Temperature of the QGP: An (experimental) overview

37th Winter Workshop on Nuclear Dynamics

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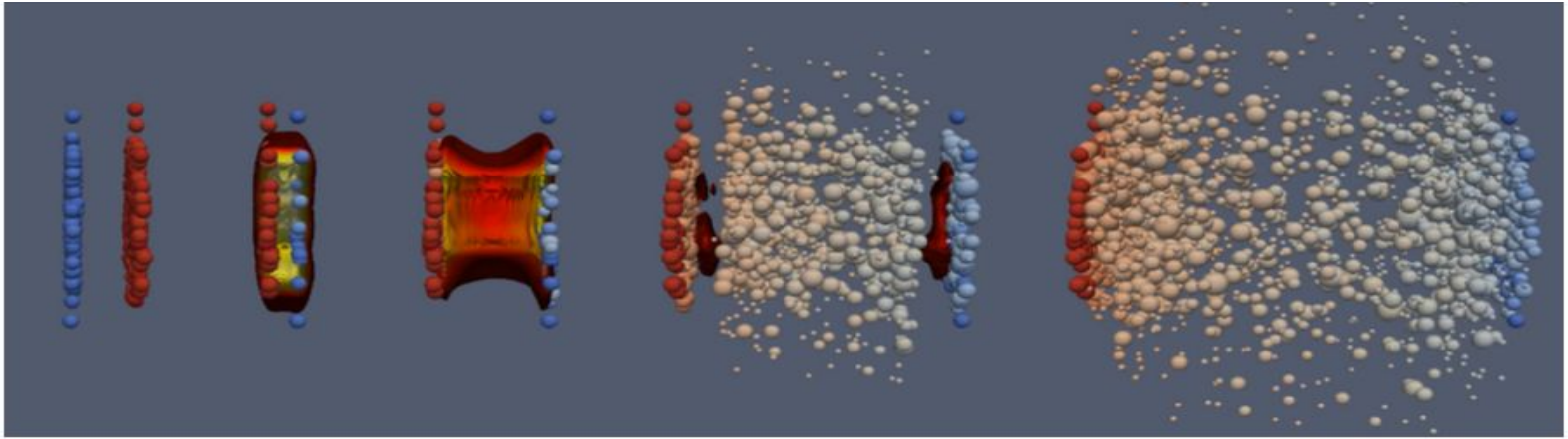
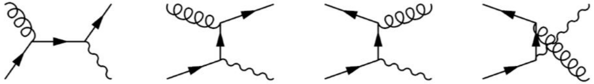
Evolution of the quark-gluon plasma

Initial state → QGP → hadronization → free streaming



Photons: inclusive = direct + decay

Direct (**Prompt** **Thermal**) **Decay (π→γγ, η→γγ)**



This talk… Temperature: theory vs. experiment, focus on real photons, and 3 questions for you!

Describing the quark-gluon plasma

Equation of state on the lattice:

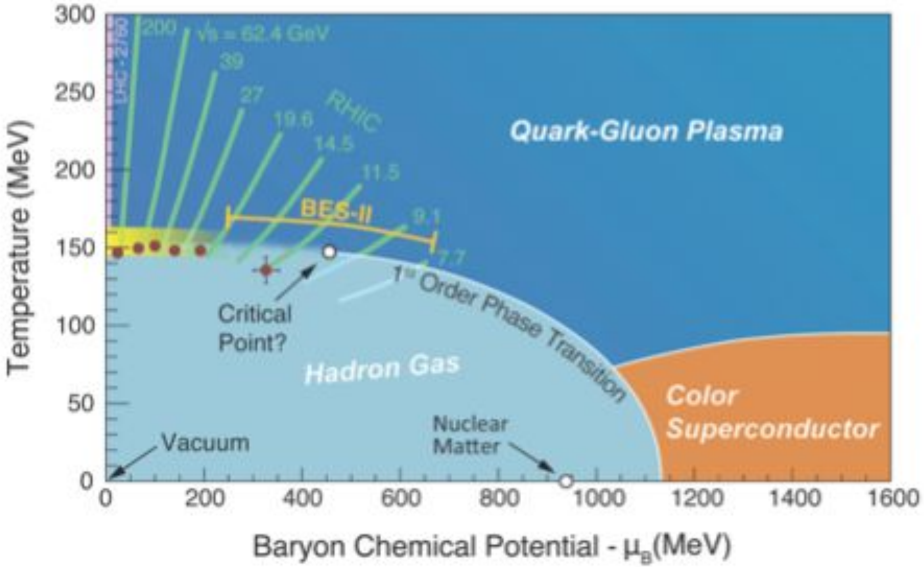
$$\frac{\Theta^{\mu\mu}(T)}{T^4} \equiv \frac{\epsilon - 3p}{T^4} = T\frac{\mathrm{d}}{\mathrm{d}T}\left(\frac{p}{T^4}\right),$$

Solved by integrating

$$\frac{p}{T^4} = \frac{p_0}{T_0^4} + \int_{T_0}^{T} \mathrm{d}T' \frac{\Theta^{\mu\mu}}{T'^5}.$$

The temperature of the system is central to our understanding!

Which temperature T is this?

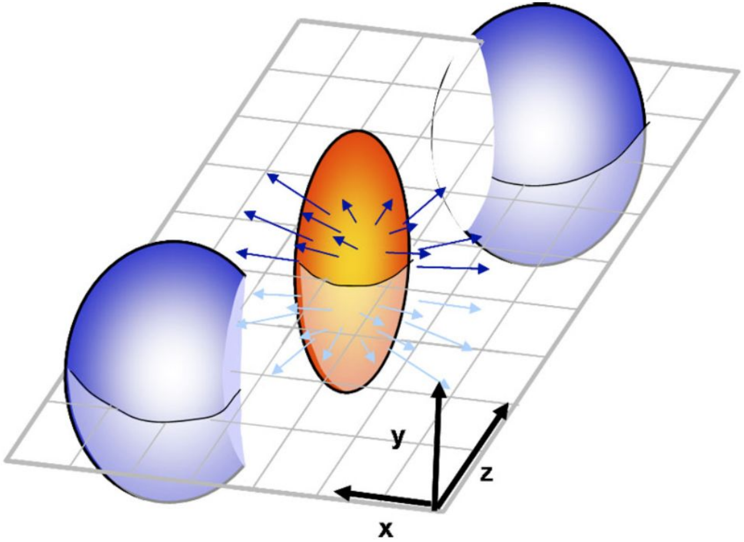


From RHIC to the LHC, we access plasmas of different temperatures, giving us insight into the space-time evolution of the system.

Question (1/3) to the audience

The impact parameter between the colliding nuclei, or overall size of the QGP depends on the impact parameter.

Experimentally this is (somewhat) controlled via “centrality”.

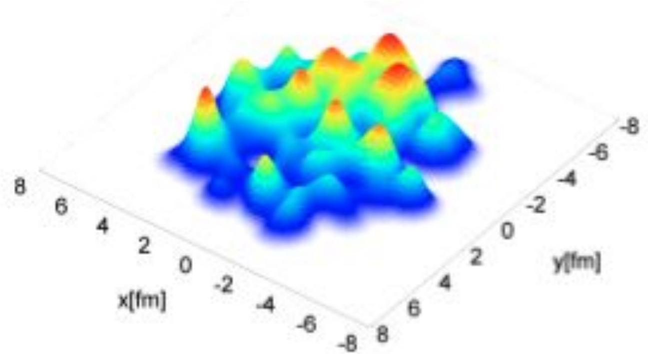


Q: How much does the temperature of the QGP change as function of collision centrality?

a) Not a lot, it is approximately flat, i.e. larger systems produce more of the same plasma.
b) changes quite dramatically.

Temperature from a theoretical point of view

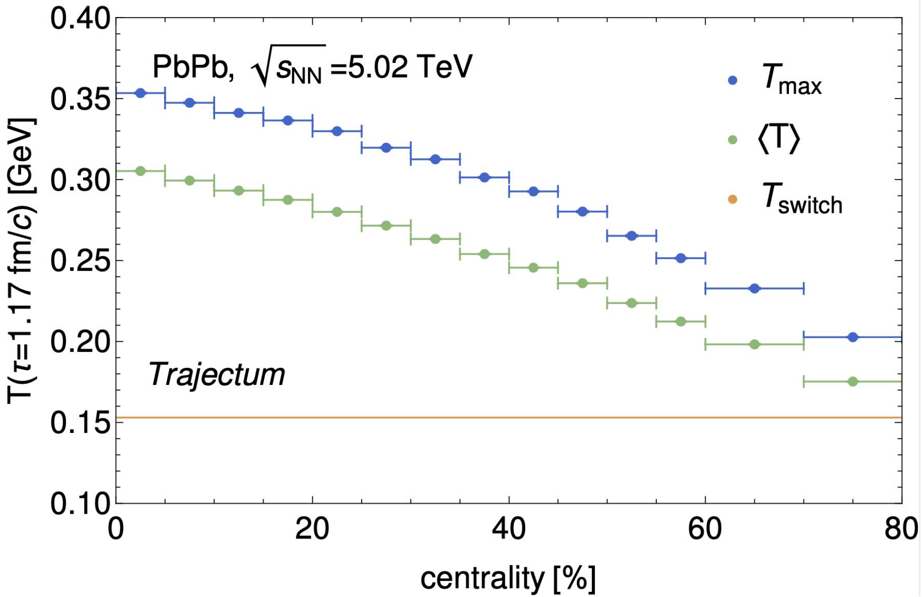
Entropy density initial (early) state



Good to realize that:

- Fluctuations induce large local temperature differences
- Nuclear thickness drives the amount of (local) binary collisions, and in turn the local temperature of the initial state
- Collisions are not just lorentz contracted disks; central collisions include larger nuclear thickness

Credits to Govert Nijs



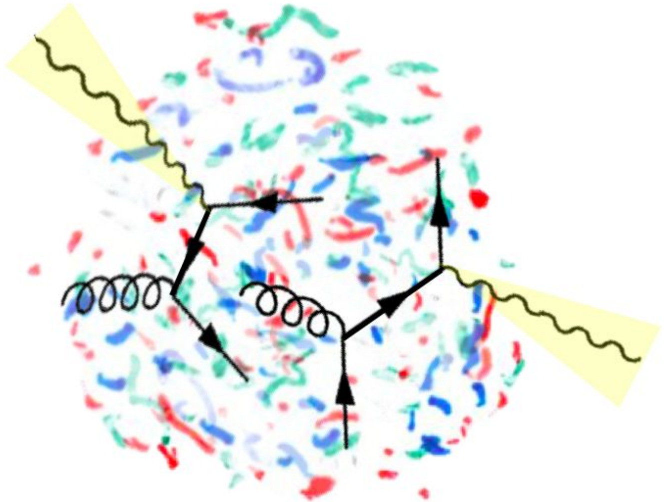
Using parameter set of the Bayesian analysis.

Doubling temperature for central collisions!

Question (2/3) to the audience

Over time, the plasma expands and cools down. In the end, the system produced a total number of thermal photons.

As in the sketch, they even escape the system unaffected, implying sensitivity to early times!



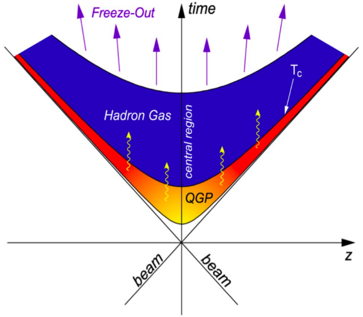
Q: One measures the direct photons. From when were most thermal photons emitted?

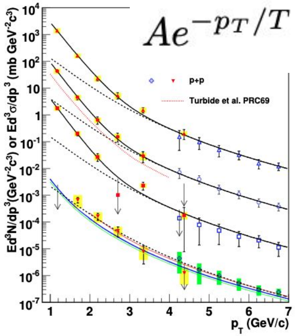
a) **First half**; most produced early on when the system is the hottest
b) **Second half**; most produced later when the system is larger and cooler

Temperature from an experimental point of view

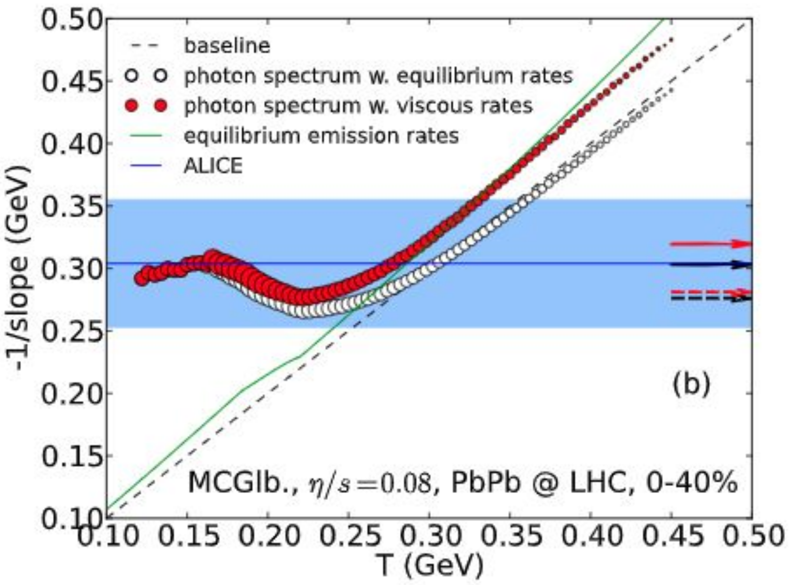
Direct photon production rate:

$$\frac{\mathrm{d}^4 N_{\gamma,\mathrm{direct}}}{\mathrm{d}^4 k} = \int \mathrm{d}^4 X \frac{\mathrm{d}^4 \Gamma_{\gamma,\mathrm{direct}}}{\mathrm{d}^4 k}(K^\mu, u^\mu(X), T(X))$$





Chun Shen et al. arXiv:1308.2440



- Instantaneous rate is highest at the start
- **Majority** is created later when the system is larger and cooler

Experimentally we can only measure an effective temperature!

The experimental method to obtain “a” temperature

1. Measure the direct photon excess and yield

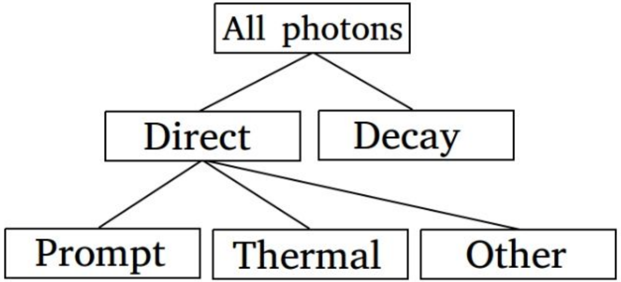
$$R_\gamma \equiv \frac{\gamma_{\mathrm{incl}}}{\pi^0_{\mathrm{param}}} \Bigg/ \frac{\gamma_{\mathrm{decay}}}{\pi^0_{\mathrm{param}}} = \frac{\gamma_{\mathrm{incl}}}{\gamma_{\mathrm{decay}}}$$

$$\gamma_{\mathrm{direct}} = \gamma_{\mathrm{incl}} - \gamma_{\mathrm{decay}} = (1 - \frac{1}{R_\gamma}) \cdot \gamma_{\mathrm{incl}}$$

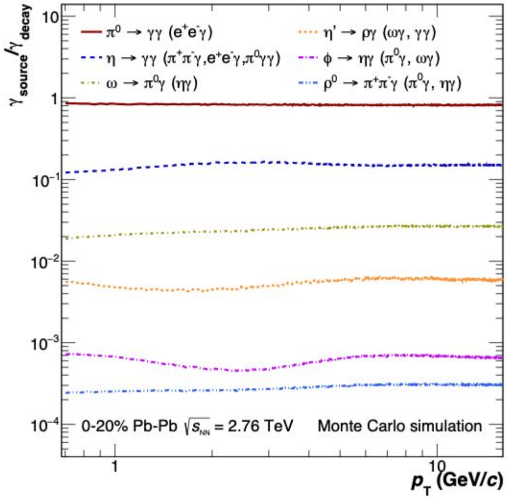
2. Fit the thermal part of the direct photon spectrum to obtain an **effective temperature**

$$Ae^{-p_T/T} + T_{AA}A_{pp}(1 + p_T^2/b)^{-n}$$

Alternatively, compare results in data to full model calculations → discussed later.

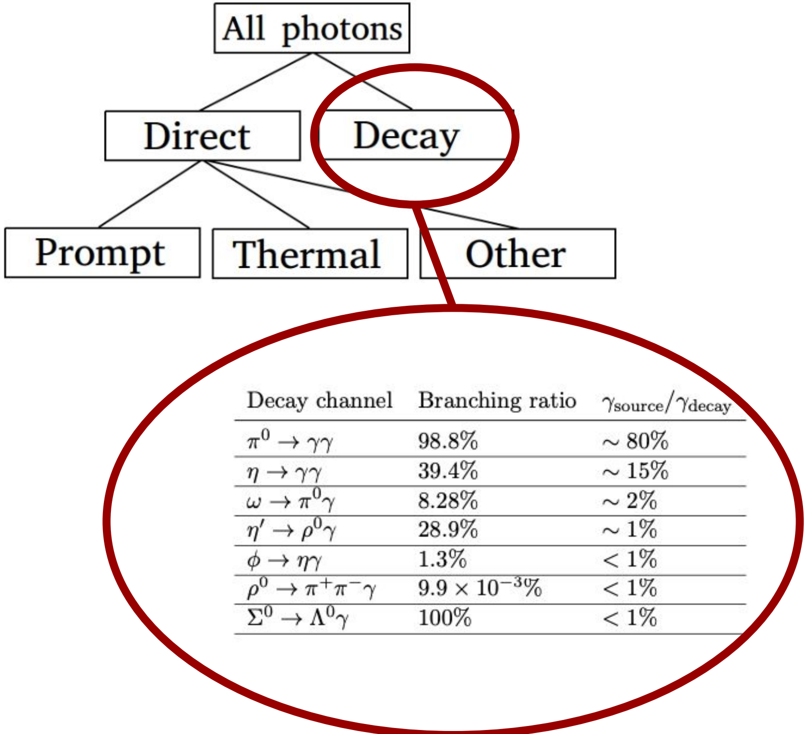

All photons
Direct
Decay
Prompt
Thermal
Other

ALICE arXiv:1509.07324



The big experimental complication

When measuring a photon → the source is unknown


All photons

Direct

Decay

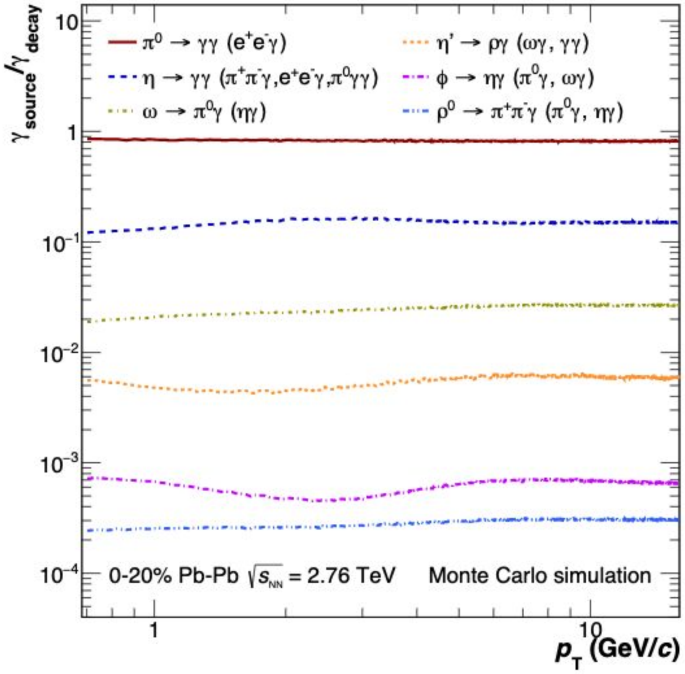
Prompt

Thermal

Other

Decay channel	Branching ratio	$\gamma_{\text{source}}/\gamma_{\text{decay}}$
$\pi^0 \to \gamma\gamma$	98.8%	$\sim 80\%$
$\eta \to \gamma\gamma$	39.4%	$\sim 15\%$
$\omega \to \pi^0\gamma$	8.28%	$\sim 2\%$
$\eta' \to \rho^0\gamma$	28.9%	$\sim 1\%$
$\phi \to \eta\gamma$	1.3%	$< 1\%$
$\rho^0 \to \pi^+\pi^-\gamma$	$9.9 \times 10^{-3}\%$	$< 1\%$
$\Sigma^0 \to \Lambda^0\gamma$	100%	$< 1\%$

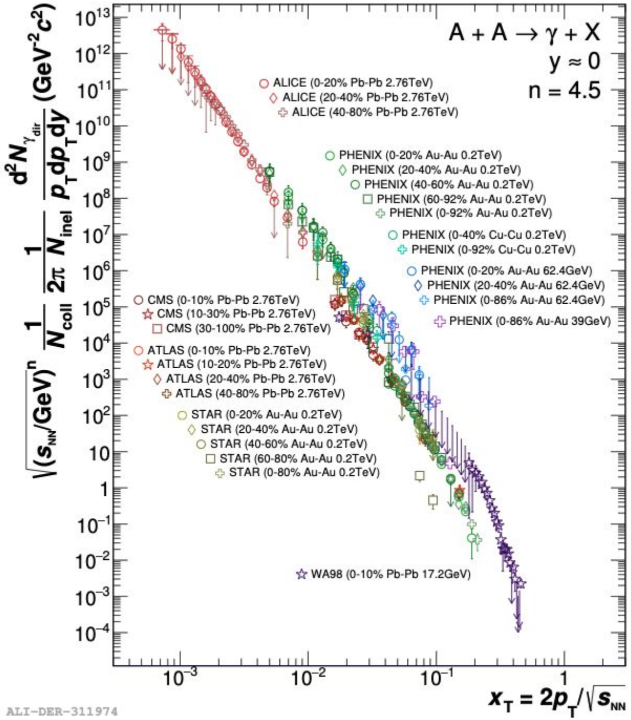
ALICE arXiv:1509.07324



Question (3/3) to the audience

The largest experimental background for direct photon measurements comes from hadronic decays; π→γγ, η→γγ.

The signal to background depends on both the temperature of the QGP(signal), as well as the hadronic cross sections(background).

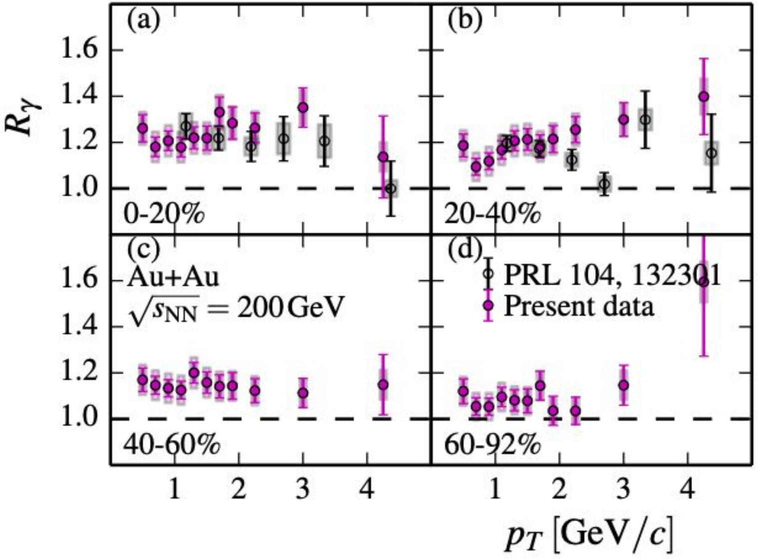


Q: At which beam energy is the fraction of inclusive photons over decay photons larger?

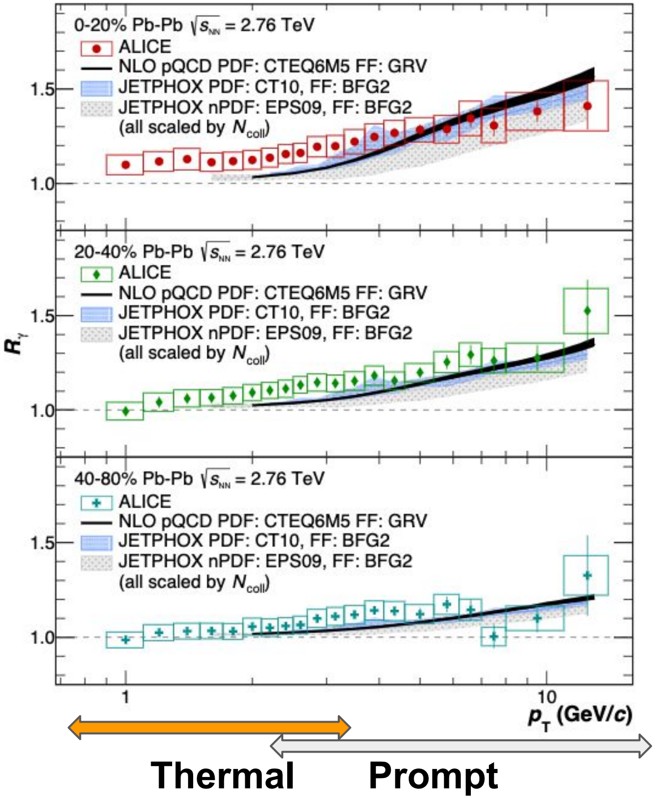
a) at LHC energies, as the temperature of the QGP is higher.
b) at RHIC energies, as the pion spectrum is steeper.

Direct photon excess at the LHC and RHIC

PHENIX arXiv:1405.3940



ALICE arXiv:1509.07324



Although the temperature is larger at the LHC, the pion spectrum is much steeper at RHIC. This leads to a larger S/B at RHIC for the direct photon excess.

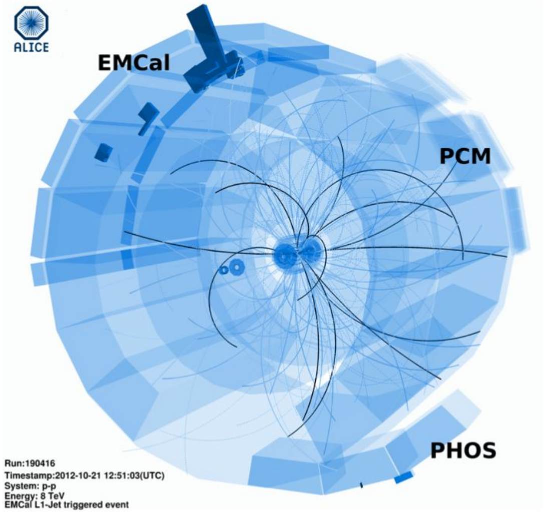
Photon reconstruction in ALICE

Calorimetric (EMCal + PHOS):

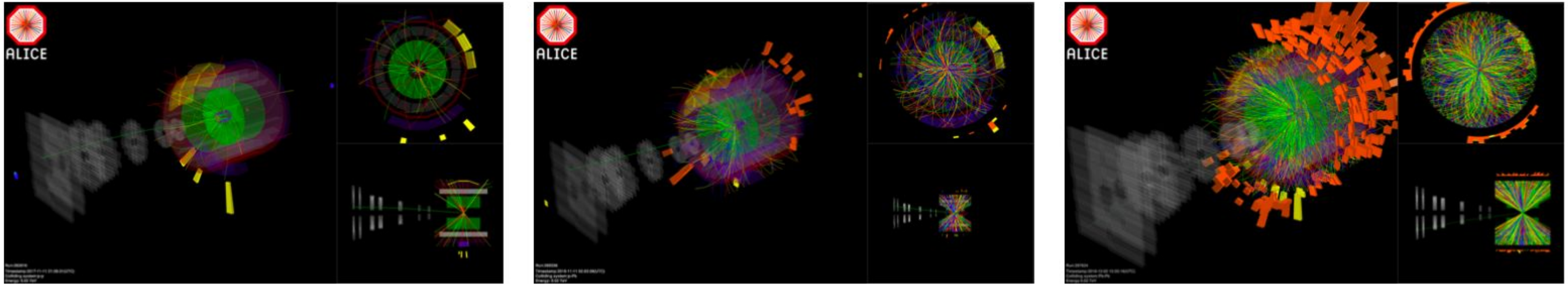
Single photons down to ~ 100-400 MeV

Photon conversion method (ITS + TPC):

Single photons down to ~ 50 MeV



The large challenge is handling the large multiplicities encountered in central Pb-Pb collisions!



Result at RHIC

PHENIX dilepton measurement, AuAu collisions at 200 GeV.

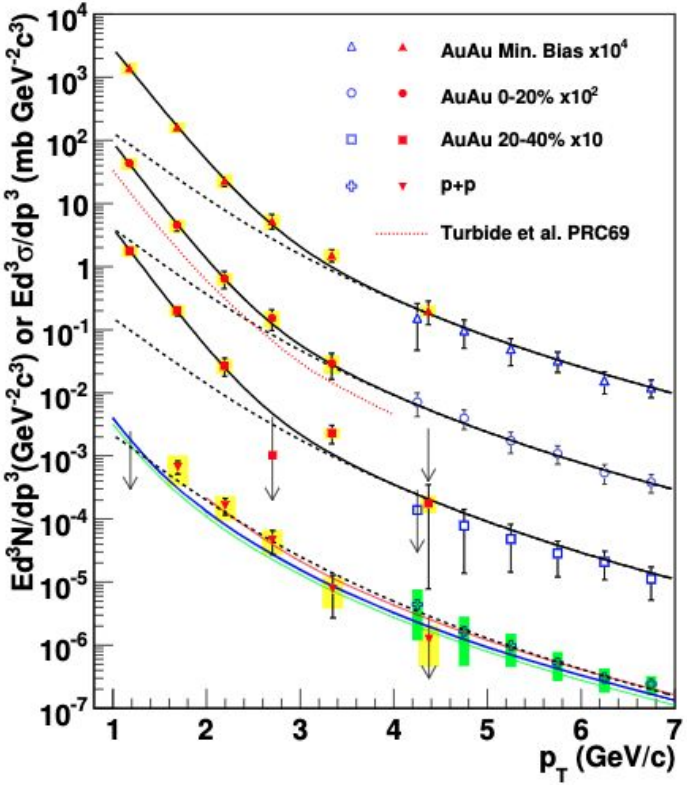
Extraction of the effective temperature using a fit on both the thermal and prompt component

$$Ae^{-p_T/T} + T_{AA}A_{pp}(1 + p_T^2/b)^{-n}$$

Result: $T_{eff} = 221 \pm 19^{stat} \pm 19^{syst}$

Will be interesting to see what follows with the upcoming large dataset runs.

PHENIX arXiv:0804.4168



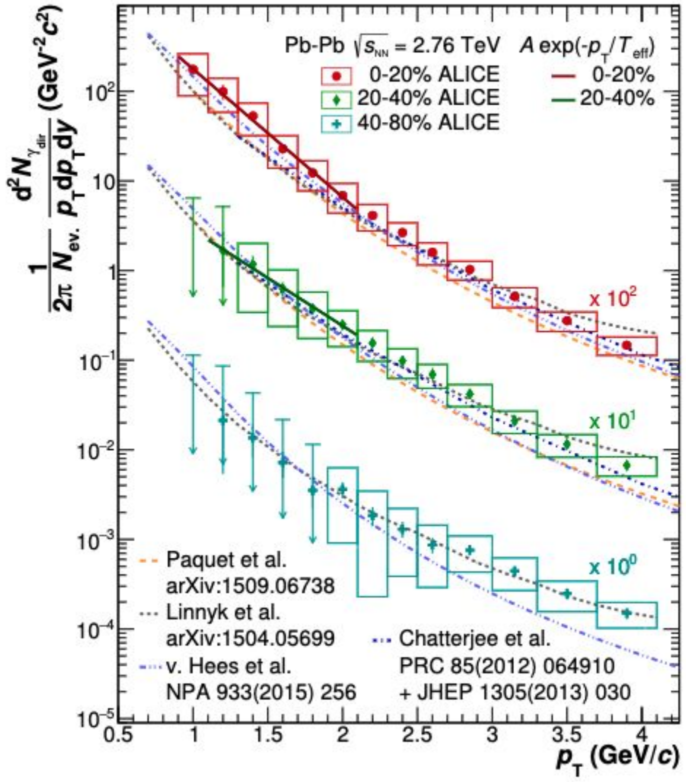
Main result at the LHC

Direct photon production in Pb-Pb collisions at 2.76 TeV.

- Combination of the PHOS and PCM measurement, starting at 900 MeV.
- Most central collisions show the most significant excess of thermal photons.
- Data consistent with hydrodynamical calculations.
- Thermal fit at low momentum ($\exp(-p_T/T_{eff})$):
    - **297**$\pm 12^{stat} \pm 41^{syst}$ MeV for centrality 0-20%
    - **410**$\pm 84^{stat} \pm 140^{syst}$ MeV for centrality 20-40%
- Might seem inconsistent with theory, errors are large.

No result *yet* at 5 TeV. Promising LHC Run 2 dataset with ~x10 statistics and further optimized photon reconstruction.

ALICE arXiv:1509.07324



More insights from theory

RHIC data compared to various model calculations with different initial temperatures

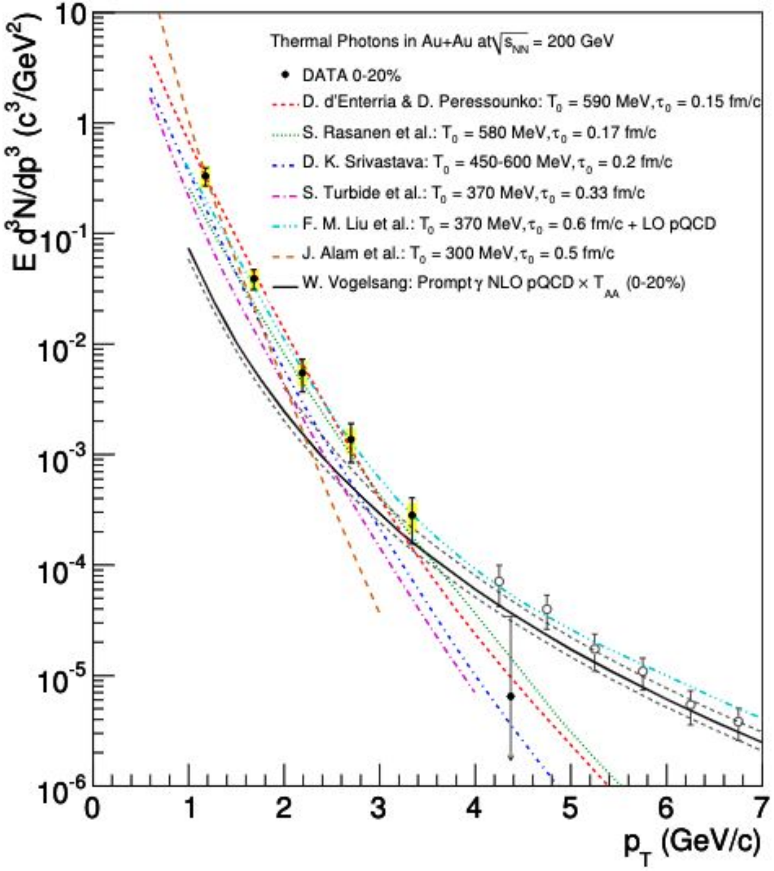
- Slight preference for models with higher initial temperatures (T_0 ~ 500 MeV)
- Predictions are steeper for lower initial temperatures

However, since we now have bayesian parameter estimation, we no longer should “turn the knob” of the temperature.

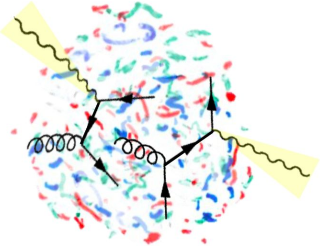
What should we do now? (in my opinion)

- Precise model study of the effective temperature as function of collision centrality; how exactly is T_{eff} related to the initial temperature
- Include photon data in the bayesian parameter estimation, study parameter posteriors

PHENIX arXiv:0912.0244



Summary



The temperature of the QGP is a central part of our calculations, but experimentally difficult to access.

- It is important to know which temperature (T) we are talking about.
  - **T(t=0,x)** → governed by the physics of the initial state, input to hydro phase
  - **T(t,x)** → local temperature of the plasma during the evolution
  - **<T>(t),<<T>>** → average temperature, at time t, or over its entire evolution
  - **T_{eff}** → the only temperature we can access experimentally
- Experiments at RHIC and LHC are dominated by a decay photon background → able to measure the direct photon excess and calculate the spectra.

Future measurements:

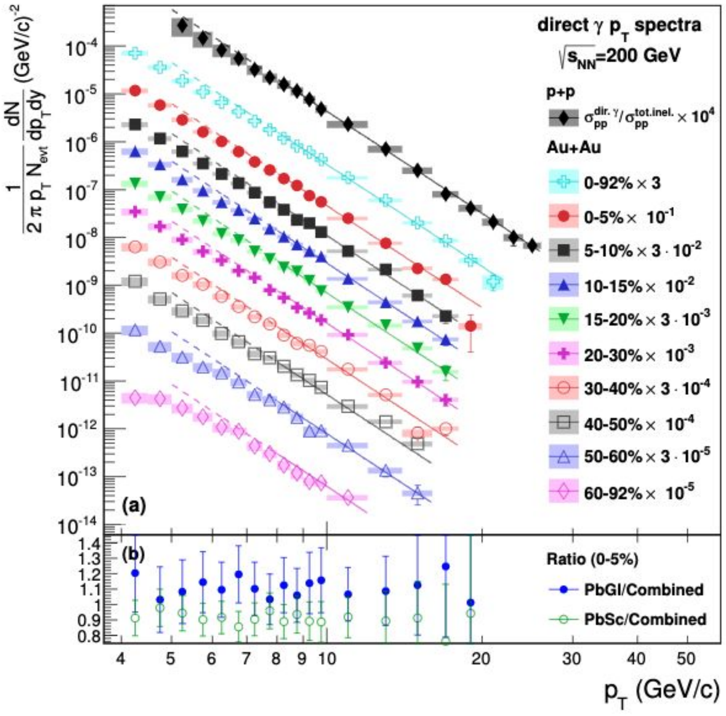
- Large datasets on disk / incoming while understanding better and better the photon reconstruction capabilities of our detectors.
- More virtual direct photons, measuring the temperature via the dilepton invariant mass continuum. Highly anticipated for LHC run 3 and beyond!

Backup

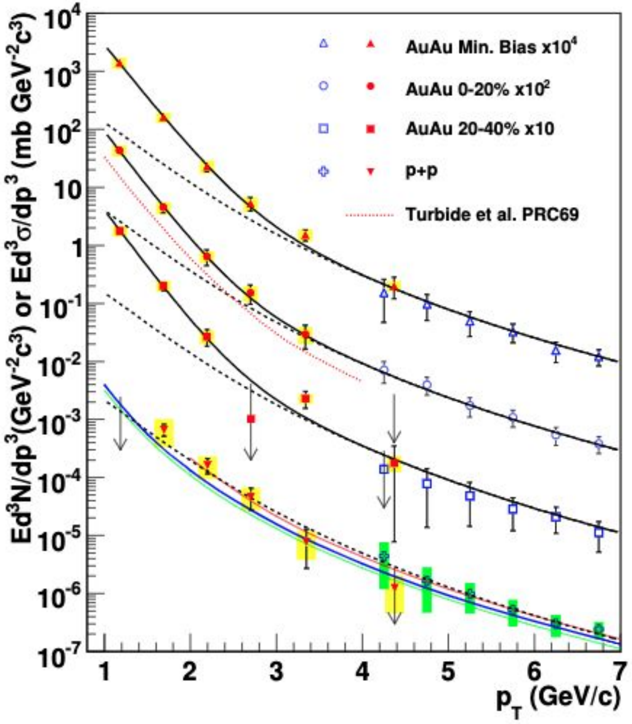
The questions

1. Do you expect that the temperature of the QGP is either:
    - a) approximately the same as function of collision centrality,
    - b) changes dramatically, where more peripheral is colder
2. When are most thermal photons emitted
    - a) early on when the system is the hottest
    - b) later when the system is larger and cooler
3. The fraction of inclusive photons over decay photons is
    - a) larger at the LHC, as the temperatures are larger
    - b) larger at RHIC, as the pion spectra is steeper

Selection of results at RHIC



$$Ae^{-p_T/T} + T_{AA}A_{pp}(1 + p_T^2/b)^{-n}$$



PHENIX dilepton measurement

PHENIX arXiv:0804.4168

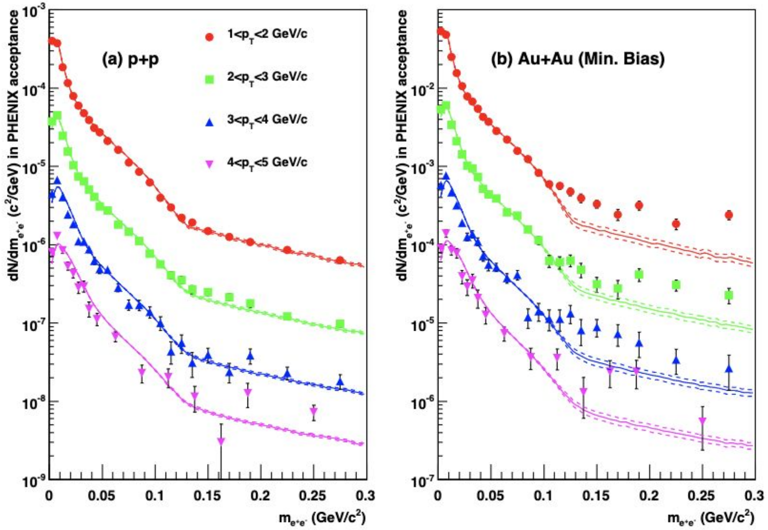


FIG. 1: (color online) The measured e^+e^- pair invariant mass distributions. The p_T ranges are shown in the legend. The solid curves represent an estimate of hadronic sources; the dashed curves represent the uncertainty in the estimate.

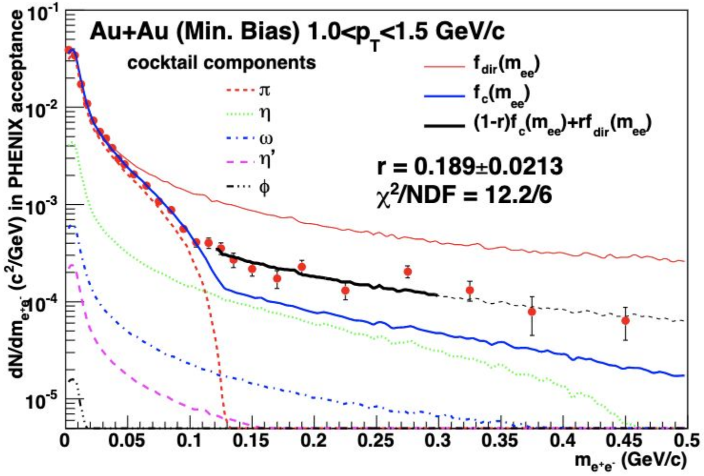
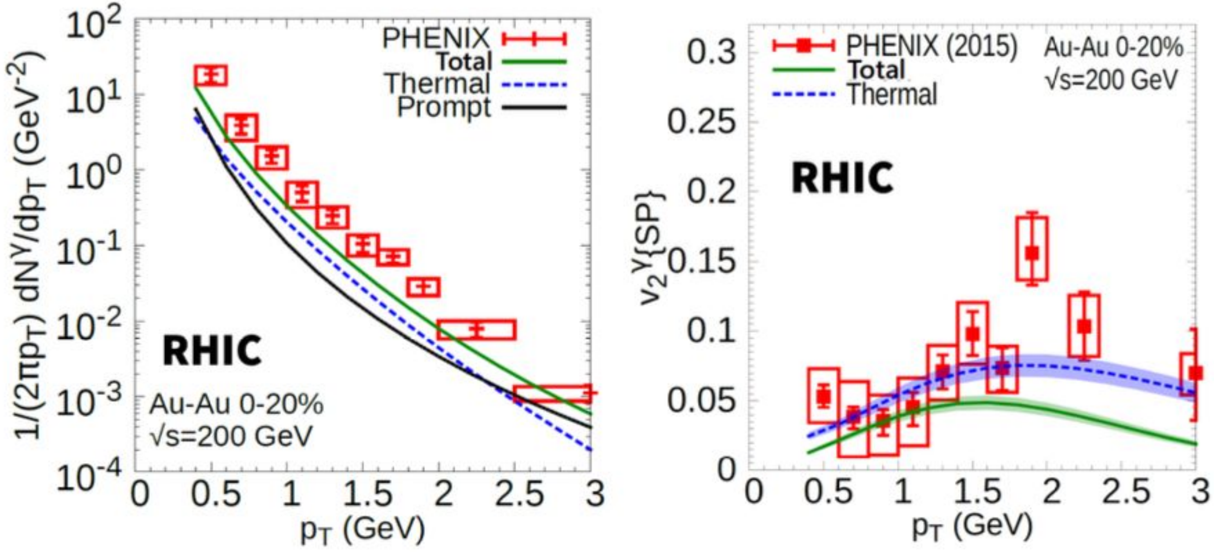


FIG. 2: (color online) Electron pair mass distribution for Au + Au (Min. Bias) events for $1.0 < p_T < 1.5$ GeV/c. The two-component fit is explained in the text. The fit range is $0.12 < m_{ee} < 0.3$ GeV/c^2. The dashed (black) curve at greater m_{ee} shows $f(m_{ee})$ outside of the fit range.

Direct photon puzzle

Inability to describe both the yield and flow of direct photons.



Higher temperature, yield ⇧, flow ⇩ ↔ Lower temperature, yield ⇩, flow ⇧