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Using dileptons to estimate the initial temperature of QCD matter^{1,2}

Greg Jackson

Subatech, CNRS/Nantes U./IMT-Atlantique

– AG du GDR QCD • Tours • May 2024 –

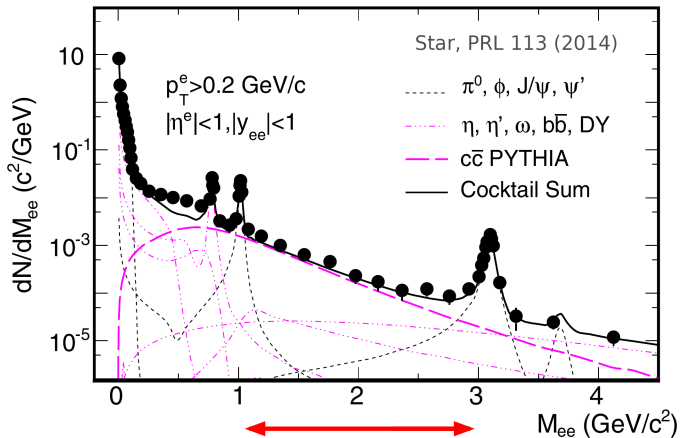
¹ based on collaboration w/ J. Churchill, L. Du, C. Gale and S. Jeon

² supported by the ANR under grant No. 22-CE31-0018

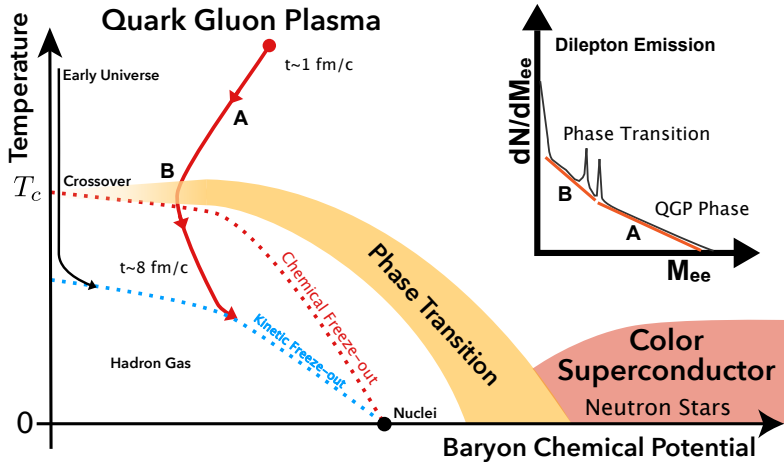
Electromagnetic probes

Invariant mass spectrum of *dileptons pairs*, e.g. from $q\bar{q} \rightarrow \gamma^* \rightarrow e^+e^-$

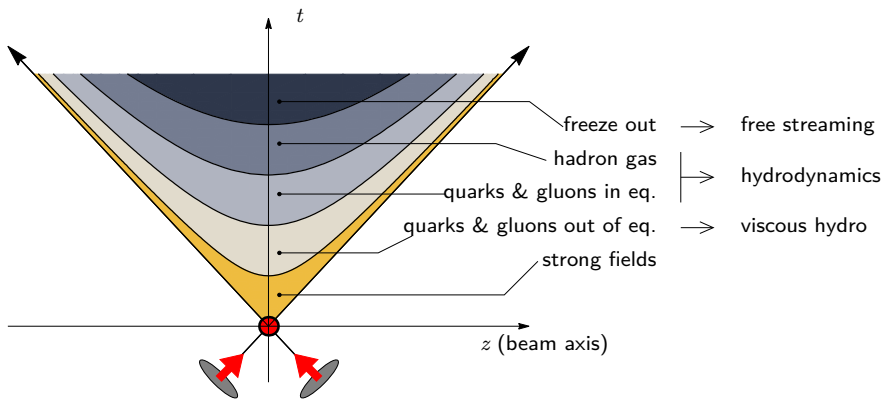
Au + Au $\sqrt{s_{NN}} = 200$ GeV (MinBias)



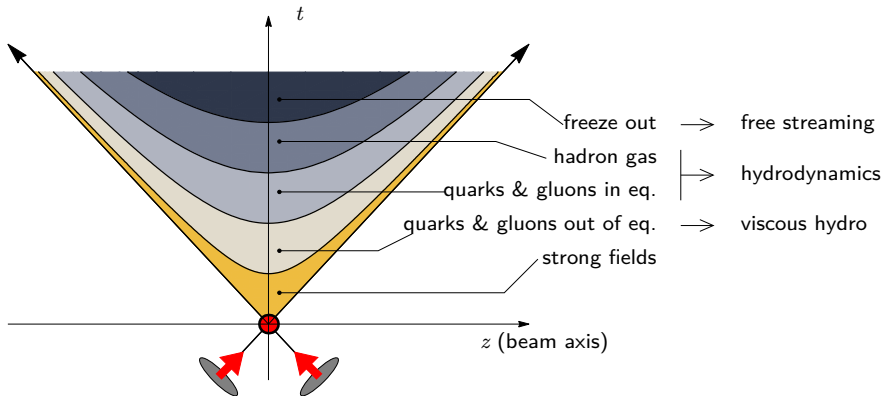
Intermediate Mass Range (IMR) = 1 ... 3 GeV



[STAR collaboration (2024)]



- $\tau \sim 0.2 \text{ fm}/c$ production of light quarks & gluons
- $1 - 2 \text{ fm}/c$ thermalisation rapid (?)
- $2 - 10 \text{ fm}/c$ **quark-gluon plasma**
- $10 - 20 \text{ fm}/c$ hadron gas
- $\tau \rightarrow \infty$ dilute, no further interactions



$\tau \sim 0.2 \text{ fm}/c$

$1 - 2 \text{ fm}/c$

$2 - 10 \text{ fm}/c$

$10 - 20 \text{ fm}/c$

$\tau \rightarrow \infty$

production of light quarks & gluons

thermalisation rapid (?)

quark-gluon plasma

hadron gas

dilute, no further interactions

} beginning

- middle

} end

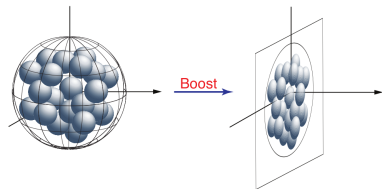
Beginning: (initial conditions)

Pedestrian approach:

sample nucleons with,
Monte Carlo (Glauber)

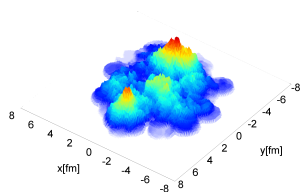
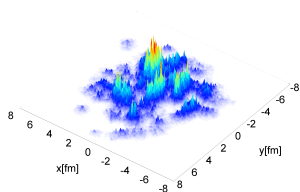
public code: T_RENTO

[Moreland, Bernhard, Bass (2014)]



For the connoisseur: IP-Glasma / KLN / EKRT / ...

(classical YM action in 2D, sat. scale Q_s ... valid at high- E)



[Eskola, Kajantie, Ruuskanen, Tuominen (1999)]

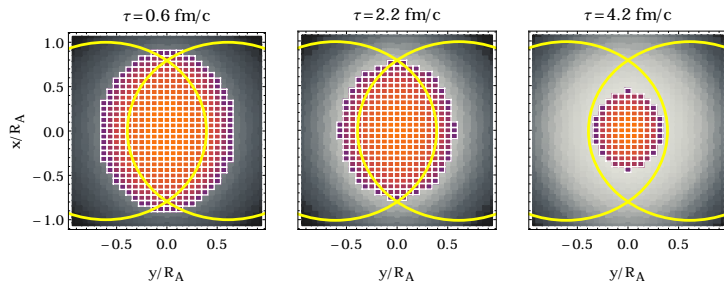
[Schenke, Tribedy, Venugopalan (2012)]

Middle: (hydrodynamical simulation)

from IC: get energy density $e(x, y, \dots)$ at τ_0

[Kurkela, et al. (2019)]

... then discretize & evolve in spacetime:



VISH2+1 = **VI**scous **H**ydrodynamics in (2+1) dim. [Song, Heinz (2008)]
(using SHASTA = SHarp And Smooth Transport Algorithm)

MUSIC = **MUS**(cl) for **I**on **C**ollisions [Schenke, Jeon, Gale (2010)]
(MUSCL = Monotonic Upstream-centered Schemes for Conservation Laws)

End: (“particlization”)

convert $T^{\mu\nu}(X)$ and $J^\mu(X)$ into **hadrons**
(in a way that conserves E and \mathbf{p})

[Huovinen, Petersen (2012)]

[Cooper, Frye (1974)]

$$\text{freeze-out: } E \frac{dN}{d^3\mathbf{p}} = \int_{\Sigma} d\sigma_{\mu} P^{\mu} f_{\text{B/F}} \left(\frac{P \cdot u(X)}{T(X)} \right)$$

(for MUSIC, this is done with iS3D:

<https://github.com/derekeverett/iS3D>)

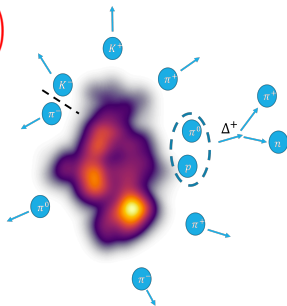
... then hadronic transport, e.g.:

UrQMD = **U**ltra-relativistic **Q**uantum **M**olecular **D**ynamics

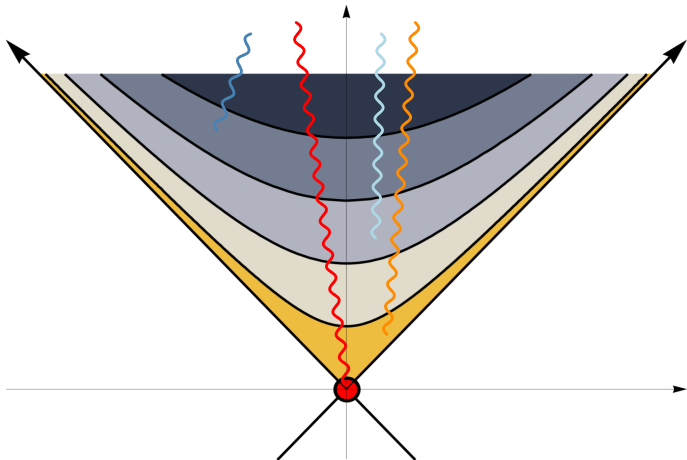
[Bleicher, et al. (1999)]

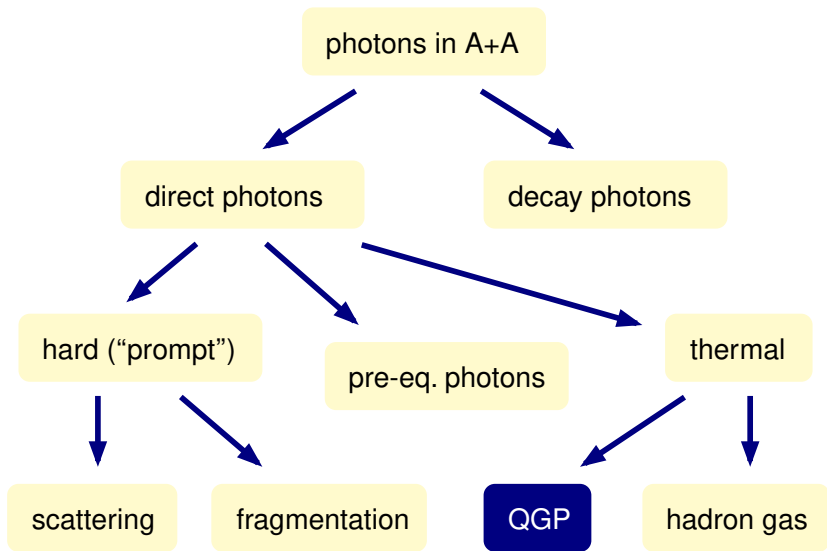
SMASH = **S**imulating **M**any **A**ccelerated **S**trongly interacting **H**adrons

[Weil, et al. (2016)]



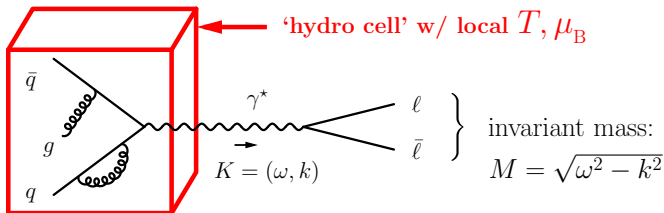
photons in A+A





Basic relations from pert. theory

[McLerran, Toimela (1995)]
[Gale, Kapusta (1991)]



Emission rate per unit volume, $\Gamma_{\ell\bar{\ell}}$, of an **equilibrated** QGP

$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} = \frac{\alpha_{\text{em}}^2 \sum_{f=1}^{n_f} Q_f^2}{3\pi^3 M^2 (e^{\omega/T} - 1)} \times B\left(\frac{m_\ell^2}{M^2}\right) \times \rho_V(\omega, \mathbf{k})$$

- Quark charge-fractions: Q_f (in units of the electron charge)
- Kinematic factor: $B(x) \equiv (1 + 2x)\Theta(1 - 4x)\sqrt{1 - 4x}$
- Spectral function $\rho_V \equiv \rho_\mu^\mu$

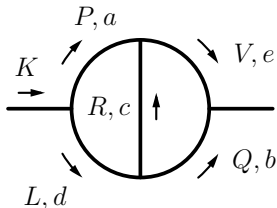
$$\rho_{\mu\nu}(\omega, \mathbf{k}) = \text{Im} \left[\Pi_{\mu\nu}^{\text{ret}}(\omega + i0^+, \mathbf{k}) \right]$$

QCD corrections

$$\Pi^{\mu\nu} = \left[\sum_{l=0}^{\infty} g_s^{2l} \Pi_{(l)}^{\mu\nu} \right] + O(e^2); \quad \alpha_s = \frac{g_s^2}{4\pi}$$

$$= \text{---} \circ \text{---} + \text{---} \left(\begin{array}{c} | \\ \text{---} \\ | \end{array} \right) \text{---} + \text{---} \left(\begin{array}{c} \text{---} \\ \text{---} \\ \text{---} \end{array} \right) \text{---} + \dots$$

Project 2-loop result onto 'basis' of **master diagrams** and evaluate:



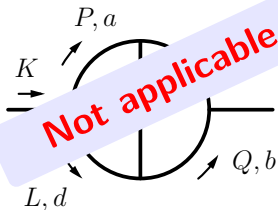
$$\rho_{abcde}^{(m,n)}(\omega, \mathbf{k}) \equiv \text{Im} \oint_{P,Q} \frac{p_0^m q_0^n}{P^{2a} Q^{2b} (K-P-Q)^{2c} (K-P)^{2d} (K-Q)^{2e}}$$

QCD corrections

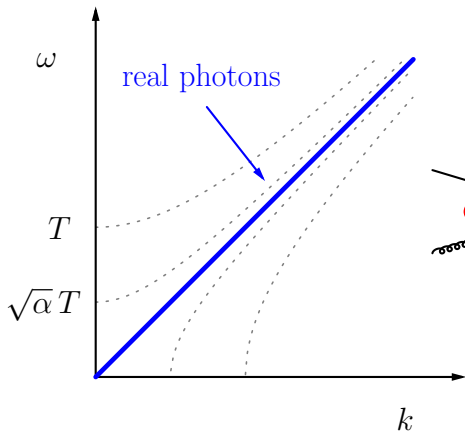
$$\Pi^{\mu\nu} = \left[\sum_{l=0}^{\infty} g_s^{2l} \Pi_{(l)}^{\mu\nu} \right] + O(e^2); \quad \alpha_s = \frac{g_s^2}{4\pi}$$

$$= \text{tree} + \text{1-loop} + \text{2-loop} + \dots$$

Project 2-loop result onto 'basis' of **master diagrams** to evaluate:



$$\rho_{abcde}^{(m,n)}(\omega, \mathbf{k}) \equiv \text{Im} \oint_{P,Q} \frac{p_0^m q_0^n}{P^{2a} Q^{2b} (K-P-Q)^{2c} (K-P)^{2d} (K-Q)^{2e}}$$



Thermal Screening

$$\frac{d\sigma}{dt} = \frac{-\pi \alpha_{em} \alpha_s}{3s^2} \frac{t^2 + s^2}{ts}$$



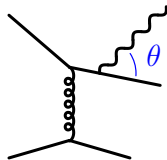
$$+ \dots \sim \alpha_s T^2$$

[Kapusta, Lichard, Seibert (1991)]

[Baier, et al (1992)]

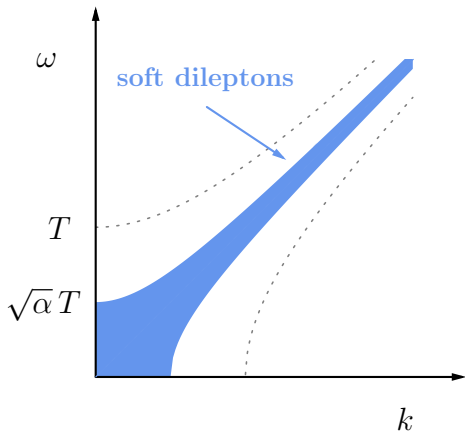
Landau-Pomeranchuk-Migdal (LPM)

$$\int \frac{d \cos \theta}{E(1 - \cos \theta)} = \infty$$



LO: [Arnold, Moore, Yaffe (2001)] ,

NLO: [Ghiglieri, et al (2013)]



LO: [Aurenche, et al (2002)]

NLO: [Ghiglieri, Moore (2014)]

light-like correlator

↓ [Caron-Huot (2009)]

Effective
Field Theory

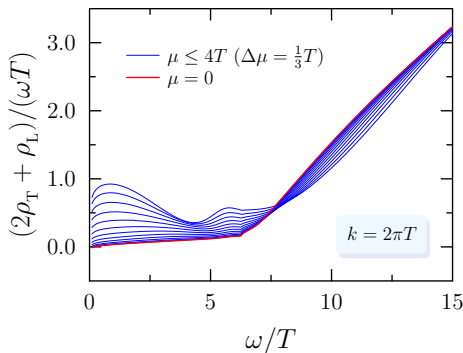
'ladder diagrams' for $M^2 \ll T^2 \rightarrow$ LPM effect + *Hard Thermal Loops*

$$\rho_{\mu\nu}(\omega, \mathbf{k}) = \text{Im} \left[\mu \text{---} \left(\text{---} \text{---} \text{---} \text{---} \text{---} \text{---} \text{---} \text{---} \text{---} \right) \text{---} \nu \right]$$

Combine LPM effect with strict 2-loop truncation,

[Ghisoiu, Laine (2014)]

$$\begin{aligned} \rho(\omega, k) \Big|_{\text{resummed}}^{\text{NLO}} &= \rho \Big|^{1\text{-loop}} + \rho \Big|^{2\text{-loop}} + \rho \Big|_{\text{beyond } O(g^2)}^{\text{LPM}} \\ &= \text{diagram 1} + \left(\text{diagram 2} + \text{diagram 3} \right) + \text{diagram 4} \end{aligned}$$



NB: Spectral fncs. can be checked with Euclidean corr. computable on the lattice:

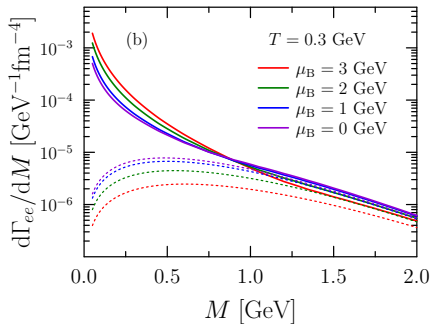
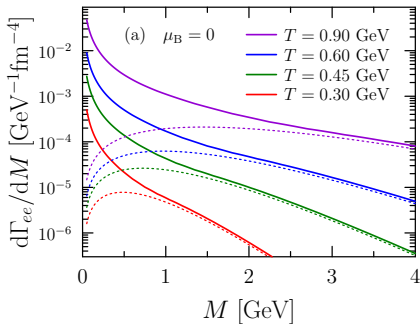
$$G(\tau) = \int_0^\infty d\omega \rho(\omega) \mathcal{K}(\omega, \tau)$$

\Rightarrow see [GJ, Laine (2019)]
and [Ali, et al. (2024)]

$\left(\rho_V \text{ determined for } \omega > k \text{ in [Laine (2013)] , and } \omega < k \text{ in [GJ (2019)]} \right)$

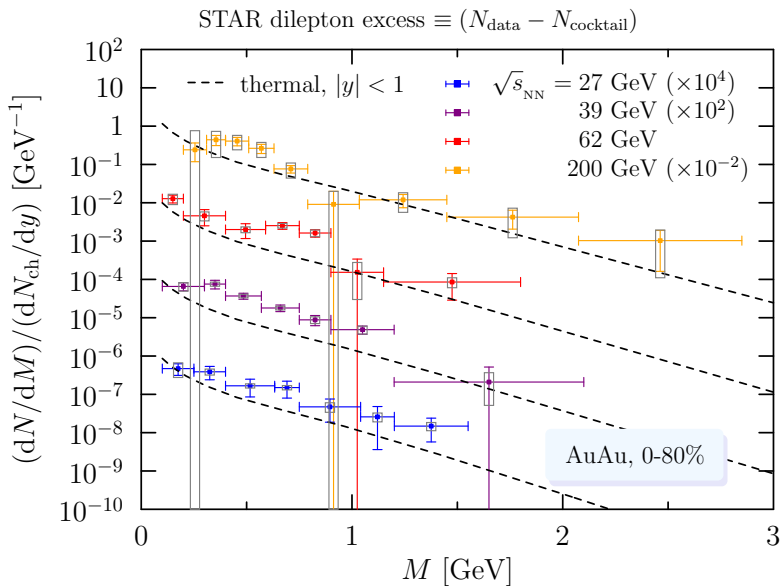
rate from a **static source**:

$$\frac{d\Gamma_{\ell\bar{\ell}}}{dM} = \int_{\mathbf{k}} \frac{M}{\sqrt{M^2 + k^2}} \frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}}$$



- dileptons are a good thermometer!
- ... but a poor “baryometer”

* in these, and subsequent, plots: $\alpha_s = 0.3$



*see also: [\[Burnier, Gastaldi \(2015\)\]](#) (LHC energies)

for large $M \gg T$ and μ_B :

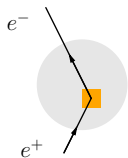
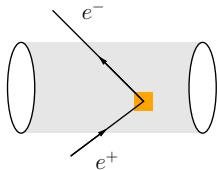
$$\frac{d\Gamma_{e\bar{e}}}{dM} \propto (MT_{\text{eff}})^{3/2} \exp(-M/T_{\text{eff}})$$

\Rightarrow determine T_{eff} from the 'inverse slope' of the spectrum

What physics does this *effective* temperature represent?

in simulations we can access the full history, so the method can be tested!

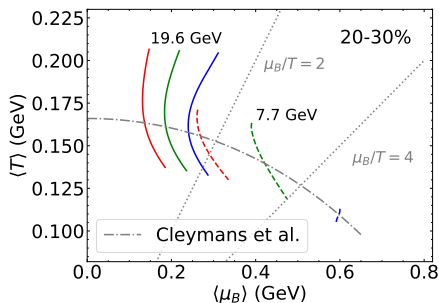
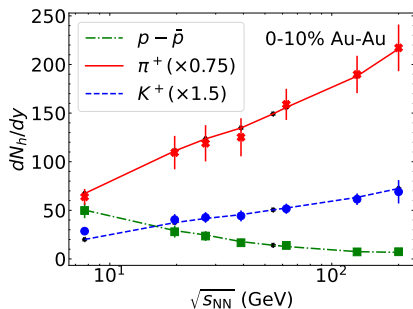
$$\frac{dN_{e\bar{e}}}{d^4K'} = \int dt \int d^3\mathbf{x} \left. \frac{d\Gamma_{e\bar{e}}}{d\omega d^3\mathbf{k}} \right|_{K^\mu = \Lambda^{\mu\nu} K'_\nu}$$



note: $\rho_V(\omega, k)$ evaluated at $\omega = K'_\mu u^\mu$, $k = \sqrt{(K'_\mu u^\mu)^2 - M^2}$

Calibrating the thermometer

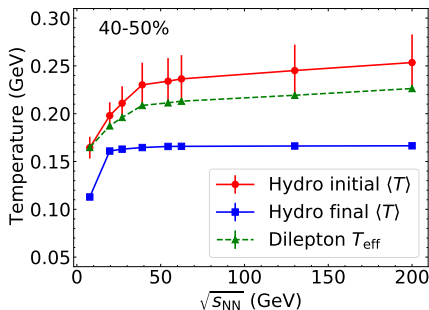
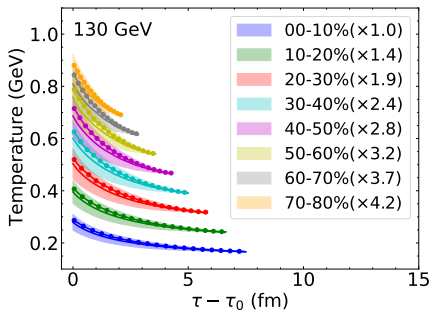
- MC-Glauber initial conditions (at finite μ_B)
- Hydro with MUSIC (including viscous corrections)
- Equation of state: NEOS-B (neglects strangeness and μ_e)
- Hydro stops at $e_{fo} = 0.26 \text{ GeV}/\text{fm}^3$
- Freeze-out (iS3D) and hadronic scatterings w/ UrQMD



code public: <https://github.com/LipeiDu/DileptonEmission>

Calibrating the thermometer

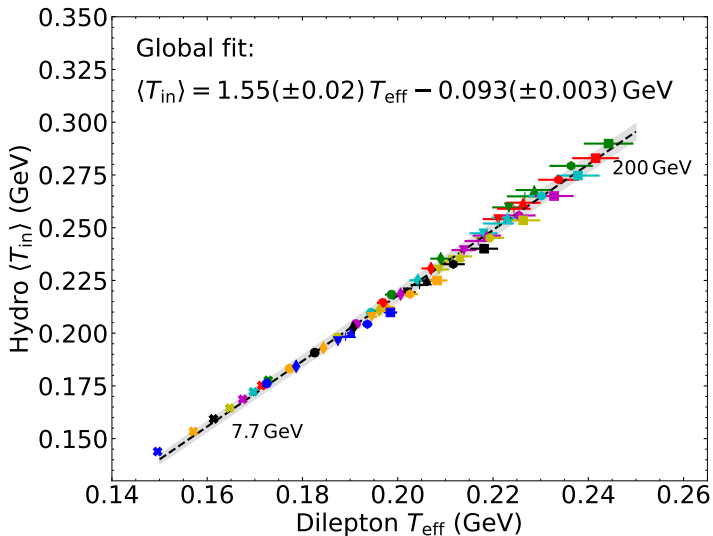
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code public: <https://github.com/LipeiDu/DileptonEmission>

T_{eff} represents the *initial* temperature!

[Churchill, et al. (2024)]



... predicted over 40 years ago (!!)

[Kajantie, Miettinen (1981)]

Summary

Arxiv: 2211.09575
2311.06675
2311.06951

- thermal dilepton yields at NLO+LPM
⇒ predicted from first principles, at finite T and μ_B
- extracted 'effective' temperature
⇒ linear relationship between T_{eff} and T_{in}

