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

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Основная цель данной работы — найти быстрый и надежный способ определения времени столкновения протонов в эксперименте SPD. Основываясь на физике процесса, из входного потока реконструированных треков частиц мы производим выборку пионов, которая используется для вычисления несмещённой оценки времени столкновения. Точность оценки составляет около 30 пс. Метод является быстрым (не более 300 нс на одно событие) и надёжным, что позволит обрабатывать большой поток входных событий в эксперименте SPD.

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, from the input flux of reconstructed particles' tracks we identify a 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 will allow to process the high flux of input events at the SPD experiment.

PACS: 44.25.+f; 44.90.+c

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 [1]. 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 perform particle identification.

The idea of this project is to find a fast simple method to obtain an unbiased estimation of the *pp*–collision time. We incorporate a priori knowledge about the process to accelerate solution of the problem.

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Determination of *pp*–collision time

The *pp*–collision time t_0 can be reconstructed from the time measurements by the TOF detector. In the SPD experiment the TOF detector will have a cylindrical geometry: two end-caps and the barrel with the radius 1 m and the length about 3 m [1]. The detector's geometry provides a complete coverage except two circular regions around the beam pipe. A short distance between the collision point and the TOF dictates the requirement for the TOF time resolution to be better than $\sigma_t = 70$ ps. The t_0 can be determined for multitrack events, when several particles originated from the same *pp*-vertex intersect the active area of the TOF detector, thus the detector measures hit moments t_i. For *pp*-collisions at $\sqrt{s} = 27$ GeV events of interest will have multiplicity of more then 5 charged tracks. By the track reconstruction the hit in the TOF is linked to the corresponding track, its length L_i and momentum p_i will be measured by the SPD Vertex and Straw detectors. For charged particles with $p_\perp > 0.5$ Gev/c the relative precision of the momenta measurement is required to be 2%.

The expected time of flight for a particle with mass m_i reads

$$t_{\text{tof}}(m_i) = \frac{L_i}{c}\sqrt{1 + \frac{m_i^2 c^2}{p^2}} \tag{1}$$

where a mass hypothesis m_i can correspond to a charged π, K or proton. At the SPD conditions relativistic pions with momenta higher 0.5 GeV/c can not be distinguished from electrons by their time-of-flight. Other particle types are rare and corresponding mass hypotheses can be taken into account as will be shown later.

To find the *pp*–collision time t_0 in the event with n reconstructed charged tracks we minimize the sum of squared residuals between time measurements and the predicted times of particles crossings the TOF detector:

$$\chi^2(\{m_i\}_n) = \sum_{i=1}^{n} \frac{(t_0 + t_{\text{tof}}(m_i) - t_i)^2}{\sigma_t^2 + \sigma_{\text{tof}_i}^2} = \sum_{i=1}^{n} \frac{(t_0 - t_{\text{diff}}(m_i))^2}{\sigma_t^2 + \sigma_{\text{tof}_i}^2}. \tag{2}$$

If all particle types were known the estimation of *pp*–collision time is

$$\hat{t}_0 = \sum_i \frac{t_{\text{diff}}(m_i)}{\sigma_t^2 + \sigma_{\text{tof}_i}^2} \cdot \left(\sum_i \frac{1}{\sigma_t^2 + \sigma_{tof_i}^2} \right)^{-1}. \tag{3}$$

Uncertainty σ_{tof_i} in the predicted time-of-flight is mainly due to momentum resolution ($\sigma_p/p \sim 0.02$). For fast particles σ_{tof_i} is much smaller than the time resolution of the TOF detector ($\sigma_t = 70$ ps). The latter doesn't depend on the particle's type, thus a mean of $t_{\text{diff}}(m_i)$ can serve as a good estimate of the *pp*–collision time.

According to Eq. (2) the determination of *pp*–collision time is an optimization problem to minimize χ^2 as a function of t_0 and mass hypotheses

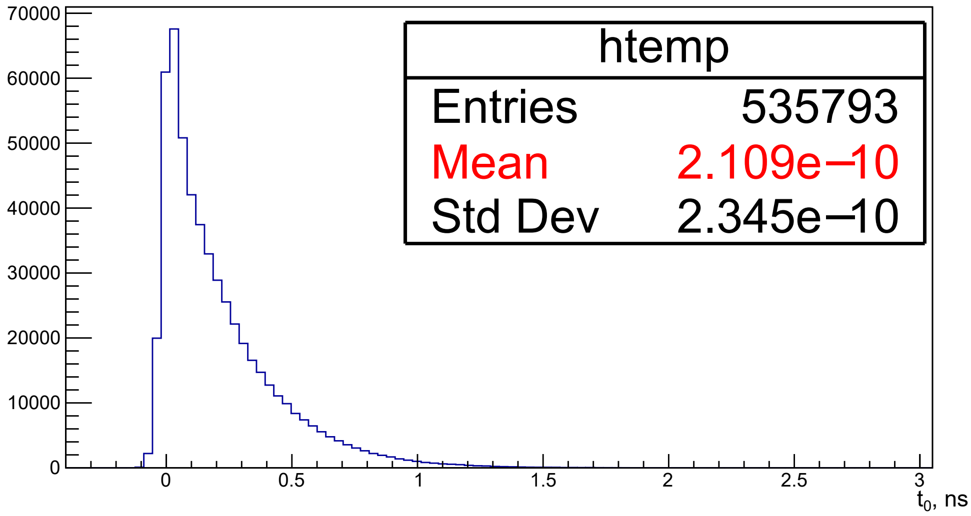

Fig. 1: t_0-distribution under hypothesis that all particles are pions.

$\{m_i\}_n$ for reconstructed charged tracks in the event. One can try to solve (2) by a brute-force search, which checks all possible combinations of particles and selects the one with the minimal χ^2. Even if only three types of particles are allowed ($\pi/K/p$), the brute-force algorithm has too high complexity of $O(3^n)$ operations, thus it takes up to few seconds to find the minimum for events with higher multiplicity. To avoid an exhaustive search one can try to combine tracks in subgroups and finds a near optimal solution faster, this approach was applied in works [2] and [3]. Another direct approach is to incorporate some optimization algorithm, which will shuffle through the parameter space towards the minimum. In the following we report how an a priori knowledge about the physics of the pp-collisions can be used to accelerate solution of the problem.

Physics motivations and the "Sliding window" method

Pions are most abundant secondary particles originated from inelastic pp-collisions at $\sqrt{s} = 27$ GeV. Instead of checking all possible mass combinations in eq. (2), one can attribute the pion mass to every charge particle in order to estimate the time of pp-collision. Without surprise the distribution of reconstructed $\hat{t}_0$ exhibits a big tail in this case (fig. 1). As masses of misidentified kaons or protons are replaced by the smaller pion's mass, their estimated time-of-flights are shifted to shorter times, thus this simplification results in $\hat{t}_0$ estimations biased to delayed values. The difference in time-of-flight between heavier particles and the pion is more pronounced at softer momenta, while relativistic particles can not be distinguished by their TOF at short distances between the collision point and the TOF detector at the SPD (fig. 2).

For momentum $p_{\max} = 1.5$ GeV$/c$ kaon's time-of-flight is by about 0.2 ns longer than for the pion with the same momentum. Even slower kaons are delayed by more than $3\sigma_t$ with respect to pions (fig. 3). If one sorts all

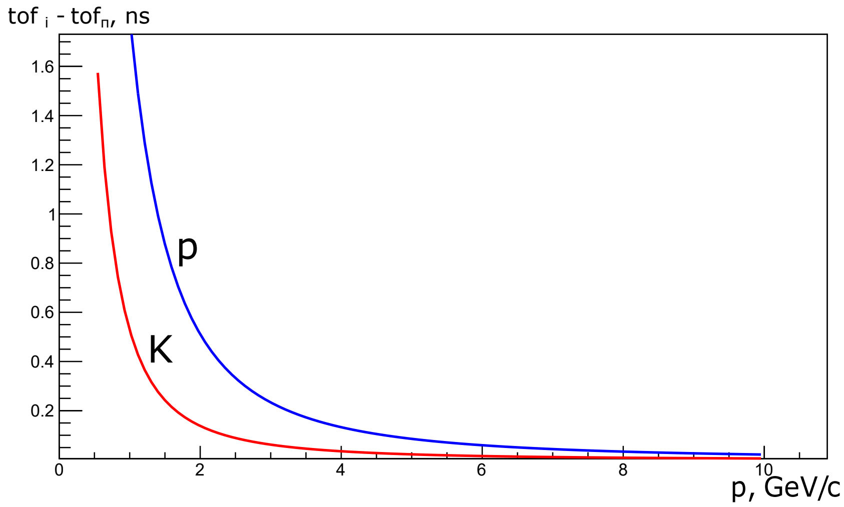

Fig. 2: Difference in time-of-flight between kaons and pions (solid line), protons and pions (dashed line)

reconstructed particles with momenta below 1.5 GeV/c by their $t_{\rm diff}$ under pion's mass hypothesis, pions will be at the lower range and almost all of them fall into $\pm 3\sigma_t$ range around unknown t_0. At the same time misidentified heavy particles will be delayed by at least $3\sigma_t$ and scattered. As the next step one can slide a window of the $6\sigma_t$ length along the sorted $t_{\rm diff}$ in order to identify a window's position with the most $t_{\rm diff}$ inside it. As pions are by far most abundant secondaries, in most events the tracks inside the found range will represent a pure pions sample. Then the pp–collision time is estimated as a mean of timings, which have fallen into the $6\sigma_t$ window. The method requires at least 3 tracks to be within the search window, about 90% of events fulfills this criterion.

The distribution of pp–collision times $\hat{t}_0$ obtained by the sliding window method is shown in fig. 4. The $\hat{t}_0$-estimation is unbiased with resolution about 32 ps. The sliding window methos allows to provide pp-collision time for track reconstruction and for particle identification by TOF. The typical programme execution time is about 300 ns. Thus the sliding window method allows to process a high flux of input events at the SPD.

The momentum range was chosen in the way the estimation of the event collision time $\hat{t}_0$ to be unbiased. The estimation of a mean of the sample variance (for tracks within the $6\sigma_t$-window) as a function of the upper momentum limit $p_{\rm max}$ is shown in fig. 5. It's value is consistent with the fit result in fig. 4. As the crosssection of pions inclusively produced in pp-collisions is peaked at momenta below 1 GeV/c, the increase of the upper limit $p_{\rm max}$ will only slightly improve the statistical uncertainty of the $\hat{t}_0$ estimations. But an increase of $p_{\rm max}$ will introduce a bias towards delayed $\hat{t}_0$ due to misidentified kaons.

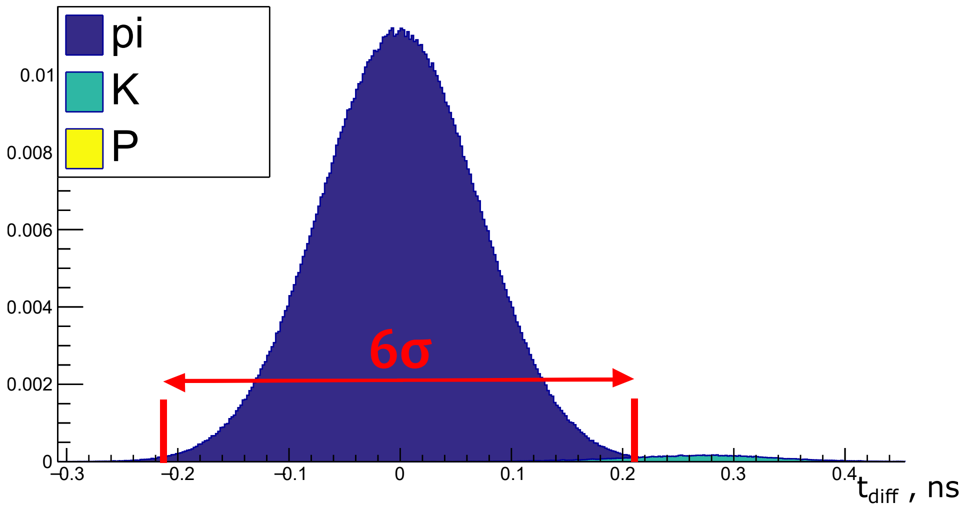

Fig. 3: Distribution of slow t_{diff} of π and misidentified K with momentum < 1.5 GeV/c and more than 3 slow reconstructed particles in event. Protons are out of figure's upper range on t_{diff}.

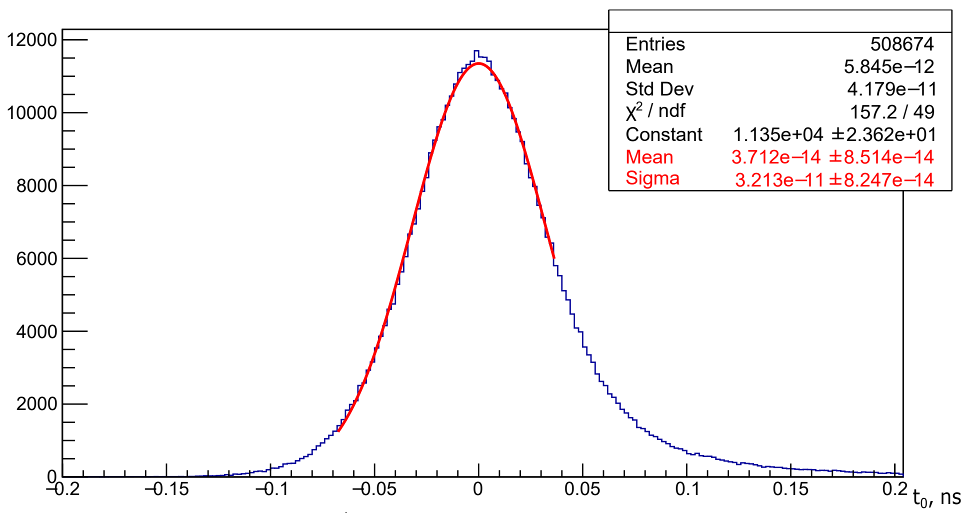

Fig. 4: Reconstructed $\hat{t}_0$-distribution by the sliding window method

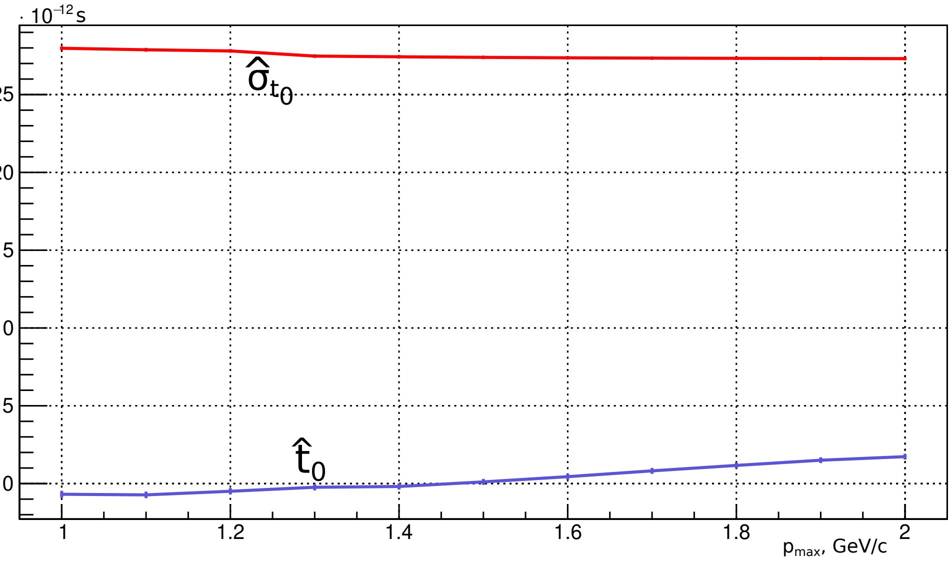

Fig. 5: Mean estimations of $\hat{t}_0$ and $\sigma_{\hat{t}_0}$ as functions of the upper momentum limit $p_{\max}$.

Results and conclusions

In this work we propose the sliding window method to reconstruct time of *pp*-collisions from the measurements by the SPD TOF detector. From the input flux of reconstructed tracks we identify a pure sample of pions which is used to calculate the unbiased estimation of the event collision time with resolution about 32 ns. The sliding window method can provide *pp*-collision time for track reconstruction and for particle identification by their time-of-flight. The typical time to find t_0 by the sliding window method is about 300 ns. The fast determination of *pp*-collision time allows to process the high flux of input events at the SPD experiment.

This work was made by the grant of the START programme at JINR. Authors would like to thank Semyon Yurchenko and other members of the SPD Collaboration for fruitful discussions and support.

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