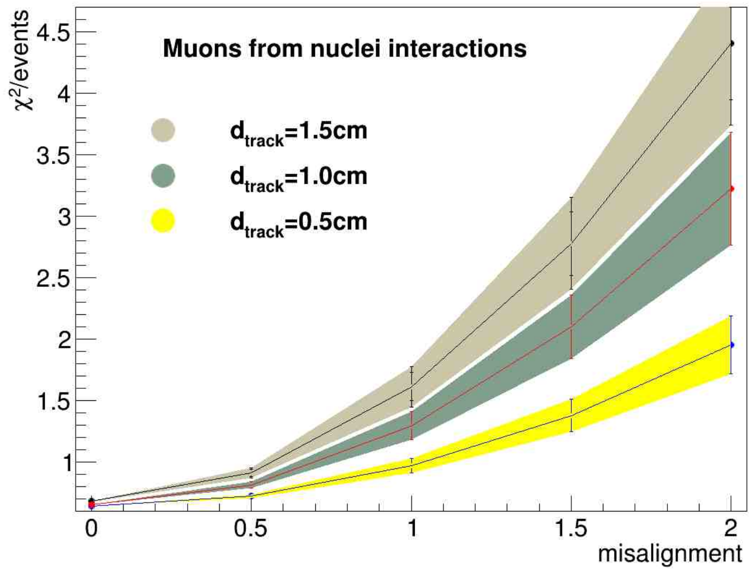
The detector consists of many elements and the position of each in space is random. Thus, a set of random parameters determines a specific alignment.
Let's try to introduce an average measure of deviation of the real TPC alignment from the ideal one, and then, depending on it, investigate the errors of the reconstructed tracks.

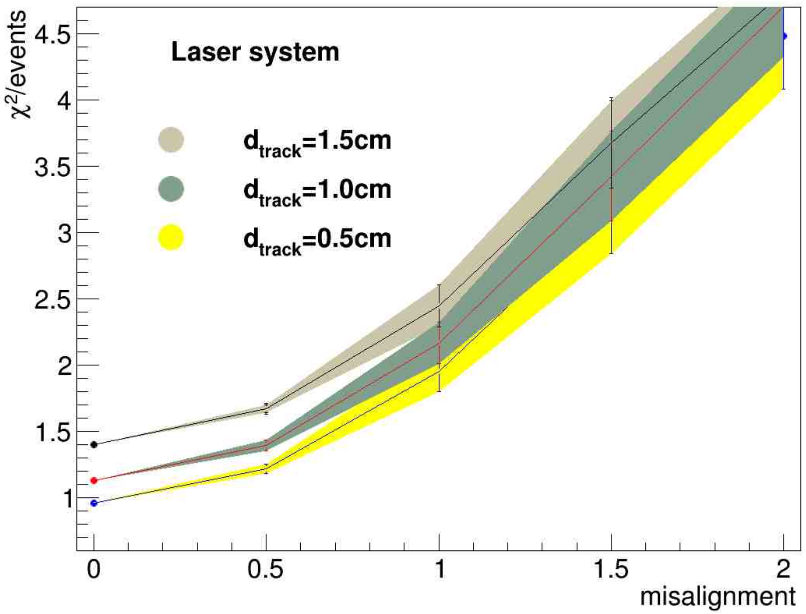
Misalignment units

Let's consider a set of alignments of TPC that differ from the theoretical one so that the displacements of the origin of the sector local coordinates are evenly distributed over the segment [-A,A] cm, and Euler angles are also evenly distributed in the interval [-A,A] degrees.

A is a double absolute value of deviations of the global sector parameters from their theoretical values. We will take A as a measure of incorrect alignment of the TPC (misalignment).







The value A defines the set of alignments. The center of the band is the average over the set. Error bars are RMS values.
The derivative on left plots is significantly higher than on the right. This fact explains the higher accuracy of the alignment finding using cosmic and laser rays.

Misalignment & track parameters

Simulation conditions

Single muons born in the beam point distributed along the beam with the sigma 50cm around zero point.
pT of muons is evenly smeared in [0.03,1.5] GeV.
pZ of muons is evenly smeared so that the muon track is inside the TPC.

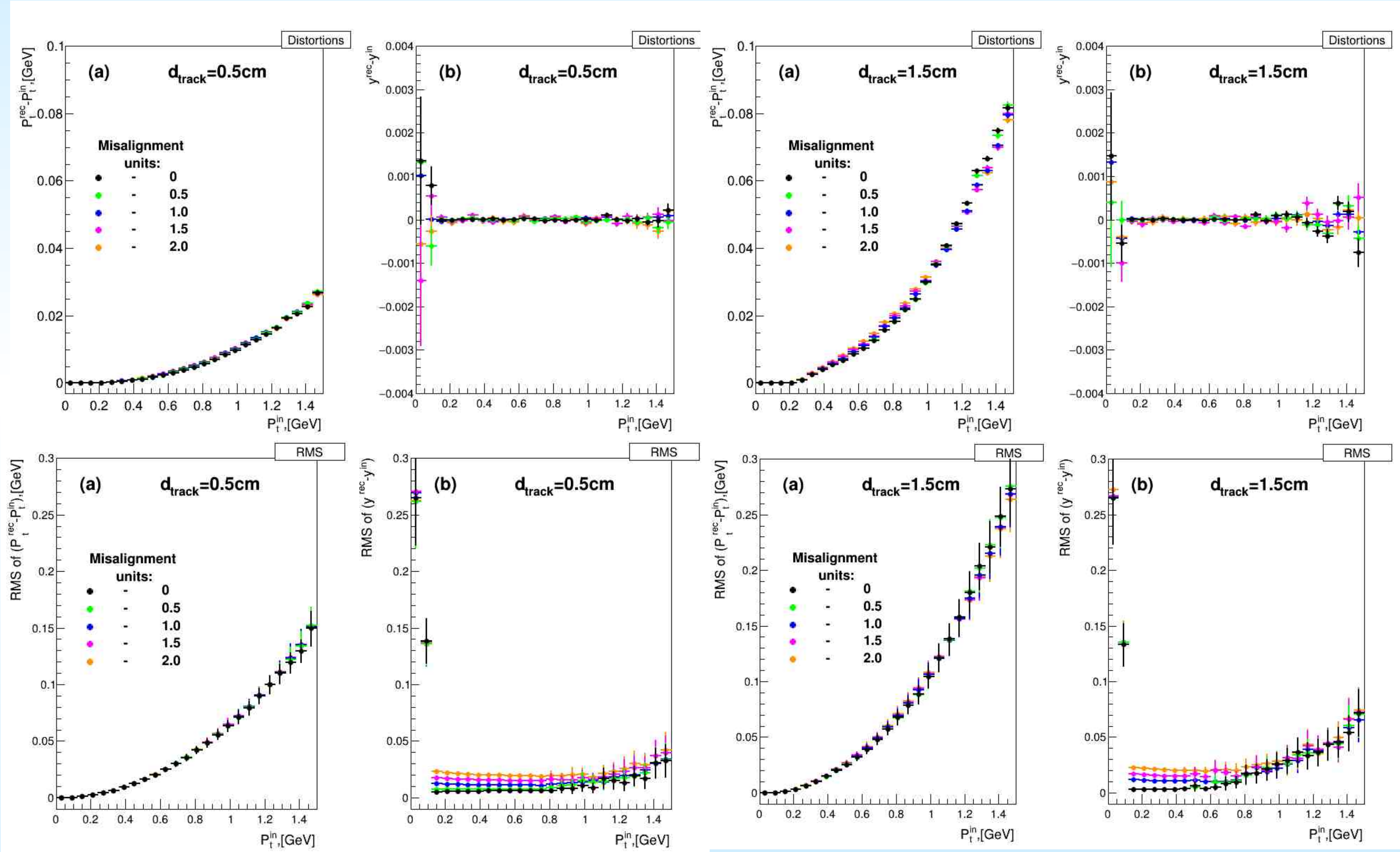
The variant of calculations is determined by two parameters:
a) d_{trac} is the width of the track projection,
b) A is the misalignment value.

For each value of d_{track}, 100 alignments sets of the misalignment A were random selected.
For each random alignment, 24,000 tracks were simulated.
Each set of track hits was reconstructed with the theoretical alignment which is incorrect for the set.

Deviations of the restored track parameters from real ones were calculated for:

transverse momentum P_t
and
rapidity y.

Misalignment & track parameters



Conclusion

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- For the Time Projection Camera, a measure of deviation of the used alignment from the real one has been introduced.
- The influence of the misalignment on reconstructed track parameters is low.
- The simulation of track reconstruction shows the systematic dependence of the reconstructed pT on its value. The systematic shift depends on the track projection width which is a function of the gas and the electric field in the camera.
  The developed alignment tools for the MPD TPC allow to estimate its value using experimental data and to introduce the correction in the reconstructed track parameters.

The end

Thank you!