Electromagnetic probes of heavy-ion collisions

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Institute for Nuclear Theory Workshop:
Precision Spectroscopy of QGP Properties
with Jets and Heavy Quarks

THE OHIO STATE
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JETSCAPE

Outline

Part I: Modelling of the QCD Medium

- Viscous hydrodynamics & Hadronic observables

Part II: Sources of Dileptons

- Quark Gluon Plasma (QGP) Rate (w/ dissipative corrections)
- Hadronic Medium (HM) Rate (w/ dissipative corrections)
- Dilepton Cocktail

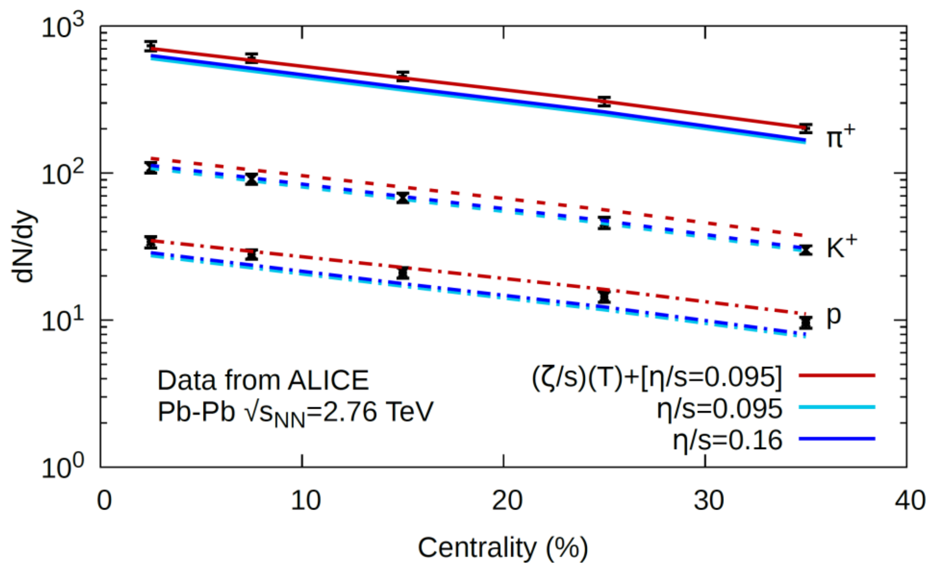
Part III: Dilepton yield and elliptic flow

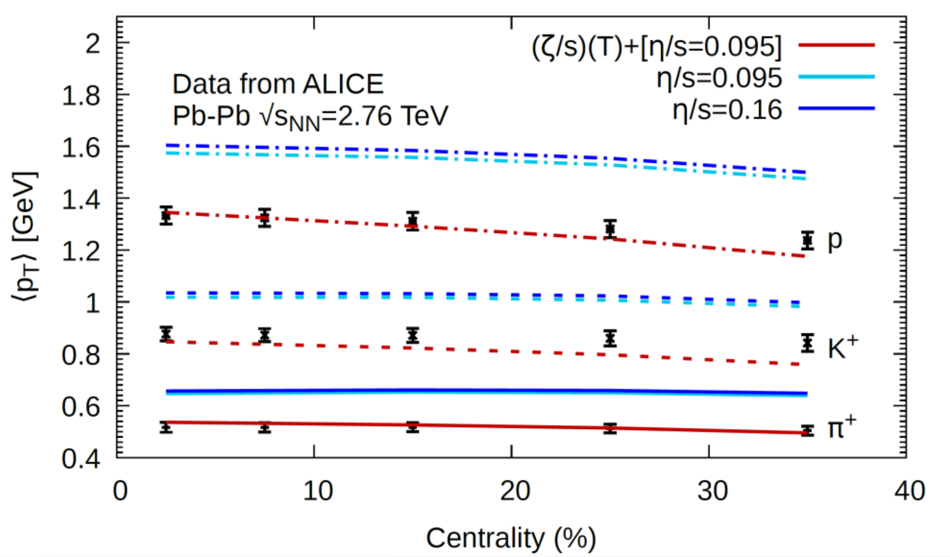
- Effects of bulk viscosity on thermal (HM+QGP) dileptons
- Dilepton cocktail contribution

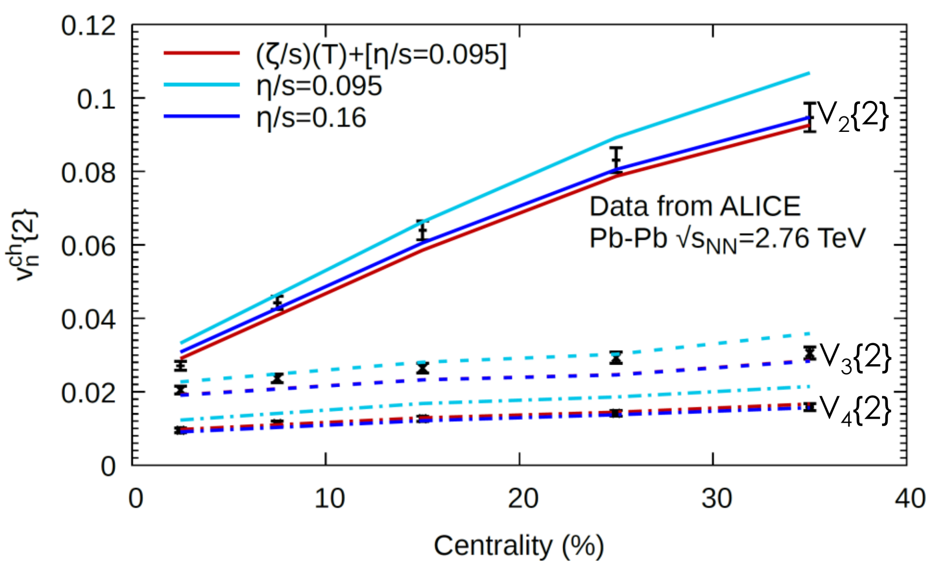
Conclusion and outlook

An improvement in the description of hadronic observables

- IP-Glasma + Viscous hydrodynamics + UrQMD [Ryu et al., PRL **115**, 132301]







- T_{switch} = 145 MeV at LHC
- Crucial ingredient : Bulk Viscosity
- Via the same modelling, an improved description of v_n of direct photons [Paquet et al., PRC **93**, 044906] was done.
- Dileptons are now also included.

Viscous hydrodynamics & bulk pressure

- Dissipative hydrodynamic equations including coupling between bulk and shear viscous terms:

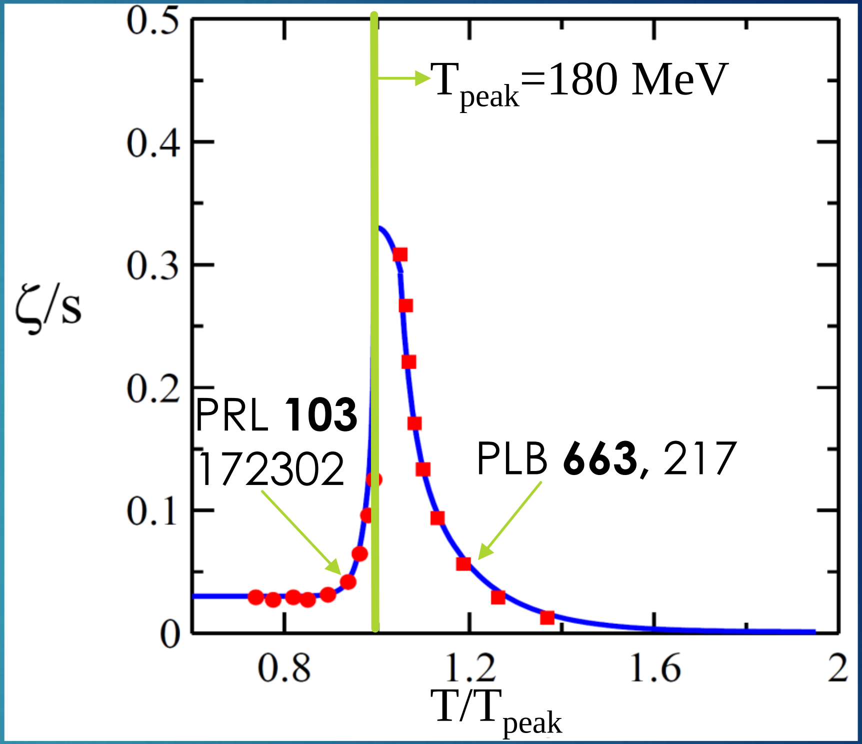
$$\partial_\mu T^{\mu\nu} = 0$$

$$T^{\mu\nu} = T_0^{\mu\nu} - \Pi\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$T_0^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu}$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu}$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \phi_7\pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$



T_{peak}=180 MeV

PRL **103** 172302

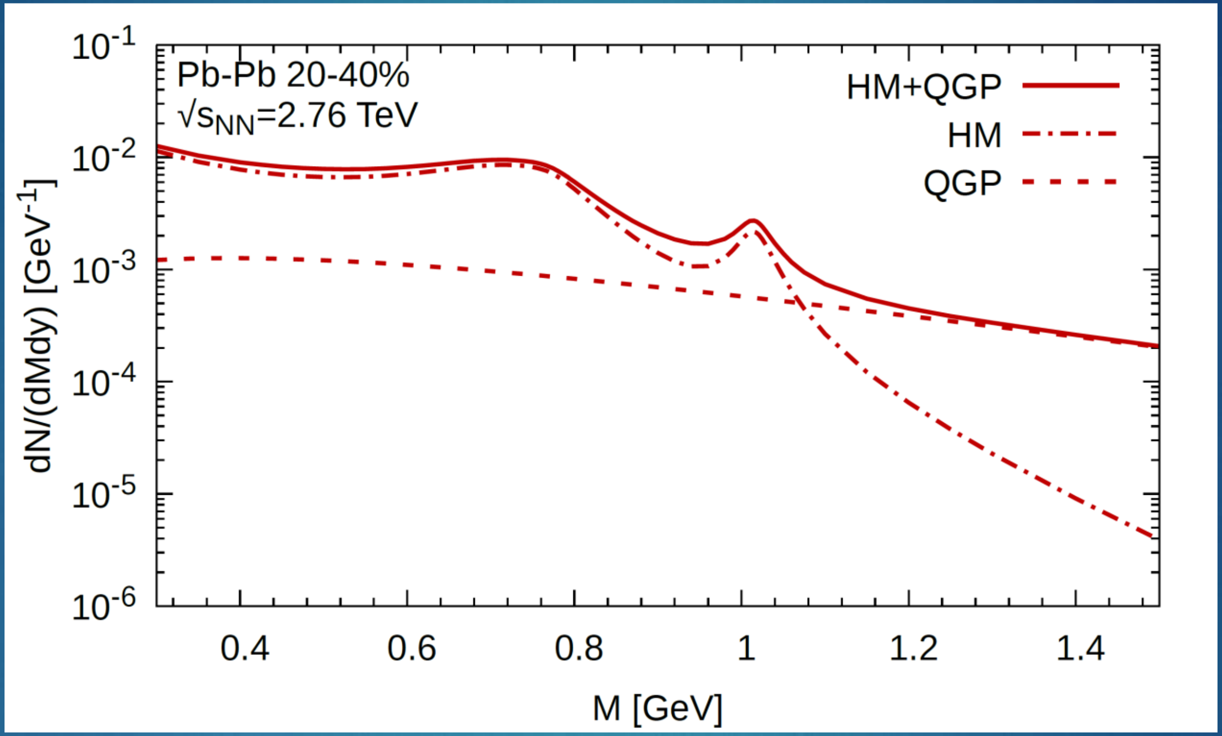
PLB **663**, 217

$\eta/s = constant$

- Other than ζ and η, all transport coefficients are in G.S. Denicol et al. PRD **85** 114047, PRC **90** 024912.
- $P(\varepsilon)$: Lattice QCD EoS [P. Huovinen & P. Petreczky, NPA **837**, 26]. (s95p-v1)

Dileptons and goal of this presentation

- Unlike photons, dileptons have an additional d.o.f. the invariant mass.



- Goal : Use the invariant mass distribution to investigate the influence bulk viscous pressure on thermal dileptons at RHIC and LHC.

Thermal dilepton rates from HM

- The rate involves:

$$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\frac{m_V^4}{g_V^2}\left\{-\frac{1}{3}\left[Im\; D_V^R\right]_\mu^\mu\right\} n_{BE}\left(\frac{q\cdot u}{T}\right)$$

- Self-Energy [Eletsky, et al., PRC **64**, 035202]

$$\Pi_{Va} = -\frac{m_a m_V T}{\pi q}\int\frac{d^3k}{(2\pi)^3}\frac{\sqrt{s}}{k^0} f_{Va}(s)\, n_a(x)\,; \quad where \quad x = \frac{u\cdot k}{T}$$

- Viscous extension to thermal distribution function

$$T_0^{\mu\nu} + \pi^{\mu\nu} - \Pi\Delta^{\mu\nu} = \int\frac{d^3k}{(2\pi)^3 k^0} k^\mu k^\nu\left[n_{a,0}(x) + \delta n_a^{shear}(x) + \delta n_a^{bulk}(x)\right]$$

$$\delta n_a^{shear} = n_{a,0}(x)\left[1 \pm n_{a,0}(x)\right]\frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2(\varepsilon + P)}$$

The usual 14-moment expansion of Boltzmann equation in the RTA limit, see e.g. PRC **68**, 034913

$$\delta n_a^{bulk} = -\frac{\Pi\left[\frac{z^2}{3x} - \left(\frac{1}{3} - c_s^2\right)x\right]}{15(\varepsilon + P)\left(\frac{1}{3} - c_s^2\right)^2} n_{a,0}(x)\left[1 \pm n_{a,0}(x)\right]; \quad where\ z = \frac{m}{T}$$

RTA limit of Boltzmann equation, see PRC **93**, 044906

- Therefore: $\Pi_{Va} \rightarrow \Pi_{Va}^{ideal} + \delta\Pi_{Va}^{shear} + \delta\Pi_{VA}^{bulk}$

Bulk viscous corrections: QGP rate

- The Born rate

$$\frac{d^4R}{d^4q} = \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3} n_q(x) n_{\bar{q}}(x) \sigma v_{12} \delta^4(q - k_1 - k_2); \quad where\ \ x = \frac{u \cdot k}{T}$$

- Shear viscous correction is obtained using the usual 14-moment expansion of the Boltzmann equation in the RTA limit.

- Bulk viscous correction derived from a generalized Boltzmann equation, which includes thermal quark masses (m) [PRD **53**, 5799]

$$k^\mu \partial_\mu n \ - \frac{1}{2}\frac{\partial(m^2)}{\partial \boldsymbol{x}} \cdot \frac{\partial n}{\partial \boldsymbol{k}} = C[n]$$

- In the RTA approximation with α_s a constant [PRC **93**, 044906]

$$\delta n_q^{bulk} = -\frac{\Pi\left[\frac{z^2}{x} - x\right]}{15(\varepsilon + P)\left(\frac{1}{3} - c_s^2\right)} n_{FD}(x)[1 - n_{FD}(x)]; \quad where\ z = \frac{m}{T}$$

- Therefore: $\dfrac{d^4R}{d^4q} = \dfrac{d^4R^{ideal}}{d^4q} + \dfrac{d^4\delta R^{shear}}{d^4q} + \dfrac{d^4\delta R^{bulk}}{d^4q}$

Dilepton Cocktail

- For $0.3 < M < 1\,GeV$, sources of cocktail dileptons considered here are originating from $\eta, \eta', \omega, \phi$ mesons.

- Dileptons originate from Dalitz decays $\eta, \eta' \to \gamma \ell^+ \ell^-$, $\omega \to \pi^0 \ell^+ \ell^-$ and $\phi \to \eta \ell^+ \ell^-$ as well as direct decays $\omega, \phi \to \ell^+ \ell^-$.

- Using the Vector Dominance Model (VDM), the dynamics of these decays has been computed in Phys. Rept. **128**, 301.

- Note that the ρ meson is not included in the cocktail (yet!) as this is a broad resonance and its width needs to be carefully included when computing cocktail momentum distribution.

Dilepton Cocktail

- The goal here to obtain the final hadronic distribution of $\eta, \eta', \omega, \phi$ to be decayed into dileptons. Two methods will be used:
    1. *Direct hadron production from hydrodynamic simulation (Cooper-Frye prescription including only hadronic resonance decays)*
    2. *Note that Cooper-Frye prescription needs to be modified in order to take into account the width of the ρ meson. This will be done in the future.*
    3. *Hadrons produced after UrQMD*

- Note that there is no dynamical generation of dileptons during UrQMD evolution.
- UrQMD is only used to improve the momentum distribution of mesons (notably by capturing hadronic collisions).

Anisotropic flow

- Flow coefficients

$$\frac{dN}{dMp_T dp_T d\phi dy} = \frac{1}{2\pi} \frac{dN}{dMp_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos(n\phi - n\Psi_n)\right]$$

- Three important notes:

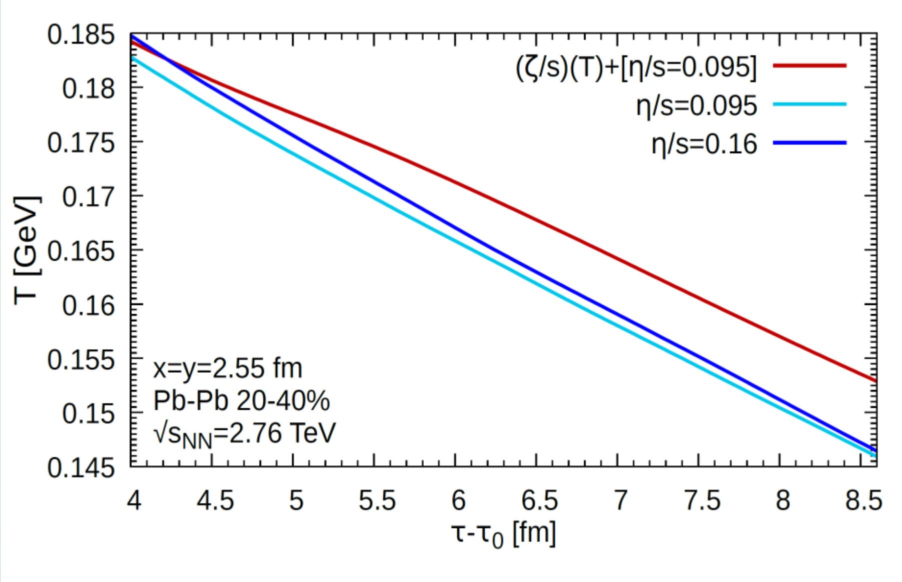
1. Within an event: v_n's are a yield weighted average of the different sources (e.g. HM, QGP, …).
2. The switch between HM and QGP rates we are using a linear interpolation, in the region $184\ MeV < T < 220 MeV$, given by the EoS [NPA **837**, 26]
3. Averaging over events: the flow coefficients (v_n) are computed via

$$v_n\{SP\} = \frac{\left\langle v_n^{\gamma^*} v_n^h \cos\left[n\left(\Psi_n^{\gamma^*} - \Psi_n^h\right)\right]\right\rangle}{\left\langle \left(v_n^h\right)^2 \right\rangle^{1/2}}$$

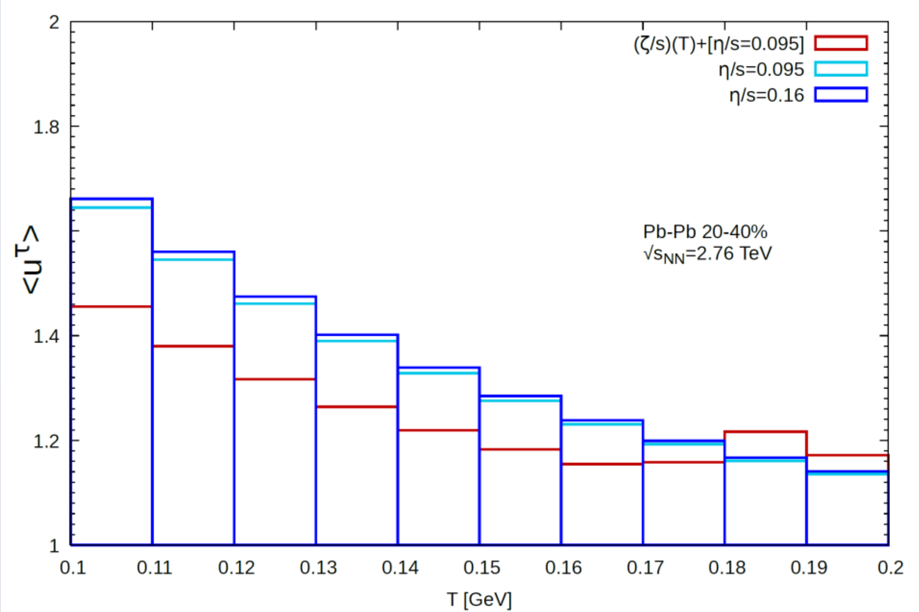
Paquet et al., PRC **93**, 044906
Vujanovic et al., PRC **94,** 014904

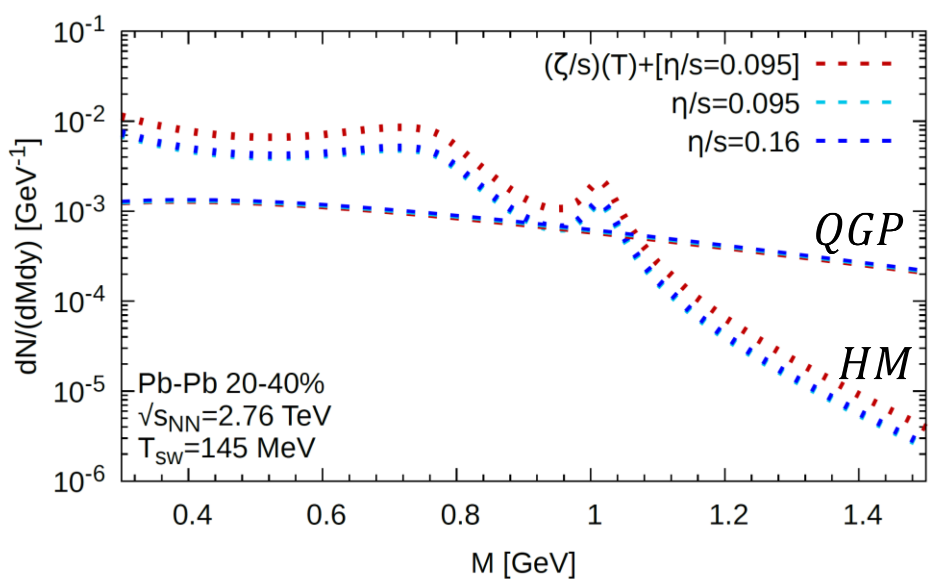
- Lastly, the temperature at which hydrodynamics (or thermal) dilepton radiation are stopped is $T_{switch} = 145$ MeV at LHC, while at RHIC $T_{switch} = 165$ MeV. Cocktail dileptons follow.

Bulk viscosity and dilepton yield at LHC

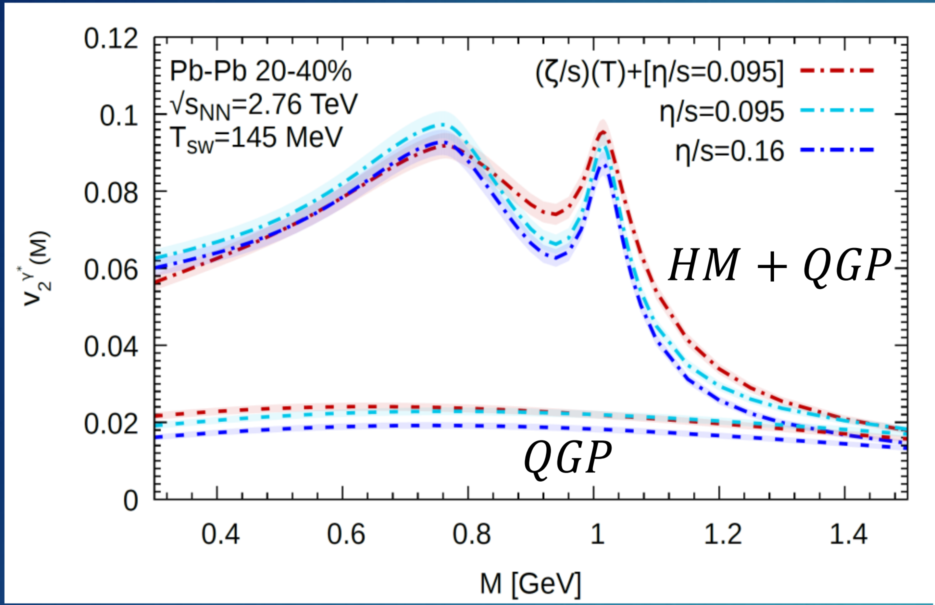


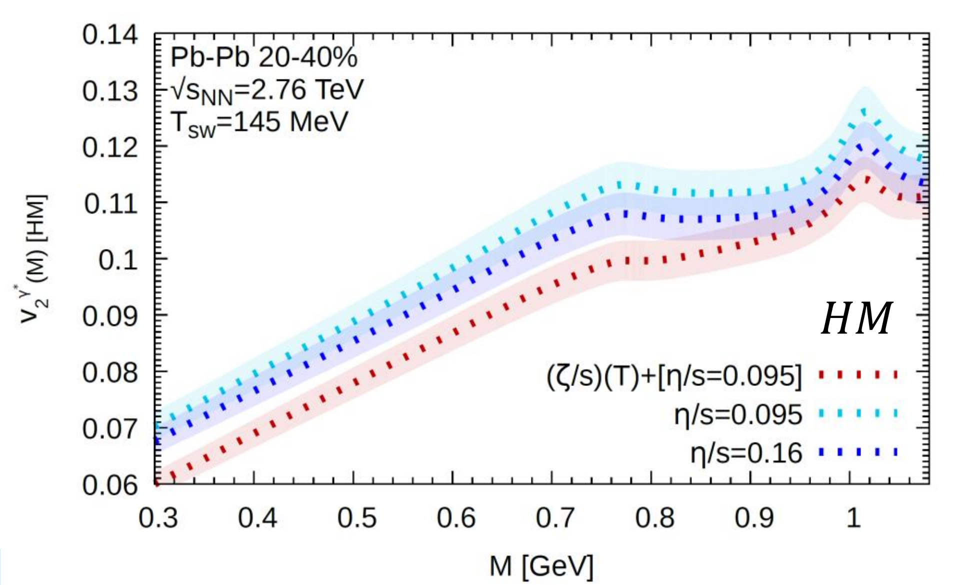
- Bulk viscosity reduces the cooldown rate of the medium, by viscous heating and also via reduction of radial flow acceleration at late times.
- Dilepton yield is increased in the HM sector, since for $T < 184\ MeV$ purely HM rates are used.



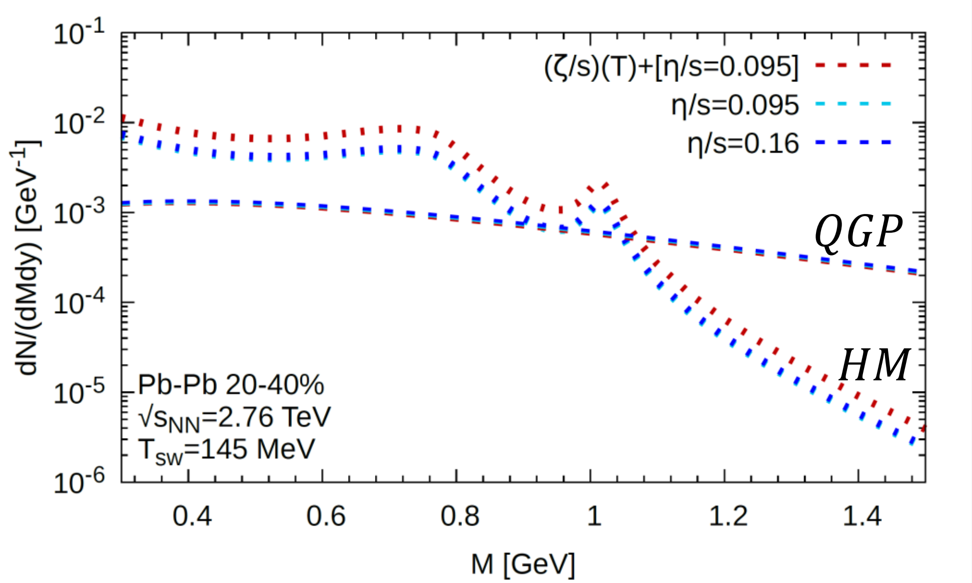


Bulk viscosity and dileptons at LHC





- The effects of bulk viscosity on thermal $v_2(M)$ are quite intricate…



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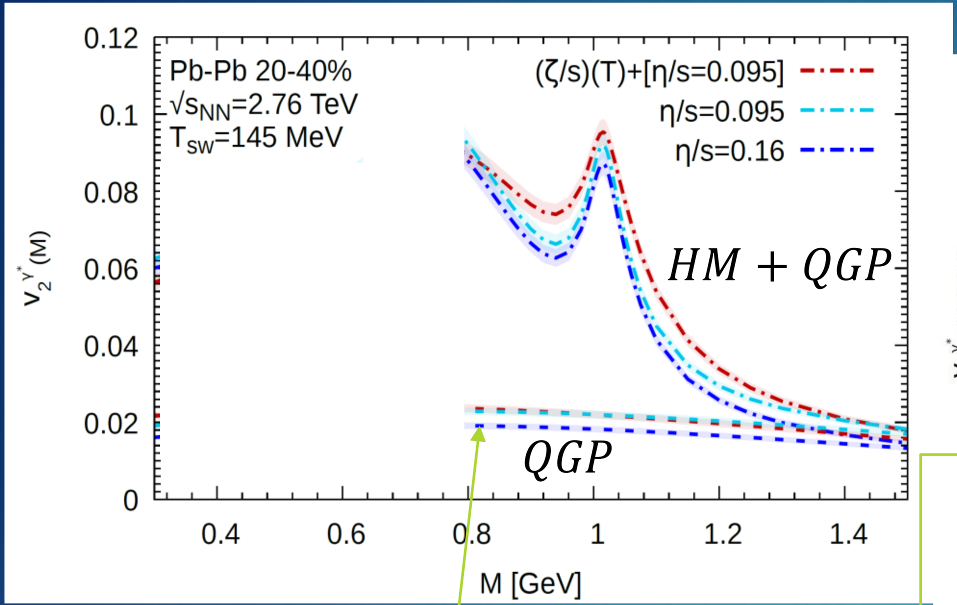
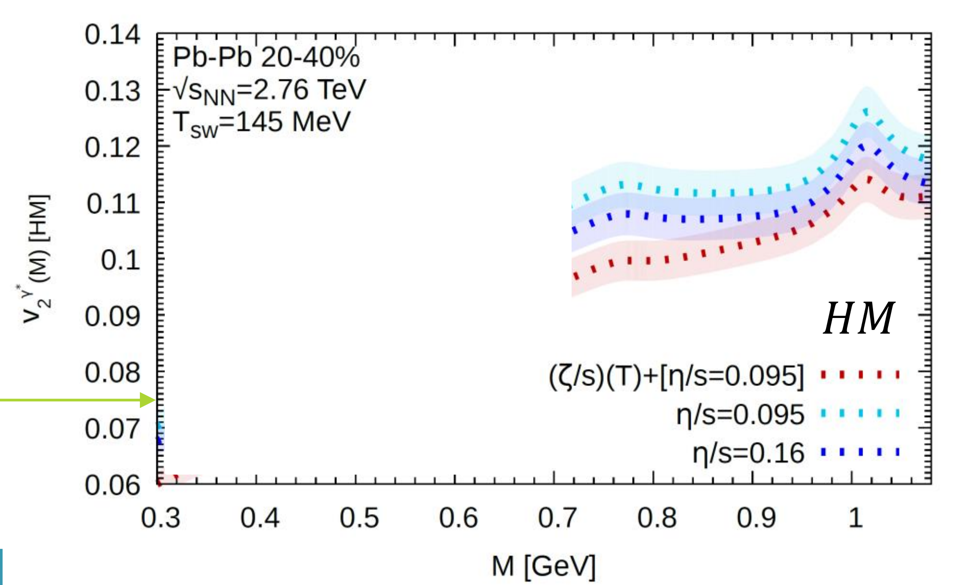
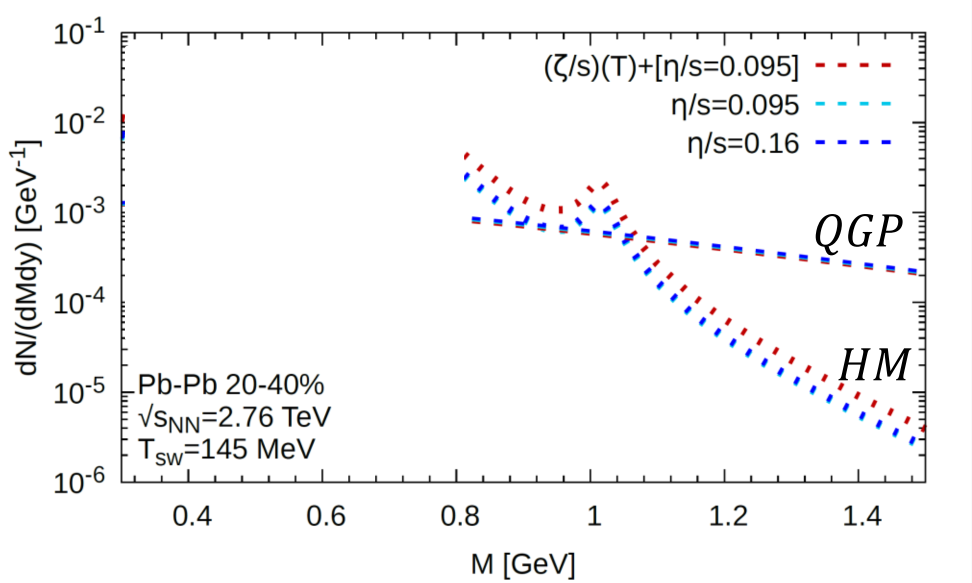
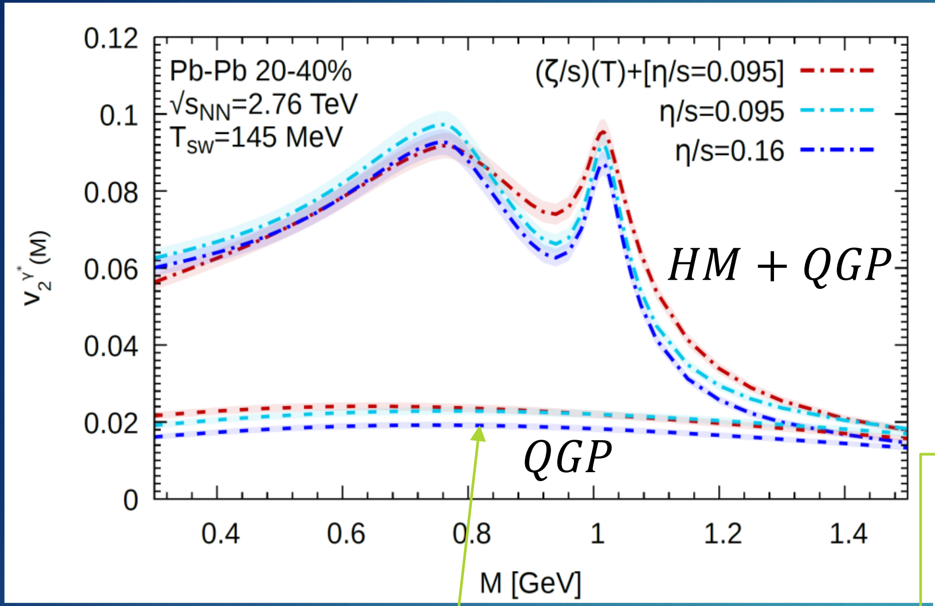


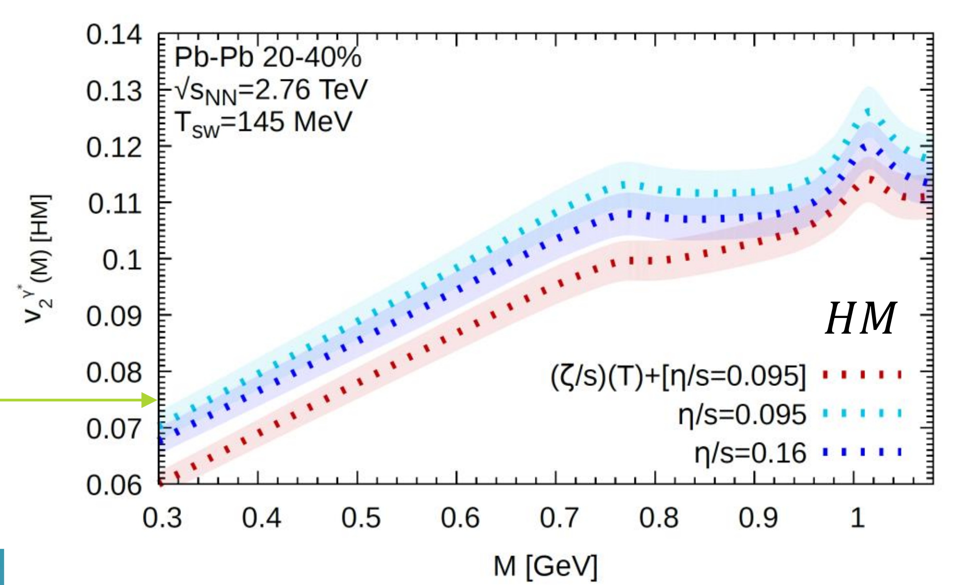


- Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:
  - $M > 0.8\ GeV$: the yield goes from being HM dominated to being QGP dominated. Though, ζ does $\downarrow v_2^{HM}(M)$, it also increases HM yield and $\therefore$ weight to $v_2^{HM}(M)$. So, thermal $v_2(M) \uparrow$.

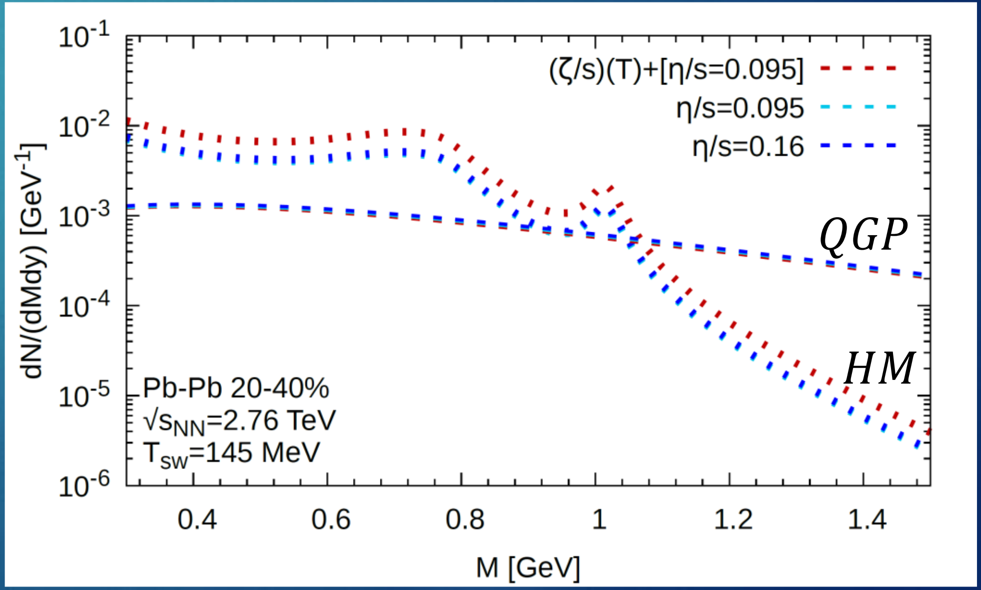


Bulk viscosity and dileptons at LHC

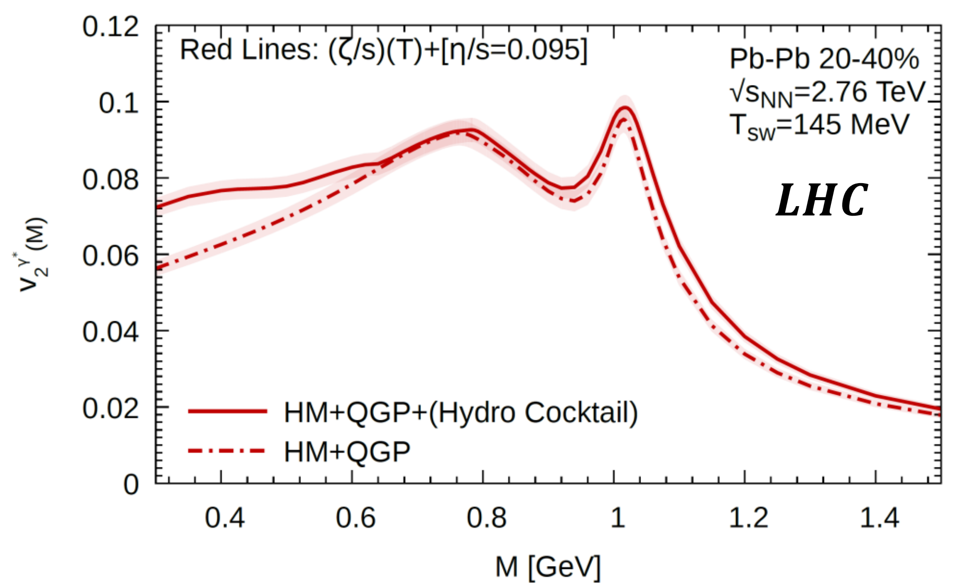


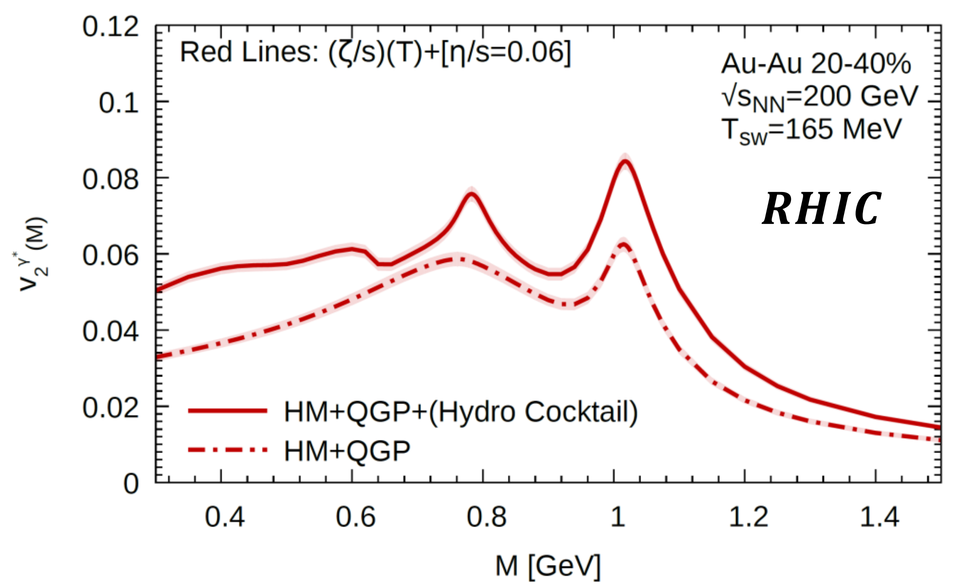


- Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:
  - $M > 0.8\ GeV$: the yield goes from being HM dominated to being QGP dominated. Though, ζ does $\downarrow v_2^{HM}(M)$, it also increases HM yield and $\therefore$ weight to $v_2^{HM}(M)$. So, thermal $v_2(M)\uparrow$.
  - $M < 0.8\ GeV$: HM yield dominates. There are cancellation between ↑ HM yield owing to ζ and $\downarrow v_2^{HM}(\mathrm{M})$.



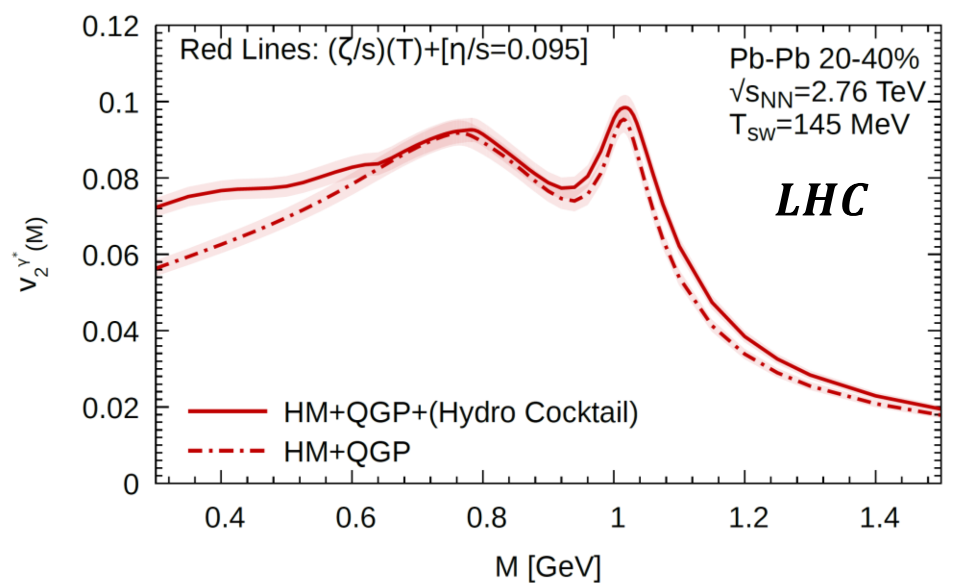
Thermal + Cocktail dileptons: LHC/RHIC

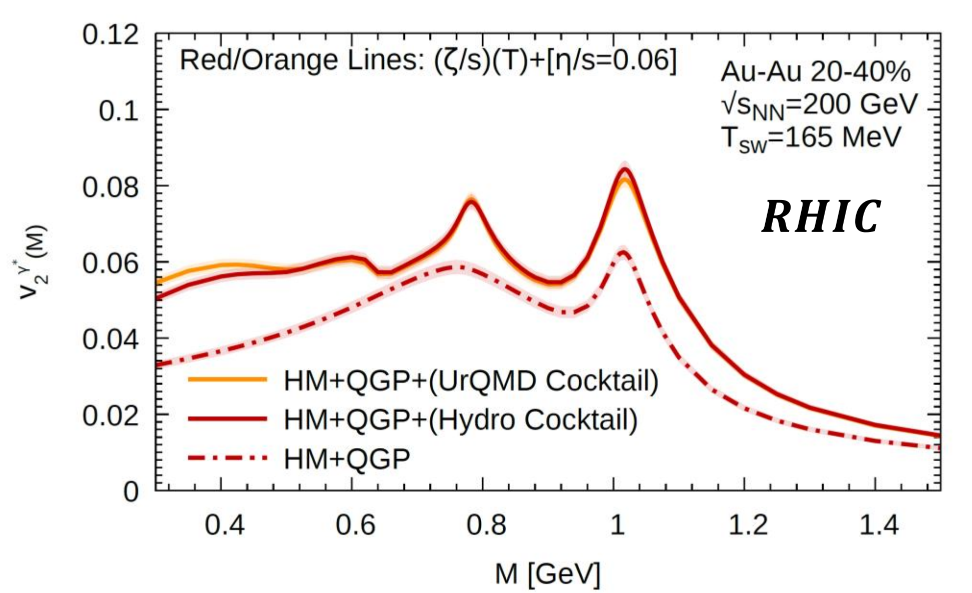




- At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65\ GeV$.
- At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant.

Thermal + Cocktail dileptons: LHC/RHIC

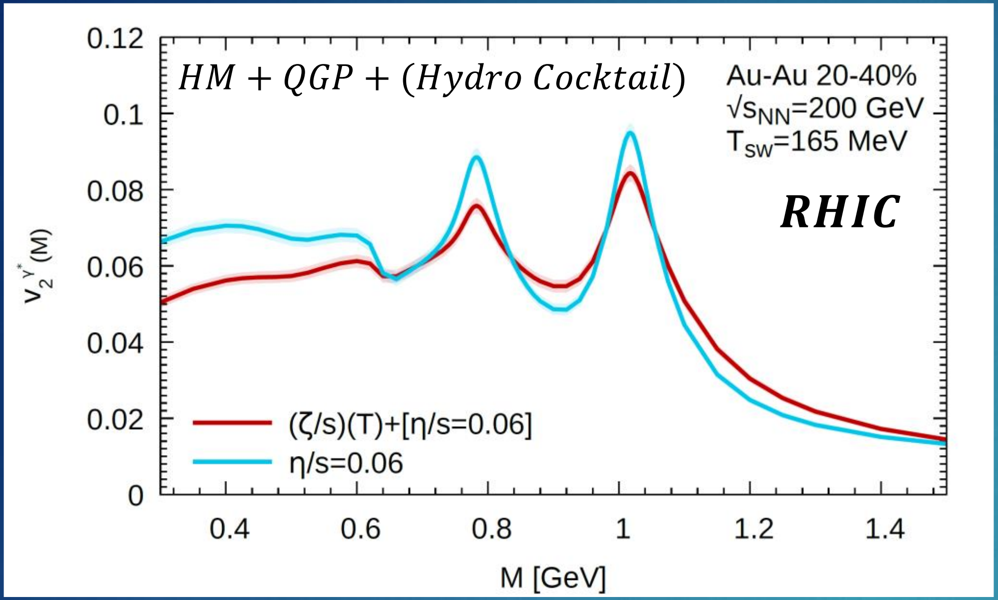


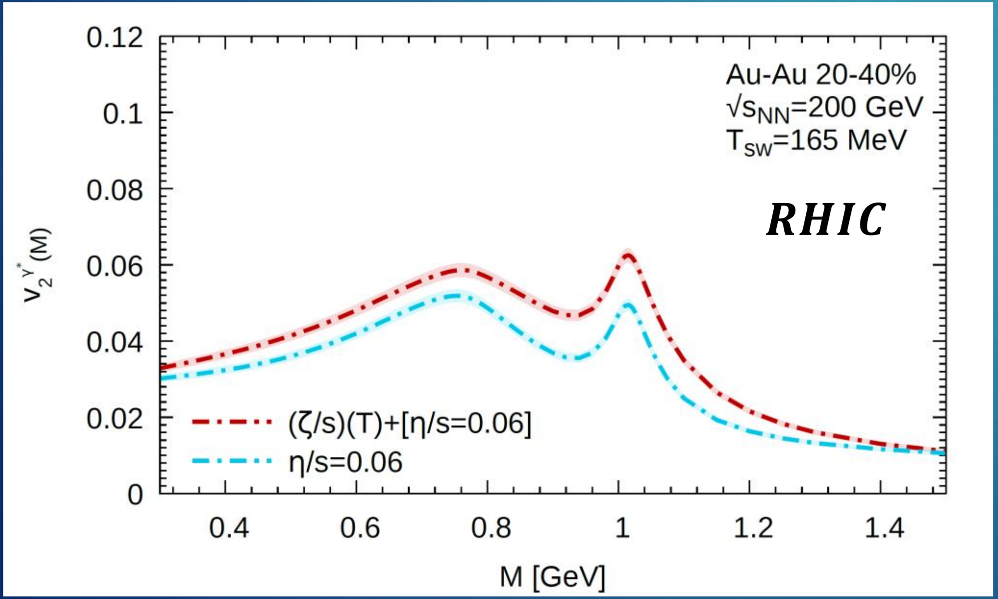


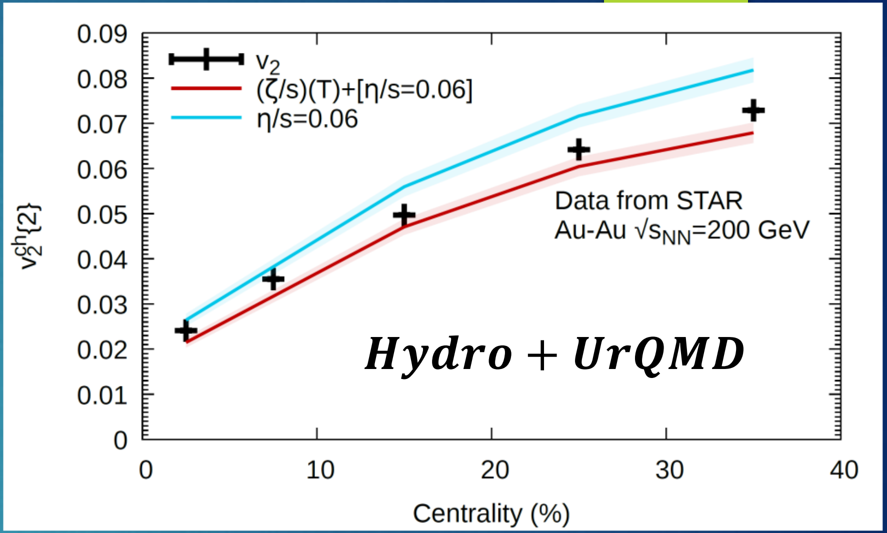
- At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65\ GeV$.

- At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant. However, the method employed to obtain the cocktail (e.g. Hydro vs UrQMD) is less important.

Thermal + Cocktail dileptons at RHIC

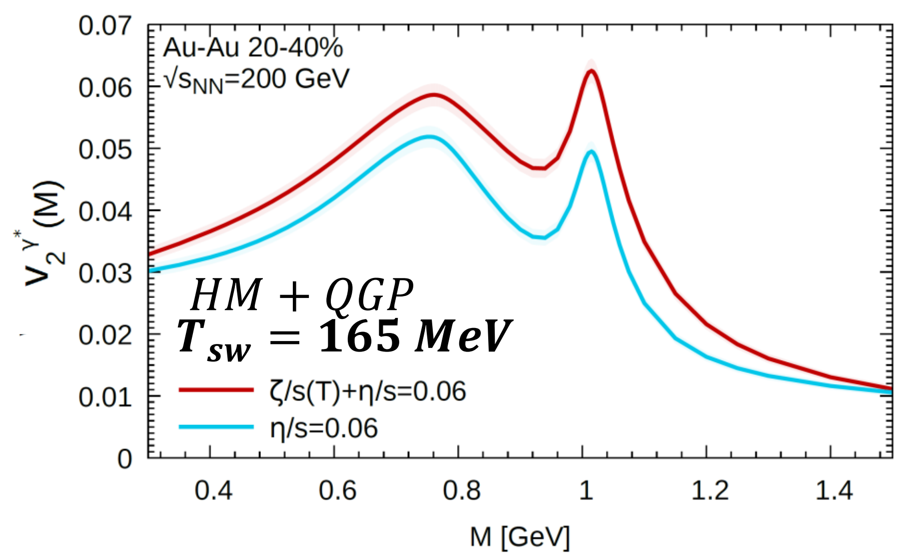


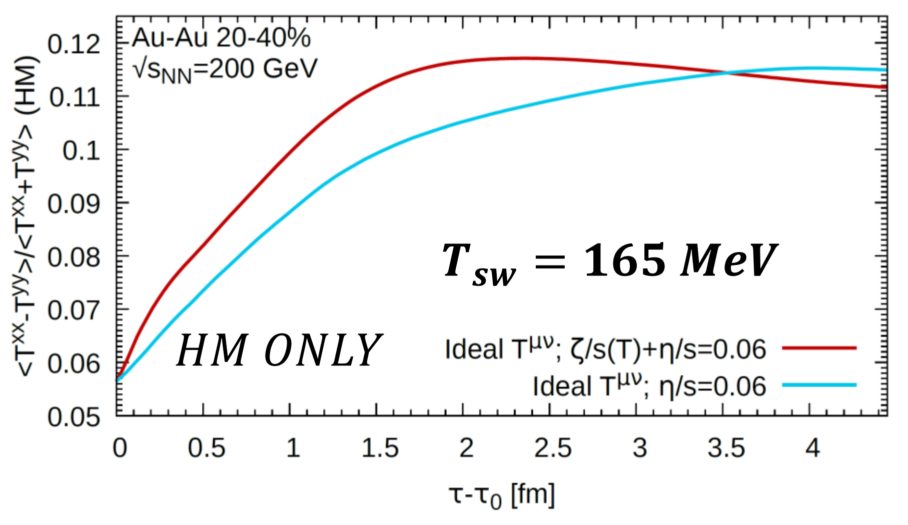




- Comparing the behaviour of dilepton $v_2(M)$ and charged hadron $v_2^{ch}\{2\}$, one notices that the ordering of the curves is the same, except in for $M \sim 0.7\, GeV, M \sim 0.9\, GeV$ and $M > 1.1\, GeV$.
- Thermal radiation contributes significantly in those M regions, and bulk viscosity ↑ $v_2(M)$.

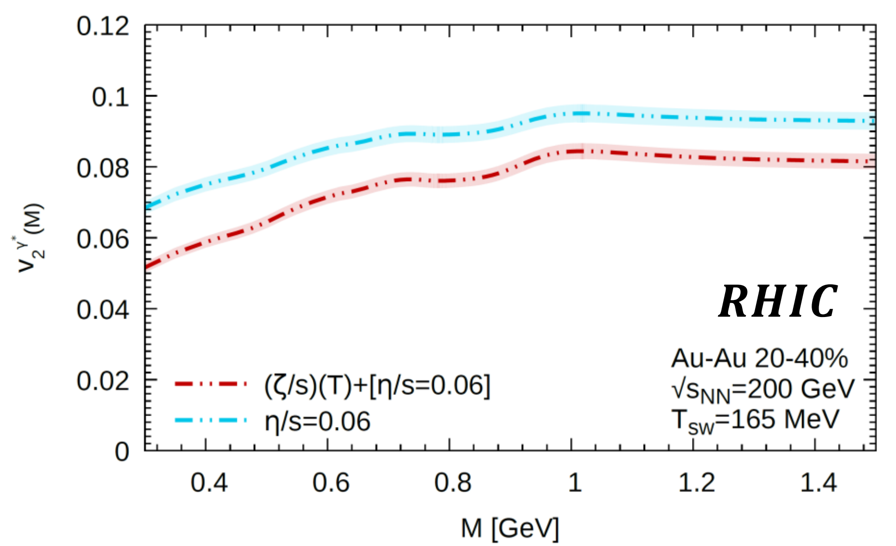
Bulk viscosity and dileptons at RHIC

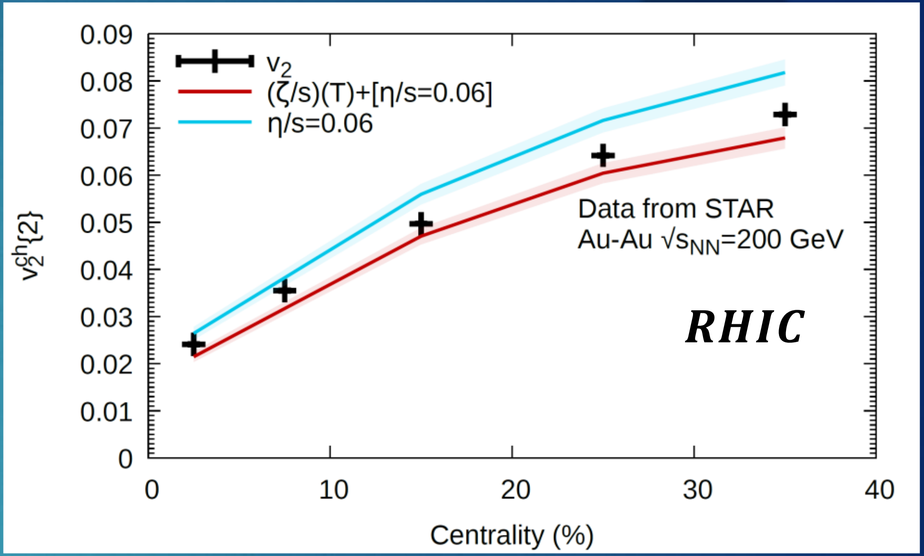




- The increase in anisotropic flow build-up, can also be seen via the hydrodynamic momentum anisotropy $\varepsilon_P = \frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle}$
- $\langle T^{xx} \pm T^{yy}\rangle \equiv$
$$\equiv \frac{1}{N_{events}} \sum_{i}^{N_{events}} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp \left(T_i^{xx} \pm T_i^{yy}\right)$$
where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp$ integrates over a space-time region in HM.
- Hadrons emitted at late time are sensitive to ε_P at late times. Dileptons are emitted throughout the entire evolution and therefore are picking up the entire evolution history of ε_P.

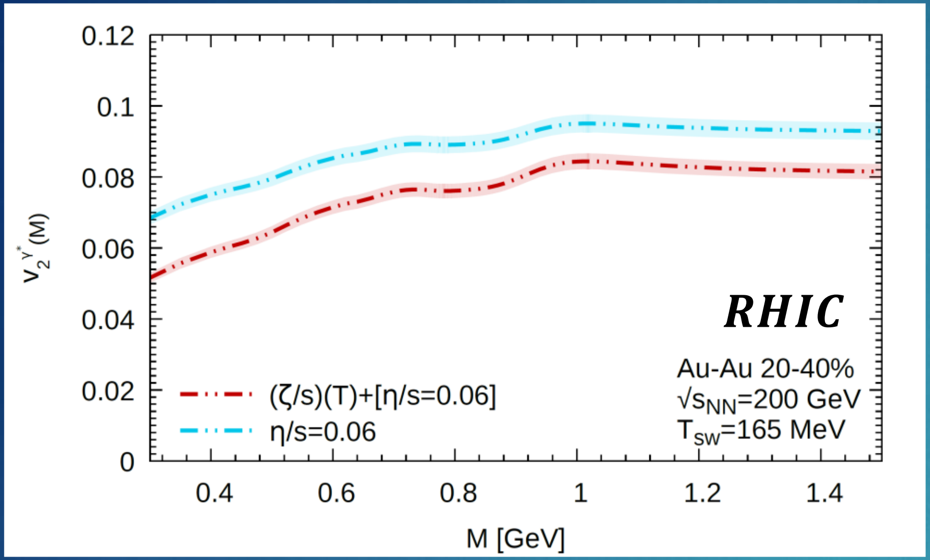
Bulk viscosity and dileptons at RHIC

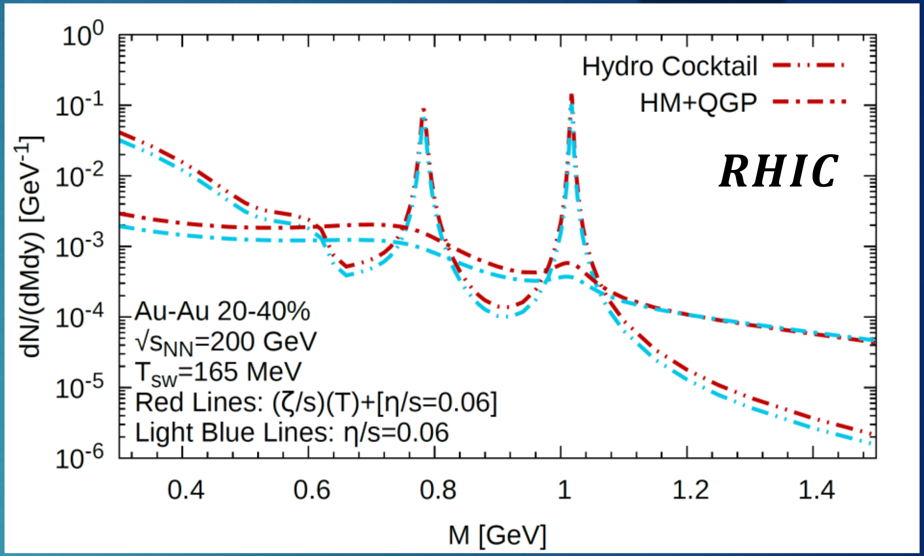


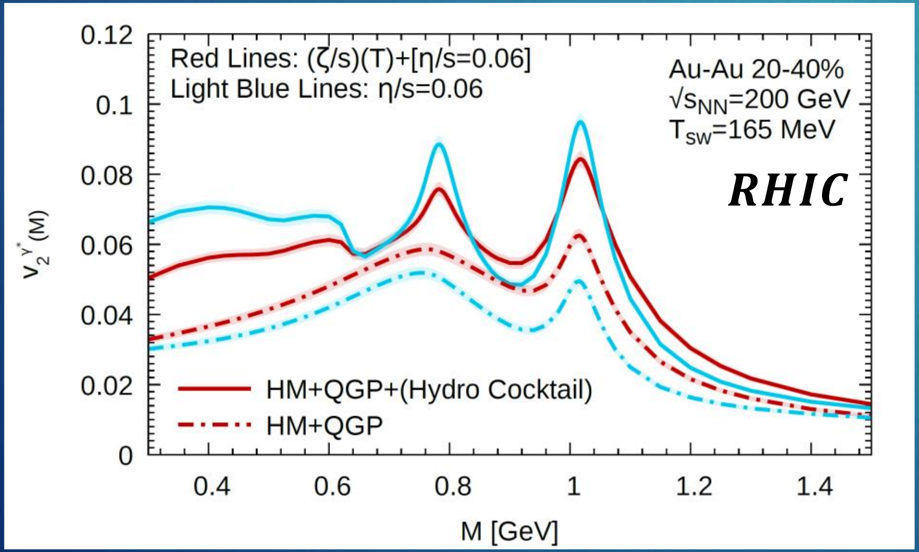


- The $v_2(M)$ of dileptons from the cocktail, which are emitted at late times, behaves similarly to the $v_2^{ch}\{2\}$ charged hadron.

Bulk viscosity and dileptons at RHIC







- The $v_2(M)$ of dileptons from the cocktail, which are emitted at late times, behaves similarly to the $v_2^{ch}\{2\}$ charged hadron.
- The interplay between the thermal and cocktail yields generates the final $v_2(M)$.

Conclusions

- Starting from IP-Glasma initial conditions for the hydro evolution, a first thermal and cocktail dilepton calculation was performed, with bulk viscosity in the hydro evolution, both at RHIC and LHC energies.

- Bulk viscosity increases the yield of thermal dileptons owing to viscous heating and reduction in radial flow acceleration at later times.

- The presence of the dilepton cocktail is more important for the total $v_2(M)$ at top RHIC energy, than at collision LHC energy.

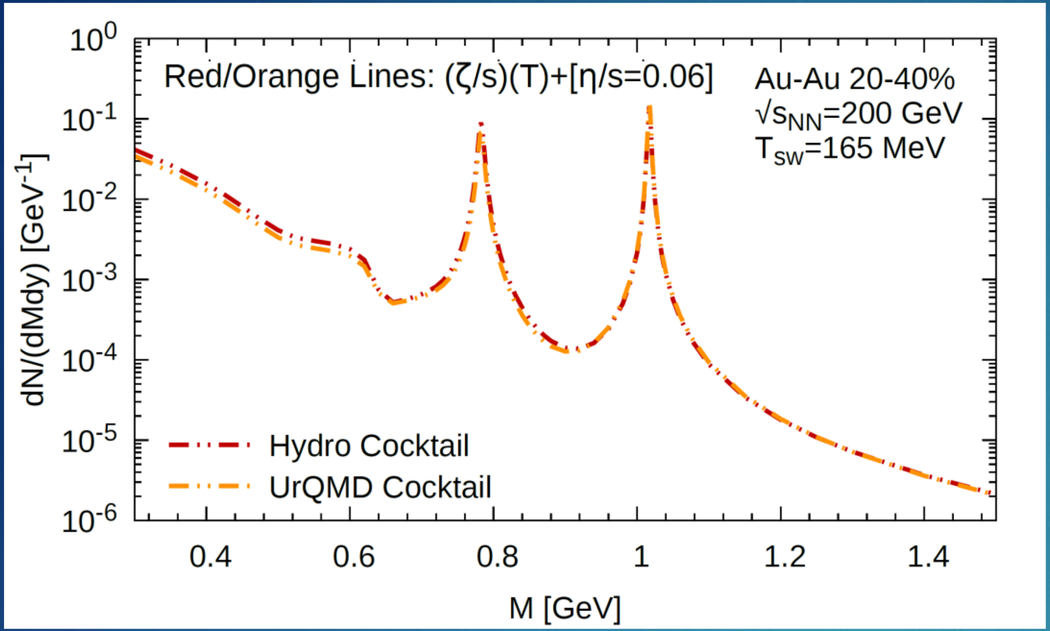
- Though bulk viscosity does generate interesting dynamics at RHIC, which are reflected in the thermal dilepton $v_2(M)$, the dilepton cocktail masks part of these dynamics.

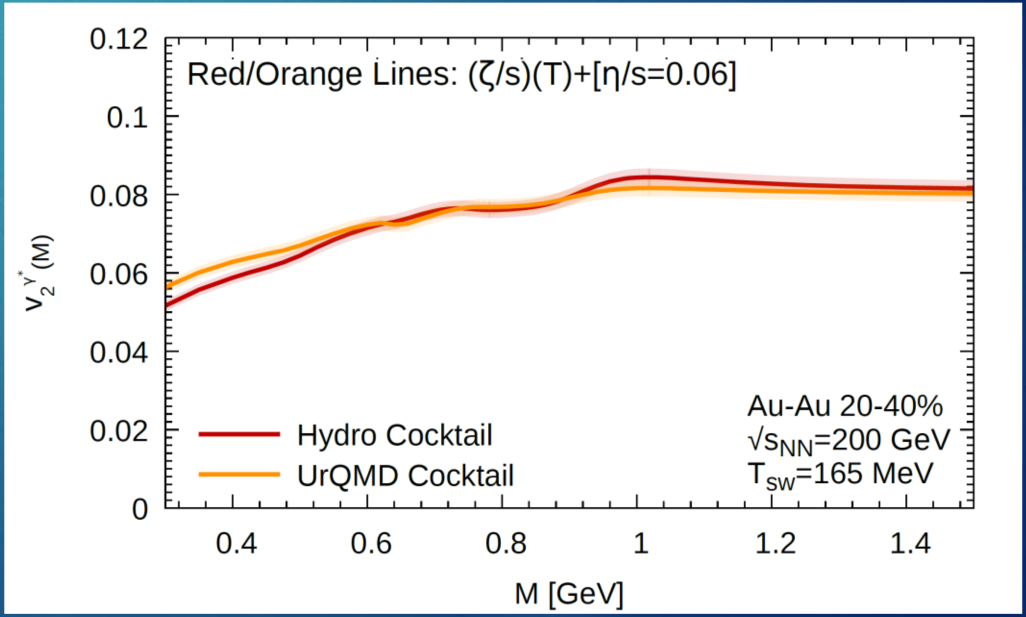
Outlook

- Investigate the dynamics of elastic vs inelastic collisions in a (hadronic) transport model that includes dynamical dilepton radiation (i.e. SMASH), and study their effects on dilepton $v_2(M)$.
- Include semi-leptonic decays of open charm hadrons in the low to intermediate mass range, so that comparison with dilepton data can be made.

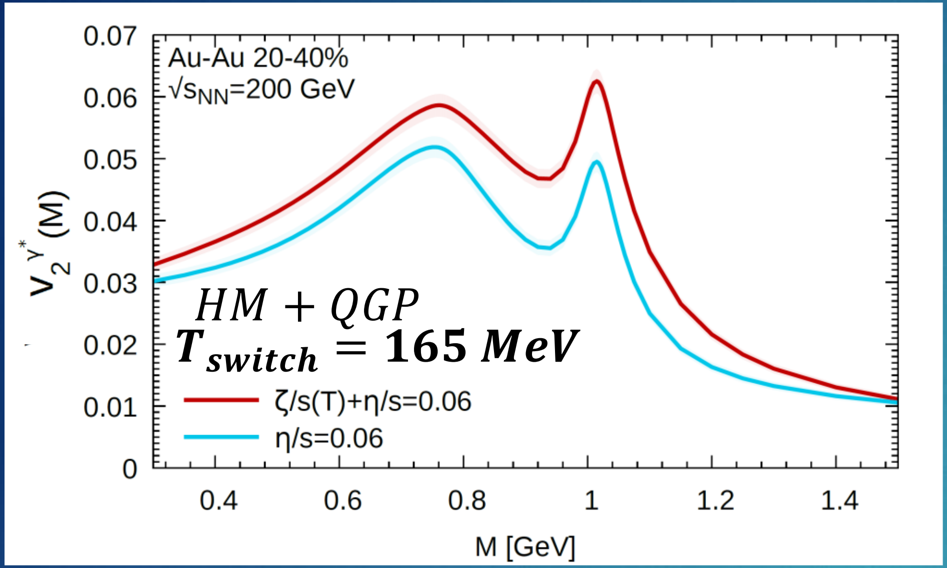
Backup Slides

Cocktail: Hydro vs UrQMD at RHIC



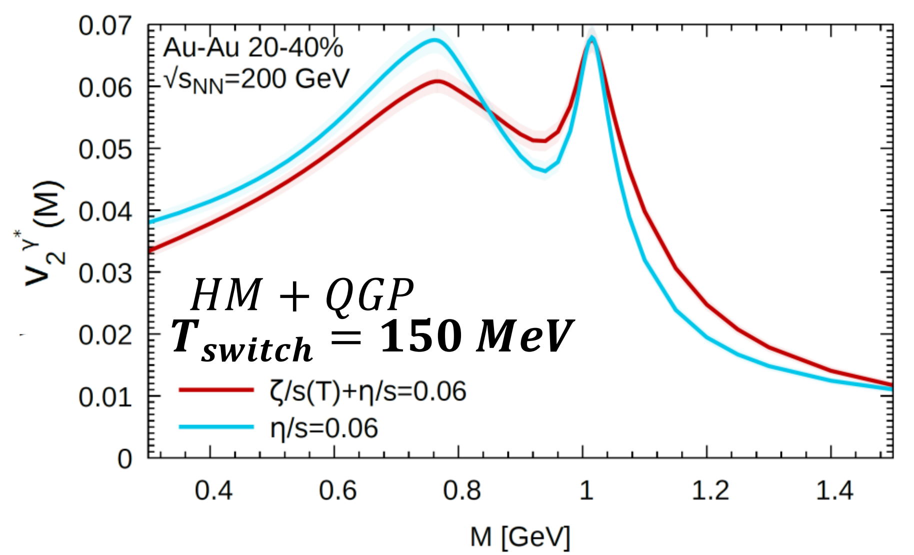


Bulk viscosity and dileptons at RHIC



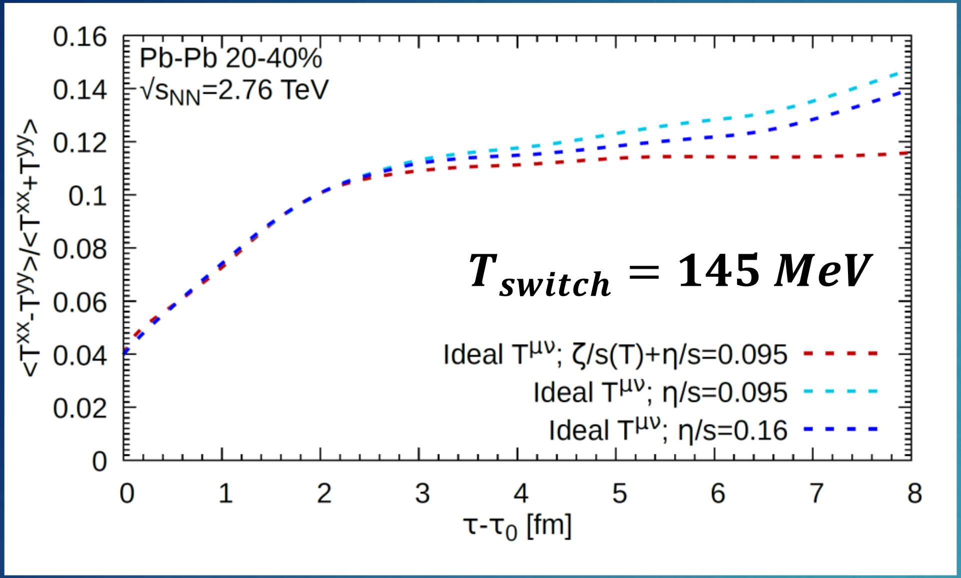
- As mentioned, the ↑ $v_2(M)$ with bulk viscosity is influenced by switching temperature.

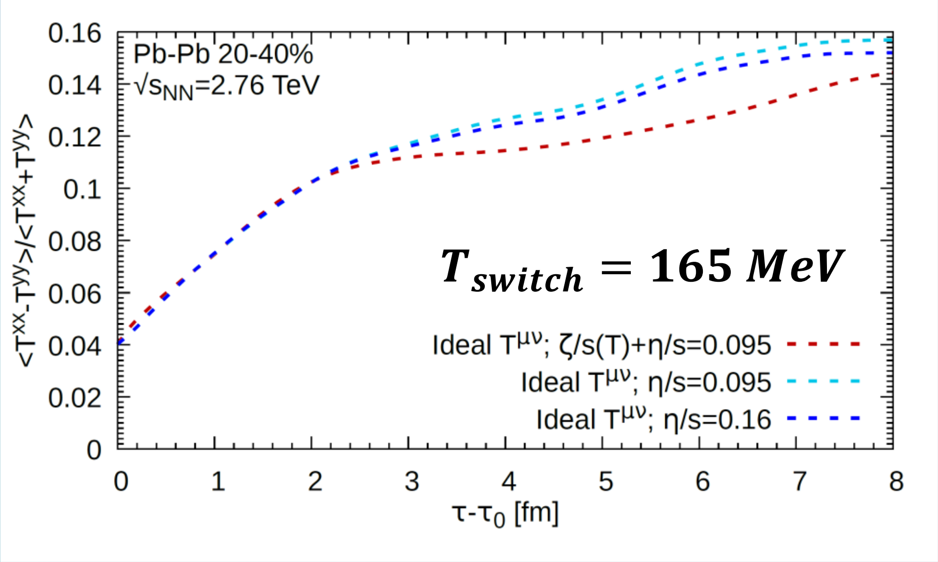
Bulk viscosity and dileptons at RHIC

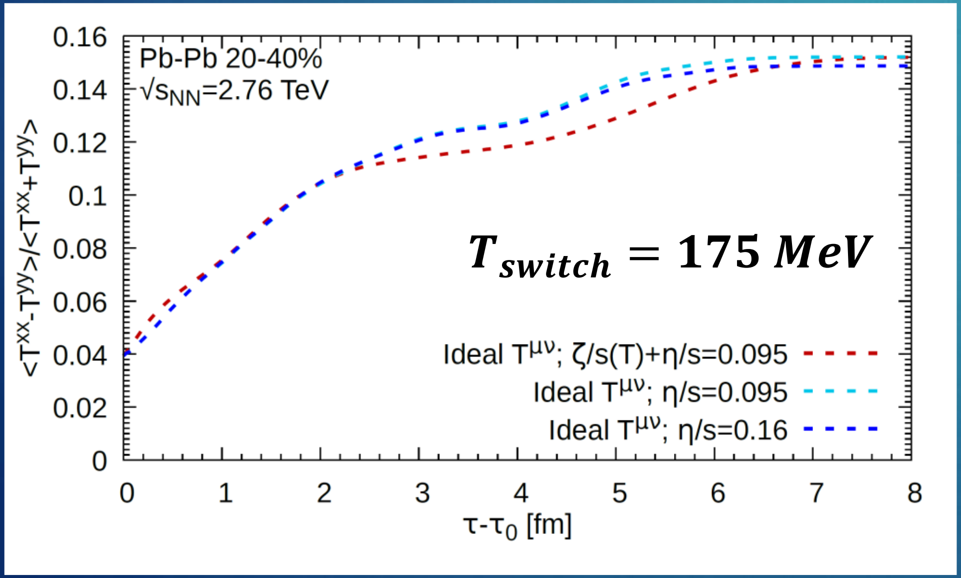


- As mentioned, the ↑ $v_2(M)$ with bulk viscosity is influenced by switching temperature.
- Indeed, running the hydrodynamical evolution until $\boldsymbol{T_{switch} = 150\ MeV}$, the effect is reduced, but is still present in the $M \sim 0.9\ GeV$ & $M > 1.1\ GeV$ regions.

$\frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}$ evolution at LHC with different T_{switch}

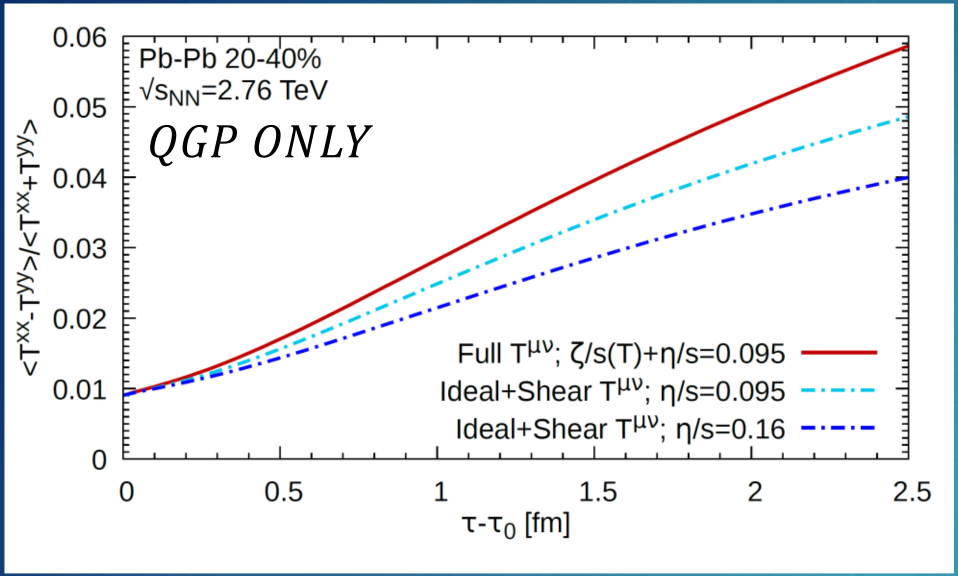






- $\frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \equiv \frac{\sum_i \int d^2 x_\perp \left(T_i^{xx} - T_i^{yy}\right)}{\sum_i \int d^2 x_\perp \left(T_i^{xx} + T_i^{yy}\right)}$ where the $\int d^2 x_\perp$ integrates only the **HM** phase with $T > 145$ MeV, $T > 165$ MeV, and $T > 175$ MeV.

Bulk viscosity and QGP v_2 at LHC

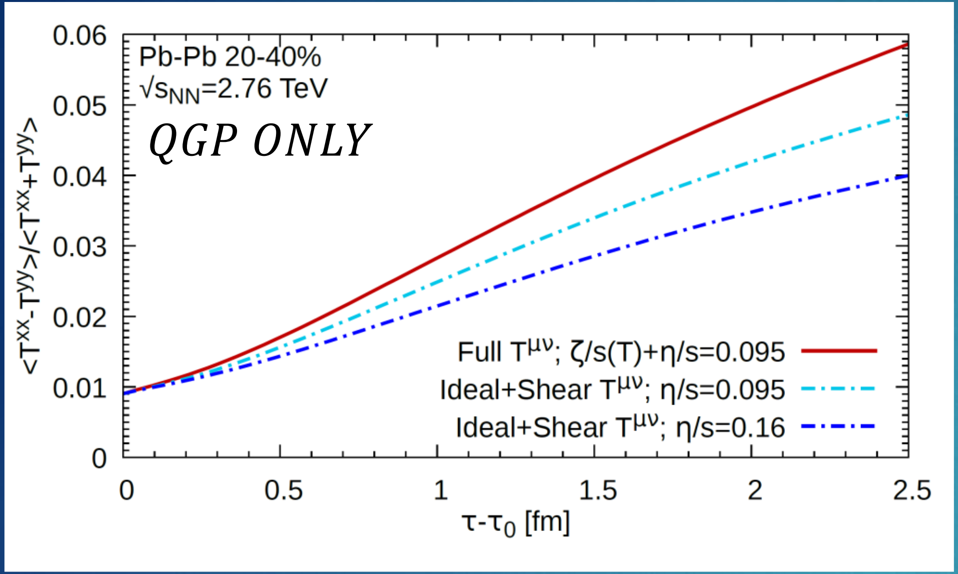


- $\langle T^{xx} \pm T^{yy} \rangle \equiv$

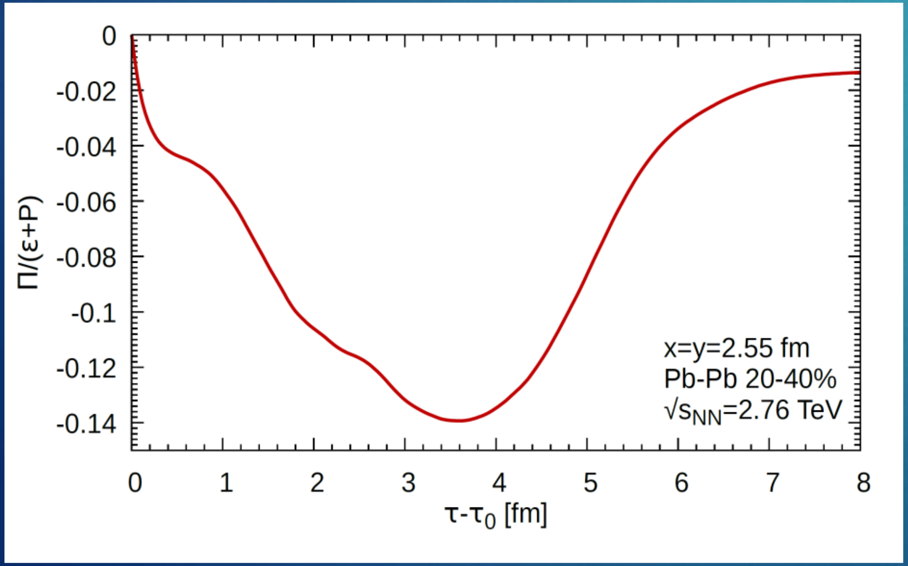
  $$\equiv \frac{1}{N_{events}} \sum_{i}^{N_{events}} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp \left(T_i^{xx} \pm T_i^{yy}\right)$$

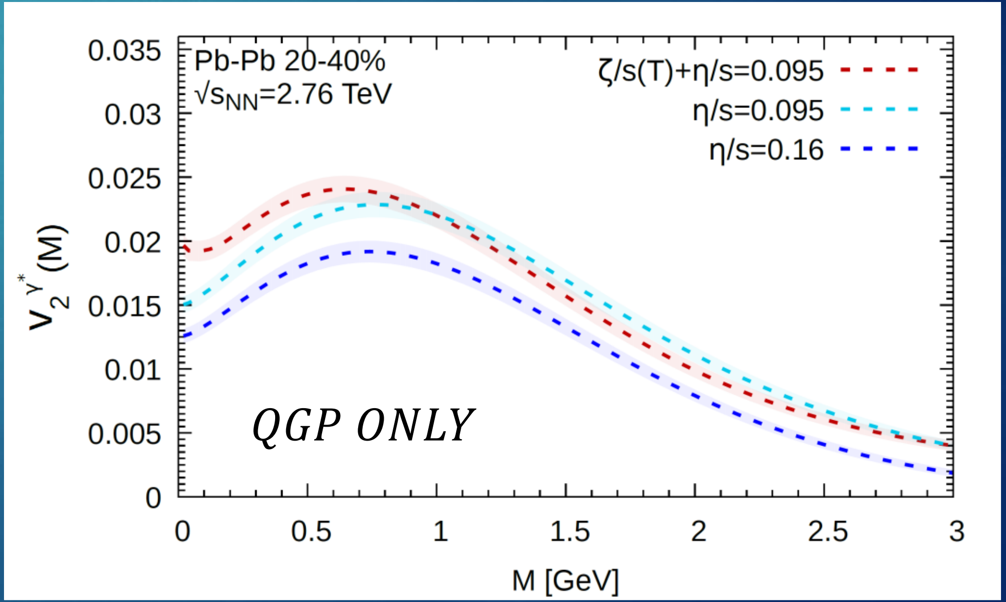
  where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ integrates only over the **QGP** phase.

$$\delta n_a^{bulk} = -\frac{\Pi\left[\frac{z^2}{3}\frac{1}{x} - \left(\frac{1}{3}-c_s^2\right)x\right]}{15(\varepsilon+P)\left(\frac{1}{3}-c_s^2\right)^2}\, n_{a,0}(x)\left[1\pm n_{a,0}(x)\right];\ z=\frac{m}{T};\ x=\frac{u\cdot k}{T}$$



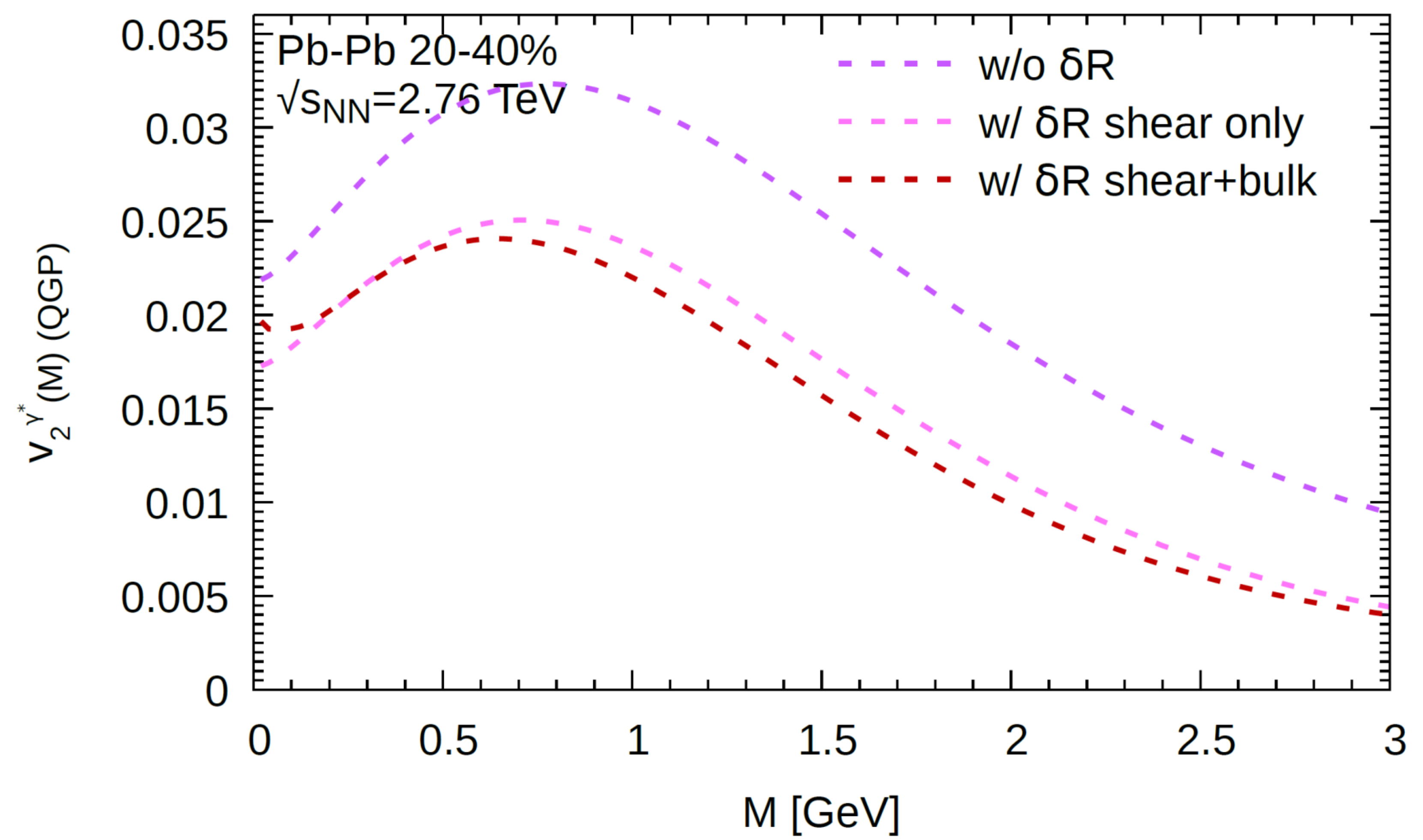
- $\delta n^{bulk} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP v_2, as $\frac{\Pi}{\varepsilon+P}$ doesn't change sign.



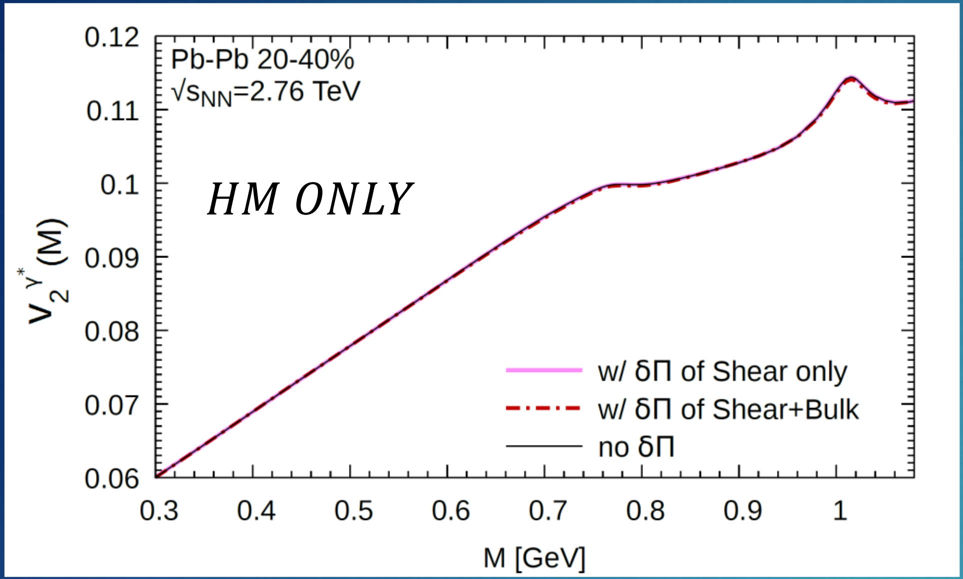


Viscous correction in the QGP

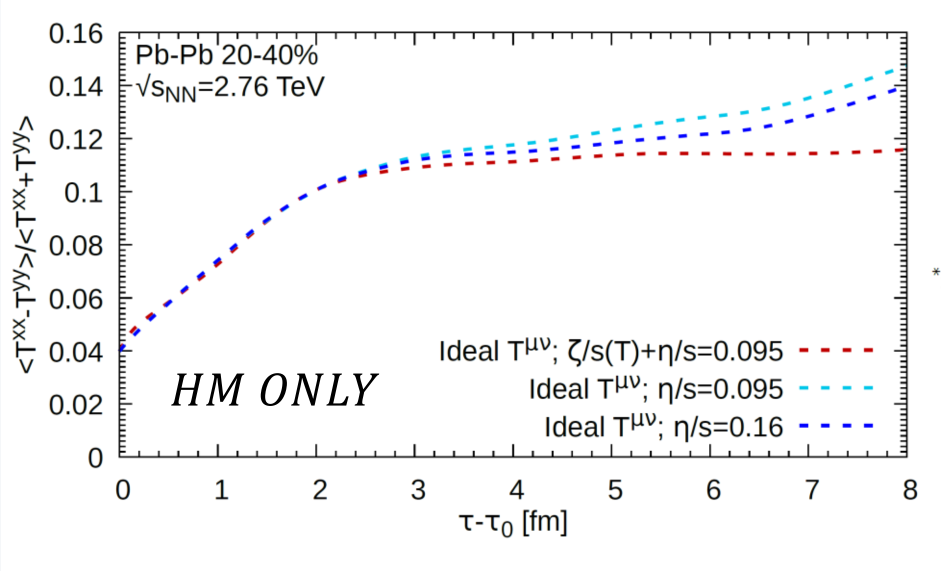
- Effects of viscous corrections on the QGP $v_2(M)$

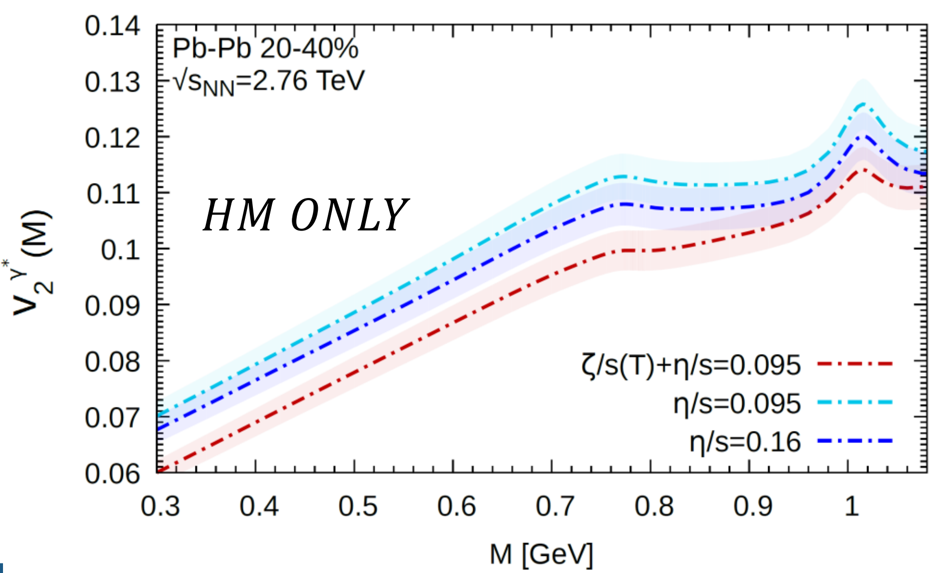


Bulk viscosity and HM v_2 at LHC



- However, HM dileptons are modestly affected by δn effects.
- v_2^{HM} is only affected by flow anisotropy.
- Where $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ in $\langle T^{xx} \pm T^{yy} \rangle$ integrates only over the **HM** region.





NLO QGP dilepton results

- Some diagrams contributing at LO & NLO