Status and prospectives for Geant4 string models, FTF and QGS

(What was astonished us in 2020 -2022?)

V._Uzhinsky, 26.09.2022

1. G4 FTF and QGS model among other models:
   Pythia8, Angantyr, SMASH, EPOS 1.99, PHSD;
   no FLUKA, MCMPx (LA QGSM), MARS (Today there is only slow evolution of MC models! Main struggle is for neutrino interactions.)

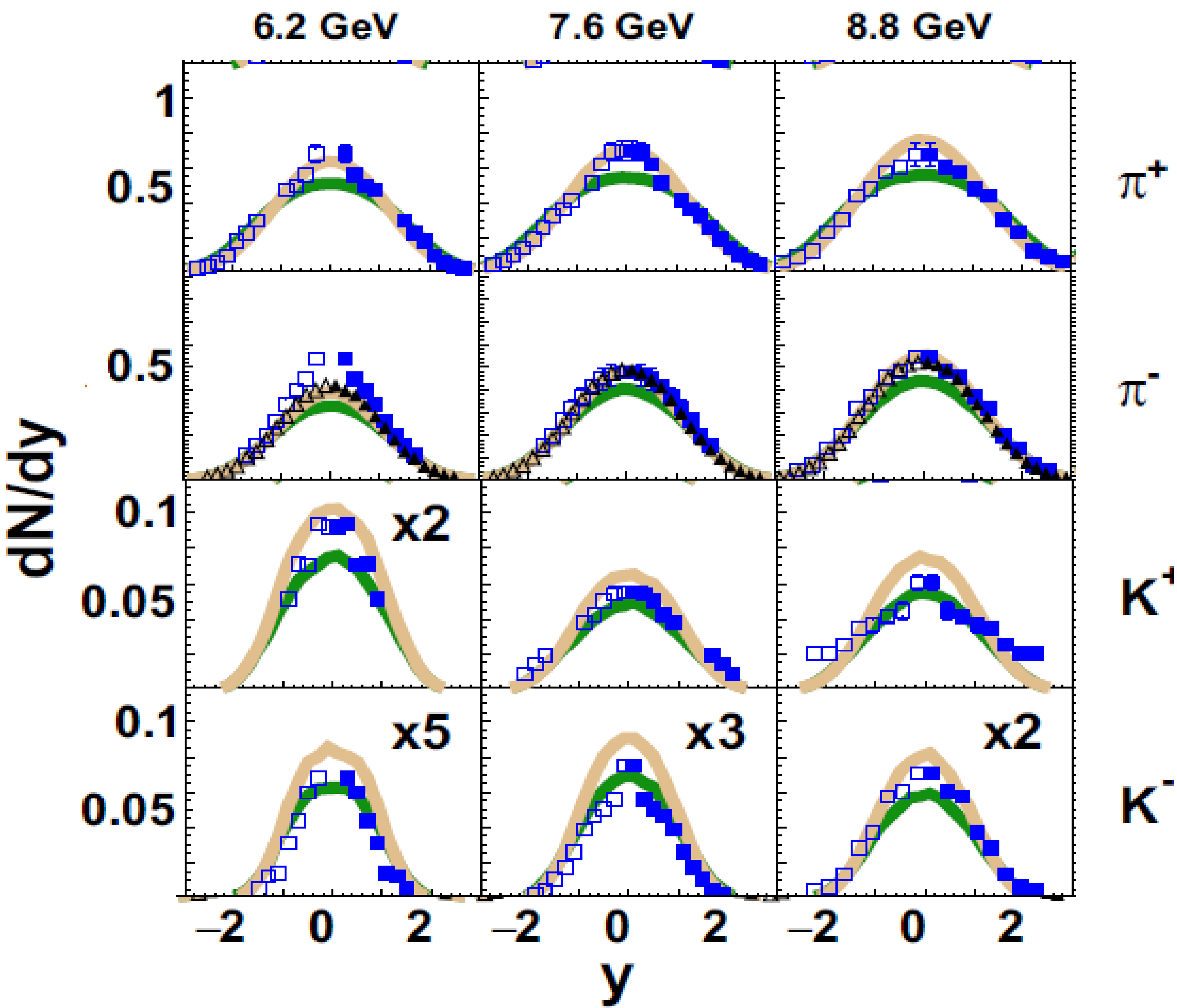
2. Application of FTF model for simulations of nucleus-nucleus interactions (Ar-40 + Sc-45, Be-7 + Be-9, NA61/SHINE data) (2021)

3. Strange particle's production in pp-interactions (latest data by NA61/SHINE collab.) (2022)

Conclusion (all together 42 slides)

PHSD + PYTHIA 8.2 (V. Kireyeu et al. Eur. Phys. J. A (2020) 56:223)

Plab 20 GeV/c 31 GeV/c 40 GeV/c PP interactions



Green lines
PHSD

Grey lines
Pythia 8

Pythia 8
Pi+, Pi- OK

K+, K- too many!

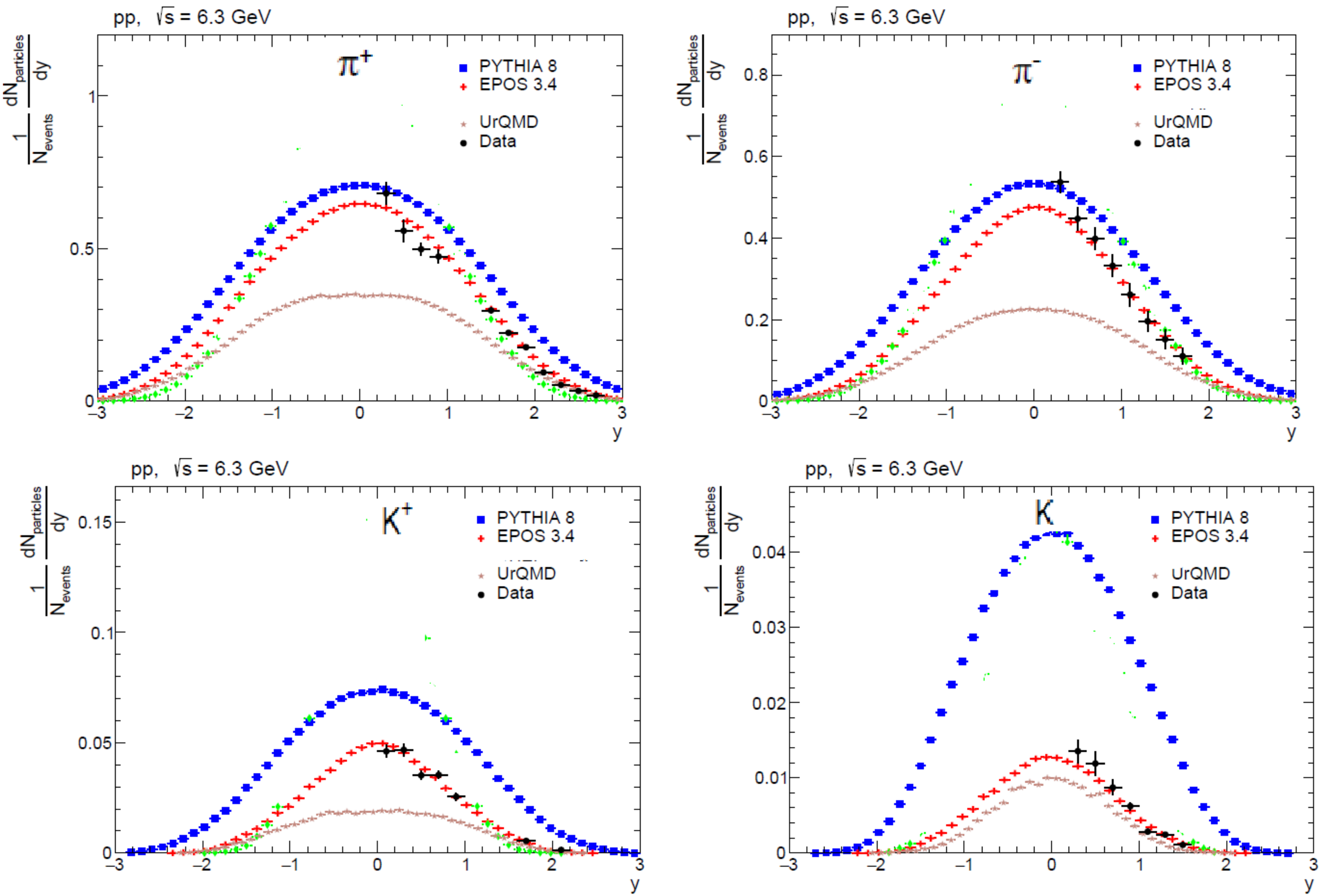
PHSD
Pi+, Pi- less!

K+, K- OK

Rapidity distributions of particles. Data – NA61/SHINE

Performance of Monte Carlo models of pp collisions, Plab = 19 GeV/c

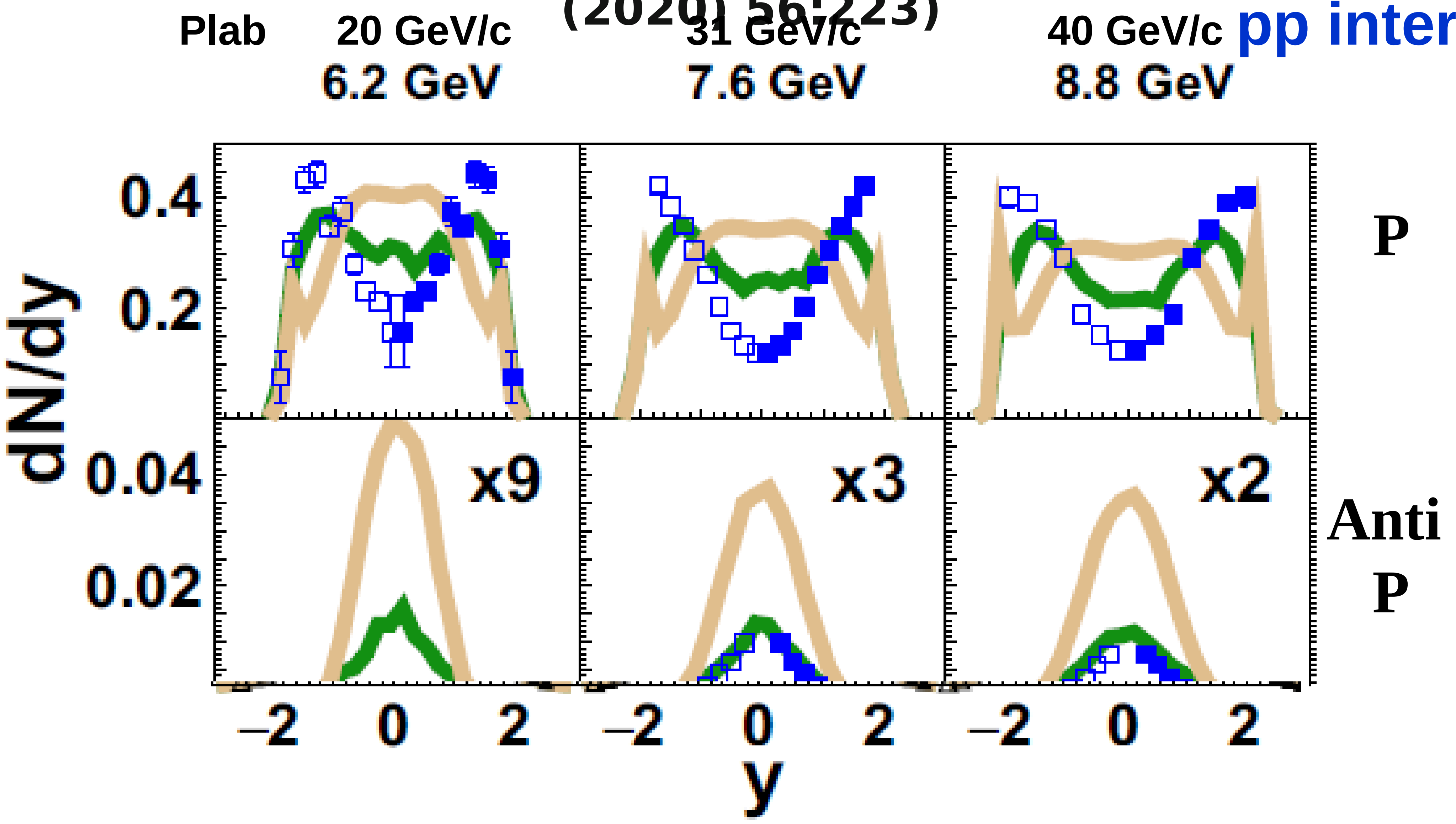
Maxim Azarkin, Martin Kirakosayn P.N. Lebedev Physics Institute, **2103.07222**



EPOS works well at Ecms > 5 GeV! Pythia …?

PHSD + PYTHIA 8.2 (V. Kireyeu et al. Eur. Phys. J. A (2020) 56:223)

pp inter



Rapidity distributions of particles. Data – NA61/SHINE

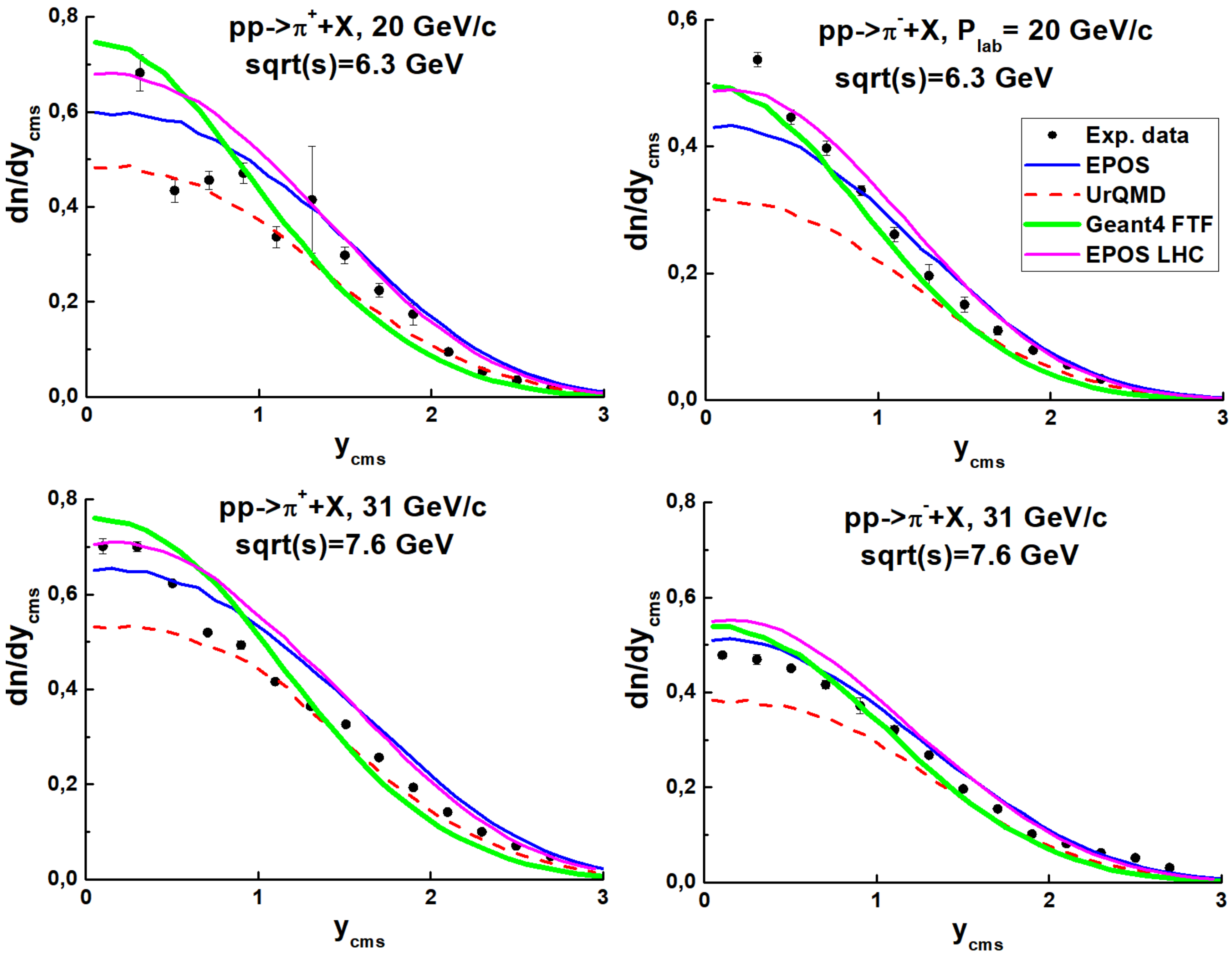
Green lines PHSD

Grey lines Pythia 8

Pythia 8 All bad!

PHSD P bad! Only anti P - OK

EPOS 1.99, Geant4/FTF, UrQMD, EPOS-LHC

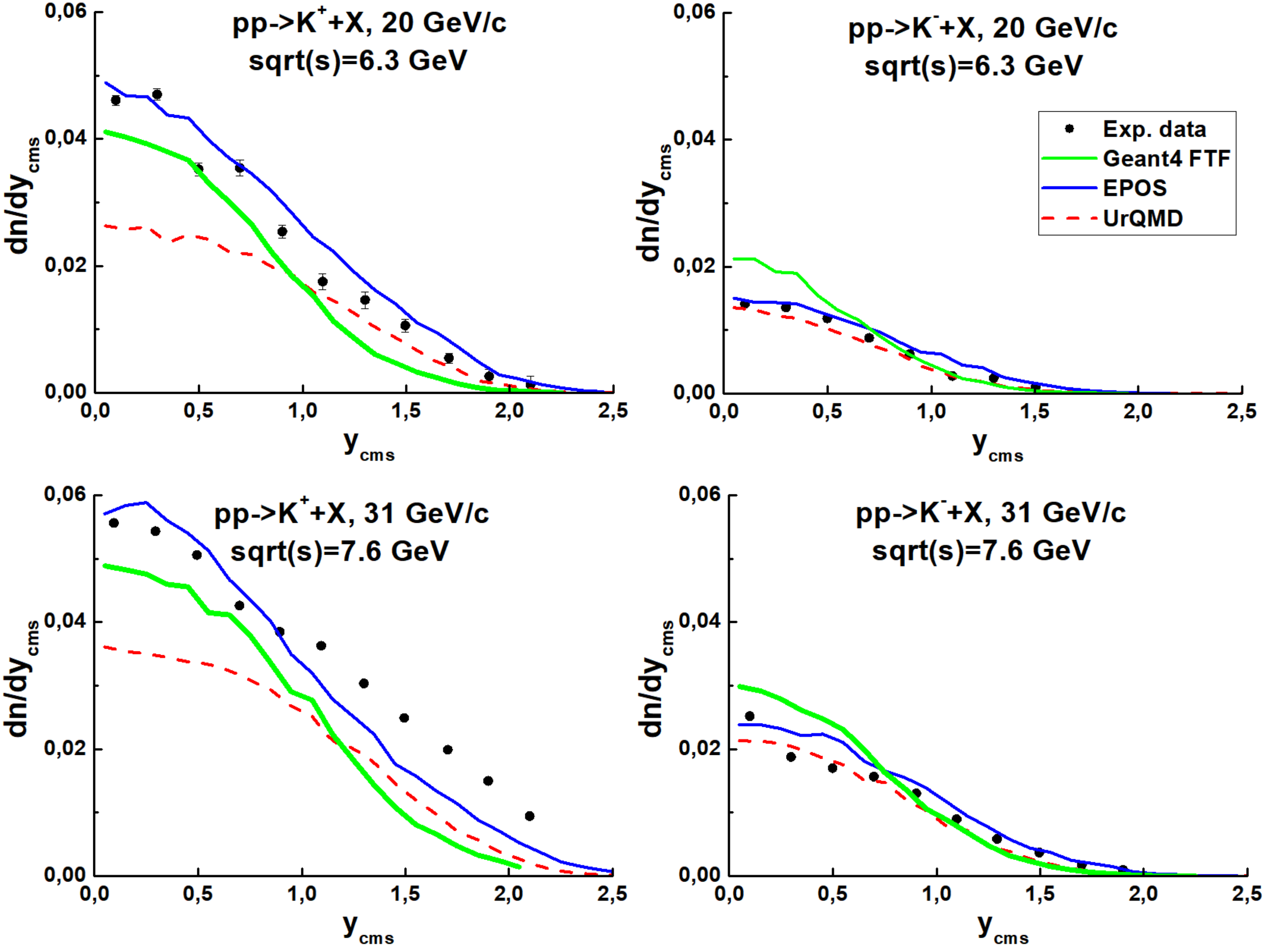


UrQMD under-estimates meson production

EPOS, FTF
It is complicated to say, what model is better!

Experimental data for Pi+ scatters too strongly!

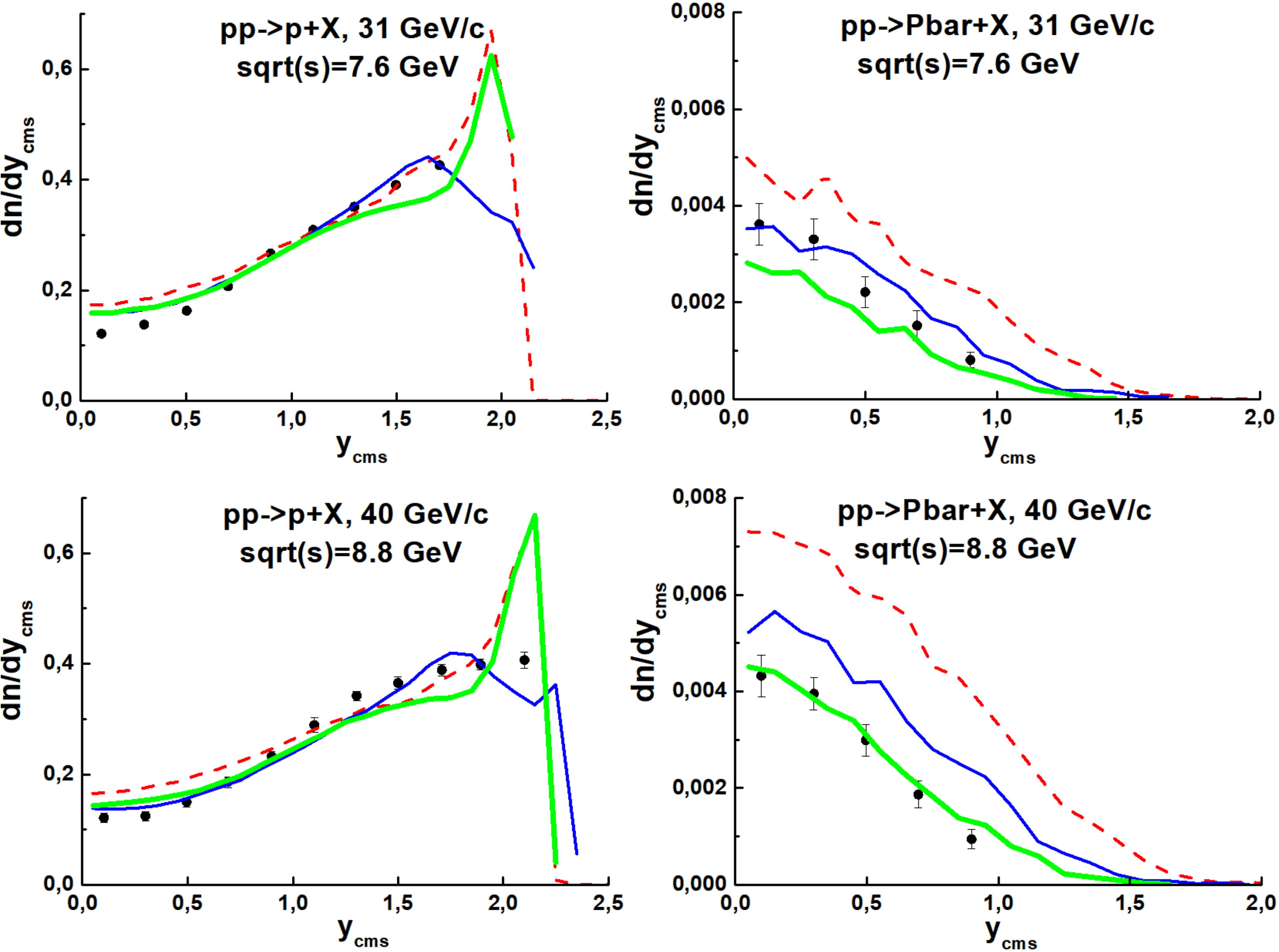
EPOS 1.99, Geant4/FTF, UrQMD



UrQMD under-estimates K+ meson production

EPOS, FTF It is complicated to say, what model is better!

EPOS 1.99, Geant4/FTF, UrQMD



UrQMD over-estimates anti-proton production

EPOS
No diffraction in the model!

SUMMARY

Pythia 8 OK at Ecmc >= 9 GeV

It would be well to tune it for K+, K- and anti-proton

EPOS 1.99 & EPOS-LHC OK at Ecmc >= 5 GeV

It would be well to include quark exchange processes and a good diffraction

Geant4 FTF OK at Ecmc >= 3 GeV

It would be well to improve (2020) spectra of K+ and K-

Below Ecmc 3 GeV

~~UrQMD~~ ㅂ SMASH (C++ re-incarnation of UrQMD)

FTF model : basic assumptions

B.Andersson et al. Nucl. Phys. B281 289 (1987)
B.Nilsson-Almquist, E.Stenlund, Comp. Phys. Comm. 43 387 (1987).

Fig. 1: Processes of string's creations considered in the FTF model.

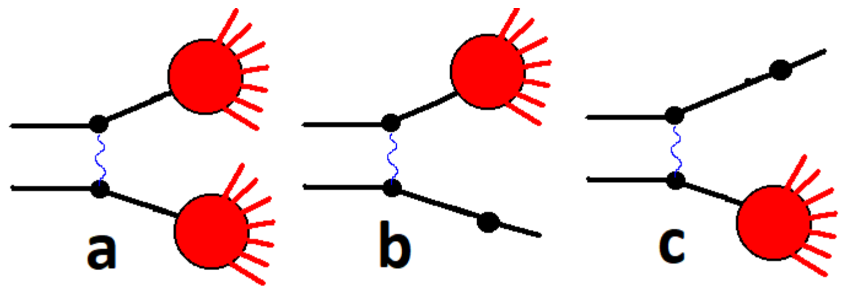
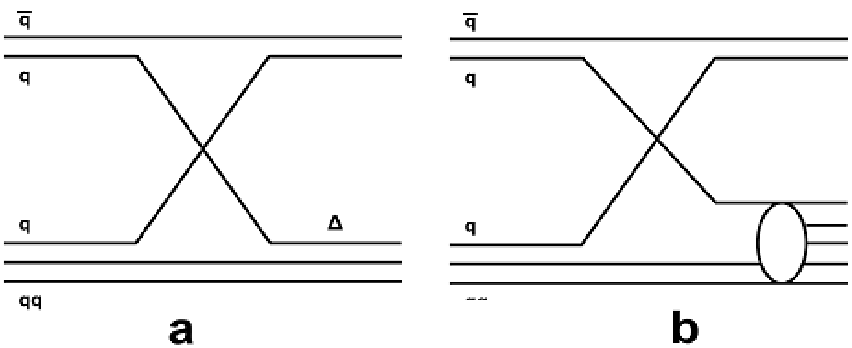


Fig. 2 Additional quark exchange processes in the FTF model.

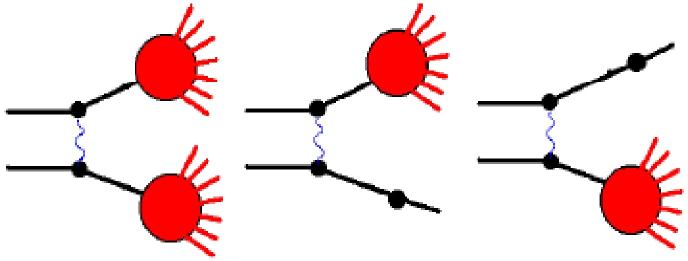


String mass distribution

$$dW/dP^- = (1-f)\frac{1}{\ln\left(P^-_{max}/P^-_{min}\right)}\, 1/P^- + f\frac{1}{P^-_{max} - P^-_{min}},$$

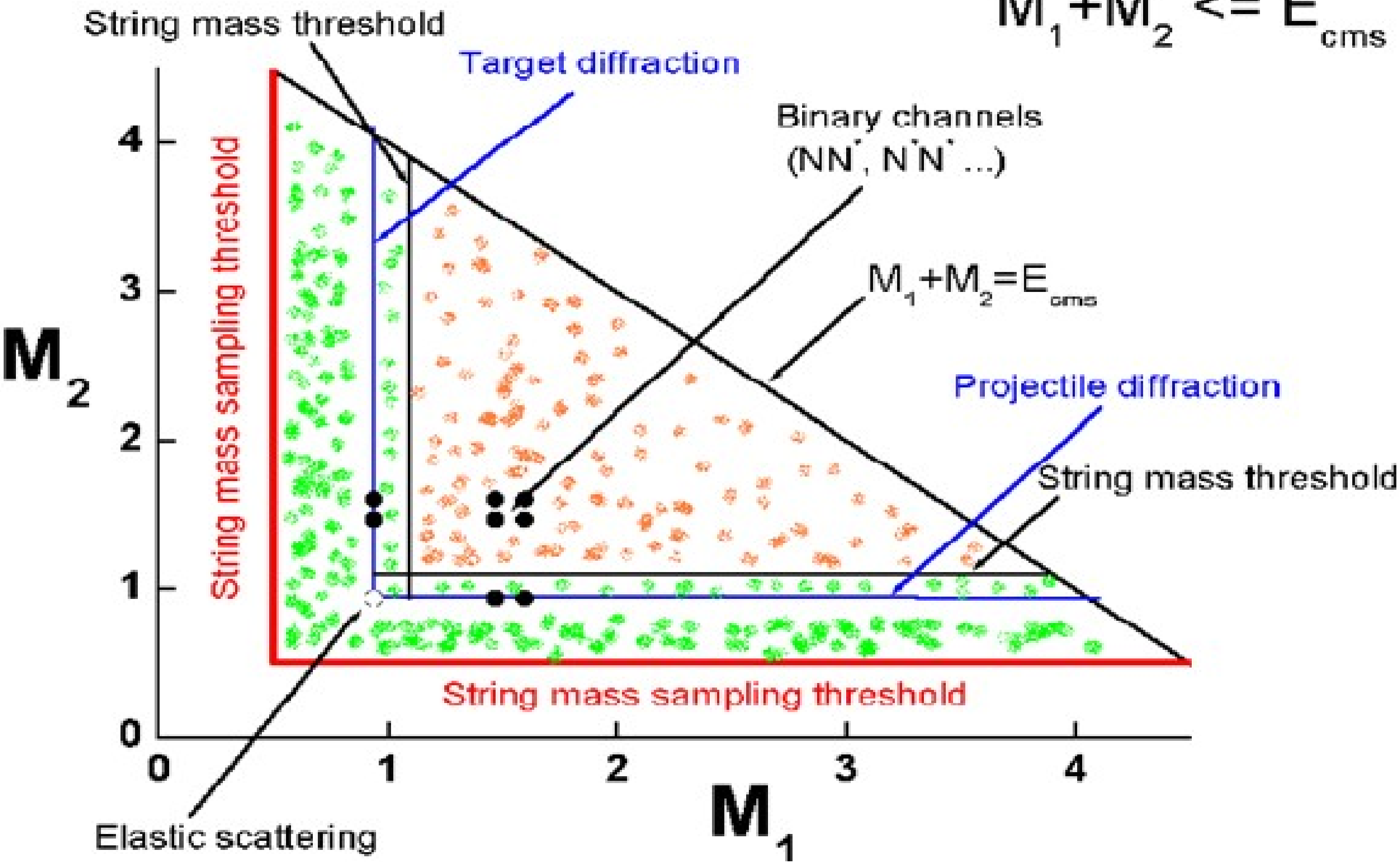
$$P^- = \sqrt{M^2 + P_T^2 + P_z^2} - P_z \simeq (M^2 + P_T^2)/2\, P_z \; (P_z \to \infty) \qquad f = 0.55$$

FTF model : basic assumptions



B.Andersson et al. Nucl. Phys. B281 289 (1987)
B.Nilsson-Almquist, E.Stenlund,
Comp. Phys. Comm. 43 387 (1987).

$M_1+M_2 <= E_{cms}$



UrQMD Md=1.46

$$NN \to N\Delta_{1232}$$
$$NN \to NN^*$$
$$NN \to N\Delta^*$$
$$NN \to \Delta_{1232}N^*$$
$$NN \to \Delta_{1232}\Delta^*$$
$$NN \to \Delta\Delta \text{ excitation}$$

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

<Pt> - Xf correlations in pp interactions, 158 and 400 GeV/c

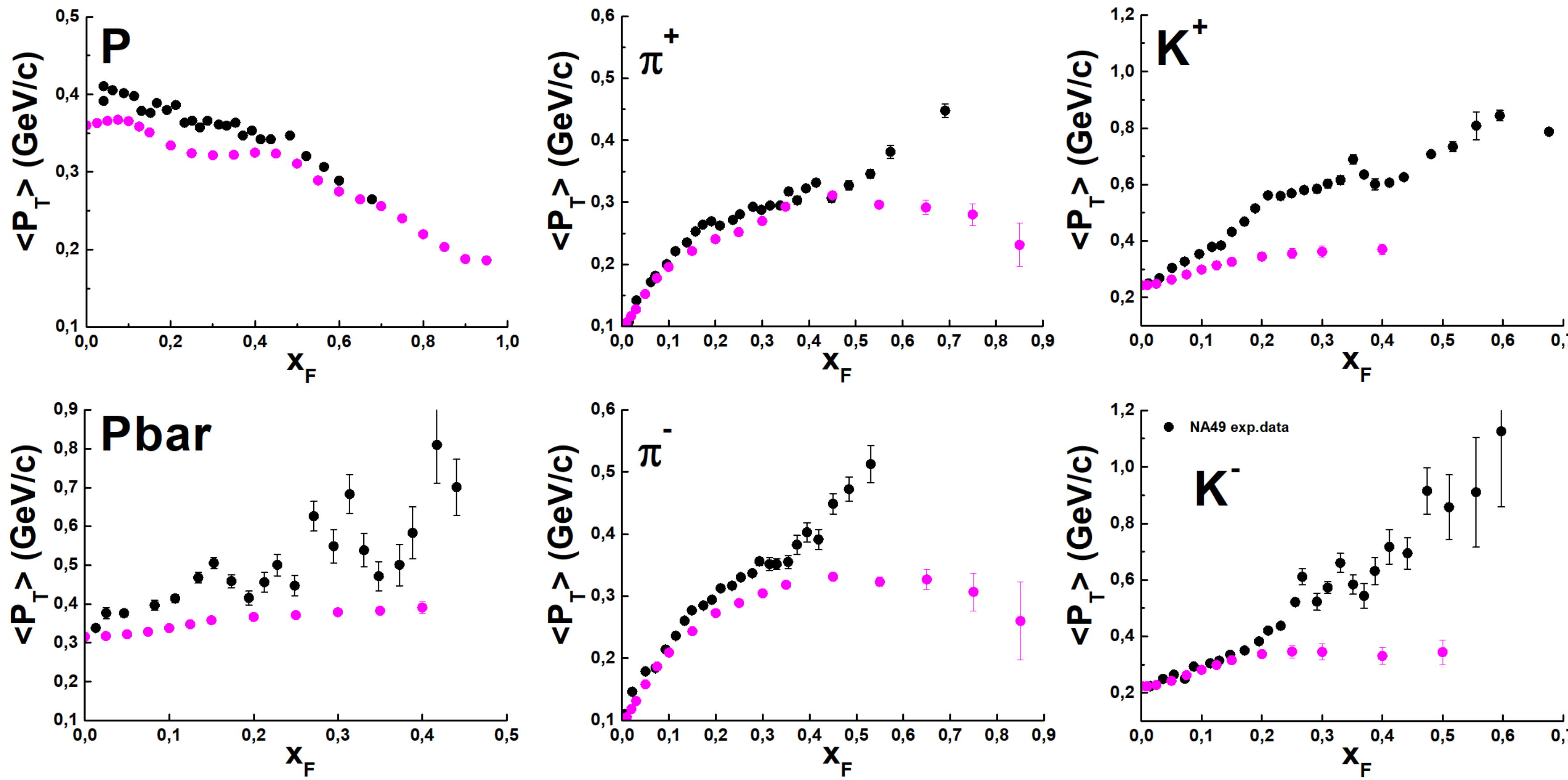
Problem of FTF. Solved in 2020!

The NA49 Collaboration, Eur. Phys. J. C 45, 343–381 (2006), Pi-mesons

The NA49 Collaboration, Eur. Phys. J. C (2010) 65: 9–63, P and Pbar

The NA49 Collaboration, Eur. Phys. J. C (2010) 68: 1–73, K-mesons

LEBC-EHS Collaboration, 400 GeV/c pp-interactions, Z. Phys. C50, 405 (1



The nature of changes at transition from SqrtSnn from 17.3 – 27 GeV is unknown!

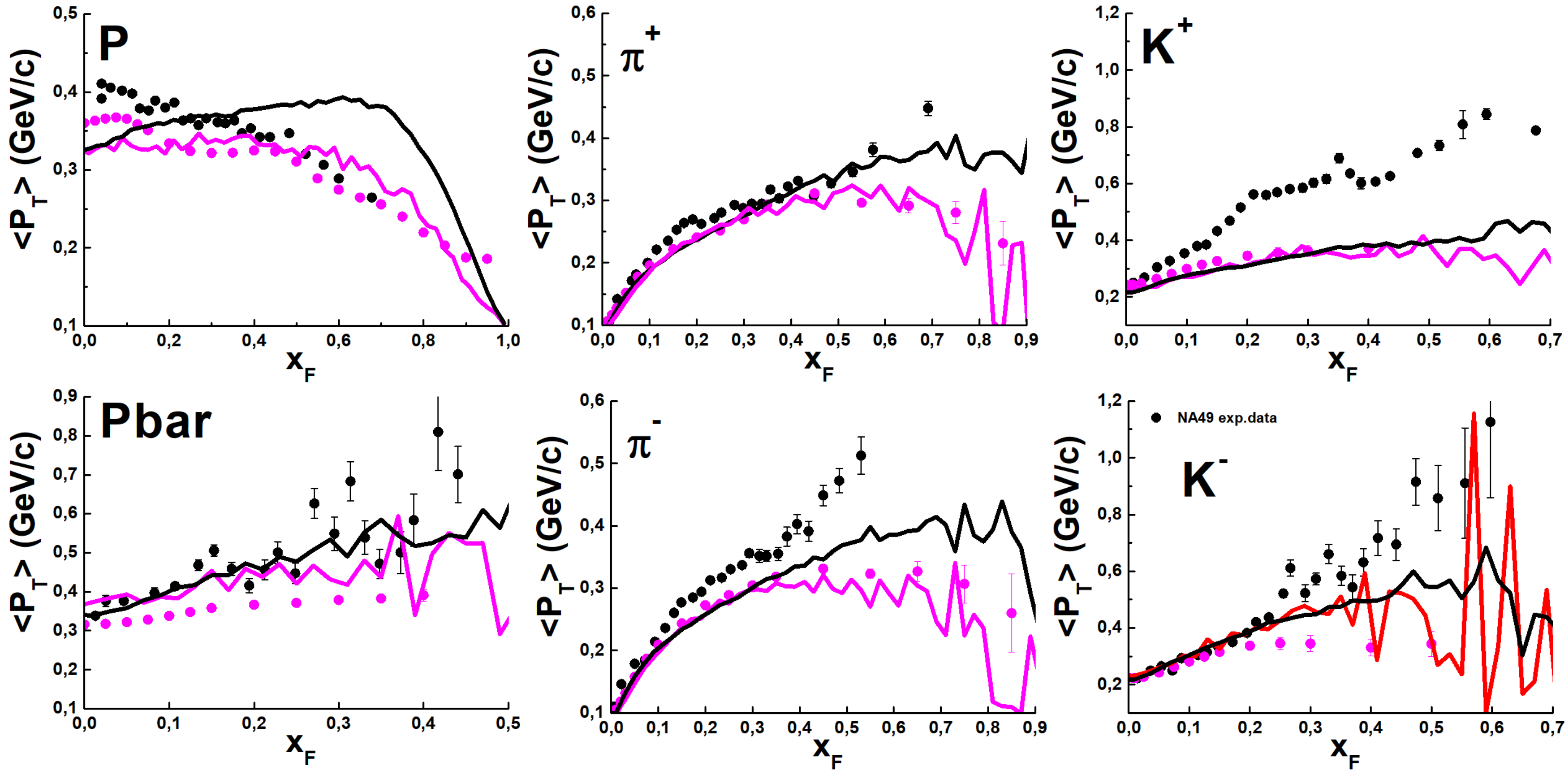
<Pt> - Xf correlations in pp interactions, 158 and 400 GeV/c

Problem of FTF. Initial situation. Solved in 2020!

The NA49 Collaboration, Eur. Phys. J. C 45, 343–381 (2006), Pi-mesons

The NA49 Collaboration, Eur. Phys. J. C (2010) 65: 9–63, P and Pbar
The NA49 Collaboration, Eur. Phys. J. C (2010) 68: 1–73, K-mesons

LEBC-EHS Collaboration, 400 GeV/c pp-interactions, Z. Phys. C50, 405 (1991)

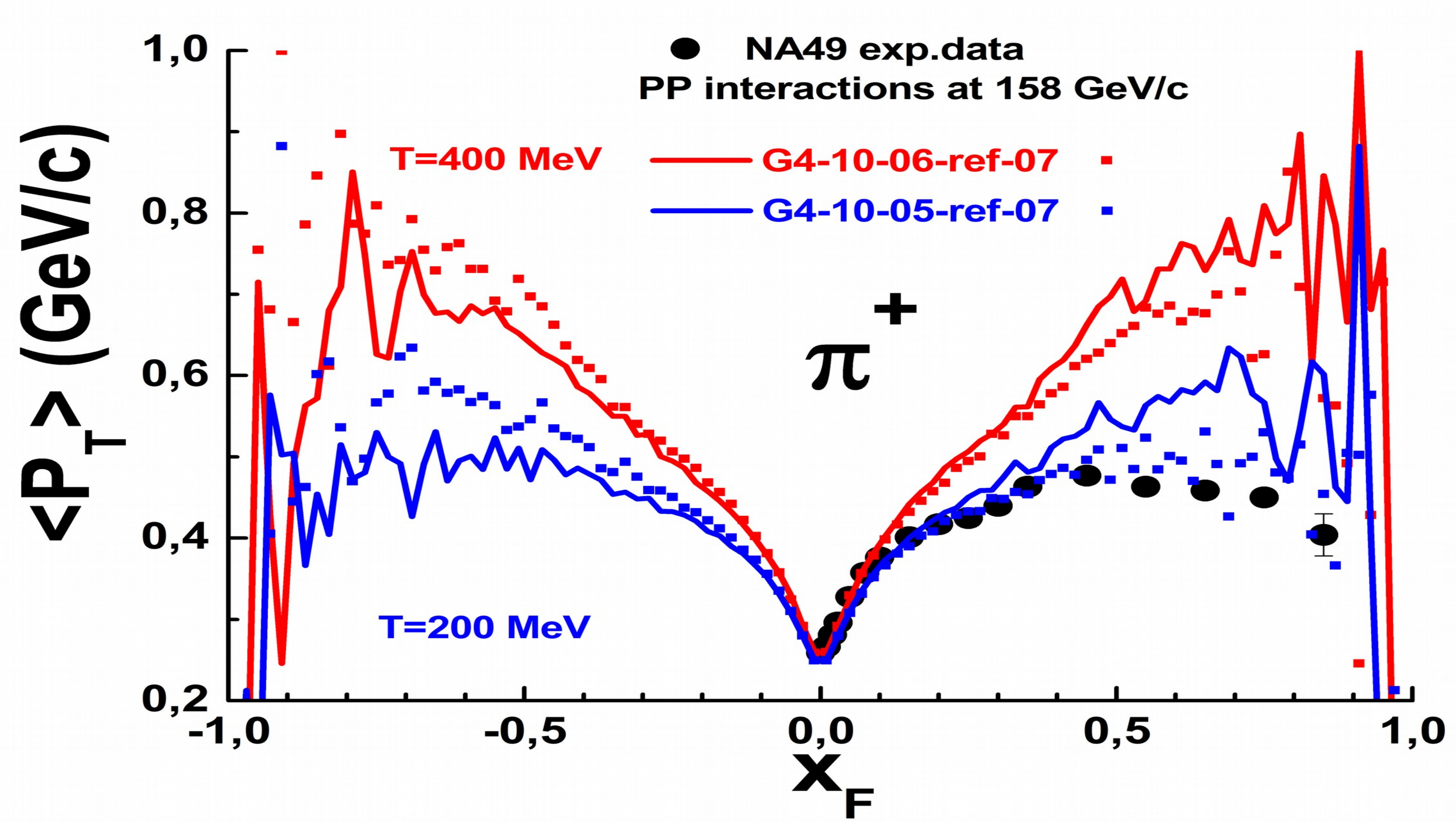


Geant FTF model results at 158 (magenta) 400 (black).

Struggle for Pt-Xf correlations in FTF

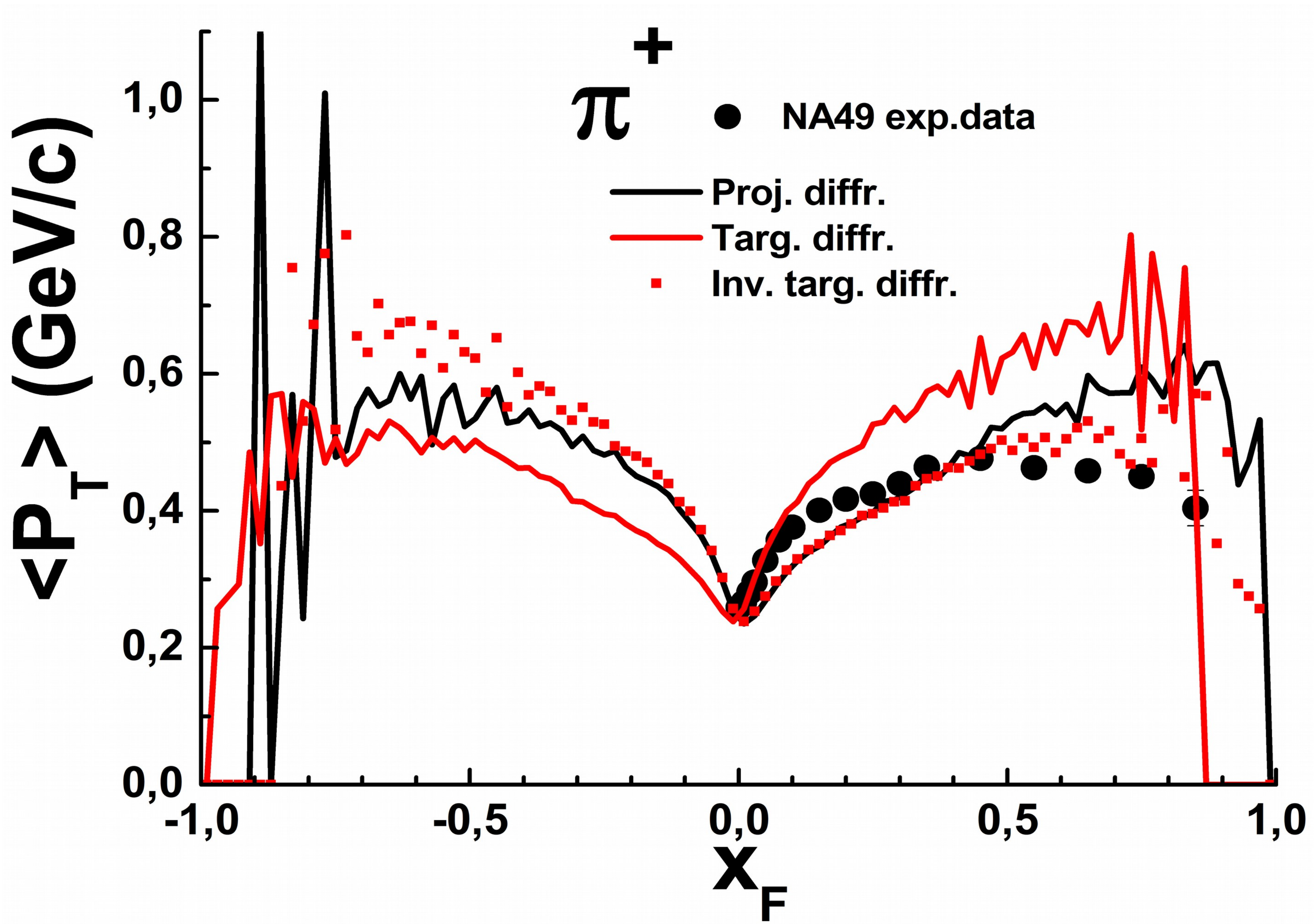
V. Uzhinsky, 16 Sept.

Problem! Asymmetry! PP interactions, 158 GeV/c

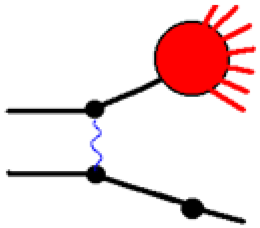


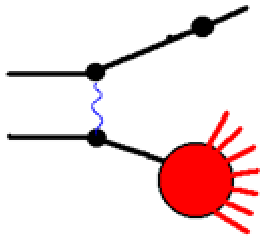
What to do?

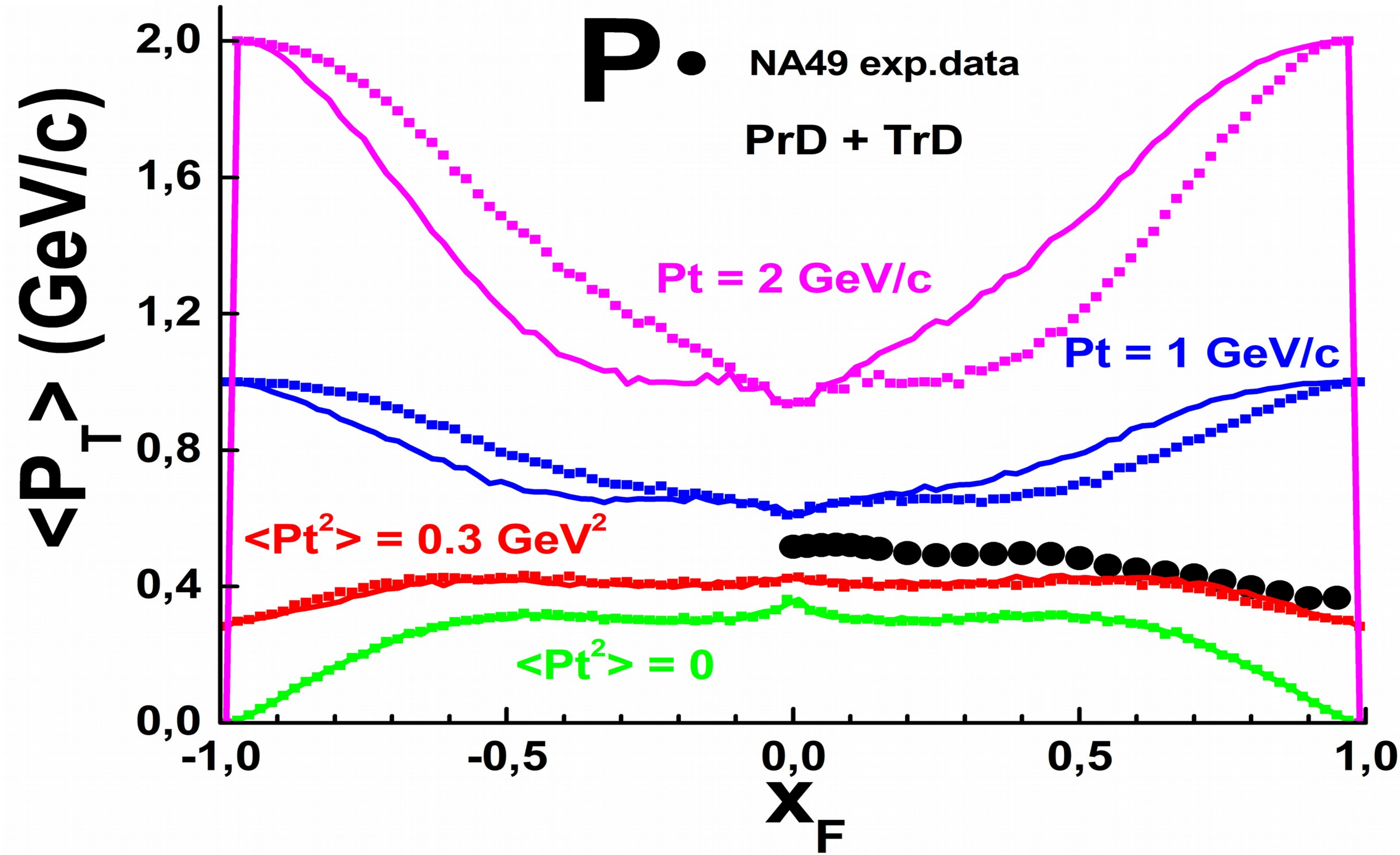
Projectile and target diffractions



Projectile and target diffractions
Extremal condition







The asymmetry is increased with Pt!

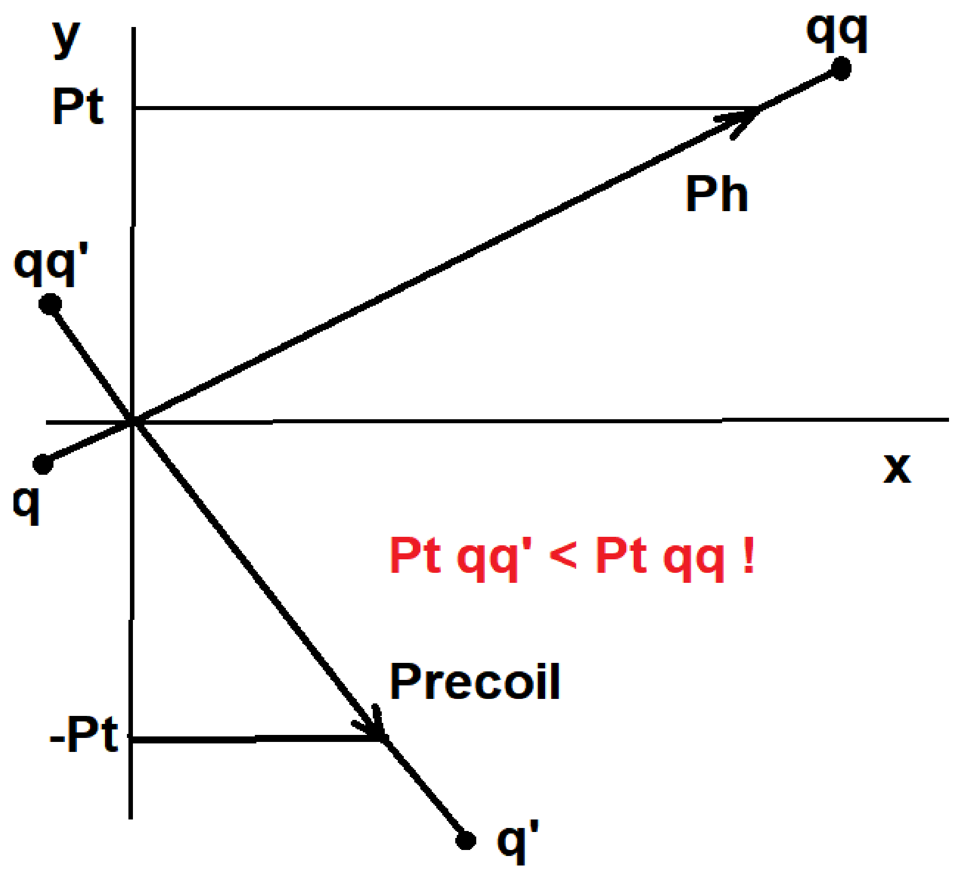
Source: FTF model : Create strings

FTF

1. Choose a process
2. Calculate string masses V
3. Calculate Pt V
4. Create strings ?

The question is:
How to subdivide a hadron into quark and di-quark?

Algorithm implemented in Geant4

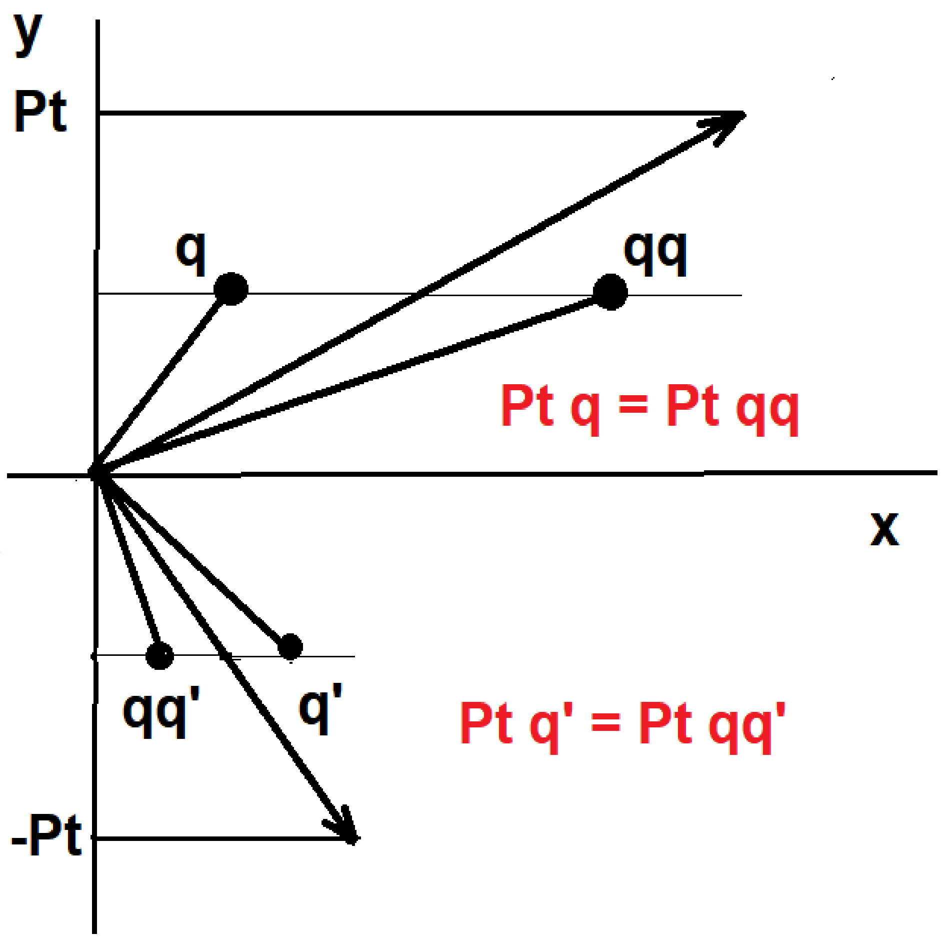


Massless q and qq!
Collinear Pq, Pqq and Ph

$$E_h = P_{qq} + |P_q|$$
$$P_h = P_{qq} - |P_q|$$

$$P_{qq} = (E_h + P_h)/2$$
$$P_q = (E_h - P_h)/2$$

Solution: Algorithm now implemented in Geant4 (invented by me)

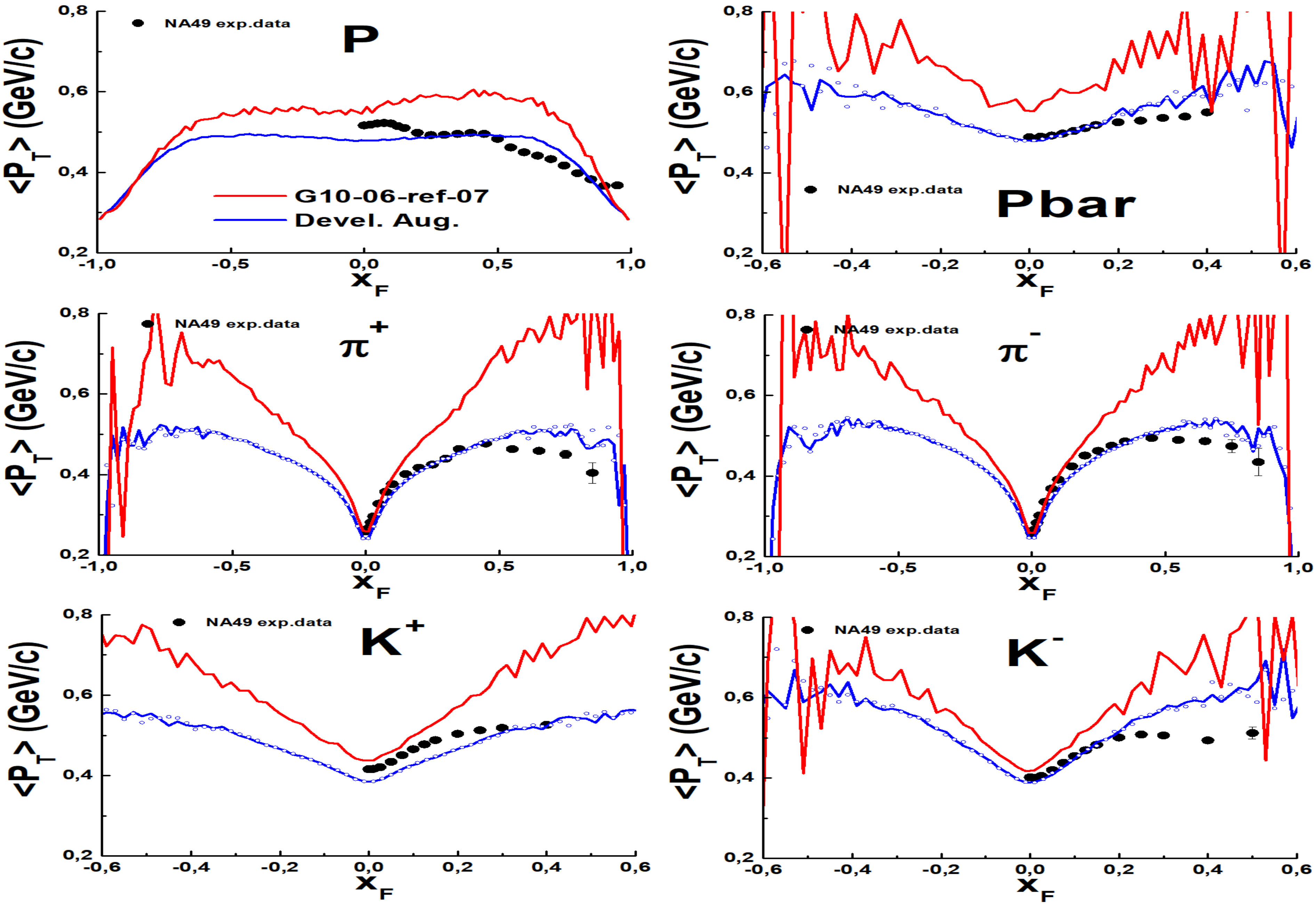


Massless q and qq!

$$\vec{P}_h = \vec{P}_q + \vec{P}_{qq}$$
$$\vec{P}_q = \vec{P}_{qq} = \vec{P}_h/2$$

$$P_{z,q/qq} = P_{z,h}/2 \pm$$
$$\pm \frac{1}{2}\sqrt{P_{z,h}^2 + \left[m_{T,h}^4 - 4\,E_h^2\,(P_{T,h}/2)^2\right]/m_{T,h}^2}$$

Final Pt – Xf correlations, 158 GeV/c



<Pt> - Xf correlations in pp interactions, 158 and 400 GeV/c

The NA49 Collaboration, Eur. Phys. J. C 45, 343–381 (2006), Pi-mesons

The NA49 Collaboration, Eur. Phys. J. C (2010) 65: 9–63, P and Pbar

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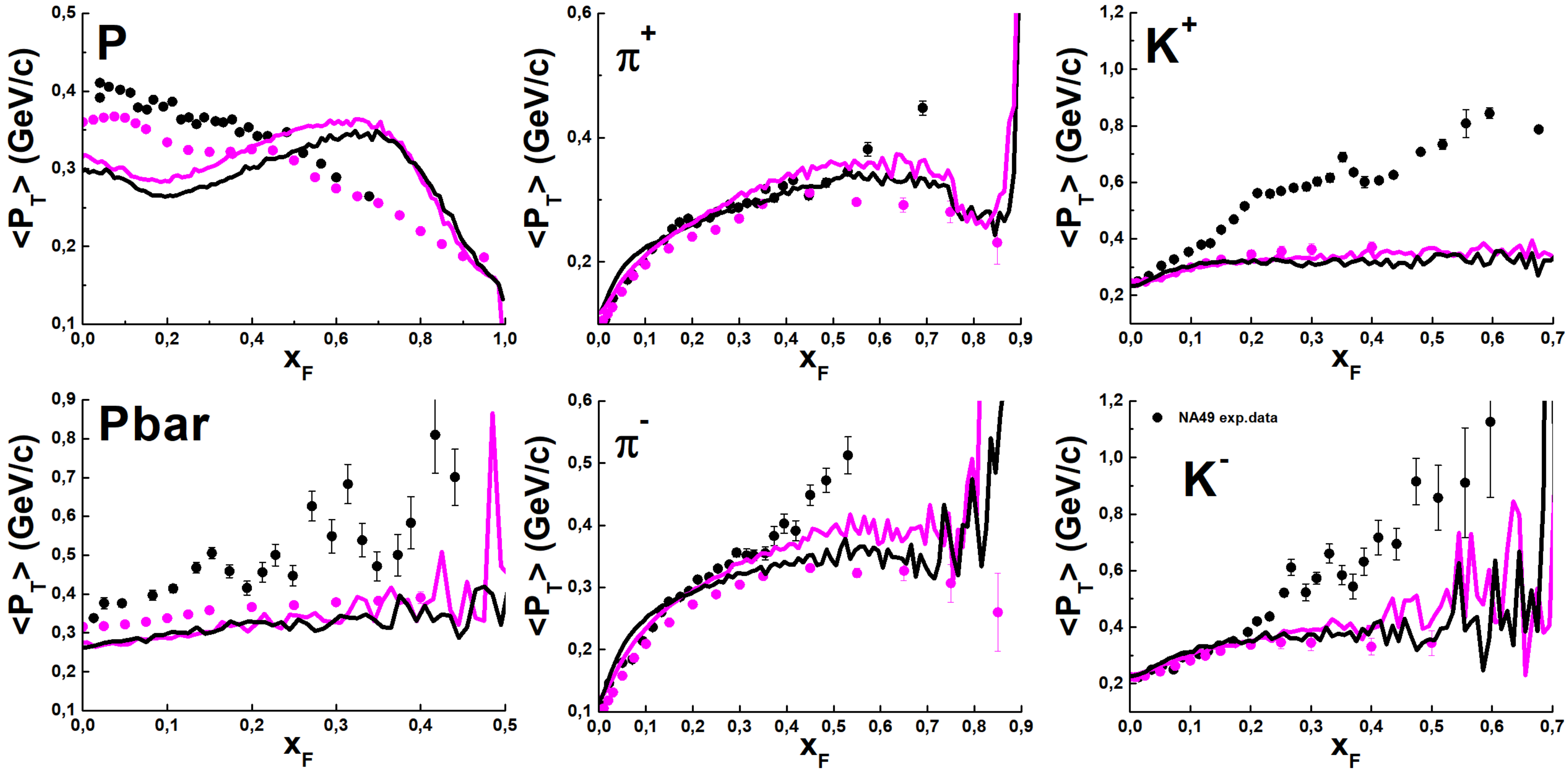
LEBC-EHS Collaboration, 400 GeV/c pp-interactions, Z. Phys. C50, 405 (1991)



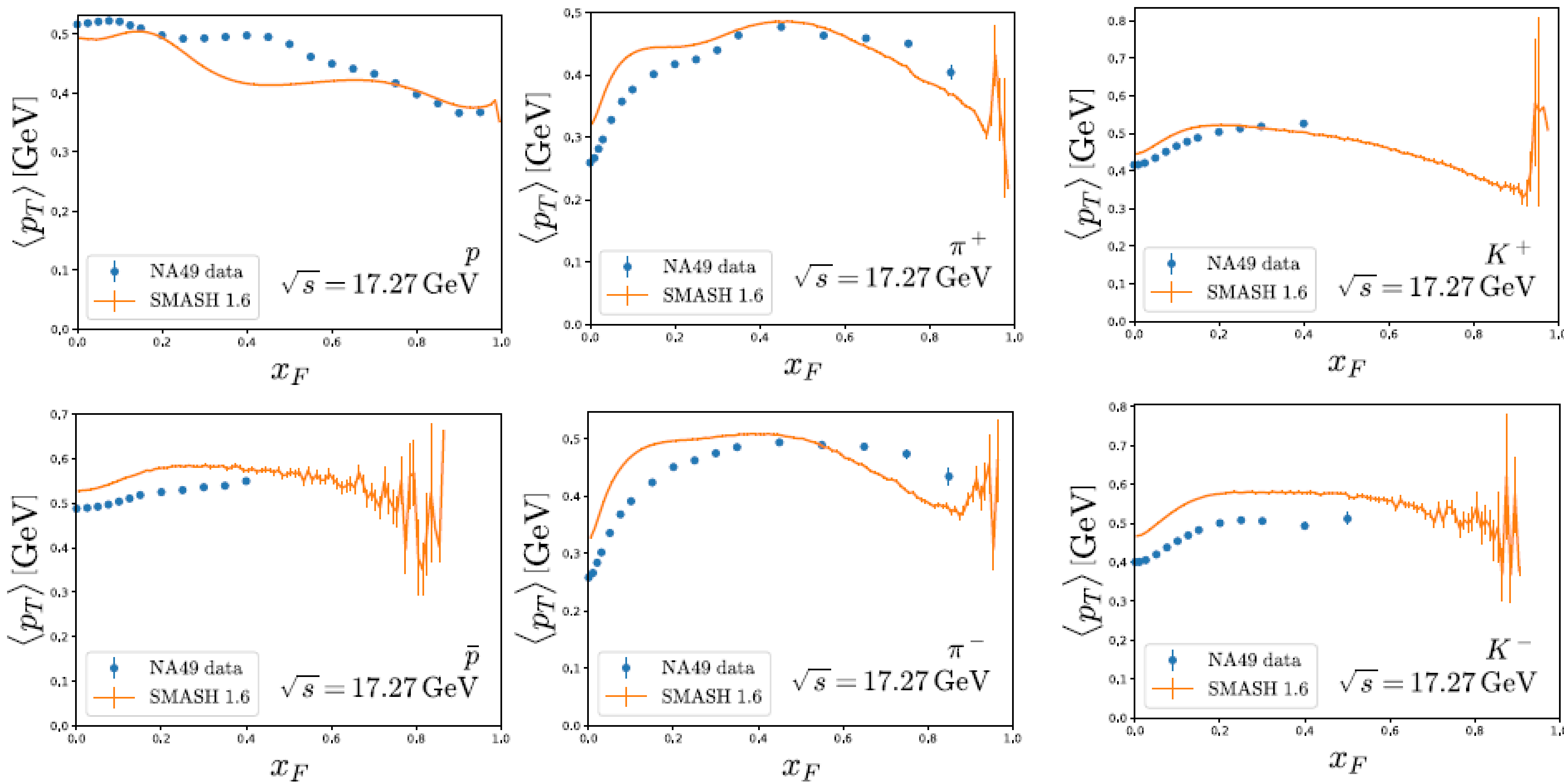
Pythia 6.4 results for 158 and 400 GeV/c.

<Pt> - Xf correlations in pp interactions, 158 GeV/c

The NA49 Collaboration, Eur. Phys. J. C 45, 343–381 (2006), Pi-mesons

The NA49 Collaboration, Eur. Phys. J. C (2010) 65: 9–63, P and Pbar

The NA49 Collaboration, Eur. Phys. J. C (2010) 68: 1–73, K-mesons



SMASH results for 158 GeV/c.

Particle production via strings and baryon stopping within a hadronic transport approach

J Mohs, S Ryu and H Elfner, J. Phys. G: Nucl. Part. Phys. 47 (2020) 065101

Geant4 FTF model works well in nucleus-nucleus interactions at energies below 10 GeV in CMS

A. Galoyan and V. Uzhinsky

ArXiv: 2101.08494 [hep-ex] 21 Jan. 2021

Spectra and mean multiplicities of π^- in *central* Ar-40+Sc-45 collisions at 13*A*, 19*A*, 30*A*, 40*A*, 75*A* and 150*A*GeV/*c* beam momenta measured by the NA61/SHINE spectrometer at the CERN SPS, The NA61/SHINE Collaboration

The results (Exp.) represent the first measurements on pion production in an intermediate size collision system at SPS energies.

The new measurements were compared to predictions of Epos1.99, Urqmd3.4 and Hijing models. None of them provides a consistent description of the new NA61/SHINE measurements in Ar+Sc collisions.

What's about Geant4 FTF (Fritiof) model?

It was a subject of our studies in 2021

Eur. Phys. J. C81 (2021) 73, published on line 22 Jan. 2021, ArXiv: 5 Oct. 2020

Measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in ^{7}Be+^{9}Be collisions at beam momenta from 19A to 150A GeV/c with the NA61/SHINE spectrometer at the CERN SPS

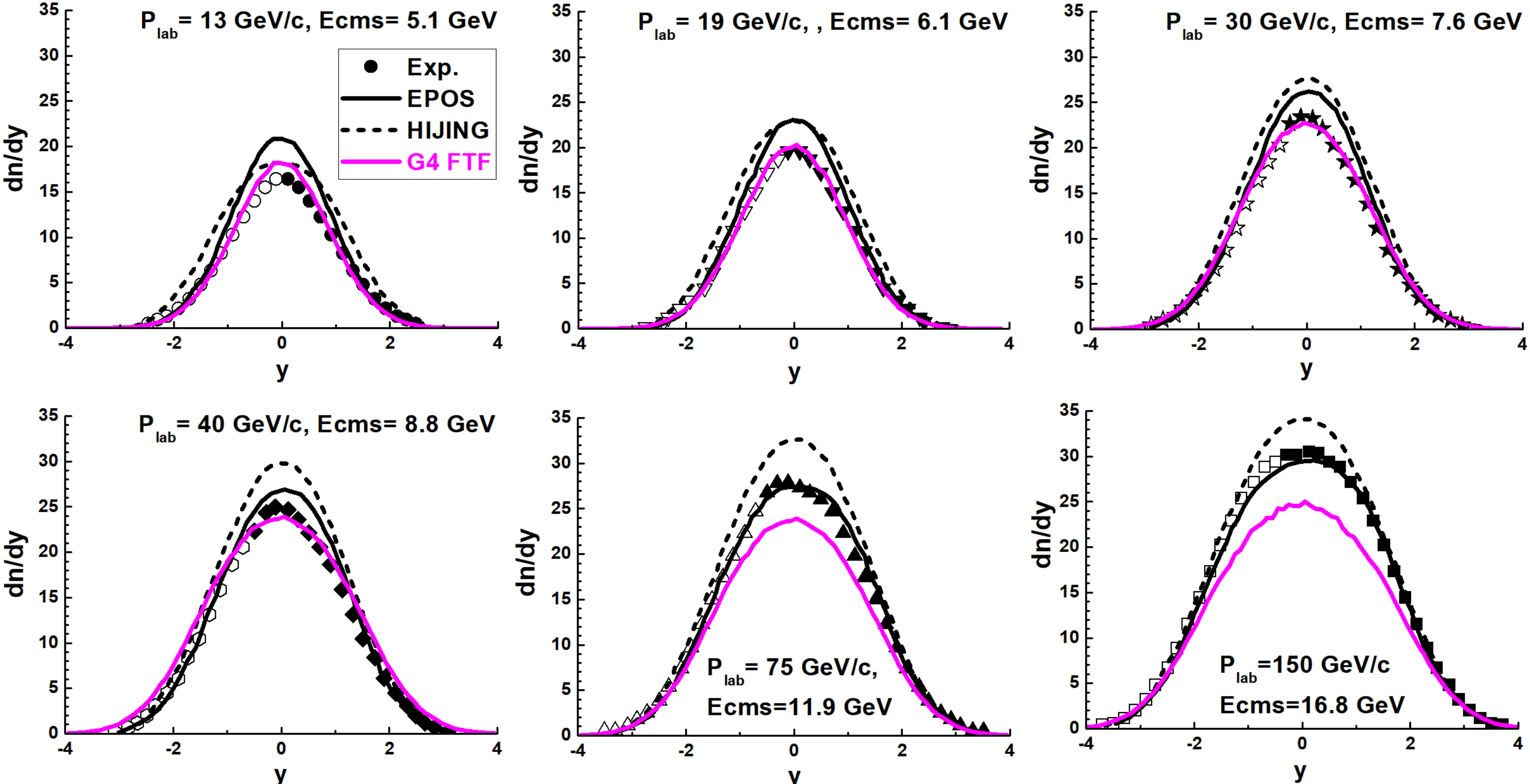
The NA61/SHINE Collaboration

The results were compared with predictions of the models:
Epos 1.99, Urqmd 3.4, Ampt 1.26, Phsd 4.0 and Smash 1.6.

None of the models reproduces all features of the presented results.

What's about Geant4 FTF (Fritiof) model?

NA61/SHINE data on Ar-40 + Sc-45 and FTF model
5 % centrality, dn/dy of π-mesons



HIJING overestimates all data. No tuning!

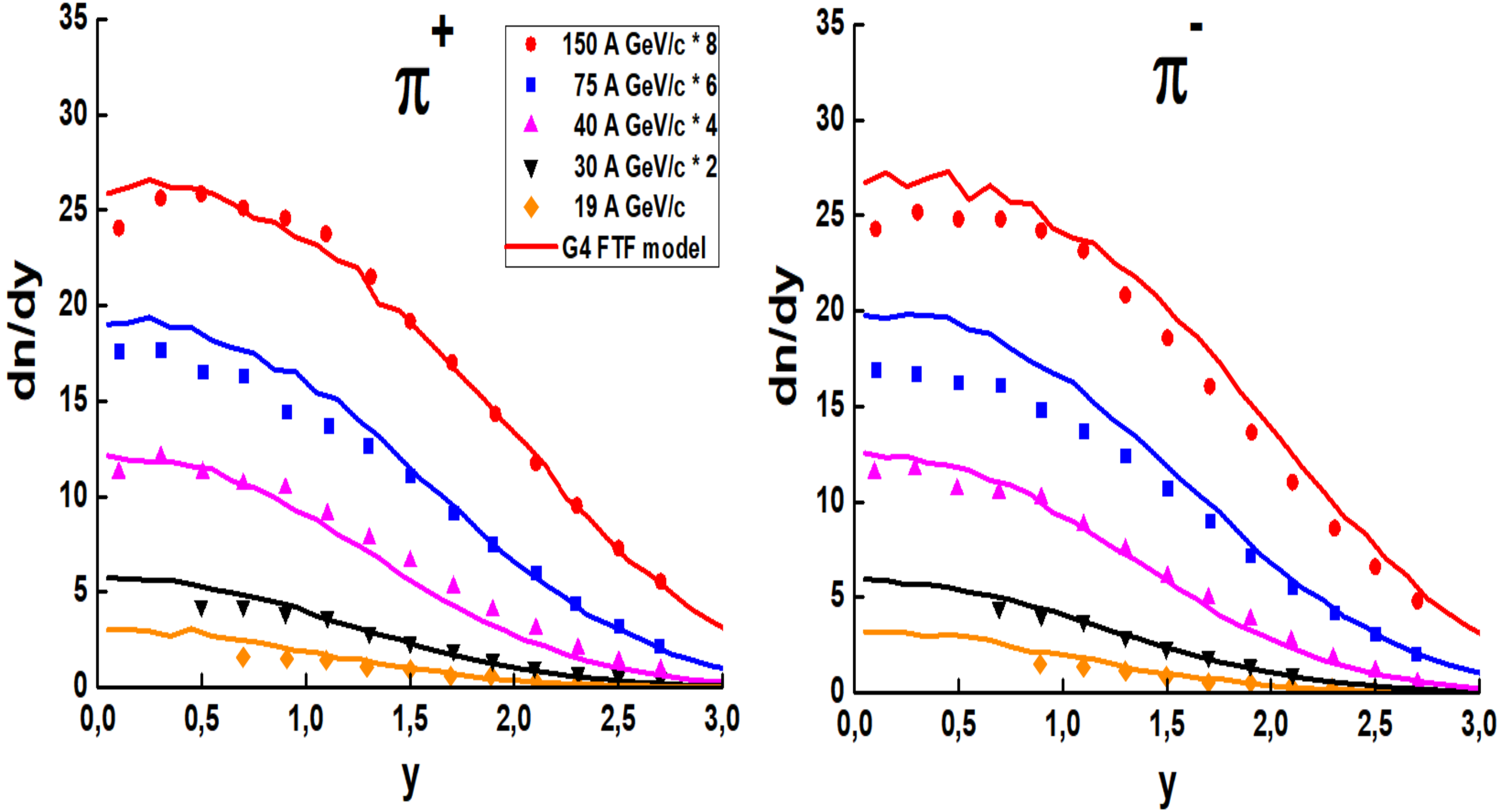
EPOS overestimates data at Ecmc < 10 GeV, at > 10 GeV – OK. No tuning!

Geant4 FTF – OK at Ecmc < 10 GeV, underestimates at Ecms > 10 GeV.

Main problem – Centrality!

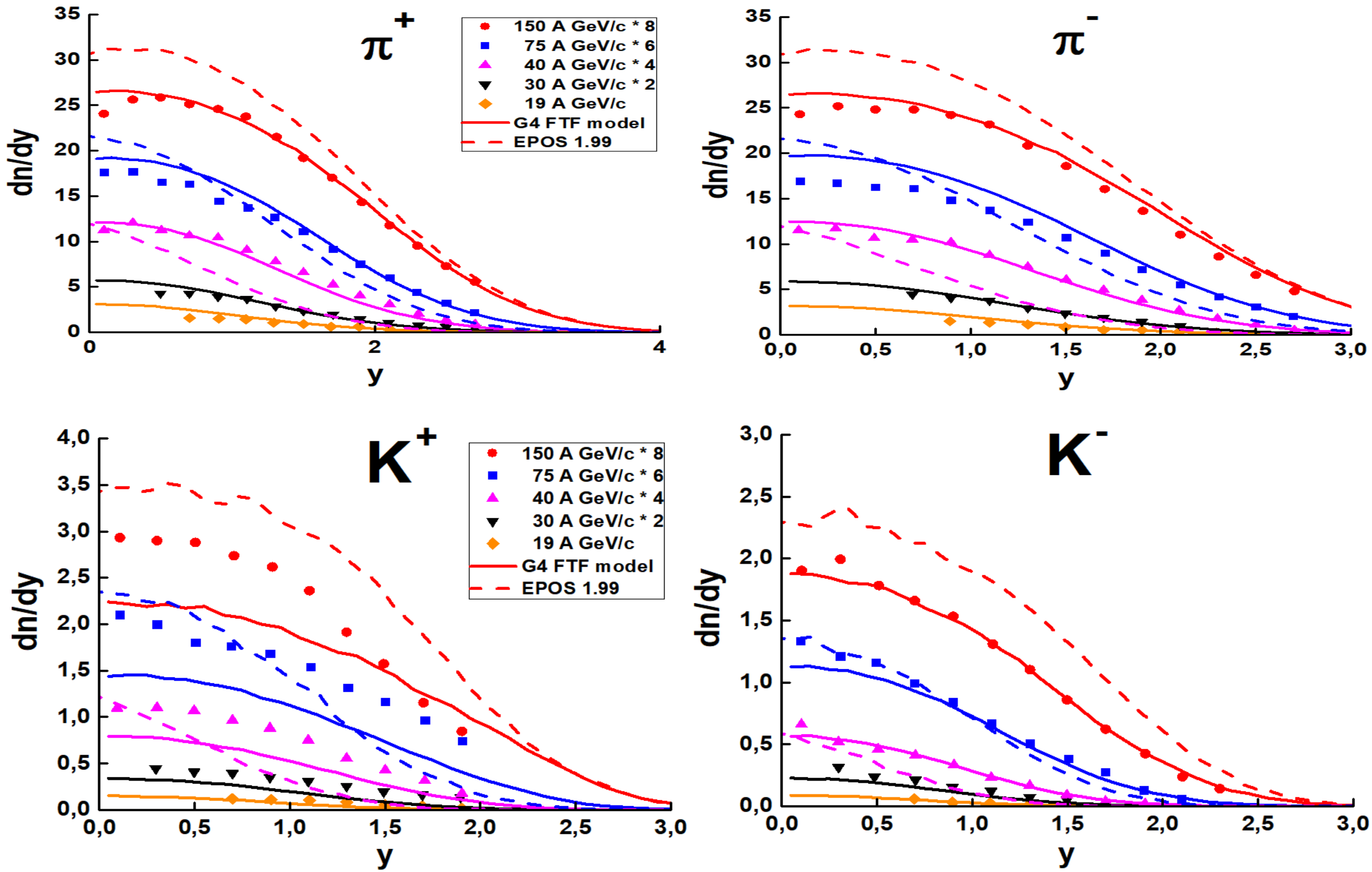
QGP at 7 or 10 GeV?

NA61/SHINE data on Be-7 + Be-9 and FTF model
20 % centrality + acceptance maps. Bmax = 2.1 fm

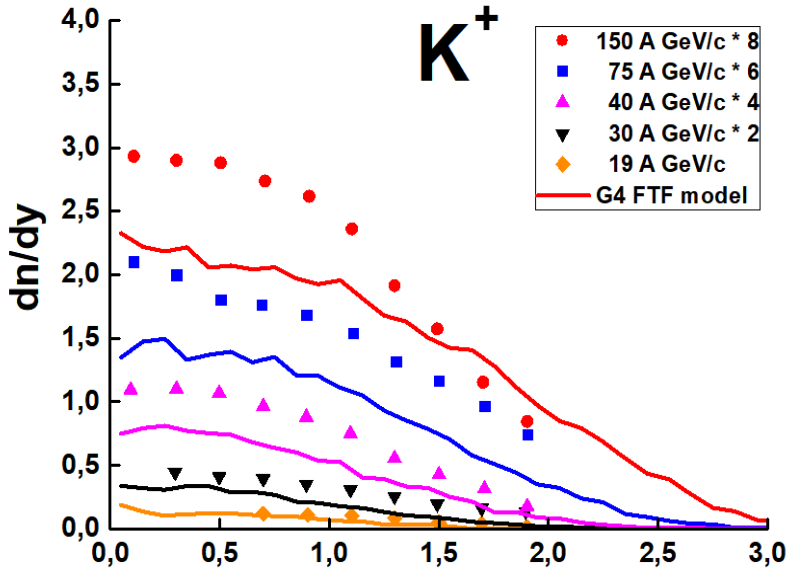


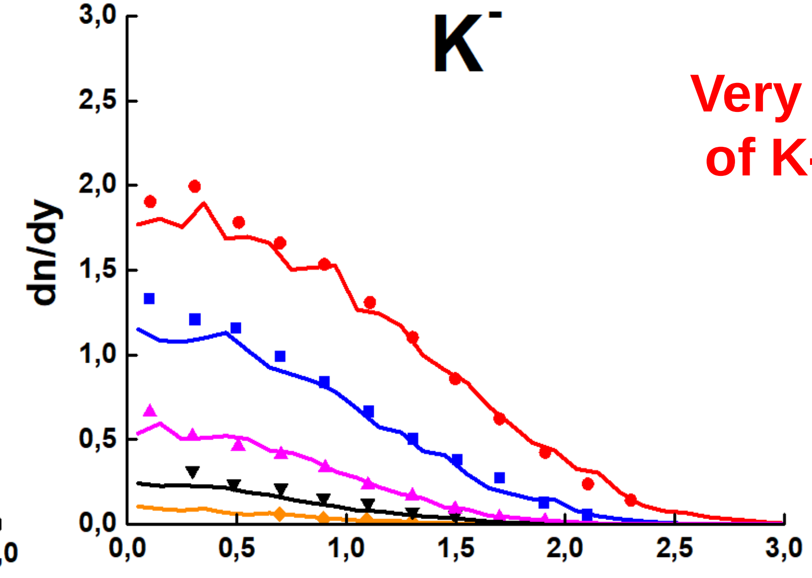
Very good agreement of FTF calculations with the data!

NA61/SHINE data on Be-7 + Be-9, 20 % centrality
EPOS 1.99 – Horror, horror! FTF – OK nearly.

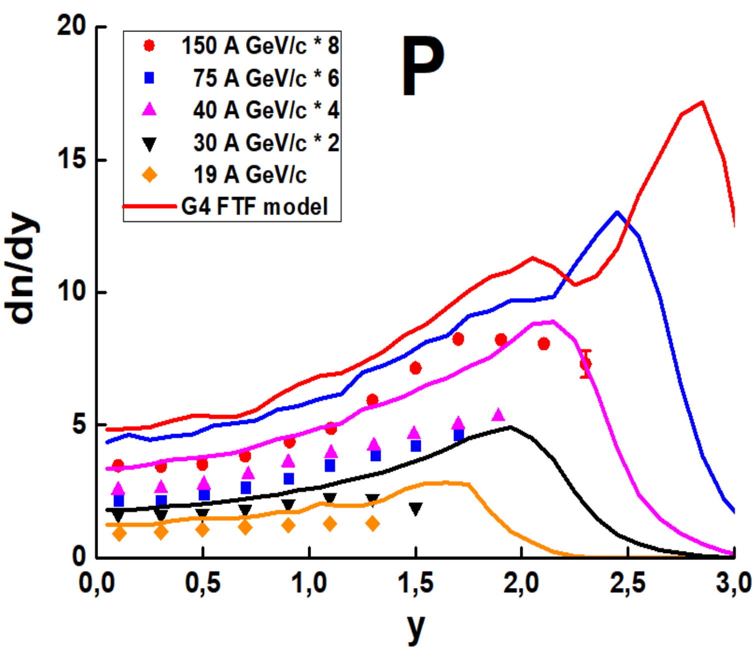


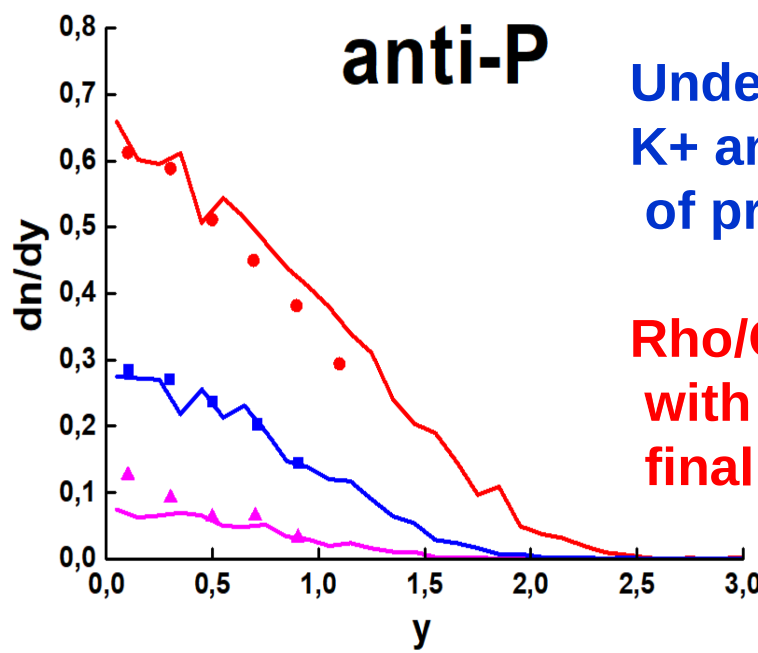
NA61/SHINE data on Be-7 + Be-9 and FTF model
20 % centrality + acceptance maps. Bmax = 2.1 fm





Very good description of K- and anti-protons!





Underestimation of K+ and overestimation of protons!

Rho/Omega/Pi interact. with nucleons in final states!

NA61/SHINE data on Be-7 + Be-9, 20 % centrality.

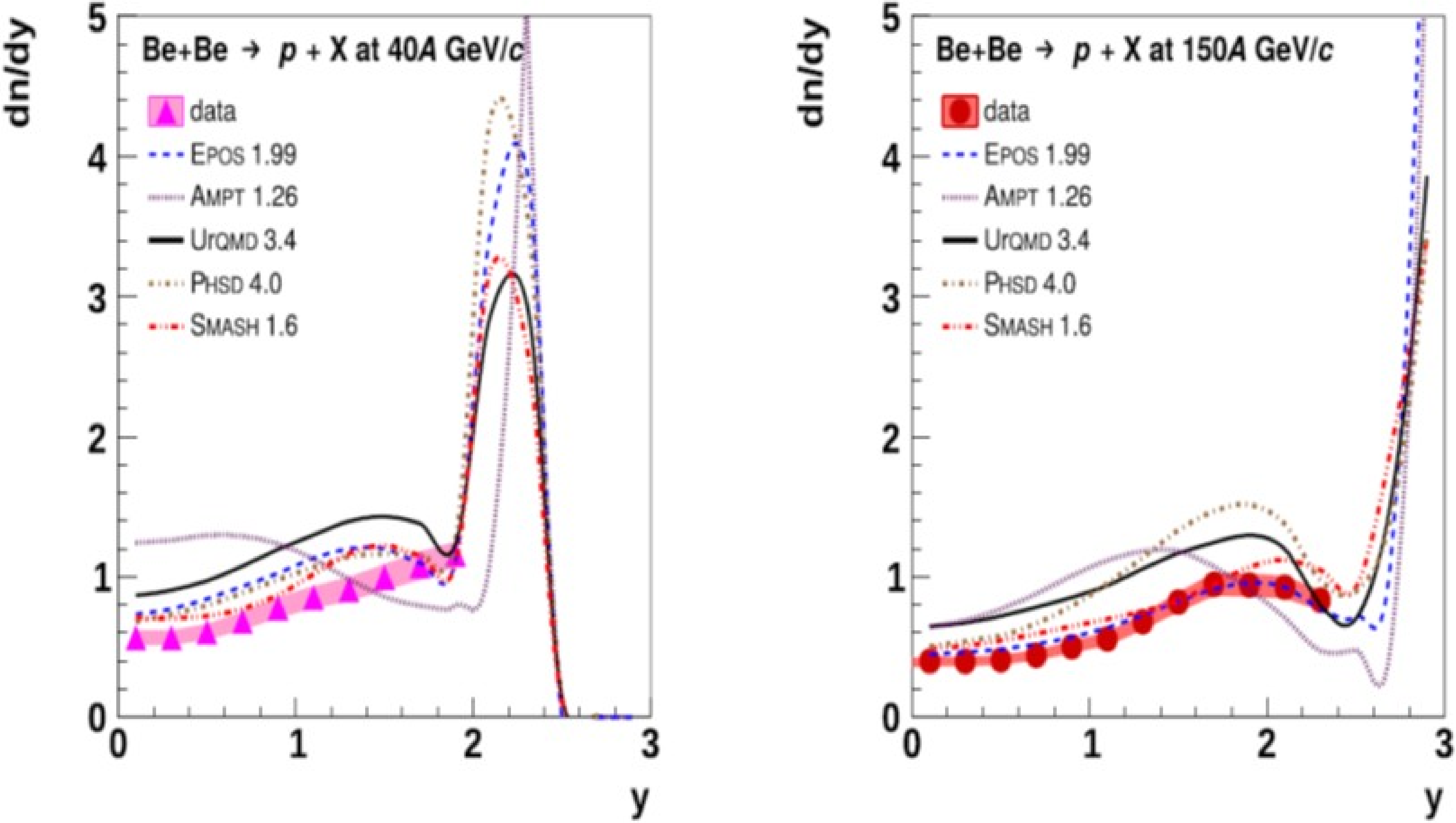
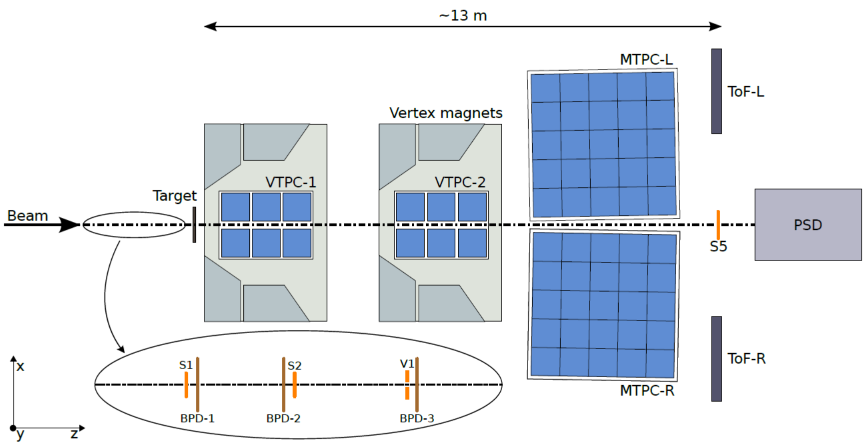
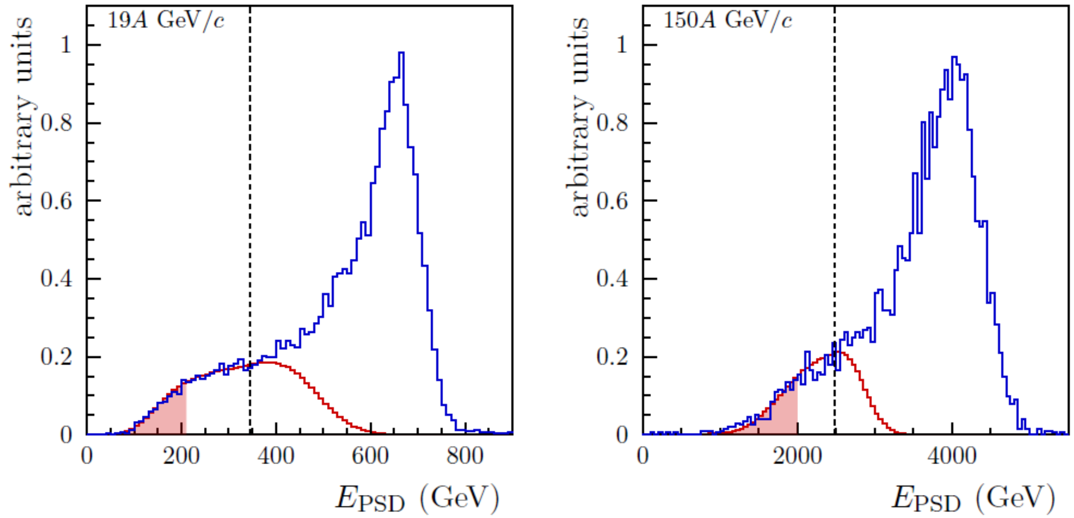


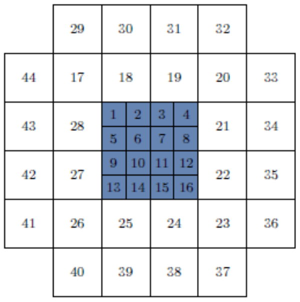
Fig. 31 Proton rapidity distribution in the 20% most *central* Be+Be collisions at 40*A* and 150*A* GeV/*c* compared with predictions of the EPOS 1.99 [16,31] (blue dashed line), URQMD 3.4 [33,34] (black solid line), AMPT 1.26 [35–37] (violet dotted line), PHSD 4.0 [38,39] (brown dashed-dotted line) and SMASH 1.6 (red dashed-double dotted line) [40,41] models

NA61/SHINE data on Ar-40 + Sc-45 and FTF model

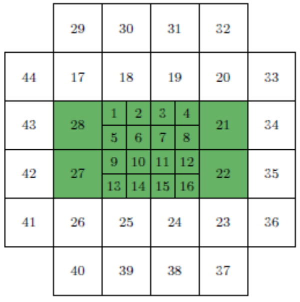
5 % centrality ? Projectile Spectator Detector (PSD) ?



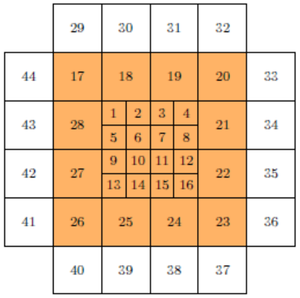




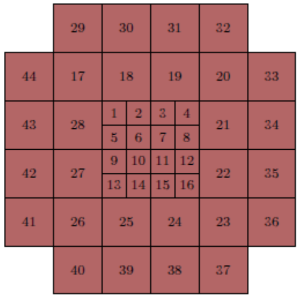
T2 trigger



150A GeV/c



75A, 40A, 30A GeV/c



19A, 13A GeV/c

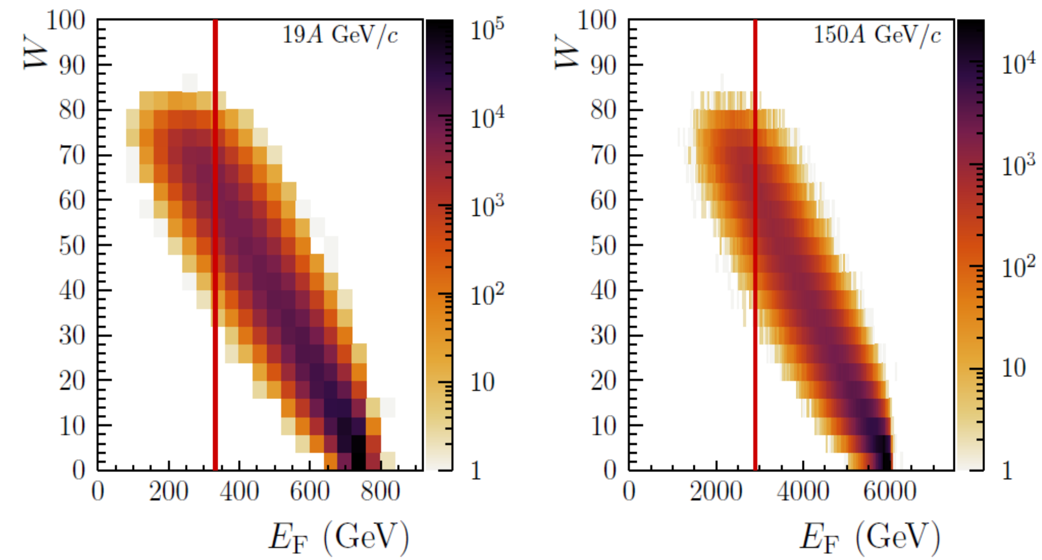


Figure 4: Distributions of W versus E_F for all inelastic collisions at 19A (*left*) and 150A GeV/c (*right*) beam momenta calculated from the EPOS1.99 model. The vertical red lines show the value of the cut on E_F for selecting the 5% most *central* collisions.

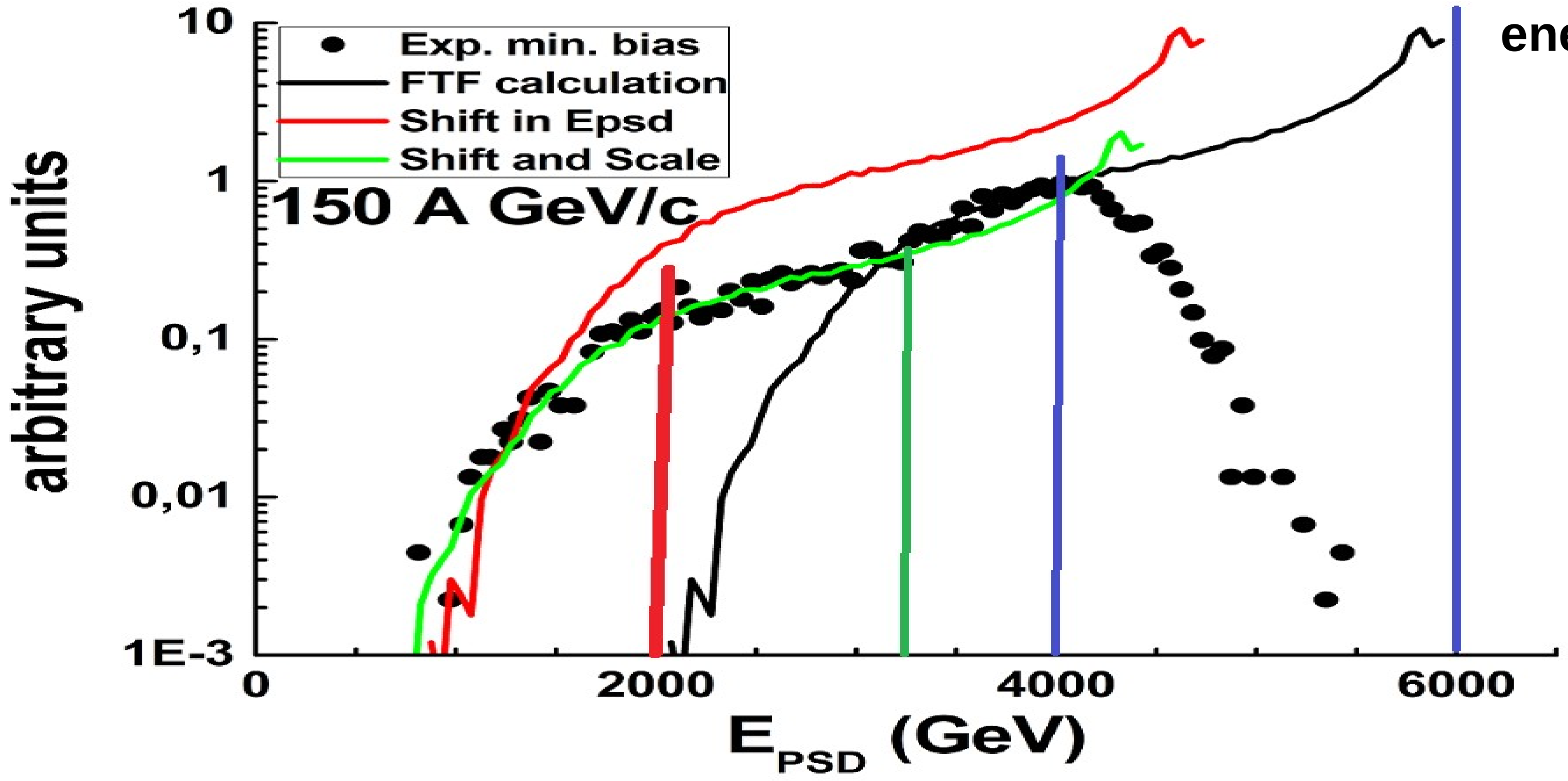
NA61/SHINE data on Ar-40 + Sc-45 and FTF model

5 % centrality, problem of the tail ?

Huge discrepancy between data and FTF calculations!

Where is 2000 GeV disappeared?

Beam energy



Vertical lines: Red - exp. selection;
Green - th. Selection.

Leakage, saturation of light, calibration, non-linearity???

Geant4 FTF Model Description of the NA61/SHINE Collaboration Data on Strange Particle Production in pp-interactions

2022

A. Galoyan and V. Uzhinsky, 20.04.2022

Latest data by the NA61/SHINE collaboration

Measurement of ϕ meson production in $p + p$ interactions at 40, 80 and 158 GeV/c with the NA61/SHINE spectrometer at the CERN SPS Eur. Phys. J. C (2020) 80:199

$K^*(892)^0$ meson production in inelastic $p+p$ interactions at 40 and 80 GeV/c beam momenta measured by NA61/SHINE at the CERN SPS

Arxiv, December 20. 2021

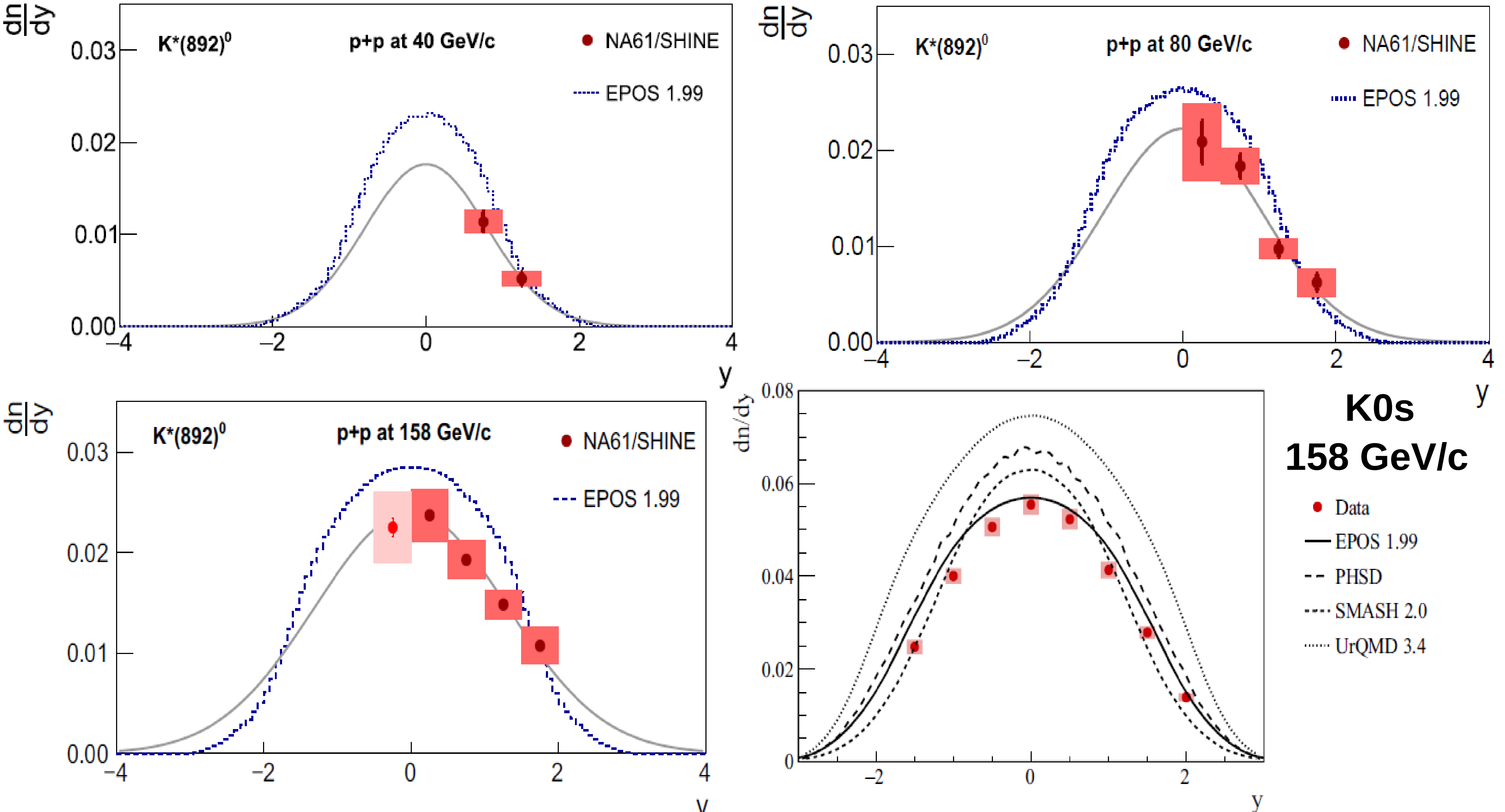
$K^*(892)^0$ meson production in inelastic p+p interactions at 158 GeV/c beam momentum measured by NA61/SHINE at the CERN SPS Eur. Phys. J. C (2020) 80:460

Measurements of Ξ^- and $\overline{\Xi}^+$ production in proton–proton interactions at $\sqrt{s_{NN}}$ = 17.3 GeV in the NA61/SHINE experiment

Eur. Phys. J. C (2020) 80:833

2022

$K^*(892)^0$ meson production in inelastic p+p interactions at 158 GeV/c beam momentum measured by NA61/SHINE at the CERN SPS



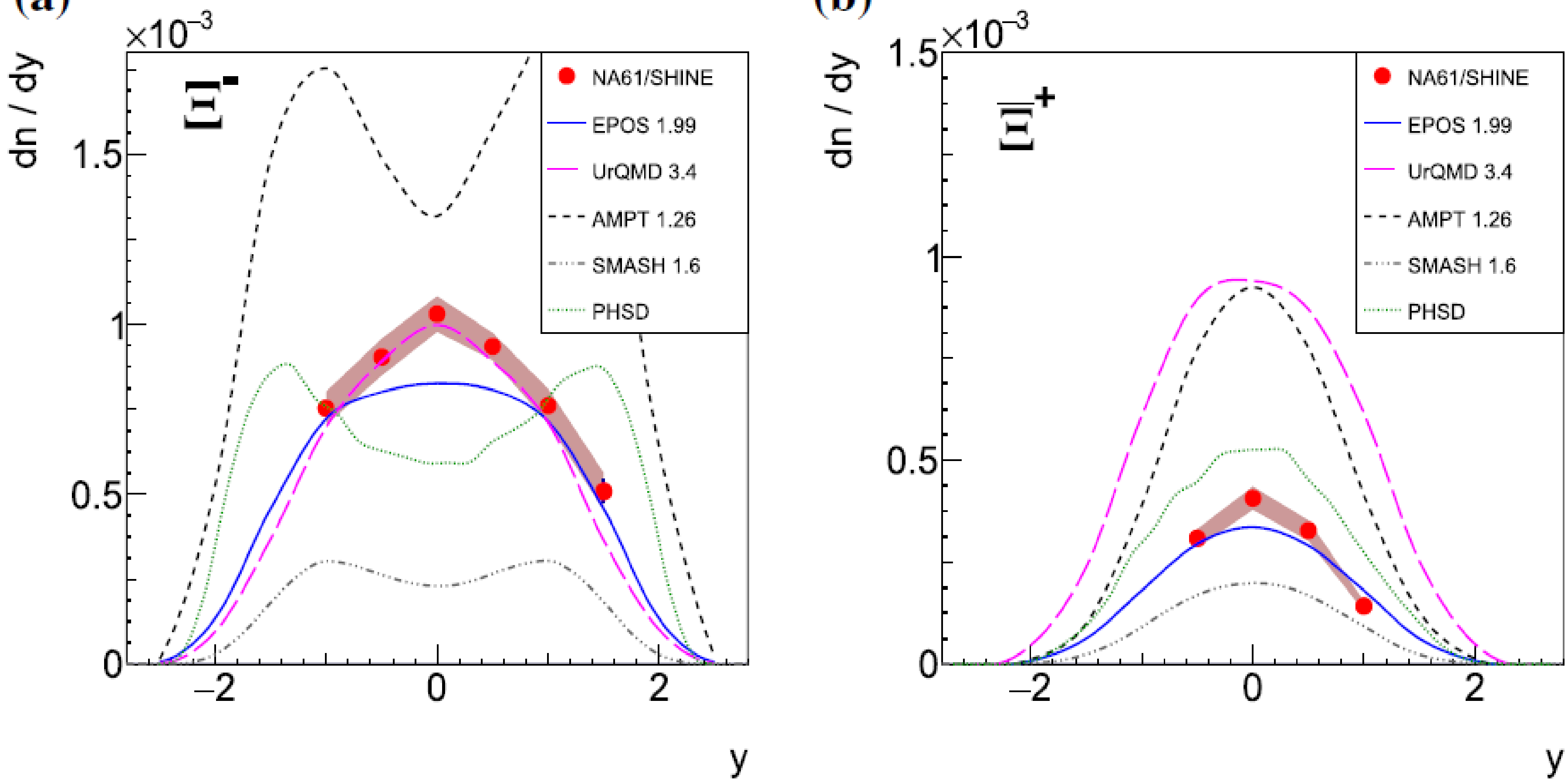
EPOS cannot describe the K*0 data!

There is no model able to describe the data on K0s except EPOS!

2022

Measurements of Ξ^- and $\overline{\Xi}^+$ production in proton–proton interactions at $\sqrt{s_{NN}}$ = 17.3 GeV in the NA61/SHINE experiment

Eur. Phys. J. C (2020) 80:833



No MC model able to describe production of vector mesons and Xi hyperons!

The main idea:

Yield of K*0 ≈ Ps-sbar * Pvec,
Yield of K+- ≈ Ps-sbar * Pps + Decay prod. of K*'s

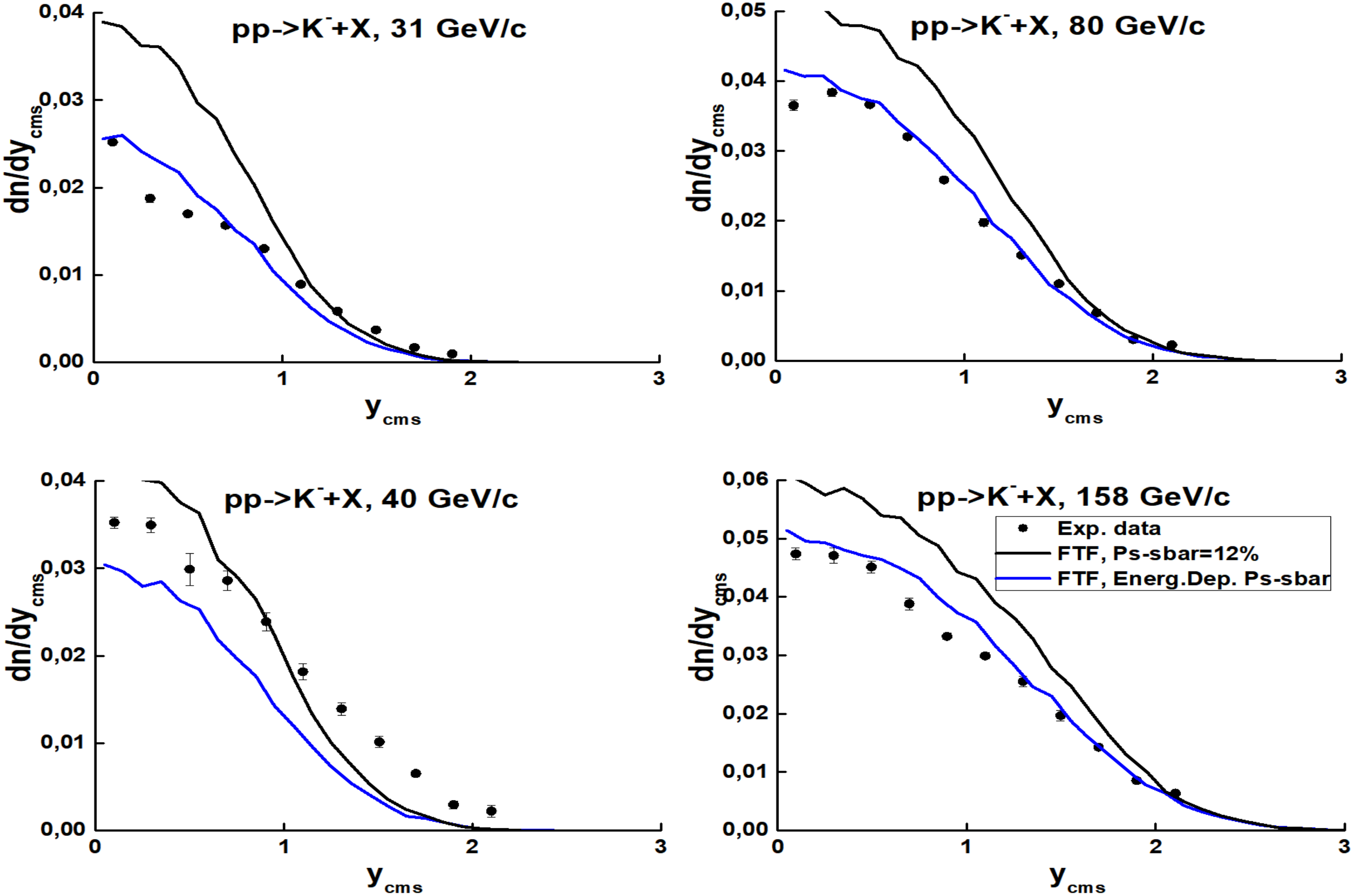
Ps-sbar – probability of pair of strange quark prod. 12 %
Ppsm – probability of pseudoscalar meson production 0.5
Pvec = 1-Pps - probability of vector meson production 0.5

A Parametrization of the Properties of Quark Jets

R.D. Field, R.P. Feynman *Nucl.Phys.B* 136 (1978) 1

2. 7.1. Recursive scheme
(iii) One decides on the spin-parity of the primary meson, according to (2.4
(i.e., pseudoscalar or vector with equal probabilities.

Geant4 FTF model: tune of Ps-sbar (12 %)



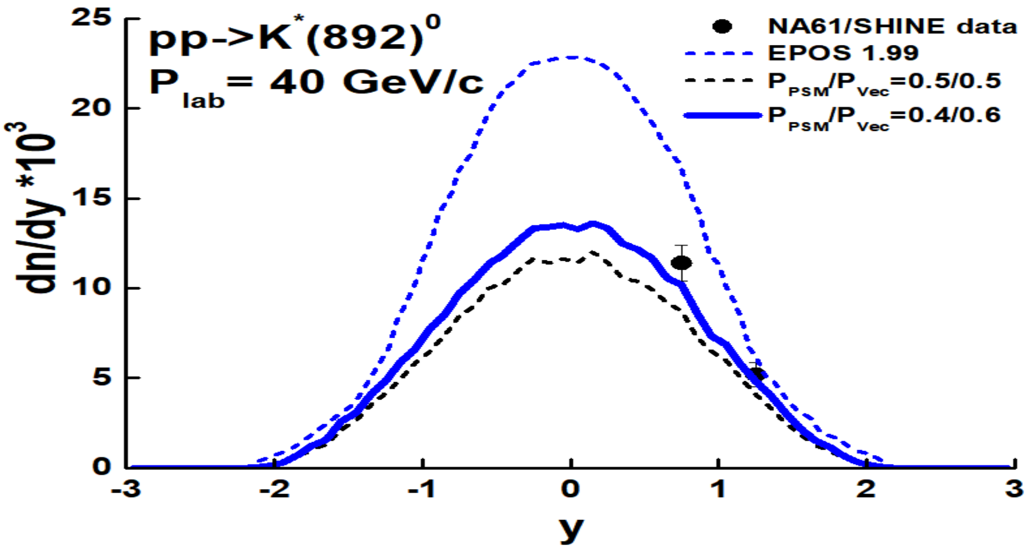
Black lines:
Ps-sbar =12 %

Blue lines:
Ps-sbar = 0.12* **[1 – (Mth/Mstr)$^{2.5}$]**

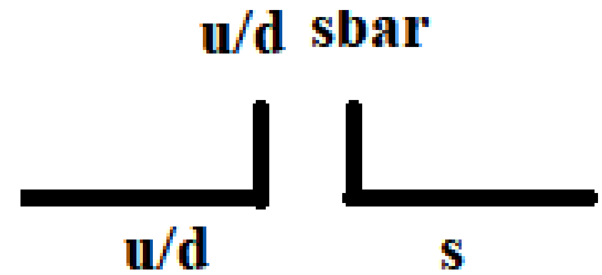
Measurements of $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$ spectra in proton-proton interactions at 20, 31, 40, 80 and 158 GeV/*c* with the NA61/SHINE spectrometer at the CERN SPS

NA61/SHINE Collaboration, Eur. Phys. J. C (2017) 77:671

Geant4 FTF model: tune Ppsm

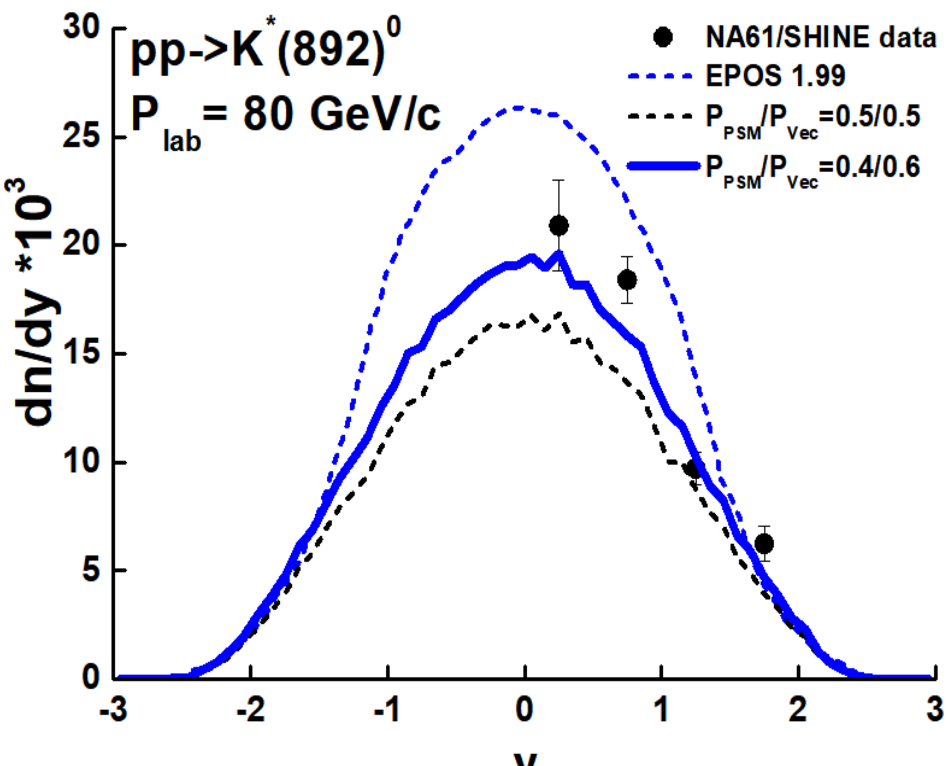


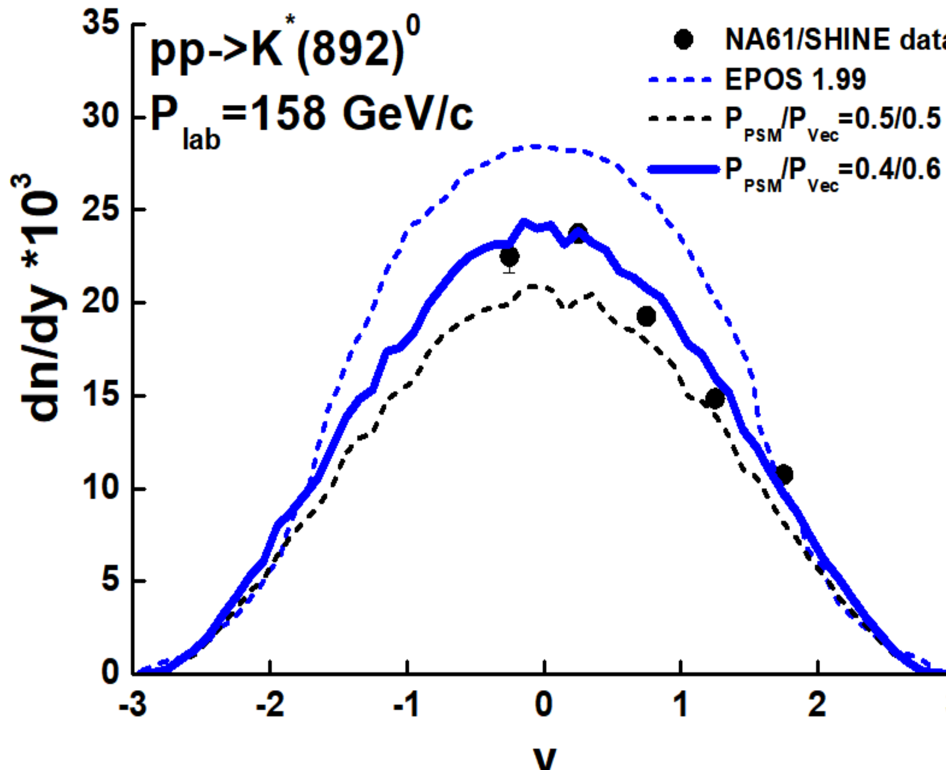
Meson - PS/V (0.5/0.5 Std)



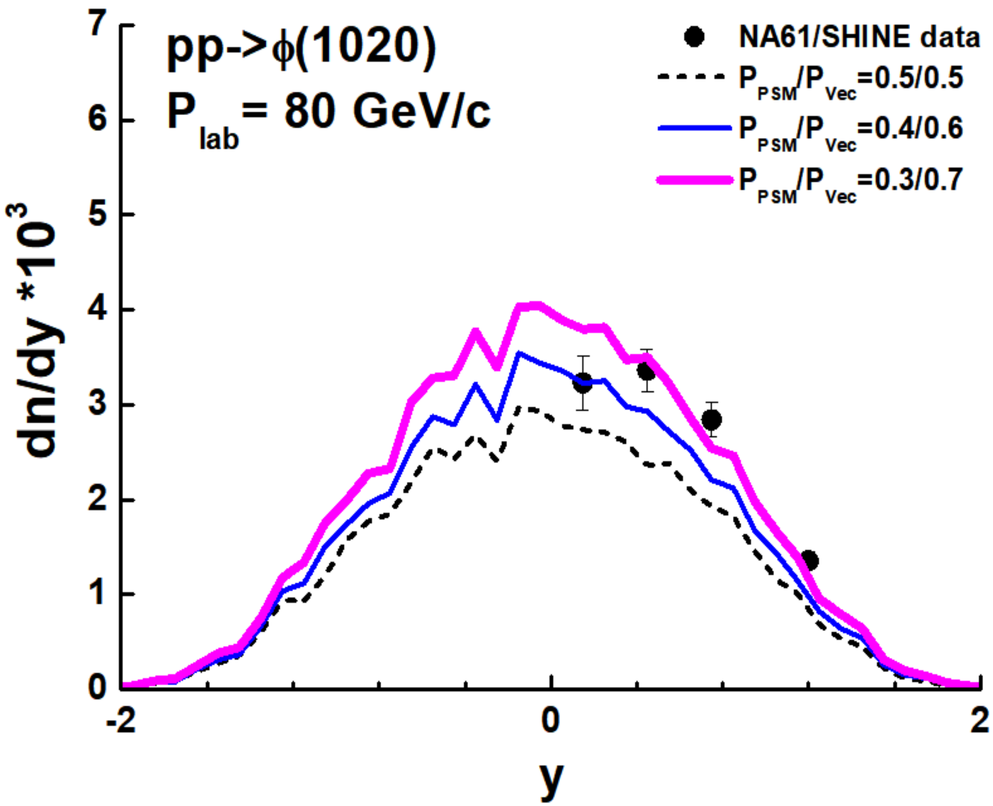
Ps-sbar = 12% (Std.)

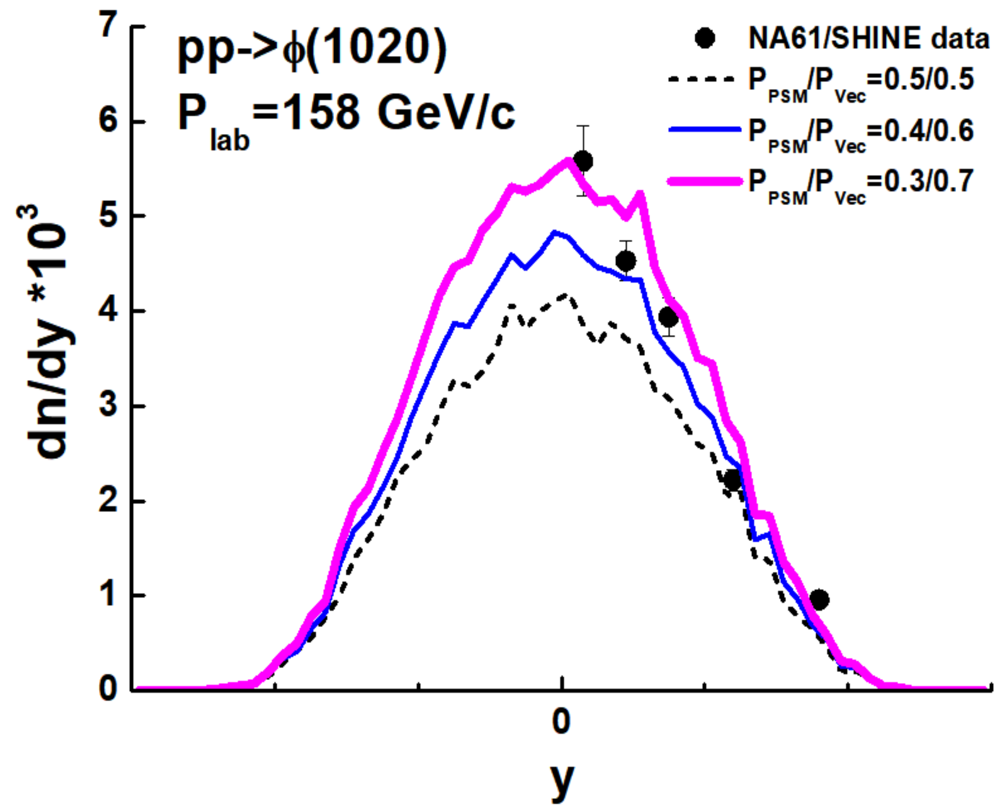
New PS/V - 0.4/0.6

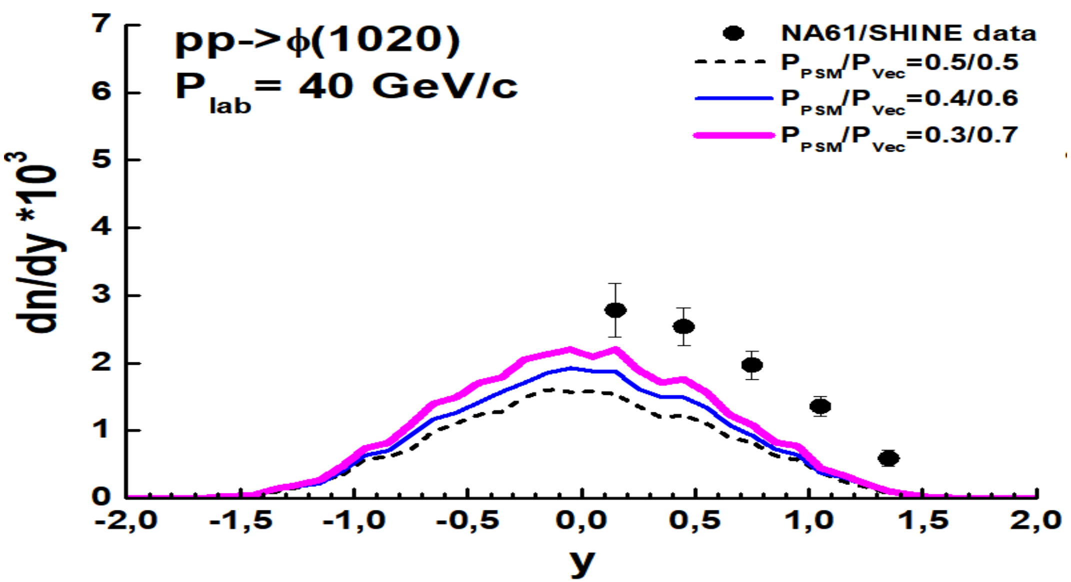




Problem of Phi meson description, Ppsm/Pvec=0.3/0.7

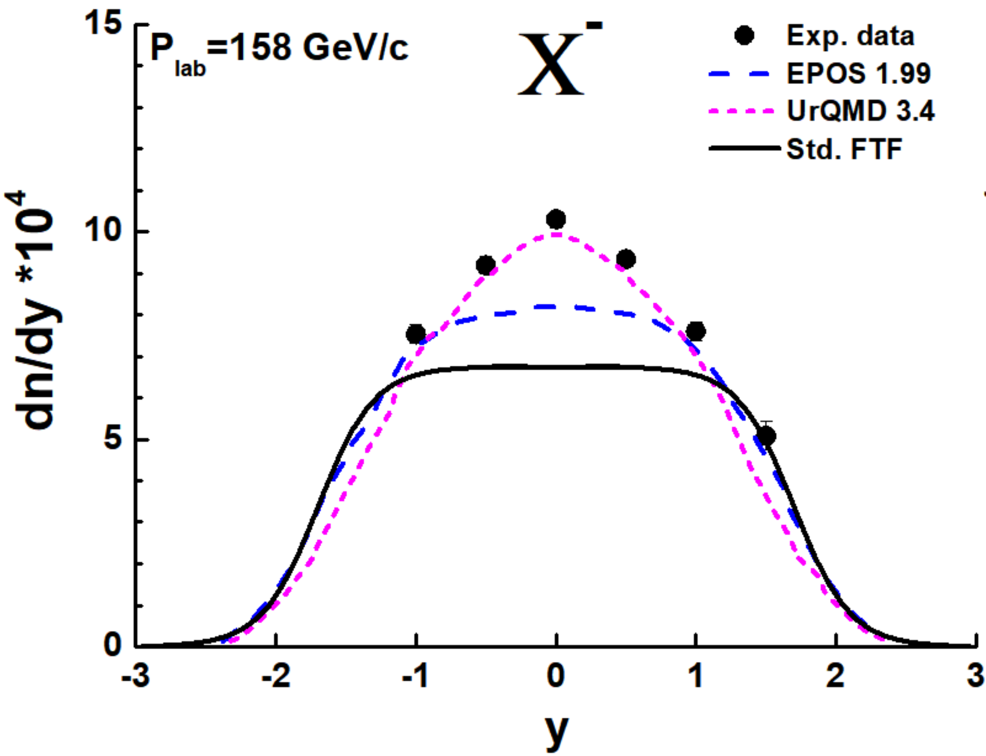


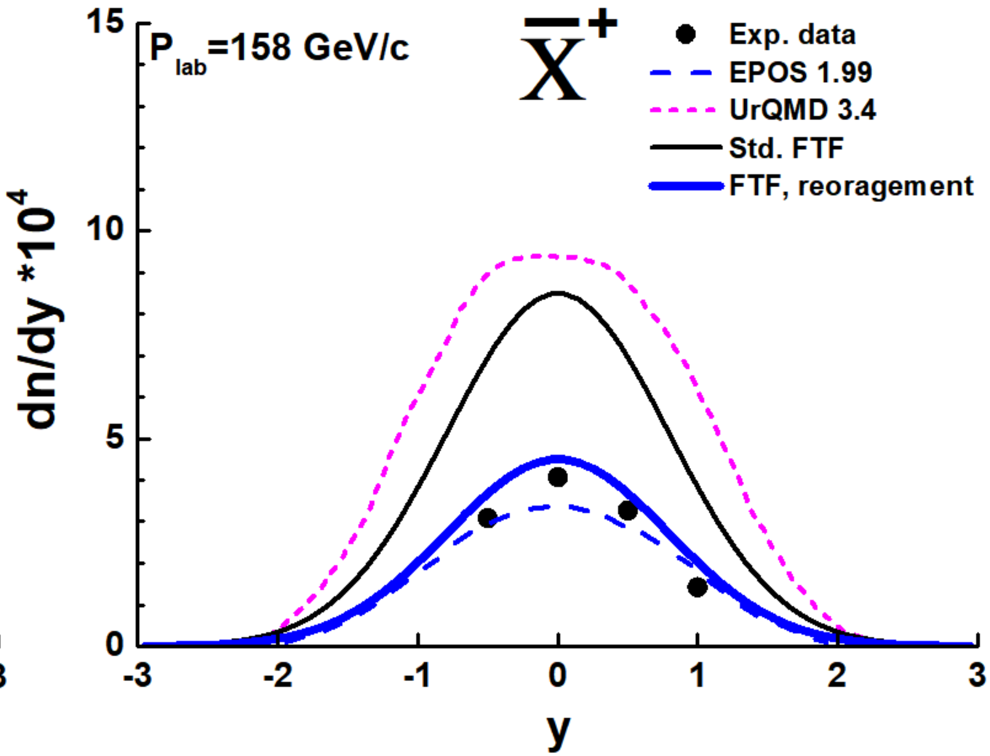




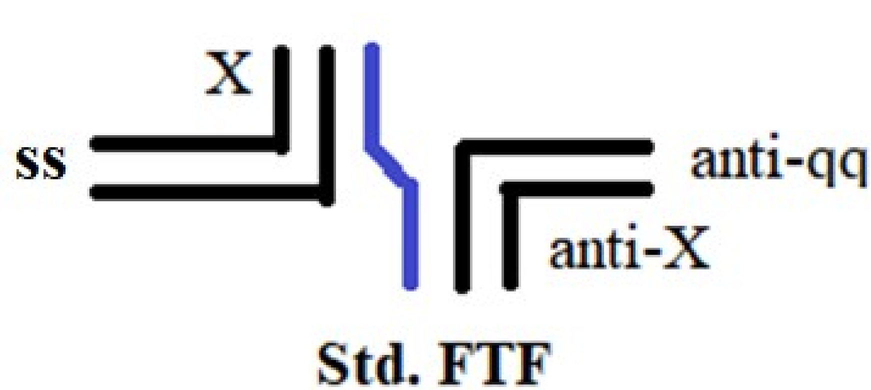
Pythia 6.4 In the program, the spin S is first chosen to be either 0 or 1. This is done according to parameterized relative proba-bilities, where the probability for spin 1 by default is taken to be **0.5** for a meson consisting only of u and d quark, **0.6** for one which contains s as well, and **0.75** for quarks with c or heavier quark, in

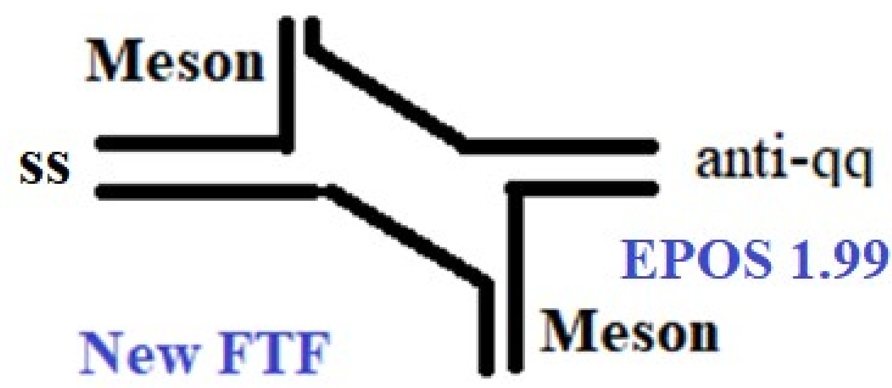
Problem of X-hyperon production



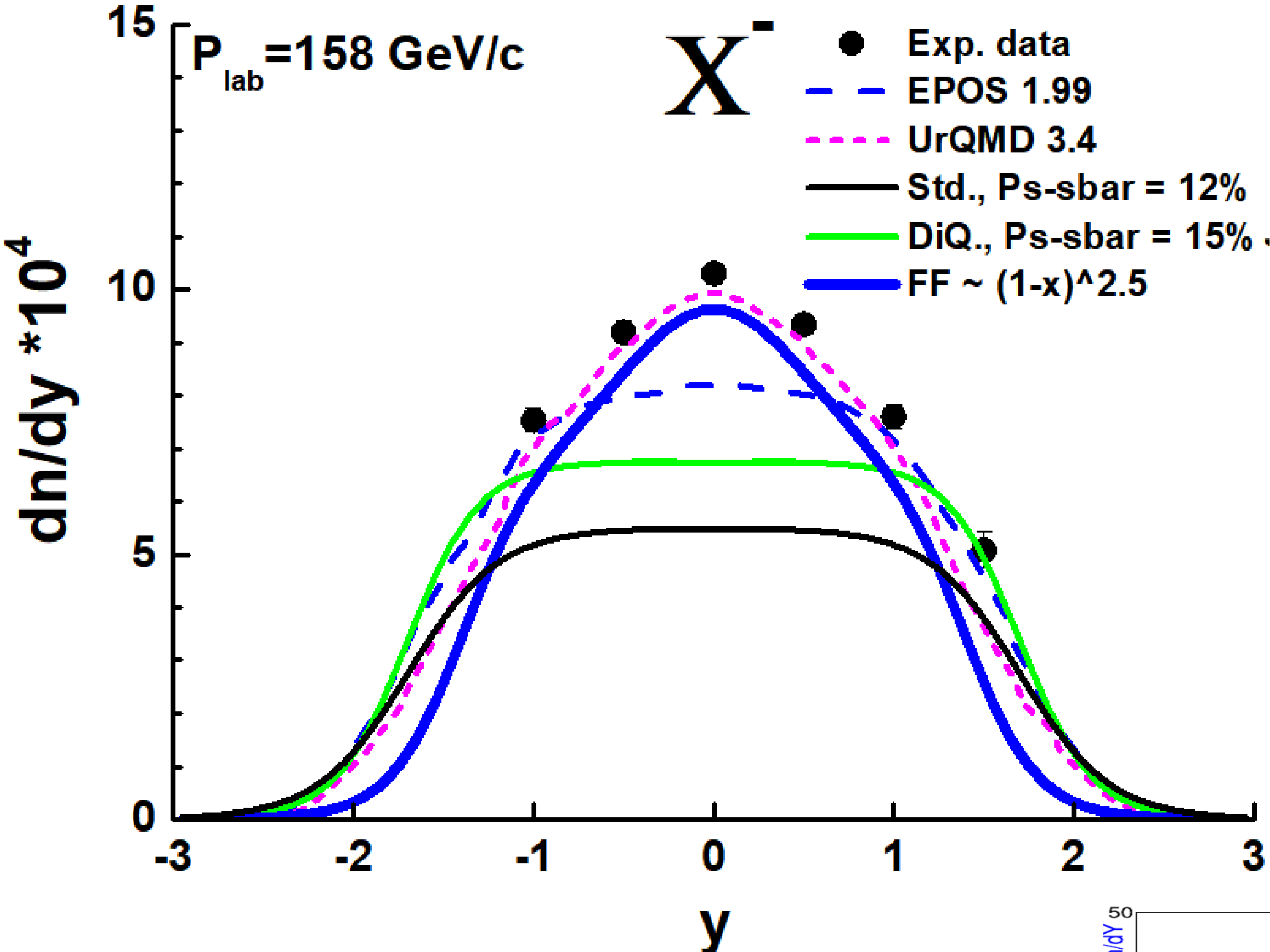


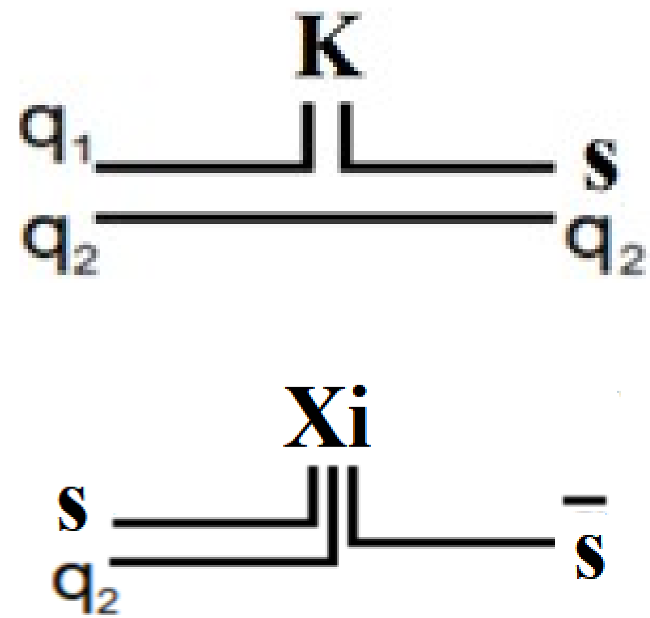
Anti-X mainly produced at Last String Decay!





Problem of Hi-hyperon production





Ps-sbar ?

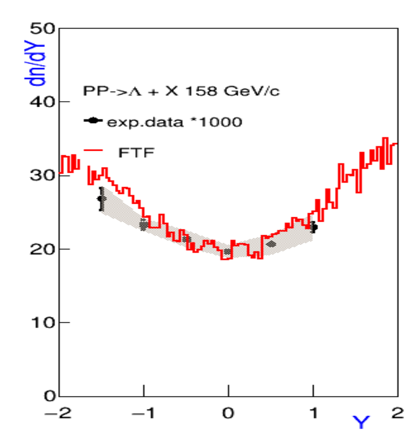
12 or 15 %?

LUND symmetric fragmentation function

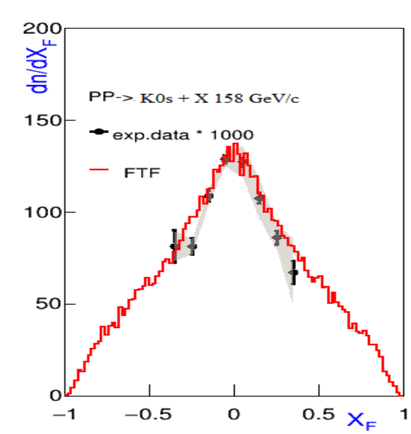
For mesons $f(z) \propto \frac{1}{z} z^{a_\alpha} \left(\frac{1-z}{z}\right)^{a_\beta} \exp\left(-\frac{bm_\perp^2}{z}\right)$

For baryons, a'la Kaidalov $f(z) = \frac{c}{(z_{max} - z_{min})^c} (z - z_{min})^{c-1}$

New FF for Hi - $f(z) \sim (z_{max} - z)^{c-1}$

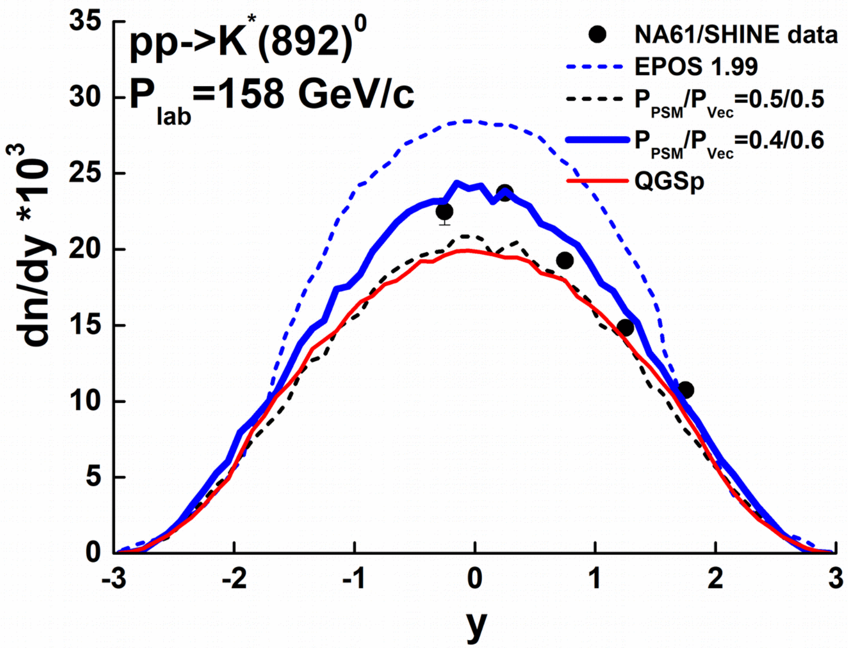


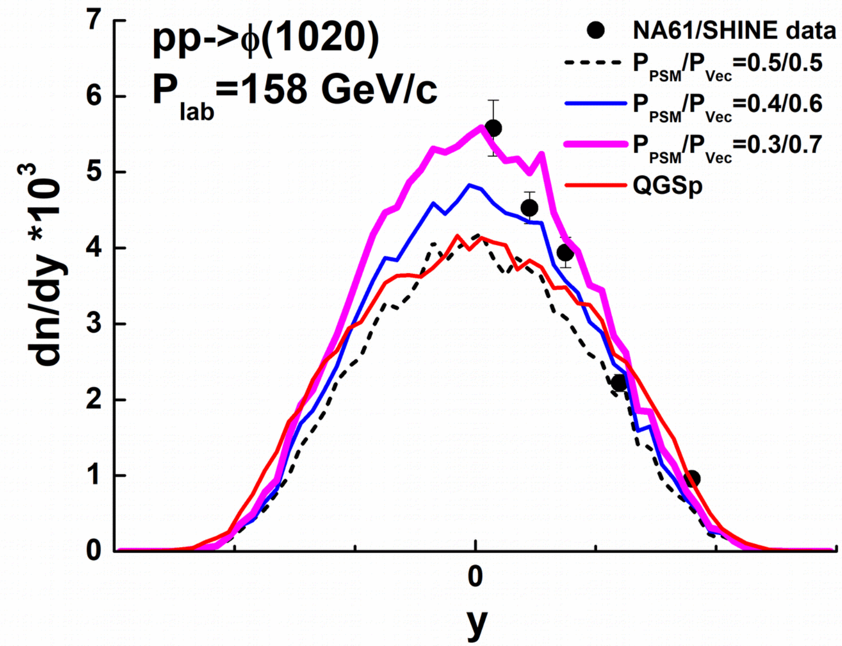
Lambda

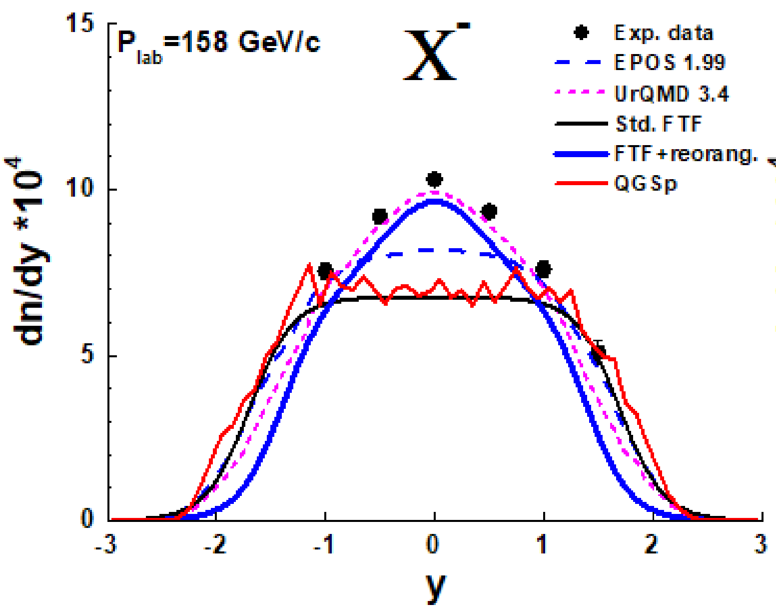


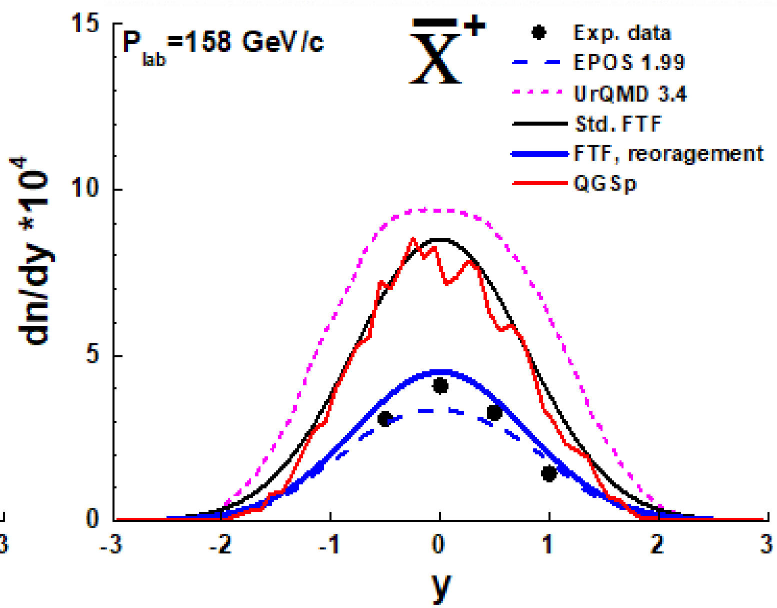
K0s

Geant4 QGS model







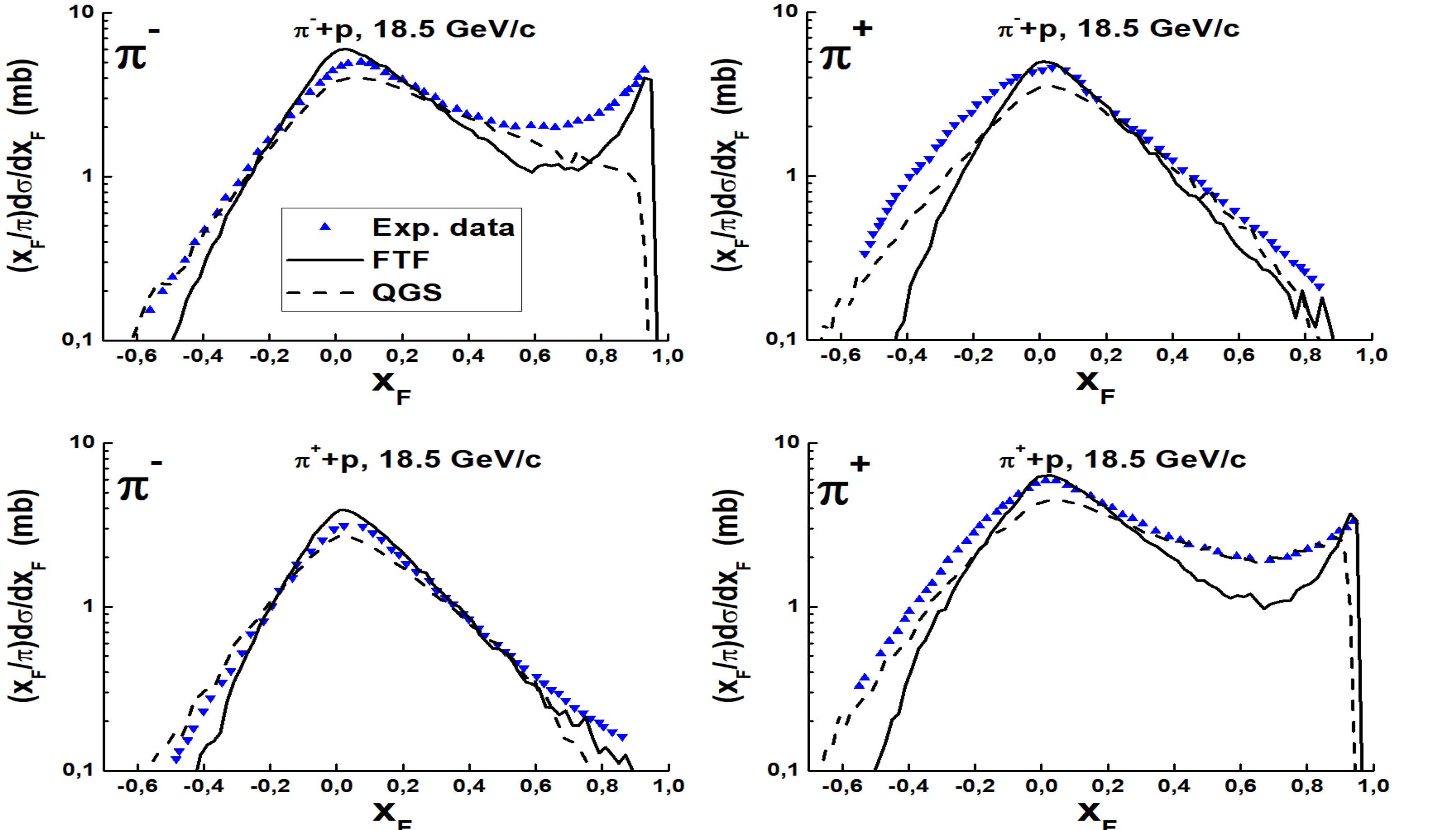


Some work has to be done!

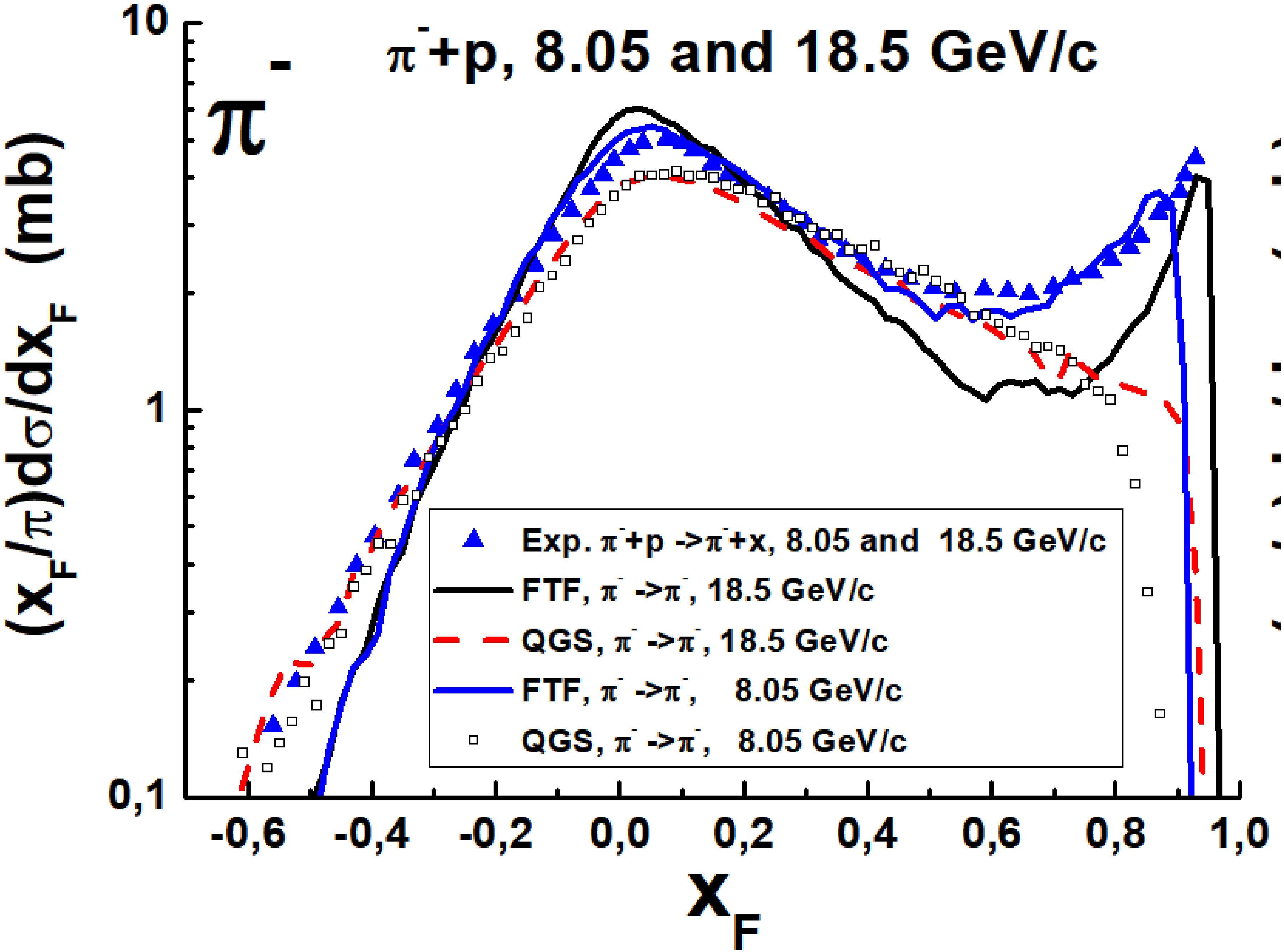
Meson production in Pi-P interactions at Plab = 8.05 and 18.5 GeV/c

Phys.Rev.D 10 (1974) 3579, Inclusive pi0 production in pi- p and pi+ p interactions at 18.5 GeV/c, N.N. Biswas et al.

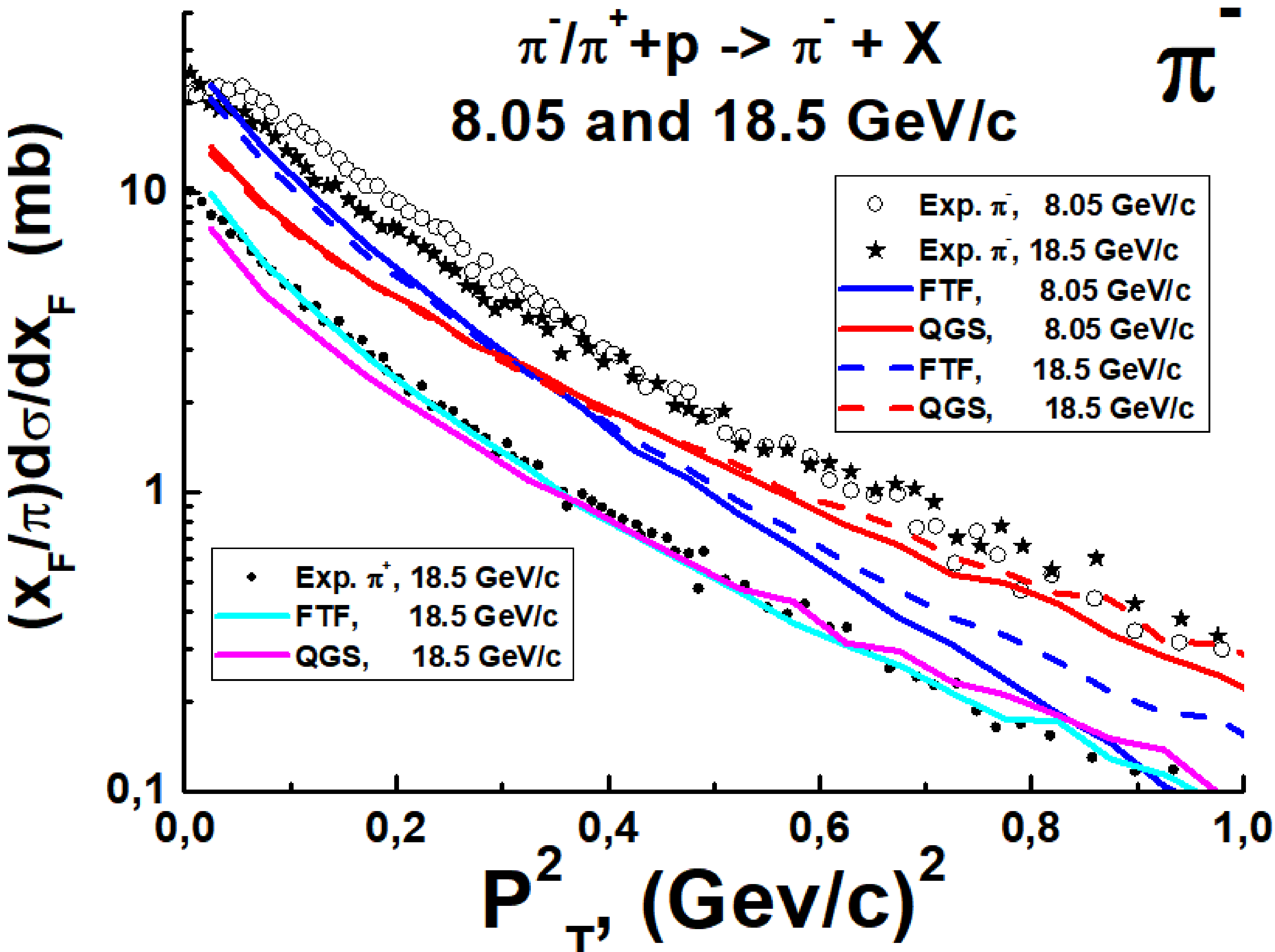
Phys.Rev.D 8 (1973) 1947, Compilation of data for pi+- p inclusive reactions at 8 and 18.5 gev/c. i. single-particle distributions, J.T. Pow



Meson production in Pi-P interactions at Plab = 8.05 and 18.5 GeV/c



Meson production in Pi-P interactions at Plab = 8.05 and 18.5 GeV/c



Conclusion

1. Main problem of the models – bad description of PP interactions!

SUMMARY

Geant4 FTF **OK at Ecmc >= 3 GeV**

Pythia 8 OK at Ecmc >= 8 GeV It would be well to tune for K+, K- and anti-proton

EPOS 1.99 & EPOS-LHC OK at Ecmc >= 5 GeV It would be well to include quark exchange processes

Below Ecmc 3 GeV
UrQMD ㅂ SMASH (C++ re-incarnation of UrQMD) can be used.

2. Geant4 FTF works well for nucleus-nucleus interactions at energies in NN CMS below and upper 12 GeV!

There is a problem with strange particles!

Summary

1. New hadron splitting algorithm is implemented in the core of the FTF model.

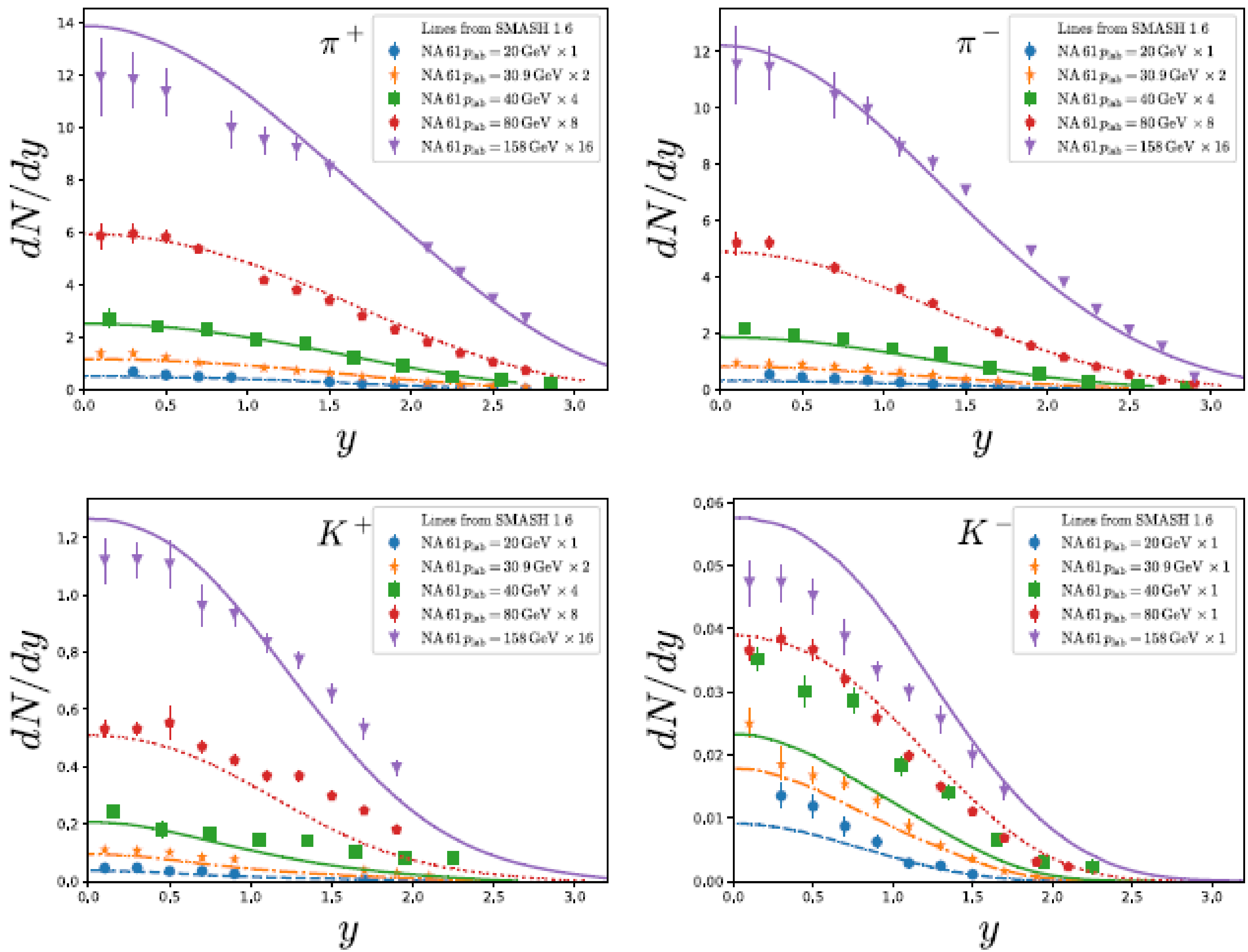
2. Problem of asymmetry of Pt – Xf correlations is solved.

3. Good description of NA49 and NA61/SHINE exp. data on pp interactions is reached.

Future task:

Revision and tuning of the FTF model for meson interactions with nucleons and nuclei
Update of the QGS model
Implementation of paticle's formation time in the models
Validate FTF for nucleus-nucleus interactions
Re-thinking of the connection of soft and hard interactions
Inclusion of QGP a'la EPOS LHC

J Mohs, S Ryu and H Elfner : J. Phys. G47 (2020) 065101 (**SMASH, Fig. 19, pp**)
Particle production via strings and baryon stopping within a hadronic transport approach



J Mohs, S Ryu and H Elfner : J. Phys. G47 (2020) 065101 (**SMASH , Fig. 19, pp**)

Particle production via strings and baryon stopping within a hadronic transport approach