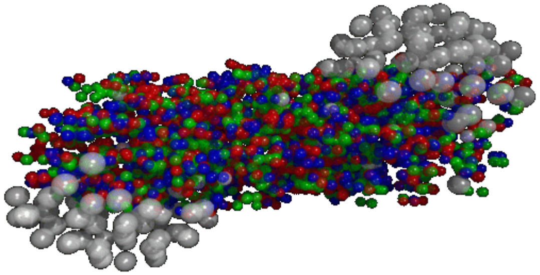

HIC for FAIR
Helmholtz International Center

Hybrid Approaches to Heavy Ion Collisions and Future Perspectives

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Thanks to

- Hannah Petersen (now at Duke U)
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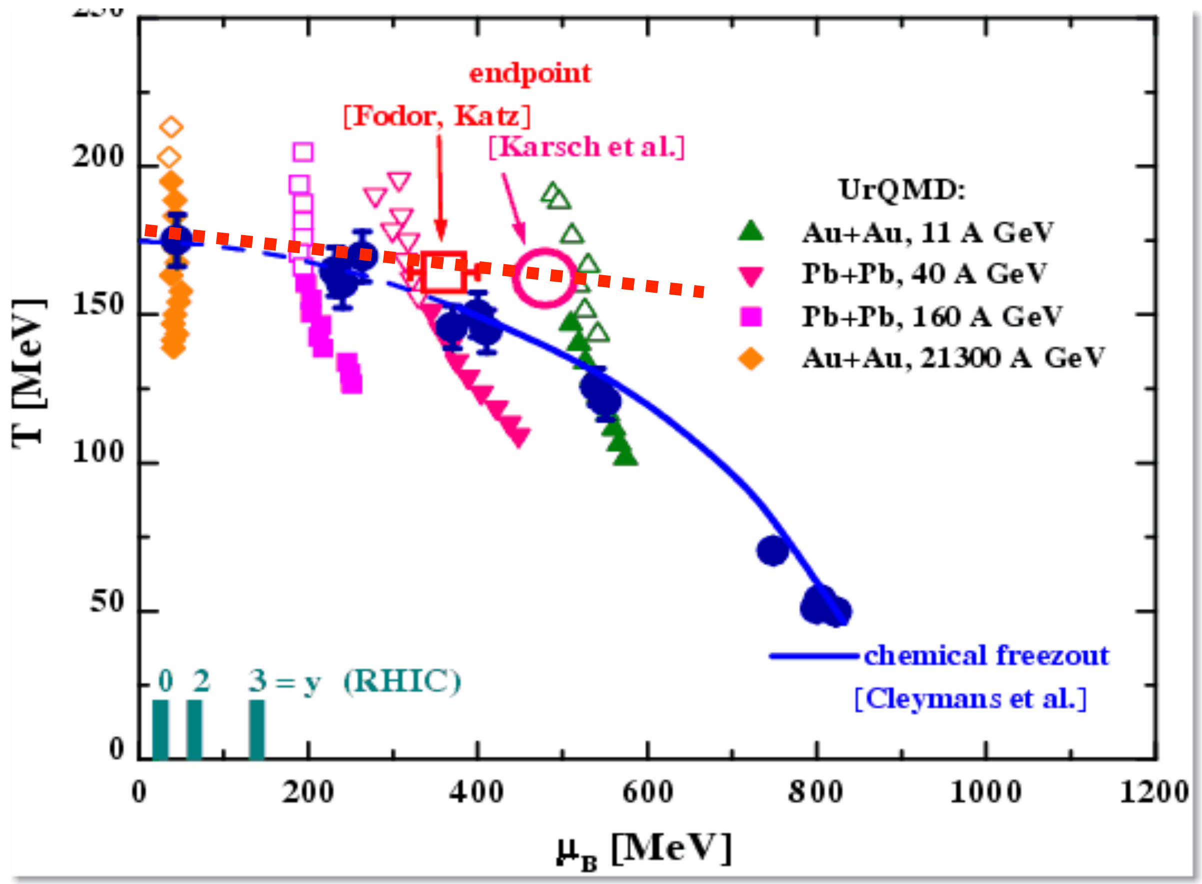
- Dirk Rischke
- Horst Stoecker

Outline

- Model Description
  - Initial Conditions
  - Equations of State
  - Freeze-out Scenarios
- Multiplicities and Spectra
- HBT Results
- Leptonic Probes
- Open Questions
- Conclusions

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

The QCD Phase Diagram



E. Bratkovskaya, M.B. et al., PRC 2005

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:

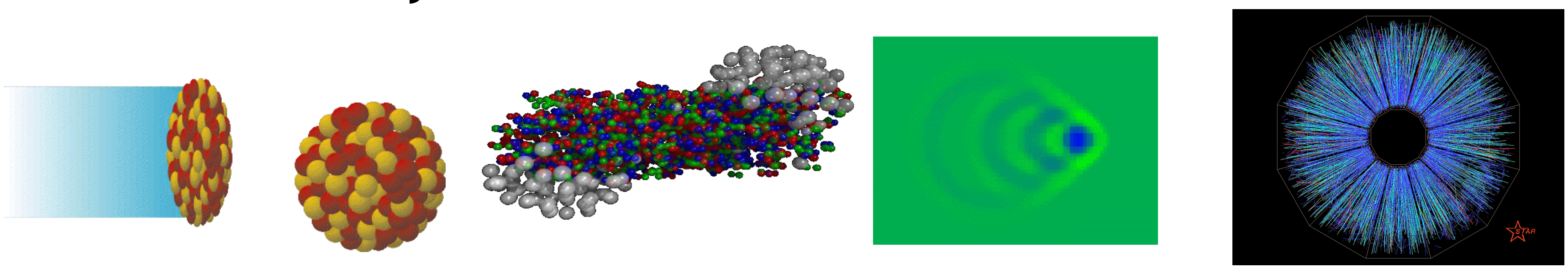
- Results On Transverse Mass Spectra Obtained With Nexspherio
  F. Grassi, T. Kodama, Y. Hama, J.Phys.G31:S1041-S1044,2005
- See also recent work of K. Werner, M. Bleicher, T. Pierog (2010)

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

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

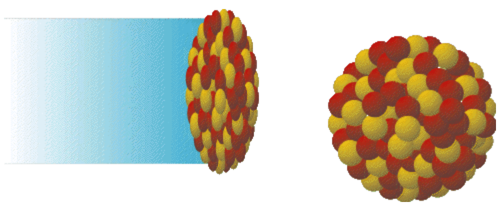
2) Hydrodynamic evolution **or** Transport calculation

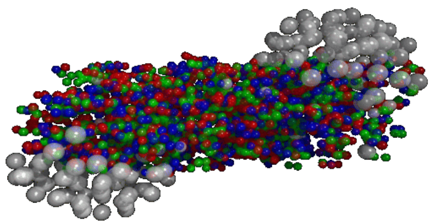
3) Freeze-out via hadronic cascade (UrQMD)

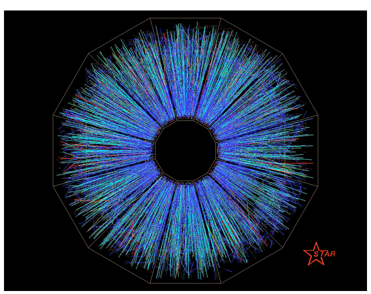
(Petersen et al., PRC 78:044901, 2008, arXiv: 0806.1695)

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

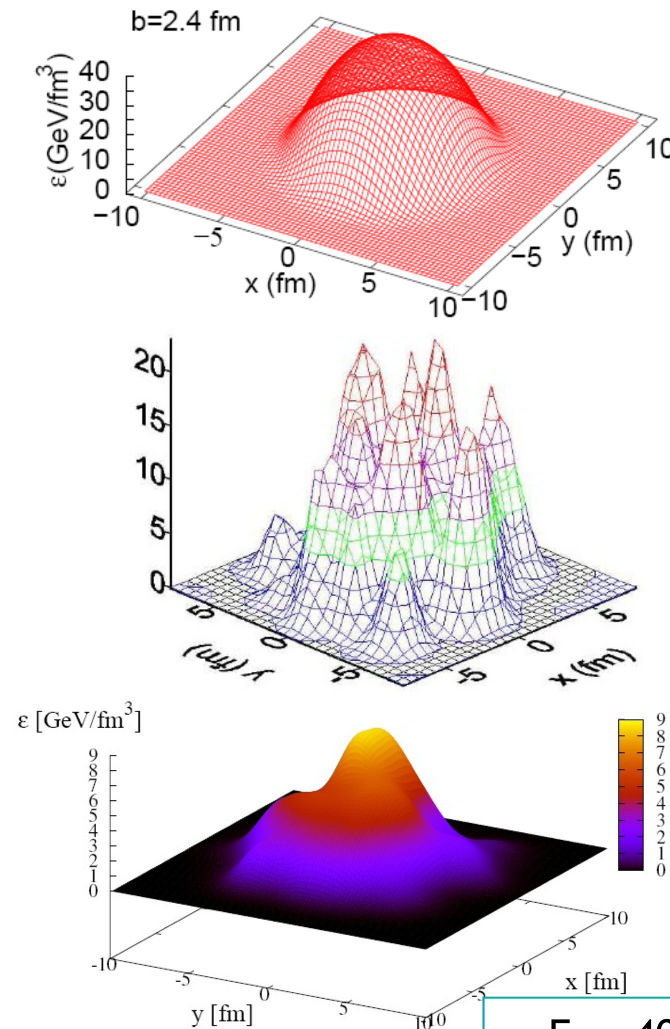
Very successful in describing different observables in a broad energy range
But: modeling of the phase transition and hadronization not yet possible

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



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

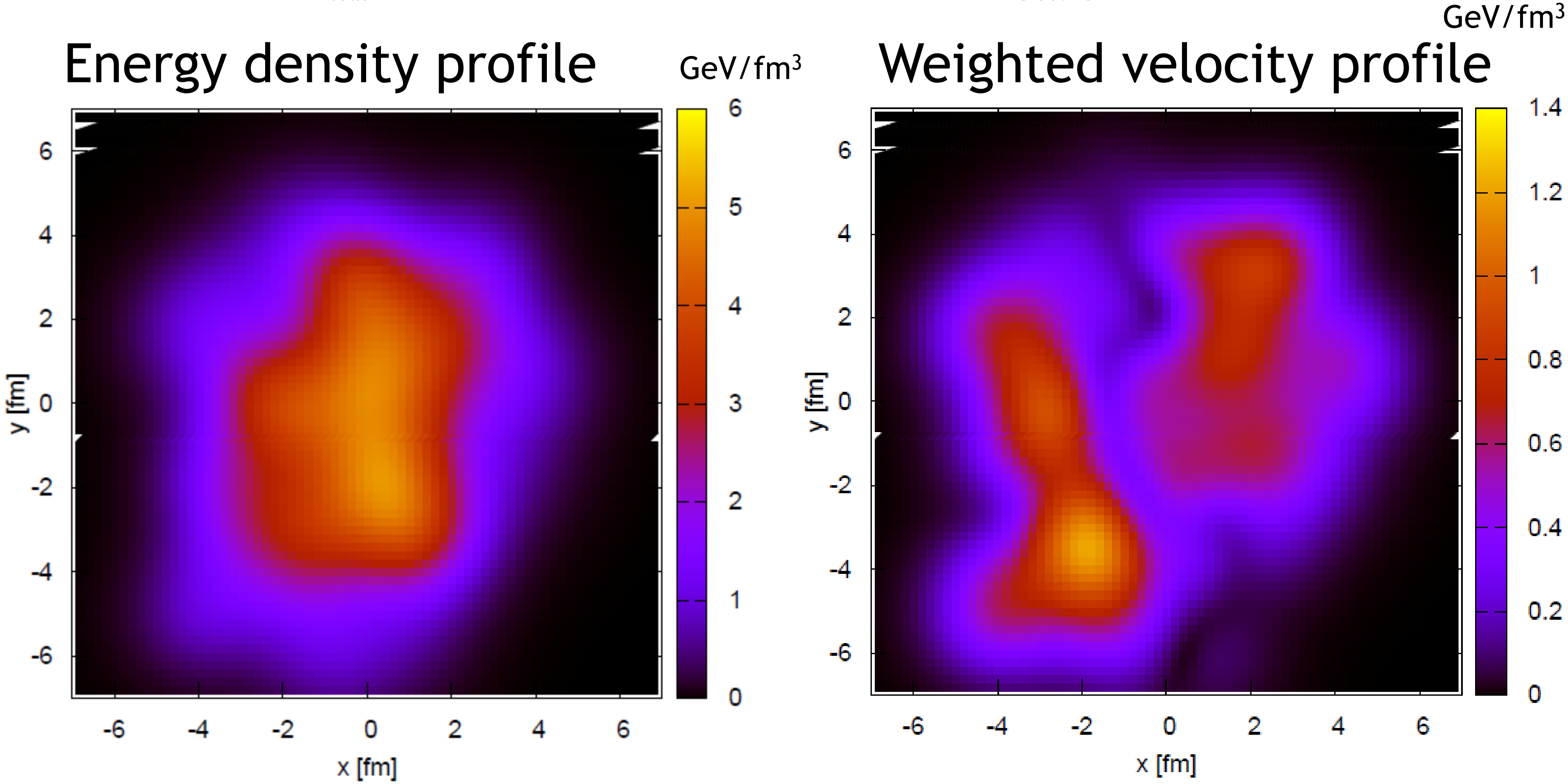
E_{lab}=40 AGeV
b=0 fm

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

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

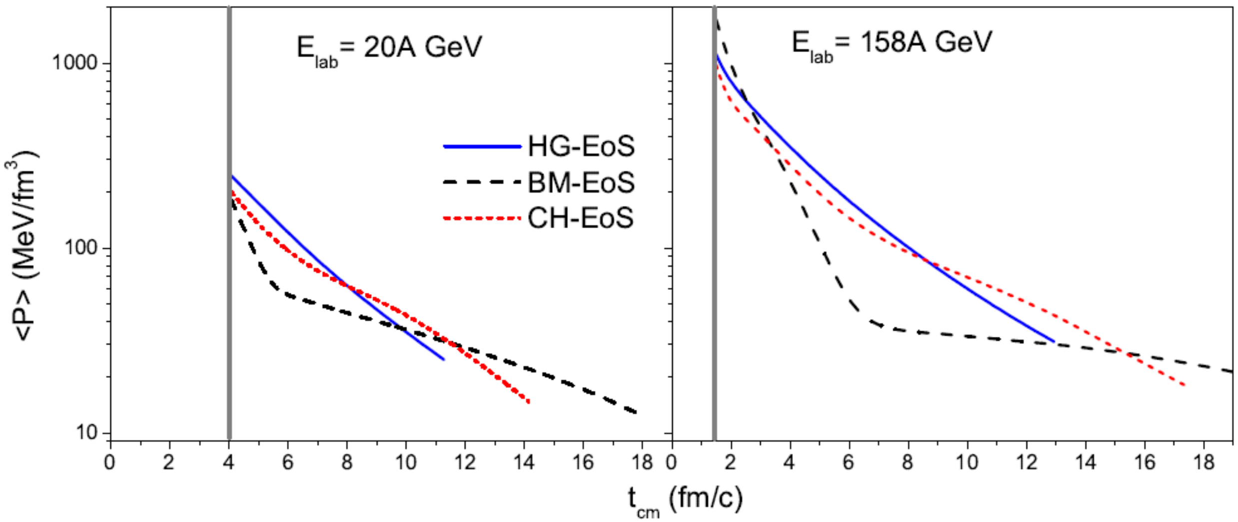
(H.Petersen et.al., arXiv:0901.3821, PRC 2009

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,

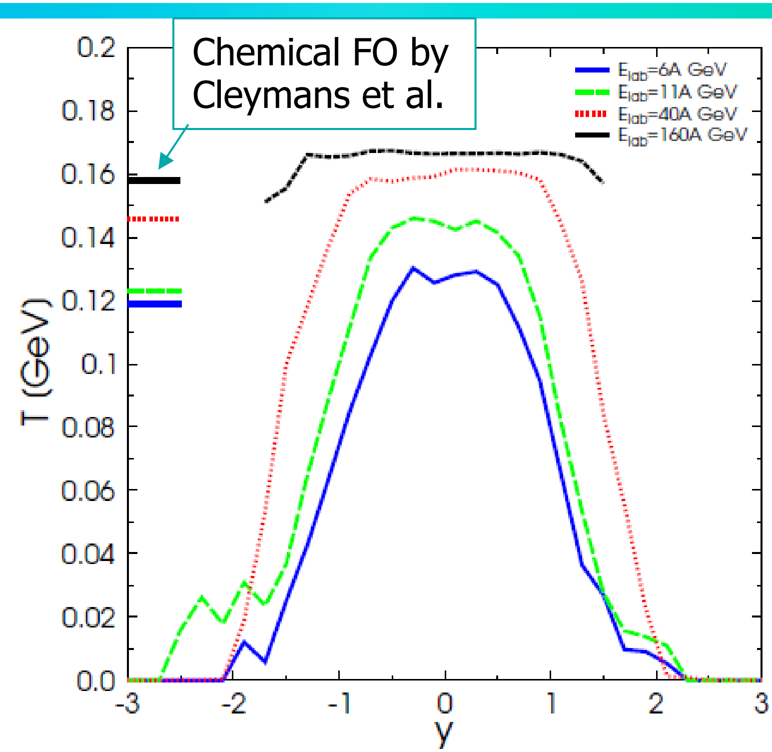
D. Zschiesche et al., PLB 547, 7, 2002

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)



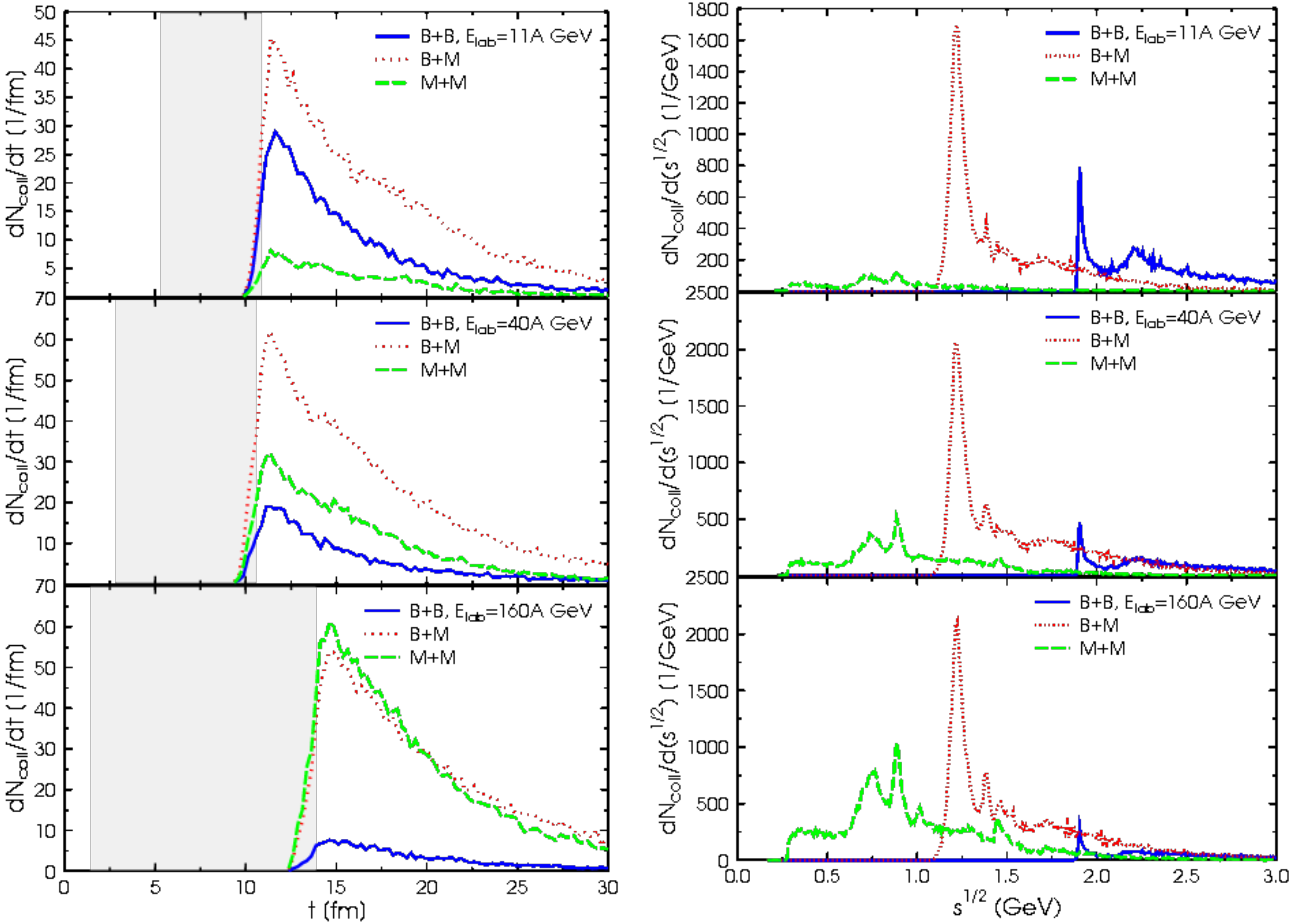
- Particle distributions are generated according to the **Cooper-Frye** formula

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

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)



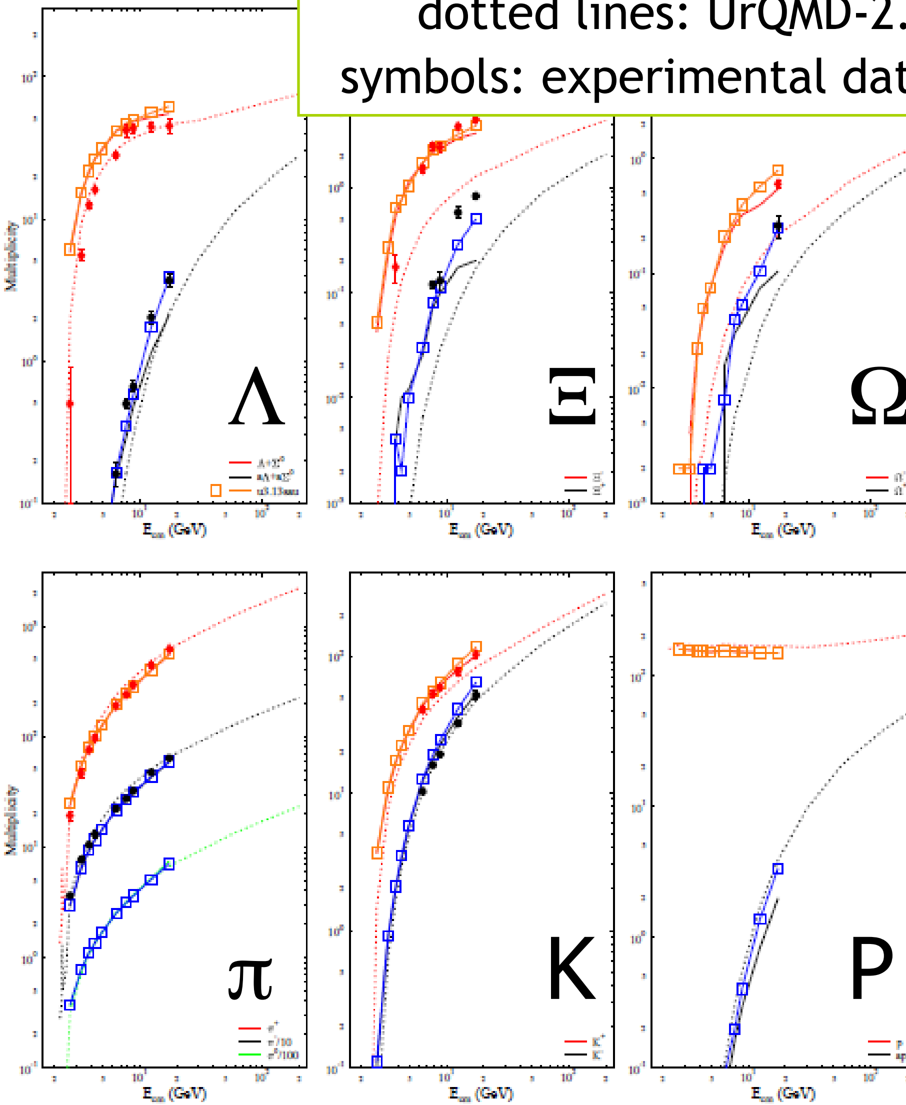
Multiplicities vs. Energy

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



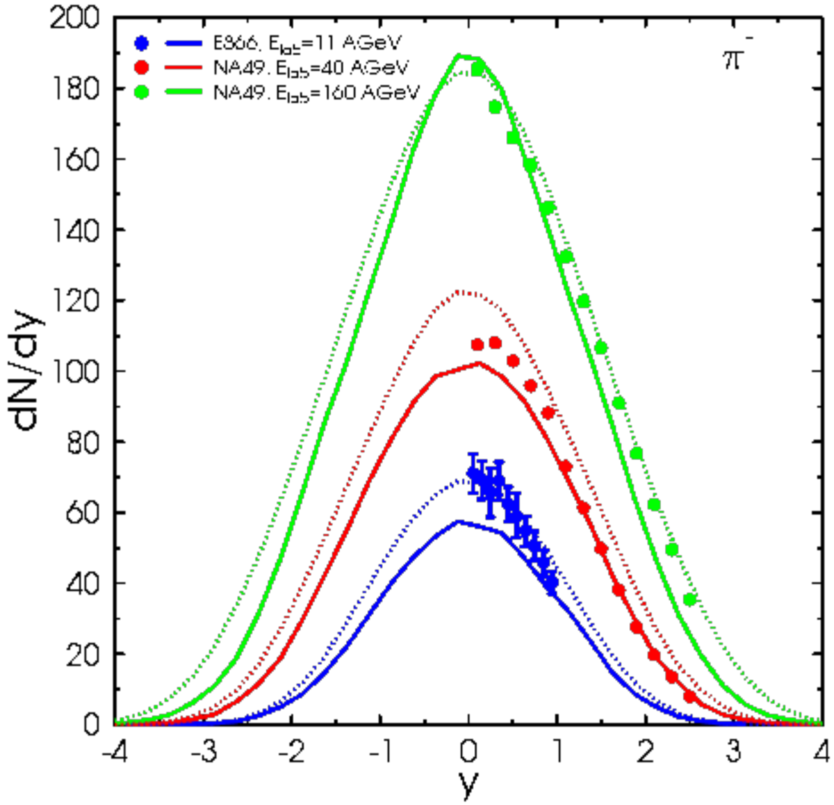
(Petersen et al., PRC 78:044901, 2008)

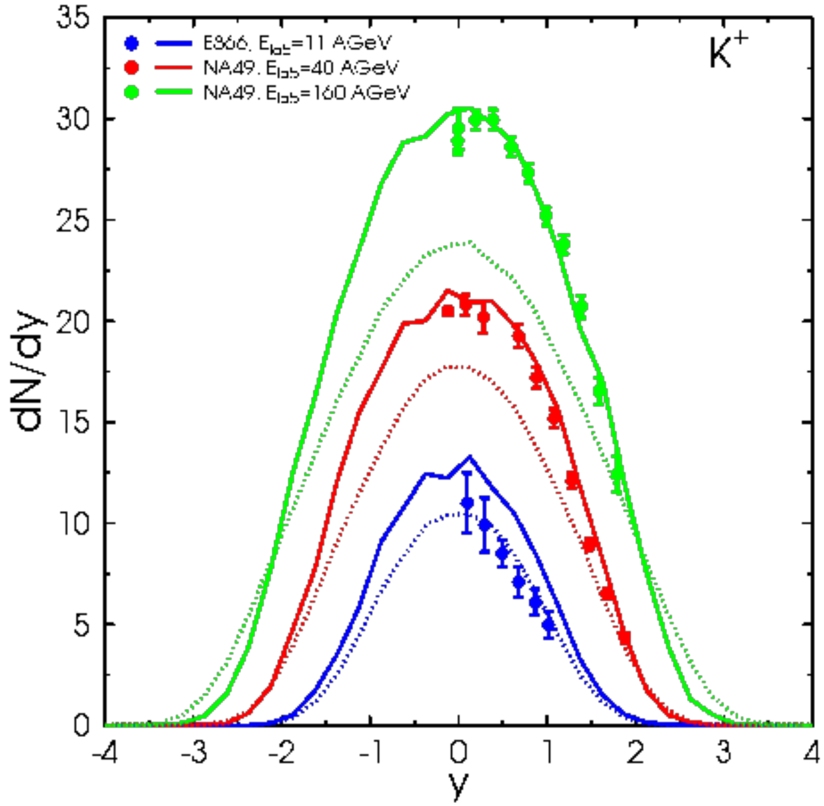
Central (b<3.4 fm) Pb+Pb/Au+Au collisions

Data from E895, NA49

Rapidity Spectra

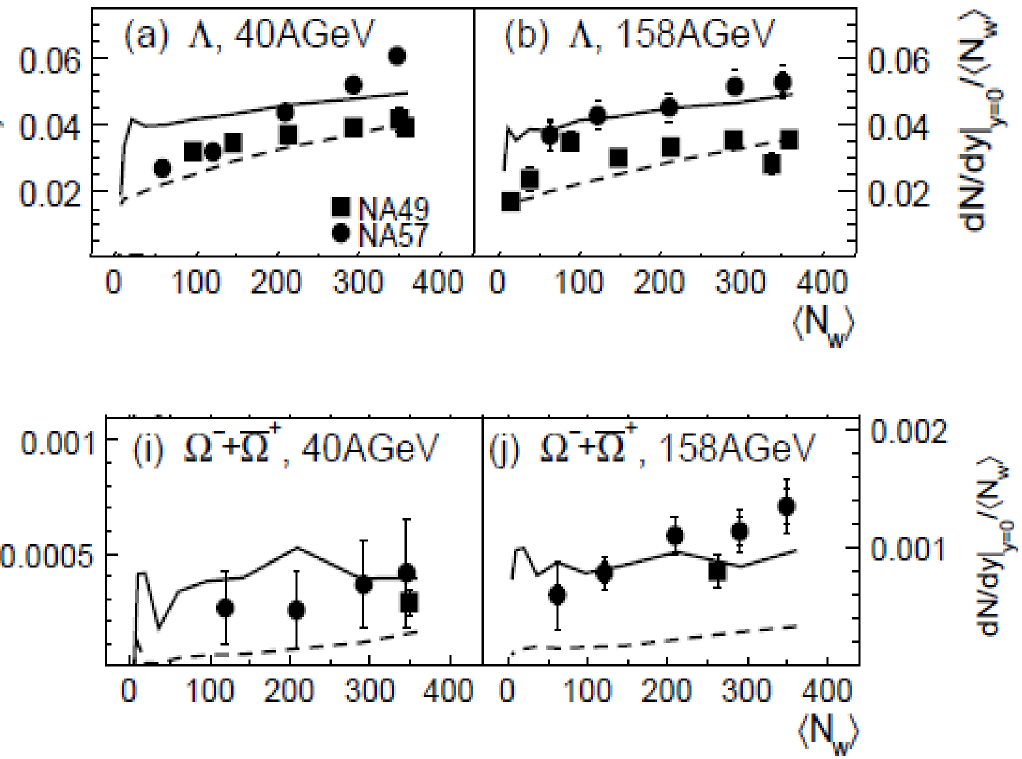
full lines: hybrid model
dotted lines: UrQMD-2.3
symbols: experimental data





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

Strangeness Centrality Dependence



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

—— hybrid model (GF)

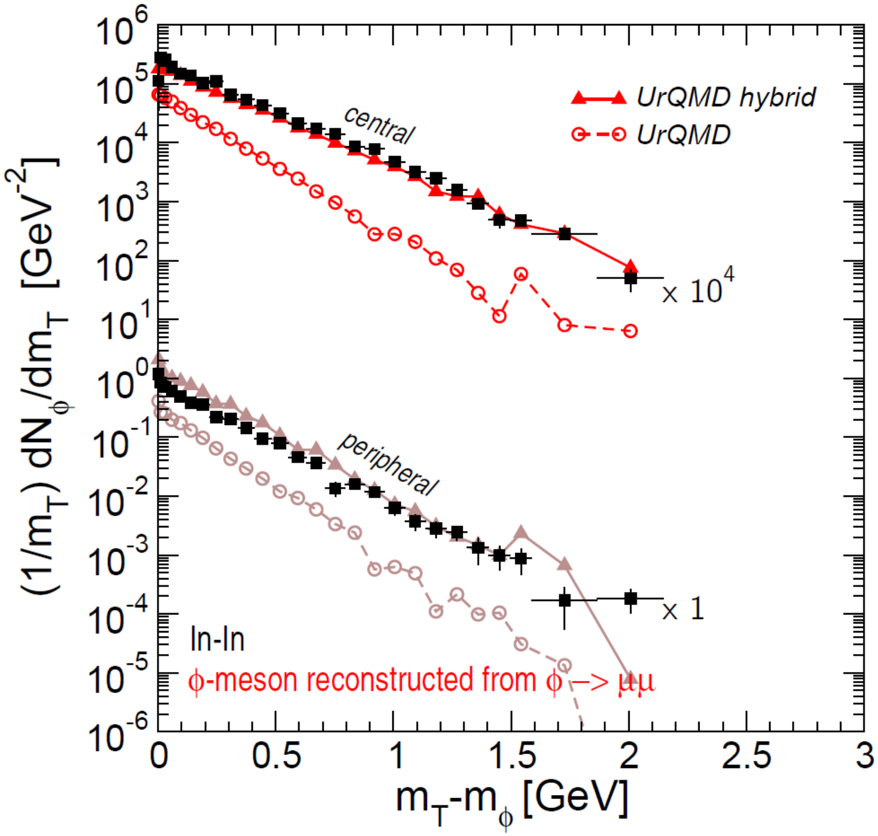
----- UrQMD-2.3

Pb+Pb collisions for different centralities

(Petersen et al., arXiv: 0903.0396)

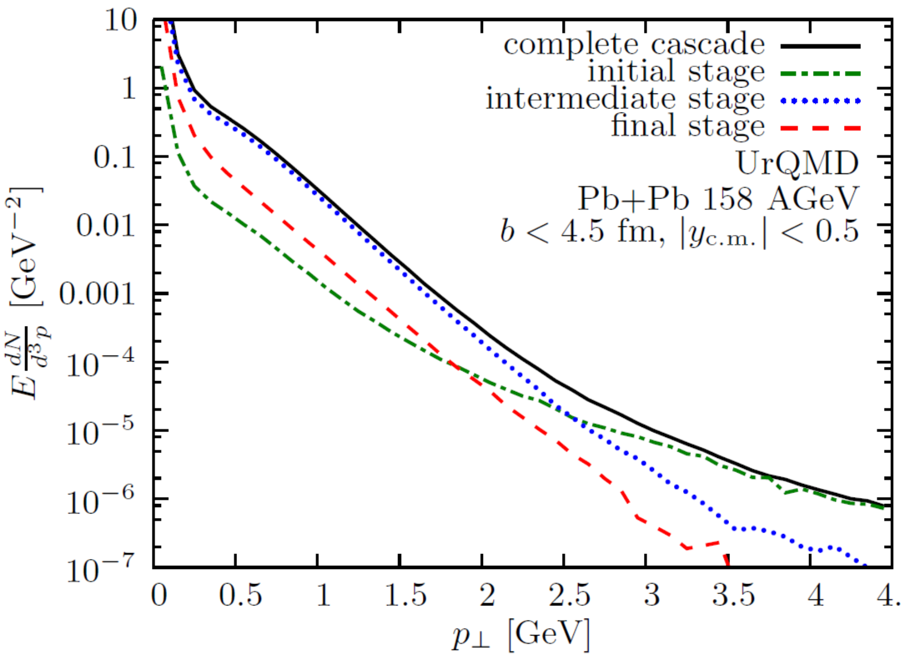
The Phi

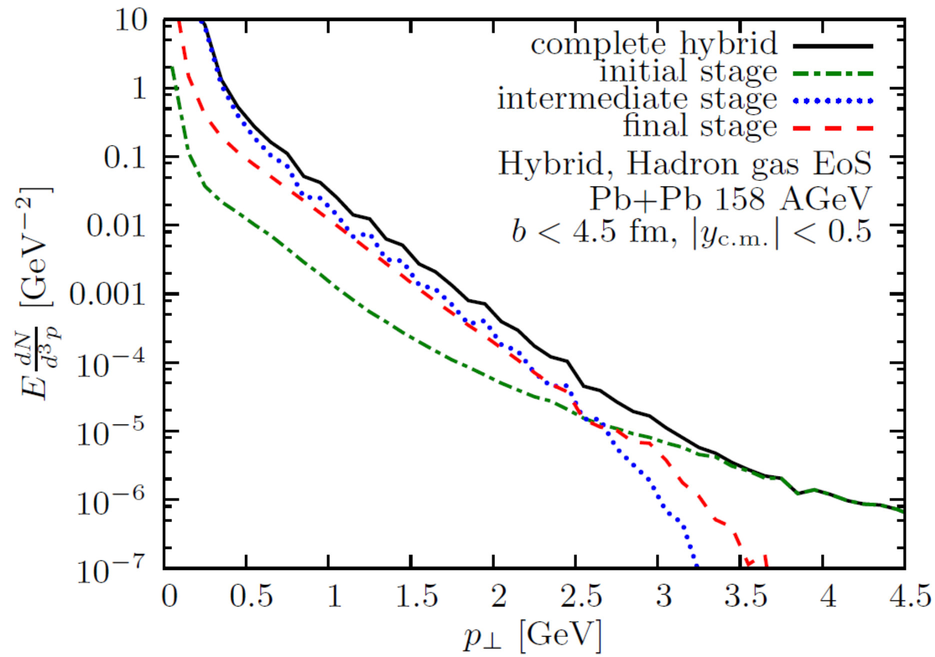
- Comparison between
  - NA60 data
  - UrQMD
  - Hybrid model
- Thermalization is essential to describe phi yield and slope
- Stronger deviation from transport for central reactions



E. Santini, PRC (2010)

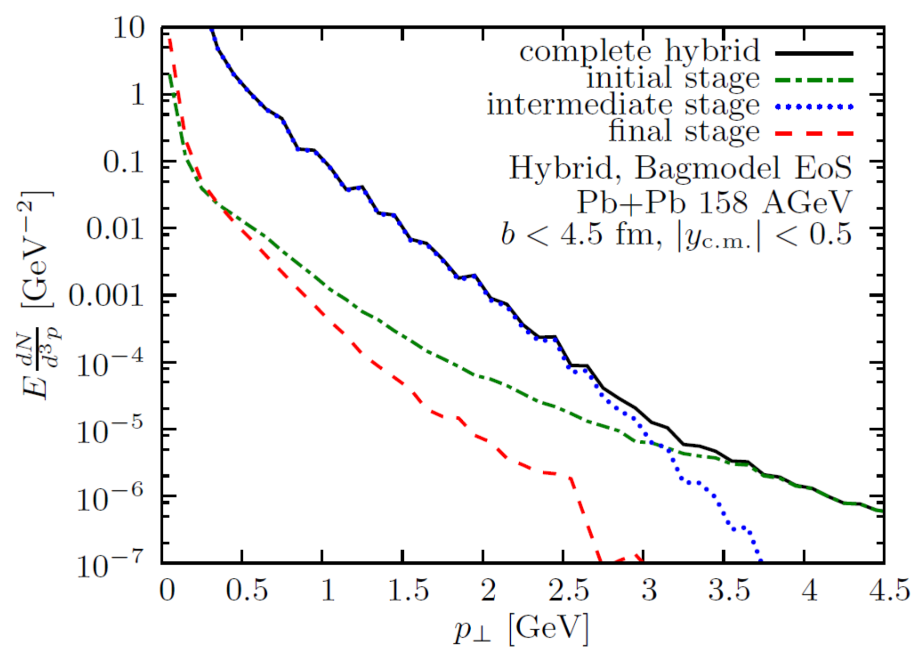
Data: NA60



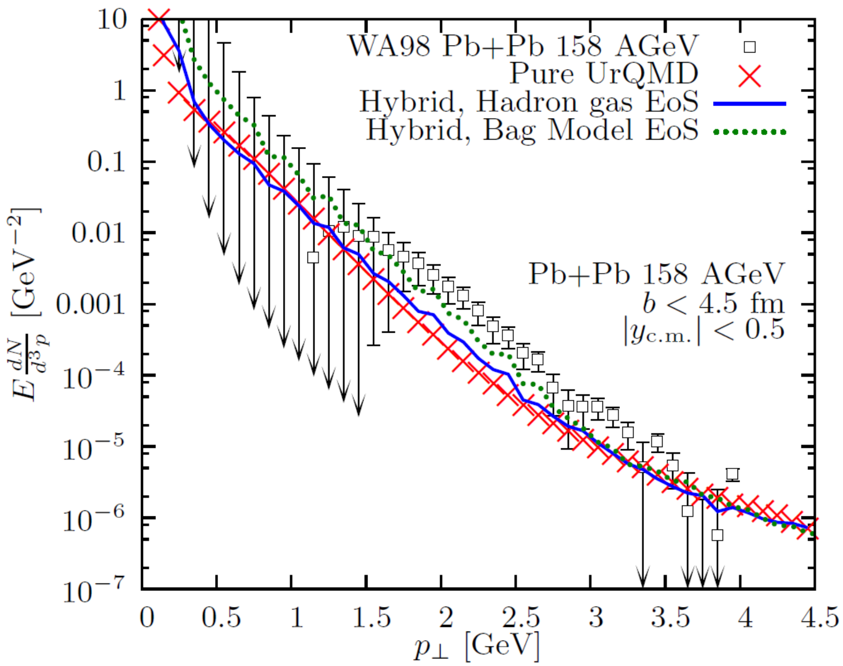


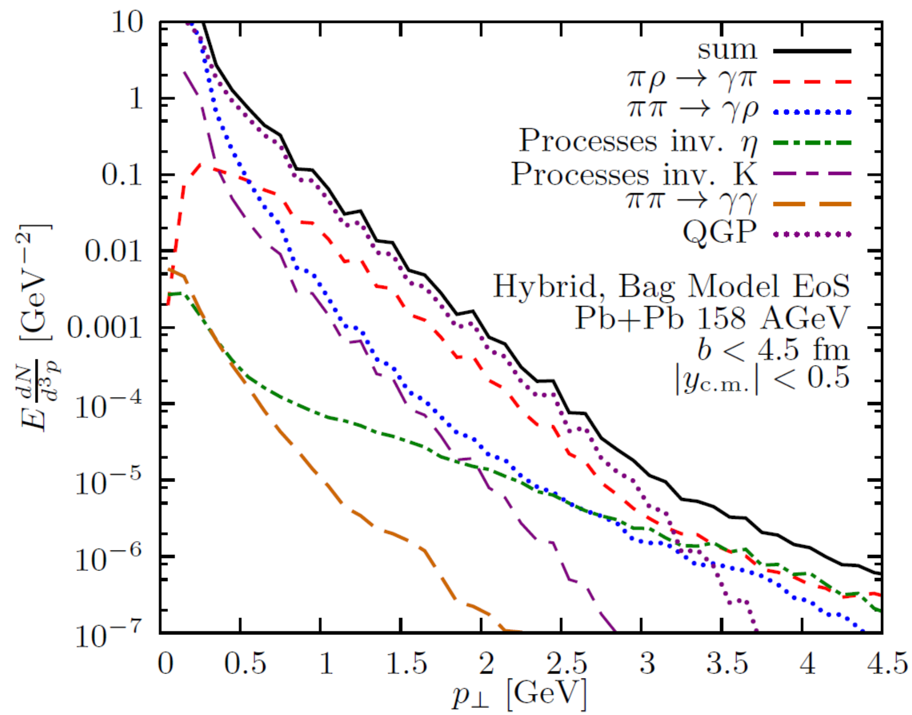
Differential Photon spectra

Clear enhancement of Photon production with QGP



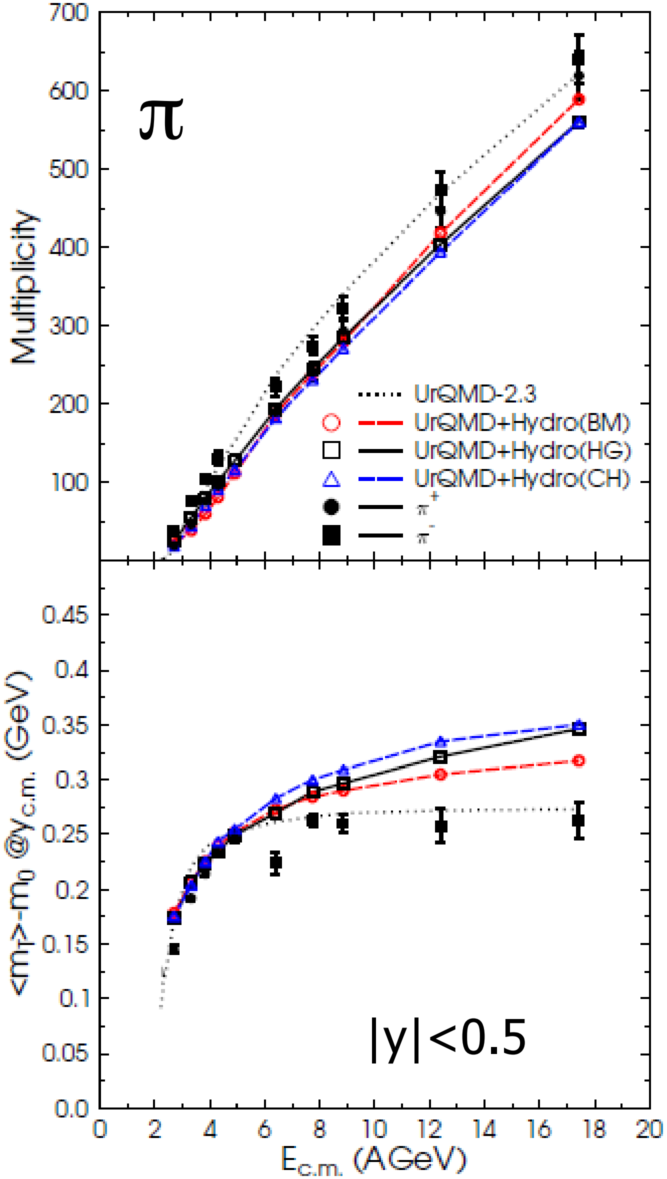
Comparison to data





Bjoern Bauechle, MB, PRC (2010)

$<m_T>$ Excitation Function



Data from E866, NA49

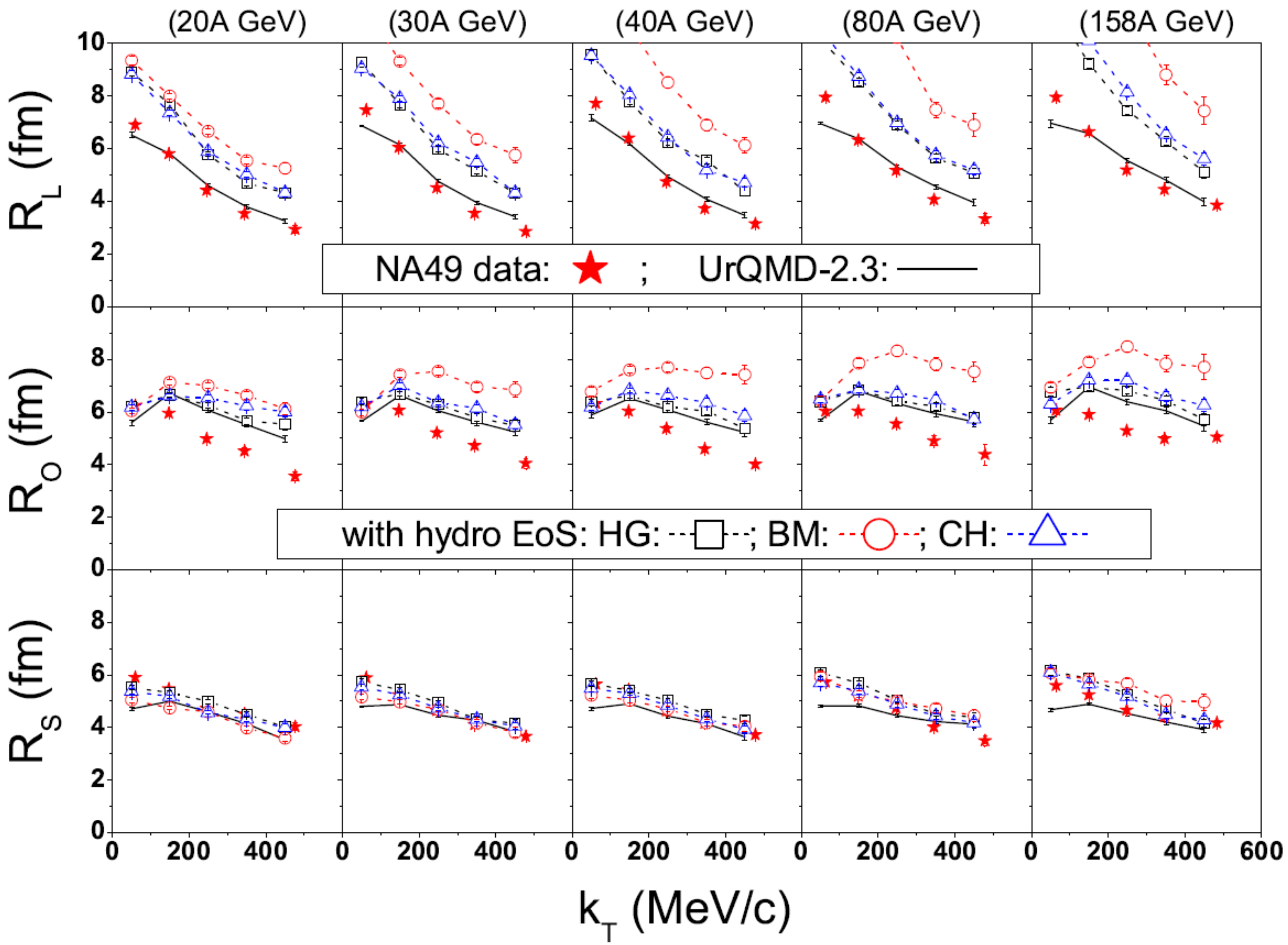
- Resonance excitations and non-equilibrium effects in intermediate energy regime lead to a **softening** of the EoS in pure UrQMD calculation
- Hybrid calculation with hadronic EoS just rises as a function of beam energy
- Even strong first order phase transition leads only to a small effect

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

Gradual freeze-out for hybrid calculation

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

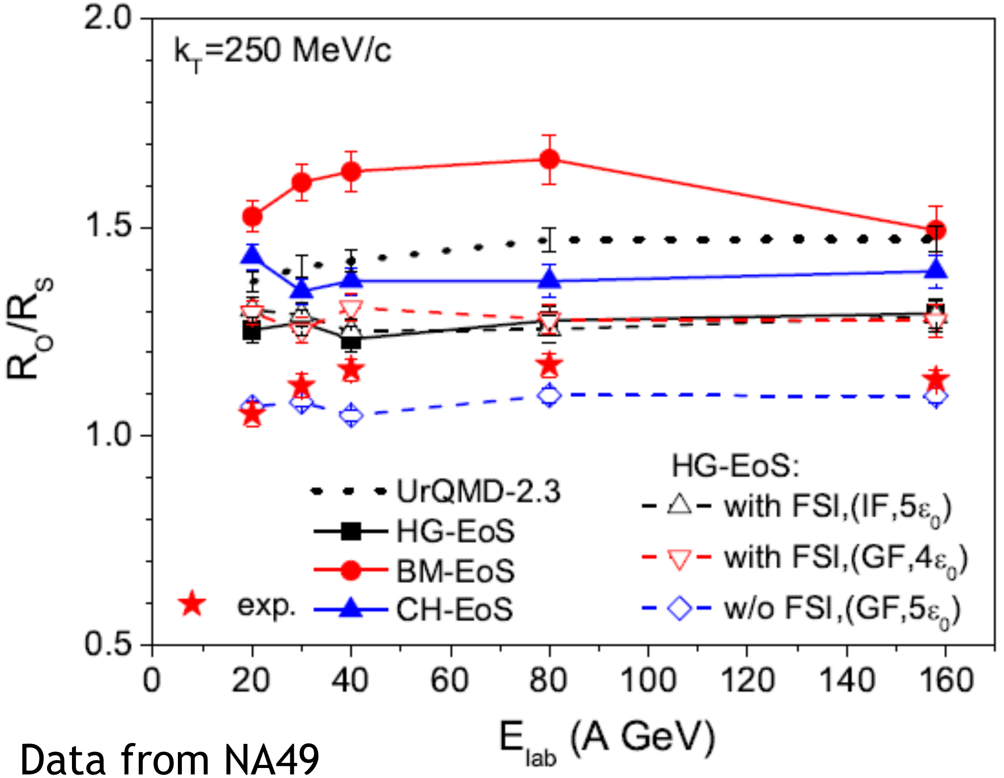
HBT radii (EoS effects)



(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

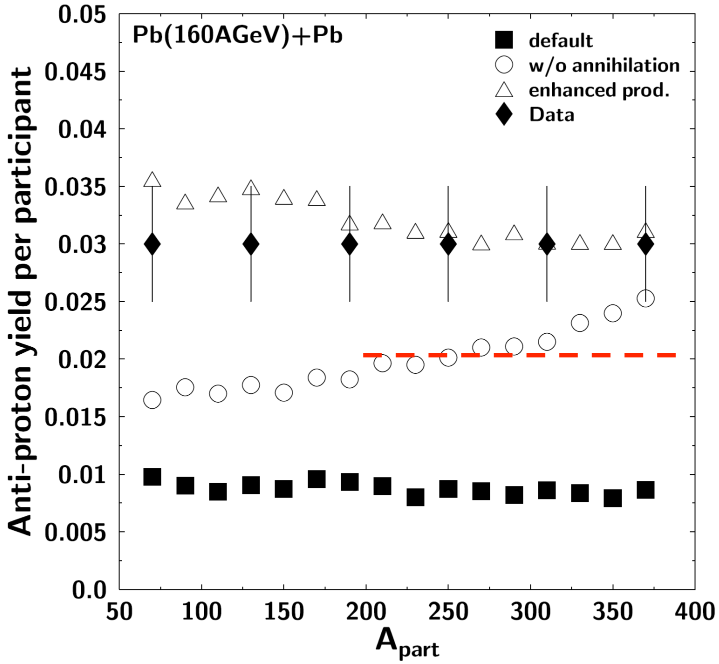
(Q. Li et al., PLB 674, 111, 2009)

- 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)

Findings

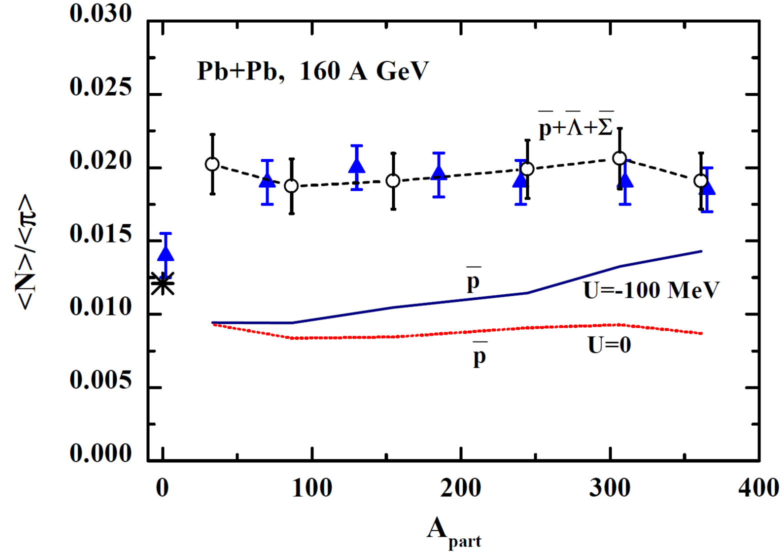
- Intermediate hydrodynamics improves description of the data
- (+) Strangeness
- (+) HBT
- (+) Elliptic flow
- (+) Photons / dileptons
- (+) allows direct testing of EoS
- (-) radial flow (viscosities)
- (+/-) no understanding of phase transition
- (+/-) no understanding of thermalisation

Thermalisation: multi-particle interactions



MB, PLB 2000
“np→BBbar may be important”

See also Rapp, Shuryak 2001, Wetterich, Stachel, PBM 2002



Cassing, NPA 2001

$$\frac{d}{dt}\rho_{\bar{Y}} = -\langle\langle \sigma_{\bar{Y}N} v_{\bar{Y}N} \rangle\rangle \Big\{ \rho_{\bar{Y}}\rho_N - \sum_n \mathcal{R}_{(n,n_Y)}(T,\mu_B,\mu_s)(\rho_\pi)^n(\rho_K)^{n_Y} \Big\}$$

Hagedorn States

From Belkacem, Bleicher, Stoecker 1998, nucl-th/98040058, PRC 1998

However, in the above sums, string degrees of freedom (which can be considered as heavy mass resonances with small life times) are not taken into account. Therefore, a direct comparison with the UrQMD model (which includes these degrees of freedom) shall yield different results at high energy densities. The same results from the UrQMD box model and the corresponding statistical model can only be expected if strings (or higher mass resonances) are included in the statistical model. For this, the Hagedorn mass spectrum [35] for the strings given by:

$$\rho^{(s)}(m) = \rho_0^{(s)} m^{a_H} \exp(m/T_H) \tag{6}$$

- First steps to implement Hagedorn states in dynamical simulations are currently underway (cf. talk by C. Greiner)

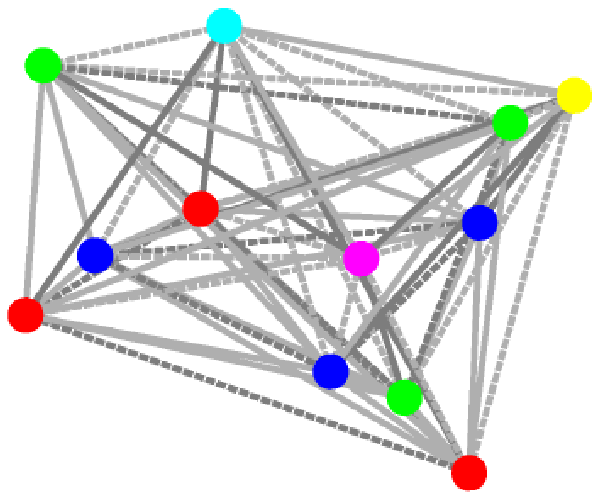
Hadronisation

- How to go from partonic matter to hadronic matter?
  - energy conservation?
  - free quarks in the end?
  - what to do with gluons?
  - decrease in entropy?
  - transition to fragmentation?

Quark Molecular Dynamics

Hamiltonian of the model :

$$H = \sum_{i=1}^{N} \sqrt{\mathbf{p}_i^2 + m_i^2} + \frac{1}{2} \sum_{i \neq j} C_{ij} V(|\mathbf{r}_i - \mathbf{r}_j|)$$



- Potential :

  linear potential $V(r) = \kappa r$
- Color factor C_{ij} :

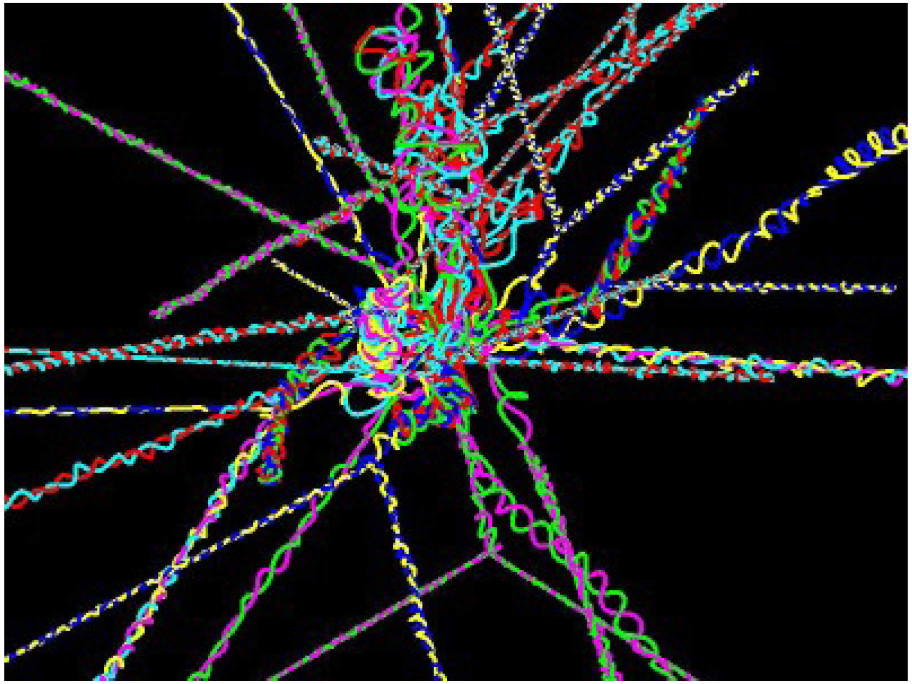
  can be attractive or repulsive depending on the color of the quarks
- Quarks :

  classical point-particles with light masses $m_{u,d} = 5$ MeV, $m_s = 150$ MeV

Trajectories

qMD features :

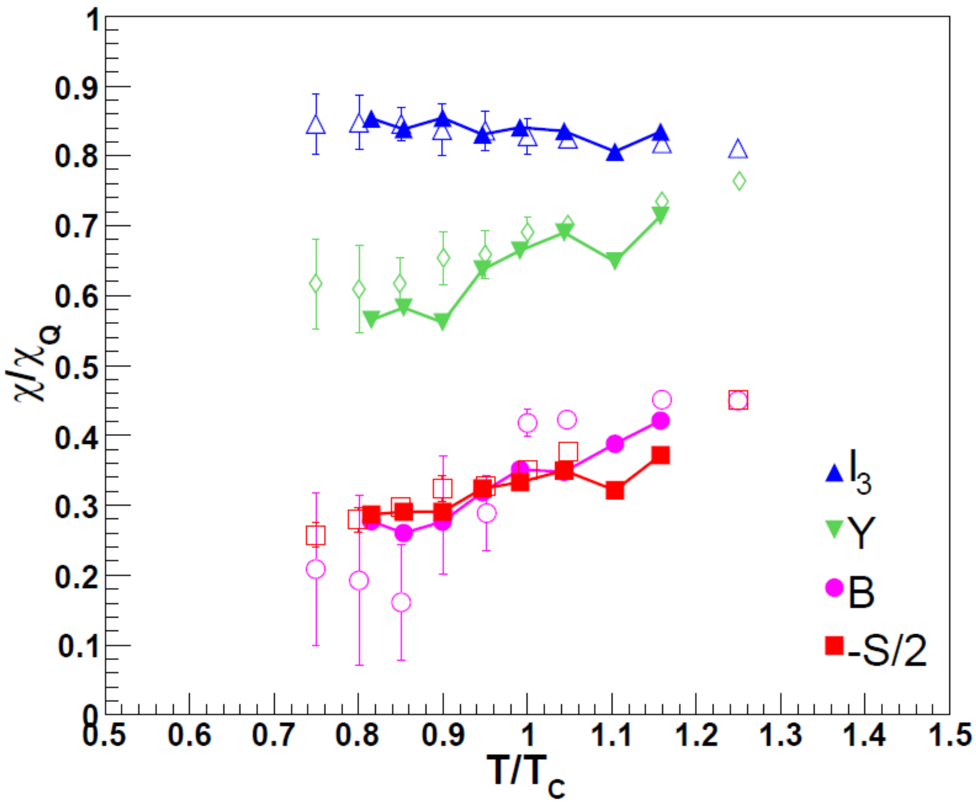
- mesons
- baryons
- confinement
- recombination
- out-of-equilibrium



M. Hofmann Ph.D. thesis

Hofmann, Bleicher, Scherer, Neise, Stoecker, Greiner. Phys.Lett.B478:161-171,2000.

Susceptibilities



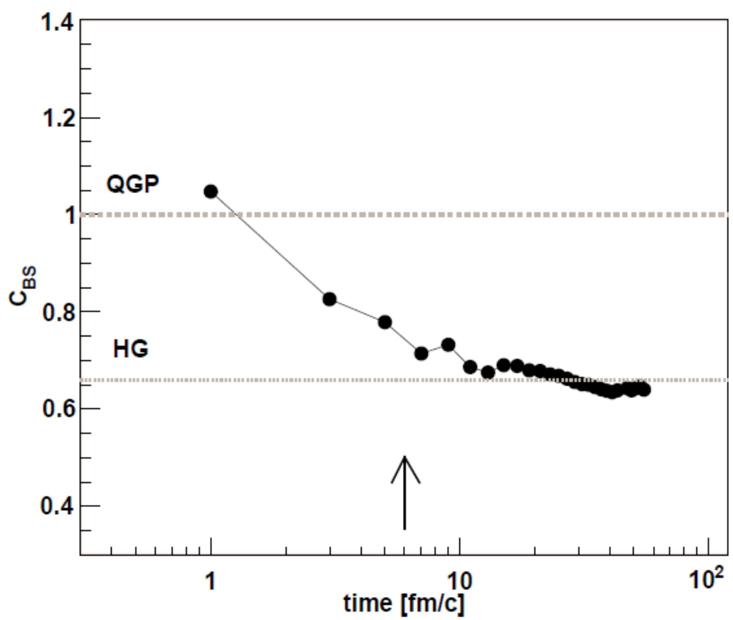
Open symbols : lattice data from Gavai, Gupta. Phys.Rev.D73:014004,2006

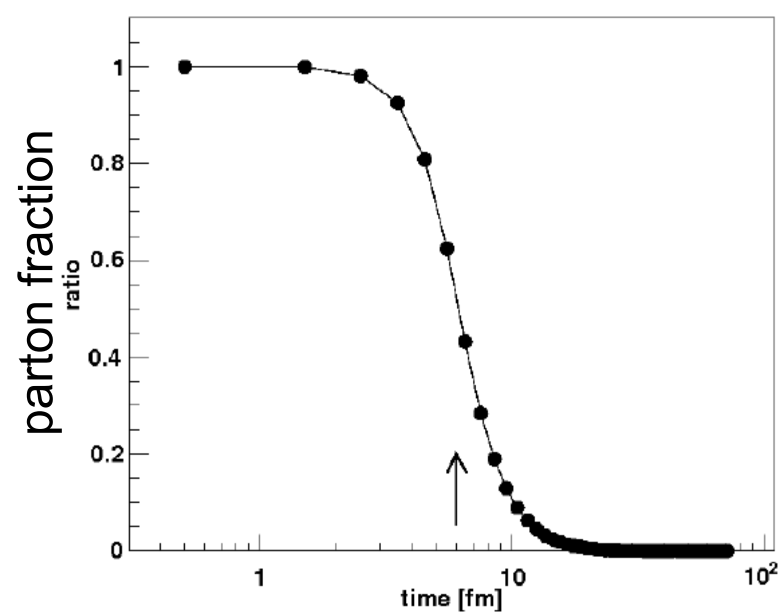
Full symbols with lines are the result of qMD calculations

- Strangeness, baryon charge and isospin susceptibilities are well reproduced
- Model may be trustful around T_c

Time evolution

- Hadronisation blurs the signatures from the QGP phase (here C_{BS}, also true for others)

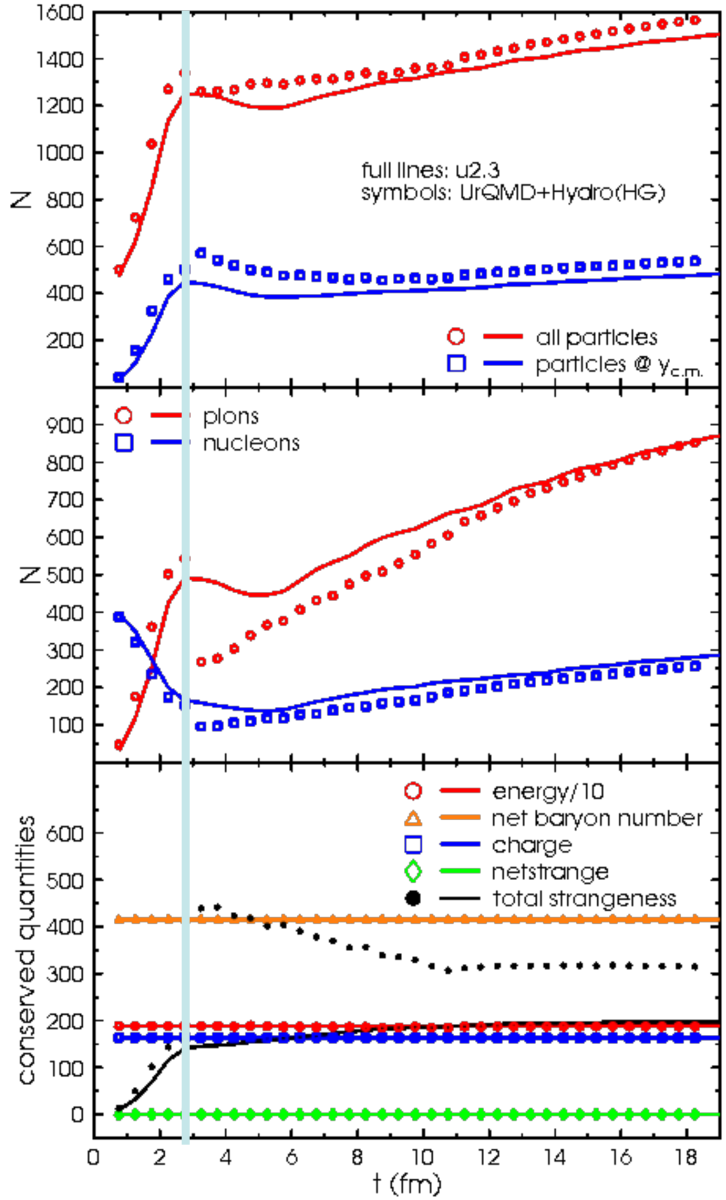




Conclusions

- 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-CBM** energy range (but also available for RHIC and LHC)
- Particle multiplicities and spectra are reasonably reproduced, **strangeness** enhanced
- Open tasks:
  - understand thermalisation
  - multi-particle interactions
  - hagedorn states in dynamical models
  - hadronisation
  - critical phenomena/fluctuations

Time Evolution



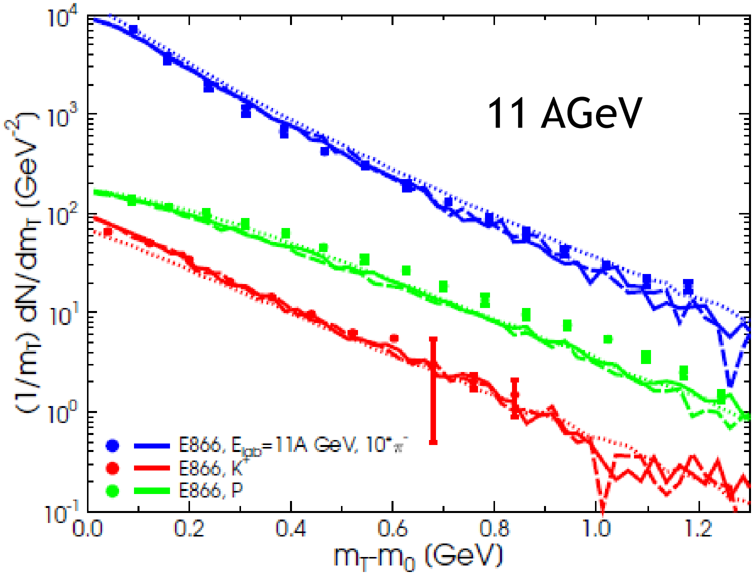
Central Pb+Pb collisions at 40A GeV:

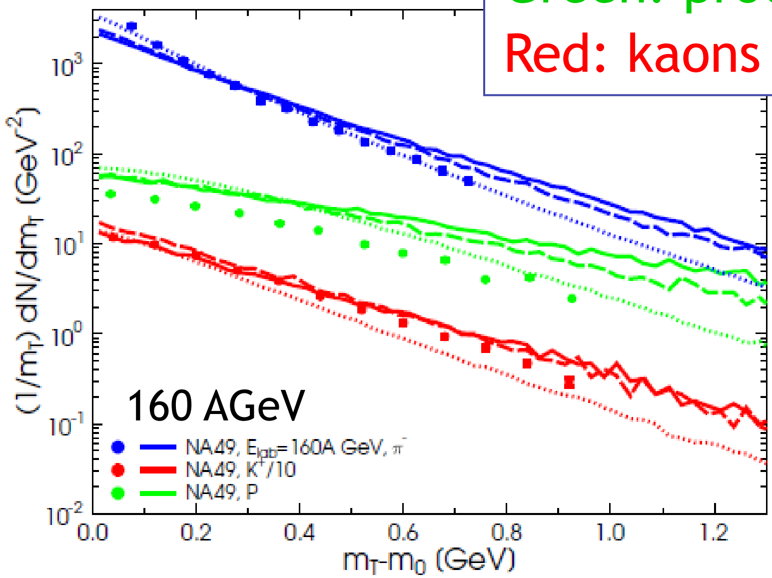
- Number of particles decreases in the beginning due to resonance creation
- Qualitative behaviour very similar in both calculations

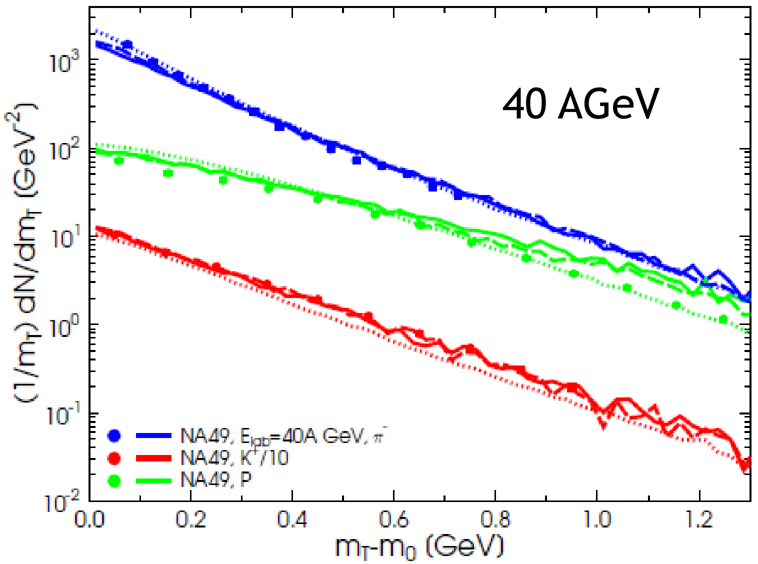
→ UrQMD **equilibrates** to a rather large degree

m_T Spectra

Blue: pions
Green: protons
Red: kaons







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

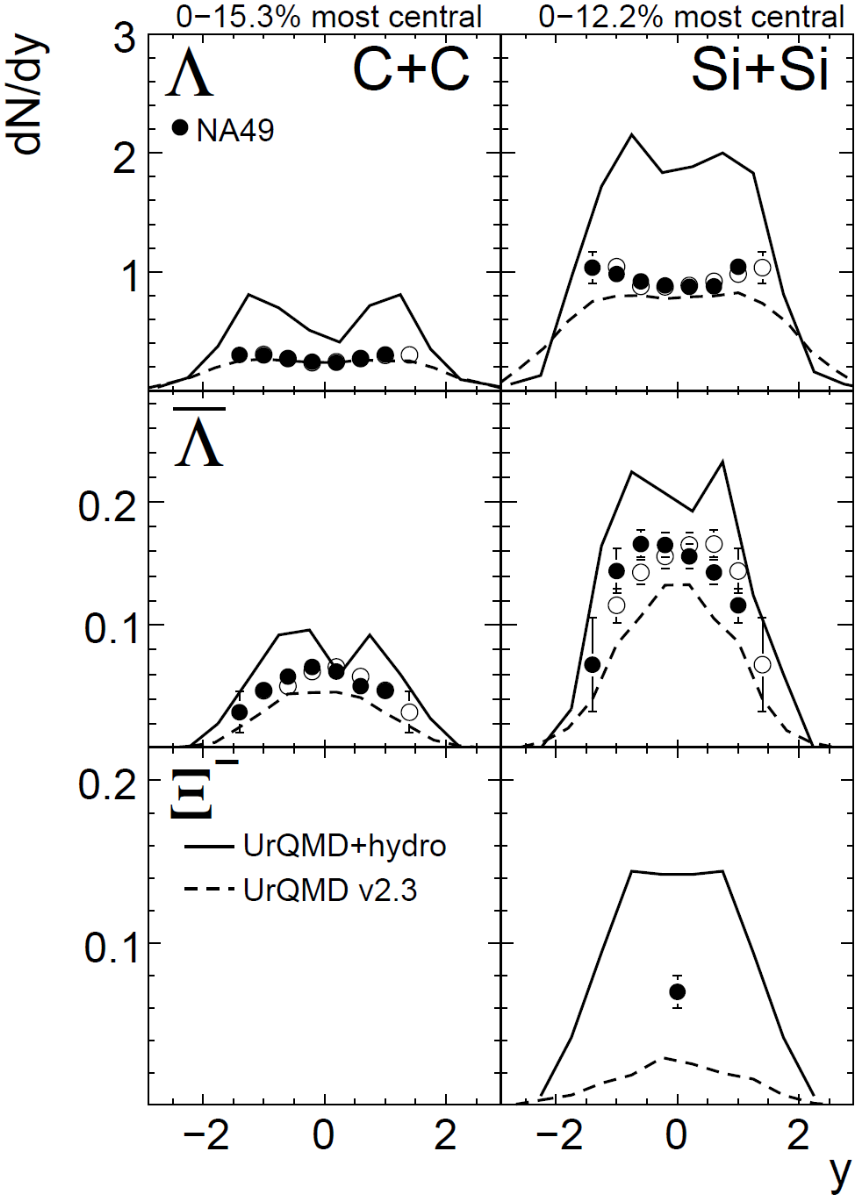
- m_T spectra are very similar at lower energies (11,40 AGeV)
- $<m_T>$ is higher in hydro calculation at E_{lab}=160 AGeV

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

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

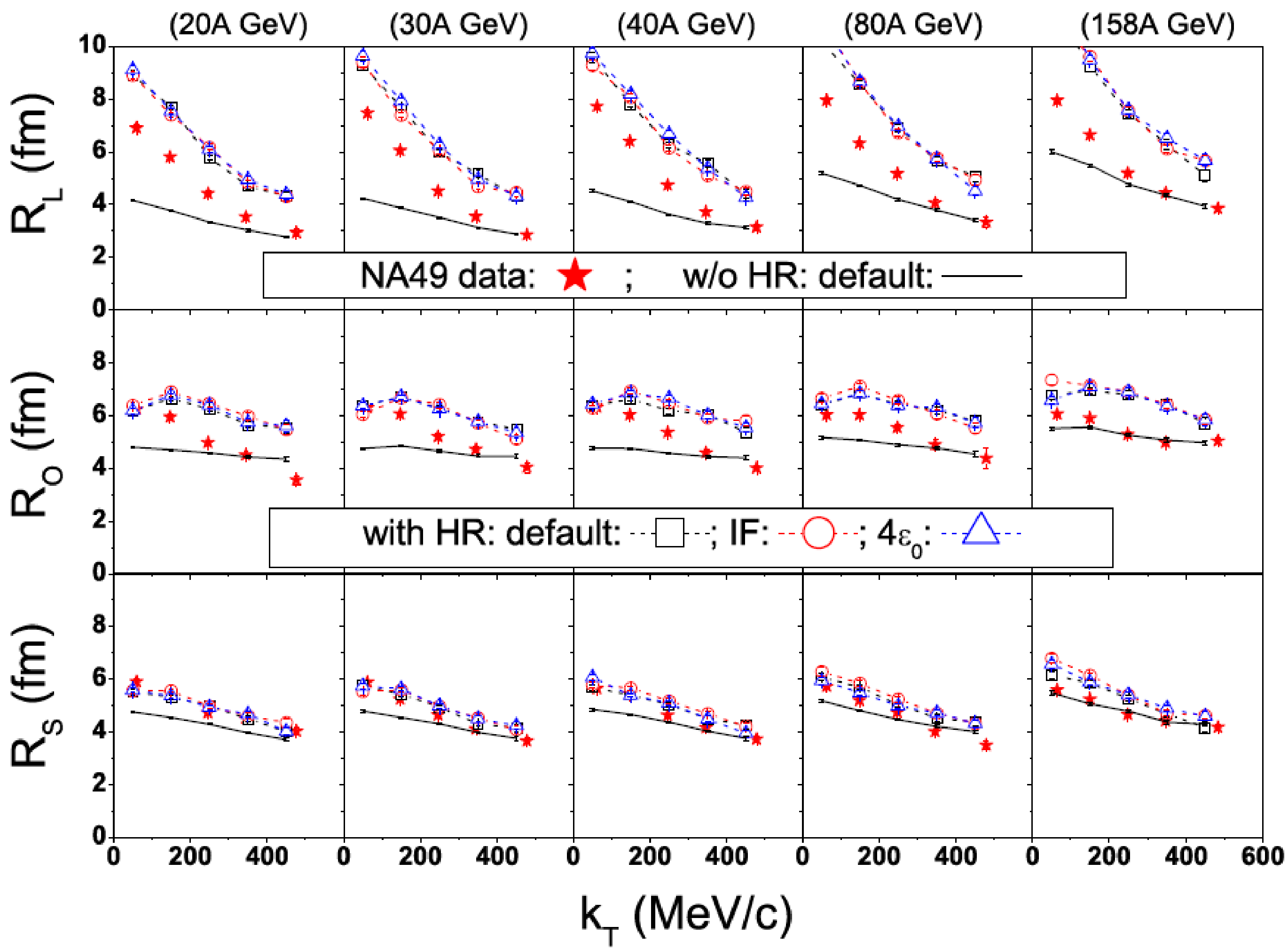
Limitations in small systems

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



(Petersen et al., arXiv: 0903.0396)

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

Hadronic channels

$$\pi + \pi \to \gamma + \rho, \quad \pi + \rho \to \gamma + \pi$$

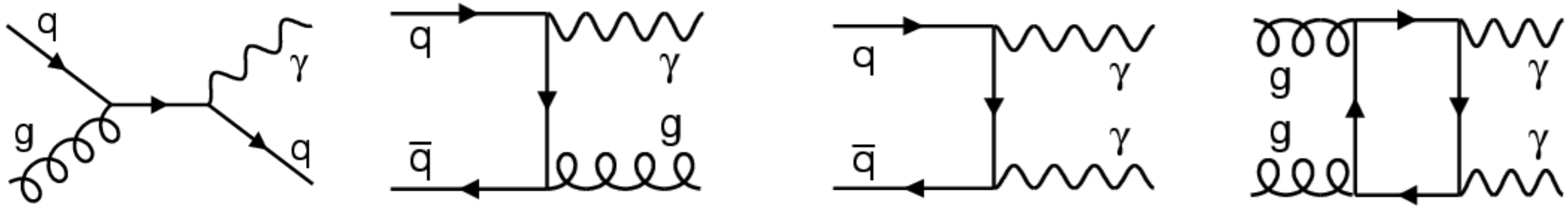
$$\pi + \pi \to \gamma + \eta, \quad \pi + \eta \to \gamma + \pi, \quad \pi + \pi \to \gamma + \gamma$$

$$\pi + K^* \to \gamma + K, \ \pi + K \to \gamma + K^*, \ \rho + K \to \gamma + K, \ K + K^* \to \gamma + \pi$$

Example for a differential cross section:

$$\frac{d\sigma}{dt}\left(\pi^\pm \rho^0 \to \gamma \pi^\pm\right) = \frac{\alpha g_\rho^2}{12 s p_{\mathrm{c.m.}}^2}\left[2 - \frac{s(m_\rho^2 - 4m_\pi^2)}{(s - m_\pi^2)^2} - \frac{(m_\rho^2 - 4m_\pi^2)}{t - m_\pi^2}\left(\frac{s - m_\rho^2 + m_\pi^2}{(s - m_\pi^2)(t - m_\pi^2)} + \frac{m_\pi^2}{(t - m_\pi^2)}\right)\right]$$

Partonic channels



→ from QGP: sensitivity to parton density and temperature

→ from initial state: sensitivity to PDFs (gluon!)

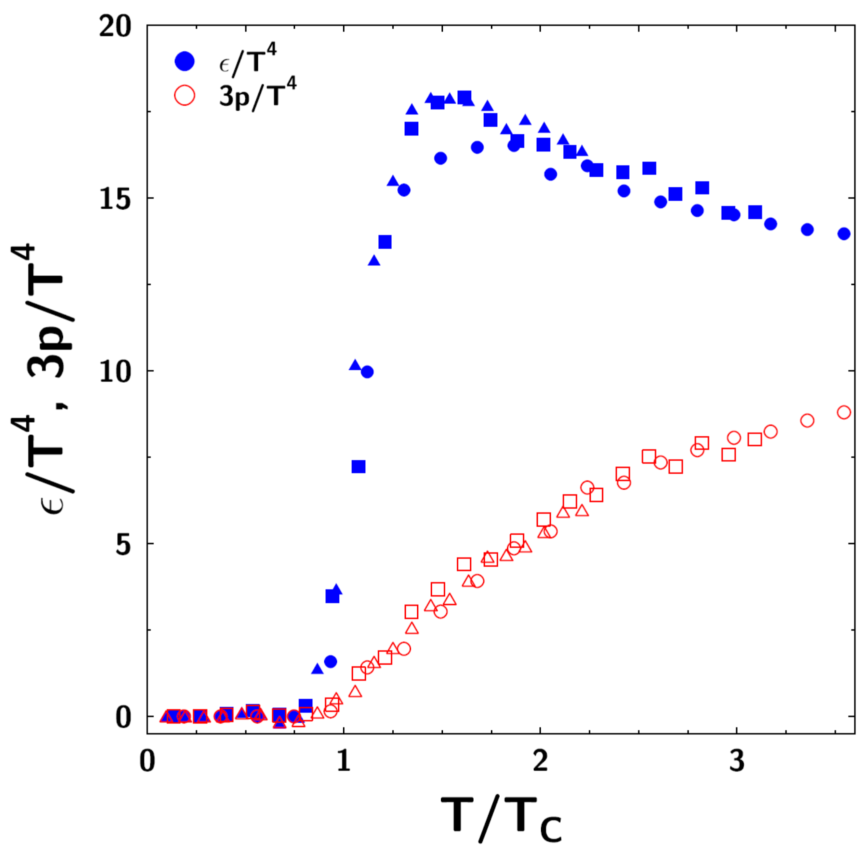
Cross section Refs

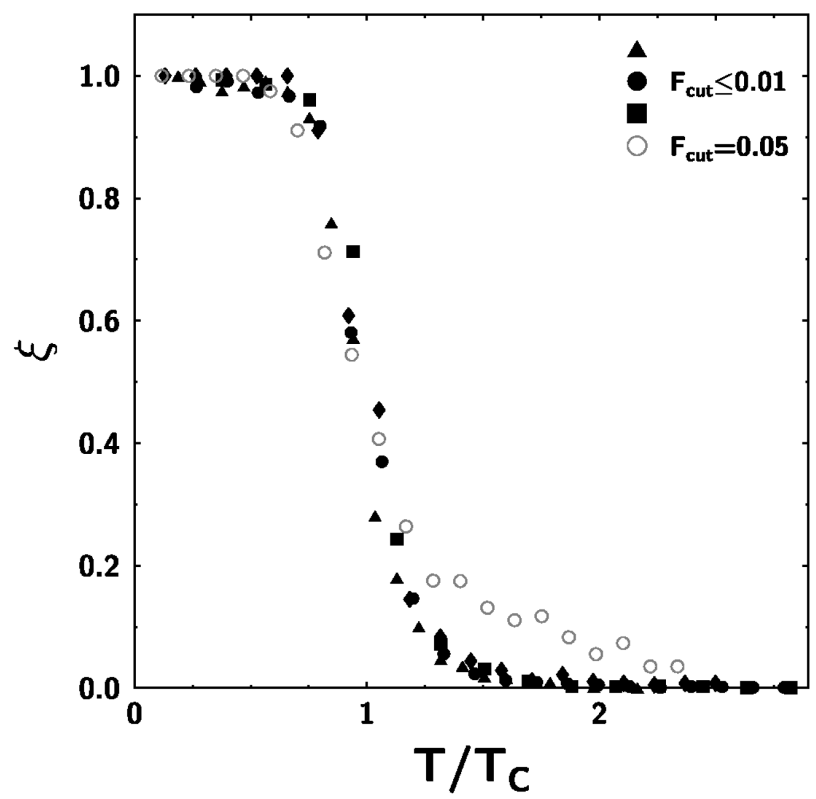
[1] E.g. Aurenche, Fontannaz *et. al*, PRD **73**, 094007 (2006)

[2] Turbide, Rapp and Gale, PRC **69**, 014903 (2004); Turbide, Gale *et al.*, PRC **72**, 014906 (2005); Liu and Werner, arXiv:0712.3612 [hep-ph]; Vitev and Zhang, arXiv:0804.3805 [hep-ph]; Haglin, PRC **50**, 1688 (1994); Haglin, JPG **30**, L27 (2004), Chatterjee *et al.*, Nucl. Phys. A **830** (2009) 503C

[3] Dumitru, Bleicher, Bass, Spieles, Neise, Stöcker and Greiner, PRC **57**, 3271 (1998); Huovinen, Belkacem, Ellis and Kapusta, PRC **66**, 014903 (2002); Li, Brown, Gale and Ko, arXiv:nucl-th/9712048; Bratkovskaya and Cassing, NPA **619**, 413 (1997); Bratkovskaya, Kiselev and Sharkov, arXiv:0806.3465 [nucl.th]

Some properties: equilibrium





Tc ~ 140 MeV

$\xi = N_{hadrons} / N_{all\ \ particles}$