EPOS 2 and LHC

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- **Two developments:**
  - Full EPOS: try to understand all pp and AA data above few 100 GeV, do things the best way possible :
    - CPU time is no issue!!
  - EPOS for CRs: simplified version, which is fast, but grasps the essential features of Full EPOS
- **This talk:**
  - Full EPOS, in particular “collective effects in pp@LHC”

Outline

- **Introduction**
- **The EPOS model**
- **Collective effects**
  - In AA : ridge@RHIC
  - In pp : ridge@LHC
- **Comparison to LHC**

Introduction

- One decade of RHIC experiments (heavy ion, pp, and dAu scattering,up to 200 GeV)

heavy ion collisions produce matter which expands as an almost ideal fluid

- mainly because azimuthal anisotropies can be explained on the basis of ideal hydrodynamics (mass splitting etc)

LHC pp results: first signs for collective behavior as well ...

Approach (1)

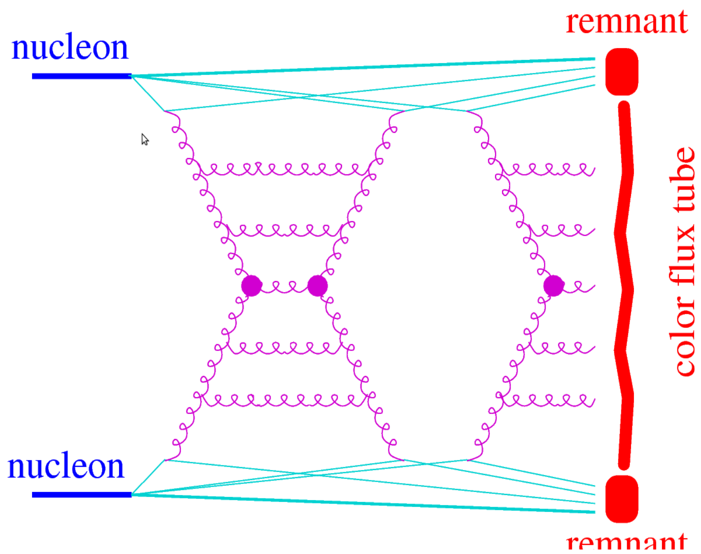
- **pp@LHC treated as AuAu@RHIC:**
  - Multiple scattering approach EPOS (marriage of pQCD and Gribov-Regge) :
    - initial condition for a hydrodynamic evolution if the energy density is high enough
  - event-by-event procedure
    - taking into the account the irregular space structure of single events :
      - ridge structures in two-particle correlations
  - core-corona separation :
    - only a part of the matter thermalizes;
  - 3+1 D hydro evolution
    - conservation of baryon number, strangeness, and electric charge

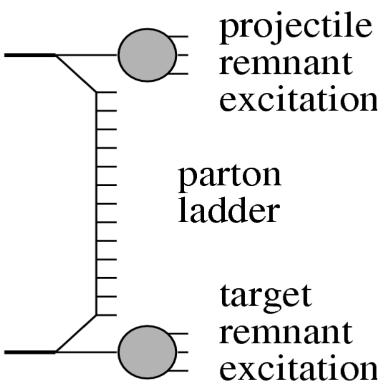
Approach (2)

- **pp@LHC treated as AuAu@RHIC:**
  - parton-hadron transition
    - realistic equation-of-state, compatible with lattice gauge results
    - cross-over transition from the hadronic to the plasma phase
  - hadronization,
    - Cooper-Frye, using complete hadron table
    - at an early stage (166 MeV, in the transition region)
    - with subsequent hadronic cascade procedure (UrQMD)

- **details see:**
  - arXiv:1004.0805, arXiv:1010.0400, arXiv:1011.0375 (ridge in pp)

The EPOS Model





EPOS* is a parton model, with many binary parton-parton interactions, each one creating a parton ladder.

- Energy-sharing : for cross section calculation AND particle production
- Parton Multiple scattering
- Outshell remnants
- Screening and shadowing via unitarization and splitting
- Collective effects for dense systems

EPOS can be used for minimum bias hadronic interaction generation (h-p to A-B) from 100 GeV (lab) to 1000 TeV (cms) : used for air shower !

EPOS designed to be used for particle physics experiment analysis (SPS, RHIC, LHC)

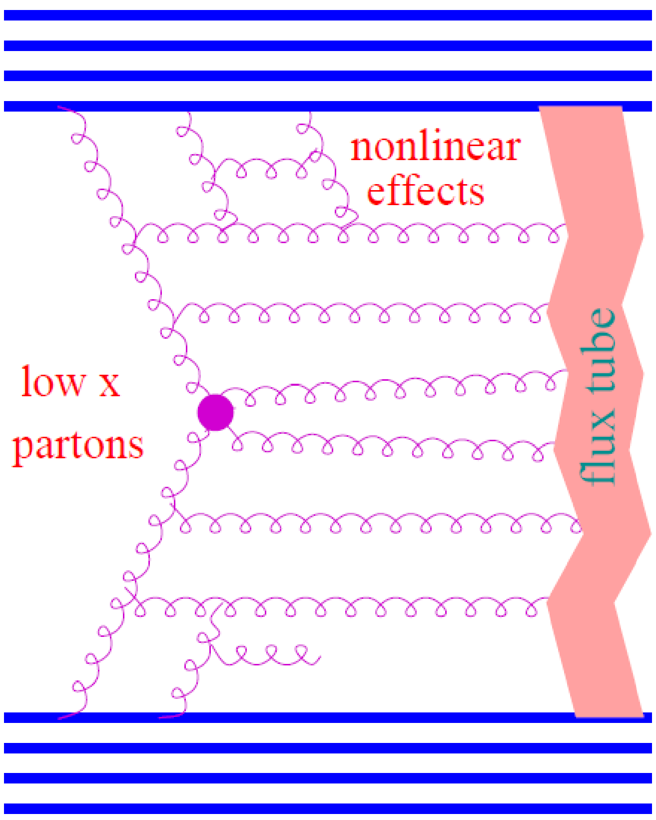
Multiple Scattering

- **Quantum mechanical treatment of multiple scattering quite involved!**
  - same energy sharing between the parallel scatterings is taken into account for cross section and particle production.

- **Details:**
  - Talk at the CORSIKA school
  - **Parton-based Gribov-Regge Theory**, H. J. Drescher, M. Hladik, S. Ostapchenko, T.Pierog, and K. Werner, Phys. Rept. 350 (2001) 93-289;
    - Cutting rule techniques
      - partial cross sections for exclusive event classes
    - simulation with the help of Markov chain techniques.

Elementary scatterings - flux tubes

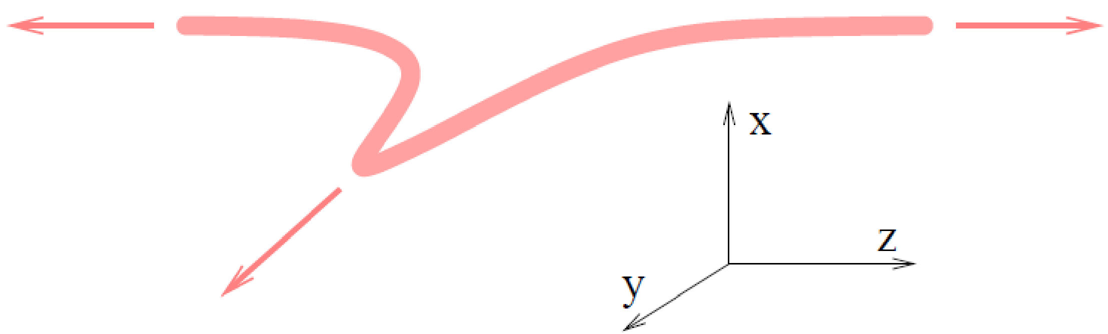
- **AA - even pp:**
  - many elementary collisions happening in parallel
  - elementary scattering = "parton ladder"



- Parton evolutions from the projectile and the target side towards the center (small x)
- Evolution equation
  - DGLAP
- Parton ladder = quasilongitudinal color field ("flux tube")
  - relativistic string
- Intermediate gluons
  - kink singularities in relativistic strings
- Fragmentation : production of quark-antiquark pairs
  - fragments – identified with hadrons

Kinky Strings

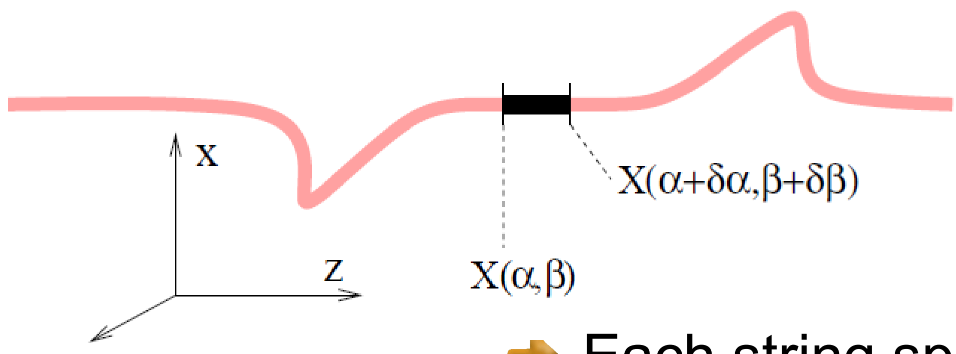
- **mainly longitudinal object** (here parallel to the z-axis)
  - ➔ due to the kinks there are string pieces moving transversely (in y-direction in the picture).

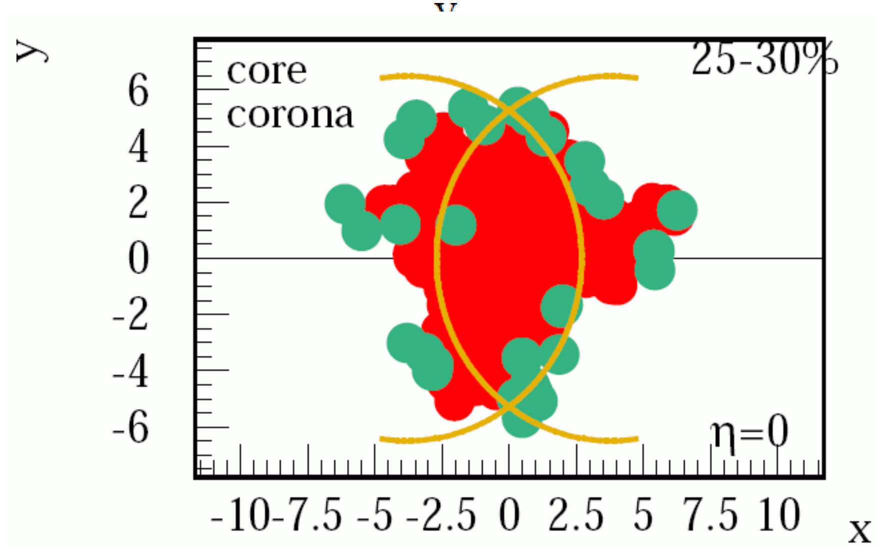


  - ➔ But despite these kinks, most of the string carries only little transverse momentum!

High Density Core Formation

- **Heavy ion collisions or very high energy proton-proton scattering:**
  - the usual procedure has to be modified, since the density of strings will be so high that they cannot possibly decay independently : **core**





- Each string splitted into a sequence of string segments, corresponding to widths δα and δβ in the string parameter space
- If energy density from segments high enough
  - segments fused into core
- If low density (corona)
  - segments remain hadrons

Energy Density

- **Initial conditions at proper time $\tau=\tau_0$**
  - Energy tensor :

$$T^{\mu\nu}(x) = \sum_i \frac{\delta p_i^\mu \delta p_i^\nu}{\delta p_i^0} g(x - x_i), \quad \delta p = \left\{ \frac{\partial X(\alpha,\beta)}{\partial \beta}\delta\alpha + \frac{\partial X(\alpha,\beta)}{\partial \alpha}\delta\beta \right\}$$

  - Flavor flow :

$$N_q^\mu(x) = \sum_i \frac{\delta p_i^\mu}{\delta p_i^0} q_i \, g(x - x_i), \quad q \in \{u, d, s\}$$

- **Evolution according to the equations of ideal hydrodynamics:**

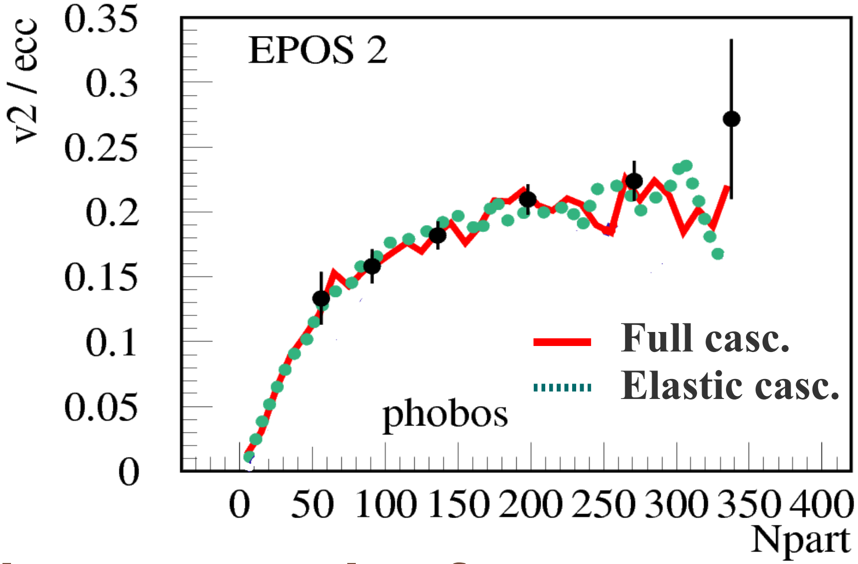
$$\partial_\mu T^{\mu\nu} = 0, \quad \text{using } T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$$

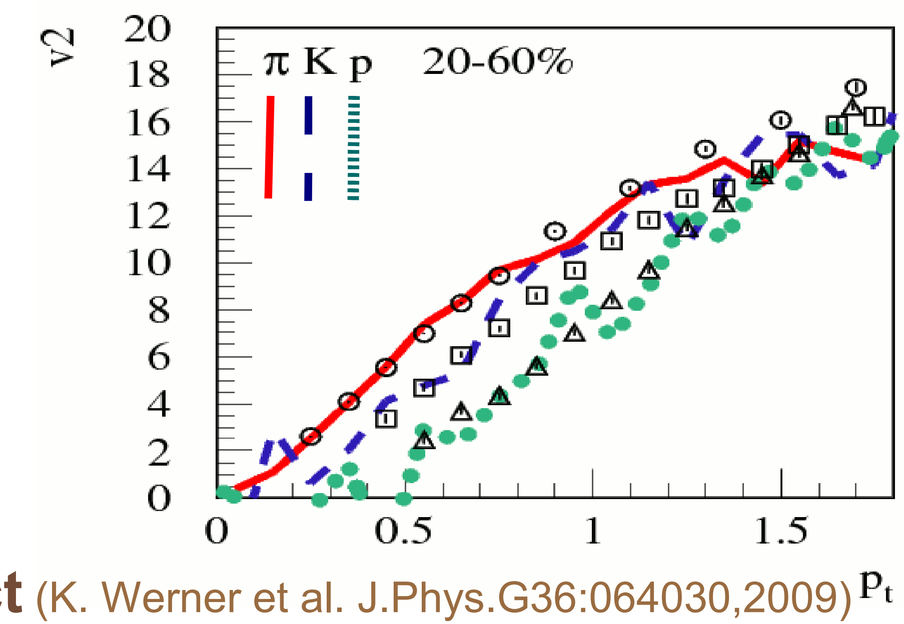
$$\partial N_k^\mu = 0, \quad N_k^\mu = n_k u^\mu,$$

with $k = B, S, Q$ referring to respectively baryon number, strangeness, and electric charge.

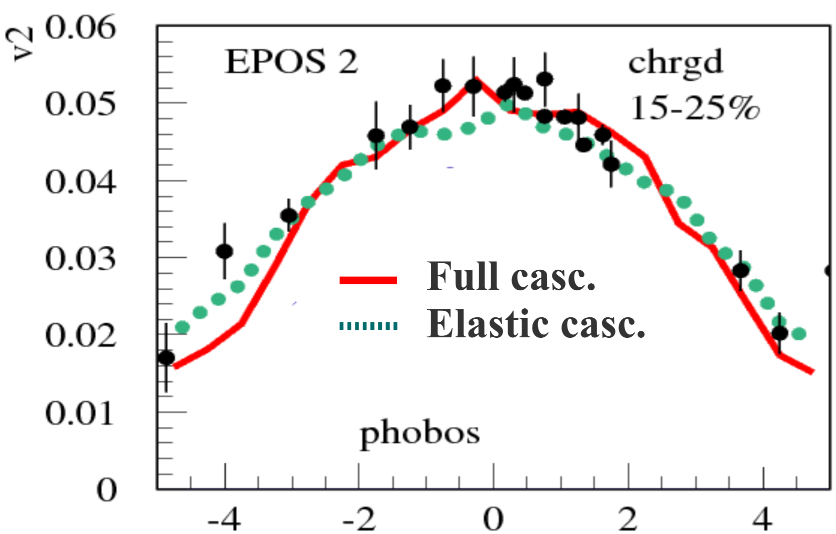
Check with Heavy Ions : AuAu@RHIC

➜ Early freeze-out (166MeV) + hadr. cascade





Important role of core-corona effect (K. Werner et al. J.Phys.G36:064030,2009)

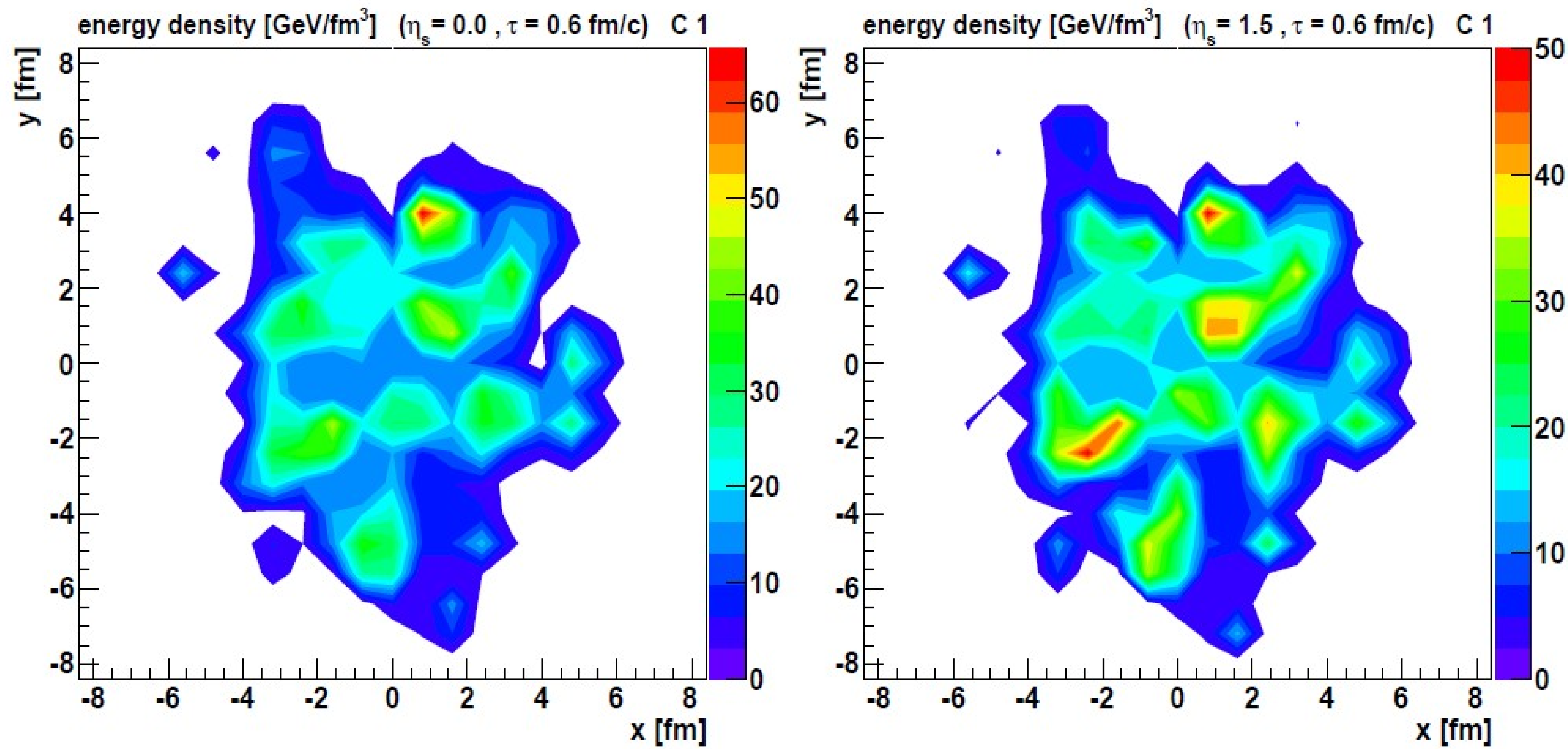


- **After checking successfully hundreds of particle spectra in AuAu**

  ➜ Event-by-event analysis

Event-by-Event Energy Density : AuAu

- Bumpy structure of energy density in transverse plane, but translational invariance
  - pseudorapidity extension of flux tubes



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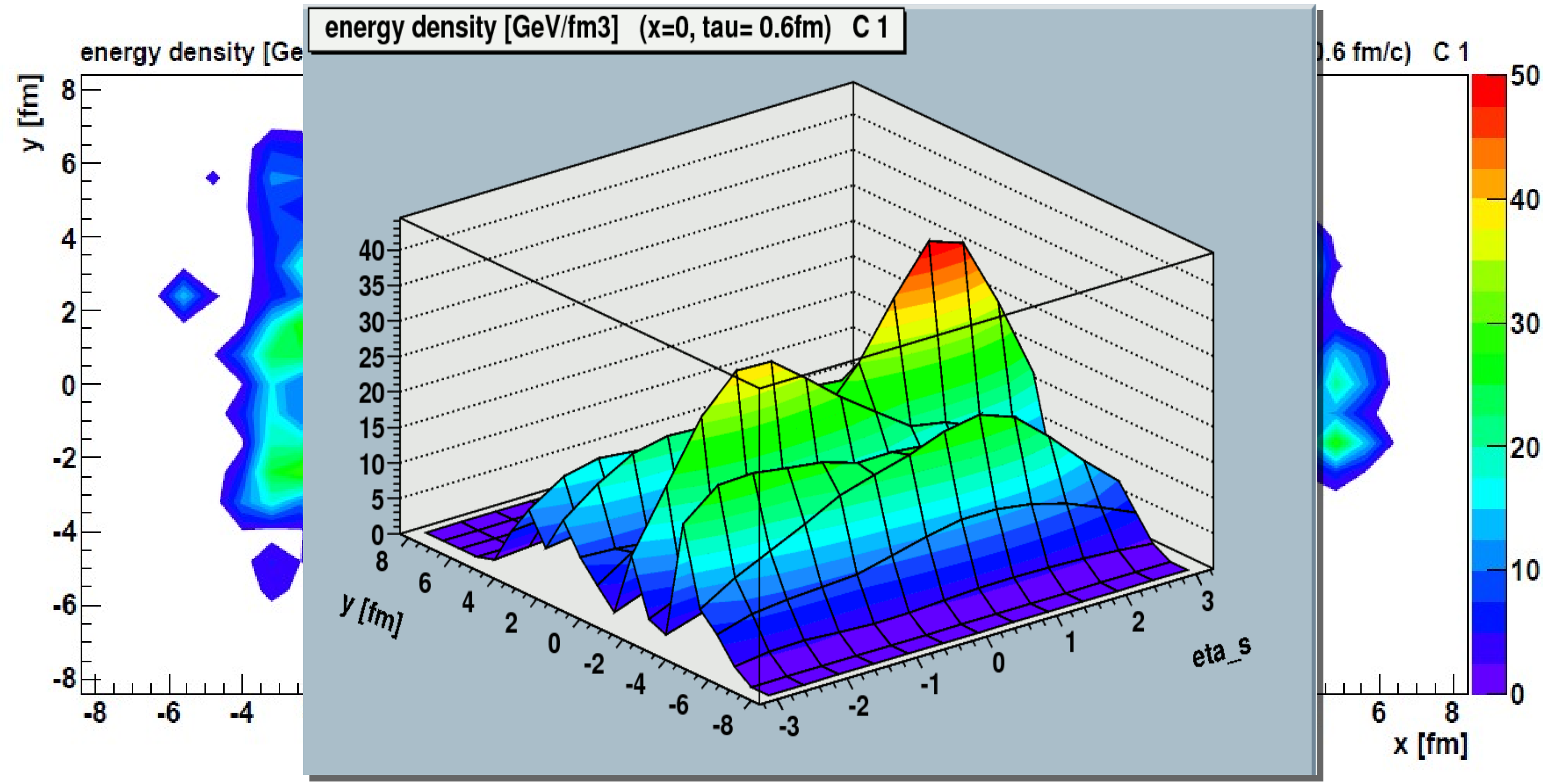
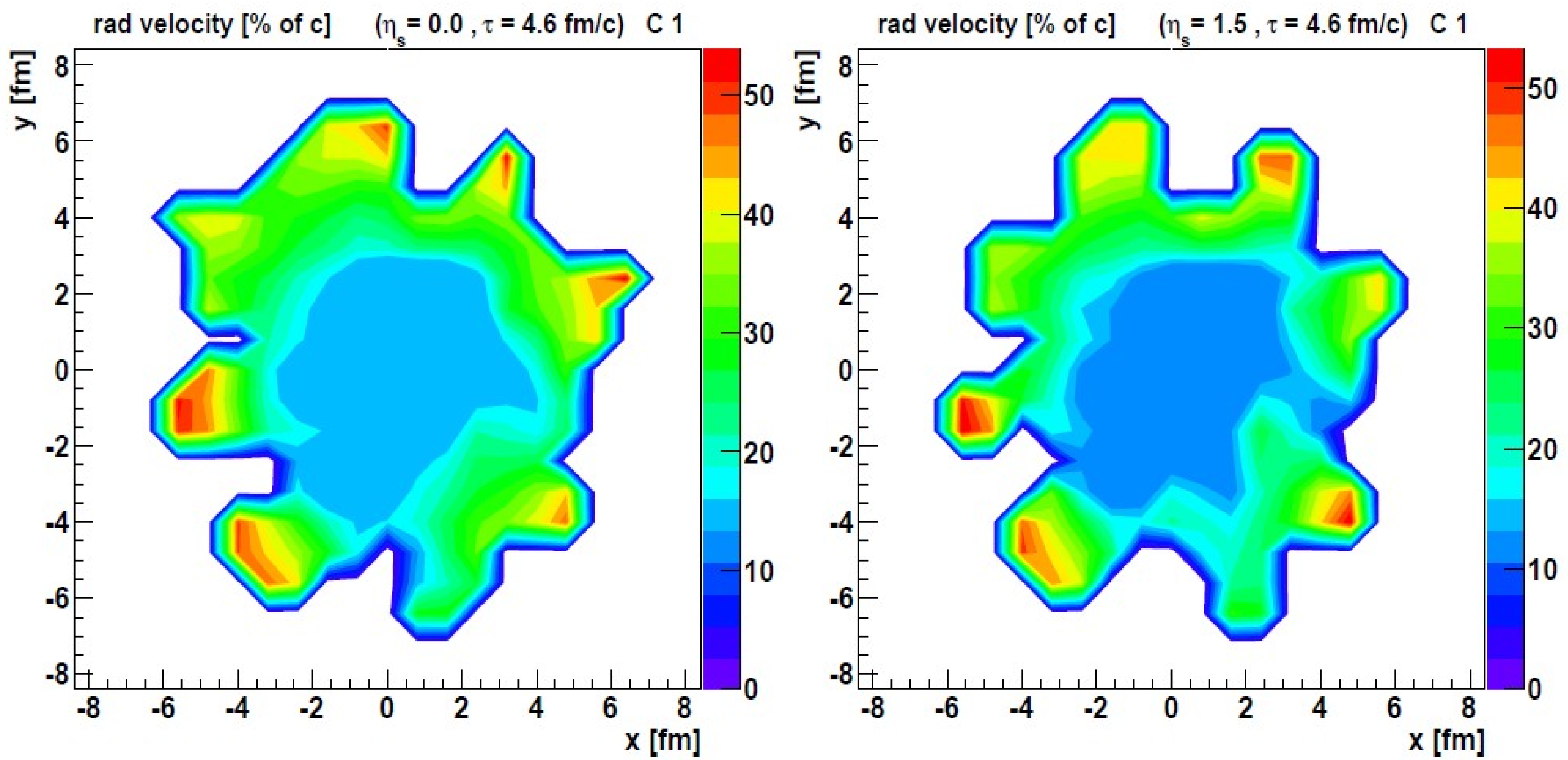


Event-by-Event Radial Flow : AuAu

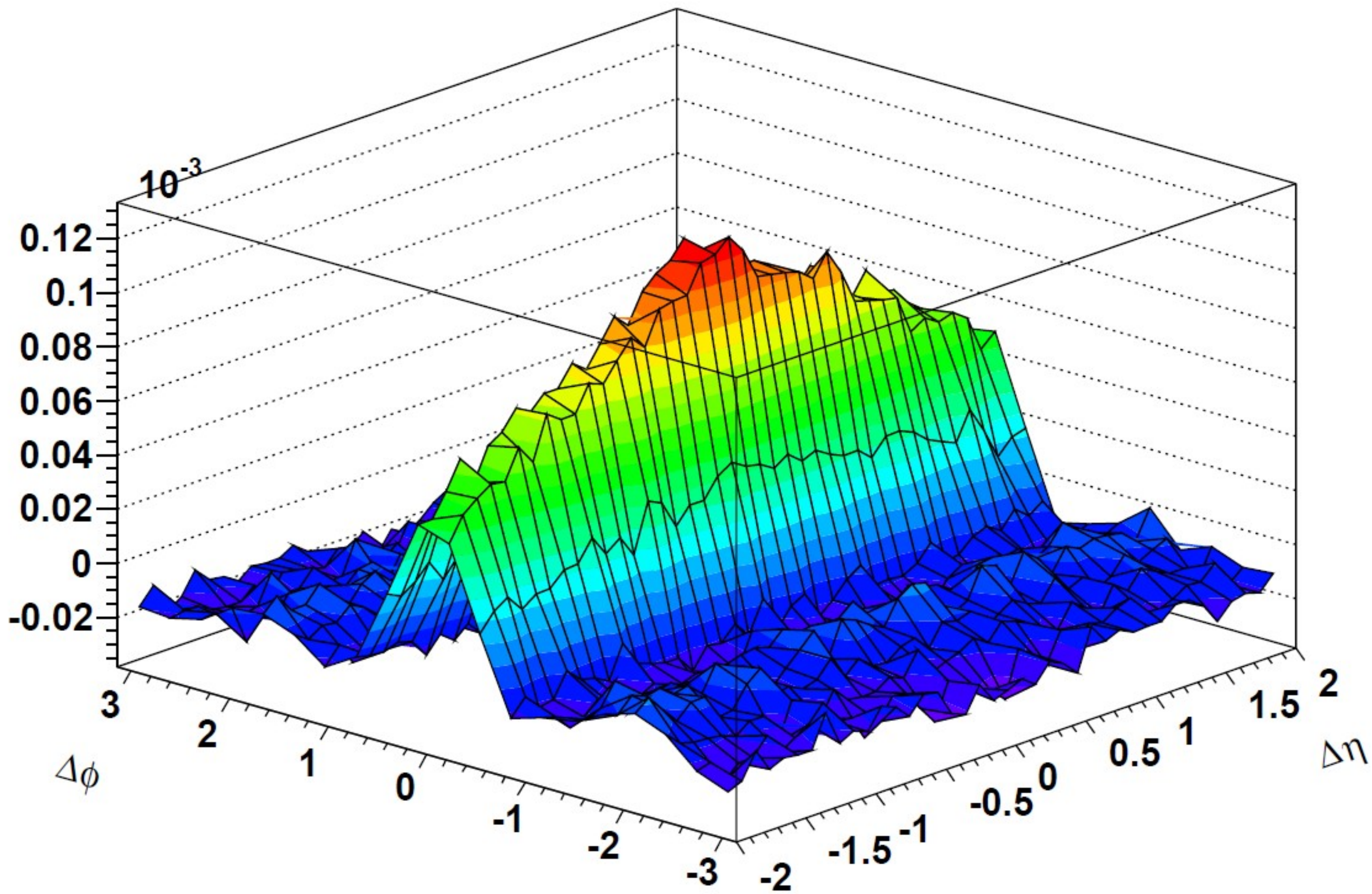
- **Leads to translational invariance of transverse flows**



➔ give the same collective push to particles produced at different values of η_s at the same azimuthal angle

AuAu : Di-hadron correlation

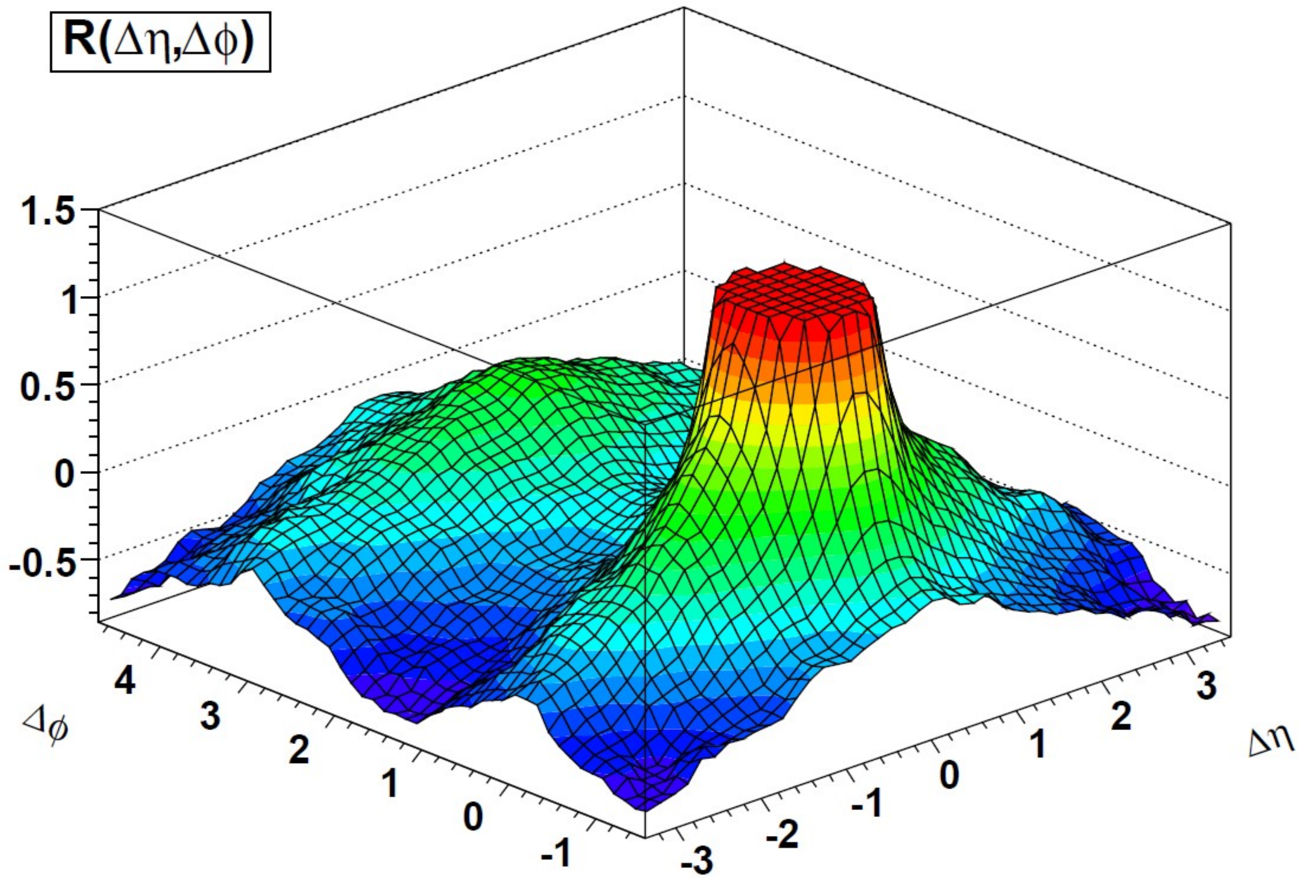
- ridge-structure in the dihadron correlation dN/dΔηdΔφ for free



AuAu 0-10%, $3 < p_t^{\mathrm{trig}} < 4\,\mathrm{GeV/c}$ $2 < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trig}}$

pp@7 TeV : Di-hadron correlation

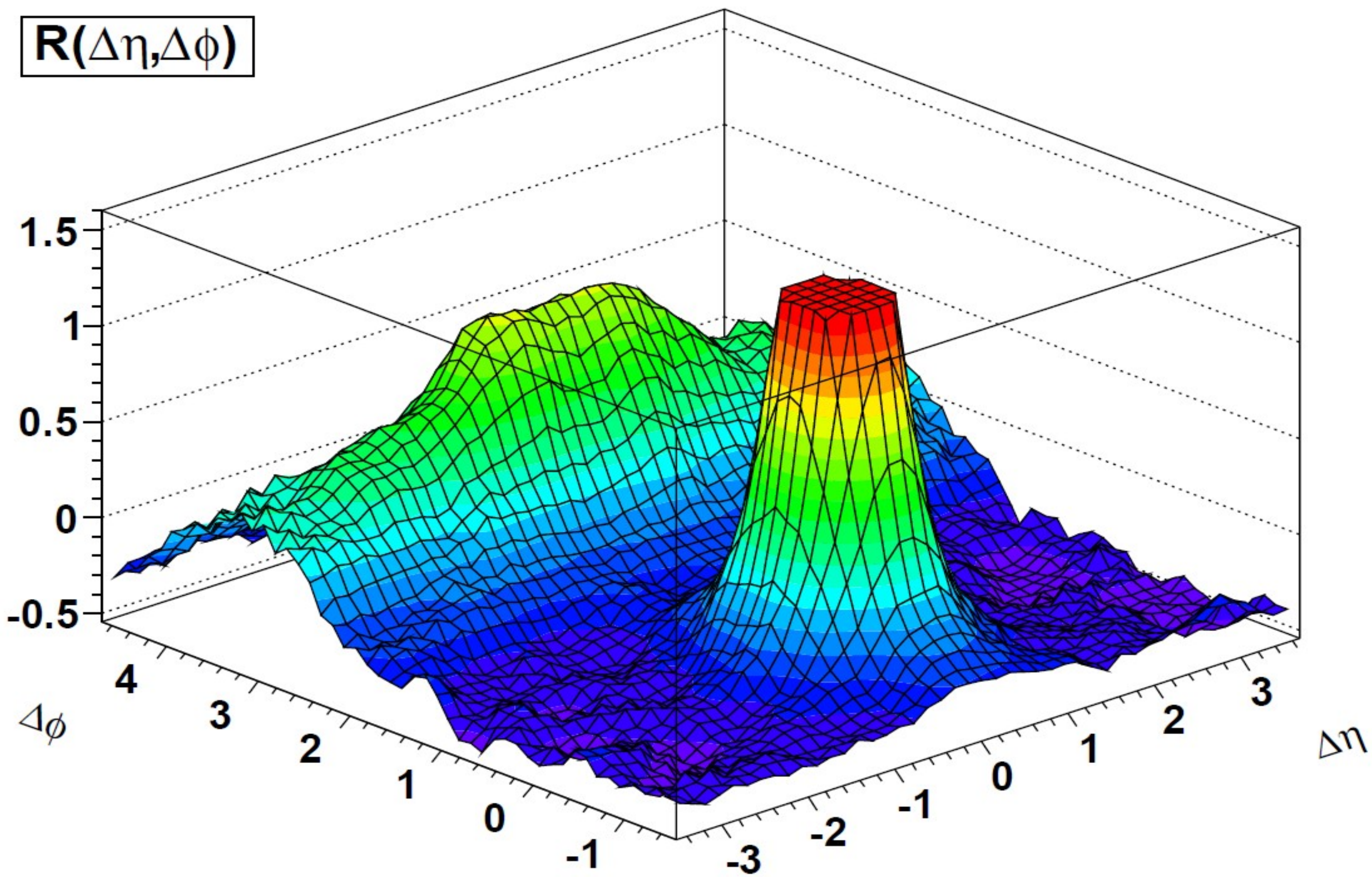
- Our calculation provides a similar ridge structure in pp@LHC using particles with 1 < pt < 3GeV/c, for high multiplicity events



close in form and magnitude compared to the CMS result
(5.3 times mean multipl., compared to 7 in CMS)

pp@7 TeV : no Hydro

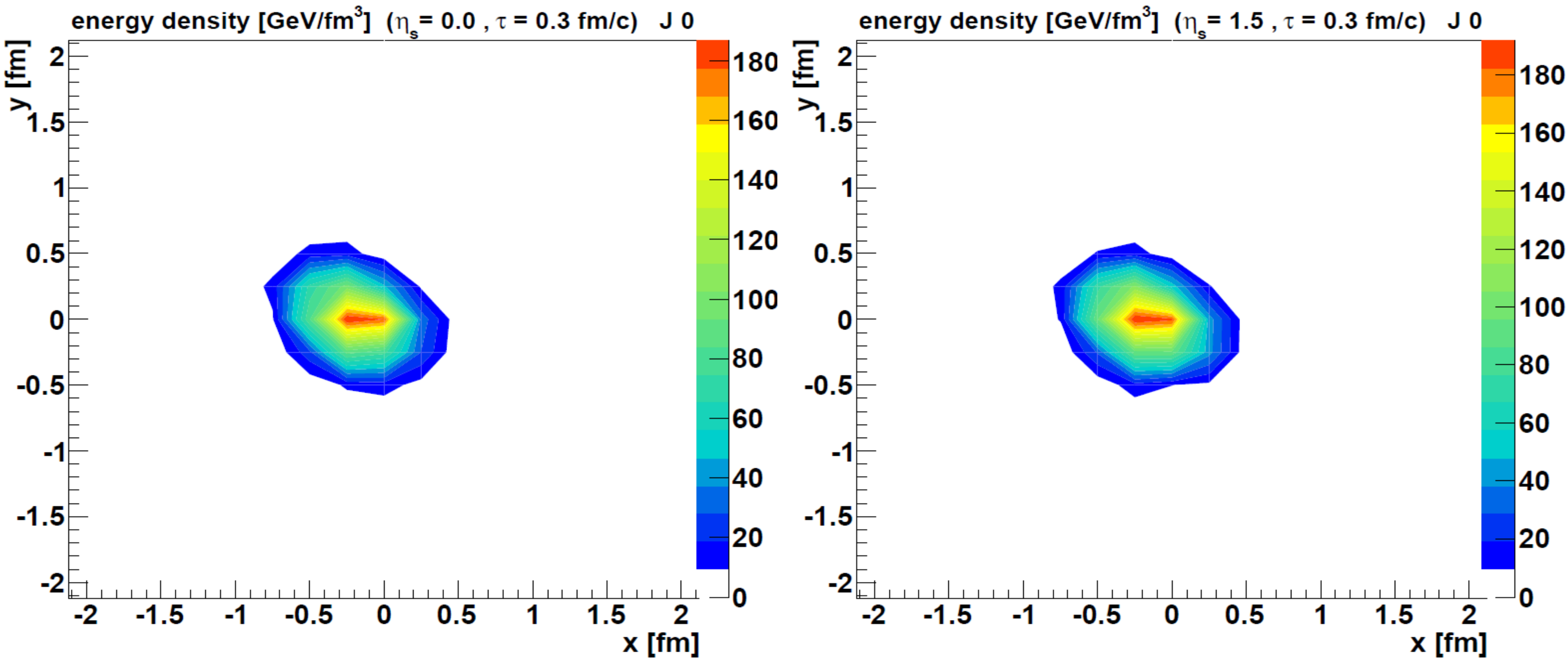
- Calculation without hydro => NO RIDGE



hydrodynamical evolution “makes” the effect! HOW?

Event-by-Event Energy Density : pp

- Random azimuthal asymmetries of initial energy density but translationally invariant
  - pseudorapidity extension of flux tubes



Initial energy density in the transverse plane for two different η_s

Event-by-Event Energy Density : pp

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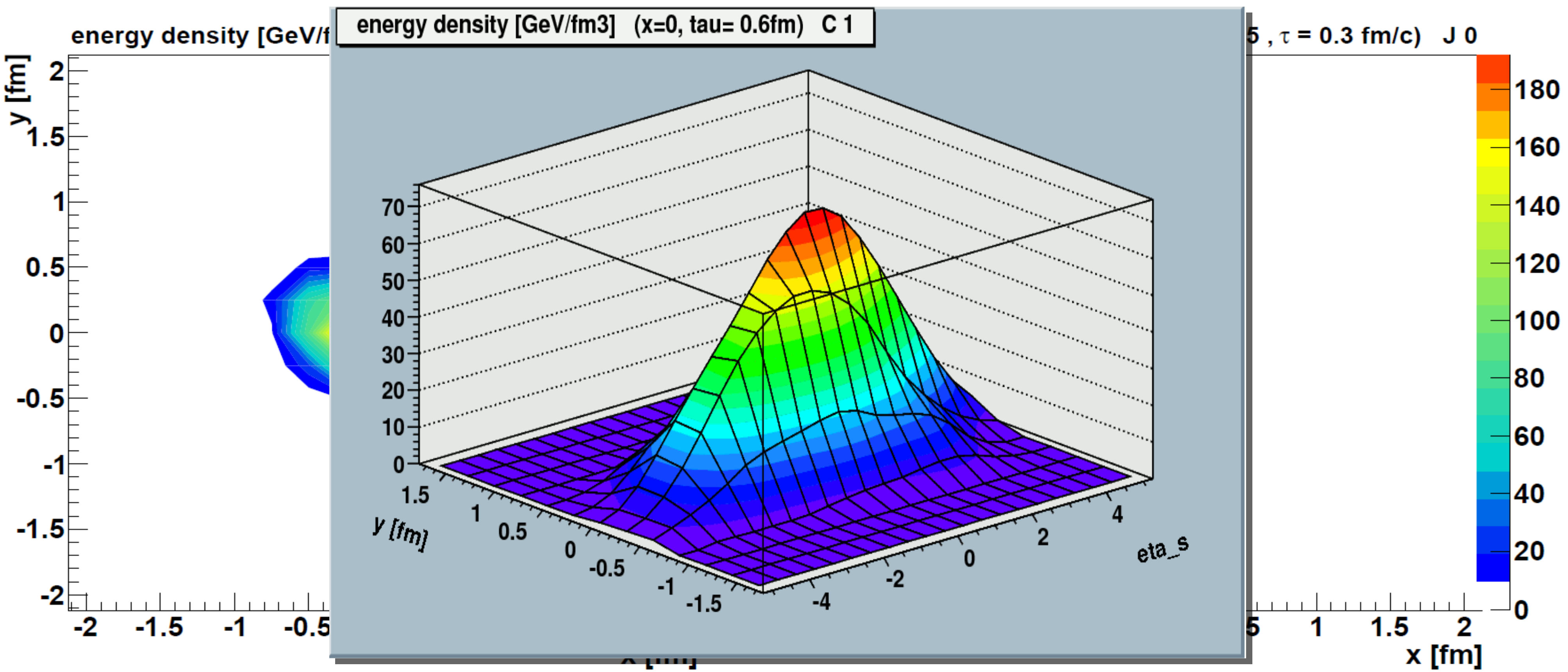
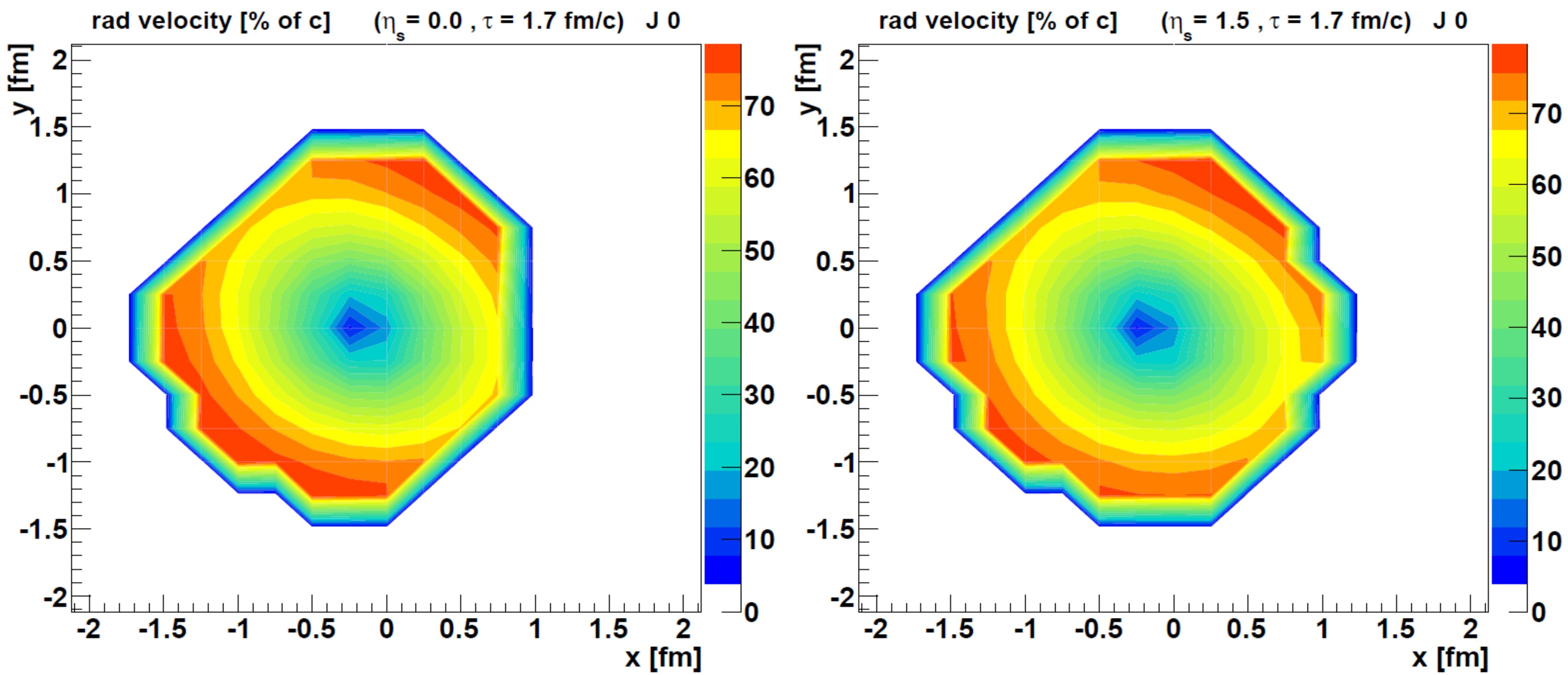


Initial energy density in the transverse plane for two different η_s

Event-by-Event Radial Flow : pp

- Elliptical initial shapes leads to asymmetric flows as well translationally invariant (in η_s)



Radial flow velocity at a later time in the transverse plane

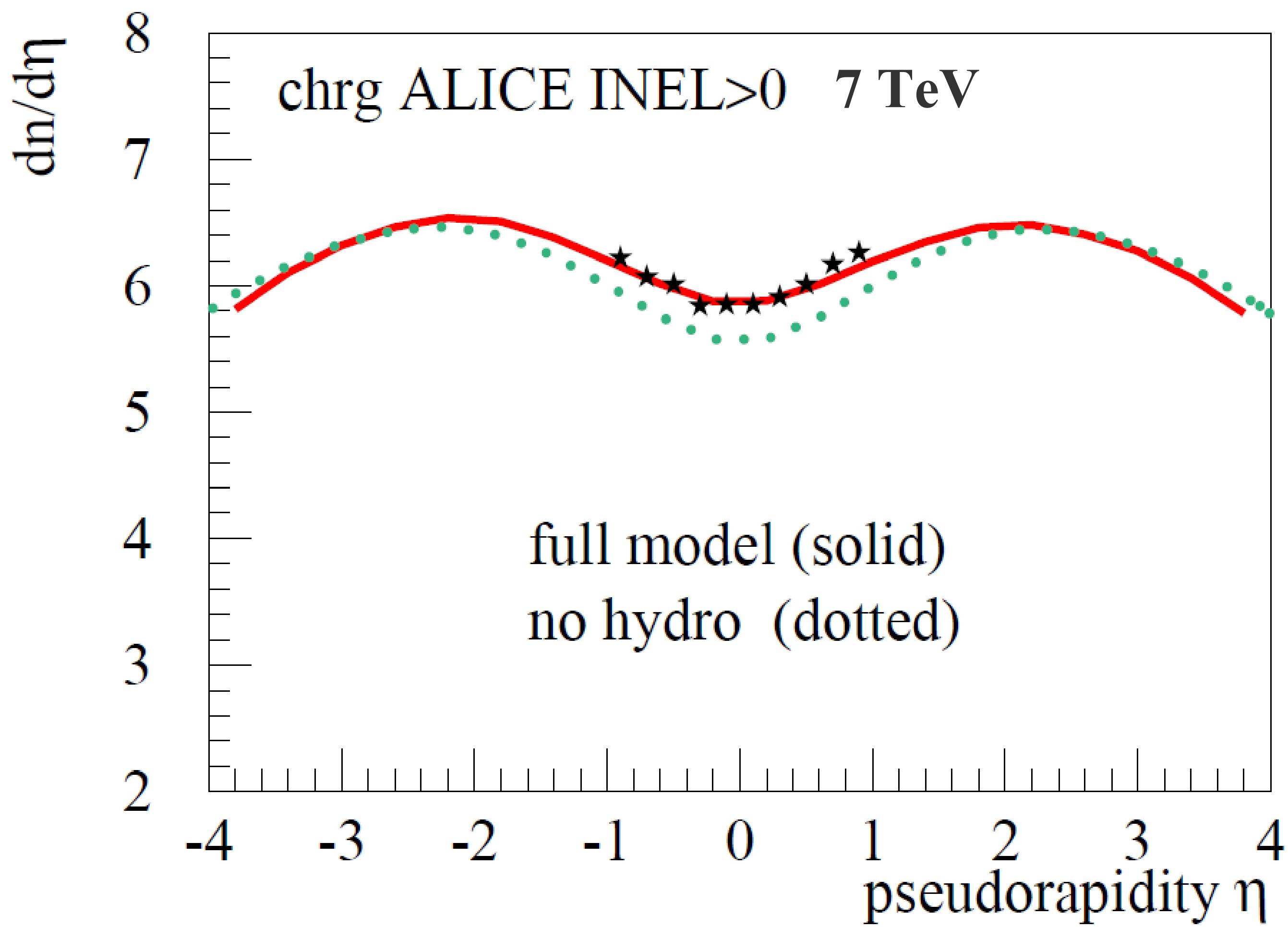
Summary Ridge in pp

- **Translational invariance of the flow asymmetry means:**
  - The system gives an increased collective push
  - to particles produced at different values of ηs
  - at the same azimuthal angle corresponding to a flow maximum

→ ΔηΔφ correlation

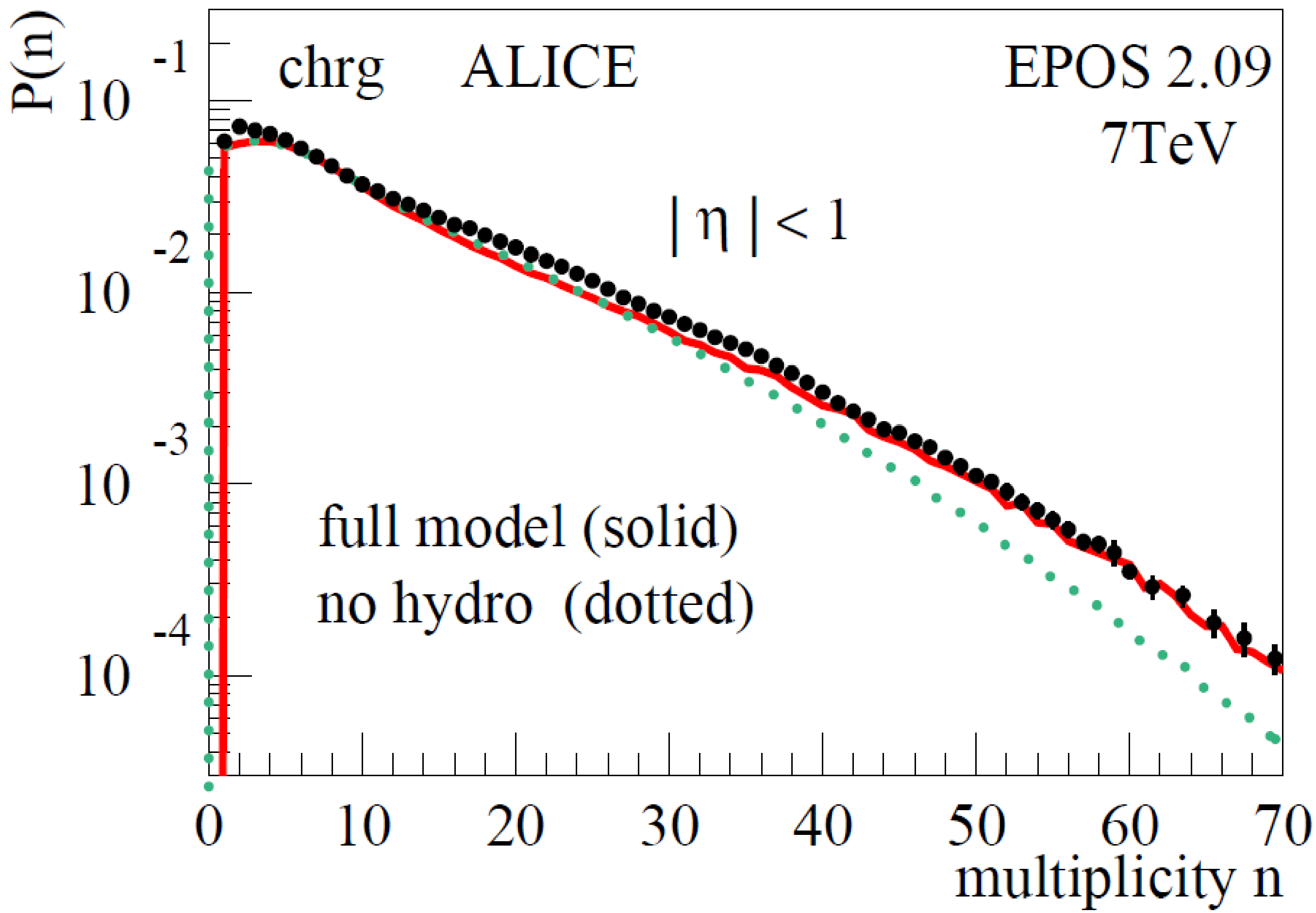
Pseudorapidity Distribution

- Little effect of hydro in MinBias dn/deta



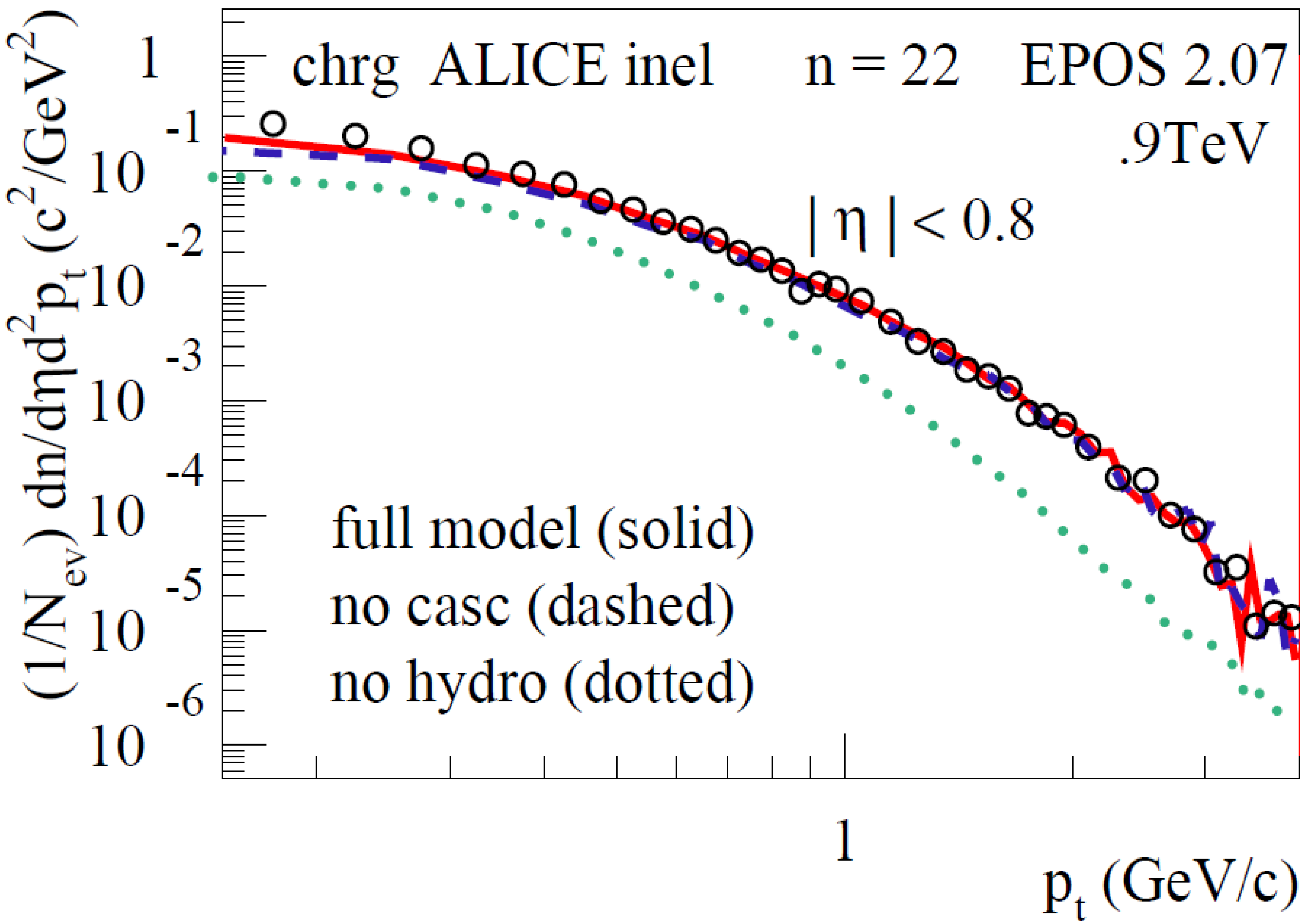
Multiplicity Distribution

- Little effect of hydro in MinBias dn/deta



Pt Distribution

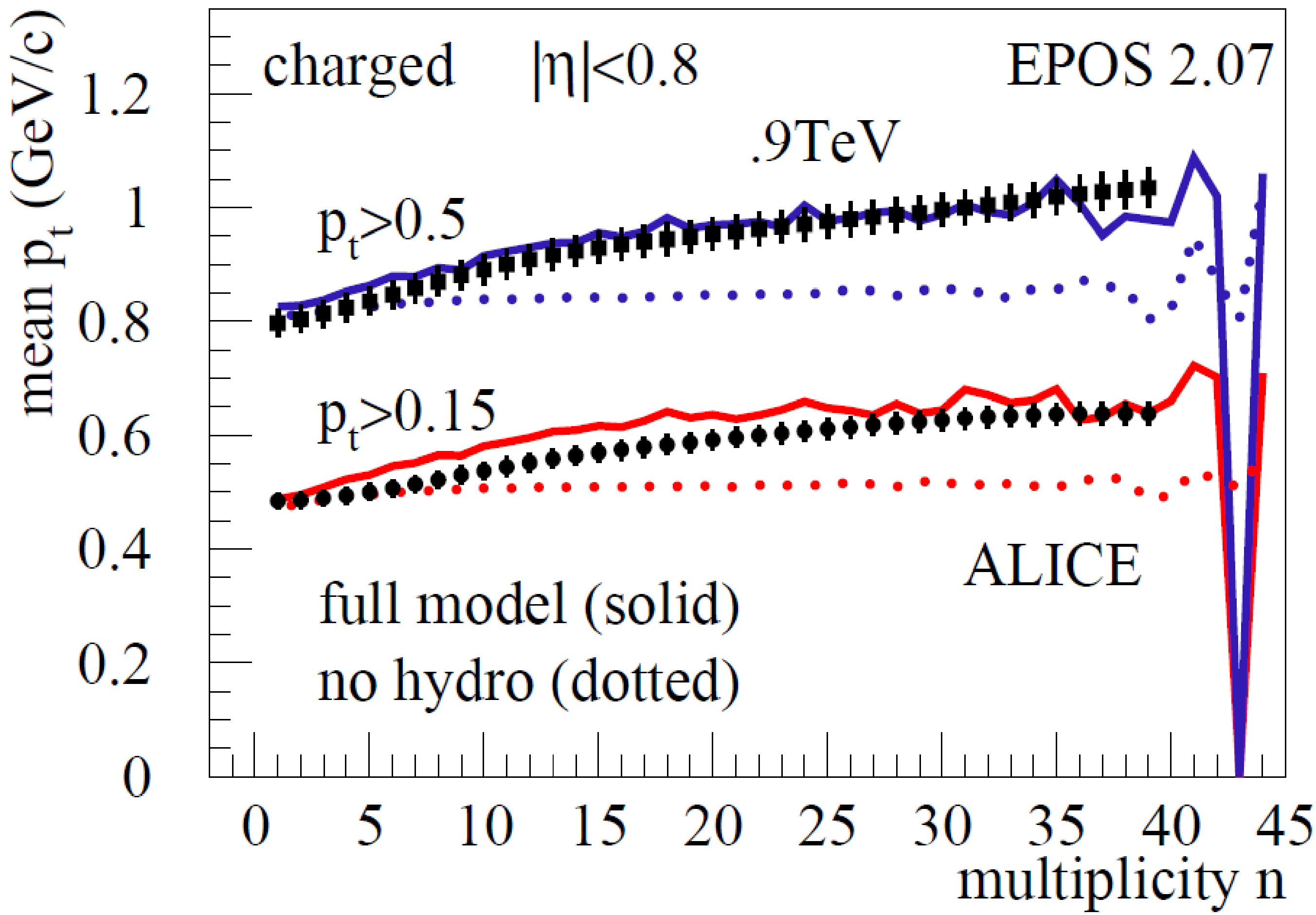
- Big effect for Pt distributions for high multiplicity events (here 900 GeV)



Flow !

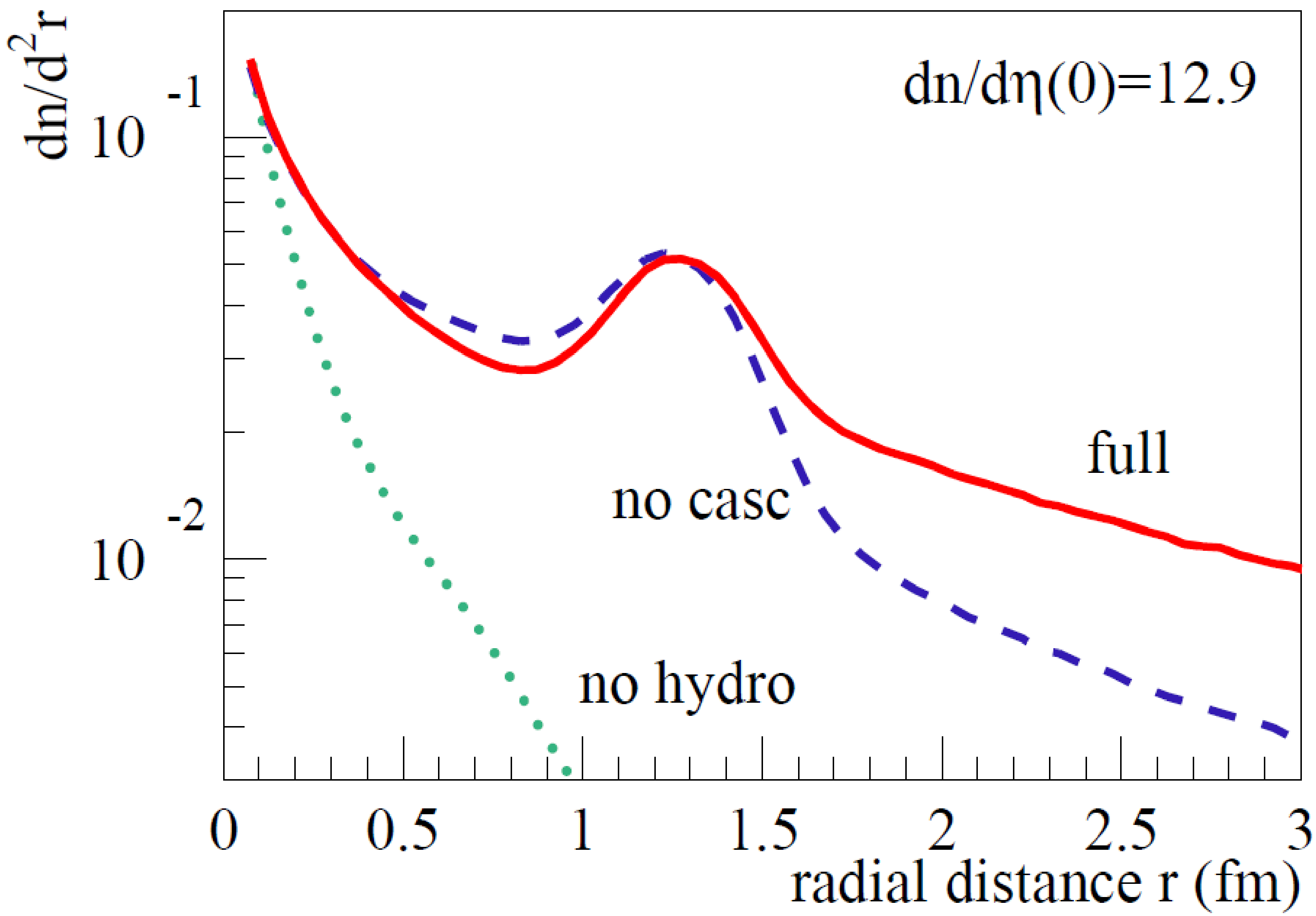
Pt Distribution

➜ Summarized in <Pt> versus multiplicity (here 900 GeV)



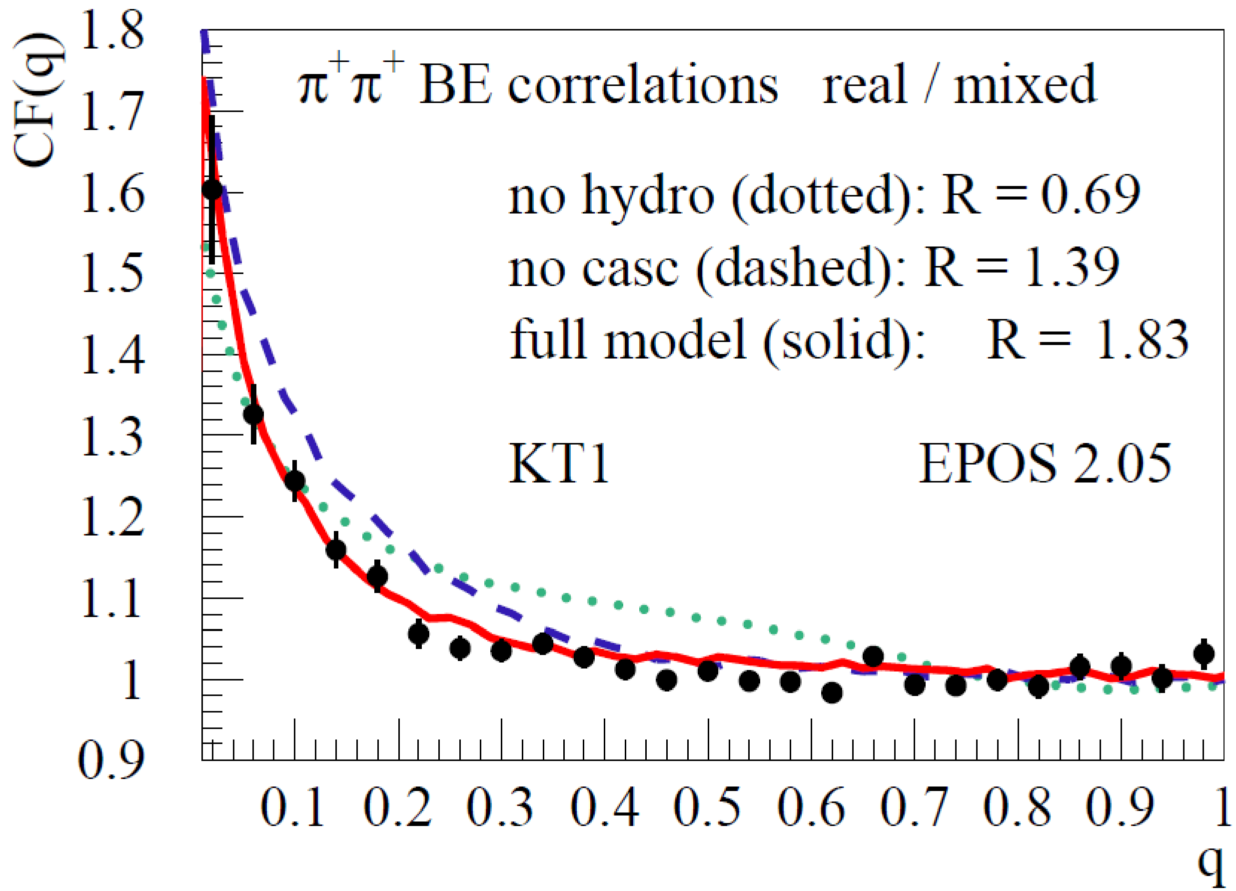
Radius of Particle Emission

- Space-time structure strongly affected (here 900 GeV)



Bose-Einstein Correlations

- Consequences for Bose-Einstein correlations



ALICE data. Radii R from exponential fit.

KT1= [100, 250], KT3= [400, 550], KT5= [700, 1000]

Summary

EPOS 2 :

- Improved screening and diffractive treatment to multiple scattering in better agreement with LHC
- Complete 3D hydrodynamical calculation

Hydro on event-by-event basis :

- for AuAu@RHIC, explains naturally nontrivial features as “ridge” correlations, elliptical flow
- Explains some nontrivial pp results (ridge, BE correlations)

On-going developments :

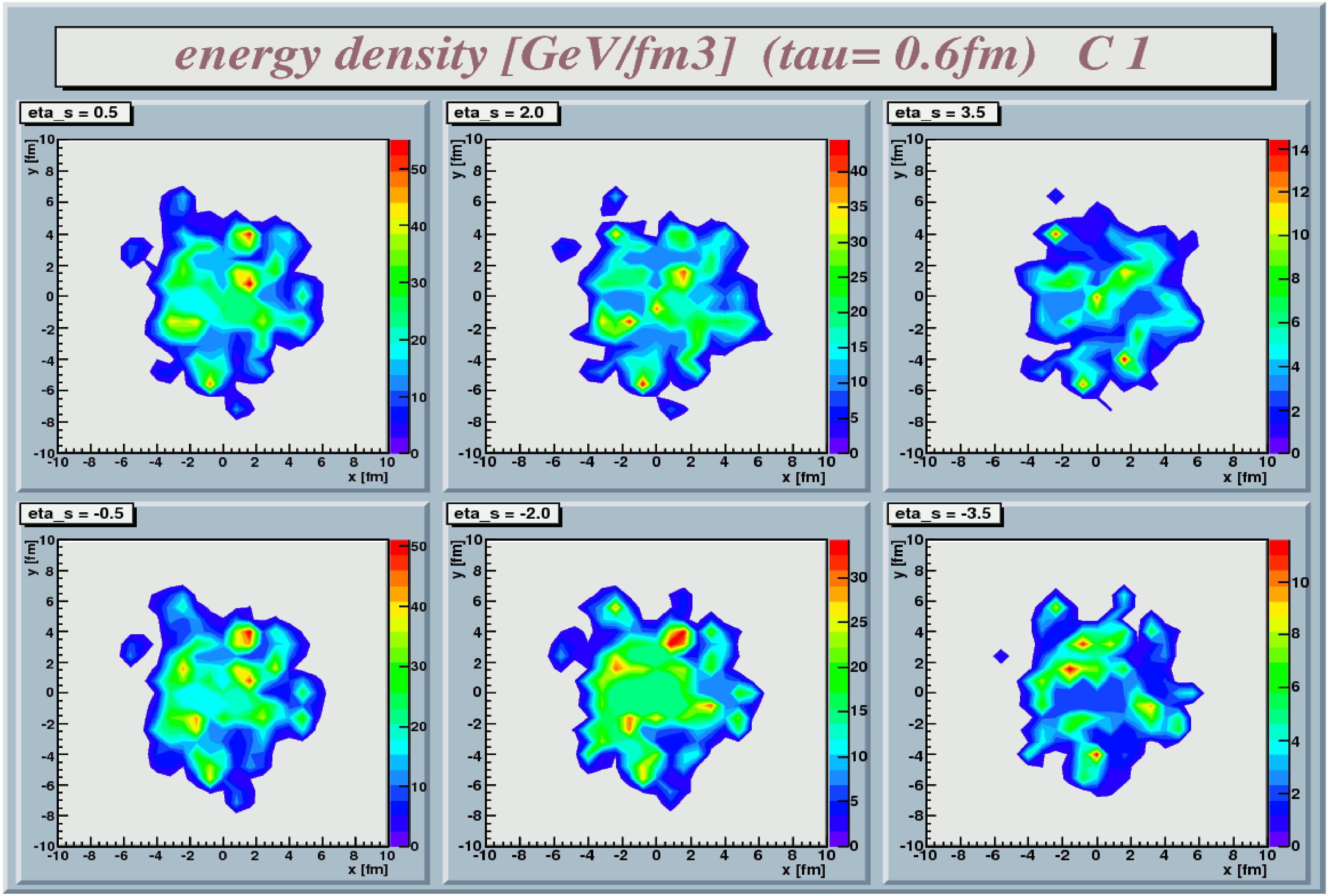
- Test all Min Bias LHC data
- Improvement of hard events (jets) in MB
- Selection of hard processes (specific born Pt)
- Both at the same time : underlaying events

Outlook for Cosmic Rays

- **Preliminary results using EPOS 2 in EAS simulations :**
  - No dramatic change in Xmax
    - Small reduction compare to EPOS 1.99
  - New : diquark in hard string end
    - More muons than EPOS 1.99
  - Need more data on baryon number at LHC to constrain muon number
    - mid rapidity (ALICE)
    - a bit more forward (LHCf)
    - very forward (LHCf)

Thank you !

Initial Conditions AuAu@RHIC



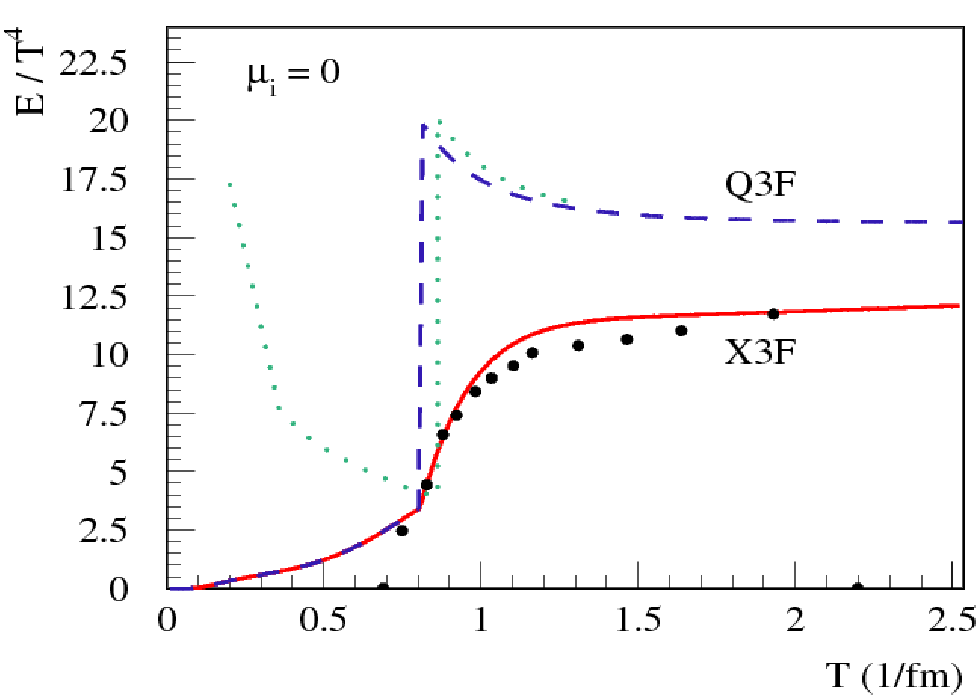
EoS

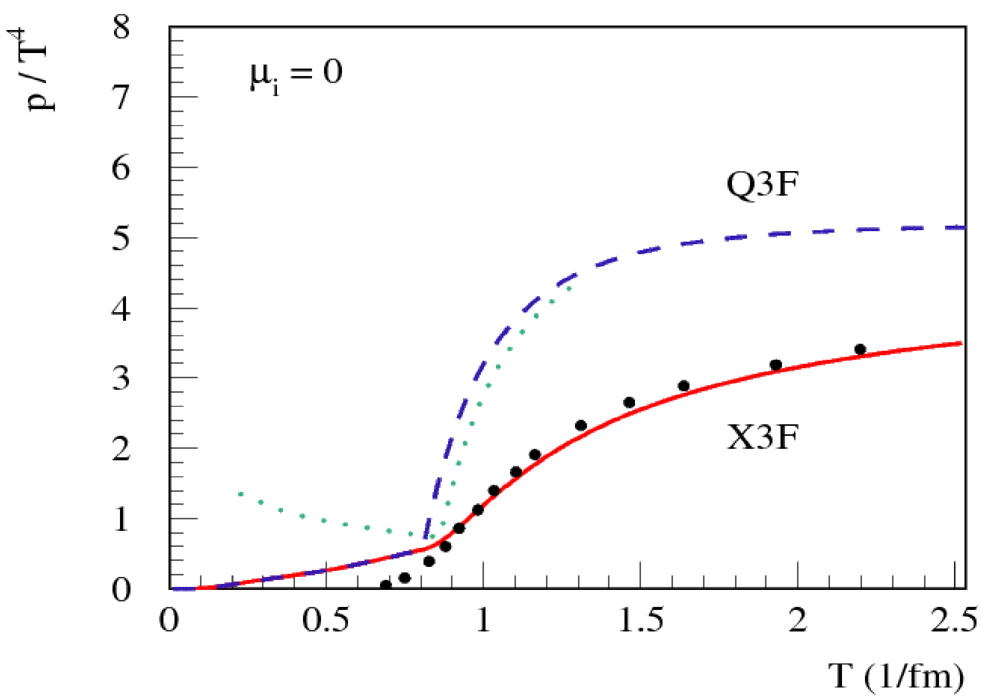
Hirano: QG & resonance gas => 1st order PT, PCE, $\mu_B = \mu_S = \mu_Q = 0$

Q3F: QG & "complete" resonance gas => 1st order PT, excl volume correction, μ_B, μ_S, μ_Q considered, parameters as in Spherio

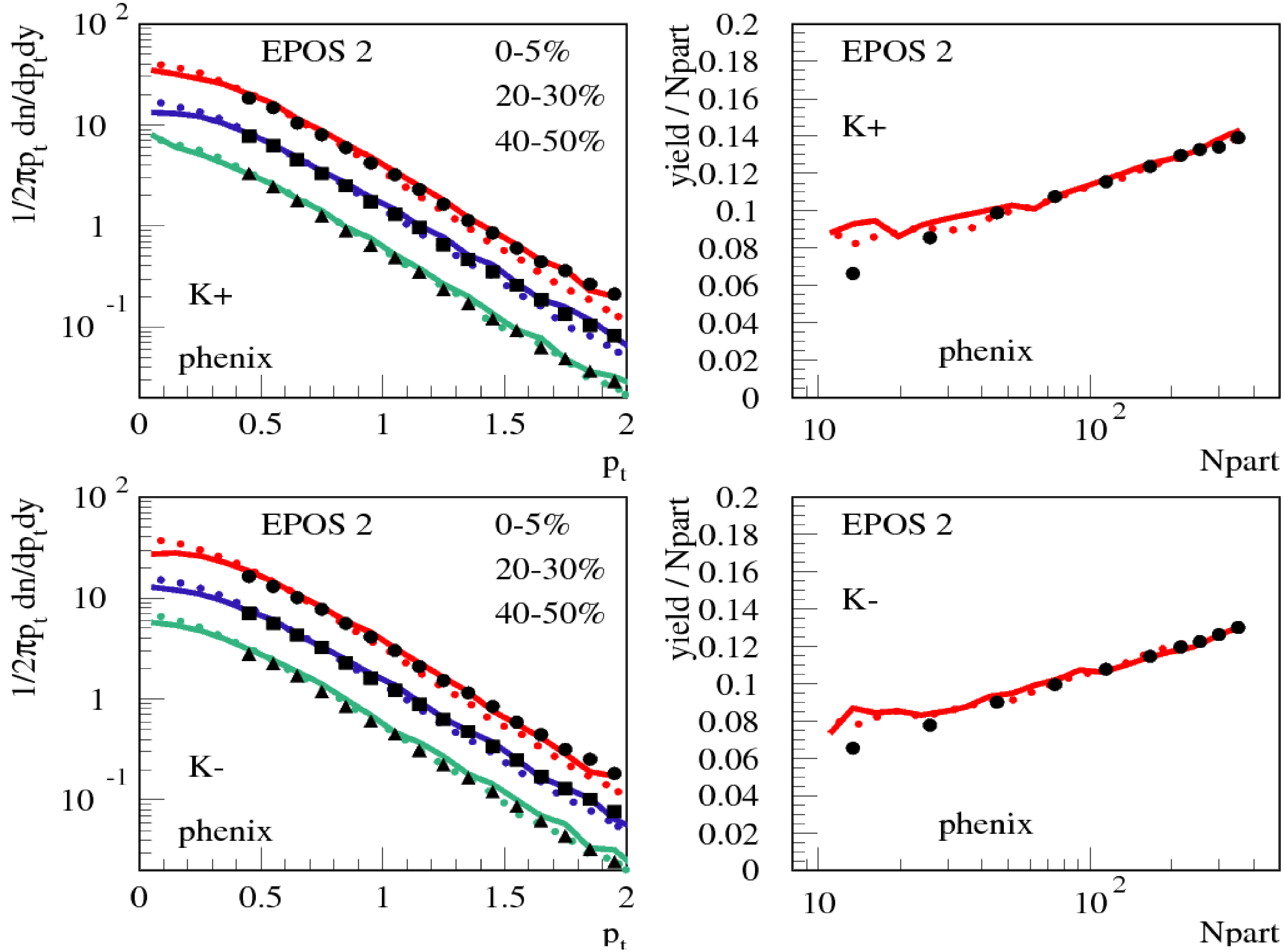
X3F: crossover : $p = p_Q + \lambda(p_H - p_Q)$, $\lambda = \exp(-\frac{T-Tc}{\delta})\theta(T - T_c) + \theta(T_c - T)$

"data": Y. Aoki, Z. Fodor, S.D. Katz , K.K. Szabo, JHEP 0601:089,2006





AuAu : Kaon



solid lines: with hadronic cascade

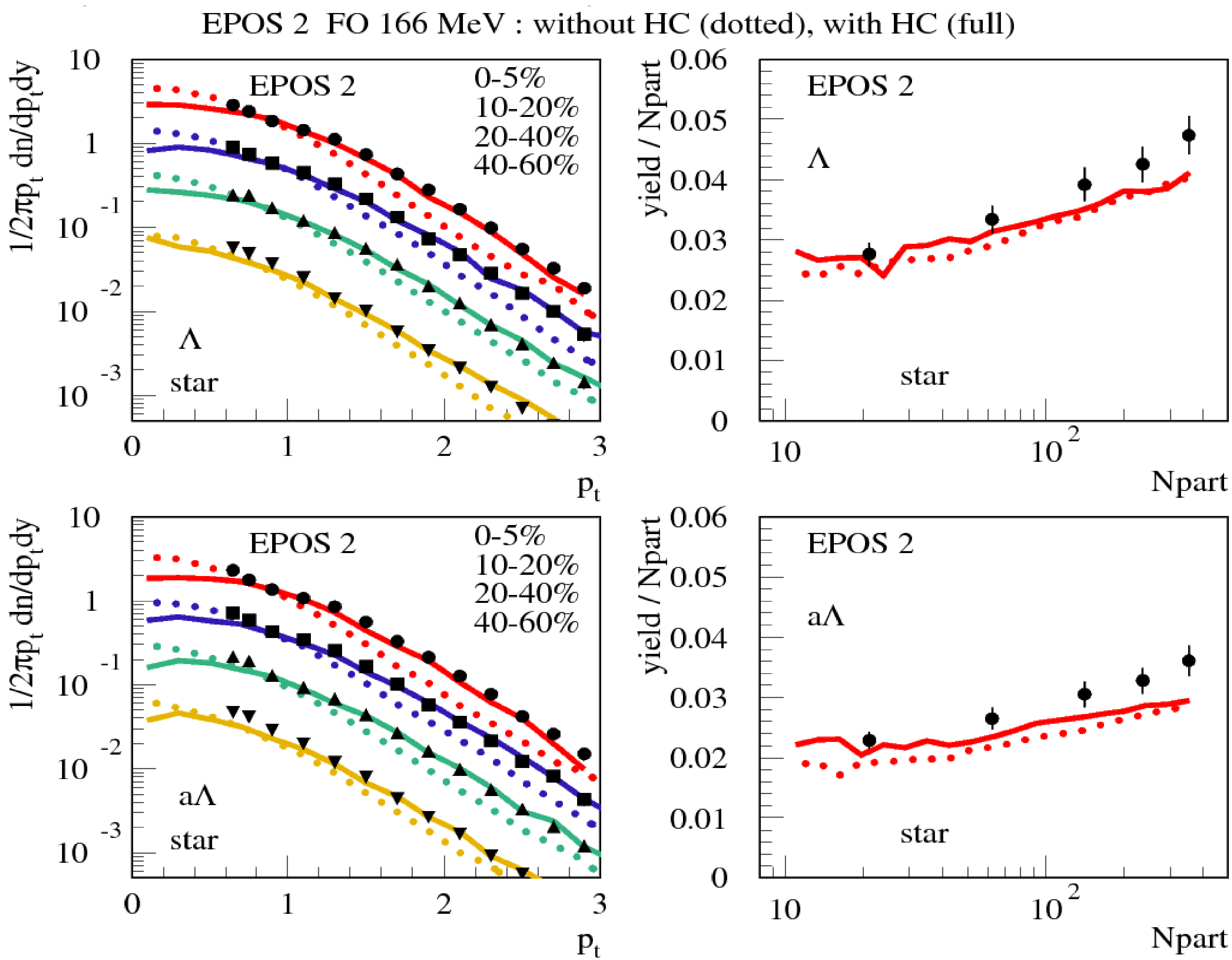
dotted lines: w/o cascade

AuAu : Lambda

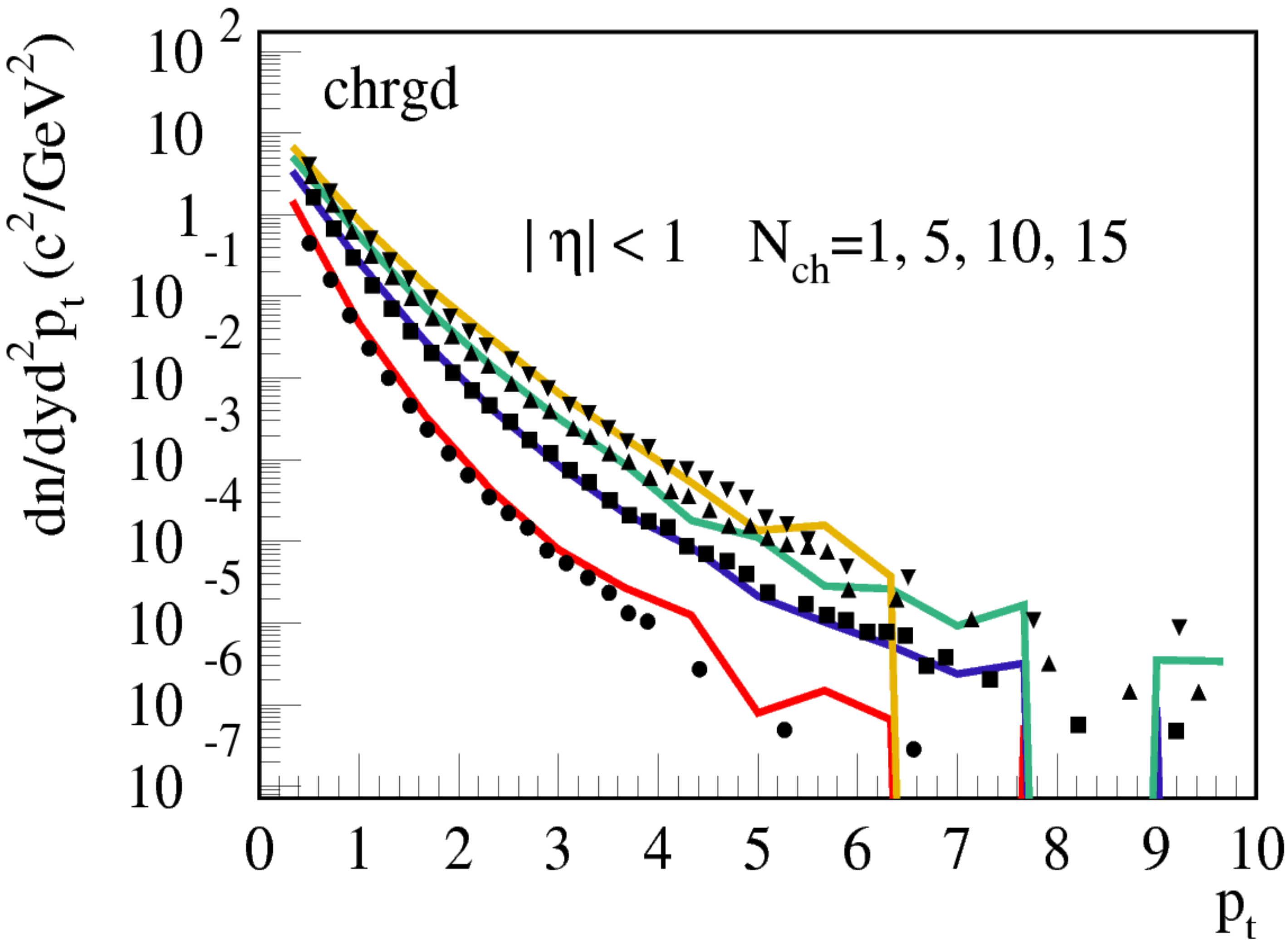
for better visibility:

pt spectra scaled by

1/2 (10-20%)
1/4 (20-40%)
1/8 (40-60%)



Pt distribution CDF ap-p@1.8 TeV with Hydro



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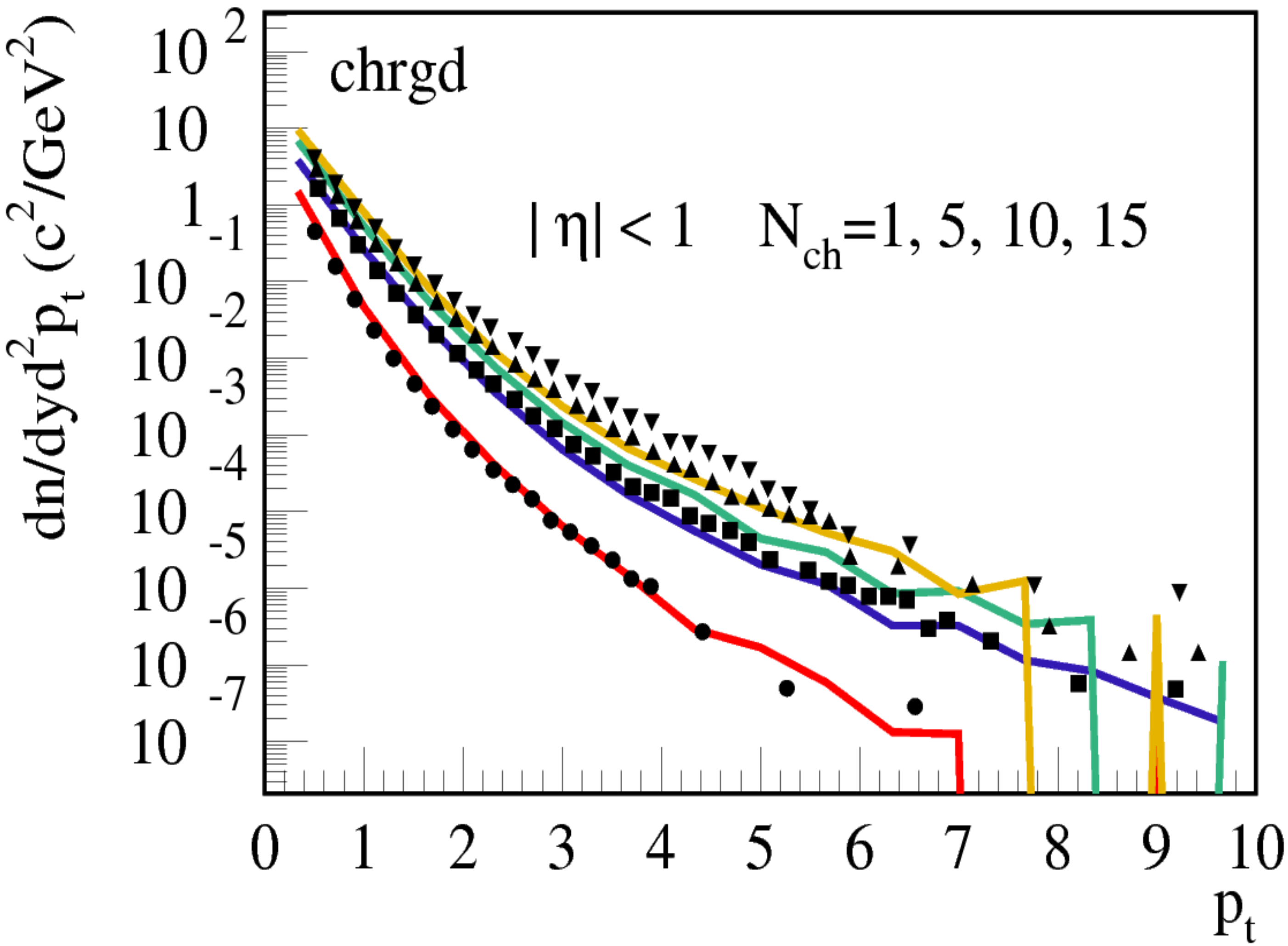
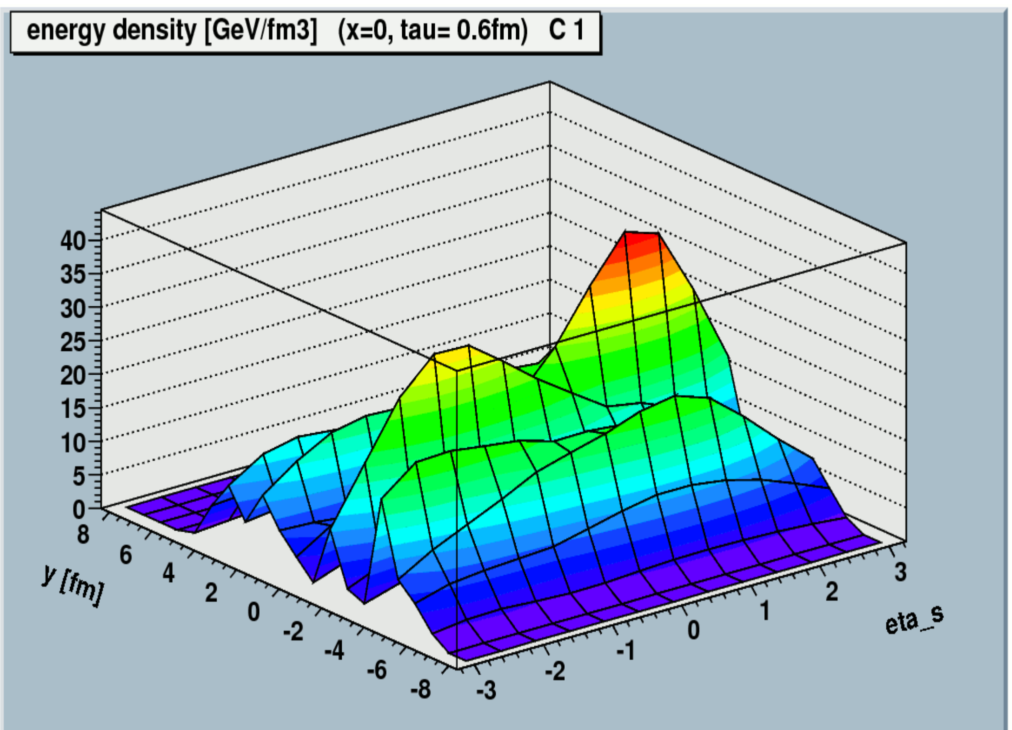
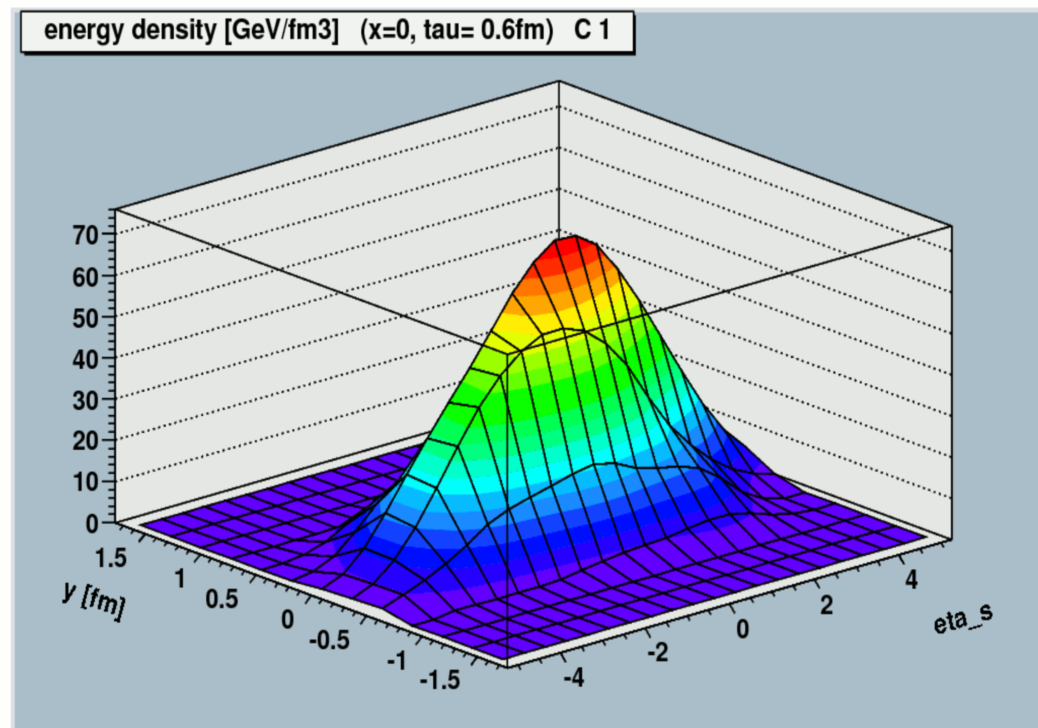


Hydro in pp : Initial Conditions

- **Initial conditions from multiple interactions :**
  - 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)

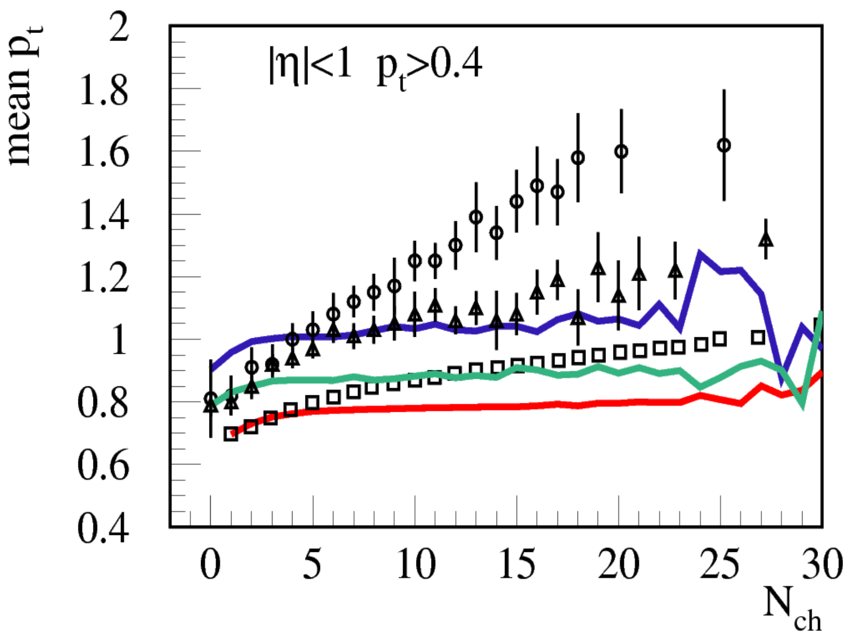




$<p_t>$ vs multiplicity ap-p@1.8 TeV : EPOS 2

- **Using small flux tube size**
  - Very good description of CDF data
  - No additional parameter
  - Hadron mass dependence

No collective effects



hydro+hadronic cascade