



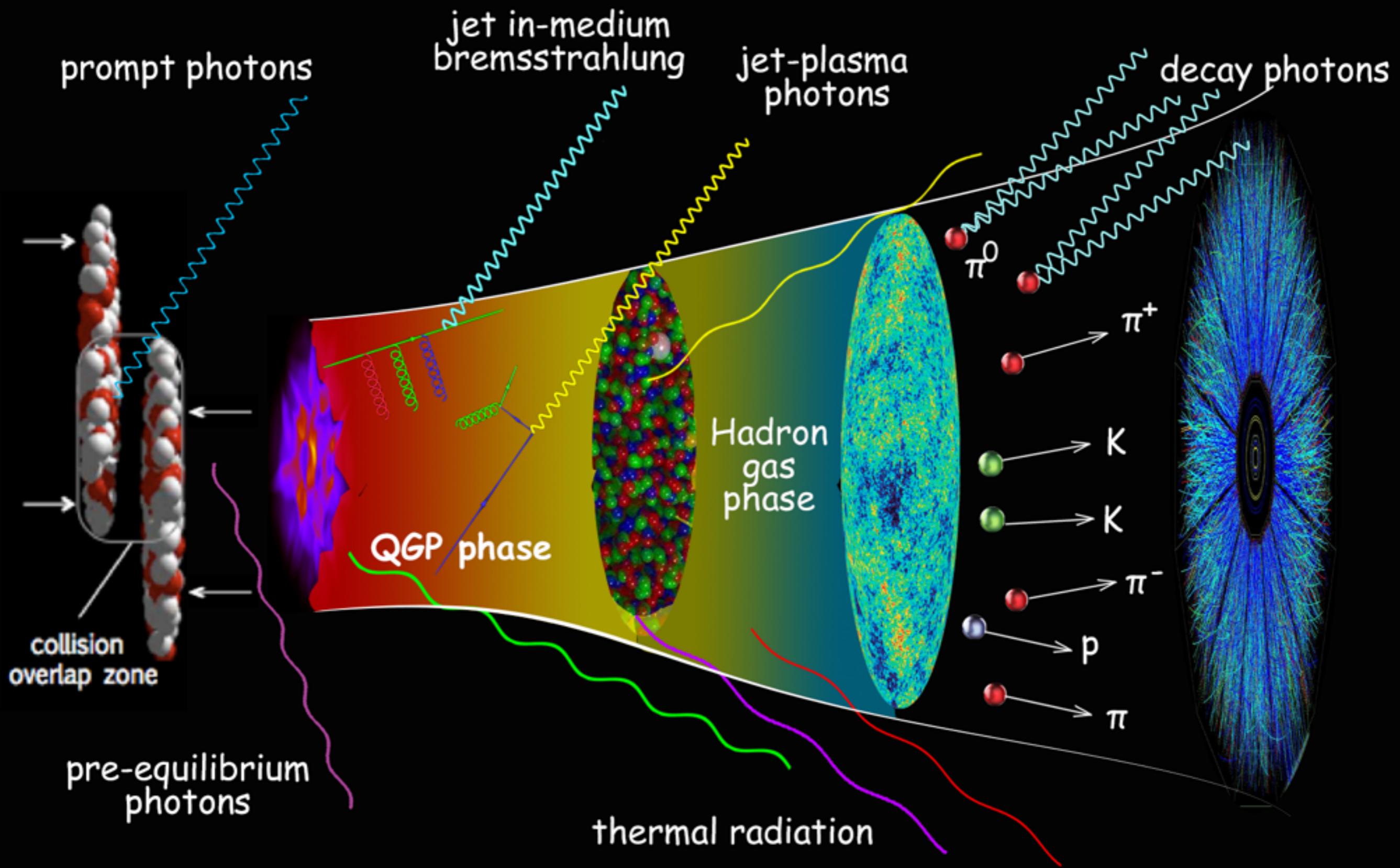
McGill

Theory Overview of Electromagnetic Radiation from QCD Matter

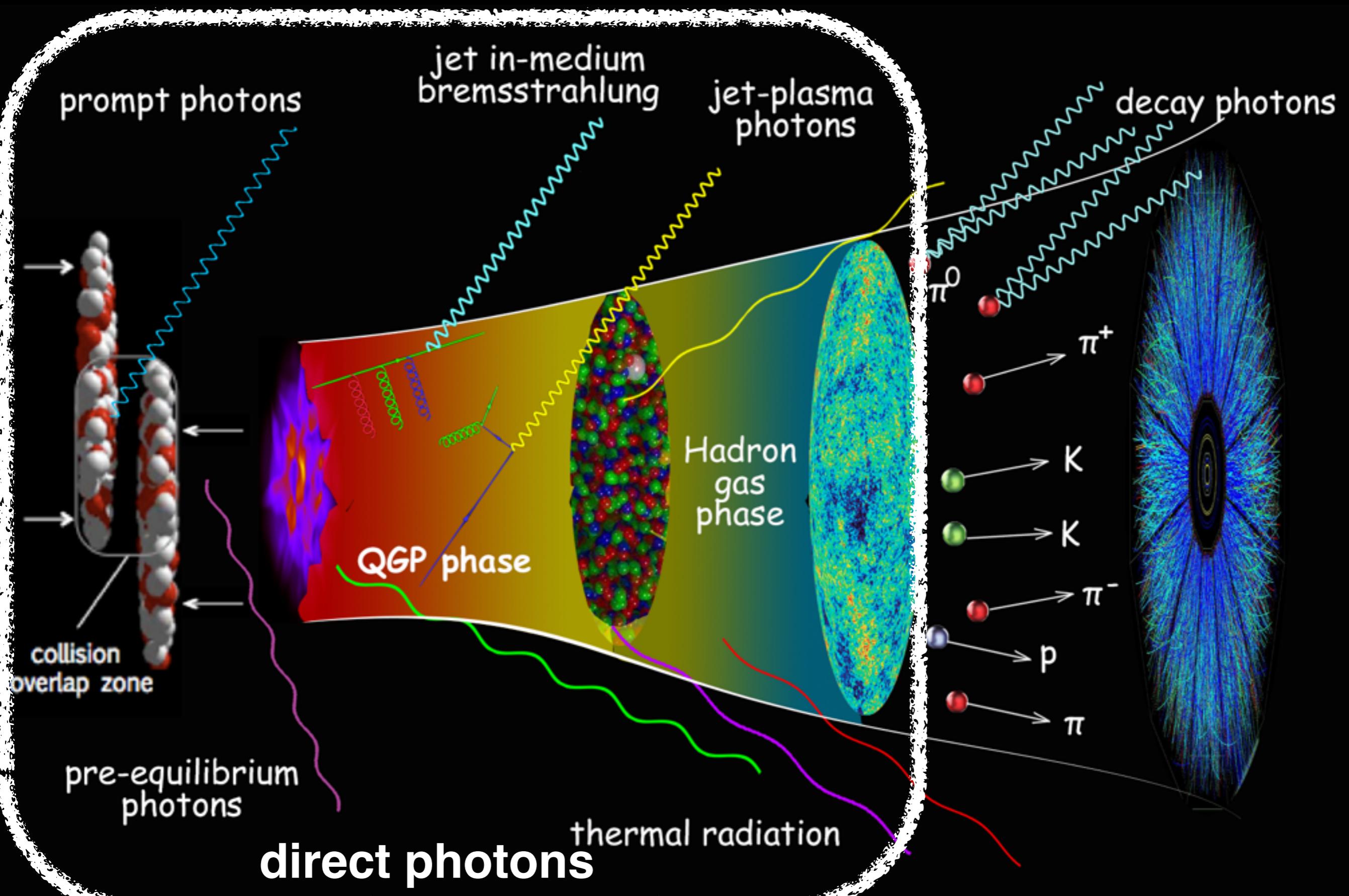
Chun Shen
McGill University



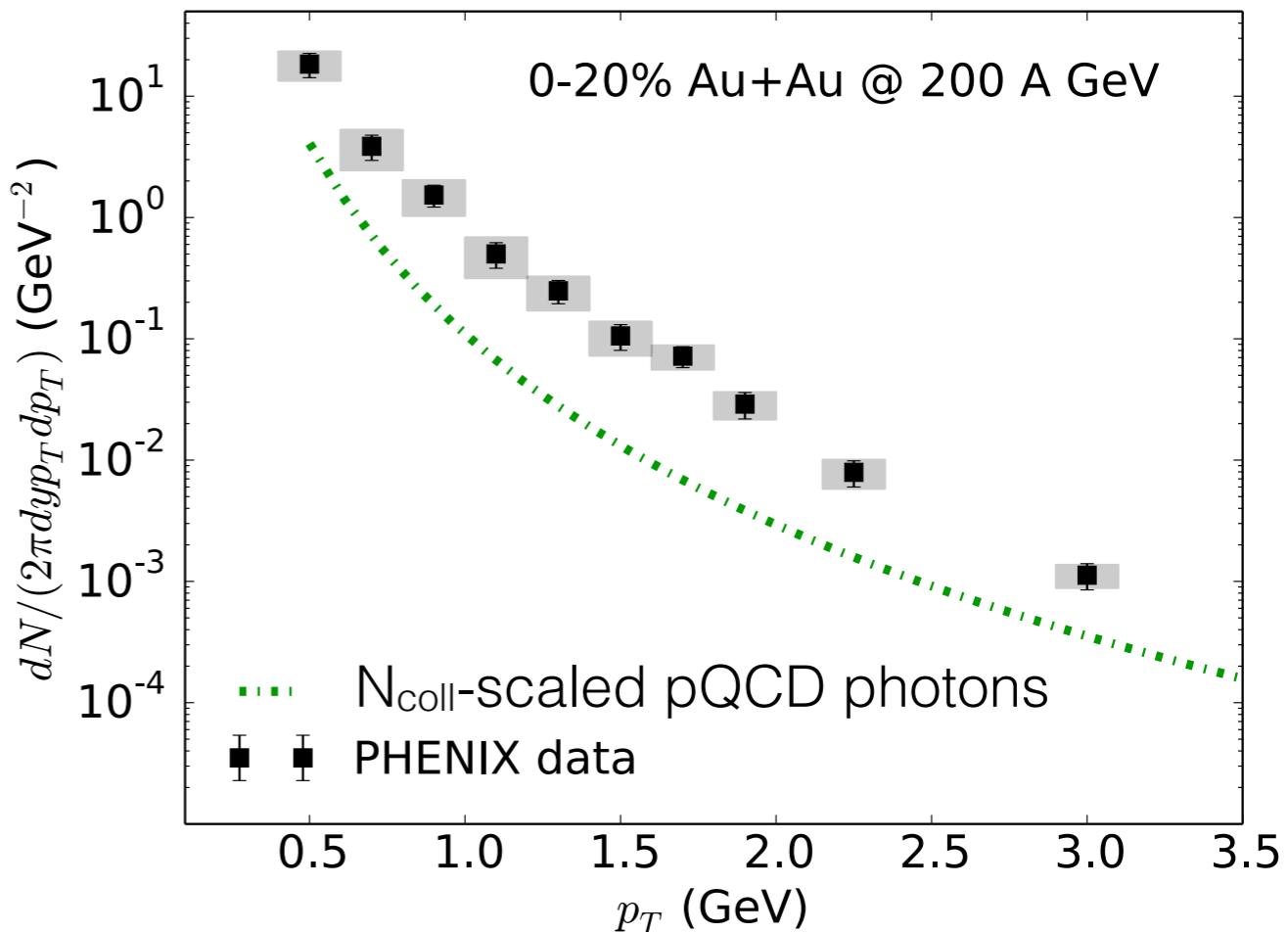
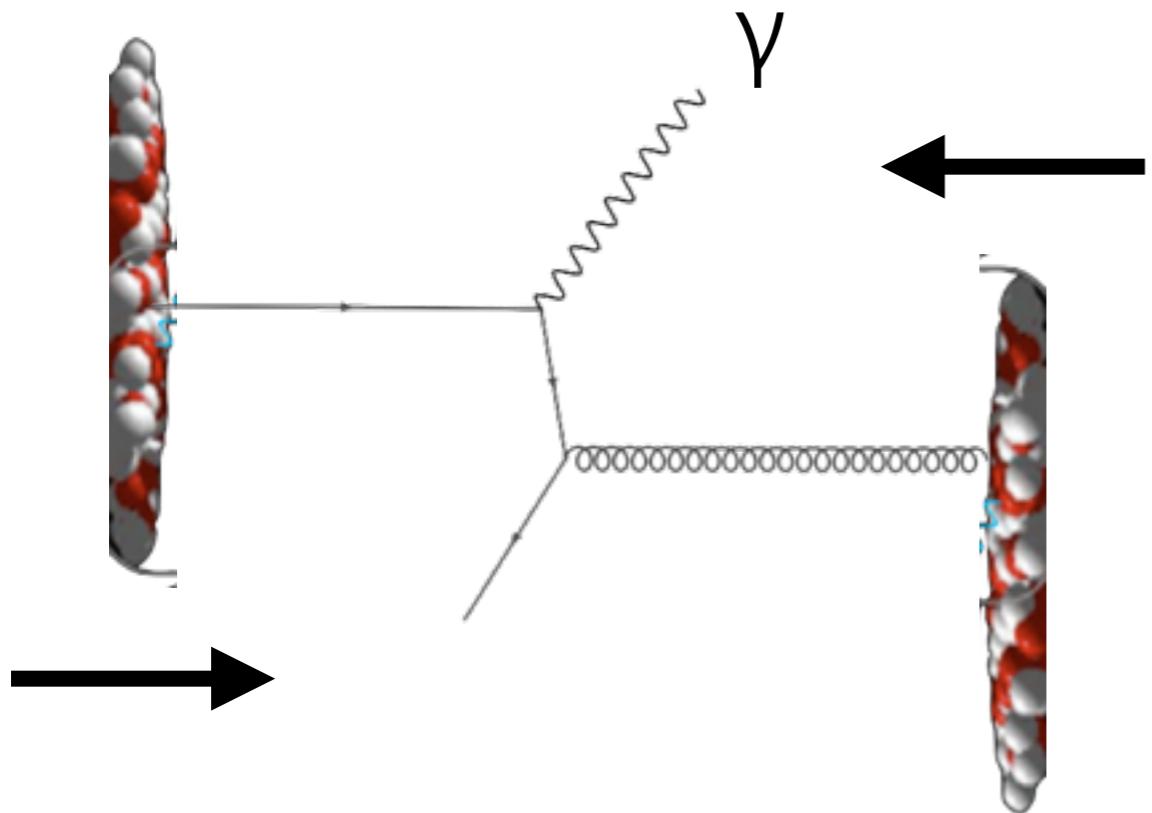
Relativistic Heavy-ion Collisions



Relativistic Heavy-ion Collisions



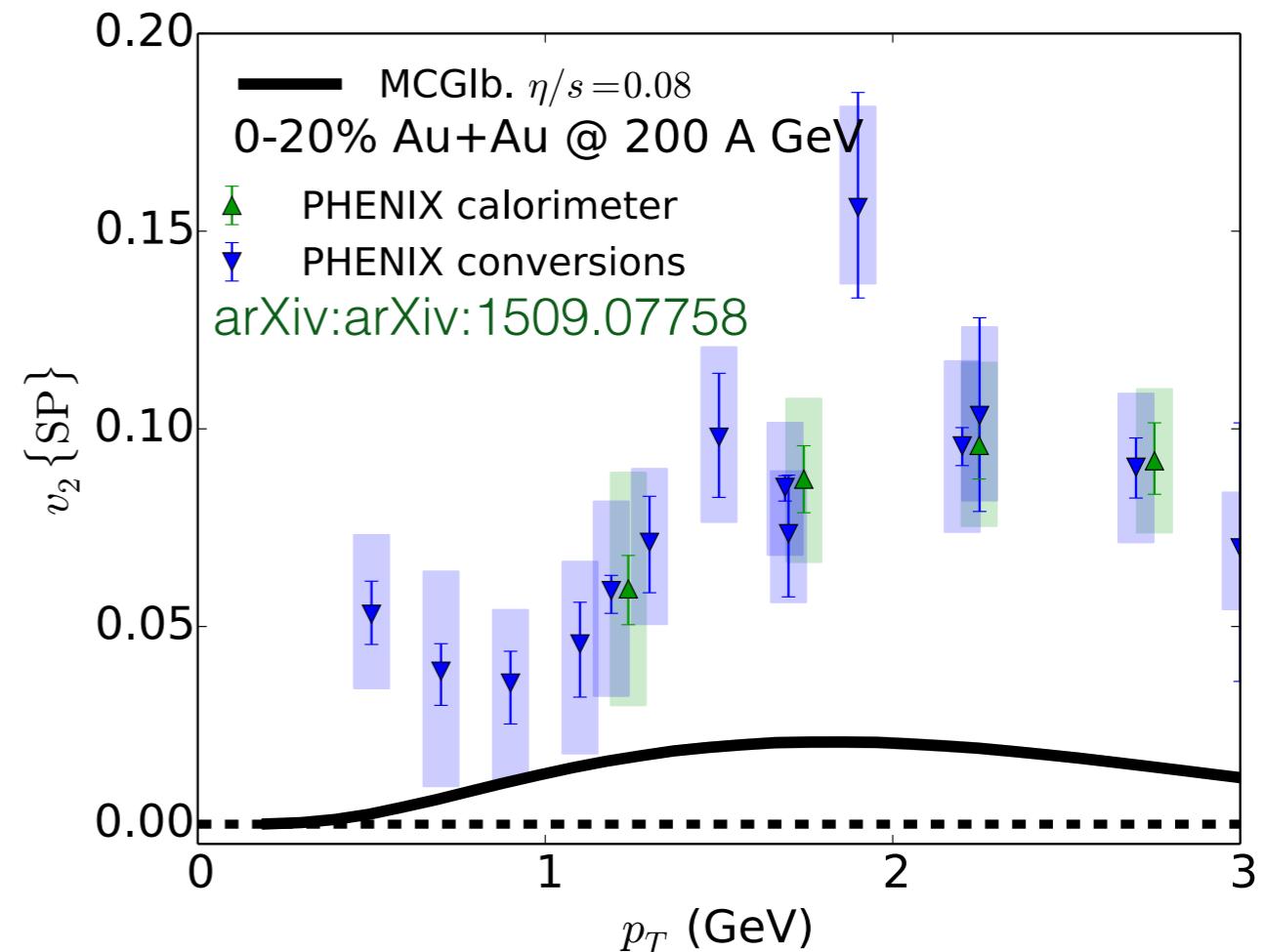
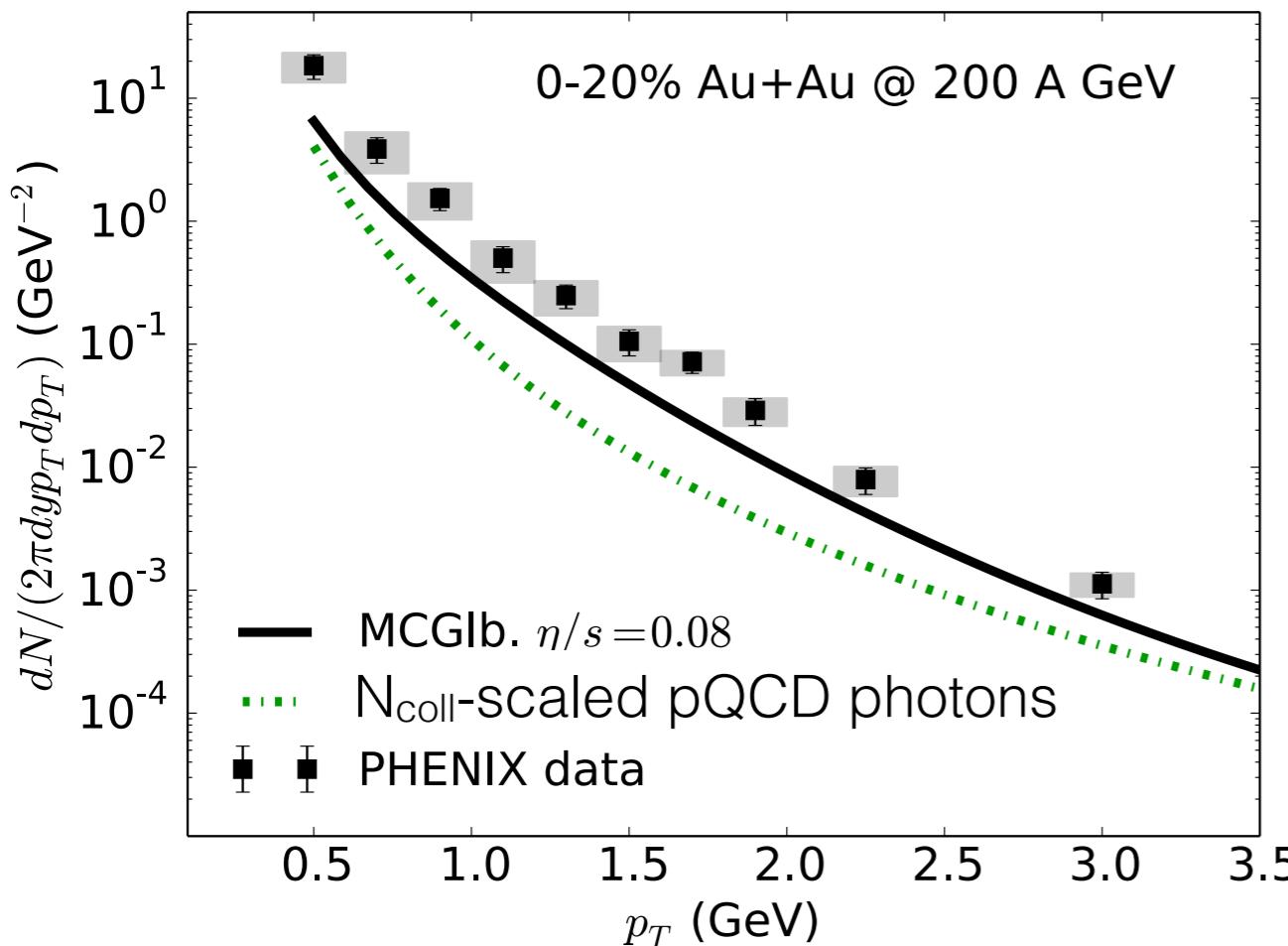
Direct photons



- Large excess of direct photons over the prompt background (N_{coll} -scaled pQCD results) in AA collisions

Model-data comp. as of last QM

C. Shen, U. Heinz, J. -F. Paquet, I. Kozlov, and C. Gale, Phys. Rev. C **91**, 024908 (2015)

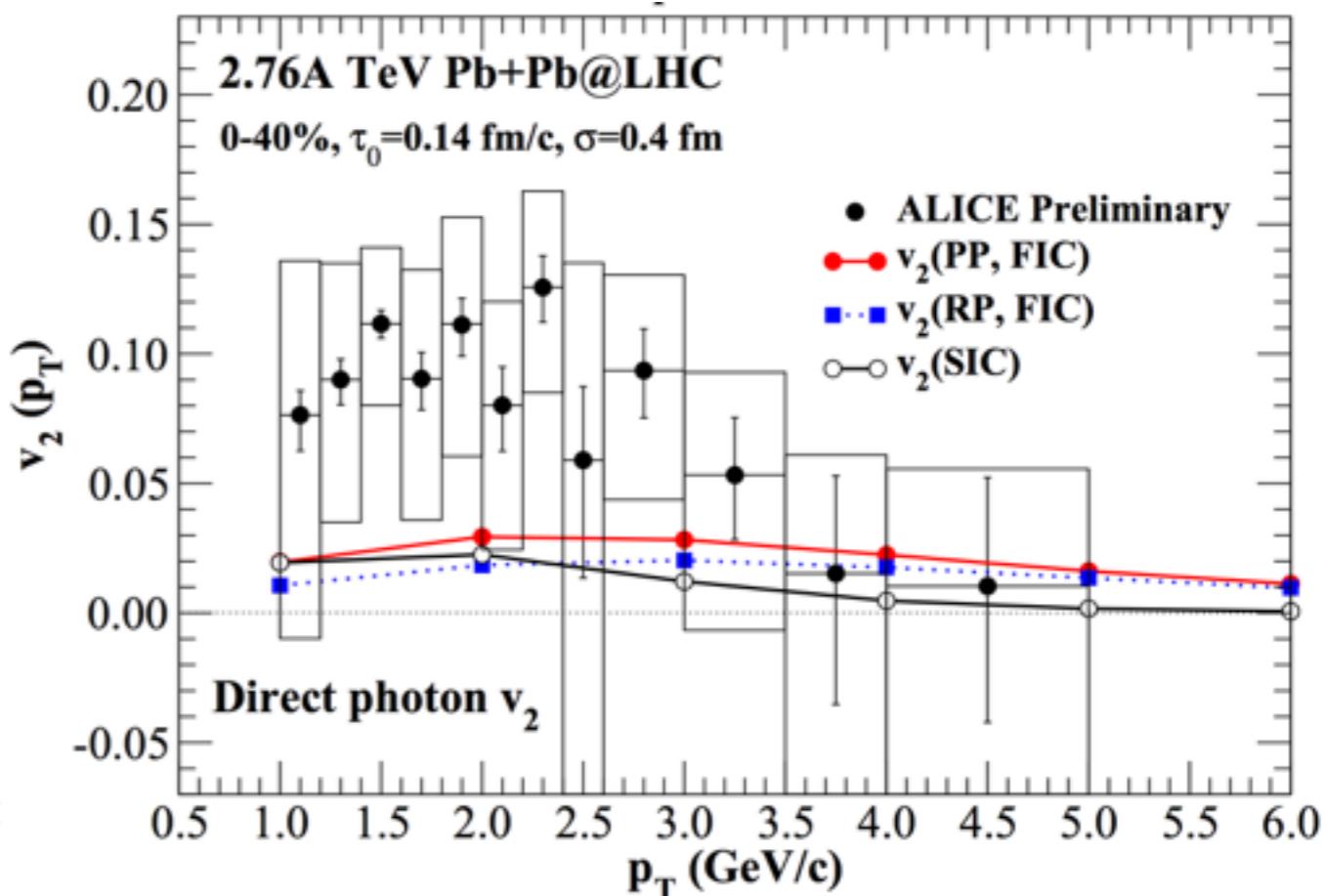
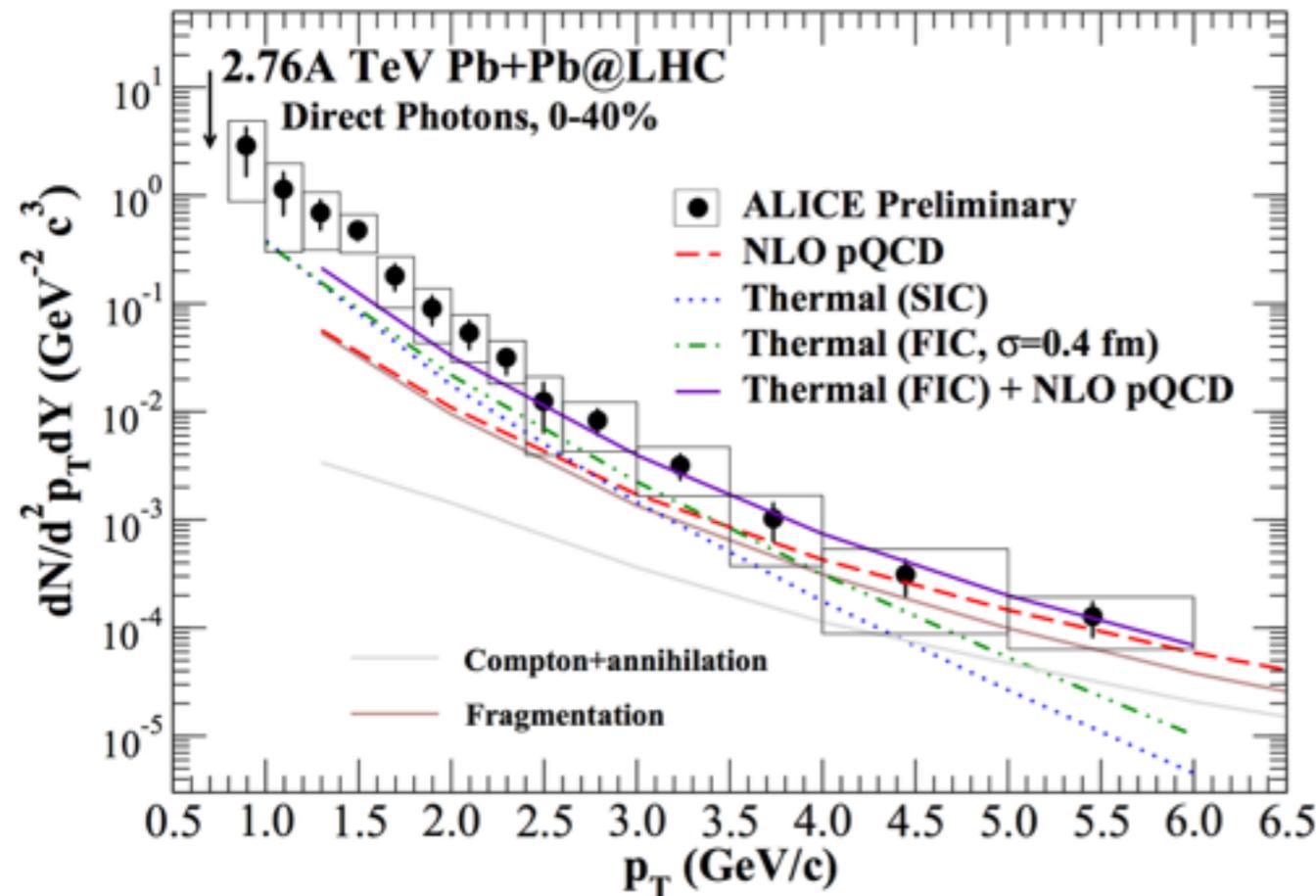


- Previous hydrodynamical calculation **underestimated** the direct photon observables at RHIC



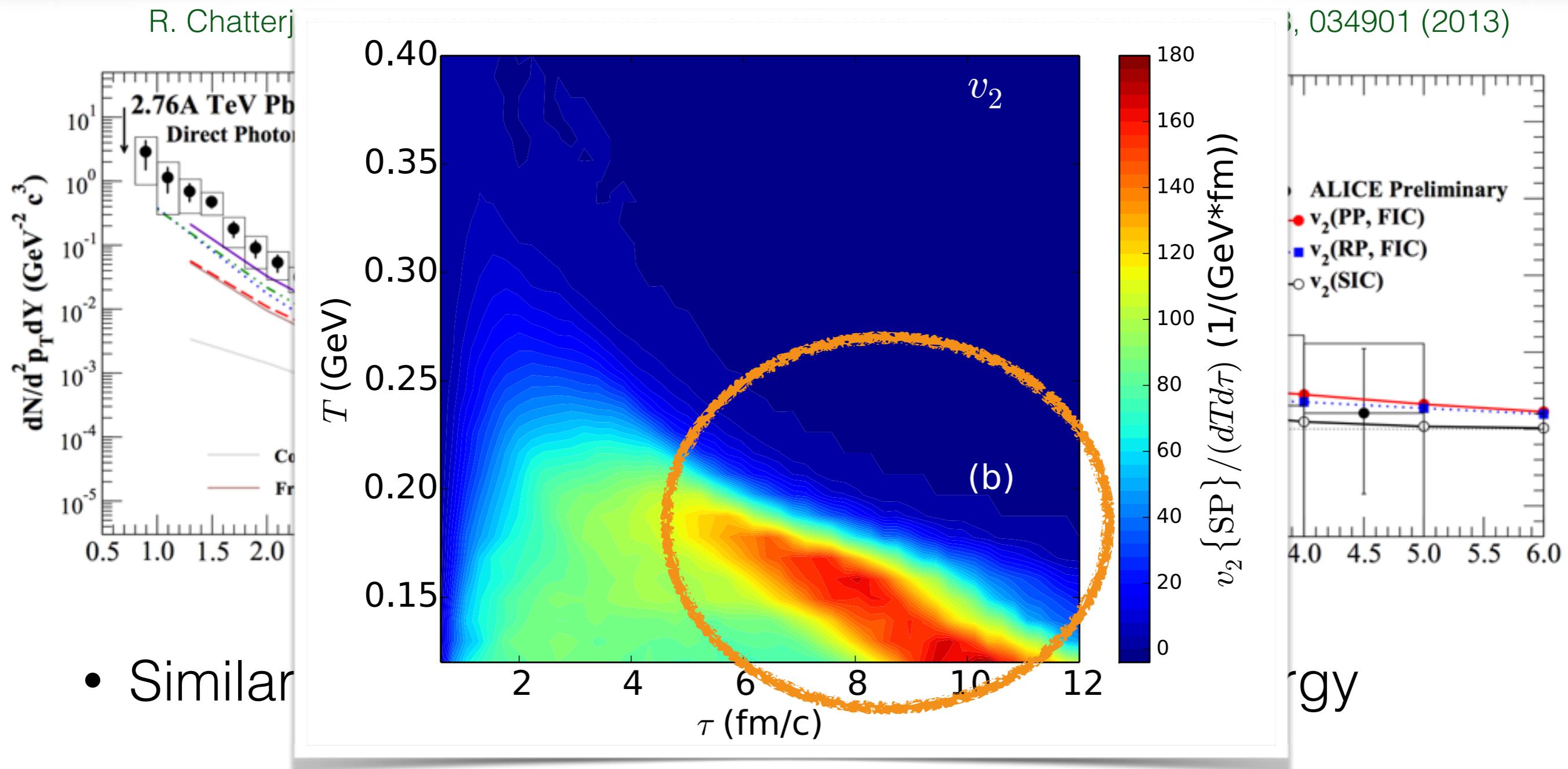
Model-data comp. as of last QM

R. Chatterjee, H. Holopainen, I. Helenius, T. Renk and K. J. Eskola, Phys. Rev. C **88**, 034901 (2013)



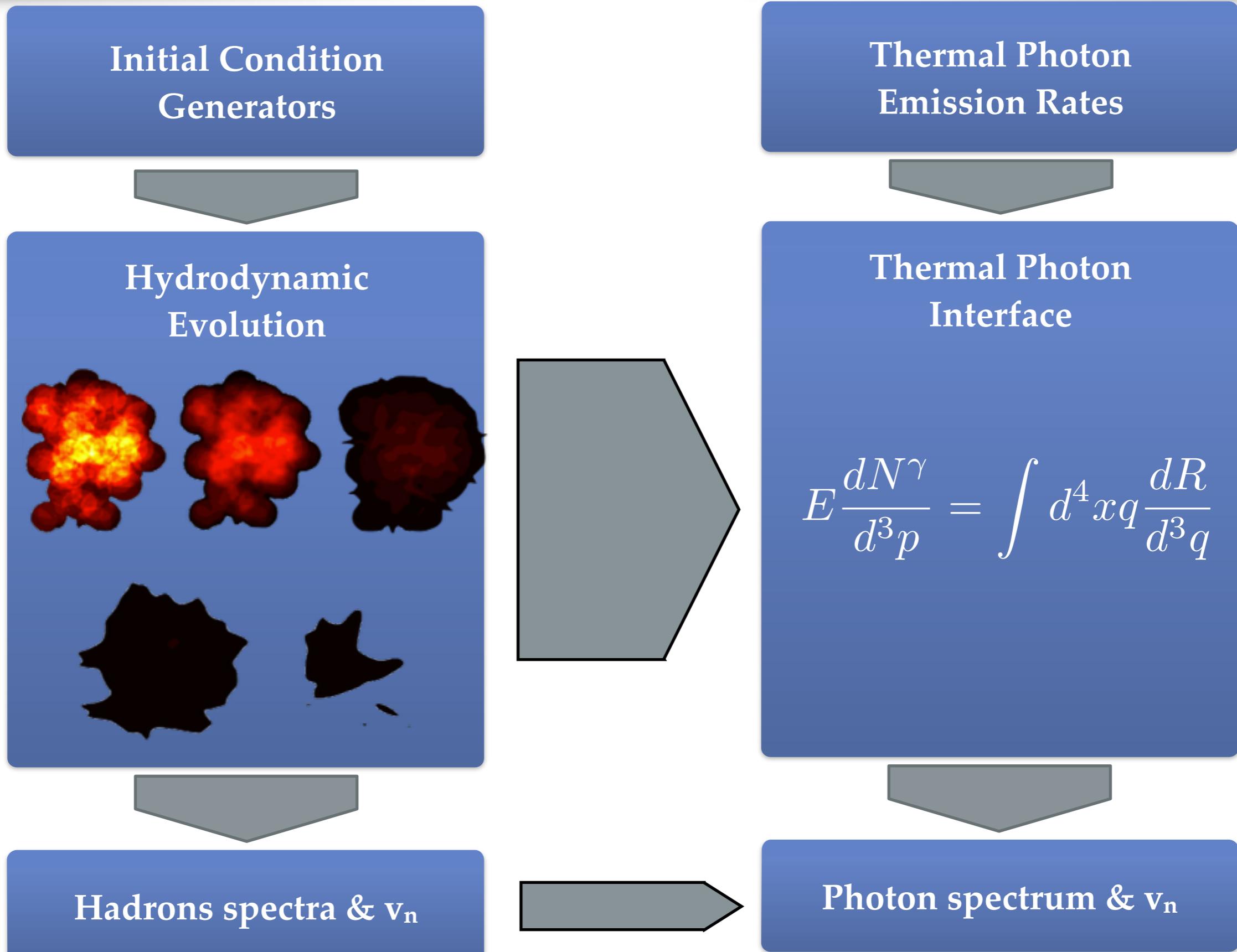
- Similar tension with data observed at LHC energy

Model-data comp. as of last QM

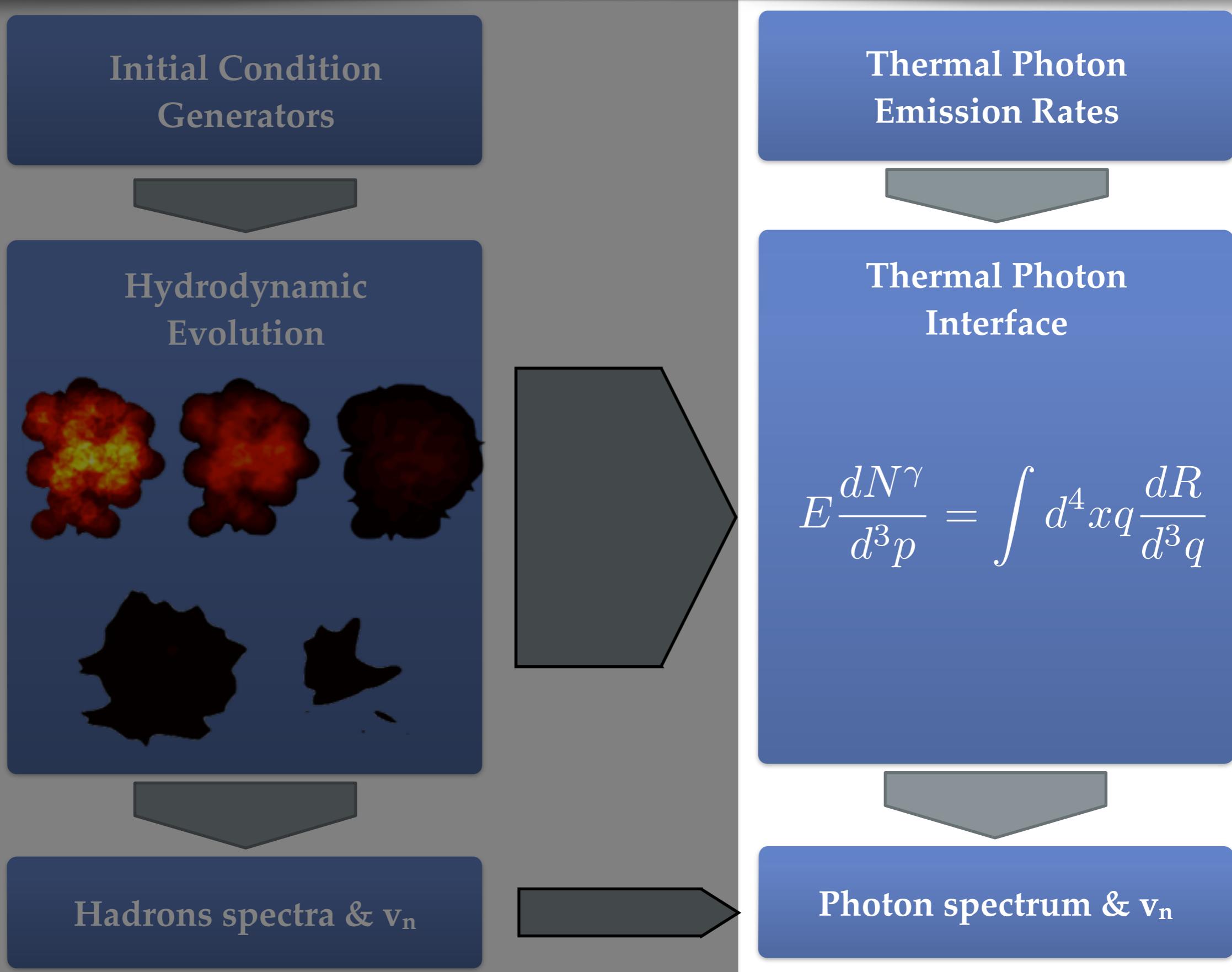


Data favor more late stage photon emission

Framework of modelling direct photons



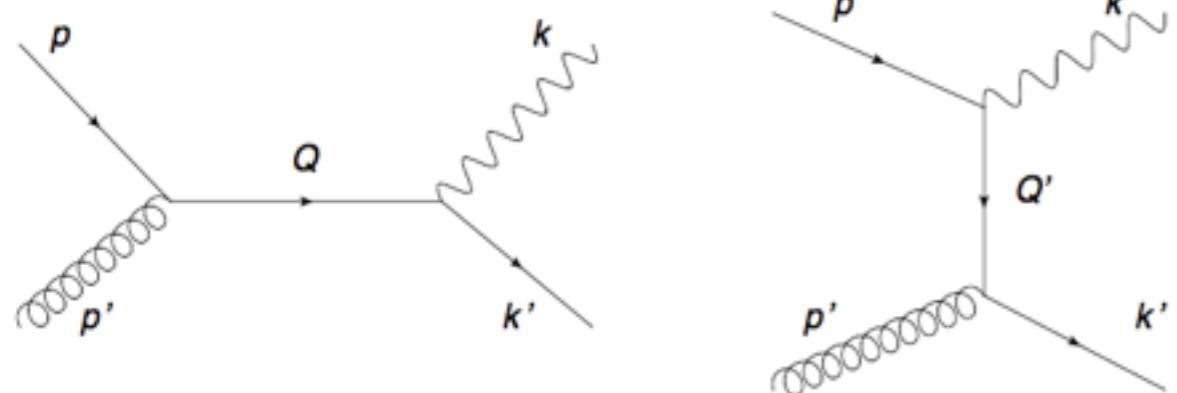
Framework of modelling direct photons



Photon emission rate

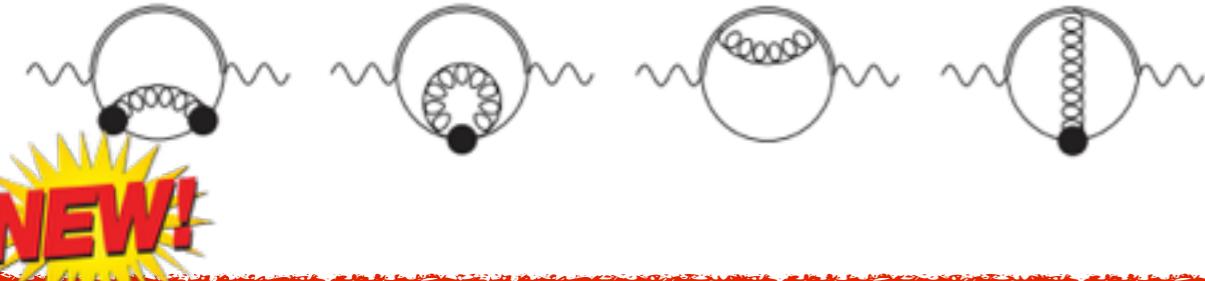
QGP

LO: AMY JHEP **0112**, 009, (2001)



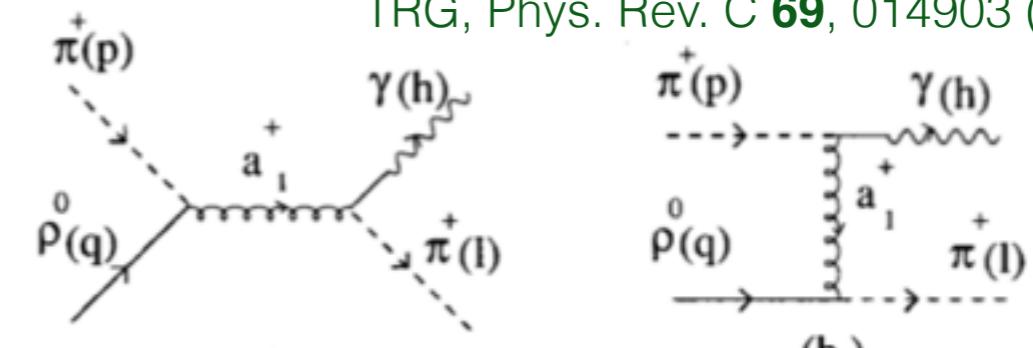
$$\text{Re} \left(\left[\begin{array}{c} \text{gluons} \\ \text{quarks} \end{array} \right] \left| \begin{array}{c} \text{gluons} \\ \text{quarks} \end{array} \right. \right)$$

NLO: J. Ghiglieri *et al.*, JHEP **1305**, 010 (2013)



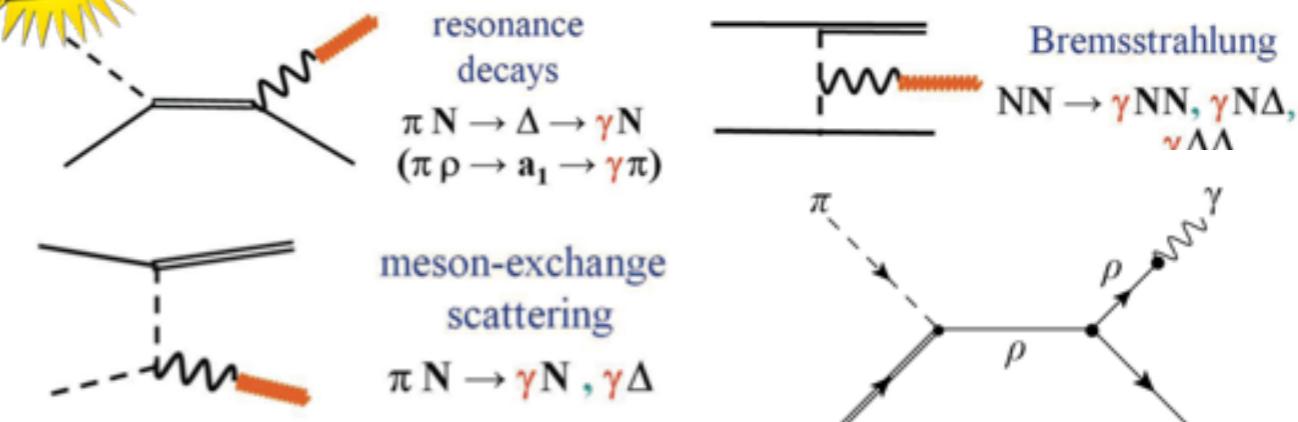
Hadron Gas

TRG, Phys. Rev. C **69**, 014903 (2004)



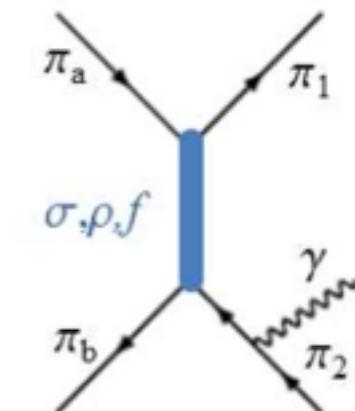
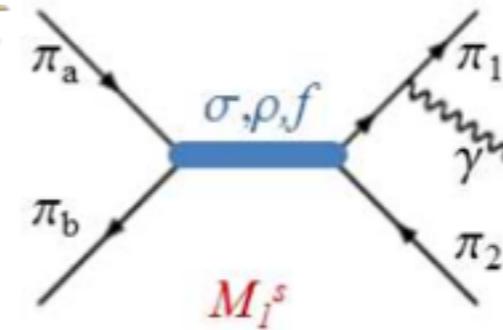
R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999)
(Heffernan, Hohler, Rapp 2015)

NEW!



W. Liu and R. Rapp, Nucl. Phys. A **796**, 101 (2007)
O. Linnyk, *et al.*, arXiv:1504.05699 [nucl-th]

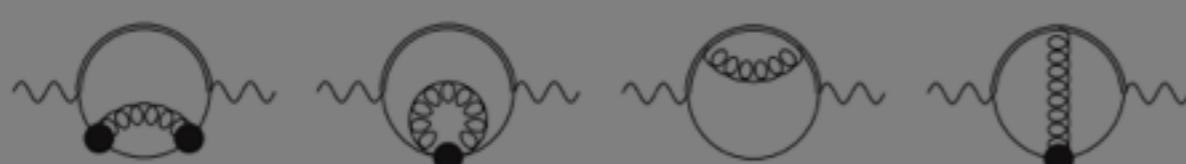
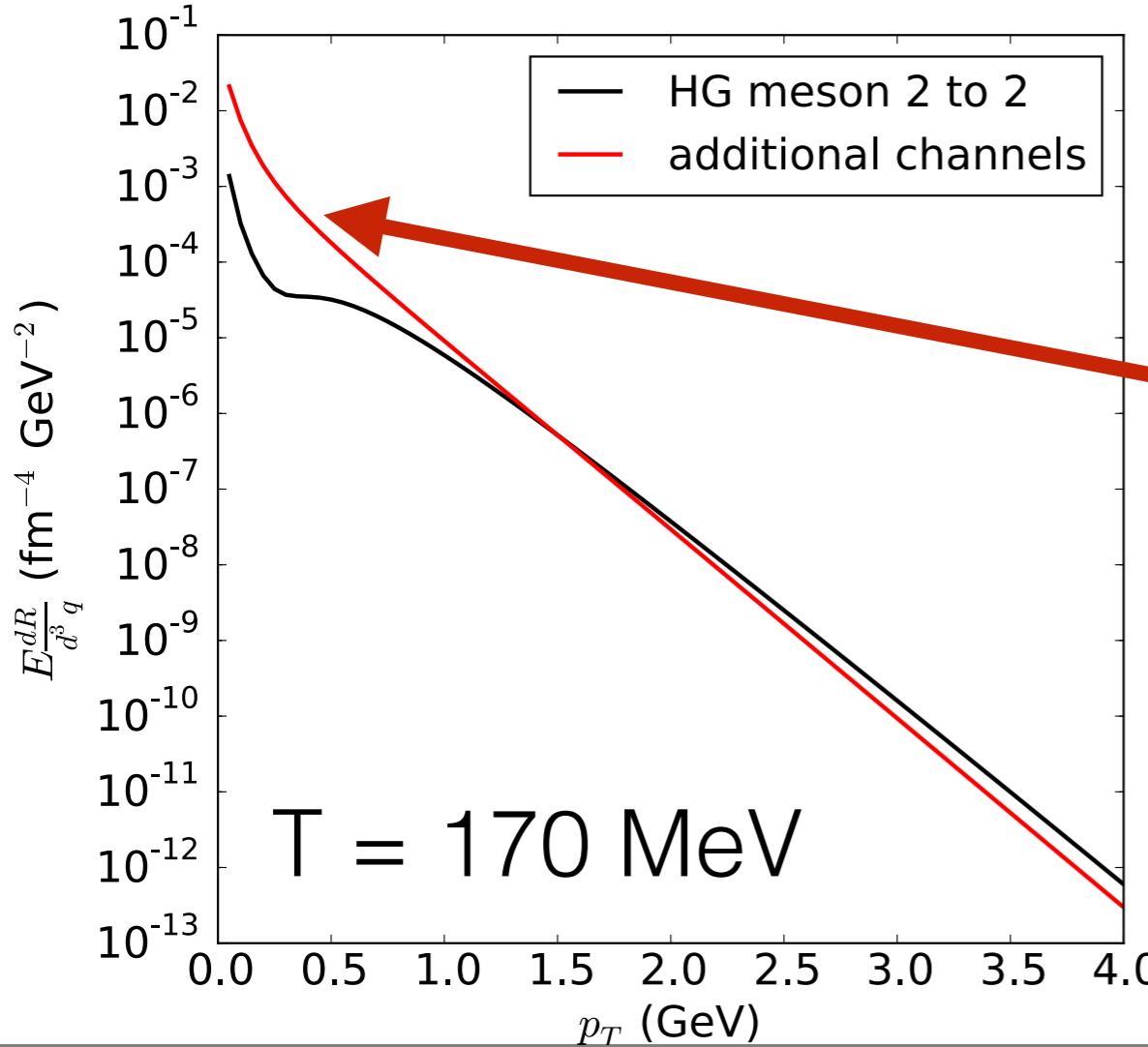
NEW!



Photon emission rate

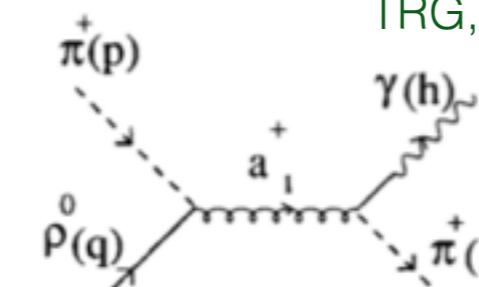
QGP

LO: AMY JHEP **0112**, 009, (2001)



Hadron Gas

TRG, Phys. Rev. C **69**, 014903 (2004)

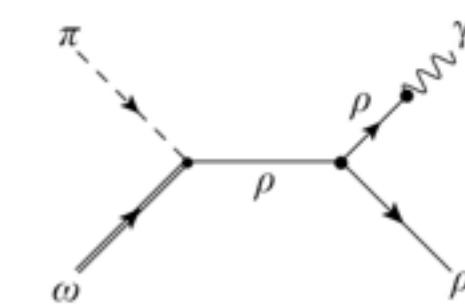
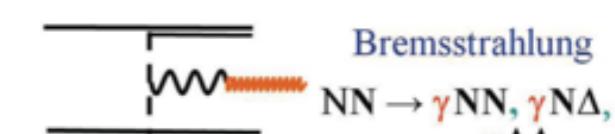


(a)

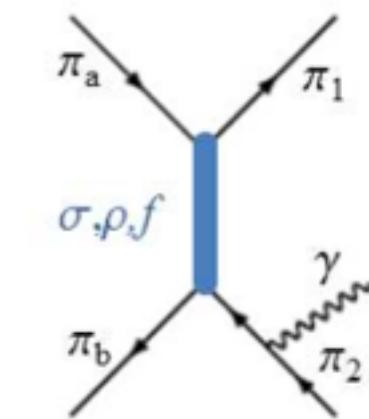
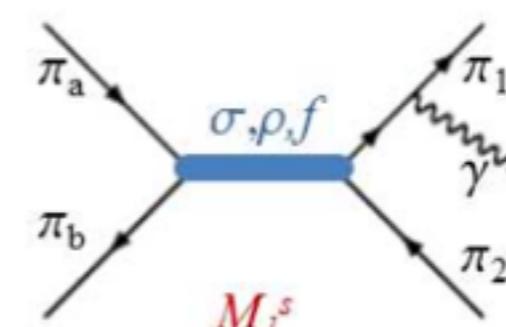
R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999)
resonance decays
 $\pi N \rightarrow \Delta \rightarrow \gamma N$
($\pi \rho \rightarrow a_1 \rightarrow \gamma \pi$)



meson-exchange scattering
 $\pi N \rightarrow \gamma N, \gamma \Delta$



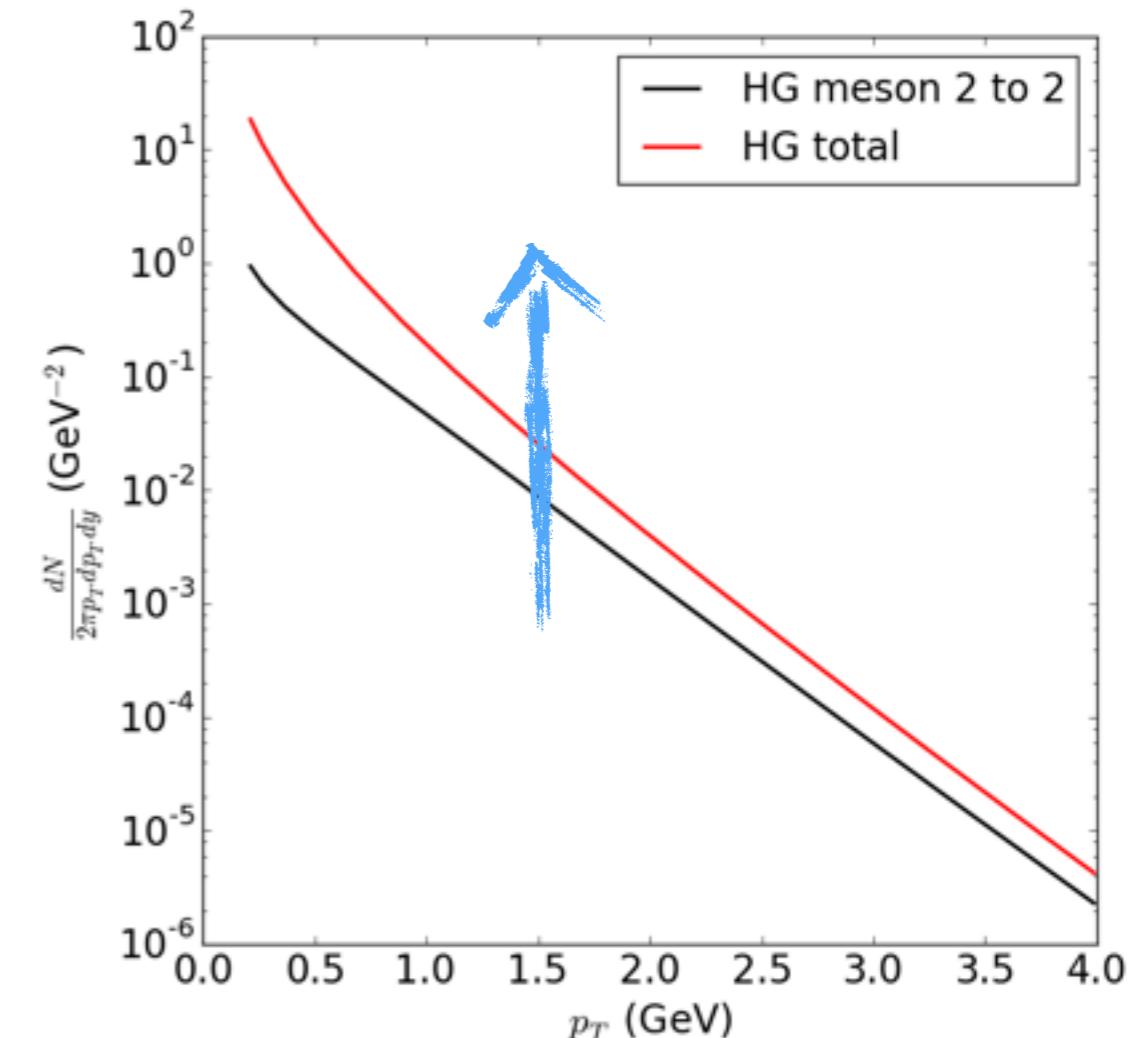
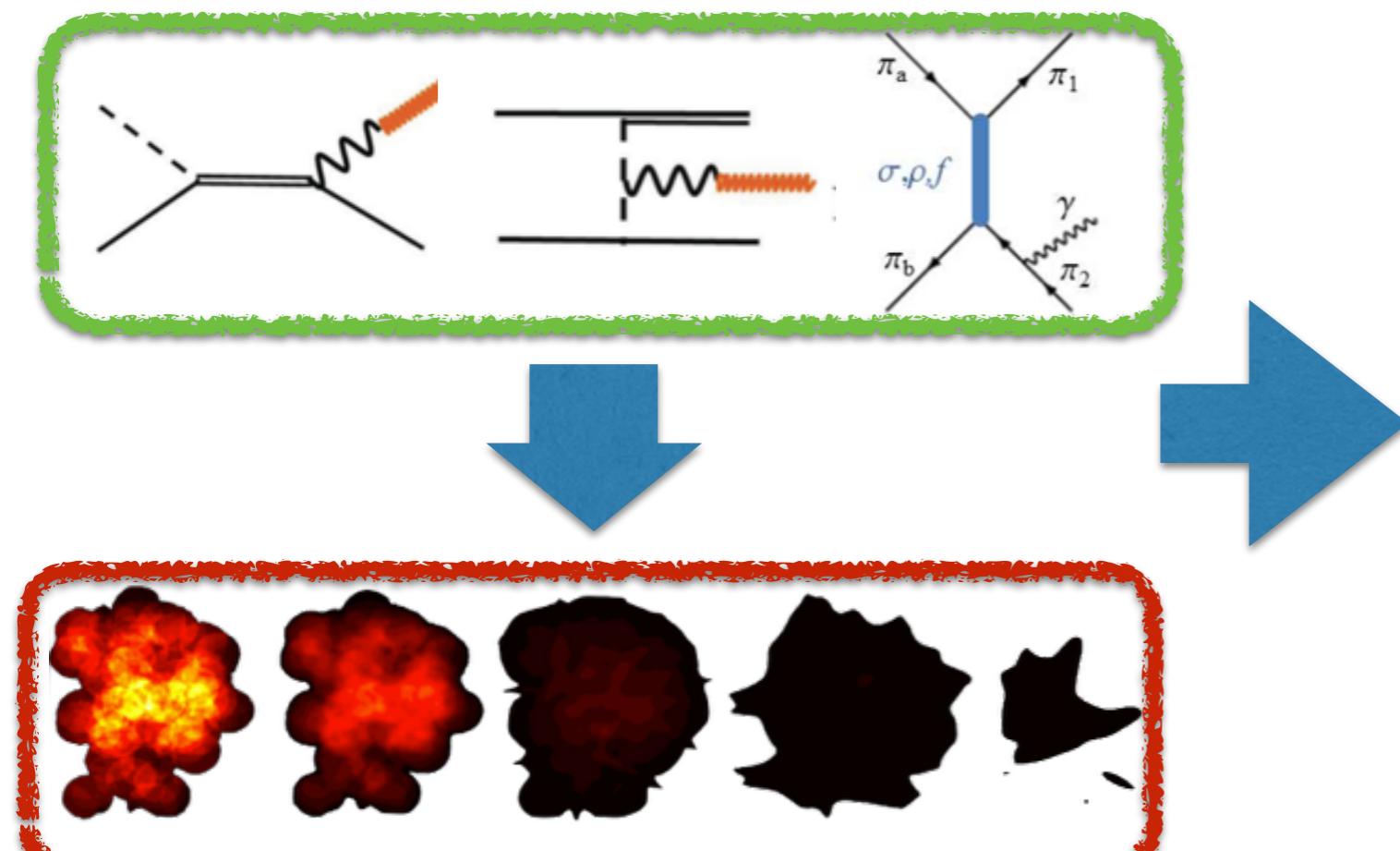
W. Liu and R. Rapp, Nucl. Phys. A **796**, 101 (2007)
O. Linnyk, et al., arXiv:1504.05699 [nucl-th]



(Heffernan, Hohler, Rapp 2015)

From photon emission rates to final spectra

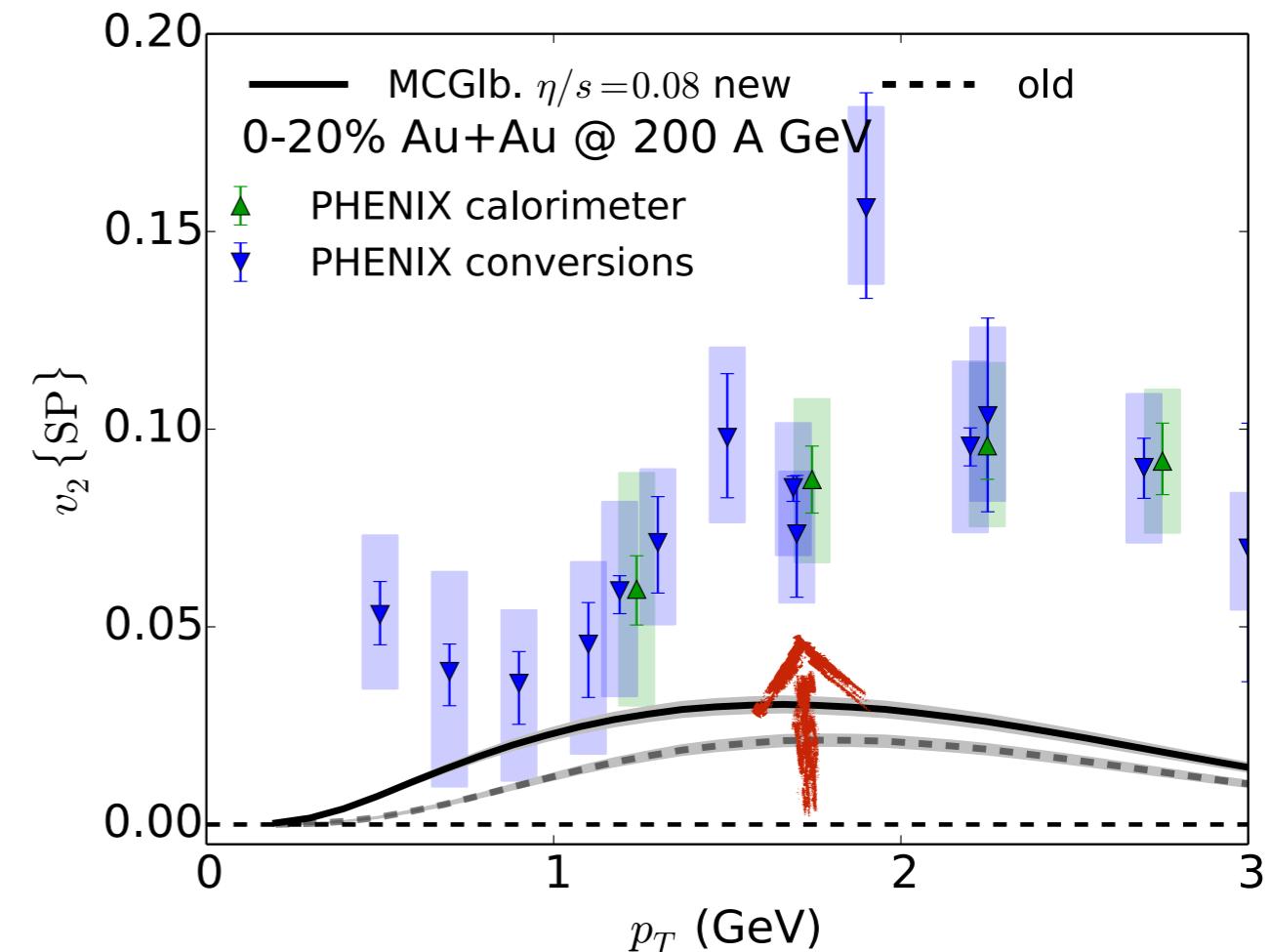
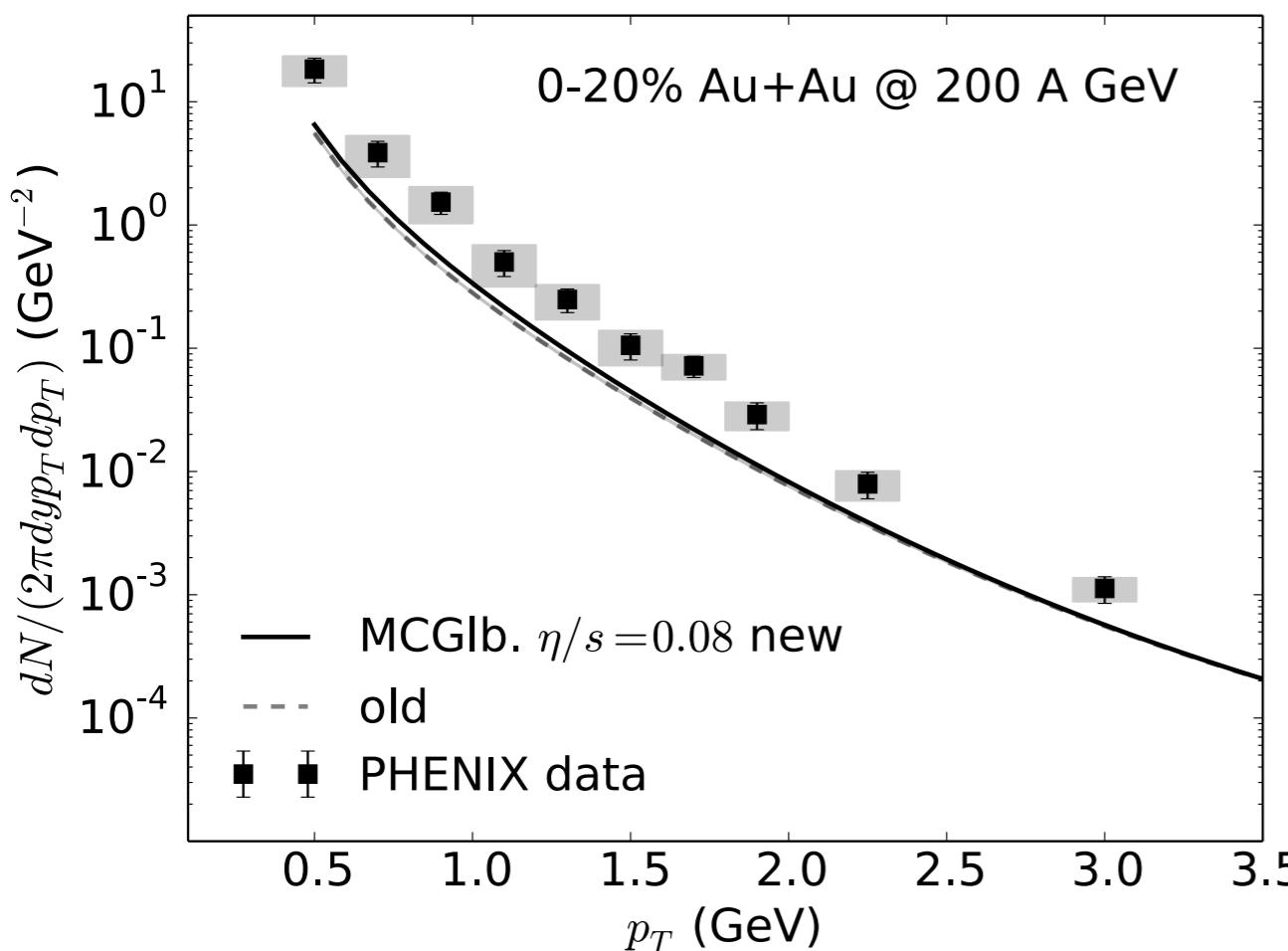
M. Heffernan, P. Hohler and R. Rapp, Phys. Rev. C **91**, 027902 (2015); arXiv:1506.09205



- Hydrodynamic radial flow increases hadronic thermal photon yield by a factor of 4

More hadronic photons with large anisotropy

Effect of updating the rates



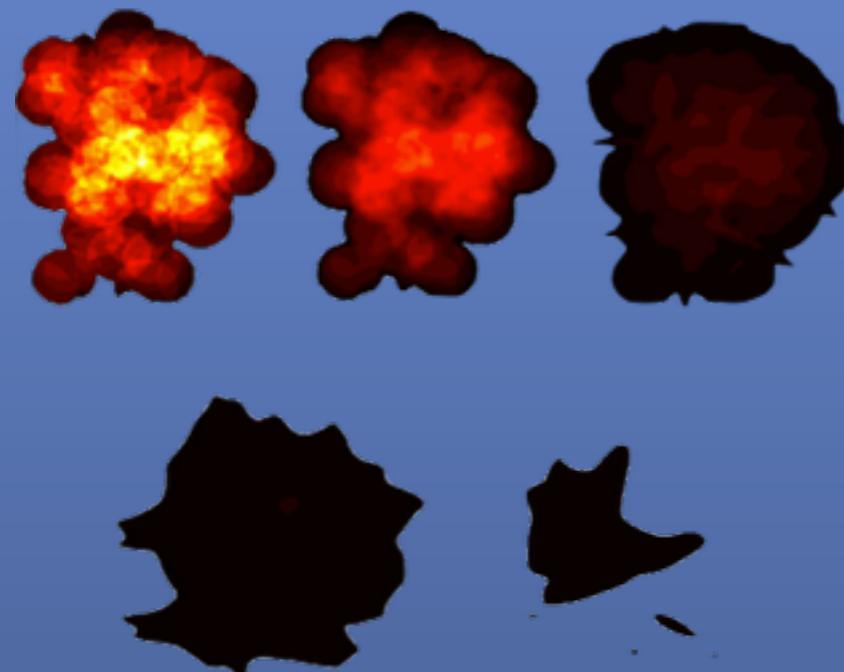
- The effect of additional emission channels:
 - direct photon **spectra** increased by ~20%
 - direct photon **v_2** increased by ~40%

More hadronic photons with large anisotropy

Improving bulk evolution

Initial Condition
Generators

Hydrodynamic
Evolution



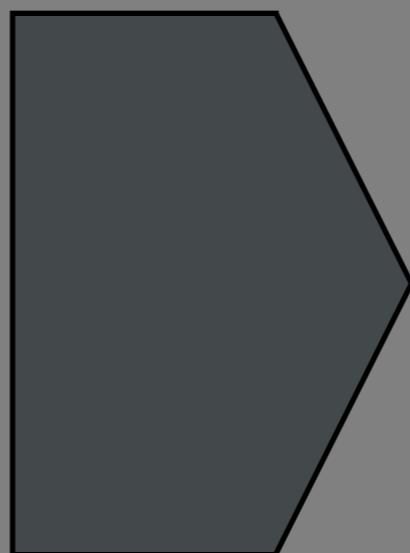
Hadrons spectra & v_n

Thermal Photon
Emission Rates

Thermal Photon
Interface

$$E \frac{dN^\gamma}{d^3 p} = \int d^4 x q \frac{dR}{d^3 q}$$

Photon spectrum & v_n



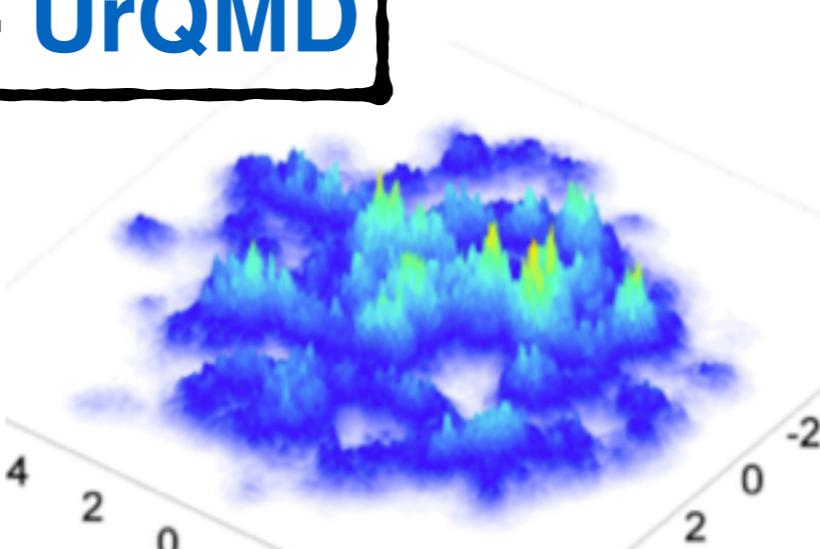
New developments in hydrodynamics

Ryu, Paquet, Shen, Denicol, Schenke, Jeon, and Gale, Phys.Rev.Lett. 115 (2015) 13, 132301

IP-Glasma + MUSIC + UrQMD

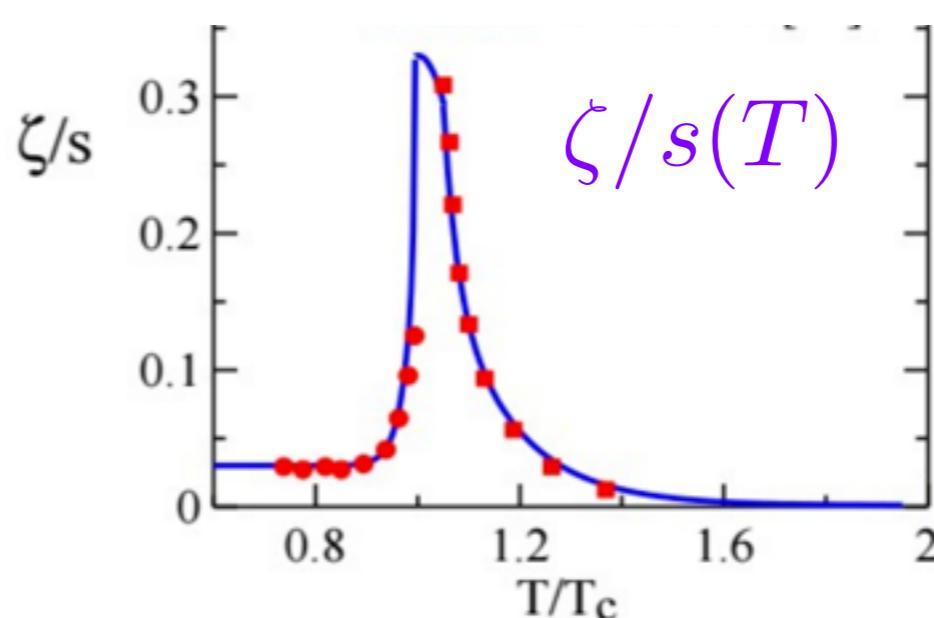
Poster: Ryu 0831

Paquet Wed 09:00



$$\begin{aligned} \tau_\pi \Delta_{\alpha\beta}^{\mu\nu} \dot{\pi^{\alpha\beta}} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} \\ &\quad - \delta_{\pi\pi}\pi^{\mu\nu}\theta - \tau_{\pi\pi}\Delta_{\alpha\beta}^{\mu\nu}\pi^{\alpha\lambda}\sigma_\lambda{}^\beta + \phi_7\Delta_{\alpha\beta}^{\mu\nu}\pi^{\alpha\lambda}\pi_\lambda{}^\beta \\ \tau_\Pi \dot{\Pi} + \Pi &= -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \end{aligned}$$

$$\eta/s = 0.095$$

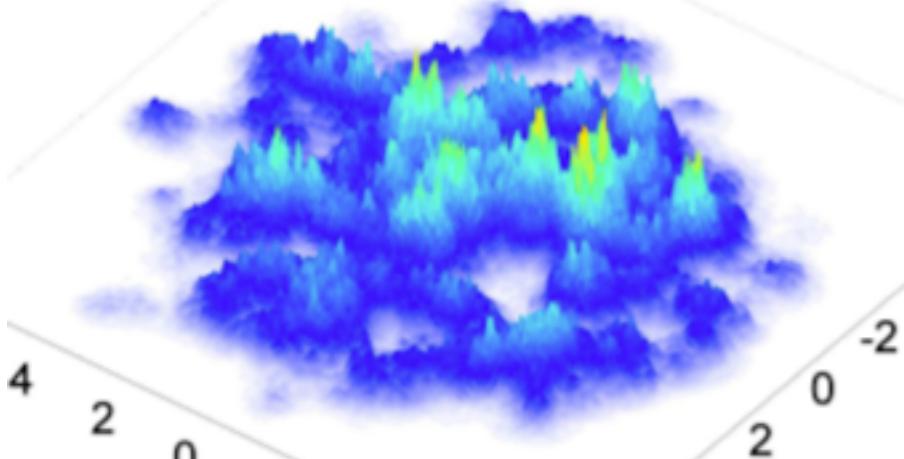


New developments in hydrodynamics

Ryu, Paquet, Shen, Denicol, Schenke, Jeon, and Gale, Phys.Rev.Lett. 115 (2015) 13, 132301

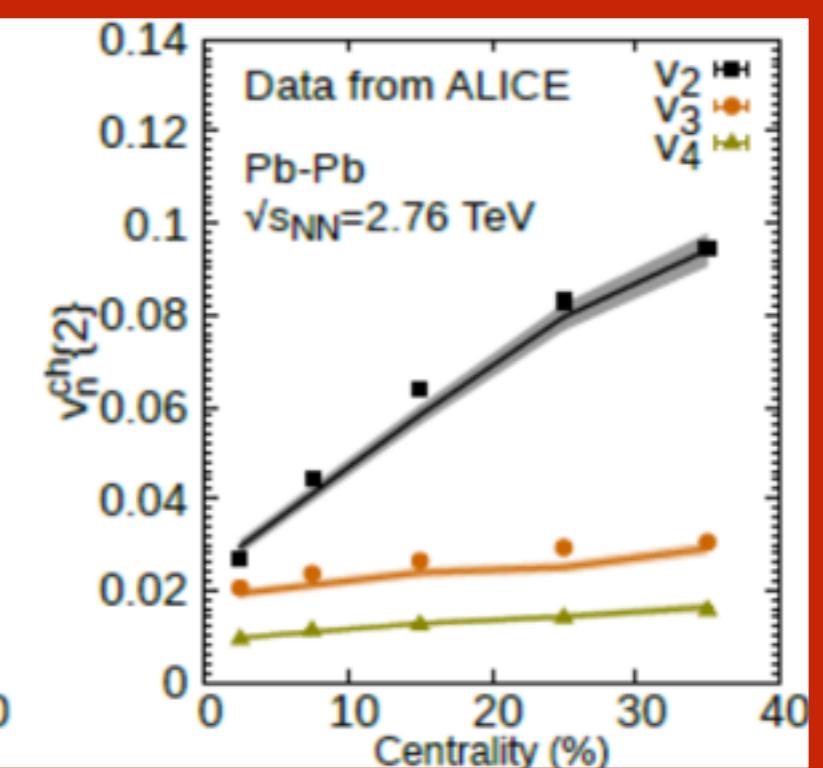
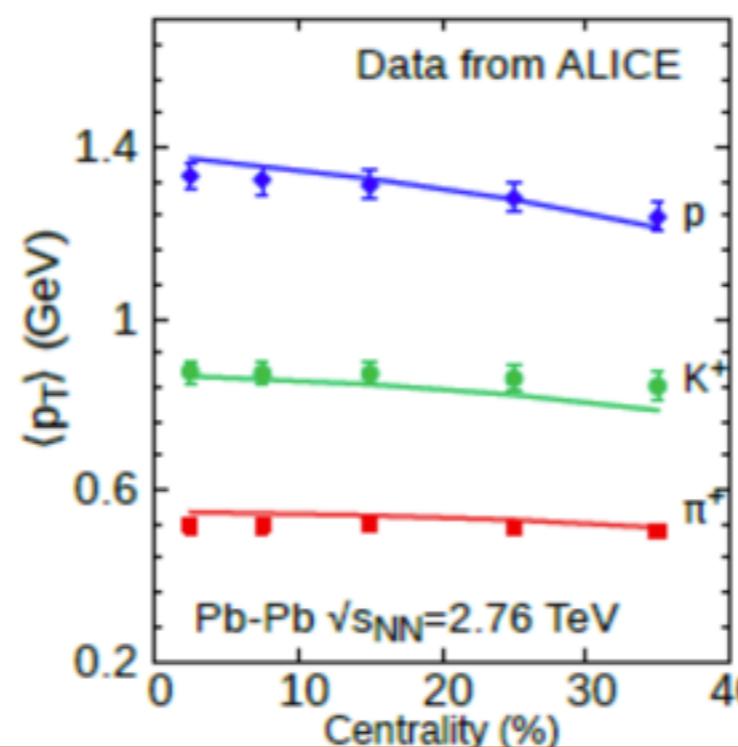
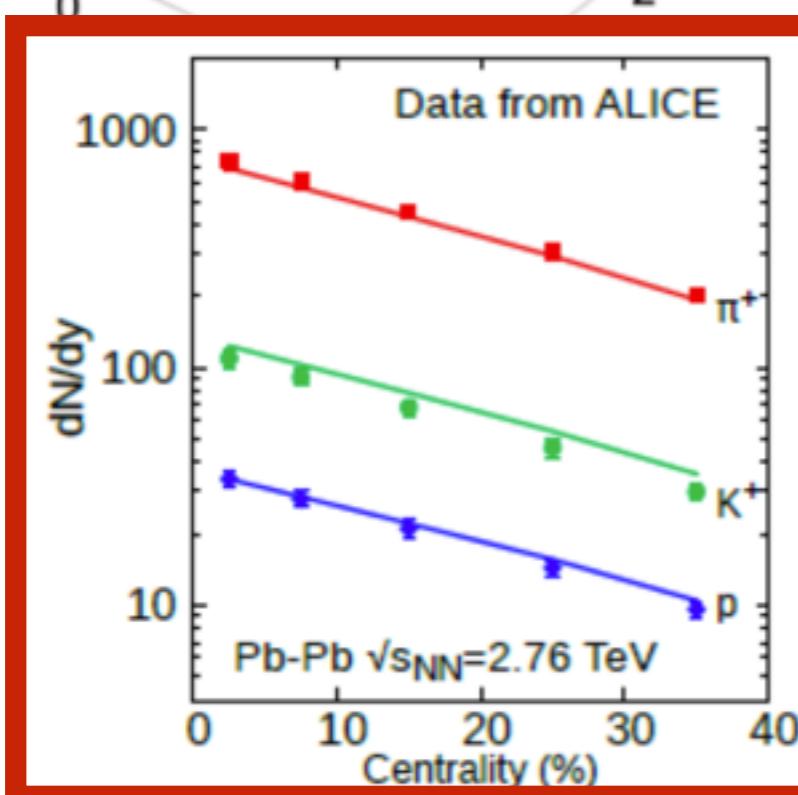
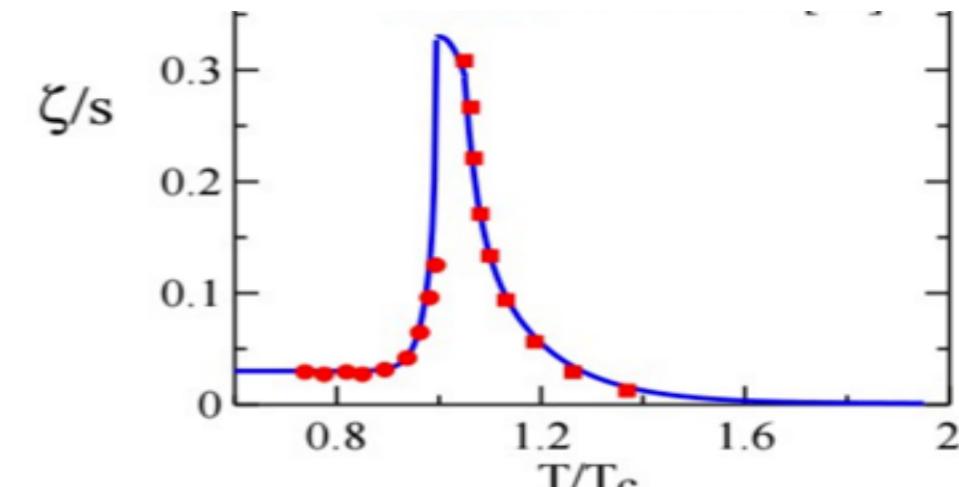
IP-Glasma + MUSIC + UrQMD

Paquet Wed 09:00 Poster: Ryu 0831



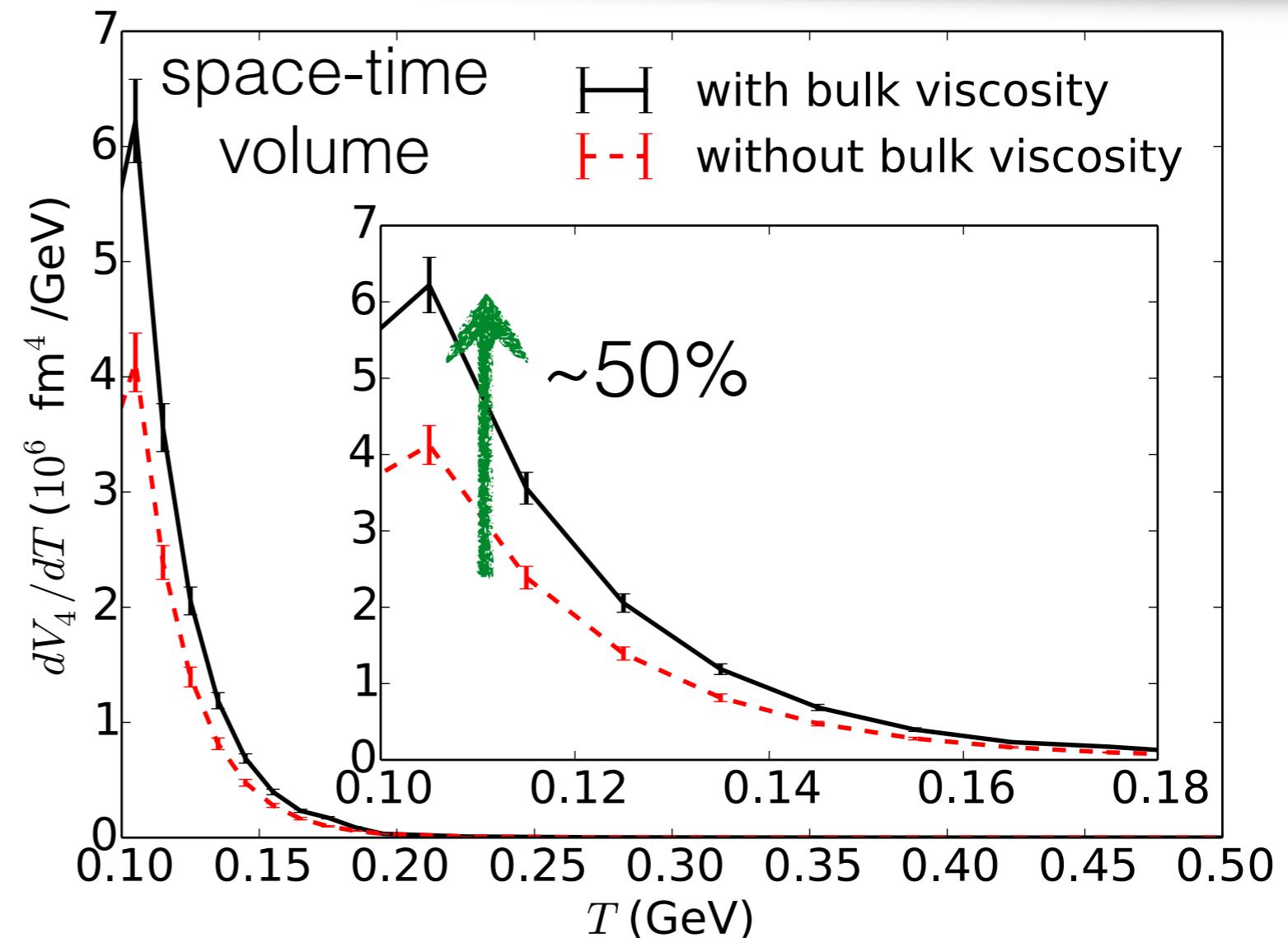
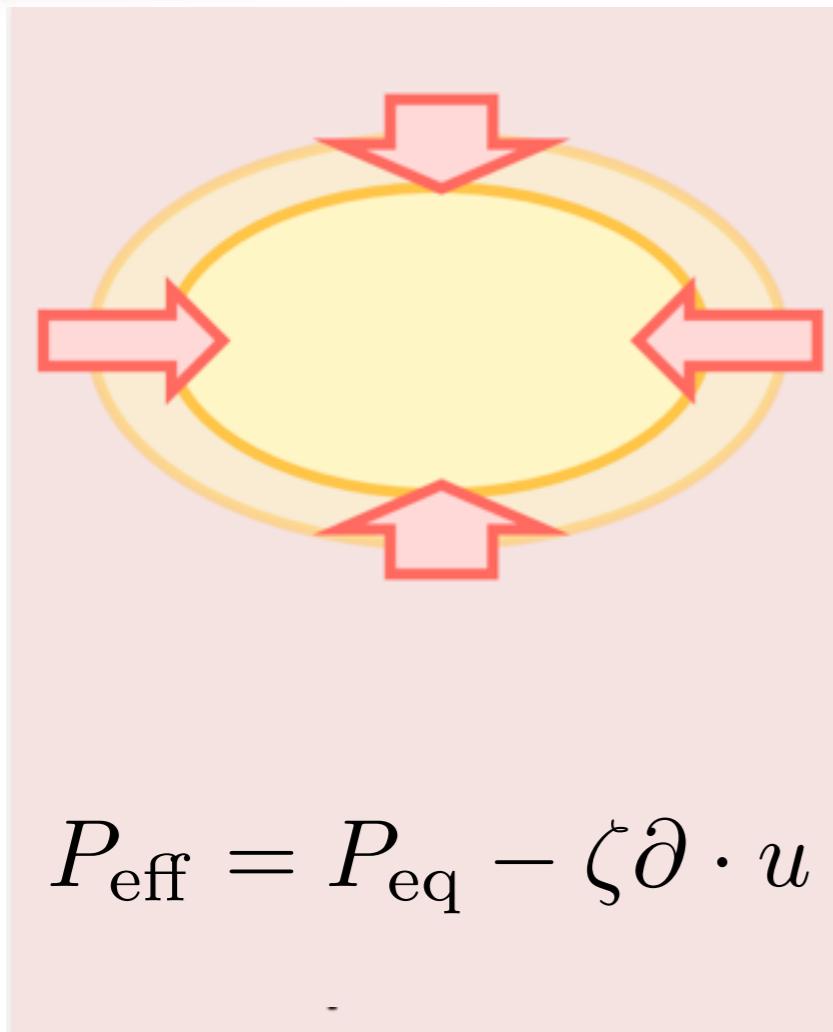
$$\eta/s = 0.095$$

$$\zeta/s(T)$$



- Excellent agreement with global hadronic observables
- Bulk viscosity is **essential**

Bulk viscous effects on space-time evolution

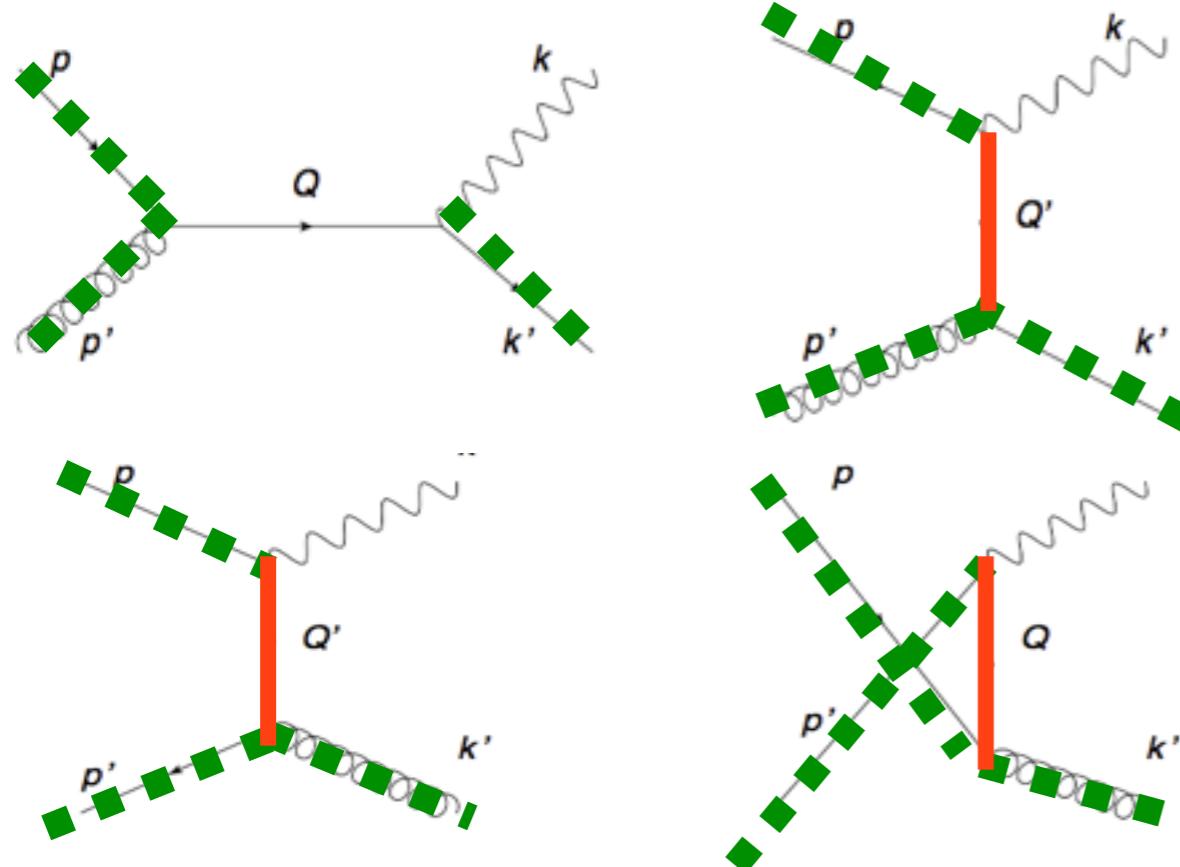


- Bulk viscosity reduces **radial flow** by $\sim 10\%$
→ less blue shift
 - Bulk viscosity increases **space-time volume** by $\sim 50\%$ in the hadronic phase
→ more hadronic photons
- More space-time volume in late stage evolution**

Viscous corrections to photon emission

QGP

C. Shen *et al.*, Phys. Rev. C **91**, 014908 (2015)



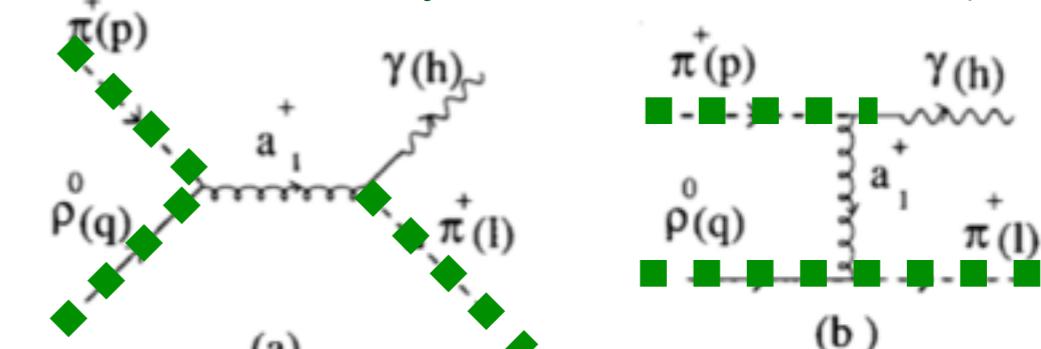
$$f = f_{\text{eq}} + \delta f$$

NLO: J. Ghiglieri *et al.*, JHEP **1305**, 010 (2013)

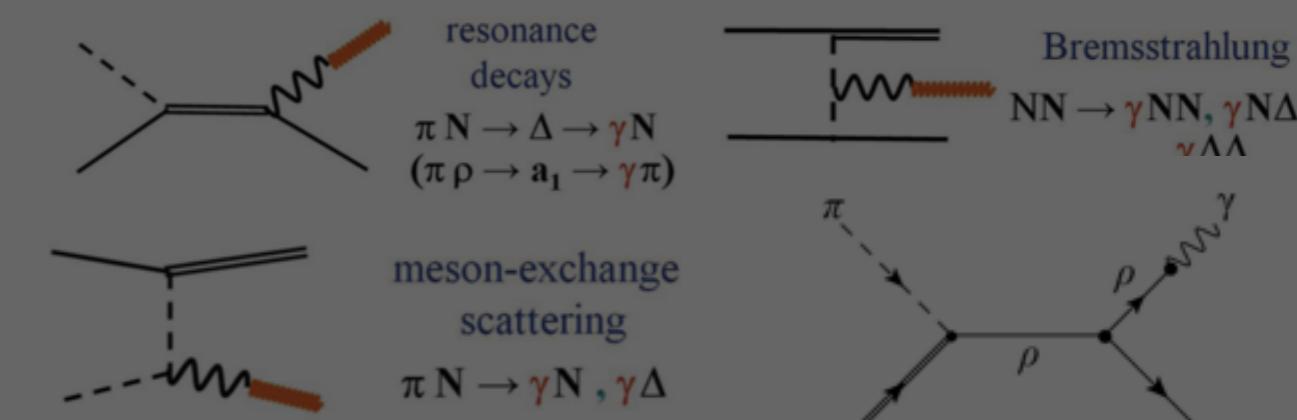


Hadron Gas

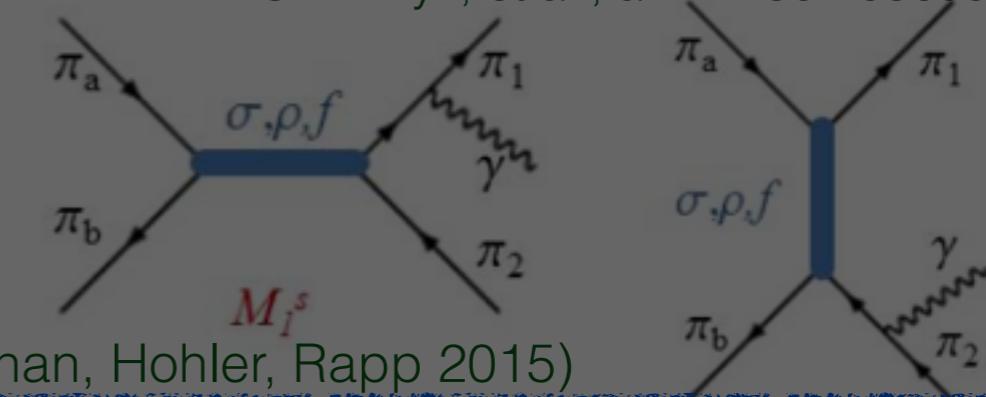
M. Dion, *et al.*, Phys. Rev. C **84**, 064901 (2011)



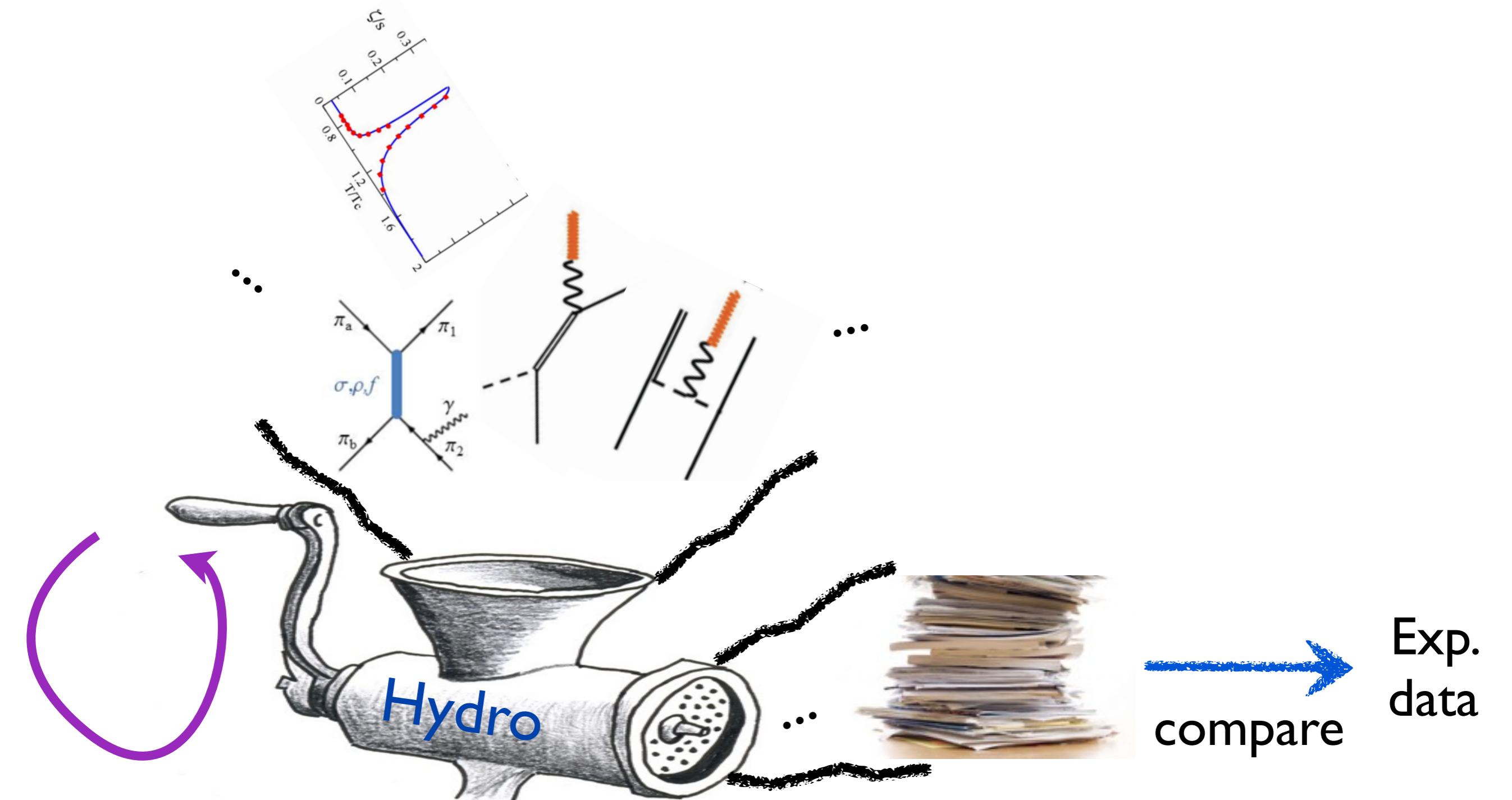
R. Rapp and J. Wambach, Eur. Phys. J. A **6**, 415 (1999)



W. Liu and R. Rapp, Nucl. Phys. A **796**, 101 (2007)
O. Linnyk, *et al.*, arXiv:1504.05699 [nucl-th]

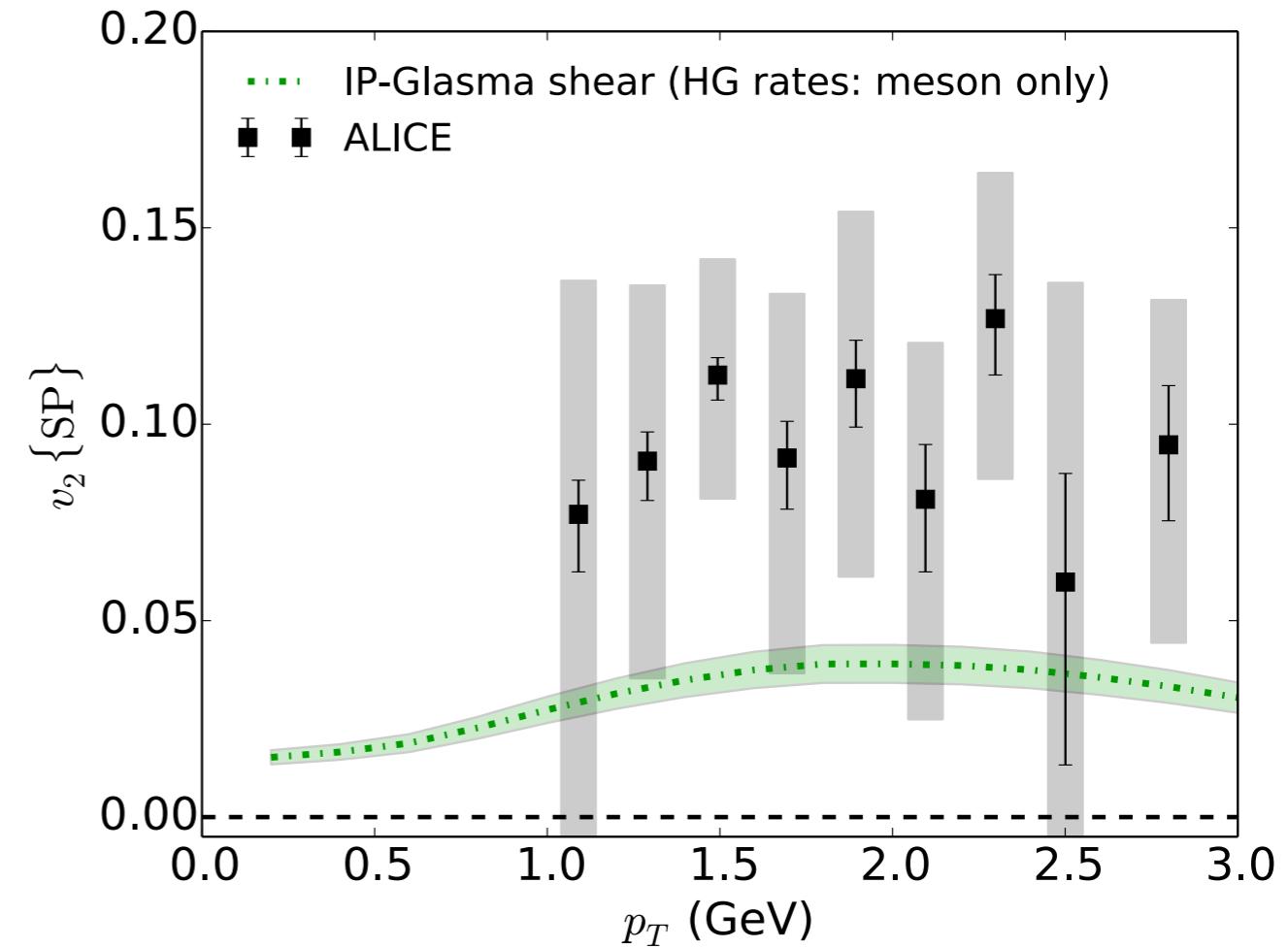
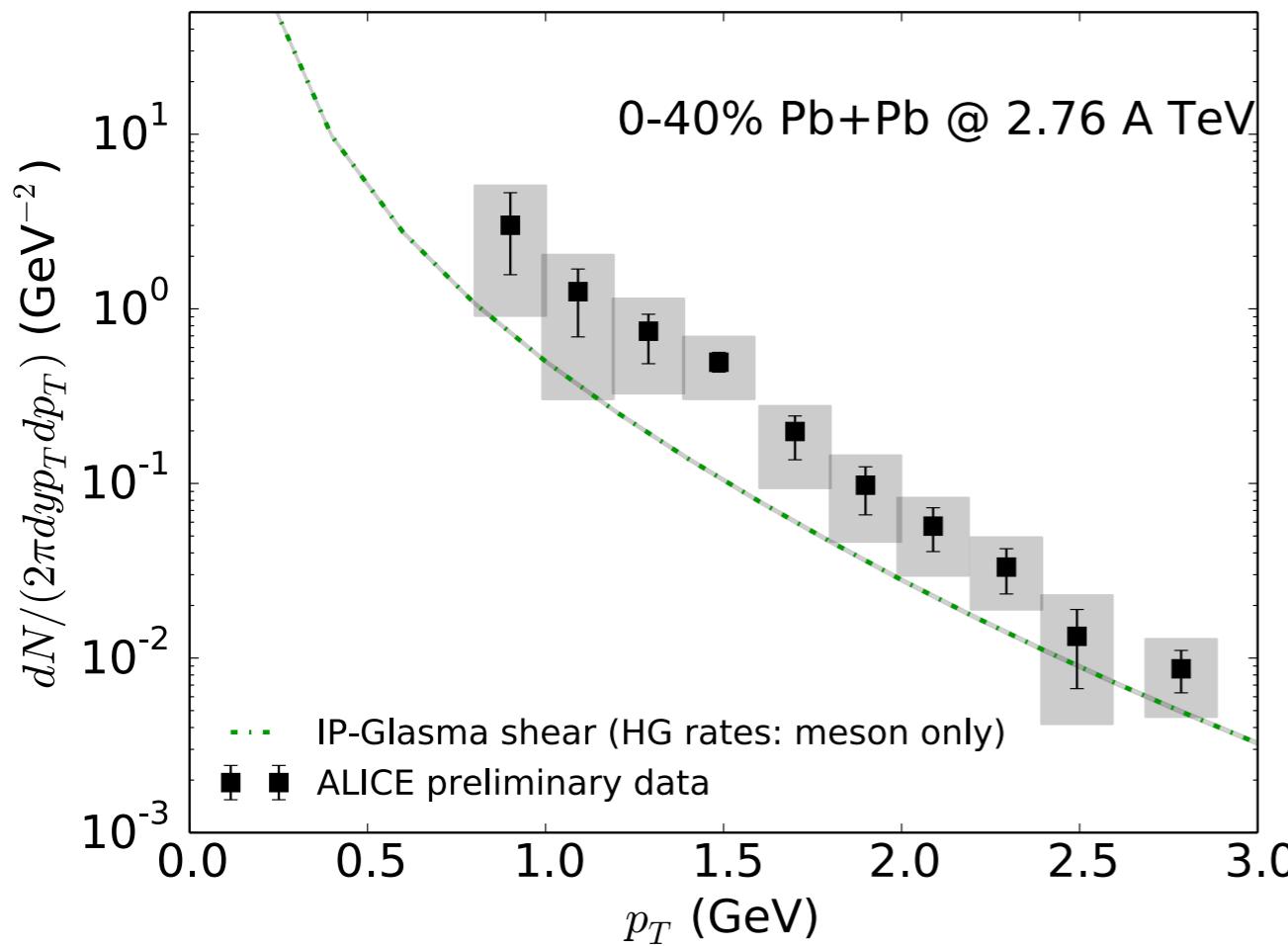


(Heffernan, Hohler, Rapp 2015)



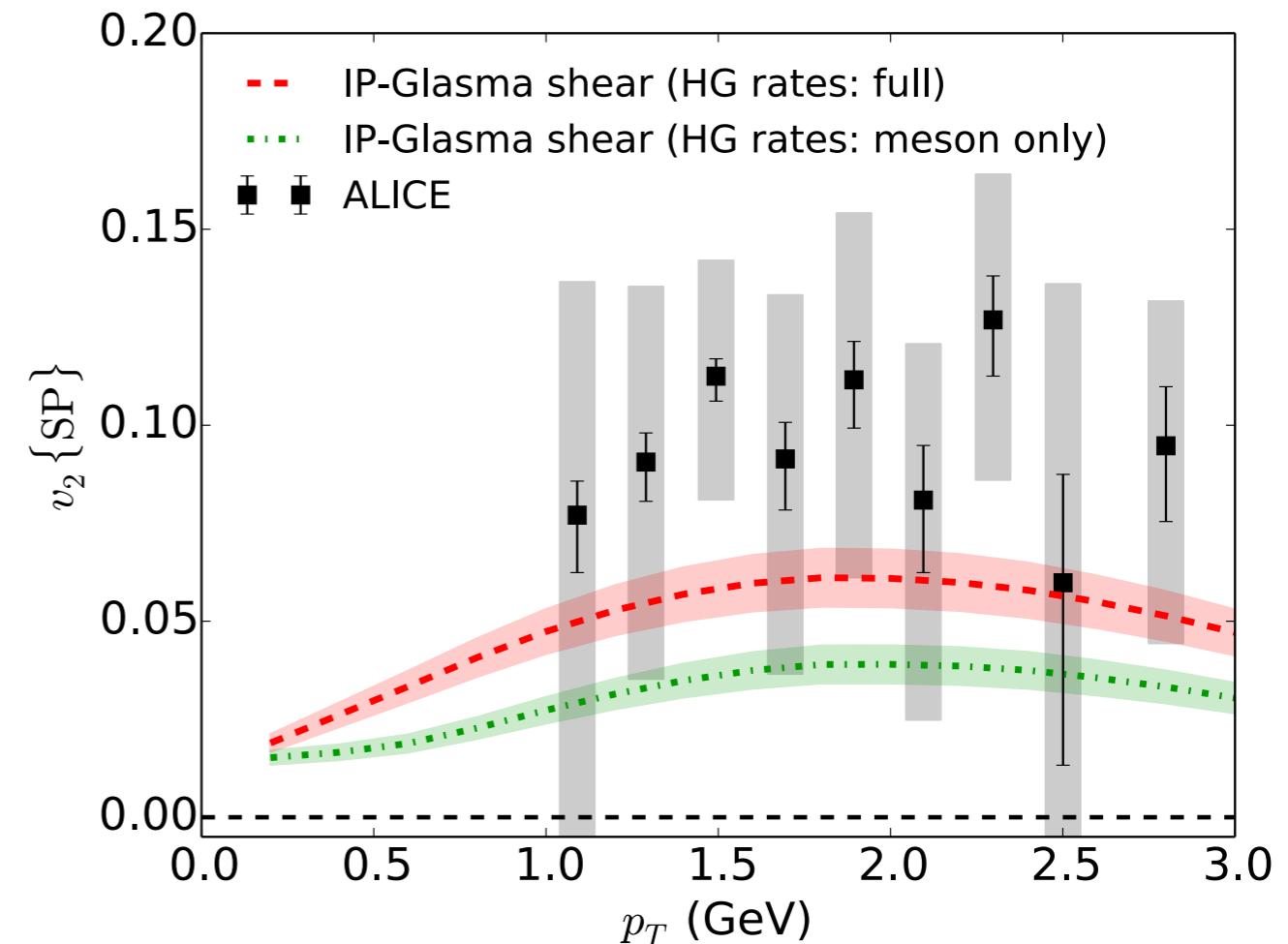
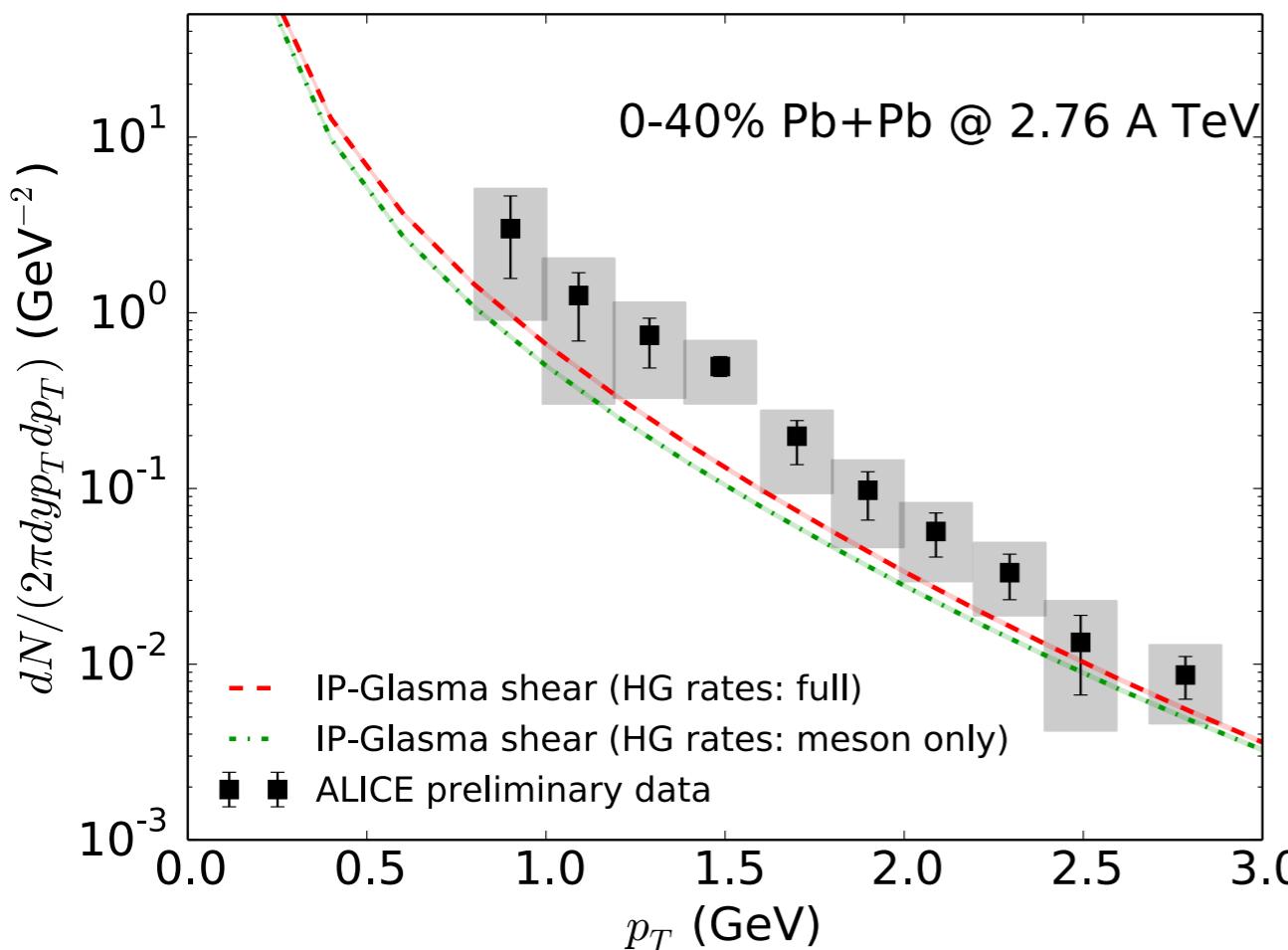
Towards resolving the direct photon flow puzzle?

With **previous** hadronic rates ...



Towards resolving the direct photon flow puzzle?

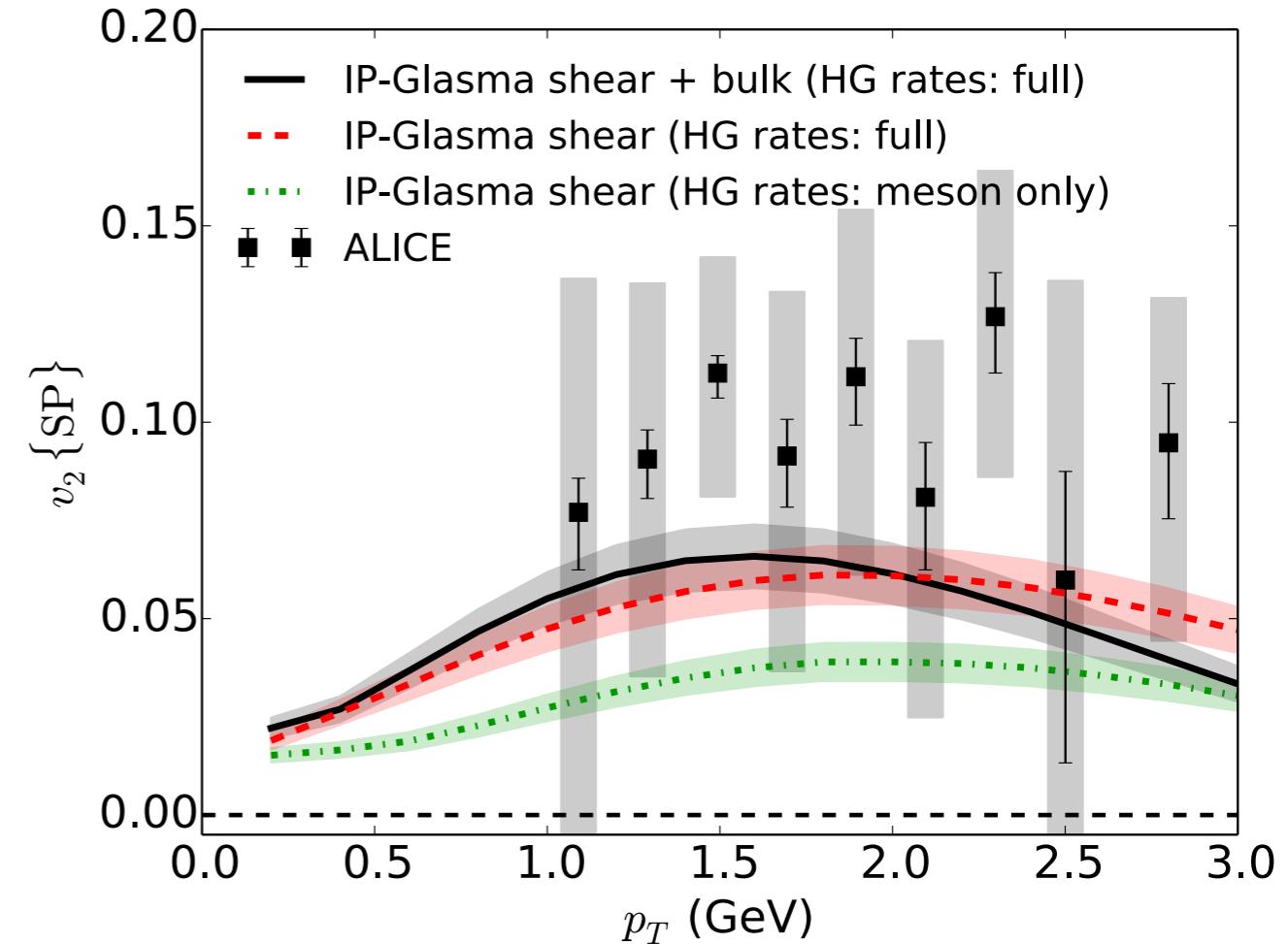
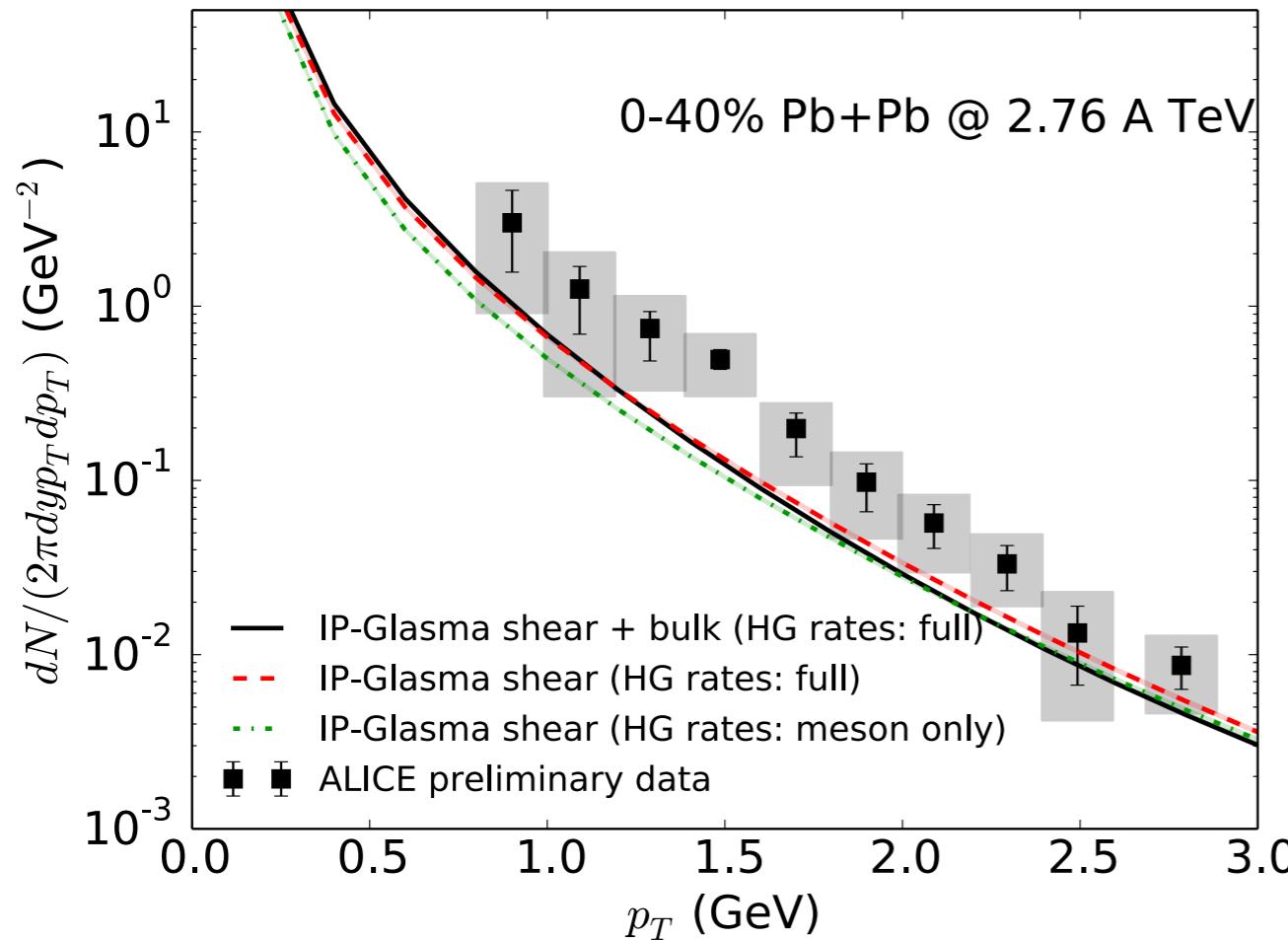
With **full** hadronic rates



- **Additional hadronic emission channels** increase the direct photon spectrum by 30% and v_2 by 40%

Towards resolving the direct photon flow puzzle?

With full hadronic rates and **bulk** viscosity



Paquet, *et al.*, arXiv:1509.06738

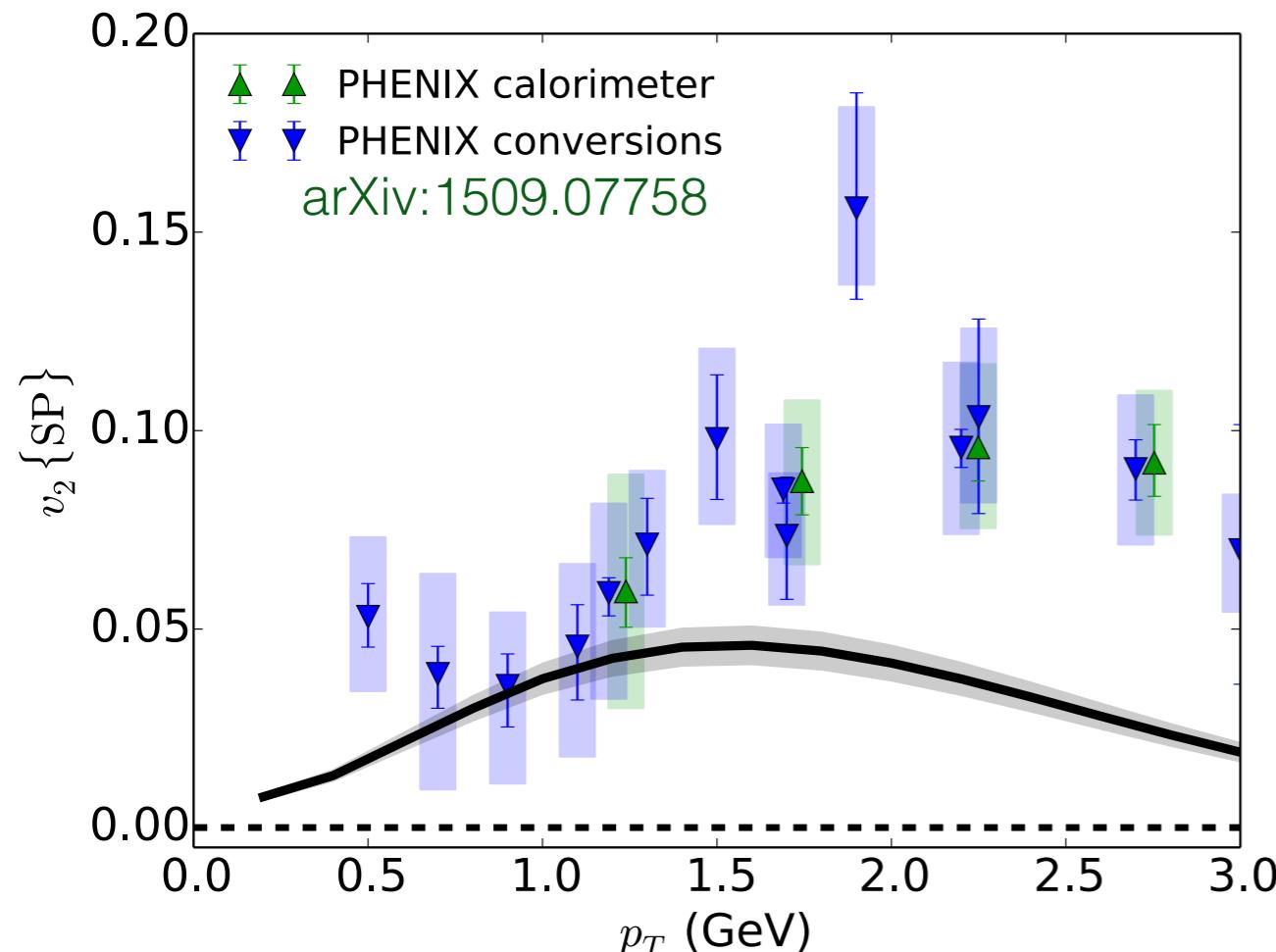
- **Additional hadronic emission channels** increase the direct photon spectrum by 30% and v_2 by 40%
- **Bulk viscosity** makes photon spectrum softer and increases its elliptic flow

Towards resolving the direct photon flow puzzle?

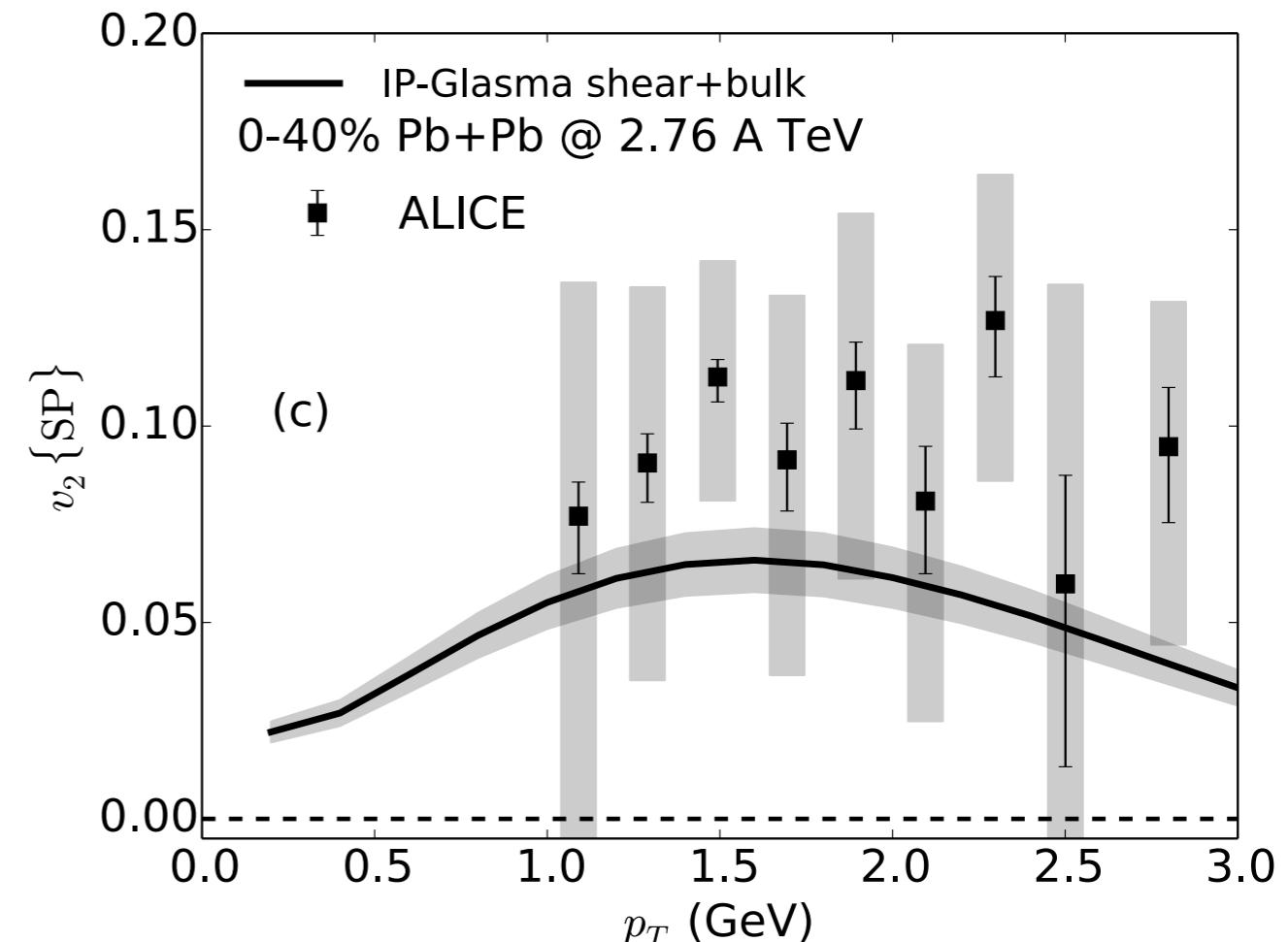
RHIC

Paquet, *et al.*, arXiv:1509.06738

LHC



arXiv:1509.07758



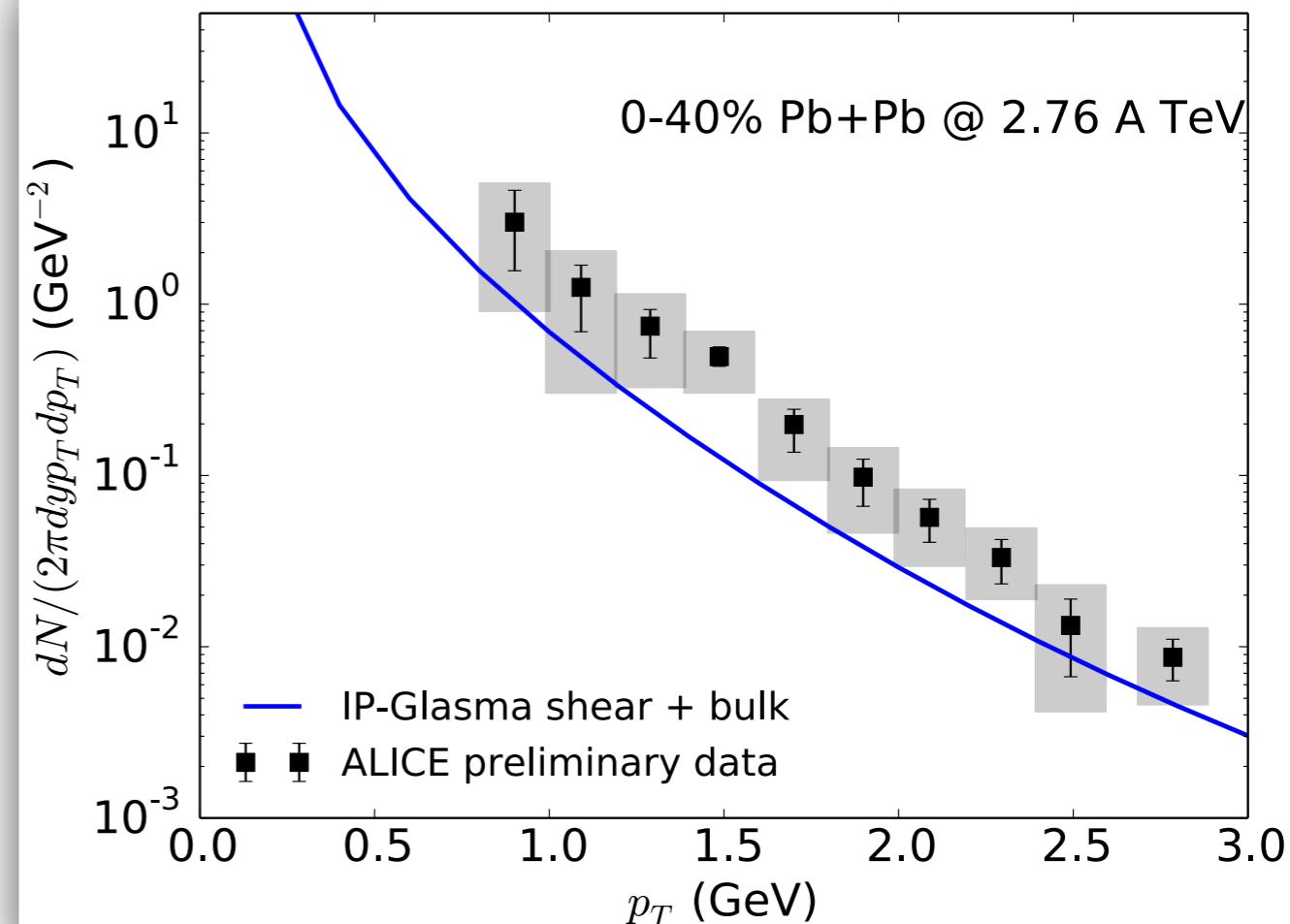
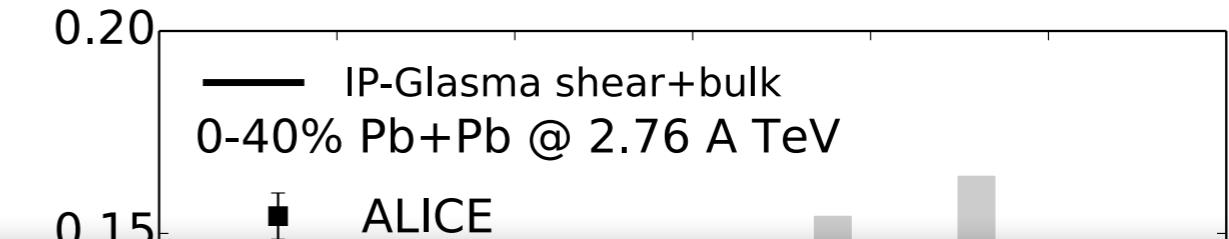
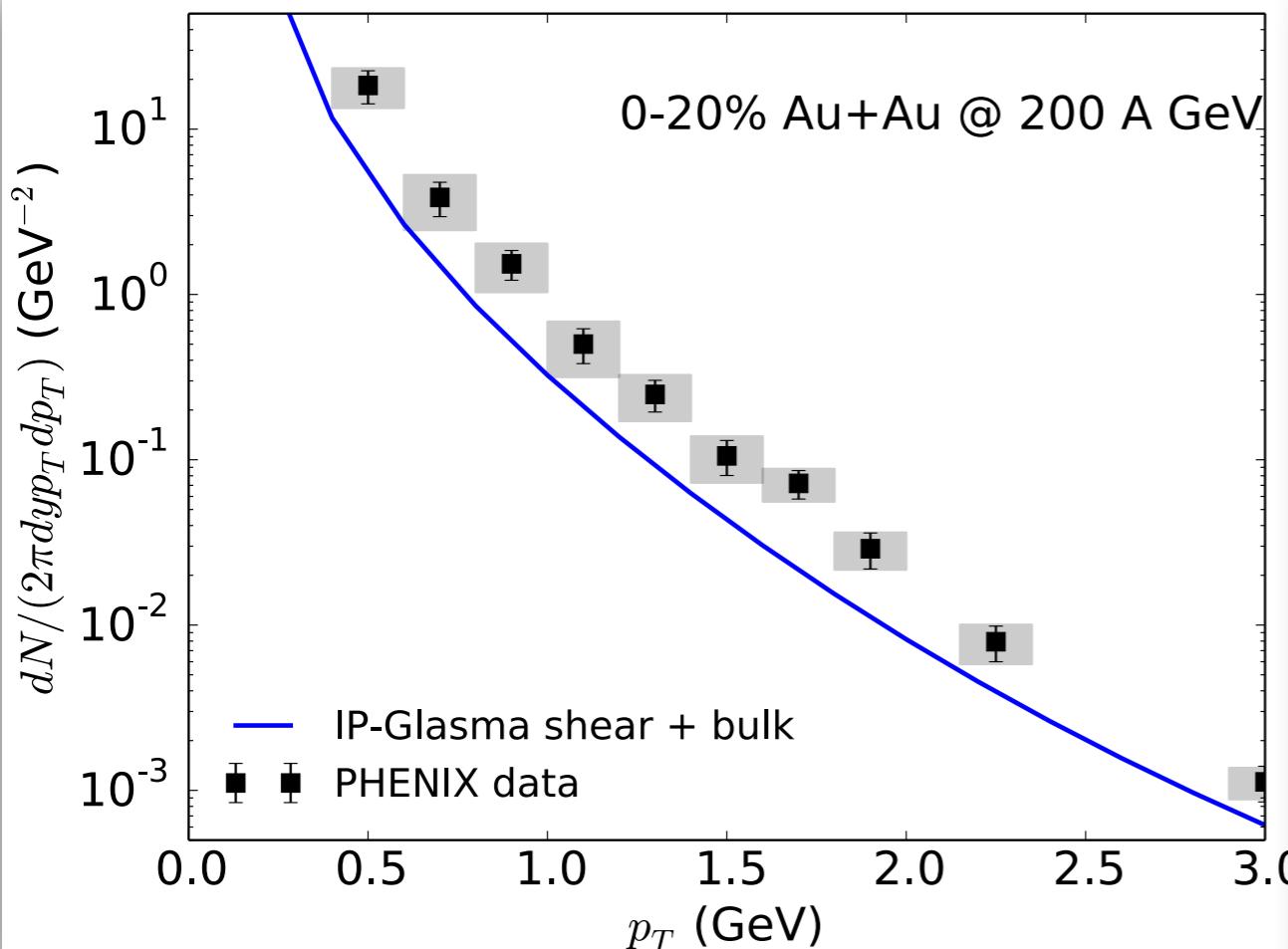
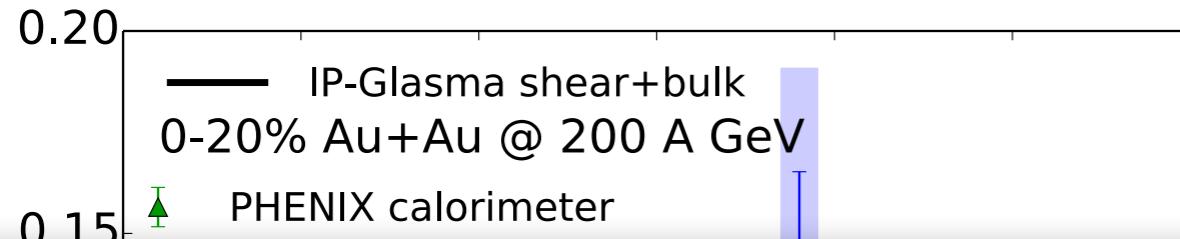
- Latest calculations shows **much reduced tension** between theory and experiment

Towards resolving the direct photon flow puzzle?

RHIC

Paquet, *et al.*, arXiv:1509.06738

LHC



between theory and experiment

More hadronic emission?

A closer look at the rates

❖ Non-perturbative corrections — Semi QGP

Y. Hidaka, S. Lin, R. D. Pisarski and D. Satow, arXiv:1504.01770

D. Satow and W. Weise, arXiv:1505.03869

C. Gale *et al*, Phys. Rev. Lett. **114**, 072301 (2015)

Poster: Yoshimasa 0707

- Near T_c , QGP photon emission rates are suppressed by about a factor of 10

Increases the importance of hadronic photons

❖ An alternative hadronic rate

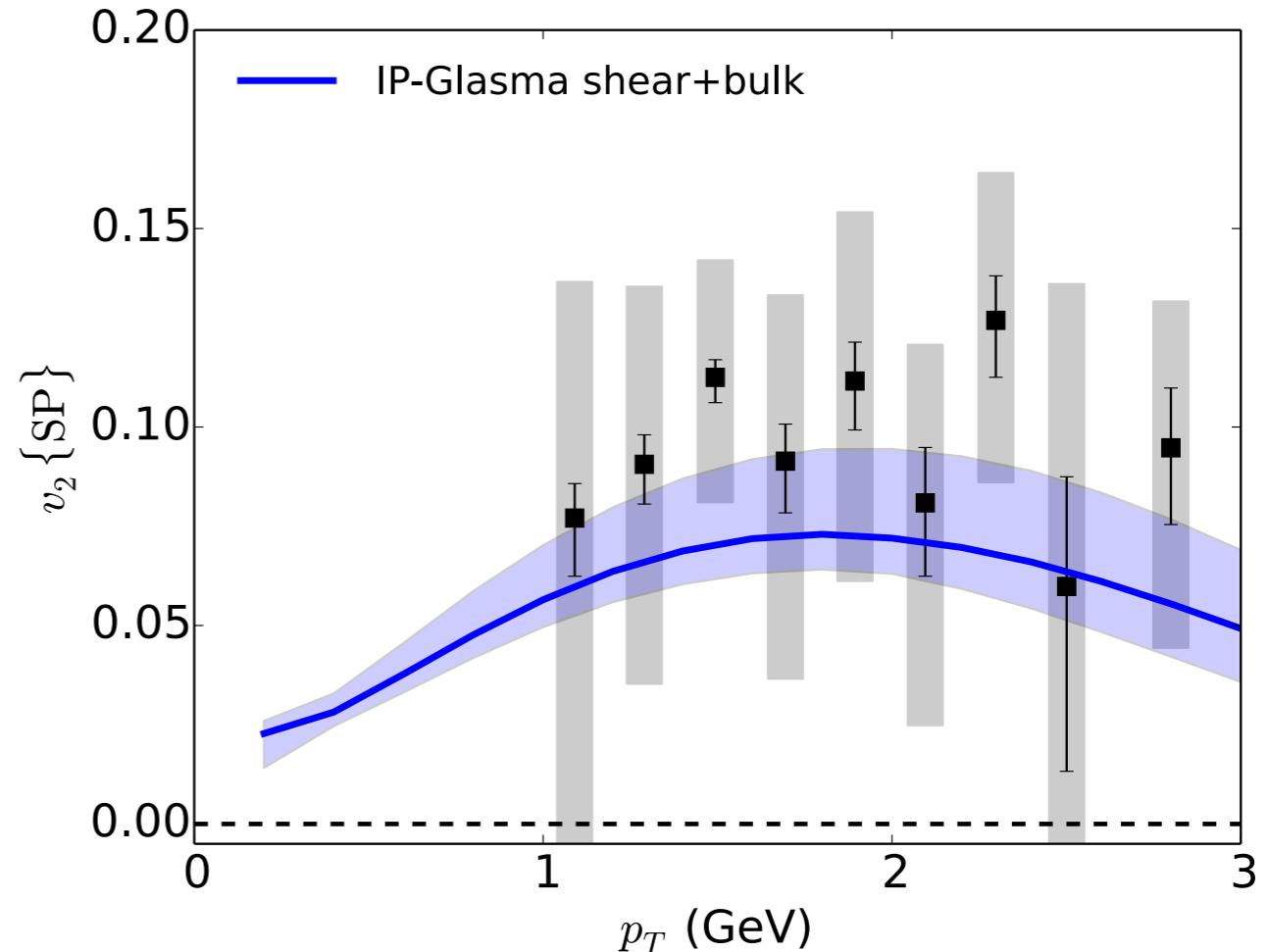
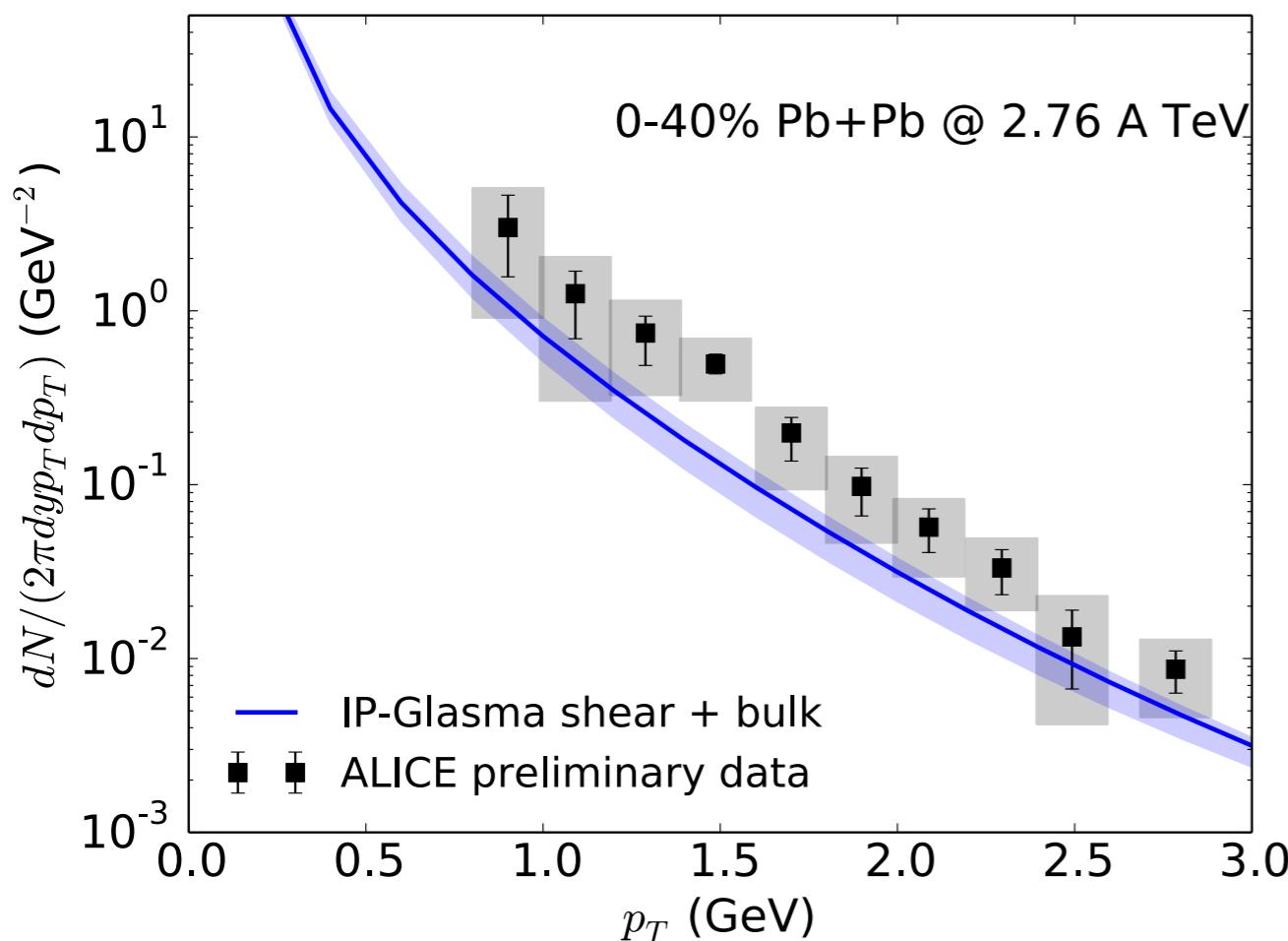
K. Dusling and I. Zahed, Phys. Rev. C **82**, 054909 (2010)

- Hadronic rates computed from spectral function approach
- A factor of ~2 larger than the TAMU/McGill rate

More hadronic photons with large anisotropy

A closer look at the rates

Paquet, *et al.*, arXiv:1509.06738



- The band shows the results calculated with combinations of the three different rates
(TAMU/McGill, Semi QGP, Dusling/Zahed)
- relatively small variation** of direct photon observables

Bremsstrahlung in transport

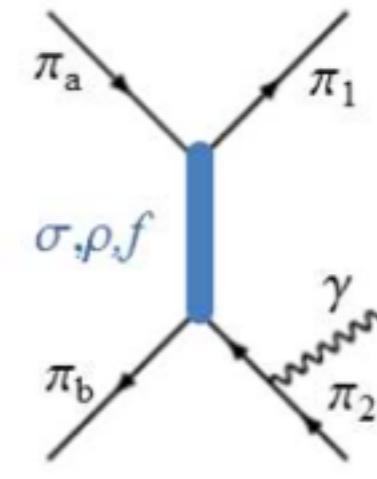
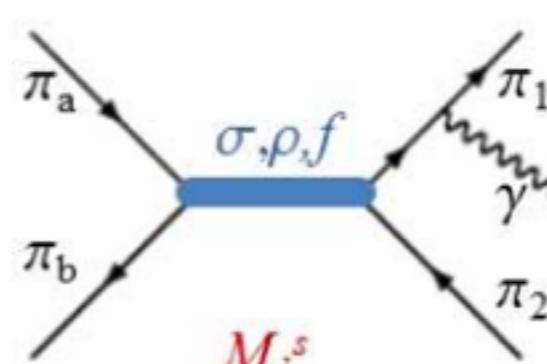
O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing and E. L. Bratkovskaya, arXiv:1504.05699

Poster: Linnyk 0714

- Including:

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

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



Improved soft photon approximation (SPA)

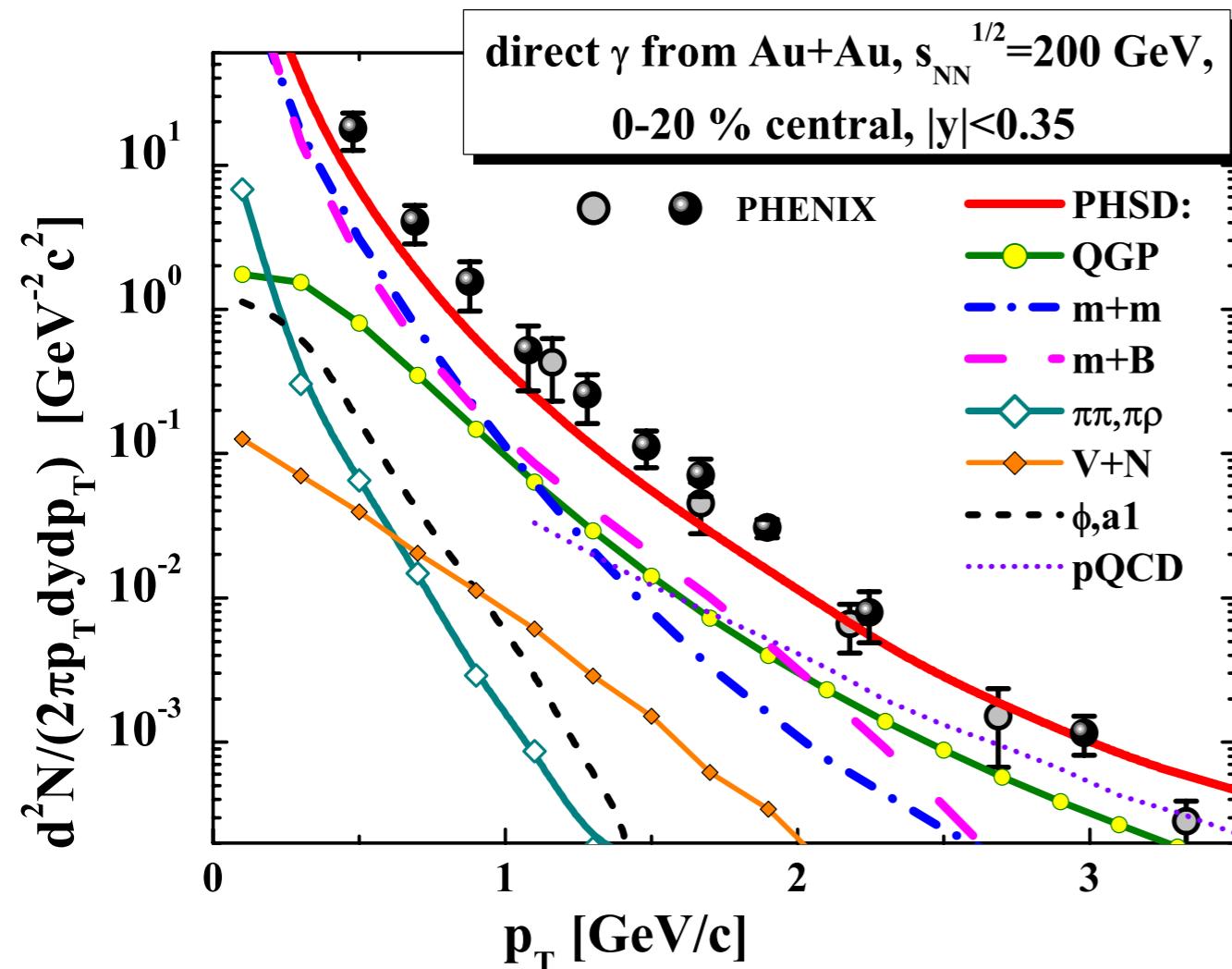
$$q_0 \frac{d\sigma^\gamma(s)}{d^3q} = \frac{\alpha_{EM}}{4\pi} \int_{-\lambda(s_2, m_a^2, m_b^2)/s_2}^0 |\epsilon \cdot J(q, t)|^2 \frac{d\sigma_{el}(s_2)}{dt} dt.$$

$$s_2 \equiv (p_a + p_b - q)^2$$

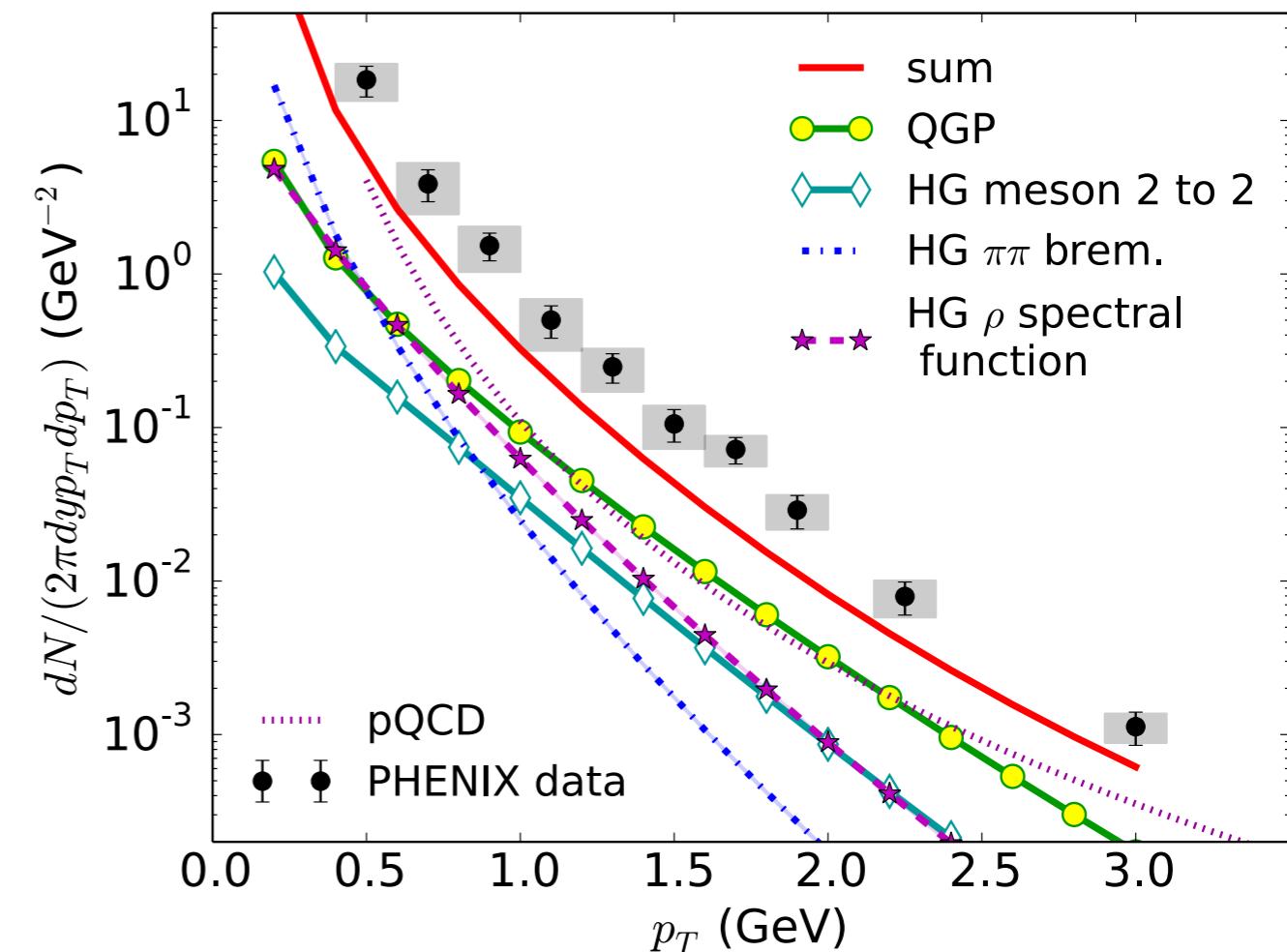
More hadronic emission with large anisotropy

Transport approach vs hydrodynamics

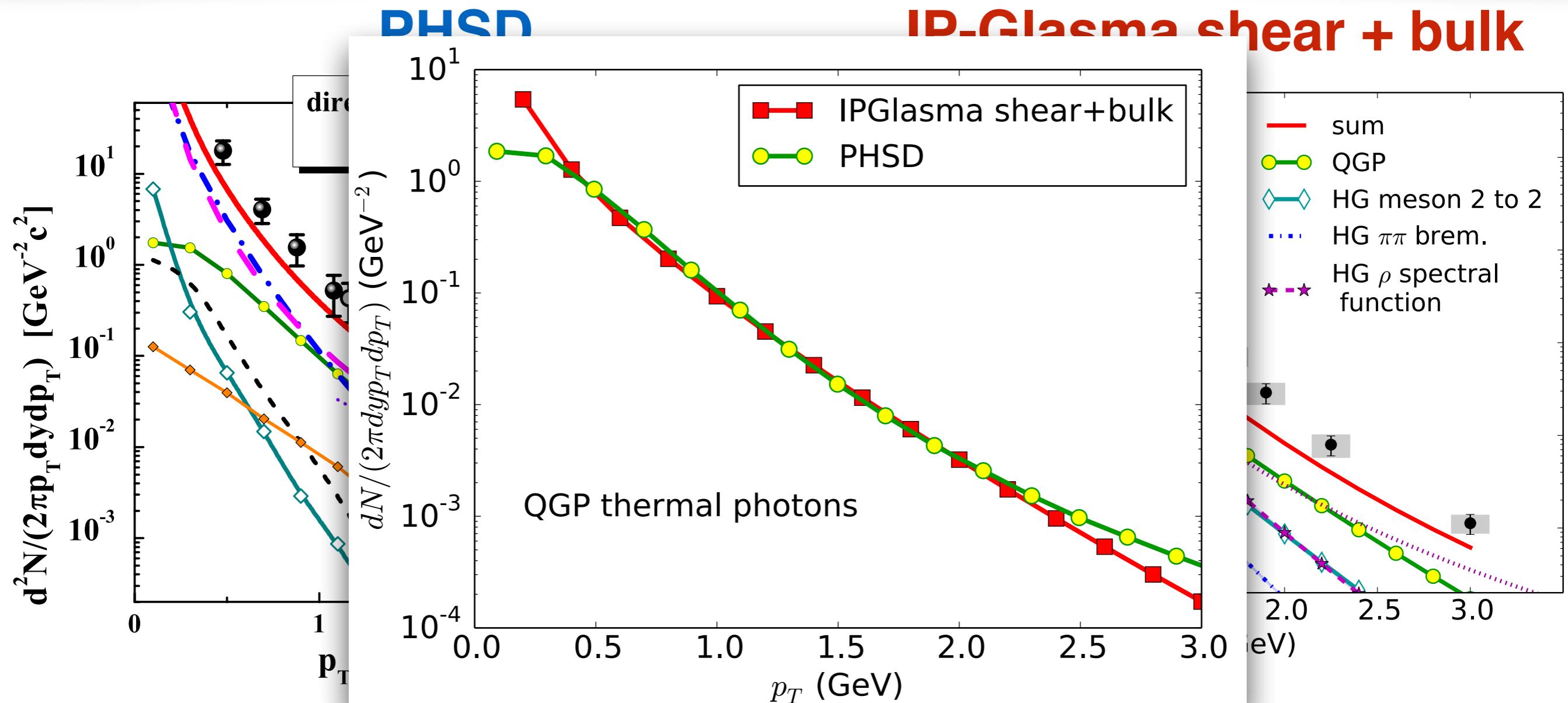
PHSD



IP-Glasma shear + bulk



Transport approach vs hydrodynamics

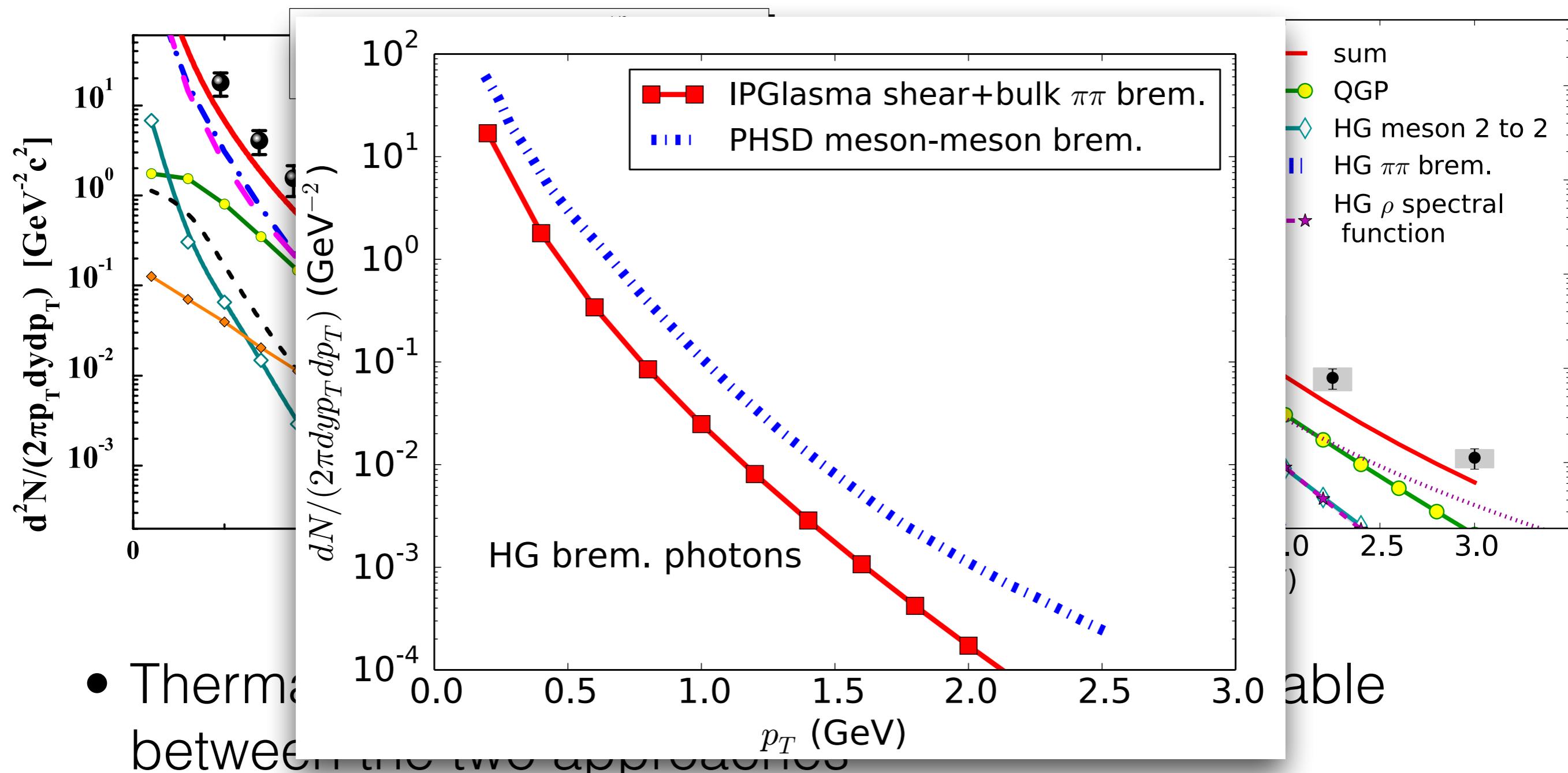


- Thermal photons from QGP phase are comparable between the two approaches

Transport approach vs hydrodynamics

PHSD

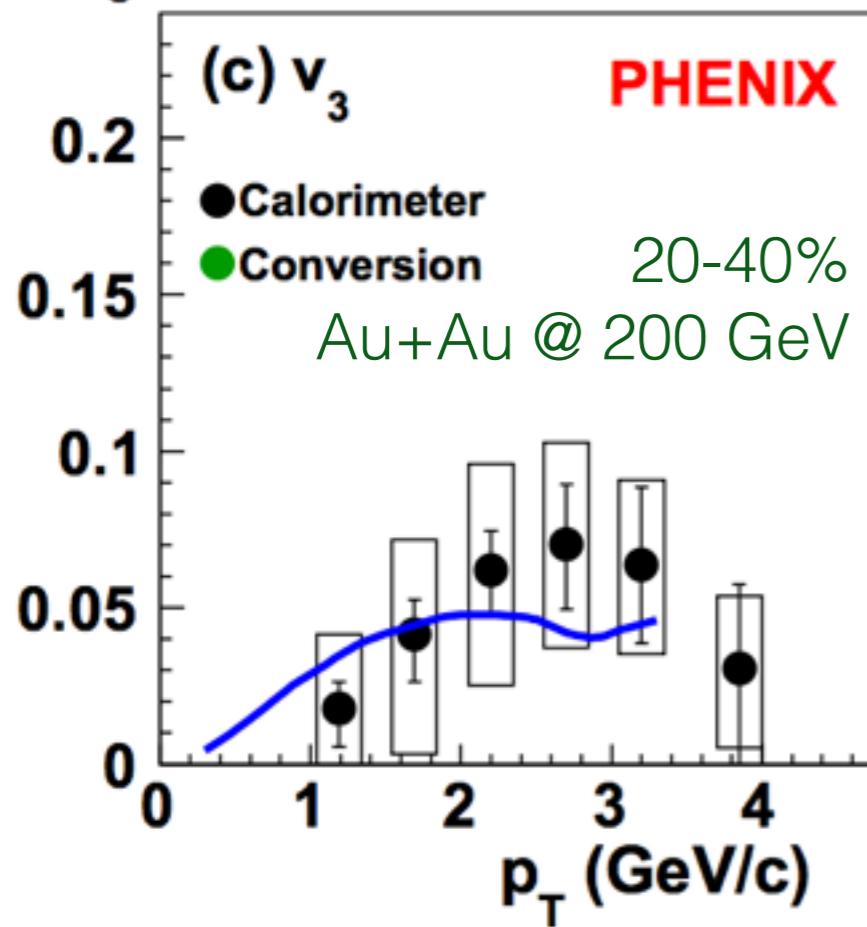
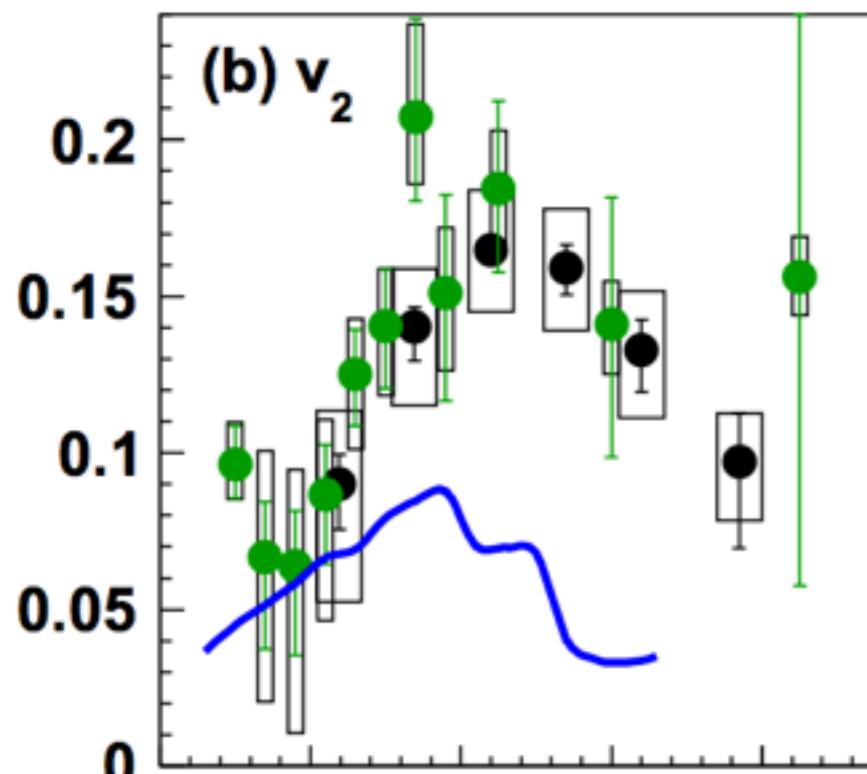
IP-Glasma shear + bulk



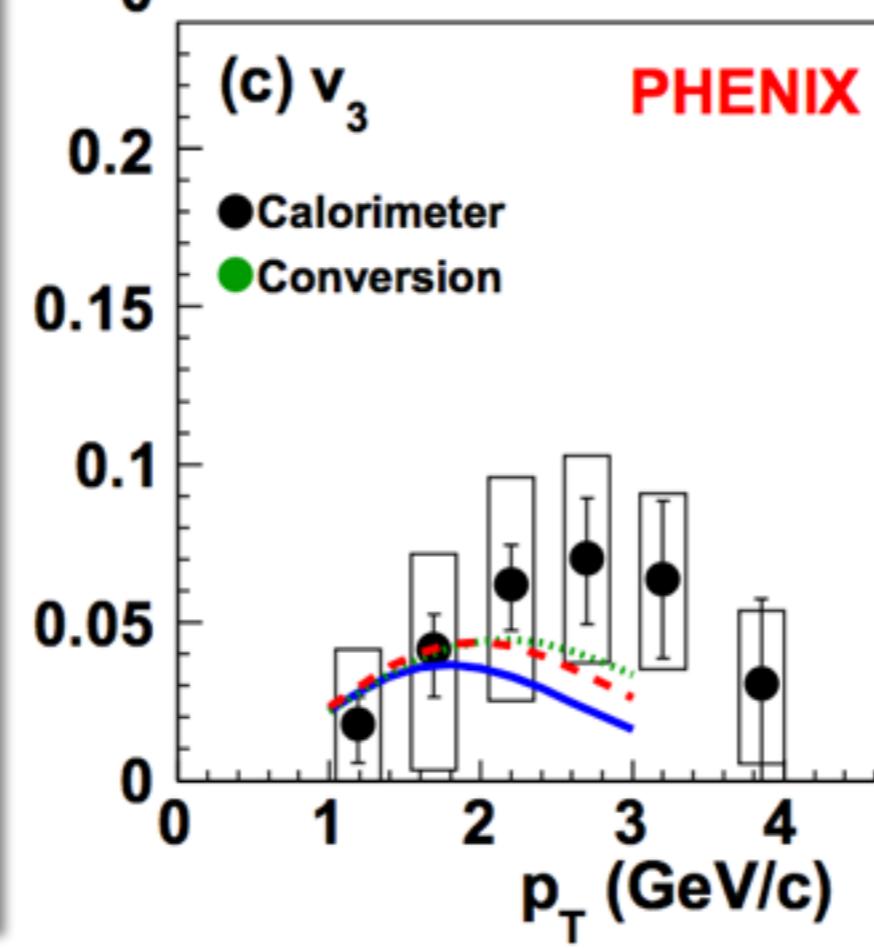
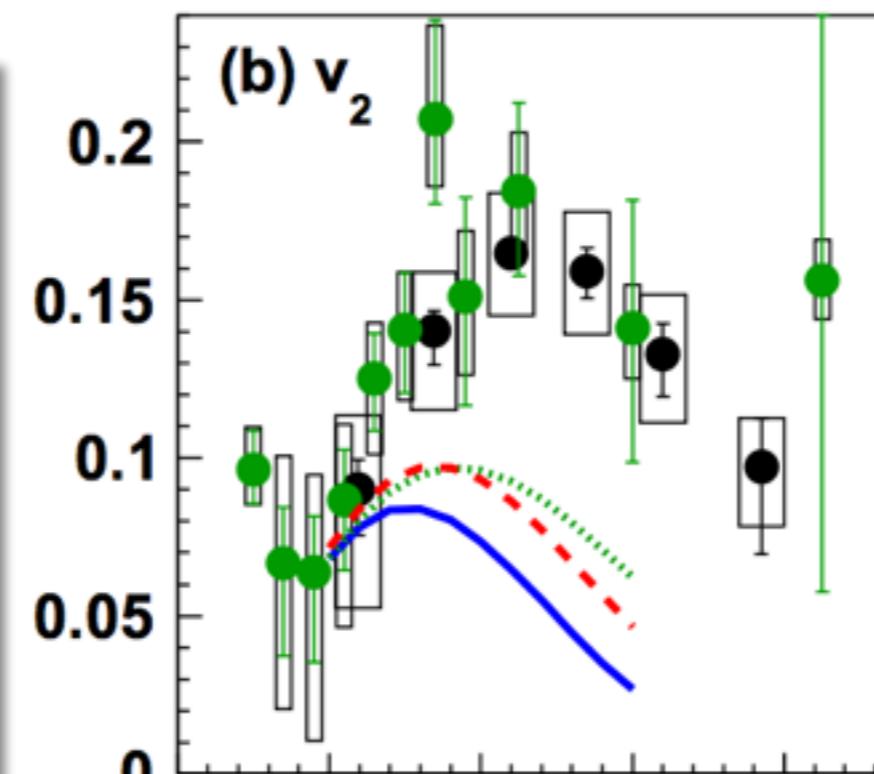
- Thermal radiation is comparable between the two approaches
- The origin of the difference in hadronic radiation needs further investigation in the future

Transport approach vs hydrodynamics

PHSD



IP-Glasma shear + bulk



arXiv:1509.07758

- Similar level of agreement with measured direct photon v_2 and v_3

Other developments...

Non-thermal contributions

- ◆ A Tsallis tail in the quark distribution

L. McLerran and B. Schenke, arXiv:1504.07223 [nucl-th].

A power law tail in
particle distribution

(0+1)-d Bjorken
expansion



average emission time
delayed by ~ 2 fm/c

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delayed by $\sim 2 \text{ fm/c}$

◆ Late quark chemical equilibration

F. Gelis et al., JPG 30, S1031

F. M. Liu and S. X. Liu, Phys. Rev. C **89**, 034906 (2014)

A. Monnai, Phys. Rev. C **90**, 021901 (2014)

- Reduced photon production because the gluons dominate early stage

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◆ Jet induced/fragmentation photons

Hattori Wed 09:30

G. Y. Qin, J. Ruppert, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C **80**, 054909 (2009)

G. Y. Qin and A. Majumder, Phys. Rev. C **91**, 044906 (2015)

- large virtuality jets emit more photons, more isotropically

Non-thermal contributions

♦ A Tsallis tail in the quark distribution

L. McLerran and B. Schenke, arXiv:1307.23 [nucl-th].

A power law tail in
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F. Gelis et al., JPG 30, S1031

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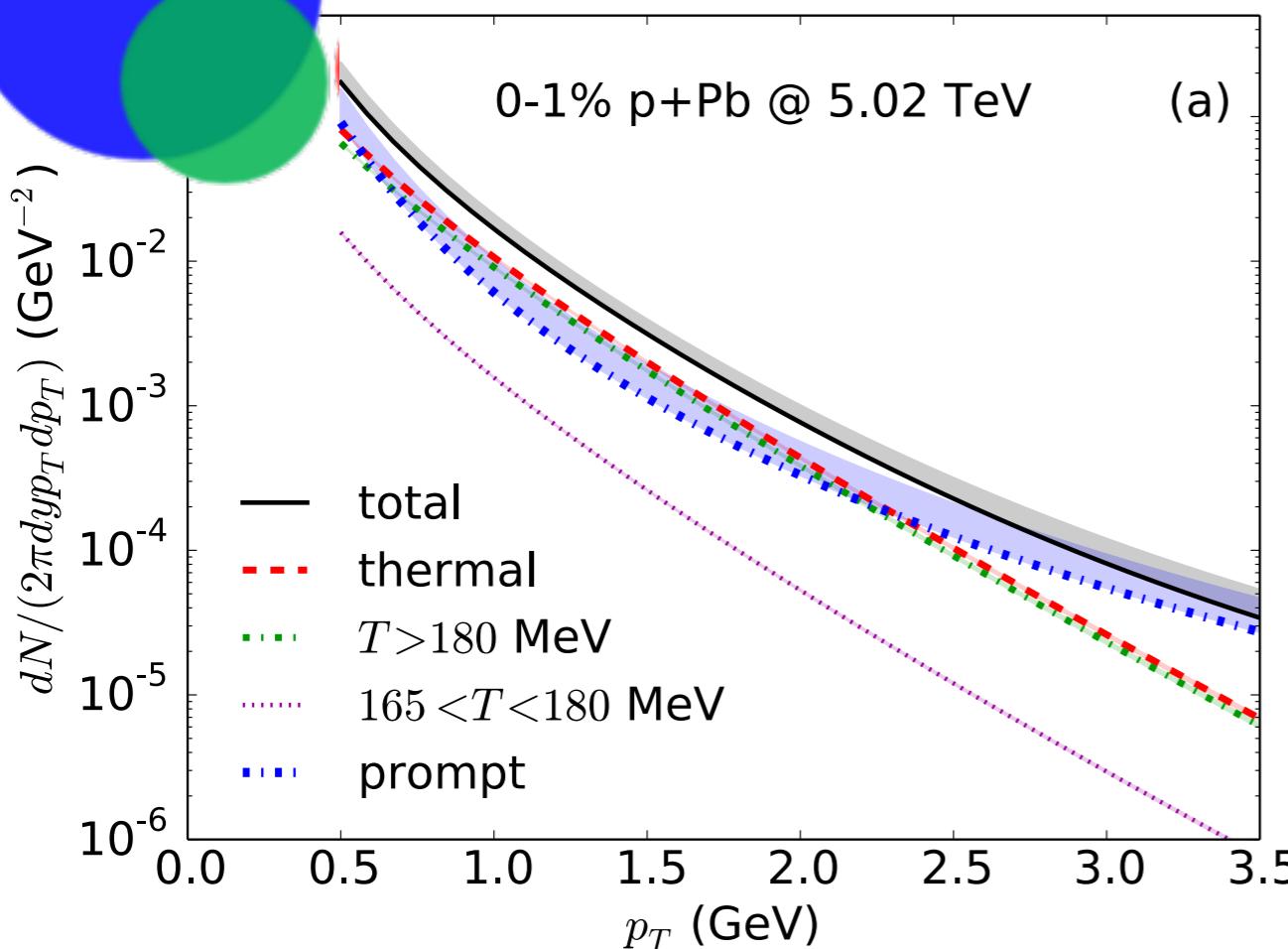
Need to embed into realistic hydrodynamical model

Electromagnetic Probes: a microscope for the QCD matter

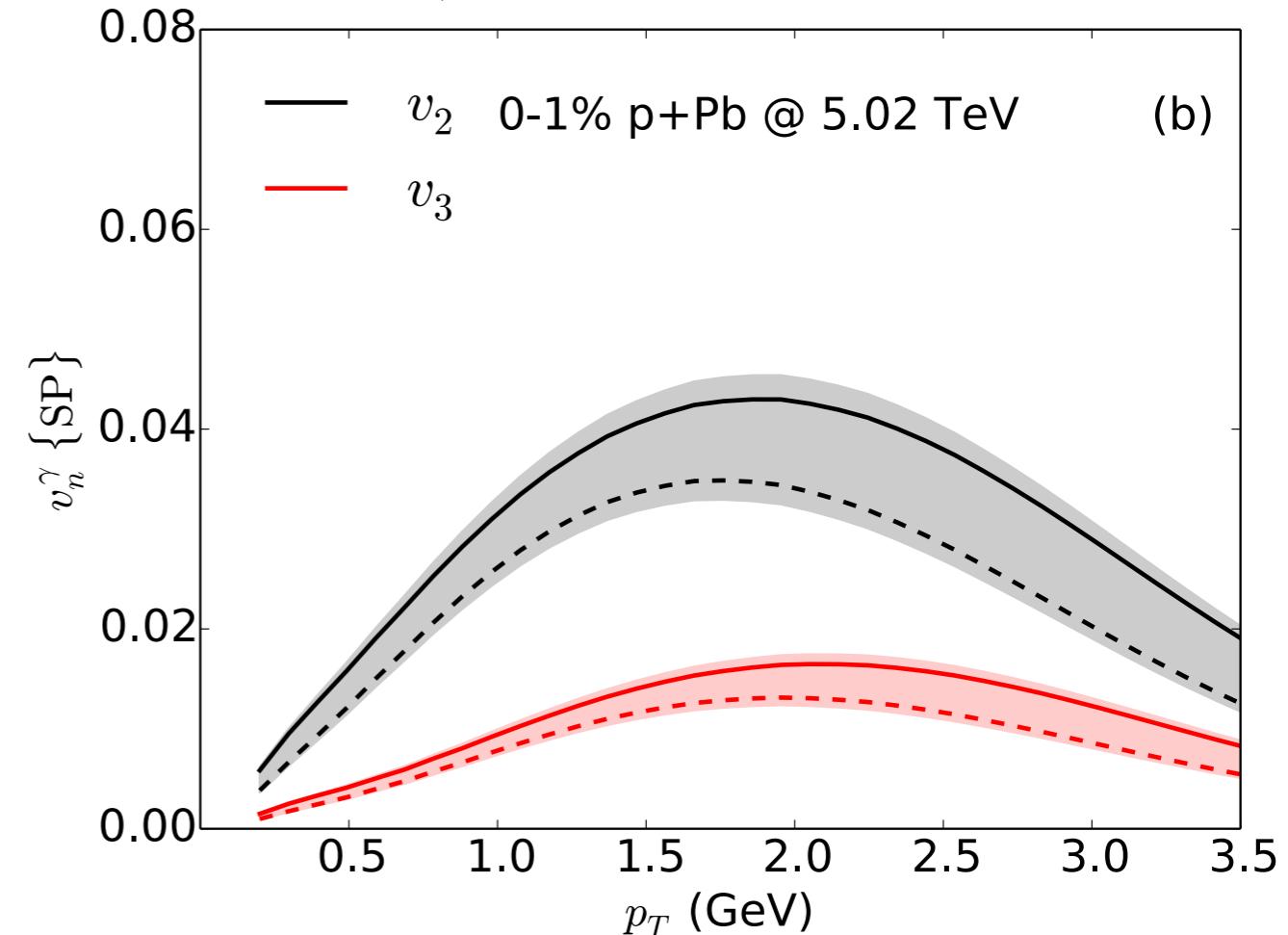


Thermal emission in small systems

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, arXiv:1504.07989



(a)

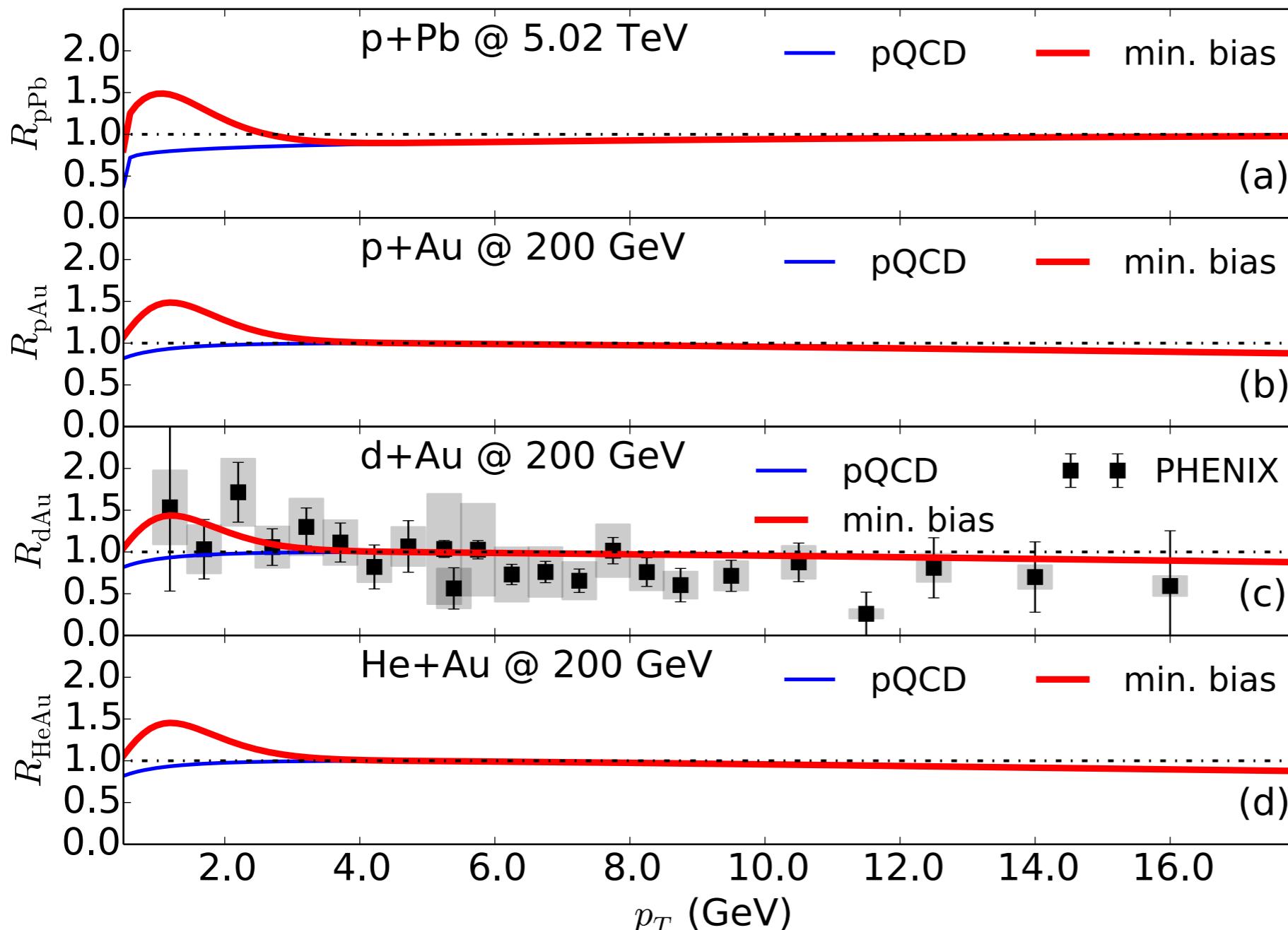


(b)

- In 0-1% p+Pb collisions, thermal photon can out-shine prompt photons
- **Sizeable** direct photon anisotropy in central p+Pb collisions!

Thermal emission in small systems

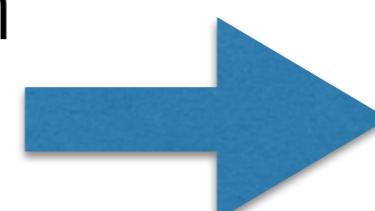
C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, arXiv:1504.07989



$$R_{pA} = \frac{\left(\frac{dN^\gamma}{dy p_T dp_T} \right)_{pA}}{\langle N_{\text{coll}} \rangle \left(\frac{dN^\gamma}{dy p_T dp_T} \right)_{pp}}$$

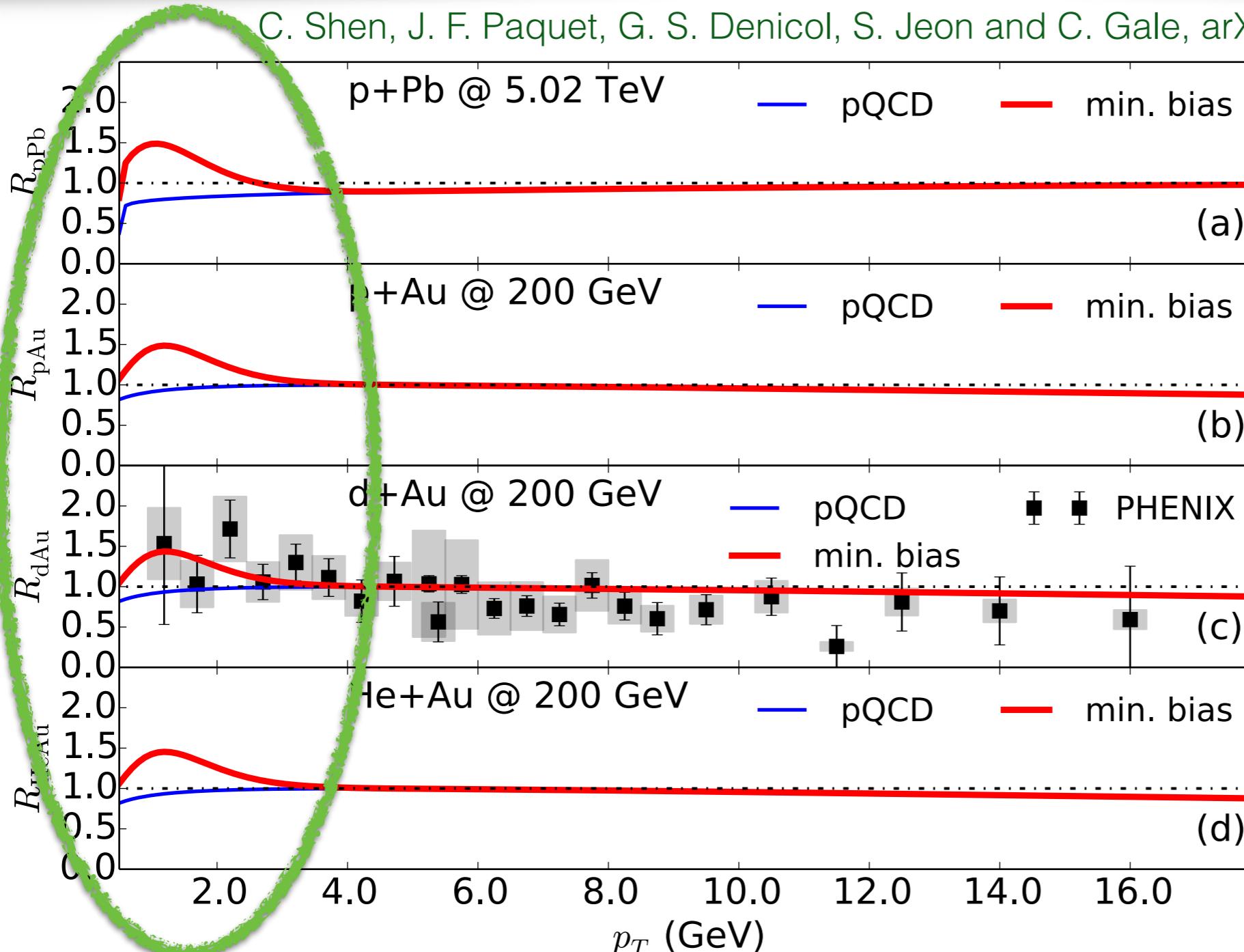
Gale Mon 17:00

- Thermal photon radiation can leave **visible imprint** in the **minimum bias** R_{pA}



a **signature** of hot medium

Thermal emission in small systems



$$R_{pA} = \frac{\left(\frac{dN^\gamma}{dy p_T dp_T} \right)_{pA}}{\langle N_{\text{coll}} \rangle \left(\frac{dN^\gamma}{dy p_T dp_T} \right)_{pp}}$$

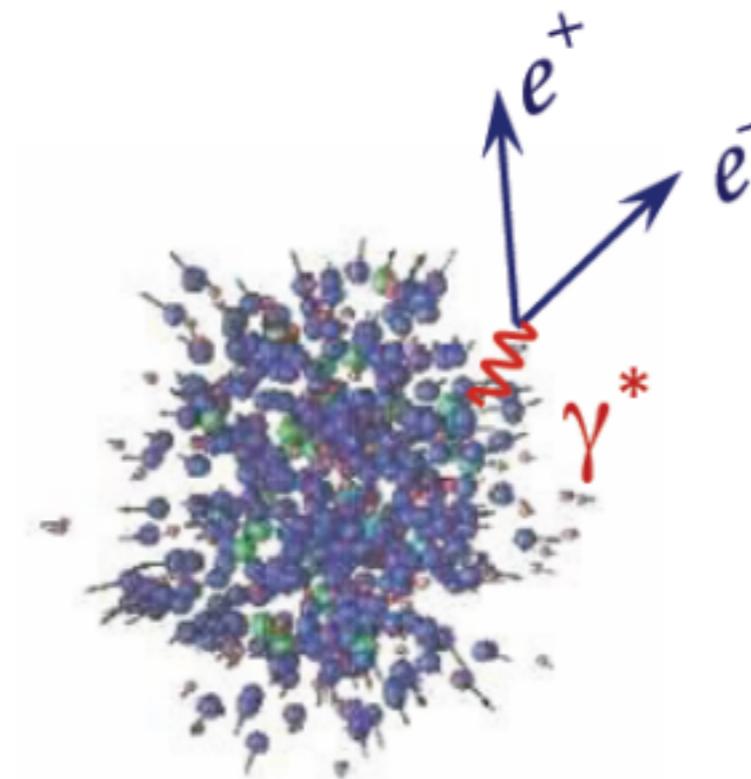
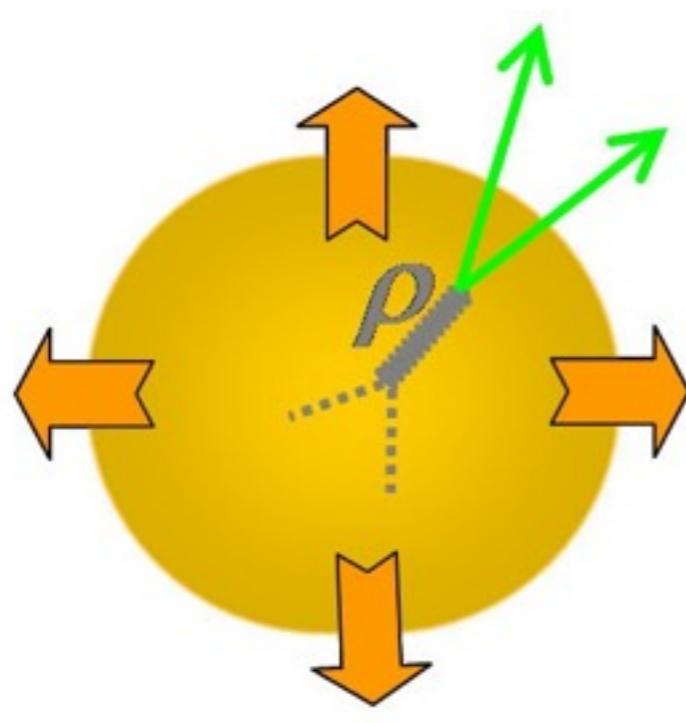
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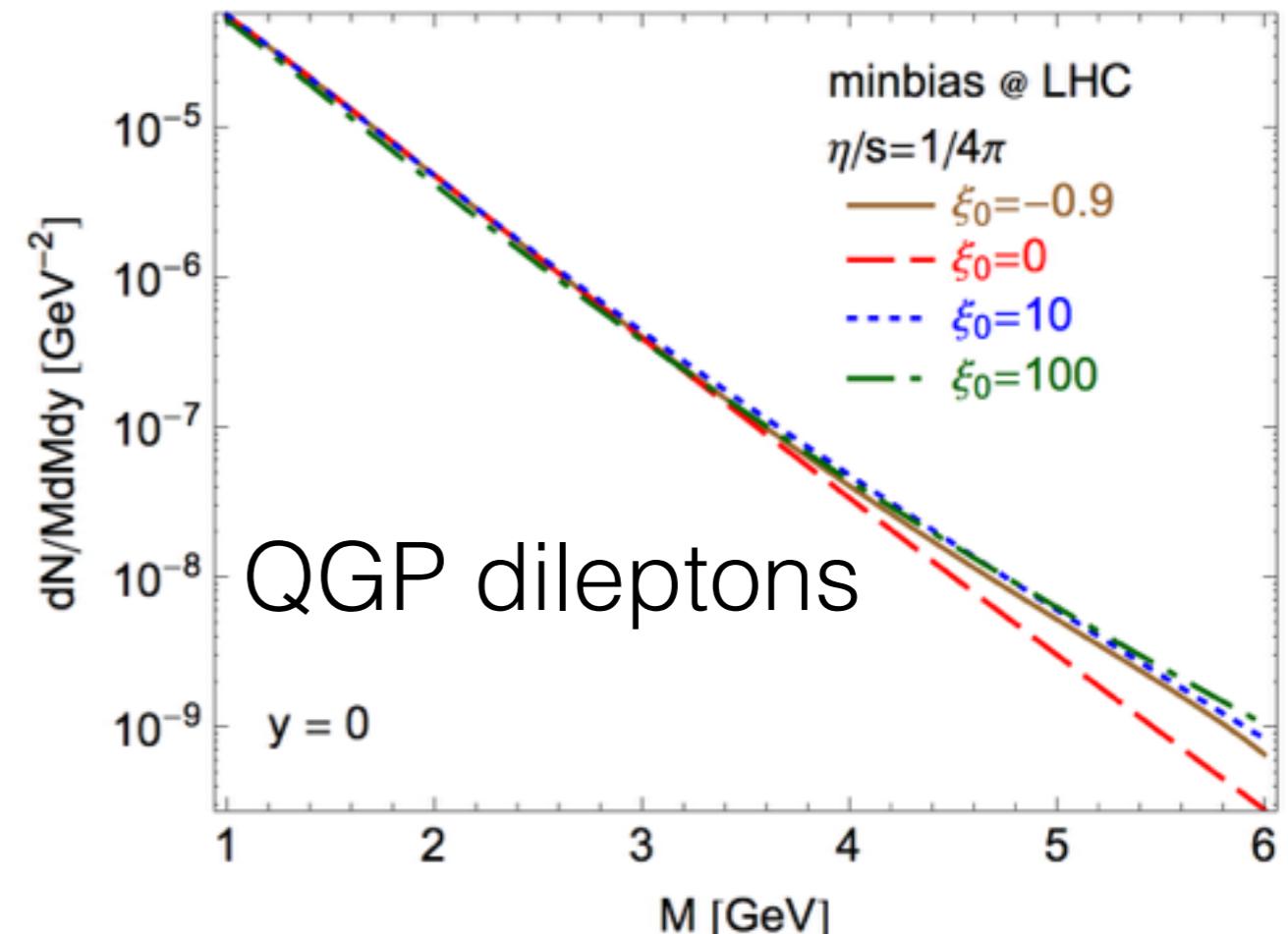
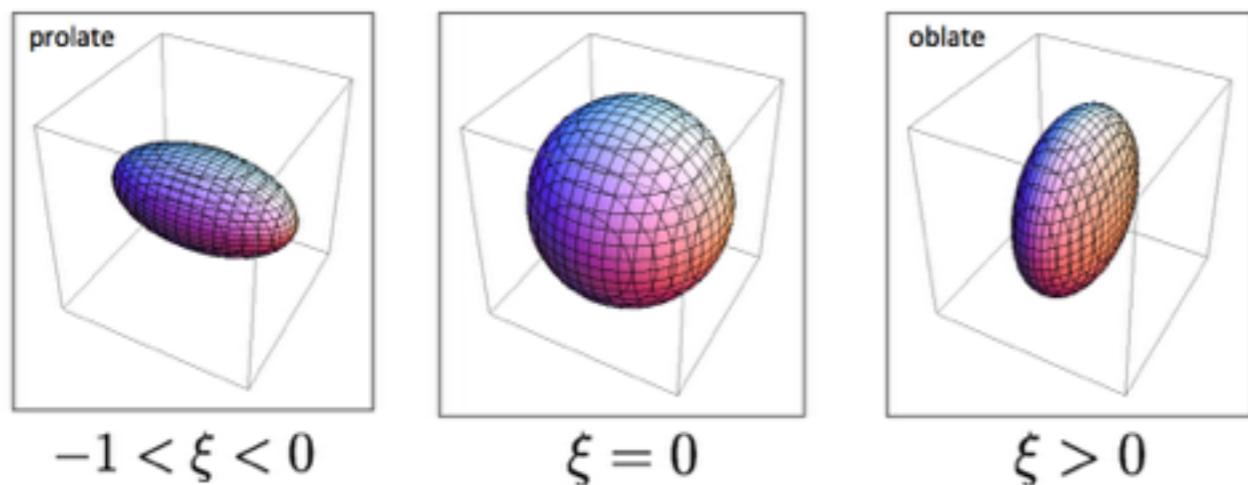
Dilepton signals



Dileptons probing early stage dynamics

R. Ryblewski and M. Strickland, arXiv:1501.03418 [nucl-th]

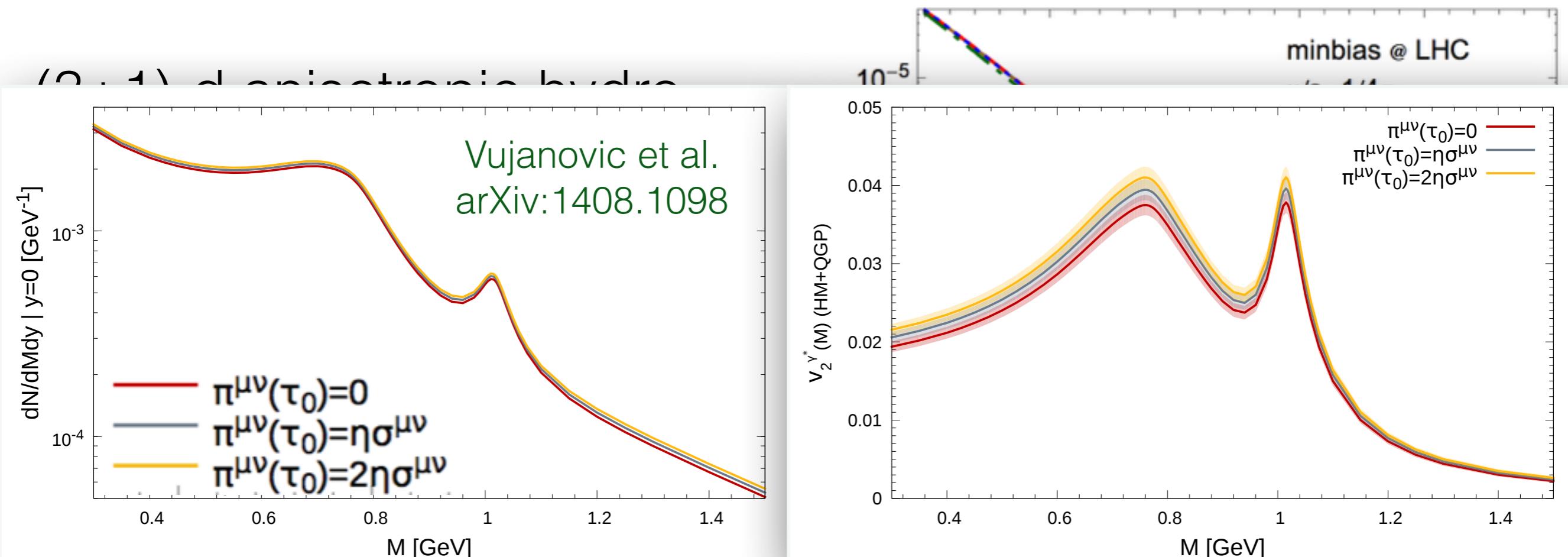
(3+1)-d anisotropic hydro



- The QGP dilepton mass spectra show large sensitivity to the initial particle momentum configuration

Dileptons probing early stage dynamics

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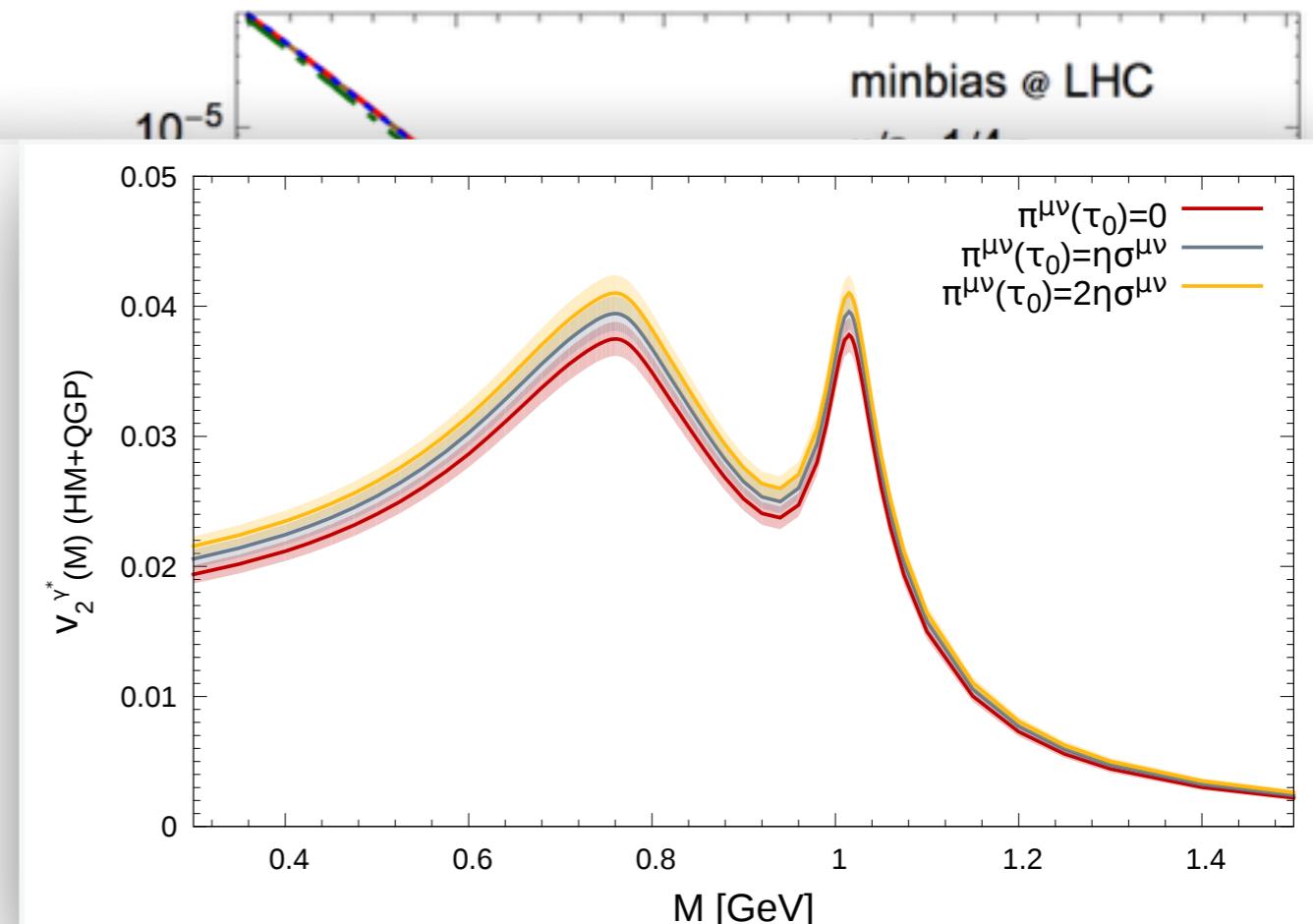
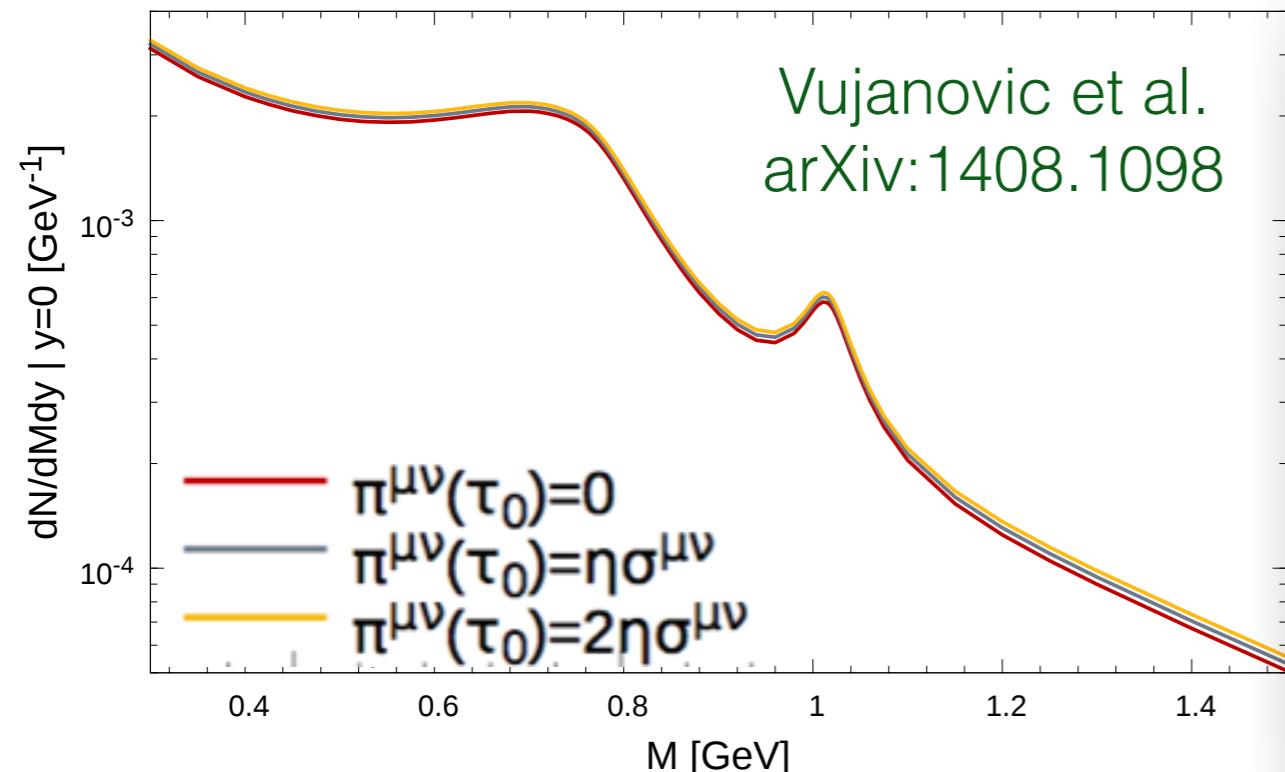


- The QGP dilepton mass spectra show large sensitivity to the initial particle momentum configuration
- Similar observation seen in traditional hydrodynamic simulations; sensitivity to initial $\pi^{\mu\nu}$

Dileptons probing early stage dynamics

R. Ryblewski and M. Strickland, arXiv:1501.03418 [nucl-th]

(QGP) dilepton mass spectra by hydro



- The QGP dilepton mass spectra show large sensitivity to the initial particle momentum distribution.
 - Similar observations in traditional hydrodynamic simulations, sensitive to initial $\pi^{\mu\nu}$.
- sensitive to early stage dynamics**

Conclusion

- Electromagnetic probes are very **sensitive** to:
 - initial conditions/pre-equilibrium flow
 - non-equilibrium properties/transport coefficients
 - dynamics in the cross-over region
- Recent theory improvements increase the relative weight of hadronic photon emission
 - theoretical direct photon v_2 is **larger**
- New ideas (Tsallis tail, late quark chemical equilibration, ...) need to be **tested** by building on current state-of-the-art calculations
- Photons are **clean** probes of small collision systems

Outlook

- Important input from experiments:
 - ➔ Low p_T (< 1 GeV) photons in pp collisions
provides baseline for all larger systems
 - ➔ Reduce systematic uncertainties in the current direct photon measurements
from qualitative description to quantitative study
 - ➔ Direct photon R_{pA} (proton-nucleus) for min. bias and central collisions
 - ➔ Direct photon anisotropic flow in small systems
important, complementary diagnostic tool for small systems

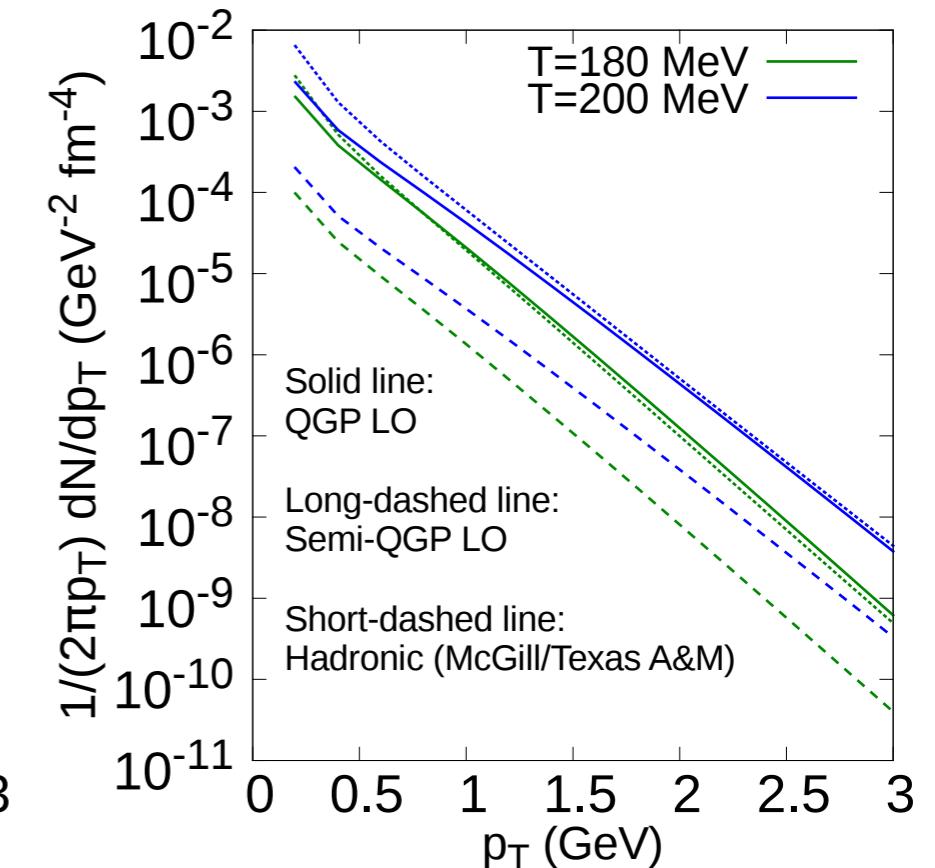
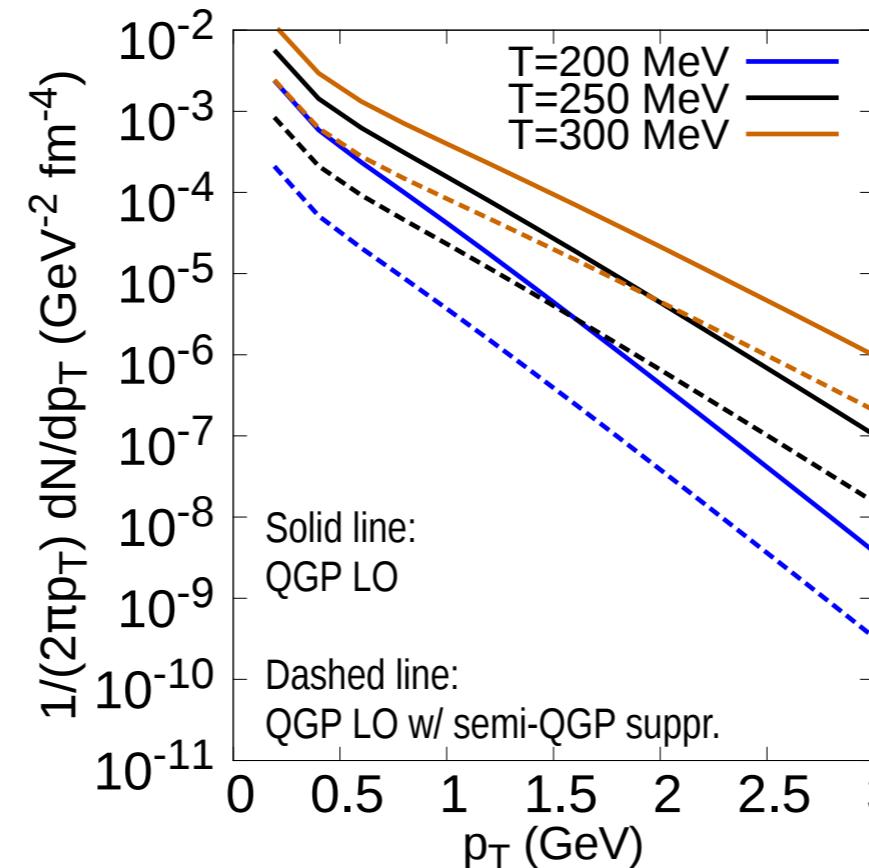
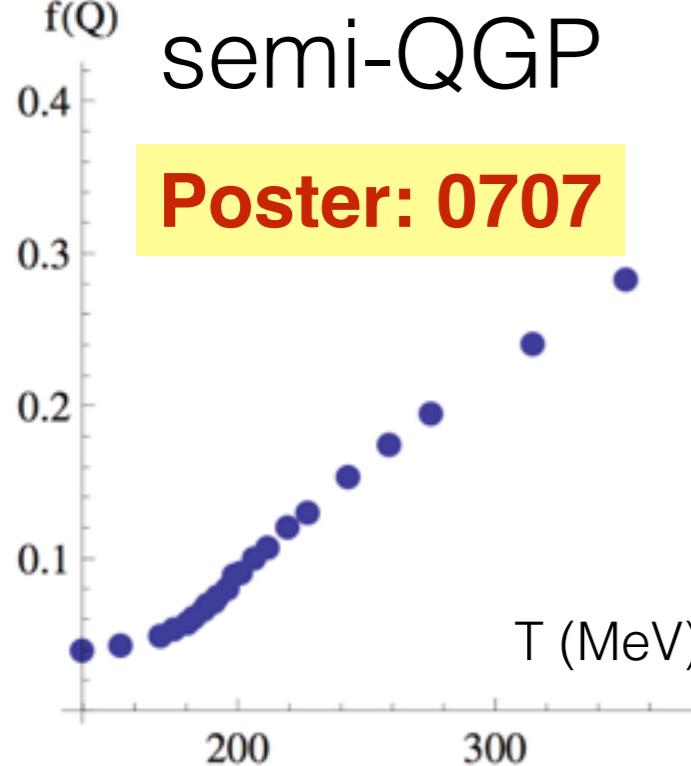
Back up

Non-perturbative corrections around T_c

C. Gale *et al*, Phys. Rev. Lett. **114**, 072301 (2015)

Y. Hidaka, S. Lin, R. D. Pisarski and D. Satow, arXiv:1504.01770

D. Satow and W. Weise, arXiv:1505.03869



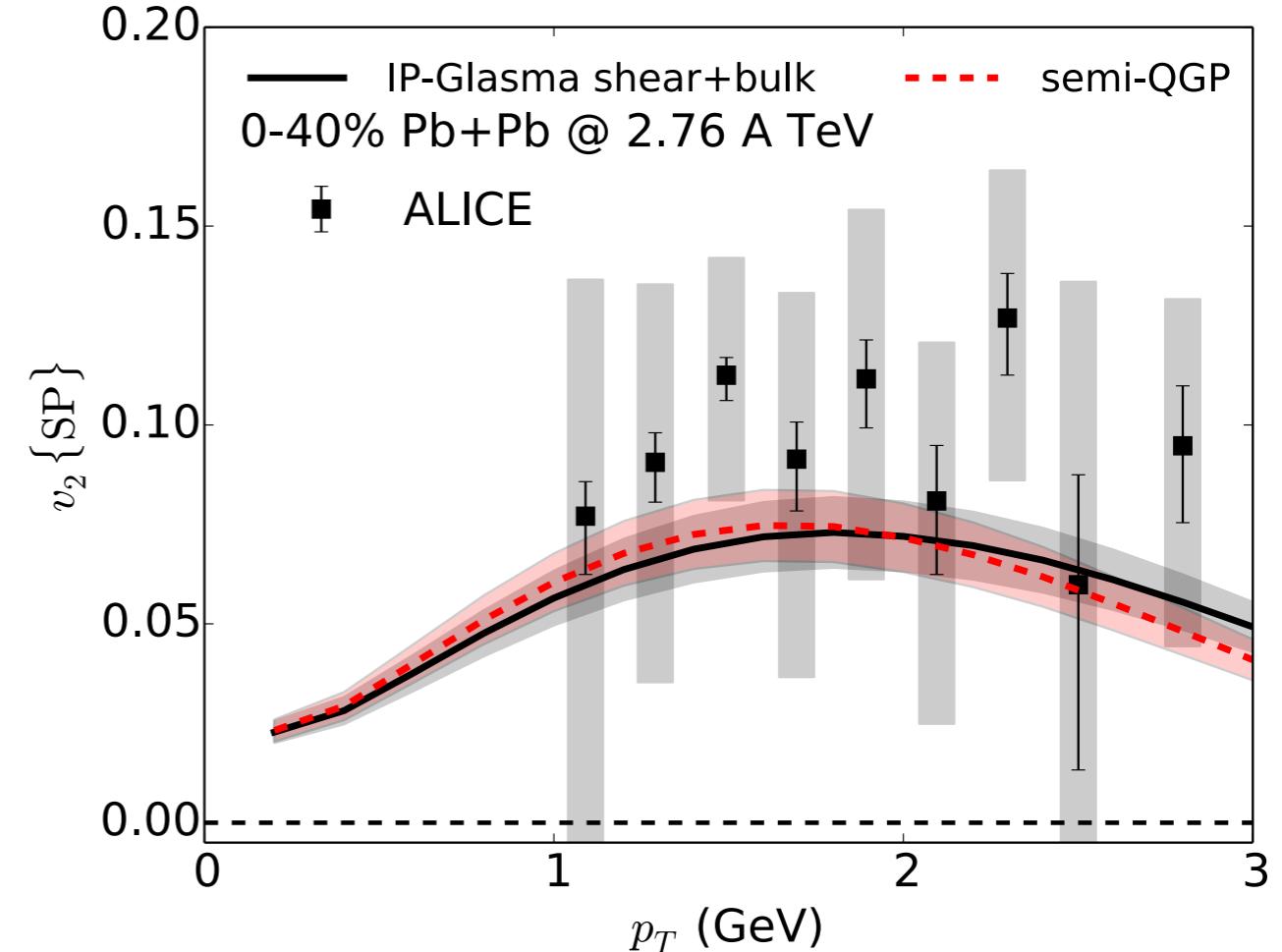
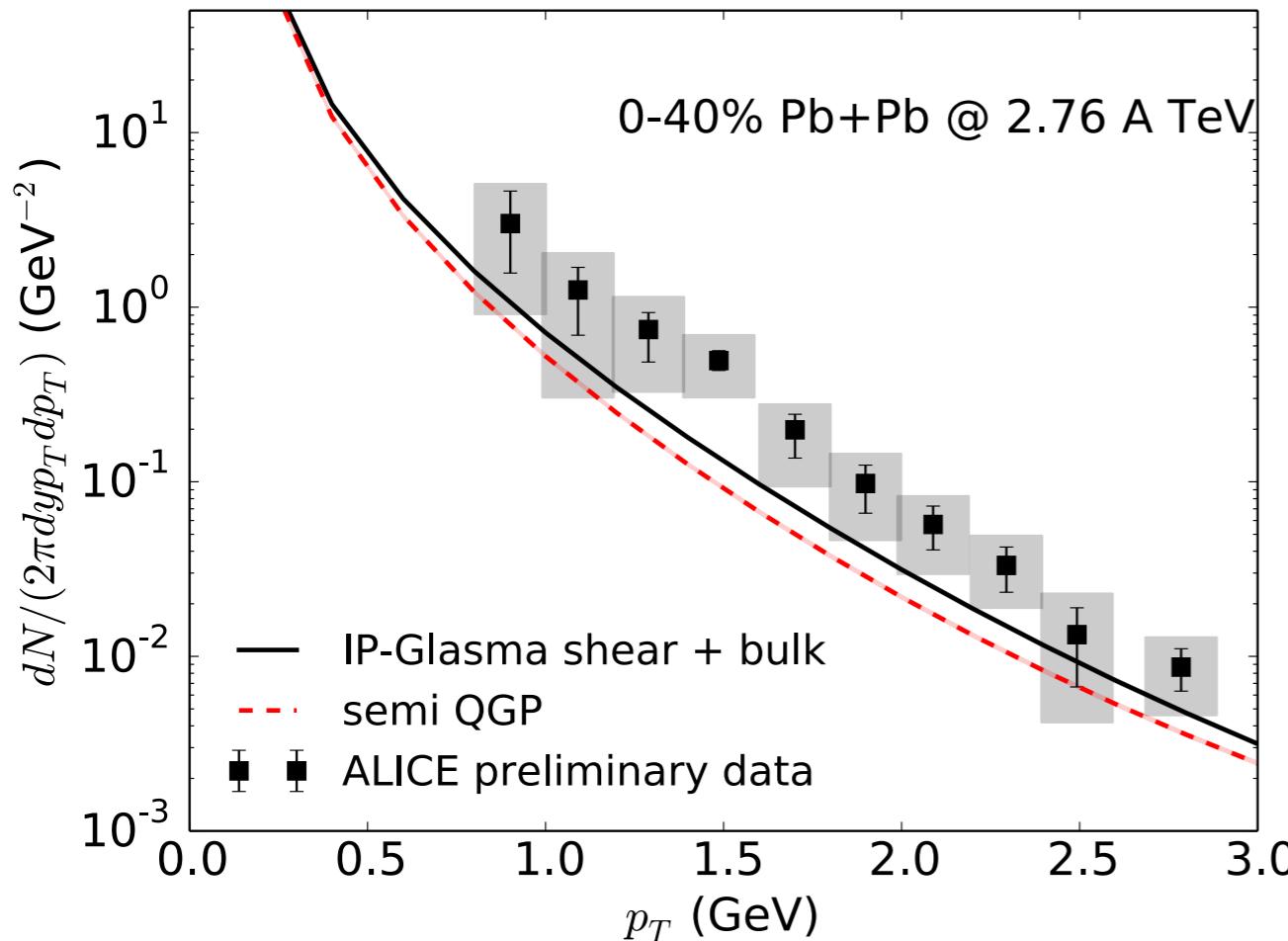
- QGP photon emission rates are suppressed by factor of 10 near T_c
- Mismatch between QGP and HG rates at same temperature
- A similar suppression is seen by fitting lattice EOS with a quasi-particle model

A.~Monnai, arXiv:1504.00406

Poster: 0715

Non-perturbative corrections around T_c

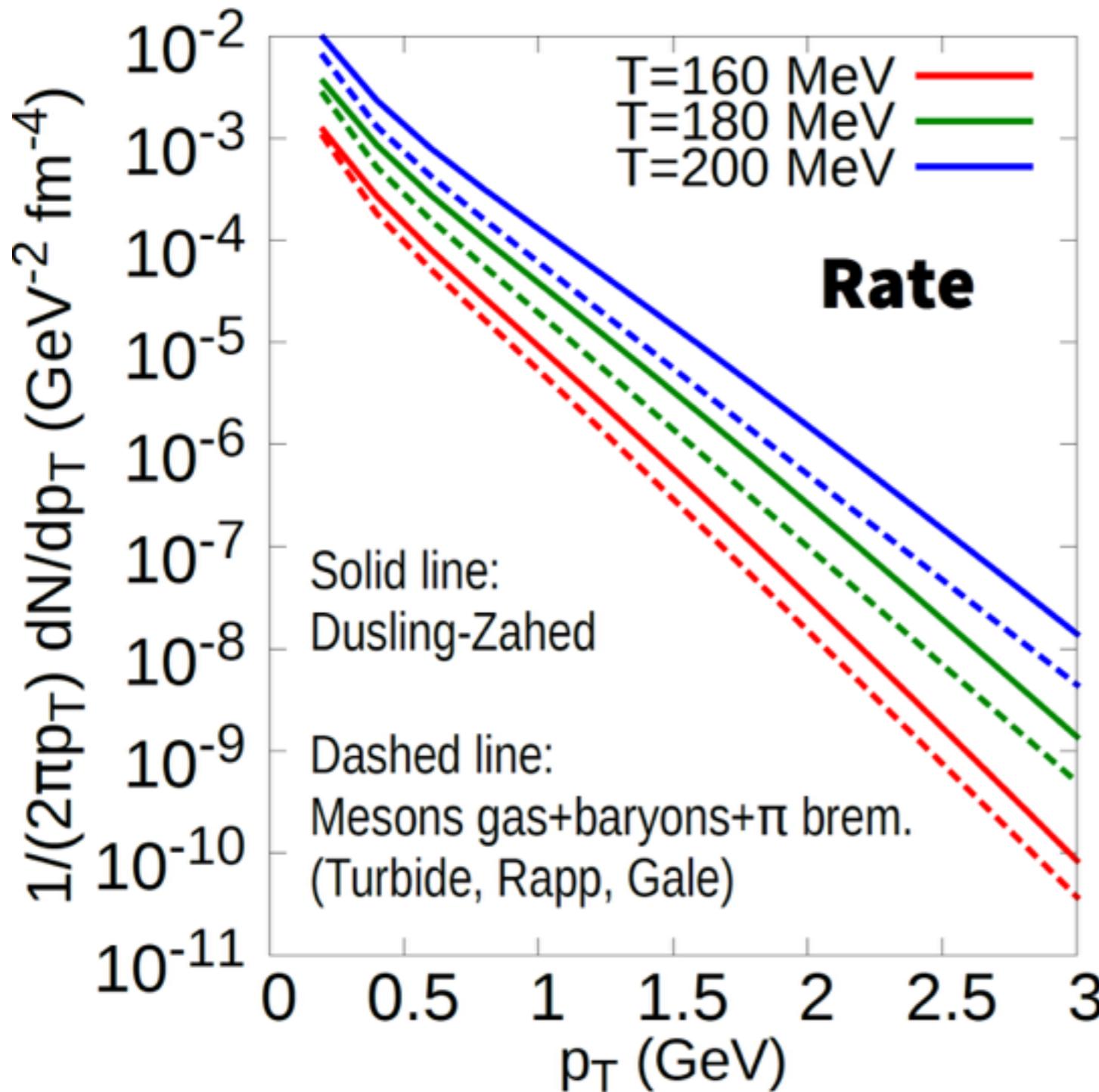
Paquet, *et al.*, arXiv:1509.06738



- Semi-QGP suppresses the direct photon spectrum by $\sim 30\%$
- The direct photon v_2 unchanged
- Semi-QGP scenario slightly increase direct photon v_2 but worsens the agreement with the direct photon spectrum

Alternative in hadronic rates

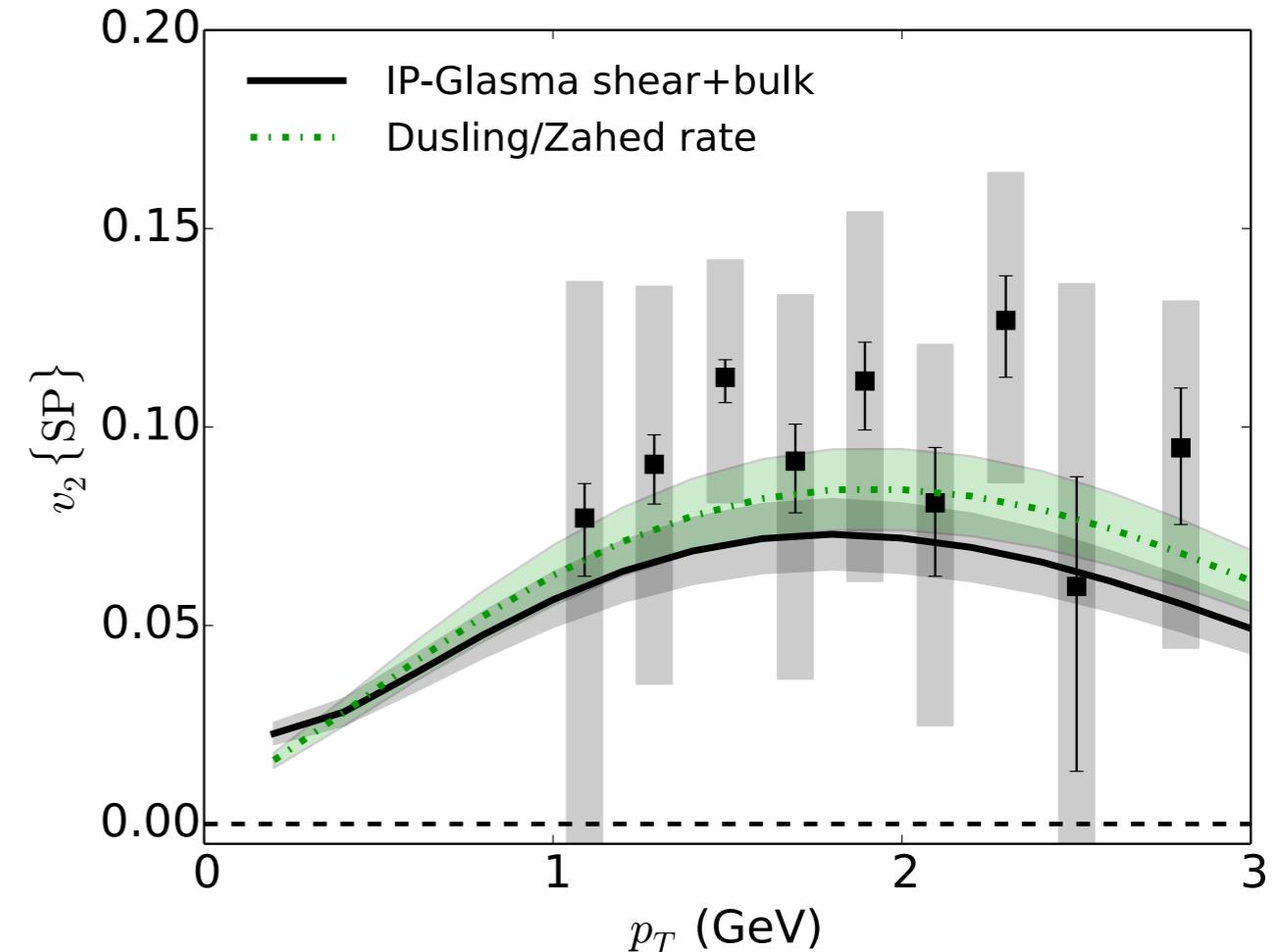
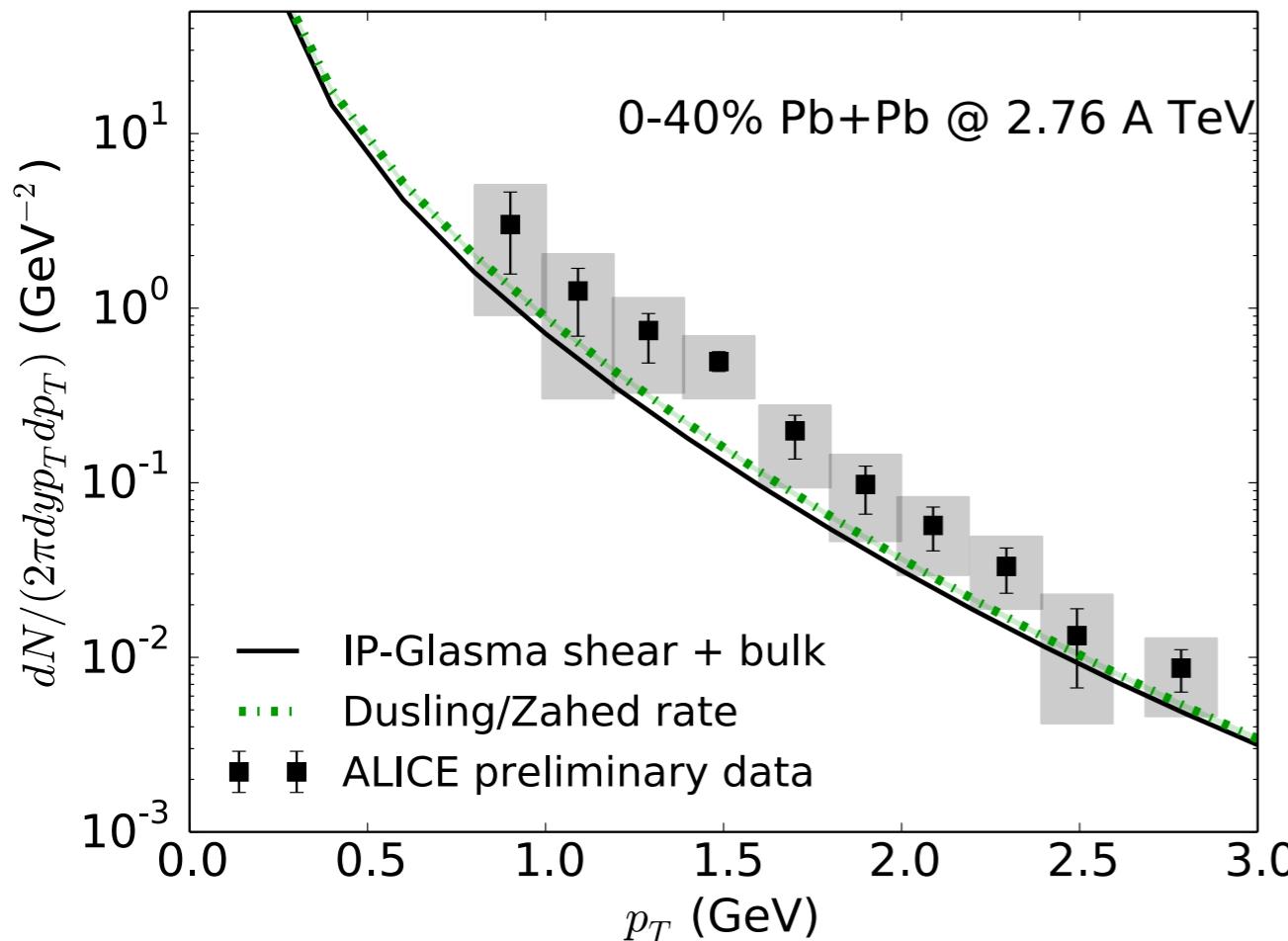
K. Dusling and I. Zahed, Phys. Rev. C **82**, 054909 (2010)



- Dusling/Zahed rate is systematically larger compared to TRG rate
- The relative differences increases from 40% to 100% as T increases from 100 MeV to 180 MeV

Alternative in hadronic rates

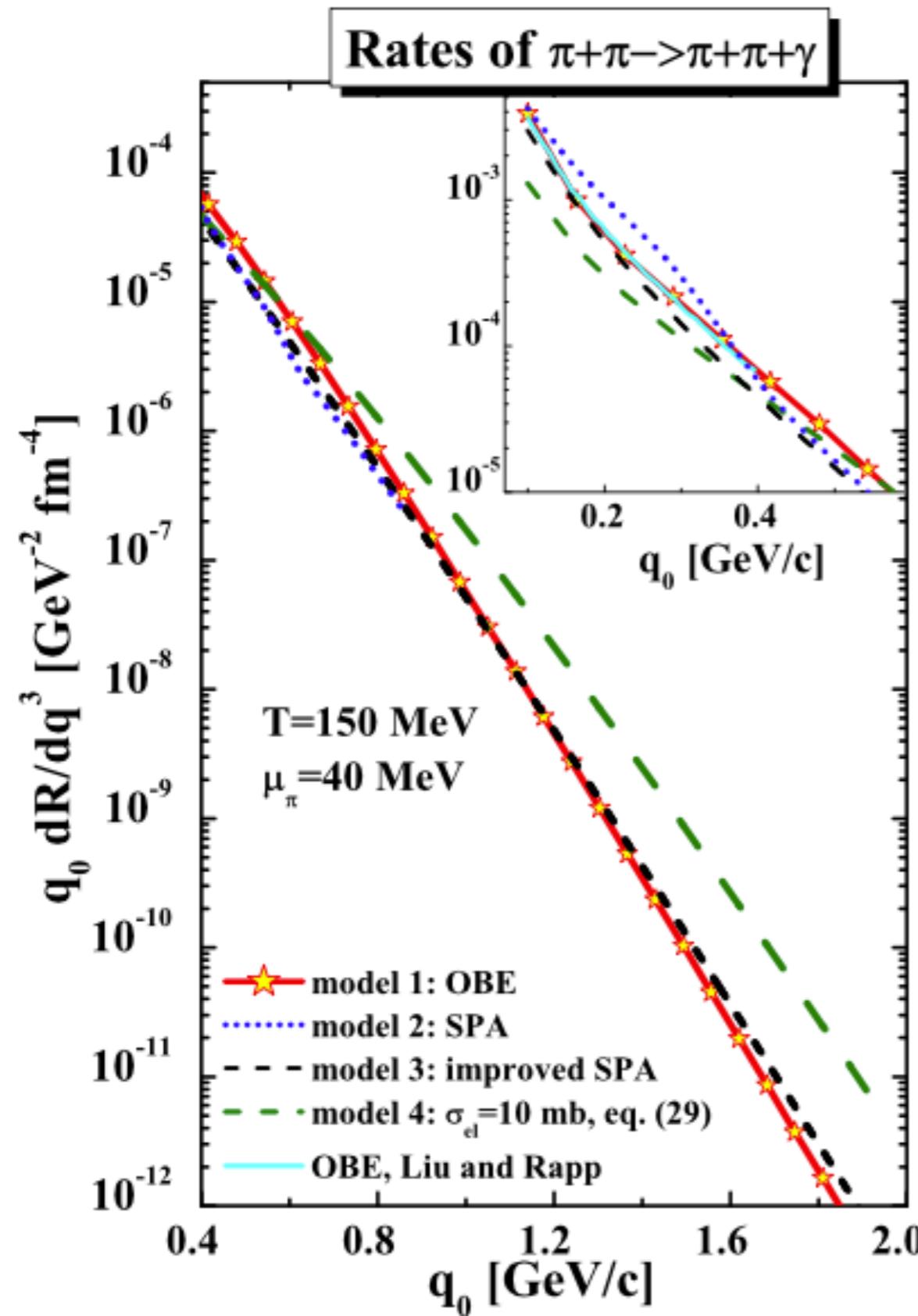
Paquet, *et al.*, arXiv:1509.06738



- Dusling/Zahed rate increases the direct photon spectrum by $\sim 20\%$
- The direct photon v_2 is increased due to more hadronic photon emission near T_c

Transport approach

O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing and E. L. Bratkovskaya, arXiv:1504.05699



- Including:



Improved soft photon approximation (SPA)

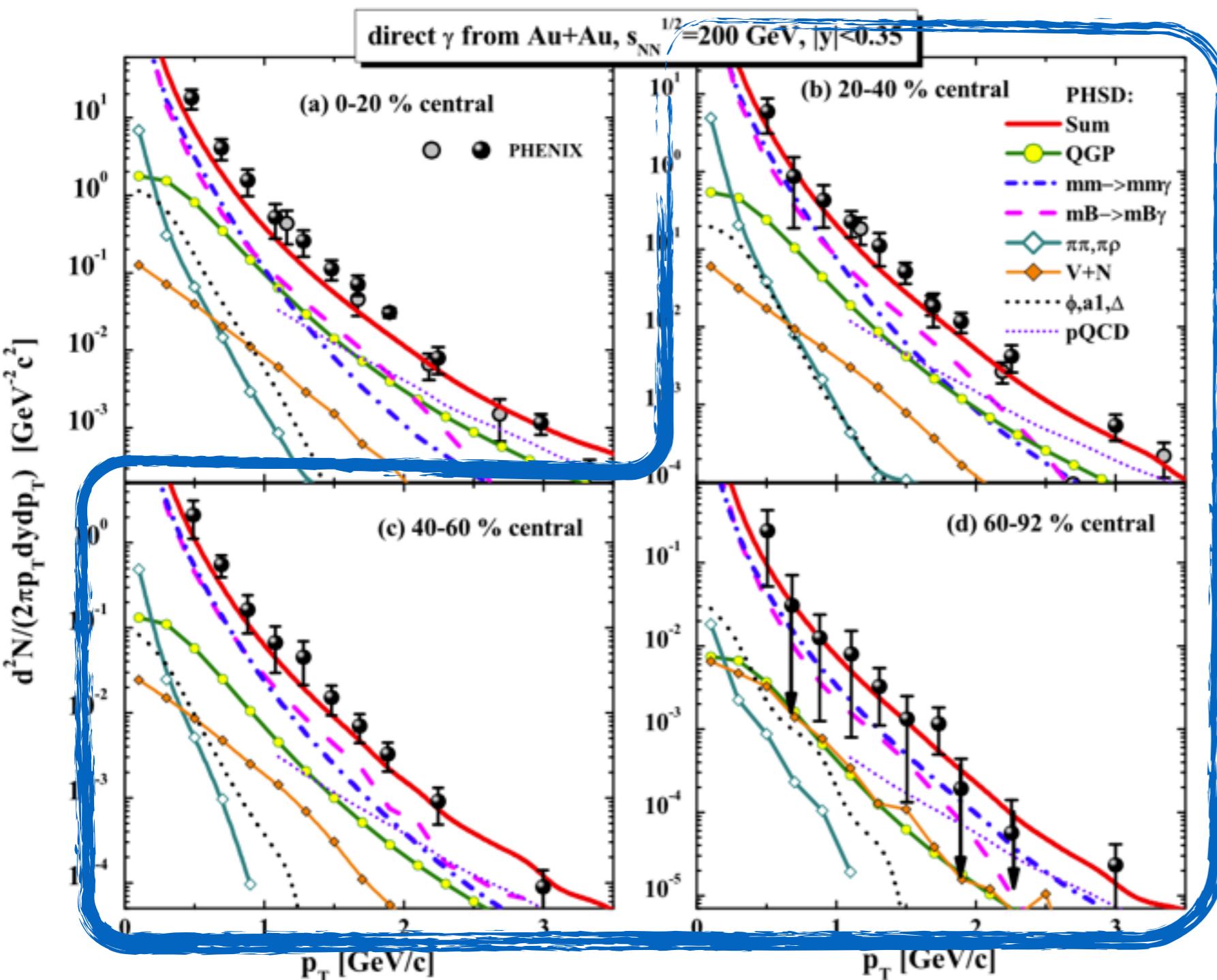
$$q_0 \frac{d\sigma^\gamma(s)}{d^3q} = \frac{\alpha_{EM}}{4\pi} \int_{-\lambda(s_2, m_a^2, m_b^2)/s_2}^0 |\epsilon \cdot J(q, t)|^2 \frac{d\sigma_{el}(s_2)}{dt} dt.$$

$$s_2 \equiv (p_a + p_b - q)^2$$

- The quality of improved SPA is tested against other model calculations for $\pi+\pi$ bremsstrahlung

Transport approach

O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing and E. L. Bratkovskaya, arXiv:1504.05699 [nucl-th]



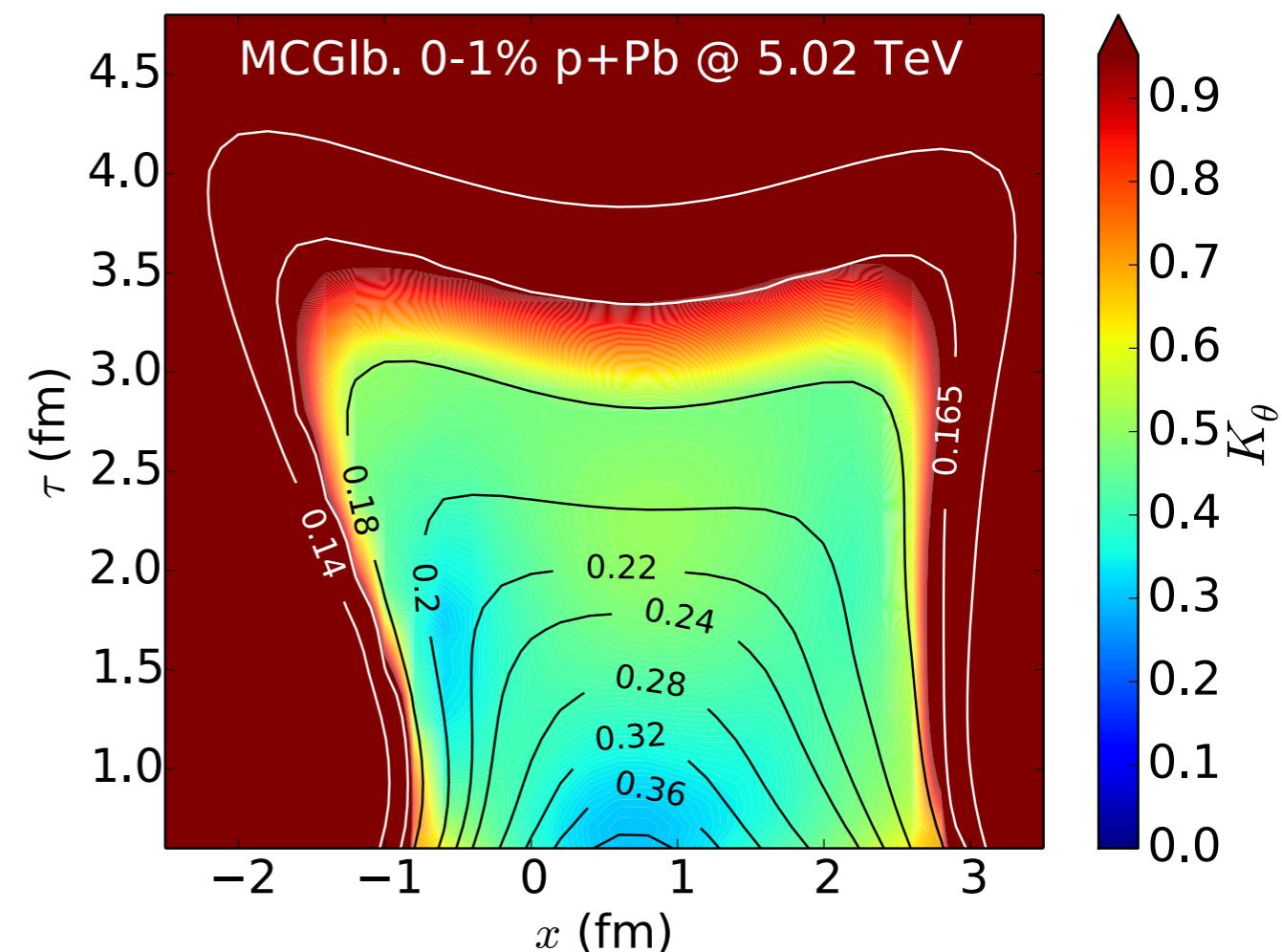
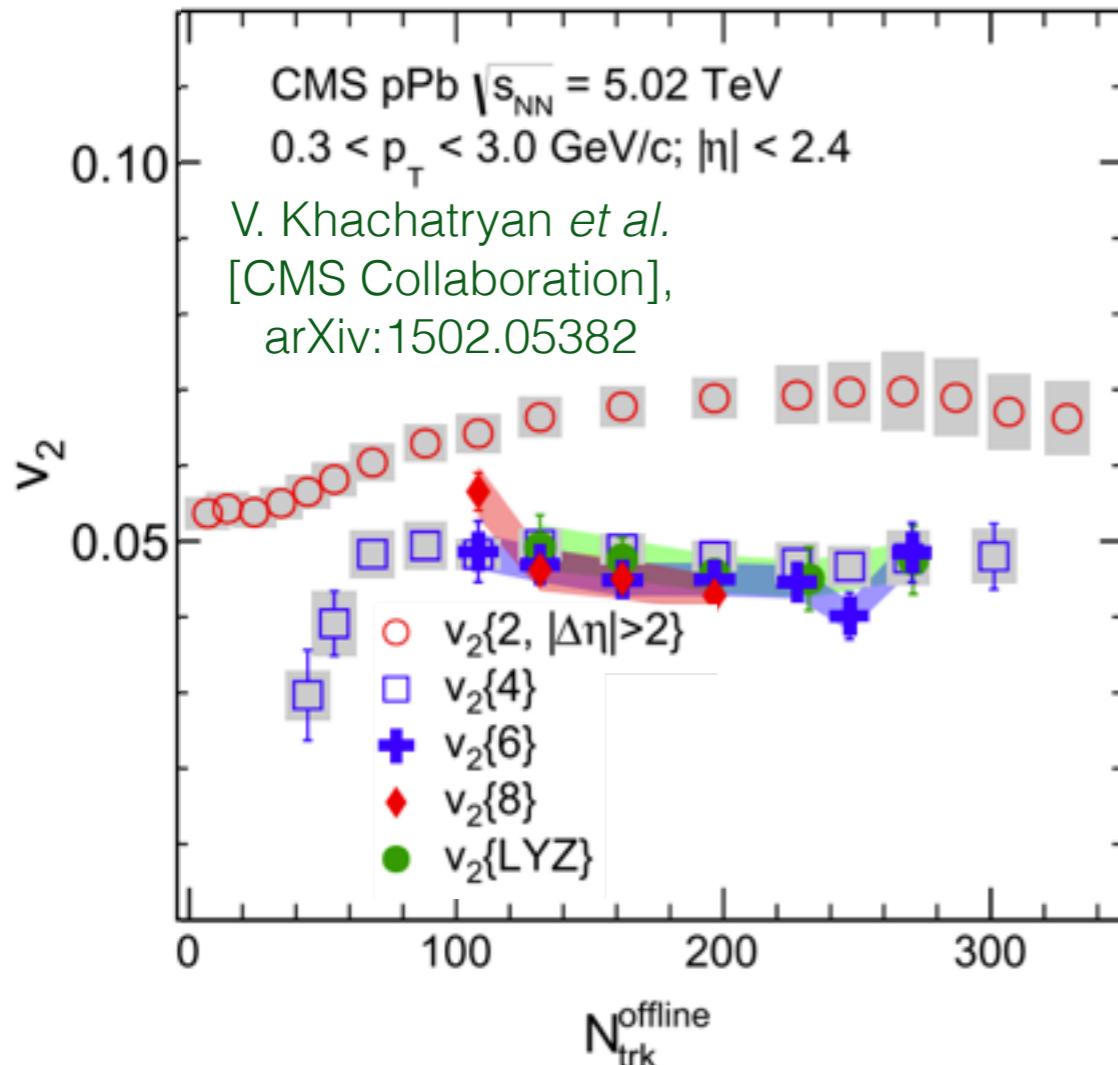
- Good description of the direct photon spectra from semi-central to peripheral centralities
- Majority of the thermal photons are emitted from meson-meson and meson-baryon bremsstrahlung

Thermal emission in small systems

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, arXiv:1504.07989

Collective behavior are observed in high multiplicity p+Pb and d+Au collisions at the RHIC and LHC

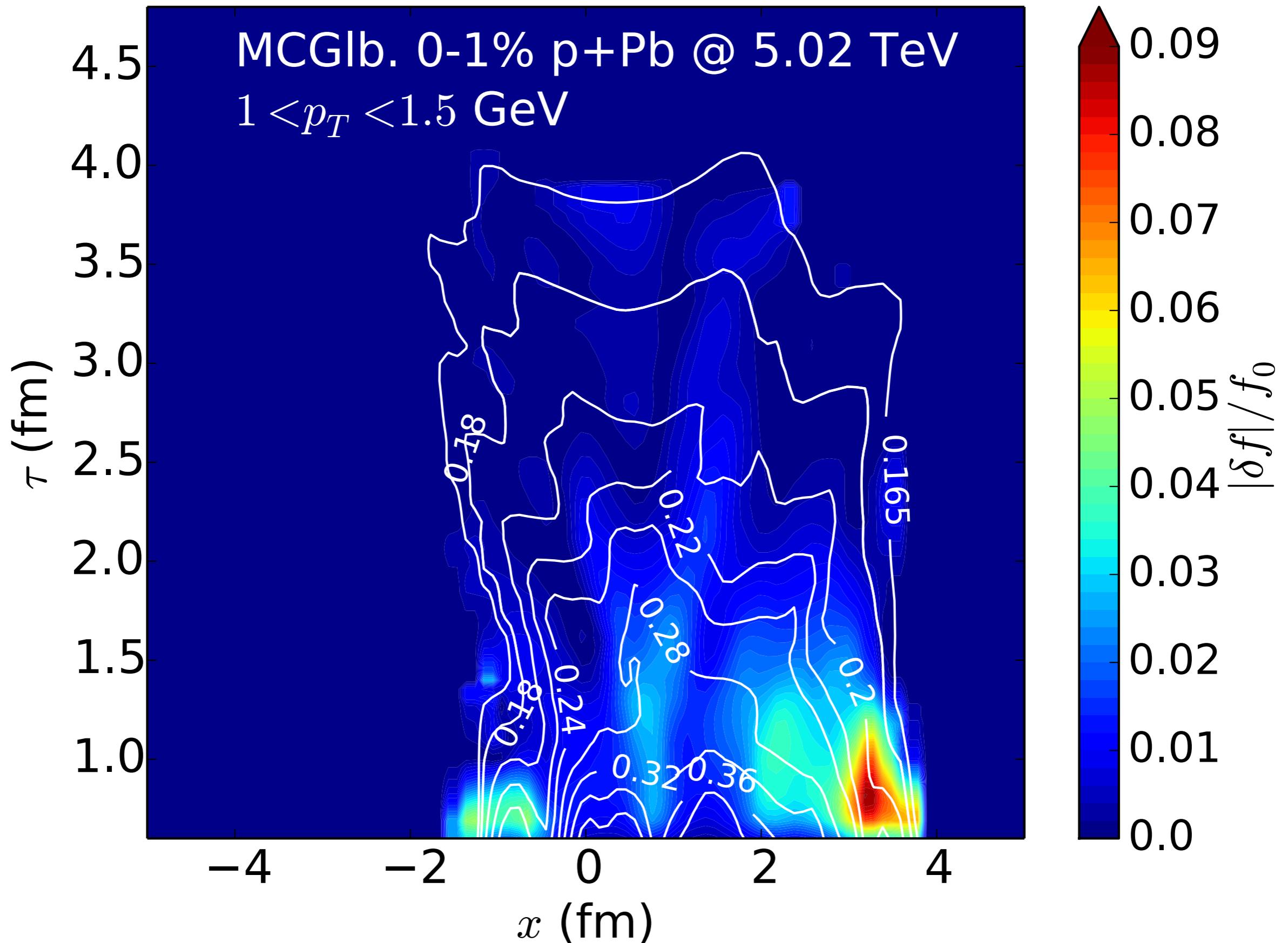
Gale Mon 17:00



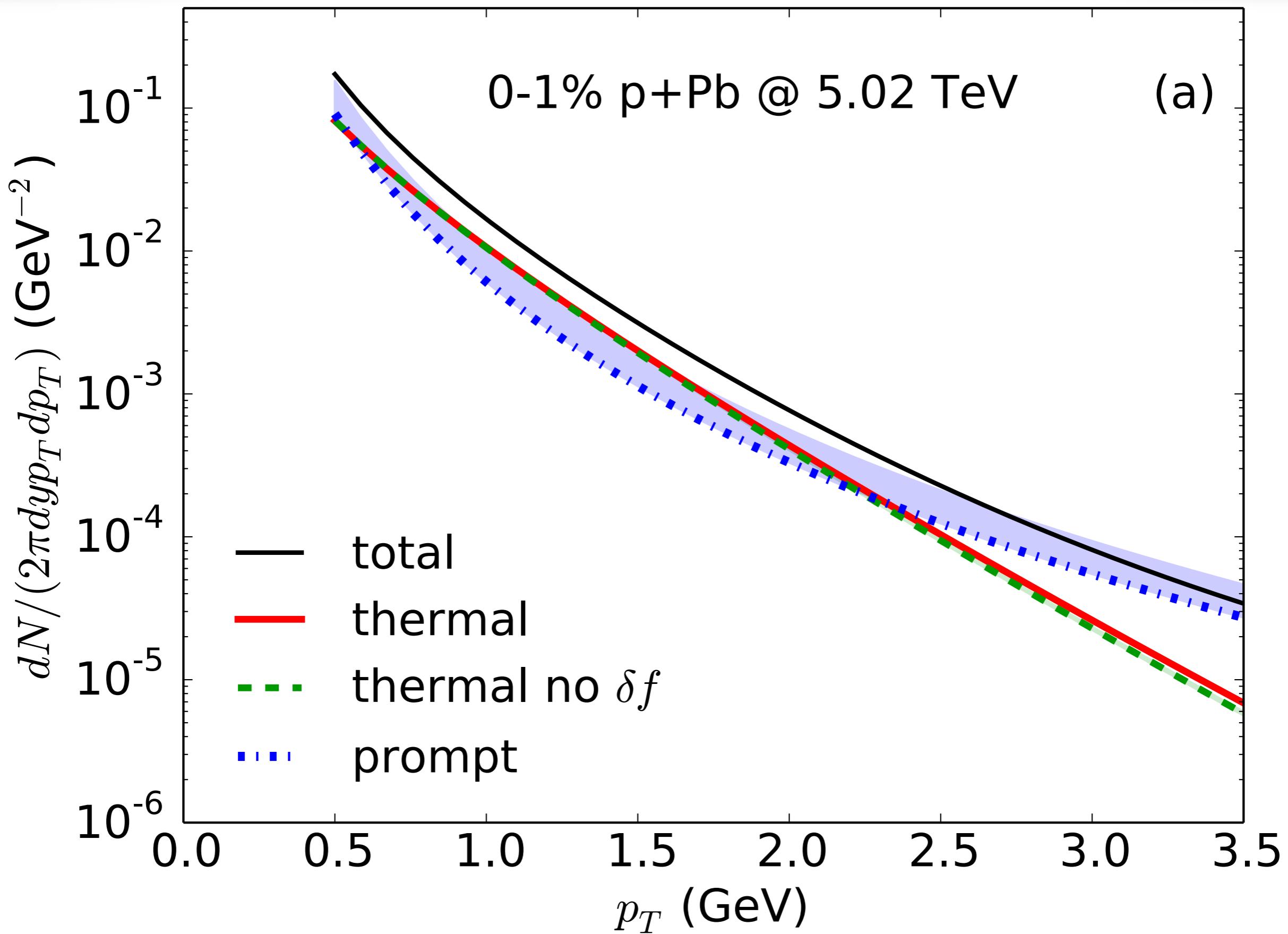
Within hydrodynamic framework, we find central p+Pb collisions can reach high temperature and the estimated Knudsen number is small

$$K_\theta = \frac{5\eta}{(e + \mathcal{P})} \partial_\mu u^\mu$$

viscous correction in pA

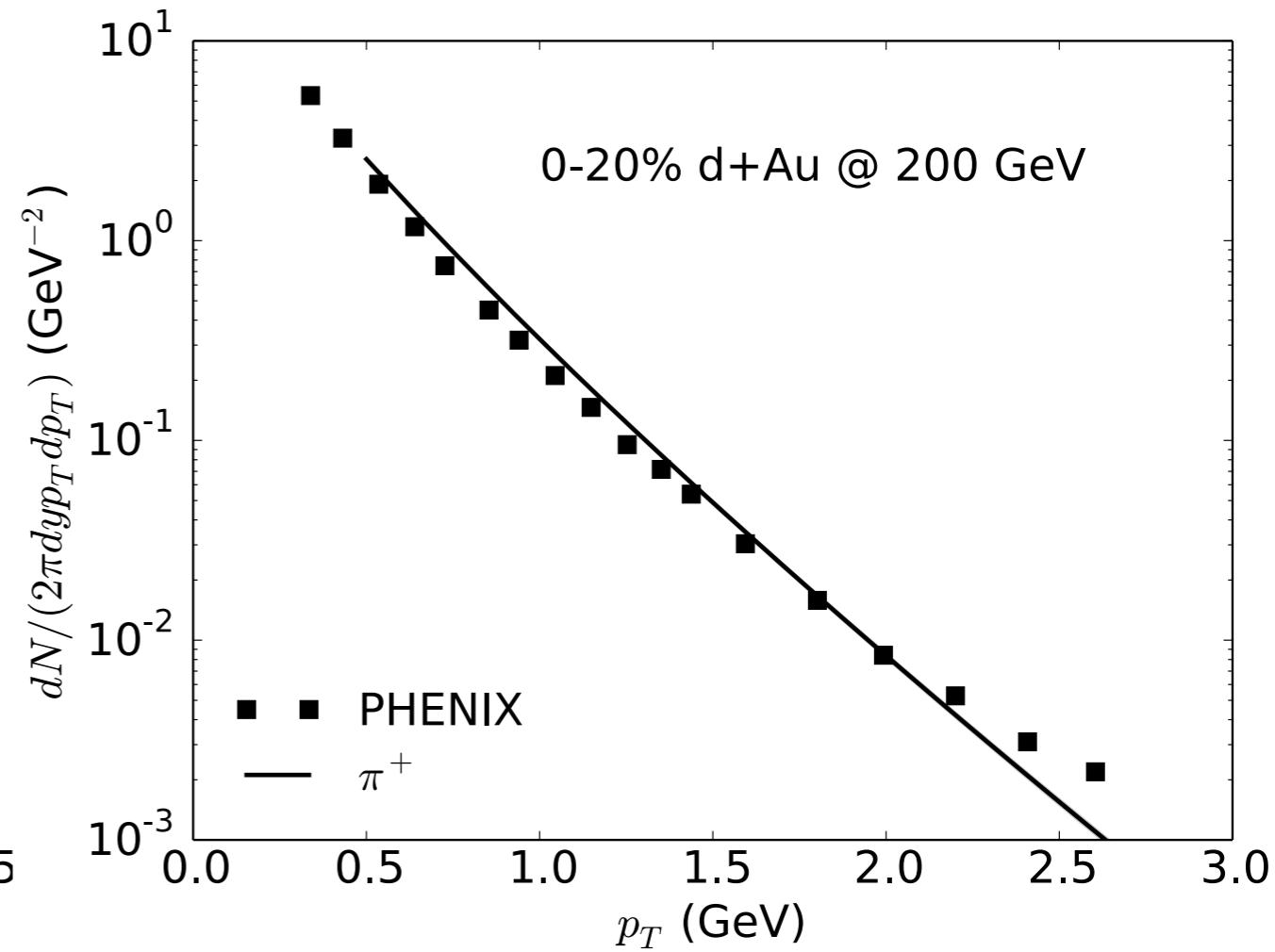
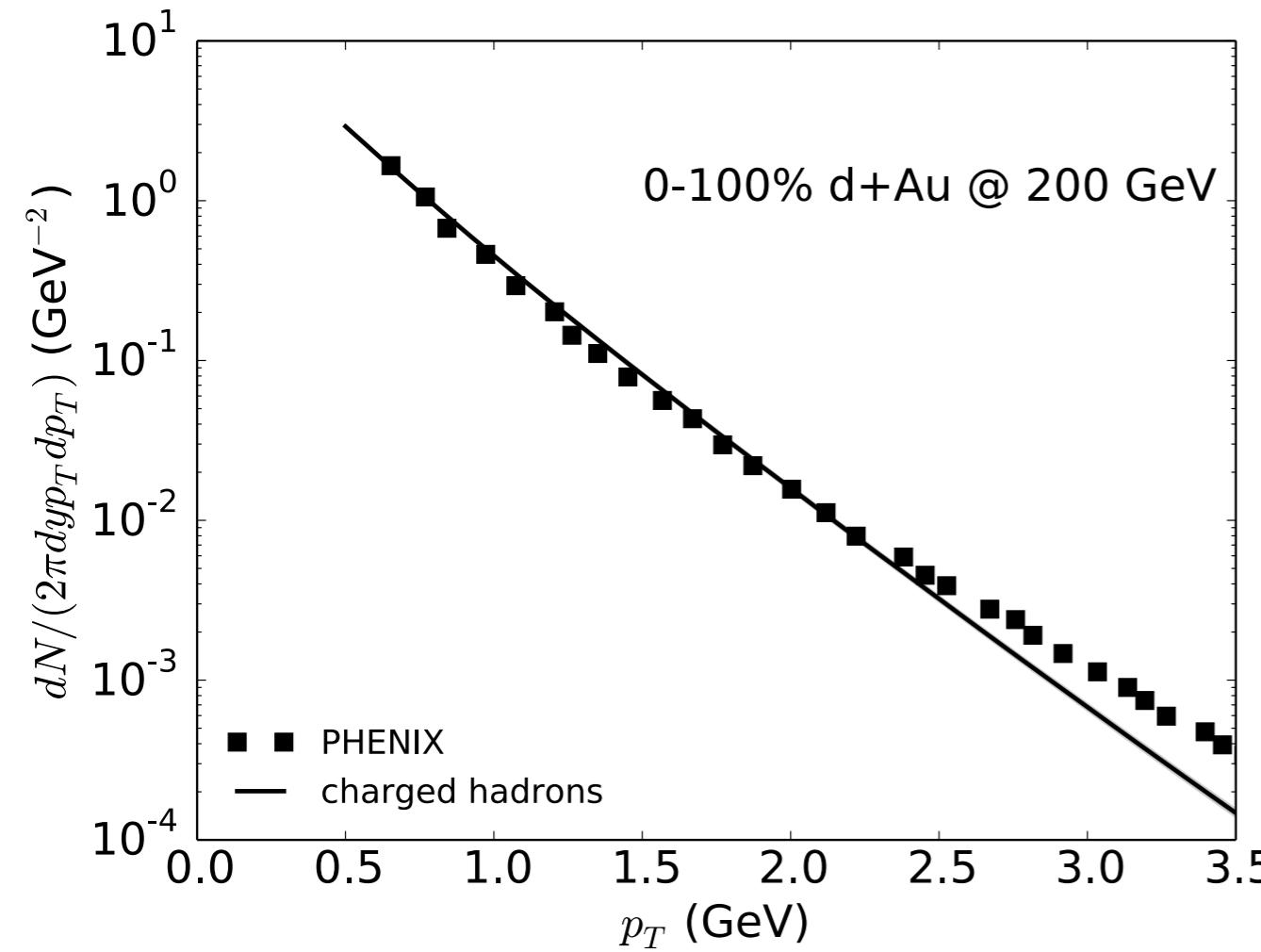


viscous correction in pA



Calibrate medium

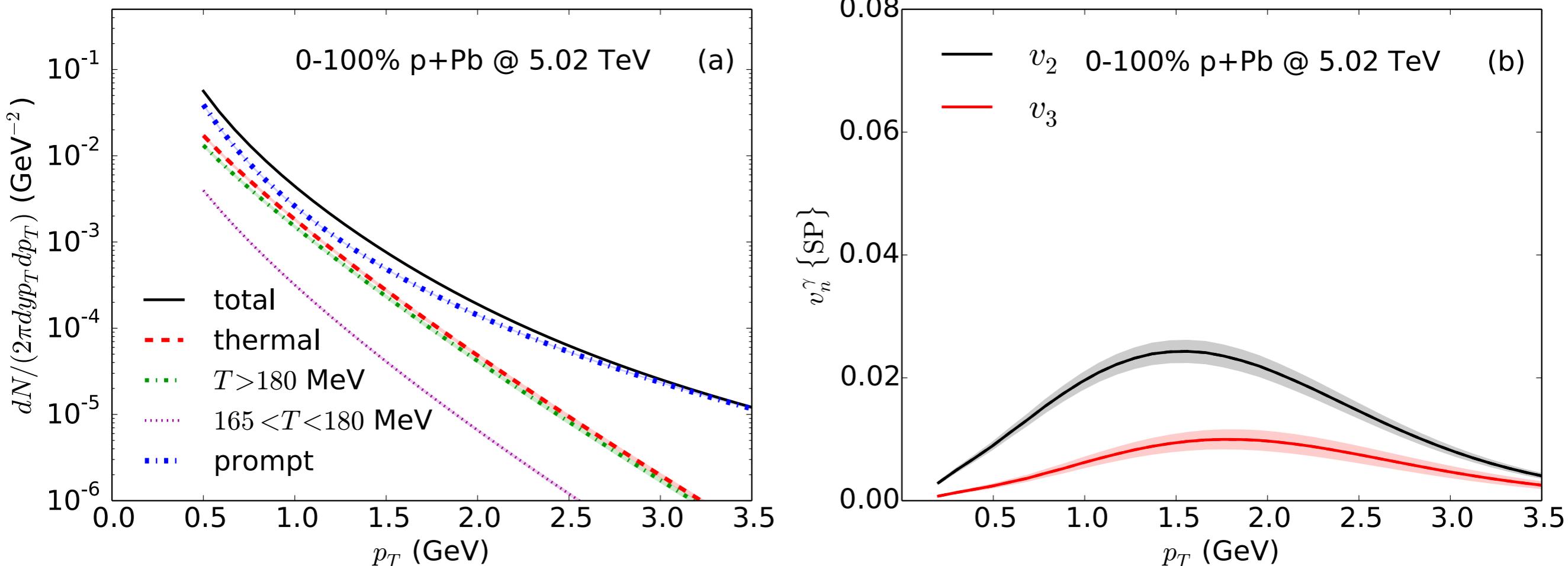
p+Pb @ 5.02 TeV	$\langle N_{\text{coll}} \rangle$	$\frac{dN^{\text{ch}}}{d\eta} \mid_{ \eta <0.5}$	$\langle p_T \rangle(\pi^+) \text{ (GeV)}$	$v_2^{\text{ch}}\{2\}$	$v_3^{\text{ch}}\{2\}$
0-1%	15.4 ± 0.03	57.6 ± 0.3	0.59 ± 0.01	0.056 ± 0.001	0.018 ± 0.001
0-100%	6.6 ± 0.01	16.6 ± 0.3	0.51 ± 0.02	0.034 ± 0.001	0.007 ± 0.001
d+Au @ 200 GeV	$\langle N_{\text{coll}} \rangle$	$\frac{dN^{\text{ch}}}{d\eta} \mid_{ \eta <0.5}$	$\langle p_T \rangle(\pi^+) \text{ (GeV)}$	$v_2^{\text{ch}}\{2\}$	$v_3^{\text{ch}}\{2\}$
0-100%	8.05 ± 0.01	8.85 ± 0.19	0.46 ± 0.02	0.025 ± 0.001	0.003 ± 0.001



(2+1)-d hydro can give a reasonable description of the hadronic data

Thermal emission in small systems

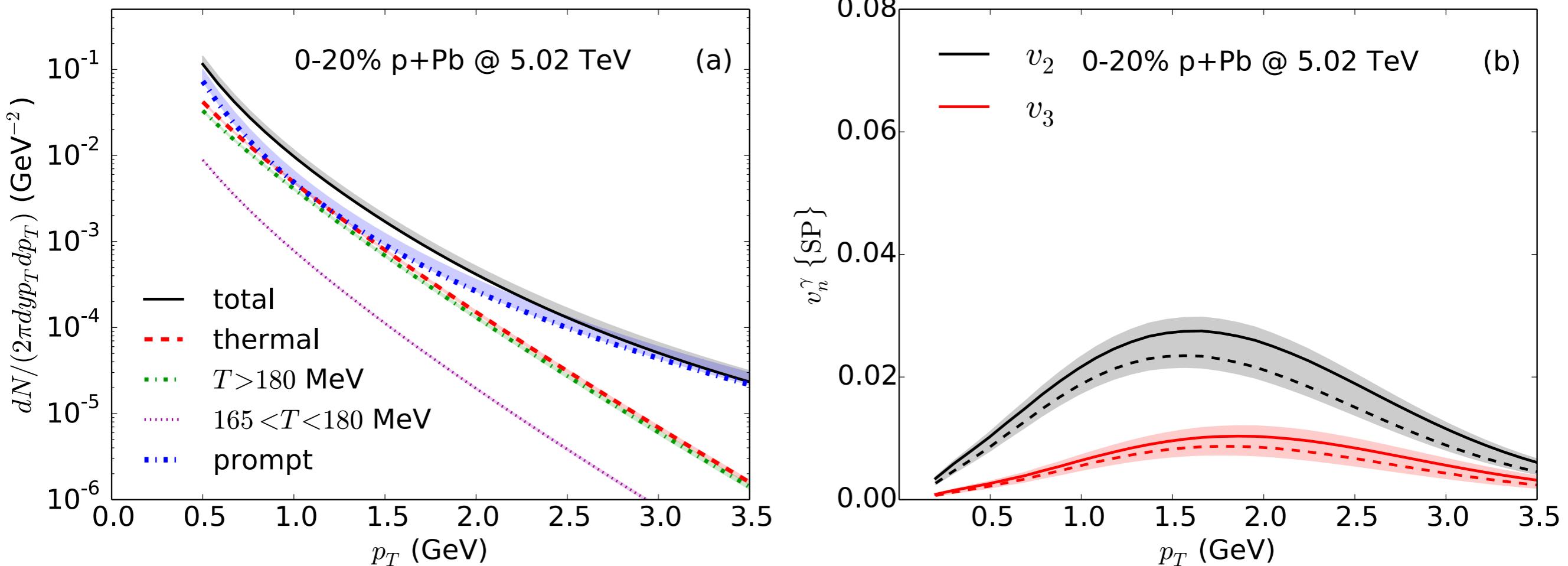
C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, arXiv:1504.07989



- In minimum bias p+Pb collisions, thermal photons are small compare to prompt photons
- There is sizeable direct photon anisotropic in p+Pb collisions

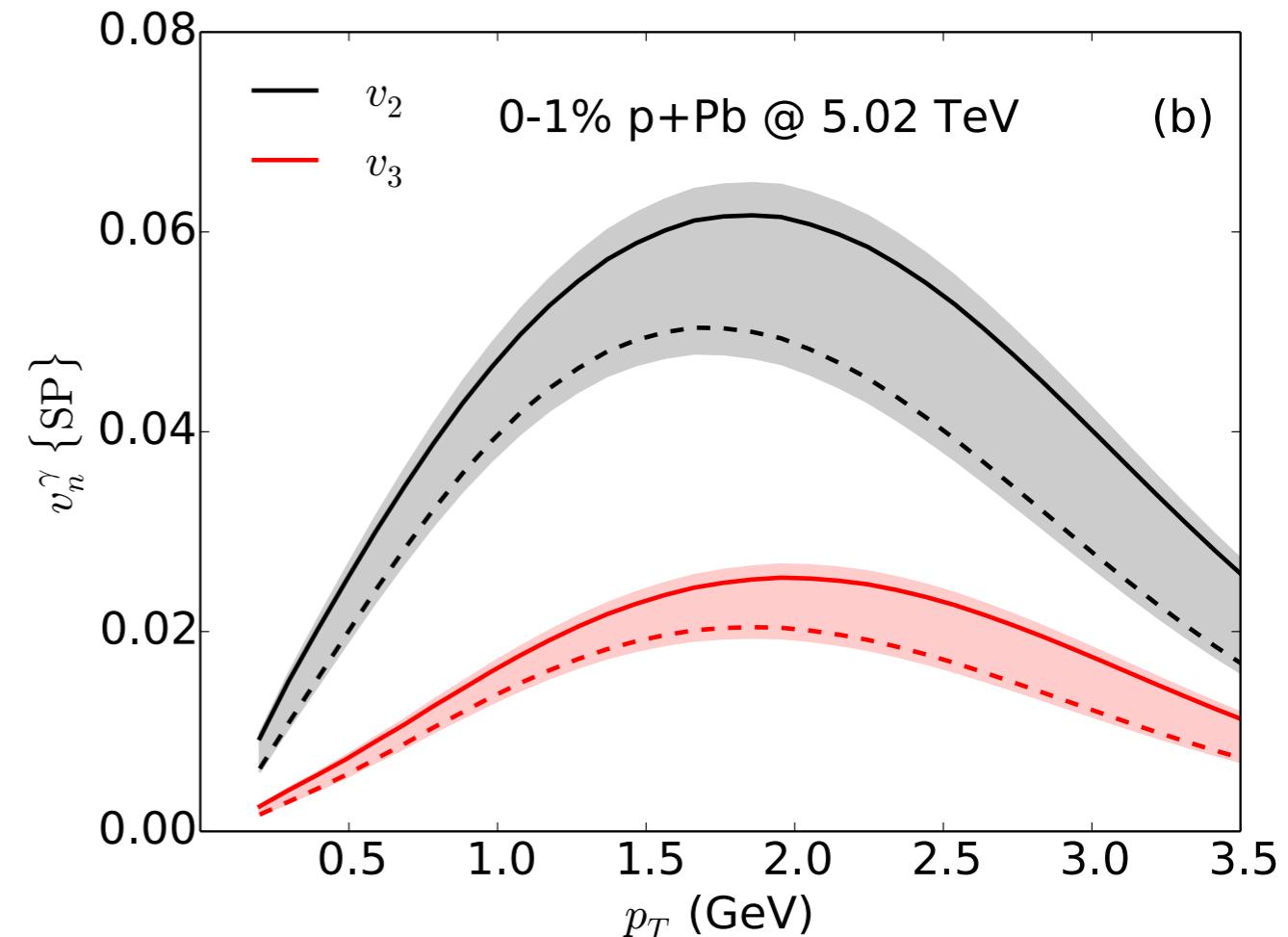
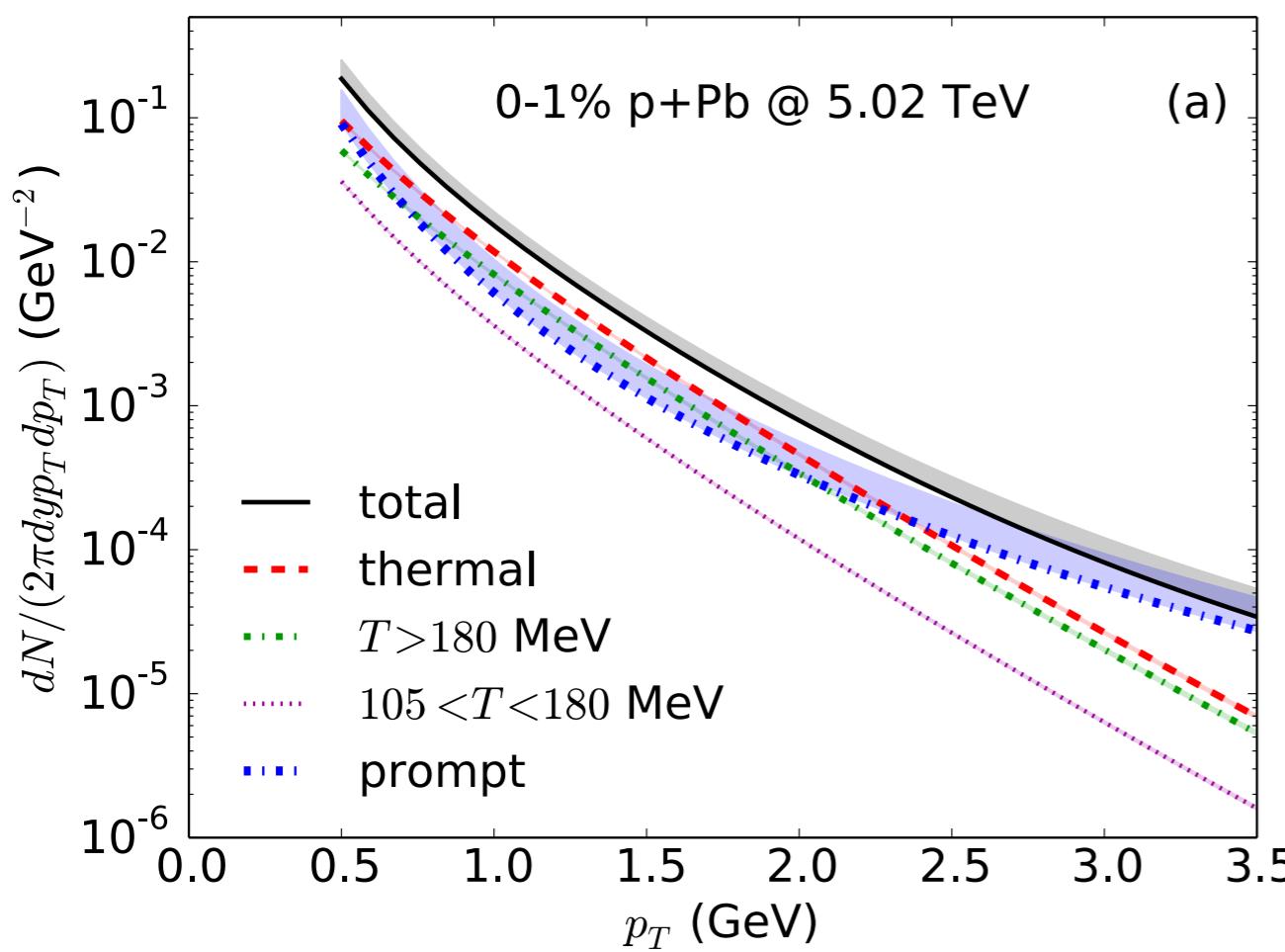
Thermal emission in small systems

C. Shen, J. F. Paquet, G. S. Denicol, S. Jeon and C. Gale, arXiv:1504.07989



- In 0-20% p+Pb collisions, thermal photons become comparable to prompt photons
- There is sizeable direct photon anisotropic in central p+Pb collisions

Direct photons

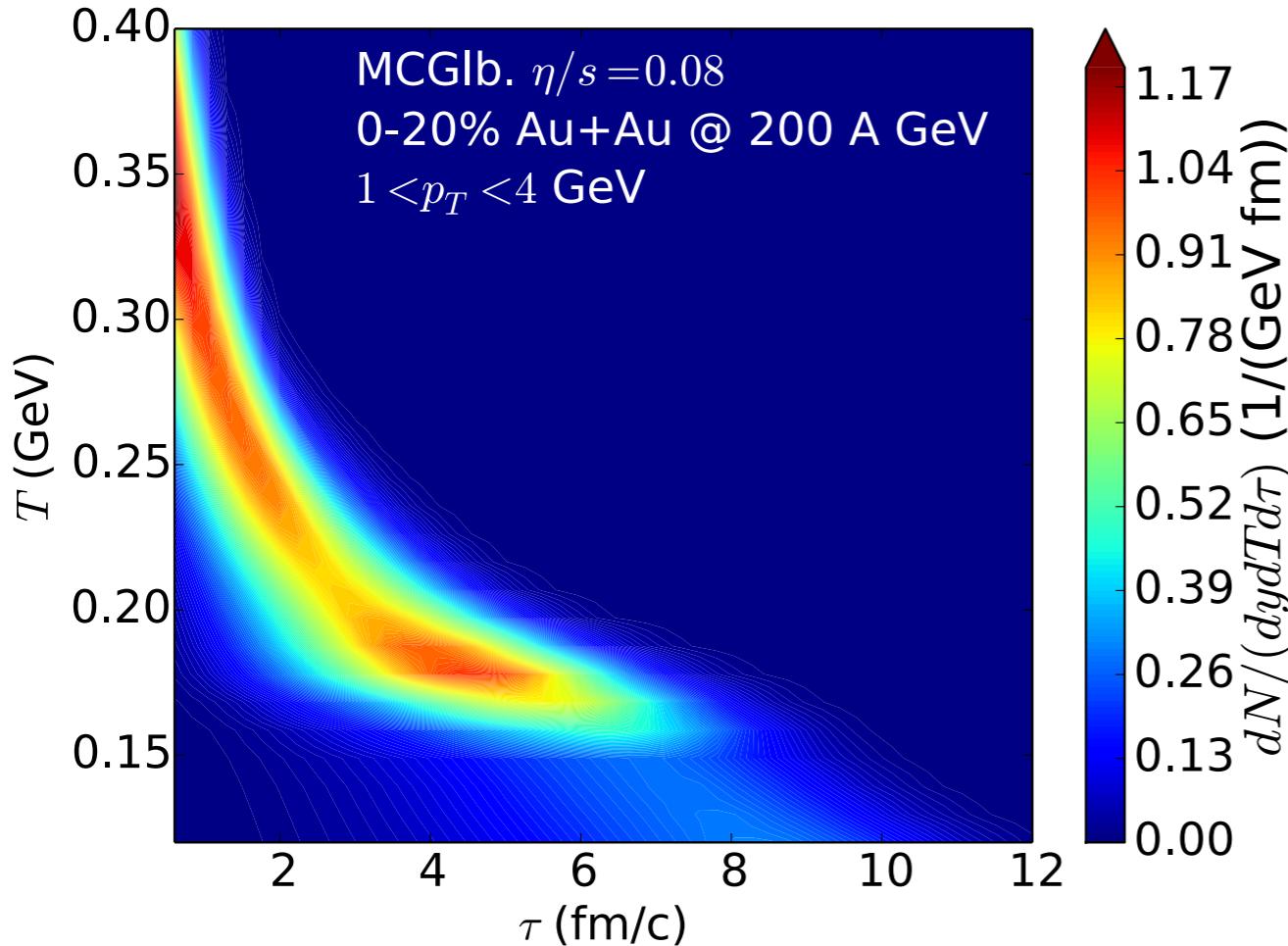


- In 0-1% p+Pb collisions, thermal photons can shine over prompt photons
- There is sizeable direct photon anisotropic in central p+Pb collisions

Thermal photon tomography

$$1 \leq p_T \leq 4 \text{ GeV}$$

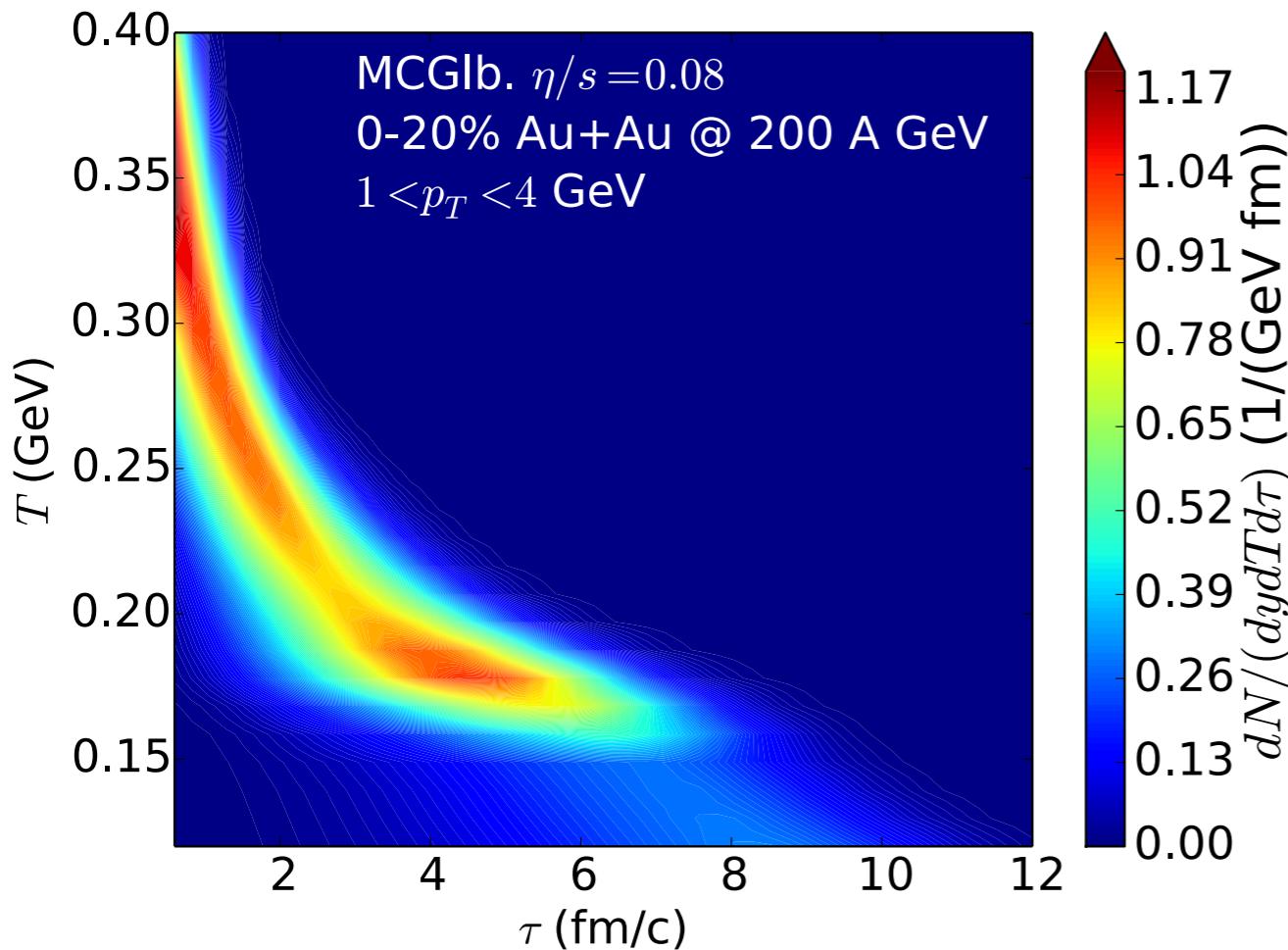
C. Shen, U. Heinz, J. F. Paquet, I. Kozlov, and
C. Gale, Phys. Rev. C **91**, 024908 (2015)



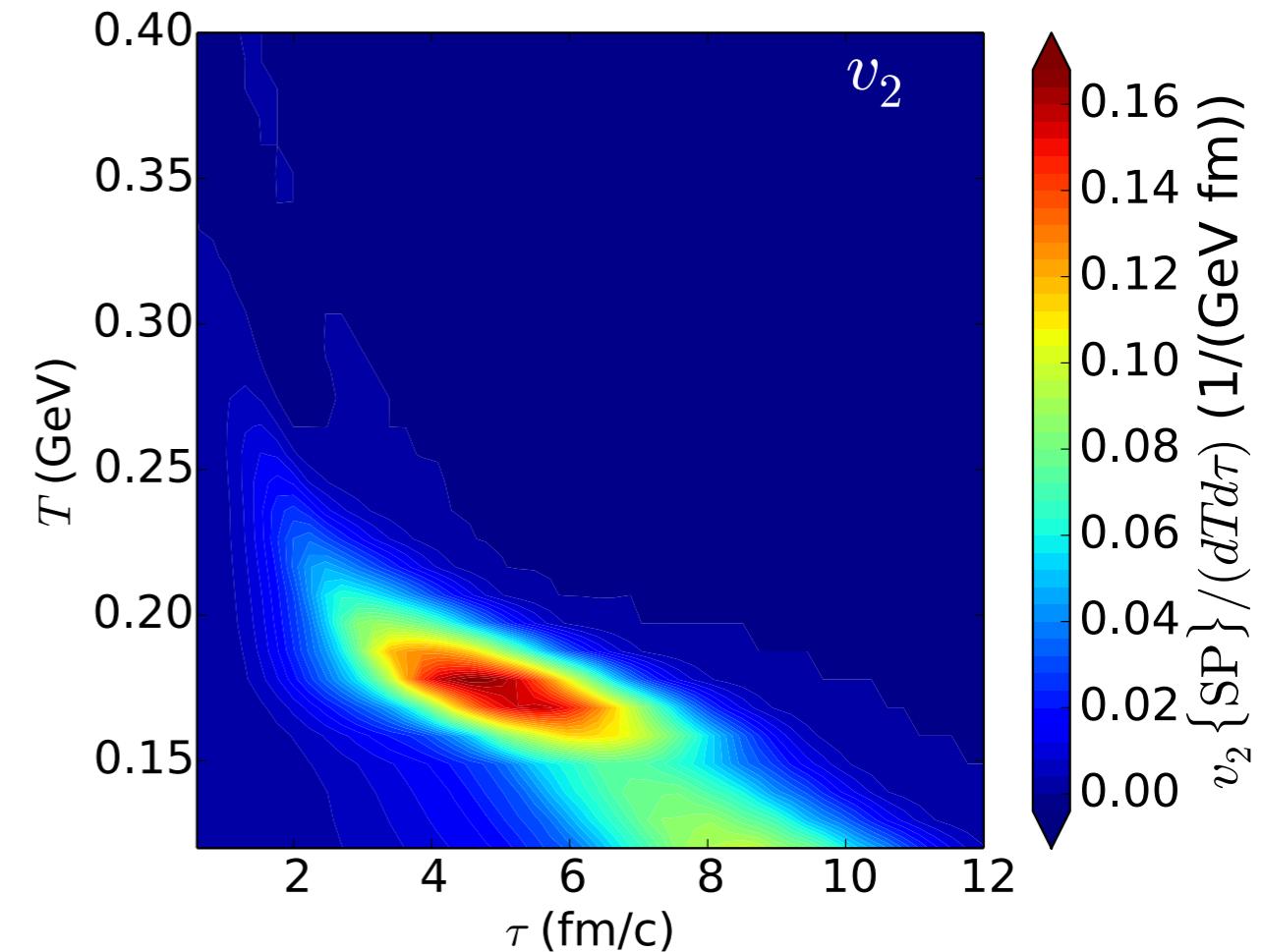
- By cutting hydro medium both in T and τ , we observe a **two-wave** structure in thermal photon emission
 - early time production — high rates at high temperatures
 - near transition region — growth of space-time volume

Thermal photon tomography

$$1 \leq p_T \leq 4 \text{ GeV}$$



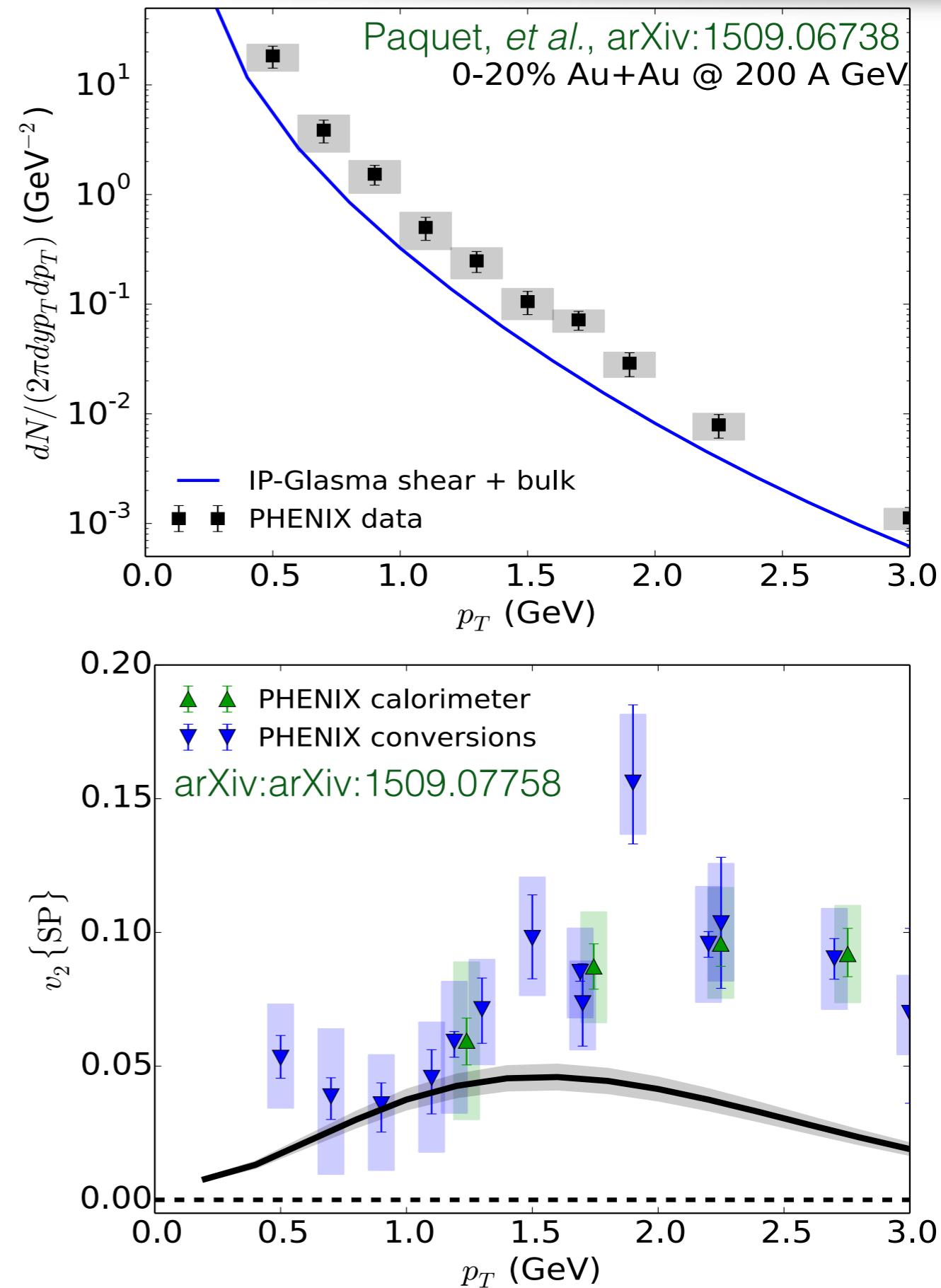
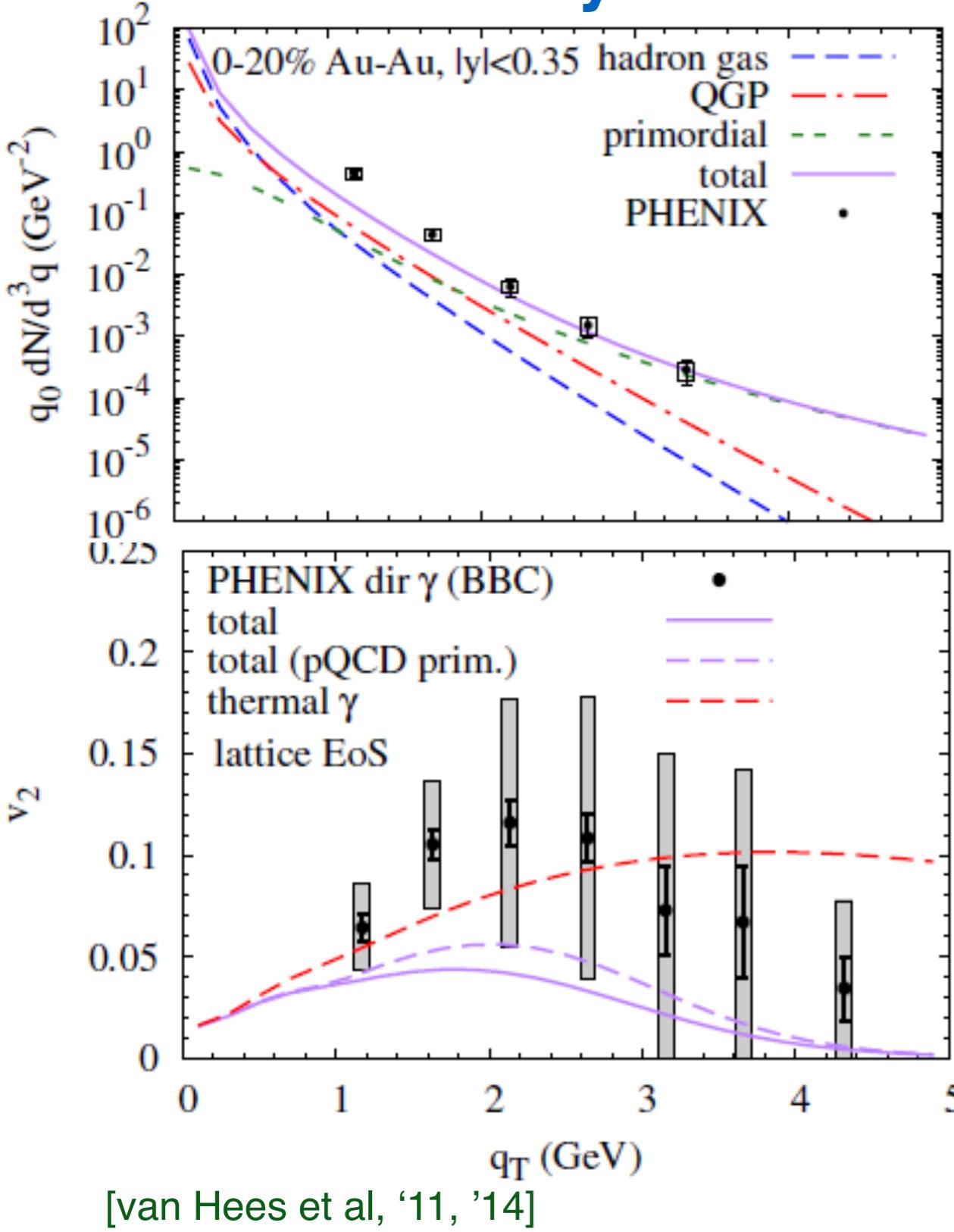
C. Shen, U. Heinz, J. F. Paquet, I. Kozlov, and C. Gale, Phys. Rev. C **91**, 024908 (2015)



- By cutting hydro medium both in T and τ , we observe a **two-wave** structure in thermal photon emission
- Thermal photon v_2 is mostly coming from the transition region, $T = 150\text{--}200 \text{ MeV}$, $\tau = 3 \sim 8 \text{ fm}$ @ RHIC

Towards resolving the direct photon flow puzzle

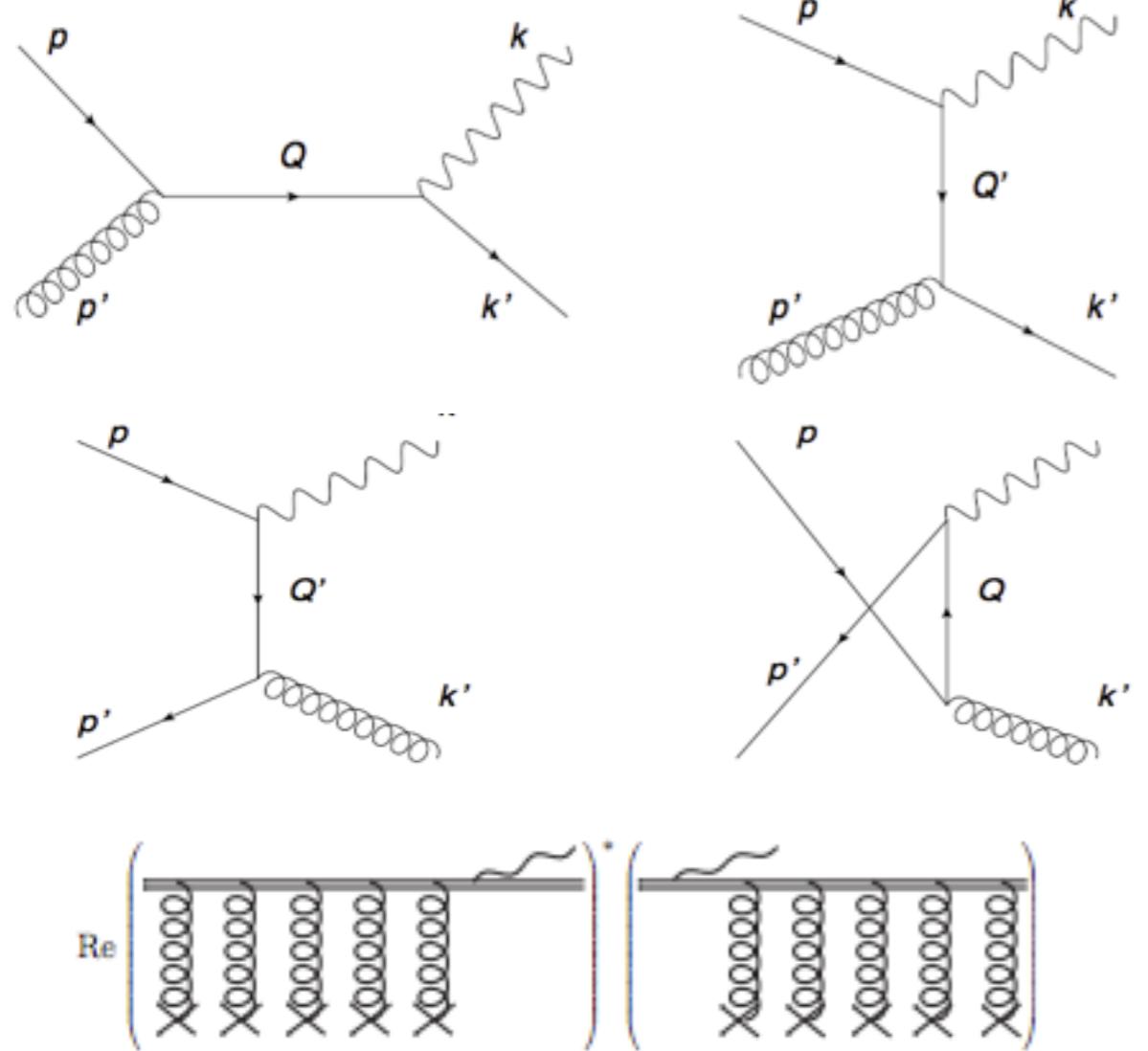
ideal hydro



Photon emission rate

QGP

LO: AMY JHEP **0112**, 009, (2001)

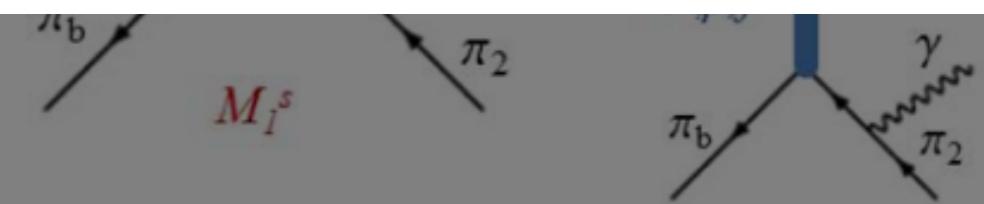
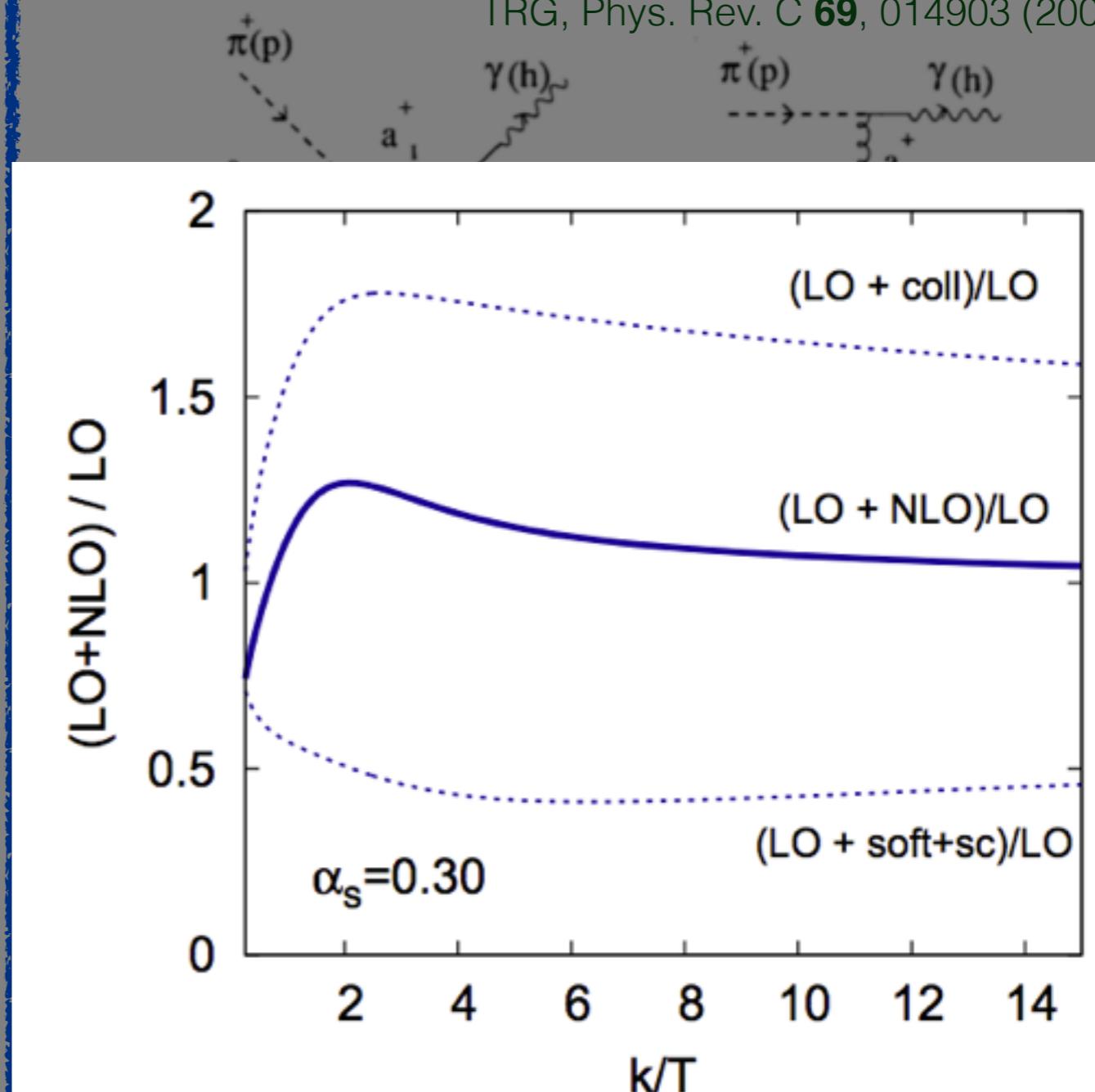


NLO: J. Ghiglieri *et al.*, JHEP **1305**, 010 (2013)



Hadron Gas

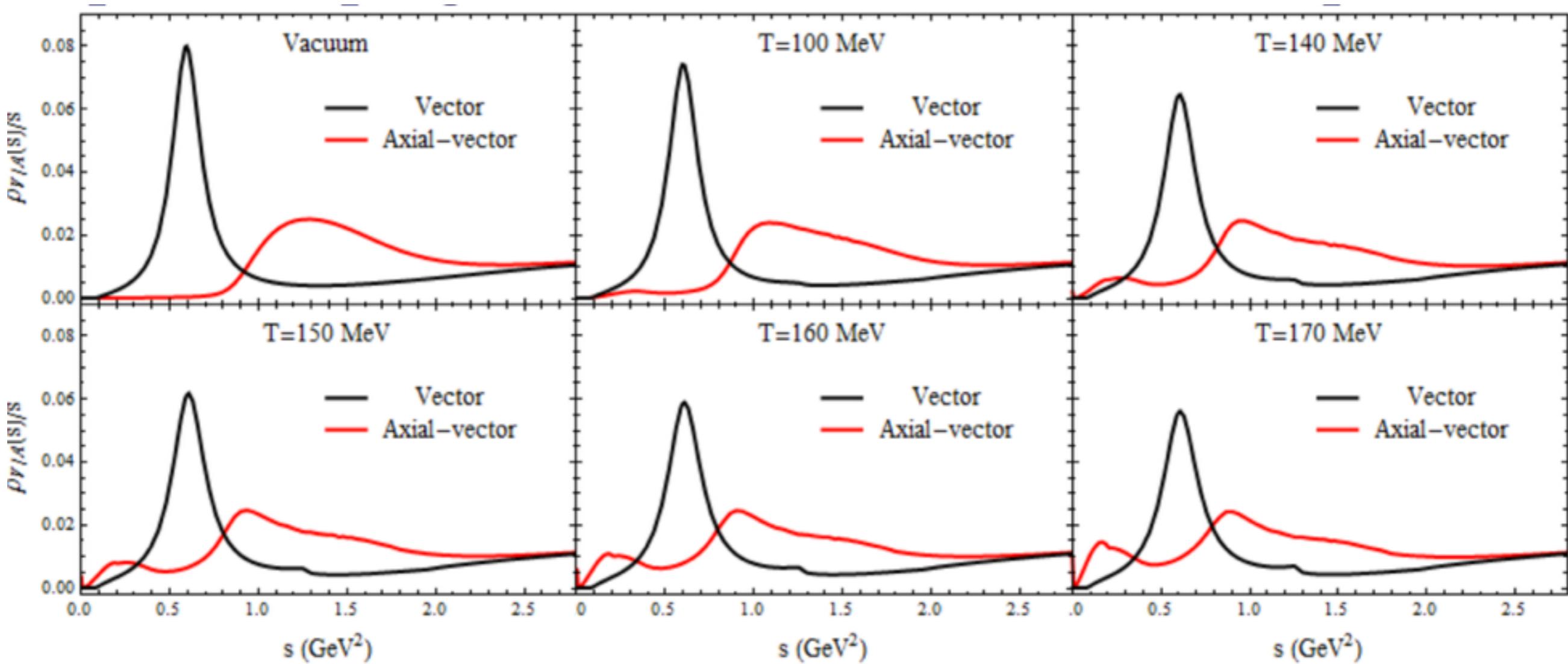
TRG, Phys. Rev. C **69**, 014903 (2004)



(Heffernan, Hohler, Rapp 2015)

Vector/axial-vector meson melting

P. M. Hohler and R. Rapp, Phys. Lett. B **731**, 103 (2014); arXiv:1509.05466 [hep-ph]



- The temperature progression of vector + axial vector spectral functions shows that chiral mass-splitting “burns off” as mechanism for chiral restoration