Flow and transport properties: Assessment and outlook

Jean-François Paquet

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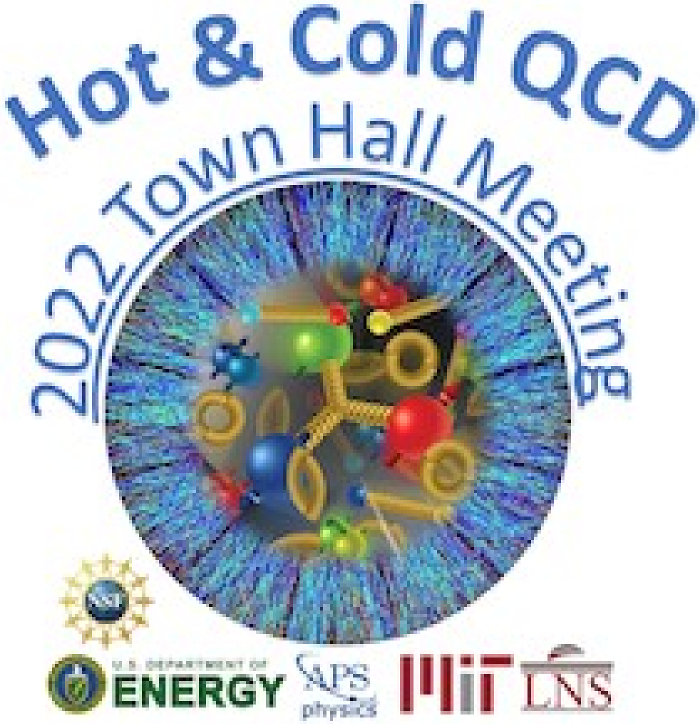
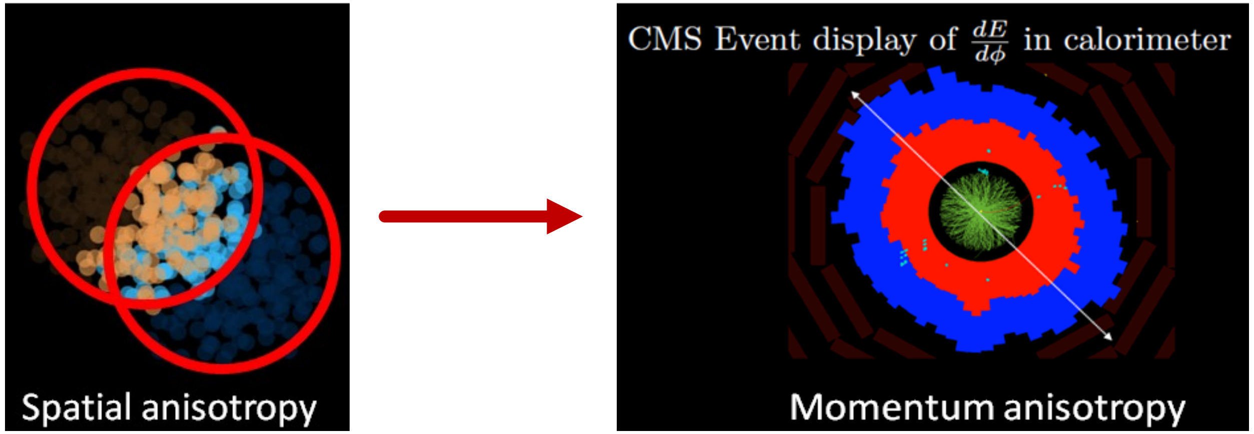
VANDERBILT UNIVERSITY

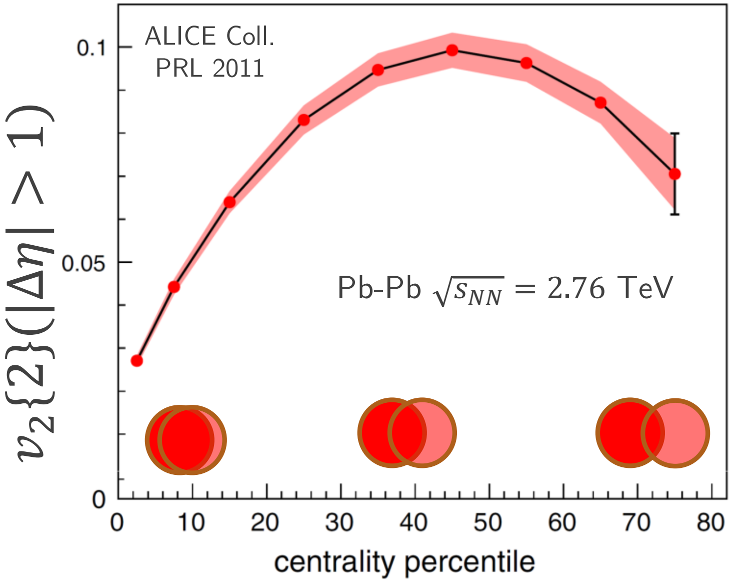


From impact geometry to momentum anisotropy



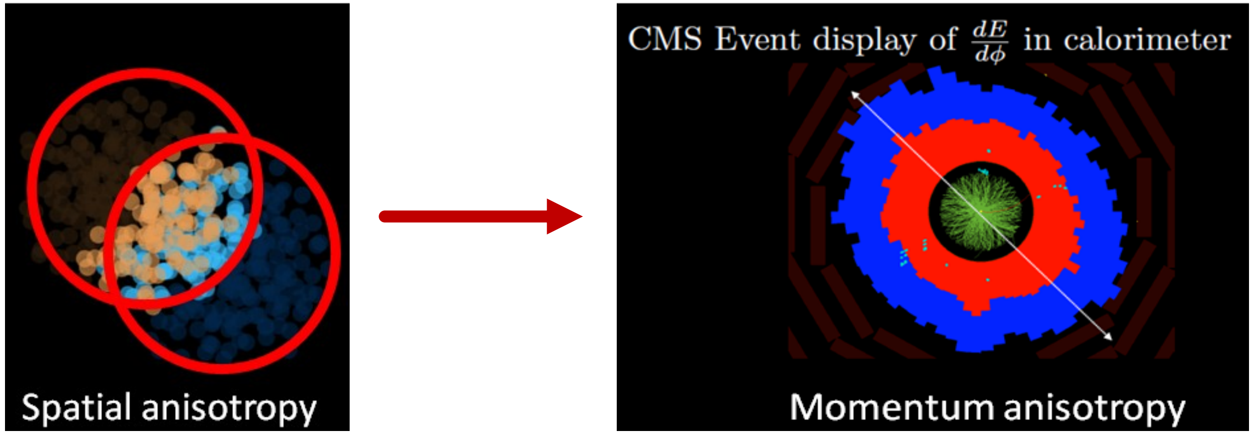
Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard

"Elliptic flow"



- Spatial anisotropy from partial overlap of nuclei & fluctuation
- Interactions transfer spatial anisotropy into momentum one
- Rapid development of momentum anisotropies consistent with strongly-coupled system

From impact geometry to momentum anisotropy



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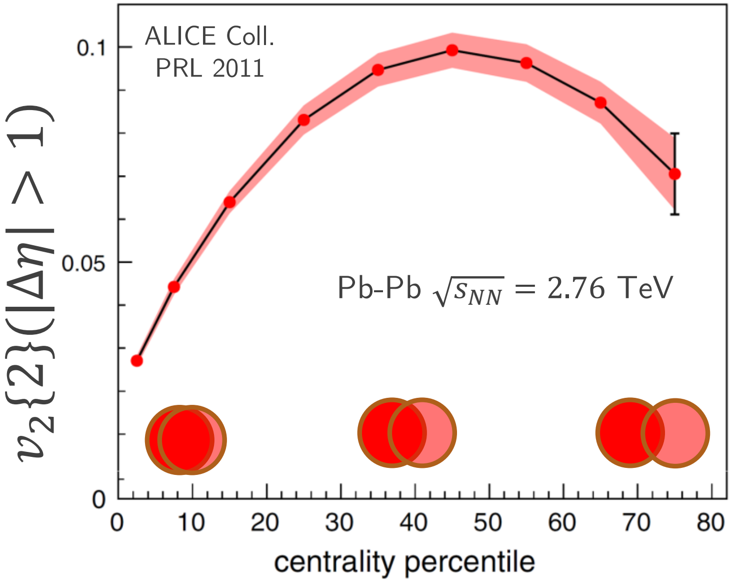
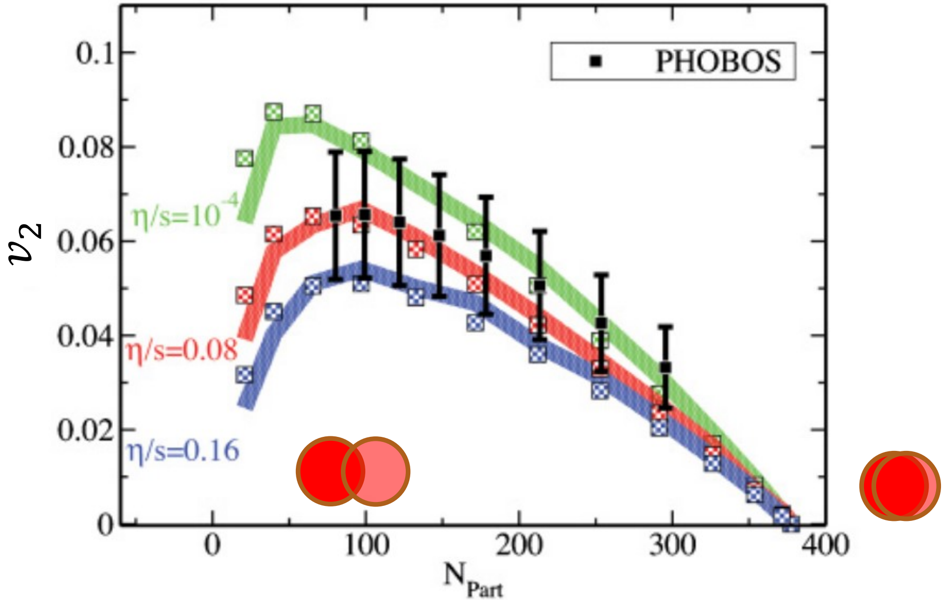


Luzum and Romatschke (2009) PRC

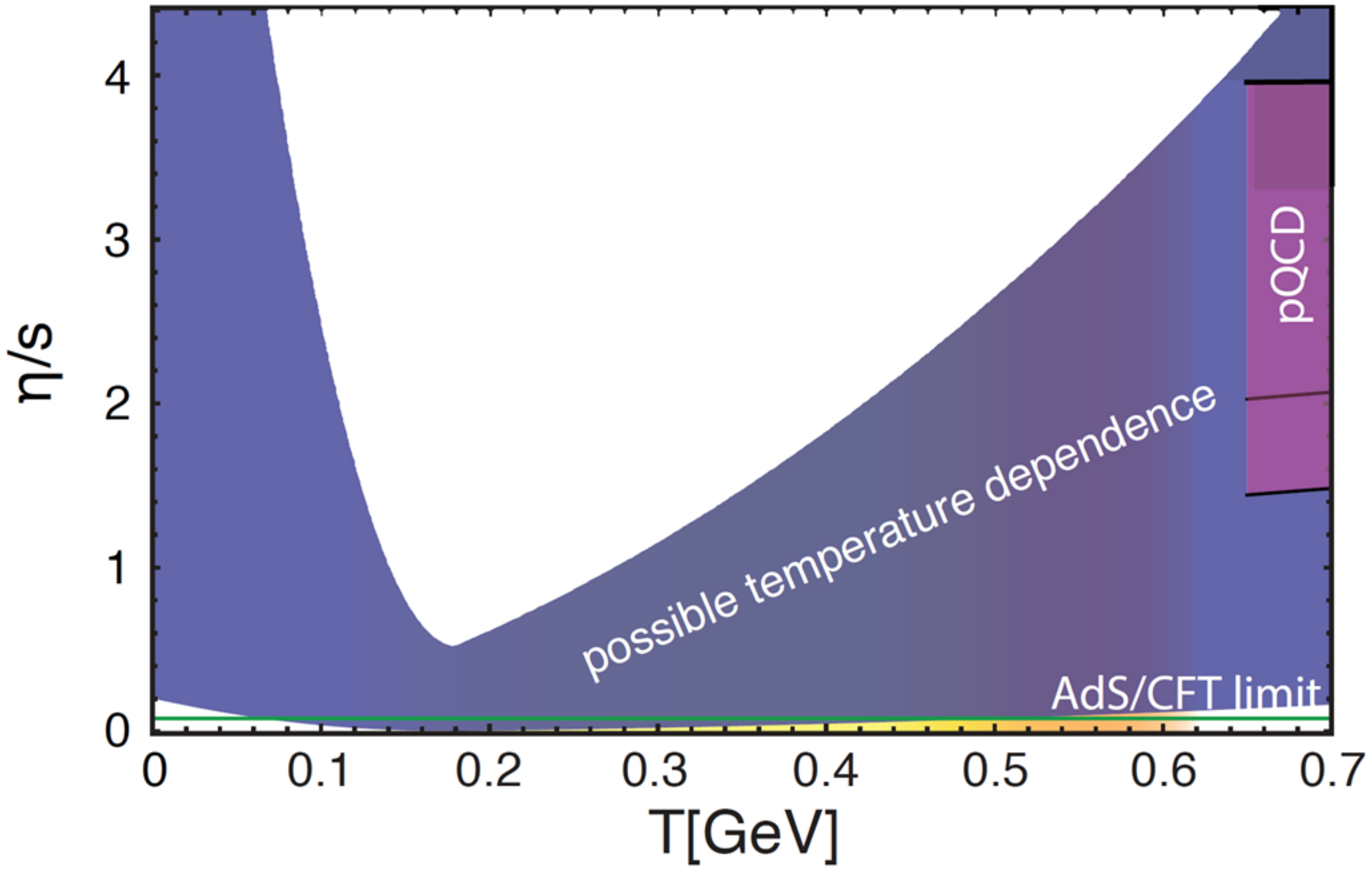


Effect of shear viscosity on v_2

(Shear viscosity inversely related to strength of interaction)

Shear and bulk viscosity of strongly-coupled quark-gluon plasma

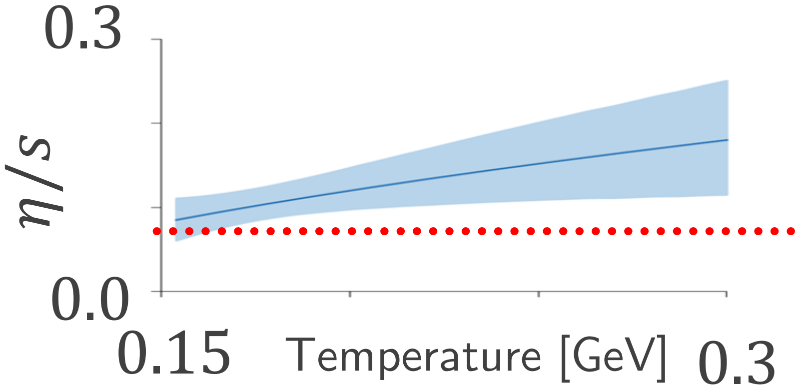
Modified from the Hot QCD White Paper 2015



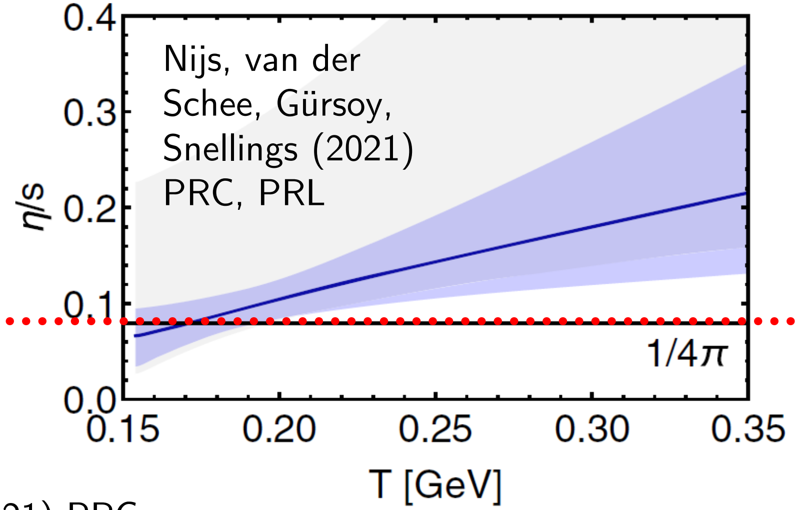
- Constrain temperature dependence of shear viscosity?
  - Minimum value?
  - Where is the minimum?
  - Increase at low and high temp.?
- Study bulk viscosity and constrain its temperature dependence?
  - Peak?

Shear viscosity calibrations

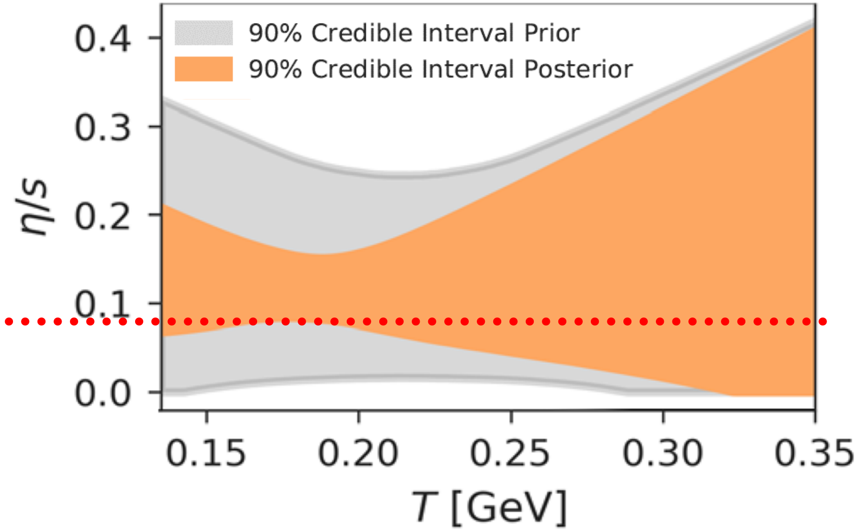
Bernhard, Moreland, Bass (2019) Nat.Phys.



Similar results from Parkkila, Onnerstad, Kim (2021) PRC

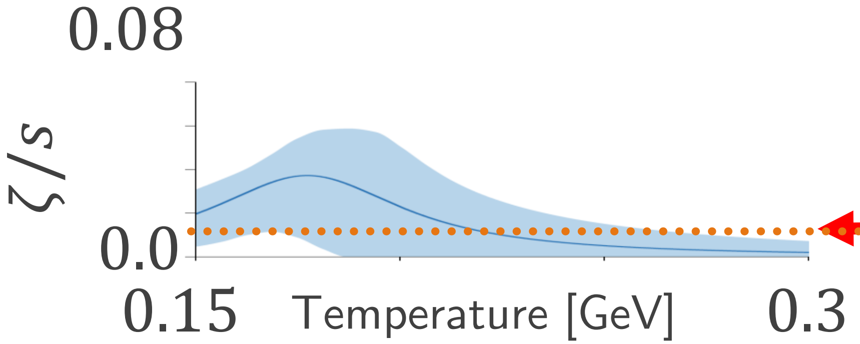

Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

JETSCAPE Collaboration, (2021) PRC, PRL



Bulk viscosity calibrations

Bernhard, Moreland, Bass (2019) Nat.Phys.

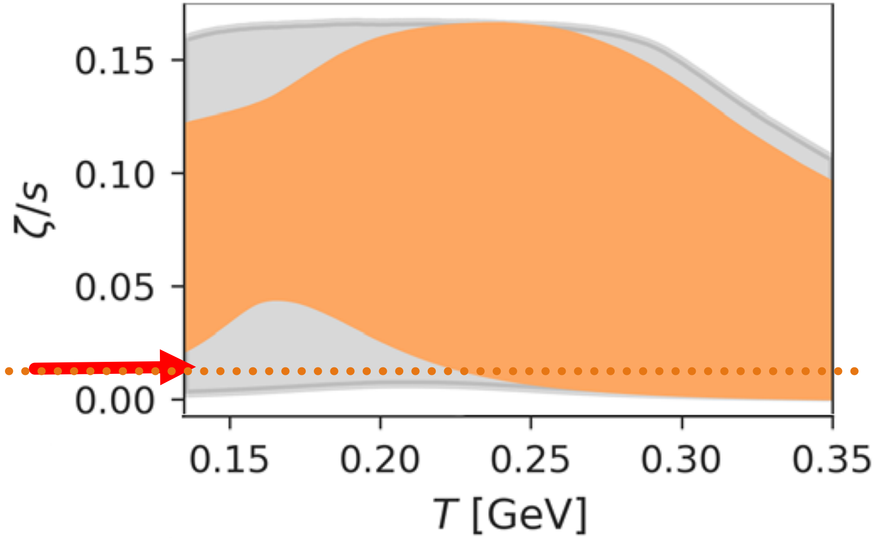


Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

$\zeta/s < 0.01$

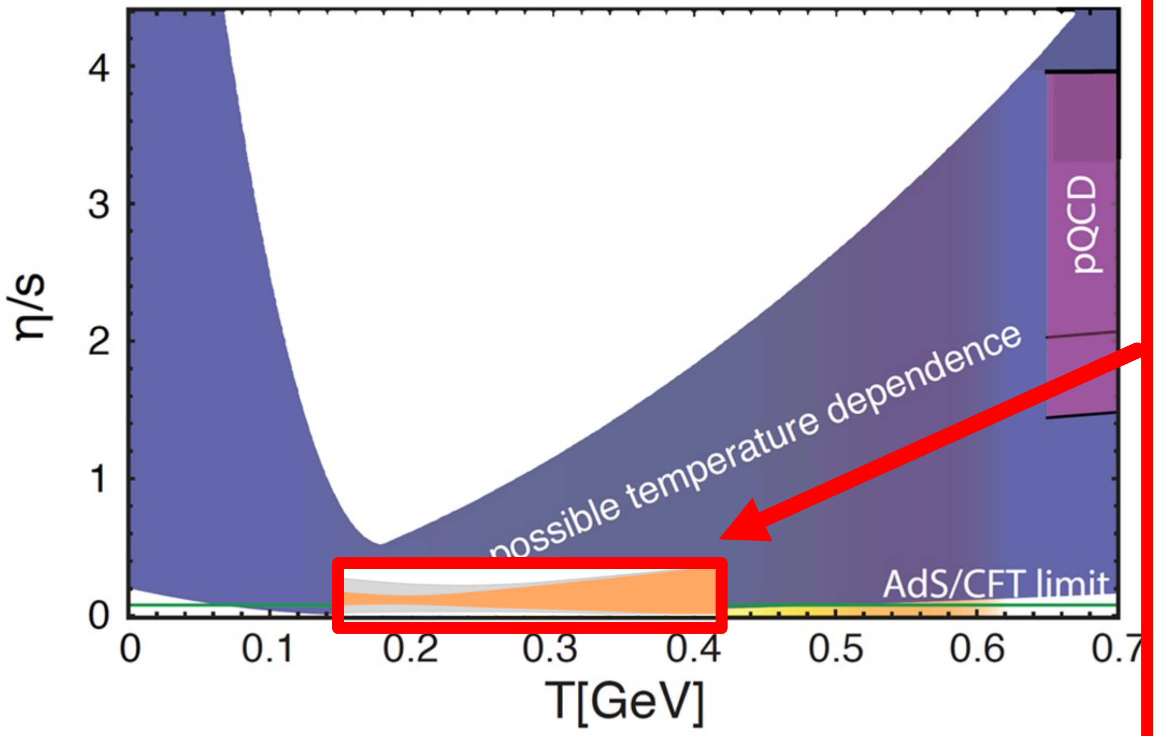
Parkkila, Onnerstad, Kim (2021) PRC: $\zeta/s < 0.03$

JETSCAPE Collaboration, (2021) PRC, PRL

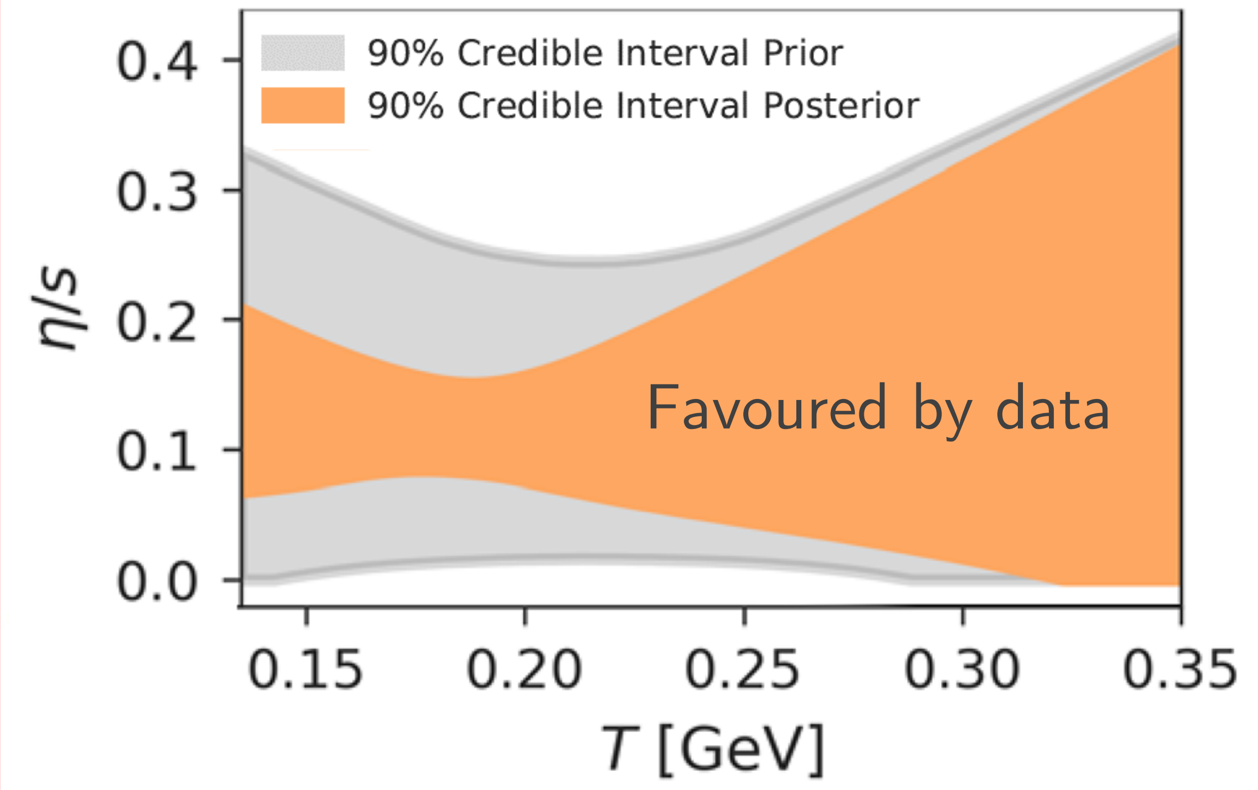


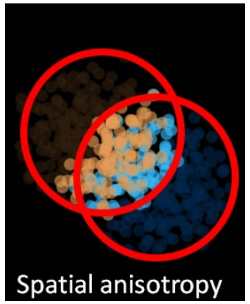
Shear viscosity of strongly-coupled quark-gluon plasma

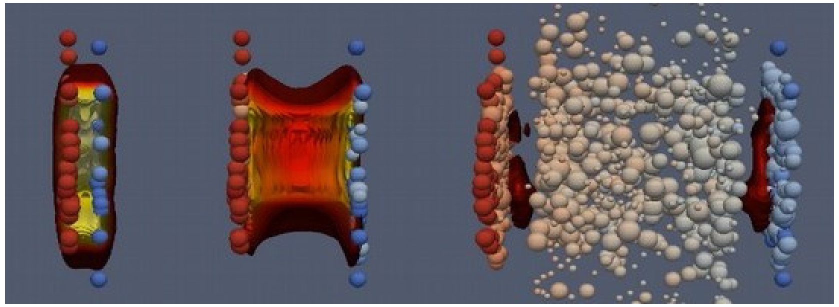
Modified from the Hot QCD White Paper 2015

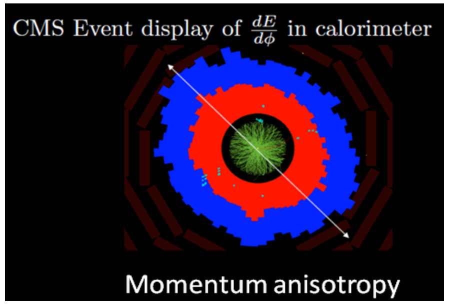


JETSCAPE Collaboration, (2021) PRC, PRL







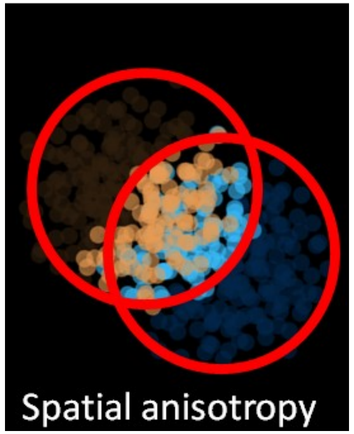


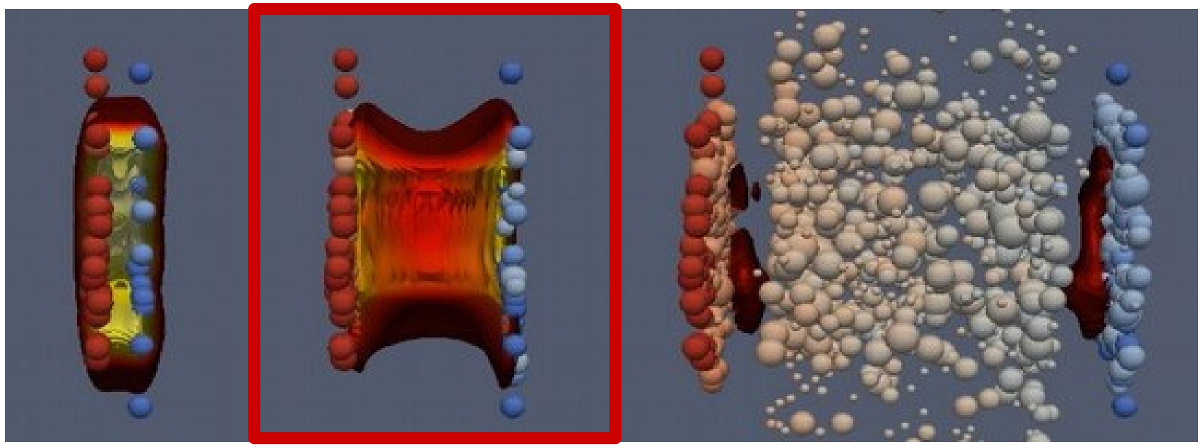
OUTLOOK ON CONSTRAINING THE VISCOSITIES:

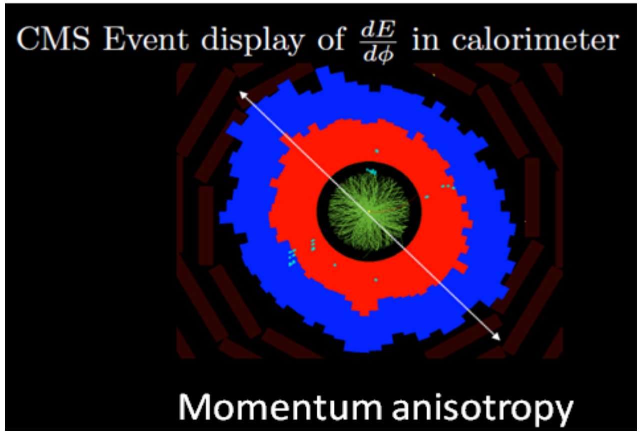
BEYOND THE CURRENT "STANDARD MODEL" OF COLLISIONS

Multistage simulations of heavy ion collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard







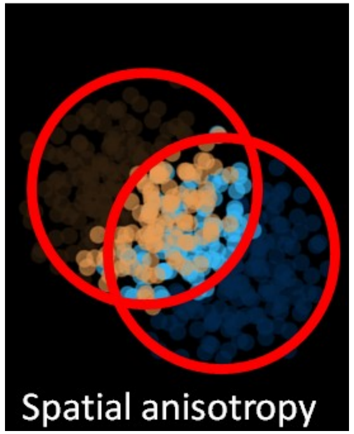
Energy deposition → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

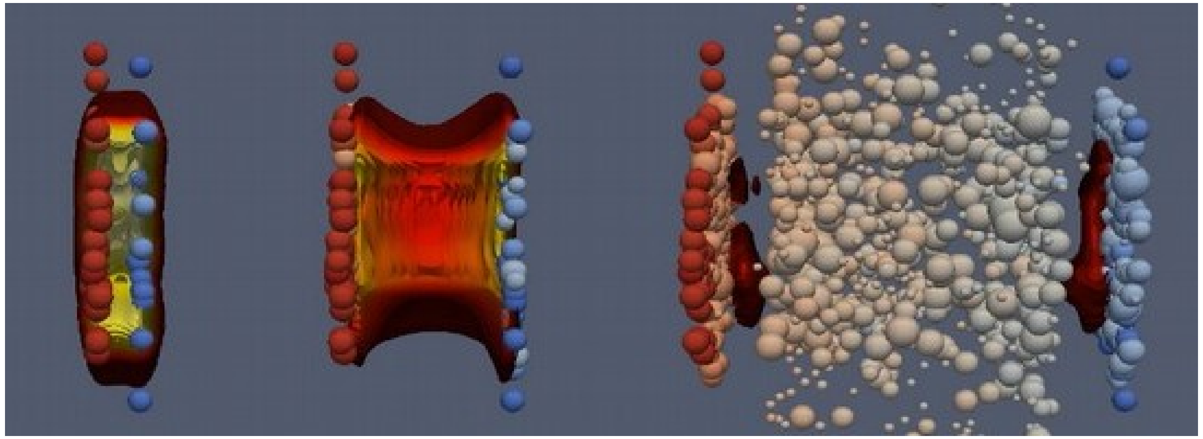
- Energy-momentum tensor of plasma: $T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$
- Conservation of energy and momentum: $\partial_\nu T^{\mu\nu} = 0$
- Mueller-Israel-Stewart-type relativistic viscous hydrodynamics

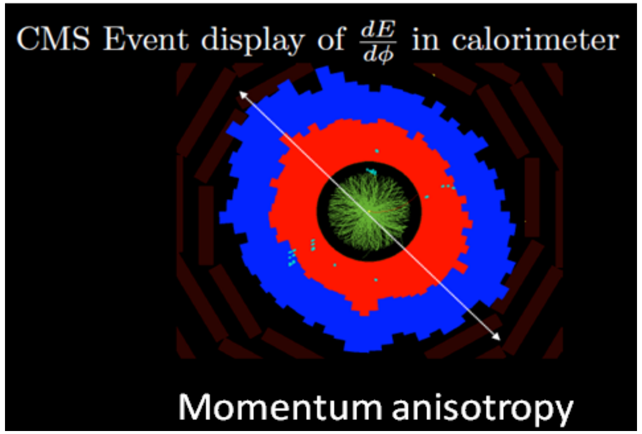
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} + \boxed{\pi^{\mu\nu} = 2\,\eta(T)(\partial^\mu u^\nu +} \cdots) + (2^{\text{nd}}\text{ order}); \quad \tau_\Pi \dot{\Pi} + \boxed{\Pi = -\zeta(T)\,\partial_\mu} u^\mu + (2^{\text{nd}}\text{ order});$$

Beyond the current “standard model” of collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard





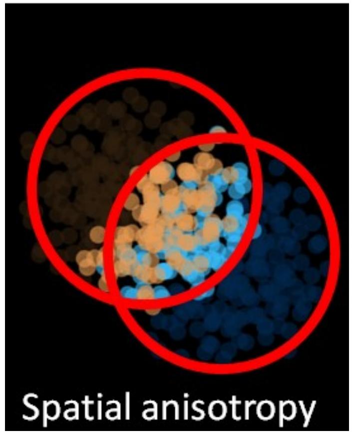


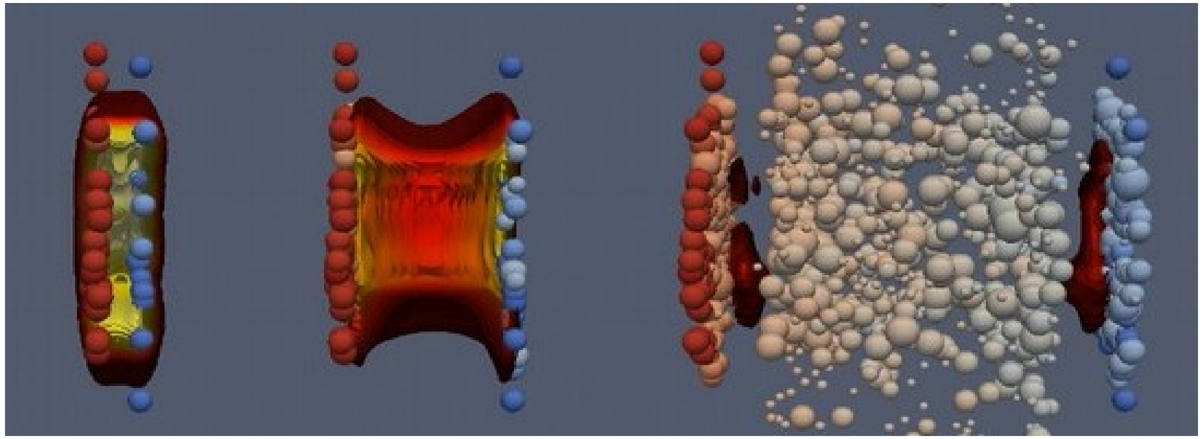
Energy deposition → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

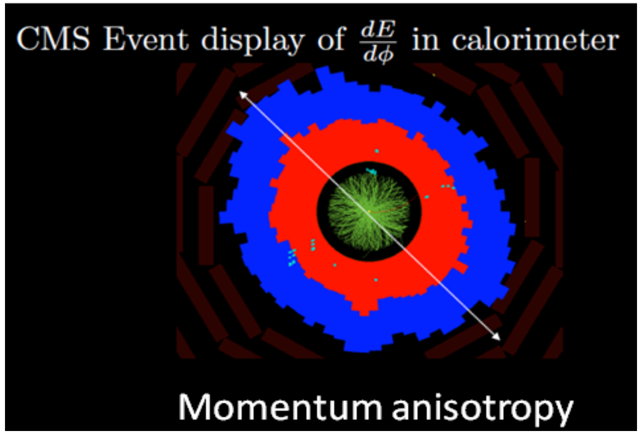
- Theoretical uncertainties limit accuracy of constraints on viscosity

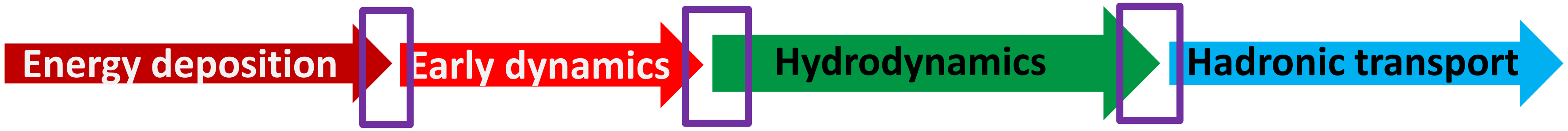
Beyond the current “standard model” of collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard



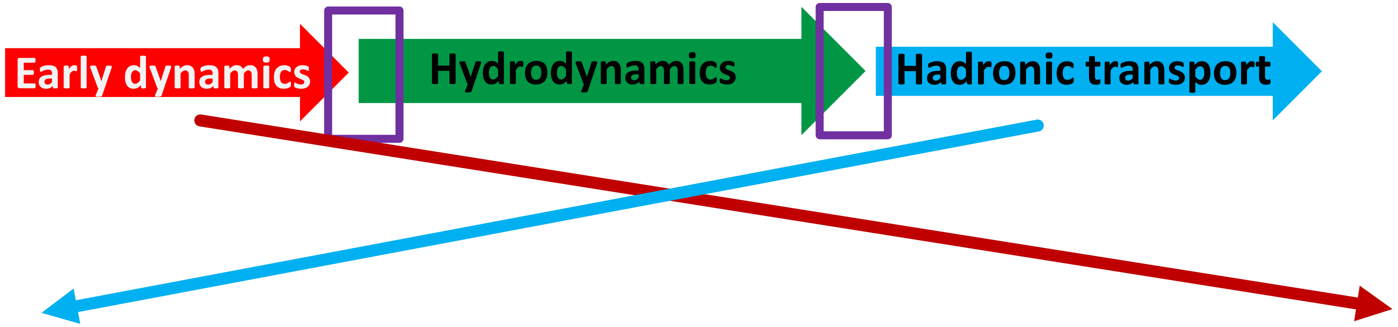




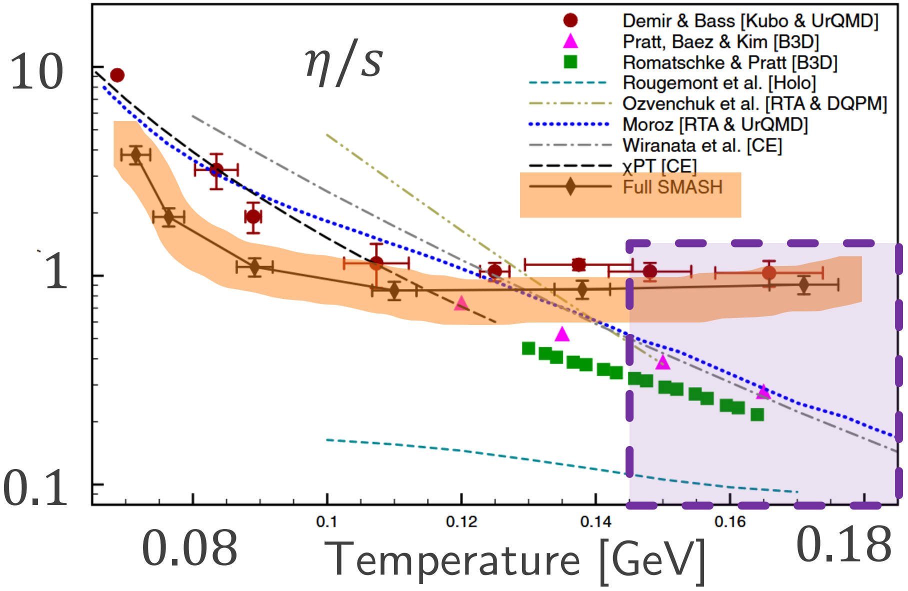


- Theoretical uncertainties limit accuracy of constraints on viscosity
  - Need smooth transition between stages of collision

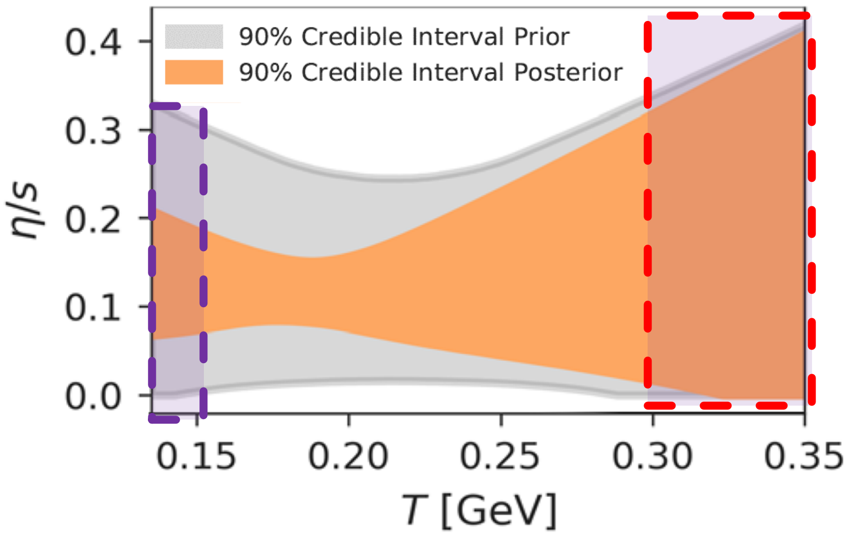
Smooth transition between models and their viscosities



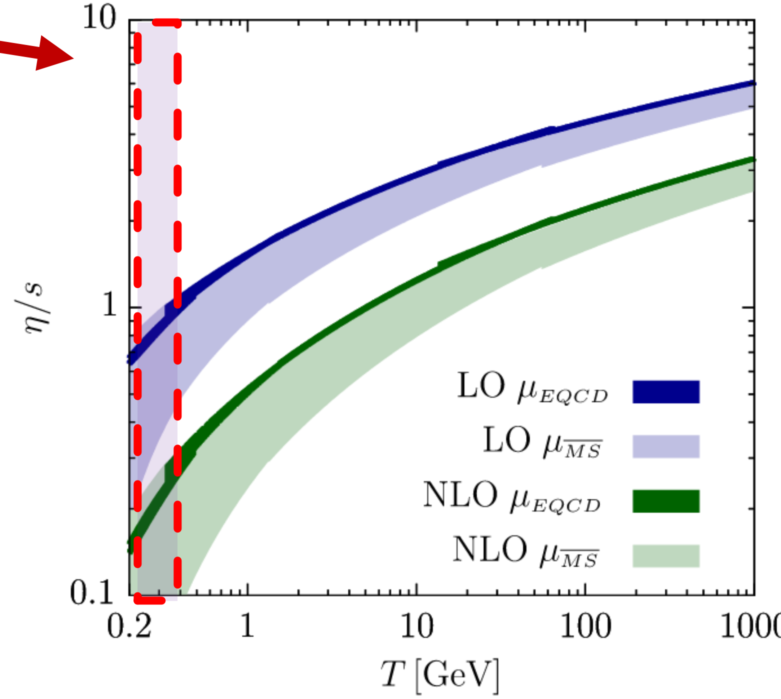
Rose, Torres-Rincon, Schäfer, Oliinychenko, Petersen (2018) PRC



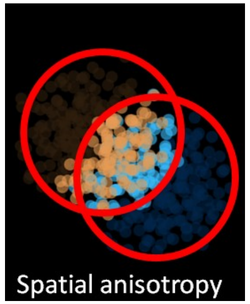
Interacting hadronic gas for $T <\sim 150$ MeV

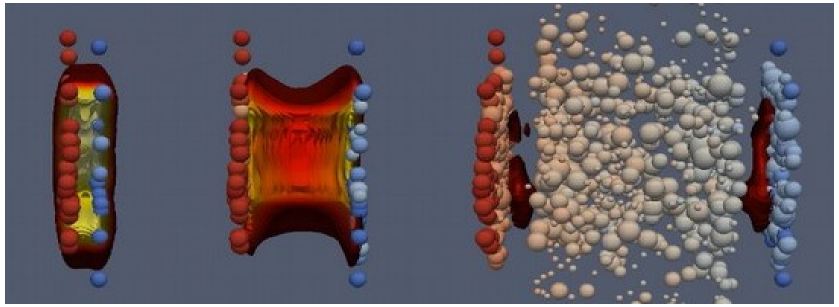


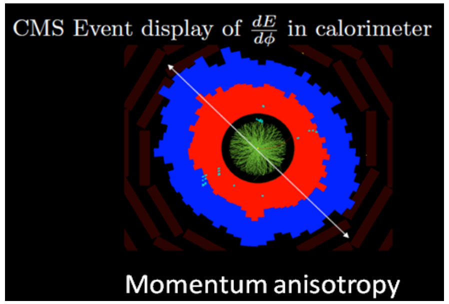
Ghiglieri, Moore, Teaney (2018) JHEP



Weakly-coupled quark-gluon plasma at high temperature



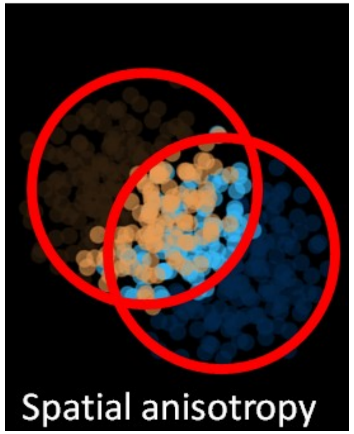


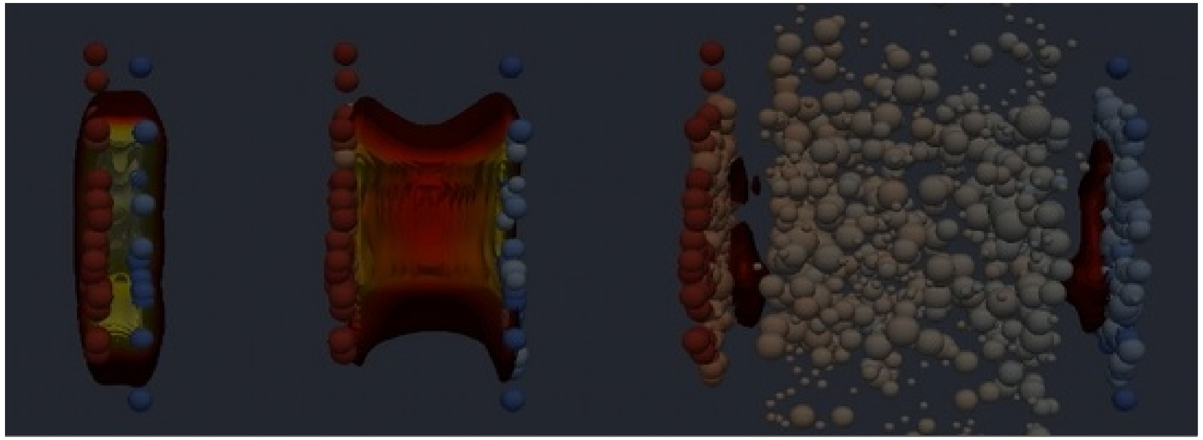


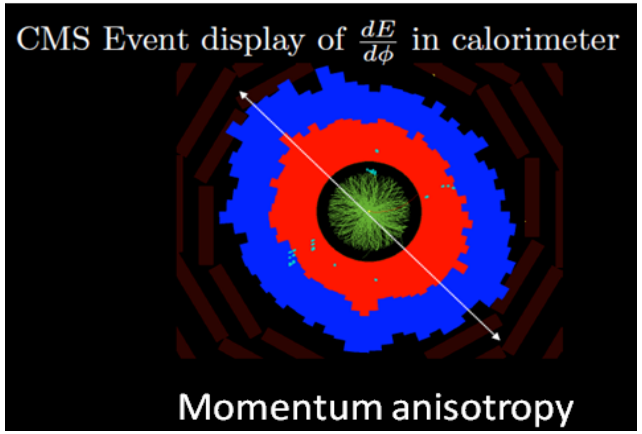
OUTLOOK ON CONSTRAINING THE VISCOSITIES:

EXPERIMENTAL AND THEORETICAL COLLABORATIONS

Leverage observables that target specific stages

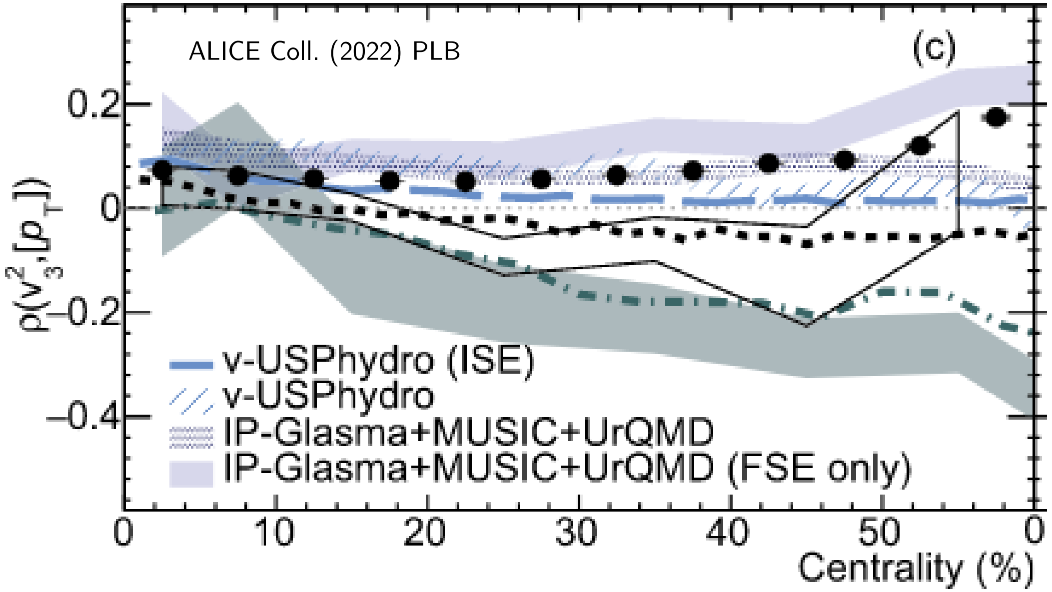






Energy deposition

Constraining energy deposition: See J. Jia's talk on Sat.



$$\rho_n = \frac{\left\langle \frac{E_i}{S}\varepsilon_n^2 \right\rangle - \left\langle \frac{E_i}{S} \right\rangle \left\langle \varepsilon_n^2 \right\rangle}{\sigma_{E_i/S}\sigma_{\varepsilon_n^2}} \frac{f'(\langle E_i/S \rangle)}{|f'(\langle E_i/S \rangle)|}$$

Giacalone, Gardim, Noronha-Hostler, Ollitrault (2020) PRC

Considering theoretical uncertainties of observables

- Viscosity is probed through the hydrodynamic phase

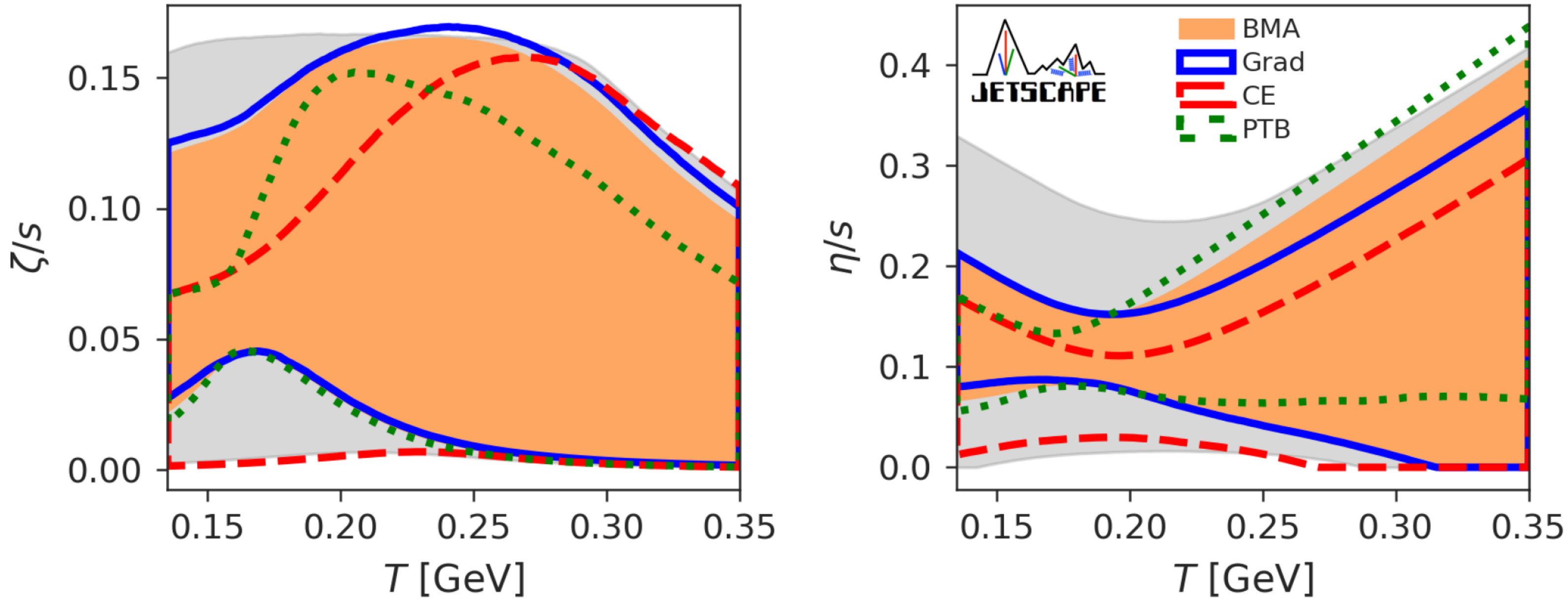
Energy deposition → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

$$\partial_\nu T^{\mu\nu} = 0; \qquad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu P^\nu f_n(P)$$

Hadron momentum distributions; deviate from Fermi-Dirac/Bose-Einstein distribution

JETSCAPE Collaboration, (2021) PRC, PRL



Considering theoretical uncertainties of observables

- Viscosity is probed through the hydrodynamic phase

Energy deposition

Early dynamics

Hydrodynamics

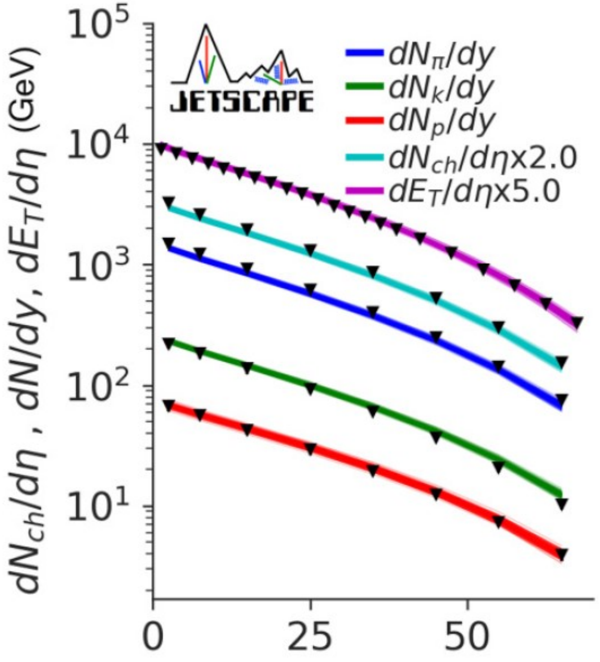
Hadronic transport

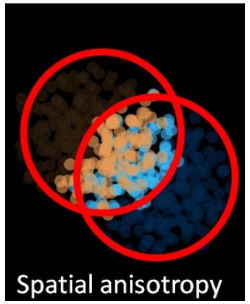
$$\partial_\nu T^{\mu\nu} = 0; \qquad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

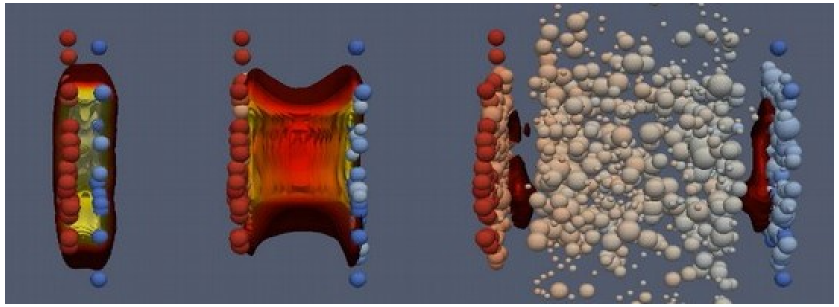
Reduced modelling uncertainties for energy/momentum-based observables (e.g. transverse energy)

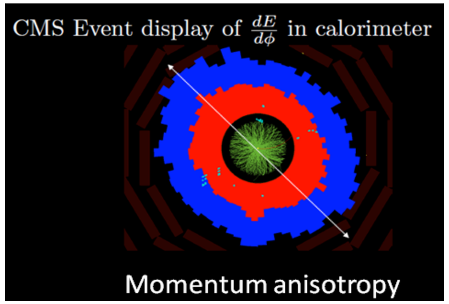
[Analogy: inclusive and exclusive observables in p-p collisions]

- Also, consider the objective of the measurement
  - E.g. smaller systems (p+A) to push our understanding
  - Larger central collisions to constrain viscosity







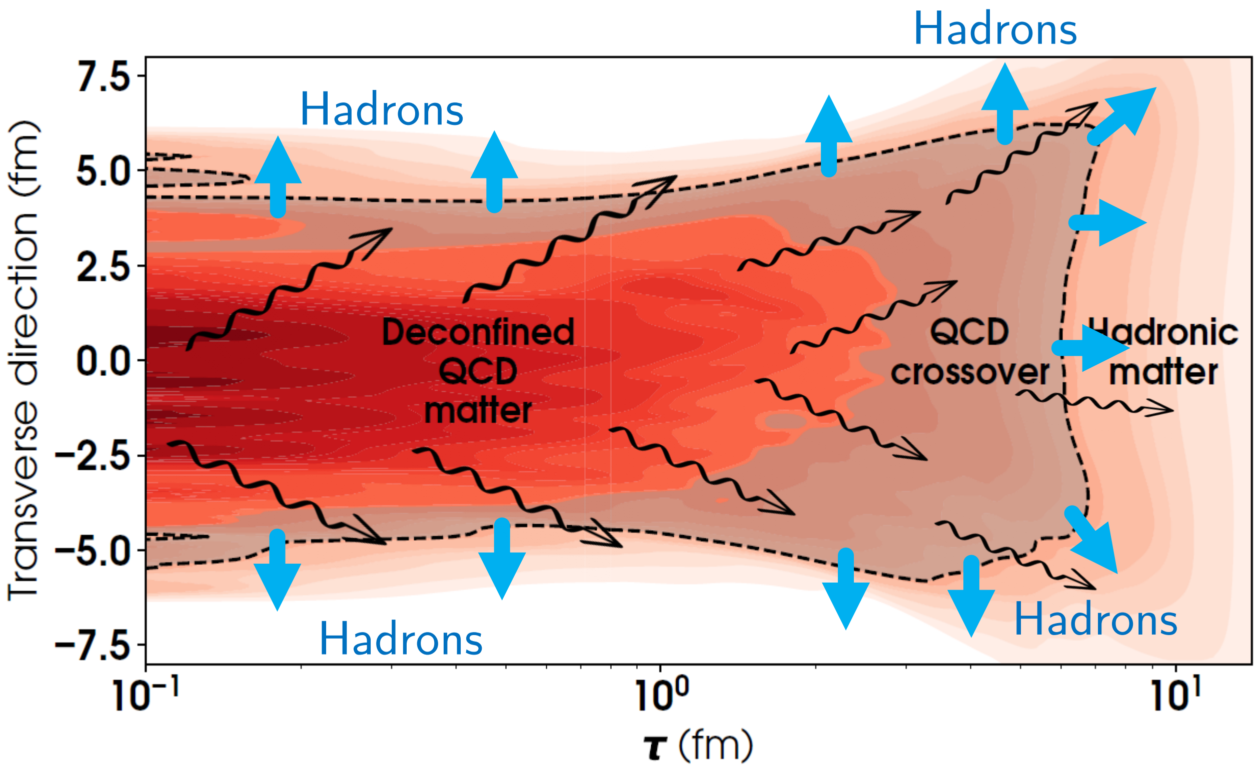


OUTLOOK ON CONSTRAINING THE VISCOSITIES:

MULTIMESSENGER

Beyond soft hadrons: electromagnetic probes

- Photons (γ) and dileptons (l^+l^-) are "holistic" probes: produced at all stages, reflects the local properties of the plasma



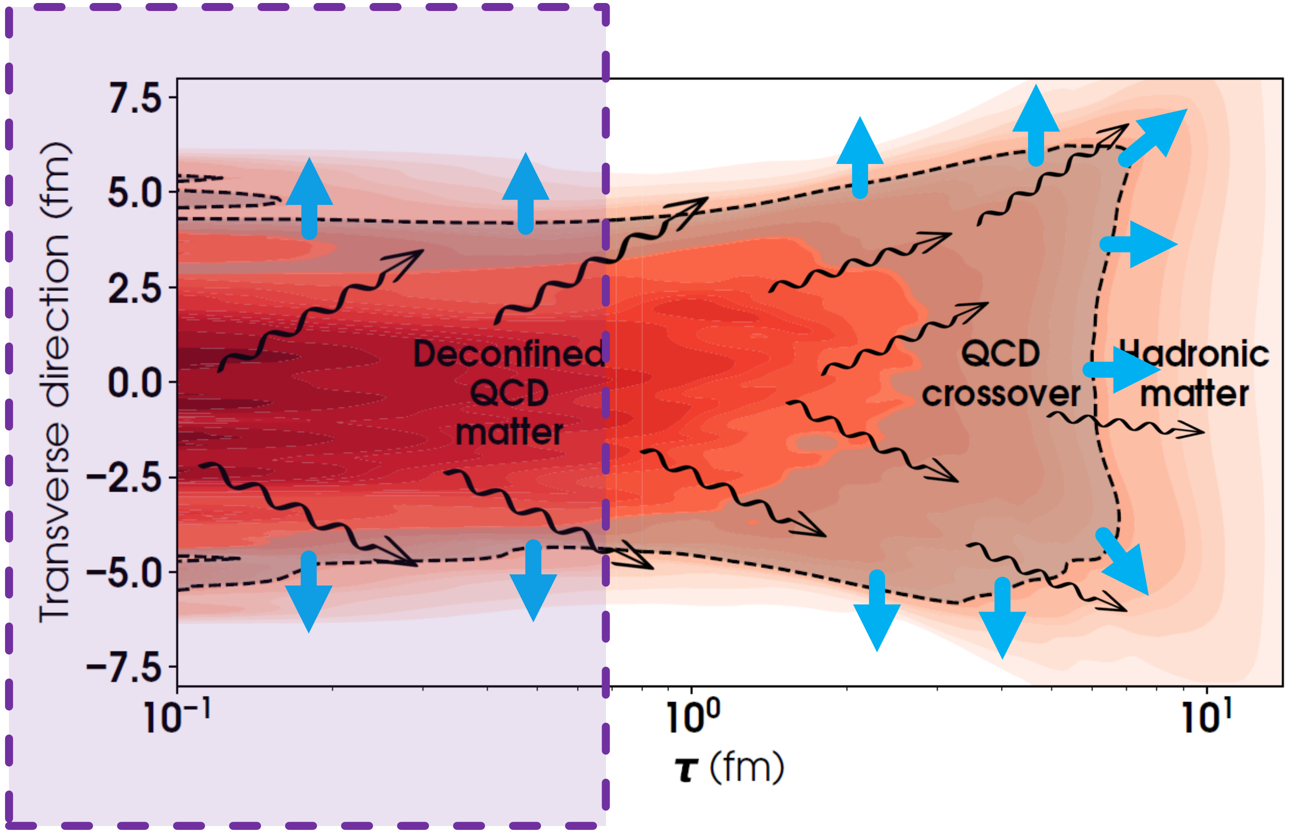
Considerable progress over past decade:

- Emission rates studied at NLO and on lattice
- Pre-equilibrium photons & dileptons
- γ & l^+l^- from hadronic transport

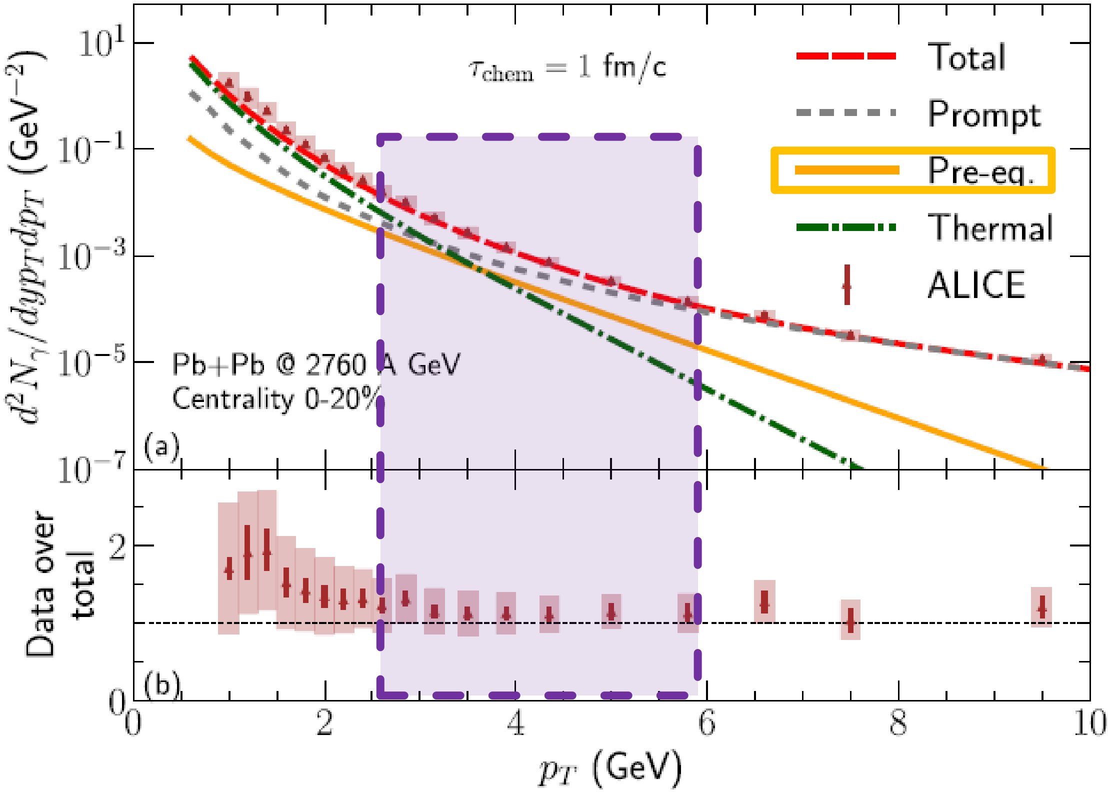
Considerable opportunities with more&better data

Beyond soft hadrons: electromagnetic probes from early time

- Photons (γ) and dileptons (l^+l^-) are "holistic" probes:
produced at all stages, reflects the local properties of the plasma



Gale, Paquet, Schenke, Shen (2022) PRC



Beyond soft hadrons: electromagnetic probes from early time

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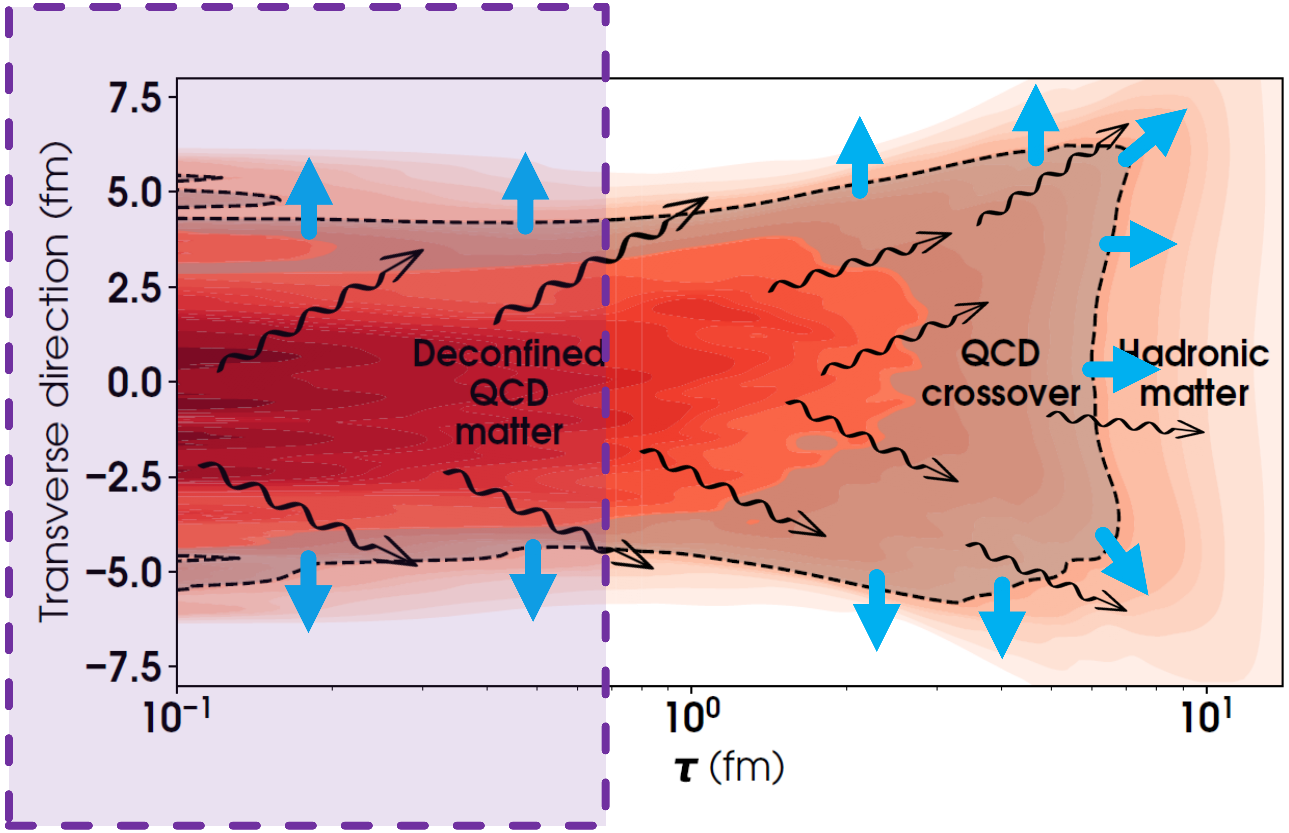

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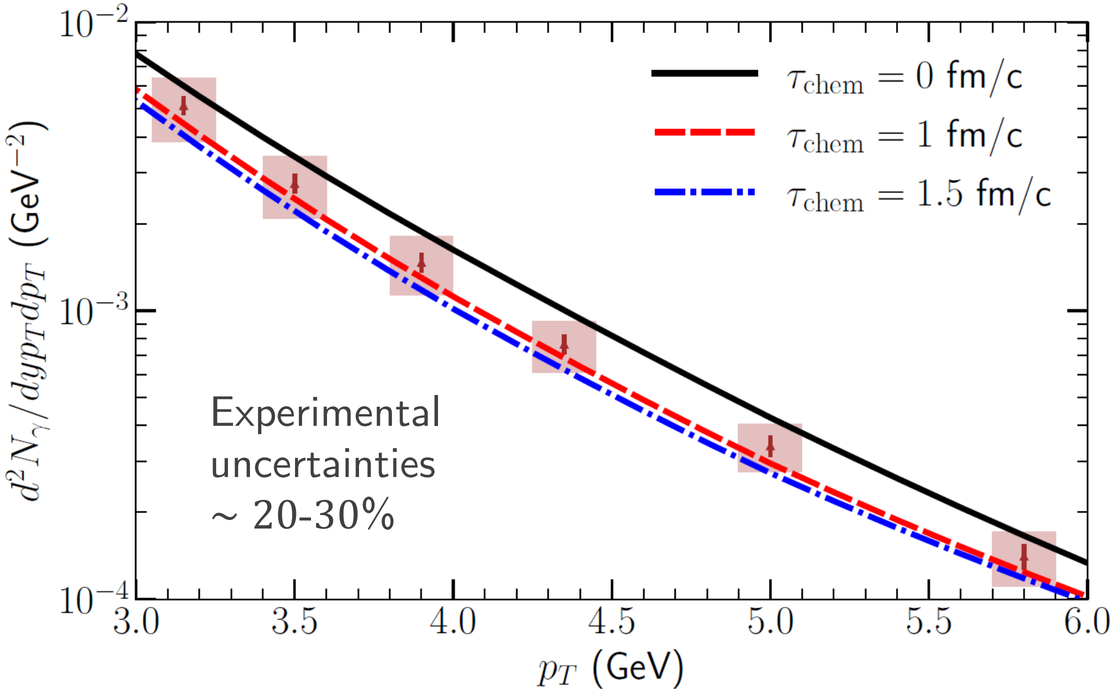
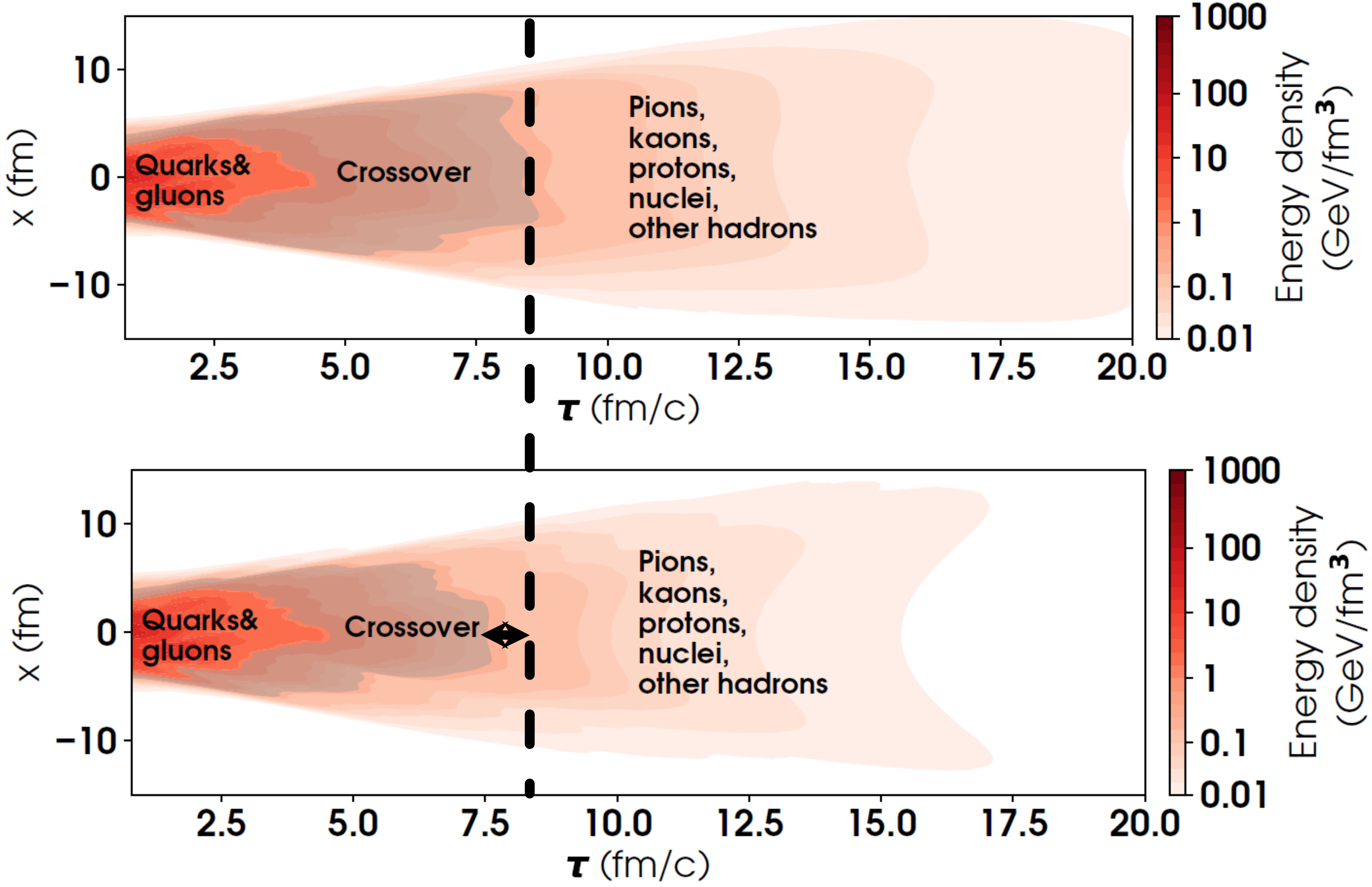
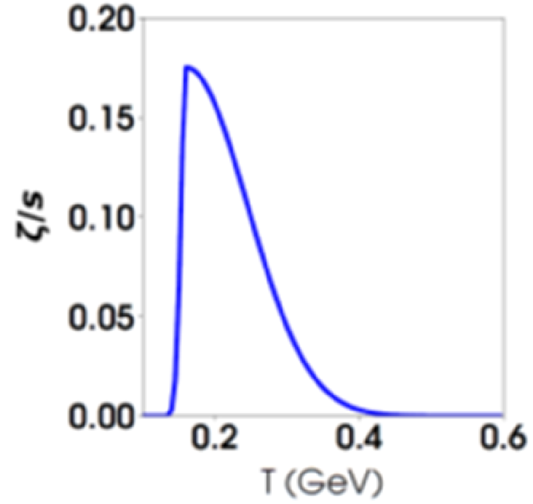
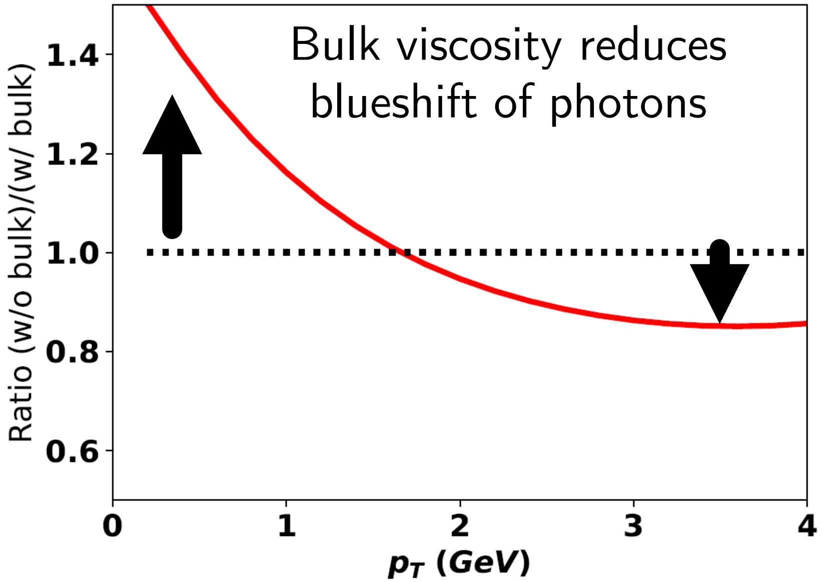
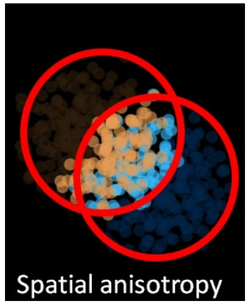


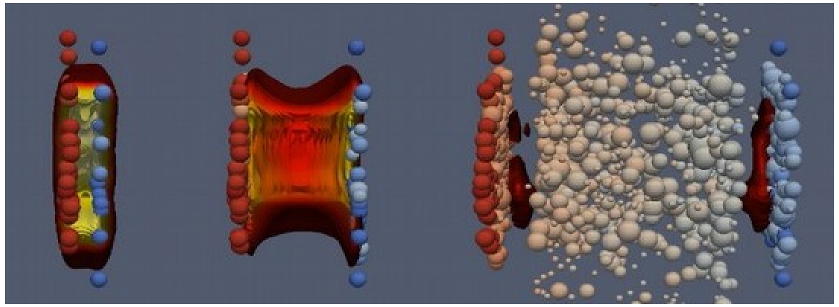
Beyond soft hadrons: electromagnetic probes

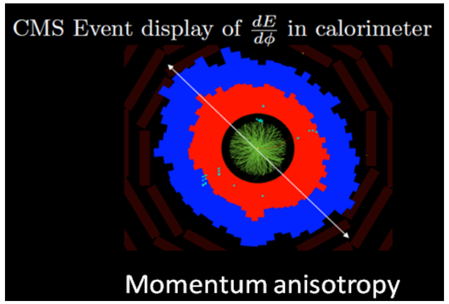





Bulk viscosity reduces blueshift of photons







MORE TRANSPORT COEFFICIENTS

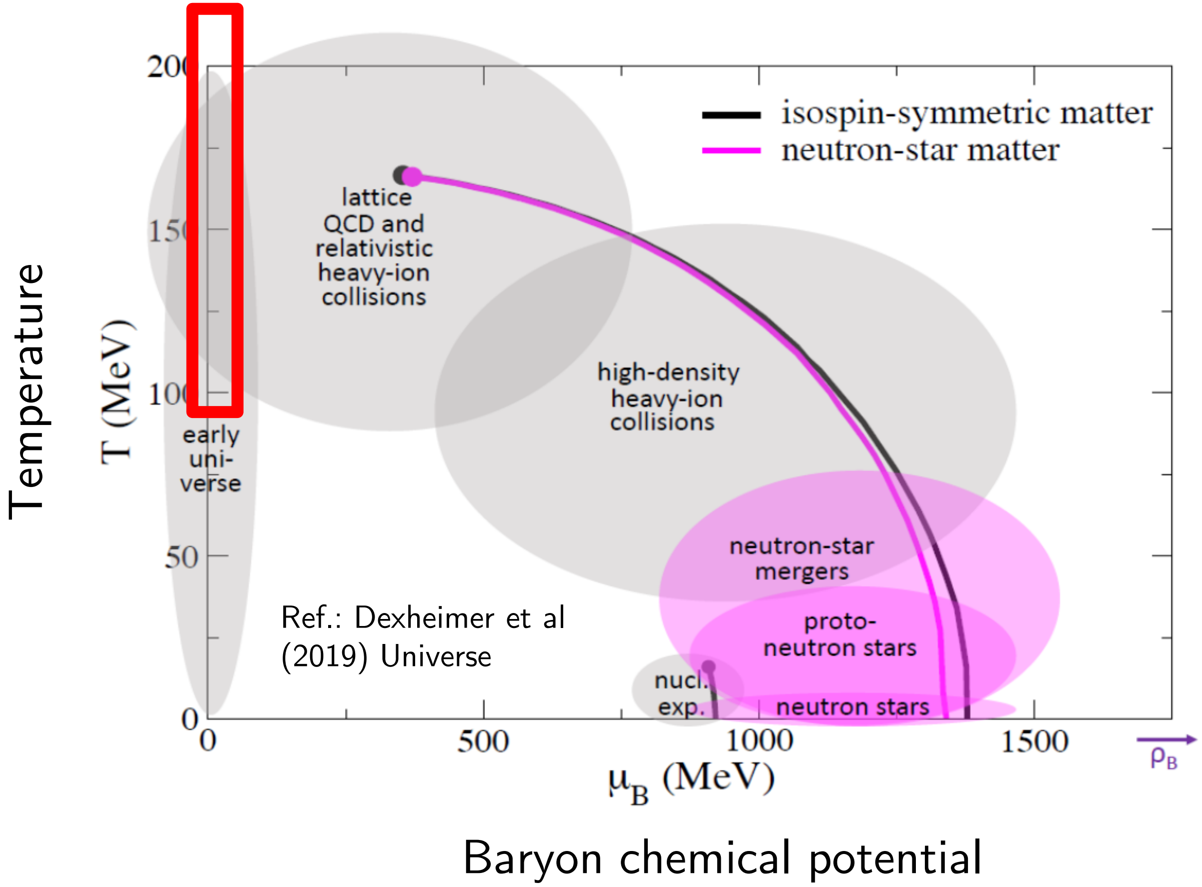
More transport coefficients

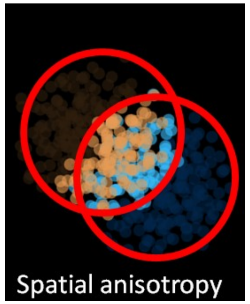
- Other conserved charges: e.g. finite baryon density
  - $\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$
  - Charge diffusion

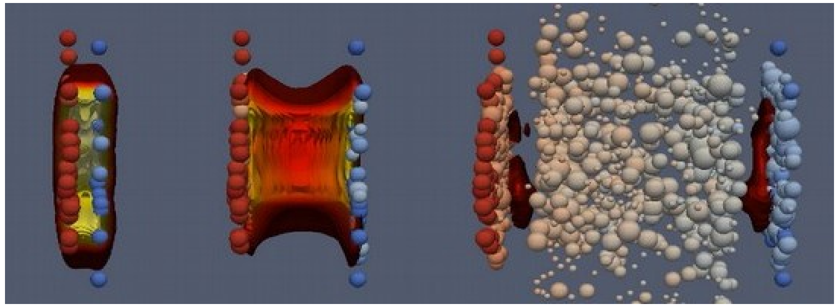
- Second order transport coefficients? (need to account for hydrodynamic fluctuations?)

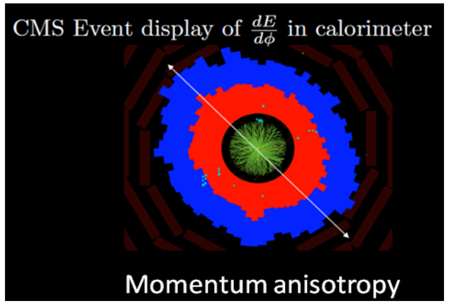
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta}\dot{\pi}^{\alpha\beta} + \pi^{\mu\nu} = 2\,\eta(\partial^\mu u^\nu + \cdots)$$

$$+ (2^{\text{nd}}\text{ order})$$




Spatial anisotropy



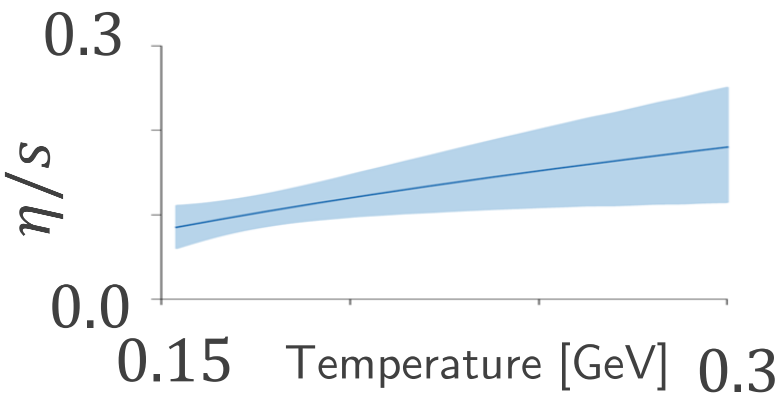

CMS Event display of $\frac{dE}{d\phi}$ in calorimeter
Momentum anisotropy

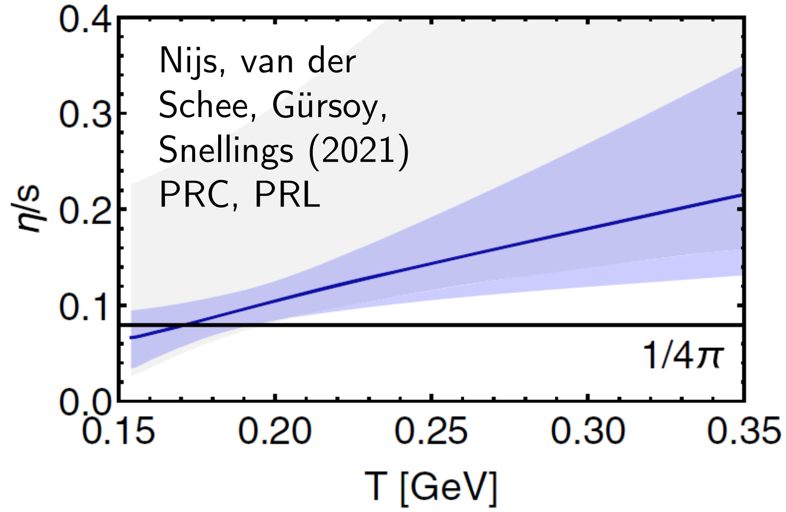
SUMMARY

Summary

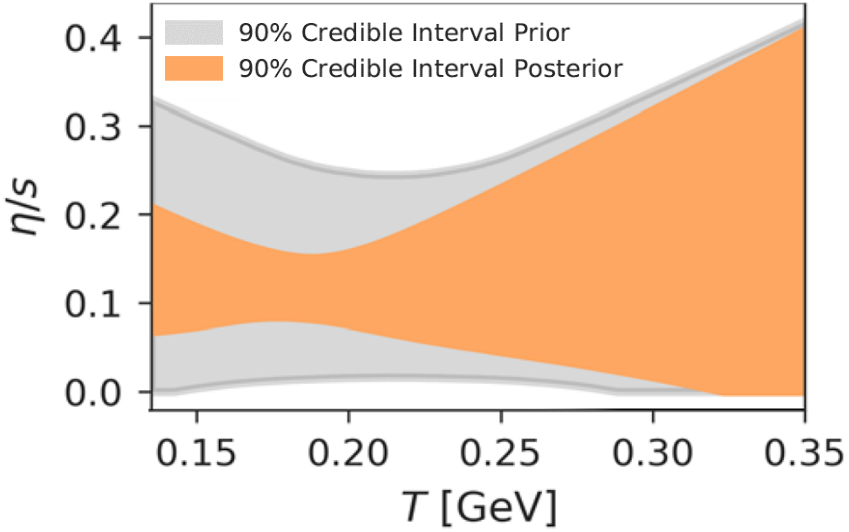
- Considerable progress over past decade, with strong community involvement

Bernhard, Moreland, Bass (2019) Nat.Phys.




Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL

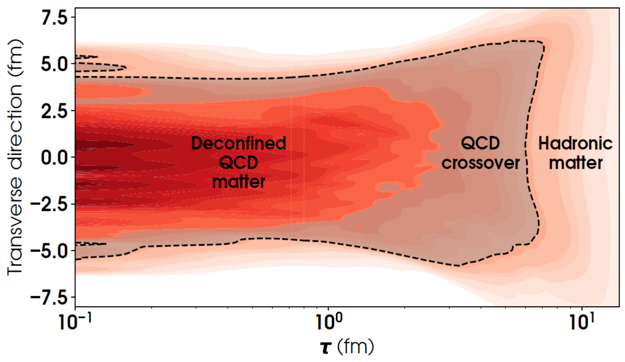
JETSCAPE Collaboration, (2021) PRC, PRL



- Specific shear viscosity η/s at T=150-200 MeV remains constrained around 0.1-0.15
- Temperature dependence of specific bulk viscosity ζ/s still under investigation

Outlook

- Precision constrains on viscosities with community-wide efforts
  - Consider capabilities of theory to describe measurements
  - Measurements to isolate and study specific collision stages
  - Leverage photons and dileptons, and additional probes



- Necessitates continued strong funding of:
  - Theoretical research groups, including multidisciplinary ones (e.g. statistics)
  - Topical collaborations and other theory/experimental collaboration

Support critical to ensure that the knowledge generated by analyses of RHIC data are fully incorporated into our understanding of emergent QCD.

QUESTIONS?

MANY THANKS TO STEFFEN A. BASS, CHARLES GALE, ANDREW GORDEEV, WEIYAO KE, BERNDT MUELLER, GOVERT NIJS, BJOERN SCHENKE, DEREK SOEDER, CHUN SHEN, PRITHWISH TRIBEDY, JULIA VELKOVSKA AND MANY MORE FOR THEIR INPUT

BACKUP

Considering theoretical uncertainties of observables

- Viscosity is probed through the hydrodynamic phase

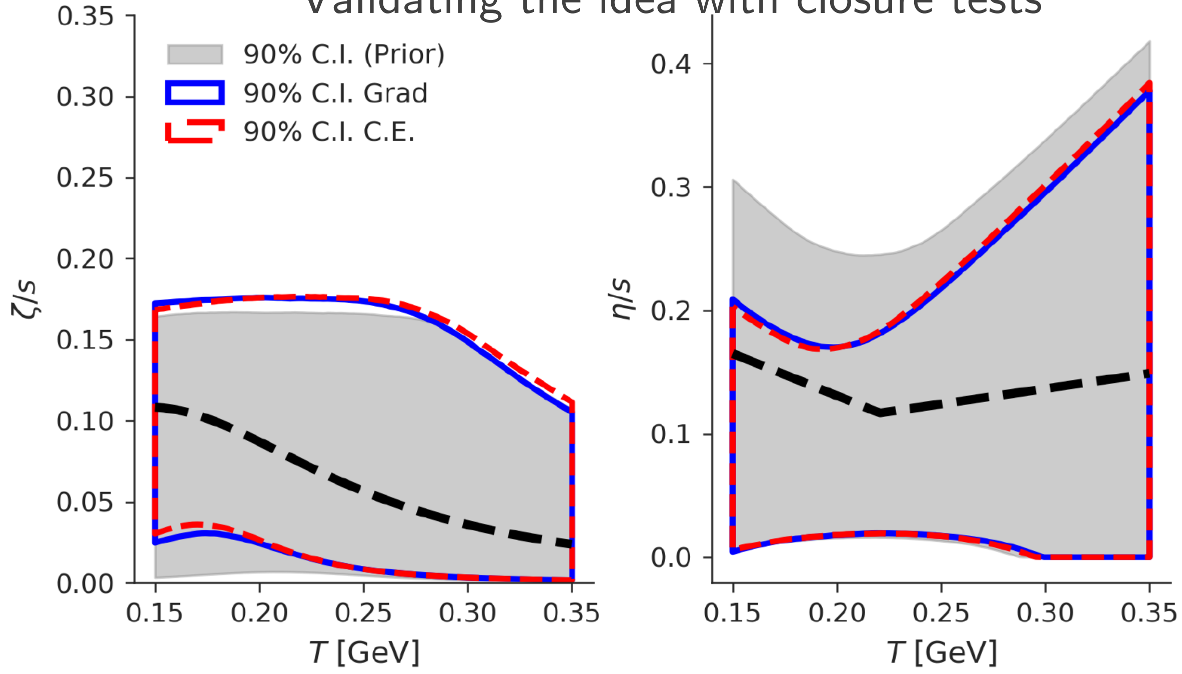
Energy deposition → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

$$\partial_\nu T^{\mu\nu} = 0; \qquad T^{\mu\nu} = \epsilon u^\mu u^\nu - (P(\epsilon) + \Pi)(g^{\mu\nu} - u^\mu u^\nu) + \pi^{\mu\nu}$$

$$T^{\mu\nu} = \sum_n g_n \int \frac{d^3P}{(2\pi)^3 P^0} P^\mu P^\nu f_n(P)$$

Hadron momentum distributions; deviate from Fermi-Dirac/Bose-Einstein distribution

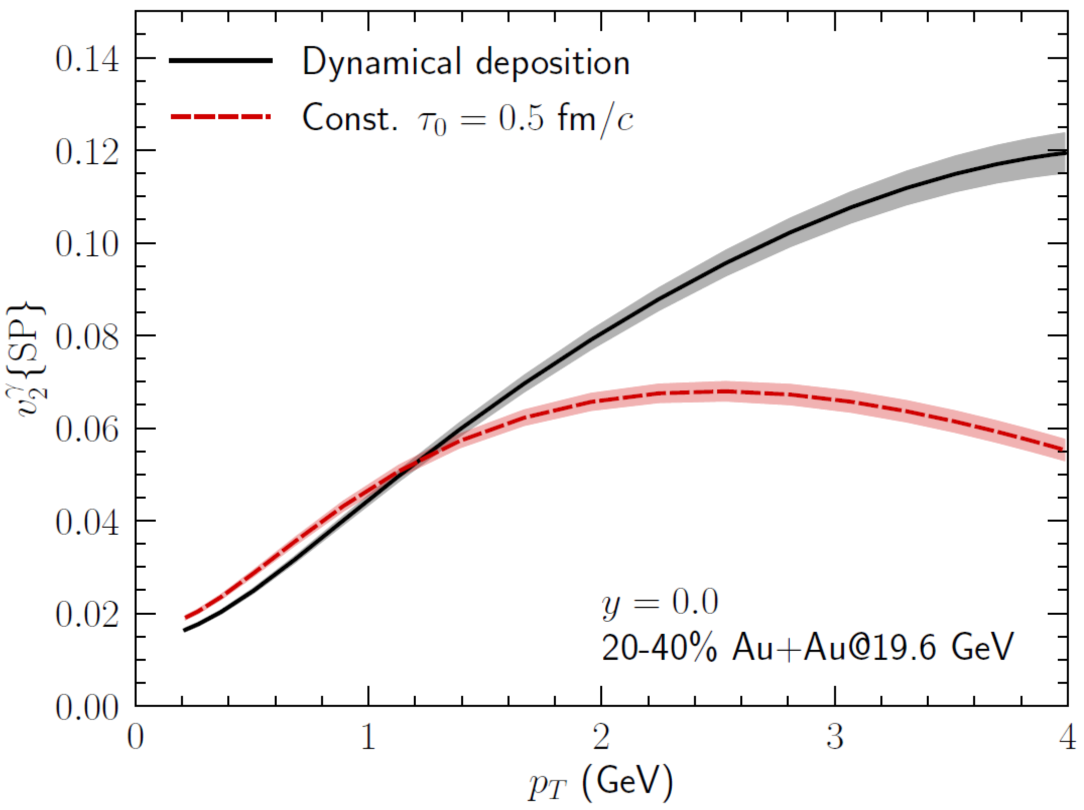
Validating the idea with closure tests



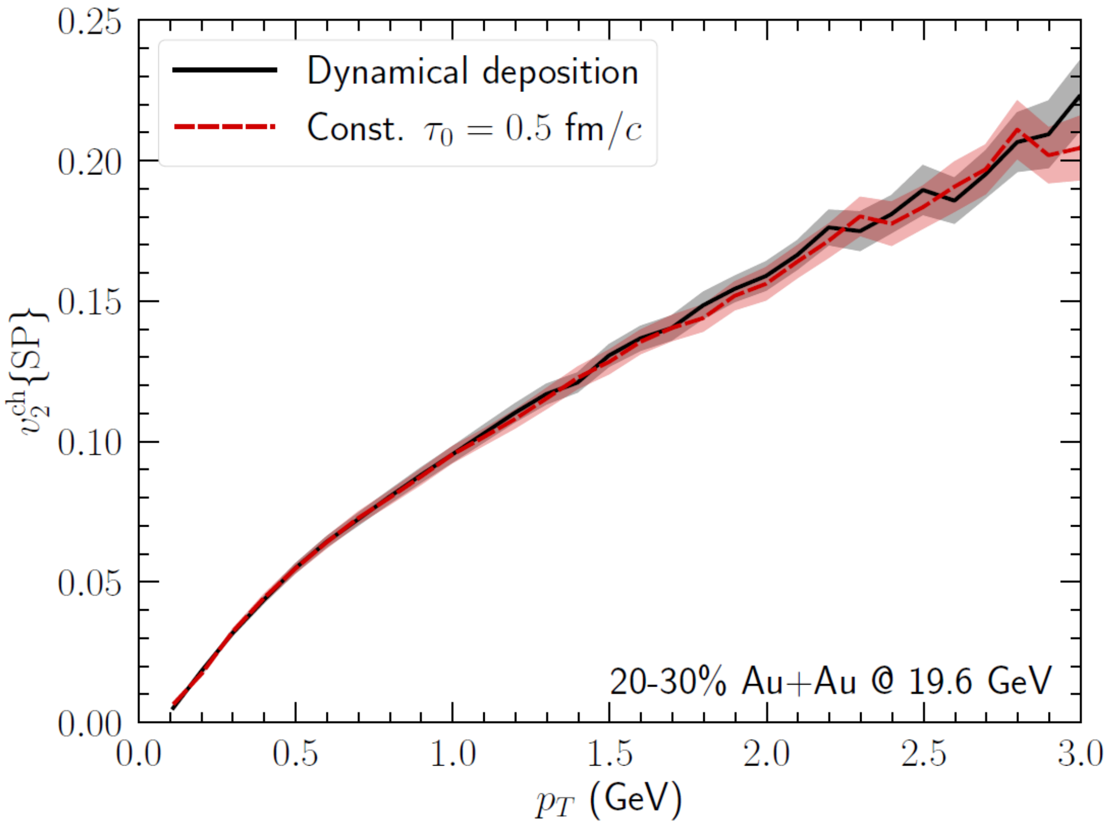
Derek Everett, J-F Paquet, Matt Luzum, unpublished

Photons: probing the early stage of the collisions

Photons

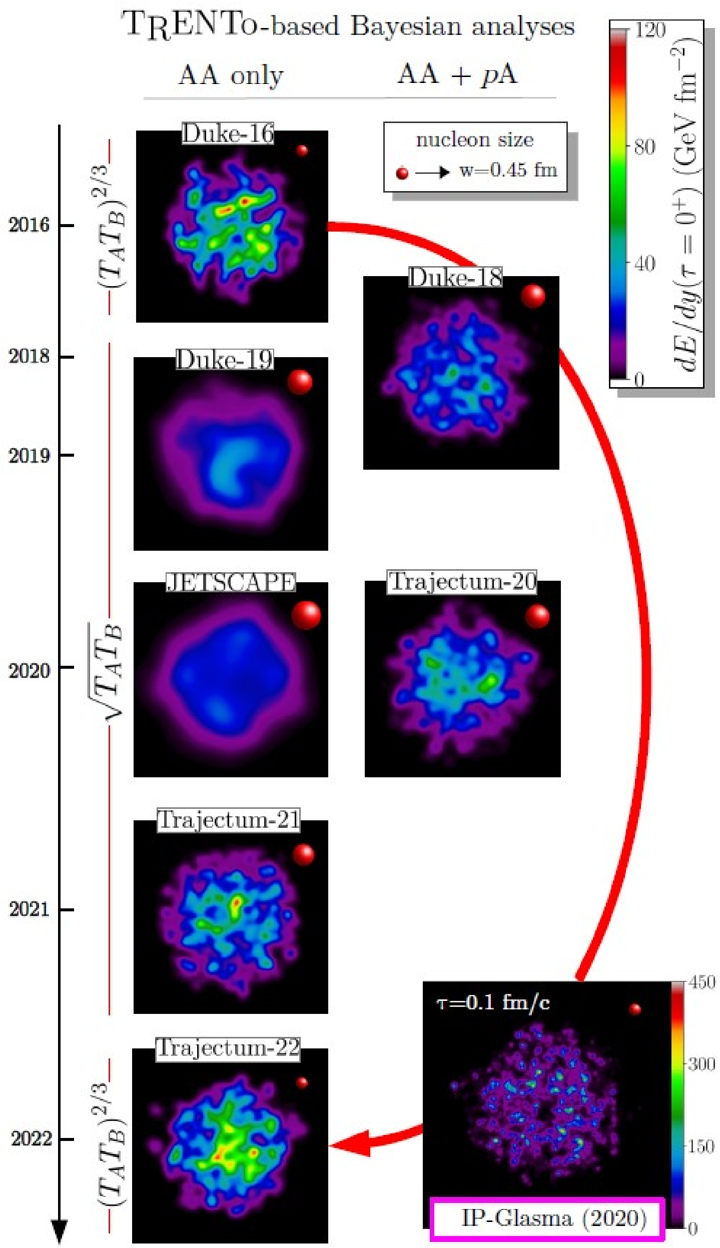


Hadrons



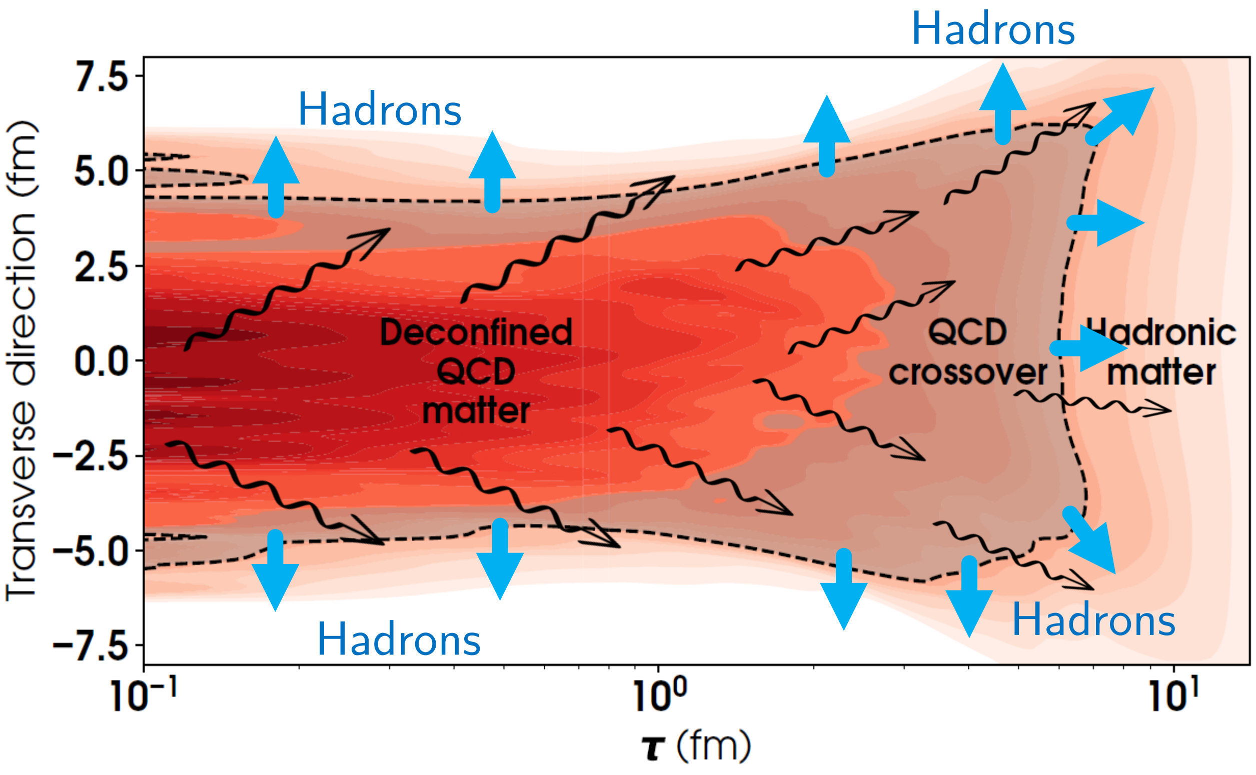
Energy deposition

Giacalone, arXiv:2208.06839

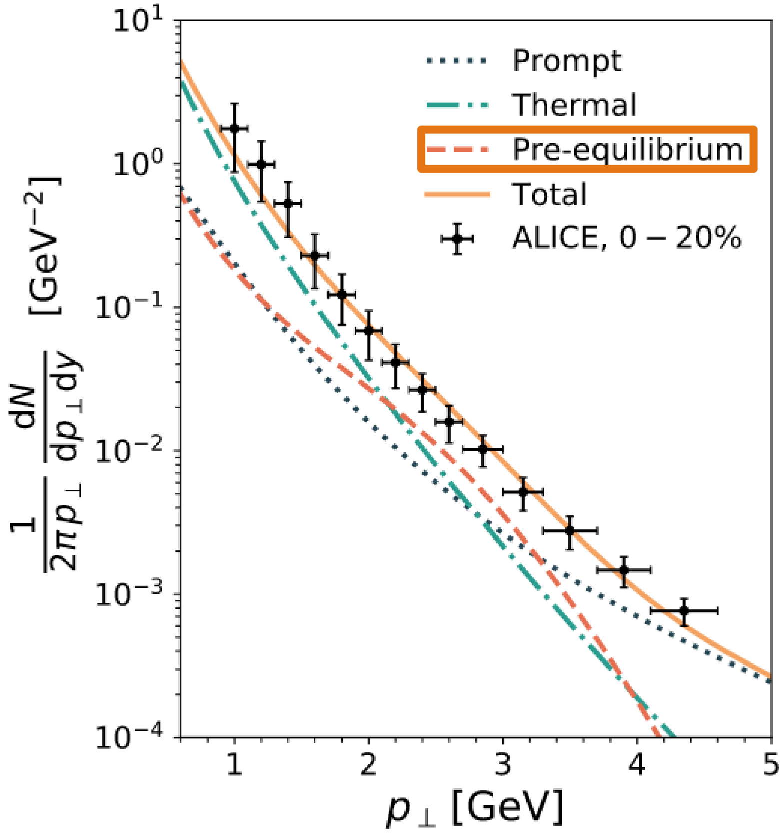


Beyond soft hadrons: electromagnetic probes

- Photons (γ) and dileptons (l^+l^-) are "holistic" probes: produced at all stages, reflects the local properties of the plasma

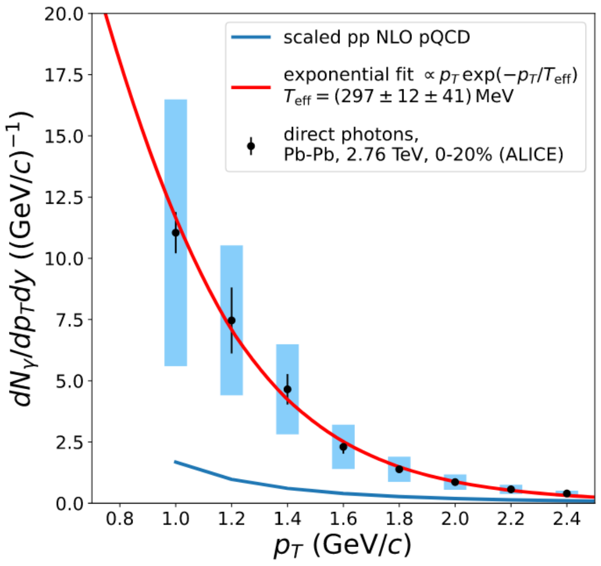


Garcia-Montero et al (2020) PRC

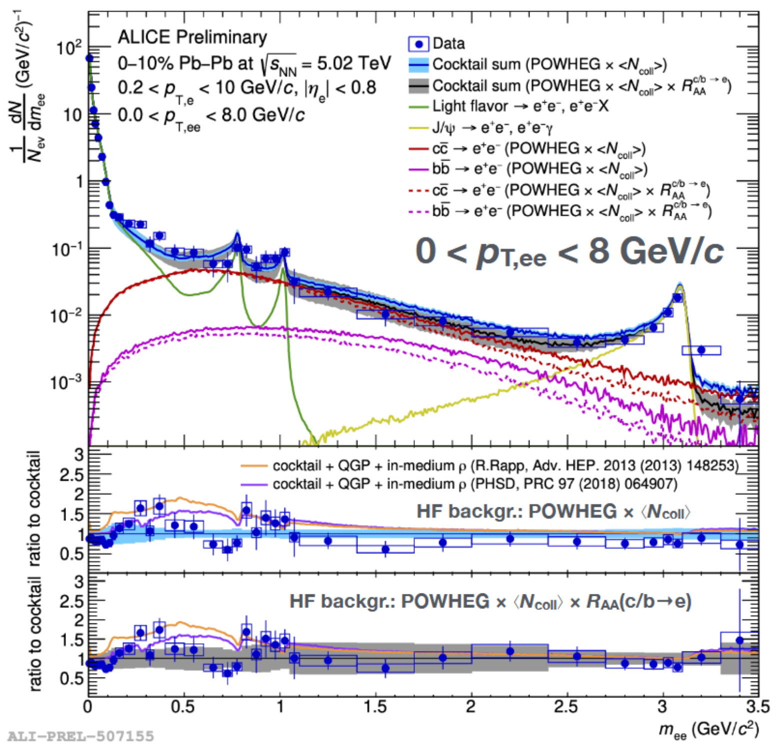


Future of viscosity measurements: multimessenger

- Photons (γ) and dileptons (l^+l^-) are “holistic” probes: produced at all stages, reflects the local properties of the plasma



ALICE 2016, K. Reygers

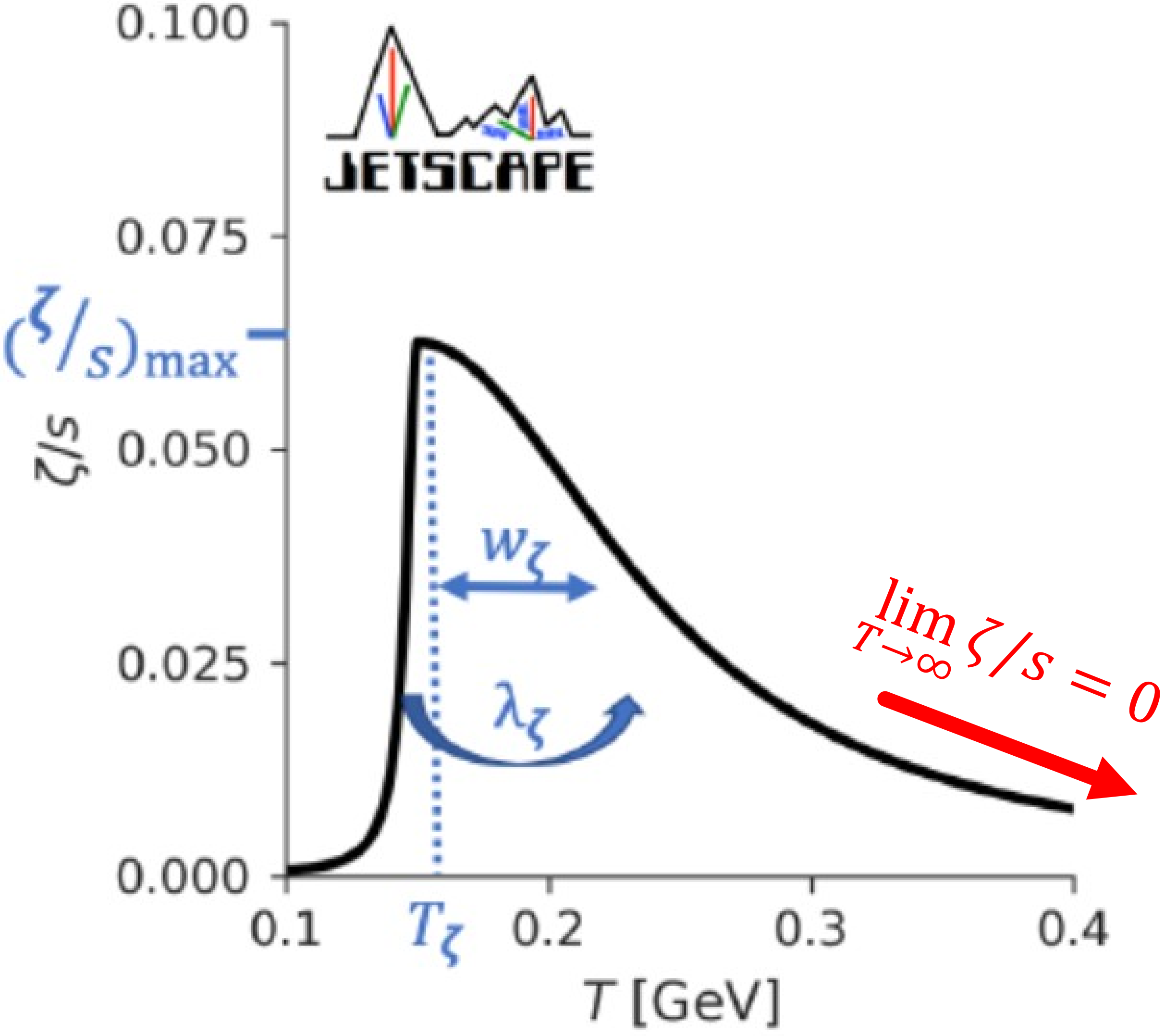


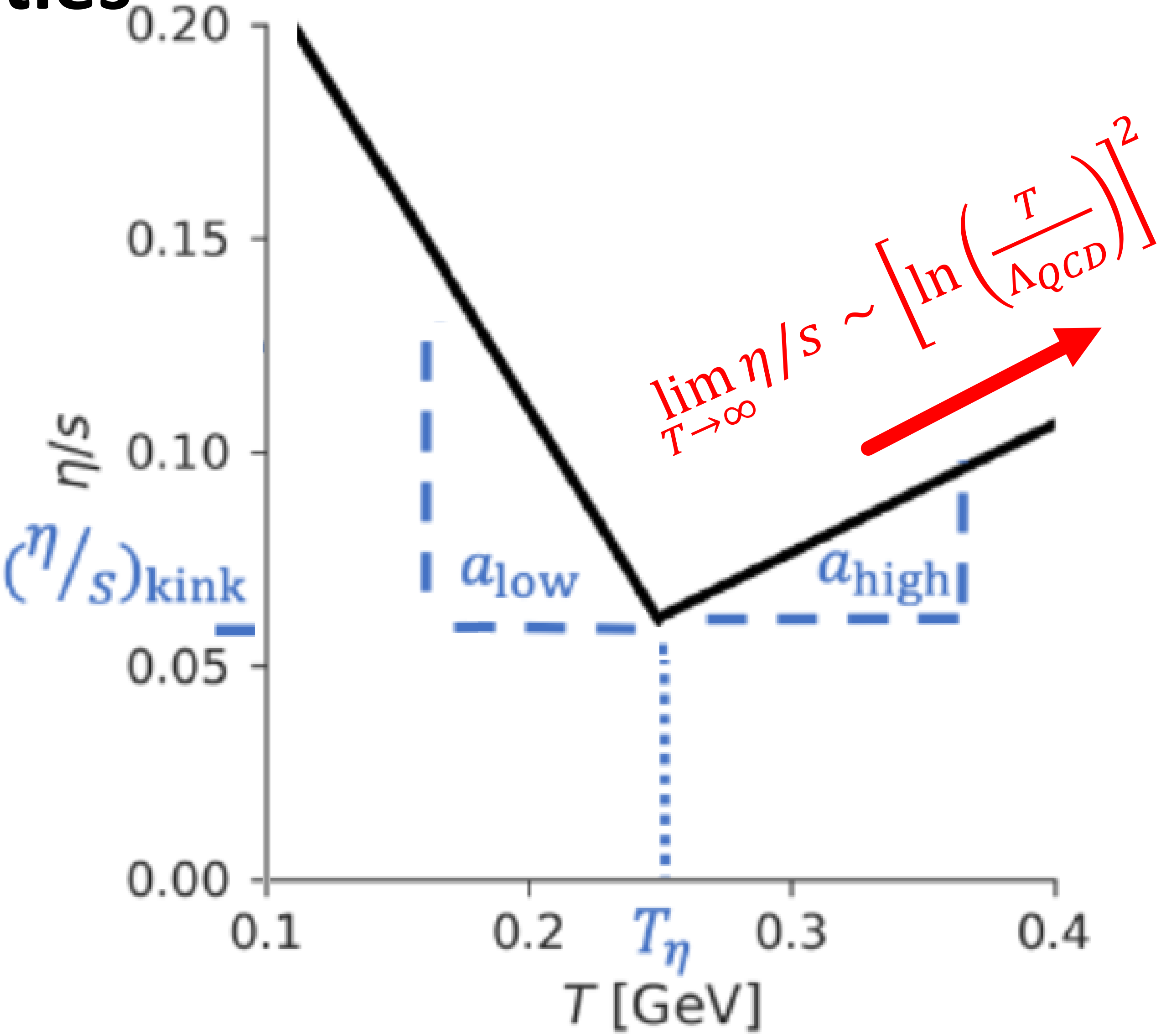
Considerable progress over past decade:

- Emission rates studied at NLO and on lattice
- Pre-equilibrium photons & dileptons
- γ & l^+l^- from hadronic transport
- Can help probe viscosities but also validate initial stage

Limited data is a challenge (few measurements, large uncertainties)

Parametrization of the viscosities





ORIGINS OF MOMENTUM ANISOTROPY

The initial momentum distribution is already anisotropic

The Color Glass Condensate predicts anisotropic particle production because of

1. Local anisotropies in the color fields
2. Local density gradients
3. Quantum interference effects

Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009)
Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008)
Dumitru, Jalilian-Marian PRD 81 094015 (2010)
Dusling, Venugopalan PRD 87 (2013)
A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212
V. Skokov. Phys.Rev.D91 (2015) 054014
T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061
Kovner, Skokov, Phys.Rev. D98 (2018) no.1, 014004
...

BUT INITIAL STATE EFFECTS ARE THERE

Our calculation using the IP-Glasma initial state and hydrodynamics includes both effects

Initial state anisotropies are significant and can affect the final result at low multiplicity

$$Q_\varepsilon = \frac{\mathrm{Re}\langle \mathscr{E} V_2^* \rangle}{\sqrt{\langle |\mathscr{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

CORRELATION OF THE FINAL ELLIPTIC FLOW V_2 WITH

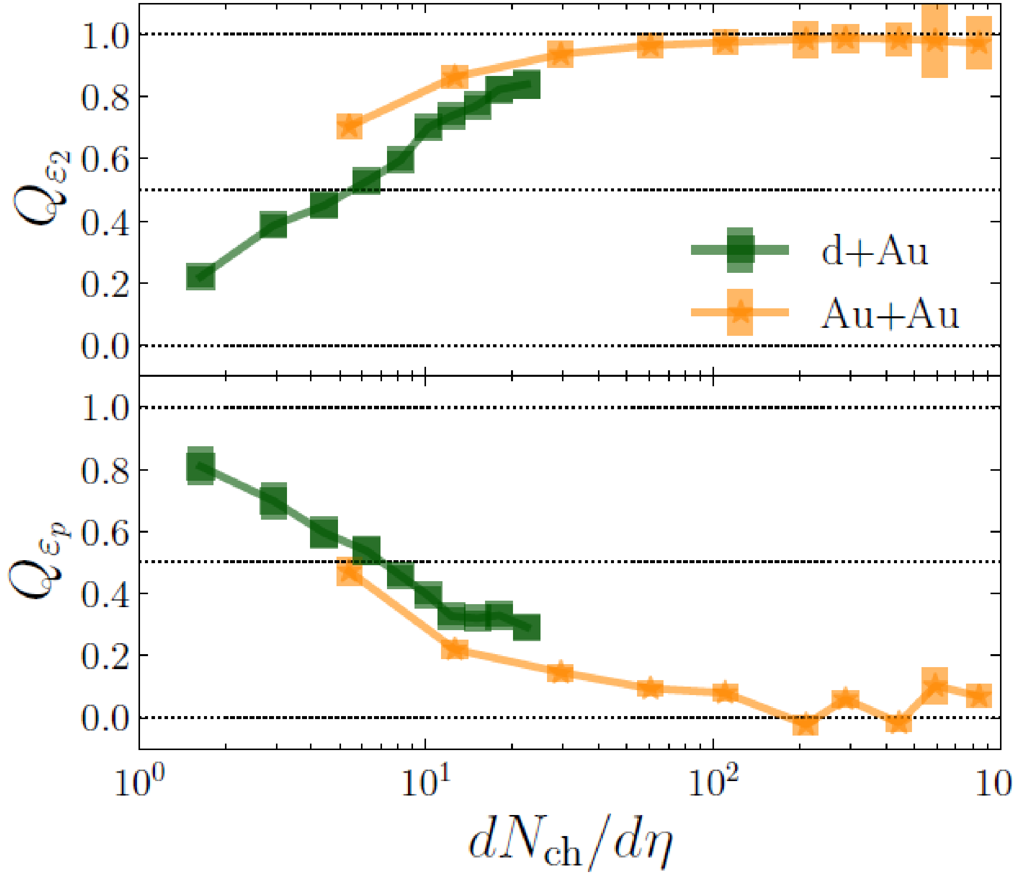
THE GEOMETRIC ELLIPTICITY

$$\mathscr{E}_2 = \varepsilon_2 e^{i2\psi_2} = \frac{\langle x^2 - y^2 \rangle + i\langle 2xy \rangle}{\langle x^2 + y^2 \rangle}$$

AND

THE INITIAL MOMENTUM ANISOTROPY

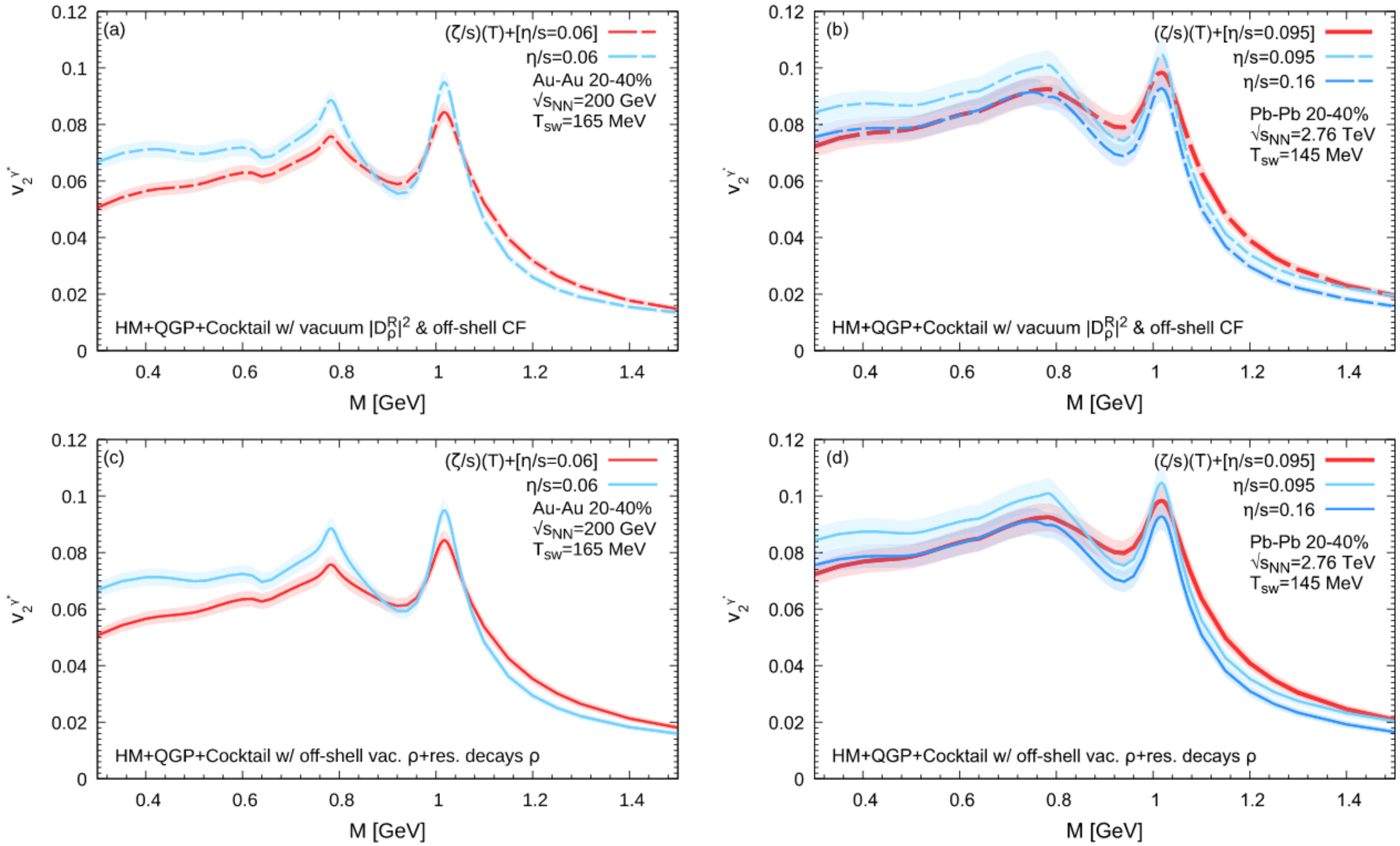
$$\mathscr{E}_p = \varepsilon_p e^{i2\psi_2^p} = \frac{\langle T^{xx} - T^{yy} \rangle + i\langle 2T^{xy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$$



B. Schenke, C. Shen, P. Tribedy
Phys.Lett.B 803 (2020) 135322

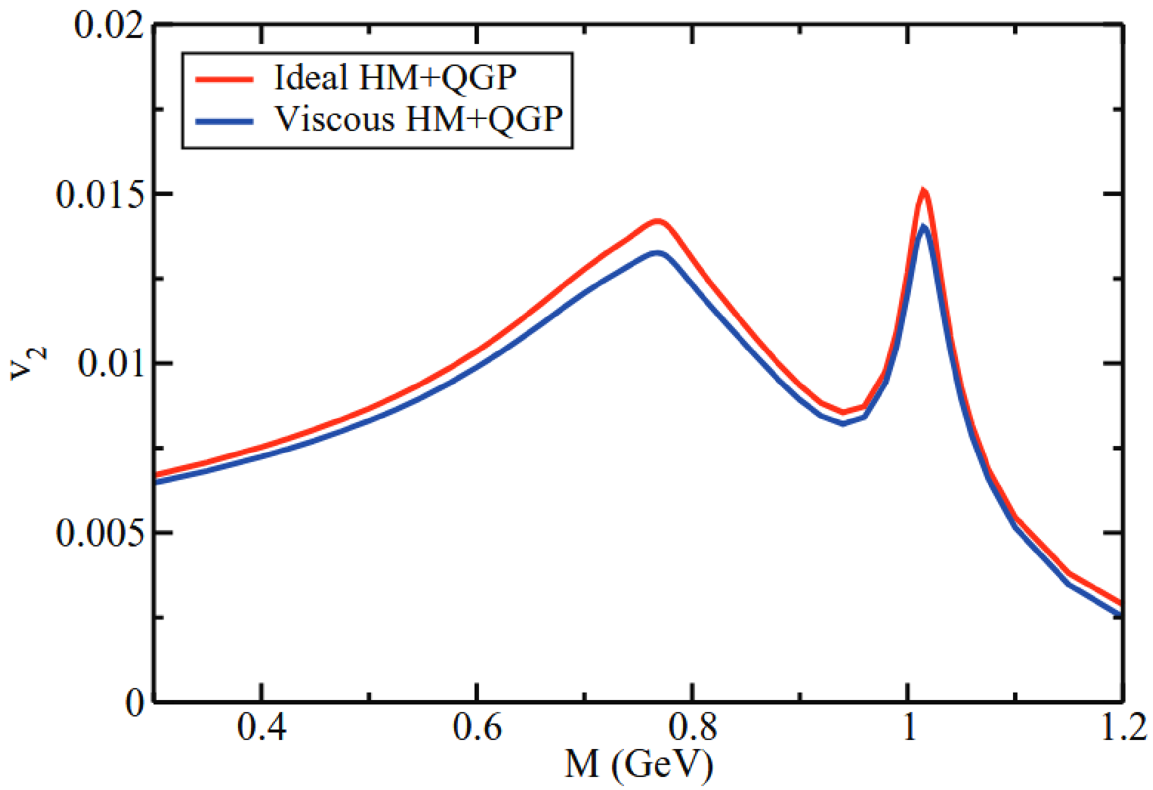
Dilepton sensitivity to bulk viscosity

Vujanovic et al (PRC) 2020



Dilepton sensitivity to shear viscosity

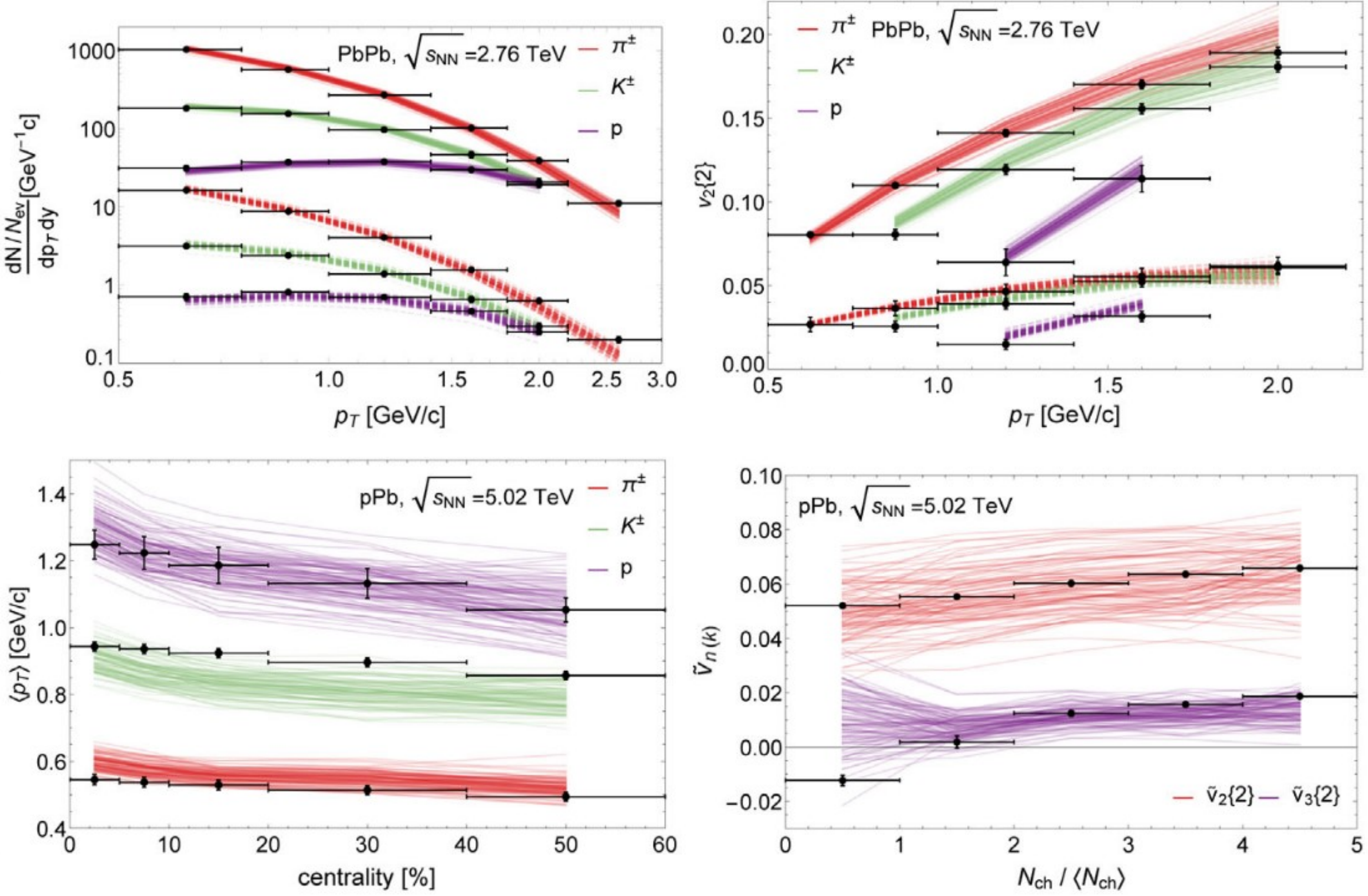
Vujanovic et al (PRC) 2014



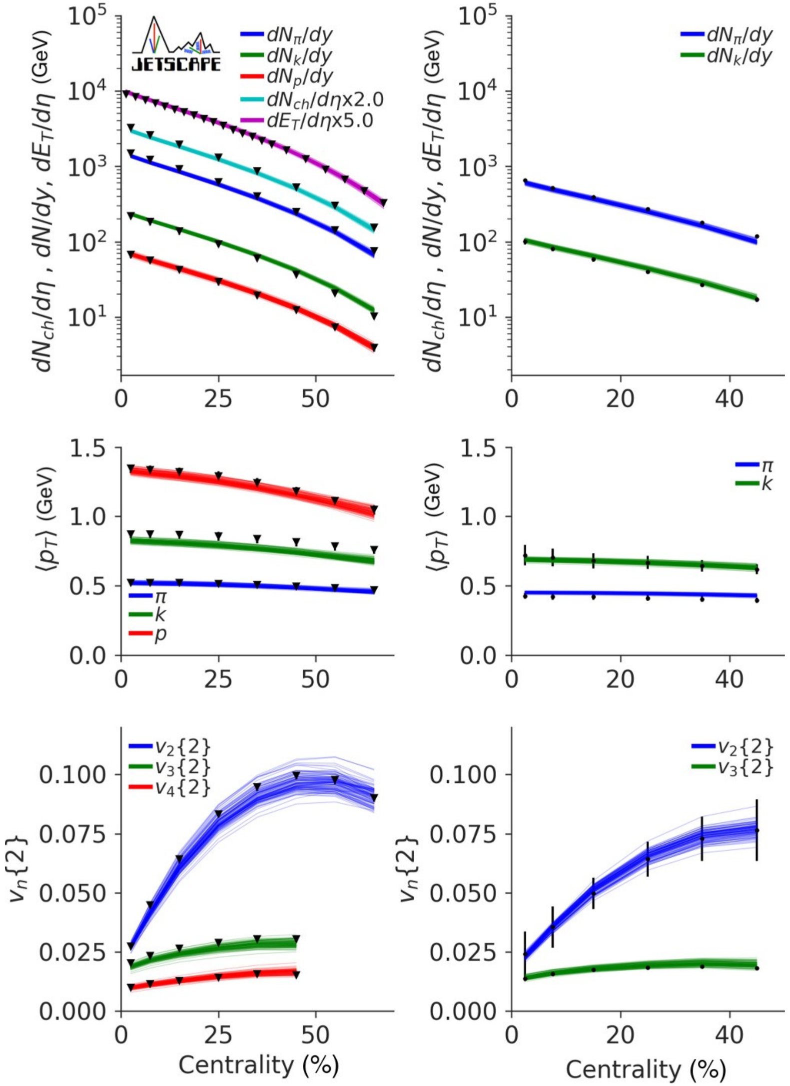
Hydrodynamic-based simulations of heavy ion collisions

- Successful in describing broad sets of measurements

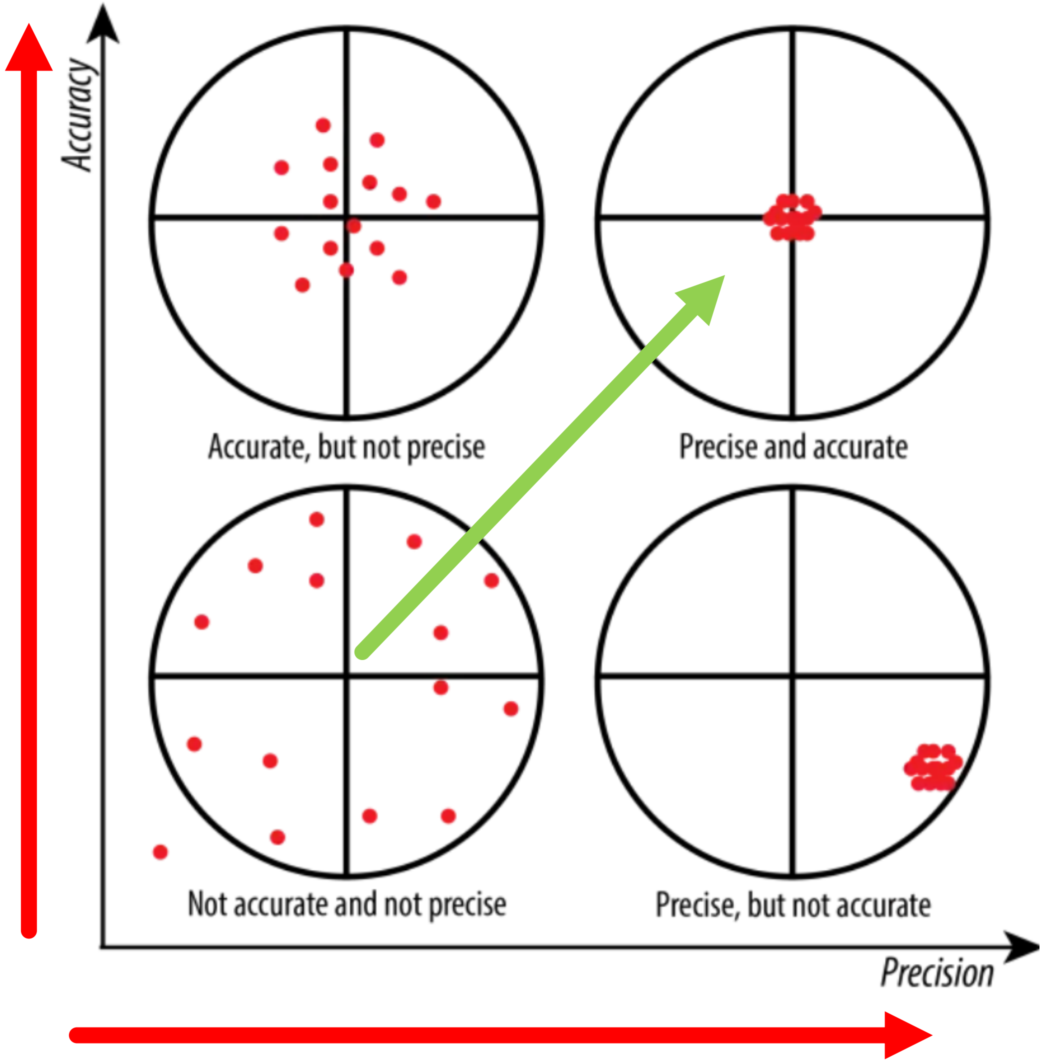
Nijs, van der Schee, Gürsoy, Snellings (2021) PRC, PRL



JETSCAPE Collaboration, (2021) PRC, PRL



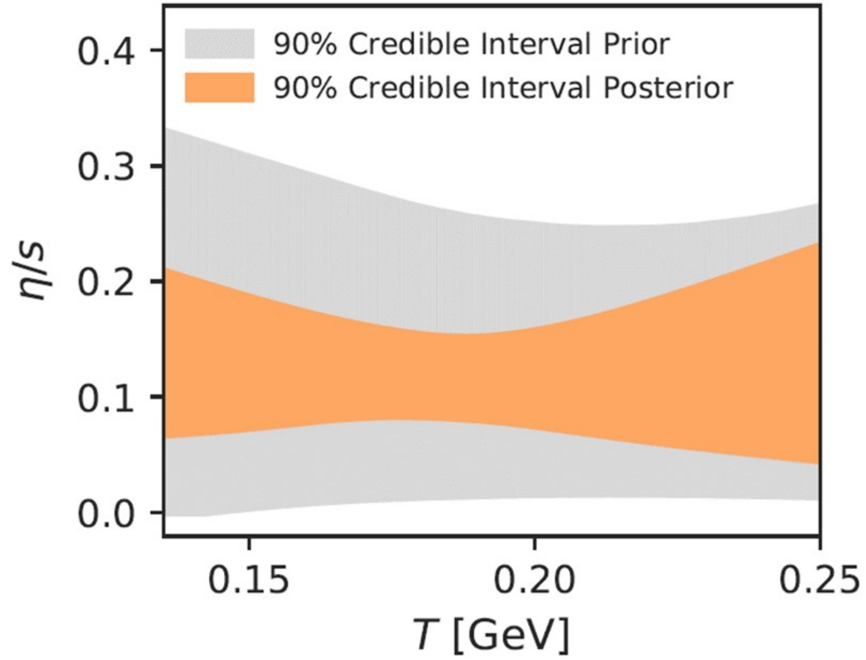
Precision vs accuracy



Quantify model uncertainties

Compare with more data

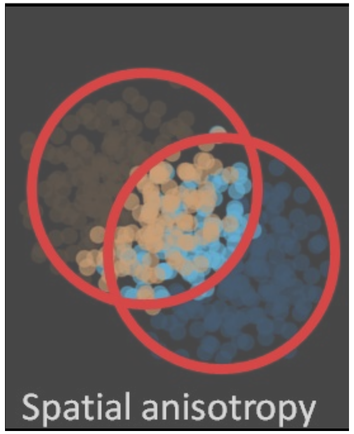
- Adding data = stronger constraints on viscosity [Precision]
- Relaxing model assumptions = weaker but more accurate constraints [Accuracy]

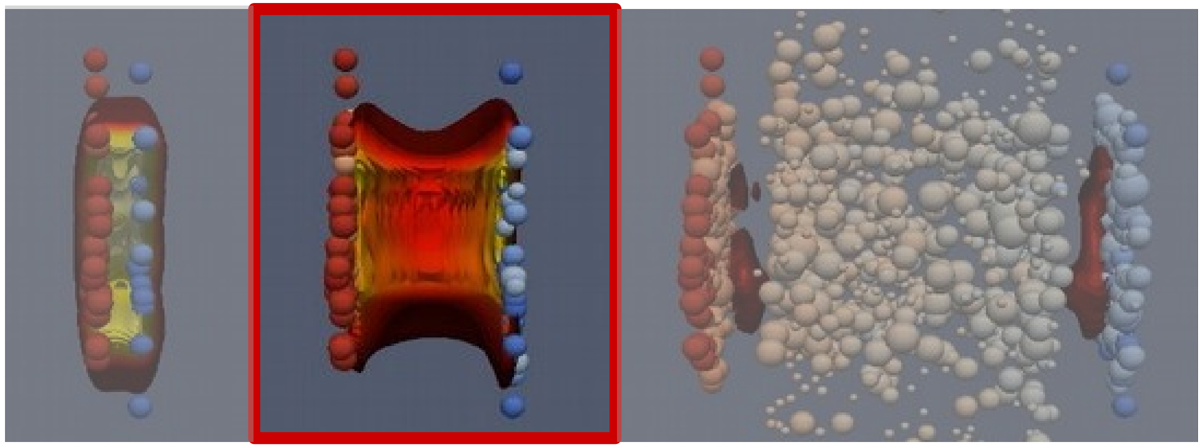


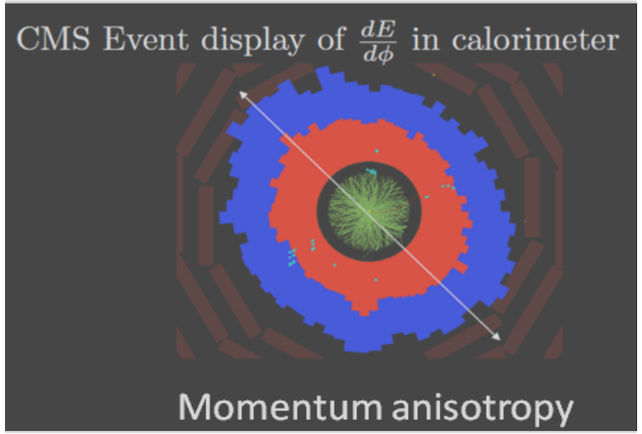
Ref.: https://wp.stolaf.edu/it/gis-precision-accuracy/

Strongly-coupled quark-gluon plasma

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard



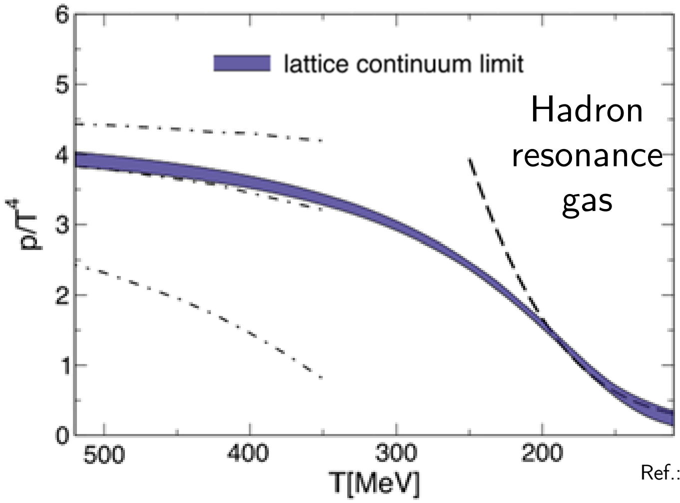




Ref: Review of Particle Physics

Strongly-coupled quark-gluon plasma

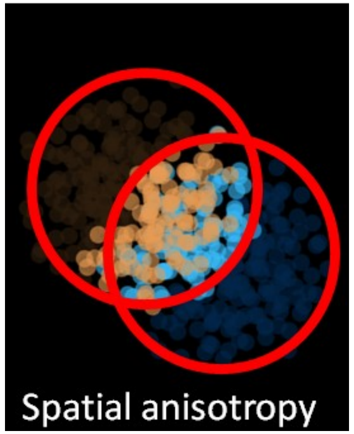
- Liquid phase characterized by macroscopic properties:
  - Equation of state
  - Transport coefficients (viscosities, …)

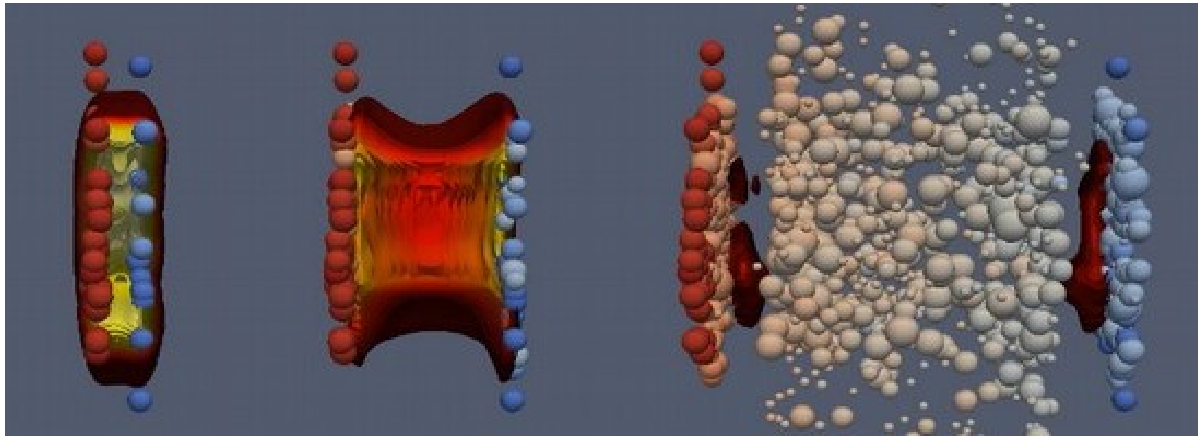


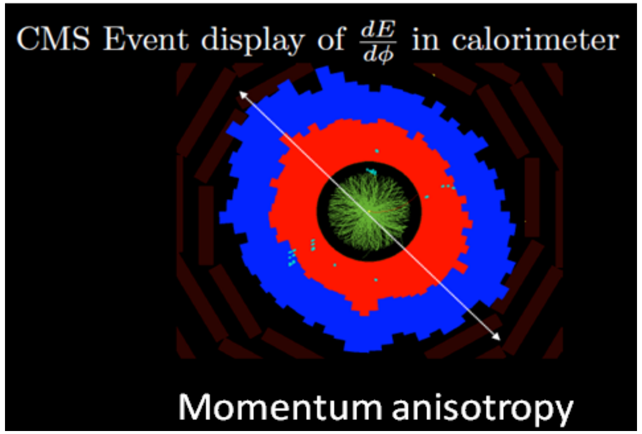
Ref.: Borsányi et al (2014) PLB

Interaction and expansion

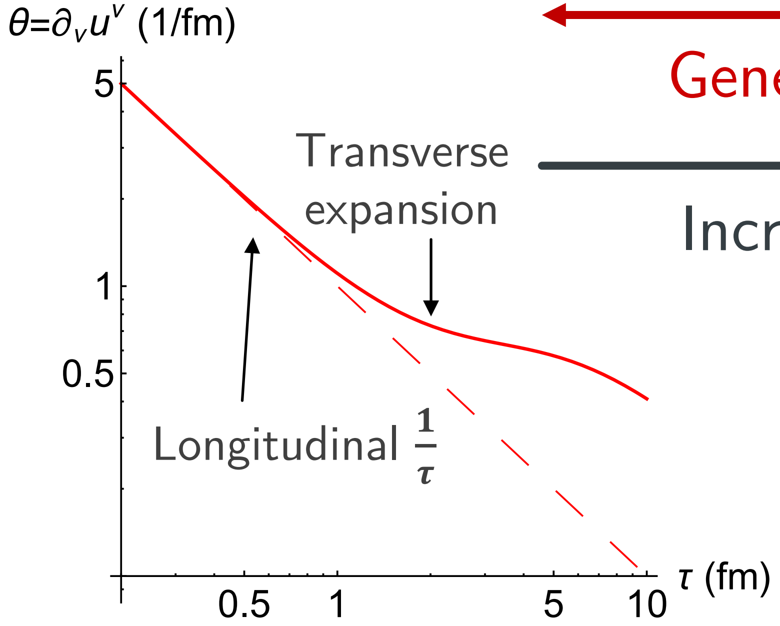
Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard





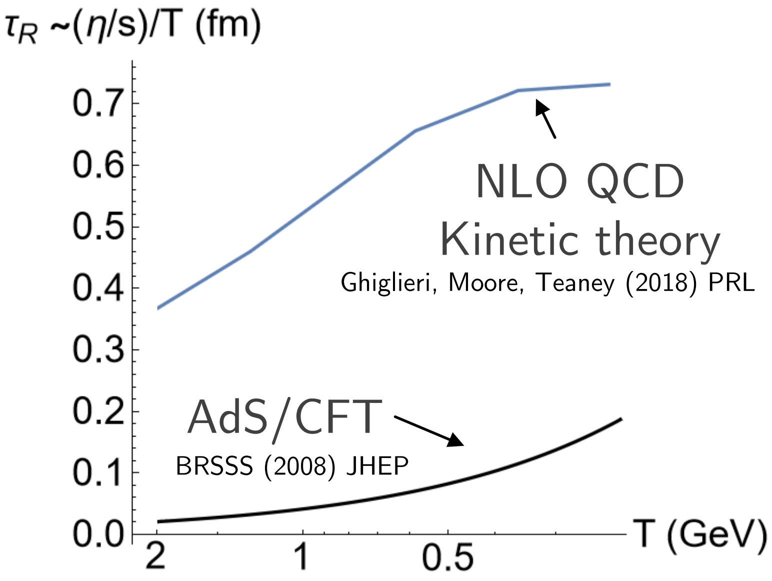


Ref: Review of Particle Physics



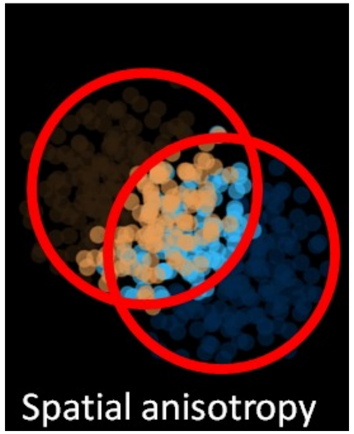
General decrease in expansion rate

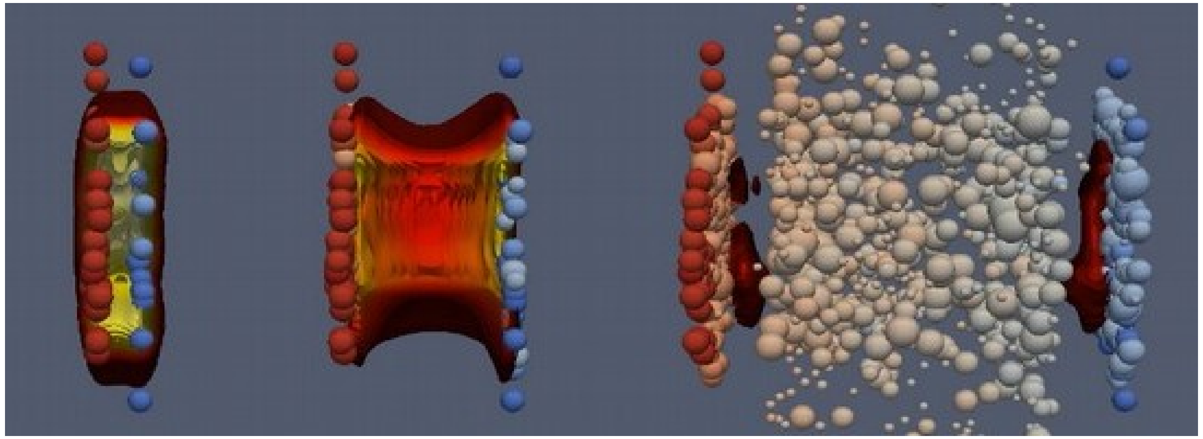
Increase in local equilibration time (relaxation time)

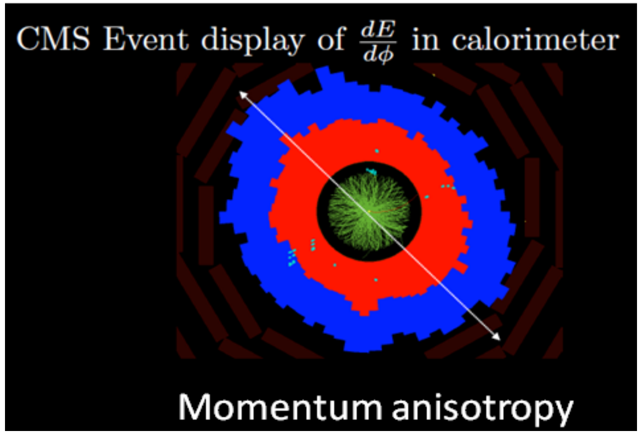


Beyond the current "standard model" of collisions

Based on figures by Derek Teaney, CMS Coll., MADAI, H. Elfner and J. Bernhard



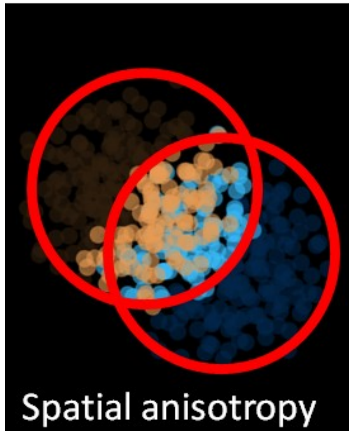


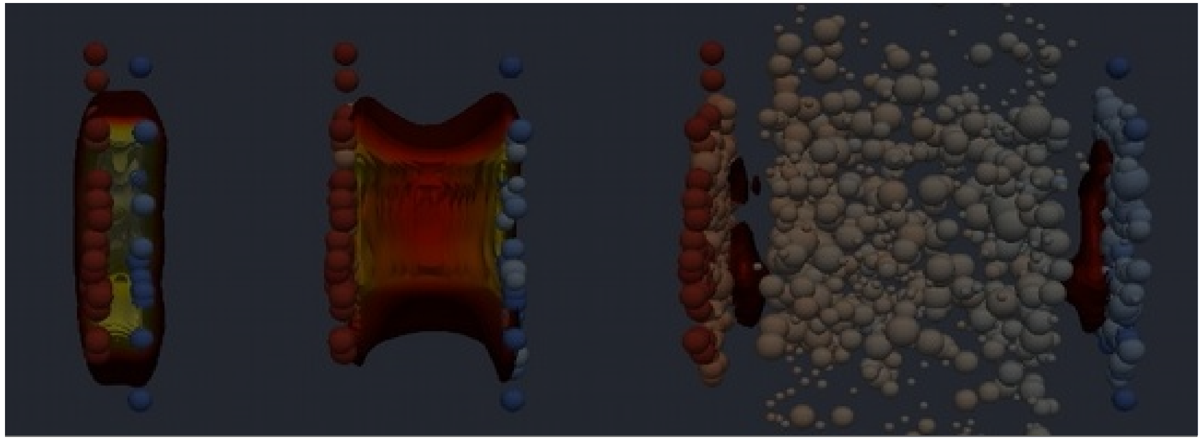


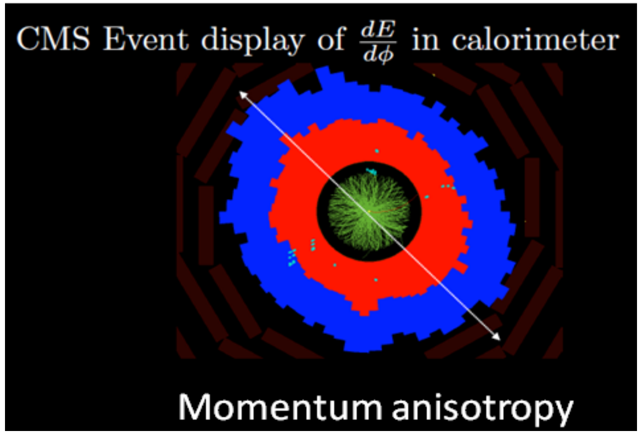
Energy deposition → **Early dynamics** → **Hydrodynamics** → **Hadronic transport**

- Theoretical uncertainties limit accuracy of constraints on viscosity
  - Need smooth transition between stages of collision
  - Address challenges with viscous hydrodynamics (causality, large gradients, …)

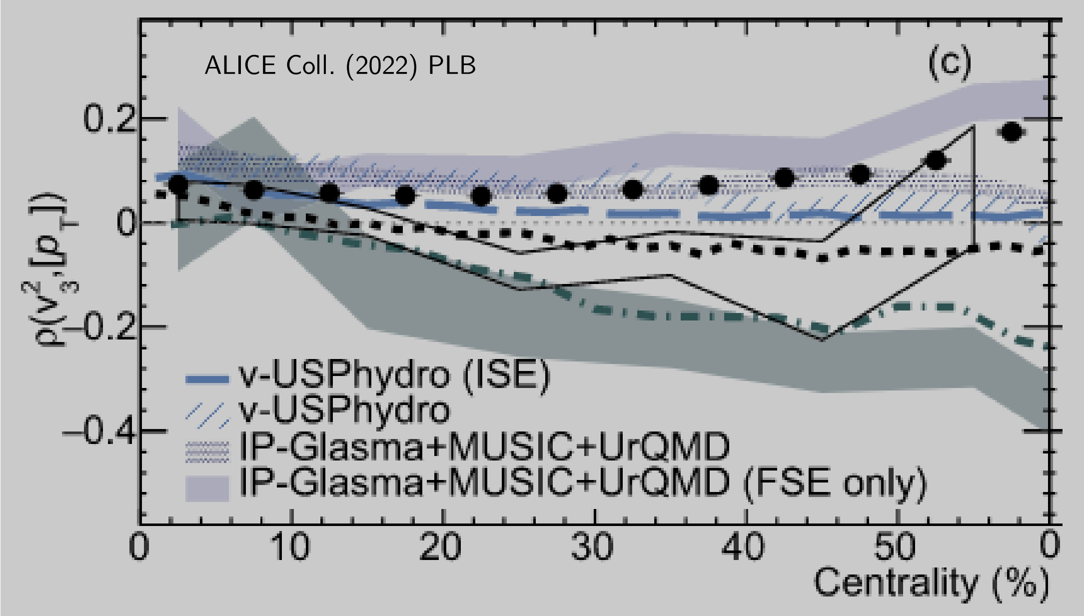
Targeted observables

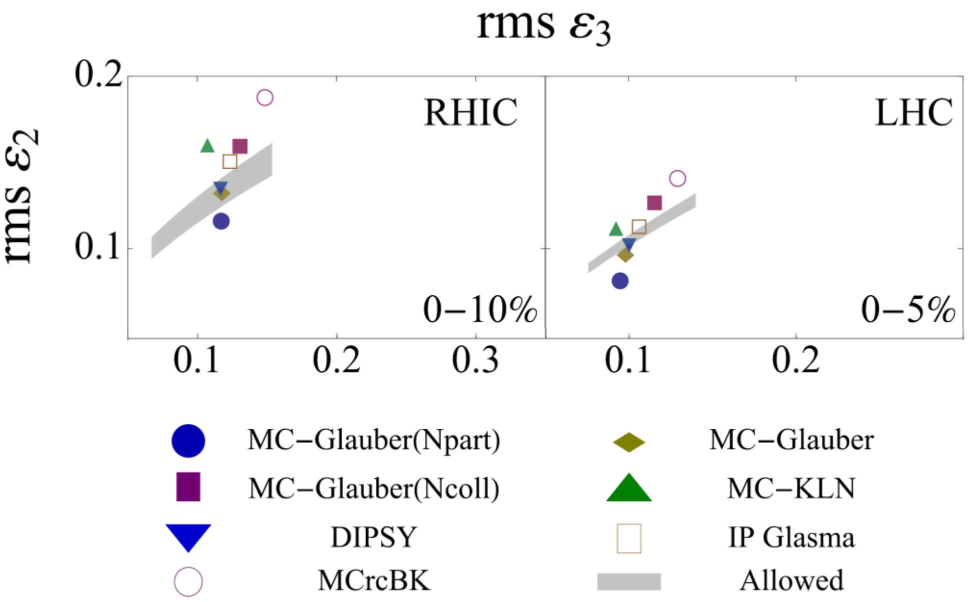






Energy deposition





Retinskaya, Luzum, Ollitrault (2014) PRC