Photon and Dilepton Production in Semi-QGP and its effect on elliptic flow

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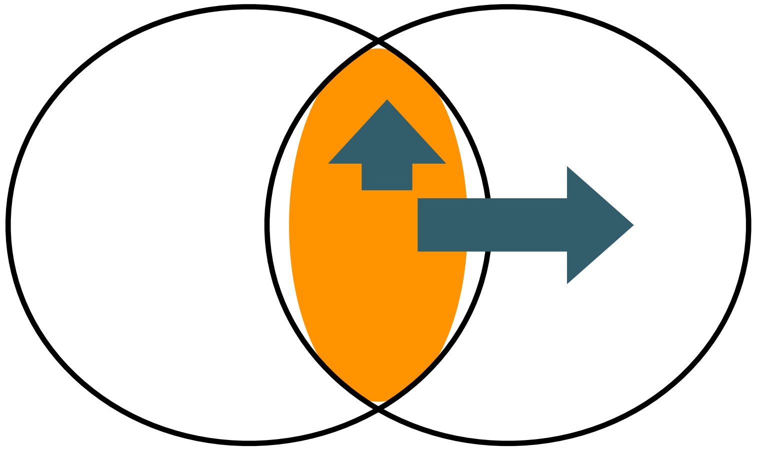
Outline

- Introduction: Electromagnetic Probe, Semi-QGP
- Dilepton Production
- Photon Production
- Effect on Photon v_2

Electromagnetic Probe

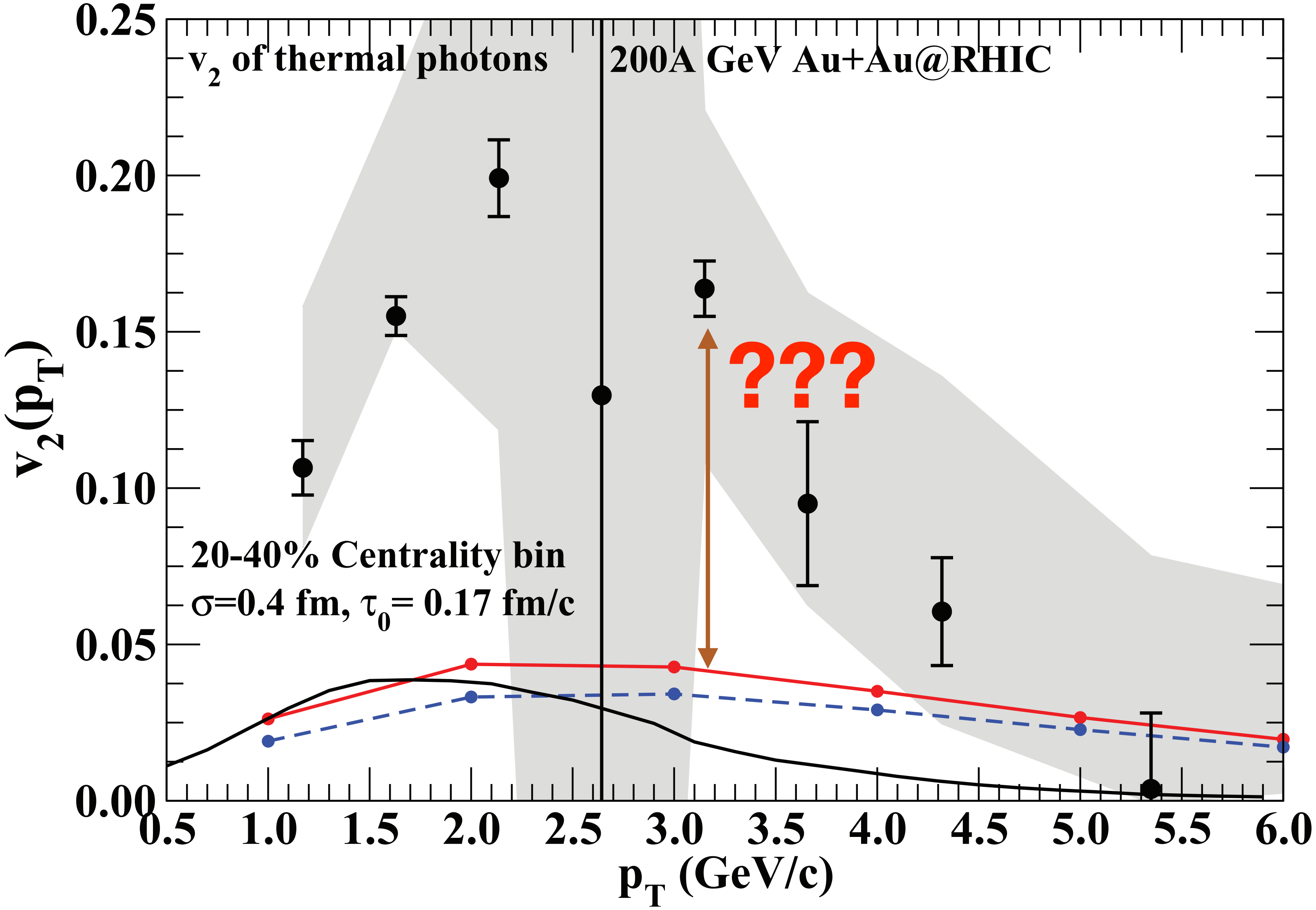
Electromagnetic probe (lepton, photon) is phenomenologically important because

- Once generated, it goes out without interacting with medium.
- It reflects the microscopic properties of medium like quark spectrum.
- It also reflects **the macroscopic properties like elliptic flow.**



Electromagnetic Probe

<u>Photon v_2 puzzle</u>: theory prediction of v_2 is much smaller than experimental data



Theory: Rupa Chatterjee et al., PRC **88**, 034901 (2013)
Experiment: PHENIX Collaboration, PRL **109**, 122302 (2012).

One possible solution:
considering
(partial) confinement effect

Effect of confinement

In QGP, Polyakov loop is used as (quasi) order parameter of deconfinement transition.

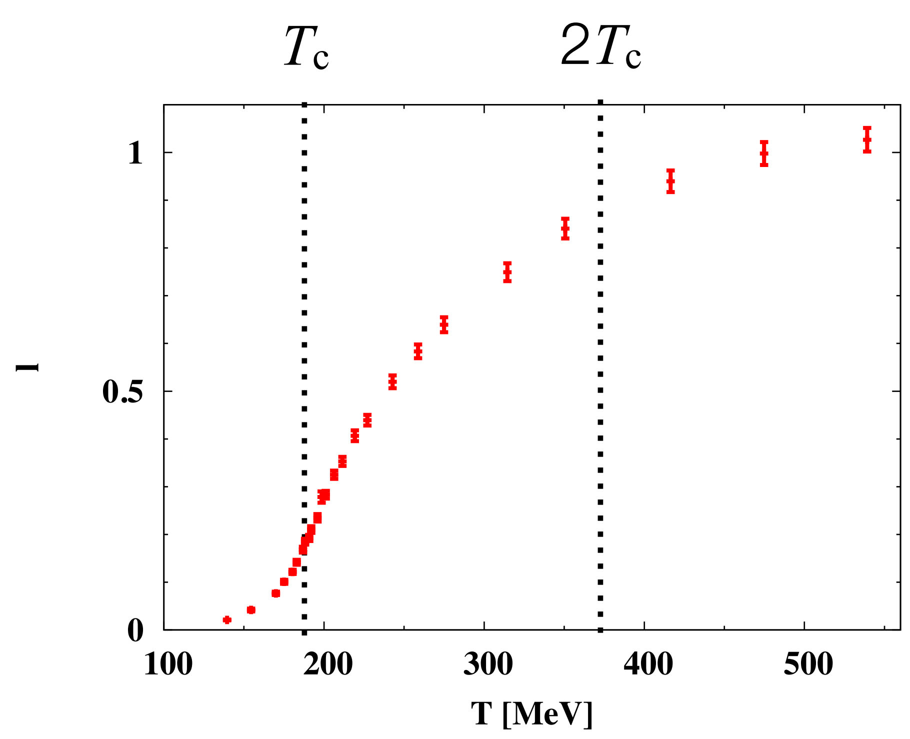
$$l \equiv \frac{1}{N_c} \mathrm{Tr} \left\langle \mathcal{P} \exp\left(\int_0^\beta d\tau g A^0(\tau, \vec{x}) \right) \right\rangle$$

l=1 ➡ Deconfined

l=0 ➡ Confined

Semi-QGP

$0 < l < 1$ even around $\sim 2T_c$.



Lattice QCD: A. Bazavov et al.,
PRD **80**, 014504 (2009)

It is necessary to consider effect of nontrivial l even in QGP phase.

(Semi-QGP)

Semi-QGP

Y. Hidaka and R. D. Pisarski, PRD **80**, 036004 (2009)

Simple model to analyze effect of Polyakov loop in perturbative computation:

QCD Lagrangian + background gluon

(quark ψ, gluon fluctuation a) (A_0)

$$\mathcal{L}[a,\psi,\bar{\psi}] = i\sum_{j=1}^{N_f}\bar{\psi}_j \not{D}[a]\psi_j - \frac{1}{4}F^{\mu\nu a}[a]F^{a}_{\mu\nu}[a]$$

$$a_0 \longrightarrow A_0 + a_0$$

$$(A_0)^{ab} = \frac{\delta^{ab}Q^a}{g} = (Q, -Q, 0)/g$$

cf: PNJL model: integrate out gluon

K. Fukushima, Phys. Lett. B **591**, 277 (2004)

Semi-QGP

E. Gava and R. Jengo, Phys. Lett. B **105**, 285 (1981)
Y. Burnier, M. Laine and M. Vepsalainen, JHEP **1001**, 054 (2010)
N. Brambilla, J. Ghiglieri, P. Petreczky and A. Vairo, Phys. Rev. D **82**, 074019 (2010).

After removing perturbative correction to l, background gluon is obtained from l obtained from lattice calculation.

$$l(Q=0) = 1 + \delta l(Q=0)$$

$$\delta l(Q=0) = \frac{g^2 C_f m_D}{8\pi T}$$

$$C_f \equiv (N_c^2-1)/(2N_c)$$

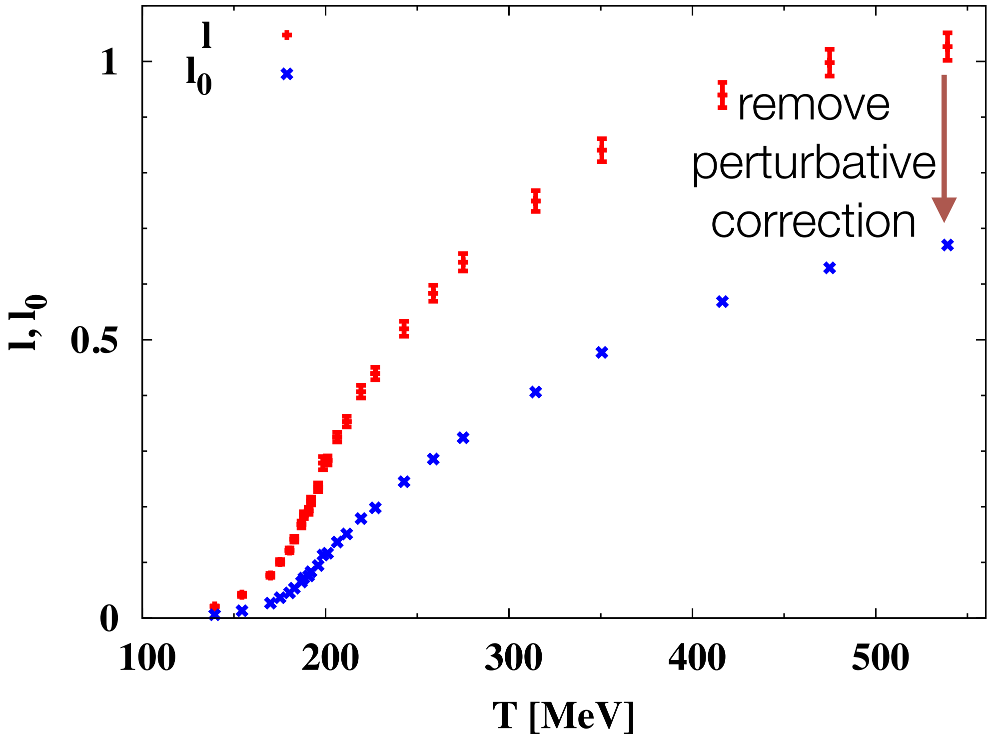
(g: running coupling at one-loop
m_D: Debye mass of gluon at one-loop)

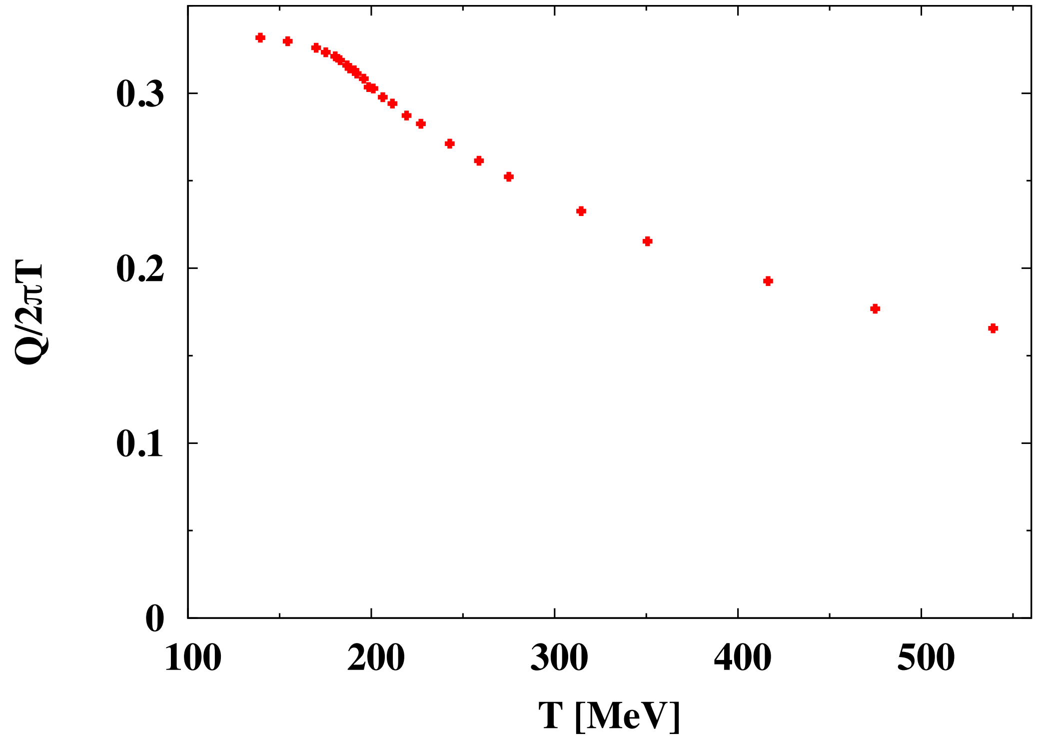
assumption

$$l(Q) = e^{\delta l(Q=0)} \underline{l_0(Q)}$$

Polyakov loop after subtraction

$$l_0 = \frac{1+2\cos\beta Q}{3}$$





Semi-QGP

Fourier transformation

$$\overline{\psi}\gamma^0(\partial_0 + igA_0)\psi \quad \Rightarrow \quad -\overline{\psi}_a\gamma^0(E - iQ_a)\psi_a$$

imaginary chemical potential coupled with color charge

quark distribution: $$\frac{1}{e^{\beta(E-iQ_a)}+1}$$

gluon distribution: $$\frac{1}{e^{\beta(E-iQ_a+iQ_b)}-1}$$

Statistical Confinement

confinement phase

$$\frac{1}{N_c}\sum_a \frac{1}{e^{\beta(E-iQ_a)}+1} \Rightarrow \frac{1}{e^{\beta N_c E}+1}$$

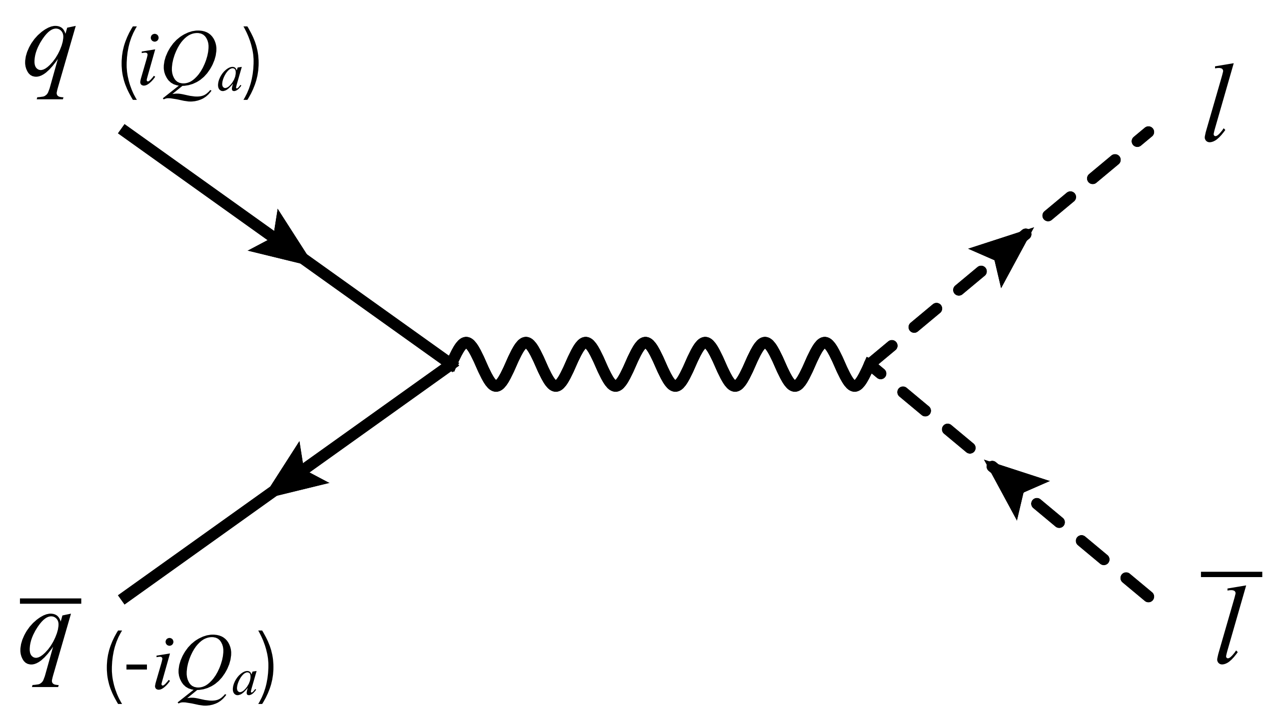
T is scaled by N_c in confined phase.

(Distribution is suppressed: **statistical confinement**)

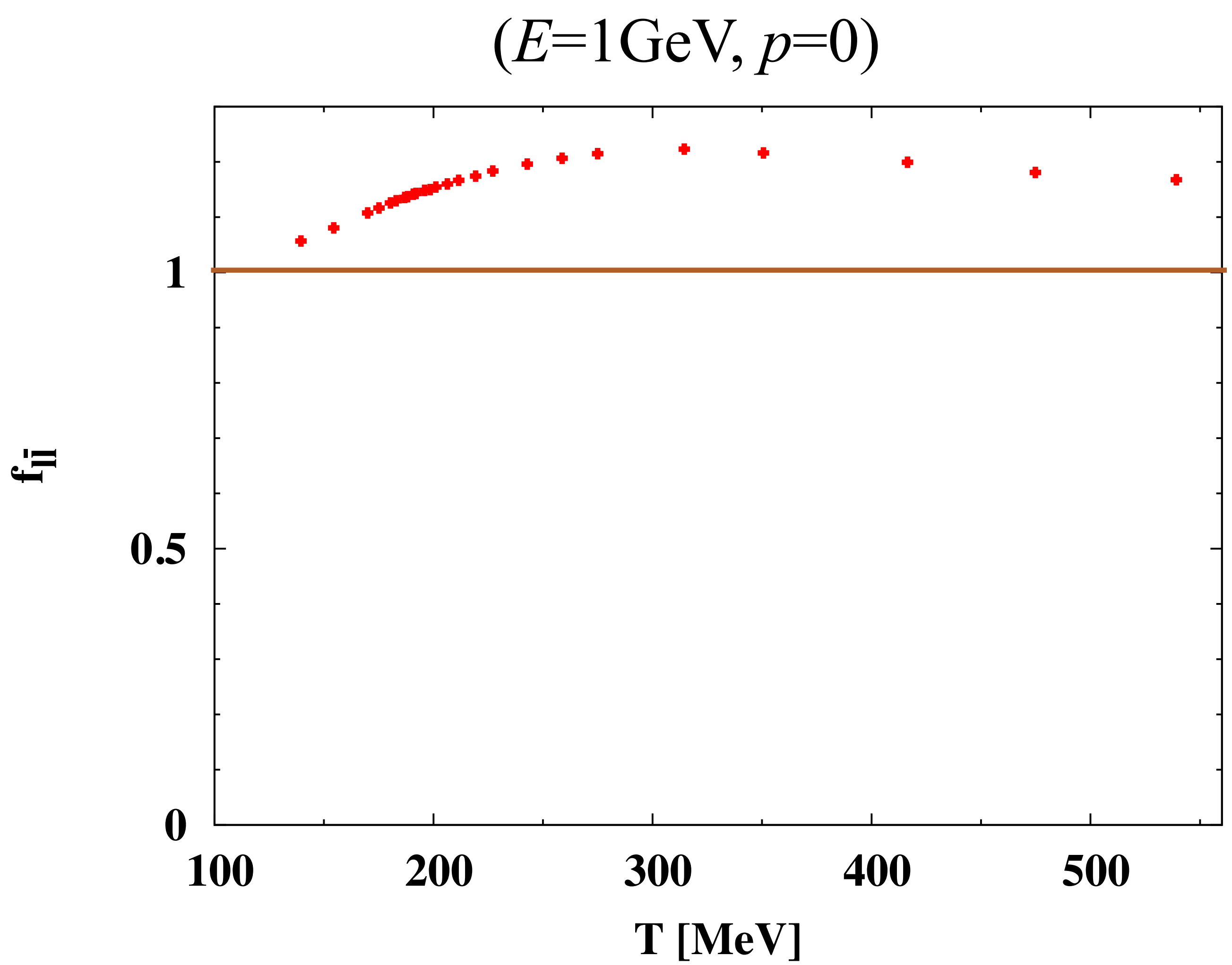
Dilepton Production

2⇄2 scattering (pair annihilation)

Distribution function is modified



Dilepton Production — Result



$$\frac{d\Gamma}{d^4p} = f_{l\bar{l}}(Q)\frac{d\Gamma}{d^4p}\bigg|_{Q=0}$$

$$f_{l\bar{l}}(Q) \equiv \widetilde{f}_{l\bar{l}}(Q)/\widetilde{f}_{l\bar{l}}(0)$$

$$\widetilde{f}_{l\bar{l}} = 1 - \frac{2T}{3p}\ln\frac{1+3\ell e^{-p_-/T}+3\ell e^{-2p_-/T}+e^{-3p_-/T}}{1+3\ell\, e^{-p_+/T}+3\ell e^{-2p_+/T}+e^{-3p_+/T}}$$

$$p_\pm = \frac{E\pm p}{2}$$

$$\frac{d\Gamma}{d^4P}\bigg|_{Q=0} = \frac{\alpha_{em}}{6\pi^4}\, n(E)\left(1-\frac{2T}{p}\ln\frac{1+e^{-p_-/T}}{1+e^{-p_+/T}}\right)$$

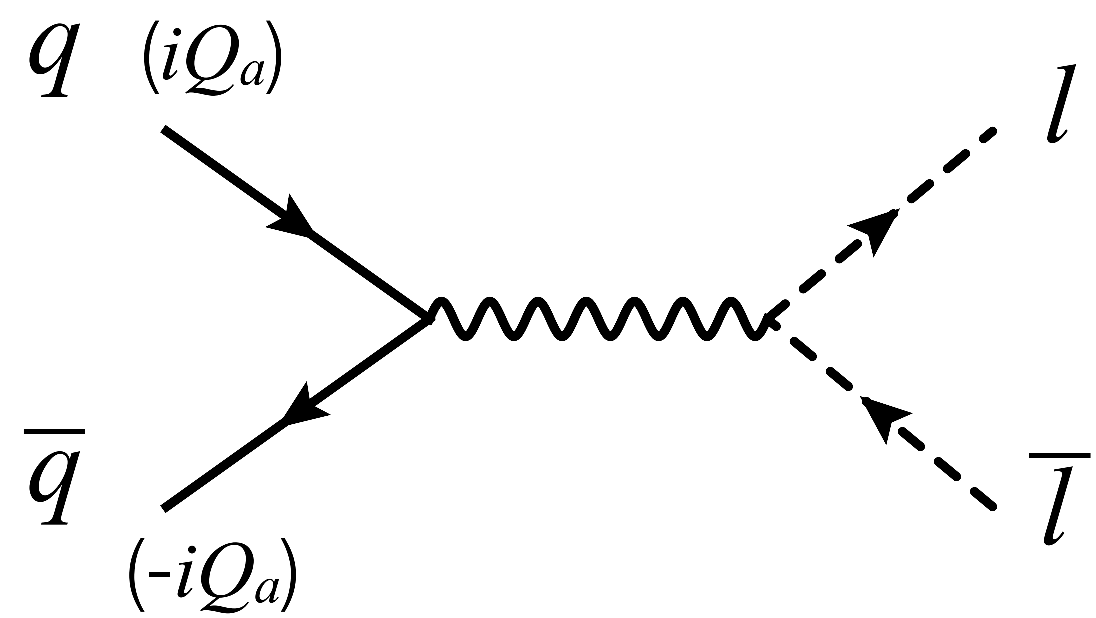
$$n(k^0) \equiv (e^{\beta k^0}-1)^{-1}$$

Not suppressed, even slightly enhanced!

(Naively, confinement reduces chance of 2⇄2 scattering, thus suppresses dilepton production)

Physical Interpretation of Dilepton Enhancement

(Opposite imaginary chemical potentials)
<u>Mesonic, Color Singlet</u>



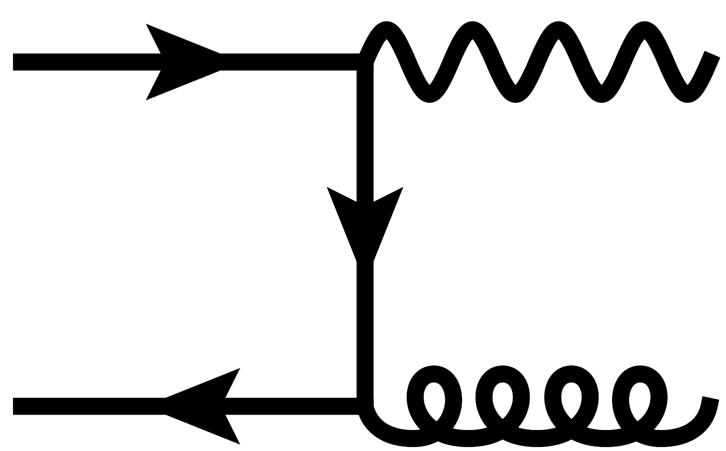
Boltzmann approximation: $$\overset{q}{e^{-\beta(E_1 - iQ_a)}} \times \overset{\overline{q}}{e^{-\beta(E_2 + iQ_a)}} = e^{-\beta(E_1+E_2)}$$

The phases cancels, *NO* suppression due to Polyakov loop!!

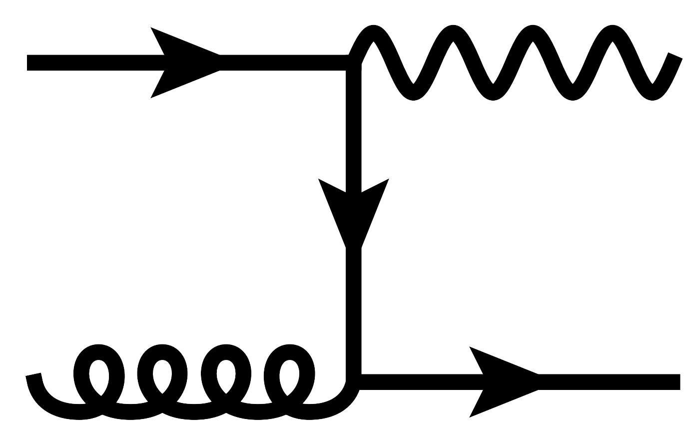
Photon Production

2⇄2 scattering

(pair annihilation)



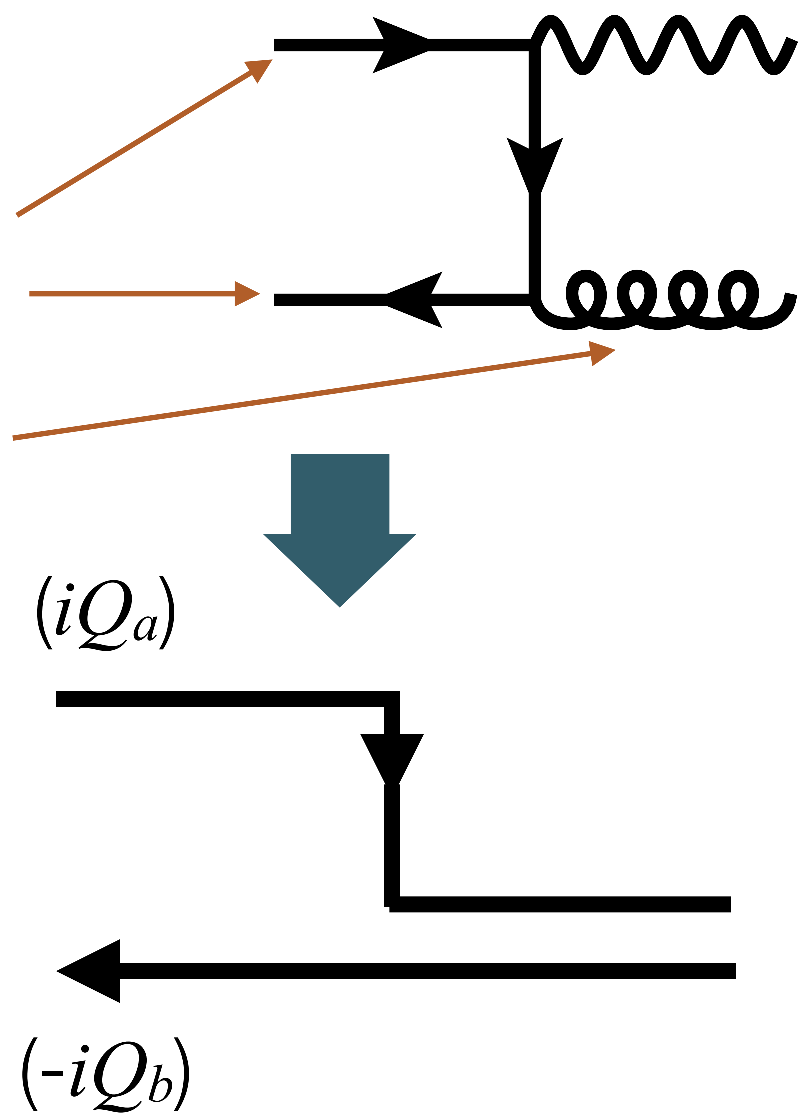
(Compton scattering)



Photon Production

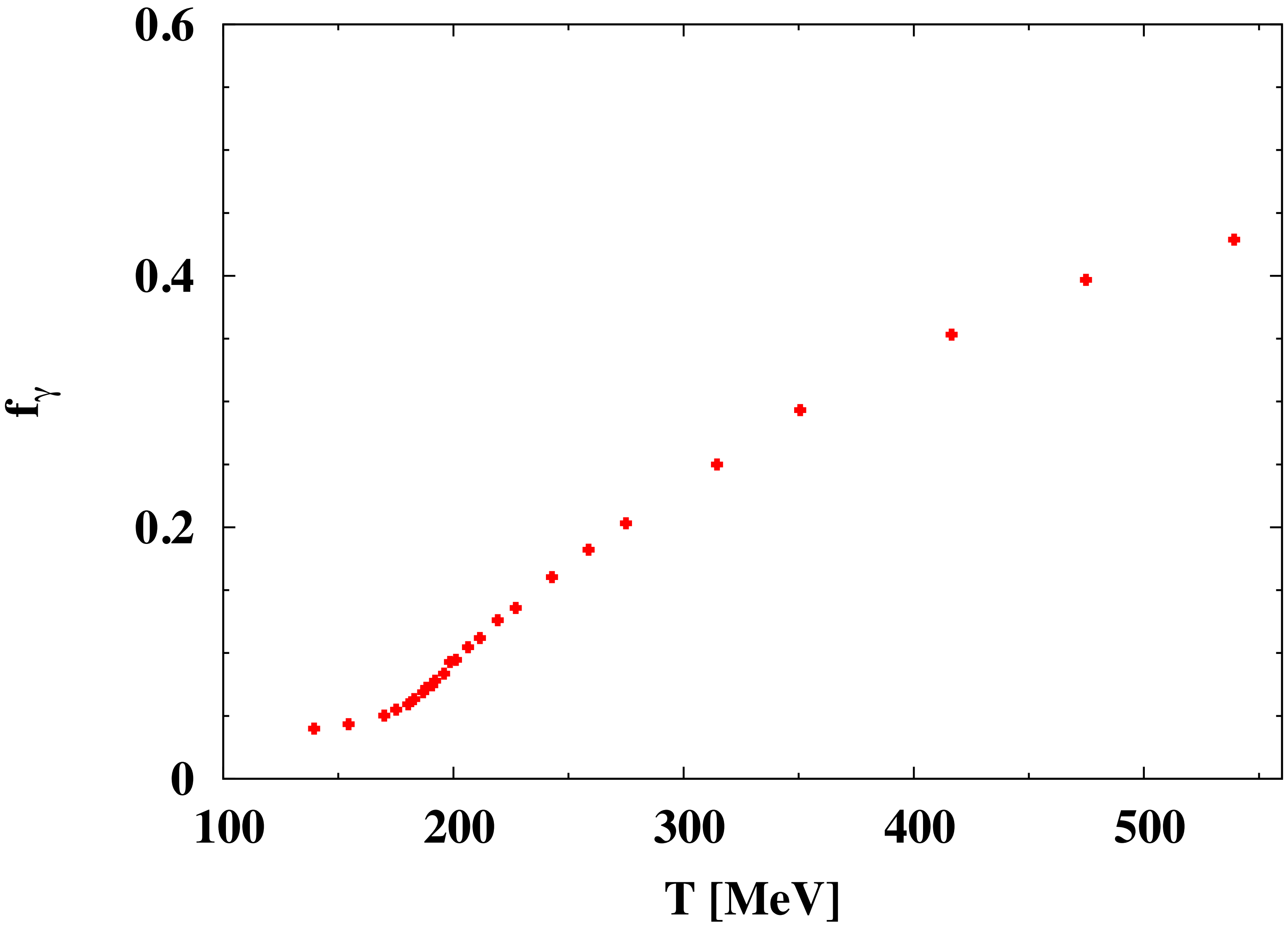
Color structure (double line notation)

Distribution function is modified



Two independent color indices.

Photon Production — Result



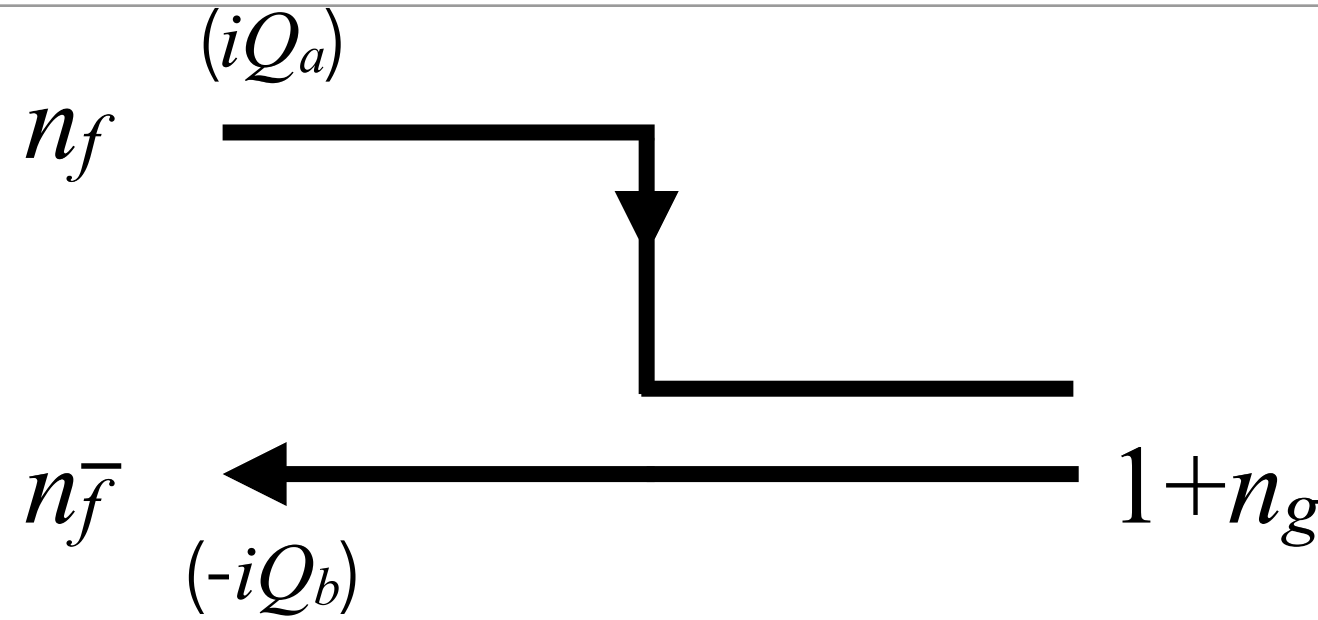
$$E\frac{d\Gamma}{d^3p}\bigg|_{Q\neq 0} = f_\gamma(Q)\; E\frac{d\Gamma}{d^3p}\bigg|_{Q=0}$$

$$E\frac{d\Gamma}{d^3p}\bigg|_{Q=0} = \frac{\alpha_{em}\alpha_s}{3\pi^2}\; \mathrm{e}^{-E/T}\; T^2\; \ln\left(\frac{E}{g^2T}\right)$$

$$f_\gamma(Q) = 1 - 4\,q + \frac{10}{3}\,q^2 \qquad\qquad q = \frac{Q}{2\pi T}$$

Suppressed.

Interpretation of Photon Production Suppression



q $\bar{q}$ g (final state)

Boltzmann approximation: $$\frac{1}{N_c^2}\sum_{a,b} e^{-\beta(E_1 - iQ_a)} \times e^{-\beta(E_2 + iQ_b)} \times 1 = e^{-\beta(E_1+E_2)} \times l^2$$

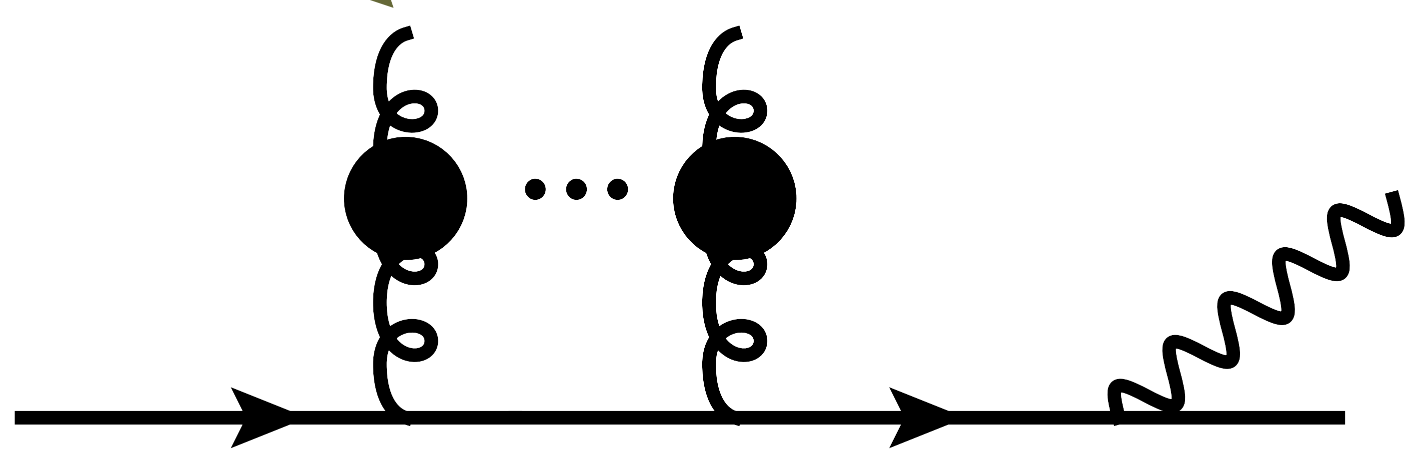
Due to the Pauli blocking in final state, the phases do not cancel, and the process is suppressed!!

LPM contribution

P. B. Arnold, G. D. Moore and L. G. Yaffe, JHEP **0111**, 057 (2001).

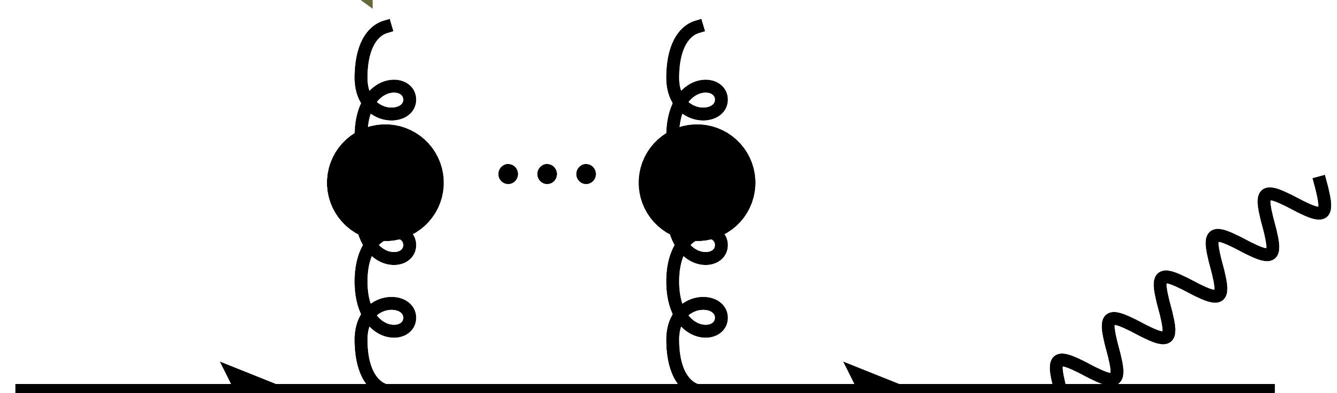
When Q_a=0, LPM diagram is as large as 2 to 2 one.

$$\frac{1}{e^{\beta E}-1} \simeq \frac{T}{E} \gg 1 \qquad (E\sim gT)$$



LPM contribution is suppressed

$$\frac{1}{e^{E-i(Q_a-Q_b)}-1} \begin{pmatrix} \simeq \dfrac{T}{E} \gg 1 & (a{=}b) \\ \sim 1 & (a{\neq}b) \end{pmatrix}$$

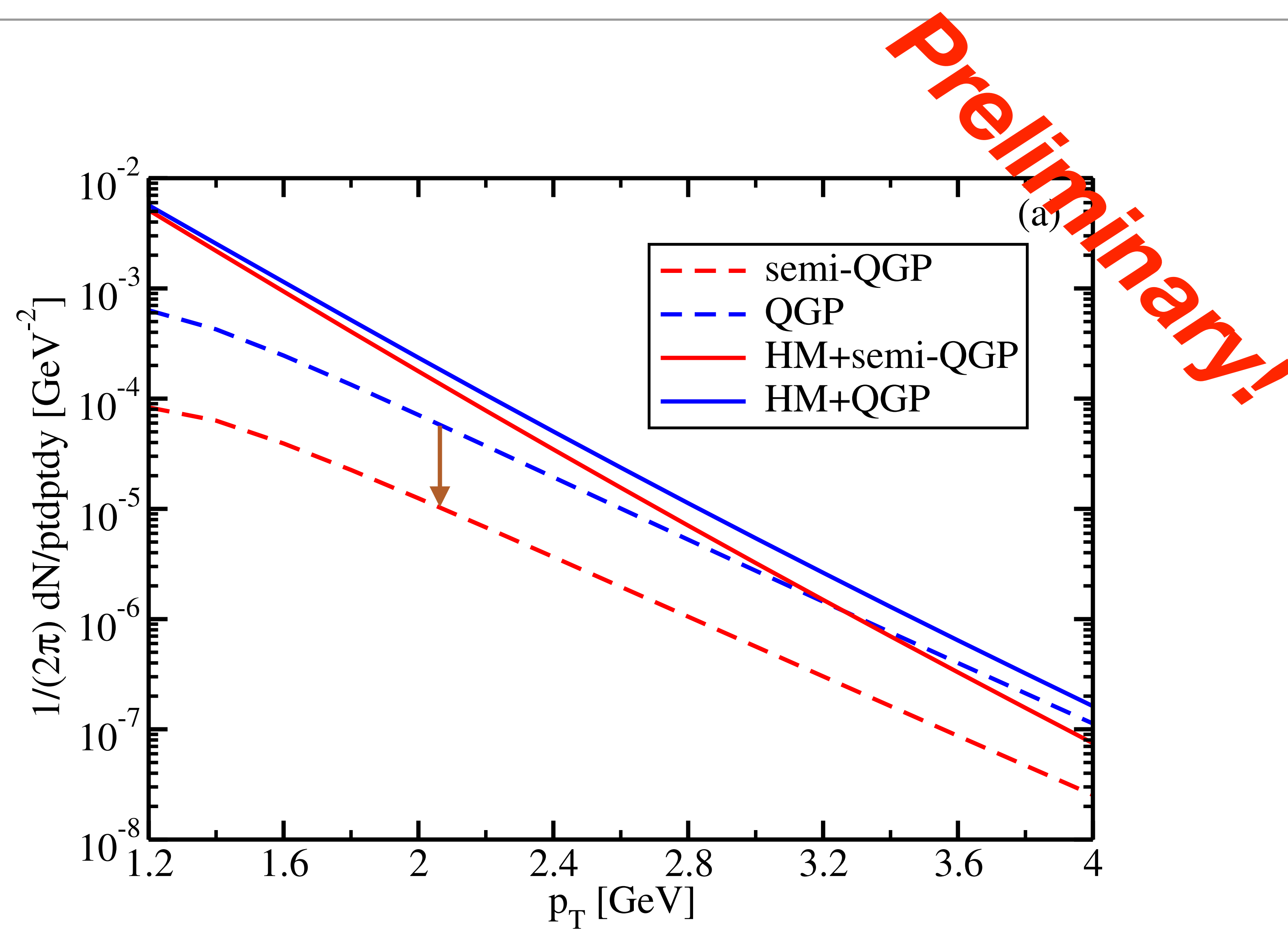


LPM diagram is suppressed by 1/N_c.

Collaboration with **C. Gale, S. Jeon, J-F. Paquet, V. Skokov, G. Vujanovic**

Effect on Elliptic Flow (v_2)

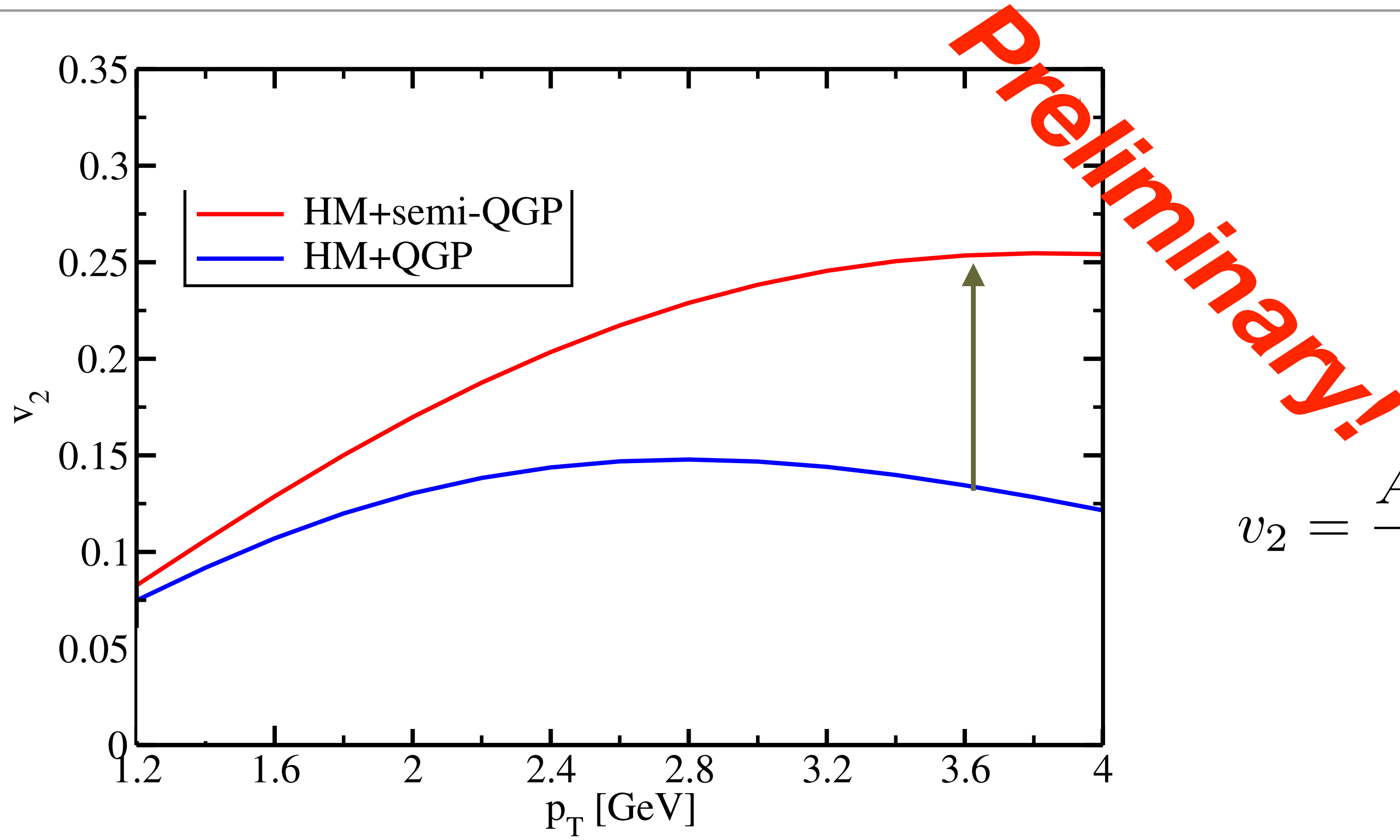
Calculation with Hydrodynamics (MUSIC):



QGP Photon is suppressed.

Collaboration with **C. Gale, S. Jeon, J-F. Paquet, V. Skokov, G. Vujanovic**

Effect on Elliptic Flow (v_2)



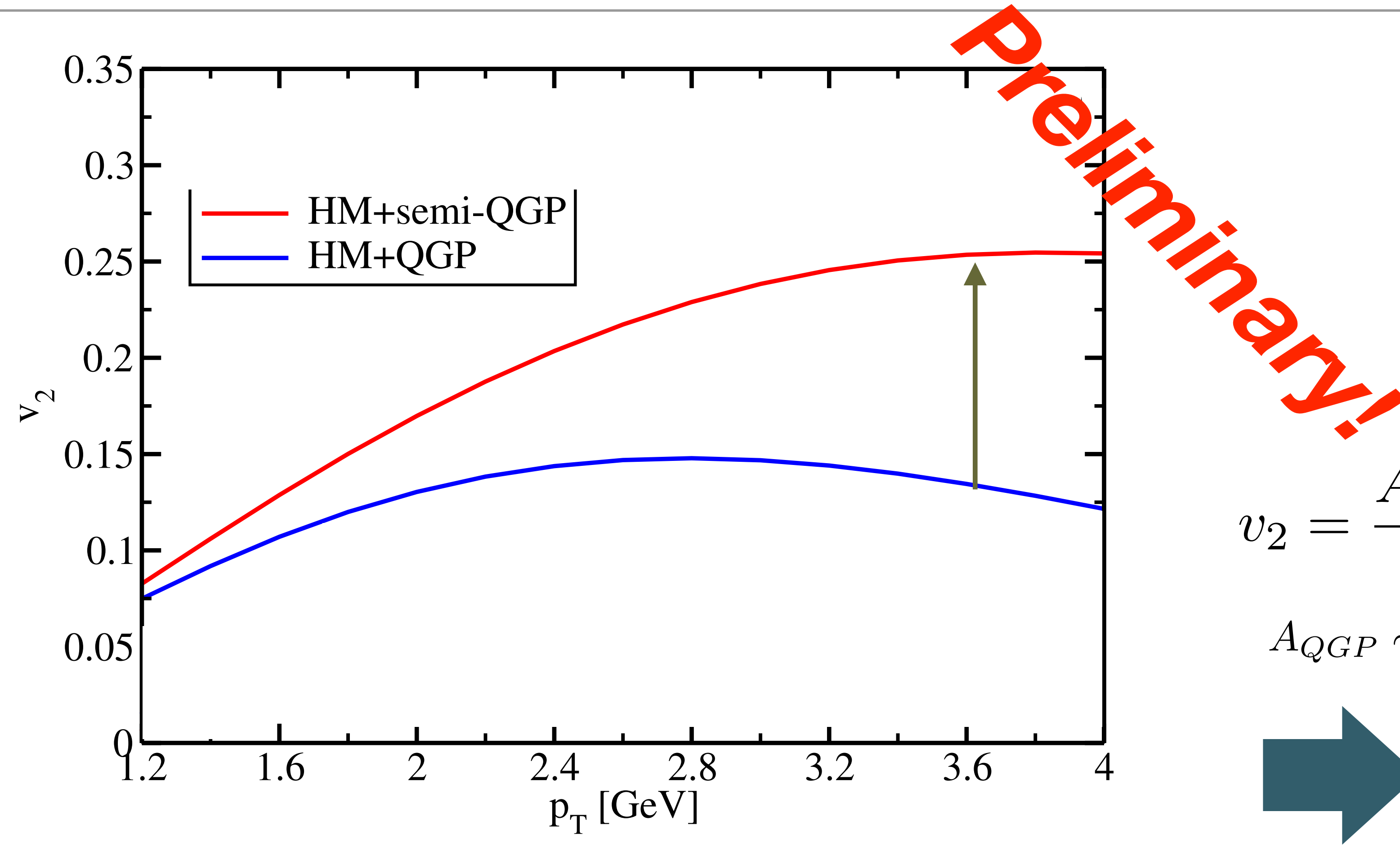
$$v_2 = \frac{A_{QGP} v_2^{QGP} + A_{Hadron} v_2^{Hadron}}{A_{QGP} + A_{Hadron}}$$

Since hadron photon has large v_2, reducing QGP photon makes total v_2 larger.

Possible solution of v_2 puzzle

Collaboration with **C. Gale, S. Jeon, J-F. Paquet, V. Skokov, G. Vujanovic**

Effect on Elliptic Flow (v_2)



$$v_2 = \frac{A_{QGP} v_2^{QGP} + A_{Hadron} v_2^{Hadron}}{A_{QGP} + A_{Hadron}}$$

$A_{QGP} \sim 0$

$\Rightarrow v_2^{Hadron}$

Since hadron photon has large v_2, reducing QGP photon makes total v_2 larger.

$\Rightarrow$ Possible solution of v_2 puzzle

Summary

- We calculated **the production rates of dilepton and real photon** by using a model which takes into account **the Polyakov loop effect** in perturbative QCD calculation.

- We found that **the photon production rate is suppressed** while **the dilepton production is enhanced** in this model.

- We saw that **the LPM effect is suppressed** in large N_c compared with 2 to 2 scattering.

- We found that the **Polyakov loop effect increases total v_2**, which suggests that **considering this effect can be a possible solution of photon v_2 problem**.

Future Work

- Full leading-order calculation of photon production and v_2. (2 to 2 beyond leading-log, LPM effect)
- Improvement of hydro simulation. (prompt photon, viscosity effect…)