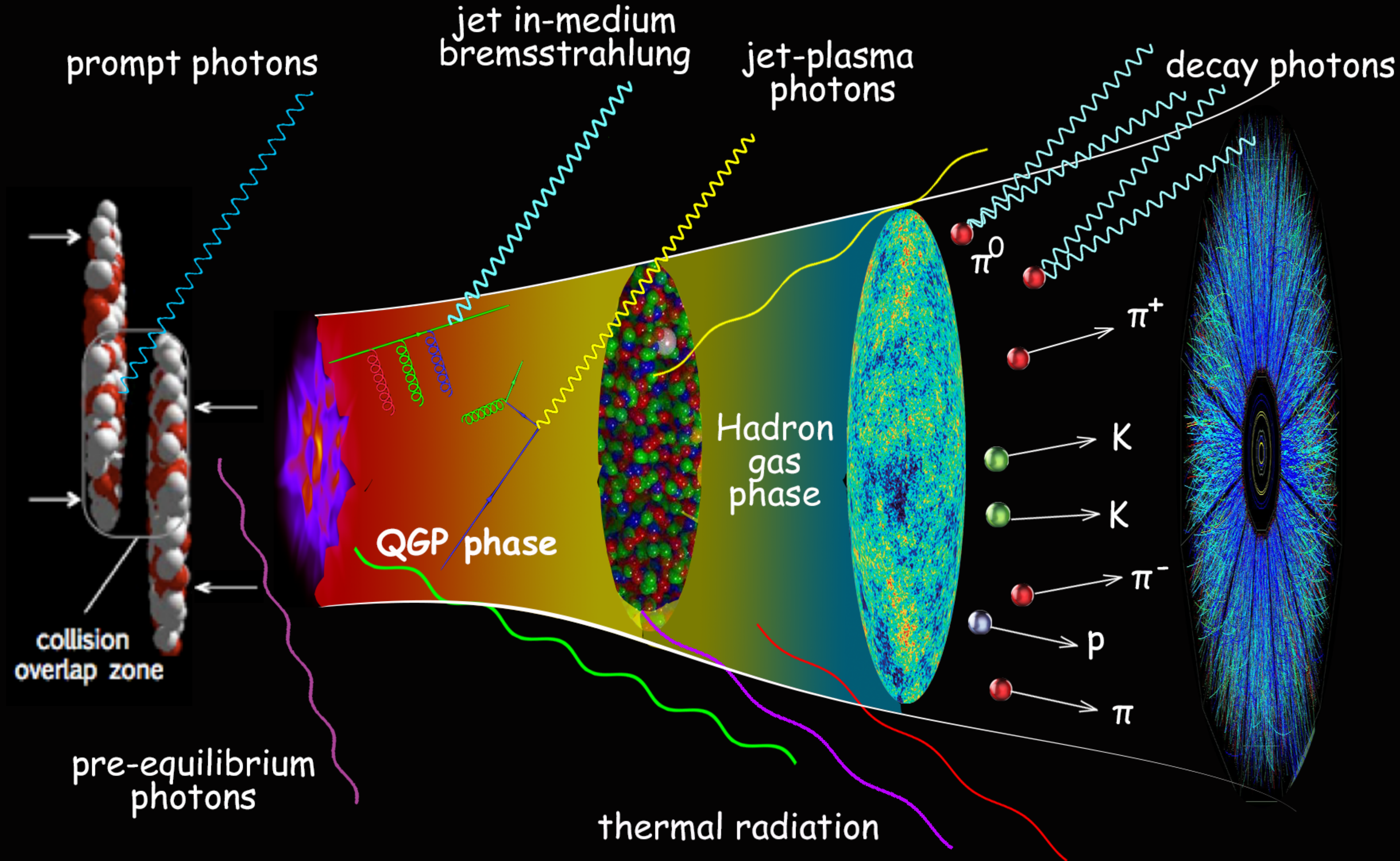
Photon Puzzle at RHIC: a theory perspective

Chun Shen
Brookhaven National Laboratory

Feb. 2, 2017, APS GPH meeting 2017, Washington

Photons in Relativistic Heavy-ion Collisions



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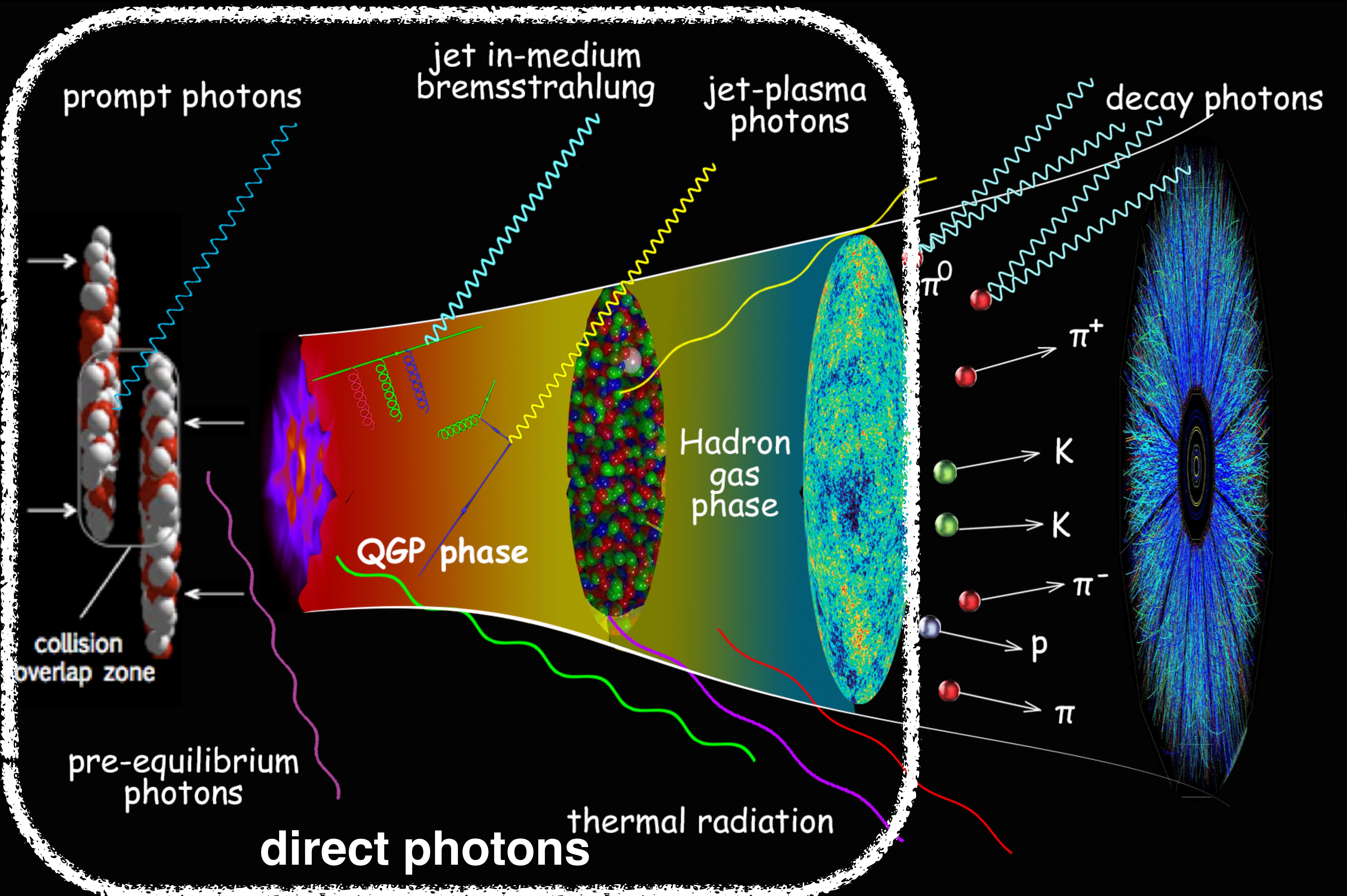
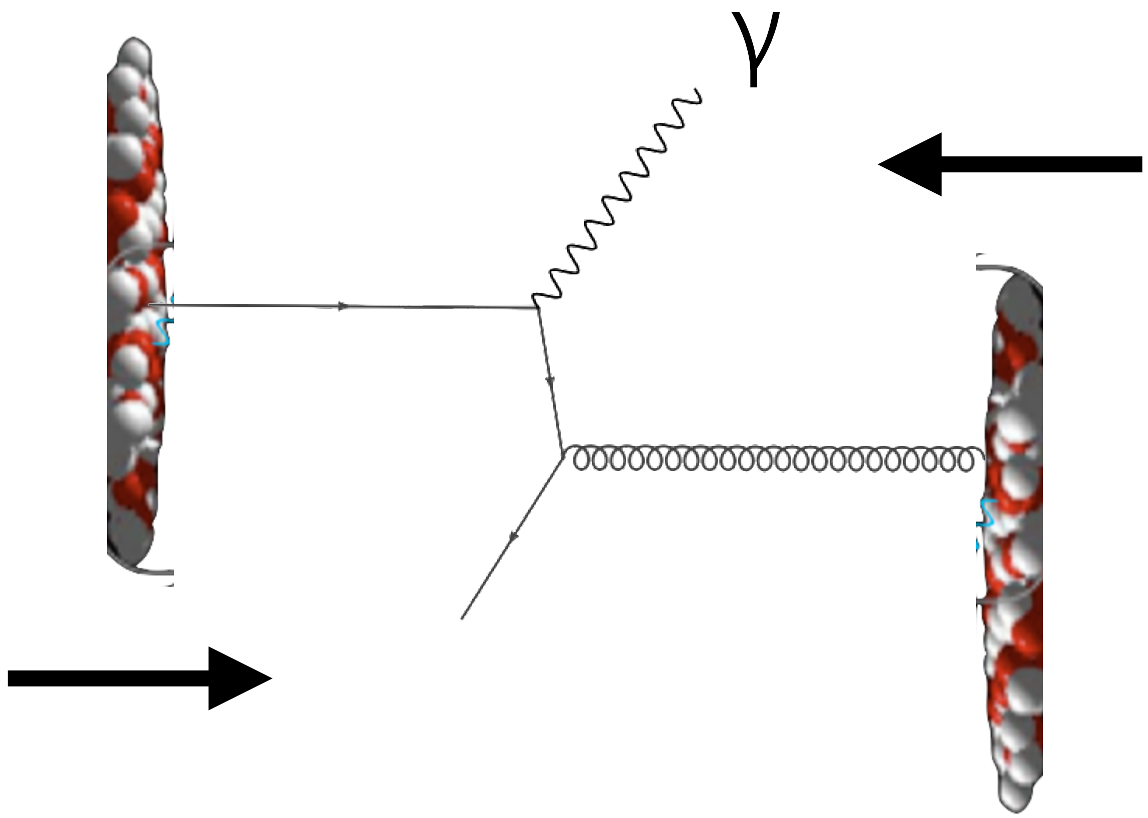
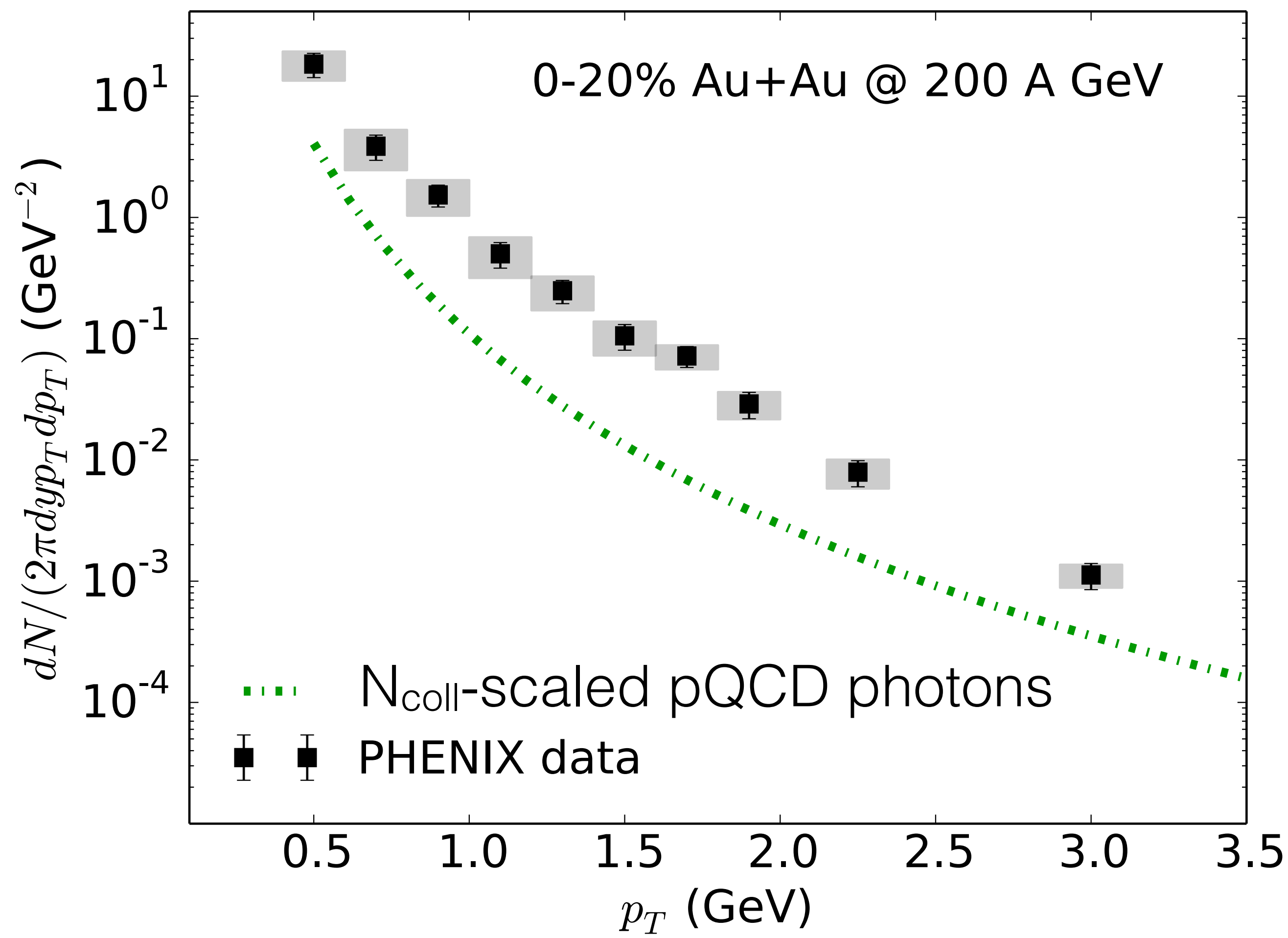


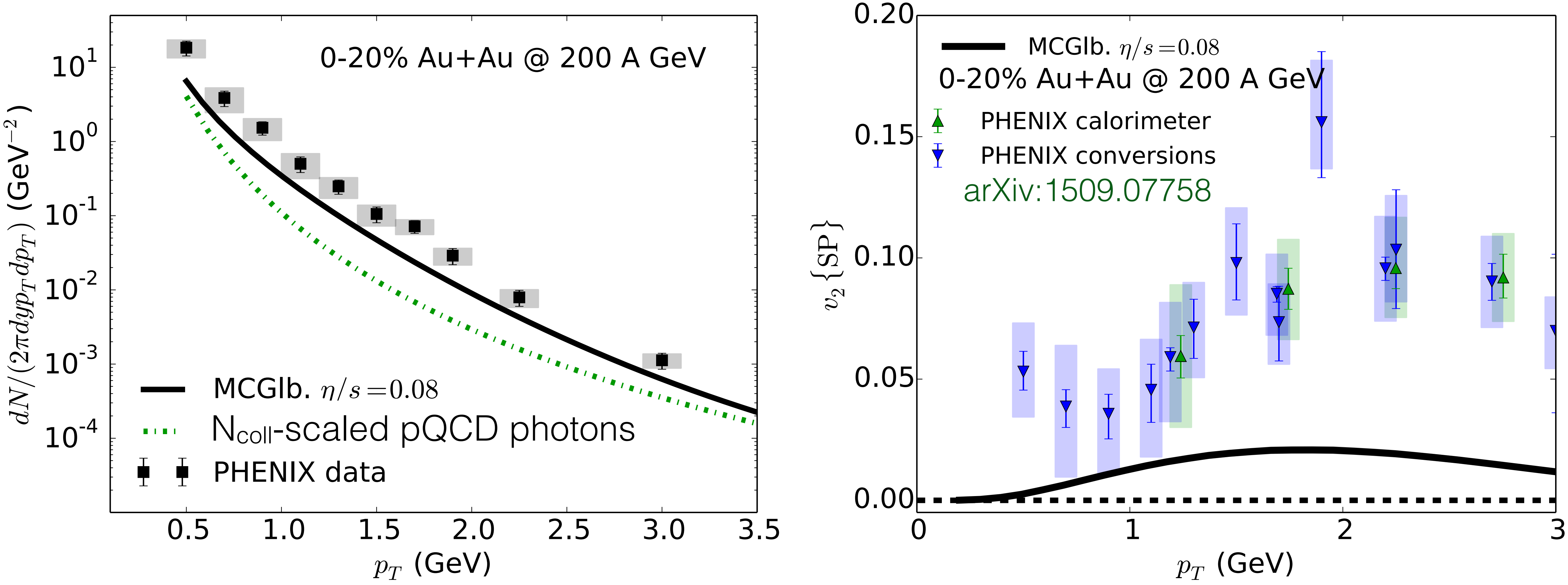




- Large excess of direct photons over the prompt background (N_{coll}-scaled pQCD results) in AA collisions

Direct photon flow puzzle

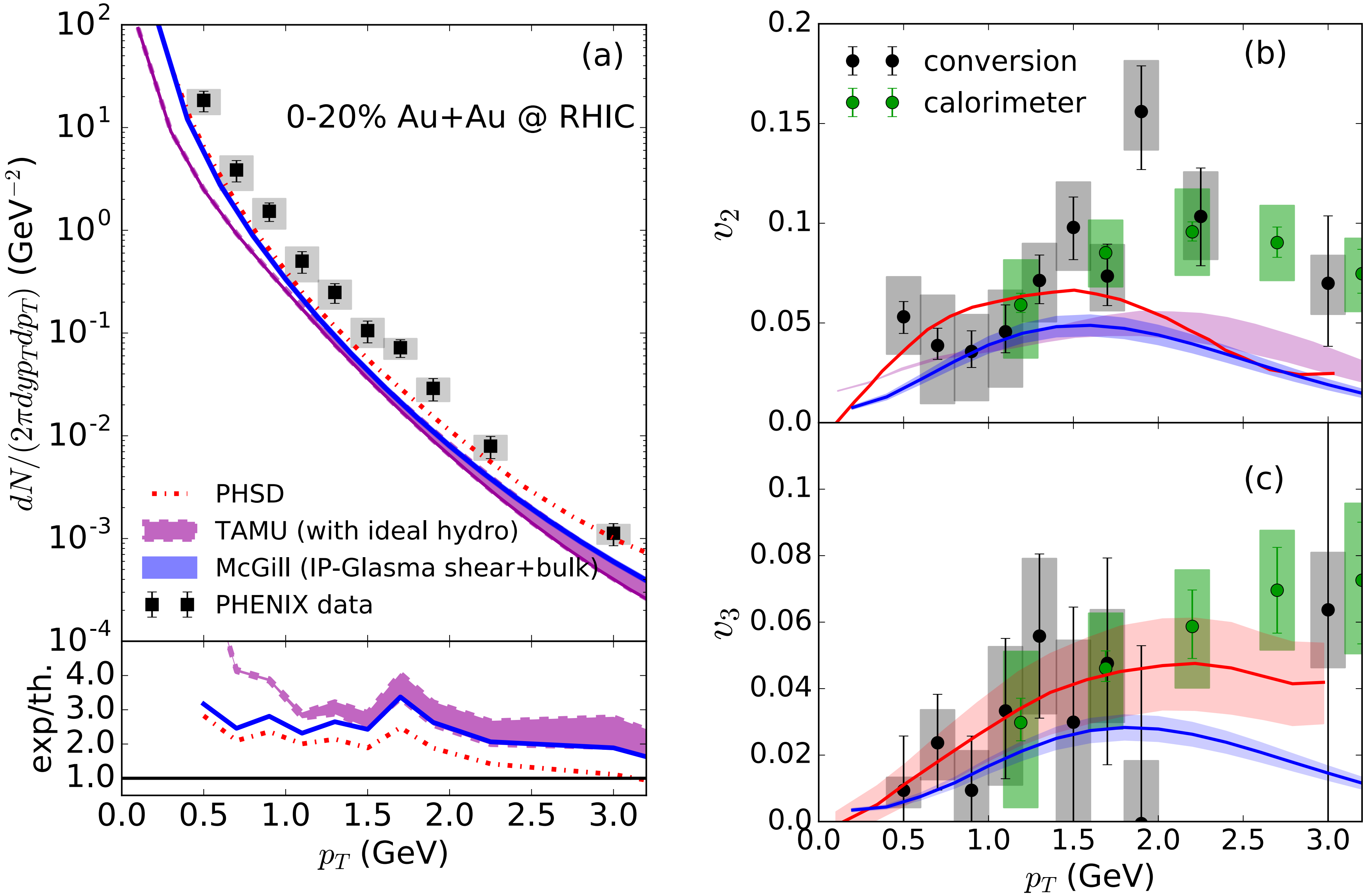
C. Shen, U. Heinz, J. -F. Paquet, I. Kozlov, and C. Gale, Phys. Rev. C **91**, 024908 (2015)



- Previous hydrodynamical calculation underestimated the direct photon observables at RHIC

Current state-of-the-art model-data comparison

C. Shen, Nucl Phys. A **956**, 184 (2016)

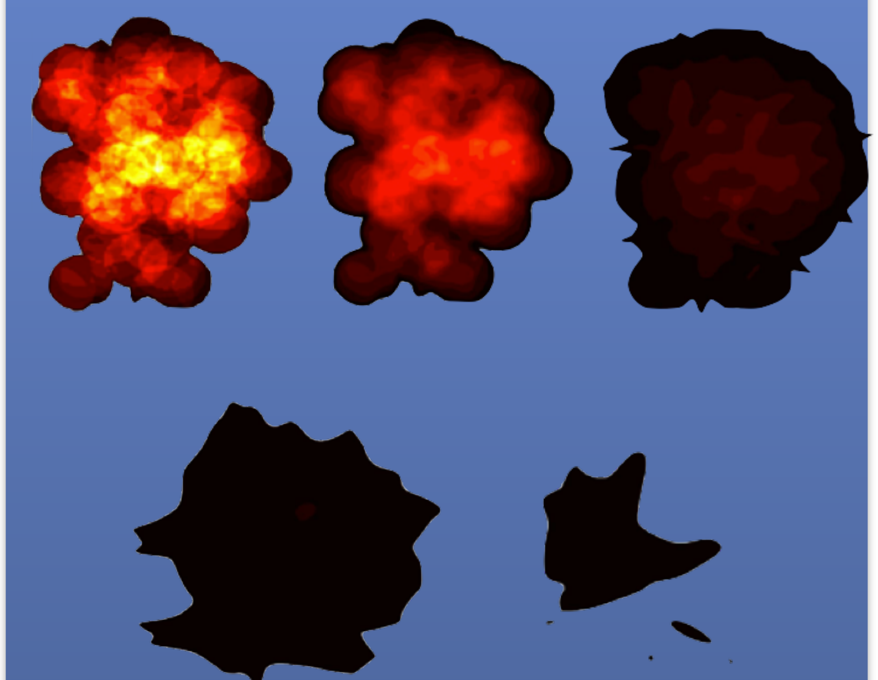


- Tension between experimental measurement and theoretical calculation is much <u>reduced</u>; But not totally resolved …

Framework of modelling direct photons

Initial Condition Generators

Hydrodynamic Evolution



Hadrons spectra & v_n

Thermal Photon Emission Rates

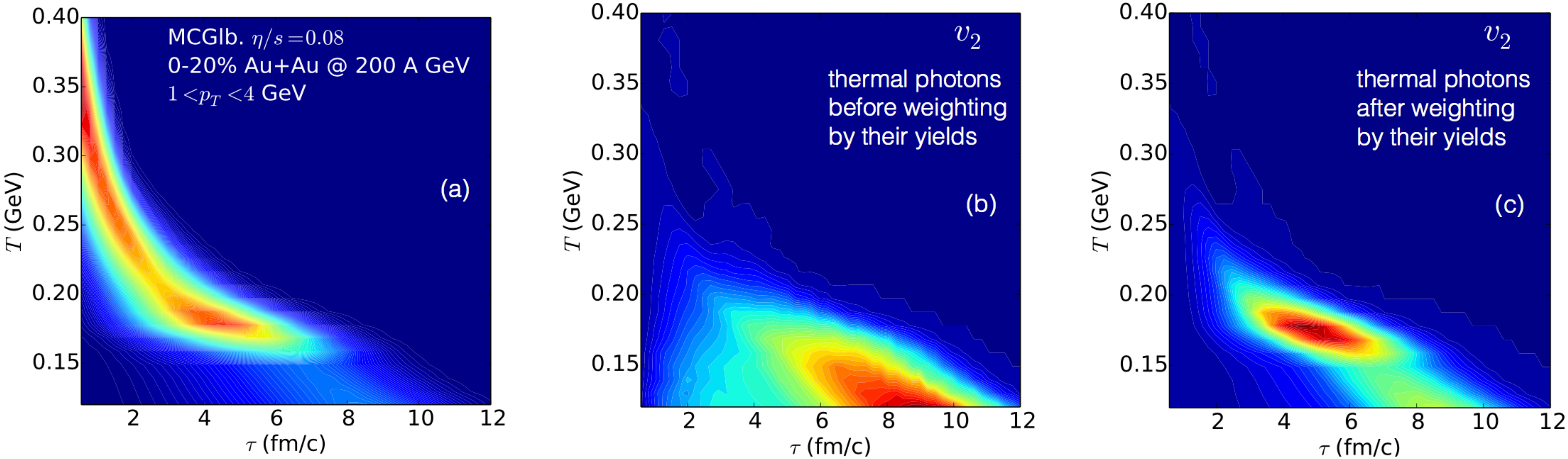
Thermal Photon Interface

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

Photon spectrum & v_n

Space-time picture of thermal photon emission

C. Shen, Nucl Phys. A **956**, 184 (2016)

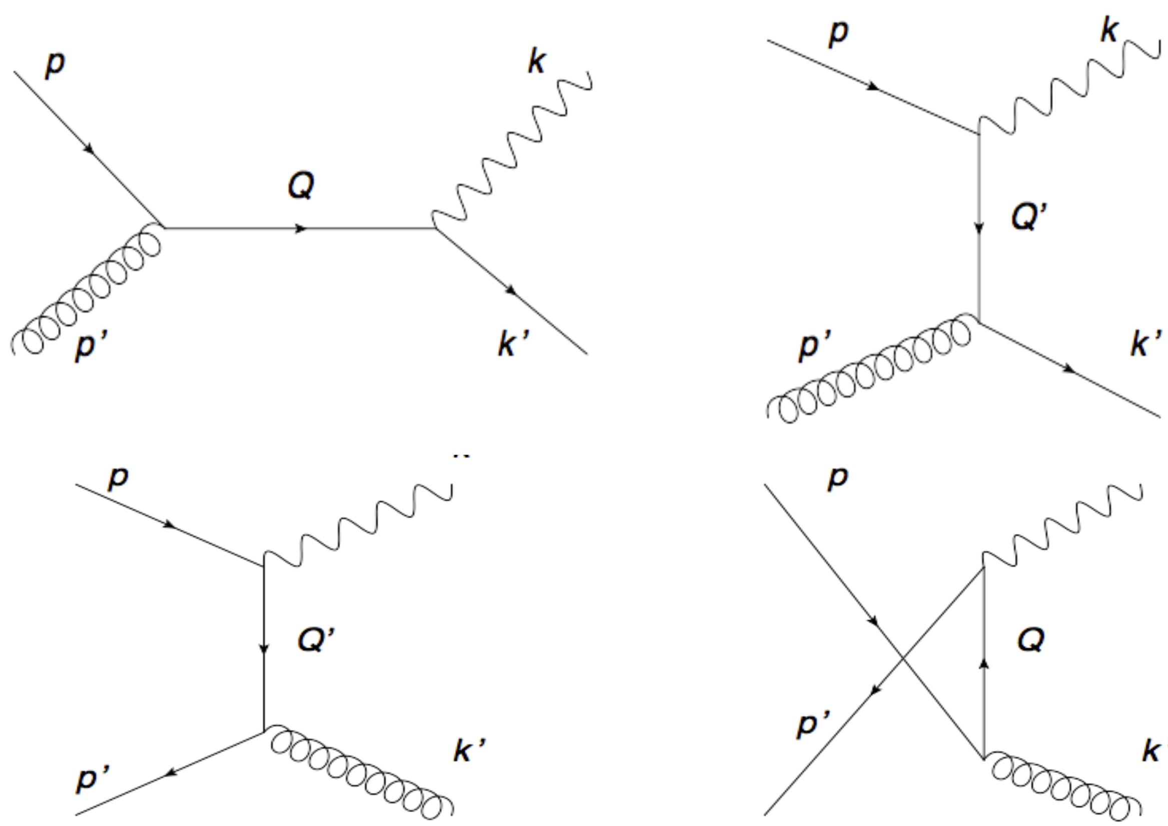


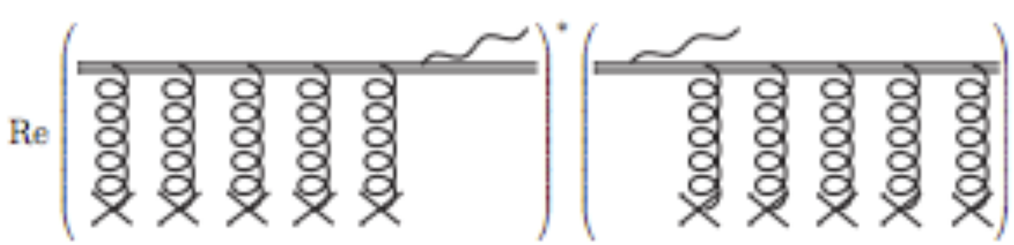
- By cutting hydro medium both in T and τ, we observe a **two-wave** thermal photon production
- Thermal photon v_n probes the transition region, T = 150~ 200 MeV, τ = 3 ~ 8 fm @ RHIC

Photon emission rate

QGP

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

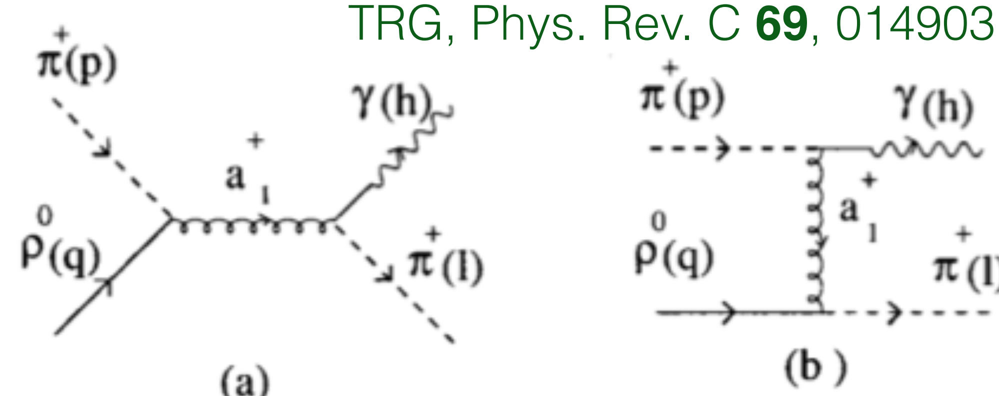




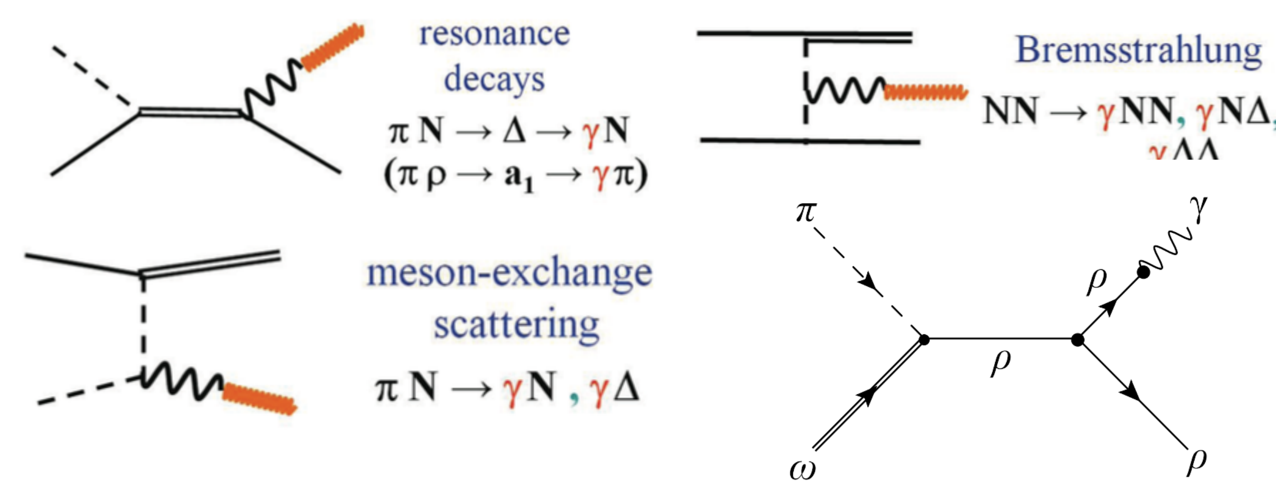
NLO: J. Ghiglieri *et al.*, JHEP **1305**, 010 (2013)

Hadron Gas

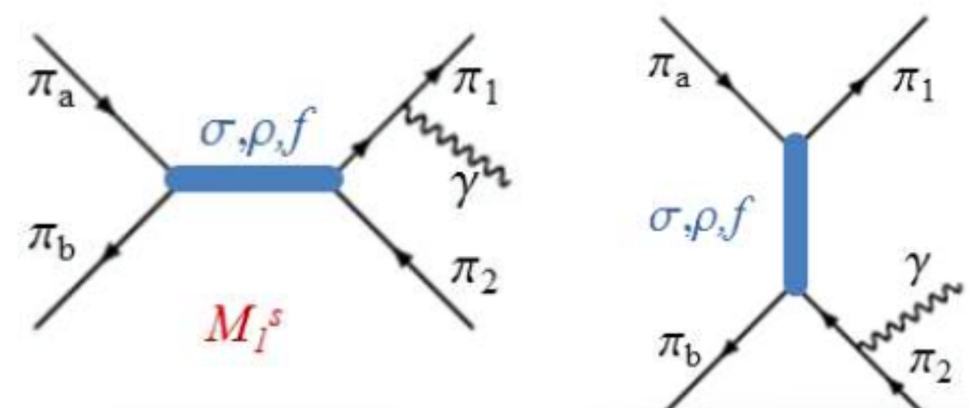
TRG, Phys. Rev. C **69**, 014903 (2004)



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



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



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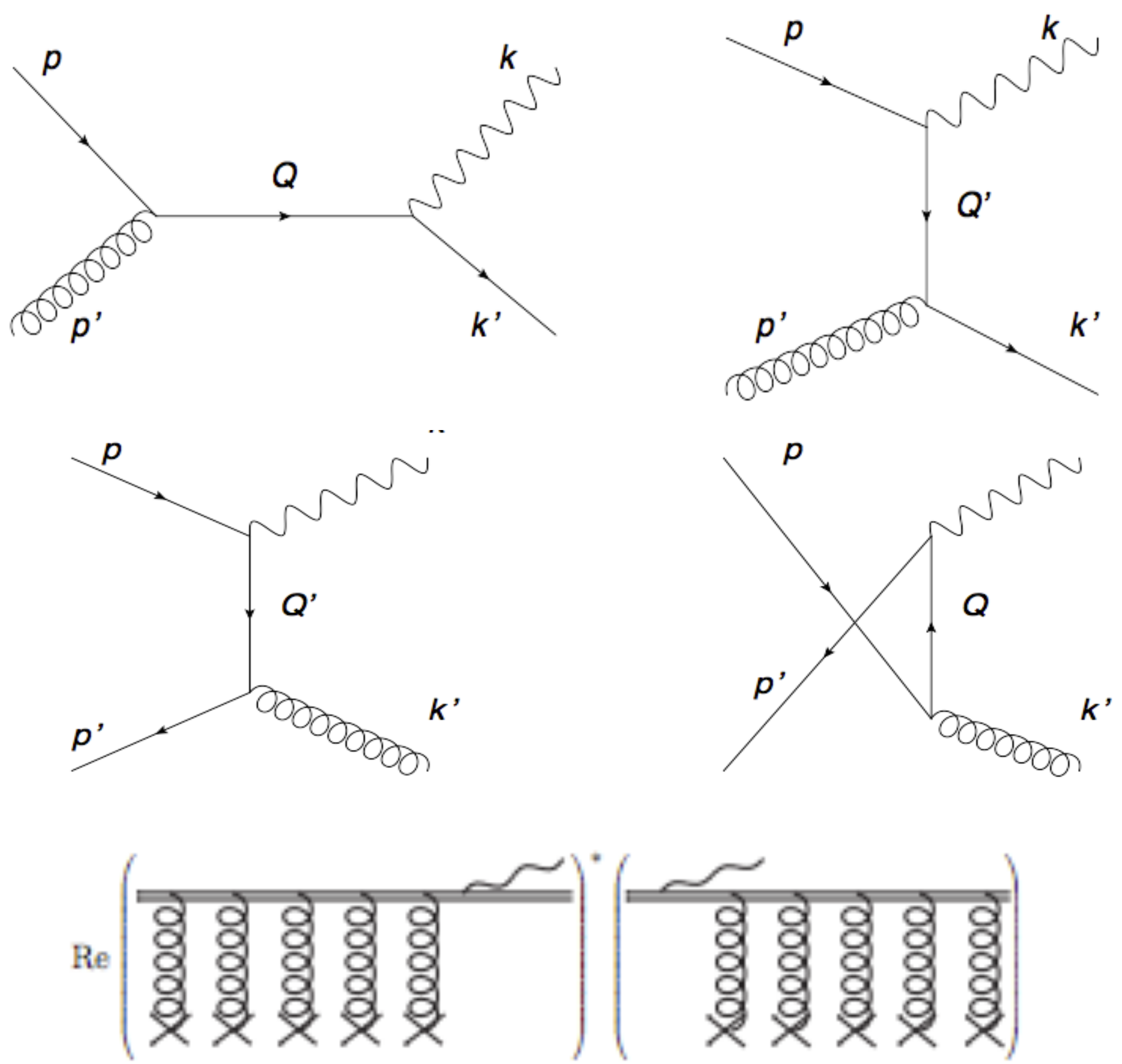

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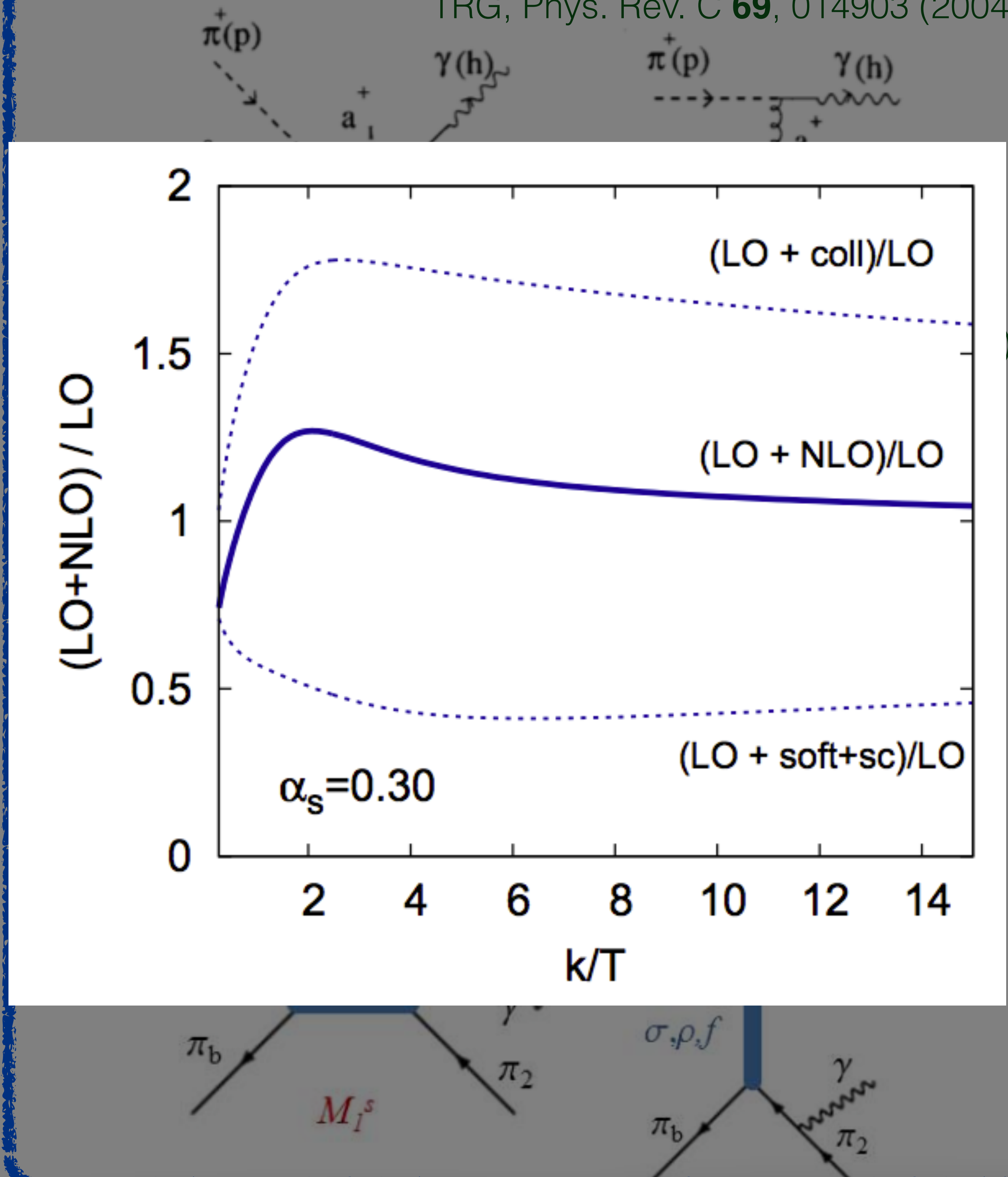

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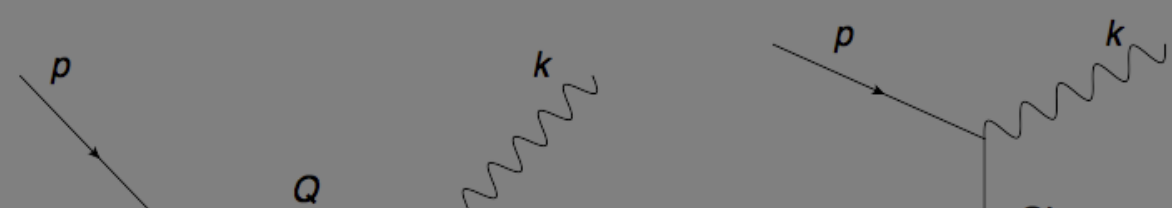

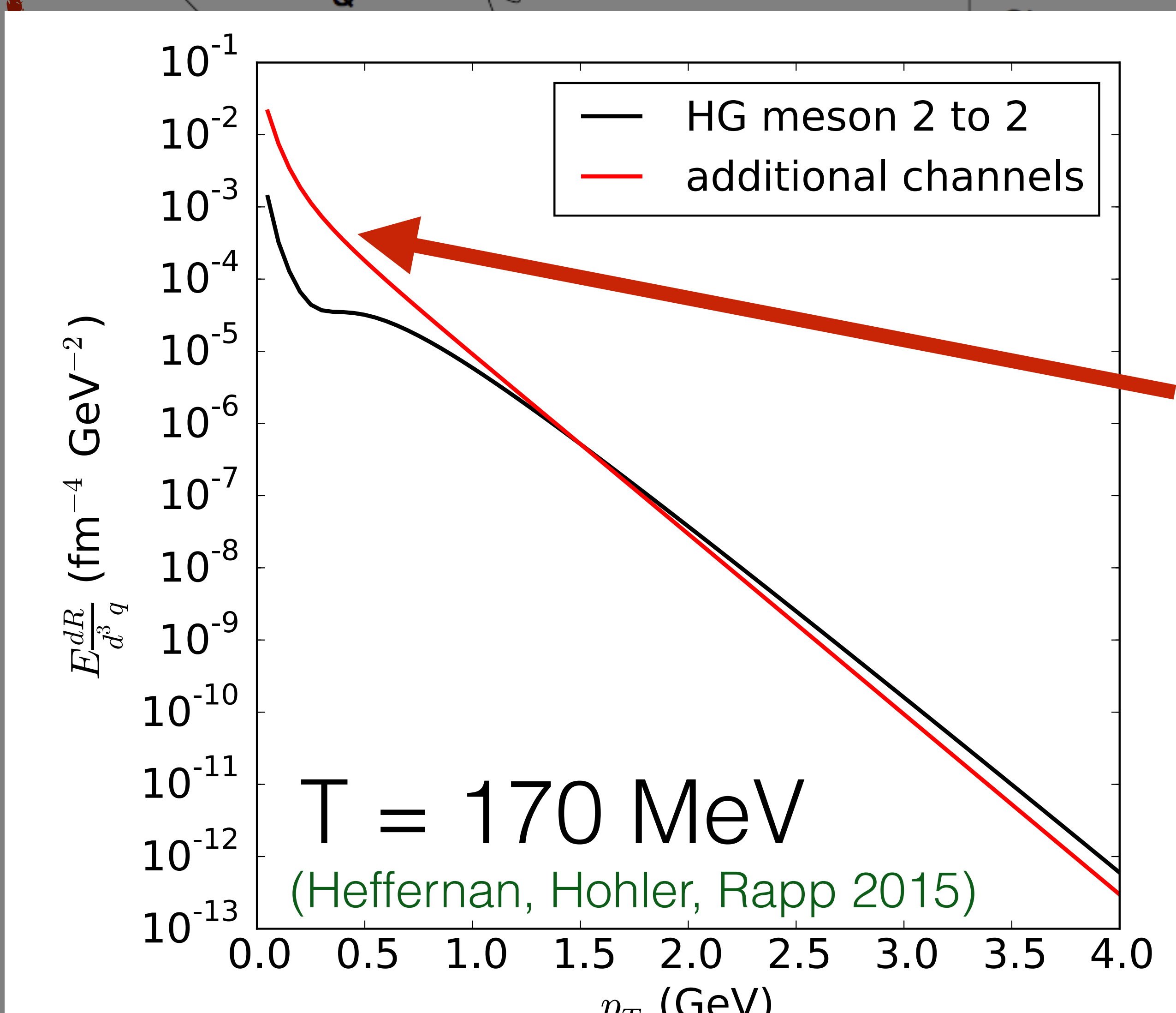

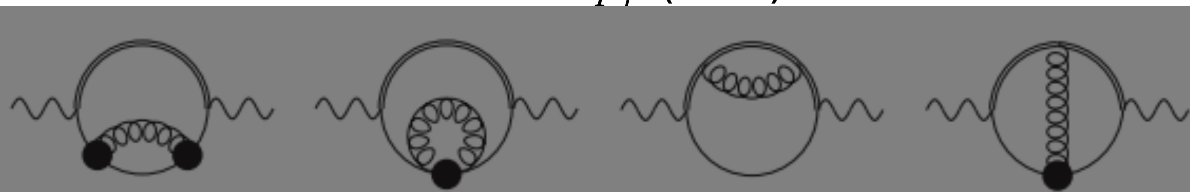

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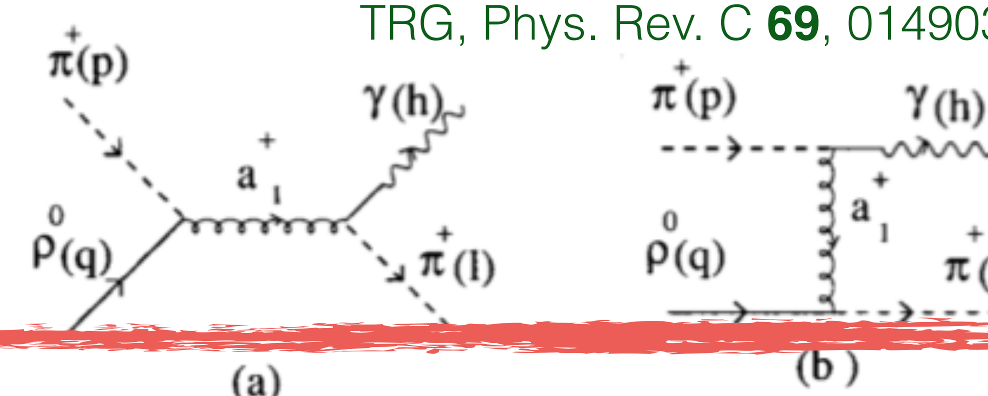

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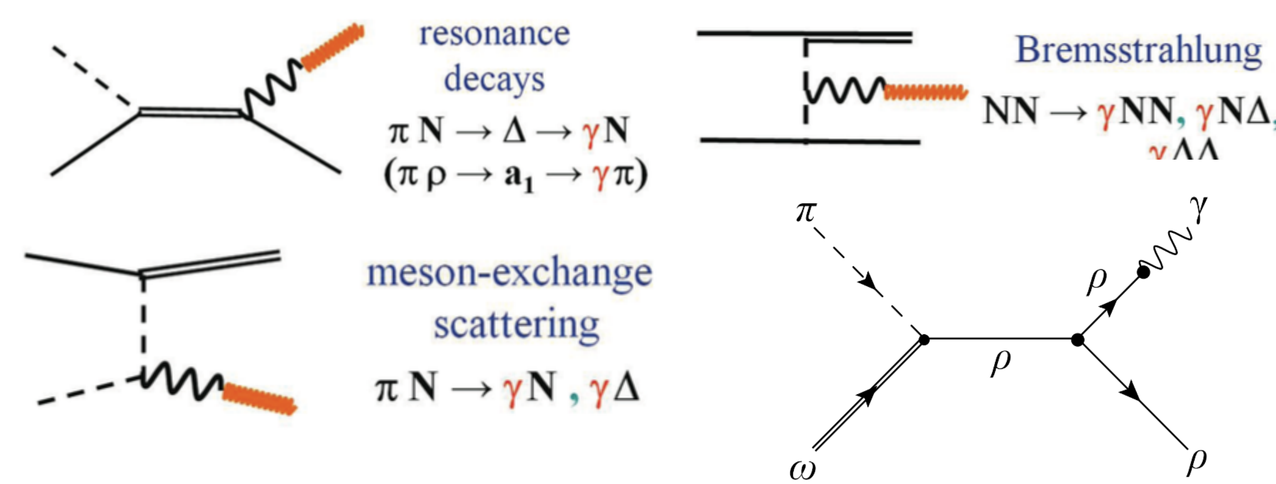

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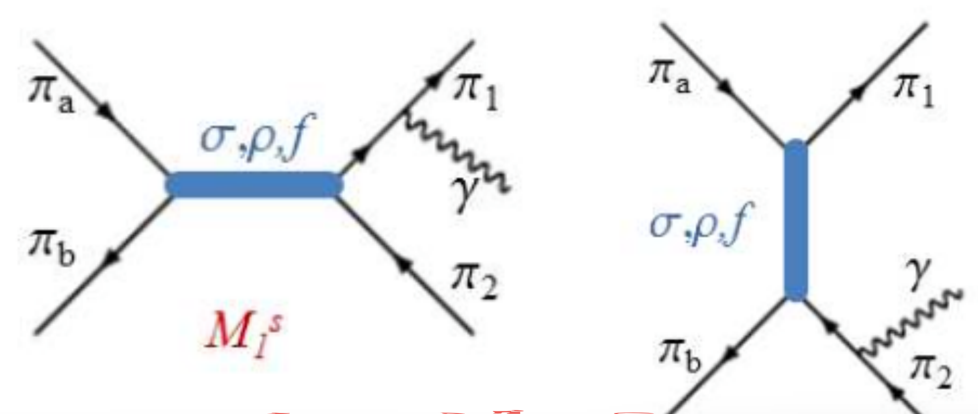

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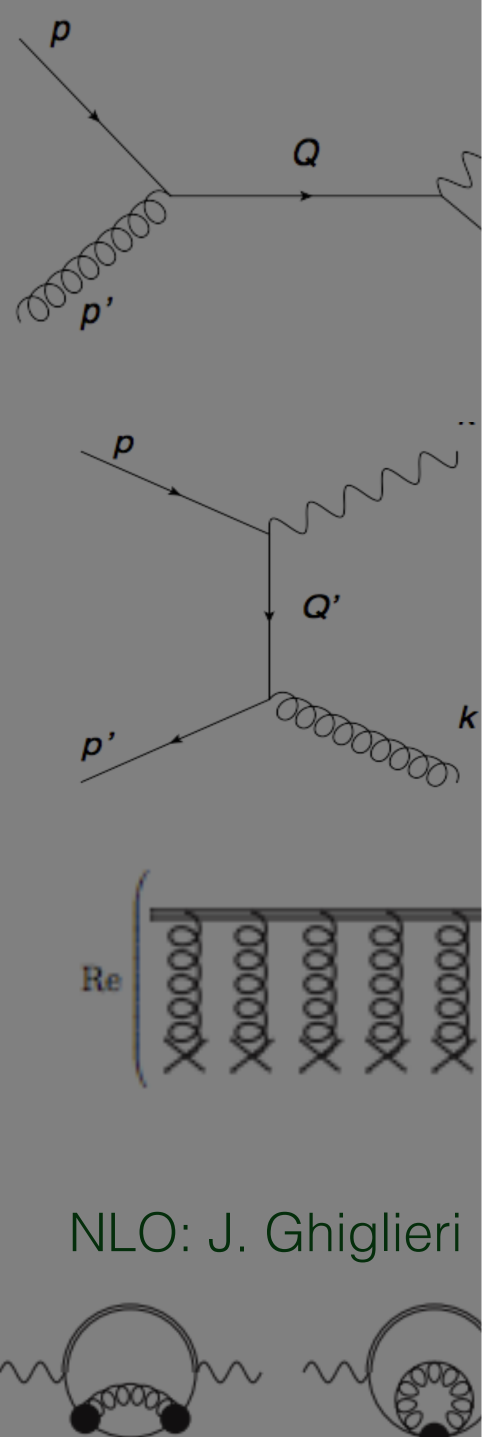

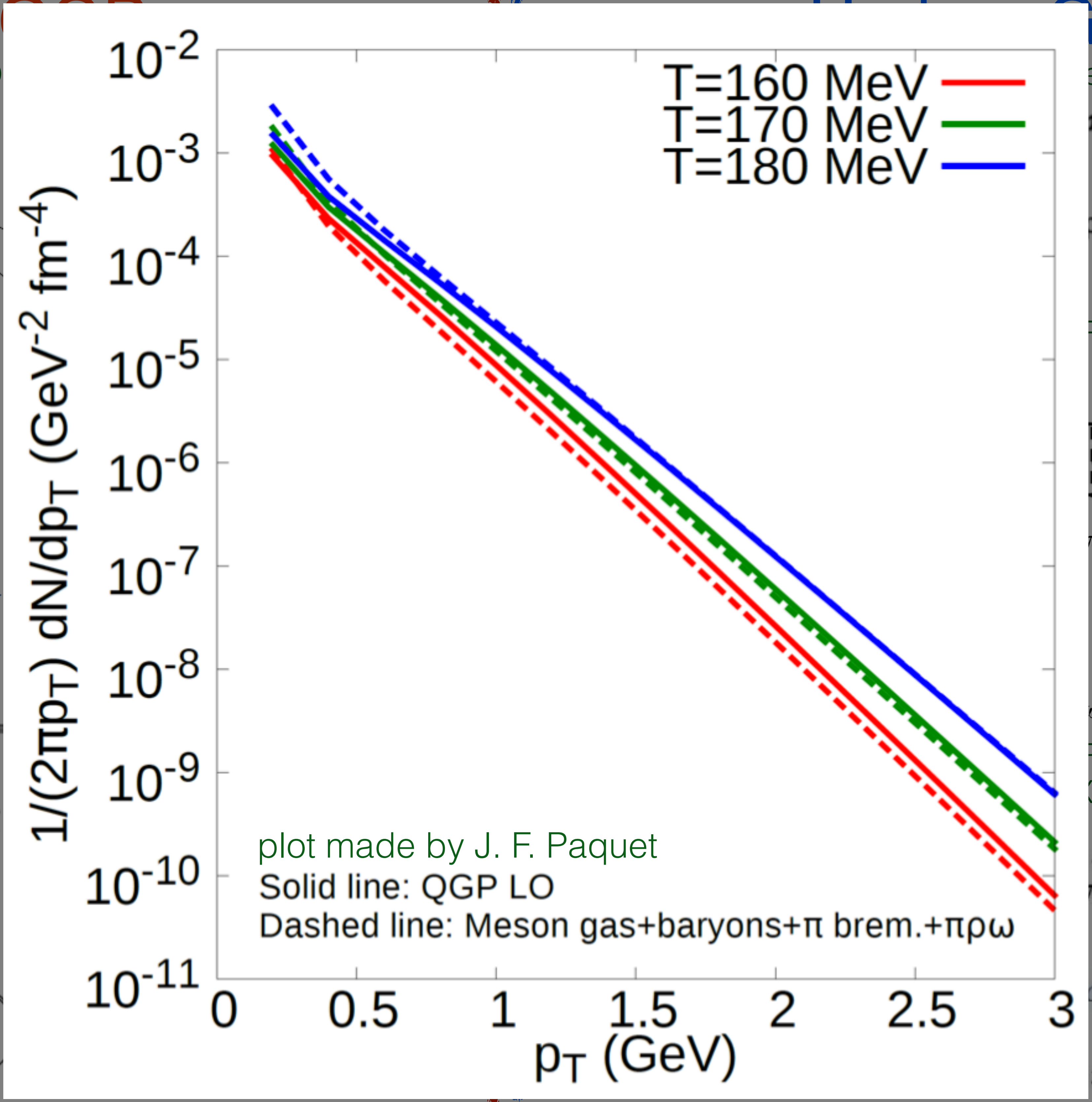

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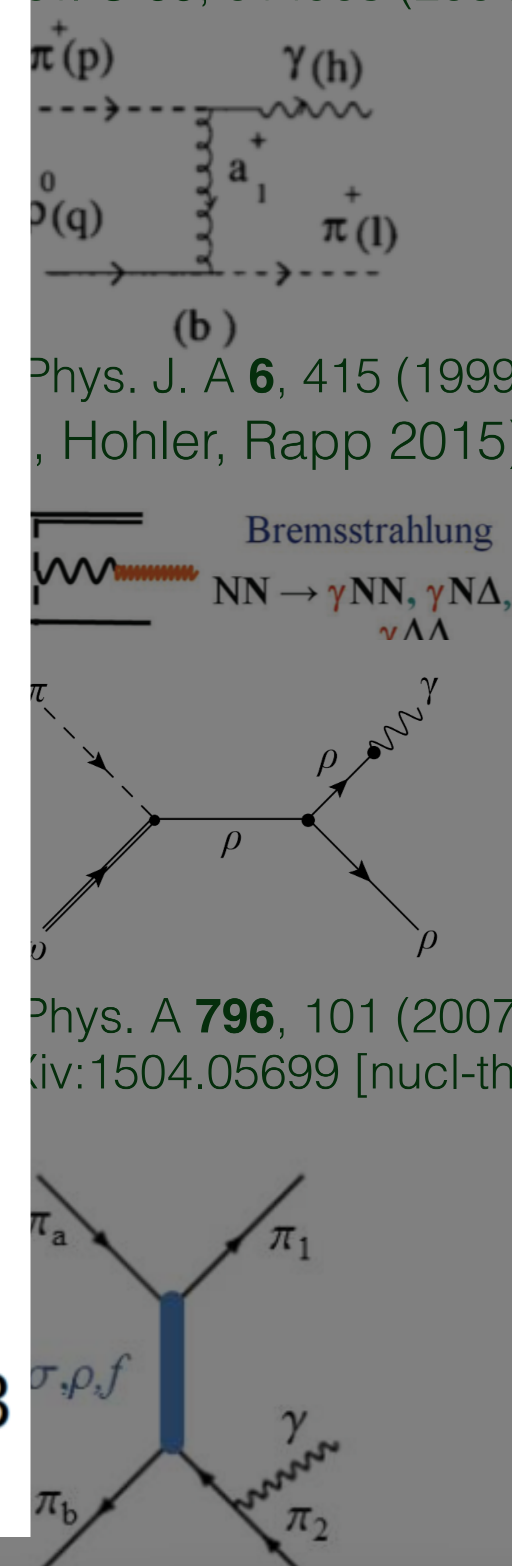


...Phys. A **796**, 101 (2007)

...iv:1504.05699 [nucl-th]

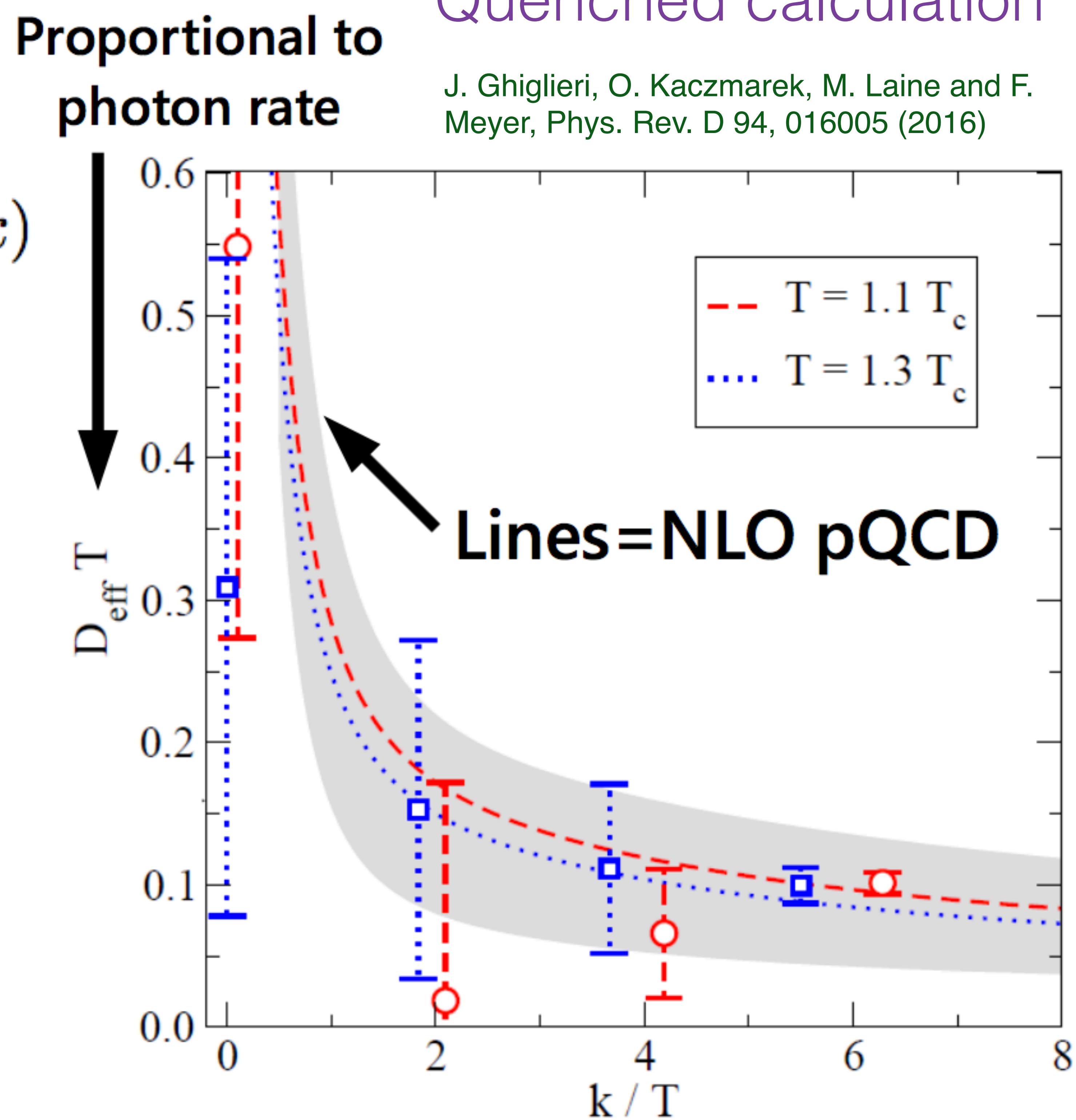
Recent development from Lattice QCD

$$\frac{d\Gamma_\gamma(\mathbf{k})}{d^3\mathbf{k}} = \frac{2\alpha_{\rm em}\chi_{\rm q}}{3\pi^2} n_{\rm B}(k) D_{\rm eff}(k)$$

- Perturbative photon rates agree with the Lattice QCD results remarkably in the transition region for k/T > 2

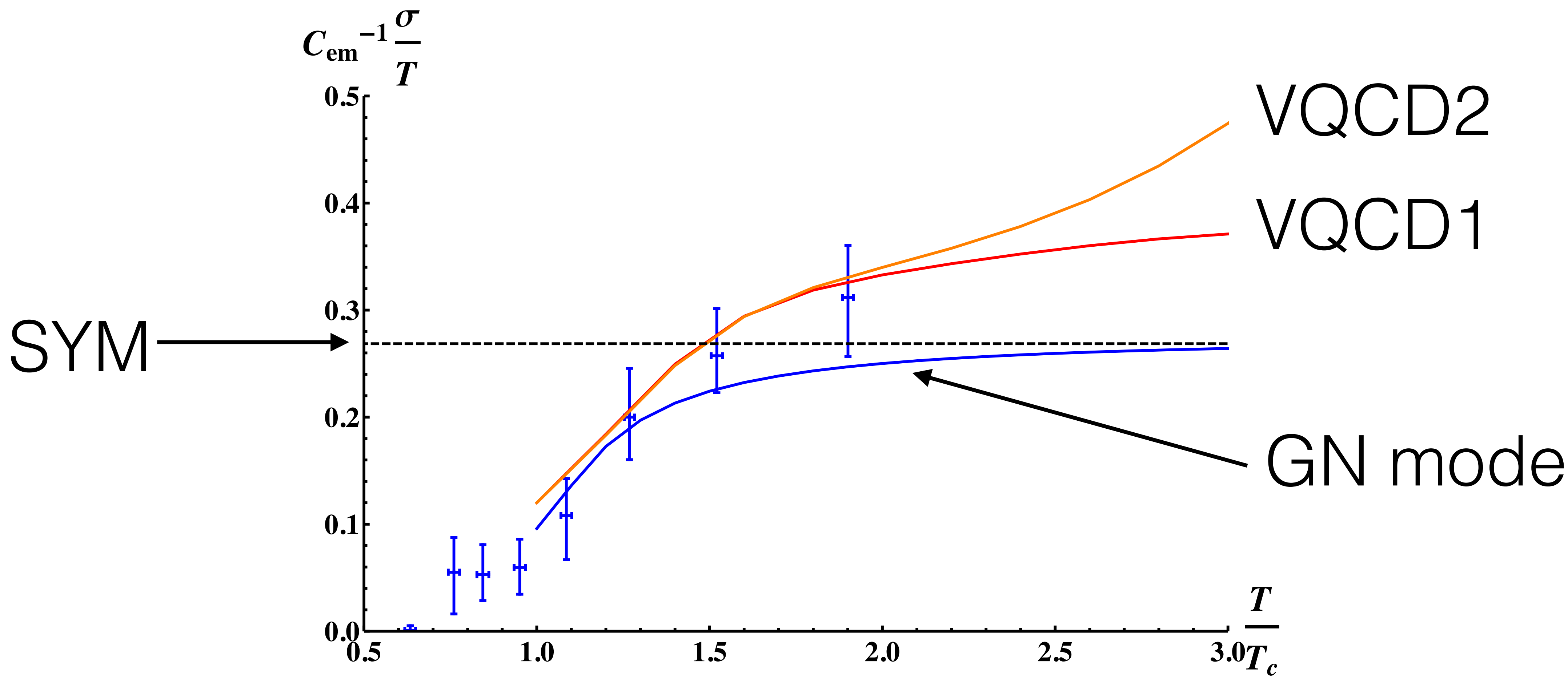
Quenched calculation

J. Ghiglieri, O. Kaczmarek, M. Laine and F. Meyer, Phys. Rev. D 94, 016005 (2016)



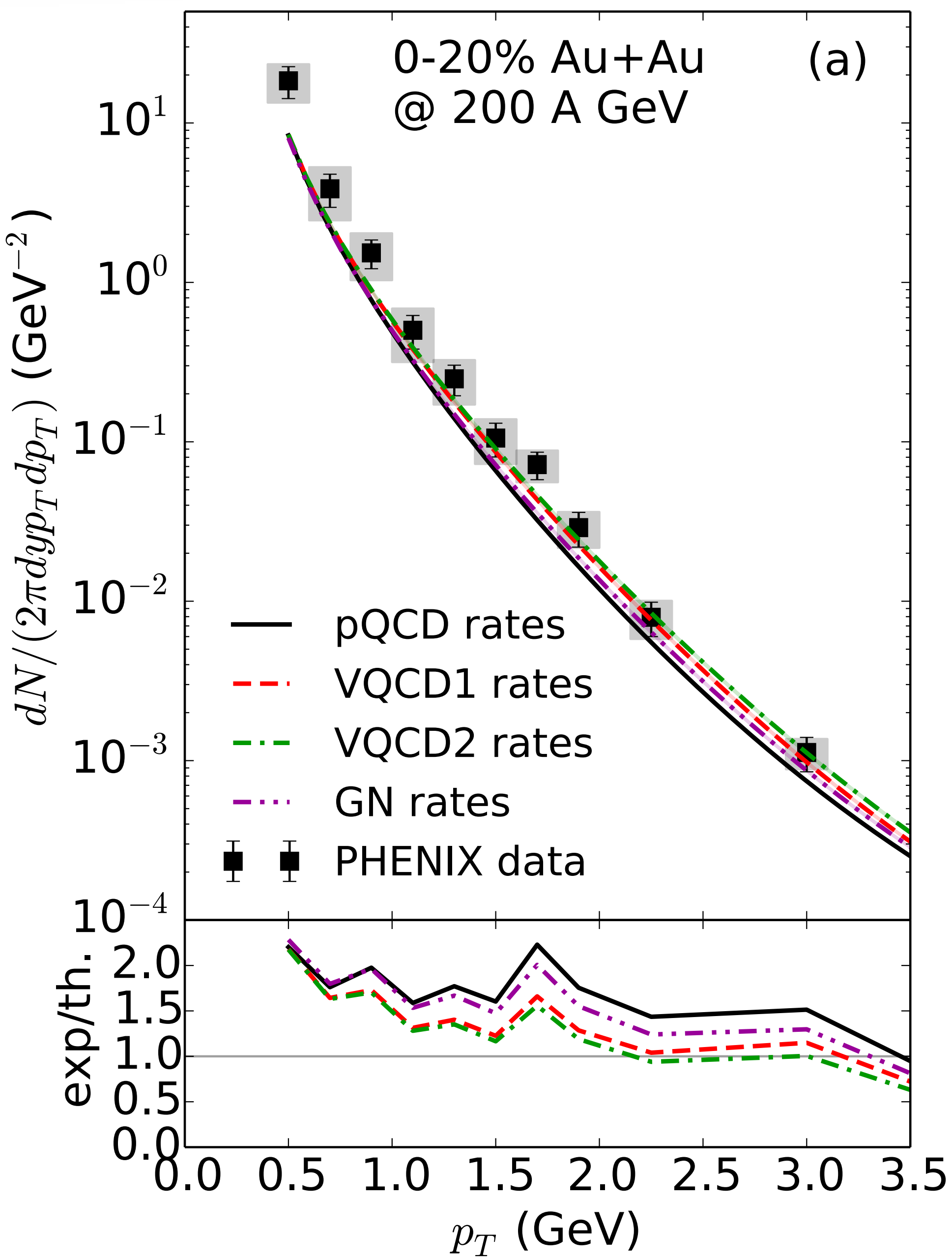
Photons from holographic QCD

I. Iatrakis, E. Kiritsis, C. Shen and D.L. Yang, arXiv:1609.07208 [hep-ph]
G. Aarts, C. Allton, A. Amato, P. Giudice, S. Hands and J. I. Skullerud, JHEP **1502**, 186 (2015)



- Photon rates from strongly-coupled gauge theories are derived and constrained by the lattice QCD electric conductivity

Photons from holography



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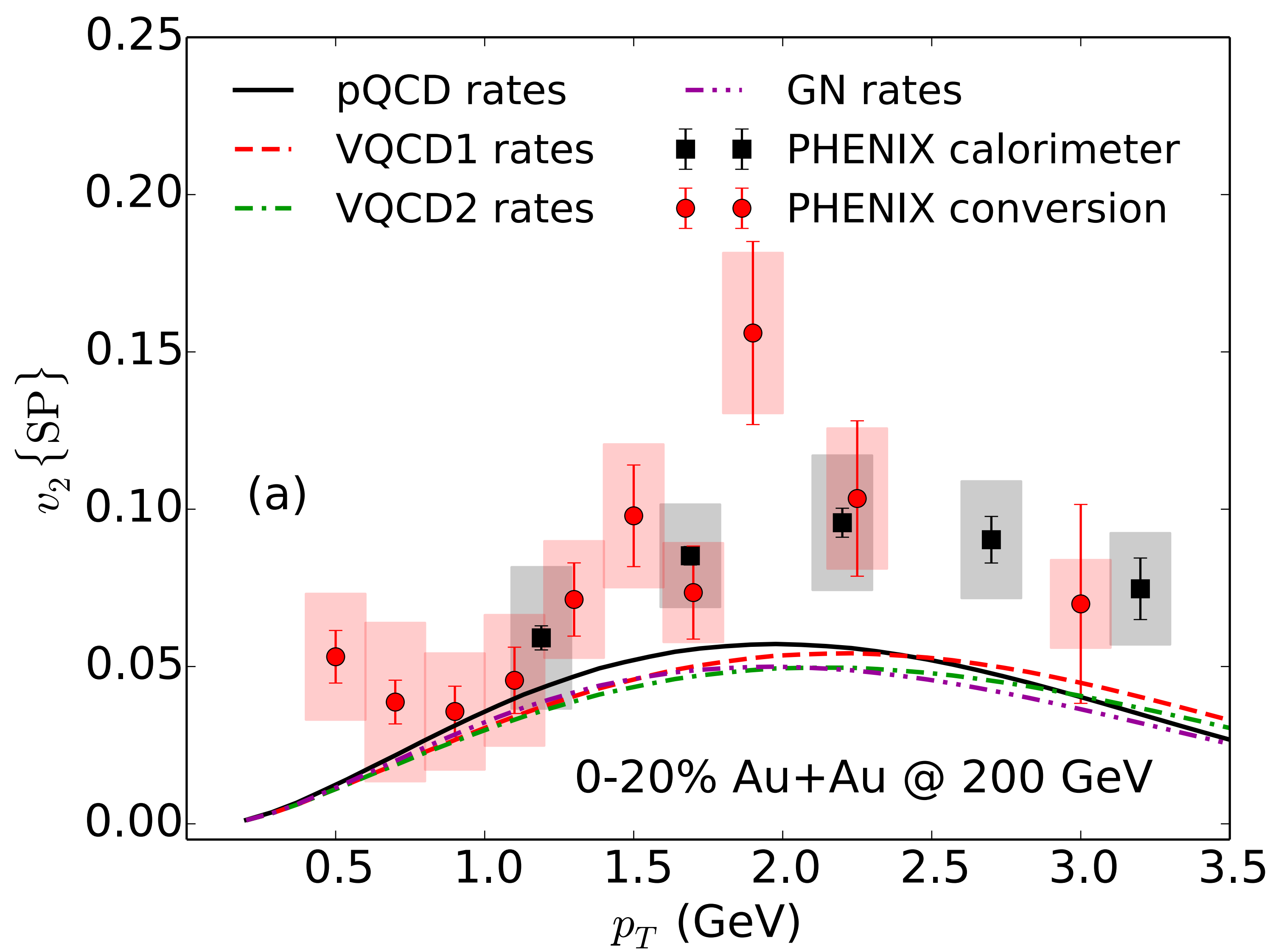

no viscous correction

- Photon rates from strongly-coupled theories give very similar direct photon spectra and v_2

Out-of-equilibrium correction to photon rates

J.F. Paquet, C. Shen, G.S. Denicol, M. Luzum, B. Schenke, S. Jeon and C. Gale, Phys. Rev. C 93, 044906 (2016)

$$k\frac{d^3\Gamma}{d^3k} = k\frac{d^3\Gamma^{\rm eq}}{d^3k} + \frac{\pi^{\mu\nu}k_\mu k_\nu}{2(e+P)}\Gamma^{\rm shear} - \Pi\Gamma^{\rm bulk}$$

Rate	Ideal	Shear correction	Bulk correction
QGP — $2 \to 2$	[52]	Yes [57]	Forward scattering approximation
QGP — Bremsstrahlung	[52]	No	No
Hadronic — Meson gas (π, K, ρ, K^*, a_1)	[26]	Yes [18, 58]	Yes [this work]
Hadronic — ρ spectral function (incl. baryons)	[26, 27]	No	No
Hadronic — $\pi + \pi$ bremsstrahlung	[27, 59]	No	No
Hadronic — π-ρ-ω system	[28]	No	No

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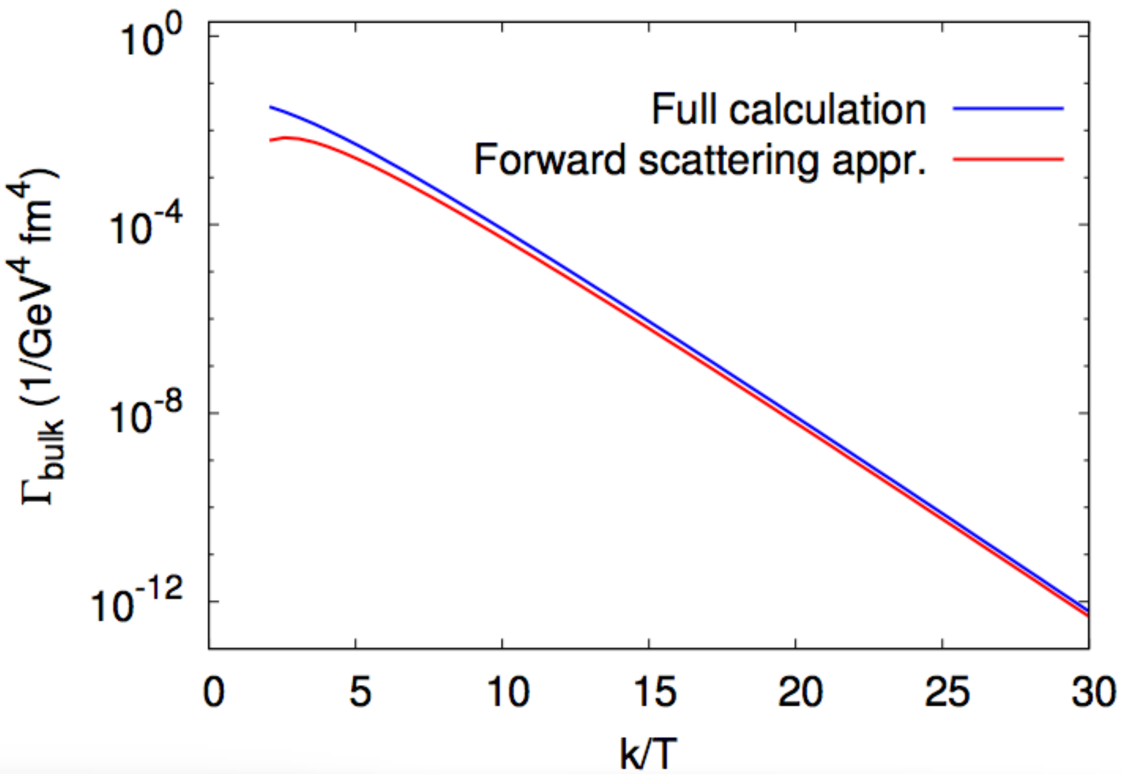
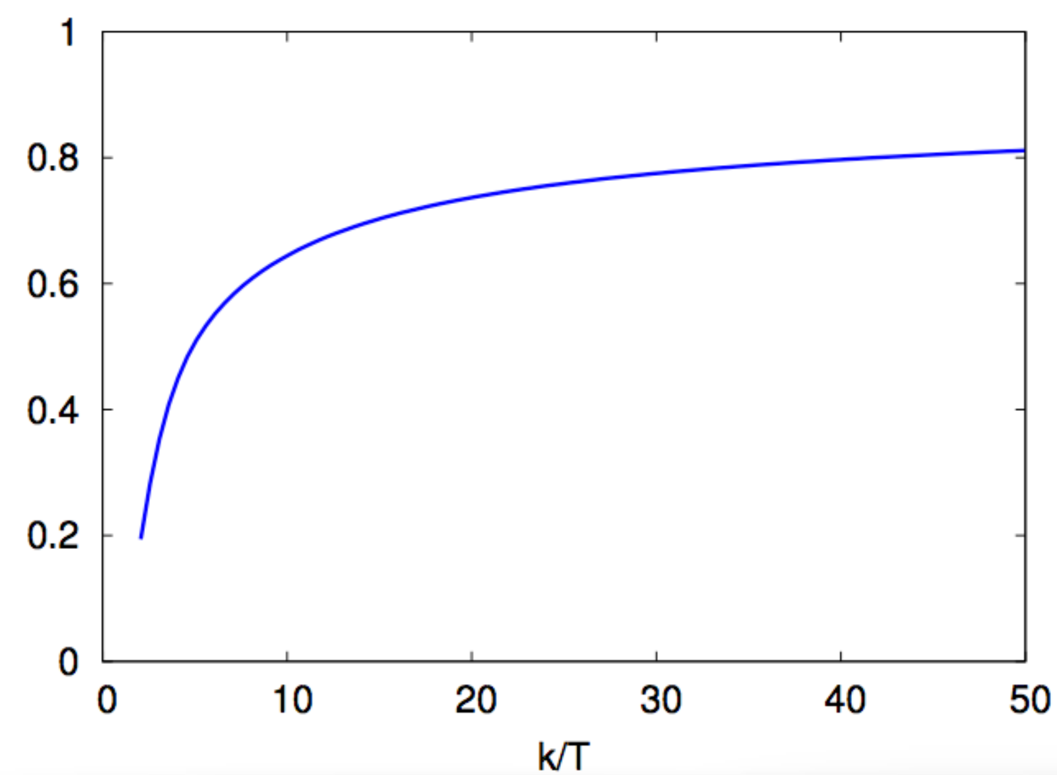
S. Hauksson, C. Shen, S. Jeon and C. Gale, arXiv:1612.05517 [nucl-th].





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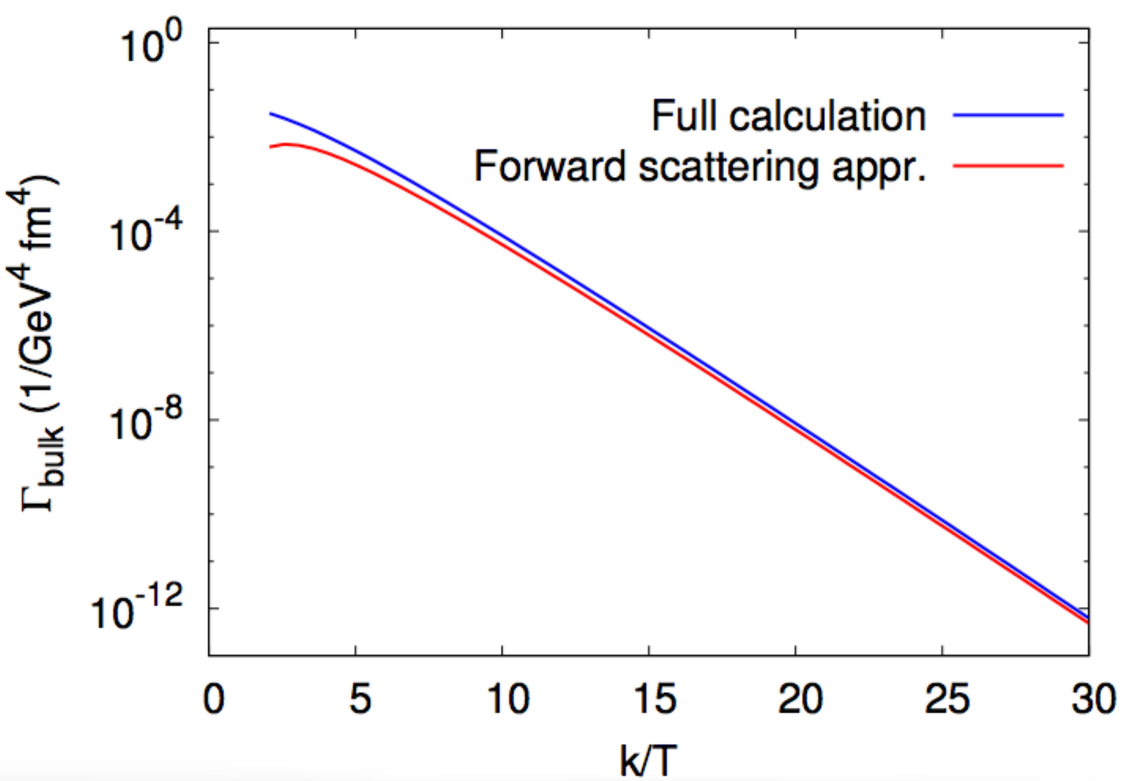

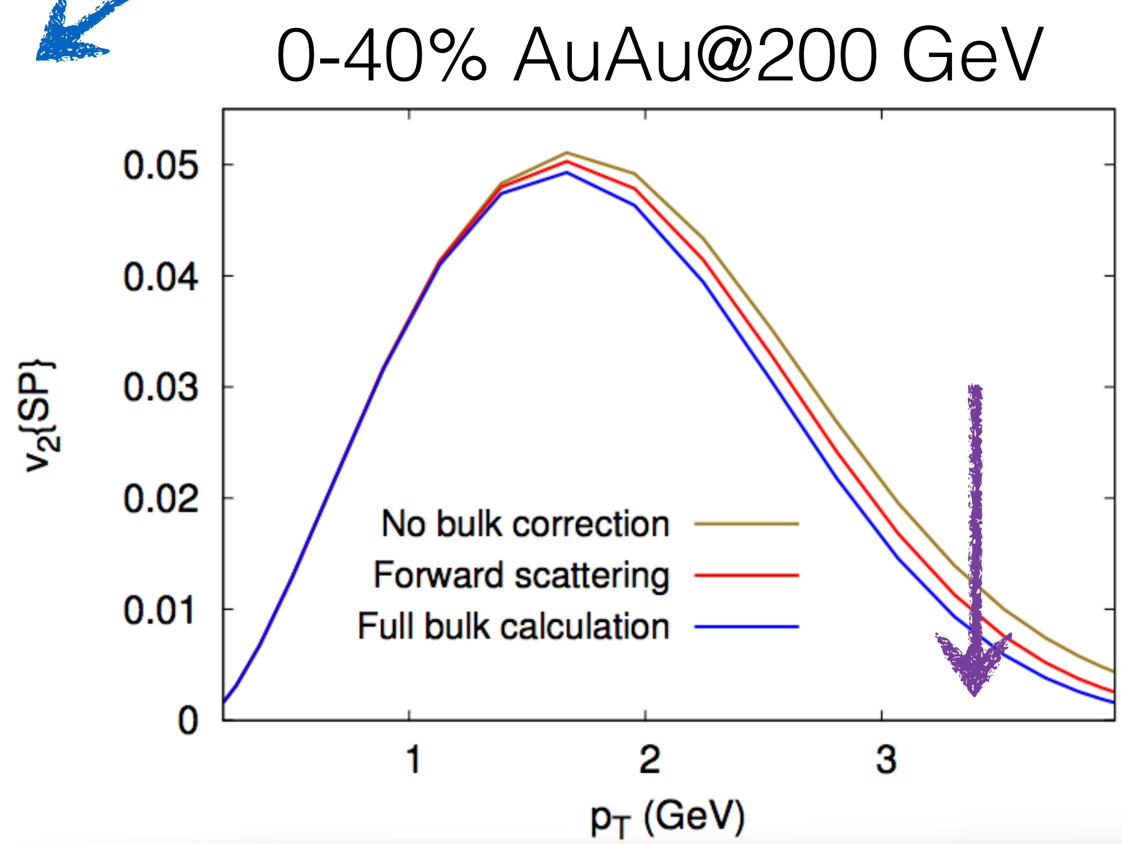

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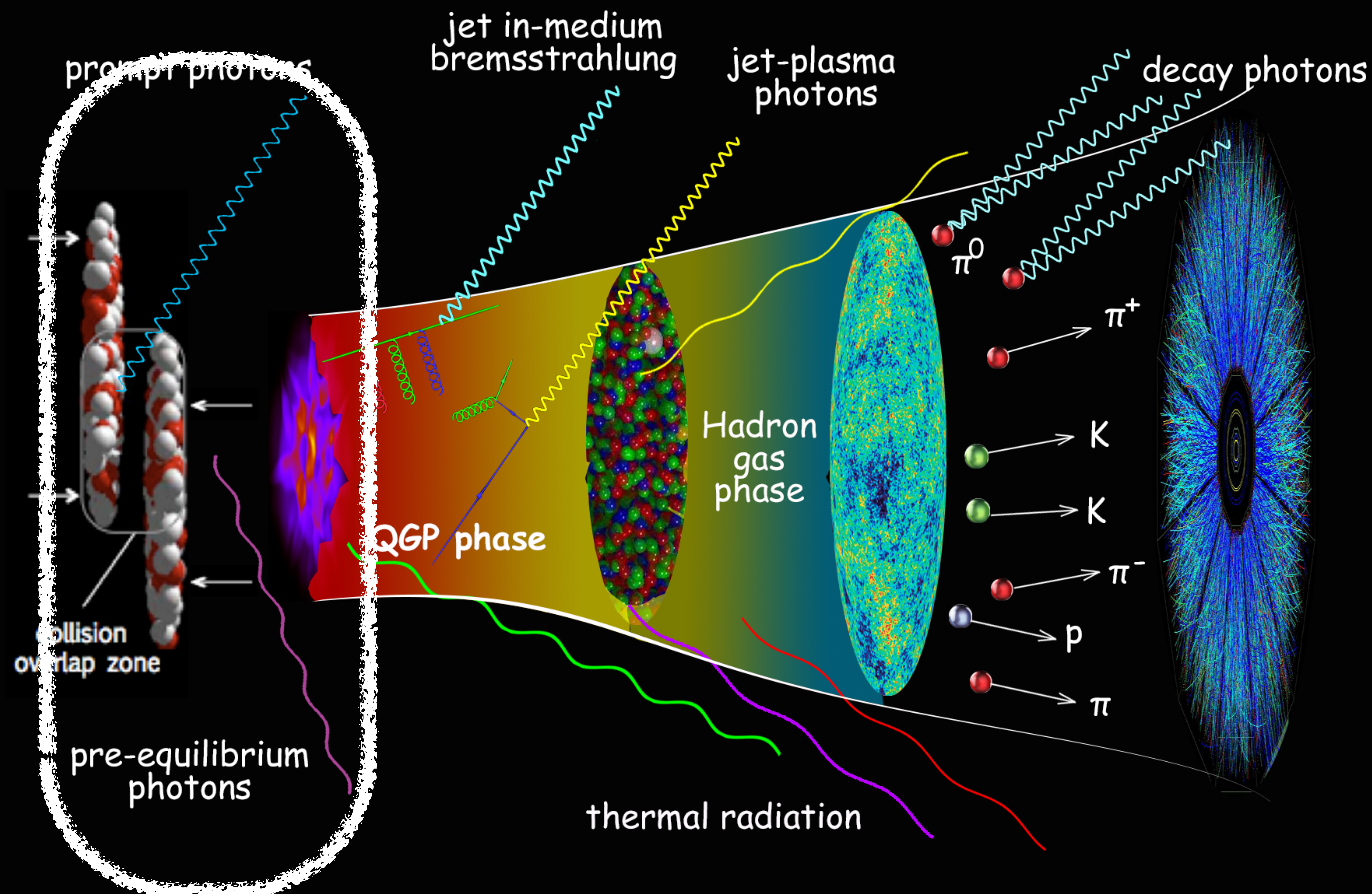
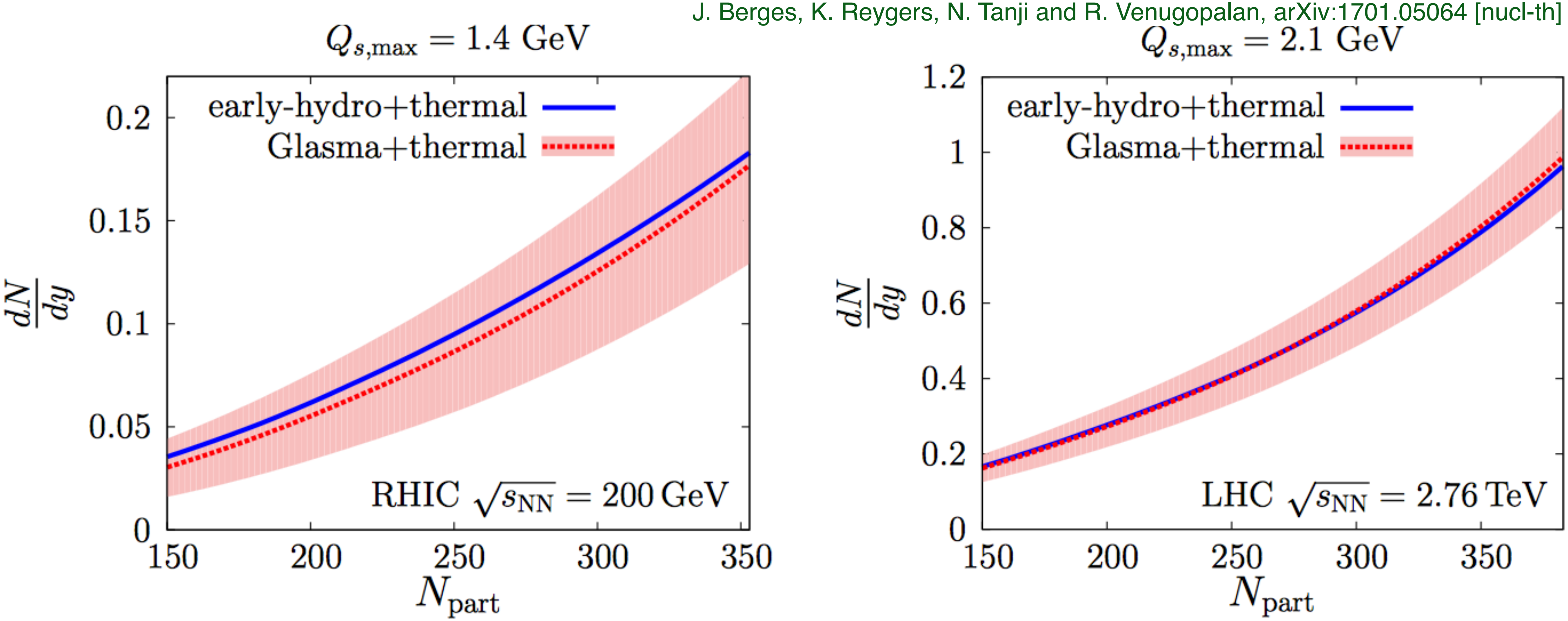


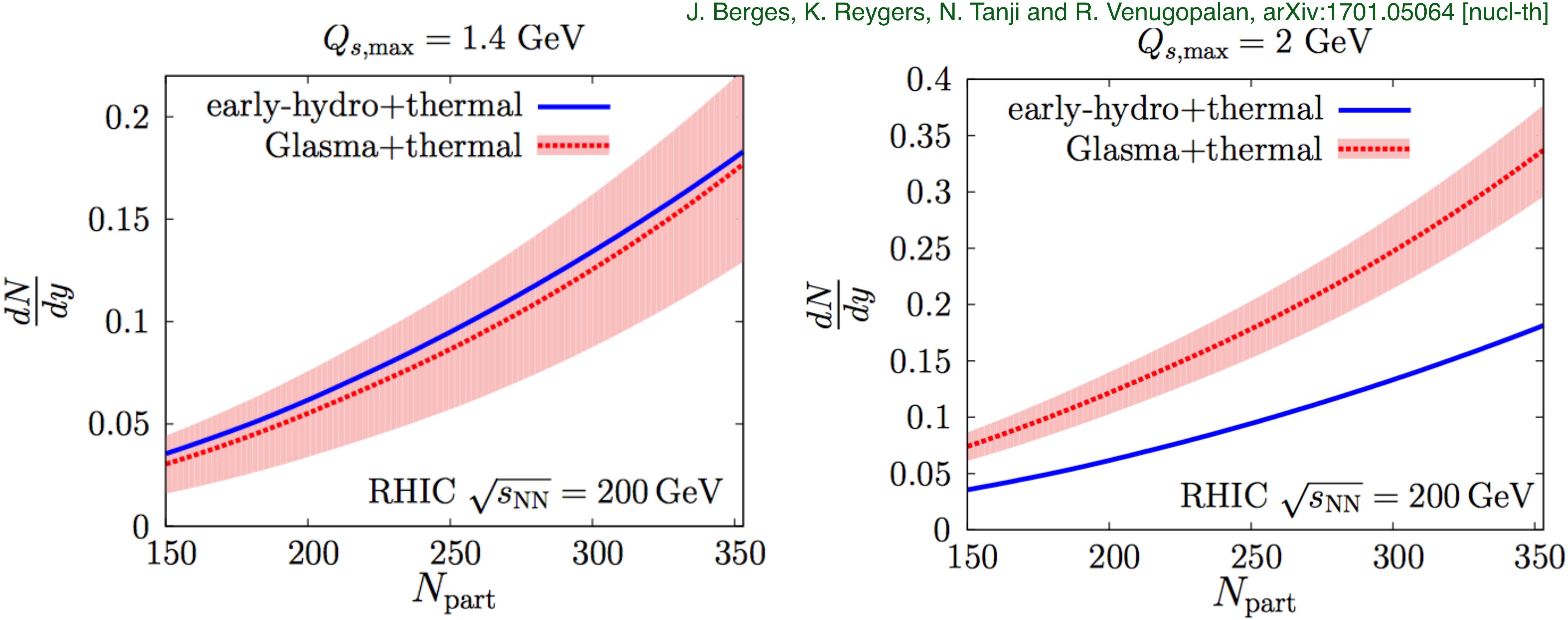
Pre-equilibrium photons

J. Berges, K. Reygers, N. Tanji and R. Venugopalan, arXiv:1701.05064 [nucl-th]



- Pre-equilibrium photons from the Glasma phase is comparable to a hydro estimation assuming early thermalization scenario

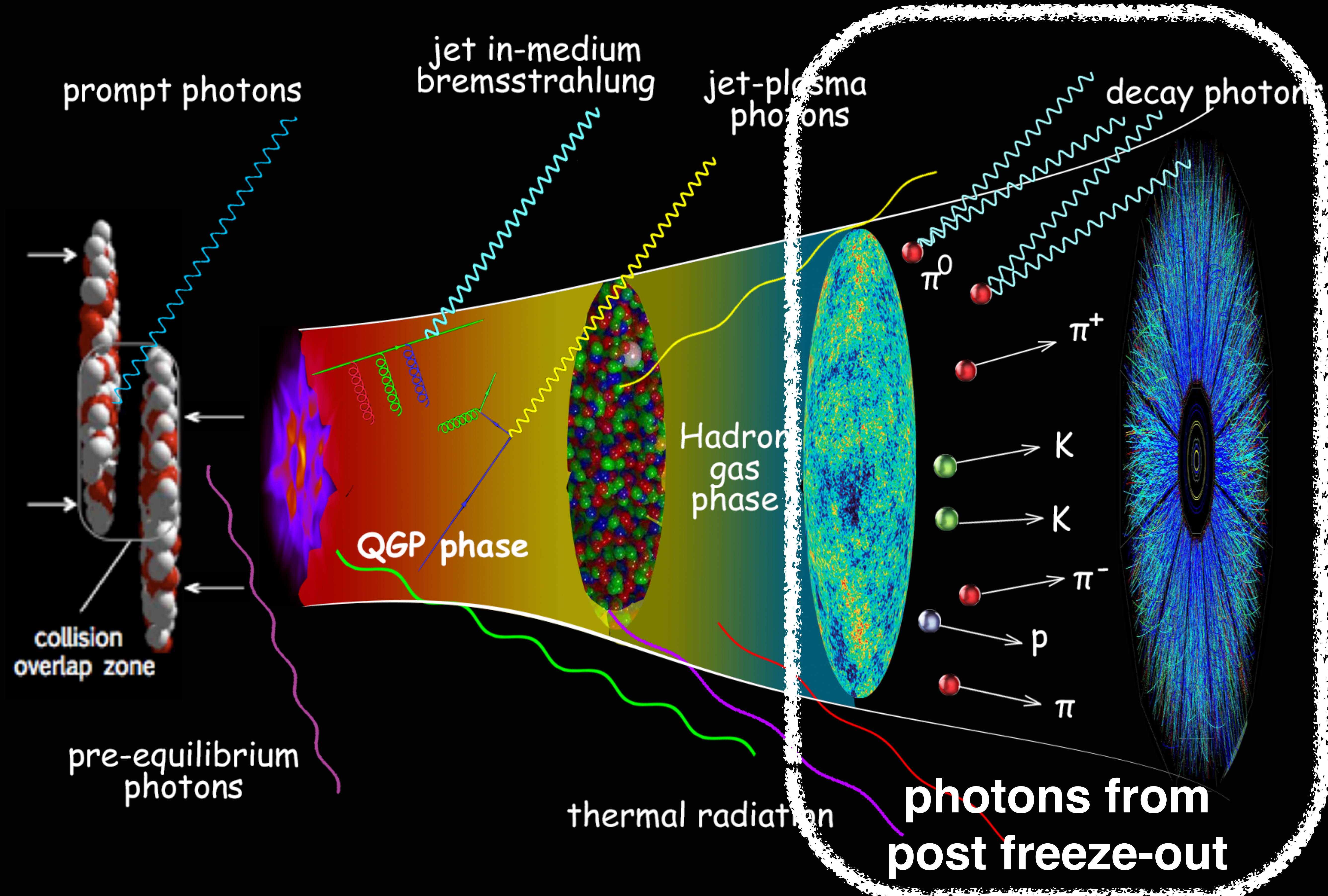
J. Berges, K. Reygers, N. Tanji and R. Venugopalan, arXiv:1701.05064 [nucl-th]



- Pre-equilibrium photons from the Glasma phase is comparable to a hydro estimation assuming early thermalization scenario

- Glasma photon production shows strong sensitivity to the choice of Q_s; Quest for more realistic calculations

Photons in Relativistic Heavy-ion Collisions

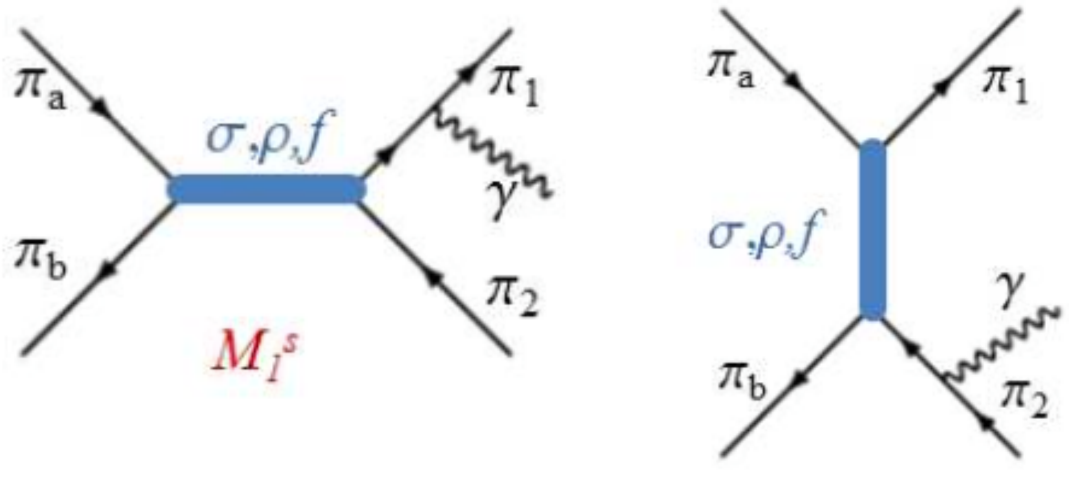


O. Linnyk, V. Konchakovski, T. Steinert, W. Cassing and E. L. Bratkovskaya, arXiv:1504.05699

- Including:

$$m + m \to m + m + \gamma$$

$$m + B \to m + B + \gamma$$



Improved soft photon approximation (SPA)

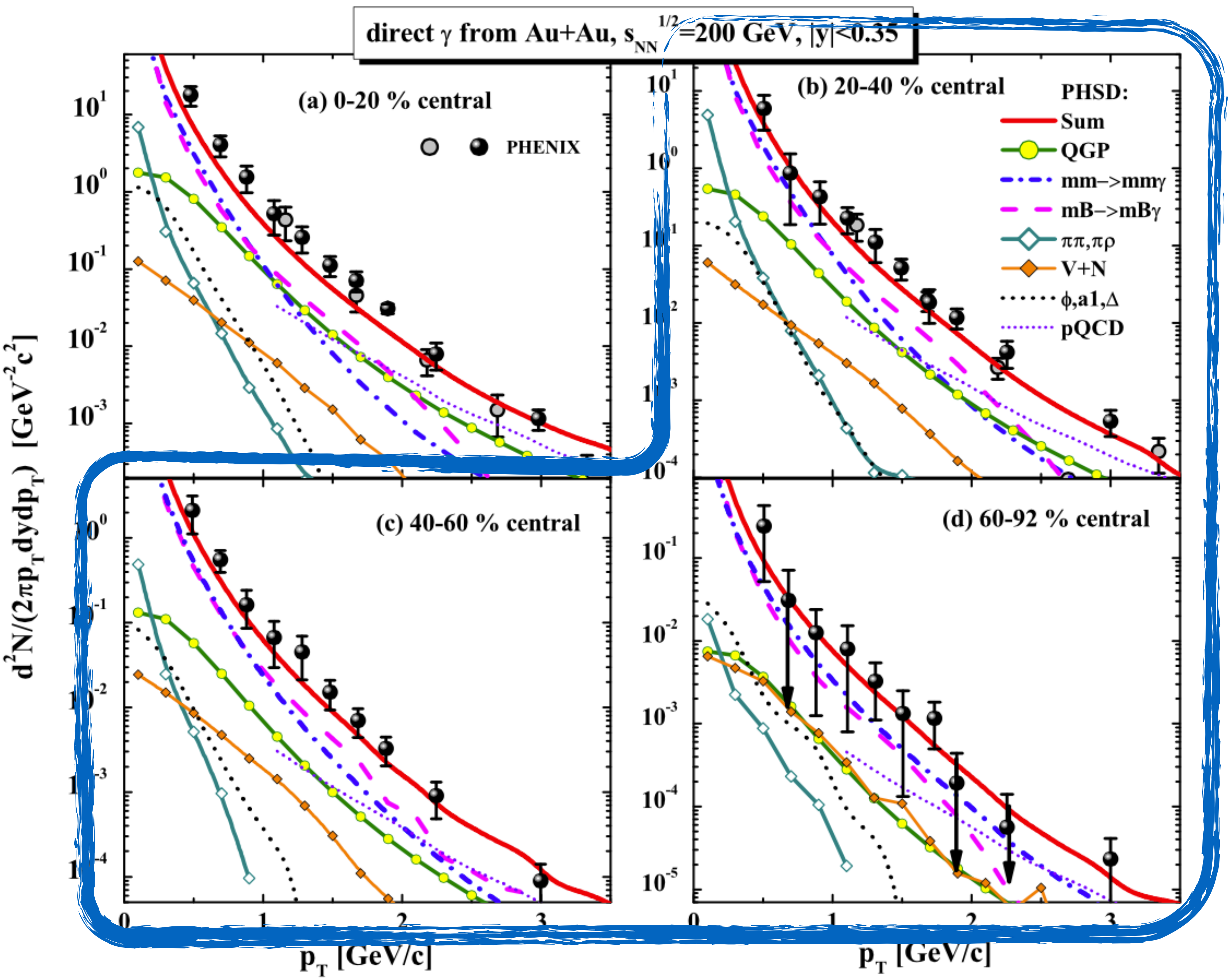
$$q_0 \frac{d\sigma^\gamma(s)}{d^3 q} = \frac{\alpha_{EM}}{4\pi} \int_{-\lambda(s_2, m_a^2, m_b^2)/s_2}^{0} |\epsilon \cdot J(q,t)|^2 \frac{d\sigma_{el}(s_2)}{dt} dt.$$

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

More hadronic emission with large anisotropy

Transport approach

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

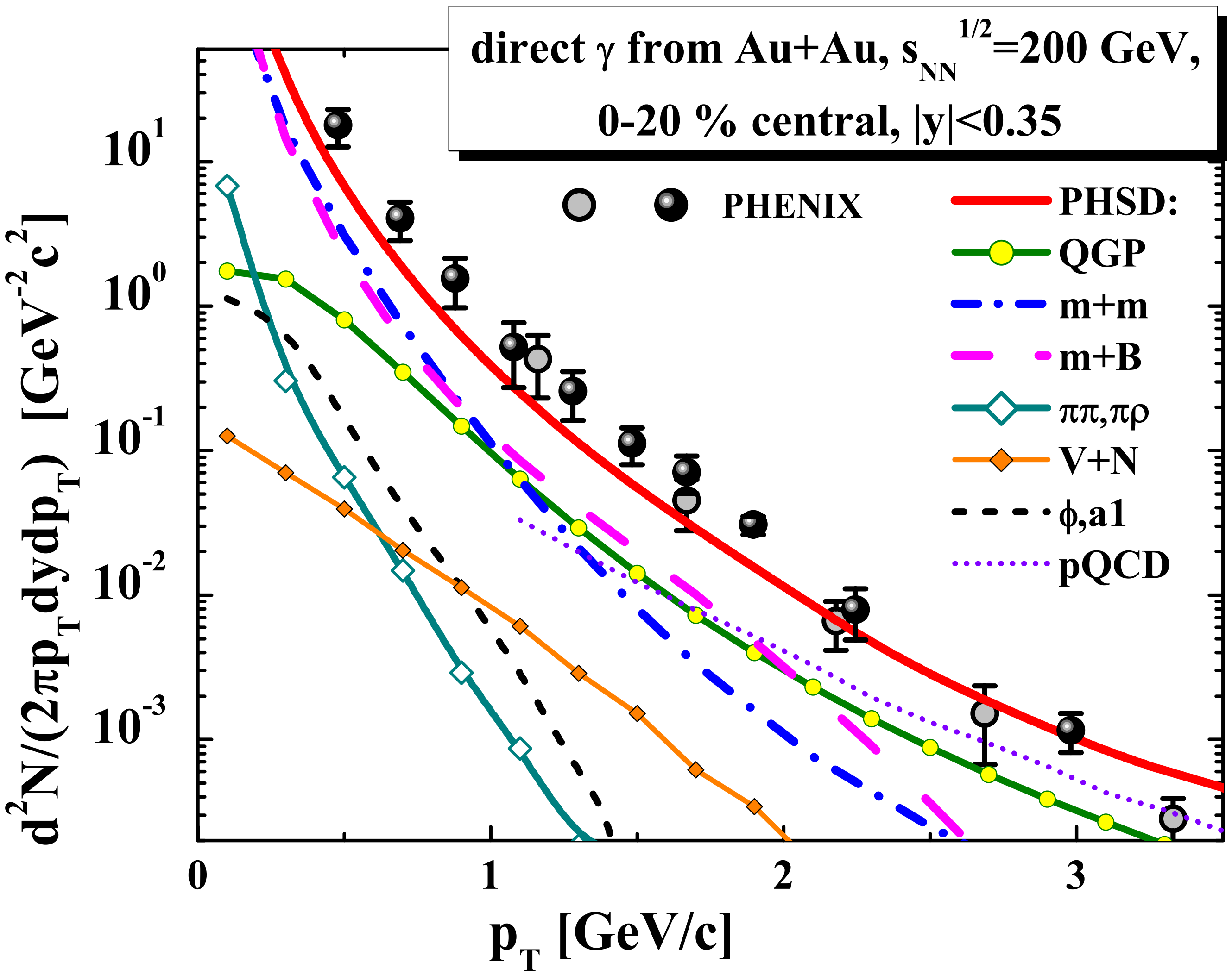


- Good description of the direct photon spectra from semi-central to peripheral centralities

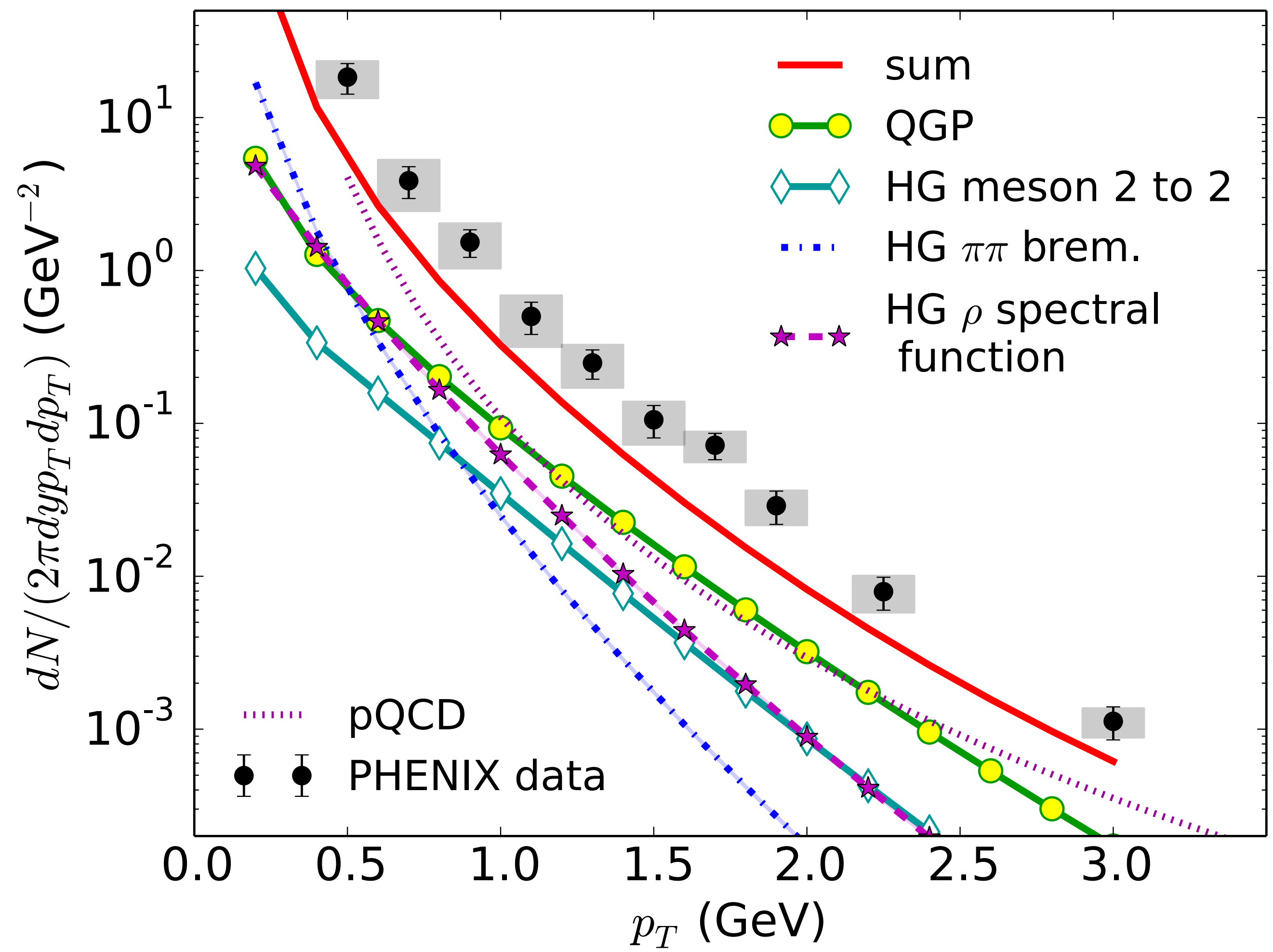
- Majority of the thermal photons are emitted from meson-meson and meson-baryon bremsstrahlung

Transport approach vs hydrodynamics

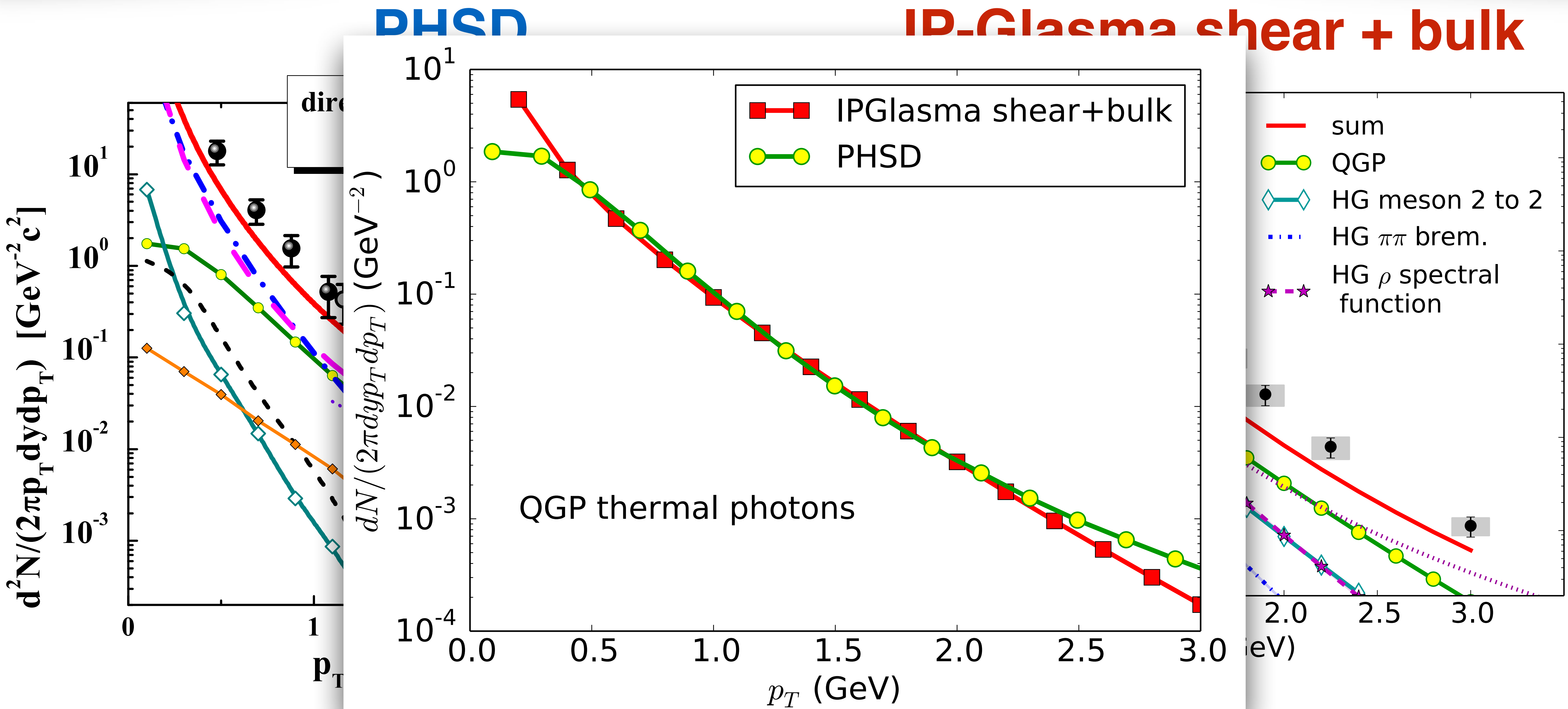
PHSD



IP-Glasma shear + bulk



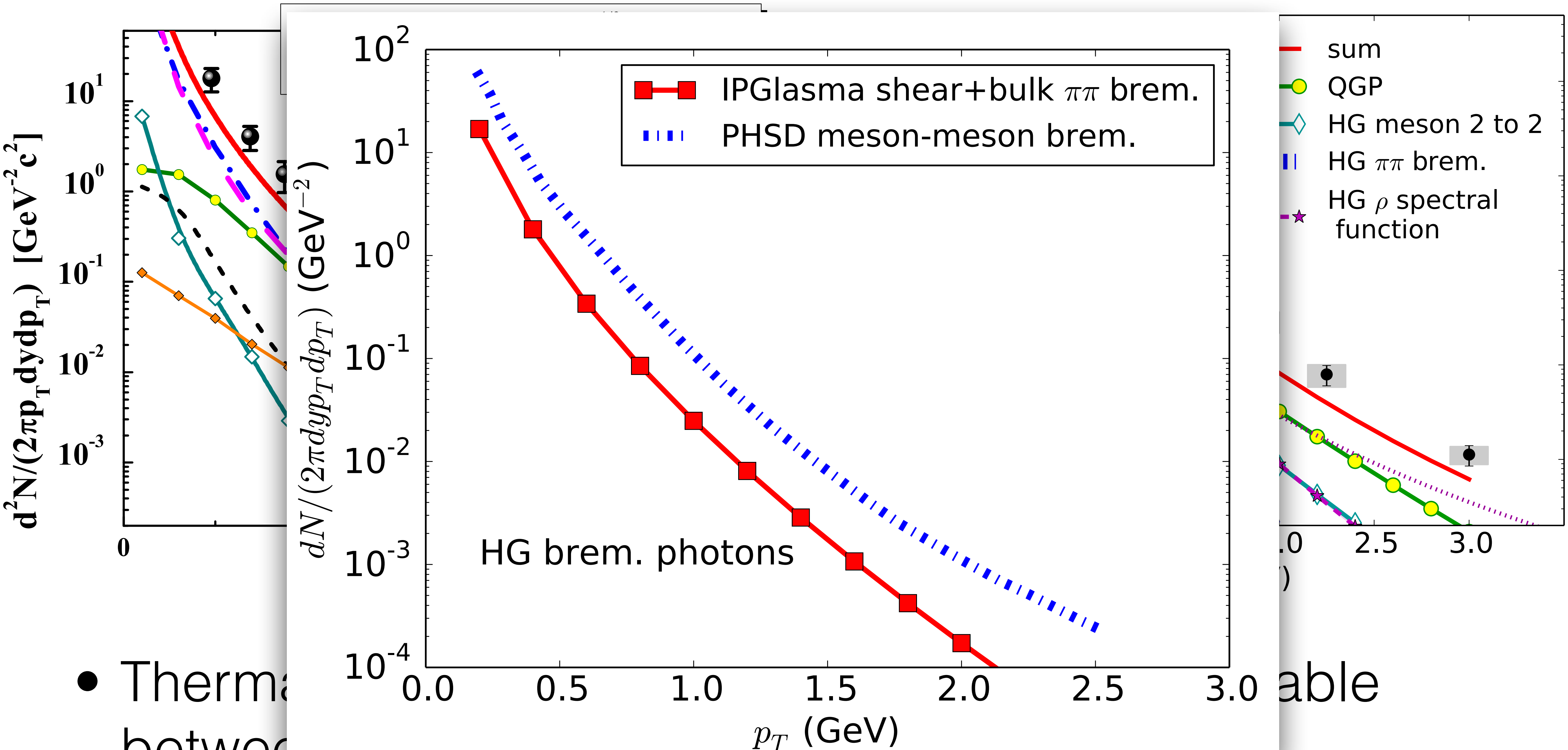
Transport approach vs hydrodynamics



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

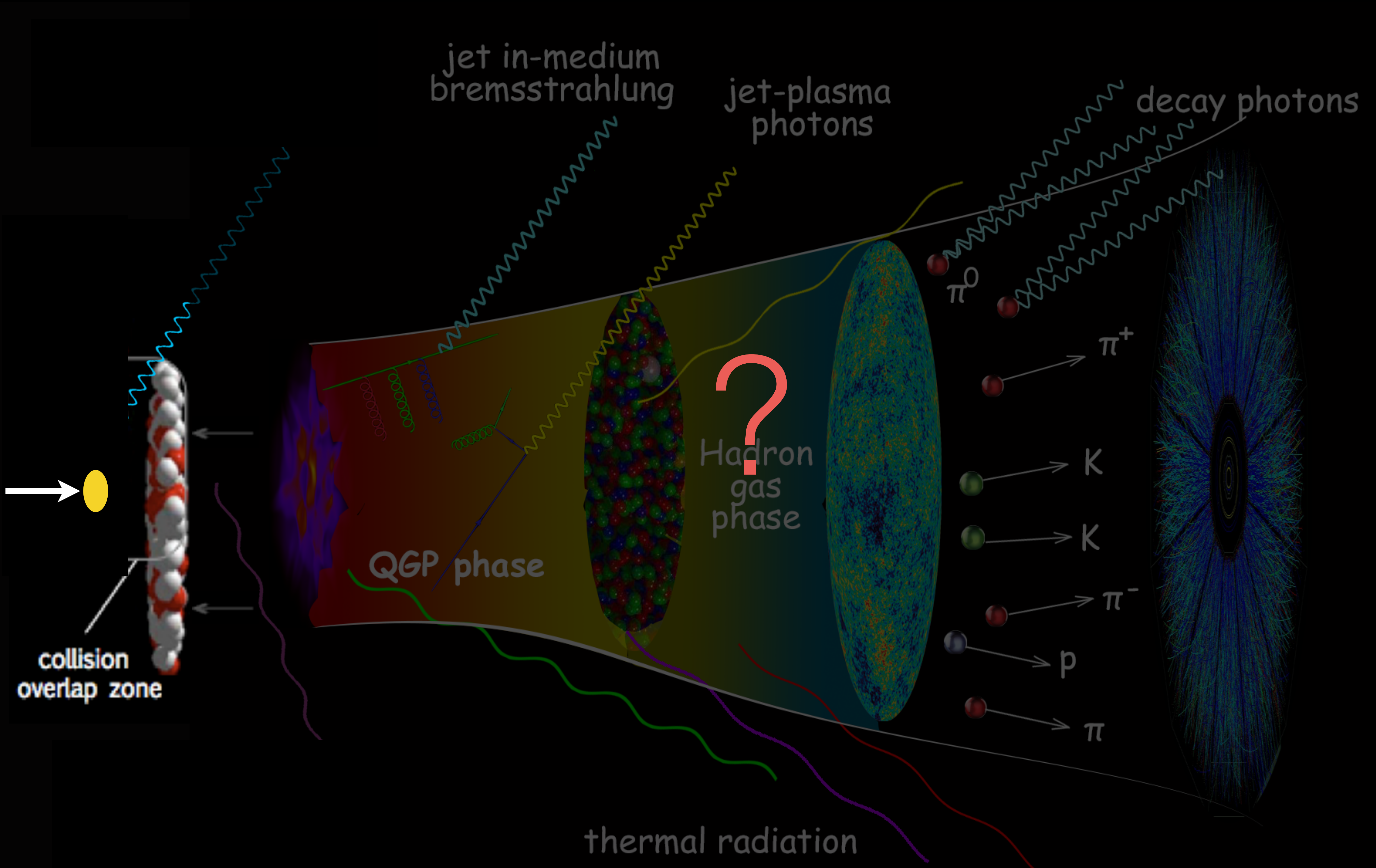
Transport approach vs hydrodynamics

PHSD **IP-Glasma shear + bulk**

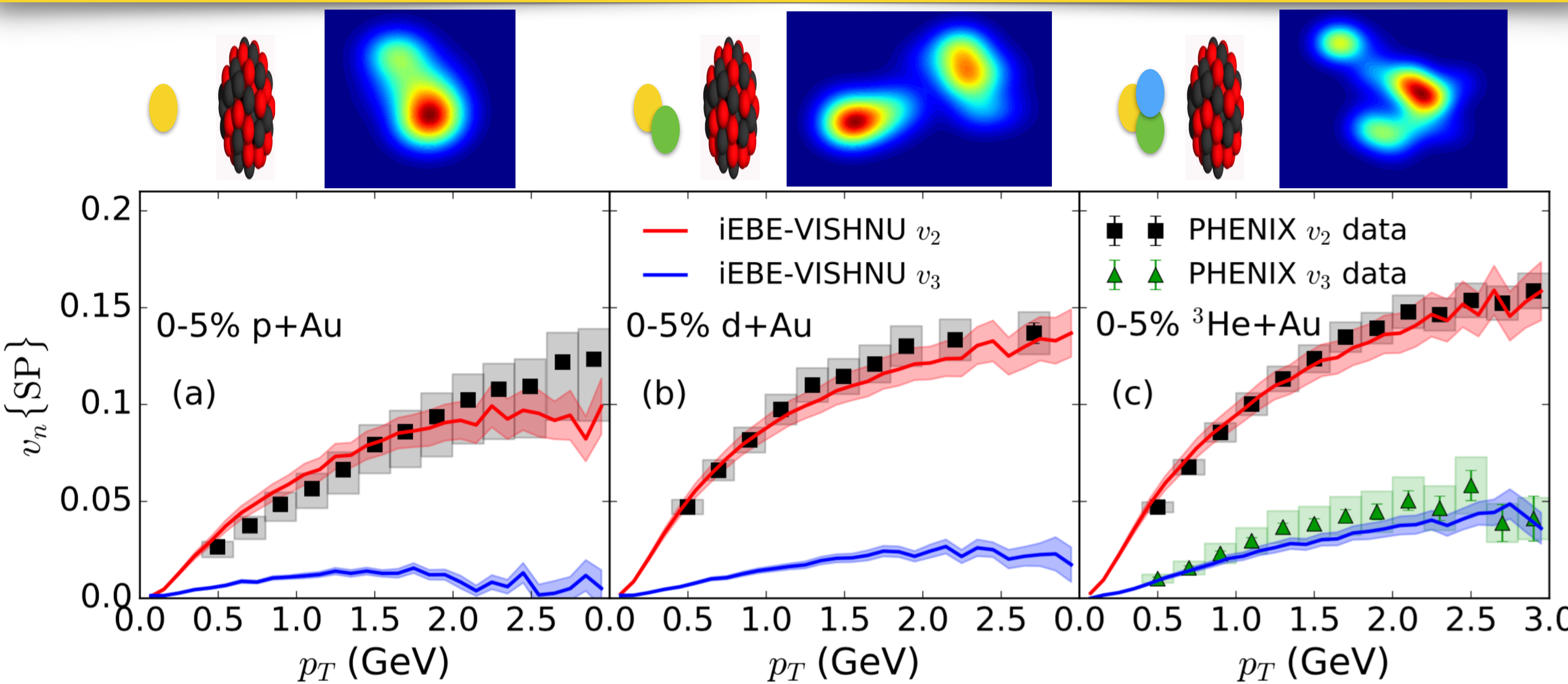


- Therma … able between … the two approaches
- The origin of the difference in hadronic radiation needs further investigation in the future

Photons in small systems



Small systems with different geometry



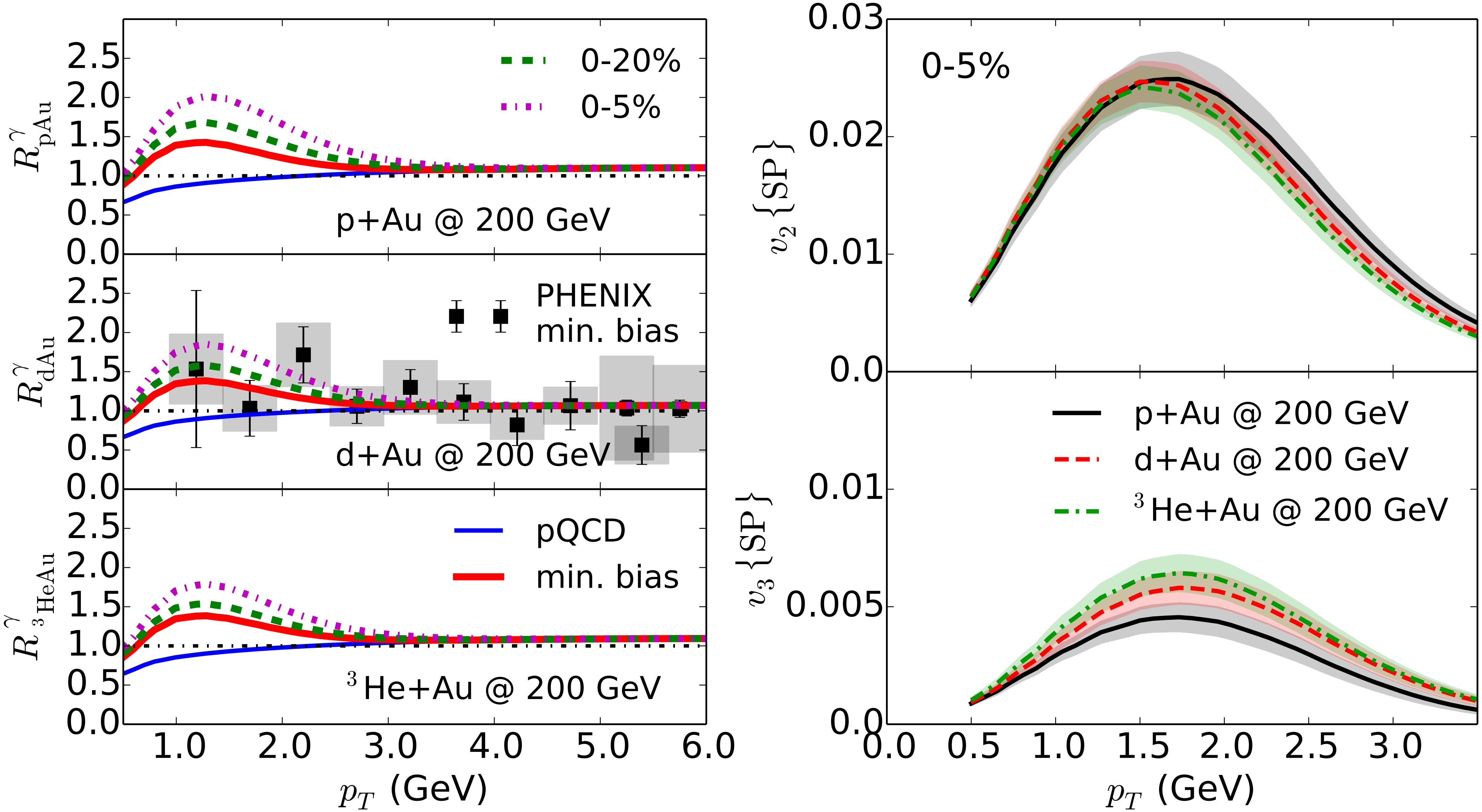
C. Shen, *et al.*, Phys. Rev. C **95**, 014906 (2017)

- Hydrodynamic response converts spatial gradients into measured momentum anisotropy

Indication of a strongly coupled QCD matter?

Thermal radiation in small systems

C. Shen, *et al.*, Phys. Rev. C **95**, 014906 (2017)

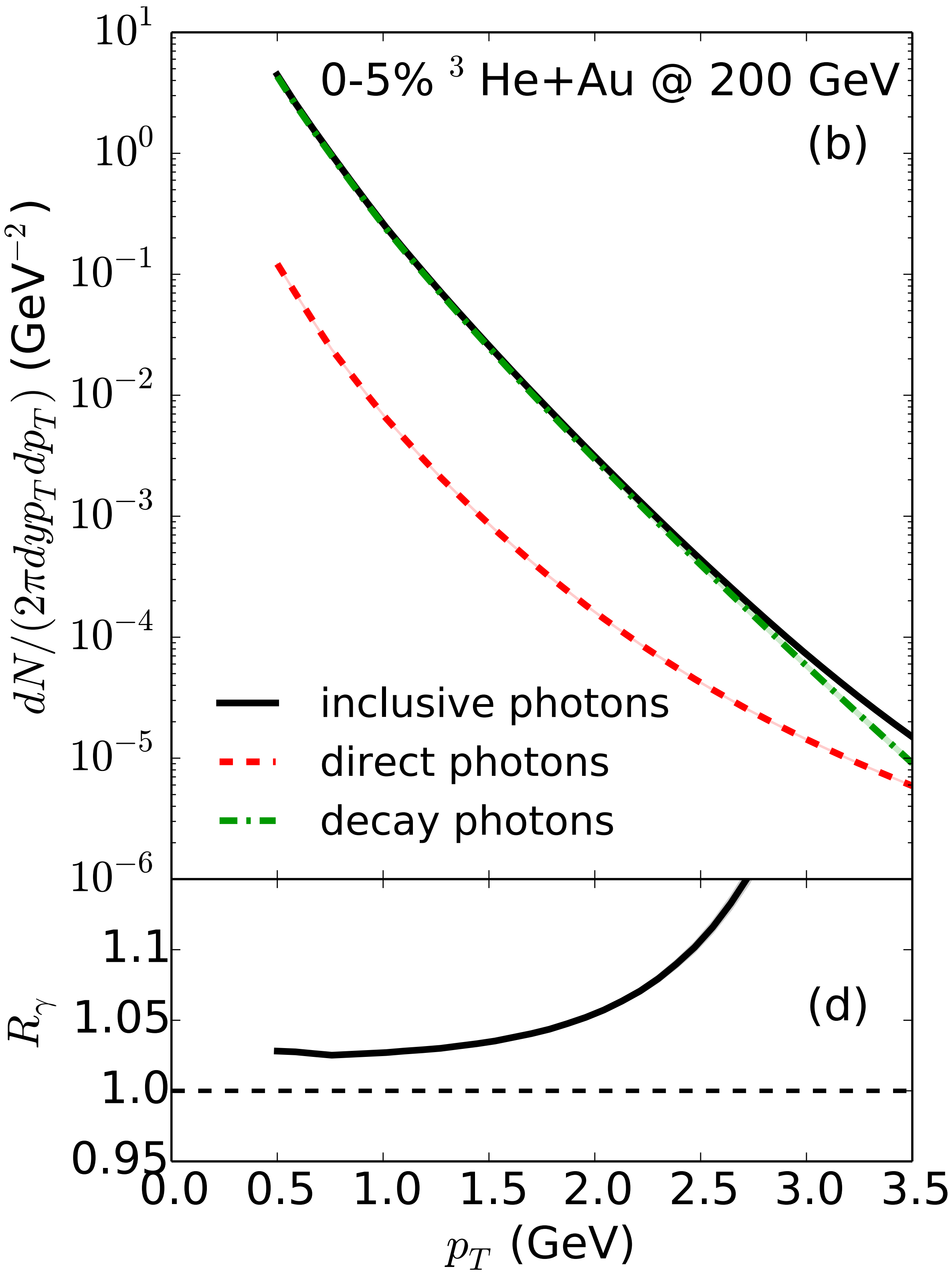


$$R^{\gamma}_{pA} = \frac{dN/(dy p_T dp_T)|_{\rm pA}}{N_{\rm coll} dN/(dy p_T dp_T)|_{\rm pp}}$$

Signature of a nearly thermalized medium in small systems

Inclusive and decay photons

C. Shen, *et al.*, Phys. Rev. C **95**, 014906 (2017)



$$R^\gamma = \frac{dN^{\text{incl.}}/(dy p_T dp_T)}{dN^{\text{decay}}/(dy p_T dp_T)}$$

- The excess of thermal photons over background decay photons is small,

$$R^\gamma \sim 1.03$$

- Similar R^γ for p+Au and d+Au collisions
- **It is a challenging measurement!**

Conclusion

- Electromagnetic probes are very sensitive to:
  - initial conditions/pre-equilibrium dynamics
  - non-equilibrium properties/transport coefficients
  - dynamics in the cross-over region

- Recent theory improvements provide more reliable thermal photon emission rates

  Lattice QCD — Strongly-coupled theories — bulk viscous correction

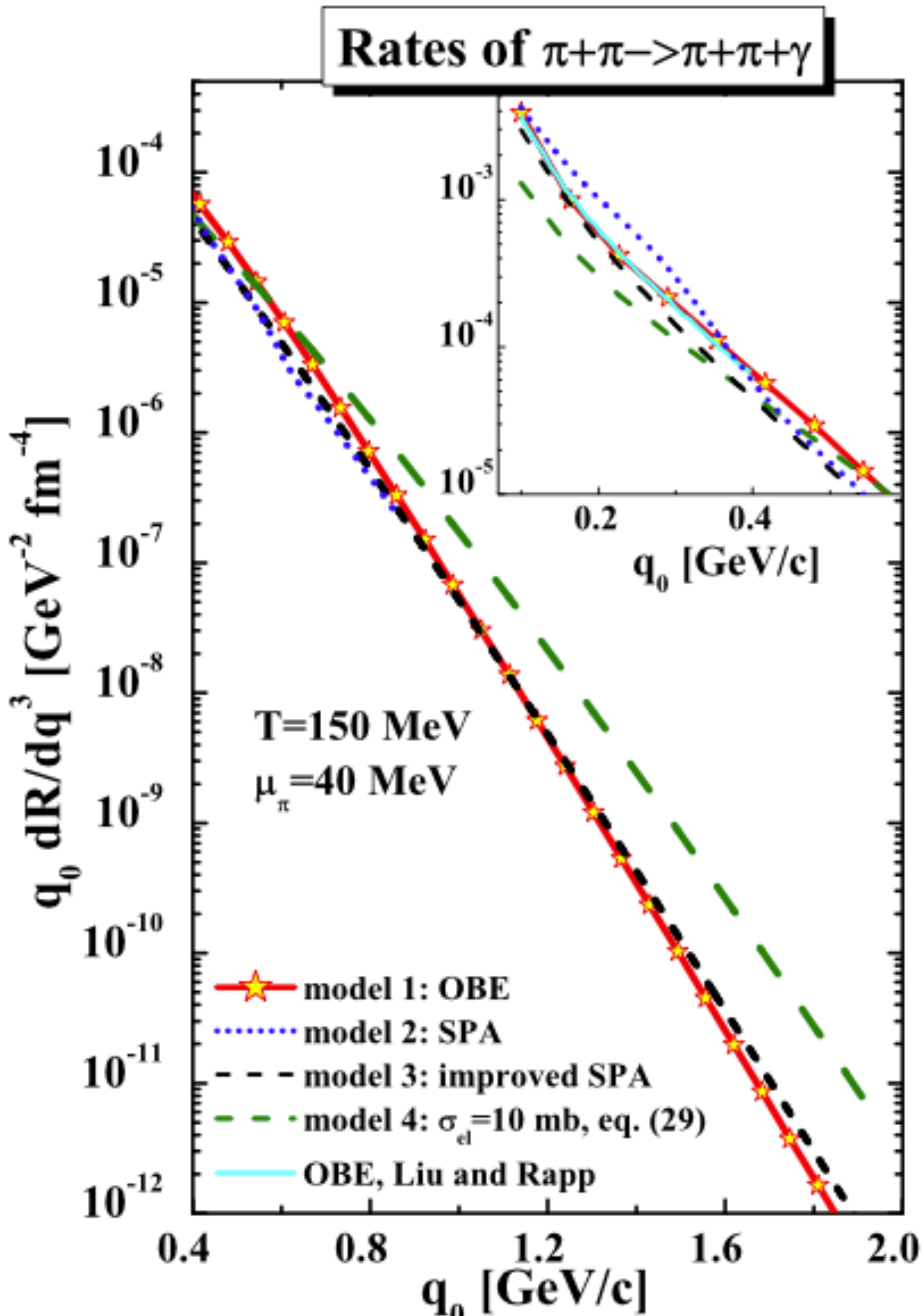
- Pre-equilibrium photon production is explored

- Photons are clean probes of small collision systems


BACKUP

Transport approach

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



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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 π+π bremsstrahlung