Thermal photons in A+A collisions at RHIC energies

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How to calculate thermal photon yield

$$\frac{d^3N_\gamma}{dy\, d^2P_t} = \int_\Omega R(T,\mu,u)\, d^4x$$

R – emission rate from the unit 4-volume at a temperature **T(x)** and chemical potential μ**(x)**, boosted with 4-velocity **u(x)**;

Ω – space-time volume, occupied by the system.

Key features of calculations:

- **Emission rates for QGP and RHG**
- **Dynamic model:**
  - **Fireball;**
  - **2+1 Bjorken hydrodynamics;**
  - **3+1 hydro;**
  - **Initial conditions: τ_0 (ε_0 or T_0)**
  - **EoS**

Pre-equilibrium contribution:

- Neglect it;
- Use cascade models;
- Model with hydro.

Thermal photon emission rate from QGP

Compton and annihilation ($qg \to q\gamma$, $qq \to g\gamma$) processes in HTL framework

J.I. Kapusta, P. Lichard, D. Seibert, Phys. Rev. **D44**, 2774 (1991); Erratum, *ibid* **D47**, 4171 (1993).
R. Baier, H. Nakkagawa, A. Niegawa, K. Redlich, Z. Phys. **C53**, 433 (1992).

Annihilation with rescattering and bremsstrahlung

P. Aurenche, F. Gelis, R. Kobes, E. Petitgirard, Z. Phys. **C75**, 315 (1997).
P. Aurenche, F. Gelis, R. Kobes, H. Zaraket, Phys. Rev **D58**, 085003 (1998).
P. Aurenche, F. Gelis, H. Zaraket, JHEP **0205**, 043 (2002).
P. Aurenche, F. Gelis, H. Zaraket, Phys. Rev. **D62**, 096012 (2000).

Inclusion of the LPM effect

P. Arnold, G.D. Moore, L.G. Yaffe, JHEP **0111**, 057 (2001).
P. Arnold, G.D. Moore, L.G. Yaffe, JHEP **0112**, 009 (2001).
P. Arnold, G.D. Moore, L.G. Yaffe, JHEP **0206**, 030 (2002).

Complete calculations in α and α_s

Thermal photon emission rate from hadron gas

Photon emission in reactions in π,ρ,η,ω gas

J. I. Kapusta, P. Lichard, and D. Seibert, Phys. Rev.D 44, 2774 (1991);

Added a_1 as a intermediate state in $\pi\rho\rightarrow a_1\rightarrow\pi\gamma$

L. Xiong, E. V. Shuryak, and G.E. Brown, Phys. Rev.D 46, 3798 (1992).

Consistent treatment of contribution of a_1 resonance

C. Song, Phys. Rev. C 47, 2861 (1993).

Exploring effects of hadron mass modifications in hot matter

P. Ko and S. Rudaz, Phys. Rev. D 50, 6877(1996).

J.K. Kim, P. Ko, K. Y. Lee and S. Rudaz, Phys. Rev.D 53, 4787(1996).

S. Sarkar, J. Alam, P. Roy, A. K.Dutt-Mazumder, B. Dutta-Roy and B. Sinha, Nucl. Phys. A 634, 206 (1998);

P. Roy, S. Sarkar, J. Alam and B. Sinha, Nucl. Phys. A 653, 277 (1999).

Y. C. Shin, M. K. Cheoun, K. S. Kim and T. K. Choi, Eur. Phys. J. A 14, 87 (2002).

Inclusion of the contribution of strange mesons, ω in t-channel and baryons

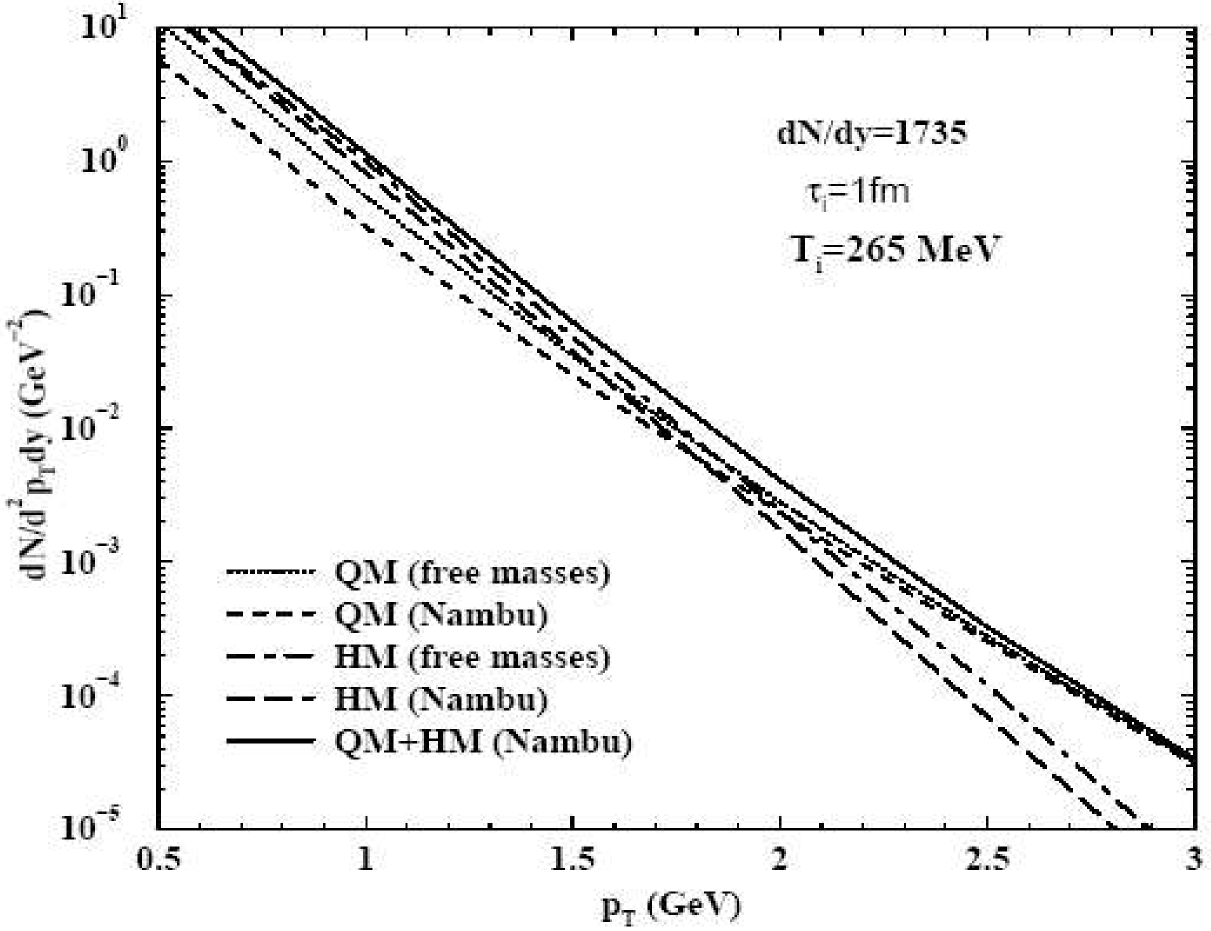
S. Turbide, R. Rapp and C. Gale, hep-ph/0308085.

Jan-e Alam, Pradip Roy and Sourav Sarkar, hep-ph/0310168

Extensive set of reactions involving π,ρ,ω,a_1,K,N

Calcutta group

J. e. Alam, S. Sarkar, T. Hatsuda, T. K. Nayak and B. Sinha, Phys. Rev. C 63 (2001) 021901.



QGP emission rate:
Two loop, no LPM effect

HG emission rate:
π,ρ,ω,a_1 within different models

Model:
2+1 Bjorken hydrodynamics

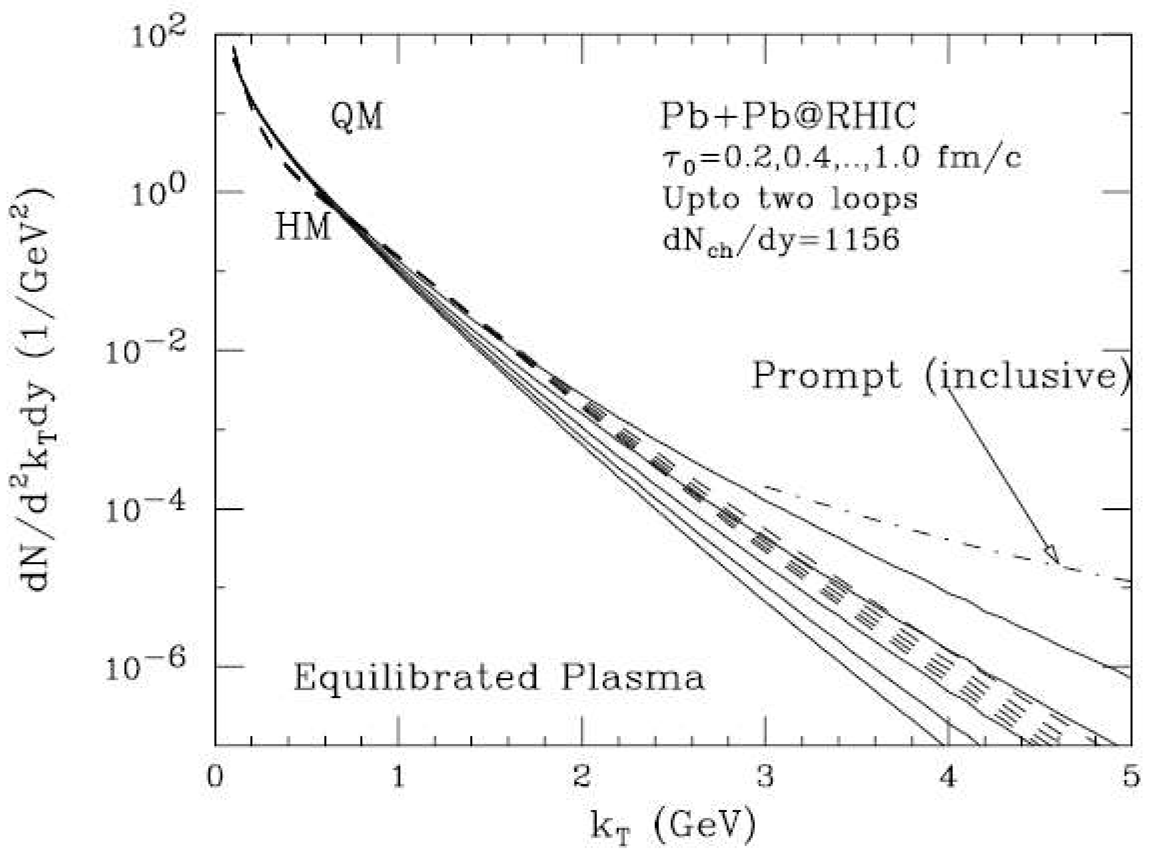
In. Cond:
T_i = 265 MeV, τ_i=1 fm/c

EoS:
Bag model (π,ρ,ω,η,a_1,N in HG)

Evolution is not fitted neither to hadron multiplicity nor to hadron spectra.

D.K.Srivastava

D. K. Srivastava, Pramana 57 (2001) 235.



QGP emission rate:
Two loop, no LPM effect

HG emission rate:
emission from π,ρ,a_1 gas

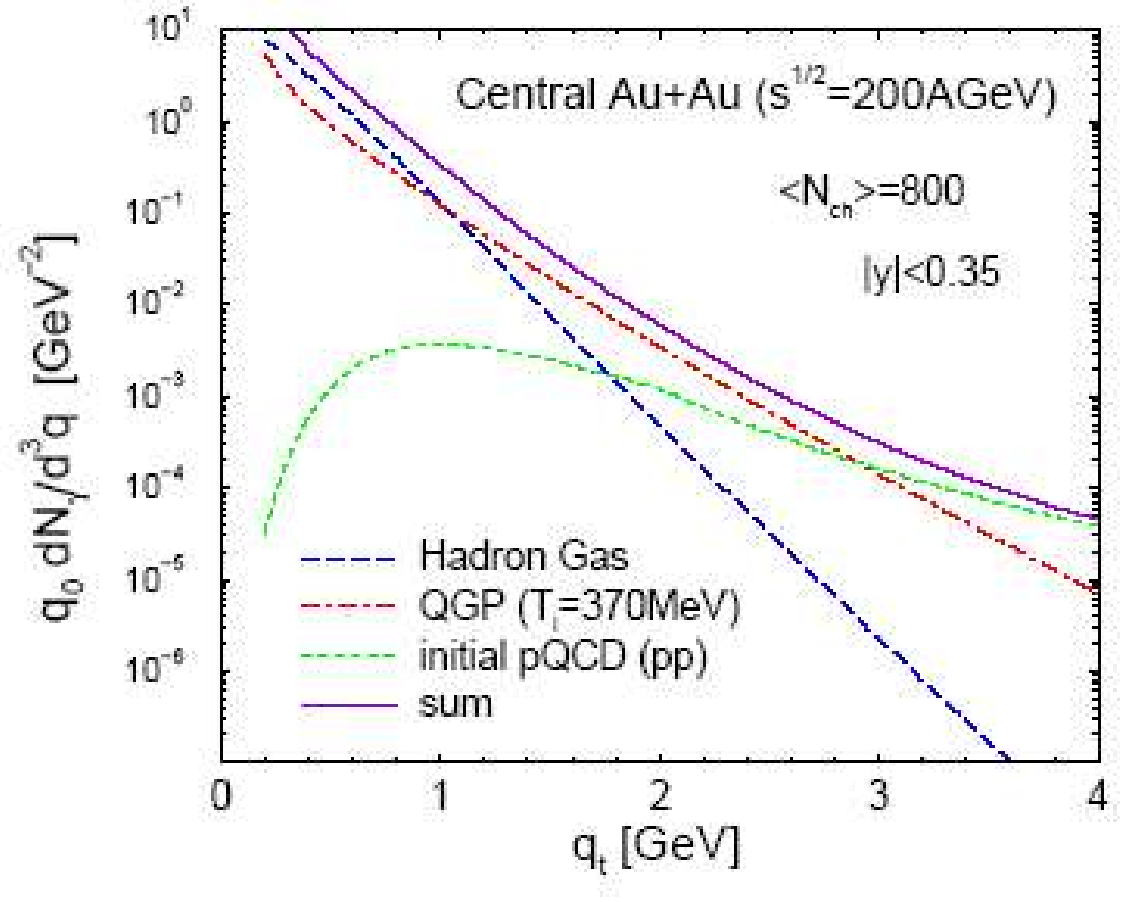
Model:
2+1 Bjorken hydrodynamics

In. Cond:
T_i = 670-390 MeV,
τ_i = 0.2-1 fm/c

EoS:
Bag model (π,ρ,ω,η,a_1,N in HG)

Montreal group

S.Turbide, R.Rapp and C.Gale, Phys. Rev. C 69, 014903 (2004).



QGP emission rate:
two loop with LPM effect

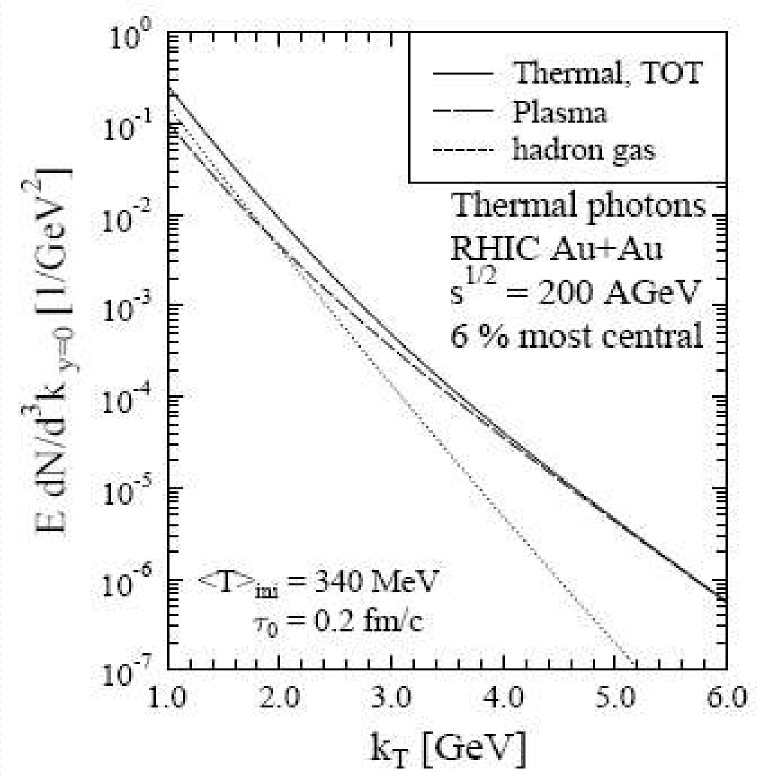
HG emission rate:
emission from π,ρ,a_1,K,N gas

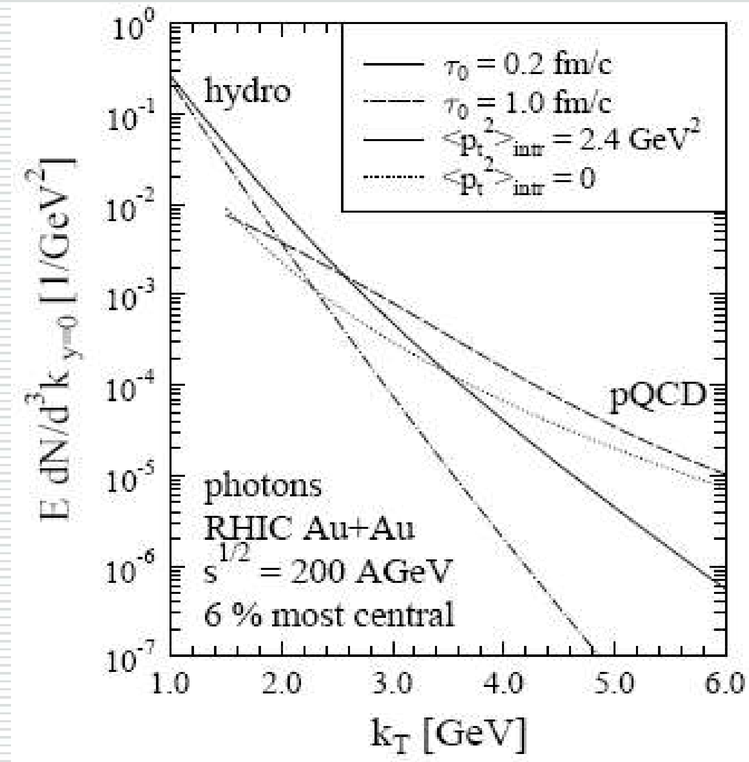
Model:
Fireball model with fixed longitudinal and transverse accelerations.

In.Cond.:
$T_i \sim 370$ MeV
$\tau_i = 0.3$ fm/c

Jyvaskyla group

S.S.Rasanen, Nucl.Phys.A 715 (2003) 717.
F.Gelis, H.Niemi, P.V.Ruuskanen, S.S.Rasanen, J.Phys.G30:S1031-S1036,2004



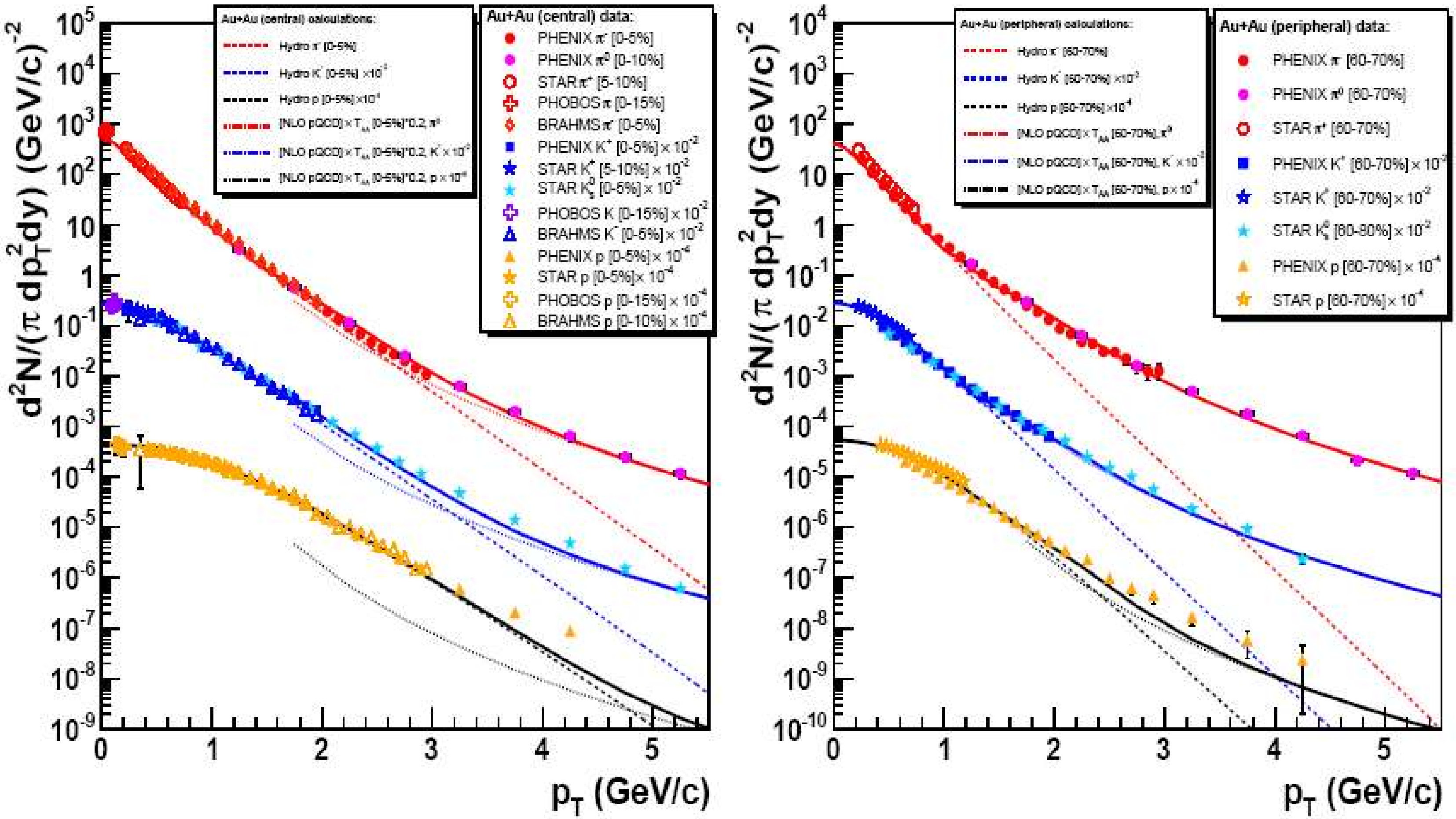


QGP emission rate: two loop with LPM effect
HG emission rate: emission from π,ρ,a_1 gas
Model: 2+1 Bjorken hydrodynamics
In. Cond: T_i = 580 MeV, τ_i=0.17 fm/c
EoS: Bag model (rich hadronic gas)

Evolution fit to reproduce hadron spectra

BNL-Moscow group

D.d'Enterria and D.Peressounko, nucl-th/0503054



QGP emission rate: two-loop with LPM effect

HG emission rate: emission from π,ρ,ω,a_1,K,N gas

Model: 2+1 Bjorken hydrodynamics;

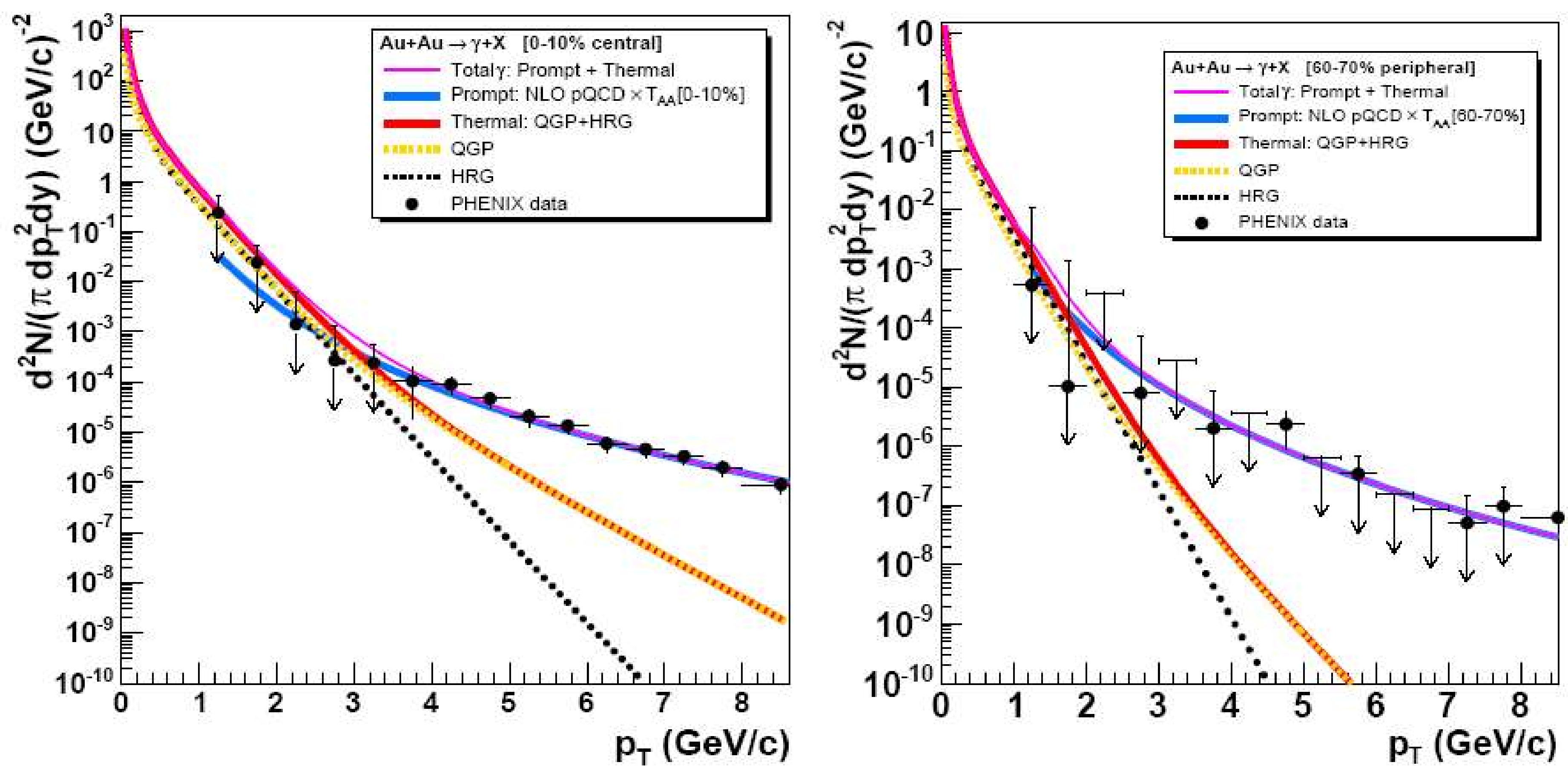
In.Cond: τ_i=0.15 fm/c; T_i=610 MeV

EoS: Bag model (~400 species in HG)

Evolution is fit to π,K,p spectra

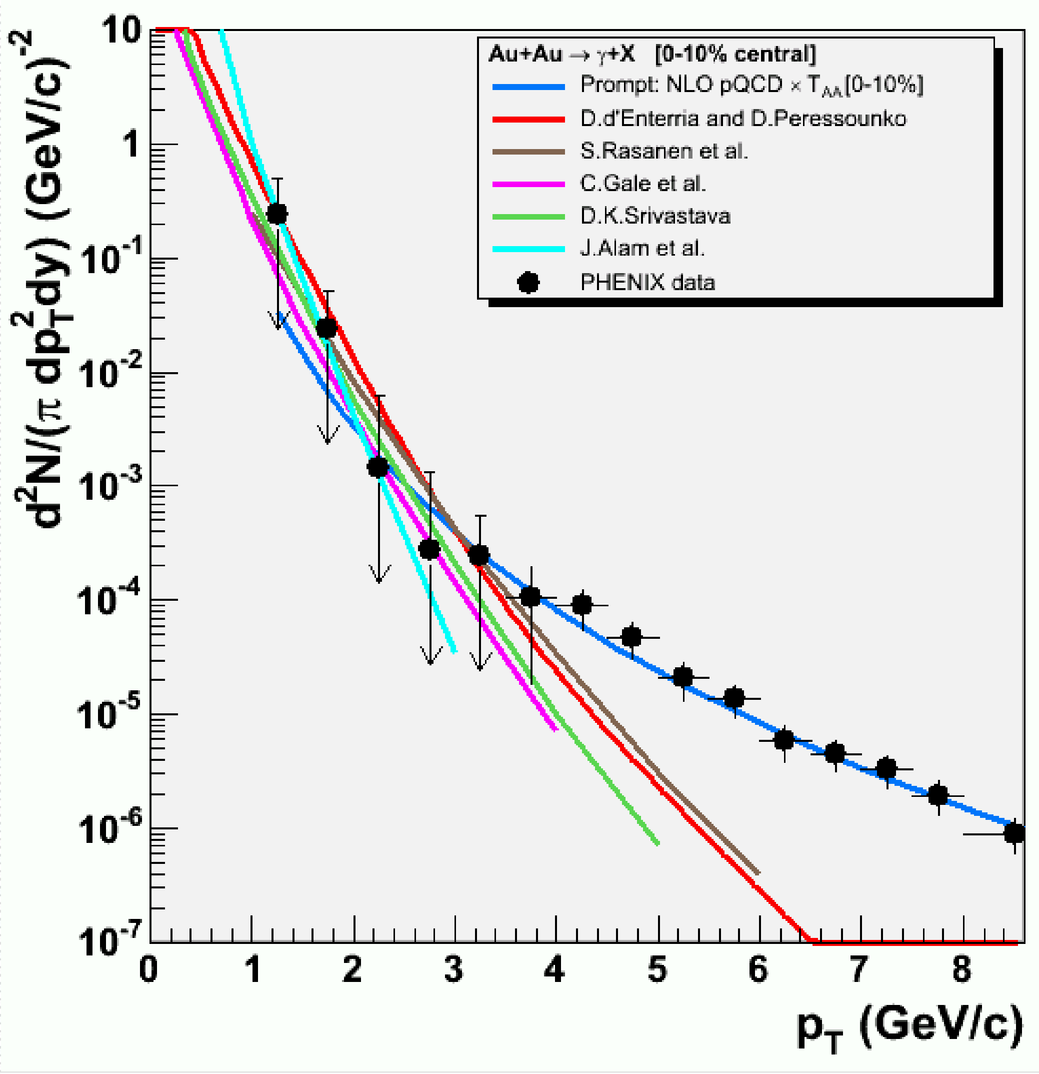
BNL-Moscow group

D.d'Enterria and D.Peressounko, nucl-th/0503054



pQCD: L.E. Gordon and W. Vogelsang, Phys. Rev. D 48 (1993) 3136;
Phys. Rev. D 50 (1994) 1901.
PHENIX data: S.S.Adler et al., Phys. Rev. Lett. 94, 232301 (2005)

Comparison of predictions to PHENIX data



All calculations predict considerable thermal contribution below 3 GeV

All calculations agree with data within errors.

Calculations with similar initial time (temperature) result in similar spectra. Dependence on used emission rates and details of description of evolution is modest.

What is next?

Calculate centrality dependence of the thermal photon spectrum:
Exploring dependence on the initial energy density.

Can we go further?

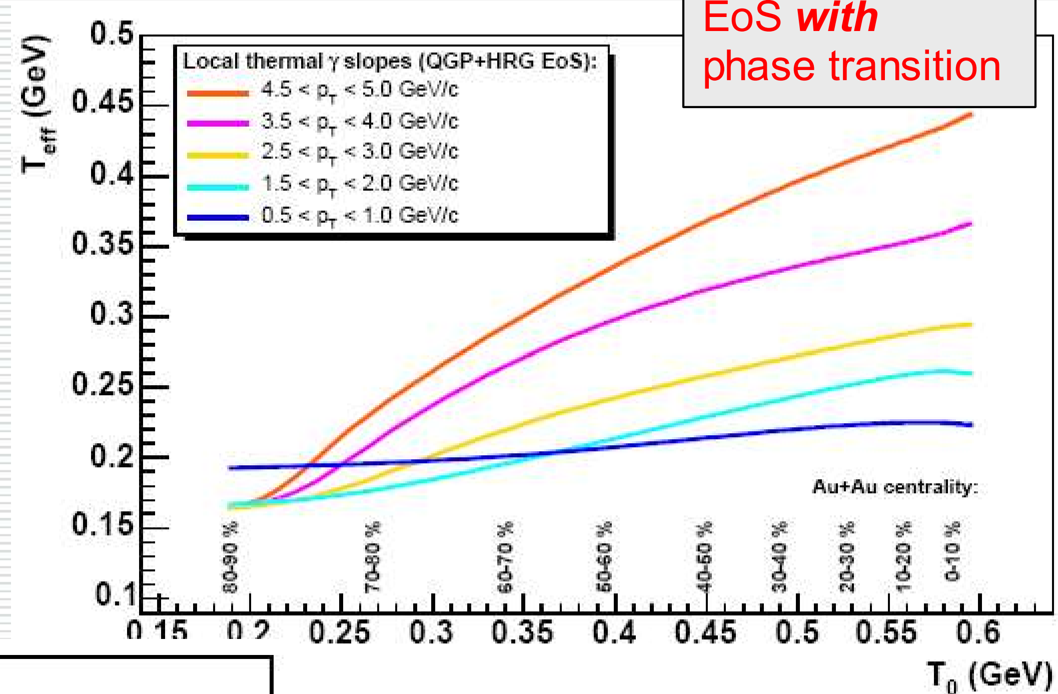
- Since thermal photons reflect temperature in the medium, can we extract this temperature directly by measuring slope?
- Can we extract the number of effective degrees of freedom in hot matter by comparing thermal photon slope and entropy or energy density?

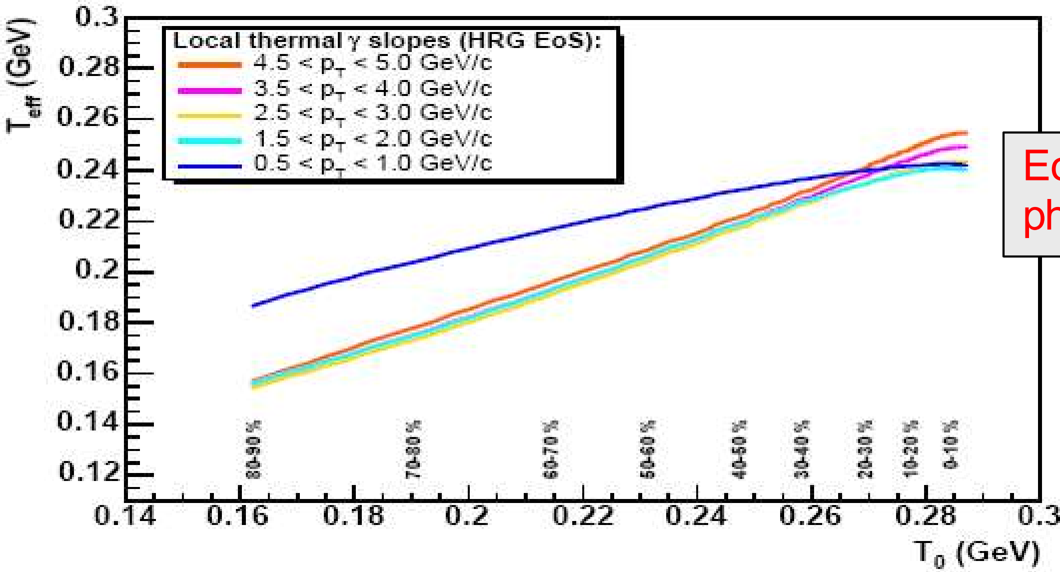
Correlation between apparent and initial temperature

Smearing of effective temperature:
- Final thickness of matter
- Temperature gradients T(r)
- Collective velocity

Does correlation survive?

EoS ***with*** phase transition



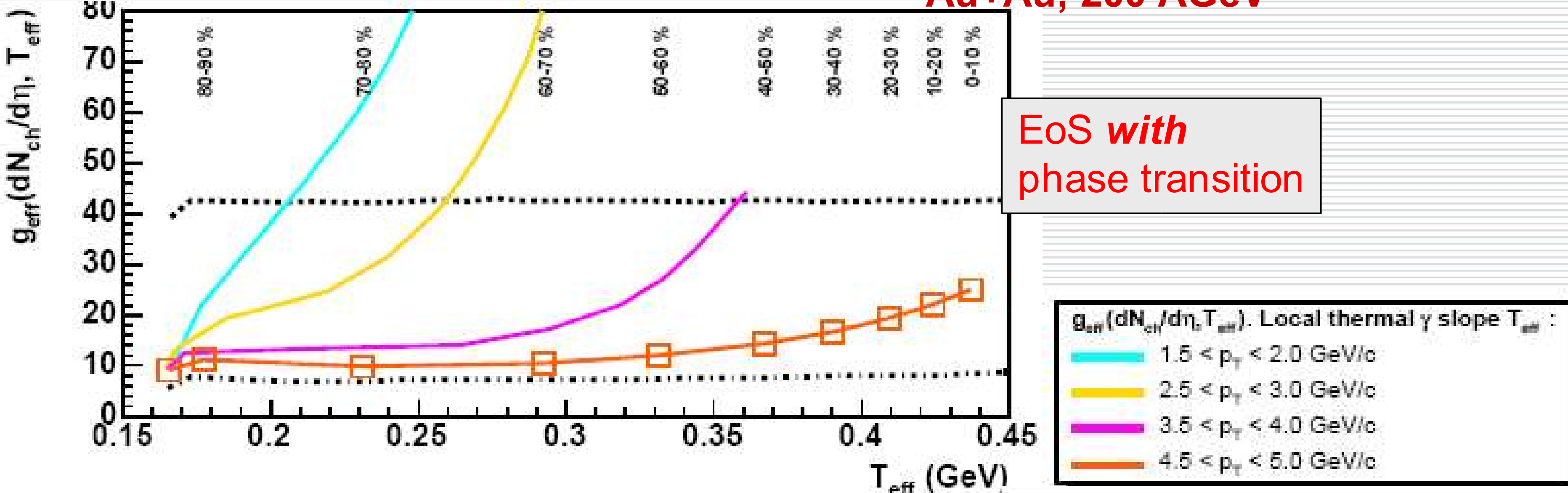


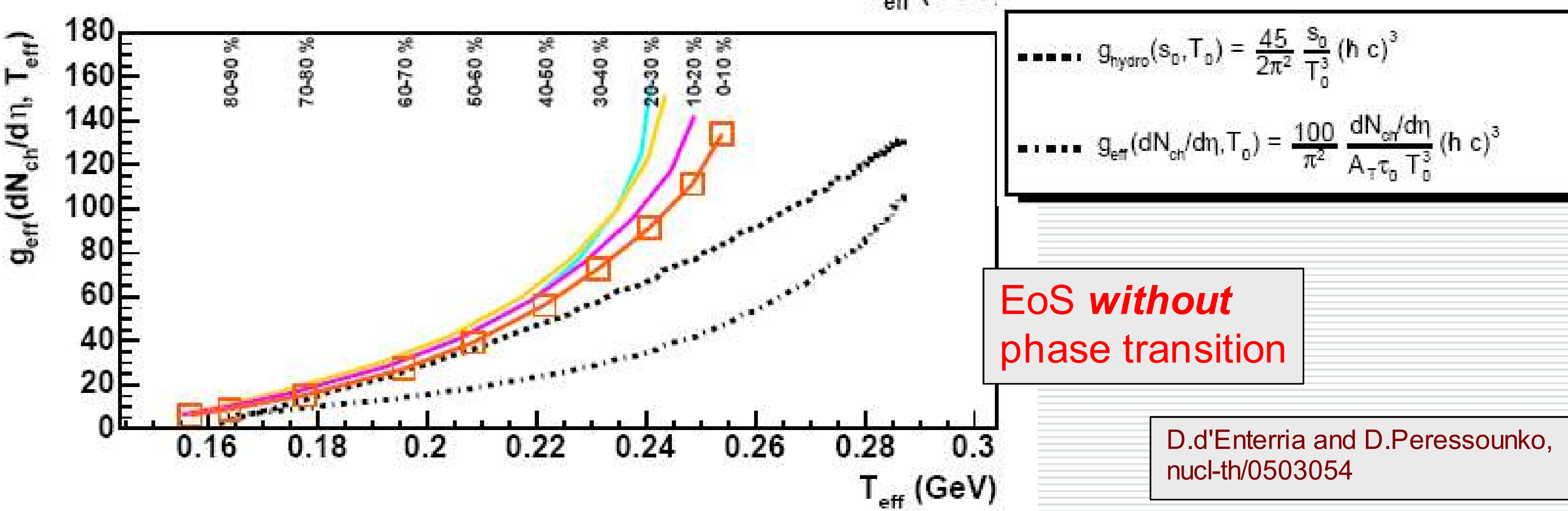
EoS ***without*** phase transition

D.d'Enterria and D.Peressounko, nucl-th/0503054

Correlation between apparent temperature and $dN_{ch}/d\eta$

Au+Au, 200 AGeV





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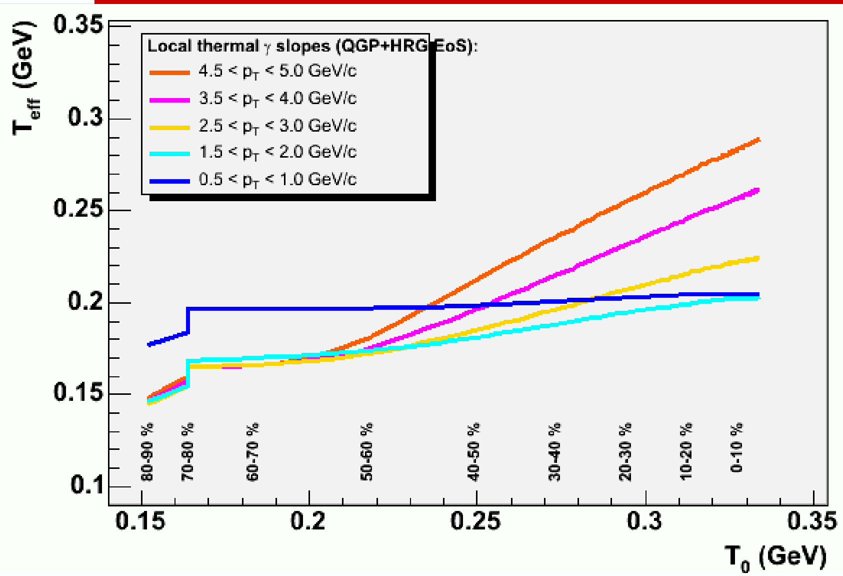
Correlation between apparent temperature and $dN_{ch}/d\eta$

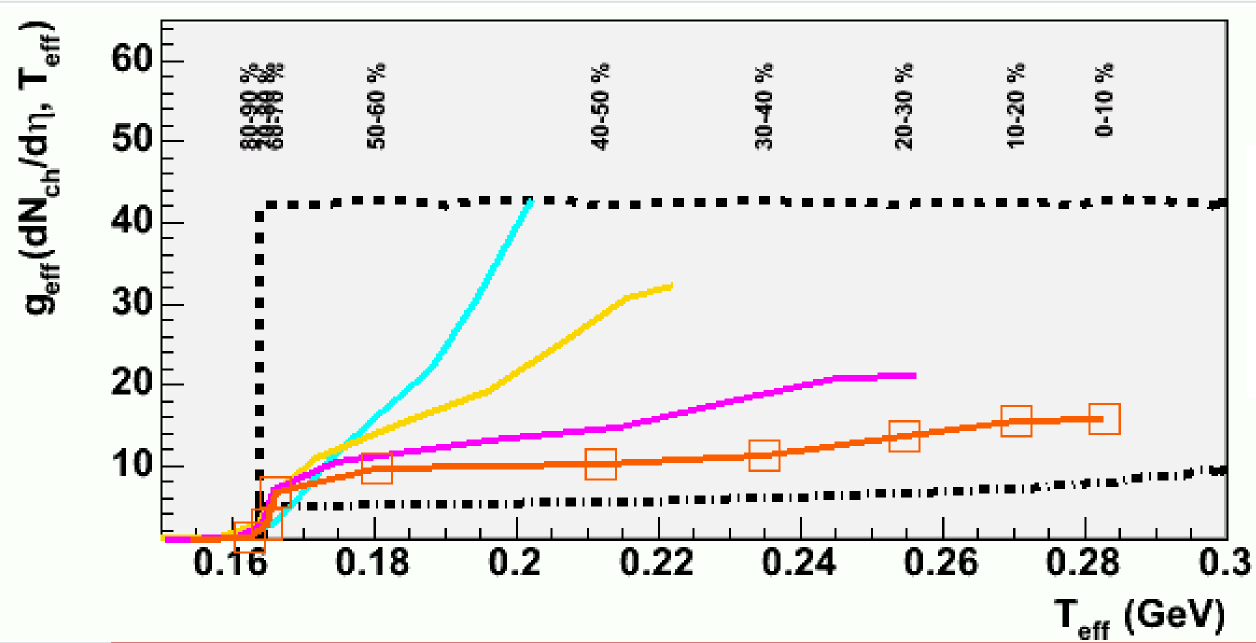


Au+Au, 62 AGeV

$\tau_i = 4R/\gamma = 0.45$ fm/c

$$g_{hydro}(s_0, T_0) = \frac{45}{2\pi^2}\frac{s_0}{T_0^3}(\hbar c)^3$$

$$g_{eff}(dN_{ch}/d\eta, T_0) = \frac{100}{\pi^2}\frac{dN_{ch}/d\eta}{A_T \tau_0 T_0^3}(\hbar c)^3$$



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Conclusions

- At top RHIC energy thermal photons contribute to direct photon spectrum at P_t<3 GeV: more precise data are necessary to make any conclusion.

- Thermal photon spectrum depends mainly on initial temperature and in much smaller extend on details of evolution and emission rates.

- Correlation between apparent temperature of thermal photons and maximal initial temperature in the collision is not destroyed by evolution: maximal temperature can be extracted just by measuring inverse slope at as high P_t as possible.

- One can directly explore phase transition by confronting apparent slope of thermal photons and charged hadron multiplicity.