Hydrodynamics in Small Collision Systems from LHC to RHIC

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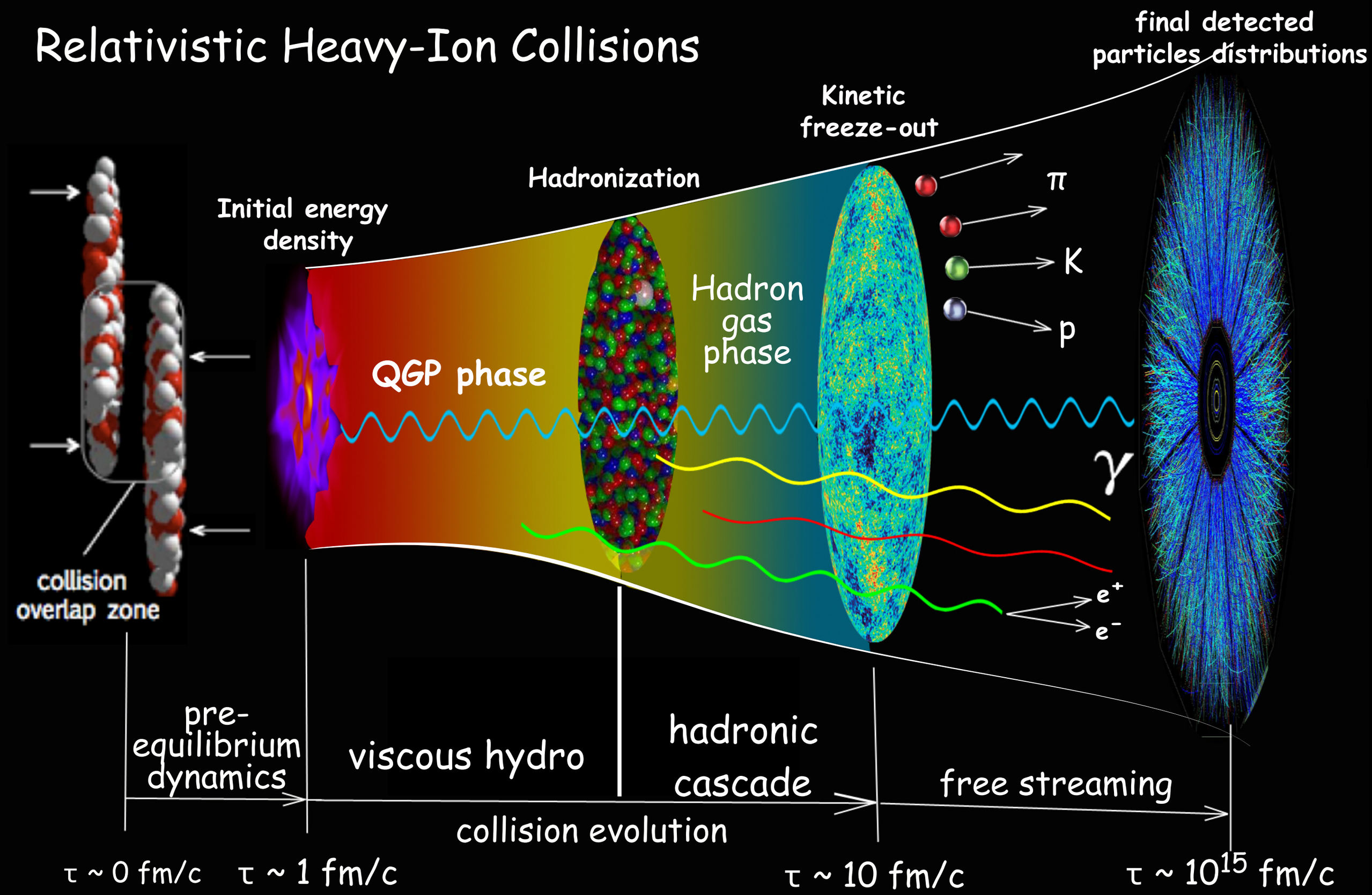
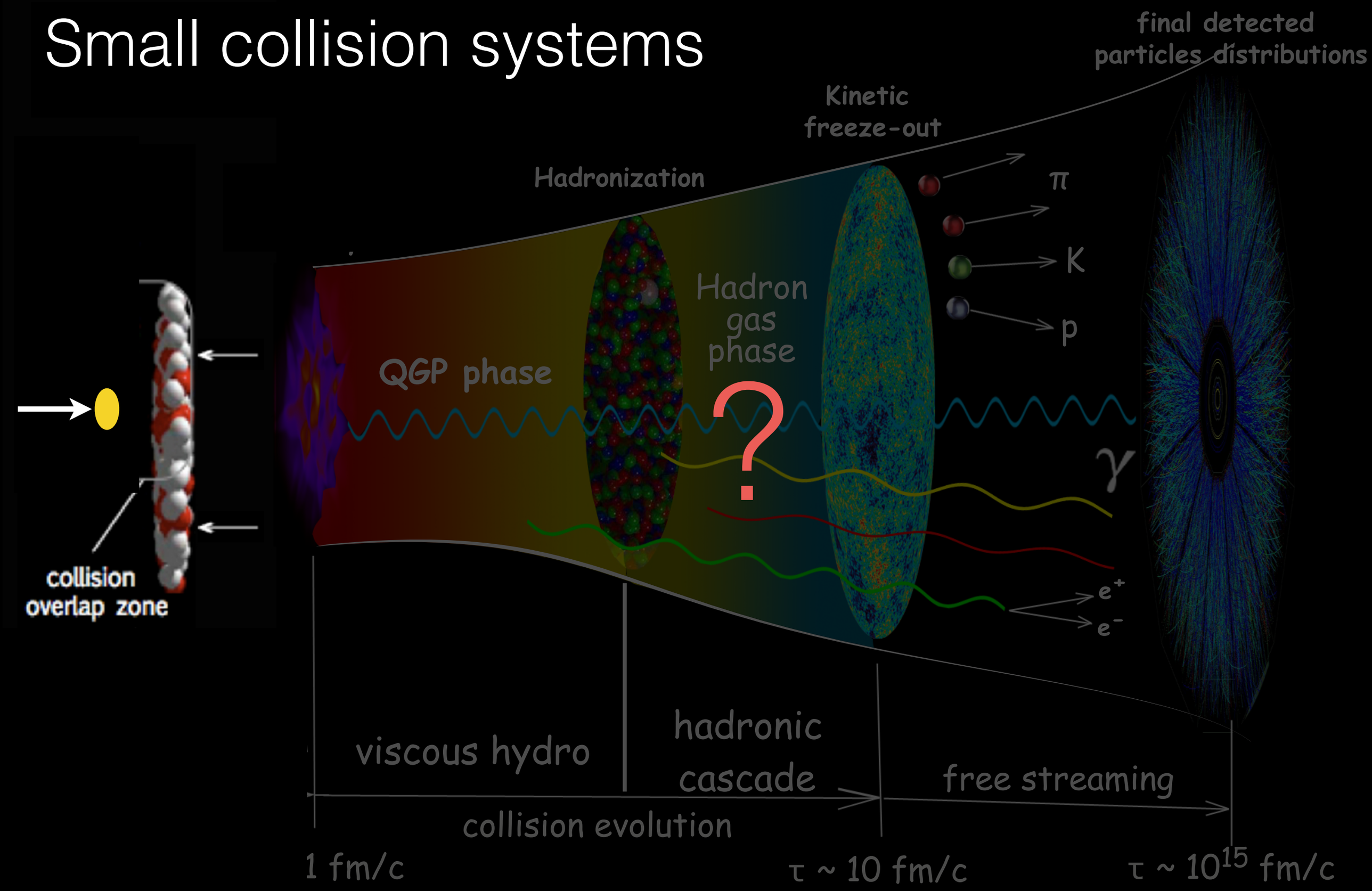
Relativistic Heavy-Ion Collisions

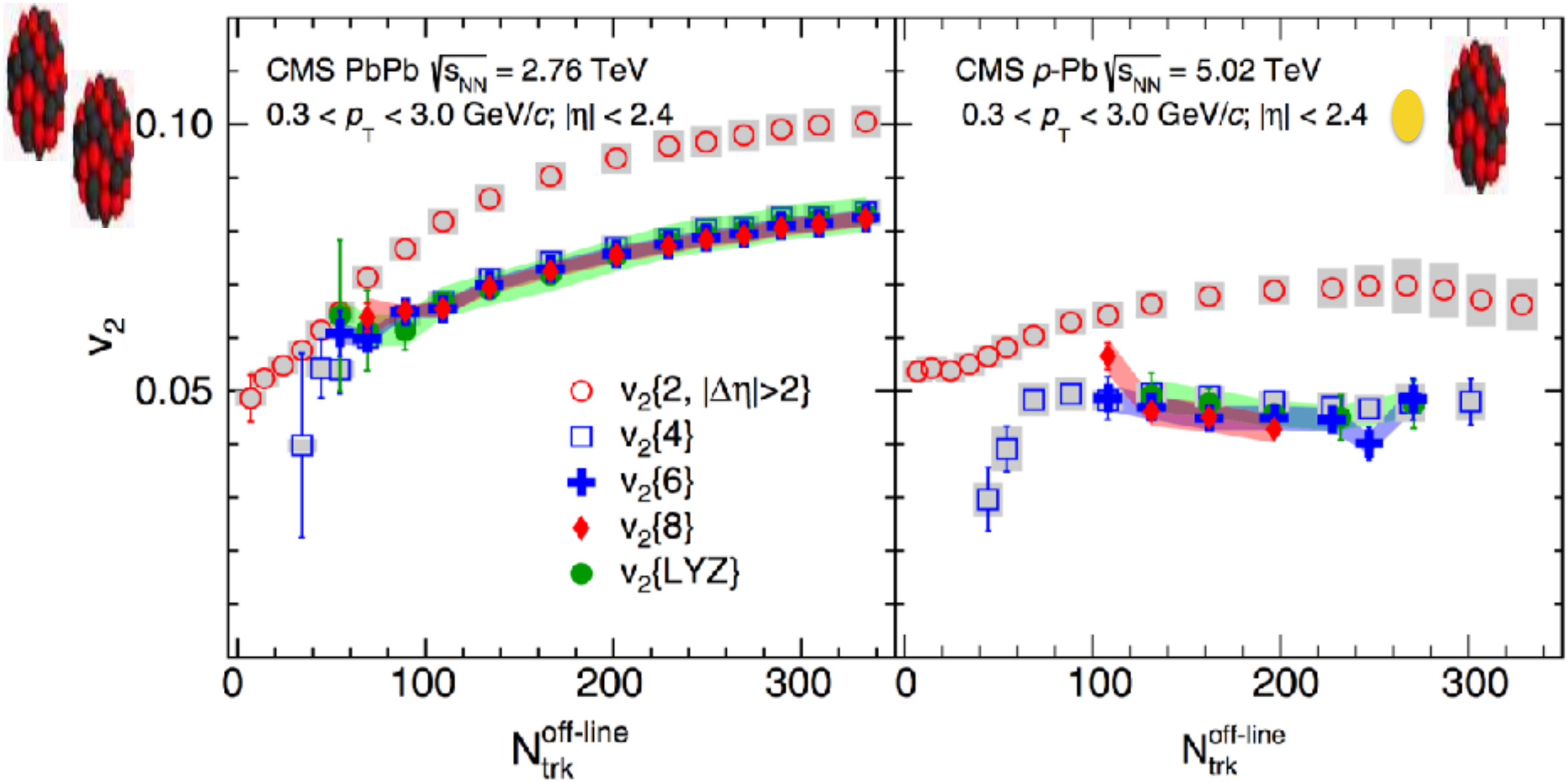


Small collision systems



Interpretation: Strong final state effects

CMS Collaboration, Phys. Rev. Lett. **115**, 012301 (2015)

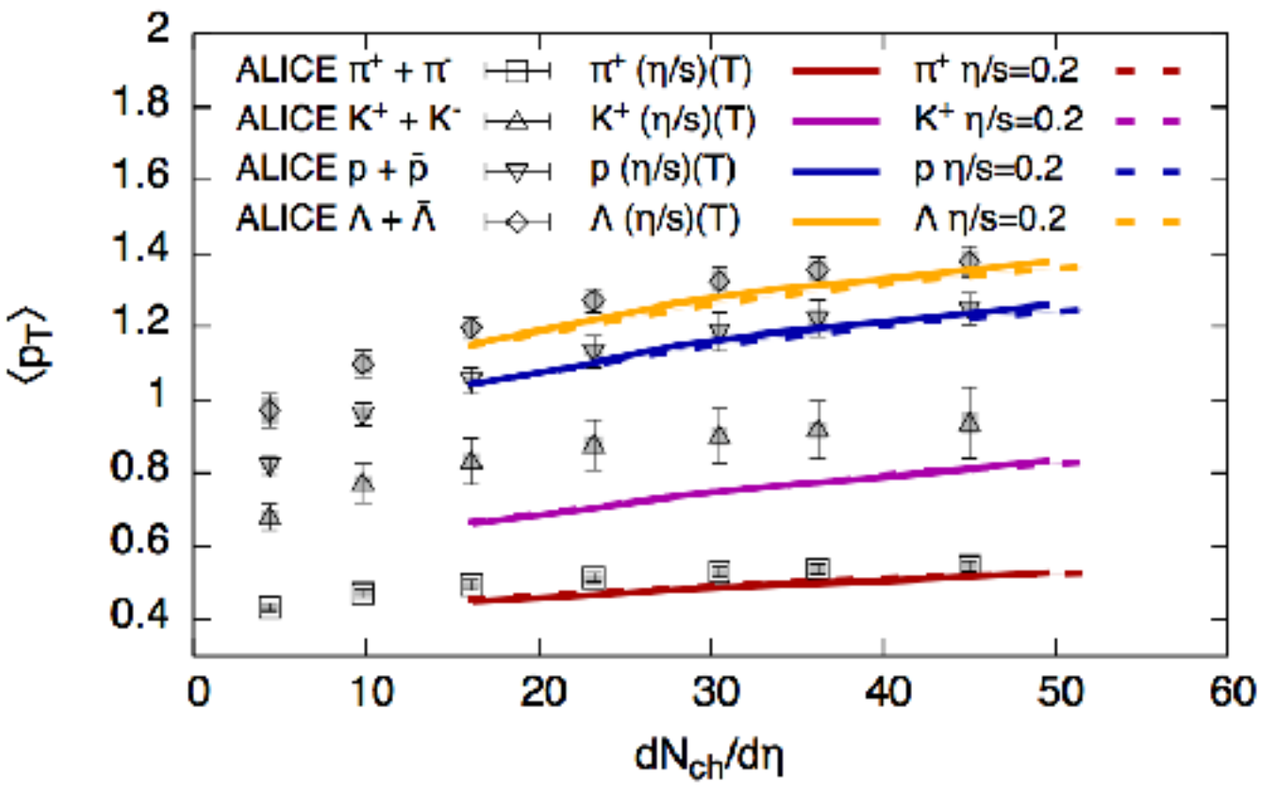


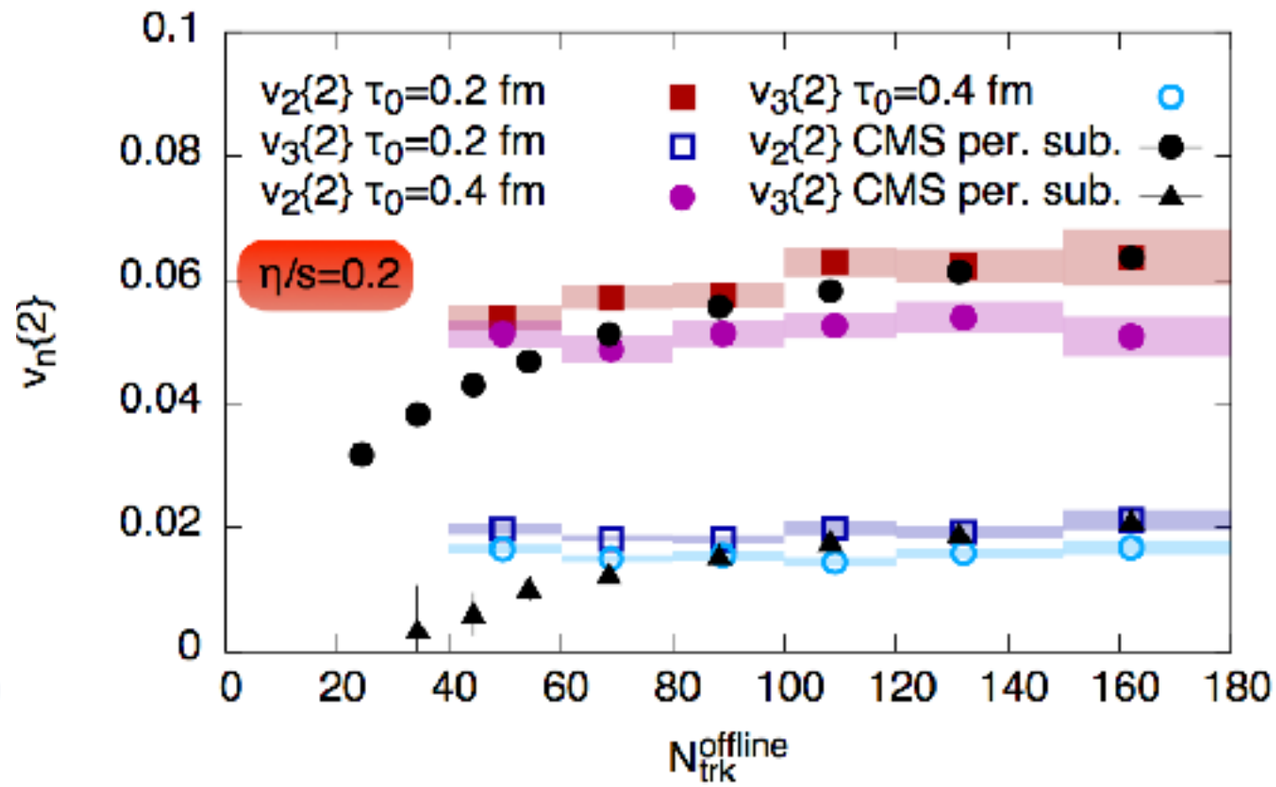
- Measurements of anisotropic flow coefficients indicate strong *multi-particle interactions* in both <u>small</u> and large collisions systems

Global observables in small systems

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

IP-Glasma + MUSIC + UrQMD:

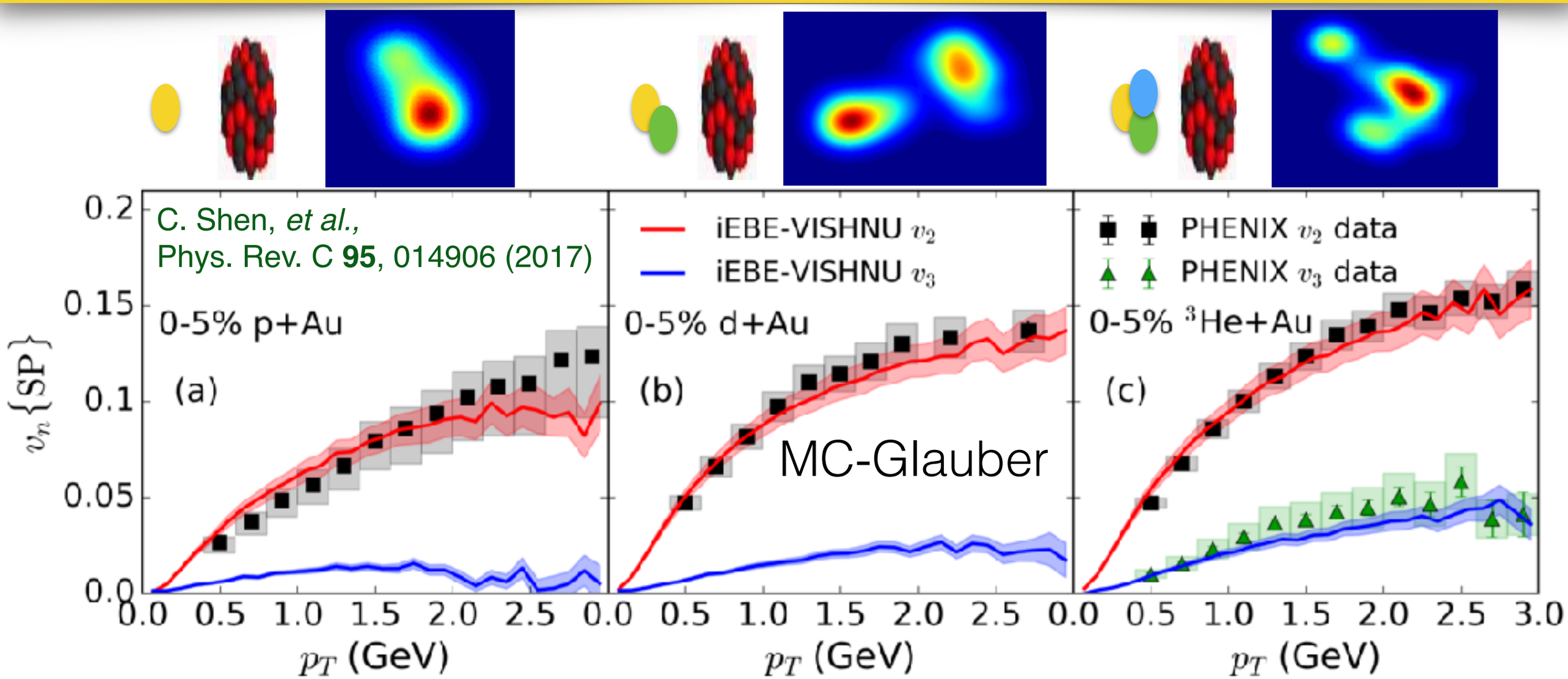




- Hydrodynamic simulations reproduce particle mean-p_T and anisotropic flow coefficients fairly well

Indication of a strongly coupled QCD matter?

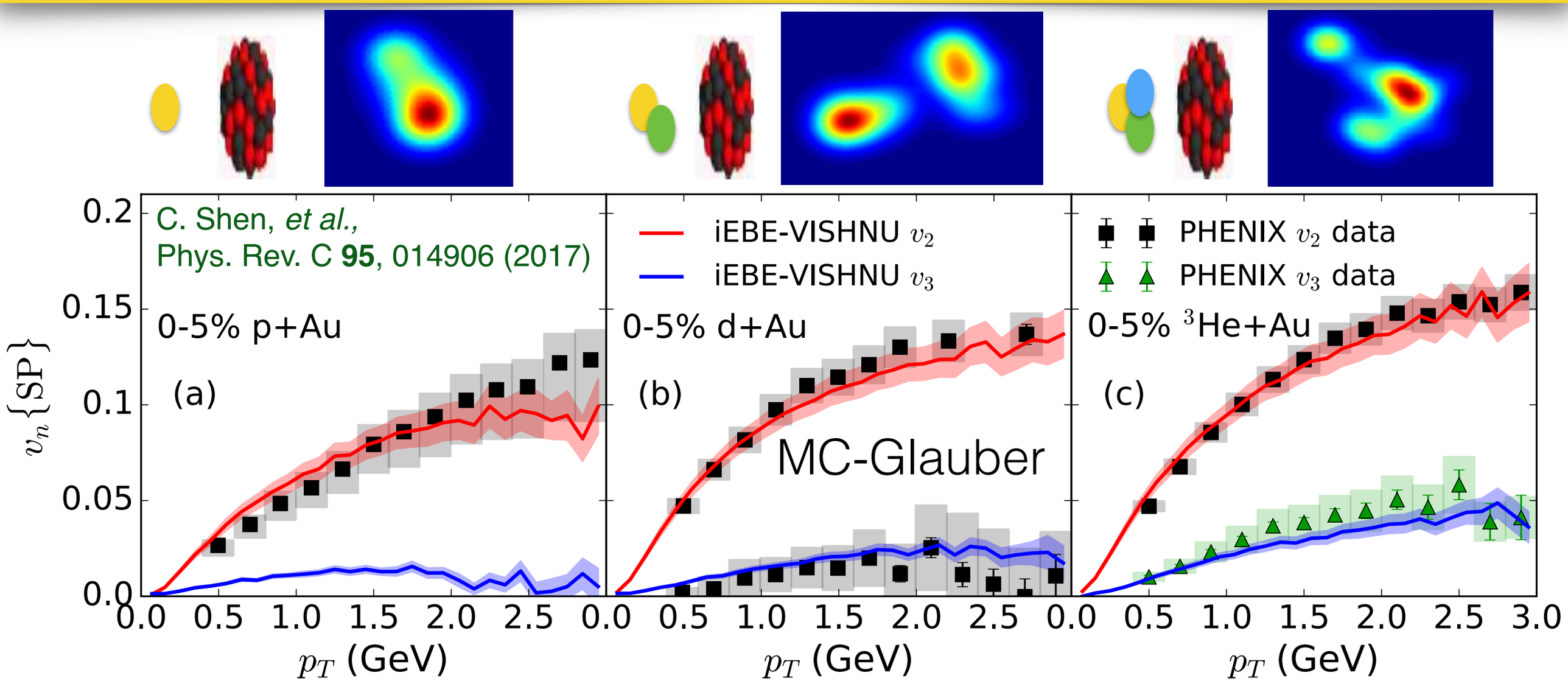
Small systems with different geometry



- Hydrodynamic response converts spatial gradients into measured momentum anisotropy

Indication of a strongly coupled QCD matter?

Small systems with different geometry

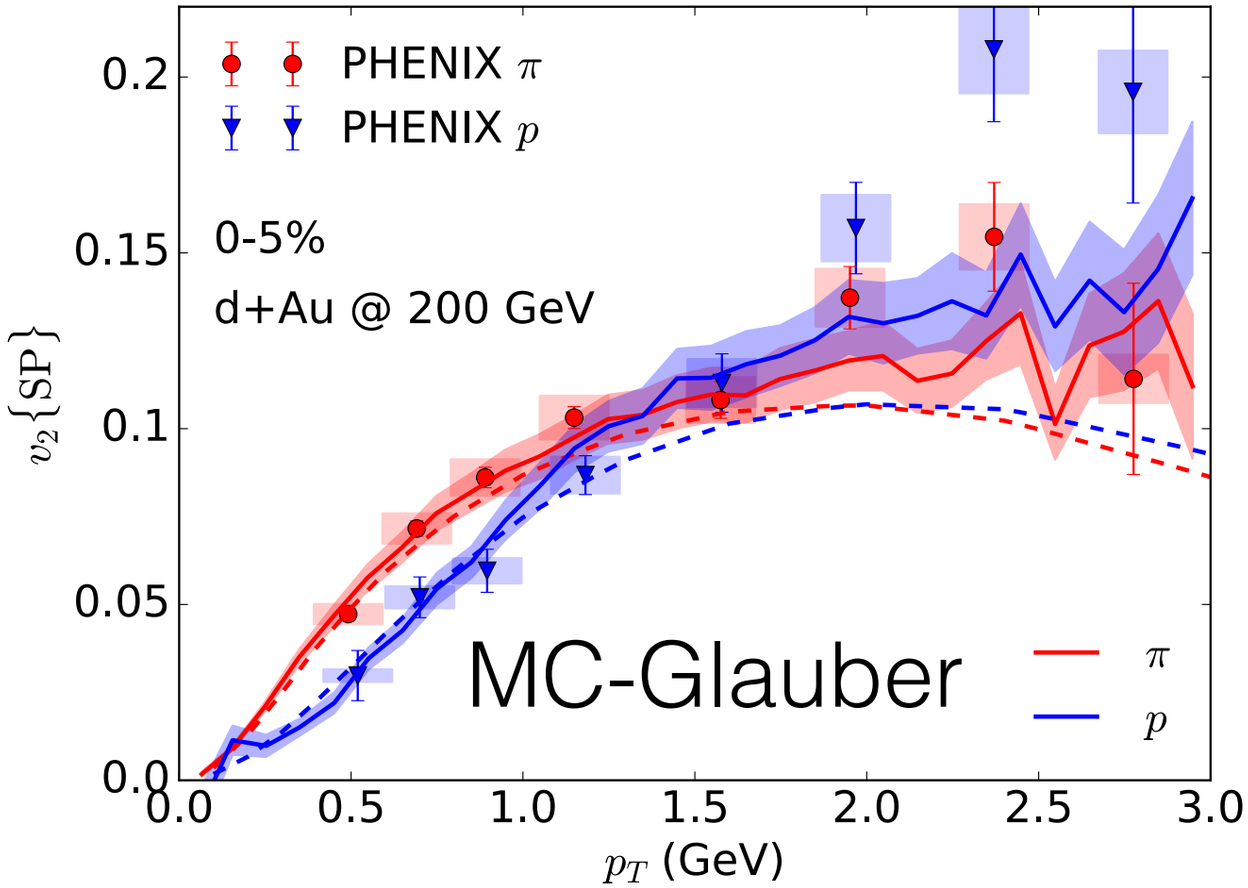


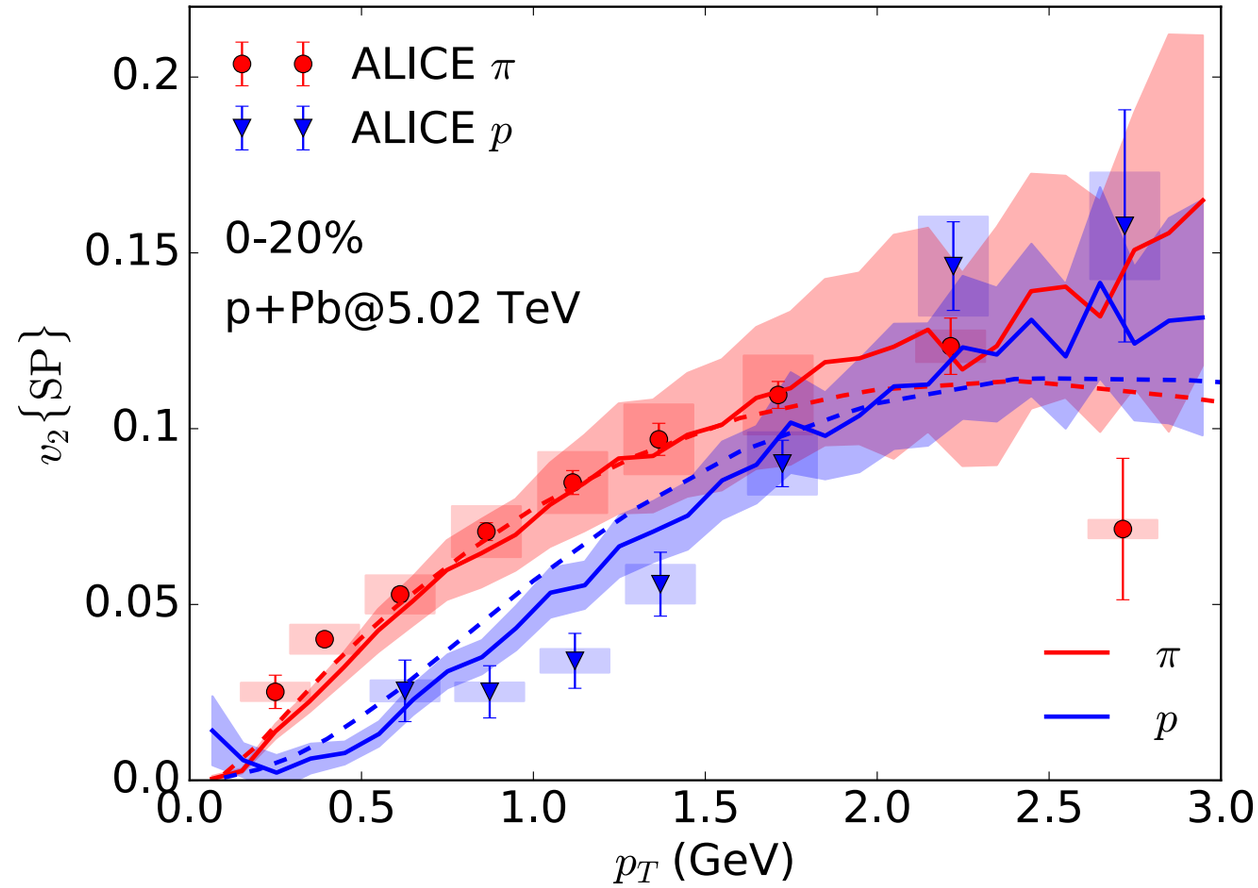
- Hydrodynamic simulations predicted v_3 in d+Au collisions at 200 GeV

Indication of a strongly coupled QCD matter?

pid $v_2(p_T)$ mass splitting in small systems

C. Shen,J. F. Paquet, G. Denicol, S. Jeon and C. Gale, Phys. Rev. C **95**, 014906 (2017)





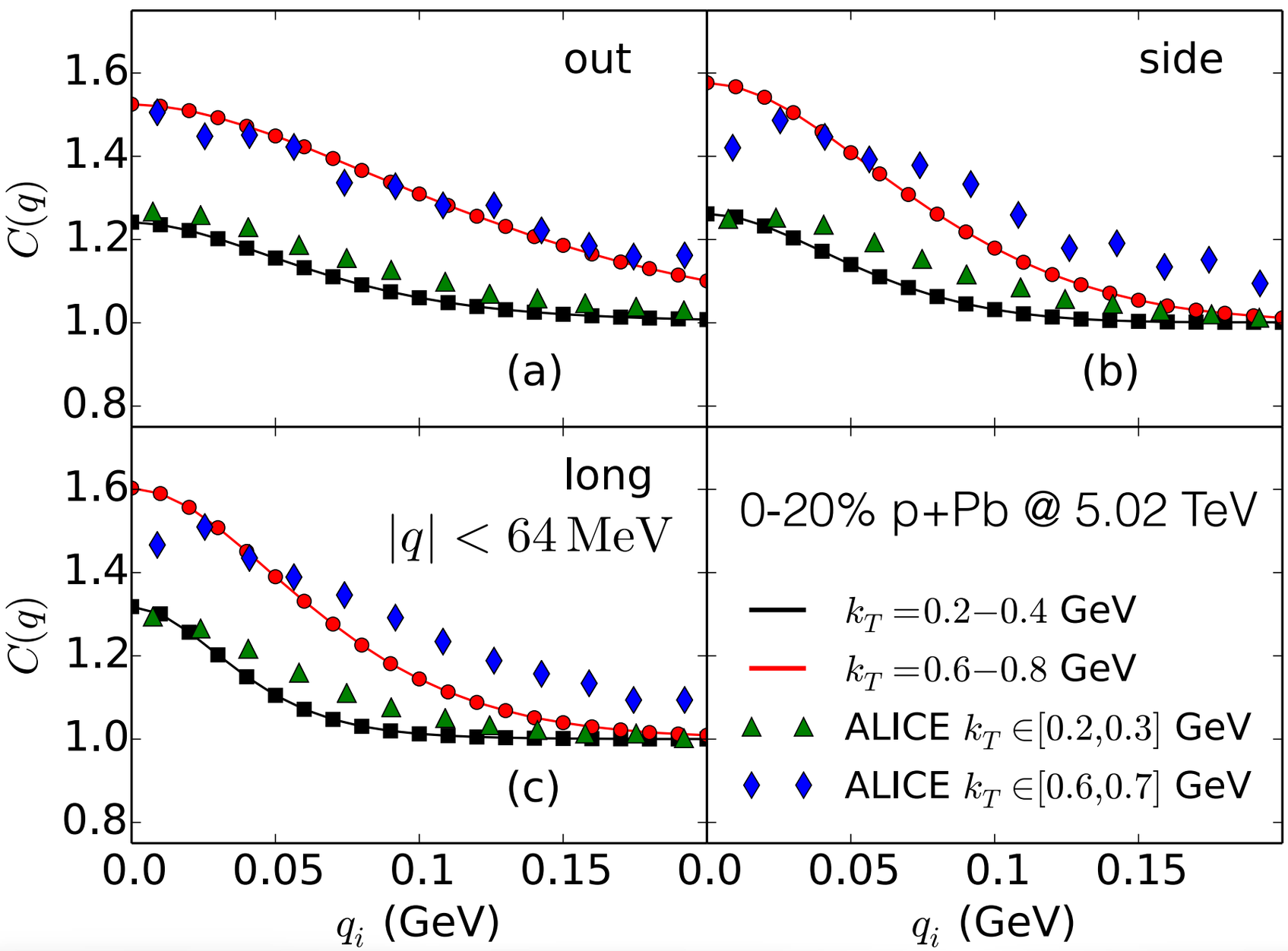
- The interplay between radial and elliptic flow in the hydrodynamic simulations can reproduce the mass splitting of pid $v_2(p_T)$ in small collision systems

Indication of a strongly coupled QCD matter?

HBT correlation

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

$$C(q) = 1 + \frac{\frac{1}{\langle N_{\rm pair}\rangle}\langle \sum_{ij} \cos(q_{ij}\cdot x_{ij})\rangle}{\frac{1}{\langle N_{\rm mixpair}\rangle}\langle N_{\rm mixpair}(q)\rangle}$$

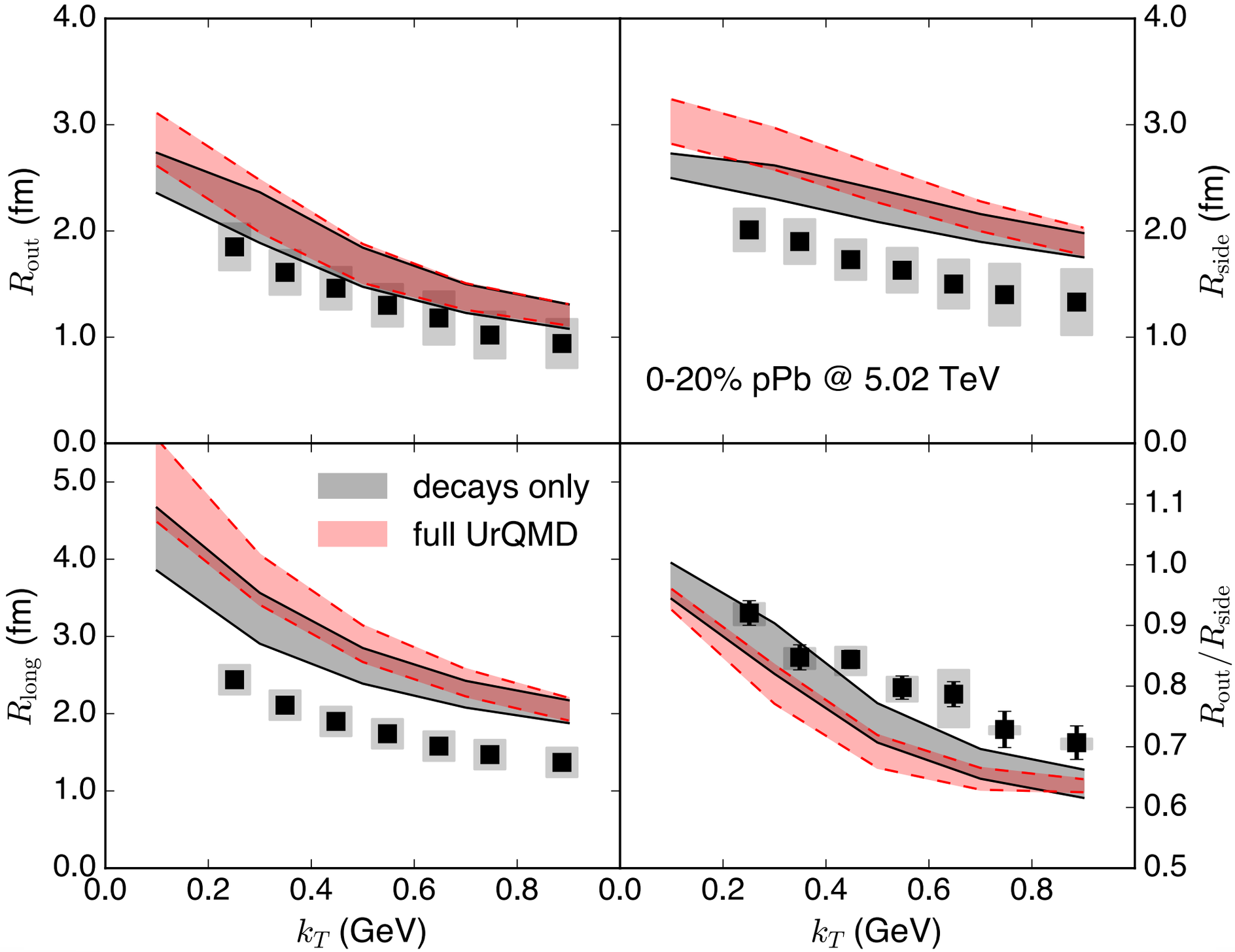


- $C(q_{out})$ agrees reasonably with the ALICE data
- Correlation function is too narrow in the side and long directions

HBT Radii

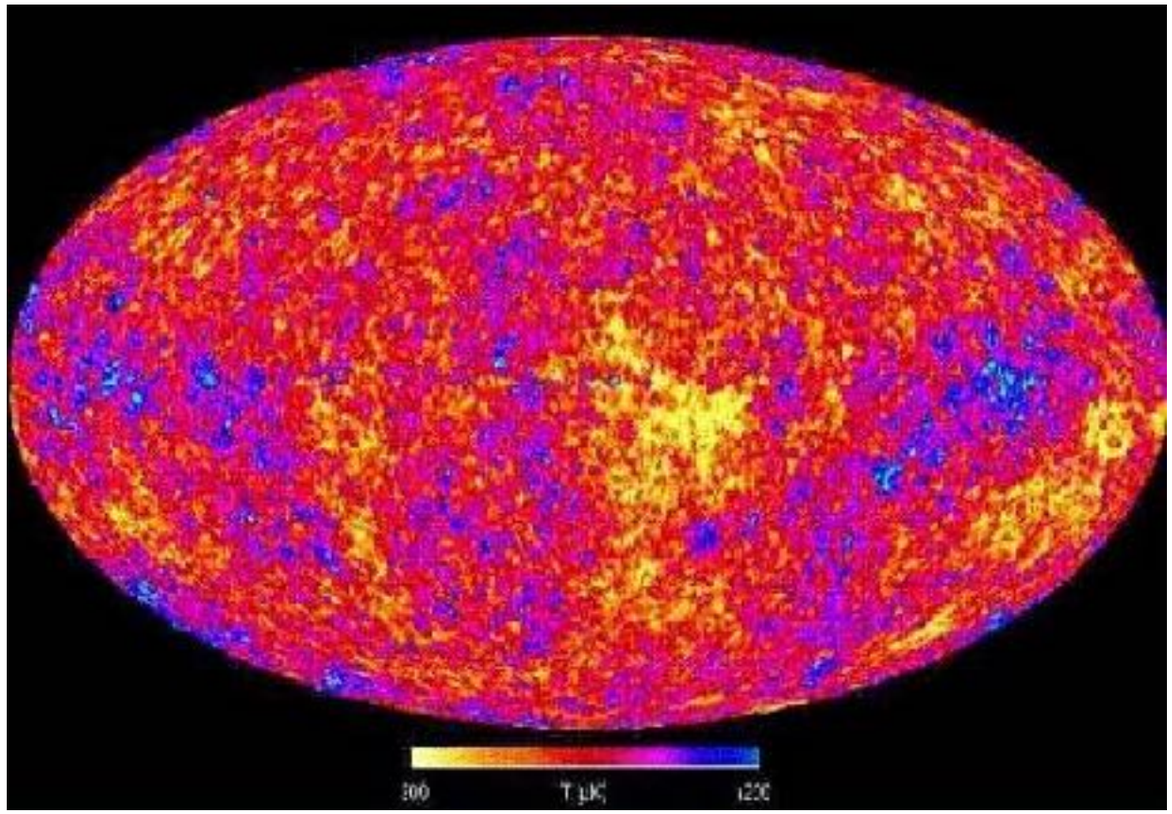
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



Probes for Quark Gluon Plasma

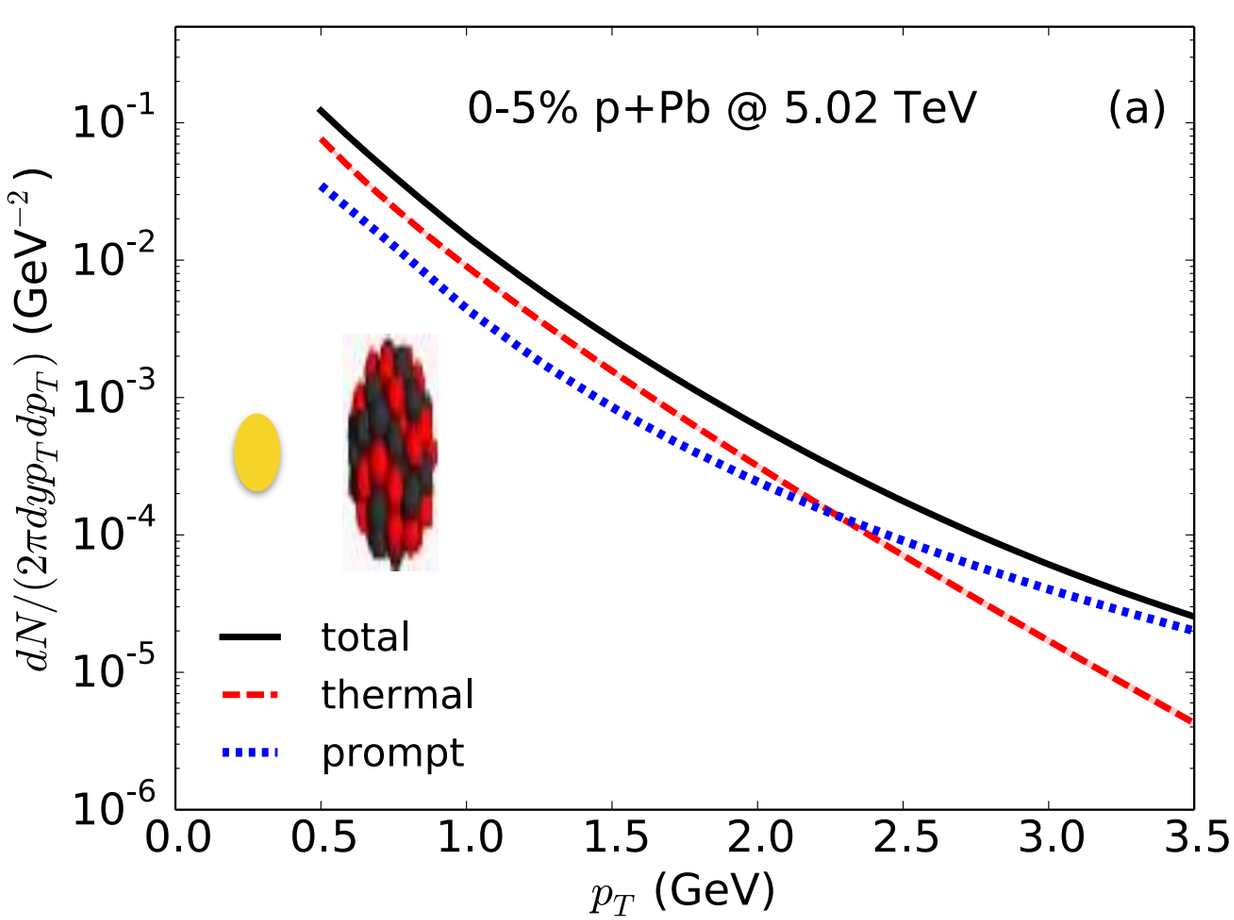
- Electromagnetic radiation

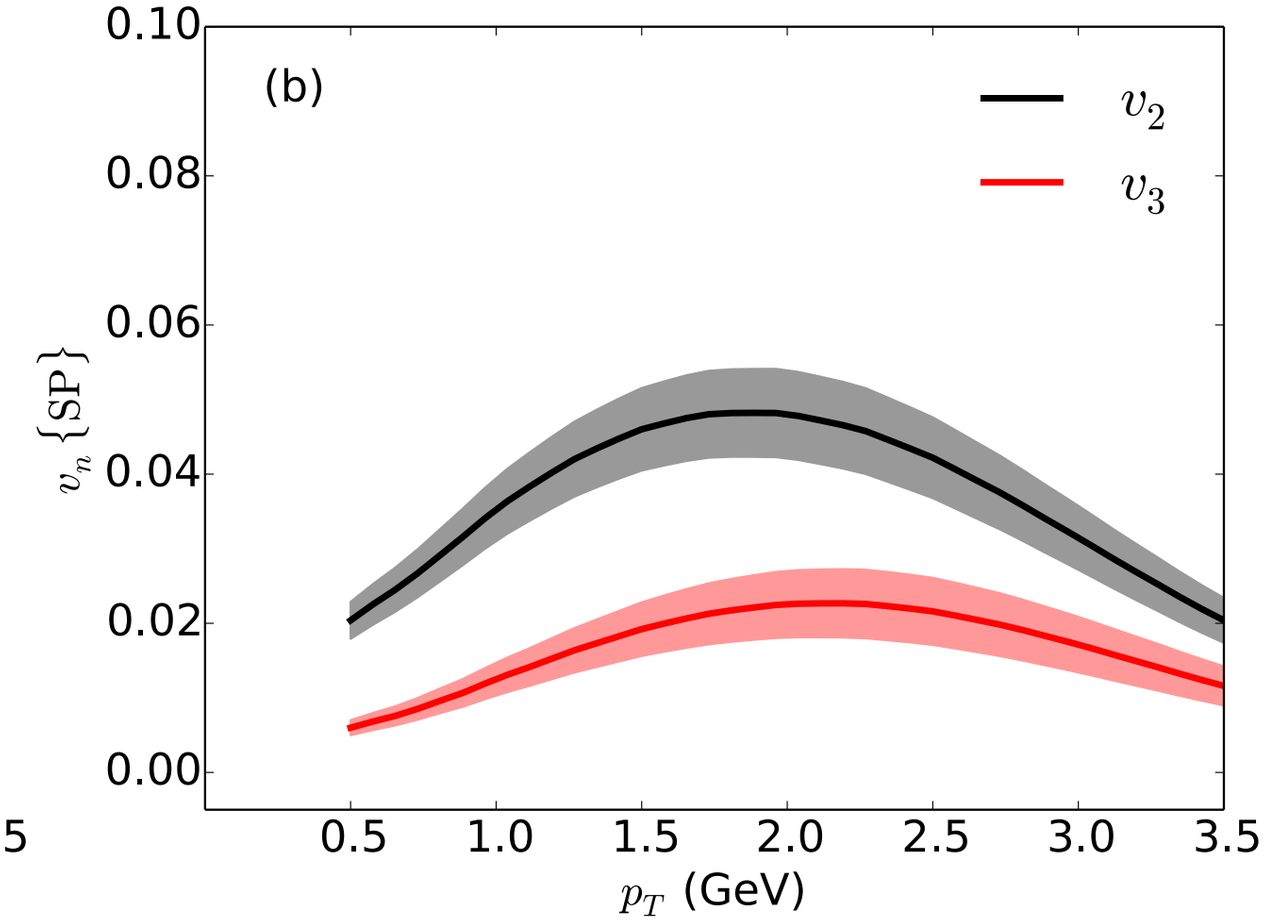


Probing the internal degree of freedom

Thermal radiation in small systems

C. Shen,J. F. Paquet, G. Denicol, S. Jeon and C. Gale, Phys. Rev. C **95**, 014906 (2017)



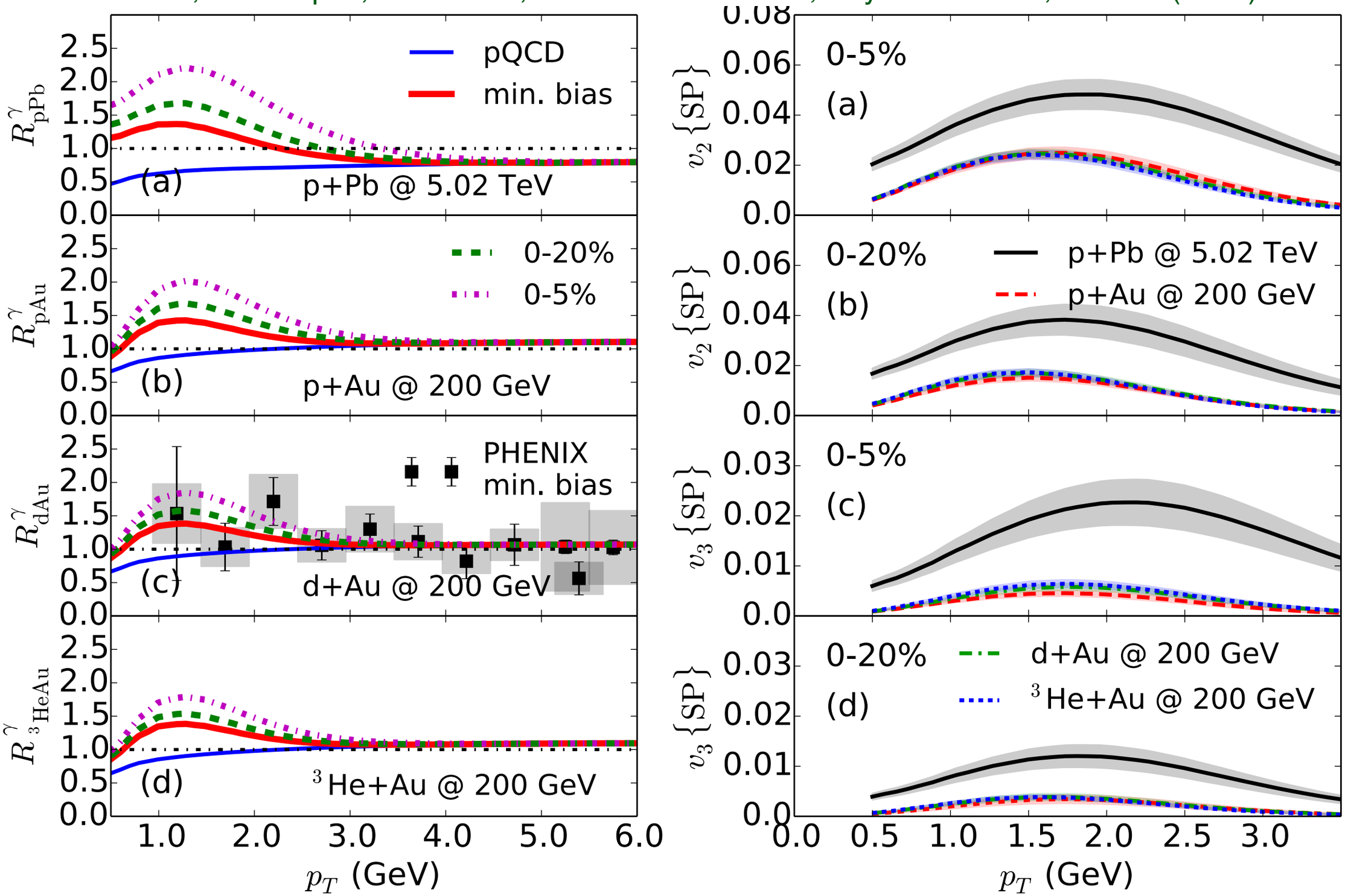


- In 0-5% p+Pb collisions, thermal photon can out-shine prompt photons
- <u>Sizeable</u> direct photon anisotropy in central p+Pb collisions

Signature of a nearly thermalized medium in small systems

Thermal radiation in small systems

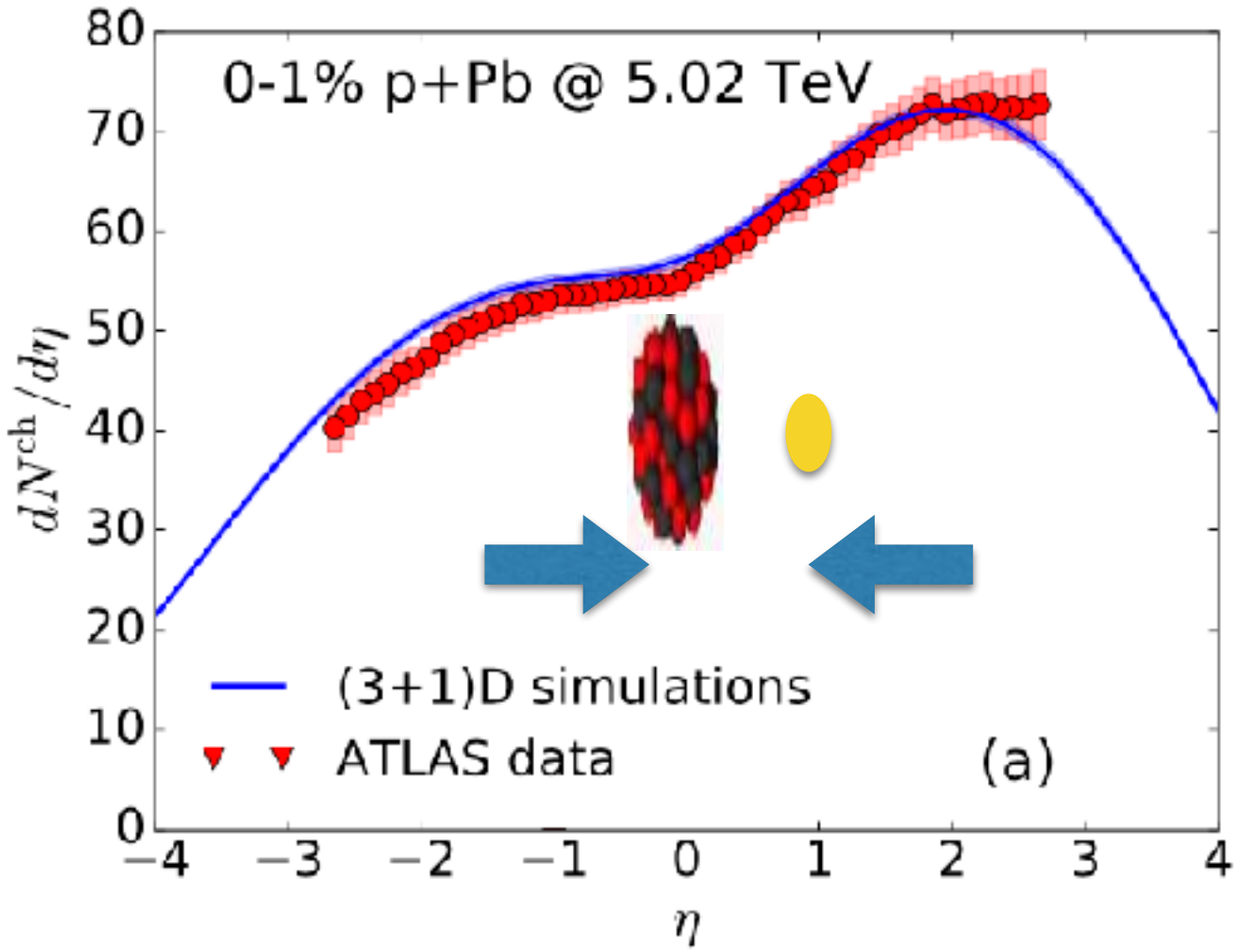
C. Shen,J. F. Paquet, G. Denicol, S. Jeon and C. Gale, Phys. Rev. C **95**, 014906 (2017)

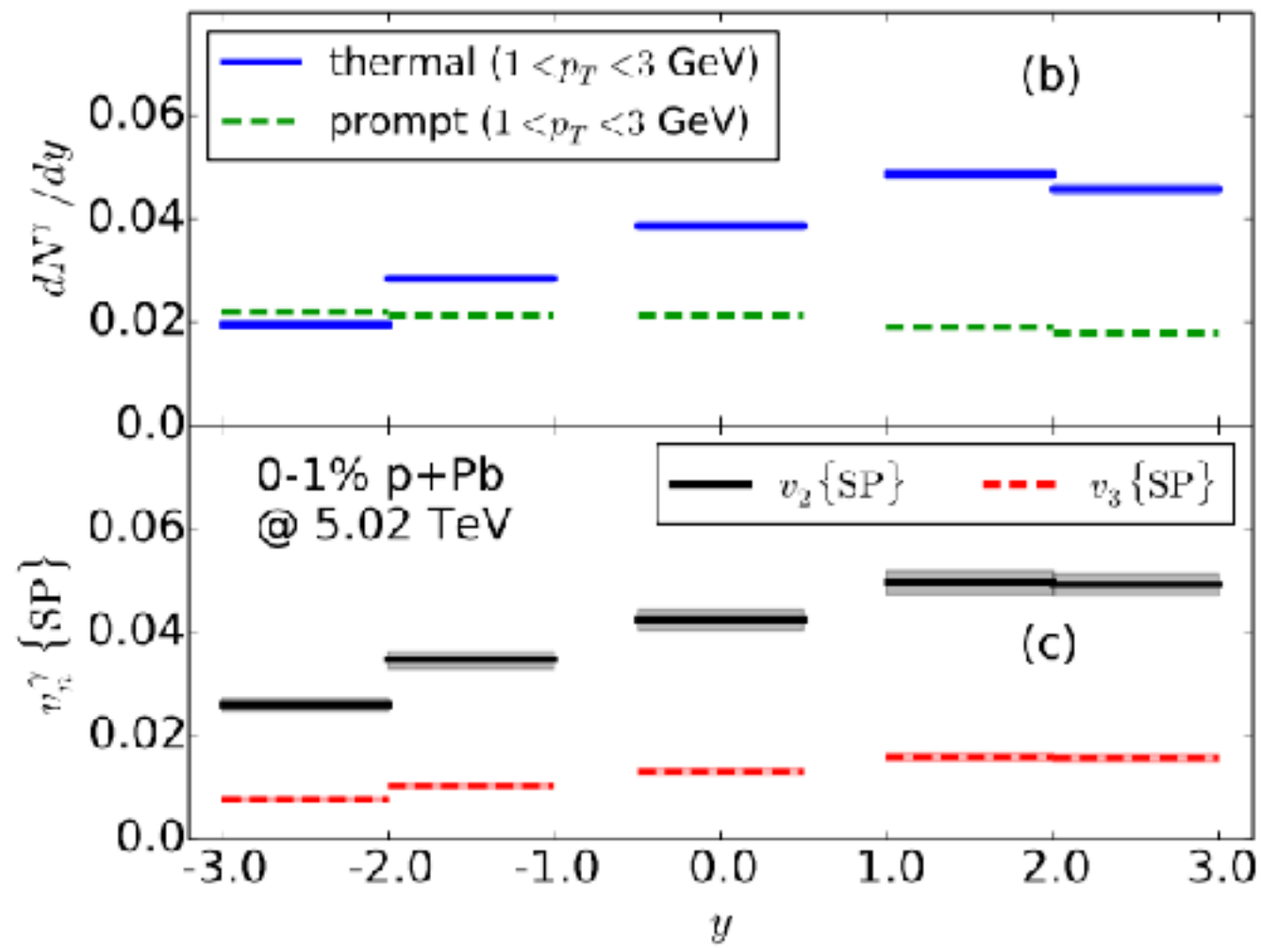


Signature of a nearly thermalized medium in small systems

Rapidity dependence of thermal radiation

C. Shen, J. F. Paquet, G. Denicol, S. Jeon and C. Gale, arXiv:1612.05464

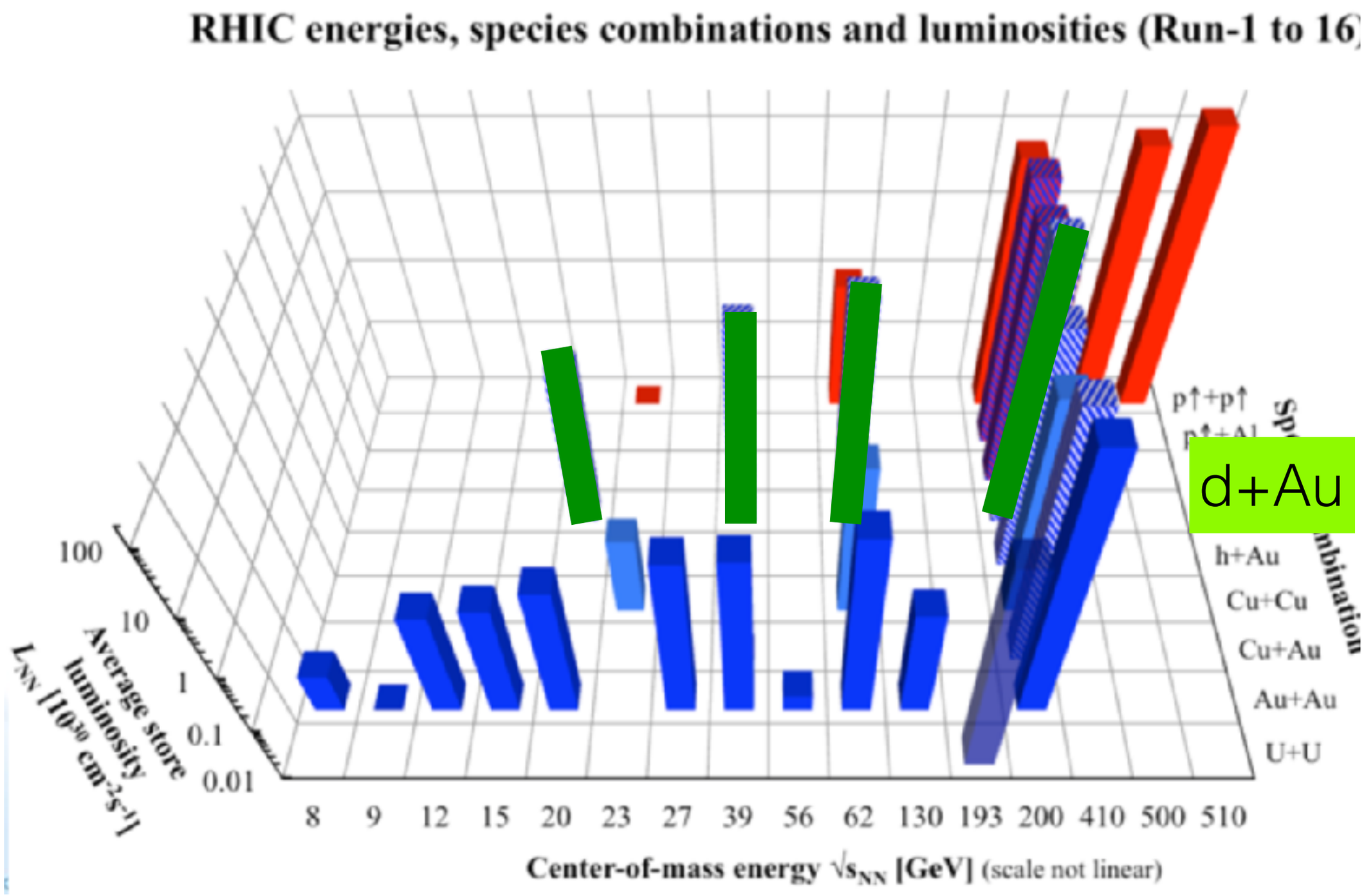




- Rapidity dependences of thermal and prompt photon productions are opposite to each other
- More thermal radiation in the nuclear shadowing region

disentangle prompt photons from thermal radiation

d+Au collisions at BES energies…



picture taken from http://www.agsrhichome.bnl.gov/RHIC/Runs/

Dissipative hydrodynamics

Energy momentum tensor

$$T^{\mu\nu} = e u^\mu u^\nu - (P + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

Conserved currents

$$J^\mu = n u^\mu + q^\mu$$

Equations of motion

$$\begin{aligned} \partial_\mu T^{\mu\nu} &= 0 \\ \partial_\mu J^\mu &= 0 \end{aligned} \quad + \quad P(e, n)$$

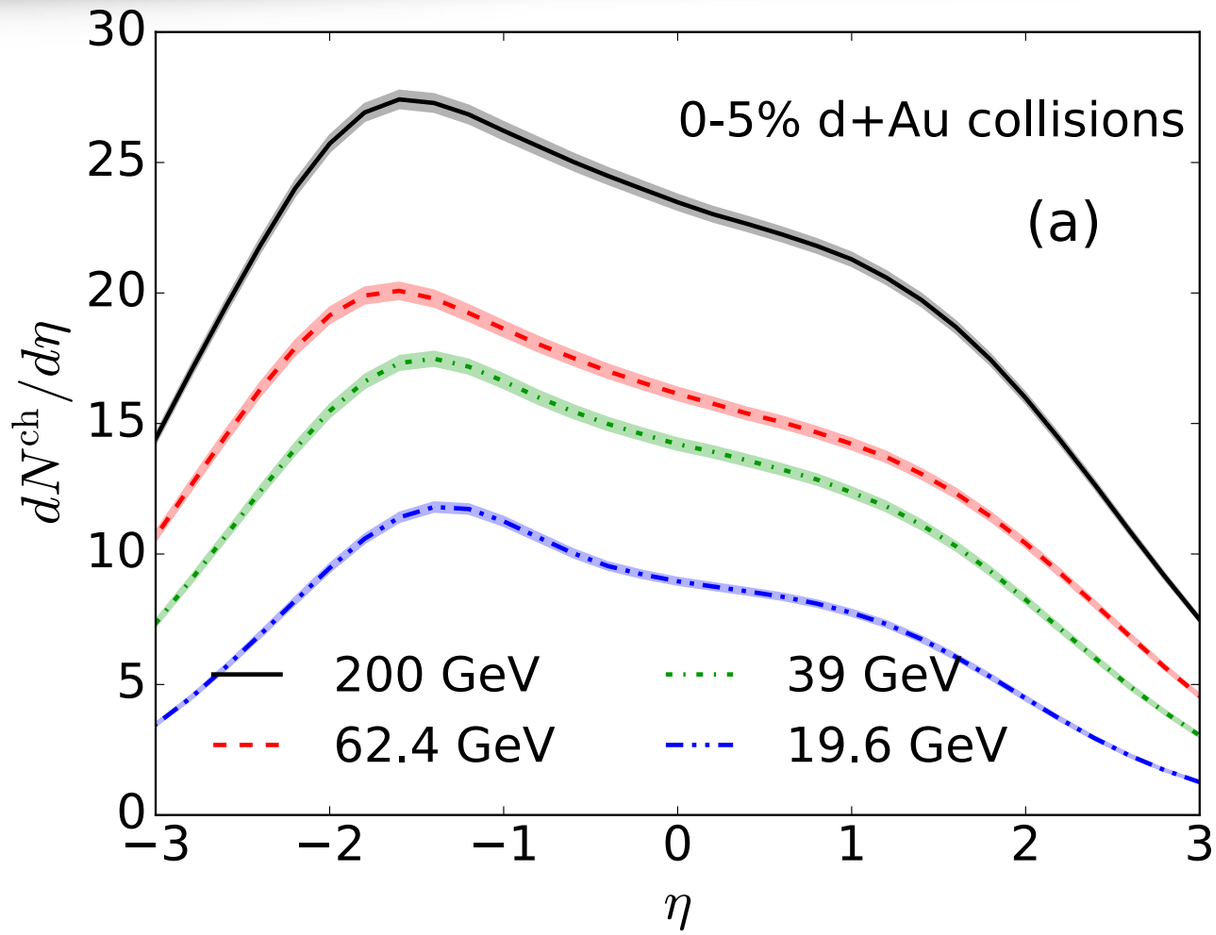
Dissipative quantities are evolved with 2nd order Israel-Stewart type of equations

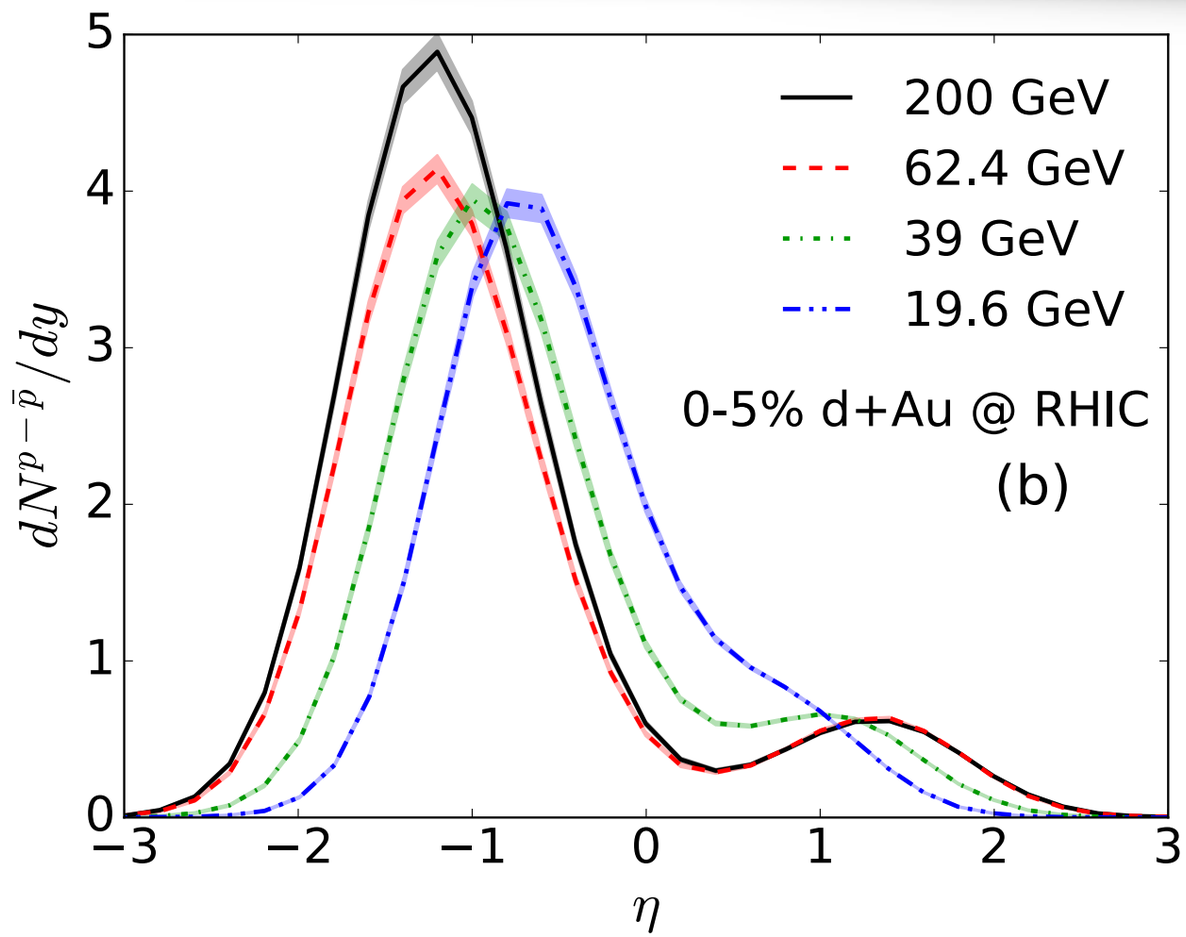
At Navier-Stokes limit,

$$\pi^{\mu\nu} \sim 2\eta \nabla^{\langle\mu} u^{\nu\rangle} \quad \Pi \sim -\zeta \partial_\mu u^\mu \quad q^\mu \sim \kappa \nabla^\mu \frac{\mu}{T}$$

$$\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$$

Doping baryons in small QGP droplets

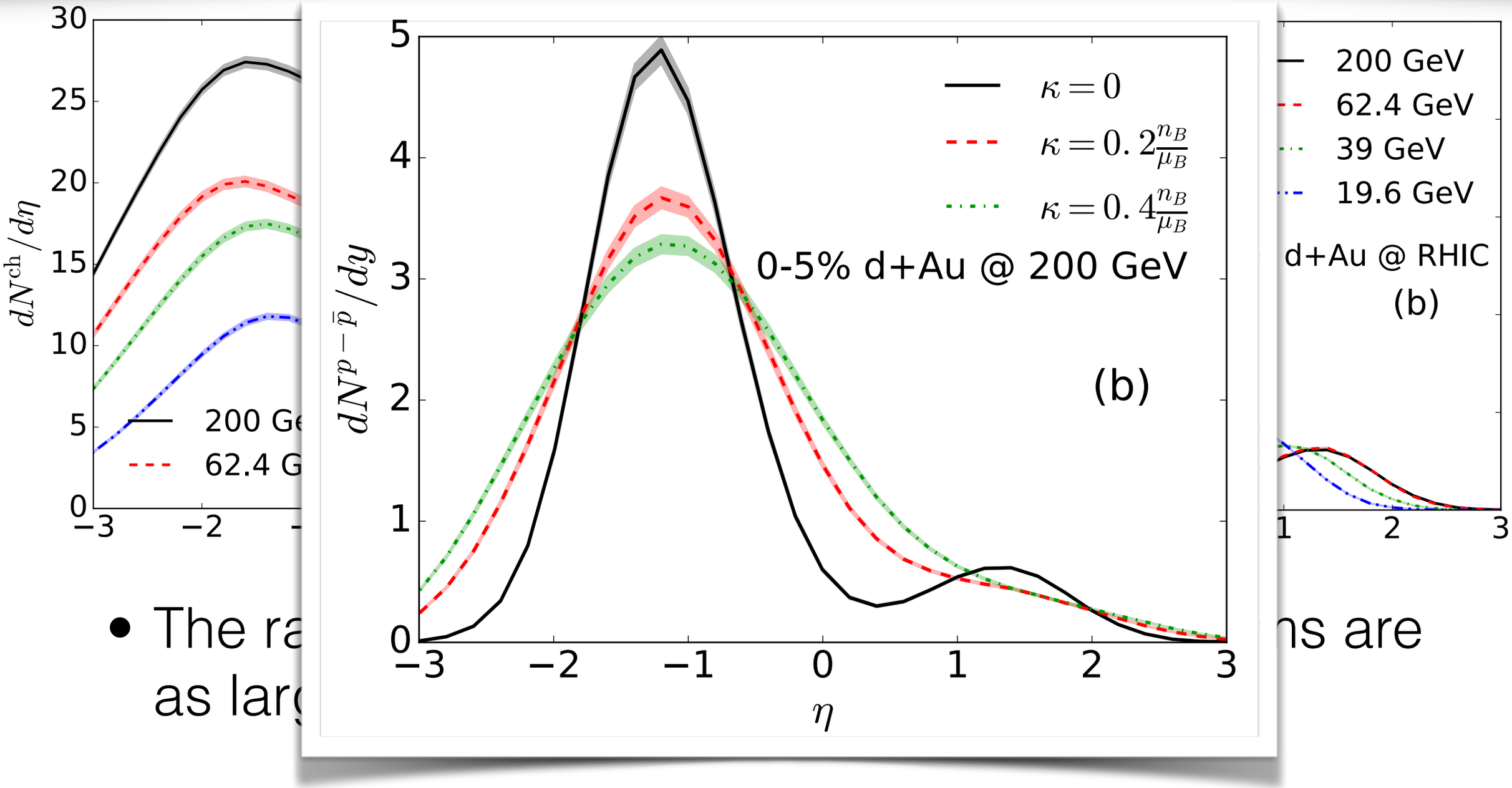




C. Shen, *et al.* preliminary

- Full (3+1)-d viscous hydrodynamic simulations with non-zero net baryon density
- The rapidity distribution of net protons can shed lights on initial baryon stopping at different collision energies

Doping baryons in small QGP droplets

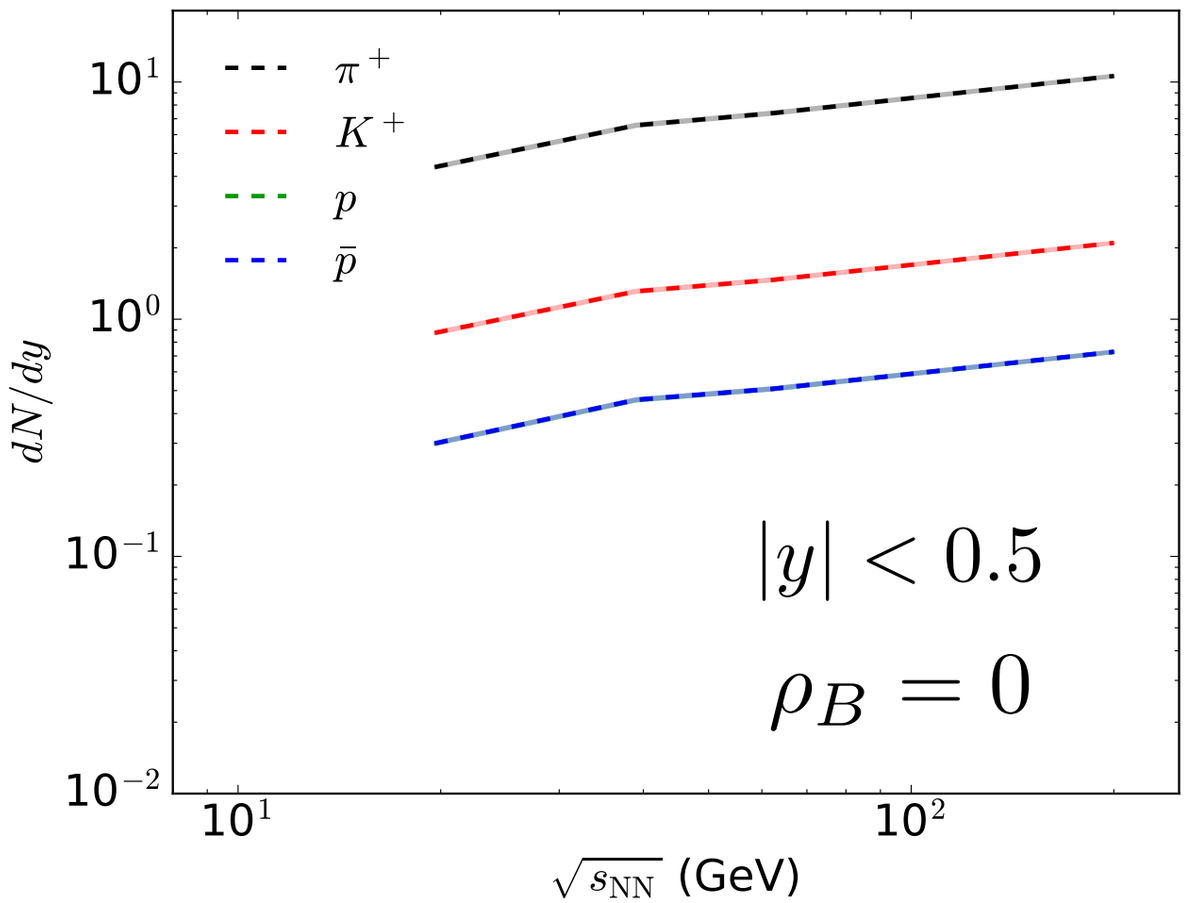


- The ra ns are as larg

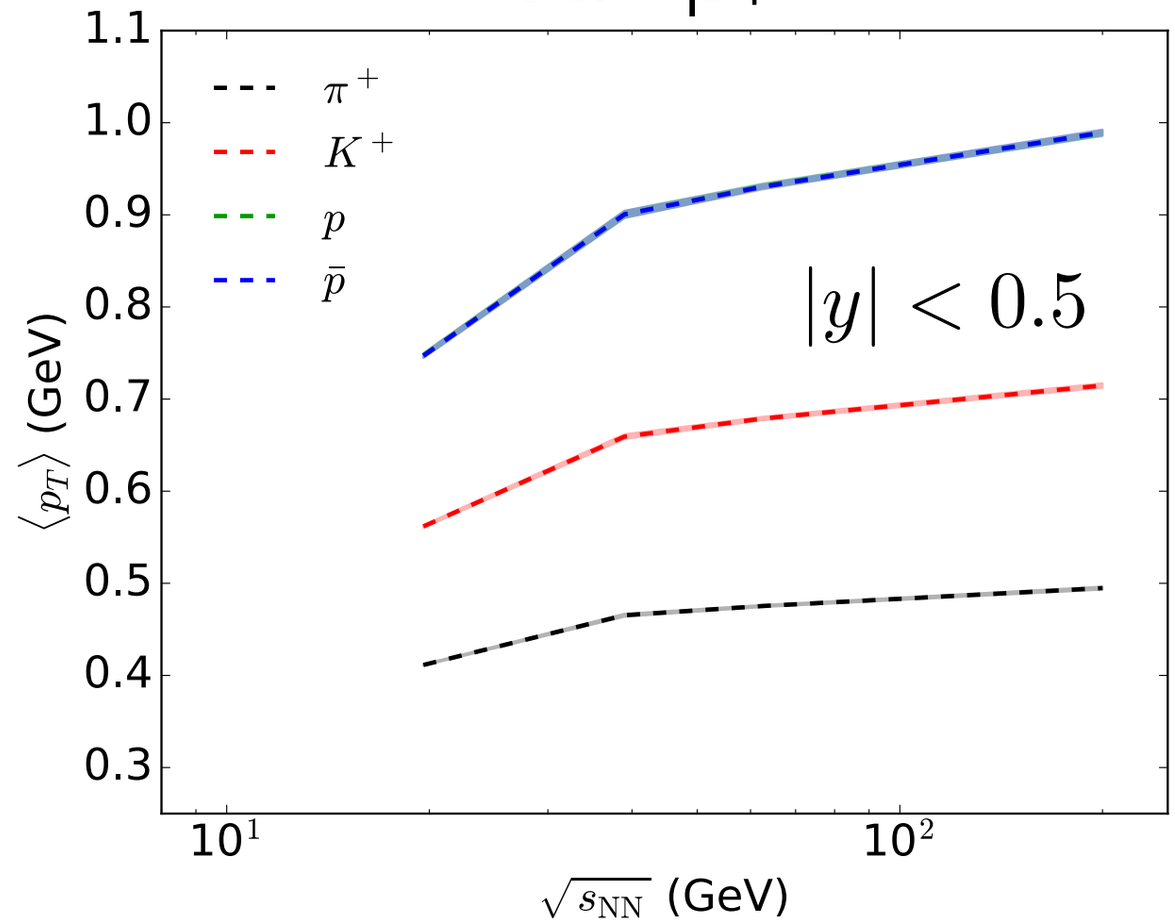
- More net baryon transport in rapidity with a larger net baryon diffusion constant

Collision energy dependence of pid observables

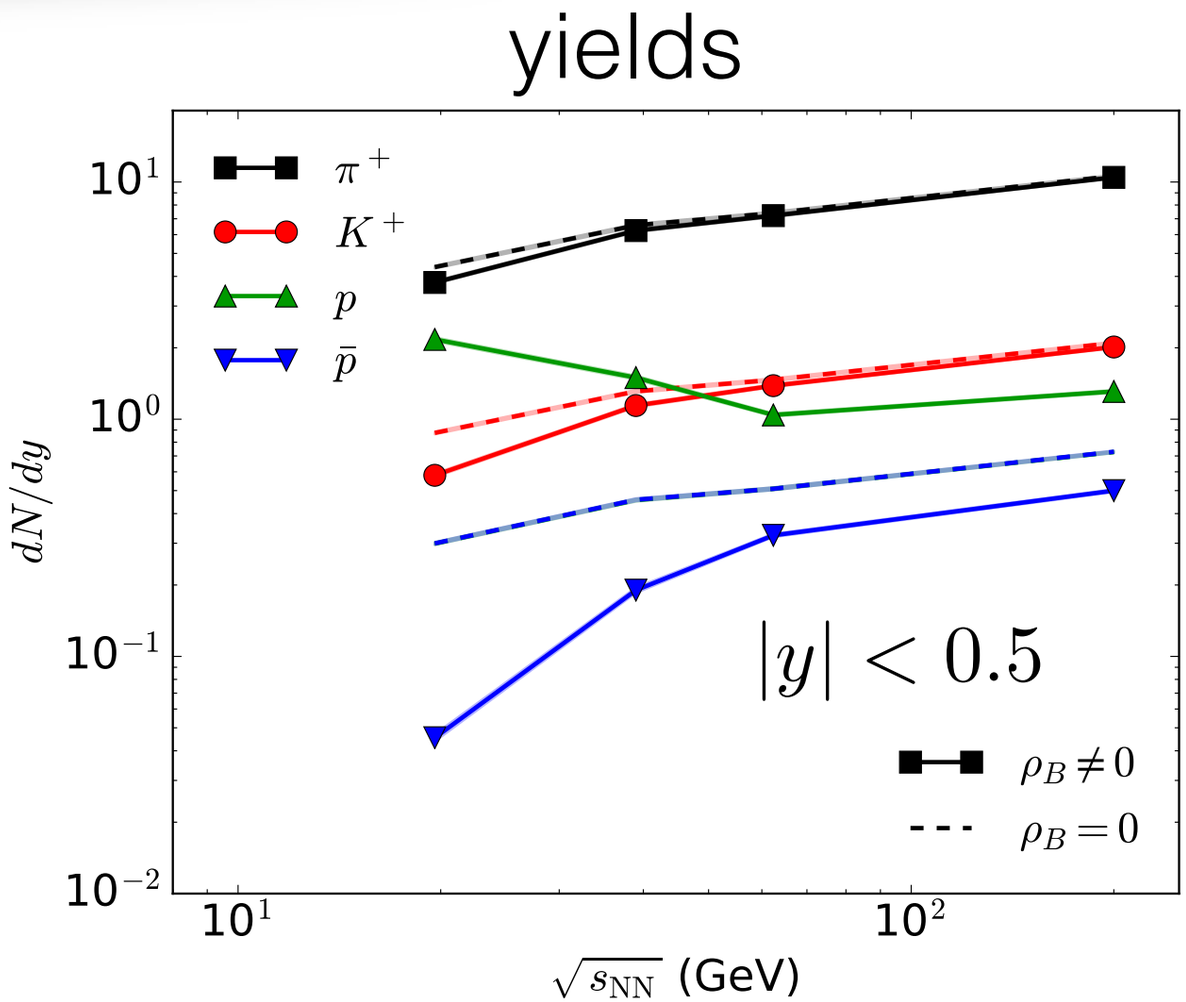
yields

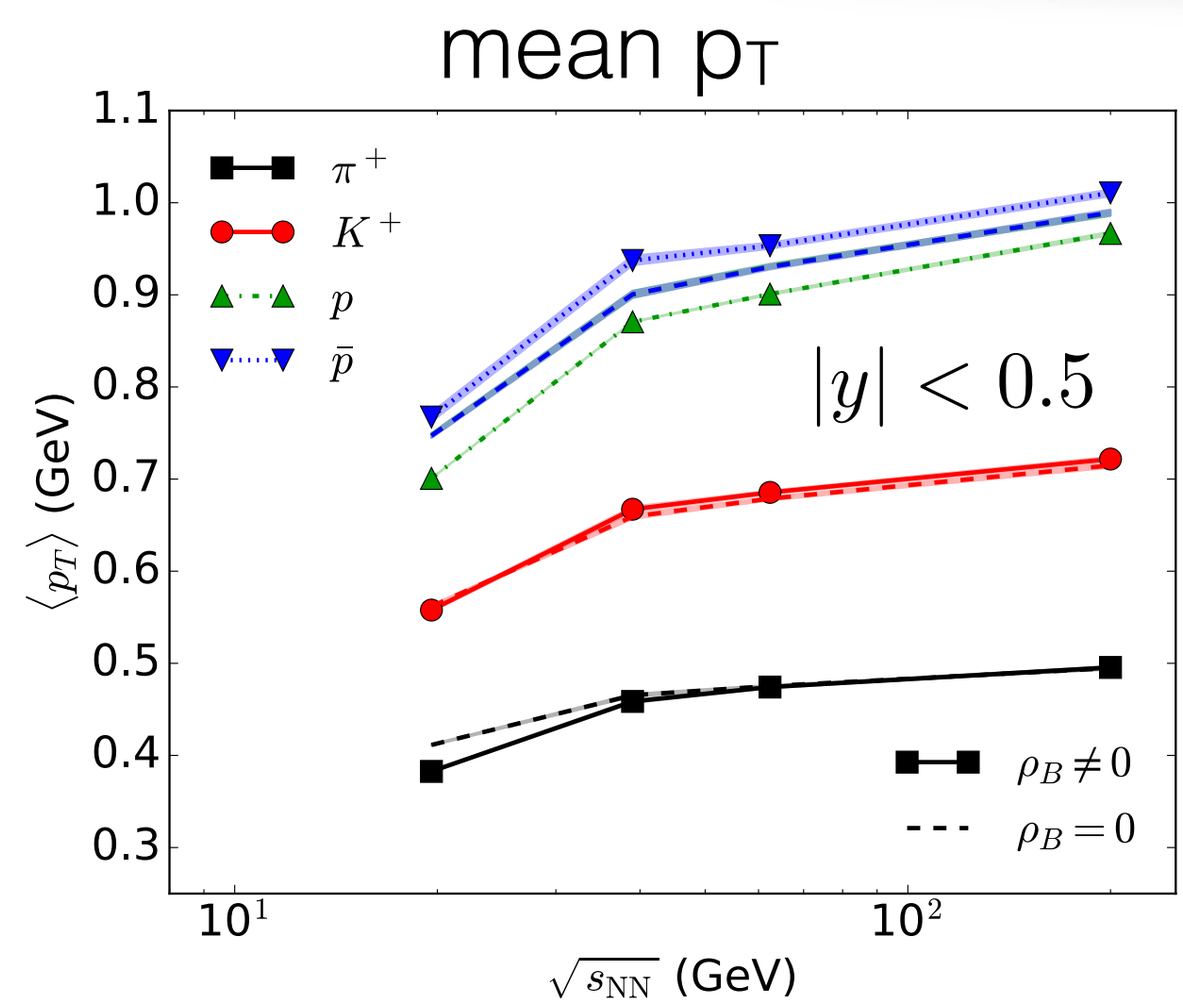


mean p_T



Collision energy dependence of pid observables

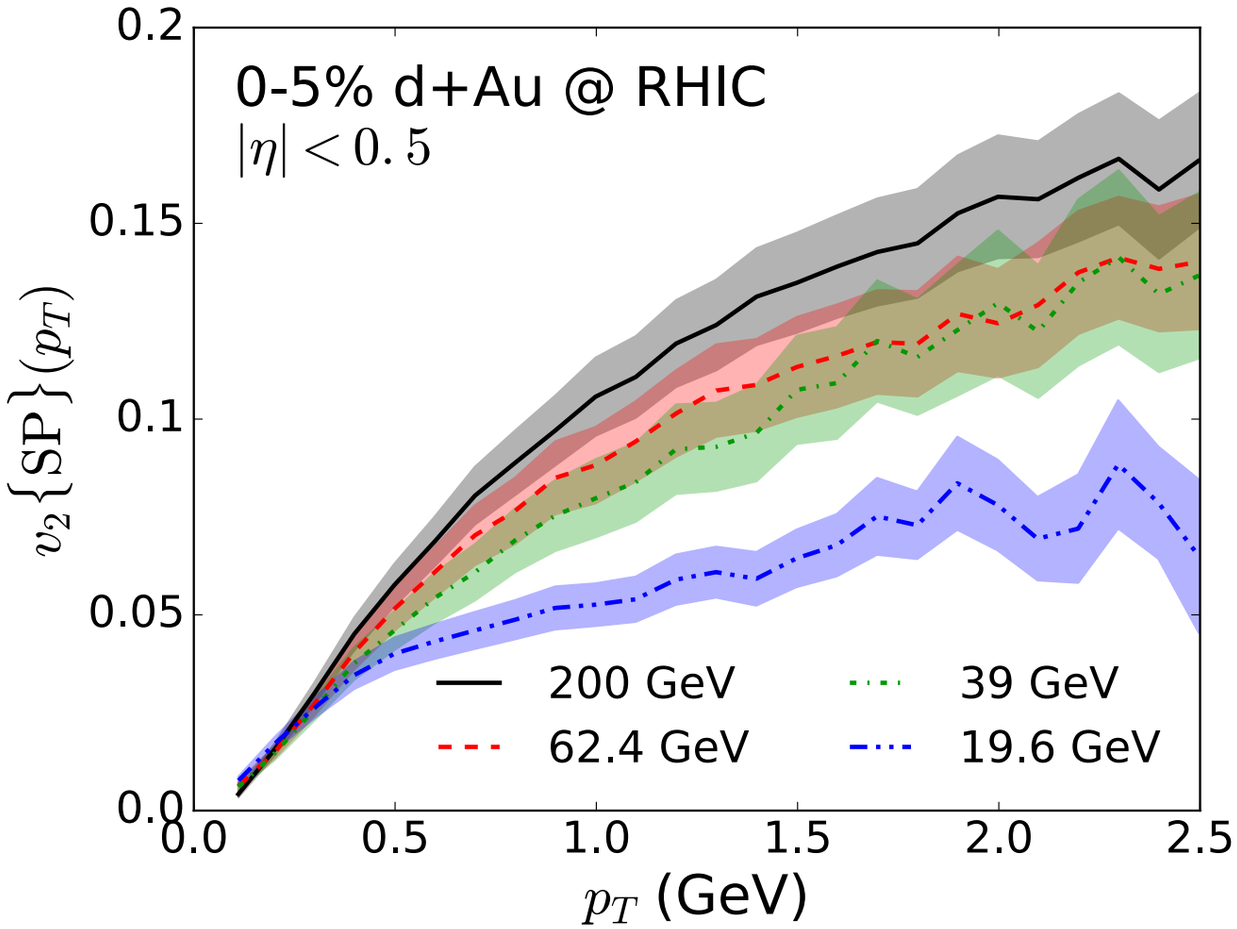


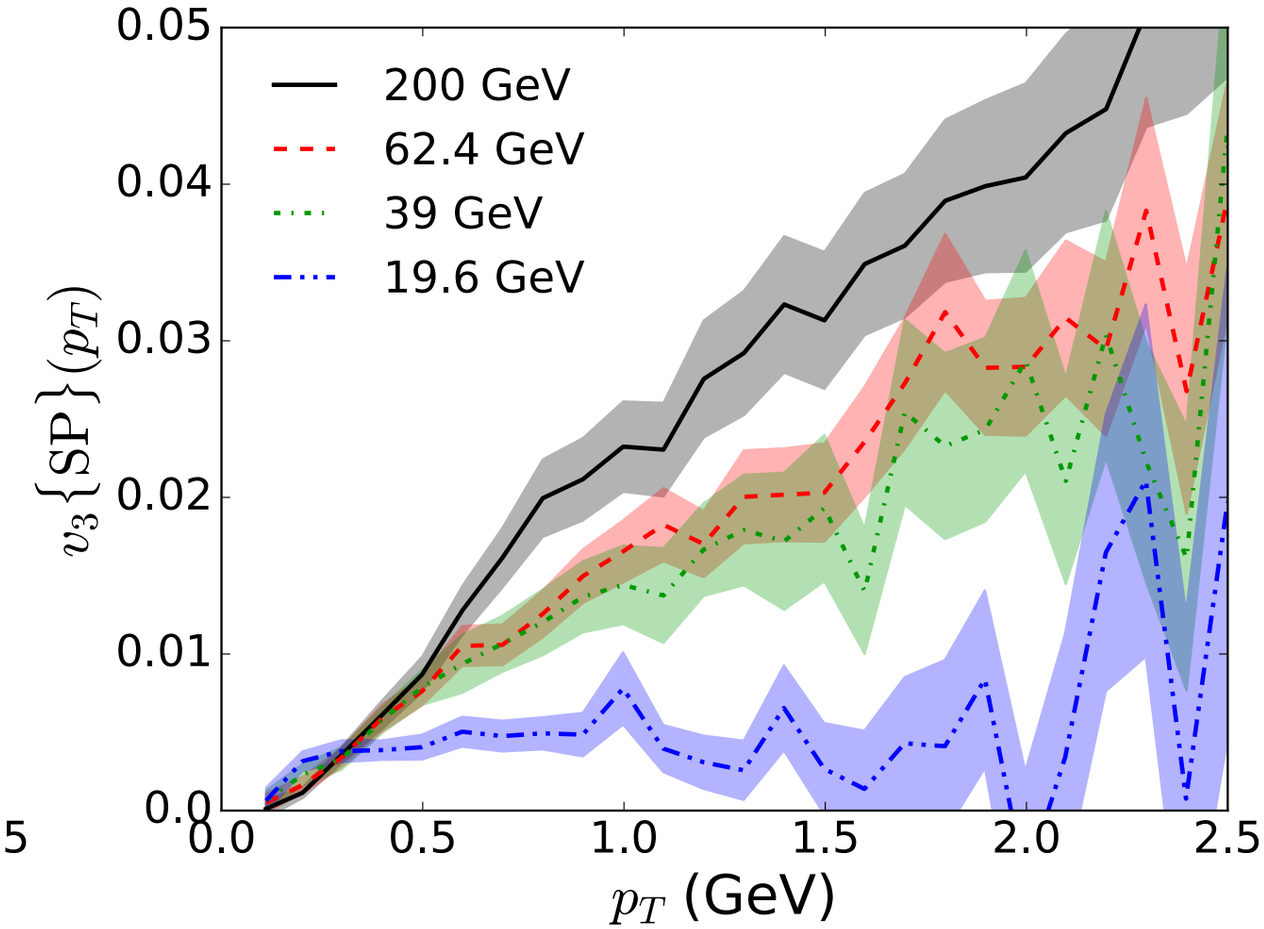


- Proton yield increases as the collision energy decreases
- Anti-protons have a larger mean-p_T than protons

Charged hadron $v_n(p_T)$ at different $\sqrt{s}$

C. Shen, *et al.* preliminary



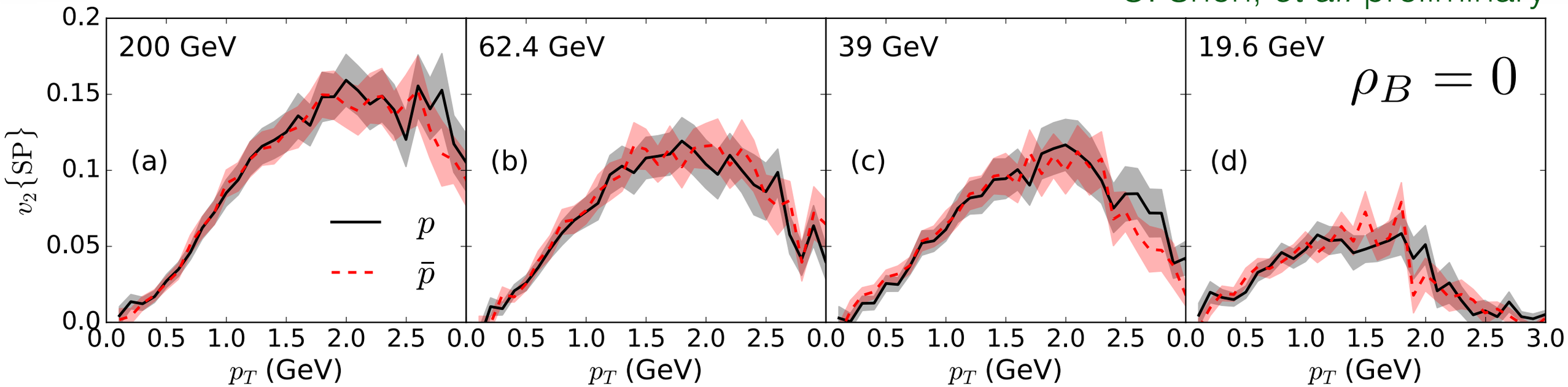


- Sizeable charged hadron v_2 is found at all 4 collision energies
- Charged hadron v_3 is very small at 19.6 GeV

A strong collision energy dependence

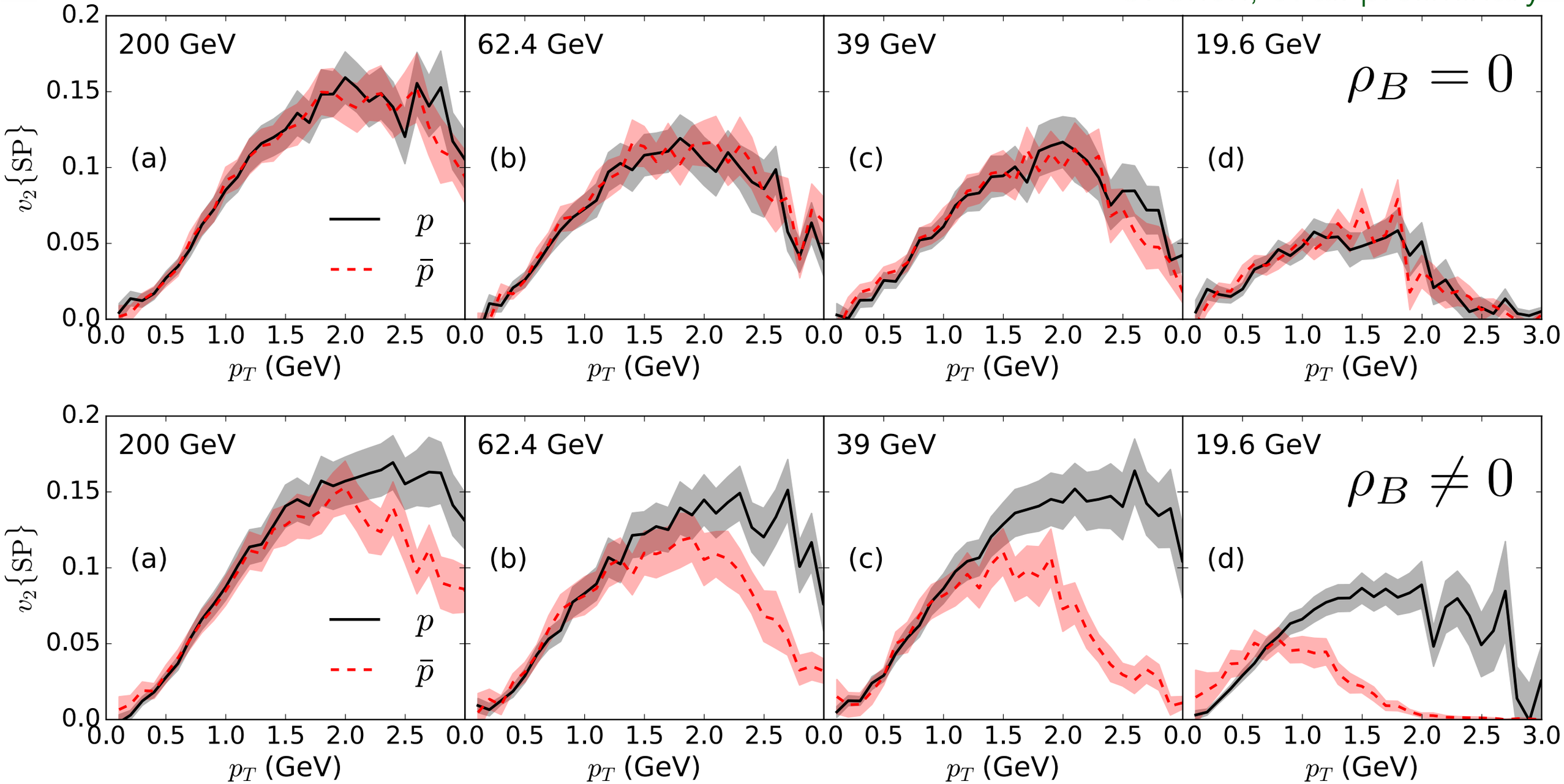
$v_2(p)$ vs $v_2(\bar{p})$

C. Shen, *et al.* preliminary



$v_2(p)$ vs $v_2(\bar{p})$

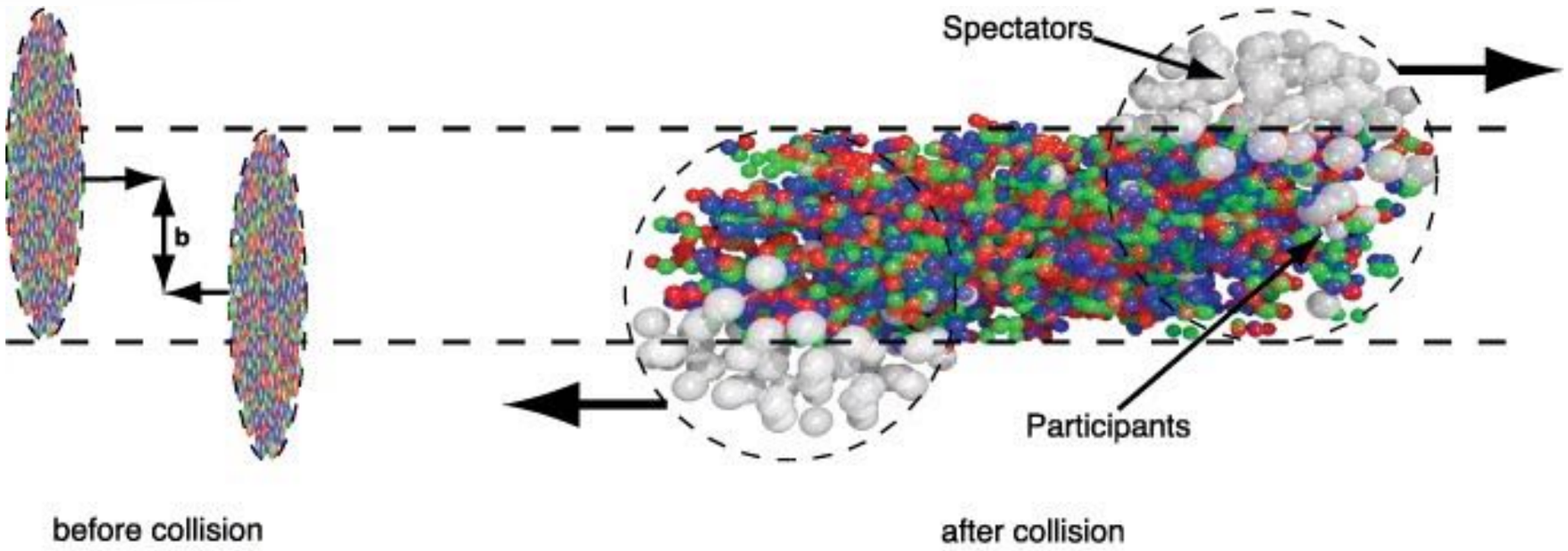
C. Shen, *et al.* preliminary



- Proton v_2 deviates from anti-proton v_2 at $p_T > 1.5$ GeV

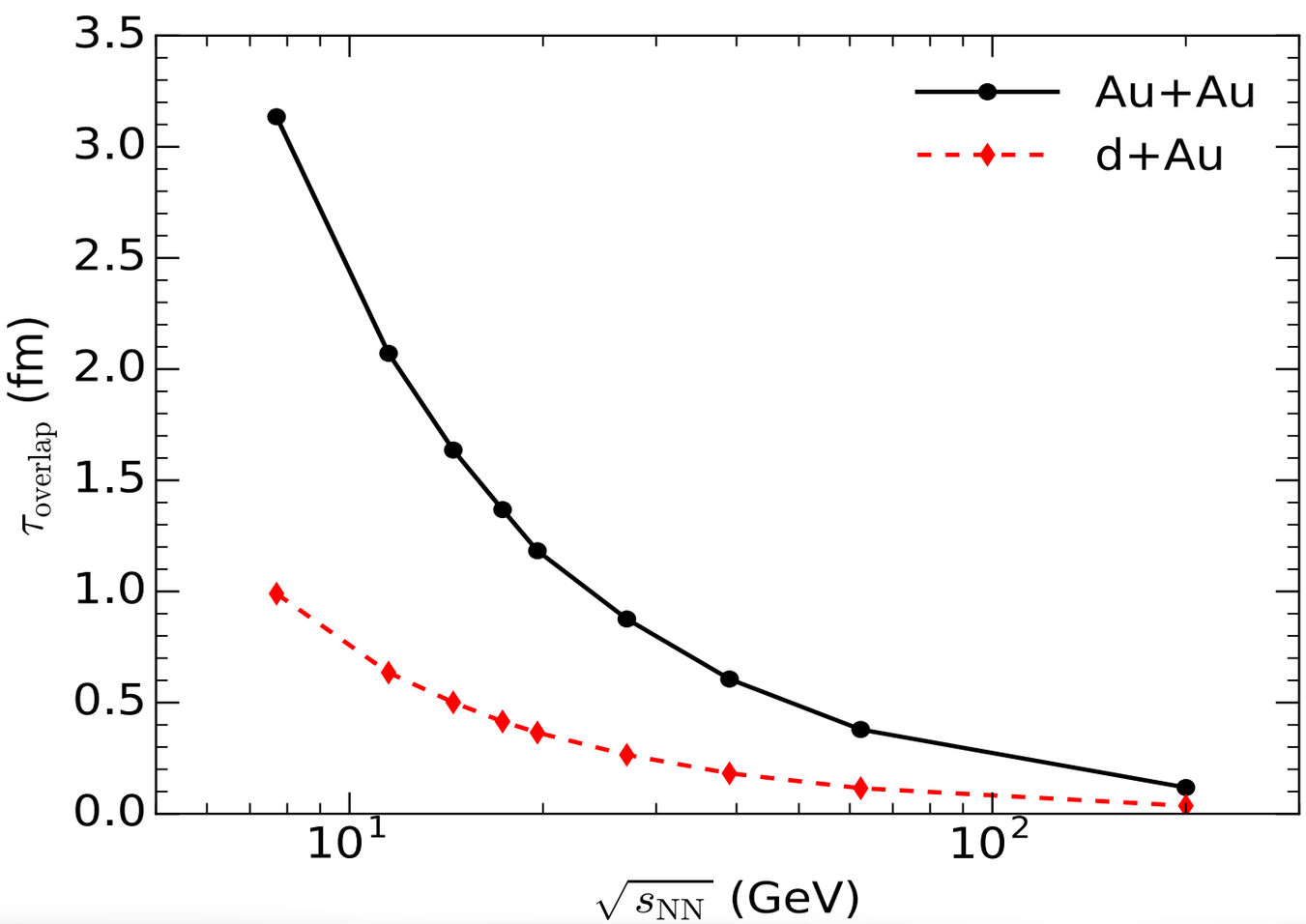
Predictions for d+Au beam energy scan

Hydrodynamics at low collision energies



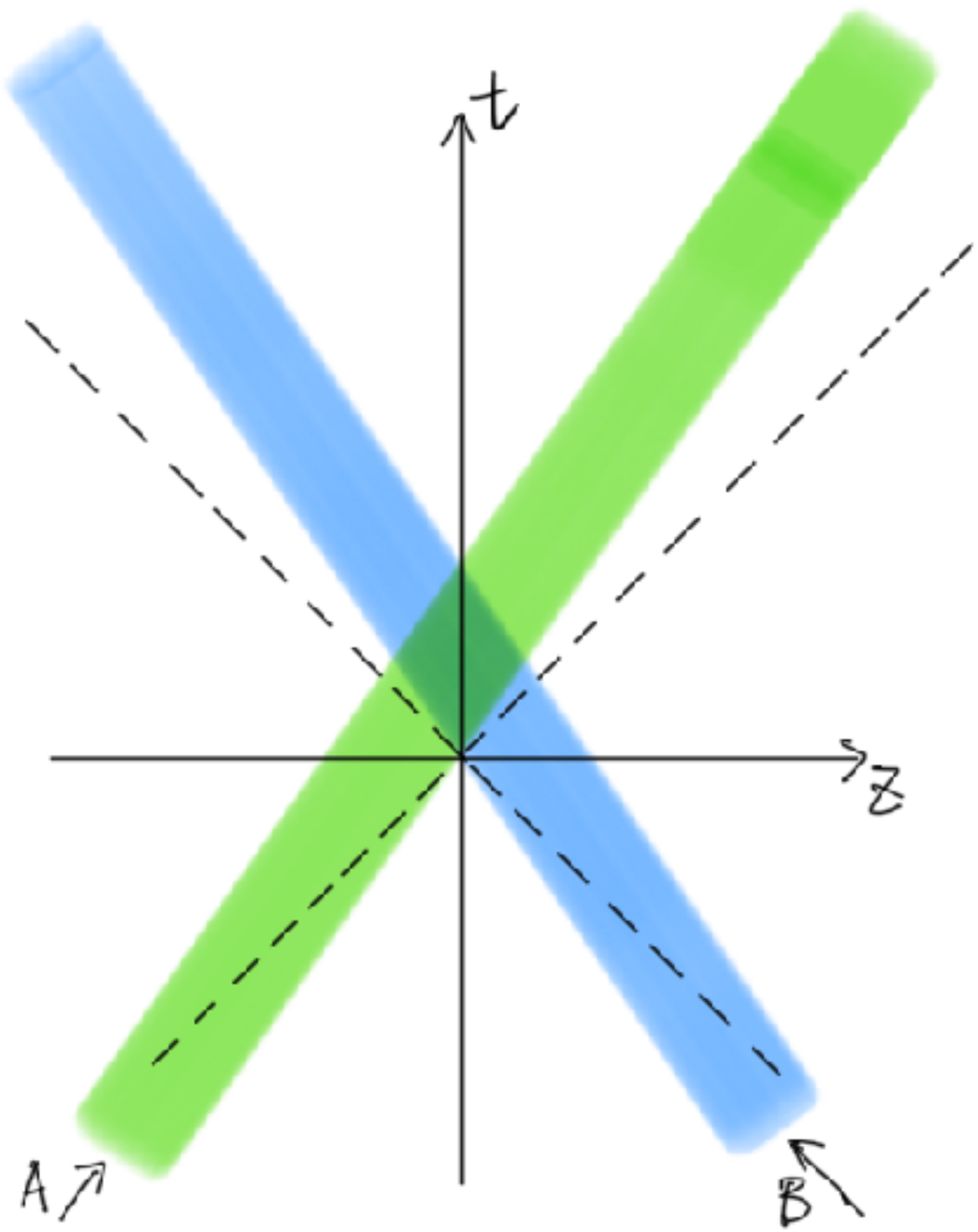
Two nuclei overlapping time

$$\tau \sim \frac{2R}{\gamma v_z}$$



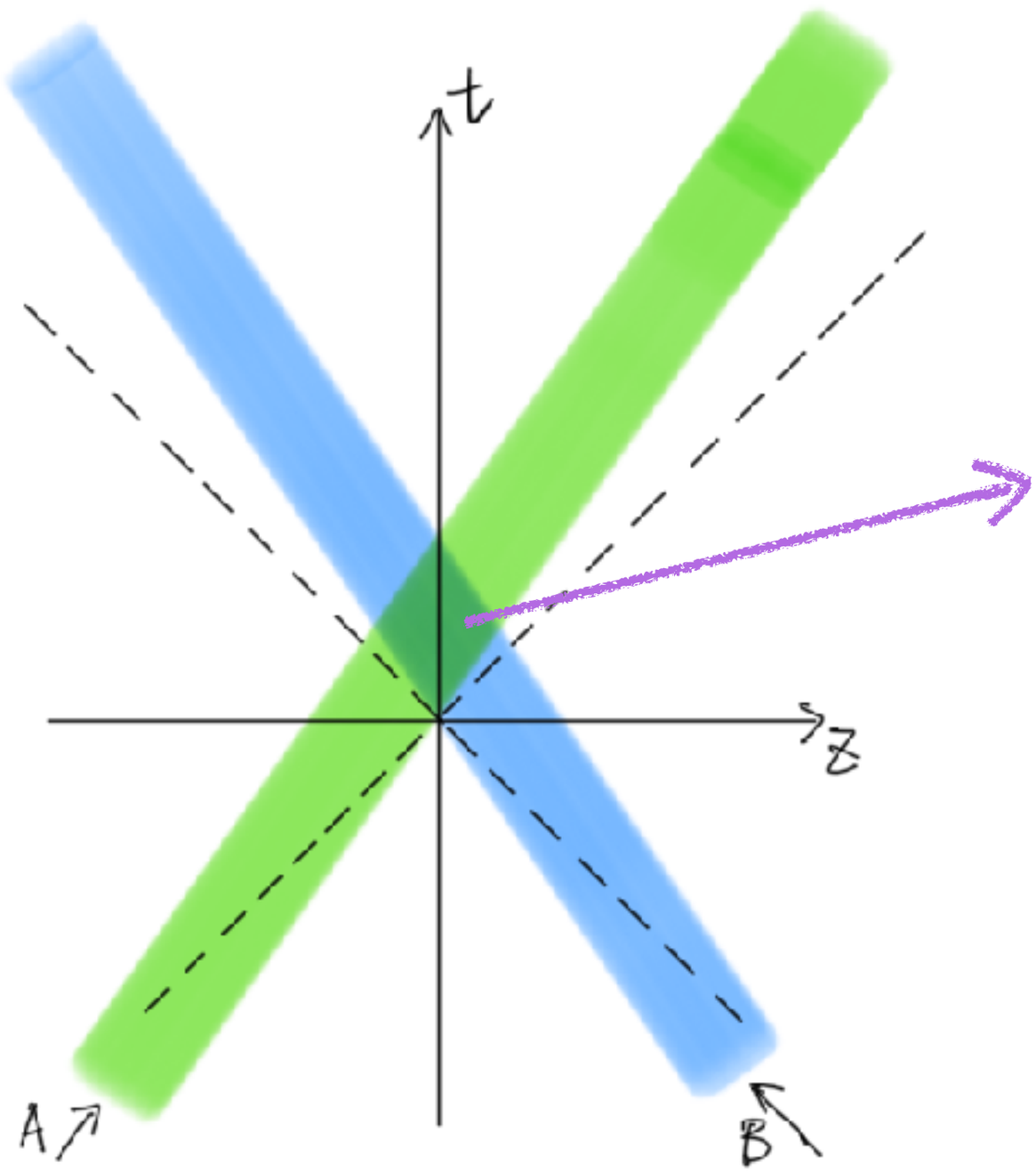
- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

Go beyond the Bjorken approximation



- The finite widths of the colliding nuclei are taken into account

Go beyond the Bjorken approximation



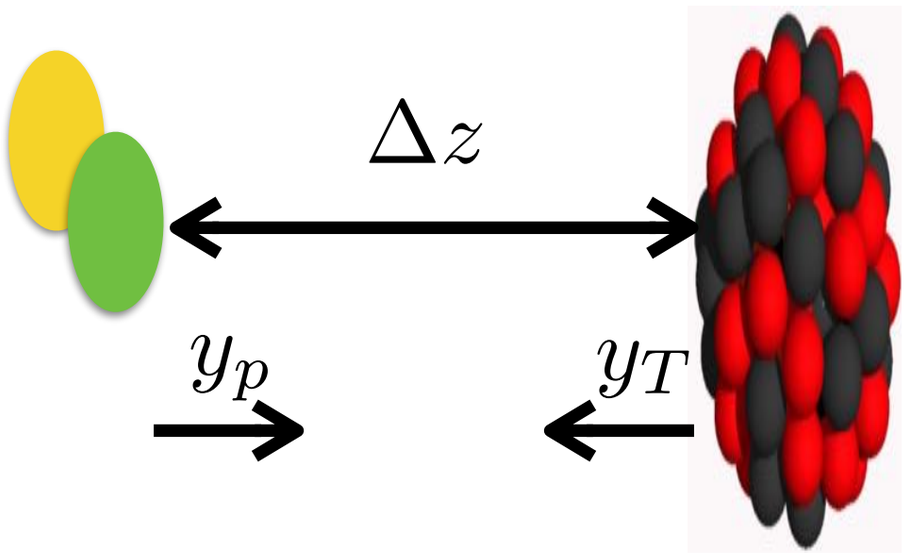
- The finite widths of the colliding nuclei are taken into account

The interaction zone is not point like

$$y \neq \eta_s$$

A 3D MCGlauber model

In collaboration with B. Schenke



- Collision time and 3D spatial position are determined for every binary collision

A 3D MCGlauber model

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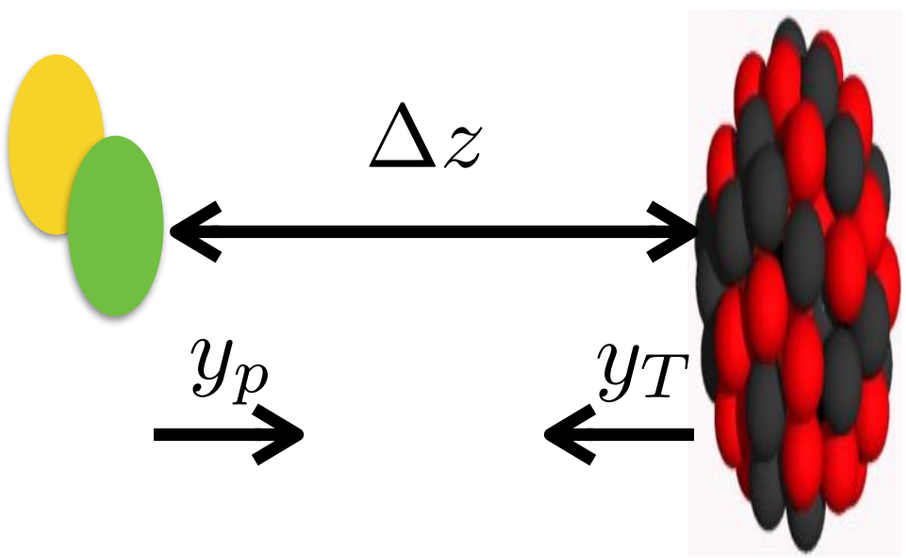

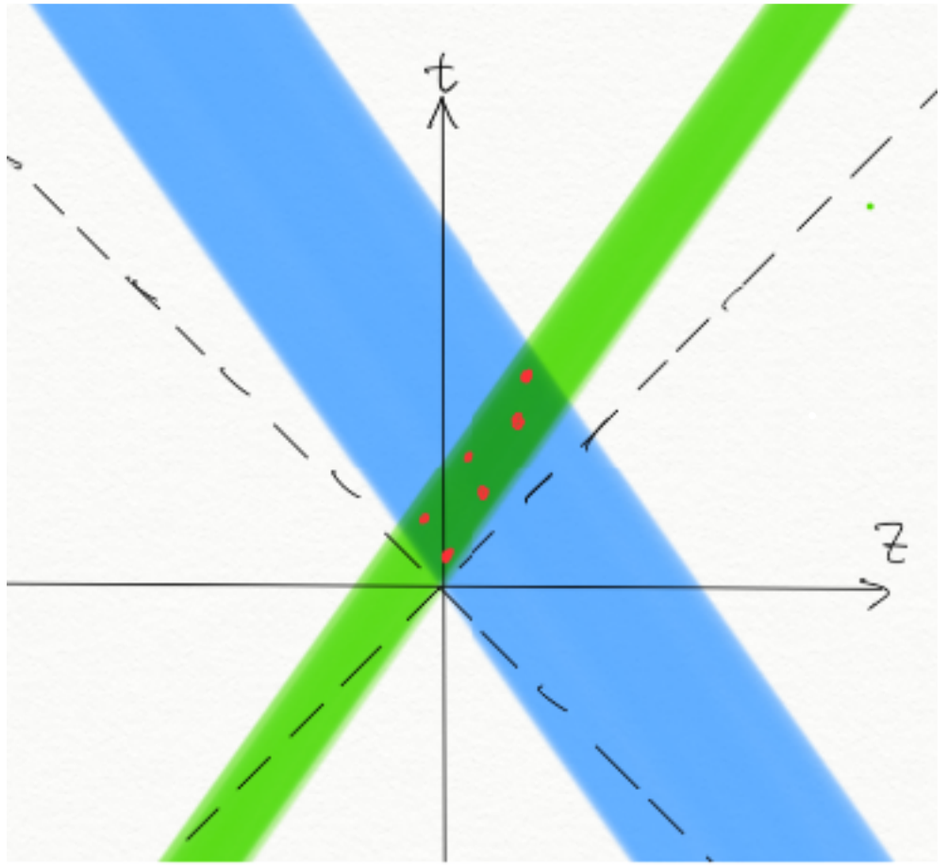

- Collision time and 3D spatial position are determined for every binary collision
- Strings that carry energy and charges are produced at randomly selected collision points

A 3D MCGlauber model

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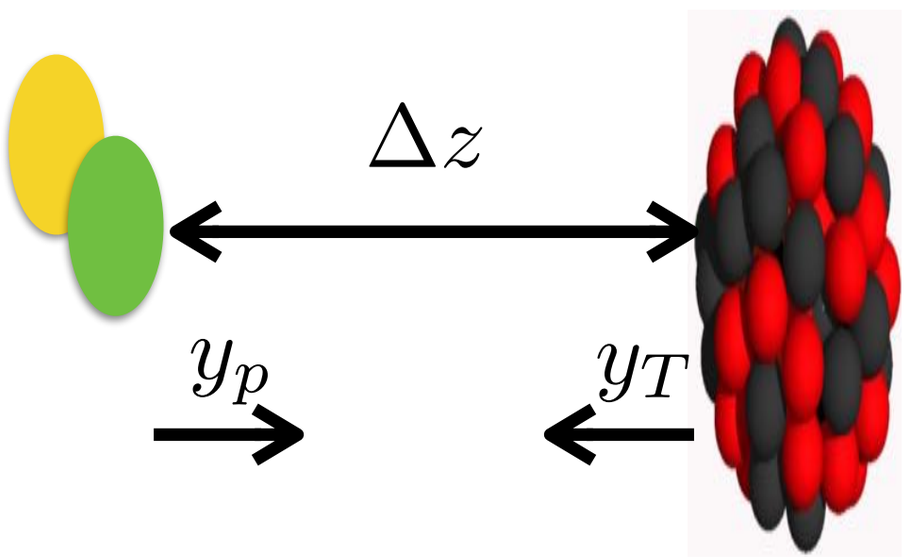
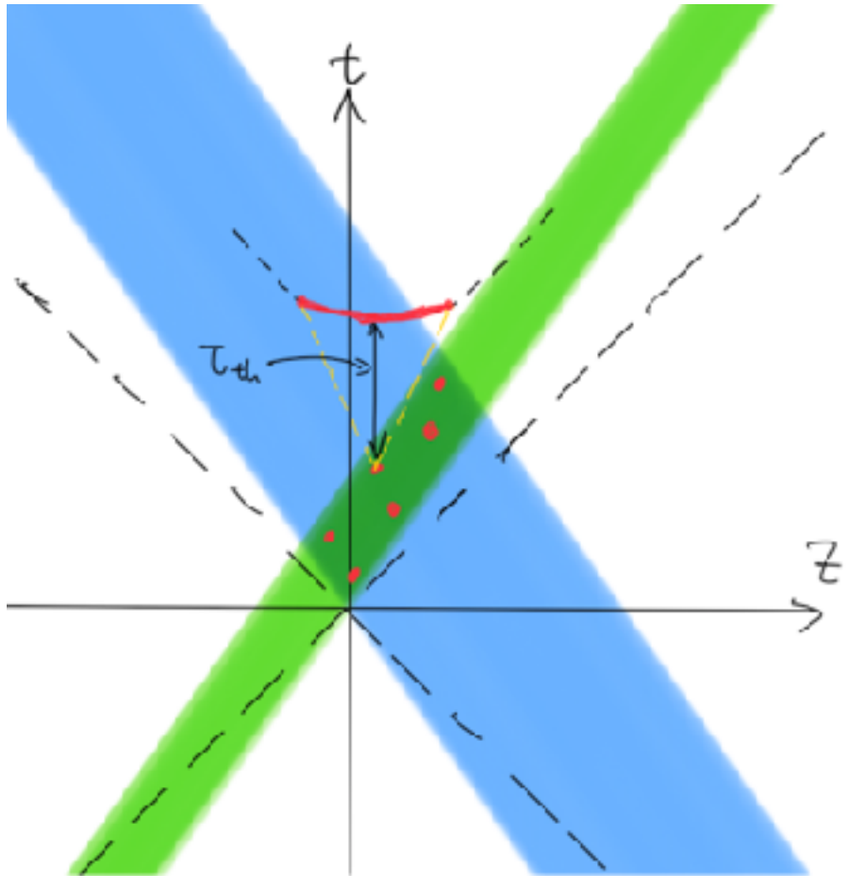
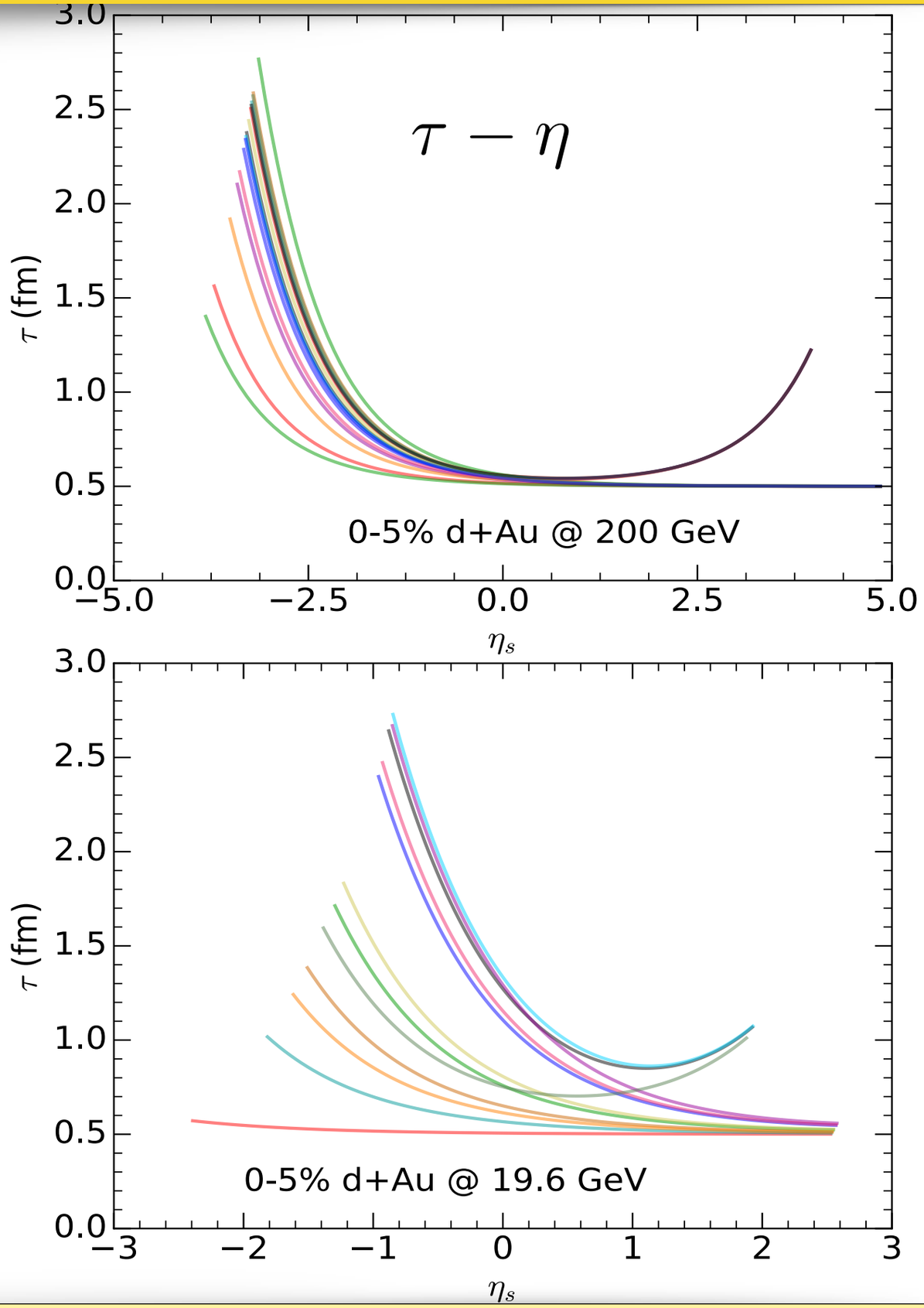
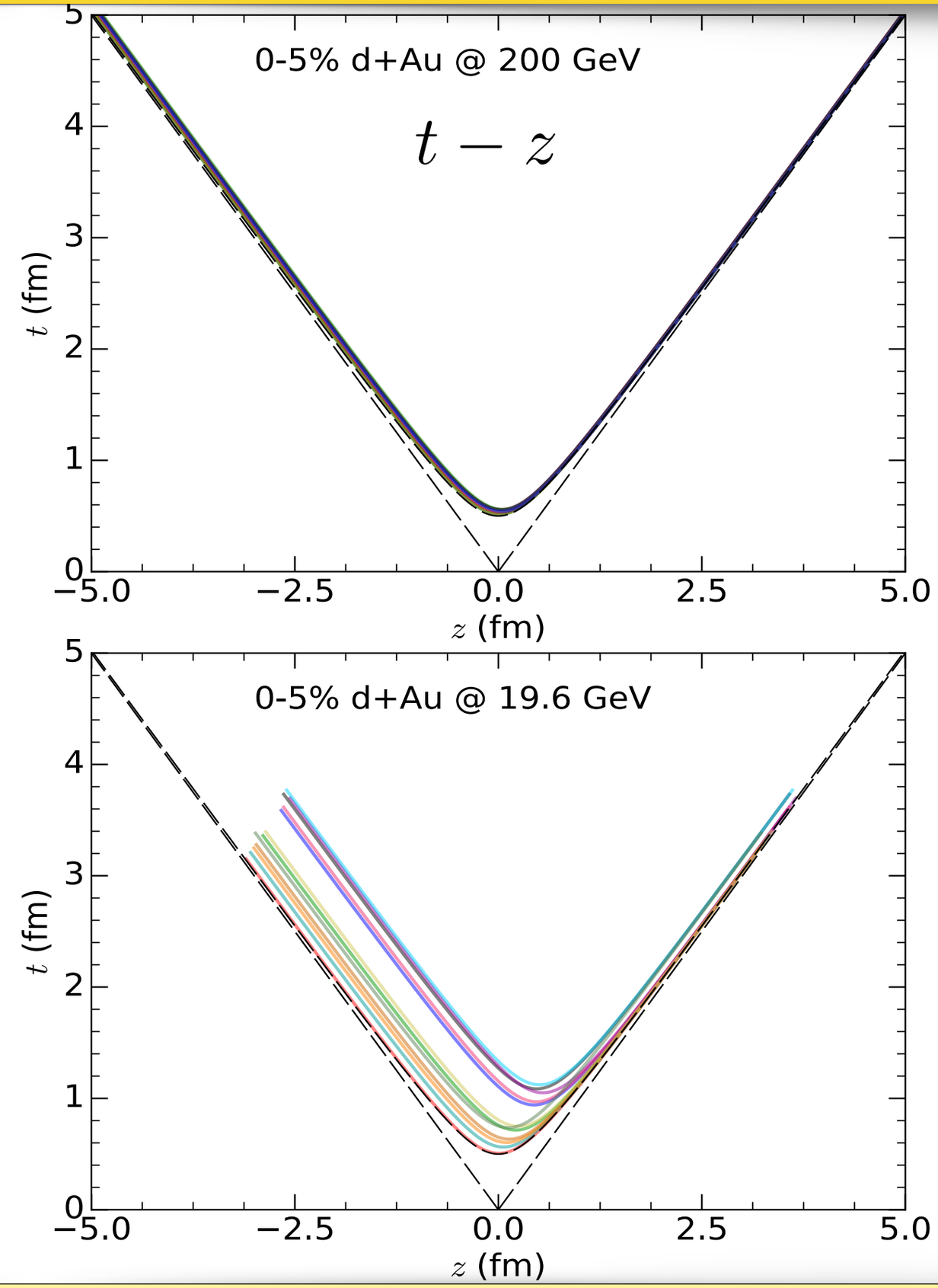




- Collision time and 3D spatial position are determined for every binary collision
- Strings that carry energy and charges are produced at randomly selected collision points
- Strings are decelerated with constant string tension before thermalized to medium

A 3D MCGlauber model

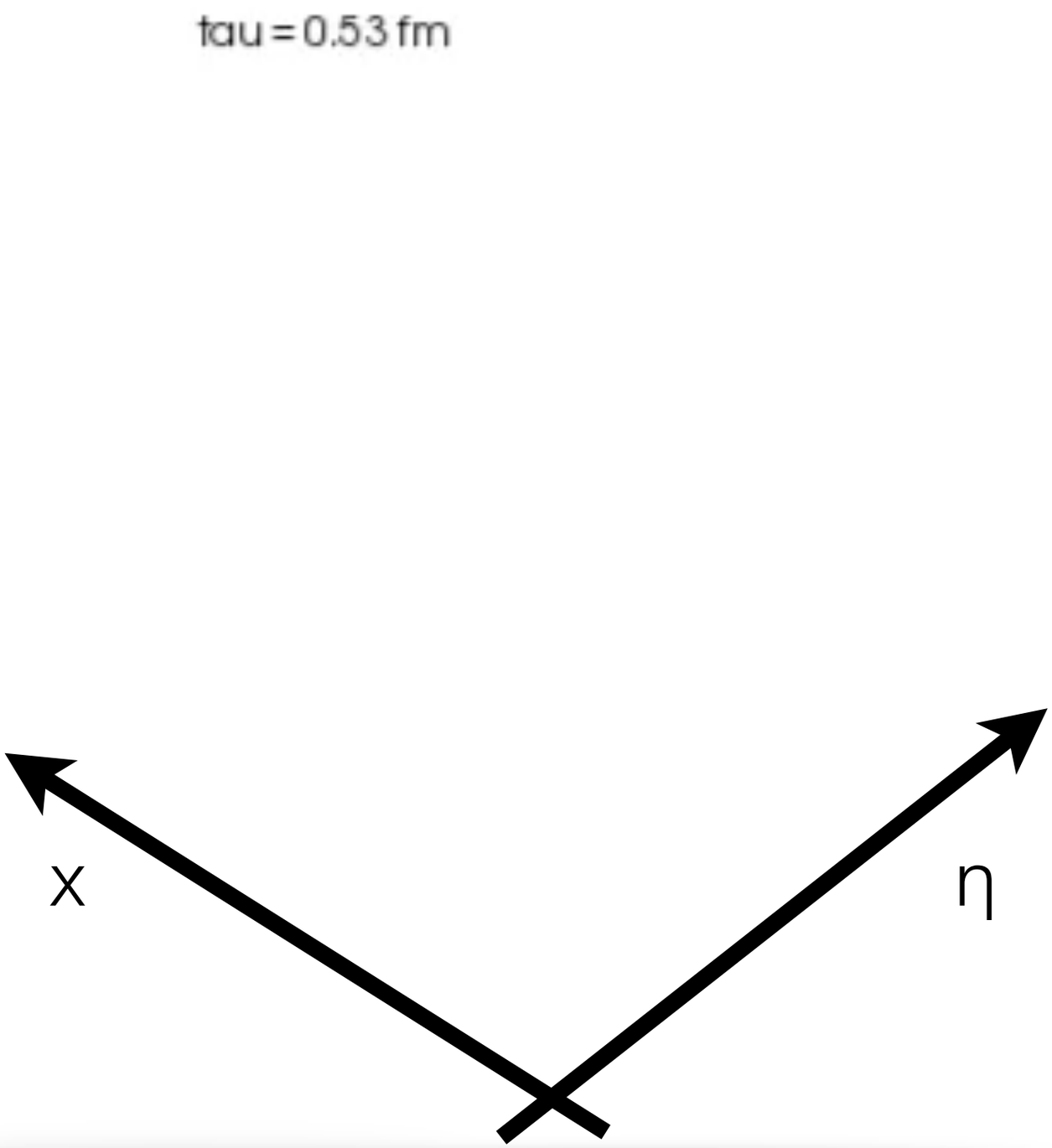


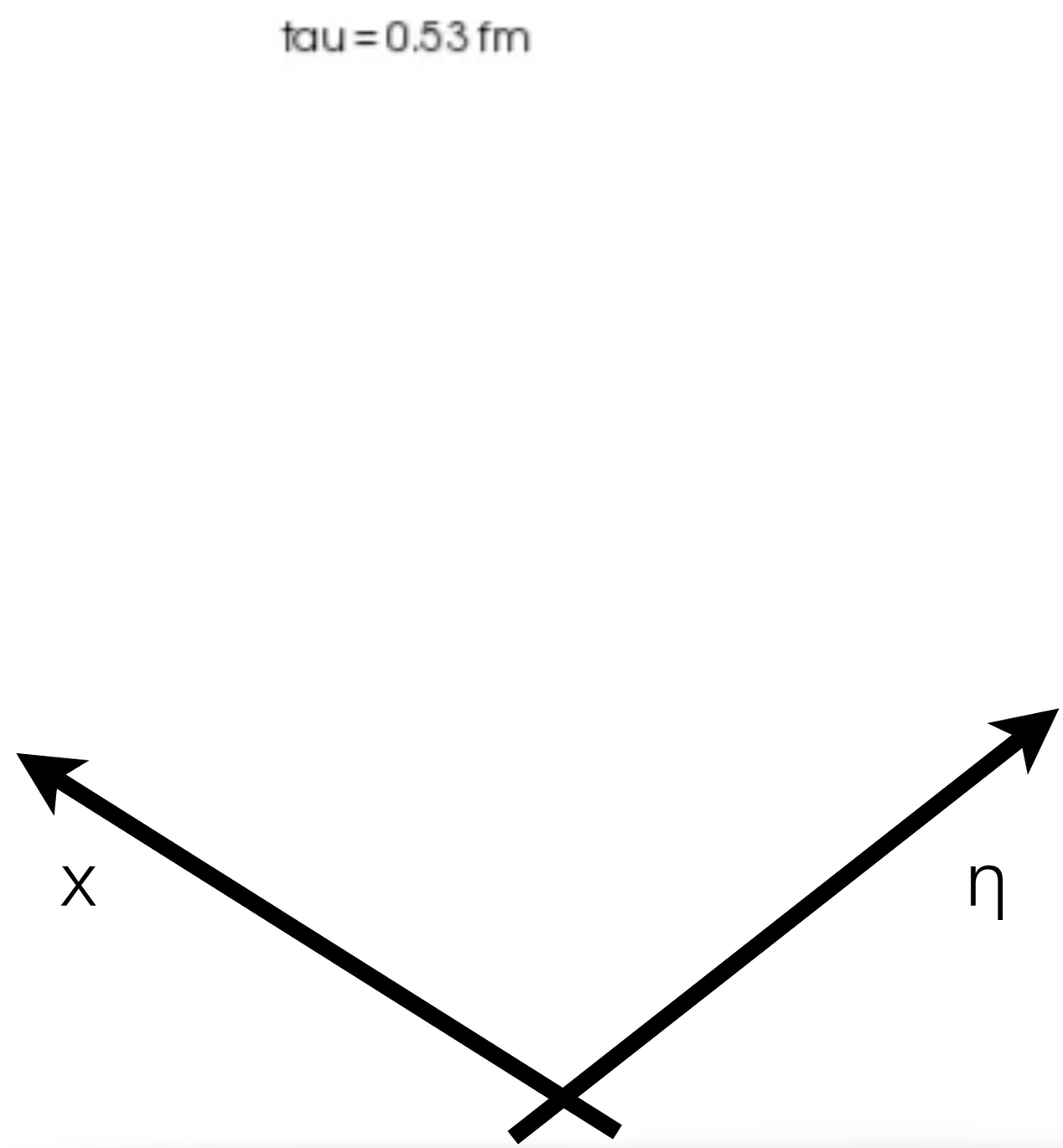


Evolution of a d+Au collision in 3D

energy density

net baryon density





Conclusion

- Hydrodynamic simulations can *quantitatively* describe the particle spectra, v_n, HBT radii measured in small collision systems at RHIC and LHC energies

- Direct photons provide us with an additional tool to elucidate the nature of the QCD matter created in small systems

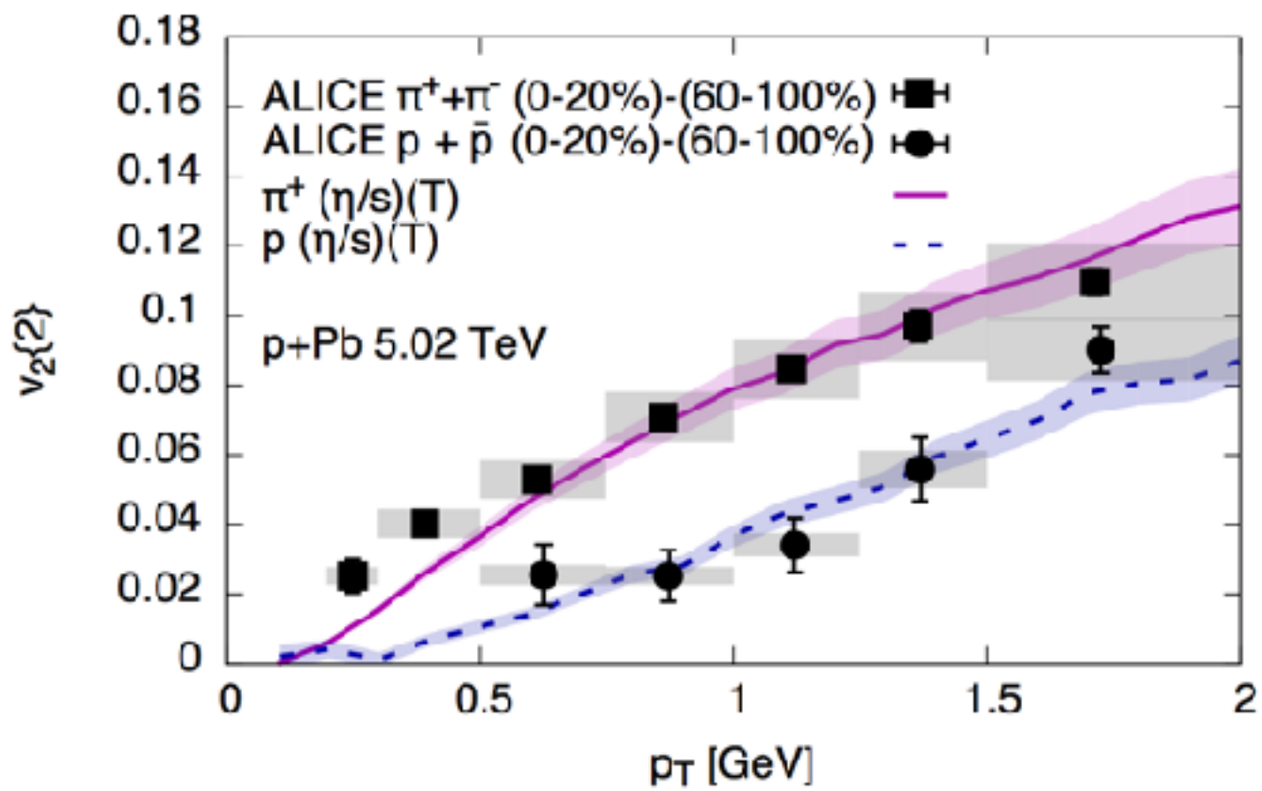
- Observables in d+Au collisions at BES energies can shed light on understanding the effect of net baryon density on system's collective dynamics

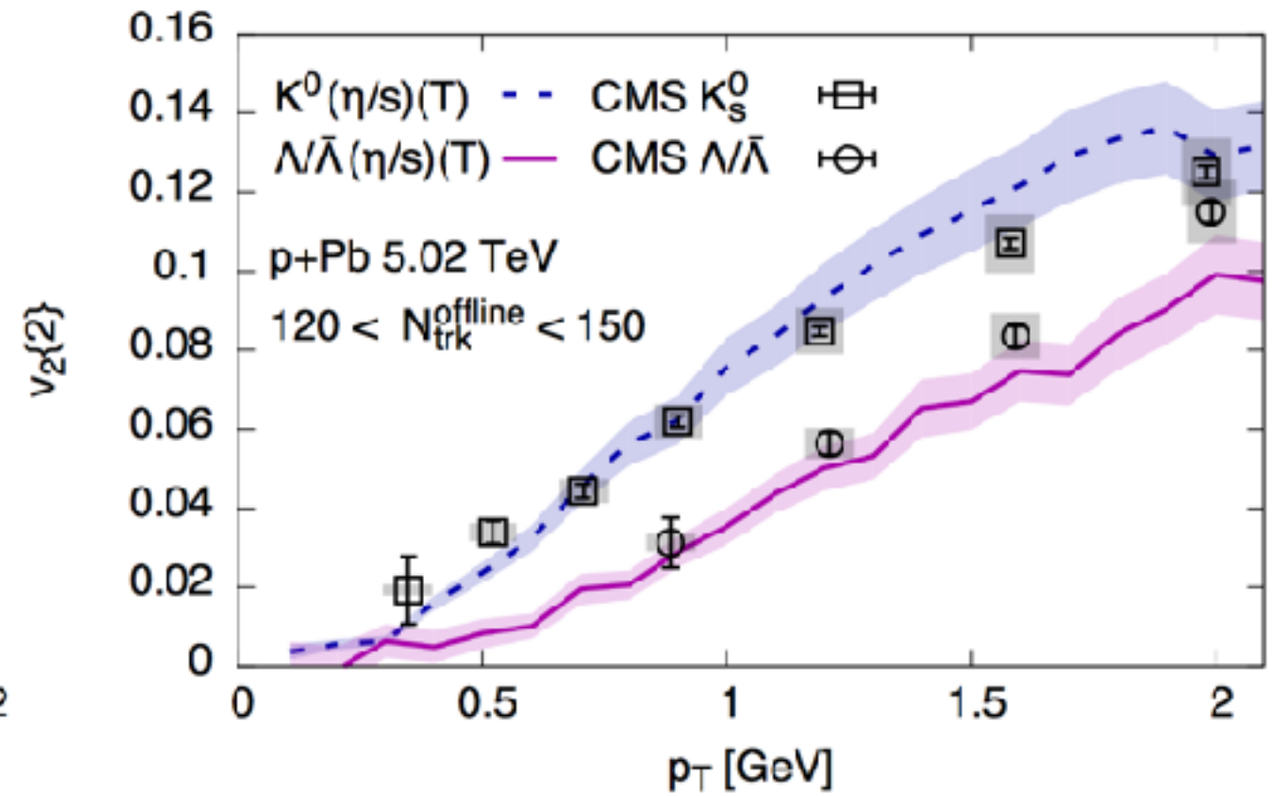
BACKUP

pid $v_2(p_T)$ mass splitting in small systems

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

IP-Glasma + MUSIC + UrQMD:

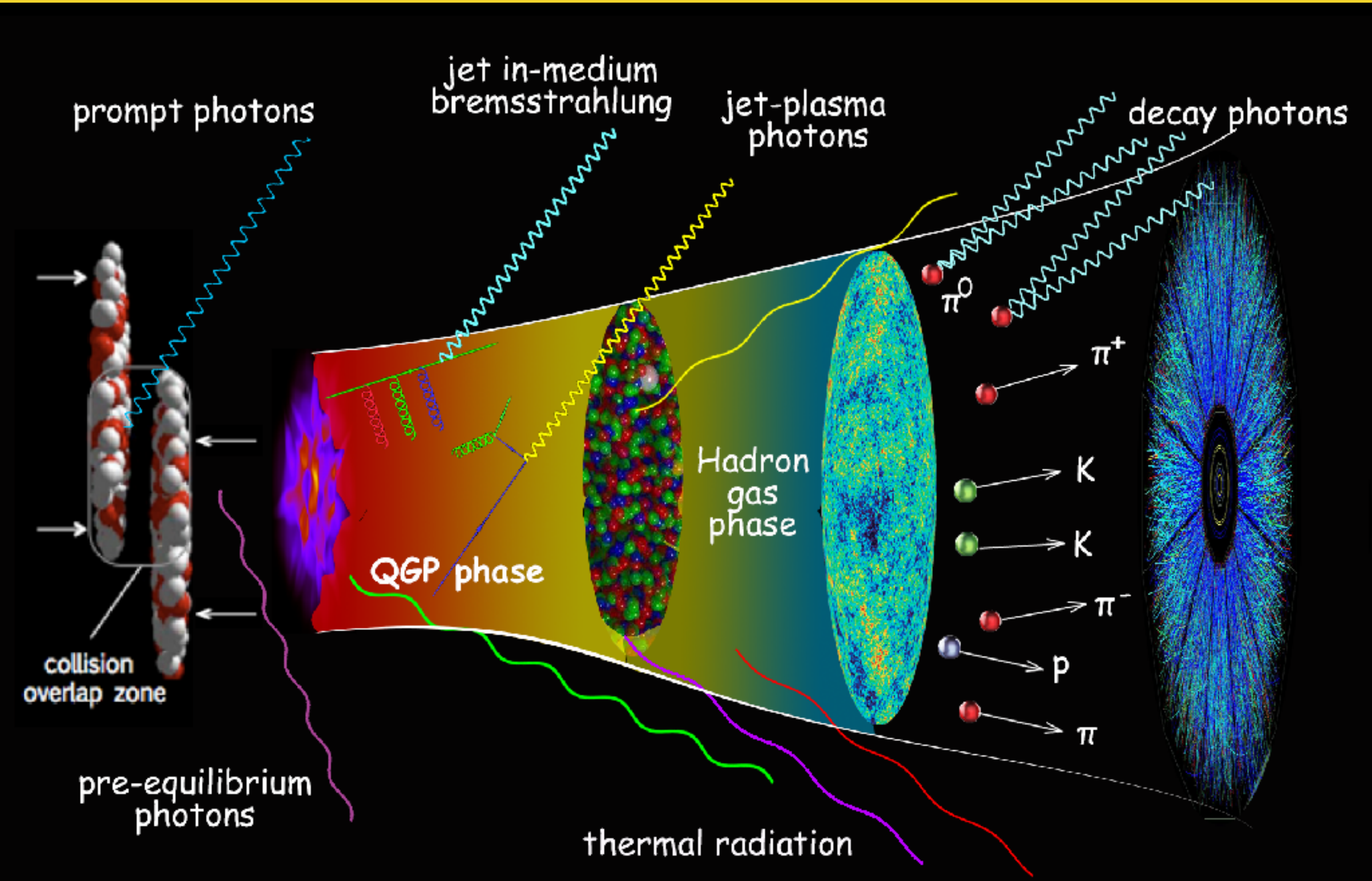




- The interplay between radial and elliptic flow in the hydrodynamic simulations can reproduce the mass splitting of pid $v_2(p_T)$ in small collision systems

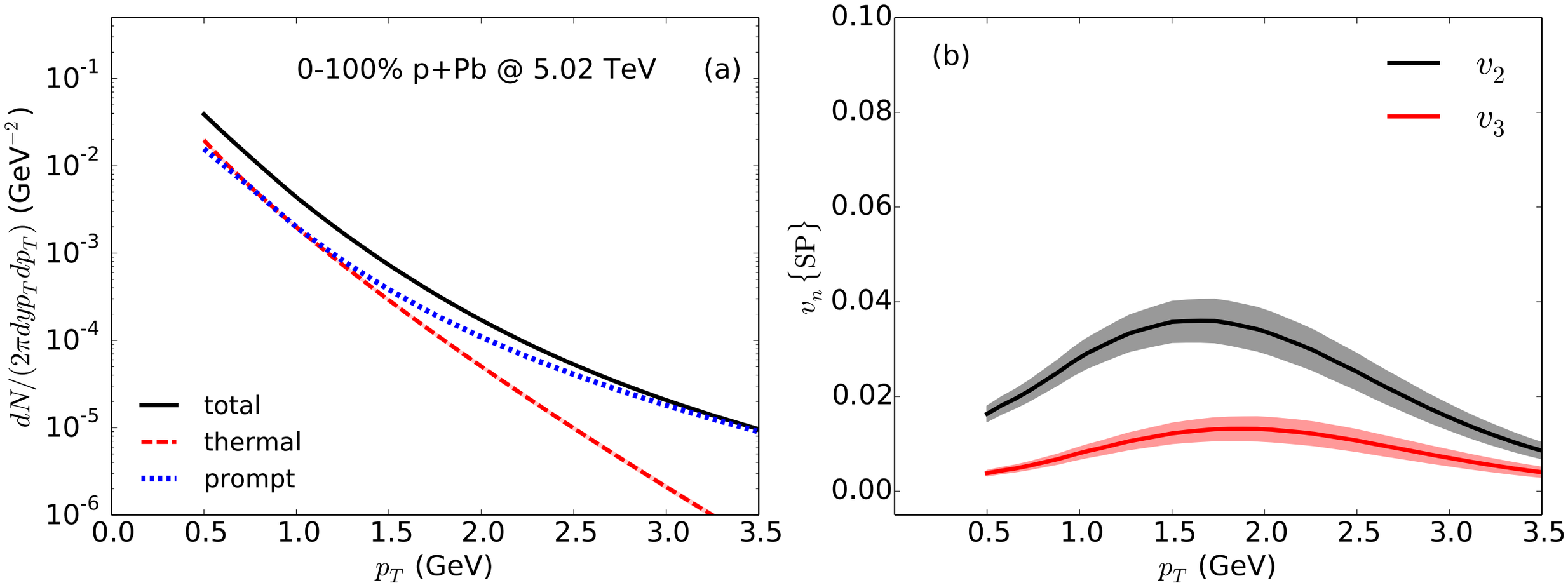
Indication of a strongly coupled QCD matter?

EM radiation in heavy-ion collisions



Thermal radiation in small systems

C. Shen, *et al.*, arXiv:1609.02590



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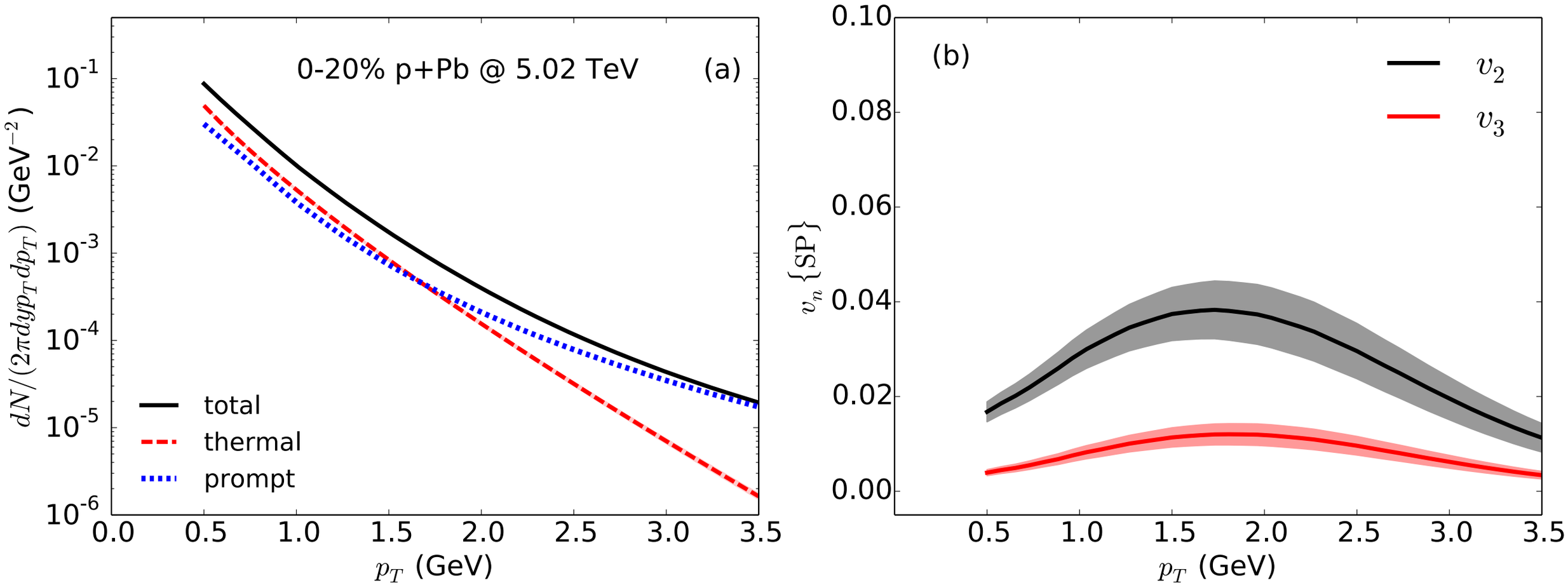
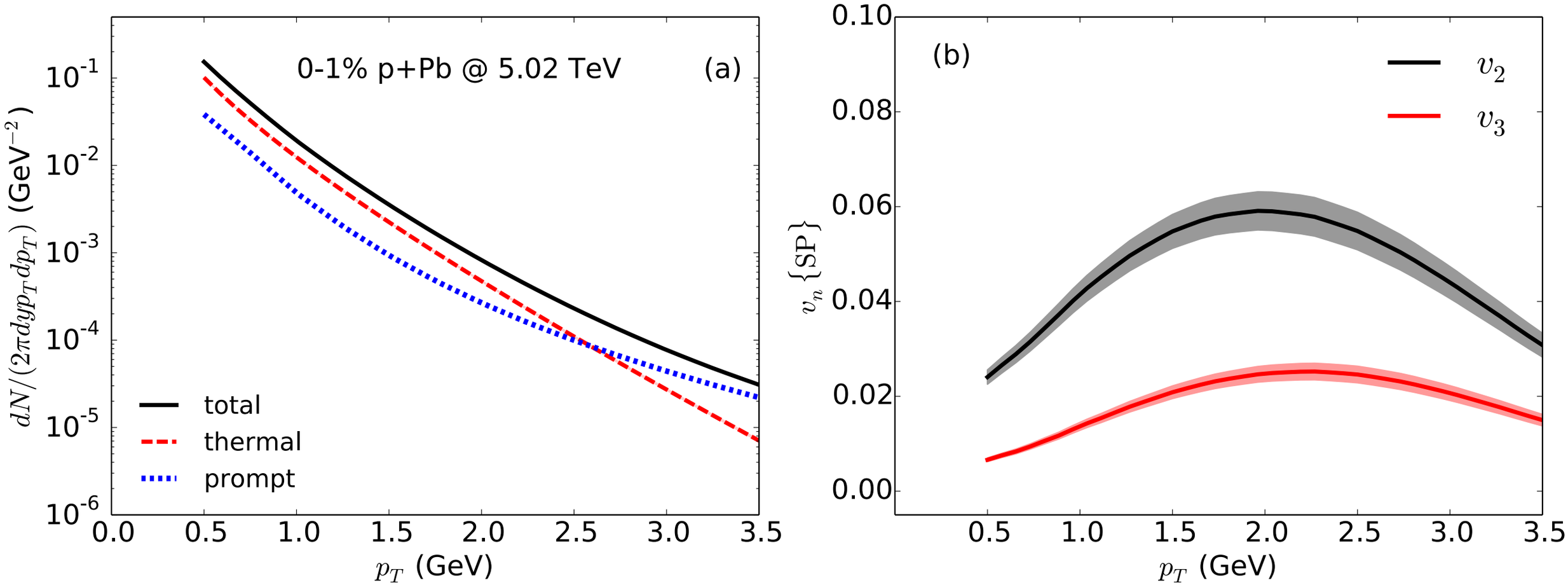


- In 0-20% p+Pb collisions, thermal photons become comparable to prompt photons
- There is small direct photon anisotropic in central p+Pb collisions

Thermal radiation in small systems

C. Shen, *et al.*, arXiv:1609.02590



- In 0-1% p+Pb collisions, thermal photon can out-shine prompt photons
- <u>Sizeable</u> direct photon anisotropy in central p+Pb collisions

Signature of a nearly thermalized medium in small systems

How does thermal radiation shine out?

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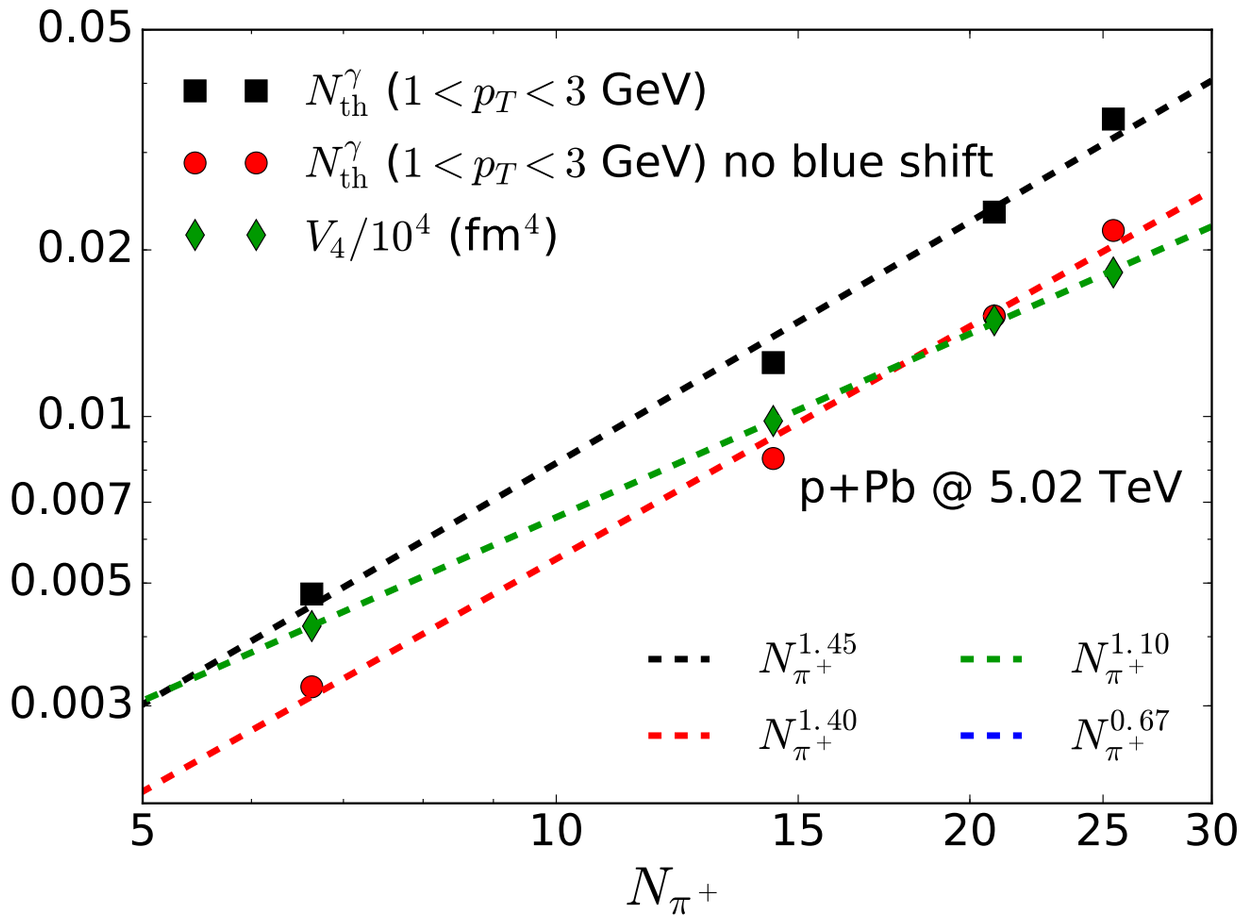

- Thermal photon production is determined by the space-time volume, temperature and flow distributions

How does thermal radiation shine out?

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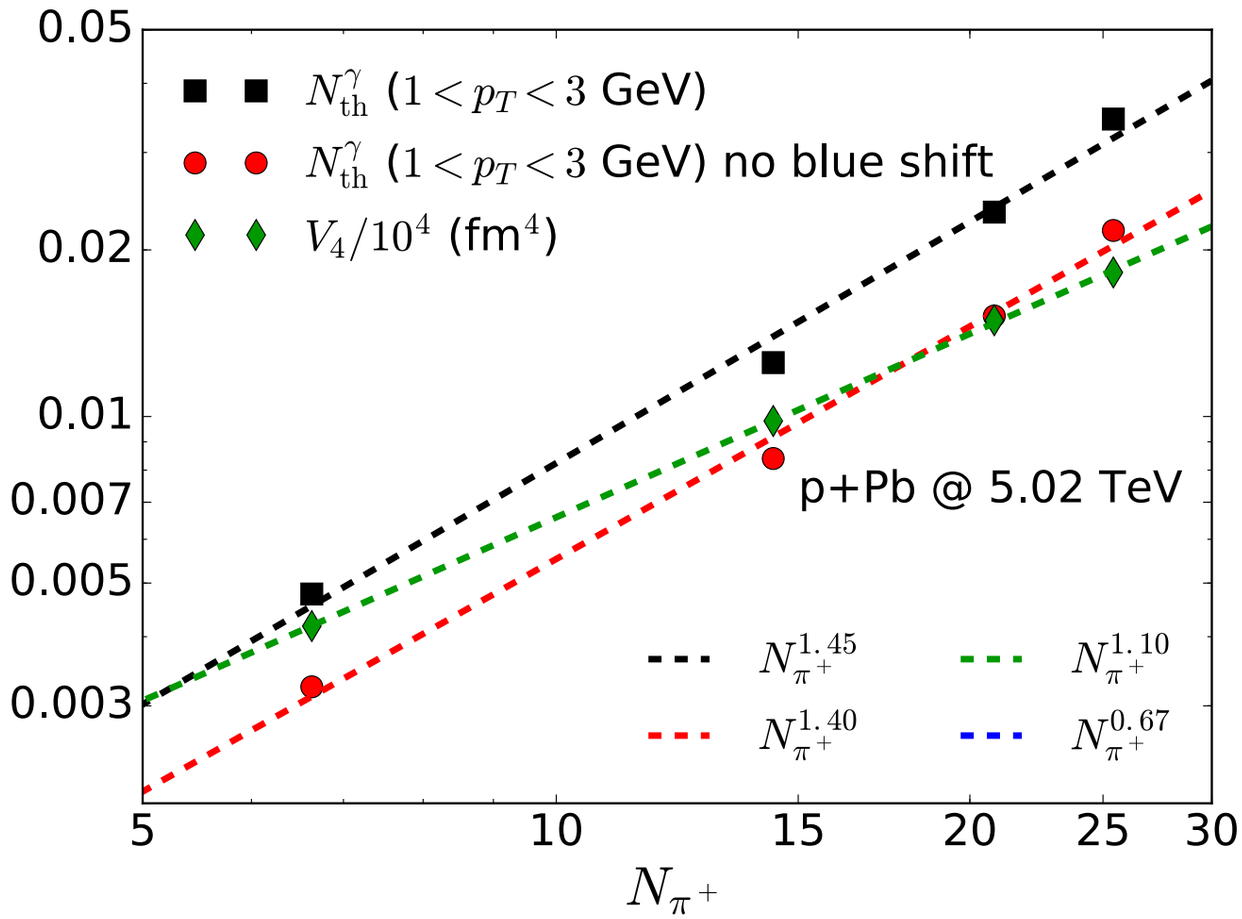

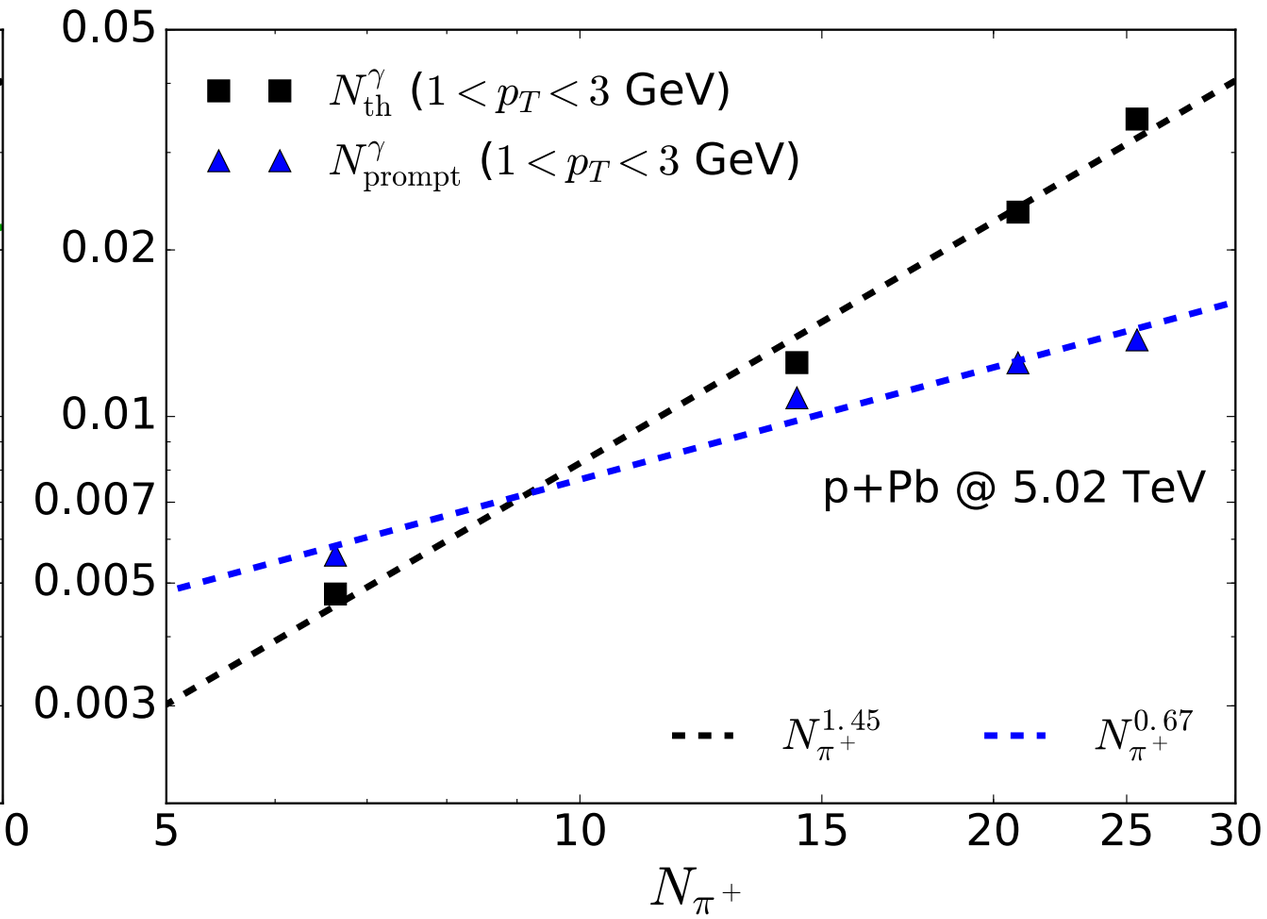

- Thermal photon production is determined by the space-time volume, temperature and flow distributions
- Prompt photons show much weaker centrality dependence

(2+1)D vs (3+1)D simulations

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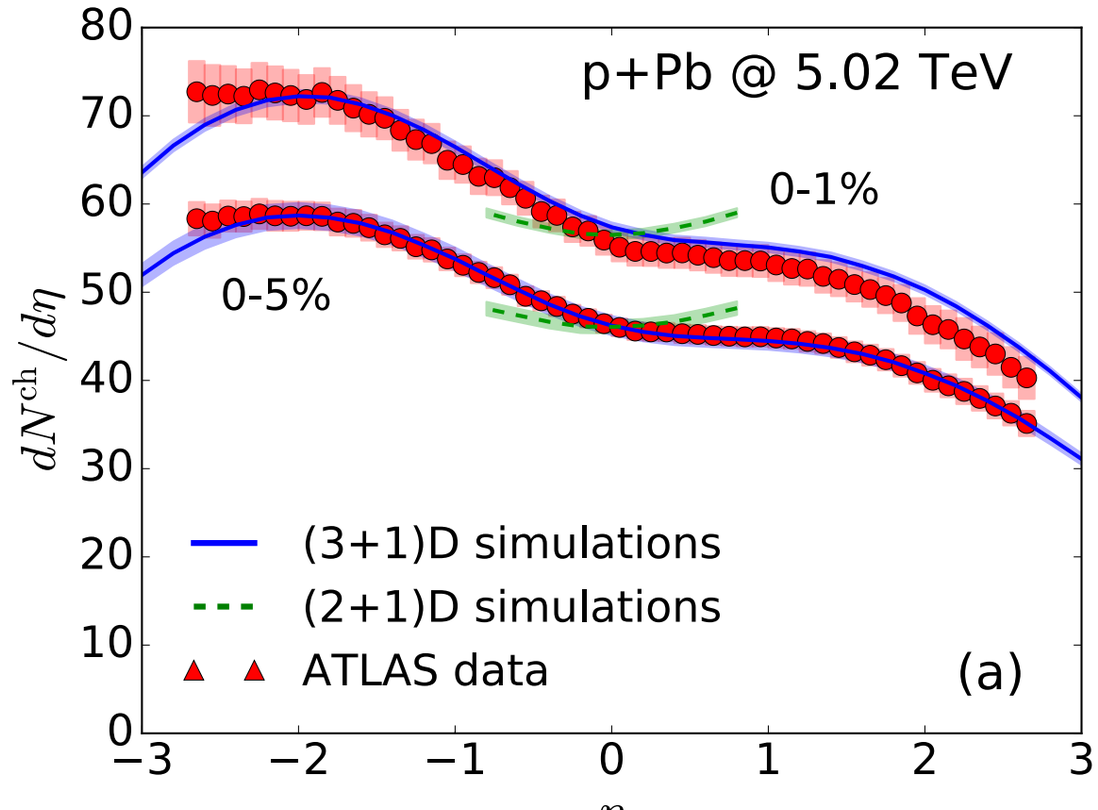
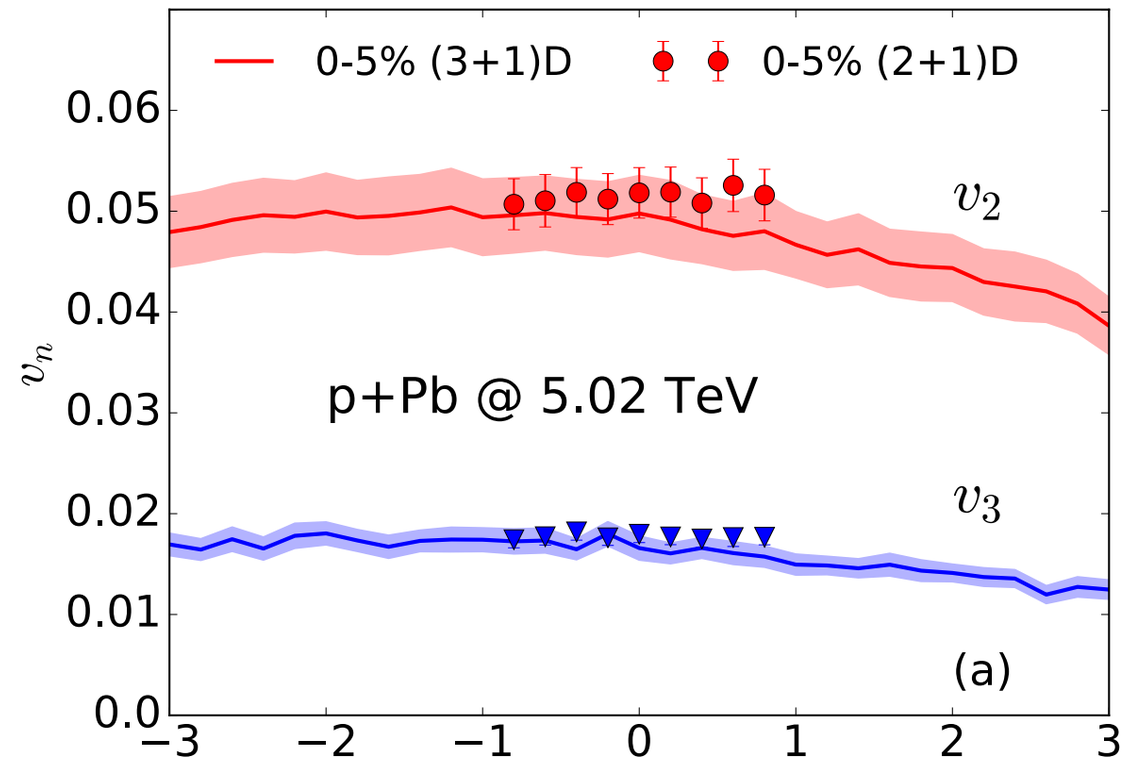
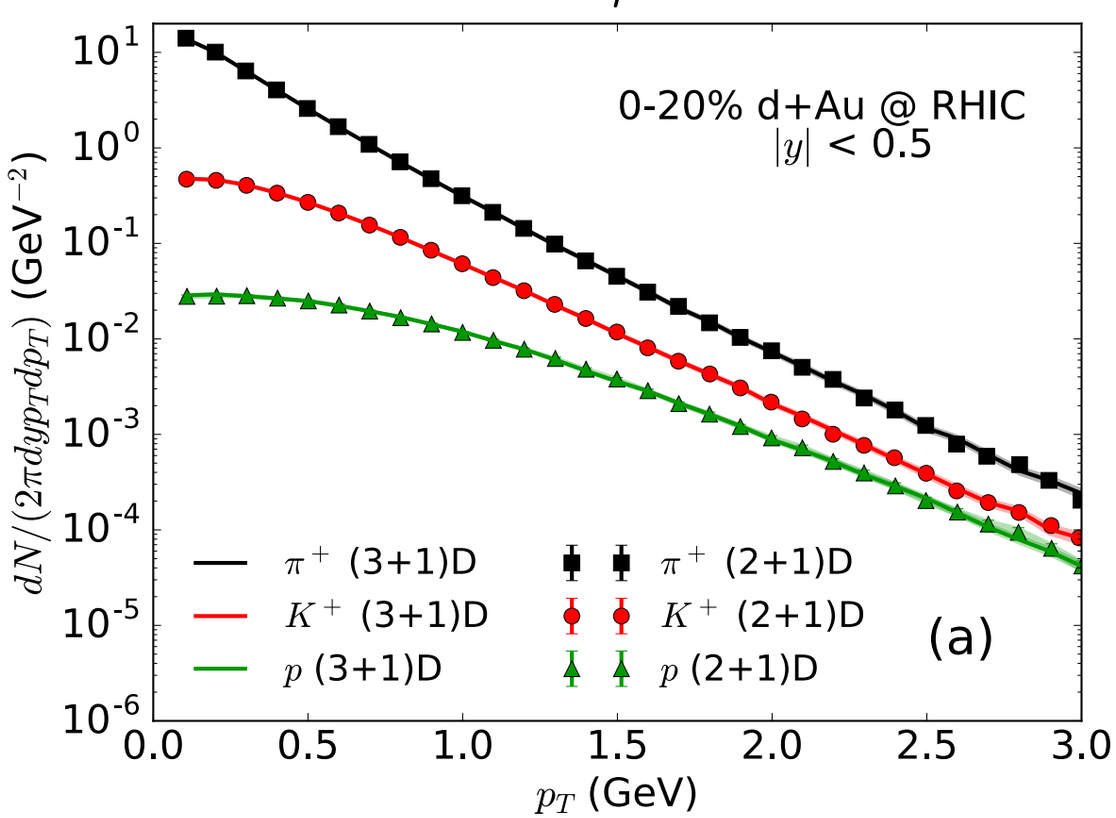
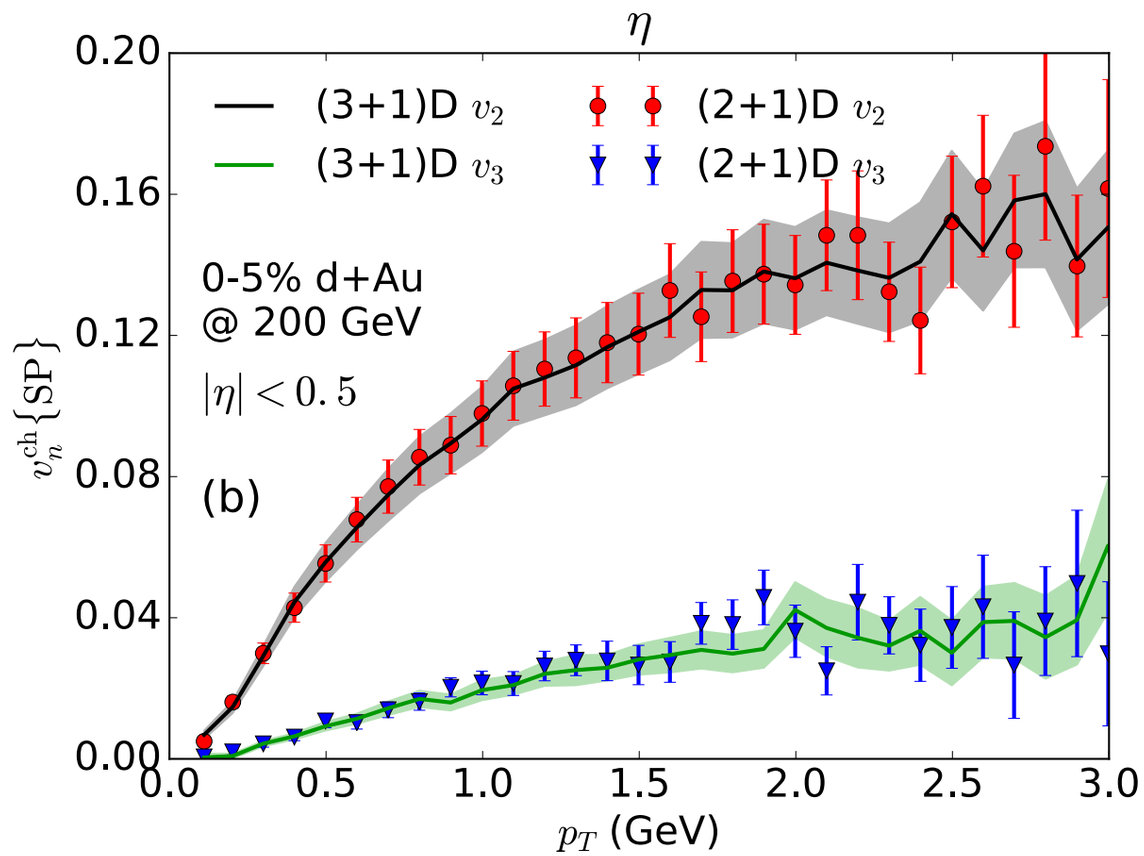
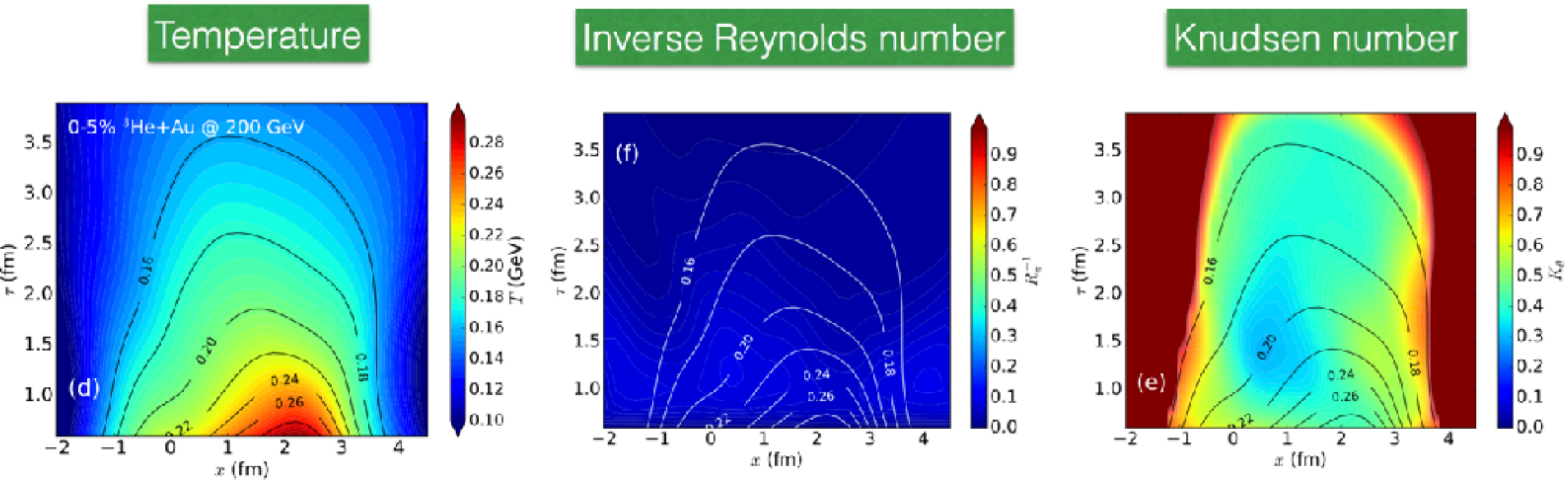








Validity of hydrodynamic simulations



C. Shen, *et al.* preliminary

$$Rn^{-1} = \frac{\sqrt{\pi^{\mu\nu}\pi_{\mu\nu}}}{e+\mathcal{P}} \qquad Kn = \frac{l_{micro}}{L_{macro}} = \tau_\pi \theta$$

- The small inverse Reynolds number and the Knudsen number in the high temperature regions support the hydrodynamic description

Particle spectra in small systems

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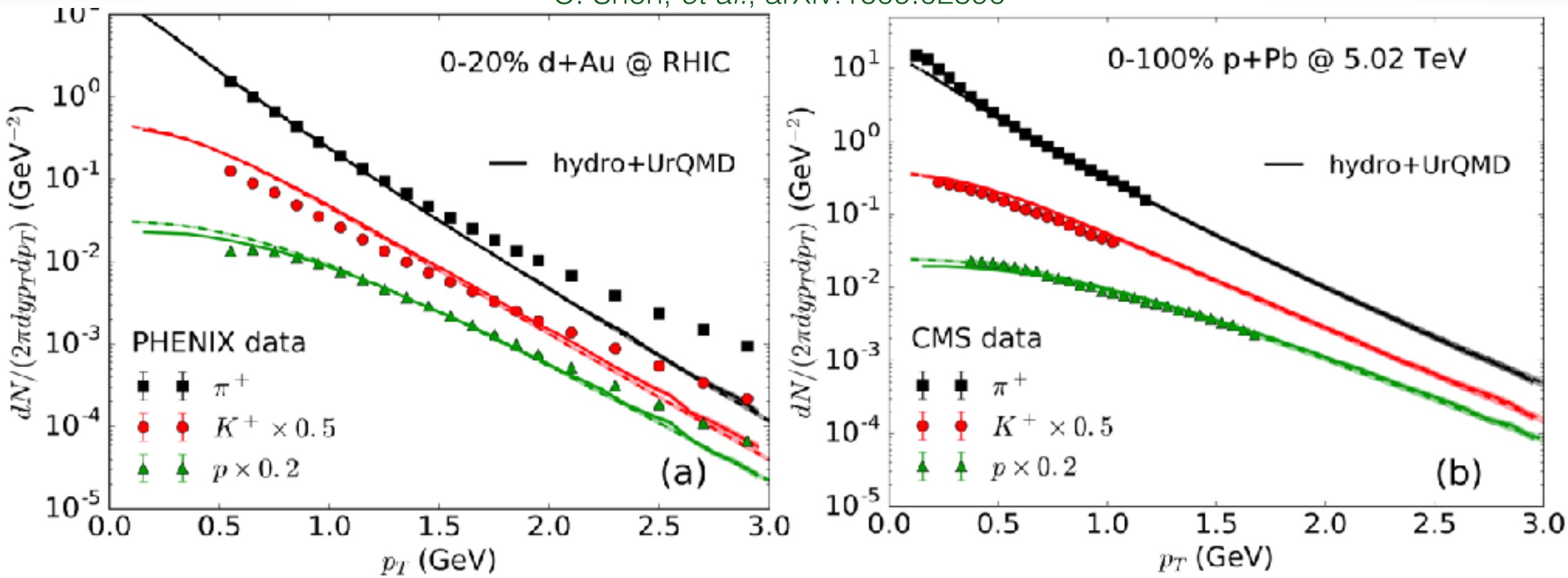

- Hydrodynamic model can describe the identified particle spectra for $p_T < 1.5$ GeV

Inclusive and decay photons

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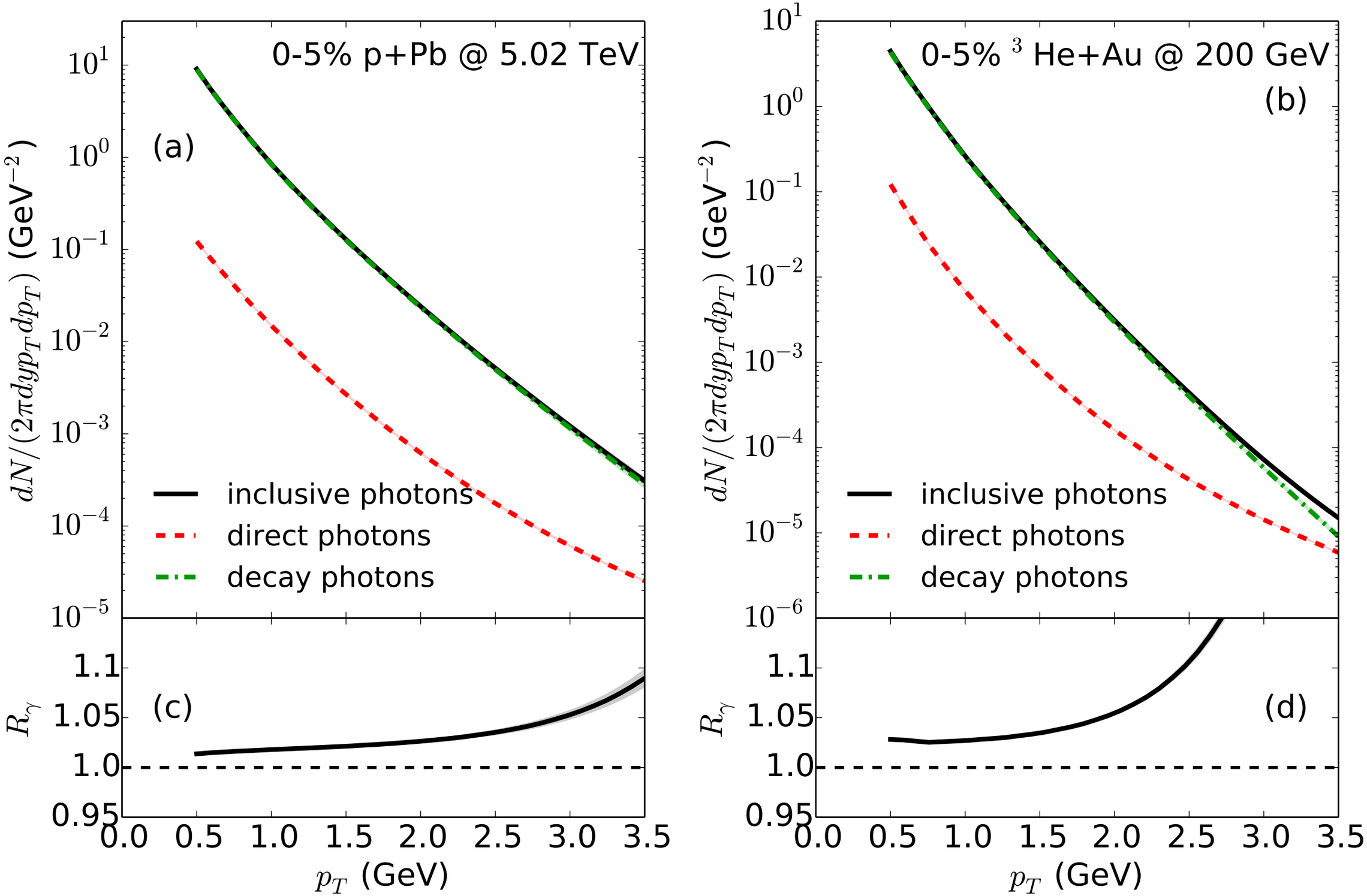

Sensitivity on initial τ_0

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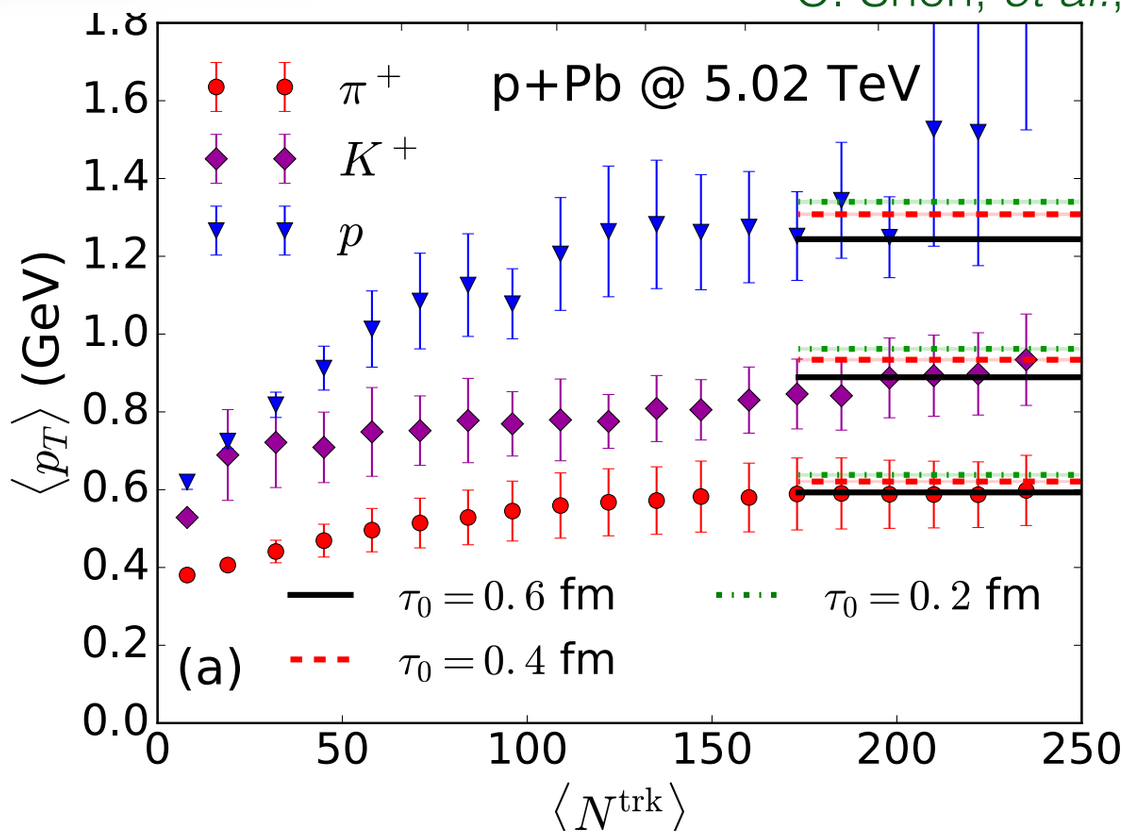

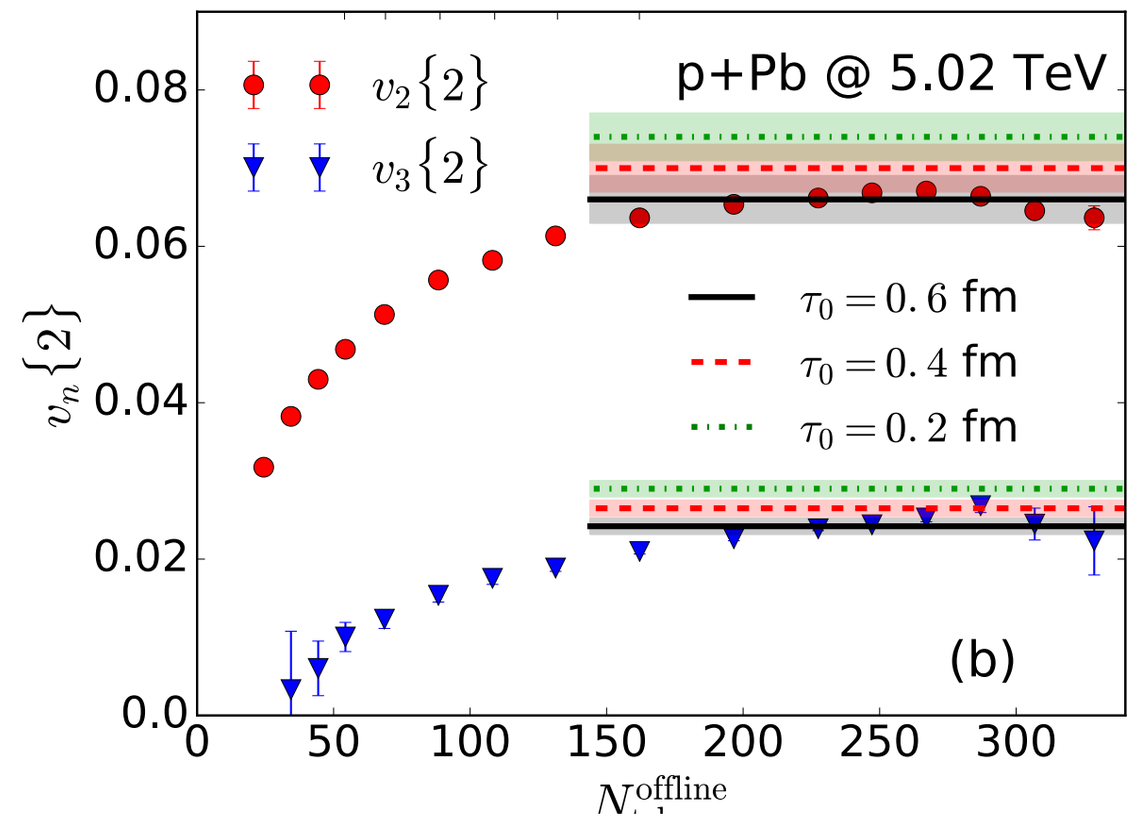

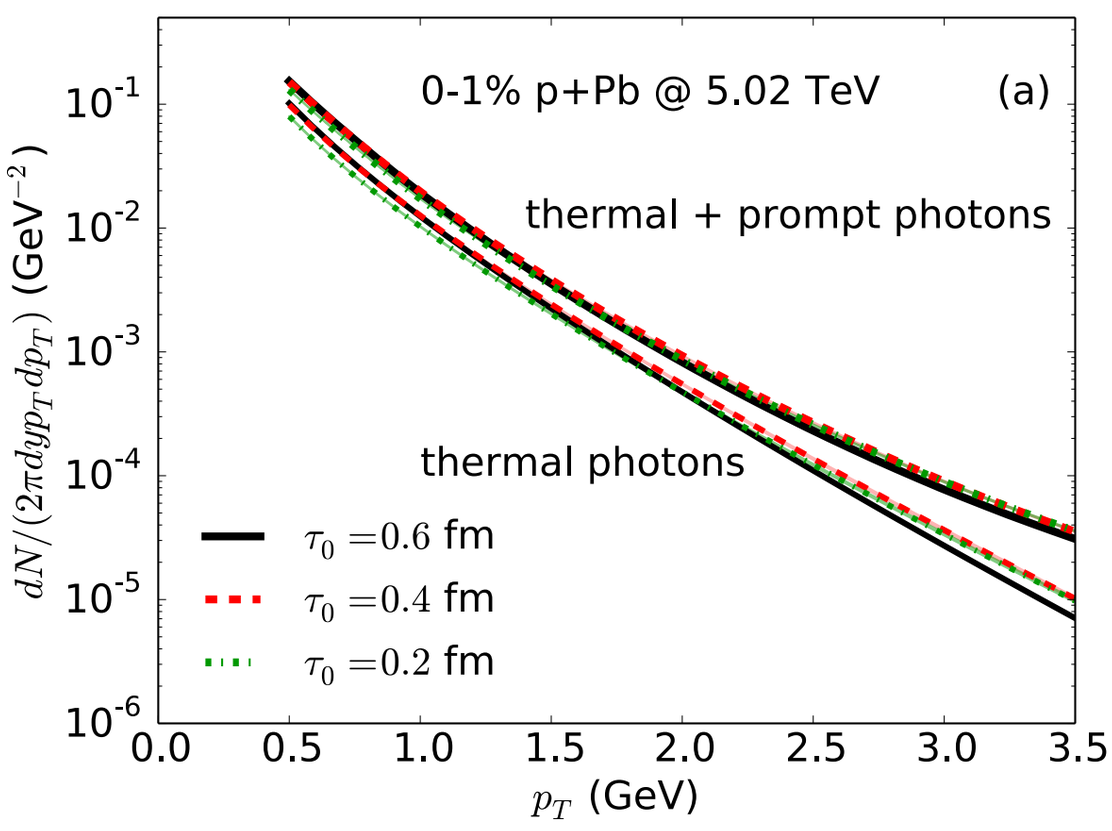

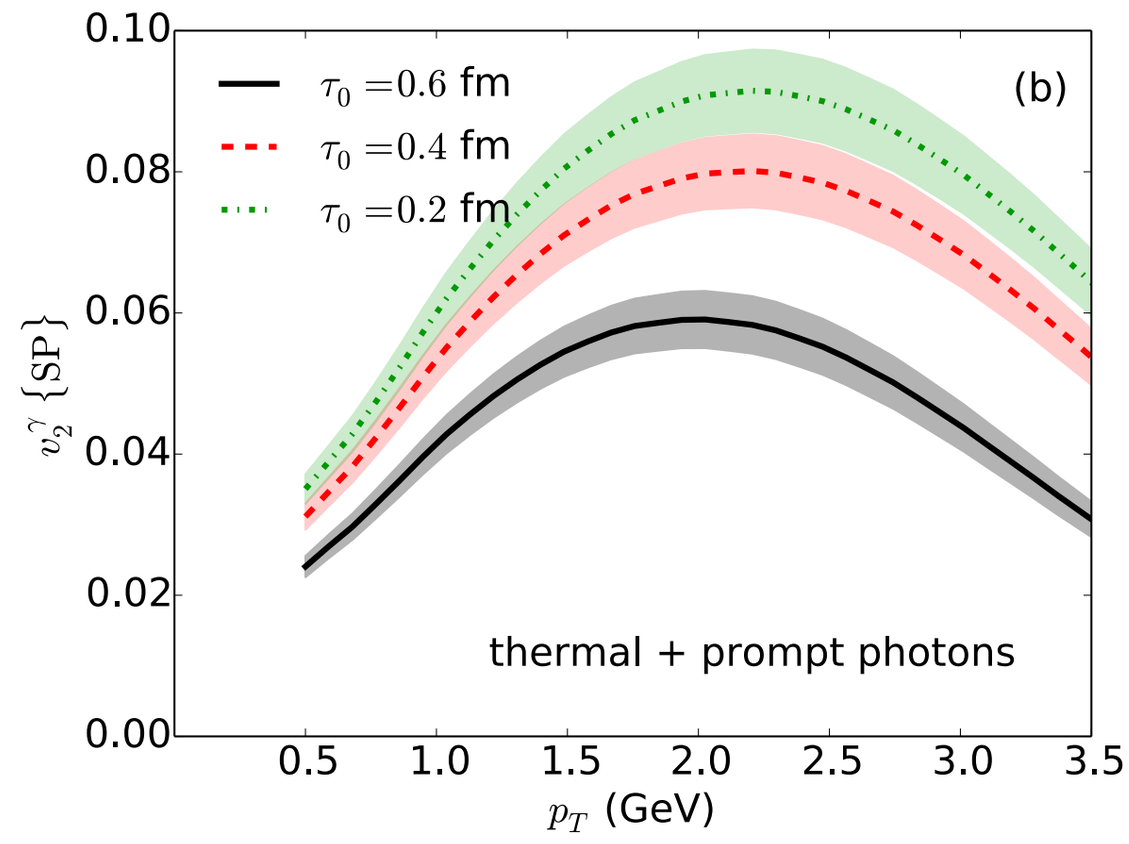

Is viscous correction in control?

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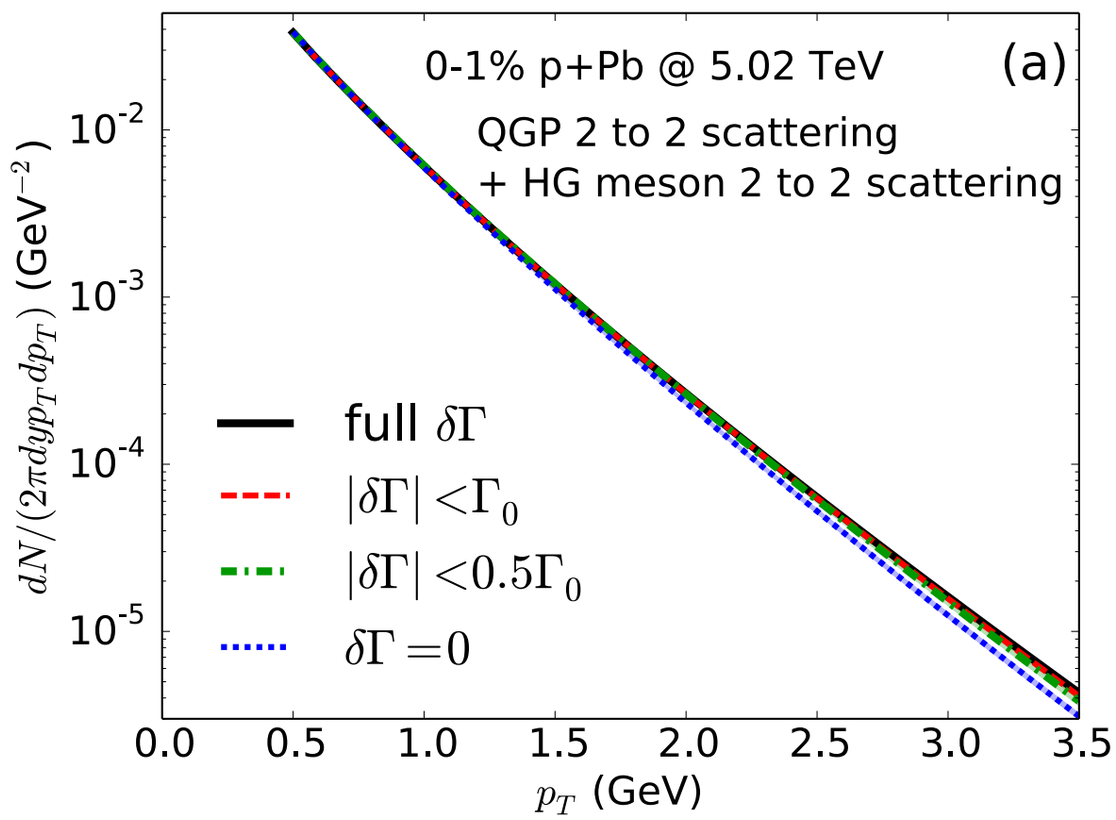

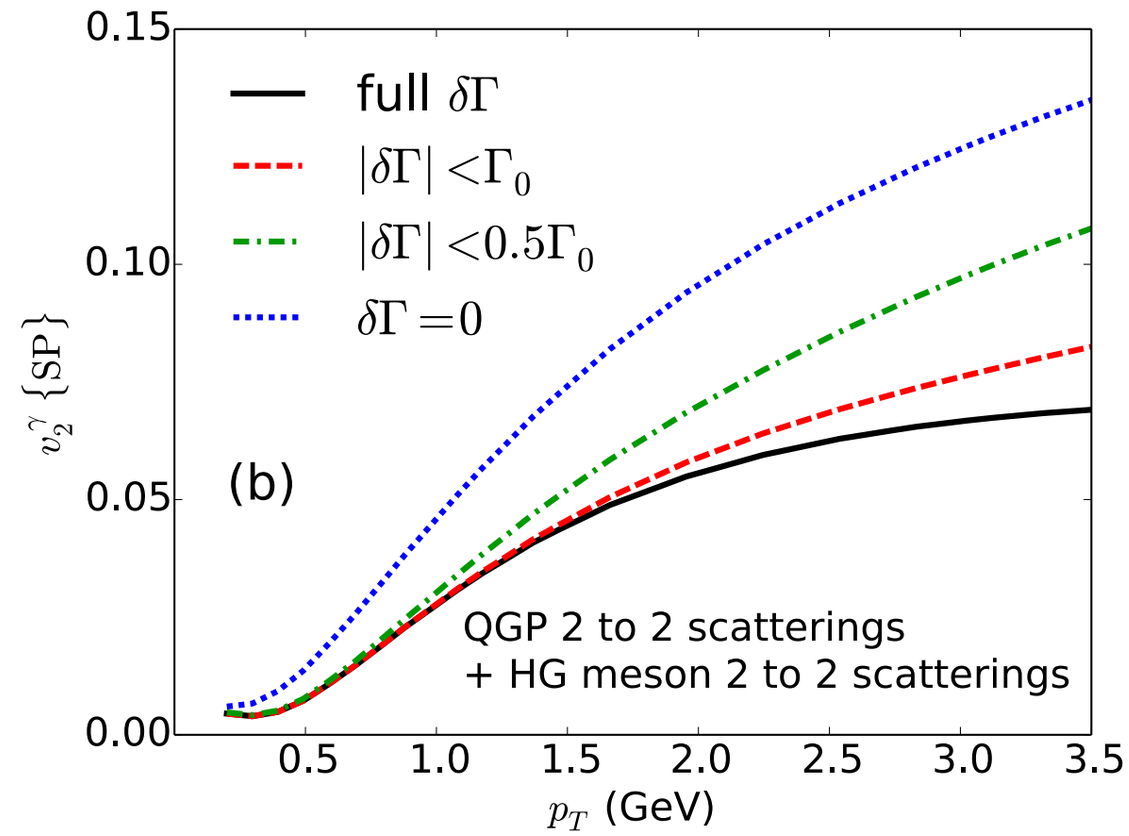

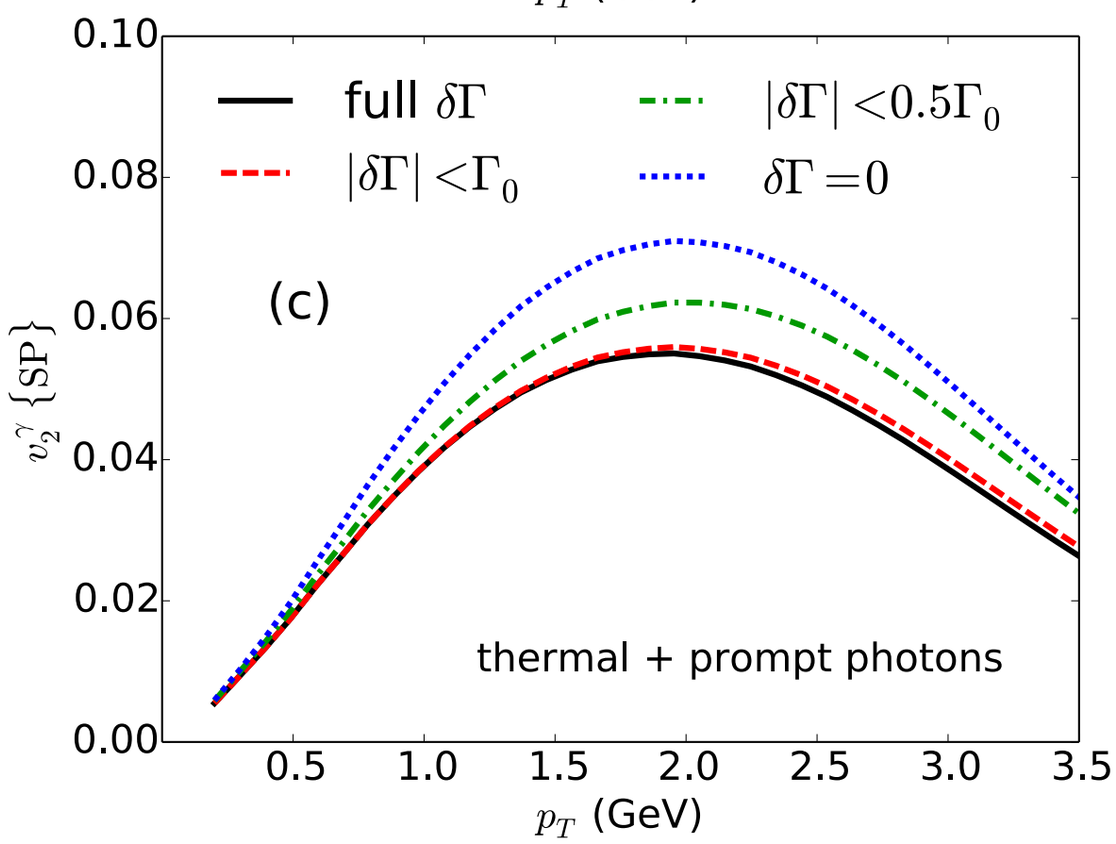

- For $|\delta\Gamma| < \Gamma_0$, effect on thermal photon spectra and v_2 is small
- For $|\delta\Gamma| < 0.5\Gamma_0$, some visible effect on thermal photon v_2

Is viscous correction in control?

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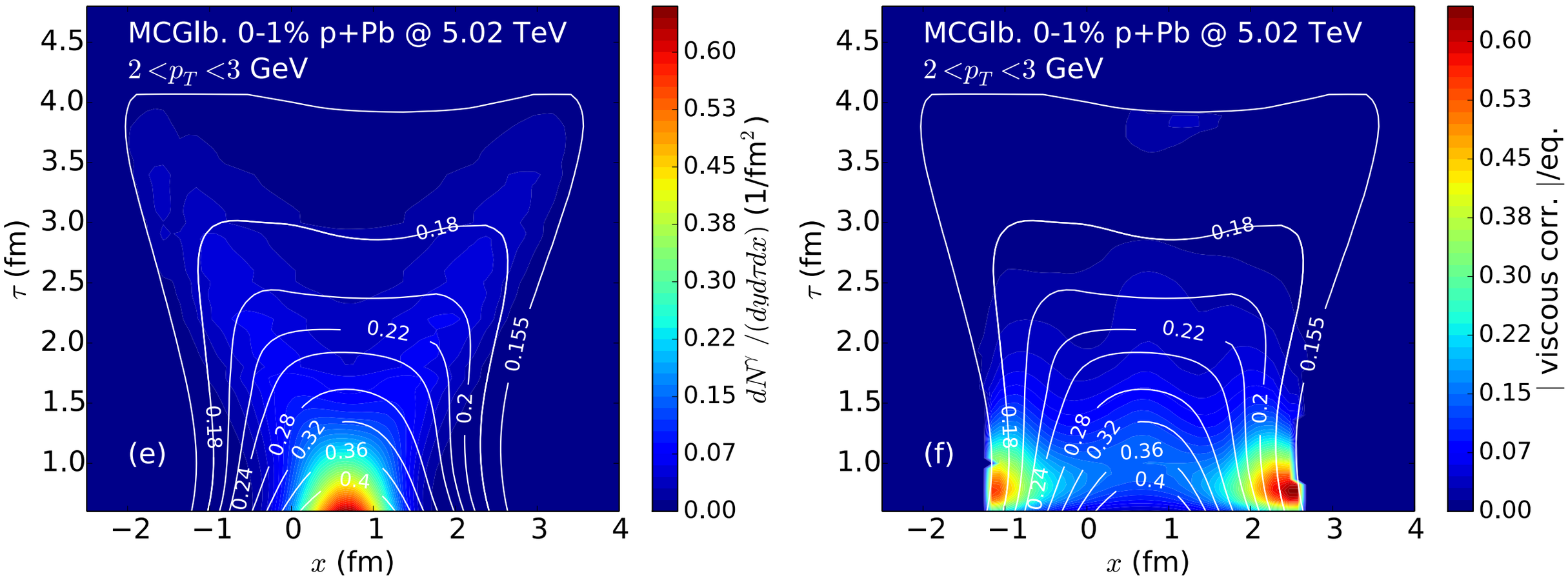

- The large viscous correction is at the early time around the edge of the fireball where the thermal photon emission is low

Thermal radiation in pp collisions

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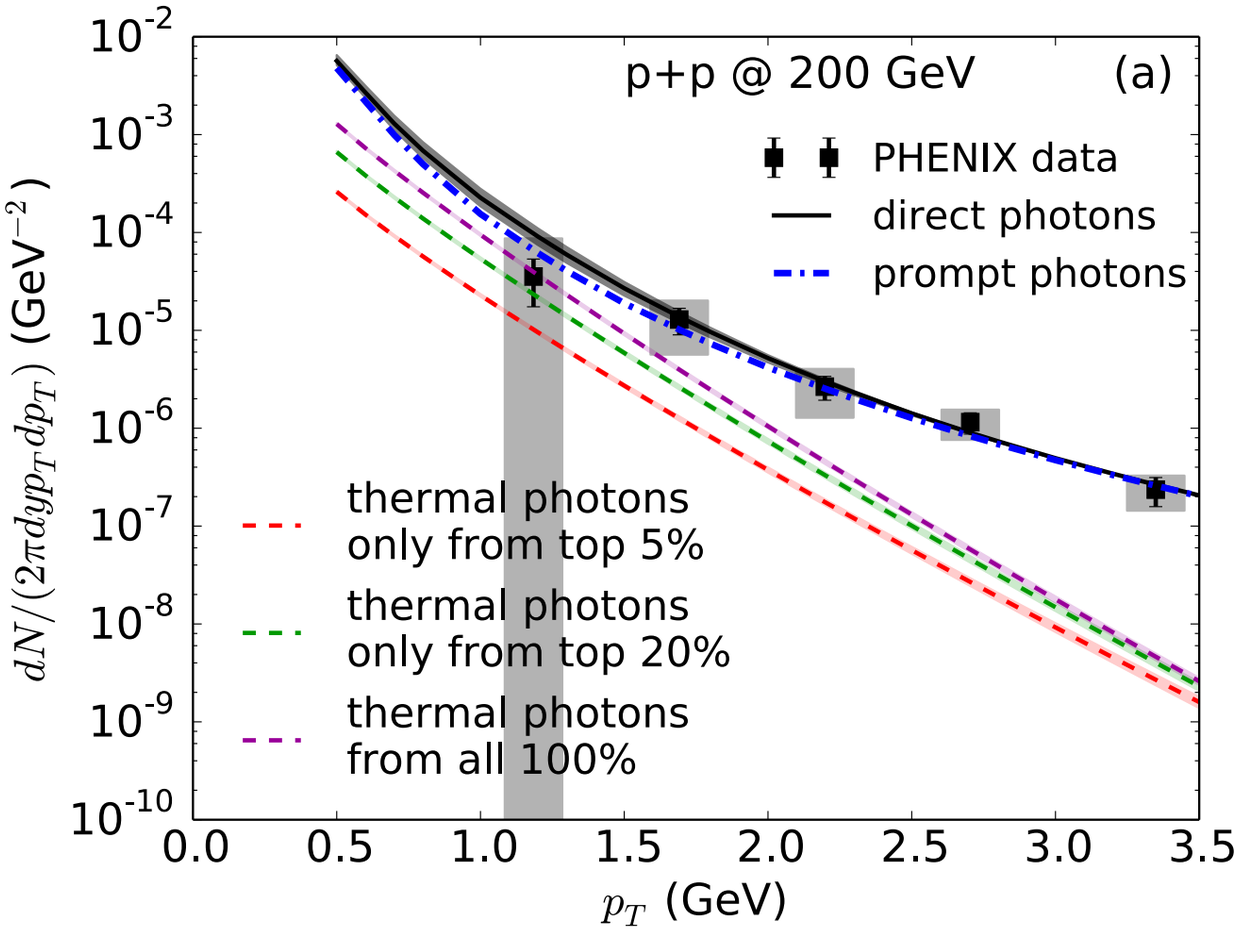

- Thermal radiation provides a small contributions to minimum bias pp collisions

Thermal radiation in pp collisions

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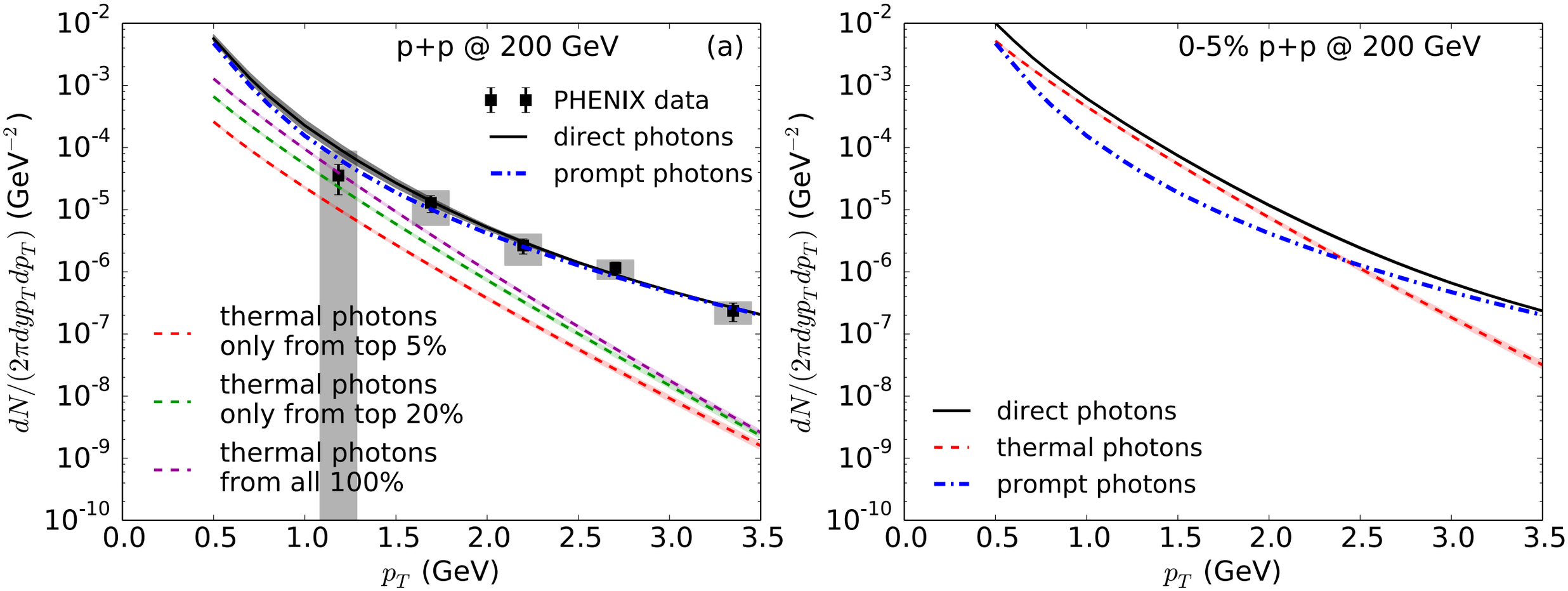

- Thermal radiation provides a small contributions to minimum bias pp collisions
- In high multiplicity pp events, thermal photons can also shine out of the prompt background