Photon and dilepton production in semi-QGP

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June 9, 2015

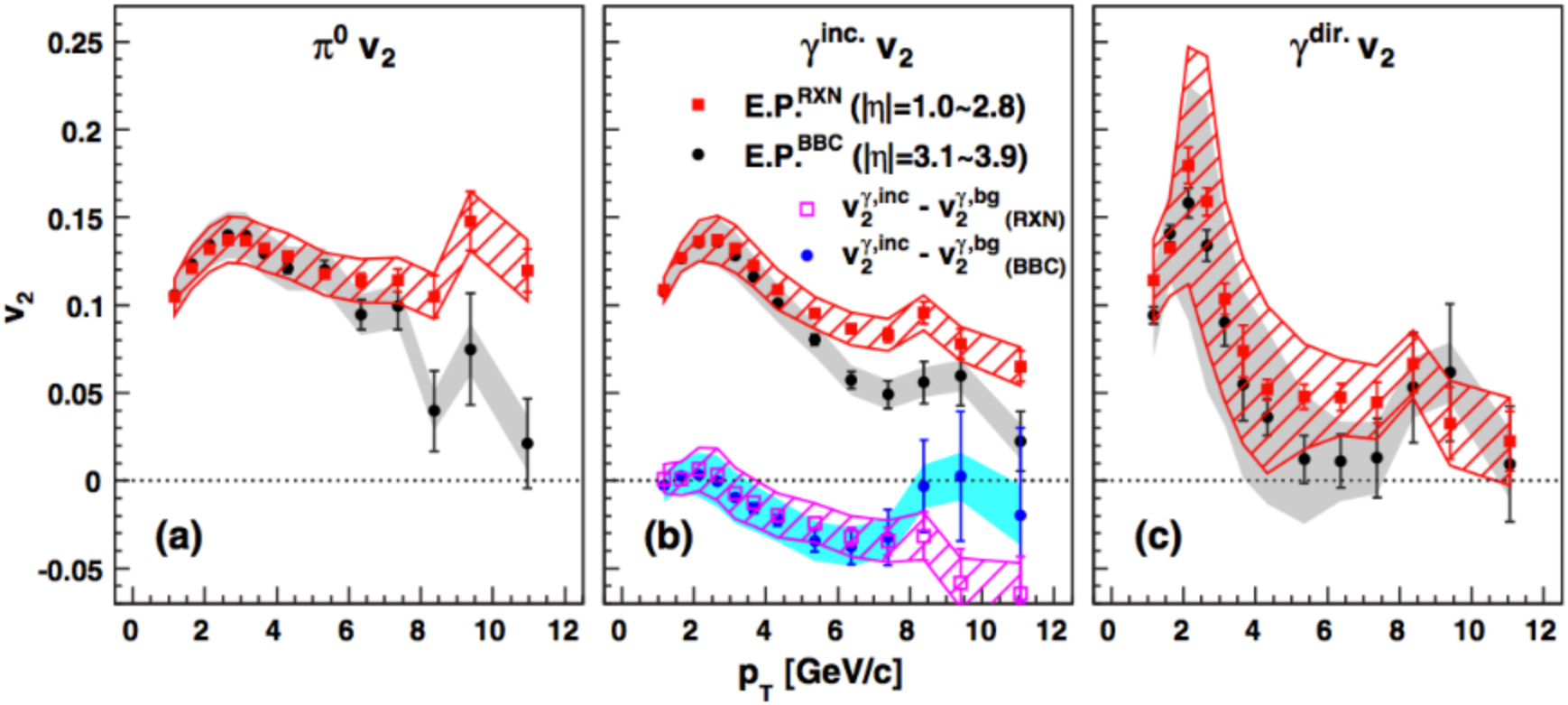
Hidaka, SL, Pisarski, Satow **1504.01770**

Hidaka et al PRL 2015

Outline

- Puzzles of photon in RHIC&LHC experiment
- Thermal photon in semi-QGP
- (Non-perturbative) Effect of Polyakov loop on quark/gluon number densities
- Dilepton enhancement in semi-QGP
- Photon suppression in semi-QGP
- Phenomenological implications of photon/dilepton production in semi-QGP

Puzzle of photon v2



PHENIX, PRL 2012

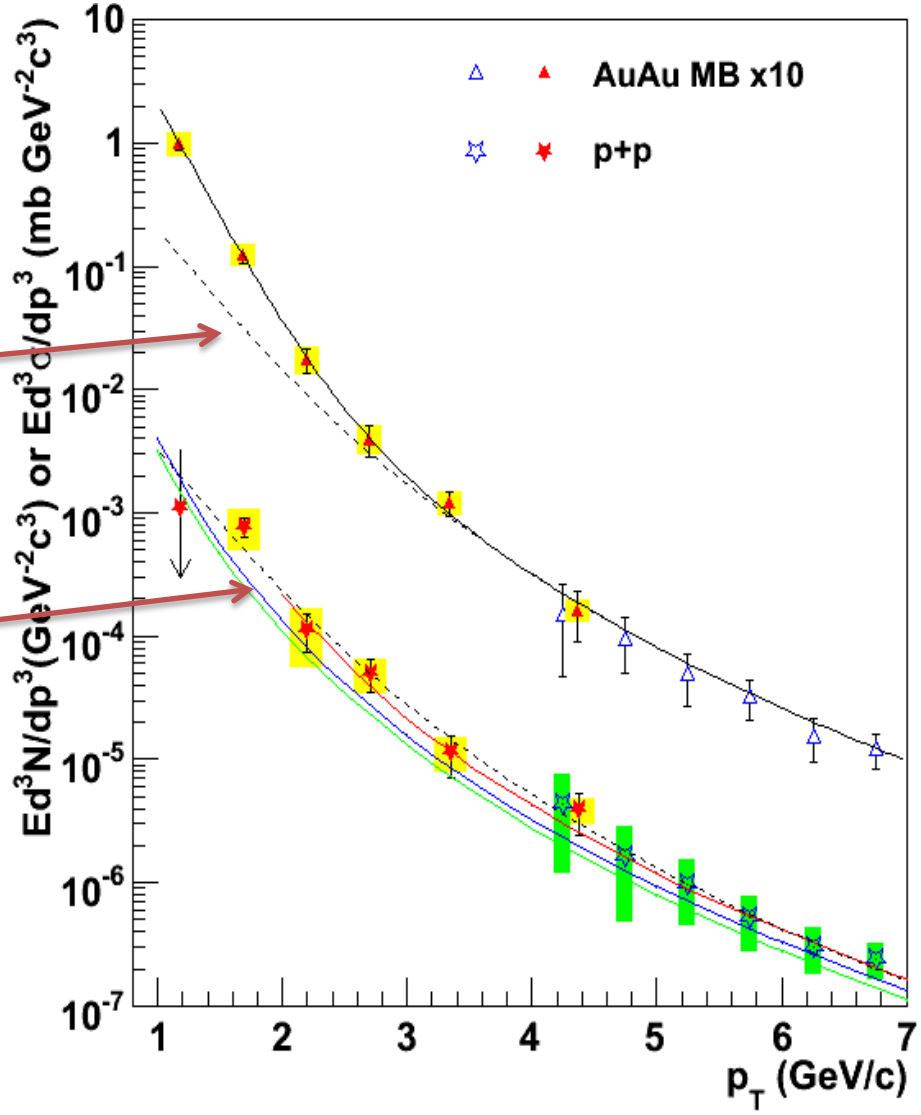
v2 of photons comparable with v2 of pions at p_T < 4GeV

Prompt photons and QGP photon expected to have negligible flow

Photon yield puzzle

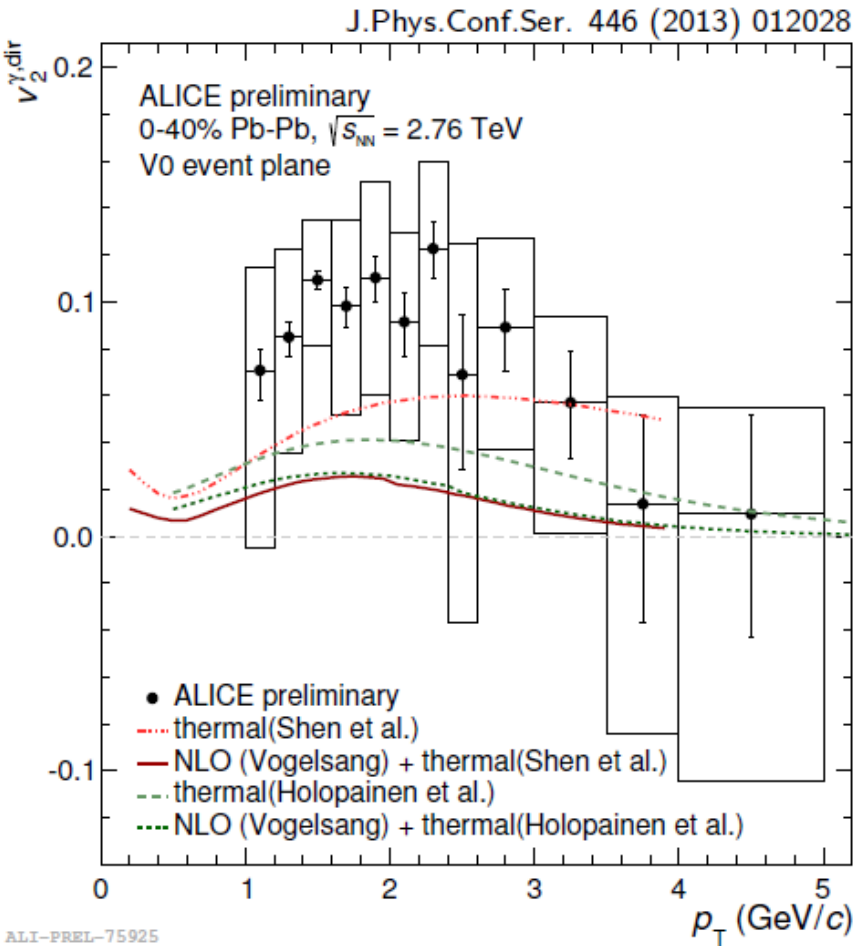
scaled pQCD fails to describe photon yield in AA collisions

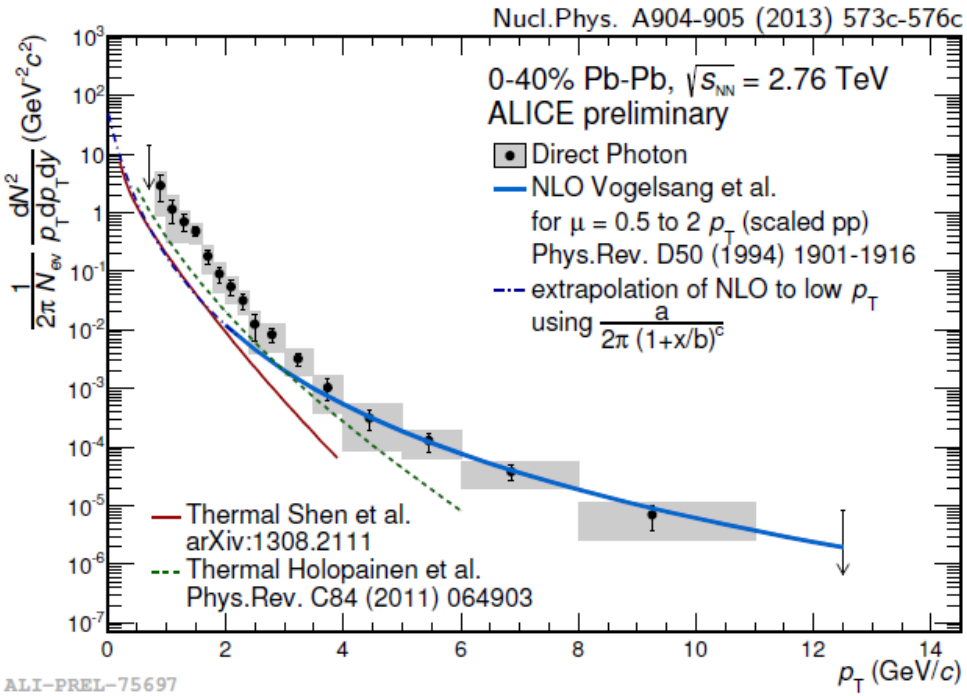
pQCD fits well photon yield in pp collisions



PHENIX Phys.Rev.Lett 104 (2010) 132301

Photon puzzle: flow and yield





Both v2 and yield of photons below 4GeV underpredicted by current models.

Different sources of direct photon

- Prompt photon (pQCD)
- Thermal photon: QGP phase + hadronic phase
- Pre-equilibrium photon (Glasma)?

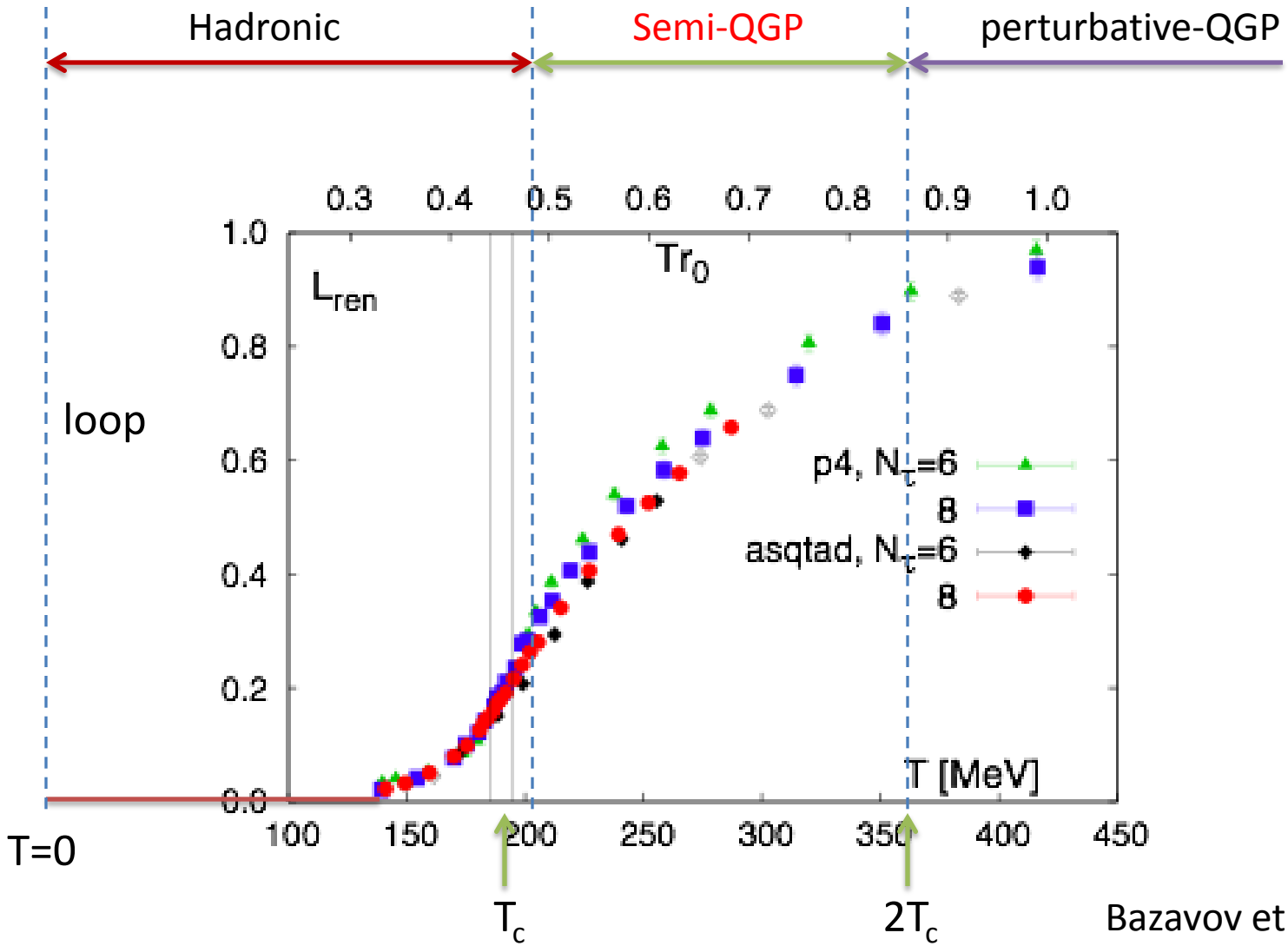
Do we understand well photon rate in QGP phase?

What is known:
LO: Arnold, Moore and Yaffe JHEP 2001
NLO: Ghiglieri, Hong, Kurkela, Lu, Moore and Teaney, JHEP 2013
20% increase for phenomenologically interesting coupling

This talk: Any non-perturbative effect?

Polyakov loop in QCD

Semi-QGP in QCD, smooth rise of Polyakov loop $\ell(\vec{x}) = \frac{1}{N_c}\,\mathrm{tr}\,\mathcal{P}\exp\left(\int_0^{1/T} d\tau\, A_0(\vec{x},\tau)\right)$



Bazavov et al, PRD 2009

Polyakov loop from color charge

Polyakov loop $\ell(\vec{x}) = \frac{1}{N_c} \mathrm{tr}\, \mathcal{P} \exp\left(\int_0^{1/T} d\tau\, A_0(\vec{x},\tau)\right)$ generated non-perturbatively

Modeled the loop by classical mean field

$$A_0 = \begin{pmatrix} -Q/g & & \\ & 0 & \\ & & Q/g \end{pmatrix} \sim 1/g$$

$$\ell = \frac{1}{3}\left(1 + 2\cos\left(\frac{Q}{T}\right)\right)$$

Dumitru, Guo, Hidaka, Korthals Altes, Pisarski, PRD 2011, 2012

quarks $\tilde{n}_a(E) = \frac{1}{e^{(E-iQ^a)/T}+1}$

gluons $n_{ab}(E) = \frac{1}{e^{(E-i(Q^a-Q^b))/T}-1}$

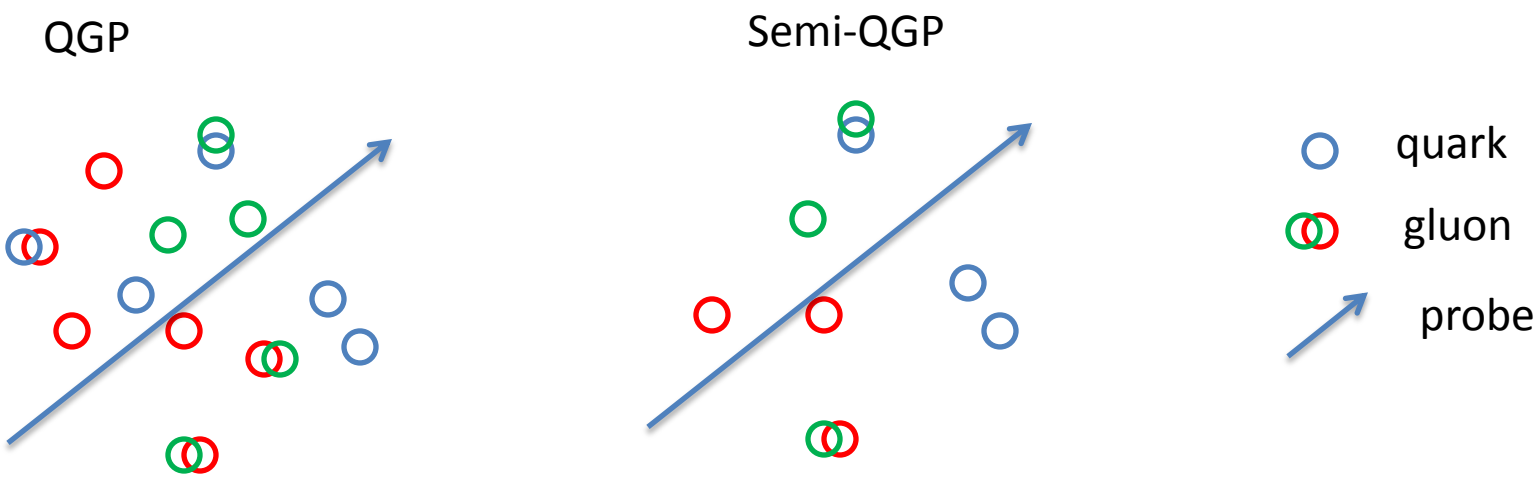
Q as imaginary chemical potential, reduces quark and gluon number densities

$$\frac{1}{N}\sum_{a=1}^{N} \frac{1}{e^{(E-iQ_a)/T}+1} \sim \ell e^{-E/T}$$

$$\frac{1}{N}\sum_{a=1}^{N} \frac{1}{e^{(E-iQ_a+iQ_b)/T}-1} \sim \ell^2 e^{-E/T}$$

$$E \gg T, l \to 0$$

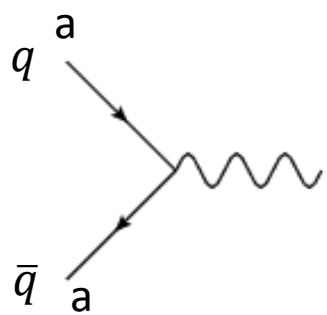
Reduction of d.o.f. & transports



less d.o.f. to scatter off ⟹ Suppression of energy loss & viscosity

Hidaka,Pisarski, PRD, 2008
SL, Pisarski, Skokov, PLB 2014

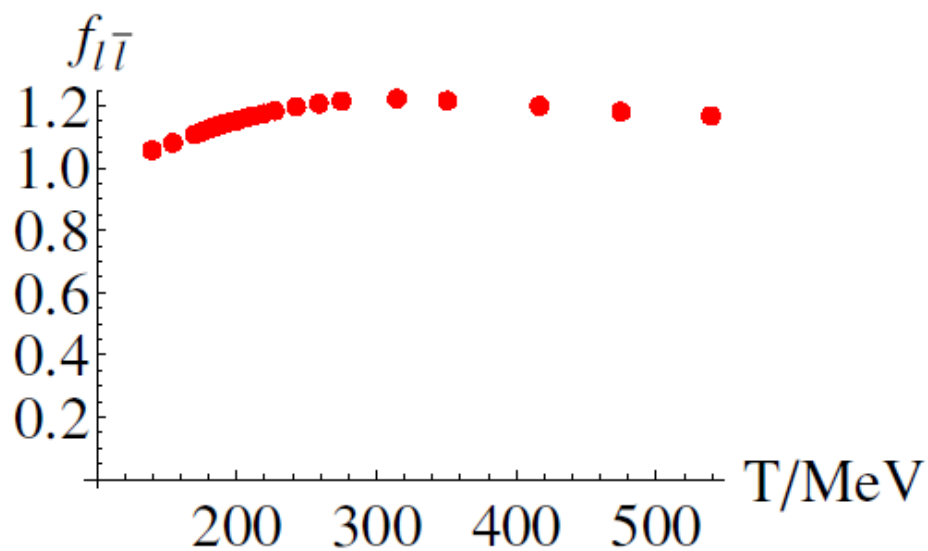
Dilepton production in semi-QGP



Reduced of quark number density leads to suppression in dilepton rate? NO!

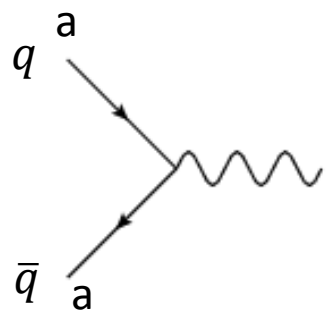
$$\left.\frac{d\Gamma}{d^4P}\right|_{Q\neq 0} = f_{l\bar{l}}(Q)\left.\frac{d\Gamma}{d^4P}\right|_{Q=0}$$

semi-QGP perturbative-QGP



Dilepton production in semi-QGP

2 to 1 process



Boltzmann approximation

$$\sum_{a=1}^{N} \tilde{n}_a(E/2)\, \tilde{n}_{\bar{a}}(E/2) \sim \sum_{a=1}^{N} e^{-(E/2-iQ^a)/T} e^{-(E/2+iQ^a)/T}$$

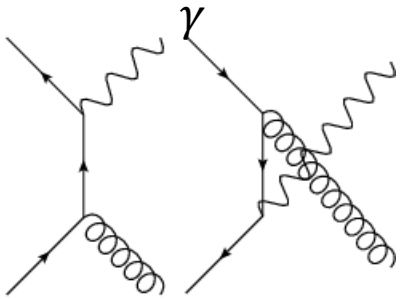
Effect of Q cancel out!

The effect of imaginary chemical potential cancels for a color singlet initial state.

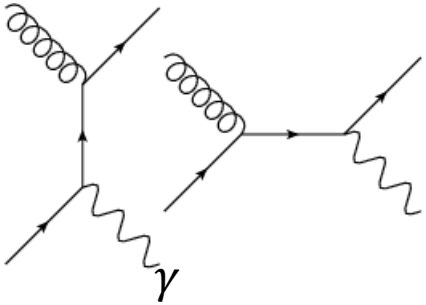
The rate is even enhanced beyond Boltzmann approximation!

Photon production at Q=0: 2 to 2 processes

Pair annihilation

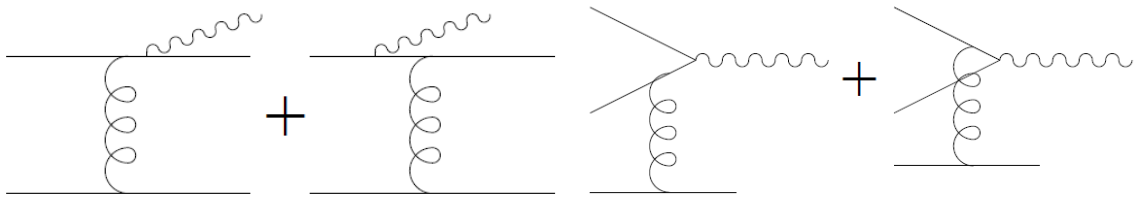


Compton scattering

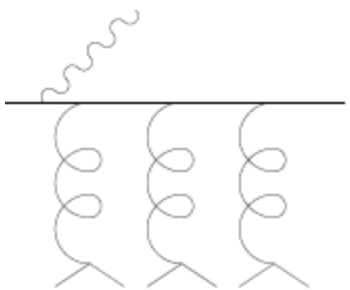


Baier et al, Z.Phys.C 1992
Kapusta et al, PRD 1991

Photon production at Q=0: collinear emission



bremsstrahlung pair annihilation



photon formation time $\sim(m^2/T)^{-1}\sim(g^2T)^{-1}$
quark mean free path $\sim\Gamma^{-1}\sim(g^2T)^{-1}$
Multiple scatterings not indepdendent, LPM effect important

Aurenche, Gelis, Zaraket, PRD 2000
Arnold, Moore, Yaffe, JHEP 2001/2002

Photon production at Q≠0: 2 to 2 processes

Hard momentum exchange

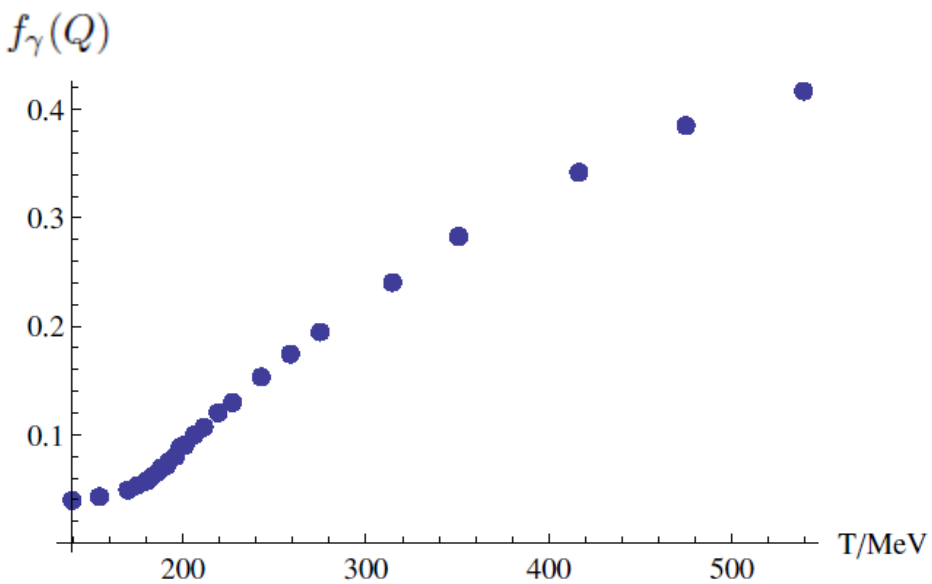
$$p\frac{d\Gamma}{d^3p} = \sum_f q_f^2 \, \frac{1}{2} \, \alpha_{\rm em} \, \alpha_s \, \frac{T^2}{\pi^2} \, e^{-p/T} \, \ln\left(\frac{pT}{\mu^2}\right) f_\gamma(Q)$$

Soft momentum exchange

$$p\frac{d\Gamma}{d^3p} = \sum_f q_f^2 \, \frac{1}{2} \, \alpha_{\rm em}\alpha_s \, \frac{T^2}{\pi^2} \, e^{-p/T} \, \ln\left(\frac{\mu^2}{g^2T^2}\right) f_\gamma(Q)$$

same factor

Cutoff μ dependence cancels out

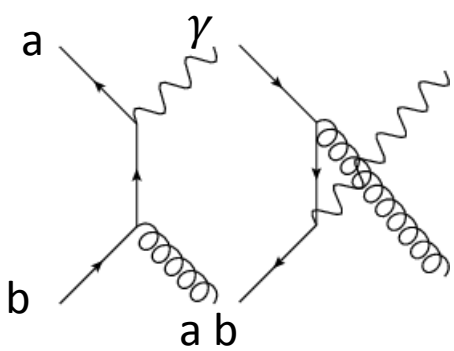


$$p\frac{d\Gamma}{d^3p} = f_\gamma(Q) \; p\frac{d\Gamma}{d^3p}\bigg|_{\rm pQGP}$$

Strong suppression at leading logarithmic order

Suppression of photon from 2→2 processes

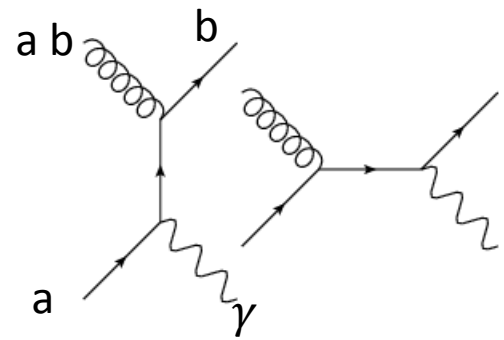
Pair annihilation



$$e^2 g^2 \sum_{a,b} e^{-(E_1 - iQ^a)/T} e^{-(E_2 + iQ^b)/T} |\mathcal{M}_\gamma^{ab}|^2$$

No cancellation!

Compton scattering



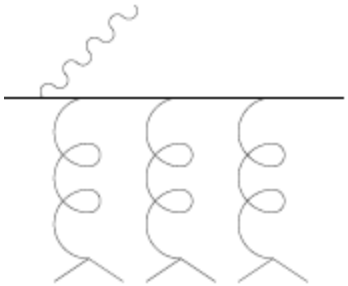
$$e^2 g^2 \sum_{a,b} e^{-(E_1 - iQ^a)/T} e^{-(E_2 + iQ^a - iQ^b)/T} |\mathcal{M}_\gamma^{ab}|^2$$

Partial cancellation

Effect of imaginary chemical potential does not cancel out completely as initial states not a color singlet.

Suppression of photon rate from 2 → 2 processes.

Photon production at Q≠0: collinear emission



Hard quark scattering with arbitrary number of soft gluons contributes at the same order due to collinear enhancement

quark $p_{\parallel} \sim T, p_{\perp} \sim gT$

gluon $q_{\perp} \sim gT$

Collinear enhancement needs Soft gluons in QGP give additional Bose-Einstein enhancement

$$E \sim gT, \qquad \frac{1}{e^{E/T}-1} \sim \frac{1}{g}$$

In semi-QGP $E \to E - i(Q_a - Q_b), \qquad \frac{1}{e^{(E-iQ_a+iQ_b)/T-1}} \sim O(1)$

Q ~ T hard, Bose-Einstein enhancement occurs only when a=b.

⟹ Quarks only scatter with diagonal gluons in collinear emission of photons

$1/N$ suppression

Collinear emission: large N approximation

photon formation time $\sim \frac{1}{\delta E_e} \sim \frac{T}{{m_e}^2} \sim \frac{1}{g^2 T}$

quark mean free path $\sim \frac{1}{\Gamma_e} \sim \frac{1}{N g^2 T}$

Multiple scatterings not important at large N, LPM effect suppressed

$$p\frac{d\Gamma_\gamma}{d^3p} \simeq \frac{\alpha_{\rm em}\alpha_s \sum_f q_f^2}{\pi^2}\,\frac{4Tp}{3}\sum_e \mathcal{G}\left(\frac{M_e}{m_e}\right)\,e^{-p/T}$$

NO LPM effect

Compared to collinear hard photons in perturbative QGP with LPM

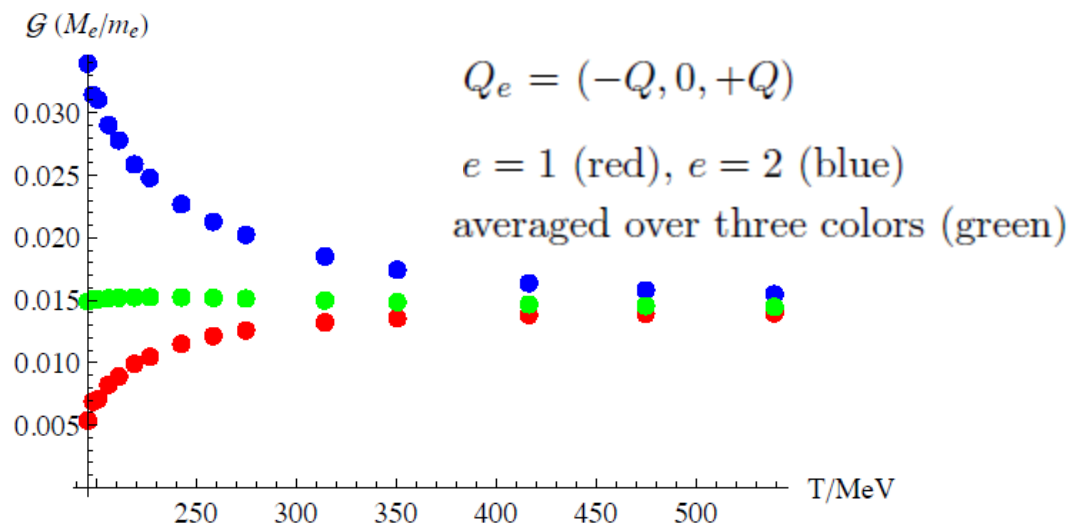
$$\mathrm{p}\frac{d\Gamma_\gamma}{d^3p} \sim \mathrm{N}\, p^{1/2} e^{-p/T}$$

p>>T in phenomenology

photon from inelastic pair annihilation

M_e: gluon Debye mass

m_e: asymptotic quark thermal mass



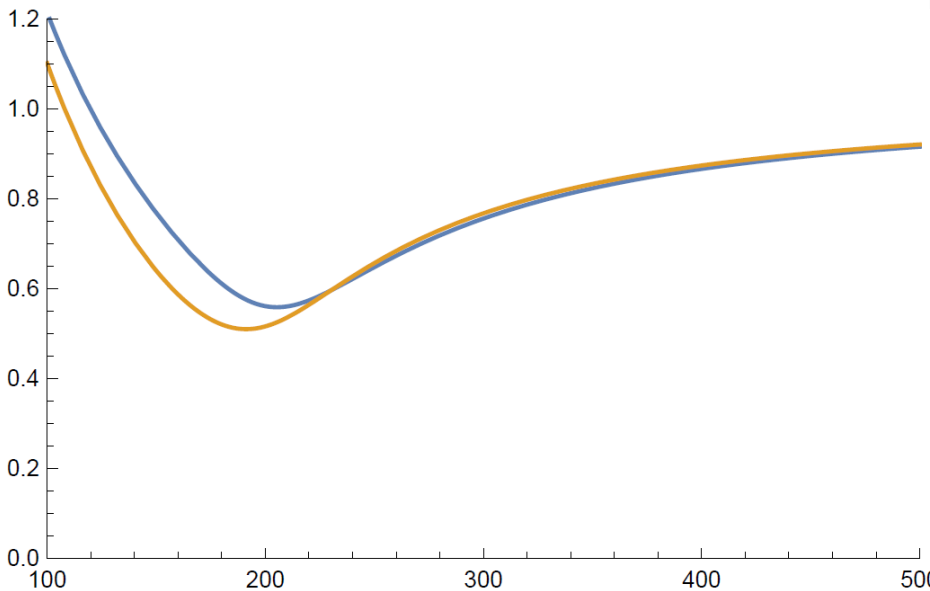
Collinear emission at N=3

Quark only scatters with diagonal gluons, but LPM effect not suppressed
Need to solve the integral equation:

$$i\delta E_e\, \mathbf{f}_{e\perp}(\mathbf{k},p) = 2\mathbf{k}_\perp + \int \frac{d^3q}{(2\pi)^3}\, C_e(\mathbf{q},p)\, [\mathbf{f}_{e\perp}(\mathbf{k}+\mathbf{q},p) - \mathbf{f}_{e\perp}(\mathbf{k},p)]$$

Need Debye masses for two diagonal gluons

$M_D(Q \neq 0)$
$/M_D(Q = 0)$



T/MeV

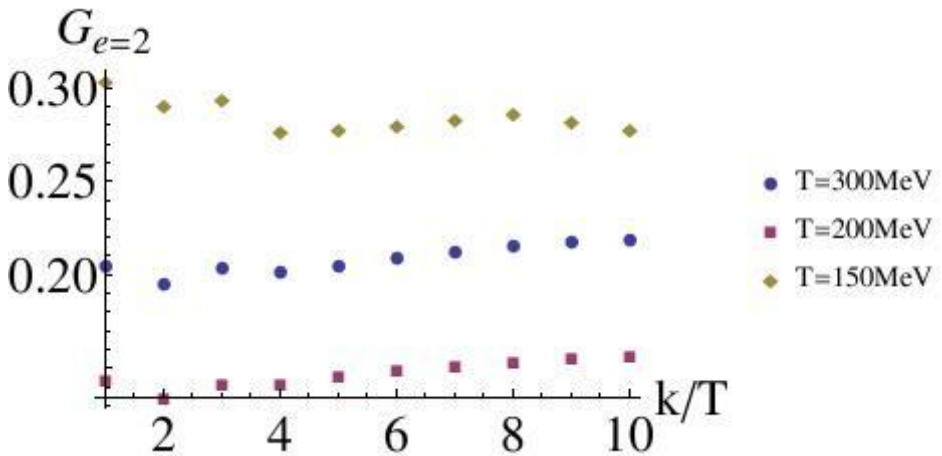
Debye mass from matrix model

Dumitru, Guo, Hidaka, Korthals Altes, Pisarski, PRD 2011, 2012

Collinear emission at N=3

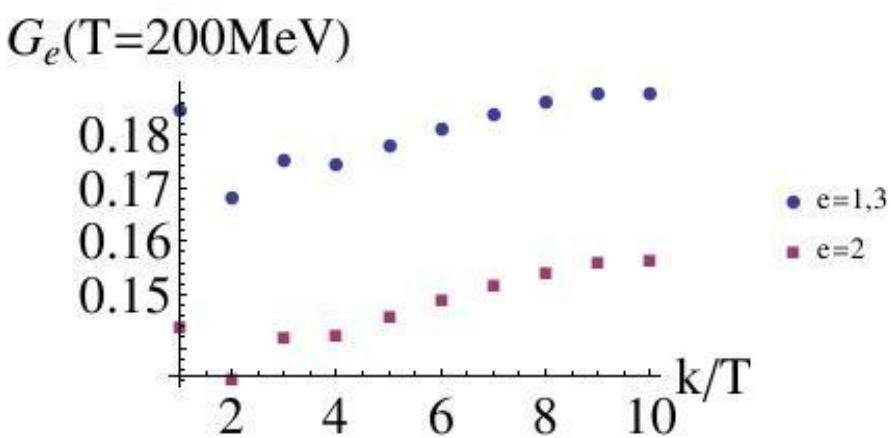
$$p\frac{d\Gamma_{coll}}{d^3p}(Q \neq 0) = p\frac{d\Gamma_{coll}}{d^3p}(Q = 0)\sum_e \frac{G_e(k,T)}{N}$$

For inelastic pair annihilation k>>T
e labels color of quarks

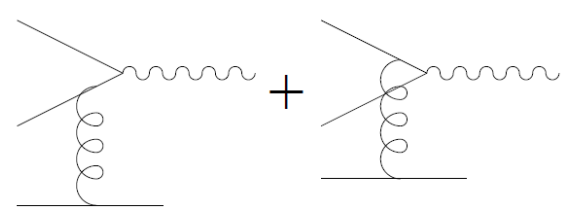


- roughly a factor of 1/4, because only two (diagonal) out of eight gluons participating in scattering
- low G_e at T=200MeV due to low Debye masses.

$$Q^a = (-Q,\ 0,\ Q)$$



- The case e=1,3($Q_e \neq 0$) enhanced as compared to the case e=2 ($Q_e = 0$) has an enhancement as the initial state is color singlet



Between semi-QGP and perturbative QGP

As T increases, Q approaches zero.

1. All gluons (diagonal and non-diagonal) participate in scattering with quarks. The factor $\frac{1}{4} \to 1$
2. Debye masses all approaches perturbative Debye mass
3. Quark distribution function approaches the case Q=0

2 to 2 rate affected by 2 and 3
Collinear rate affected by 1, 2 and 3

Phenomenological implications

Dilepton

Semi-QGP enhances N_{QGP}, lowering the overall v2

$$v2_{QGP} < v2_{HM}$$

$$v2 = \frac{v2_{QGP} * N_{QGP} + v2_{HM} * N_{HM}}{N_{QGP} + N_{HM}}$$

Photon

Semi-QGP suppresses significantly N_{QGP}, enhancing the overall v2

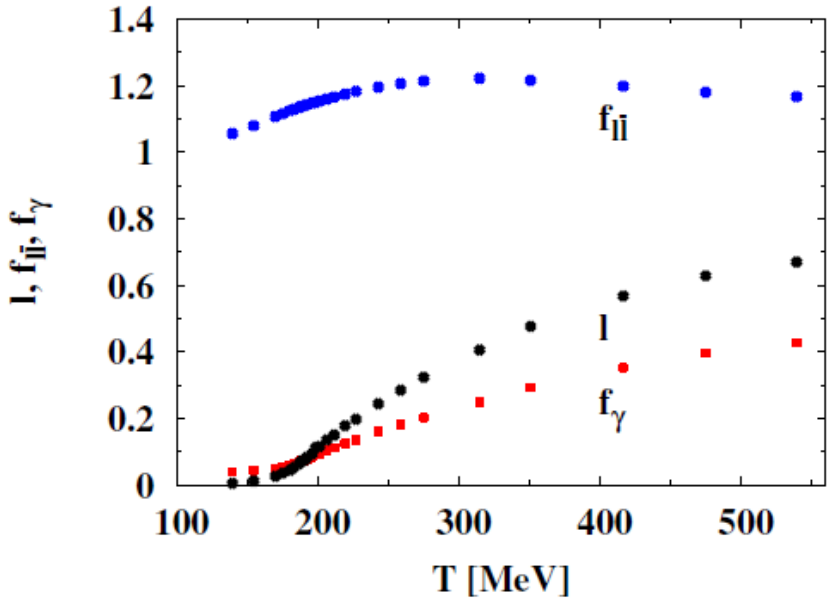
$$v2_{QGP} < v2_{HM}$$

$$v2 = \frac{v2_{QGP} * N_{QGP} + v2_{HM} * N_{HM}}{N_{QGP} + N_{HM}}$$

Model of semi-QGP suggests different behavior in photon and dilepton v2

Suppressed photon rate in semi-QGP does not help solve photon yield puzzle.
BUT, uncertainties large for photon rate from other sources, e.g. prompt photon

Summary

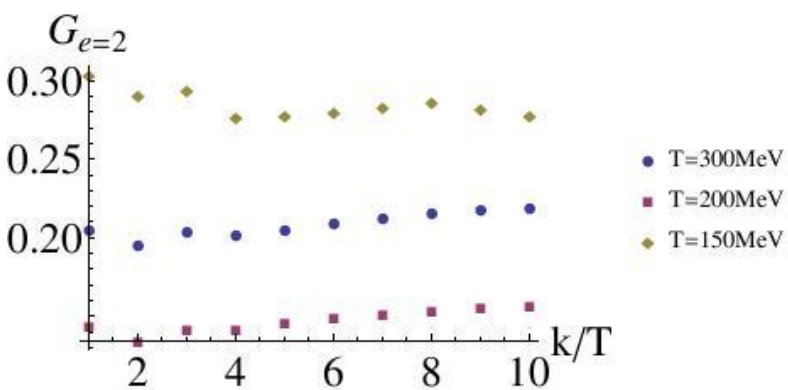


$$\left.\frac{d\Gamma}{d^4P}\right|_{Q\neq 0} = f_{l\bar{l}}(Q)\,\left.\frac{d\Gamma}{d^4P}\right|_{Q=0}$$

$$\left.E\frac{d\Gamma}{d^3p}\right|_{Q\neq 0} = f_\gamma(Q)\,\left.E\frac{d\Gamma}{d^3p}\right|_{Q=0}$$

Dilepton 2→1 rate: mild enhancement
Photon 2 →2 rate: strong suppression

$$p\frac{d\Gamma_{coll}}{d^3p}(Q\neq 0) = p\frac{d\Gamma_{coll}}{d^3p}(Q=0)\sum_e \frac{G_e(k,T)}{N}$$



Photon collinear rate (inelastic pair annihilation): suppressed by 1/4 because of decoupling of non-diagonal gluons

Non-perturbative effect enhances v2 of photon and suppresses v2 of dilepton

Thank you!

Matrix Model

$$V_{pt} = V_{gl} + V_{qk},$$

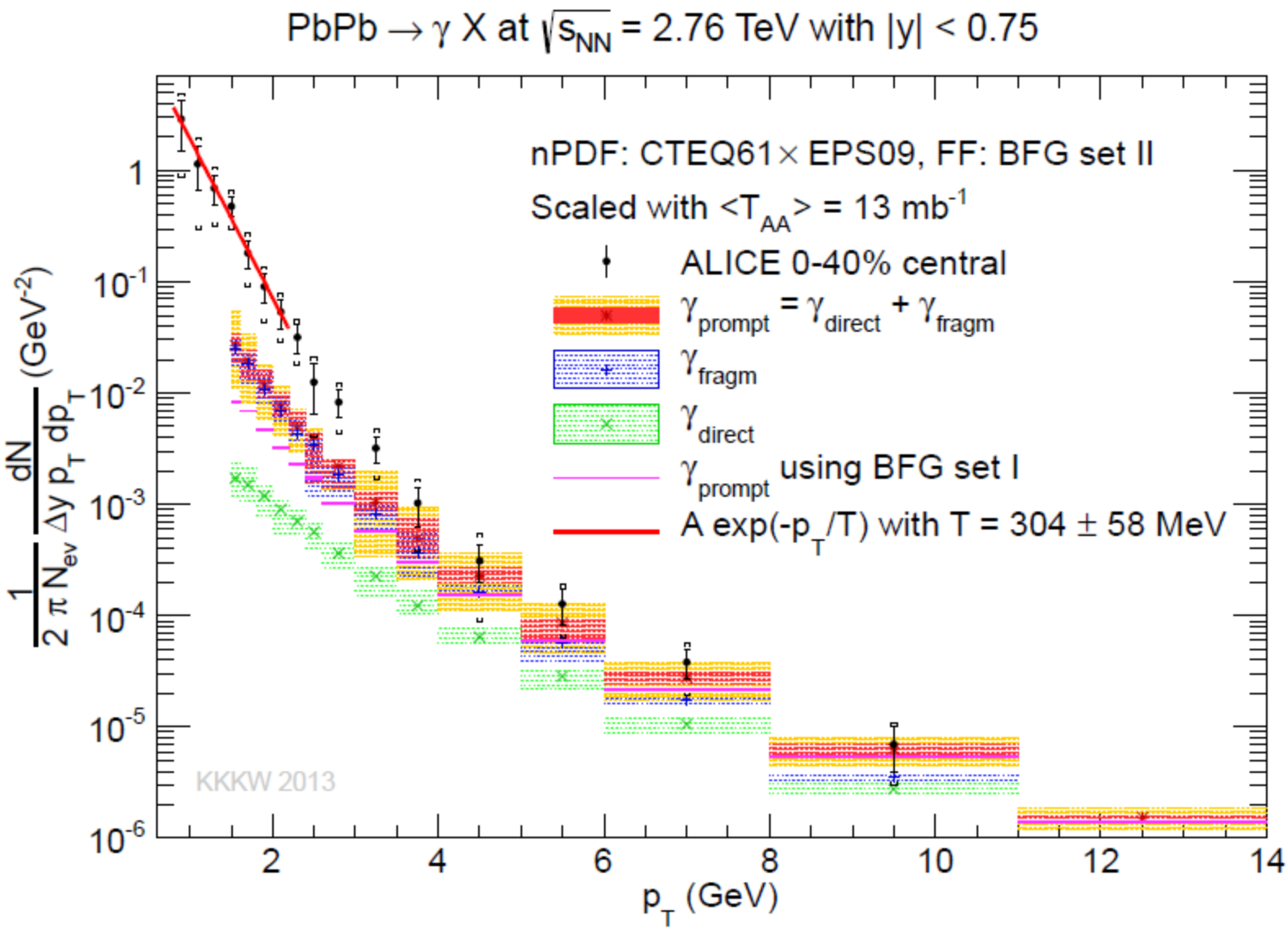
$$V_{gl} = -\frac{(N^2-1)\pi^2}{45}T^4 + \frac{2\pi^2}{3}T^4 \sum_{ab} B_4(q_a - q_b),$$

$$V_{qk} = -\frac{7\pi^2}{180}NN_fT^4 - \frac{4\pi^2}{3}N_fT^4 \sum_{e} B_q(q_e),$$

$$V_{npt} = -\frac{2\pi^2}{3}T^2T_d^2 \left(\frac{c_1}{5}\sum_{ab} B_2(q_a - q_b) + c_2 \sum_{ab} B_4(q_a - q_b) = \frac{N^2-1}{60}c_3 \right)$$

q_a found by minimizing $V_{pt} + V_{npt}$

Prompt photon uncertainty large

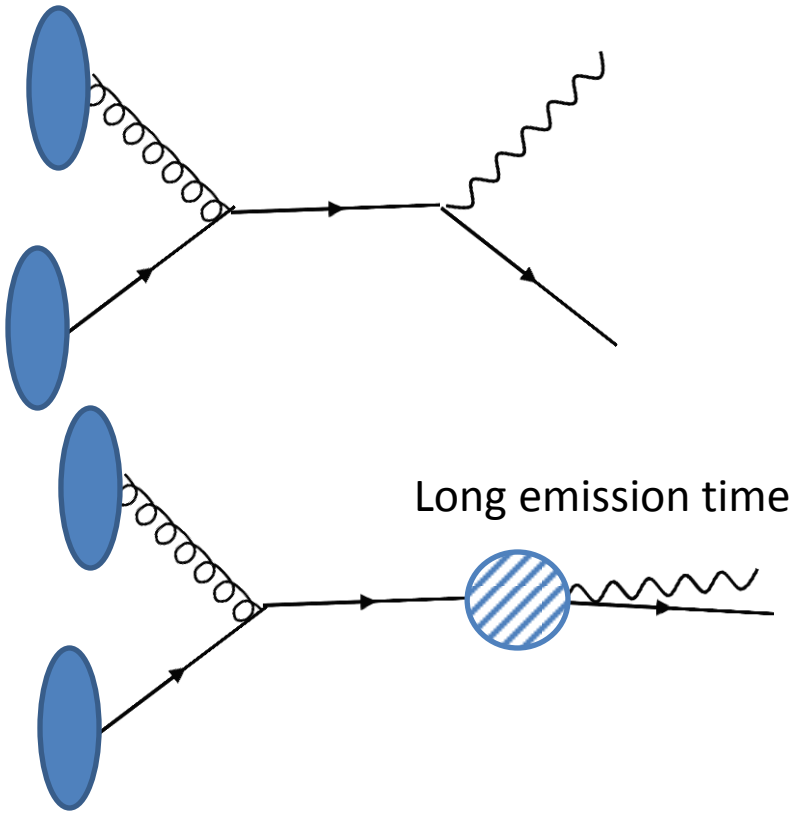


direct (hard scattering)

Klasen et al, JHEP 2013

Prompt photon

Prompt photon = hard scattering photon + collinear fragmentation photon

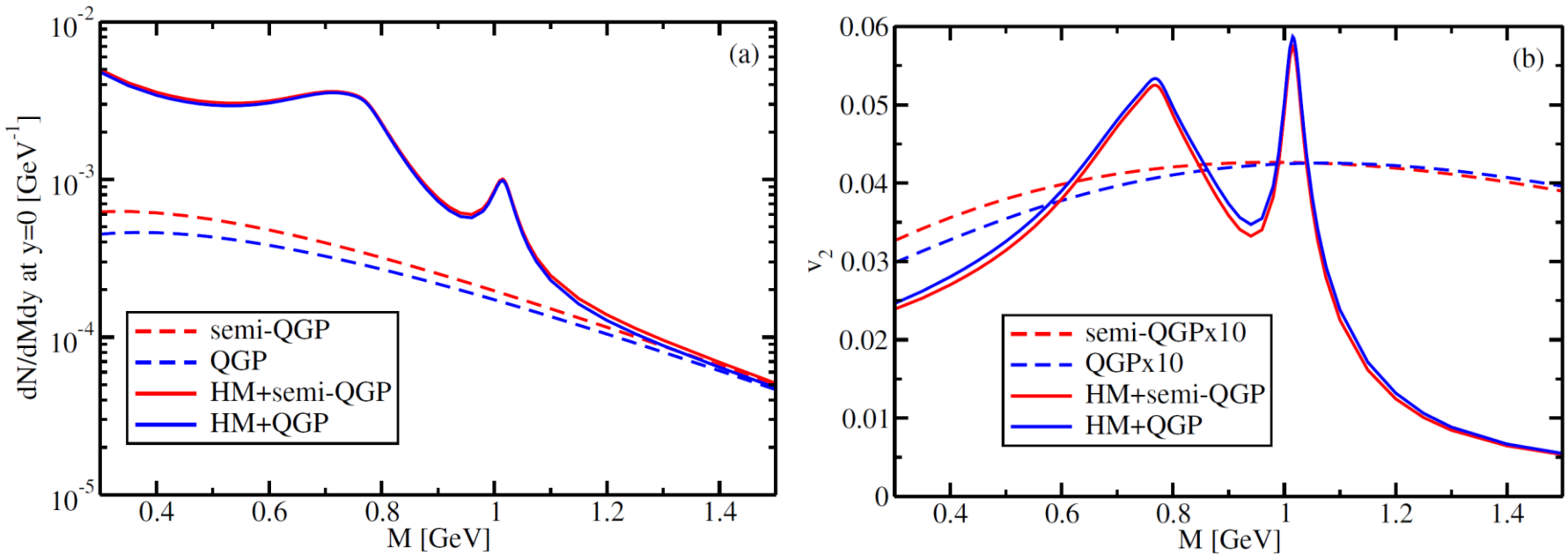


hard scattering photon
sensitive to nuclear PDF
nPDF x nPDF ≠ pp scaled

fragmentation photon sensitive to fragmentation function

Klasen et al, JHEP 2013

Dilepton (RHIC): QGP + hadronic matter

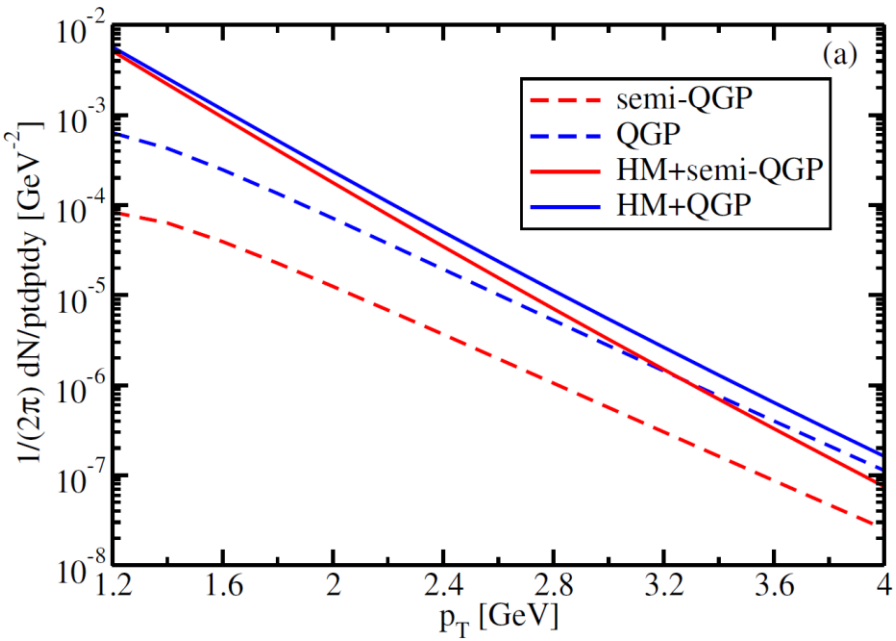


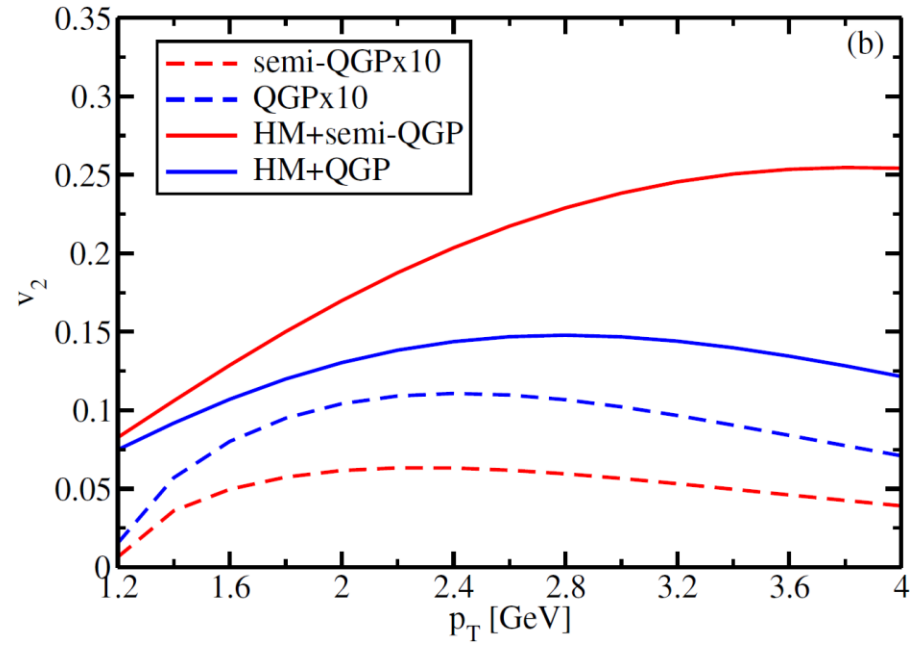
Semi-QGP enhances N_{QGP}, lowering the overall v2

$$v2_{QGP} < v2_{HM}$$

$$v2 = \frac{v2_{QGP} * N_{QGP} + v2_{HM} * N_{HM}}{N_{QGP} + N_{HM}}$$

Photon (RHIC): QGP + hadronic matter





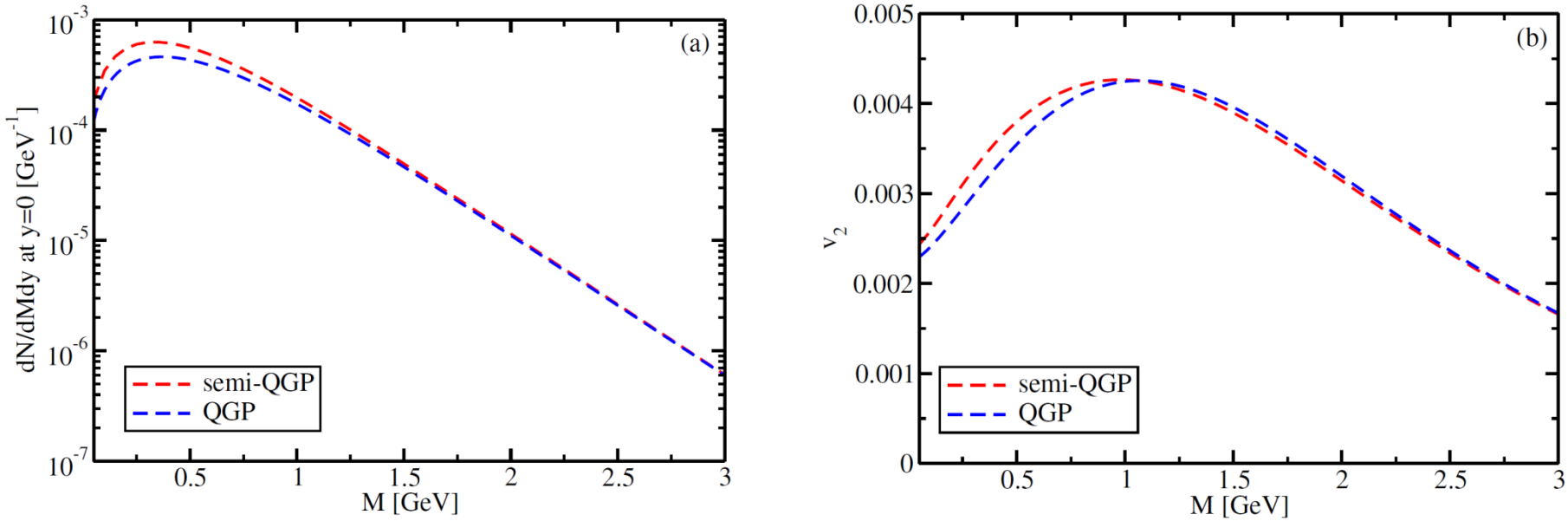
Semi-QGP suppresses significantly N_{QGP}, enhancing the overall v2 $v2_{QGP} < v2_{HM}$

$$v2 = \frac{v2_{QGP} * N_{QGP} + v2_{HM} * N_{HM}}{N_{QGP} + N_{HM}}$$

Model of semi-QGP suggests different behavior in photon and dilepton v2

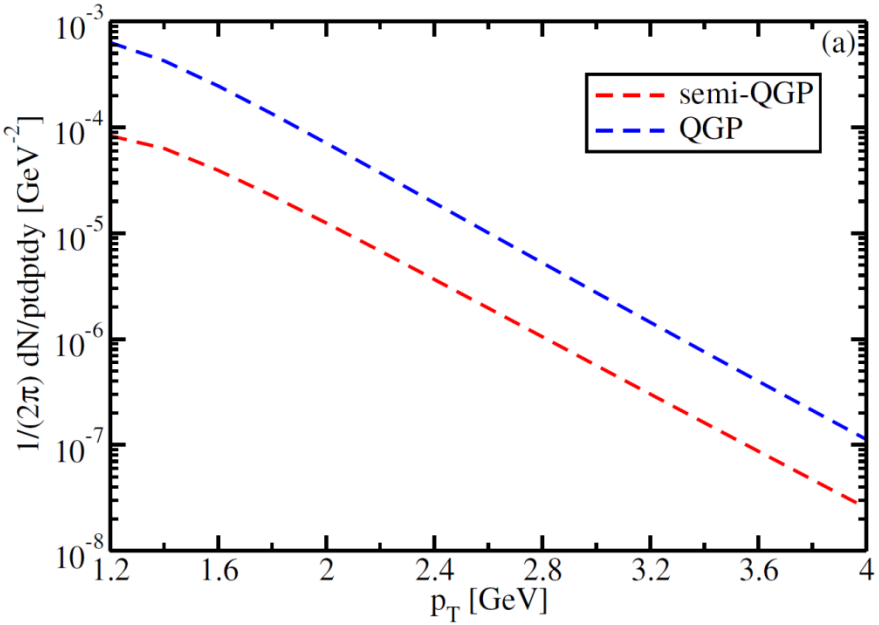
A more complete study will need constant under the log plus collinear rate

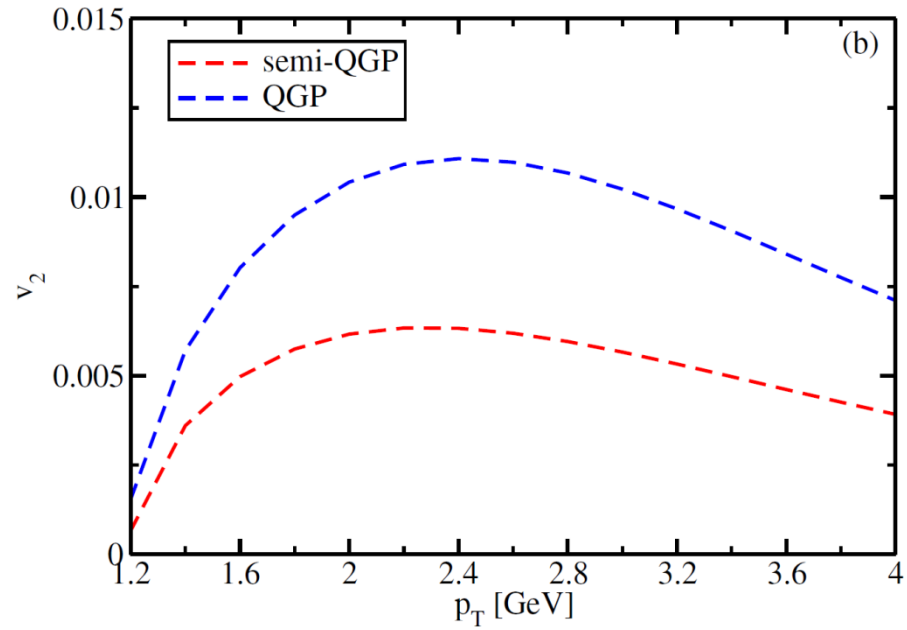
Dilepton (RHIC): no significant change

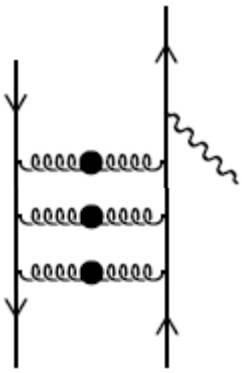


Modest enhancement in semi-QGP, no significant change to v2

Photon (RHIC): strong suppression





Strong suppression in semi-QGP.

semi-QGP increases the weight of photons at high T (less suppression).
Photon produced at high T experience less v2.