

Hard Dilepton and Photons, *near* T_c

[arXiv.org: 1409.4778](https://arxiv.org/abs/1409.4778): the “*Gang of Nine*”:

Analytic computations:

Yoshimasa Hidaka: RIKEN@Nishina (& RIKEN@BNL, '07-'09)

Shu Lin: RIKEN@BNL

Daisuke Satow: JPS, RIKEN@BNL → ECT Trento

Vladimir Skokov : BNL ('11-'13) → Western Michigan → RIKEN@BNL ('15)

RDP: BNL & RIKEN@BNL

3+1 dimensional (ideal) hydrodynamics (MUSIC):

McGill Univ.: Charles Gale, & Sangyong Jeon,
& students, *Jean-Francois Paquet, Gojko Vujanovic*

The Quark-Gluon Plasma *near* T_c

Low T to $\sim T_c$: hadronic resonance gas, χ perturbation theory....

$2T_c$ to $10^7 T_c$: *must* resum perturbation theory

Gold standard: Hard Thermal Loop perturbation theory at *three* loop order!

1402.6907: Haque, Bandyopadhyay, Andersen, Mustafa, *Mike Strickland, Nan Su*

In heavy ion collisions, isn't high T the most important?

Assume Bjorken hydrodynamics: in the central plateau, $T \sim \frac{1}{\tau^{1/3}}$

Strickland: $T_f = 160$ MeV. RHIC, $T_i = 400$ MeV. LHC, $T_i = 600$ MeV.

In Bjorken hydro, as $T_i \rightarrow \infty$, $\langle T \rangle \rightarrow \frac{3}{2} T_f = 215$ @ RHIC; = 227 @ LHC

For photon production, $\sim T^4$,

$$T_i \rightarrow \infty, (\langle T^4 \rangle)^{1/4} = 3^{1/4} T_f^{3/4} T_i^{1/4} = 237 \text{ @ RHIC; } = 272 \text{ @ LHC}$$

The region *near* T_c matters *most*

Effective models *near* T_c

Experimentally, the region near T_c is important at *both* RHIC and the LHC

For quantities in equilibrium, many models: Polyakov NJL....

For dynamical processes:

Dynamical Quasi-Particle Model: *Elena Bratkovskaya, Olena Linnyk,*
Cassing +...: 1409.4190 + ...

Functional Renormalization Group: *Pawlowski & Rennecke*, 1403.1179

Center Domains: *Asakawa, Bass, Muller*, 1208.2426

Chromo-magnetic Plasma: *Liao, Shuryak*, 0810.4416

AdS/CFT: holography, top down, bottom up...

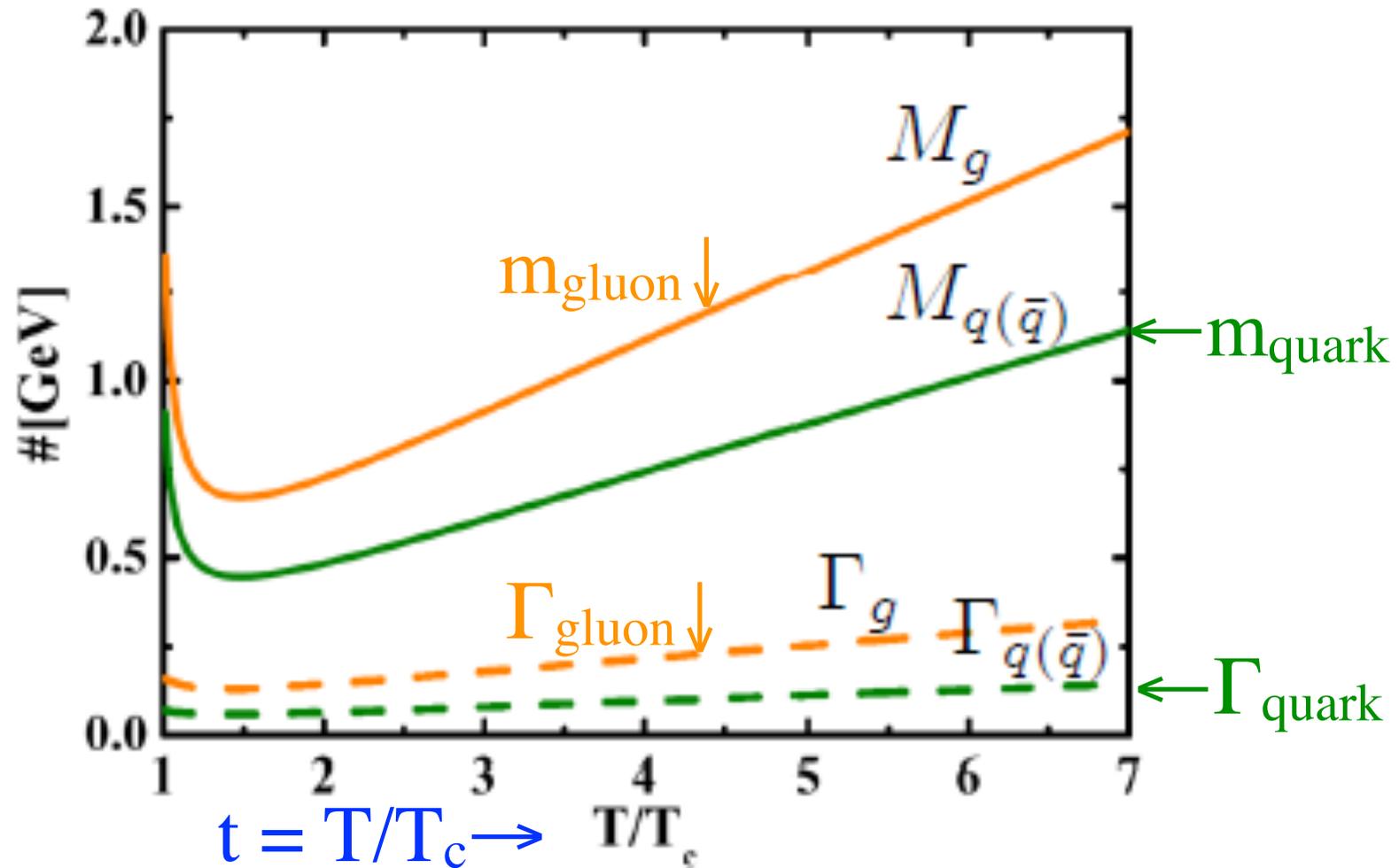
Here: “semi”-Quark Gluon Plasma

Dynamical Quasi-Particle Model

Peshier, ph/0403225; Peshier & Cassing, ph/0502138; Cassing, 0704.1410, 0707.3033

$T > 1.2 T_c$: “perturbative” quasi-particles, mass $m \sim T$

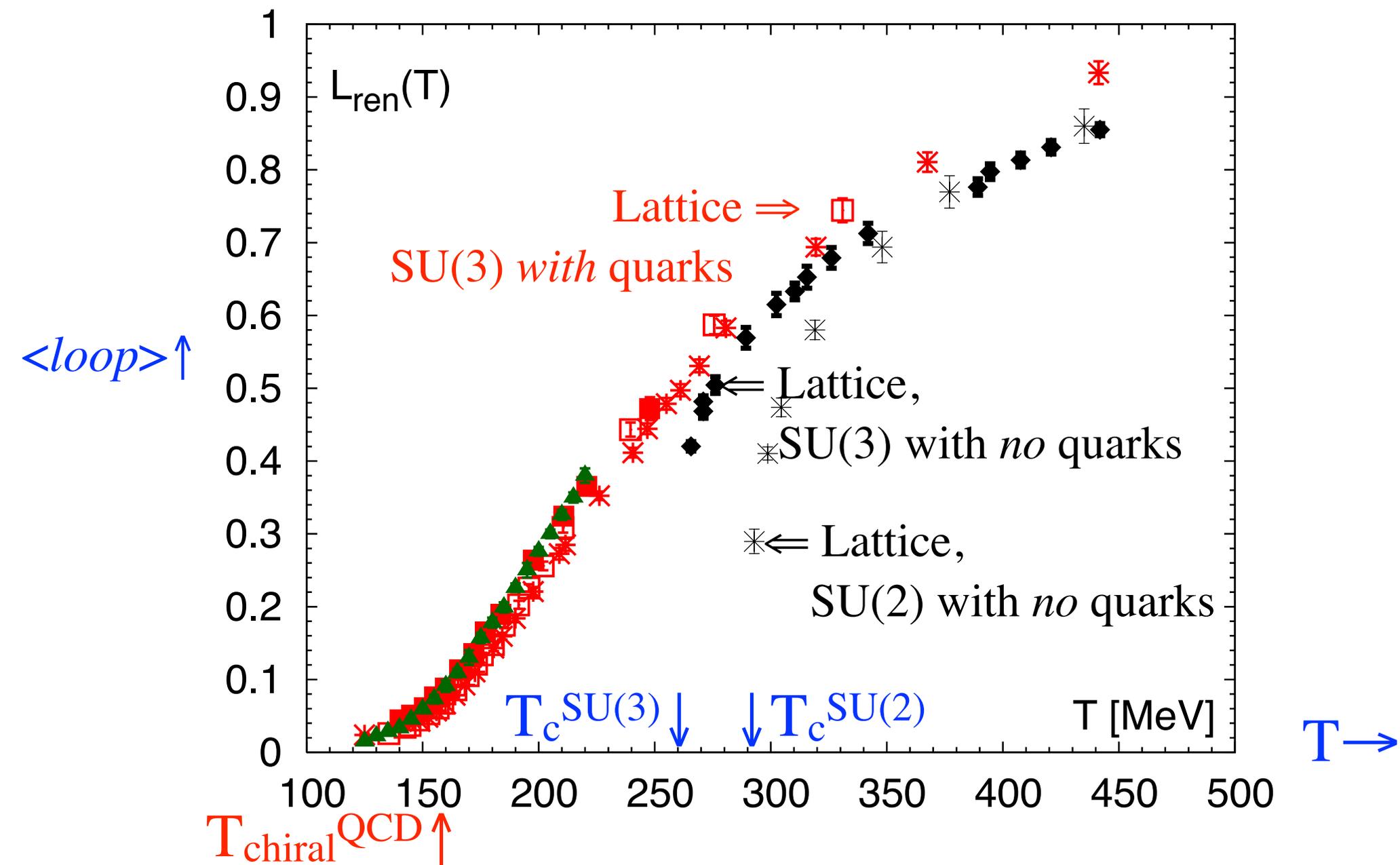
$T < 1.2 T_c$: quasi-particles *heavy*, so the pressure becomes *small*
also include nonzero widths for the quasi-particles



Lattice: Polyakov Loop with and without quarks

Order parameter for deconfinement: Polyakov loop

Lattice: Bazavov & Petreczky, 1110.2160



“Semi”-QGP

Polyakov Loop:
$$\ell = \frac{1}{3} \text{tr } \mathcal{P} \exp \left(i g \int_0^{1/T} A_0 d\tau \right)$$

Simplest approximation to give a non-trivial loop: constant, diagonal A_0 :

$$A_0^{cl} = \frac{Q}{g} , \quad Q = \frac{2\pi T}{3} q(T) \lambda_3 ; \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Depends upon single function, $q(T)$, fixed from pressure(T).

Only need two parameters to fit pressure, 't Hooft loop

However, for the Polyakov loop....

1-parameter matrix model, two colors

Dumitriu, Guo, Hidaka, Korthals-Altes, RDP '10: to usual perturbative potential,

$$V_{pert}(q) = \frac{4\pi^2}{3} T^4 \left(-\frac{1}{20} + q^2(1-q)^2 \right)$$

Add - *by hand* - a non-pert. potential $V_{non} \sim T^2 T_c^2$. Also add a term like V_{pert} :

$$V_{non}(q) = \frac{4\pi^2}{3} T^2 T_c^2 \left(-\frac{c_1}{5} q(1-q) - c_2 q^2(1-q)^2 + \frac{c_3}{15} \right)$$

Now just like any other mean field theory. $\langle q \rangle$ given by minimum of V_{eff} :

$$V_{eff}(q) = V_{pert}(q) + V_{non}(q) \qquad \left. \frac{d}{dq} V_{eff}(q) \right|_{q=\langle q \rangle} = 0$$

$\langle q \rangle$ depends nontrivially on temperature.

Pressure value of potential at minimum:

$$p(T) = -V_{eff}(\langle q \rangle)$$

Latent heat, and a 2-parameter model, three colors

Latent heat, $e(T_c)/T_c^4$: 1-parameter model too small:

1-para.: 0.33. **BPK**: $1.40 \pm .1$; **DG**: $1.67 \pm .1$.

$$c_3(T) = c_3(\infty) + \frac{c_3(1) - c_3(\infty)}{t^2}, \quad t = \frac{T}{T_c}$$

2-parameter model, $c_3(T)$. Like MIT bag constant

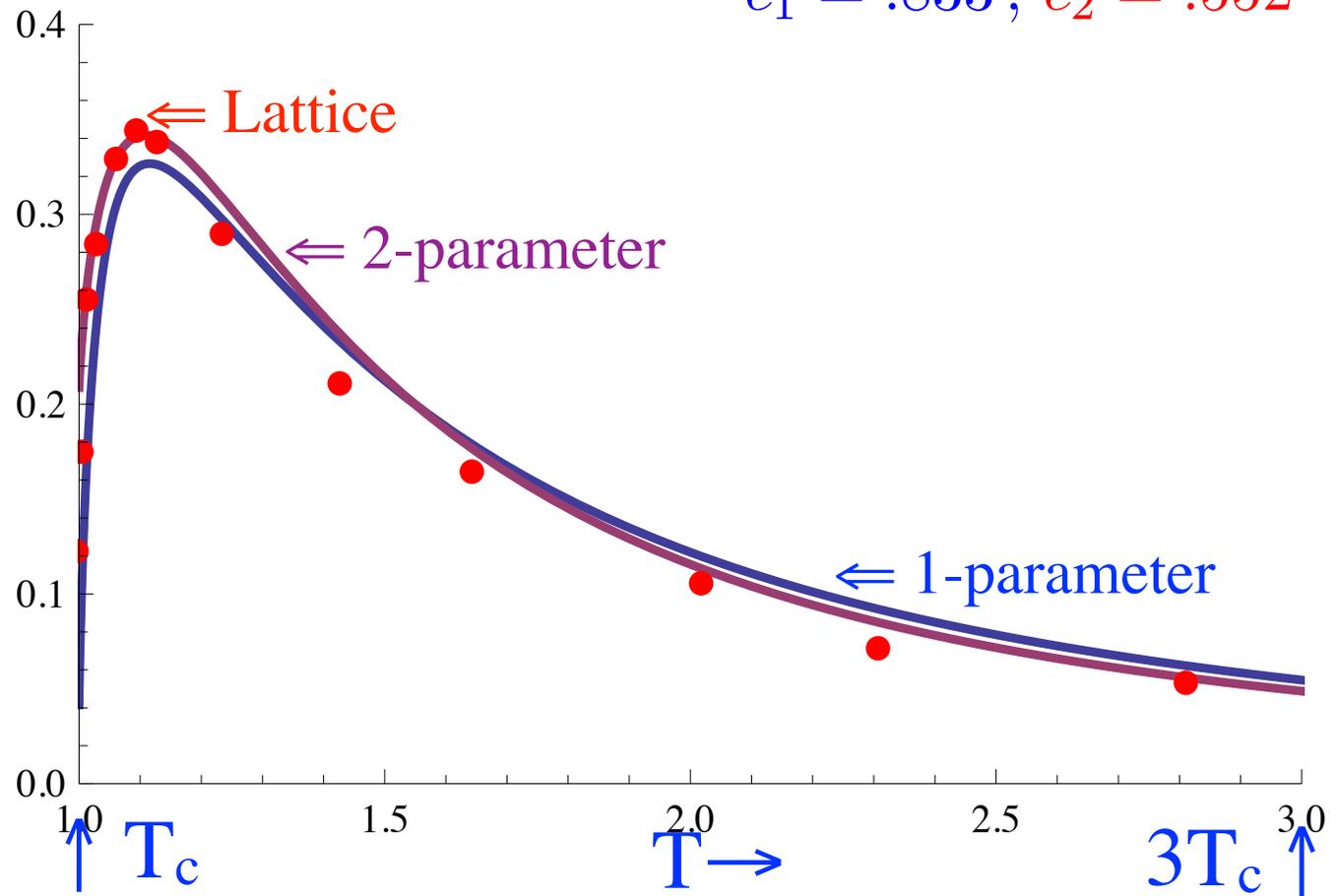
WHOT: $c_3(\infty) \sim 1$. *Fit* $c_3(1)$ to DG latent heat

$$c_3(1) = 1.33, \quad c_3(\infty) = .95$$

Fits lattice for $T < 1.2 T_c$, overshoots above.

$$c_1 = .833, \quad c_2 = .552$$

$$\frac{e - 3p}{8T^4} \uparrow$$



Lattice latent heat:

Beinlich, Peikert,

Karsch (BPK)

lat/9608141

Datta, Gupta (DG)

1006.0938

't Hooft string (Z(2) interface) tension, two colors

σ vanishes as $T \rightarrow T_c$, $\sigma \sim (t-1)^{2\nu}$.

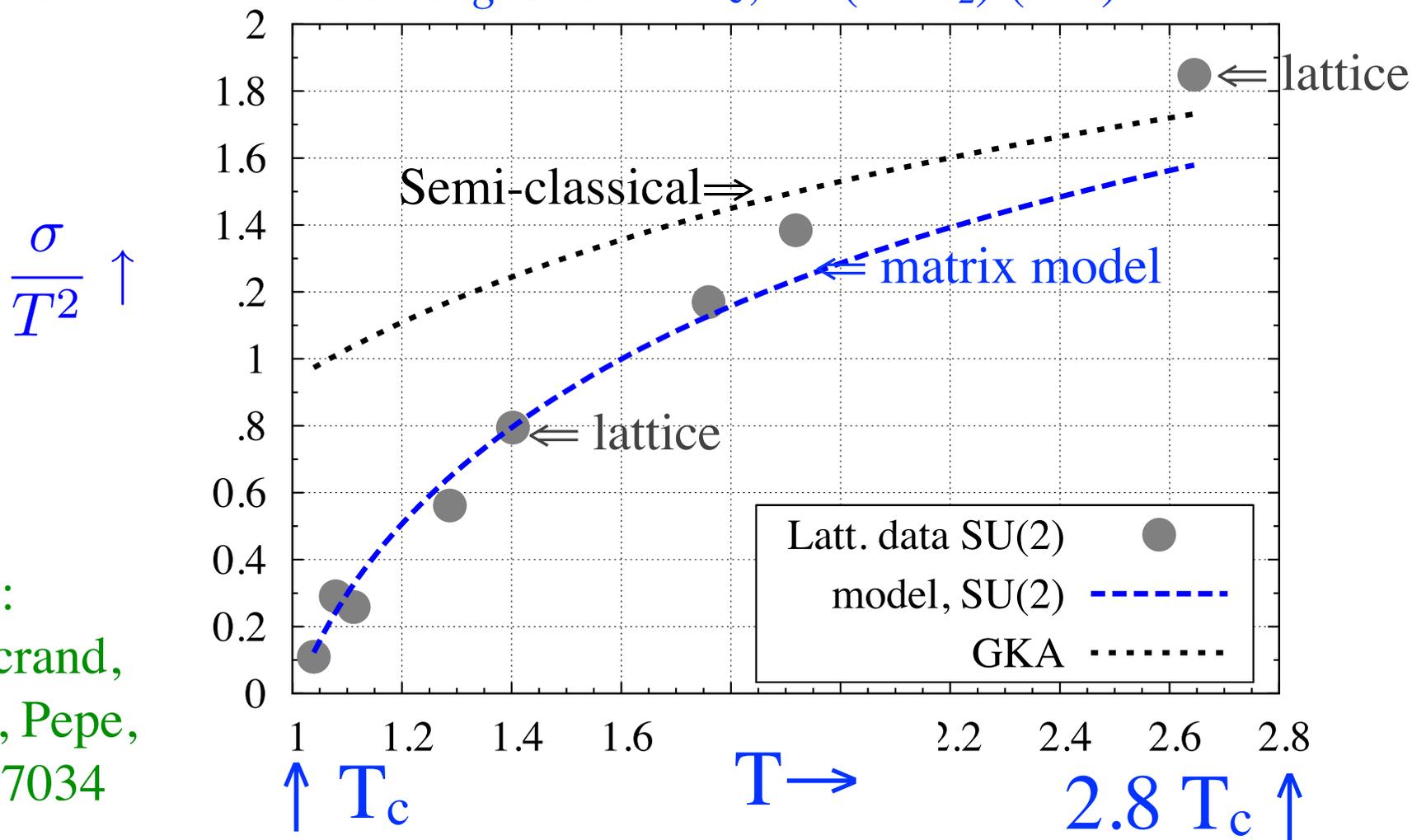
Ising $2\nu \sim 1.26$; Lattice: ~ 1.32 .

Matrix model: ~ 1.5 : c_2 important.

$$\sigma(T) = \frac{4\pi^2 T^2}{3\sqrt{6g^2}} \frac{(t^2 - 1)^{3/2}}{t(t^2 - c_2)}, \quad t = \frac{T}{T_c}$$

Semi-class.: **GKA '04**. Include corr.'s $\sim g^2$ in matrix $\sigma(T)$ (ok when $T > 1.2 T_c$)

N.B.: width of interface *diverges* as $T \rightarrow T_c$, $\sim \sqrt{(t^2 - c_2)/(t^2 - 1)}$.



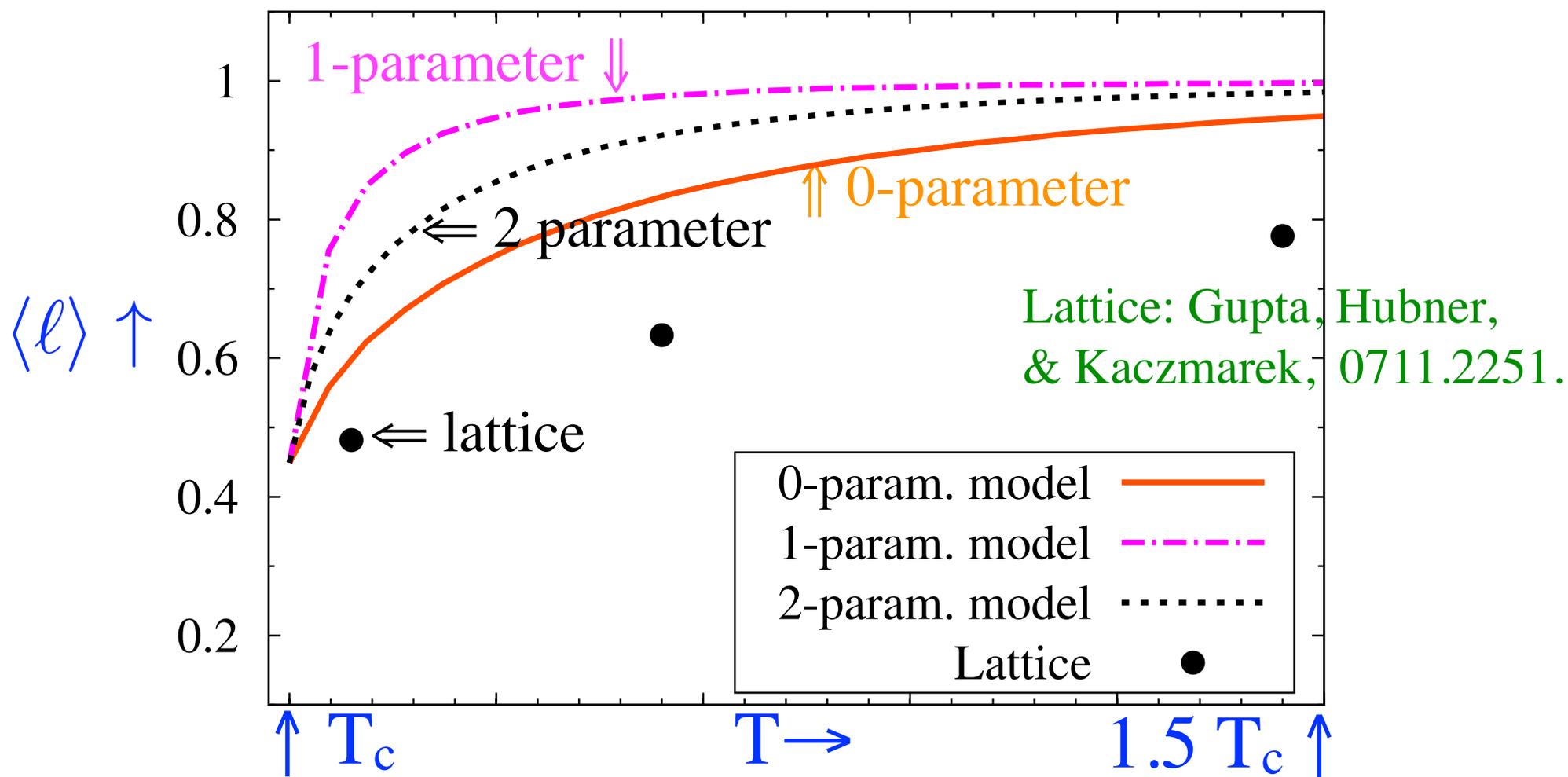
Lattice:
de Forcrand,
D'Elia, Pepe,
lat/0007034

Polyakov loop vs lattice - ?

Polyakov loop from the lattice *nothing* like Matrix Model

Model: transition region *narrow*, to $\sim 1.2 T_c$. Lattice: loop *wide*, to $\sim 4.0 T_c$.

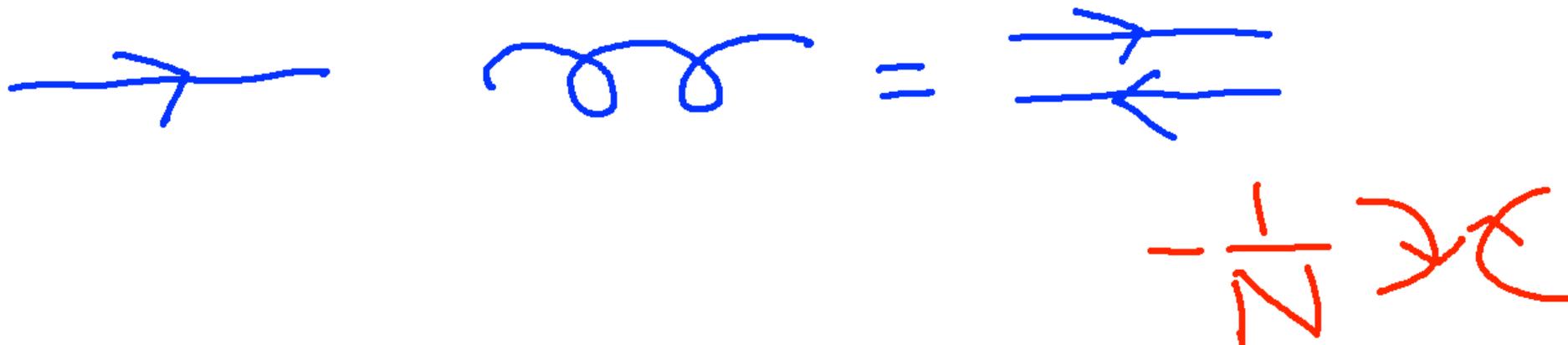
Need magnetic excitations? In practice: take $Q \sim T q(T)$ from the lattice



Semi-QGP in imaginary time

Imaginary time: in background A^0_{cl} , energies carry color.

Quarks carry one line of color, gluons two:



Quarks: $p_0 = 2\pi T(n + 1/2) \rightarrow p_0 - iQ^a$

Gluons: $p_0 = 2\pi Tn \rightarrow p_0 - i(Q^a - Q^b)$

The background field acts like an **imaginary** chemical potential for color.

Semi-QGP in real time

Statistical distribution functions those for imaginary chemical potential:

$$\tilde{n}_a(E) = \frac{1}{e^{(E-iQ^a)/T} + 1} \quad n_{ab}(E) = \frac{1}{e^{(E-i(Q^a-Q^b))/T} - 1}$$

For three colors, color chemical potential:

$$Q^a = \frac{2\pi T}{3} q(T) (1, -1, 0)$$

When $Q \sim T$, the *only* soft gluons have $Q^a = Q^b$: *diagonal* elements.

For N colors: $\sim N^2$ off-diagonal gluons, and $\sim N$ diagonal gluons

In the semi-QGP, soft gluons are suppressed by $1/N$.

Suppression of color near T_c

Consider energetic particles, $E \gg T$, Boltzmann statistics

$$\tilde{n}_a(E) \sim e^{-(E-iQ^a)/T}$$

$$n_{ab}(E) \sim e^{-(E-i(Q^a-Q^b))/T}$$

While the $n(E)$'s are complex, sums over color are real.

Polyakov loop:

$$\ell = \frac{1}{N} \sum_{a=1}^N e^{iQ^a/T}$$

Summing over color,

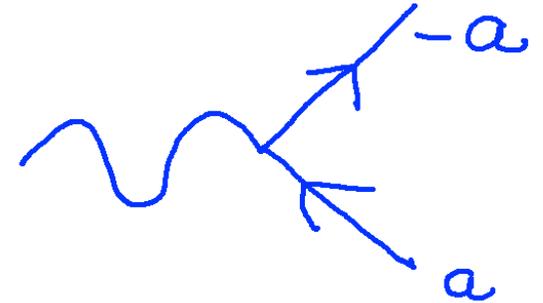
$$\frac{1}{N} \sum_{a=1}^N \tilde{n}_a(E) = e^{-E/T} \ell$$

$$\frac{1}{N} \sum_{a,b=1}^N \tilde{n}_{ab}(E) = e^{-E/T} \ell^2$$

Near T_c , where loop small, quarks suppressed by loop; gluons by loop *squared*.

Hard dileptons: same!

Dileptons: off shell photon goes to quark anti-quark pair.
Consider dileptons back to back, total momentum = 0.



Diagrams same, only the distribution functions change.

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

(Imaginary) chemical potential: **sign of Q^a flips between q and q bar.**

Large E : with Boltzmann statistics,

$$\sum_a \tilde{n}_a(E) \tilde{n}_{-a}(E) \sim e^{-(E-iQ^a)/T} e^{-(E+iQ^a)/T} = e^{-2E/T}$$

So Q^a 's drop out: # dileptons *identical* in deconfined and confined phases!

Soft Dileptons: *more* in confined phase

High T: $Q^a=0$. As $E \rightarrow 0$, # dileptons:
Fermi-Dirac dist. fnc. finite at $E = 0$.

$$\tilde{n}(0)^2 \sim \frac{1}{4}$$

In the confined phase, Polyakov loop = 0, find amazing identity:

$$\frac{1}{N} \sum_{a=1}^N \tilde{n}_a(E) \tilde{n}_{-a}(E) \sim n(E) \stackrel{E \rightarrow 0}{=} \frac{T}{E}$$

More dileptons in the confined phase!

Confined phase only in the pure gauge theory, but interesting point of principle.

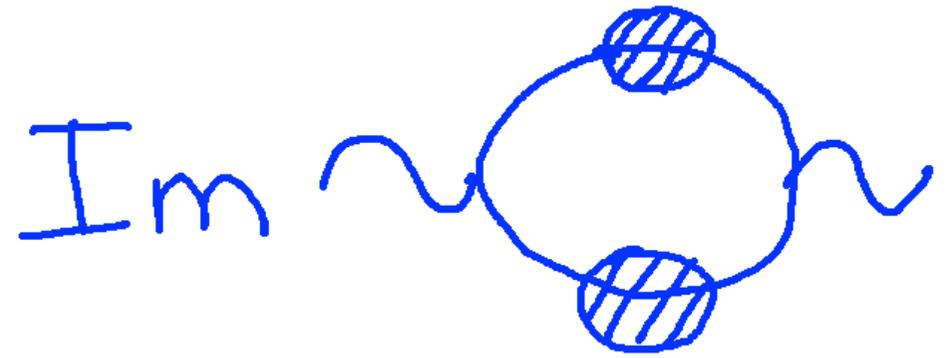
“Statistical confinement”: quark anti-quark forms “boson”,
which exhibits Bose-Einstein enhancement. But *no* dynamics of confinement.

N.B.: in dynamical quasi-particle model, as $T \rightarrow T_c$ quarks heavier,
but width increases, so also obtain enhanced dilepton rate.

Dileptons

Explicitly, we computed the diagram:

Here, propagators with hatched dot are just $p_0 \rightarrow p_0 - i Q^a$. Very straightforward



$$f_{\ell\bar{\ell}} = \# \text{ dileptons} \begin{pmatrix} Q \neq 0 \\ Q = 0 \end{pmatrix}$$

$$f_{\ell\bar{\ell}} = 1 - \frac{2T}{3p} \log \frac{1 + 3\ell e^{-p_-/T} + 3\ell e^{-2p_-/T} + e^{-3p_-/T}}{1 + 3\ell e^{-p_+/T} + 3\ell e^{-2p_+/T} + e^{-3p_+/T}}$$

When $Q = 0$, # dileptons $\sim \alpha_{\text{em}}$. Photon momentum = (E, p) , $E_{\pm} = (E \pm p)/2$.

Polyakov loop = ℓ : = 1 in the perturbative QGP, and = 0 in the confined phase.

Ratio # dileptons, vs T

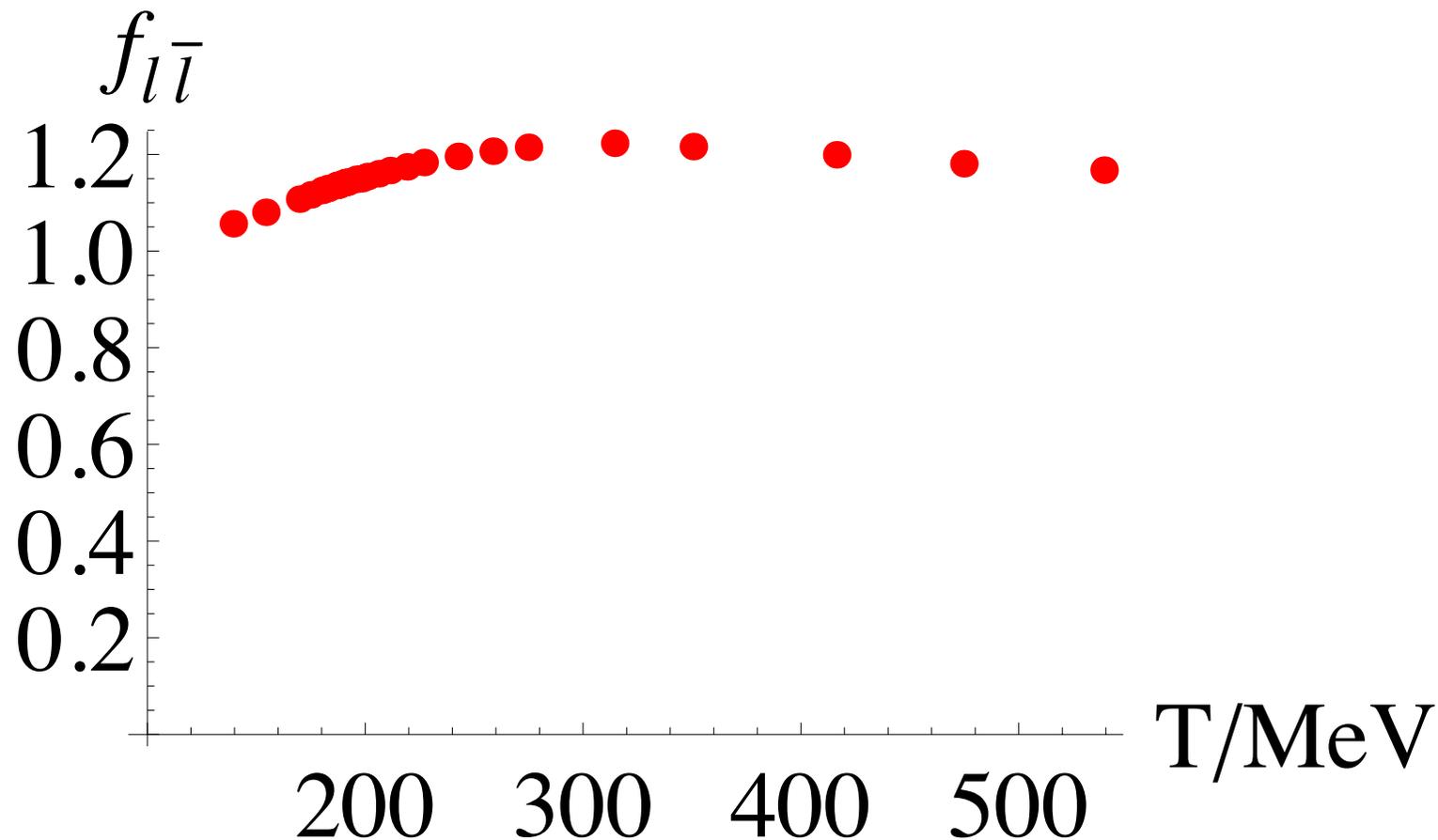
Below ratio of # dileptons, vs T. Ratio semi-QGP/perturbative QGP.

Take QCD coupling same, so only function of Q^a 's, taken from the lattice.

Mild enhancement of dileptons at small E.

Lee, Wirstam, Zahed, Hansson, ph/9809440:

Condensate in $\sim \langle A_0^2 \rangle$; equivalent to expanding to $\sim \langle Q^2 \rangle$.



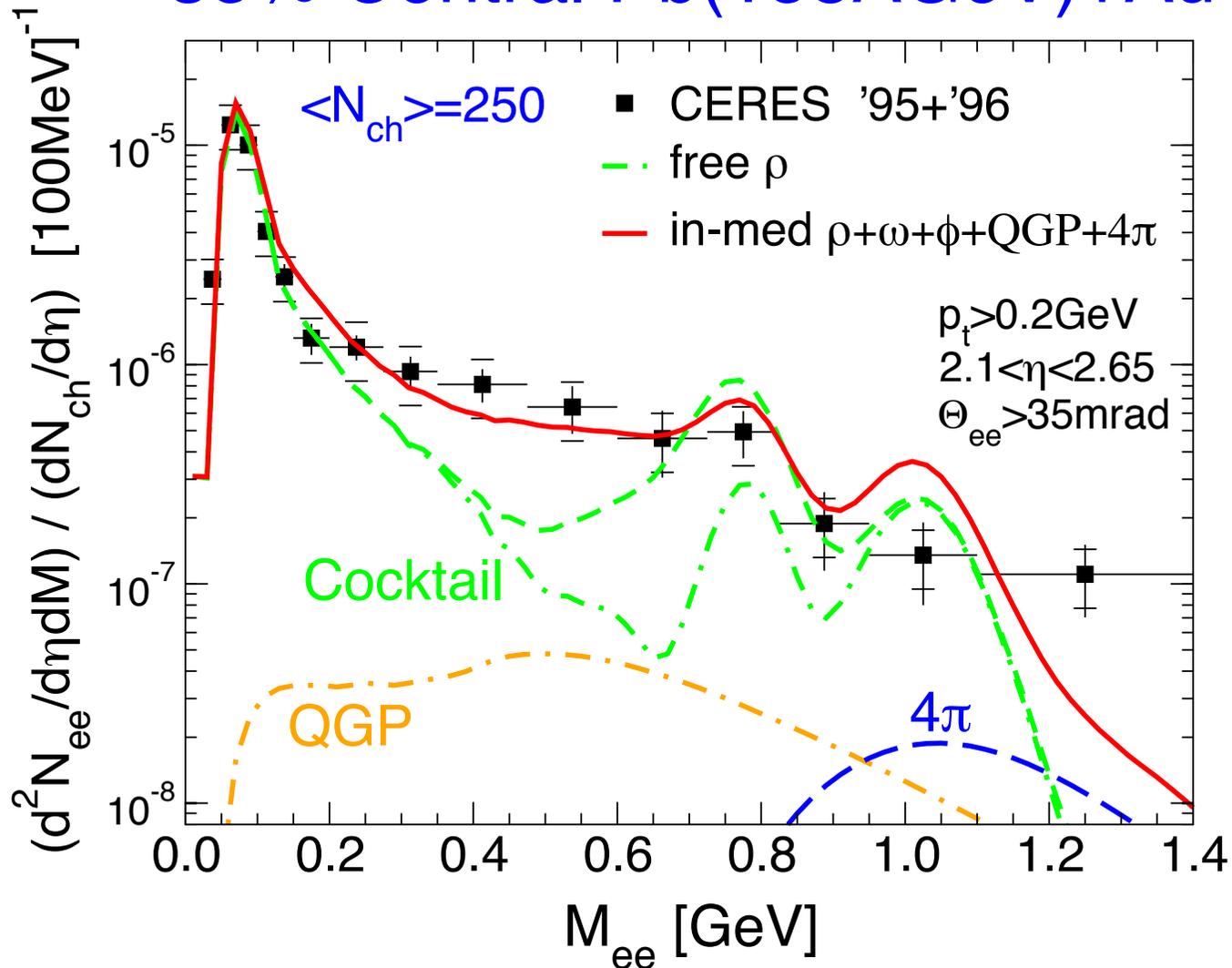
Experiment: dilepton excess below the ρ

CERES/NA45, $\sqrt{s} = 8.8$ GeV/A.

Below the ρ , QGP small, dominated by hadronic cocktail.

Need medium broadened ρ to fit data: so need to fit semi-QGP to hadronic phase

35% Central Pb(158A GeV)+Au

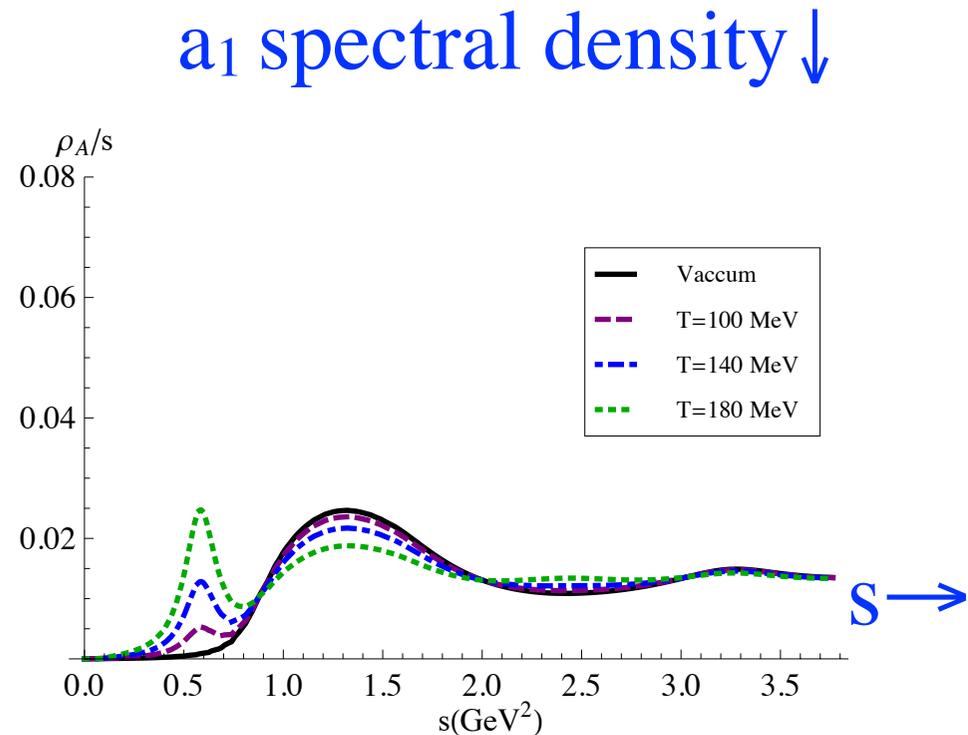
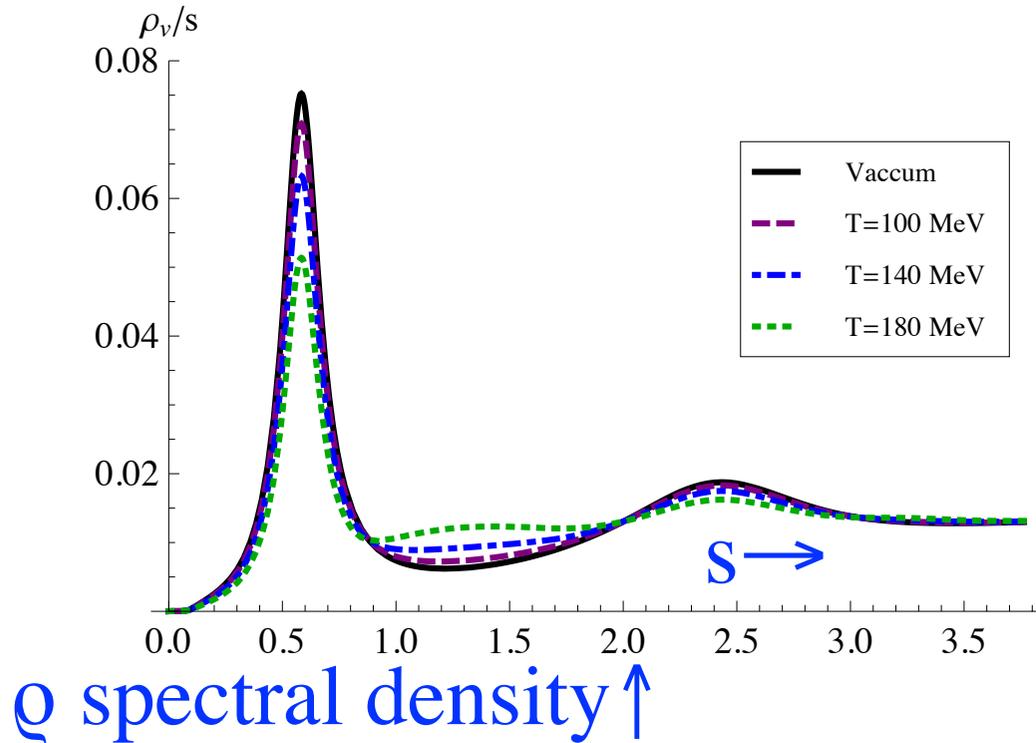


Rapp,
1306.6394

Where does the ρ go?

As $T \rightarrow T_\chi$, χ symmetry \Rightarrow ρ and a_1 spectral densities degenerate. *But how?*
Brown & Rho (PRL'91) ρ goes *down*. RDP, ph/9503328: ρ goes *up*.

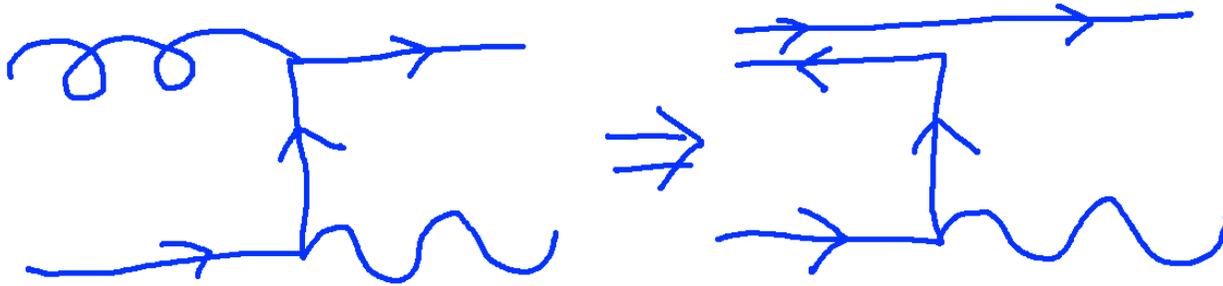
Holt, Hohler, & Rapp, 1210.7210: ρ and a_1 peaks *don't* move, just broaden: ?



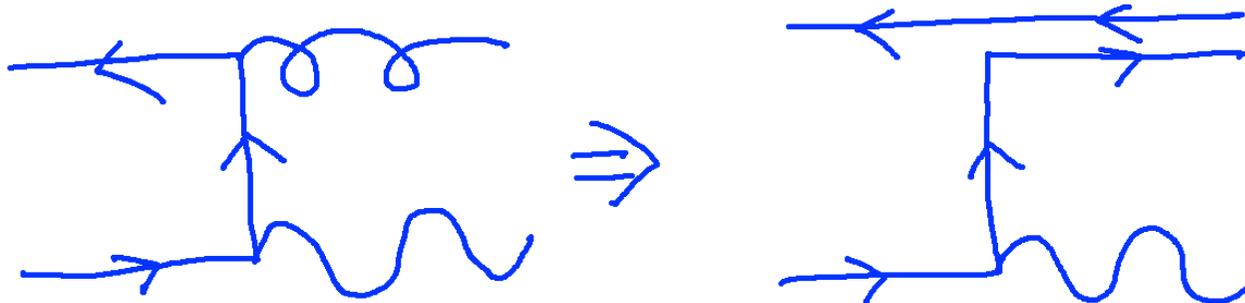
Ayala, Dominguez, Loewe, Mizher, Zhang, 1210.2588, 1309.4135, 1405.2228:
find the ρ *does* move....down :(

Production of hard photons

Photon on the mass shell cannot go to quark anti-quark; must also emit a gluon
At leading order, two processes. **Compton scattering:**

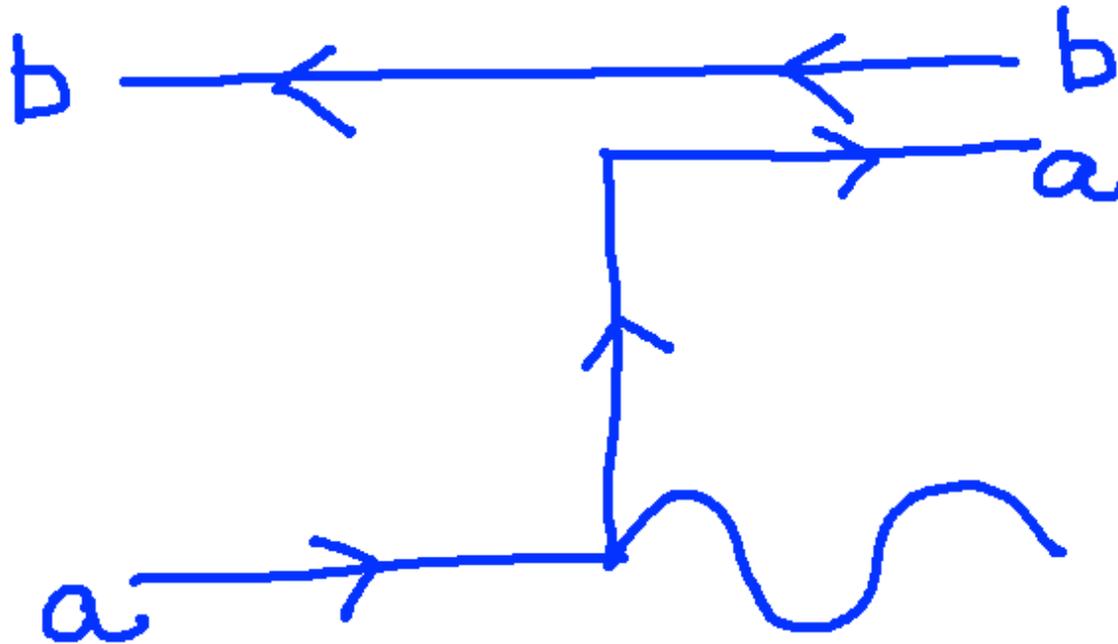


Pair annihilation:



Suppression in confined phase by $1/N^2$

In double line notation: diagram suppressed by loop unless colors of quark and anti-quark the same, $a = -b$:



But if $a = -b$, diagonal gluon, suppression of $1/N$.

And, if $a = -b$, tracelessness of gluon implies extra factor of $1/N$, or $1/N^2$ in all.

Similar suppression for Compton scattering.

Photon production: computation

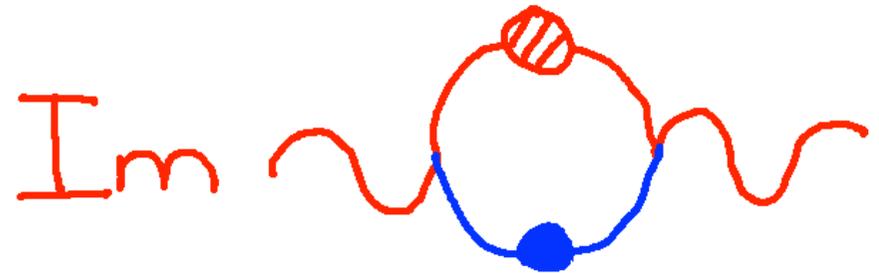
Photon momentum “hard”, $P = (E, p)$, $E = p \gg T$. Denote by red lines.
Internal lines can be soft, E or $p \sim T$; denote by blue lines.

Diagrams with one soft quark line:

Hatched blob: $Q^a \neq 0$

Solid blob: HTL with $Q^a \neq 0$

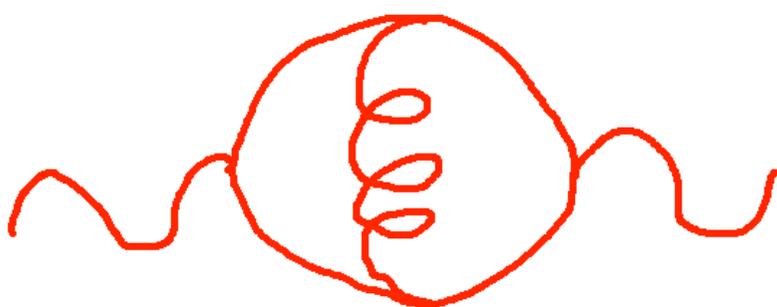
Exhibits logarithmic UV divergence, when the soft quark line becomes hard.



Also two loops diagrams, in which all lines are hard.

All lines below should be hatched, with $Q^a \neq 0$.

Exhibits logarithmic IR divergence, when the gluon line becomes soft.



Strong suppression of real photons in the confined phase

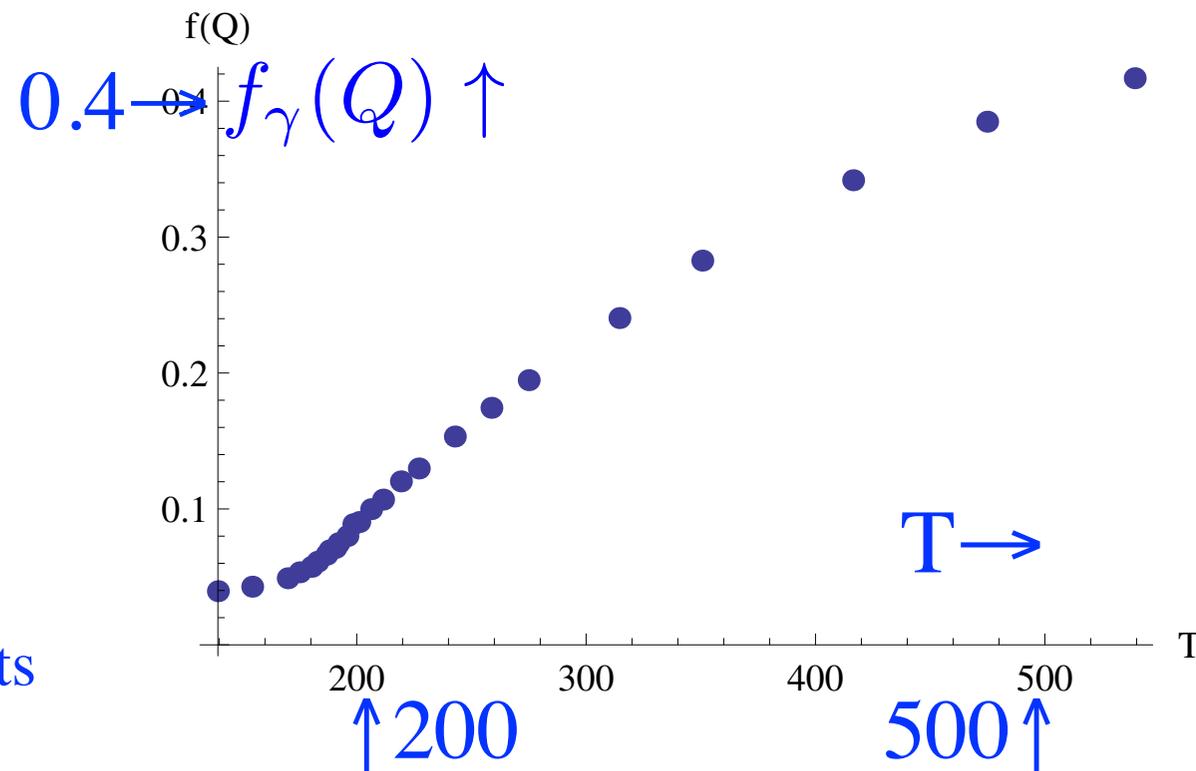
Summing soft + hard, logarithms cancel. For hard photons, very simple result:

$$f_\gamma(Q) = \# \text{ photons} \left(\begin{array}{l} Q \neq 0 \\ Q = 0 \end{array} \right) = 1 - 4q + \frac{10}{3}q^2 ; \quad q = \frac{Q}{2\pi T}$$

In the confined phase, $q_{\text{conf}} = 1/3$,
find *huge* suppression:

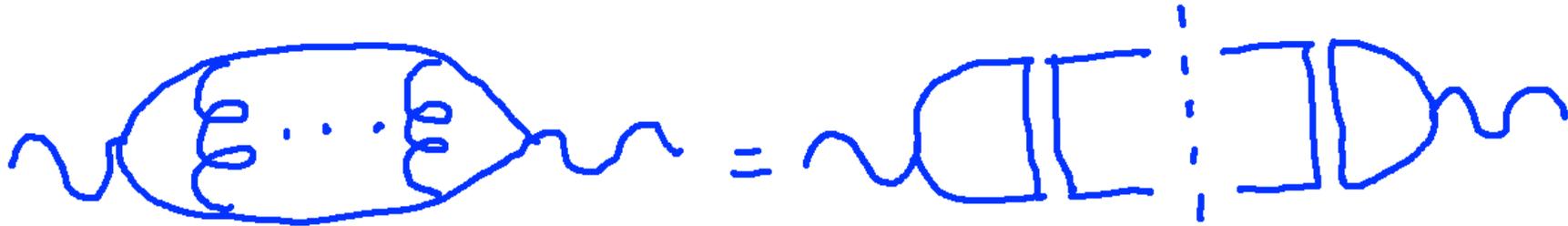
$$f_\gamma(q_{\text{conf}}) = \frac{1}{3N^2} = \frac{1}{27}$$

Suppression is so large that it persists
even to $T \sim 500$ MeV.



Heh, what about Landau-Pomeranchuk-Migdal!

In the perturbative QGP, even at leading order in g^2 , LPM \Rightarrow need to resum an *infinite* set of ladder diagrams: Arnold, Moore & Yaffe, [ph/0111107](#), [ph/0204343](#)



Each new rung is down by g^2 , but for soft gluon, $k \sim gT$, compensated by Bose-Einstein enhancement times energy denominator,

$$g^2 n(gT) \frac{T}{ip_0 - E_k + E_{p-k}} \sim g^2 \frac{T}{gT} \frac{T}{gT} \sim 1$$

Semi-QGP: only soft gluons are *diagonal*, so LPM is suppressed by $1/N$.

What we did: only $2 \rightarrow 2$ processes, at leading logarithmic order.

Did compute LPM correction, term is large for $N = 3$.

Need to compute complete process, including LPM. Will do....

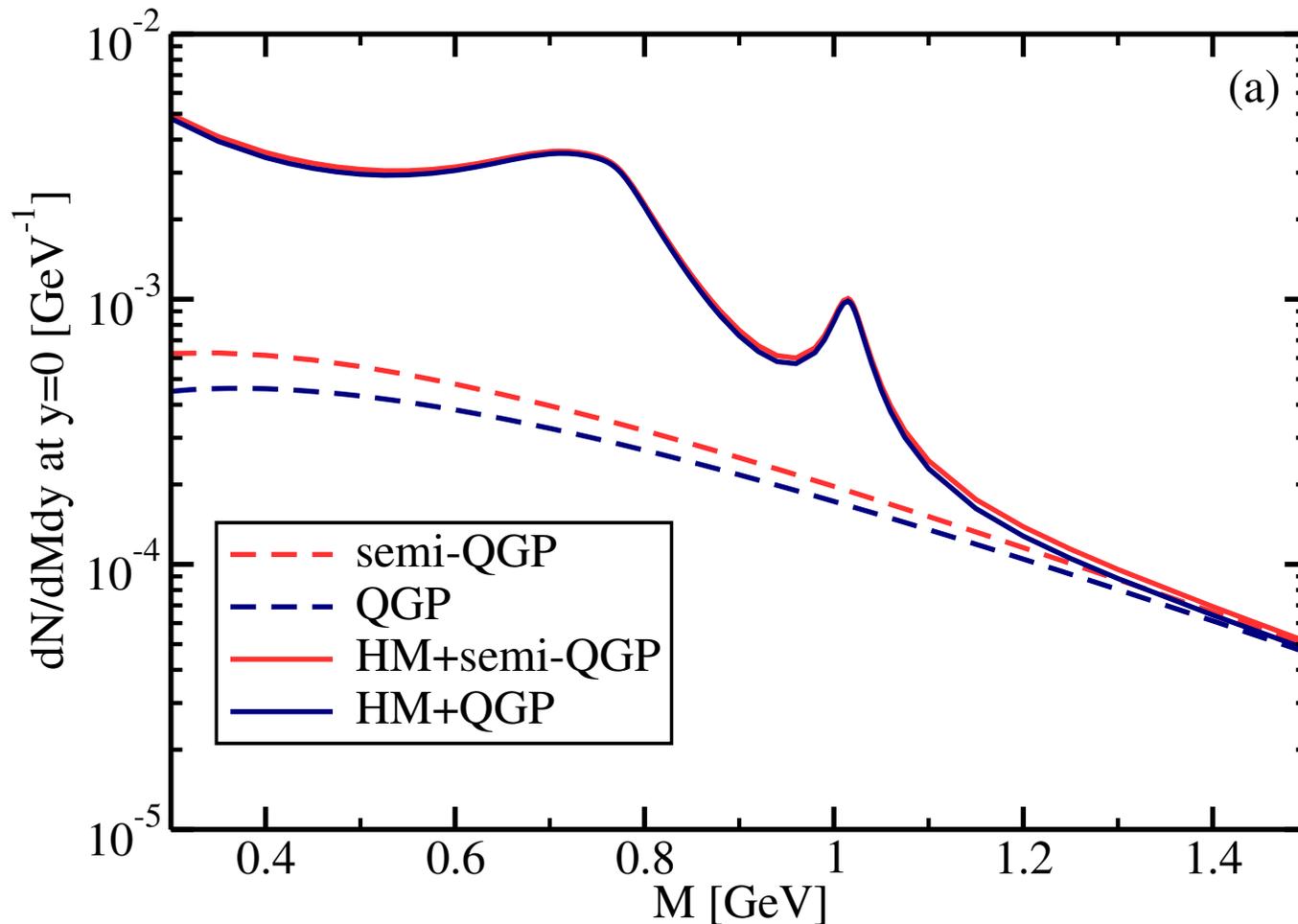
Hydrodynamics: # dileptons

MUSIC: 3+1 hydro @ RHIC: $\sqrt{s} = 200$ GeV/A, central collisions

Preliminary analysis: only ideal hydro.

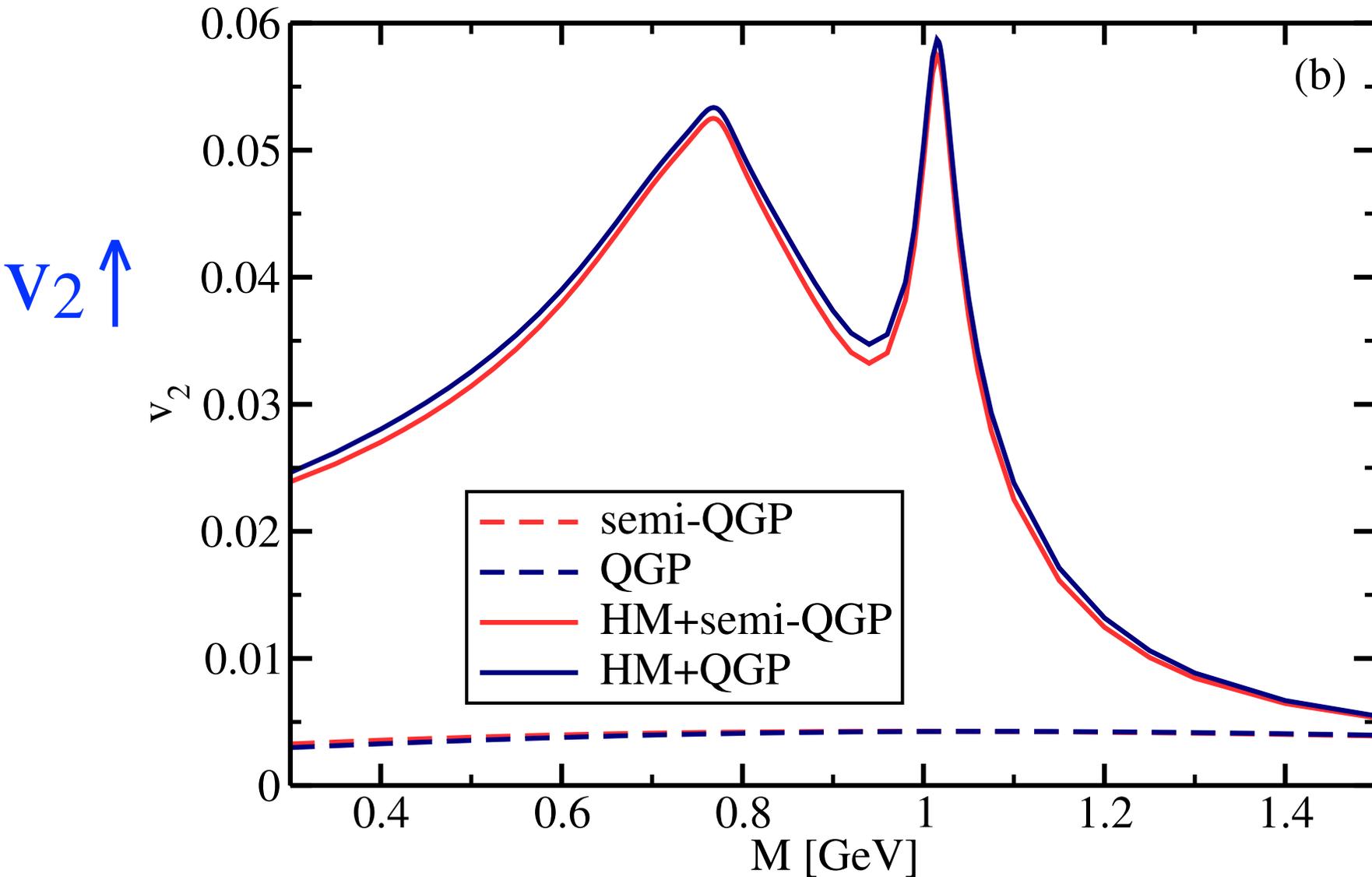
Small enhancement of dileptons in semi-QGP, swamped by hadronic phase.

No matching of semi-QGP to hadronic phase: clearly essential.



Hydrodynamics: dilepton v_2

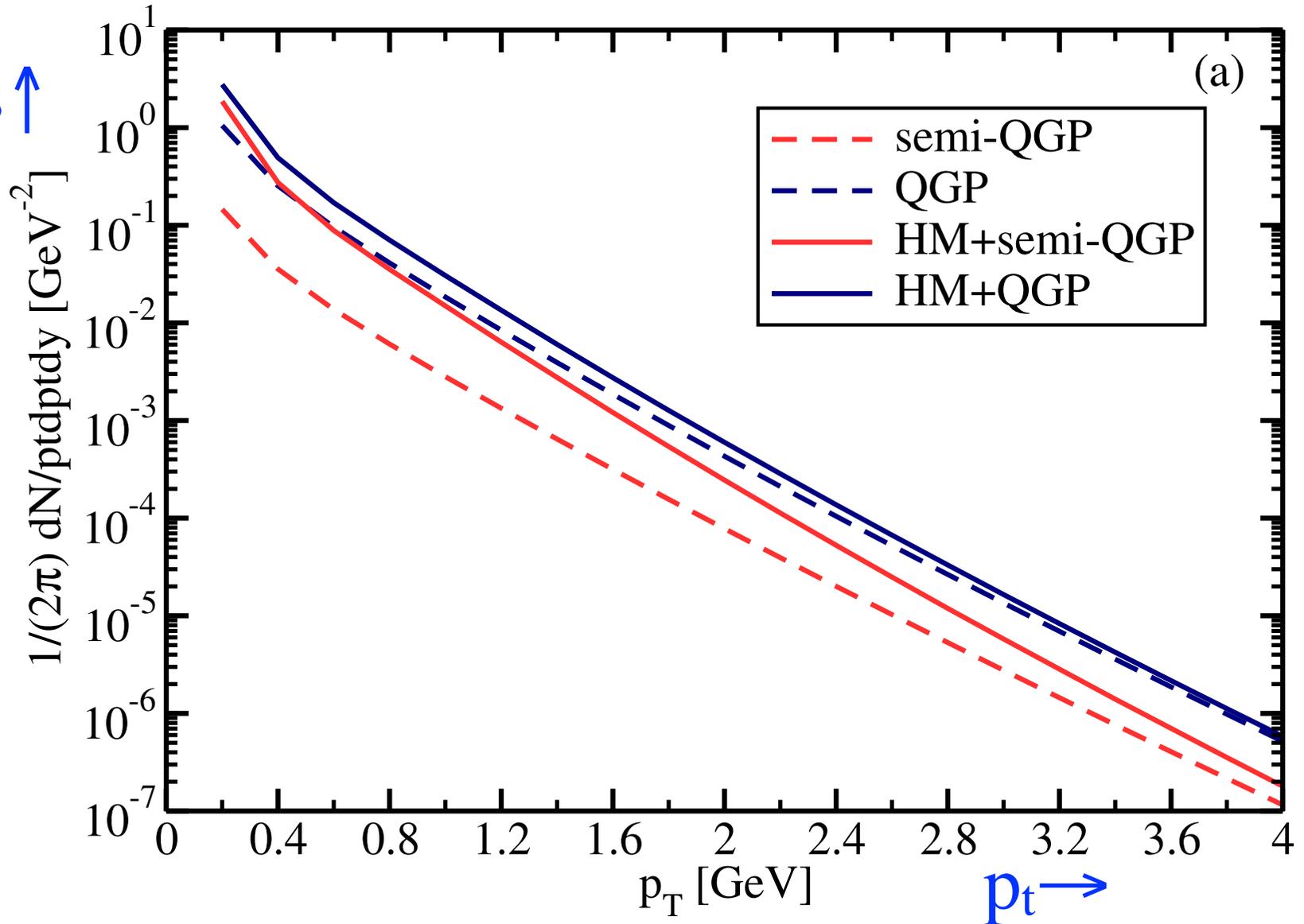
Since # dileptons dominated by hadrons, effect on elliptic flow, v_2 , small.



Hydrodynamics: # photons

In semi-QGP, *far* fewer photons above T_c .

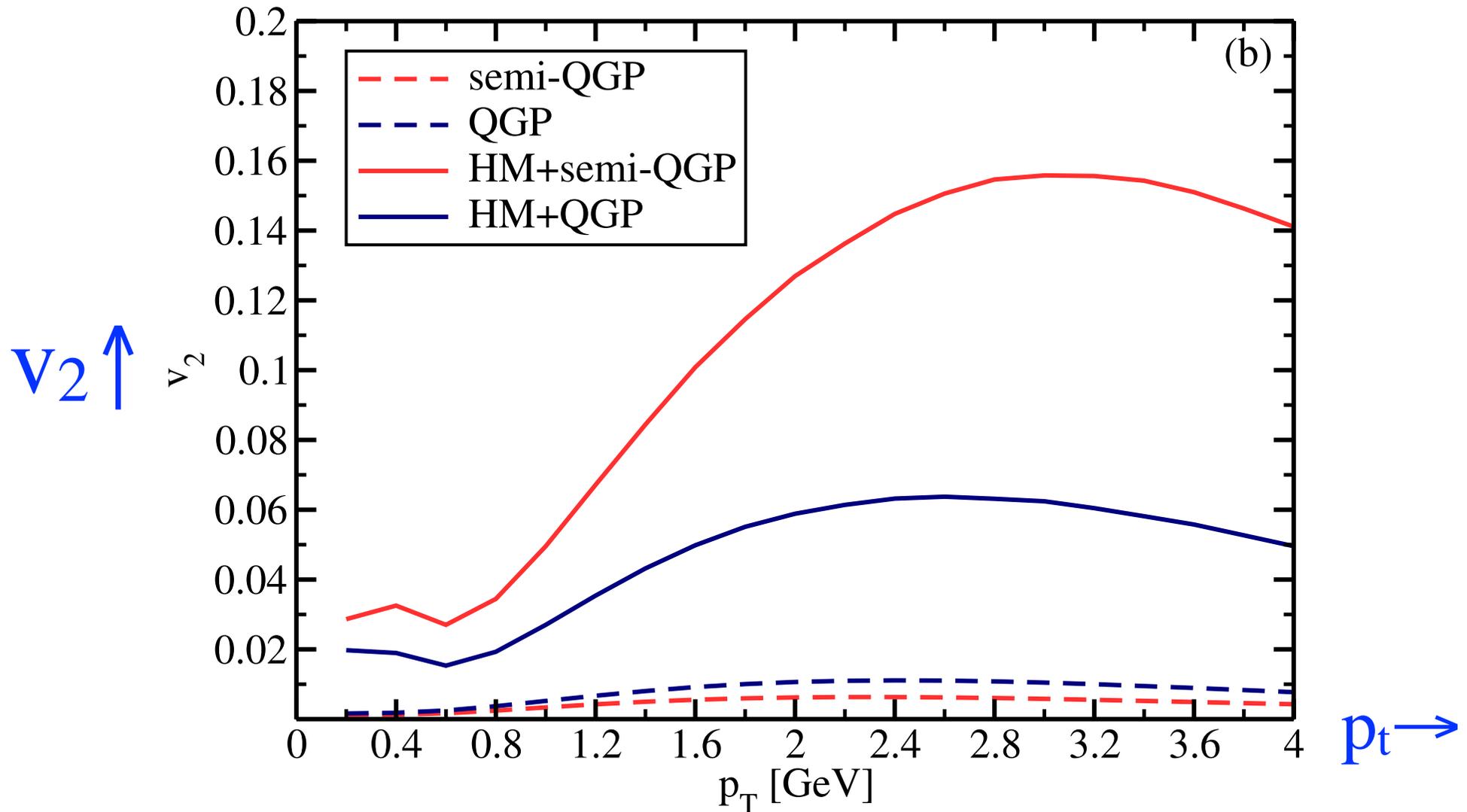
photons \uparrow



Hydrodynamics: photon elliptic flow, v_2

Fewer photons near T_c in semi-QGP has a big effect on the total v_2 .
Tends to bias the total v_2 to that in hadronic phase. Small “dilution” by QGP.

Possible solution to experimental puzzle of “big” v_2 for photons?



PHENIX vs theory: puzzle of the “missing” photons

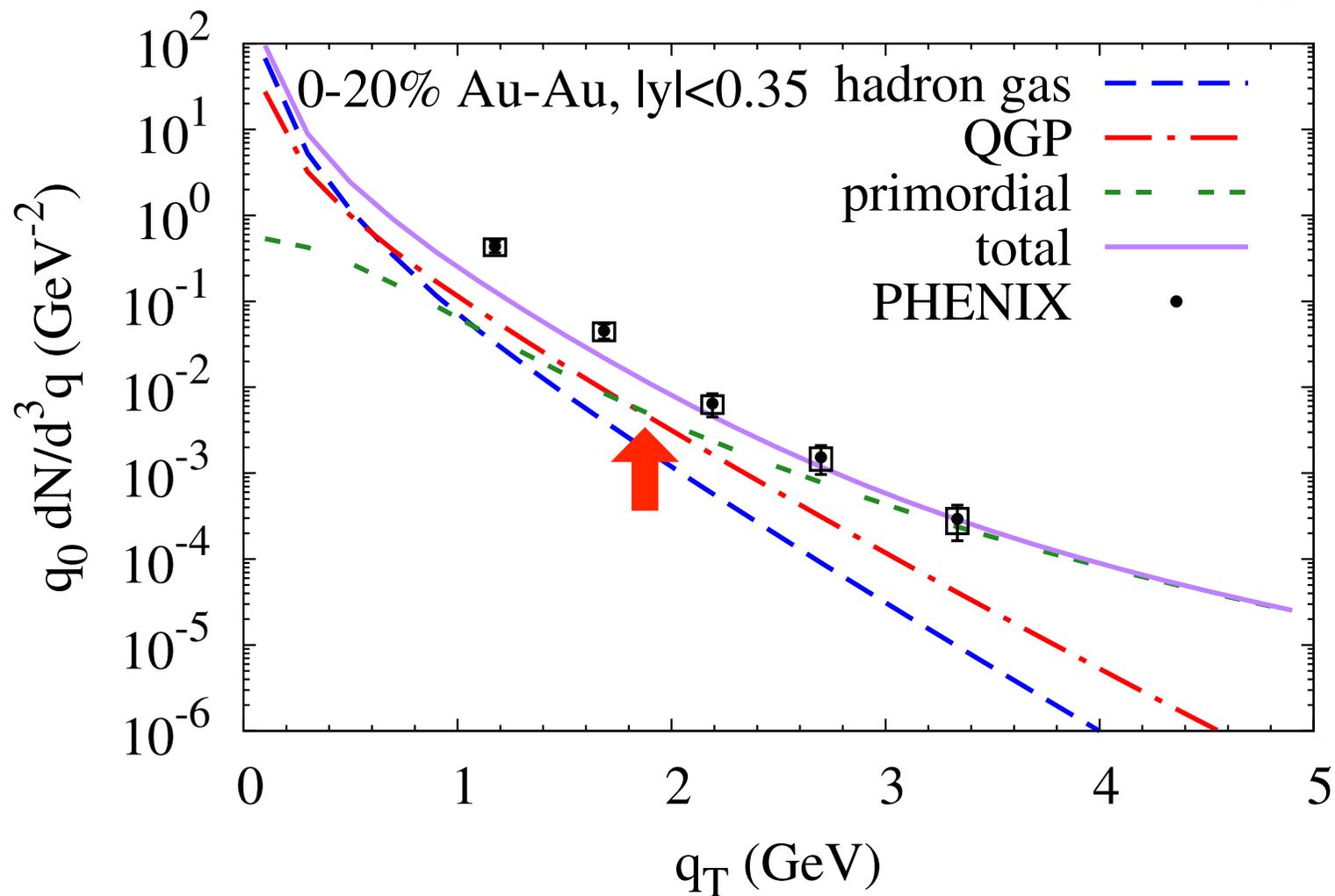
Sources of photons: QGP, hadron gas, “primordial” = hard initial processes

PHENIX: more photons than expected?

At RHIC: “primordial” photons appear to dominate above $p_t \sim 2 \text{ GeV}$

Experiment much larger than theory?

van Hees, He, Rapp, 1404.2846

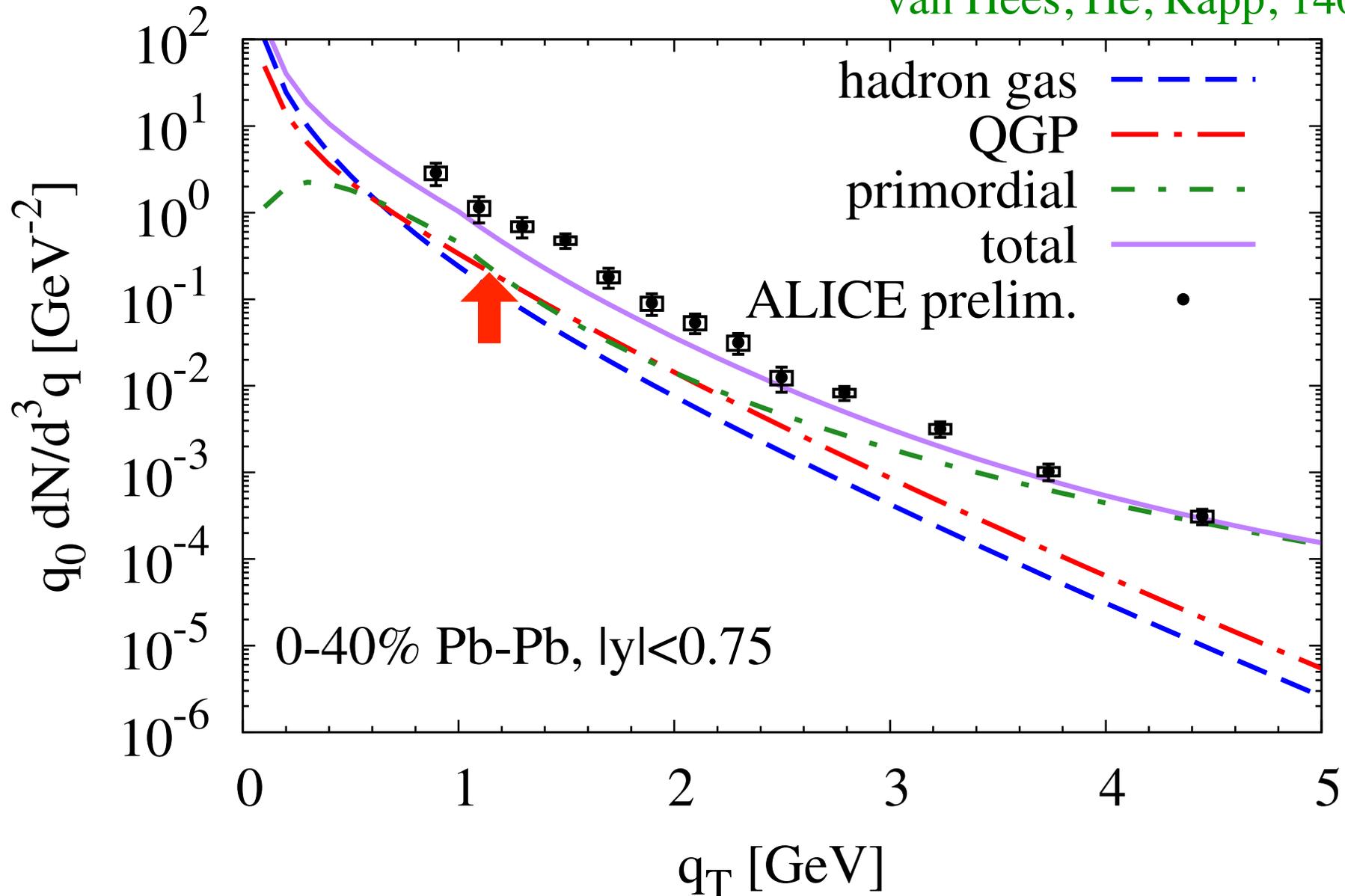


ALICE vs theory: puzzle of the “missing” photons

At LHC, “primordial” appears to dominate above $p_t \sim 1$ GeV

Again, experiment much larger than theory?

van Hees, He, Rapp, 1404.2846



Hadronic contribution to photons?

Dusling & Zahed, 0911.2426

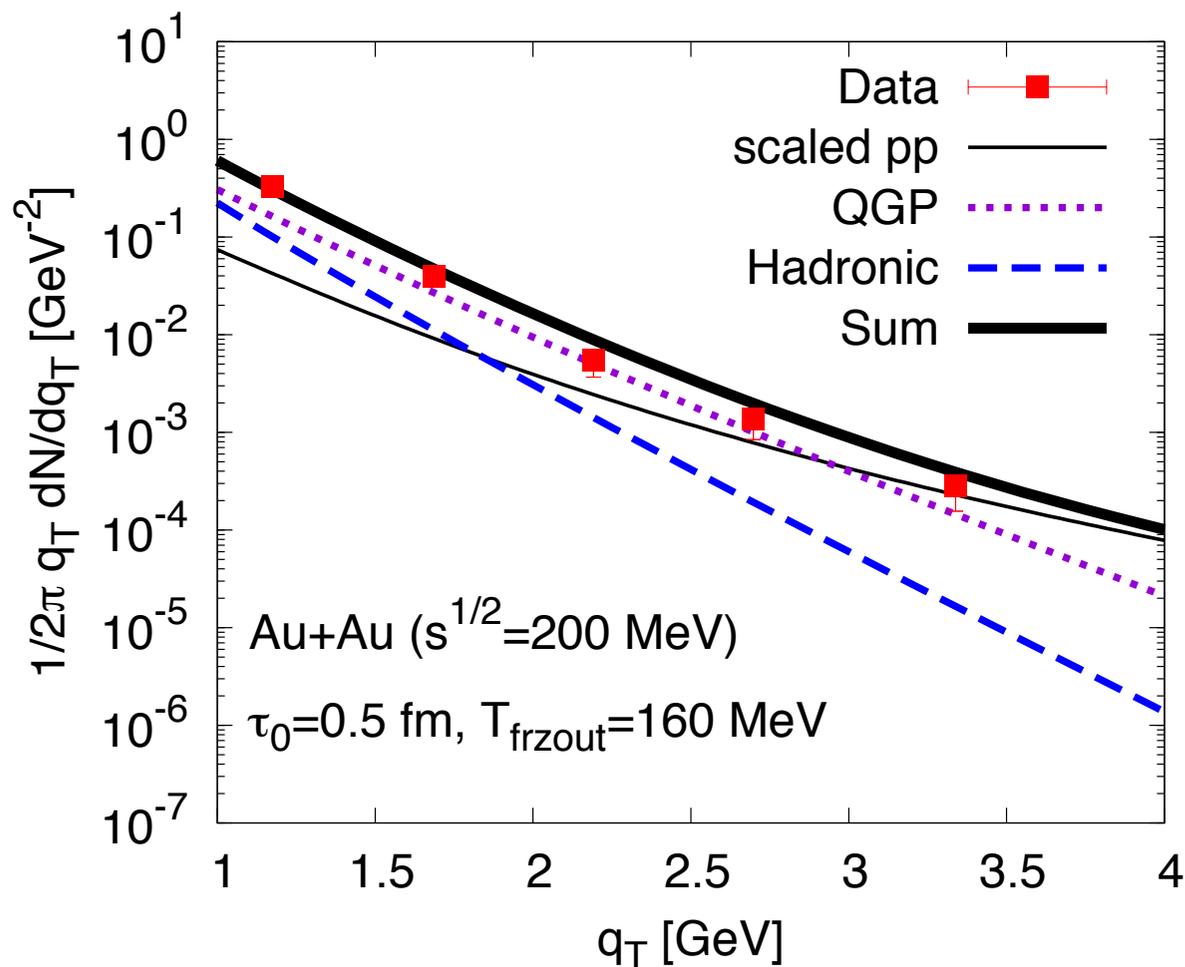
Do virial expansion, need

$$\langle \pi | J_V(x) J_V(0) | \pi \rangle ; \langle \pi\pi | J_V(x) J_V(0) | \pi\pi \rangle$$

Use experimental input (R, τ decay) :

find hadronic contribution much larger than other analyses;

Resolves puzzle of the “missing” photons?

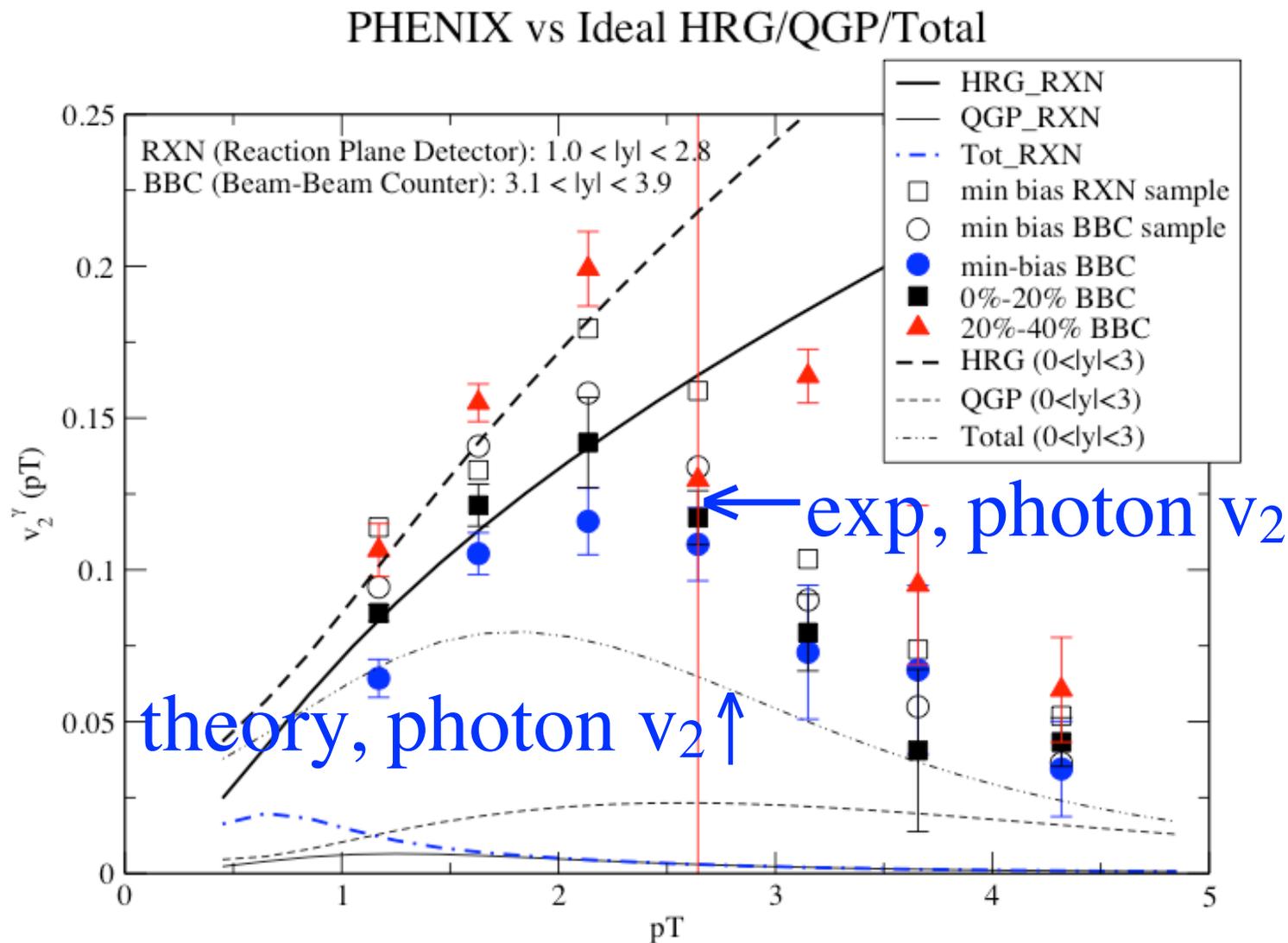


Photon elliptic flow still too big by $\sim 2!$

Dusling & Zahed, unpublished,

RIKEN@BNL workshop on “Thermal Photons & Dileptons”, Aug. '14

<http://www.star.bnl.gov/~ruanlj/?dir=TPD2014/&file=Zahed.pptx>

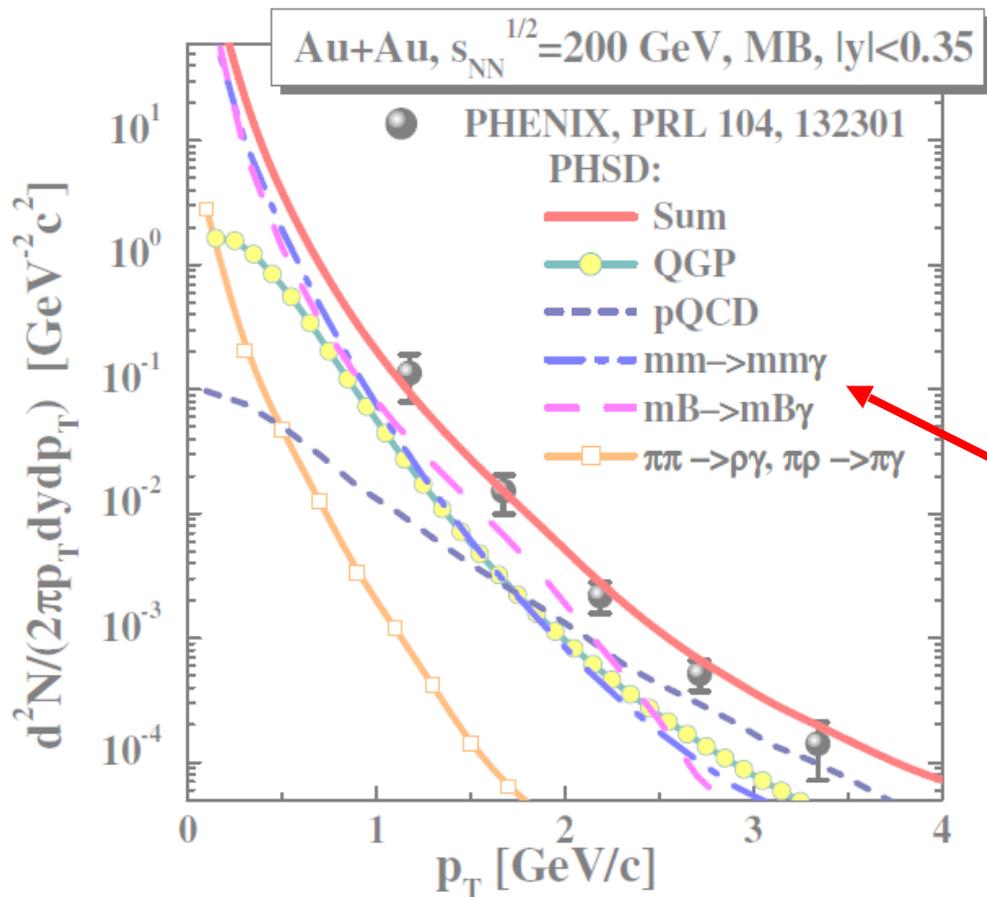


PHSD: photon spectra at RHIC: QGP vs. HG ?



Linnyk et al., PRC88 (2013) 034904;
PRC 89 (2014) 034908

- Direct photon spectrum (min. bias)



PHSD:

- QGP gives up to ~50% of direct photon yield below 2 GeV/c

! sizeable contribution of hadronic sources
- meson-meson (mm) and meson-Baryon (mB) bremsstrahlung

$$m+m \rightarrow m+m+\gamma,$$

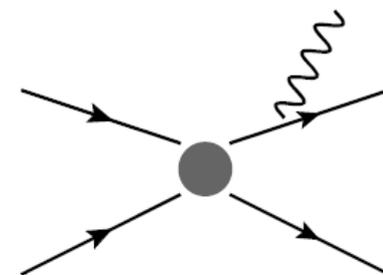
$$m+B \rightarrow m+B+\gamma,$$

$$m=\pi,\eta,\rho,\omega,K,K^*,$$

$$\dots$$

$$B=\rho$$

!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !



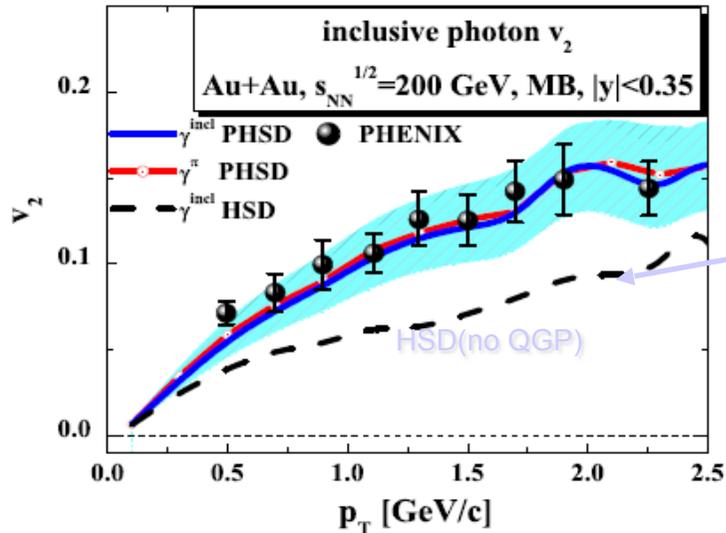
| The slope parameter T_{eff} (in MeV) | | | |
|--|--------------|--------------|---------------------|
| PHSD | | | PHENIX [38] |
| QGP | hadrons | Total | |
| 260 ± 20 | 200 ± 20 | 220 ± 20 | $233 \pm 14 \pm 19$ |

Are the direct photons a barometer of the QGP?



Do we see the **QGP pressure** in $v_2(\gamma)$ if the photon productions is **dominated by hadronic sources**?

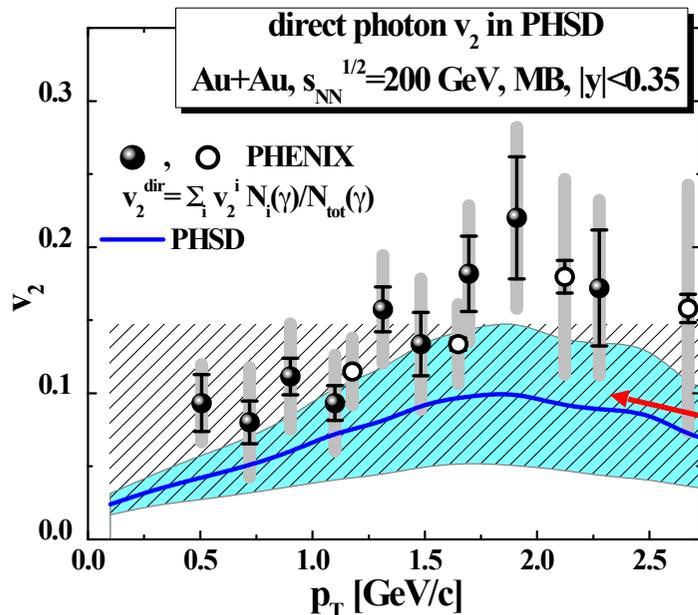
PHSD: Linnyk et al.,
PRC88 (2013) 034904;
PRC 89 (2014) 034908



1) $v_2(\gamma^{incl}) = v_2(\pi^0)$ - inclusive photons mainly come from π^0 decays

■ HSD (without QGP) underestimates v_2 of hadrons and inclusive photons by a factor of 2, whereas the PHSD model with QGP is consistent with exp. data

→ The **QGP causes the strong elliptic flow of photons indirectly**, by enhancing the v_2 of final hadrons due to the partonic interactions



Direct photons (inclusive(=total) – decay):

2) $v_2(\gamma^{dir})$ of direct photons in PHSD underestimates the PHENIX data: $v_2(\gamma^{QGP})$ is very small, but QGP contribution is up to 50% of total yield → lowering flow

→ PHSD: $v_2(\gamma^{dir})$ comes from **mm and mB bremsstrahlung!**

Hunt for the Quark Gluon Plasma



The Quark Gluon Plasma as an Unicorn.
Experimentalists are the hunters, so....“All theorists are...”