Photon Elliptic Flow: Possible Mechanisms of Enhancement

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RHIC and AGS Annual Users' Meeting

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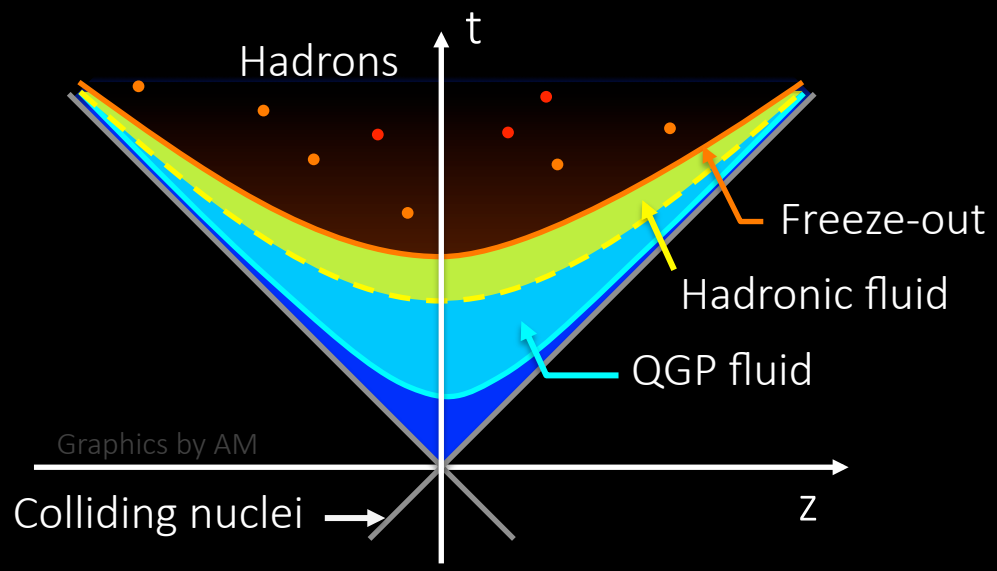
Introduction

- Heavy-ion collisions: Hadronic point of view



Hadronic transport (> 10 fm/c)

Freeze-out

Hydrodynamic stage (~1-10 fm/c)

Equilibration

Glasma (~0-1 fm/c)

Little bang

Color glass condensate (< 0 fm/c)

- Color opaque

  Most information before freeze-out is lost in "thermal hadrons"

Introduction

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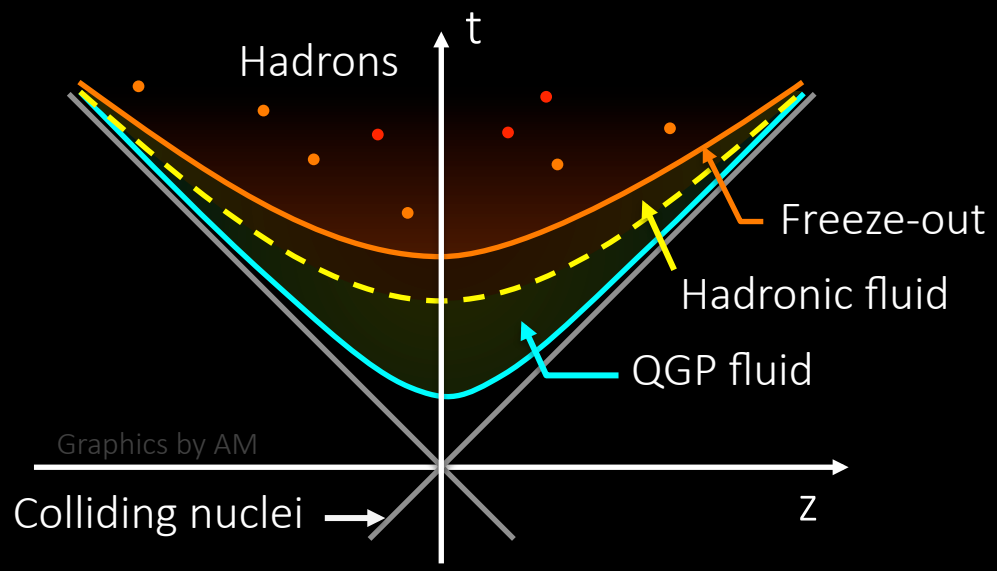

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Electroweak transparent

Photons retain information during time-evolution

Introduction

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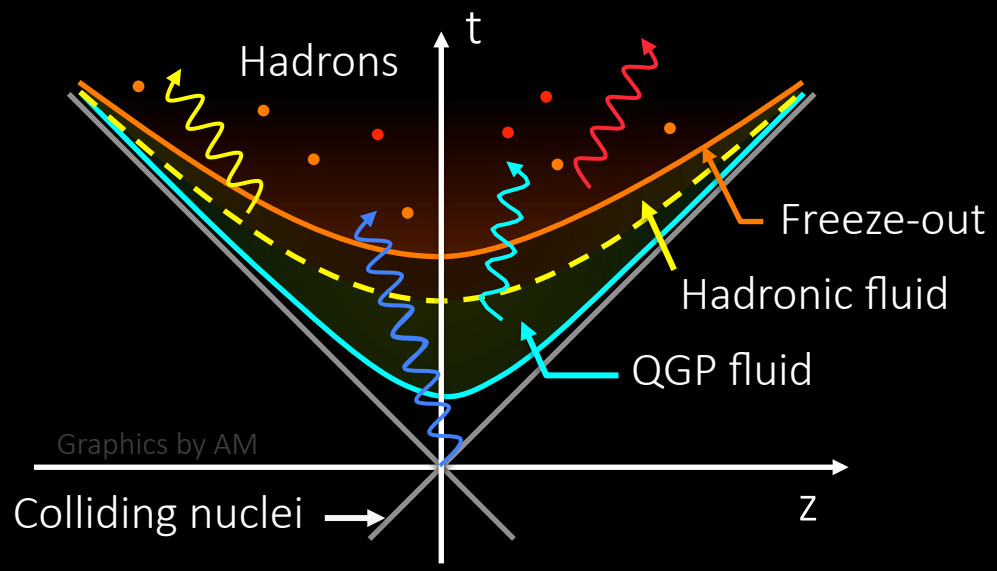


Decay photons
- from hadronic decay

Thermal photons (hadronic)
Thermal photons (QGP)
- from black-body radiation

Prompt photons
- from hard processes

Direct photons

Color opaque

Most information before freeze-out is lost in "thermal hadrons"

Electroweak transparent

Photons retain information during time-evolution

Introduction

- Heavy-ion observable: p_T spectra
  - Direct photon p_T spectra

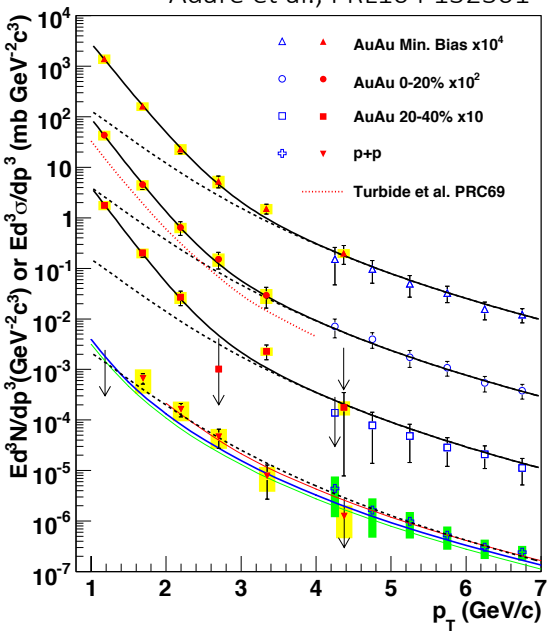
    Thermal photon slope T_{RHIC} = 221 ± 38 MeV

    ⇨ T_{init} = 300-600 MeV implied from theoretical estimation

    Cf: Slope parameter for LHC is T = 304 ± 51 MeV

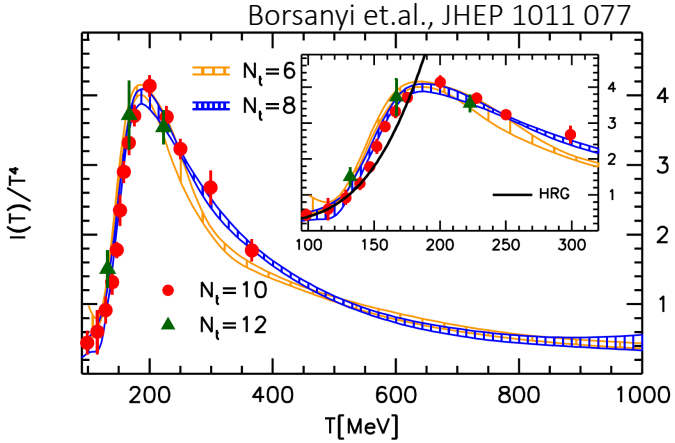
    Wilde et al., arXiv:1210.5958

Adare et al., PRL104 132301



  - Comparison with Lattice QCD

Borsanyi et.al., JHEP 1011 077

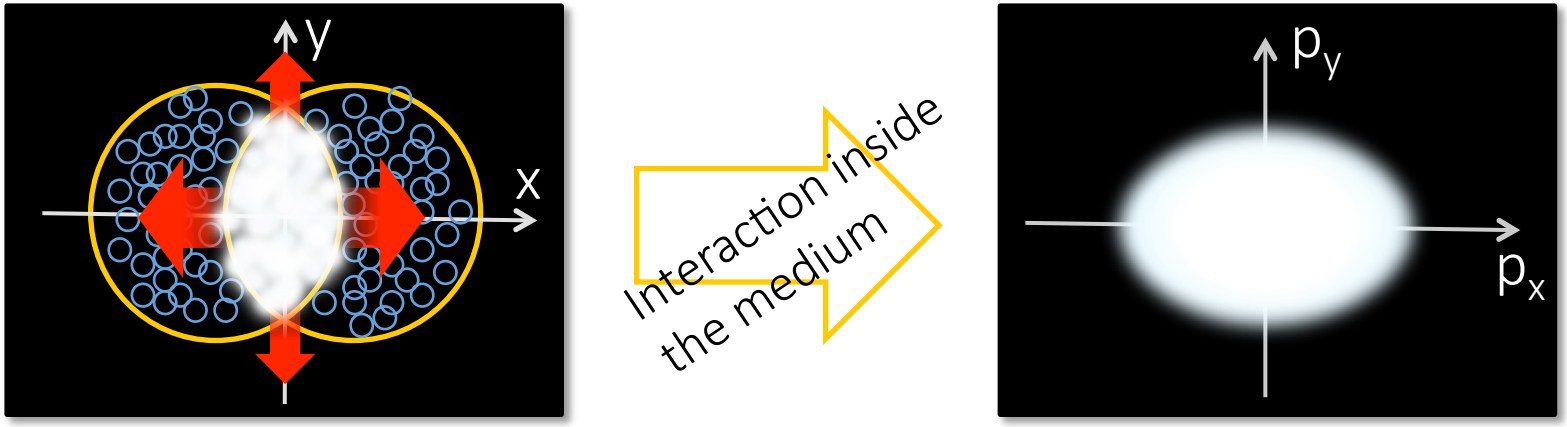


Crossover temperature: T_c ~ 170 MeV

⇨ Heavy-ion photons are an evidence for the realization of QGP

Introduction

- Heavy-ion observable: Elliptic flow (v_2)
  - $$\frac{dN}{d\phi} = \frac{N}{2\pi}[1 + 2v_1\cos(\phi - \Psi_1) + 2v_2\cos(2\phi - 2\Psi_2) + 2v_3\cos(3\phi - 3\Psi_3) + \ldots]$$

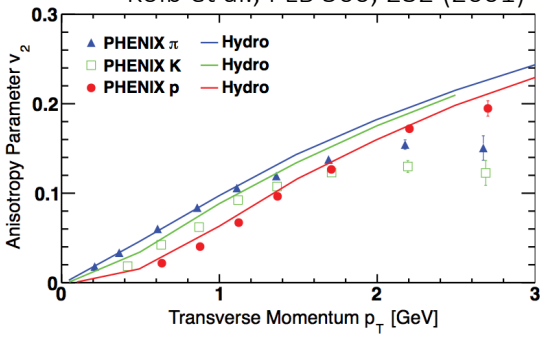


Spatial anisotropy

Momentum anisotropy

- Hadron v_2 is found to be large
  - ⇨ It follows hydrodynamic description
  - ⇨ An "evidence" for strongly-coupled QGP; early equilibration of bulk medium (τ < 1 fm/c)?

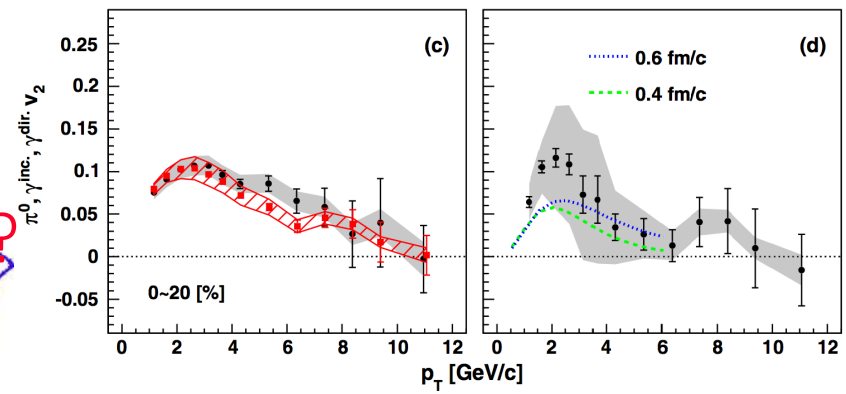
Kolb et al., PLB 500, 232 (2001)



Introduction

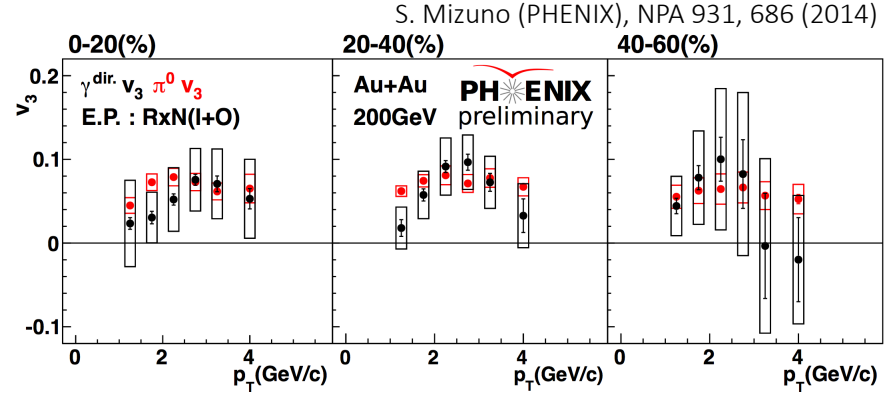
- Experimental results: photons
  - Direct photon v_2 is found to be large
    - ⇨ Comparable to pion v_2 (Hydro models imply smaller v_2)
    - ⇨ No definite answer so far; recognized as "photon v_2 puzzle"

PHENIX, PRL 109, 122302 (2012)



  - Direct photon v_3 is indicated to be large
    - ⇨ Similar to pion v_3
    - ⇨ The enhancement is at least partially due to the properties of the medium itself

S. Mizuno (PHENIX), NPA 931, 686 (2014)



Photon v_n puzzle

- Direct photons = prompt photons + thermal photons

$$E\frac{dN}{d^3p} = ABT_{AB} \times E\frac{d\sigma^{pp}}{d^3p} + \int E\frac{dR_{\rm thermal}}{d^3p}(u^\mu, T)dx^4 + E\frac{dN_{\rm addtional}}{d^3p}?$$

- Modifications in thermal photon emission?
  - Emission rate: Liu & Liu, PRC 89, 034906 (2014); Monnai, PRC 90, 021901 (2014); Hees, He & Rapp, NPA 933, 256 (2015); Gale et al., PRL 114, 072301 (2015); Monnai, 1504.00406; McLerran & Schenke, 1504.07223
  - Bulk evolution: Hees, Gale & Rapp, PRC 84, 054906 (2011); Dion et al, PRC 84, 064901 (2011); Linnyk et al., PRC 88, 034904 (2013); Linnyk et al., PRC 89, 034908 (2014); Heinz, Liu & Shen, 1403.8101; Shen et al, PRC 91, 024908 (2014)
- Modifications in prompt photon emission? Monnai, 1408.1410
- Other sources of photons (e.g. glasma)? McLerran & Schenke, NPA 933, 256 (2014)
- Other effects (e.g. magnetic field)? Basar, Kharzeev & Skokov, PRL 109, 202303 (2012); Bzdak & Skokov, PRL 110, 192301 (2013); Goloviznin et al., JTEPL 98, 61 (2013); Basar, Kharzeev & Shuryak, PRC 90, 014905 (2014)
- Experimental data needs more statistics?

It could be a combination of those or something entirely different

Photon v_n puzzle

- In this talk we consider
  - Effects of quark chemical equilibration

    AM, Phys. Rev. C 90, 021901(R) (2014)

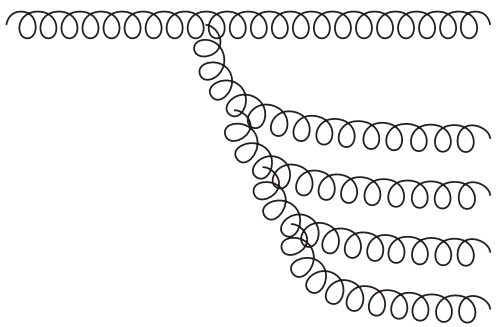
  - Effects of in-medium interaction on phase-space distribution

    AM, arXiv:1504.00406 [nucl-th]

Effects of chemical equilibration

- Properties of bulk medium

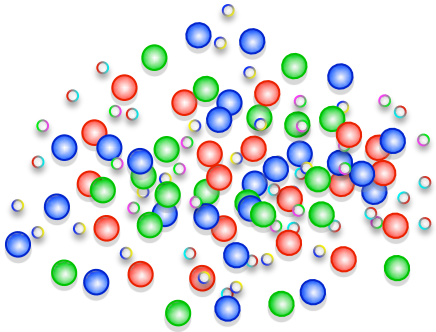
$\tau < 0$ fm/c



- Color glass condensate: Colliding two nuclei are saturated gluons

"Little bang"

$\tau \sim 1$-10 fm/c



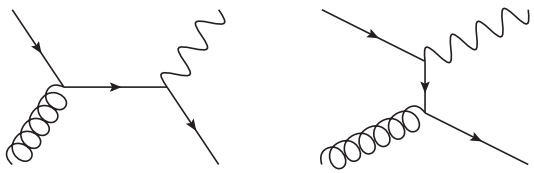
- QGP/hadronic fluid: A plasma of equilibrated quarks and gluons

Chemical equilibration does not necessarily coincide with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)

Effects of chemical equilibration

- "Gluons do not shine"

Compton scattering



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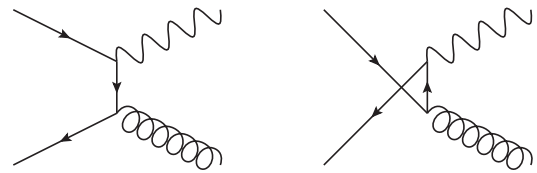
Pair annihilation



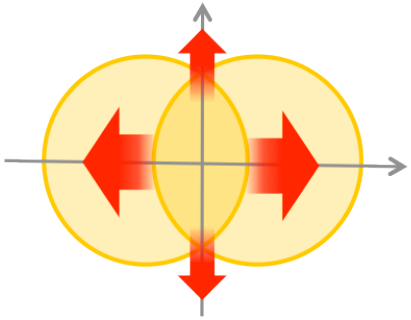
+ ...

- Flow anisotropy develops along with time evolution in hydrodynamics:

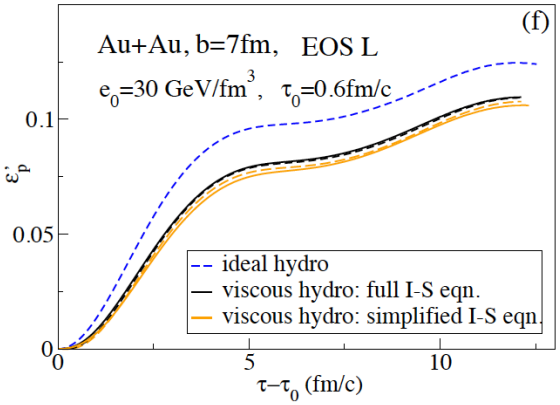
$$Du^x = \frac{1}{e+P}\nabla^x P$$

$$\vee$$

$$Du^y = \frac{1}{e+P}\nabla^y P$$



Song & Heinz, PRC 78, 024902



The contribution from later stage becomes large; photon v_2 can be enhanced

Effects of chemical equilibration

- Hydrodynamic equations of motion
  - Energy-momentum conservation

$$\partial_\mu T_g^{\mu\nu} + \partial_\mu T_q^{\mu\nu} = 0$$

  - Rate equations

$$\partial_\mu N_q^\mu = 2r_b n_g - 2r_b \frac{n_g^{\rm eq}}{(n_q^{\rm eq})^2} n_q^2$$

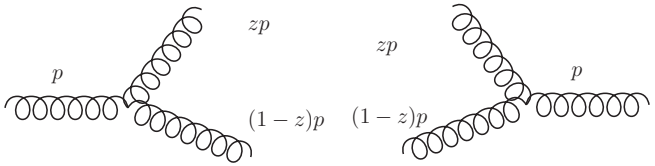
$$\partial_\mu N_g^\mu = (r_a - r_b) n_g - r_a \frac{1}{n_g^{\rm eq}} n_g^2 + r_b \frac{n_g^{\rm eq}}{(n_q^{\rm eq})^2} n_q^2 + r_c n_q - r_c \frac{1}{n_g^{\rm eq}} n_q n_g$$

r_a, r_b, r_c : reaction rates

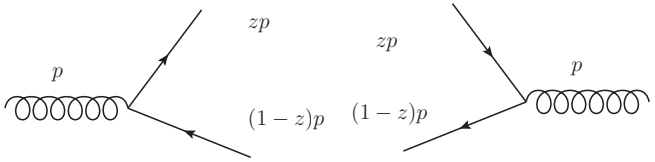
$n_q^{(\rm eq)}, n_g^{(\rm eq)}$: parton densities (in equilibrium)

How do we know equilibrium densities?

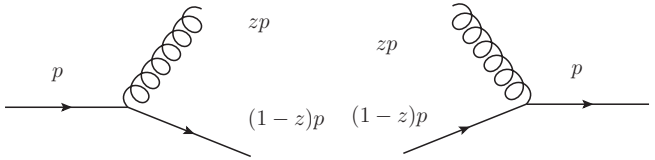
(a) gluon splitting



(b) quark pair production



(c) gluon emission from a quark

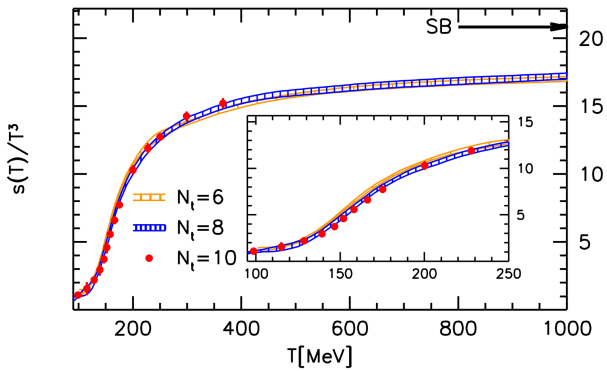


QCD kinetic theory

- "QGP is not an ideal gas"

Equation of state

Borsanyi et al., JHEP 1011, 077 (2010)



- Lattice QCD:
SB limit is not reached

Inconsistent

Phase-space distribution

$$f_0 = \frac{1}{e^{\sqrt{p^2+m^2}/T} \pm 1}$$

- Non-interacting gas:
Bose-Einstein or Fermi-Dirac distributions

f_q and f_g require in-medium corrections (≠ viscosity) which affect equilibrium densities *and* photon emission rate

*Hadrons are not affected because hadron resonance gas works

QCD kinetic theory

- Quasi-particle distribution

$$f^i_{\rm eff} = \frac{1}{\exp\left(\omega_i/T\right) \pm 1}$$

where $\omega_i = \sqrt{p^2 + m_i^2} + W^i_{\rm eff}$

In-medium correction: $W^i_{\rm eff}(T)$

E.g. Biro et al., Phys. Atom. Nucl. 66, 982

Thermodynamic consistency

$$\frac{\partial \Phi_i}{\partial T}\Big|_{\mu=0} = -\int \frac{g_i d^3p}{(2\pi)^3} \frac{\partial \omega_i}{\partial T} f^i_{\rm eff}$$

- Thermodynamic relations

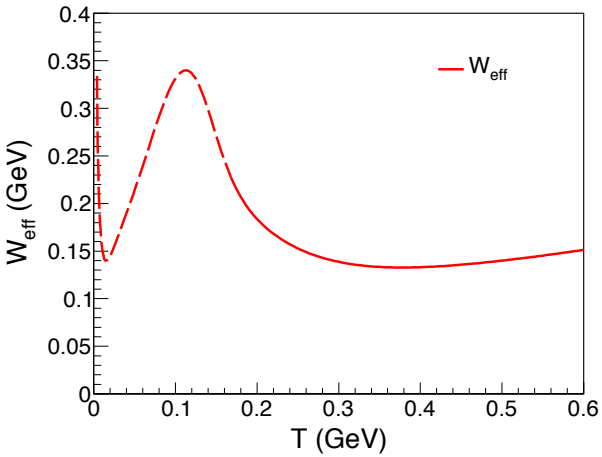
Partition function: $\ln Z_i = \pm V \int \frac{g_i d^3p}{(2\pi)^3} \ln\left[1 \pm \exp\left(-\frac{\omega_i}{T}\right)\right] - \frac{V}{T}\Phi_i(T)$

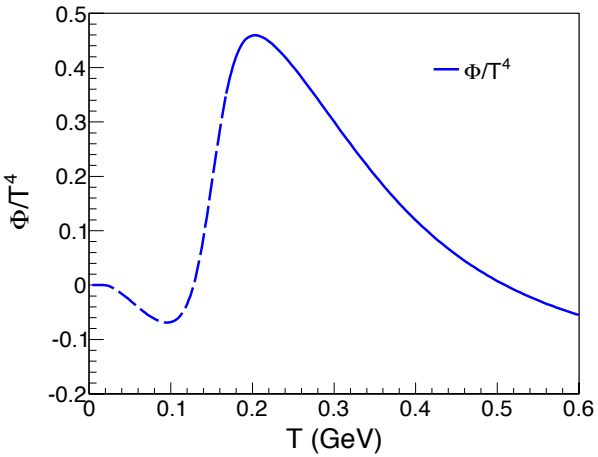
Energy density: $e = -\frac{1}{V}\sum_i \frac{\partial \ln Z_i}{\partial \beta} = \sum_i \int \frac{g_i d^3p}{(2\pi)^3} \omega_i f^i_{\rm eff} + \Phi$

Pressure: $P = \frac{1}{V}\sum_i T \ln Z_i = \frac{1}{3}\sum_i \int \frac{g_i d^3p}{(2\pi)^3} \mathbf{p} \frac{\partial \omega_i}{\partial \mathbf{p}} f^i_{\rm eff} - \Phi$

QCD kinetic theory

- Quasi-particle distribution
  - Effective interaction $W^i_{\rm eff}(T)$ and background field contribution $\Phi_i(T)$ are determined by lattice QCD EoS





Note: quasi-particle picture is better than ideal gas but may not be best

- We have n^g_{eq} and n^q_{eq}
- Thermal photon emission rate is also modified; it leads to additional enhancement of v_2

Input for the model

- Thermal photon emission rate
  - $$E\frac{dR^\gamma}{d^3p} = \frac{1}{2}\left(1-\tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\rm hadron}}{d^3p} + \frac{1}{2}\left(1+\tanh\frac{T-T_c}{\Delta T}\right)E\frac{dR^\gamma_{\rm QGP}}{d^3p}$$

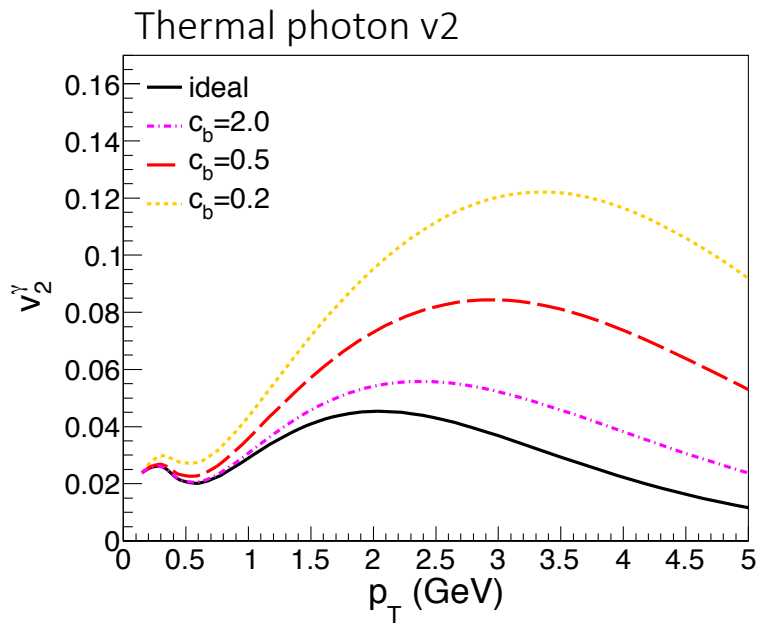
    Turbide, Rapp and Gale, PRC 69, 014903 — Strickland, PLB 331. 245

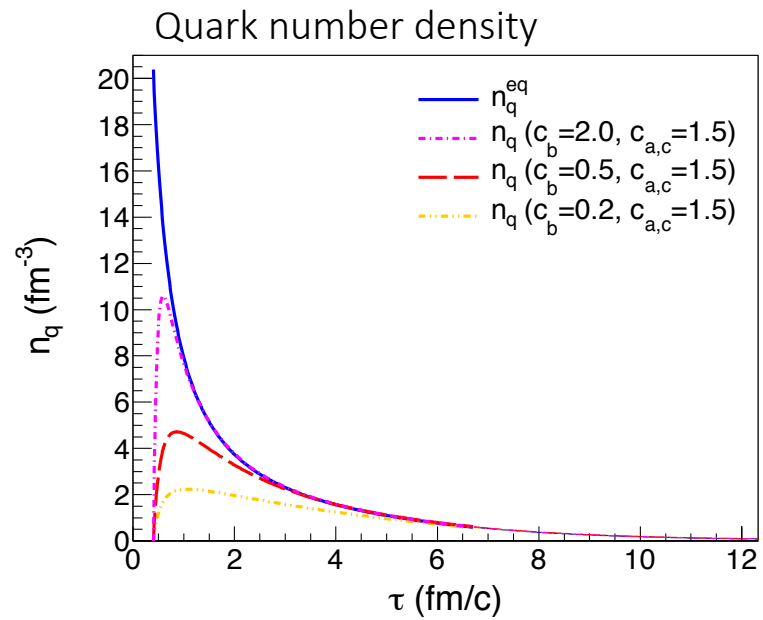
    where $T_c = 0.17\ \mathrm{GeV}$ and $\Delta T = 0.017\ \mathrm{GeV}$ with $f_i = (n_i/n_i^{\rm eq})f_i^{\rm eff}$

- Hydrodynamic parameters (Initial conditions + fluid properties)
  - Gluon energy distribution: MC Glauber (200 GeV Au-Au at b = 6 fm)
  - Quark energy distribution: 0 GeV/fm^3
  - Initial time: 0.4 fm/c
  - Equation of state: Lattice QCD
  - Chemical reaction rates: $r_i = c_i T$ where c_i ranges are $0.2 \le c_b \le 2$ ($\tau_b \sim 0.5$–5 fm/c) and $0 \le c_{a,c} \le 3$ ($\tau_{a,c} \sim 0.3$–∞ fm/c)

Thermal photon v_2

- With chemical equilibration (and ideal distribution)



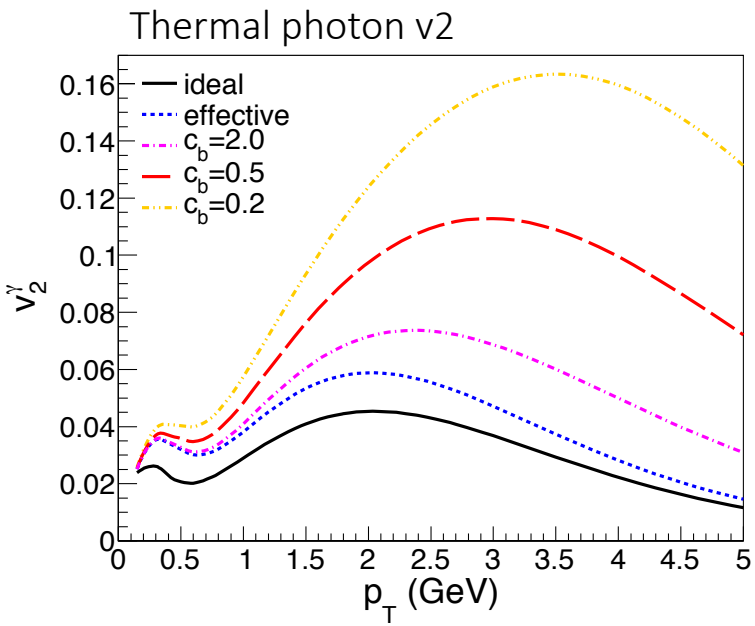


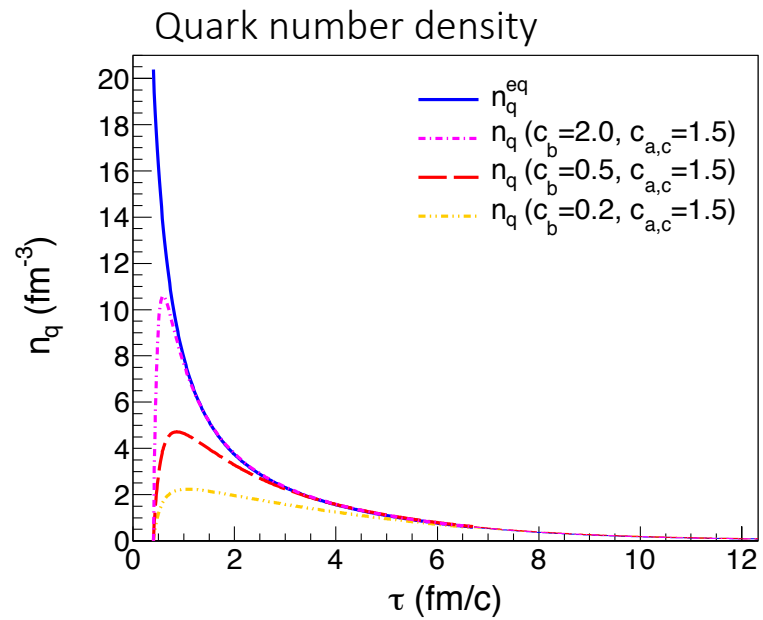
Late quark chemical equilibration ($\tau_{\rm chem} \sim 1/c_b T$) leads to visible enhancement of thermal photon v_2

$\tau_{\rm chem} \sim 2\ {\rm fm}/c$ is motivated in an early equilibration model (AM and B. Müller, arXiv: 1403.7310) $\Leftrightarrow$ $c_b = 0.5$ for $T \sim 0.2\ {\rm GeV}$

Thermal photon v_2

- With chemical equilibration and effective distribution





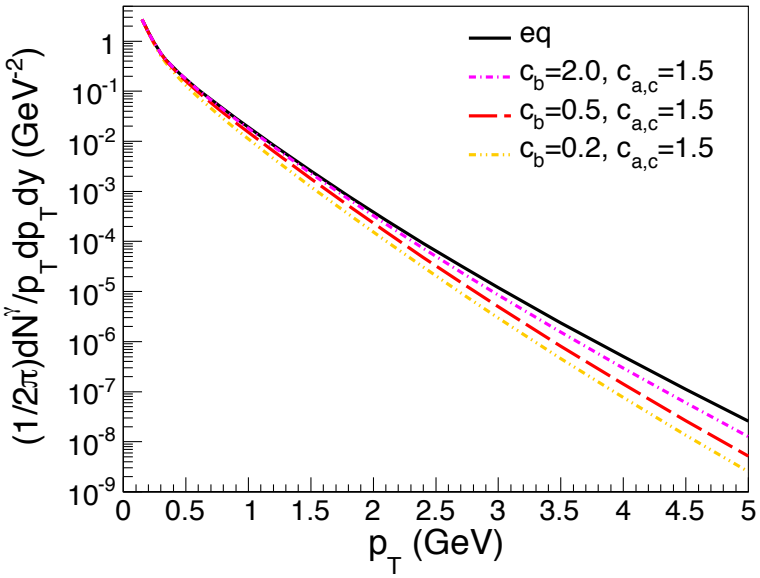
In-medium corrections to parton distribution functions additionally enhance thermal photon v_2

Note: Prompt photons are not included – they will reduce v_2

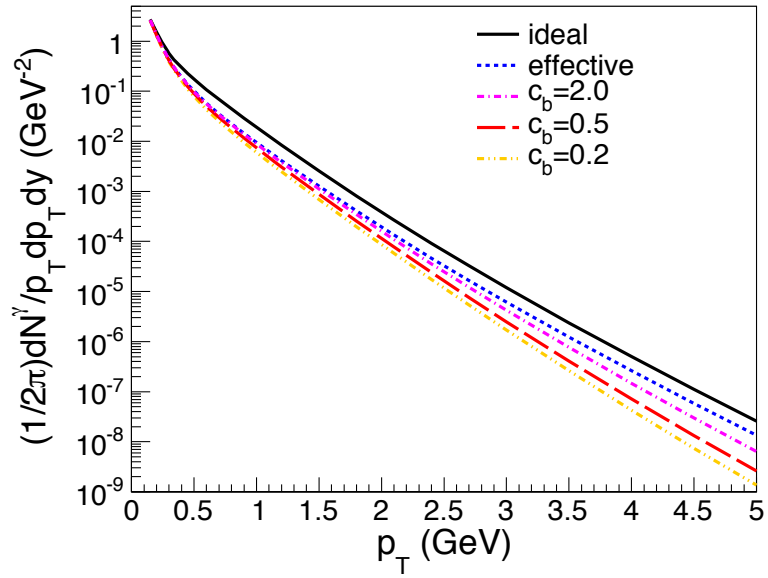
Thermal photon p_T spectra

- With chemical equilibration

Ideal distribution



Effective distribution



p_T spectrum is reduced by both late quark chemical equilibration and in-medium corrections

More sophisticated photon emission rate and dynamical EoS are required

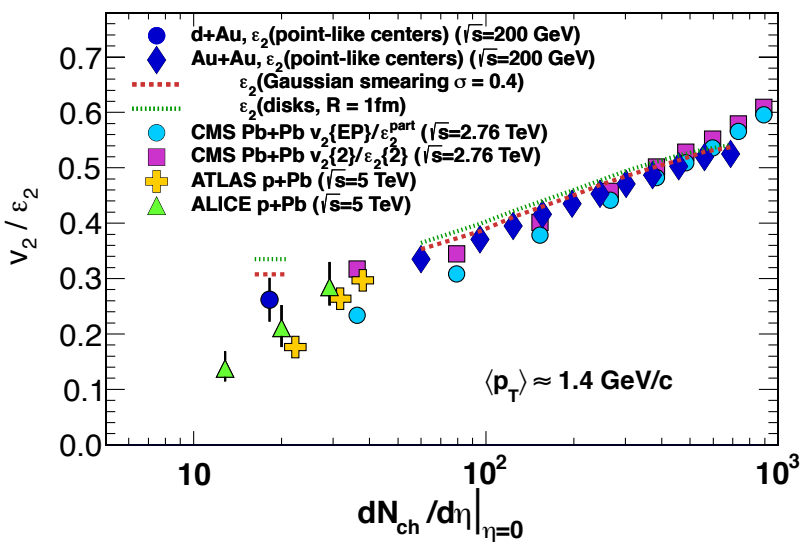
(Cf. Gelis et al., JPG 30, S1031)

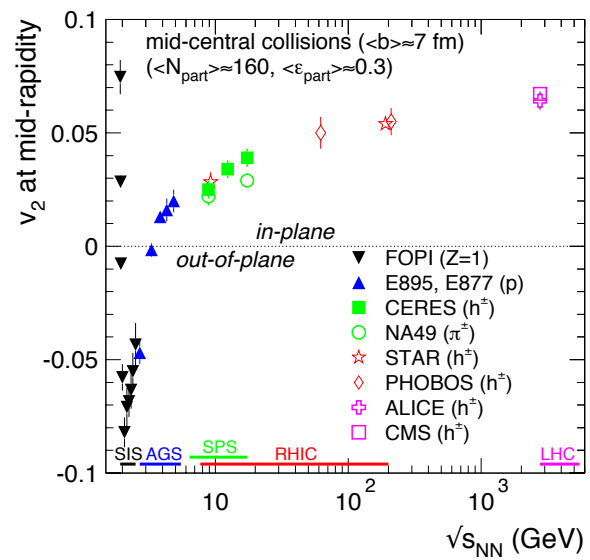
Summary and outlook

- Direct photons are essential in understanding the QGP
  - Flow harmonics are large: "Photon v_2 puzzle"
  - Thermal photon anisotropy is enhanced by late quark chemical equilibration
    - Early equilibration from CGC to QGP may be a key
  - In-medium corrections to phase-space distributions can also enhance v_2
    - Emission rates are consistent with lattice QCD equation of state
  - Photon spectra is reduced by those mechanisms and prompt photons will reduce v_2 enhancement
  - We need additional mechanisms - increase photons in later stages? Or introduce v_2 to prompt photons?

Summary and outlook

- Some theory-experiment prospects
  - Higher harmonics v_4 and v_5 of direct photons
  - Photons from small systems (d-Au, He^3-Au etc.)
    - Will they be similar to hadronic v_n? Are they from the same origin?
  - Photons from systems at lower energies
    - Is there a medium? Will there be squeeze-out for photons?





The end

Thank you!

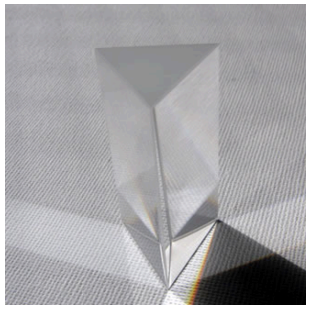
Medium refraction

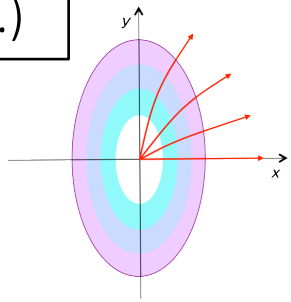
AM, arXiv:1408.1410 [nucl-th]

- A lens and prism
  - A transparent medium can be refractive
    - ⇨ A transparent QCD medium can work as a 4-dimensional lens
    - ⇨ Geometrical anisotropy (ε_2, ε_3, ...) is directly mapped onto photon flow harmonics (v_2, v_3, ...)
    - ⇨ I investigate the effects of medium refraction
  - Fermat's principle

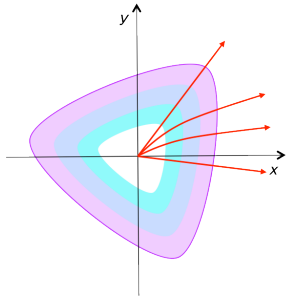
$$\frac{d^2x}{d\tau} = \frac{1}{2}\frac{dn^2}{dx}, \quad \frac{d^2y}{d\tau} = \frac{1}{2}\frac{dn^2}{dy}$$

    - ⇨ The path of a ray is determined by the gradient in refractive index n





Elliptic flow



Triangular flow

QGP optics

- A model for the refractive index
  - Hard thermal loop estimations imply

$$n^2(T,\omega) = 1 - \frac{\omega_p^2(T)}{\omega^2}$$

Parameterized as
$\omega_p^2(T) = a^2 T^2$

Doppler effects (due to flow)
$$\omega = \frac{\omega_0}{\gamma(1+\beta\cos\Delta\phi)}$$

This is a model – one may find, e.g., a pseudo critical behavior

  - Speed of light in the plasma

Phase velocity: $v_{\rm ph} = \frac{1}{n} > 1$

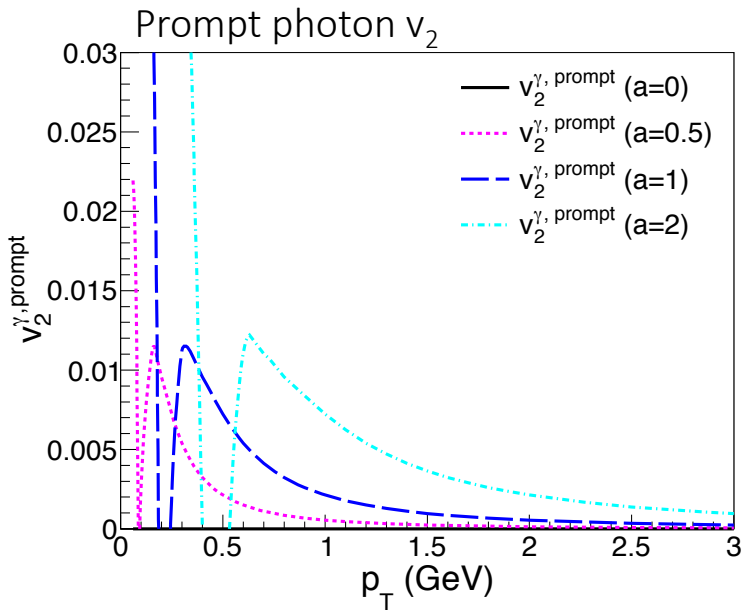
Refraction in the medium

Group velocity: $v_{\rm g} = \frac{\partial\omega}{\partial k} = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} < 1$

Causality is not violated

Numerical results

- Prompt photon flow harmonics (= 0 if no refraction)



(I) Positive prompt photon v_2 is generated for non-absorptive region

Not large enough to explain the large direct photon v_2

- Thermal photons are necessary
- Pseudo-critical behavior of refractive index?

(II) Negative prompt photon v_2 in ultra-low momentum region

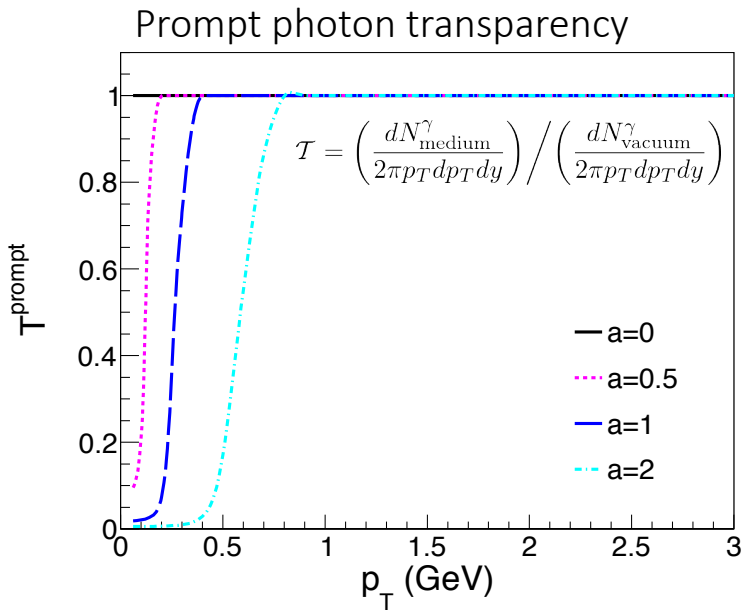
Absorptive region with $n^2 < 0$ forms a "dark core"

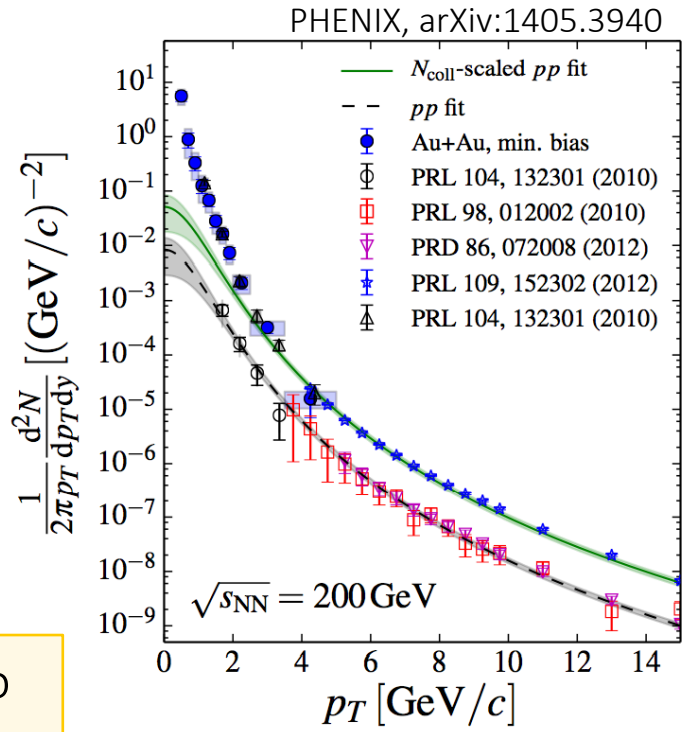
(III) Positive prompt photon v_2 near $p_T = 0$

Semi-opaque medium: easier to come out of minor axis

Numerical results

- Prompt photon transparency





The transparency decreases below ω_p due to imaginary refractive index

Experimental data seem to show no sudden reduction above 0.5 GeV

⇨ a < 1-2 is preferred; constraint on QGP plasma frequency?