JOINT INSTITUTE FOR NUCLEAR RESEARCH

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Geant4 FTF generator validation on proton-proton experiment data

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Abstract

Recently, the NA61/SHINE collaboration has published experimental data on proton-proton interactions at the wide energy range of projectile protons from 20 GeV/c up to 158 GeV/c [1]. The authors have compared the data with various model calculations (UrQMD 3.4, EPOS 1.99). It was also found in the literature that there is no one model that can describe all these data. Among them there was not Geant4 FTF model. For verification of the FTF model of the Geant4 toolkit [2], we have performed simulations of the proton-proton interactions at various energies.

Geant4 FTF generator was implemented in SPDRoot [3] before. SPDRoot is a software of the future experiment – Spin Physics Detector (SPD) [4] at the NICA collider. Particle collisions in SPDRoot can be simulated by various models such as Pythia, FTF, UrQMD and others. In this report, we show comparison of model calculations with the pointed experimental data on proton-proton interaction at various energies. We conclude that FTF model of the Geant4 toolkit can describe the proton-proton experimental data quite well.

At the end, it will be presented the FTF model simulation of charmed particles production in proton-proton collisions in a comparison with the corresponding experimental data.

Our calculations have been done inside the SPDRoot software installed at HybriLIT cluster of LIT, JINR.

1 Introduction

In 2017 [1], the NA61/SHINE collaboration published experimental data on pp interactions at various projectile momenta: 20, 31, 40, 80, 158 GeV/c. The plots in Fig. 1 present rapidity distribution of protons, π^+, π^-, K^+, K^- mesons at P_{lab} =20 GeV/c. Points are experimental data with statistical errors, shadowed bands show systematic errors. The authors of the cited paper compared their data with calculations by UrQMD and EPOS models (Fig. 1). As one can see, UrQMD strongly underestimates the experimental data, whereas the EPOS model gives more accurate calculations, however they are far away from ideal ones.

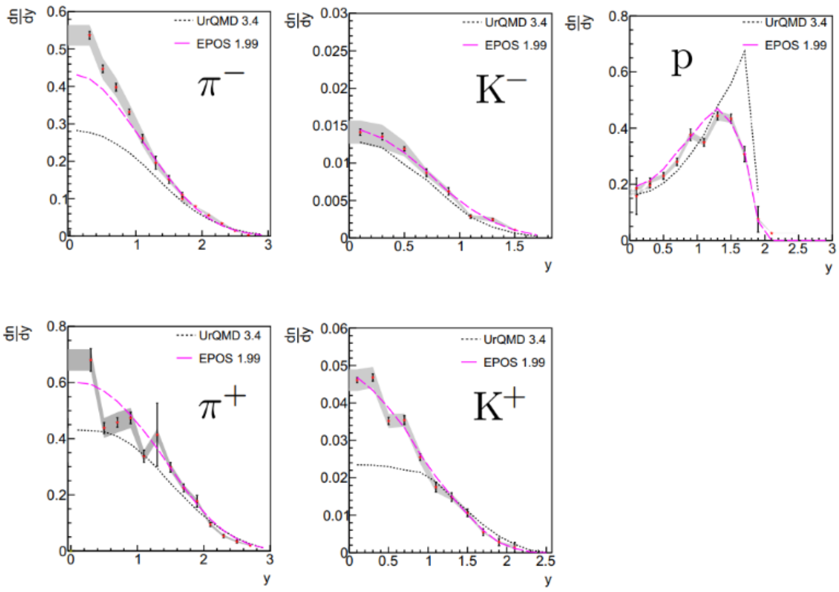

Figure 1: Rapidity distribution of $\pi^+, \pi^-, K^+, K^- andp$ produced in inelastic $p+p$ interactions at 20 GeV/c. Calculations by EPOS (dashed lines) and UrQMD (dotted lines) models were performed by the collaboration.

There is a little bit better situaltion at energy equal to 31 GeV (Fig. 2). There are still problems with K^+ mesons, though other particle estimations are closer to the data. UrQMD model gives a higher yield of anti-protons than the experimental data. Also, I want to emphasize that we have terrible UrQMD results for anti-protons at any observed energy.

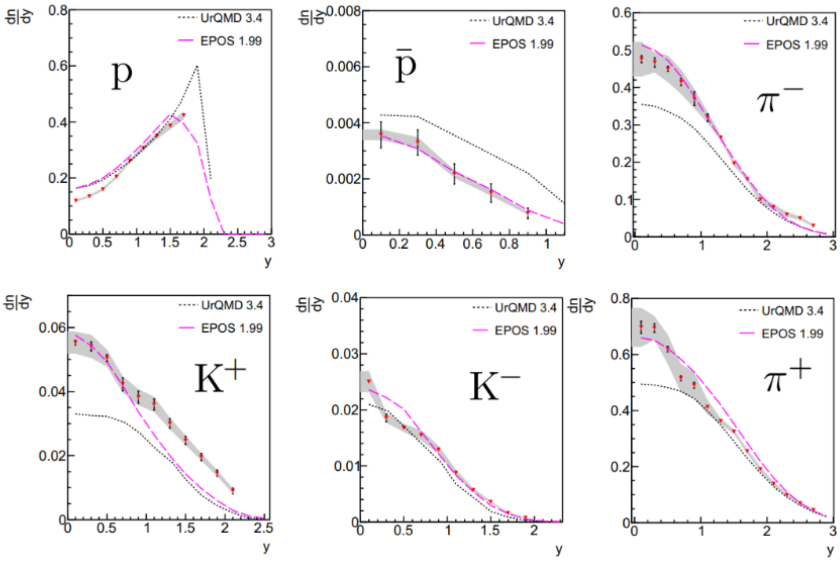

Figure 2: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 31 GeV/c. Calculations by EPOS (dashed lines) and UrQMD (dotted lines) models were performed by the collaboration.

Nearly the same situation was observed for the particle productions at 40, 80 and 158 GeV/c [1], except the fact that K^- estimation accuracy increases with energy growth for the UrQMD model.

Recently, the same experimental data have been compared with calculations by PHSD and Pythia models [5]. This comparison is shown on the Fig. 3. The first row shows proton rapidity distributions at various CMS energies. As seen in the Fig. 3, the Pythia model doesn't describe the proton and anti-proton rapidity distributions at all energies. The differences between the data and the calculations are smaller for K^+ and K^- mesons. The model becomes quite accurate for π^+, π^- mesons. At the same time, the PHSD model gives more satisfactory estimations, however, it gives wrong shapes of the distributions for protons at 6.2, 7.6, 8.8 GeV and overestimates the experimental data at 12.3 and 17.3 GeV.

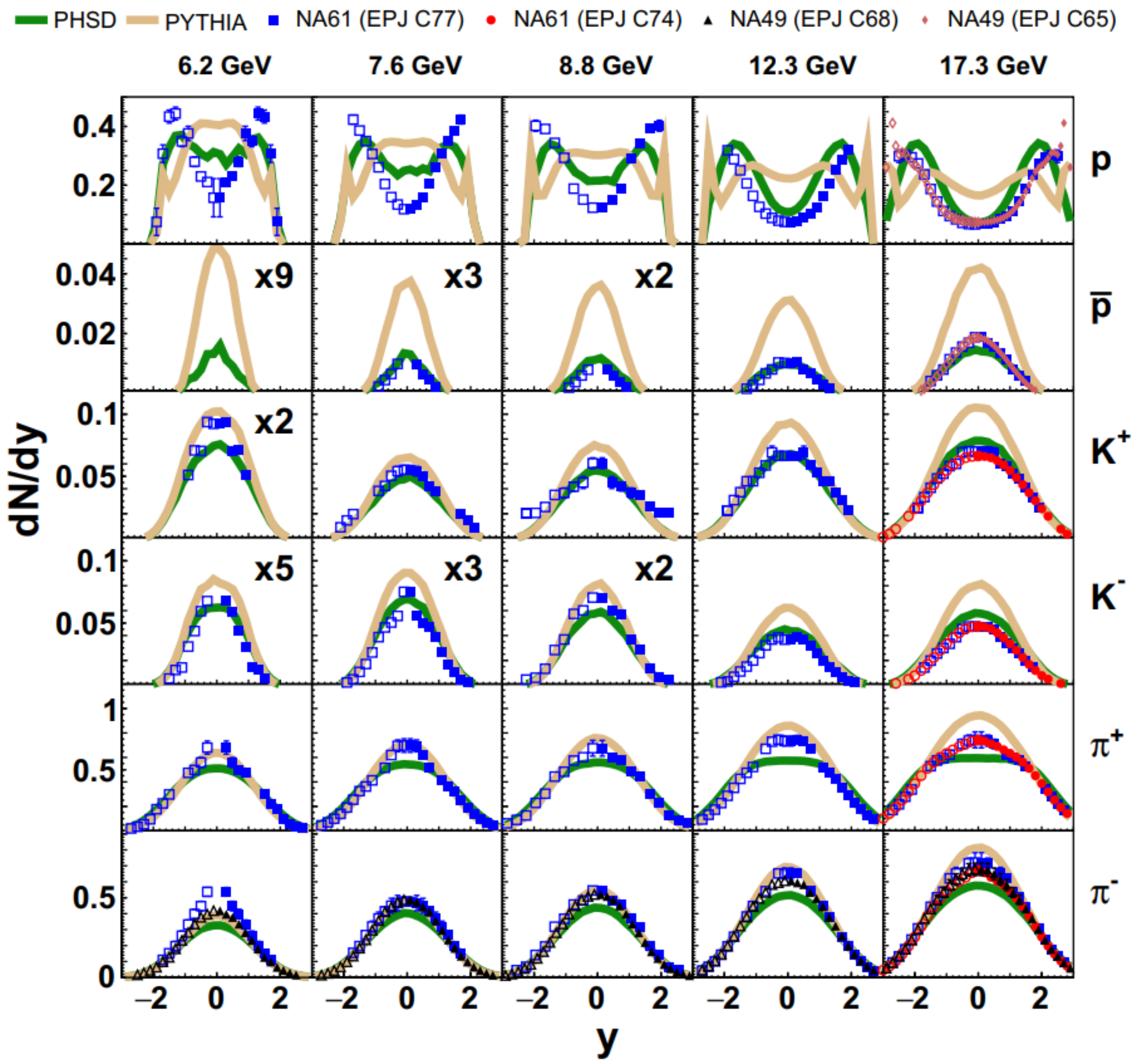

Figure 3: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at various energies (given in CMS). Calculations were obtained by Pythia (yellow lines) and PHSD (green lines) models.

2 FTF generator results for proton-proton interaction and comparison with NA61/SHINE data

For simulations of realistic proton-proton events, we used the FTF generator of the Geant4 toolkit [2]. Geant4 is a huge package aimed to simulate elementary particles interactions with matter. It is applied in many branches of science and technology. The Geant4 FTF model is based on the Fritiof model [6], [7] of the LUND university. Main assumptions of the Fritiof model are quite simple. It is assumed, that hadrons turn into excited states due to inelastic interactions. Excited states of hadrons are characterized by masses. Usually, masses are increased at excitations. The excited states are considered as quark-gluon strings.

For decay and fragmentation of the quark-gluon strings, the Lund fragmentation model is used.

For validation of the Geant4 FTF model in SPDRoot, we installed current version of SPDRoot at HybriLIT cluster of LIT JINR. For installation, we used external libraries: **FairSoft/apr21patches**, **FairRoot/v18.4.2**. In the frame of SPDRoot, simulations of proton-proton interactions at initial projectile momenta 20, 31, 40, 80 and 158 GeV/c by the FTF generator have been done.

The following figures – Fig. 4, Fig. 5, Fig. 6, Fig. 7 and Fig. 8 show our simulation results in a comparison with the experimental data of the NA61/SHINE collaboration.

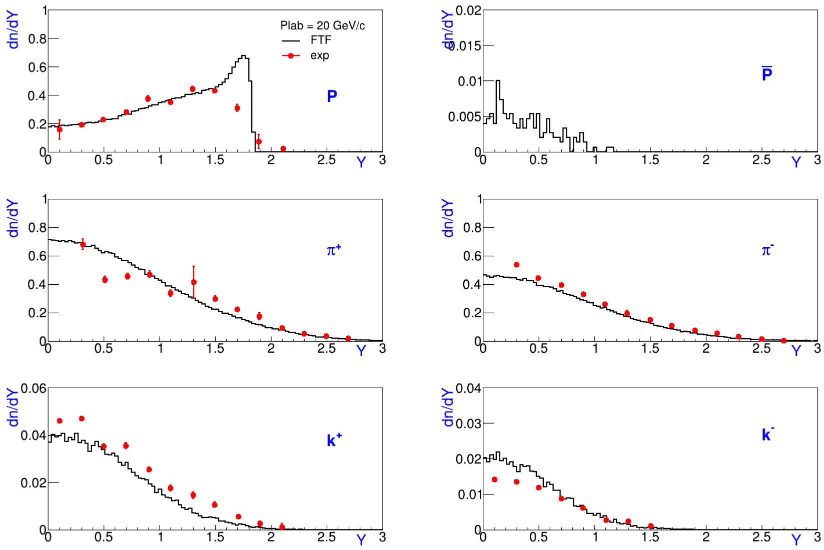

Figure 4: Rapidity distributions of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 20 GeV/c. Calculations were obtained by FTF (black lines) model. Red points represent the experimental data.

As one can see, experimental data on anti-protons are absent at initial projectile momenta 20 GeV/c due to low energy. The experimental data on protons, π^+ and π^- mesons are described quite well at all energies. There are some disagreements of the model calculations with the experimental data on K^+ and K^- mesons.

The differences between the experimental data and the FTF calculations on K+ and K- mesons decrease with the energy increasing, as it can be seen in Fig. 5, Fig. 6, Fig. 7 and Fig. 8.

The experimental data on rapidity distributions of π^+ and π^- mesons are in good agreement with the FTF calculations at the projectile momenta 20, 30, 40, 80 GeV/c. At the initial momentum 158 GeV/c, the FTF model underestimates

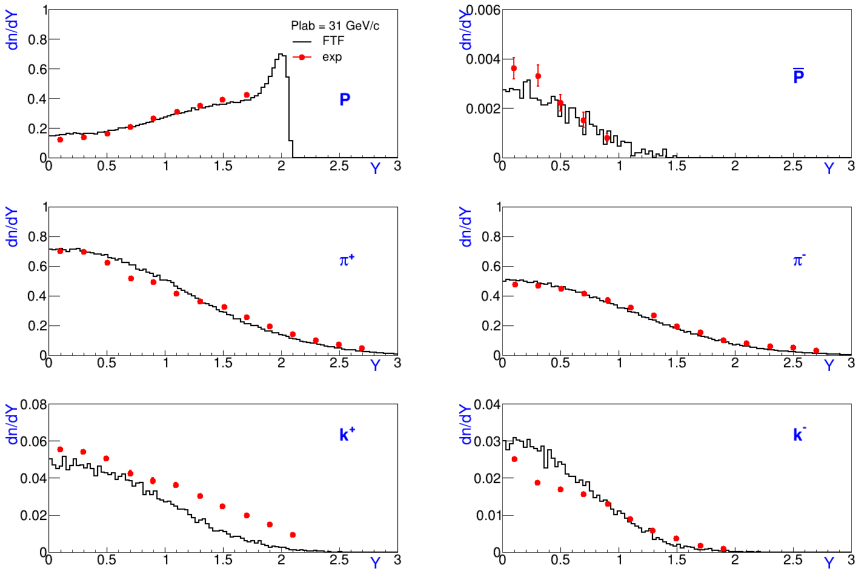

Figure 5: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 31 GeV/c. Calculations were obtained by FTF (black lines) model. Red points represent the experimental data.

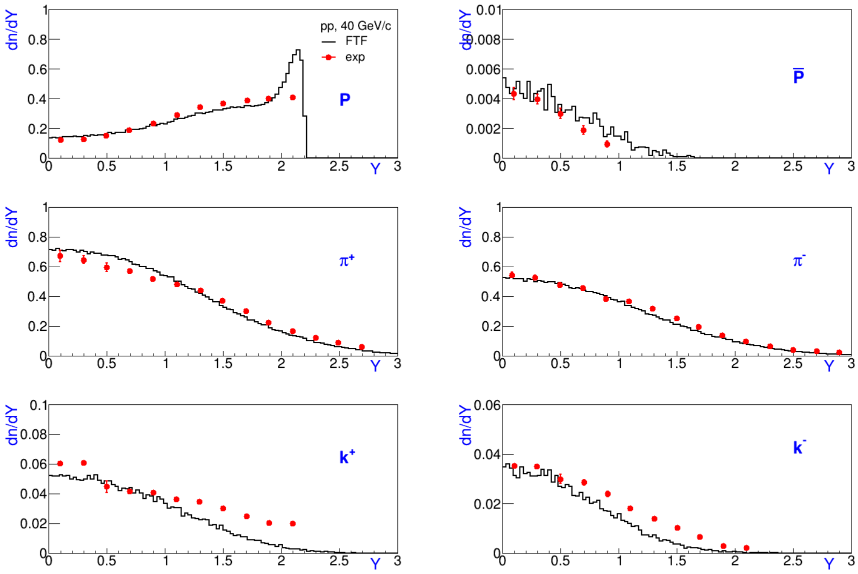

Figure 6: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 40 GeV/c. Calculations were obtained by FTF (black lines) model. Red points represent experimental data.

the yield of π^- mesons.

On the whole, we can conclude the FTF model works quite well in a wide energy range for pp interactions.

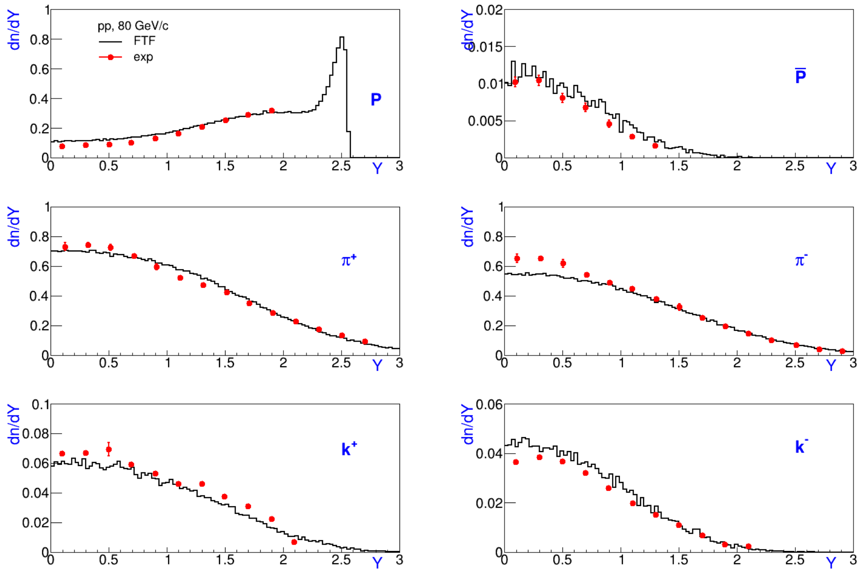

Figure 7: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 80 GeV/c. Calculations were obtained by FTF (black lines) model. Red points represent experimental data.

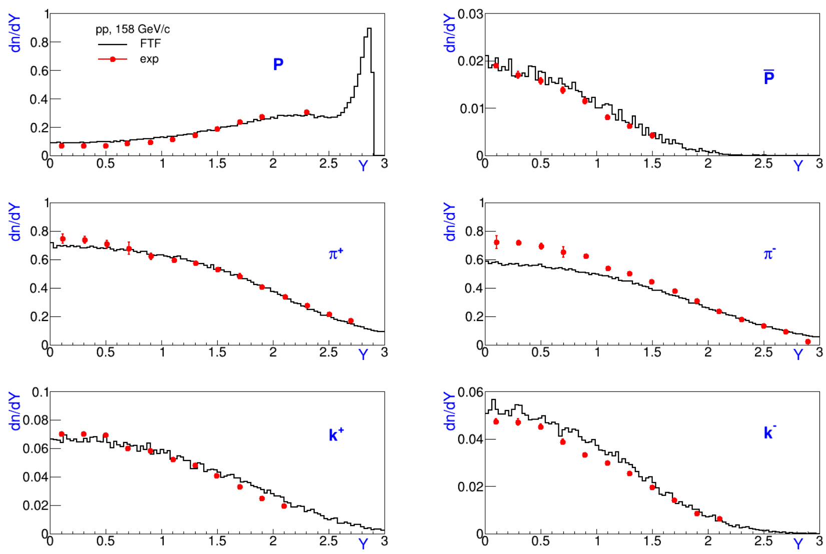

Figure 8: Rapidity distribution of $\pi^+, \pi^-, K^+, K^-, p$ and $\bar{p}$ produced in inelastic $p+p$ interactions at 158 GeV/c. Calculations were obtained by FTF (black lines) model. Red points represent experimental data.

2.1 Production of Λ hyperons in FTF model

Very interesting experimental data on Λ hyperons production in inelastic $p+p$ interactions at 158 GeV/c were published by the NA61/SHINE collaboration [8]
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On the left plots in Fig.9, comparisons of the experimental data on rapidity distribution (upper plot) and Feyman X distribution (bottom plot) of the Λ hyperons with various model calculations are given. The experimantal data are shown with systematical and statistical errors. There are also shown calculations by UrQMD 3.4, EPOS 1.99 and Fritiof 7.02 models. The UrQMD and Fritiof 7.02 models overestimate the multiplicity of the Λ hyperons. EPOS model describes Λ spectra quite well.

On the right side, the same experimental data and FTF calculations on Λ hyperons production in proton-proton interactions are presented. The FTF model results are in a better agreement with the experimental data on the Λ hyperons than other model simulation results.

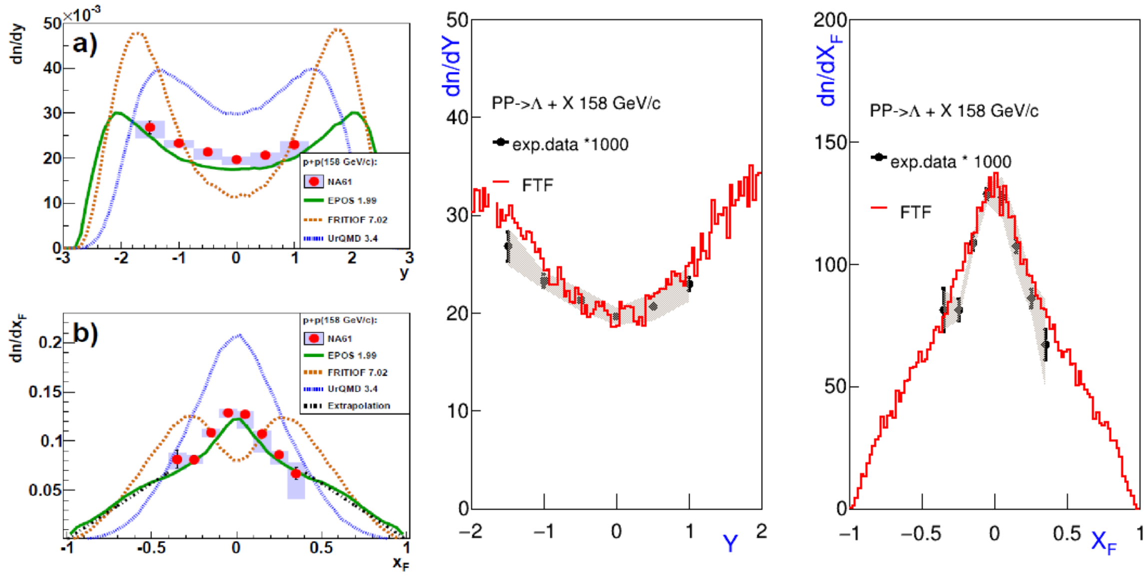

Figure 9: Rapidity and X_F distributions of the Λ hyperons produced in inelastic $p+p$ interactions at 158 GeV/c. Calculations were obtained by the FTF (red lines) model. Points with error bars represent the experimental data [8]. Left plots are taken from [8]

3 Production of charmed particles in FTF model

Charmed particles production was observed and measured in fixed target experiments performed in CERN, Fermilab and DESY with hadron beams at energies from 200 GeV up to 900 GeV. Charmed particles production was studied by all RHIC and LHC collaborations. It is expected that the charmed particles will be copiously produced at future accelerator - FCC. Investigation of the charmed particles production in proton-proton interactions is one of the important SPD tasks. Thus, a realistic simulation of charmed particle production in

$p+p$ interactions is very needed. In the current version of SPDRoot, production of "soft" charmed particles is realised. For our verification of the charmed particles production in the FTF generator in SPDRoot, we have used experimental data on the properties of charmed particles, D-mesons, produced in 400 GeV/c $p+p$ interactions [9]. The experimental data were obtained by the high resolution hydrogen bubble chamber (LEBC) in association with the European Hybrid Spectrometer at the CERN SPS. In accordance with the experimental data, we have simulated by FTF model the $p+p$ interactions at the projectile initial energy 400 GeV/c. In the Fig. 10, we present the experimental data in a comparison with the FTF model calculations.

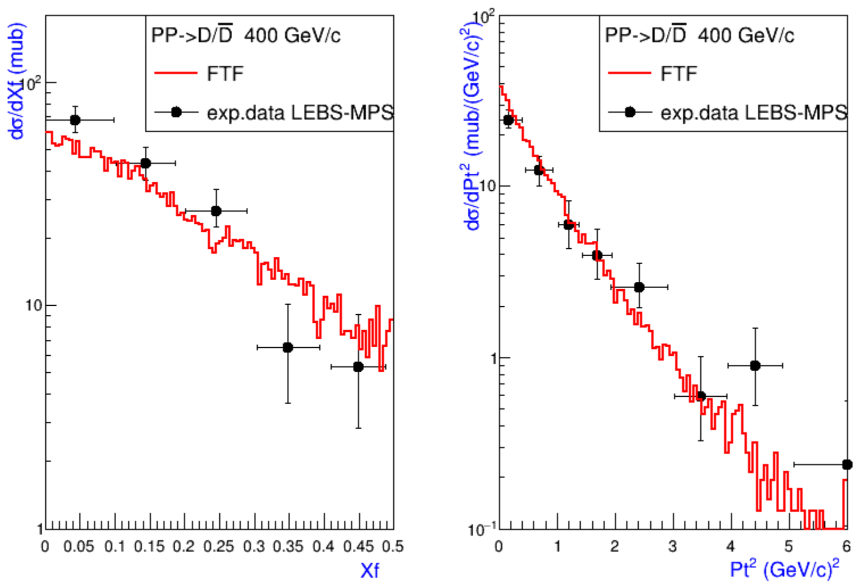

Figure 10: X_f and P_t^2 distribution of D mesons: D^+, D^-, D_0 and $\bar{D}_0$ produced in the inelastic $p+p$ interactions at 400 GeV/c. Red lines are FTF model calculations. Points with error bars represent the experimental data.

On the left figure, we present Feyman X distribution of all D mesons produced in the $p+p$ interactions. On the right figure, we show squared transverse momentum distribution of all D mesons. We took into account D^+, D^-, D_0 and $\bar{D}_0$ mesons. On the whole, we have a reasonable agreement between the FTF calculations and the experimental data within the large error bars.

4 Conclusion

1) We have completed the FTF model validation for the proton-proton experimental data at various energies: 20, 31, 40, 80 and 158 GeV/c presented by the NA61/SHINE collaboration.

2) It is shown, that the FTF model well describes rapidity spectra of π^+ and π^- mesons, protons and anti-protons produced at initial energies 20, 31, 40, 80 and 158 GeV/c. Though, there are some disagreements between the K^+, K^- meson experimental data and the FTF calculations, which decrease at energy growth.

3) FTF model calculations are in a good agreement with the experimental data on rapidity and X_F distributions of the Λ hyperons produced in the proton-proton interactions at 158 GeV/c.

4) In the current version of the FTF model in SPDRoot, the charmed particles are produced. The model results on X_F and P_t^2 distributions of D-mesons produced in proton-proton interactions at initial momentum 400 GeV/c are in a reasonable agreement with the experiment data.

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