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A concept of the transition radiation detector for a hadron separation in a forward direction of the LHC experiments

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Abstract.
Studying of hadron production in forward direction at the LHC energy has a great interest both for understanding of the fundamental QCD processes and also in applied areas such as the description of ultra-high energy cosmic particle interactions. The energies of secondary hadrons in such studies almost reach the maximum energy available at the LHC of ∼6 TeV, which corresponds to a Lorentz γ-factor up to 10^4 and above. The only effective technique able to identify particles in this range is based on the transition radiation detectors (TRD). Prototypes of such kind of detector were built and tested at the CERN SPS accelerator. Some experimental results obtained in these tests are briefly presented here and compared with Monte Carlo (MC) simulations. MC model demonstrates a good agreement with the experiment. On this basis a concept of a full-scale TRD optimized for the hadron identification in the TeV energy region is proposed. Different particle identification techniques were considered and examined. The expected detector performance to reconstruct secondary hadrons produced in forward direction at the LHC is presented.

1. Introduction
With growing energies of particles at modern and planned accelerator experiments as well as in various cosmic-ray experiments there is a need to identify particles including hadrons with Lorentz γ-factors up to $\sim 10^5$. An example of such an experiment can be the measurement of the inclusive cross sections in the forward region for the production of charged particles in proton-proton, proton-nucleus and nucleus-nucleus interactions at the center-of-mass energies of 14 TeV [1]. In these collisions, secondary hadrons (mainly pions, kaons and protons)

are produced with momenta in the TeV range. Since in this energy scale the hadrons have the velocities $1-\beta < 10^{-5}$, the only particle identification technique able to effectively separate hadrons is based on the properties of the X-ray transition radiation (TR) production.

A typical TRD consists of a multi-foil radiator followed by an X-ray (usually gaseous) detector. Most of the existing TRDs are designed to separate electrons from hadrons and they use the threshold effect of the TR production. In these detectors the TR yield starts to be significant at γ-factor of $\sim 5\times10^2$ and saturates due to interference effects in multi-foil radiators already at $\sim 2\times10^3$. But with the increase of particle energies at modern or planned experiments particle identification (PID) at much higher γ-factors is required. Main characteristics of emitted TR are defined by radiator parameters: foil thickness l_1, distance l_2 between foils and plasma frequency w_1 of the foil material. Both the threshold and saturation γ-factors are functions of these parameters: $\gamma_{\rm thr} \sim l_1 w_1/c$ and $\gamma_{\rm sat} \sim 0.6\sqrt{l_1 l_2}/c$ respectively. By changing the parameters of the radiator, the sensitivity of a TRD can be tuned to a certain γ-factor range.

In order to study these possibilities in detail, a dedicated TRD prototypes based on straw proportional tubes were built and tested at the CERN SPS accelerator. The response of TRD prototypes equipped with several types of radiators to particles with different γ-factors was studied. On the basis of obtained experimental data, a Monte Carlo model was developed, which includes a detailed description of the detector response. In this paper we present some results of test-beam measurements and compare them with MC simulation results using the developed simulation model. On this basis a concept of a full-scale TRD optimized for the hadron identification in the TeV energy region is proposed. Different particle identification techniques were considered and examined. The expected detector performance to reconstruct secondary hadrons produced in forward direction at the LHC is presented.

2. Test beam measurements

The TRD prototypes with different detector geometry and various radiators were produced and tested on CERN SPS accelerator with several types of beam particles: 20 GeV pions and electrons, and muons with 120, 180 and 290 GeV energy, covering Lorentz factor range from ≈ 140 to $\approx 3.6\times10^4$. A typical experimental set-up and schematic view of the TRD prototype are shown in figure 1. In this set-up beam particles crossed 22 layers of thin-walled proportional chambers (straws) of 4 mm diameter filled with Xe/CO_2 (70%/30%) gas mixture. Similar straw chambers are used in the Transition Radiation Tracker [2] of the ATLAS experiment [3] at the LHC. TR and $\mathrm{d}E/\mathrm{d}x$ energy deposition in straw gas were measured by QDCs, calibrated using Fe^{55} source.

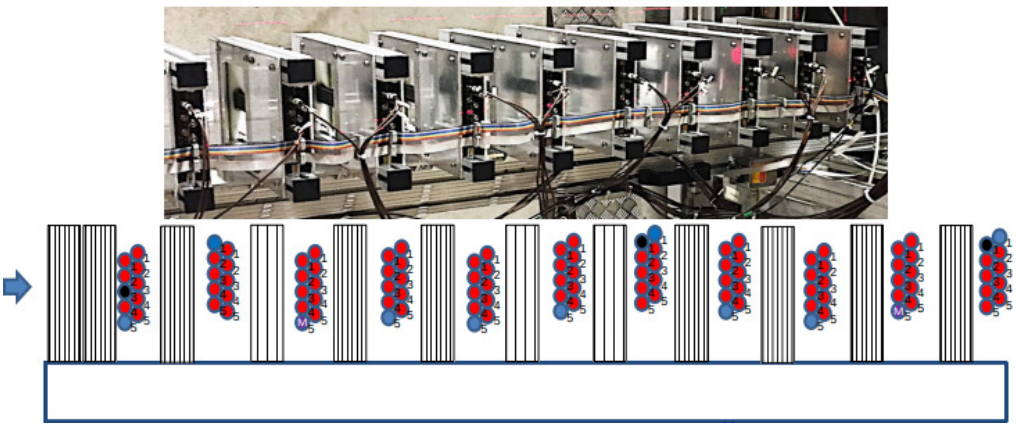

Figure 1. Photo and schematic view of the TRD straw prototype.

More details about test beam measurements with different TRD prototypes, radiators and gas mixtures can be found in [4–7].

3. Monte Carlo simulation and comparison with test beam data

A dedicated and reliable model of the detector operation is a very important component of the detector development at any stage. In order to describe in detail the performance of tested TRD prototypes, Monte Carlo simulations were performed. The MC program includes detailed descriptions of the detector geometry and the materials (radiator blocks and straw tubes, including straw walls and anode wires). It simulates the production of TR photons in radiators and their absorption in materials and in the working gas based on the approaches described in [8]. Ionization losses ($\mathrm{d}E/\mathrm{d}x$) in the detectors are simulated using PAI model [9]. In order to obtain a good agreement with measurements, some apparatus effects which have essential influence on the observed data must be taken into account. TR generation on the straw walls, photo- and delta-electrons path in the active gas in straws, space charge effects in the electron amplification process near the anode wire, were considered in the Monte Carlo model. More detailed description of the MC program can be found in [6, 10].

A comparison of the simulation results and experimental data was done for all tested TRD prototypes with different radiators and beam particles. As an example, spectra of energy registered in straws for set-up with Mylar radiators for different beam particles are shown in figure 2. A good agreement between data and MC is observed. Such comparisons have been done for other detector configurations, radiators, and gas mixtures as well – more examples can be found in [6,7,10]. Good MC/data agreement for differential and integral spectra of the energy loss in the detector for any tested experimental conditions gives a confidence in the simulation results of a full-scale TRD for the TeV energy range hadron identification.

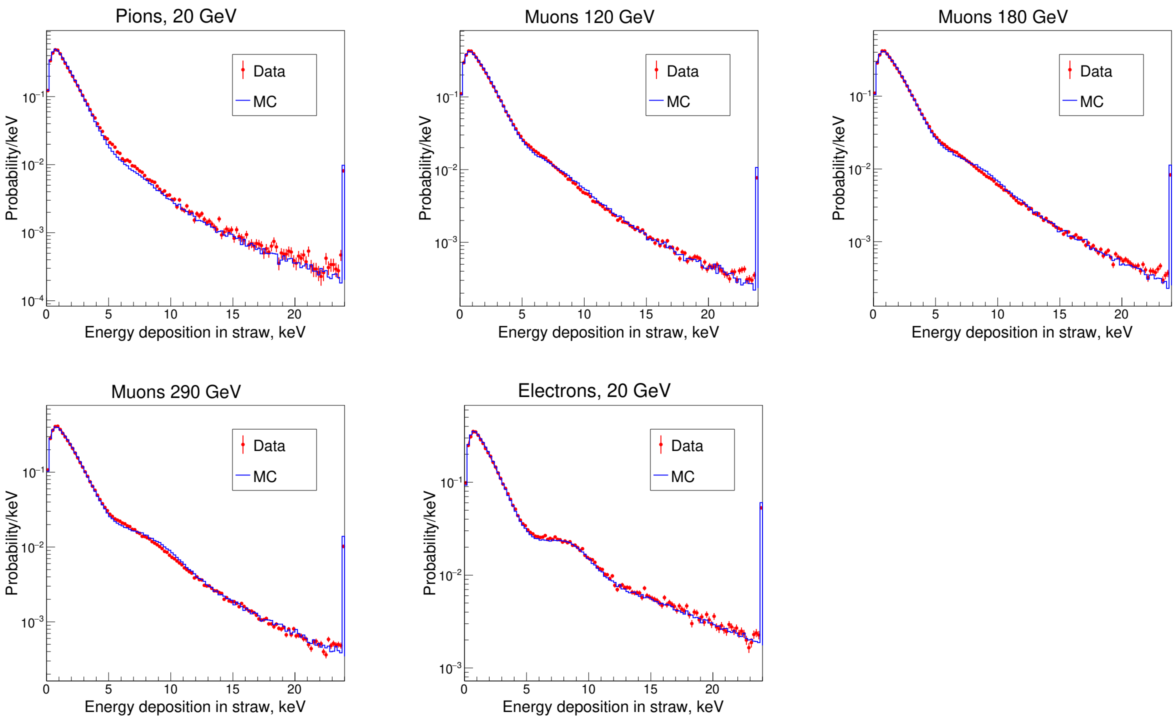

Figure 2. Comparison of experimental and simulated energy spectra registered in the straws with Mylar radiators and different beams. Right-most bins of histograms include overflow.

4. LargeTRD concept and performance

As it was already mentioned, a TRD operation range is mainly defined by the radiator parameters. Changing the radiator foil thickness and the distances between foils, one can tune detector sensitivity to a certain γ-factor range. Generally an increase of the TR generation threshold and saturation point requires an increase of the foil thickness. There is no a single radiator design which can cover a wide range of γ-factors for hadron identification. For this reason a use of radiators with different parameters is required.

One of the possibilities to expand the γ-factors range is to exploit a knowledge about the energy of TR photons. TR energy spectrum has many maxima and each maximum has its own γ-factor dependence. This feature can be used to build a single detector which has a few γ-factor responses and could significantly enhance the TRD performance. In any case, in order to produce a sufficient number of TR photons the set-up should contain quite a large number of radiator-detector blocks.

Based on the above considerations, several possible configurations of TRD for hadron identification in TeV energy scale were simulated using our fine-tuned MC model. The expected performance of one of the options is presented below.

The full scale TRD consists of two sub-detectors with different properties. Sub-detector 1 contains 50 sets of radiator interleaved with double straw layers (100 straw layers in total). Each radiator has 30 polyethylene (PE) foils of 25 μm thickness spaced by 500 μm. Second sub-detector has 100 sets of radiator followed by double straw layers (200 straw layers in total). In this detector each radiator is made from 12 PE foils of 75 μm thickness spaced by 3 mm. TR photons produced in this radiator have a relatively high energy (up to 30 keV and above). In order to increase a photon absorption efficiency, the working gas pressure in straws was chosen to be 1.5 bar (abs). A total length of the proposed set-up containing two sub-detectors is 6.3 meters.

MC simulation takes into account electromagnetic and nuclear interactions in the detector materials, multiple scattering, TR photons production and absorption, $\mathrm{d}E/\mathrm{d}x$ losses in the working gas, path of secondary particles (photo- and delta-electrons) in the working gas volume etc. PID methods are based on calculation of the number of straws on the particle track with energy deposition belonging to some energy intervals. The probability to get a hit in straw from a few keV to a few tens of keV depends mainly on the number and on the energy of absorbed TR photons with some contribution of delta electrons produced by ionizing particle. Three types of hit straws are considered: in the first sub-detector with the energy deposition above 6 keV, and in the second sub-detector – with the energy deposition in the range of 8–17 keV and above 17 keV. A probability to have hits in these intervals have different Lorentz-factor dependencies. Figure 3 shows the mean number of straws in the LargeTRD with hits in these energy intervals as a function of particle energy for three types of particles: pions, kaons and protons. The different detector response for the three types of hadrons is clearly visible.

There are two types of tasks for particle identification in experiments which use different PID approaches. One of them is the identification of the particle type in each individual event. Another one is related to integral measurements such as of a beam composition determination or measurements of the proportion of each particle type produced at certain conditions (inclusive cross section or momentum spectra measurements).

For the particle identification in individual events we use a maximum likelihood method. A likelihood value for each particle type hypothesis is defined as a product of three probabilities: $L_i = P_{1i}P_{2i}P_{3i}$, where the i index corresponds to hadron type: π, K, or proton, and P_1, P_2, P_3 are probabilities to have numbers of hits in straws in the energy intervals as it was defined above. The particle type is chosen on the basis of the maximum value of L_i. The PID efficiency is defined as the fraction of particles of a given type that are identified correctly with this method. Figure 4 shows the PID efficiency for different types of particles as a function of particle energy.

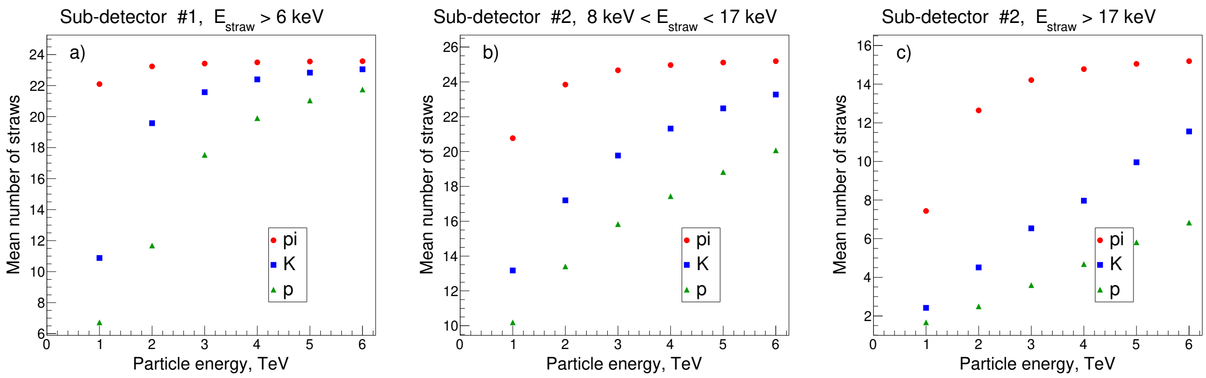

Figure 3. Dependencies of number of straws with high energy deposition on registered particle type and energy. a) first sub-detector, $E_{\mathrm{straw}} > 6$ keV, b) second sub-detector, 8 keV $< E_{\mathrm{straw}} <$ 17 keV, c) second sub-detector, $E_{\mathrm{straw}} >$ 17 keV.

In general, efficiency are reduced with increasing of particle energy due to a TR yield saturation at high γ-factors. Kaons have the lowest PID efficiency because of intermediate mass value and, as a consequence, high probability to be misidentified as a π or as a proton.

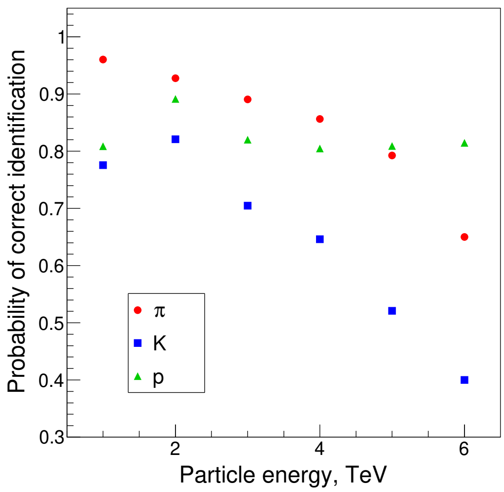

Figure 4. Fraction of correctly identified hadrons of different type as a function of particle energy.

PID in individual events is a key element for the reconstruction of a type and a mass of particle using its decay products. Figure 5 shows an example of the invariant mass reconstruction of D^0 meson produced in a forward direction at LHC using products of $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ decay with the proposed TRD setup. One sees that it allows to increase signal/background ratio in D^0 peak region from $\sim$ 0.02 to 0.21, with D^0 reconstruction efficiency of 74%. Note that the remaining background under D^0 peak is dominated by an irreducible combinatorial $\mathrm{K}^-\pi^+$ pairs.

Another important task of the LargeTRD is the reconstruction of the composition of particles produced in the forward region of the LHC. For this purpose another PID method based on the Bayesian approach [11] was used. In this method the values of the so-called priors, which serve as a 'best guess' of the true particle yields per event are determined with an iterative procedure. More details concerning this method implementation can be found in [7].

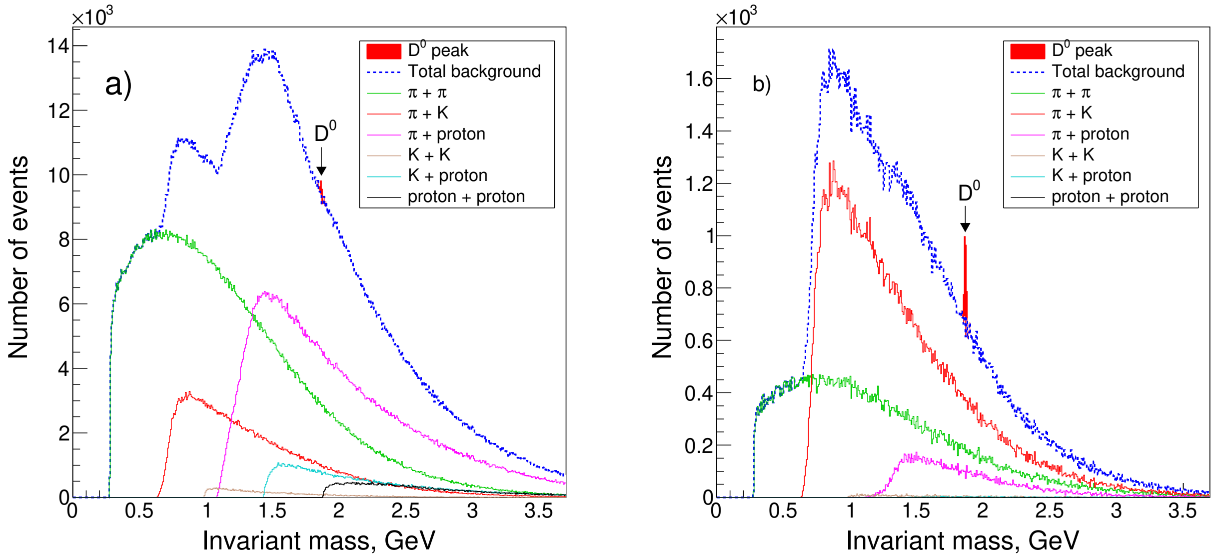

Figure 5. Invariant mass of opposite-charged hadron pairs: peak of $D^0 \to K^-\pi^+$ decay with the yield of different combinatorial background. (a) all before particle identification, (b) after identification of $K^-\pi^+$ pairs with the LargeTRD.

Simulation results of hadron composition reconstruction for positively and negatively charged particles produced in a forward direction of LHC is shown in figure 6. One sees that the LargeTRD with described approach allows to reconstruct the particle compositions even though they differ by about two orders of magnitude.

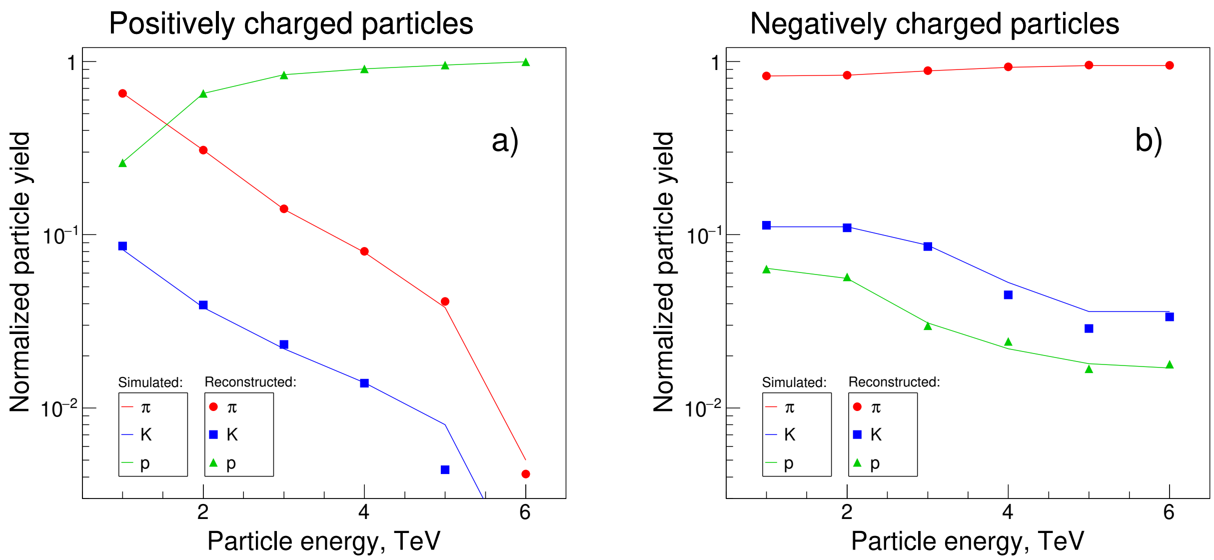

Figure 6. Hadron composition reconstruction in the LargeTRD with the Bayesian method. The lines indicate the fraction of particles generated in p-p collisions in the planned study of charged hadron production (MC), the markers – reconstructed fraction of particle of different types. (a): positively charged particles, (b): negatively charged particles.

5. Conclusions

A concept of large-scale TRD for identification of TeV energy hadrons produced in forward direction at the LHC is proposed and simulation results are presented. The performance simulation of this detector is based on the MC model which describes well the experimental results obtained with the detector prototypes. Detector parameters were tuned for effective particle identification both in individual events and for reconstruction of integral particle composition at different energies. It was demonstrated that the proposed detector allows to reconstruct the hadron composition with the high accuracy in the TeV energy range, and also allows to improve the signal-to-background ratio for reconstruction of events like $\mathrm{D}^0 \to \mathrm{K}^- \pi^+$ by one order of magnitude.

Acknowledgments

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