Electromagnetic Radiation and the modelling of heavy-ion collisions

ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

TRENTO, ITALY

Institutional Member of the European Expert Committee NUPECC

Castello di Trento (“Trint”), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

Electromagnetic Radiation from Hot and Dense Hadronic Matter

Trento, November 26-30, 2018

Main topics

Electromagnetic radiation from hot and dense strongly interacting matter
Status of our understanding of current experimental methods and results
The “photon flow puzzle”
Progress in photon and dilepton production theory
Future experiments

Key-note participants

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[Image: physics.org]

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McGill University

Outline

Most of this talk: real and virtual photons(*) of, at the most, a couple of GeV's

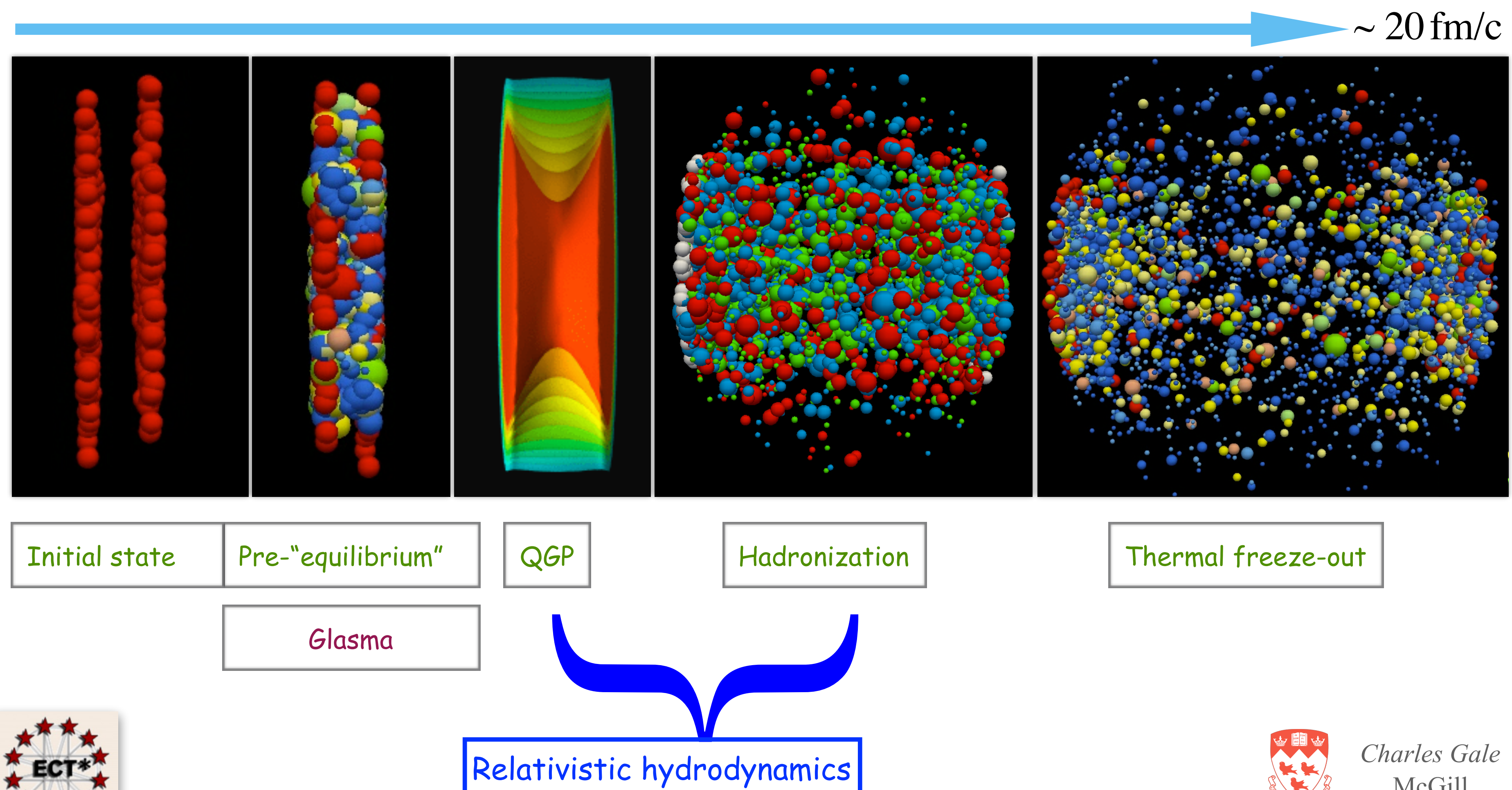
Photons can be **soft** and still **penetrating**

They enjoy a unique status

- (Very brief) Review of the physics of the bulk system
  - Reaction modelling and EM emission are indissociable
- Electromagnetic radiation, theory status and updates
  - The "photon flow puzzle"
  - Towards a complete treatment of "viscous photons"
  - Pre-hydro photons
  - BES-energies radiation
  - Dileptons
  - Small systems

(*) Photons **and** dileptons

Relativistic nuclear collisions: The emergence of a "standard picture"



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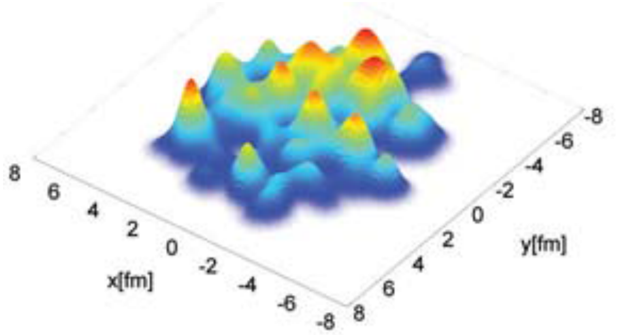
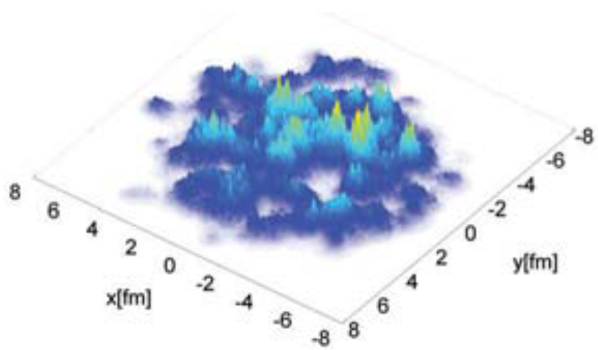
Much progress in the calculation of the initial state

Energy density

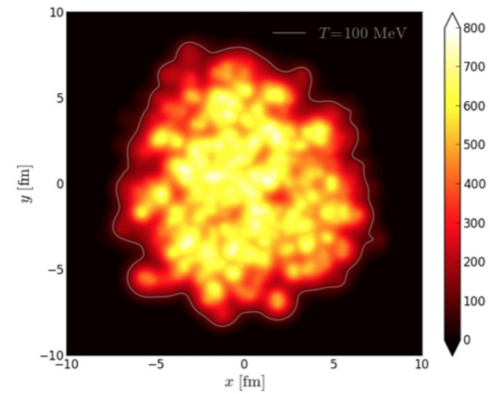


MC-Glauber
Nucleons



IP-Glasma
Colour fields

Schenke, Tribedy, and Venugopalan, PRL (2012)



EKRT
Saturated NLO
pQCD minijets

Niemi, Eskola, Paatelainen, PRC (2015)

Also: Effective kinetic theory; 3D IP-Glasma…

The success of fluid dynamics modelling at RHIC and at the LHC: The existence of collectivity

- Viscous relativistic fluid dynamics

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + T^{\mu\nu}_{\text{diss}}; \qquad T^{\mu\nu}_{\text{ideal}} = (\varepsilon + P)u^{\mu}u^{\nu} - Pg^{\mu\nu};$$

$$T^{\mu\nu}_{\text{diss}} = \pi^{\mu\nu}(\eta) - \Delta^{\mu\nu}\Pi(\zeta) \qquad \Delta^{\mu\nu} = g^{\mu\nu} - u^{\mu}u^{\nu}$$

- To first order in the velocity gradient: Navier-Stokes
- To higher order:

Israël & Stewart, Ann. Phys. (1979);
Baier et al., JHEP (2008);
Denicol et al., PRD (2012);
Denicol et al., PRC (2014);
Jeon & Heinz, Int. J. Mod. Phys. E (2015)

η, ζ are shear and bulk viscosities

- Resistance to deformation, and to volume expansion
- A fundamental property of QCD

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One lesson from hydro: Matter behaves collectively

Calculating transport coefficients

- Kubo relation:

$$\eta = \frac{1}{20}\lim_{\omega\to 0}\frac{1}{\omega}\int d^4x\, e^{i\omega t}\langle[S^{ij}(t,\vec{x}),S^{ij}(0,\vec{0})]\rangle\theta(t)$$

$$S^{ij} = T^{ij} - \delta^{ij}P$$

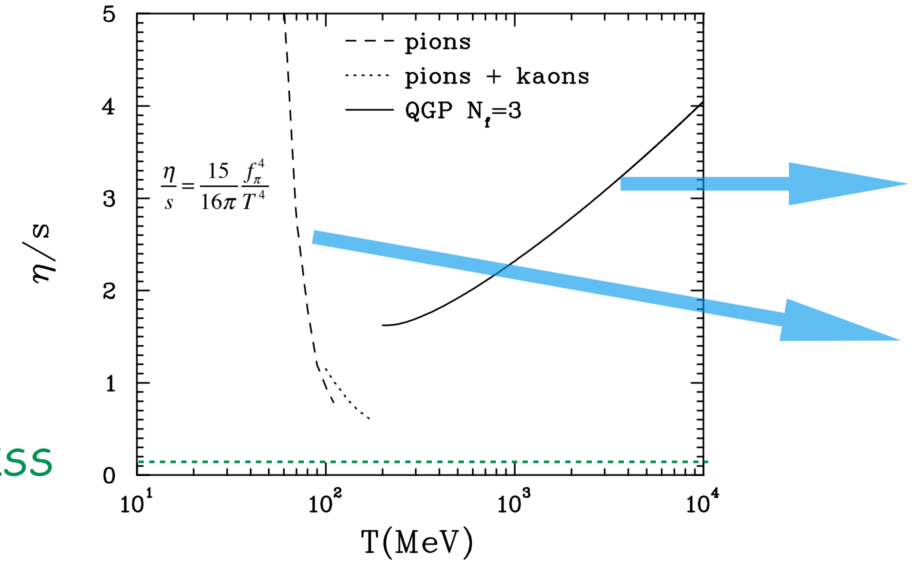
For finite-temperature QCD, can be calculated

- Perturbatively: Arnold, Moore, Yaffe JHEP (2000, 2003)
- On the lattice: H. B. Meyer PRD(2007); (2009)
  Sakai, Nakamura LAT2007
- Using FRG techniques Haas, Fister, Pawlowski PRD (2014)
  Christiansen et al., PRL (2015)
- Using Schwinger-Dyson Liu, Rapp 1612.09138
- Using strong-coupling AdS/CFT techniques:

$$\eta / s \geq \frac{1}{4\pi}$$

Policastro, Son, Starinets PRL(2001)
Kovtun, Son, Starinets (KSS) PRL(2003)

Calculating transport coefficients, II

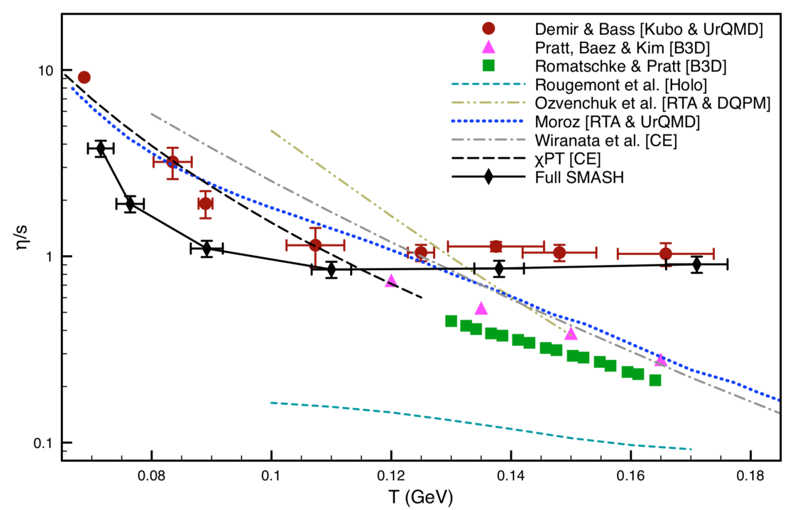


KSS

Arnold, Moore, Yaffe JHEP (2003)

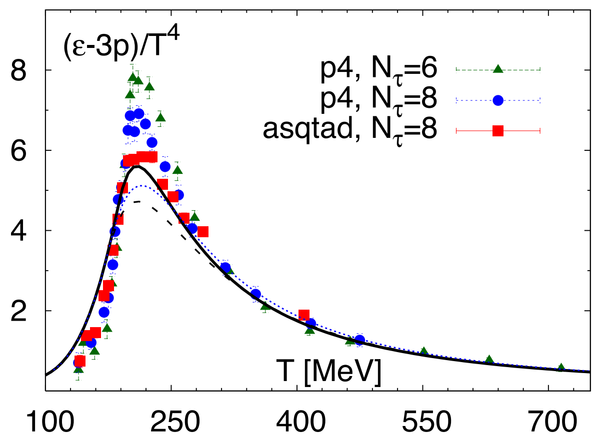
Prakash, Prakash, Venugopalan, Welke
Phys. Rep. (1993)

Csernai, Kapusta, McLerran PRL (2006)



J.-B. Rose, QM 2018

What about bulk?

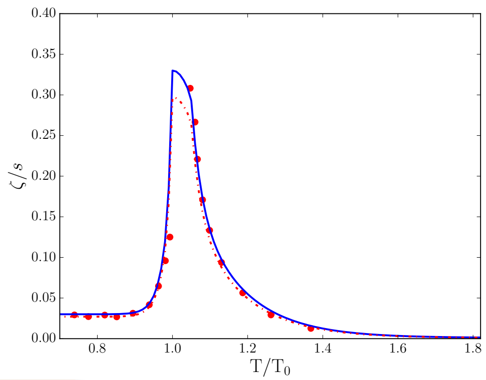


Huovinen and Petreczky, Nucl. Phys. A (2010)

- For a non-conformal fluid, the bulk viscosity is not zero
- Around, and sightly above, T_c, the bulk viscosity will matter

Kharzeev, Tuchin PLB (2007); JHEP (2008)
Czajka et al., PRC 2018

$$T^{\mu\nu} = -Pg^{\mu\nu} + \omega u^{\mu} u^{\nu} + \Delta T^{\mu\nu}$$



The dissipative terms, to second order: $\Delta T^{\mu\nu} = \mathfrak{F}^{\mu\nu}[\eta, \zeta, \chi]$

- Calculations now incorporate these

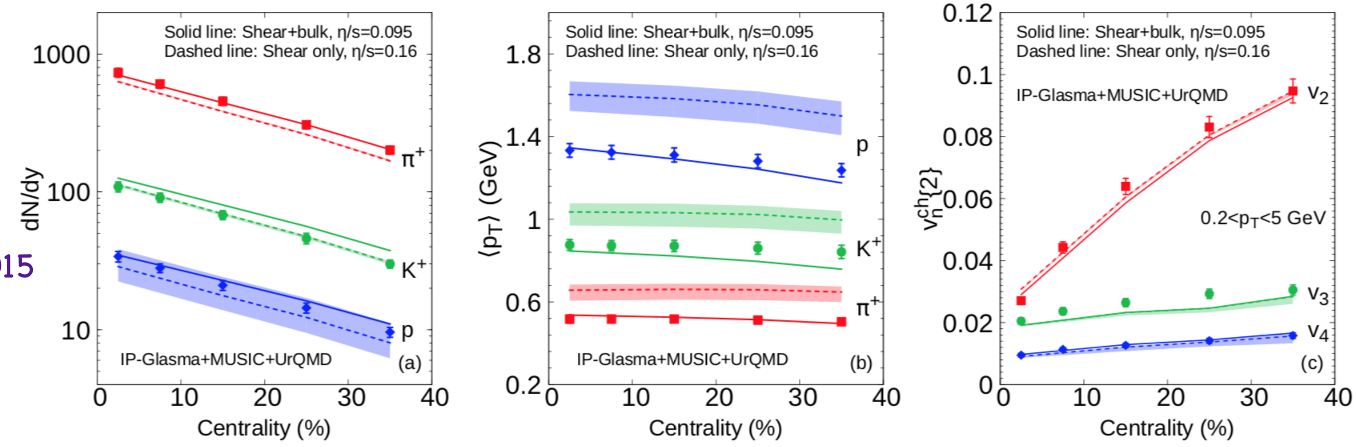
  S. Ryu et al., PRL (2015); PRC 2018; J. E. Bernhard et al., PRC (2016)

- The hydro description is still in evolution: Extract the transport coefficients from analyzing data

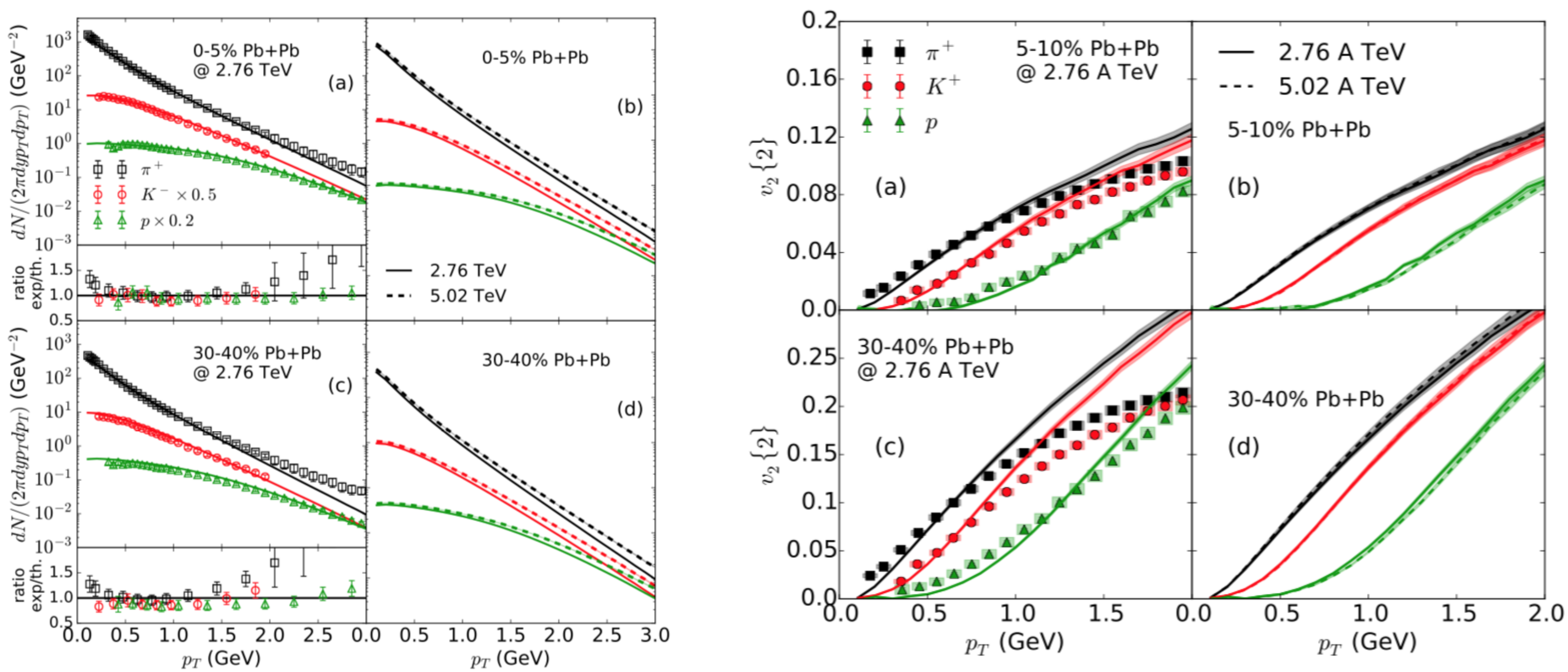
The situation with hadrons

- The bulk viscosity reduces the average p_T: it acts as a negative pressure $\Pi \sim -\zeta\theta$

S. Ryu et al., PRL 2015



S. McDonald et al., PRC 2017



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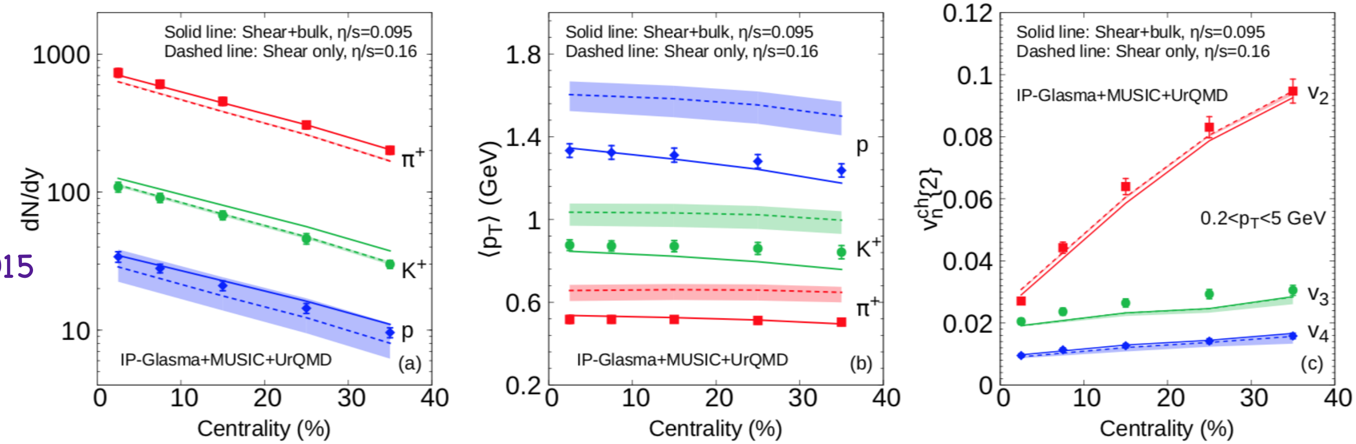
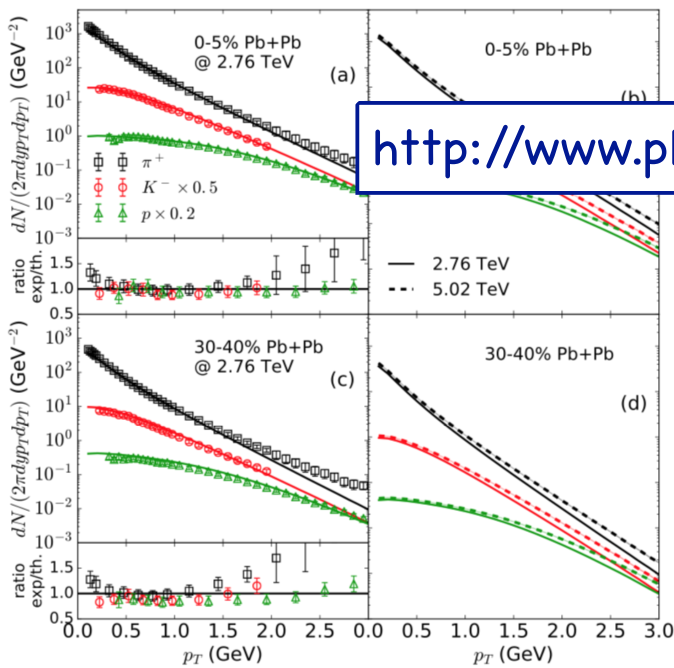
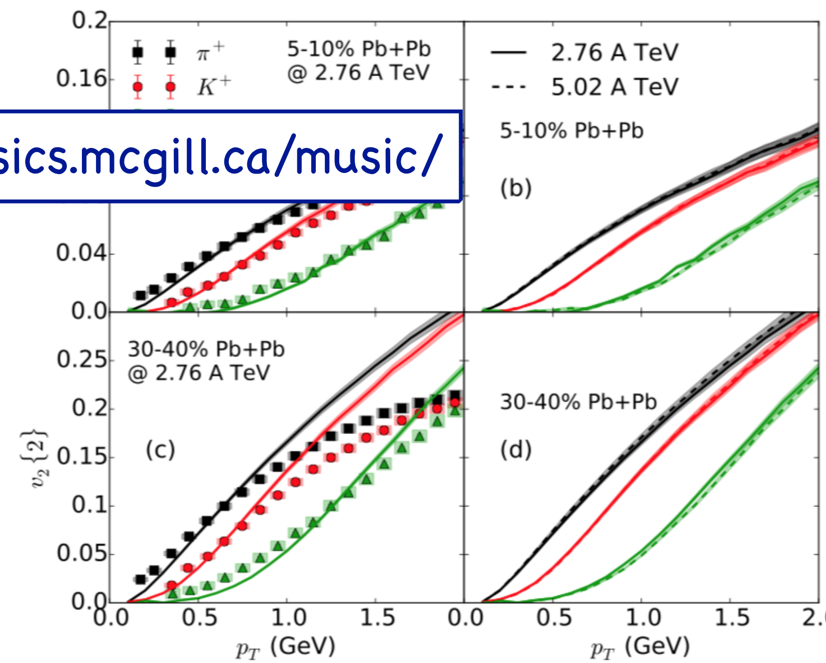


S. McDonald et al., PRC 2017

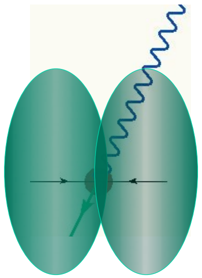


http://www.physics.mcgill.ca/music/

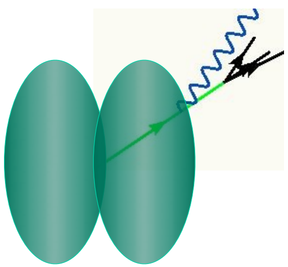


DIRECT PHOTONS

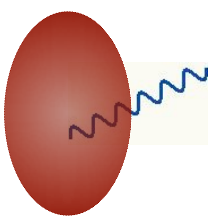
Photon Sources (real and/or virtual)



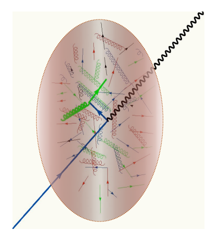
Hard direct photons. pQCD with shadowing
Non-thermal



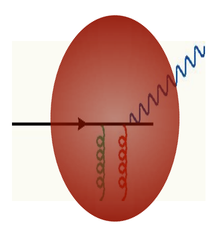
Fragmentation photons. pQCD with shadowing
Non-thermal



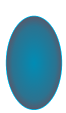
Thermal photons
"Thermal"



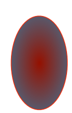
Jet-plasma photons
"Thermal"



Jet in-medium bremsstrahlung
"Thermal"



Pre-hydro?



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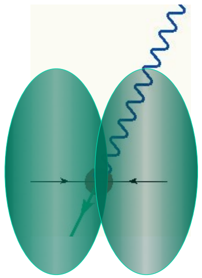
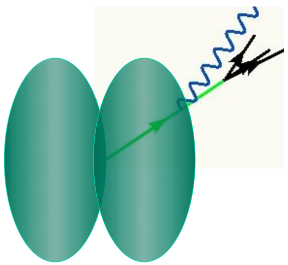
DIRECT PHOTONS

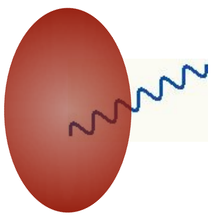
Photon Sources (real and/or virtual)



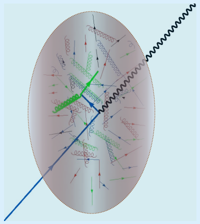
Hard direct photons. pQCD with shadowing
Non-thermal



Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
"Thermal"



Jet-plasma photons
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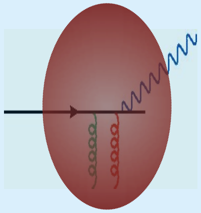

Jet in-medium bremsstrahlung
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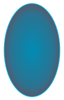
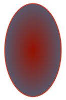


Pre-hydro?



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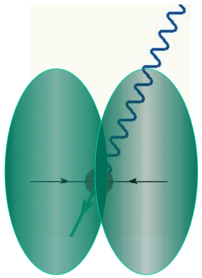
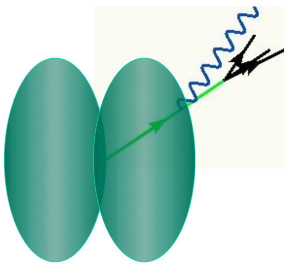
DIRECT PHOTONS

Photon Sources (real and/or virtual)



Hard direct photons. pQCD with shadowing
Non-thermal



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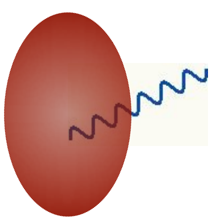
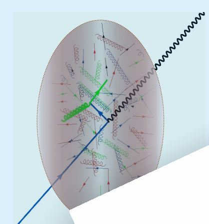
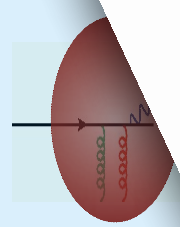


Thermal photons
"Thermal"





Pre-hydro?

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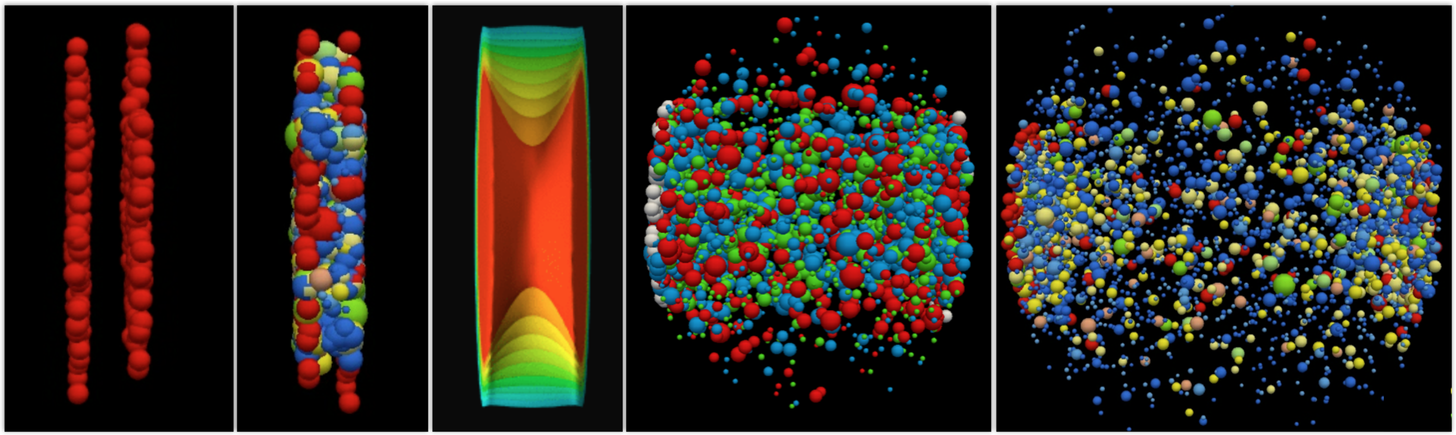
Direct photons and HIC modelling

- Unlike hadrons, photons are emitted throughout the entire space-time history of the HIC



pQCD photons
"pre-hydro" photons

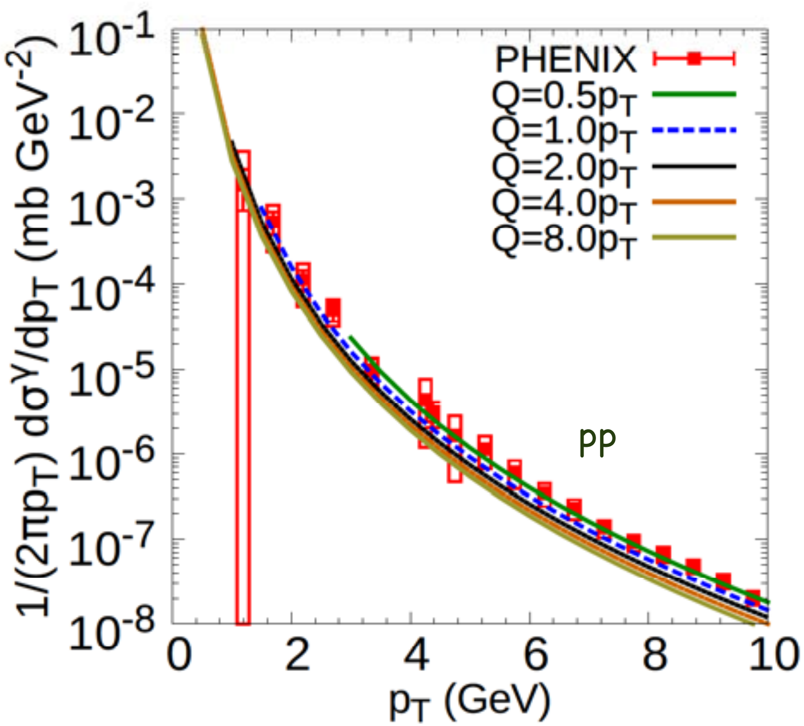
Plasma photons

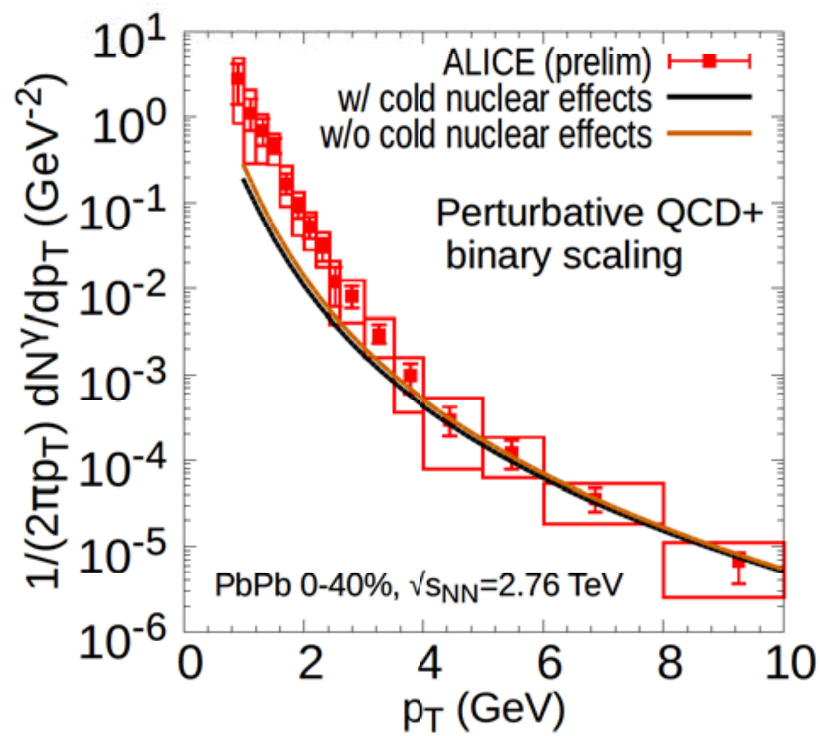
Hadronic medium photons

Decay photons
Late stage reactions

pQCD Photons

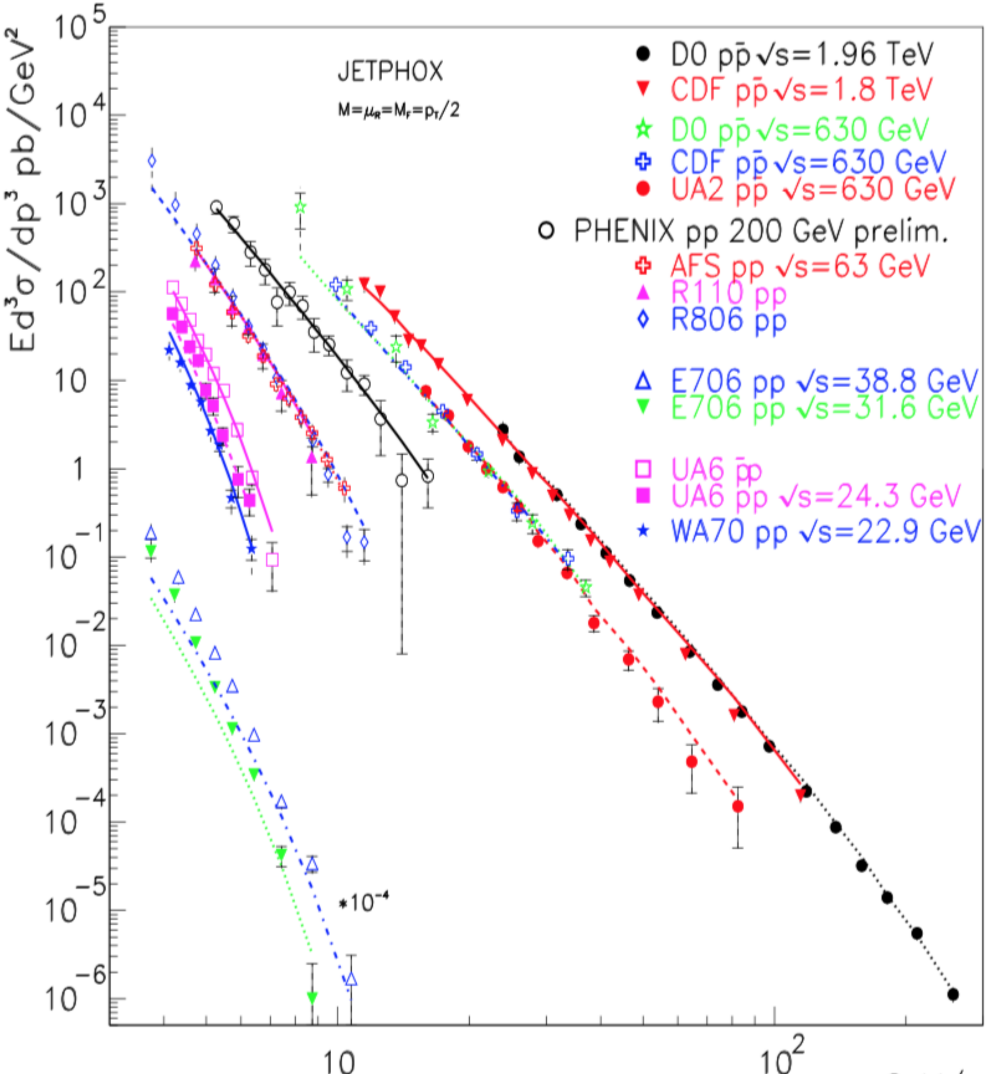
- Calculated @ NLO in pQCD
  - INCNLO, P. Aurenche et al., Eur. PJC (2000)
  - CTEQ6.1m, BFG-2, Isospin, EPS09
  - Measurement!





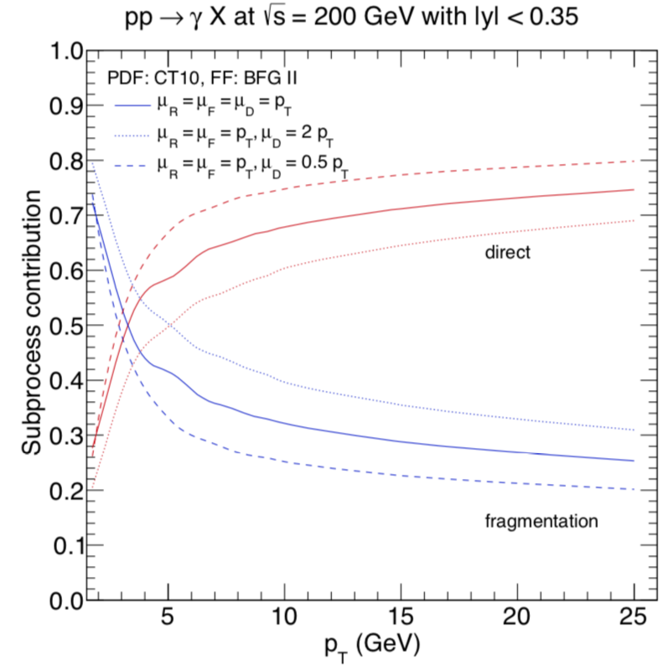
J.-F. Paquet, PhD Thesis (2015)

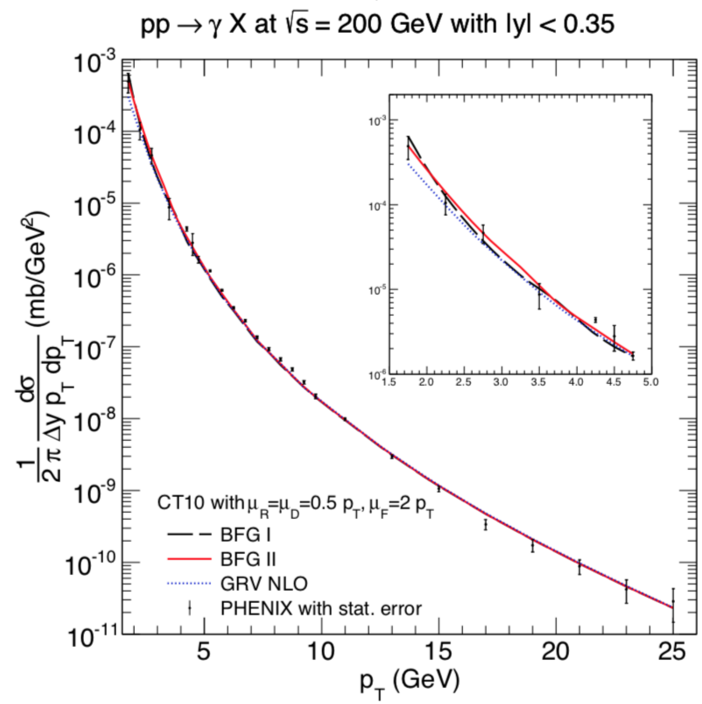
pQCD Photons



Aurenche et al., PRD (2006)

Klasen, König, Eur. PJC (2014)





Info Carried by the thermal radiation

$$dR = -\frac{g^{\mu\nu}}{2\omega}\frac{d^3k}{(2\pi)^3}\frac{1}{Z}\sum_i e^{-\beta K_i}\sum_f (2\pi)^4\delta(p_i - p_f - k)$$
$$\times\langle f | J_\mu | i\rangle\langle i | J_\nu | f\rangle$$

Thermal ensemble average of the current-current correlator

Emission rates:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(photons)}$$

$$E_+E_-\frac{d^6R}{d^3p_+d^3p_-} = \frac{2e^2}{(2\pi)^6}\frac{1}{k^4}L^{\mu\nu}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \qquad \text{(dileptons)}$$

Feinberg (76); McLerran, Toimela (85); Weldon (90); Gale, Kapusta (91)

- QGP rates have been calculated up to NLO in α_s in FTFT

  Ghiglieri et al., JHEP (2013); M. Laine JHEP (2013)

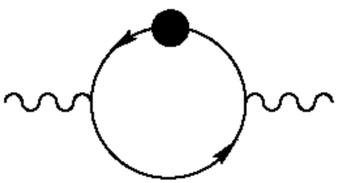
  ...and on the lattice (dileptons)

  Ding et al., PRD (2011)

- Hadronic rates C. Gale, Landolt-Bornstein (2010) Turbide, Rapp, Gale PRC (2004)

Photon rates@LO

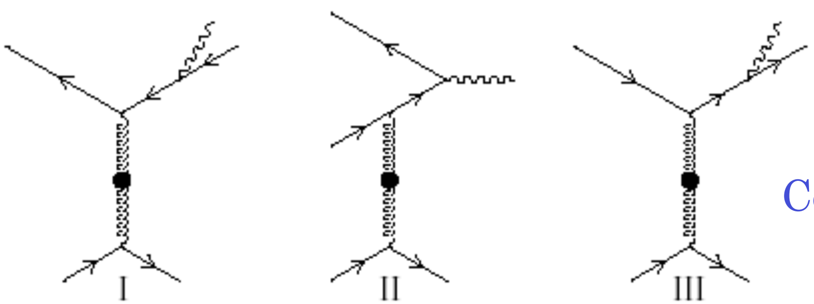
Thermal Photons from hot QCD: HTL program (Klimov (1981), Weldon (1982), Braaten & Pisarski (1990); Frenkel & Taylor (1990))



$$\mathrm{Im}\,\Pi^{\mu}_{R\ \mu} \sim \ln\left(\frac{\omega T}{m_{\mathrm{th}}^{2}}\right)$$

Kapusta, Lichard, Seibert (1991)
Baier, Nakkagawa, Niegawa, Redlich (1992)

Going to two loops: Aurenche, Kobes, Gélis, Petitgirard (1996)
Aurenche, Gélis, Kobes, Zaraket (1998)



Co-linear singularities:

$$\alpha_s^{2}\left(\frac{T^{2}}{m_{th}^{2}}\right) \sim \alpha_s$$

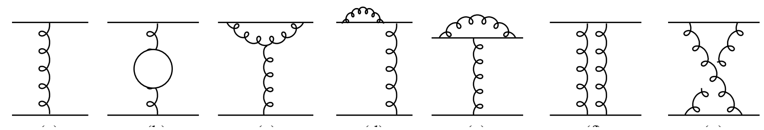
2001: Results complete at $O(\alpha_s)$

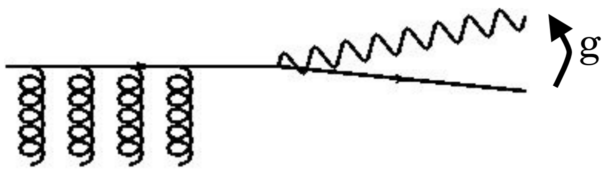
Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Photon rates@NLO

Ghiglieri, Hong, Kurkela, Lu, Moore, Teaney, JHEP (2013)

The two main contributions:

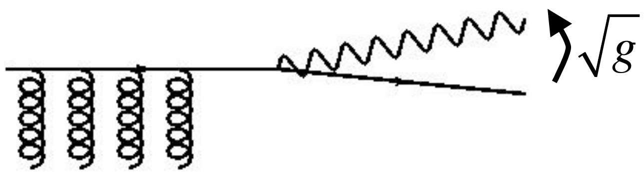




$$C(q_T)_{\mathrm{LO}} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \Rightarrow \mathrm{NLO}$$

Simon Caron-Huot PRD (2009)

Enhanced at NLO



Larger angle bremmstrahlung

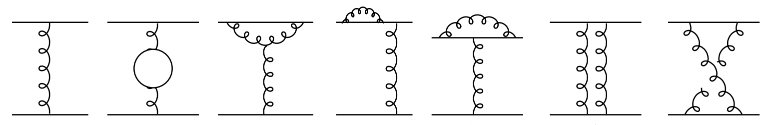
Suppressed at NLO

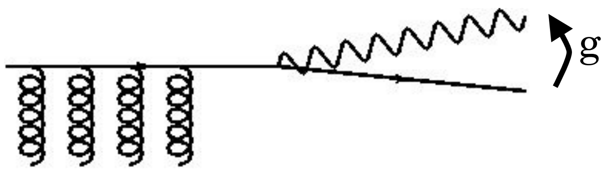
J. Ghiglieri's talk

Photon rates@NLO

Ghiglieri, Hong, Kurkela, Lu, Moore, Teaney, JHEP (2013)

The two main contributions:





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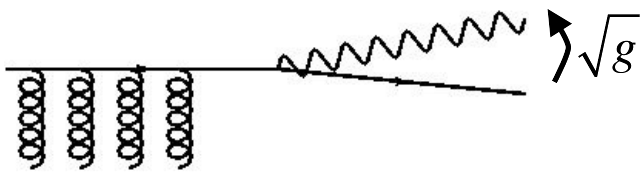
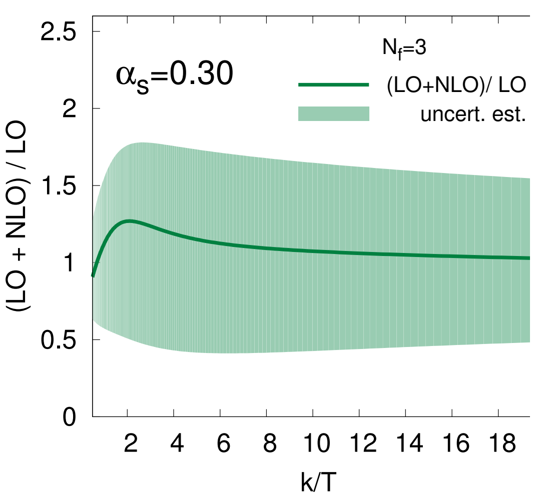
Simon Caron-Huot PRD (2009)

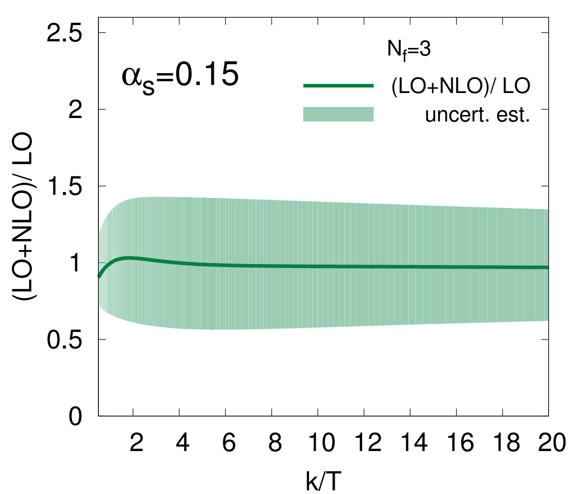
Enhanced at NLO



Larger angle bremmstrahlung

Suppressed at NLO





- Net correction to photon production rate is modest, for all k/T
- Study results consistent with those of lattice estimates:

Ghiglieri, Kaczmareck, Laine, Meyer, JHEP (2016)

J. Ghiglieri's talk

Charles Gale
McGill

Photon rates II

Thermal Photons from a hot ensemble of hadrons

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

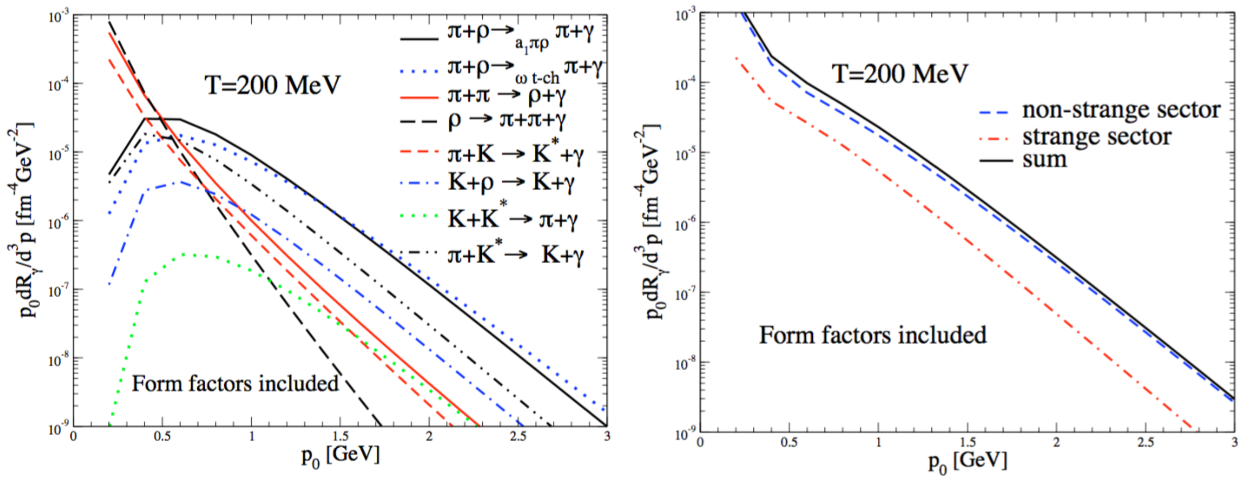
$$q_0 \frac{d^3R}{d^3q}\bigg|_{1+2\to 3+\gamma} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1) f(E_2)\left[1 \pm f(E_3)\right]}{2(2\pi)^3}$$

Consider all the reaction and radiative decay channels of combinations of:

$\{\pi, K, \rho, \omega, K^*, a_1\}$ With hadronic form factors

Chiral, Massive Yang-Mills:

- O. Kaymakcalan, S. Rajeev, J. Schechter, PRD 30, 594 (1984)
- Ulf G. Meissner, Phys. Rept. 161, 213 (1988)



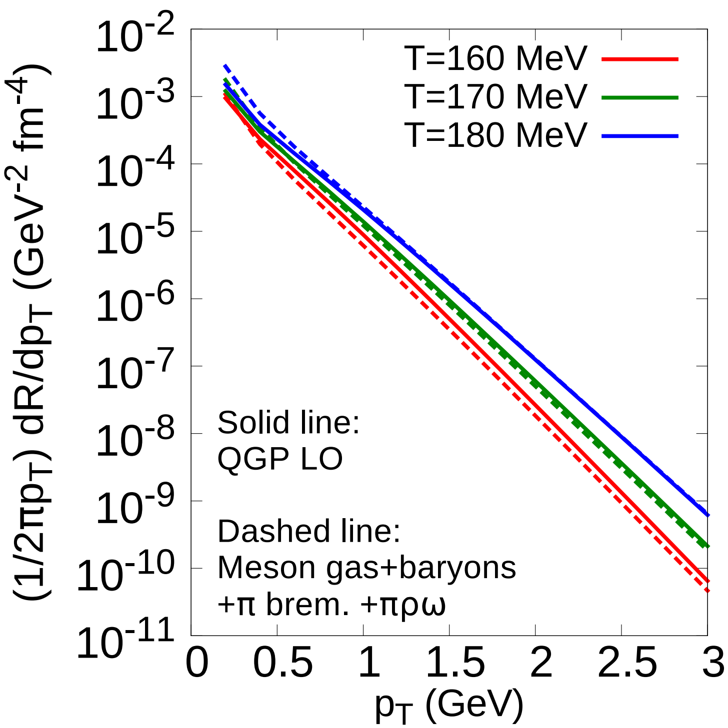
Turbide, Rapp, Gale, PRC (2004) ; S. Turbide, PhD Thesis (2006)

Parameters and form factors are constrained by hadronic phenomenology:

- Masses & strong decay widths
- Electromagnetic decay widths
- Photoabsorption data
- Others: e.g. $a_1 \to \pi + \rho$

- All reactions combining light and intermediate mass mesons and baryons
- $\pi\pi$ and πK bremsstrahlung   Heffernan, Hohler, Rapp, PRC (2015)

Comparing the rates:



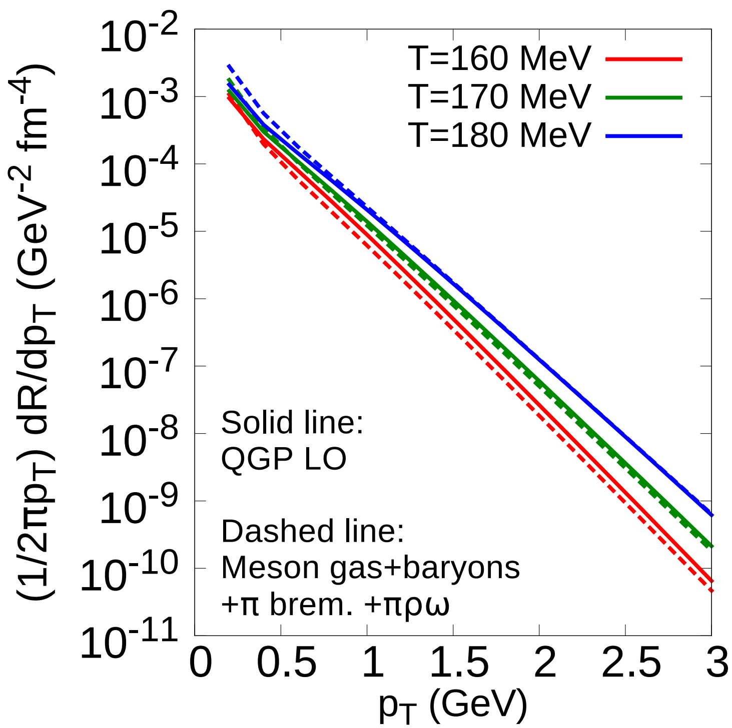
J.-F. Paquet et al., PRC (2016)

Then:

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X E\frac{d^3\Gamma}{d\mathbf{k}}(K\cdot u(X), T(X))$$

- All reactions combining light and intermediate mass mesons and baryons
- $\pi\pi$ and πK bremsstrahlung   Heffernan, Hohler, Rapp, PRC (2015)

Comparing the rates:



J.-F. Paquet et al., PRC (2016)

Then:

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X E\frac{d^3\Gamma}{d\mathbf{k}}(K\cdot u(X), T(X))$$

⚠ Viscosity??

Charles Gale
McGill

Where we are with "viscous photon" rates (no NLO):

SOME BOXES ARE (STILL) EMPTY

Rate/viscous correction	Ideal	I+Shear	I+S+Bulk
QGP: 2->2	AMY (2001)	Shen et al., PRC (2015)	• Paquet et al., PRC (2016) • Hauksson, Jeon, Gale (2017)
QGP: LPM-Brem.	AMY (2001)		Hauksson, Jeon, Gale (2017)
Hadronic: Meson reactions	• Turbide et al. , PRC (2004) • van Hees et al., PRC (2011)	• Dion et al., PRC (2011) • Paquet et al., PRC (2016)	Paquet etal., PRC (2016)
Hadronic: Meson-Meson Brem.	• Liu et al., NPA (2007) • Linnyk et al., PRC (2015)		
Hadronic: Baryons	• Rapp et al., ANP (2000) • Turbide et al., PRC (2004) • Paquet et al., PRC (2016)		

(An incomplete reference list)

Calculating with a system out of equilibrium

In-medium **hadrons**:

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3} \frac{1}{\exp[(u^\mu p_\mu - \mu)/T] \pm 1}$$

$$f \to f_0 + \delta f, \quad \delta f = f_0(1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

$$q_0 \frac{d^3R}{d^3q} = \int \frac{d^3p_1}{2(2\pi)^3 E_1} \frac{d^3p_2}{2(2\pi)^3 E_2} \frac{d^3p_3}{2(2\pi)^3 E_3} (2\pi)^4 |M|^2 \delta^4(\ldots) \frac{f(E_1) f(E_2) [1 \pm f(E_3)]}{2(2\pi)^3}$$

Photons:

- Recalculate all the rates
- Integrate rates with viscous hydro

$$E\frac{d^3N}{d\mathbf{k}} = \int d^4X E \frac{d^3\Gamma}{d\mathbf{k}}(K^\mu, u^\mu(X), T(X), \pi^{\mu\nu}(X), \Pi(X))$$

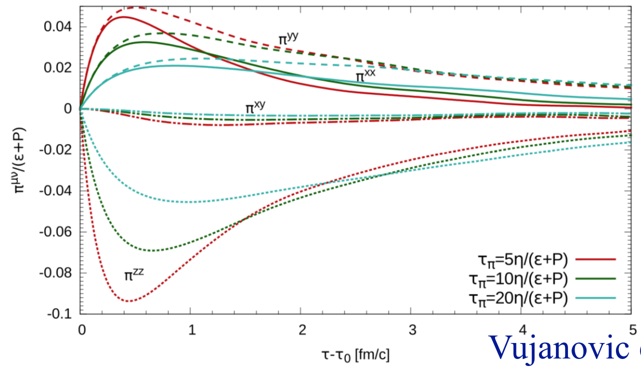
M. Dion, MSc thesis (2011), Dion et al., PRC (2011);
Shen et al., PRC (2014), Paquet et al., (2016)

"Viscous photons"

Can't directly compare rates with and without viscous corrections

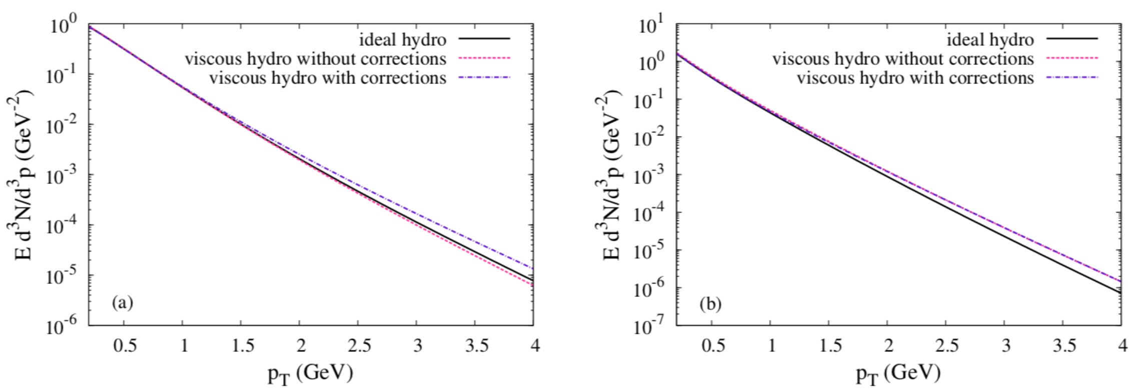
Shear

$$f \to f_0 + \delta f, \quad \delta f = f_0(1 \pm (2\pi)^3 f_0) p^\alpha p^\beta \pi_{\alpha\beta} \frac{1}{2(\varepsilon + P)T^2}$$

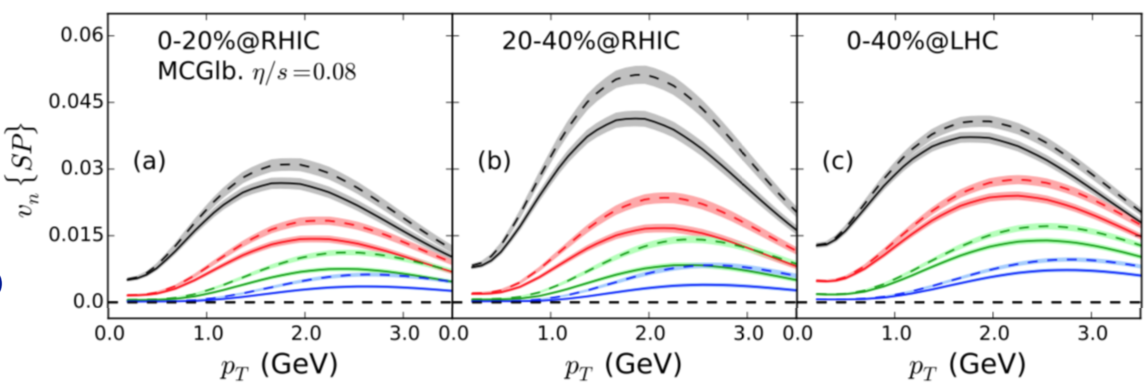


Vujanovic et al., PRC (2015)

Dion et al., PRC (2011)



Shen et al., PRC (2015)



Au+Au (RHIC)
Pb+Pb (LHC, 2.76TeV/A)

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McGill

"Viscous photons" (II)

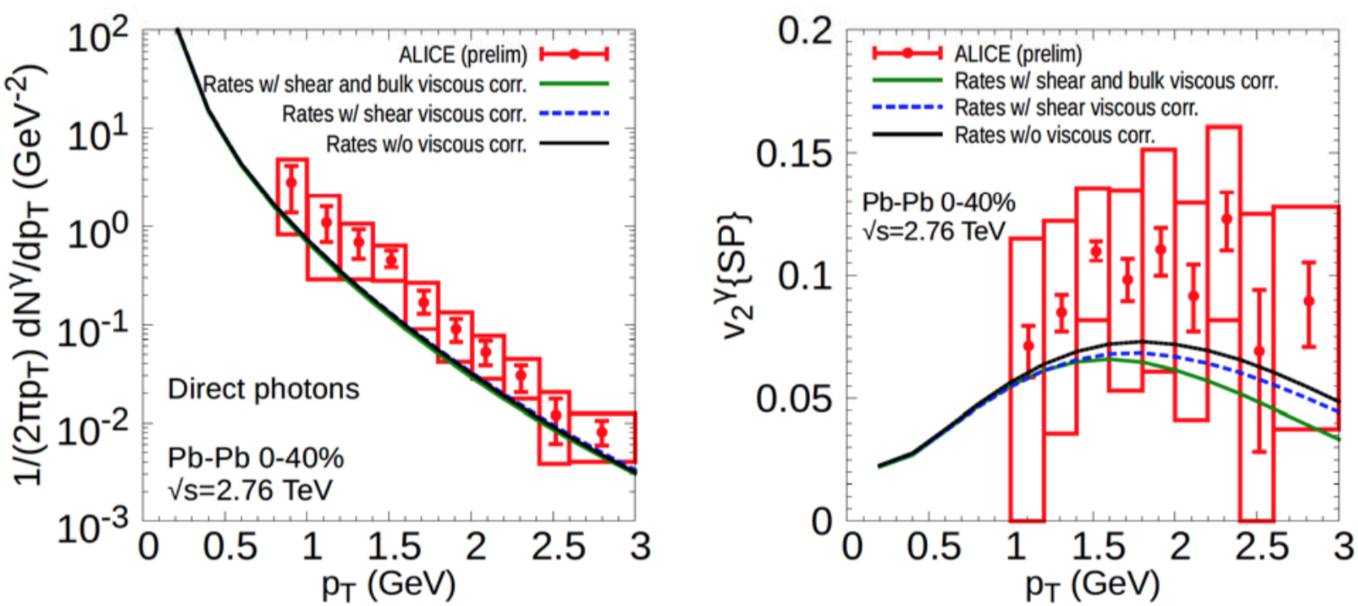
Bulk

$$\delta f_i = -\frac{\Pi}{T\hat{\zeta}}\left(f_{0i}\tilde{f}_{0i}\right)\left[\left(c_s^2 - \frac{1}{3}\right)E_i + \frac{m_i^2}{3E_i}\right]$$

$$\hat{\zeta} = \frac{1}{3T}\sum_i^N \int dK_i\, m_i^2\, g_i f_{0i}\tilde{f}_{0i}\left[\left(c_s^2 - \frac{1}{3}\right)E_i + \frac{m_i^2}{2E_i}\right]$$

(Massive hadrons)

Paquet et al., PRC (2011)
Czajka et al., PRC (2018)



J-.F. Paquet, PhD thesis (2015)

ECT*

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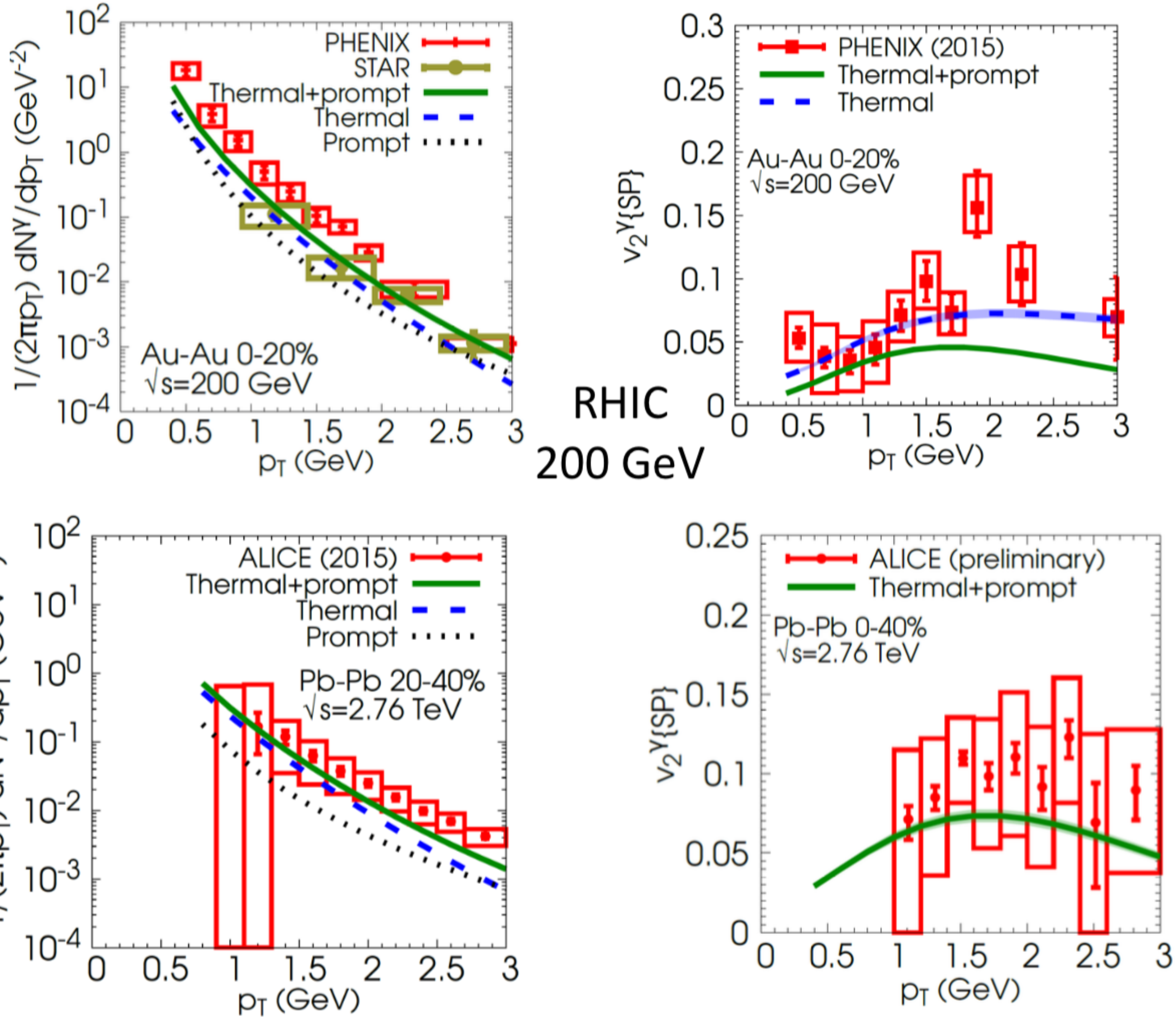
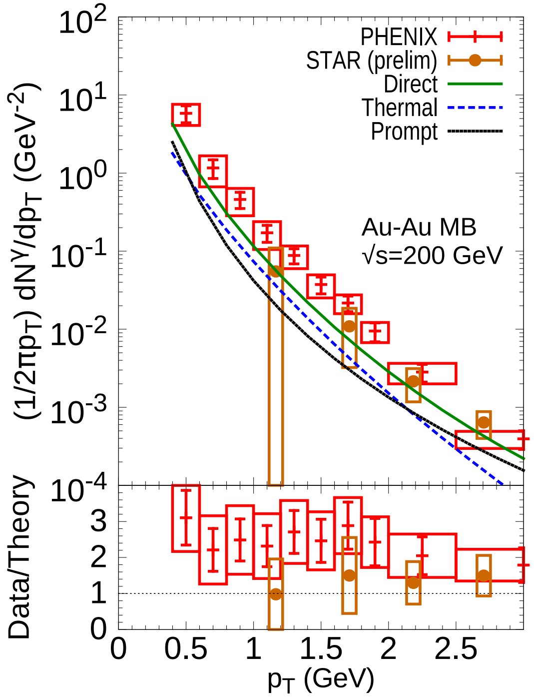
Update: Yields & Flow

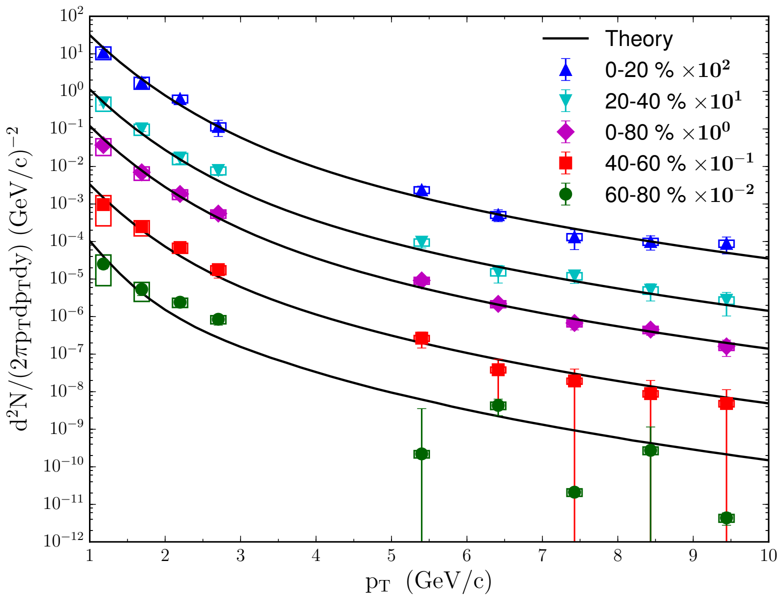


LHC 2760 GeV

Paquet, Shen, McDonald, Jeon, Gale, in preparation

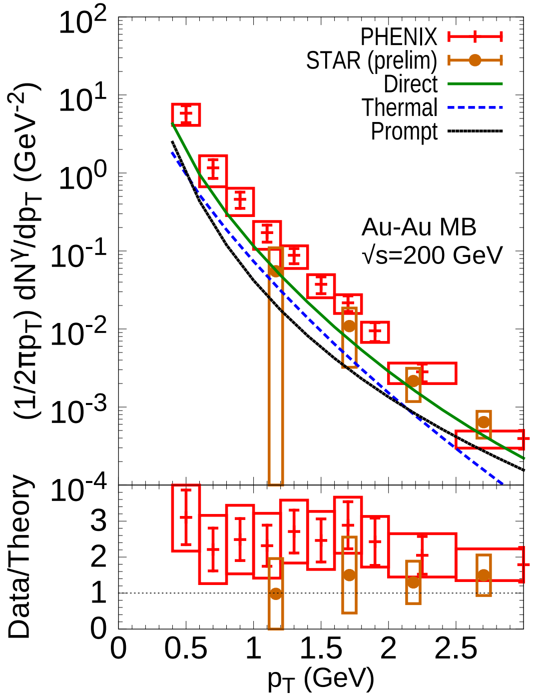
Photon summary II
STAR

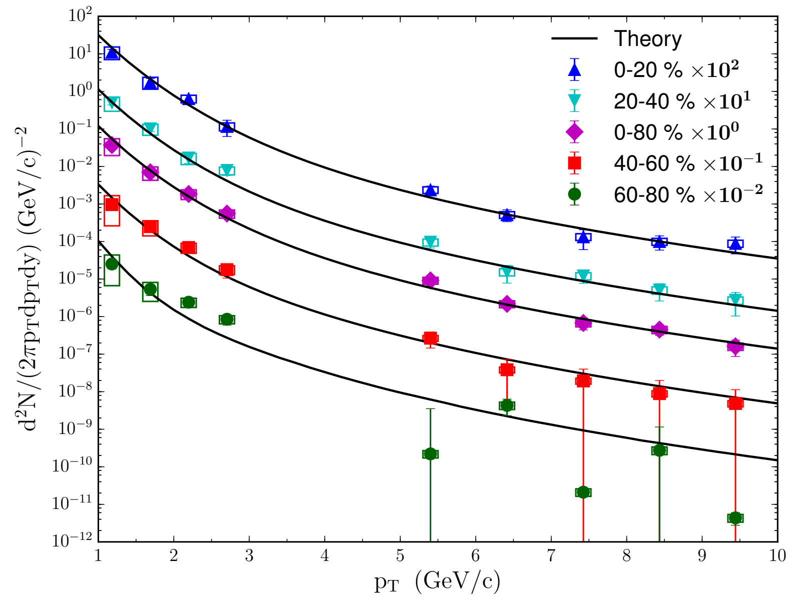




STAR arXiv:1607.01447

PHOTON SUMMARY II
STAR

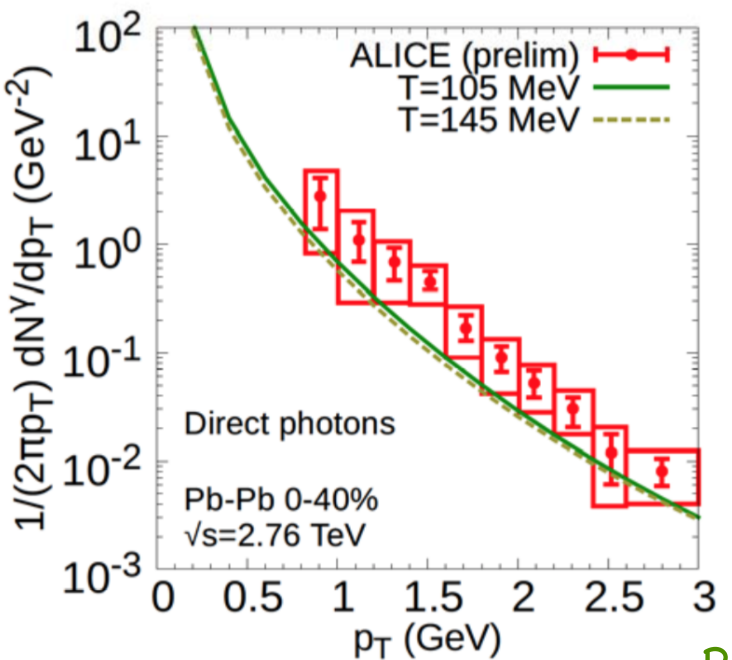


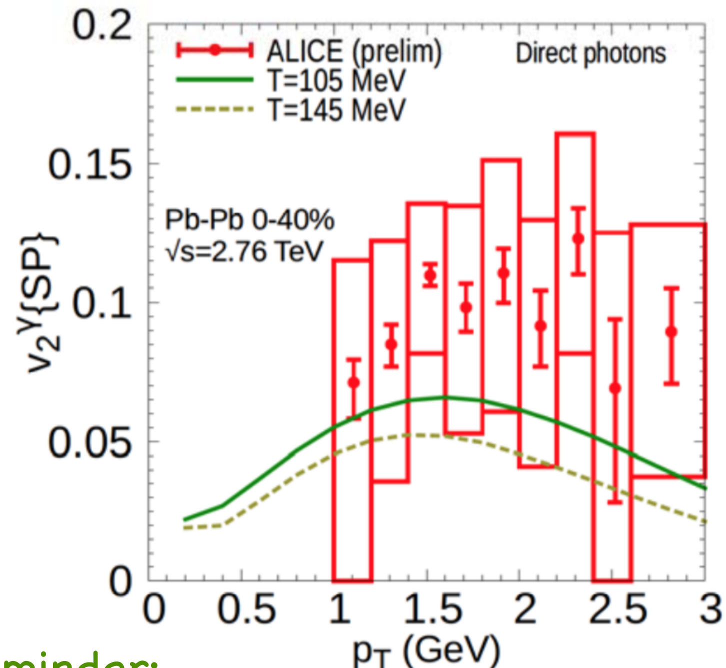


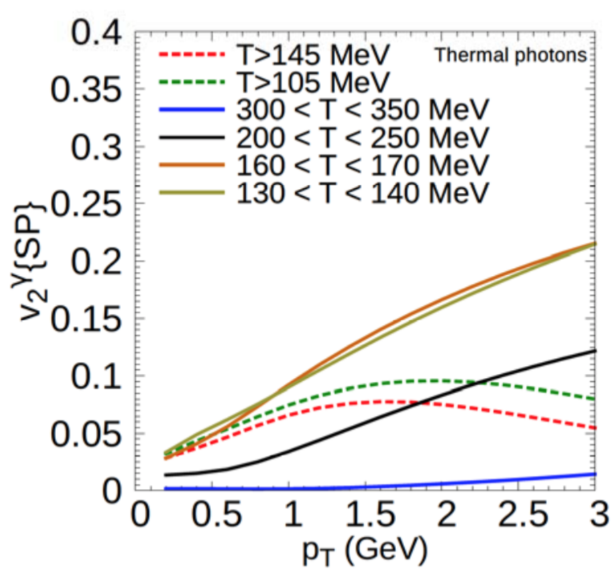
STAR arXiv:1607.01447

- MB: STAR 0-80%, PHENIX 0-92%
- Manifest tension between STAR and PHENIX photon data
- STAR yield and calculation in good (better) agreement

Analyzing the yields and flow







Reminder:

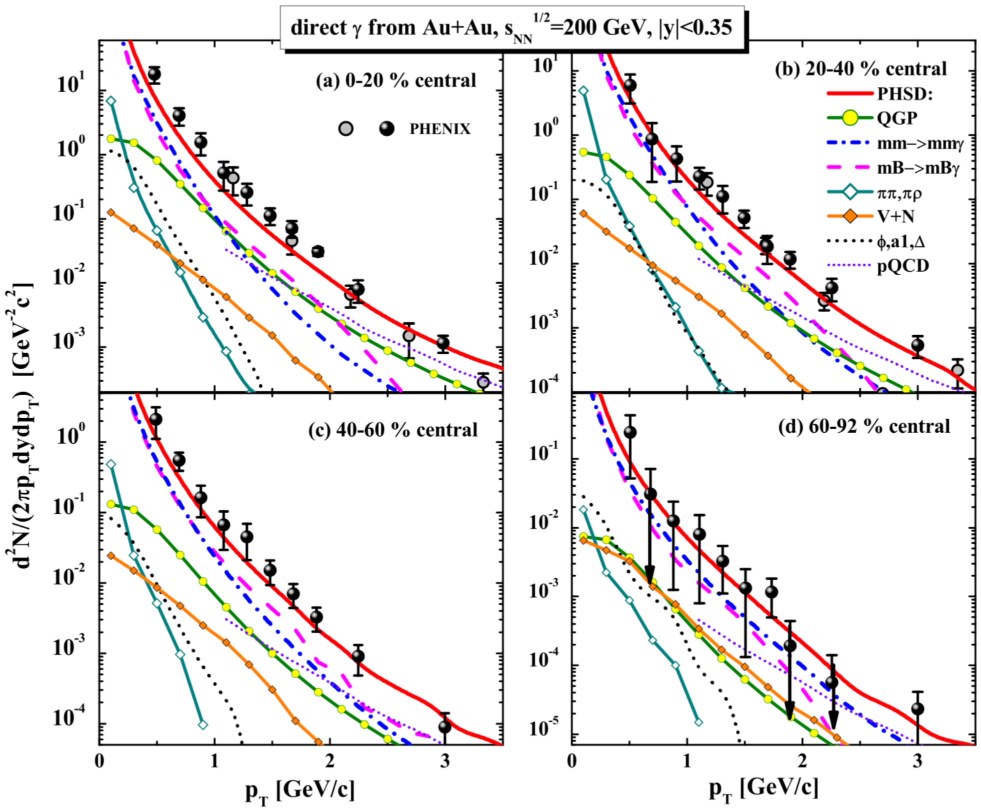
- No jet-medium photons
- No in-medium jet fragmentation photons
- A consistent treatment of viscous effects on LPM photons is missing (see later)
- Photons from final hadronic stage [See A. Schaefer's talk]

Applications:

- Photon tomography: Temperature/early-time dynamics

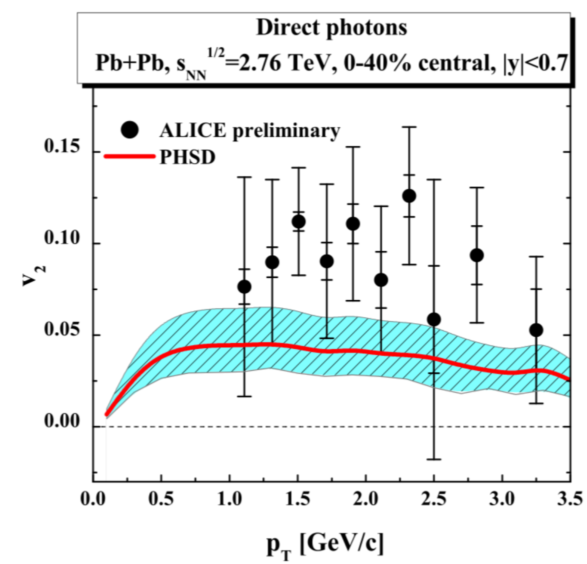
Charles Gale
McGill

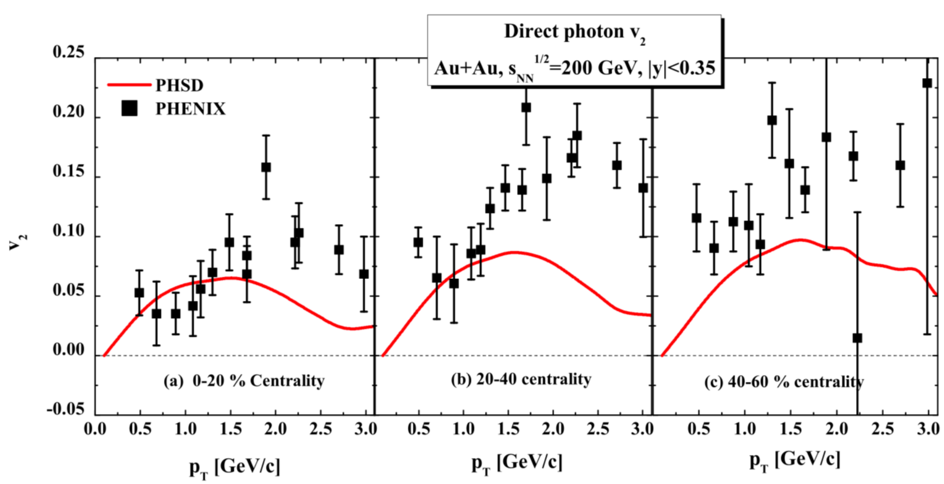
The "pre-hydro" photons?



PHSD

- The contribution of equilibrium vs. non-equilibrium stages?
- Fugacities





W. Cassing's talk

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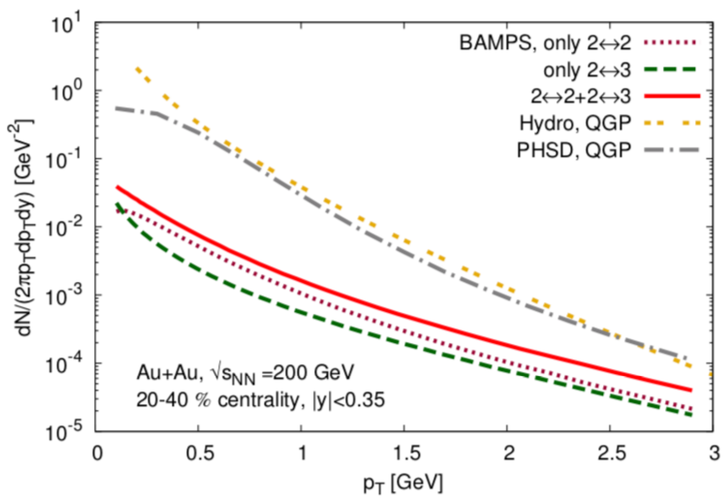
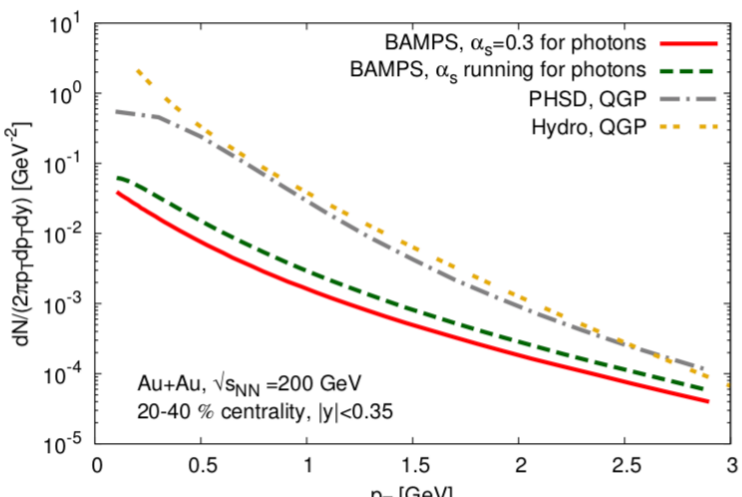
McGill

The pre-hydro photons?

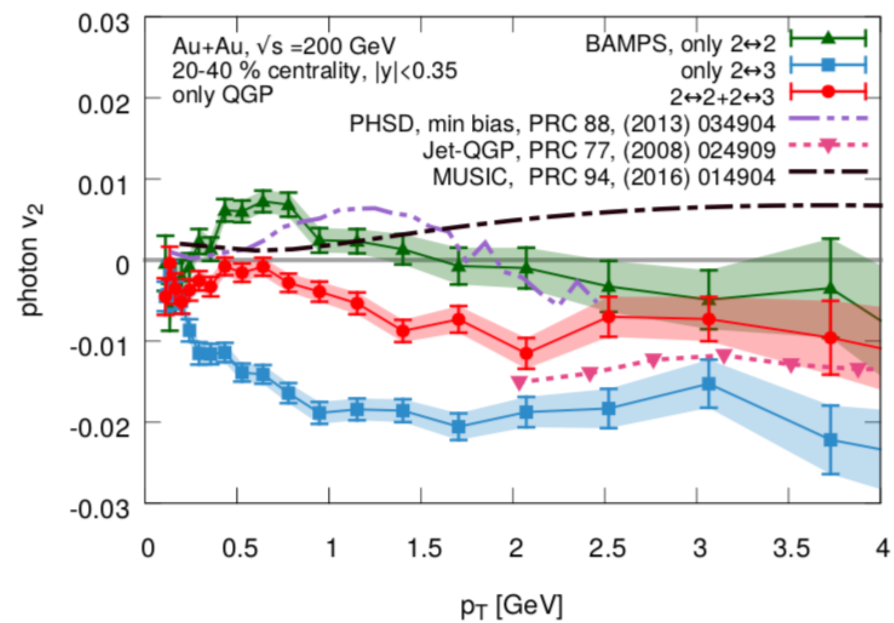
BAMPS

$$k^{\mu}\partial_{\mu}f^{i}=C^{2\to 2}\left[f\right]+C^{2\leftrightarrow 3}\left[f\right]$$





- Compton, $q\bar{q}$
- Brem/LPM (added)

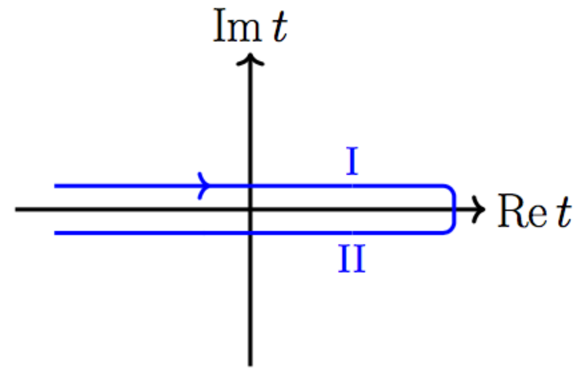


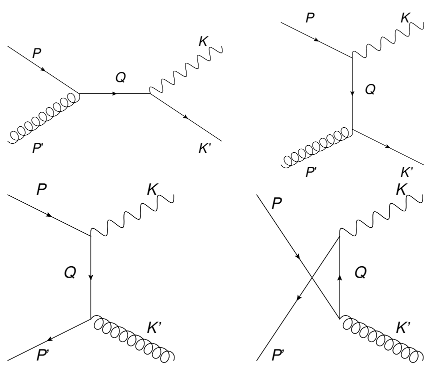
Pre-hydro radiation: intriguing results

M. Greif's talk

Calculating photon rates complete at LO, for a system out of equilibrium (I)

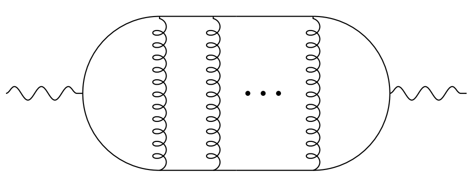
$$\omega \frac{d^3R}{d^3k} = \frac{i}{2(2\pi)^3} (\Pi_{12})^{\mu}{}_{\mu}$$





$2 \rightarrow 2$

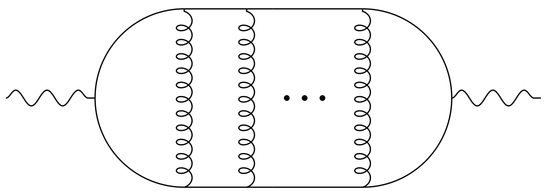
Schenke, Strickland, PRD (2007)
Shen et al., PRC (2015)



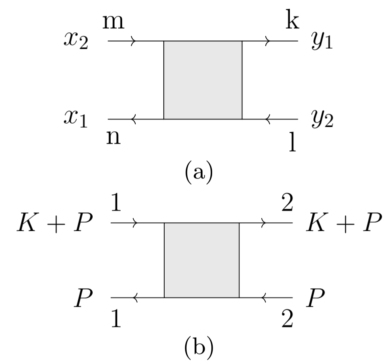
Landau-Pomeranchuk-Migdal

c.f. Majumder, Gale PRC 2002

Calculating photon rates complete at LO, for a system out of equilibrium (II)



$\rightarrow$

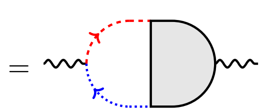


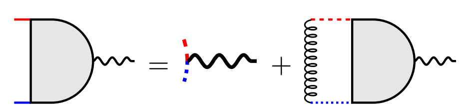
Multiple insertions of 4-point functions

$$S_{1122}(x_1,x_2;y_1,y_2) = \langle T_c\{\bar{\psi}_1(x_1)\psi_1(x_2)\bar{\psi}_2(y_1)\psi_2(y_2)\}\rangle$$

Using the r/a basis $\quad \phi_r = \frac{1}{2}(\phi_1+\phi_2), \quad \phi_a = \phi_1 - \phi_2,$

One can derive expression for hard quark and soft gluon propagators, to leading order, and construct the self-energy





Without using the KMS condition $G_{12}(Q) = -e^{-\beta Q^0} G_{21}(Q)$

Hauksson, Jeon, Gale, PRC 2017

Photons from a medium out of equilibrium

$$\omega \frac{dR}{d^3k} \sim \int_{\mathbf{p}_\perp} [\ldots]\, \mathbf{p}_\perp \cdot \mathrm{Re}\,\mathbf{f}(\mathbf{p}_\perp)$$

Obtain a Boltzmann-like equation:

$$\mathbf{p}_\perp = i\delta E\, \mathbf{f}(\mathbf{p}_\perp) + \int_{\mathbf{q}_\perp} \mathcal{C}(\mathbf{q}_\perp)[\mathbf{f}(\mathbf{q}_\perp) - \mathbf{f}(\mathbf{q}_\perp + \mathbf{p}_\perp)]$$

- Solve numerically for **f** by a functional expansion
- C is a scattering kernel
- No reliance on the KMS condition
- Perturbative treatment
- In the appropriate limit, same result as AMY kinetic theory
- Formalism can be applied to jet-medium interaction at finite temperature
- ...work in progress; more to come...

S. Hauksson's talk

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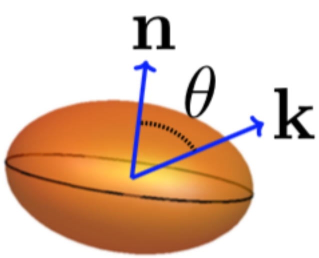
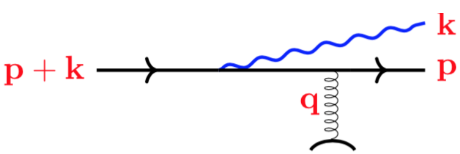
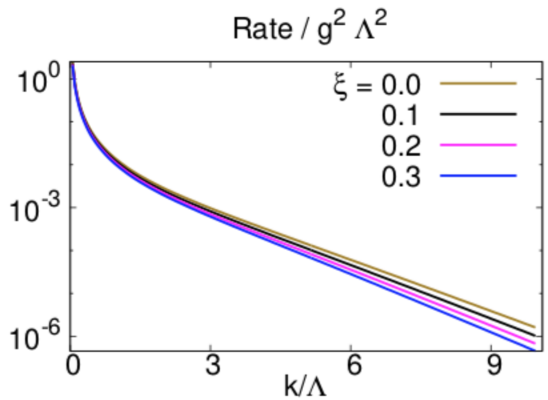
(preliminary) Exploration of the phenomenology

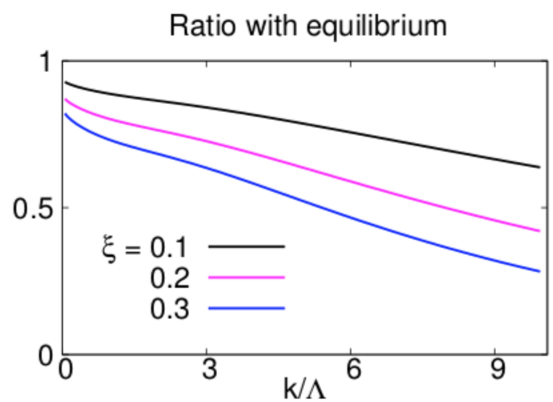
Assume $f(\mathbf{p}) \sim f_{\mathrm{eq}}(\sqrt{\mathbf{p}^2 + \xi(\mathbf{p}\cdot\mathbf{n})^2} / \Lambda)$

$\theta = 0^\circ$





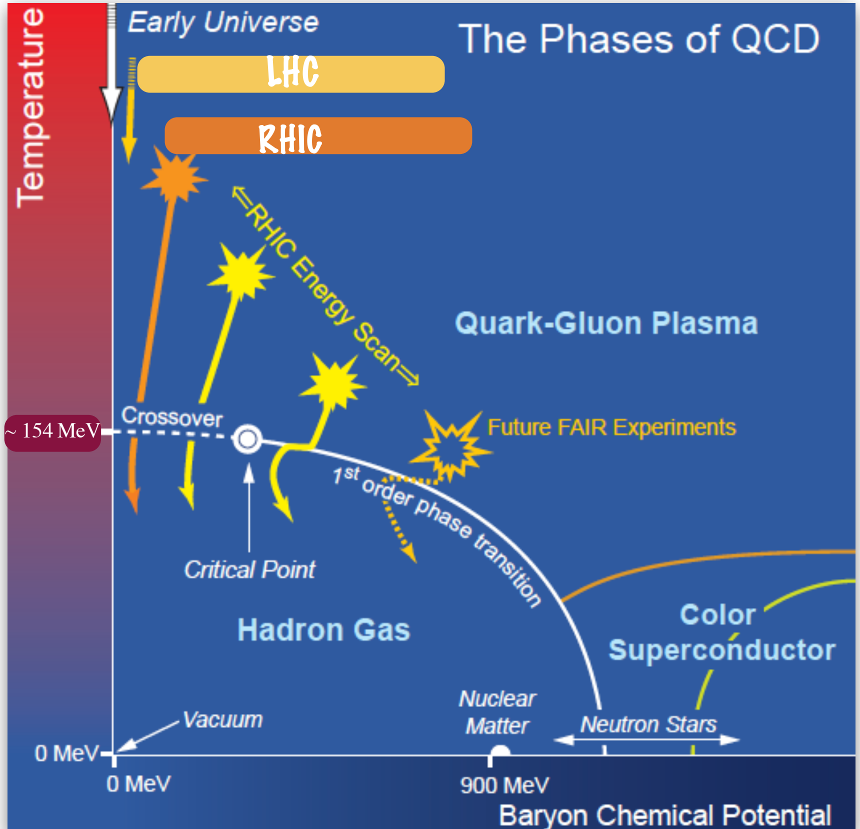




$$G_{rr} \sim \frac{1}{p^0 - i\Gamma} \rightarrow \frac{1}{p^0 - i\Gamma}(1 - e^{ip^0 t} e^{\Gamma t})$$

- Less interactions with soft gluon exchanges
- Leads to a path-dependent photon emission rate: effect on photon flow

Photons from lower energy heavy-ion collisions?



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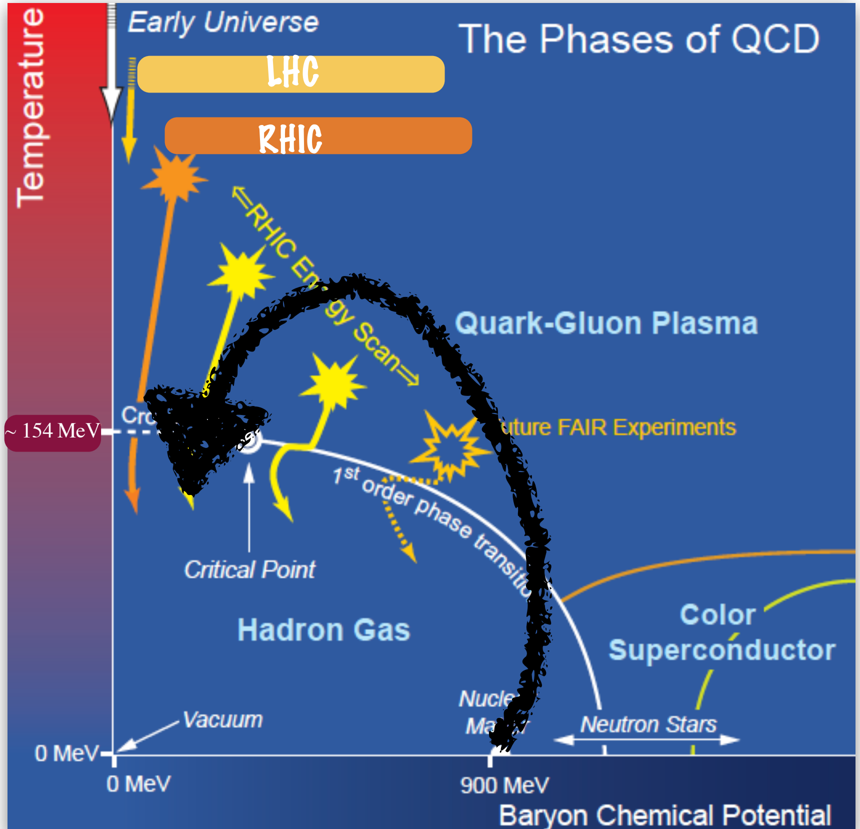
Photons from lower energy heavy-ion collisions?



Using photons to explore collision dynamics at low energies/high baryon density

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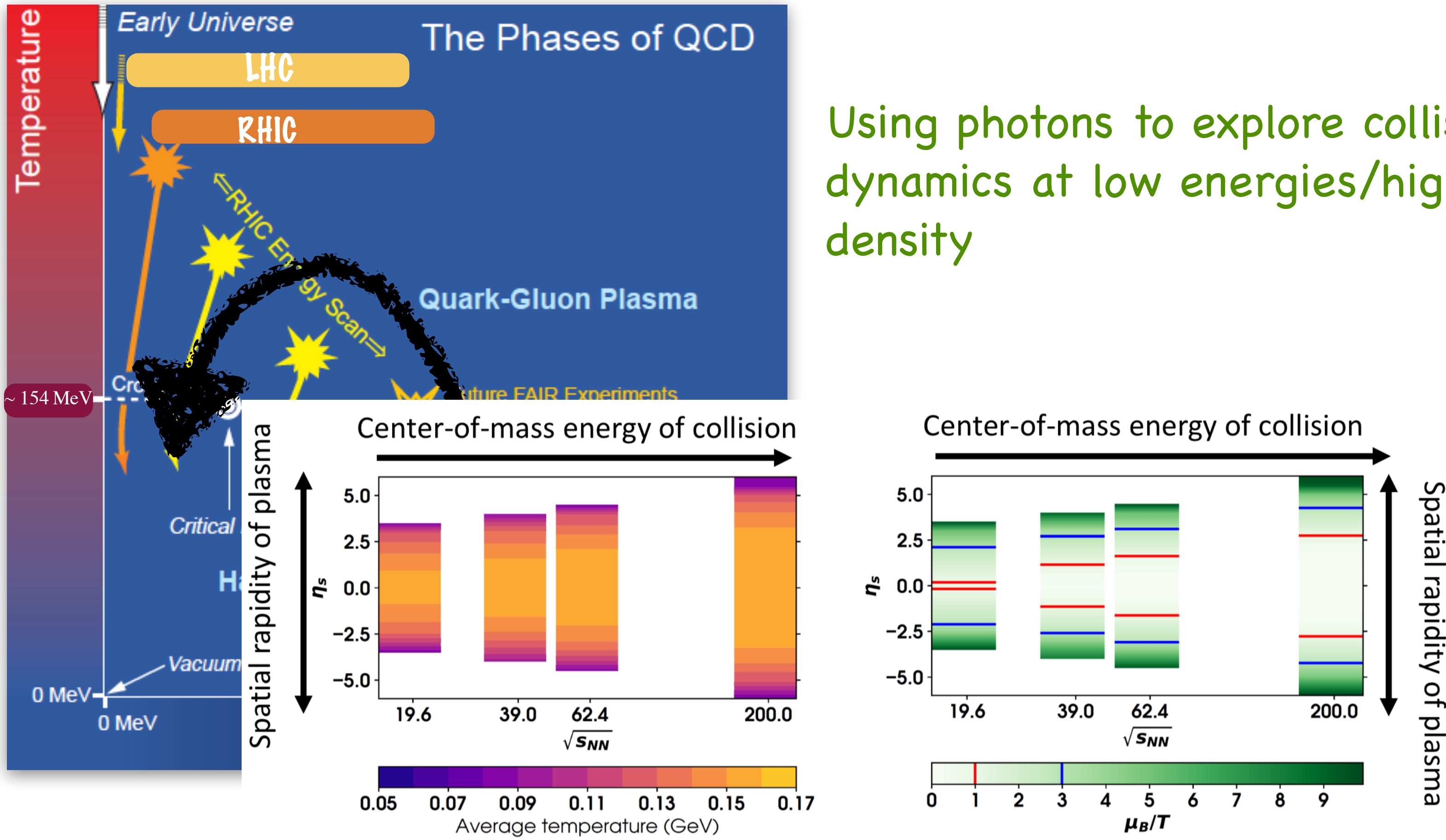
Photons from lower energy heavy-ion collisions?

Using photons to explore collision dynamics at low energies/high baryon density



Temperature averaged over the plasma's lifetime

(depend on freeze-out energy density)

Baryon chemical potential to temperature ratio

(markers at μ_B/T=1 and μ_B/T= 3 to guide the eye)

J.-F. Paquet et al., in preparation

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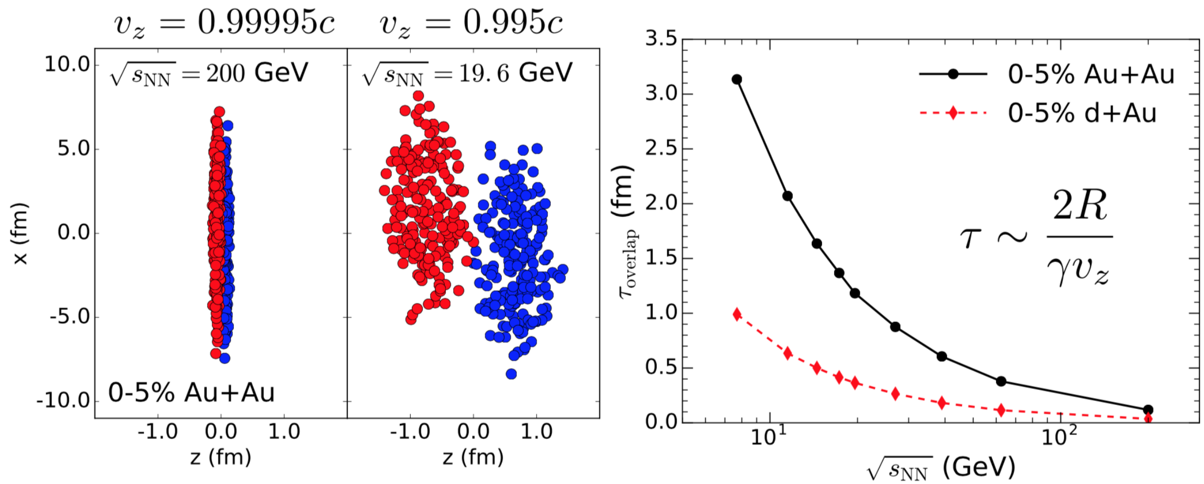
Hadronic dynamics at lower energies



Shen and Schenke, 1710.00881

Dynamical initialization Algorithm:

- Each pair of colliding nucleons is identified
- A string connects them
- The string ends are decelerated through some (phenomenological) algorithm
- The deceleration dictates the energy assigned to the string profile
- The energy is fed into the hydro source term
- The baryon density associated with the string ends is fed into the baryonic density

Hadronic dynamics at lower energies

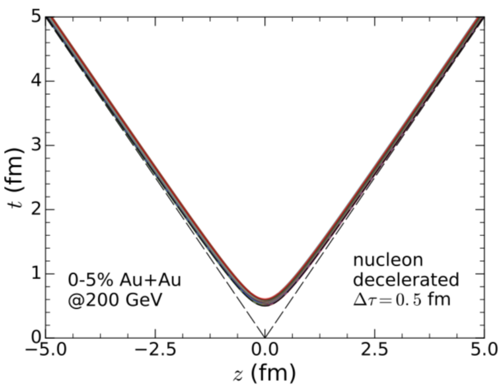
- Dynamical initial state
- 3D hydro with baryon current
- Finite baryon density EOS

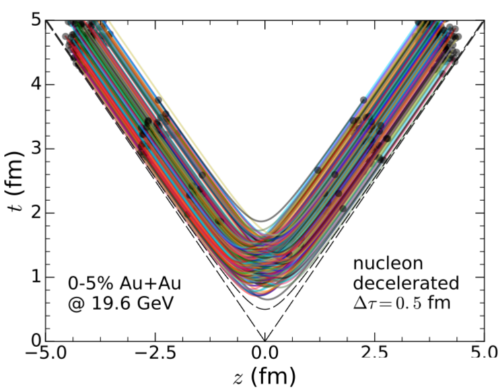
$$\partial_\mu T^{\mu\nu} = S^\nu$$

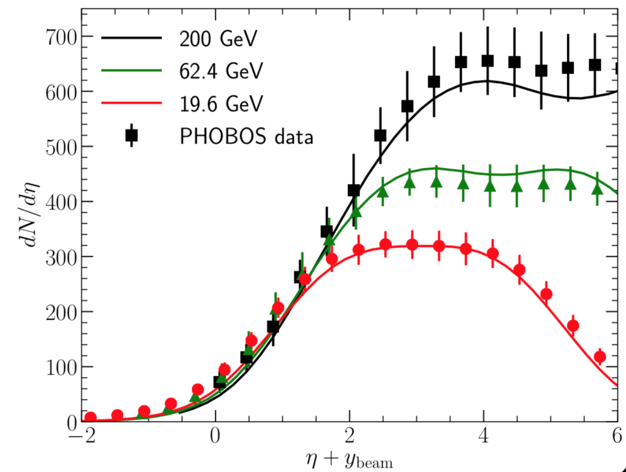
$$\partial_\mu J^\mu_{\rm B} = \rho_{\rm B}$$

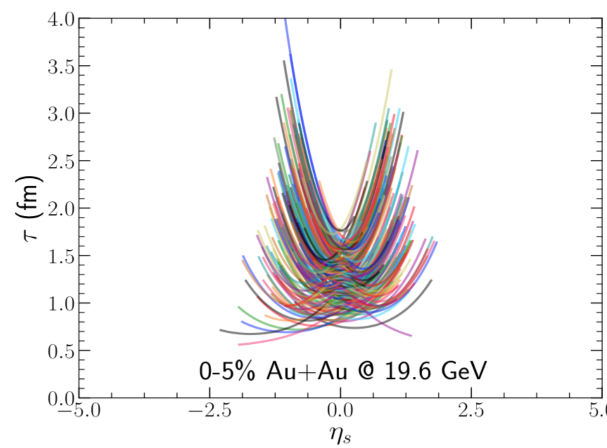
Shen and Schenke, 1710.00881

Denicol et al., 1804.10557



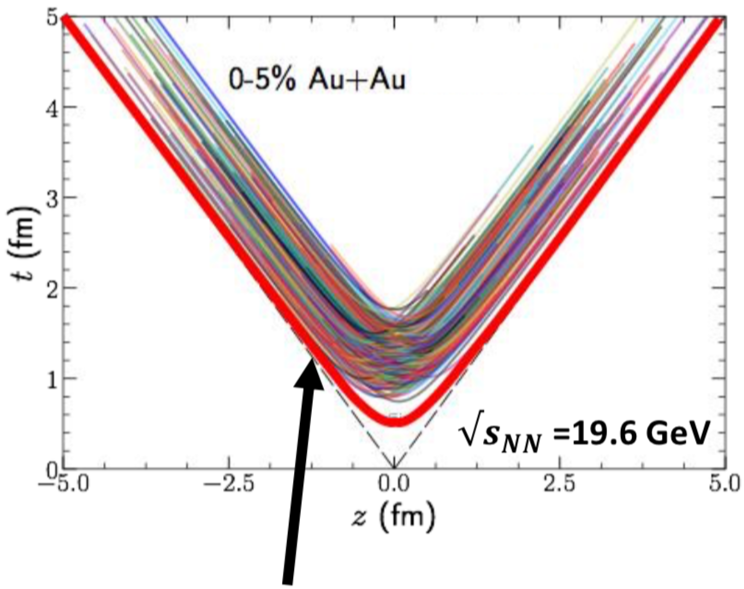






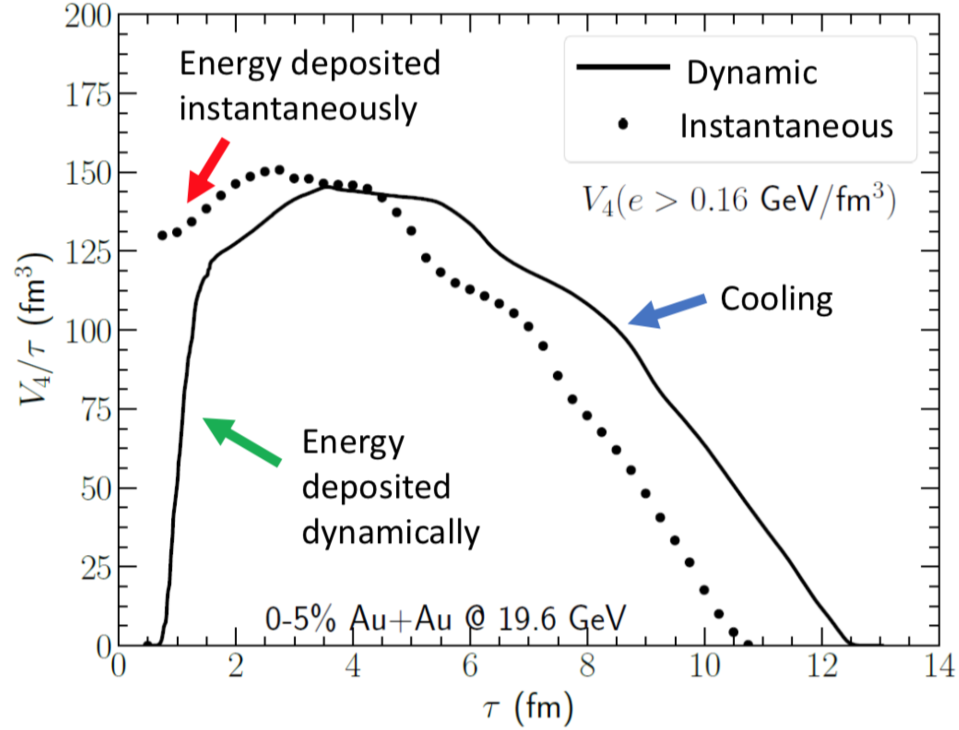
The dynamics of gradual energy deposition

Energy & baryon number **deposited over extended time** period **at lower $\sqrt{s_{NN}}$**



"Instantaneous" energy deposition (high collision energy limit)

Space-time 4-volume (above freeze-out) versus time

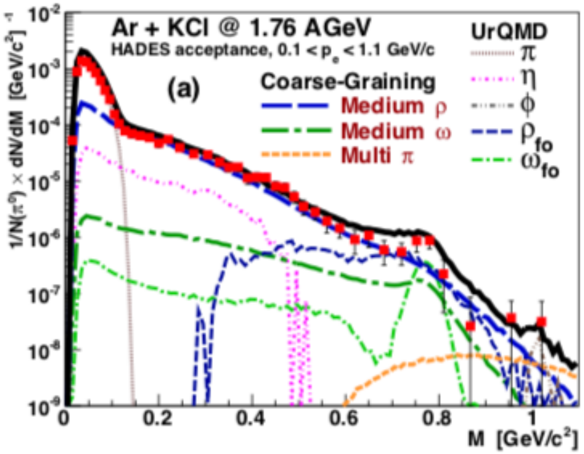


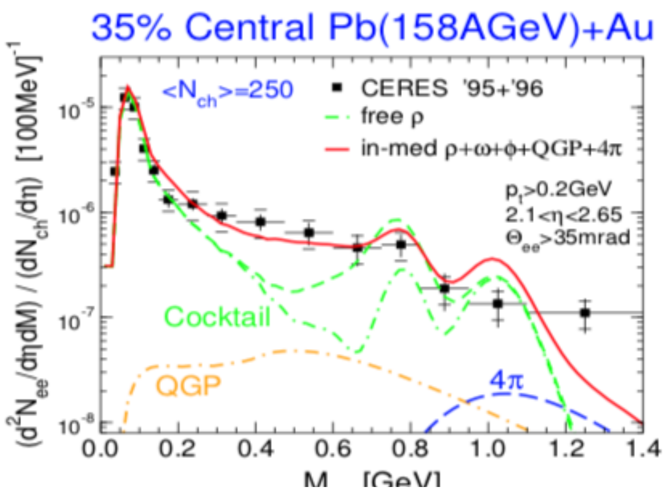
- Suppression of the early-time/high-pT photons
- Enhancement of v_2

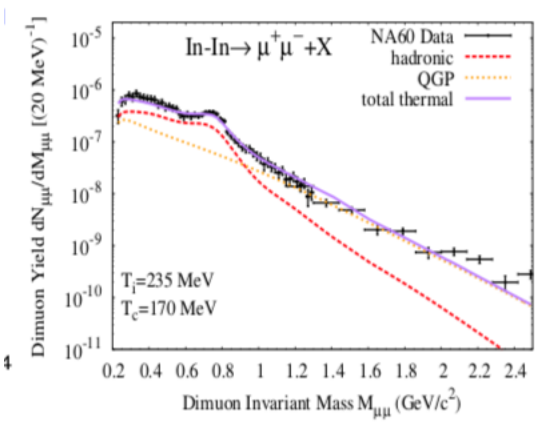
C. Shen's talk

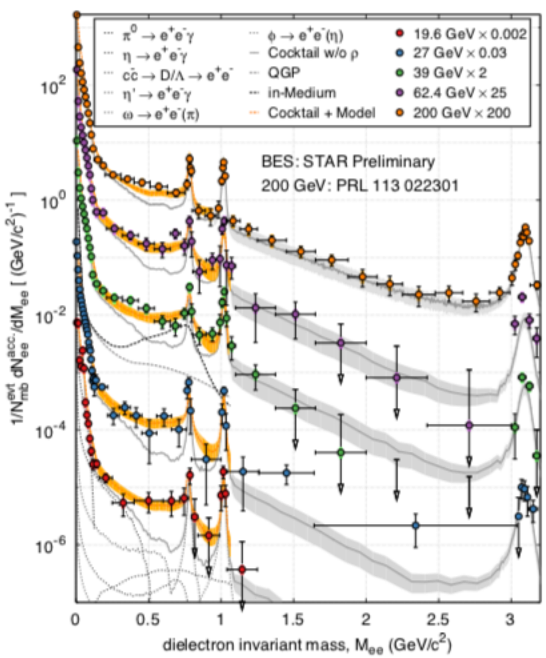
Charles Gale
McGill

Dileptons: Theory-experiment comparison









- At all energies: Important/ dominant contribution from vector meson (mostly rho) mass broadening
- No dilepton flow

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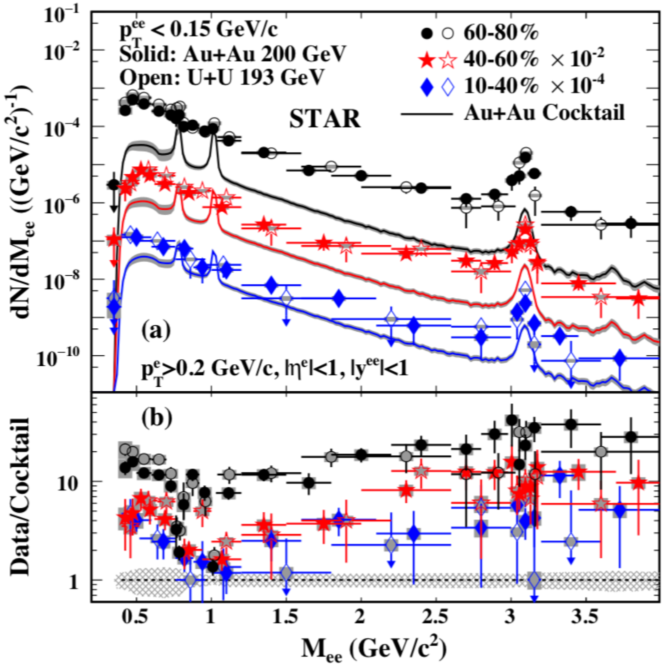
New development: low pT dileptons

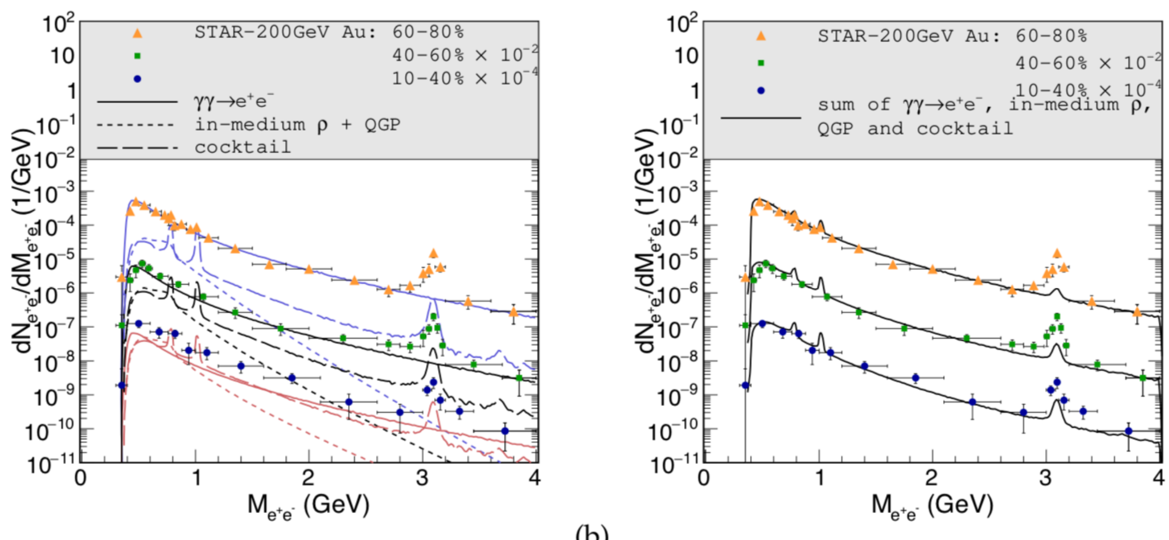
$p_T < 0.15$ GeV



Adam et al. [STAR], PRL 2018

- Large enhancement over cocktail
  - Evidence for light-by-light scattering?

Zha et al., PLB (2018)



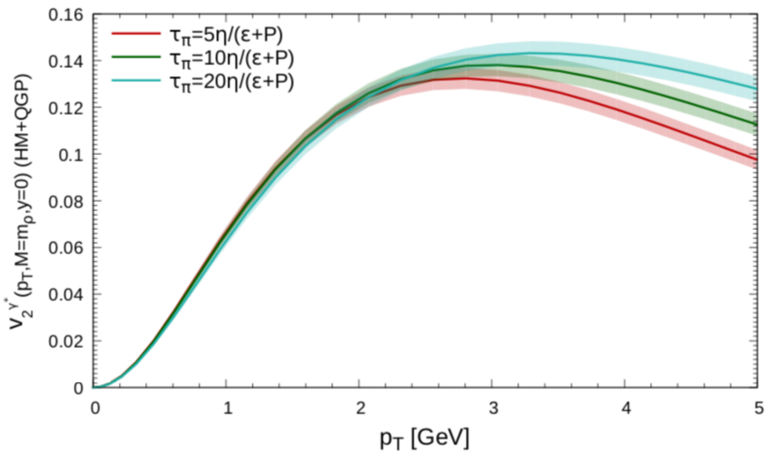
Zlusek-Gawenda et al., arXiv:1809.07049

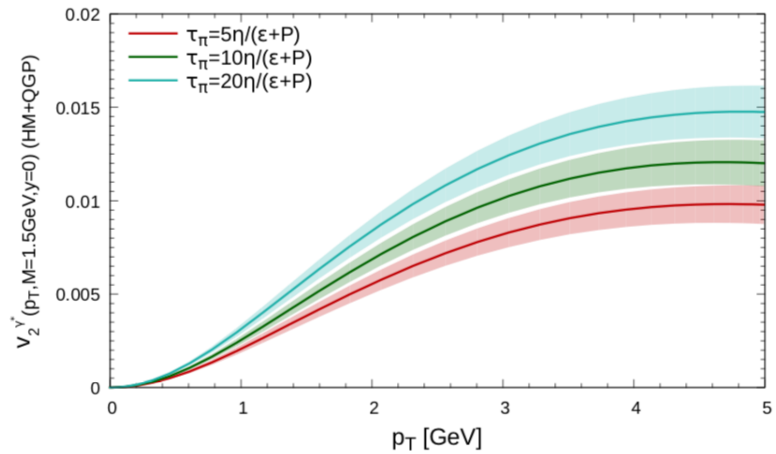
R. Rapp's talk

Charles Gale
McGill

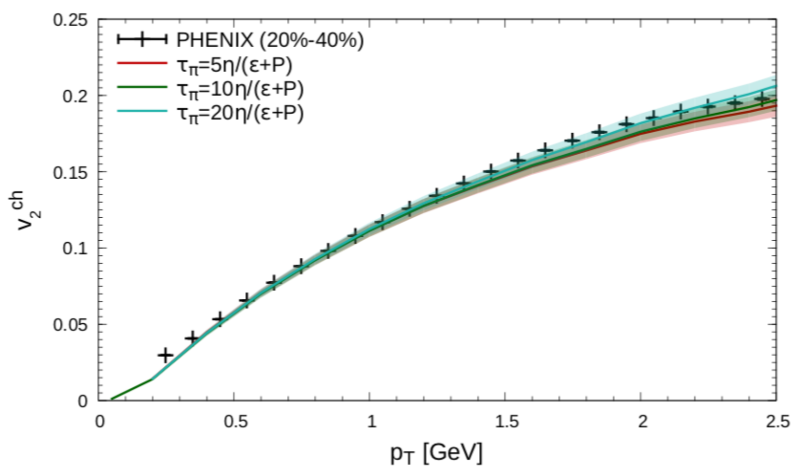
Dilepton flow

Au+Au, 20-40%, RHIC





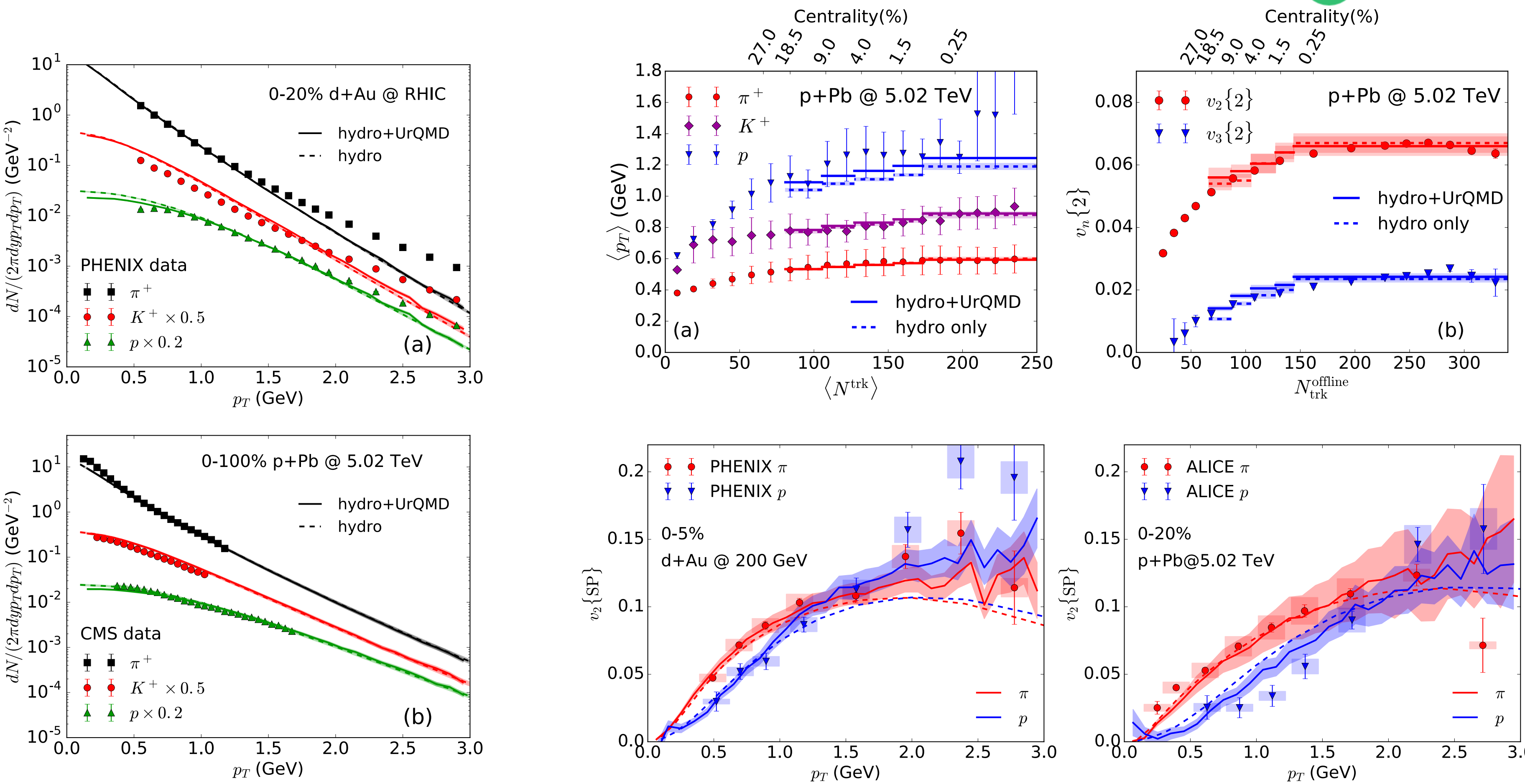
Vujanovic et al., PRC 2016



$$\tau_\pi \dot{\pi}^{\mu\nu} \sim \pi^{\mu\nu} - \pi^{\mu\nu}_{\rm NS}$$

- Privileged, even **unique,** access to early times and therefore to details of the transport coefficients!

Collectivity in small systems?

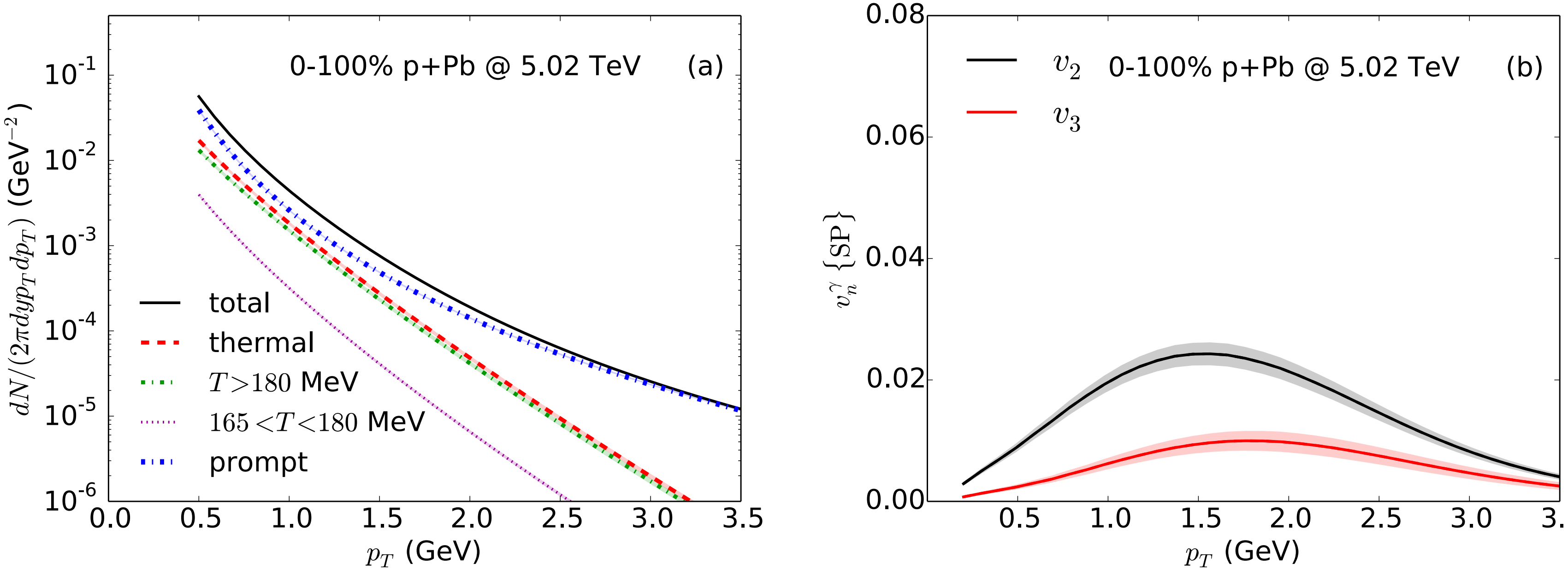


C. Shen et al., PRL (2016)

- Agreement between theory and measurement for spectra, centrality tracking, and flow
- $< p_T >$ values in agreement within uncertainties

Photon results

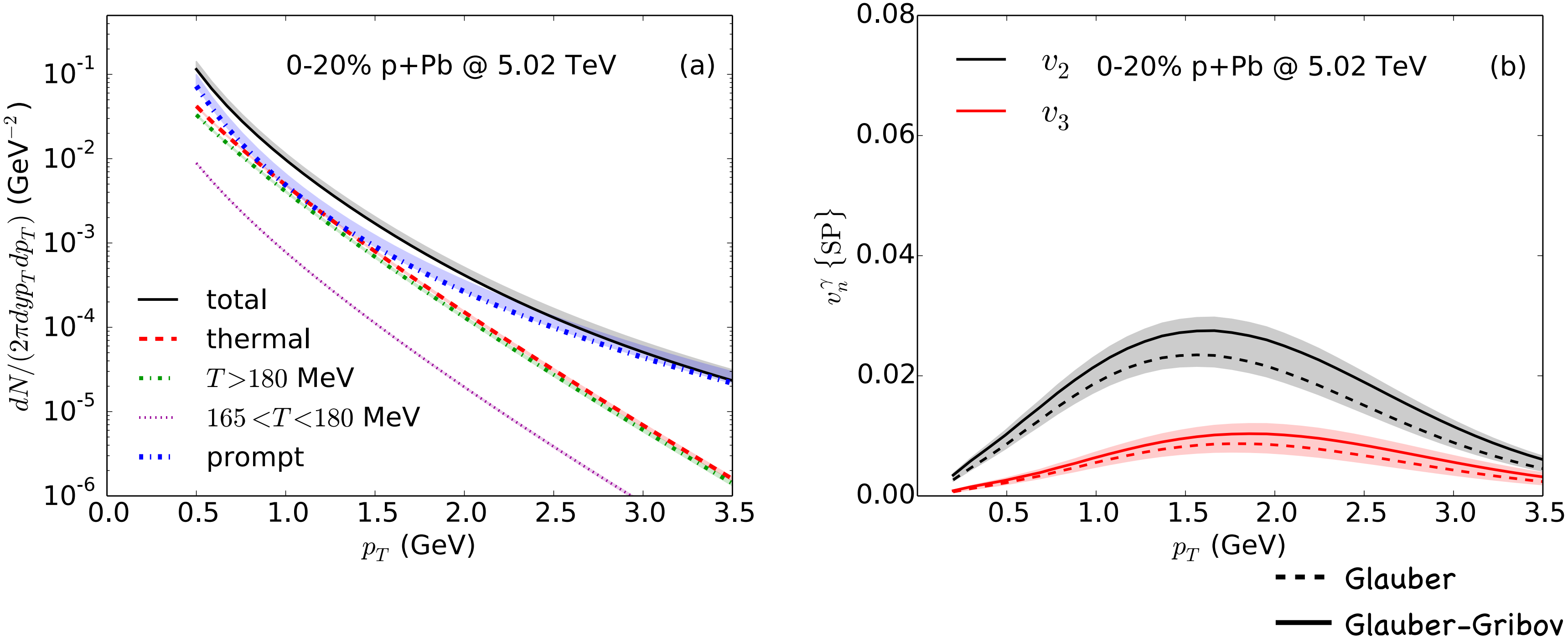
Min. bias



- For minimum bias p+Pb collisions, thermal photons are suppressed w.r.t. prompt photons, but are still visible in the total yield
- Prompt photons: NLO pQCD
- There is however a clear photon elliptic flow, and a photon triangular flow

Photon results

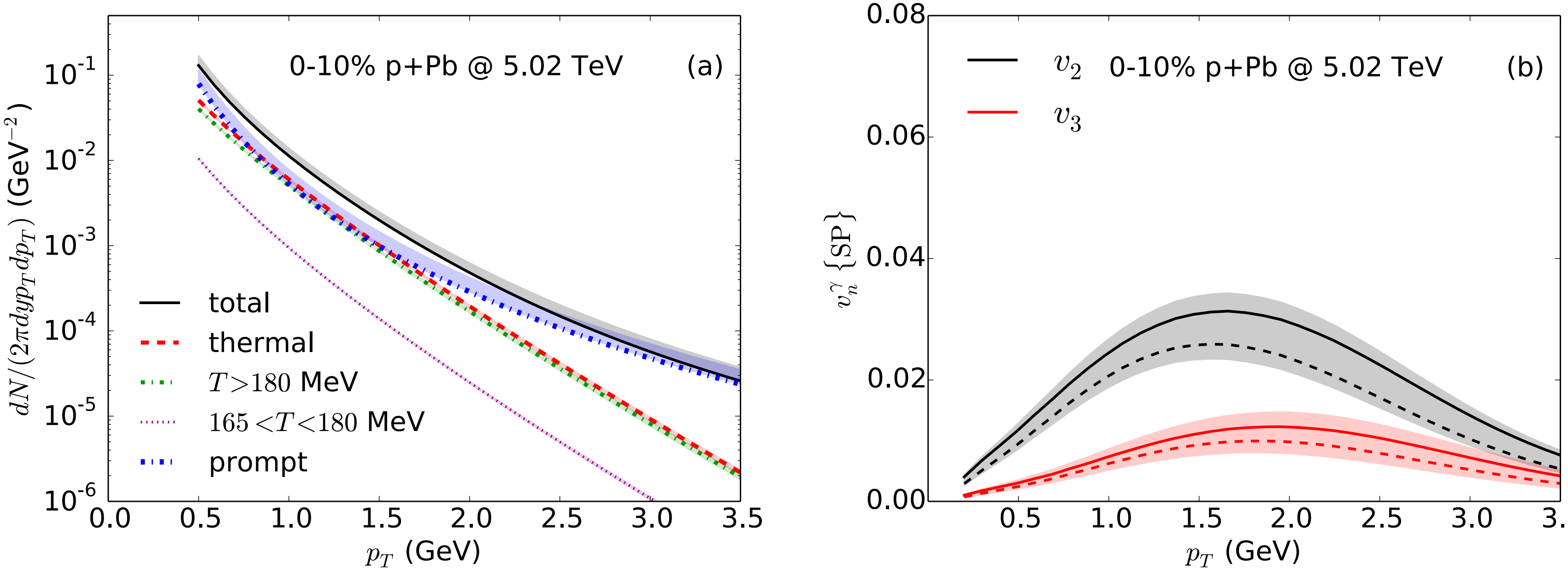
0-20%



- In the 0-20% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows

Photon results

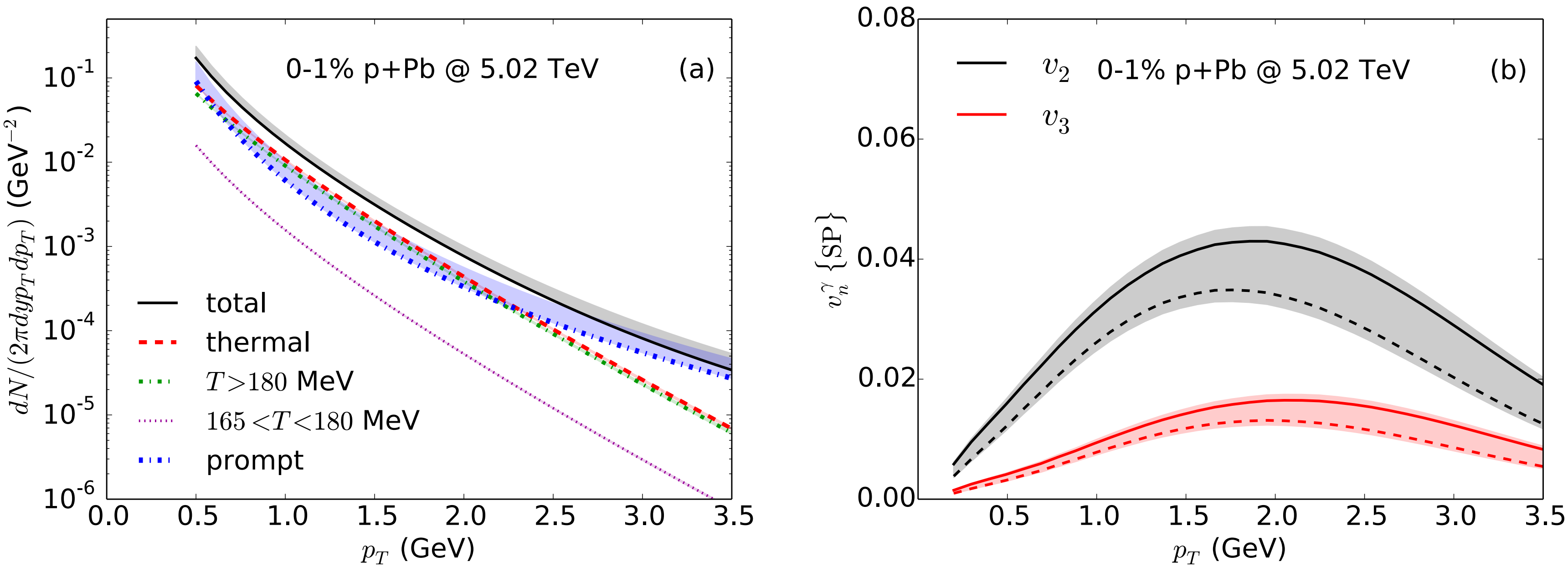
0-10%



- In the 0-10% centrality range, the thermal photons compete with the prompt, up to intermediate p_T
- Larger elliptic and triangular flows

Photon results

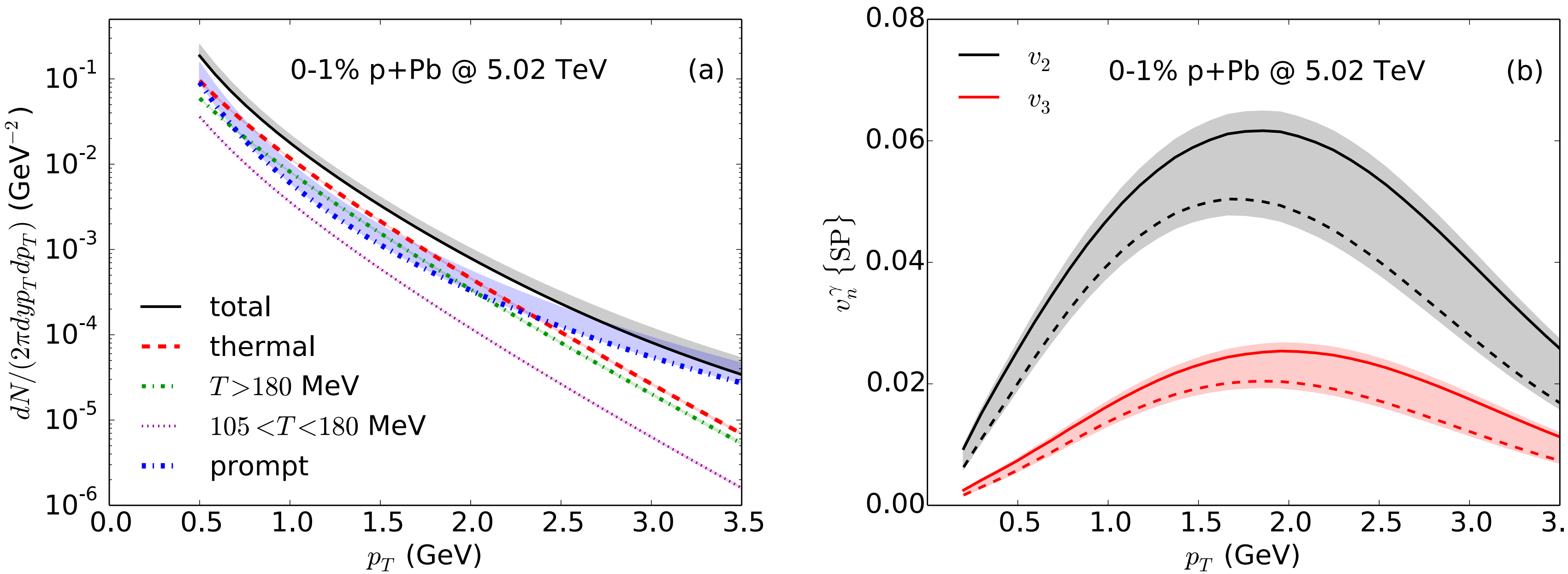
0-1%



- In the 0-1% centrality range, a clear thermal photon signal over the prompt photon contribution; a factor of 3 @ 1.5 GeV
- There is a clear photon elliptic flow, and a photon triangular flow
- T_{dec} is kept high: arguably even a lower limit to the thermal contributions

Photon results

0-1%



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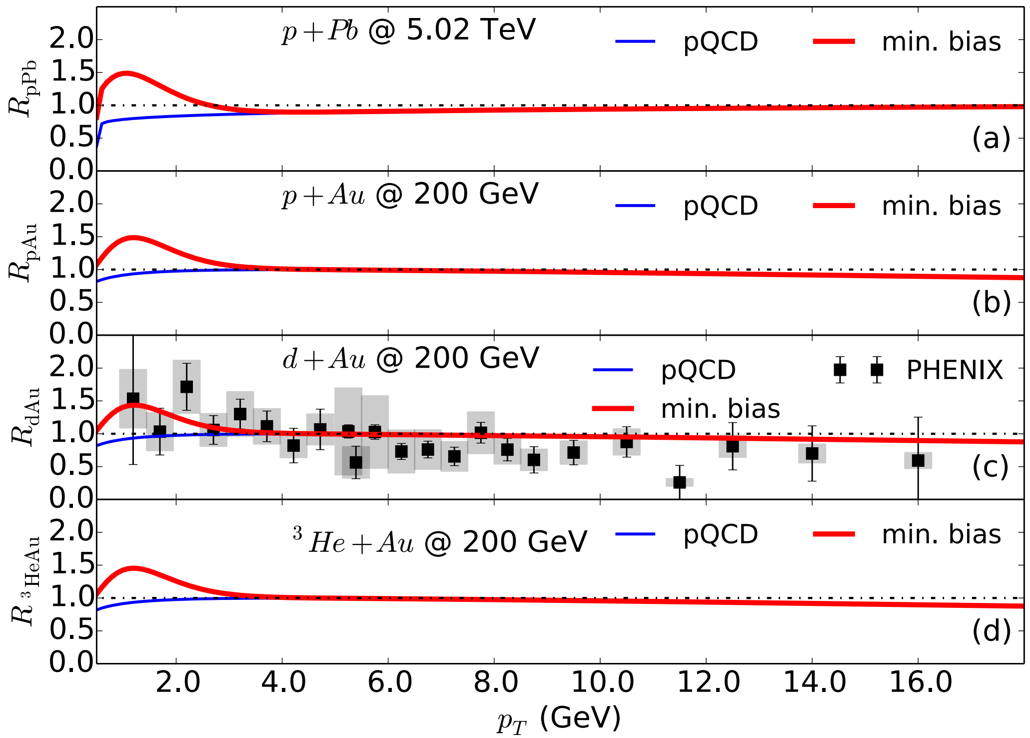
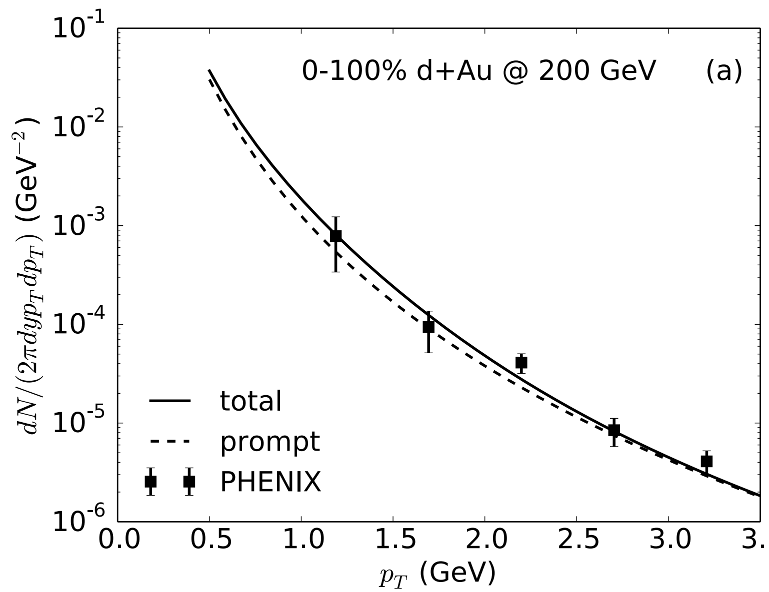
Comparing against what is currently known, and some predictions

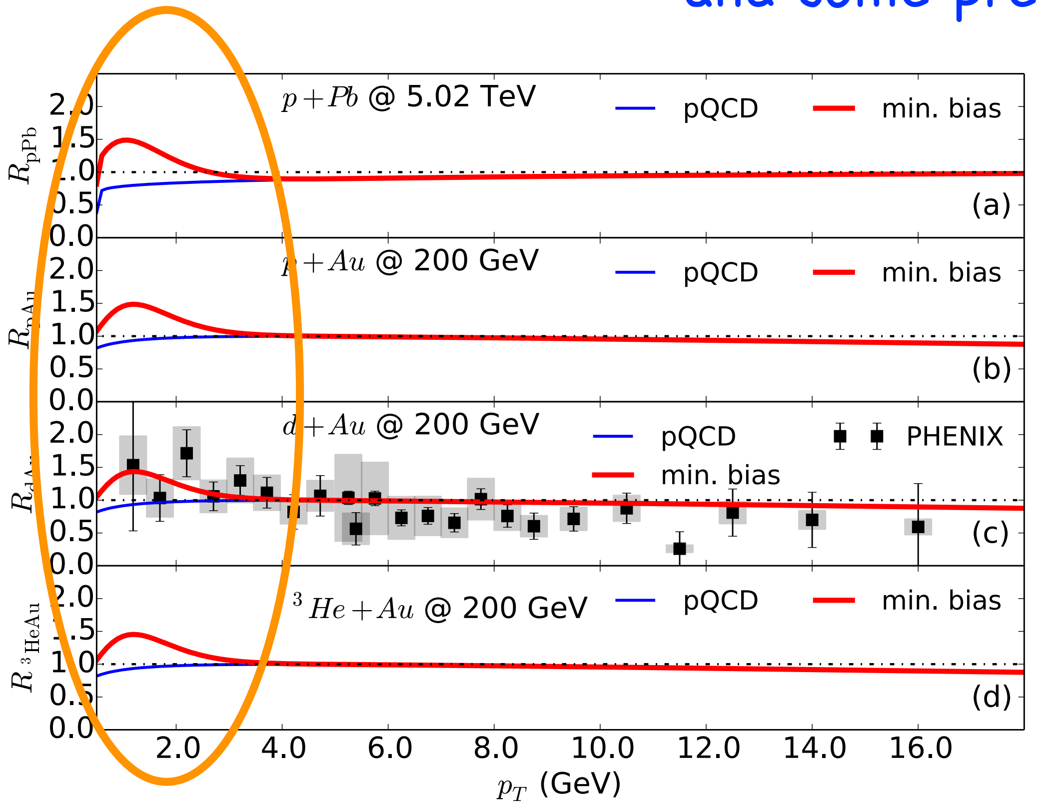


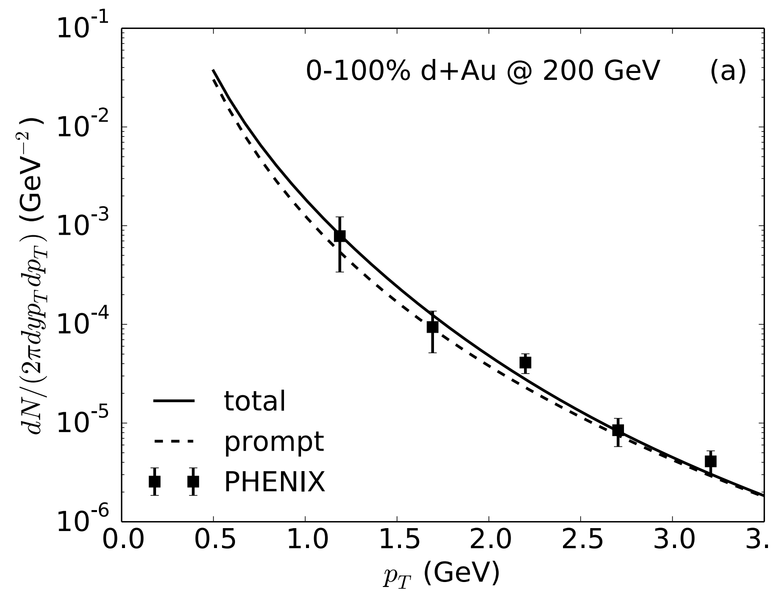


- Thermal radiation can leave a measurable imprint even on min. bias R^{γ}_{pPb}
- An additional empirical support to the existence of a medium with features of collectivity

C. Shen et al., PRL (2016)

Comparing against what is currently known, and some predictions





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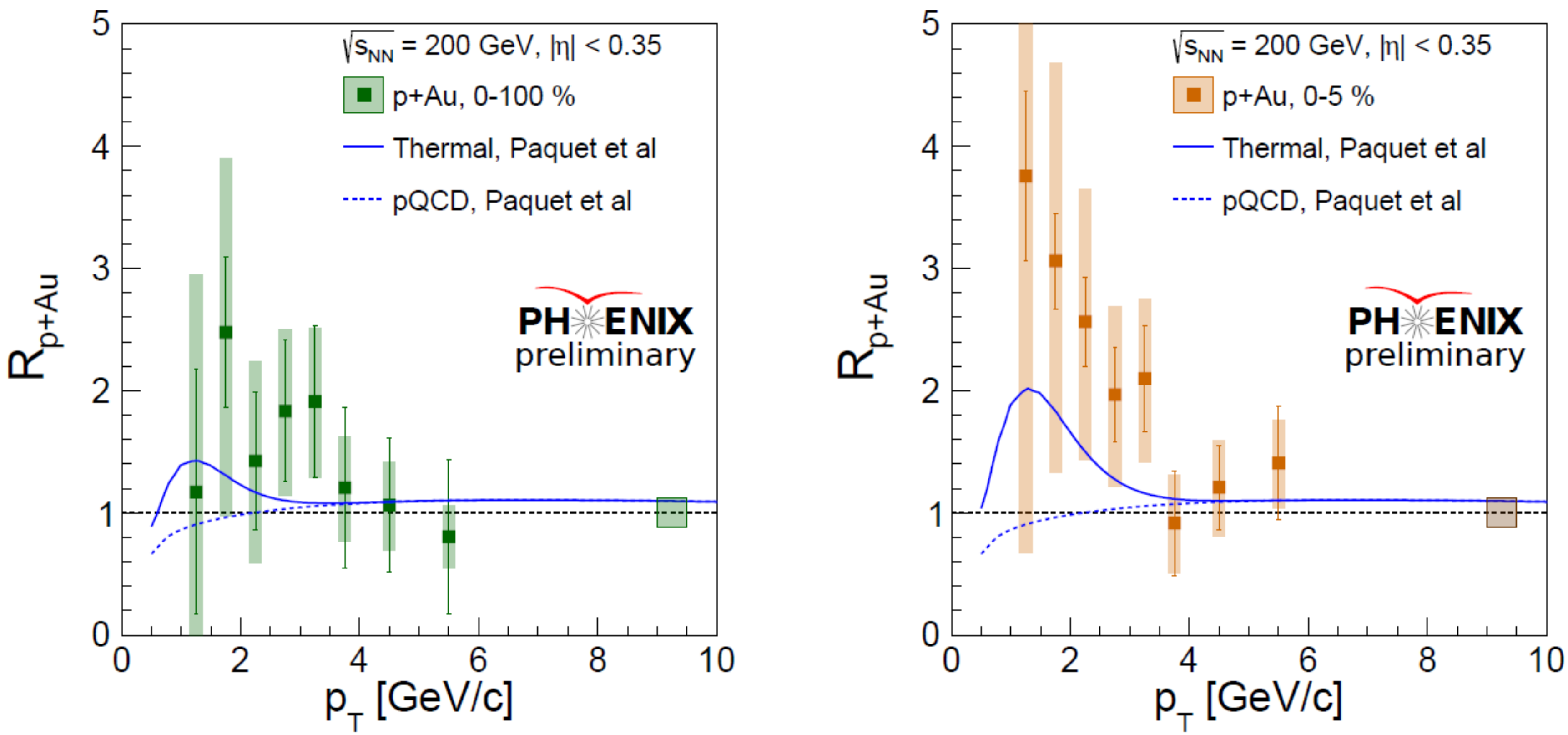
C. Shen et al., PRL (2016)

NEW Shown for the first time at Quark Matter 2018:

Small Systems: PHENIX Preliminary R_{pA}



Vladimir Khachatryan, Quark Matter 2018, Venice

Conclusions

- Photons (real and virtual) are unique probes
  - Early stages of the reaction, T, viscosities…
  - Parton content (q,g…)
- Info about electromagnetic observables inform the modelling of bulk matter
- Much progress in theory - towards a comprehensive theory of photons from out of equilibrium media
  - Application to jets coming
- Update on the "photon flow puzzle"
- EM radiation: valuable probe of early time dynamics in lower energy collisions
- Thermal photons in pA collisions?!

Conclusions (cont'nd)

- Low pT photons in pp, measurement?
- STAR/PHENIX photons
- Photon multiplicity scaling [A. Drees' talk]
- Non-equilibrium radiation, new developments
- Dilepton flow measurements at RHIC and LHC
- Effect of magnetic fields
- Jet-photon conversion
- …

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There is work for all!