Multiple Scattering and hydrodynamical evolution in pp@LHC

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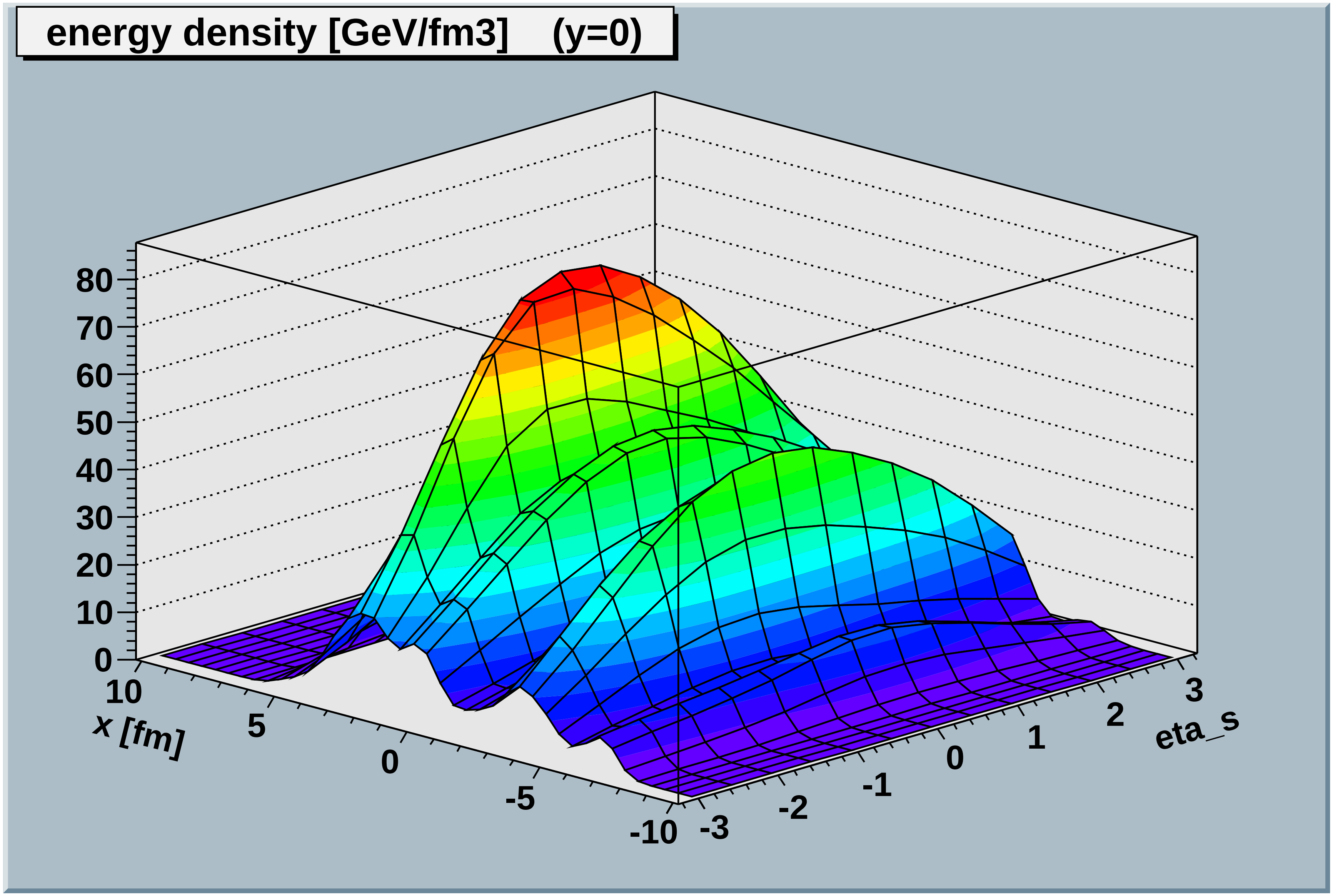
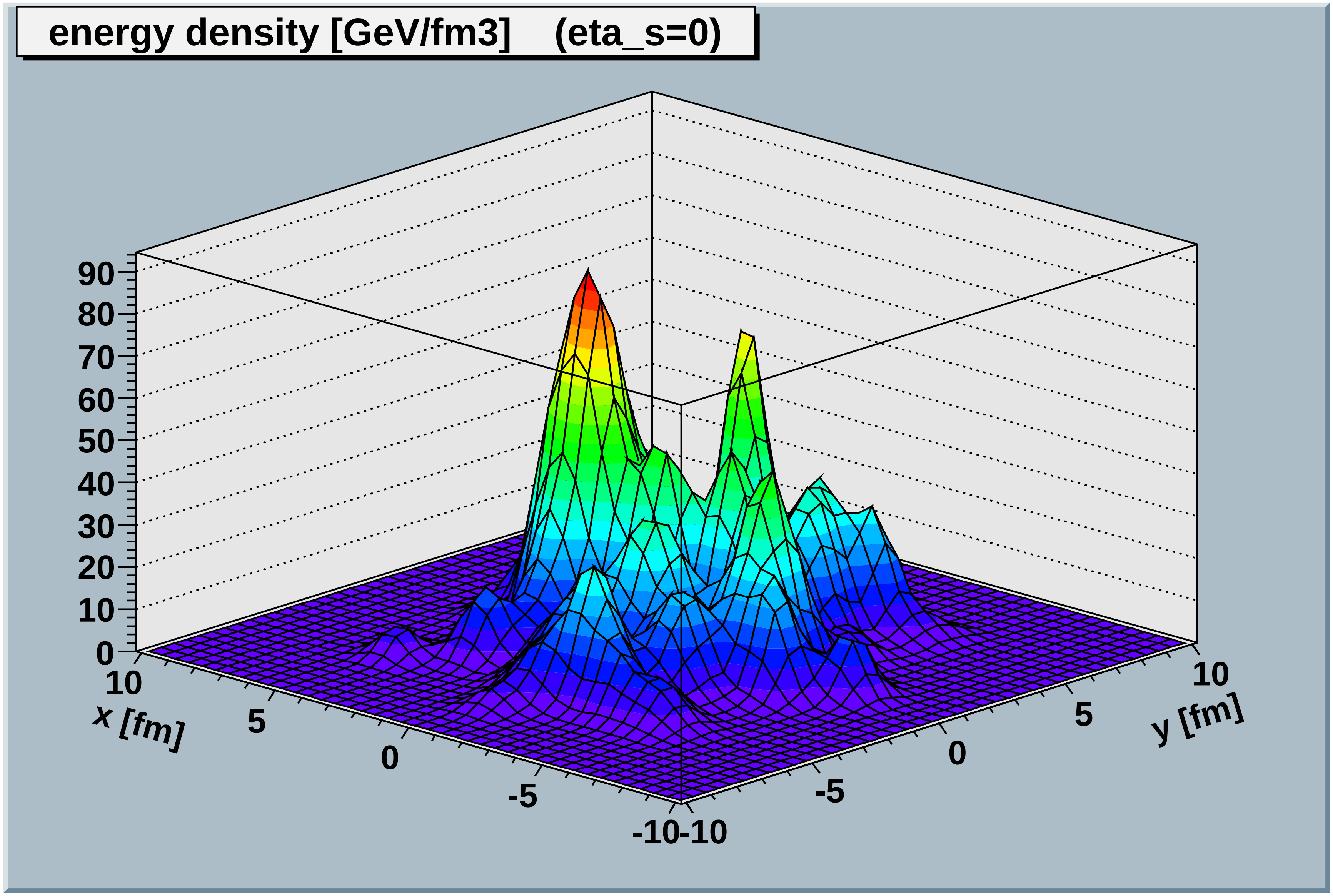
in collaboration with T. Pierog, S. Porteboeuf, T. Hirano, Y. Karpenko, M. Bleicher, S. Haussler

EPOS energy density (0.6fm/c) central AuAu



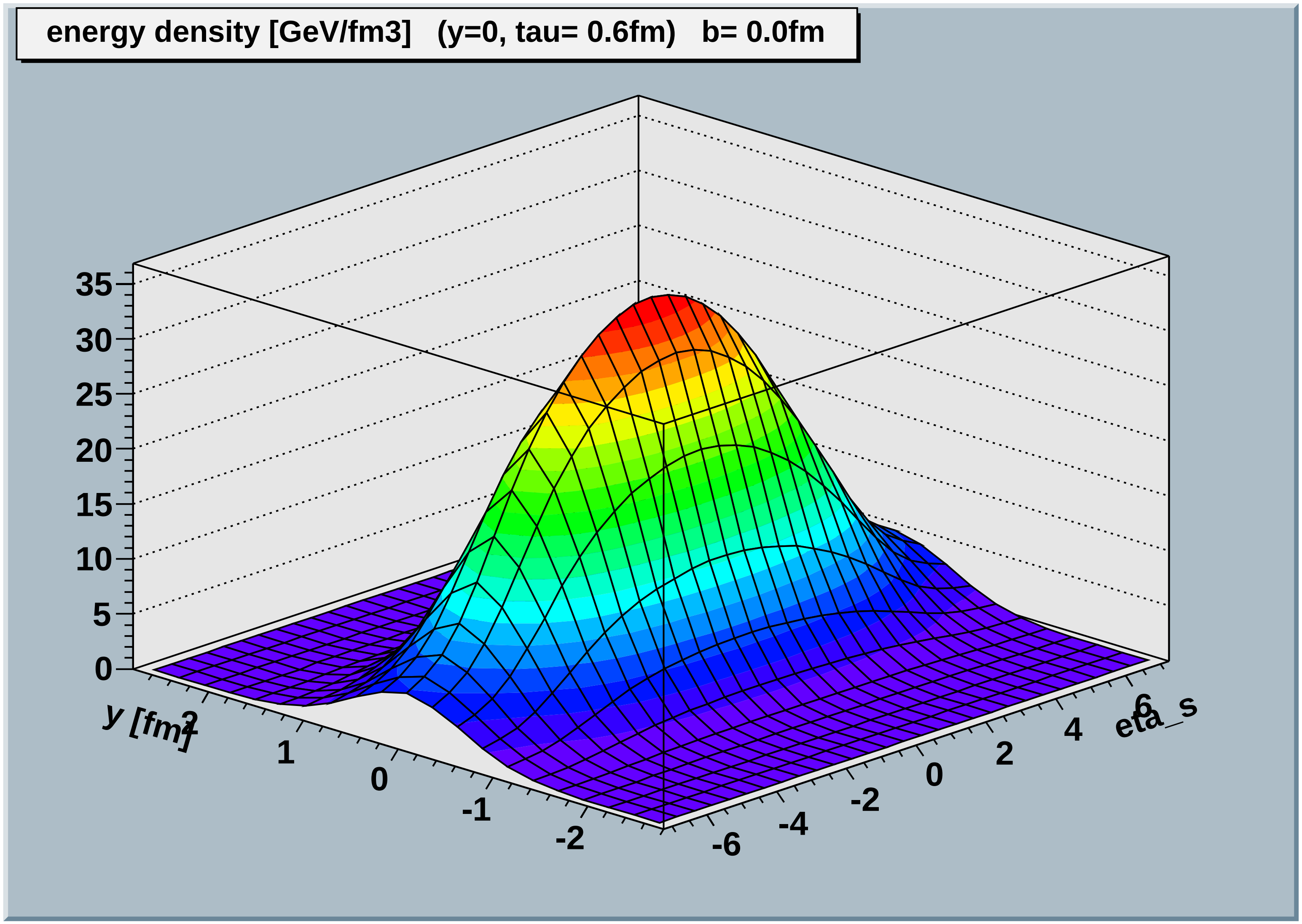
typically several ridges

... in transverse direction



several peaks ($\hat{=}$ ridges in $\eta - x$)

EPOS energy density (0.6fm/c) “central” pp



single ridge

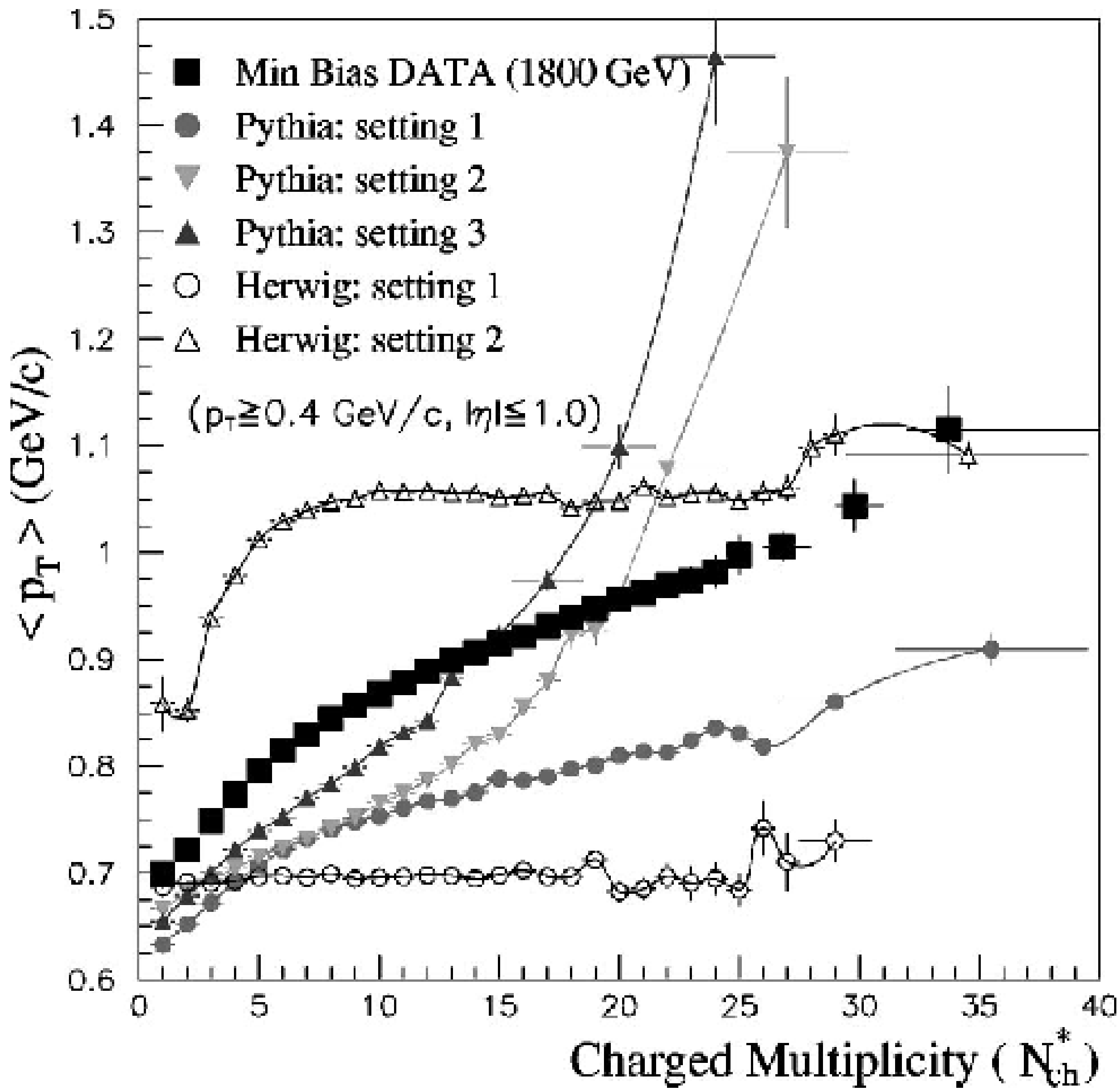
- ▷ **Size of the fluctuations in AuAu small, similar to what will be achieved in pp@LHC**
- ▷ **If hydro is applicable for AuAu@RHIC, it should be so for pp@LHC, if one reaches high energy densities...**
- ▷ **Here, multiple scattering will help !!**

Multiple scattering in pp

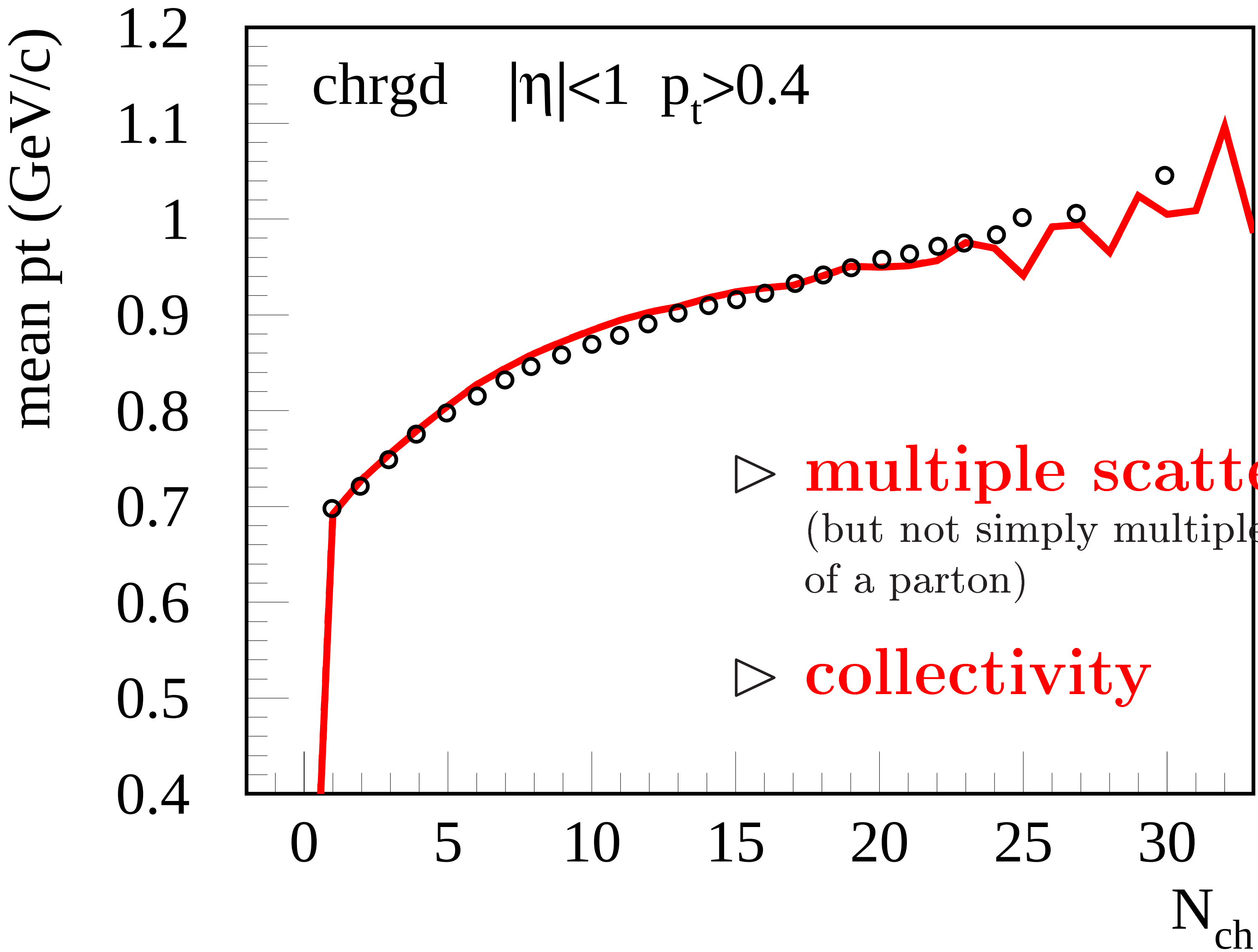
pp@1800GeV
data: CDF

Phys. Rev. D
Vol 65,
072005 (2002)

recent activities in Pythia community



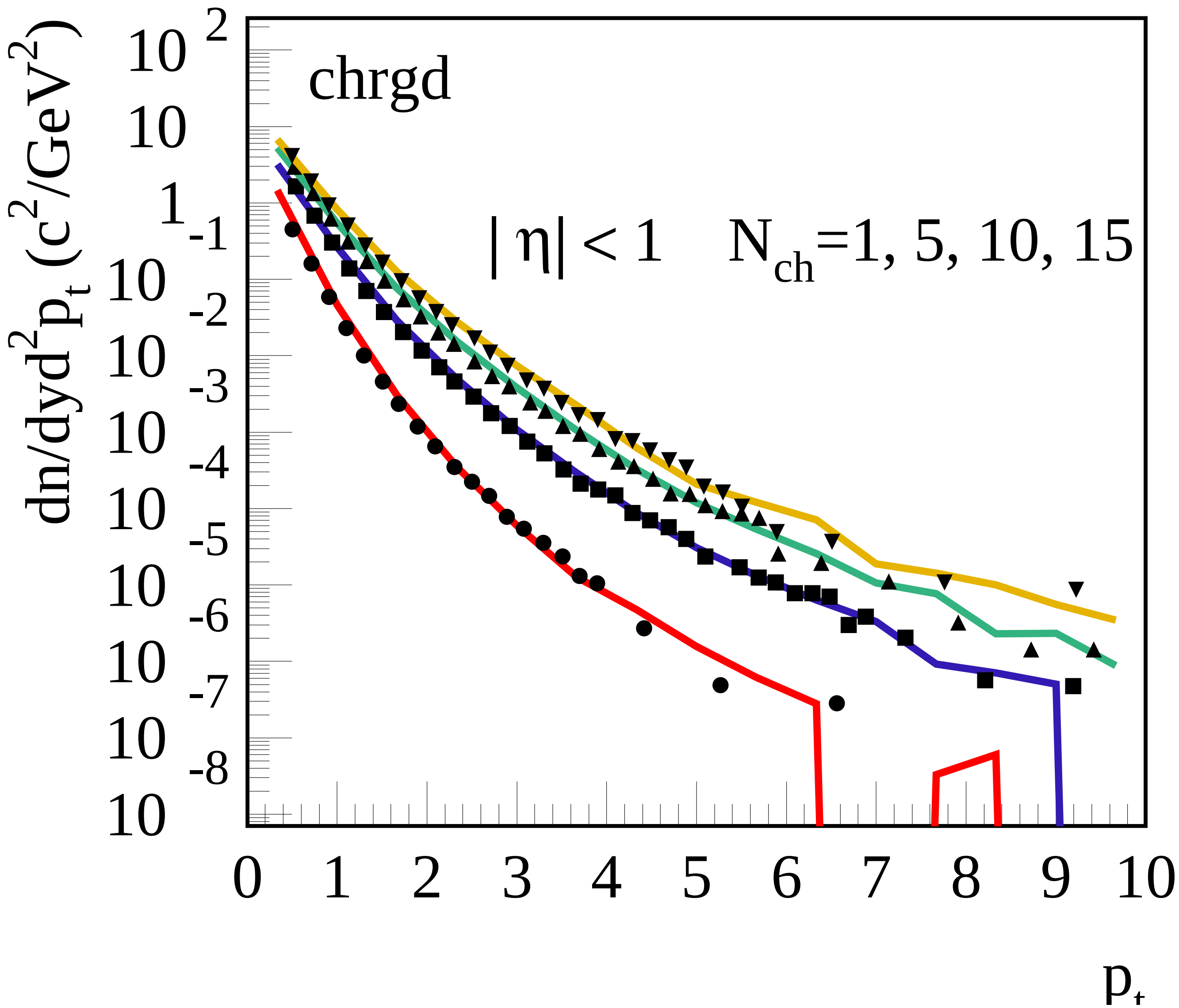
pp@1800GeV **points: CDF** **curve EPOS**



▷ **multiple scattering**
(but not simply multiple scattering of a parton)

▷ **collectivity**

pp@1800GeV,points: CDF,curves EPOS



In EPOS:

high multiplicity related to multiple scattering

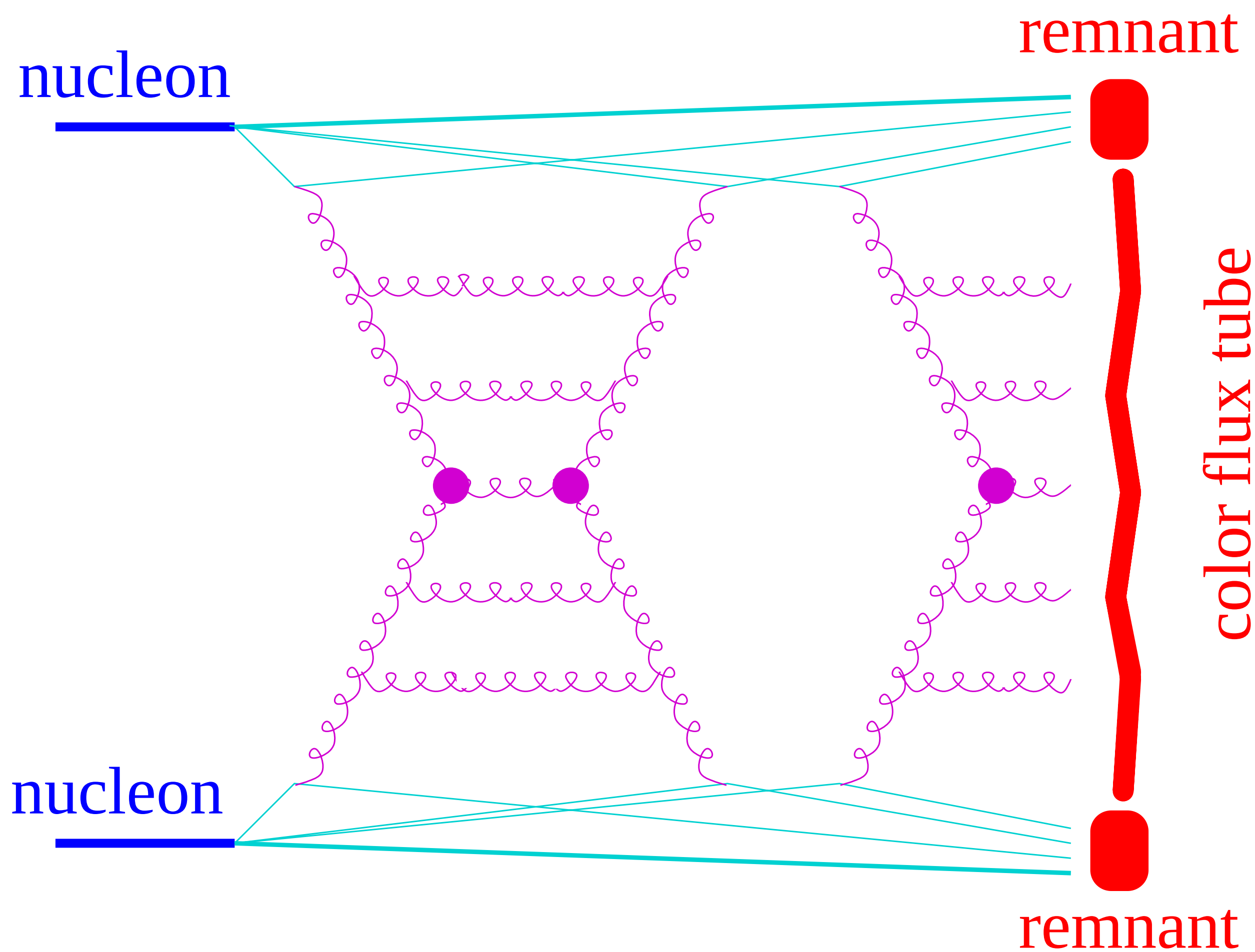
but multiple scattering also favours hard scatterings – just higher probability

EPOS: multiple exchange of ladders

Multiple scattering
with energy sharing

Squaring graphs
→ cut diagrams
→ cutting rule techniques

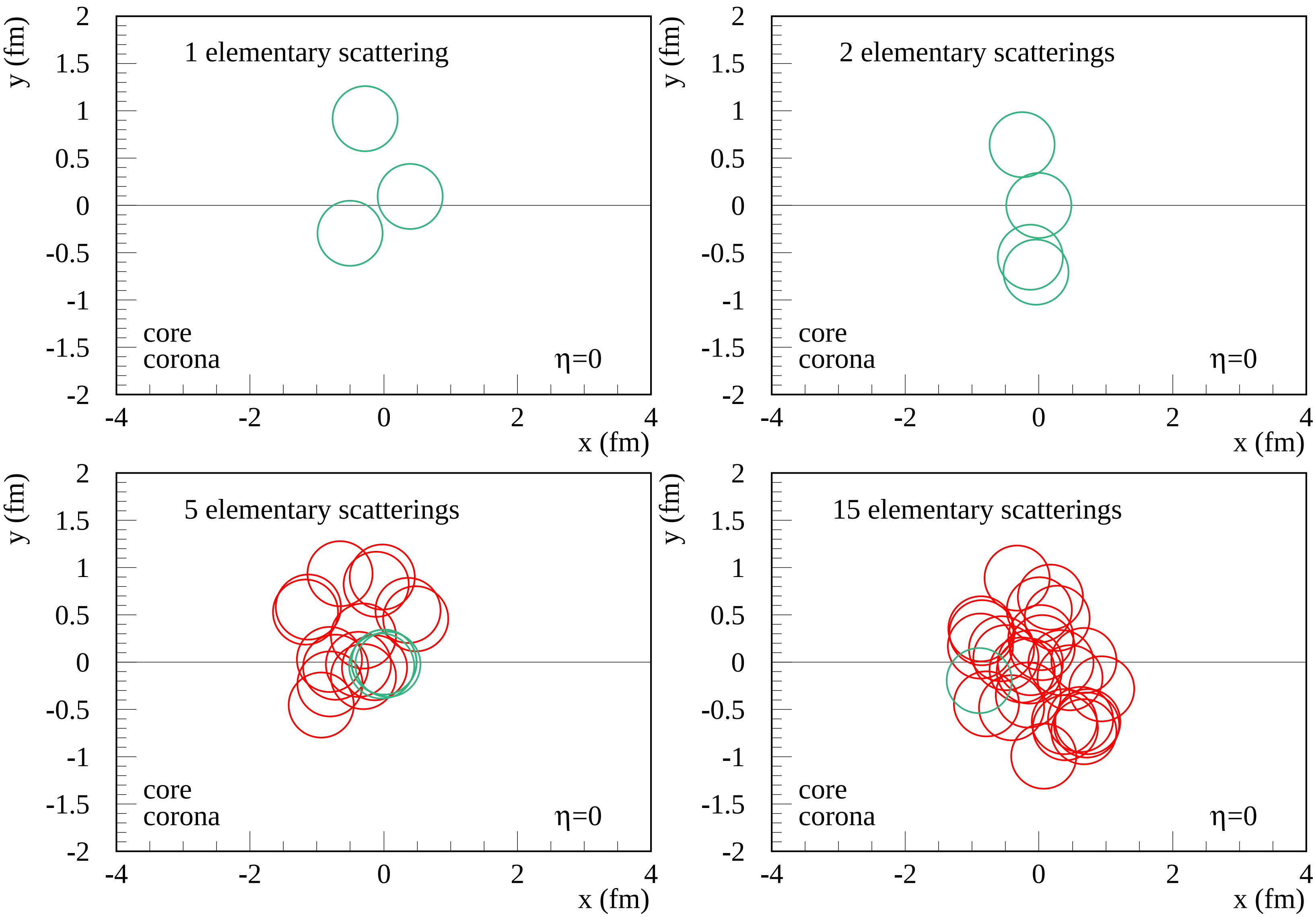
Energy sharing:
Markov chain
techniques



Particle production
from **remnants** and **flux tube** decays (→strings)

Parton-based Gribov-Regge Theory, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289; Parton ladder splitting and the rapidity dependence of pt spectra in dAu collisions at RHIC, K. Werner, F.M. Liu, T. Pierog, Phys. Rev. C 74, 044902 (2006)

Core-corona approach in pp



Core-corona in AA:

▷ separation of volume into (central) core and (peripheral) corona part

Completely different in pp:

▷ separation of events into two classes: core and corona events

▷ Energy density comparable to AuAu@RHIC

▷ Size comparable to size of fluctuations in AuAu@RHIC

▷ we propose (and we do) for pp:
hydrodynamical expansion + statistical decay based on EPOS flux tube initial conditions – event-by-event

Only core used to compute initial conditions for hydrodynamical evolution

at τ_0 : from space and momentum four-vectors of string segments, we get

- ▷ energy density $\varepsilon(\vec{x})$,
- ▷ flow velocity $\vec{v}(\vec{x})$
- ▷ net flavor densities $f(\vec{x})$

H.J. Drescher, S. Ostapchenko, T. Pierog, and K.Werner, hep-ph/0011219, Phys.Rev.C65:054902,2002

$$T^{\mu\nu} = \frac{1}{\Delta V}\sum_{i\in\Delta V}\frac{p_i^\mu p_i^\nu}{p_i^0}$$

$$N_q^\mu = \frac{1}{\Delta V}\sum_{i\in\Delta V}\frac{p_i^\mu}{p_i^0}\,q_i$$

with

$$p = \int_A^B \left\{\frac{\partial X(r,t)}{\partial t}dr + \frac{\partial X(r,t)}{\partial r}dt\right\}$$

$$X(r,t) = X_0 + \frac{1}{2}\left[\int_{r-t}^{r+t} g\,(\xi)\,d\xi\right]$$

A, B: two neighboring points on X

$$g(r) = v_k \quad \text{for } r_{k-1} \le r \le r_k,\ 1 \le k \le n$$

$v_k = p_k/p_k^0$, $r_k = p_k^0/\kappa$

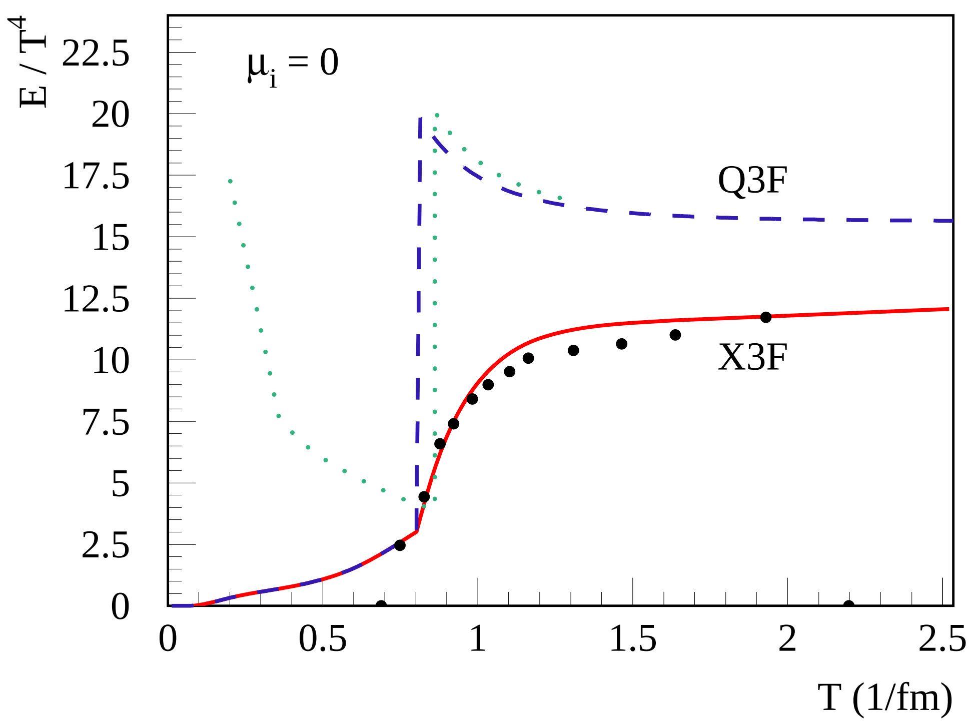
p_k = parton four-momentum

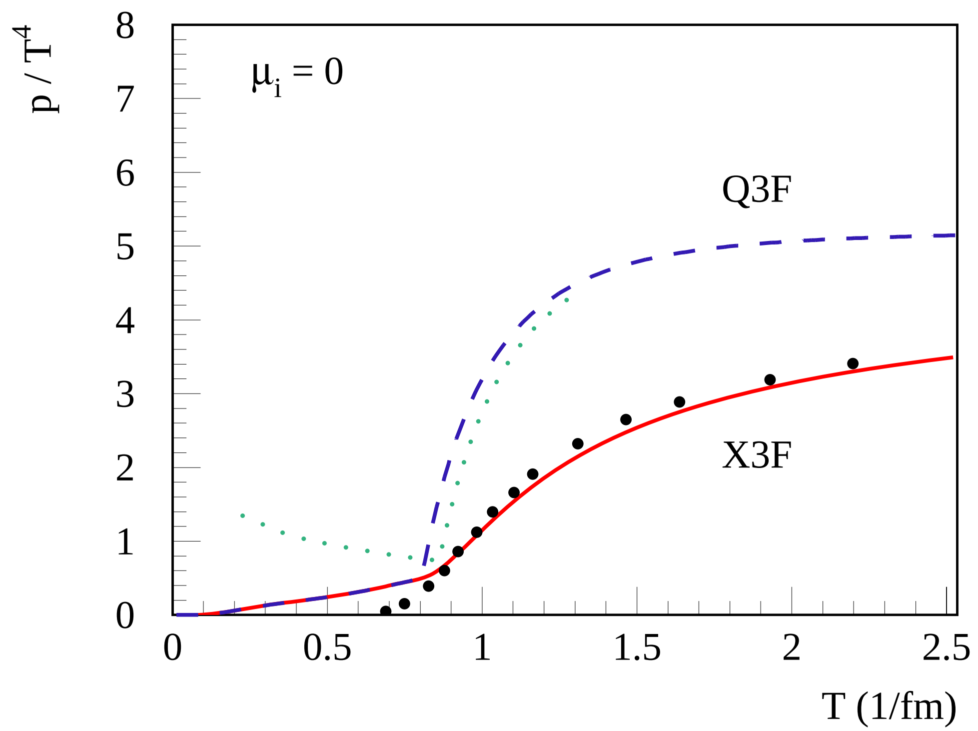
Hydro code - Yuri Karpenko, Kiev & Nantes (unpublished)

- C++ code, coupled directly to EPOS
- Code based on Godunov method: introducing finite cells and computing fluxes between cells using the (approximate) Riemann problem solution for each cell boundary.
- Use relativistic HLLE solver to solve Riemann problems
- To achieve more accuracy in time: predictor-corrector scheme is used for the second order of accuracy in time, i.e. the numerical error is $O(dt^3)$, instead of $O(dt^2)$
- To achieve more accuracy in space : to achieve the second order scheme, the linear distributions of quantities (conservative variables) inside cells are used. The conservative quantities are $(e + p * v^2)/(1 - v^2)$, $(e + p) * v/(1 - v^2)$.
- The code is written in hyperbolic coordinates

EoS: Massless quarks and gluons + bag, hadron resonance gas

- ▷ "Hirano" : PCE, $\mu_B = \mu_S = \mu_Q = 0$
- ▷ "Q3F": 1st order PT, excl volume correction, μ_B, μ_S, μ_Q considered, parameters as in Spherio
- ▷ "X3F" crossover" : $p = p_Q + \lambda(p_H - p_Q)$, $\lambda = \exp(-\frac{T-Tc}{\delta})\theta(T-T_c) + \theta(T_c - T)$



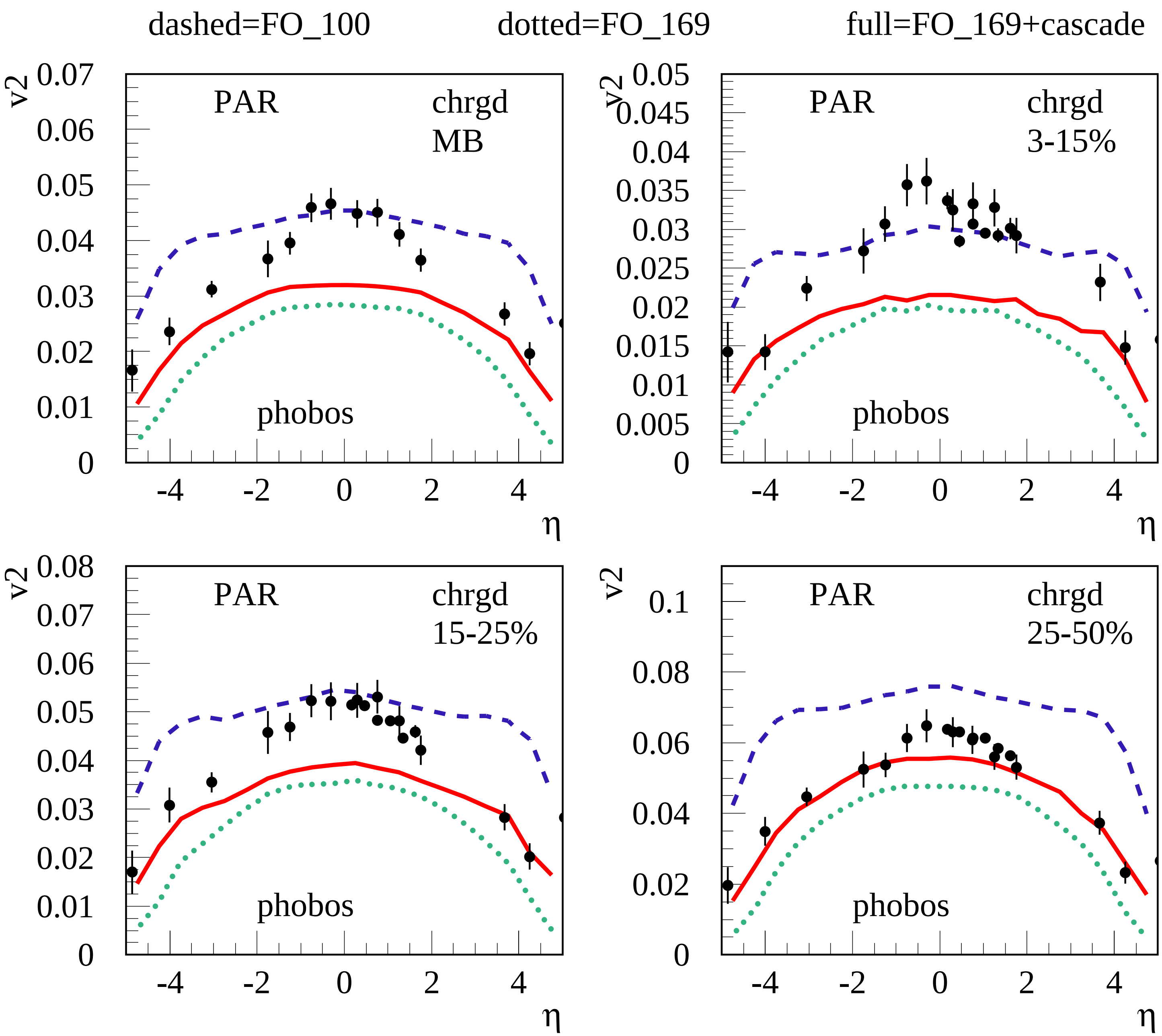


Checking hydro procedures against AuAu@RHIC

Understand what observables are affected by the different elements:

- ▷ flux-tube initial condition
- ▷ core-corona procedure
- ▷ three flavor cross-over EoS
- ▷ EbE treatment
- ▷ hadronic FS cascade
- ▷ hadron table
- ▷ not considered: viscosity, initial flow

Elliptical flow *(Hirano initial condition & PCE EoS)*



dashed:
pure hydro, FO at 100 MeV

dotted:
pure hydro, FO at 169 MeV.

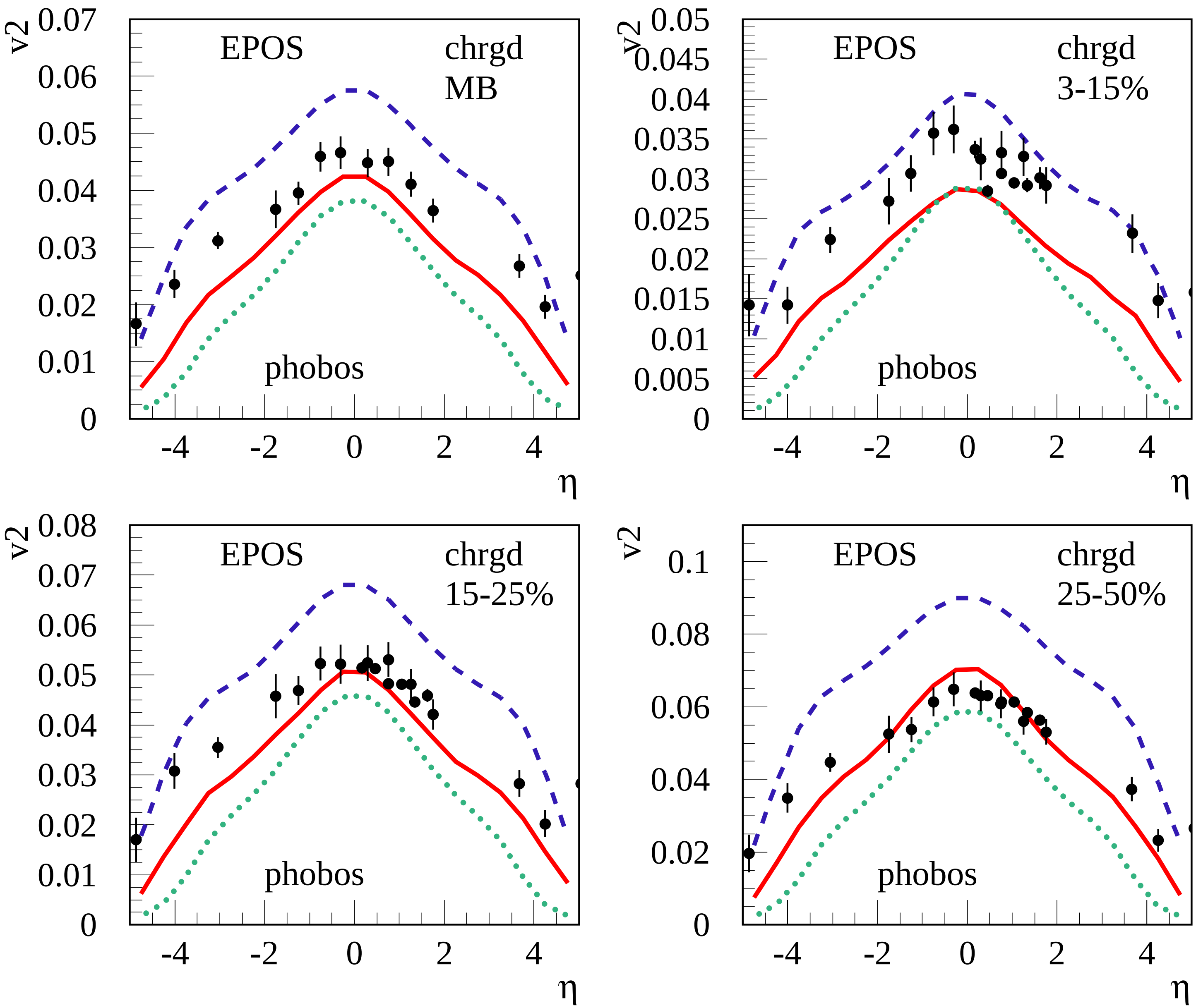
full:
hydro, FO at 169 MeV, + hadronic cascade

(UrQMD in collaboration with S.Haussler, M.Bleicher, S. Porteboeuf)

$T_c = 170\text{MeV}$

Elliptical flow *(EPOS initial condition, only core)*

dashed=FO_100 dotted=FO_169 full=FO_169+cascade



dashed:
pure hydro, FO at 100 MeV

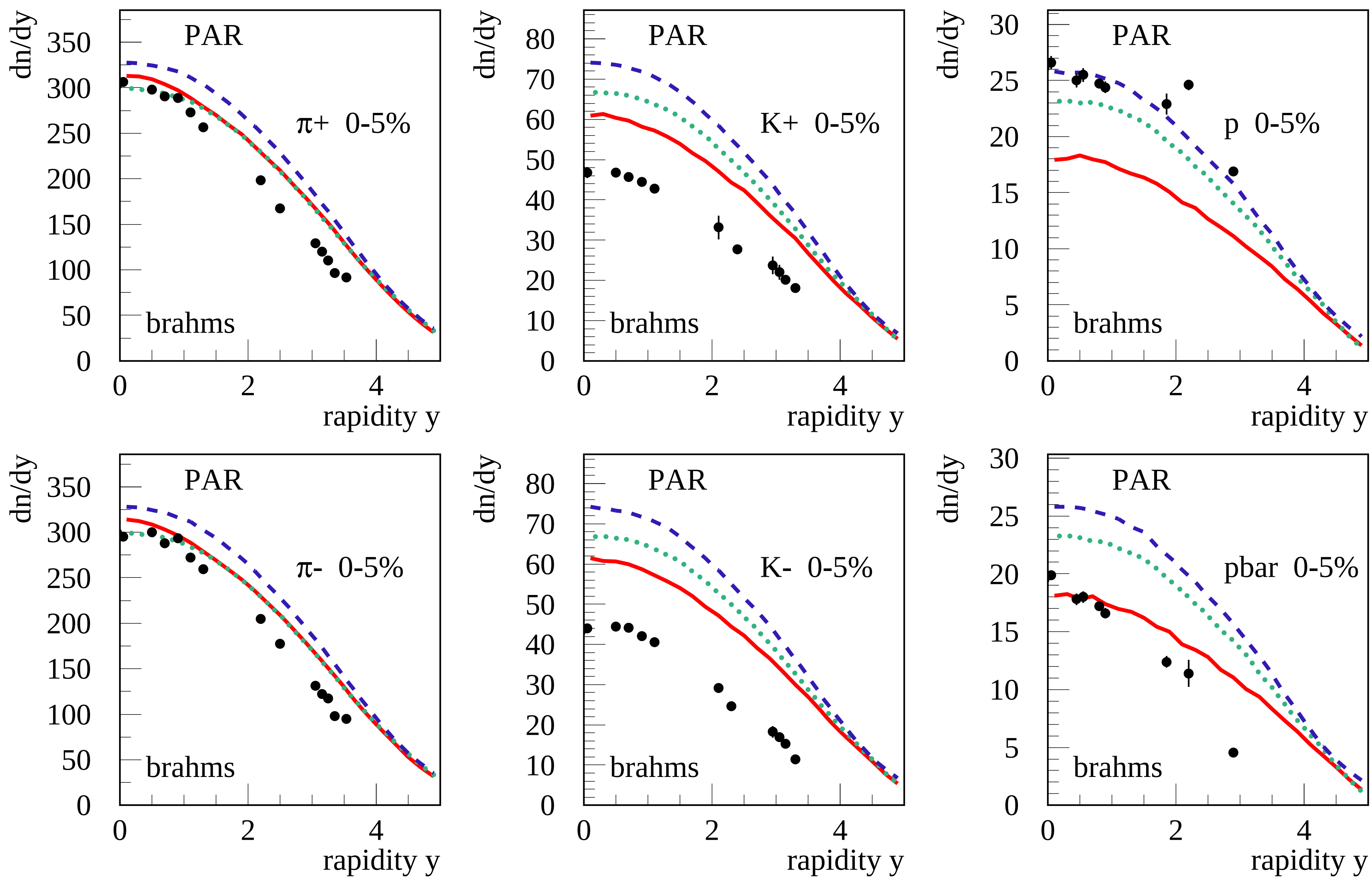
dotted:
pure hydro, FO at 169 MeV.

full:
hydro, FO at 169 MeV, + hadronic cascade

EPOS here means pure hydro, no corona

Yields *(Hirano initial cond & PCE EoS)* *≈EPOS*

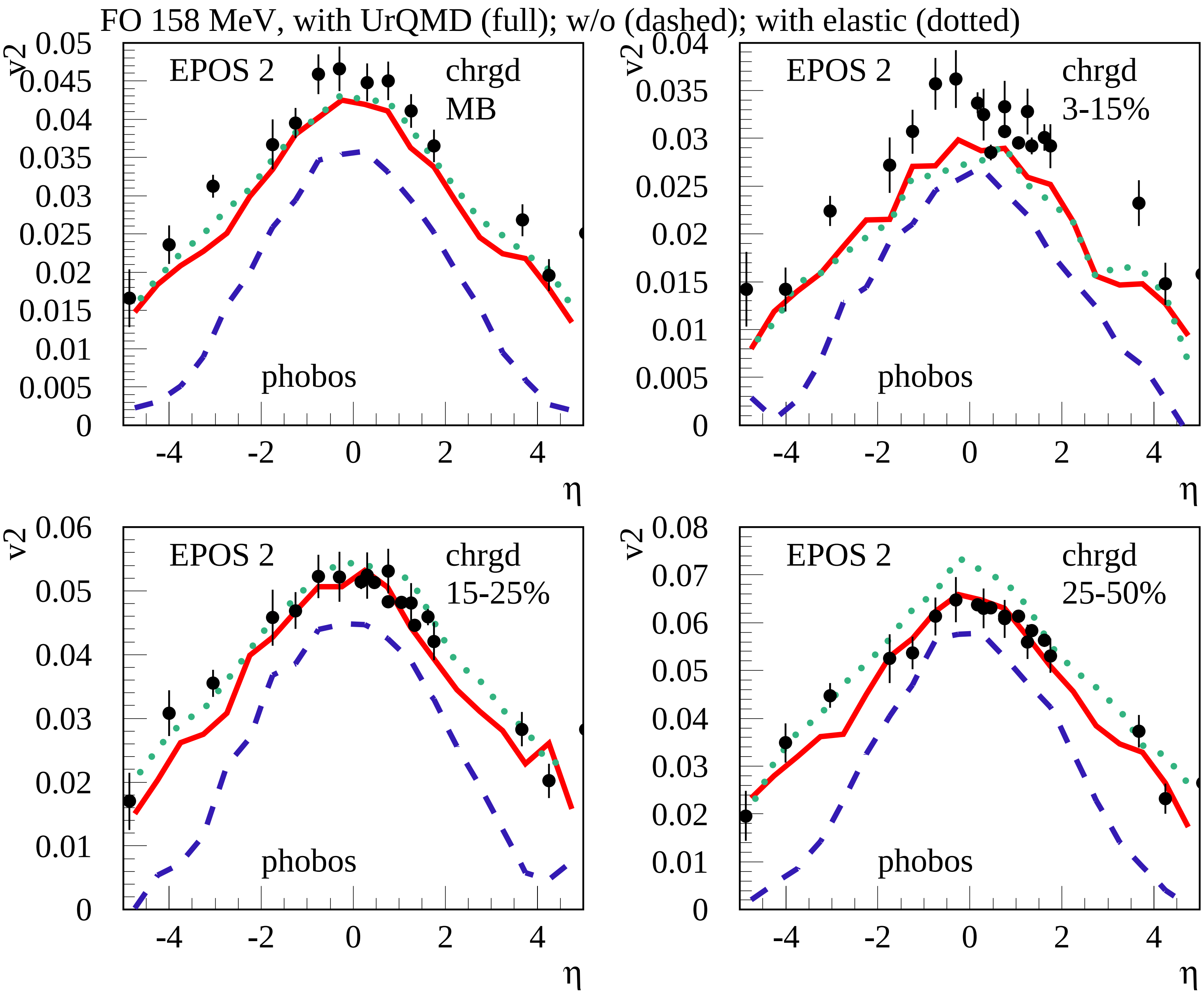
dashed=FO_100 dotted=FO_169 full=FO_169+cascade



In the following:

- ▷ flux-tube initial condition
- ▷ core-corona procedure
- ▷ three flavor cross-over EoS (X3F)
- ▷ EbE treatment
- ▷ hadronic FS cascade

EPOS & 3DHydro, FO at 158MeV, EoS X3F, EbE

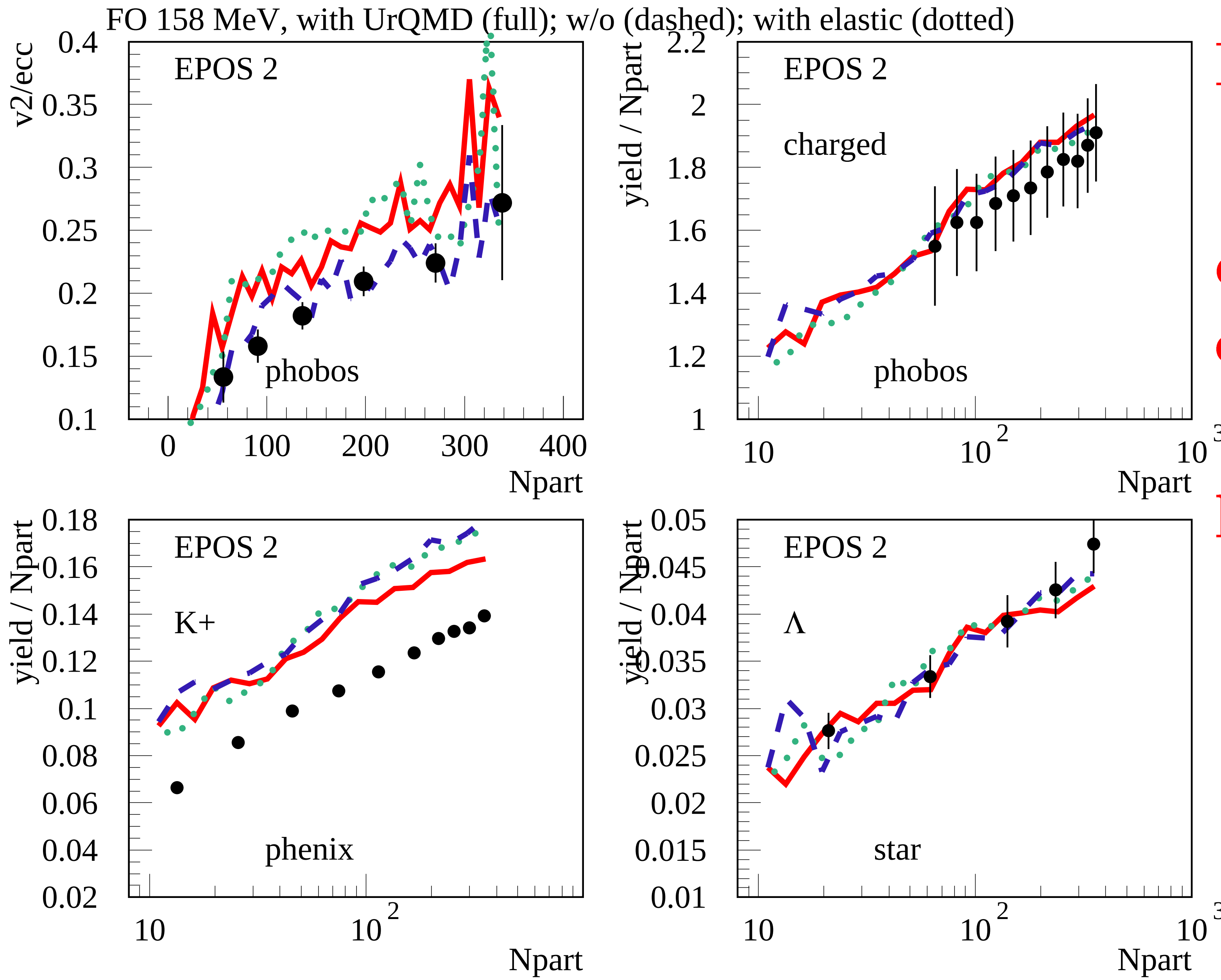


hadronic cascade, elastic, no cascade

important: flux-tube core-corona

EoS Q3F ≈20% lower

v2/ecc, chrgd, K, Λ -yields per part. (Npart)

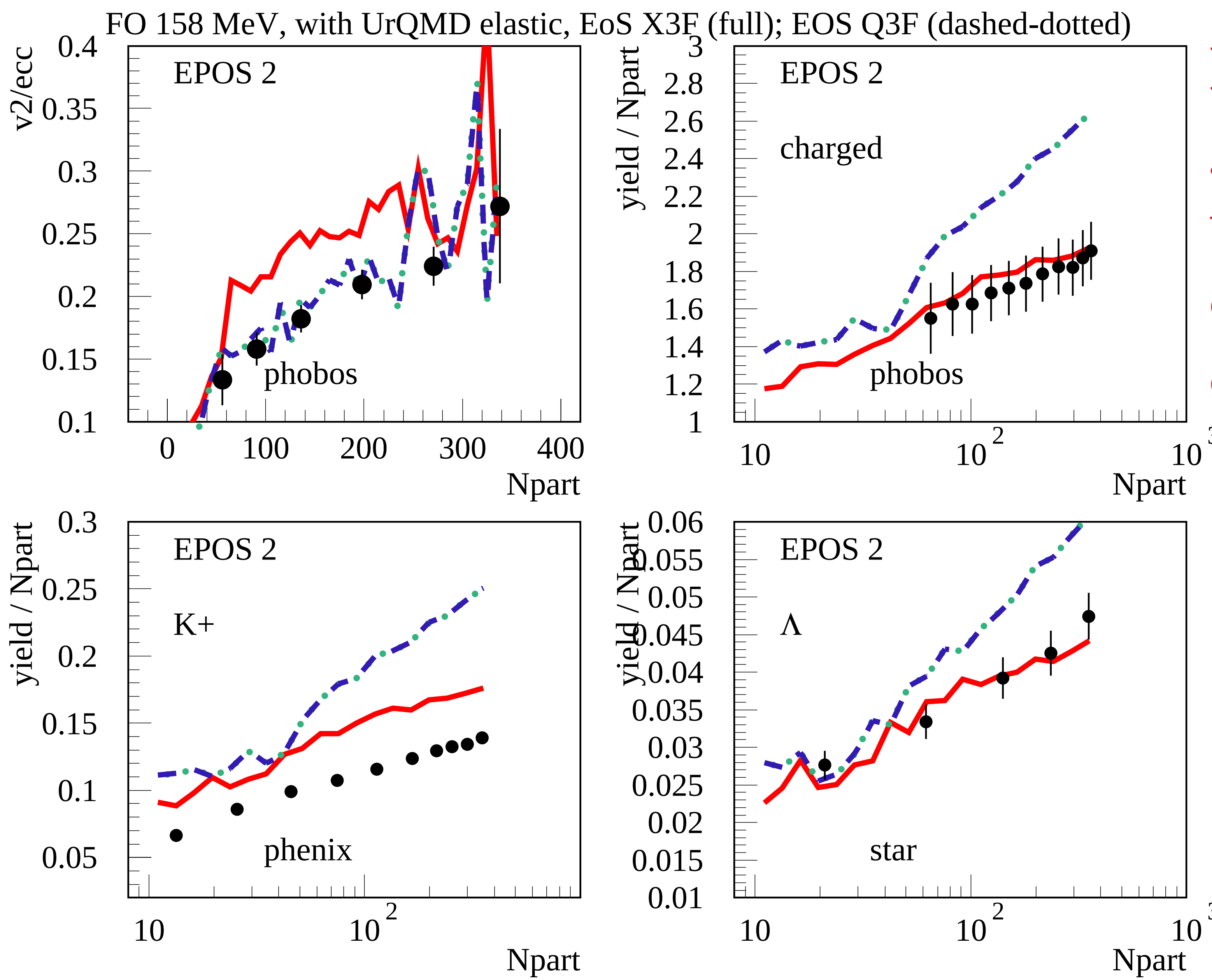


EoS X3F

core-corona effect

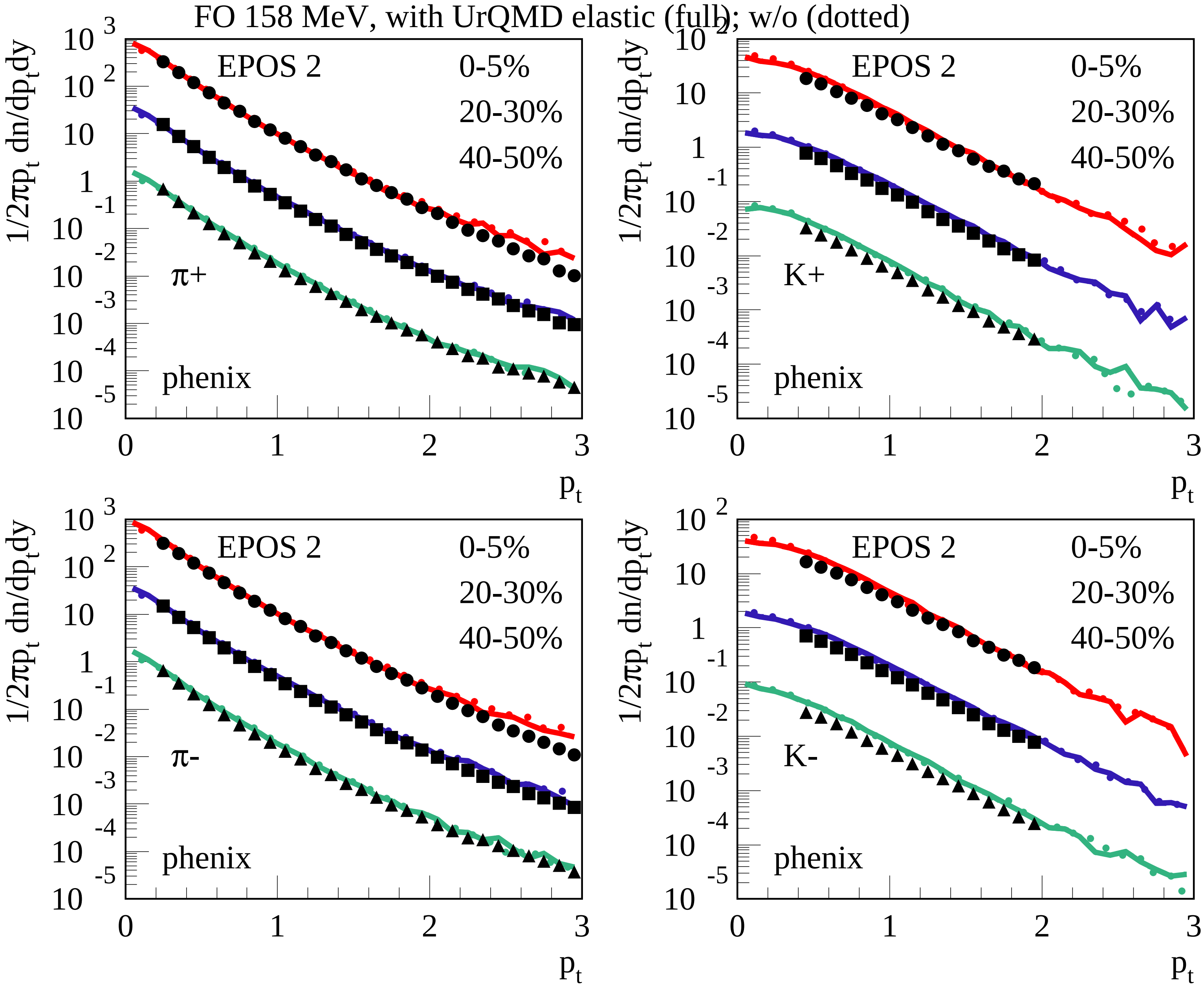
kaon excess

comparing EoS Q3F and X3F



EoS Q3F gives too steep centrality dependence !!

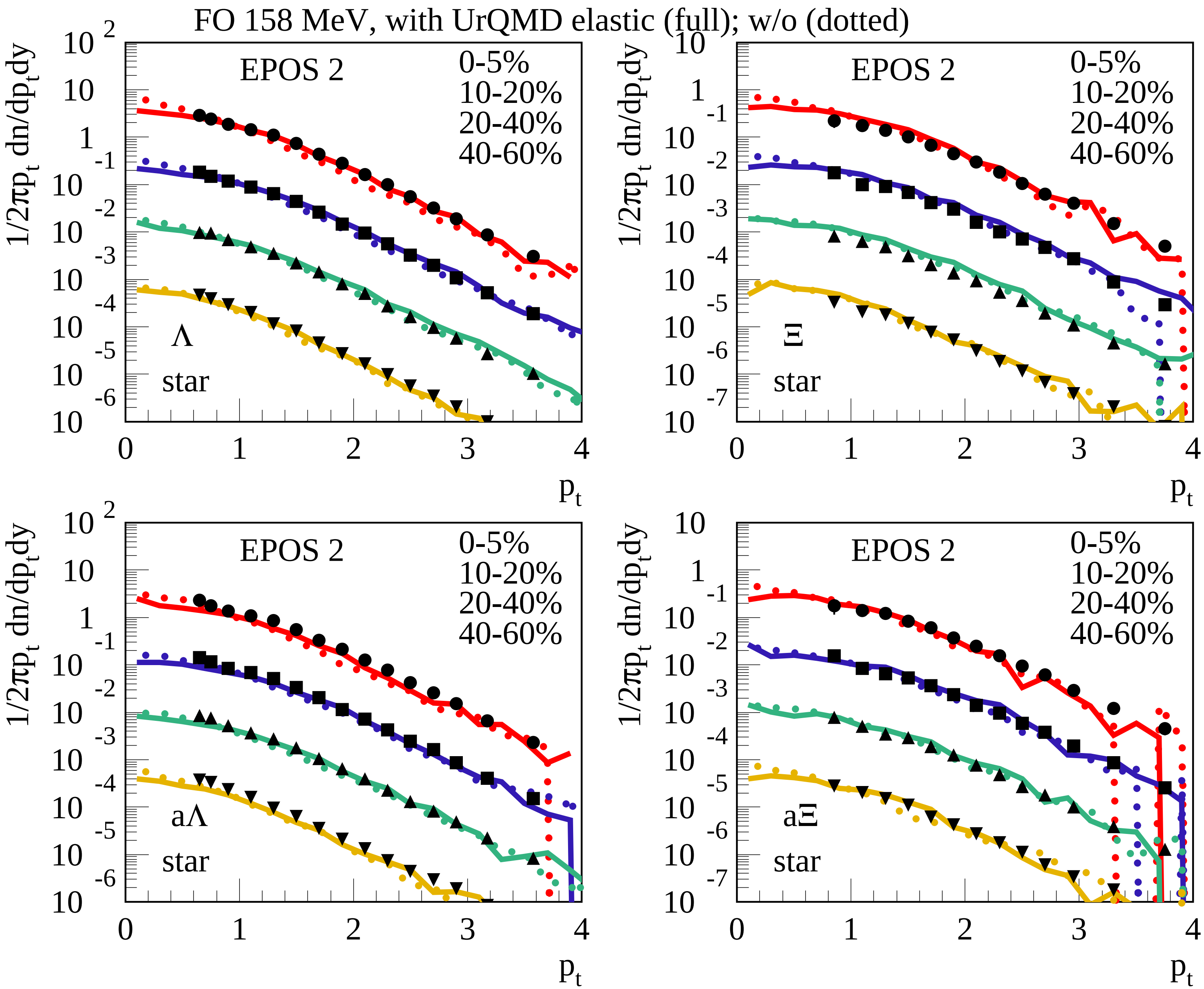
pt spectra of pi and K



soft & hard (w/o eloss)

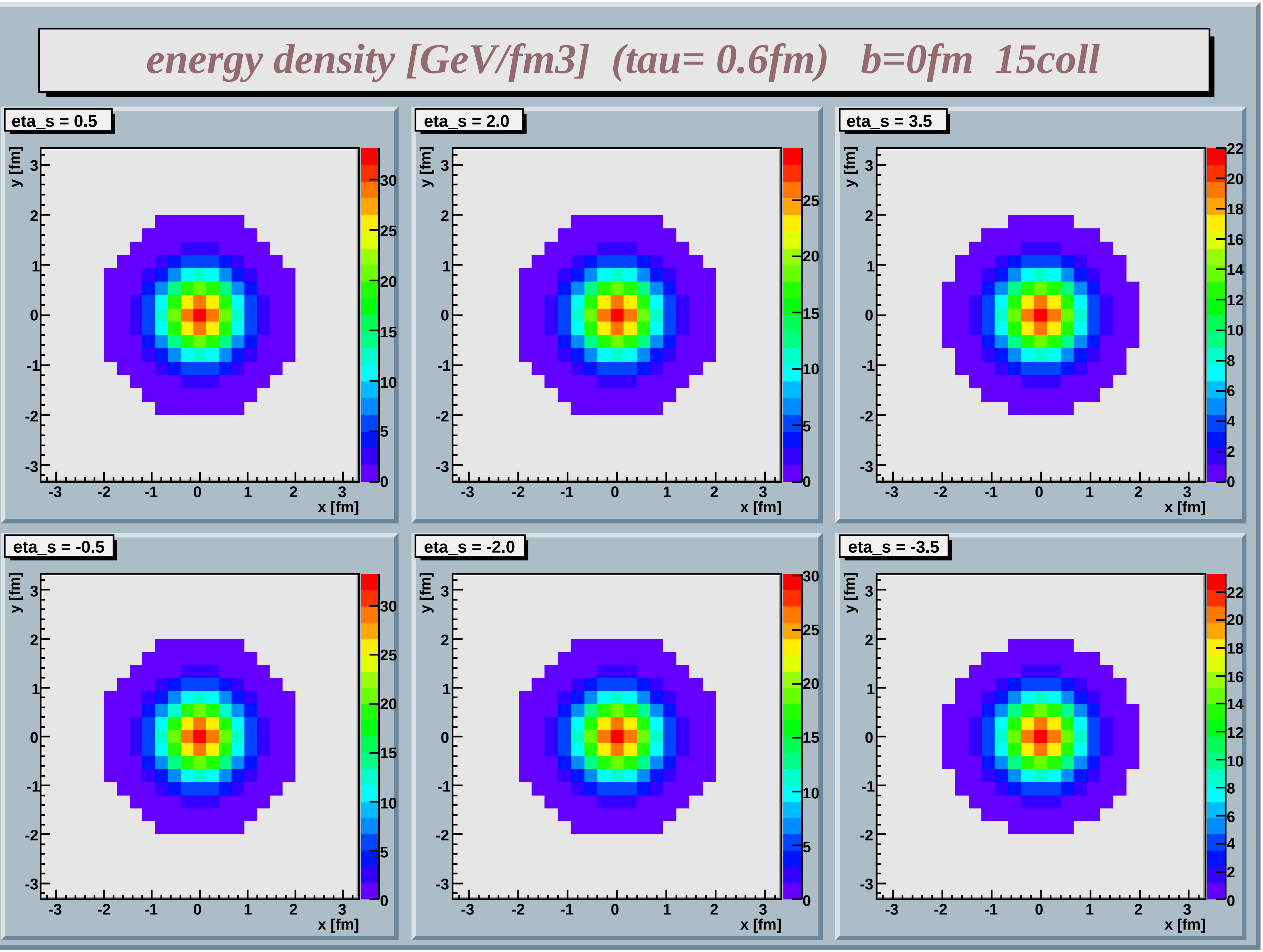
kaon excess

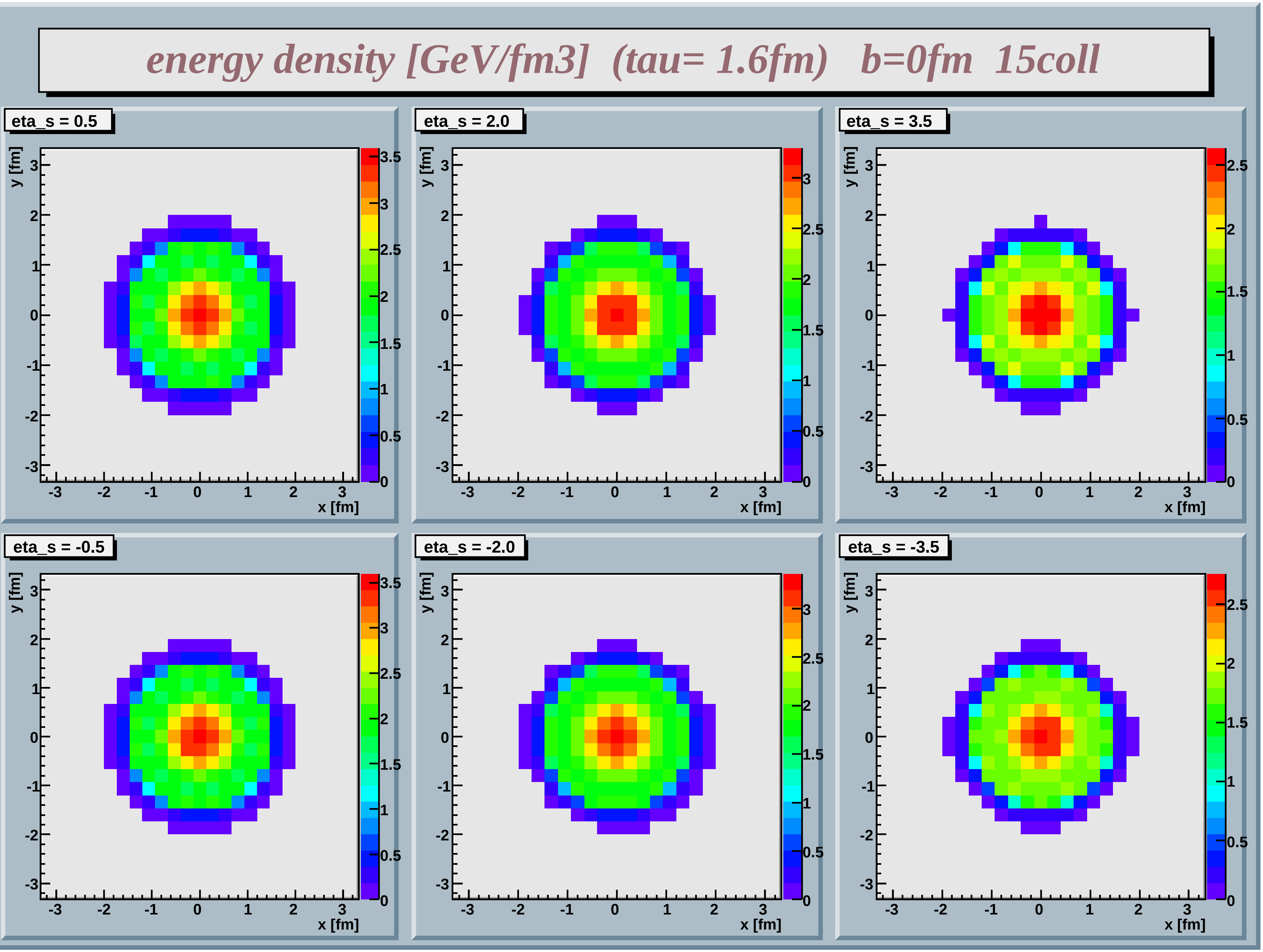
pt spectra of Λ and Ξ

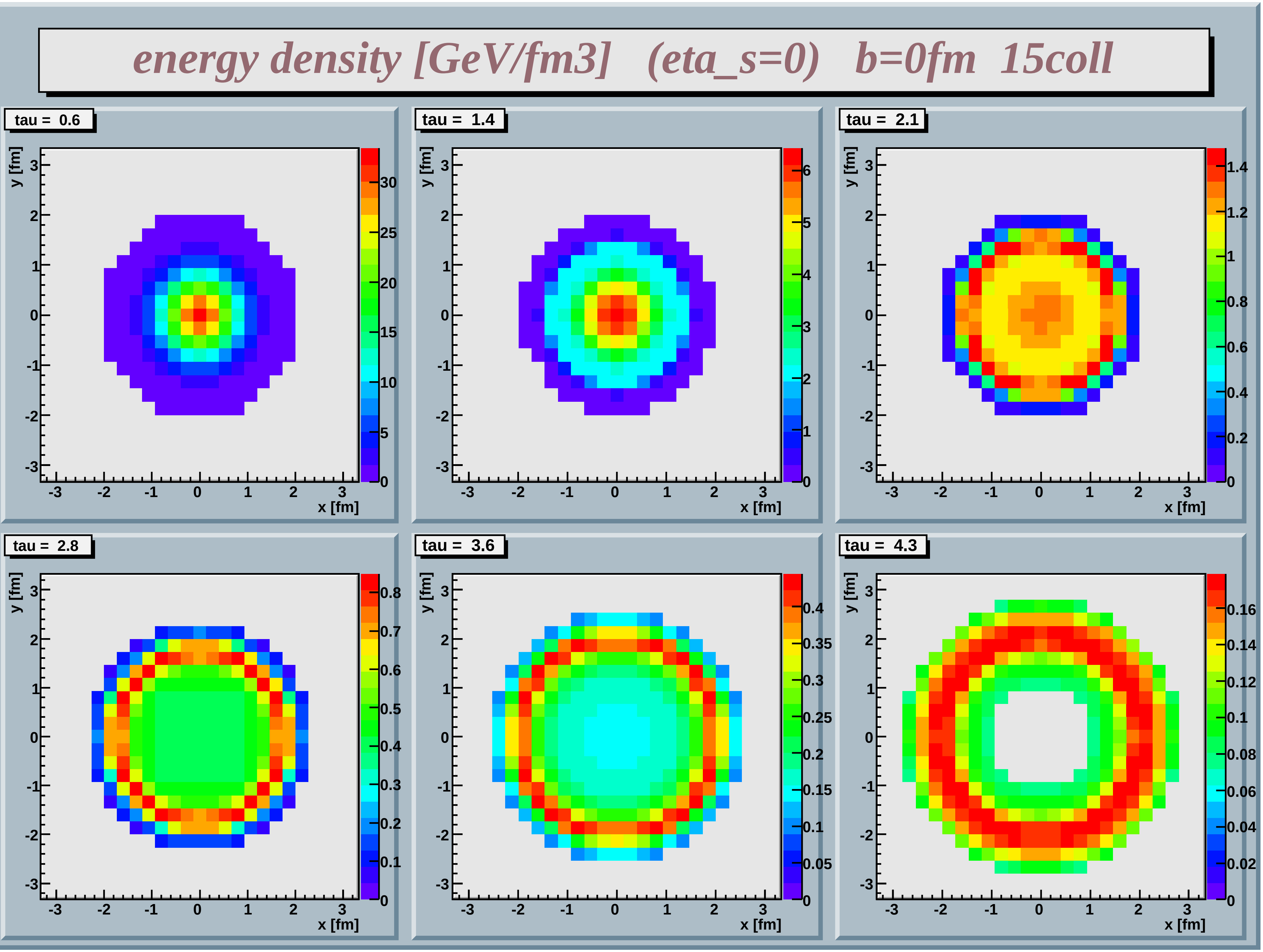


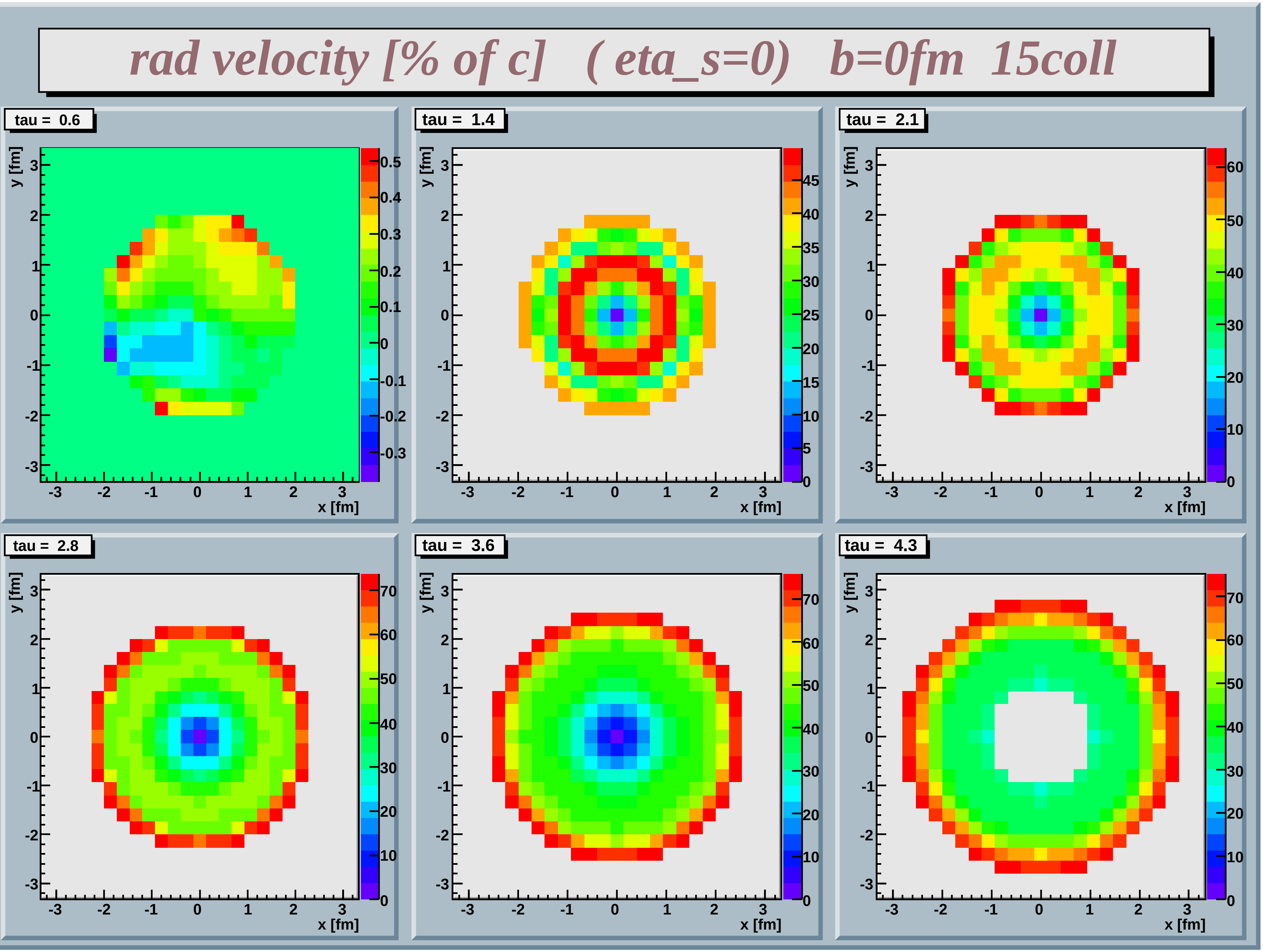
FO 158 MeV and elastic rescattering

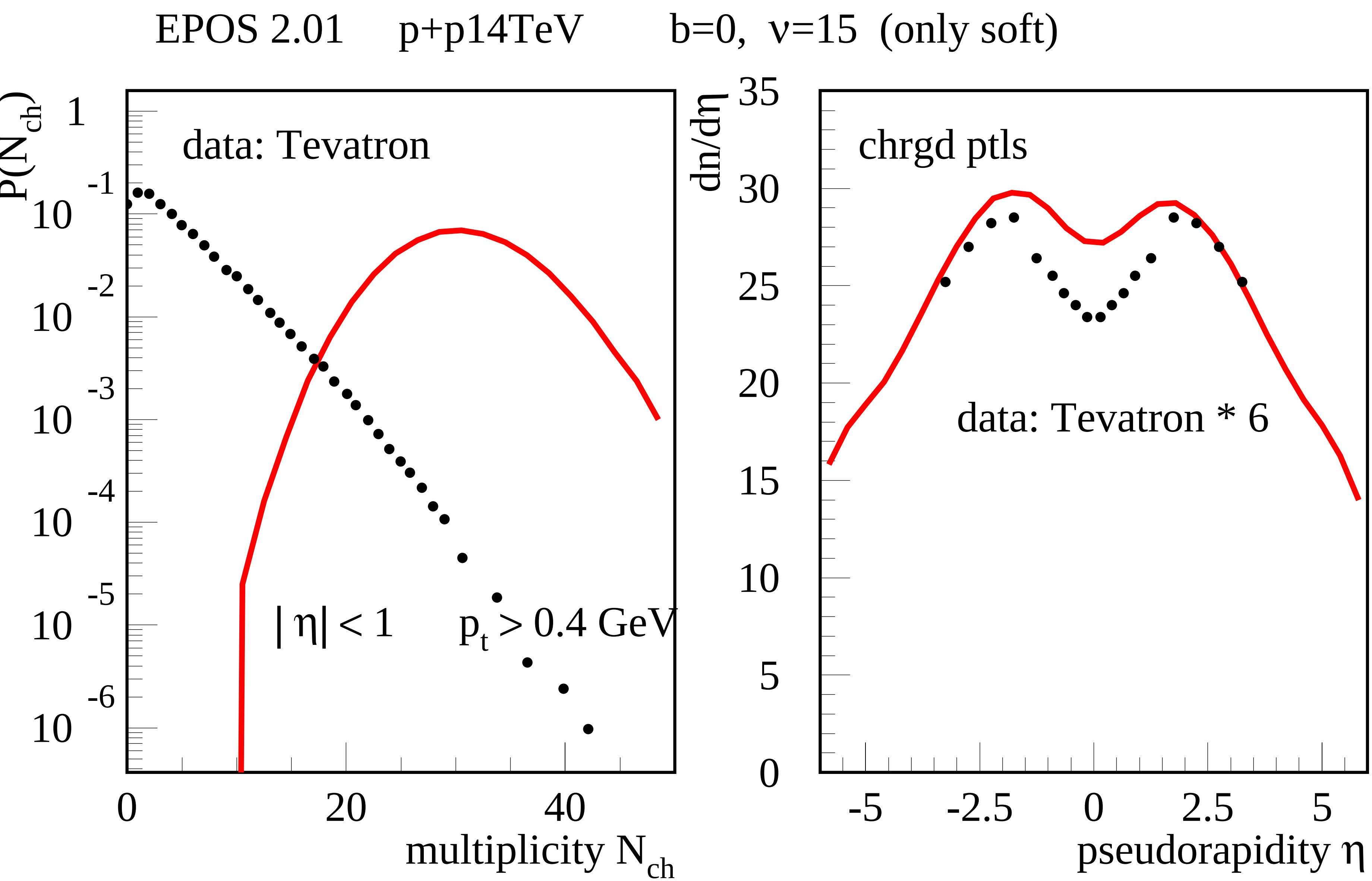
back to pp

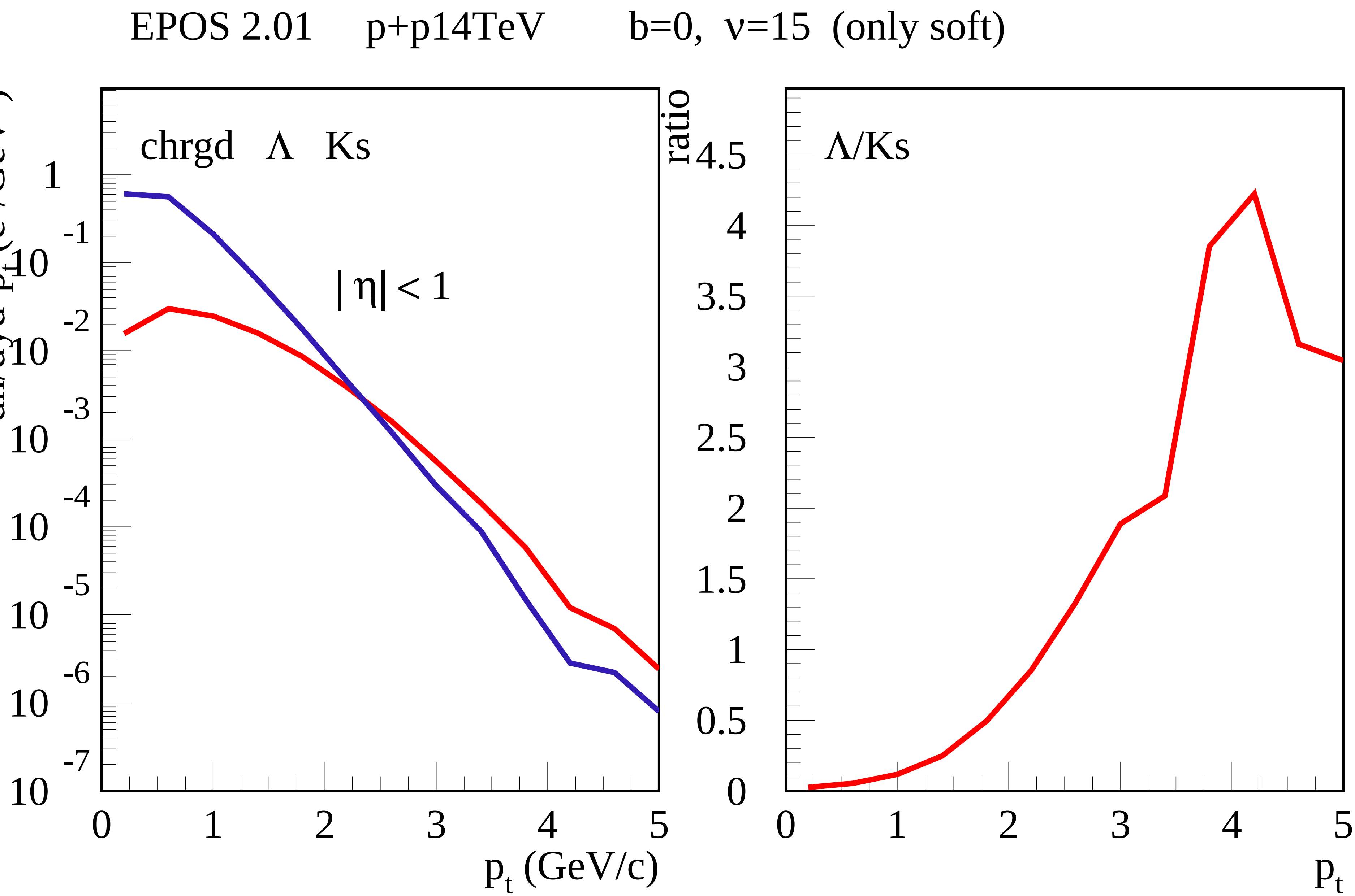

energy density [GeV/fm3] (tau= 0.6fm) b=0fm 15coll
eta_s = 0.5
eta_s = 2.0
eta_s = 3.5
eta_s = -0.5
eta_s = -2.0
eta_s = -3.5
x [fm]
y [fm]


energy density [GeV/fm3] (tau= 1.6fm) b=0fm 15coll
eta_s = 0.5
eta_s = 2.0
eta_s = 3.5
eta_s = -0.5
eta_s = -2.0
eta_s = -3.5
x [fm]
y [fm]

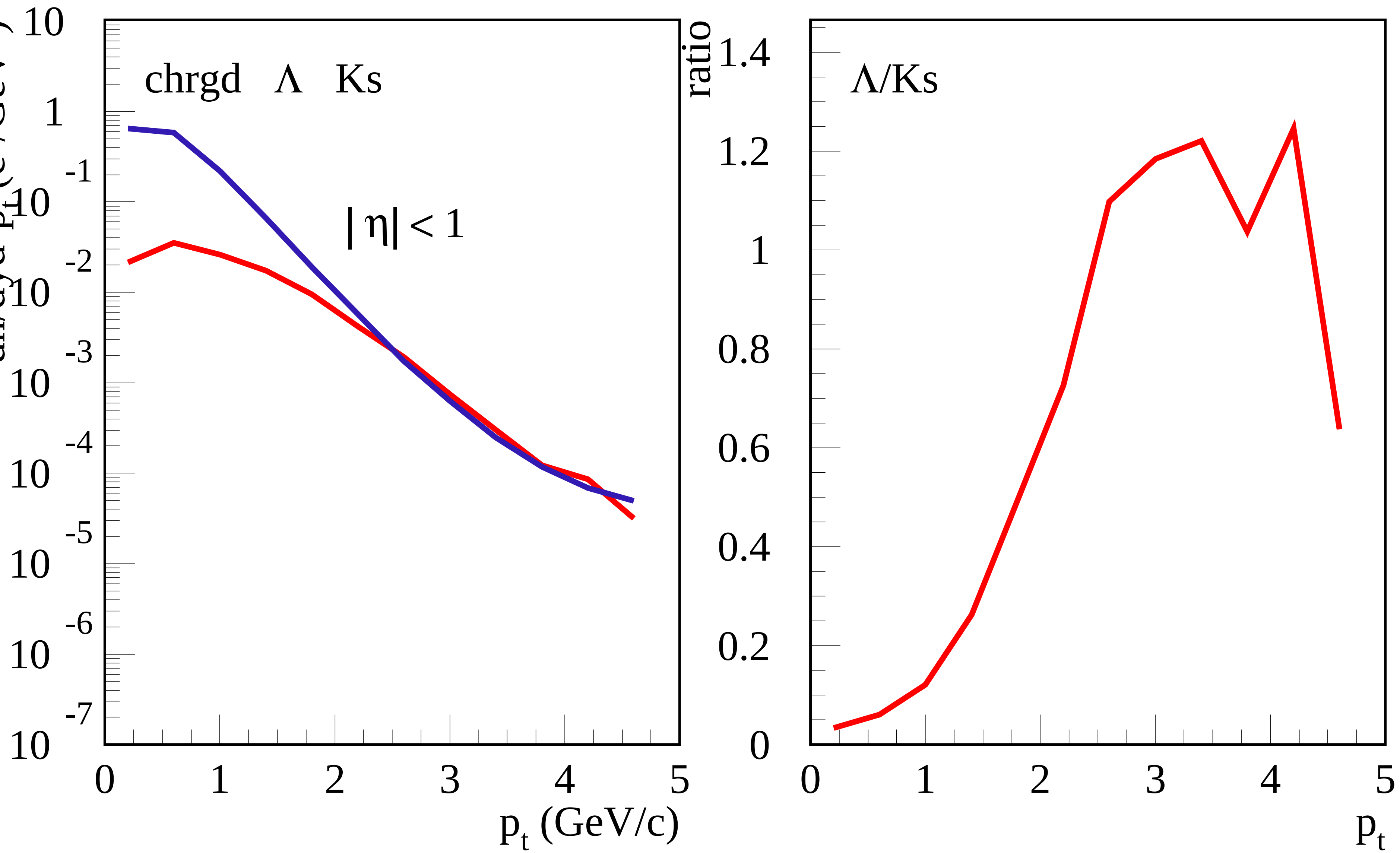

energy density [GeV/fm3] (eta_s=0) b=0fm 15coll
tau = 0.6
tau = 1.4
tau = 2.1
tau = 2.8
tau = 3.6
tau = 4.3
x [fm]
y [fm]


rad velocity [% of c] (eta_s=0) b=0fm 15coll
tau = 0.6
tau = 1.4
tau = 2.1
tau = 2.8
tau = 3.6
tau = 4.3
x [fm]
y [fm]


EPOS 2.01 p+p14TeV b=0, ν=15 (only soft)
P(N_ch)
data: Tevatron
|η| < 1
p_t > 0.4 GeV
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0
20
40
multiplicity N_ch
dn/dη
chrgd ptls
data: Tevatron * 6
35
30
25
20
15
10
5
0
-5
-2.5
2.5
pseudorapidity η

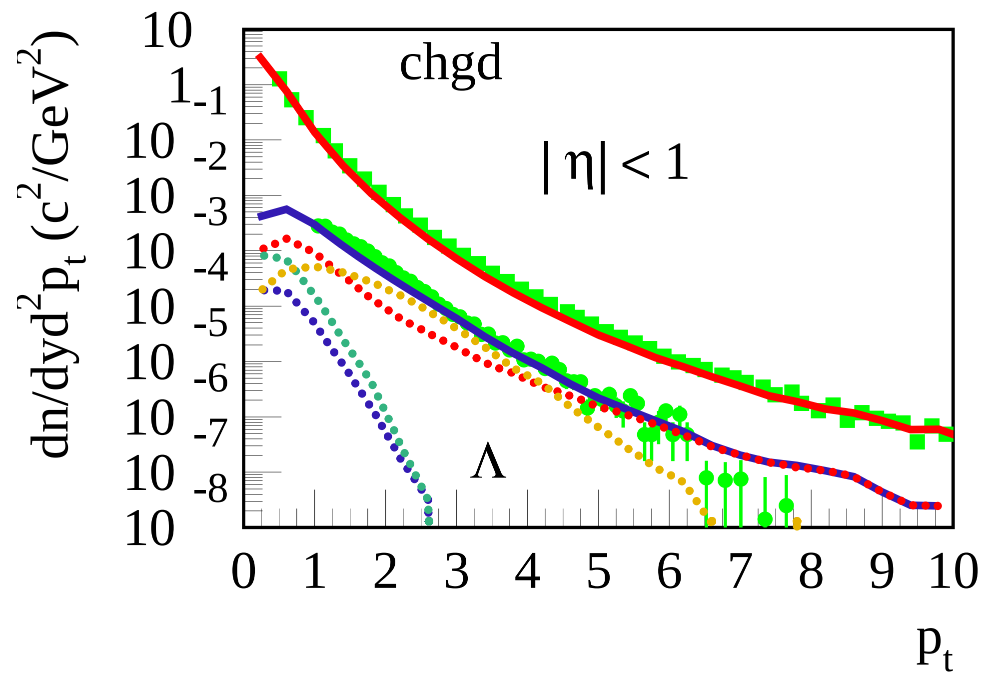

EPOS 2.01 p+p14TeV b=0, ν=15 (only soft)
chrgd Λ Ks
| η| < 1
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0 1 2 3 4 5
p_t (GeV/c)
ratio
Λ/Ks
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
p_t

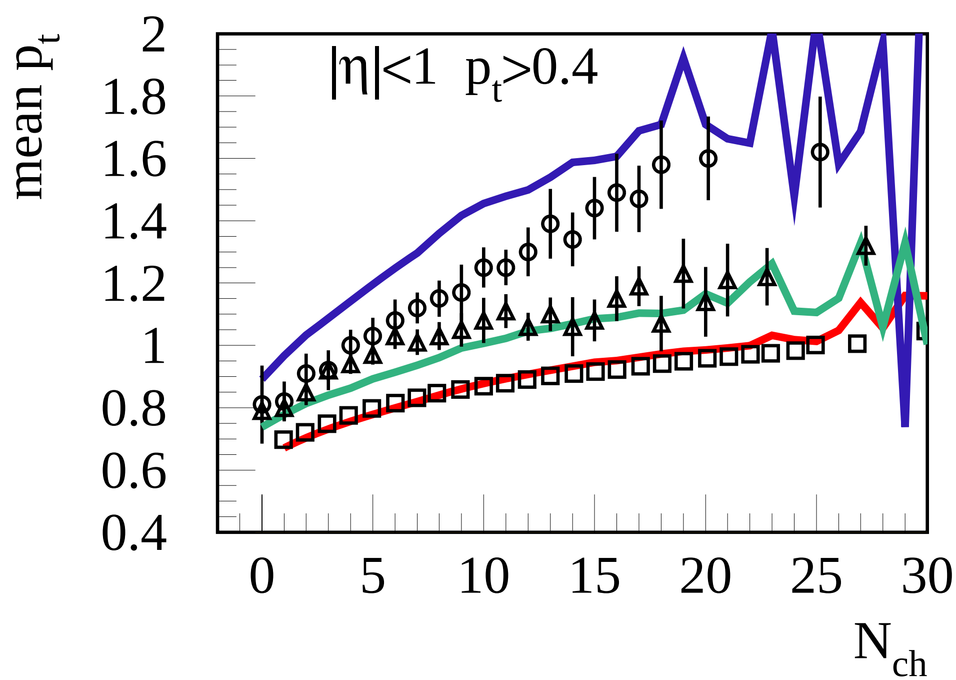
EPOS 2.01 p+p14TeV b=0, ν=15 (soft+hard)



Collective effects at Tevatron?

Charged particle and lambda pt spectra: different shapes (as in AA)





Tevatron 1.8 TeV

EPOS 1

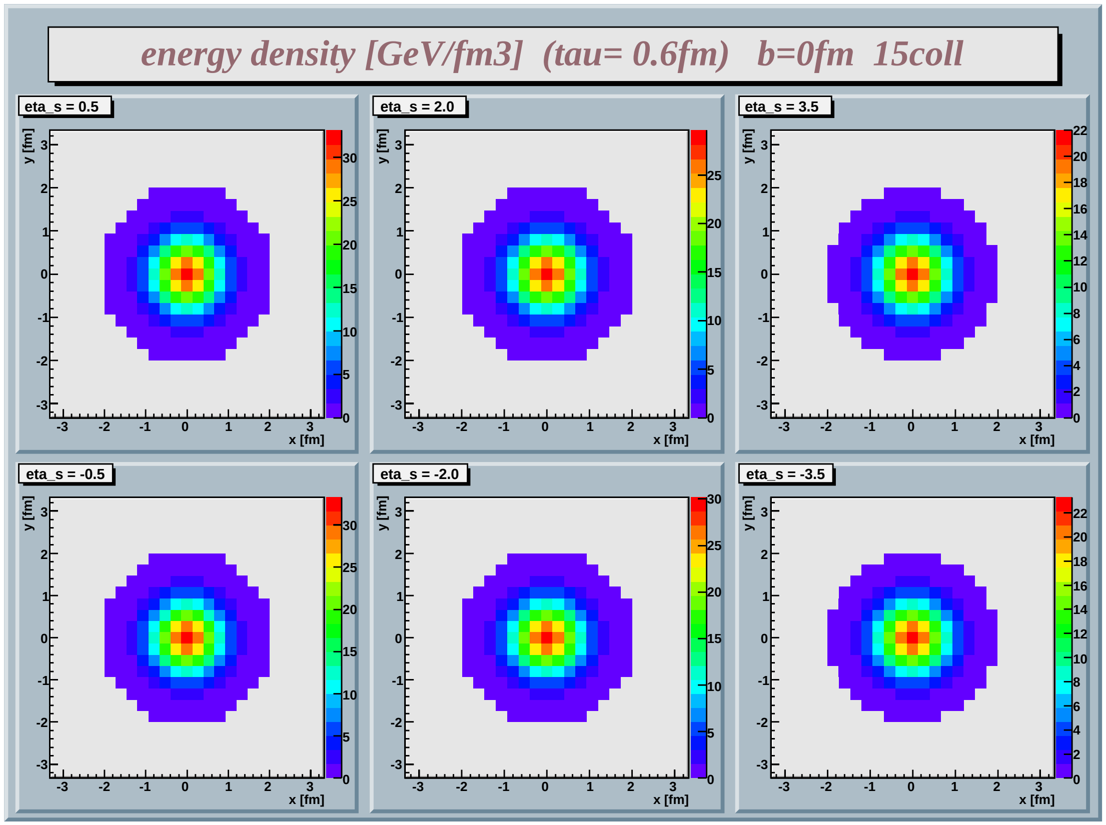
Increase of mean pt vs multiplicity of charged ptls, K_s, Λ (as in AA)

For pp & LHC, one should study the "centrality" dependence of observables:

- ▷ mean pt
- ▷ multi-strange baryon yields
- ▷ ratios of pt spectra
- ▷ jet fragmentation functions
- ▷ heavy quark production

Initial state effects (multiple scattering) and final state effects (flow, energy loss)

Also: multiple scattering events should exhibit long range y correlations coming from the η_s correlation of the initial flux tubes



study particle yields, spectra, ... at forward rapidity as a function of the backward multiplicity

This should clearly exhibit the flux tube structure

to summarize

- ▷ Core-corona procedure separates events into two classes: core and corona events
- ▷ Multiple scattering provides high energy density "core events"
- ▷ core events should expand collectively, decay statistically
- ▷ EPOS 2 features
  - flux-tube initial cond based on multiple scattering
  - core-corona procedure
  - three flavor cross-over EoS (X3F)
  - EbE treatment
  - hadronic FS cascade
  - full hadron set