JOINT INSTITUTE FOR NUCLEAR RESEARCH
Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Fast way to determine pp – collision time at the SPD experiment

Supervisor:
Dr. Mikhail Zhabitsky

Student:
Filonchik Polina, Russia
Moscow Institute of Physics
and Technology

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1 Abstract

The main task of this work is to find a fast and robust way to determine pp–collision time t_0 at the SPD experiment. Using physics motivations we identify a clean subset of pions which is used to calculate the unbiased estimation of the event collision time. The uncertainty of the estimation is about 30 ps. This method is fast (less than 300 ns per event) and reliable, thus it allows to process the high flux of input events at the SPD experiment.

2 Introduction

The Spin Physics Detector, one of the two facilities of the future NICA collider at the Joint Institute for Nuclear Research, is for studying the nucleon spin structure and spin-related phenomena with polarized proton and deutron beams [3]. Understanding how dynamics of the quarks and gluons determine the structure and the fundamental properties of the nucleon is one of the interesting unsolved problems of QCD.

The main task of this work is to determine *pp*–collision time based on measurements by the Time-Of-Flight (TOF) detector. Using the time when a particle intersects the detector and information about reconstructed tracks one can solve this problem. The *pp*–collision time allows to reconstruct tracks with high accuracy and to make particle identification.

Determination of *pp*–collision time is an optimization problem. There is a brute-force algorithm, where all available variants of particles are checked. It is very slow method. There is also a genetic algorithm, which works faster while searching suitable combination of particles. The idea of this project is to use faster simple methods to receive an unbiased estimation of *pp*–collision time. We incorporate a priori knowledge about the process to accelerate solution of the problem.

3 Project goals

The goal of this project is to a find fast and robust way to determine *pp*-collision time t_0. All particles are treated as pions as they are most abundant in events. We will use physics motivations to identify a clean subset of pions to determine t_0.

4 Determination of *pp*–collision time

4.1 Setup and selection

Using information about particles trajectories and hits from TOF detector to determine time of *pp*-collision:

1. Resolution of TOF detector $\sigma_t = 70$ ps;
2. Momentum resolution: $\frac{\sigma_p}{p} = 5\%$ (or 2%);
3. TOF radius is 1 m and length of 3 m.

Selection of hits and events:

1. Particles with momentum $p > 0.5$ GeV/c;
2. Events containing five or more particles with the above-mentioned condition.

The collision data was generated by the Pythia8-based programme written by Semyon Yurchenko [4].

4.2 General information

In this work we use a method to find *pp*-collision time described in the article [2] and [1]. To find the *pp*–collision time t_0 we minimize the sum of squared residuals between TOF measurements and predicted times of particles crossings the TOF detector:

$$\chi^2 = \sum_{i=1}^{n} \frac{(t_0(m_i) - (t_i - tof_i))^2}{\sigma_t^2 + \sigma_{tof_i}^2} \tag{1}$$

For a fixed mass hypothesis Fermat' theorem reads:

$$\frac{\partial \chi^2}{\partial t_0} = \sum_{i=1}^{n} 2\frac{t_0 - (t_i - tof_i)}{\sigma_t^2 + \sigma_{tof_i}^2} = 0 \tag{2}$$

and an estimation of t_0 is found:

$$\hat{t}_0 = \sum_i \frac{t_{diff_i}}{\sigma_t^2 + \sigma_{tof_i}^2} \cdot \left(\sum_i \frac{1}{\sigma_t^2 + \sigma_{tof_i}^2} \right)^{-1} \tag{3}$$

where

$$t_{diff_i} = t_i - tof_i\ . \tag{4}$$

Time of flight for every particle is calculated by formula:

$$tof = \frac{L}{c}\sqrt{1 + \frac{m^2c^4}{p^2c^2}}. \tag{5}$$

According to fig. 1 pions and electrons have close time of flight (TOF) at momentum higher 0.5 GeV/c. Thus electrons and pions are fast non-distinguished at high momenta.

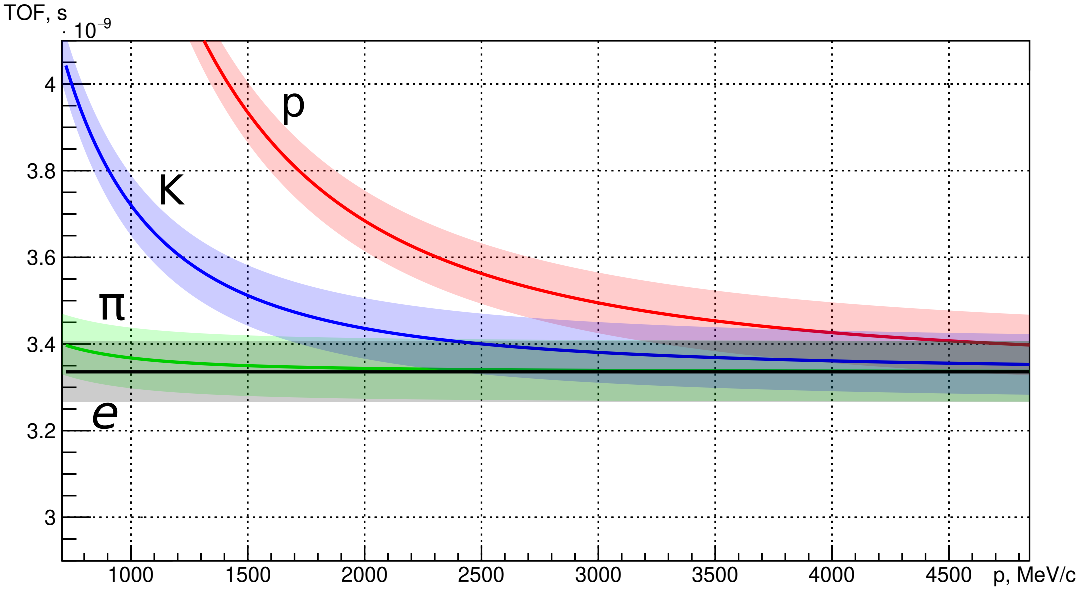

Figure 1: Dependence of TOF on momentum p

Here the time of flight is calculated treating all particles as pions. In this assumption it is determined by formula (5), where the mass of each particle m will be the mass of pion. In this case the resolution of time of flight σ_{tof} is less than the resolution of TOF detector σ_t:

$$\sigma_{tof} = \sigma_p \cdot \left|\frac{dt_{tof}}{dp}\right| = \sigma_p \frac{L}{\sqrt{1 + \frac{m_\pi^2 c4}{p^2c^2}}} \cdot \frac{m_\pi^2c^4}{p^3c^3} < \sigma_{tof}(p = 0.5\, GeV/c) \approx 20\ ps\ . \tag{6}$$

In the next steps the resolution of time of flight σ_{tof} will not be used.

4.3 Physics motivations

As pions are most abundant in events, we treat all particles as pions. In this case there is a big tail in the distribution of pp–collision time (fig. 2). This tail is connected with

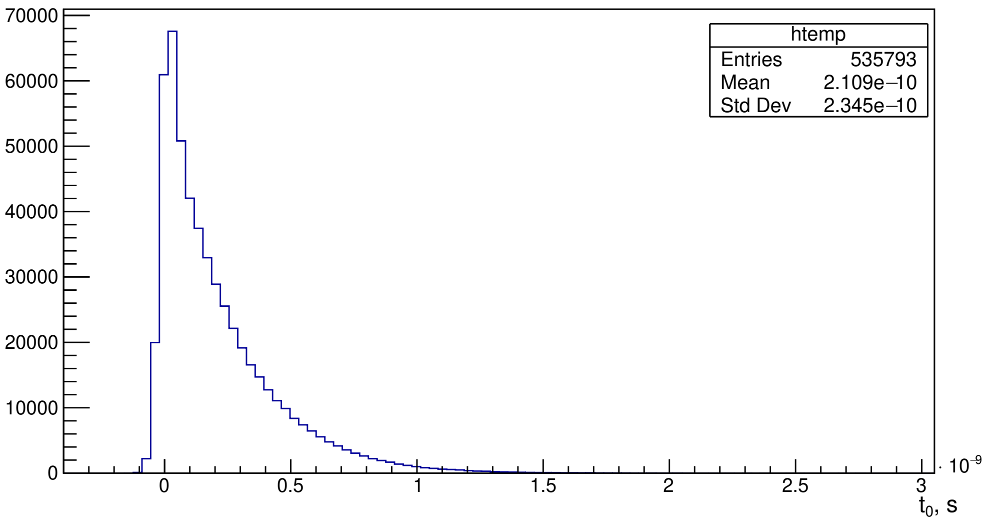

Figure 2: t_0-distribution under hypothesis that all particles are pions.

heavy particles, kaons and protons, which bias t_0 to positive values because their time of flight tof_i is longer than for pions tof_π (fig. 3).

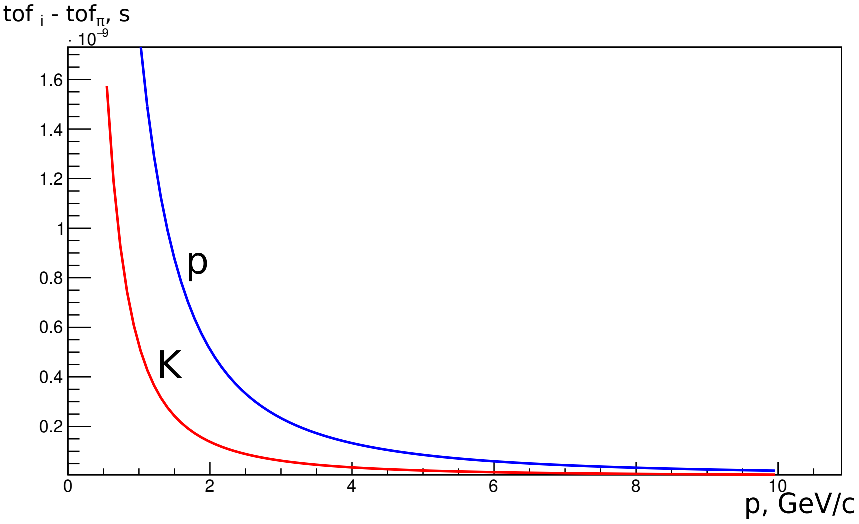

Figure 3: Difference of time of flight between kaons and pions; protons and pions

On fig. 4 the typical time differences t_{diff} (4) between the detector's signal t_i and TOF of pions is shown. One can see the most of particles are around zero. These particles are mainly pions as observed on the cumulative distribution function of $\pi^{\pm}$ as a function of charge multiplicity (fig. 5). In most of events pions comprise more than 60% of all particles.

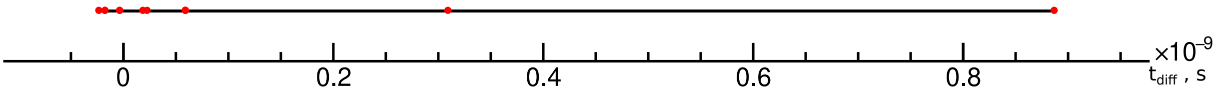

Figure 4: Typical difference between the detector's signal and TOF of pions

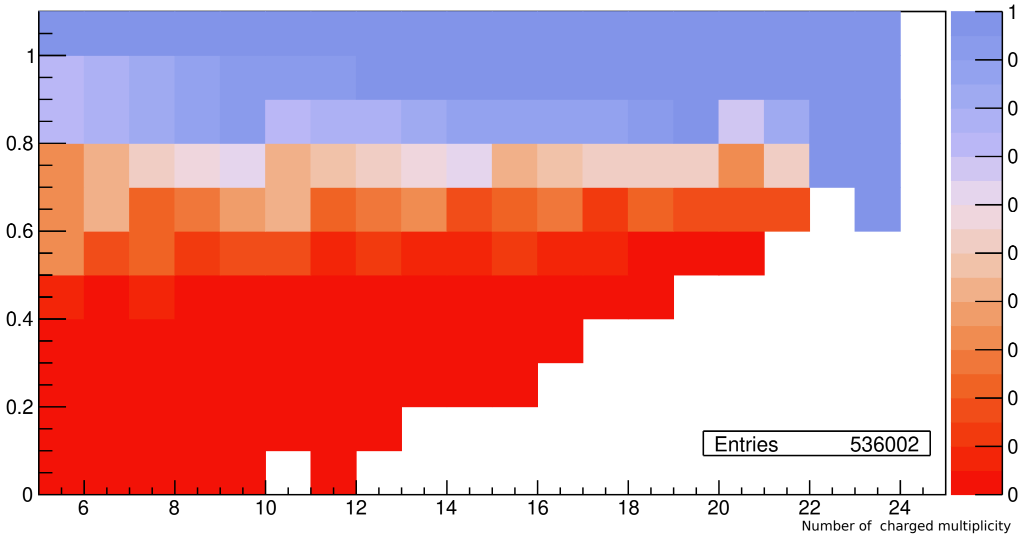

Figure 5: CDF of $\pi^{\pm}$ appearance as a function of charge multiplicity (each column is normalized to 1)

Thus the next idea is to take 60 or 70% of earliest particles in each event, because mainly it would be pions, and to determine pp–collision time t_0 by this subset of particles. Distribution of t_0 is shown on fig. 6 and on fig. 7. But the estimation of t_0 is biased. In the case of 60% the bias is in negative values as slow pions are discarded. In the case of 70% the compensated biased estimation is observed. The loss of slow pions is compensated by an admixture of heavy particles misidentified as pions.

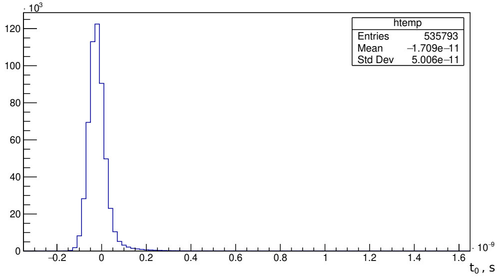

Figure 6: t_0-distribution, where only 60% of earliest tracks of event

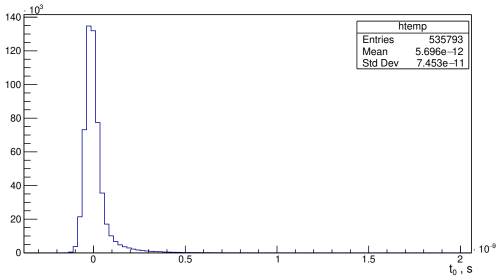

Figure 7: t_0-distribution, where 70% of earliest tracks of event

4.4 Sliding "window"

Kaons and protons are slower tha pions (fig. 3). At low momenta tof difference is more pronounced. For momentum 1.5 GeV/c kaons are delayed by about 0.2 ns with respect to pions. On fig. 8 there is the distribution of time difference between detector's time and TOF for pions and misidentified kaons for particles with momentum less than 1.5 GeV/c and with 3 or more particles in each event with this condition. The blue area corresponds to pions, the turquoise one is to kaons. Protons are out of figure's range. The most part of all corresponding tracks is clearly to be around to zero and to consists of pions. Kaons are shifted to positive values on 0.2-0.3 nanoseconds. The idea is to take the "window" with size of $6\sigma_t$ because almost 100% of pions fall into this range. This window would slide along time difference t_{diff}. It would search where the maximal number of tracks of each event lies. The pp–collision time is estimated as a mean of timings, which have fallen into the search window. The distribution of pp–collision time t_0 obtained by sliding window method is shown on fig. 9. The t_0–estimation is unbiased with resolution $\sigma \approx 32$ ps. The typical programme execution time is about 300 nanoseconds.

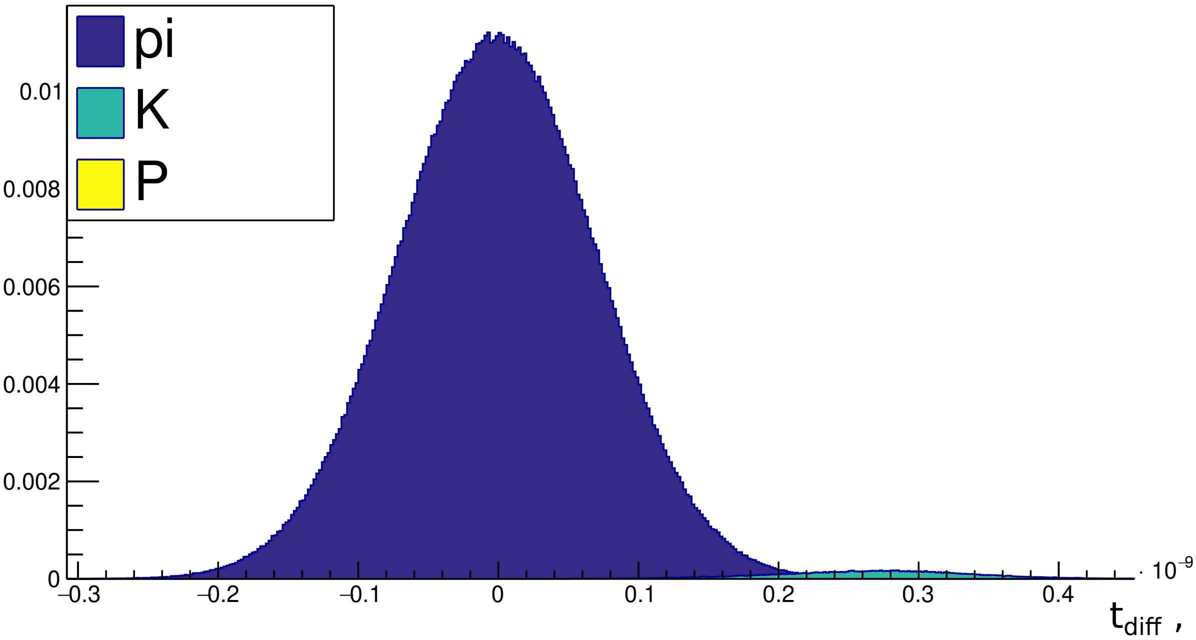

Figure 8: Distribution t_{diff} of π and misidentified K for momentum < 1.5 GeV/c and more than 3 particles in event with this condition.

4.5 Determination of an optimal momentum range

The momentum range was chosen to the estimation of the event collision time $\hat{t}_0$ to be unbiased. On the fig. 10 the upper limit p_{max} of this range is seen to be about 1.5 GeV/c. The estimation of a mean of the sample variance, determined by formula

$$\sigma_{t_0} = \sqrt{\sum_i \frac{(t_{diff_i} - t_0)^2}{n(n-1)}}\,, \tag{7}$$

is between 25 and 30 ns, what is much bigger than the error of t_0-estimation. This mean was estimated with help of fitting by normal distribution fig. 11.

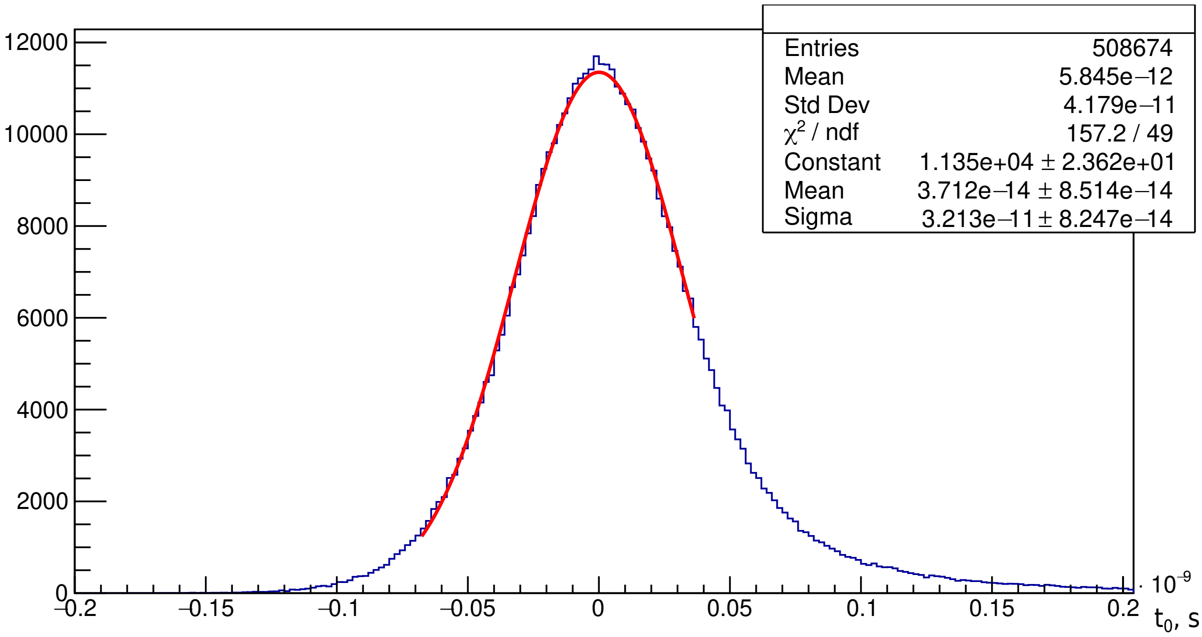

Figure 9: t_0-distribution with sliding window method

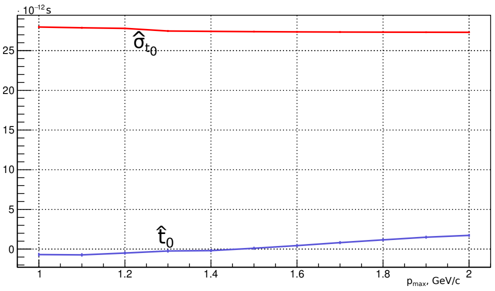

Figure 10: Dependence mean estimations of t_0 and σ_{t_0} on momentum upper limit p_{max}.

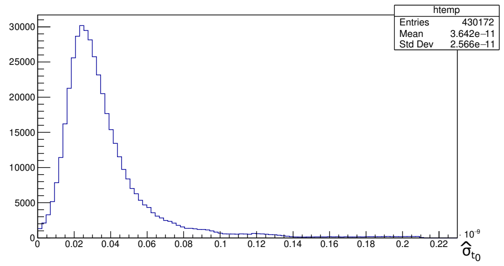

Figure 11: Distribution of sample variance $\hat{\sigma}_{t_0}$ of t_0.

On the fig. 12 the acceptance rate is shown. It is the ratio of the number of events having 3 or more particles with momentum less than p_{max} in range of $\pm 3\sigma$ to the number of events with initial restrictions (more than 5 particles moving with momenta higher than 0.5 GeV/c in each event). For momentum limit 1.5 GeV/c the acceptance rate is around 90%.

On the tab. 1 one can see the acceptance rate for different number of particles with momentum less than 1.5 GeV/c in each event. "Ratio" is the ratio of count of events with momentum less than 1.5 GeV/c and having fixed multiplicity over all number of events with initial restrictions. The third column contains the ratio of the counts of events which are in range of $\pm 3\sigma$ over all events taking part in determination of t_0. The last column shows the part of examined events to be in range $\pm 3\sigma$.

multiplicity	ratio	$\pm 3\sigma$	$\pm 3\sigma$ / ratio
3	0.103	0.089	0.864
4	0.163	0.142	0.87
5	0.176	0.157	0.892
> 5	0.558	0.514	0.921

$$ratio = \frac{N(tracks = n \; and \; 0.5 < p < 1.5 \text{ GeV}/c)}{N(\text{any } n)}$$

Table 1: Dependence of acceptance rate on multiplicity of event with selection's restrictions. Multiplicity stands for the number of charged tracks with $0.5 < p < 1.5$ GeV/c.

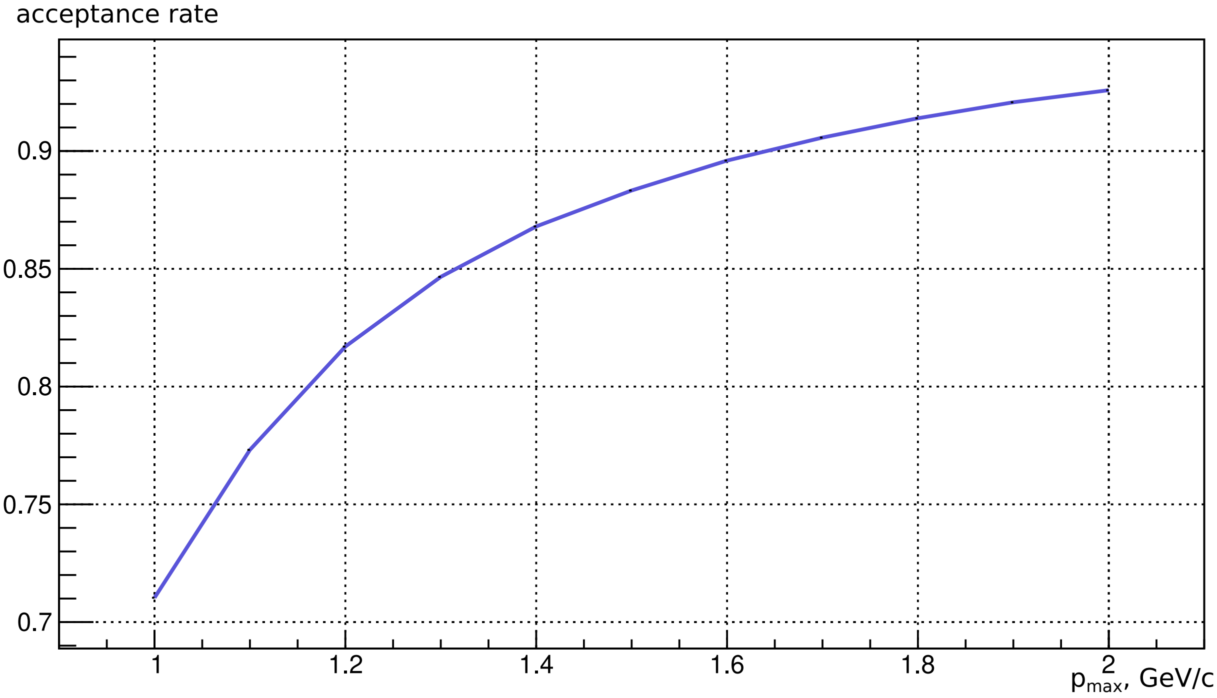

Figure 12: Dependence of acceptance rate on momentum limit p_{max}

Thus the events with higher multiplicities are characterized by better resolution and higher acceptance rate.

4.6 Particle identification

Determination of pp–collision time allows us to make particle identification (PID). The square of mass was calculated from (5) by

$$m^2c^4 = p^2c^2\left(\left(\frac{t \cdot c}{L}\right)^2 - 1\right) \tag{8}$$

The correct PID can be established up to 1.5 GeV/c for π/K-separation and up to 3.5 GeV/c for K/p-separation. One can see two artefacts on fig. 13. The first of them is a

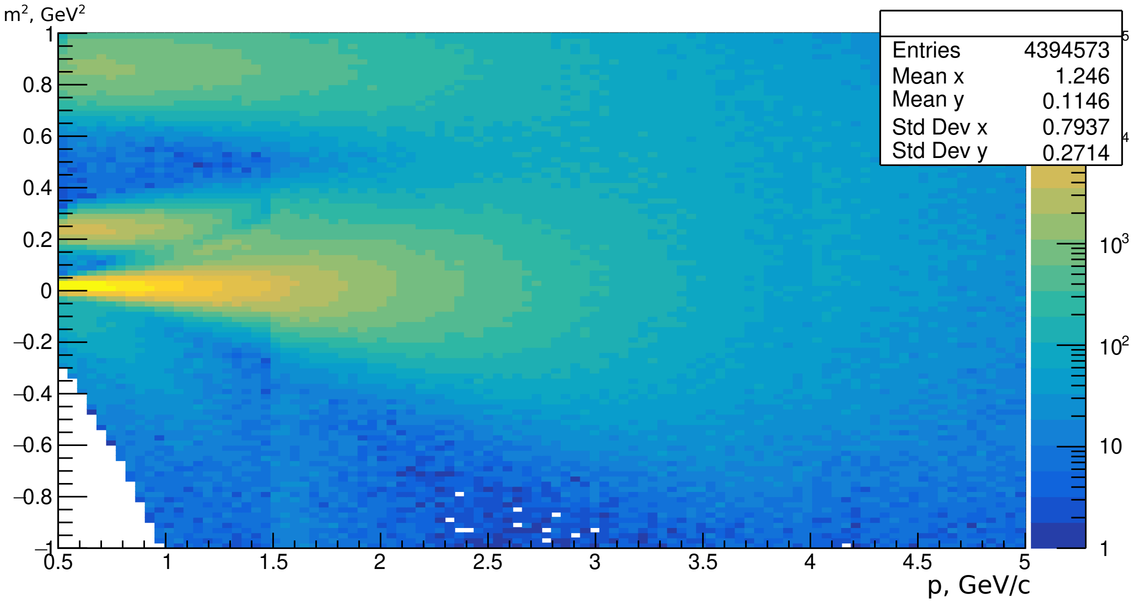

Figure 13: Dependence m^2 on p.

threshold at the momentum 1.5 GeV/c due to selection criteria. The second artefact is a dip between kaons and pions ridges due to misidentified fast kaons.

5 Results and conclusions

The typical time to find t_0 by the sliding window method is about 300 ns. This is in 10^3 times faster than by the genetic algorithm and 10^6 times faster than by the brute-force algorithm. The estimation of *pp*–collision time t_0 is unbiased with resolution $\sigma = 32$ ns. The fast determination of *pp*–collision time allows to process the high flux of input events at the SPD experiment.

6 Acknowledgements

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References

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