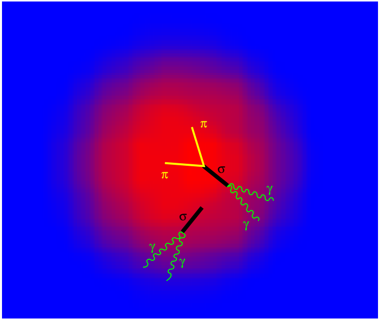
Dynamics of pion annihilation into 2 γ's in heavy ion collisions

V. Toneev and V. Skokov
(on behalf of working group)

The Bogoliubov Laboratory of Theoretical Physics,
Joint Institute for Nuclear Research, Dubna

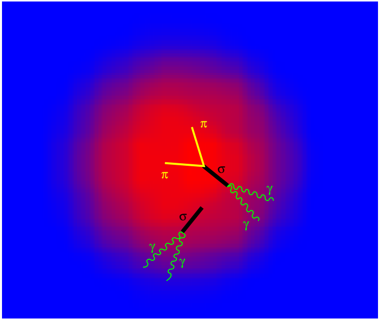
July 7, 2005

Introduction



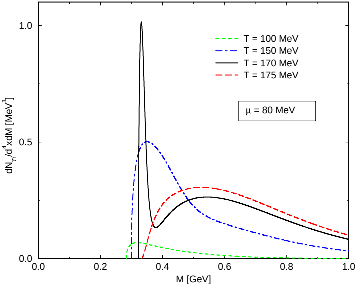
- in medium effects

Introduction



M.K.Volkov, E.A.Kuraev, D.Blaschke, G.Röpke and S.Schmidt, Phys. Lett. **B424** (1998) 235

[arXiv:hep-ph/9706350]



- in medium effects

$$\frac{d^2N_{\gamma\gamma}}{dM} = M \int d^4x \int d\eta \int_0^{2\pi} d\phi \int_0^{\infty} p_T \; dp_T \; \frac{d^8N_{\gamma\gamma}(T(x), M, \eta, p_T)}{d^4x \; d^4p} \; Acc(M, \eta, p_T)$$

Initial conditions, entropy creation

Entropy creation and fireball formation are calculated within the transport code: **QGSM** (quark-gluon string model to proceed into a cascade model at the energies considered) that defines an initial state for subsequent hydro stage

$$\frac{df_i(x,p)}{dt} = \sum_j C_{ij}^{gain} - \sum_j C_{ji}^{loss}$$

$$(i = N, \Delta, \dots, hyperons, \pi, K, \eta, \rho, \omega \dots)$$

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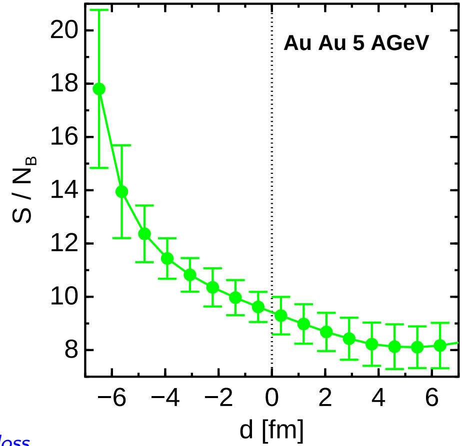
for participants (central collision)



relative nuclei distance

$$\frac{df_i(x,p)}{dt} = \sum_j C_{ij}^{gain} - \sum_j C_{ji}^{loss}$$

$$(i = N, \Delta, \ldots, hyperons, \pi, K, \eta, \rho, \omega \ldots)$$

Hydrodynamic equations

Isentropic expansion of the formed fireball is described by **3D relativistic hydrodynamics** using calculated energy and baryon densities as well as velocity profile (Flux corrected SHASTA is applied)

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- Equation of state (EoS)

$$P = P(\varepsilon, n_B).$$

Statistical quark-hadron mixed phase EoS

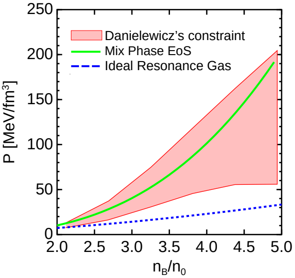
(V.D. Toneev et al., J. Phys. G **27** (2001) 827 [nucl-th/0011029])

Hadronic sector

generalized Zimanyi mean-field model, (Nucl. Phys. **A484**, 647 (1988))

- Saturation properties of nuclear matter (Binding energy, pressure, incompressibility at normal density)
- Danielewicz's constraint (P. Danielevicz, R. Lacey, and W.G. Lynch, Science **298**, 1592 (2002) [nucl-th/0208016])

$T = 0$



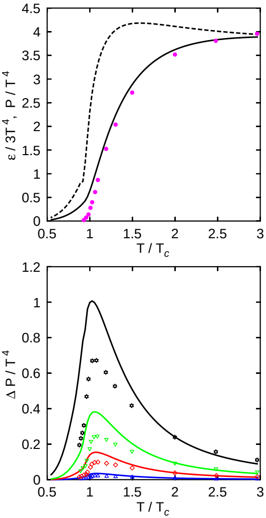
EoS

Quark-gluon sector

Quasiparticle gas of interacting quarks and gluons

- Asymptotic of quark masses in HTL approximation (!)
- Comparison with lattice QCD results for $N_f = 2 + 1$

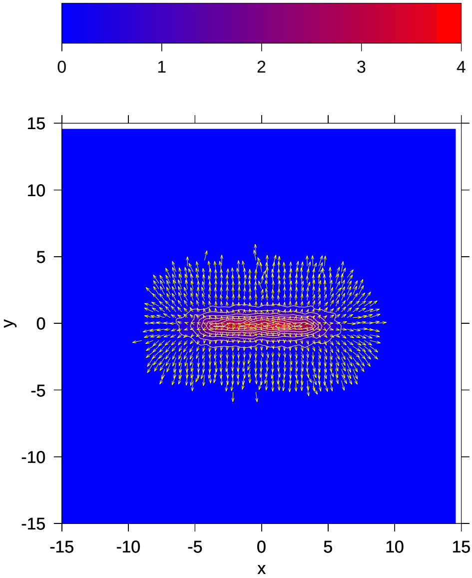
  (Z. Fodor and S.D. Katz, JHEP **203**, 14 (2002) [hep-lat/0106002]; JHEP **404**, 50 (2004) [hep-lat/0402006])



$$\Delta P = P(T, \mu_B) - P(T, \mu_B = 0)$$

$\mu_B = 100,\ 210,\ 330,\ 530\ MeV$ (from the bottom)

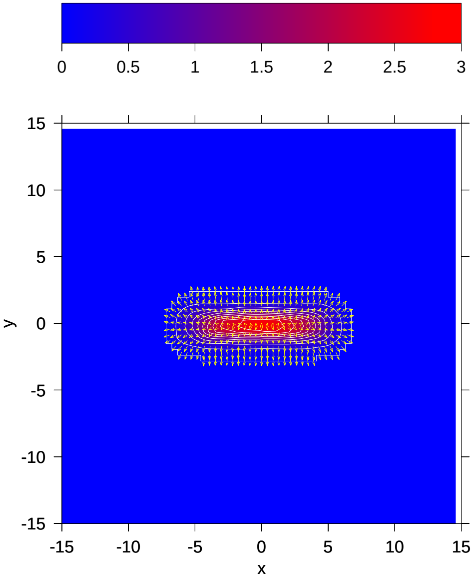
Time evolution of the fireball energy density



$t = 0.0$ fm/c;

Au+Au (5 AGeV)

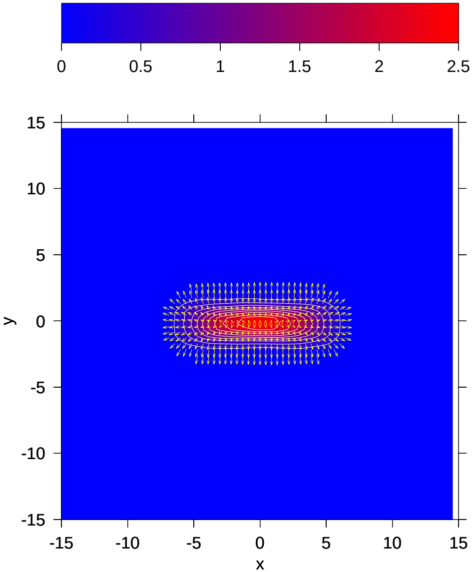
Time evolution of the fireball energy density



$t = 0.3$ fm/c

Time evolution of the fireball energy density

$t = 0.6$ fm/c



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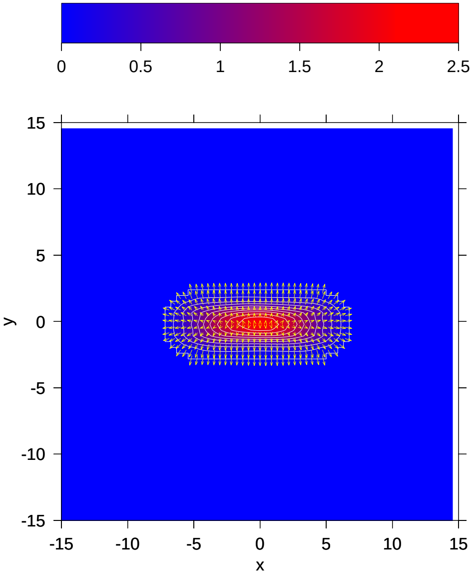
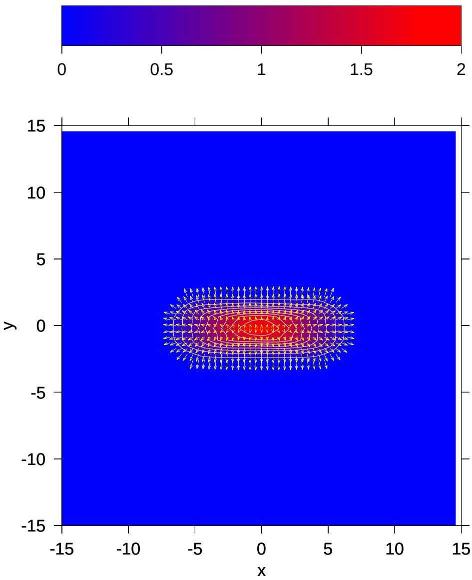


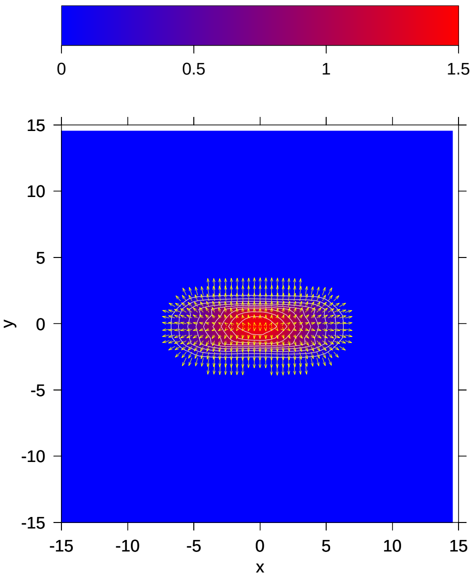
$t = 0.9$ fm/c

Time evolution of the fireball energy density



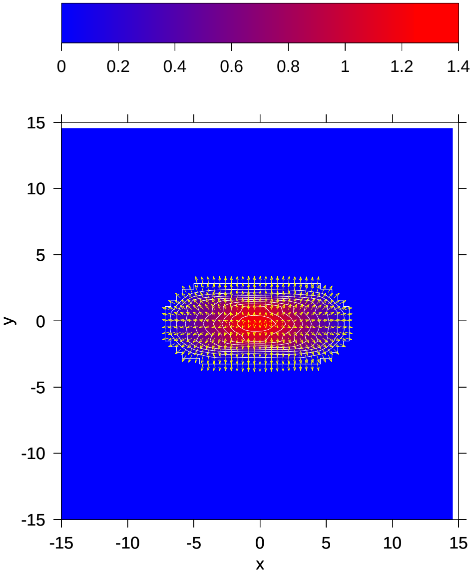
$t = 1.2$ fm/c

Time evolution of the fireball energy density



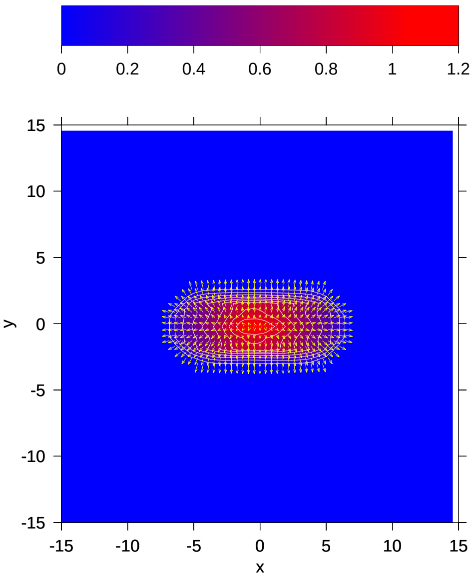
$t = 1.5$ fm/c

Time evolution of the fireball energy density



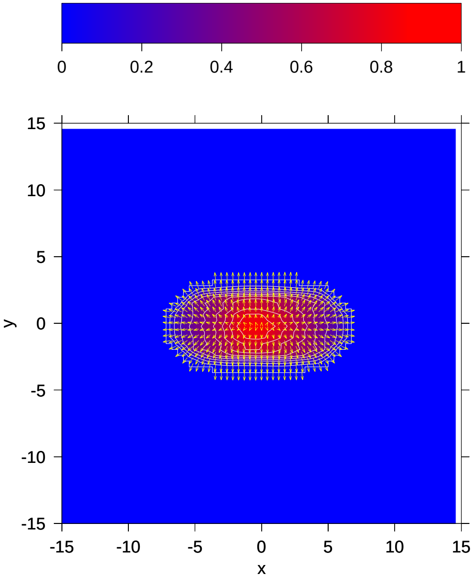
$t = 1.8$ fm/c

Time evolution of the fireball energy density



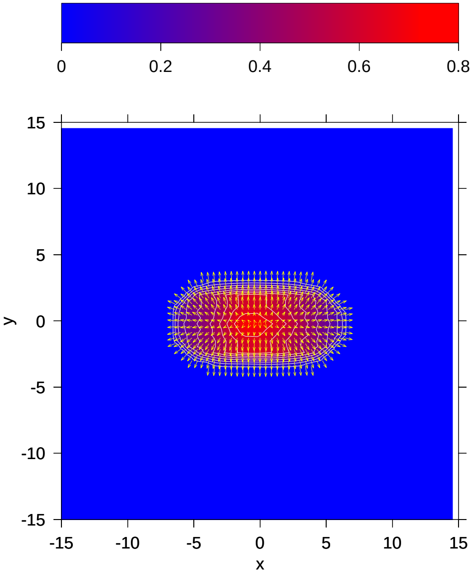
$t = 2.1$ fm/c

Time evolution of the fireball energy density



$t = 2.4$ fm/c

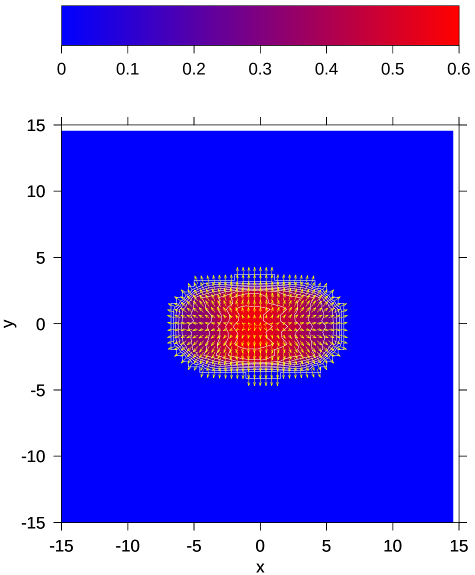
Time evolution of the fireball energy density



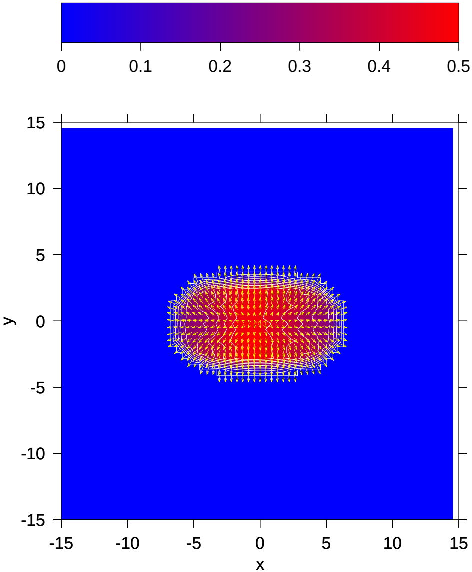
$t = 2.7$ fm/c

Time evolution of the fireball energy density

$t = 3.0$ fm/c

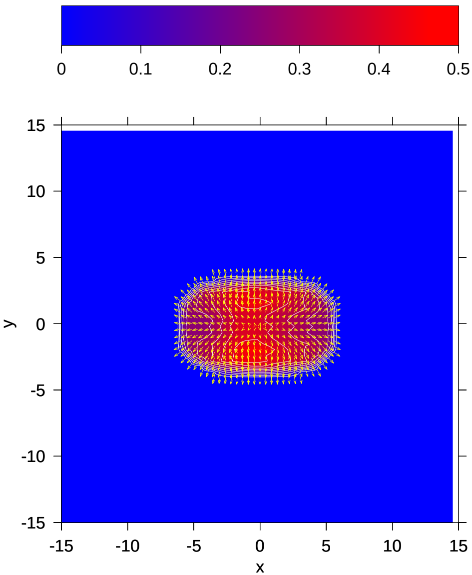


Time evolution of the fireball energy density



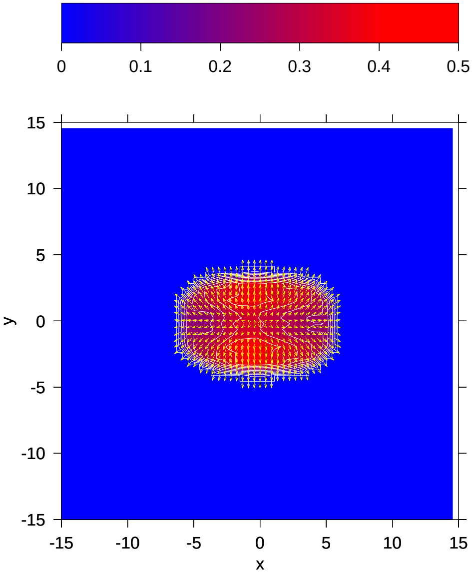
$t = 3.3$ fm/c

Time evolution of the fireball energy density



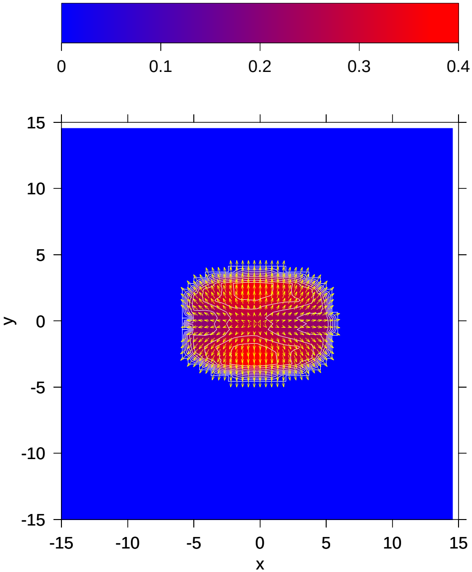
$t = 3.6$ fm/c

Time evolution of the fireball energy density



$t = 3.9$ fm/c

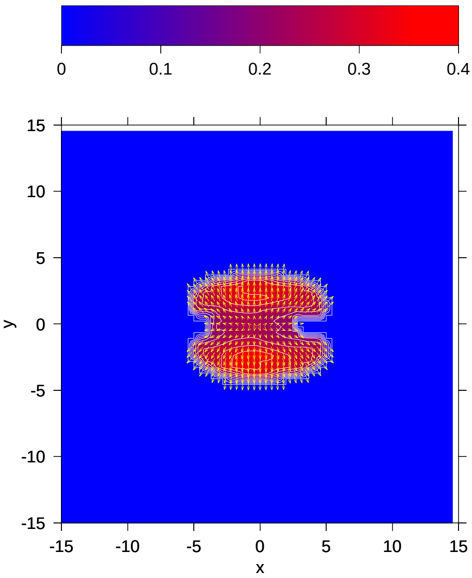
Time evolution of the fireball energy density



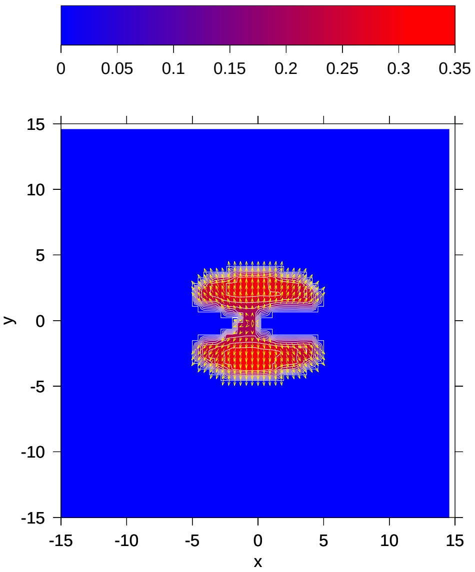
$t = 4.2$ fm/c

Time evolution of the fireball energy density

$t = 4.5$ fm/c

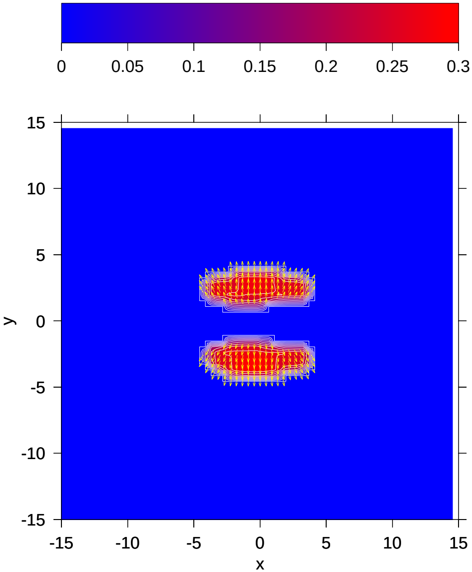


Time evolution of the fireball energy density



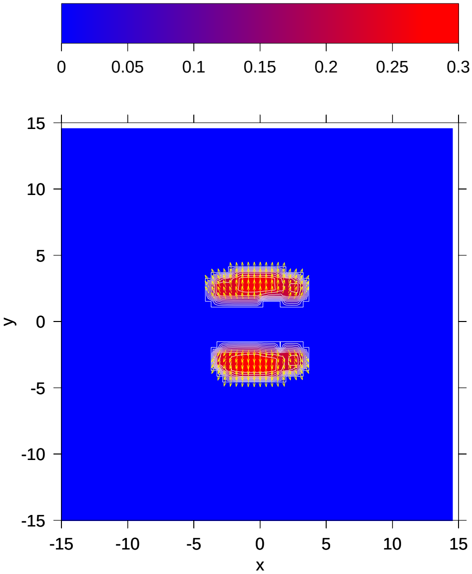
$t = 4.8$ fm/c

Time evolution of the fireball energy density



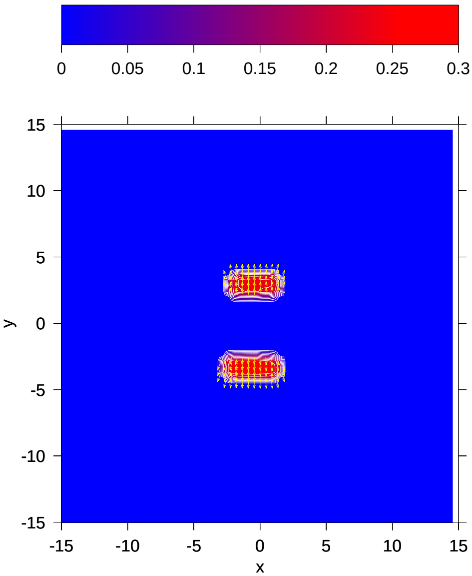
$t = 5.1$ fm/c

Time evolution of the fireball energy density



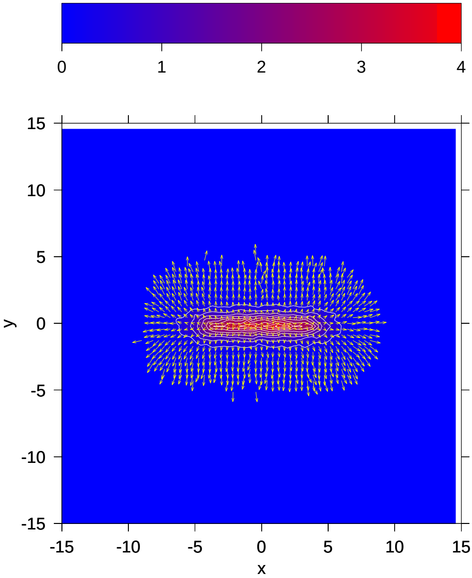
$t = 5.4$ fm/c

Time evolution of the fireball energy density



$t = 5.7$ fm/c

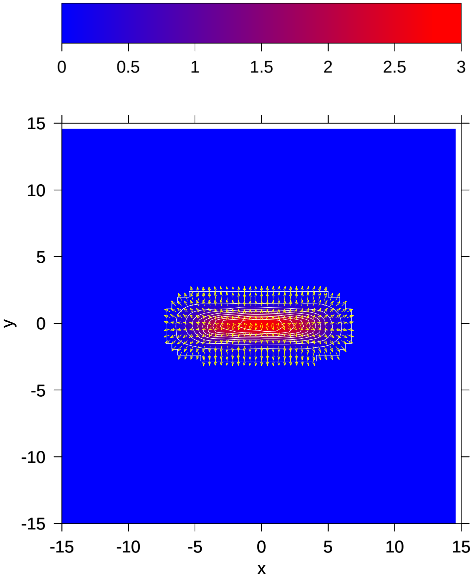
Time evolution of the fireball energy density



$t = 0.0$ fm/c;

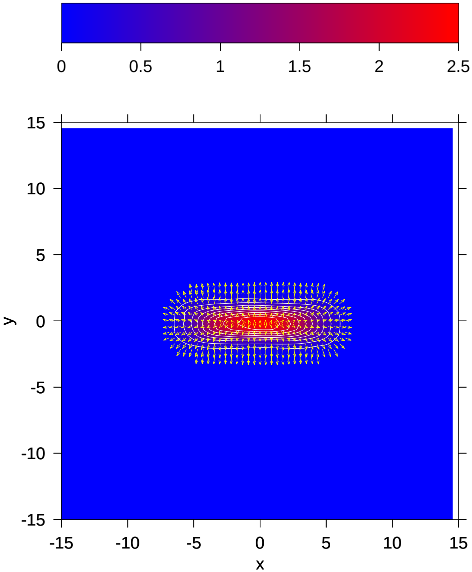
zoomed

Time evolution of the fireball energy density



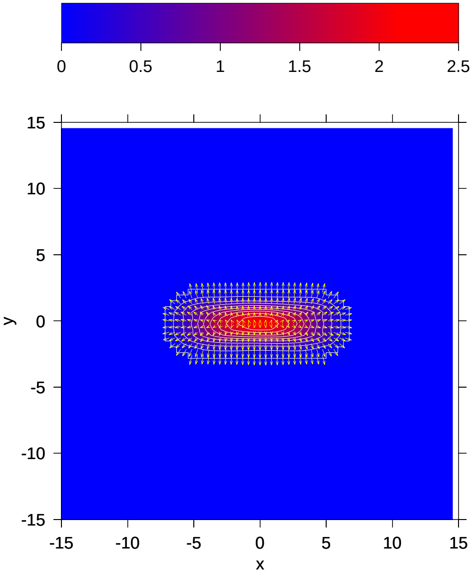
$t = 0.3$ fm/c

Time evolution of the fireball energy density



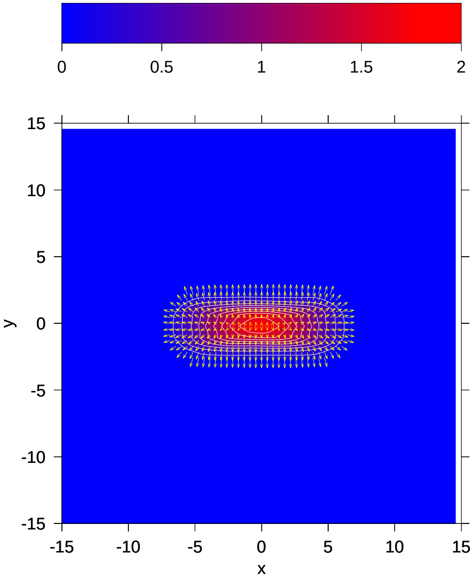
$t = 0.6$ fm/c

Time evolution of the fireball energy density



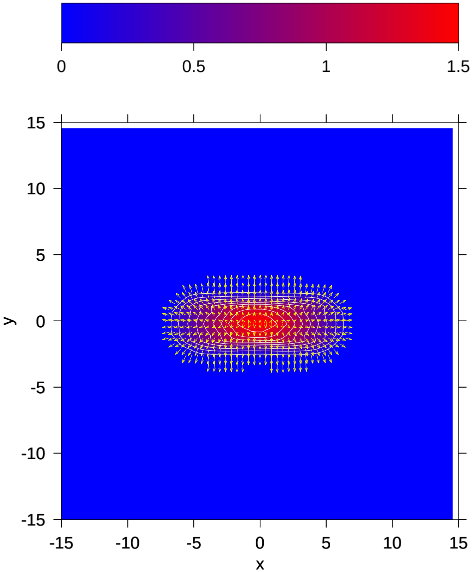
$t = 0.9$ fm/c

Time evolution of the fireball energy density



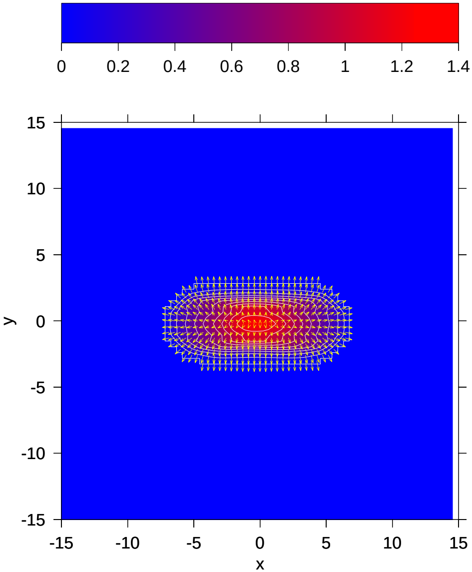
$t = 1.2$ fm/c

Time evolution of the fireball energy density

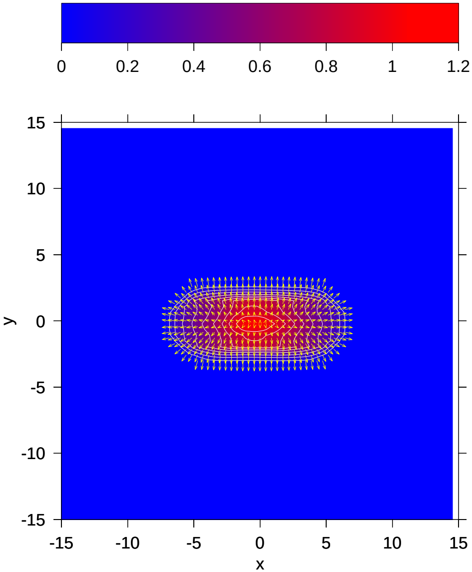


$t = 1.5$ fm/c

Time evolution of the fireball energy density

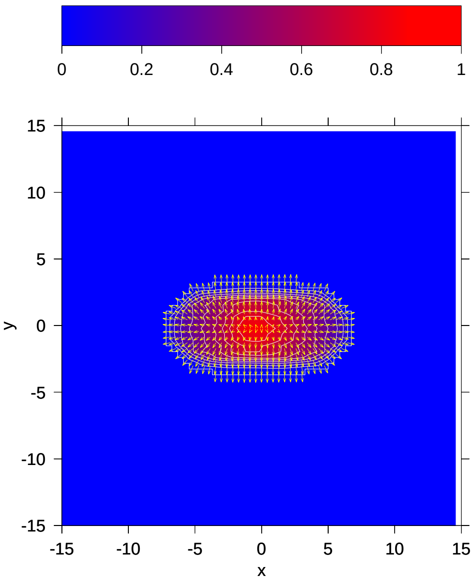


$t = 1.8$ fm/c



$t = 2.1$ fm/c

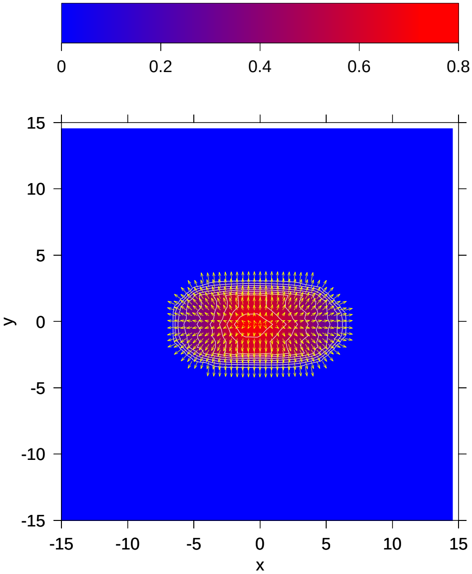
Time evolution of the fireball energy density



$t = 2.4$ fm/c

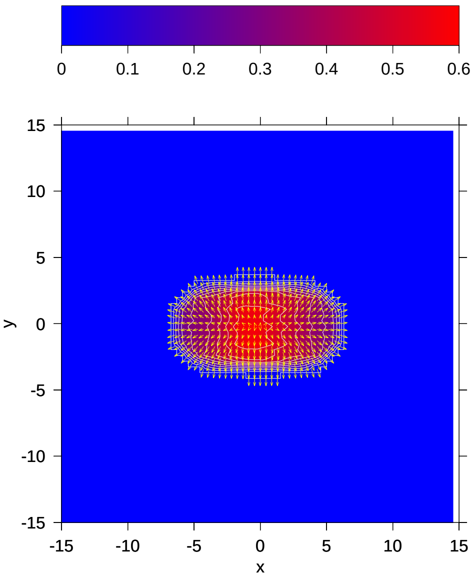
Time evolution of the fireball energy density

Dynamics of pion annihilation...
V. Toneev, V. Skokov
Outline
Introduction
Model description
Initial conditions
Expansion dynamics
EoS
Fireball evolution
Evolution in averages
Hadron observable
γ 's pairs
Outlook
An estimate of background



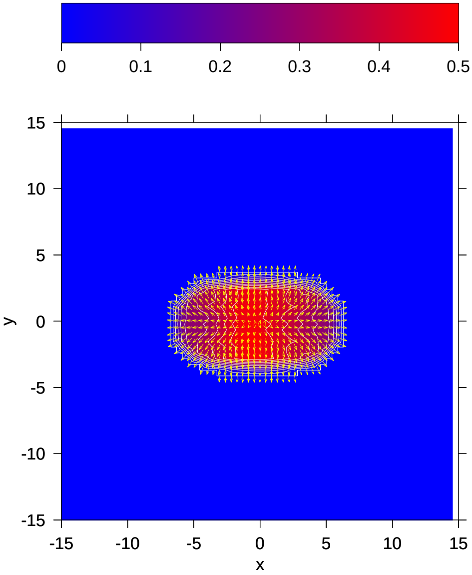
$t = 2.7$ fm/c

Time evolution of the fireball energy density



$t = 3.0$ fm/c

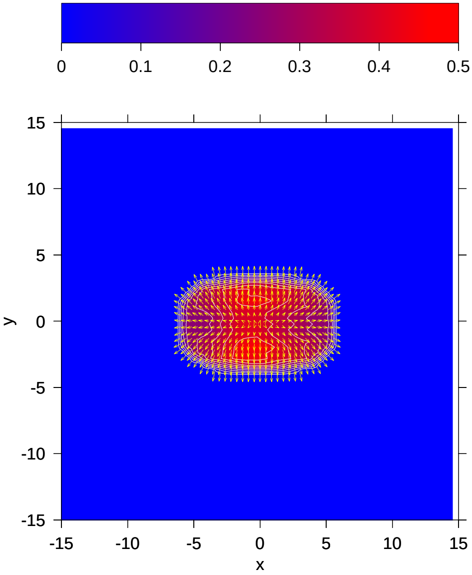
Time evolution of the fireball energy density



$t = 3.3$ fm/c

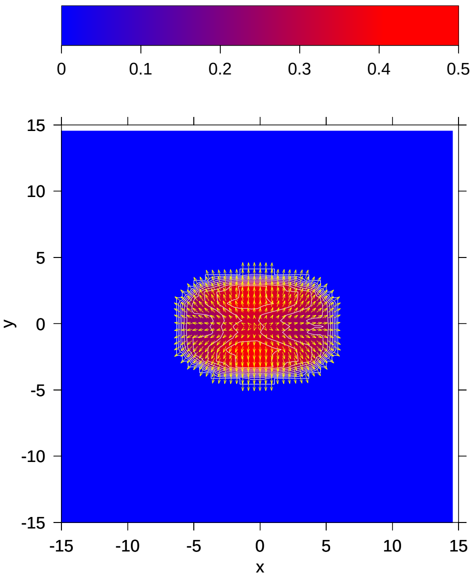
Time evolution of the fireball energy density

$t = 3.6\ \mathrm{fm}/c$



Time evolution of the fireball energy density

$t = 3.9$ fm/c



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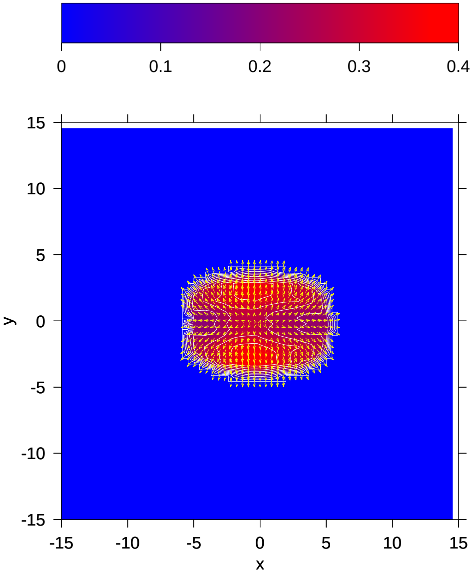
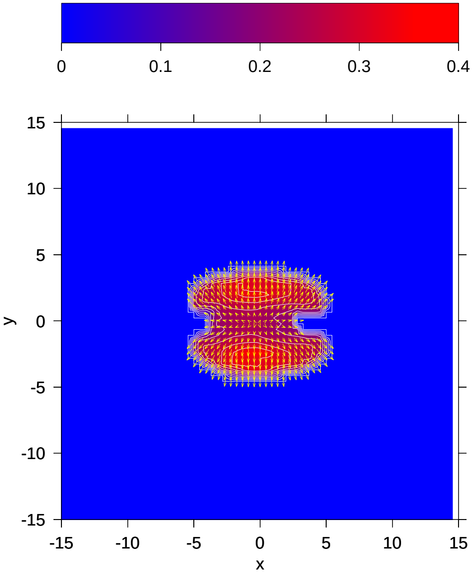


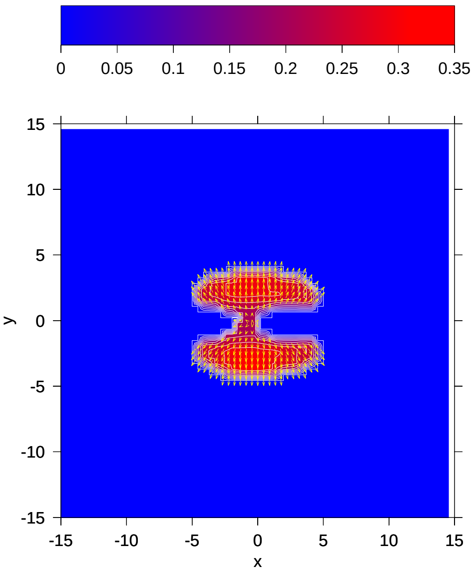
$t = 4.2$ fm/c

Time evolution of the fireball energy density



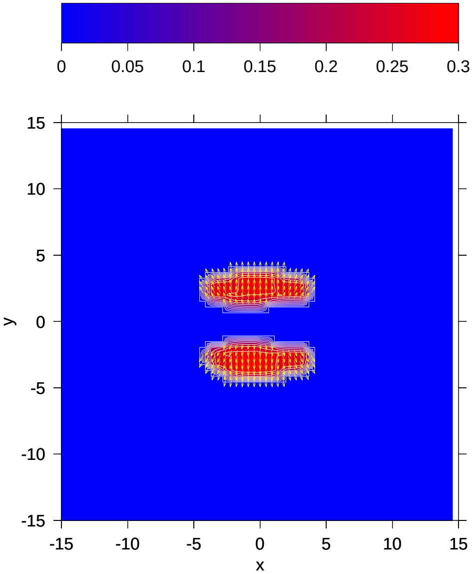
$t = 4.5$ fm/c

Time evolution of the fireball energy density



$t = 4.8$ fm/c

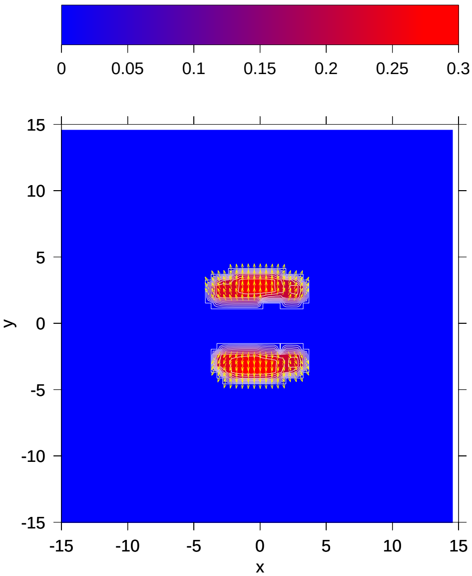
Time evolution of the fireball energy density



$t = 5.1$ fm/c

Time evolution of the fireball energy density

$t = 5.4$ fm/c



Time evolution of the fireball energy density

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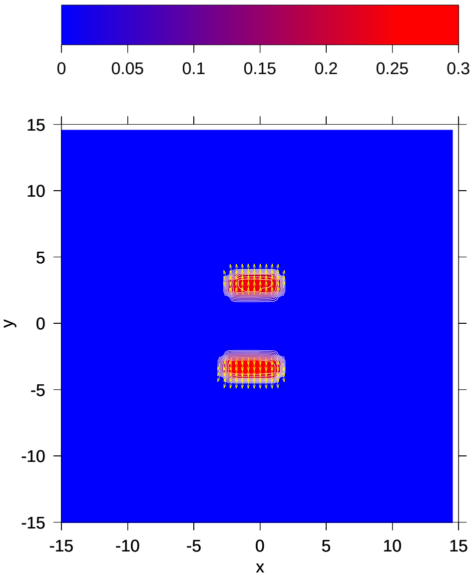
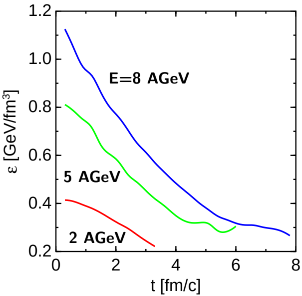


Average quantities

$Au + Au \ (E \ AGeV)$

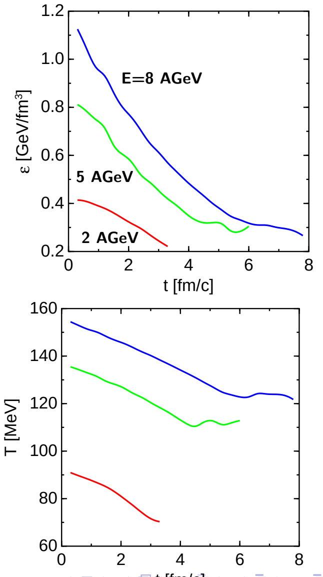
- Average energy density (mixed phase EoS ; freezeout is included)



Average quantities

$Au + Au\ (E\ AGeV)$

- Average energy density (mixed phase EoS ; freezeout is included)
- Average temperature



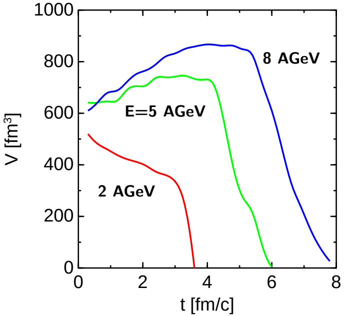
Average quantities

$Au + Au \ (E \ AGeV)$

- Evolution of the system volume

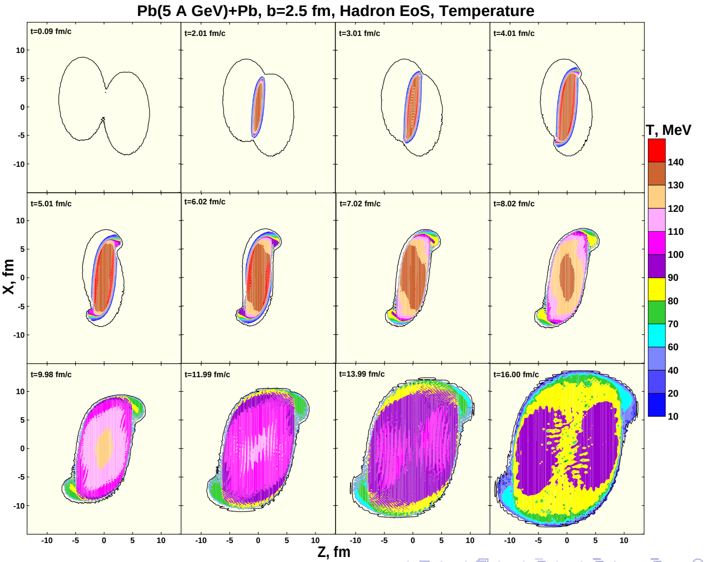
  There are two stages: "pure" expansion and freezeout

expansion⇓



⇑freezeout

Comparison with 3-fluid hydro (nucl-th/0503088)



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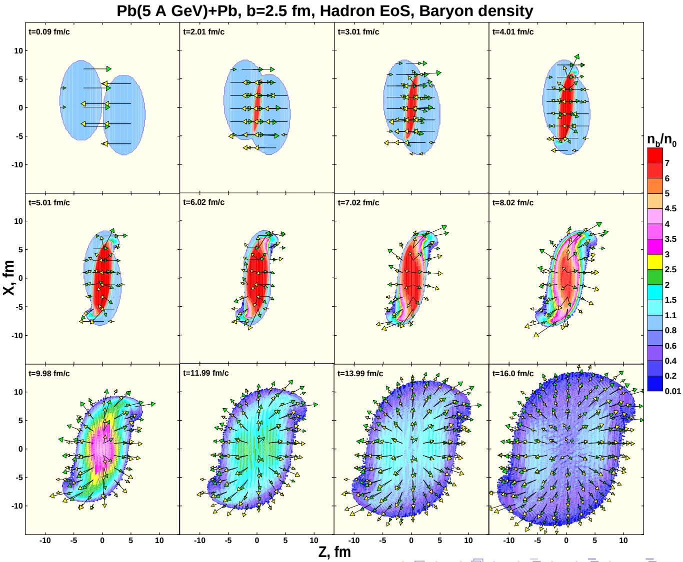
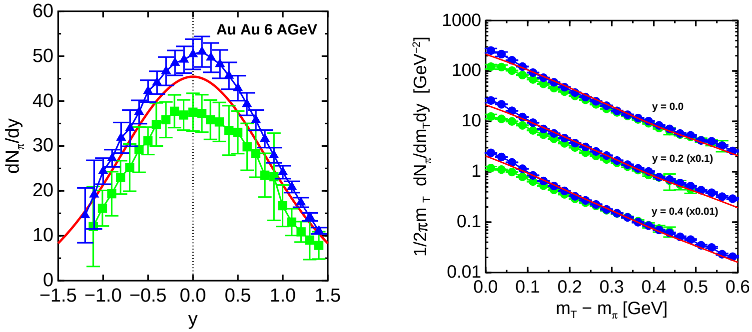


Comparison with observable

Pion (π^- and π^+) distributions from central ($\frac{\sigma_{trig}}{\sigma_{tot}} = 5\%$) $Au + Au$ ($6\ AGeV$) *collisions*



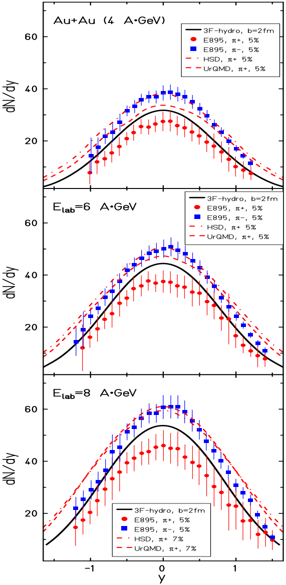
J. L. Klay *et al.* (E895 Collab.), Phys. Rev. C **68**, 054905 (2003)

Yu.B.Ivanov, V.N.Russkikh and V.D.Toneev, nucl-th/0503088

Pion (π^- and π^+) distributions from central $Au + Au$ collisions

Experimental data are from:
J. L. Klay *et al.* (E895 Collab.),

Phys. Rev. C **68**, 054905 (2003)



NJL model summary for $\pi^+\pi^- \to \gamma\gamma$

See Yudichev' talk

$$\sigma^{\pi^+\pi^-\to\gamma\gamma}(s) = \sigma_{Born}(s) + \sigma_{interf}(s) + \sigma_{res}(s)$$

$$\sigma_{Born}(s) = 16\sigma_0 \left(2 - \kappa^2 - \frac{1-\kappa^4}{2\kappa} \ln\left[\frac{1+\kappa}{1-\kappa}\right]\right),$$

$$\sigma_{interf}(s) = 4\sigma_0\ s\ \mathrm{Re}\left[\mathcal{A}_{\pi^+\pi^-\to\gamma\gamma}(s)\right] \frac{1-\kappa^2}{\kappa} \ln\left[\frac{1+\kappa}{1-\kappa}\right]$$

$$\sigma_{res}(s) = \sigma_0\ s^2\ \left|\mathcal{A}_{\pi^+\pi^-\to\gamma\gamma}(s)\right|^2$$

where $\sigma_0 = \pi\alpha^2/4s\kappa$, $\kappa^2 = 1 - 4{M_\pi}^2(T,\mu)/s$, and

$$\mathcal{A}_{\pi^+\pi^-\to\gamma\gamma} = \frac{1}{(6\pi f_\pi(T,\mu))^2}\left[\frac{40m(T,\mu)}{M^2{}_\sigma(T,\mu) - s - i\sqrt{s}\,\Gamma_\sigma(s|T,\mu)} \times\ f_1(\mu,T) - f_2(\mu,T)\right]$$

NJL model summary for $\pi^+\pi^- \to \gamma\gamma$

The quark mass at finite T and μ is given by the gap equation

$$m(T,\mu) - m_0 = 8m(T,\mu)G\; I_1^{\Lambda}(m|T,\mu)$$

$$I_1^{\Lambda}(m|T,\mu) = \frac{N_c}{4\pi^2}\int^{\Lambda}\frac{k^2}{E(k)}\left(1 - n(k;T,\mu) - \bar{n}(k;T,\mu)\right)dk$$

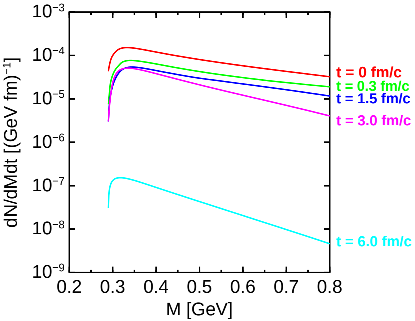
$T=\mu=0$	G [GeV^{-2}]	Λ [MeV]	m_0 [MeV]
Type I, $M_\pi, f_\pi, <\psi\bar{\psi}>$	11.7205	618.7	5.76
Type II, $M_\pi, f_\pi, \rho\to\pi\pi$	3.4105	1037.4	2.08

The photon pair production rate

$$\frac{dN_{\gamma\gamma}}{d^4x dM} = 4M\int\frac{d^3p_1}{(2\pi)^3}\int\frac{d^3p_2}{(2\pi)^3}\, v_{\rm rel}\,\sigma^{\pi\pi\to\gamma\gamma} n_\pi(p_1)\, n_\pi(p_2) \times \delta\left(M^2 - (p_1+p_2)^2\right)$$

$\mathbf{Au + Au}$ (5 AGeV)

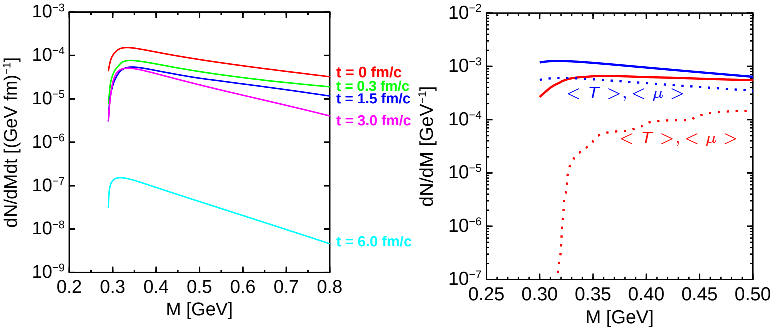
"Standard" (Type I) NJL



γ 's pairs; time slices and integral

Au + Au (5 AGeV)

"Standard" (Type I) NJL — vacuum case; — in-medium



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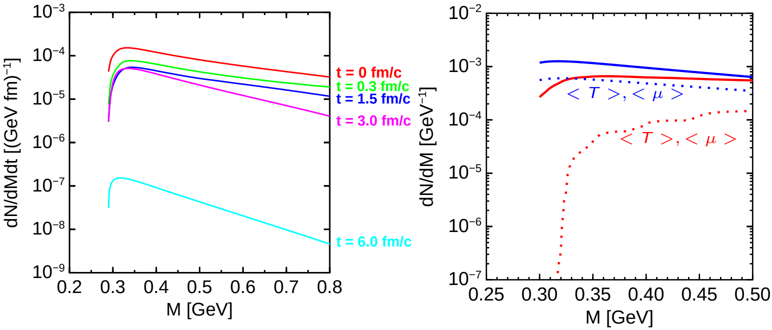
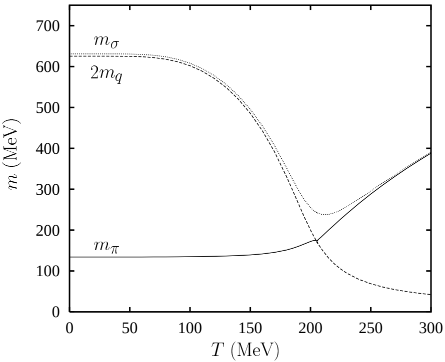


The resonance contribution is not visible

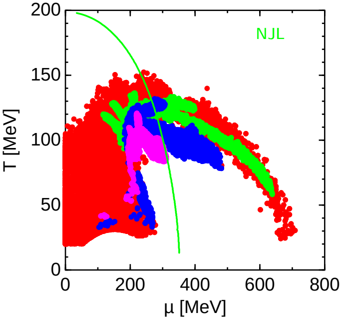
T-dependent masses

$\mu = 0$

P.Rehberg, Yu.L.Kalinovski and D.Blaschke, Nucl. Phys. **A 622** (1997) 478



$t = 0\ \mathrm{fm/c}$
$t = 1.5\ \mathrm{fm/c}$
$t = 3\ \mathrm{fm/c}$
$t = 4.5\ \mathrm{fm/c}$



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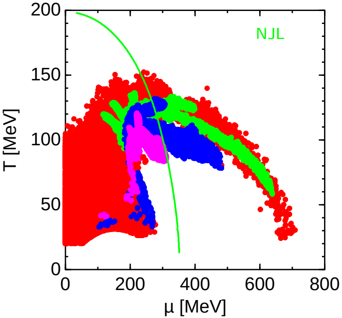
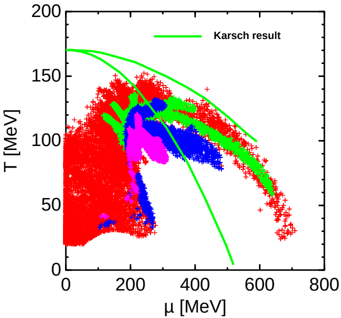
C.R.Allton, S.Ejiri *et al.*, Nucl. Phys. Proc. Suppl. **141** (2005) 186



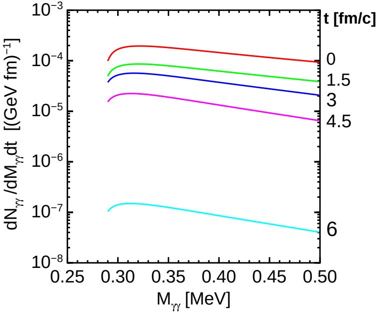


t-slices and integrals

$Au + Au$ $(5\ AGeV)$

new parameterization (V.Yudichev)

$$\frac{1}{G} \rightarrow \frac{1}{G} + 0.23\,T^2 - 0.04\,T\mu - 0.06\frac{\mu^2}{0.3+\mu^2} \quad [GeV^2]$$



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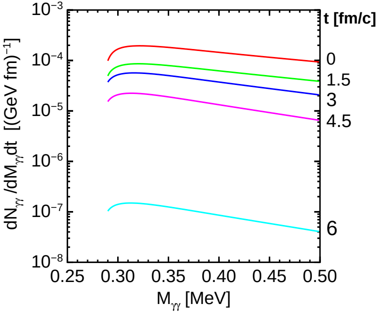
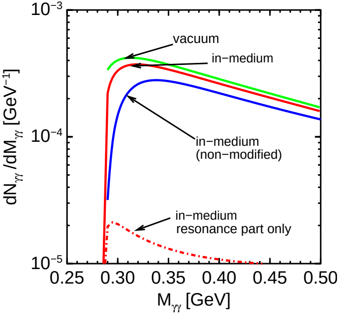




$\pi\pi$ annihilation and direct σ meson decay

$Au + Au$ (5 $AGeV$)

$$\Gamma_{\sigma\to\gamma\gamma}(T,\mu) = \frac{25\alpha^2 f_1^2(T,\mu)}{576\pi^3 f_\pi^2(T,\mu)} \int_0^\infty \rho_\sigma(s) s^{3/2} ds,$$

where the meson spectral function

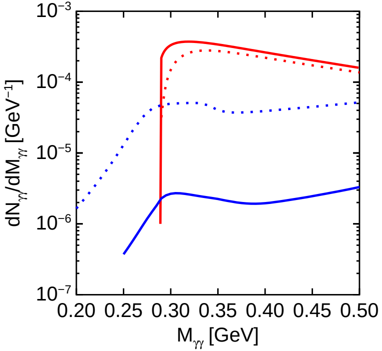
$$\rho_\sigma(s) = \frac{1}{N} \frac{M_\sigma(T,\mu)\Gamma_\sigma(T,\mu)}{(s - M_\sigma^2(T,\mu))^2 + M_\sigma^2(T,\mu)\Gamma_\sigma^2(T,\mu)}$$

Dotted lines:

$$\frac{1}{G} \to \frac{1}{G} + 0.6T^2 \qquad \boxed{T_c = 150 \text{ MeV}}$$

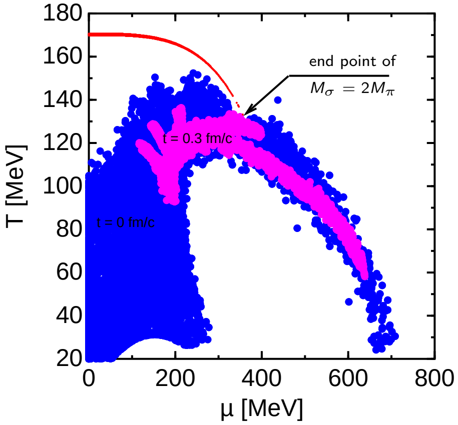
$\pi\pi$ annihilation

σ meson decay



$T - \mu$ representation

$\sigma_{Born} < \sigma_{interf} + \sigma_{res}$



Outlook

- T, μ dependence of model parameters is crucial
- The yield of $dN_{\gamma\gamma}/dM$ is higher if in-medium effects are neglected (?)
- Pion annihilation into γ's together with decay of direct σ meson may result in step-like structure near $M \approx 2M_\pi$ (but the Born term dominates)
- Higher bombarding energies ?

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- Higher bombarding energies ?

The signal of in-medium meson modification is very weak if any

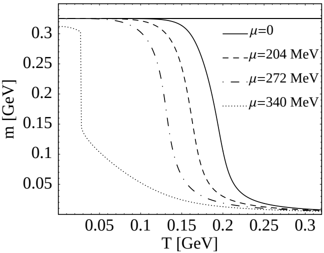
but

UNCERTAINTIES are still very LARGE

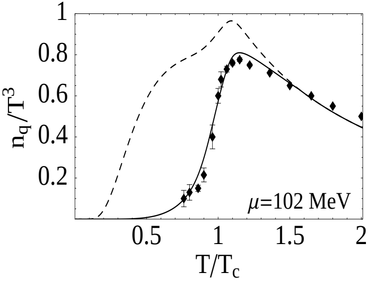
♣ T, μ dependence of $M_\sigma, M_\pi, f_\pi, m_q, \Gamma_\sigma$

PNJL: C.Ratti, M.A.Thaler and W.Weise, hep-ph/0506234

constituent quark mass



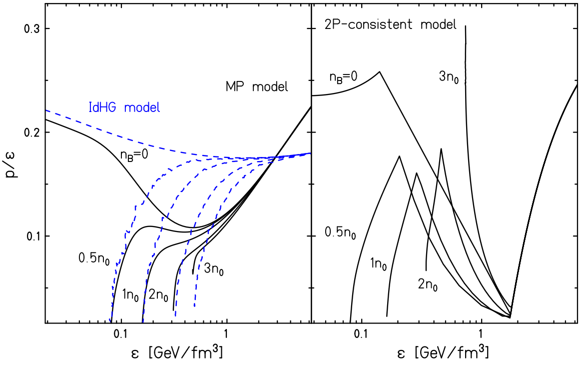
quark number density



both the chiral limit and lattice data for finite T, μ are described

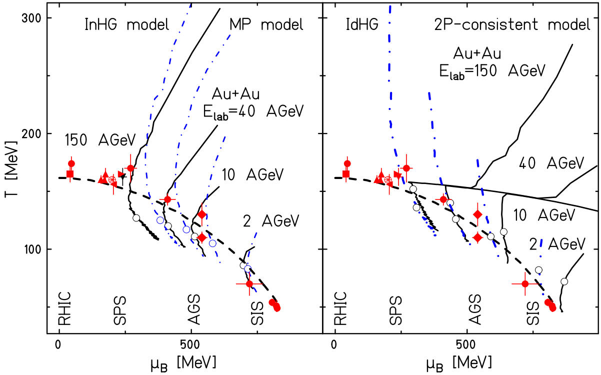
♣ Equation of State: the softest point effect

(V.D. Toneev, J. Cleymans, E.G. Nikonov, K. Redlich and A.A. Shanenko, J. Phys. G **27** (2001) 827 [nucl-th/0011029])



Dynamical trajectories in $(T - \mu_B)$ plain for different EoS (simplified expansion treatment)

(V.D. Toneev, J. Cleymans, E.G. Nikonov, K. Redlich and A.A. Shanenko, J. Phys. G **27** (2001) 827)



An estimate of background

QGSM model is used

An estimate of background

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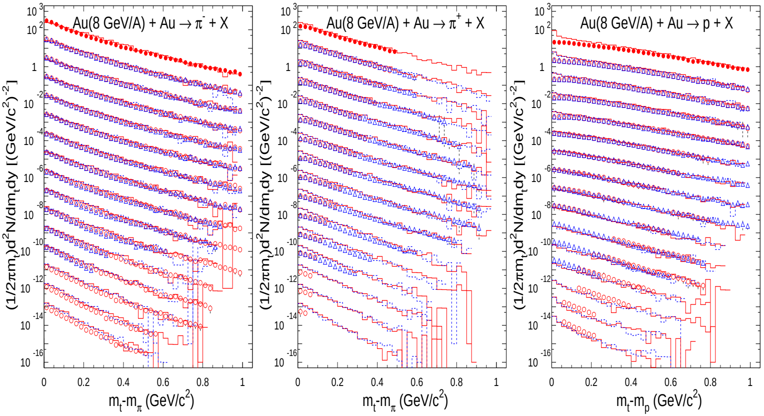
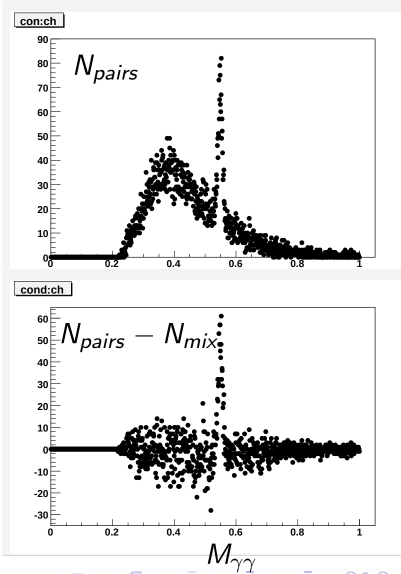
(K.Gudima)



$p + C$ simulation (N.Amelin)

Photon pair effective mass distribution

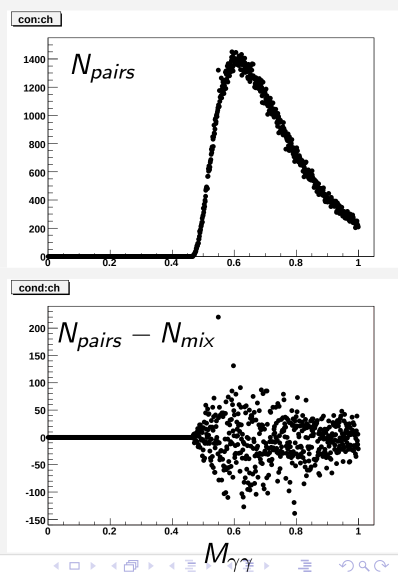
10^6 events of $p + C$ of inelastic collisions at the beam energy 4.6 $AGeV$ have been simulated. Selection conditions close to those in the PHOTON-2 experiment were applied to see η meson ($m_\eta = 0.549\ GeV$)



$Pb + Pb$ simulation (N.Amelin)

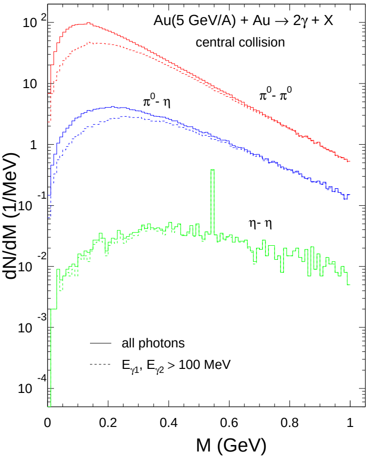
Photon pair effective mass distribution

$2 \cdot 10^4$ events of $Pb + Pb$ of inelastic collisions at the beam energy 4.6 $AGeV$ have been simulated. Selection conditions close to those in the PHOTON-2 experiment were applied to see η meson ($m_\eta = 0.549$ GeV) at the given statistics



- signal level $\sim 3 \cdot 10^{-4} [GeV^{-1}]$; peak-value of π^0 $\sim \frac{10^2 \cdot 10^3}{5000} = 20$
  $\frac{S}{B} \sim \frac{3 \cdot 10^{-4}}{20} \sim 10^{-5}$ ($\nearrow$ for non-peak)

$N_{events} = 5 \cdot 10^3$ (K.Gudima)



estimate without experimental cuts

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- $n_{\pi\pi\to\gamma\gamma} = \int \frac{dN}{dM} dM \sim 10^{-4}$; $n_{\pi^0} \approx 60$
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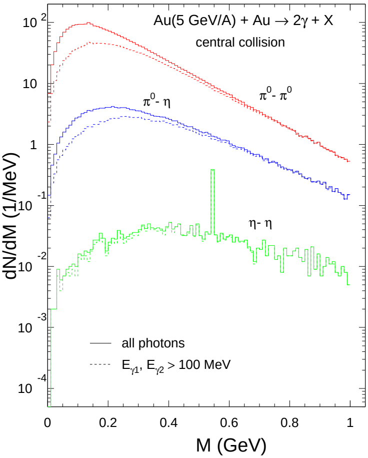

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acceptance ?

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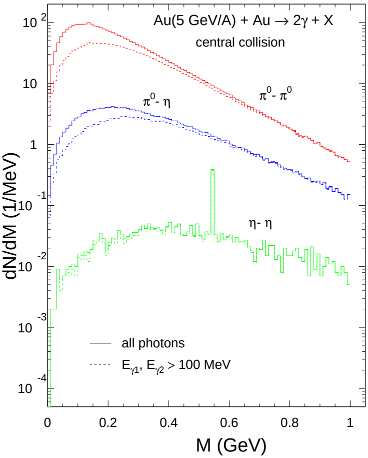

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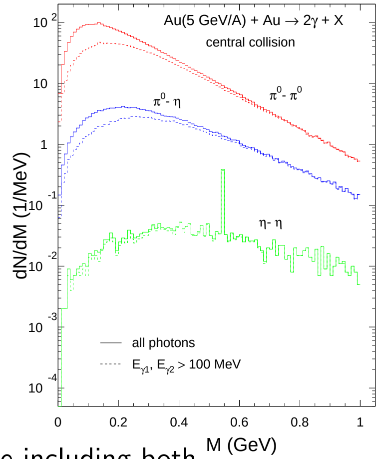

- For proper estimate new code including both T, μ-dependent signal and background is needed