Photons and Di-Leptons from Hybrid Models

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This model can be downloaded from www.urqmd.org
Best birthday wishes also from
- Horst
- Dirk
- and Carsten
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)
Outline

• Motivation
• Model
• Photons
• Dileptons
• Conclusions
Present Hybrid Approaches

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

- Integrated (open source) UrQMD 3.3
- Hadronic dissipative effects on elliptic flow in ultrarelativistic heavy-ion collisions.
- 3-D hydro + cascade model at RHIC.
- Results On Transverse Mass Spectra Obtained With Nexspherio
- EPOS+Hydro+UrQMD at LHC
- MUSIC@RHIC and LHC
  B. Schenke, S. Jeon, C. Gale, …
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)

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 
  \[
  (p^\mu \partial_\mu) f = I_{\text{coll}}
  \]
  
  Collision criterium 
  \[
  d_{\text{min}} \leq d_0 = \sqrt{\frac{\sigma_{\text{tot}}}{\pi}}
  \]

- **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

Marcus Bleicher, JoeFest, Montreal 2012
Initial State

- Contracted nuclei have passed through each other
  \[ t_{\text{start}} = \frac{2R}{\gamma v} \]
  - 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)

\( E_{\text{lab}} = 40 \text{ AGeV} \)
\( b = 0 \text{ fm} \)
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

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D. Rischke et al., NPA 595, 346, 1995,
D. Zschiesche et al., PLB 547, 7, 2002
Papazoglou et al., PRC 59, 411, 1999
Phase diagram for the chiral EoS

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

- Full line: Deconfinement
- Dashed line: Chiral PT

1) Transition from hydro to transport when $\varepsilon < 730$ MeV/fm$^3$ ($\approx 5 \times \varepsilon_0$) in all cells of one transverse slice (Gradual freeze-out, GF)

→ similar to 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 $\mu_B$ and $\mu_S$

- Rescatterings and final decays calculated via hadronic cascade (UrQMD)
Final State Interactions (after Hydro)
Recent developments in SHASTA

- Idea: use graphic cards to speed-up computation
- done with
  Jochen Gerhard, Volker Lindenstruth

Converting legacy code to modern architecture

- SHASTA code in FORTRAN was used as part of UrQMD
  - Resembling physics of shock waves, conservation laws, ultra relativistic effects.
- Execution was slowly, hindering the creation of significant statistics.
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.
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
Bremsstrahlung from a Microscopic Model of Relativistic Heavy Ion Collisions

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Why direct photons?

- Sensitivity to scattering rate in the fireball
- Sensitivity to the constituents of the matter
- Hadronic products rescatter → information lost
- Photons keep information!

Caveat:
Many decay photons

Direct Photons…
…all photons which do not come from hadronic decays
- thermal and pre-equilibrium photons calculated
- Prompt photons irrelevant at FAIR
Photon sources

- **Transport**

  \[ \pi^\pm \pi^\mp \rightarrow \gamma \rho^0, \]

  \[ \pi^\pm \pi^0 \rightarrow \gamma \rho^\pm, \]

  \[ \pi^\pm \rho^0 \rightarrow \gamma \pi^\pm, \]

  \[ \pi^\pm \rho^\mp \rightarrow \gamma \pi^0, \]

  \[ \pi^0 \rho^\pm \rightarrow \gamma \pi^\pm, \]

  \[ \pi^\pm \pi^\mp \rightarrow \gamma \gamma. \]

- **Hydrodynamics**

  \[ \pi \pi \rightarrow \gamma \rho, \]

  \[ \pi \rho \rightarrow \gamma \pi, \]

  \[ \pi K^* \rightarrow \gamma K, \]

  \[ \pi K \rightarrow \gamma K^*, \]

  \[ \rho K \rightarrow \gamma K, \]

  \[ K^* K \rightarrow \gamma \pi. \]

Rates: hadronic and partonic

- Hadronic rate parametrization:

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


- QGP rate:

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

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

note that only the \( \pi \pi \rightarrow \gamma \), and the \( \pi \rho \rightarrow \gamma \) are included in both sets
ρ mass treatment

- ρ may be created on pole mass ($m_\rho$ fixed) or with Breit-Wigner-distribution ($m_\rho$ Breit-Wigner).
- Effect on spectra small

fig: Bäuchle, MB, PRC 81 (2010) 044904
Comparison rates: Transport vs. Hydro

- UrQMD in a box, temperature fixed → extract rates
- Comparison with thermal rates: Good agreement!
Transport vs hydro

Not much difference if same sources are taken into account

NB. here one is sensitive to collision rates!
Comparison to data

Comparisons

Hybrid, QGP: Channels

Bjoern Bauechle, MB, PRC (2010)
Direct Photon spectra at SPS

- Partonic EoS hit data without pQCD, Hadronic EoS hit data with pQCD
- Treatment of pQCD unclear → no definite answer about QGP
Direct Photon spectra at RHIC

- Clear separation hadronic vs. partonic
- Partonic calc. fit data
- Reasons for missing contributions: Late equilibration, hadronic treatment of early times?

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
Direct Photon spectra at FAIR

- No prompt photon (pQCD-) contributions
- clear separation between hadronic and partonic EoS
- yield rather low (factor 10 less compared to SPS)
Channels: Hadronic/Partonic/pQCD

- Partonic emission enhanced w.r.t. hadronic emission
Cascade calculation
Average emission time \approx 8 \text{fm}
Above $p_t = 2.5 \text{ GeV}$, early times dominate

Bäuchle, MB, PLB 695 (2011) 489-494
Virtual Photons (DiLeptons)

\[
\frac{d^8 N_{\rho\rightarrow ll}}{d^4 x d^4 q} = - \frac{\alpha^2 m_\rho^4}{\pi^3 g_\rho^2} \frac{L(M^2)}{M^2} \frac{f_B(q_0; T)}{I_m} D_{\rho}(M, q; T, \mu_B)
\]

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

Transverse Dynamics of the Lepton pairs

- Increase of effective temperature
- Dominance of QGP at $M=1$ GeV

Marcus Bleicher, JoeFest, Montreal 2012
Conclusions

- Integrated, 3+1d, fast hybrid model with fluctuating initial conditions
- Allows for good understanding of Photon and DiLepton spectra
- 'No' special adjustment for different probes or energies!

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