Theory of electromagnetic probes

Jacopo Ghiglieri

Theory of electromagnetic probes

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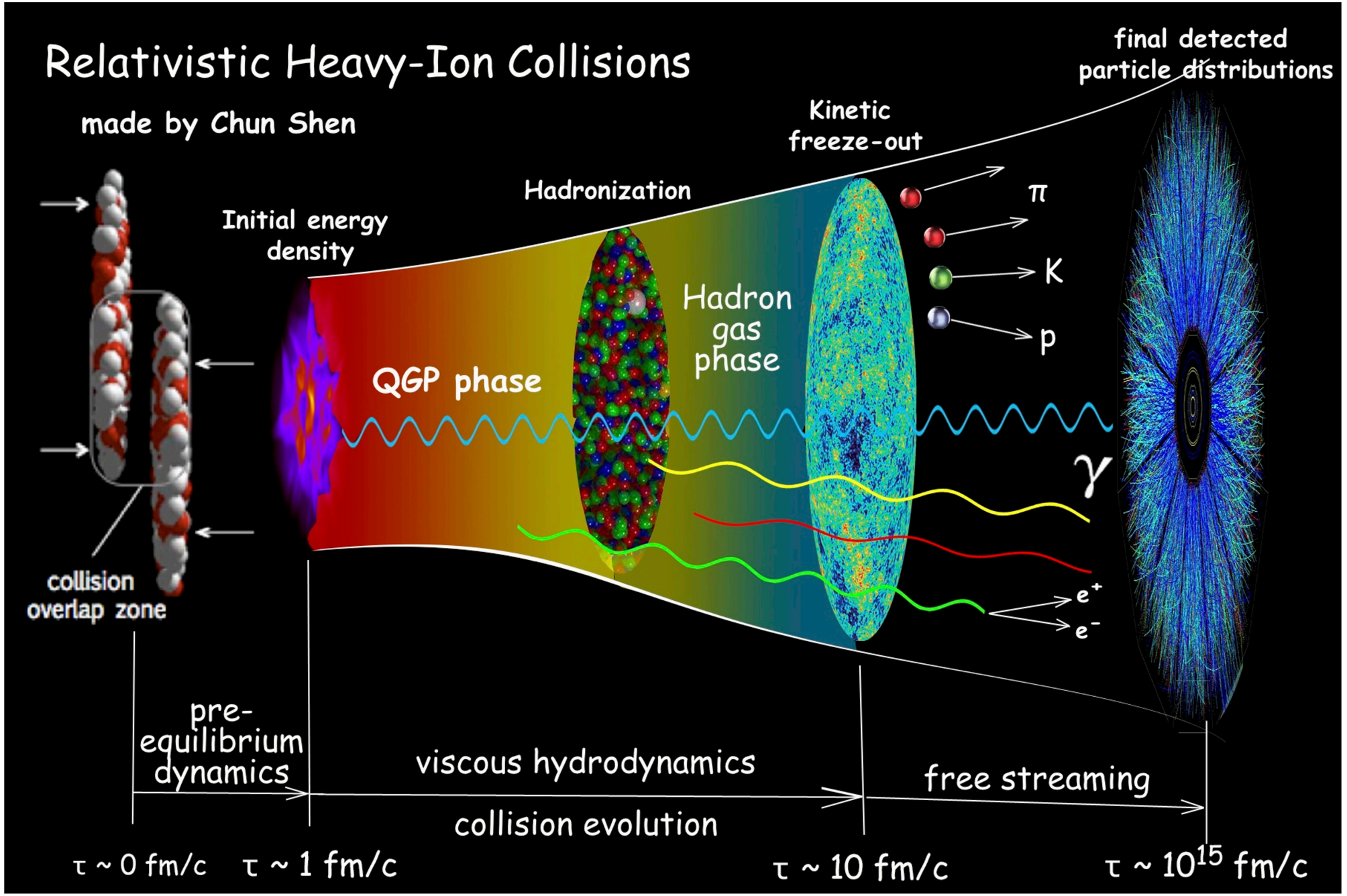
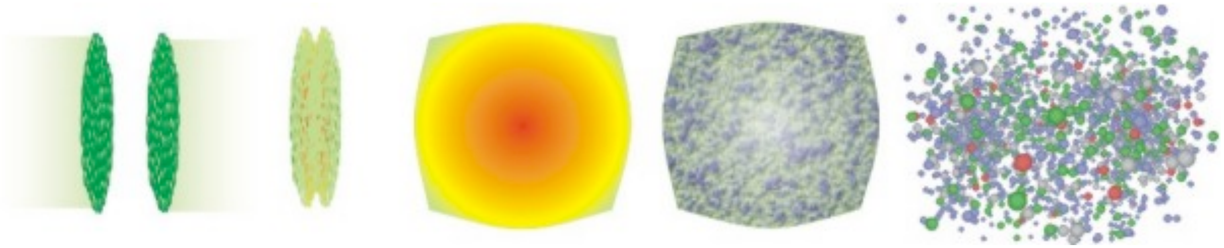
LHCb IFT Workshop, July 1st 2024


Relativistic Heavy-Ion Collisions
made by Chun Shen
final detected particle distributions
Kinetic freeze-out
Hadronization
Initial energy density
Hadron gas phase
QGP phase
π
K
p
γ
e+
e-
collision overlap zone
pre-equilibrium dynamics
viscous hydrodynamics
free streaming
collision evolution
τ ~ 0 fm/c
τ ~ 1 fm/c
τ ~ 10 fm/c
τ ~ 10^15 fm/c

How EM probes are made
(and what they tell us)

- The hard partonic processes in the heavy ion collision produce quarks, gluons and *prompt photons and dileptons*, W and Z bosons. They can tell us about nPDFs, photon-tagged hadrons and jets
- At a later stage, quarks and gluons form a plasma
  - Scatterings of (pre)thermal partons produce *QGP photons and dileptons*. thermalisation, T, hydro
  - A jet traveling can radiate *jet-thermal photons*. Jet quenching
- Later on, hadronization. *hadron gas photons and dileptons*. T, T_c, hydro
- (Some) hadrons decay into *decay photons and dileptons*

In this talk



- Theoretical description: convolution of microscopic rates over the macroscopic (hydro) evolution of the medium
- In this talk
  - overview and recent results on the microscopic rates, mostly up to the *thermal phase*
  - Photons and dileptons in and before equilibrium from pQCD

How to compute rates

- $\alpha \ll 1$ implies that photon production is a rare event and that rescatterings and back-reactions are negligible: medium is transparent to/not cooled by photons
- At leading order in QED and to all orders in QCD the photon and dilepton rates are given by

$$\frac{dN_\gamma}{d^4X d^3k} = \frac{d\Gamma_\gamma(k)}{d^3k} = -\frac{\alpha}{4\pi^2 k}\int d^4X e^{iK\cdot X}\,\mathrm{Tr}\rho J^\mu(0)\,J_\mu(X)$$

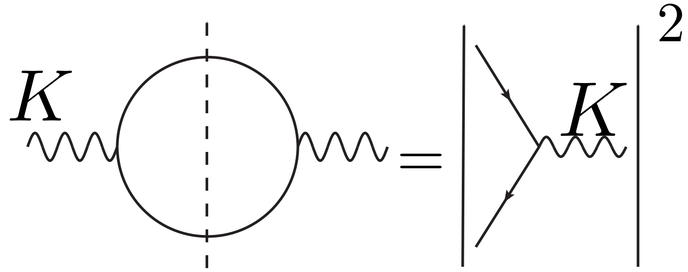
$$\frac{d\Gamma_{l^+l^-}(k)}{dk^0 d^3k} = -\frac{\alpha^2}{6\pi^3 K^2}\int d^4X e^{iK\cdot X}\,\mathrm{Tr}\rho J^\mu(0)\,J^{}_{\nu\ \mu}(X)$$

ρ density operator, J electromagnetic current

The basics of pQCD photons

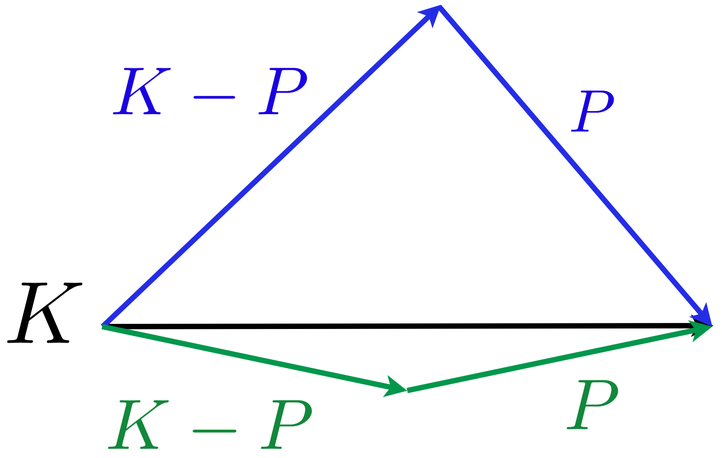
$$\frac{d\Gamma_\gamma(k)}{d^3k} = -\frac{\alpha}{4\pi^2 k}\int d^4X e^{iK\cdot X}\,\mathrm{Tr}\rho J^\mu(0)\,J_\mu(X) \qquad J^\mu = \sum_{q=uds} e_q \bar{q}\gamma^\mu q :$$

- Real, hard photon: $k^0=k\gtrsim T$
- At one loop ($\alpha_{\rm EM}\, g^0$):



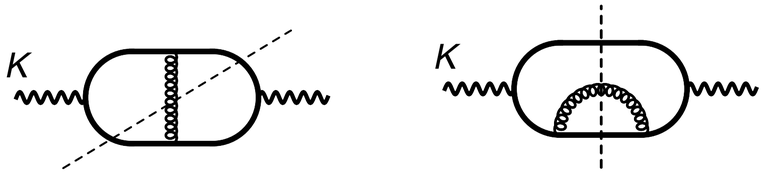
Kinematically forbidden. Need to kick one of the quarks off-shell. Works for dileptons

- Leading order photon is $\alpha_{\rm EM}\, g^2$
- Strength of the kick (virtuality) naturally divides the calculation in the distinct 2↔2 processes and collinear processes

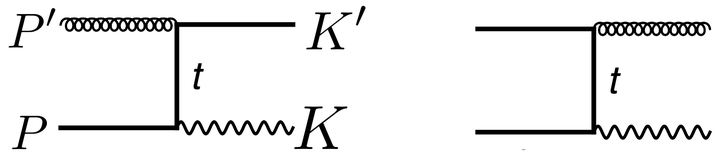


$2 \leftrightarrow 2$ processes

- Cut two-loop diagrams ($\alpha_{\rm EM}\, g^2$)



$2 \leftrightarrow 2$ processes (with crossings and interferences):

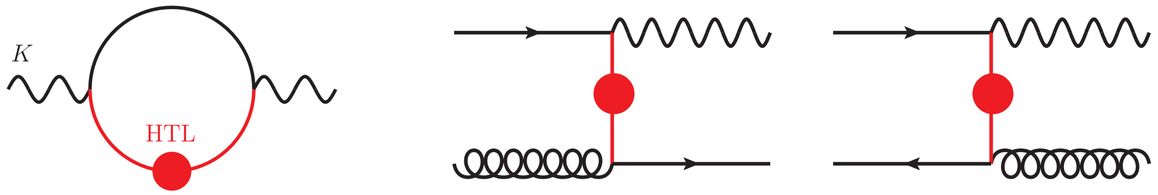


$$\int_{\text{ph. space}} f(p) f(p') (1 \pm f(k')) |\mathcal{M}|^2 \delta^4(P + P' - K - K')$$

- Equivalence with kinetic theory: distributions x matrix elements
- IR divergence (Compton) when t goes to zero

$2 \leftrightarrow 2$ processes

- The IR divergence disappears when **Hard Thermal Loop** resummation is performed Braaten Pisarski **NPB337** (1990)



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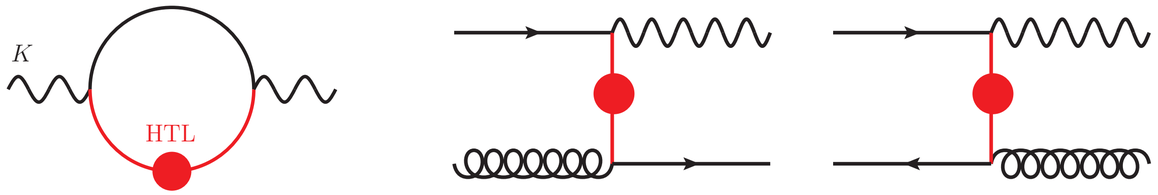
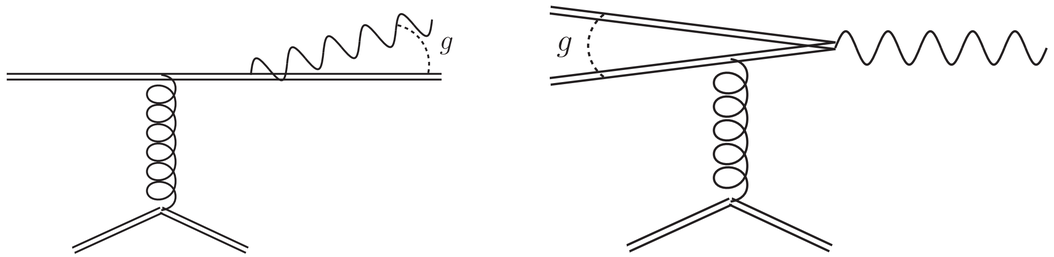


- In the end one obtains the result

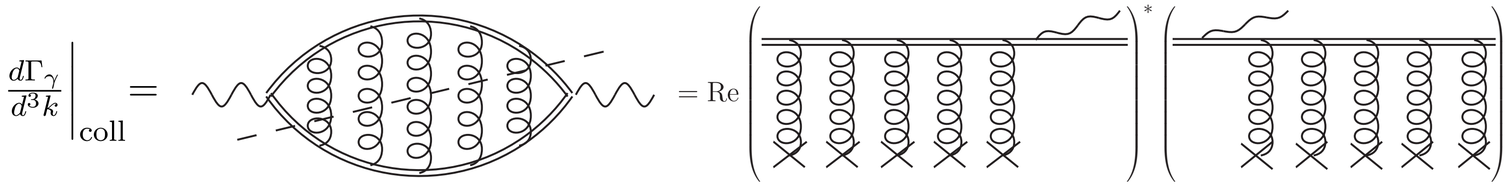
$$\left.\frac{d\Gamma_\gamma}{d^3k}\right|_{2\leftrightarrow 2} \propto e^2 g^2 \left[\log\frac{T}{m_\infty} + C_{2\leftrightarrow 2}\left(\frac{k}{T}\right)\right]$$

Kapusta Lichard Siebert **PRD44** (1991) Baier Nakkagawa Niegawa Redlich **ZPC53** (1992)

Collinear processes

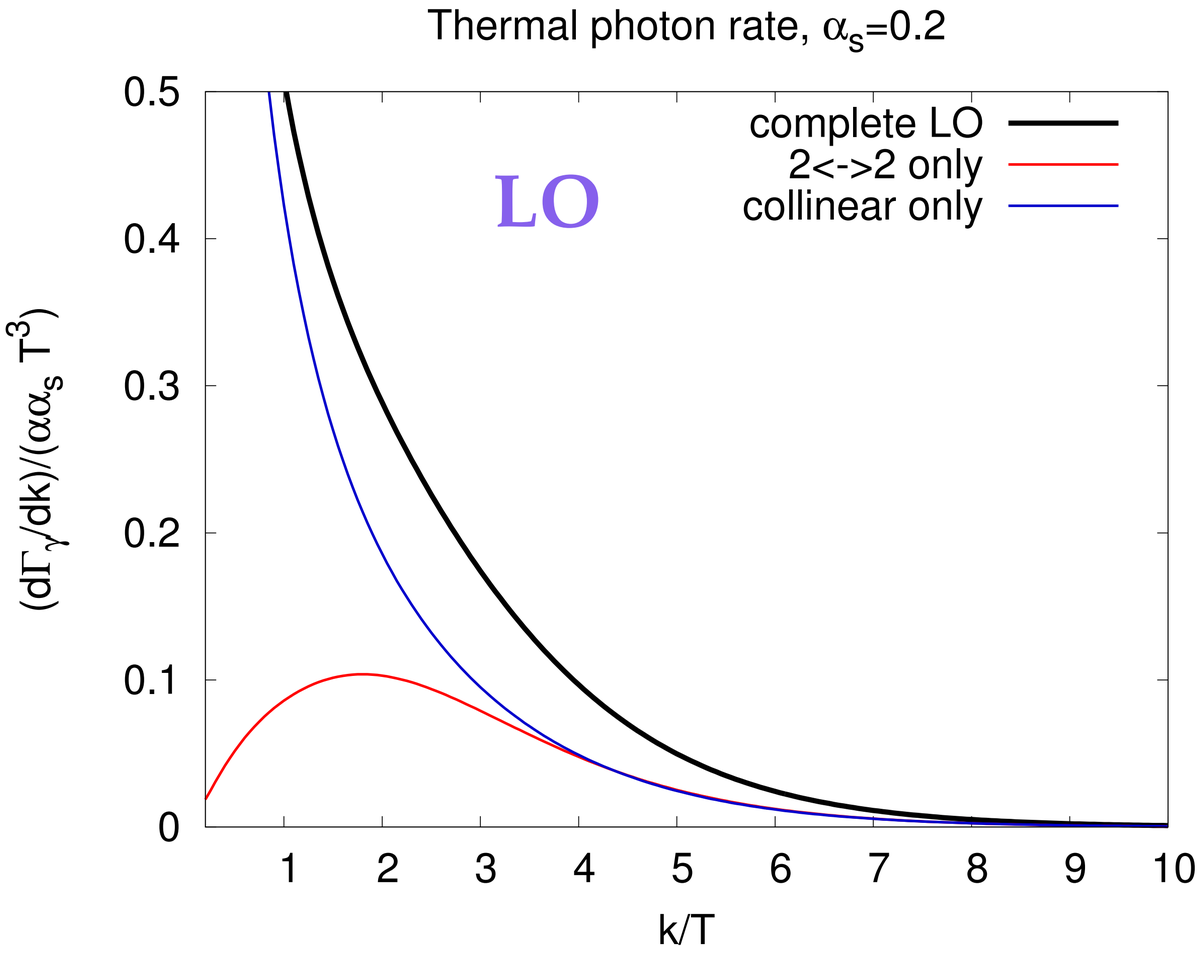


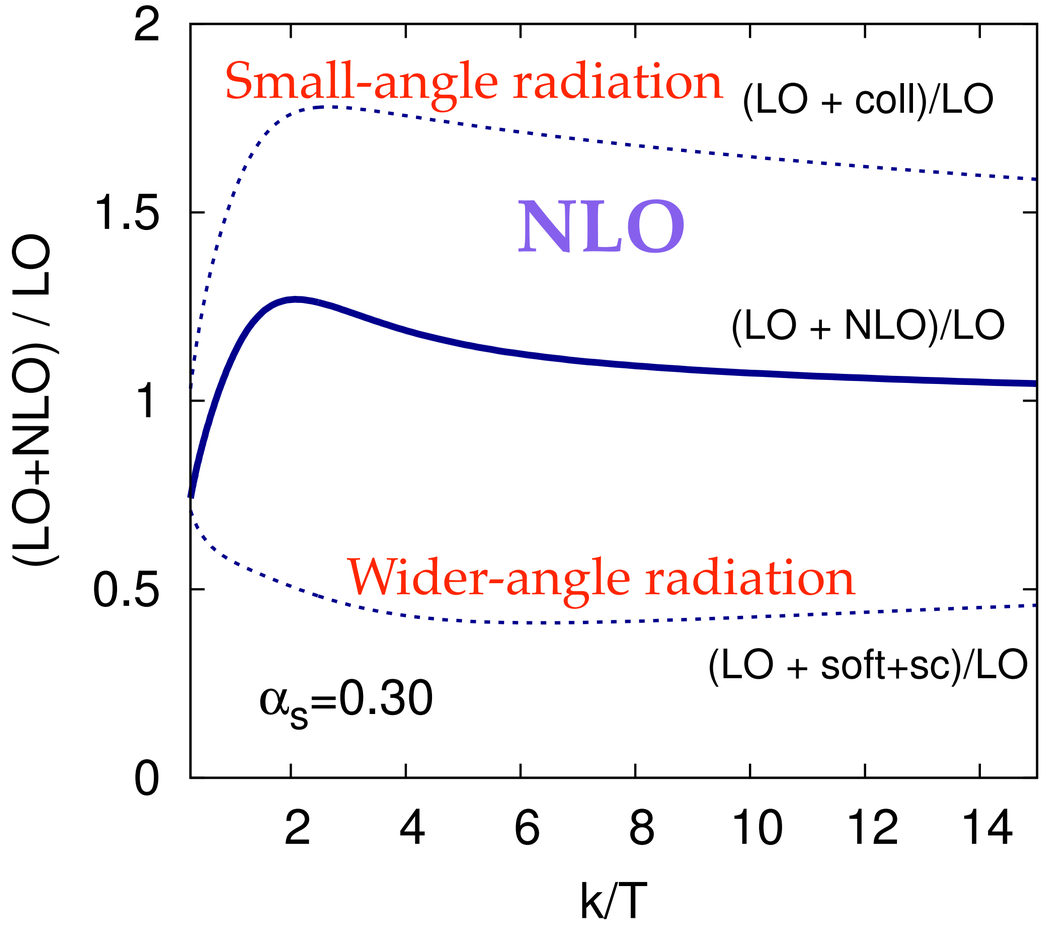
- These diagrams contribute to LO if small (g) angle radiation/annihilation Aurenche Gelis Kobes Petitgirard Zaraket 1998-2000
- Photon formation times is then of the same order of the soft scattering rate ⇒ interference: *LPM effect*
- Requires resummation of infinite number of ladder diagrams



AMY (Arnold Moore Yaffe) **JHEP** 0111, 0112, 0226 (2001-02)

QGP photons



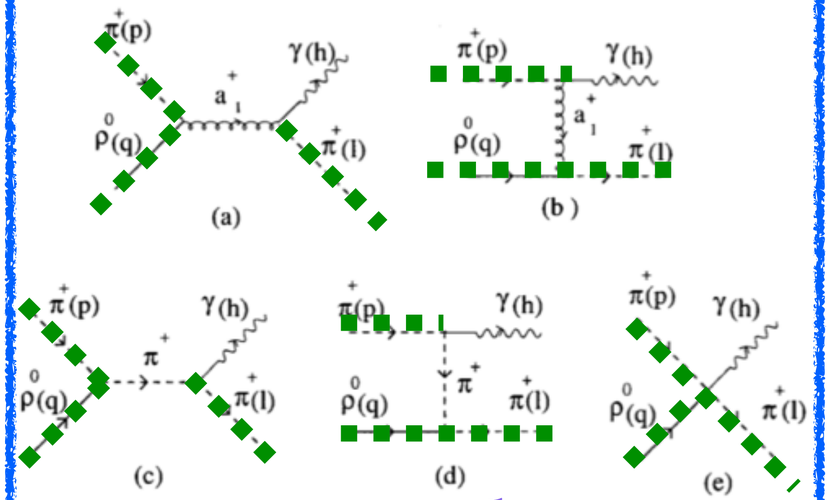


LO: AMY (2001-02) **NLO:** JG Hong Kurkela Lu Moore Teaney **JHEP0503** (2013)

Hadronic photons

Hadronic photons

Hadron Gas

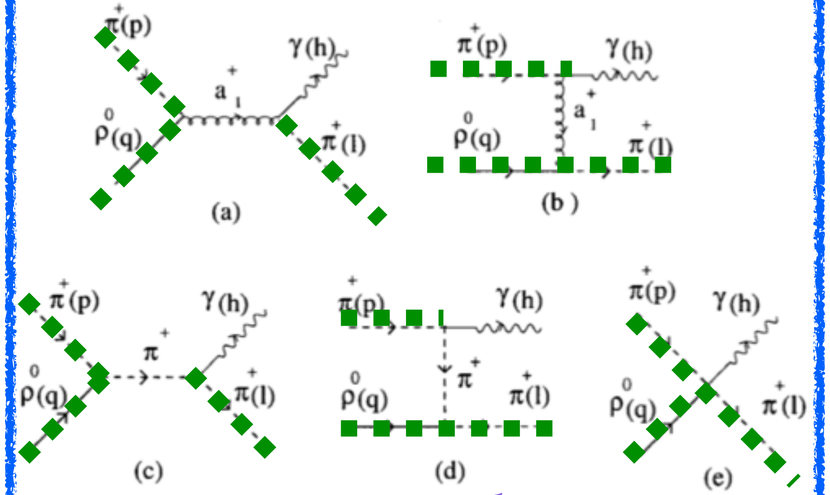


+bremsstrahlung

6(15)

Hadronic photons

Hadron Gas



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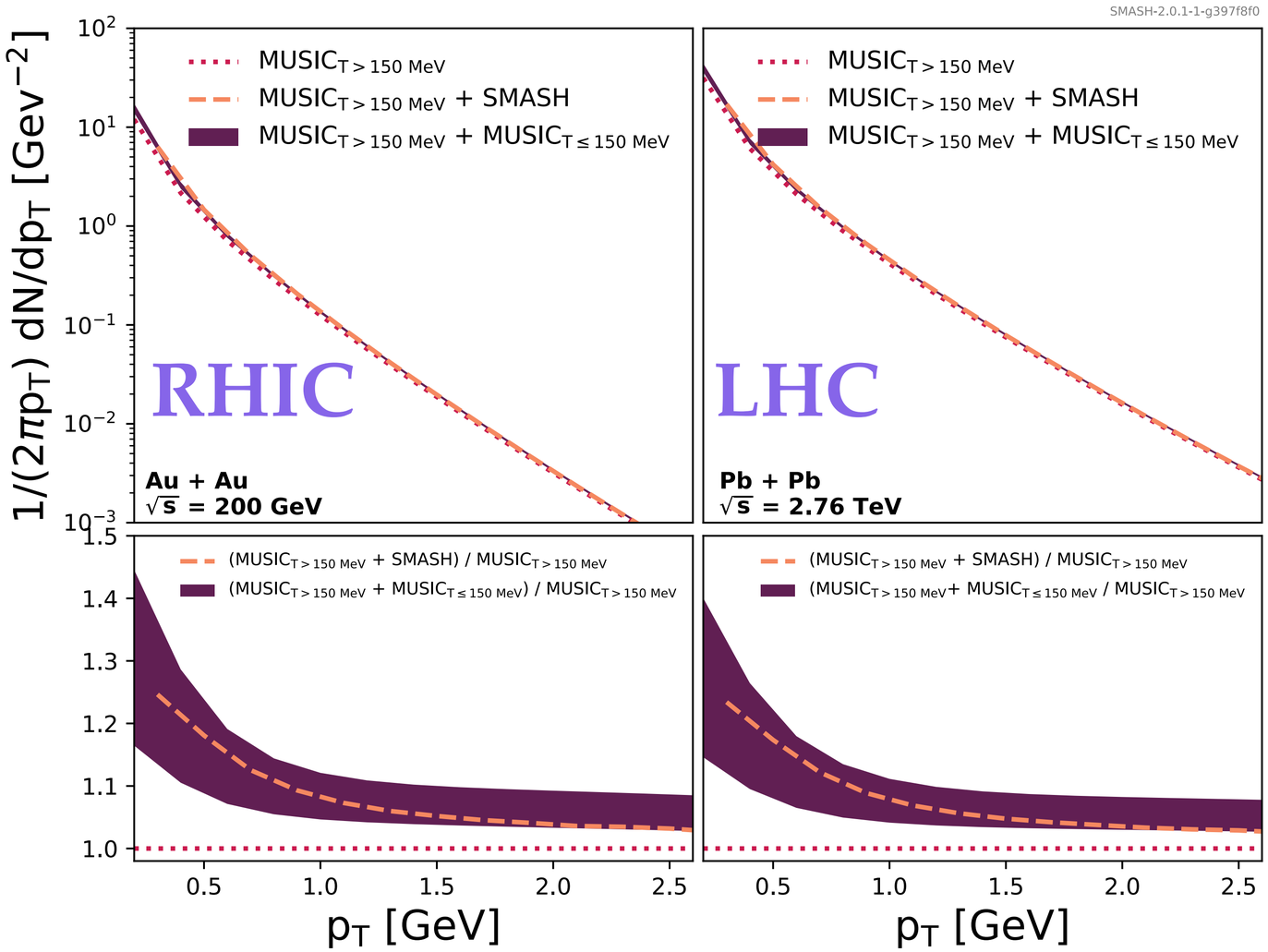
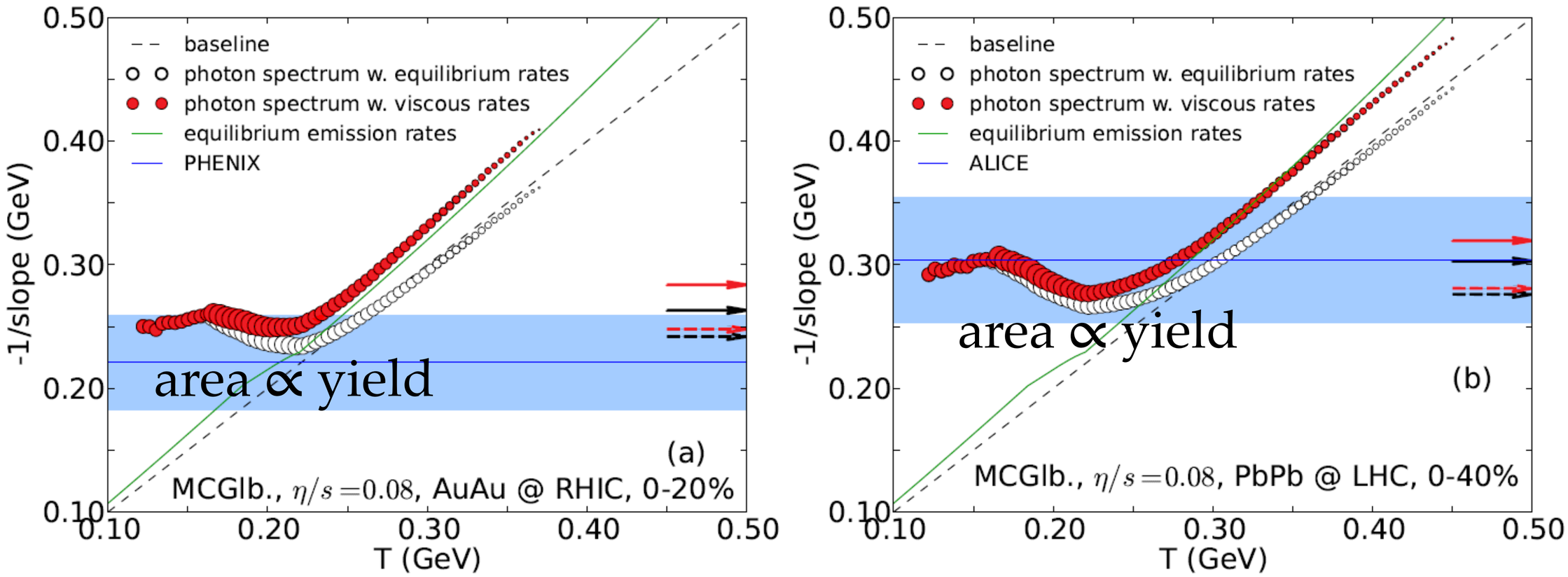
6(15)



Schäfer Garcia-Montero Paquet Elfner Gale **2111.13603**

From QGP photons to data

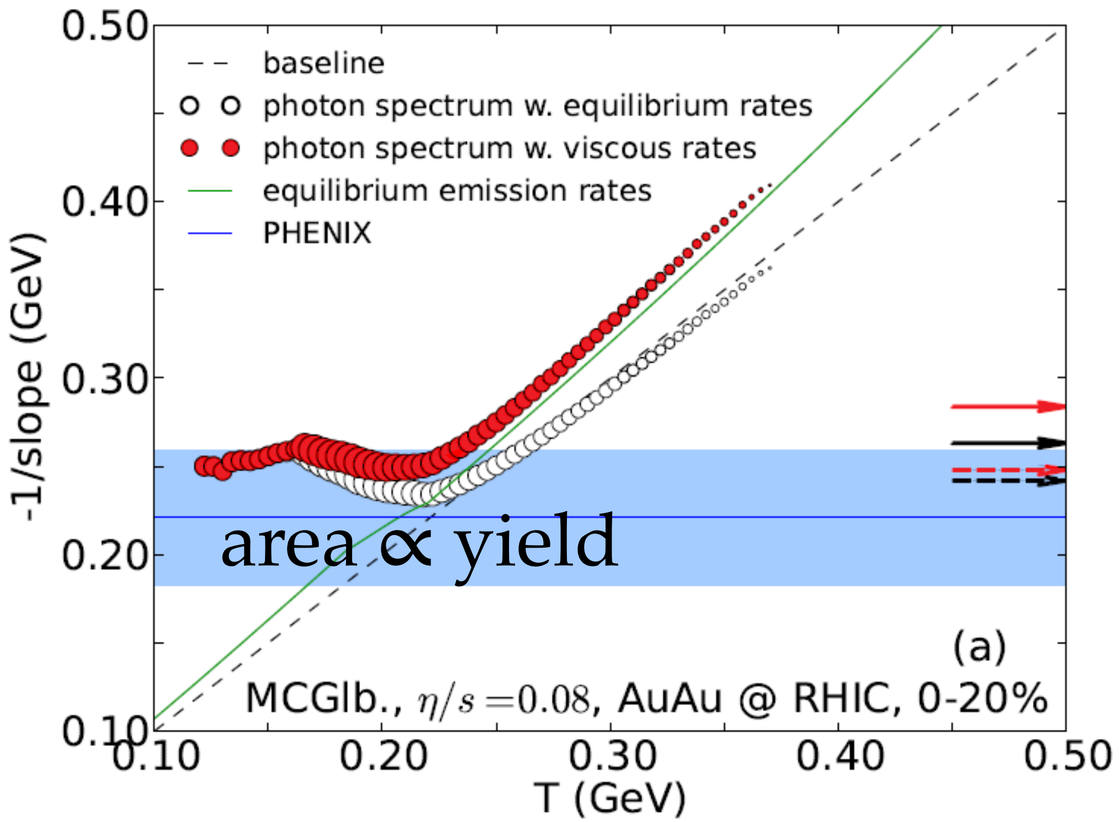
- The macroscopic expansion of the fireball gives rise to blueshift: the observed inverse slope of the direct photon spectrum at low p_T is not the real temperature

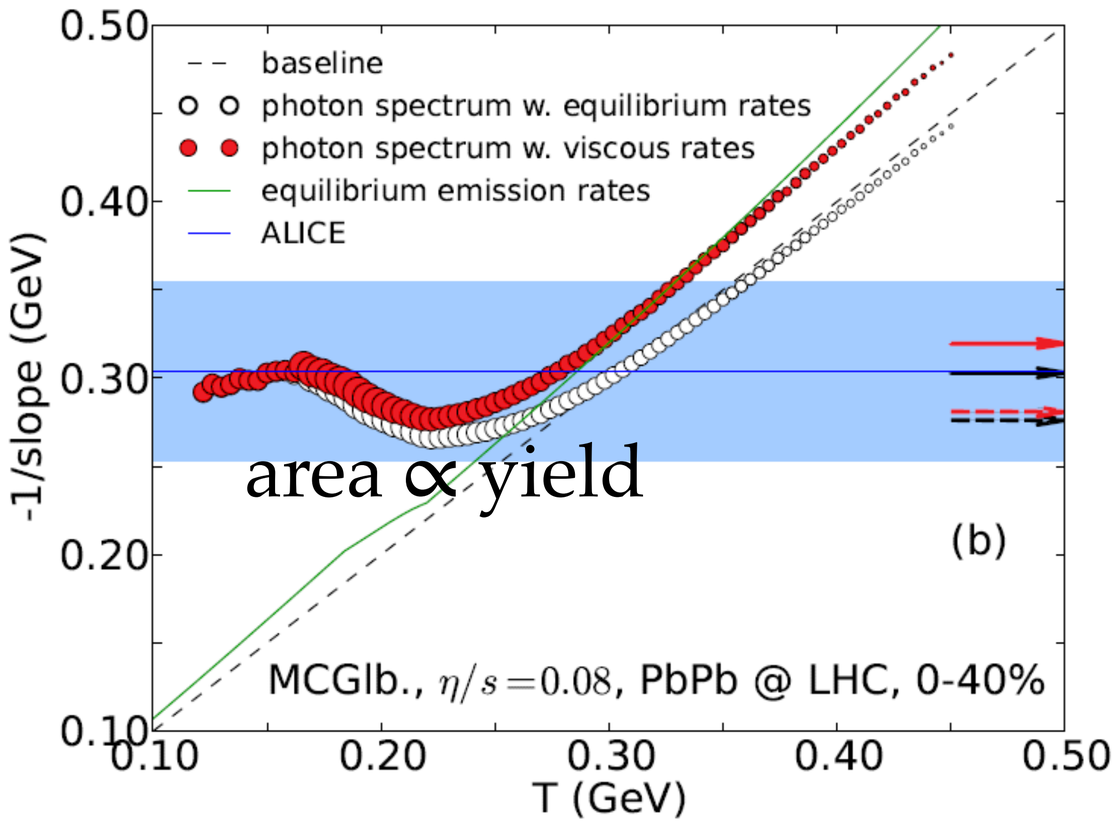


Shen Heinz Paquet Gale **1308.2440**

From QGP photons to data

- Importance of viscous corrections, i.e. perturbations around partonic equilibrium from shear flow





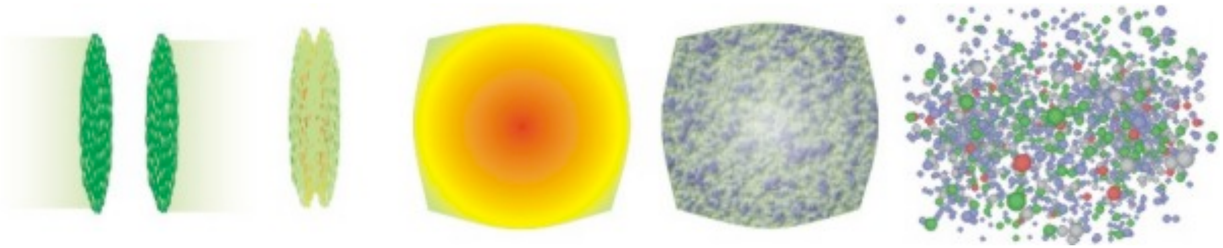
Shen Heinz Paquet Gale **1308.2440**

Bottom-up thermalisation

- Competition between expansion and interaction, attractor solution when they balance out

$$\left(\frac{\partial}{\partial t} - \frac{p_z}{\tau}\frac{\partial}{\partial p_z}\right) f(\mathbf{p}) = -C^{2\leftrightarrow 2} - C^{1\leftrightarrow 2}$$

- Expansion is driven by the specifics of the heavy-ion collision and the initial state, drives the system away from equilibrium. Interaction among the constituents tends to isotropize the system.



Baier Mueller Schiff Son (2001) Kurkela Moore (2011)

fig. Mazeliauskas

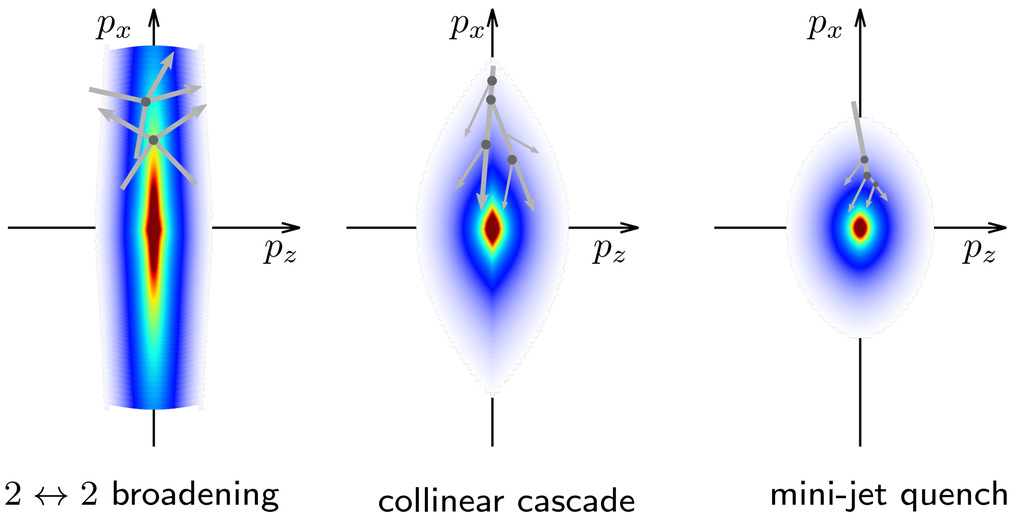
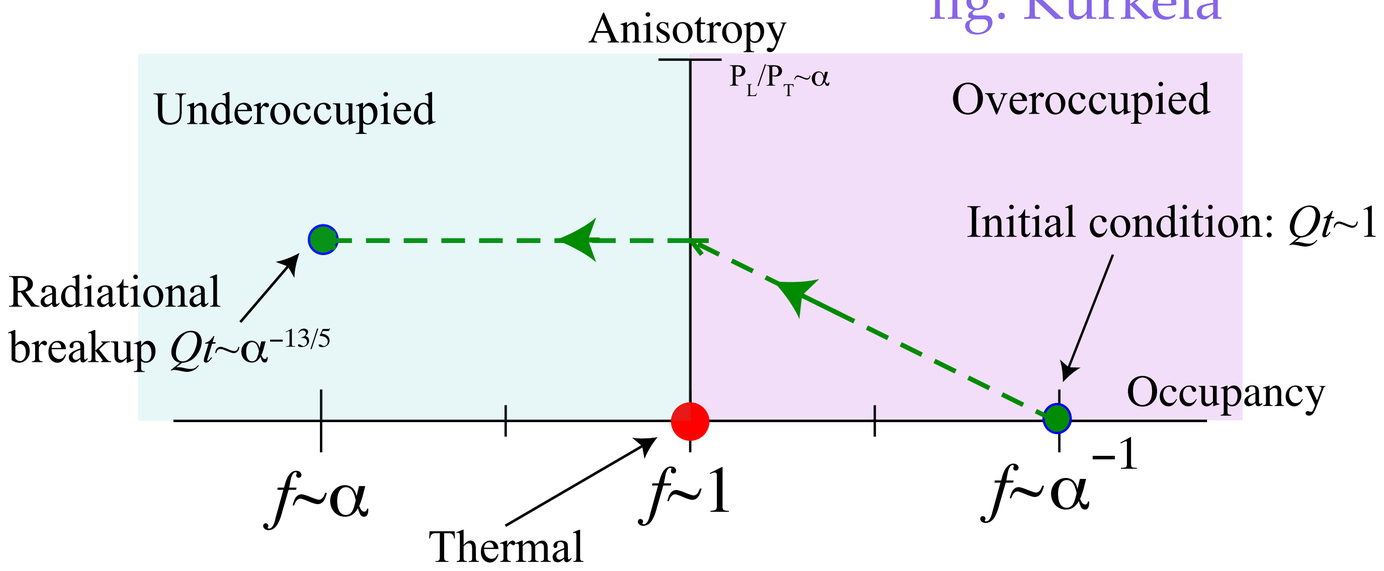


fig. Kurkela



- Initially
  - strong isotropizing effect of interactions
  - gluon-rich system
- Later, bremsstrahlung in the cascade and mini-jet quench

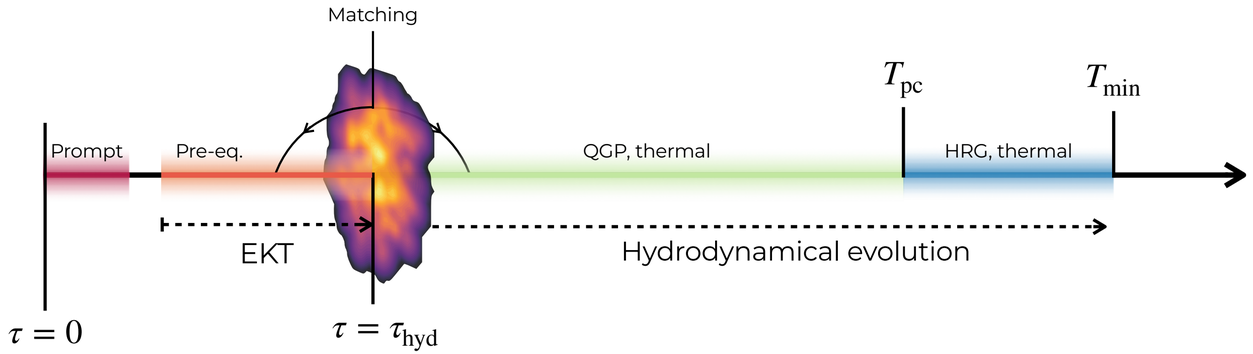
Baier Mueller Schiff Son (2001) Kurkela Moore (2011)

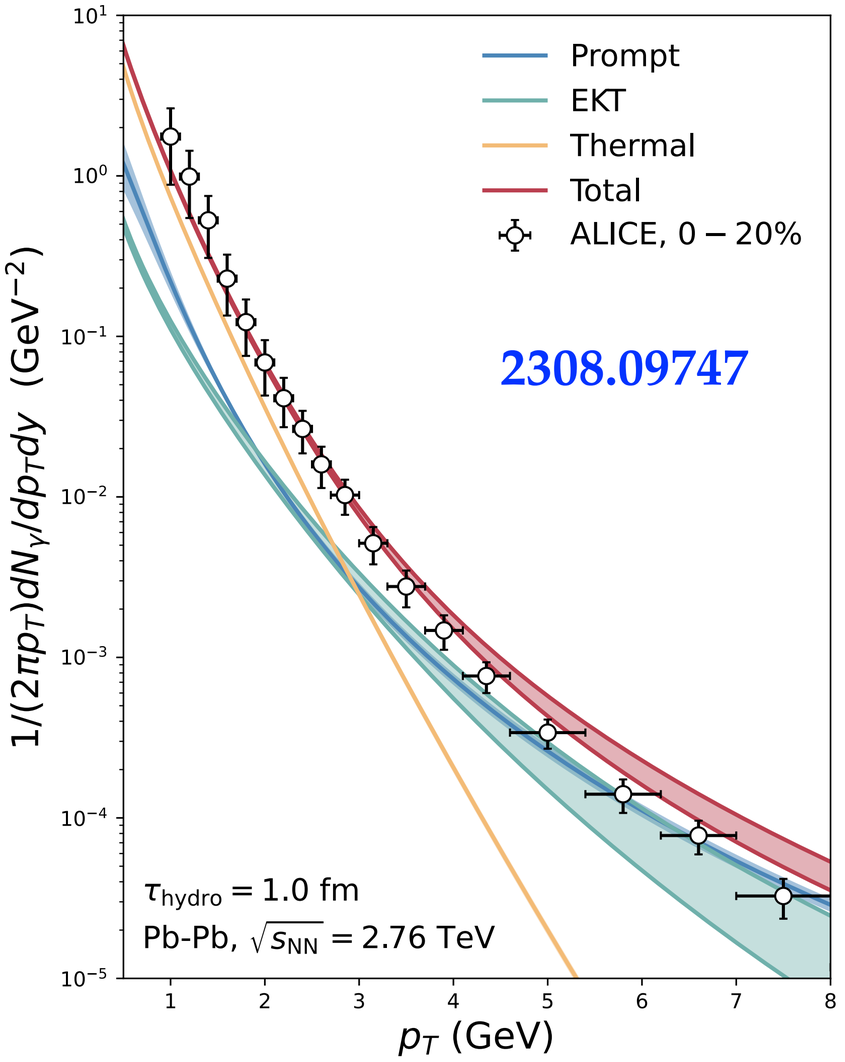
Pre-equilibrium photons

- Two competing effects:

↓ Quark number suppression and short duration of the phase

↑ Higher energy for the early quarks





Garcia-Montero Mazeliauskas Plaschke Schlichting **2308.09747**

Pre-equilibrium photons

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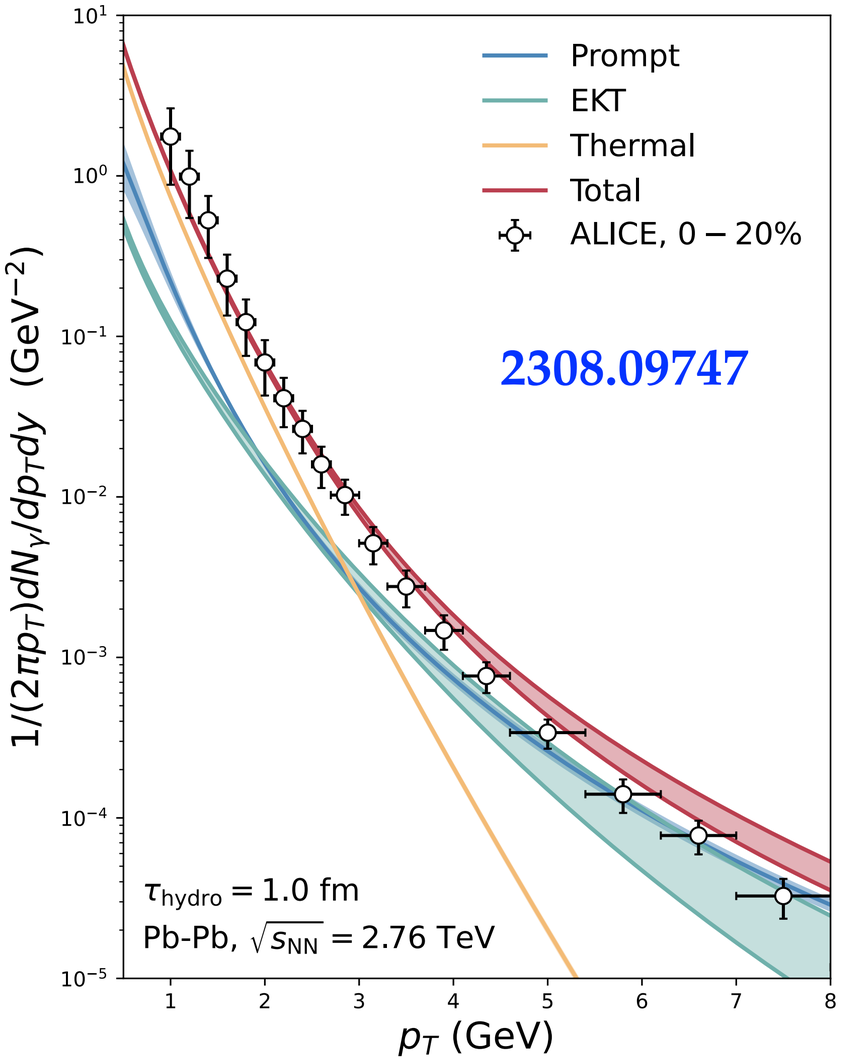
See also

Churchill Yan Jeon Gale **2008.02902**

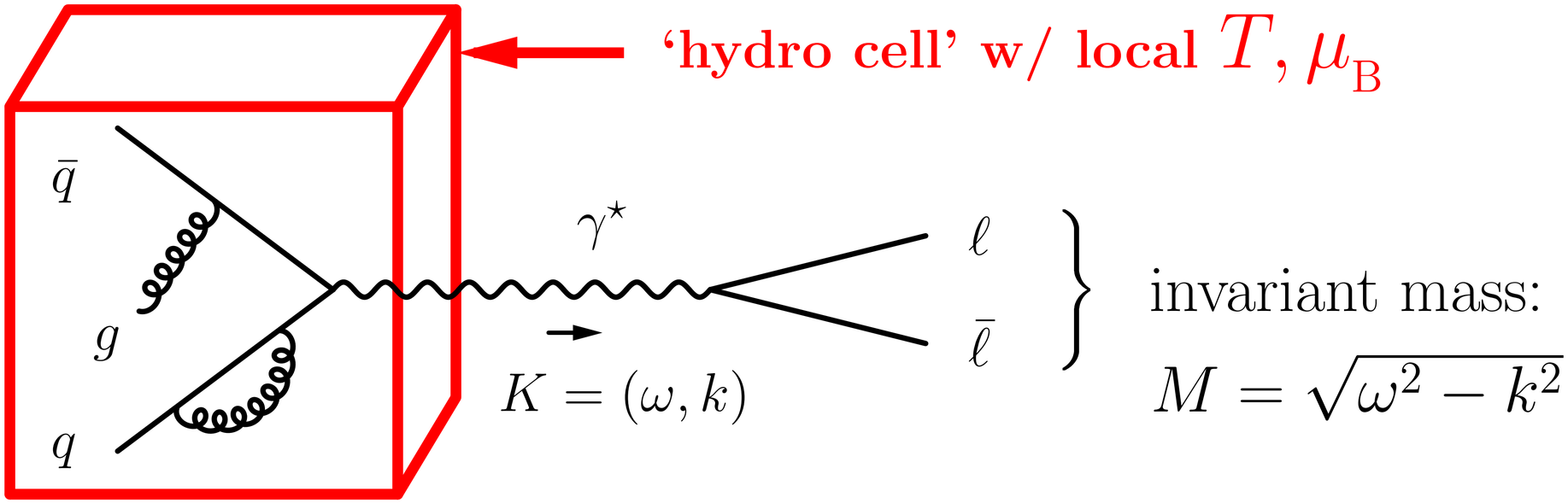
Garcia-Montero **1909.12294**

Garcia-Montero Mazeliauskas Plaschke Schlichting **2308.09747**



pQCD dileptons

fig. Jackson

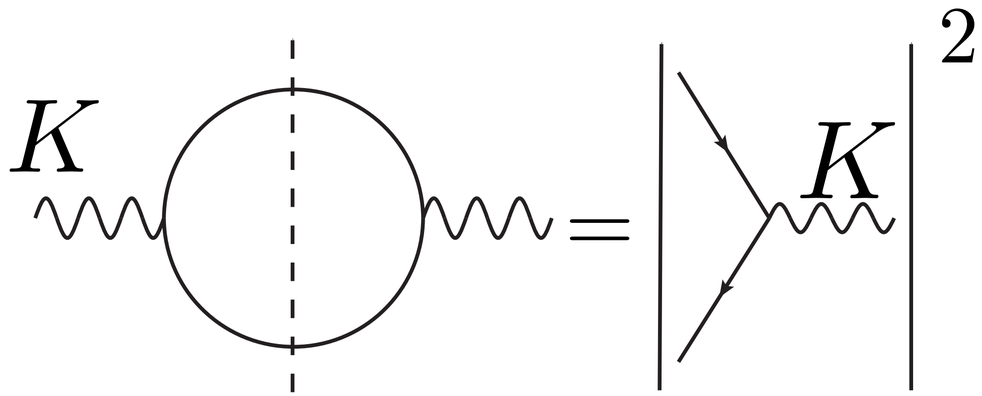


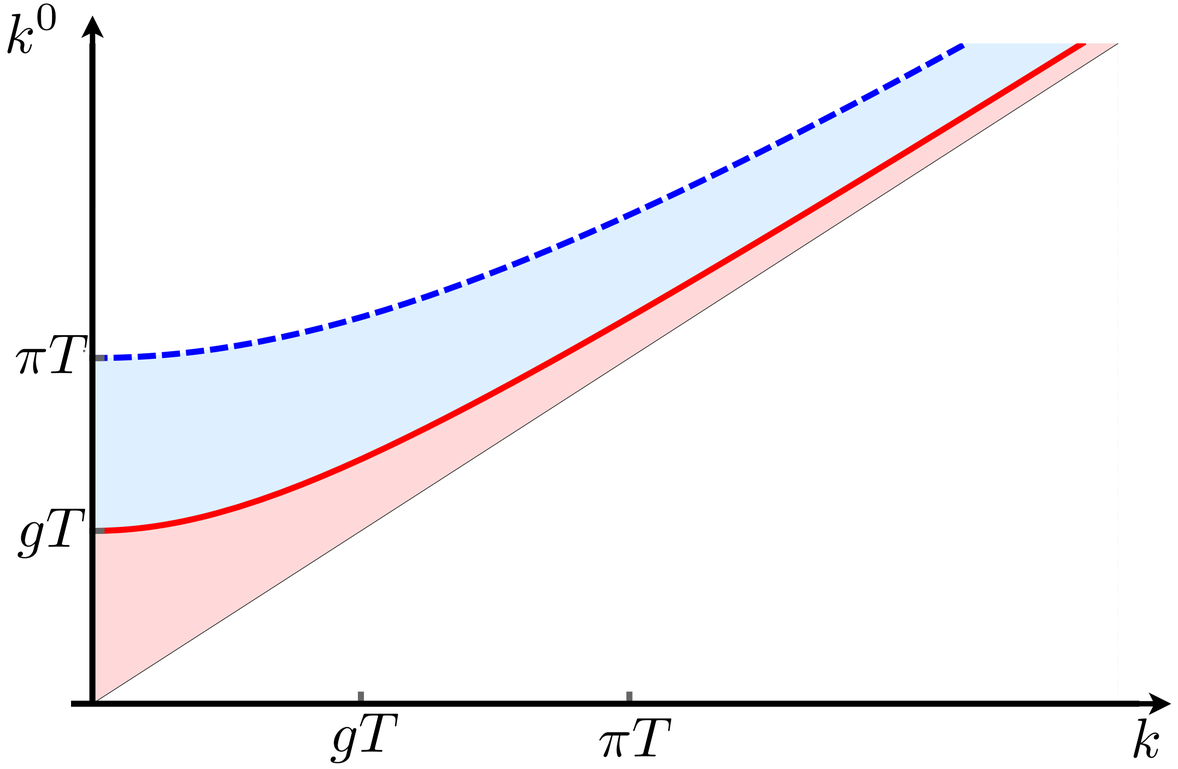
pQCD dileptons

- Consider non-zero virtuality $k^0 > k \geq 0$.

$$\frac{d\Gamma_{l^+l^-}(k)}{dk^0 d^3k} = -\frac{\alpha^2}{6\pi^3 K^2} \int d^4X e^{iK\cdot X} \mathrm{Tr}\rho J^\mu(0)\, J_\mu(X)$$

- Born contribution present, gets larger as invariant mass $M^2 = K^2$ grows





pQCD dileptons

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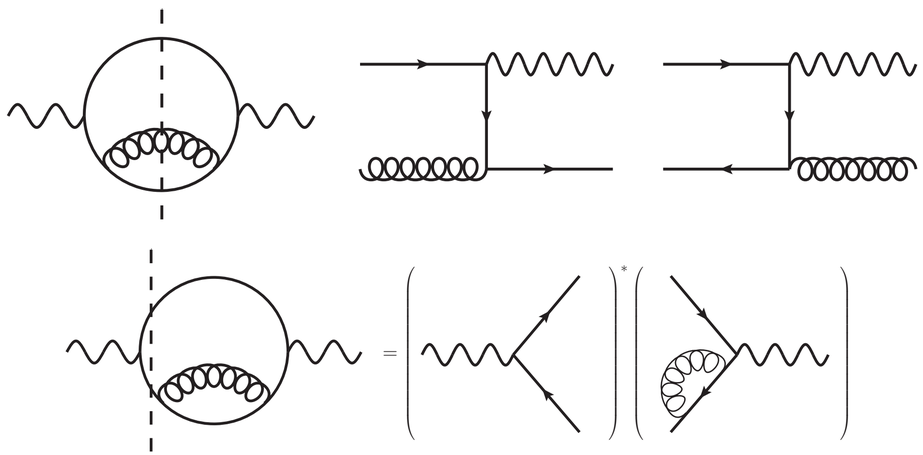
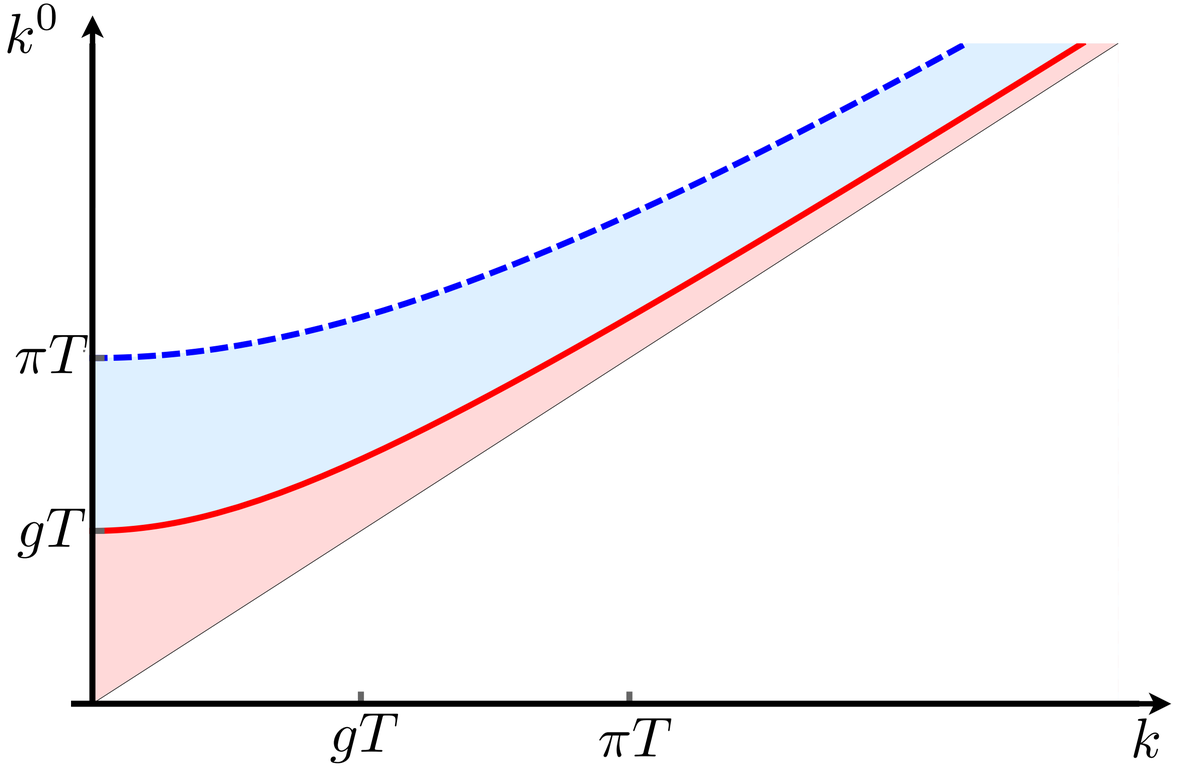
- If $K^2 \sim T^2$ loop corrections: real and virtual (with IR cancellations)





NLO results Laine **JHEP1311** (2013) extended to spacelike region in Jackson **PRD100** (2019)

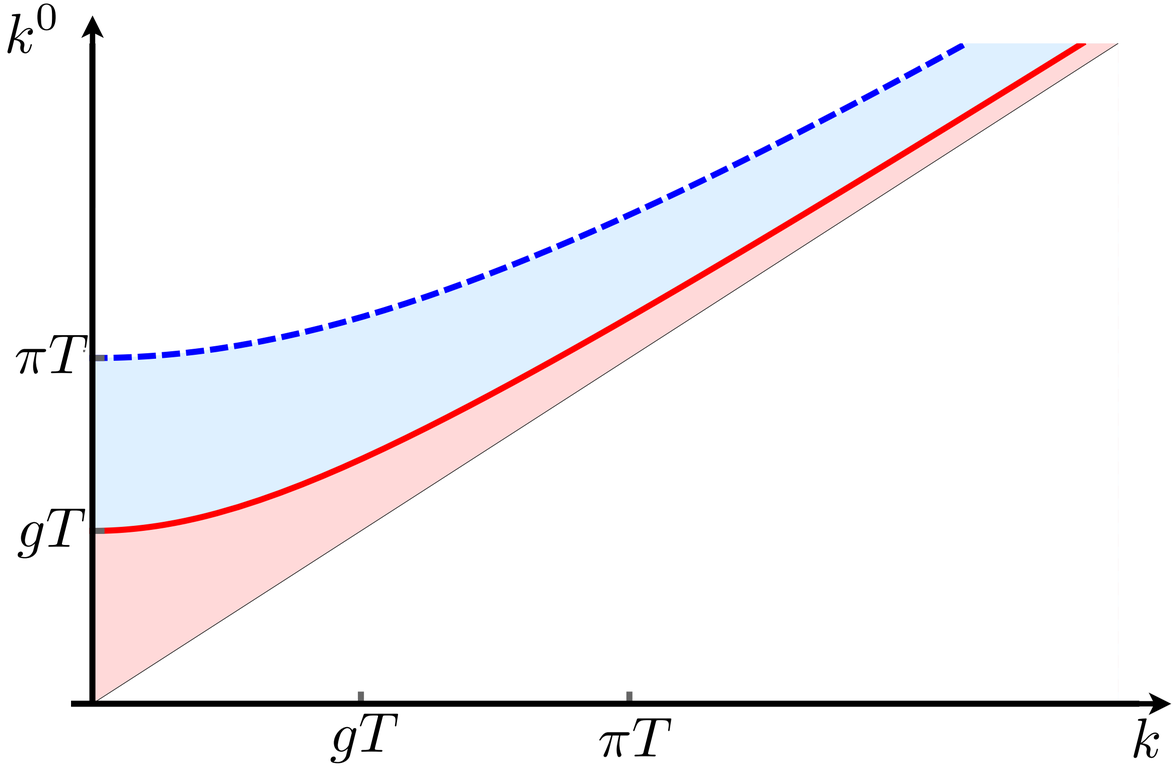
pQCD dileptons

- Consider non-zero virtuality $k^0 > k \geq 0$.

$$\frac{d\Gamma_{l^+l^-}(k)}{dk^0 d^3k} = -\frac{\alpha^2}{6\pi^3 K^2} \int d^4X e^{iK\cdot X} \mathrm{Tr}\rho J^\mu(0)\, J_\mu(X)$$

- If $K^2 \ll T^2$ LPM and/or HTL resummations are again necessary, similar to $K^2 = 0$
  Braaten Pisarski Yuan **PRL64** (1990),
  Aurenche Gelis Moore Zaraket **JHEP0212** (2002)
  NLO results JG Moore **JHEP1412** (2014)

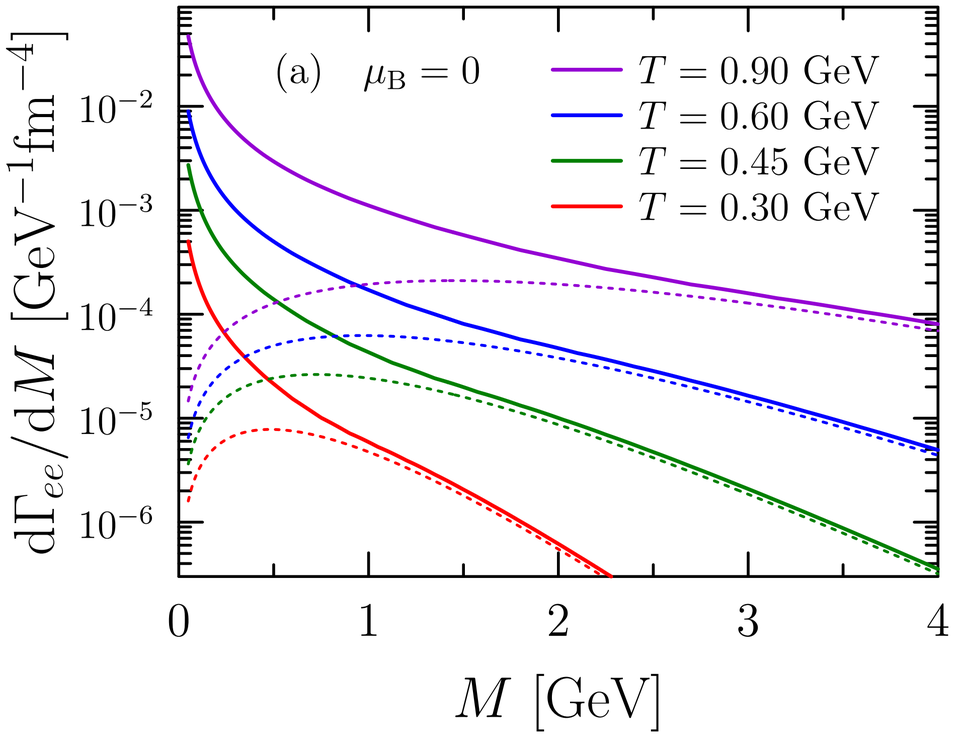
- Finite-k rate available at NLO for all $K^2 \geq 0$
  Ghisoiu Laine **JHEP1410** (2014) JG Moore (2014)
  JG Laine, JHEP2201 (2021)

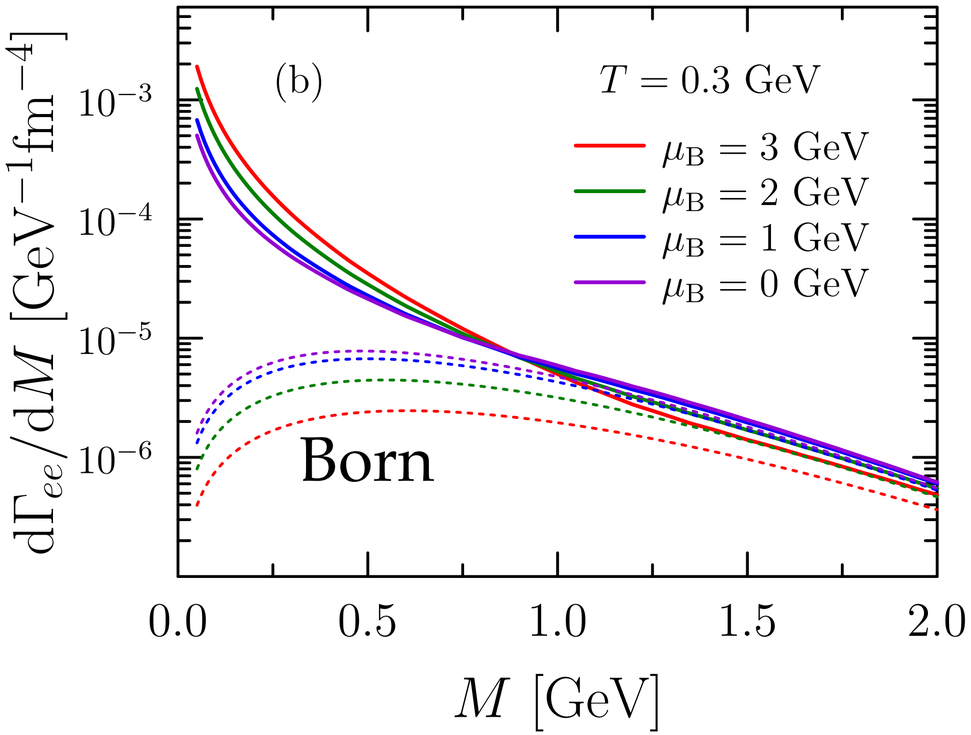


pQCD dileptons

rate from a **static source**:

$$\frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}M} = \int_{\boldsymbol{k}} \frac{M}{\sqrt{M^2+k^2}} \frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}\omega\,\mathrm{d}^3\boldsymbol{k}}$$



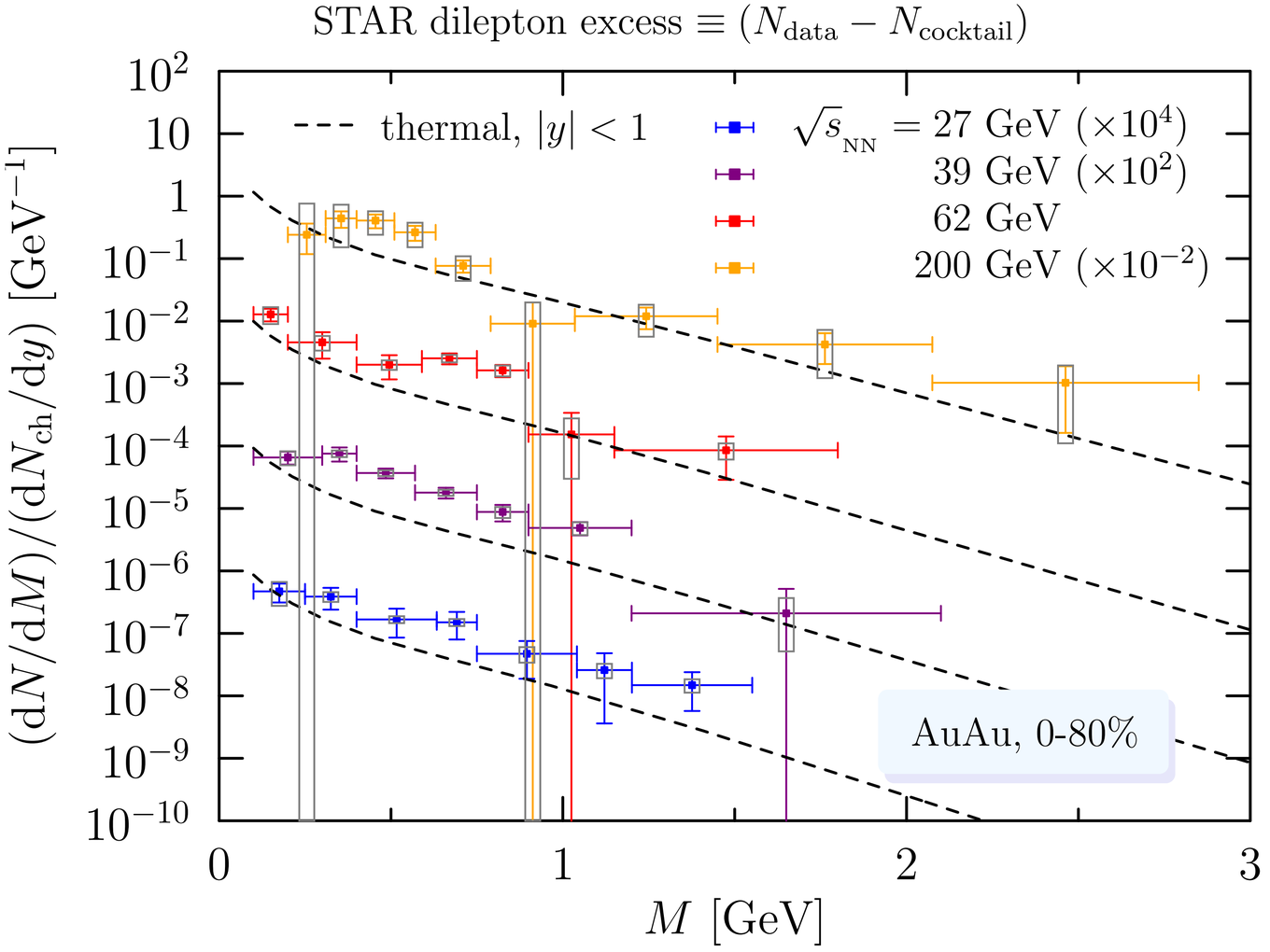


Churchill Du Gale Jackson Jeon **2311.06951 2311.06675**

Connecting pQCD dilepton rates to data

$M \gg T$ $\quad \dfrac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}M} \propto (MT_{\mathrm{eff}})^{3/2} \exp\left(-M/T_{\mathrm{eff}}\right)$

- Look at intermediate masses
- Full stack to connect microscopic rates to data
  - MC-Glauber IC
  - MUSIC hydro
  - Freeze-out and hadronic afterburner with UrQMD

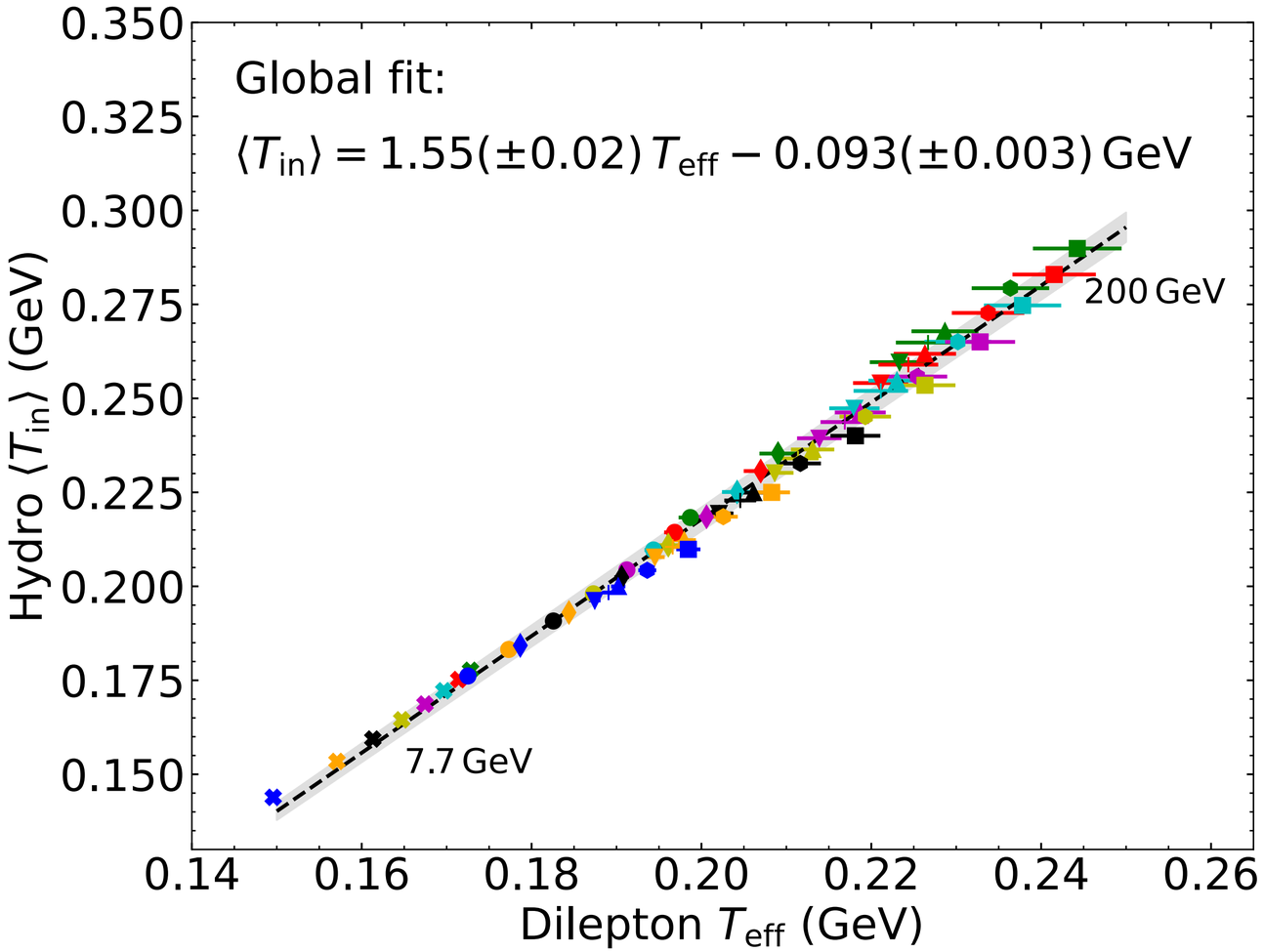


Churchill Du Gale Jackson Jeon **2311.06951 2311.06675**

Connecting pQCD dilepton rates to data

$M \gg T$ $\quad \boxed{\frac{\mathrm{d}\Gamma_{\ell\bar{\ell}}}{\mathrm{d}M} \propto (MT_{\mathrm{eff}})^{3/2} \exp\left(-M/T_{\mathrm{eff}}\right)}$

- Linear relation between highest temperature in the hydro phase and effective temperature in the intermediate mass regime
- Predicted in Kajantie Miettinen (1981)



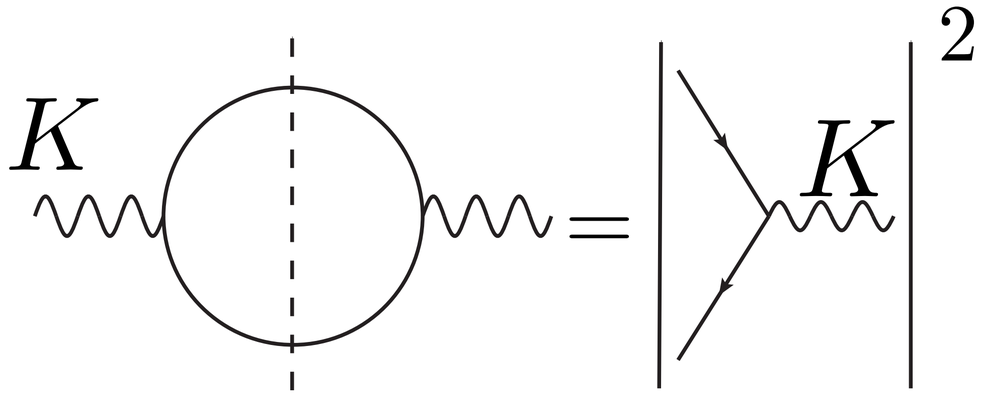
Churchill Du Gale Jackson Jeon **2311.06951 2311.06675**

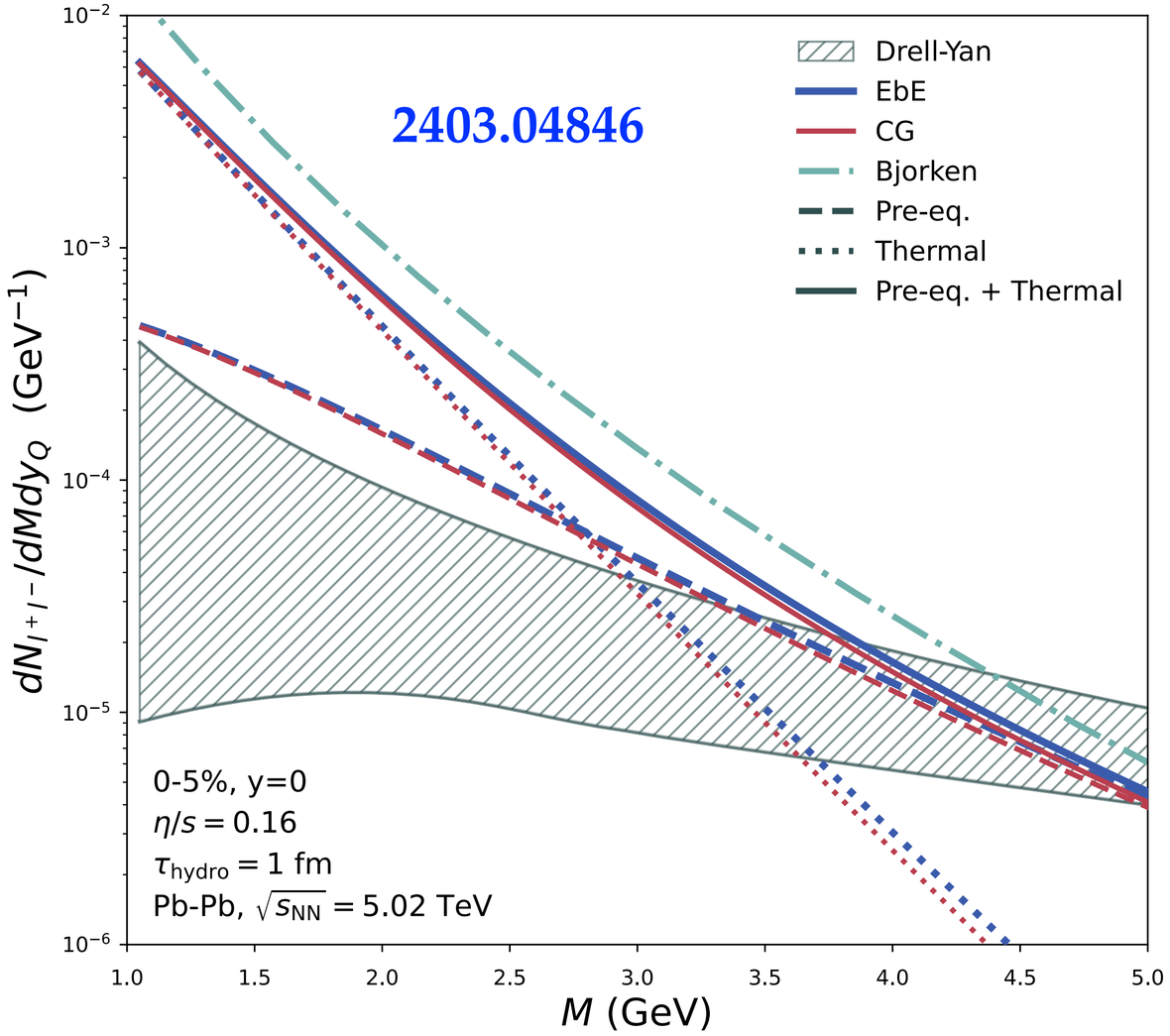
Pre-equilibrium dileptons

- Two competing effects:

↓ Quark number suppression and short duration of the phase

↑ Higher energy for the early quarks





Garcia-Montero Plaschke Schlichting **2403.04846** Coquet Du Ollitrault Schlichting Winn **2309.00555 2104.07622**

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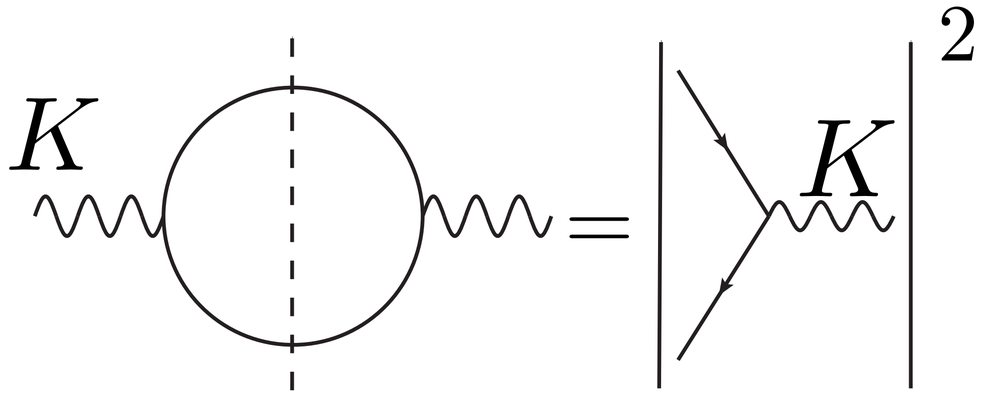
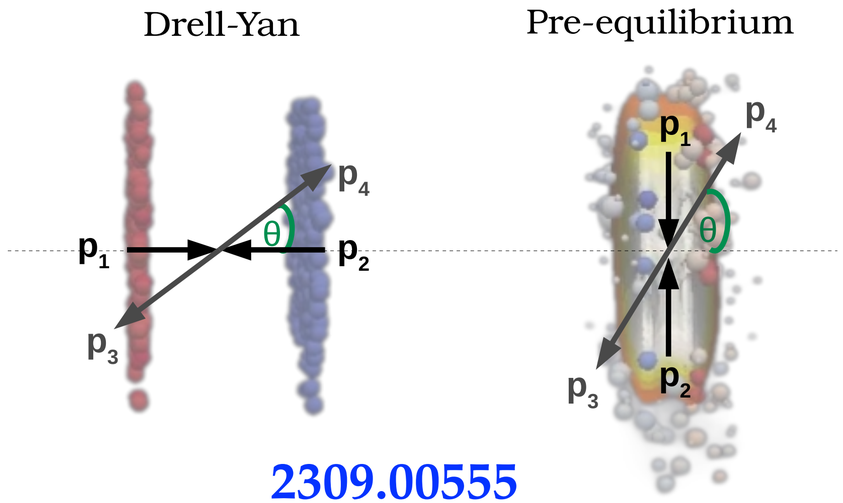




2309.00555

- Quadrupole moment of the angular distribution sensitive to change in polarization

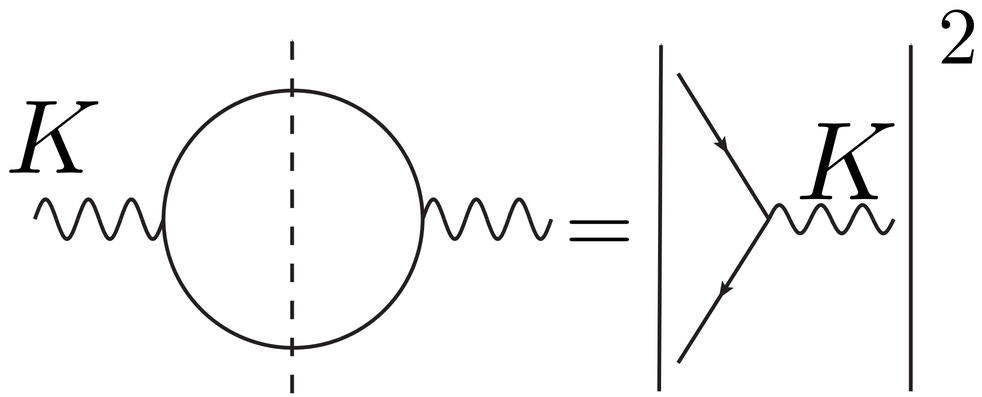
Garcia-Montero Plaschke Schlichting **2403.04846** Coquet Du Ollitrault Schlichting Winn **2309.00555 2104.07622**

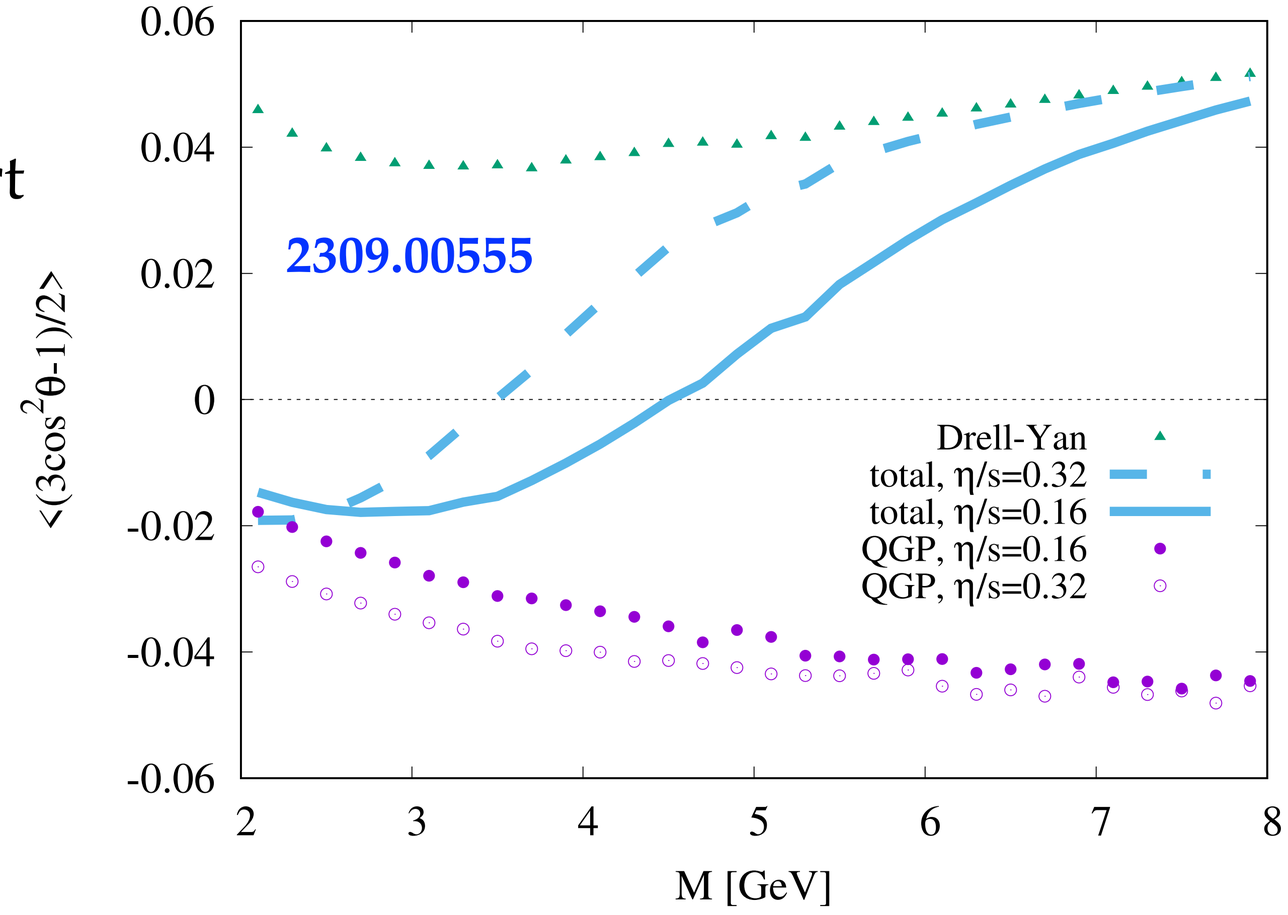
Pre-equilibrium dileptons

- Two competing effects:

↓ Quark number suppression and short duration of the phase

↑ Higher energy for the early quarks



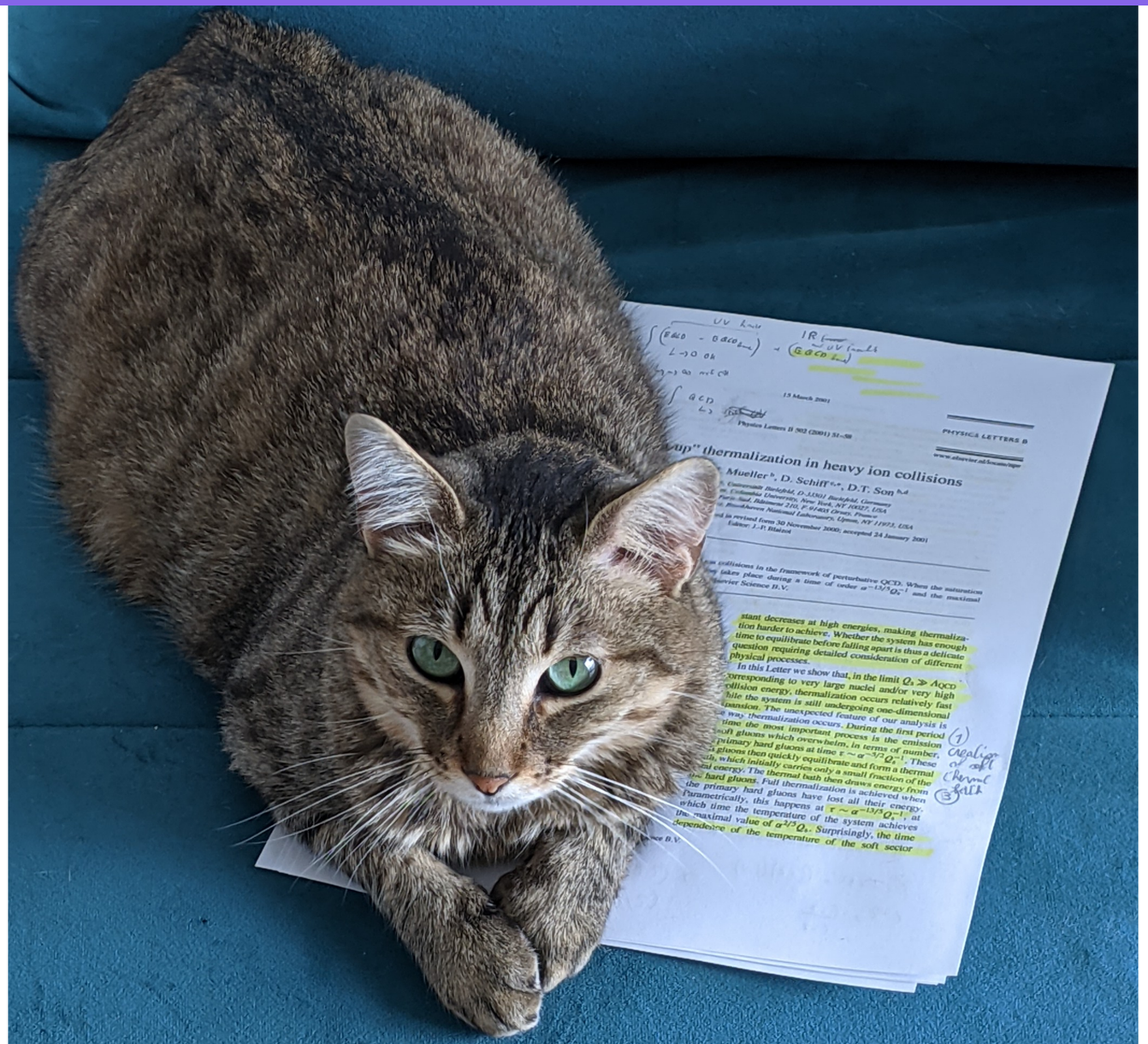


Garcia-Montero Plaschke Schlichting **2403.04846** Coquet Du Ollitrault Schlichting Winn **2309.00555 2104.07622**

Conclusions

- Theoretical description: convolution of microscopic rates over the macroscopic (hydro) evolution of the medium
- Many theory advancements in connecting the two and in pre-equilibrium emission
  - Pre-eq. photon and dileptons overtake thermal radiation at some point
  - Linear relationship between highest temperature and effective temperature for dileptons
  - Angular structure of dileptons could shed light on their origin

Backup


PHYSICS LETTERS B
up" thermalization in heavy ion collisions
Mueller b, D. Schiff c,*, D.T. Son b,d
In this Letter we show that, in the limit $Q_s \gg \Lambda_{QCD}$
creation of soft
thermal
soft

And the lattice?

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- What is measured directly is the Euclidean correlator

$$G_E(\tau, k) = \int d^3x J_\mu(\tau, \mathbf{x}) J_\mu(0,0) e^{i\mathbf{k}\cdot\mathbf{x}}$$

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- Analytical continuation $G_E(\tau, k) = G^<(i\tau, k)$

$$G_E(\tau, k) = \int_0^\infty \frac{dk^0}{2\pi} \rho_V(k^0, k) \frac{\cosh\left(k^0(\tau - 1/2T)\right)}{\sinh\left(\frac{k^0}{2T}\right)} \qquad W^<(K) = n_B(k^0)\, \rho_V(k^0, k)$$

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- It contains much more info (full spectral function), but hidden in the convolution. Inversion tricky, discrete dataset with errors

And the lattice?

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$$G_E(\tau, k) = \int d^3x J_\mu(\tau, \mathbf{x}) J_\mu(0,0) e^{i\mathbf{k}\cdot\mathbf{x}}$$

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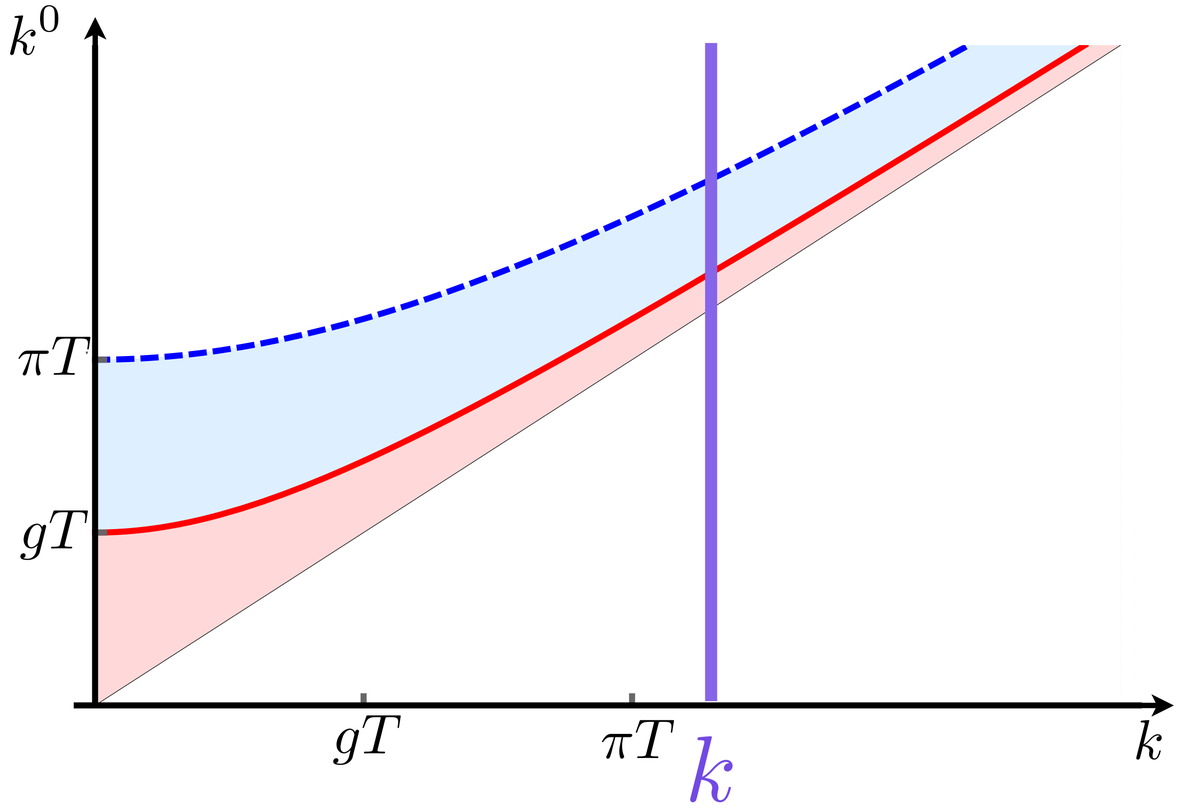
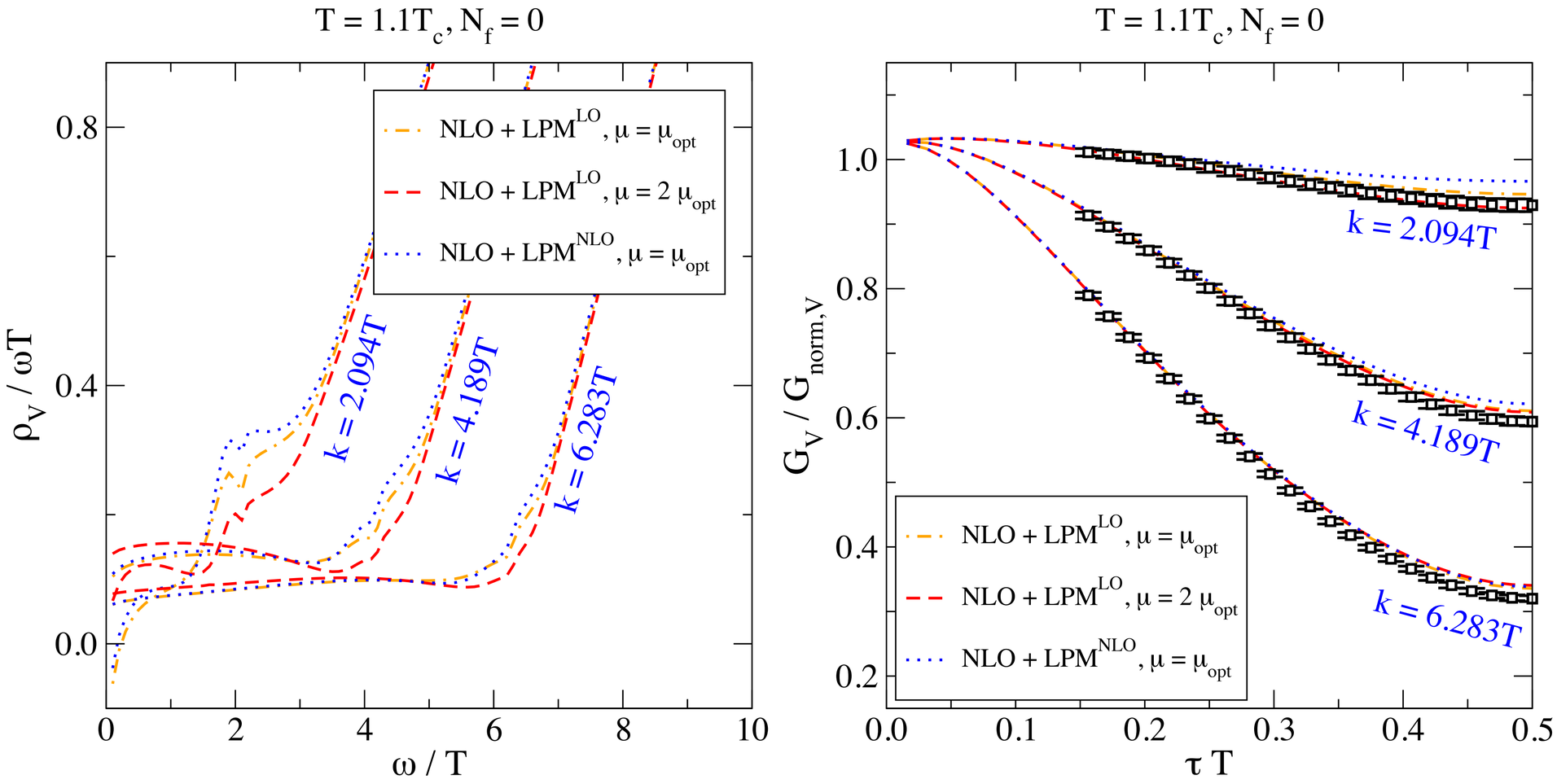


- If k>0 spf describes DIS ($k^0<k$), photons ($k^0=k$) and dileptons ($k^0>k$)



- Plots and spectral function from Jackson Laine **JHEP1109** (2019)
  Quenched lattice from JG Kaczmarek Laine F.Meyer **PRD94** (2016)

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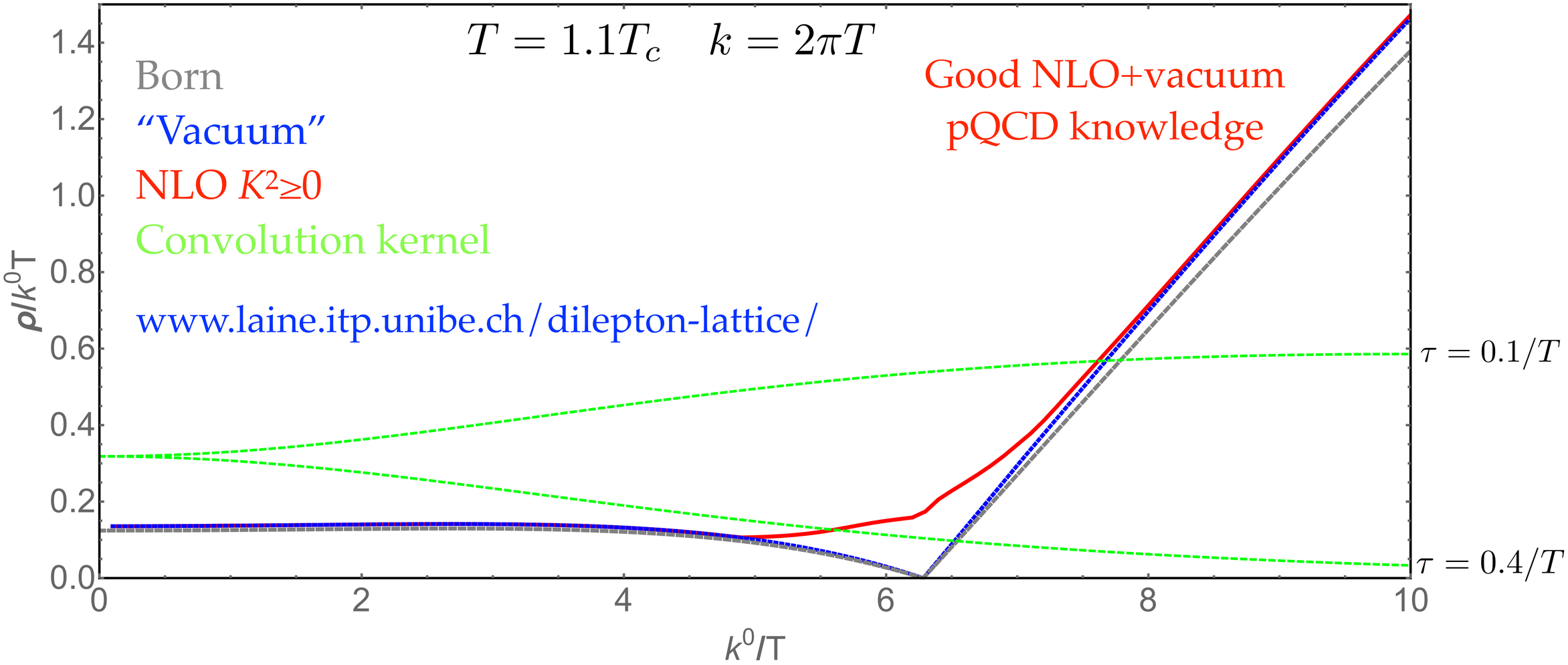
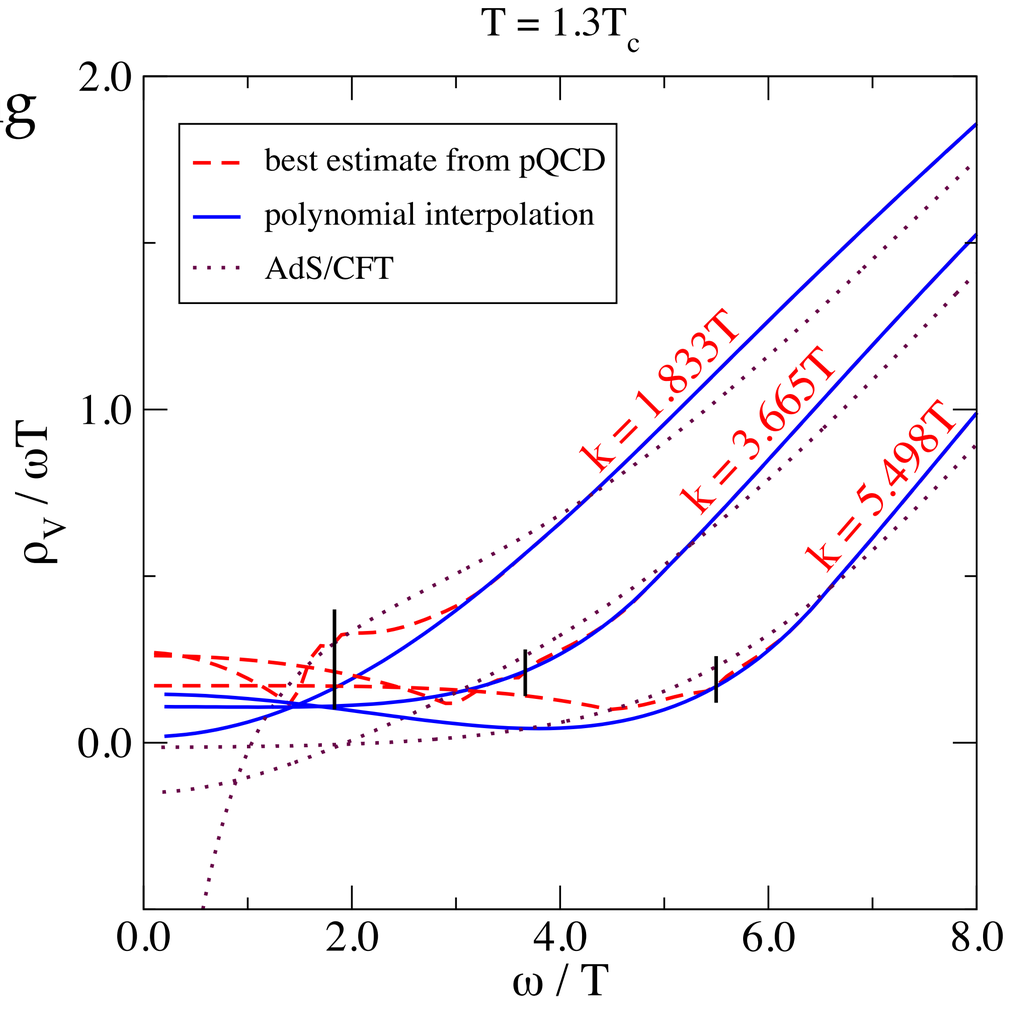


Fitting to the lattice

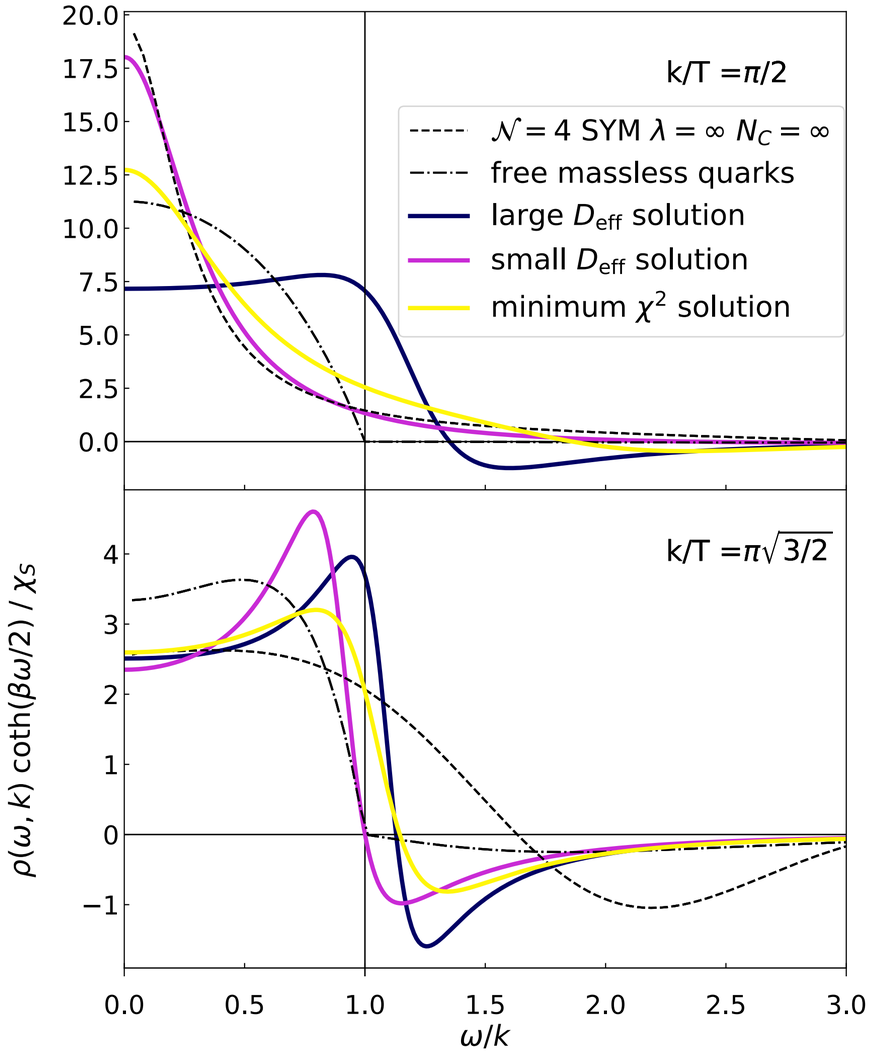
- Main idea: assume a fitting form for the spf, relying on Ansätze
- Get the Euclidean correlator from this ansatz spf and fit the spf coeffs to the lattice data
- Two approaches so far
  - Quenched, continuum extrapolated lattice data, **standard vector spf** $\rho_V=2\rho_T+\rho_L$
  - Convolution dominated by (well-understood) vacuum physics at $\omega \gg k$
    JG Kaczmarek Laine F.Meyer **PRD94** (2016)



Fitting to the lattice

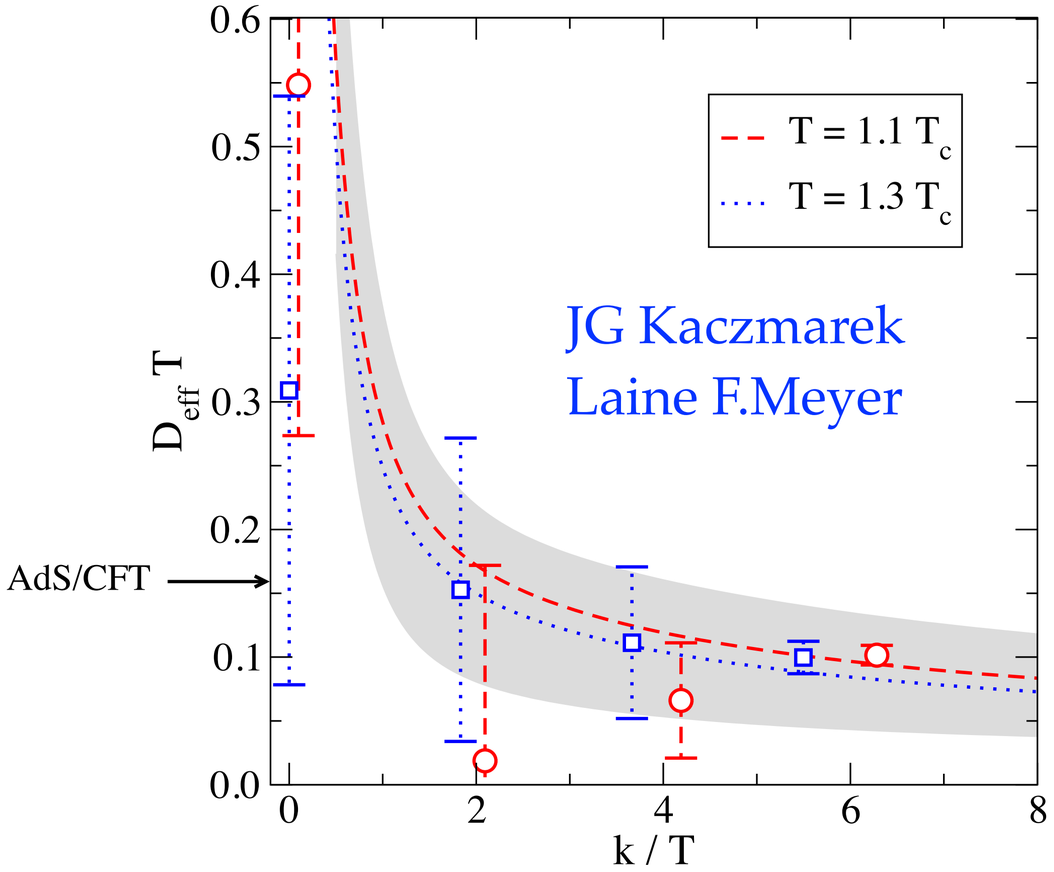
- Main idea: assume a fitting form for the spf, relying on Ansätze
- Get the Euclidean correlator from this ansatz spf and fit the spf coeffs to the lattice data
- Two approaches so far
  - N_f=2 continuum extrapolated, **modified spf** $\rho_{\text{Mainz}}=2\rho_T-2\rho_L$
  - Vacuum contribution vanishes identically (Lorentz invariance). $\rho_{\text{Mainz}}(\omega=k)=\rho_V(\omega=k)$

Brandt Francis Harris H.Meyer Steinberg
1710.07050 Cè Harris H.Meyer Steinberg Toniato
PRD102 (2020)

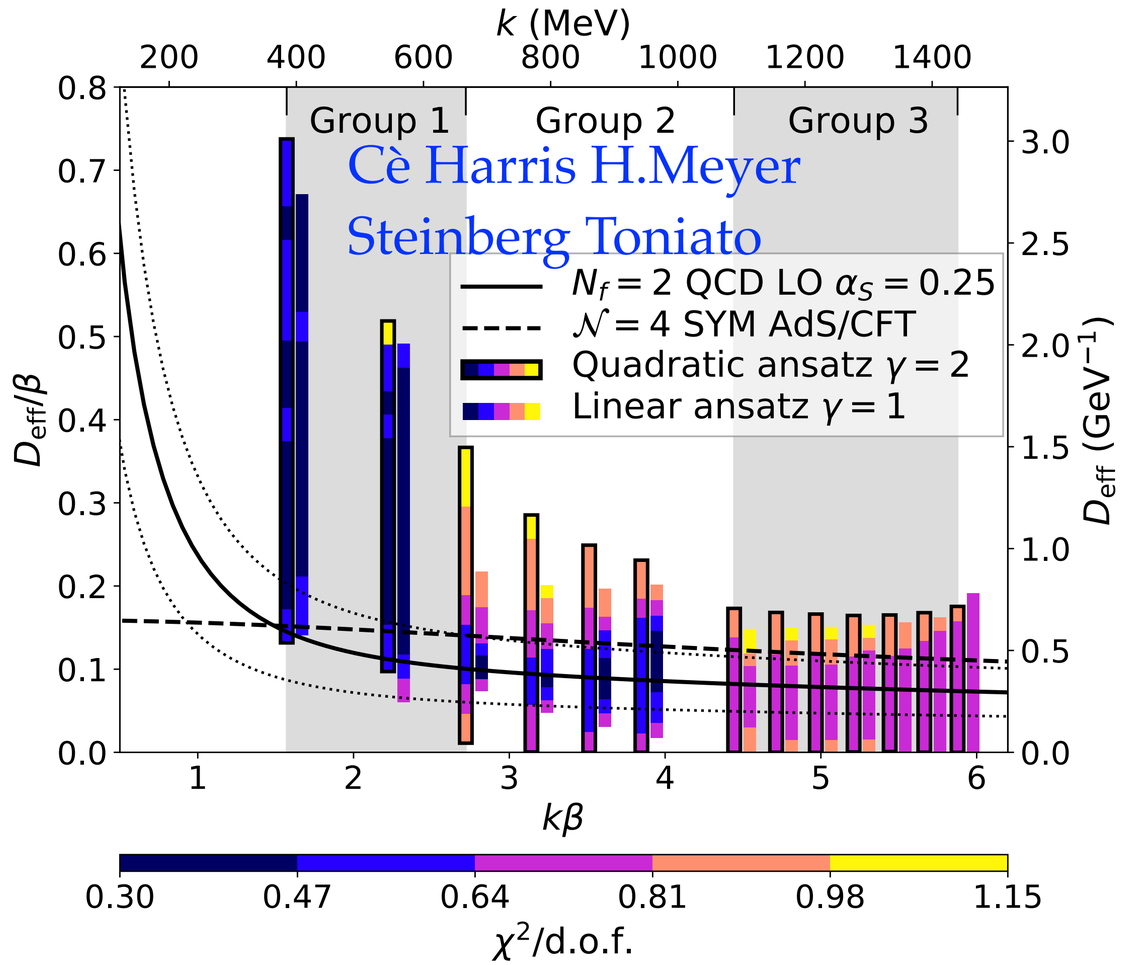


Fitting to the lattice

- Define $D_{\rm eff}(k) \equiv \begin{cases} \dfrac{\rho_{\rm V}(k,\mathbf{k})}{2\chi_{\rm q} k} & , \quad k > 0 \\ \lim\limits_{\omega\to 0^+} \dfrac{\rho^{ii}(\omega,\mathbf{0})}{3\chi_{\rm q}\omega} & , \quad k = 0 \end{cases}$



- In the hydro limit $k \ll T$ $D_{\rm eff} \to D$ $\quad \sigma = e^2 \sum_{f=1}^{N_{\rm f}} Q_f^2 \chi_{\rm q} D$



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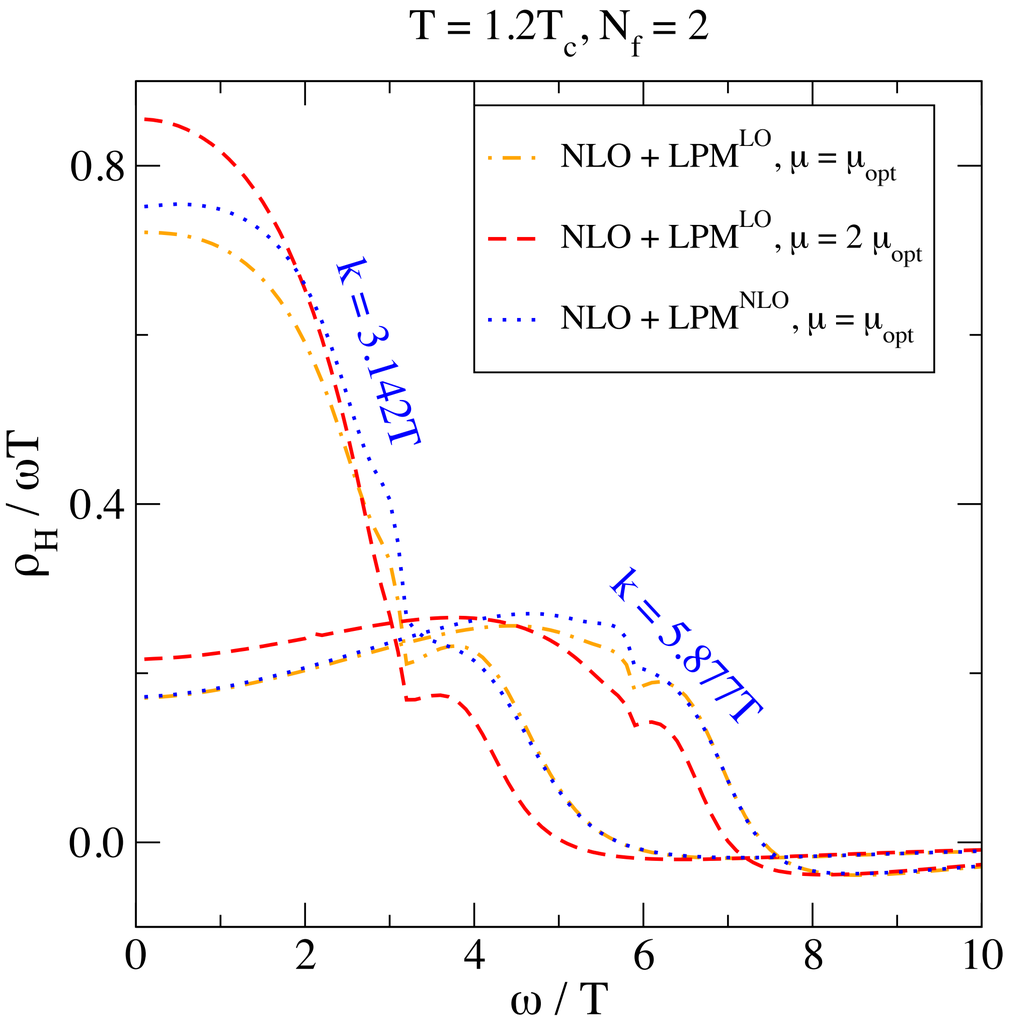
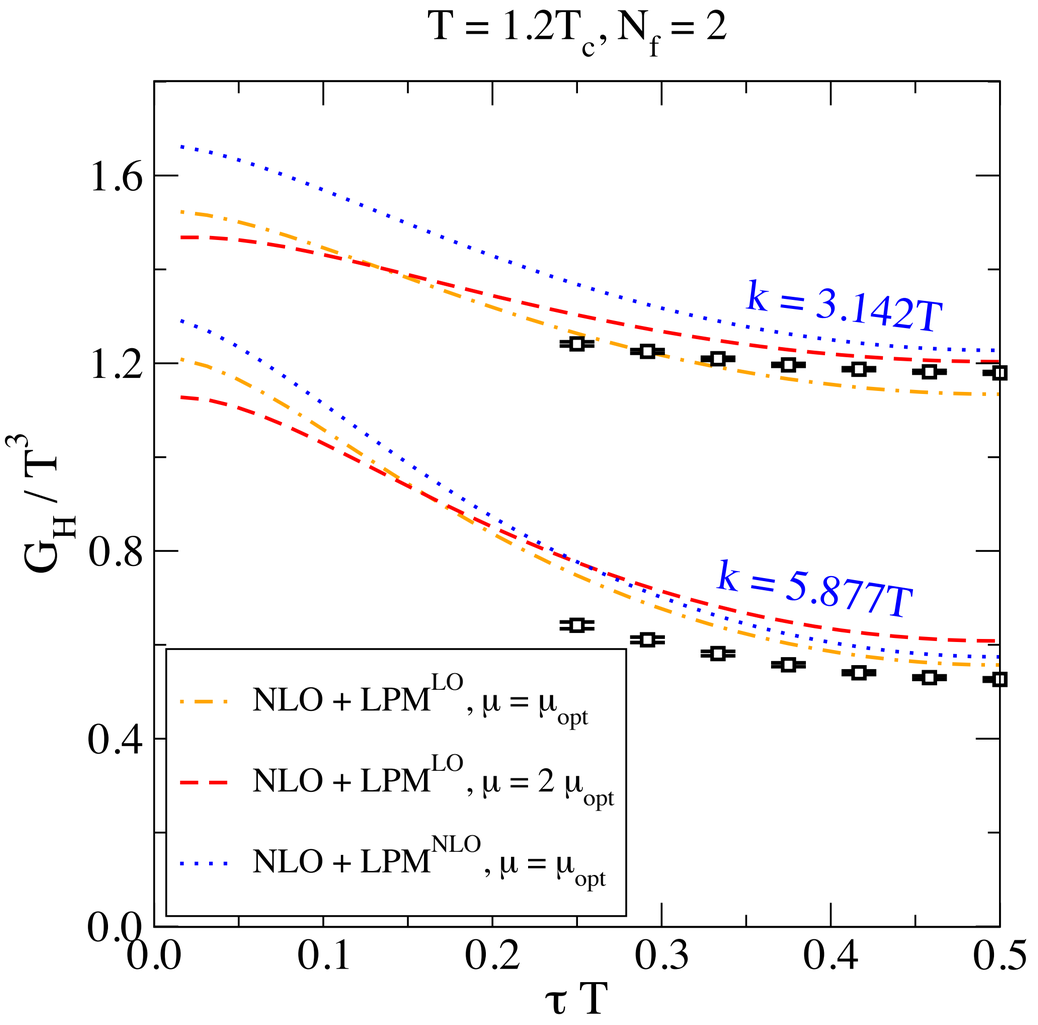
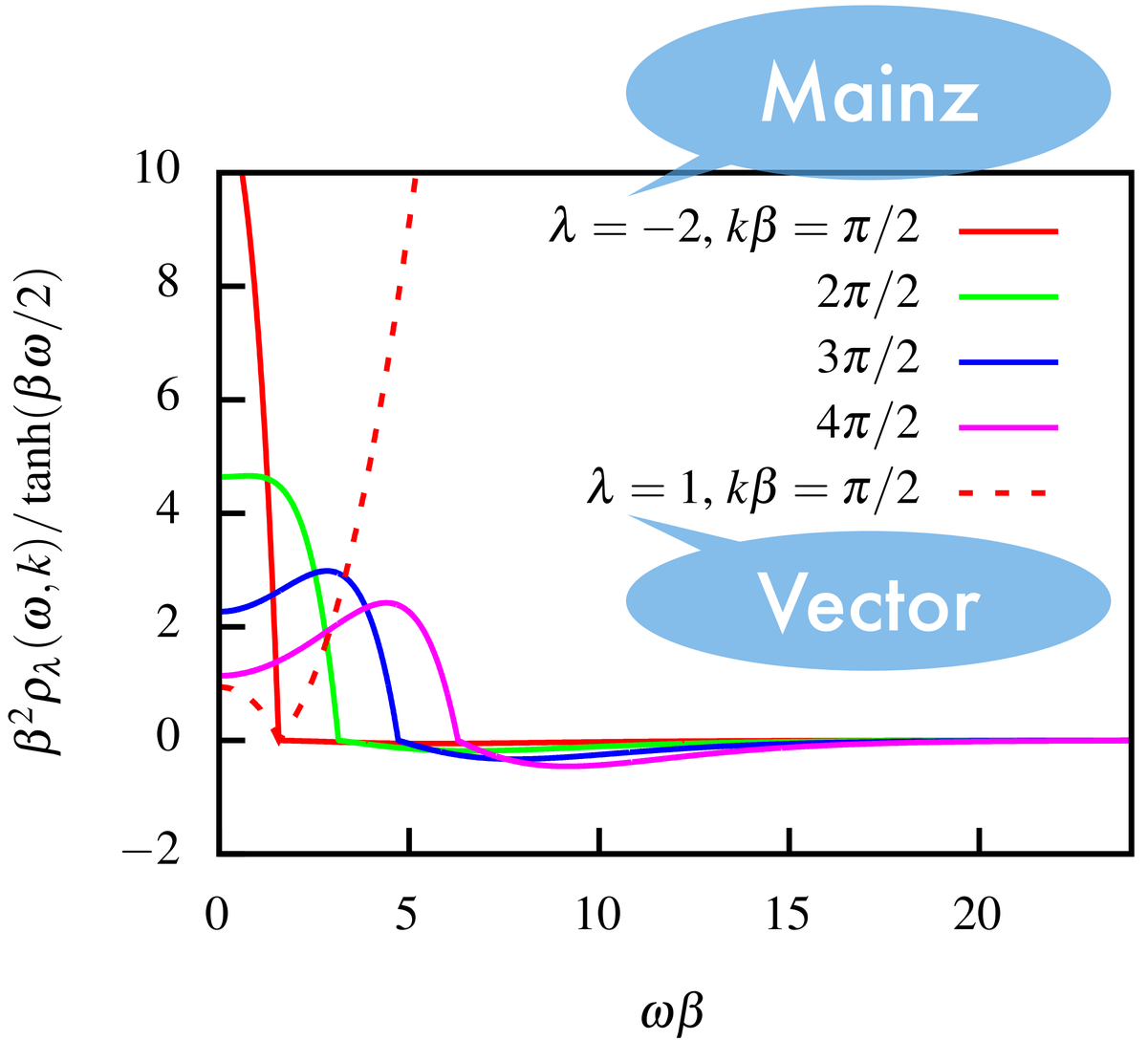




- Plots and spectral function from Jackson Laine **JHEP1109** (2019)
  Lattice from Cè Harris H.Meyer Steinberg Toniato **PRD102** (2020)

- Backus-Gilbert method: linear map from the space of functions in the time domain, G, to the space of functions on the frequency domain, ρ_{BG}
- It is exact for constant spfs and advantageous for a slowly varying spf
- The Mainz spf might indeed be slowly varying, or at least much slower than the vector one

LO pQCD spf



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