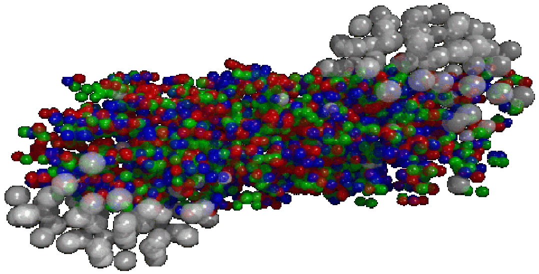

An Integrated Hydro+Boltzmann Approach to Heavy Ion Reactions at FAIR

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Thanks to

- Hannah Petersen
- Jan Steinheimer
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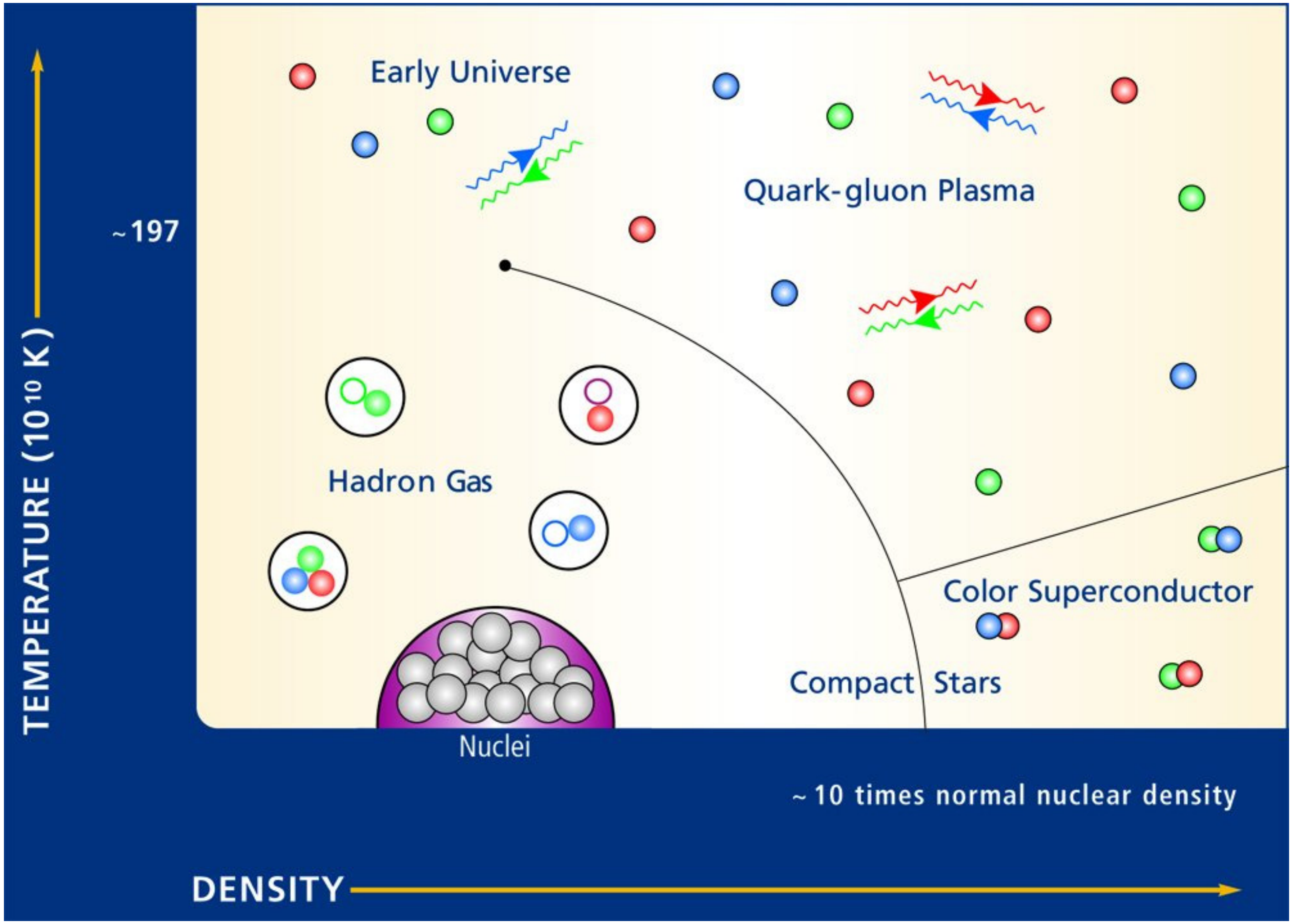
Outline

- Model Description
  - Initial Conditions
  - Equations of State
  - Freeze-out Scenarios
- Multiplicities and Spectra
- HBT Results
- Elliptic Flow Excitation Function
- Differential Flow Results
- Conclusions

(Petersen et al., PRC 78:044901, 2008, arXiv: 0806.1695)
(Petersen et al., arXiv: 0901.3821, PRC in print)

The QCD Phase Diagram

http://www.ice.csic.es/en/graphics/phase.jpg



In heavy ion collisions heated and compressed nuclear matter is produced under controlled conditions

Hybrid Approaches (history)

- Hadronic freezeout following a first order hadronization phase transition in ultrarelativistic heavy ion collisions.
  S.A. Bass, A. Dumitru, M. Bleicher, L. Bravina, E. Zabrodin, H. Stoecker, W. Greiner, Phys.Rev.C60:021902,1999
- Dynamics of hot bulk QCD matter: From the quark gluon plasma to hadronic freezeout.
  S.A. Bass, A. Dumitru, Phys.Rev.C61:064909,2000
- Flow at the SPS and RHIC as a quark gluon plasma signature.
  D. Teaney, J. Lauret, Edward V. Shuryak, Phys.Rev.Lett.86:4783-4786,2001
- A Hydrodynamic description of heavy ion collisions at the SPS and RHIC.
  D. Teaney, J. Lauret, E.V. Shuryak, e-Print: nucl-th/0110037
- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
  T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys.Lett.B636:299-304,2006
- 3-D hydro + cascade model at RHIC.
  C. Nonaka, S.A. Bass, Nucl.Phys.A774:873-876,2006
- Results On Transverse Mass Spectra Obtained With Nexspherio
  F. Grassi, T. Kodama, Y. Hama, J.Phys.G31:S1041-S1044,2005

Present Approaches

(3+1)dim. hydrodynamics

with nonequilibrium initial conditions (Nexus) and isothermal freeze-out or continuous emission scenario:

- Results On Transverse Mass Spectra Obtained With Nexspherio
  F. Grassi, T. Kodama, Y. Hama, J.Phys.G31:S1041-S1044,2005

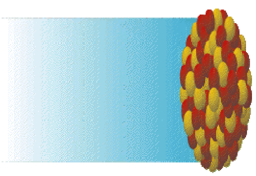
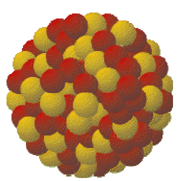
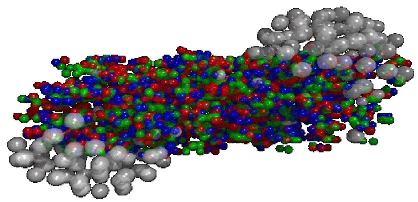
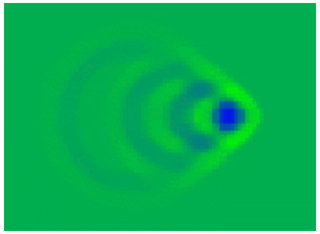
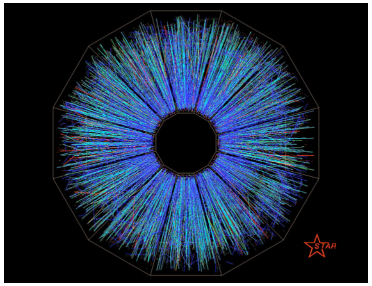
with Glauber or CGC initial conditions and hadronic afterburner:

- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
  T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys.Lett.B636:299-304,2006
- 3-D hydro + cascade model at RHIC.
  C. Nonaka, S.A. Bass, Nucl.Phys.A774:873-876,2006

- See also recent work of K. Werner

Hybrid Approach

- Essential to draw conclusions from final state particle distributions about initially created medium
- The idea here: Fix the initial state and freeze-out
  → learn something about the EoS and the effect of viscous dynamics

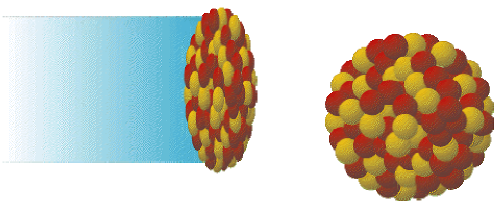






1) Non-equilibrium initial conditions via UrQMD	2) Hydrodynamic evolution **or** Transport calculation	3) Freeze-out via hadronic cascade (UrQMD)

(Petersen et al., PRC 78:044901, 2008, arXiv: 0806.1695)

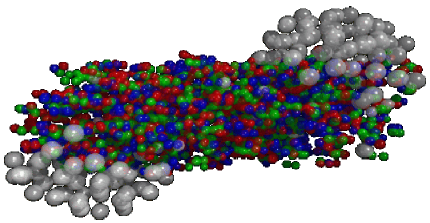
The UrQMD transport approach

UrQMD = Ultra-relativistic Quantum Molecular Dynamics



- Initialisation:

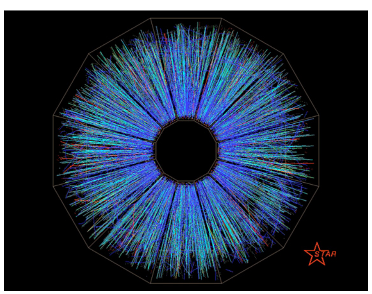
  Nucleons are set according to a Woods-Saxon distribution with randomly chosen momenta $p_i < p_F$



- Propagation and Interaction:

  Rel. Boltzmann equation $\left(p^{\mu}\partial_{\mu}\right)f = I_{coll}$

  Collision criterium $d_{\min} \leq d_0 = \sqrt{\frac{\sigma_{tot}}{\pi}}$



- Final state:

  all particles with their final positions and momenta

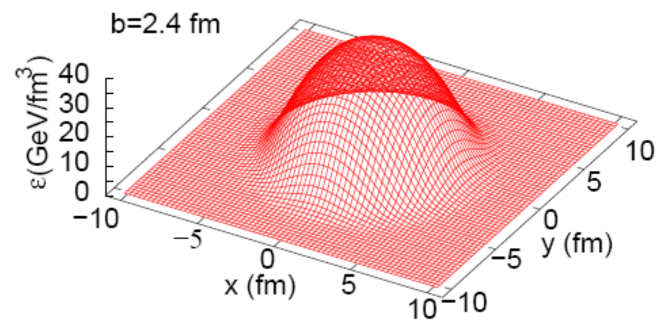
Very successful in describing different observables in a broad energy range
But: modeling of the phase transition and hadronization not yet possible

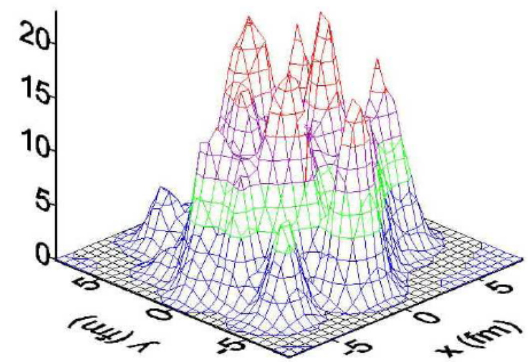
Initial State

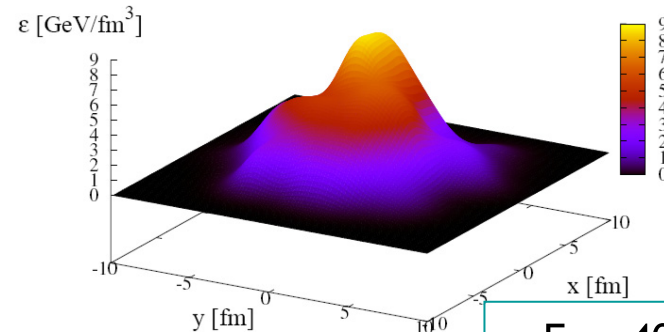
- Contracted nuclei have passed through each other

$$t_{start} = \frac{2R}{\gamma v}$$

  - Energy is deposited
  - Baryon currents have separated
- Energy-, momentum- and baryon number densities are mapped onto the hydro grid
- **Event-by-event fluctuations** are taken into account
- Spectators are propagated separately in the cascade







E_{lab}=40 AGeV
b=0 fm

(nucl-th/0607018, nucl-th/0511021)

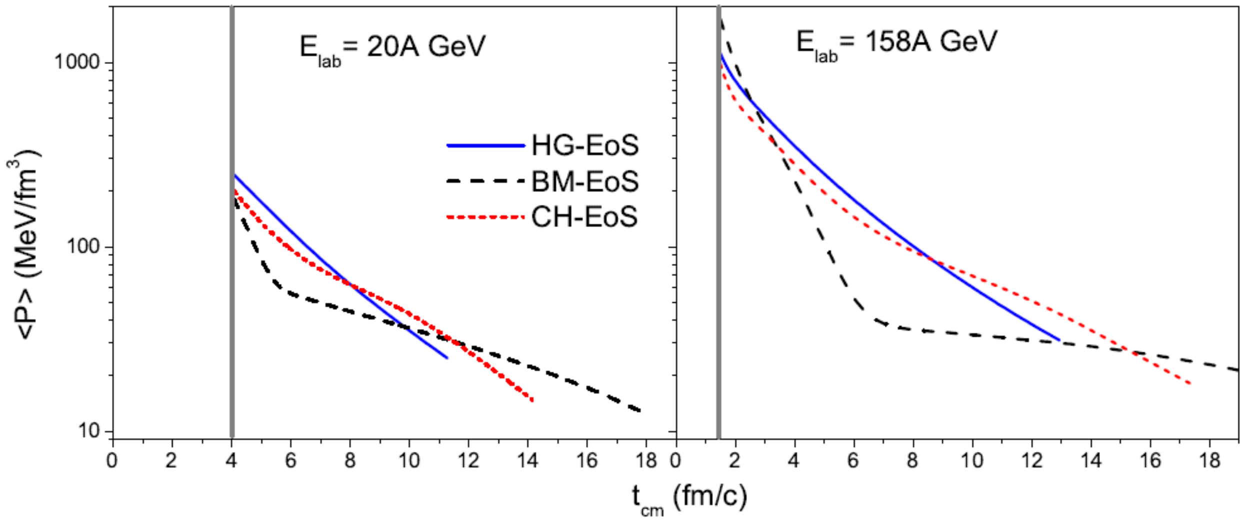
(J.Steinheimer et al., PRC 77,034901,2008)

Equations of State

Ideal relativistic one fluid dynamics:

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{and} \quad \partial_\mu (n u^\mu) = 0$$

- HG: **Hadron gas** including the same degrees of freedom as in UrQMD (all hadrons with masses up to 2.2 GeV)
- CH: **Chiral EoS** from SU(3) hadronic Lagrangian with first order transition and critical endpoint
- BM: **Bag Model EoS** with a strong first order phase transition between QGP and hadronic phase



D. Rischke et al., NPA 595, 346, 1995,

D. Zschiesche et al., PLB 547, 7, 2002

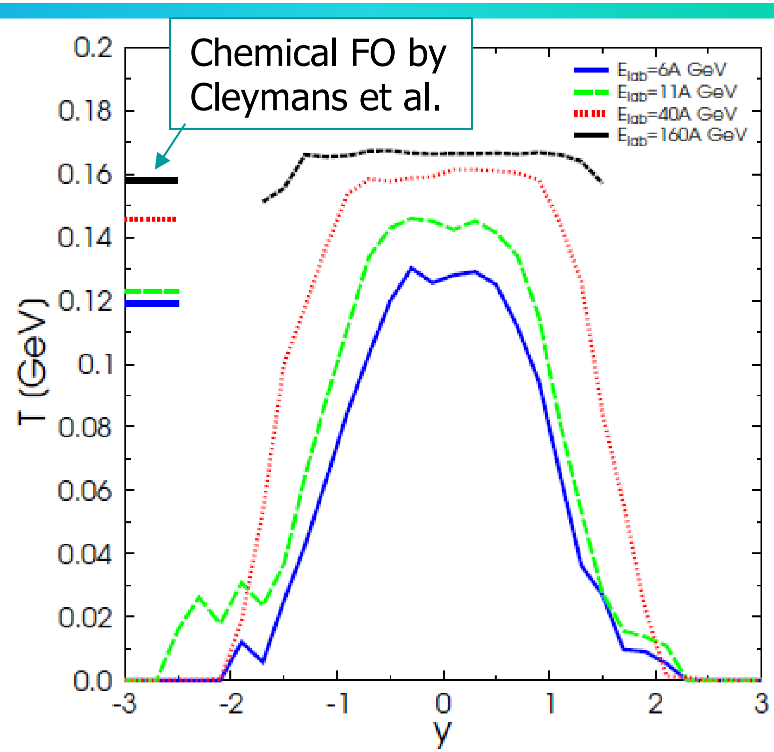
Papazoglou et al., PRC 59, 411, 1999

Freeze-out

1) Transition from hydro to transport when ε < 730 MeV/fm³ ($\approx 5 * \varepsilon_0$) in all cells of one transverse slice (**Gradual freeze-out**, GF)

→ iso-eigentime criterion

2) Transition when $\varepsilon < 5^* \varepsilon_0$ in all cells (**Isochronuous** freeze-out, IF)



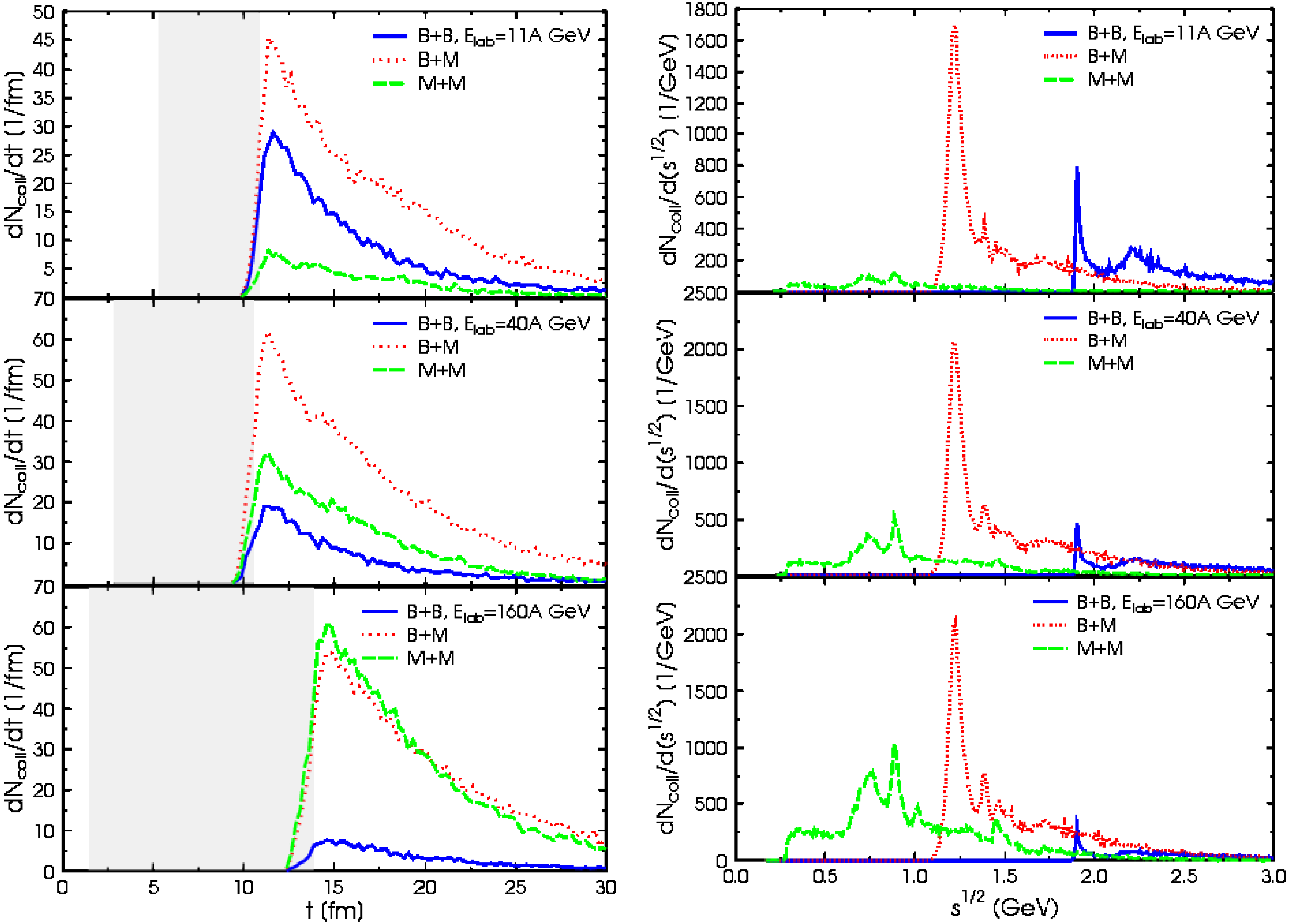
- Particle distributions are generated according to the **Cooper-Frye** formula

$$E\frac{dN}{d^3p} = \int_\sigma f(x,p)p^\mu d\sigma_\mu$$

with boosted Fermi or Bose distributions f(x,p) including μ_B and μ_S

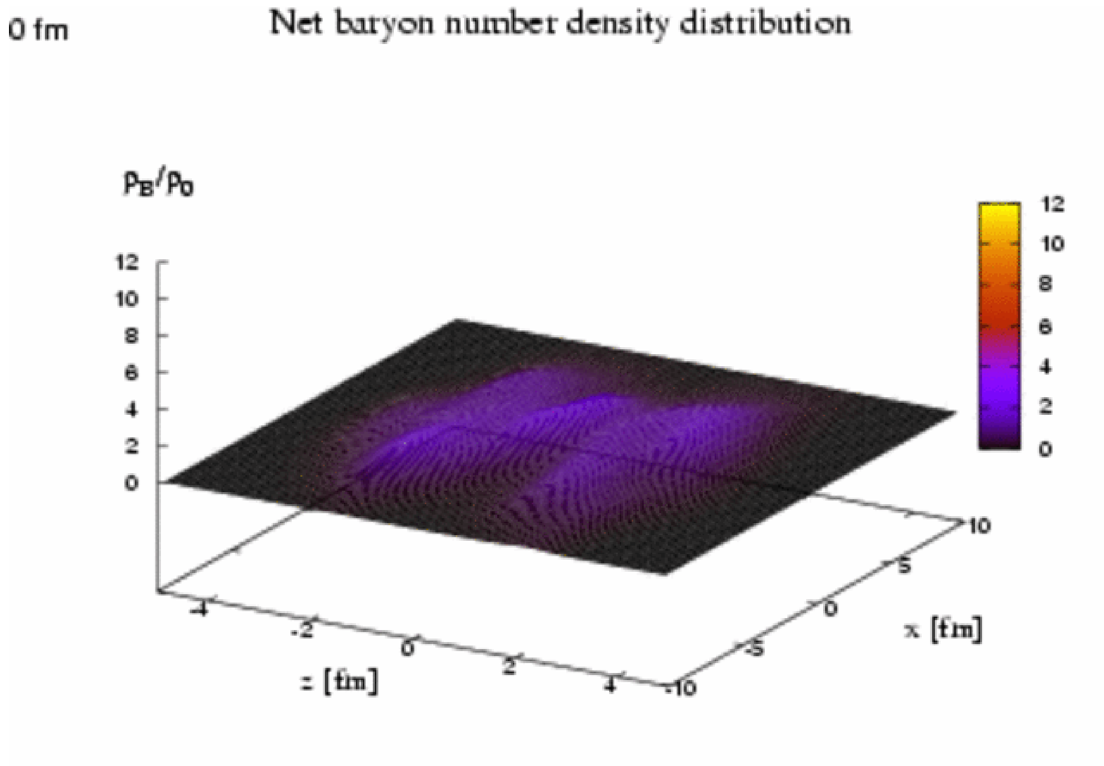
- Rescatterings and final decays calculated via **hadronic cascade** (UrQMD)

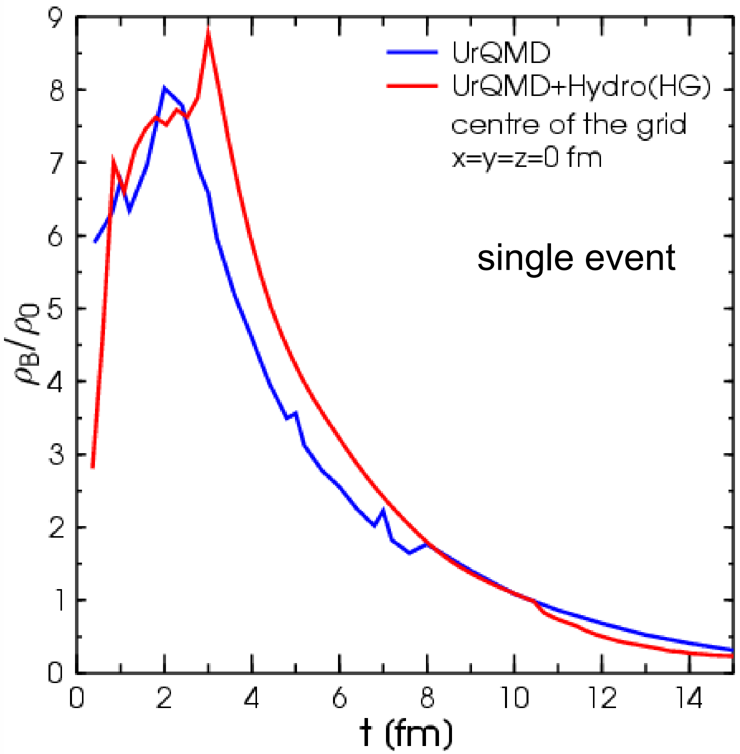
Final State Interactions (after Hydro)



Baryon density distribution

Time evolution of the baryon density is smooth

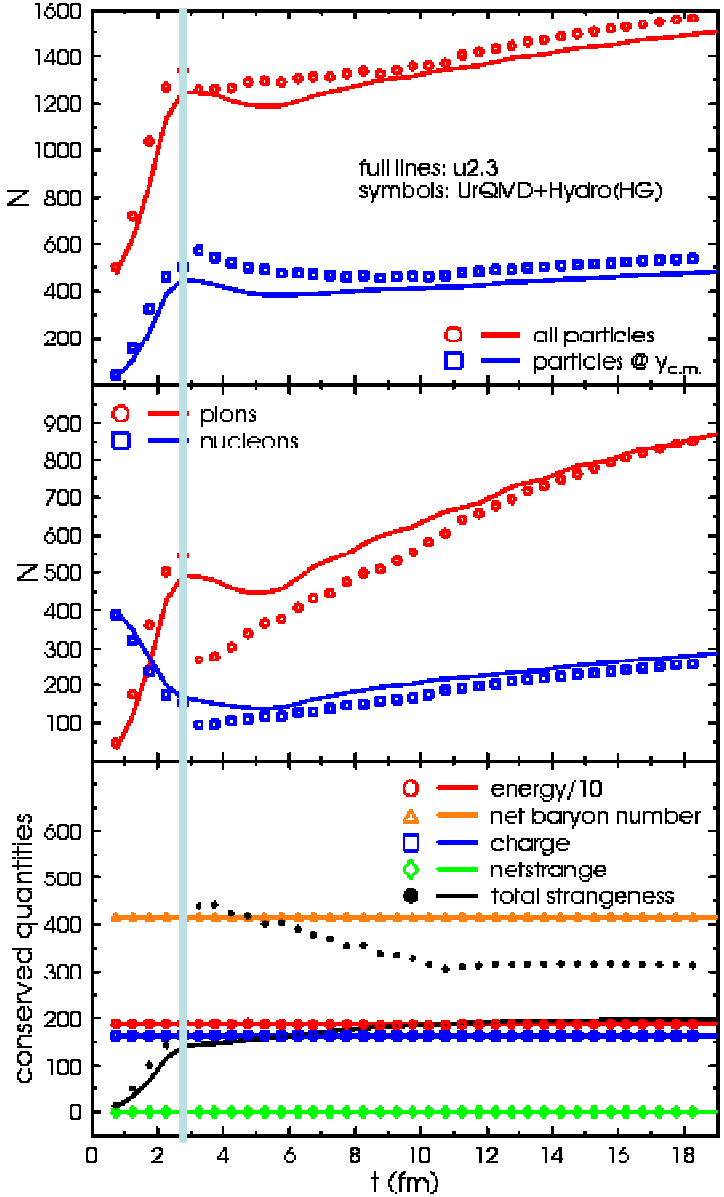




1) in the reaction plane

2) in a central cell

Time Evolution

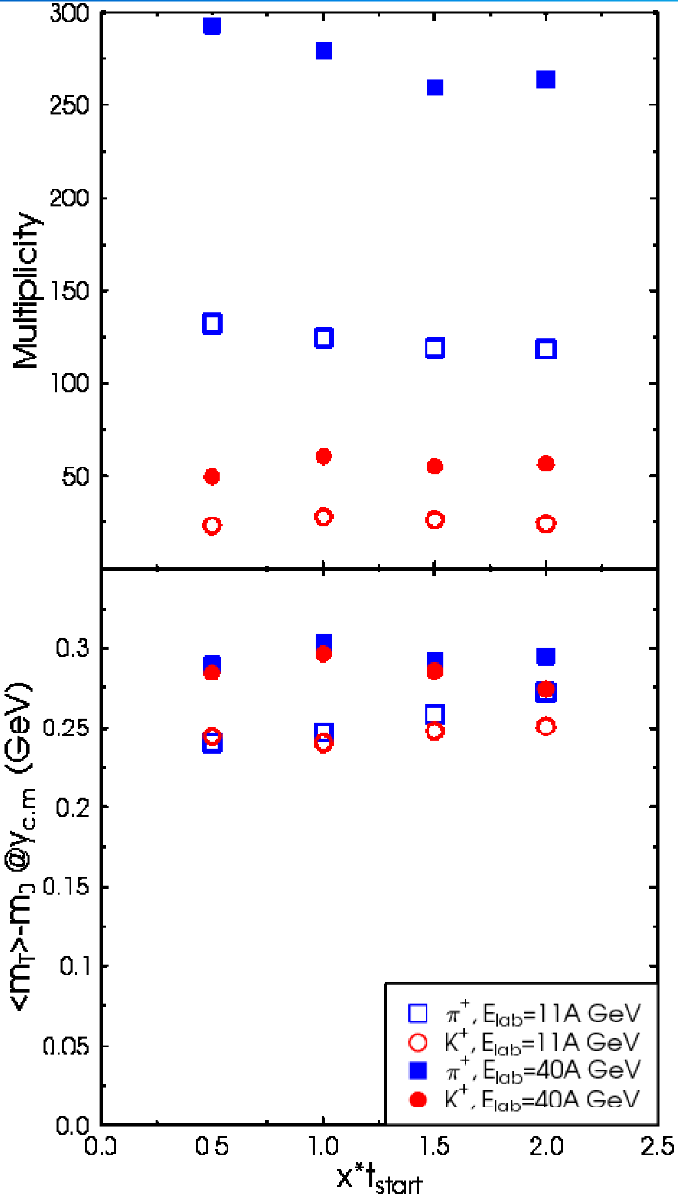


Central Pb+Pb collisions at 40A GeV:

- Number of particles decreases in the beginning due to resonance creation
- Qualitative behaviour very similar in both calculations

→ UrQMD **equilibrates** to a rather large degree

Dependence on t_{start}

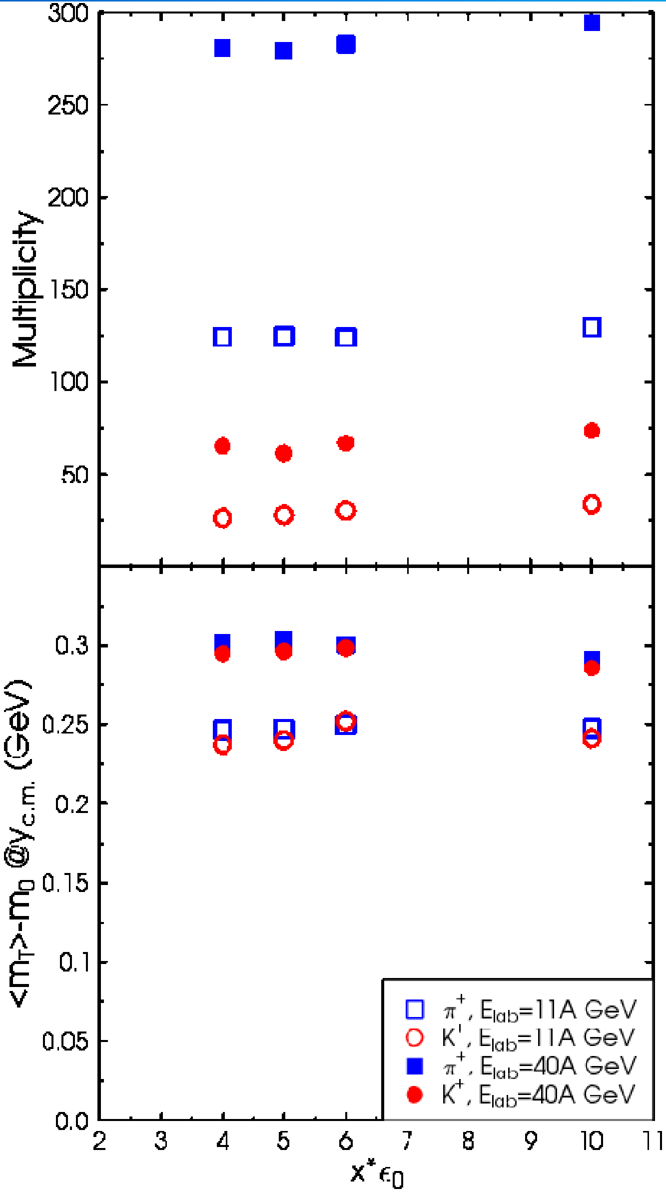


Variation of starting time by a factor 4 changes results only by 10 %

Full symbols: 40 AGeV

Open symbols: 11 AGeV

Dependence on Freeze-out

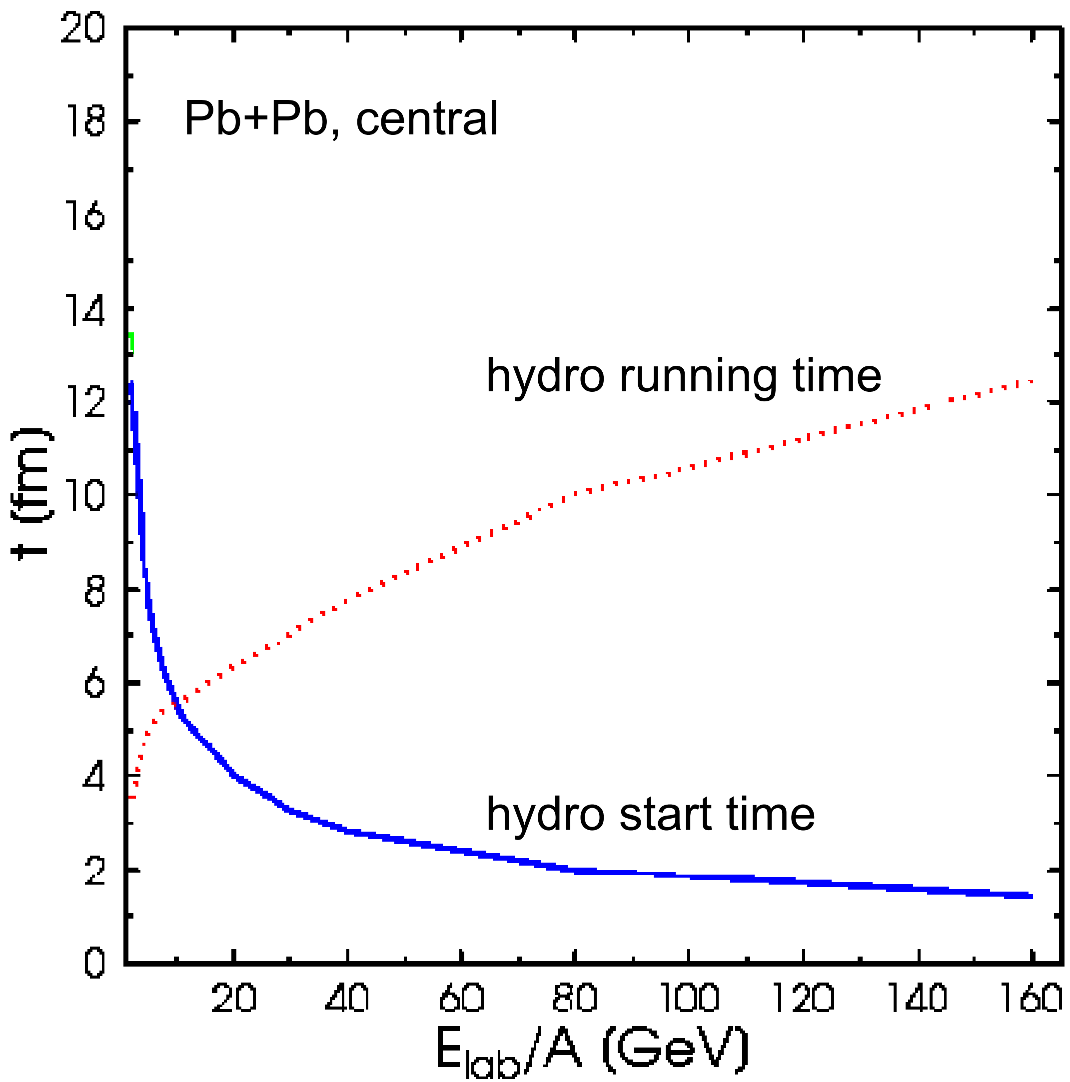


- Variation of the freeze-out criterium does not affect the meson multiplicities and mean transerve masses

Full symbols: 40 AGeV

Open symbols: 11 AGeV

Time scales



Pb+Pb, central
hydro running time
hydro start time
t (fm)
E_lab/A (GeV)
0
2
4
6
8
10
12
14
16
18
20
20
40
60
80
100
120
140
160

Multiplicities vs. Energy

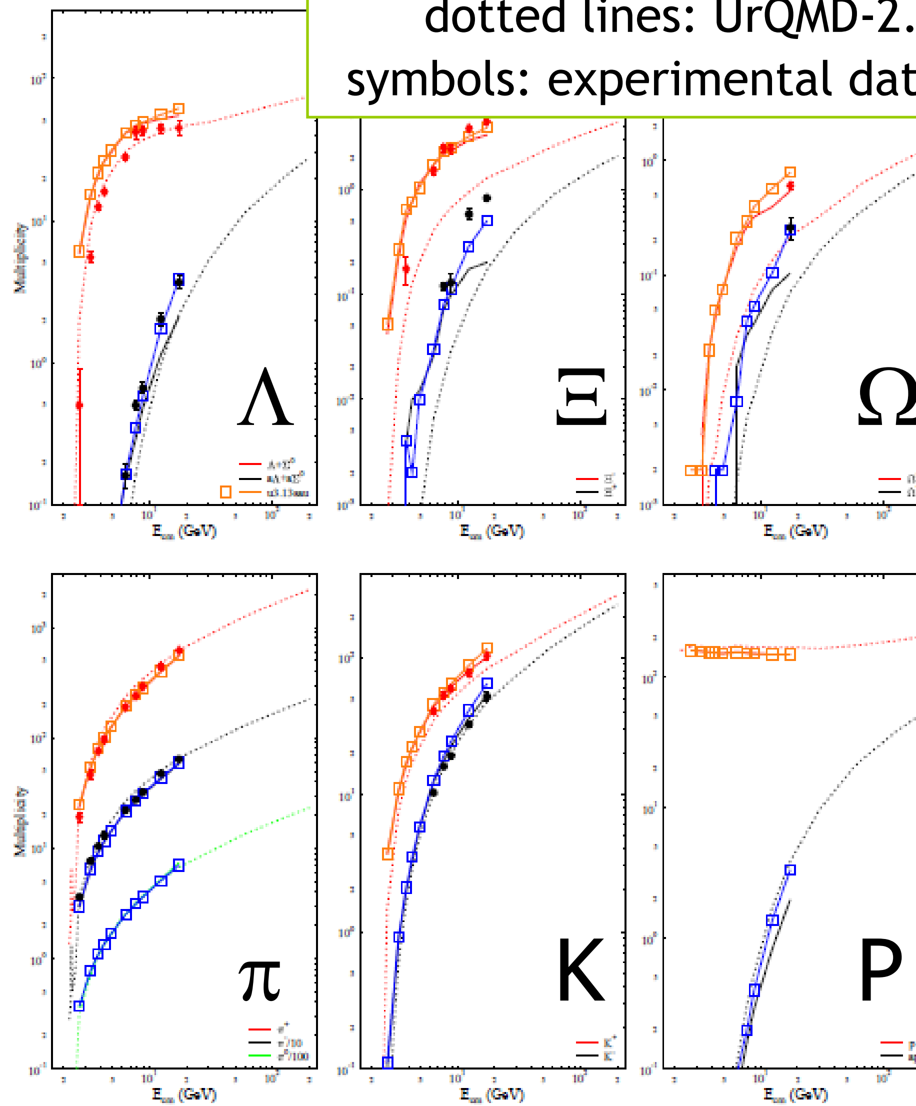
full lines: hybrid model (IF)
squares: hybrid model (GF)
dotted lines: UrQMD-2.3
symbols: experimental data

- Both models are purely hadronic without phase transition, **but** different underlying dynamics

→ Results for particle multiplicities from AGS to SPS are surprisingly **similar**

→ **Strangeness** is enhanced in the hybrid approach due to local equilibration

Central (b<3.4 fm) Pb+Pb/Au+Au collisions

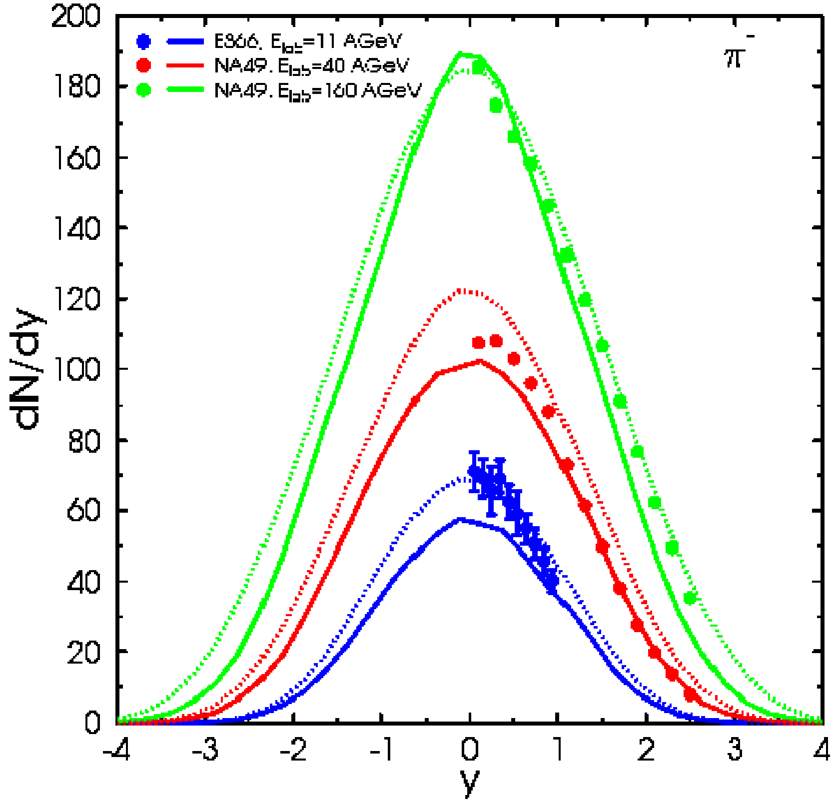


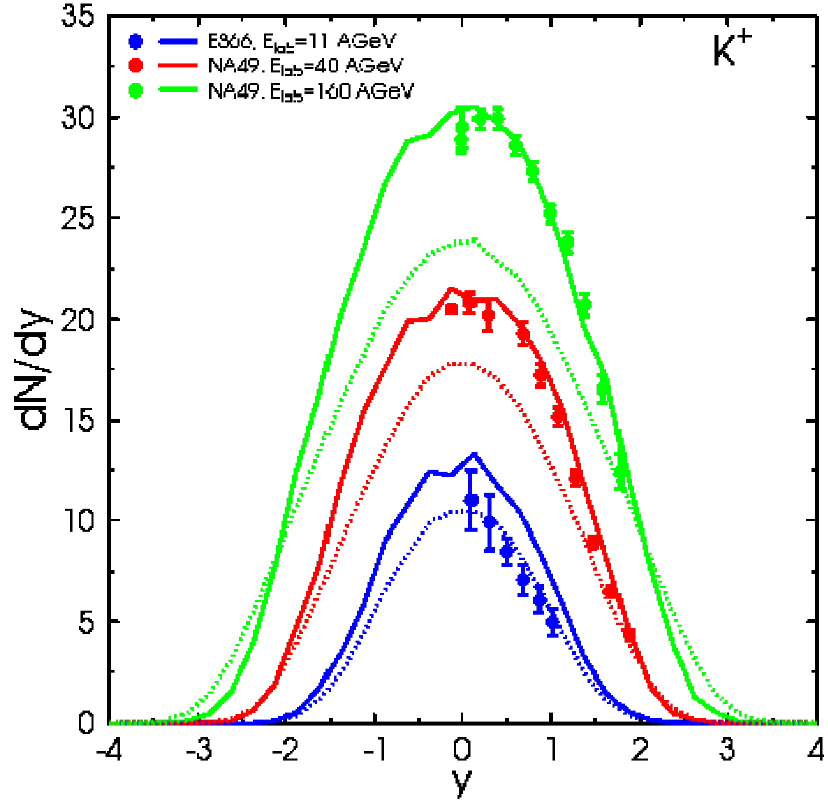
(Petersen et al., PRC 78:044901, 2008)

Data from E895, NA49

Rapidity Spectra

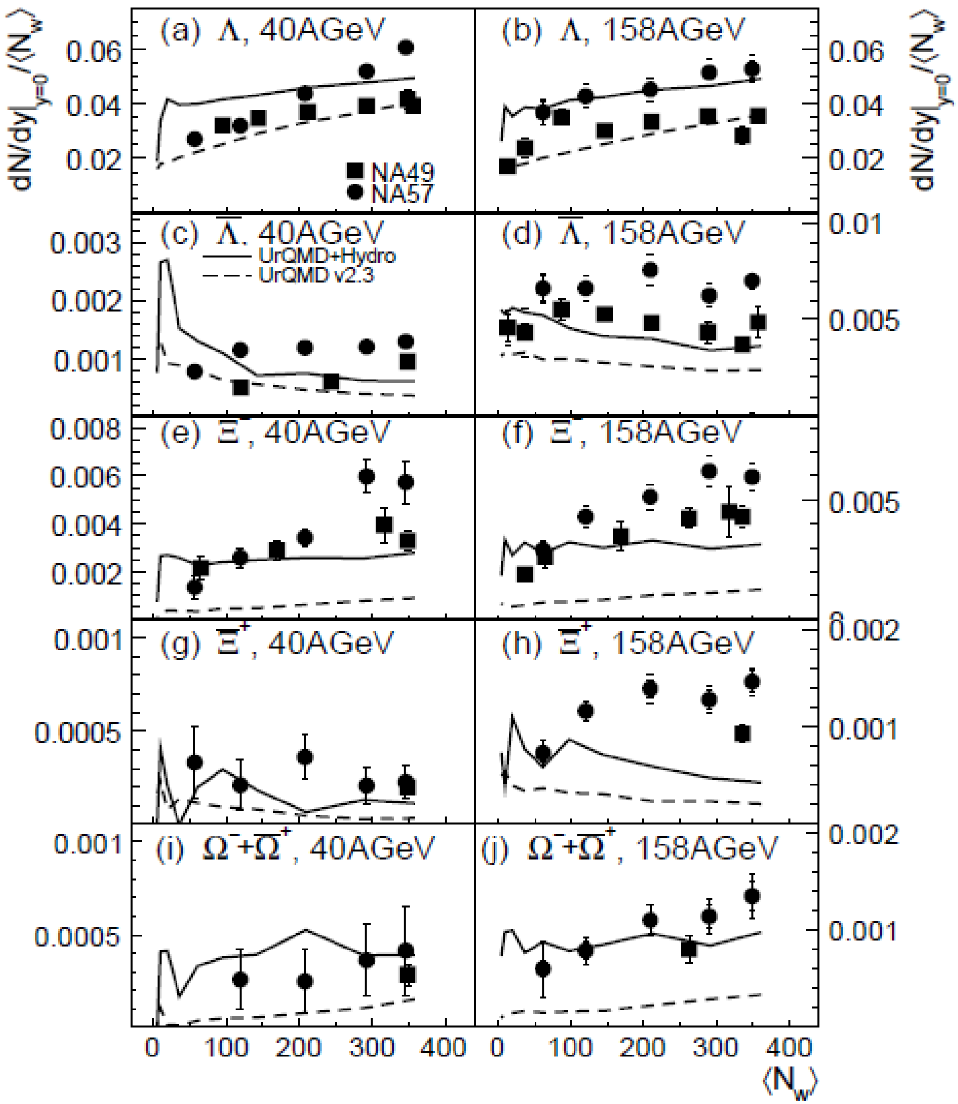
full lines: hybrid model
dotted lines: UrQMD-2.3
symbols: experimental data





→ Rapidity spectra for pions and kaons have a very **similar shape** in both calculations

Strangeness Centrality Dependence



Pb+Pb collisions for different centralities

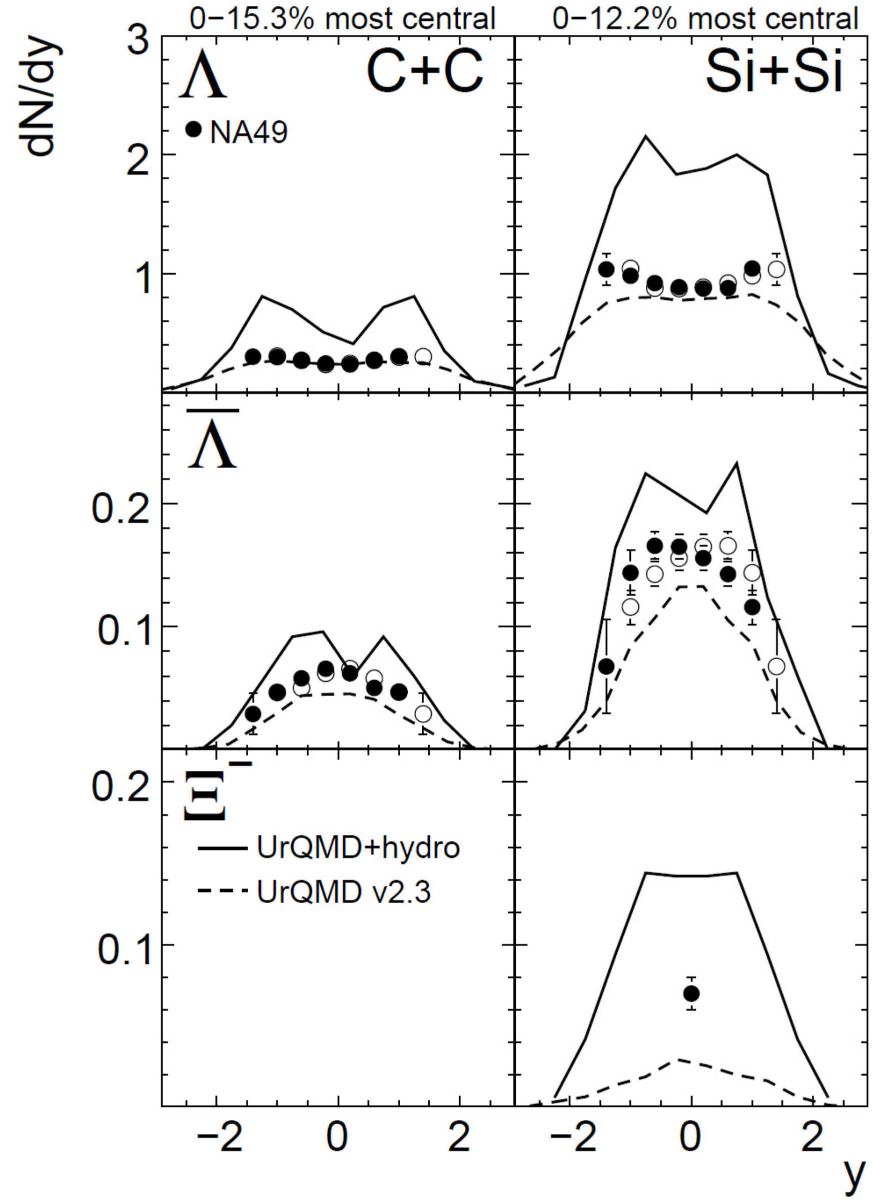
- Thermal production of the particles at transition from hydro to transport
- Centrality dependence of **multistrange hyperons** is improved

——	hybrid model (GF)
-----	UrQMD-2.3

(Petersen et al., arXiv: 0903.0396)

Limitations in small systems

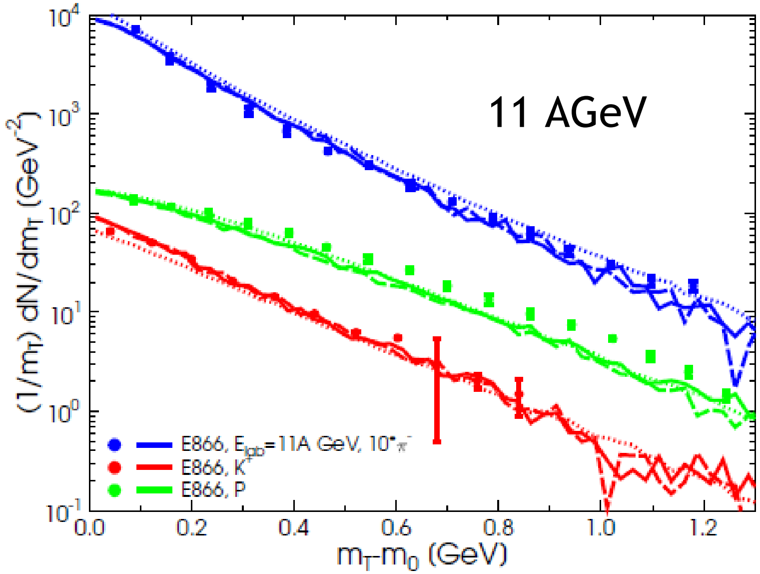
- Small systems lack sufficient thermalisation
- Lambda's etc are still driven by initial state

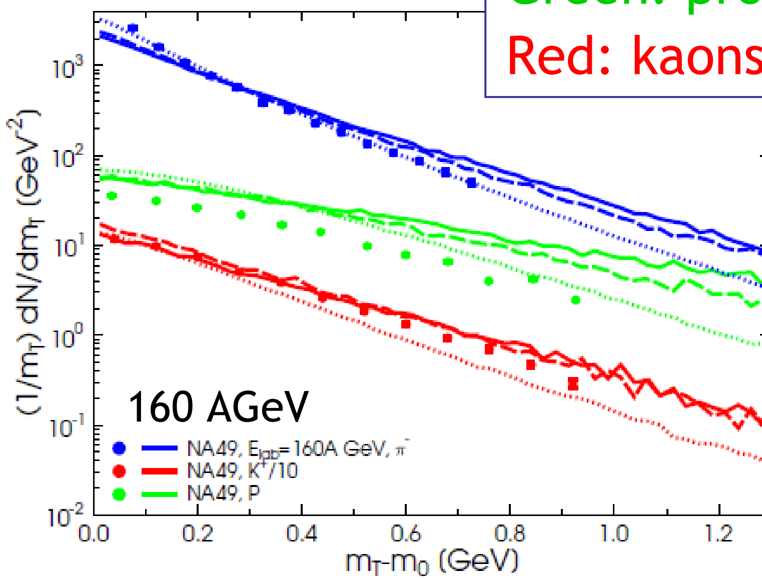


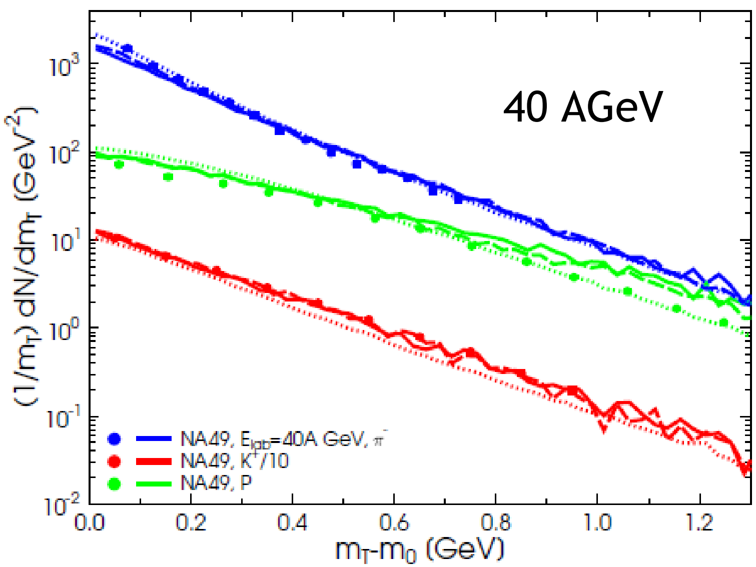
(Petersen et al., arXiv: 0903.0396)

m_T Spectra

Blue: pions
Green: protons
Red: kaons







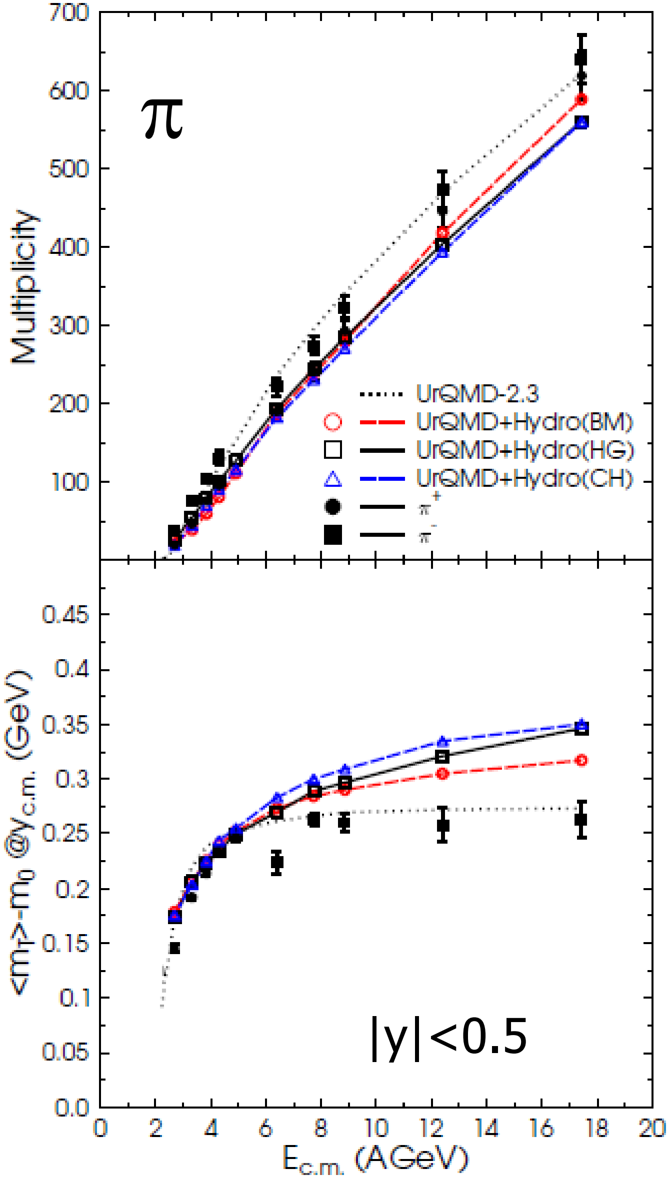
Full line: hybrid model (IF)
Dashed line: hybrid model (GF)
Dotted line: UrQMD-2.3

Central (b<3.4 fm) Pb+Pb/Au+Au collisions

- m_T spectra are very similar at lower energies (11,40 AGeV)
- $\langle m_T \rangle$ is higher in hydro calculation at E_{lab}=160 AGeV

(Petersen et al., PRC 78:044901, 2008)

$<m_T>$ Excitation Function



Data from E866, NA49

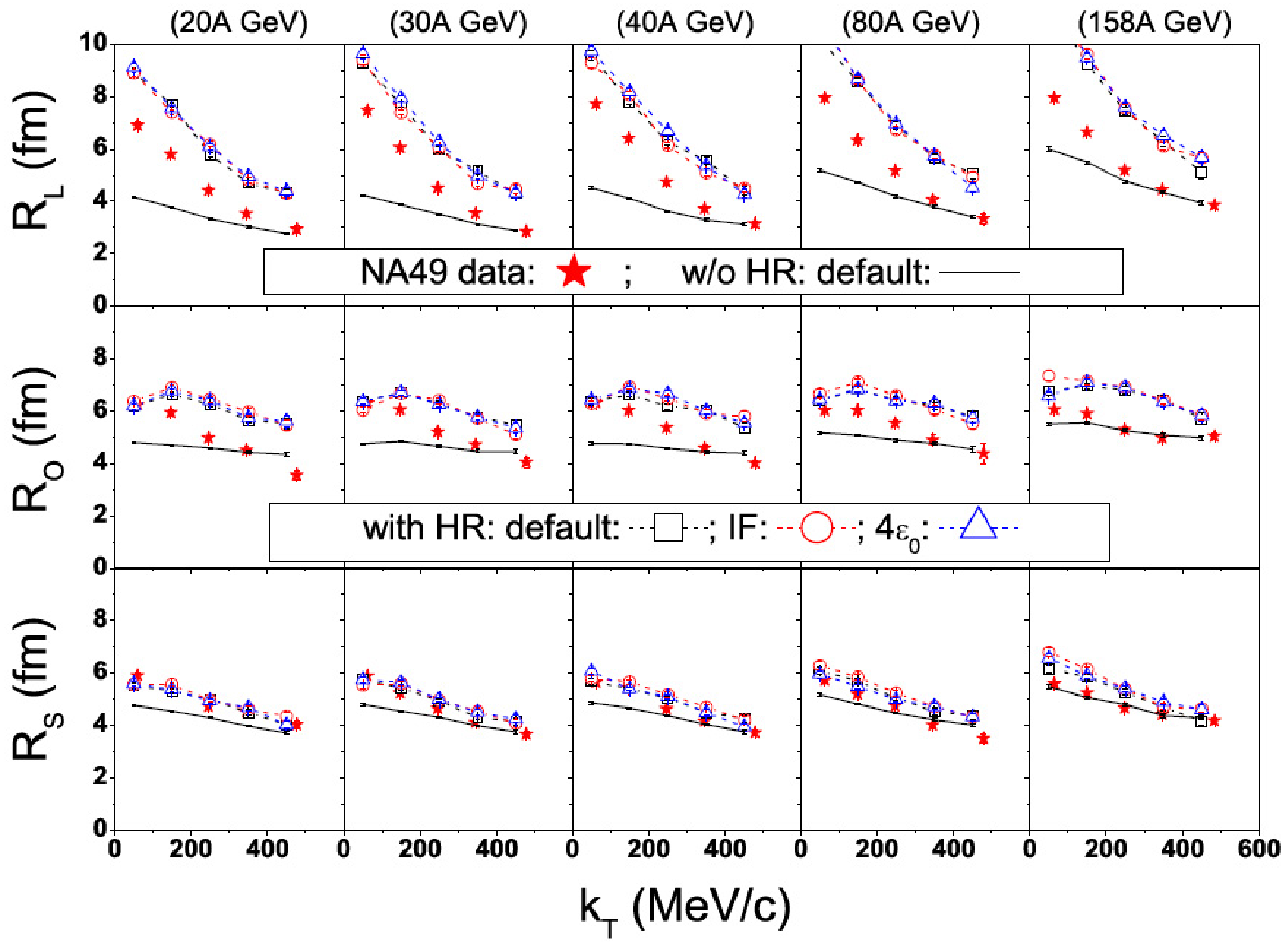
- Resonance excitations and non-equilibrium effects in intermediate energy regime lead to a **softening** of the EoS in pure UrQMD calculation
- Hybrid calculation with hadronic EoS just rises as a function of beam energy
- Even strong first order phase transition leads only to a small effect

Central (b<3.4 fm) Au+Au/Pb+Pb collisions,

Gradual freeze-out for hybrid calculation

(Petersen et al., JPG 36, 055104, 2009)

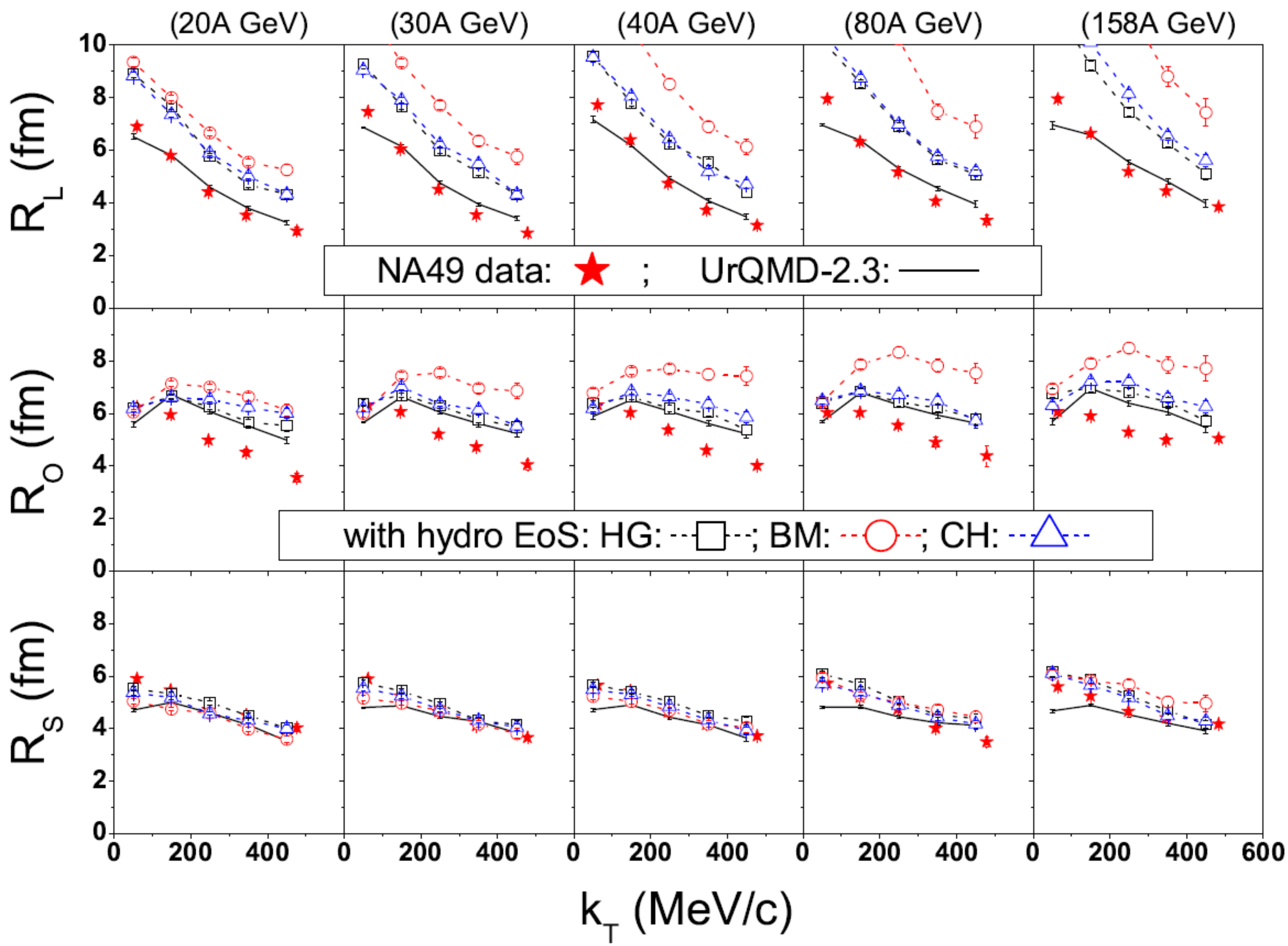
HBT radii (freeze-out effects)



(Q. Li et al., arXiv: 0812.0375, PLB in print)

Freeze-out effects are small, if hadronic rescattering is included

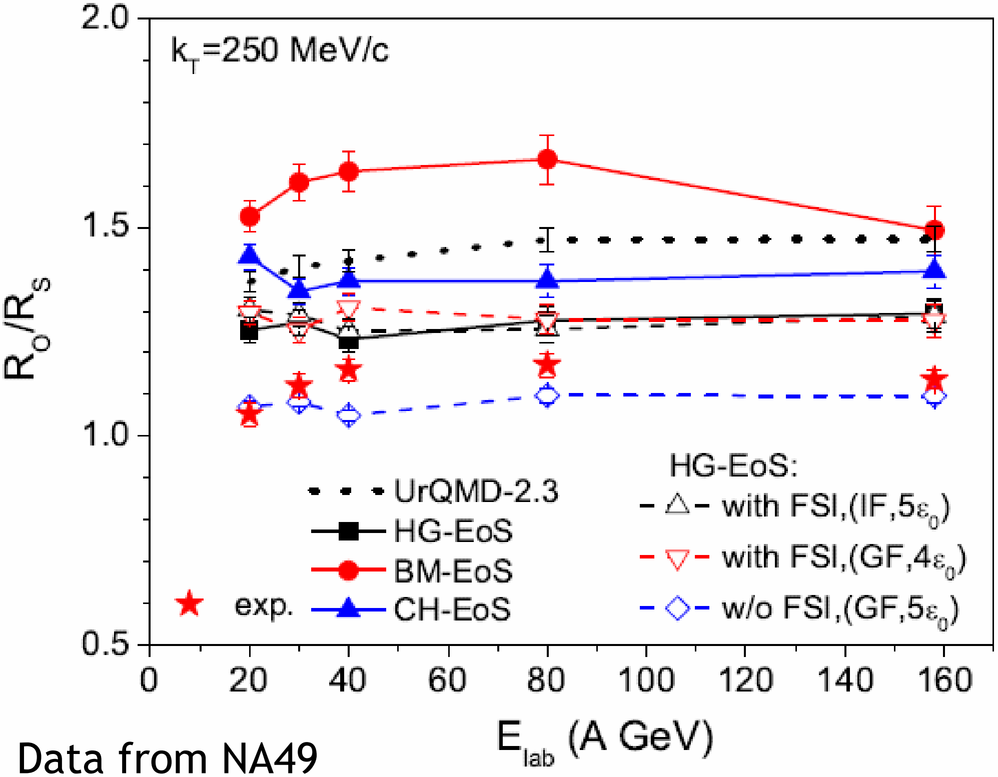
HBT radii (EoS effects)



(Q. Li et al., arXiv: 0812.0375, PLB in print)

Hydro evolution leads to larger radii, esp. with phase transition

R_O/R_S Ratio



Data from NA49

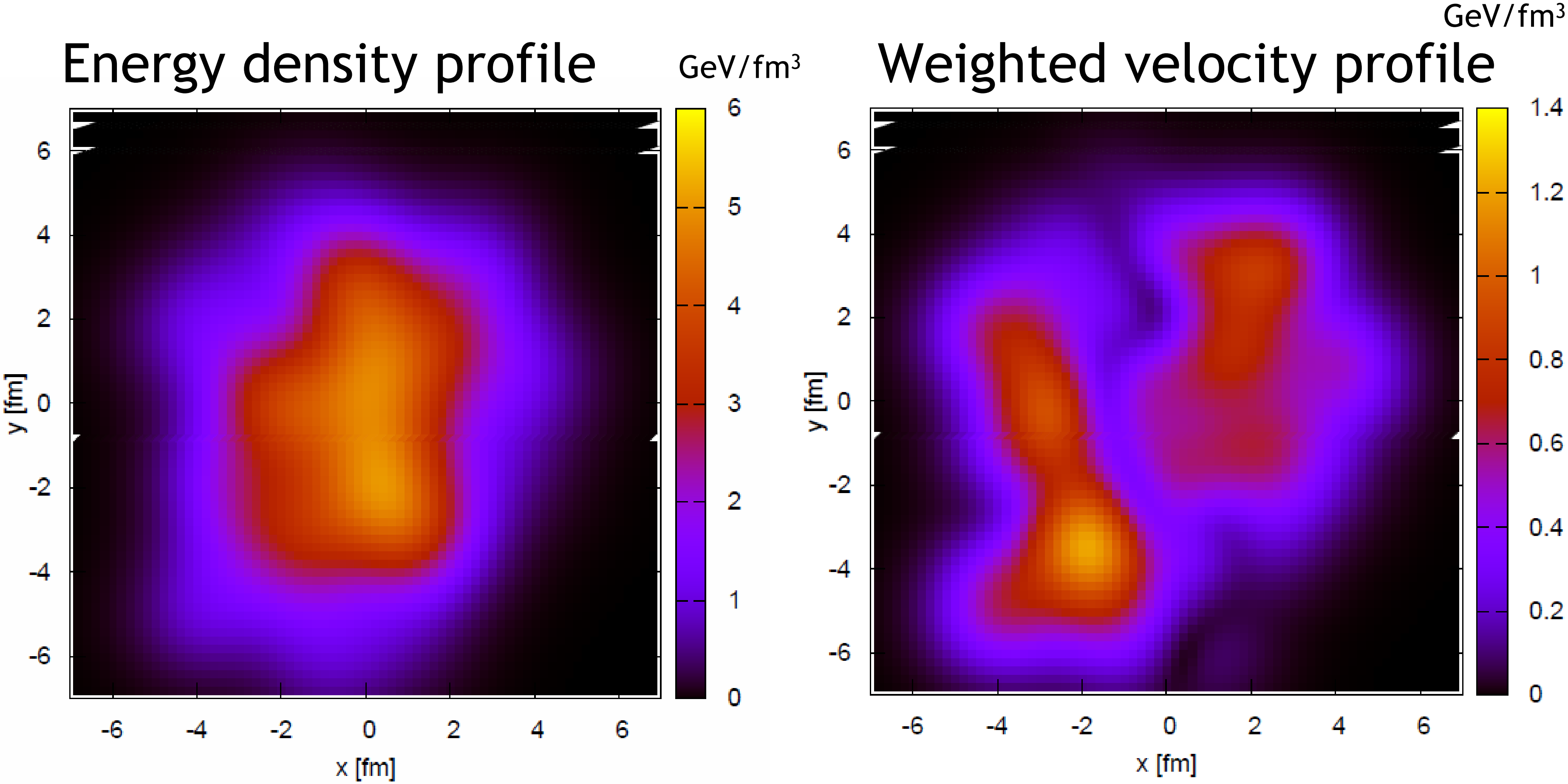
(Q. Li et al., PLB 674, 111, 2009)

- Hydro phase leads to smaller ratios
- Hydro to transport transition does not matter, if final **rescattering** is taken into account
- **EoS dependence** is visible, but not as strong as previuosly predicted (factor of 5)

Initial State for Non-Central Collisions

Pb+Pb at E_{lab}=40 AGeV with b= 7fm at t_{start}=2.83 fm

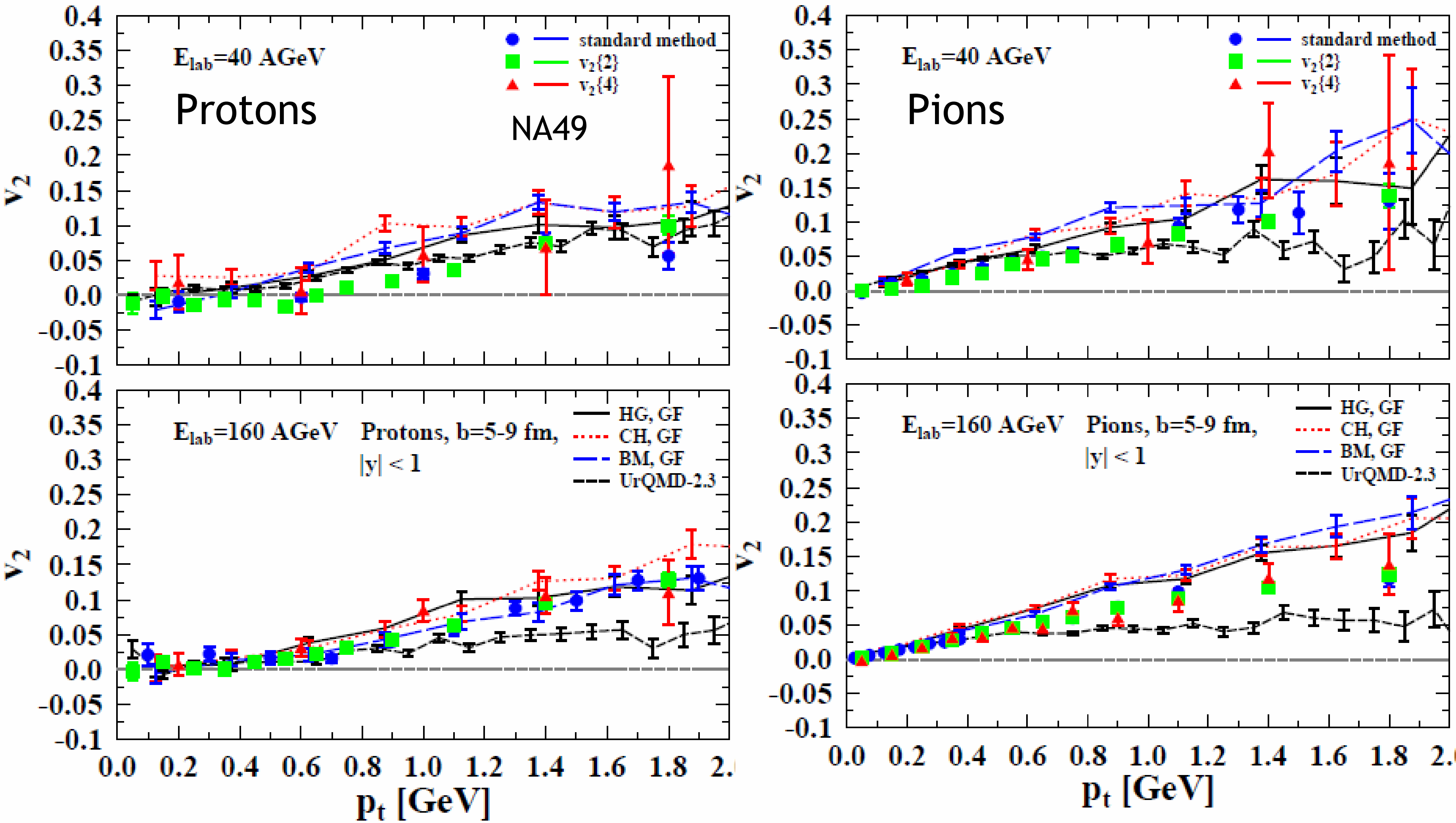
Energy density profile | Weighted velocity profile



→Event-by-event fluctuations are taken into account

(H.P. et.al., arXiv:0901.3821, PRC in print)

v2 -Transverse Momentum Dependence

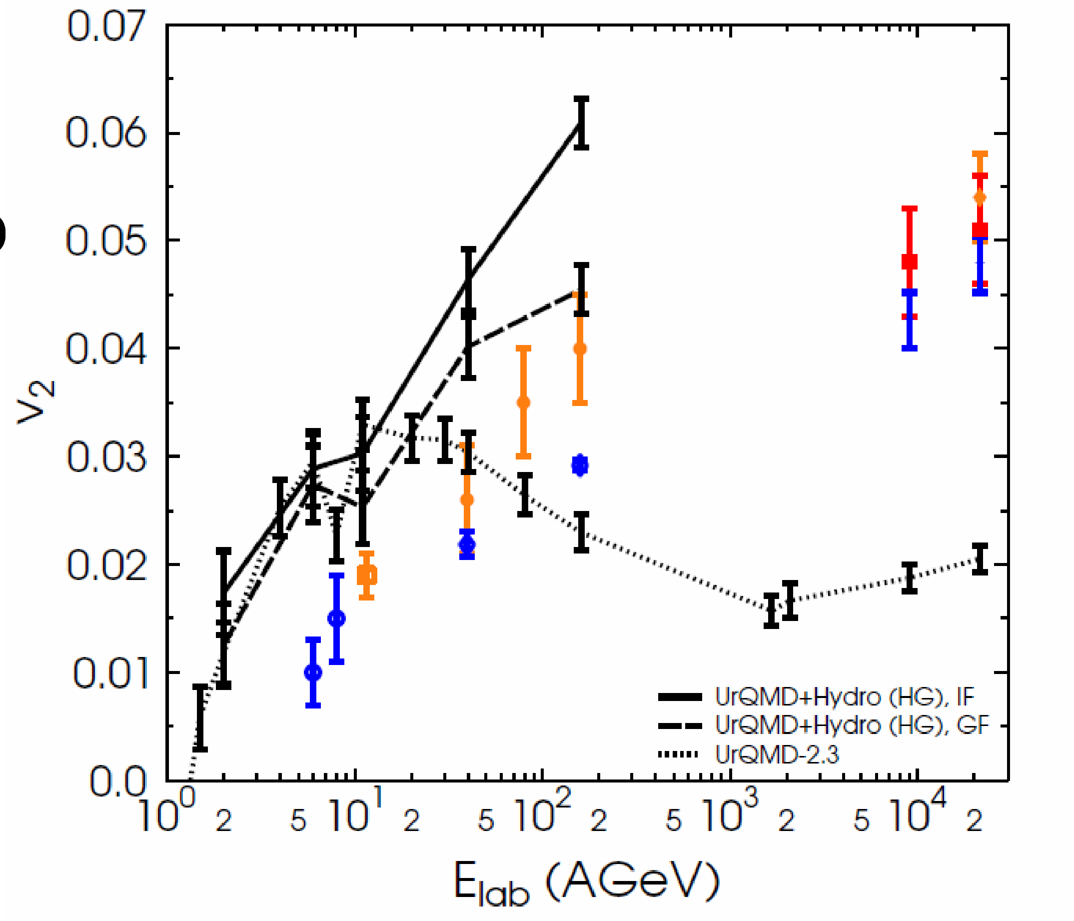


(NA49, PRC 68, 034903, 2003)

Hydro phase leads to higher flow values, but weak EoS dependence

Elliptic Flow

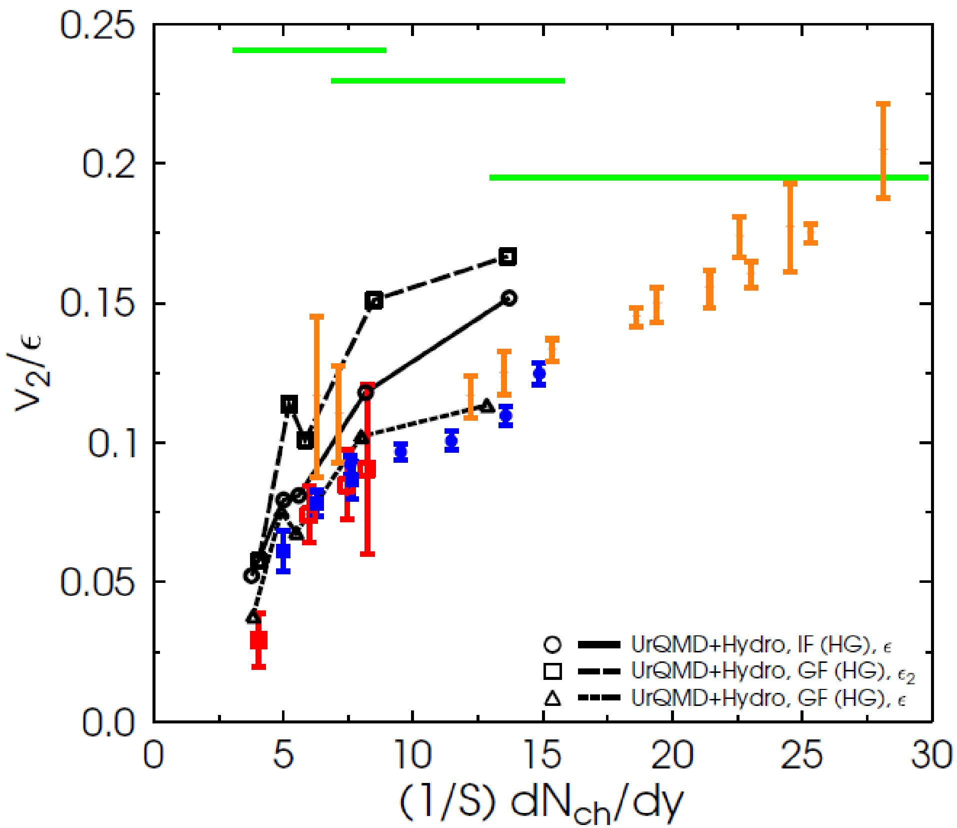
- Smaller **mean free path** in the hot and dense phase leads to higher elliptic flow
- At lower energies: hybrid approach reproduces the pure UrQMD result
- **Gradual freeze-out** leads to a better description of the data



(Petersen et.al., arXiv:0901.3821, PRC in print)

Data from E895, E877, NA49, Ceres, Phenix, Phobos, Star

v_2/ε Scaling



- More **realistic** initial conditions and freeze-out

→ Qualitative behaviour nicely reproduced

- Uncertainty due to **eccentricity** calculation
- Uniqueness of the **hydro limit** is questioned

(Petersen et.al., arXiv:0901.3821, PRC in print)

Data and hydro limits from NA49 compilation, PRC 68, 034903, 2003

Conclusions

- Hybrid approach combines the advantages of a **transport** and a **hydrodynamic** prescription
- **Integrated approach** with the same initial conditions and freeze-out for different EoS
- Well suited for the **FAIR-HADES, FAIR-CBM** energy range

- Particle multiplicities and spectra are reasonably reproduced, **strangeness** enhanced
- Transverse momentum spectra indicate importance of **non-equilibrium effects**
- **Phase transition** is visible in HBT radii, but long fireball lifetime so far not supported by the existing data
- Flow results depend crucially on **initial conditions** and freeze-out