Non-equilibrium Electromagnetic Radiation from Heavy-ion collisions

EMMI RRTF 2021

Charles Gale
McGill University

[Image: physics.org]

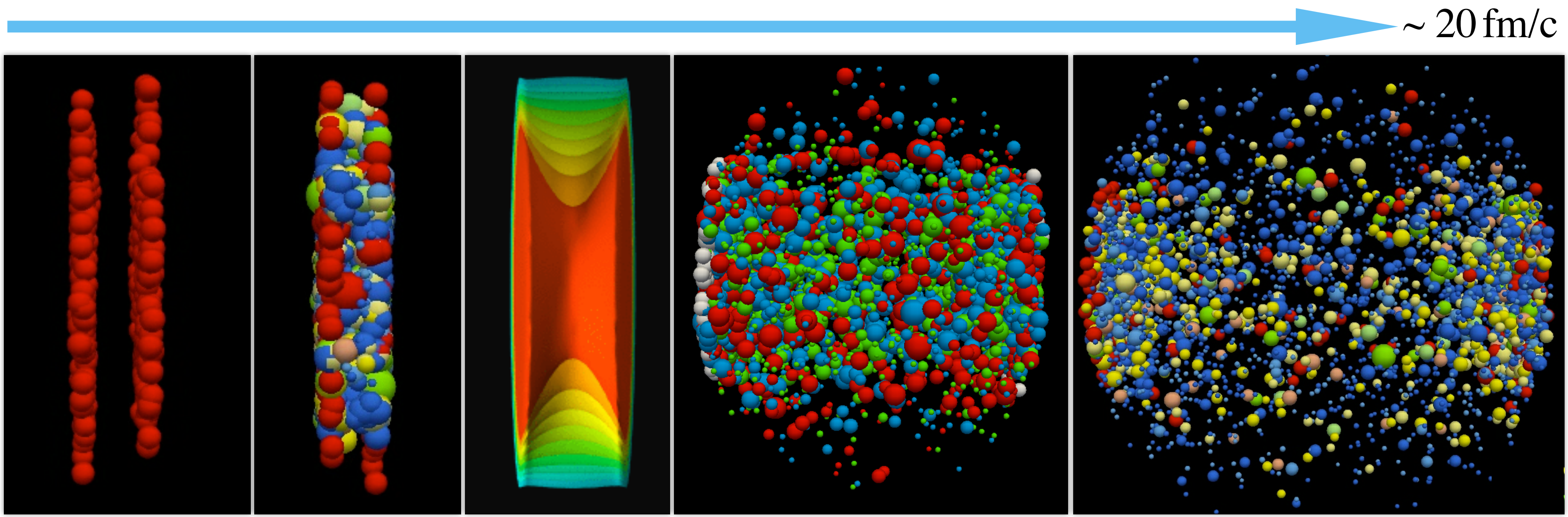
Outline

- Most of this talk: real photons of a few GeV
- Photons can be **soft** and still **penetrating**

They enjoy a unique status

- Near equilibrium, photons carry information about local conditions at emission: temperature.
- What about the contributions away from equilibrium?

Relativistic nuclear collisions: The "standard picture"



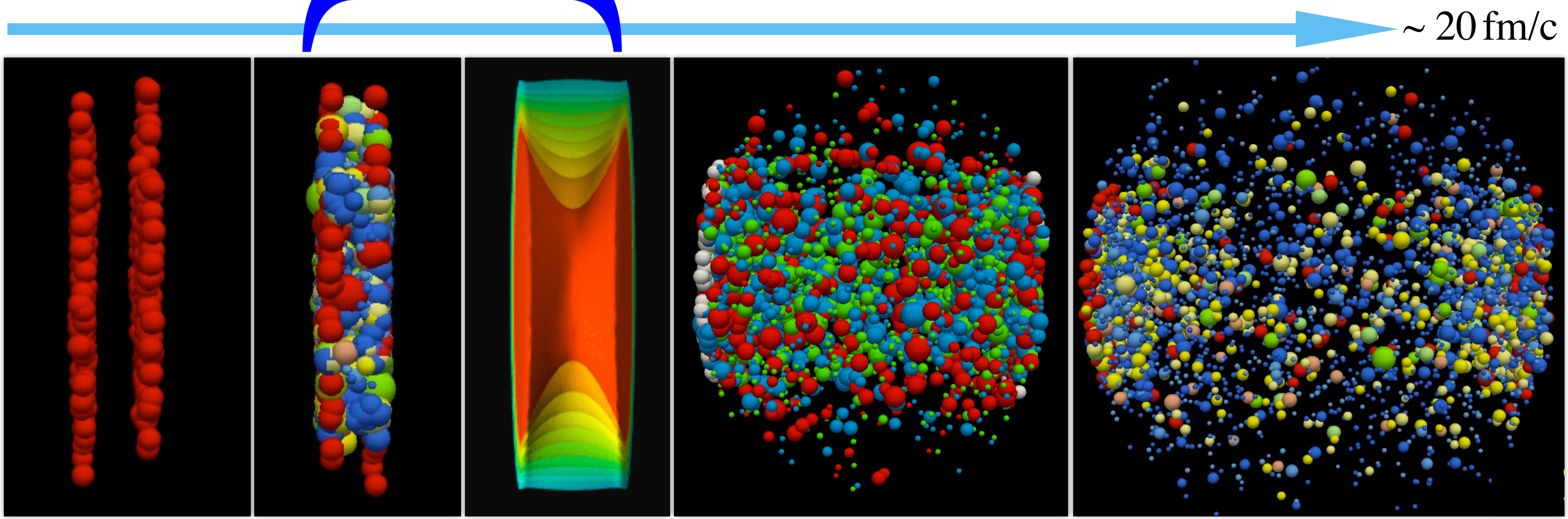
Initial state | Pre-"equilibrium" | QGP | Hadronization | Thermal freeze-out

Glasma

Relativistic hydrodynamics

Relativistic nuclear collisions: The “standard picture”

This talk



Initial state

Pre-“equilibrium”

Glasma

QGP

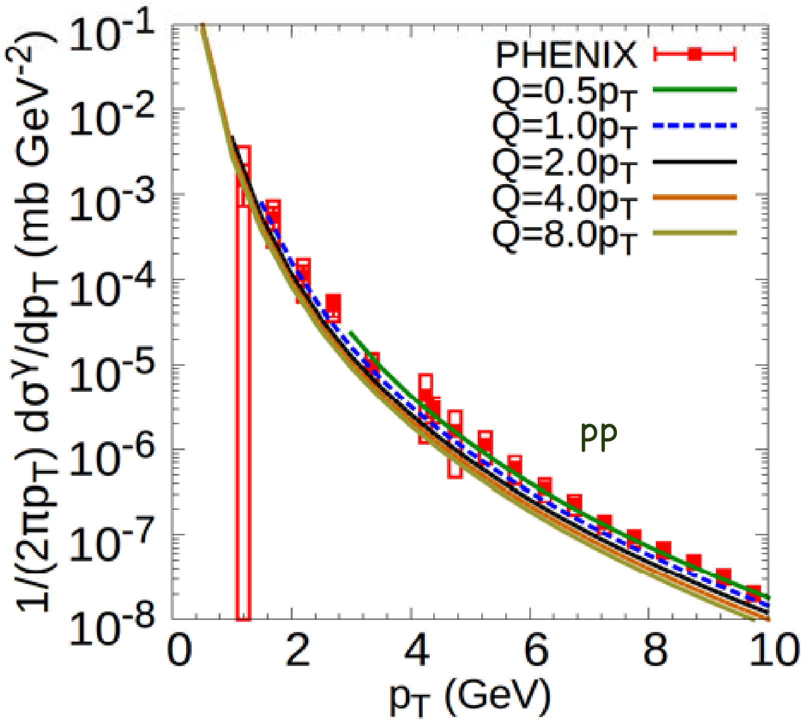
Hadronization

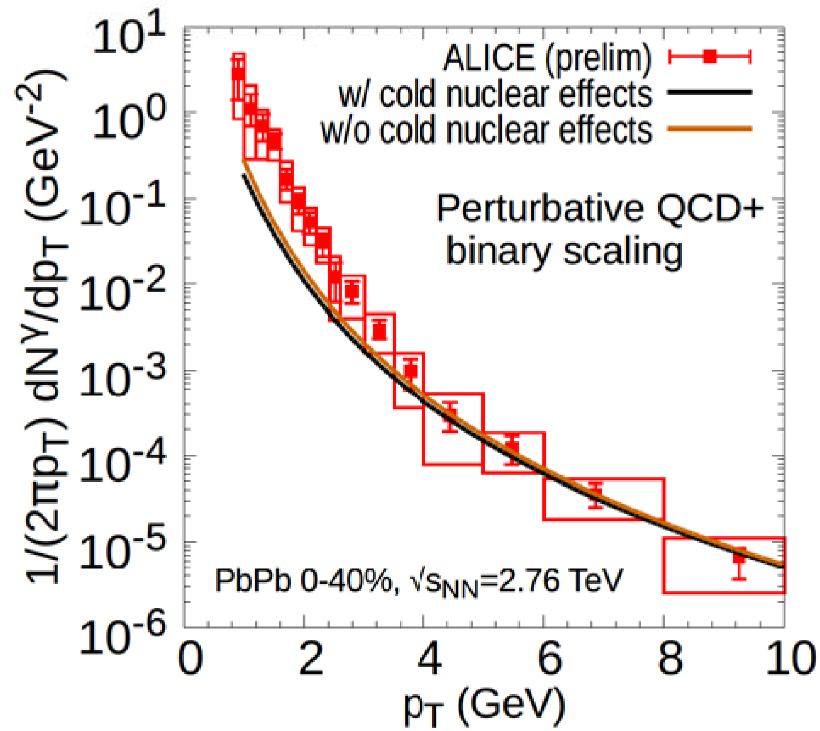
Thermal freeze-out

Relativistic hydrodynamics

"Extreme non-equilibrium": pQCD Photons

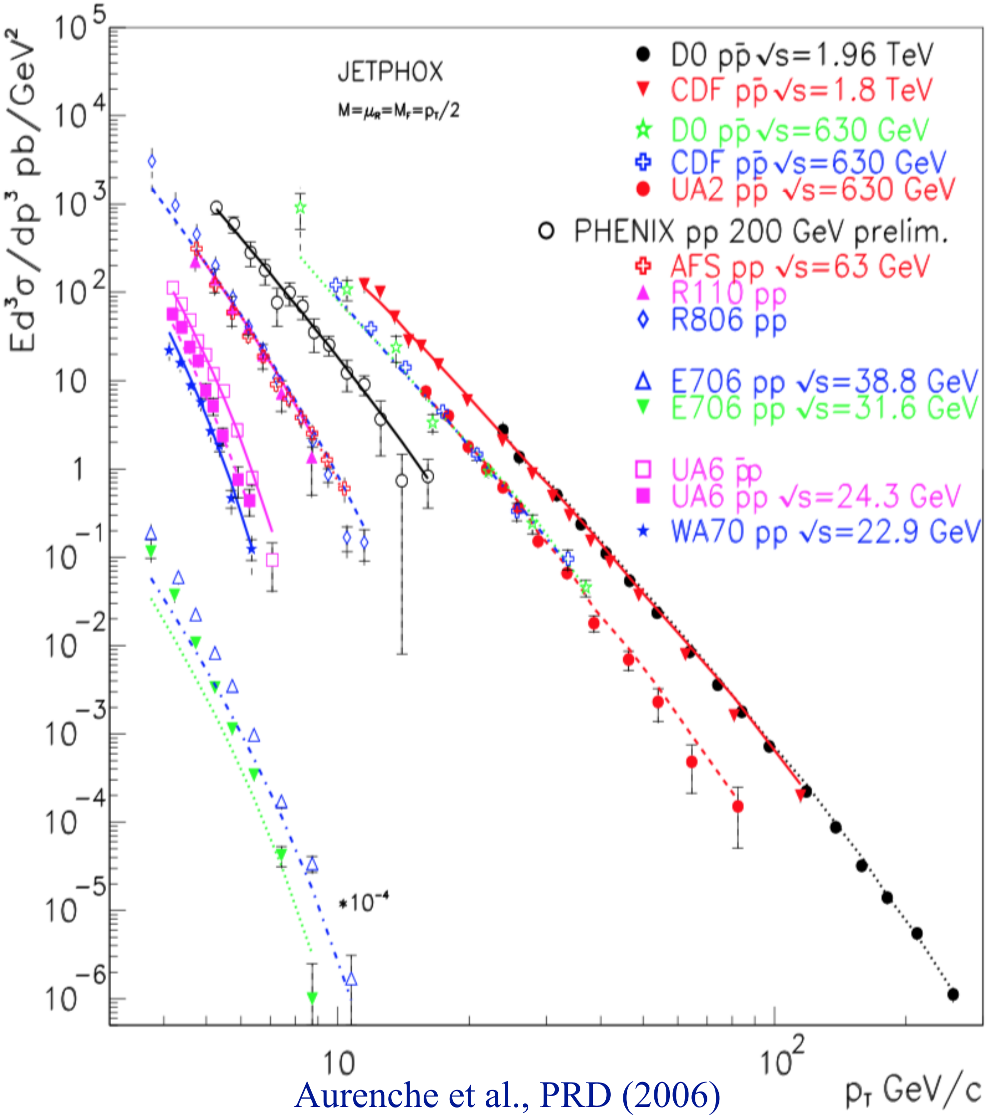
- Calculated @ NLO in pQCD
  - INCNLO, P. Aurenche et al., Eur. PJC (2000)
  - CTEQ6.1m, BFG-2, Isospin, EPS09
  - Measurement!





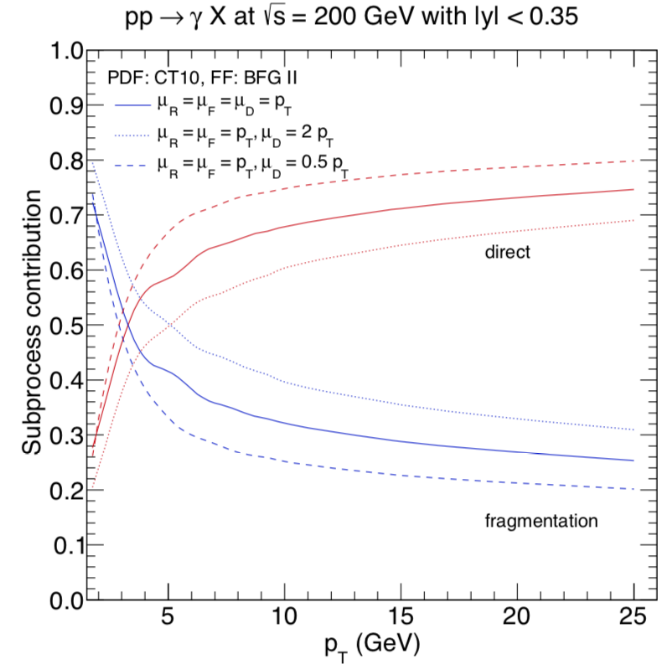
J.-F. Paquet, PhD Thesis (2015)
Paquet et al., PRC (2016)

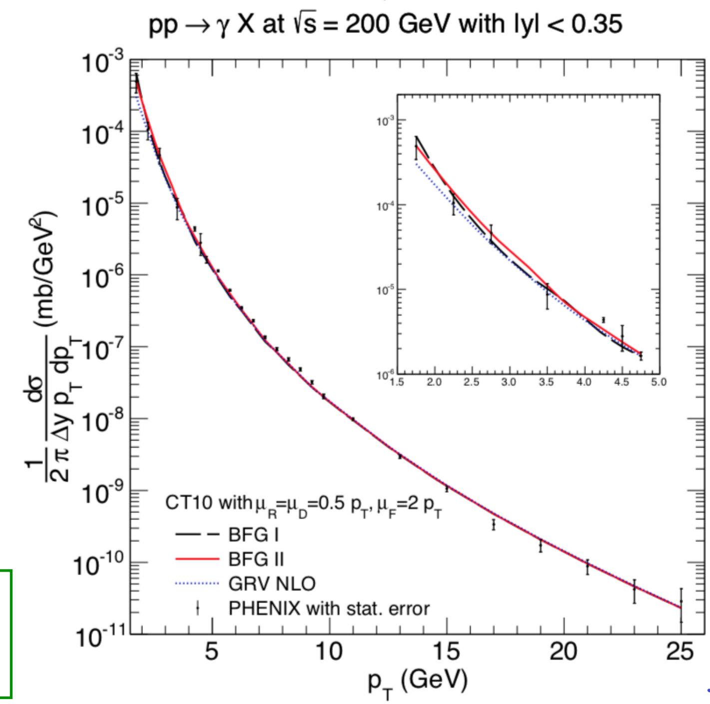
pQCD photon calculations carry uncertainties



Aurenche et al., PRD (2006)

Klasen, König, Eur. PJC (2014)





Kaufmann, Mukherjee, Vogelsang, CERN Proc. 2018

Fragmentation component: $e^+e^- \to (\text{jet}\,\gamma)\,X$

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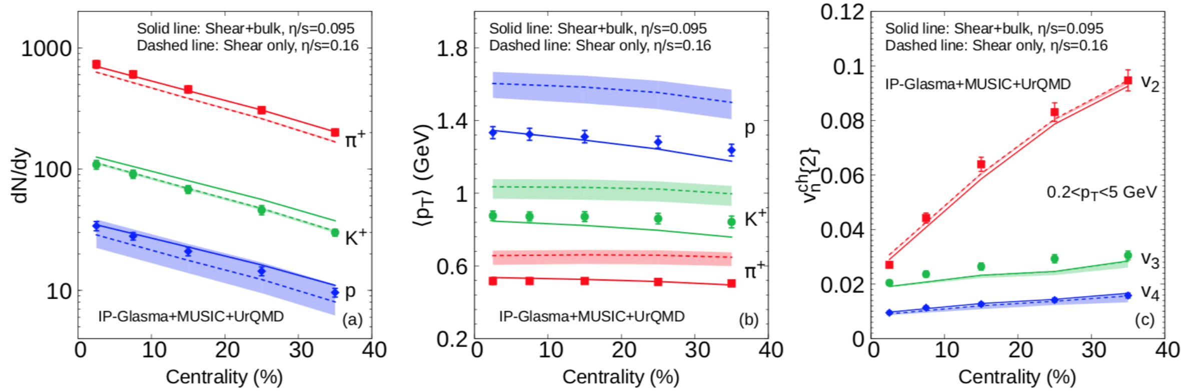
Different paths to non-equilibrium physics

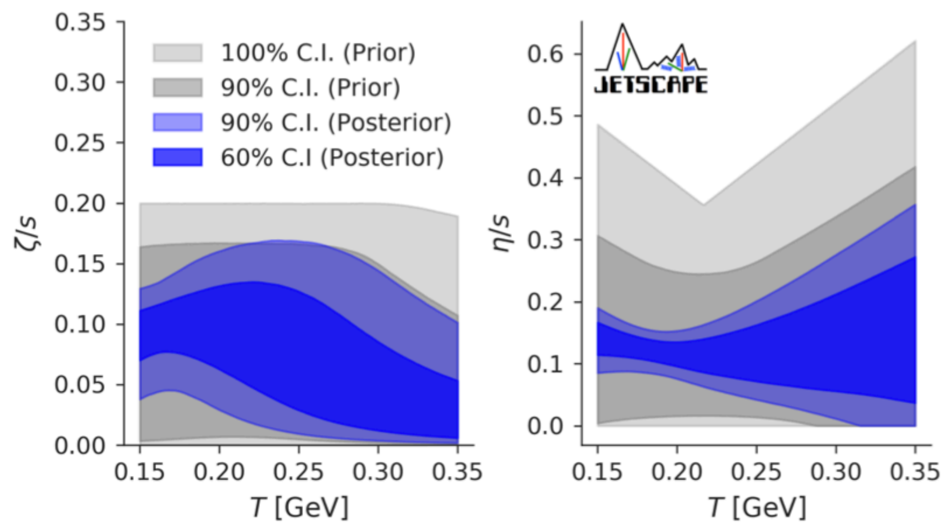
- "Top-down": start from ideal hydrodynamics, incorporate corrections

$$f_{\mathrm{eq}} \to f_{\mathrm{eq}} + \delta f(\mathbf{p}, u^{\mu}, \eta, \zeta)$$

S. Ryu et al., PRL 2015
Pb+Pb, 2.76 A TeV



JETSCAPE Collab.,
PRC 2021; PRL 2021



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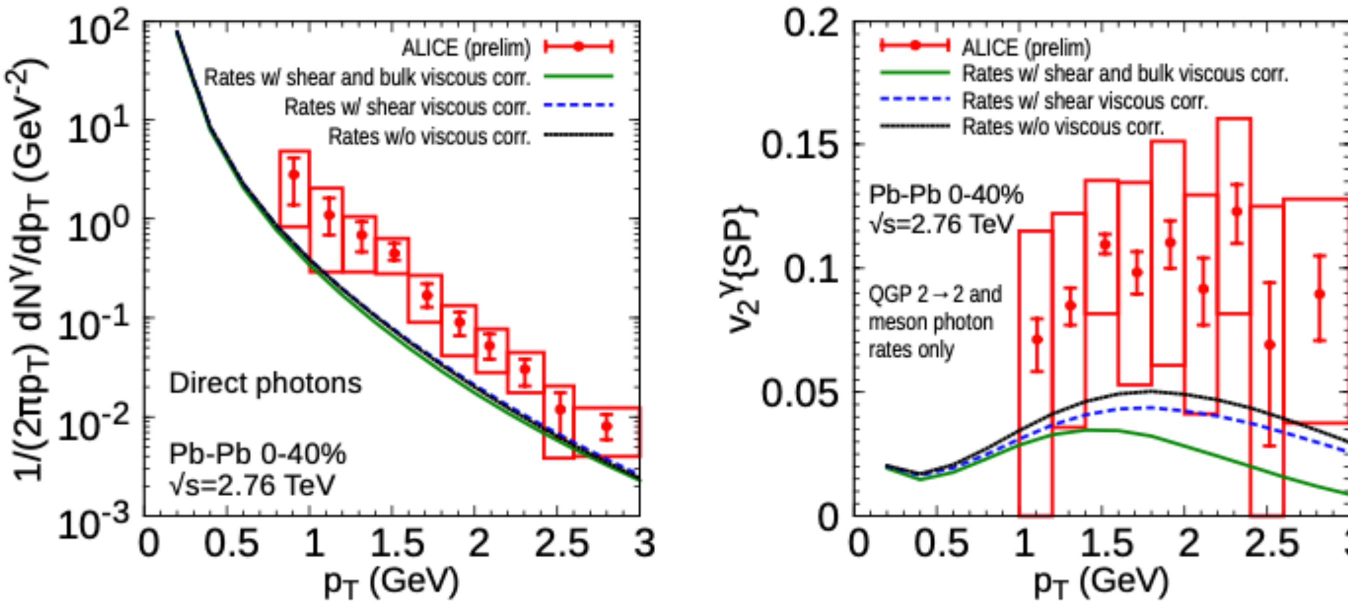
Effect on photons

$$q_0 \frac{d^3R}{d^3q}\bigg|_{1+2\to3+\gamma} = \int \frac{d^3p_1}{2(2\pi)^3E_1}\frac{d^3p_2}{2(2\pi)^3E_2}\frac{d^3p_3}{2(2\pi)^3E_3}(2\pi)^4\left|M\right|^2\delta^4(\ldots)\frac{f(E_1)f(E_2)\left[1\pm f(E_3)\right]}{2(2\pi)^3}$$



(*)

(*) Issue with the LPM calculation in an out-of-equilibrium medium

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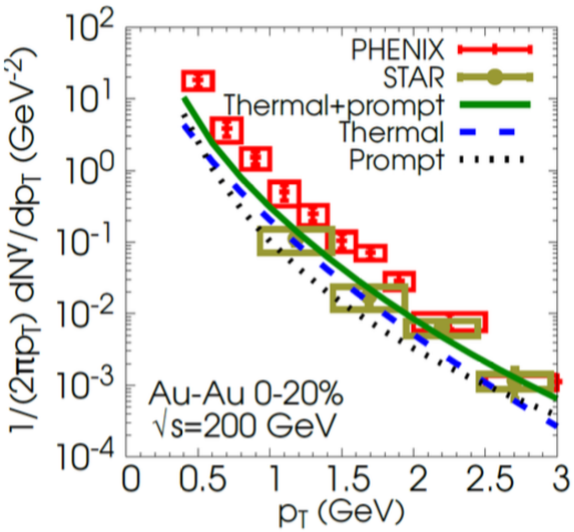
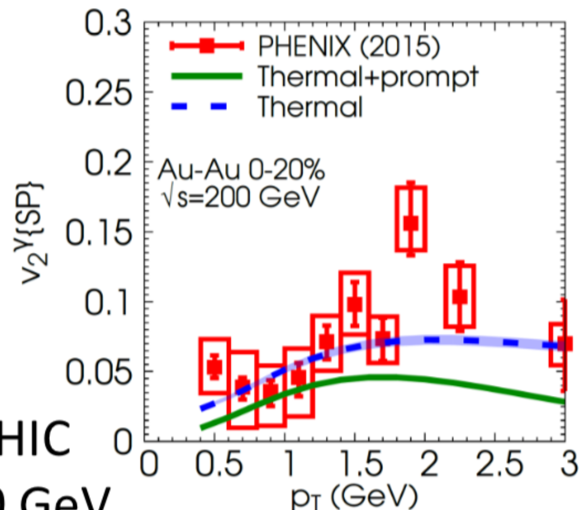
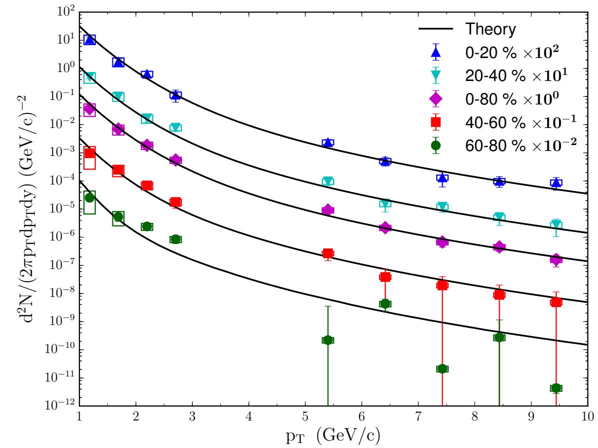
Yields & Flow

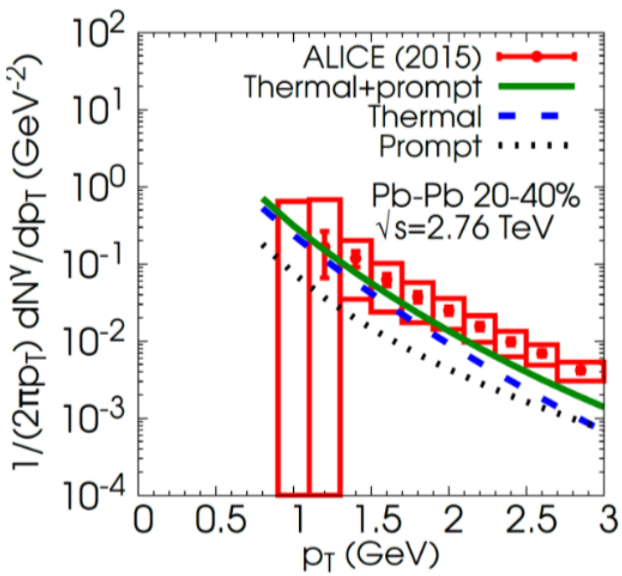


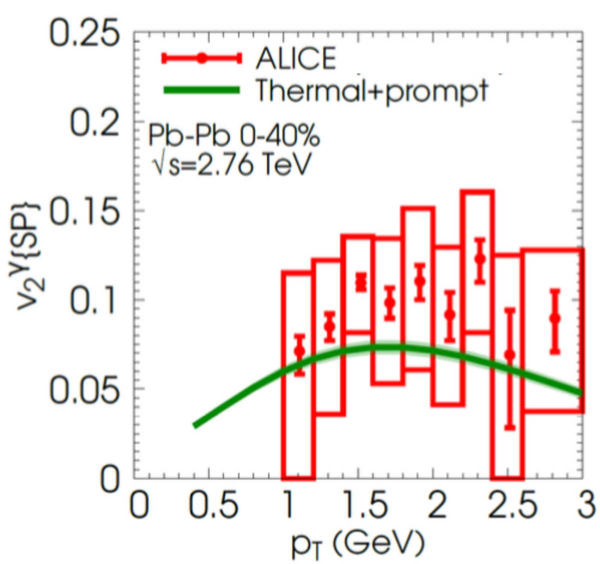


RHIC
200 GeV



STAR





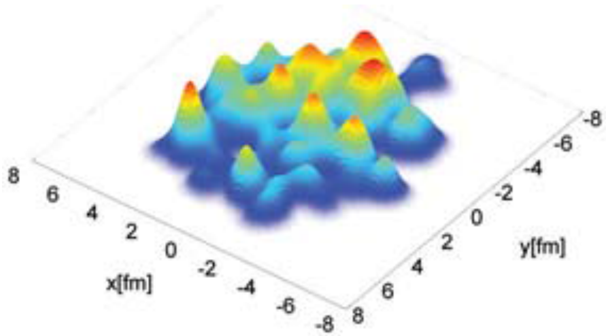
LHC 2760 GeV

Paquet, Shen, McDonald, Jeon, Gale, (2019)

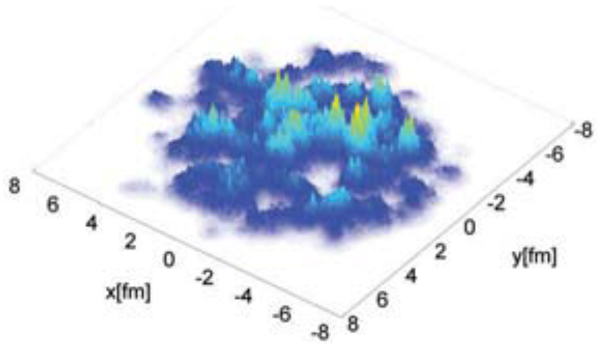
- "Bottom-up": start from initial state, work towards hydrodynamization

Much progress in the calculation of the initial state

Energy density

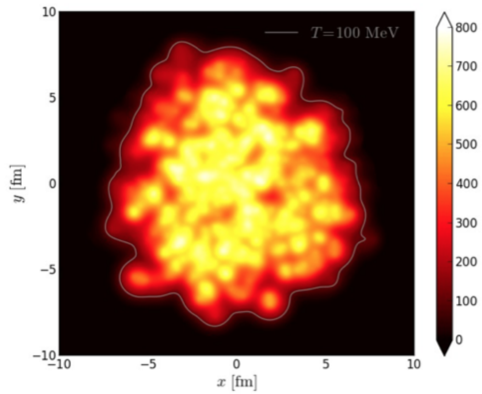


MC-Glauber
Nucleons



IP-Glasma
Colour fields

Schenke, Tribedy, and Venugopalan, PRL (2012)



EKRT
Saturated NLO pQCD minijets

Niemi, Eskola, Paatelainen, PRC (2015)

$T_R ENT_O$, Effective kinetic theory; 3D IP-Glasma…

Discuss two approaches:

1) A Transport treatment of the early stages

$$D_t f^a_{\mathbf{p}} = \mathscr{C}\left[f^a_{\mathbf{p}}\right]$$

Treat the collision integral assuming that small momentum transfer dominates -> diffusion approximation

Blaizot, Wu, Yan, Nucl. Phys. A (2014)

Obtain two Fokker-Planck-like coupled equations

$$D_t f_g = -\nabla_{\mathrm{p}} \cdot \mathscr{J}_g + \mathscr{S}_g$$
$$D_t f_q = -\nabla_{\mathrm{p}} \cdot \mathscr{J}_q + \mathscr{S}_q$$

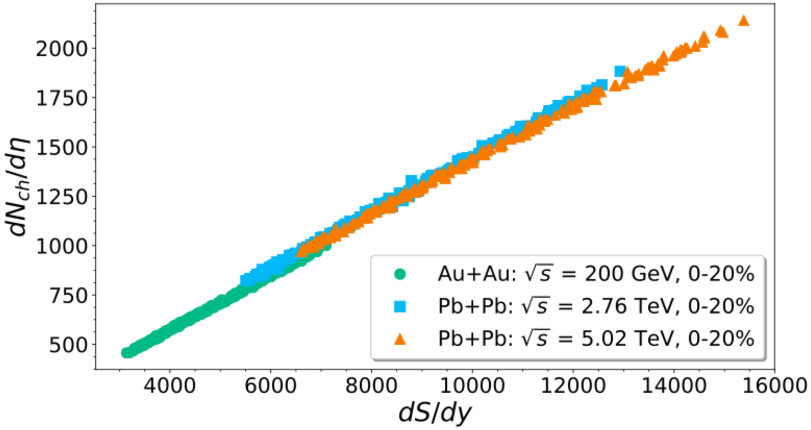
= diffusion + source

Initialize at $\tau \sim 1/Q_s$ with $f_g\left(\tau_0, p\right) = f_0\, \theta\left(1 - \frac{\sqrt{p_\perp^2 + p_z^2 \xi^2}}{Q_s}\right)$

Romatschke, Strickland PRD (2003)

An initial gluon-rich medium

Match with final states



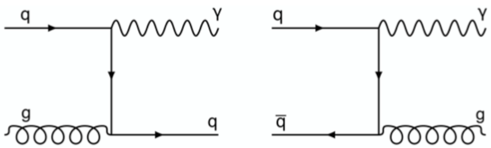
Churchill, Yan, Jeon, Gale PRC (2021)

$$\frac{dS}{dy} \sim 7.14 \frac{dN_{\mathrm{ch}}}{d\eta} \rightarrow \tau A_T \left(s_g + s_q\right)$$

Use $\tau = 0.4$ fm/c, fix f_0

	$\sqrt{s_{NN}}$ [TeV]	dS/dy	A_T [fm^2]	Q_s [GeV]	f_0 ($\xi = 1.0$)	f_0 ($\xi = 1.5$)
RHIC	0.20	5000	100.58	1.0	2.25	3.81
LHC	2.76	13700	124.25	1.0	6.65	11.10
				2.0	5.75	9.50
LHC	5.02	14500	127.75	1.0	7.00	11.75
				2.0	6.00	10.25

Summing up Compton and annihilation contributions



$$\frac{dN}{dy_p\, d^2\mathbf{p}_\perp} = \frac{16\, A_T}{3\pi^2} \alpha \alpha_s \mathscr{L}' \int \tau\, d\tau\, dy\, f_q(p_\perp, \tilde{p}_z, \tau) \mathscr{I}_c$$

$$\mathscr{I}_c = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{1}{p} \left(f_g + f_q\right)$$

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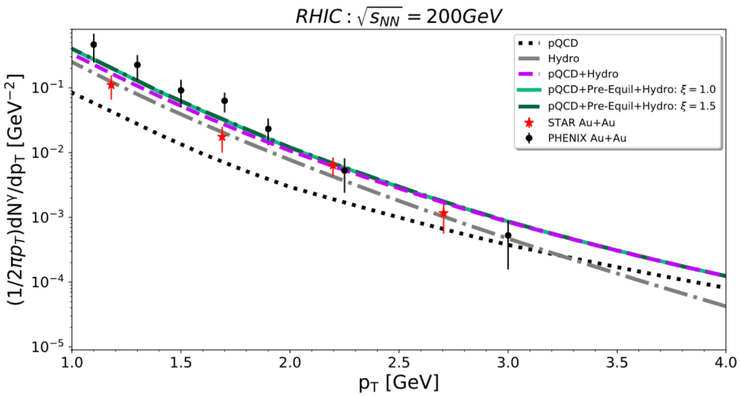
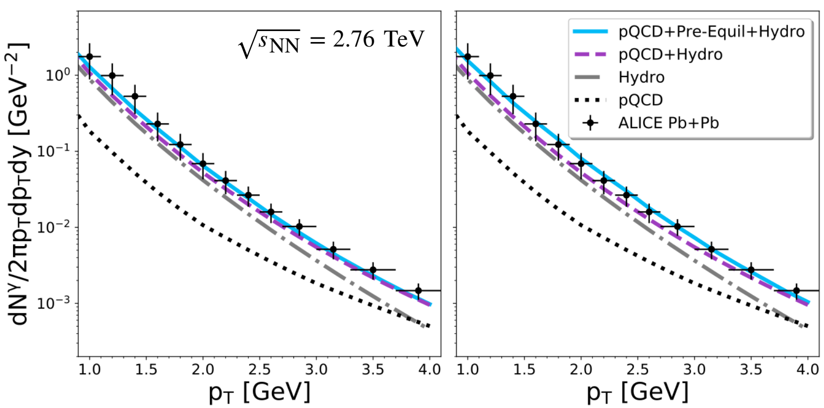
"PRE-HYDRO" PHOTONS

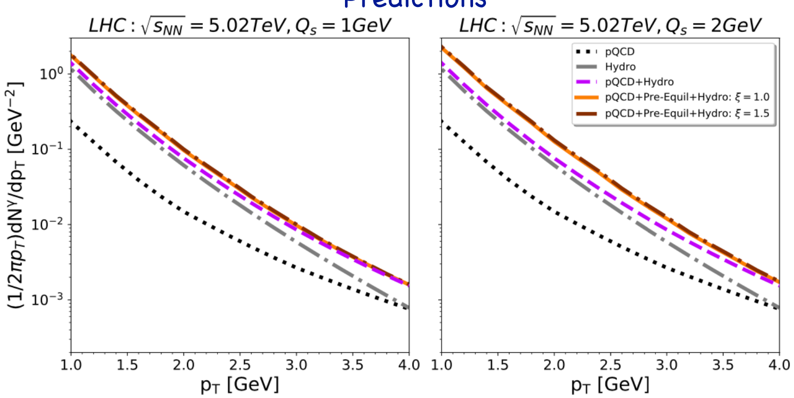


- Extra yield $\sim 15\,\%$ @ $p_T \sim 2$ GeV
- Little effect of initial gluon momentum asymmetry



- Extra yield $\sim 25 - 60\,\%$ @ $p_T \sim 2$ GeV
- Little effect of initial gluon momentum asymmetry

Predictions



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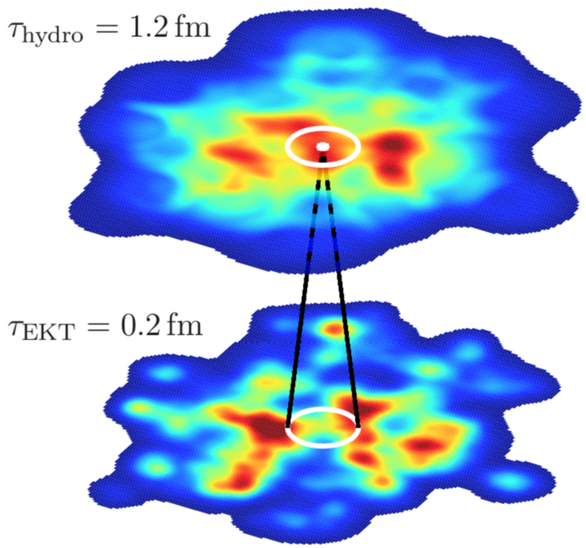
2) Another approach to pre-hydro evolution: KøMPøST

An EKT approach to the pre-hydro phase



$$\partial_\tau f_{\mathbf{x},\mathbf{p}} + \frac{\mathbf{p}}{|\mathbf{p}|} \cdot \nabla_{\mathbf{x}} f_{\mathbf{x},\mathbf{p}} - \frac{p^z}{\tau} \partial_{p^z} f_{\mathbf{x},\mathbf{p}} = \mathscr{C}\left[f_{\mathbf{x},\mathbf{p}}\right]$$

$$T^{\mu\nu}(t_{EKT}, \mathbf{x}) = \bar{T}^{\mu\nu}_{\rm x} + \delta T^{\mu\nu}_{\rm x}(t_{EKT}, \mathbf{x})$$

Average $T^{\mu\nu}$ evaluated over causal circle

$$\bar{T}^{\mu\nu}(\tau) = \nu_g \int \frac{d^3\mathbf{p}}{(2\pi)^3} \frac{p^\mu p^\nu}{p^0} \bar{f}(\tau, \mathbf{p})$$

Linear response:

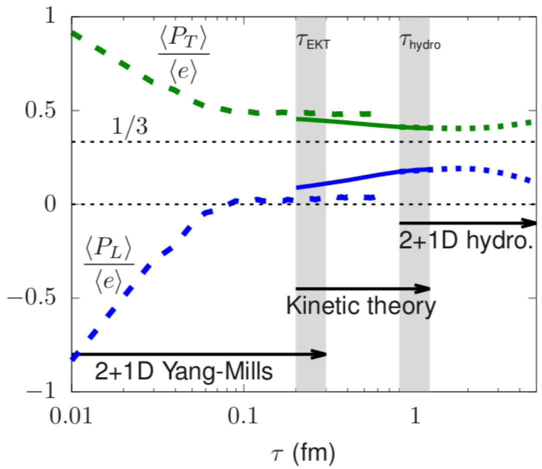
$$\frac{\delta T^{\mu\nu}(\tau, \mathbf{x})}{\bar{T}^{\tau\tau}_{\mathbf{x}}(\tau)} = \frac{1}{\bar{T}^{\tau\tau}_{\mathbf{x}}(\tau_0)} \int d^2\mathbf{x}_0\, G^{\mu\nu}_{\alpha\beta}\left(\mathbf{x}, \mathbf{x}_0, \tau, \tau_0\right) \delta T^{\alpha\beta}_{\mathbf{x}}(\tau_0, \mathbf{x}_0)$$

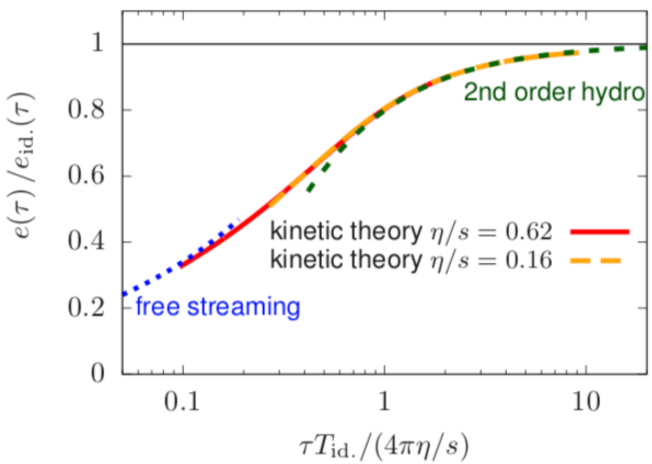
Advantages:

- BE is 6+1 dimensions in general
- Owing to scaling property, Green's functions can be evaluated and stored

Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019); PRC 2019

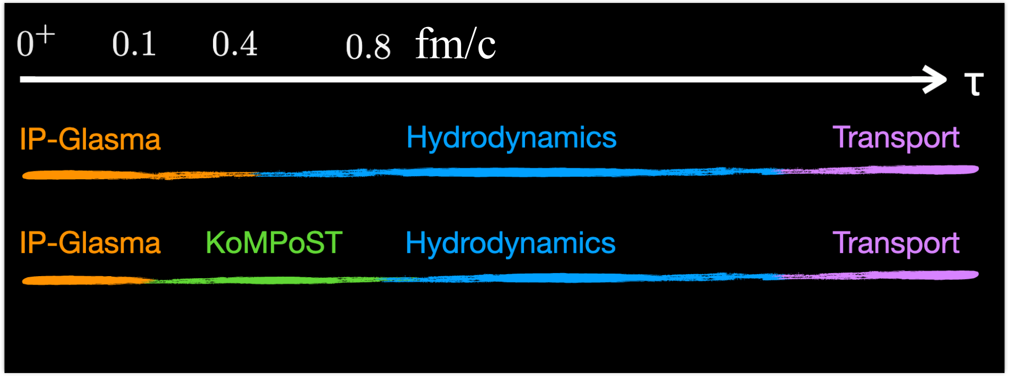
KøMPøST: an interface between early times & hydrodynamics



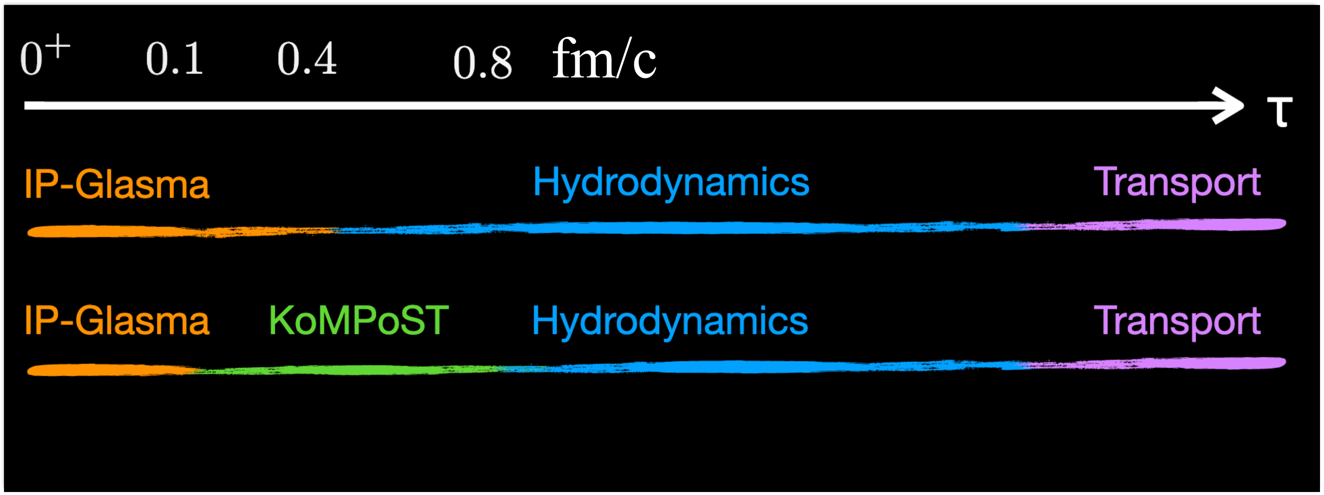


Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019)

Road map:



From early to late times:

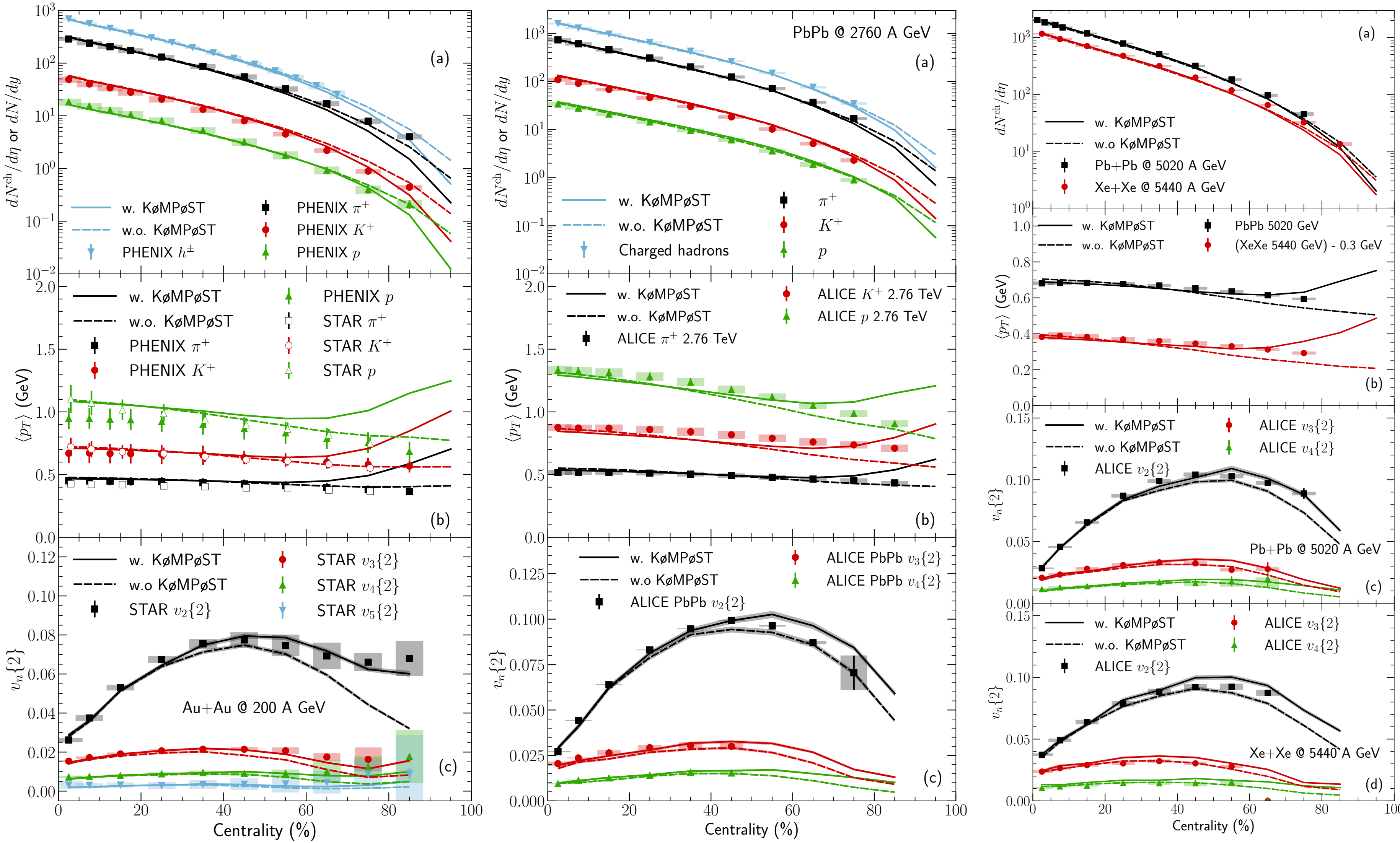


IP-Glasma | KøMPøST | MUSIC | UrQMD

$$T^{\mu\nu}_{\text{IP-Glasma}}(0^+) \rightarrow T^{\mu\nu}_{\text{KøMPøST}}(\tau_{\text{EKT}}) \rightarrow T^{\mu\nu}_{\text{Hydro}}(\tau_{\text{Hydro}}) \rightarrow T^{\mu\nu}_{\text{UrQMD}}(\tau_{\text{C-F}})$$

- KøMPøST is conformal
- It consists of gluons

Effect of pre-eq. phase: hadrons



$\eta/s = 0.12$

See also Nunes da Silva et al., PRC (2021)

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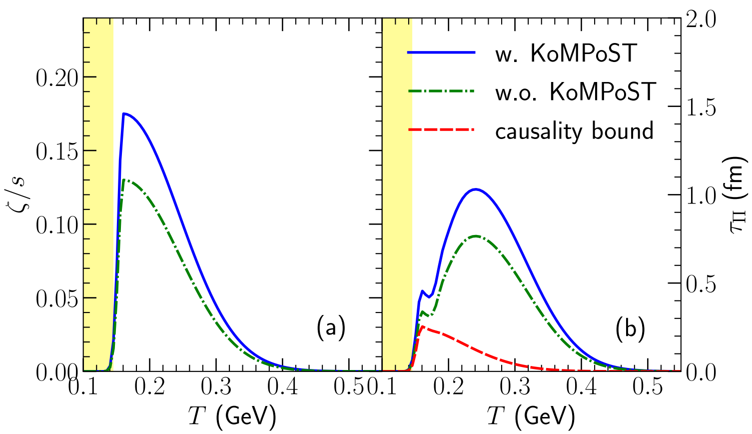
Effect of pre-eq. phase: hadrons (II)

KøMPøST is conformal; no bulk viscous effects

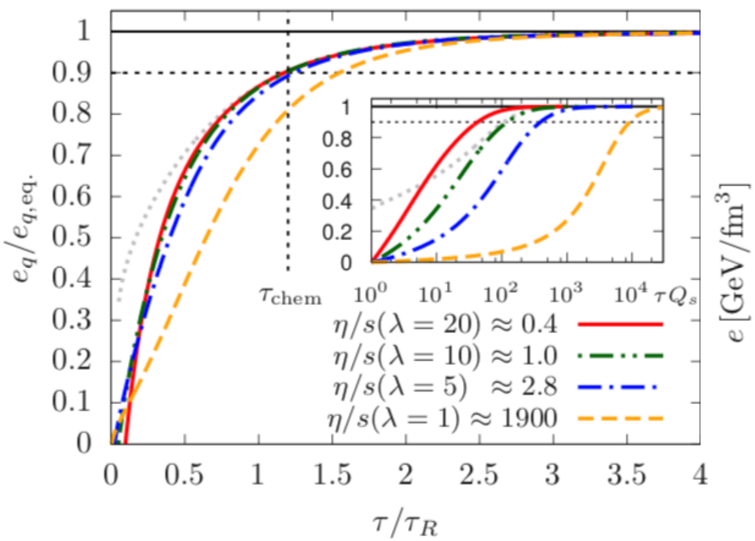
- Less entropy production
  - Increased normalization of initial energy density by 20%
- More radial flow
  - Increased bulk viscosity by 30%



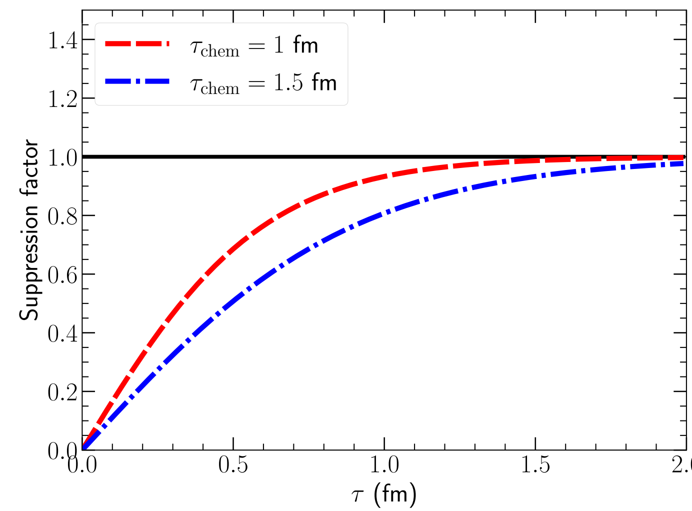
- In peripheral collisions, the lack of bulk viscous effects is the most apparent
- Hadronic observables -> Transport coefficients are sensitive to the early times dynamics
- Bayes analysis

Effect of pre-eq. phase: Photons

In KøMPøST the response functions are evaluated in pure glue kinetic theory. We need some statement about departure from kinetic equilibrium, about quark content.



Kurkela, Mazeliauskas PRL (2019)



Gale, Paquet, Schenke, Chen, arXiv:2106.11216

$$f_{\mathrm{q}} = \mathcal{S}\, f_{\mathrm{q}}^{\mathrm{eq.}}$$

- Vovchenko et al., PRC (2016)
- Oliva et al., PRC (2017)
- Churchill et al., PRC (2021)

Effect of pre-eq. phase: Photons

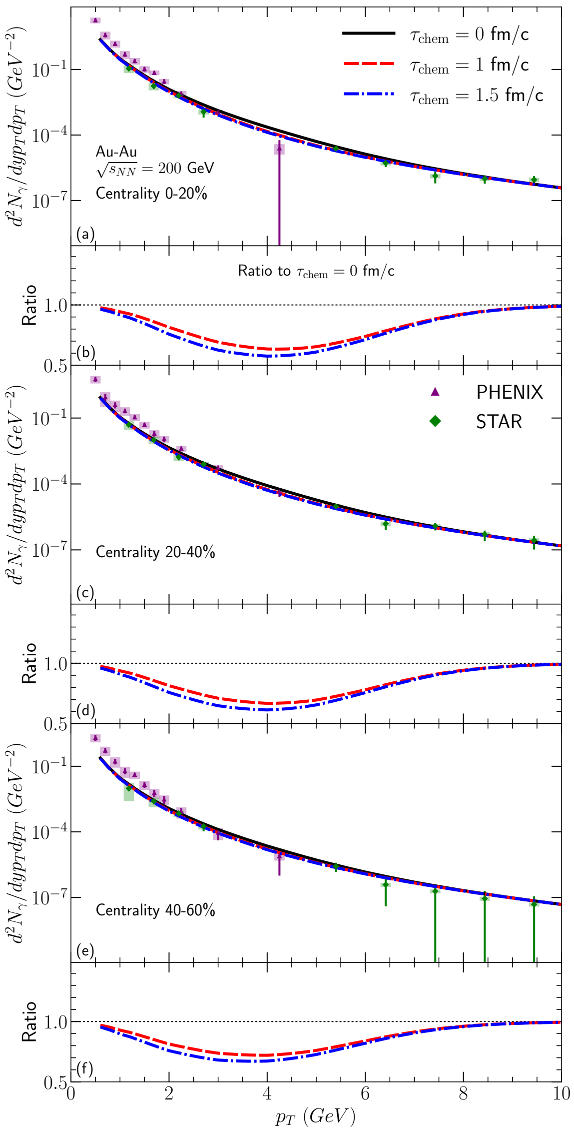
- "Cold photons" photons are calculated using pQCD@NLO
- During the KøMPøST phase, the energy density obtained from the energy-momentum tensor is used in conjunction with the QCD EOS to obtain a temperature
- The photon emission rates are integrated with the obtained T, flow velocity and viscous component profiles

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)		

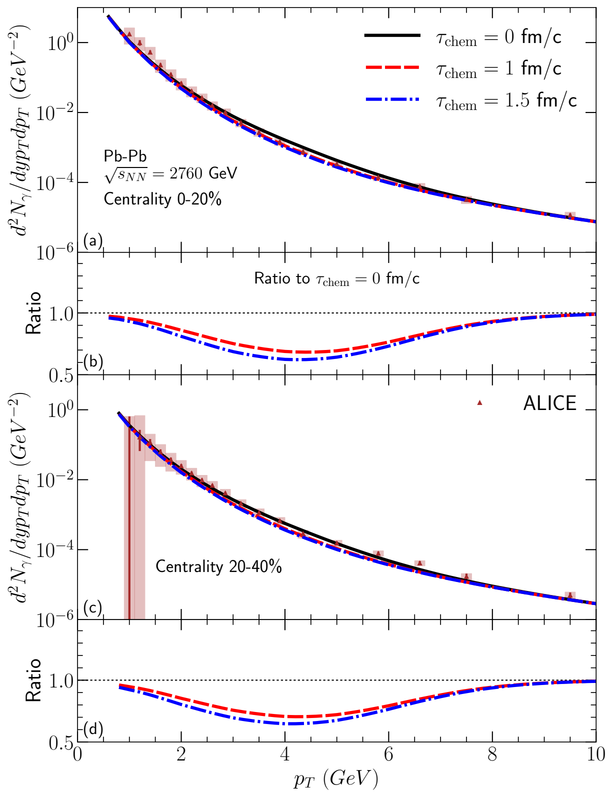
- Photons from UrQMD are added

PUTTING IT ALL TOGETHER

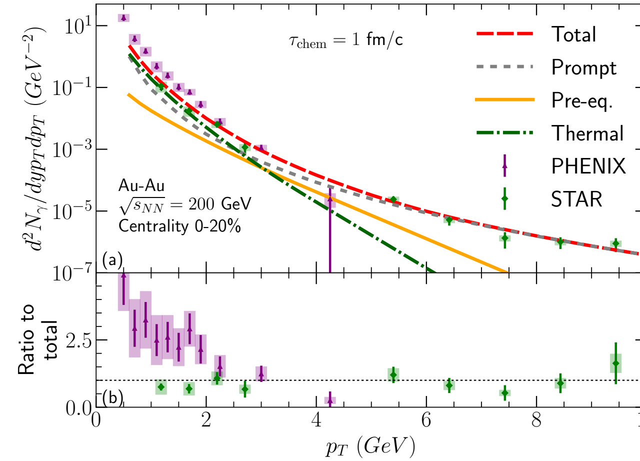
RHIC



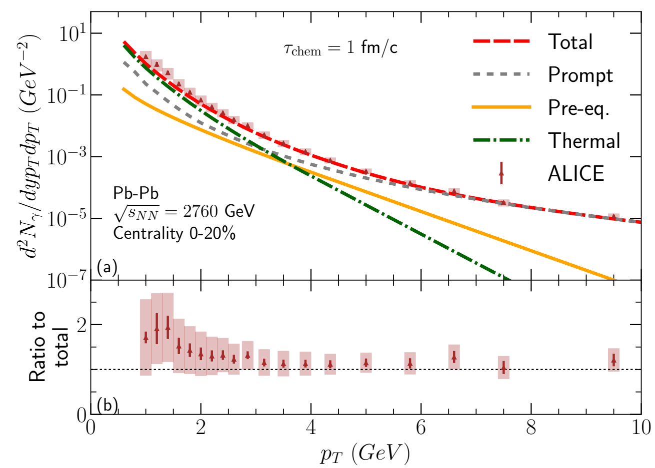
LHC



Effect of chem. eq. appears at intermediate p_T



Effect of pre-eq. photons appears at intermediate p_T



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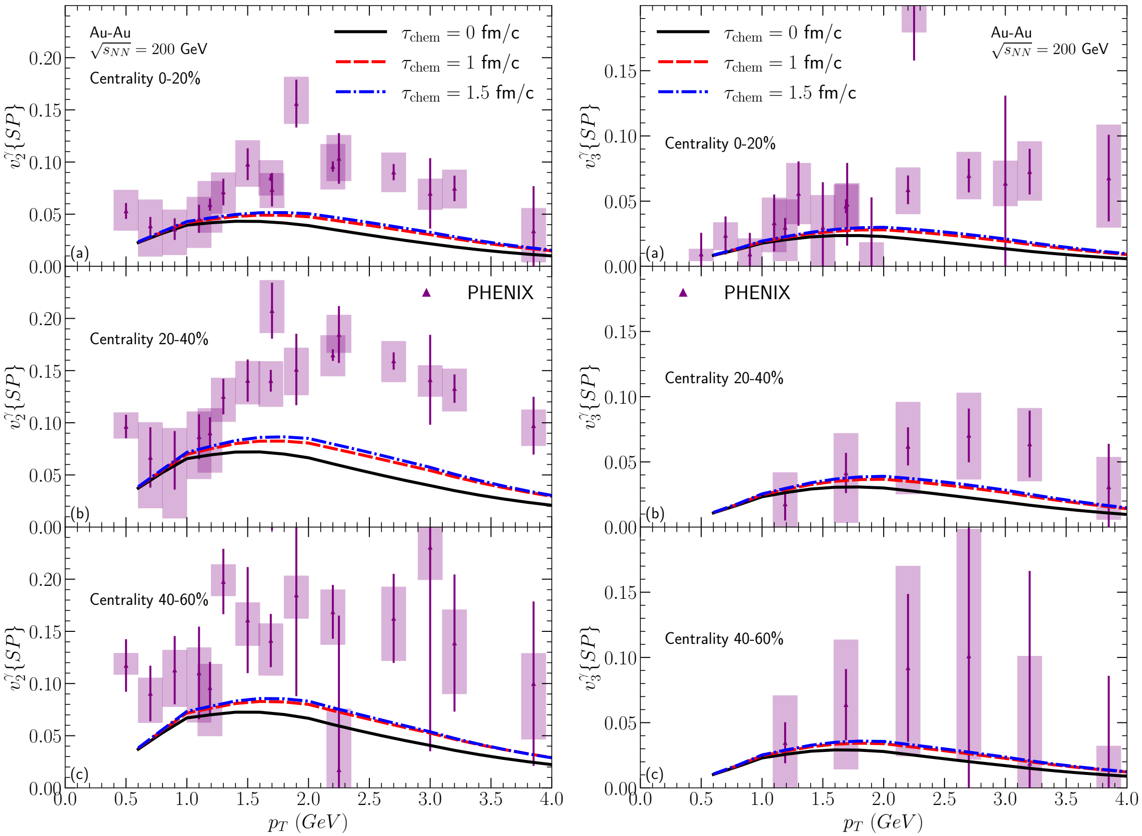
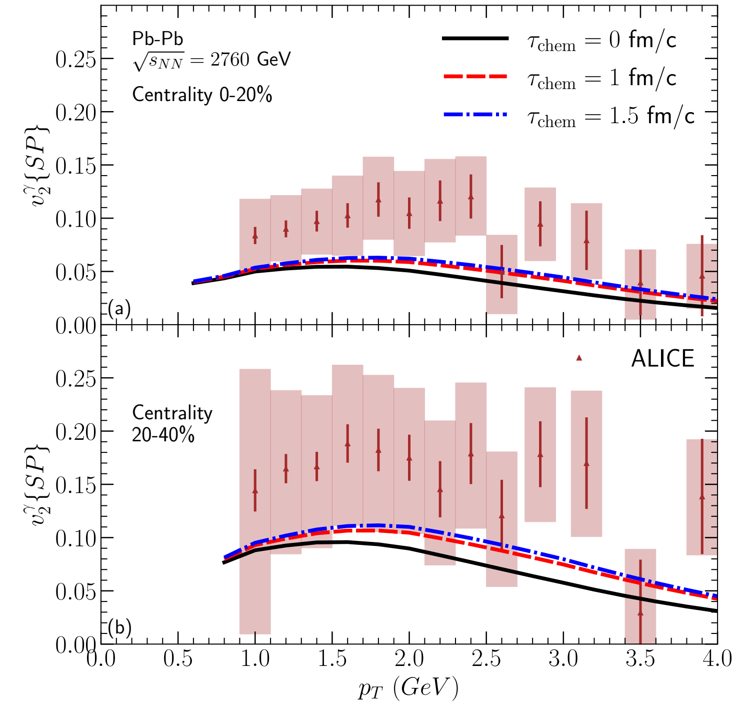
Photon momentum anisotropy

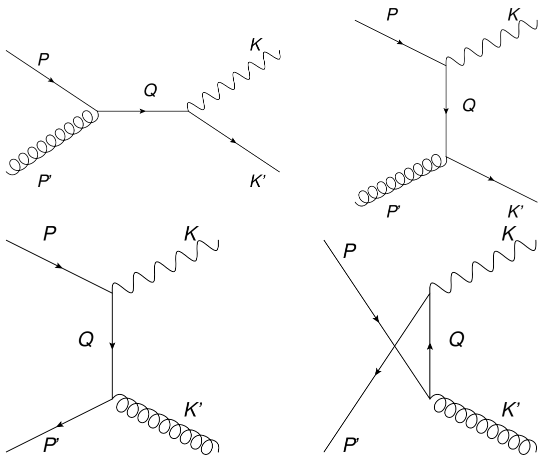




- The early time dynamics have some influence on the photon momentum anisotropy.
- The "photon flow puzzle" is more of a puzzle at RHIC than at the LHC

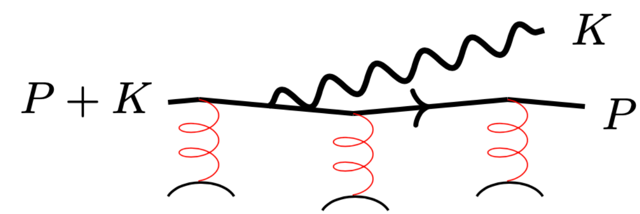
Partial conclusion: pre-hydro effects can matter and are within reach of (next?) generation analyses

More thoughts about the LPM effect in an non-isotropic medium



Chen, Paquet, Heinz, Gale, PRC (2015)

2 -> 2 scattering



Bremsstrahlung (LPM)

Problem: S. Mrowczynski, Phys. Lett. (1993) (2007); AMY, JHEP (2003); Hauksson, Jeon, Gale, NPA (2021)

The probability of photon emission is related to that of the quark being perturbed by the soft gluon fields. The collision kernel is

$$C(q_\perp) = g^2 C_F \int \frac{dq^0 dq^z}{(2\pi)^2} D_{rr}^{\mu\nu}(Q) v_\mu v_\nu 2\pi\delta(v\cdot Q)$$

$$D_{rr}^{\mu\nu}(x,y) = \frac{1}{4}\langle\{A^\mu(x), A^\nu(y)\}\rangle$$

Density of soft gluons in the medium

$$D_{rr}^{\mu\nu}(Q) = D_{\rm ret}^{\mu\omega}(Q)\,\Pi_{aa}^{\omega\xi}(Q)\,D_{\rm adv}^{\xi\nu}(Q)$$

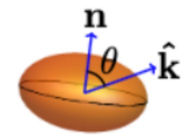
In thermal equilibrium $$D^{\mu\nu}_{rr}(Q) = \left(\frac{1}{2} + f_{\rm B}(q^0)\right)\left[D^{\mu\nu}_{\rm ret}(Q) - D^{\mu\nu}_{\rm adv}(Q)\right]$$

$$C(\mathbf{q}_\perp) = g^2 C_F T \left(\frac{1}{\mathbf{q}_\perp^2} - \frac{1}{\mathbf{q}_\perp^2 + m_D^2}\right)$$ Aurenche, Gélis, Zaraket, JHEP (2002)

$$D_{\rm ret}(t_x, t_y; \mathbf{p}) = \int \frac{dp^0}{2\pi}\, e^{-ip^0(t_x - t_y)}\, D_{\rm ret}(p^0, \mathbf{p})$$

In anisotropic media, poles develop in the upper half-plane

$$f(\mathbf{p}) = f_{\rm eq}\left(\sqrt{\mathbf{p}^2 + \xi(\mathbf{n}\cdot\mathbf{p})^2}\right)$$



$$D_{\rm ret} \sim \theta(t_x - t_y)\, e^{\gamma(\xi)(t_x - t_y)}$$ → Instabilities

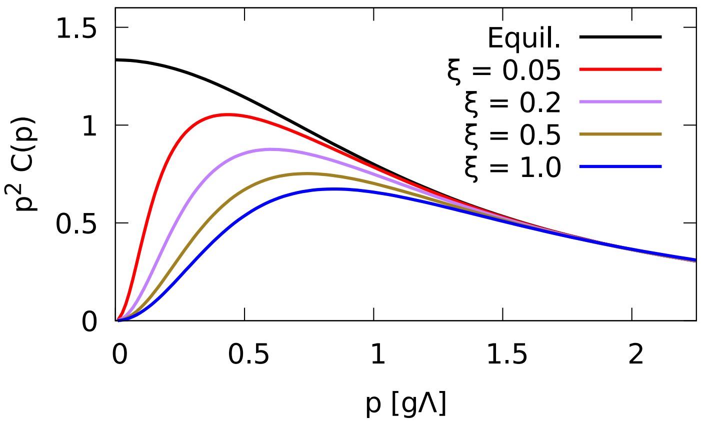
$$E^i_{\rm ind}(Q) \sim \int_{-\infty}^{t_x} dt_y e^{-\gamma t_y} = \infty$$

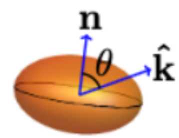
S. Mrowczynski, Phys. Lett. (1993)(2007); AMY, JHEP (2003); Romatschke and Strickland, PRD (2003);Hauksson, Jeon, Gale, NPA (2021)

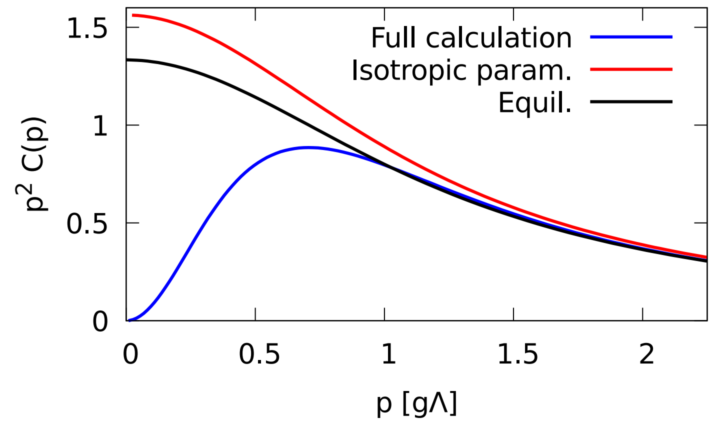
Initial value problem $$E^i_{\rm ind}(Q) \sim \int_0^{t_x} dt_y e^{-\gamma t_y} = \frac{e^{\gamma t_x} - 1}{\gamma}$$ $$\gamma \sim \xi^{3/2} g \Lambda$$

Affects the structure of $D^{\mu\nu}_{\rm rr}(Q)$ and of $C(\mathbf{q}_\perp)$

Hauksson, Jeon, Gale, arXiv:2109.04575;
S. Hauksson, PhD Thesis (2021)







$\theta = 0$

$\theta = \pi/2,\ \xi = -0.5$

Transverse momentum broadening of a hard parton,
also direct consequence on photon production

Hauksson, Jeon, Gale, arXiv:2109.04575

- Progress in non-equilibrium theory
- Paves the way to out of equilibrium simulations of photon production and jet energy loss and momentum-broadening
- Other pre-eq. dynamical calculations:

  Linnyk et al., PRC (2013); Greif et al., Nucl. Part. Phys. Proc. (2016); PRC (2017); Oliva et al., PRC (2017)

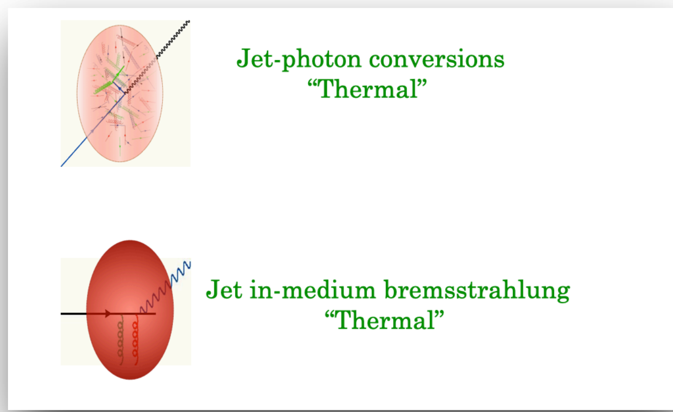
- Other sources under consideration: jets and mini-jets

A LESSER KNOWN CONTRIBUTION

Relativistic heavy-ion collisions produce jets, and (semi)hard components can exist down to the GeV scale (minijets)

Cao, Wang, Rept. Prog. Phys. 2021

"JET-MEDIUM" PHOTONS: SAME PHYSICS AS JET QUENCHING

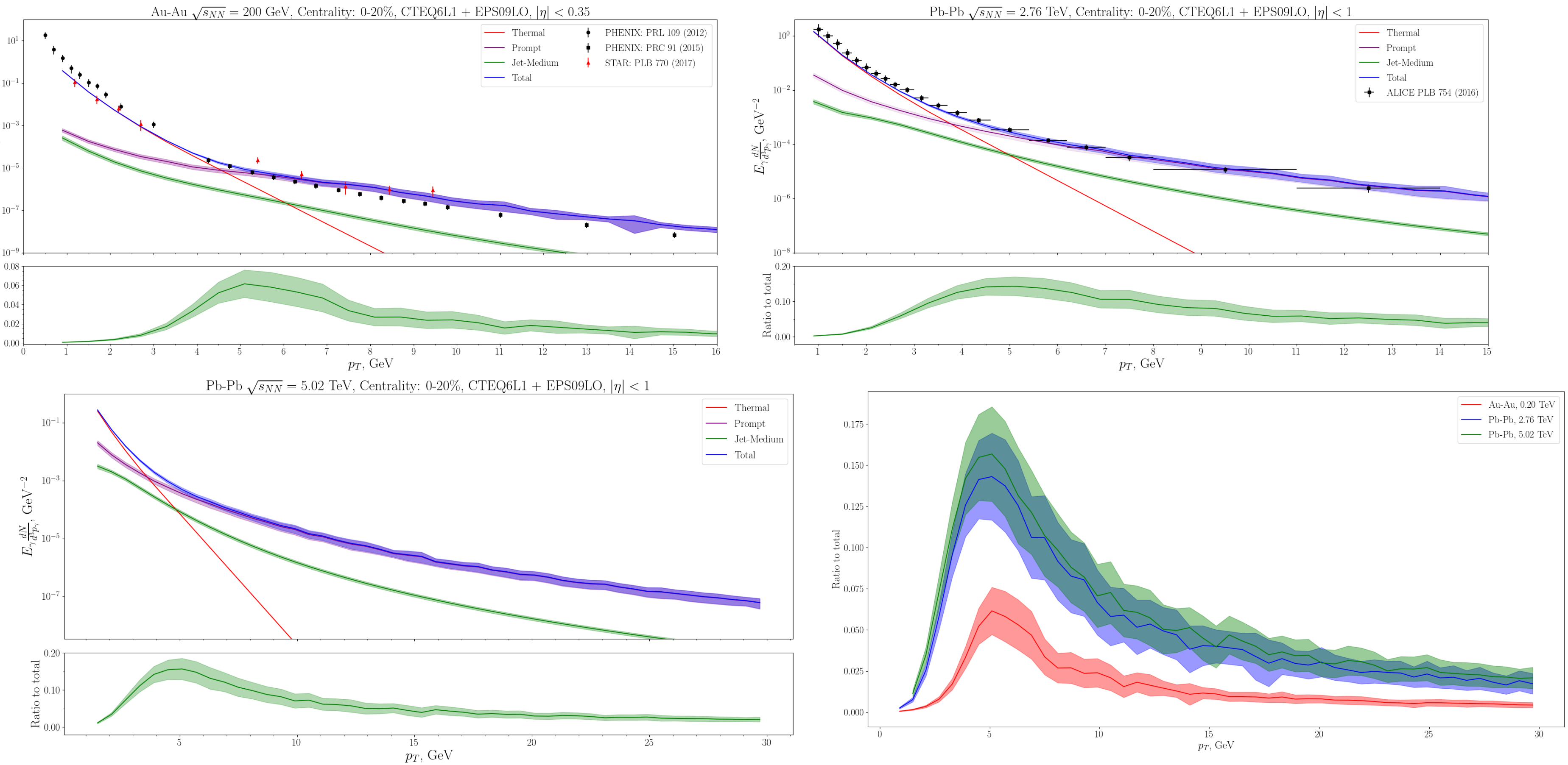


Fries, Müller, Srivastava, PRL (2004); Turbide, Gale, Jeon, Moore, PRC (2005); Turbide, Gale, Fries, PRL (2006)

- PYTHIA
- MARTINI
- jet-photon conversion; jet-photon bremsstrahlung

Rouzbeh Modarresi-Yazdi (2021)

A lesser known contribution (II)



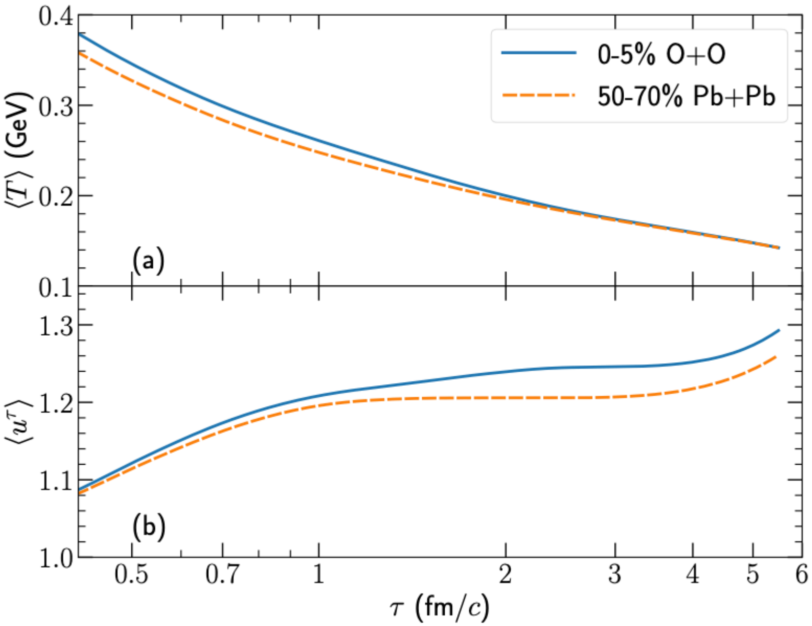
- Jet-medium photons are $\sim 15 - 20\,\%$ @LHC
- Abundance depends on energy-loss details
- v_n

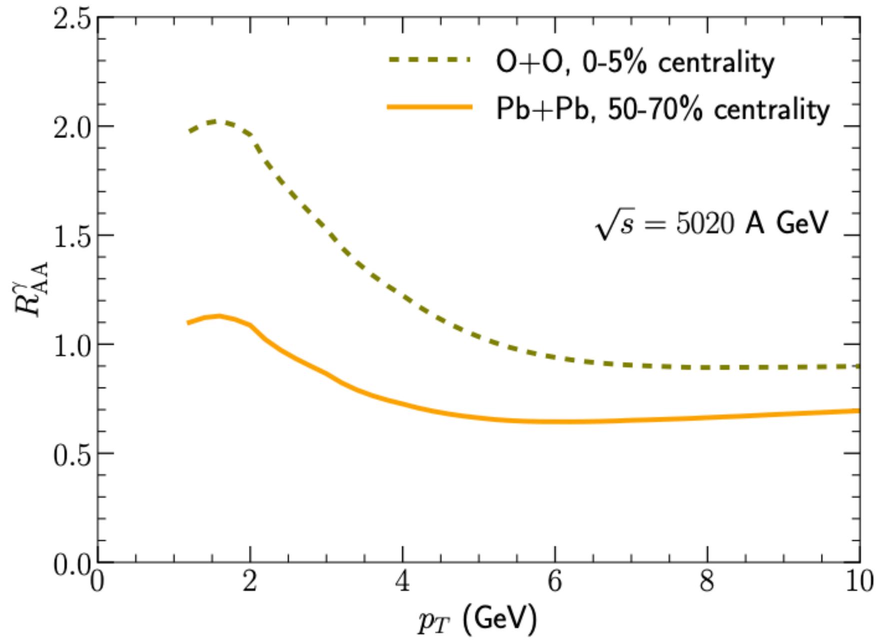
Rouzbeh Modarresi-Yazdi (2021)

Partial conclusion: needs to be integrated consistently with the other sources

Small systems?

Multiplicity in collisions @ 5 TeV: O+O (0-5%) ~ Pb+Pb (50-70%)





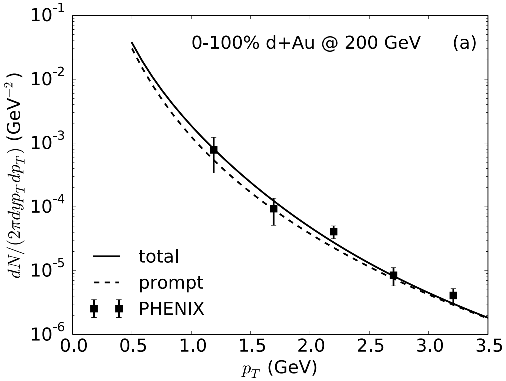
- Difficult to find evidence of higher T is small systems with hadronic observables
- R^γ_{AA} shows a clear distinction

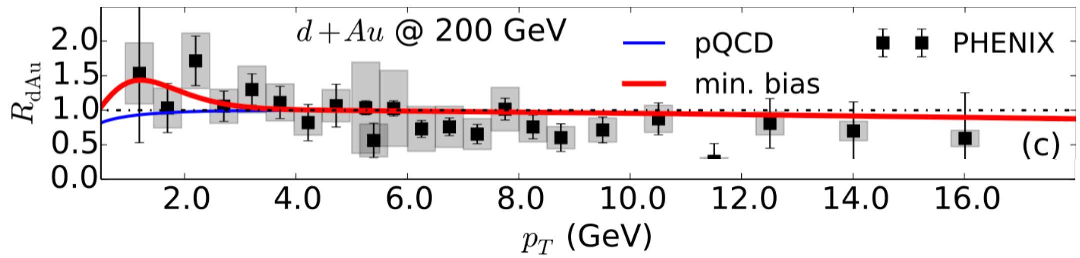
arXiv:2106.11216

Conclusions

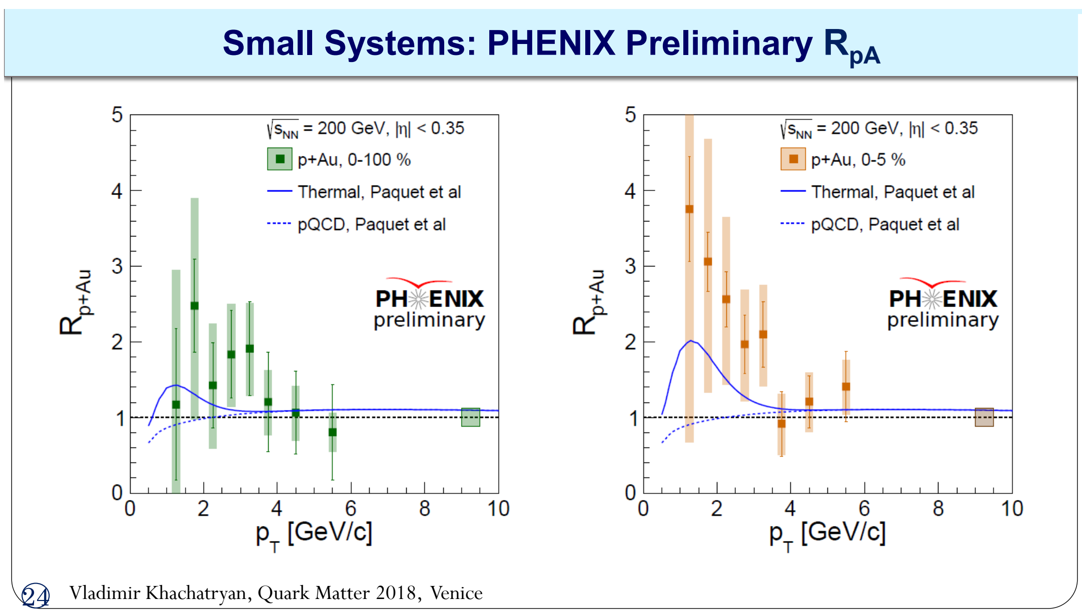
- Much work to be done in the physics of early-time heavy-ion collisions
- Pre-hydro effects matter and are within reach of experiments
- pA collisions are especially sensitive to out-of-equilibrium aspects
- Measurements of low momentum photons (real and virtual) are crucial for pQCD

Comparing against what is currently known, and a prediction

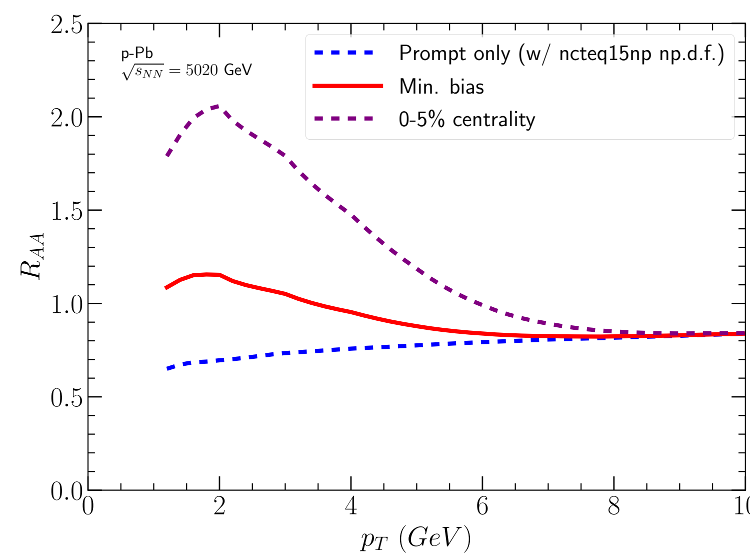




C. Shen et al., PRL (2016)



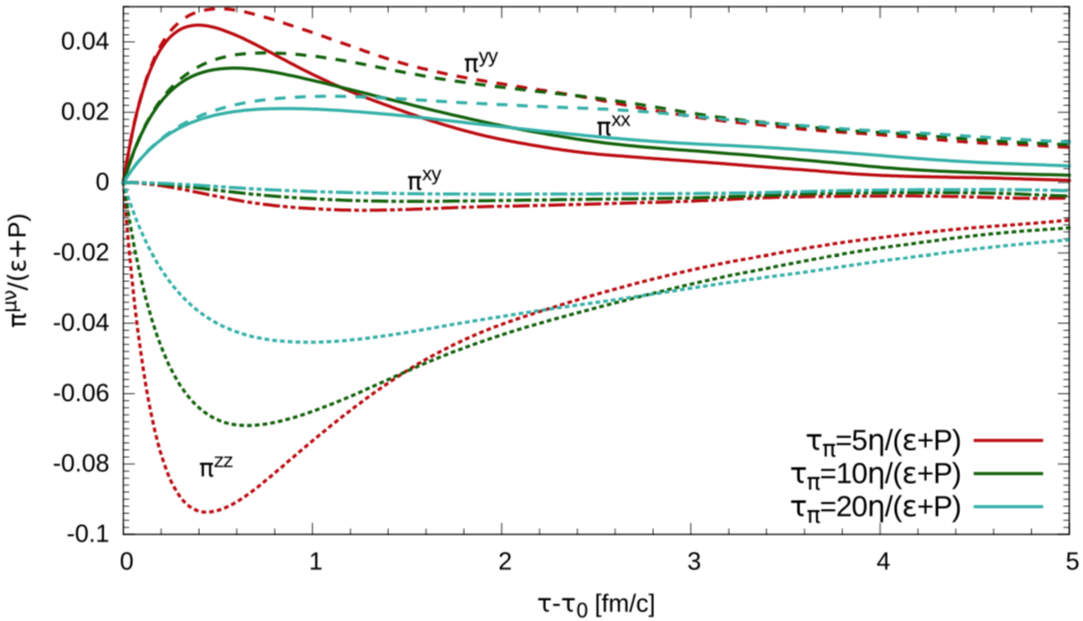
and a prediction:



Gale, Paquet, Chen, Schenke (2021)

Keeping an eye on the viscous corrections

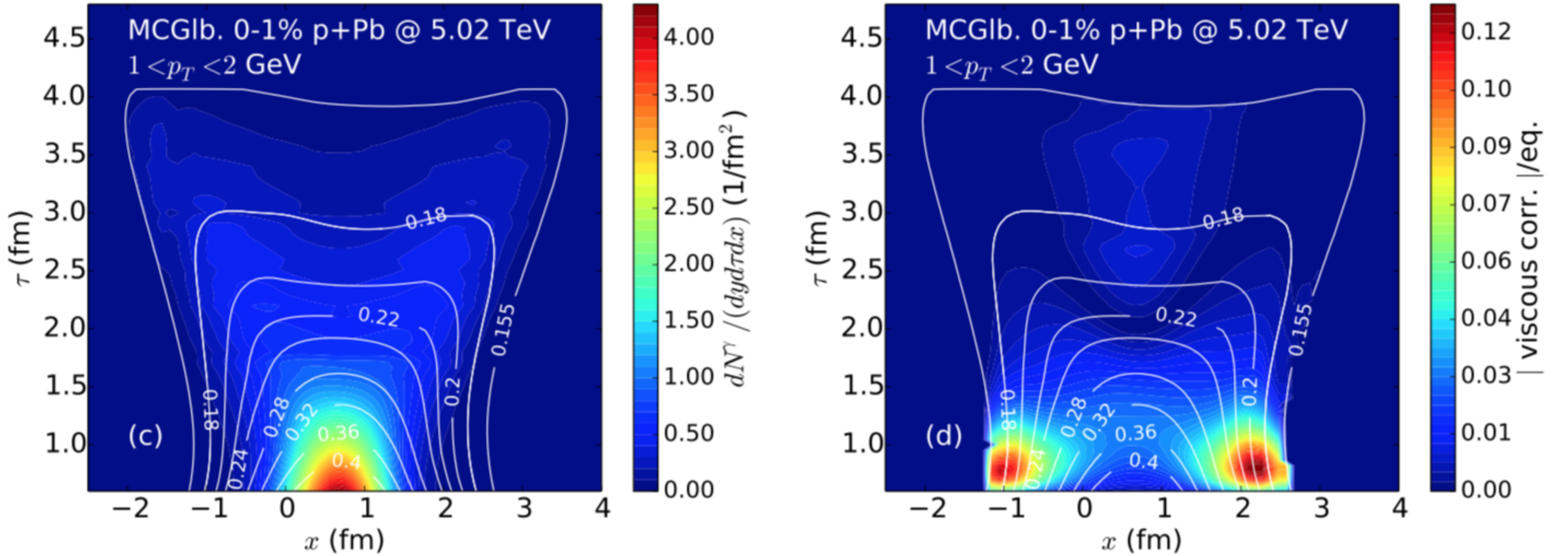
$$\delta f = f_0\left(1 \pm (2\pi)^3 f_0\right)\frac{\pi^{\mu\nu}}{2\left(\epsilon + P\right)T^2}k_\mu k_\nu$$



- Au-Au@200GeV/A, mid-central collisions

G. Vujanovic et al., PRC (2016)

Keeping an eye on the viscous corrections



C. Shen et al., PRC (2017)