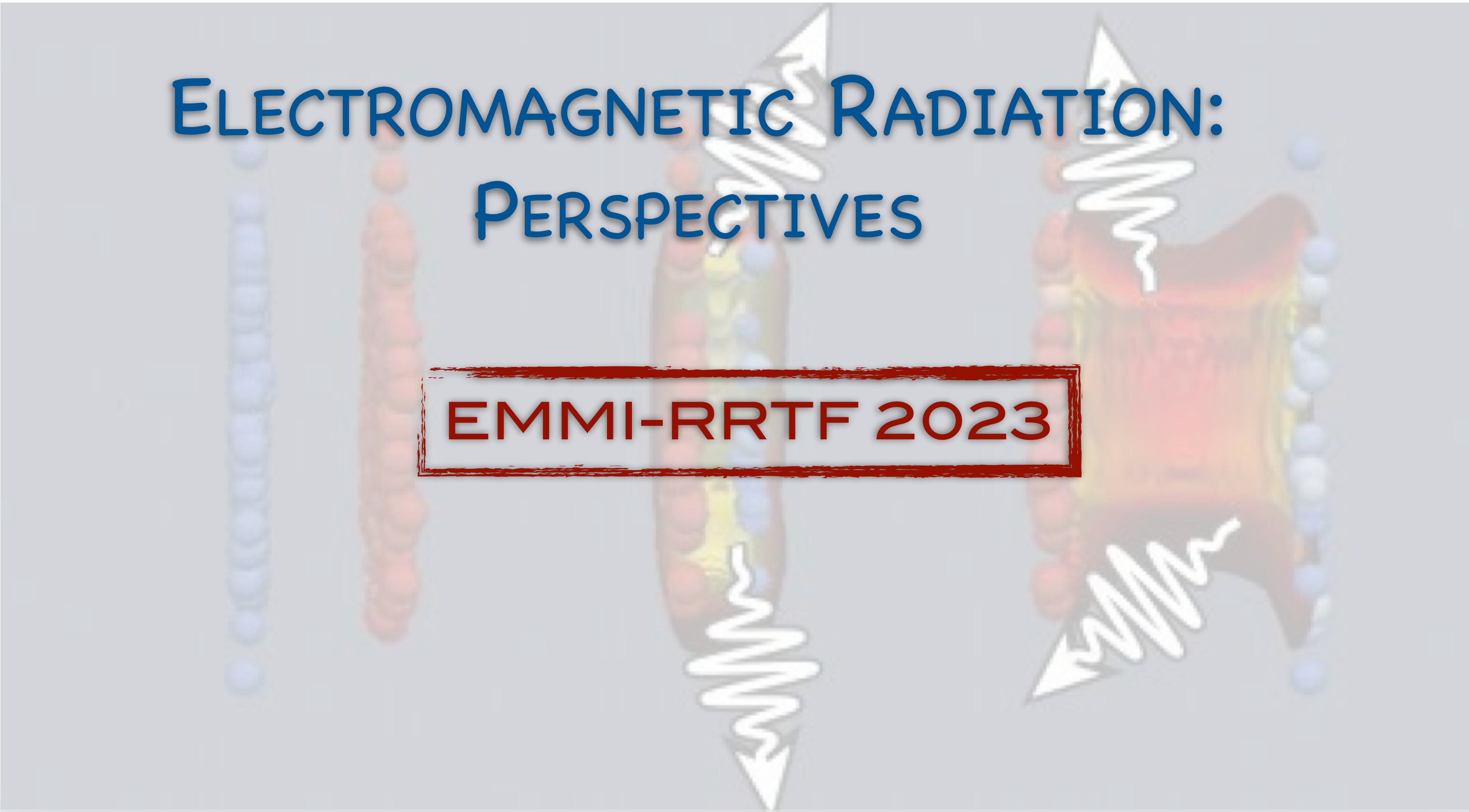
Electromagnetic Radiation: Perspectives



EMMI-RRTF 2023

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**

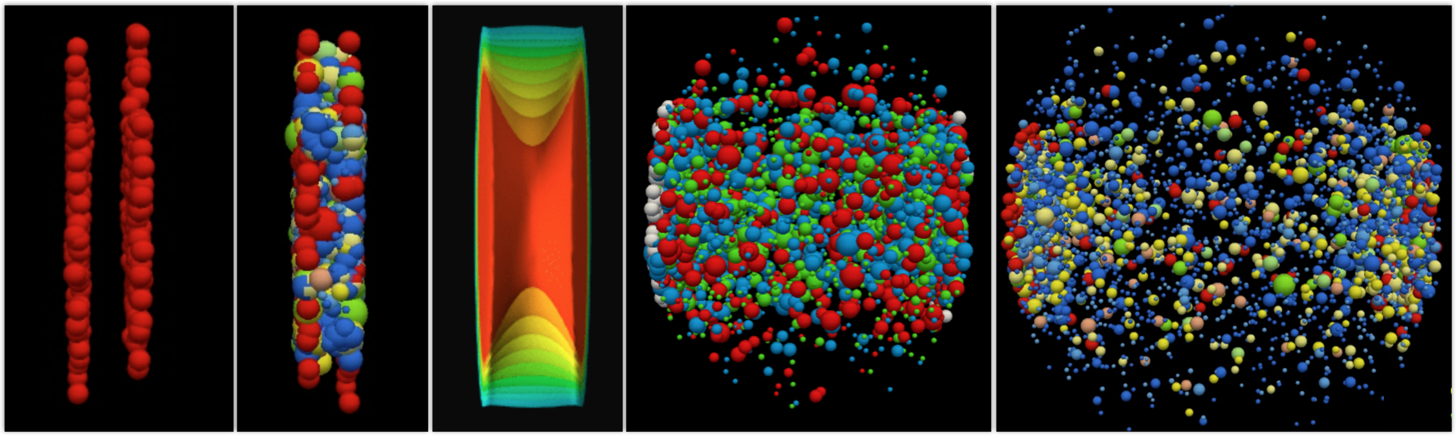
They enjoy a unique status

- Cold photons
- Pre-eq. photons
- Small systems
- Under-explored features

Disclaimer: Not a review talk, but a travelog (●)

Direct photons and HIC modelling

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



pQCD photons
"primordial" photons

"Pre-eq. photons"

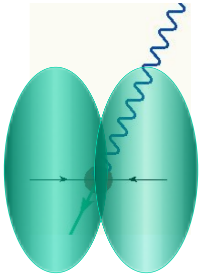
"Plasma photons"

"Hadronic medium photons"

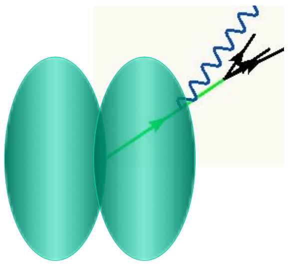
Late stage reactions
Decay photons

(*) Real & virtual

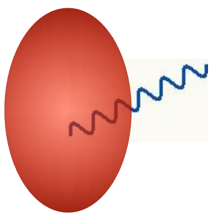
Direct photon sources
(real and/or virtual)



Hard direct photons. pQCD with shadowing
Non-thermal

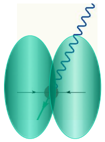


Fragmentation photons. pQCD with shadowing
Non-thermal



Thermal photons
"Thermal"

Direct photon sources
(real and/or virtual)



Hard direct photons. pQCD with shadowing
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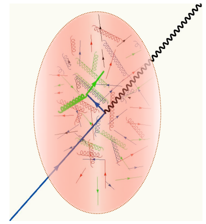
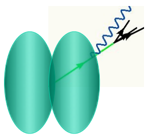


Jet-photon conversions
"Thermal"



Fragmentation photons. pQCD with shadowing
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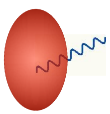
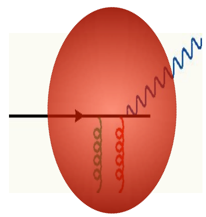
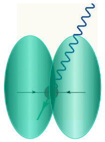


Thermal photons
"Thermal"

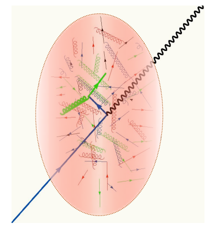


Jet in-medium bremsstrahlung
"Thermal"

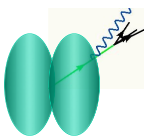
Direct photon sources
(real and/or virtual)



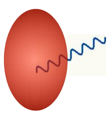
Hard direct photons. pQCD with shadowing
Non-thermal



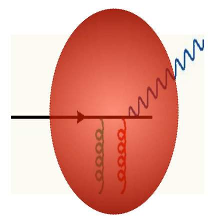
Jet-photon conversions
“Thermal”



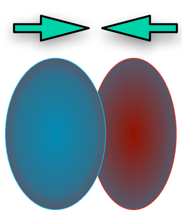
Fragmentation photons. pQCD with shadowing
Non-thermal



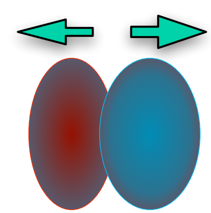
Thermal photons
“Thermal”



Jet in-medium bremsstrahlung
“Thermal”



Pre-hydro?



Post-hydro?

About photon fragmentation functions

$$\frac{d}{d\log\mu^2} D_i^\gamma(z,\mu^2) = \sum_j P_{ij}(z,\mu^2) \otimes D_j^\gamma(z,\mu^2)$$

The evolution kernels

$$P_{ij}(z,\mu^2) = \sum_{m,n} \left(\frac{\alpha(\mu^2)}{2\pi}\right)^m \left(\frac{\alpha_s(\mu^2)}{2\pi}\right)^n P_{ij}^{(m,n)}(z)$$

Can be written as (LO in α)

$$\frac{d}{d\log\mu^2} D_i^\gamma(z,\mu^2) = k_i^\gamma(z,\mu^2) + \sum_j P_{ji}(z,\mu^2) \otimes D_j^\gamma(z,\mu^2)$$

Perturbative

Non-perturbative

Little new info on photon FF over the last 25 years. Most data used to fit FF are single-inclusive photon production, in hadronic reactions dominated by direct photon production

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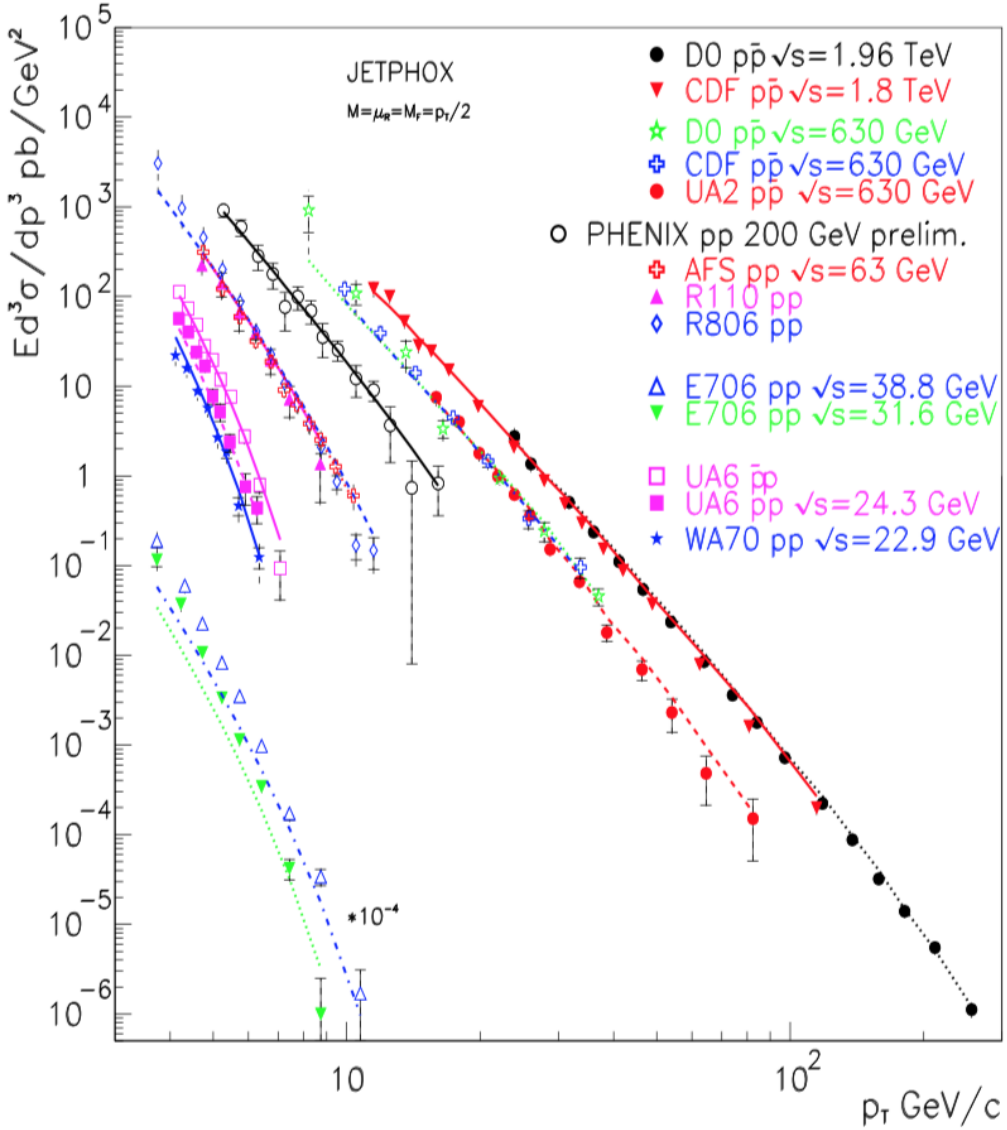
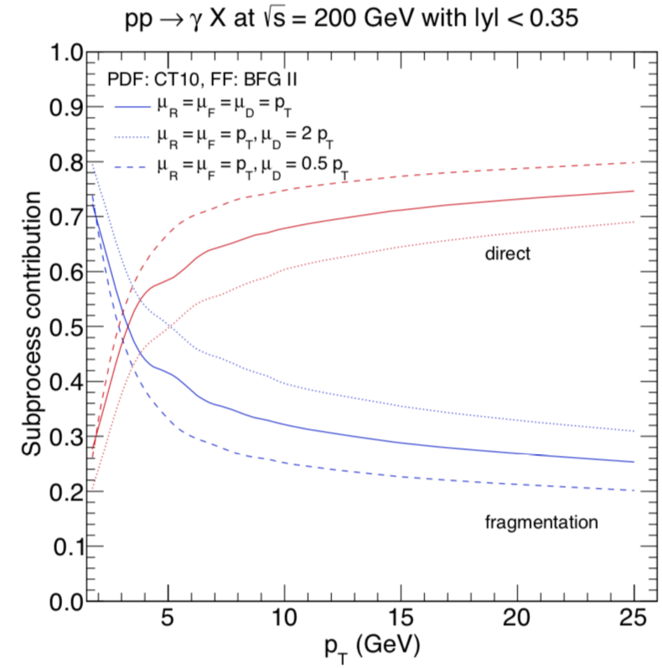
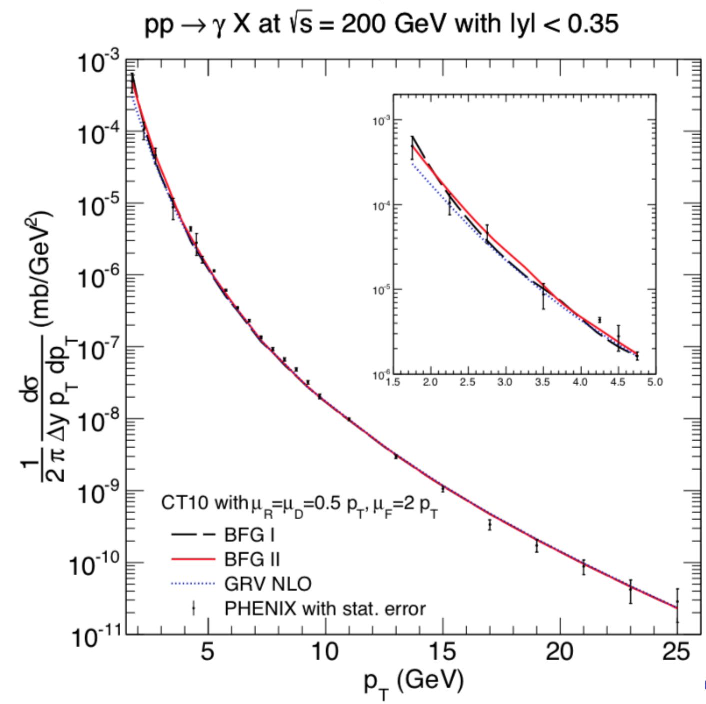
pQCD photon calculations and uncertainties



Aurenche et al., PRD (2006)

Klasen, König, Eur. PJC (2014)





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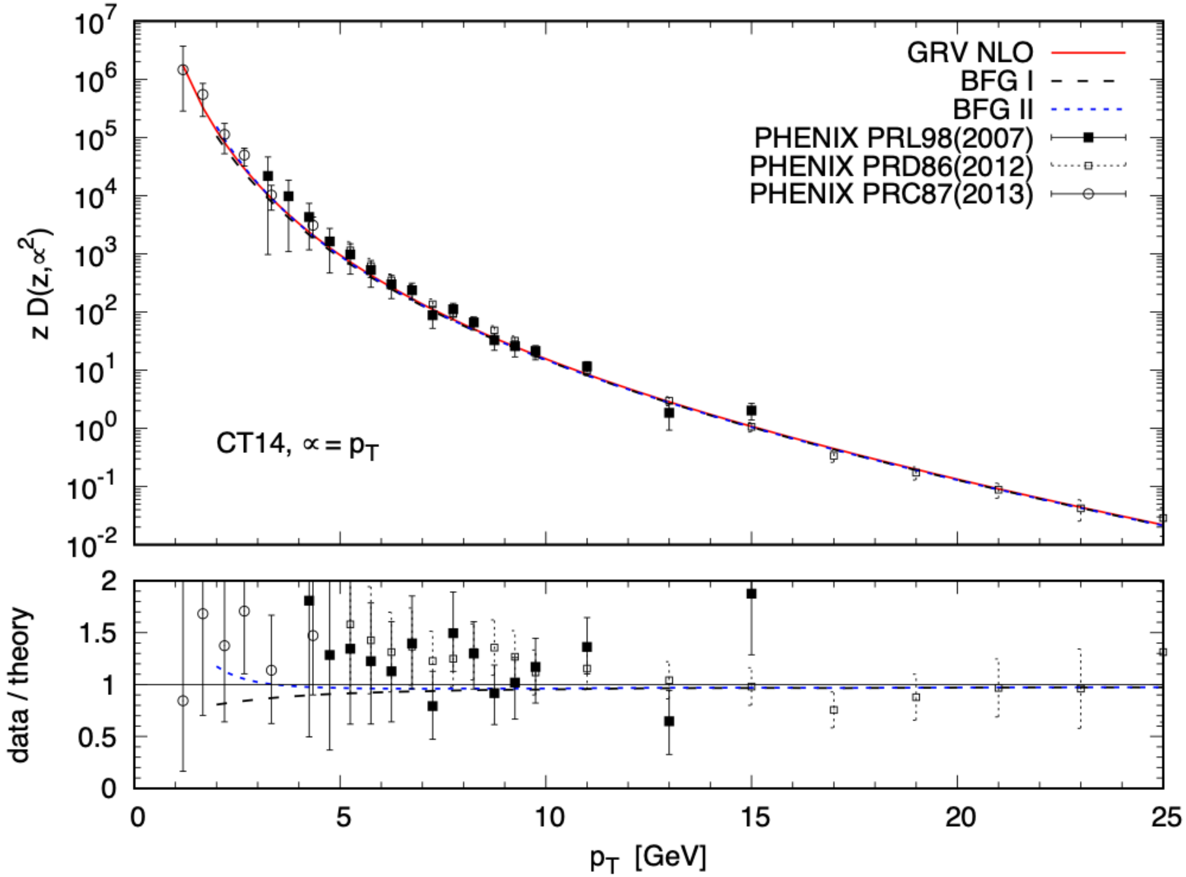
pQCD photon calculations and uncertainties



Kaufmann, Mukherjee, and Vogelsang, arXiv: 1708.06683

Stresses the need for a direct photon measurement in nucleon-nucleon collisions

Kaufmann, Mukherjee, Vogelsang, CERN Proc. 2018
Fragmentation component: $e^+e^- \to (\mathrm{jet}\,\gamma)\,X$

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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:

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \quad \text{(photons)} \quad \left(= \frac{i}{2(2\pi)^3}(\Pi^\gamma_{12})^\mu_\mu \right)$$

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

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

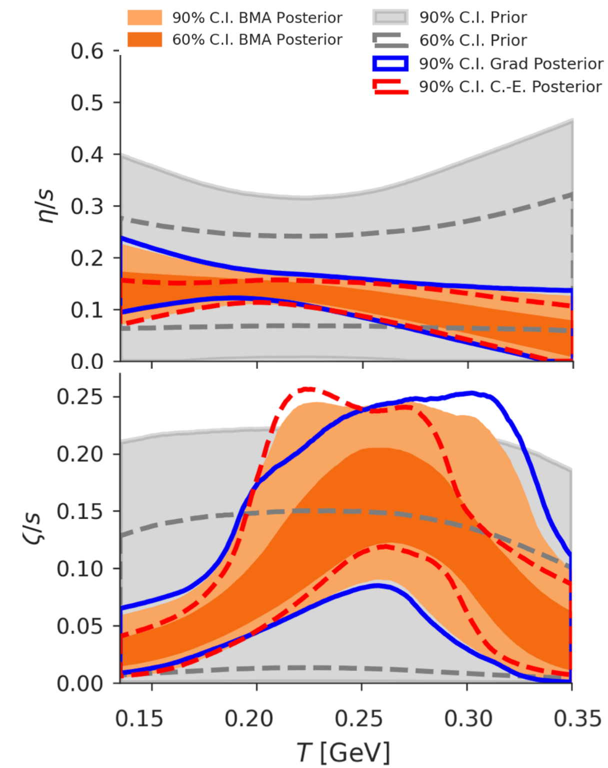
  Turbide, Rapp, Gale PRC (2004)
  C. Gale, Landolt-Bornstein (2010)
  Heffernan, Hohler, Rapp PRC (2015)

Photons and fluid dynamics

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

$$f_0(u^\mu p_\mu) = \frac{1}{(2\pi)^3}\frac{1}{\exp[(u^\mu p_\mu - \mu)/T]\pm 1} \qquad f_0 \to f_0 + \delta f(\pi,\zeta)$$

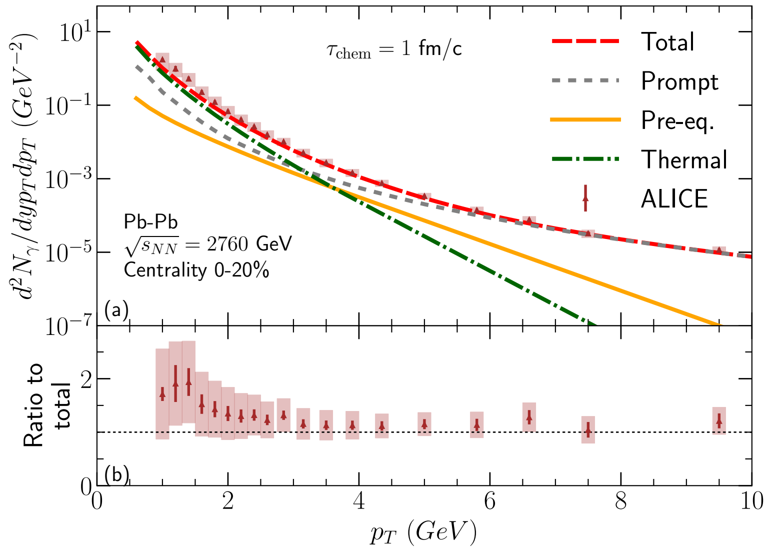
Rate/viscous correction	Ideal	I+Shear	I+S+Bulk
QGP: 2->2	AMY (2001)	Shen et al., PRC (2015)	• Paquet et al., PRC (2016) • Hauksson, Jeon, Gale (2017)
QGP: LPM-Brem.	AMY (2001)		Hauksson, Jeon, Gale (2017)
Hadronic: Meson reactions	• Turbide et al. , PRC (2004) • van Hees et al., PRC (2011)	• Dion et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

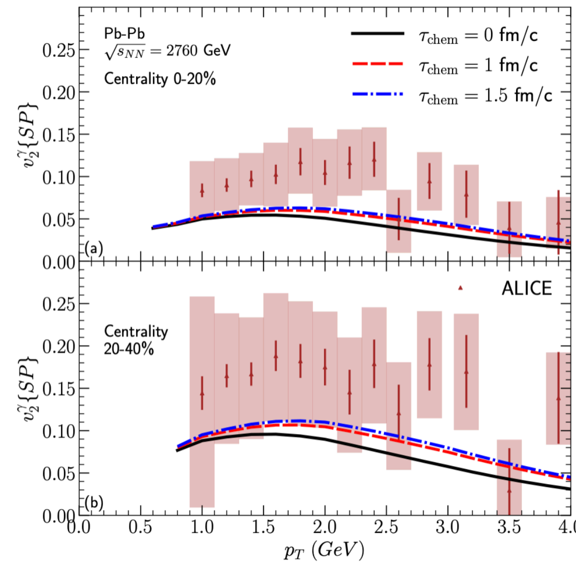


Heffernan, Gale, Jeon, Paquet 2306.09619

- NLO rates not shown
- Work left to be done to make hydro and photon emission consistent

The revealing power of photons in small systems





Gale, Paquet, Schenke, Shen, PRC (2022)

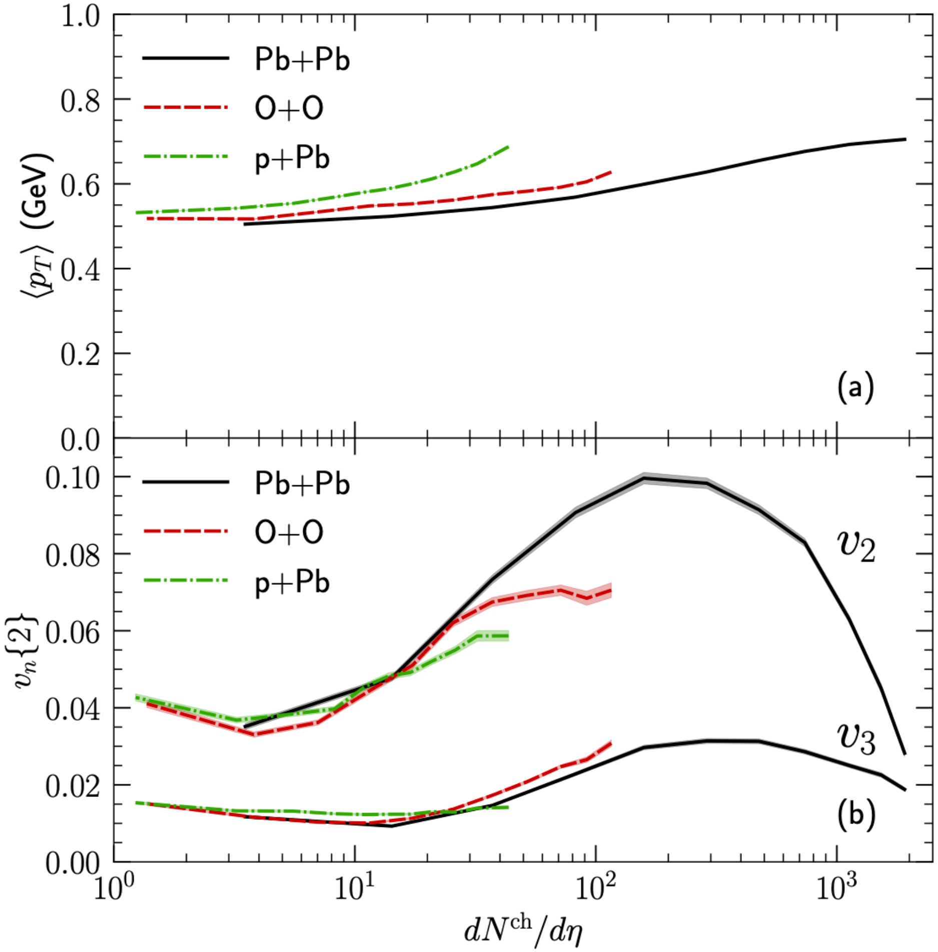
"Small systems" can be used to explore particle production mechanisms as a function of system size

$$dN_{\rm ch}/d\eta\,|^{\rm O+O}_{\rm MB} \approx dN_{\rm ch}/d\eta\,|^{\rm Pb+Pb}_{70-80\%}$$

$$dN_{\rm ch}/d\eta\,|^{\rm O+O}_{0-5\%} \approx dN_{\rm ch}/d\eta\,|^{\rm Pb+Pb}_{50-70\%}$$

Also useful for jet studies Huss, Kurkela, Mazeliauskas et al., PRC (2021), PRL (2021)

Hadronic observables & system size



Small systems have larger p_T at same multiplicity. Larger gradients

At a given multiplicity,

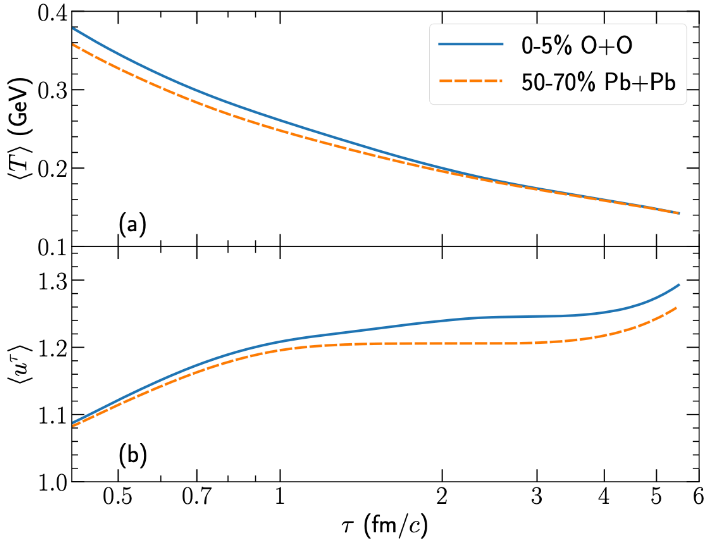
$v_2(\mathrm{Pb}+\mathrm{Pb}) > v_2(\mathrm{O}+\mathrm{O}) > v_2(\mathrm{p}+\mathrm{Pb})$

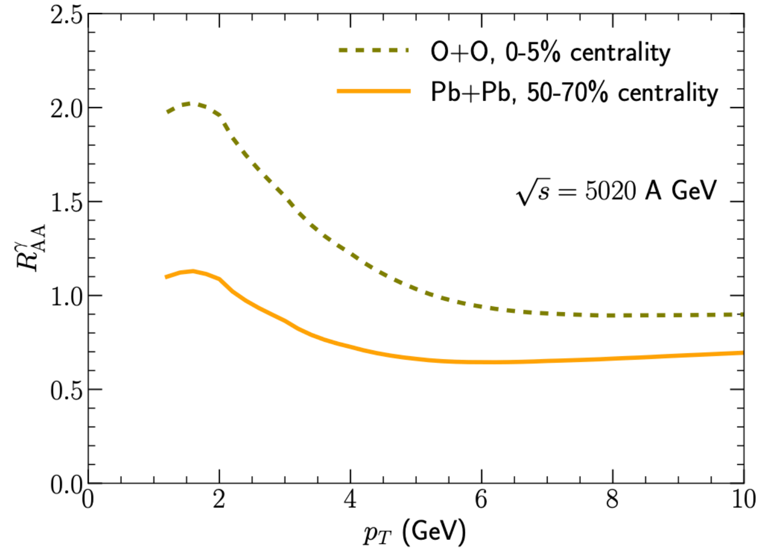
$v_3 \approx$ constant

Gale, Paquet, Schenke, Shen, PRC (2022)

At equivalent multiplicities:

$$dN_{\rm ch}/d\eta\,|^{\rm O+O}_{0\text{–}5\%} \approx dN_{\rm ch}/d\eta\,|^{\rm Pb+Pb}_{50\text{–}70\%}$$

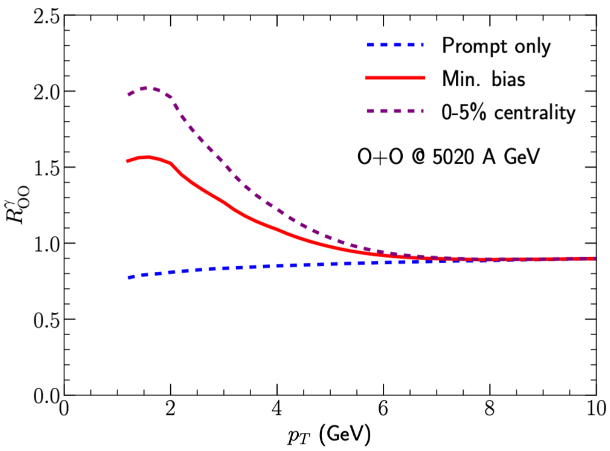




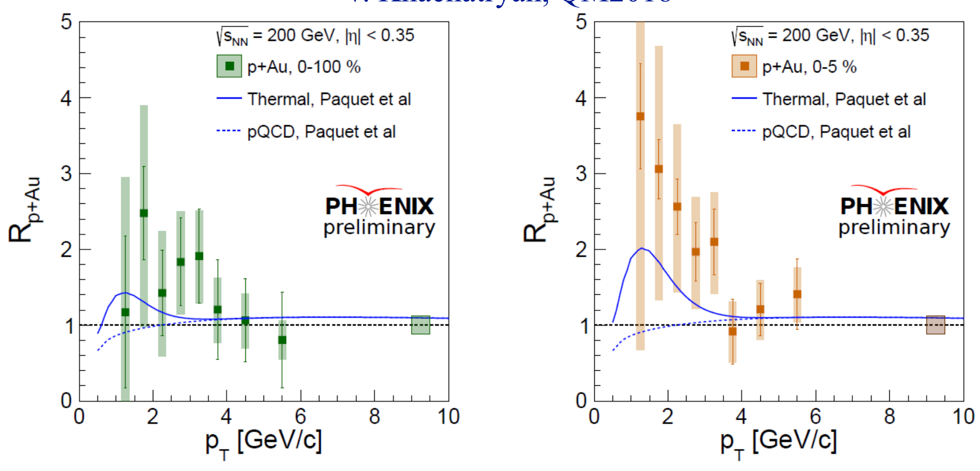
Smaller systems have a higher T; difficult to assess with hadronic observables

For $p_T \sim 2$ GeV, $R^\gamma_{\rm OO}$ is enhanced by $\sim 80\%$

Gale, Paquet, Schenke, Shen, PRC (2022)



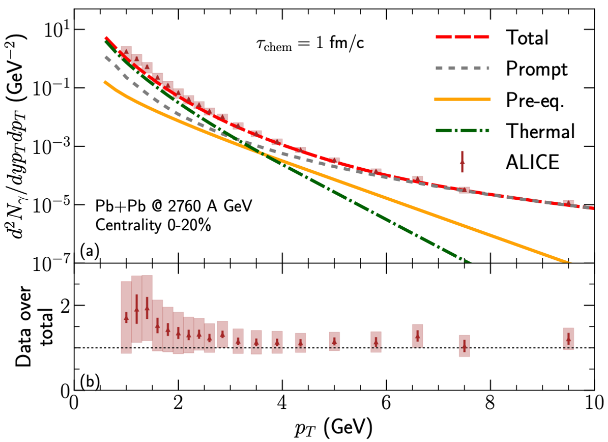
V. Khachatryan, QM2018

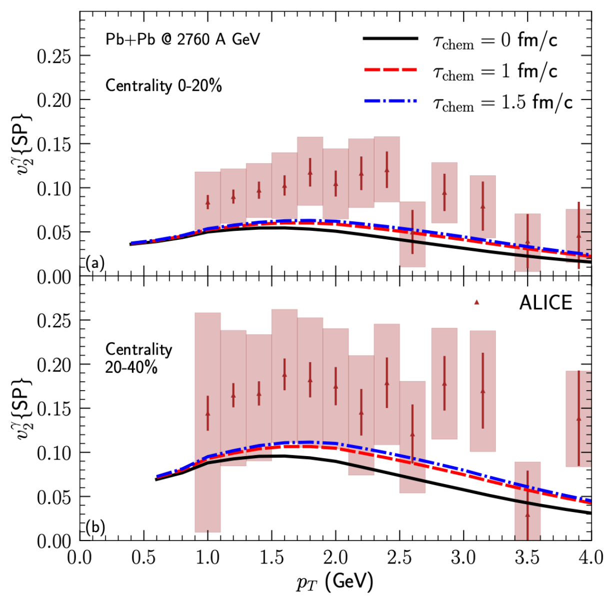


Partial conclusion(s)

- Small systems explore modelling aspects
- Photons are ideal probes
  - Sensitive to both the modelling and to local conditions
- Nucleon-nucleon baseline is, again, very important

“Pre-hydro” photons?

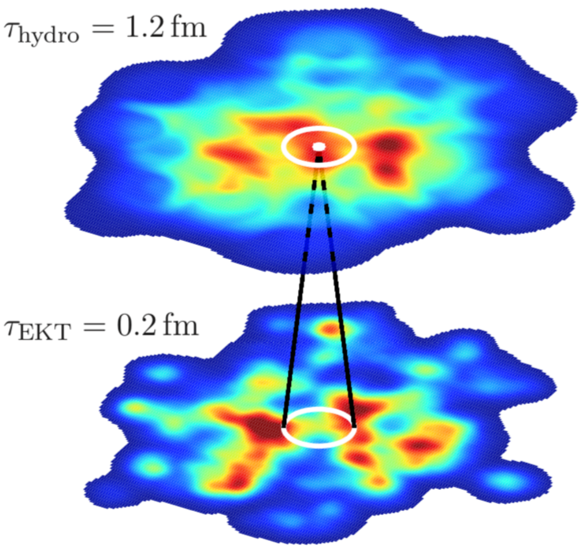




- Kinetic theory approach
  - BAMPS (M. Grief, PhD (2018))
  - PHSD (O. Linnyk et al., Prog. Nucl. Part. Phys. (2016))
  - J. Churchill et al., PRC (2021)
  - KøMPøST, PRC (2022)
  - …
- Field theory approach
  - M. Strickland, PLB (1994)
  - R. Baier, M. Dirks, K. Redlich, D. Schiff, PRD (1997)
  - J. Serreau, JHEP (2004)
  - S. Hauksson, S. Jeon, C. Gale, PRC (2018)
  - …

Some words about KøMPøST;
An EKT approach to the pre-hydro phase

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



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

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

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

Linear response:

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

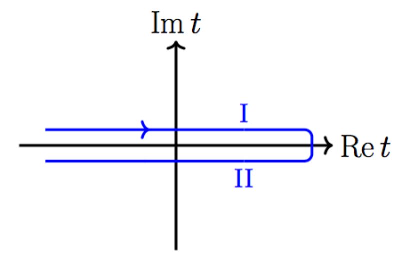
- BE is 6+1 dimensions in general
- Owing to scaling property, Green's functions can be evaluated and stored

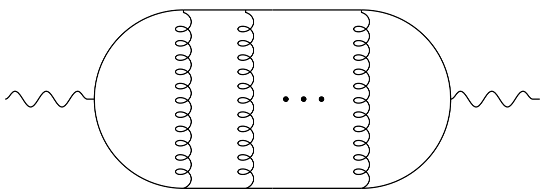
Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019); PRC 2019

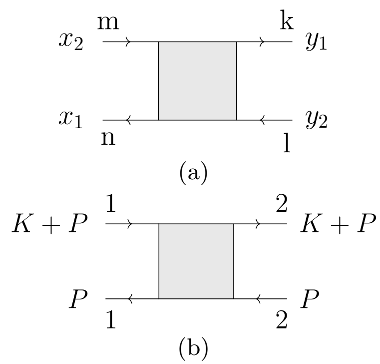
- KøMPøST is conformal
- KøMPøST has gluons only

Non-equilibrium field theory approach

$$\omega\frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3}\,\mathrm{Im}\Pi^R_{\mu\nu}(\omega,k)\frac{1}{e^{\beta\omega}-1} \rightarrow \omega\frac{d^3R}{d^3k} = \frac{i}{2(2\pi)^3}(\Pi_{12})^{\mu}{}_{\mu}$$







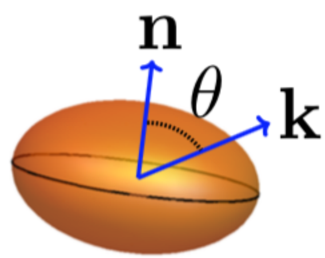
One can derive expression for hard quark and soft gluon propagators, to leading order, and construct the self-energy without using the KMS condition $G_{12}(Q) = -\,e^{\beta Q^0}G_{21}(Q)$

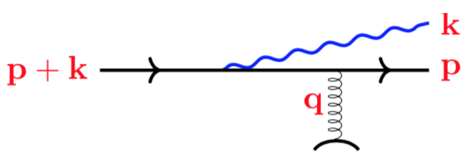
And the ladder diagrams are summed up in a Schwinger-Dyson equation

S. Hauksson, PhD (2021)

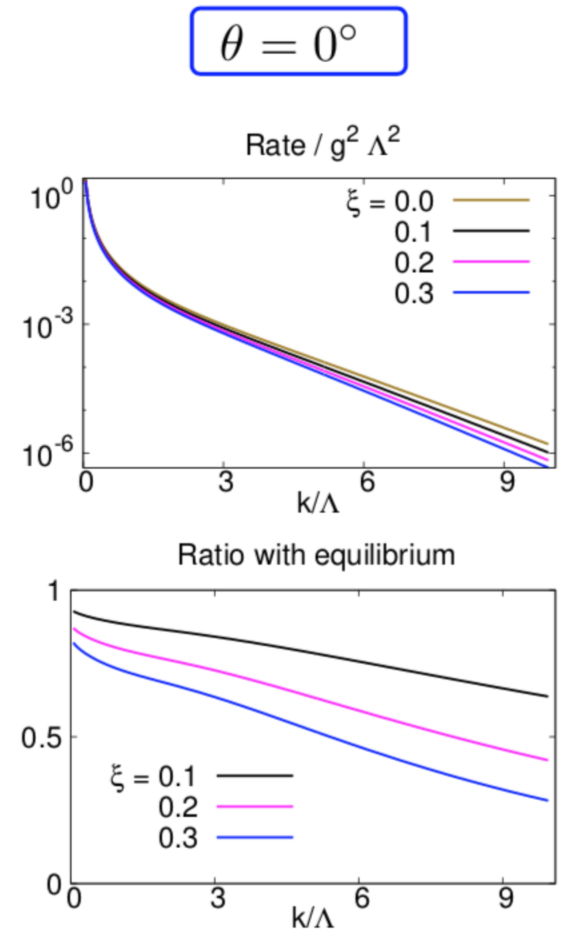
Field theory approach still to be implemented
A preliminary exploration of the phenomenology

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





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

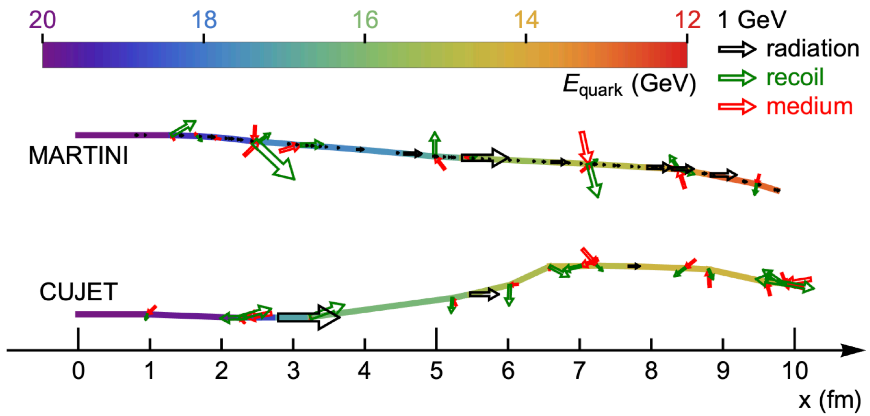


(Much) More needs to be done

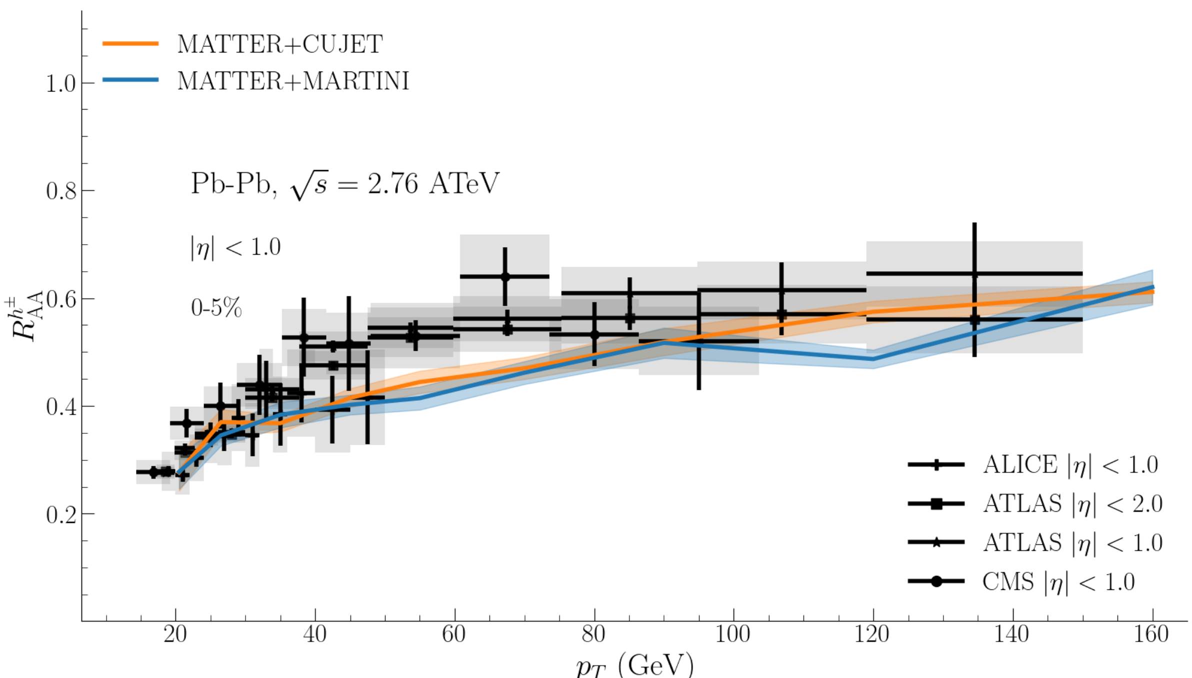
RHIC-BES

Other "pre-hydro" source: (Mini)jet-medium photons

First part: jet propagation



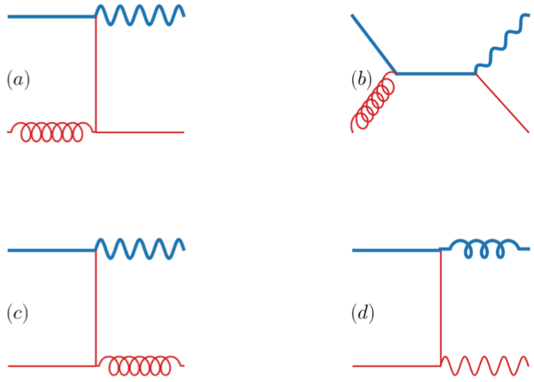
Brick temperature: T = 0.3 GeV



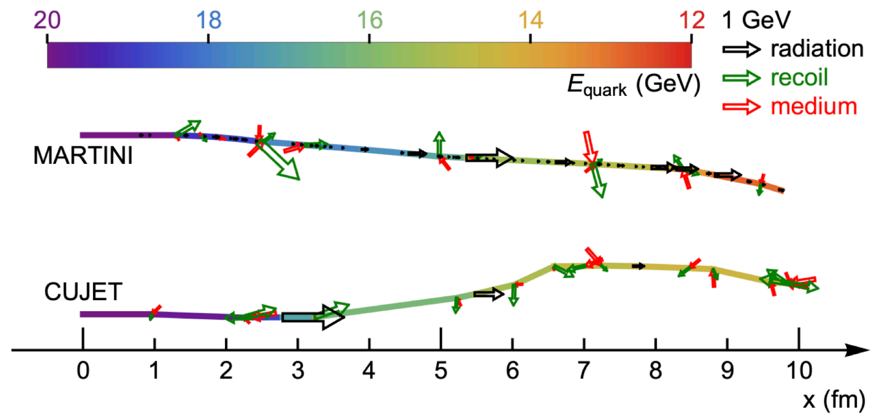
- Ensure that charged particle R_{AA}^{ch} is consistent
- Ensure that R_{AA}^{jet} is consistent

R. Modarresi-Yazdi, HP2023

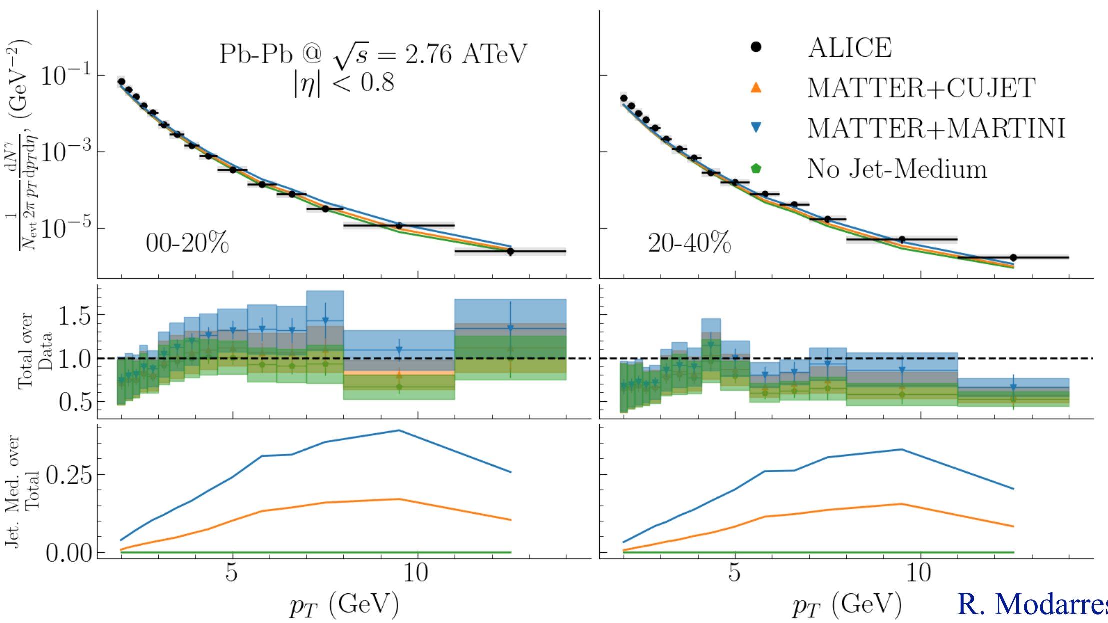
Other "pre-hydro" source: (Mini)jet-medium photons



Jet-photon conversion at LO



Brick temperature: T = 0.3 GeV



R. Modarresi-Yazdi, HP2023

- A source to consider
- Jet and hydro evolution needs to be concurrent
- Details of the parton shower are important
- And also …

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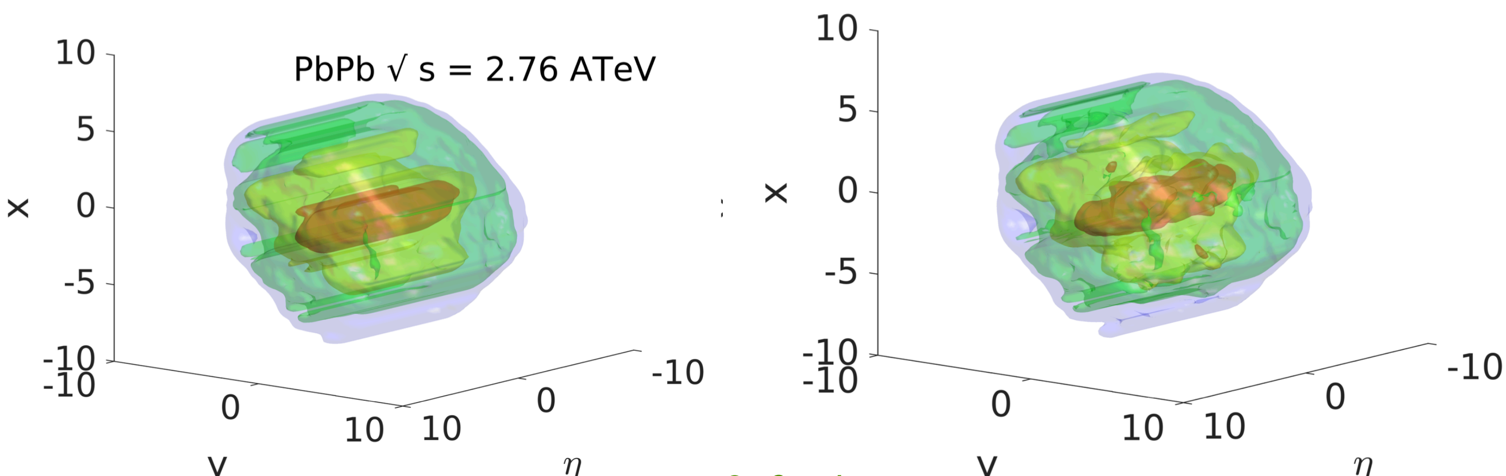
… A consistent treatment requires the medium to also be influenced by jets

- Neufeld, Müller, PRL (2019)
- Tachibana, Chang, Qin, PRC (2017)
- CoLBT Chen et al., PLB (2018)
- Tachibana QM2018
- Pablos, Singh, Gale, Jeon PRC (2022)

Isotherms

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



(a) No jets.

$\tau = 3$ fm/c

(c) $p^{\mathrm{J}}_{\mathrm{min}} = 7$ GeV.

Pablos, Singh, Gale, Jeon PRC (2022)

The presence of minijets contributes to energy & entropy

p^J_{min}	η/s
No jets	0.13
10 GeV	0.125
7 GeV	0.1

Not in EM calculations

EMMI-RRTF

Those early photon sources interpolate between pQCD photons and thermal photons

Help with the "photon flow puzzle"? Not necessarily...

The net v_2^γ is a weighted average: $v_n \sim \frac{1}{N} \int \frac{dN}{d^2p_T dy} \cos(n\phi)\, d\phi$

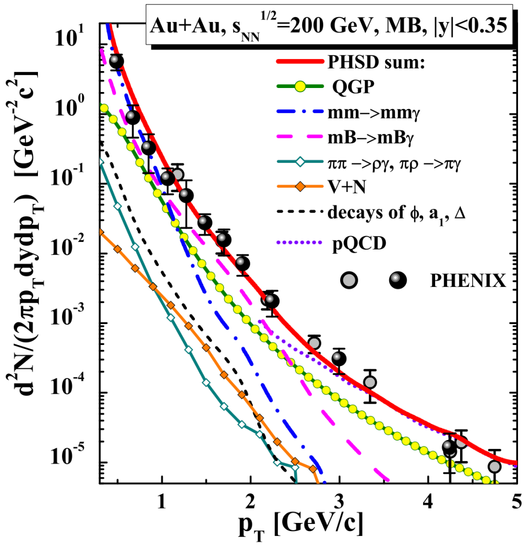
$N = N_1 + N_2$

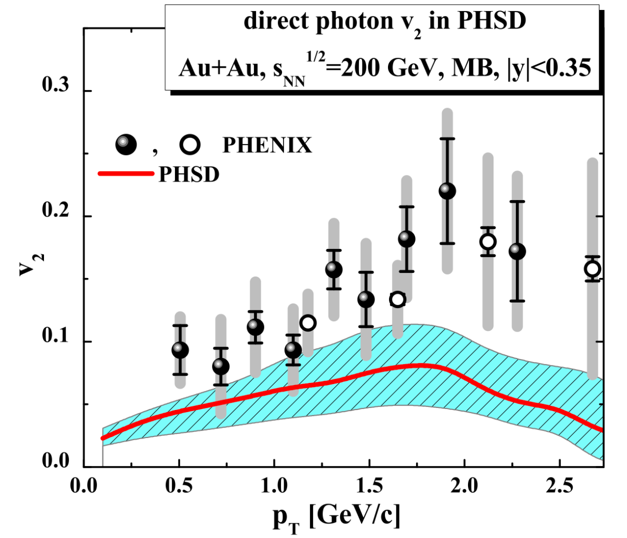
$$v_n \sim \frac{1}{N}\left[\int_1 \frac{dN_1}{d^2p_T dy} \cos(n\phi)\, d\phi + \int_2 \frac{dN_2}{d^2p_T dy} \cos(n\phi)\, d\phi\right]$$

$$= \frac{1}{N}\left[N_1 v_n^{(1)} + N_2 v_n^{(2)}\right]$$

In general, early sources have small v_2

How about "late photons"?...





Linnyk, Konchakovski, Steinert, Cassing, Bratkovskaya, PRC (2015)

- (Late-time)Bremsstrahlung worth more exploration
  - Current progress with SMASH
- Hadronization photons?

  Young and Pratt, PRC (2016); Fuji, Itakura, Miyashi, Nonaka PRC (2022)
- Magnetic field effect?

  Ayala et al., PRD (2017); Wang, Shovkovy 2307.07557

Squeezing more info out of EM radiation: Photon polarization

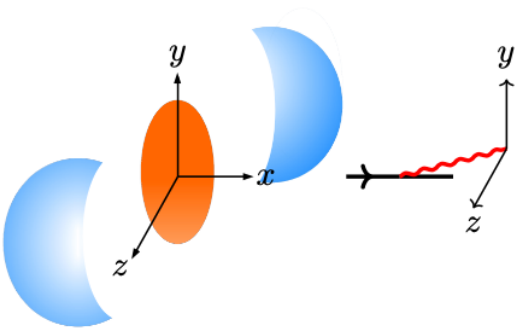
Assuming an anisotropic Parton distribution

$$f(\mathbf{p}) = \sqrt{1+\xi}\, f_{\rm iso}\left(\sqrt{\mathbf{p}^2 + \xi p_z^2}\right)$$

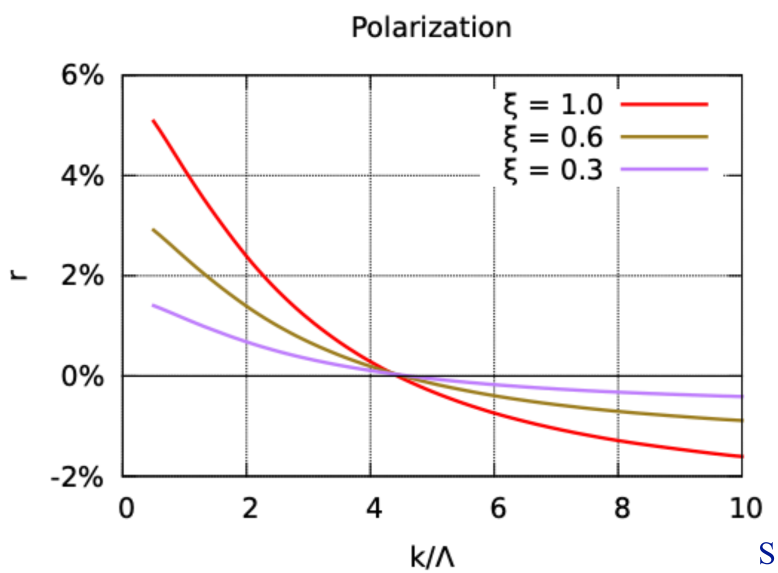
Debye mass in the scattering kernel

$$m_D^2(\phi_{\mathbf{q}}) = \left(1 - \frac{2\xi}{3}\right) m_{D_0}^2 + \xi m_{D_0}^2 \cos^2\phi_{\mathbf{q}}$$

$$\mathscr{C}(\mathbf{q}_\perp) = g^2 C_F \Lambda \left(\frac{1}{q_\perp^2} - \frac{1}{q_\perp^2 + m_D^2(\phi_{\mathbf{q}})}\right)$$



$$r = \frac{k\frac{d\Gamma_z}{d^3k} - k\frac{d\Gamma_y}{d^3k}}{k\frac{d\Gamma_z}{d^3k} + k\frac{d\Gamma_y}{d^3k}}$$



$$P_L/P_T \approx 0.57$$
$$0.68$$
$$0.81$$

- Net Polariz. is a competition between bremsstrahlung and pair annihilation

S. Hauksson and C. Gale, 2306.10307

How about virtual photons?

Recall:

$$\omega \frac{d^3R}{d^3k} = -\frac{g^{\mu\nu}}{(2\pi)^3} \mathrm{Im}\,\Pi_{\mu\nu}(\omega, \mathbf{k}) \frac{1}{e^{\beta\omega} - 1}$$

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

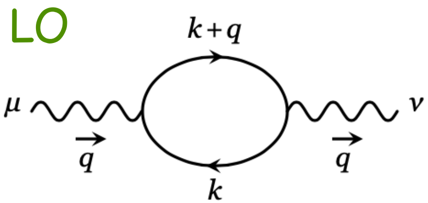
Feinberg (76); McLerran, Toimela (85); Weldon (90); Gale, Kapusta (91)

Rewrite as:

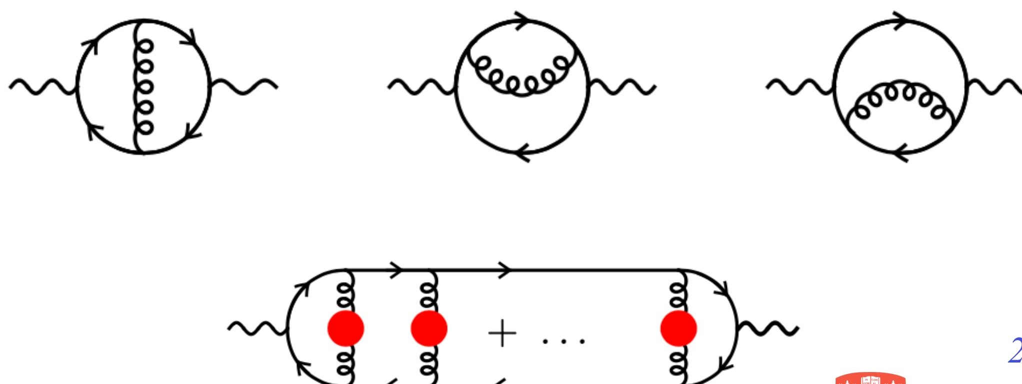
$$\mathrm{Im}\,\Pi_{\mu\nu} = \rho_{\mu\nu} = \mathbb{P}^{\mathrm{T}}_{\mu\nu}\, \rho_{\mathrm{T}} + \mathbb{P}^{\mathrm{L}}_{\mu\nu}\, \rho_{\mathrm{L}}$$

$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} \sim 2\, \rho_{\mathrm{T}}(\omega, \mathbf{k}) + \rho_{\mathrm{L}}(\omega, \mathbf{k})$$

LO



NLO



Aurenche, Gélis, Moore, Zaraket, JHEP (2002); Jackson, Laine, JHEP (2019)

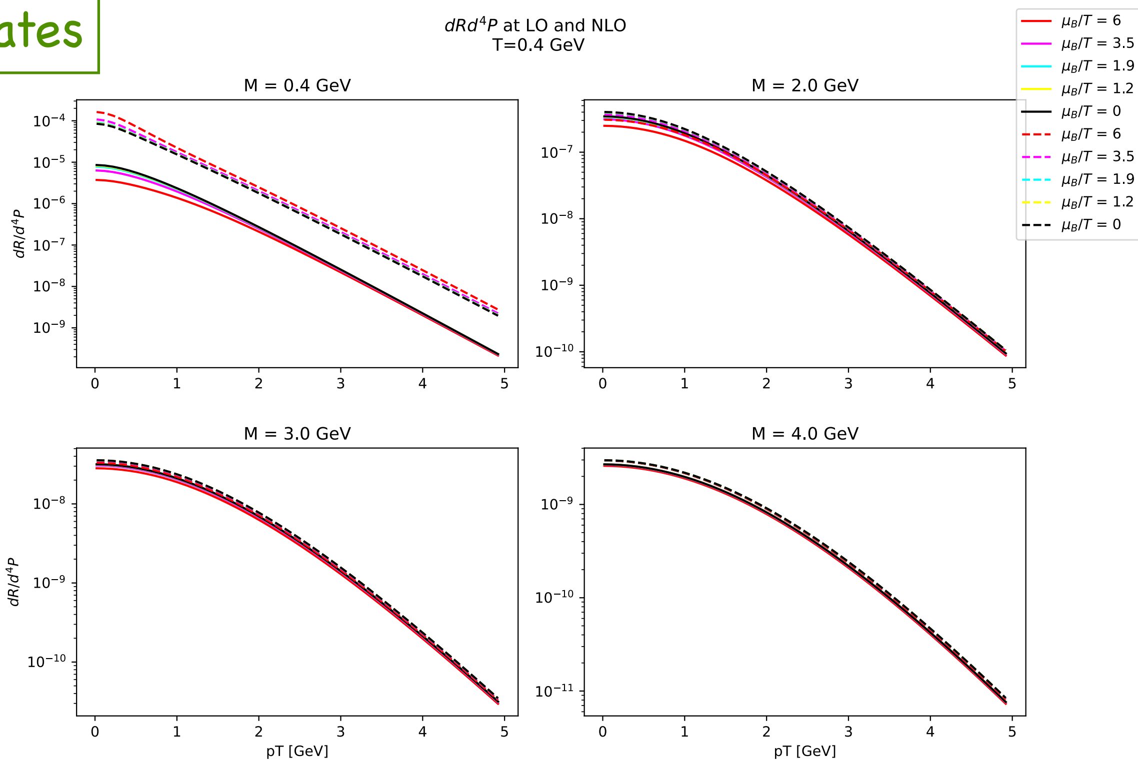
Some new development

Dilepton production @ NLO, with $\mu_B \neq 0$

$$m_D^2 = g^2\left[\left(\frac{1}{2}n_f + N_c\right)\frac{T^2}{3} + n_f\frac{\mu^2}{2\pi^2}\right] \qquad m_\infty^2 = g^2\frac{C_F}{4}\left(T^2 + \frac{\mu^2}{\pi^2}\right)$$

Churchill, Du, Forster, Gale, Gao, Jackson, Jeon 2023

Rates



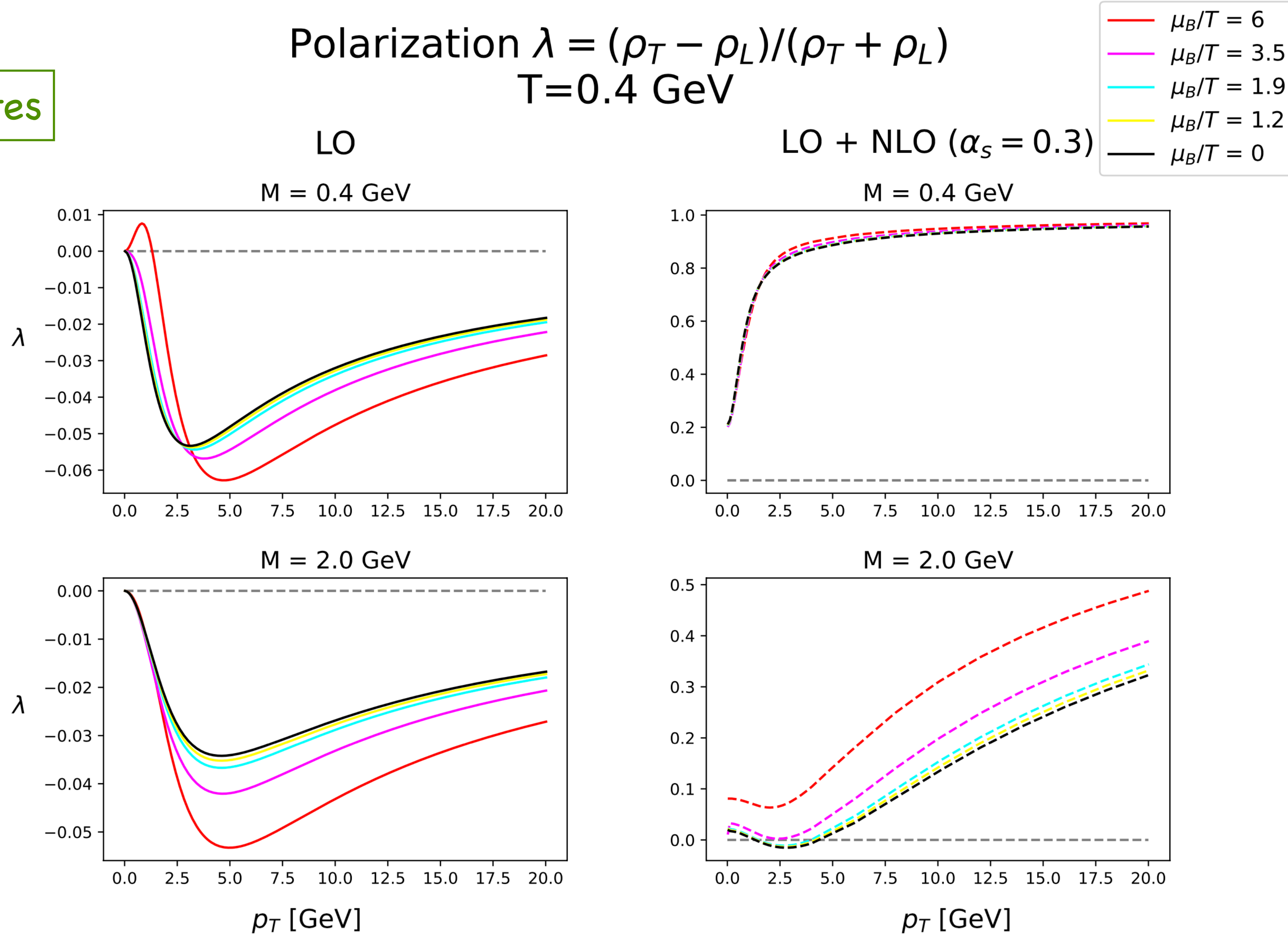
For rates (& yields), NLO+LO effect dominate over that of $\mu_B \neq 0$

Braaten, Pisarski, Yuan, PRL (1990);
S. M. H. Wong, Z. Phys. C (1992)

B. Forster 2023

Rates

Polarization $\lambda = (\rho_T - \rho_L)/(\rho_T + \rho_L)$
T=0.4 GeV



Polarization contains lot of info that is difficult to obtain otherwise

Forster, Gale, Jackson 2023

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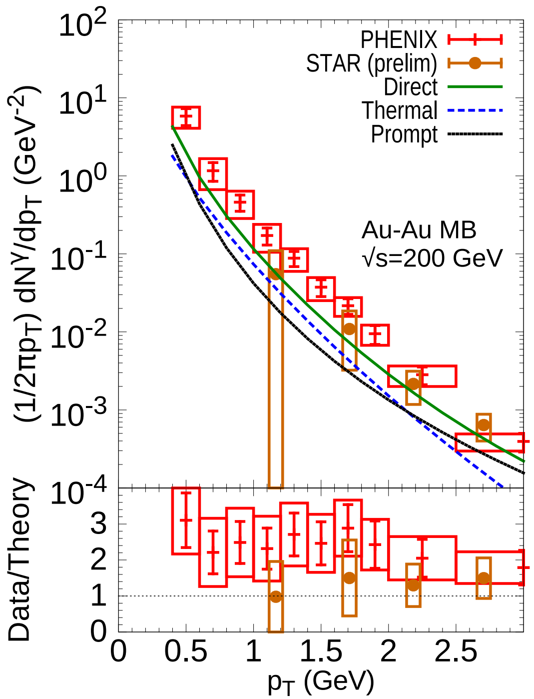
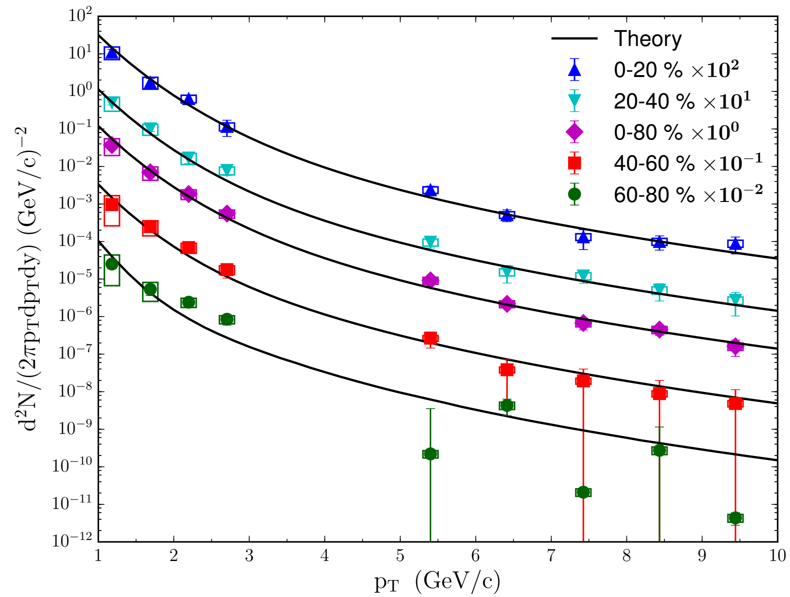
McGill

Finally, a puzzle within a "puzzle"

STAR & PHENIX





??

STAR Phys. Lett. (2017)

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

??

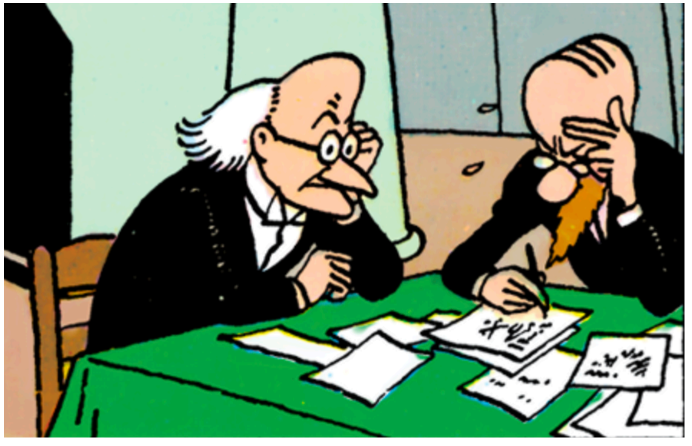
EMMI-RRTF

Charles Gale
McGill

Conclusion

- Much recent progress in modelling
  - Notably for early times
- Much recent progress in photon emission
  - e.g. @ early times

- Photons and dileptons, together, provide a more complete mapping of both the dynamics and the spectral density
- "Photon puzzle" is more obvious at RHIC
- Much work is left in theory



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Dilepton production @ NLO, with $\mu_B \neq 0$

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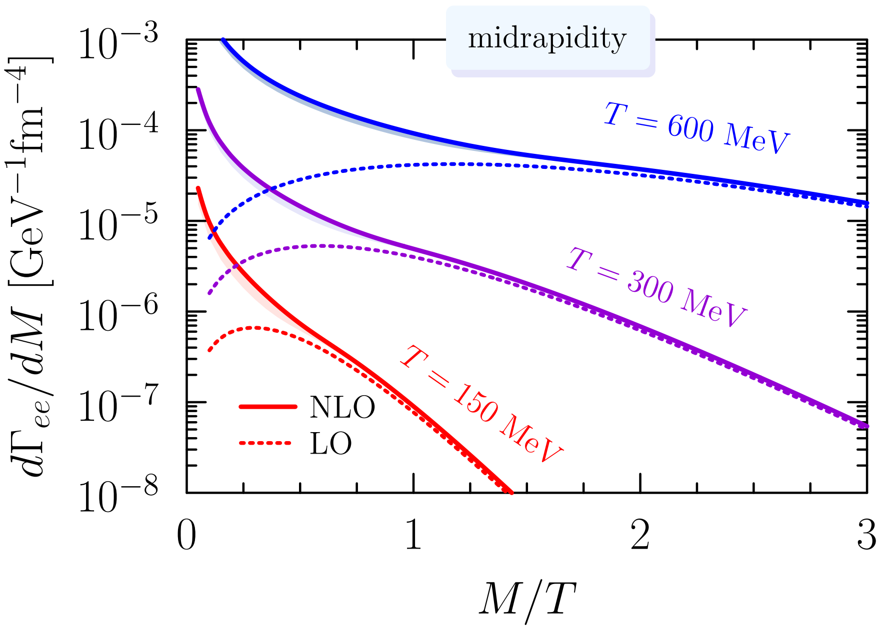
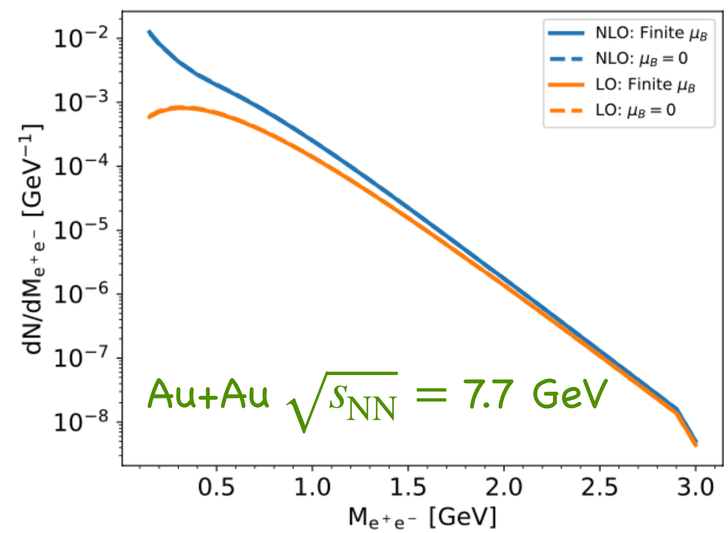
Churchill, Du, Foster, Gale, Gao, Jackson, Jeon 2023



Braaten, Pisarski, Yuan, PRL (1990); S. M. H. Wong, Z. Phys. C (1992); G. Jackson (2022)



For rates & yields, NLO+LO effect dominate largely over that of $\mu_B \neq 0$