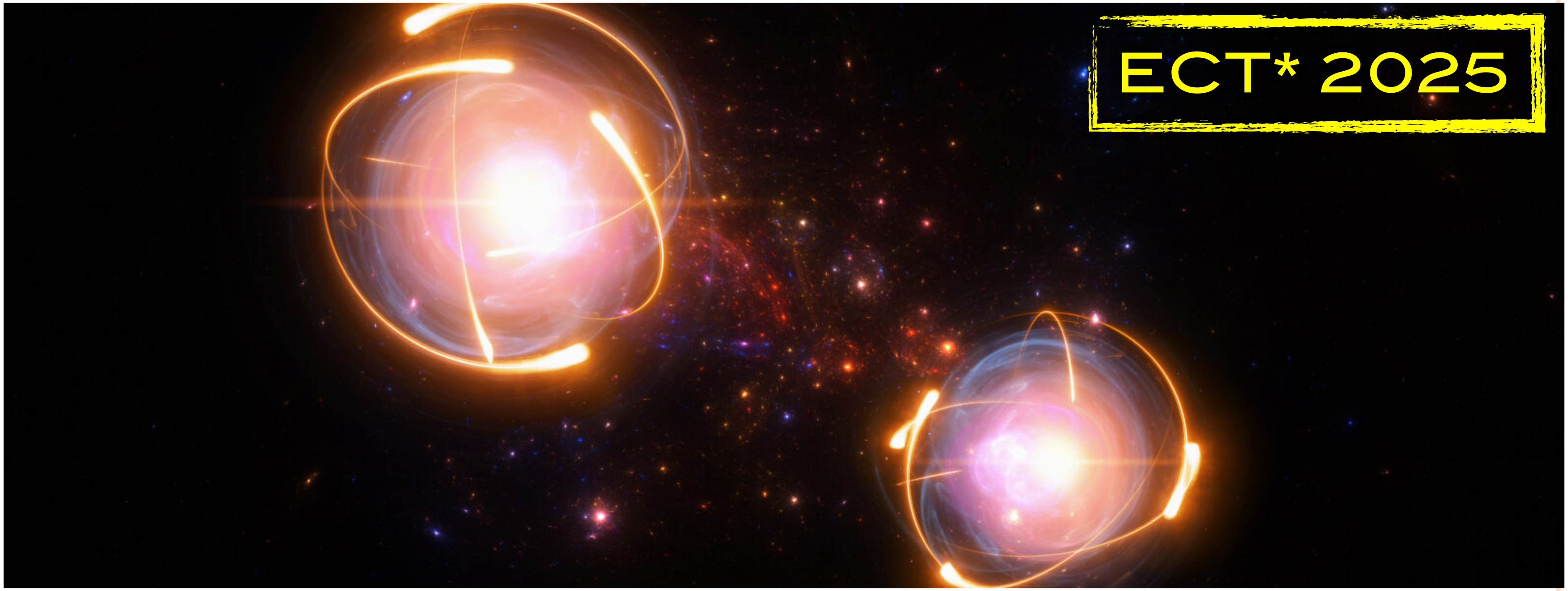
Theory overview;
real and virtual photons



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McGill University

Outline

- Most of this talk: real and virtual(*) photons
- Photons can be **soft** and still **penetrating**

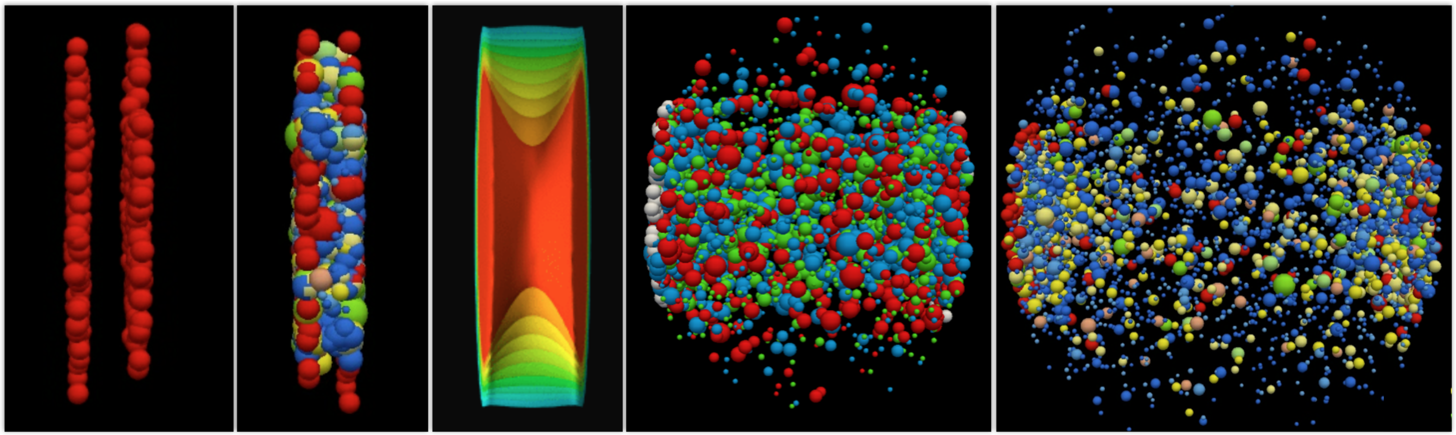
They enjoy a unique status

- Anatomy of a collision: the different stages
- Cold photons: pQCD
- EM productions rates
- (QCD) dileptons@finite μ_B
- Polarization

(*)Virtual photons == dileptons

Direct photons and HIC modelling

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



"Plasma photons"

Late stage reactions
Decay photons

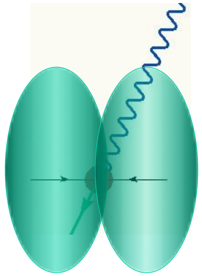
pQCD photons
"primordial" photons

"Hadronic medium photons"

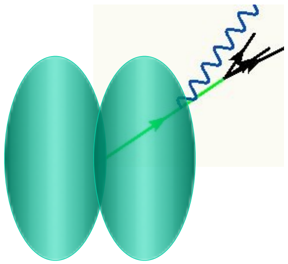
"Pre-eq. photons"

(*) Real & virtual

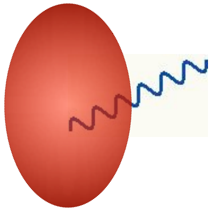
Direct photon sources
(real and/or virtual)



Hard direct photons. pQCD with shadowing
Non-thermal



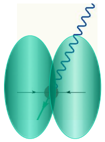
Fragmentation photons. pQCD with shadowing
Non-thermal



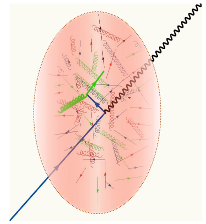
Thermal photons
"Thermal"

DIRECT PHOTON SOURCES

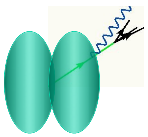
(real and/or virtual)



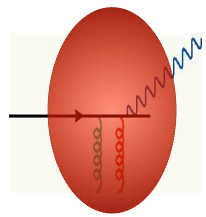
Hard direct photons. pQCD with shadowing
Non-thermal



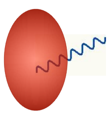
Jet-photon conversions
"Thermal"



Fragmentation photons. pQCD with shadowing
Non-thermal

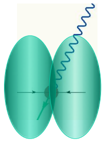


Jet in-medium bremsstrahlung
"Thermal"

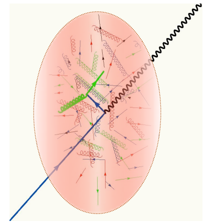


Thermal photons
"Thermal"

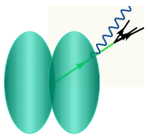
Direct photon sources
(real and/or virtual)



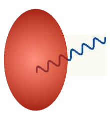
Hard direct photons. pQCD with shadowing
Non-thermal



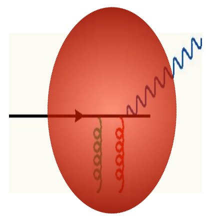
Jet-photon conversions
“Thermal”



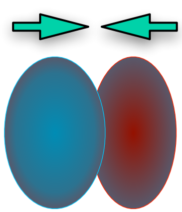
Fragmentation photons. pQCD with shadowing
Non-thermal



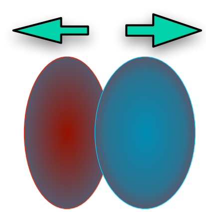
Thermal photons
“Thermal”



Jet in-medium bremsstrahlung
“Thermal”



Pre-hydro?



Post-hydro?

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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

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

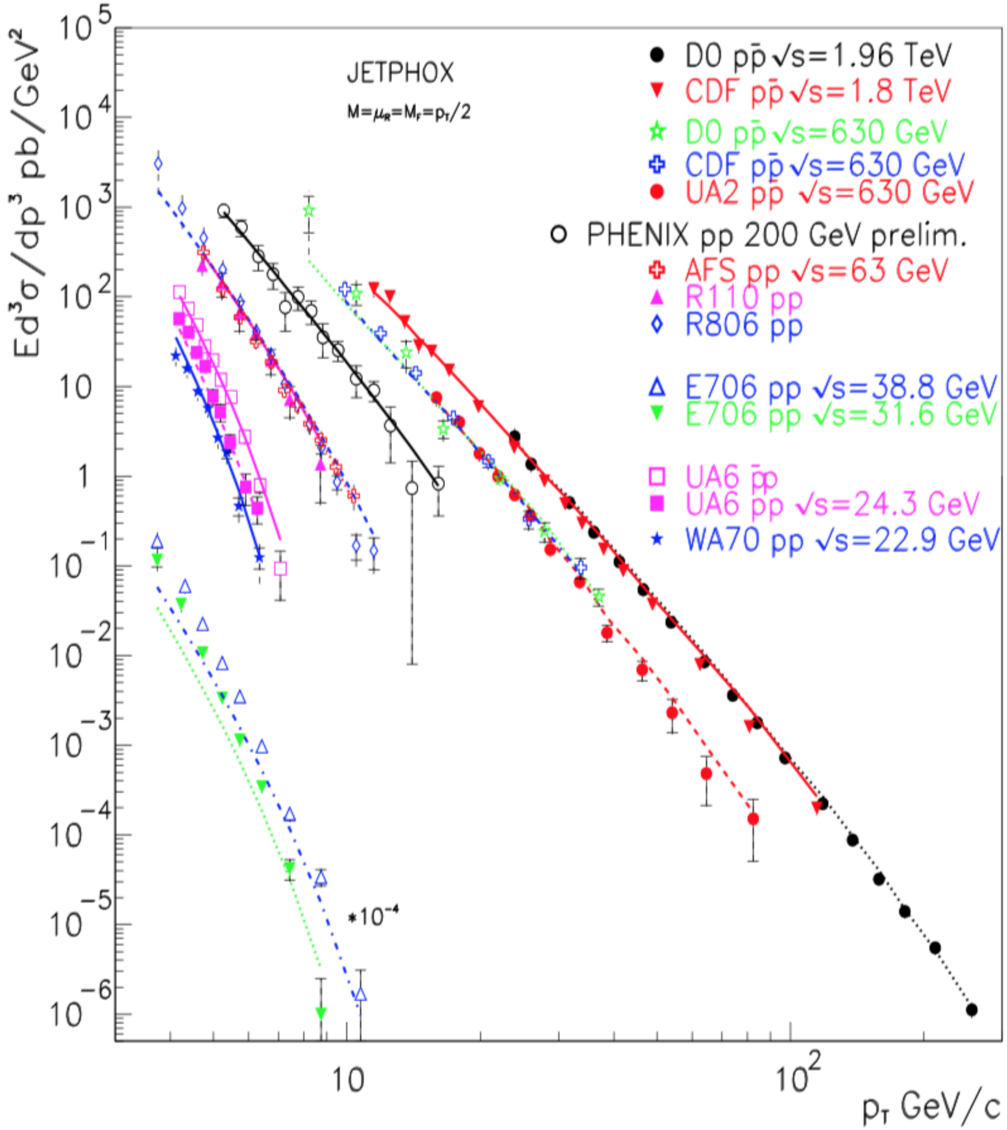
FF can be written as (LO in α)

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

Perturbative (k_i^γ) — Non-perturbative ($\sum_j P_{ji} \otimes D_j^\gamma$)

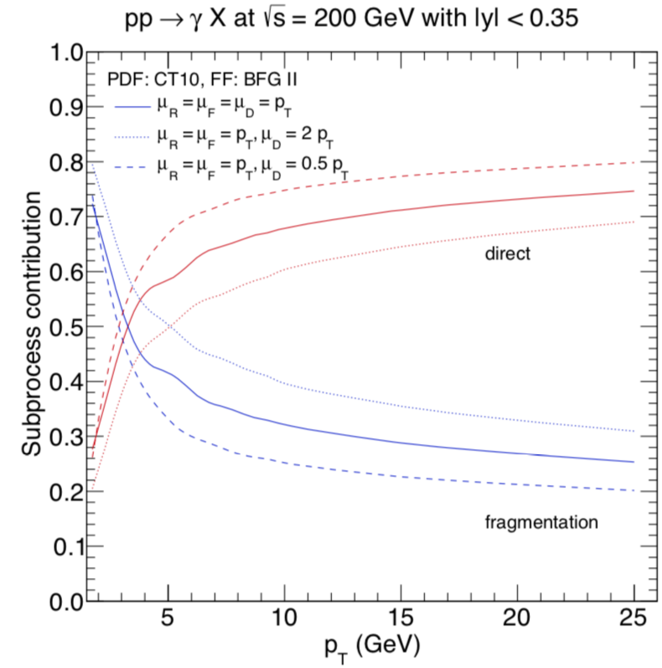
Little new info on photon FF over the last 25 years. Most data used to fit FF are single-inclusive photon production, in hadronic reactions dominated by direct photon production

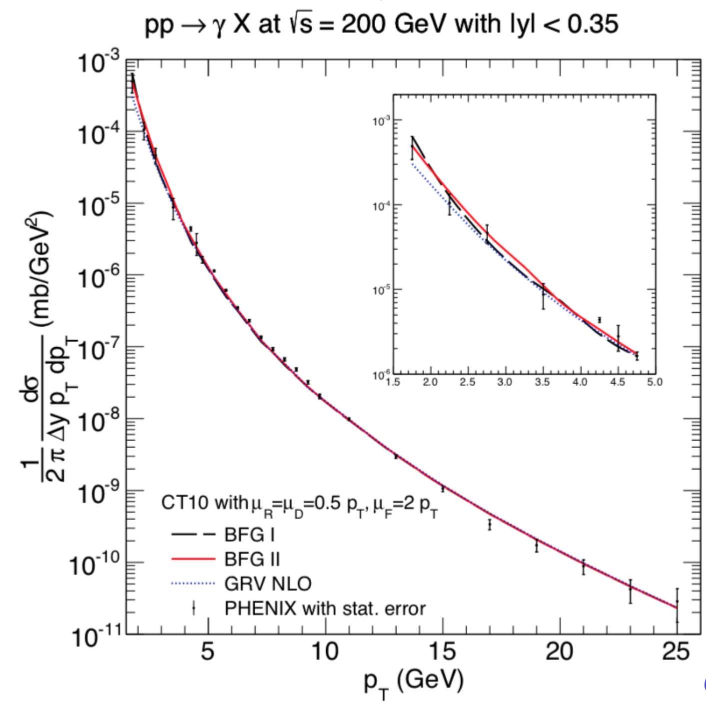
pQCD photon calculations and uncertainties



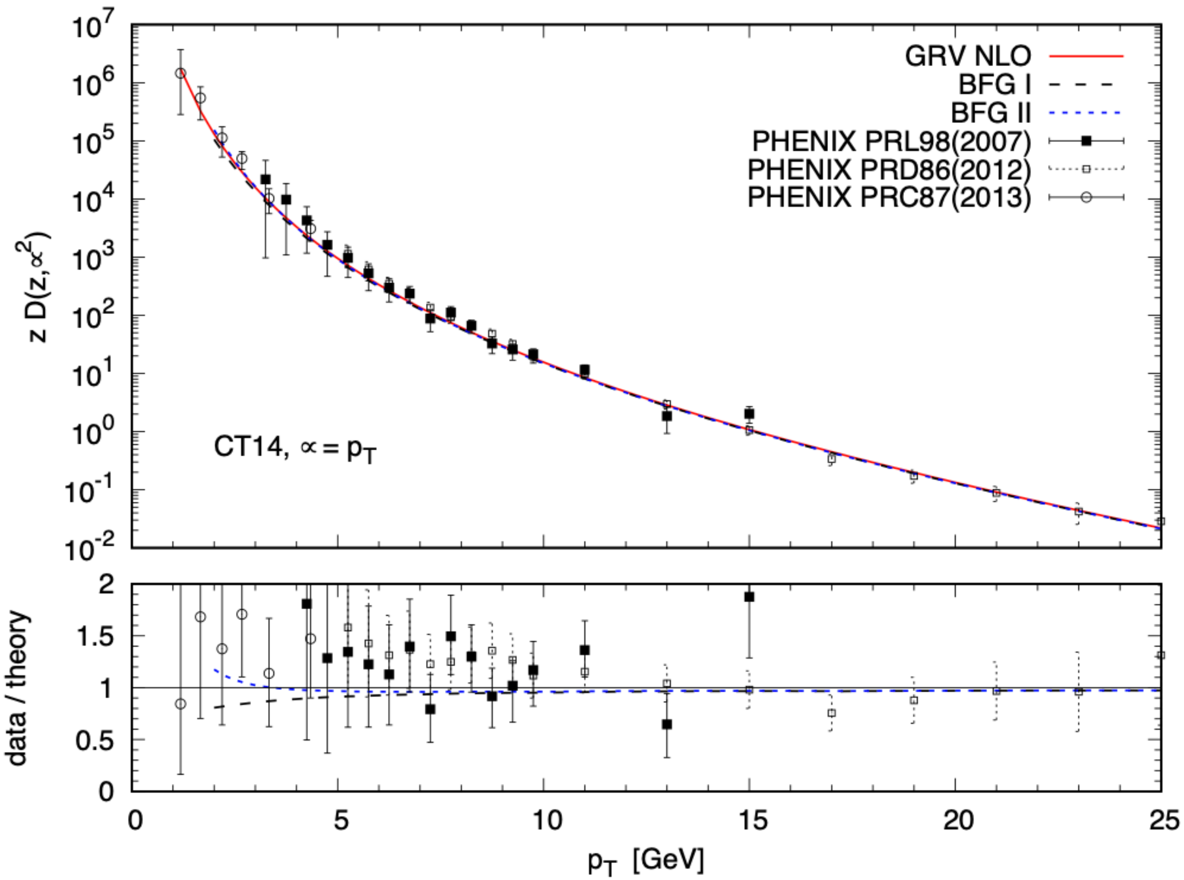
Aurenche et al., PRD (2006)

Klasen, König, Eur. PJC (2014)





pQCD photon calculations and uncertainties



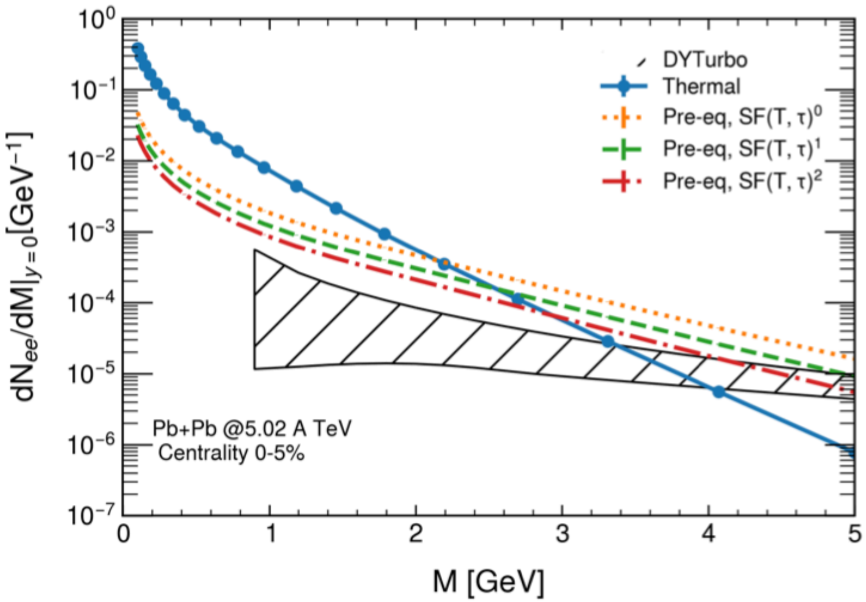
Kaufmann, Mukherjee, and Vogelsang, arXiv: 1708.06683

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

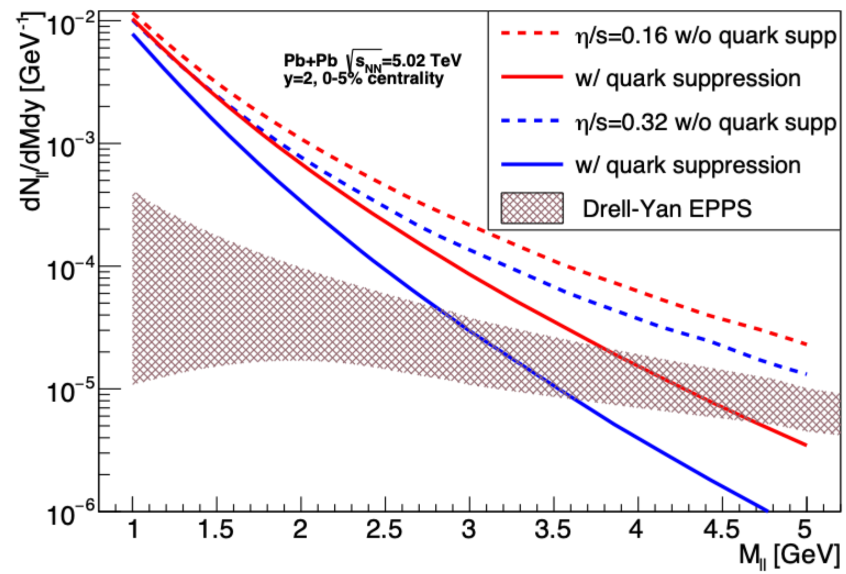
Kaufmann, Mukherjee, Vogelsang, CERN Proc. 2018
Fragmentation component: $e^+e^- \rightarrow (\text{jet}\,\gamma)\,X$

pQCD dilepton calculations and uncertainties

$$0.5\ p_T < \mu < 2\ p_T$$



Wu et al., PRC 2024



Coquet et al., PLB 2021

- Scale dependence: irreducible uncertainty
- Value of pp measurement(s)

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), Jackson and Laine, JHEP (2019)

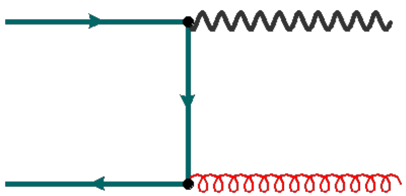
  ...and on the lattice

  Ding et al., PRD (2011), HotQCD, PRD (2024), Krasniqi et al., 2505.10295

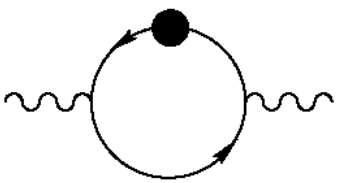
- Hadronic rates

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

Photon rates@LO



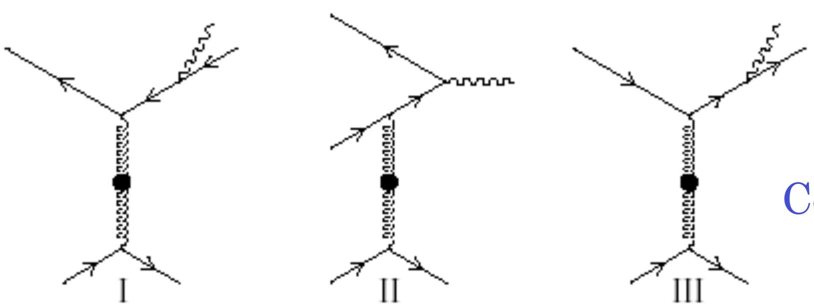
$$\sim \ln \frac{\omega T}{m_0^2}$$



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

Braaten, Pisarski (1990)
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: $\alpha_s^2\left(\frac{T^2}{m_{th}^2}\right) \sim \alpha_s$

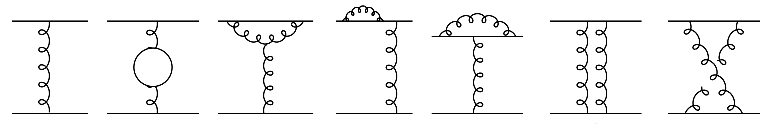
2001: Results complete at $O(\alpha_s)$

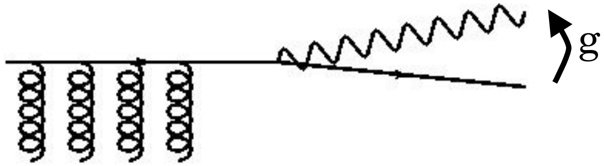
Arnold, Moore, and Yaffe JHEP **12**, 009 (2001); JHEP **11**, 057 (2001)
Incorporate LPM; Inclusive treatment of collinear enhancement, photon and gluon emission

Photon rates@NLO

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

The two main contributions:

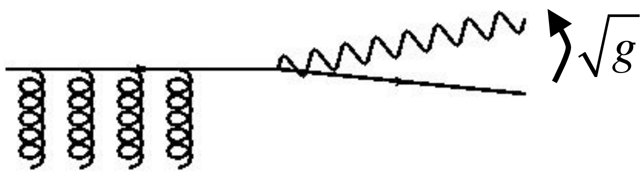




$$C(q_T)_{\rm LO} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \Rightarrow \text{NLO}$$

Simon Caron-Huot PRD (2009)

Enhanced at NLO



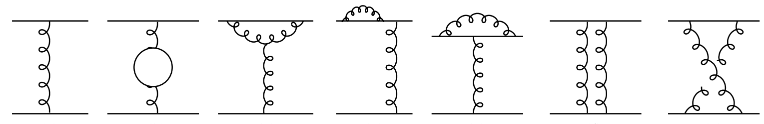
Larger angle bremmstrahlung

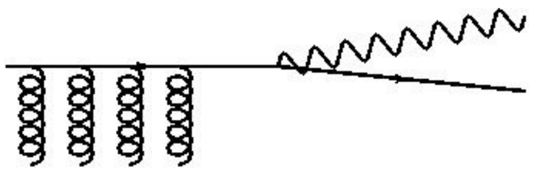
Suppressed at NLO

Photon rates@NLO

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

The two main contributions:

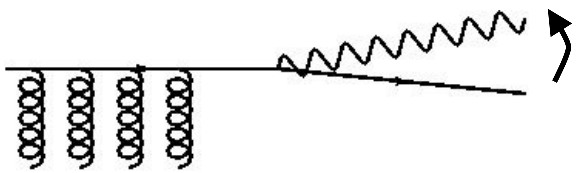




$$C(q_T)_{\text{LO}} = \frac{Tg^2 m_D}{q_T(q_T + m_D)} \Rightarrow \text{NLO}$$

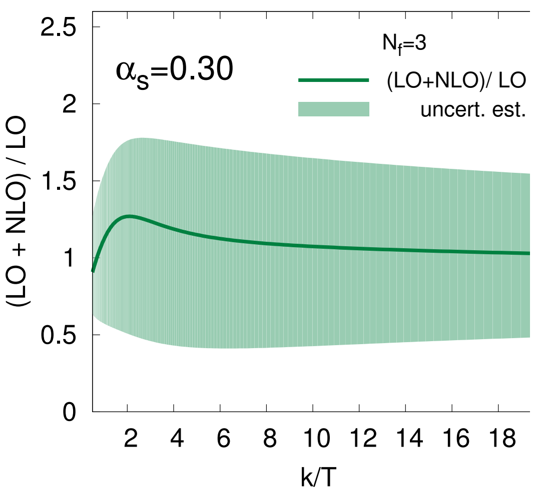
Simon Caron-Huot PRD (2009)

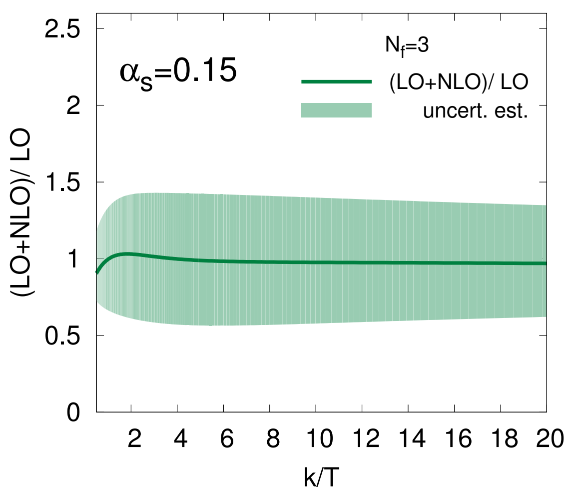
Enhanced at NLO



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

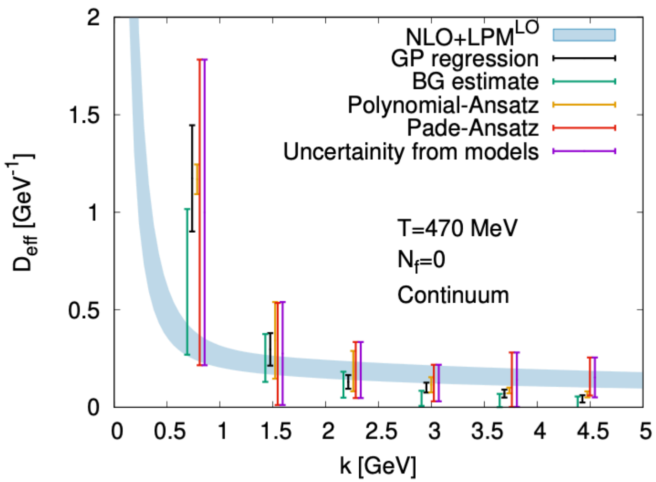
Ghiglieri, Kaczmareck, Laine, Meyer, JHEP (2016); Jackson, Laine JHEP (2019)

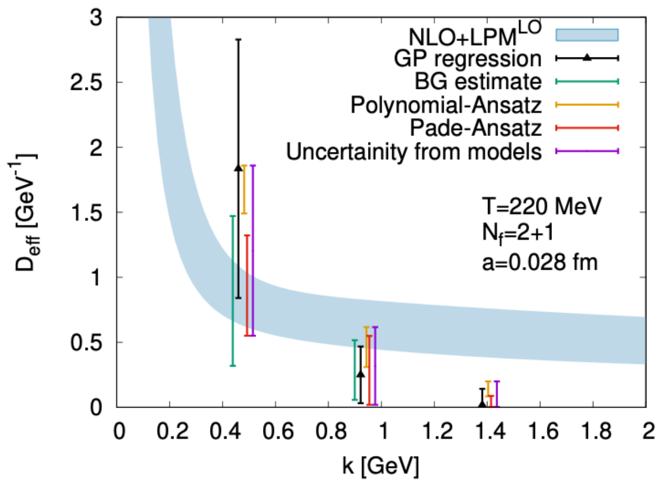
What about the lattice?

The lattice measures the Euclidean correlator:

$$G_E(\tau, \mathbf{k}) = \int \frac{dk^0}{2\pi} \rho^V(k^0, \mathbf{k}) \frac{\cosh(k^0(\tau - 1/2T))}{\sinh(\frac{k^0}{2T})}$$

Ill-posed inverse problem





Photons

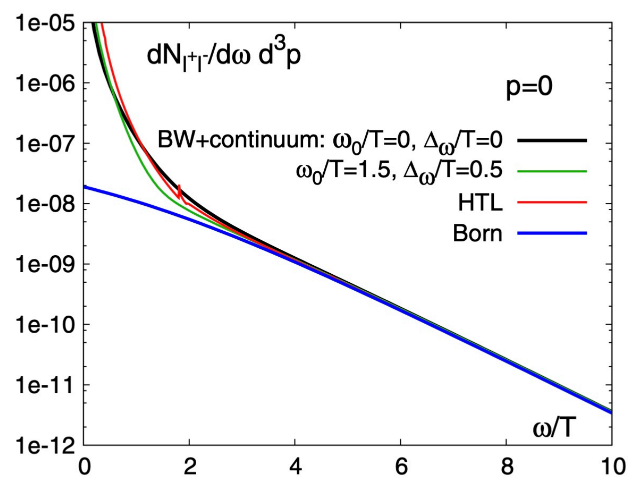
Ali et al., PRD (2024)

Krasniqi et al. arXiv: 2505.10295 "Results on the low side, but compatible with AMY"

Dileptons

$N_f = 0$

$T \simeq 1.45\, T_c$



Ding et al., PRD (2011)

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Virtual photons/Dileptons

Recall:

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

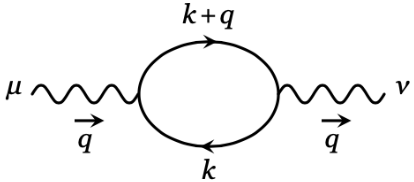
$$E_+E_- \frac{d^6R}{d^3p_+ d^3p_-} = \frac{2e^2}{(2\pi)^6} \frac{1}{k^4} L^{\mu\nu}\, \text{Im}\Pi_{\mu\nu}(\omega, \mathbf{k}) \frac{1}{e^{\beta\omega}-1}$$

Rewrite as:

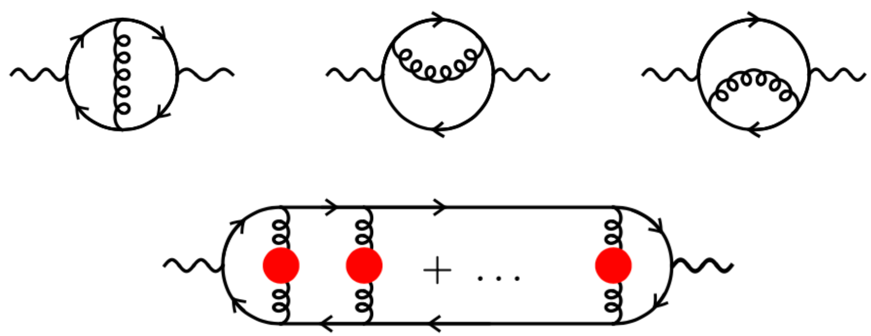
$$\text{Im}\,\Pi_{\mu\nu} = \rho_{\mu\nu} = \mathbb{P}^{\text{T}}_{\mu\nu}\,\rho_{\text{T}} + \mathbb{P}^{\text{L}}_{\mu\nu}\,\rho_{\text{L}}$$

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

LO

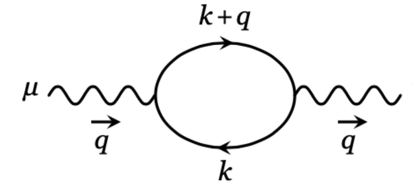


NLO



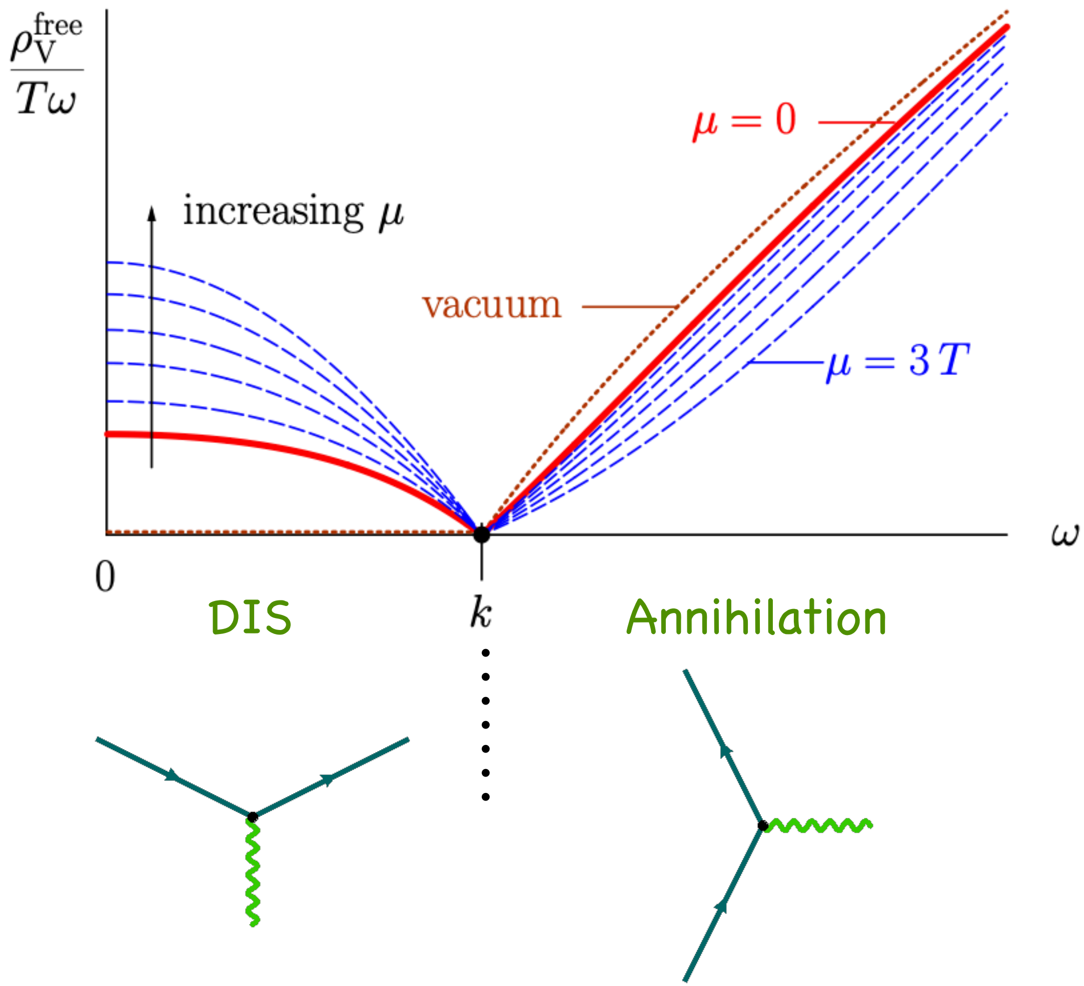
Aurenche, Gélis, Moore, Zaraket, JHEP (2002); Jackson, Laine, JHEP (2019)

Finite μ_B; 1-loop self-energy



LO

$$\rho_V = 2\rho_T + \rho_L$$



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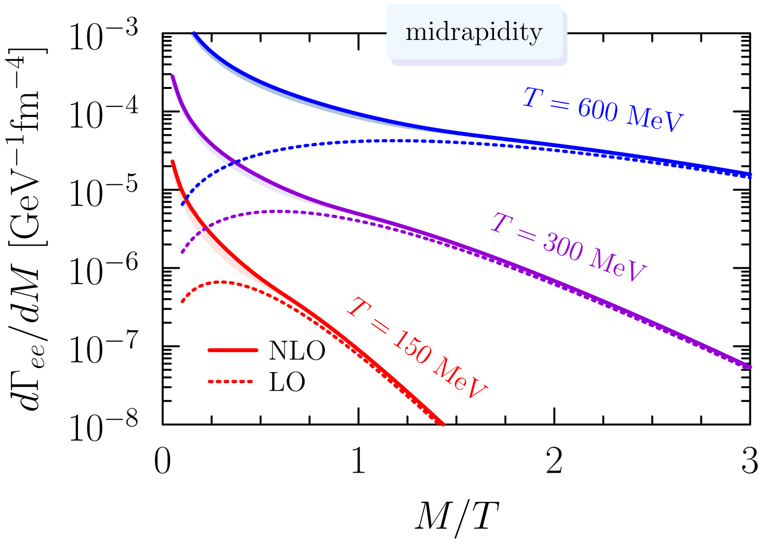
What do we know at NLO and $\mu_B \neq 0$?

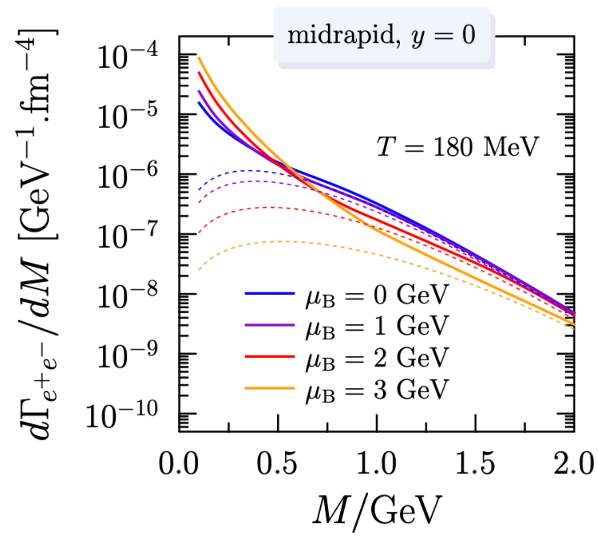
Dumitru et al., PRL (1993) [LO]
Traxler, Vija, Thoma, PLB (1995)
Gervais, Jeon, PRC (2012)
C. Shen et al., PoS (HP2024)
] γ

$\mu_B \neq 0$ $\quad m_D^2 \equiv g^2 \left[\left(\frac{1}{2} n_f + N_c \right) \frac{T^2}{3} + n_f \frac{\mu^2}{2\pi^2} \right], \; m_\infty^2 \equiv g^2 \frac{C_F}{4} \left(T^2 + \frac{\mu^2}{\pi^2} \right)$

Churchill, Du, Forster, Jackson, Gale, Gao, Jeon, PRL, PRC (2023)

$\mu_B = 0$





$\mu_B \neq 0$

NLO correction gives $\gtrsim 10\,\%$ even for 1 GeV < M < 3 GeV

Growing μ_B: enhancement at low M, suppression at intermediate M

μ_B effect more important on hadronic rates

Some interesting features seen in the spectral densities (more on this later)

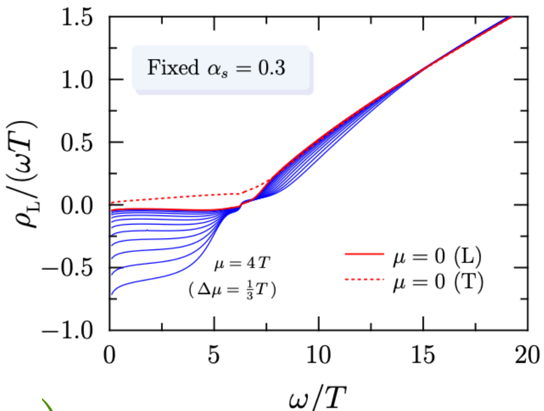
QCD Rates

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

Weldon. PRD (1990); Gale, Kapusta Nucl. Phys. B (1991)

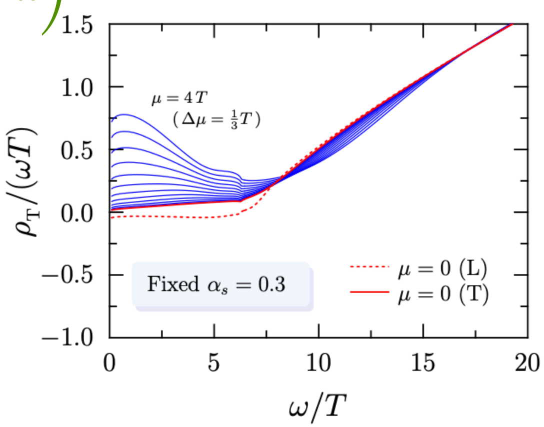
$$\frac{d\Gamma_{\ell\bar{\ell}}}{d\omega d^3\mathbf{k}} \sim \rho_V = \rho^{\mu}_{\mu} = 2\,\rho_{\mathrm{T}}(\omega,\mathbf{k}) + \rho_{\mathrm{L}}(\omega,\mathbf{k})$$

$$\rho_L = -\frac{M^2}{k^2}\rho_{00}$$

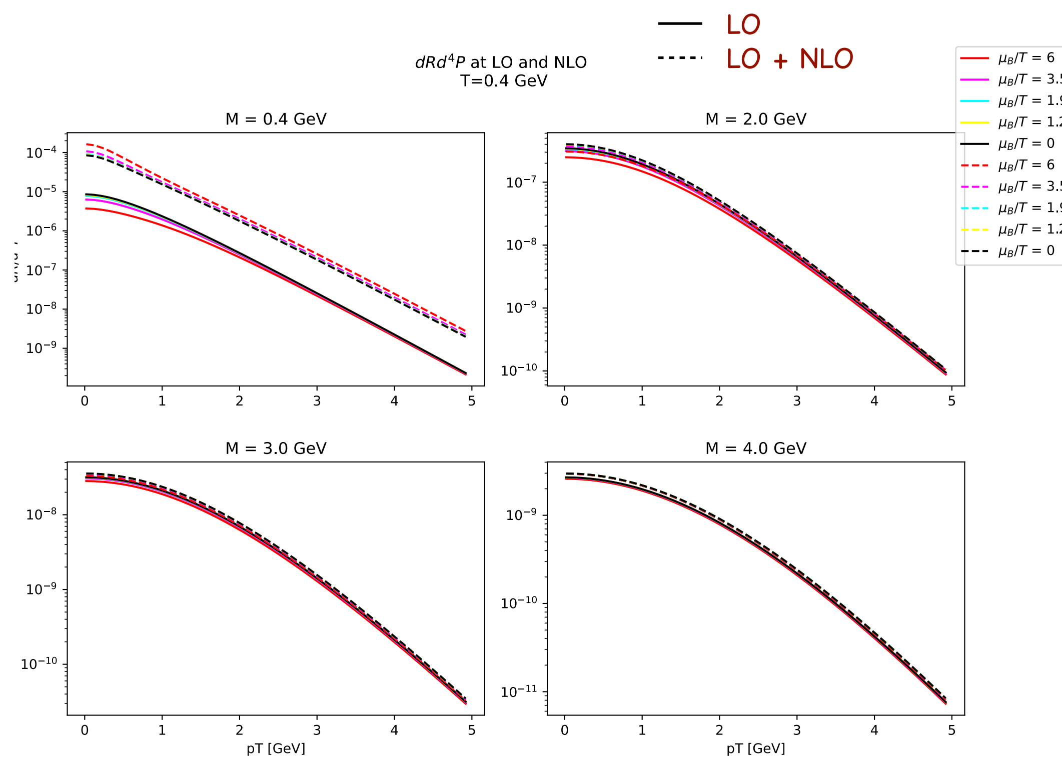


$$\rho_T = \frac{1}{2}\left(\rho^{\mu}_{\mu} + \frac{M^2}{k^2}\rho_{00}\right)$$

$(k/T = 2\pi)$



... but NLO effects dominate μ_B effects on spectra (rates)



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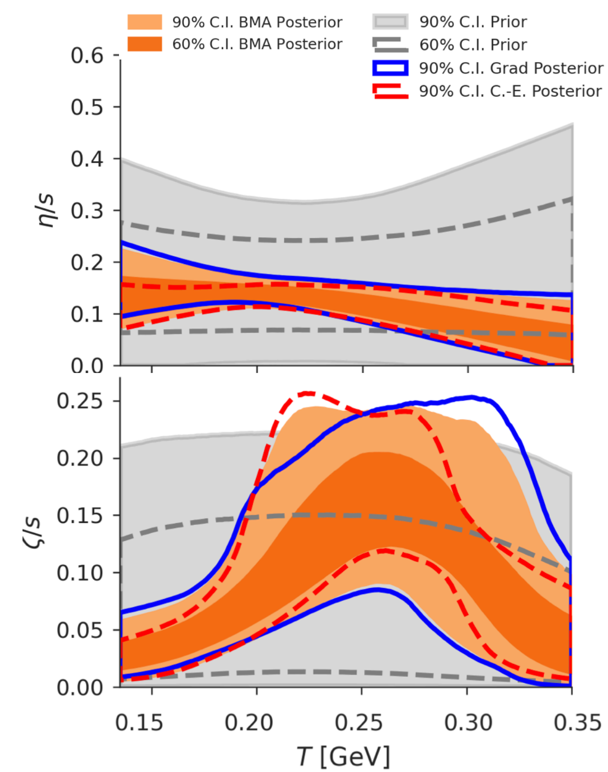
Photons and fluid dynamics

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

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

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)		

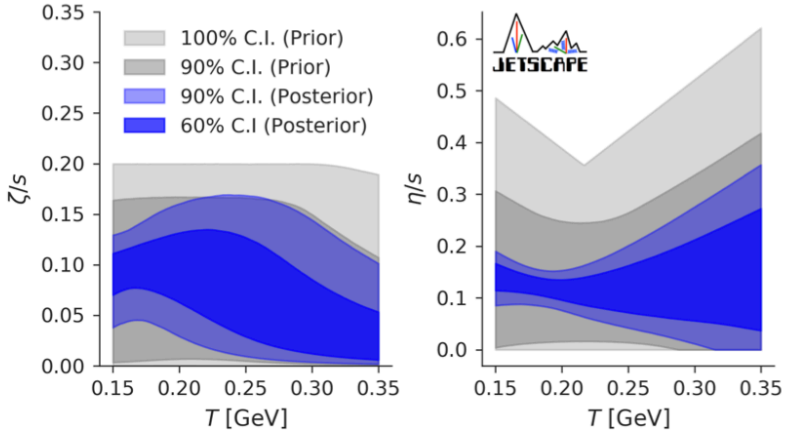


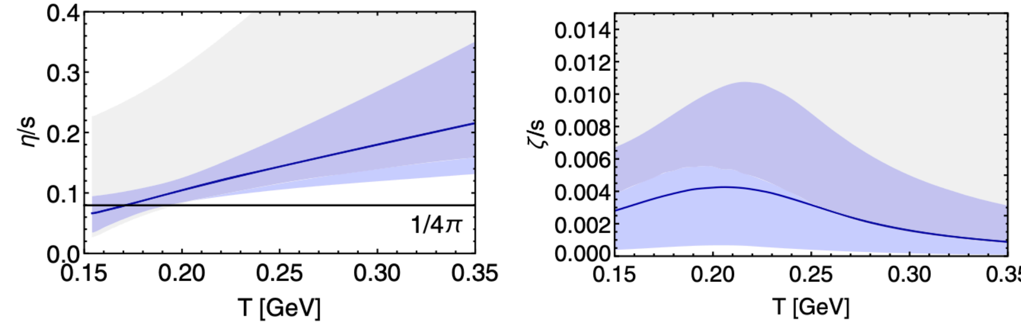
Heffernan, Gale, Jeon, Paquet PRL (2024)

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

Development: realistic dynamics in the era of statistical learning

Bayes analysis @ RHIC&LHC

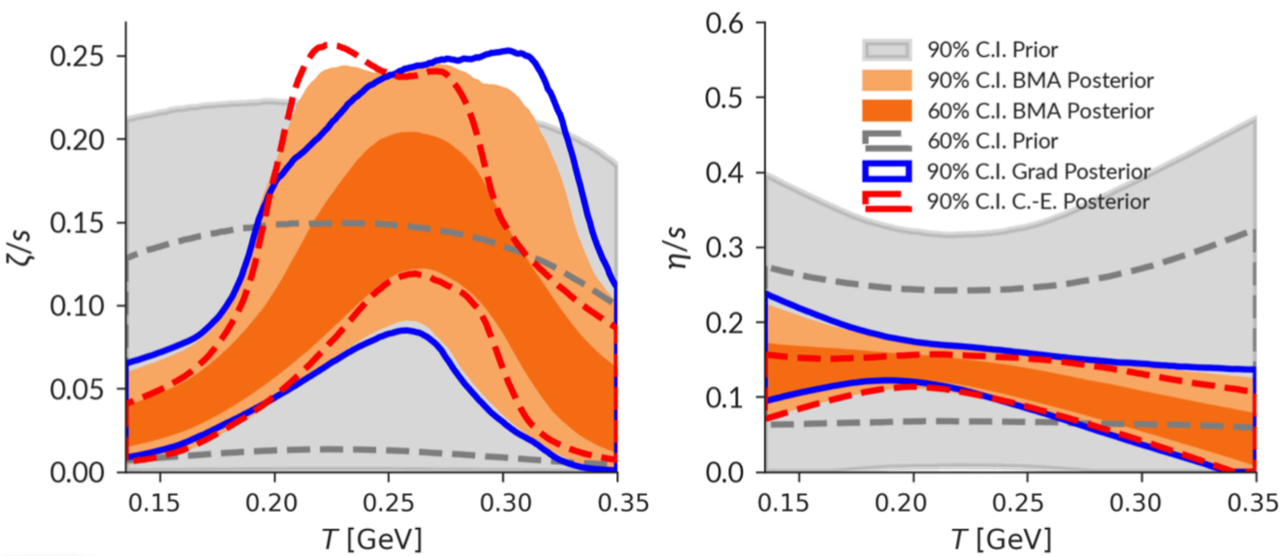




Nijs, van der Schee, Gürsoy, Snellings, PRL 2021

JETSCAPE Collab., PRC 2021; PRL 2021

T$_R$ENTo + free-streaming+MUSIC/TRAJECTUM+UrQMD/SMASH



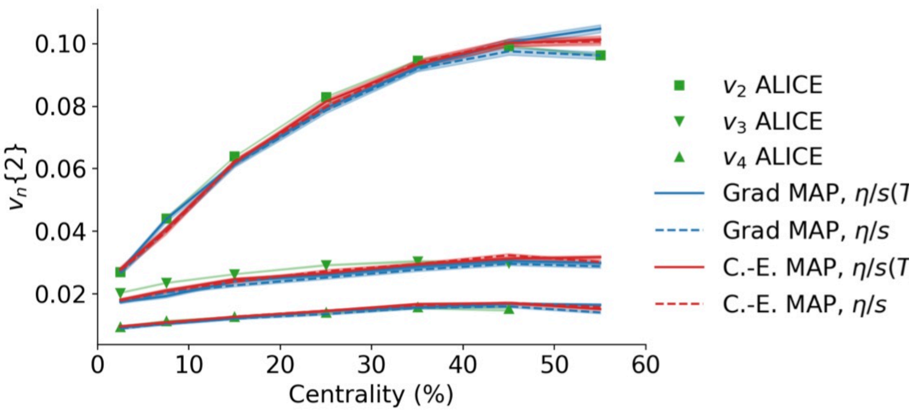
IP-Glasma+MUSIC+SMASH

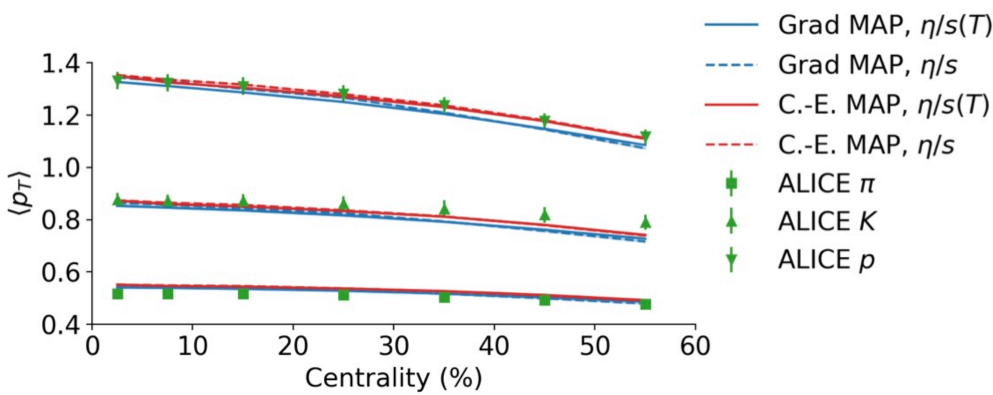
Matt Heffernan, PhD Thesis (McGill 2022);PRL, PRC (2024)

Parameter	Grad δf, η/s	Grad δf, $\eta/s(T)$	C.-E. δf, η/s	C.-E. δf, $\eta/s(T)$
μ_{Q_s}	0.72341	0.70808	0.72654	0.70858
τ_0 [fm]	0.52127	0.51291	0.40142	0.55159
$T_{\eta,\mathrm{kink}}$ [GeV]	0.150	0.22333	0.150	0.21123
$a_{\eta,\mathrm{low}}$ [GeV^{-1}]	0.000	-0.16259	0.000	0.65272
$a_{\eta,\mathrm{high}}$ [GeV^{-1}]	0.000	-0.80217	0.000	-0.89472
$(\eta/s)_{\mathrm{kink}}$	0.13577	0.13944	0.12504	0.14888
$(\zeta/s)_{max}$	0.28158	0.22085	0.17391	0.20117
$T_{\zeta,c}$ [GeV]	0.31111	0.29198	0.2706	0.25455
w_ζ [GeV]	0.02878	0.03625	0.05255	0.04506
λ_ζ	-0.96971	-0.56235	-0.14178	0.06408
T_{sw} [GeV]	0.15552	0.15429	0.15069	0.1513

Maximum a Posteriori estimates with Grad's 14-moment and Chapman-Enskog RTA viscous corrections. Estimates with (denoted $\eta/s(T)$) and without (denoted η/s) temperature-dependent specific shear viscosity are reported.

Predictions:



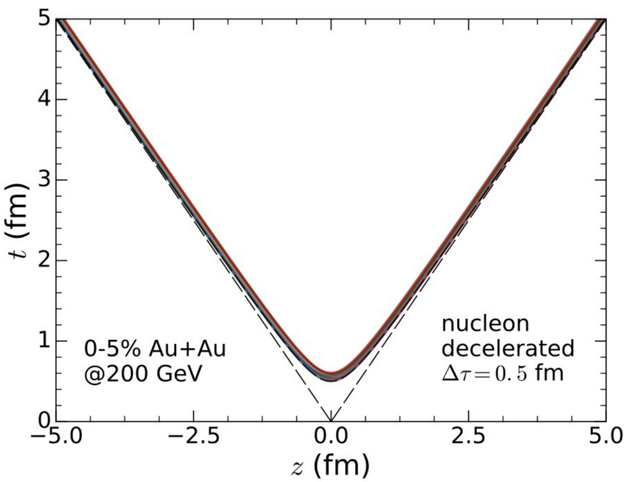


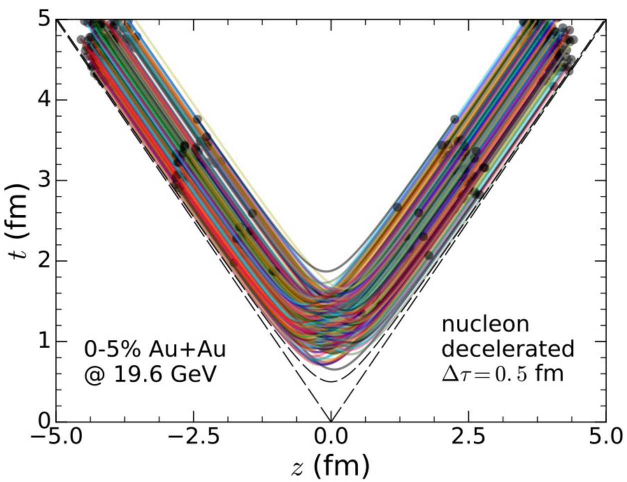
M. Heffernan et al., PRC (2024)

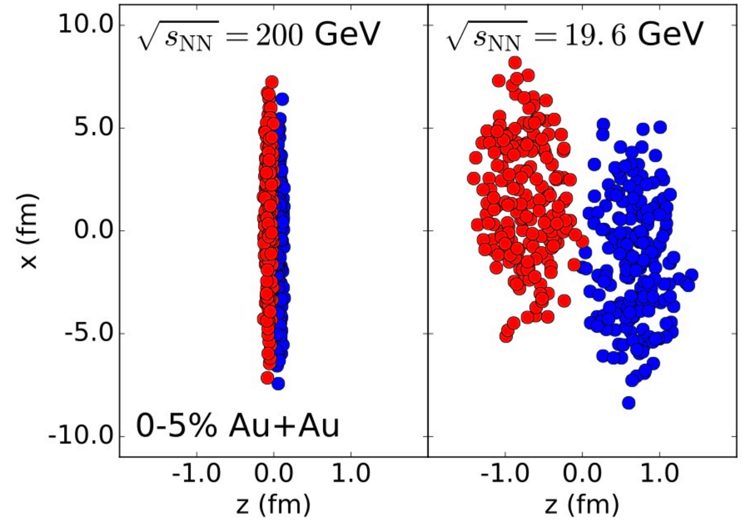
Realistic dynamics at lower energies

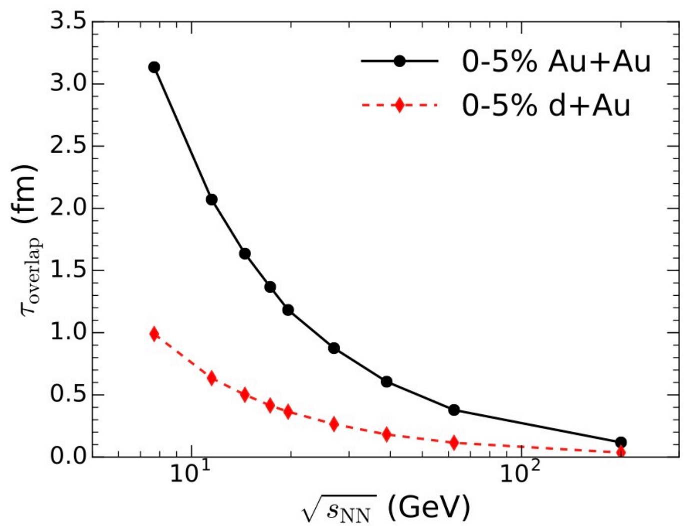
Shen and Schenke, PRC (2018)

At lower energies: pre-hydro stage. Colliding nucleons lose energy to stretched string









Hydro initialization will now spread over a range of proper times

Charles Gale
McGill

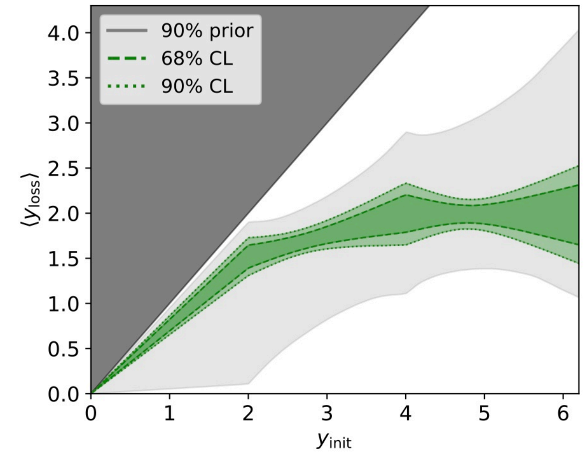
New: Bayes analysis at lower energies

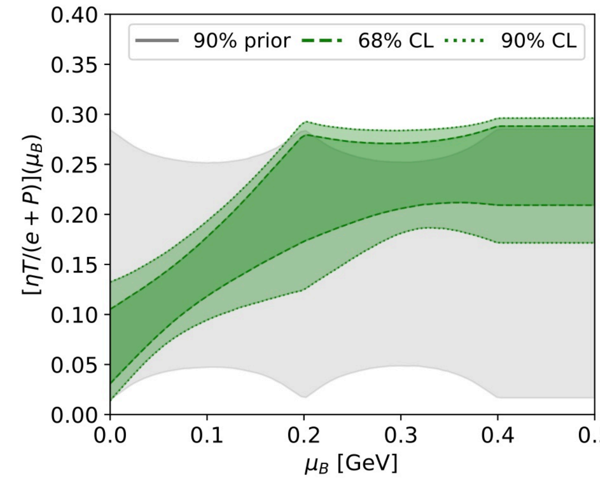
Jahan, Roch, Shen, PRC (2025)

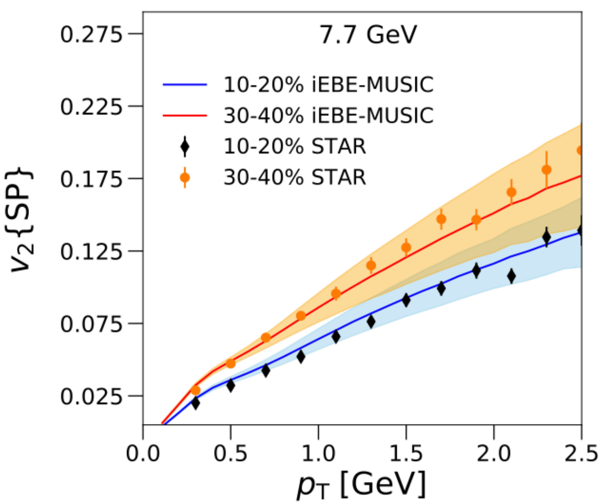
Au+Au $\sqrt{s_{NN}}$ = 7.7, 19.6, 200 GeV (EOS=HotQCD + Taylor)

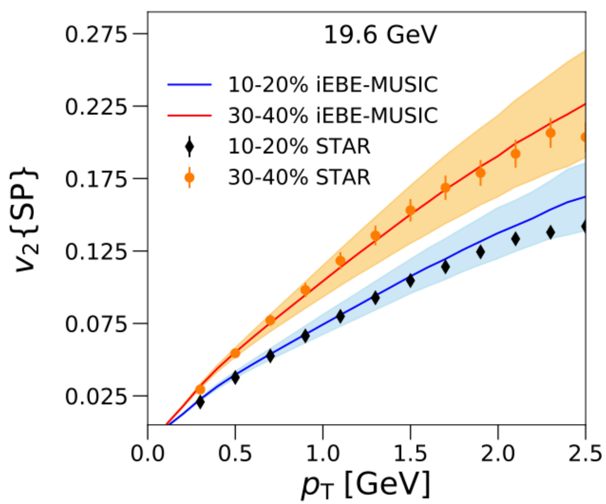
The highest likelihood parameter set obtained from the MCMC with the PCSK emulator (LHD + HPP), imposing the monotonic constraint $y_{\rm loss,2} \leq y_{\rm loss,4} \leq y_{\rm loss,6}$.

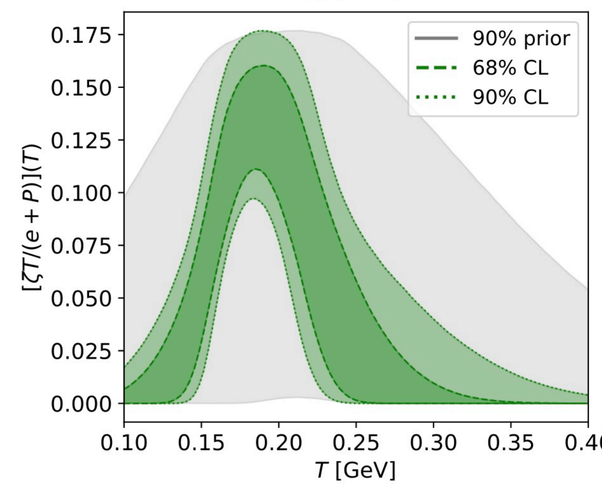
Parameter	Value	Parameter	Value
B_G [GeV^{-2}]	17.095	$\alpha_{\rm string\ tilt}$	0.884
$\alpha_{\rm shadowing}$	0.145	$\alpha_{\rm preFlow}$	0.004
$y_{\rm loss,2}$	1.467	η_0	0.045
$y_{\rm loss,4}$	1.759	η_2	0.280
$y_{\rm loss,6}$	2.260	η_4	0.287
$\sigma_{y_{\rm loss}}$	0.356	$\zeta_{\max}$	0.148
$\alpha_{\rm rem}$	0.611	$T_{\zeta,0}$ [GeV]	0.214
λ_B	0.129	$\sigma_{\zeta,+}$ [GeV]	0.018
$\sigma_x^{\rm string}$ [fm]	0.113	$\sigma_{\zeta,-}$ [GeV]	0.040
$\sigma_\eta^{\rm string}$	0.156	$e_{\rm sw}$ [GeV/fm^3]	0.350







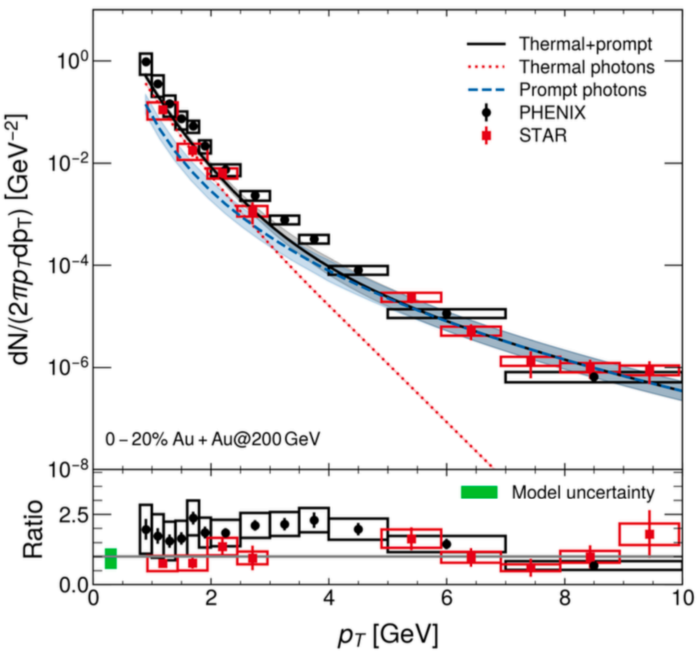




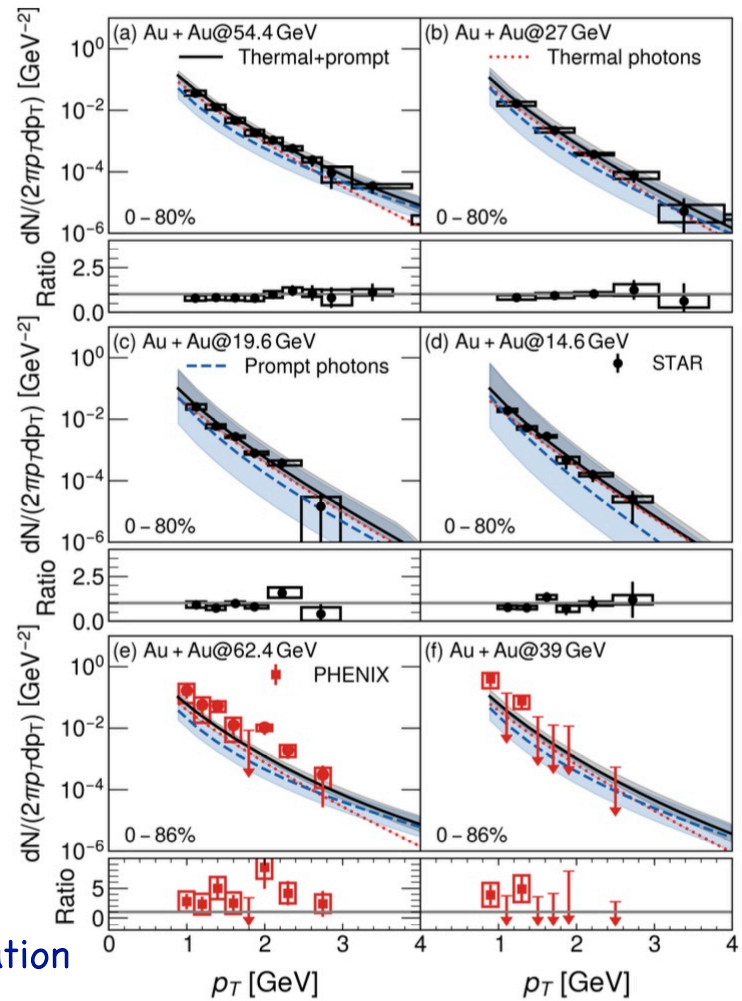
New: use the Bayesian-tuned model to calculate EM observables at BES energies

- Not emulator-based: need the full history
- Sample the 20-dimensional parameter space
- Run the multistage simulation with photon and dilepton rates
- Integrate over the full space-time

(I) Photons



- PHENIX > STAR
- High pT = prompt
- Low E_γ = new
- Bands: pQCD scale variation



Xiang-Yu Wu et al., in preparation

Putting EM probes to work: temperature extraction?

Volume 78B, number 1 PHYSICS LETTERS 11 Spetember 1797

QUARK–GLUON PLASMA AND HADRONIC PRODUCTION OF LEPTONS, PHOTONS AND PSIONS

E.V. SHURYAK
Institute of Nuclear Physics, Novosibirsk, USSR

Received 16 March 1978

Z. Phys. C – Particles and Fields 9, 341–345 (1981)

Zeitschrift für Physik C Particles and Fields

Temperature Measurement of Quark-Gluon Plasma Formed in High Energy Nucleus-Nucleus Collisions

K. Kajantie
Department of Theoretical Physics, University, SF-00170 Helsinki 17, Finland

H.I. Miettinen
Research Institute for Theoretical Physics, University, SF-00170 Helsinki 17, Finland

Received 6 March 1981

Abstract. We discuss lepton pair and real photon emission from quark-gluon plasma, which is very likely to be formed in high energy nucleus-nucleus collisions. Measurement of pair production cross-section will provide one with accurate information of the temperature of this plasma.

Nuclear Physics A400 (1983) 43c-62c. ©North-Holland Publishing Co., Amsterdam

NUCLEUS-NUCLEUS COLLISIONS: OBSERVATIONS AND EXPECTATIONS

Hans J. Specht

Physikalisches Institut der Universität
Heidelberg, Germany

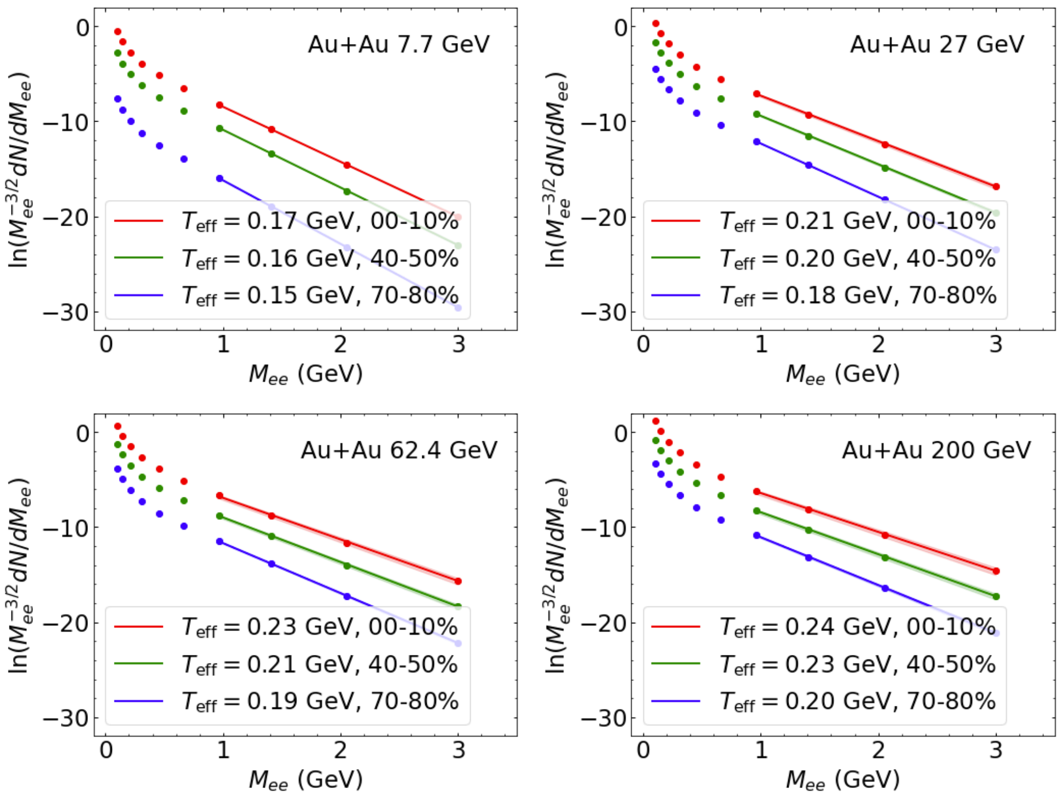
Abstract: Selected topics of nucleus-nucleus collisions between MeV/u and TeV/u are discussed, covering some recent experiments on fusion and fusion-like processes in the heavy element regime at energies around the Coulomb-barrier, some experiments on ternary exit channels at the borderline to intermediate energies, and some possible future experiments on signals associated with quark-gluon plasma formation at ultrarelativistic energies.

Putting EM probes to work

- Real photon spectrum is sensitive to local T and to blue shift: informs the modelling
- Virtual photon spectrum is invariant, but "T" depends on some details

Those two are complementary

(II) Dileptons

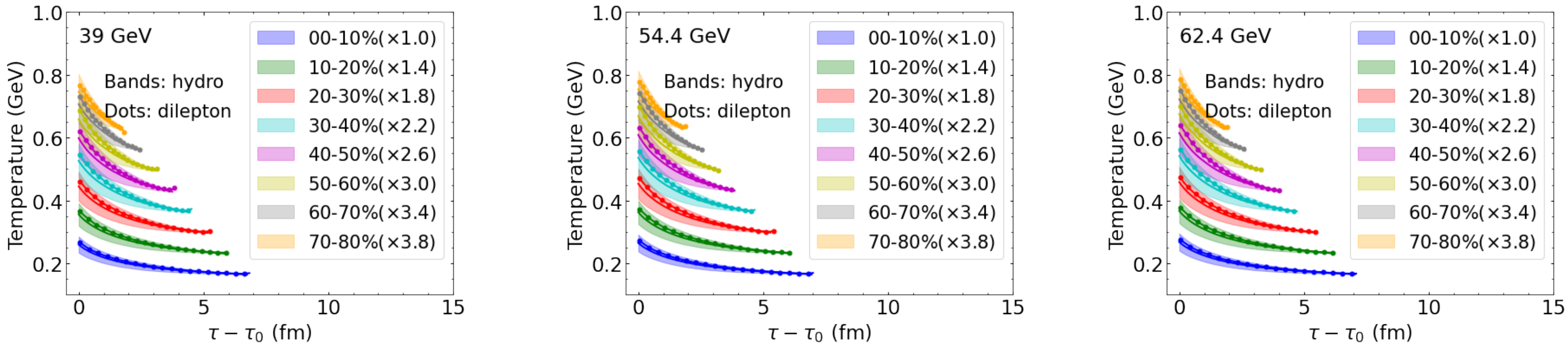


The y-axis is $\ln\left\{dN/dM \times M^{-3/2}\right\}$
The effective T is extracted from slope, considering $1 \text{ GeV} < M < 3 \text{ GeV}$

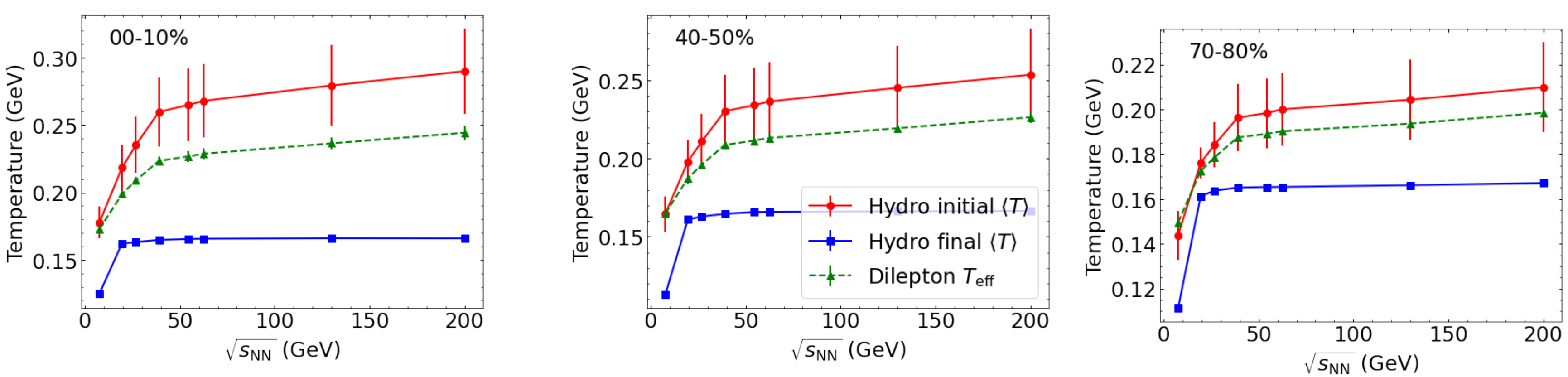
Rapp, van Hees, PLB (2016)

$T_{\rm eff}$ is energy- and centrality-dependent

Evaluating the efficacy of "the dilepton thermometer"



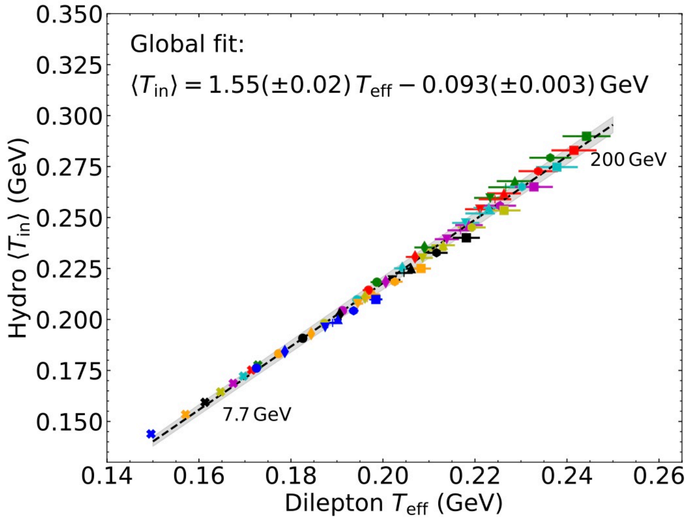
- Bands represent the temperature spread in hydro cells
- Dots are effective T read off the dilepton spectrum



- Dilepton $T_{\rm eff}$ increases with colliding energy
- We see that $T_{\rm final} < T_{\rm eff} < T_{\rm initial}$

Churchill et al., PRL (2024)

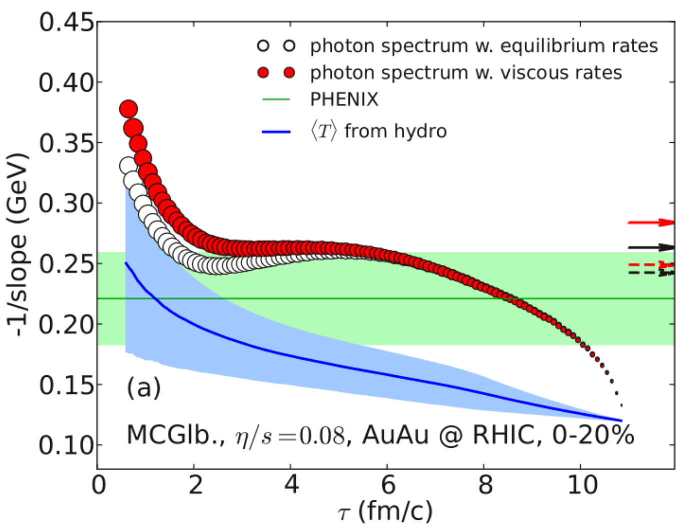
Message from photons & dileptons



Churchill et al., PRL (2024)

Dileptons

Combining all energies and centralities, the **initial** temperature in the fluid dynamical model correlates well with the effective temperature extracted from the dilepton spectrum



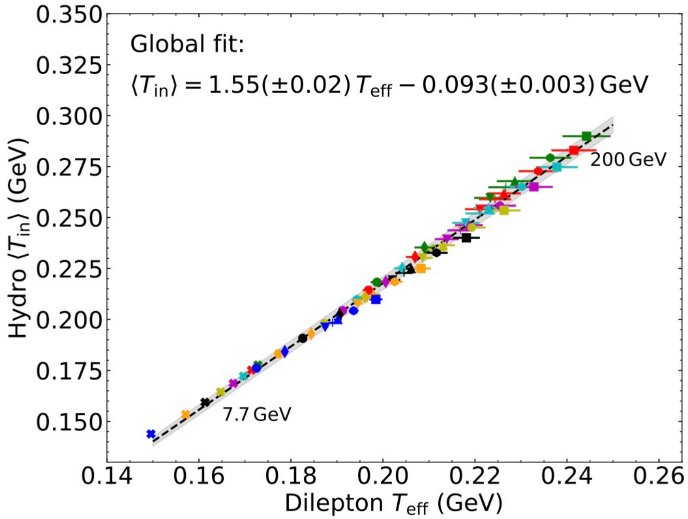
Photons

Photon "temperatures" are systematically higher than real T, but reveal some of the expansion dynamics

van Hees et al., PRC (2011)
Shen et al., PRC (2014)

$$\frac{d^3R}{d^3p} \sim \exp\left(-\gamma E + \beta\gamma E\right) \quad \longrightarrow \quad T_{\rm eff} = \sqrt{\frac{1+v}{1-v}}\,T$$

Message from photons & dileptons



Churchill et al., PRL (2024)

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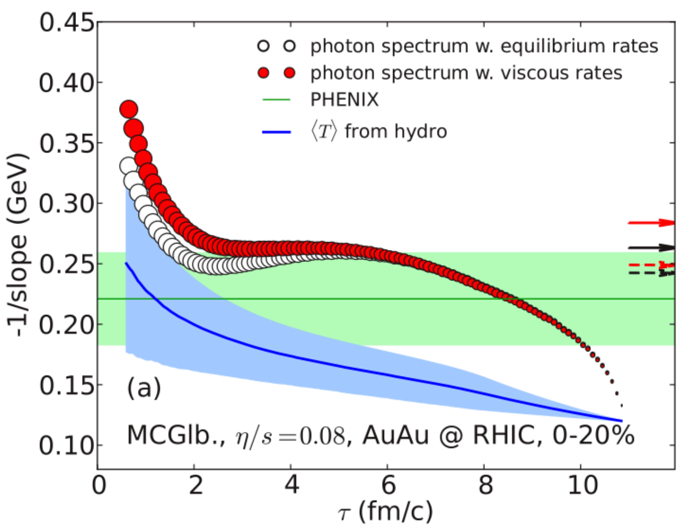

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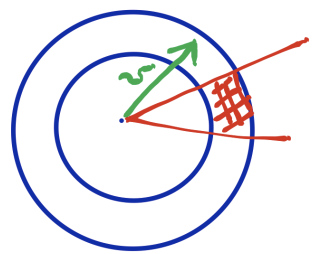

van Hees et al., PRC (2011)
Shen et al., PRC (2014)

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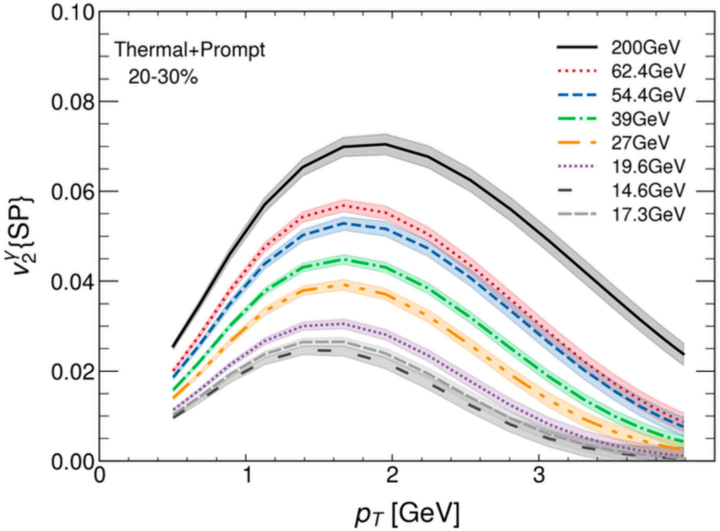
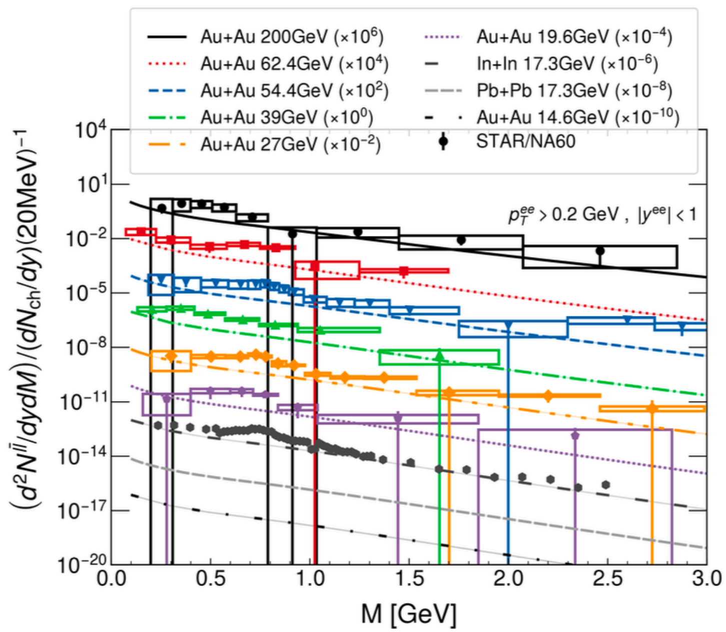
Putting EM probes to work: data in the BES range and effective temperatures



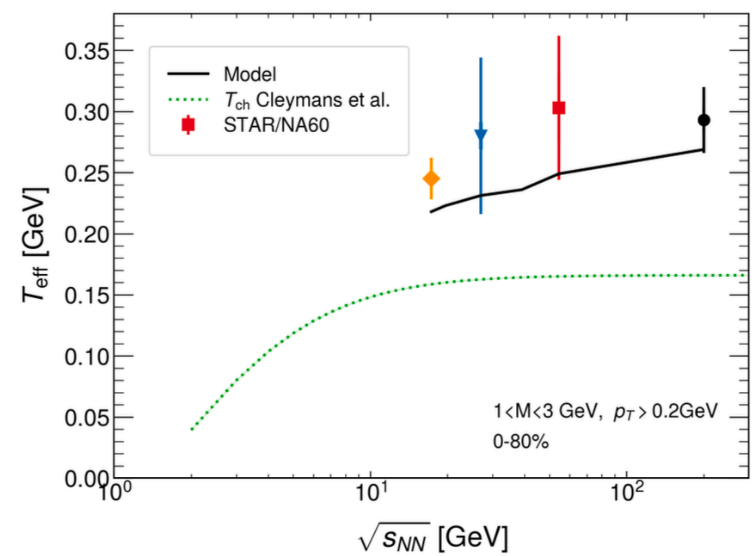
Photons (No photon v2 data yet at those energies)

Dilepton **excess** (hadronic cocktail subtracted), from STAR BES runs and NA60 measurements. Consider $M > 1$ GeV

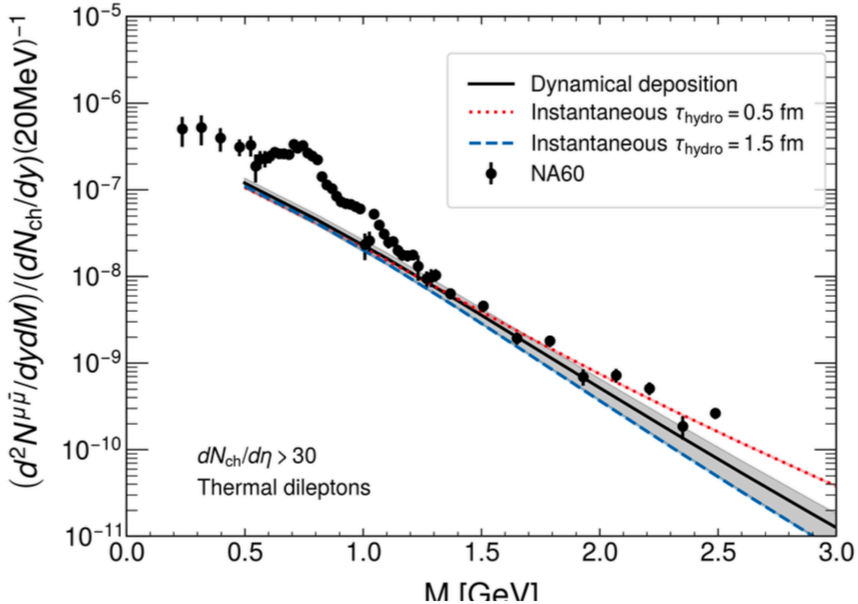
X.-Y. Wu et al., in preparation



Dilepton excess



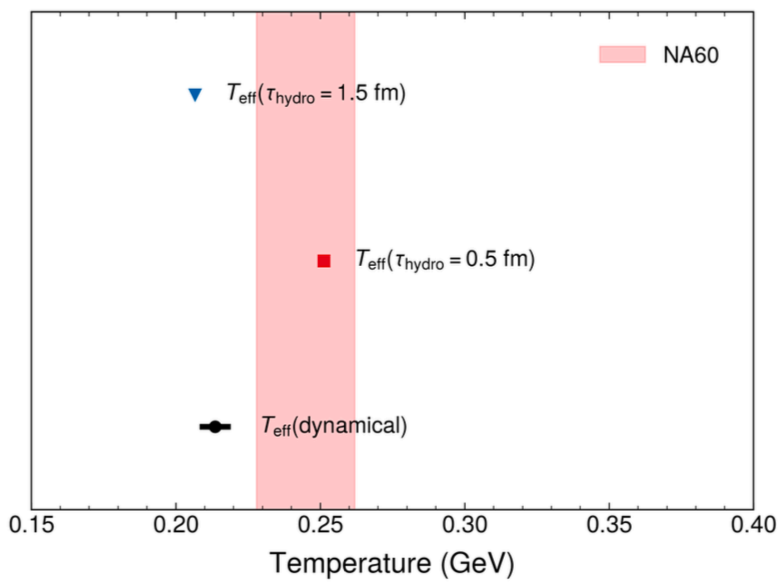
New: exploring the early stages at SPS energies



$$\sqrt{s_{NN}} = 17.3\ \text{GeV}$$

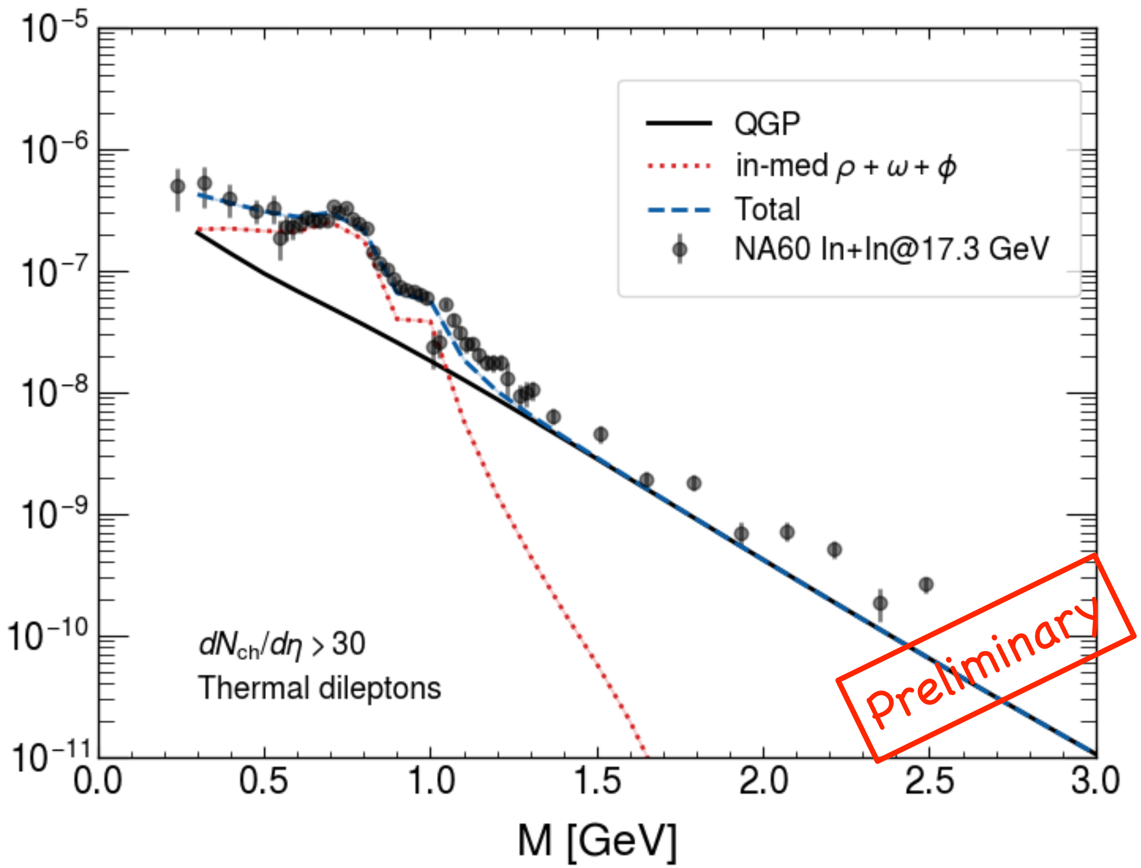
- Concentrate on IMR (for the moment)
- 3 scenarios: 3 different temperatures

X.-Y. Wu et al., in preparation



- As SPS energies, smaller "instantaneous" τ_0 not realistic
- Other choices lead to lower T values than window estimated by NA60
- Evidence for pre-equilibrium contribution(s)

Towards inclusion of spectral densities from all invariant mass regions

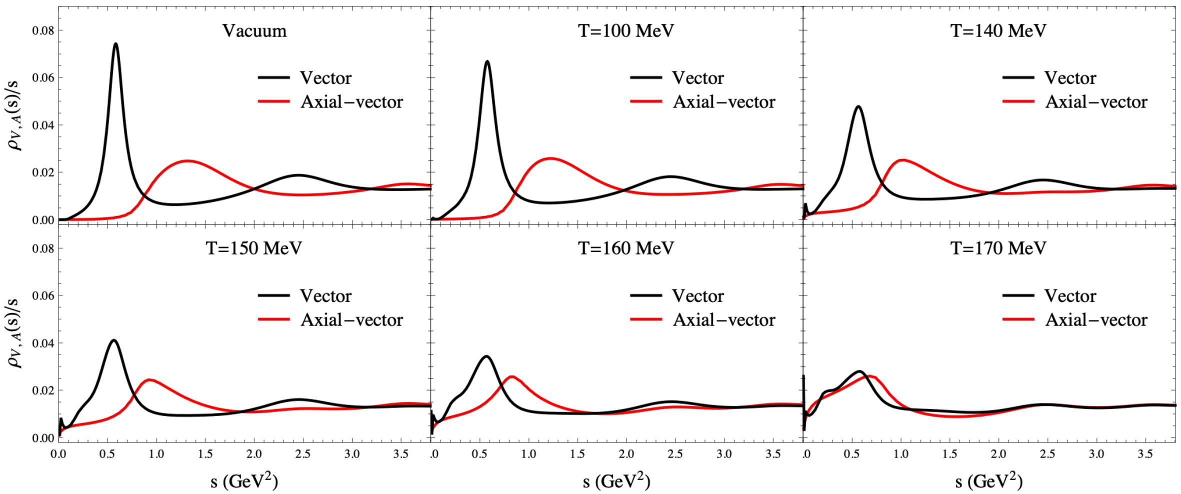


X.-Y. Wu et al., in preparation

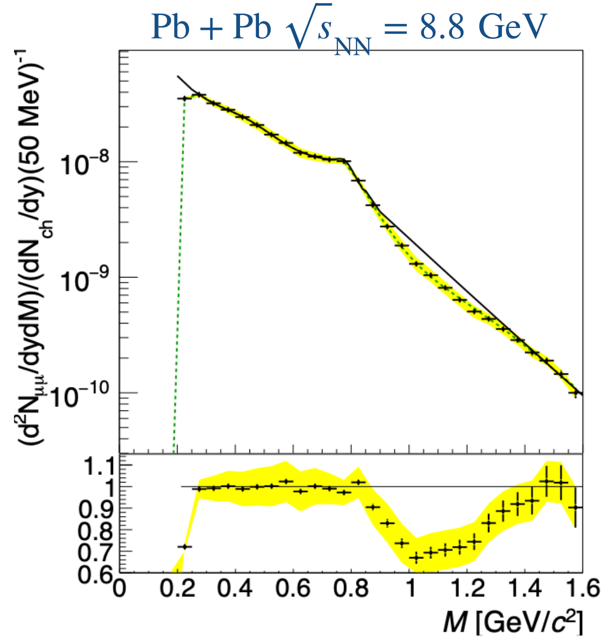
- LMR: $\rho^V_{\rho,\omega,\phi}$ from many-body hadronic theory*
- IMR: QCD (NLO, μ_B)
- Dynamical initial states+MUSIC+UrQMD
- Next: Pre-eq. Contribution, 4π, v_n ...

(*) R. Rapp

Putting EM probes to work: dileptons and fundamental symmetries

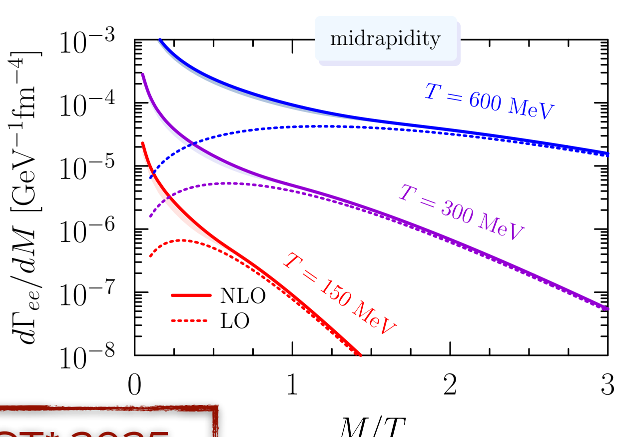


Hohler and Rapp, NPB Supp. (2021)

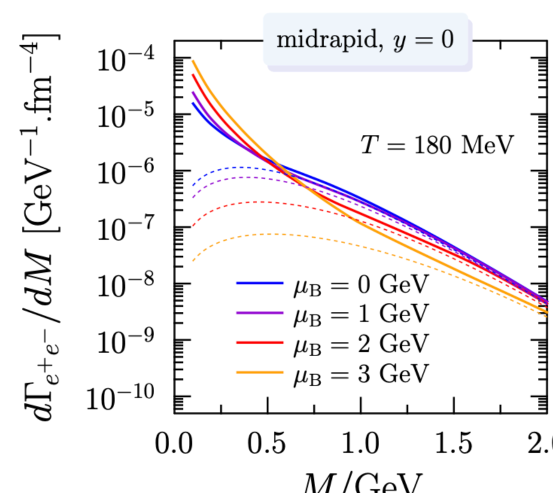


NA60+/DiCE 2503.23872

Importantly, the symmetry restoration manifests itself around $M \sim 1$ GeV ($\Delta N \sim 20-30\,\%$)...



... where hadronic and QCD physics meet. Precision physics will require controlled calculations (LMR, IMR (NLO), μ_B, realistic dynamics, etc)



A new twist: dilepton polarization

Go back to

$$E_+E_-\frac{dR_{\ell\bar{\ell}}}{d^3p_+d^3p_-} = -\frac{2e^4}{(2\pi)^6}\frac{\sum_i^{N_f} Q_i^2}{K^4}L^{\mu\nu}\rho_{\mu\nu}\, f_B(\omega)$$

$$K^\mu = p_+^\mu + p_-^\mu$$

$$\rho_{\mu\nu}(\omega,\mathbf{k}) \equiv -\,\mathrm{Im}\left[\int_0^\beta d\tau e^{i\omega_n\tau}G_{\mu\nu(\tau,\mathbf{k})}\right]_{i\omega_n\to\omega+i0^+}$$

$$G_{\mu\nu}(\tau,\mathbf{k}) = \int d^3x e^{-i\mathbf{k}\cdot\mathbf{x}}\langle J_\mu(\tau,\mathbf{x})J_\nu(0,\mathbf{0})\rangle_T$$

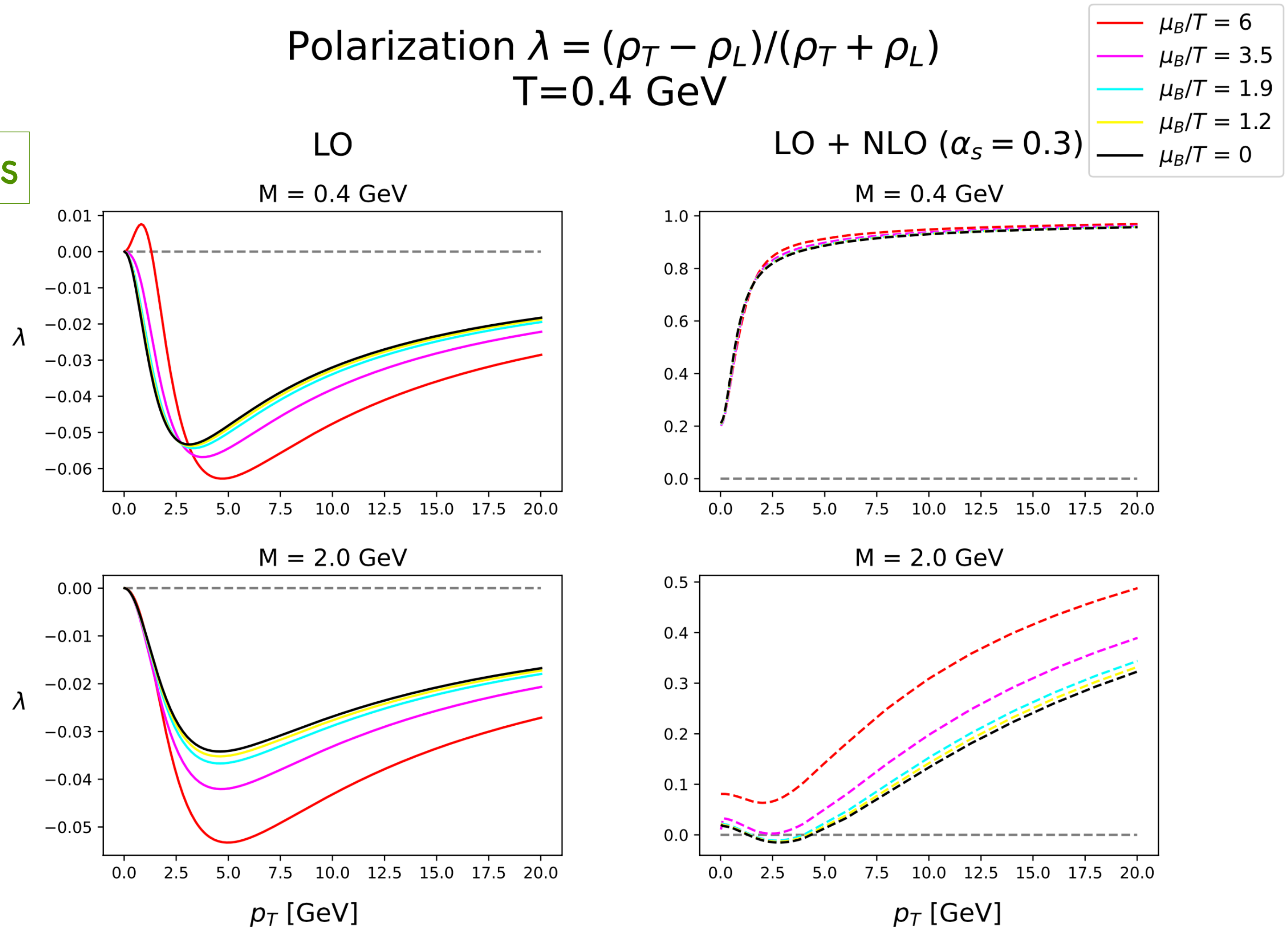
$$\rho_{\mu\nu} = P^{\mathrm{T}}_{\mu\nu}\rho_{\mathrm{T}} + P^{\mathrm{L}}_{\mu\nu}\rho_{\mathrm{L}} \qquad \rho_{\mathrm{L}} \equiv -\frac{K^2\rho_{\mu\nu}u^\mu u^\nu}{(u\cdot K)^2 - K^2}, \qquad \rho_{\mathrm{T}} \equiv \frac{\rho^\mu_\mu - \rho_{\mathrm{L}}}{2}$$

$$\frac{dR_{\ell\bar{\ell}}}{d^4K} = \frac{2\alpha_{\mathrm{em}}^2}{9\pi^2}\frac{\sum_i^{N_f} Q_i^2}{K^2}B\left(\frac{m_\ell^2}{K^2}\right)\rho_{\mathrm{V}} f_{\mathrm{B}}(\omega), \qquad \rho_{\mathrm{V}} = \rho^\mu_\mu = \rho_{\mathrm{L}} + 2\rho_{\mathrm{T}}$$

$$B(0) = 1$$

Dilepton polarization; looking at the longitudinal and transverse rates

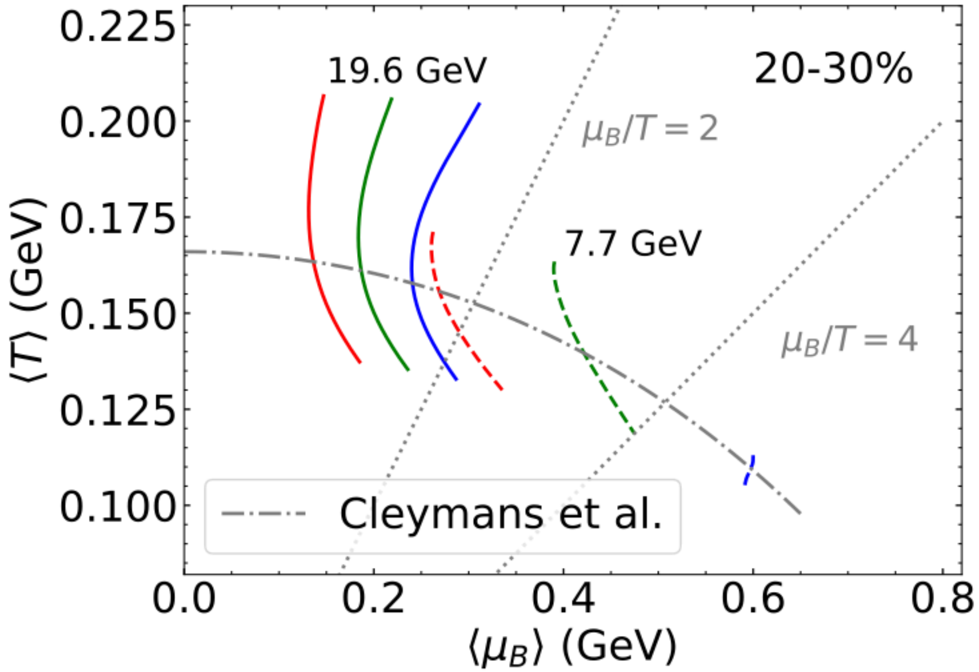
QCD Rates



- Qualitative and quantitative difference between LO and LO+NLO
- Polarization contains info on μ_B

B. Forster, MSc (2024)

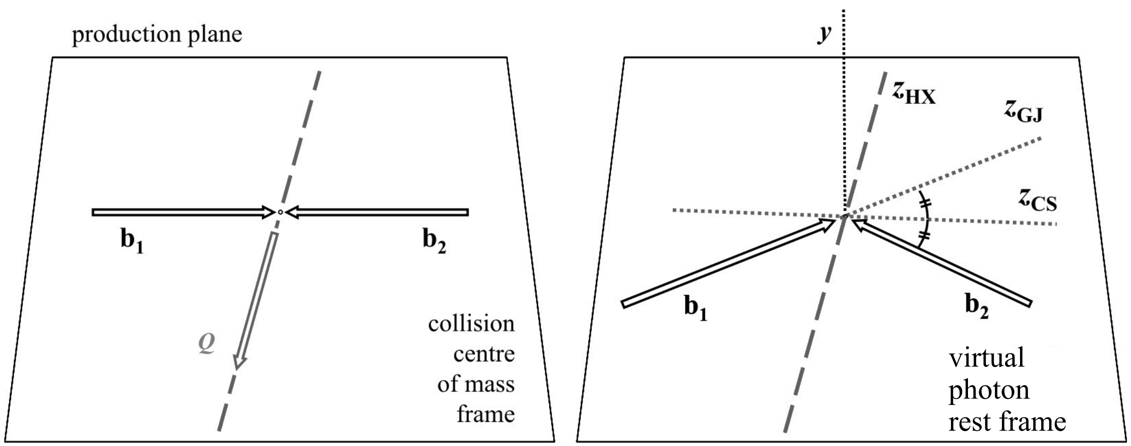
Trajectories:
Values of T and μ_B spanned at lower energies

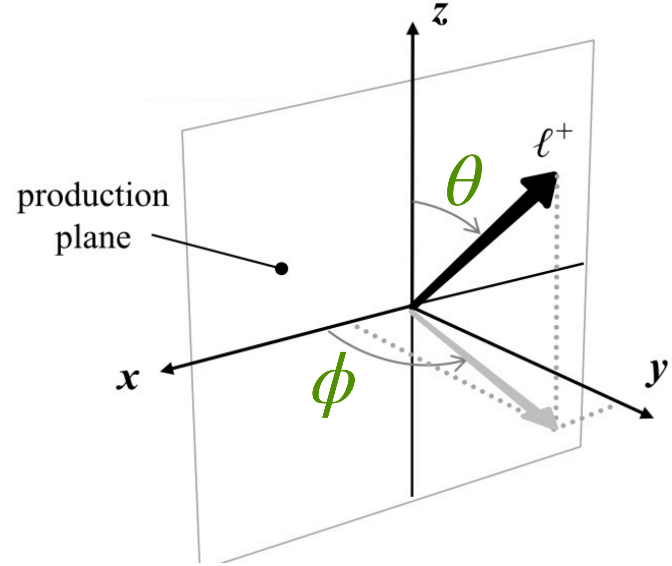


- Au + Au@19.7 and 7.7 GeV
- Hydro trajectories in three different rapidity windows: [left to right]: {-0.5, 0.5}, {0.5, 1.0}, {1.0, 1.5}
- Dot-dashed line: chemical freeze-out estimate

The dilepton polarization and the lepton angular distribution

$$\frac{dN}{d^4K d\Omega_\ell} \propto 1 + \lambda_\theta \cos^2\theta_\ell + \lambda_\phi \sin^2\theta_\ell \cos 2\phi_\ell$$
$$+\lambda_{\theta\phi} \sin 2\theta_\ell \cos\theta_\ell + \lambda_\phi^\perp \sin^2\theta_\ell \sin 2\phi_\ell$$
$$+\lambda_\theta^\perp \phi \sin 2\theta_\ell \sin\phi_\ell$$



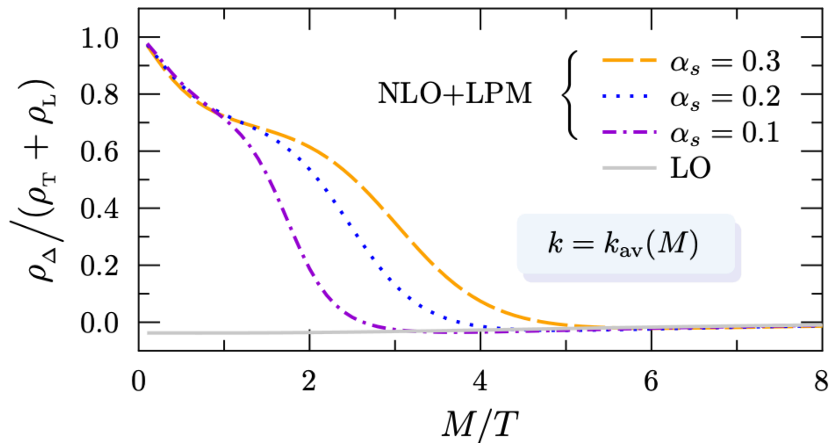


P. Faccioli et al., Eur. Phys. J. C (2010)

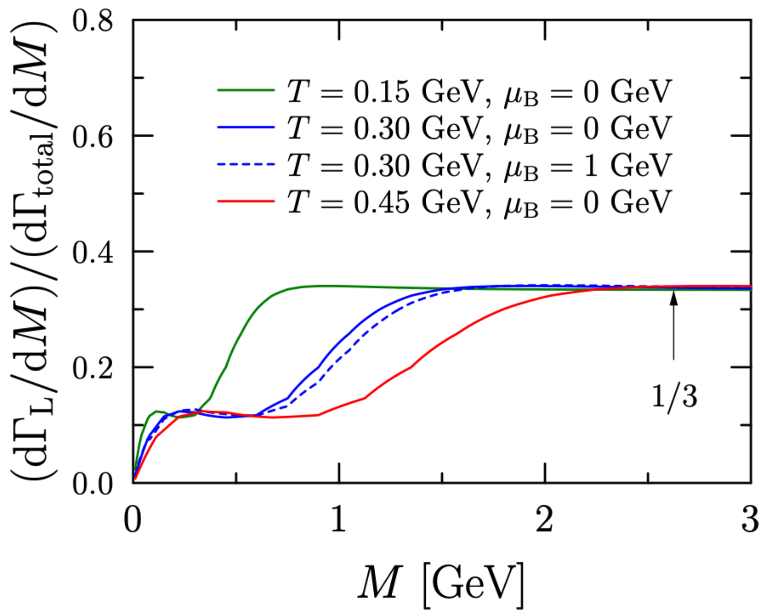
For the moment, use the HX frame

Polarization, the importance of NLO contributions

For a QCD plasma at rest:



$\mu_B = 0$



$$\lambda_\theta \simeq \frac{\rho_\Delta}{\rho_T + \rho_L}$$

$$\rho_\Delta = \rho_T - \rho_L$$

$$\omega = \sqrt{k^2 + M^2}$$

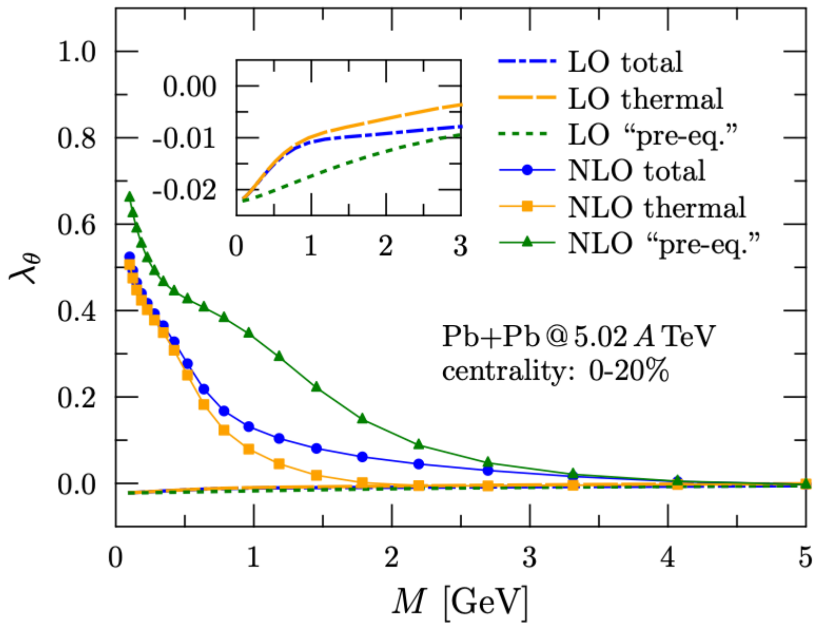
- The large M limit is like the $T \to 0$ limit for the M/T ratio. Then $\lambda_\theta \to 0$.
  OPE : $\rho_\Delta \sim k^2 (T/M)^4$
- When $M \to 0$, approaching the (real) photon point, $\rho_\Delta \to \rho_T$
- LO + NLO has the correct limit, not LO

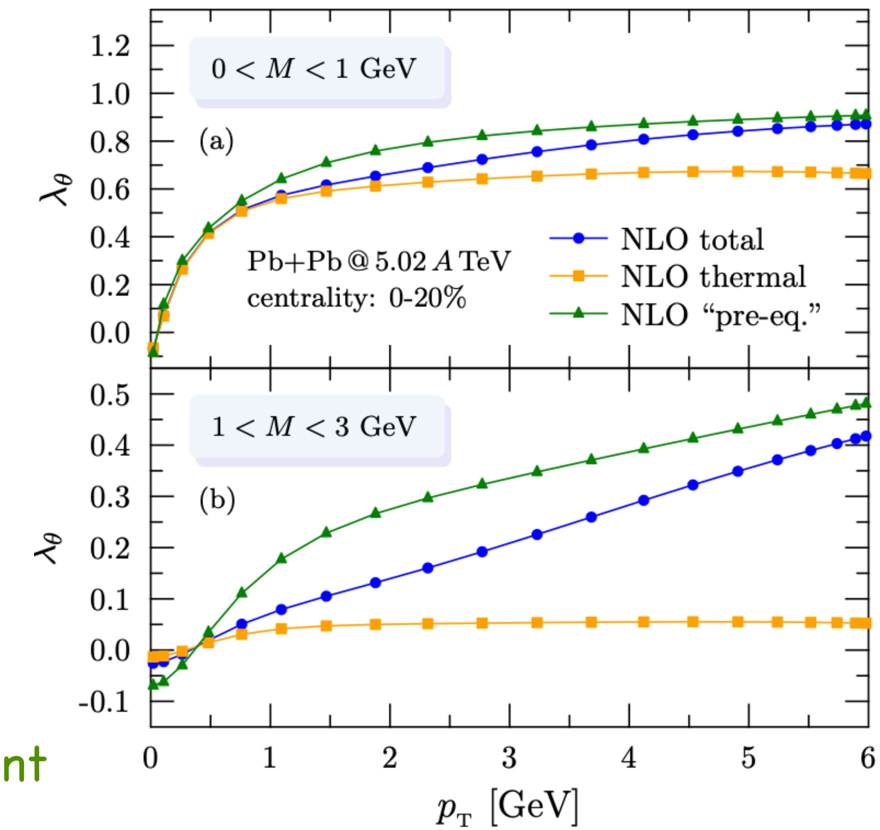
Wu et al., PRL (2025)

Charles Gale
McGill

Polarization at the LHC, and as a functions of p_T

$$\mathrm{Pb+Pb}\quad \sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV}$$





- Flow effects in polarization coefficient
- λ_θ sensitive to pre-eq. conditions
- $\lambda_\theta(p_T)$ behaviour differs in LMR and IMR

Wu et al., PRL (2025)

Dilepton polarization at all energies, next steps

- Extend result to lower E results (e.g. F. Seck et al., PLB 2025)
- Add Drell-Yan polarization
- Add pre-eq. contribution
- Small systems
- Dynamical model is important
- Non-eq. Effect in rates (transport coefficients)
- . . .

Conclusions:

- Progress in
  - NLO rates at $\mu_B \neq 0$
  - Non-eq. Contributions
  - Dilepton polarization calculations
- Much progress in dynamical evolution models
- Dynamical hadronic evolution models and EM emission are intrinsically connected
- Real photons and dileptons are complementary observables

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Thank you!