# Simulation of elastic and inelastic proton-proton interactions

A. Galoyan and V. Uzhinsky 14.05.2018

## 1. Elastic P-P interactions

1.1 Simulations of elastic P-P and Pbar-P interactions in the frame of our Unified systematic of elastic scattering data (USESD)

1.2 Structure of code for simulation of PP-elastic scatterings under ROOT.

1.3 Results of PP elastic scatering simulations with Hadronic and Coulomb interactions

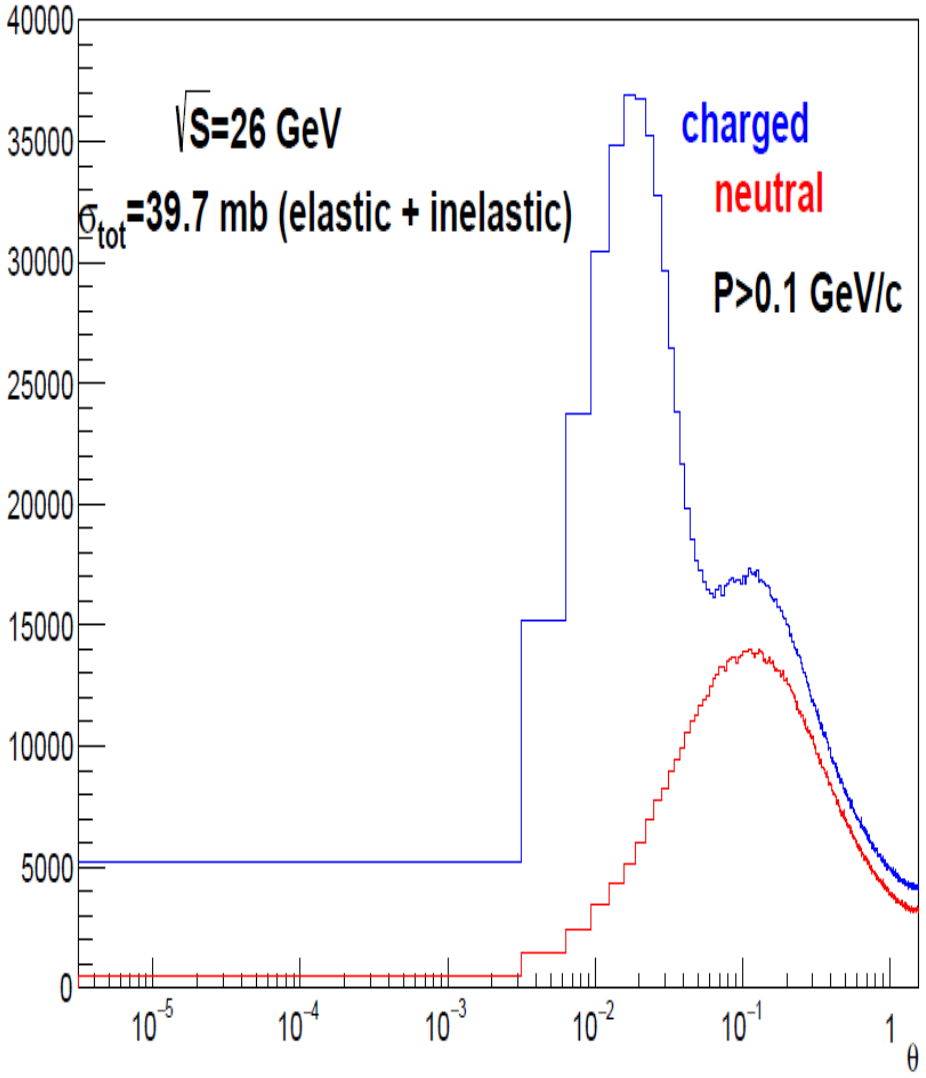
## 2. Simulations of inelastic P-P interactions at various energies in the frame of improved FTF model of Geant4 toolkit. Comparison of calculations with exp. data of NA61/SHINE.

## 3. Simulations of inelastic P-C interactions at 31 GeV/c in the frame of improved FTF model of Geant4 toolkit. Comparison of calculations with exp. data of NA61/SHINE.

FTF generator is installed in PandaRoot for simulations of Pbar-P and Pbar-A interactions. It can be used for SPD.

# Angular distributions of particles produced in PP reactions at √S=26 GeV

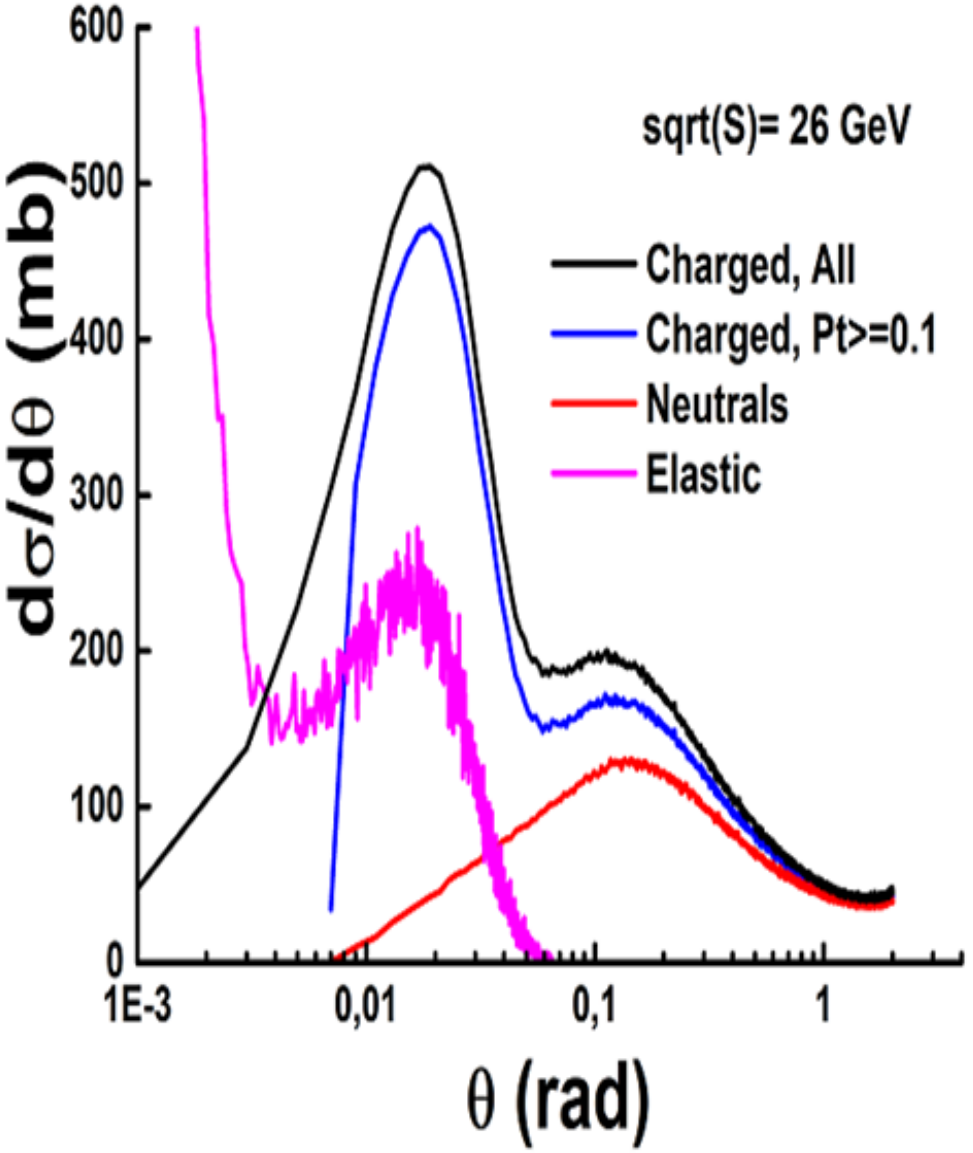
Fig. from A.Guskov




**Θmin = 0.001 grad** **FTF**

**σcoul = 6.65 mb** **σin = 32.78 mb**

**σel = 13.06 mb** **σtot = 39.7 mb**



# Diffferential cross section of elastic PbarP(PP) scatterings

Usually at low momentum transfer the cross section is parameterized as

$$\frac{d\sigma}{dt} = \frac{\pi}{k^2}\left|f_C e^{i\delta} + f_H\right|^2 = \frac{d\sigma_C}{dt} + \frac{d\sigma_{int}}{dt} + \frac{d\sigma_H}{dt},$$

where

$$\begin{aligned}
\frac{d\sigma_C}{dt} &= \frac{4\pi\alpha_{EM}^2 G^4(t)}{\beta^2 t^2}; \\
\frac{d\sigma_{int}}{dt} &= \frac{\alpha_{EM}\sigma_{Total}}{\beta|t|} G^2(t) e^{\frac{1}{2}Bt}(\rho cos\delta + sin\delta) \\
\frac{d\sigma_H}{dt} &= \frac{\sigma_{Total}^2(1+\rho^2)}{16\pi} e^{Bt}.
\end{aligned}$$

Here $d\sigma_C/dt$ and $d\sigma_H/dt$ are the Coulomb and hadronic parts of the cross section, respectively. $d\sigma_{int}/dt$ represents the interference term. $\alpha_{EM}$ is the fine structure constant.

Cahn [3] analized also the effect of the electromagnetic form factor and obtained a general expression for the phase.

**R. Cahn, Z. Phys. C15, 253-260 (1982)**

**Coulombie-Hadronic Interference in an Eikonal Model**

The proton dipol form factor $G(t) = (1+\Delta)^2$, with $\Delta = |t|/0.71$ (GeV/c)$^2$. The Coulomb phase is

$$\delta(t) = \alpha_{EM}\left[0.577 + ln\left(\frac{B|t|}{2} - 4\Delta\right) + 4\Delta ln(4\Delta) + 2\Delta\right].$$

$\sigma_{Total}$ is the hadronic total cross section, and $B$ is the so-called slope parameter. $\rho$ is the ratio of real to imaginal parts of the hadronic scattering amplitude at zero momentum transfer. The amplitude is parameterized in a simple exponential form, $f_H \propto e^{\frac{1}{2}Bt}$.

# Unified systematic of elastic Pbar-P, P-P scattering data (USESD) e-Print: **arXiv:1210.7338**

P. Brogueira and J. Dias de Deus, Eur. Phys. J. 37 (2010) 075006).

Амплитуда в представлении прицельного параметра

$$\gamma(b) = \frac{1}{1+e^{(b-R)/d}} + \frac{1}{1+e^{-(b+R)/d}} - 1$$

$$Imf_{SFF}(q) = R^2 \frac{\pi dq}{sinh(\pi dq)} \frac{J_1(Rq)}{Rq} + \frac{1}{2q^2} \frac{\pi dq}{sinh(\pi dq)} \left( \frac{\pi dq}{tanh(\pi dq)} - 1 \right) J_0(Rq) + ...$$

Real part of elastic pbar-p amplitude. Derivative dispersion relations

J.B. Bronzan, G.L. Kane, U.P. Sukhatme, Phys. Lett. 49B (1974) 227;
M.M. Block, R.N. Cahn, Rev. Mod. Phys. 57 (1985) 563

$$\mathrm{Re}\, F_{\mathrm{SAM}} \simeq \frac{\pi}{2} \frac{d}{d\ln(s)} \mathrm{Im}\, F_{\mathrm{SAM}} =$$

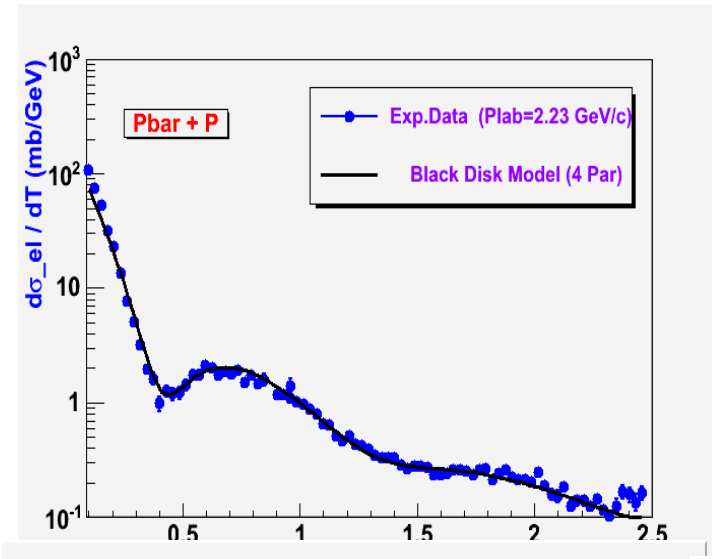
$$= \frac{\pi}{2} \left[ \frac{dR}{d\ln(s)} \frac{\partial}{\partial R} + \frac{dc}{d\ln(s)} \frac{\partial}{\partial c} \right] R^2 \frac{\pi cq}{\mathrm{sh}(\pi cq)} \frac{J_1(Rq)}{Rq} =$$

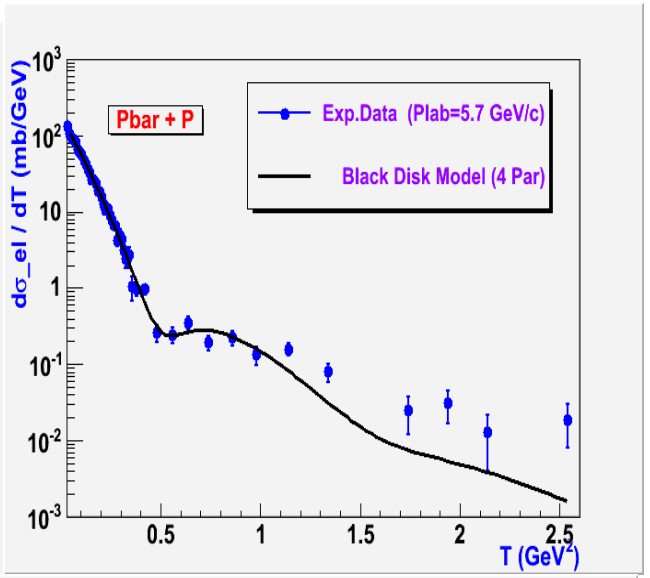
$$= \frac{\pi}{2} \frac{dR}{d\ln(s)} R \frac{\pi cq}{\mathrm{sh}(\pi cq)} J_0(Rq) + \ldots$$

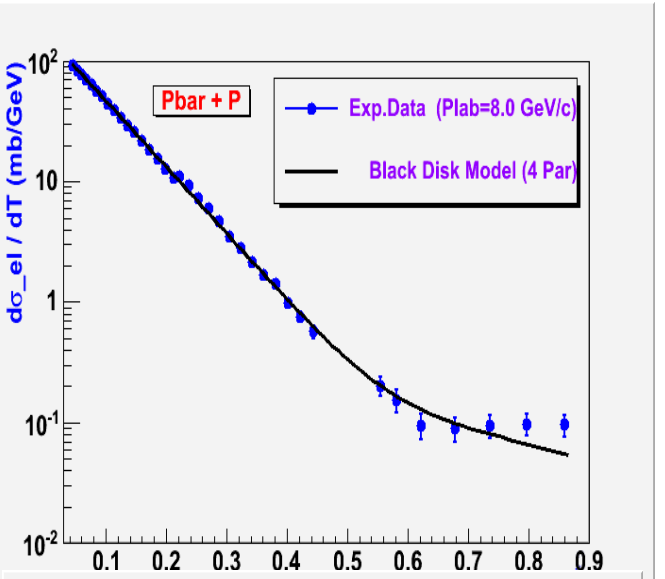
# Fitting expression (intermediate and high projectile momenta)

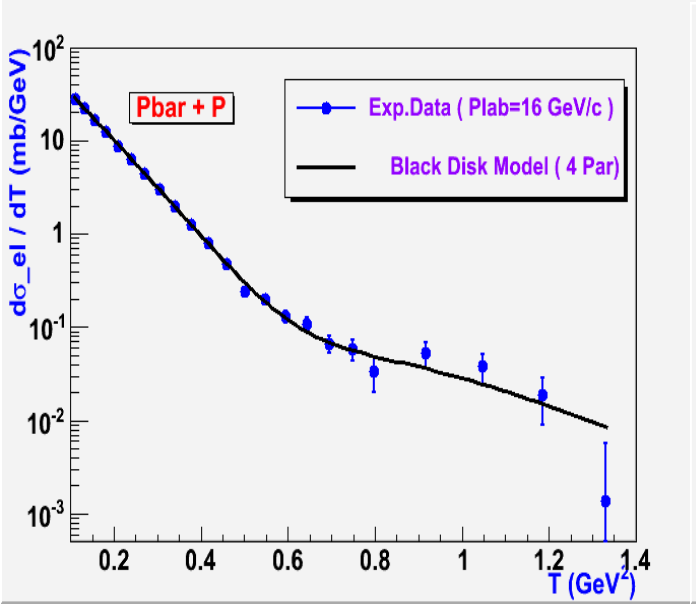
$$F(s,q) = i\ A_1 \frac{\pi d q}{\mathrm{sh}(\pi d q)} \frac{J_1(Rq)}{Rq} + A_2 \frac{\pi d q}{\mathrm{sh}(\pi d q)} J_0(Rq)$$

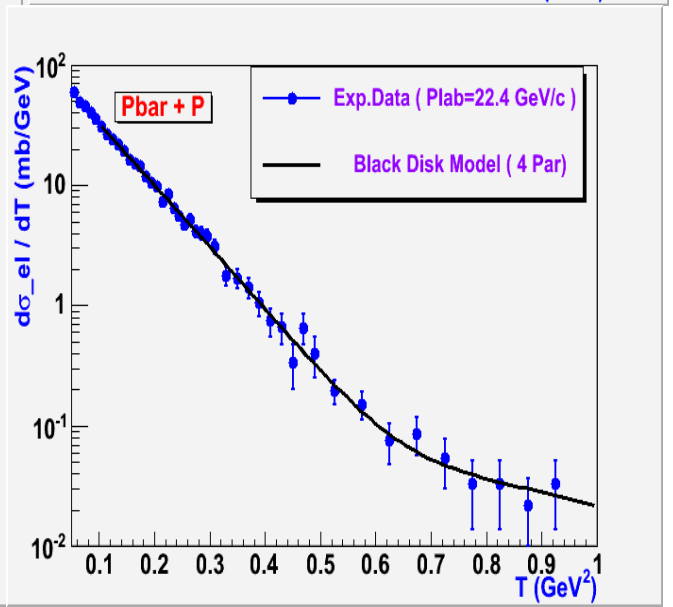
**94 sets of exp data were used from Plab=181 MeV/c up to sqrt(S)=1800 GeV**

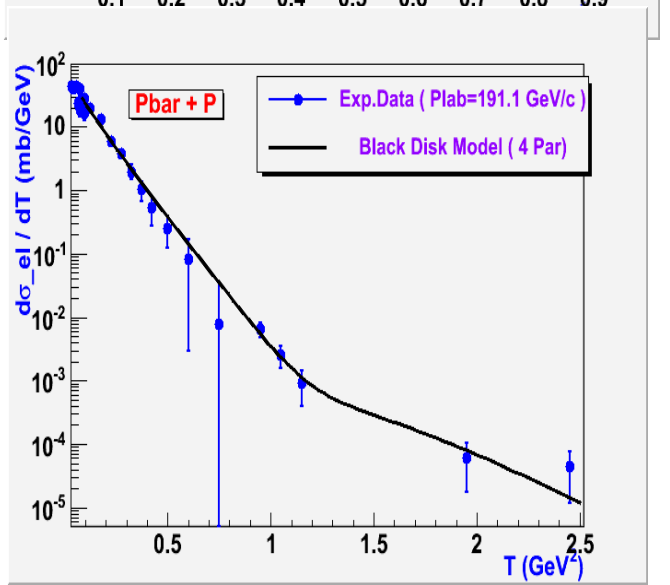


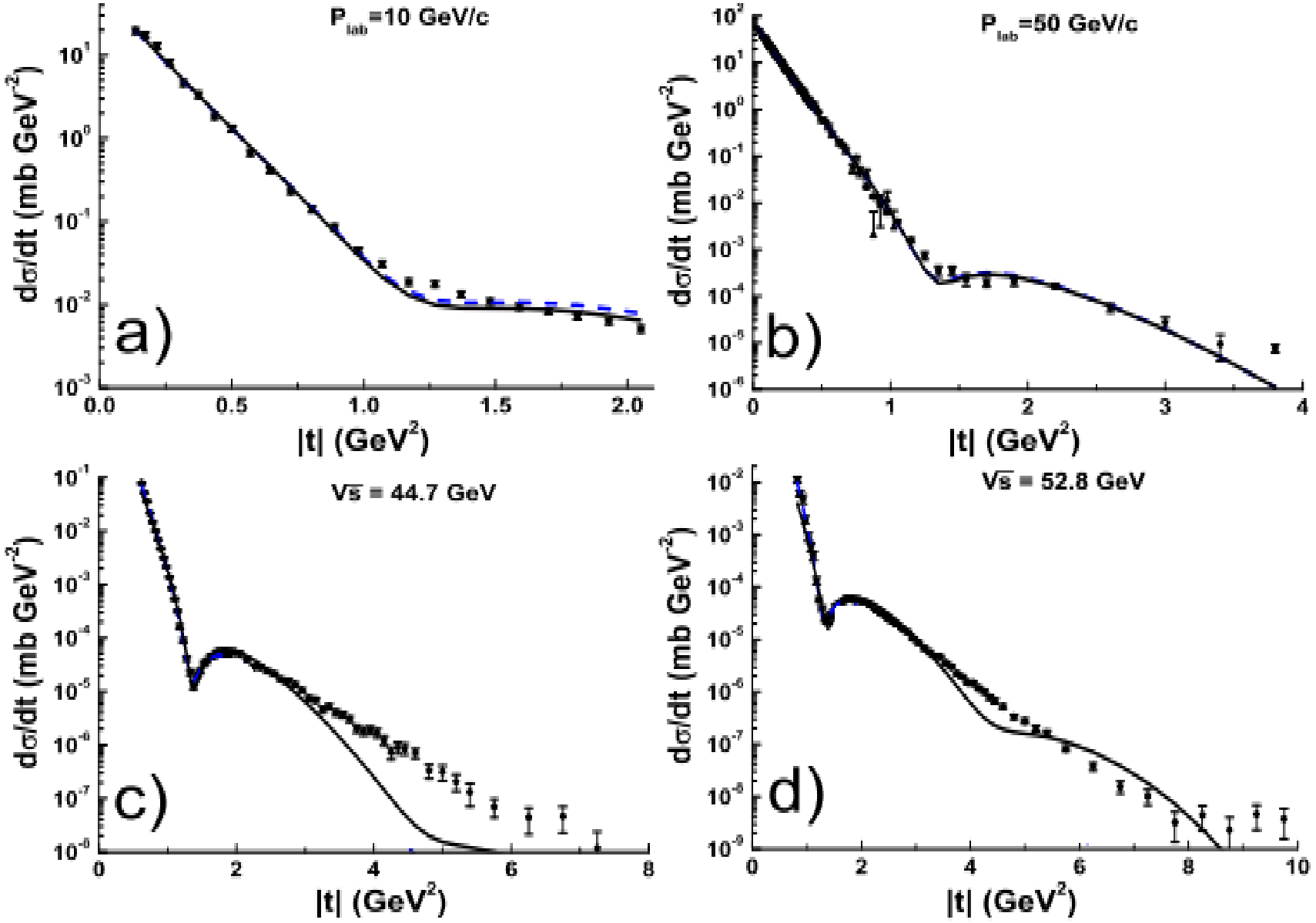



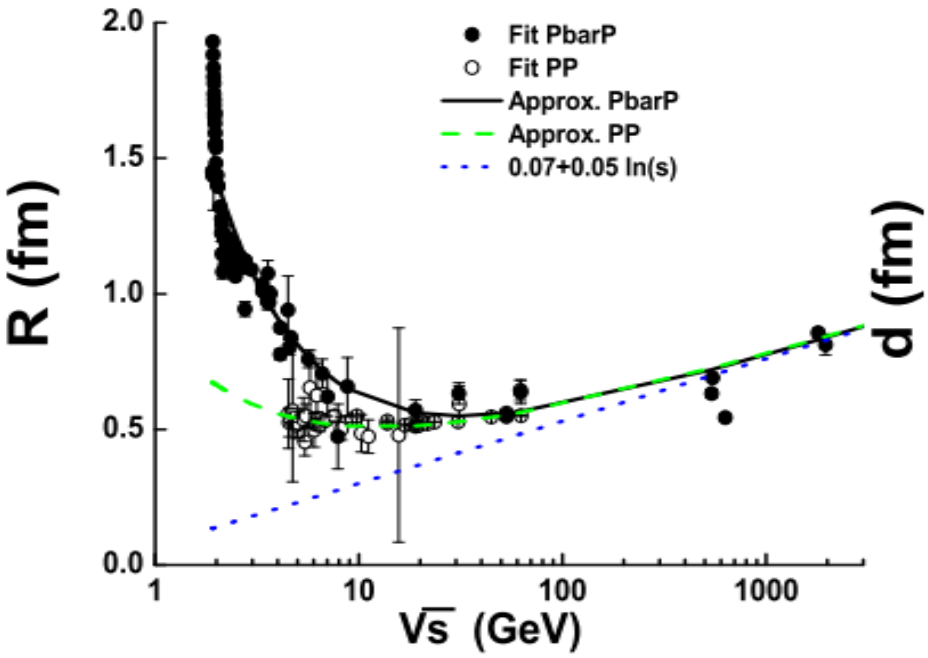



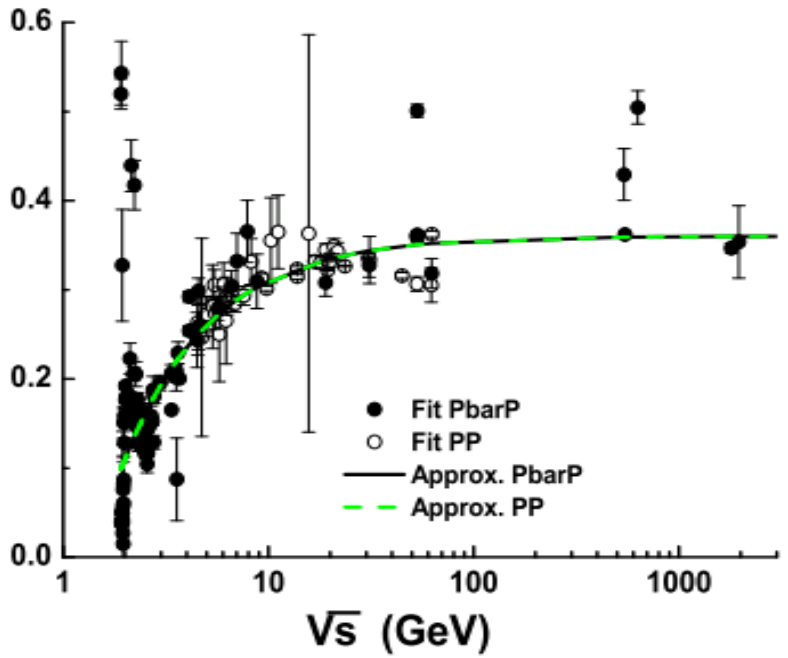
# Fitting results for elastic PP- interactions

**68 sets of exp. data on PP-scattering were used from Plab = 1 GeV/c to √S=63GeV**



# Interpolation of parameters $R_{pp}$ ($R_{pbarp}$) and $d_{pp}$ ($d_{pbarp}$)



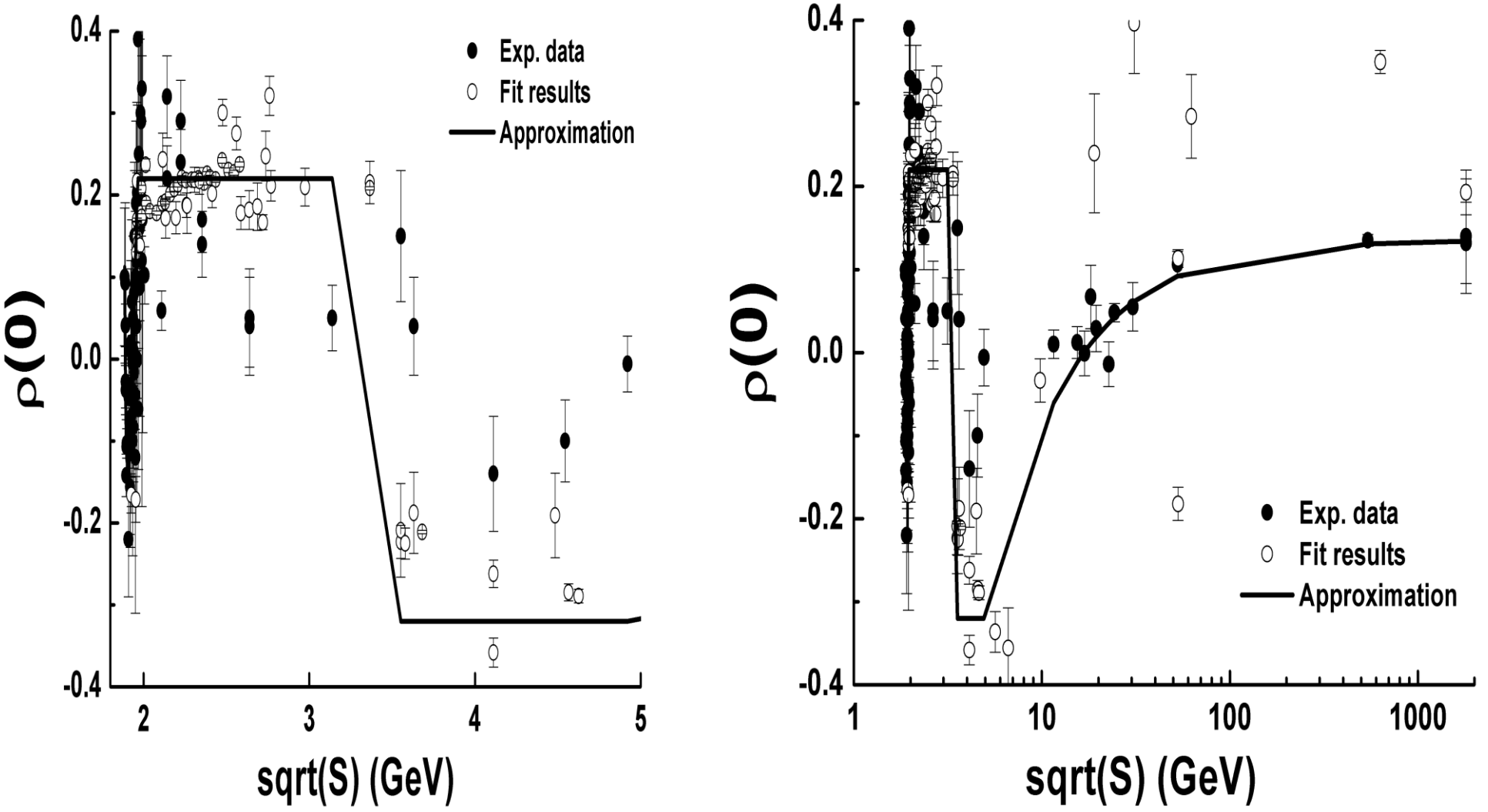




$$R_{pp} = 0.07 + 0.05 \ln s + \frac{0.6}{s^{1/4}} + \frac{0.2}{s^{1/2}}, \quad (fm),$$

$$R_{\bar{p}p} = 0.07 + 0.05 \ln s + \frac{0.4}{s^{1/4}} + \frac{2}{s^{1/2}}, \quad (fm),$$

$$d_{pp} = d_{\bar{p}p} = 0.36 - \frac{0.5}{\sqrt{s}}. \quad (fm).$$

# Interpolation of Ratio of Real to Imaginary parts of the scattering amplitude




"Structure of antiproton-proton elastic scattering amplitude" A. Galoyan, V. Uzhinsky, JETP Letters, v. 94, No 7 (2011)

# Expression for amplitude of elastic PP scatterings

**"Improved Systematic of pp Elastic Scattering Data"**
**V. Uzhinsky and A. Galoyan, hep-ph 1210.1338 (2012)**

$$Imf(s,t) = A_1 \left[ R^2 \frac{\pi dq}{sinh(\pi dq)} \frac{J_1(Rq)}{Rq} + \frac{1}{2q^2} \frac{\pi dq}{sinh(\pi dq)} \left( \frac{\pi dq}{tanh(\pi dq)} - 1 \right) J_0(Rq) \right]$$

$$Ref(s,t) = A_1 \cdot \rho \cdot (R^2/2 + \pi^2 d^2/6) \frac{\pi dq}{sinh(\pi dq)} J_0(Rq) + A_2\, e^{-B_2 q^2/2}$$

**At high energies:**

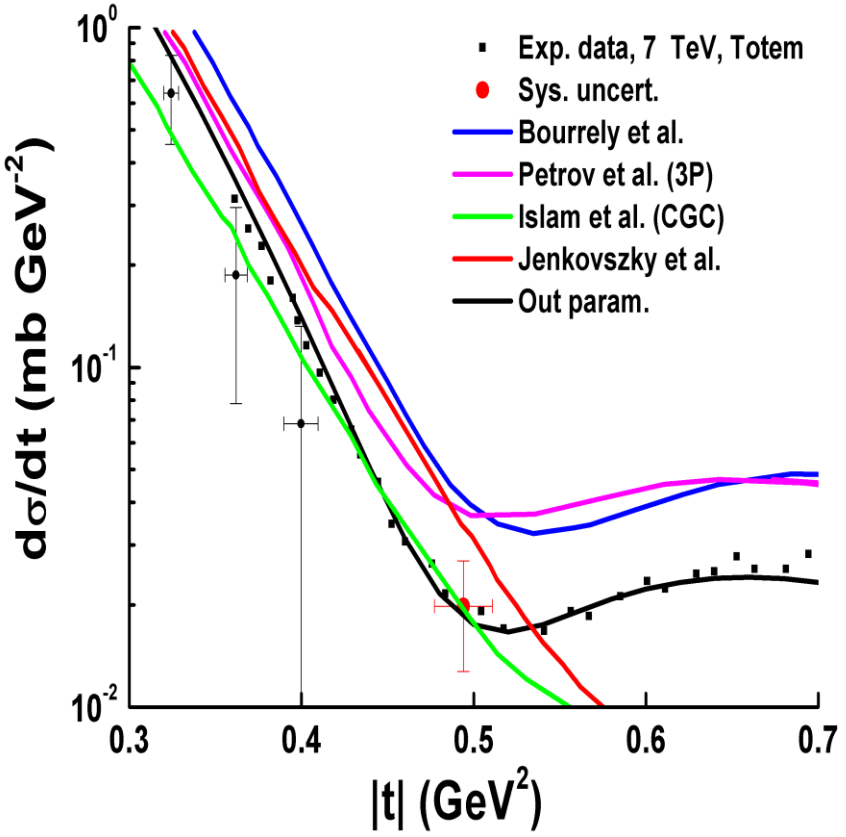
$$\rho_{pp} = 0.135 - \frac{3}{\sqrt{s}} + \frac{4}{s} + \frac{80}{s^3}$$

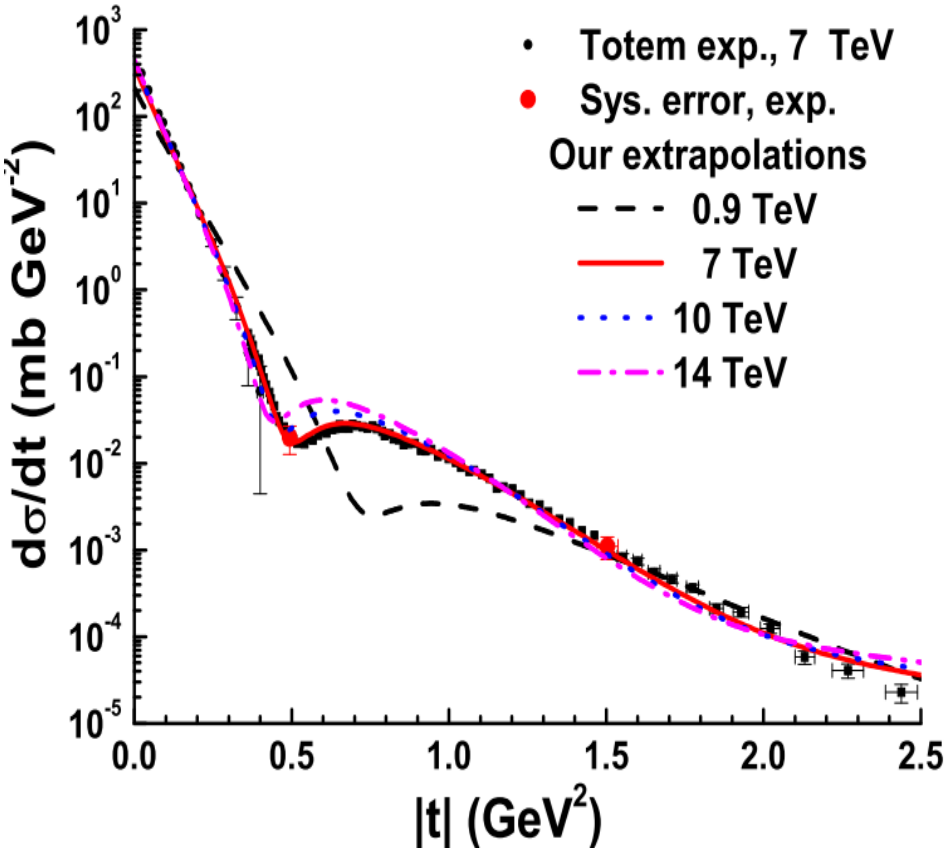
$$\rho_{\bar{p}p} = 0.135 - \frac{2.26}{\sqrt{s}}$$

# Results of Totem experiment on pp-scatterings at 7 TeV

## EPL, 95 (2011) 41001, EPL 96 (2011) 21002

R=1.07 fm, d=0.375 fm




V. Uzhinsky, A. Galoyan, Nov 2011. e-Print: arXiv:1111.4984

"Description of the Totem experimental data on elastic pp-scattering at sqrt(s)=7 TeV in the framework of unified systematic of elastic scattering data."

# Code for simulation of PP elastic scaterings

**Class for simulation of elastic P-P interactions**

**PPElastic**

**methods:**

**void Run(Double_t Plab, Int_t nevents, Double_t tetmin=-1.)**
**void Init(Double_t Plab=20., Double_t tetmin=-1.);**
**Double_t SampleInvariantT (Double_t plab, Int_t Z );**

*methods for sampling of emmision angles*

**Double_t SampleThetaLab( plab, Z);**

**Double_t SampleThetaCMS( plab, Z);**

**Main data of class**

**fT, fTetaCMS, fThetaLab, rho, B, sigma_tot etc.**

Function for PP-simulations and creating file with root Tree.

**runAndSaveTree**(Nevent, Plab, Double_t Tetmin=-1,char *fname=«PPel.root»)

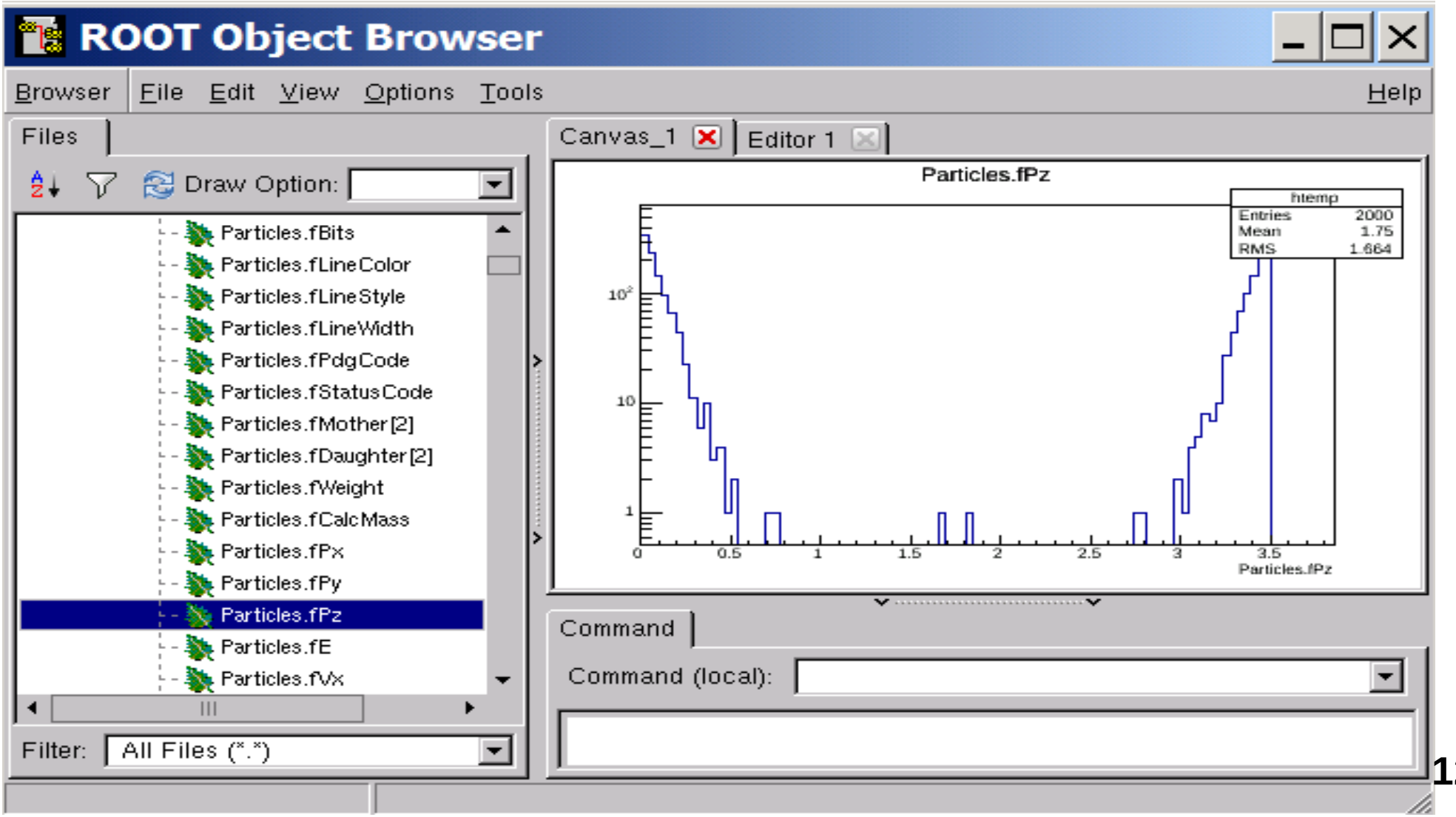
# Run of MC program for simulation of elastic PP scatterings

Simulation of 1000 PP-elastic at Plab= 3.5 GeV/c and θ min = 1 deg.

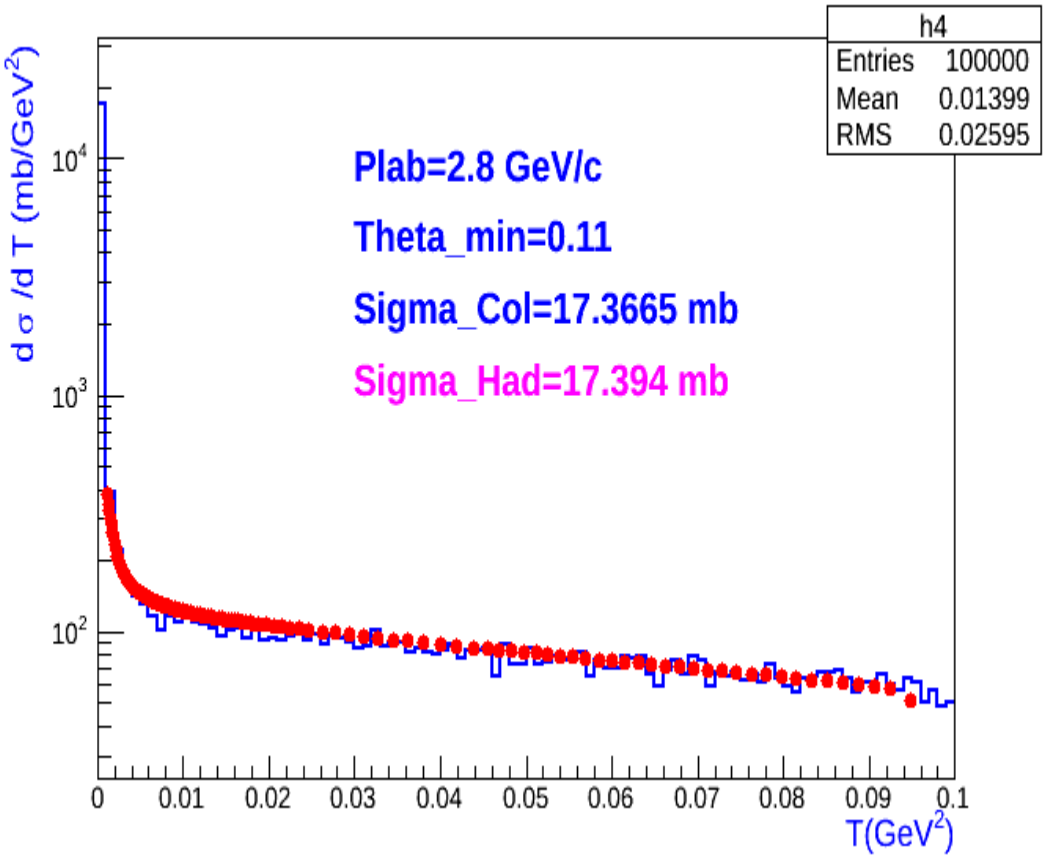
root > .L mc_ppelst.C++

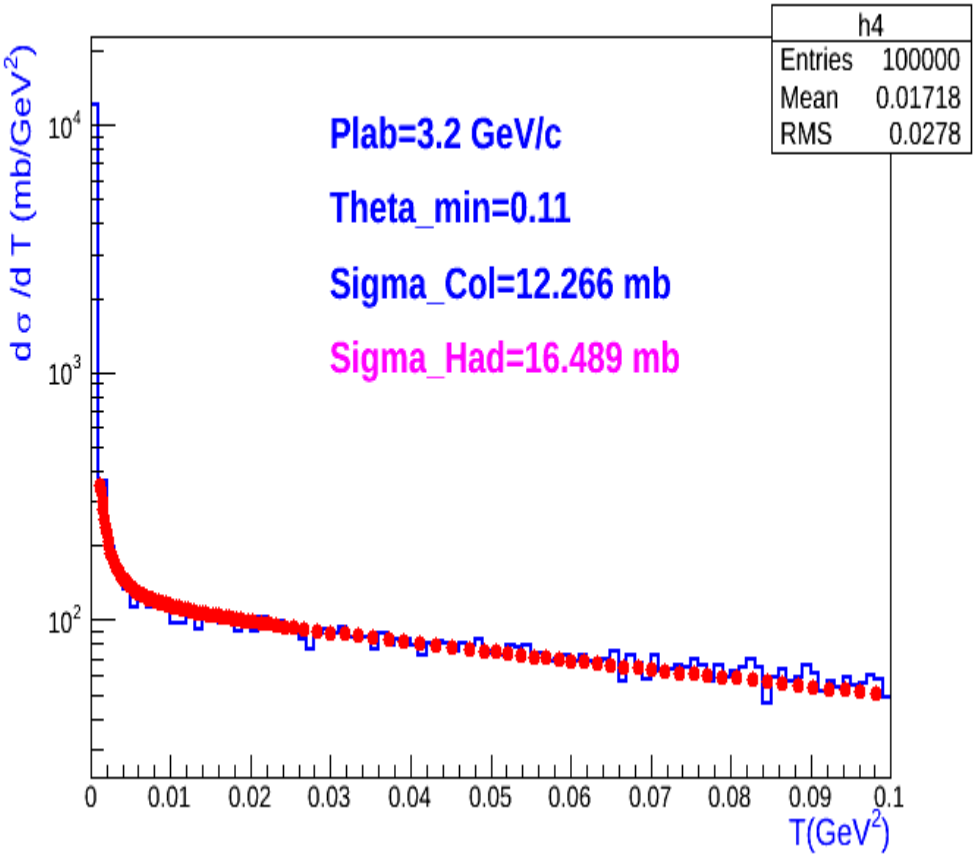
root > runAndSaveTree(1000, 3.5, 1);

Получаем Root-file PPel.root»



# Results of MC program for simulation of elastic P-P scatterings and Koala experimental data



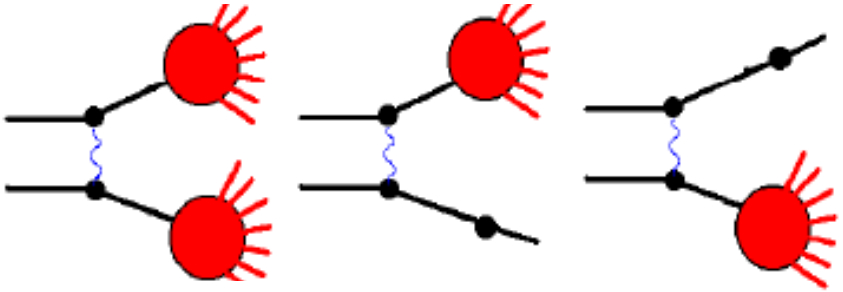

## Exp. data on proton-proton elastic scattering are described well

**"Empirical parametrization of the nucleon-nucleon elastic scattering amplitude at high beam momenta for Glauber calculations and Monte Carlo simulations".**

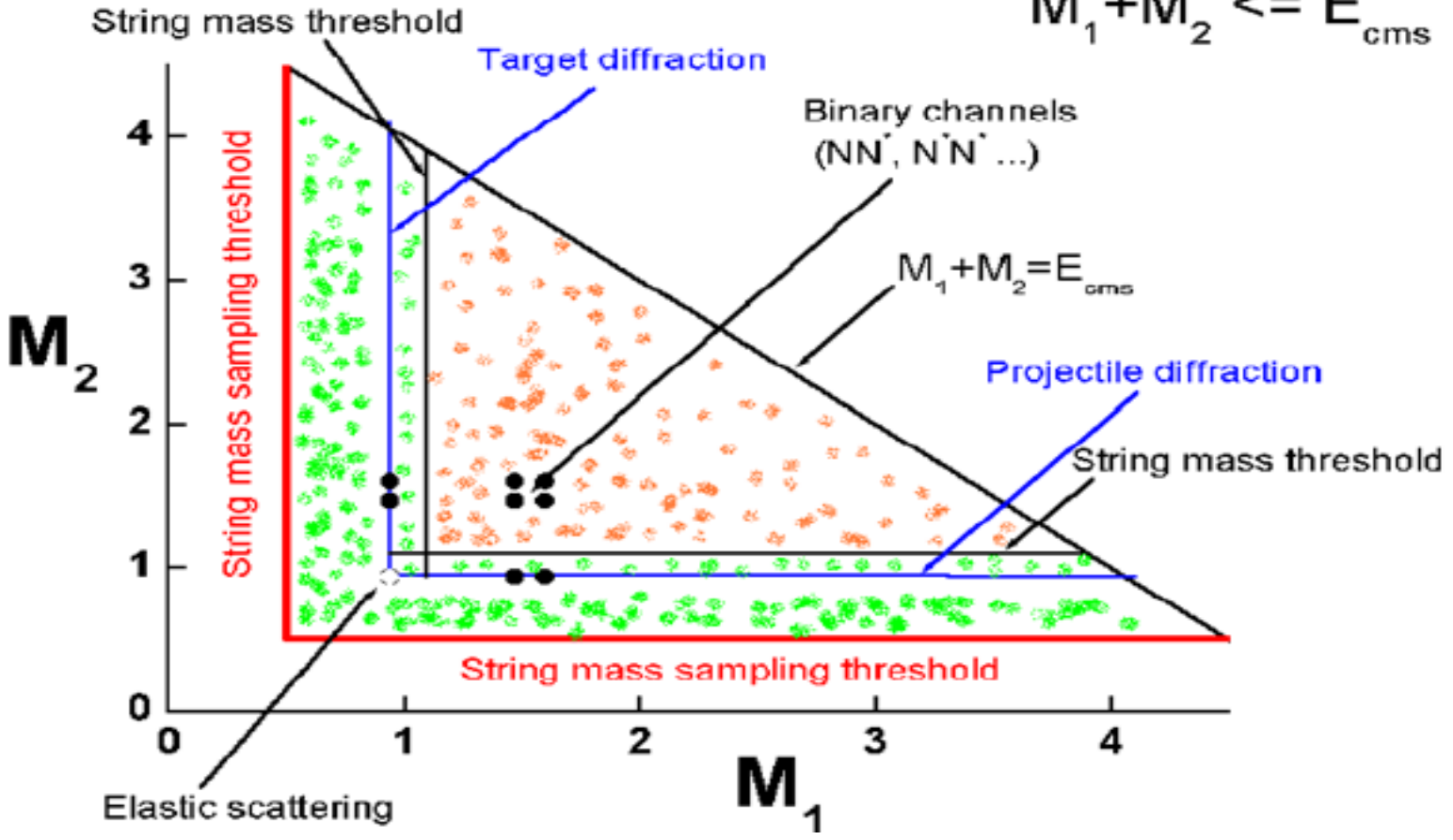
**V. Uzhinsky, A. Galoyan , Q. Hu J. Ritman , H. Xu. Phys.Rev. C94 (2016) no.6, 064003**

# Simulation of inelastic nucleon-nucleon interactions

## Fritiof model



$M_1+M_2 <= E_{cms}$




UrQMD Md=1.46

$NN \rightarrow N\Delta_{1232}$

$NN \rightarrow NN^*$

$NN \rightarrow N\Delta^*$

$NN \rightarrow \Delta_{1232}N^*$

$NN \rightarrow \Delta_{1232}\Delta^*$

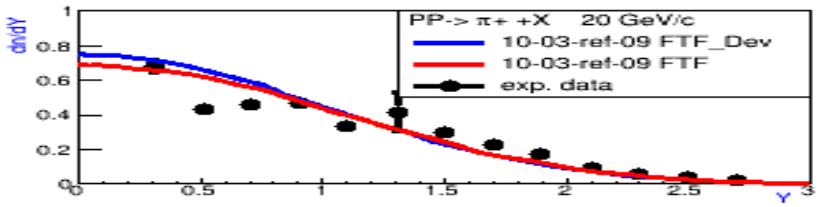
$NN \rightarrow \Delta\Delta$ excitation

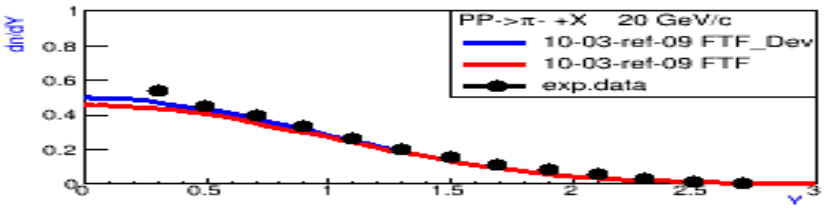
**Fritiof 1.6 – Md=1.2; Fritiof 7.0 Md=1.2; Hijing Md~2**

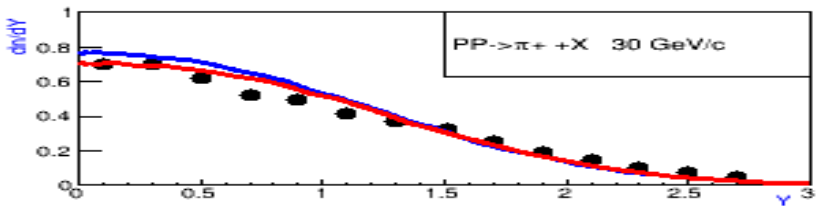
# Tuning of FTF model using exp. data of NA61/SHINE

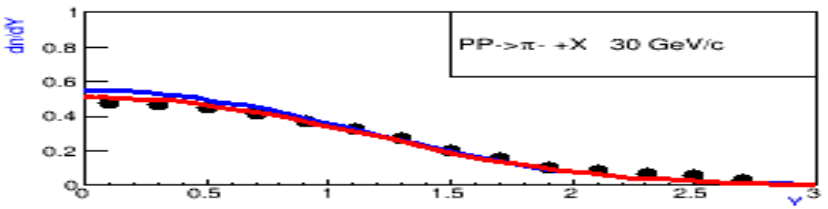
Measurements of π±, K± , p and p¯ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS.

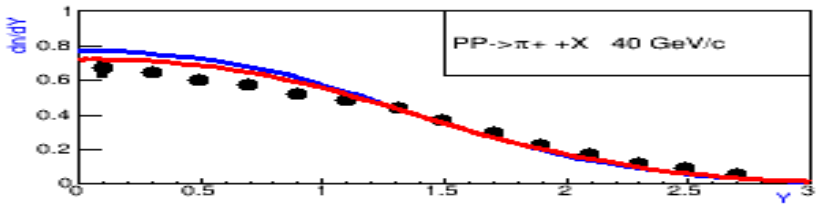
**NA61/SHINE Collaboration** **Eur.Phys.J. C77 (2017) no.10, 671**

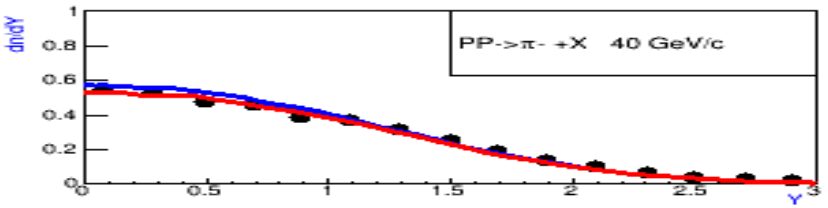


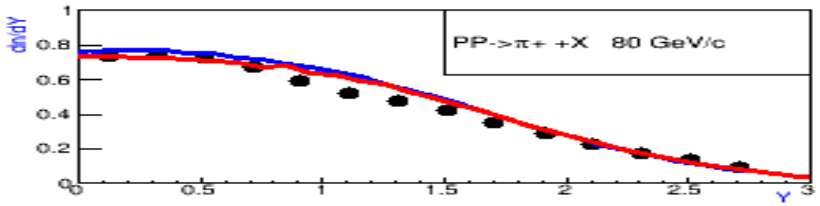



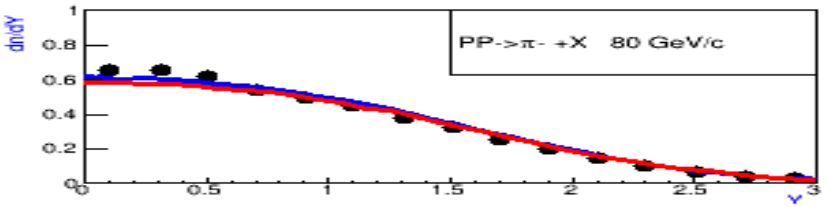



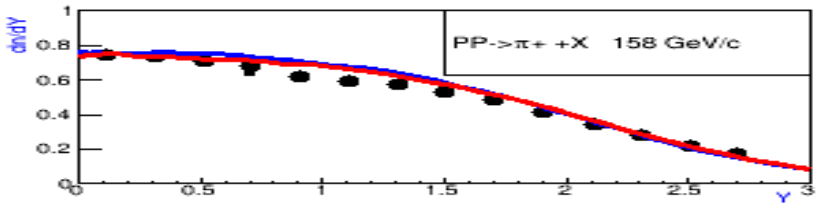



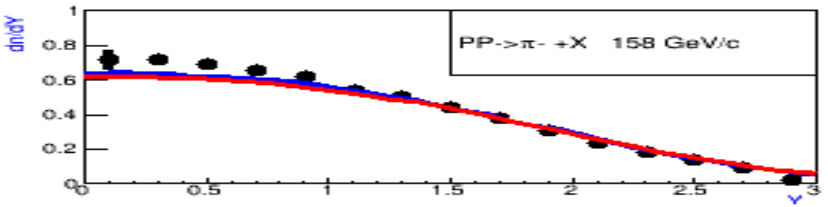



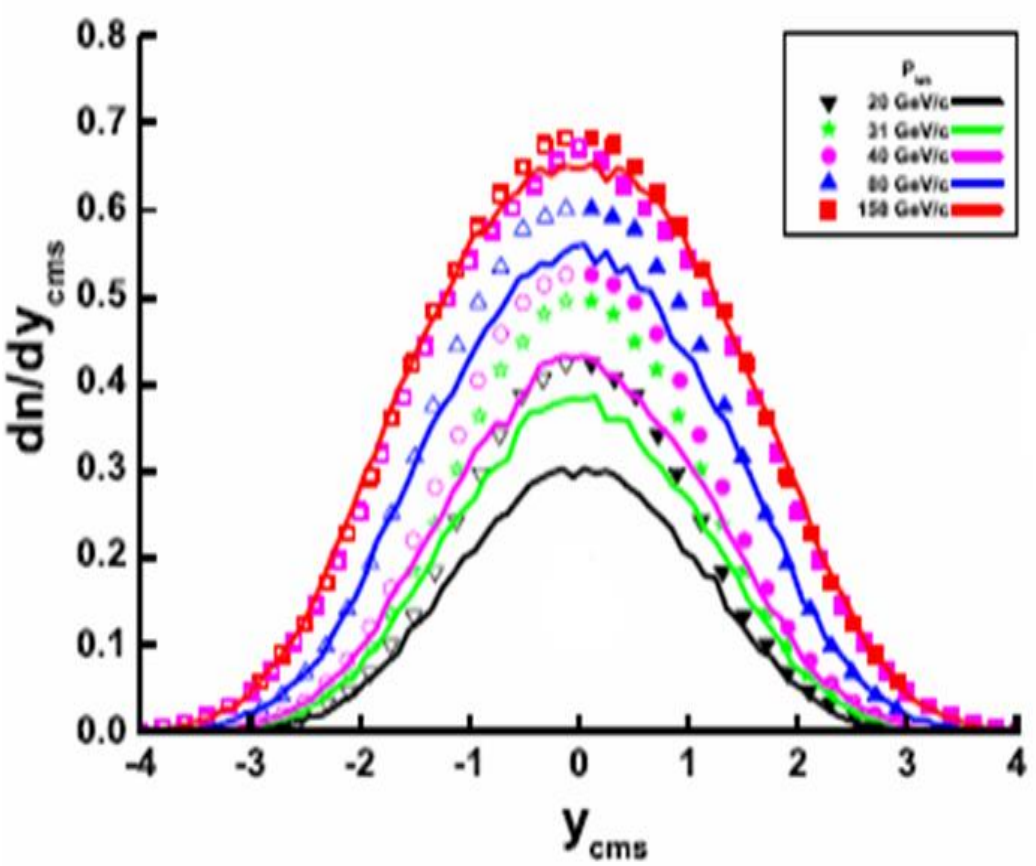



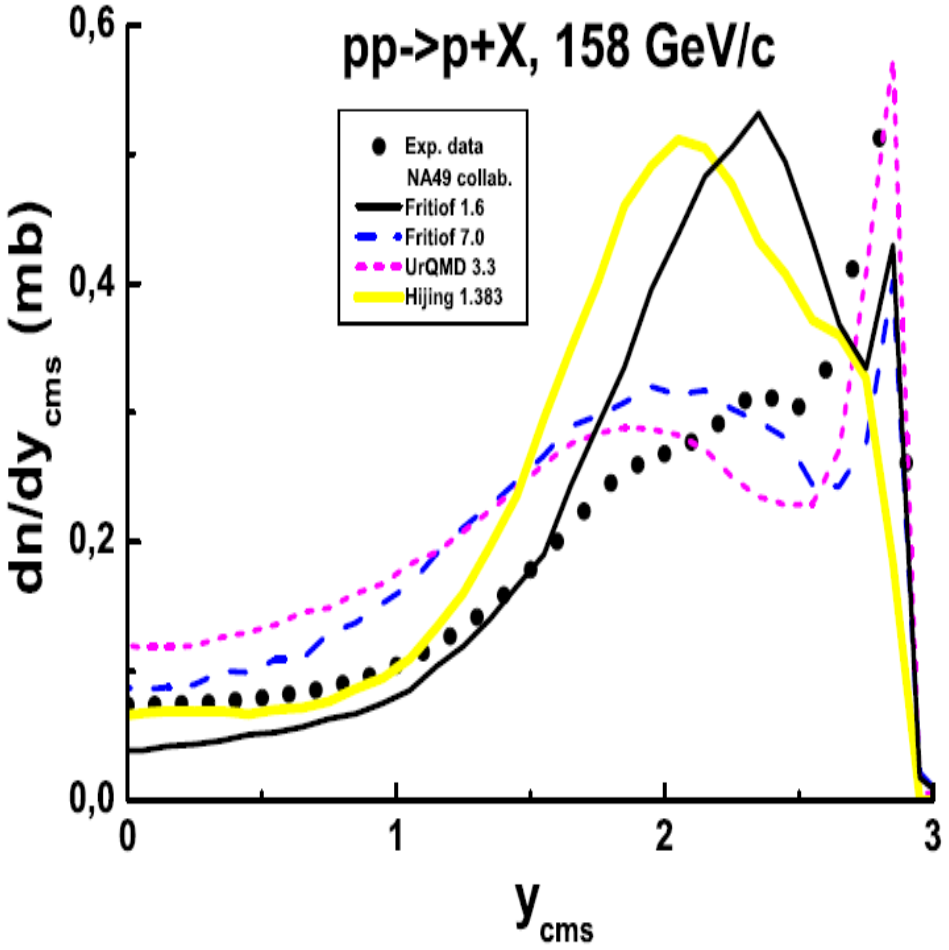



# Validation of various models for pp-interactions

**Exp. Data: NA61/SHINE, p+p ->Pi- +X,  Plab=20, 31, 40, 80, 158 GeV/c**




**V. Uzhinsky, arXiv: 1308.0737 [hep-ph]**
**Toward UrQMD Model Description of pp and pC Interactions at High Energies**

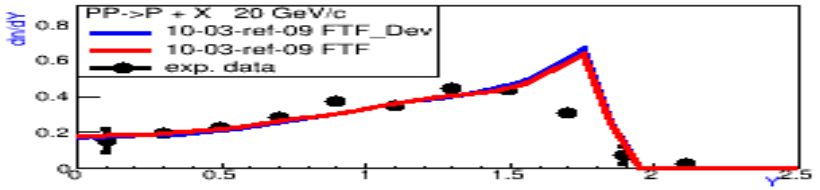
**Fritiof 1.6, Fritiof 7.0, Hijing, UrQMD**

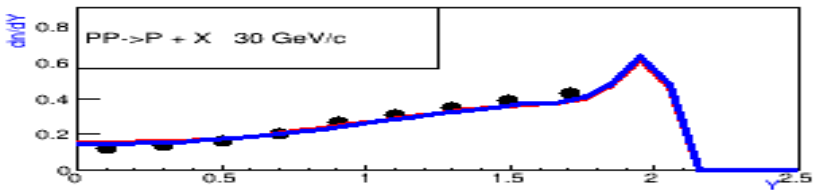
**UrQMD -> CBM, NICA/MPD**

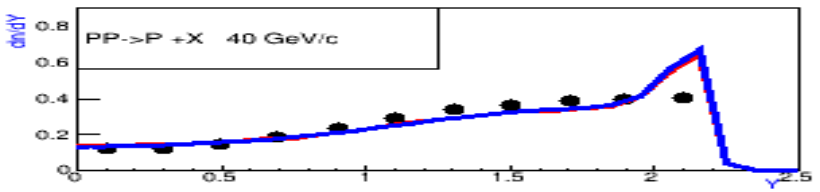
# Tuning of FTF model using exp. data of NA61/SHINE

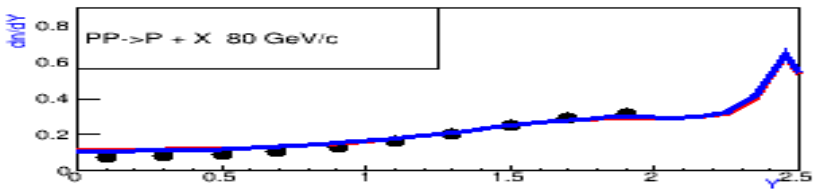
Measurements of π±, K± , p and p¯ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS.

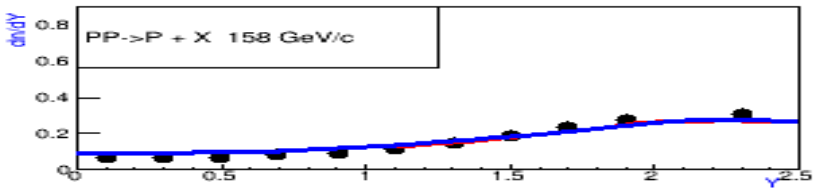
**NA61/SHINE Collaboration Eur.Phys.J. C77 (2017) no.10, 671**



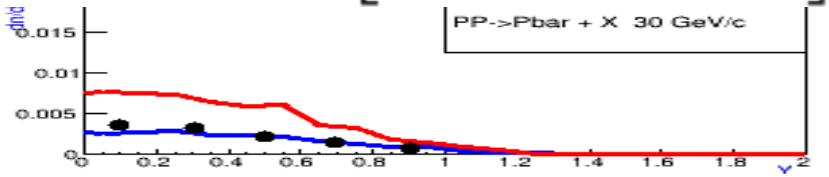



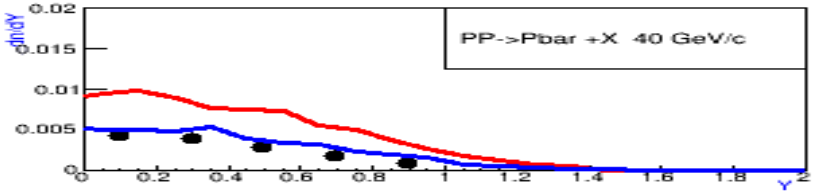



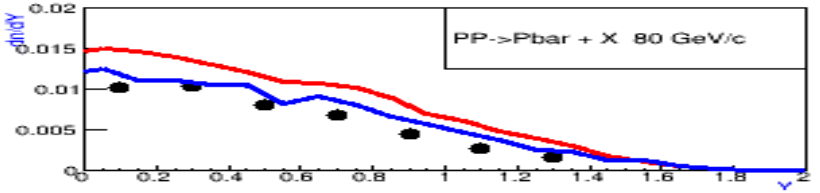



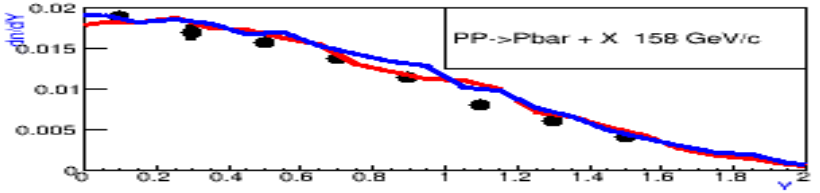

Probability of diquark-antidiquark production at string decay is chosen as:

$$P_{qq-\bar{q}\bar{q}} = 0.15 \left[1 - \left(\frac{1400 * N_b}{M_{str}}\right)^2\right]$$



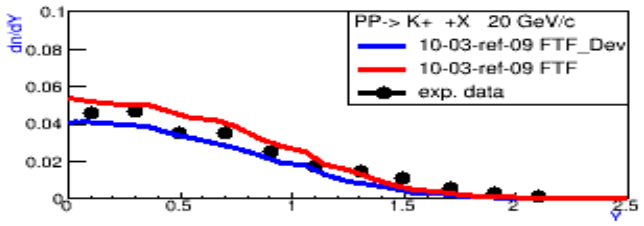



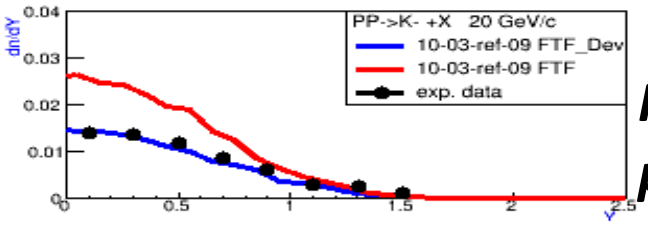



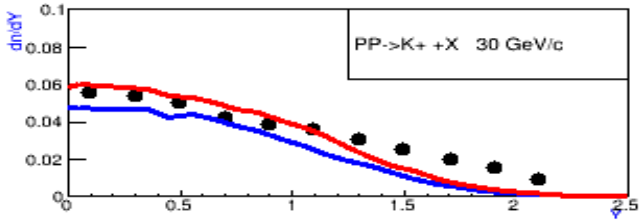
# Tuning of FTF model using NA61/SHINE data

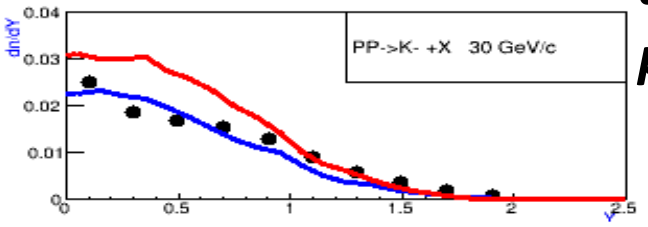
Measurements of π±, K± , p and $p^-$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS.

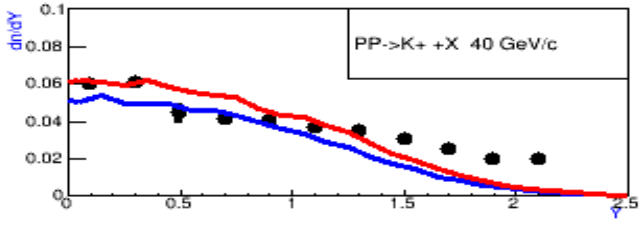
**NA61/SHINE Collaboration** **Eur.Phys.J. C77 (2017) no.10, 671**

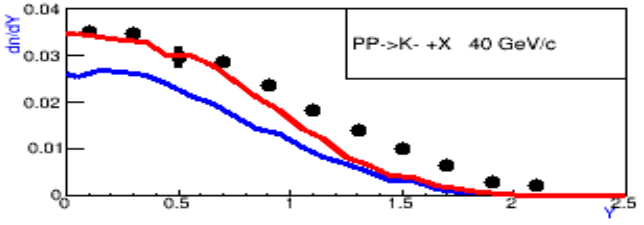


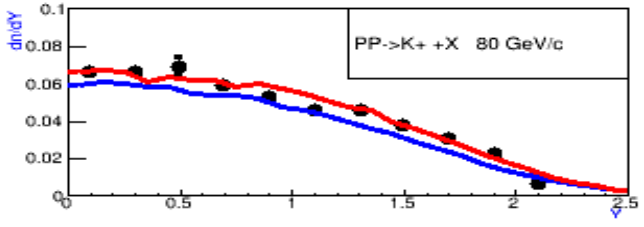



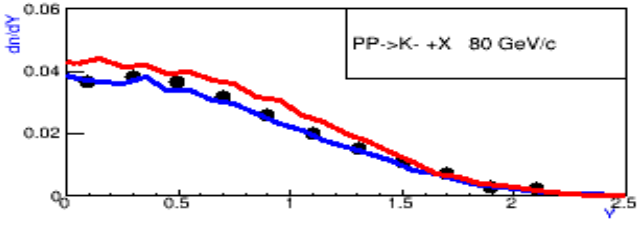



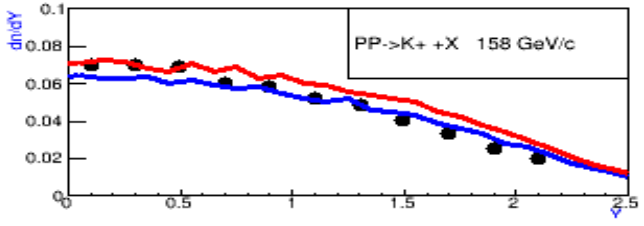



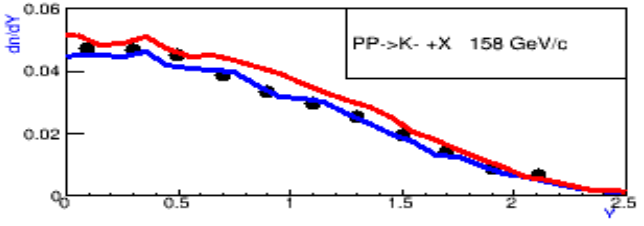



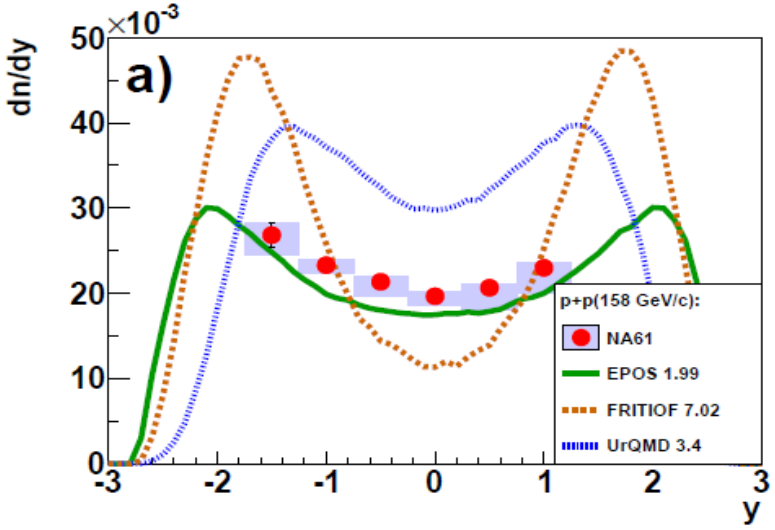

***Probability of strange q-qbar production at final string decay is changed. New probability is chosen:***

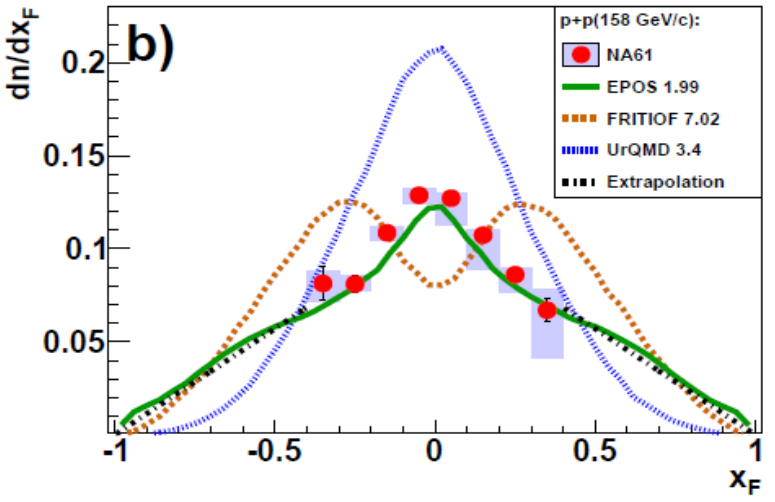
$$P_{\bar{s}\ s} = 0.108 \left[1 - \left(\frac{m_{th}}{M_{str}}\right)^4\right]$$

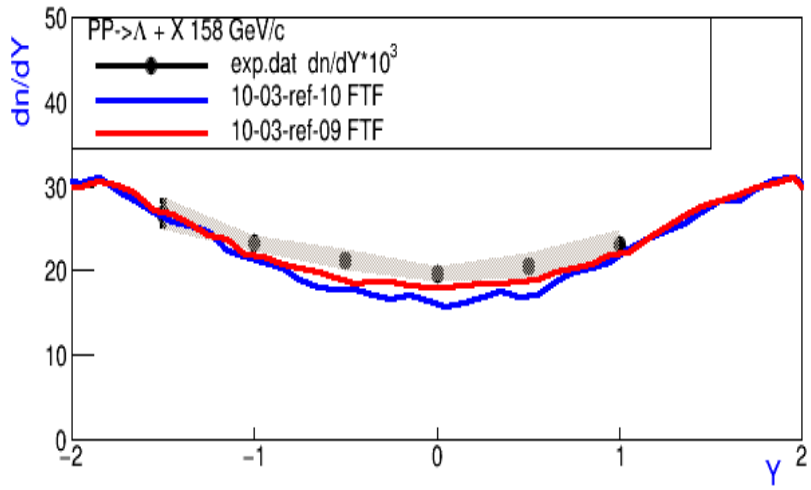
# Validation of FTF model for strange particle production

*Production of Λ -hyperons in inelastic p+p interactions at 158 GeV/c*

NA61/SHINE Collaboration **Eur. Phys. J. C76 (2016) no.4, 198**



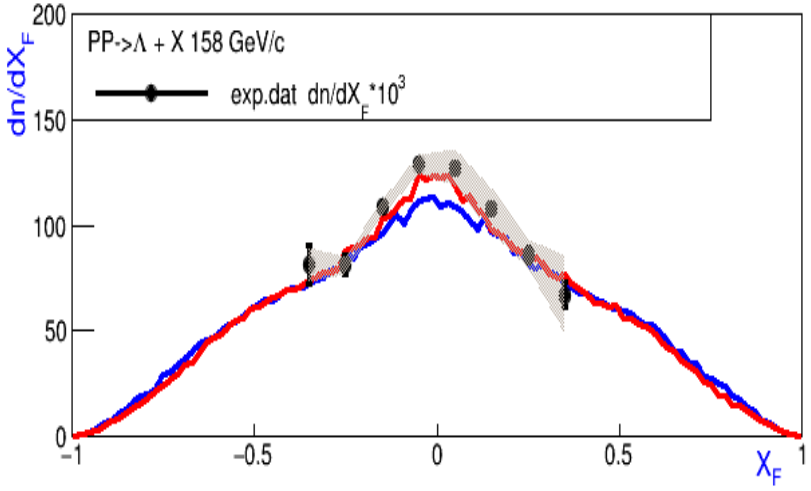



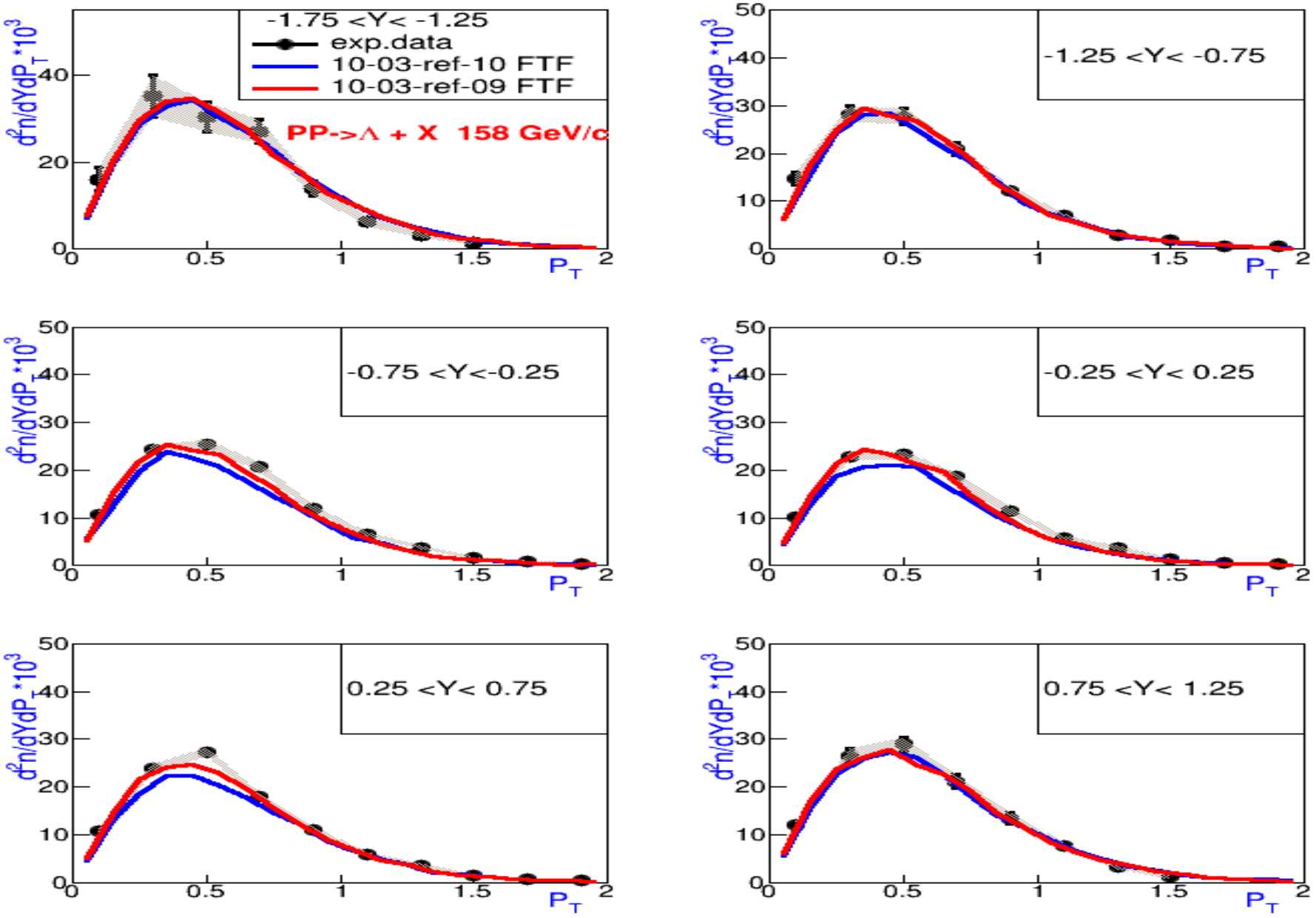

**Fig. 20** Comparison of $\frac{dn}{dy}$ (a), and $\frac{dn}{dx_F}$ (b) distributions with calculations of the EPOS [19], URQMD [34, 35] and FRITIOF [36] models. The chain line was used to extrapolate the NA61/SHINE measurements to full phase space. For details see text.

**FTF works as well as EPOS 1.99 model.**

# Validation of FTF model for strange particle production

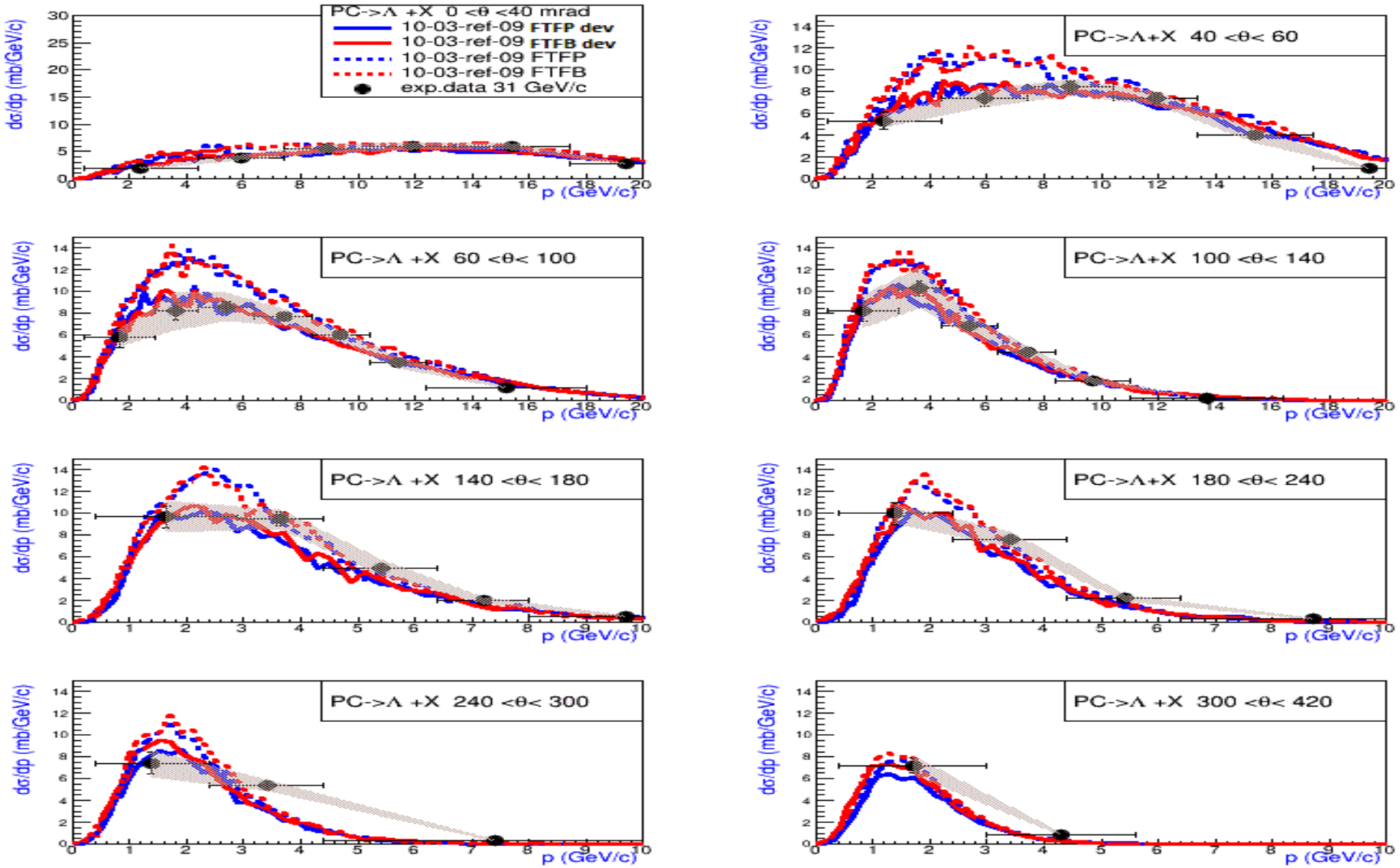
*Production of Λ-hyperons in inelastic p+p interactions at 158 GeV/c*

NA61/SHINE Collaboration **Eur.Phys.J. C76 (2016) no.4, 198**



# Validation of FTF model for strange particle production in pC, Λ

Measurements of π±, K± , K0S , Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS
Eur.Phys.J. C76 (2016) no. 2, 84

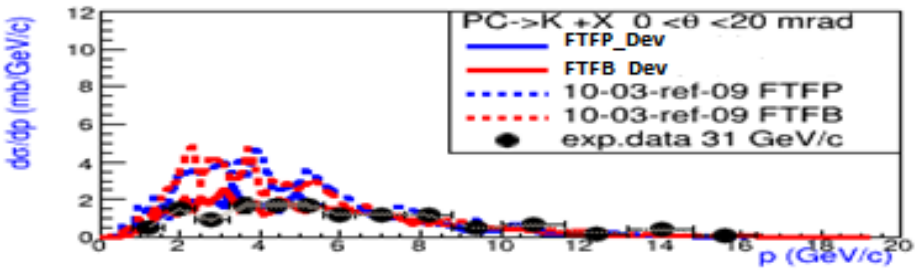


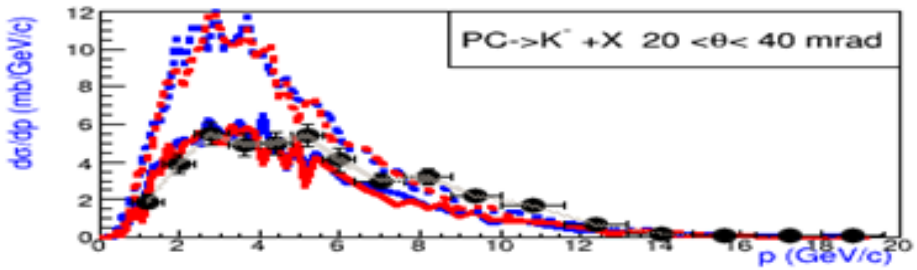

(Comparison with VENUS, GiBUU, FTFB in G4-10 is done in the paper.)

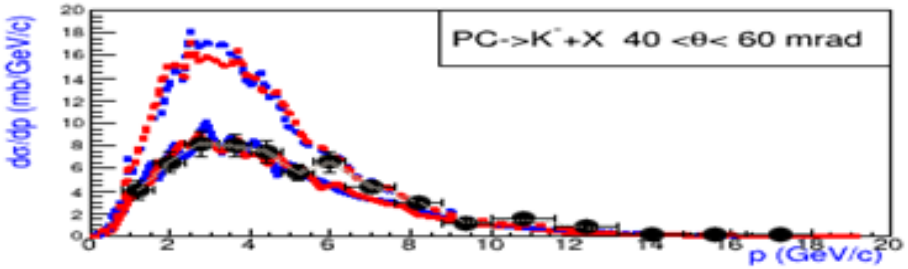
# Validation of FTF model for strange particle production in pC, K-

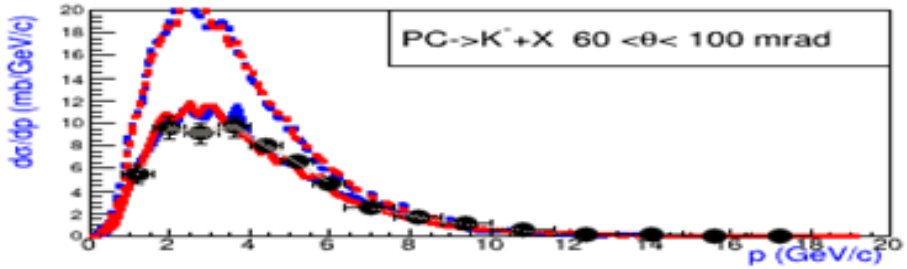
*Measurements of π±, K± , K0S , Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS*

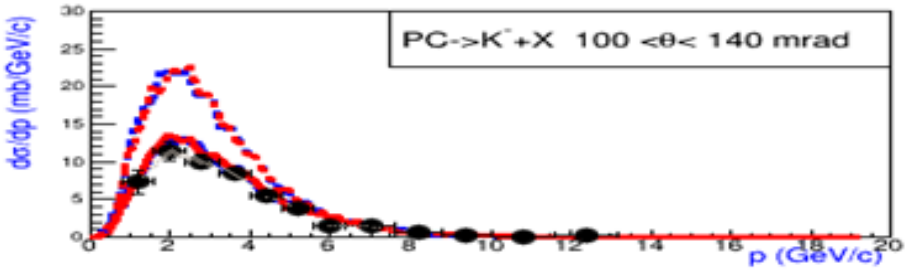
**Eur.Phys.J. C76 (2016) no.2, 84**

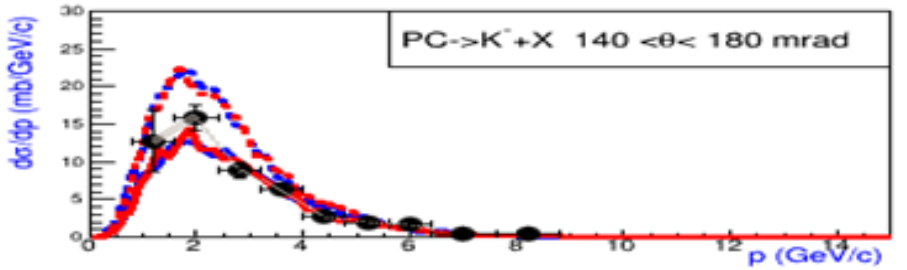


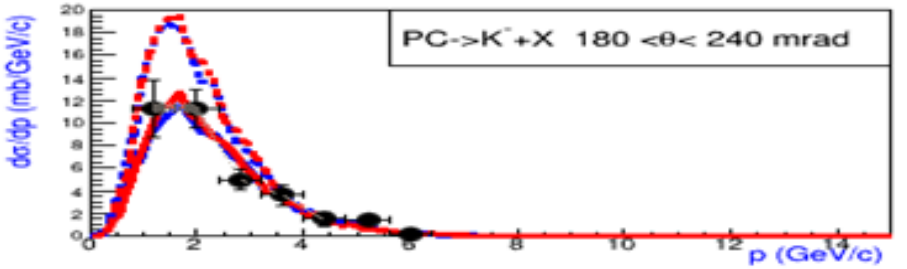



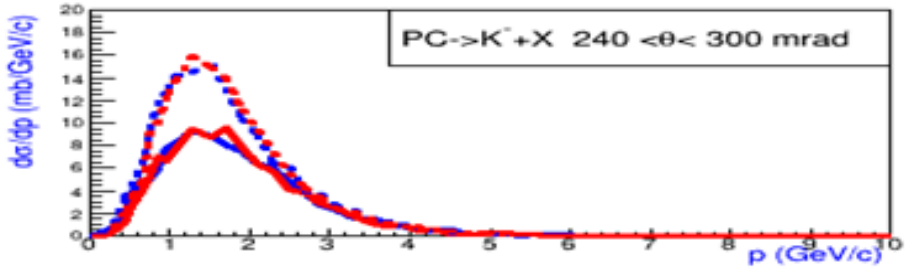



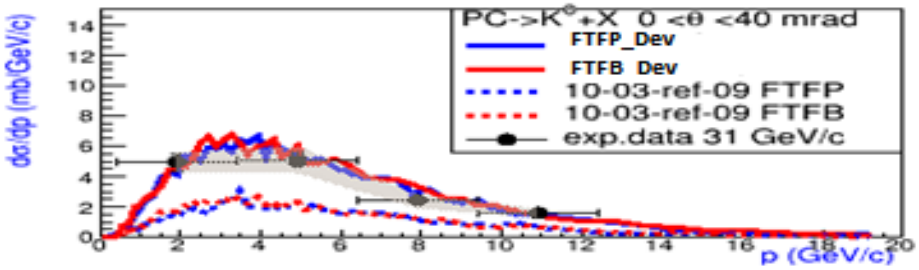



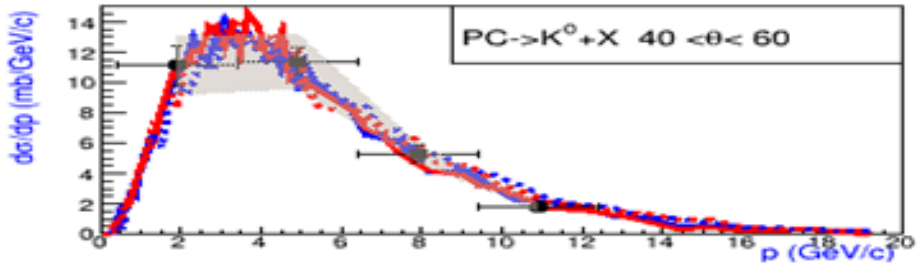



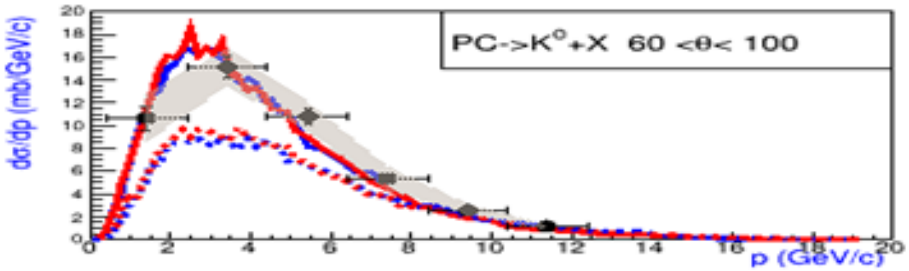



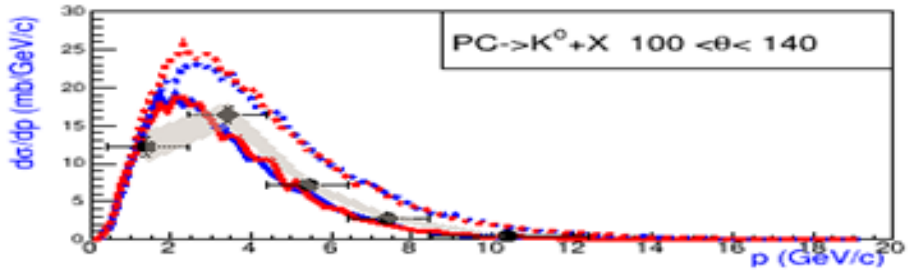
# Validation of FTF model for strange particle production in pC, K0

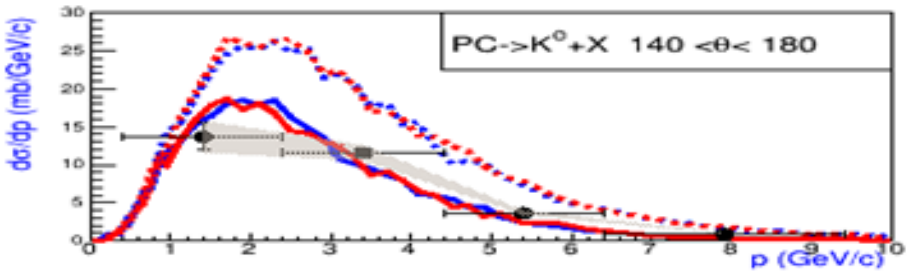
*Measurements of π±, K± , K0S , Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS*
**Eur.Phys.J. C76 (2016) no.2, 84**

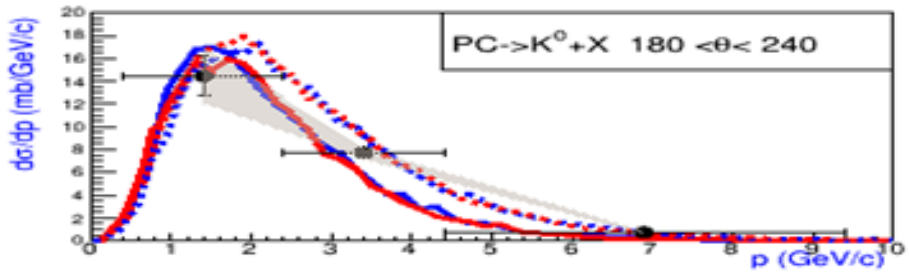


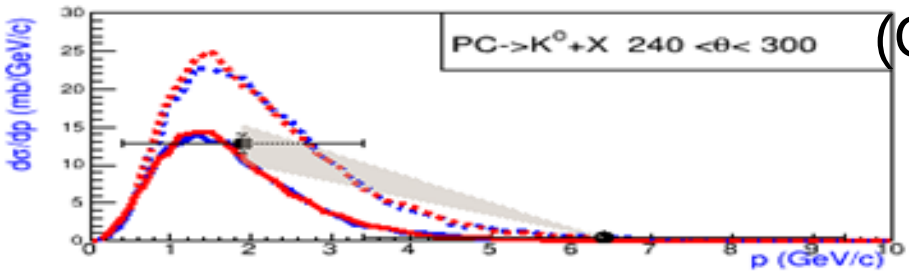




(Comparison with EPOS, FTFB in G4-09-05 is done in the paper. )

# *Simulation of inelastic P-P scatterings as background events in PandaRoot*

**FTF is implemented as primary generator of Pbar-P and Pbar-A interactions in subdirectory: pandaroot/pgenerators/FtfEvtGen.**

**Using FTF generator from PandaRoot we can simulate *inelastic P-P and P-A scatterings***

***/pgenertors/FtfEvtGen***

- ***make –f*** **Ftfmake**

***FTFGen exe file is produced***

***To simulate inelastic PP scatterings in the input file PP.mac, put***

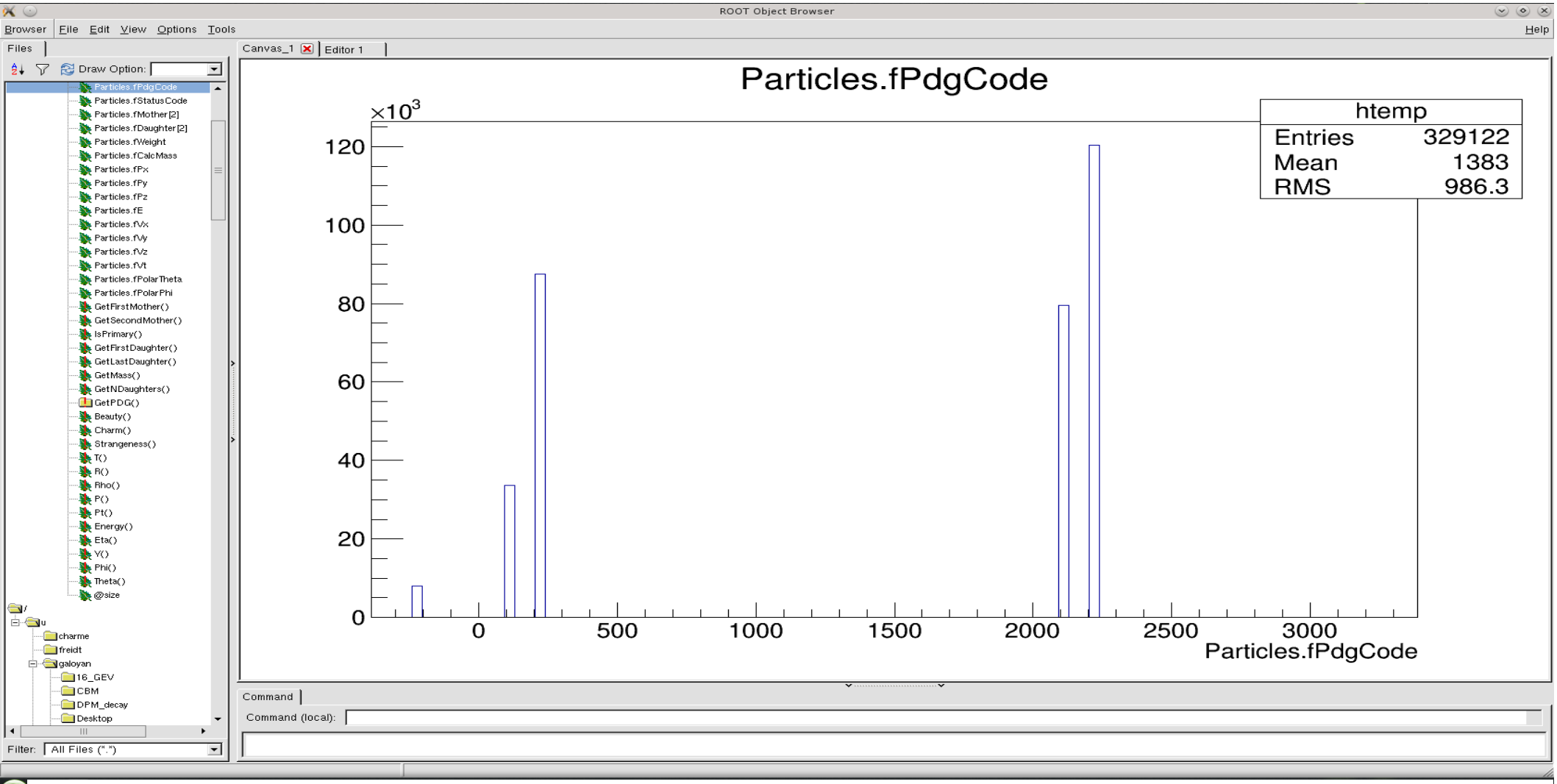
*#particle*
*proton*
*# generator*
*ftfp*
*#plab*
*momentum of projecile in GeV/c*
*#events*
*required number of generated events*

***> ./FTFGen PP.mac***

***FTF.root file will be created with all characteristics of produced particles***

# Simulation of inelastic PP scatterings as background events

## FTF.root file for PP inelastic events at initial momentum 2.8 GeV/c




## Number of produced protons and pi+ mesons is big. They can create background for elastic PP-interactions

# Conclusion

## Simulations of elastic P-P and Pbar-P interactions

- New parameterization of P-P and Pbar-P elastic scattering is proposed (USESD). Dependencies of effective parameters R and d on energy are determined.
- Good description of experimental data on elastic P-P and Pbar-P scatterings in the wide energy range (1 GeV – 1 TeV) is reached. The data of the TOTEM Collab. on P-P scattering at 7 TeV collision energy in CMS are reproduced. Predictions for higher LHC energies (10 and 14 TeV) are presented.
- MC program based on the new parameterization of hadronic part of PP elastic scattering is created. Coulomb and Interference parts of the elastic scatterings are also implemented in the program. The program operates under ROOT.

## Simulations of inelastic P-P interactions

- A new formula for *Probability* of strange q-qbar production at final string decay is proposed and implemented in the FTF model.
- A new formula for *Probability* of diquark-antidiquark production at string decay is proposed and implemented in the FTF model.
- Good agreement of model calculations and exp. data on *π±, K± , antiproton, proton and Λ –hyperon* production in proton-proton collisions is reached in wide energy range.
- The improved FTF model describes well exp. data on *π±, K± , K0, proton and Λ –hyperon* production in proton-Carbon interactions at 31 GeV/c.

FTF model is installed in PandaRoot as primary generator and can be installed in SPDRoot.

# Validation of Geant4 FTF model for NA61/SHINE exp. data

**The exp. data of NA61/SHINE are taken from papers:**

**1.** *Measurements of π±, K± , p and p¯ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS.* **NA61/SHINE Collaboration (A. Aduszkiewicz (Warsaw U.) et al.). May 6, 2017. 54pp. Published in Eur.Phys.J. C77 (2017) no.10, 671**

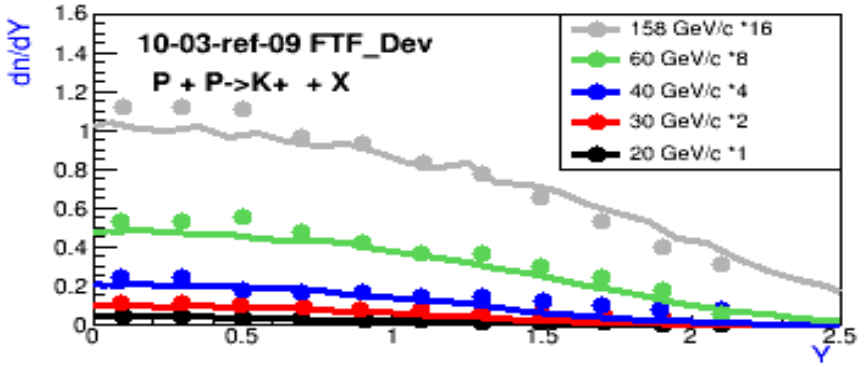
***2***. *Production of Λ -hyperons in inelastic p+p interactions at 158 GeV/c* NA61/SHINE Collaboration **Eur. Phys. J. C76 (2016) no.4, 198**

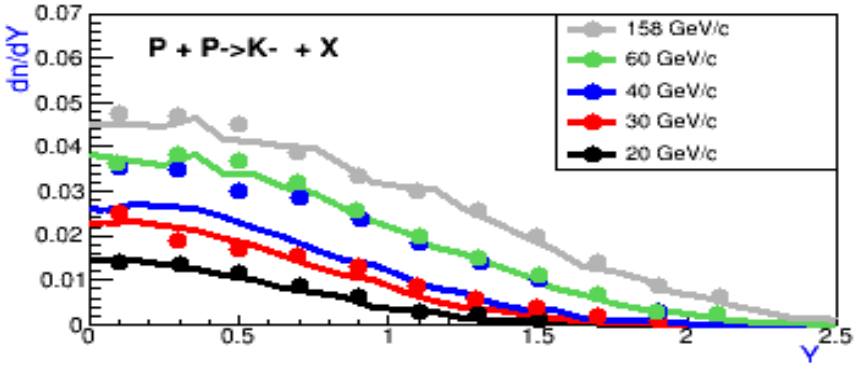
***3.*** *Measurements of π±, K± , K0S , Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS* ***NA61/SHINE Collaboration (N. Abgrall (Geneva U.) et al.). Oct 9, 2015. 76 pp. Published in Eur.Phys.J. C76 (2016) no.2, 84 e-Print: arXiv:1510.02703 [hep-ex]***

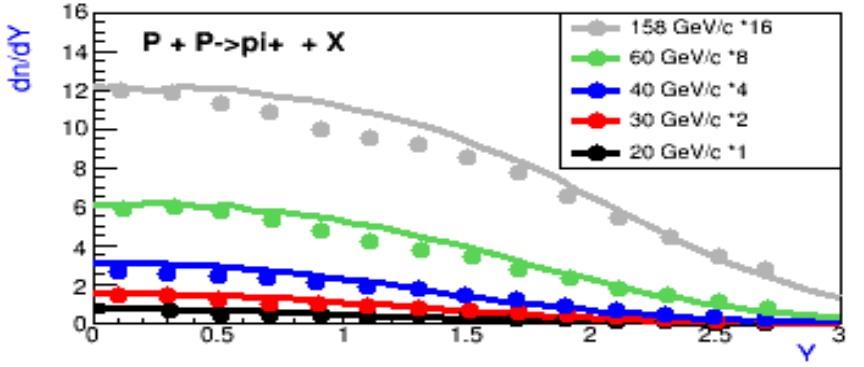
**4.** *Measurements of Hadron Production in Pion-Carbon Interactions with NA61/SHINE at the CERN SPS.*
**NA61/SHINE Collaboration (Raul R. Prado (Sao Paulo U., Sao Carlos) for the collaboration). Jul 25, 2017. Conference: C17-07-12 Proceedings. arXiv:1707.07902 [hep-ex]**

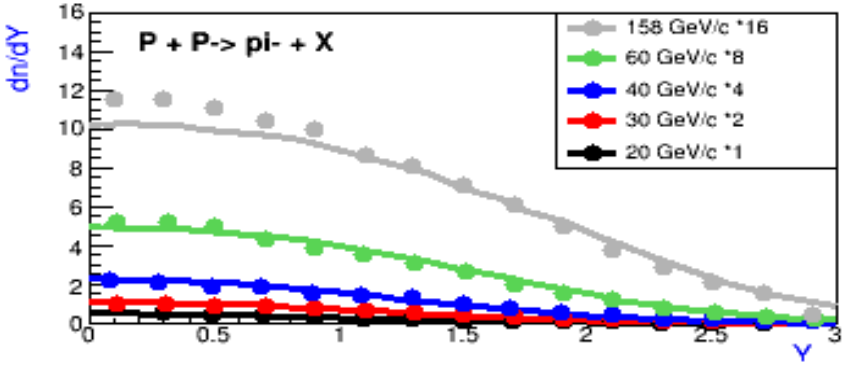
# Validation of FTF model for PP-interactions

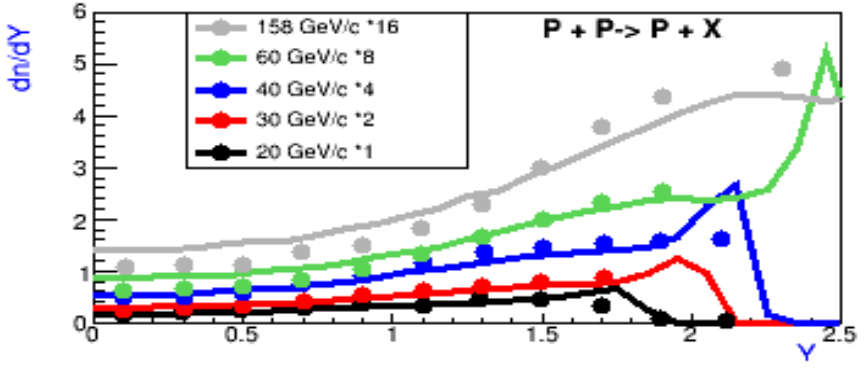
Measurements of π±, K± , p and $\bar{p}$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS.
**NA61/SHINE Collaboration** **Eur.Phys.J. C77 (2017)**

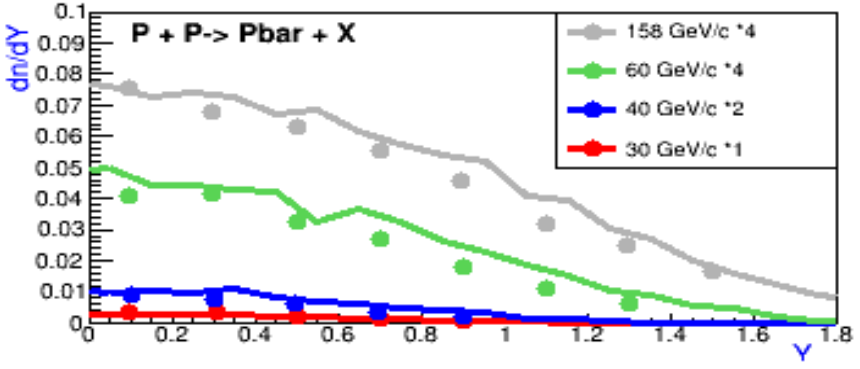


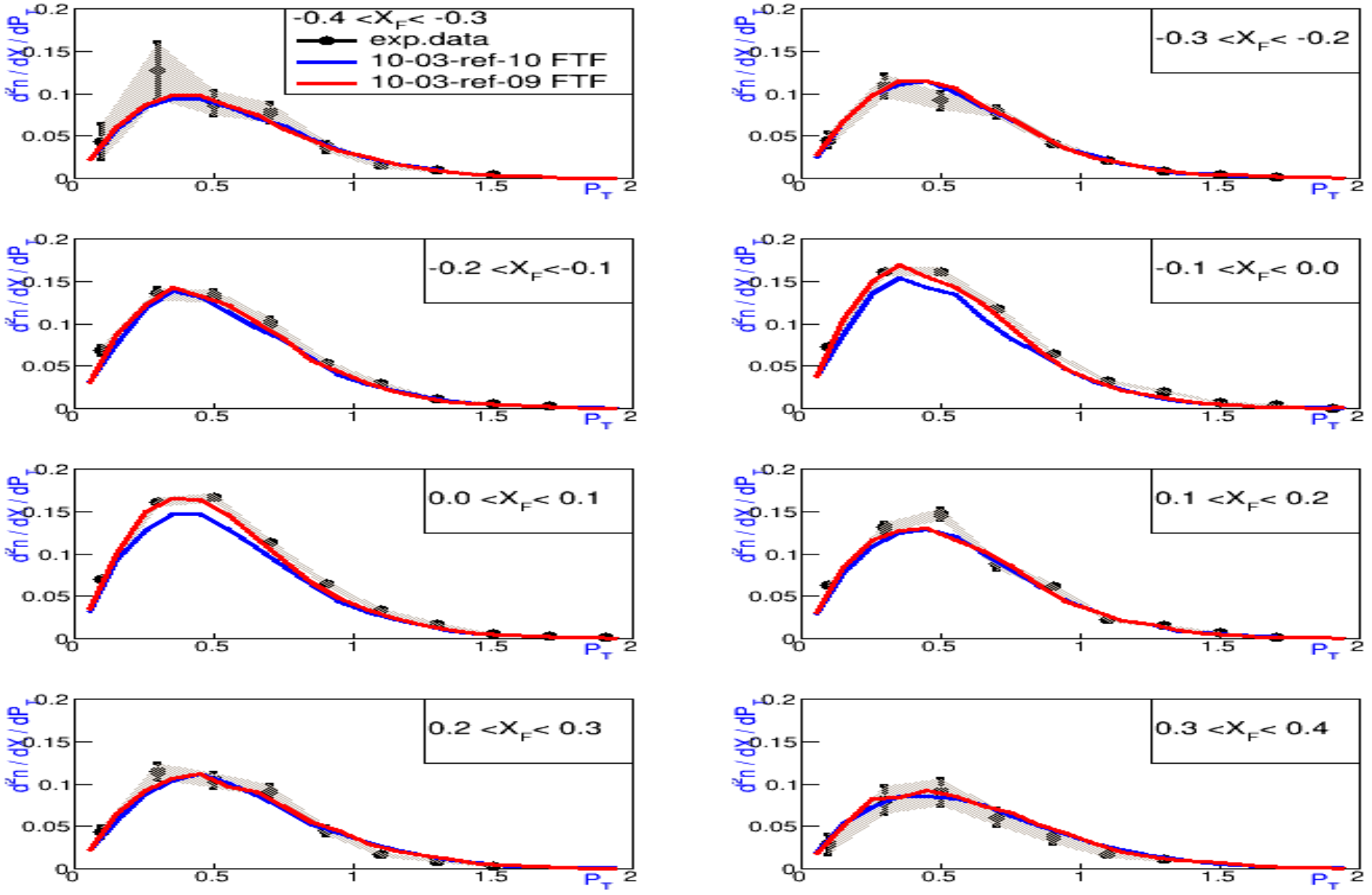



# Validation of FTF model for strange particle production

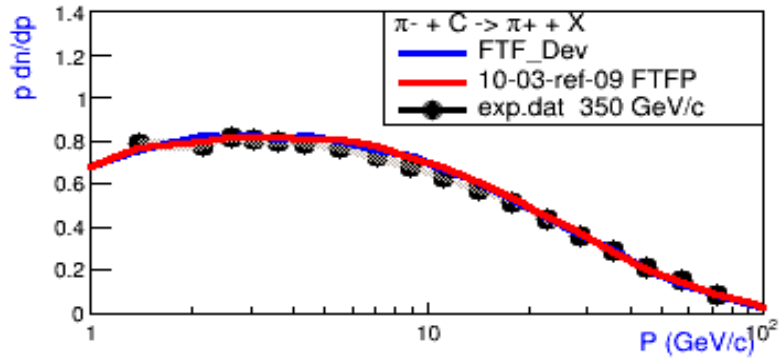
*Production of Λ-hyperons in inelastic p+p interactions at 158 GeV/c*

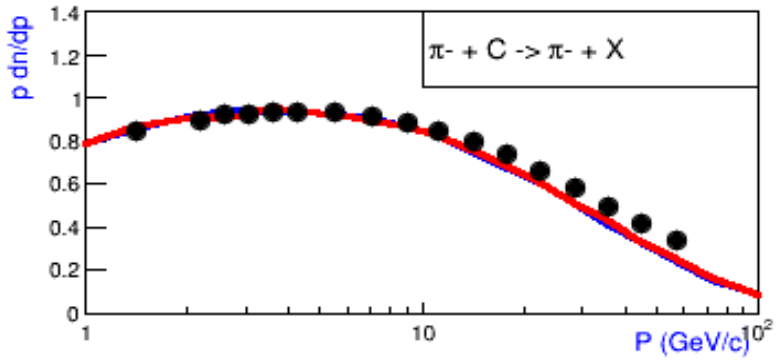
NA61/SHINE Collaboration **Eur.Phys.J. C76 (2016) no.4, 198**

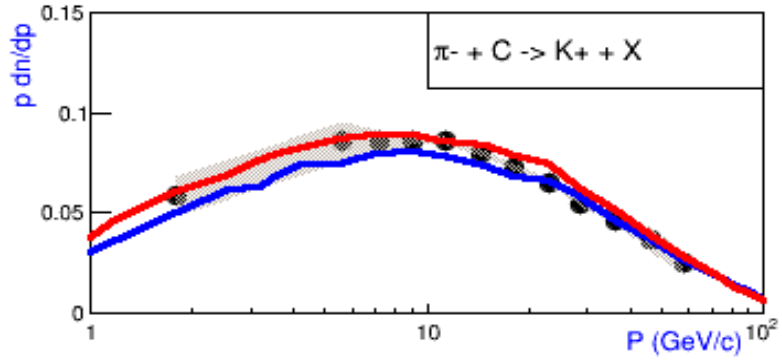


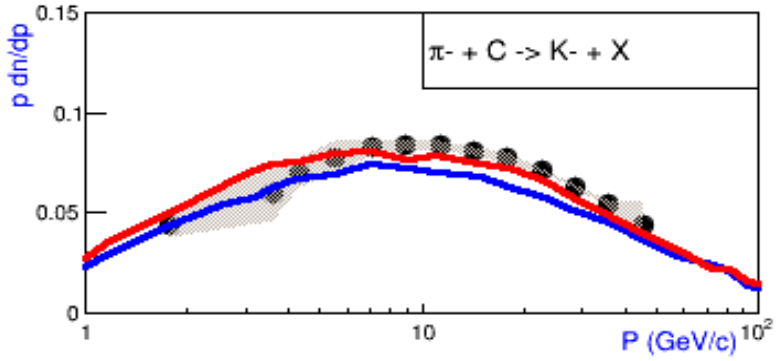
# Tuning of FTF model using NA61/SHINE data

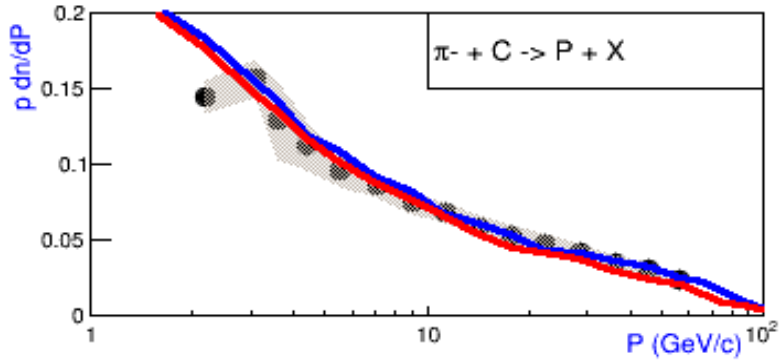
Measurements of Hadron Production in Pion-Carbon Interactions with NA61/SHINE at the CERN SPS. **NA61/SHINE Collaboration (Raul R. Prado (Sao Paulo U., Sao Carlos)**
**Jule 25, 2017. Conference: C17-07-12 Proceedings. arXiv:1707.07902**

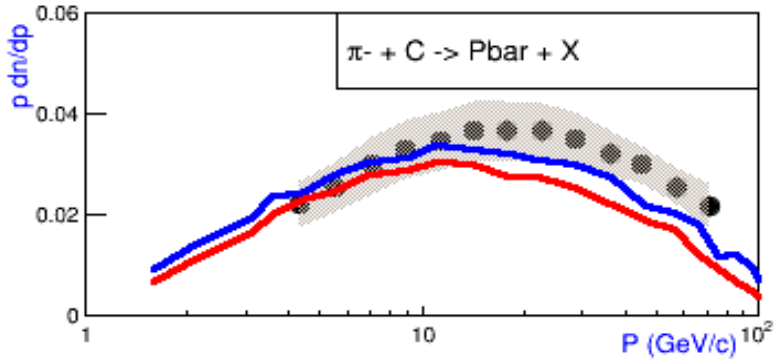


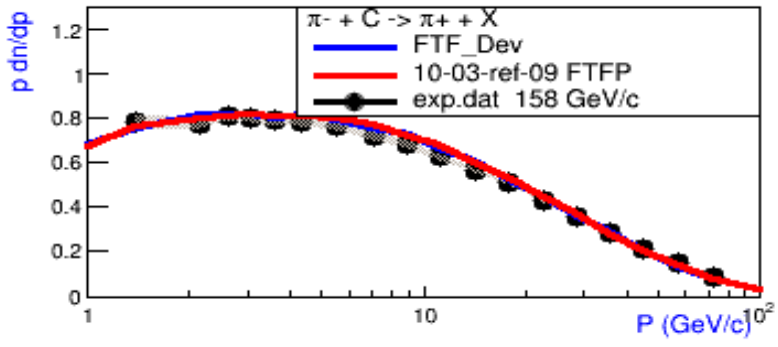



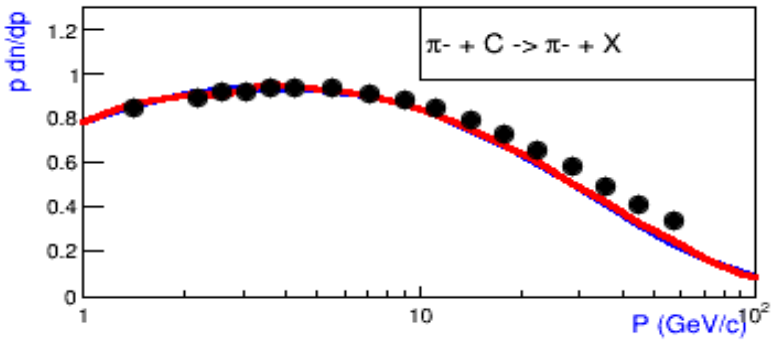



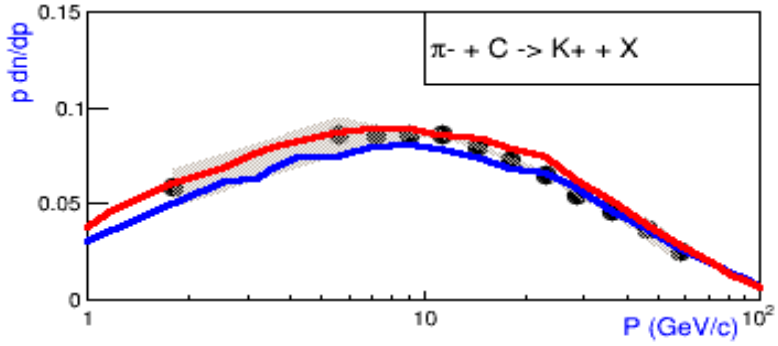



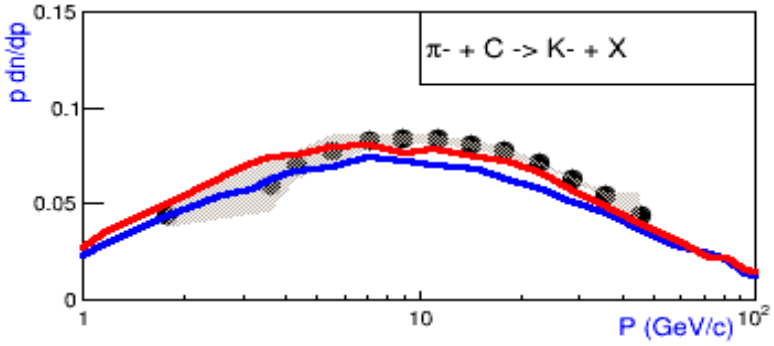
# Tuning of FTF model using NA61/SHINE data

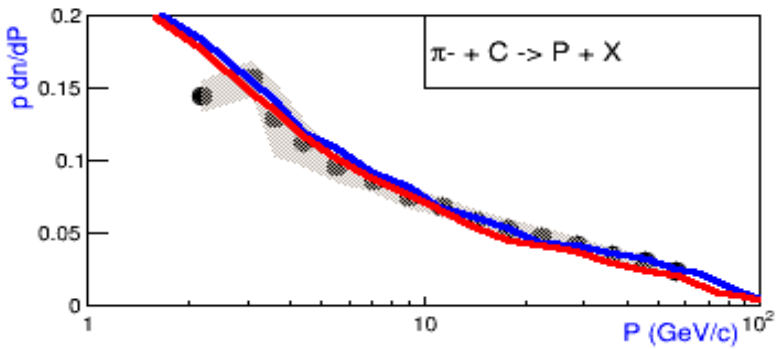
Measurements of Hadron Production in Pion-Carbon Interactions with NA61/SHINE at the CERN SPS. **NA61/SHINE Collaboration (Raul R. Prado (Sao Paulo U., Sao Carlos) for the collaboration).Jul 25, 2017. Conference: C17-07-12 Proceedings. arXiv:1707.07902**

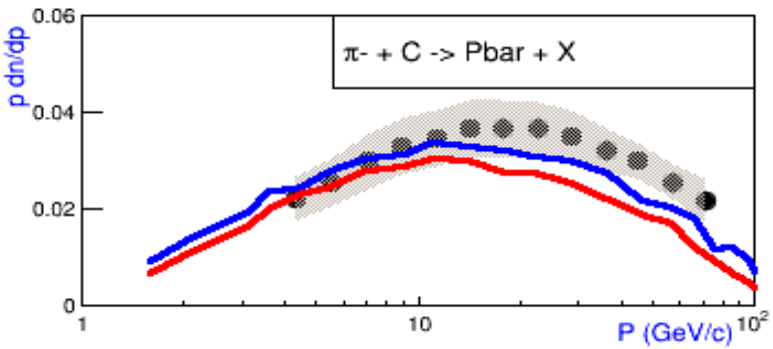


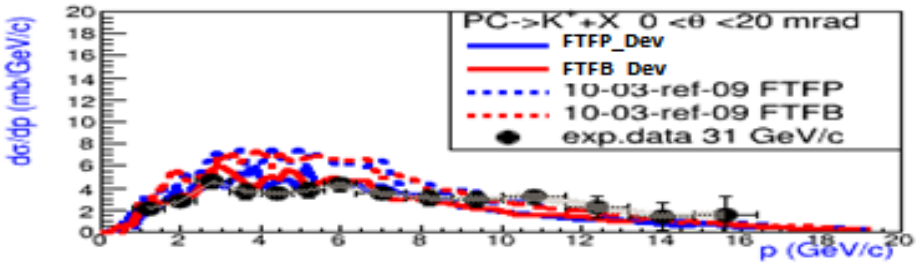



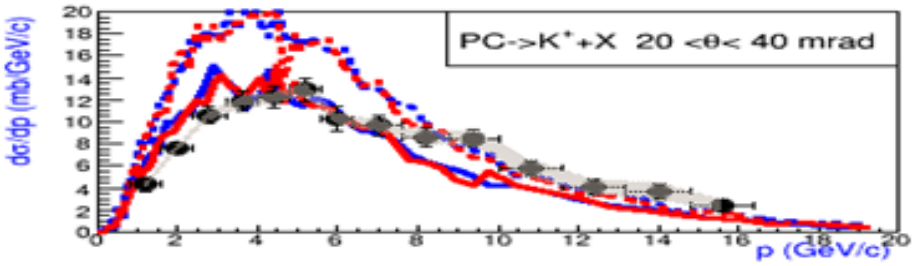



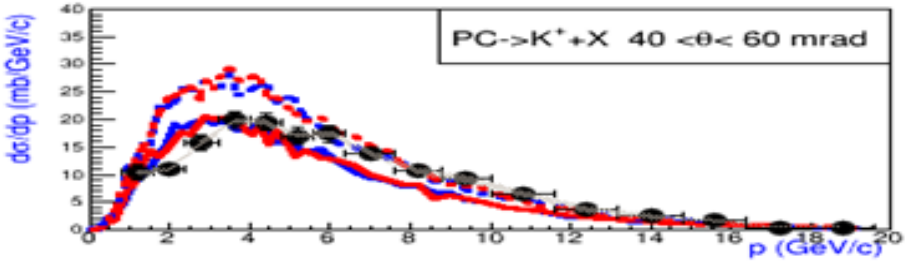
# Validation of FTF model for strange particle production in pC, K+

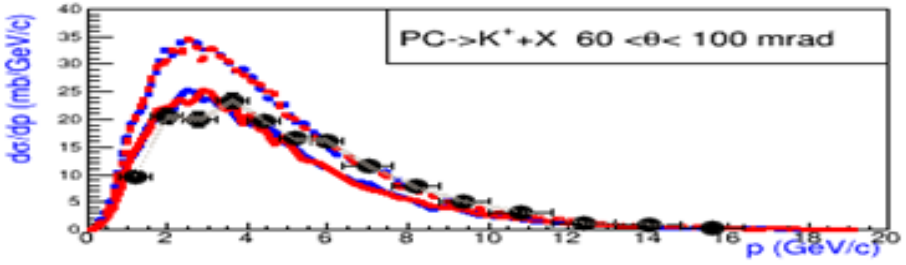
*Measurements of π±, K± , K0S , Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS*

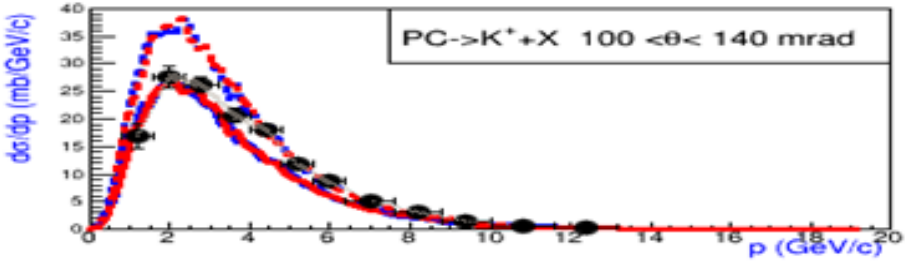
**Eur.Phys.J. C76 (2016) no.2, 84**

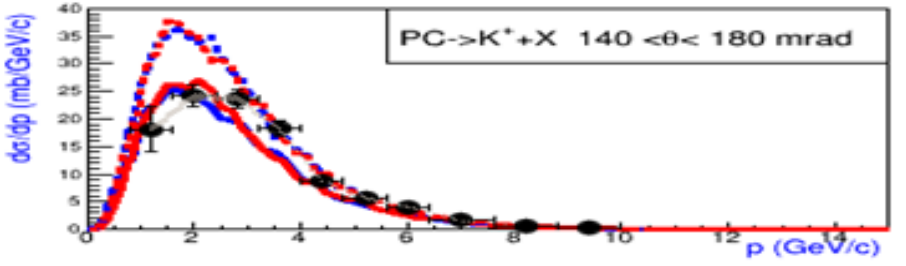


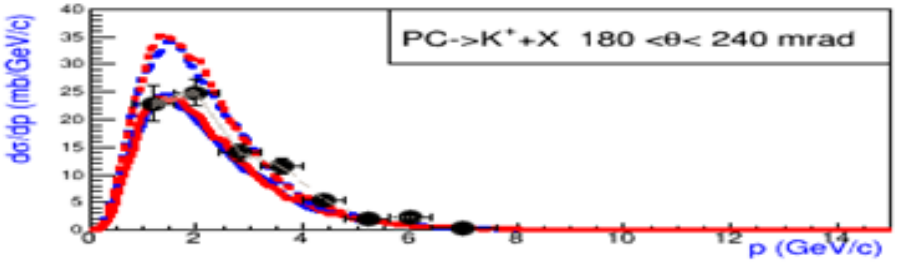



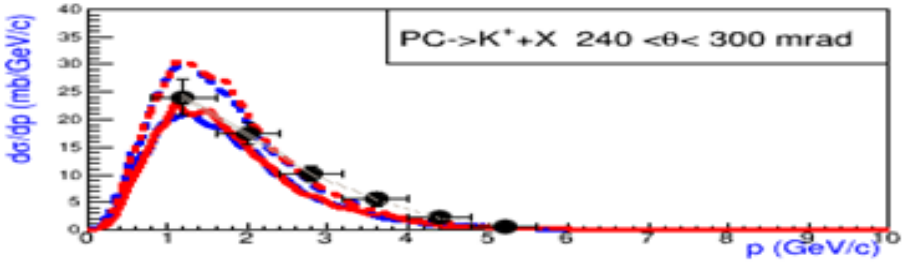



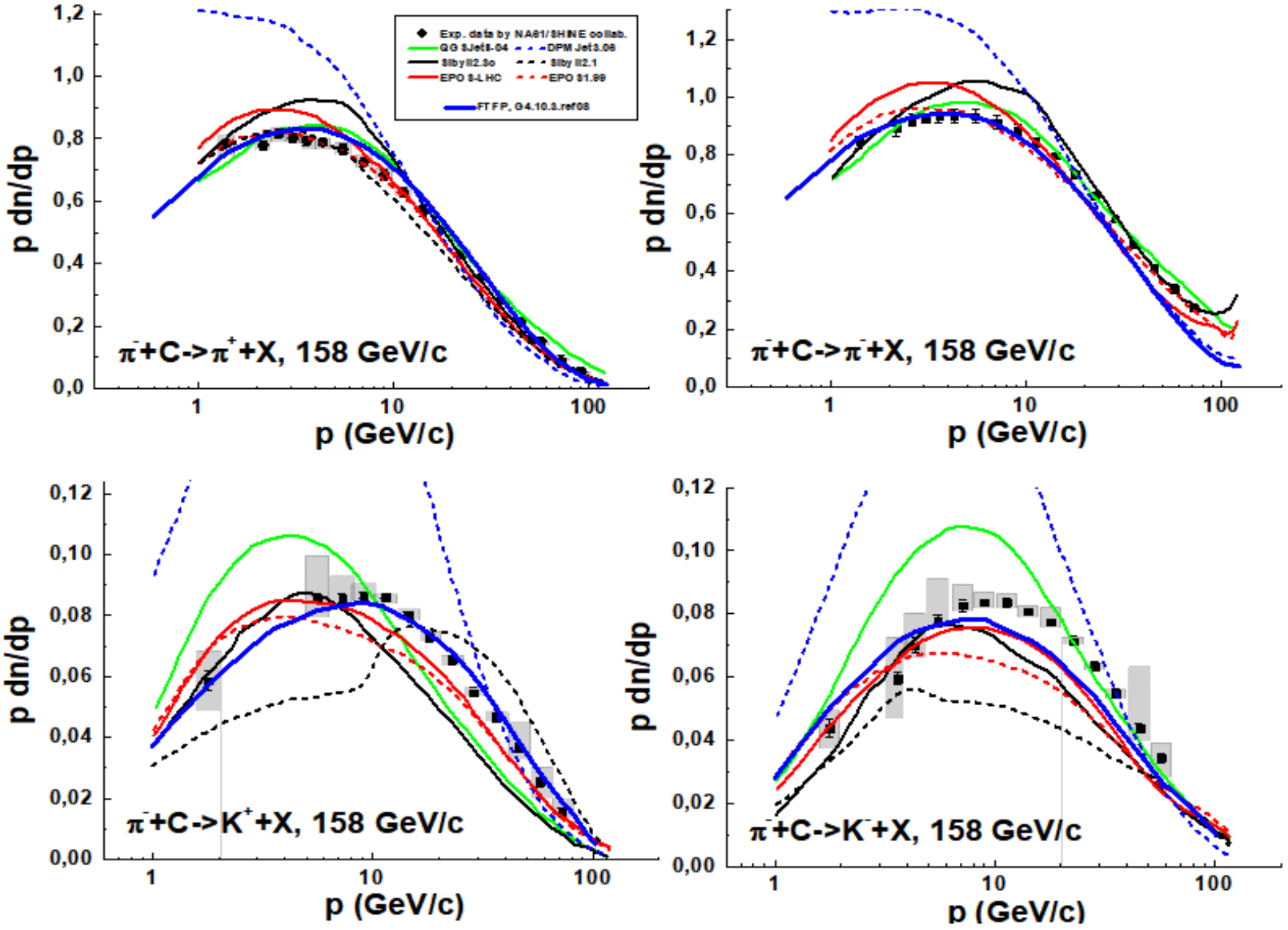



# Measurements of Hadron Production in Pion-Carbon Interactions with NA61/SHINE at the CERN SPS.

Raul R. Prado for the NA61/SHINE collaboration




**Predictions of the model are very different! FTF is OK!**