# Transport Models in Heavy Ion Collisions

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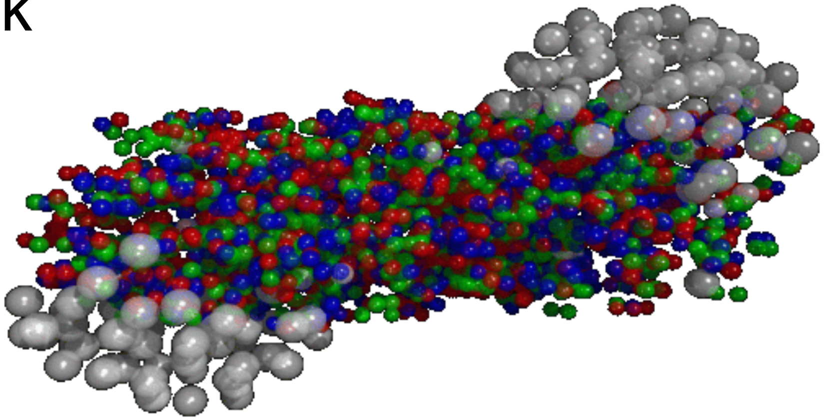


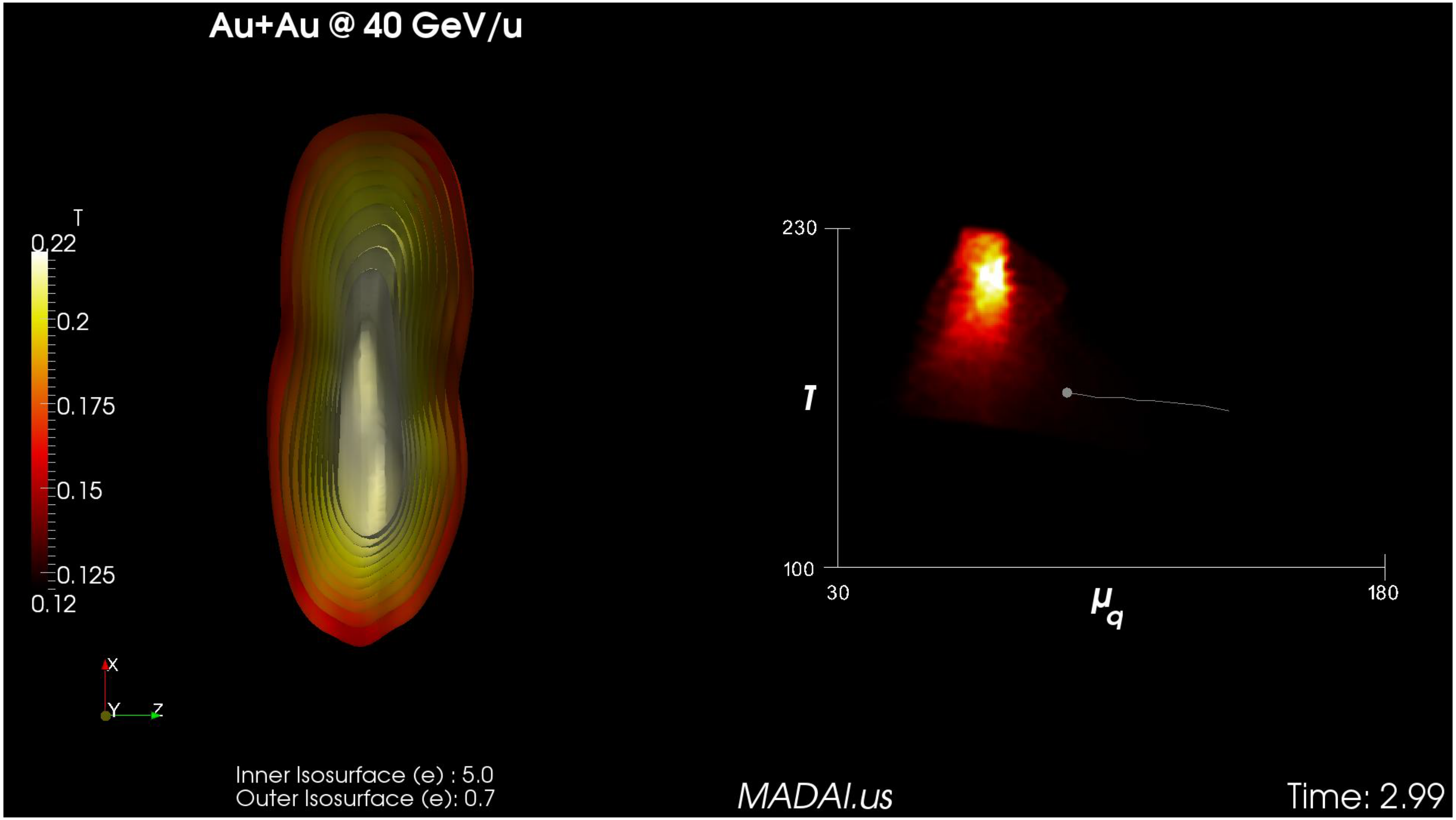
# Thanks to



- Hannah Petersen (Hybrid model) → now at FIAS
- Jan Steinheimer (Hybrid / EoS) → now at LBL
- Bjoern Baeuchle (Photons)
- Elvira Santini (Di-Leptons)
- Jochen Gerhard (GPU code)
- Yurii Karpenko (development of
  visc. hydro w/Nantes group)
- Hannu Holopainen, Pasi Huovinen (hydro freeze-out)
- Hendrik van Hees, (heavy quark Langevin)

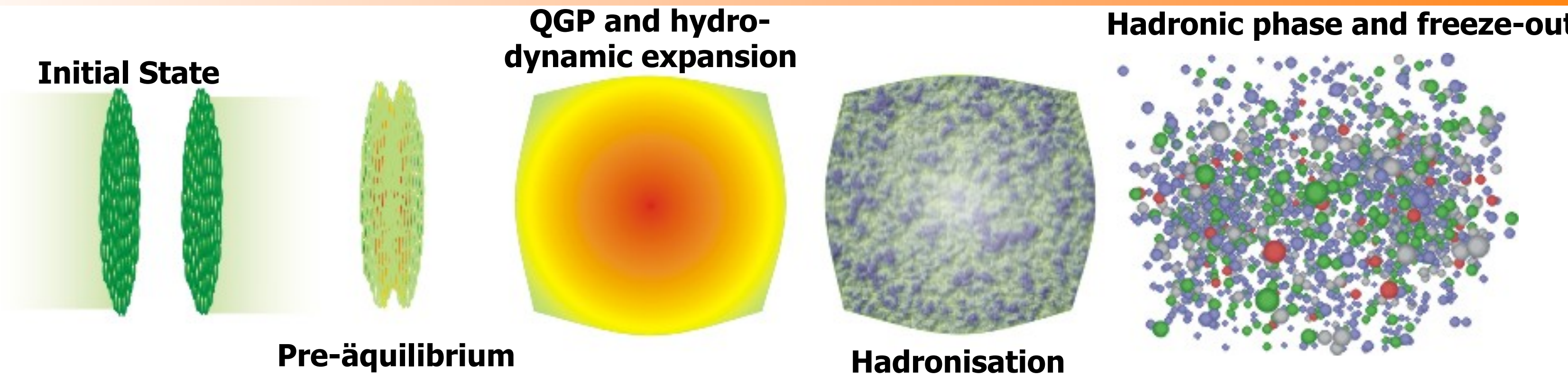
# Trajectories





# The need for dynamic simulations






**Lattice gauge-theorie (lQCD):**
- ab initio calculation of QCD quantities
- usually in thermodynamic limit

**Experiments:**
- Observes the final state and penetrating probes
- Relies on theoretical predictions for the interpretation of the data

**Transport models & phenomenology:**
- Provides explicit time and space dependence
- Direct view into the hot and dense matter
- Connects between fundamental calculations and observation

# Present Hybrid Approaches

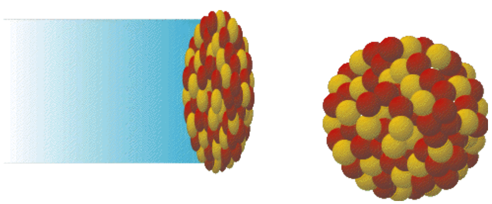


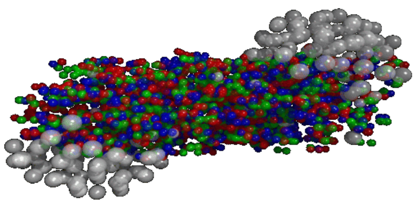
- Integrated (open source) UrQMD 3.3
  H. Petersen, J. Steinheimer, M. Bleicher, Phys. Rev. C 78:044901, 2008
- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
  T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara,
  Phys.Lett.B636:299-304,2006
- 3-D hydro + cascade 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
- EPOS+Hydro+UrQMD at LHC
  K. Werner, M. Bleicher, T. Pierog, Phys. Rev. C (2010)
- MUSIC@RHIC and LHC
  B. Schenke, S. Jeon, C. Gale, ...
- Started with S. Bass, A. Dumitru, M. Bleicher, Phys.Rev.C60:021902,1999

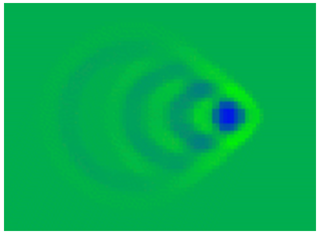
# Hybrid Approach

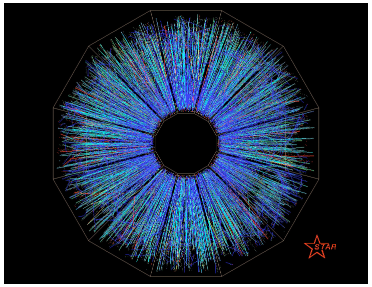
- Essential to draw conclusions from final state particle distributions about initially created medium
- The idea here: Fix the initial state and freeze-out

  → 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)

# Initial State

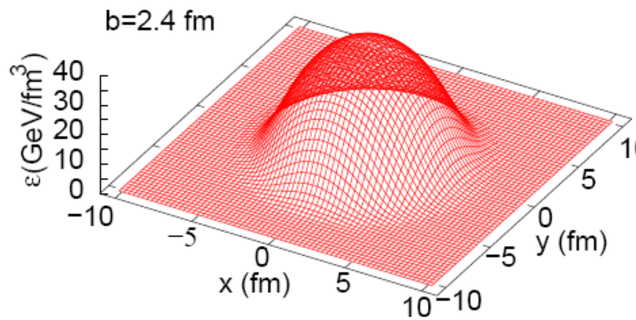


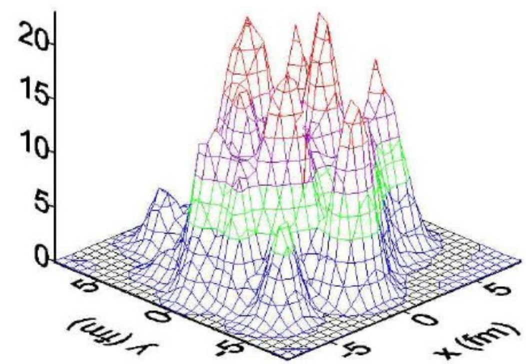
- Contracted nuclei have passed through each other

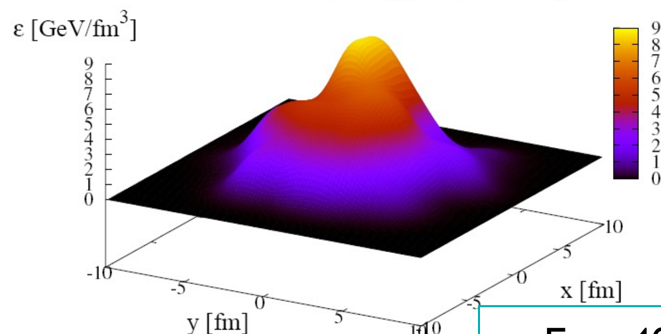
$$t_{start} = \frac{2R}{\gamma v}$$

  - 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

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




$E_{lab}$=40 AGeV
b=0 fm

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

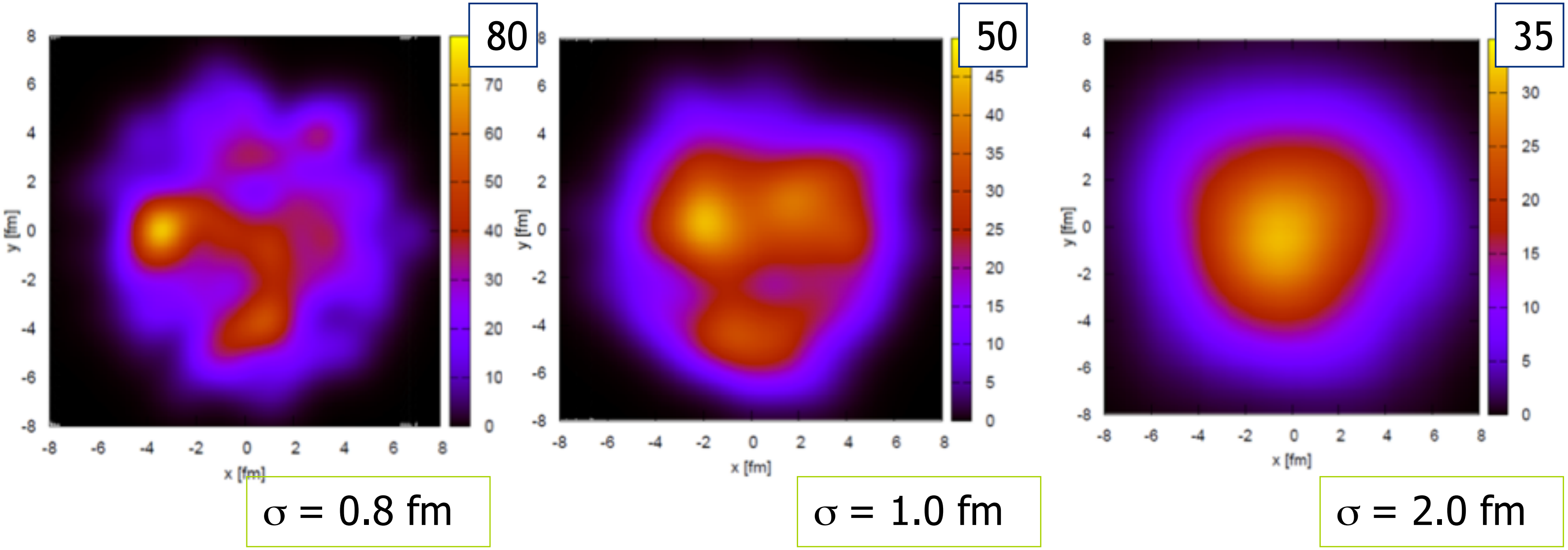
From H. Petersen

# Initial State at RHIC

- Energy-, momentum- and baryon number densities are mapped onto the hydro grid using for each particle

$$\epsilon(x,y,z) = \left(\frac{1}{2\pi}\right)^{\frac{3}{2}} \frac{\gamma_z}{\sigma^3} E_p \exp - \frac{(x-x_p)^2 + (y-y_p)^2 + (\gamma_z(z-z_p))^2}{2\sigma^2}$$

- Changing σ leads to different granularities, but also changes in the overall profile



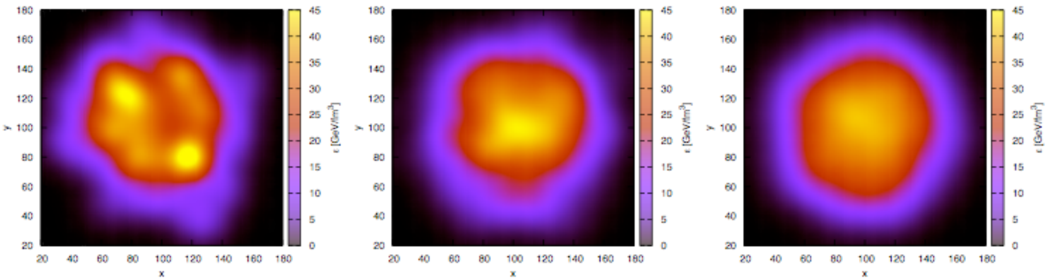

H.P. et al, PRC 83, 014916, 2011 and JPG 38, 045102, 2011

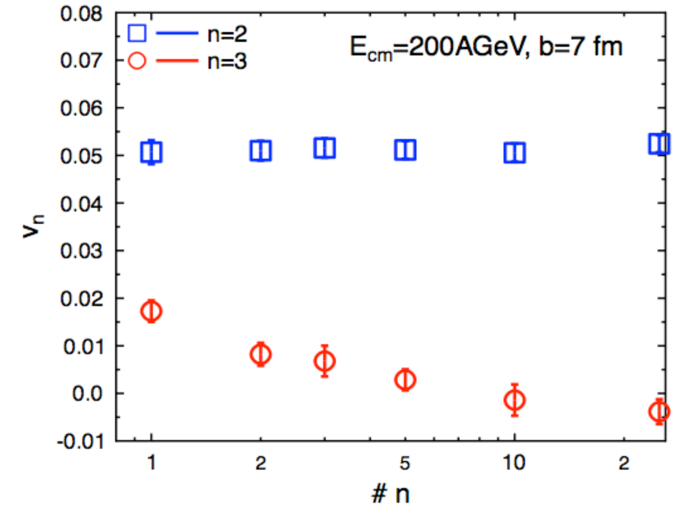
- How does changing the starting time affect the picture?

# Constraining Granularity

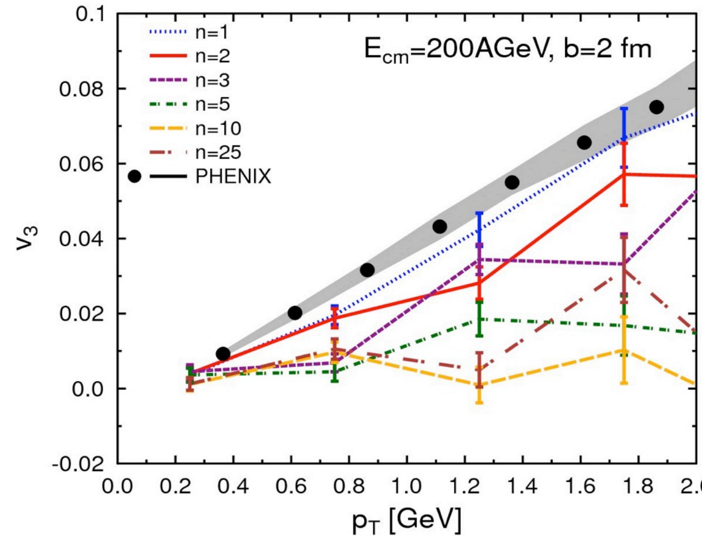


H.P. et al, J.Phys.G G39 (2012) 055102






- Triangular flow is **very sensitive** to amount of initial state fluctuations
- It is important to have final state particle distributions to apply **same analysis** as in experiment
- Single-event initial condition provides best agreement with PHENIX data
- Does that imply that the initial state is well-described by binary nucleon interactions +PYTHIA?
- Lower bound for fluctuations!



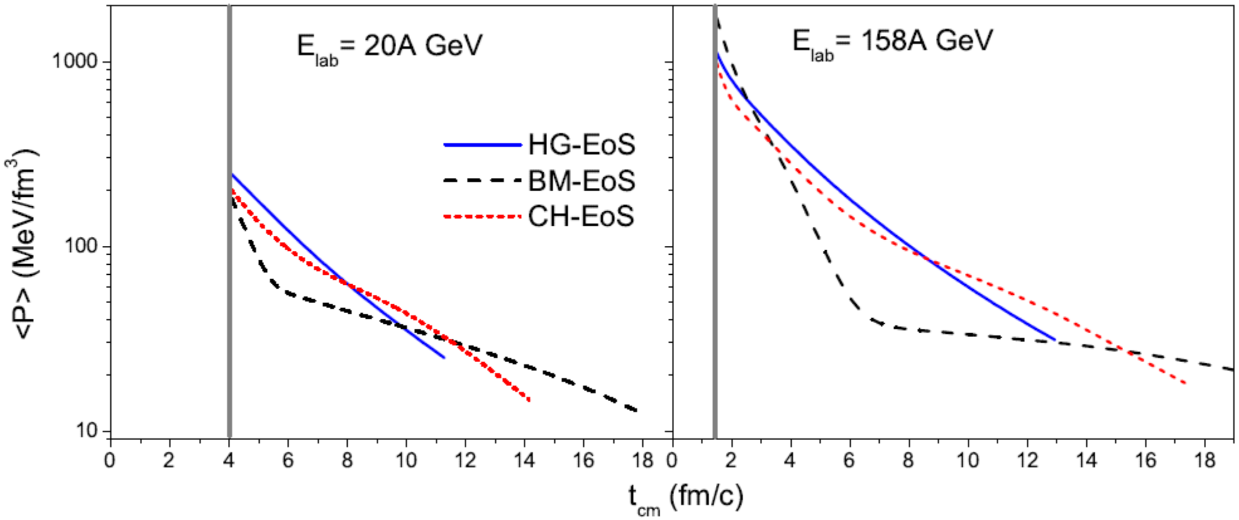

From H. Petersen

# 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 quark-meson model 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

J. Steinheimer, et al., J. Phys. G38 (2011) 035001

# Phase diagramm for the chiral EoS

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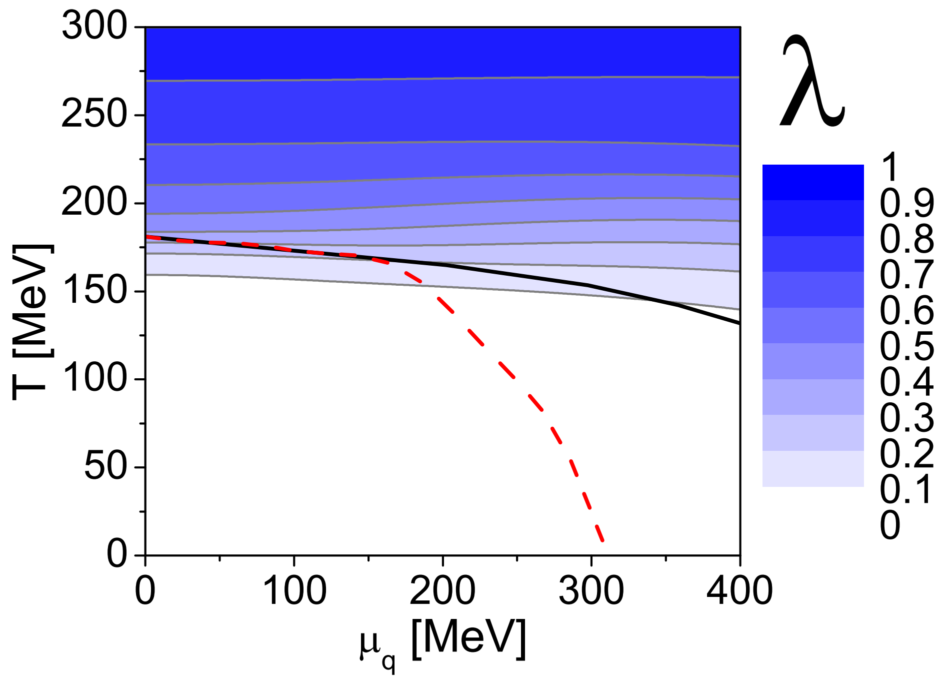
- QGP fraction lambda
- Chiral PT
- Deconfinement PT
- CEP
- Parameters fixed to lQCD




- Full line: Deconfinement
- Dashed line: Chiral PT

J. Steinheimer, S. Schramm, H. Stoecker, J. Phys. G38 (2011) 035001

# Hadronization and Cooper-Frye

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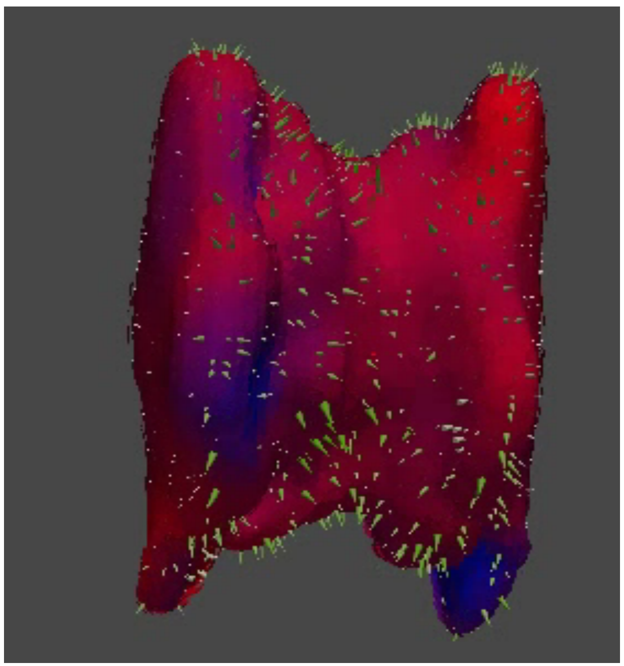
Experiments observe **finite number** of hadrons in detectors

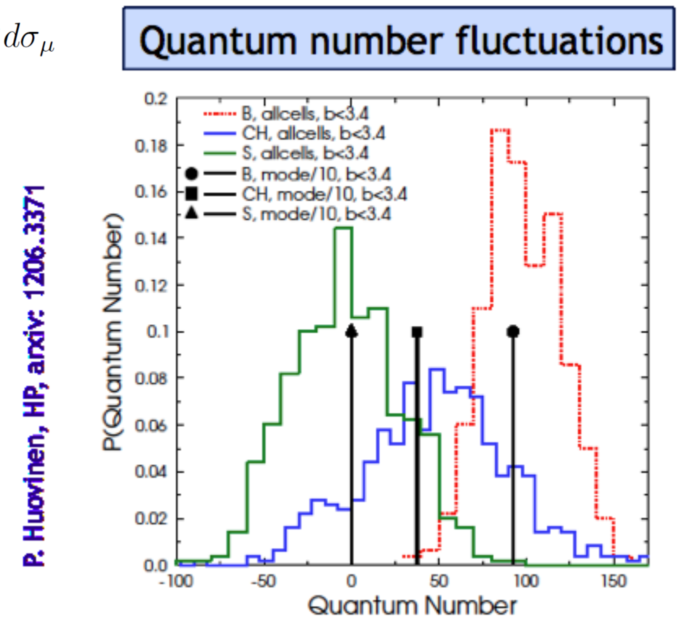
**Hadronization** controlled by the equation of state

Sampling of particles according to **Cooper-Frye** should:

- Respect **conservation laws**, maybe even locally?
- Introduces fluctuations on its own



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




Sophisticated 3D hypersurface finder to resolve interesting structures in event-by-event simulations

Petersen, Huovinen, arXiv:1206.3371

# Speeding things up: GPGPUs

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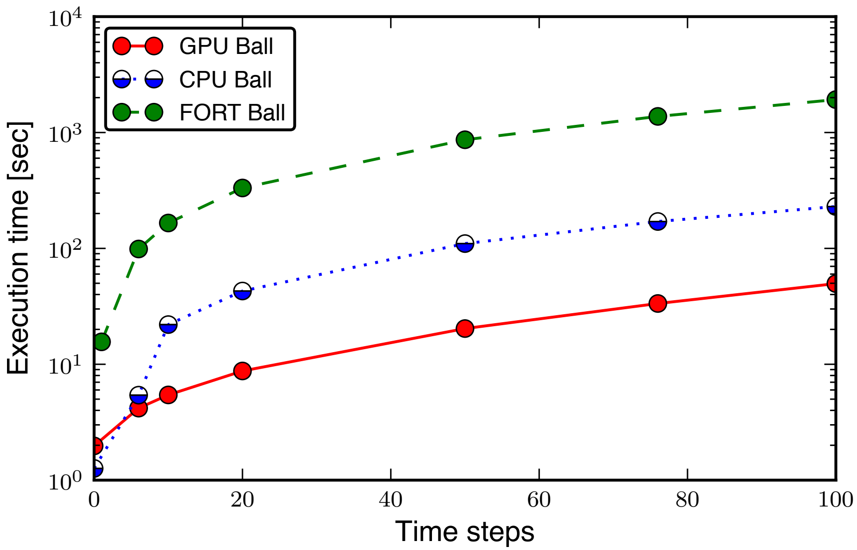
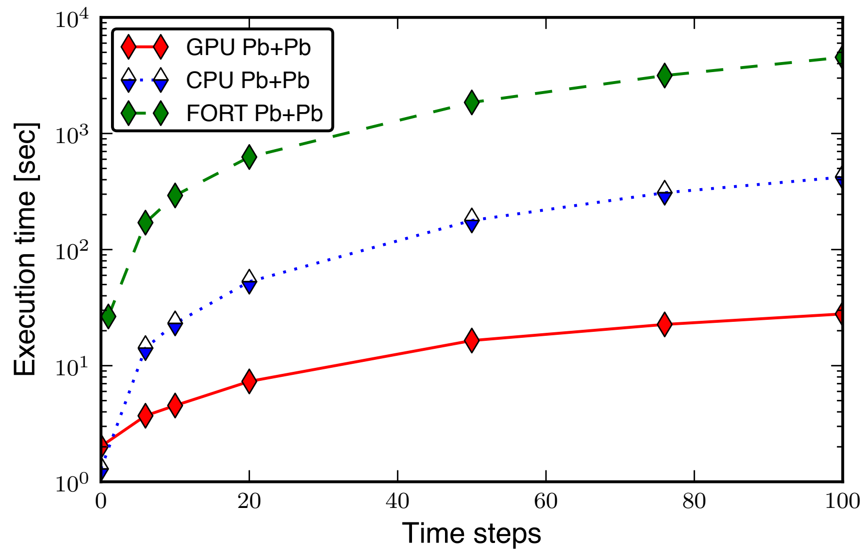


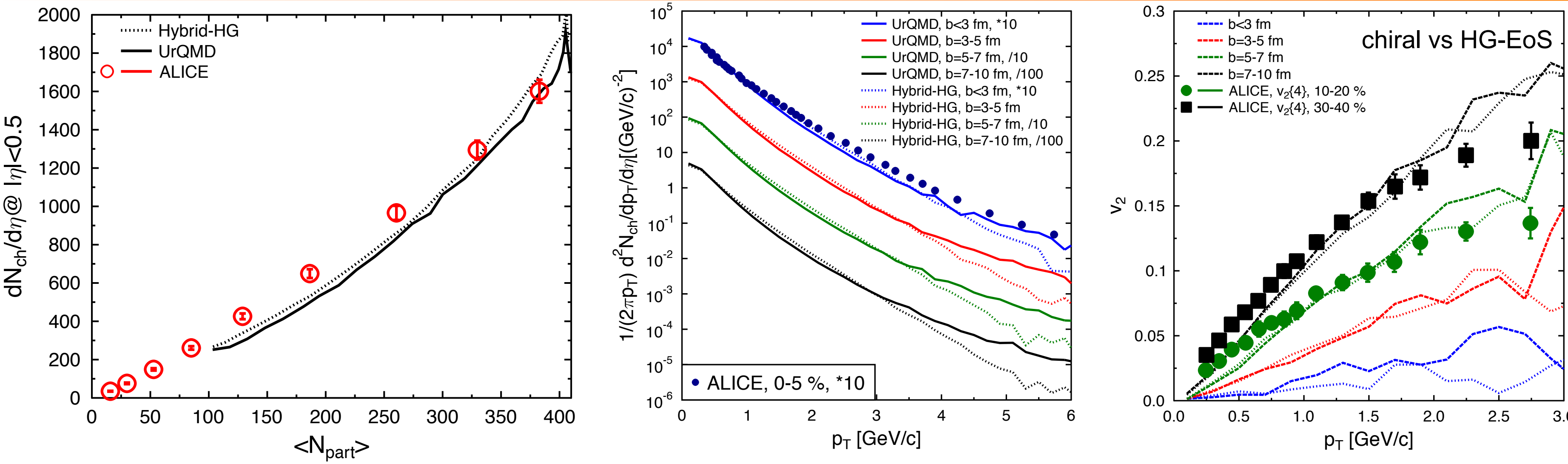

- 3+1d Simulation is working
- 100 Timesteps in FORTRAN ~60 min.
- 100 Timesteps in C++ Version ~15 min.

* 100 Timesteps in OpenCL Version ~30 sec.
* Factor 160 speed-up! (new cards: factor 400 !)

J. Gerhard, M. Bleicher, V. Lindenstruth, arXiv:1206.0919, CPC2012

# Hybrid model at LHC






- PbPb, 2.76 TeV
- Excellent description of centrality dependence,
- Transverse momenta,
- Elliptic flow.

H. Petersen, Phys.Rev. C84 (2011) 034912

# Heavy quarks at LHC

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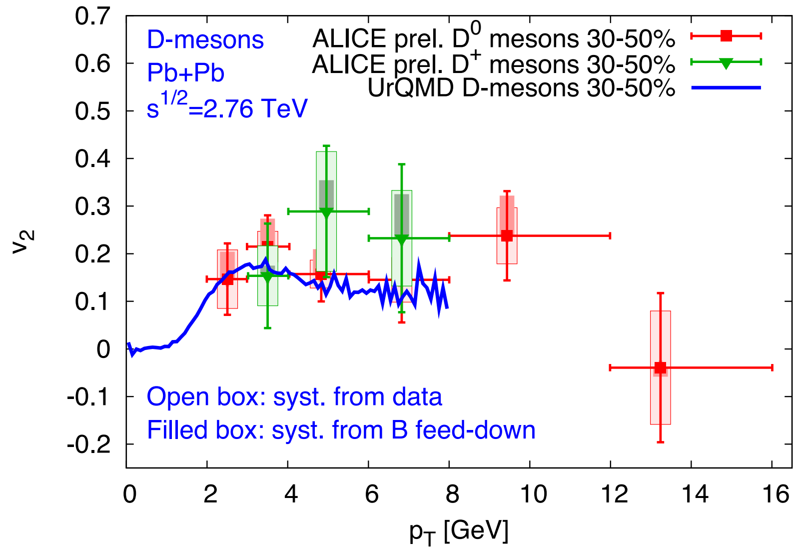
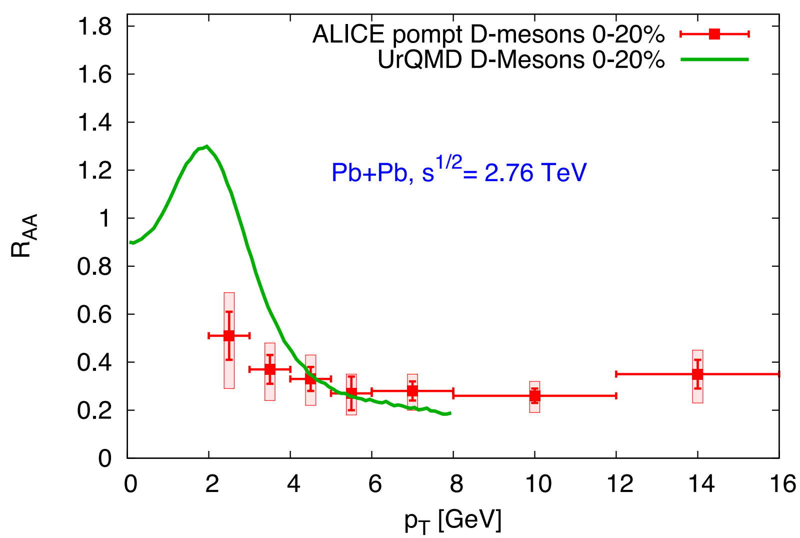


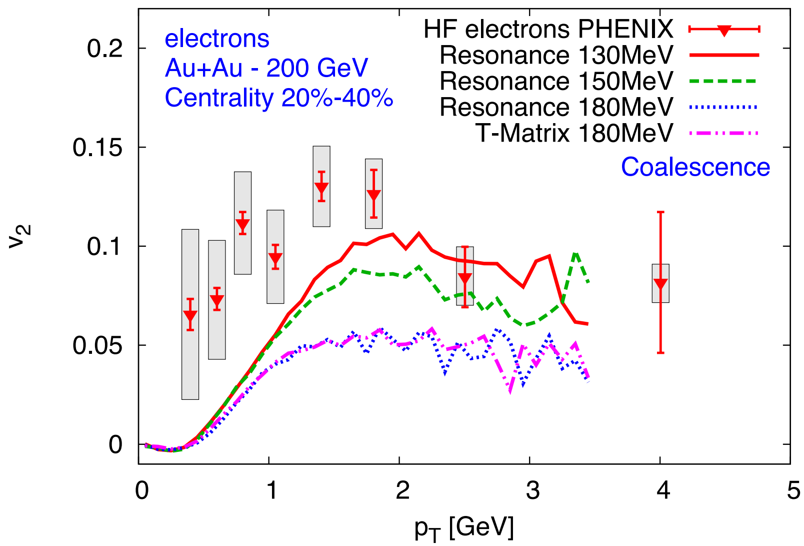



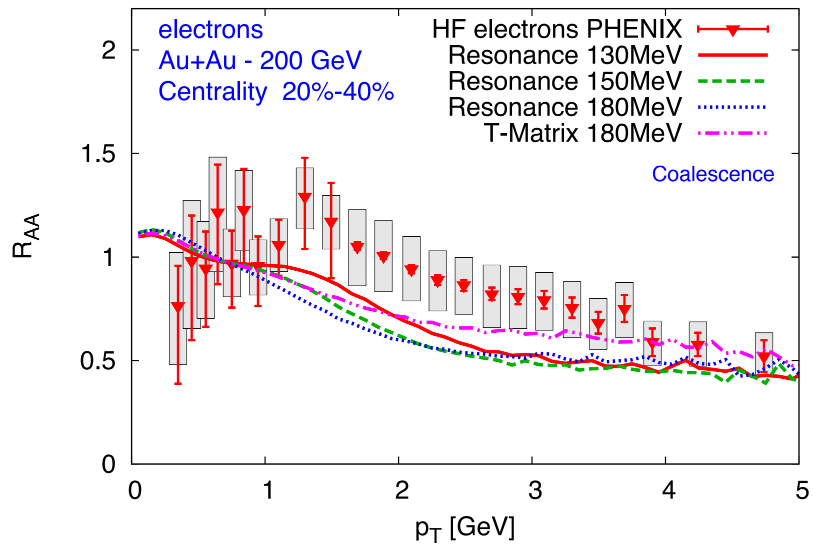

- Employ Rapp, van Hees-Langevin for heavy quarks in the dynamical background
  → good description of data

T. Lang, H. van Hees, M. Bleicher, arxiv: 1208.1643

# Heavy quarks at RHIC



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# Direct photon spectra at RHIC

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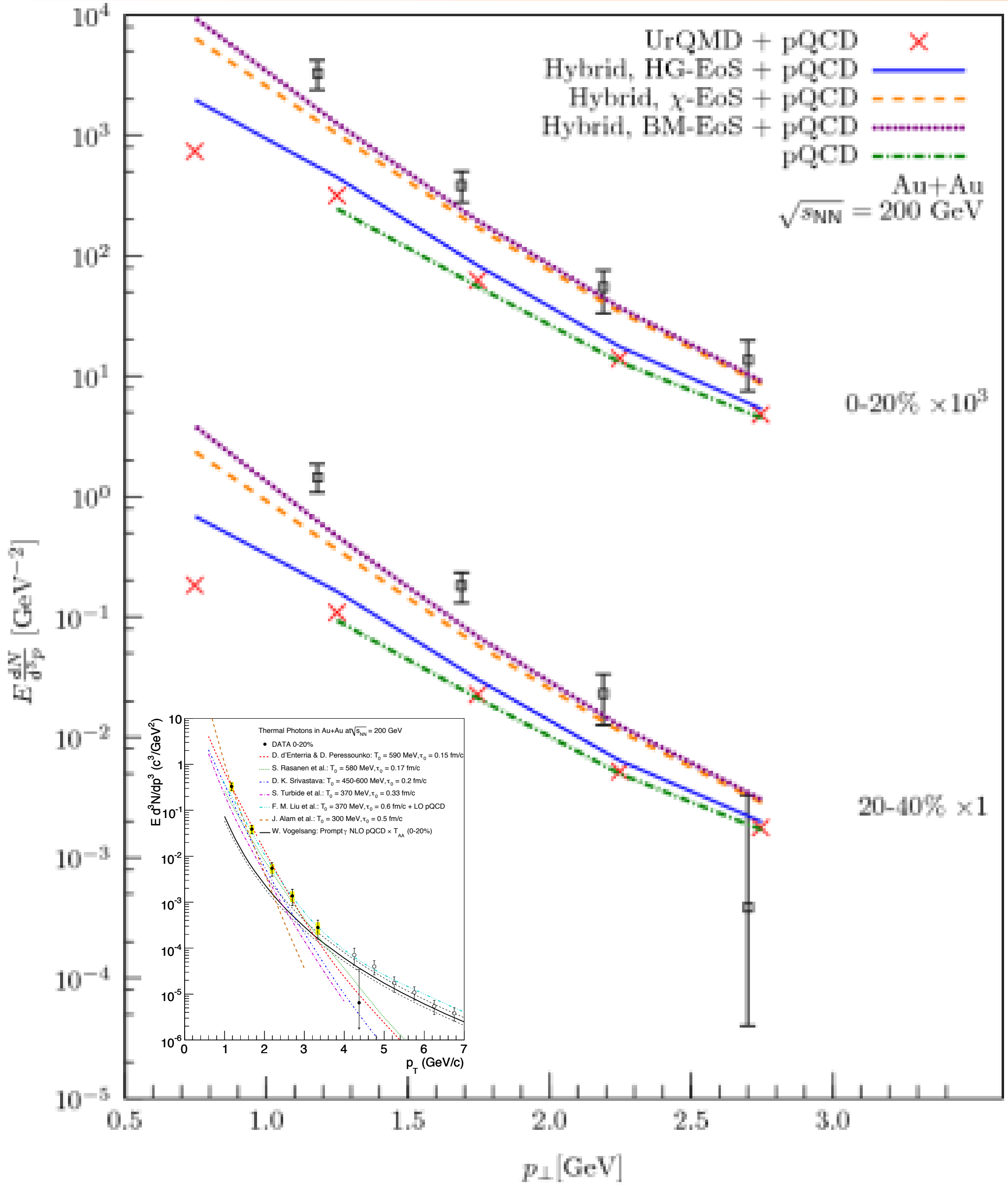



- Clear separation hadronic vs. partonic
- partonic calc. fit data
- Reasons for missing contributions in UrQMD/Hadron gas:
  - late equilibration,
  - hadronic rates,
  - shorter life time

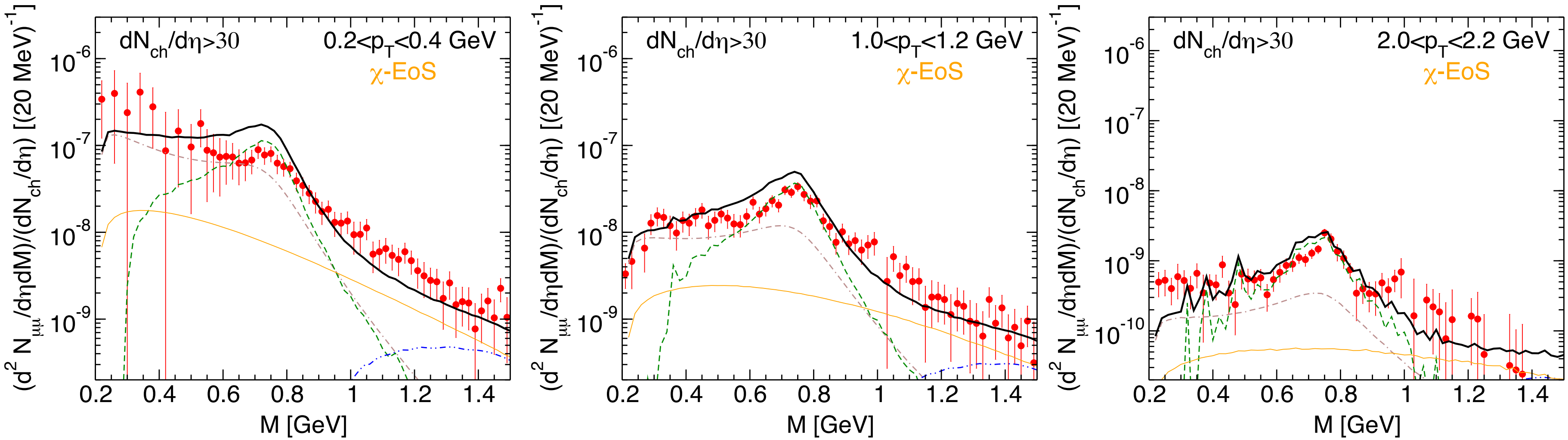
Data points from:
PHENIX, PRC 81 (2010) 034911
fig: Bäuchle, MB, PRC 82 (2010) 064901

# Virtual Photons (Di-Leptons)



$$\frac{d^8 N_{\rho^* \to ll}}{d^4x d^4q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} f_B(q_0;T)\,\mathrm{Im}\,D_\rho(M,q;T,\mu_B)$$

Self energy obtained from V.Eletsky, M. Belkacem, P. Ellis, J. Kapusta, Phys. Rev. C64 (2001) 035202




Santini, M.B. J. Steinheimer, PRC (2010)

# Rescattering and freeze-out

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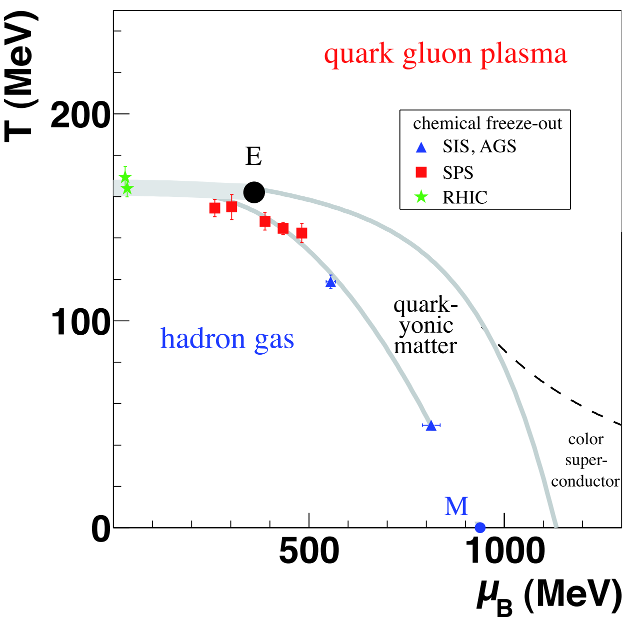


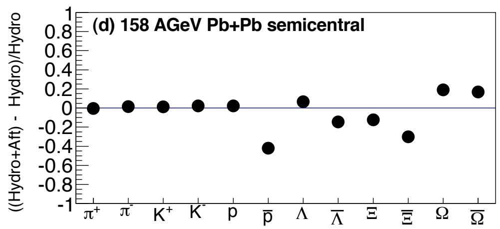


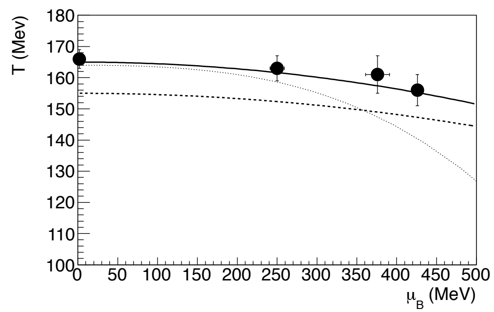


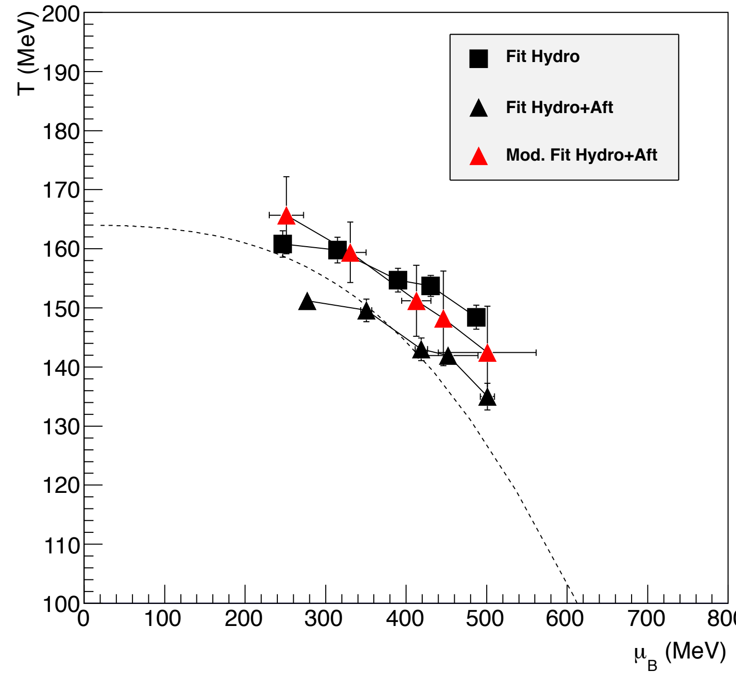


- Modification of the freeze-out parameters due to pbar annihilation
- ‚Correction‘ leads to increased temperatures in the thermal fits
- LHC: modifies p and pbar yields (solution of pbar problem)

Becattini et al, PRC85 (2012), Steinheimer et al, PRL110 (2013)

# Open questions: Initial state

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- Size of the initial state fluctuations (nucleons vs. ‚gluons‘)?
- Inclusion of interaction before hydro?
- Free streaming before hydro?
- Low energies:
  How to decouple the baryon currents?
- Initialization of shear tensor?
- Numerical stability of hydro code (shocks)?

# Open questions: Hydrodynamics

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- Viscosities (shear, bulk)?
- Which hydro approach at all (2nd? order)?
- How good are hydros w/o conserved baryon current?
- Is 2+1 dim hydro good enough?
- How to model the EoS at high mu_B?
- Effect of numerical viscosity?
- Modeling the CEP dynamically?
- How to propagate high pT particle through hydro?

# Open questions: ‚cooper-frye‘

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- Hyper surface is difficult to find (holes?)
- Negative weights for particle emission
- E-by-E conservation laws
- Equilibrium after transition?
- Mismatches in the EoS
- Non-equilibrium distribution functions