Dilepton radiation and bulk viscosity in heavy-ion collisions

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Hard Probes 2016

Wuhan, Hubei, China
September 24th 2016

Fonds de recherche
sur la nature
et les technologies
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Outline

Part I: Modelling of the QCD Medium

- Viscous hydrodynamics

Part II: Thermal Sources of Dileptons

- QGP Rate (w/ dissipative corrections)
- Hadronic Medium Rates (w/ dissipative corrections)

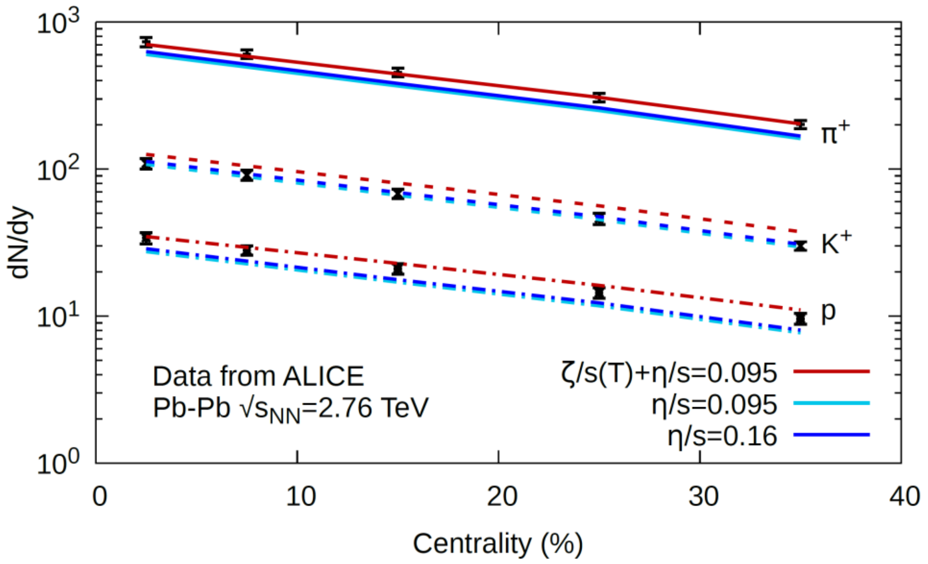
Part III: Dileptons & Dissipative Evolution

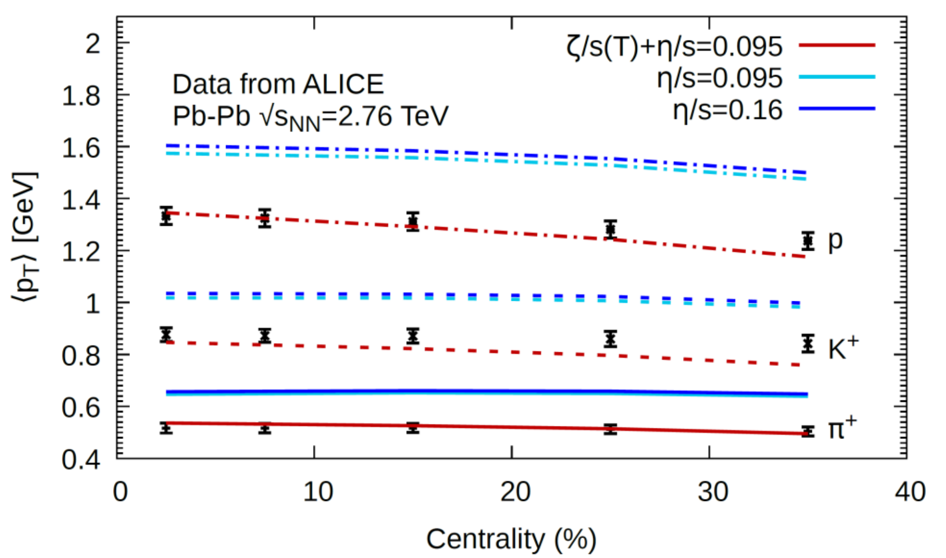
- Effects of bulk viscous pressure on dilepton yield and v_n

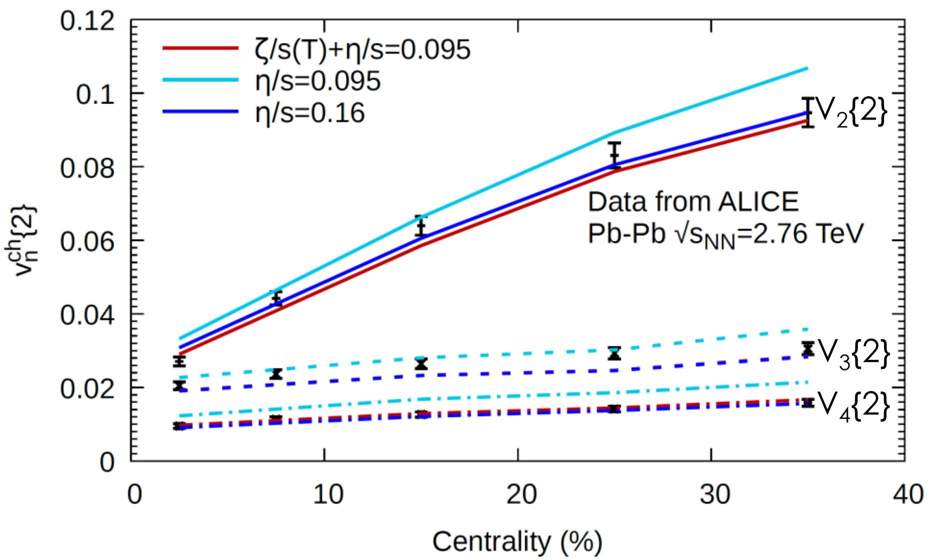
Conclusion and outlook

An improvement in the description of hadronic observables

- IP-Glasma + Viscous hydro + UrQMD [PRL **115**, 132301]







- Crucial ingredient : Bulk Viscosity
- Via the same modelling, an improved description of v_n of direct photons [PRC **93**, 044906] was done.
- Thermal dileptons are now also included.

Viscous hydrodynamics & bulk pressure

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

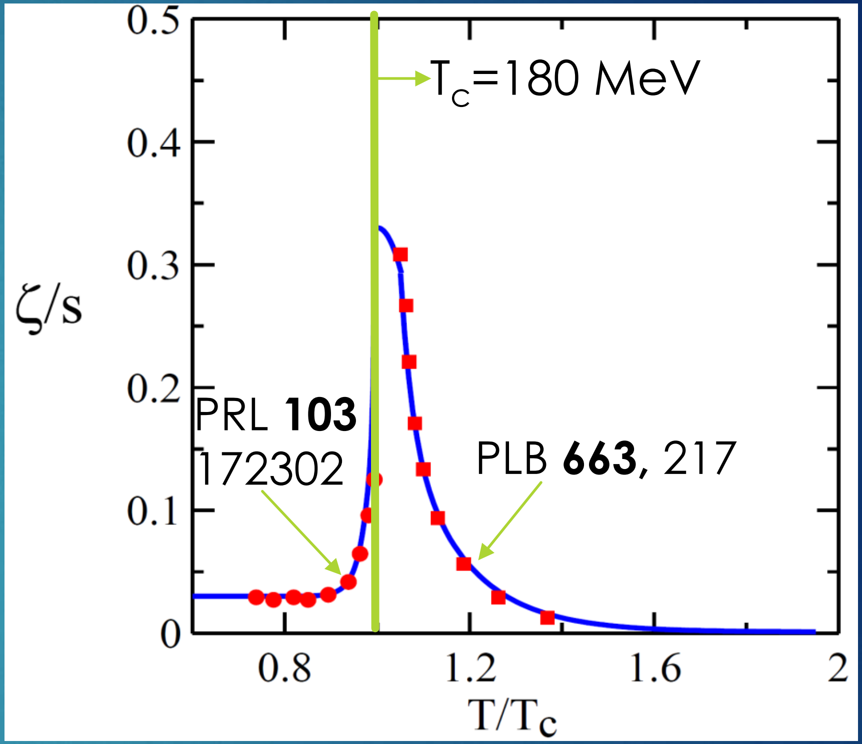
$$\partial_\mu T^{\mu\nu} = 0$$

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

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

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

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

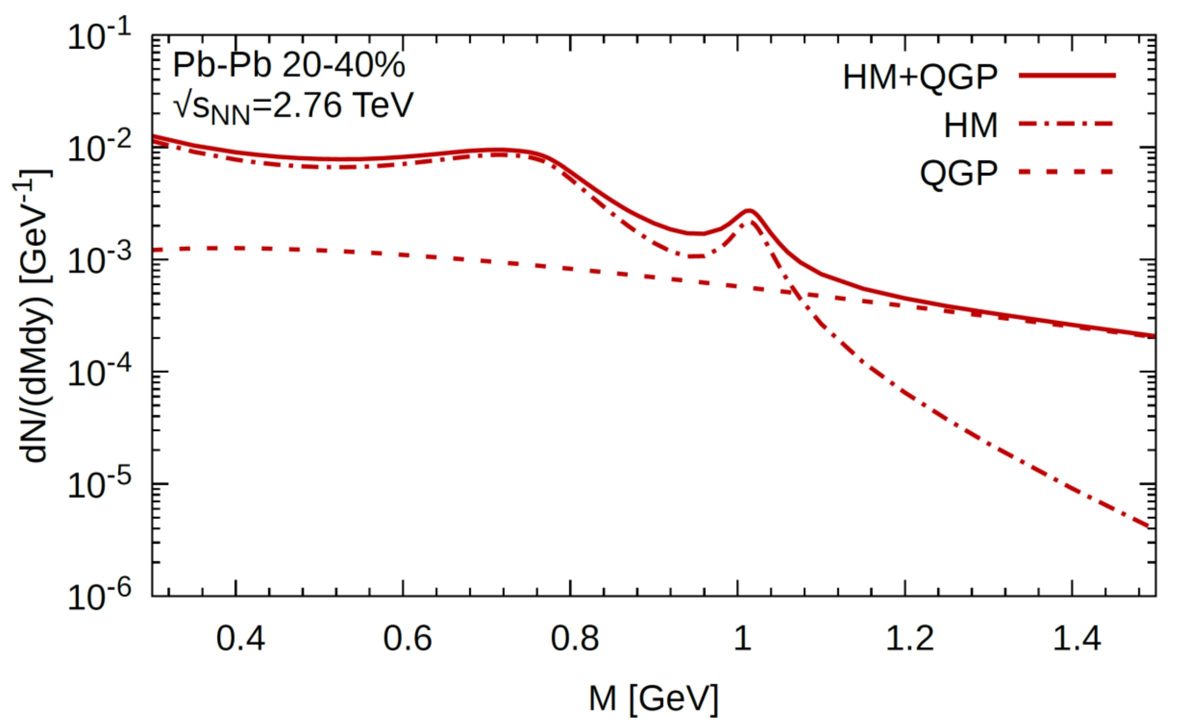


$\eta/s = constant$

- Other than ζ and η, all transport coefficients are in PRD **85** 114047, PRC **90** 024912.
- $P(\varepsilon)$: Lattice QCD EoS [Huovinen & 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.
- Note: Only dileptons from the hydro will be studied.

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 (2001)]

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

- Viscous extension to thermal distribution function

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

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

δn_a^{shear} in Israel-Stewart approx. [PRC **89**, 034904]

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

δn_a^{bulk} in RTA approx. [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 Israel-Stewart approx.

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

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:

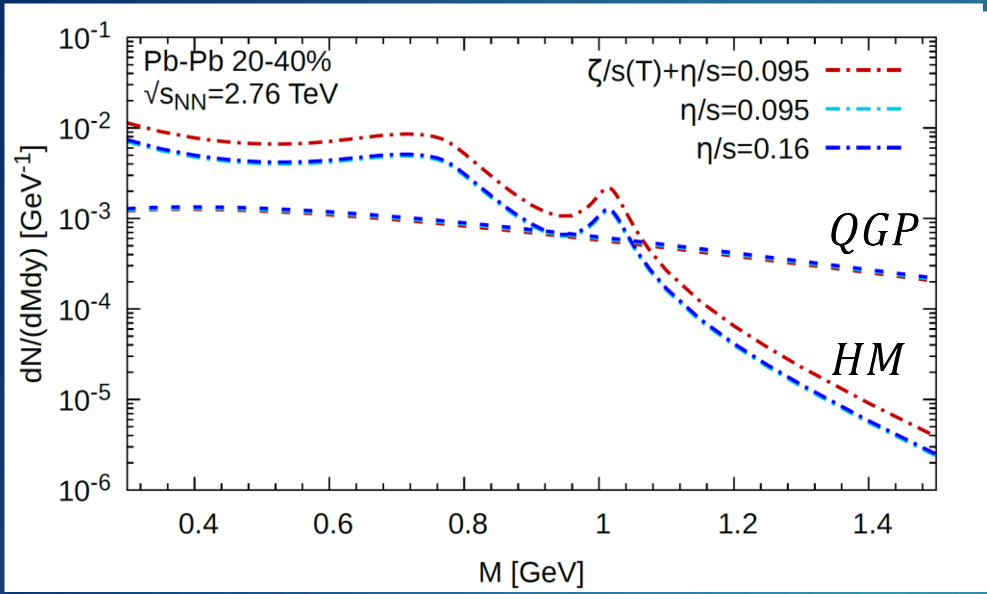
1. Within an event: v$_n$'s are a yield weighted average of the different sources (e.g. HM, QGP, ...).
2. The switch between HM and QGP rates we are using a linear interpolation, in the region $184\ MeV < T < 220 MeV$, given by the EoS [NPA **837**, 26]
3. Averaging over events: the flow coefficients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

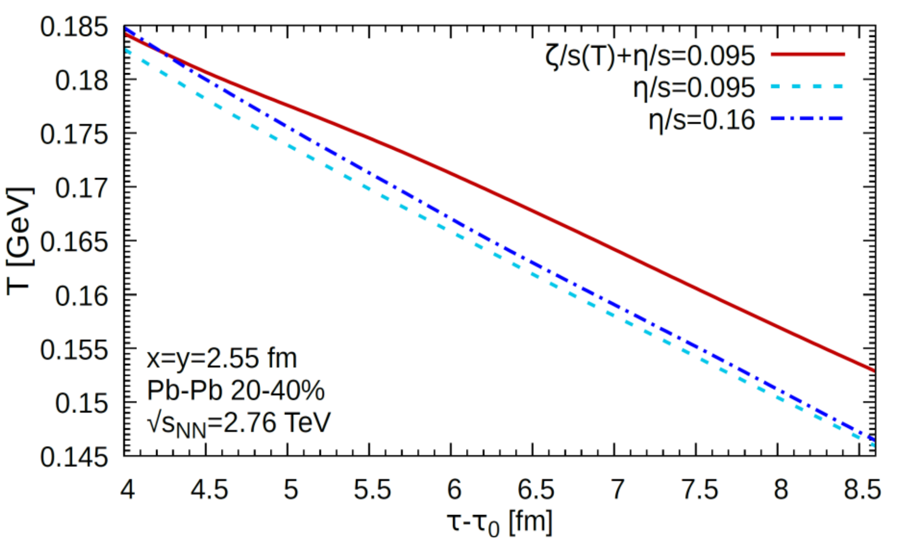
$$v_n\{SP\} = \frac{\left\langle v_n^{\gamma^*} v_n^h \cos\left[n\left(\Psi_n^{\gamma^*} - \Psi_n^h\right)\right]\right\rangle}{\left\langle \left(v_n^h\right)^2 \right\rangle^{1/2}}$$

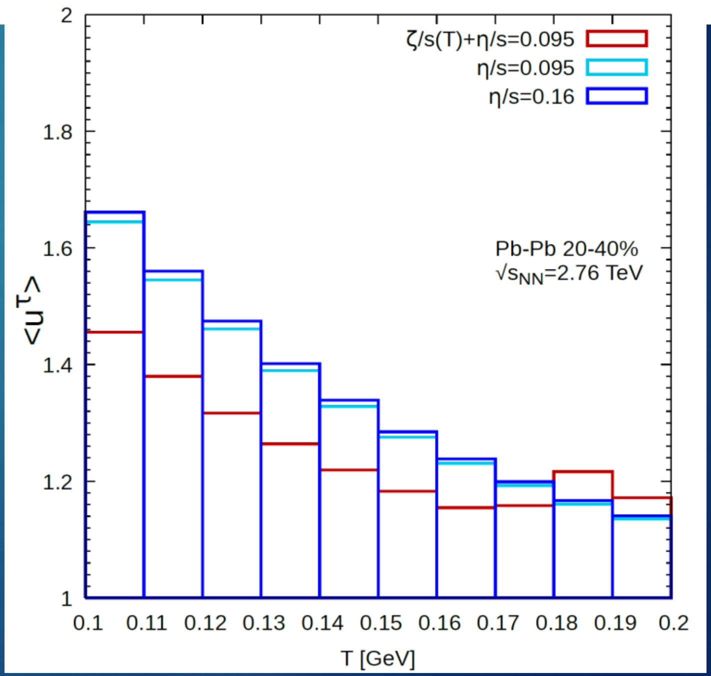
PRC **93**, 044906
PRC **94**, 014904

- Lastly the temperature at which hydrodynamics (& dilepton radiation) is stopped is $T_{switch} = 145$ MeV at LHC, while at RHIC $T_{switch} = 165$ MeV.

Bulk viscosity and dilepton yield at LHC

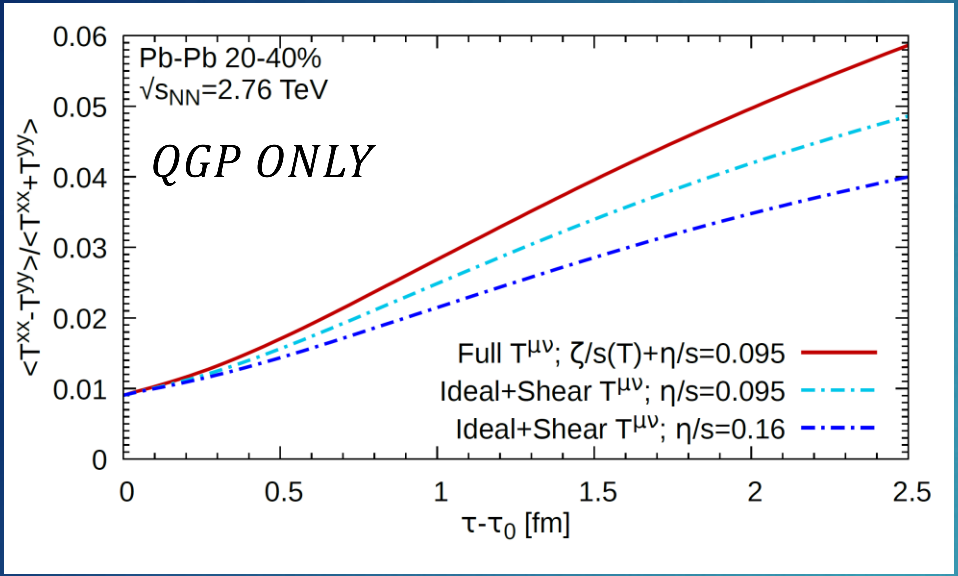






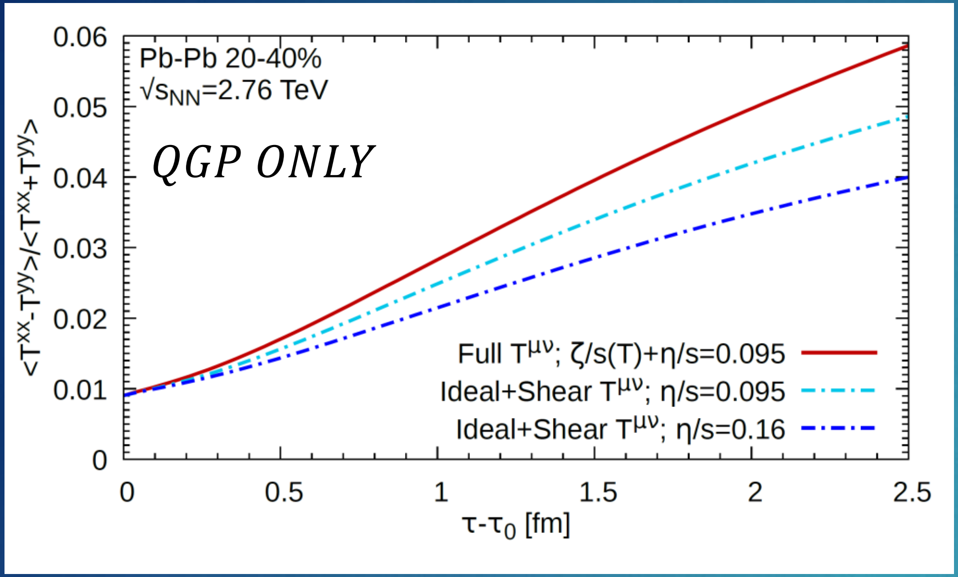
- Bulk viscosity reduces the cooldown rate of the medium, by viscous heating and also via reduction of radial flow at late times.
- Dilepton yield is increased in the HM sector, since for $T < 184\ MeV$ purely HM rates are used.

Bulk viscosity and QGP v_2 at LHC

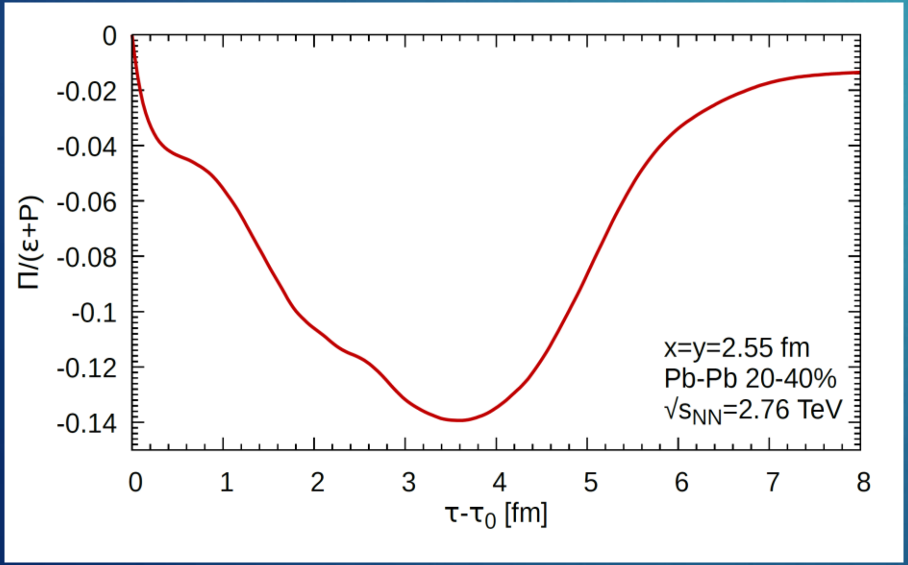


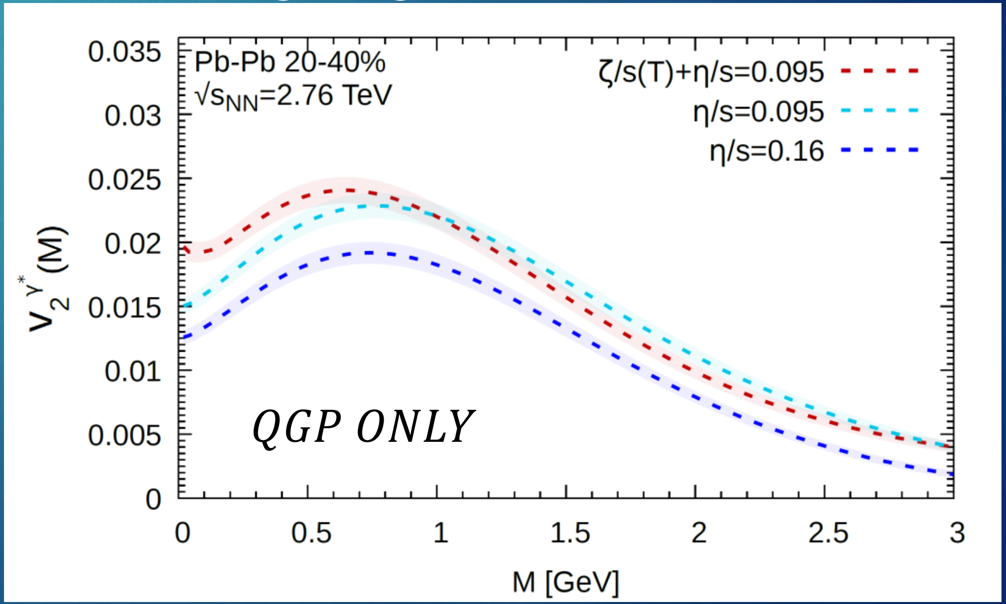
- $\langle T^{xx} \pm T^{yy}\rangle \equiv$ $$\equiv \frac{1}{N_{events}} \sum_{i}^{N_{events}} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp \left(T_i^{xx} \pm T_i^{yy}\right)$$ where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp$ integrates only over the **QGP** phase.

Bulk viscosity and QGP v_2 at LHC

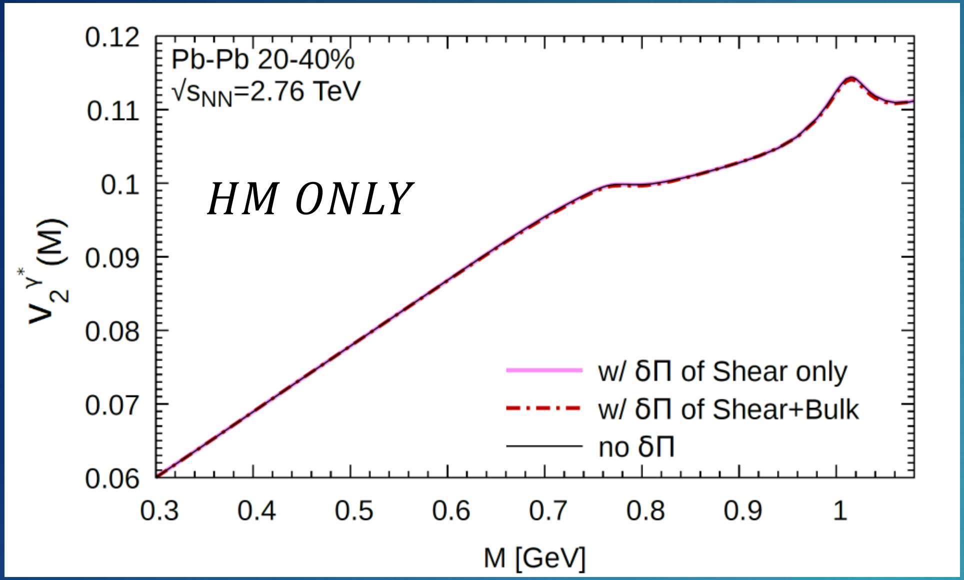


- At early times, hydrodynamic ($T^{\mu\nu}$) momentum anisotropy increases under the influence of bulk viscosity.
- $\delta n^{bulk} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP v_2, as $\frac{\Pi}{\varepsilon + P}$ doesn't change sign.

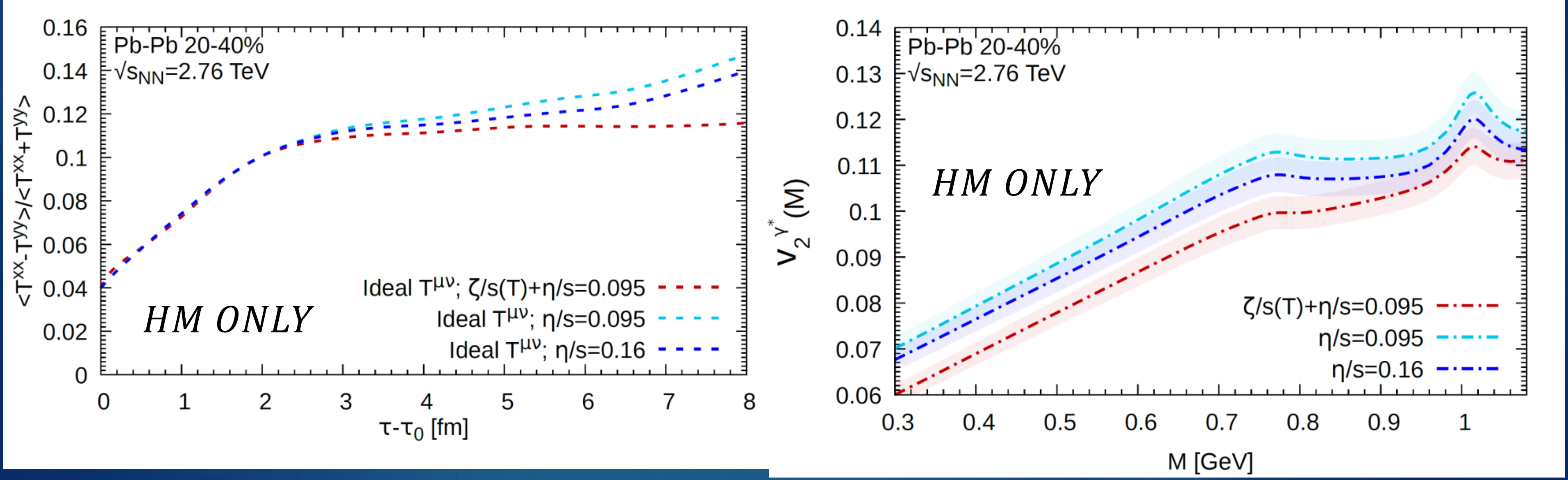




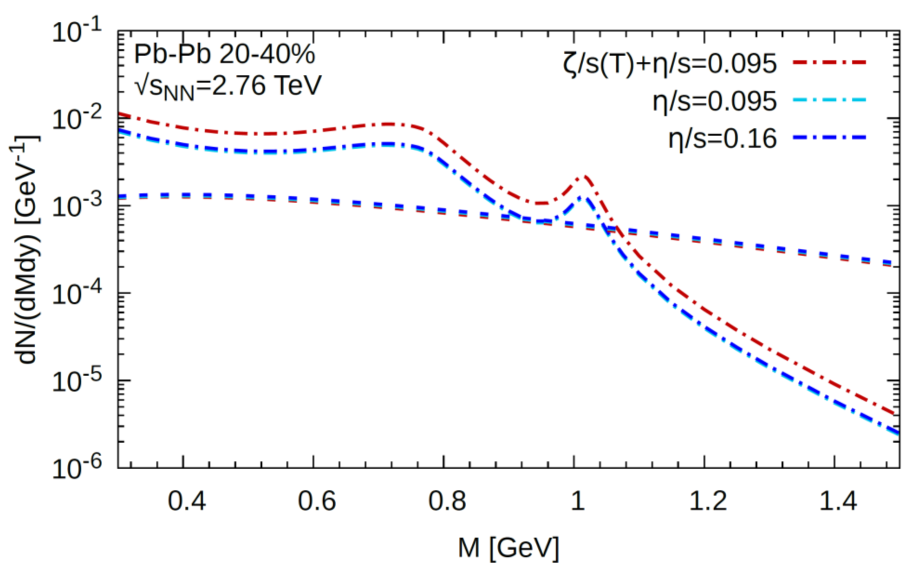
Bulk viscosity and HM v_2 at LHC

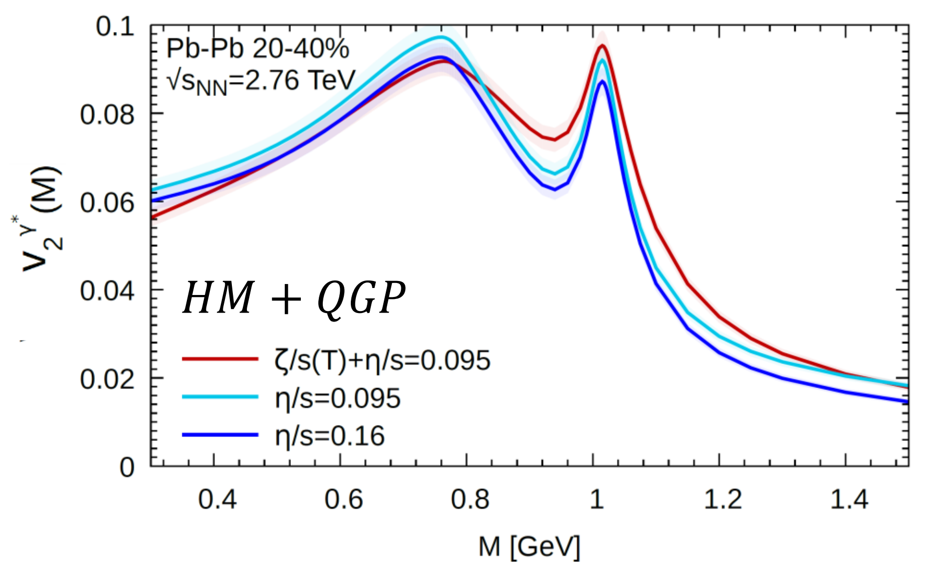


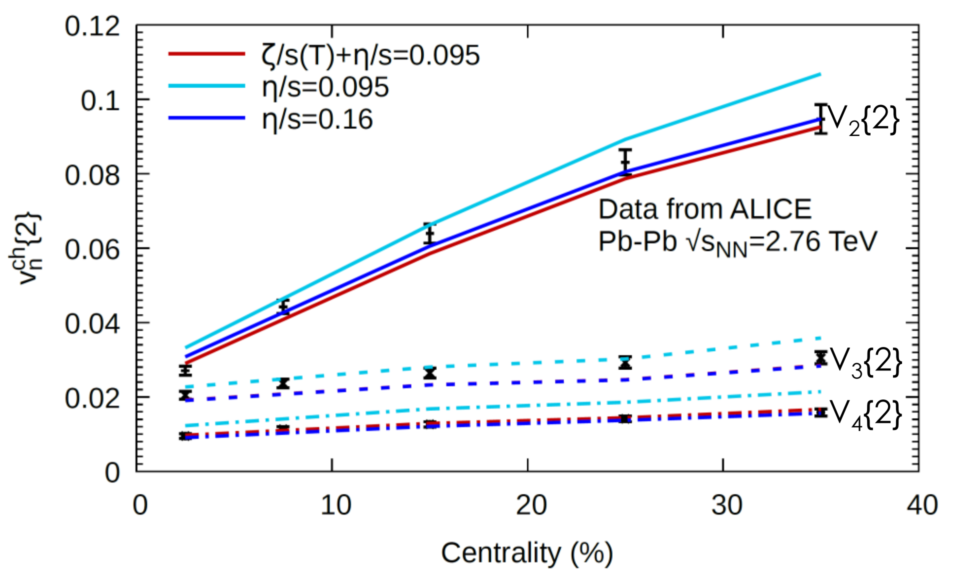
- However, HM dileptons are modestly affected by δn effects.
- v_2^{HM} is only affected by flow anisotropy.
- Where $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2x_\perp$ in $\langle T^{xx} \pm T^{yy} \rangle$ integrates only over the **HM** region.



Bulk viscosity and dileptons at LHC

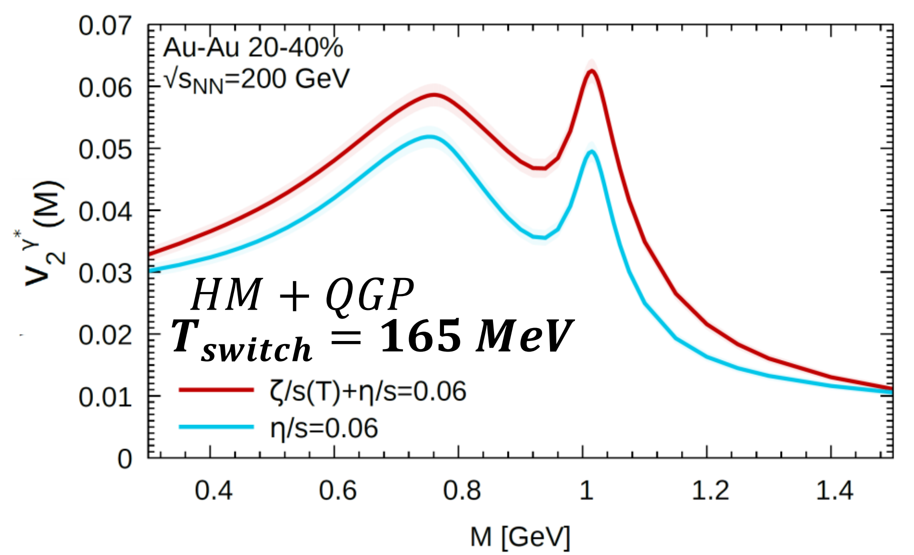


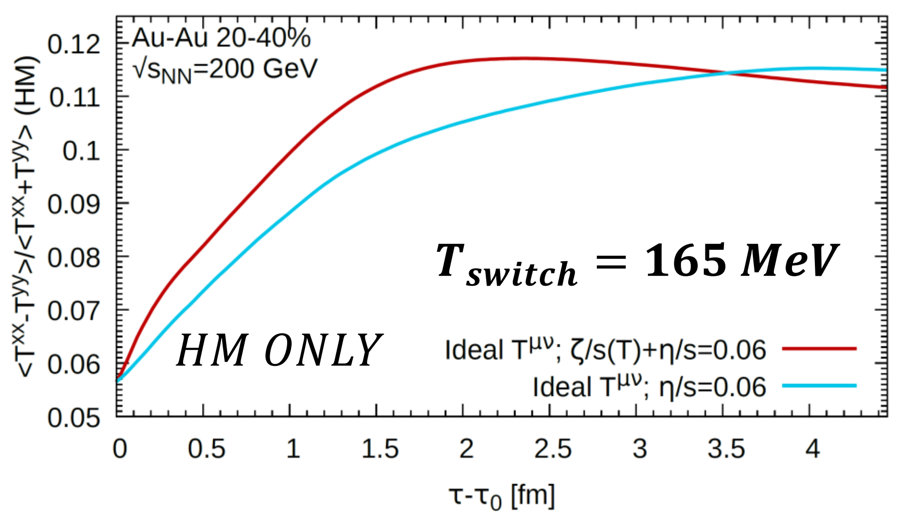




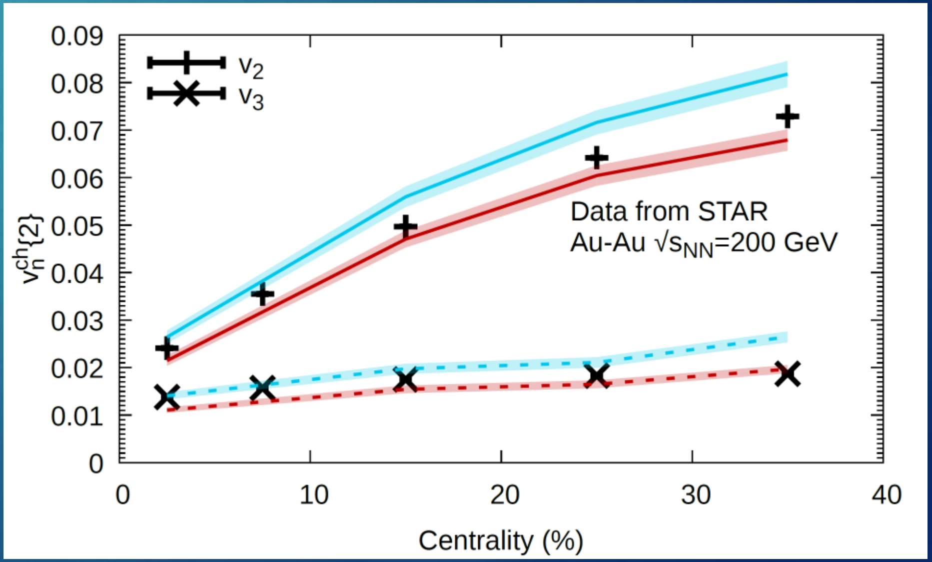
- Thermal $v_2(M)$ is a yield weighted average of HM and QGP contributions:
  - For $M < 0.8$ GeV $v_2(M)$ behaves same as charged hadrons.
  - For $M > 0.8$ GeV sector, $v_2(M) \uparrow$ because there is more weight in the HM sector.

Bulk viscosity and dileptons at RHIC

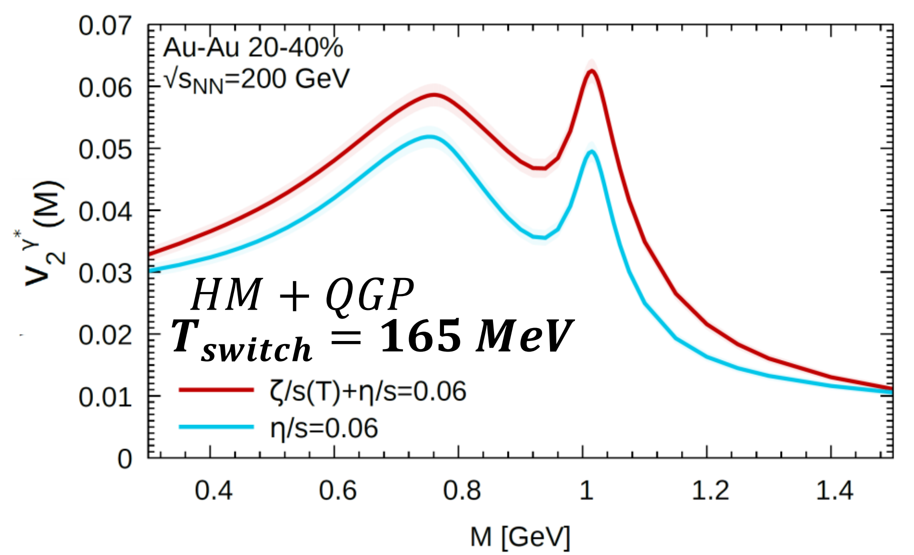


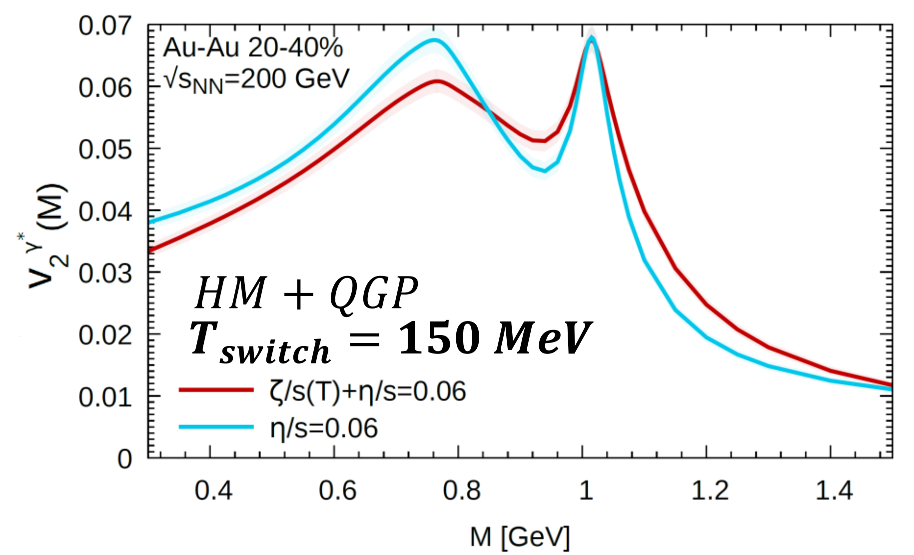


- Bulk viscosity causes an increase in anisotropic flow build-up in both the QGP and the hadronic sector which translates into an ↑ $v_2(M)$ of thermal dileptons.
- v_2^{ch} behaves in the opposite direction, as they are emitted at later times.
- This anti-correlation is a key feature of bulk viscosity at fixed η/s.



Bulk viscosity and dileptons at RHIC





- This effect is coming from the switching temperature to UrQMD.
- To mimic the effects a hadronic transport evolution would have on dileptons, hydrodynamical evolution was continued until $T_{switch} = 150\ MeV$.
- Note that hadronic transport will not generate as much anisotropic flow as hydro. Also, shear viscosity was not re-adjusted to better fit hadronic observables; e.g. v_n^{ch} is too large with current (fixed) η/s.
- A dilepton calculation from a transport approach is important. This study is underway.

Conclusions

- Performed a first thermal dilepton calculation starting from IP-Glasma initial conditions, with bulk viscosity in the hydro evolution, at both 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.

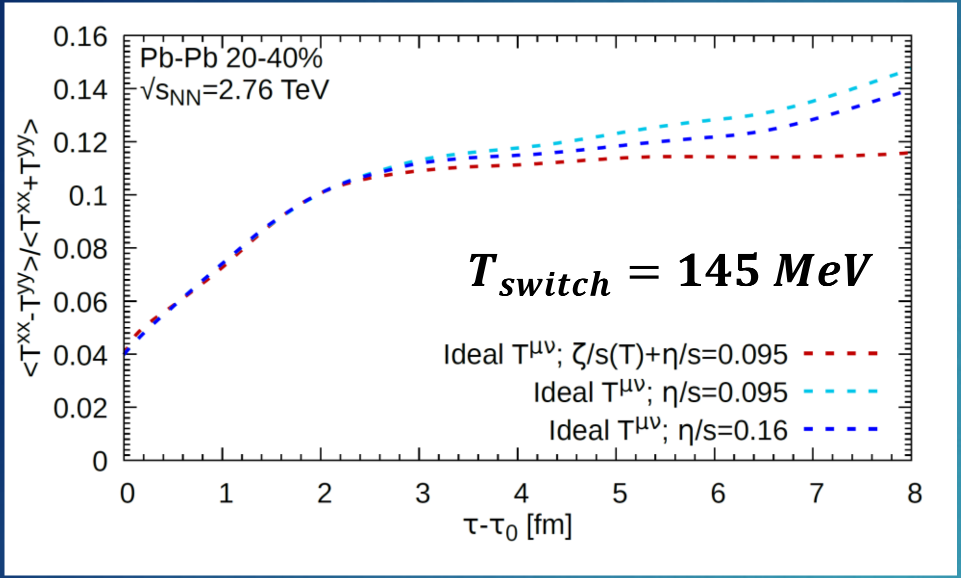
- Our calculation shows that, for a fixed η/s, there is an anti-correlation between the effects of bulk viscosity on dilepton $v_2(M)$ and charged hadron's v_2 at RHIC. This effect depends on the switching temperature T_{switch} between hydro and hadronic transport.

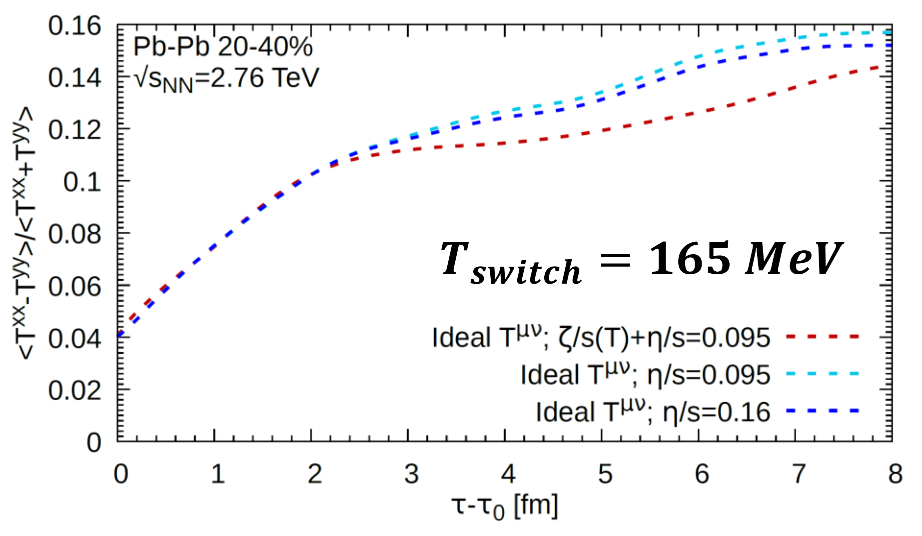
Outlook

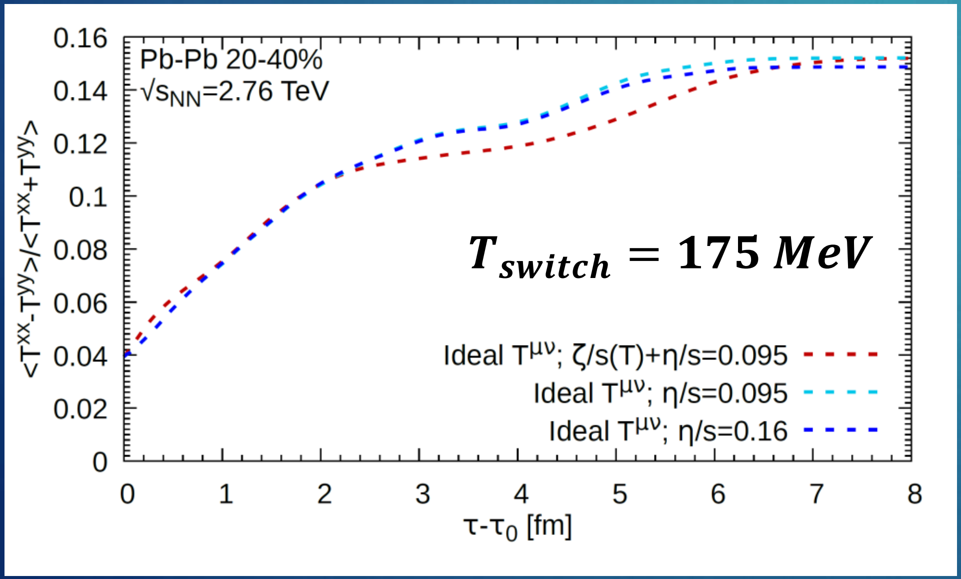
- In collaboration with Hannah Petersen's group at FIAS (in particular Jan Staudenmaier), a computation of dilepton production from the hadronic transport model SMASH is ongoing.

Backup Slides

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





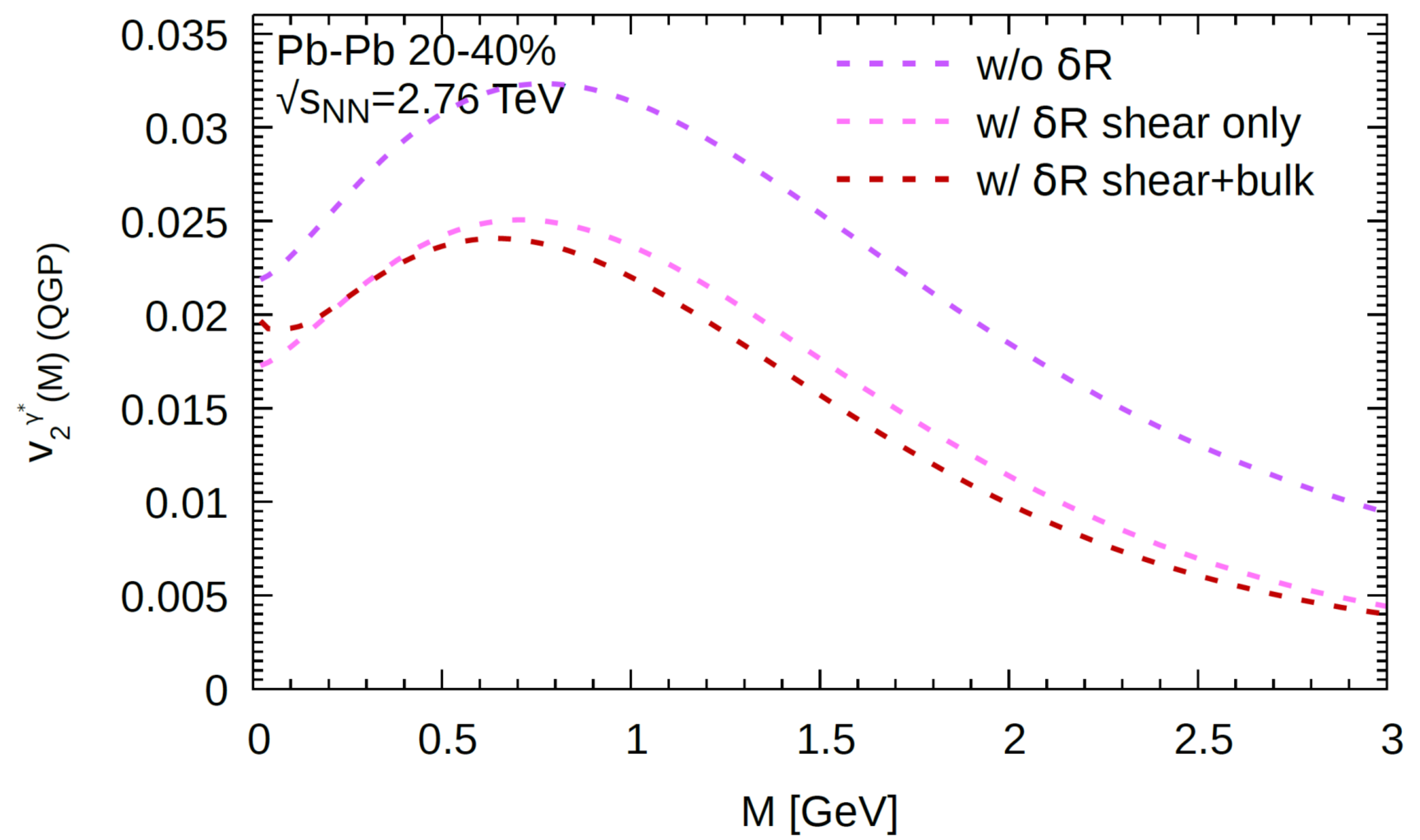


- $$\frac{\langle T^{xx}-T^{yy}\rangle}{\langle T^{xx}+T^{yy}\rangle} \equiv \frac{\sum_i \int d^2x_\perp \left(T_i^{xx}-T_i^{yy}\right)}{\sum_i \int d^2x_\perp \left(T_i^{xx}+T_i^{yy}\right)}$$

  where the $\int d^2x_\perp$ integrates only the **HM** phase with $T > 145$ MeV, $T > 165$ MeV, and $T > 175$ MeV.

Viscous correction in the QGP

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



NLO QGP dilepton results

- Diagrams contributing at LO & NLO