First light hunting: Probing some of the non-equilibrium aspects of HIC

Symposium on jet quenching in heavy-ion collisions

Charles Gale
McGill University

[Image: physics.org]

Real TITLE:

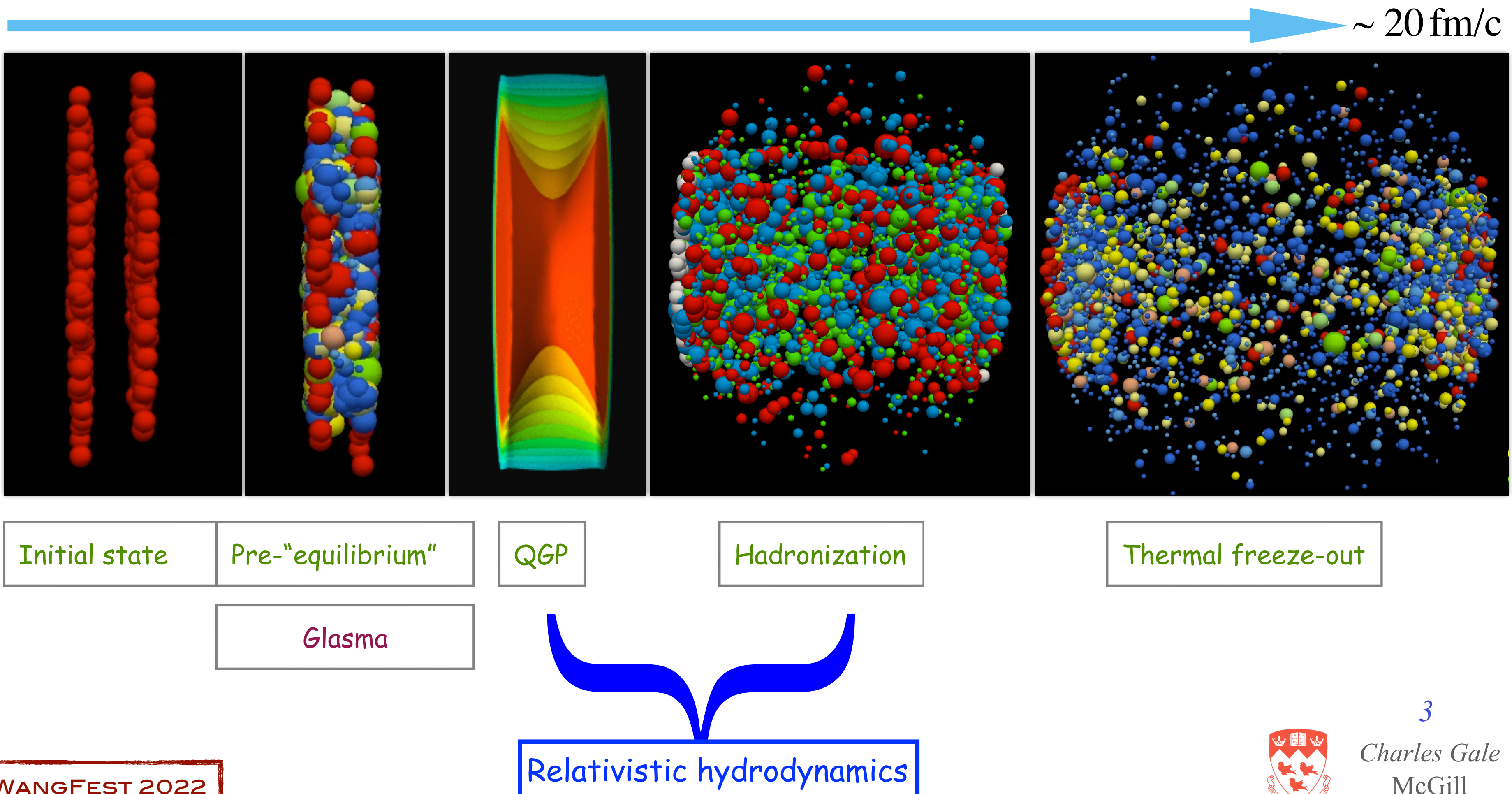
From Hard Probes Café to Heavy-Ion Tea: Three decades of hot fluids

Celebrating Xin-Nian and his career

[Image: physics.org]

Charles Gale
McGill University

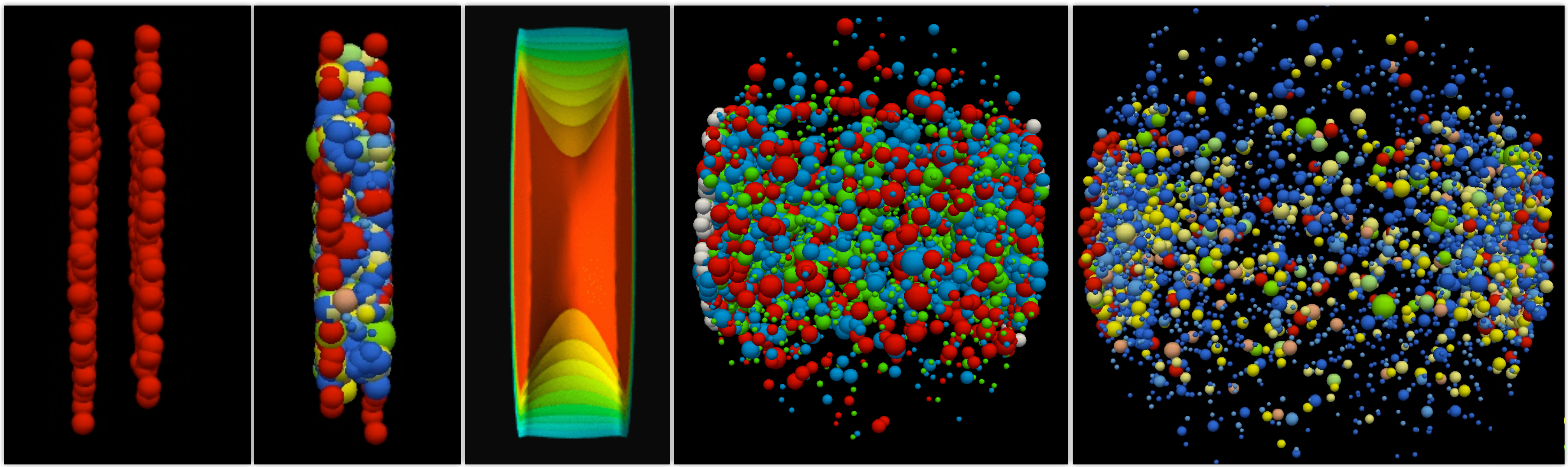
Relativistic nuclear collisions: The "standard picture"



Relativistic nuclear collisions: The "standard picture"

This talk

~ 20 fm/c



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

Glasma

Relativistic hydrodynamics

Outline

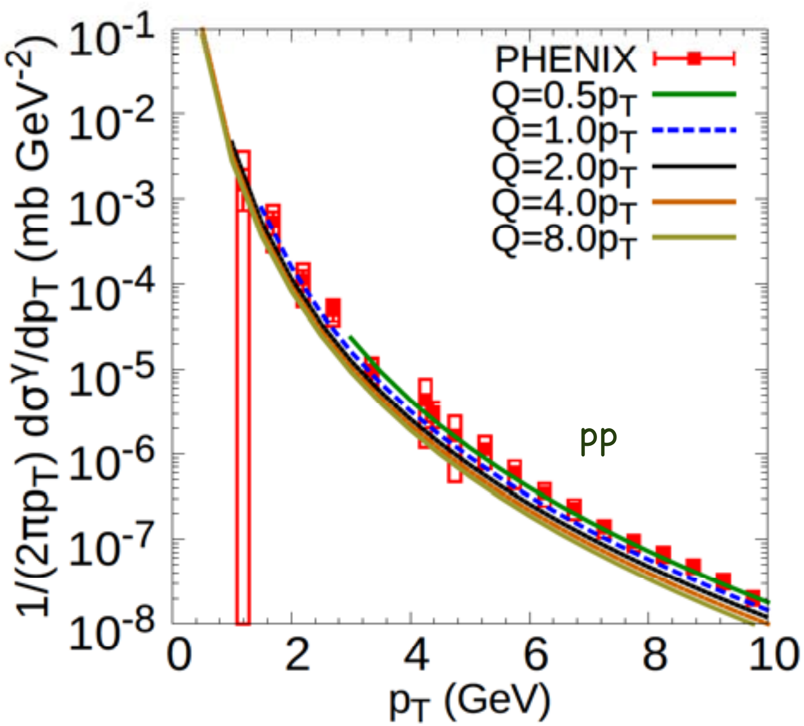
- The "standard picture" of relativistic HIC has enjoyed much phenomenological success
- There still exists fundamental questions unresolved:
  - How does matter approach "hydrodynamization" so fast?
  - Q: How well do we know the "pre-hydro" period?
  - A: Need penetrating probe(s).
    - Photons & Jets
- Photons can be **soft** and still **penetrating**

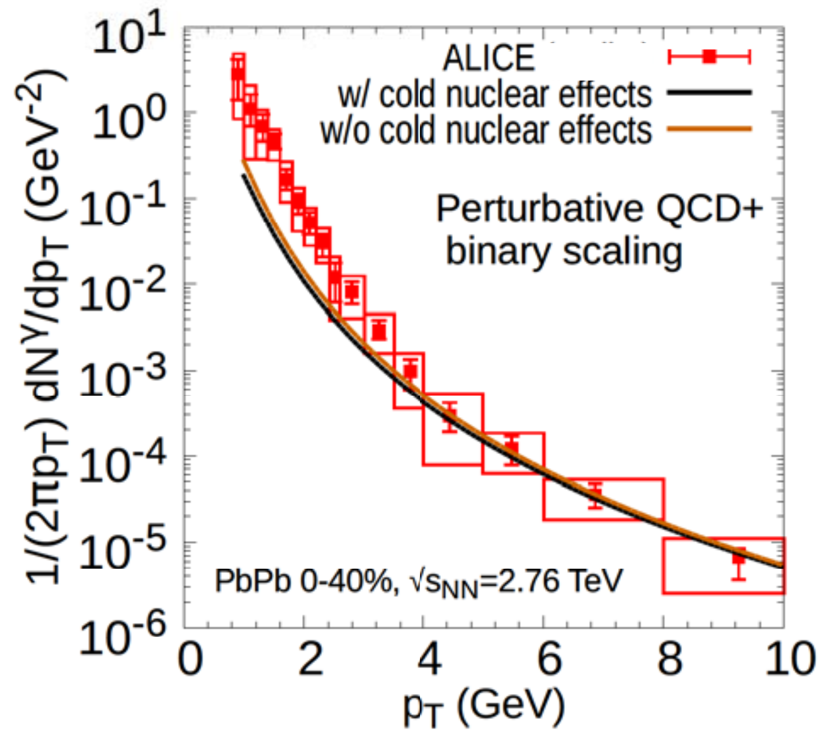
They enjoy a unique status

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

“Extreme non-equilibrium”: pQCD Photons

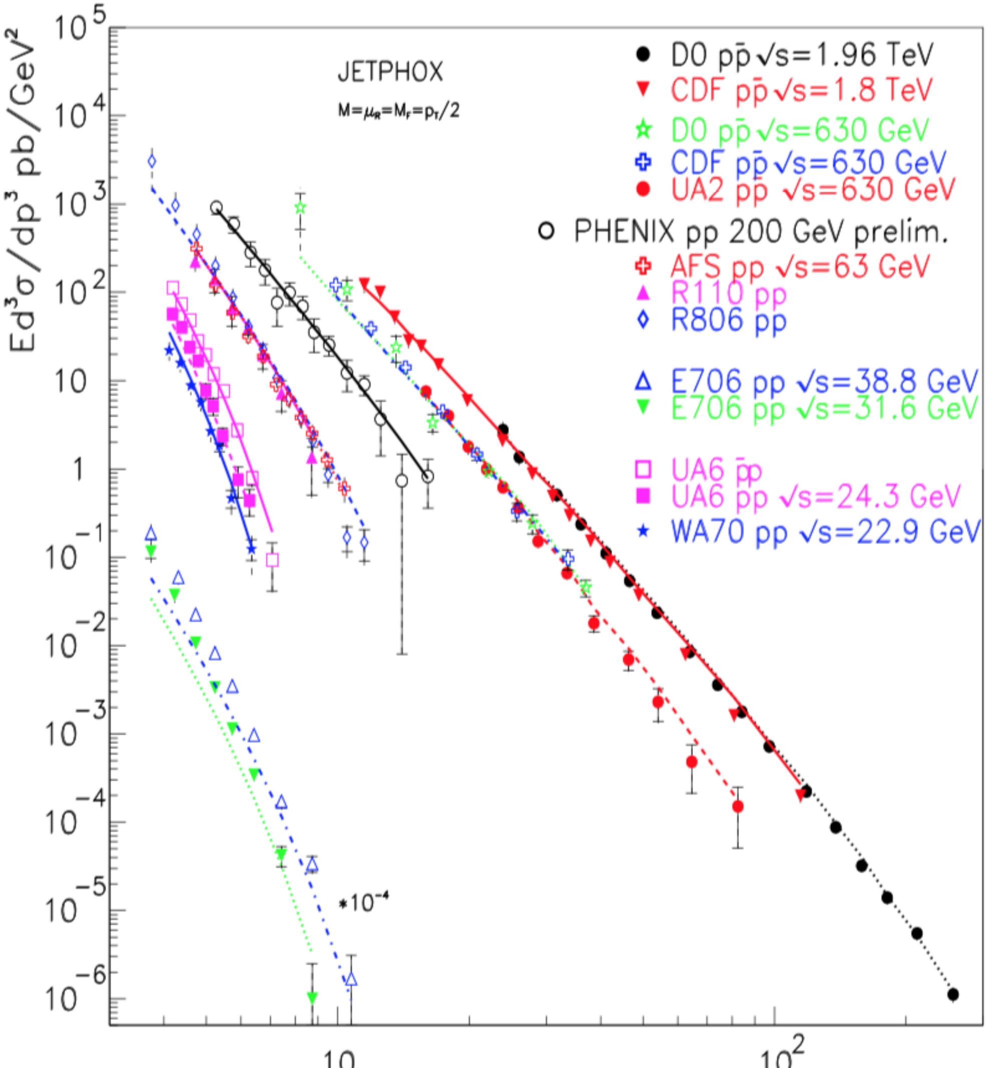
- Calculated @ NLO in pQCD
  - INCNLO, P. Aurenche et al., Eur. PJC (2000)
  - CTEQ6.1m, BFG-2, Isospin, EPS09
  - Measurement!





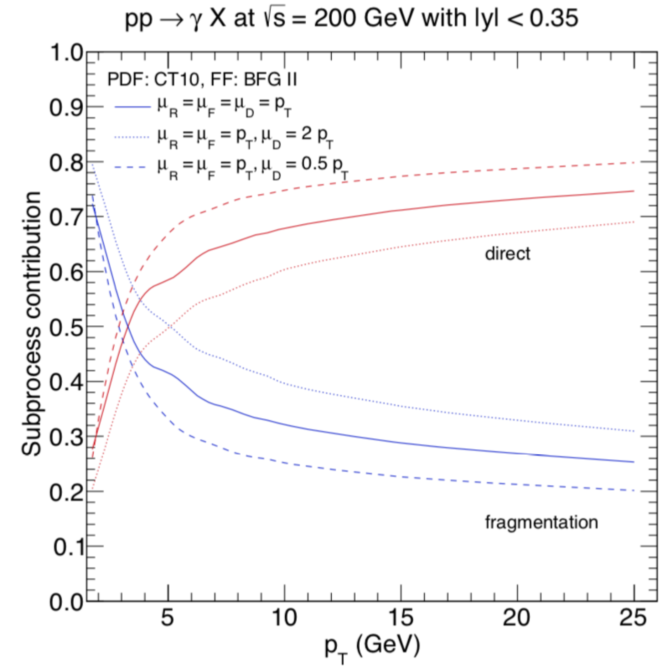
J.-F. Paquet, PhD Thesis (2015)
Paquet et al., PRC (2016)

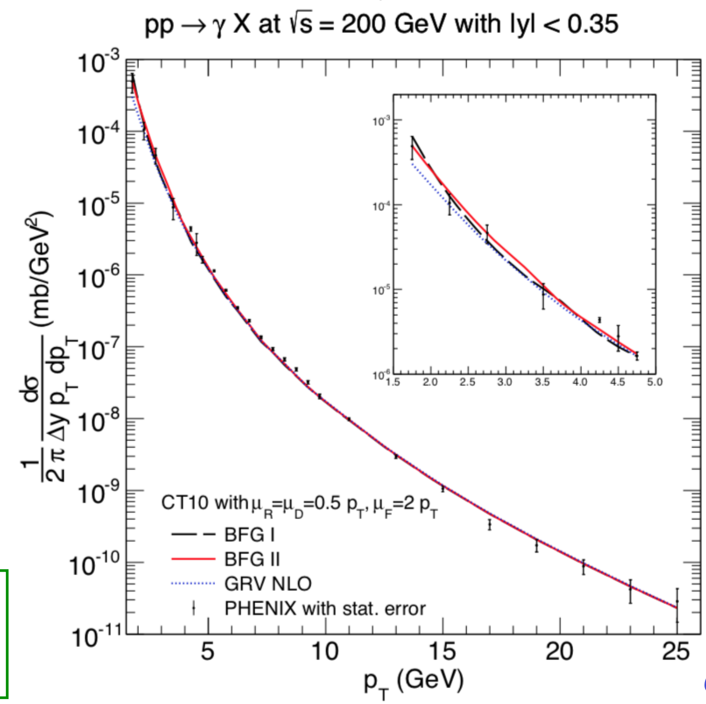
pQCD photon calculations carry uncertainties



Aurenche et al., PRD (2006)

Klasen, König, Eur. PJC (2014)



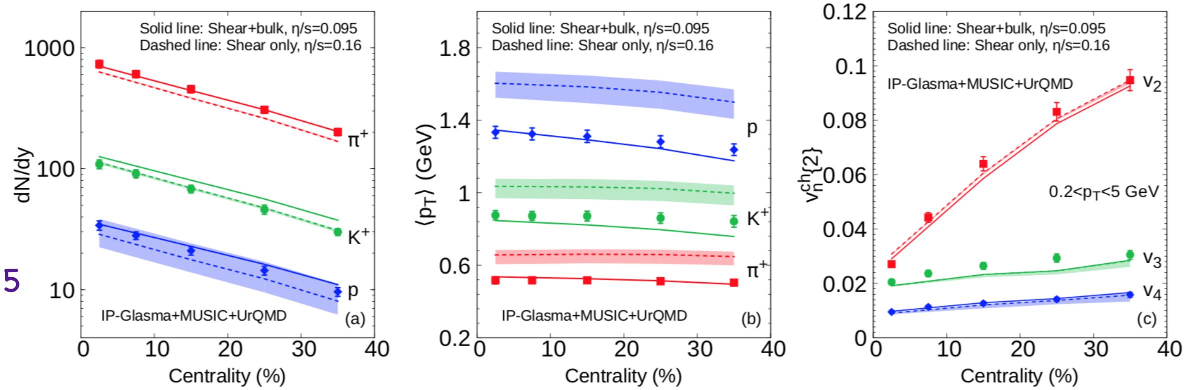


Kaufmann, Mukherjee, Vogelsang, CERN Proc. 2018

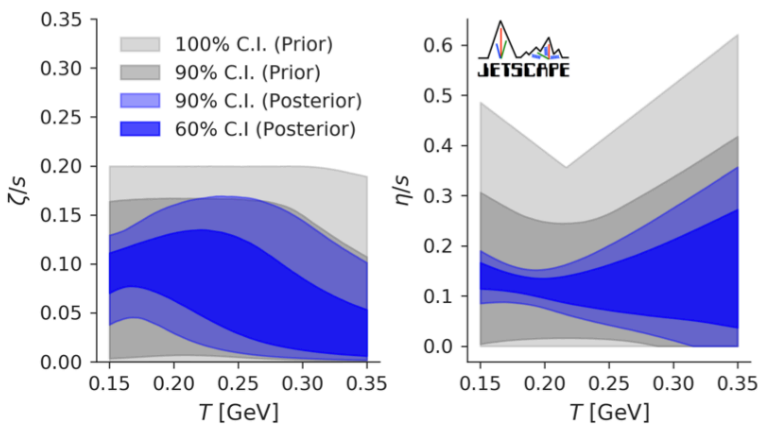
Fragmentation component: $e^+e^- \to (\mathrm{jet}\,\gamma)\,X$

Different paths to non-equilibrium physics

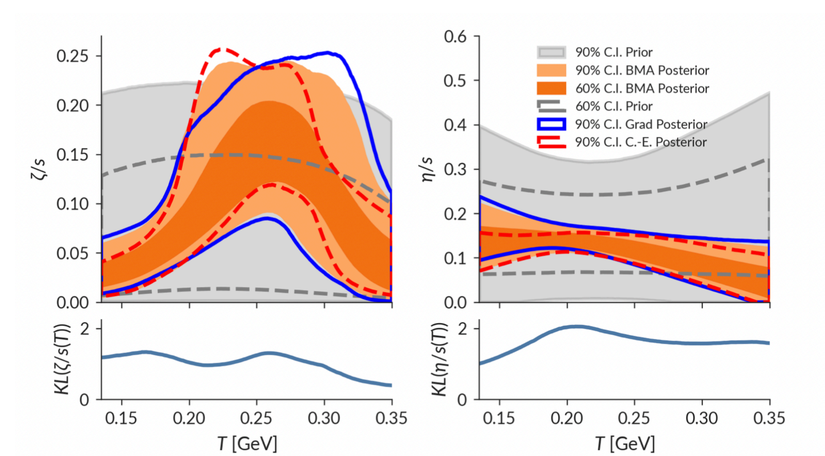
- "Top-down": start from ideal hydrodynamics, incorporate corrections $\{\pi^{\mu\nu}, \Pi\} \therefore \;\; f_{\rm eq} \to f_{\rm eq} + \delta f(\mathbf{p}, u^{\mu}, \eta, \zeta)$



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

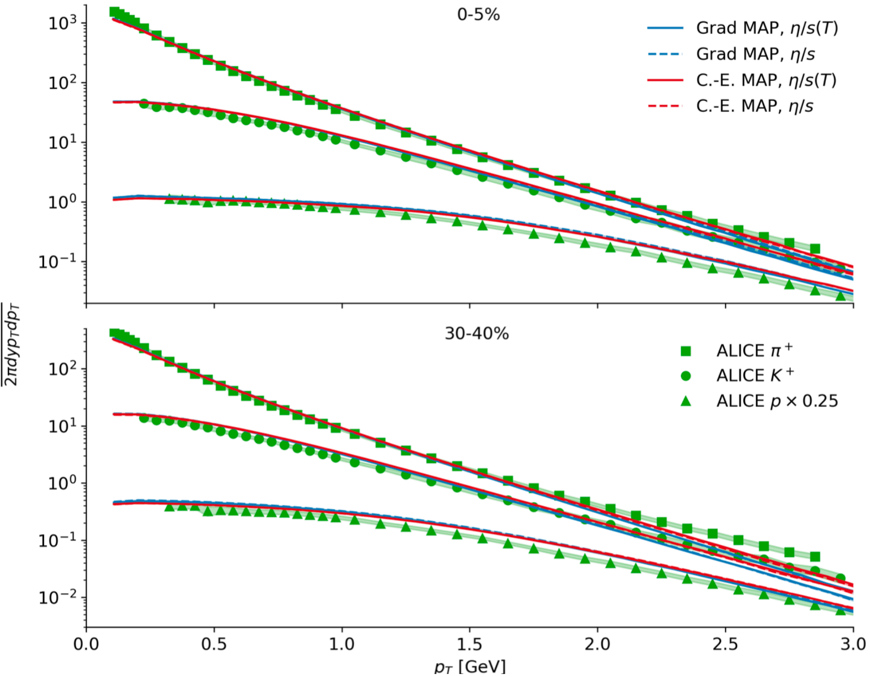


JETSCAPE Collab., PRC 2021; PRL 2021
Bernhard, Moreland, Bass, Nature Phys. (2019)
Novak et al., PRC (2014)

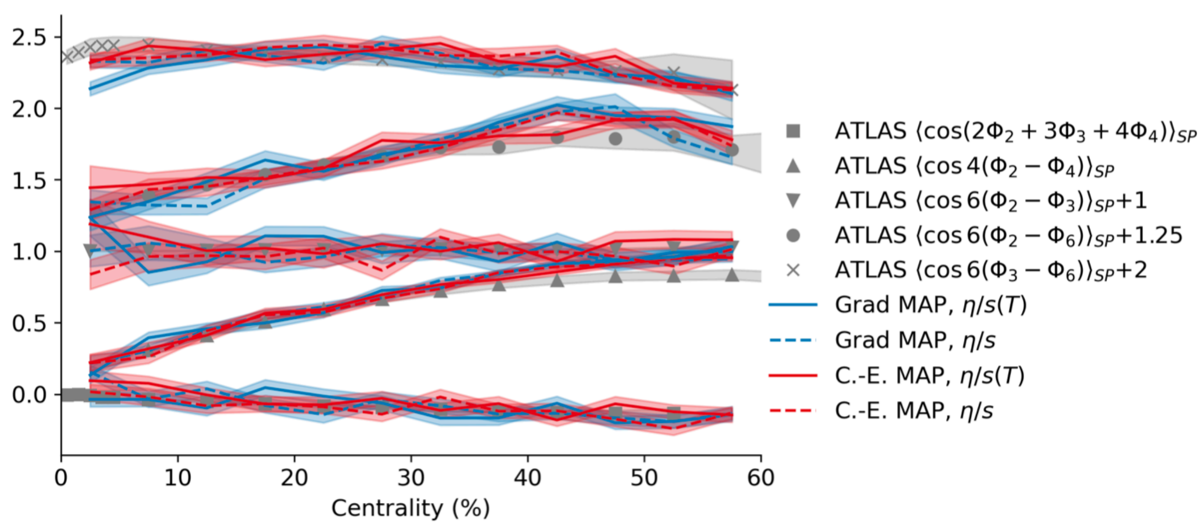


Matt Heffernan PhD thesis (McGill 2022)

Predictions



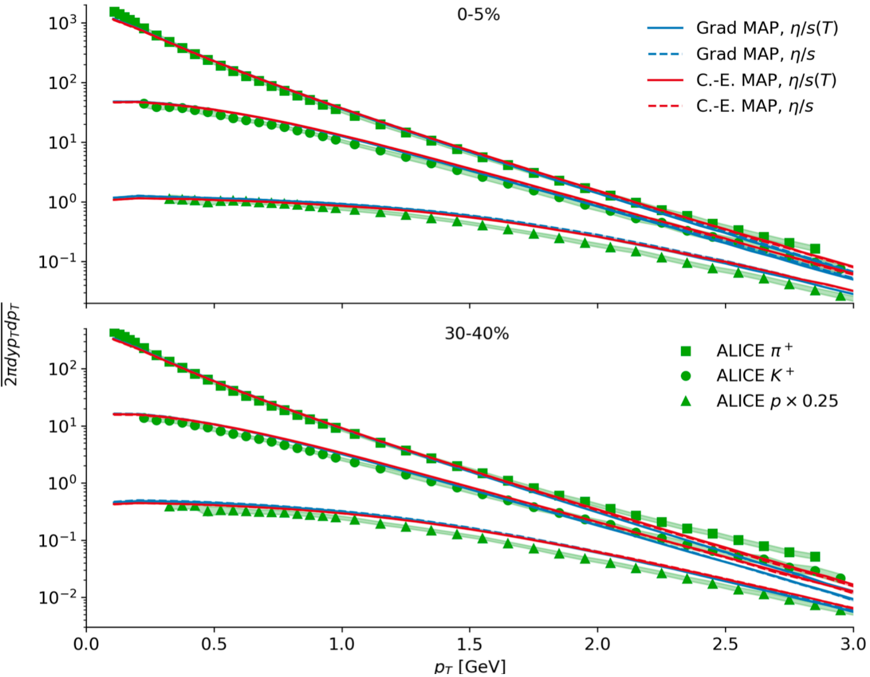
Parameter	Grad δf, η/s	Grad δf, η/s(T)	C.-E. δf, η/s	C.-E. δf, η/s(T)
μ_{Q_s}	0.72341	0.70808	0.72654	0.70858
τ_0 [fm]	0.52127	0.51291	0.40142	0.55159
$T_{\eta,\text{kink}}$ [GeV]	0.150	0.22333	0.150	0.21123
$a_{\eta,\text{low}}$ [GeV^{-1}]	0.000	-0.16259	0.000	0.65272
$a_{\eta,\text{high}}$ [GeV^{-1}]	0.000	-0.80217	0.000	-0.89472
$(\eta/s)_{\text{kink}}$	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



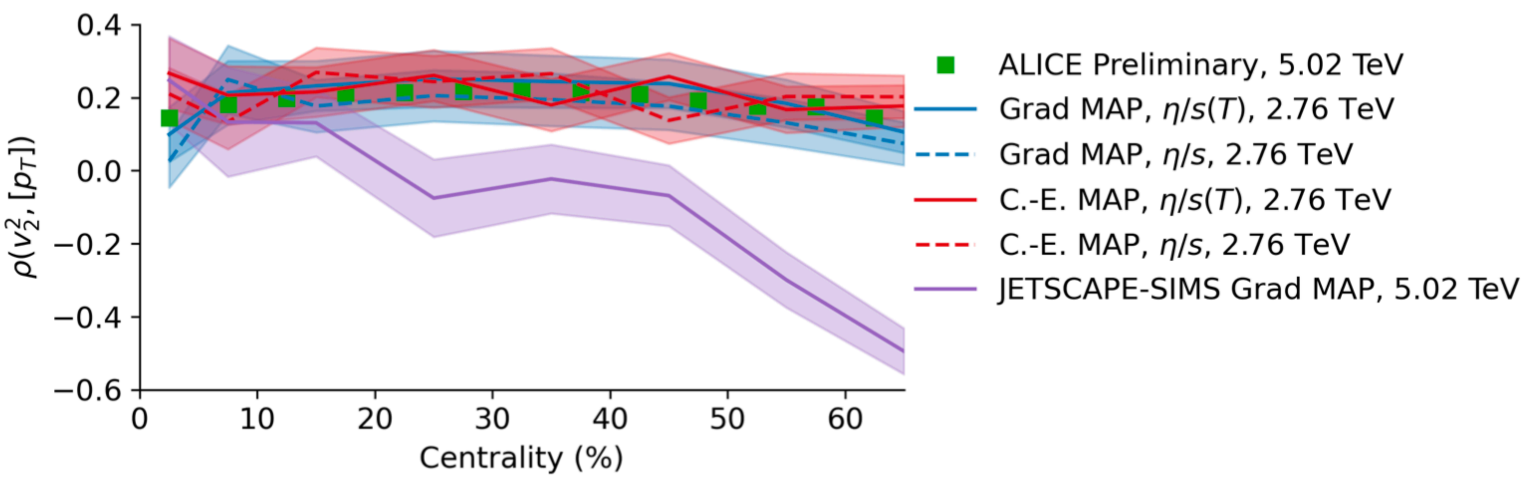
Pb+Pb, 2.76 TeV

Matt Heffernan PhD thesis (McGill 2022)

Predictions

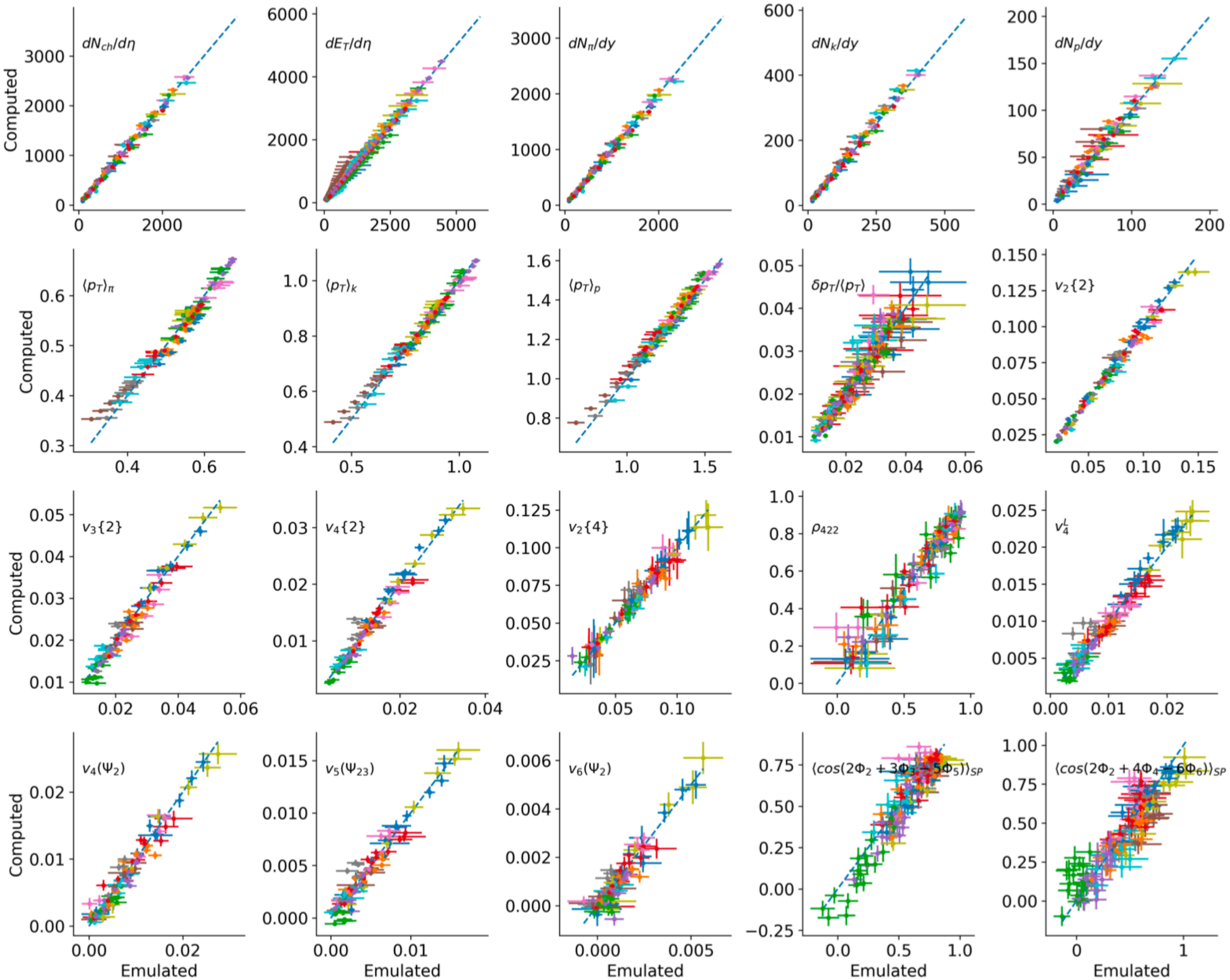


Parameter	Grad δf, η/s	Grad δf, η/s(T)	C.-E. δf, η/s	C.-E. δf, η/s(T)
μ_{Q_s}	0.72341	0.70808	0.72654	0.70858
τ_0 [fm]	0.52127	0.51291	0.40142	0.55159
$T_{\eta,\mathrm{kink}}$ [GeV]	0.150	0.22333	0.150	0.21123
$a_{\eta,\mathrm{low}}$ [GeV^{-1}]	0.000	-0.16259	0.000	0.65272
$a_{\eta,\mathrm{high}}$ [GeV^{-1}]	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



Matt Heffernan PhD thesis (McGill 2022)

One more thing…



First full-scale implementation of transfer learning in heavy-ion collisions

Hydro analyses carry precise quantitative info on the non-eq. features

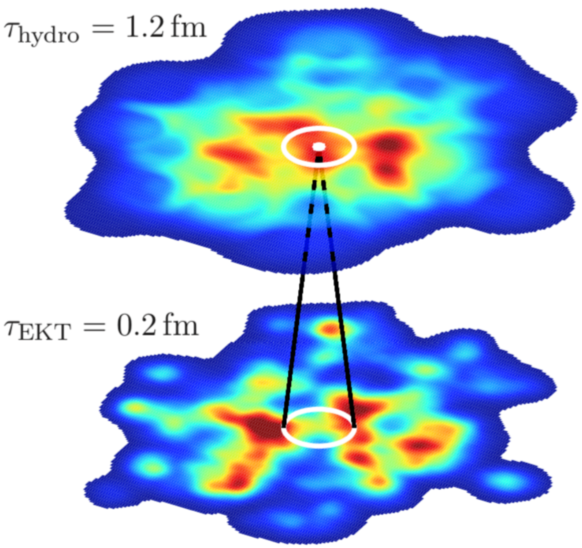
Matt Heffernan PhD thesis (McGill 2022)

Figure 6.5: Transfer learning emulated vs. computed for all observables considered. Validation points are shown with a consistent color to identify correlations between points. The diagonal dashed line is located at $y = x$, denoting perfect prediction.

Charles Gale
McGill

Pre-equilibrium physics from "the other side": 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:

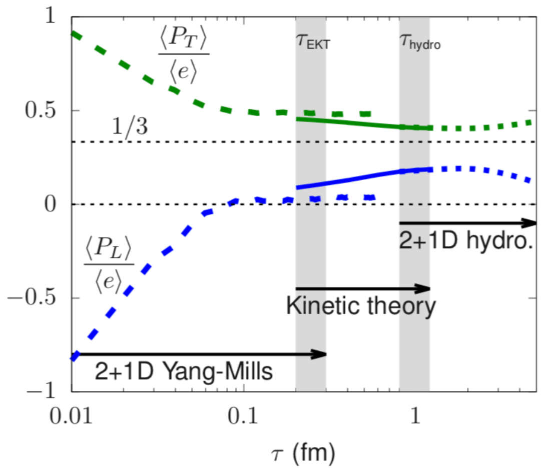
$$\frac{\delta T^{\mu\nu}(\tau, \mathbf{x})}{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau)} = \frac{1}{\overline{T}^{\tau\tau}_{\mathbf{x}}(\tau_0)} \int d^2\mathbf{x}_0\, G^{\mu\nu}_{\alpha\beta}\left(\mathbf{x}, \mathbf{x}_0, \tau, \tau_0\right) \delta T^{\alpha\beta}_{\mathbf{x}}(\tau_0, \mathbf{x}_0)$$

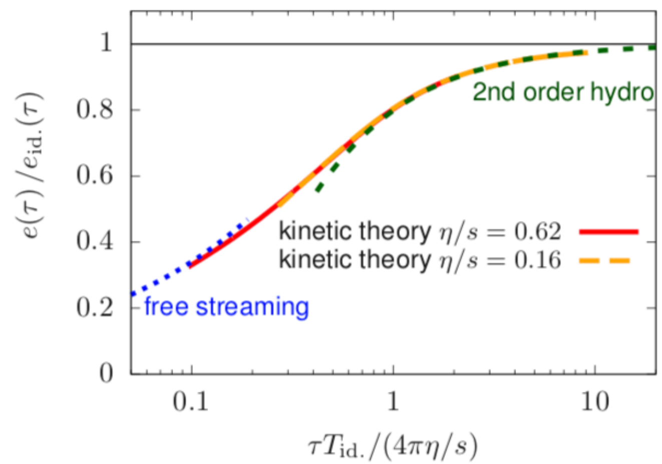
Advantages:

- 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

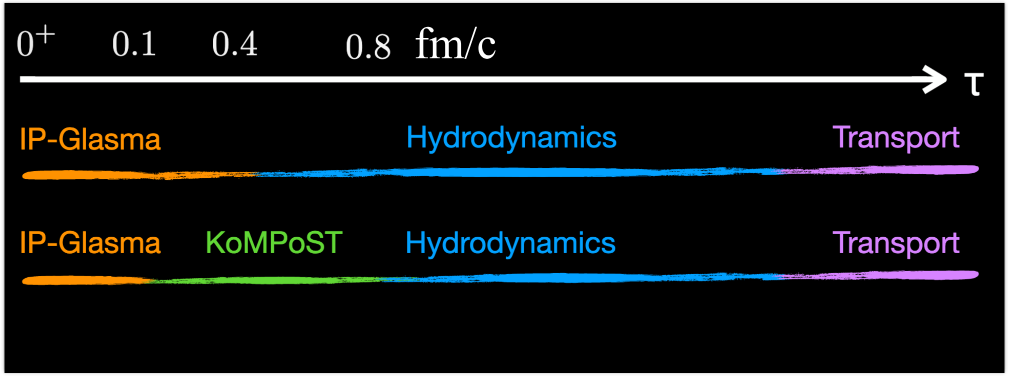
KøMPøST: an interface between early times & hydrodynamics



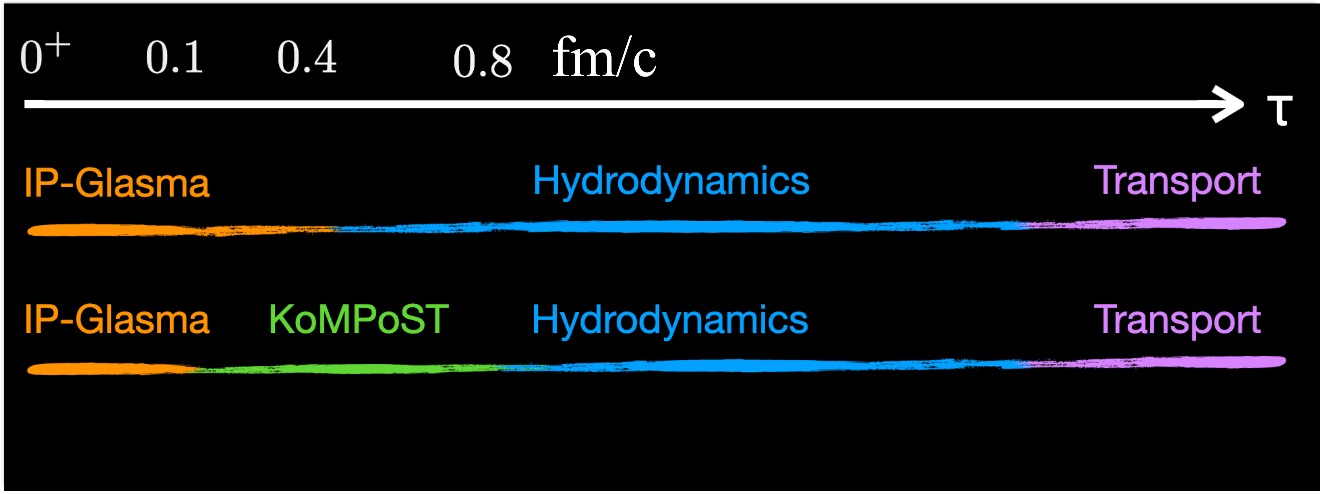


Kurkela, Mazeliauskas, Paquet, Schlichting, Teaney, PRL (2019)

Road map:



From early to late times:

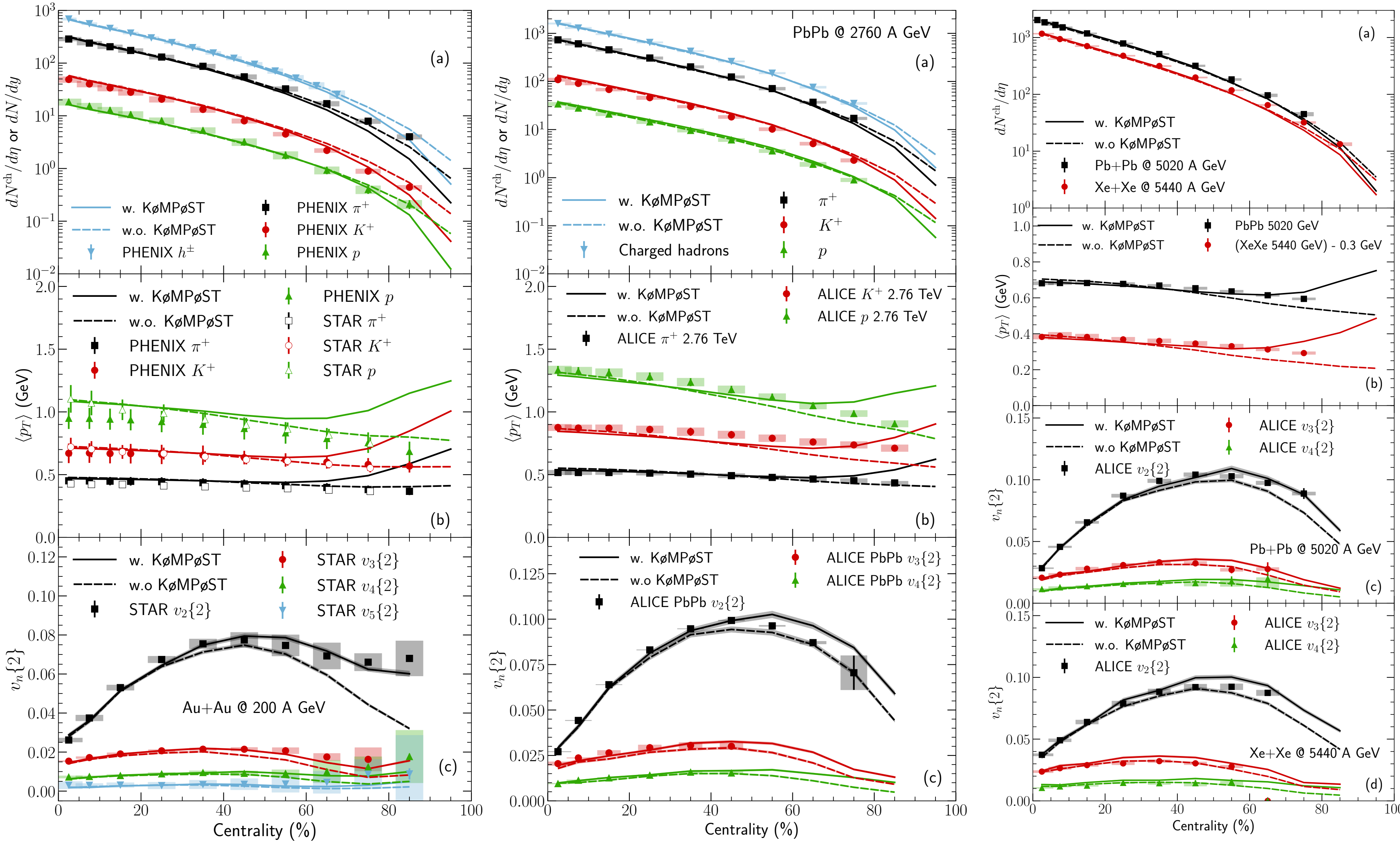


IP-Glasma | KøMPøST | MUSIC | UrQMD

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

- KøMPøST is conformal
- It consists of gluons

Effect of pre-eq. phase: hadrons



$\eta/s = 0.12$

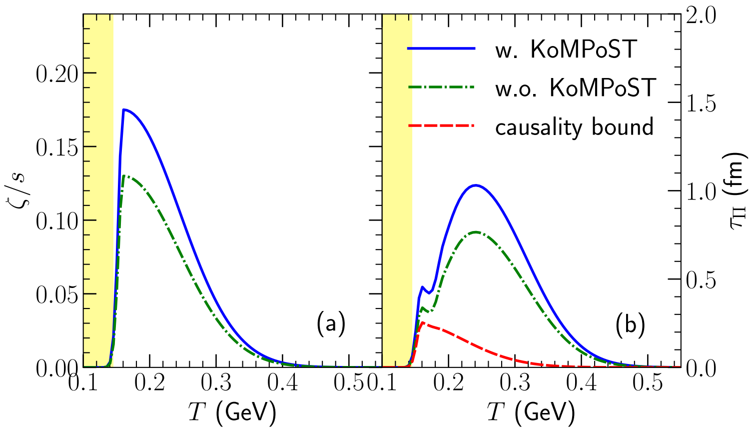
See also Nunes da Silva et al., PRC (2021)

Charles Gale
McGill

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
  - Larger bulk viscosity: +30%

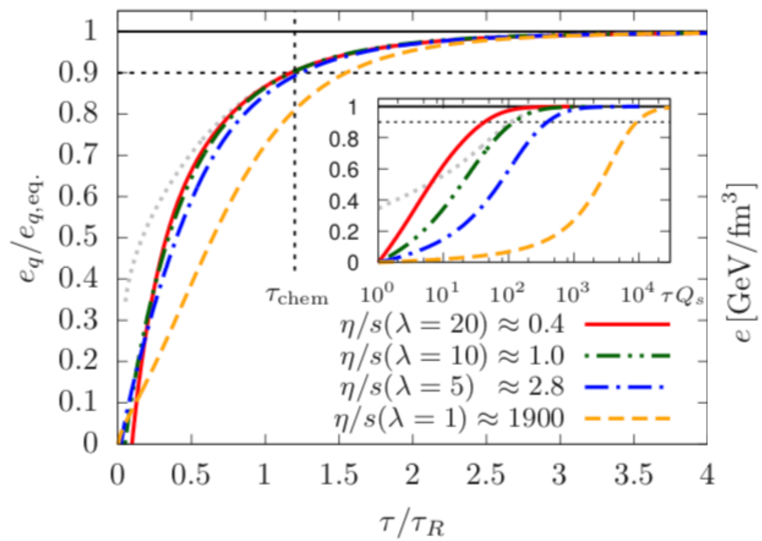


- In peripheral collisions, the lack of bulk viscous effects is the most apparent
- Hadronic observables -> Transport coefficients are sensitive to the early times dynamics

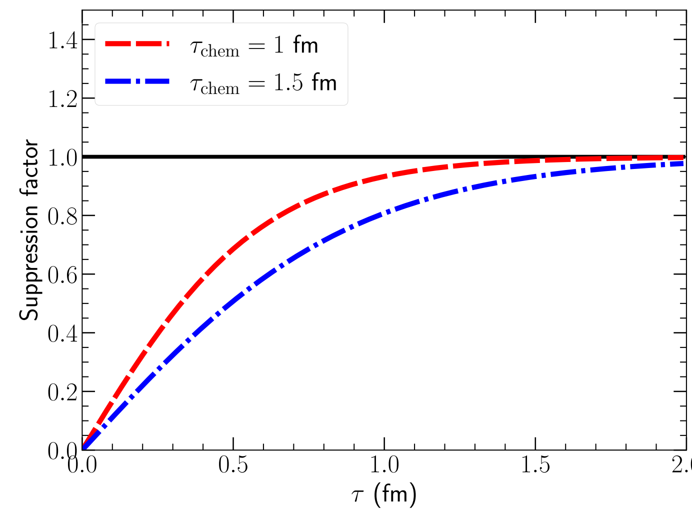
Charles Gale
McGill

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)



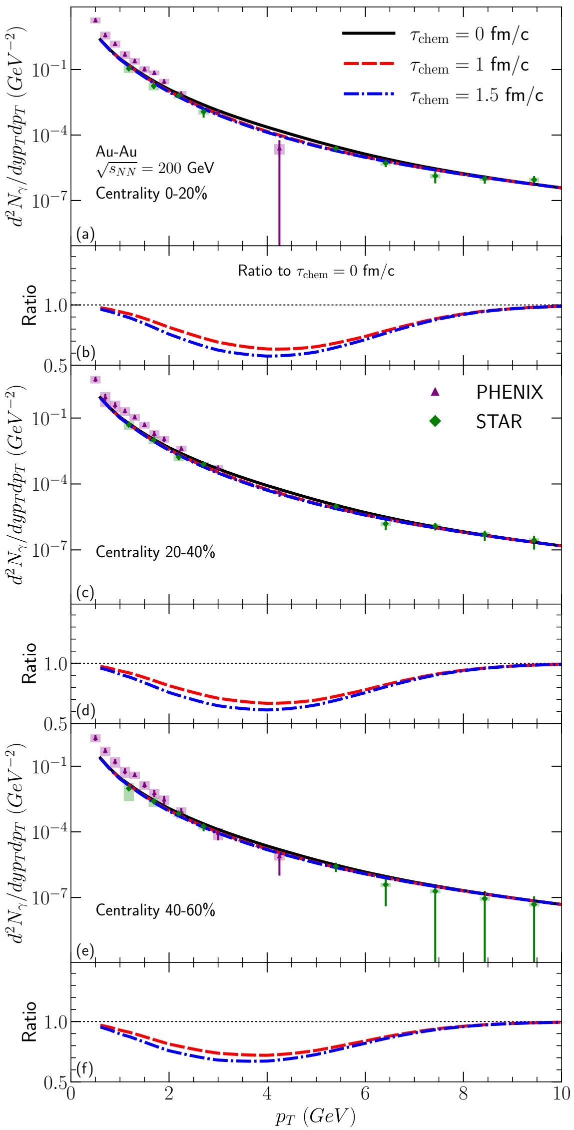
Gale, Paquet, Schenke, Chen, PRC (2022)

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

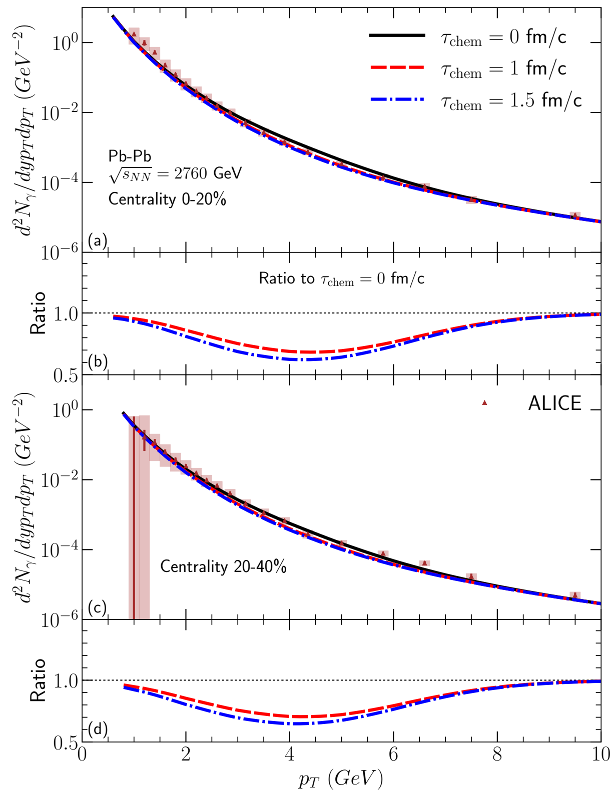
- Vovchenko et al., PRC (2016)
- Oliva et al., PRC (2017)
- Churchill et al., PRC (2021)

PUTTING IT ALL TOGETHER

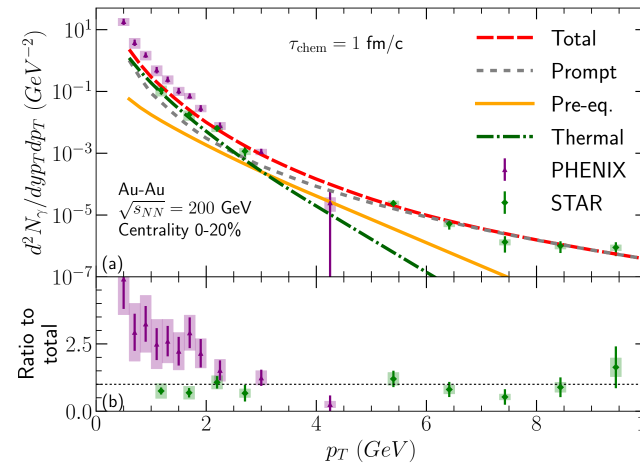
RHIC



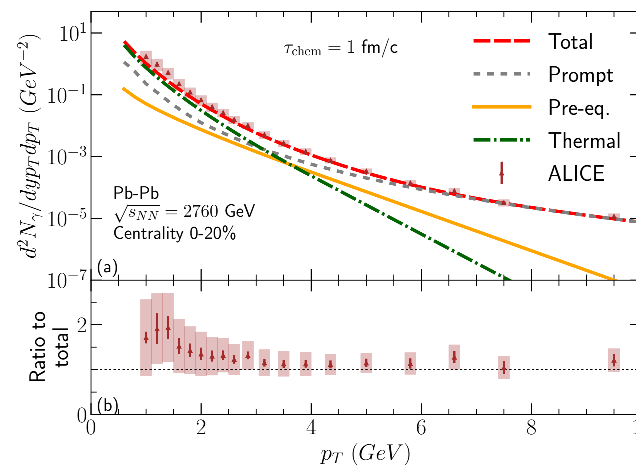
LHC



Effect of chem. eq. appears at intermediate p_T

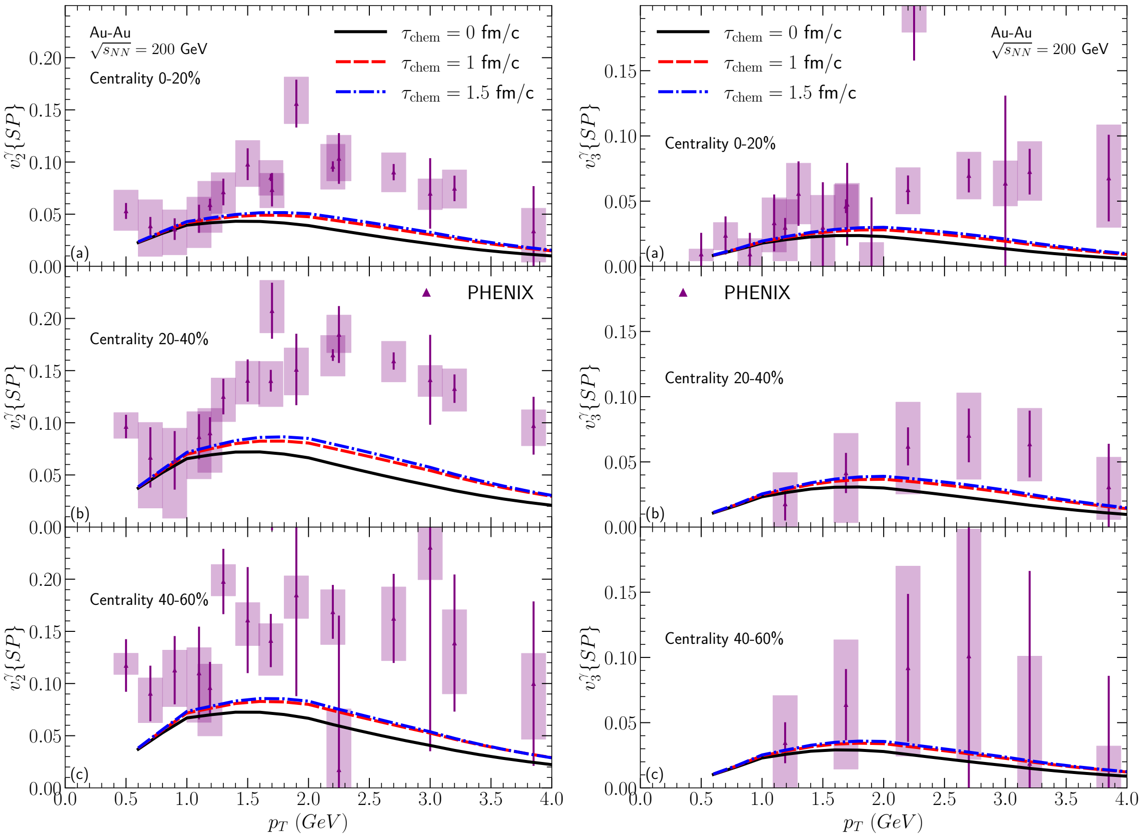


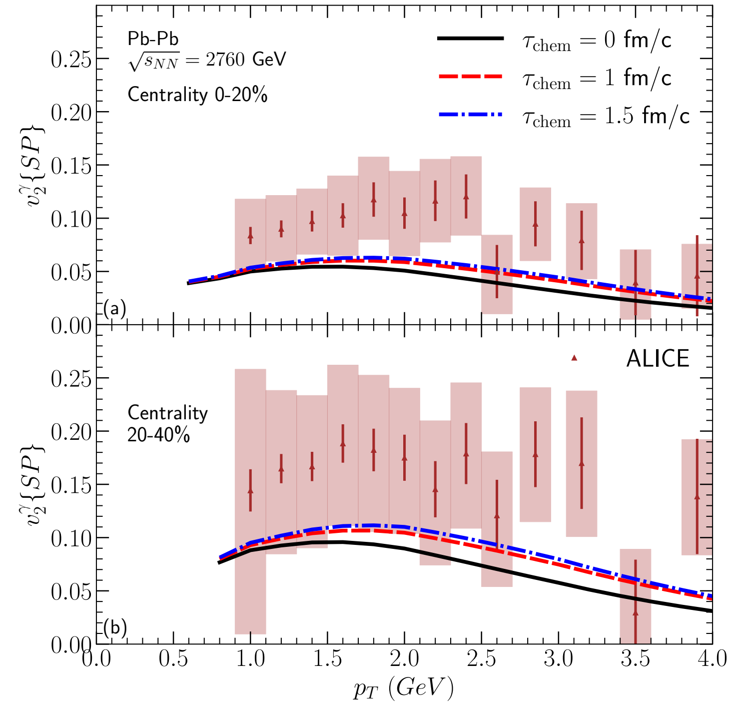
Effect of pre-eq. photons appears at intermediate p_T



Charles Gale
McGill

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

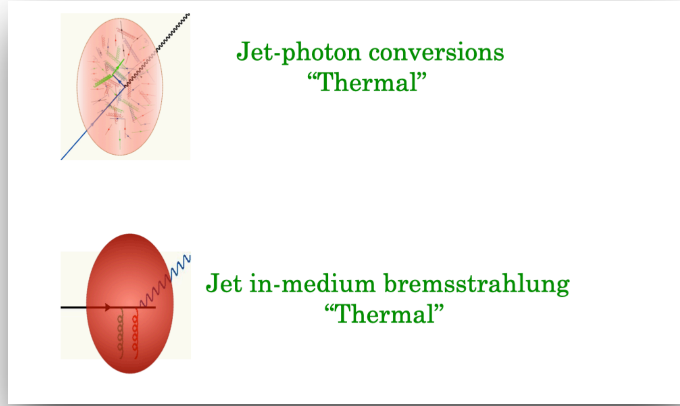
Partial conclusion: pre-hydro effects can matter and are within reach of (next?) generation (Bayesian) analyses

Another 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 (2022)

Minijets?

Flashback : 1991

- Music:
    - Nathalie Cole - Unforgettable
    - Nirvana - Nevermind
    - Pearl Jam - 10
    - M. C. Hammer - Too Legit to Quit
- Movies:
    - Terminator 2
    - Silence of The Lambs
    - JFK
- TV:
    - Seinfeld
    - Home Improvement
    - Northern Exposure
- Books:
    - The Firm - John Grisham
    - Me: Stories of My Life - Katharine Hepburn
    - The Sum of All Fears - Tom Clancy

Charles Gale
McGill

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Presented at the 4th Conference on Intersections
between Particle and Nuclear Physics,
Tucson, AZ, May 24–29, 1991, and
to be published in the Proceedings

Mini-jet and Particle Production in Ultra-Relativistic Heavy Ion Collisions

X.-N. Wang

July 1991

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

LBL-30849

Mini-jet and Particle Production in Ultra-Relativistic Heavy Ion Collisions*†

Xin-Nian Wang‡

Nuclear Science Division, Mailstop 70A-3307
Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720 USA

Abstract

Mini-jet and particle production are studied in the framework of HIJING Monte Carlo model which can describe pp and $p\bar{p}$ collisions well from ISR to Fermilab Tevatron energies. Mini-jets are shown to have eminent contributions to particle production in ultra-relativistic heavy ion collisions. However, parton shadowing and jet quenching also have important effects and can be studied by single particle distributions.

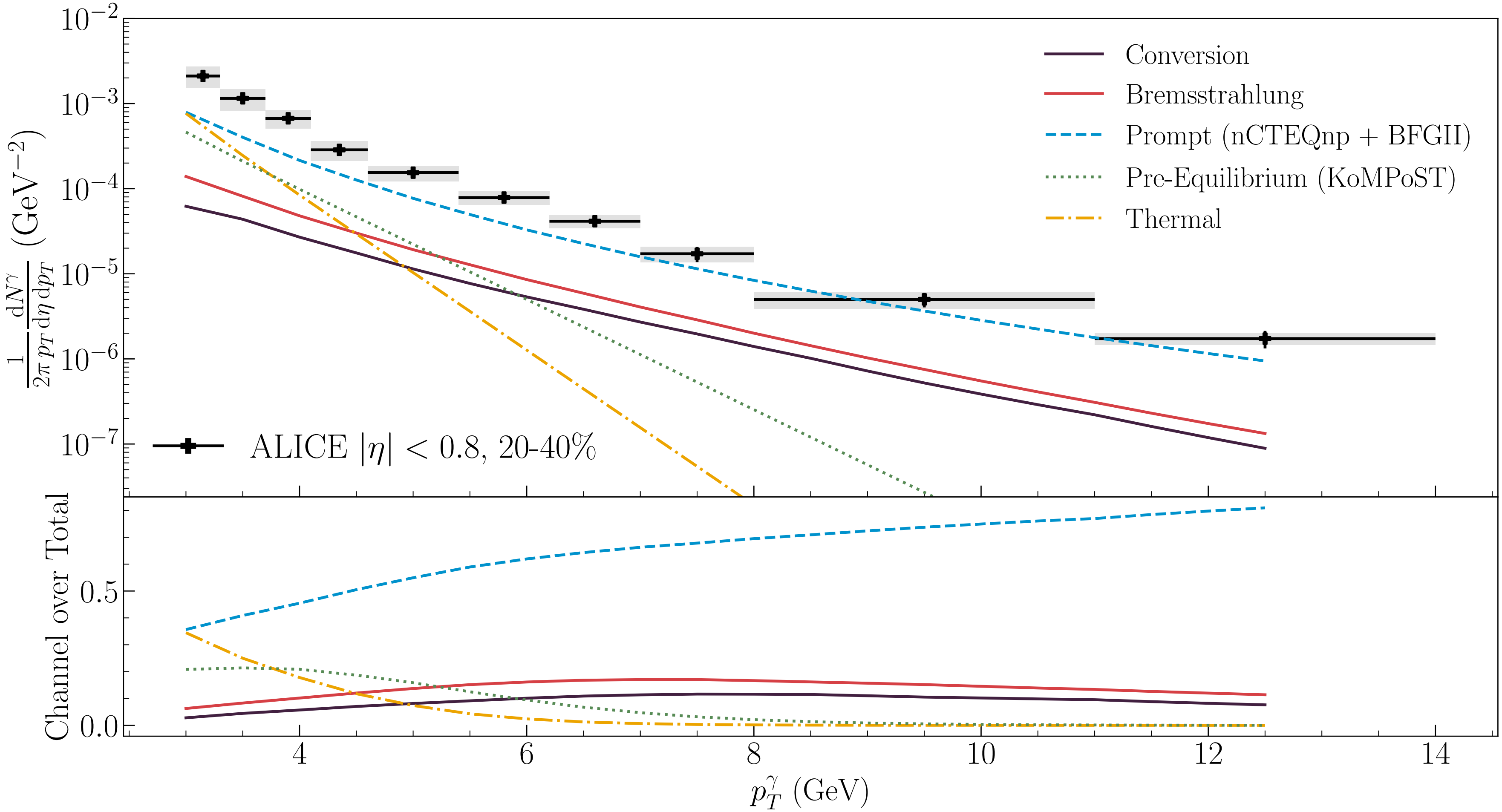
*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

†Invited talk at the 4th Conference on the Intersections between Particle and Nuclear Physics, Tucson, Arizona, May 24-29, 1991, and to be published in the proceedings

‡Address after October, 1991: Department of Physics, Duke University, Durham, NC 27706.

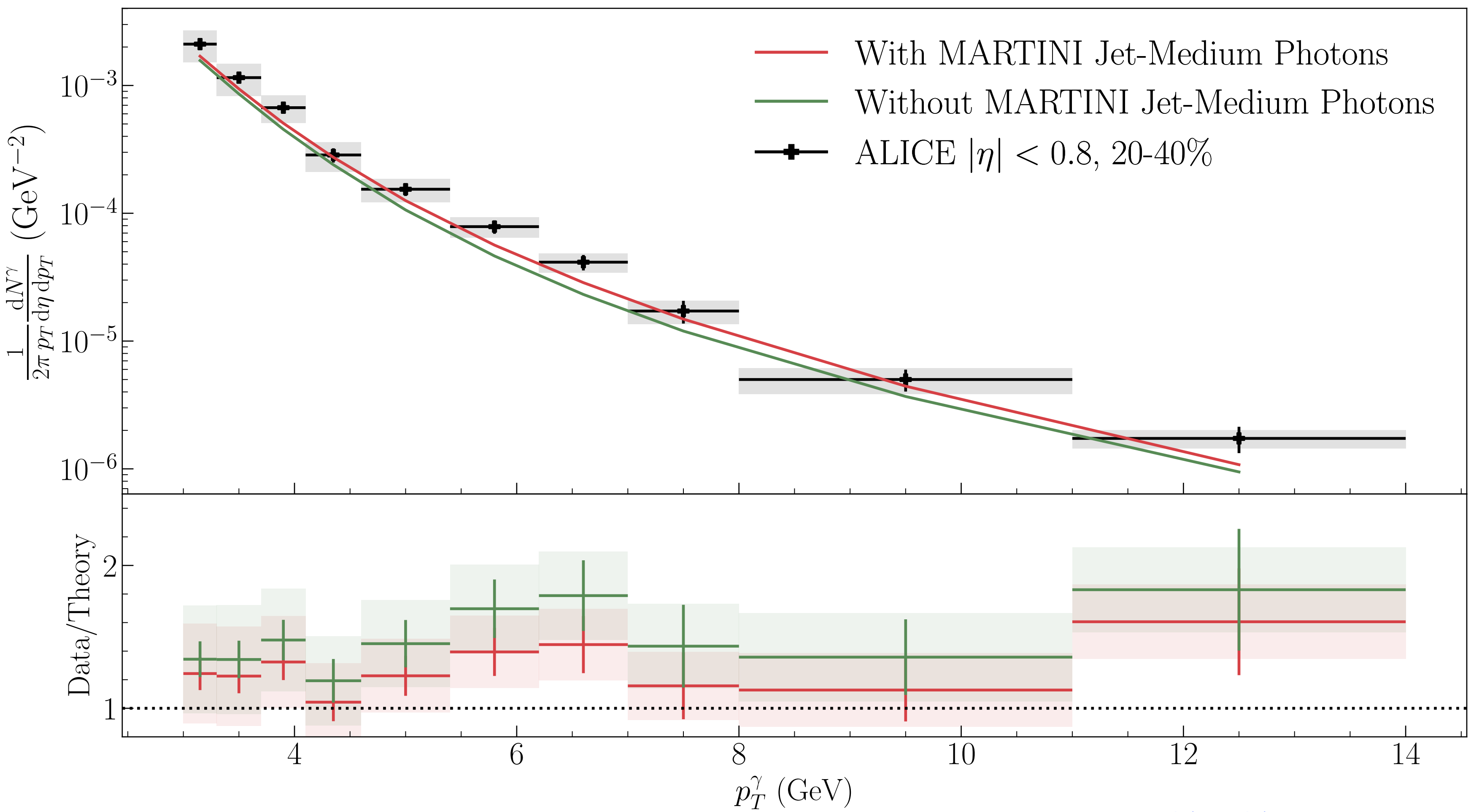
The different photon sources

Pb+Pb, 2.76 TeV



- AMY used here
- Jet-related photons $\sim 30\,\%\ @\, p_T \sim 4 - 5$ GeV

With and without jet-medium photons



Pb+Pb, 2.76 TeV

Charles Gale
McGill

Can photons be used to distinguish E-loss formalisms?

$$\frac{d\Gamma^{\rm AMY}_{i\to jk}}{dz}(p,z) = \frac{\alpha_{\rm s} P_{i\to jk}(z)}{2pz(1-z)^2}\bar{f}_j(z,p)\bar{f}_k((1-z)p) \times \int \frac{d^2\mathbf{h}_\perp}{(2\pi)^2}\mathrm{Re}\left[2\mathbf{h}_\perp \cdot g_{(z,p)}(\mathbf{h}_\perp)\right]$$

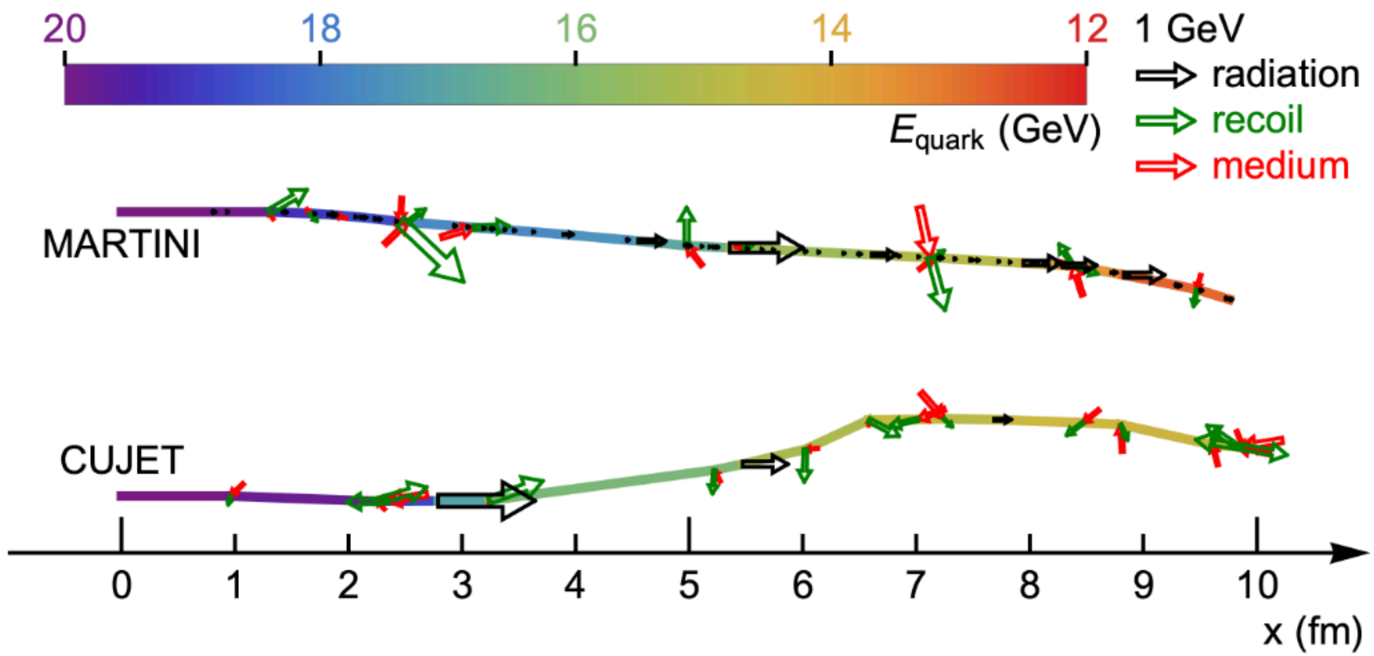
Schenke, Jeon, Gale, PRC (2009); AMY JHEP (2001)

$$\frac{d\Gamma^{\rm DGLV}_{i\to gi}}{dz}(p,z,\tau) = \frac{18C_i^R}{\pi^2}\frac{4+N_f}{16+9N_f}\rho(T)\int d^2\mathbf{k}_\perp \left[\frac{1}{z_+}\left|\frac{dz_+}{dz}\right|\alpha_s\left(\frac{\mathbf{k}_\perp^2}{z_+ - z_+^2}\right)\right.$$

$$\times \int \frac{d^2\mathbf{q}_\perp}{\mathbf{q}_\perp^2}\left[\frac{\alpha_s^2(\mathbf{q}_\perp^2)}{\mathbf{q}_\perp^2 + m_D^2}\frac{-2}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2}\left(\frac{\mathbf{k}_\perp \cdot (\mathbf{k}_\perp - \mathbf{q}_\perp)}{\mathbf{k}_\perp^2 + \chi^2} - \frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2}\right)\right.$$

$$\left.\left.\times\left(1 - \cos\left(\frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2}{2z_+ p}\tau\right)\right)\right]\right]$$

Gyulassy, Levai, Vitev, NPB (2000), Djorjevic, Gyulassy, NPA (2013)

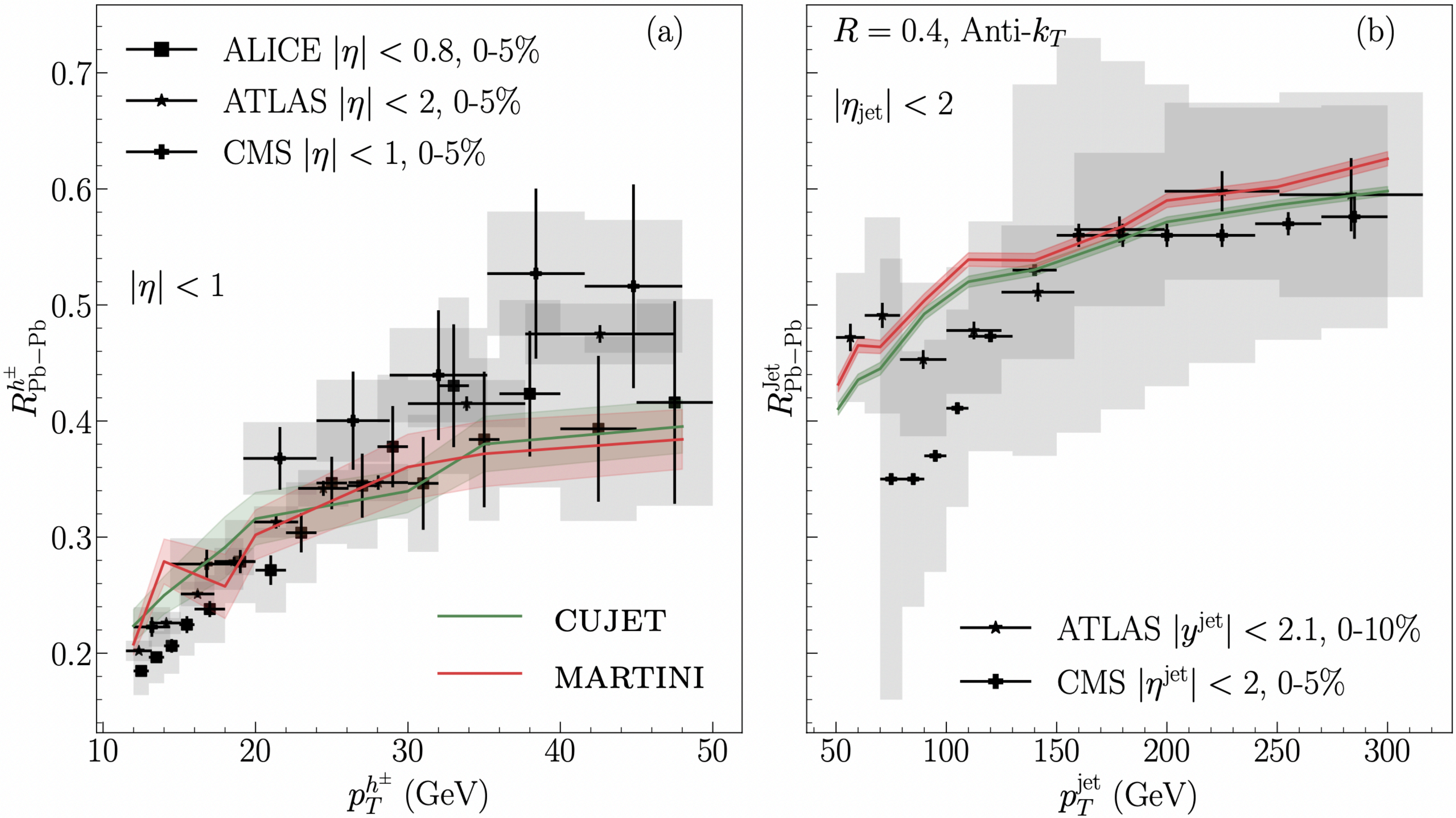


Shi et al., (2022)

Trajectory of a 20 GeV quark with MARTINI and CUJET. Final quark has $E_{\mathrm{final}} \simeq 12\ \mathrm{GeV}$

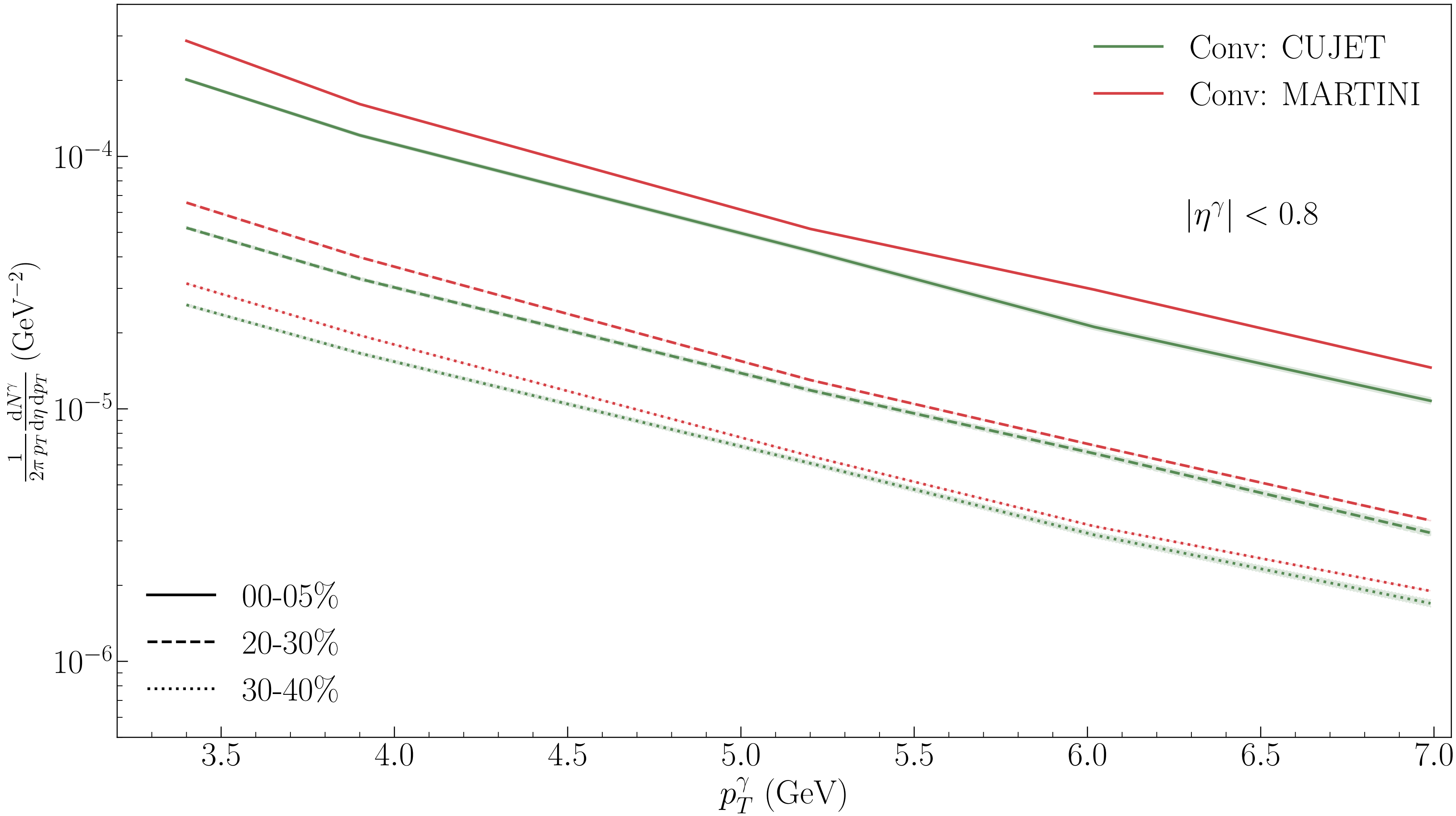
- History of parton development not the same

A previous comparison: Bass et al. (JET Coll.), PRC (2009) [ASW, HT, AMY]



Shi, Modaressi Yazdi et al. (2022)

- The value of α_s in MARTINI and CUJET is fitted to $R^{h\pm}_{AA}$
- The values of R^{jet}_{AA} follows, given the clustering parameters
- Can photons help separate those?



- MARTINI (AMY) & CUJET, $@p_T \sim 3-4$ GeV differ by 20-30%
- Bremsstrahlung contribution almost complete
- Optimistic about being able to tell the formalisms apart

Charles Gale
McGill

Conclusions

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

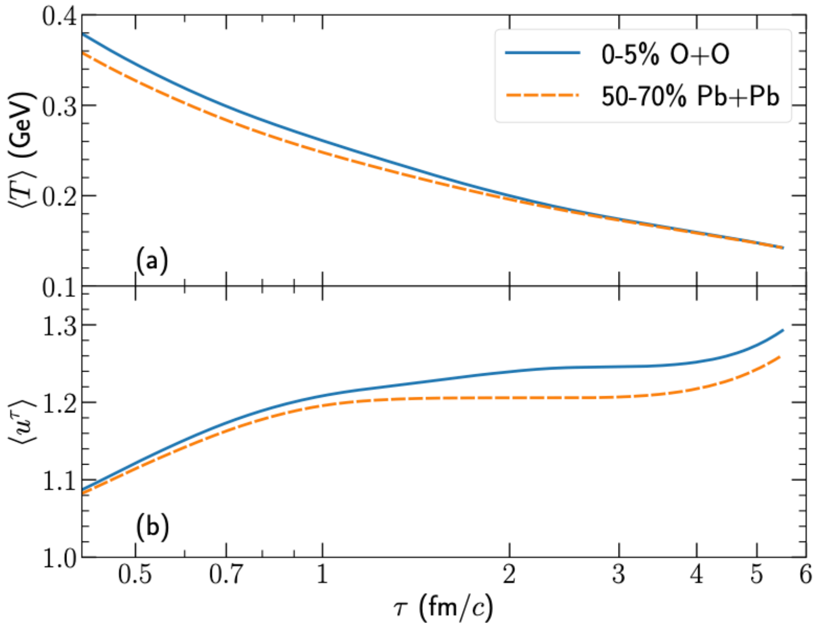
From Hard Probes Café to Heavy-Ion Tea: Three decades of hot fluids

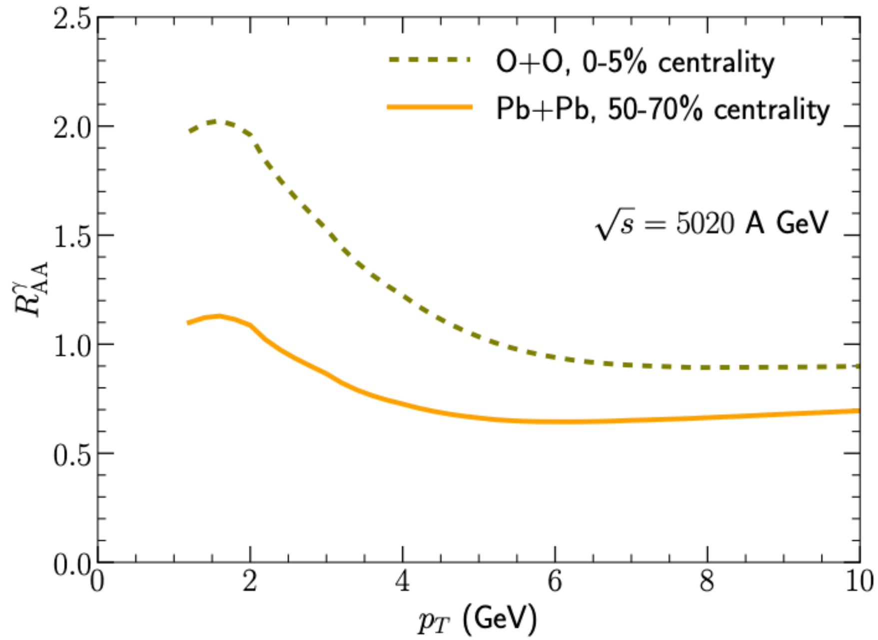
Congratulations Xin-Nian!

[Image: physics.org]

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
- $R^\gamma_{\rm AA}$ shows a clear distinction

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