2nd Conference on Heavy Ion Collisions
in the LHC Era and Beyond

Direct Photon v2 Puzzle In Heavy Ion Collisions

Fu-Ming Liu -- Central China Normal University

Current collaborators:

Sheng-Xu Liu -- Central China Normal University

Klaus Werner -- Subatech, Nantes, France

Meng Yue -- Central China Normal University

Rencontres du Vienam, Quy Nhon, 26th Jul ~ 1st Aug, 2015

Outline

- **Motivations:** Data status of direct photons and dileptons
  Puzzles from Data/model comparisons

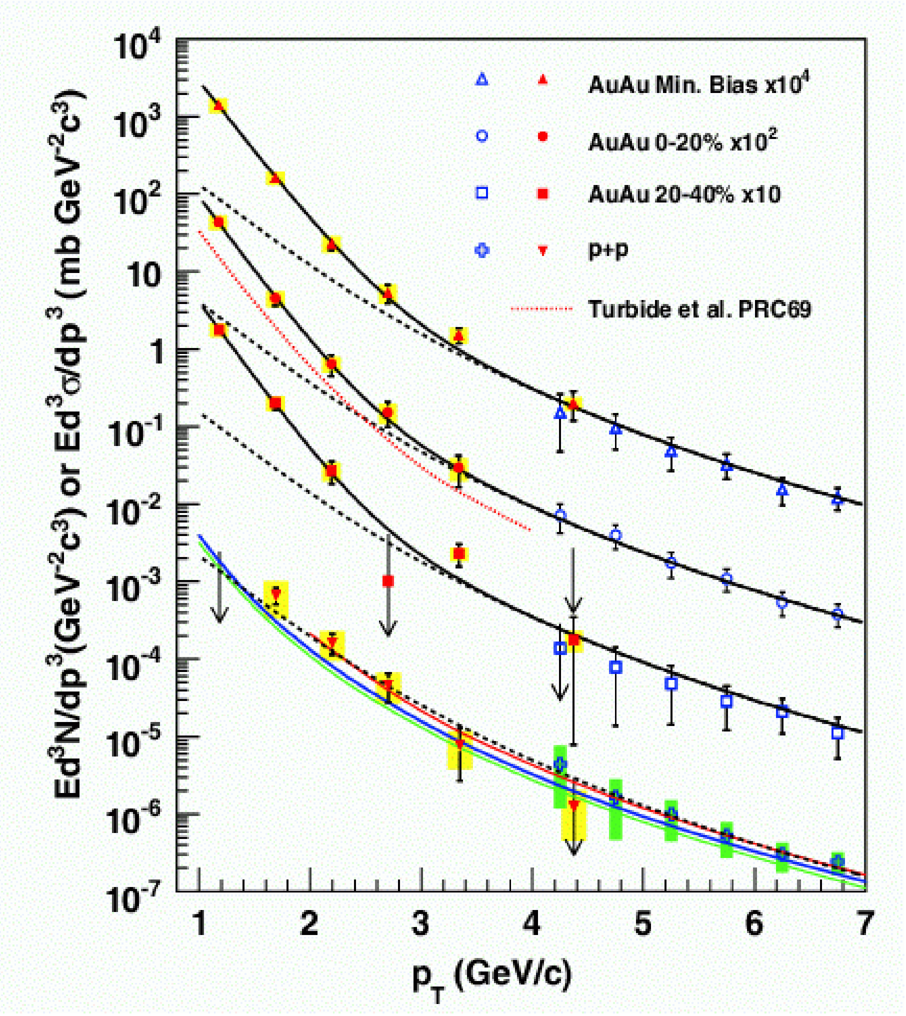
- **Our Results** of photons and dileptons from AuAu 200GeV
  (two hydro models)

- Calculation **Approach** **for photons + dileptons,** **hydro models**

- **Conclusions and outlook**

Direct Photons

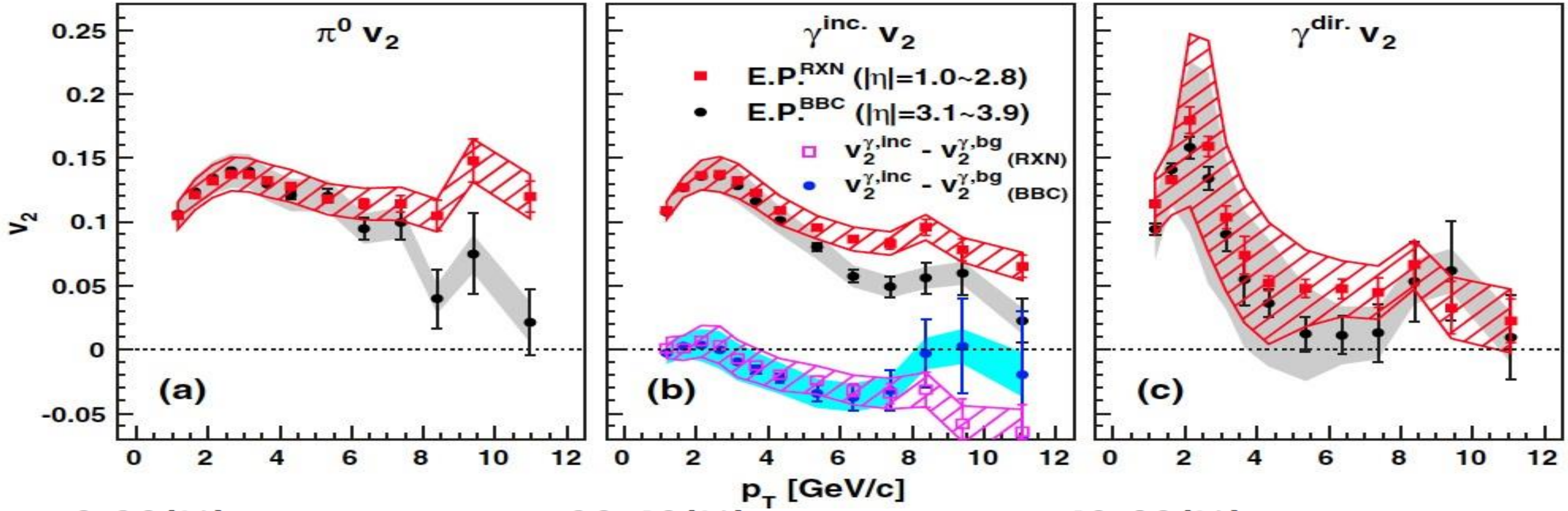
PHENIX, Phy.Rev.Lett.104, 132301 (2010)

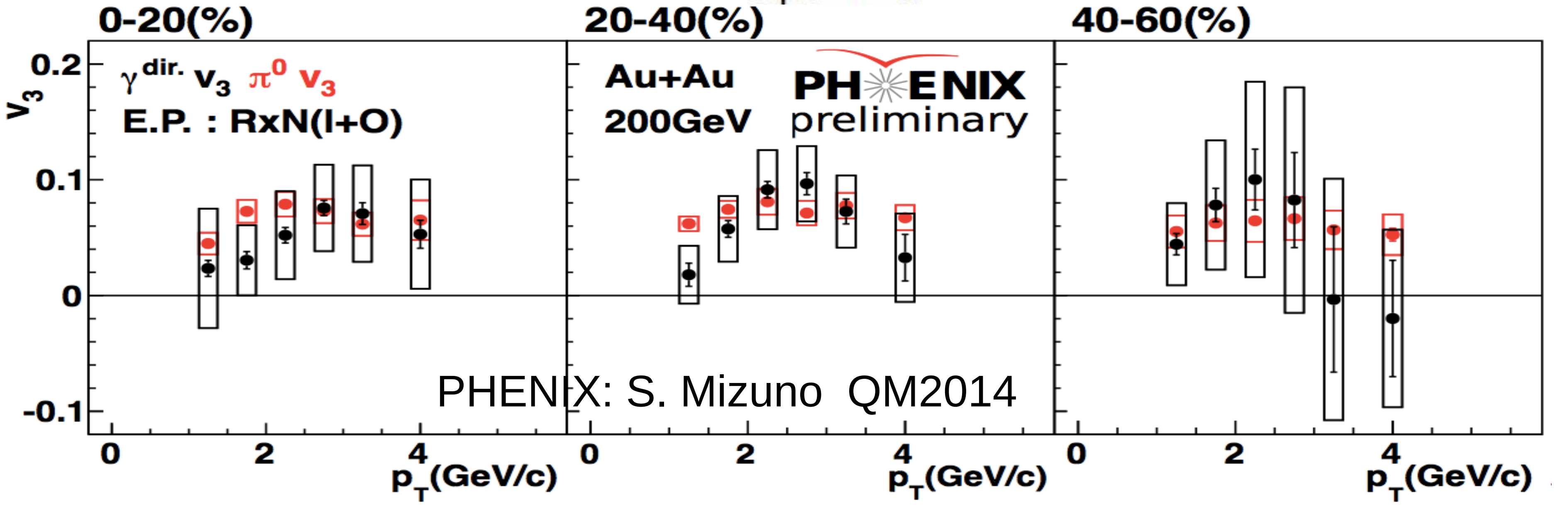


Thermal photons were observed!

Direct Photons

PHENIX, Phys. Rev. Lett. 109, 122302 (2012)





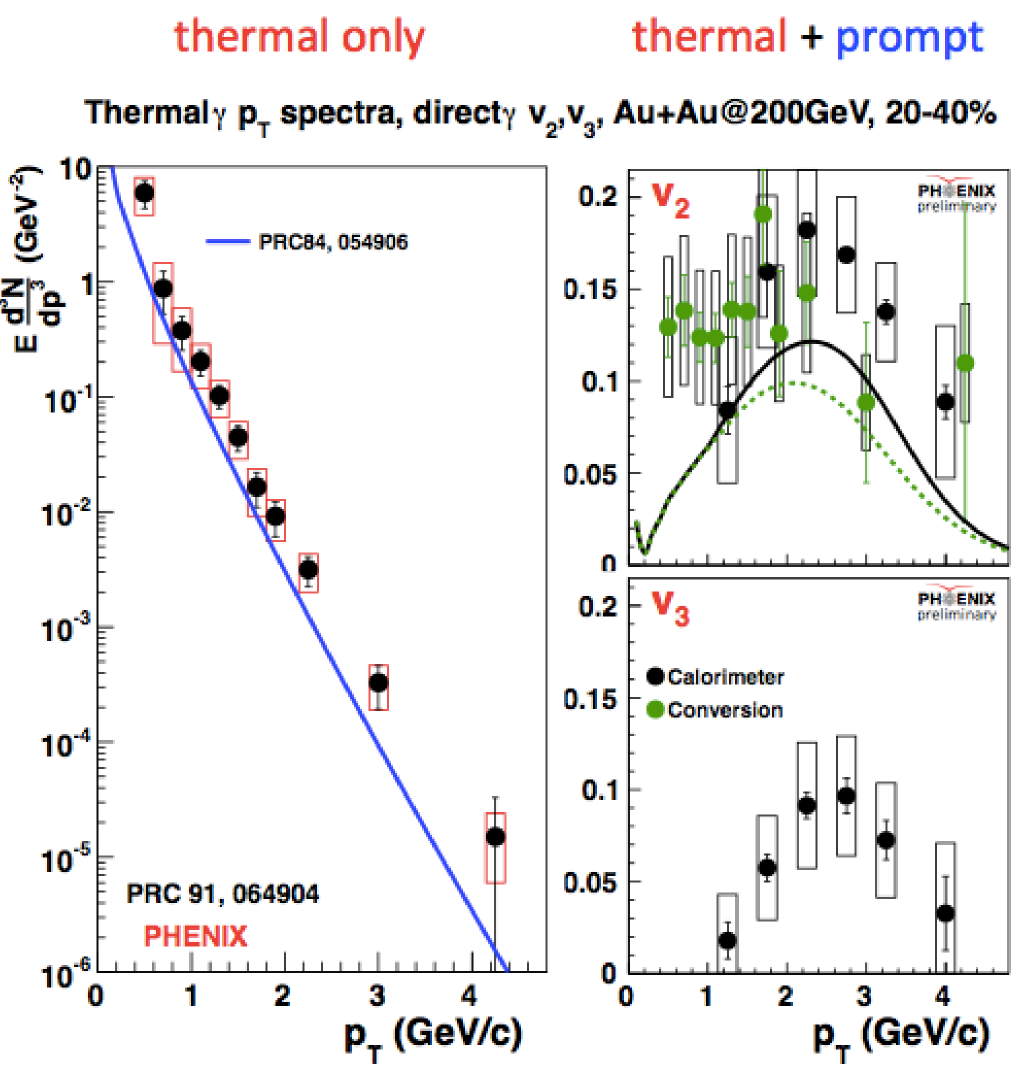
PHENIX: S. Mizuno QM2014

Puzzle of Direct photons

Model comparisons

by Stefan Bathe(PHENIX) in HP2015, McGill, June

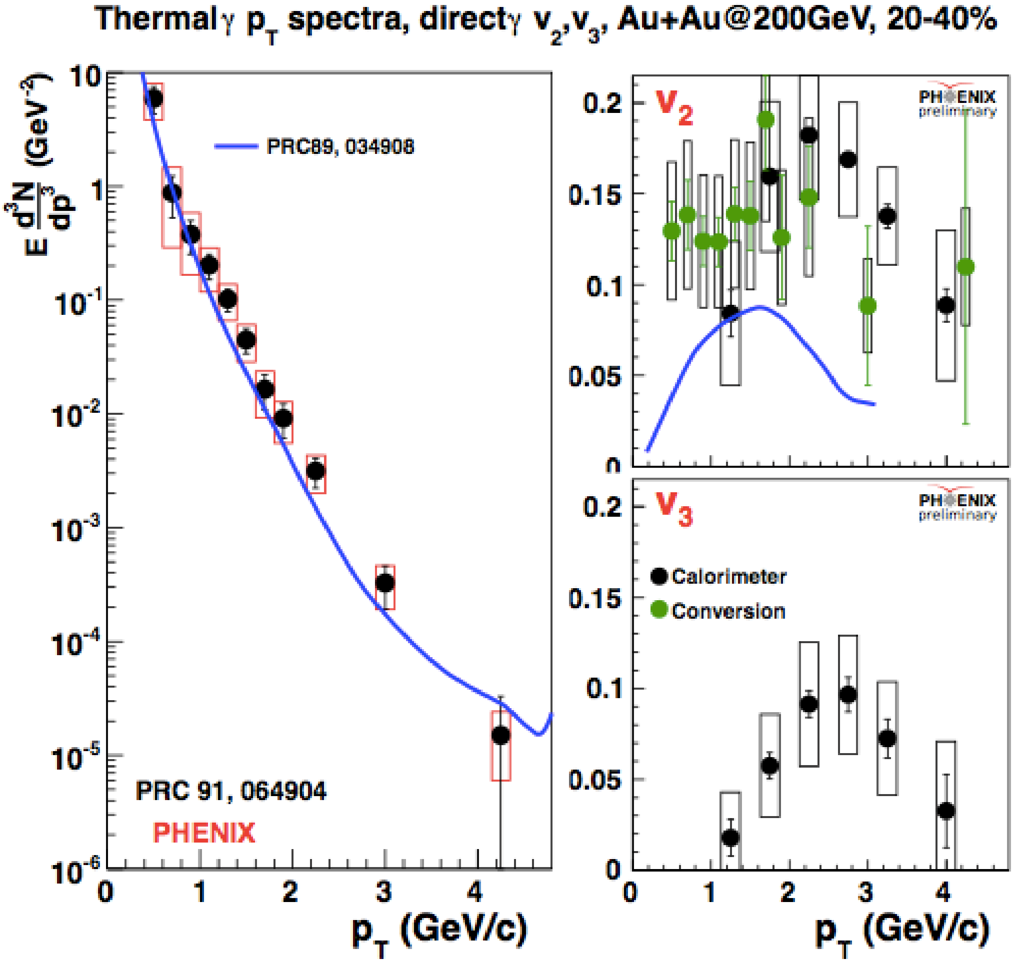
Fireball Model



- pQCD+AMY QGP+HG (ρ spectral function)
- van Hees, Gale, Rapp, PRC 84, 054906(2011)
- Blue shift of HG spectra included
- yield and v_2 only slightly low

PHSD Transport

thermal only　　　thermal + prompt

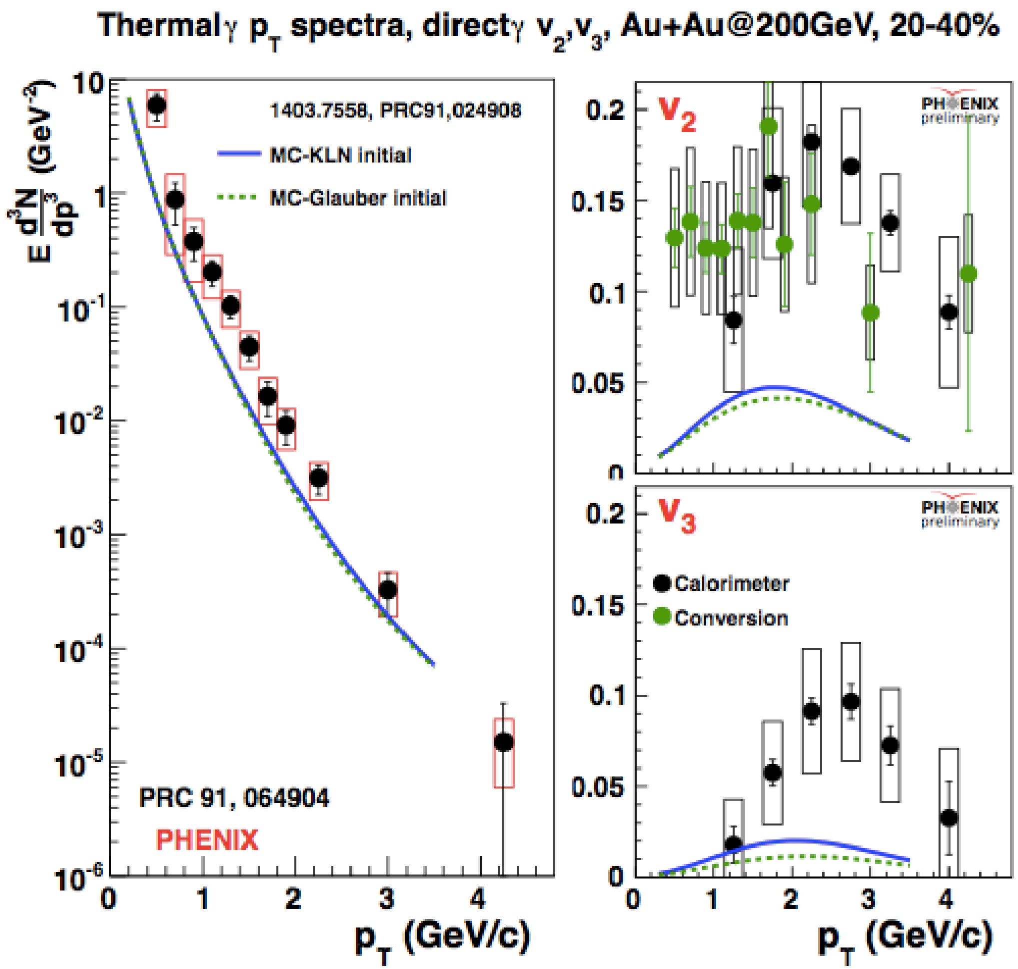


- Parton-Hadron String Dynamics
- Linnyk, Cassing, Bratkovskaya, PRC 89, 034908 (2014)
- Hadronic bremsstrahlung
- Thermal QGP photons included
- Yield well described
- v_2 low

Hydro

thermal only

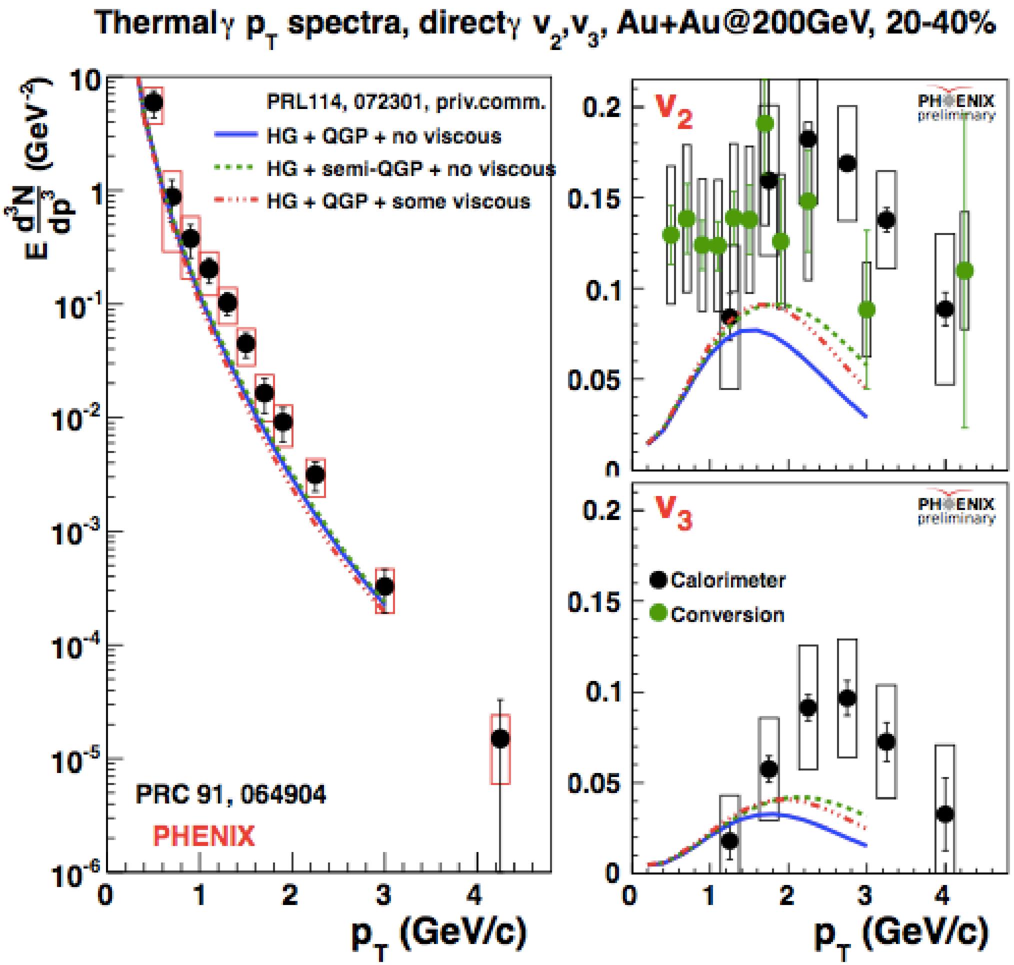
thermal + prompt



- 3+1D viscous hydro
- No pre-flow
- Shen, Heinz, Paquet, Kozlov, Gale, PRC 91, 024908 (2015)
- Both yield and v_2 low
- Better description with pre-flow→ see J.-F. Paquet's talk

Semi-QGP

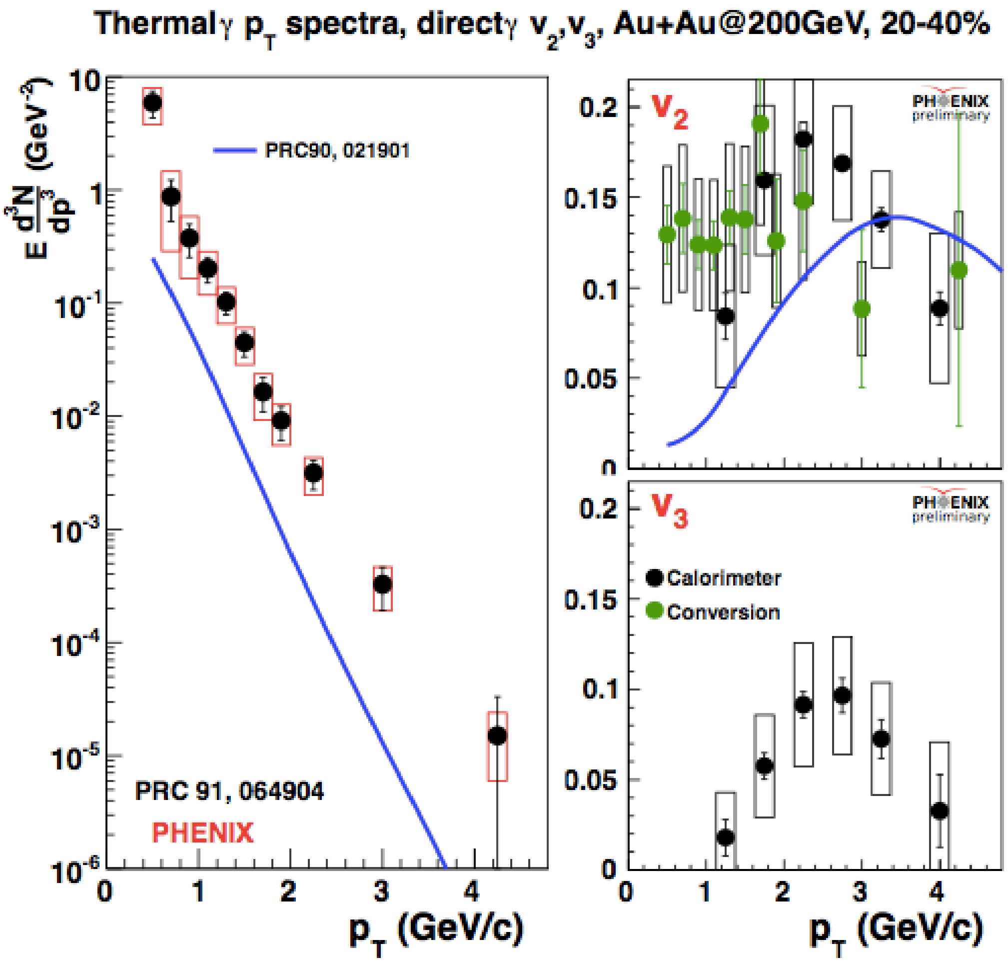
thermal only　　　thermal + prompt



- semi-QGP+HG+pQCD
- Gale et al., PRL114, 072301(2015) + private communication
- semi-QGP: reduced partonic ndf near T_c
- But transition to hadronic ndf?
- Yield fairly well described
- v_2, v_3 low

Slow Chemical Freeze-Out

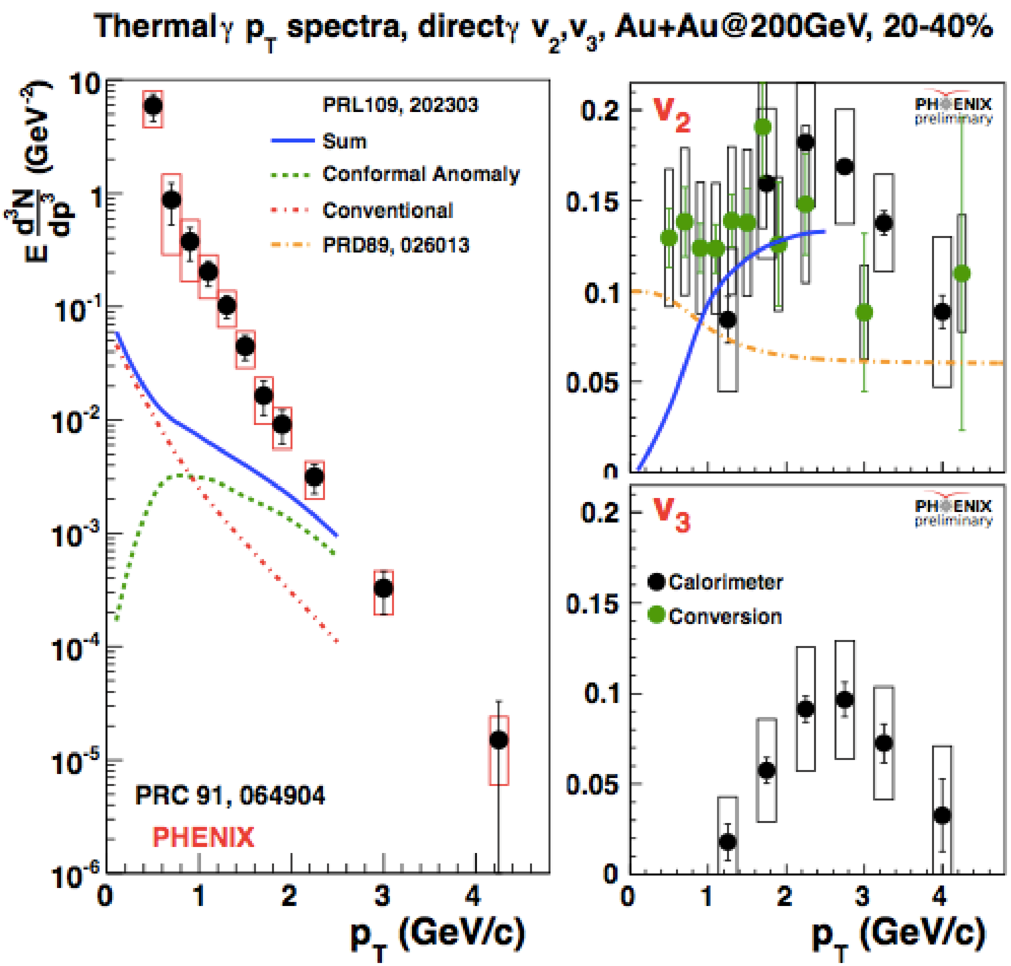
thermal only   thermal + prompt



- Monnai, PRC90, 021901(2014)
- Slow chemical freeze-out, more time to develop flow
- Neither pQCD nor HG contribution included

Magnetic Field

thermal only   thermal + prompt



- Initial strong magnetic field produces anisotropy of photon emission
- Baser, Kharzeev, Skokov, PRL109, 202303(2012),
  - Weak coupling
- Müller, Wu, Yan, PRD 89, 026013(2014)
  - strong coupling
- Only source that gives non-zero v_2 at $p_T = 0$
- No other sources included
- No v_3

Our Results

AuAu @ 200GeV, hadron data constrain

1. Understand the spectra of direct photons with Hirano's hydro.
   FML, T.Hirano, K.Werner, Y.Zhu, Phys.Rev.C79 (2009) 014905.

2. The study of thermal photon v2 with Hirano's hydro.
   FML, T.Hirano, K.Werner, Y.Zhu, Phys.Rev.C80 (2009) 034905.

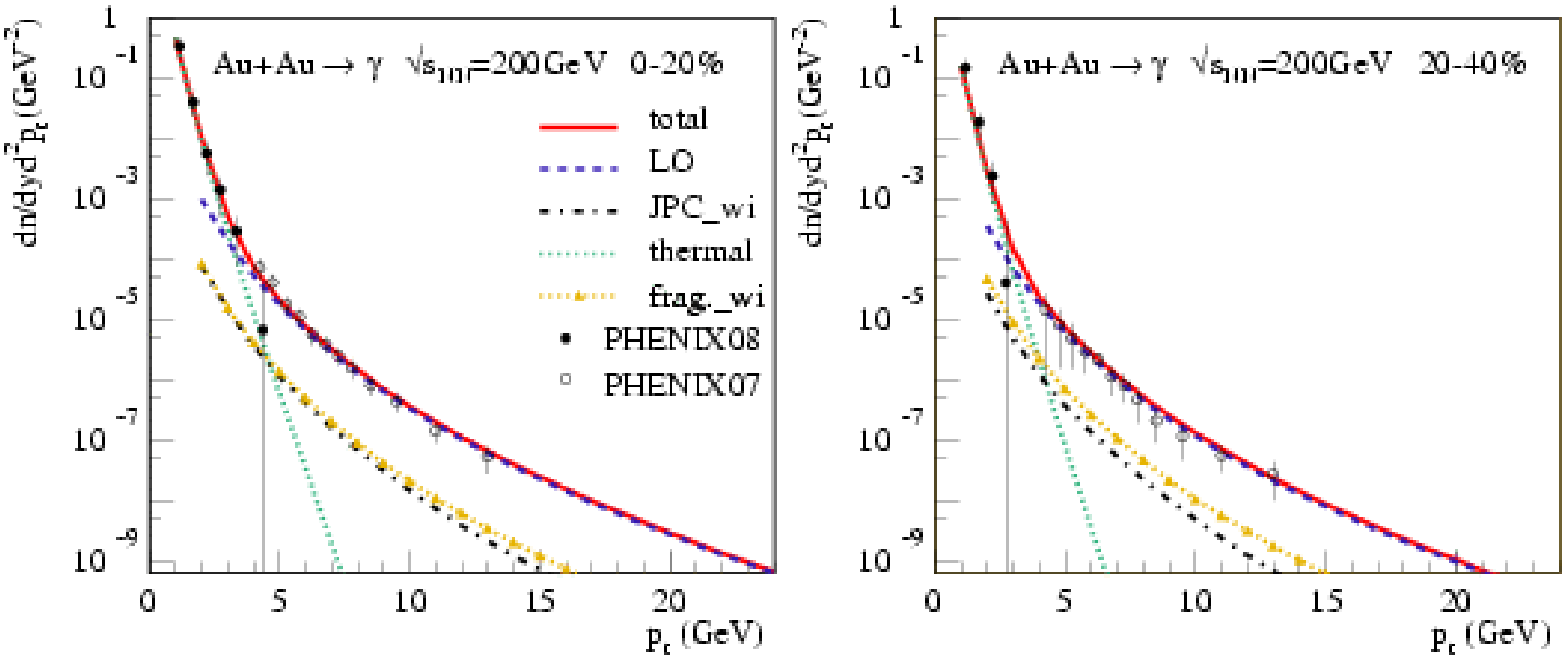
3. Try to explain the large v2 of direct photons with Hirano's hydro,
   With **delayed QGP formation.**
   FML, Shengxu Liu， Phys.Rev.C89 (2014) 3， 034906.

4. Explain the large photon v2 and predict v2 of dileptons with EPOS3.
   (Recent)

Note: No modification to any hydro parameter after hadron data are explained, for any of the upper hydro models.

1. Explain Photon Spectrum

FML, T.Hirano, K.Werner, Y.Zhu, Phys.Rev.C79 (2009) 014905.



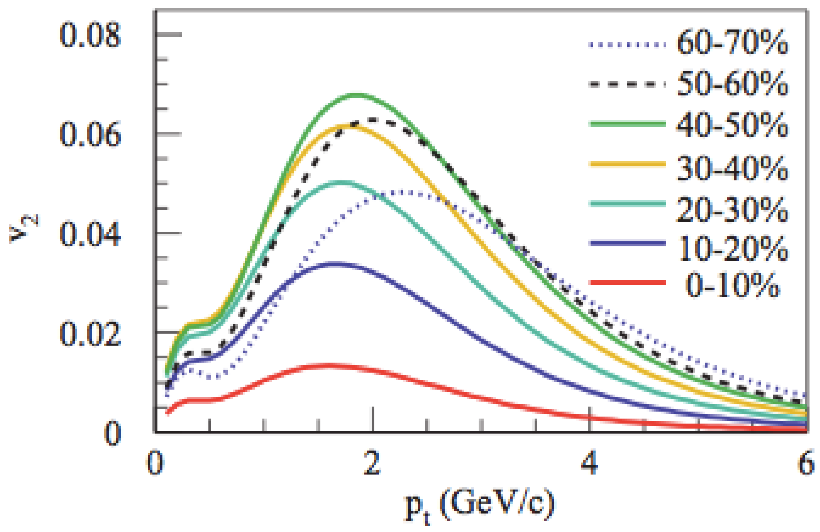
What we learn:

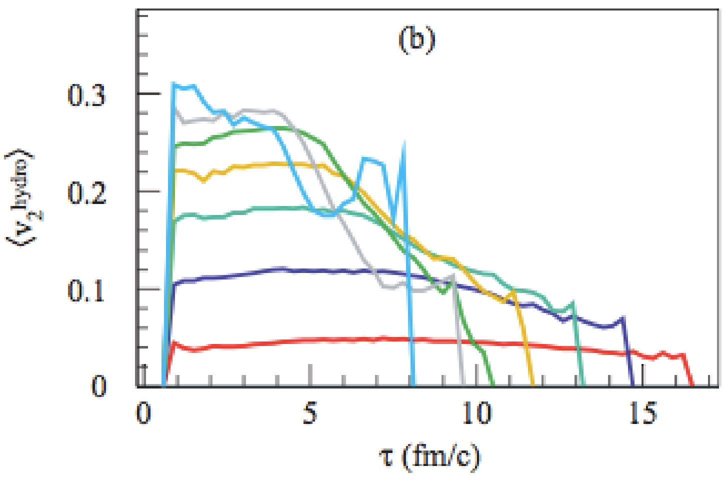
Photon spectra are explained with hadron date constrained hydro!

Understand the sources of direct photons. Roughly Prompt + thermal!

2. Study thermal photon v2

FML, T.Hirano, K.Werner, Y.Zhu, Phys.Rev.C80 (2009) 034905.





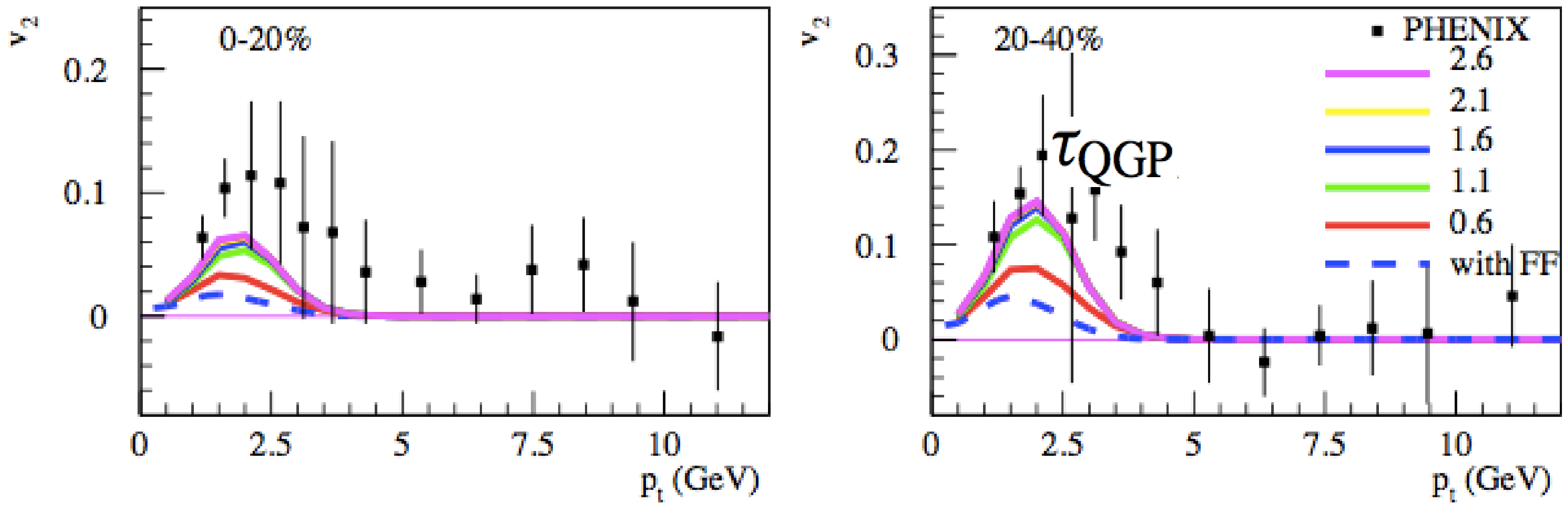
What we learn:

1. Centrality dependence tells us, Big $v_2^H = \dfrac{v_x^2 - v_y^2}{v_x^2 + v_y^2}$, big photon v2.

2. We can use this thermal photon v2 to get direct photon v2, red lines in next slide.

3. Delayed QGP formation

FML, Shengxu Liu， Phys.Rev.C89 (2014) 3，034906.



What we learn:

1. The red lines from last calculation are much lower than PHENIX measured photon v2. Similar results from other groups! The photon v2 puzzle!
2. Assume that **QGP formation is later than thermalization**, calculated photon v2 can go close to data!

Delayed QGP formation means

1. A gluon-dominant system exists in the early stage of HIC.

2. This system is very hot, but emits very little photons and leptons, because gamma line doesn't directly link to gluon line.

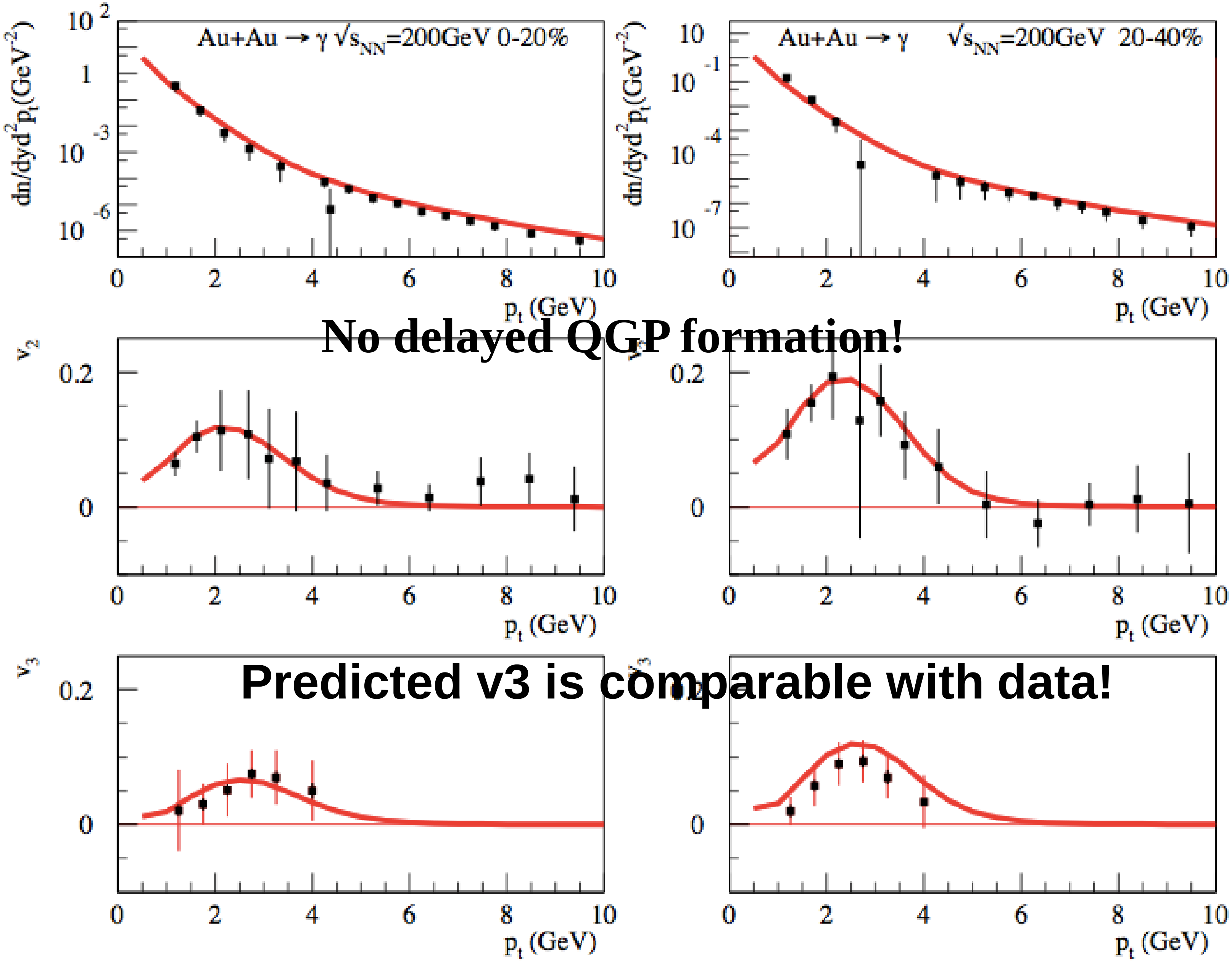
3. With the duality of energy and mass, this system provides us a possible solution to the puzzule of the dark such as black holes, dark matter/E.

FML. arXiv:1305.5284

Be cautious!

Question: Is it the **only** solution to the photon v2 puzzle?
How about other EM probes, ie, dileptons?

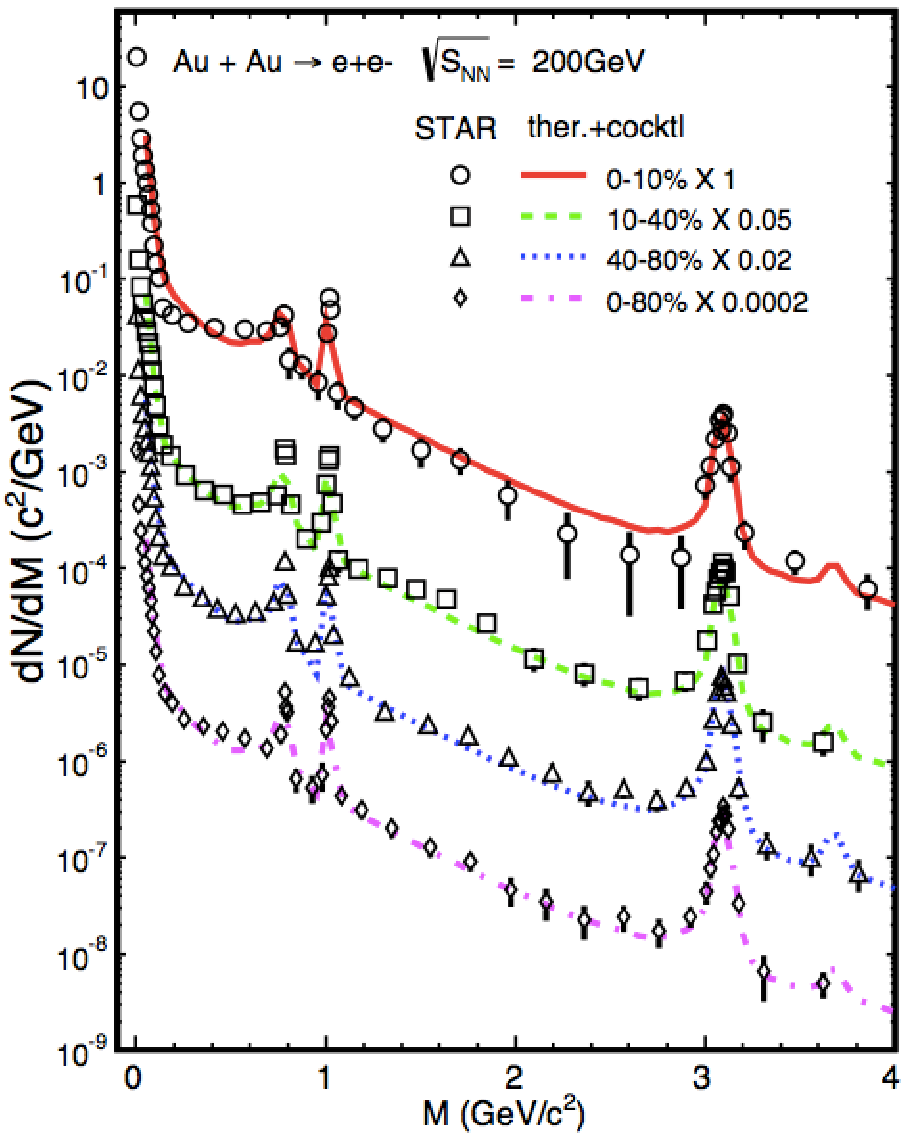
4. Recent results with EPOS3

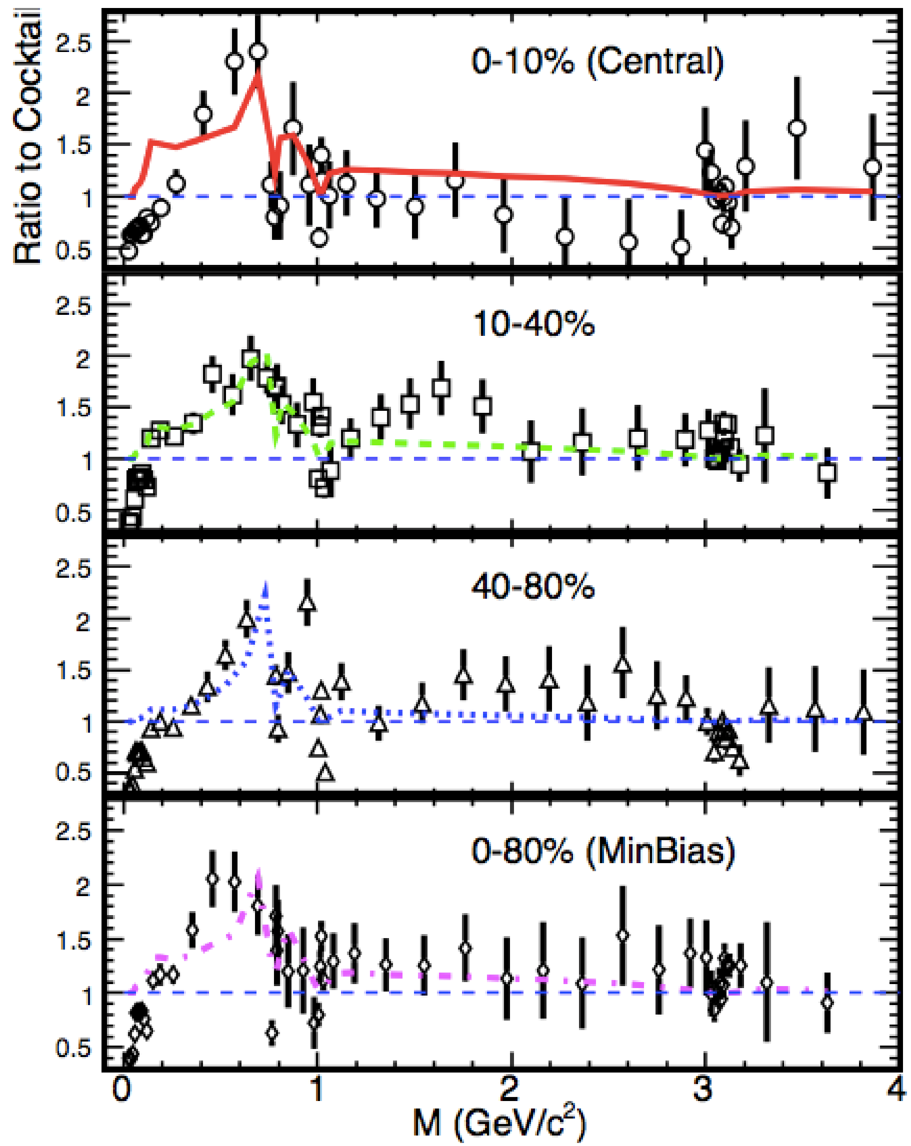


No delayed QGP formation!

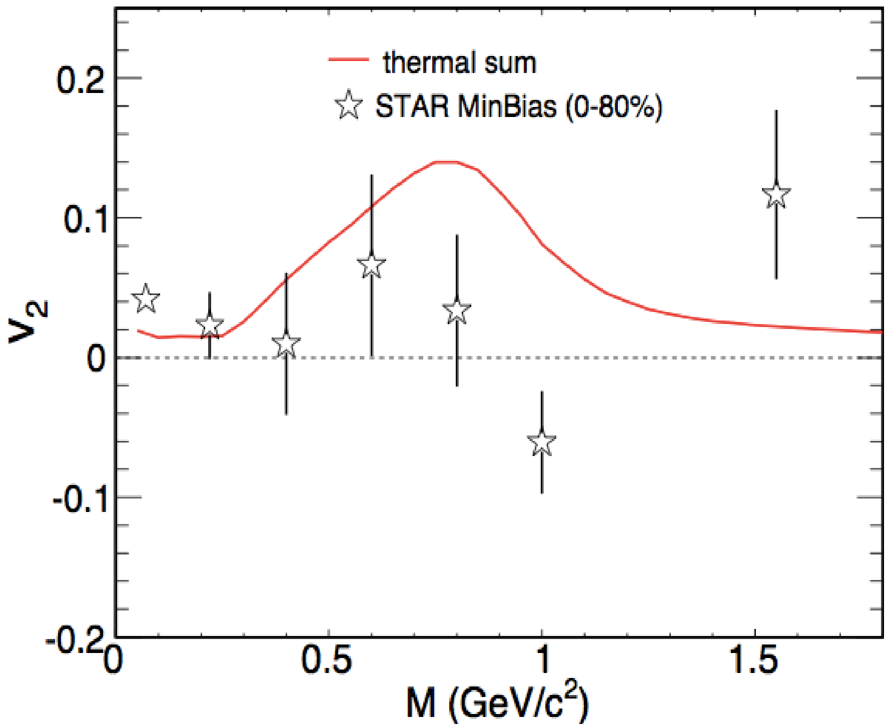
Predicted v3 is comparable with data!

Dileptons with EPOS3

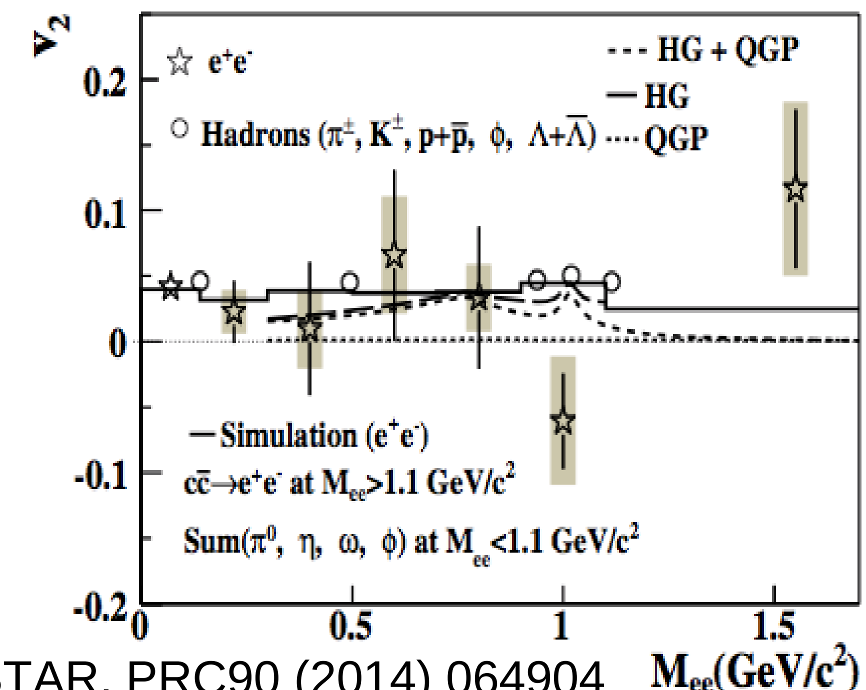




Thermal dilepton v2

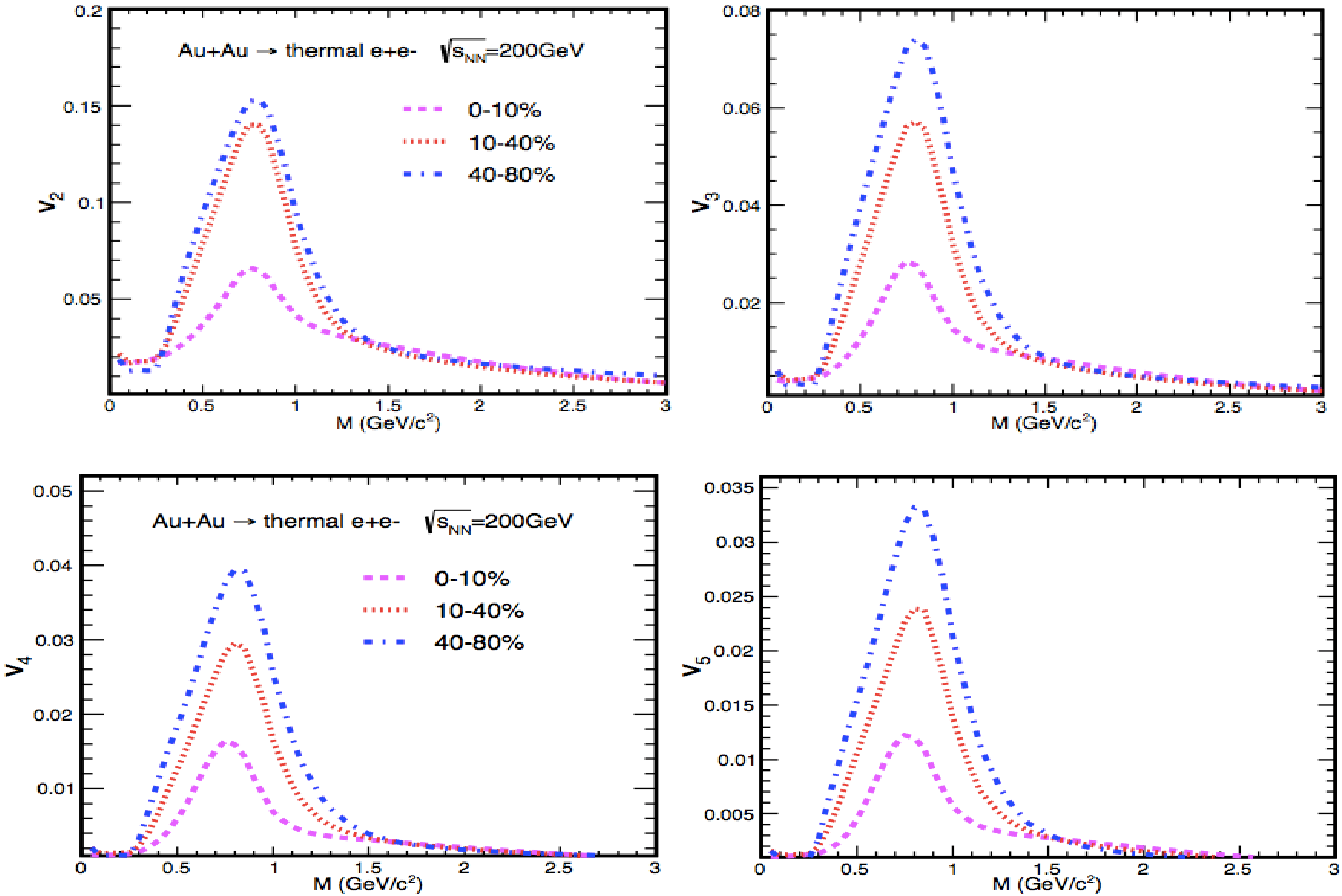


Our predicted v2 of thermal dileptons is large!



STAR, PRC90 (2014) 064904

v2, v3, v4, v5 vs. centrality



Calculation approach

1. Sources of direct photons and dileptons

2. Hydro evolution for thermal contrinution

3. Initial Condition (IC) for hydro evolution

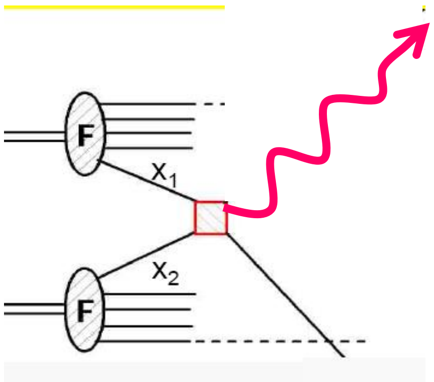
Main Sources of Direct photons

Based on High pt direct photon data

1. Prompt photons

$$\frac{d\sigma^{\text{Prompt}}}{dyd^2p_t} = \sum_{ab} dx_a dx_b G_{a/A}(x_a, M^2) G_{b/B}(x_b, M^2) \frac{\hat{s}}{\pi} \frac{d\sigma}{d\hat{t}}(ab \to cd)\delta(\hat{s}+\hat{t}+\hat{u})$$

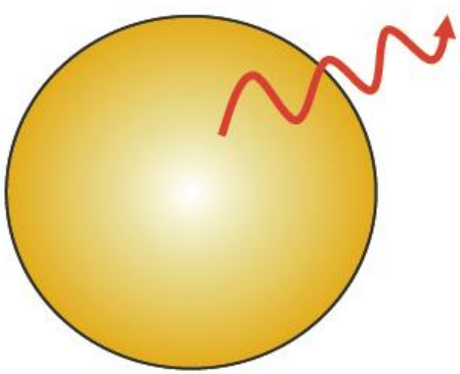
$$+\sum_{c=q,g} \int dz_c \frac{d\sigma^c}{dyd^2p_t} \frac{1}{z_c^2} D^0_{g/c}(z_c, Q^2)$$



Dominant at high pt , zero V2.

2. Thermal photons

$$\frac{dN^{\text{thermal}}}{dyd^2p_t} = \int d^4x \Gamma_{\text{thermal}}(E^*, T), \quad E^* = p^\mu u_\mu$$



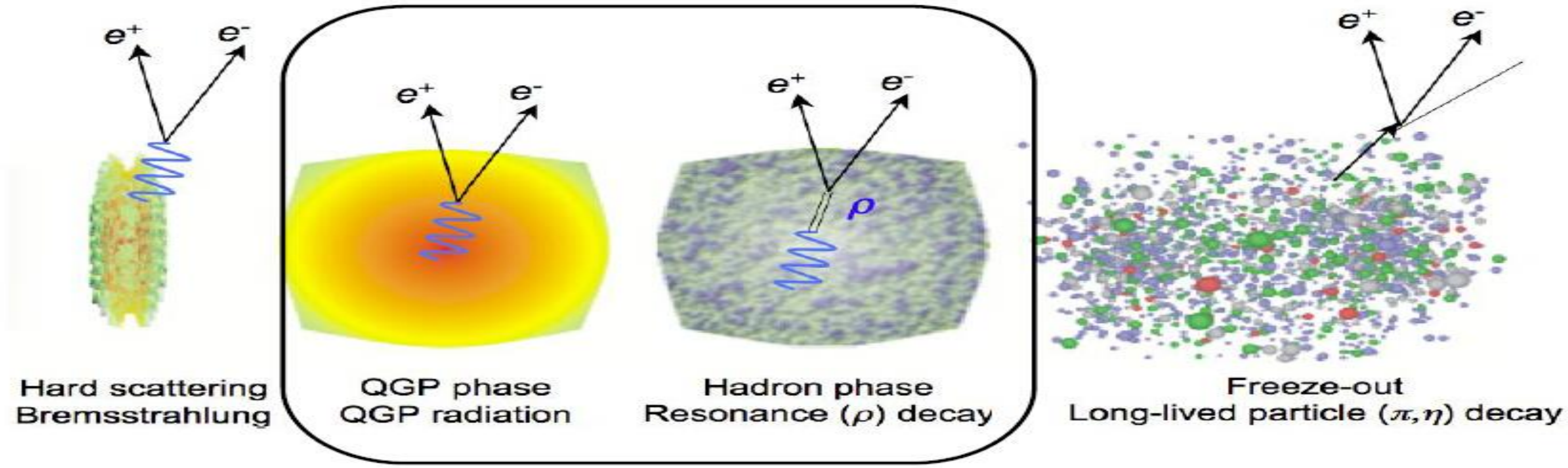
Dominate at low pt .

Photon emission rates:

QGP phase: AMY2001

HG phase: TRG2004

Dileptons from the same system



Sources of dileptons:

1. Drell-Yan
2. Light meson decay
3. Heavy flavor decay

(2 and 3: Cocktail)

4. Thermal contribution (QGP + HG)

$$M^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$$\frac{dN_{l_+l_-}}{dM} = \int d^4x \frac{Md^3q}{q^0} \frac{dN_{l_+l_-}}{d^4xd^4q}$$

Plasma in Hirano's hydro

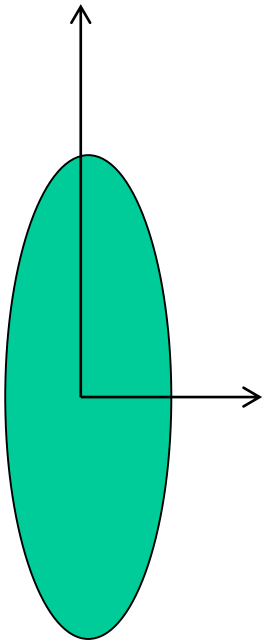
$\varepsilon, p, u^{\mu}, s, B, \ldots (\tau, x, y, z)$ described with 3+1D ideal hydrodynamics

- Initial Condition Glauber model, Wood-Saxon, initial time
- Evolution: 3D ideal hydrodynamic equation $\partial_{\mu} T^{\mu\nu} = 0$
  - EoS: 1st order phase transition at $T_c = 170\,\mathrm{MeV}$
    - QGP phase: 3 flavor free Q & G gas
    - HG phase: hadronic gas PCE
- Freeze-out: $\varepsilon^{th} = 0.08\,\mathrm{GeV/fm^3}$ or $T^{th} \sim 100\,\mathrm{MeV}$

Glauber IC in Hirano's hydro

Energy density or entropy distribution in the space:

$$\frac{dS}{d\eta_s\, d^2x_\perp} = \frac{C}{1+\alpha}\theta\left(Y_b - |\eta_s|\right) f^{pp}(\eta_s)$$
$$\times\left[\alpha\left(\frac{Y_b-\eta_s}{Y_b}\frac{dN_{\text{part}}^{A}}{d^2x_\perp} + \frac{Y_b+\eta_s}{Y_b}\frac{dN_{\text{part}}^{B}}{d^2x_\perp}\right)\right.$$
$$\left. + (1-\alpha)\frac{dN_{\text{coll}}}{d^2x_\perp}\right],$$



Parameterized rapidity distribution in *pp* collisions

$$f^{pp}(\eta_s) = \exp\left[-\theta\left(|\eta_s| - \Delta\eta\right)\frac{(|\eta_s| - \Delta\eta)^2}{\sigma_\eta^2}\right],$$

Hirano's hydro used since 2007

Many Groups developed Glauber IC:

+ fluctuations: MC-Glauber, …

+ PDF constrains: IP-Glasma,…

+ **viscosity** can not make photon v2 so big

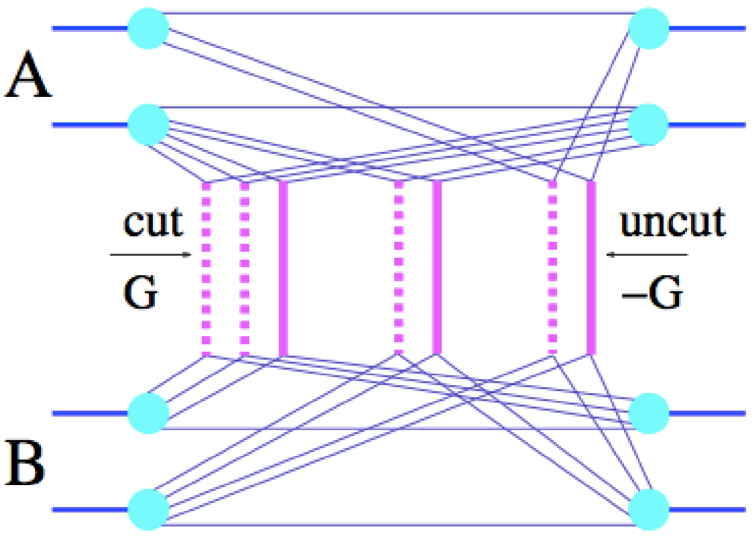
Hadron data constraints

→ Still, **under-predicted** photon v2

EPOS3 IC

For pp, pA, AA:

$$\sigma^{\rm tot} = \sum_{\rm cut\,P} \int \sum_{\rm uncut\,P} \int$$



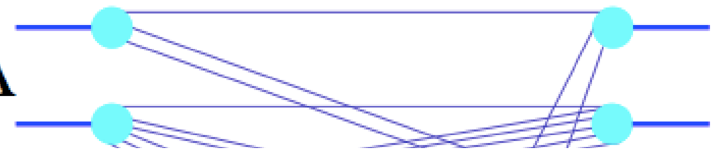
$$d\sigma_{\rm exclusive}$$

$$\mathrm{cut\,Pom}: G = \frac{1}{2\hat{s}} 2\mathrm{Im}\,\{\mathcal{FT}\{T\}\}(\hat{s}, b),\; T = i\hat{s}\,\sigma_{hard}(\hat{s})\,\exp(R^2_{\rm hard} t)$$

EPOS3 IC

For pp, pA, AA:

A



$$\sigma^{\mathrm{tot}} = \int d^2b \int \prod_{i=1}^{A} d^2b_i^A\, dz_i^A\, \rho_A\left(\sqrt{(b_i^A)^2 + (z_i^A)^2}\right)$$

$$\prod_{j=1}^{B} d^2b_j^B\, dz_j^B\, \rho_B\left(\sqrt{(b_j^B)^2 + (z_j^B)^2}\right)$$

$$\sum_{m_1 l_1} \cdots \sum_{m_{AB} l_{AB}} (1 - \delta_{0\Sigma m_k}) \int \prod_{k=1}^{AB} \left(\prod_{\mu=1}^{m_k} dx_{k,\mu}^{+} dx_{k,\mu}^{-} \prod_{\lambda=1}^{l_k} d\tilde{x}_{k,\lambda}^{+} d\tilde{x}_{k,\lambda}^{-} \right) \Bigg\{$$

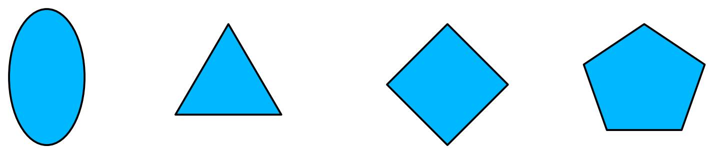
$$\prod_{k=1}^{AB} \left(\frac{1}{m_k!} \frac{1}{l_k!} \prod_{\mu=1}^{m_k} G(x_{k,\mu}^{+}, x_{k,\mu}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|) \right.$$

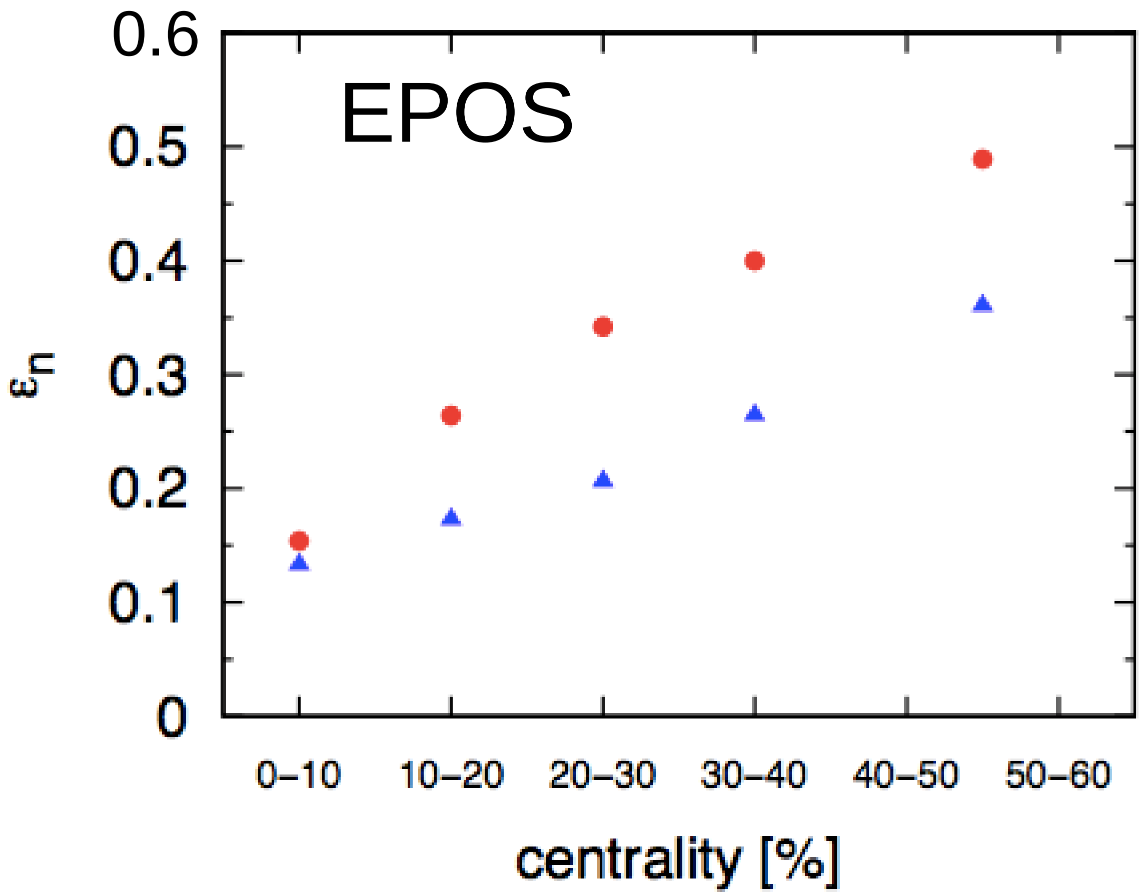
$$\left. \prod_{\lambda=1}^{l_k} -G(\tilde{x}_{k,\lambda}^{+}, \tilde{x}_{k,\lambda}^{-}, s, |\vec{b} + \vec{b}_{\pi(k)}^{A} - \vec{b}_{\tau(k)}^{B}|) \right)$$

$$\prod_{i=1}^{A} \left(1 - \sum_{\pi(k)=i} x_{k,\mu,}^{+} - \sum_{\pi(k)=i} \tilde{x}_{k,\lambda}^{+} \right)^{\alpha} \prod_{j=1}^{B} \left(1 - \sum_{\tau(k)=j} x_{k,\mu}^{-} - \sum_{\tau(k)=j} \tilde{x}_{k,\lambda}^{-} \right)^{\alpha} \Bigg\}$$

v2, v3, v4 ... e2 e3 e4

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + \sum_n 2v_n \cos n(\phi - \psi_n)\right]$$





Initial eccentricity e2 and e3

C% dependence

the same!

Conclusions and Outlook

1. Photon v2 puzzle in heavy ion collisions is important.

   We may understand the dark with lights.

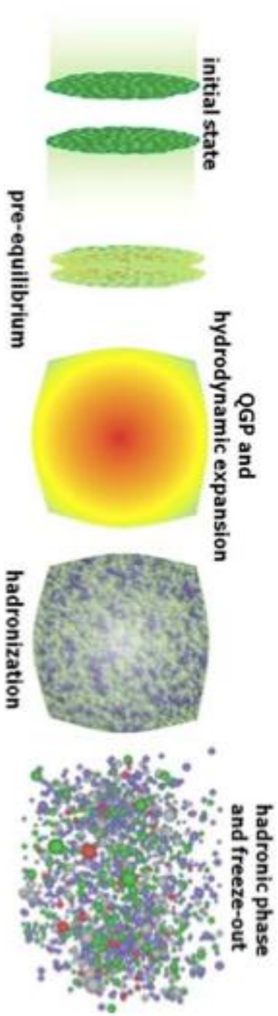
2. EPOS reproduces spectra/v2/v3 of charged hadrons, direct photons.

3. It predicts large v2 of thermal dileptons. Centrality dependence occurs not only to v2 but also v3,v4, v5.

4. More insights to v2 v3 v4? How artificial hydro ICs ?

Thank you for your attention!

Delayed QGP formation



(i) At $\tau = 0$, prompt photons are counted according to the next-to-leading-order QCD.

(ii) At $0 < \tau \leqslant \tau_0$, we have $\xi = 0$ and photon emission rate $\Gamma = 0$.

(iii) At $\tau_0 < \tau < \tau_{QGP}$, emission is estimated with $\Gamma^{low} < \Gamma < \Gamma^{up}$.

(iv) For $\tau \geqslant \tau_{QGP}$, the thermal photon emission rate covers

QGP phase-- AMY2001
HG phase -- TRG2004

Photon emission rate in non-eq.

Quark distribution $f \sim \chi f_0$ quark fugacity ξ

Photon emission rate suppressed by ξ^n

$$\Gamma^{\text{low}} = \xi \cdot \Gamma_{\text{Compton}} + \xi^2 \cdot \Gamma_{\text{annihilation}}$$
$$\Gamma^{\text{up}} = \xi \cdot \Gamma_{\text{Compton}} + \xi^2 \cdot (\Gamma_{\text{AMY}} - \Gamma_{\text{Compton}})$$

EoS $\epsilon = (d_g + \xi d_q)\dfrac{\pi^2}{30}T^4$

Is delayed QGP formation OK for explaining hadron data?

Yes, because

1) QGP is formed before hadrons freeze-out : particle yields, v2/n scaling..
2) Before QGP formation, dynamical EoS e=e(P) remains approximately the same, no matter the value of quark fugacity.

Dilepton Emission Rate

$$\frac{dN_{l^+l^-}}{d\omega d^3p} = C_{em}\frac{\alpha_{em}^2}{6\pi^3}\frac{\rho_V(\omega,\vec{p},T)}{(\omega^2-\vec{p}^2)(e^{\omega/T}-1)}$$

H. T. Ding, et al. Phys. Rev. D 83, 034504 (2011).

$r_V(w,\vec{p},T)$ **vector spectra function when p=0.**

$$\frac{dR_{q\bar{q}\to ee}}{d^4q} = \frac{\alpha^2}{4\pi^4} f^B(q_0;T)\left(\sum e_q^2\right)\left(1+\frac{2T}{q}\ln\left[\frac{1+x_+}{1+x_-}\right]+2\pi\alpha_s\frac{T^2}{M^2}KF\left(M^2\right)\ln\left(1+\frac{2.912}{4\pi\alpha_s}\frac{q_0}{T}\right)\right)$$

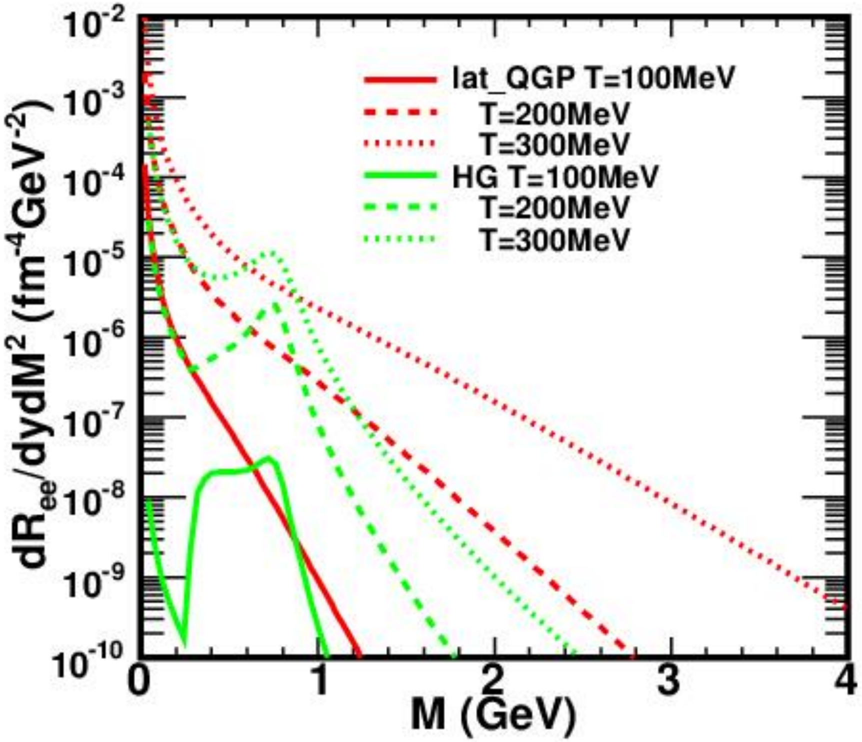
R. Rapp, Adv.High Energy Phys. 2013 (2013) 148253, arXiv:1304.2309.

$$\frac{d^4R_V}{d^4q} = -\frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\frac{m_V^4}{g_v^2}\left[\frac{\mathrm{Im}\,D_V^R}{e^{\frac{q_0}{T}}-1}\right]$$

J. I. Kapusta and C. Gale (2006)

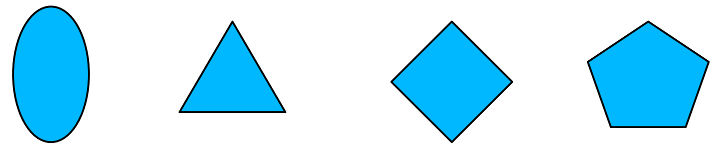
V. L. Eletsky, et al. Phys. Rev. C 64, 035202 (2001).

G. Vujanovic, et al. Phys. Rev. C 89 (2014) 034904.



Spectrum, v2, v3, v4 ...

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + \sum_n 2v_n \cos n(\phi - \psi_n)\right]$$



- In E-b-E case, ψ_n vary with event, pt and PID.

  However, it is easy to show $\langle \cos n\phi \rangle = v_n \cos n\psi_n$

  $$\langle \sin n\phi \rangle = v_n \sin n\psi_n$$

  $\langle \cdots \rangle$: average over all particles in each event

- So we can get $v_n = \sqrt{\langle \cos n\phi \rangle^2 + \langle \sin n\phi \rangle^2}$

  ψ_n

- Then take event average.