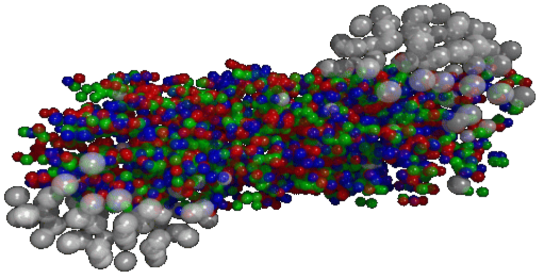

HIC for FAIR
Helmholtz International Center

Hybrid Models for Heavy Ion Collisions

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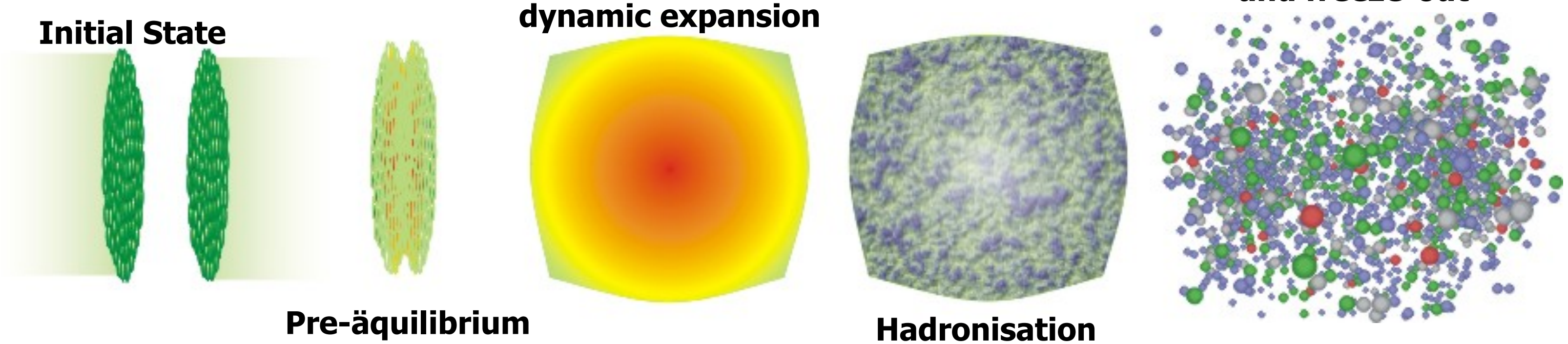
Institut für Theoretische Physik
Frankfurt Institute for Advanced Studies
Goethe Universität Frankfurt
Germany

This model can be downloaded from www.urqmd.org

Thanks to

- Hannah Petersen (Hybrid model) → now at Duke
- 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)
- Dirk Rischke (original SHASTA implementation)

Dynamic simulations



Lattice gauge-theorie (lQCD):
- ab initio calculation of QCD quantities
- usually in thermodynamic limit (infinite volume / infite time)

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 (lQCD) calculations and observation

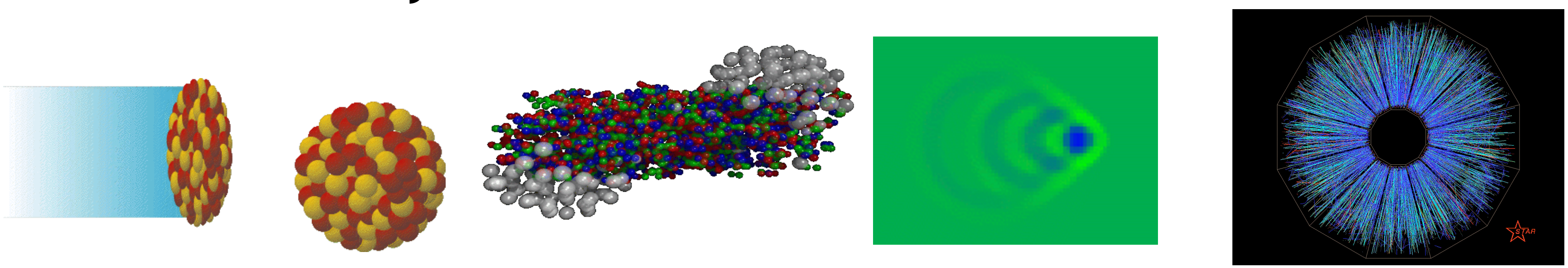
Present Hybrid Approaches

(3+1)dim. hydrodynamics with fluctuating initial conditions, continuous emission or afterburner:

- 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

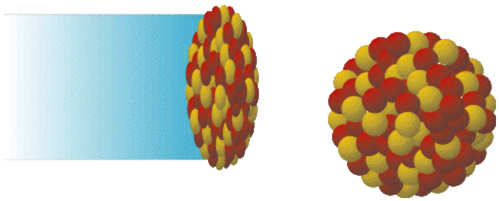


1) Non-equilibrium initial conditions via UrQMD	2) Hydrodynamic evolution **or** Transport calculation	3) Freeze-out via hadronic cascade (UrQMD)

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

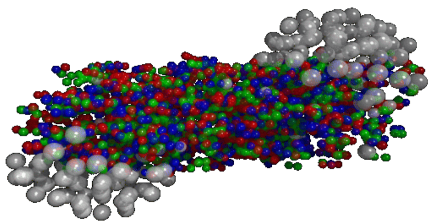
The UrQMD transport approach

UrQMD = Ultra-relativistic Quantum Molecular Dynamics



- Initialisation:

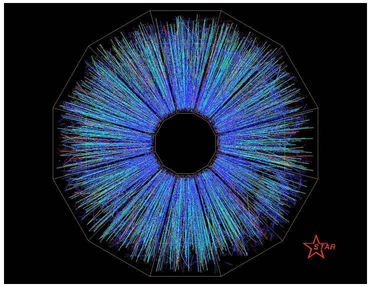
  Nucleons are set according to a Woods-Saxon distribution with randomly chosen momenta $p_i < p_F$



- Propagation and Interaction:

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

  hadrons, resonances, strings



- Final state:

  all particles with their final positions and momenta

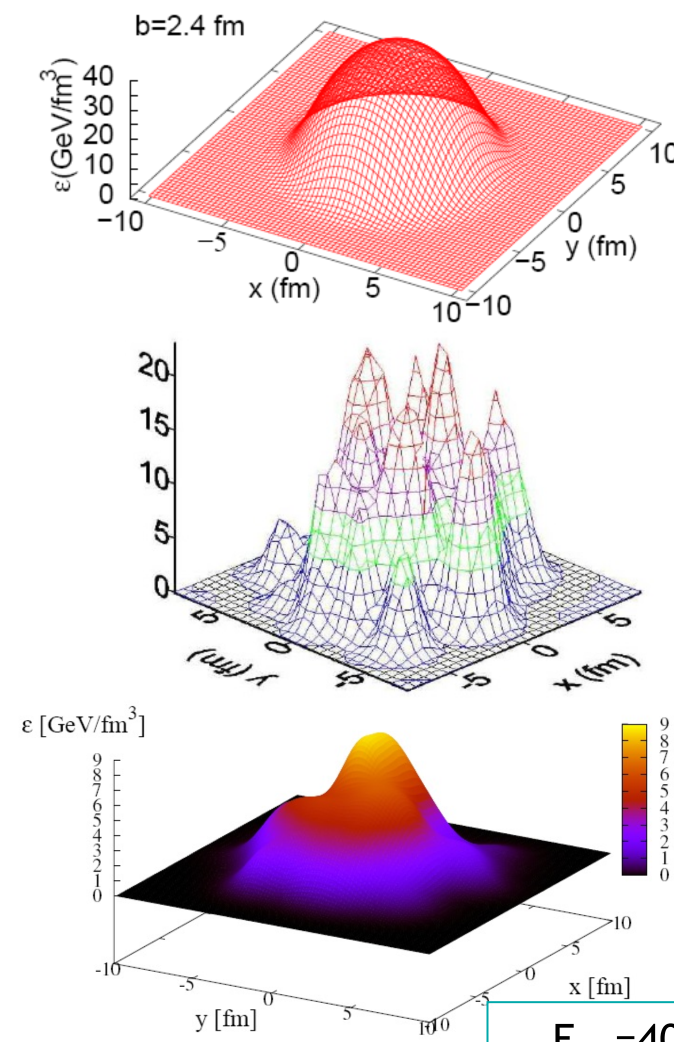
Very successful in describing different observables in a broad energy range
But: modeling of the phase transition and hadronization not yet possible

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)

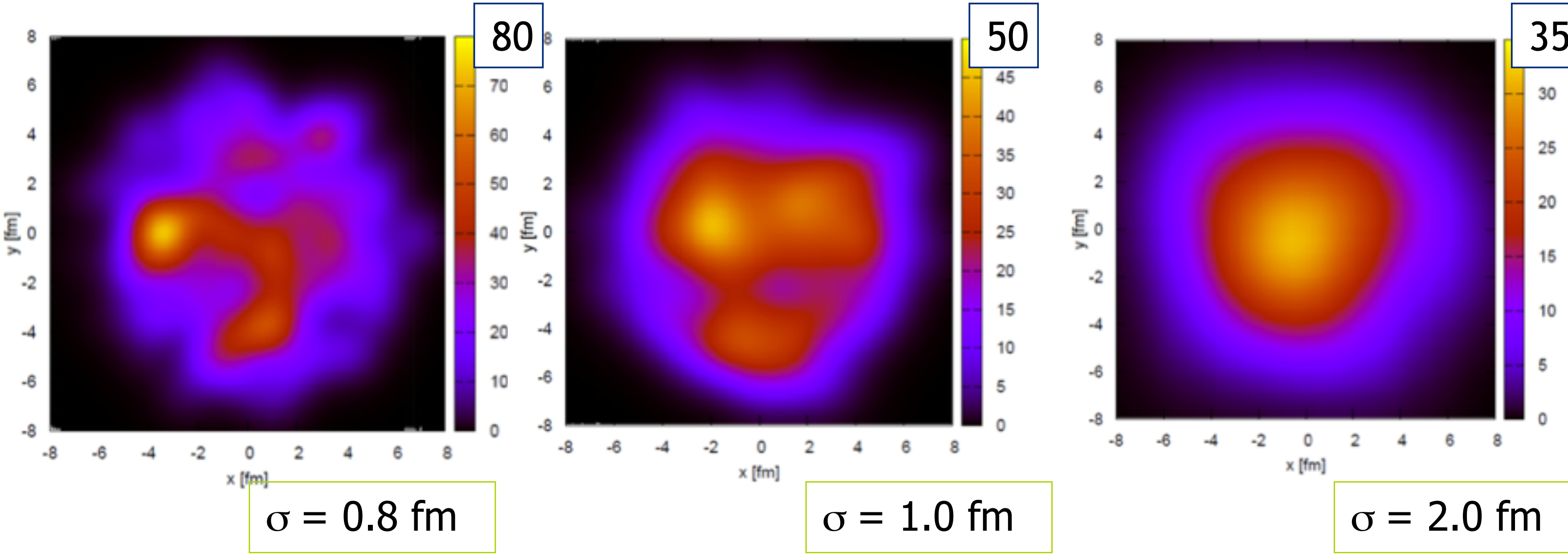
From H. Petersen

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

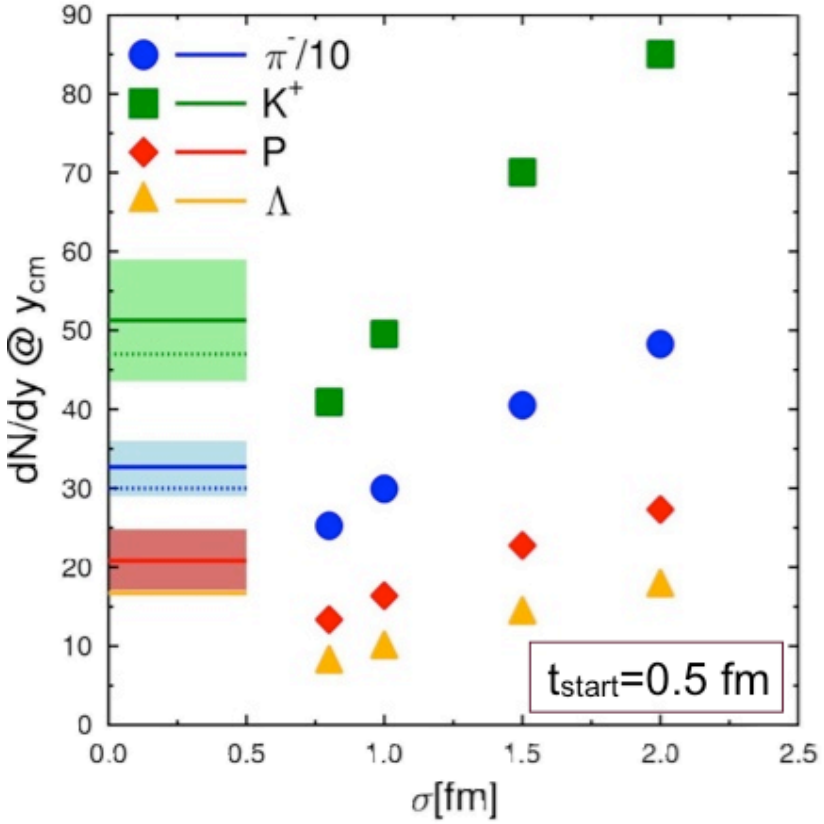


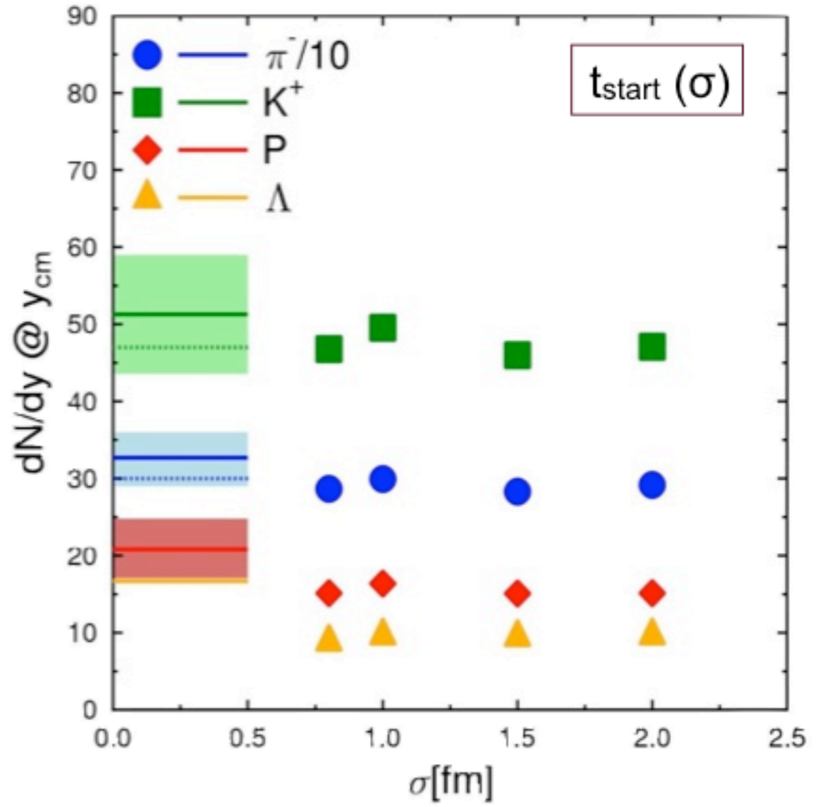
- How does changing the starting time affect the picture?

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

Starting Time Adjustment

From H. Petersen





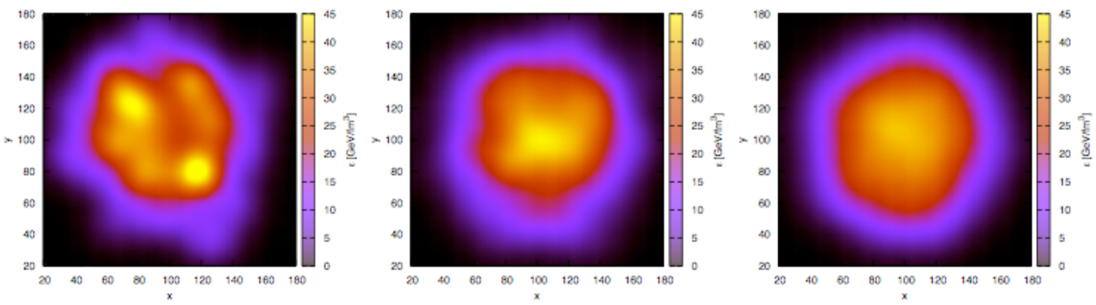
→ All four cases really produce similar yields

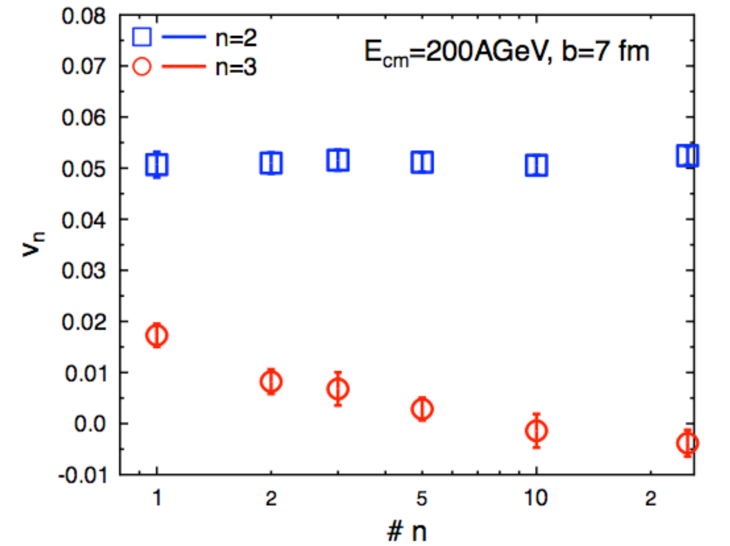
H. Petersen et al, J.Phys.G G38 (2011) 045102

From H. Petersen

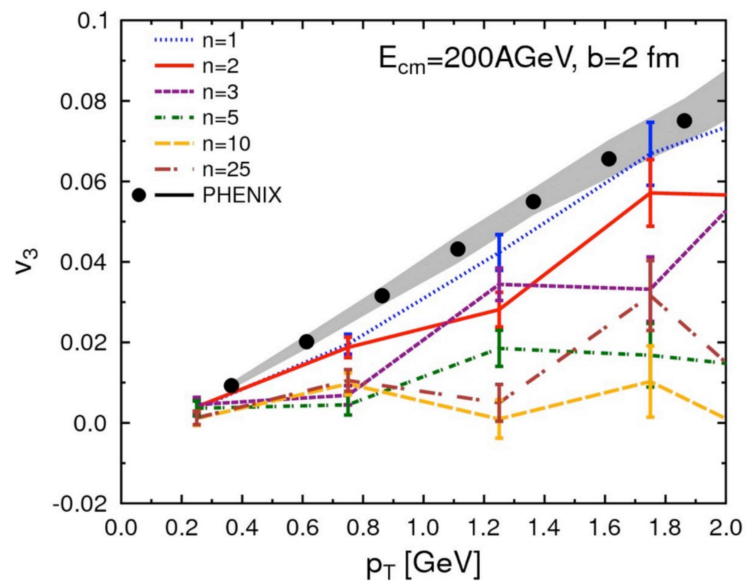
Constraining Granularity

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!



Open questions: Initial state

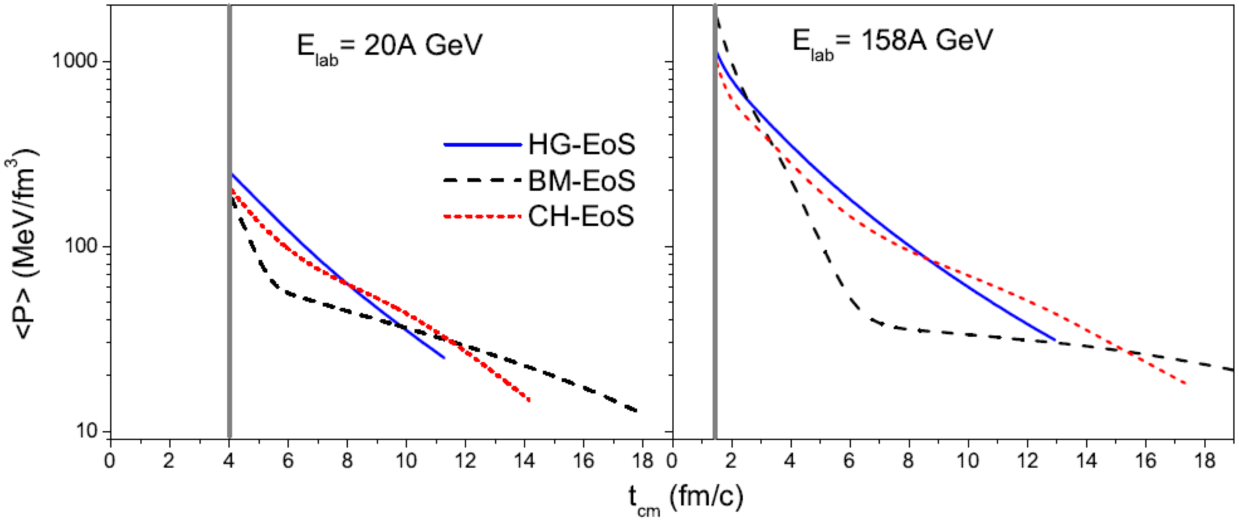
- Size of the initial state fluctuations (nucleons vs. ‚gluons‘)?
- Inclusion of interaction before hydro?
- Free streaming before hydro?
- Low energies:
  How to decouple the baryon currents?
- Initialization of shear tensor?
- Numerical stability of hydro code (shocks)?

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,

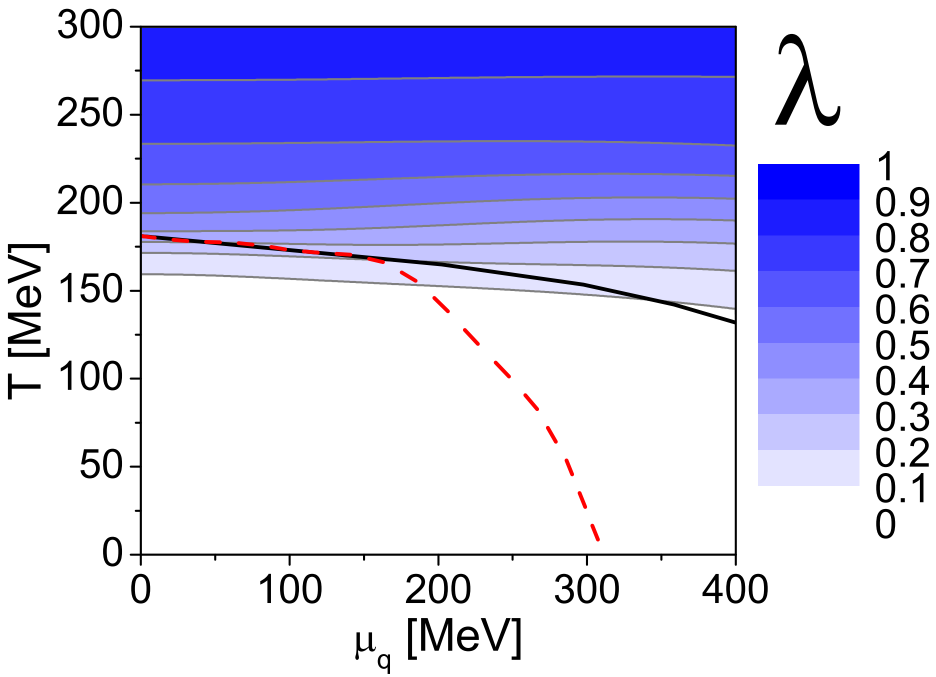
D. Zschiesche et al., PLB 547, 7, 2002

Papazoglou et al., PRC 59, 411, 1999

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

Phase diagramm for the chiral EoS

- 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

Open questions: Hydrodynamics

- 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?
- How to propagate high pT particle through hydro?
- Modeling the CEP dynamically?

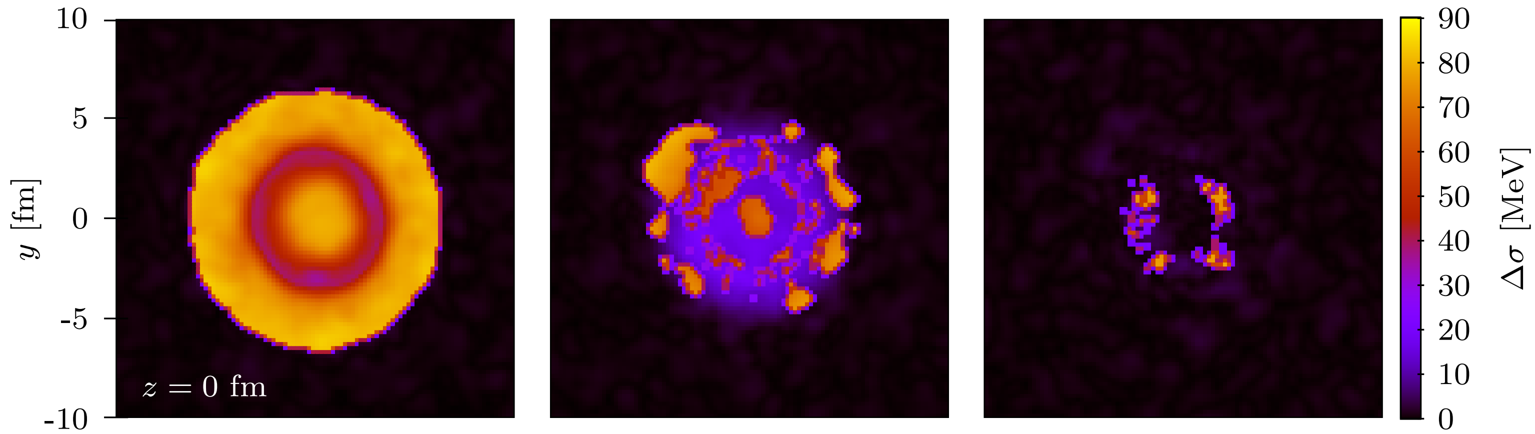
Chiral hydrodynamics

Aim: Explore signals for the onset of deconfinement and critical end point at FAIR/CBM

Method: Hydrodynamics coupled to chiral fields (sigma model) w/noise

$$\mathcal{L} = \overline{q}\left[i\left(\gamma^{\mu}\partial_{\mu} - ig_{s}\gamma^{0}A_{0}\right) - g\left(\sigma + i\gamma_{5}\vec{\tau}\cdot\vec{\pi}\right)\right]q + \frac{1}{2}\left(\partial_{\mu}\sigma\right)^{2} + \frac{1}{2}\left(\partial_{\mu}\vec{\pi}\right)^{2} - U\left(\sigma,\vec{\pi}\right) - \mathcal{U}(\ell,\bar{\ell})$$

Results: Realistic estimates (finite size and finite lifetime) for PT/CEP signals

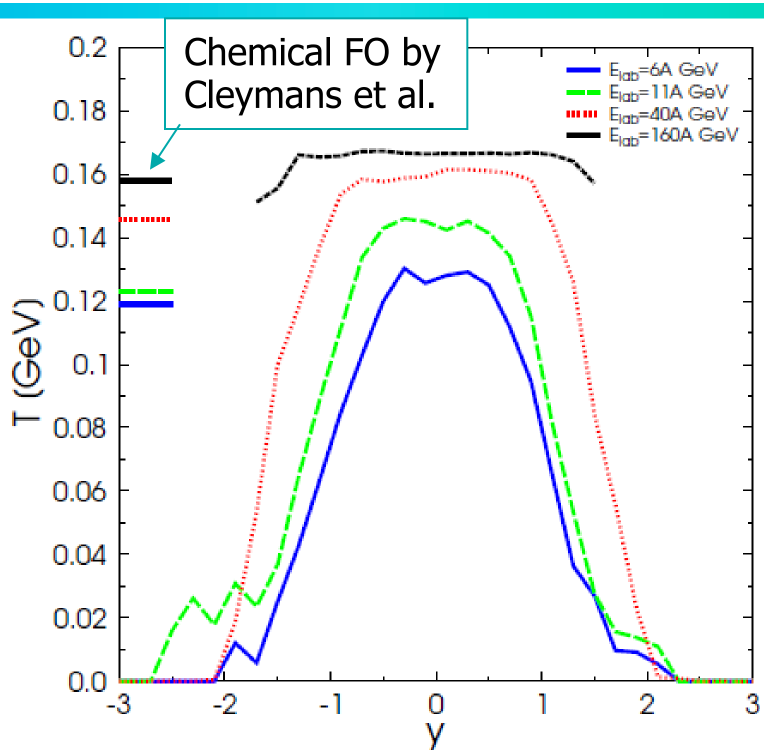


Smoothed initial conditions from 100 UrQMD event, 40 AGeV

M. Nahrgang, C. Herold, I. Mishustin, M. Bleicher, arXiv:1105.1962, Phys.Rev. C84 (2011) 024912, Phys.Lett. B711 (2012) 109-116

Freeze-out

- 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)
  - → resembles an iso-eigentime criterion
  - → Different from event-to-event



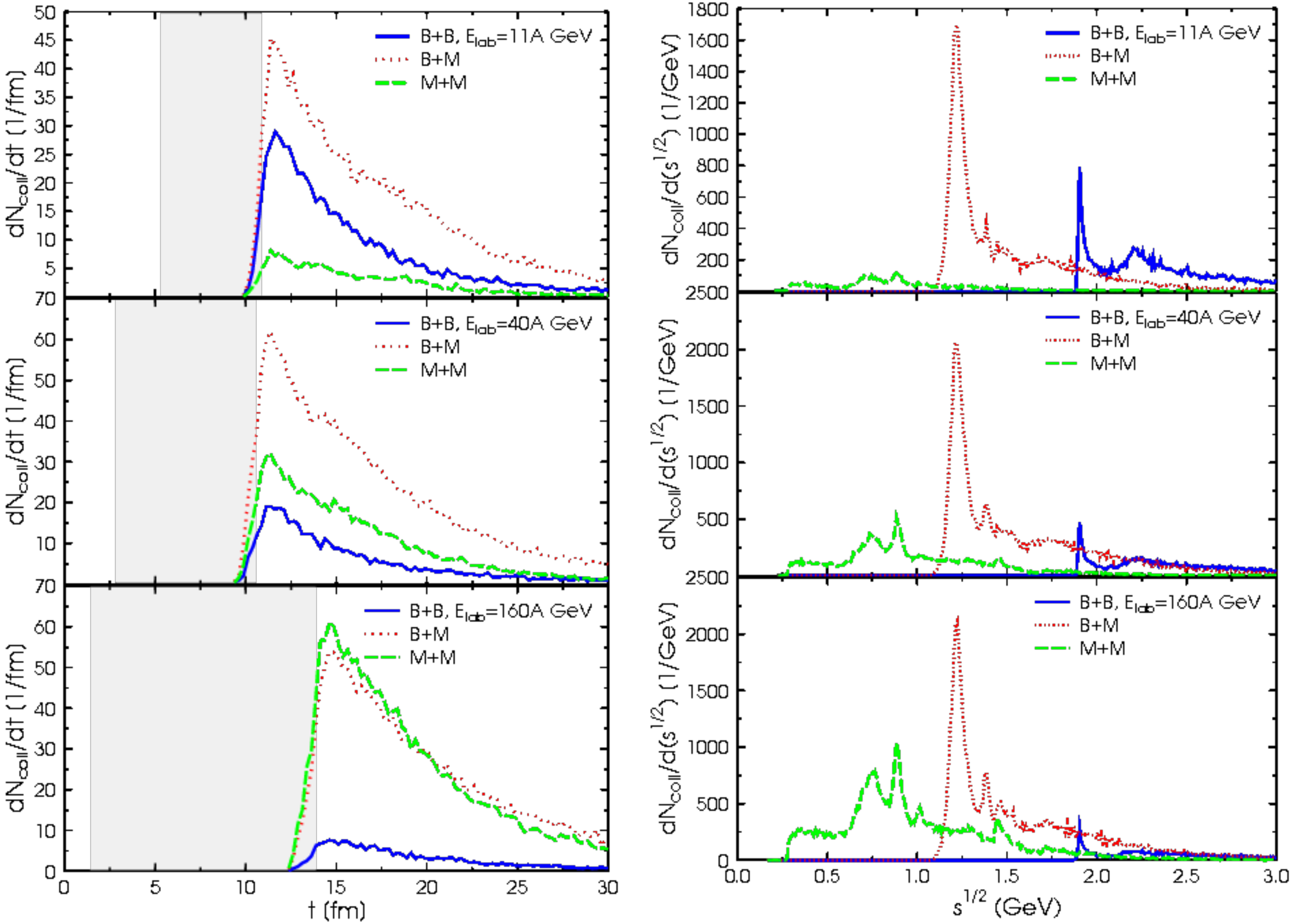
- Particle distributions are generated according to the **Cooper-Frye** formula

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

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)



Open questions

- 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
- **Speed!**

Recent developments in SHASTA

- Idea:
  use graphic cards to speed-up computation
- Relativistic Hydrodynamics on Graphic Cards.
  Jochen Gerhard, Volker Lindenstruth, Marcus Bleicher.
  e-Print: **arXiv:1206.0919 [hep-ph]**

  Computer Physics Communication in print (2012)

→ Need to convert the legacy code to modern architecture

The new C++ Code

- The Code was redesigned in C++ to allow a better maintenance.
  - Class structure and clean encapsulation allow for integration of new ideas without rewriting all the code
- Also performance optimization:
  - tripled execution speed
  - Used 80% less memory

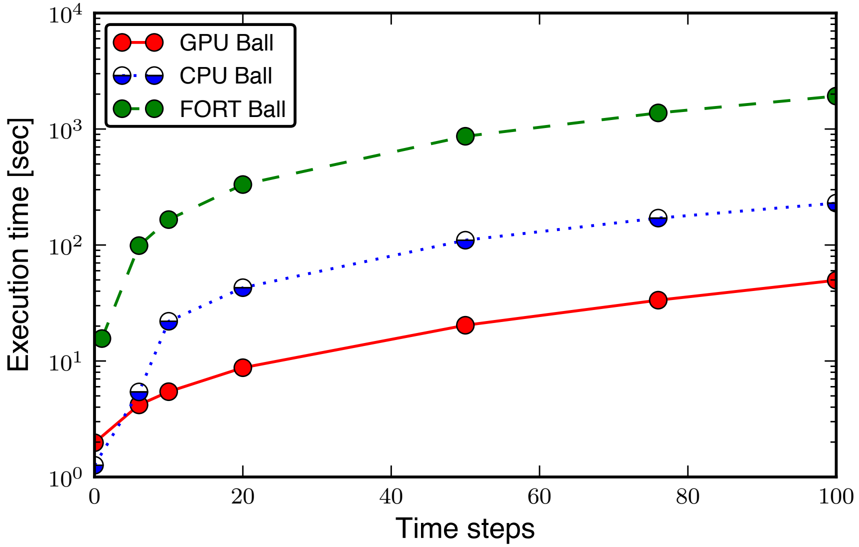
Making it even faster

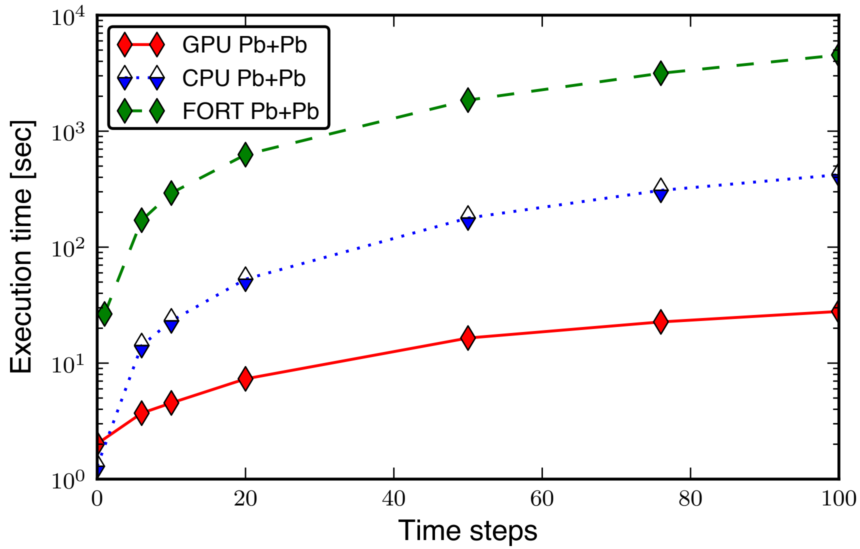
- With C++ Version as base redesign to OpenCL to work on GPGPUs
- If no GPGPUs are present usage on Multicore CPU. (With exact same code!)
- Tremendous speedup:
  up to a **factor of 160** for 3D simulation.

  (up to a factor 450 on newest graphic cards)

Realistic 3+1d simulation

- 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!





J. Gerhard, M. Bleicher, V. Lindenstruth, arXiv:1206.0919, CPC in print

- Some results

  - Photons
  - Di-Leptons
  - Heavy quarks

Photon rates: hadronic and partonic

- Hadronic rate parametrization:

$$E\frac{dR}{d^3p} = A\exp\left(\frac{B}{(2ET)^C} - D\frac{E}{T}\right)$$

S. Turbide, R. Rapp, C. Gale, Phys. Rev. C69 (2004) 014903

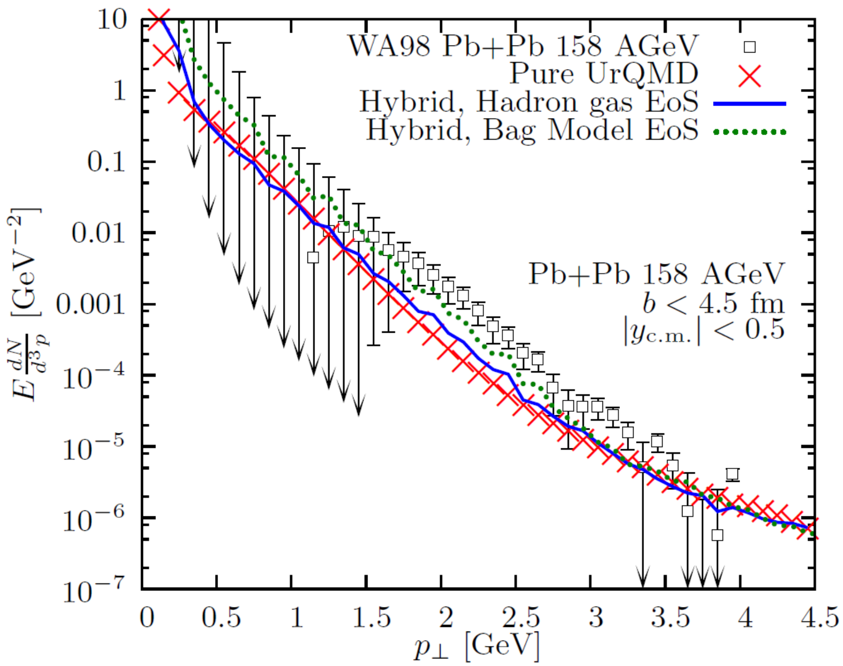
- QGP rate:

$$E\frac{dR}{d^3p} = \sum_{i=1}^{N_f} q_i^2 \frac{\alpha_{\rm em}\alpha_{\rm S}}{2\pi^2} T^2 \frac{1}{e^x+1}\left(\ln\left(\frac{\sqrt{3}}{g}\right) + \frac{1}{2}\ln(2x) + C_{22}(x) + C_{\rm brems}(x) + C_{\rm ann}(x)\right)$$

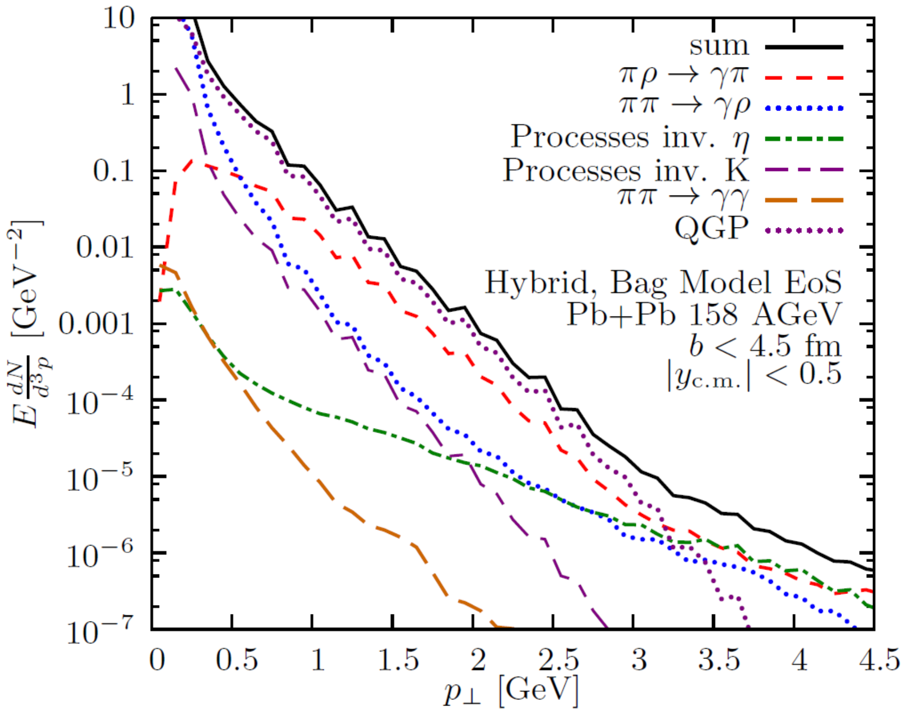
P. Arnold, G. Moore, L. Yaffe, JHEP 0112 (2001)009

Insert all rates into the hybrid model and compare to data.

Comparison to data



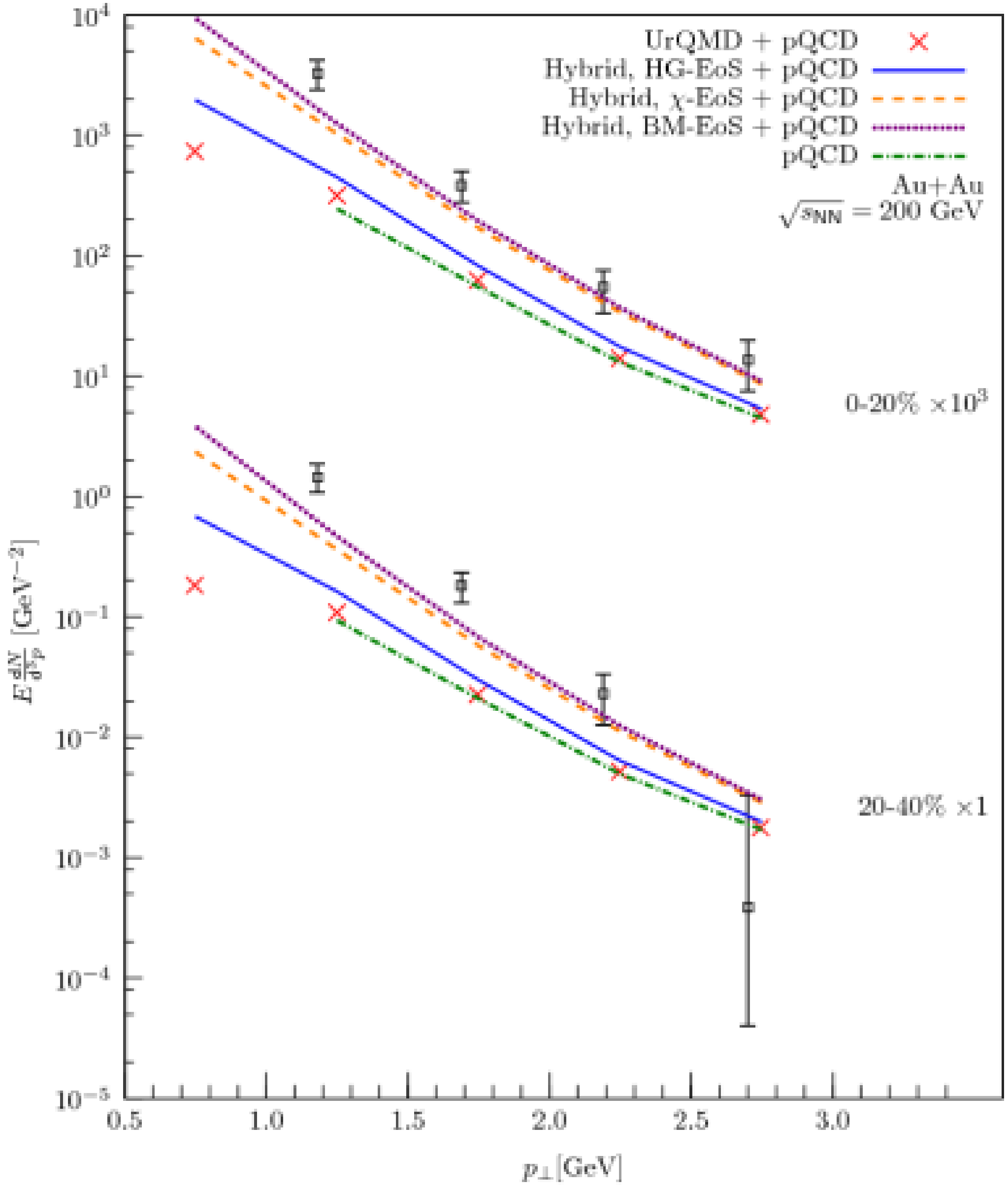
Comparisons



Hybrid, QGP: Channels

Bjoern Bauechle, MB, PRC (2010)

Direct Photon spectra at RHIC

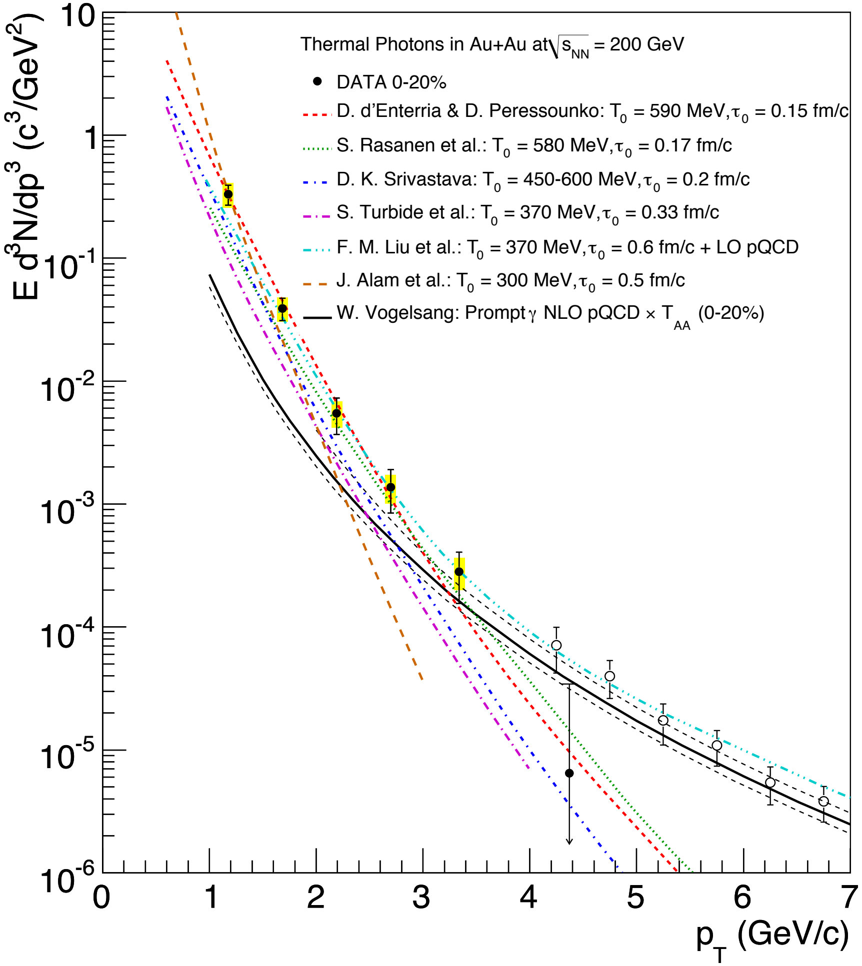


- Clear separation hadronic vs. partonic
- partonic calc. fit data
- Reasons for missing contributions in UrQMD/Hadron gas:
  - late equilibration,
  - hadronic rates,
  - shorter life time

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

Comparison to other calculations

- Similar results by others, however
- no adjustment of parameters
- no freedom on T_0, tau_0
- Consistency with hadron spectra

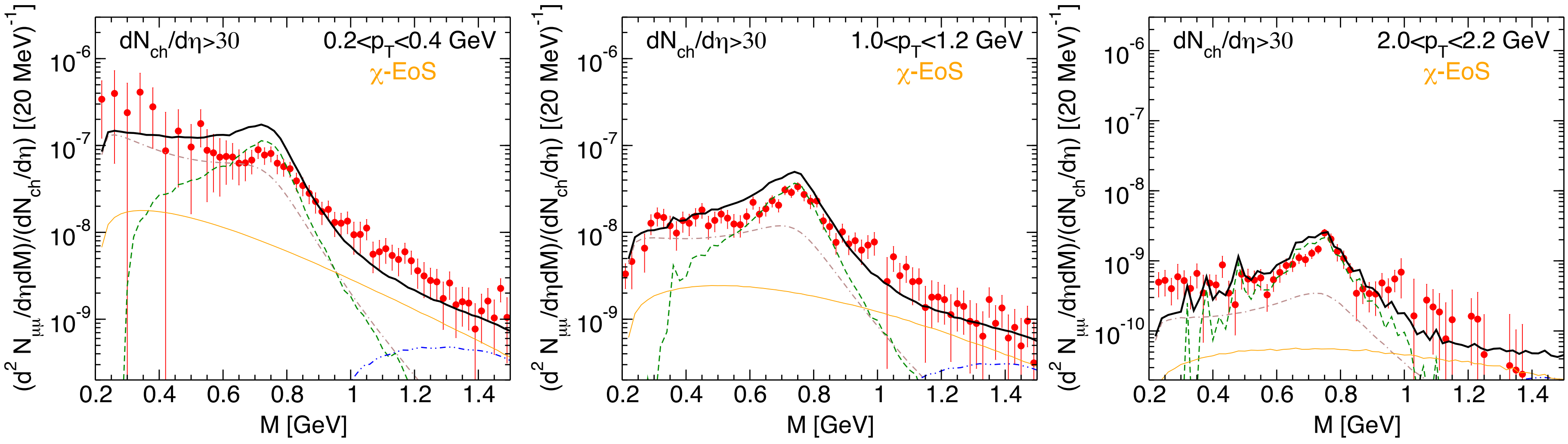


PHENIX, PRC 81 (2010) 034911

Virtual Photons (Di-Leptons)

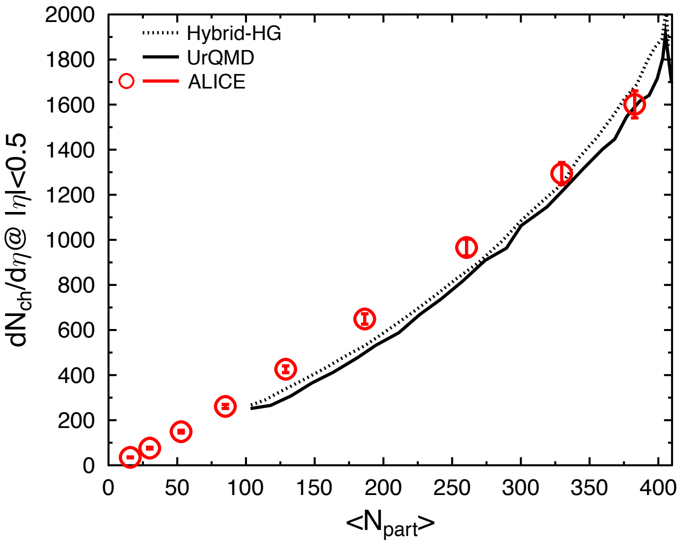
$$\frac{d^8 N_{\rho^* \to ll}}{d^4x d^4q} = -\frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} f_B(q_0;T) \,\mathrm{Im}\, D_\rho(M,q;T,\mu_B)$$

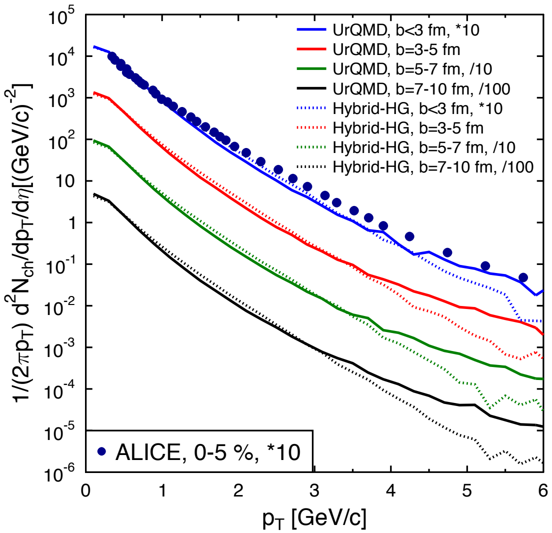
Self energy obtained from V.Eletsky, M. Belkacem, P. Ellis, J. Kapusta, Phys. Rev. C64 (2001) 035202

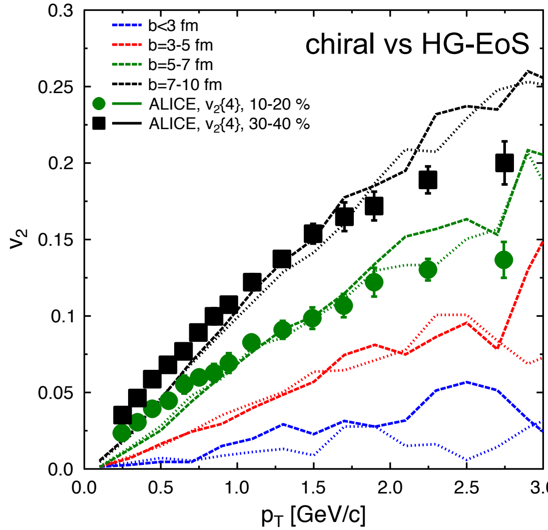


Santini, M.B. J. Steinheimer, PRC (2010)

Performance at LHC, PbPb, 2.76 TeV



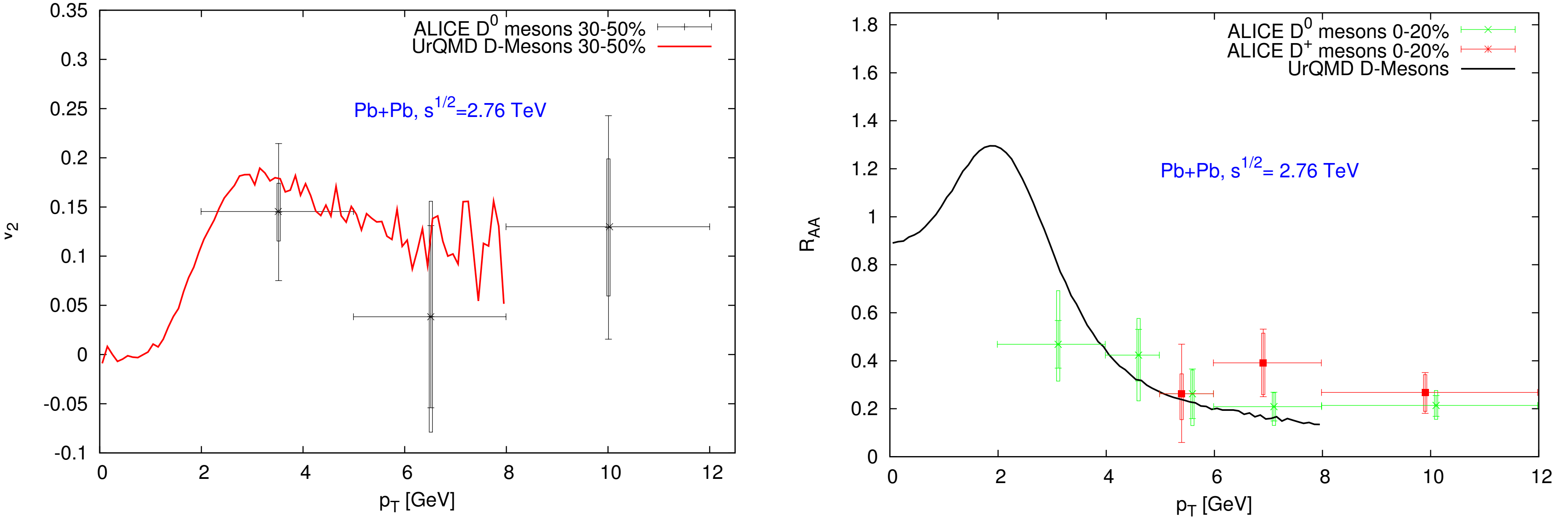




- Excellent description of centrality dependence,
- Transverse momenta,
- Elliptic flow.

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

Heavy quarks at LHC, , PbPb, 2.76 TeV



- 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

Conclusions

- Integrated, 3+1d, fast hybrid model with fluctuating initial conditions are available
- Allows for good understanding of a multitude of hadronic and leptonic observables
- No special adjustment for different probes or energies!

- However, there are devils in the details...