

Non-perturbative production rate of
photons with a lattice quark propagator
– effect of vertex correction

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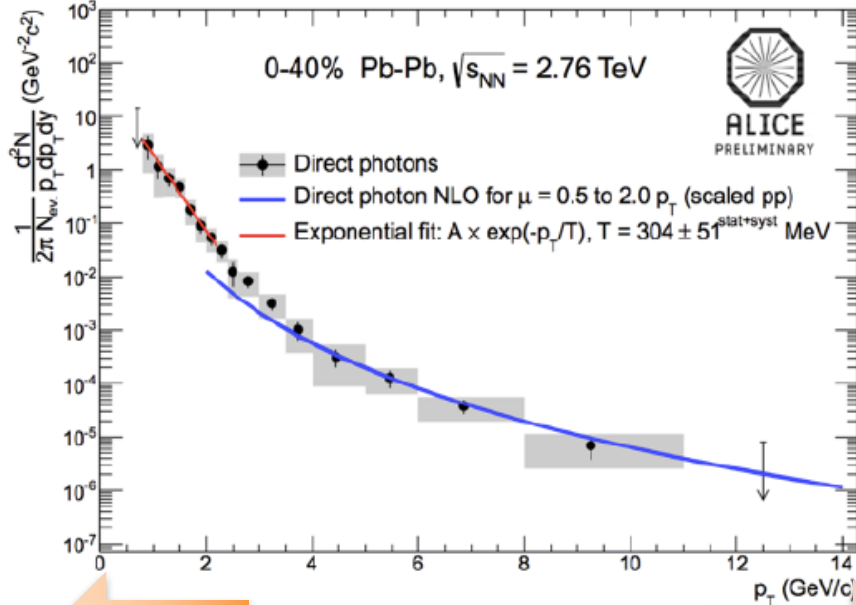
- specify physical processes
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1. Introduction

Direct photons in HIC

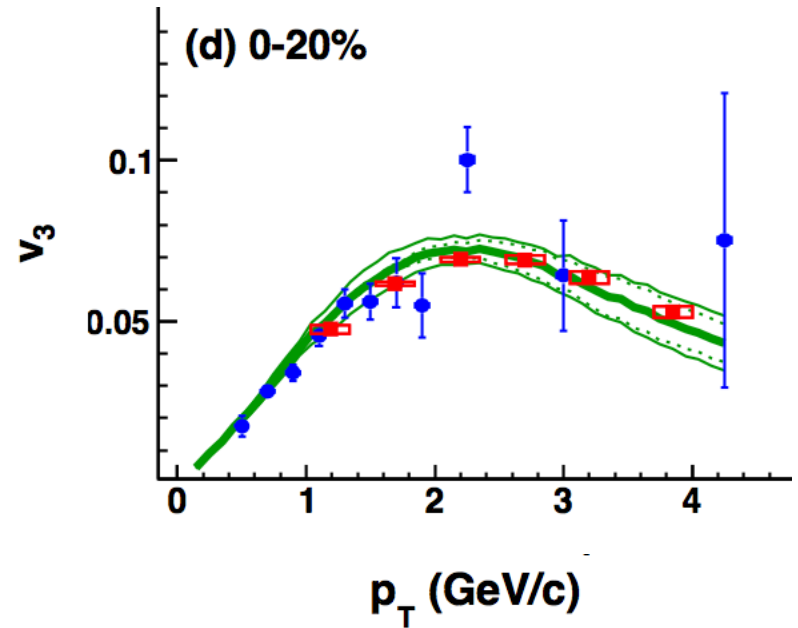
ALICE Collaboration *Phys. Lett. B* **754** (2016) 235-248



Thermal photon

Initial photon

PHENIX Collaboration arXiv:1509.07758



Large photon v_3

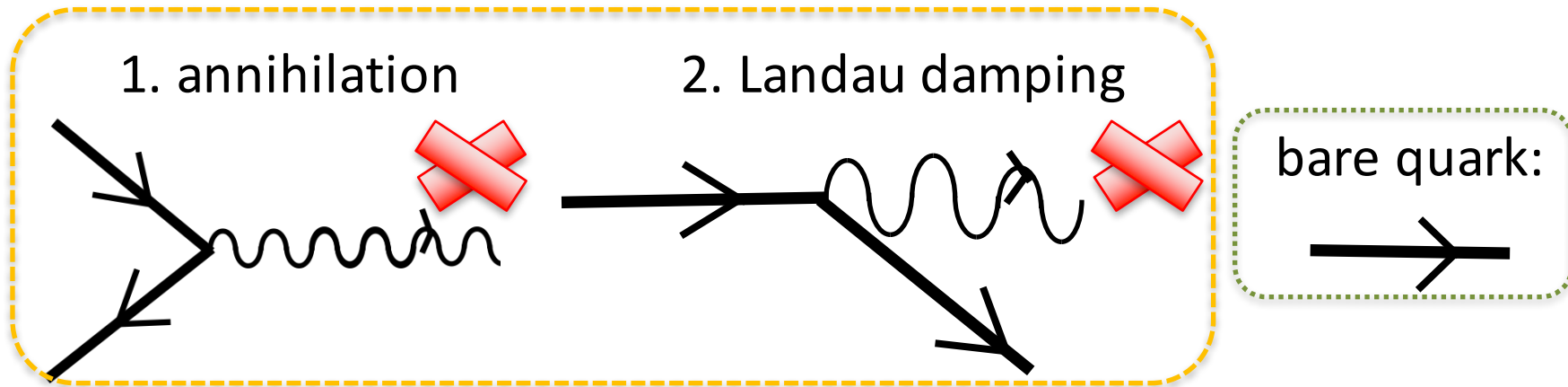
Photons as direct signals

#Penetrate media without interaction.

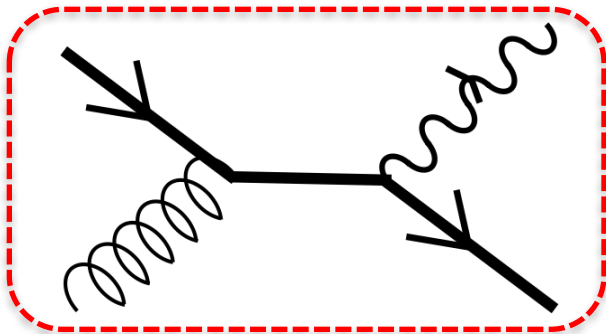
#data include information of media.

Photon production reaction

Instruction – free quark



1-loop diagram contribution to real photon production = 0.
These reactions are **forbidden** kinematically.



The simplest reaction is “ 2 -> 2 ”.

Thermal modification

Particles in enough hot medium receive thermal modification.

e. g. HTL-resummed perturbation theory.

Thermal quark has 2 particle-like (quasi-particle) states
& continuous state.

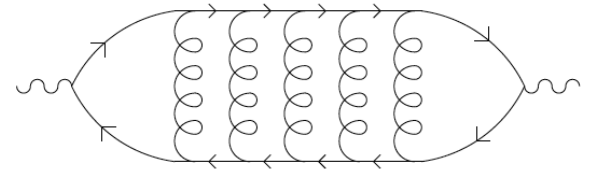


Various production dynamics
arise via thermal effects.

Thermal medium radiates photons.

Landau damping is permitted in HTL case.
Continuum part also contribute.
Ladder type diagrams are important.
& so on.

“LPM effect”



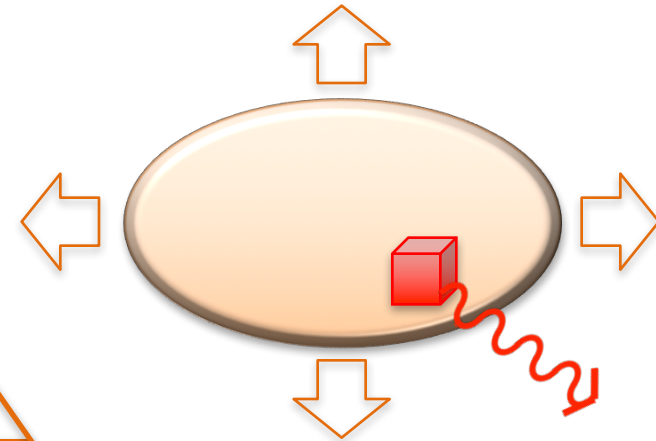
Theoretical analyses of thermal γ

Two steps to do

1. analyzing a production rate ←
2. estimating a yield based on hydro model

Thermal rates

1. perturbative analyses
2. first principle calculation on the lattice ←



the number of momenta is limited.

Our theoretical motivation

1. Research photon production reactions in medium.
2. Evaluate production rates, not directly on the lattice, but including non-perturbative effects.

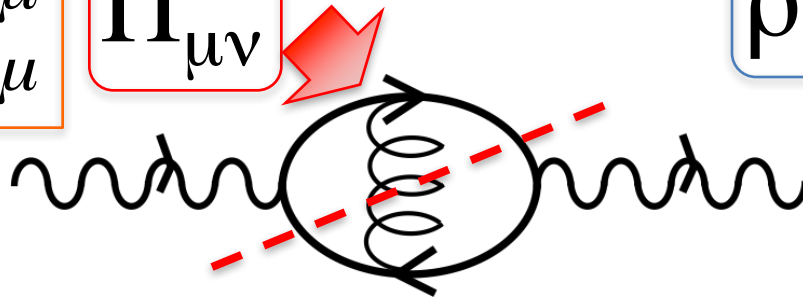
2. Method

γ production

Optical theorem

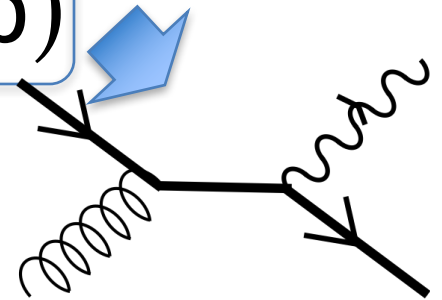
$$\rho \propto \text{Im} \Pi_{\mu}^{\mu}$$

$$\Pi_{\mu\nu}$$



γ self energy in medium

$$\rho(\omega, \mathbf{p})$$



SPF has information

Photon production rate from a thermal medium

$$\omega \frac{d\Gamma}{d^3 q} = \frac{2}{(2\pi)^3} \frac{1}{e^{\beta\omega} - 1} \text{Im} \Pi_{\mu}^{R,\mu}(\omega, \vec{q})$$

McLerran, Toimela (1985); Weldon(1990); Gale, Kapusta (1991)

Photon Self Energy

Strongly interacting



Non-perturbative analysis is desirable

Schwinger-Dyson equation

$$\Pi_{\mu\nu} = \text{[Feynman diagram: a red wavy line with a loop of two red circles with diagonal hatching, connected to another red wavy line.]}$$

Analyze non-perturbative thermal rates

||

Solve exact Schwinger-Dyson equation



No one knows an exact solution until now.

Photon Self Energy

Strongly interacting



Non-perturbative analysis is desirable

Schwinger-Dyson equation

$$\Pi_{\mu\nu} = \text{diagram}$$

exact quark propagator

$$S = \text{diagram}$$

use a lattice quark propagator



exact vertex

$$\Gamma_{\mu} = \text{diagram}$$

W-T identity



Lattice quark propagator

Karsch and Kitazawa (2007,2009), Kaczmarek *et al.* (2012)

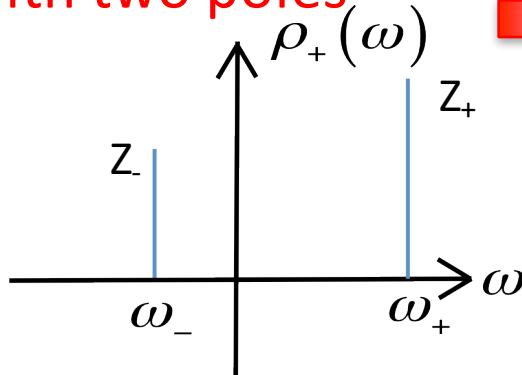
imaginary time correlator

obtained by
a first principle calculation

Analytic
continuum
problem

assumption

Fit the spectral
with two poles



to obtain this

real time quark propagator

what one wants

Only particle-like excited states
exist in a deconfined medium

This is a model.

Hard Thermal Loop quark propagator

HTL effective Lagrangian \mathcal{L}_{HTL}

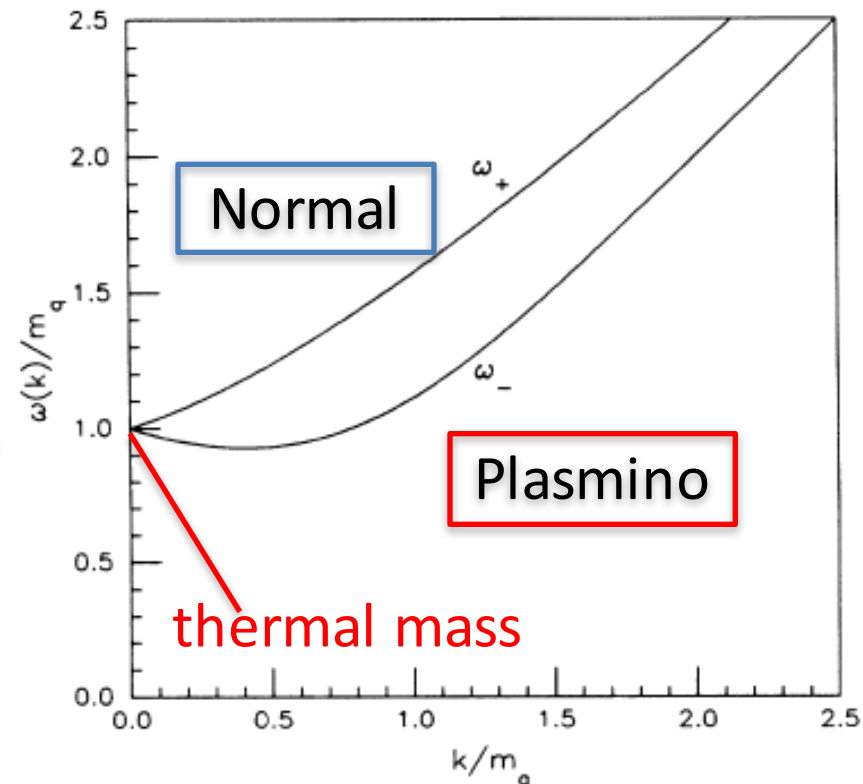
effective quark propagator

$$S(iv_n, \vec{p}) = \int d\nu \frac{\rho(\nu, \vec{p})}{iv_n - \nu}$$

ρ has a continuum part &
two poles

Considered as quasi-particles
with **thermal mass**

Quasi-quark dispersions

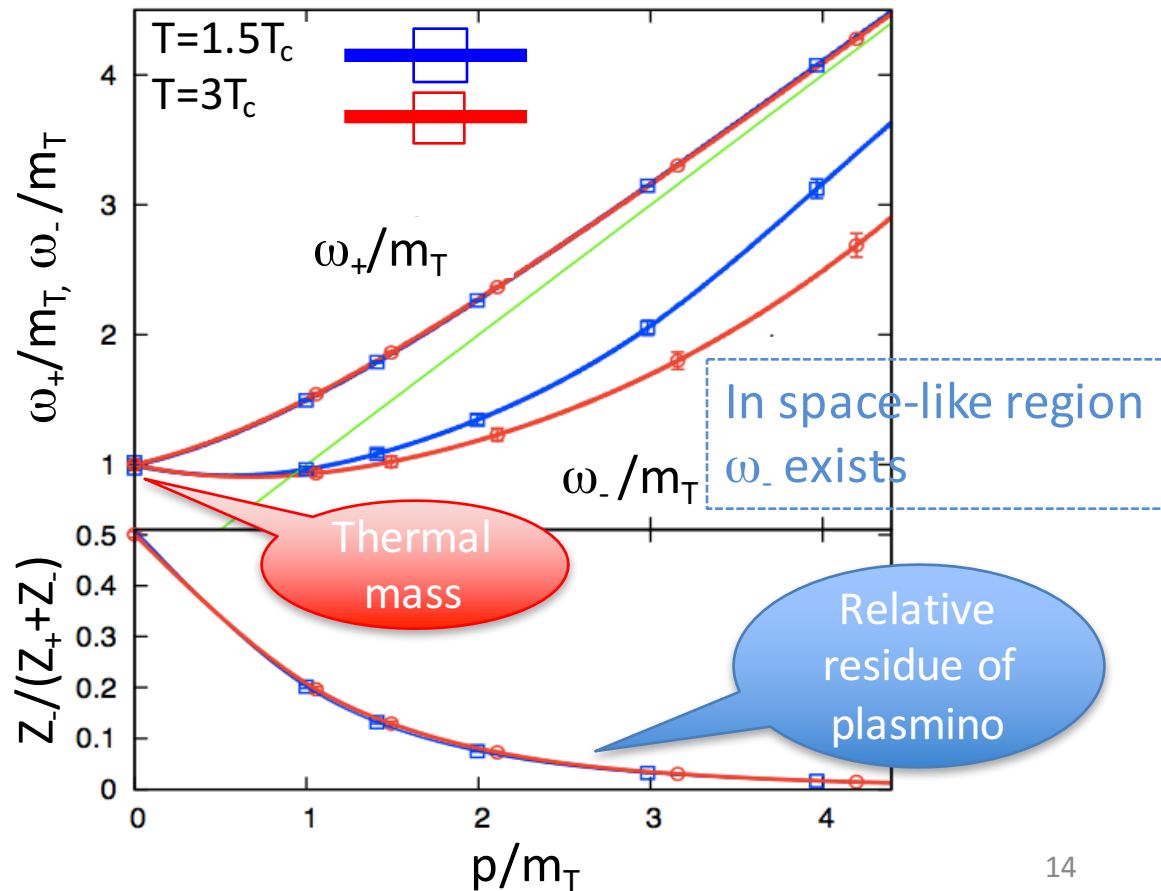
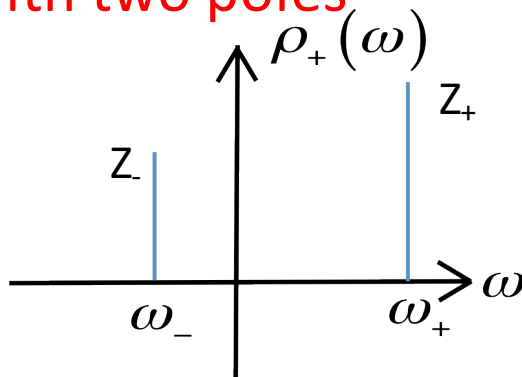


Lattice quark propagator

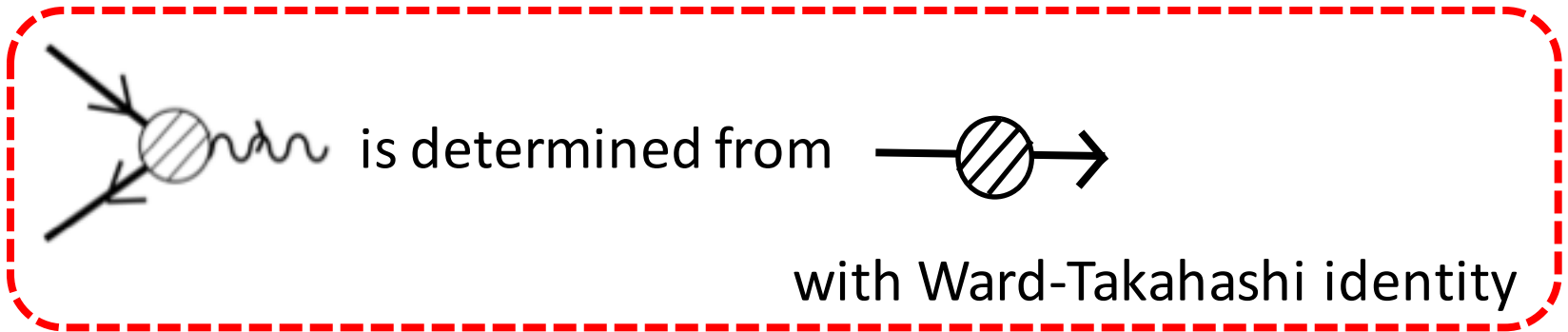
Karsch and Kitazawa (2007,2009), Kaczmarek *et al.* (2012)

- Quenched lattice
- massless quark
- Landau gauge
- $T=1.5T_c, 3T_c$
- dispersion relations

Fit the spectral
with two poles



Photon-Quark Vertex



Ward-Takahashi identity

$$q_\mu \cdot \left(\text{diagram with } p+q \text{ and } p \right)^\mu = \left(\text{diagram with } p+q \right)^{-1} - \left(\text{diagram with } p \right)^{-1}$$

The diagram on the left shows a vertex with two incoming quark lines labeled p and $p+q$, and one outgoing photon line. The diagram on the right shows the difference of two quark propagators: one with momentum $p+q$ and one with momentum p . Red arrows point to the shaded circles in the propagators, indicating they represent the lattice quark propagators.

lattice quark propagators

❖ various approximations on photon-quark & gluon-quark vertex

Ball, Chiu (1980); Harada, Kurachi, Yamawaki (2004);

Chang, Liu, Roberts(2011); Fischer, Luecker, Welzbacher (2014) etc...

Photon-Quark Vertex

$$\Gamma_0 \equiv \frac{1}{2q_0} \left[S^{-1}(p_0 + q_0, \vec{p} + \vec{q}) - S^{-1}(p_0, \vec{p} + \vec{q}) \right. \\ \left. + S^{-1}(p_0 + q_0, \vec{p}) - S^{-1}(p_0, \vec{p}) \right]$$

$$\Gamma_i \equiv \frac{-q_i}{2\vec{q}^2} \left[S^{-1}(p_0 + q_0, \vec{p} + \vec{q}) + S^{-1}(p_0, \vec{p} + \vec{q}) \right. \\ \left. - S^{-1}(p_0 + q_0, \vec{p}) - S^{-1}(p_0, \vec{p}) \right]$$

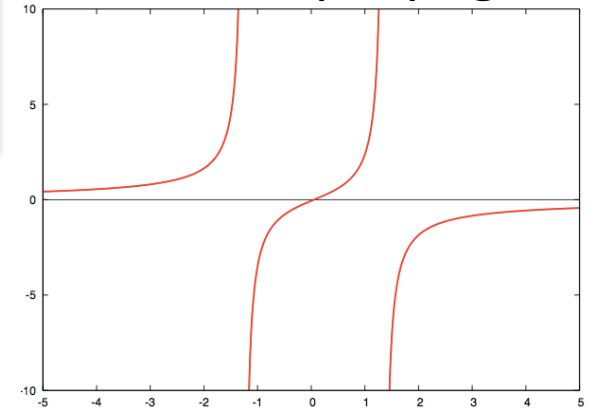
We demand

1. $\Gamma \rightarrow \gamma$ in high momentum region.
2. respect W-T identity & rotational symmetry.
3. to make evaluating $\text{tr}[S\gamma_\mu S\Gamma_\mu]$ easier.

One effect of vertex correction

“Two pole ansatz” \rightarrow S has a zero point for quark propagator

behavior of propagator



emergence of a pole in Γ_μ

Additional pole corresponds to additional channel.

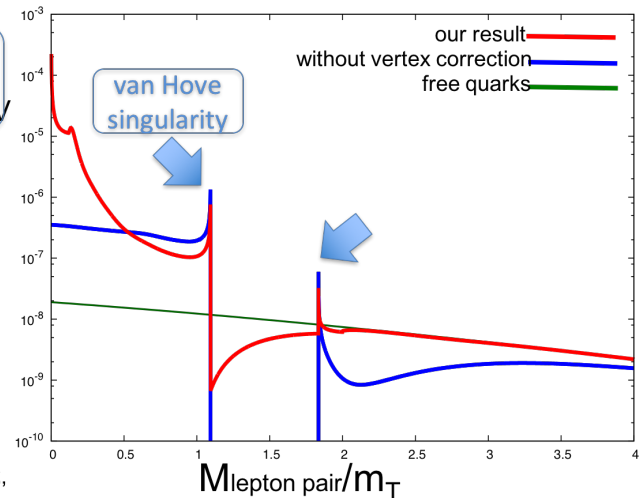
Dilepton production rate

Vertex correction buries a gap in a figure.

$T = 1.5T_c$
 $T_c = 290 \text{ MeV}$
 $m_T \sim 350 \text{ MeV}$

Rate

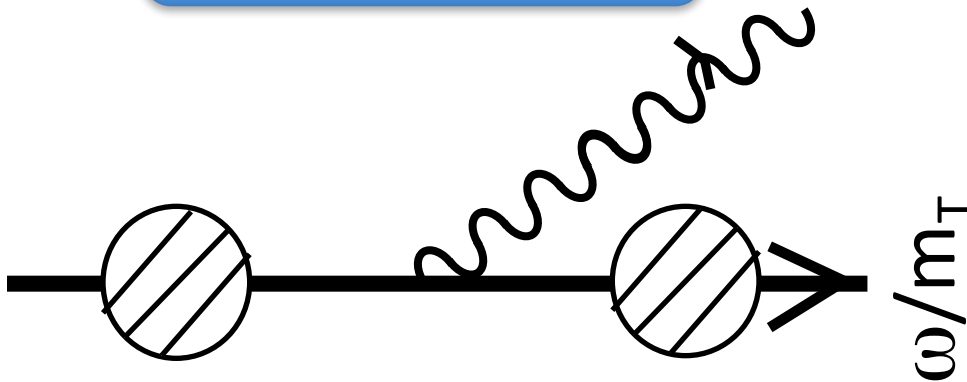
$$\left. \frac{d\Gamma}{d\omega d^3q} \right|_{\vec{q}=0}$$



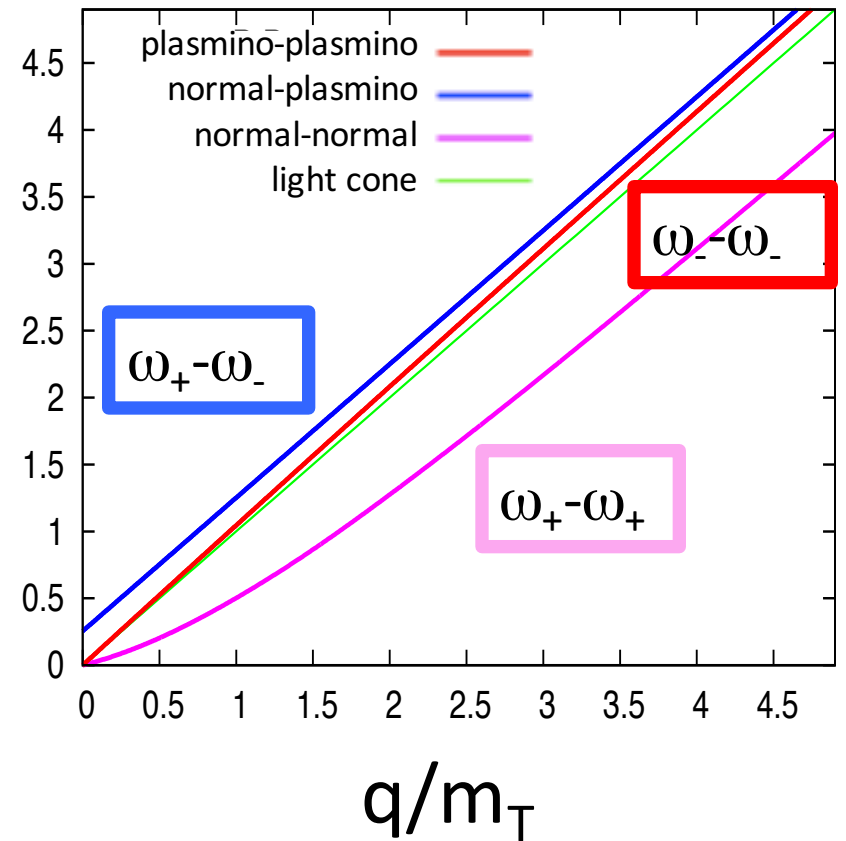
3. Results

Photon production processes

Landau damping

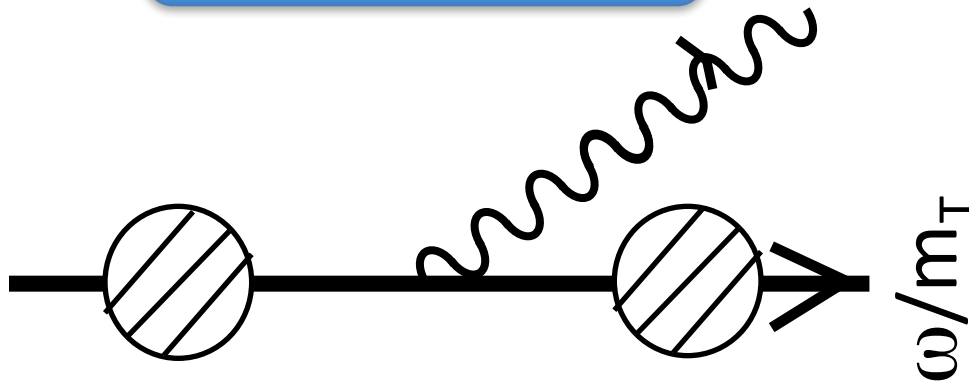


Virtual photon dispersion



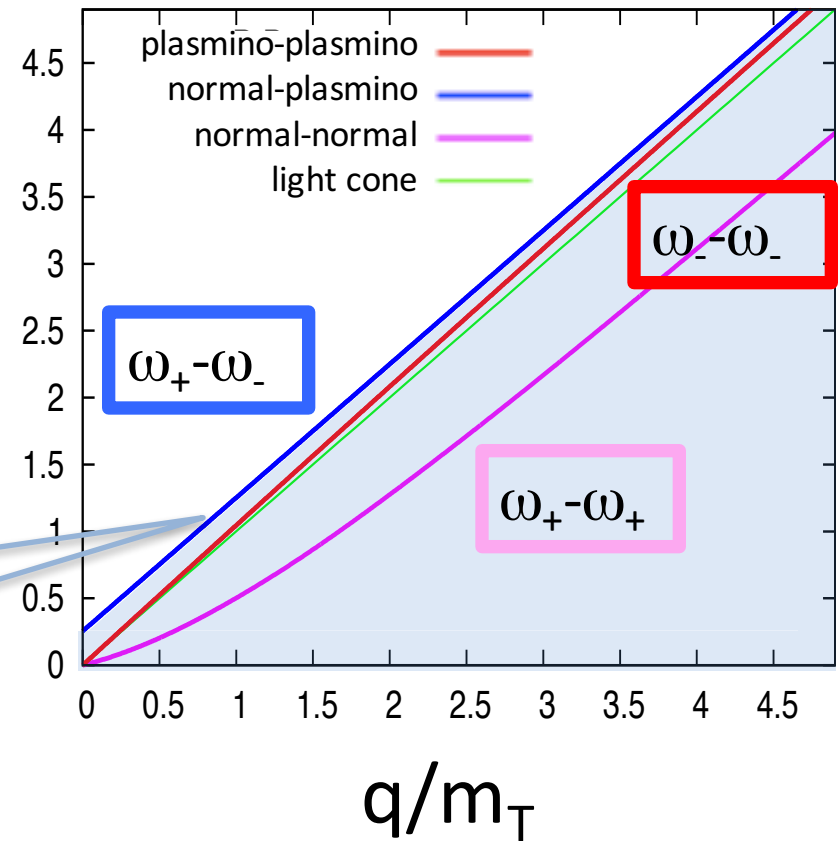
Photon production processes

Landau damping



It arises from plasmino exists in space-like region

Virtual photon dispersion

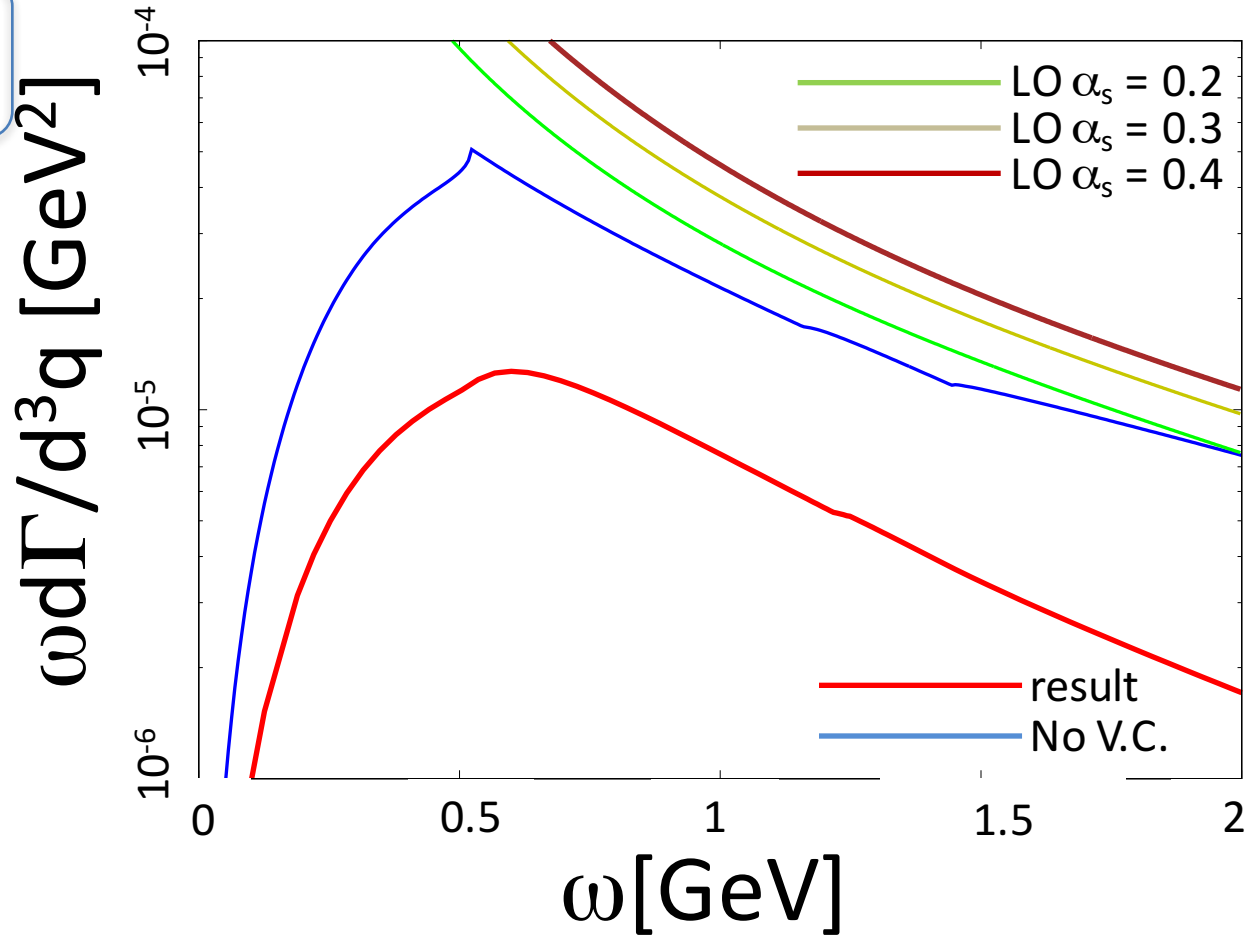


Cherenkov radiation is enough small
 10^{-5} times smaller than normal - plasmino

Photon production rate

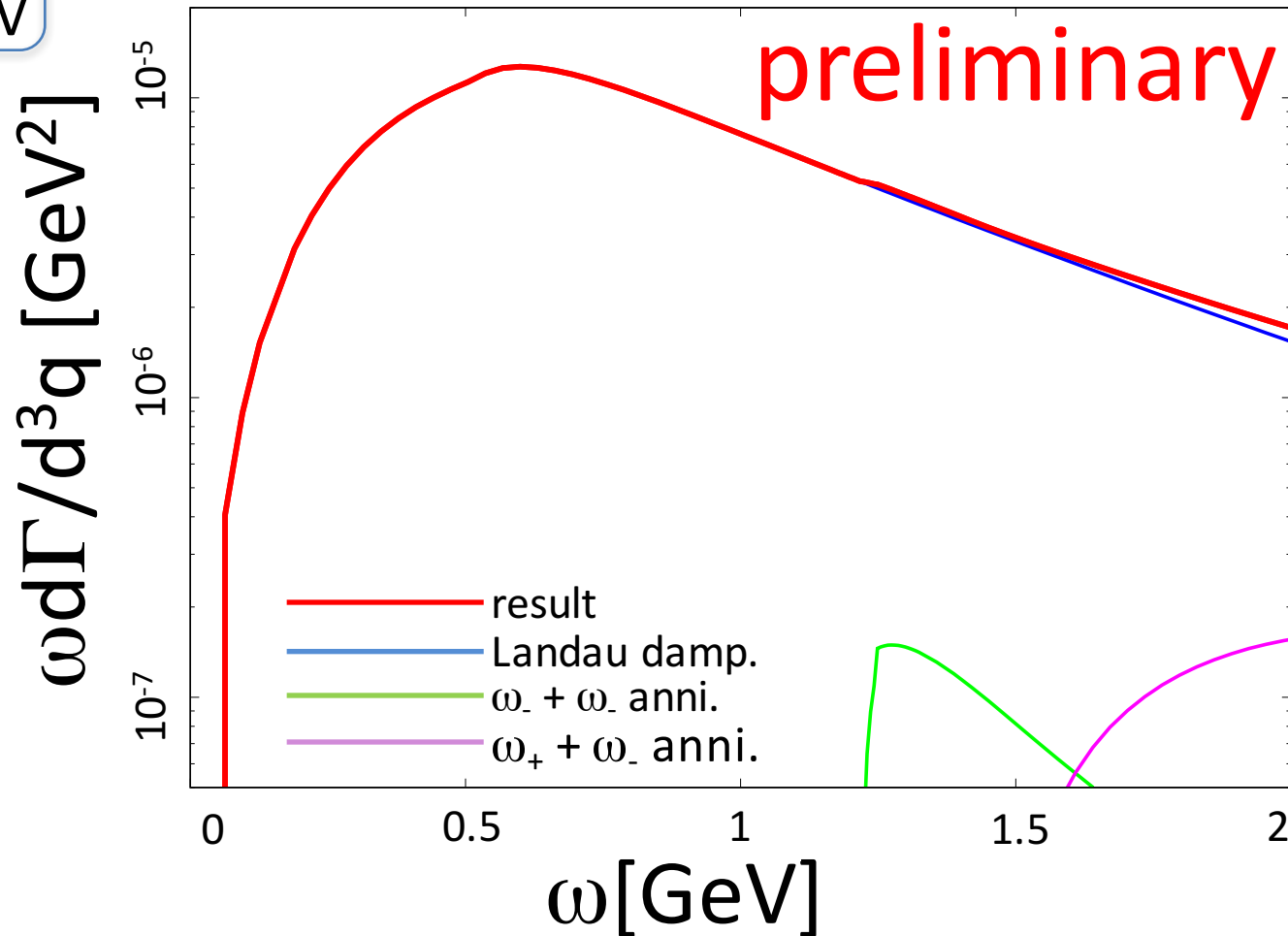
preliminary

$T=3T_c$
 $T_c=290\text{MeV}$



Decomposed rate

$T=3T_c$
 $T_c=290\text{MeV}$

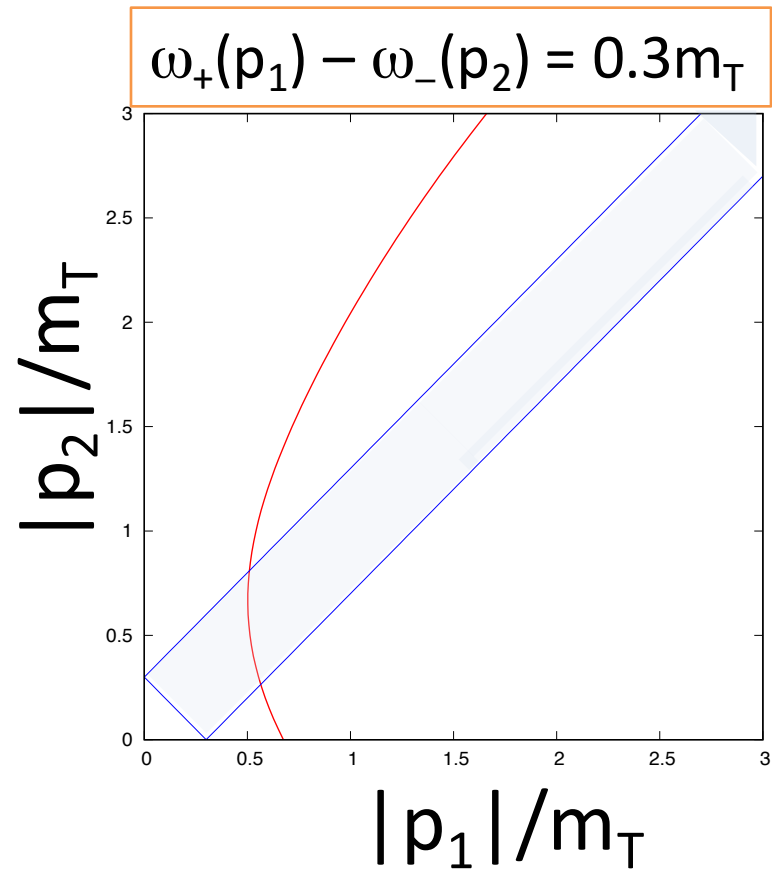
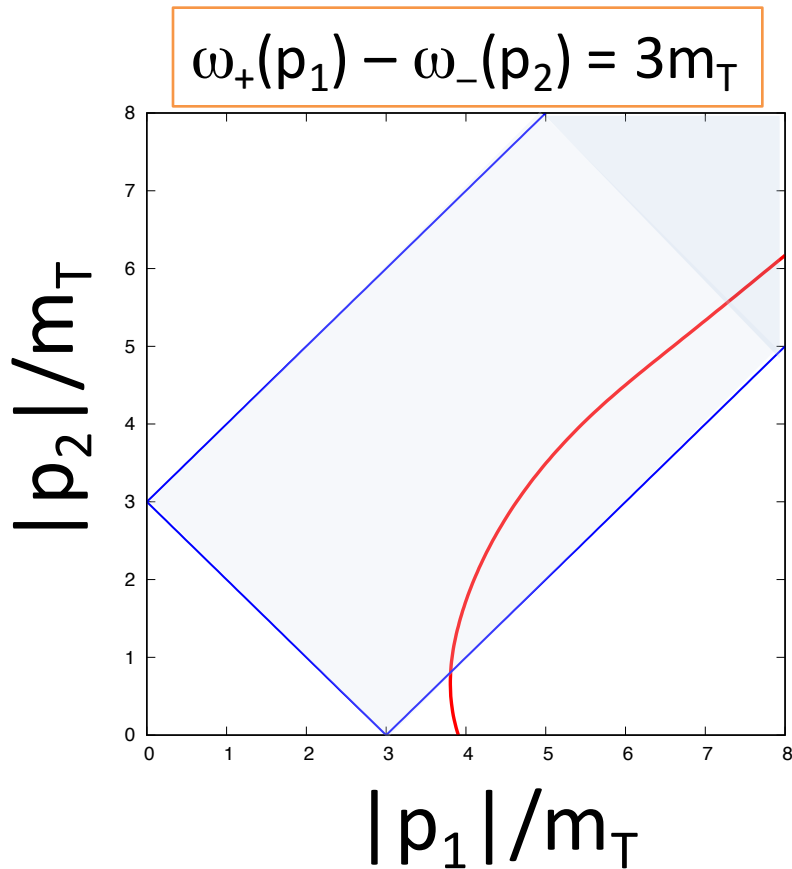


Photons produced mainly via Landau damping

Evaluate production rate

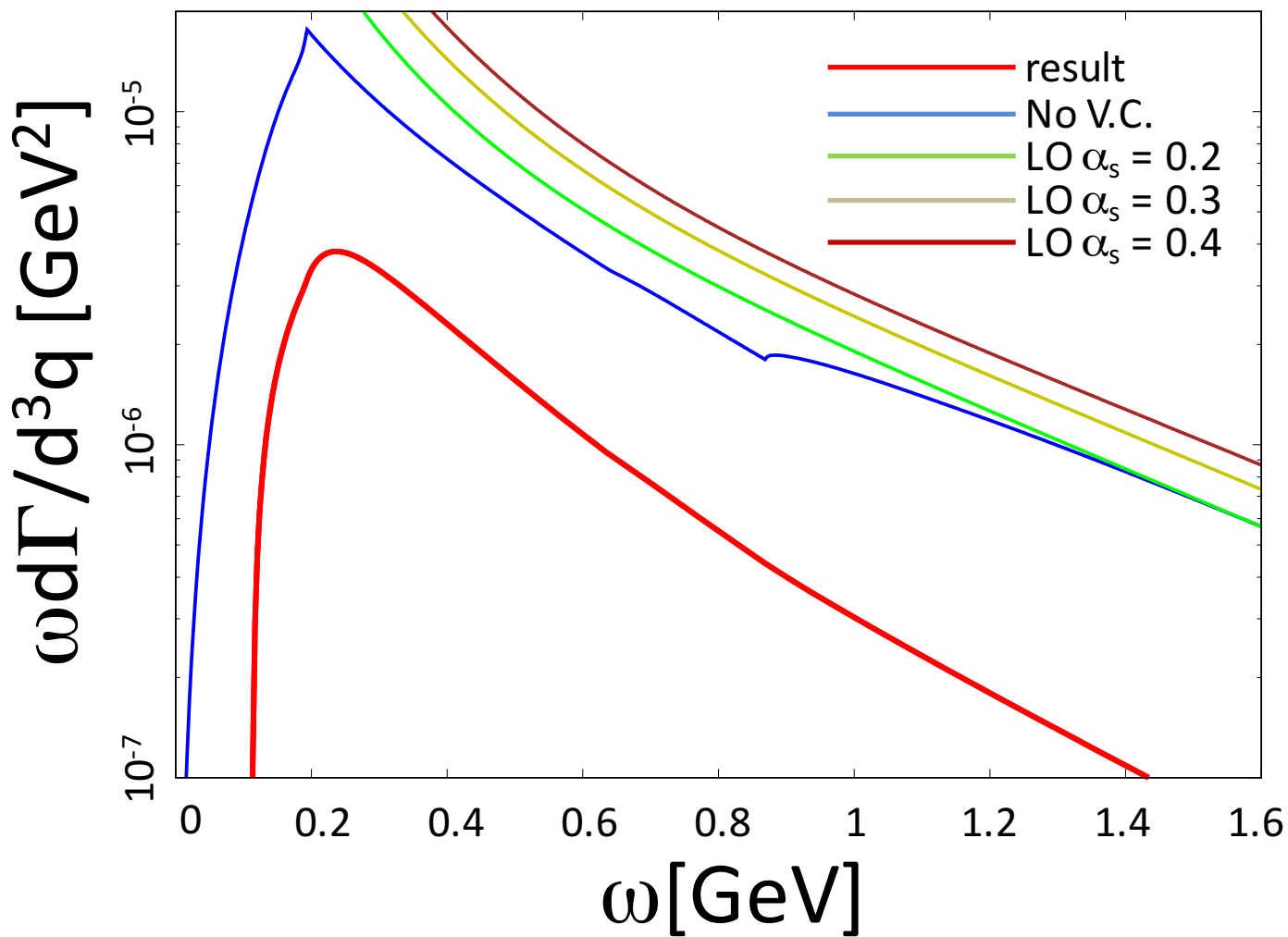
$$T=3T_c$$
$$T_c=290\text{MeV}$$
$$m_T=0.725T$$

Red lines: Contours satisfying constraints.
Estimate a rate = integral through a contour in a region.



preliminary

$1.5T_c$



4. Summary & future works

- We calculated a photon production rate using a lattice quark propagator and gauge invariant vertex.
- Photon production dynamics reflect a nature of dressed quark dispersion.
- Vertex correction has a tendency to suppress production rates.

- Evaluate total production rate including additional channel.
- Analyze finite momentum dilepton production rate with vertex correction.
- Evaluate $d\Gamma/dM_{||}$

appendix

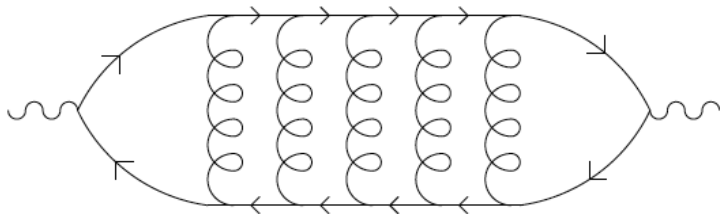
Photon rate from QGP

Perturbative analysis

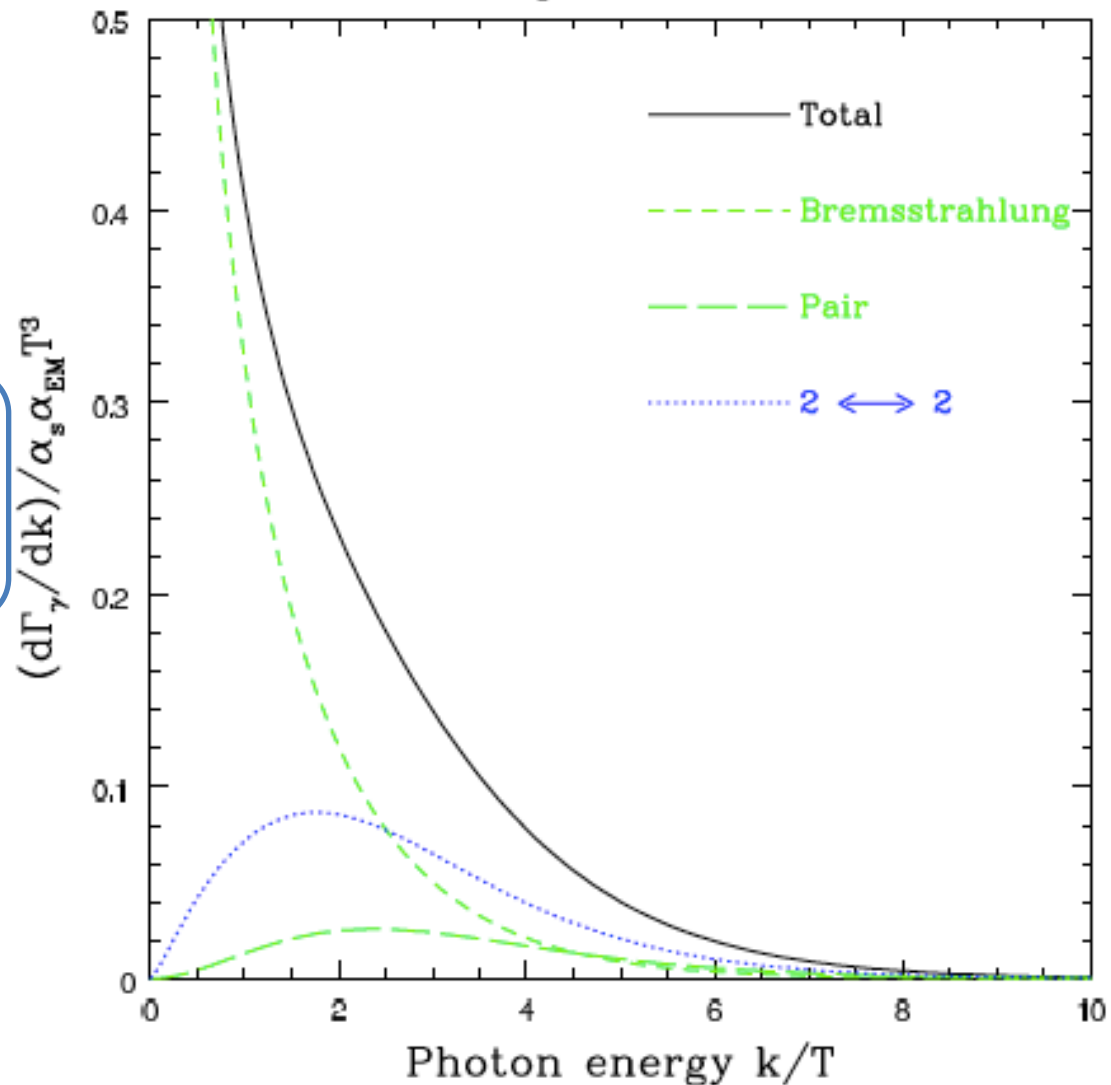
LO: Arnold, Moore, Yaffe (2001)

NLO: Jacopo *et. al.* (2013)

- careful analysis in infrared region
- consider LPM effect



Photon production rate

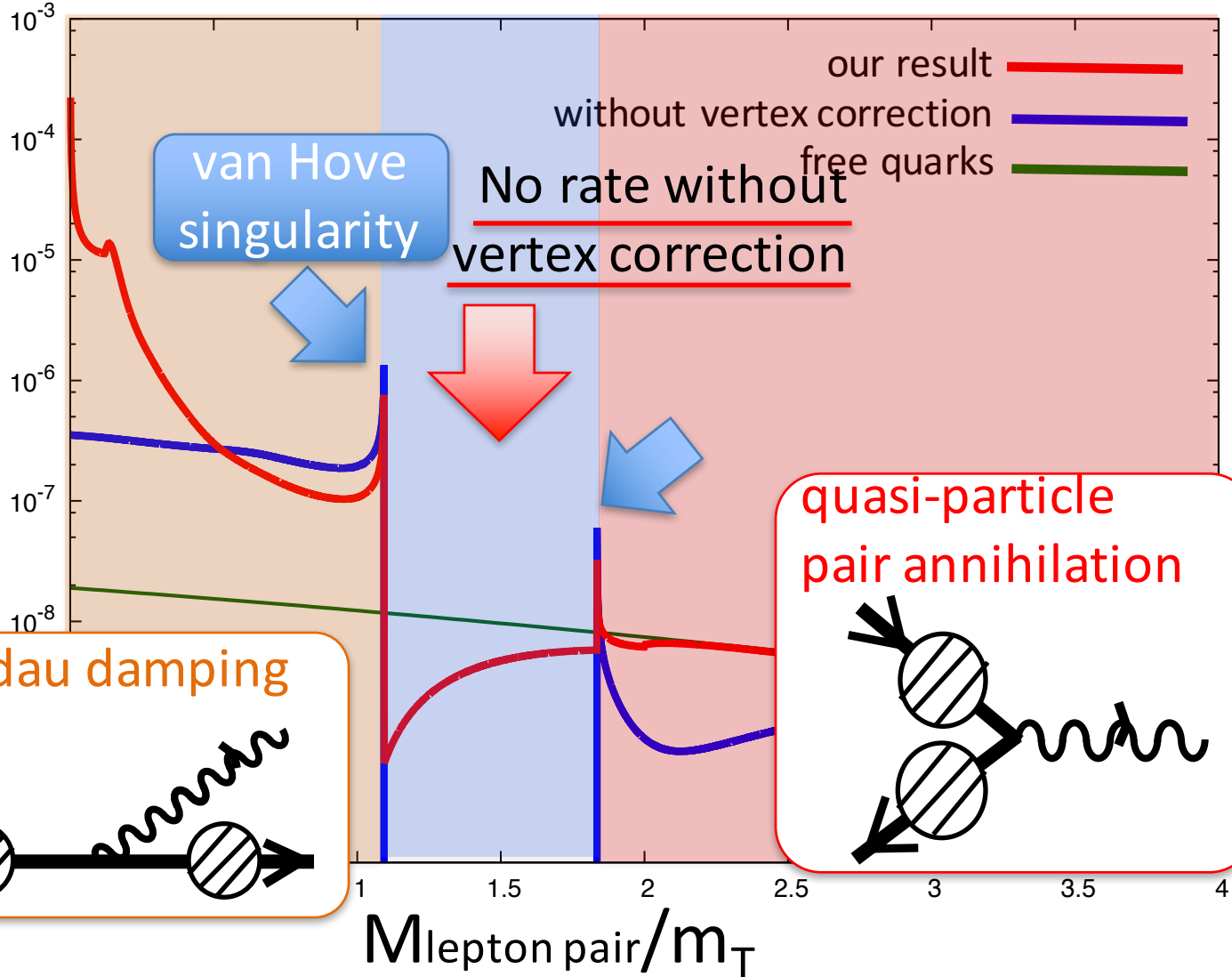


Dilepton production rate

$T = 1.5T_c$
 $T_c = 290 \text{ MeV}$
 $m_T \sim 350 \text{ MeV}$

Rate

$$\left. \frac{d\Gamma}{d\omega d^3q} \right|_{\vec{q}=\vec{0}}$$



$$S_{\mu\nu}(\tau, \vec{p}) = - \int_{-\infty}^{\infty} d\omega \frac{e^{(1/2 - \tau/\beta)\beta\omega}}{e^{\beta\omega/2} + e^{-\beta\omega/2}} \rho_{\mu\nu}(\omega, \vec{p})$$

Measurable observable
on the lattice $\sim O(10)$

Spectral "function"



Fitting by four parameters with the two-pole ansatz

$$\rho_+(\omega, \vec{p}) = Z_+(\vec{p})\delta(\omega - \omega_+(\vec{p})) + Z_-(\vec{p})\delta(\omega + \omega_-(\vec{p}))$$

$$q^i \Gamma_i = S^{-1}(p_0 + q_0, \vec{p} + \vec{q}) - S^{-1}(p_0, \vec{p}) - \underline{q_0 \Gamma_0}$$

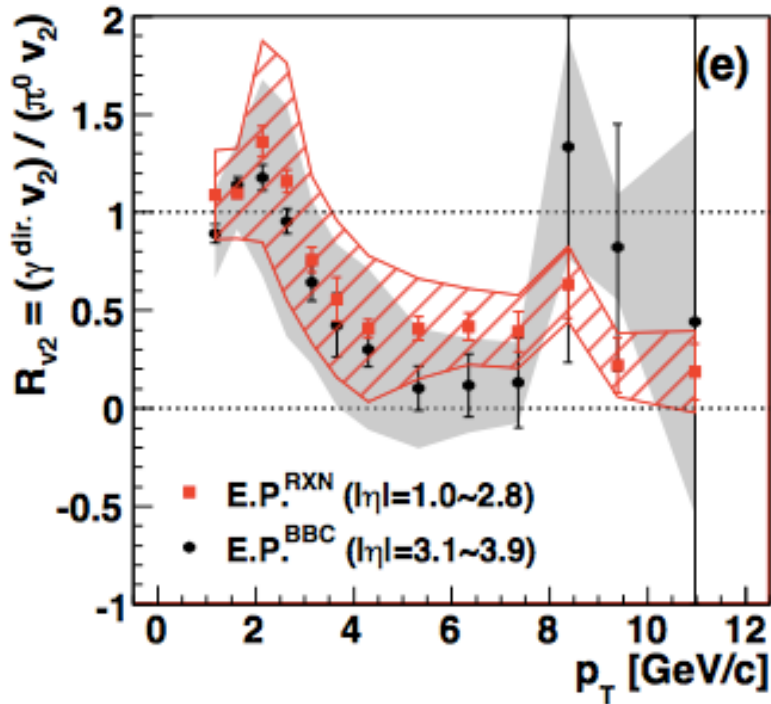
in $|\vec{q}|/q_0 \ll 1$ case

$$\begin{aligned} q_0 \Gamma_0 &= S^{-1}(p_0 + q_0, \vec{p} + \vec{q}) - S^{-1}(p_0, \vec{p}) \\ &+ \vec{q} \cdot \vec{p} \gamma_0 A(p_0 + q_0, p_0, \vec{p}^2, T) \\ &+ (\vec{q} \cdot \vec{p}) (\hat{\vec{p}} \cdot \vec{\gamma}) B(p_0 + q_0, p_0, \vec{p}^2, T) \\ &+ (\vec{q} \cdot \vec{\gamma}) C(p_0 + q_0, p_0, \vec{p}^2, T) + O(\vec{q}^2) \end{aligned}$$

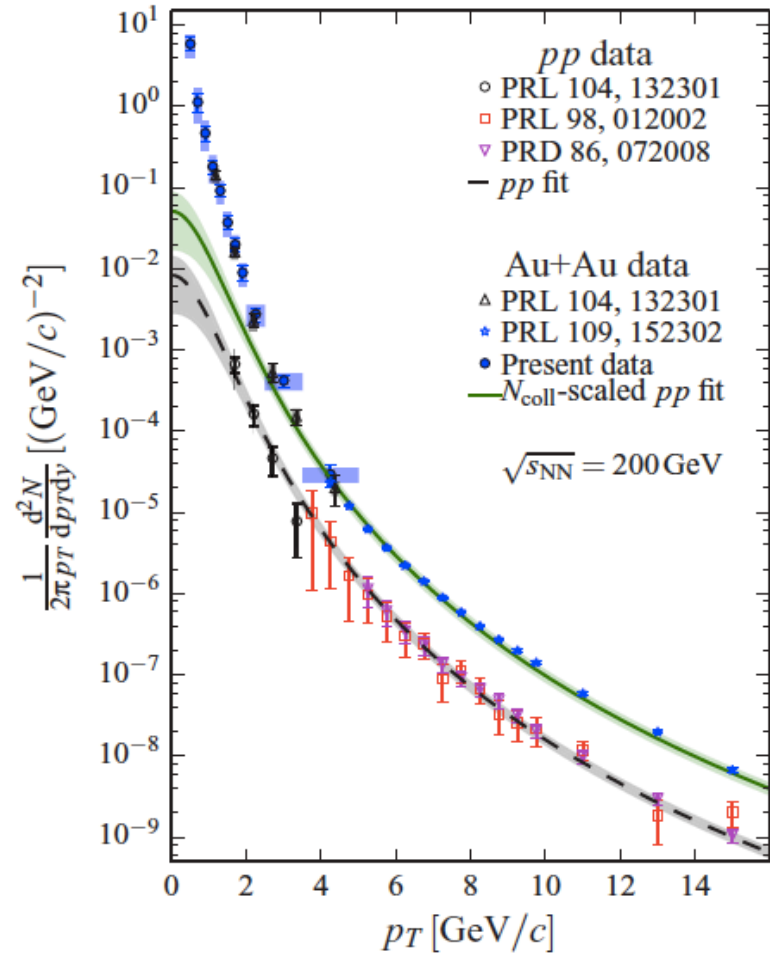
γ @ PHENIX

Au+Au @ $\sqrt{s_{NN}} = 200$ MeV

$$\gamma_{v2} \approx \pi_{v2}$$



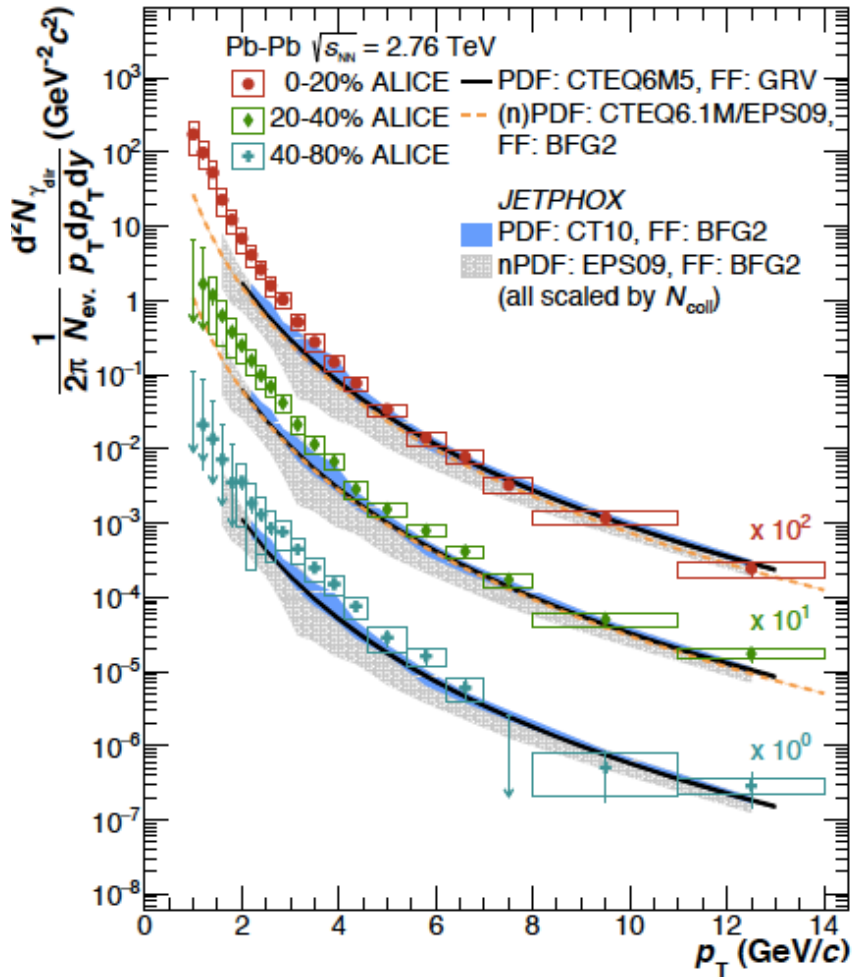
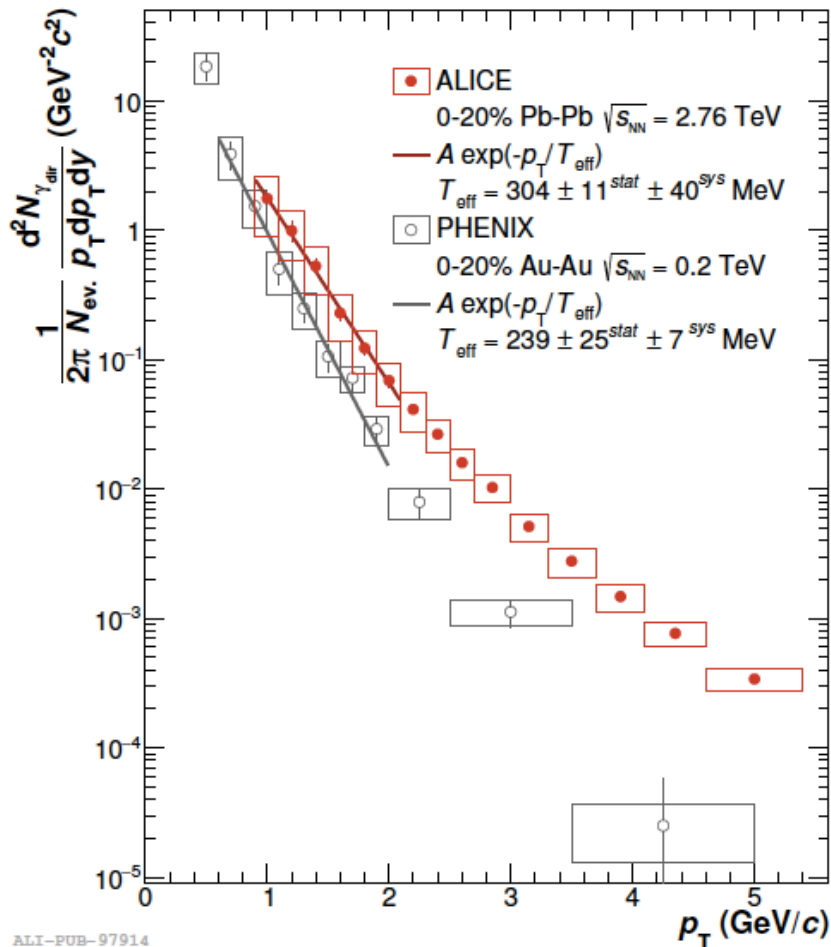
A.Adare *et al.* (PHENIX collaboration) (2012)



A.Adare *et al.* (PHENIX collaboration) (2015)

γ @ ALICE

Pb+Pb @ $\sqrt{s_{NN}} = 2.76$ GeV



arXiv:1509.07324