Hard Dilepton and Photons, *near* T_c

arXiv.org: 1409.4778 & 1502.xxxx:

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 hydrodynamics (MUSIC):

@ McGill Univ.:

Charles Gale,
Sangyong Jeon,
Jean-Francois Paquet
Gojko Vujanovic

The Quark-Gluon Plasma *near* T_c

Low T to ~ T_c: hadronic resonance gas, χ perturbation theory....

2?T_c to 10^7 T_c: *must* resum perturbation theory
Gold standard: Hard Thermal Loop perturbation theory at *three* loop order
1402.6907: Haque, Aritra Bandyopadhyay, Andersen, Mustafa, Strickland,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 $T_i \to \infty$, $\langle T \rangle \to \frac{3}{2} T_f$ = 215 @ RHIC; = 227 @ LHC

For photon production, ~ T^4,

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

In equilibrium:
Functional Renormalization Group: Pawlowski & Rennecke, 1403.1179 + …
"Perturbation" thy:Reinosa, Serreau, Tissier & Wschebor, 1407.6469, 1412.5672

Dynamical Quasi-Particle Model: Bratkovskaya, Linnyk, Cassing, 1409.4190…

Polyakov NJL models:
Chowdhury Aminul Islam, Abir, Mustafa, Ghosh, Ray, 1208.3146
C. A. Islam, S. Majumder, N. Haque, Mustafa, 1411. 6407

Center Domains:
Abishek Atreya, Sarkar, Srivastava, 1111.3027, 1404.5697, & Das, 1406.7411
Asakawa, Bass, Muller, 1208.2426

Here: "semi"-Quark Gluon Plasma

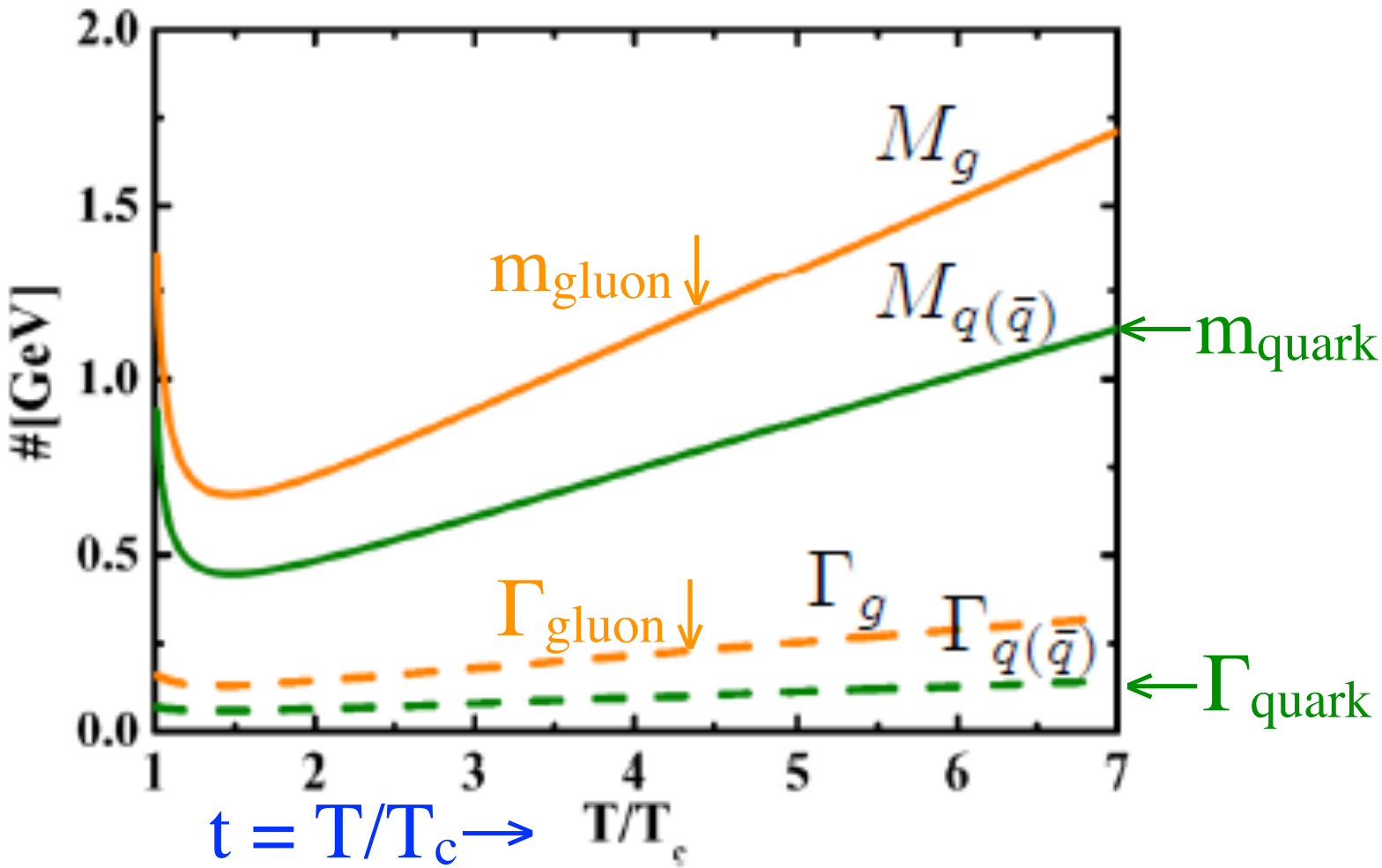
Dynamical Quasi-Particle Model

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*

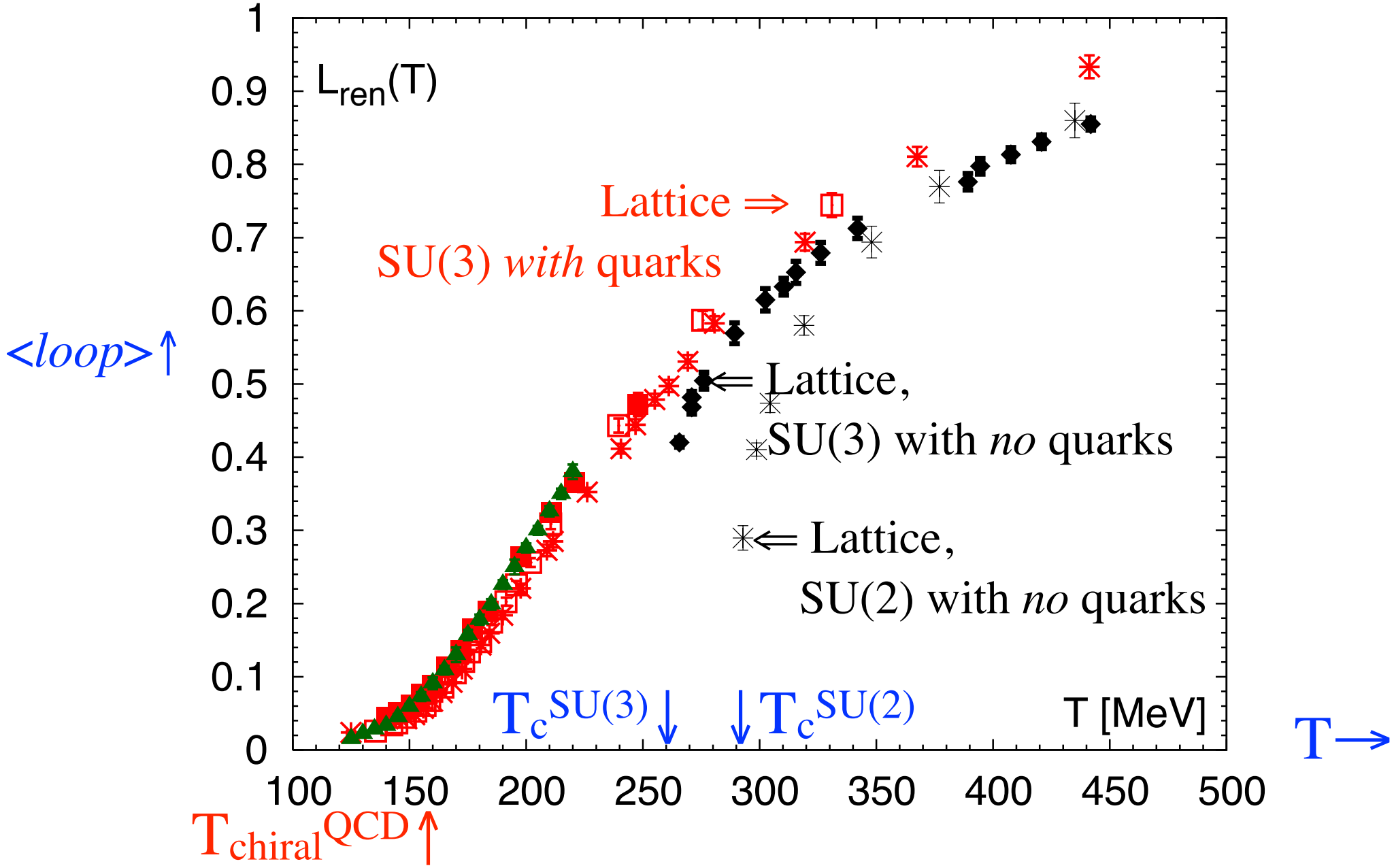
also include nonzero widths for the quasi-particles



Lattice: Polyakov Loop with and without quarks

Order parameter for deconfinement: Polyakov loop

Lattice: Bazavov & Petreczky, 1110.2160



"Semi"-QGP

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

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

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

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

Dumitru, 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}:

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

$\langle q \rangle$ 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 ± .1; DG: 1.67 ± .1.

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

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

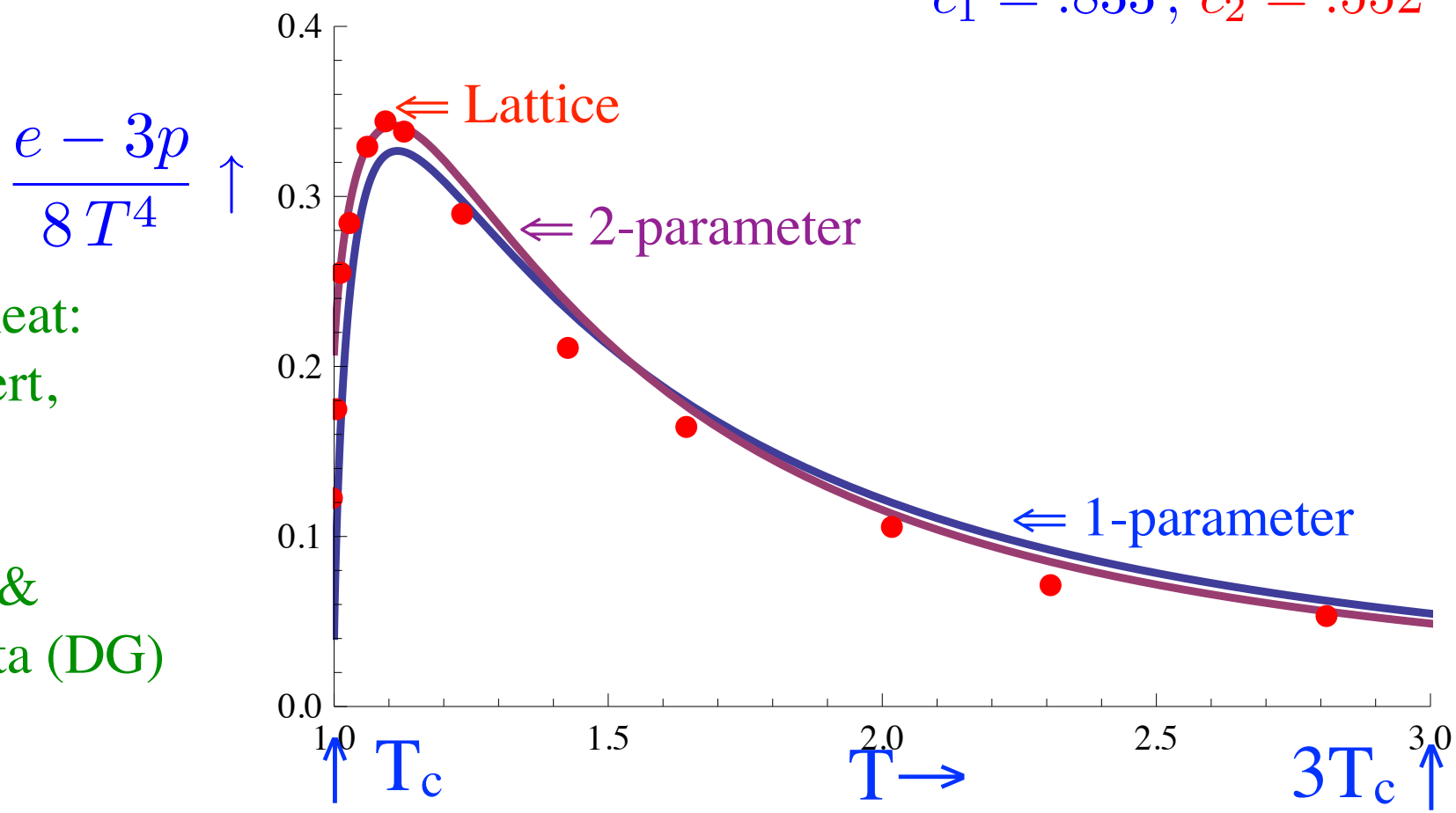
WHOT: $c_3(\infty) \sim 1$. *Fit* $c_3(1)$ to DG latent heat

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

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

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

Lattice latent heat:
Beinlich, Peikert,
Karsch (BPK)
lat/9608141
Saumen Datta &
Sourendu Gupta (DG)
1006.0938

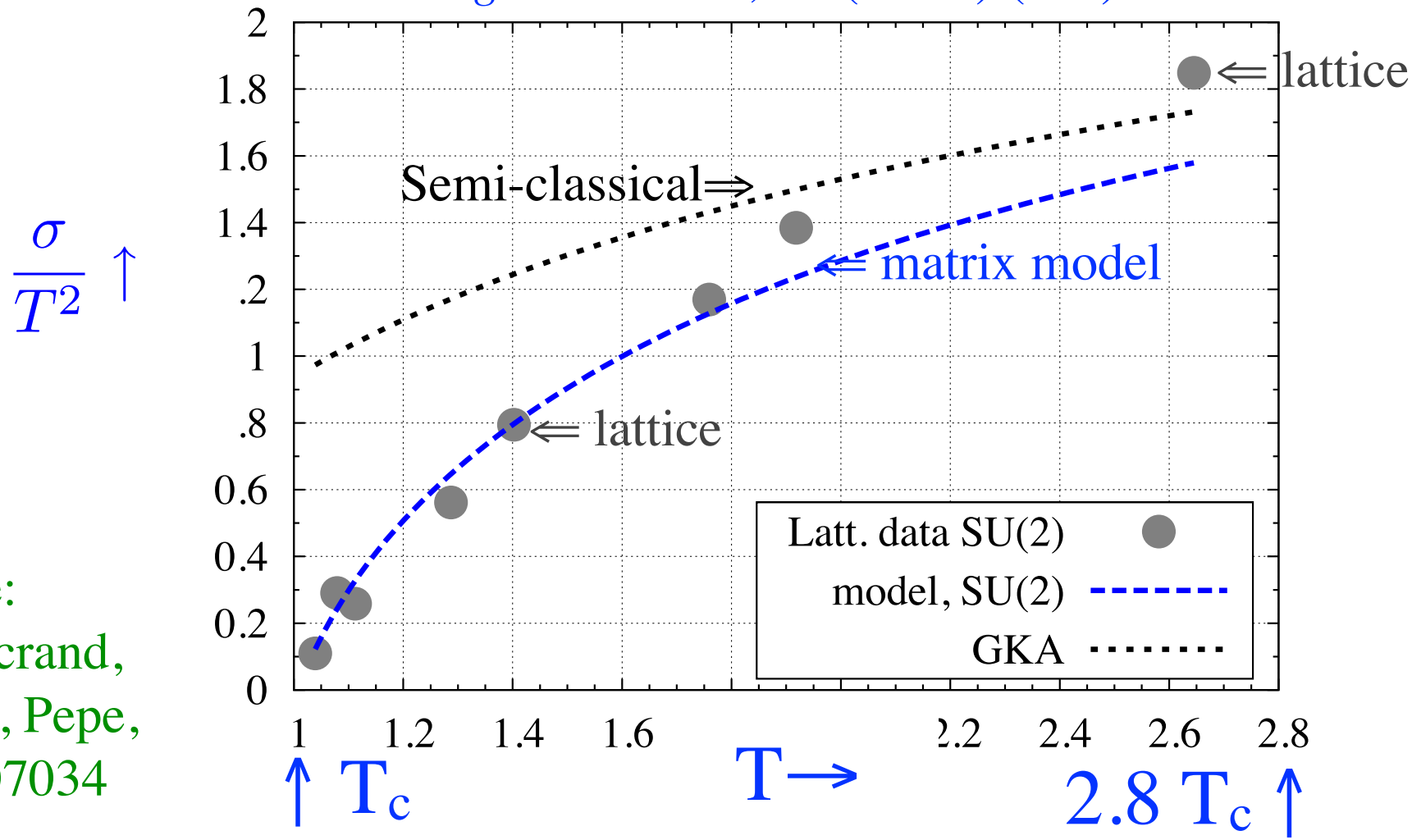


't Hooft string (Z(2) interface) tension, two colors

σ vanishes as $T \to T_c$, $\sigma \sim (t-1)^{2\nu}$.
Ising $2\nu \sim 1.26$; Lattice: ~ 1.32.
Matrix model: ~ 1.5: c_2 important.

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

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 $T \to T_c$, $\sim \sqrt{(t^2 - c_2)/(t^2-1)}$.



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

Polyakov loop vs lattice - ?

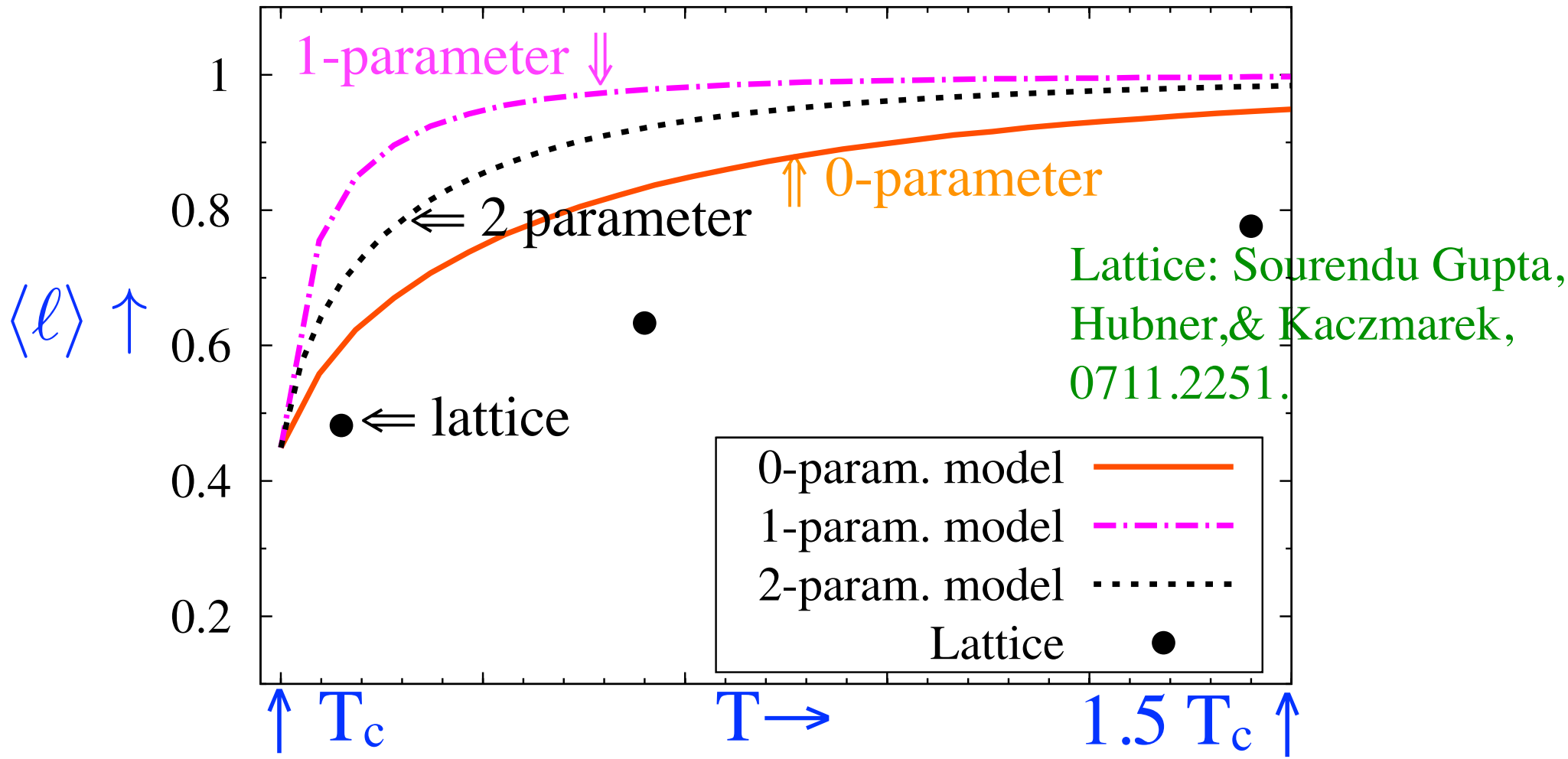
Polyakov loop from the lattice *nothing* like Matrix Model

Model: transition region *narrow*, to ~ 1.2 T_c. Lattice: loop *wide*, to ~ 4.0 T_c.

Also true for FRG, Pawlowski & Rennecke, 1403.1179 + …

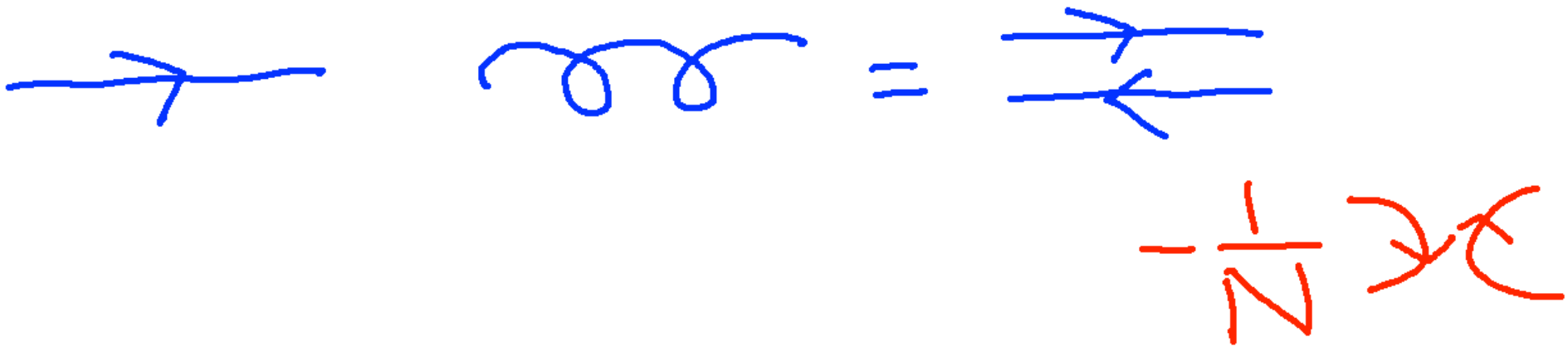
Reinosa, Serreau, Tissier & Wschebor, 1407.6469, 1412.5672

Need magnetic excitations? In practice: take Q ~ 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: $$p_0 = 2\pi T(n + 1/2) \to p_0 - iQ^a$$

Gluons: $$p_0 = 2\pi T n \to p_0 - i(Q^a - Q^b)$$

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

Semi-QGP in real time

Statistical distribution functions those for imaginary chemical potential:

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

For three colors, color chemical potential:

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

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

For N colors: ~ N^2 off-diagonal gluons, and ~ N diagonal gluons

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

Suppression of color near T_c

Consider energetic particles, E ≫ T, Boltzmann statistics

$$\widetilde{n}_a(E) \sim e^{-(E-iQ^a)/T} \qquad n_{ab}(E) \sim e^{-(E-i(Q^a-Q^b))/T}$$

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

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

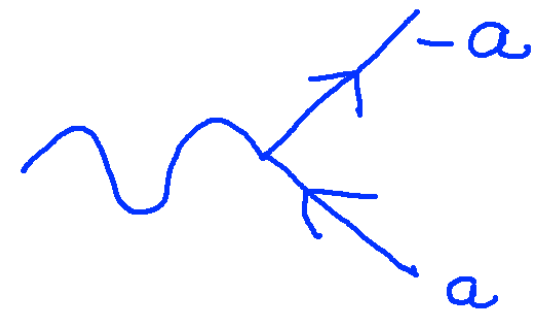
Summing over color,

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

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.

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

(Imaginary) chemical potential: sign of Q^a *flips* between q and q bar.
Large E: with Boltzmann statistics,

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

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 → 0, # dileptons:
Fermi-Dirac dist. fnc. finite at E = 0.

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

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

$$\frac{1}{N}\sum_{a=1}^{N} \widetilde{n}_a(E)\, \widetilde{n}_{-a}(E) \sim n(E) =_{E\to 0} \frac{T}{E}$$

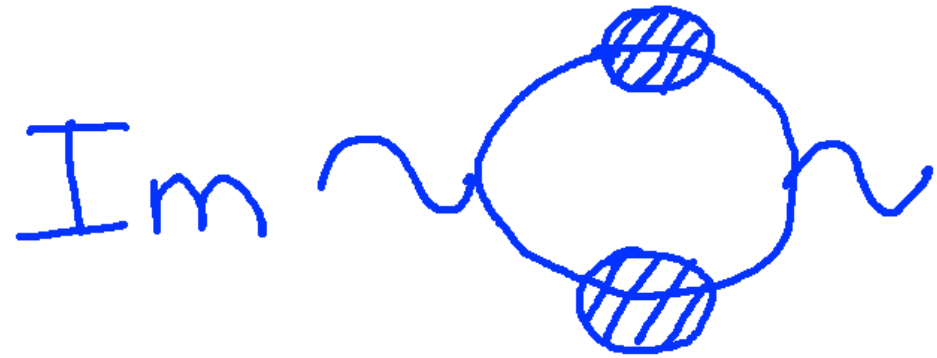
More dileptons in the confined phase!
Confined phase only in the pure gauge theory, but interesting point of principle.

"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 → 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 $p_0 \to p_0 - i\,Q^a$. *Very* straightforward



$$f_{\ell\bar{\ell}} = \#\ \text{dileptons}\left(\frac{Q \neq 0}{Q = 0}\right)$$

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

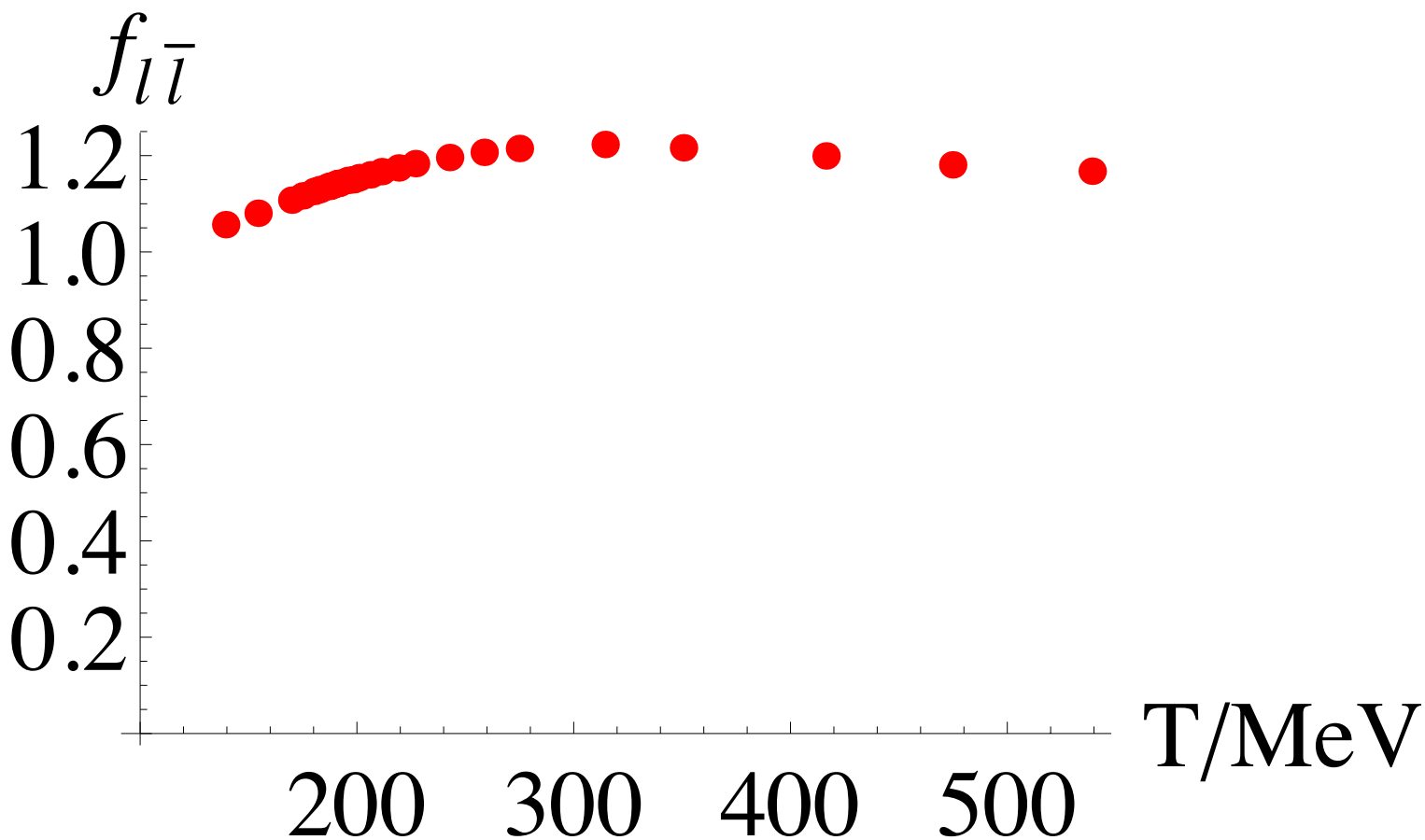
When Q = 0, # dileptons ~ α_{em}. Photon momentum = (E,p), $E_\pm = (E \pm p)/2$.
Polyakov loop = ℓ : = 1 in the perturbative QGP, and = 0 in the confined phase.
Above factor analogous to

Abishek Atreya, Sarkar, Srivastava, 1111.3027, 1404.5697, & Das, 1406.7411

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 ~ $\langle A_0^2 \rangle$; equivalent to expanding to ~ $\langle Q^2 \rangle$.

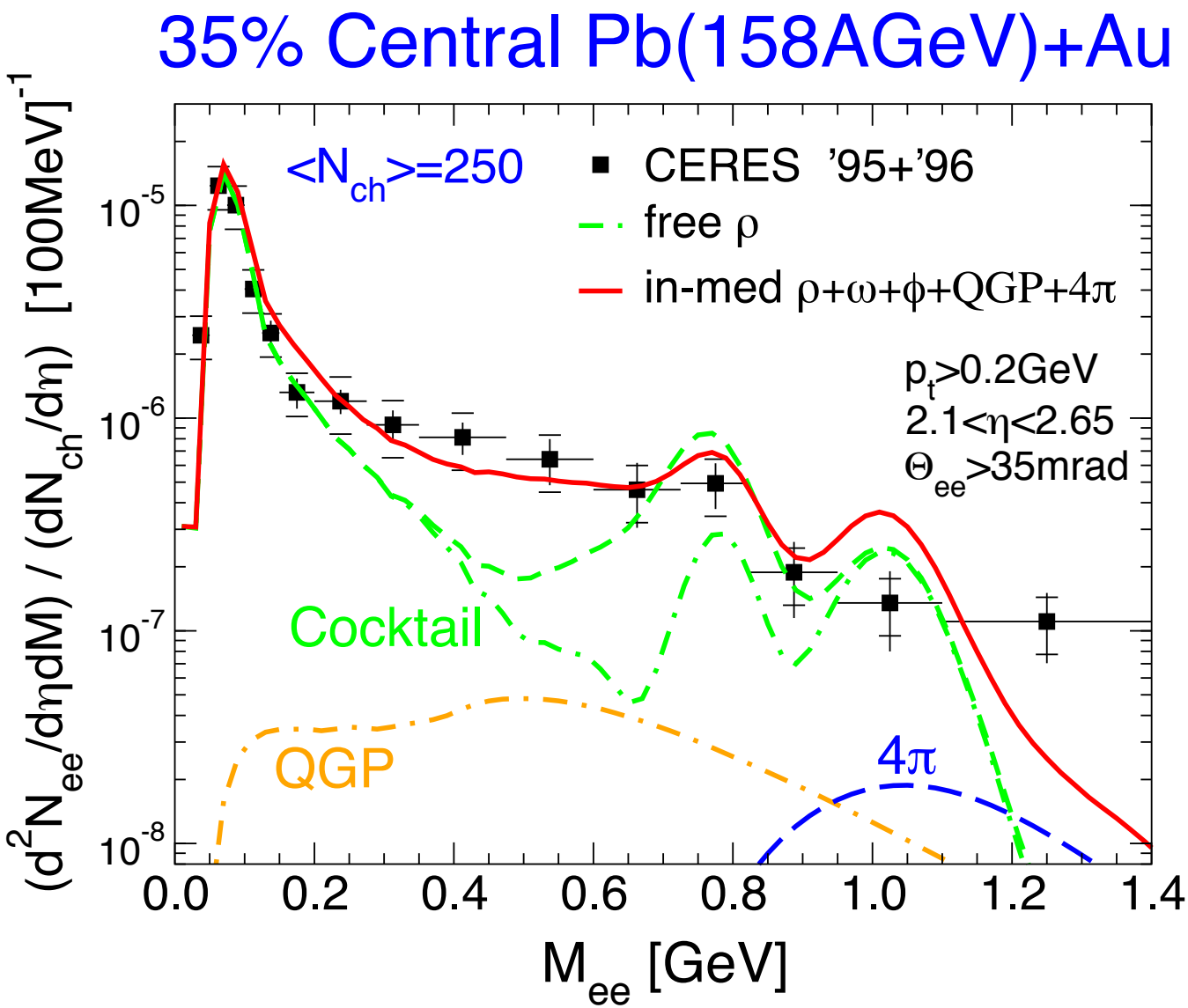


Experiment: dilepton excess below the ϱ

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



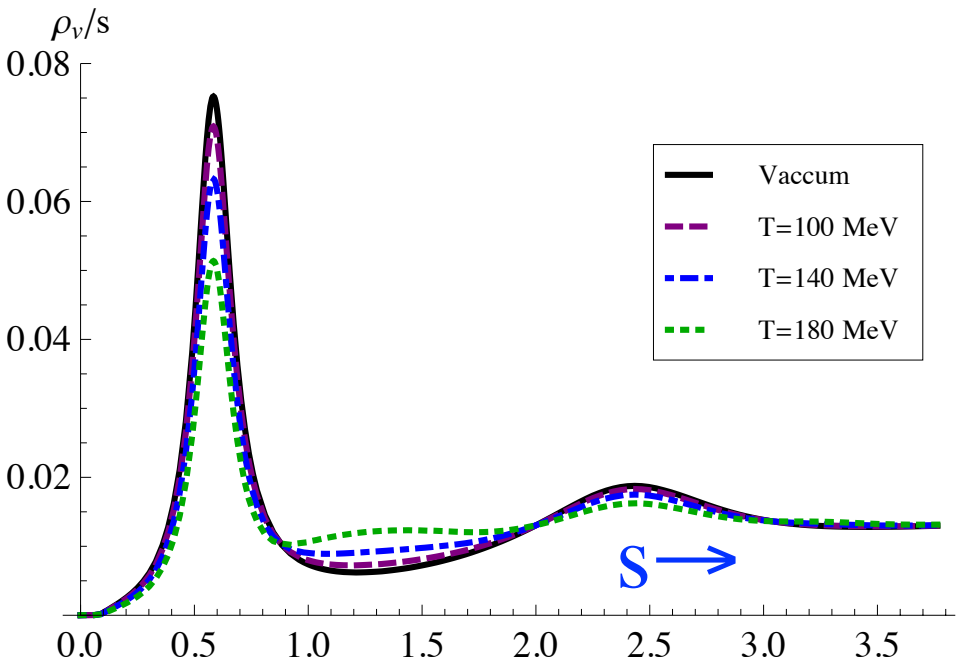
Rapp, 1306.6394

Where does the ϱ go?

As $T \to T_\chi$, χ symmetry $\Rightarrow$ ϱ and a_1 spectral densities degenerate. *But how?*

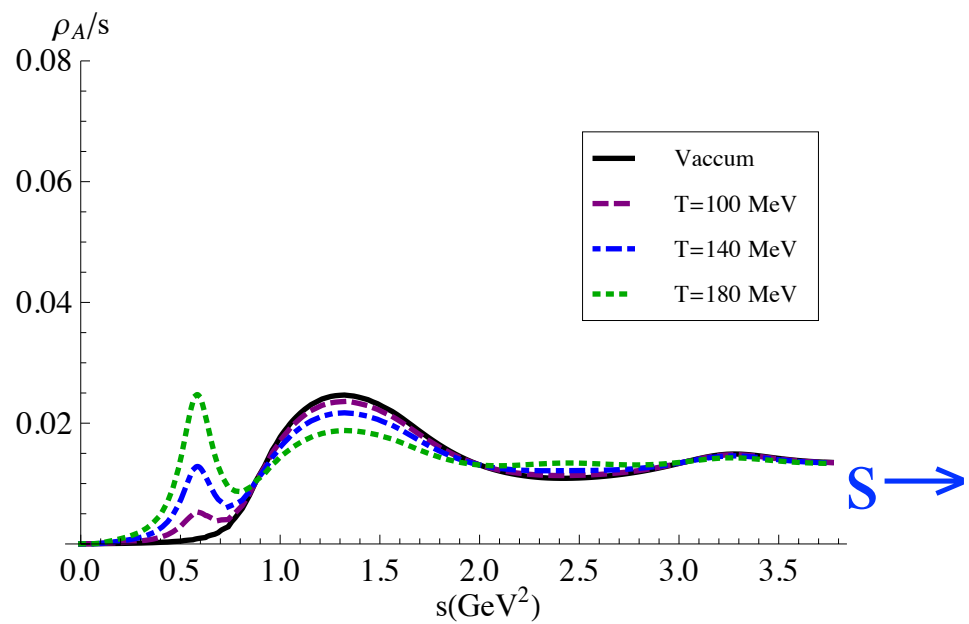
Brown & Rho (PRL'91) ϱ goes *down*. RDP, ph/9503328: ϱ goes *up*.

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



ϱ spectral density↑

a_1 spectral density↓

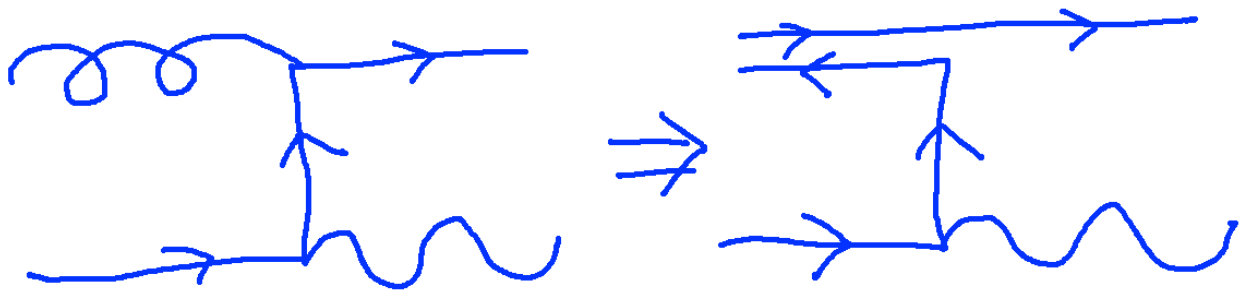


Ayala, Dominguez, Loewe, Mizher, Zhang, 1210.2588, 1309.4135, 1405.2228:

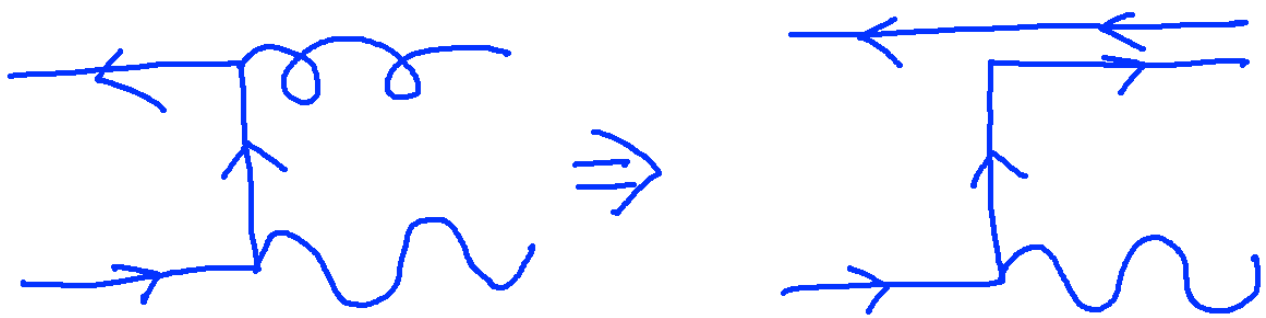
find the ϱ *does* move….down :(

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:

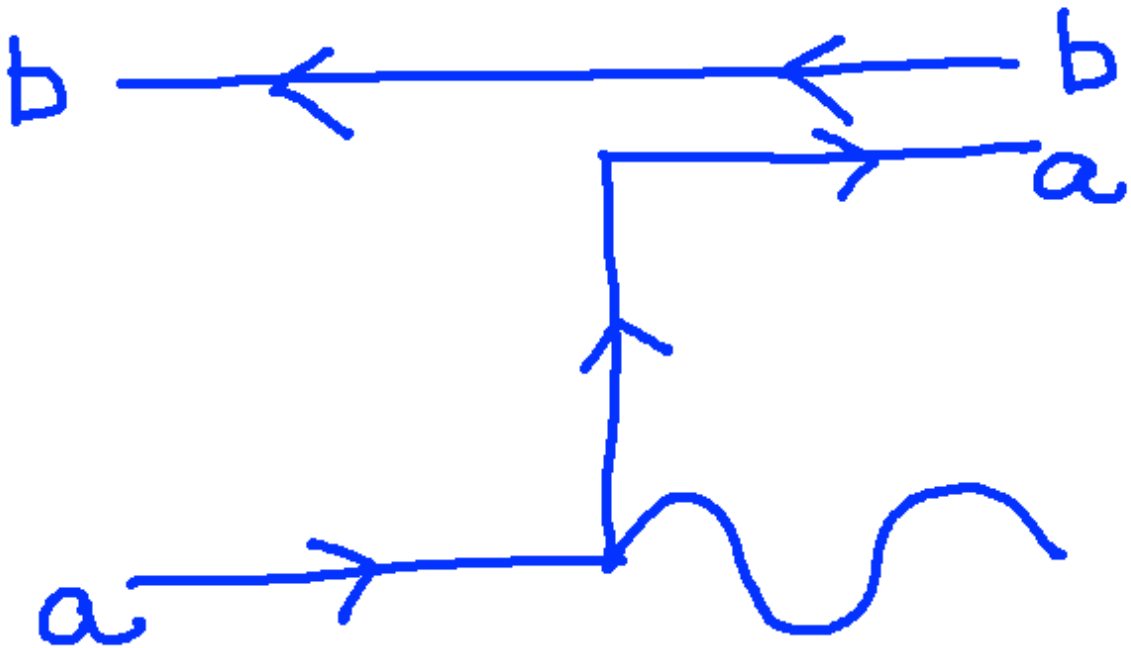


Pair annihilation:



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.

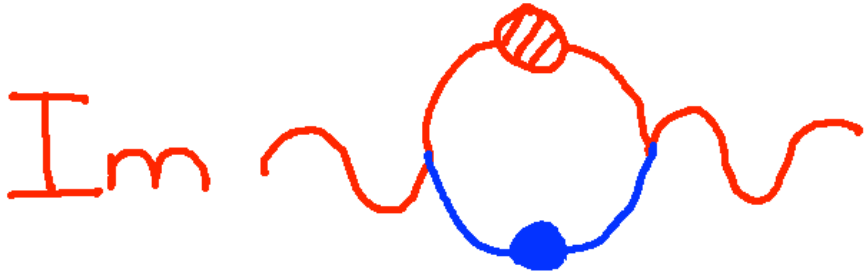
And, if a = -b, tracelessness of gluon implies extra factor of 1/N, or $1/N^2$ in all.

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.

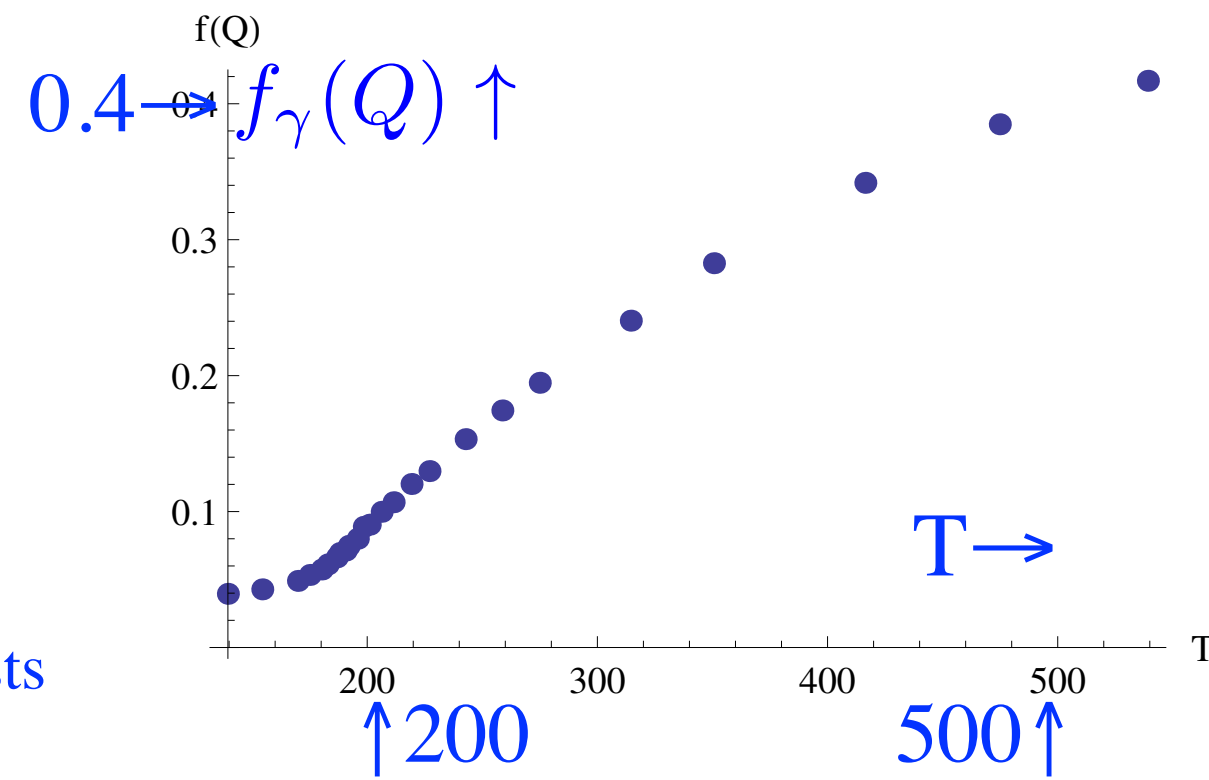
Strong suppression of real photons in the confined phase

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

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

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

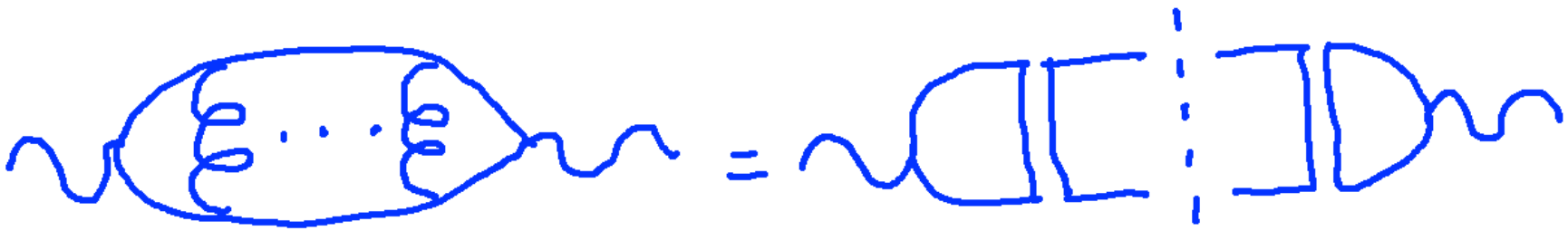
$$f_\gamma(q_{conf}) = \frac{1}{3N^2} = \frac{1}{27}$$



Suppression is so large that it persists even to T ~ 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,

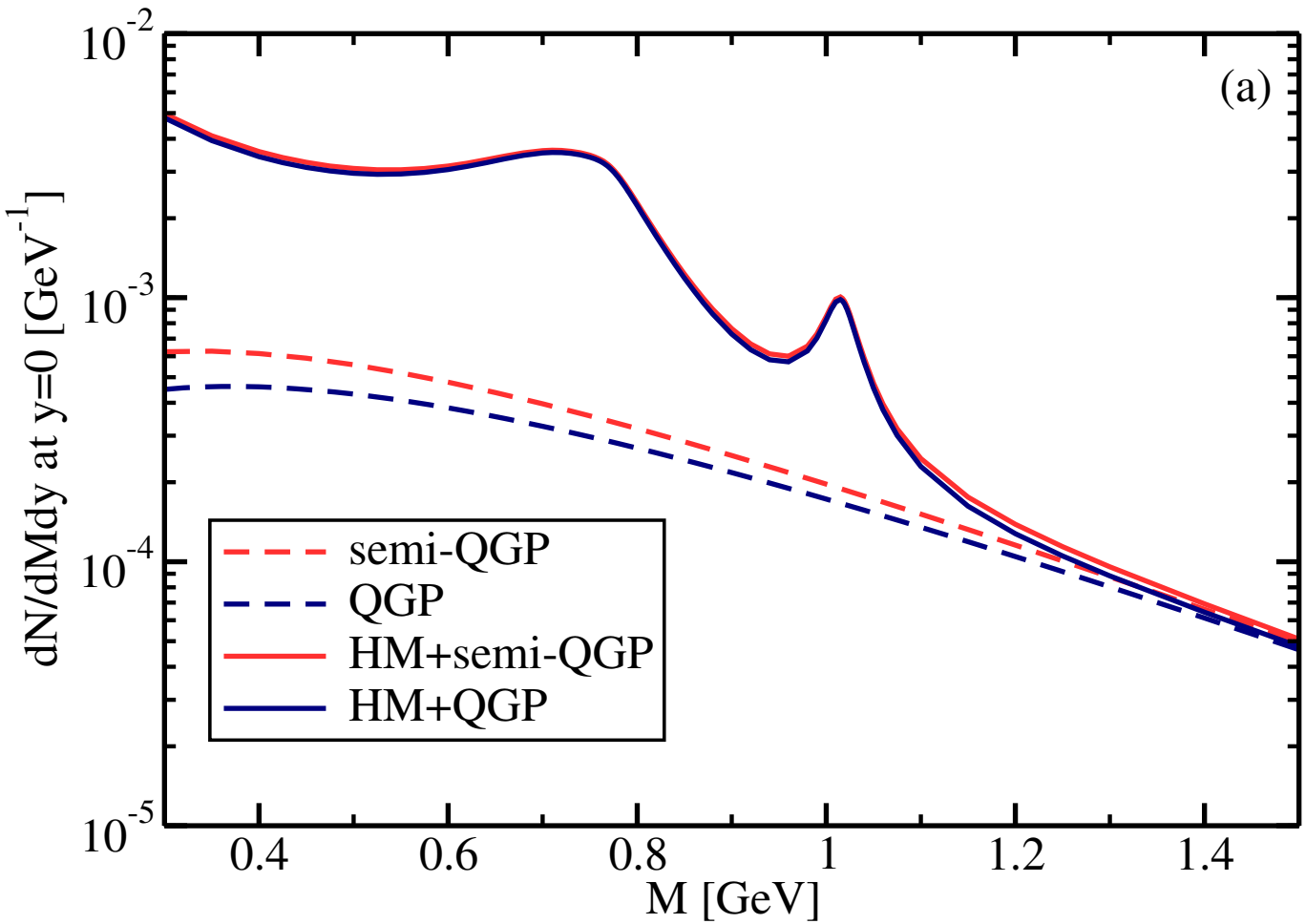
$$g^2\, n(gT)\, \frac{T}{ip_0 - E_k + E_{p-k}} \sim g^2 \frac{T}{gT}\, \frac{T}{gT} \sim 1$$

Semi-QGP: only soft gluons are *diagonal*, so LPM is suppressed by 1/N.
What we did: only $2 \to 2$ 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

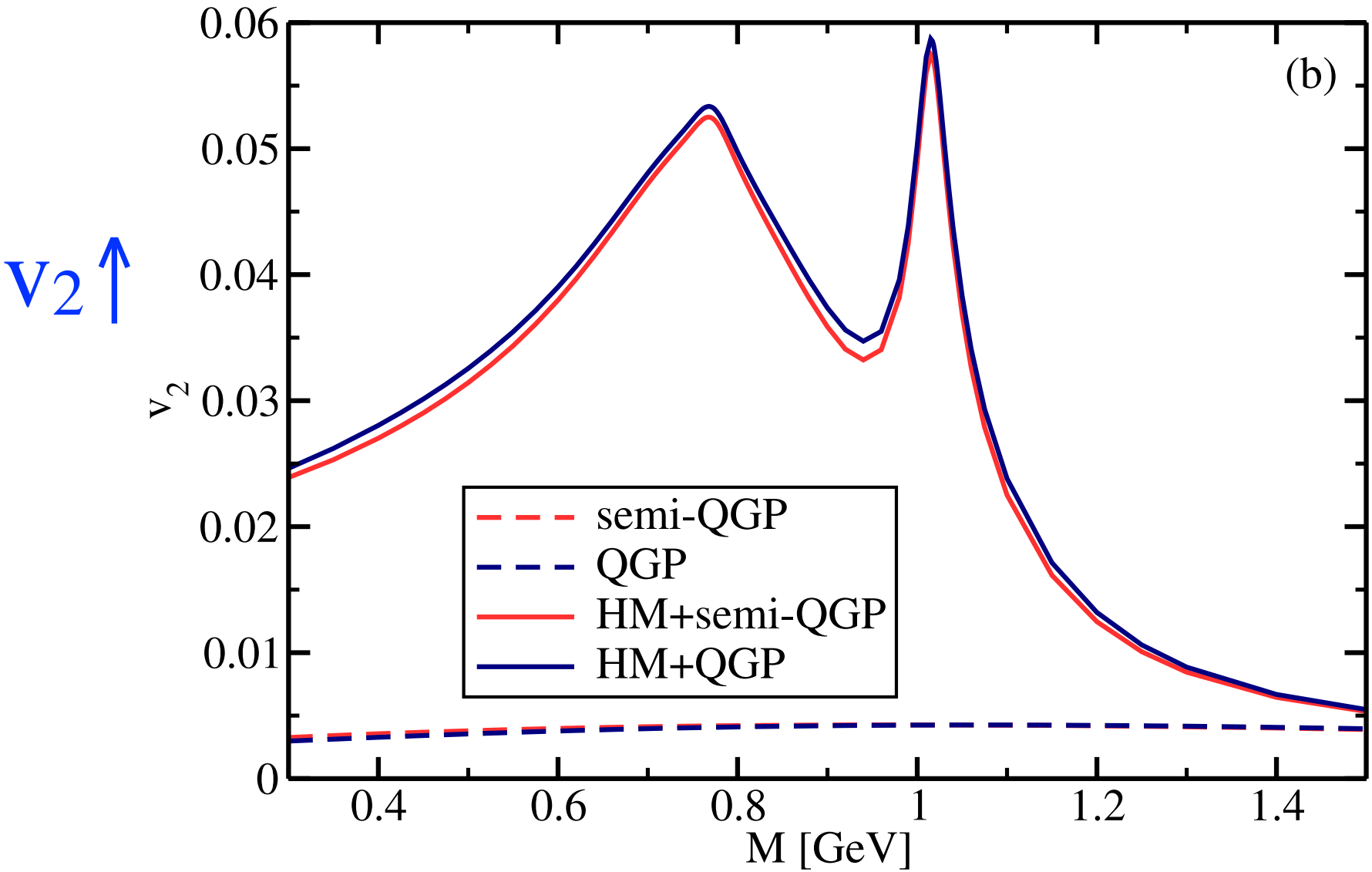
MUSIC: 3+1 hydro @ RHIC: $\sqrt{s}$ = 200 GeV/A, central collisions
Preliminary analysis: only ideal hydro.

Small enhancement of dileptons in semi-QGP, swamped by hadronic phase.
No matching of semi-QGP to hadronic phase: clearly essential.



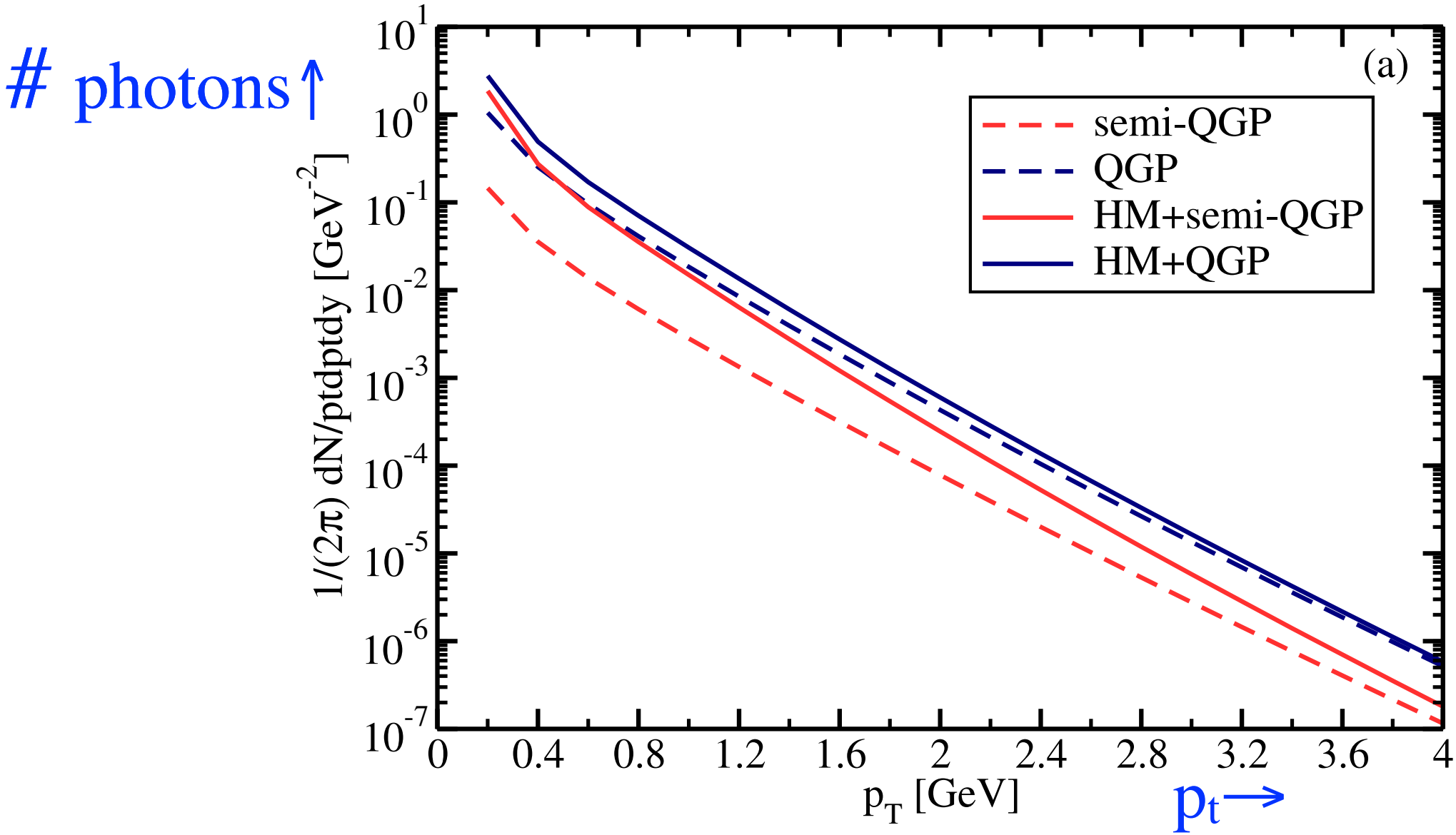
Hydrodynamics: dilepton v_2

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



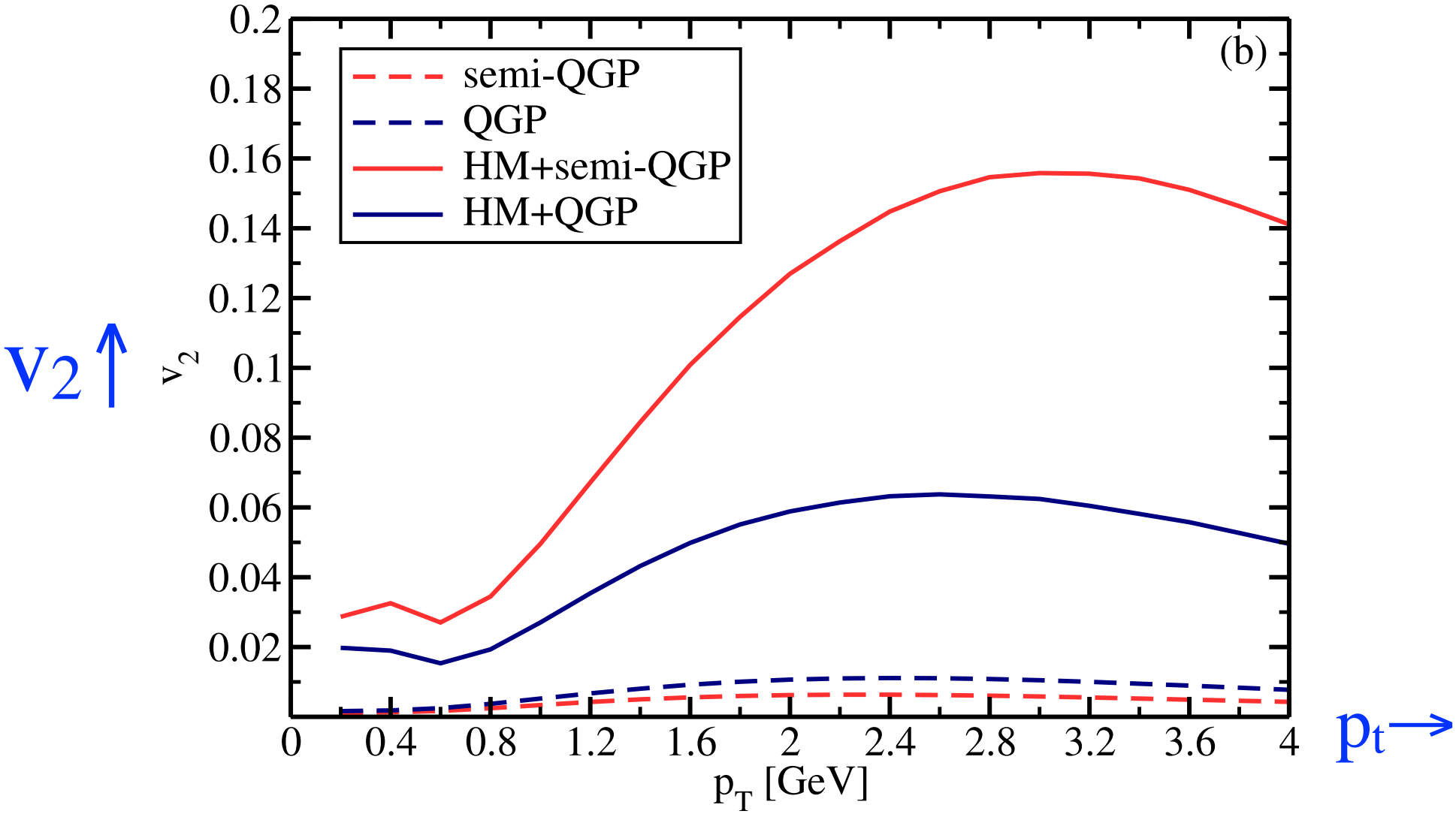
Hydrodynamics: # photons

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



Hydrodynamics: photon elliptic flow, v_2

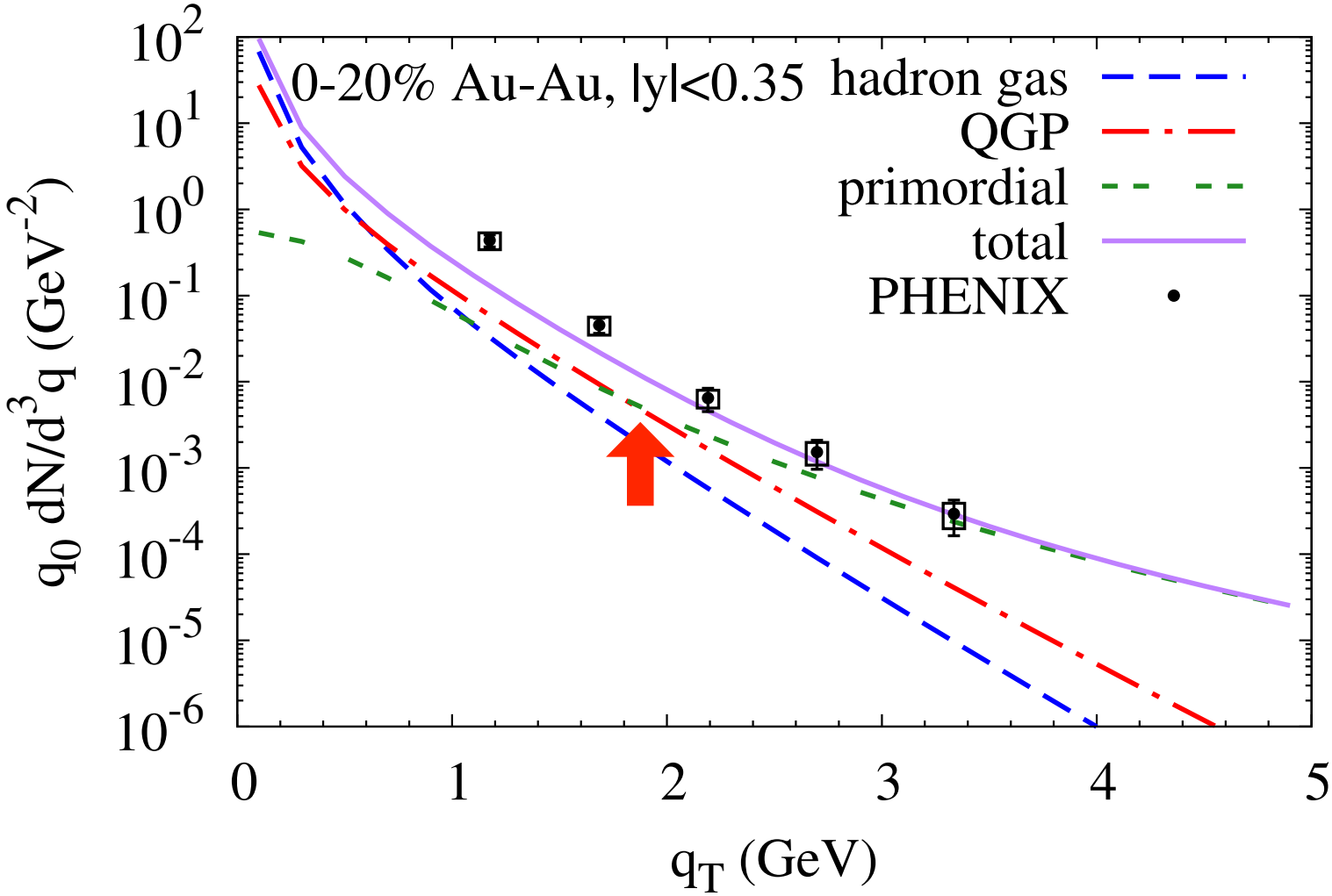
Fewer photons near T_c in semi-QGP has a big effect on the total v_2.
Tends to bias the total v_2 to that in hadronic phase. Small "dilution" by QGP.
Possible solution to experimental puzzle of "big" v_2 for photons?



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 $p_t \sim 2$ GeV
Experiment much larger than theory?

van Hees, He, Rapp, 1404.2846

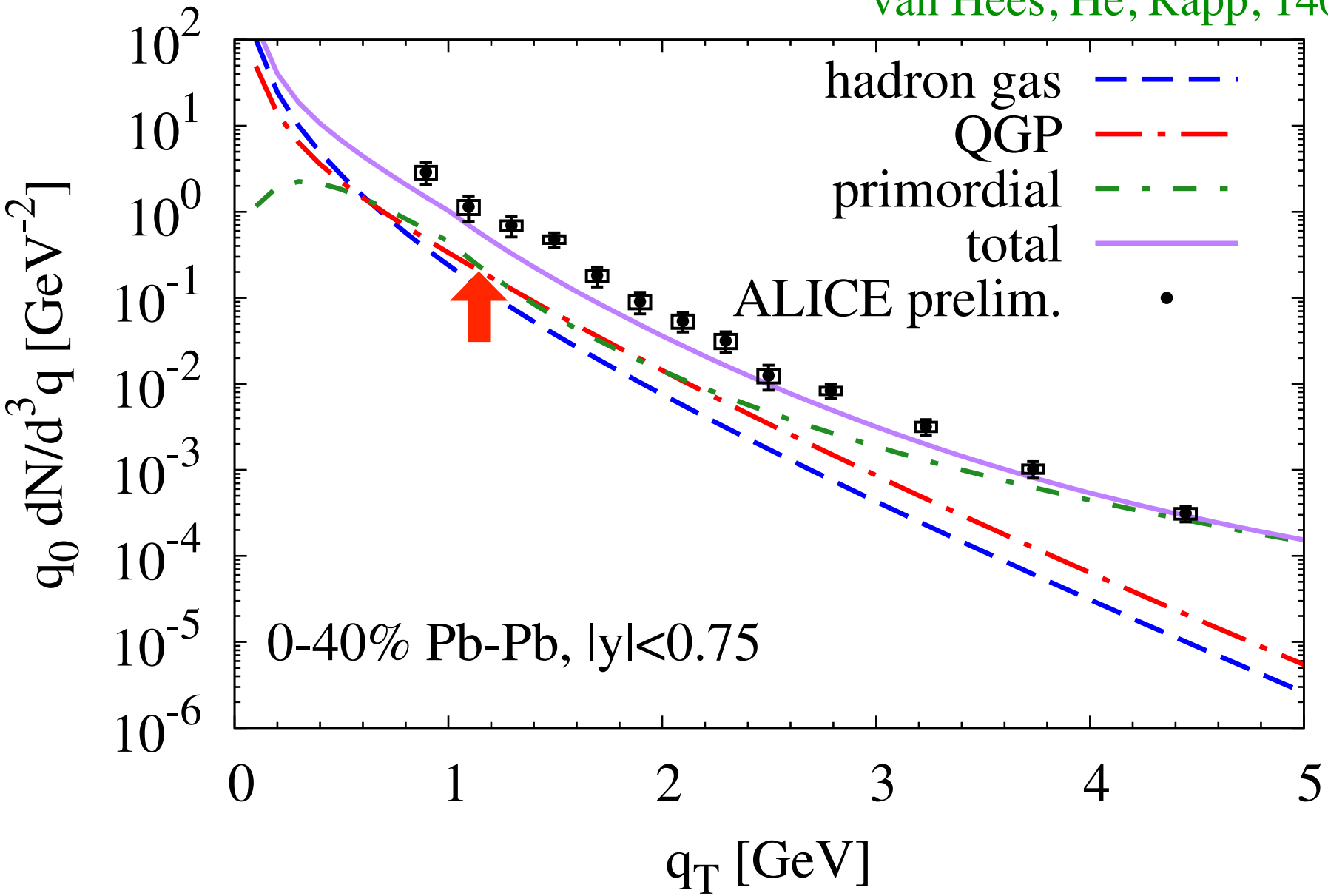


ALICE vs theory: puzzle of the "missing" photons

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?

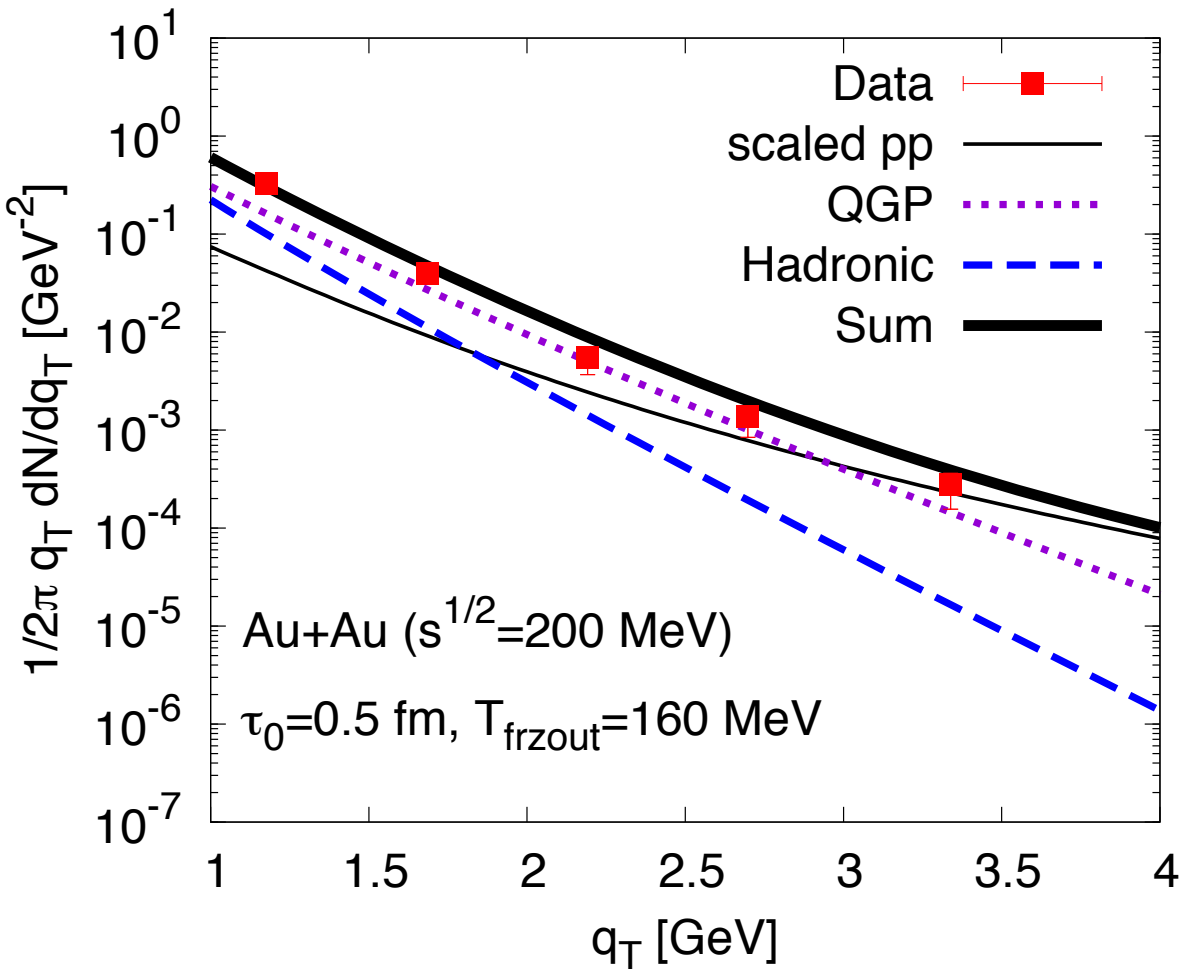
Dusling & Zahed, 0911.2426

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) :

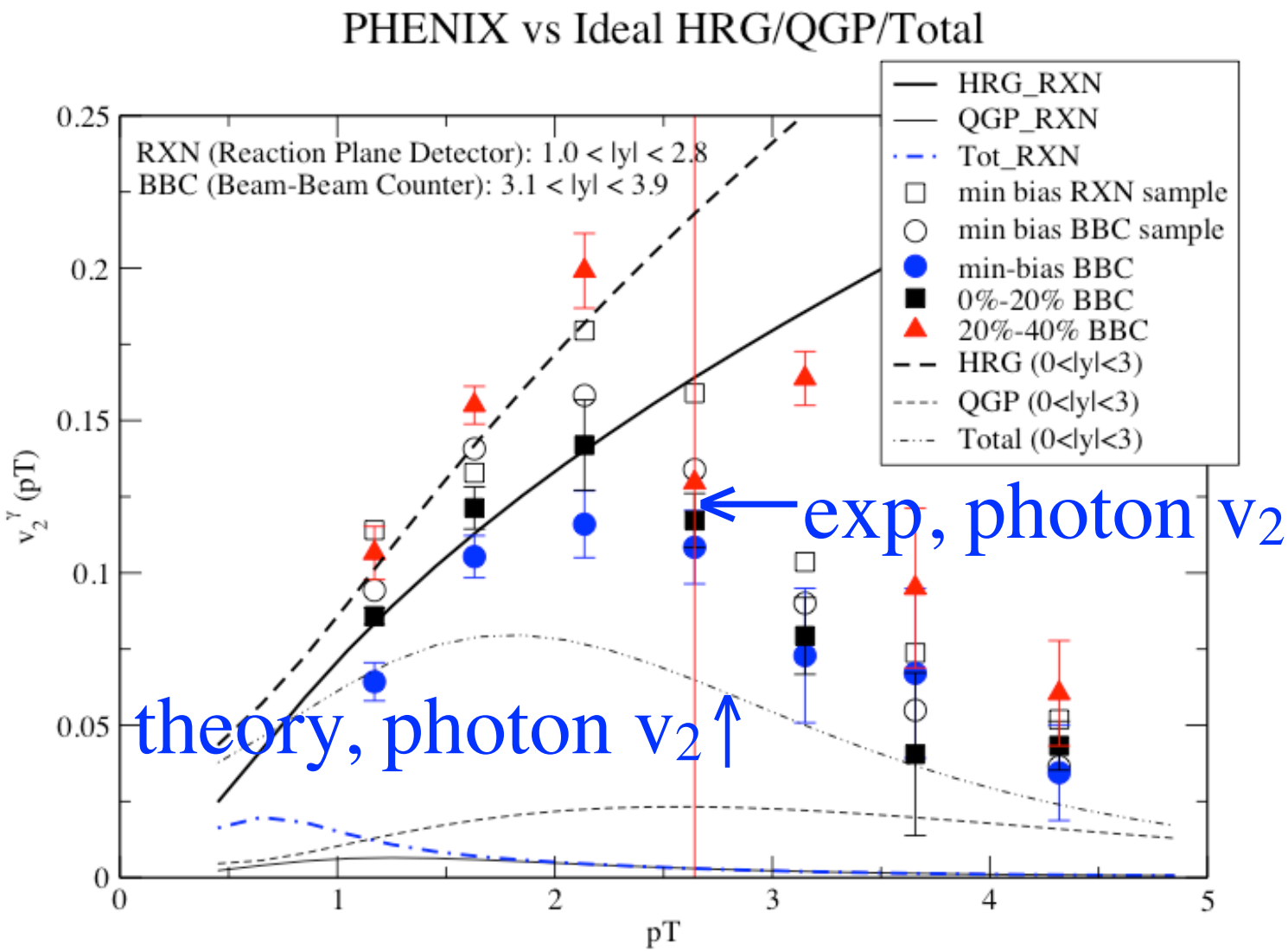
find hadronic contribution much larger than other analyses;

Resolves puzzle of the "missing" photons?



Photon elliptic flow still too big by ~ 2!

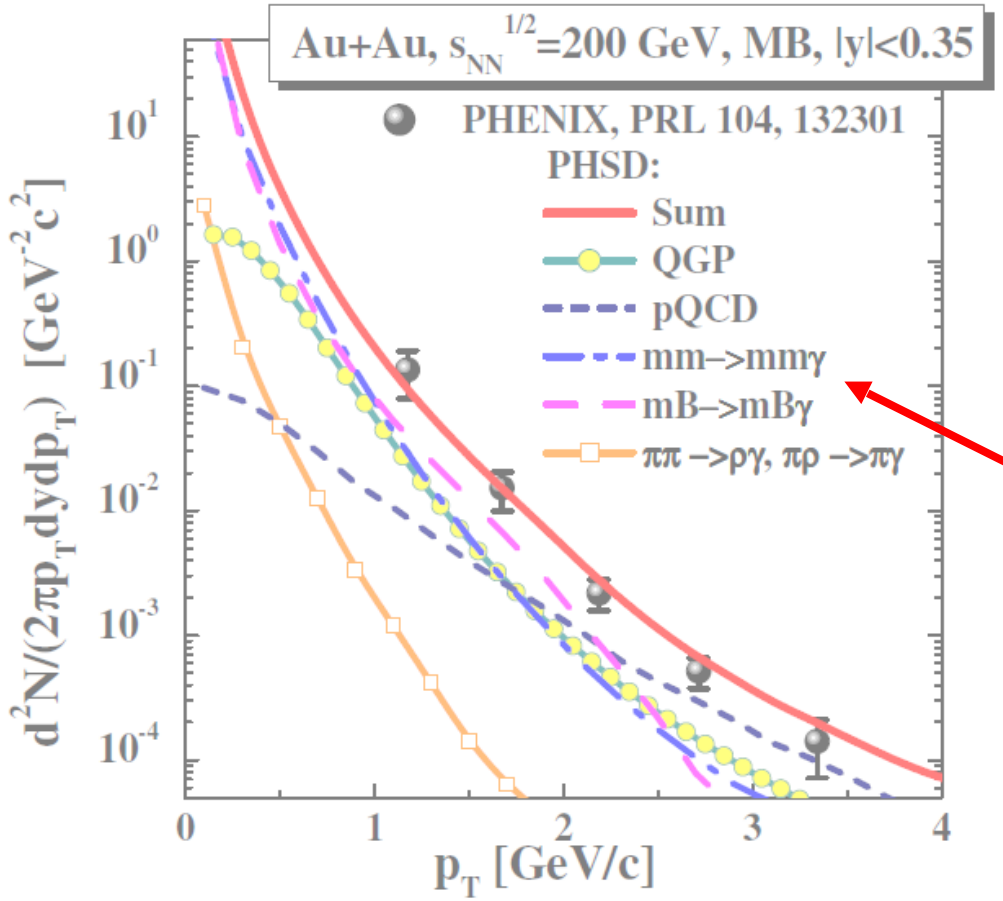
Dusling & Zahed, unpublished,
RIKEN@BNL workshop on "Thermal Photons & Dileptons", Aug. '14
http://www.star.bnl.gov/~ruanlj/?dir=TPD2014/&file=Zahed.pptx



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

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

- Direct photon spectrum (min. bias)



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

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

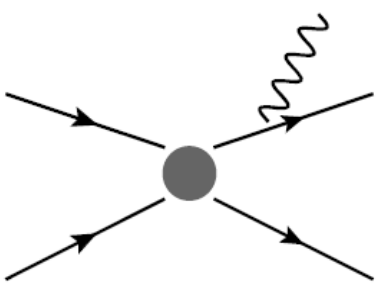
m+m→ m+m+γ,

m+B→ m+B+γ ,

m=π,η,ρ,ω,K,K,*

…

B=p

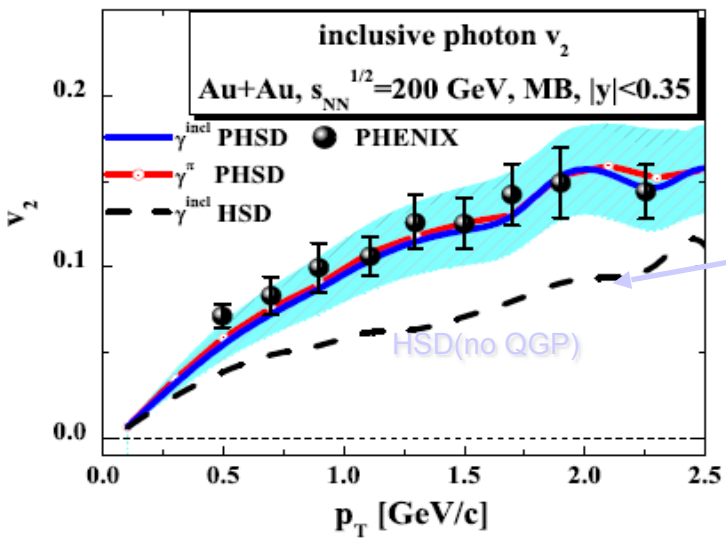


!!! mm and mB bremsstrahlung channels can not be subtracted experimentally !

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?**

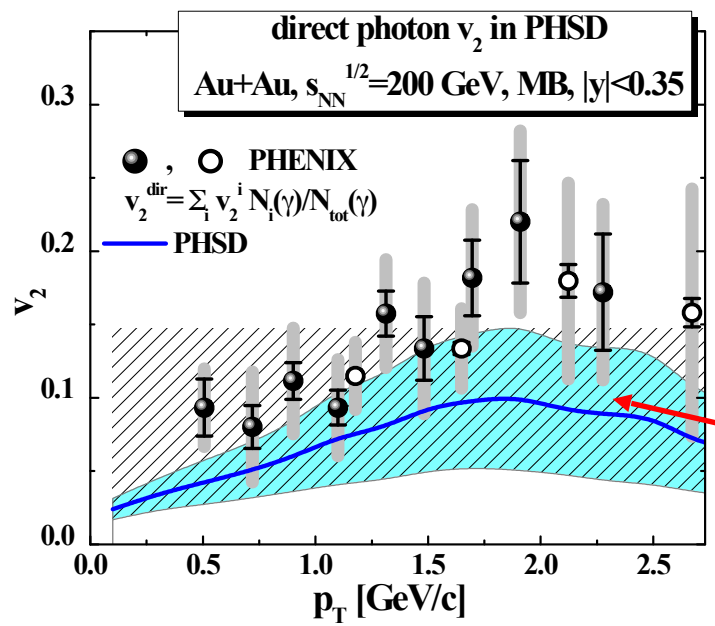
PHSD: Linnyk et al., PRC88 (2013) 034904; PRC 89 (2014) 034908



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, wheras 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...”