Predictions from the UrQMD Hybrid Model

Adapted parallel talk from Quark Matter 2009,

(based on UrQMD 3.3)

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Thanks to: Jan Steinheimer, Michael Mitrovski, Gerhard Burau, Qingfeng Li, Gunnar Gräf, Marcus Bleicher, Horst Stöcker, Dirk Rischke

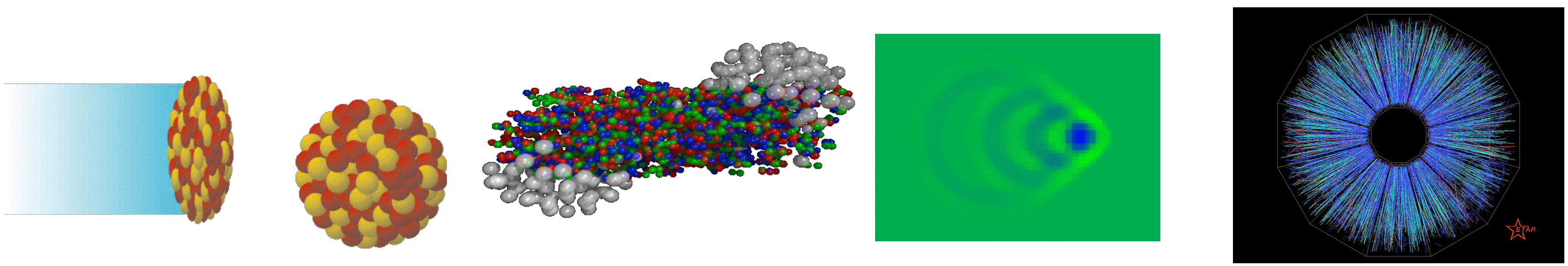
Outline

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

Recent review on Flow in Hybrid Approaches arXiv:1404.1763 (JPG focus issue)

Introduction

- 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

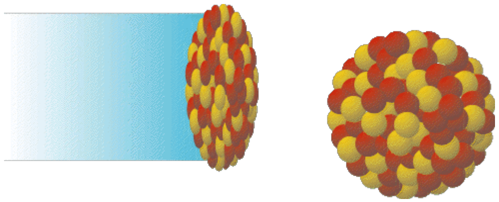
2) Hydrodynamic evolution **or** Transport calculation

3) Freeze-out via hadronic cascade (UrQMD)

UrQMD-3.4 is available at www.urqmd.org

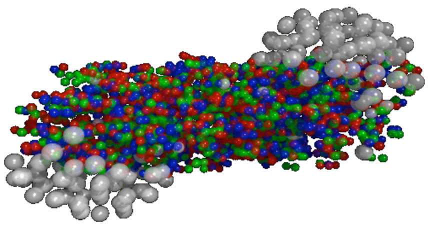
The UrQMD transport approach

UrQMD = Ultra-relativistic Quantum Molecular Dynamics



- Initialisation:

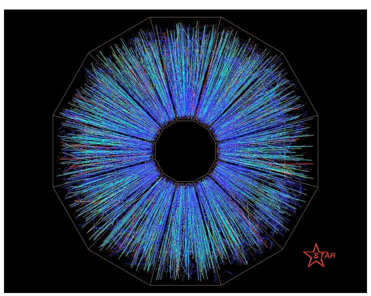
  Nucleons are set according to a Woods-Saxon distribution with randomly chosen momenta $p_i < p_F$



- Propagation and Interaction:

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

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



- Final state:

  all particles with their final positions and momenta

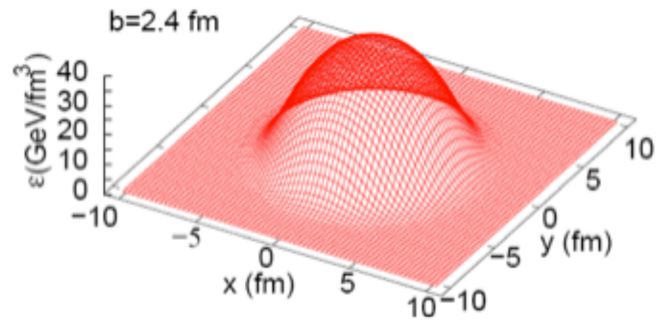
Very successful in describing different observables in a broad energy range
But: modeling of the phase transition and hadronization not yet possible

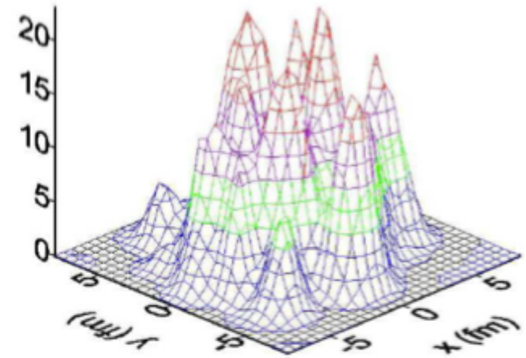
Initial State

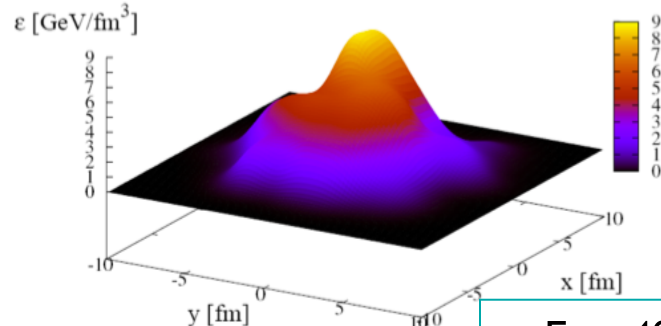
- Contracted nuclei have passed through each other

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

  - 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







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

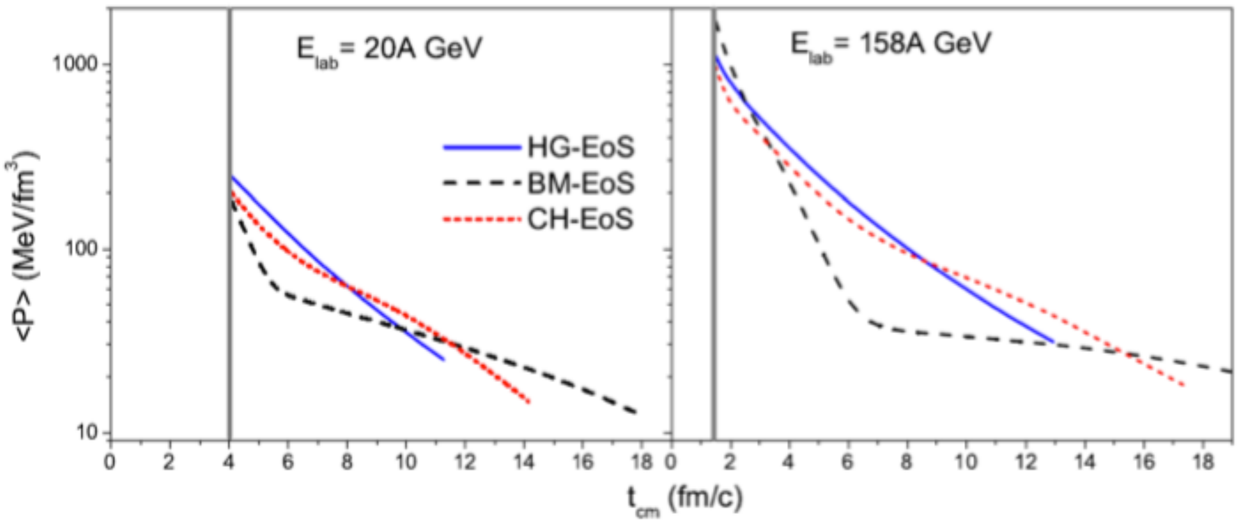
E_{lab}=40 AGeV
b=0 fm

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

(3+1)d Hydrodynamic Evolution

Ideal relativistic one fluid dynamics employing:

- 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



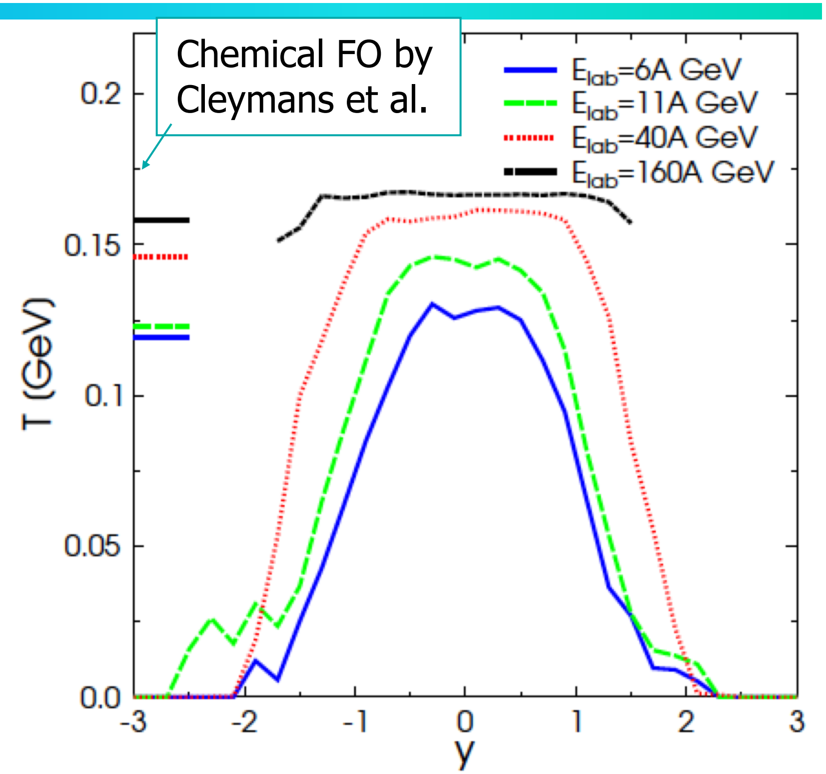
D. Rischke et al., NPA 595, 346, 1995,

D. Rischke et al., NPA 595, 383, 1995

Papazoglou et al., PRC 59, 411, 1999

Freeze-out

1) Transition from hydro to transport when
   ε < 730 MeV/fm³ (≈ 5 * ε_0)
   in all cells of one transverse slice (**Gradual freeze-out**, GF)
   → iso-eigentime criterion
2) Transition when ε < 5* ε_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 m_B and m_S

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

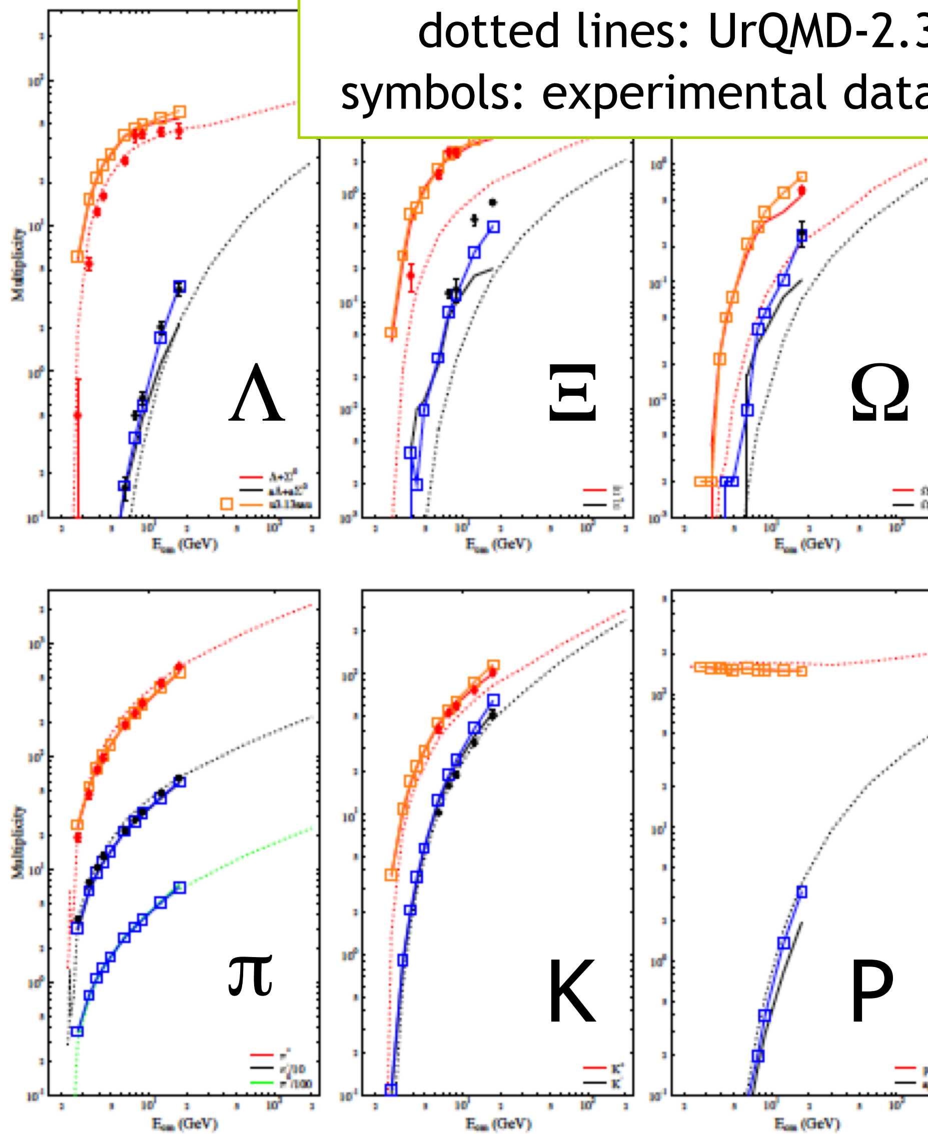
Multiplicities vs. Energy

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

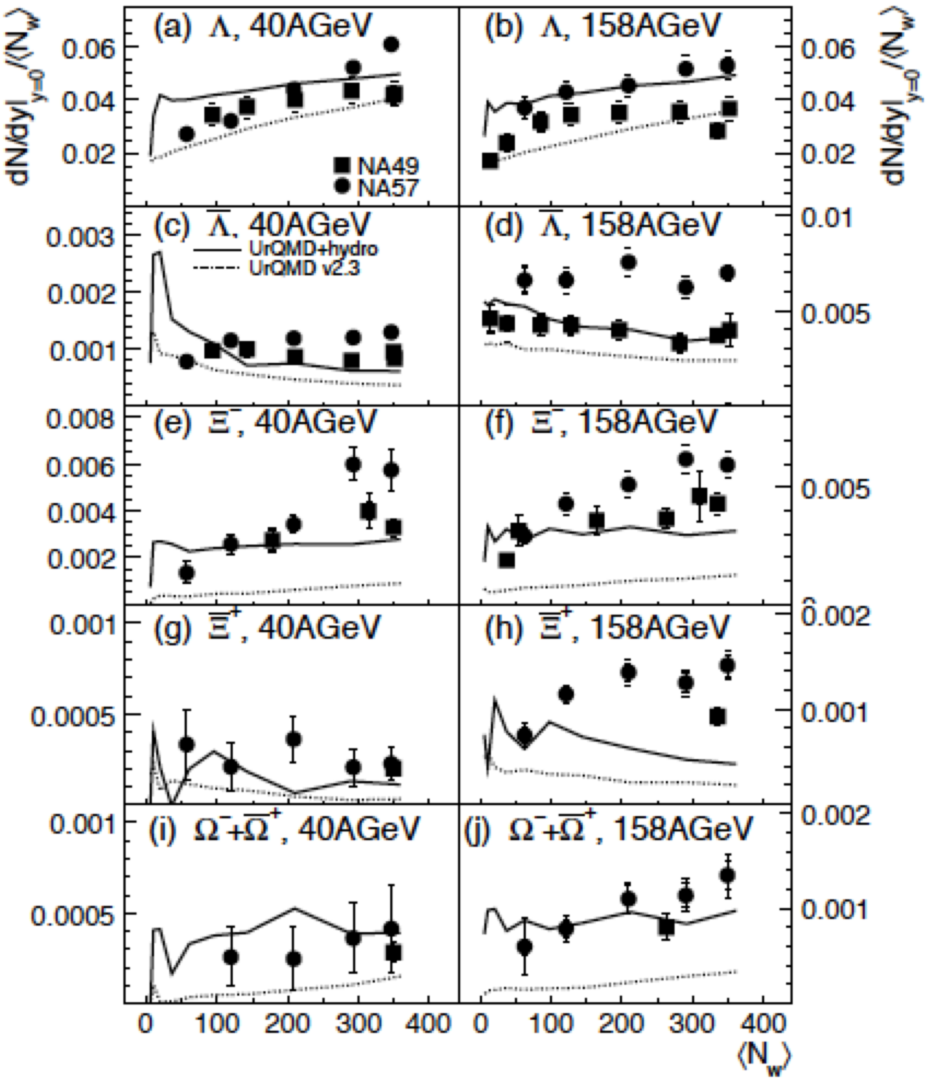


(H.P. et al., PRC 78:044901, 2008)

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

Data from E895, NA49

Strangeness Centrality Dependence



Pb+Pb collisions for different centralities

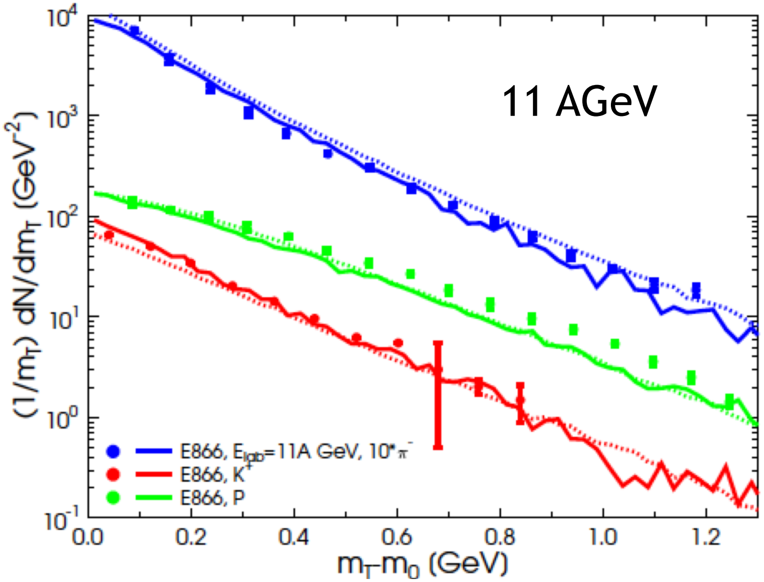
- Thermal production of the particles at transition from hydro to transport
- Centrality dependence of **multistrange hyperons** is improved

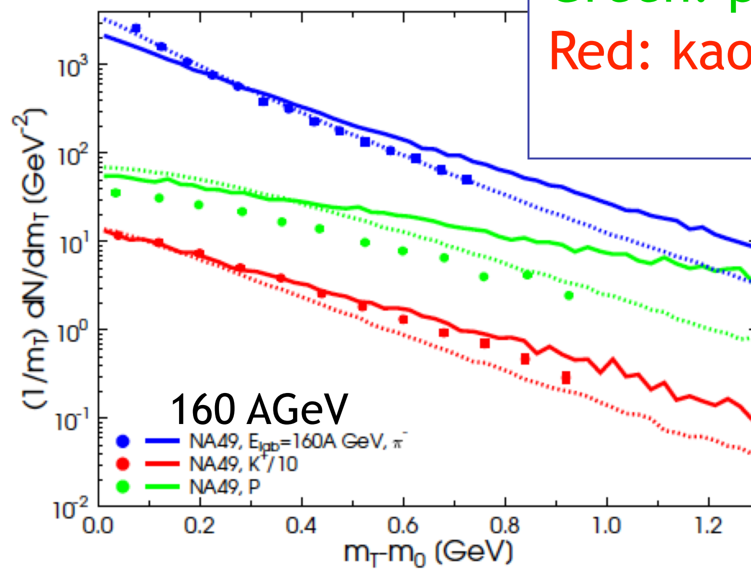
—— hybrid model (GF)
----- UrQMD-2.3

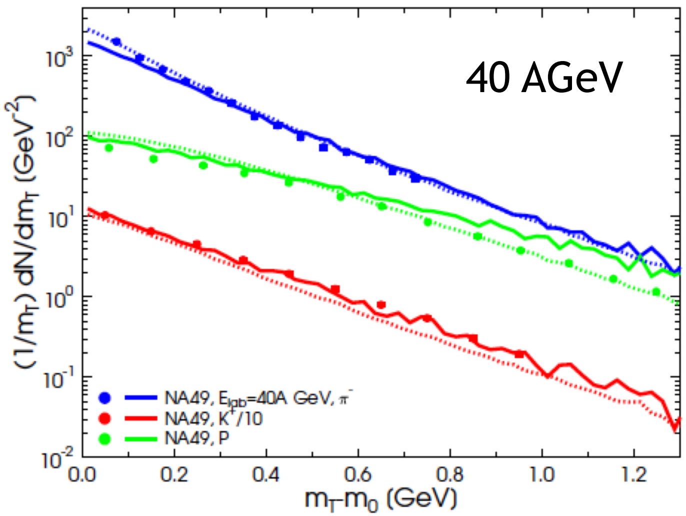
(H.P. et al., arXiv: 0903.0396)

m_T Spectra

Blue: pions
Green: protons
Red: kaons







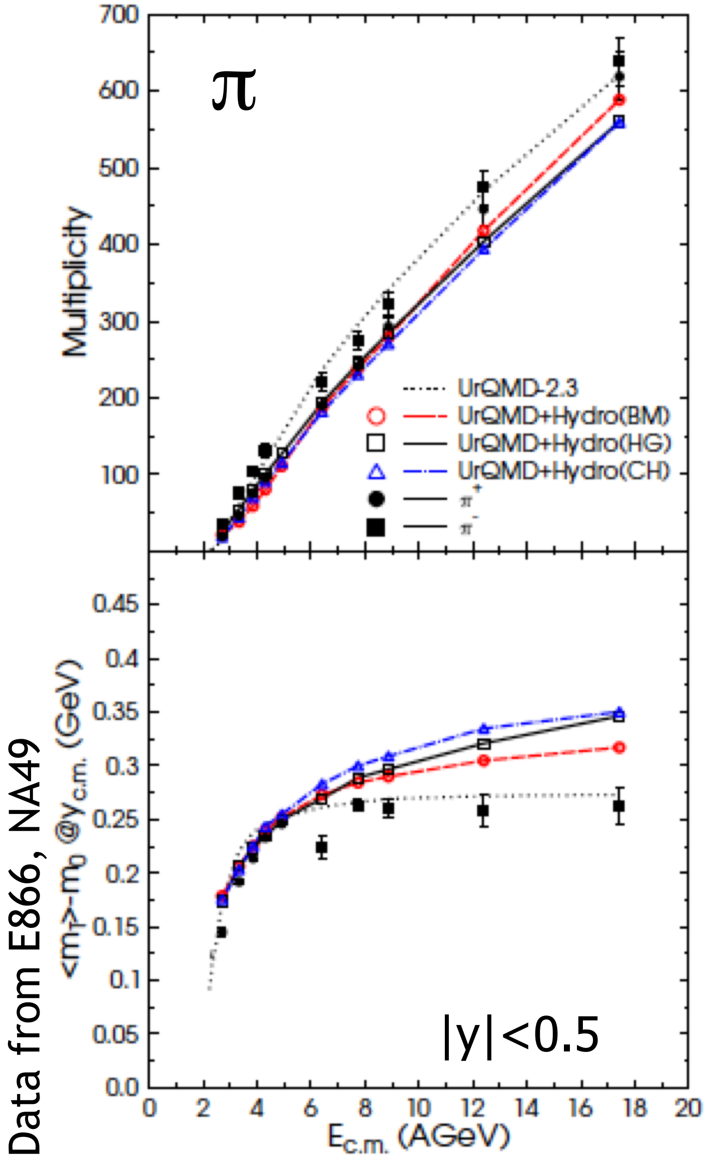
Full line: hybrid model (IF)
Dotted line: UrQMD-2.3

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

(H.P. et al., PRC 78:044901, 2008)

$\langle m_T \rangle$ Excitation Function



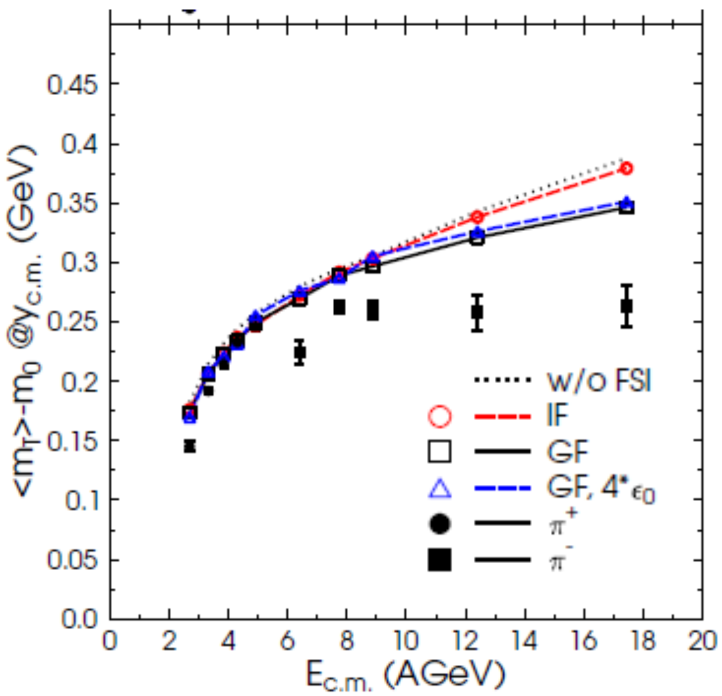
- Resonance excitations and non-equilibrium effects in intermediate energy regime lead to a **softening** of the EoS in pure UrQMD calculation
- Hybrid calculation with hadronic EoS just rises as a function of beam energy
- Even strong first order phase transition leads only to a small effect

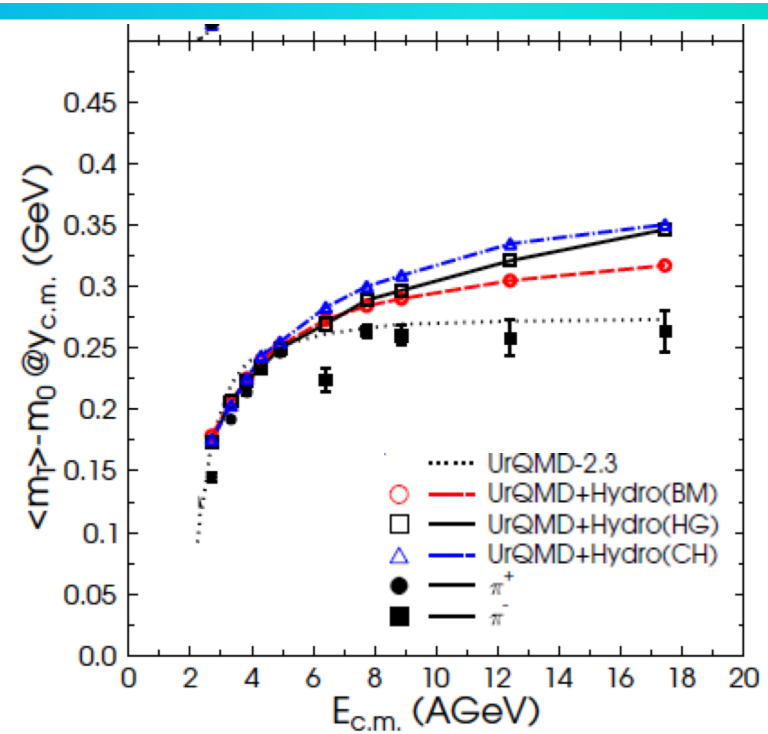
Central (b<3.4 fm) Au+Au/Pb+Pb collisions,

Gradual freeze-out for hybrid calculation

(H.P. et al., arXiv: 0902.4866, JPG in print)

<m_T> Excitation Function





Data from E866, NA49

Hadronic hydro calculation with different freeze-out scenarios

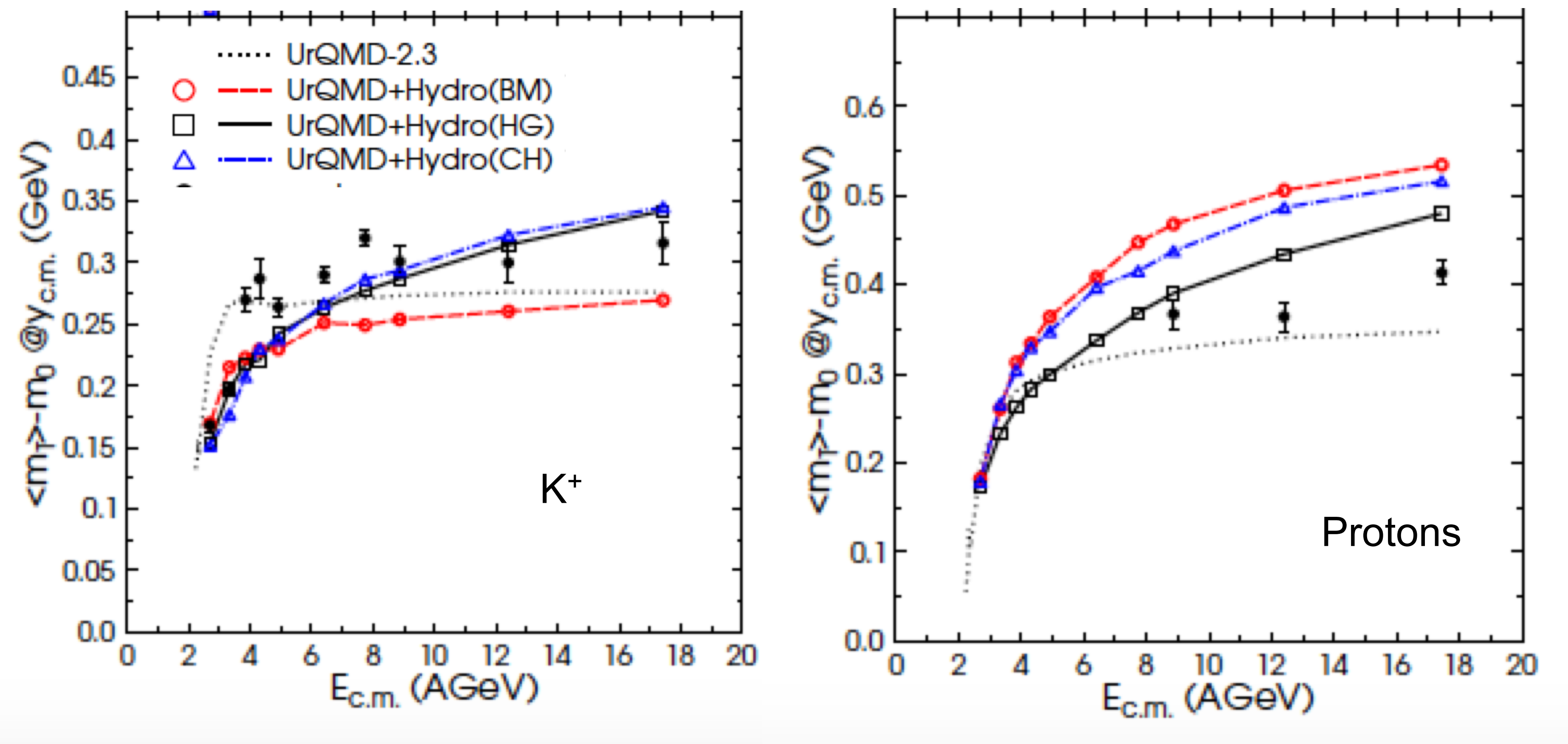
→ Freeze-out treatment is important

Dynamics (viscosity) and equation of state are crucial input

(H.P. et al., arXiv: 0902.4866, JPG in print)

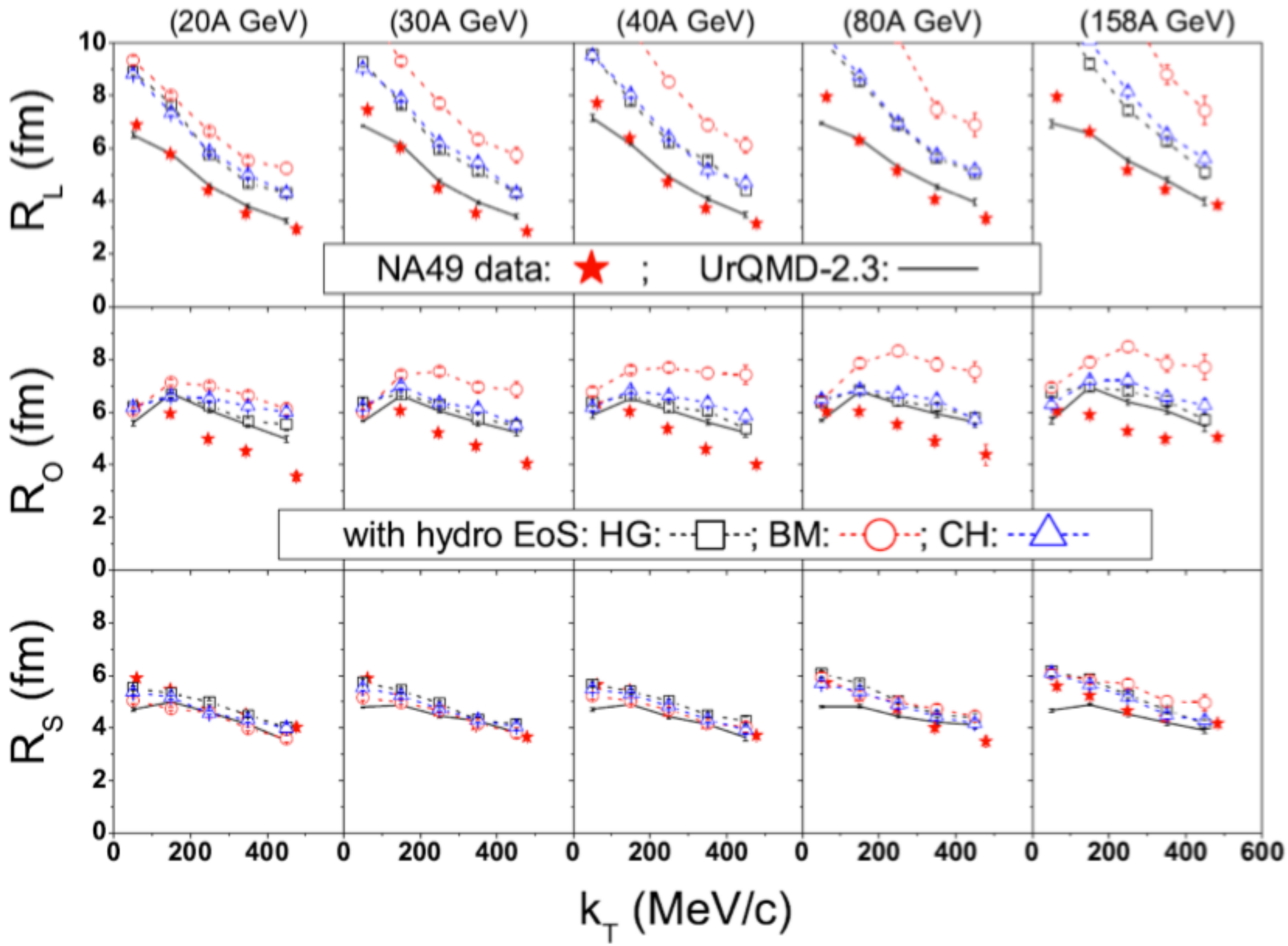
Mean Transverse Mass

- Largest effect of EoS on kaons



- Pure UrQMD and bag model yield similar results

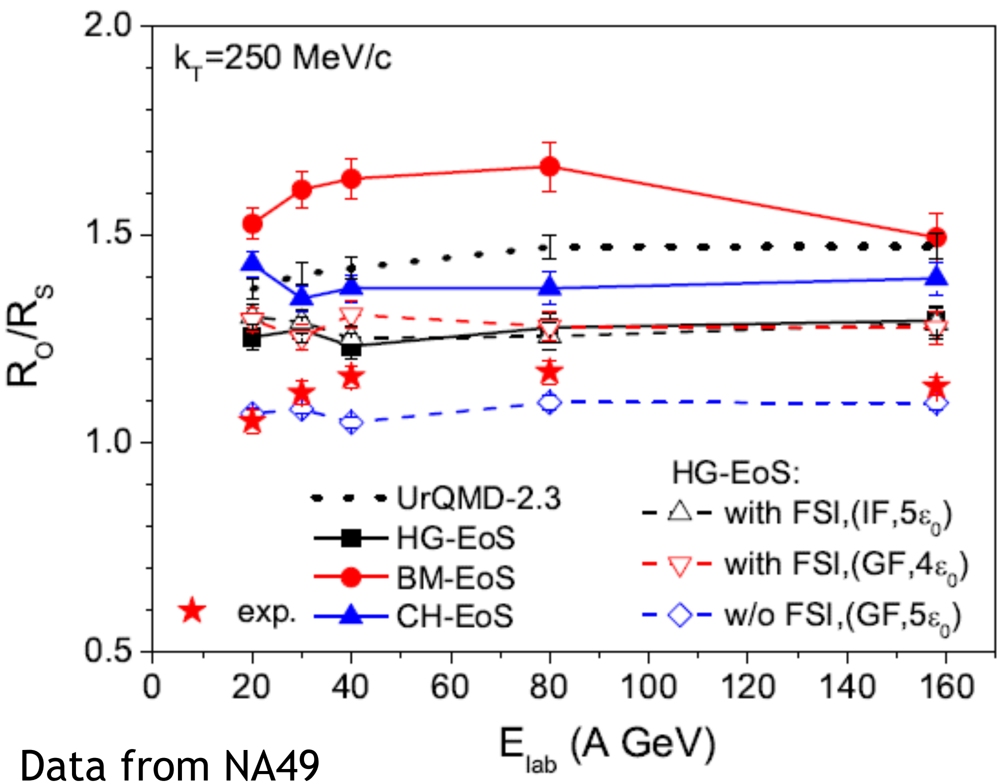
HBT radii



(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

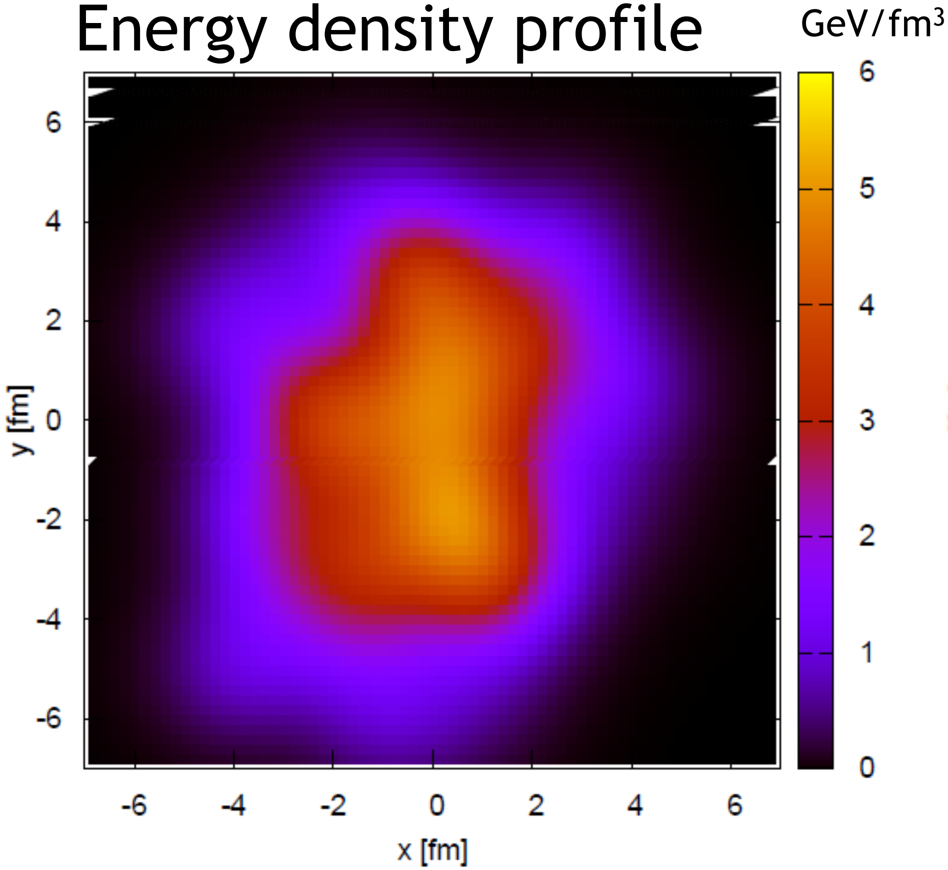
- Hydro phase leads to smaller ratios
- Hydro to transport transition does not matter, if final **rescattering** is taken into account
- **EoS dependence** is visible, but not as strong as previously predicted (factor of 10)

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

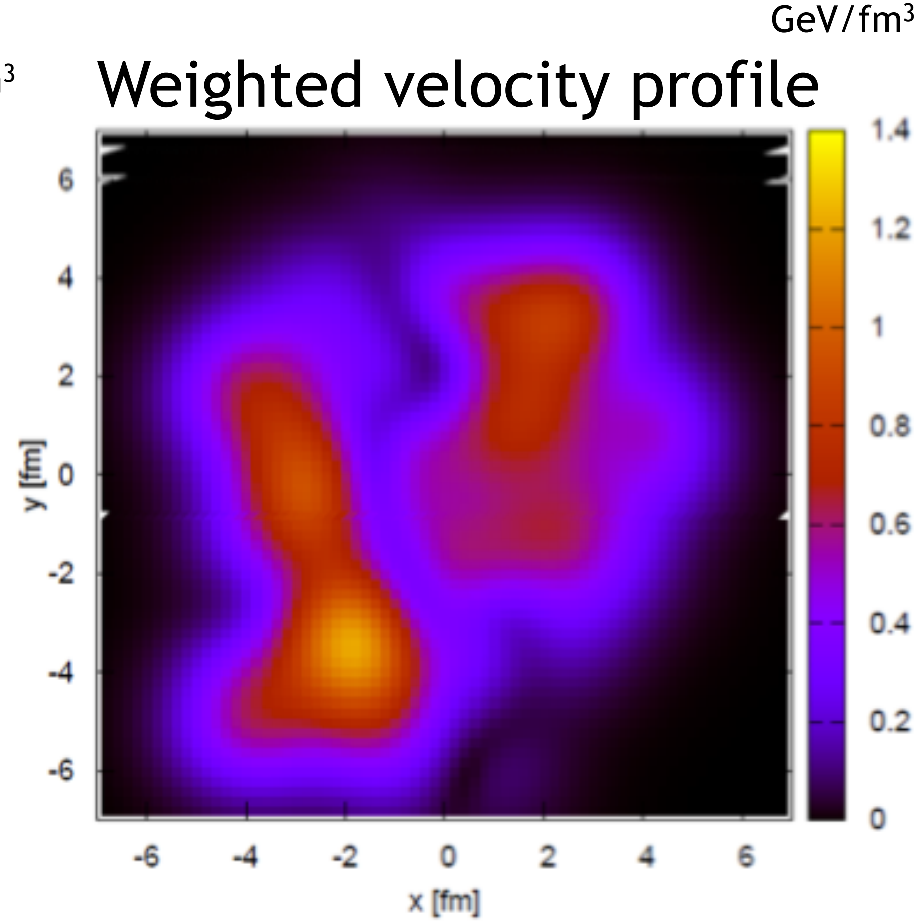
Initial State for Non-Central Collisions

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

Energy density profile



Weighted velocity profile

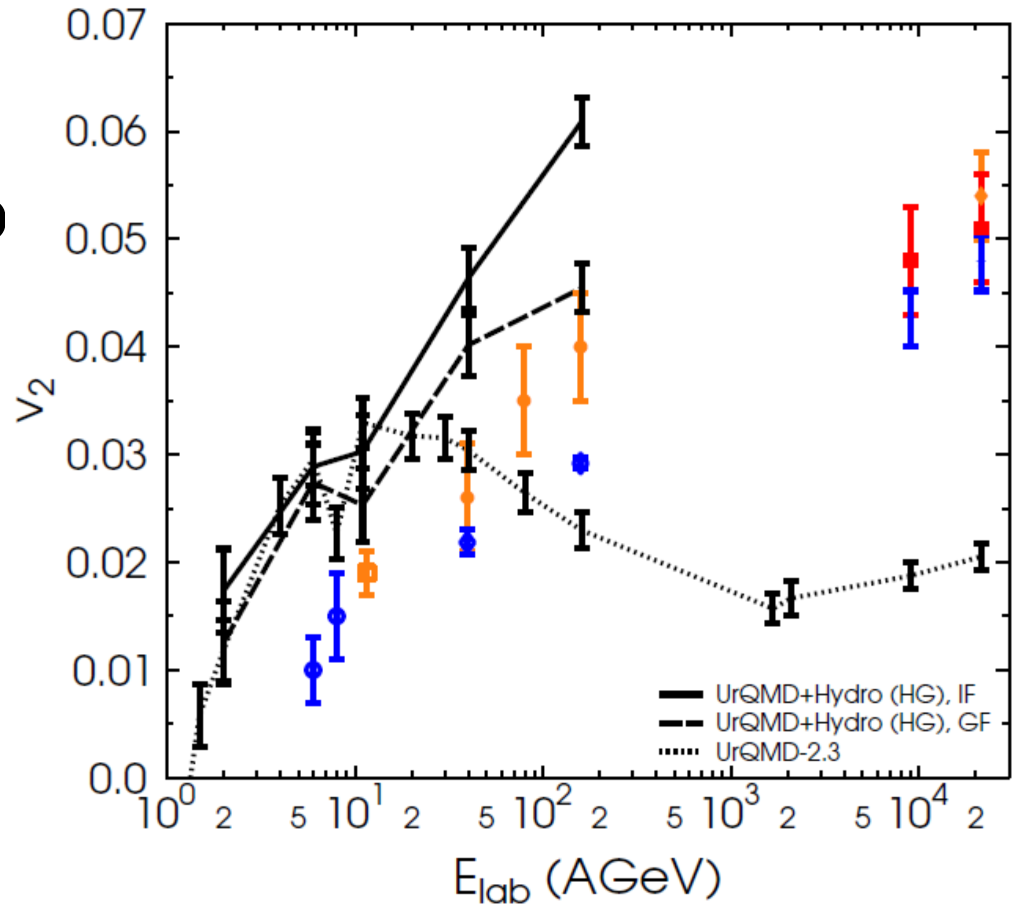


→Event-by-event fluctuations are taken into account

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

Elliptic Flow

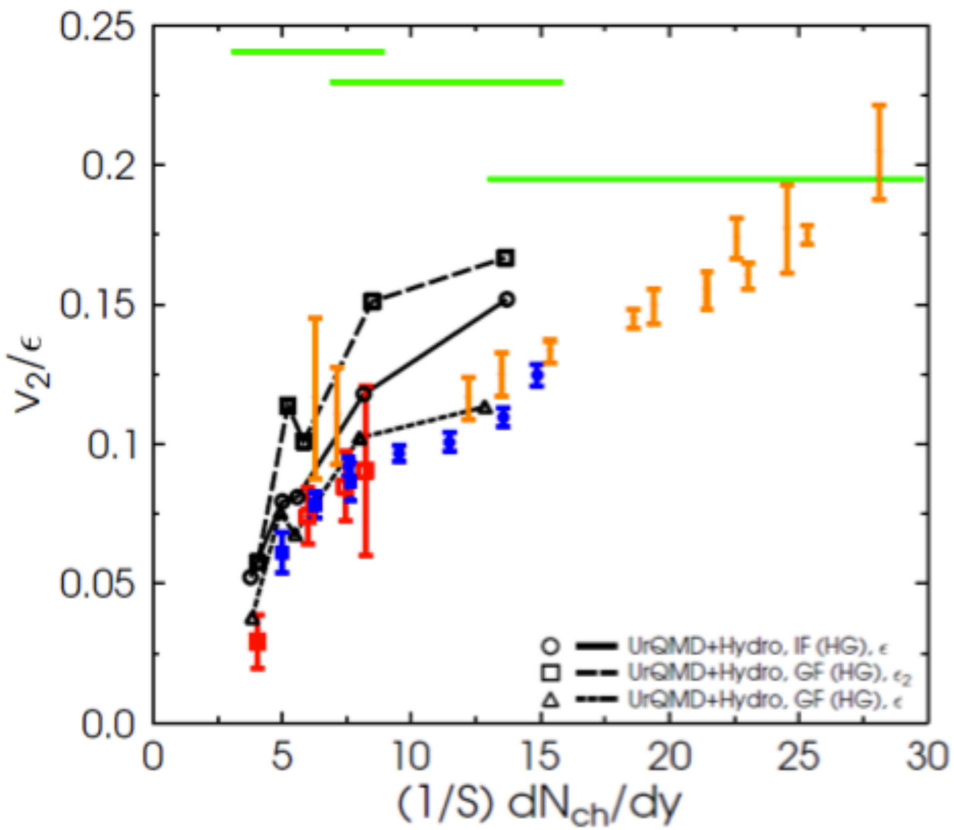
- Smaller **mean free path** in the hot and dense phase leads to higher elliptic flow
- At lower energies: hybrid approach reproduces the pure UrQMD result
- **Gradual freeze-out** leads to a better description of the data



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

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

v_2/ε Scaling



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

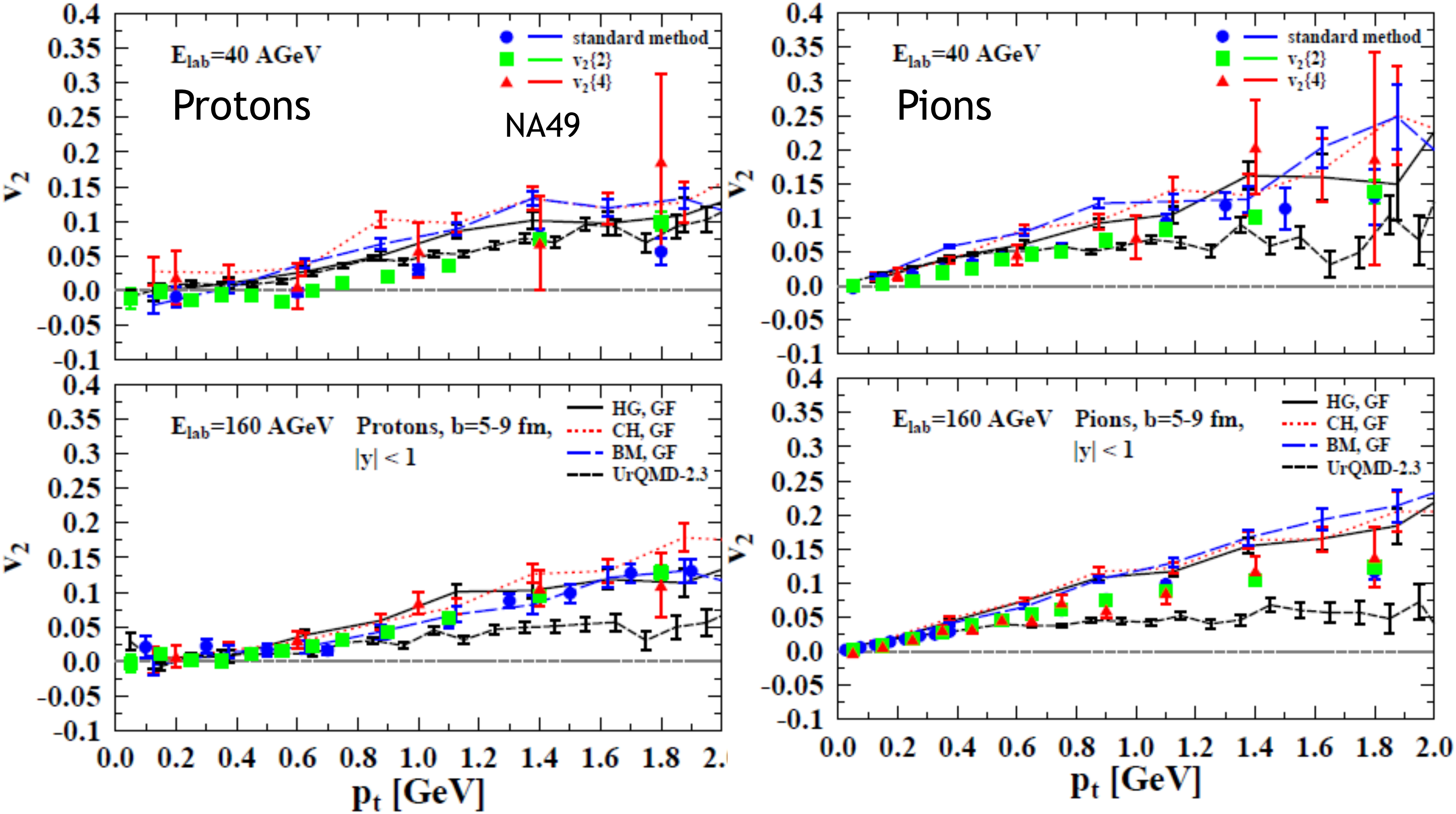
- More **realistic** initial conditions and freeze-out

→ Qualitative behaviour nicely reproduced

- Uncertainty due to **eccentricity** calculation
- Hybrid approach describes qualitatively the density dependence of the response function

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

Transverse Momentum Dependence



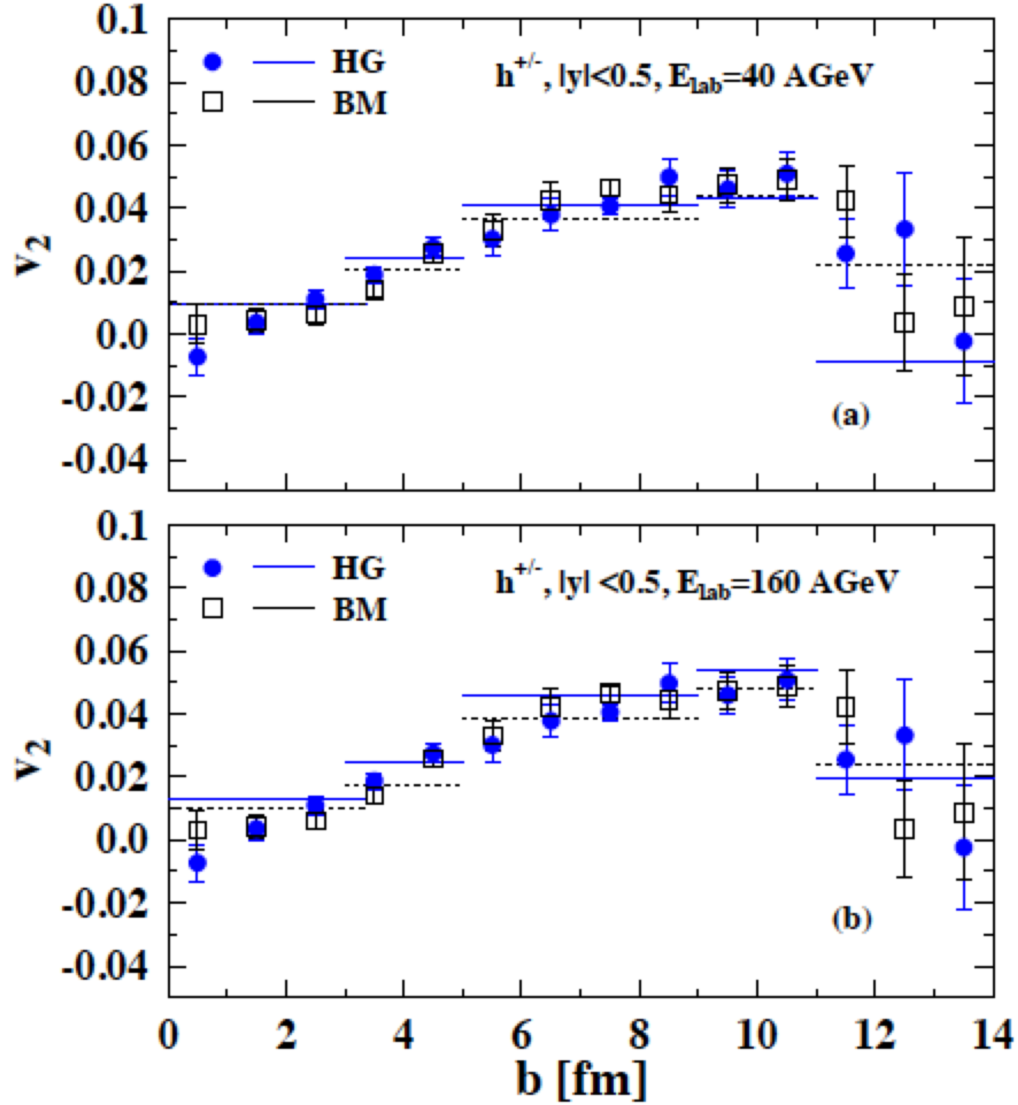
(NA49, PRC 68, 034903, 2003)

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

Equation of State and IC Fluctuations

- Symbols: Event-by-event calculations
- Horizontal lines: Averaged results
- Blue: Hadron Gas EoS
- Black: Bag Model EoS

- NO difference visible in the centrality dependence of elliptic flow



HP et al, Phys.Rev. C81 (2010) 044906

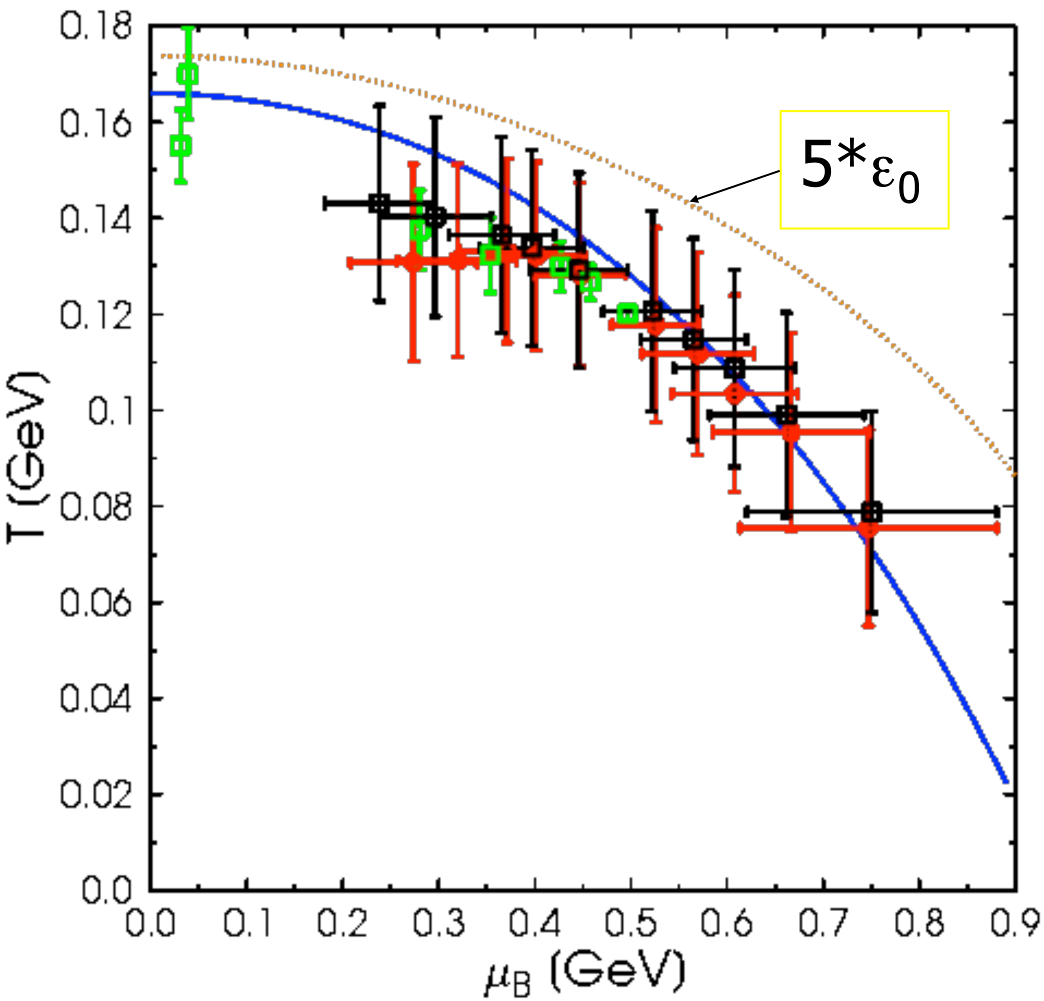
Conclusions

- **Integrated approach** with the same initial conditions and freeze-out for different EoS
- 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

- In modern hybrid approaches: +constant energy density hypersurface + viscosity + improved EoS

Backup

Freeze-out line



- Parametrization of chemical freeze-out line taken from Cleymans et al, J.Phys. G 32, S165, 2006
- Green points are from A.Dumitru et al., PRC 73, 024902, 2006

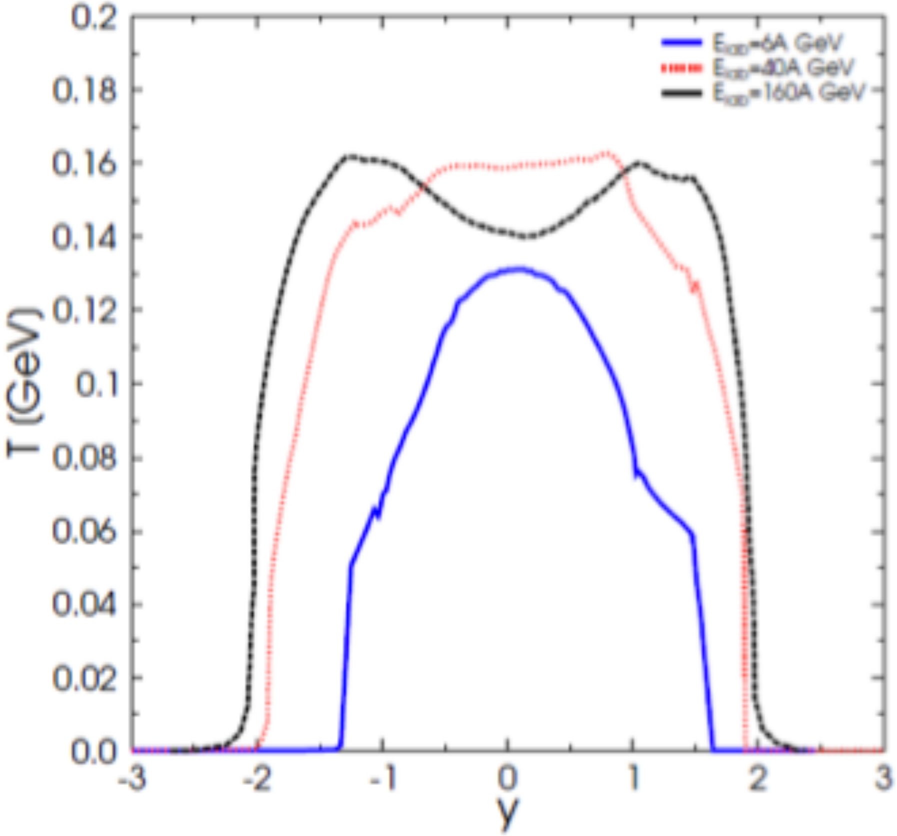
→ Mean values and widths are in line with other calculations

Black: Gradual FO

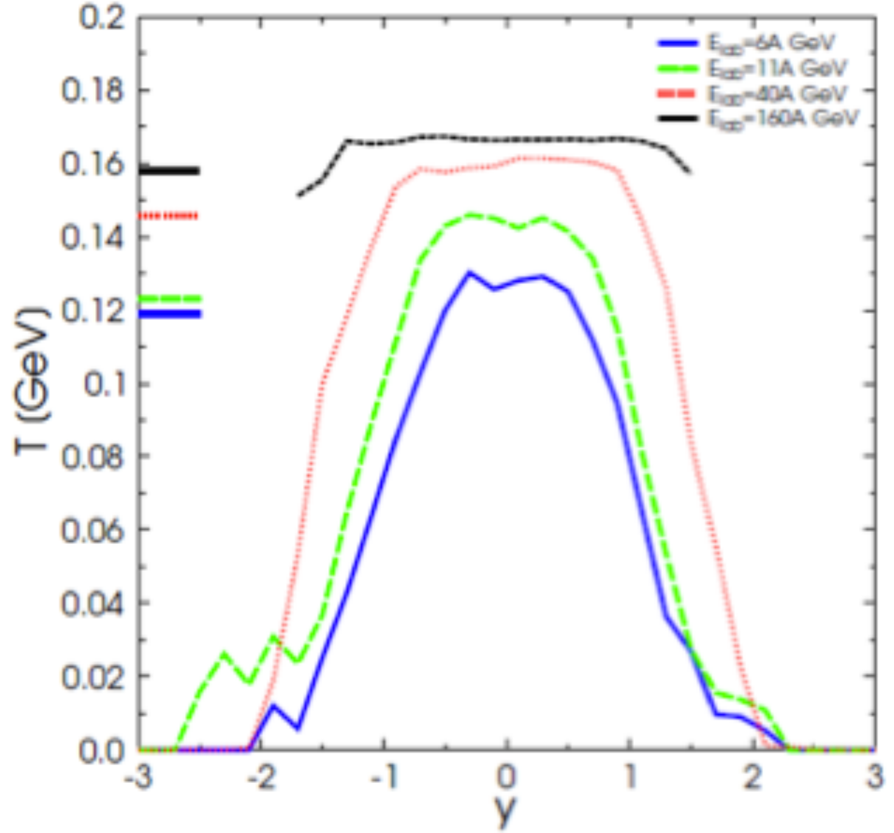
Red: Isochronuous FO

Temperature Distributions

Rapidity distribution of the freeze-out temperatures in central Au+Au/Pb+Pb collisions with hadron gas EoS

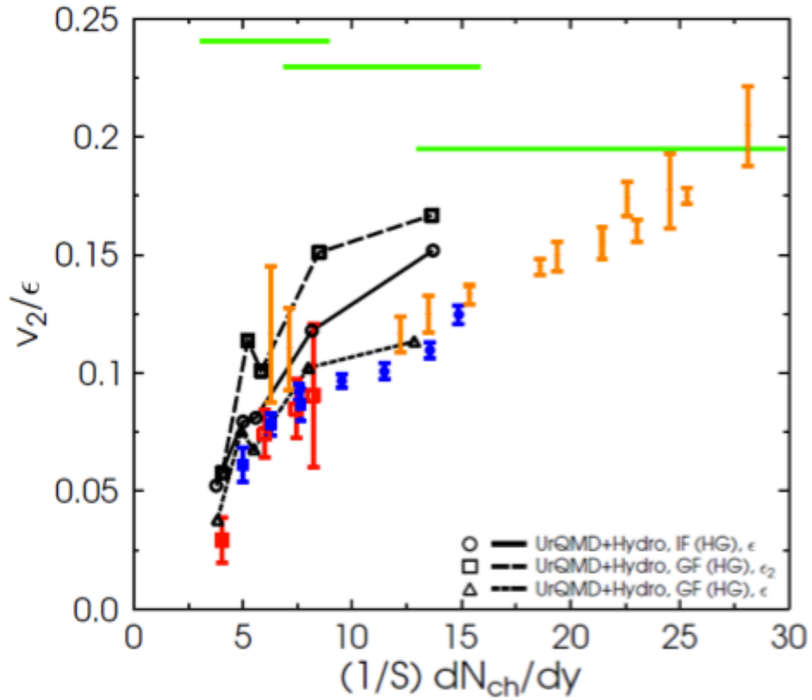


Isochronuous freeze-out



Gradual freeze-out

v_2/ε Scaling



- More realistic initial conditions and freeze-out

→ Qualitative behaviour nicely reproduced

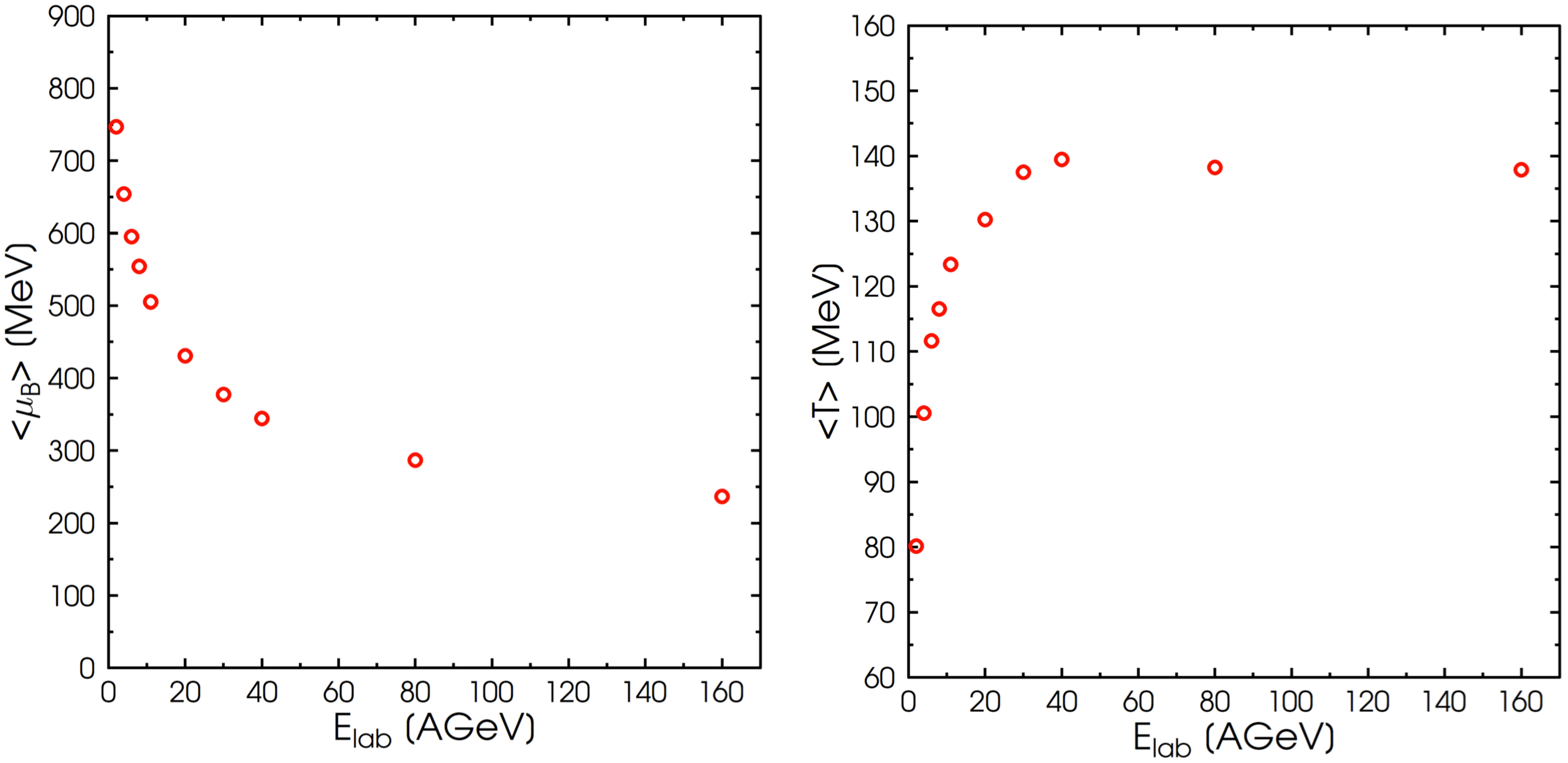
- Uncertainty due to eccentricity calculation

$$\epsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle} \qquad S = \pi\sqrt{\langle x^2 \rangle \langle y^2 \rangle} \qquad \epsilon_2 = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

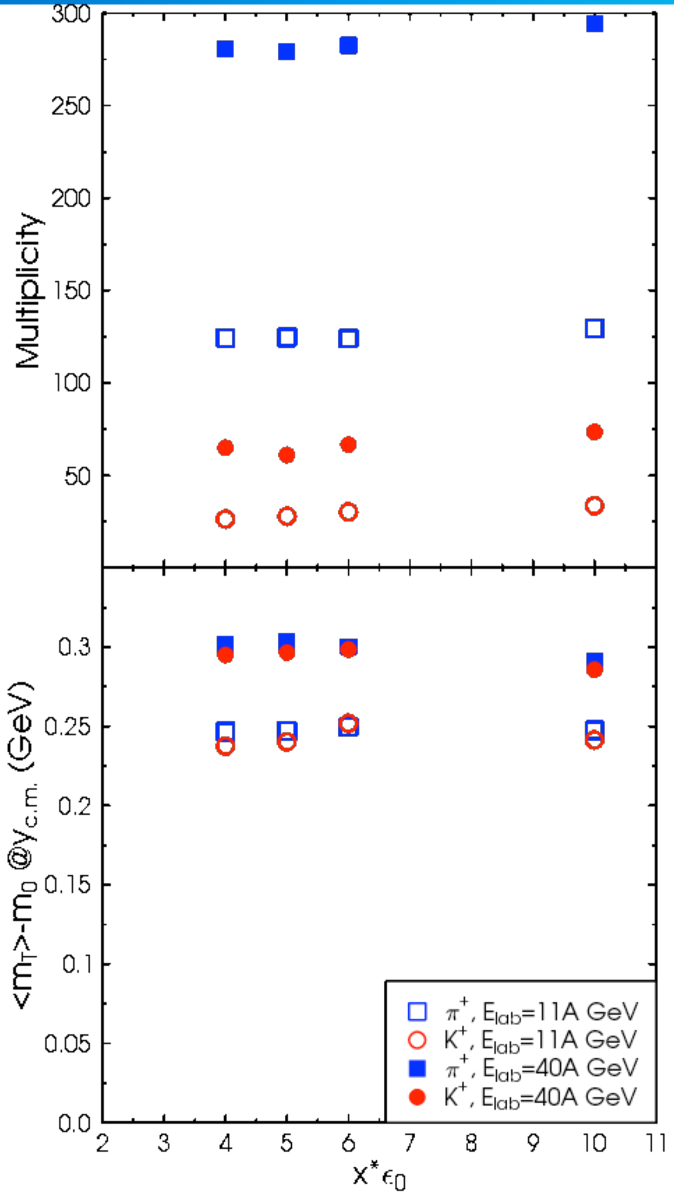
Avaraged over particles and events at the same time

Averaged first over particles and then over events

Freeze-out conditions



Dependence on Freeze-out

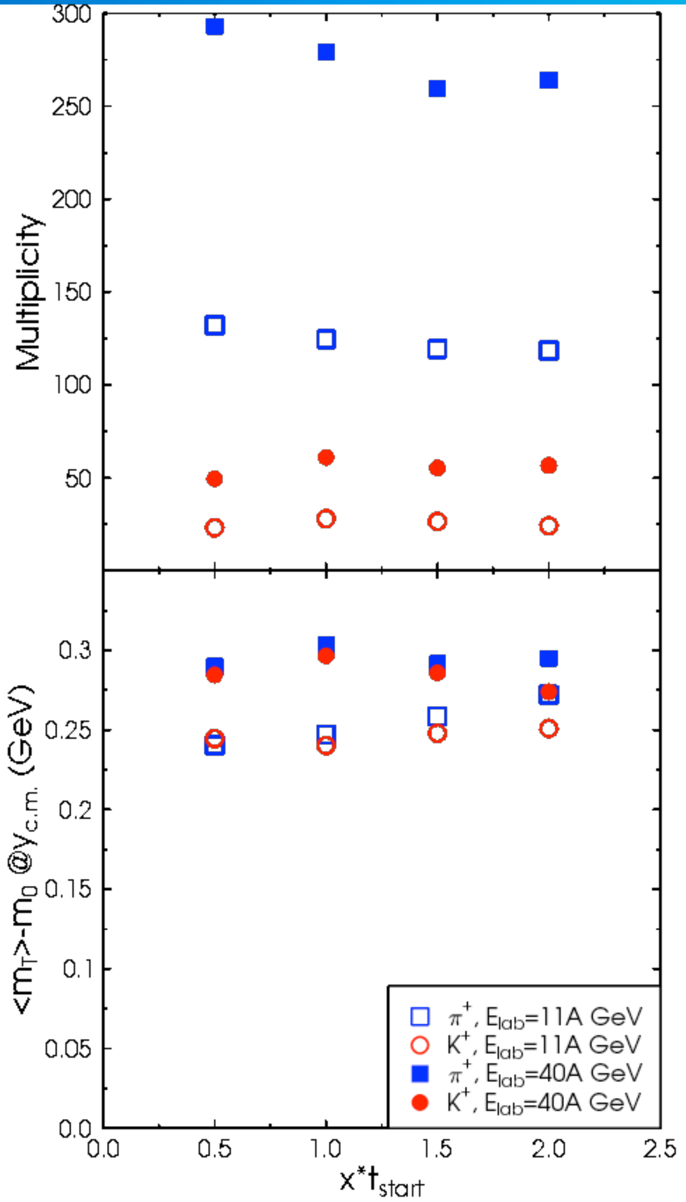


- Variation of the freeze-out criterium does not affect the meson multiplicities and mean transerve masses

Full symbols: 40 AGeV

Open symbols: 11 AGeV

Dependence on t_{start}

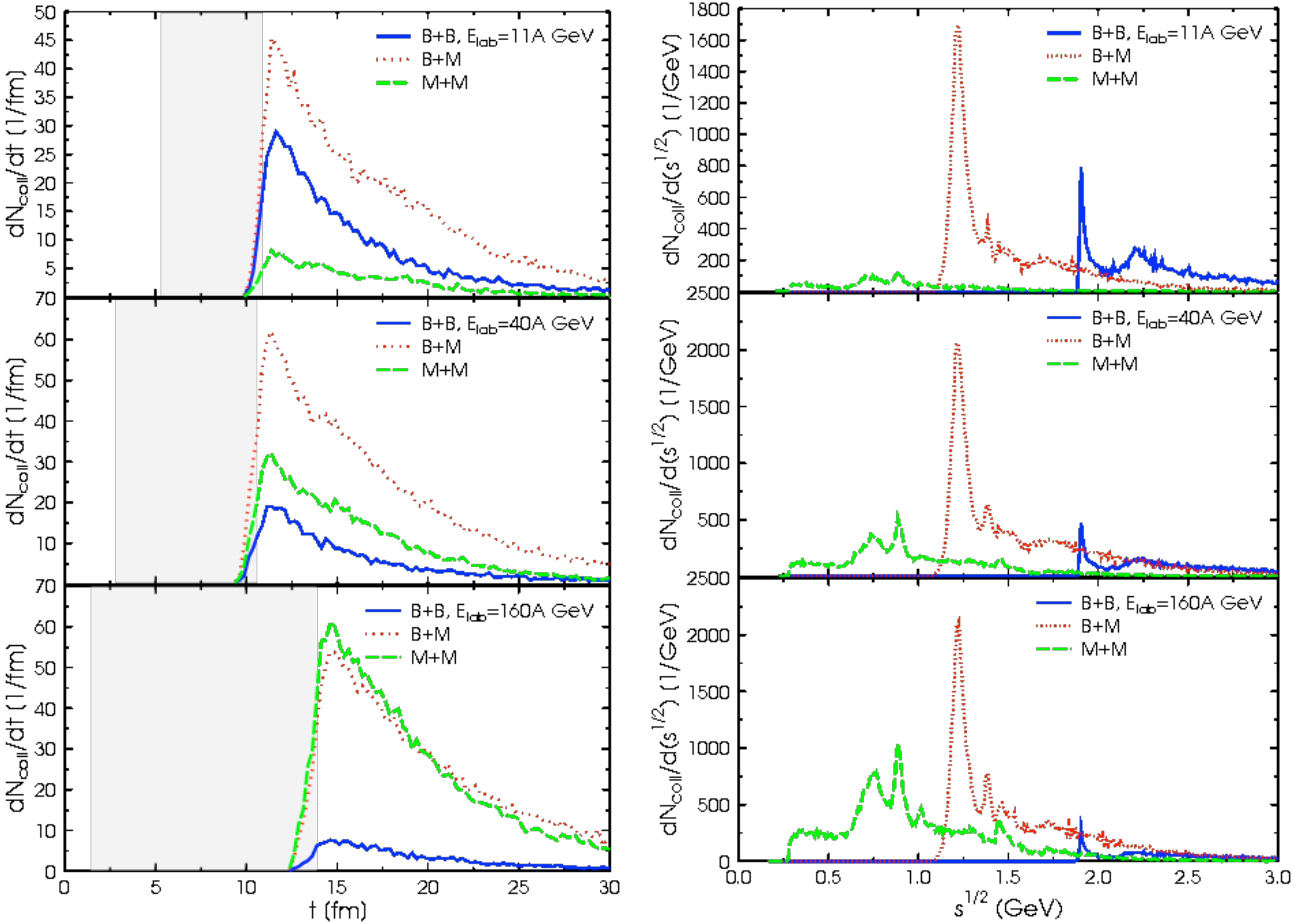


Variation of starting time by a factor 4 changes results only by 10 %

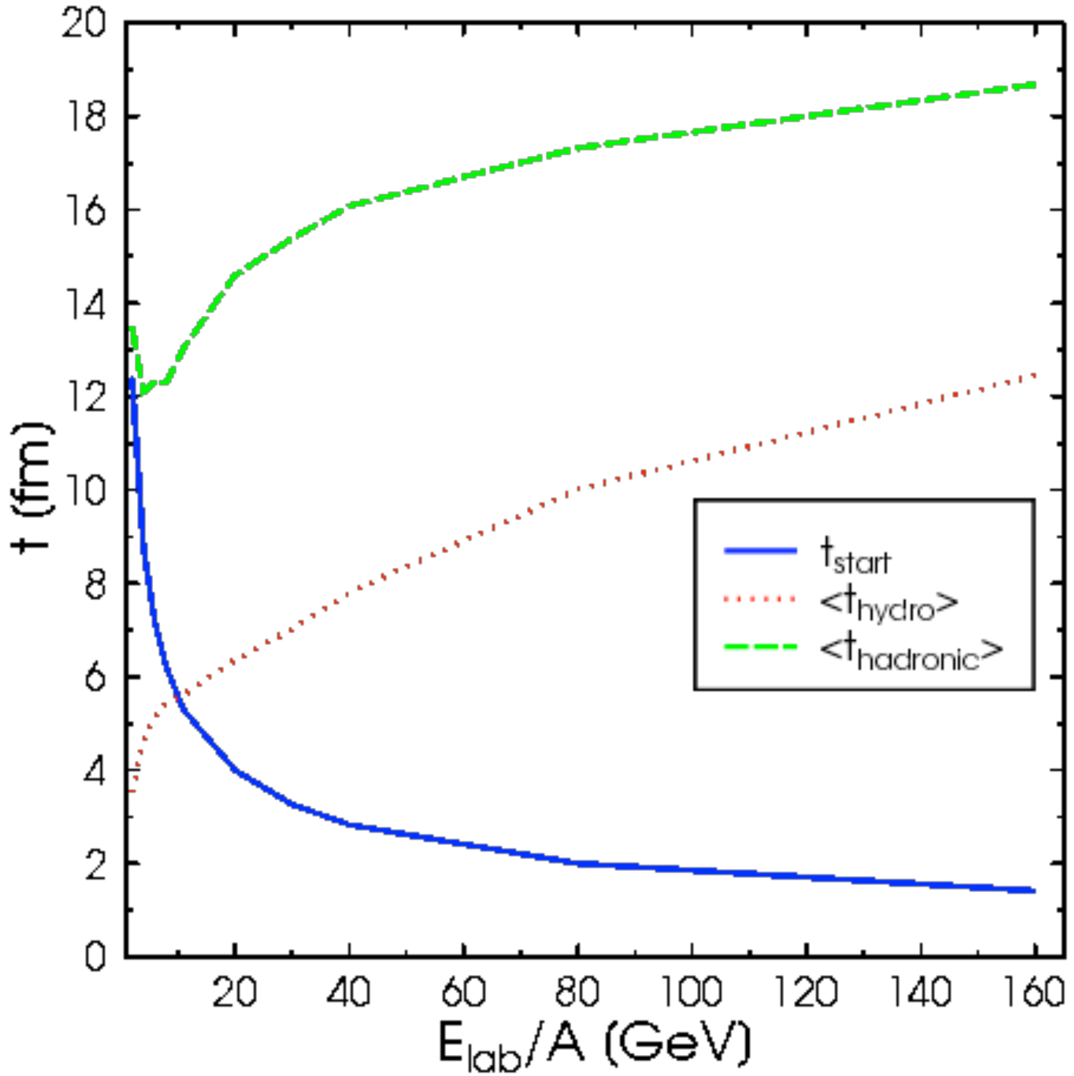
Full symbols: 40 AGeV

Open symbols: 11 AGeV

Final State Interactions

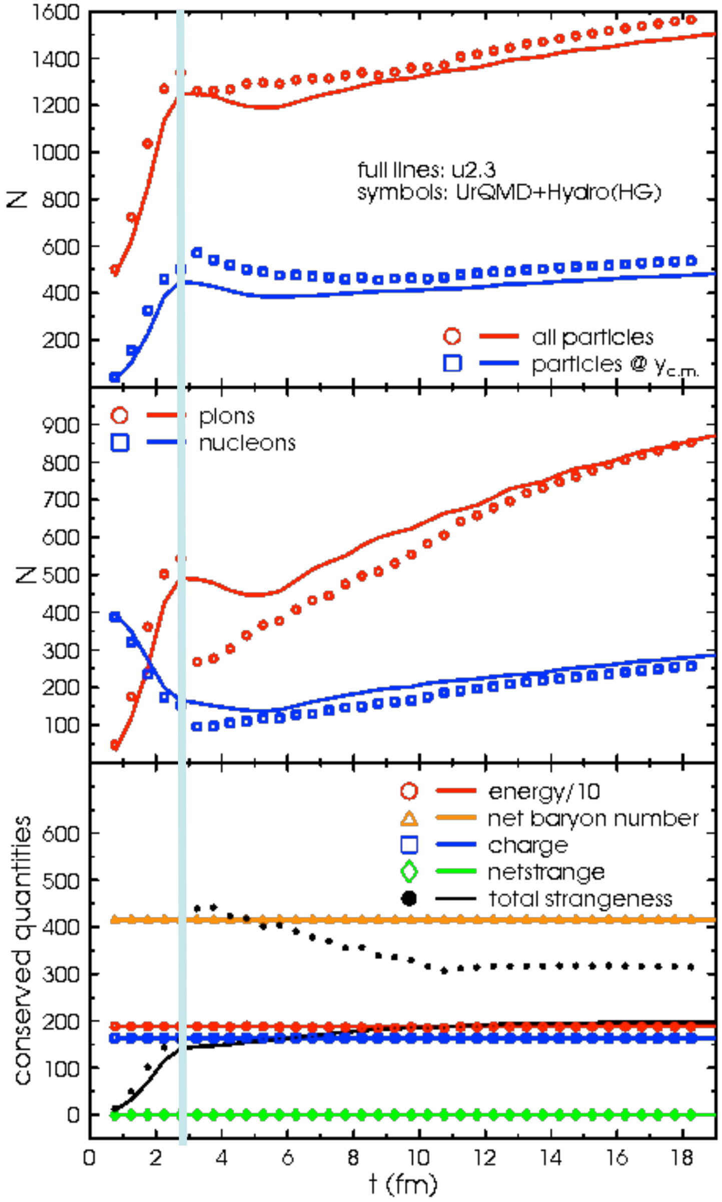


Time scales



t (fm)
E_{lab}/A (GeV)
t_{start}
$<t_{hydro}>$
$<t_{hadronic}>$
0
2
4
6
8
10
12
14
16
18
20
40
60
80
100
120
140
160

Time Evolution



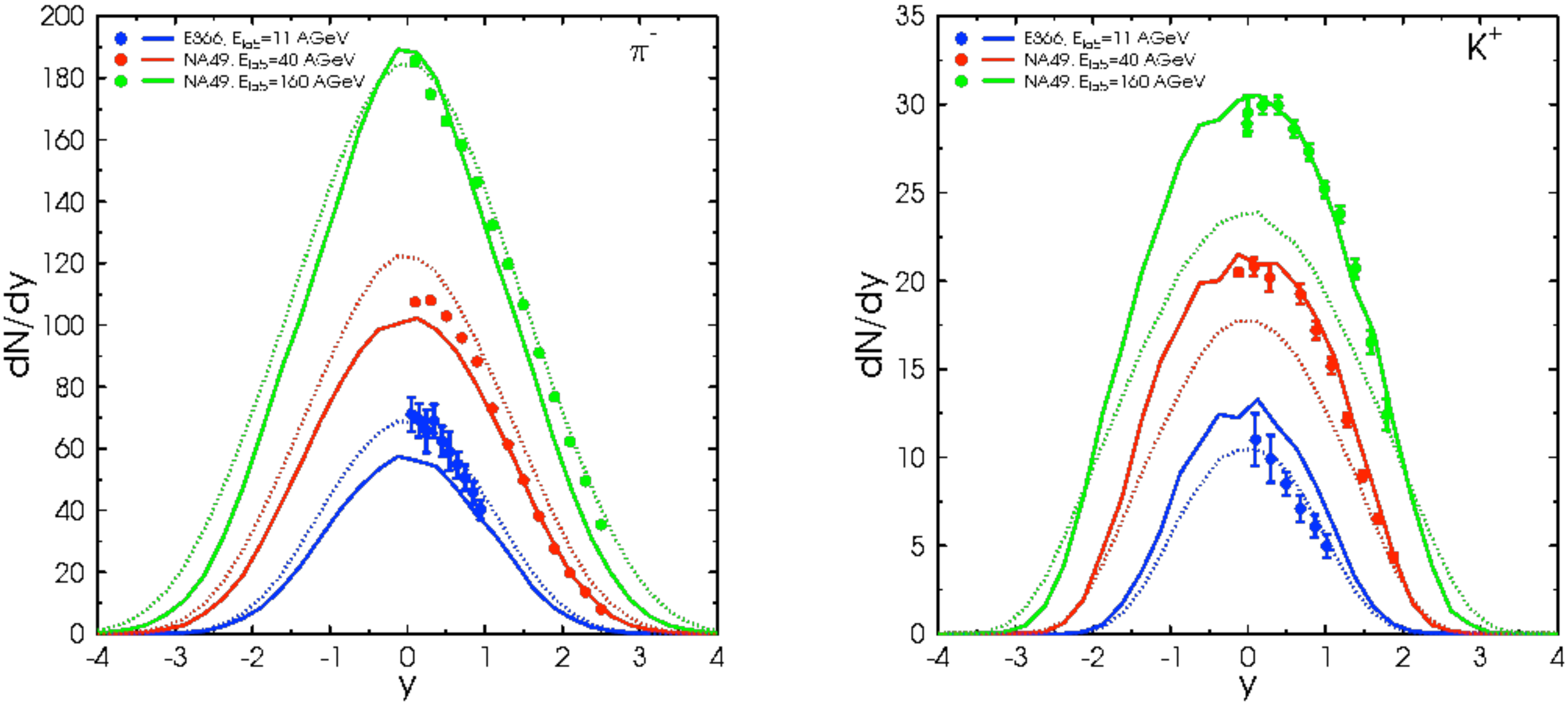
Central Pb+Pb collisions at 40A GeV:

- 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

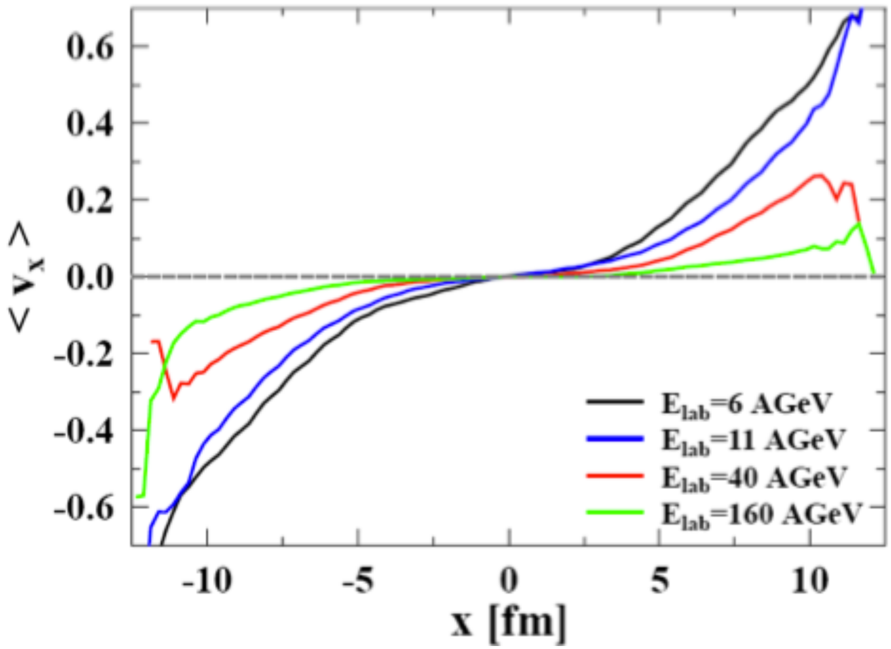
Rapidity Spectra

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

Initial Velocity Distribution



Central collisions at different beam energies

In z-direction:

Effect of Lorentz contraction visible