Direct-photon collective flow and thermal photons as QGP thermometer

Heavy-Ion Journal Club

Lucia Leardini

Physikalisches Institut
Heidelberg University

18 July 2014

Outline

Direct-photon collective flow

- v_2 of π^0, inclusive and direct photons has been measured in Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV
- v_2 of π^0 has been found consistent with inclusive photons v_2
- direct-photons v_2 is consistent with hadron and inclusive photons v_2 but vanishes at p_T >5 GeV/c

Thermal photons as QGP thermometer

- the photon spectra at p_T ~3 GeV/c can be characterized by their inverse logaritmic slope referred to as effective temperature T_{eff}
- hydrodynamic modelling can help study the contributing sources to T_{eff} and its relation with the fireball temperature
- theoretical prediction will be compared with data from RHIC and LHC

Observation of direct-photon collective flow in Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV

[arXiv:nucl-ex/1105.4126v2]

Direct-photons in the Quark-Gluon Plasma

- ✔ Direct-photons are electromagnetic probes which do not interact in the strongly interacting medium and can traverse it without further interaction
- ✔ Different production mechanisms ovelap in transverse momentum ranges but can be disentangled through their azimuthal distribution

- ✘ Photons are produced at every collision stages $\rightarrow$ large background for the direct-photon measurement

Photons in the Quark-Gluon Plasma

At high p_T ($> 4\text{GeV/c}^2$):

- photons from hard scattering ($qg \rightarrow q\gamma$, gluon Compton scattering), isotropic v_2=0
- jet fragmentation photons, v_2 >0
- jet-conversion photons, v_2 <0
- bremsstralung, v_2 <0

$\Rightarrow$ dependence from the path length, not dynamics

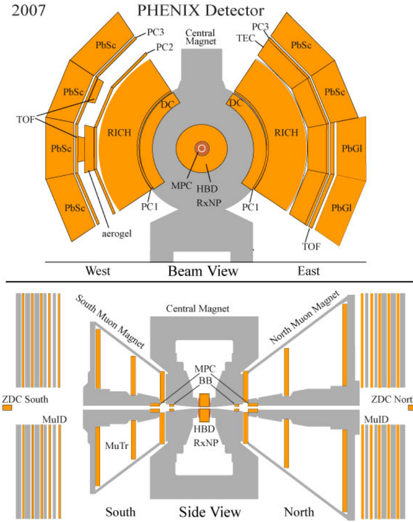
At low p_T ($1 < p_T < 4\text{GeV/c}^2$):

- thermal photons, dynamincs of medium expansion influence the azimuthal asymmetries and collectivity will persist in the hadronic phase, v_2 >0

$\Rightarrow$ thermal radiation will inherit the collective motion of the medium which can be described by near-ideal hydrodynamics

Experimental setup and dataset

- data from 2007 run, $\sim 3.0 \times 10^9$ minimum bias Au-Au collisions
- Beam-Beam counters (**BBC**, $3.1 < |\eta| < 3.9$) for event triggering and centrality estimation
- reaction plane (RP) determined by the **BBC** and by a dedicated reaction plane detector (**RxNP**, $1.0 < |\eta| < 2.8$) independently
- inclusive photons are measured with the electromagnetic calorimeter



Signal extraction

- Inclusive photons are measured with electromagnetic calorimeter
- PID, hadrons are rejected with a shower shape cut and veto on charged particles (Pad Chambers)
- Final photon sample divided in p_T ranges and binned according to $\Phi - \Psi^{RP} \rightarrow$ distribution then fitted with

$$N_0[1 + 2v_2 \cos 2(\Phi - \Psi^{RP})]$$

  in order to extract $v_2^{\gamma,meas}$
- As a cross check to the fit value, $v_2^{\gamma,meas}$ has also been measured as average cosine of particles with respect to the RP
- Further hadron correction ($p_T < 2$ GeV/c):

$$v_2^{\gamma,obs} = \frac{v_2^{\gamma,meas} - (N^{had}/N^{meas})v_2^{had}}{1 - N^{had}/N^{meas}}$$

Signal extraction

- The true v_2 for the inclusive photons is obtained by

$$v_2^{\gamma,incl} = v_2^{\gamma,obs} / \sigma_{RP}$$

where $\sigma_{RP} = \langle \cos 2(\Phi^{true} - \Psi^{RP}) \rangle$ is the RP resolution

- Large contribution to the inclusive photons comes from hadrons with photon decay channels (π^0, η, η', ω, ρ)
$\Rightarrow$ hadron yields as input in a cocktail calculation for MC to estimate $v_2^{\gamma,bg}$

- As only the π^0 spectra has been measured, other hadron yields are obtained from the $v_2^{\pi^0}(p_T)$ through m_T-scaling, under assumption that they follow the same behavior

Direct-photon excess ratio

The direct photon v_2 is expressed through the excess ratio $R_\gamma(p_T)$

$$v_2^{\gamma,dir} = \frac{R_\gamma(p_T) v_2^{\gamma,incl} - v_2^{\gamma,bg}}{R_\gamma(p_T) - 1}$$

where the direct-photon excess ratio is defined as

$$R_\gamma(p_T) = N^{incl}(p_T)/N^{bg}(p_T) = (N^{meas}(p_T) - N^{had}(p_T))/N^{bg}(p_T)$$

Values for R_γ are given by the electromagnetic calorimeter above 5 GeV/c and by the internal conversion measurement below this p_T (larger accuracy)

Systematic uncertainties

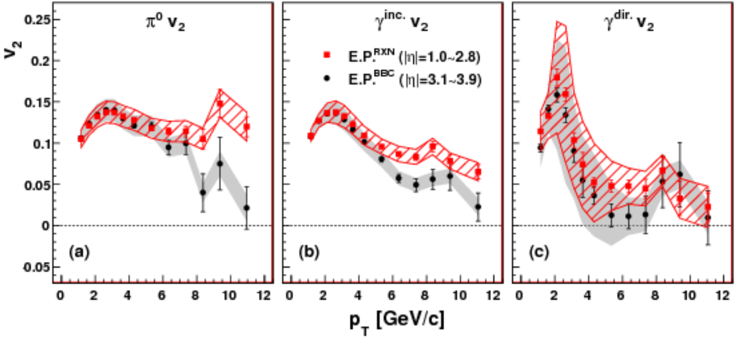
Contributing via	Source	p_T range 1 - 3 GeV/c	10 - 16 GeV/c
	(type B)		
$v_2^{\gamma,incl}$	remaining hadrons	2.2%	N/A
	v_2 extraction method	0.4%	0.6%
$v_2^{\pi^0}$	particle ID	**3.7%**	**6.0%**
	normalization	0.4%	7.2%
	shower merging	N/A	4.0%
subctration	R_γ	3.1%	2.2%
	(type C)		
common	reaction plane	**6.3%**	**6.3%**

Type B: uncertainties correlated with p_T

Type C: overall normalization uncertainty

Results - v_2 in MB collisions

v_2 in minimum bias collision using the BBC (black points) and the RxNP (red points) detectors



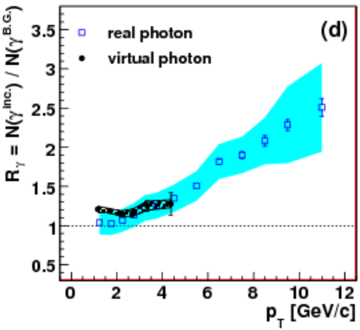
Steps of the analysis with the minimum bias sample for BBC and RXN separately: $v_2^{\pi^0}$ ans $v_2^{\gamma,incl}$ are measured , $v_2^{\gamma,dir}$ is derived

Results - v_2 in MB collisions

- bias introduced depending on the pseudorapidity region used for RP measurement: at high p_T, v_2 obtained using BBC or RXN diverges $\rightarrow$ jets modify event structure and bias the RP measurement
- bias on π^0 larger $\Rightarrow$ high p_T hadrons from jets fragments
- small bias for inclusive photons as they are a mixture of biased hadron decay photons and unbiased direct-photons

Results - R_γ in MB collisions

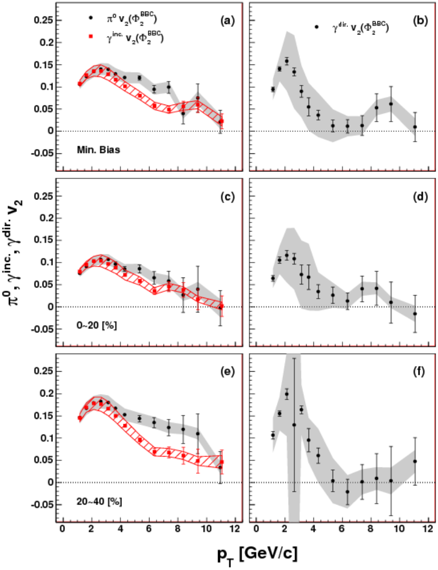
The R_γ distribution (left plot) is obtained combining the direct-photon invariant yield measurements using internal conversion (low p_T) and real photons (high p_T)



The R_{v_2} (right plot) highlights the different behaviour of the direct-photon v_2 compared to the π^0 v_2

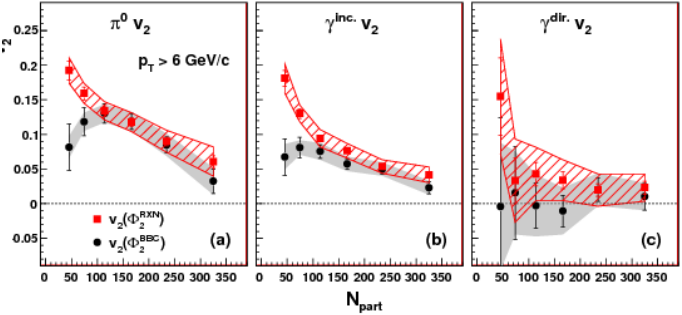
Results - v_2 centrality dependence

- ➤ large direct-photon v_2 at low p_T, comparable with π^0 flow, that descrease rapidly above 5 GeV/c
- ➤ predictions can reproduce the shape of the flow but underestimate the magnitude
- ➤ while the large direct-photon v_2 could be explained by a production mechanism at a stage at which the bulk flow is already developed, the vanishing starting at 5 GeV/c remains a puzzle



Results - integrated v_2 vs N$_{part}$ at $p_T > 6$ GeV

The influence of the location in pseudorapidity of the reaction plane detector can be clearly seen at low N$_{part}$



- π^0 v_2 higher than inclusive photon v_2 (effect of the direct-photon contribution)
- Direct-photon v_2 measurement consistent with zero at all multiplicity

Conclusions

- π^0, inclusive and direct photons v_2 has been measured in the range $1 < p_T < 13$ GeV/c in Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV
- a positive direct-photons v_2 is observed in the thermal region at low p_T (< 4 GeV/c), comparable with the π^0 and inclusive photon flow but of larger magnitude than the one predicted by theory
- at high p_T, the direct-photons v_2 is consistent with zero at all centralities, as expected if the dominant source of photon production is initial hard scattering
- experiment not sensitive to negative/positive v_2

Thermal photons as a Quark-Gluon Plasma thermometer

[arXiv:nucl-th/1308.2440v4]

Effective temperature from photon spectra

- Photons interact only electromagnetically and thus are able to traverse the medium from which they are emitted without further interaction
- As photons are emitted at all the collisions stages, their spectra are access points to the evolution of the fireball and of its temperature
- the variable used as reference and comparison to the data is the effective temperature T_{eff} which, in the low p_T region, is the measured spectra inverse logaritmic slope

$$\frac{dN}{dyp_T dp_T} \propto e^{-p_T/T_{eff}}$$

Effective temperature from photon spectra

- T_{eff} values measured are:
  - T_{eff}=211$\pm$19$\pm$19 MeV in 0-20% Au-Au collisions at $\sqrt{s_{NN}}$=200 GeV at RHIC
  - T_{eff}=304$\pm$51$\pm$51 MeV in 0-40% PbP-b collisions at $\sqrt{s_{NN}}$=2.76 TeV at LHC
- Both values are far larger than the critical temperature for hadronization, $T_c = 155 - 170$ MeV $\Rightarrow$ alternative interpretation to a QGP emission involves radiation from hadrons at temperature below T_c but due to a strong radial flow the emission spectrum is blueshifted to $T_{eff} > T_c$
- hydrodynamic model used to study the effects of collective flow on T_{eff} and emitted thermal photon spectra

Hydrodynamic model

- dynamical evolution fireball modelled with **VISH2+1** (boost-invariant hydrodynamic code)
- ensemble-averaged Monte-Carlo Glauber (MCGlb)
- initial condition propagated with the **equation of state** (EoS) **s95p-PCE-v0** with η/s=0.08 (viscosity over entropy)
- the **hydrodynamic evolution is started at τ_0= 0.6fm/c** $\rightarrow$ corrisponding to a maximum temperature in the center of the fireball equal to T_0=452 MeV for LHC and T_0=370 MeV for RHIC
- **the evolution is stopped** when the isothermal hadronic freeze-out surface has temperature **T_{surf}=120 MeV**

Hydrodynamic model

VISH2+1

- it describes transverse evolution of longitudinally boost-invariant systems without azimuthal symmetry around the beam direction
- shear viscosity included $\rightarrow$ longer QGP lifetime, larger radial flow (final state), and flatter transverse momentum spectra for emitted hadrons

s95p-PCE-v0

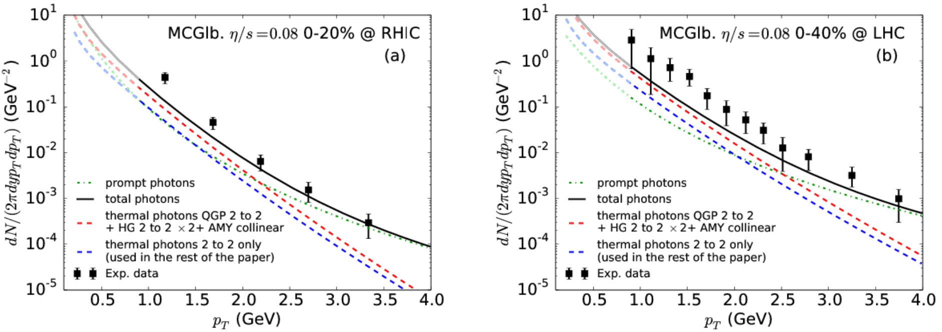
- parametrization of the QCD equation of state that combines hadron resonance gas at low temperatures with lattice QCD at high temperatures

Hydrodynamic model

- the photon emission rates used are corrected for deviation from local themal equilibrium since the evolution model incorporates viscous effect (non-zero shear viscosity)
- the emission rate from QGP and hadron gas (HG) are interpoleted to avoid discontinuities in the temperature range 184 MeV $< T <$ 220 MeV where the EoS interpoletes between the lattice QCD calculation and the HG model
- only $2 \to 2$ scattering process are included in the model
- only photon below $p_T < 4$ GeV/c are considered, contribution from hard scattering are of no interest and do not affect the inverse slope in this p_T region

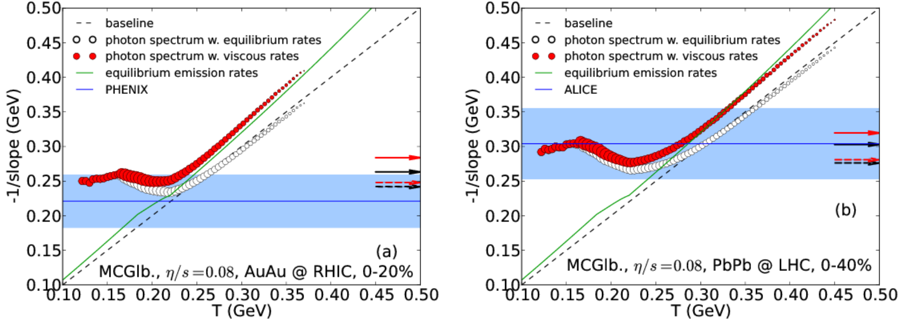
Condition used only here for the comparison model calculation - data:

- baryonic contribution included multiplying by a factor 2 the net mesonic contribution
- $2 \to 2$ ideal QGP rate is replaced by the full leading order one

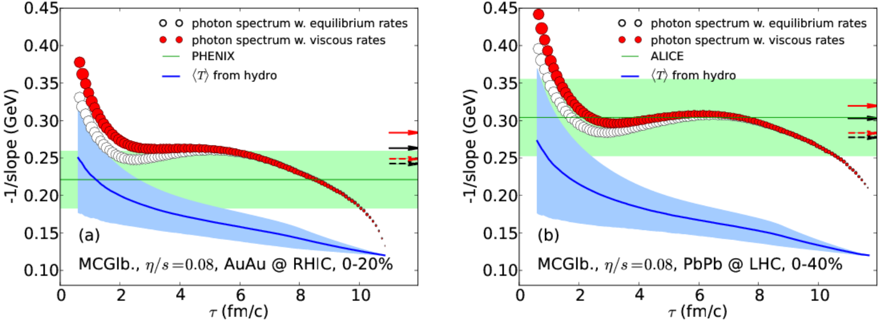


- extrapolation at low p_T using $A/(1 + P_T/p_0)^n$
- photon yield missing from the model: jet-plasma interactions and fluctuating initial states

- area of circles proportional to total photon yield emitted at that T



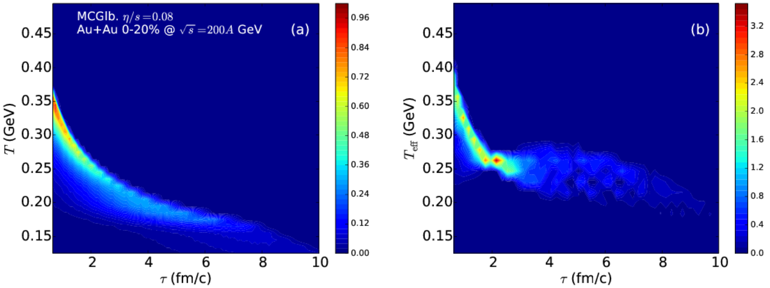
- viscous corrections to photon emission rates large at high T (larger longitudinal expansion rate), become negligible at lower T
- below T = 220 MeV the radial flow is strengthening and has a copensation effect on T_{eff} while the fireball is cooling
- below T_{ch} = 165 MeV no more radial flow is developed and the system cooling is not compensated anymore



- above 2 fm/c the effective photon temperature is strongly blueshifted by radial flow
- viscous effects on the photon emission rates are visible at early times
- while the T vs τ plot shows that early photons are associated with high yield, T_{eff} vs T plot shows that most photons are emitted from a narrow temperature band between 165 and 220 MeV

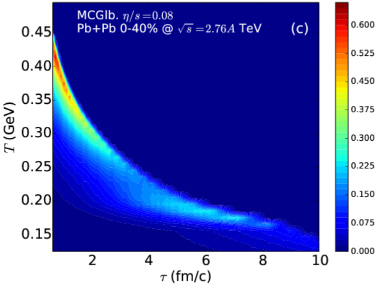
T and blue-shifted T_{eff}

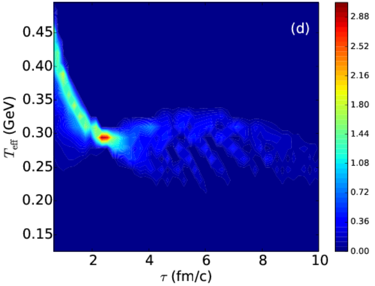
- photons are emitted with a distribution of thermodynamic temperatures for a given proper time τ
- panel (a) and (c) contour plots show differential photon yield per time τ and temperature T
- panel (b) and (d) the corresponding distribution of blue-shifted effective temperatures T_{eff}
- above 2 fm/c a shift to higher T_{eff} is visible



T and blue-shifted T_{eff}

- photons are emitted with a distribution of thermodynamic temperatures for a given proper time τ
- panel (a) and (c) contour plots show differential photon yield per time τ and temperature T
- panel (b) and (d) the corresponding distribution of blue-shifted effective temperatures T_{eff}
- above 2 fm/c a shift to higher T_{eff} is visible

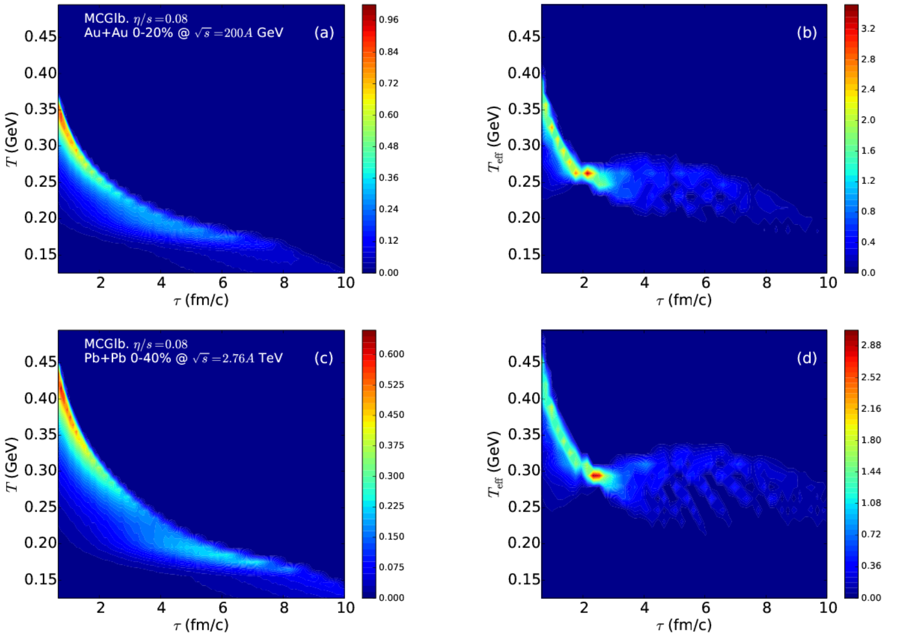




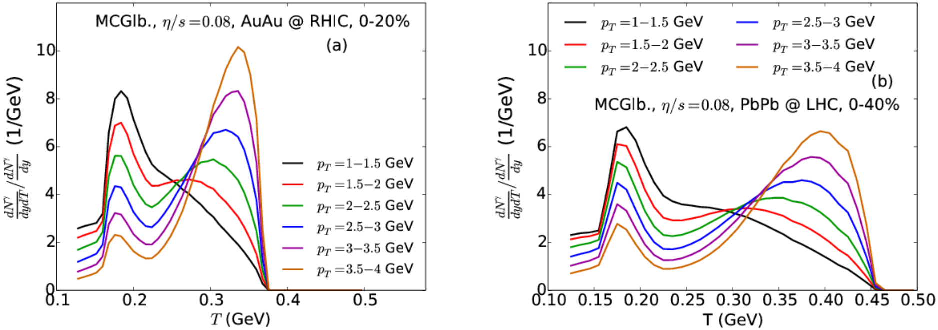
Conclusions

- thermal photons can be used as a thermometer for QGP but their interpretation requires careful and sophisticated modelling
- large observed effective temperatures of thermal photons do not prove the emission of photons from QGP at $T > T_c$ and do not reflect the initial temperature of the system
- nevertheless, a hot and dense expanding medium is needed to account for the large radial flow causing the observed effective photon temperatures
- the explanation offered by the model is that thermal photons are mostly emitted at a late stage where a strong radial flow is present and it is consistent with the elliptic flow measured at RHIC and LHC

Back up


MCGlb. $\eta/s = 0.08$
Au+Au 0-20% @ $\sqrt{s} = 200A$ GeV
(a)
(b)
MCGlb. $\eta/s = 0.08$
Pb+Pb 0-40% @ $\sqrt{s} = 2.76A$ TeV
(c)
(d)
T (GeV)
T_{eff} (GeV)
τ (fm/c)

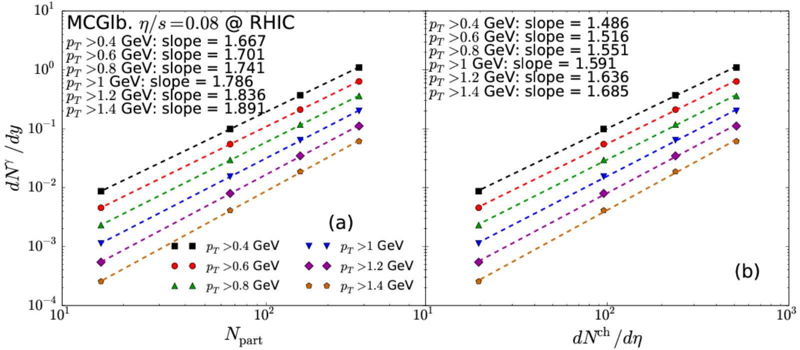
Relative photon yield as a function of T at which photons were radiated



- ➤ curves for different $p_T \Rightarrow$ thermal photons probability distribution
- ➤ at $p_T \sim$1.5 GeV, photons from transition region (T $\sim$220 MeV)
- ➤ at higher p_T: large peak at T$>$300 MeV and smaller peak at T$\sim$150-220 MeV: shift to lower photon energies due to fireball cooling is compensated (blue-shifted) by the increasing radial flow

Centrality dependence of the thermal photon yield

- Centralities: 0-20%, 20-40%, 40-60% and 60-95%



Photon yields centrality dependence studied for QGP and HG: experimentally measured centrality dependence of thermal photons closer to what predicted for HG photons than for QGP photons $\Rightarrow$ the hydrodynamic calculations underestimate photon production rate in HG phase or near phase transition