Examining hydrodynamical modelling of the QGP through dilepton radiation

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Based on **arXiv:1903.05078**

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Outline

Dileptons and hydrodynamics :

- Overview of the sensitivity of dileptons to shear-properties of the QGP

Sources of Dileptons

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

Bulk viscosity and Dileptons

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

Conclusion and outlook

Overview: Dileptons from shear dissipative hydrodynamics

Why is electromagnetic radiation an important source?

- As $\alpha_{EM} \ll \alpha_s$, real/virtual photons can escape QCD medium with negligible re-scattering
  - precise information about the medium at the moment of emission
- Hydrodynamics: (current) best description of the QCD medium in relativistic heavy-ion collisions
- Ideal hydrodynamics: simplest form of hydrodynamics

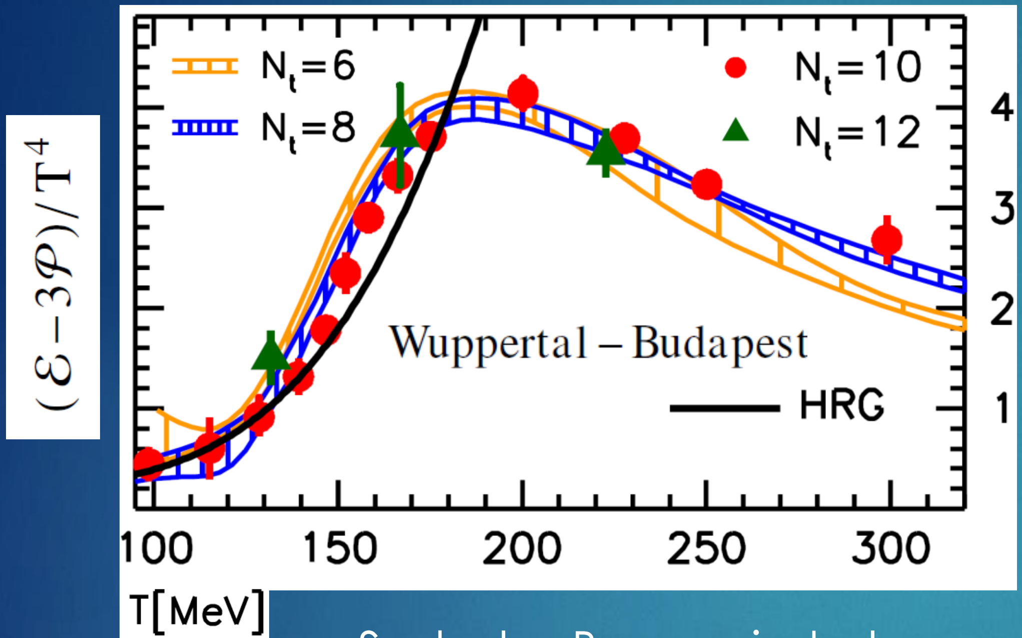
$$\partial_\mu T_0^{\mu\nu} = 0$$

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

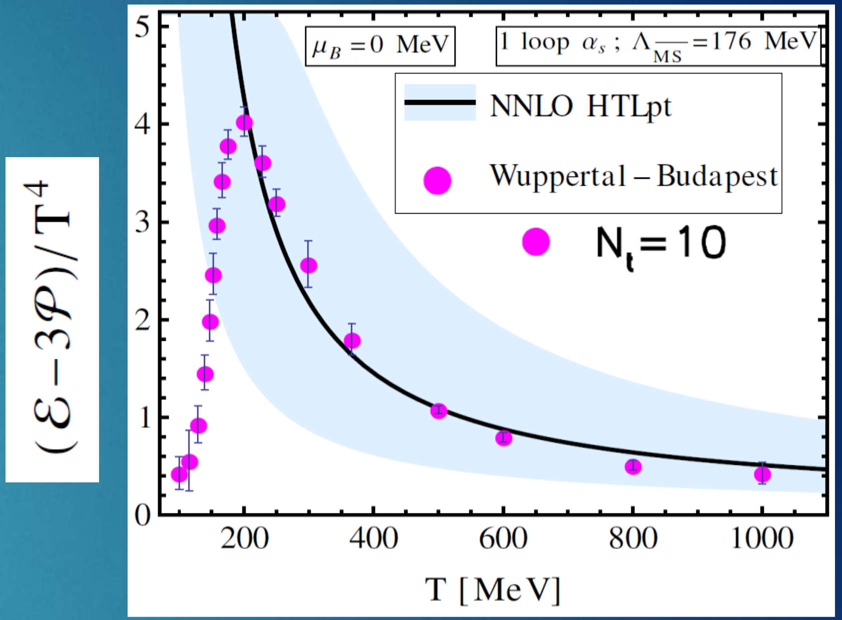
- To solve ideal hydrodynamics and match to data one needs:
  - Initial conditions, and final conditions
  - $P(\varepsilon)$: equation of state

Why is electromagnetic radiation an important source?

- $P(\varepsilon) = \int \frac{dT}{T} \frac{(\varepsilon - 3P)}{T^4}$



Szabolcs Borsanyi et al.
arXiv:1007.2580
JHEP 1011, 077 (2010)

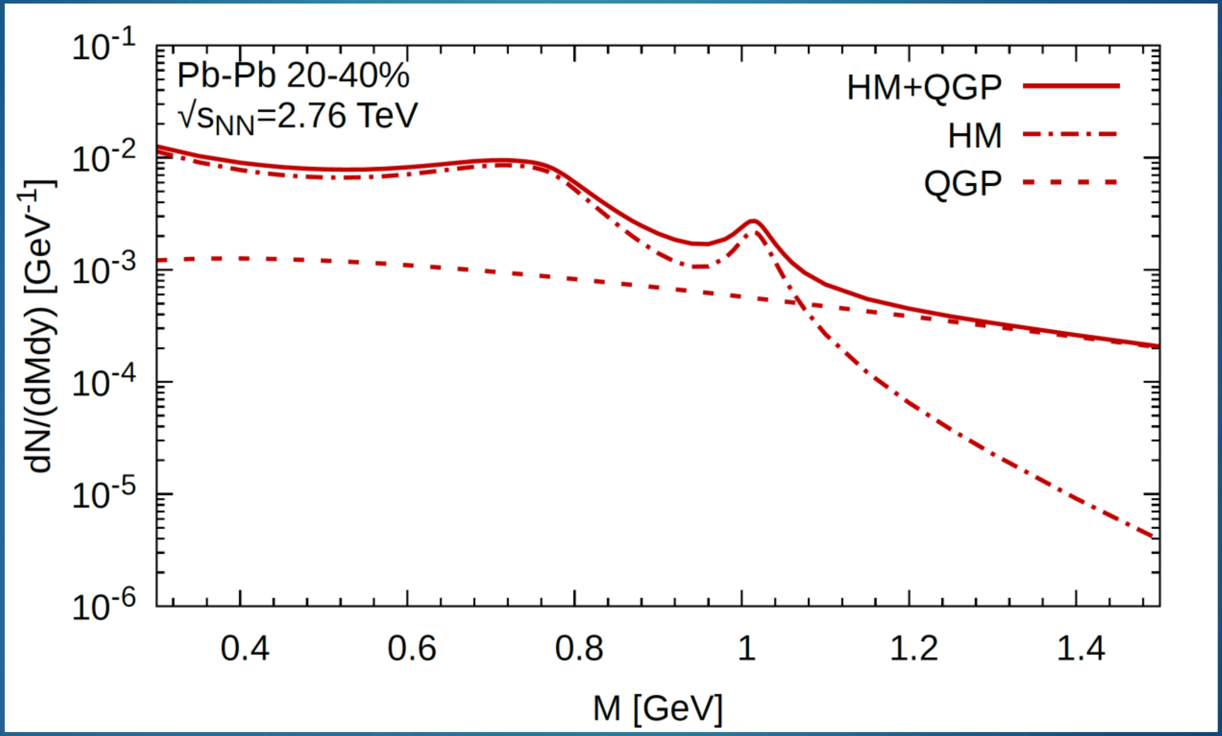


Najmul Haque et al.
arXiv:1402.6907
JHEP 1405, 027 (2014)

- Two rates used: hadronic at low T and partonic high T, for both photons and dileptons.

Photons vs Dileptons

- Why should we use dileptons?
  Dileptons have an additional d.o.f. the invariant mass
  $$M^2 = E^2 - |\vec{p}|^2$$



- Goal : Use the invariant mass distribution to investigate the influence viscosity on dileptons at RHIC and LHC.

Viscous hydrodynamics

- Dissipative hydrodynamic equations including shear viscosity

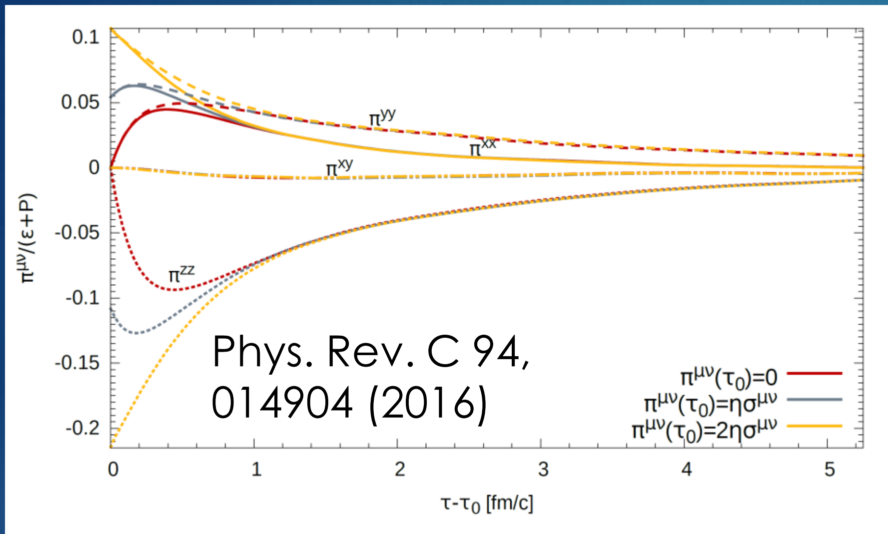
$$\partial_\mu T^{\mu\nu} = 0$$
$$T^{\mu\nu} = T_0^{\mu\nu} + \pi^{\mu\nu}$$
$$T_0^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu}$$
$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$
$$g^{\mu\nu} = diag(+,-,-,-)$$

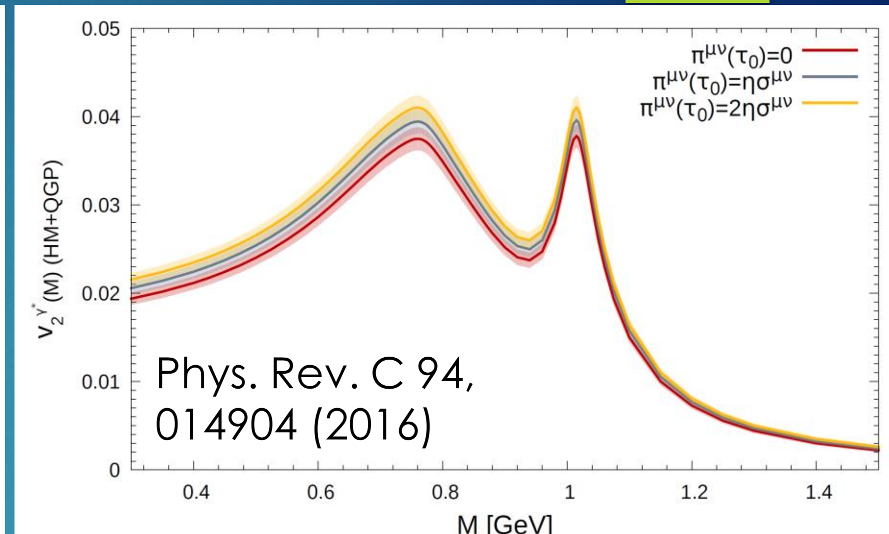
$$\begin{cases}
\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} u^\sigma \partial_\sigma \pi^{\alpha\beta} + \pi^{\mu\nu} = \pi^{\mu\nu}_{NS} - \delta_{\pi\pi}\pi^{\mu\nu}\theta \\
\tau_\pi = b_\pi \dfrac{\eta}{\varepsilon + P}; \quad \delta_{\pi\pi} = \dfrac{4}{3}\tau_\pi; \quad \theta = \partial_\sigma u^\sigma \\
\Delta^{\mu\nu}_{\alpha\beta} = \dfrac{\Delta^\mu_\alpha \Delta^\nu_\beta + \Delta^\mu_\beta \Delta^\nu_\alpha}{2} - \dfrac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta} \\
\nabla^\mu = \Delta^{\mu\nu}\partial_\nu \\
\pi^{\mu\nu}_{NS} = 2\eta\left[\dfrac{\nabla^\mu u^\nu + \nabla^\nu u^\mu}{2} - \dfrac{1}{3}\Delta^{\mu\nu}\nabla^\alpha u_\alpha\right] = 2\eta\sigma^{\mu\nu}
\end{cases}$$

- $P(\varepsilon)$: Lattice QCD EoS [P. Huovinen & P. Petreczky, NPA **837**, 26]. (s95p-v1)

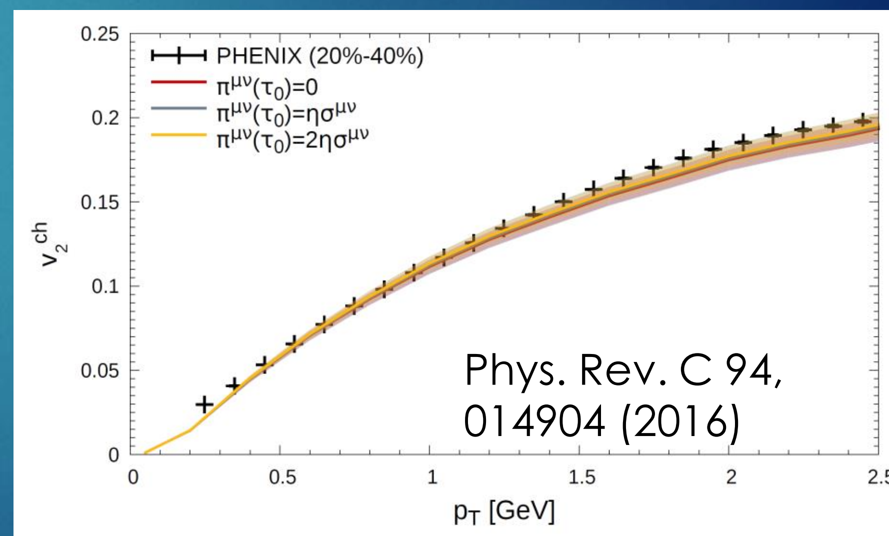
Dileptons are a sensitive probe

- Sensitivity to shear dissipative d.o.f.: dileptons vs hadrons.





- Dilepton v_2 is more sensitive to initial $\pi^{\mu\nu}$ than $v_2$of charged hadrons.



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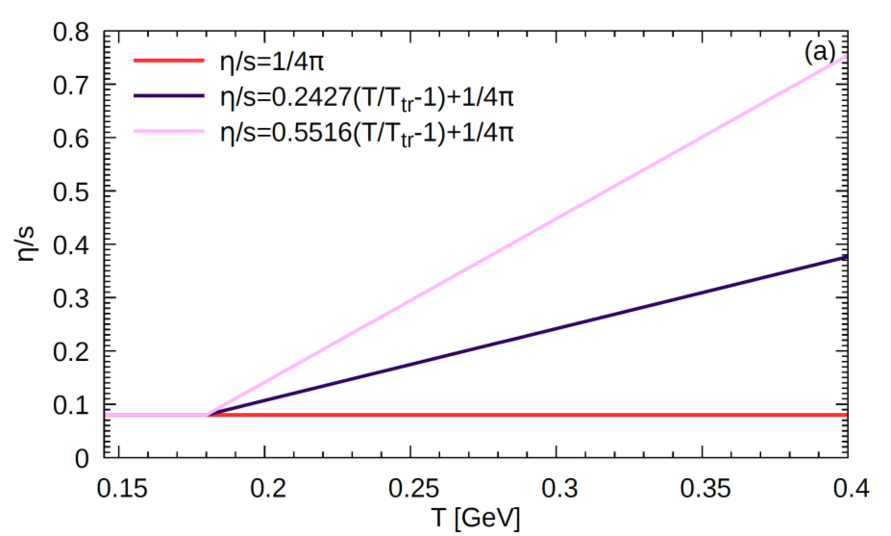
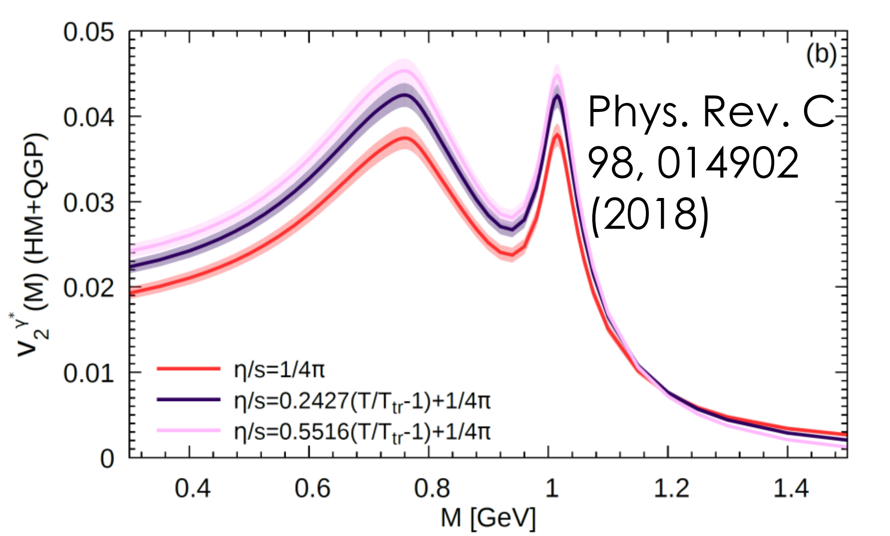
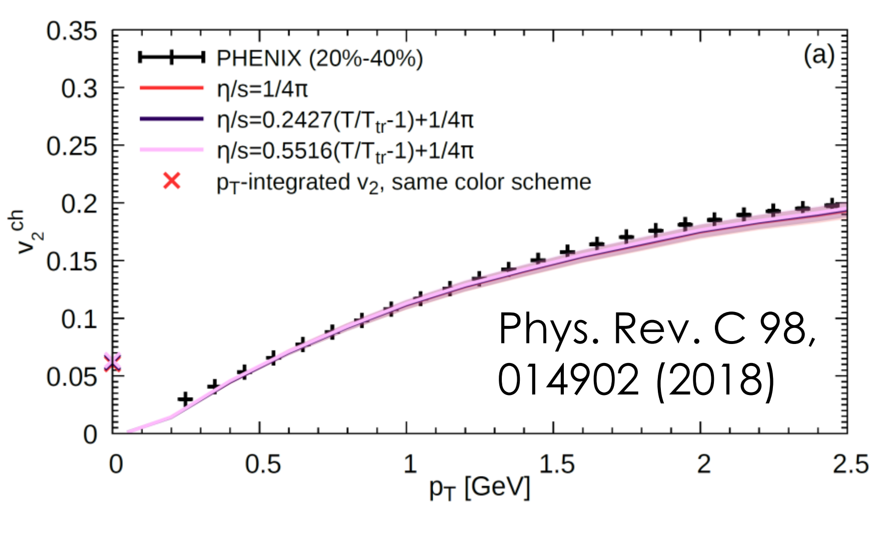




- Dileptons v_2 can easily distinguish between a $\frac{\eta}{s}(T)$ at high T, while hadron v_2 doesn't.
- What about bulk viscosity?



Viscous hydrodynamics & bulk pressure

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

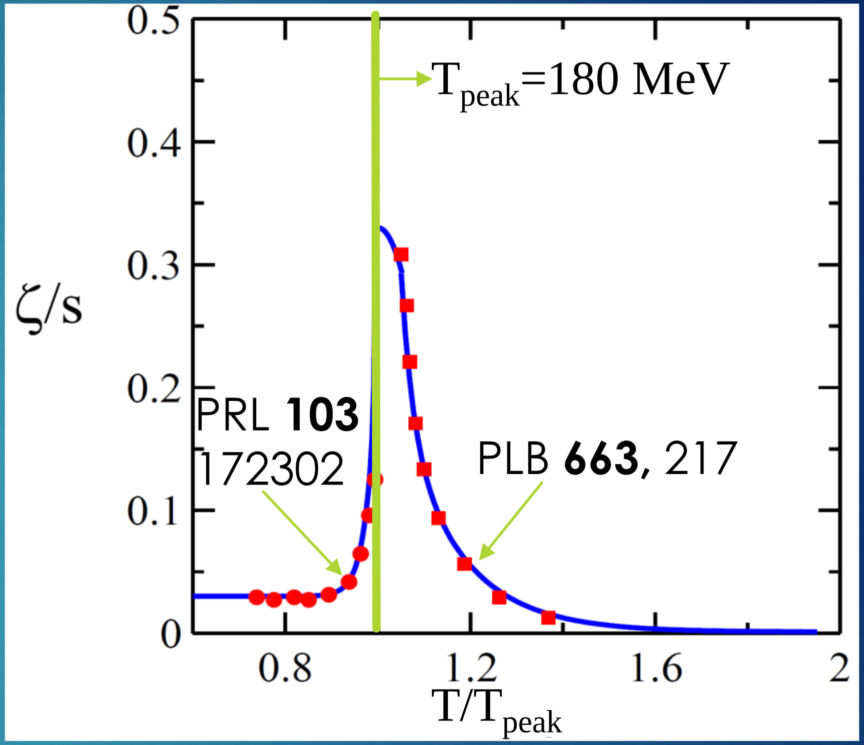
$$\partial_\mu T^{\mu\nu} = 0$$

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

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

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

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

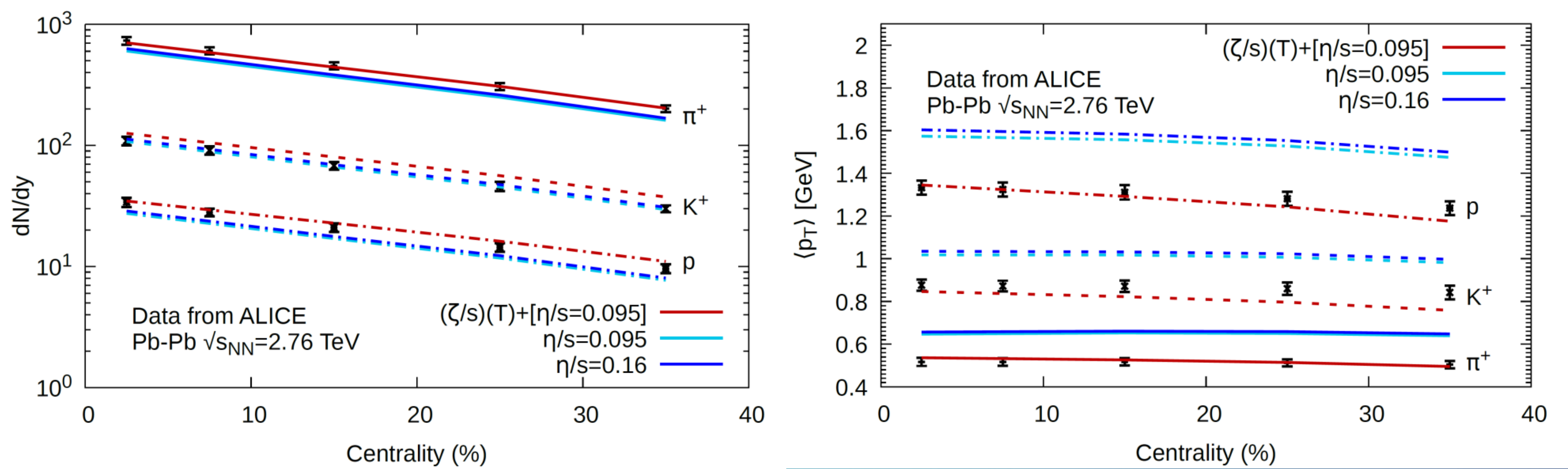


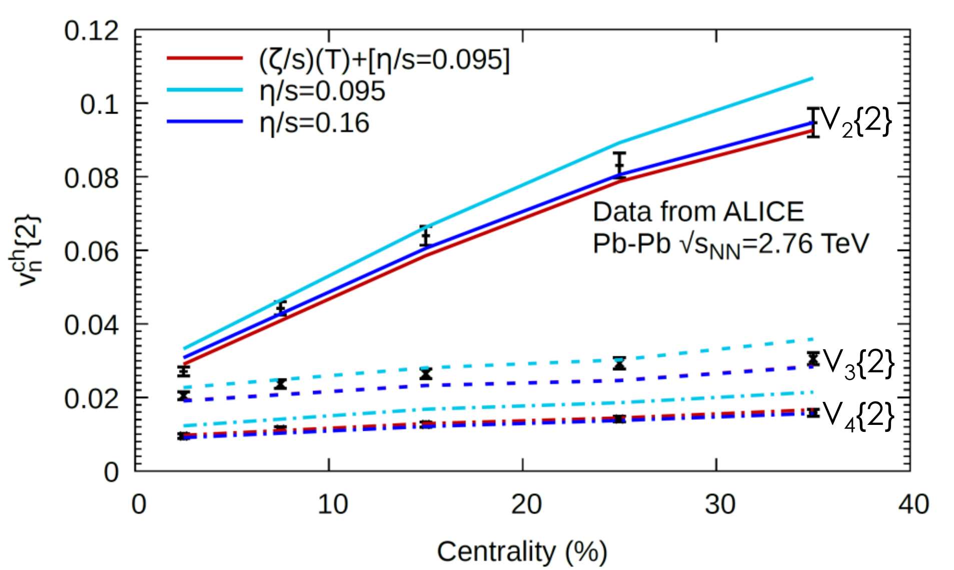
$\eta/s = constant$

- For all transport coefficient, see 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)

An improvement in the description of hadronic observables

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



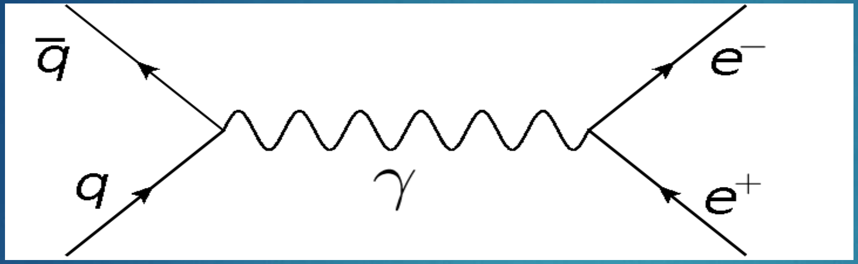


- T_{switch} = 145 MeV at LHC
- Crucial ingredient : Bulk Viscosity
- Via the same modelling, an improved description of v_n of direct photons [Paquet et al., PRC **93**, 044906] was done.
- Dileptons are now also included.

Dilepton Rates

Dilepton rates from the QGP

- An important source of dileptons in the QGP



- The rate in kinetic theory (Born Approx)

$$\frac{d^4R}{d^4q} = \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\, n(k_1^0/T)n(k_2^0/T)v_{12}\sigma\delta^4(q-k_1-k_2)$$

$$v_{12} = \frac{M^2}{2E_1 2E_2} \qquad \sigma = \frac{16\,\pi^2\alpha_{EM}^2 N_c \sum_q e_q}{3M^2}$$

- More sophisticated dileptons calculations exist: Lattice QCD, NLO pQCD
- However those have limitations…

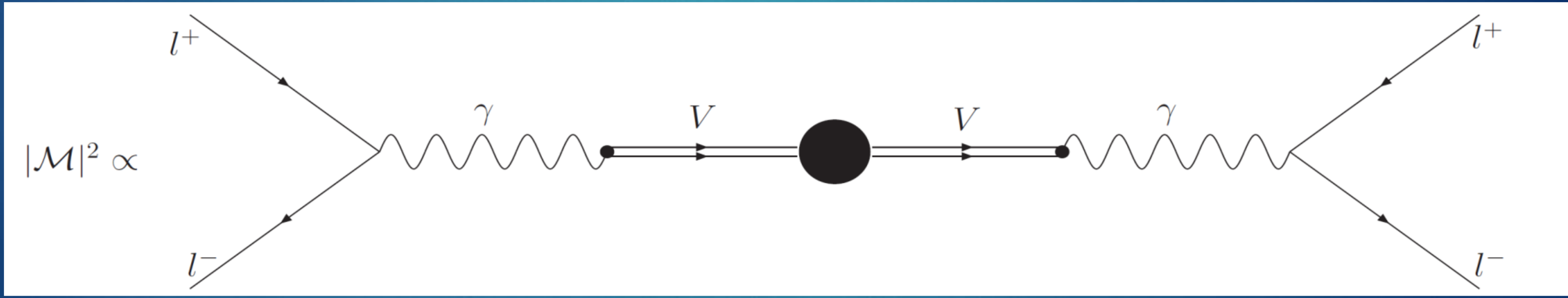
Thermal Dilepton Rates from HM

- The dilepton production rate is :

$$\frac{d^4R}{d^4q} = \frac{\alpha}{\pi^3}\frac{L(M)}{M^2}\left\{-\frac{1}{3}\left[Im\ \Pi^R_{EM}\right]^{\mu}_{\mu}\right\} n_{BE}(q^0); \quad \mathrm{L(M)} = \left(1 + \frac{2m_l^2}{M^2}\right)\sqrt{1 - \frac{4m_l^2}{M^2}}$$

- Vector Dominance Model (VDM)[first proposed by J. J. Sakurai]:

$$\mathcal{L}_I = -eA^{\mu}\left[\sum_{V=\rho,\omega,\phi}\frac{m_V^2}{g_V}V_{\mu}\right]$$



- Using VDM the dilepton rate of dilepton emission is

$$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\frac{m_V^4}{g_V^2}\left\{-\frac{1}{3}\left[Im\ D^R_V\right]^{\mu}_{\mu}\right\} n_{BE}(q^0)$$

Thermal Dilepton Rates from HM

- The dilepton production rate is :

$$\frac{d^4R}{d^4q} = \frac{\alpha^2}{\pi^3}\frac{L(M)}{M^2}\left\{-\frac{1}{3}\left[Im\ D_V^R\right]_\mu^\mu\right\} n_{BE}(q^0); \quad \mathrm{L(M)} = \left(1+\frac{2m_l^2}{M^2}\right)\sqrt{1-\frac{4m_l^2}{M^2}}$$

- Where

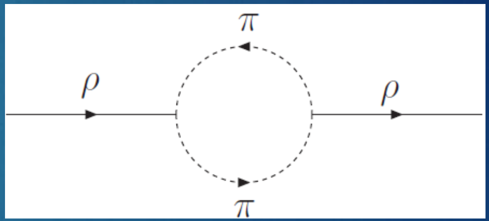
$$-Im\ D_V^R = \frac{-Im\ \Pi_V}{(M^2 - m_V^2 - Re\Pi_V)^2 + (Im\ \Pi)^2}\ ; where\ \Pi_V \equiv \Pi_V^R$$

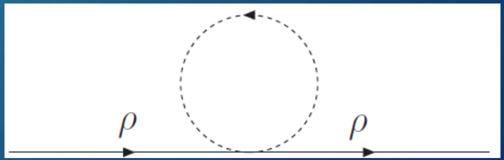
- Model based on Eletsky, et al., PRC, 64, 035202 (2001)

$$\Pi_V = \Pi_V^{Vac}(M) + \sum_a \Pi_{Va}(q,T)$$

Π_V^{Vac} is described by effective Lagrangians, e.g.

$$\Pi_{Va}(q,T) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_a(k^0/T)\frac{\sqrt{s}}{k^0} f_{Va}(s)$$





$$\mathcal{L}_{\rho\to\pi\pi} = \frac{1}{2}|D_\mu\pi|^2 - \frac{1}{2}m_\pi^2|\pi|^2 - \frac{1}{4}F^\rho_{\mu\nu}F^{\mu\nu}_\rho + \frac{1}{2}m_\rho^2\rho^\mu\rho_\mu$$

Vector meson thermal self-energies

$$\Pi_{Va}(q,T) = -4\pi \int \frac{d^3k}{(2\pi)^3} n_a(k^0/T) \frac{\sqrt{s}}{k^0} f_{Va}^{c.m.}(s)$$

- The forward scattering amplitude
  - Low energies:

$$f_{Va}^{c.m.} = \frac{1}{2q_{c.m.}} \sum_R \frac{W_{Va}^R \Gamma_{R\to Va}}{M_R - \sqrt{s} - \frac{i}{2}\Gamma_R} - \frac{q_{c.m.}}{4\pi s} \frac{(1+\exp(-i\pi\alpha_P))}{\sin(\pi\alpha_P)} r_{P,Va}\, s^{\alpha_P}$$

$$W_{Va}^R = \frac{2s_R+1}{(2s_V+1)(2s_a+1)} \frac{2t_R+1}{(2t_V+1)(2t_a+1)}$$

$$q_{c.m.} = \frac{1}{2} \frac{\sqrt{[s-(m_V+m_a)^2][s-(m_V-m_a)^2]}}{\sqrt{s}}$$

Resonances [R] contributing to ρ's scatt. amp. & similarly for ω, ϕ

$N(1700)$	$\Delta(1905)$
$N(1720)$	$\Delta(1940)$
$N(1900)$	$\Delta(2000)$
$N(2000)$	$\phi(1020)$
$N(2080)$	$h_1(1170)$
$N(2090)$	$a_1(1260)$
$N(2100)$	$\pi(1300)$
$N(2190)$	$a_2(1320)$
$\Delta(1700)$	$\omega(1420)$
$\Delta(1900)$	

  - High energies:

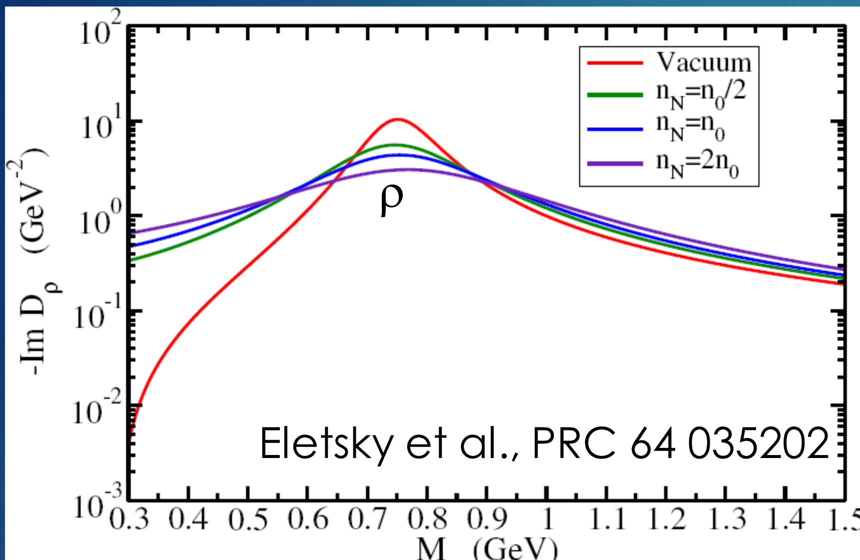
$$f_{Va}^{c.m.} = -\frac{q_{cm}}{4\pi s} \sum_i \frac{1+\exp(-i\pi\alpha_i)}{\sin(\pi\alpha_i)} r_{i,Va} s^{\alpha_i}$$

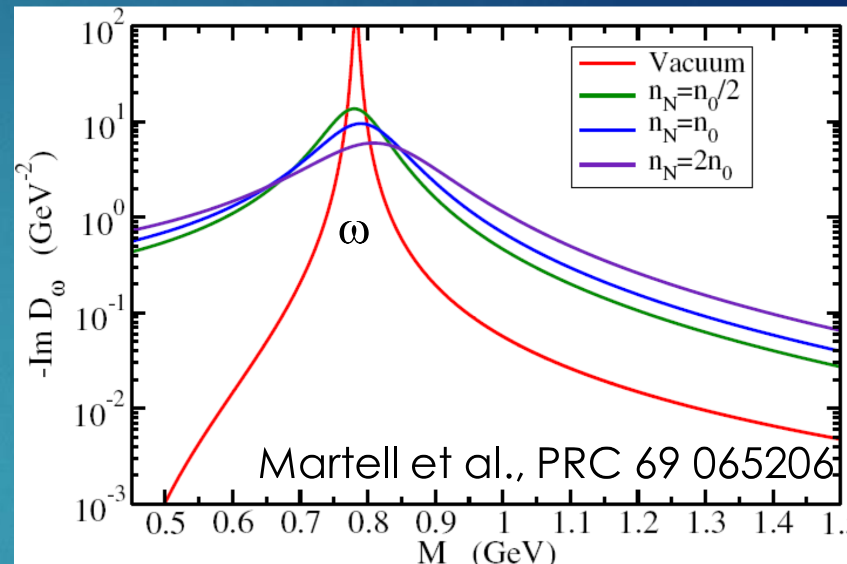
Eletsky et al., PRC 64 035202

Martell et al., PRC 69 065206

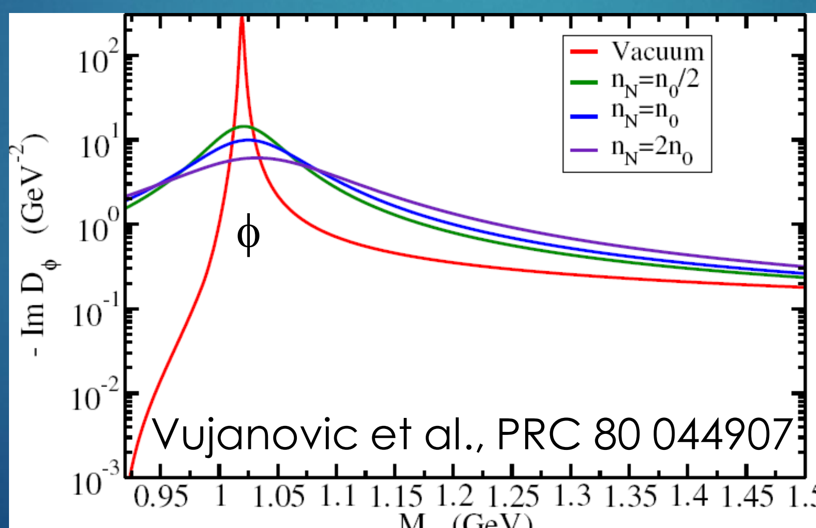
Vujanovic et al., PRC 80 044907

Imaginary part of the retarded propagator





T=150MeV
$n_0=0.17/\mathrm{fm}^3$



- In-medium properties
  1. The width of the distribution: in-medium lifetime.
  2. Shift in the peak of the distribution : in-medium mass.

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 are originating from $\eta, \eta', \rho, \omega, \phi$ mesons.

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

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

- For narrow resonances $\eta, \eta', \omega, \phi$ the Cooper-Frye formalism is used

$$\frac{E d^3 N_i^{CF}}{d^3 p} = \int d^3 \Sigma_\mu p^\mu \left[n_{0,i} + \delta n_i^{shear} + \delta n_i^{bulk} \right]$$

$$n_{0,i} = \frac{g_i/(2\pi)^3}{\exp\left(\frac{p_i \cdot u}{T}\right) \pm 1}; p_i^\mu = \left[\sqrt{m_i^2 + |\vec{p}|^2}, \vec{p} \right]$$

- The broad ρ: need to modify Cooper-Frye formula

Cocktail dileptons from the ρ

- Modified Cooper-Frye distribution

$$N_\rho = \int \frac{d^3p}{(2\pi)^3 p^0} \int d^3\Sigma_\mu p^\mu n_\rho$$

$$N_\rho = \int \frac{d^4p}{(2\pi)^4} (2\pi) 2\delta\left(p^2 - m_\rho^2\right) \Theta(p^0) \int d^3\Sigma_\mu p^\mu n_\rho$$

$$N_\rho \to \int \frac{dMdyd^2p_\perp}{(2\pi)^3} \frac{2}{\pi} \left(-Im\left[D_\rho^R(M)\right]\right) \int d^3\Sigma_\mu p^\mu n_\rho(M)$$

- The branching fraction

$$\frac{dB_{\rho\to\gamma^*}}{d(M^2)} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_V^4}{g_V^2} \frac{L(M)}{M^2} \frac{1}{-Im\left[\Pi_\rho^R\right]}$$

- Thus, the decay is

$$\frac{d^4N_{\rho\to\gamma^*}}{d^4p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_\rho^4}{g_\rho^2} \frac{L(M)}{M^2} \left|D_\rho^R(M)\right|^2 \left[\int d^3\Sigma_\mu p^\mu n_\rho(M) + res.decays\right]$$

Dilepton Cocktail

- The $V = \omega, \phi$ mesons:

$$\frac{d^4 N_{\gamma^*}}{d^4 p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_V^4}{g_V^2} \frac{L(M)}{M^2} \left| D_V^R(M) \right|^2 \left[\int d^3 \Sigma_\mu p^\mu n_V(M = m_V) + res.decays \right]$$

- The ρ will be included as follows:

$$\frac{d^4 N_{\gamma^*}}{d^4 p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_\rho^4}{g_\rho^2} \frac{L(M)}{M^2} \left| D_\rho^R(M, T = 0) \right|^2 \left[\int d^3 \Sigma_\mu p^\mu n_\rho\left(M = m_\rho\right) + res.decays \right]$$

$$\frac{d^4 N_{\gamma^*}}{d^4 p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_\rho^4}{g_\rho^2} \frac{L(M)}{M^2} \left| D_\rho^R(M, T = 0) \right|^2 \left[\int d^3 \Sigma_\mu p^\mu n_\rho(M) + res.decays \right]$$

$$\frac{d^4 N_{\gamma^*}}{d^4 p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_\rho^4}{g_\rho^2} \frac{L(M)}{M^2} \left| D_\rho^R(M, T = T_{sw}) \right|^2 \left[\int d^3 \Sigma_\mu p^\mu n_\rho(M) + res.decays \right]$$

- Resonance decays included using on-shell approximation

Anisotropic flow

- Flow coefficients

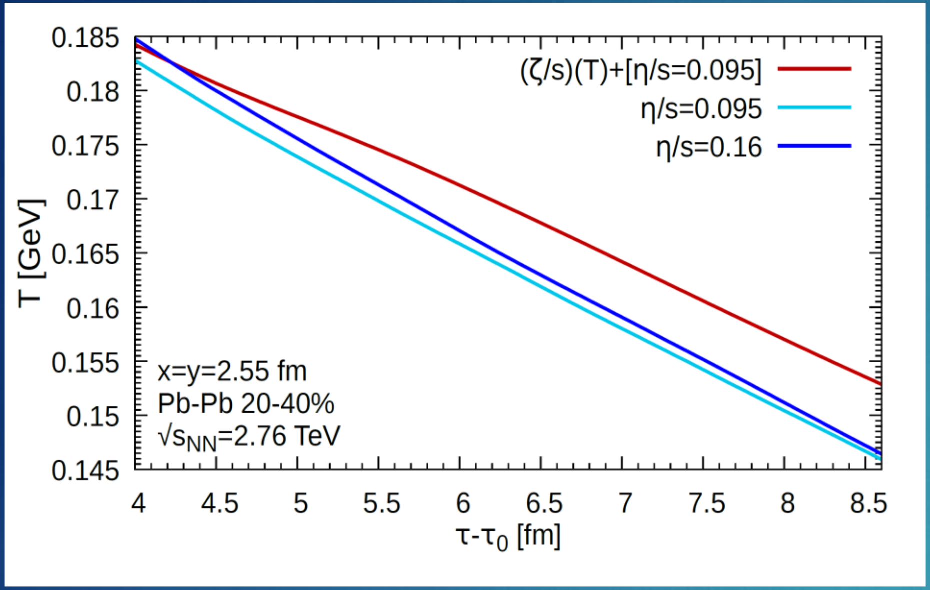
$$v_n^{\gamma^*}\{SP\} = \frac{\left\langle v_n^{\gamma^*} v_n^h \cos\left[n\left(\Psi_n^{\gamma^*} - \Psi_n^h\right)\right]\right\rangle}{\left\langle \left(v_n^h\right)^2\right\rangle^{1/2}}$$

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

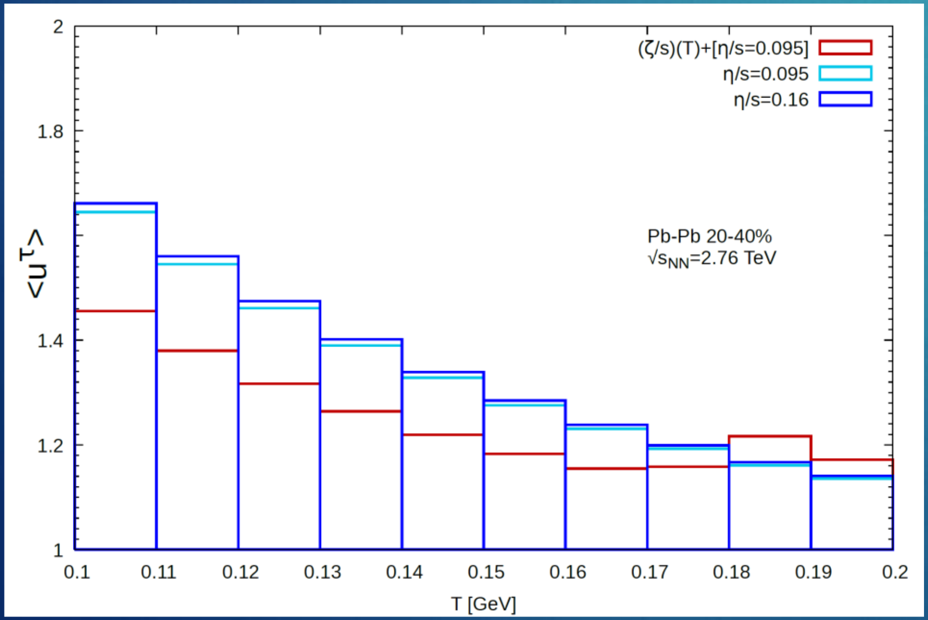
- Some important notes:
  1. <u>Within an event</u>: v_n's are a yield weighted average of the different sources (e.g. HM, QGP, …).
  2. The switch between HM and QGP rates we are using a linear interpolation, in the region $184\ MeV < T < 220 MeV$, given by the EoS [NPA **837**, 26]
- Lastly, the temperature 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.

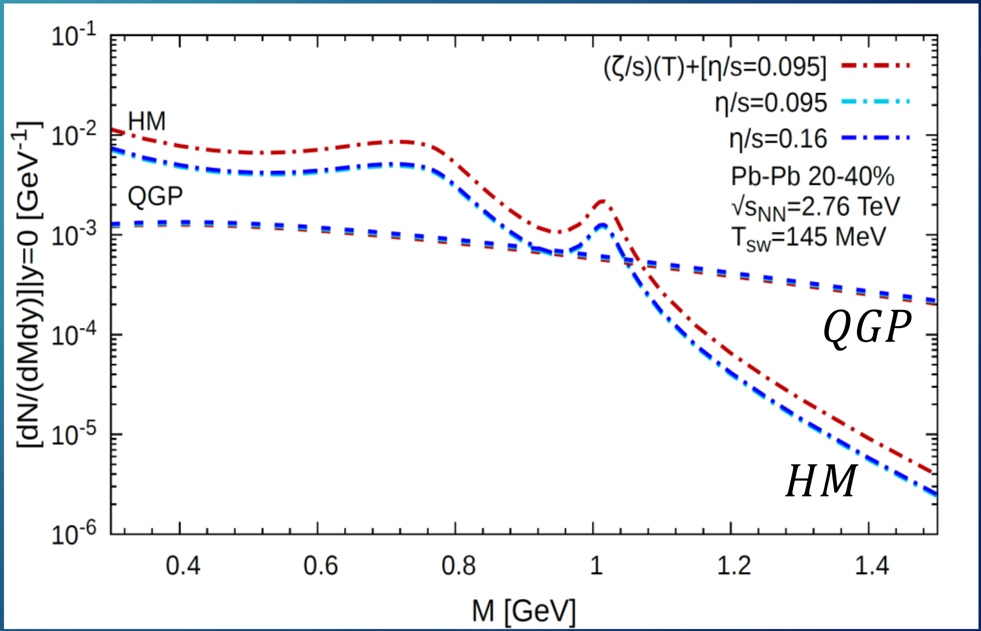
Bulk viscosity & Dileptons

Bulk viscosity and dilepton yield at LHC

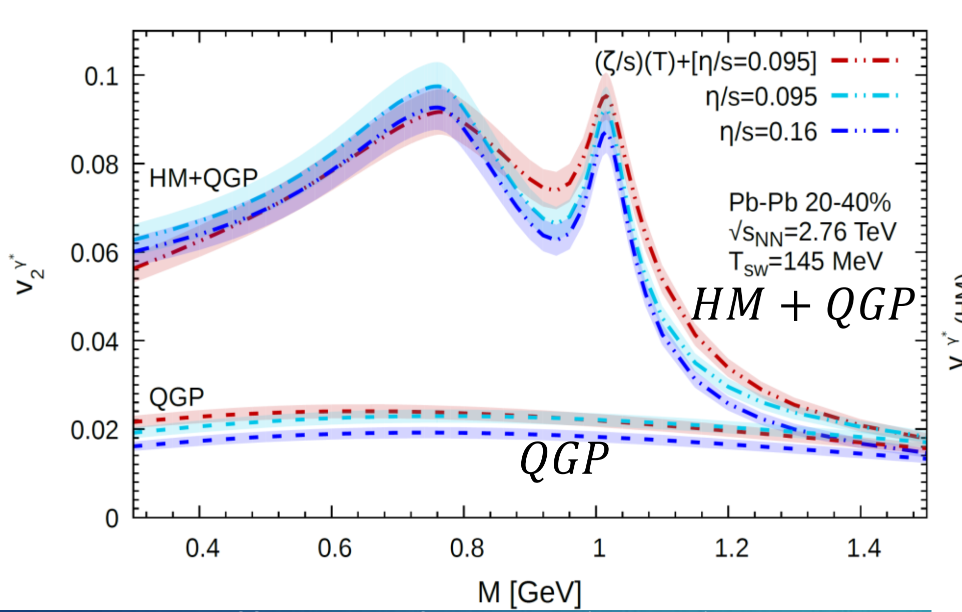


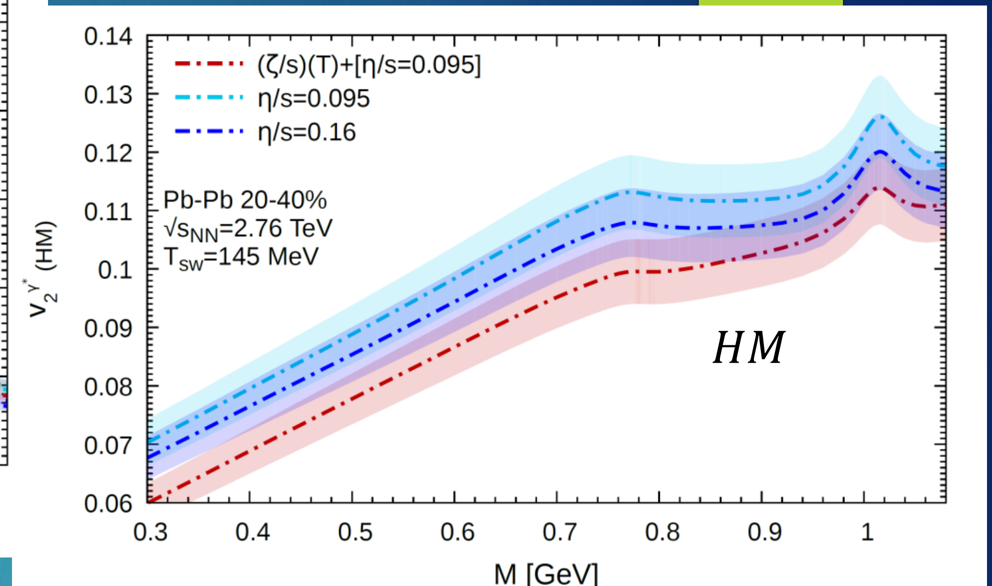
- Bulk viscosity reduces the cooldown rate of the medium, by viscous heating and also via reduction of radial flow acceleration at late times.
- Dilepton yield is increased in the HM sector, since for $T < 184\ MeV$ purely HM rates are used.

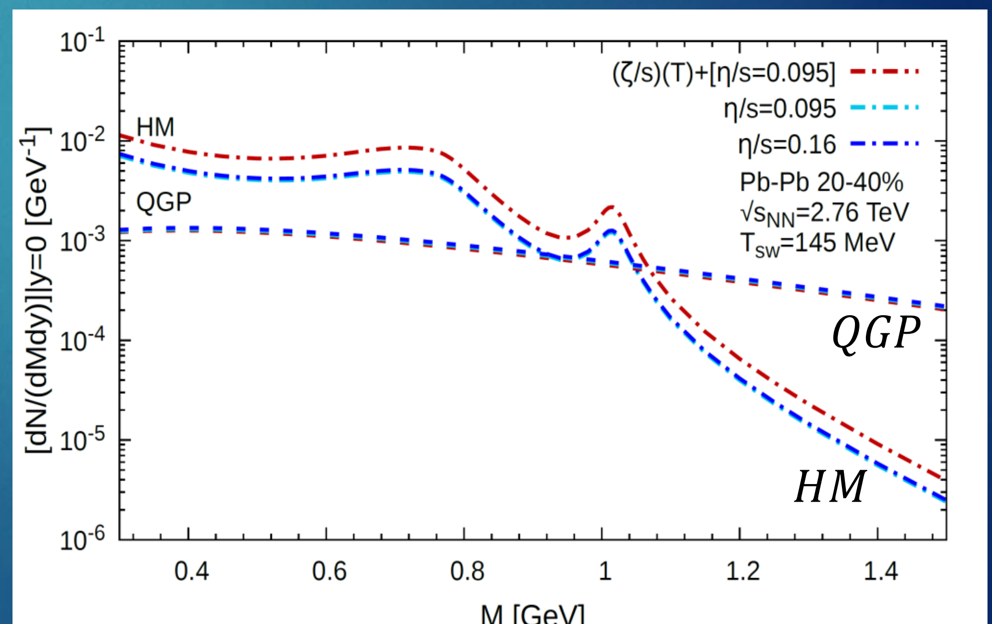




Bulk viscosity and dileptons at LHC

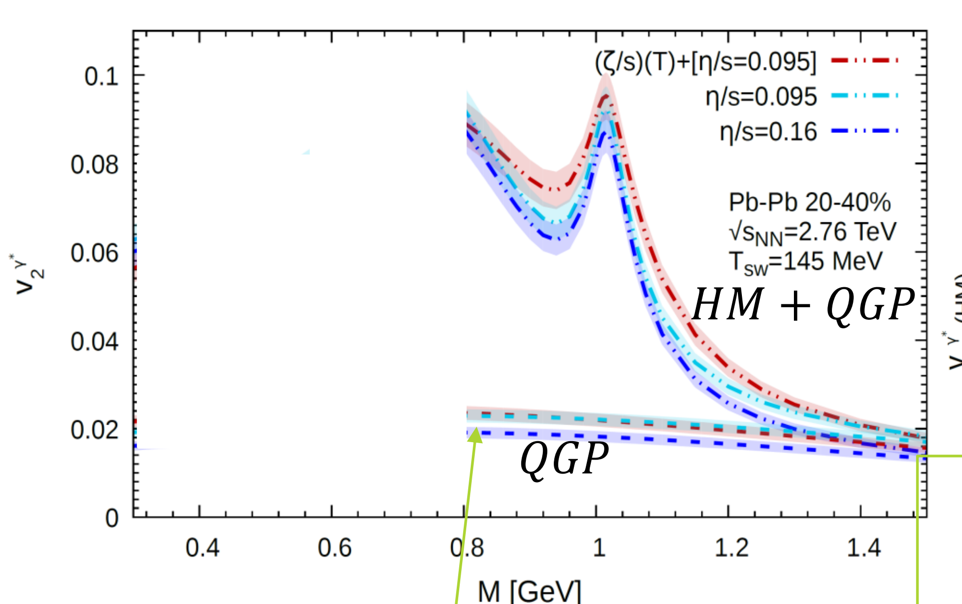


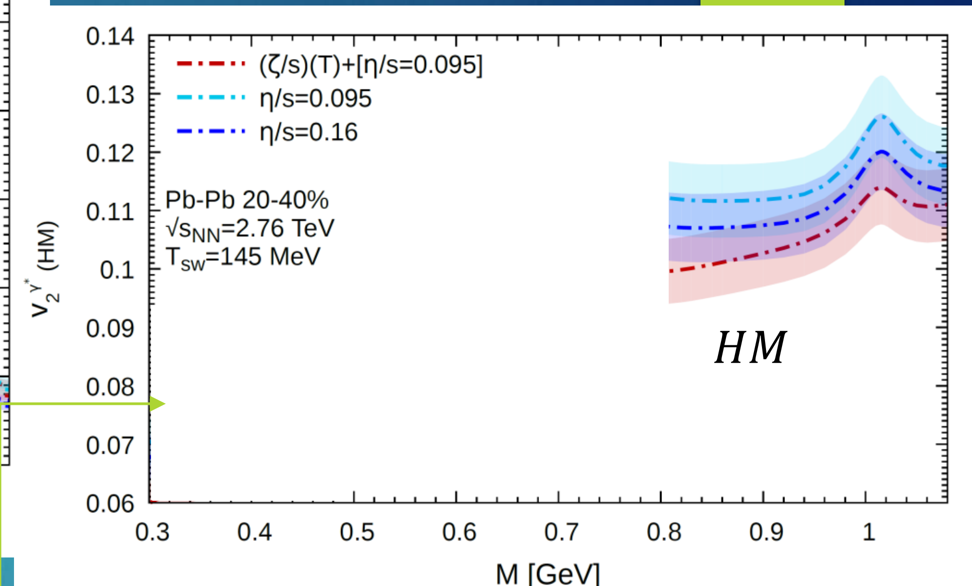




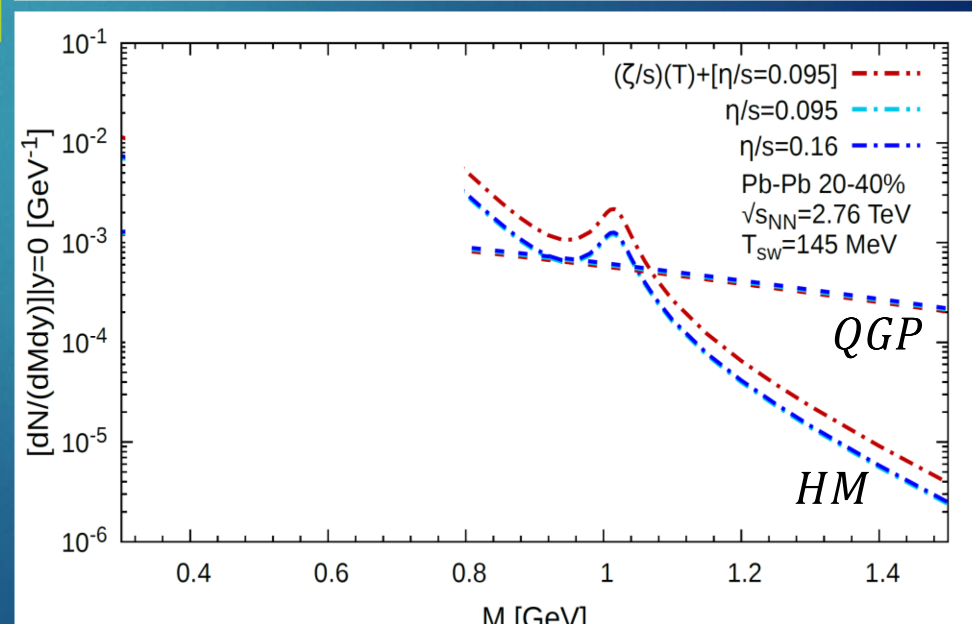
- The effects of bulk viscosity on thermal $v_2(M)$ are quite intricate…

Bulk viscosity and dileptons at LHC

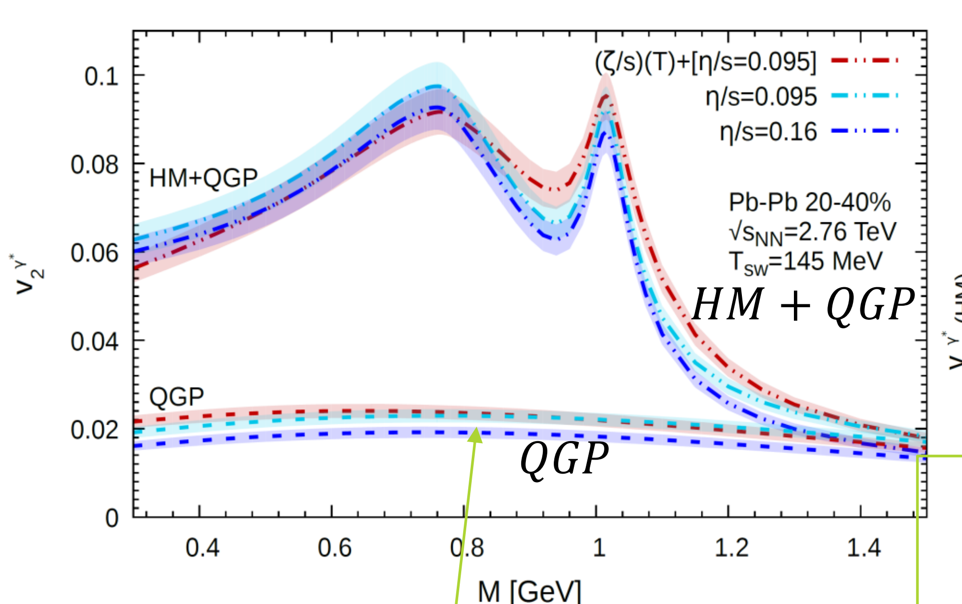


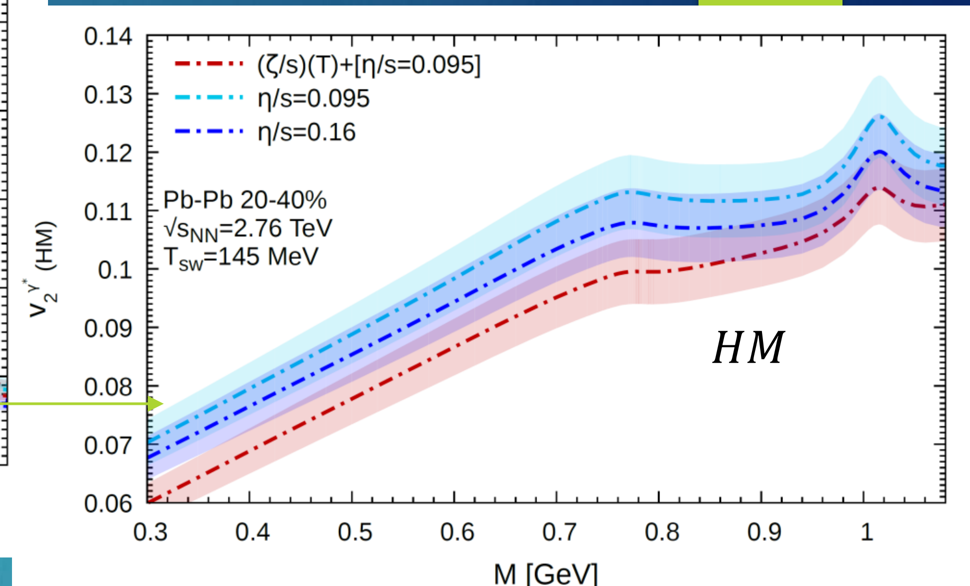


- Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:
  - $M > 0.8\ GeV$: the yield goes from being HM dominated to being QGP dominated. Though, ζ does $\downarrow v_2^{HM}(M)$, it also increases HM yield and $\therefore$ weight to $v_2^{HM}(M)$. So, thermal $v_2(M) \uparrow$.

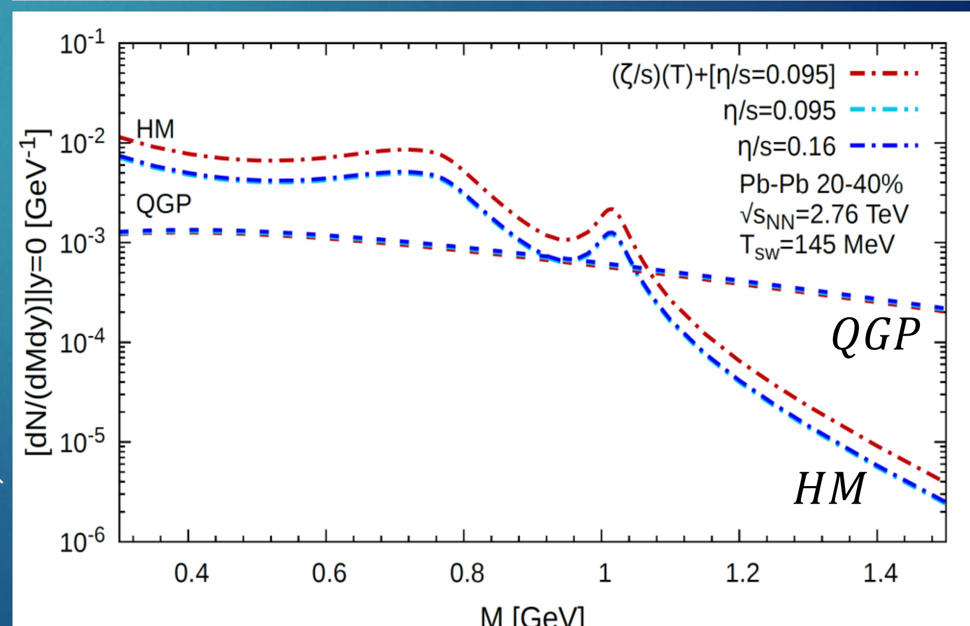


Bulk viscosity and dileptons at LHC

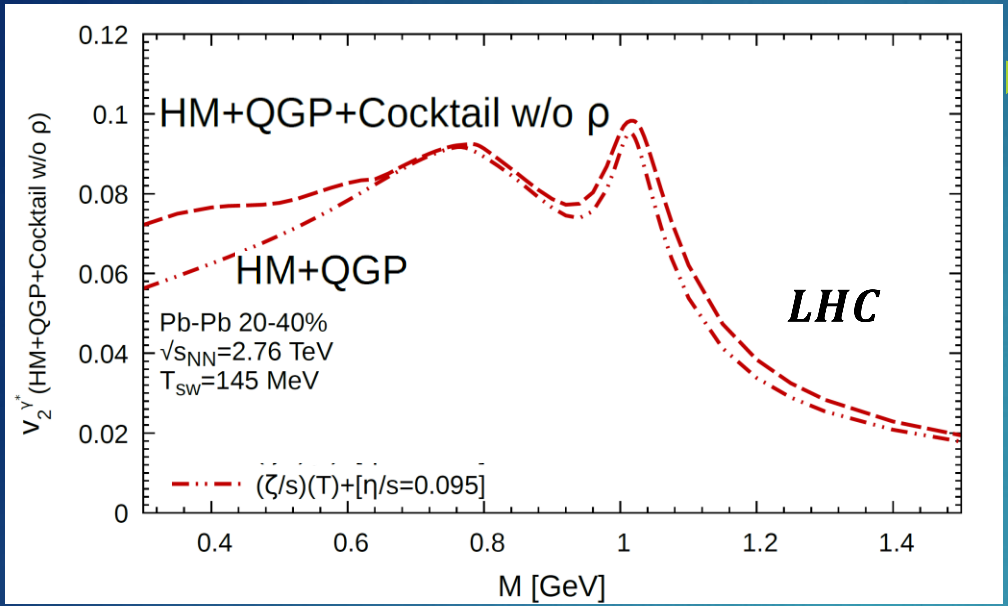


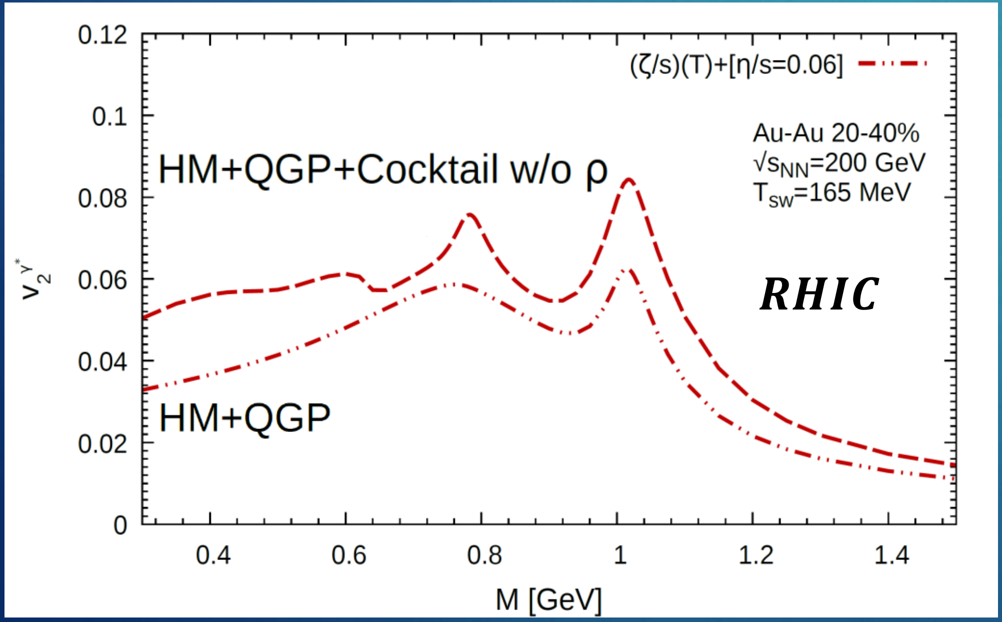


- Thermal $v_2(M)$ is a yield weighted average of QGP and HM contributions:
  - $M > 0.8\ GeV$: the yield goes from being HM dominated to being QGP dominated. Though, ζ does $\downarrow v_2^{HM}(M)$, it also increases HM yield and $\therefore$ weight to $v_2^{HM}(M)$. So, thermal $v_2(M) \uparrow$.
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



Thermal + Cocktail dileptons: LHC/RHIC

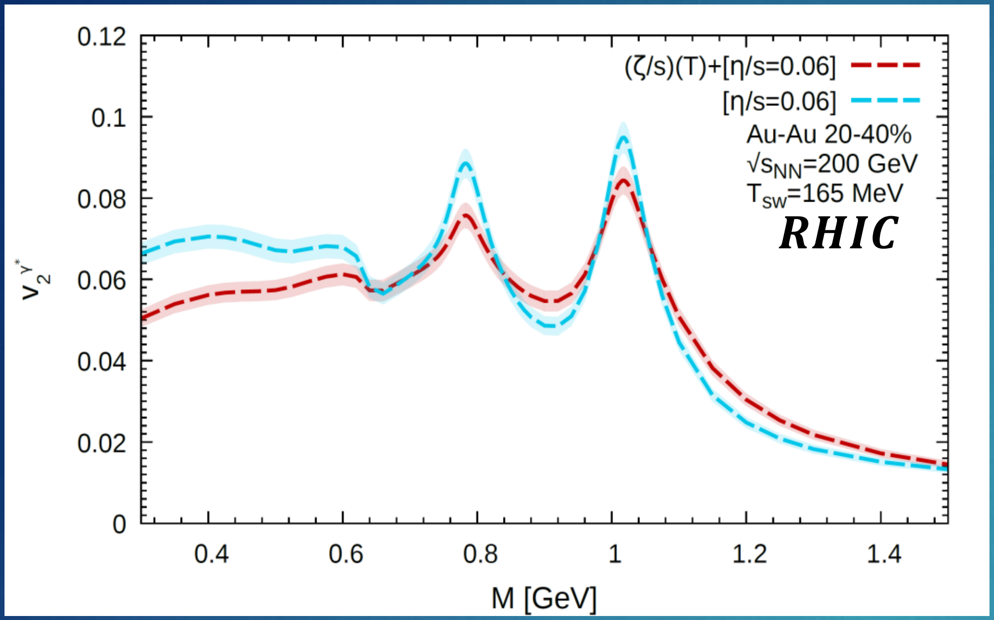


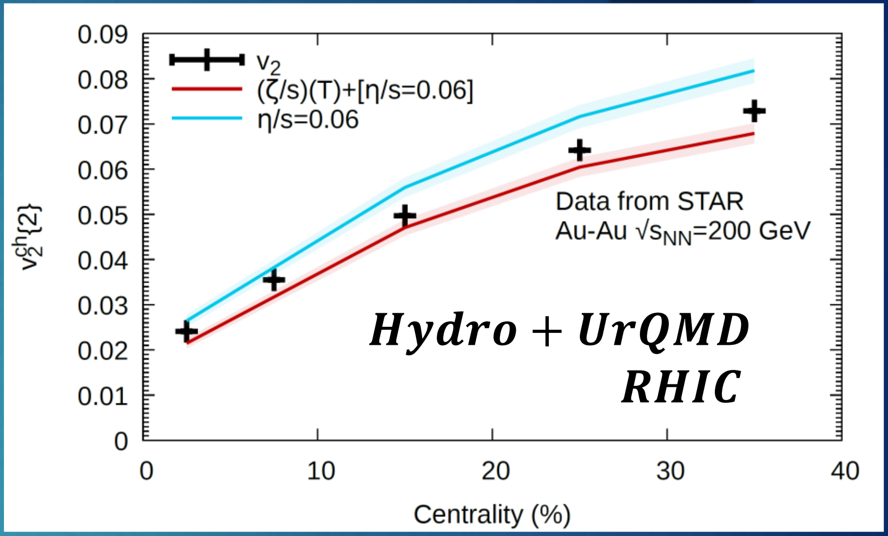


- At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65\ GeV$.

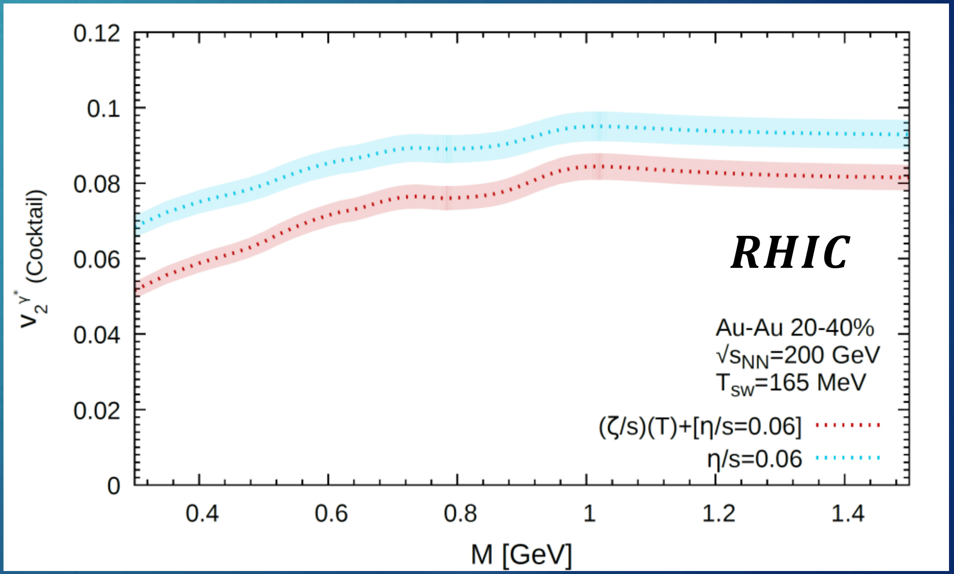
- At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$ is more significant.

Thermal + Cocktail dileptons at RHIC

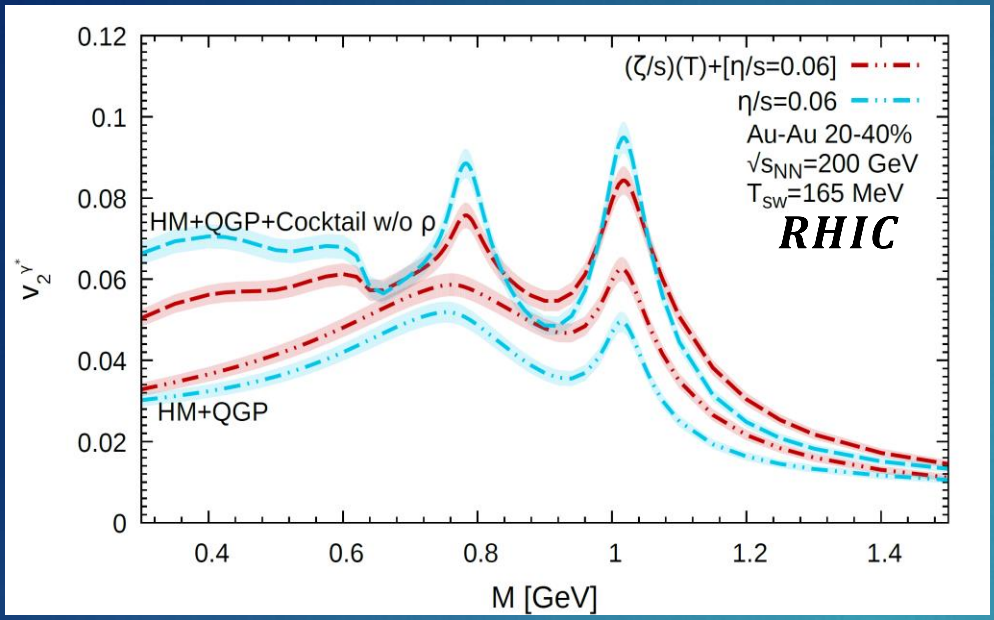


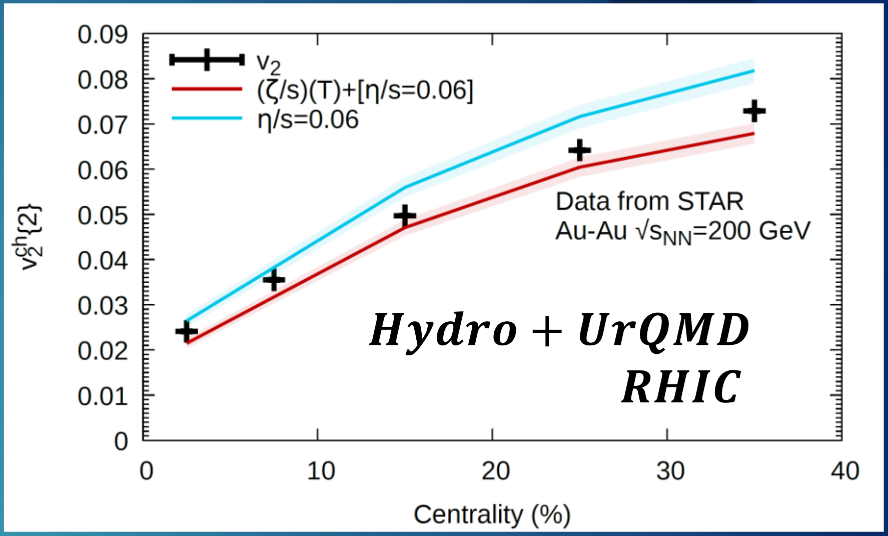


- Comparing the behaviour of dilepton $v_2(M)$ and charged hadron $v_2^{ch}\{2\}$, one notices that the ordering of the curves is the same, except in for $M \sim 0.9\ GeV$ and $M > 1.1\ GeV$.
- The cocktail is not responsible for this behaviour;

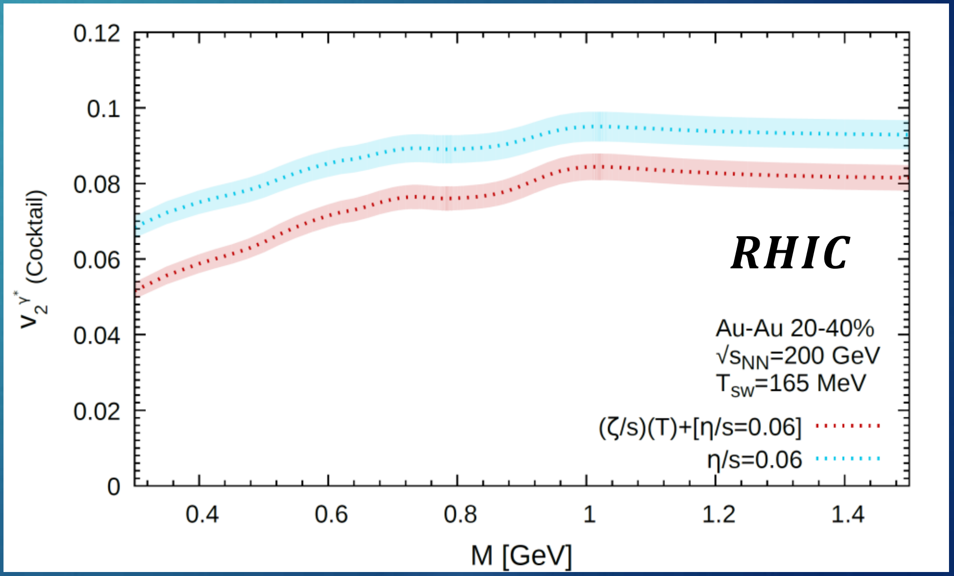


Thermal + Cocktail dileptons at RHIC

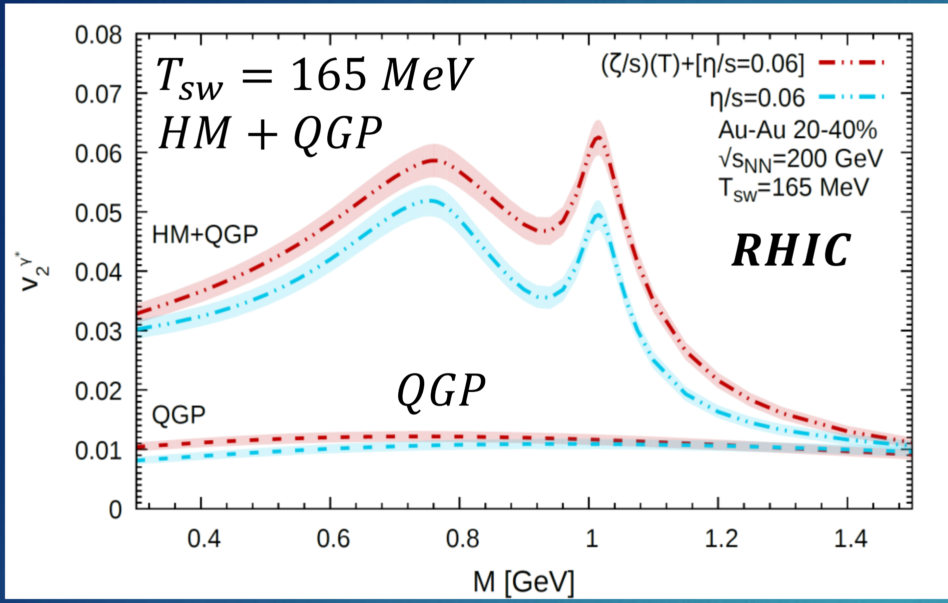


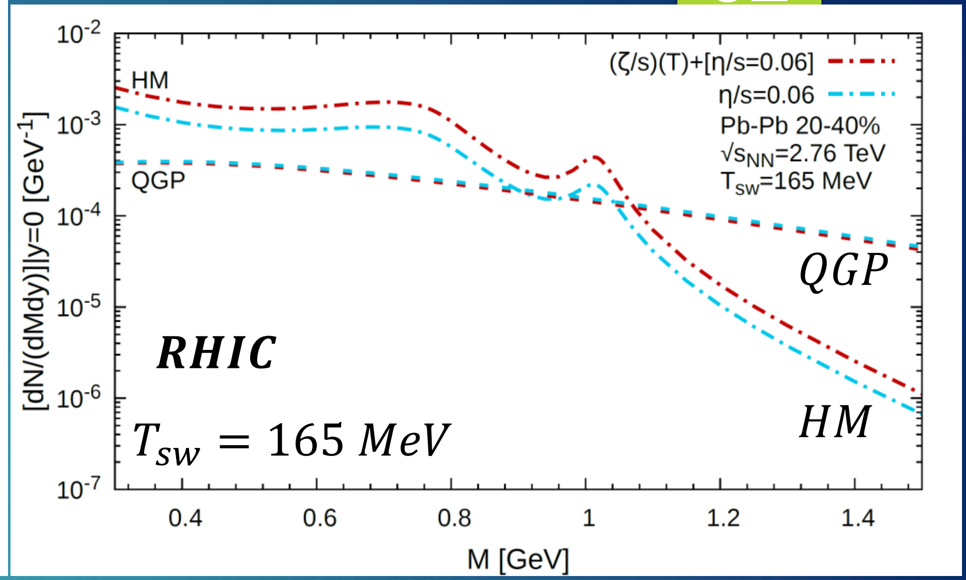


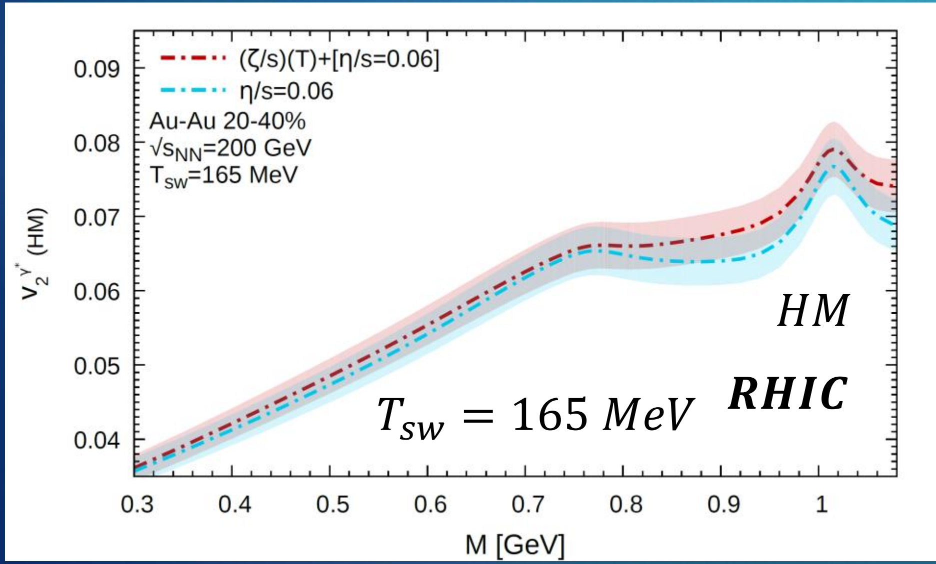
- Comparing the behaviour of dilepton $v_2(M)$ and charged hadron $v_2^{ch}\{2\}$, one notices that the ordering of the curves is the same, except in for $M \sim 0.9\ GeV$ and $M > 1.1\ GeV$.
- The cocktail is not responsible for this behaviour; the thermal contribution is.



Bulk viscosity and dileptons at RHIC

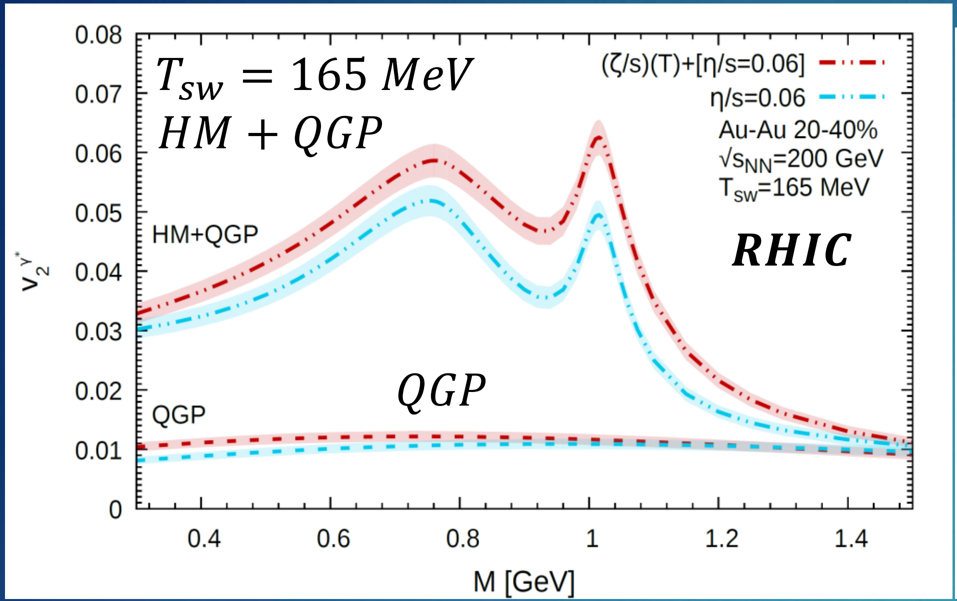


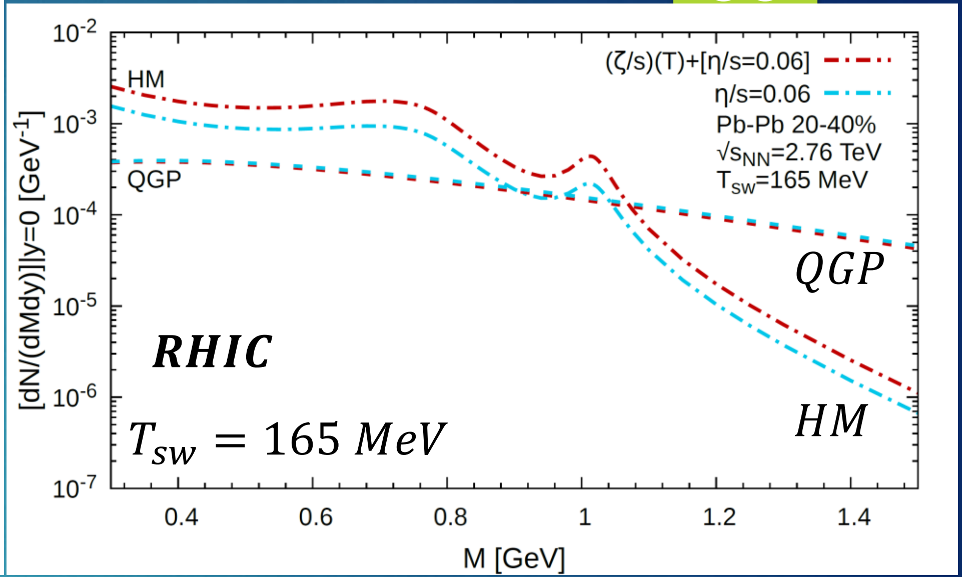


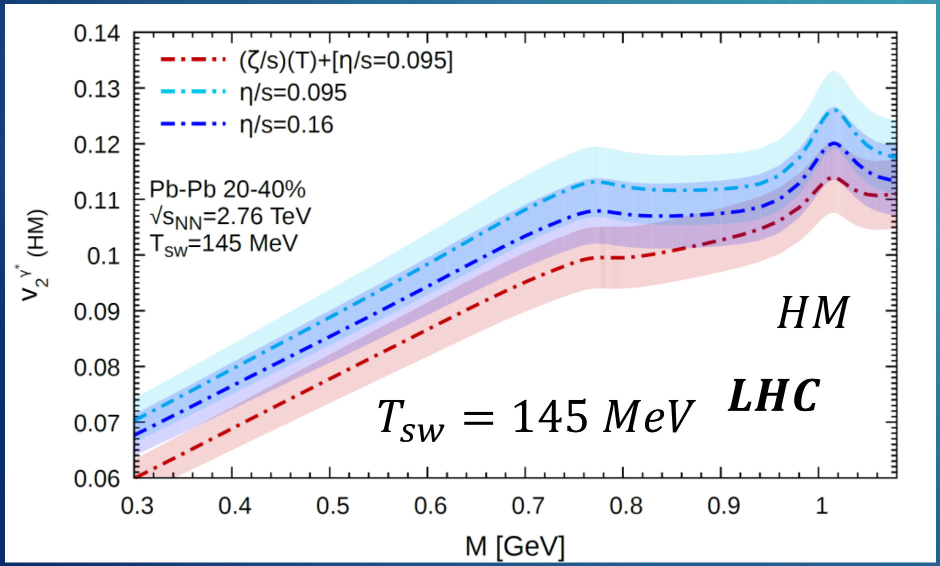


- Most of the ↑ for thermal $v_2(M)$ comes from ↑ in the yield.
- Some of the effect comes from the ↑ in the $v_2(M)$ of HM dileptons at RHIC.

Bulk viscosity and dileptons at RHIC

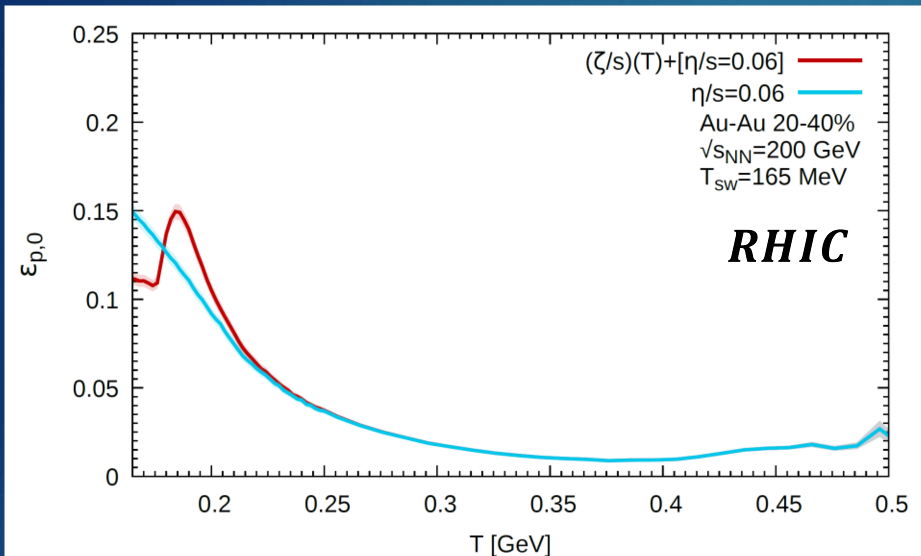


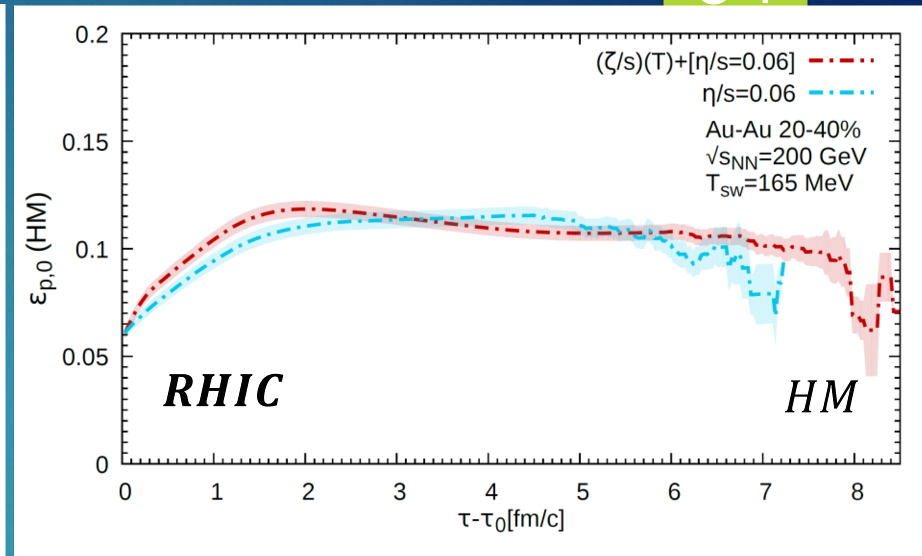




- Most of the ↑ for thermal $v_2(M)$ comes from ↑ in the yield.
- Some of the effect comes from the ↑ in the $v_2(M)$ of HM dileptons at RHIC.
- This doesn't happen at the LHC.

Bulk viscosity and dileptons at RHIC





$$\varepsilon_{p,X}(T) = \frac{1}{N_{ev}}\sum_{i=1}^{N_{ev}}\left\{\frac{\sqrt{\left[\left\langle T^{xx}_{X,i}-T^{yy}_{X,i}\right\rangle_T\right]^2+\left[2\left\langle T^{xy}_{X,i}\right\rangle_T\right]^2}}{\left\langle T^{xx}_{X,i}+T^{yy}_{X,i}\right\rangle_T}\right\}$$

$$\langle A\rangle_T = \int \tau d\tau dy dx B(T) A$$

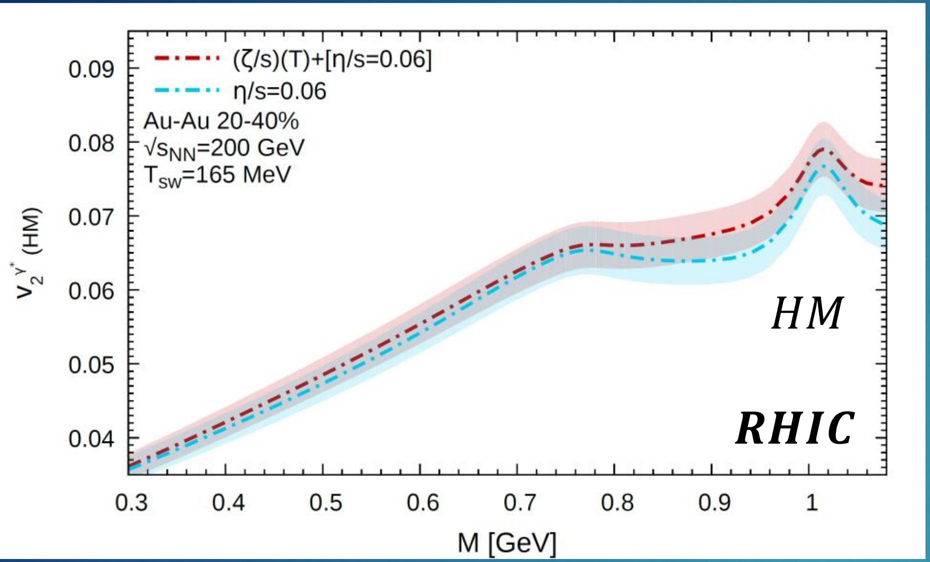
$$B(T) = \begin{cases} 1 & T(\tau,x,y)\in[T_j-\frac{\Delta T}{2},T_j+\frac{\Delta T}{2}) \\ 0 & \text{otherwise}\end{cases}$$

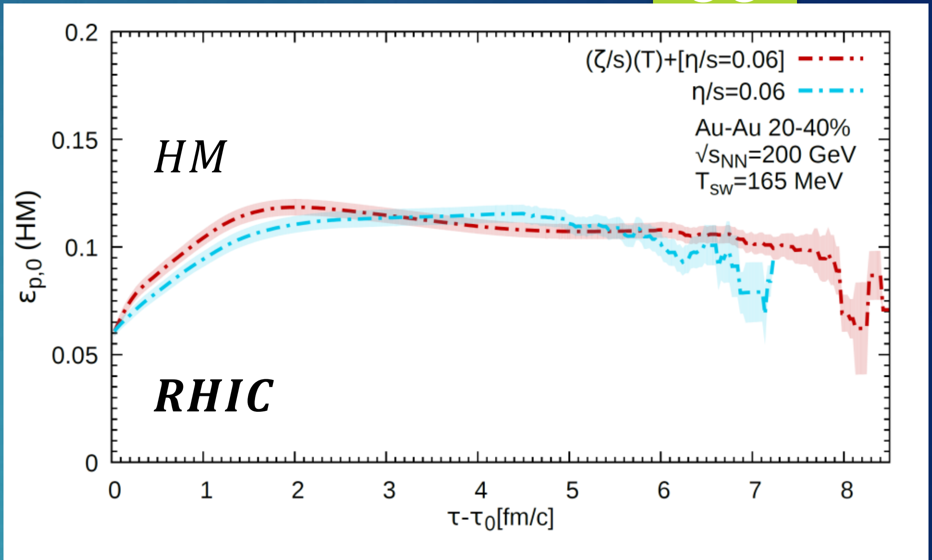
$$\varepsilon_{p,0}(\tau) = \frac{1}{N_{ev}}\sum_{i=1}^{N_{ev}}\left\{\frac{\sqrt{\left[\left\langle T^{xx}_{0,i}-T^{yy}_{0,i}\right\rangle_\tau\right]^2+\left[2\left\langle T^{xy}_{0,i}\right\rangle_\tau\right]^2}}{\left\langle T^{xx}_{0,i}+T^{yy}_{0,i}\right\rangle_\tau}\right\}$$

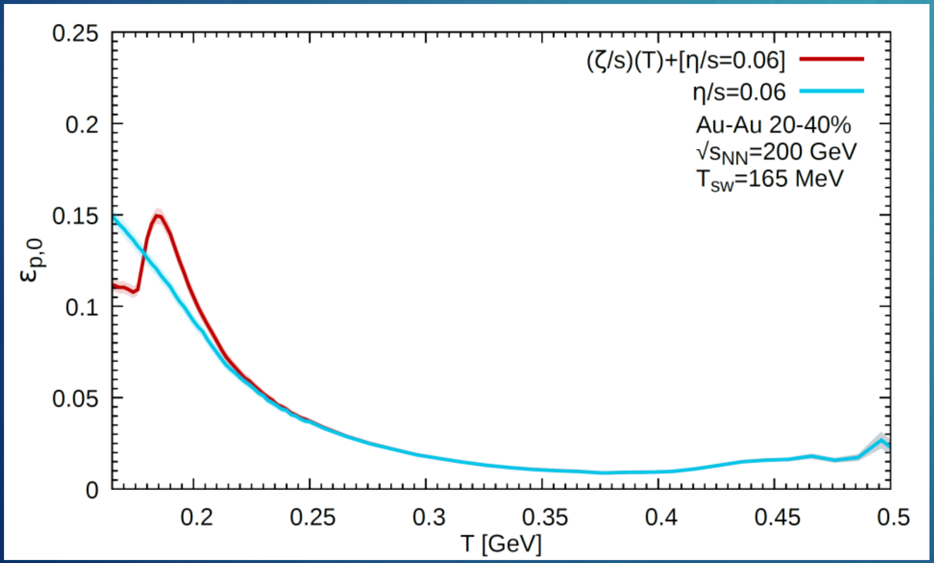
$$\langle A\rangle_\tau = \int_{\tau_0}^{\tau} \tau' d\tau' dy dx (1-f_{QGP})\Theta\left(T-T_{\rm sw}\right) A$$

- Bulk viscosity induces ↑ $\varepsilon_{p,0}$(T) in the region where $\frac{\zeta}{s}(T)$ is maximal.
- The ↑ $\varepsilon_{p,0}$(T) also causes ↑ $\varepsilon_{p,0}(\tau-\tau_0)$ (in the HM sector) at early times, which affects dileptons.

Bulk viscosity and dileptons at RHIC

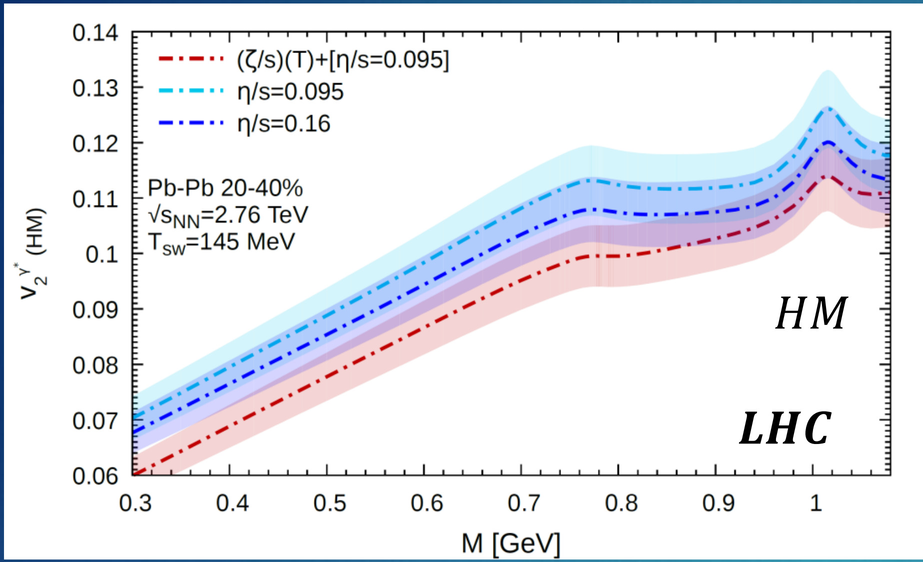


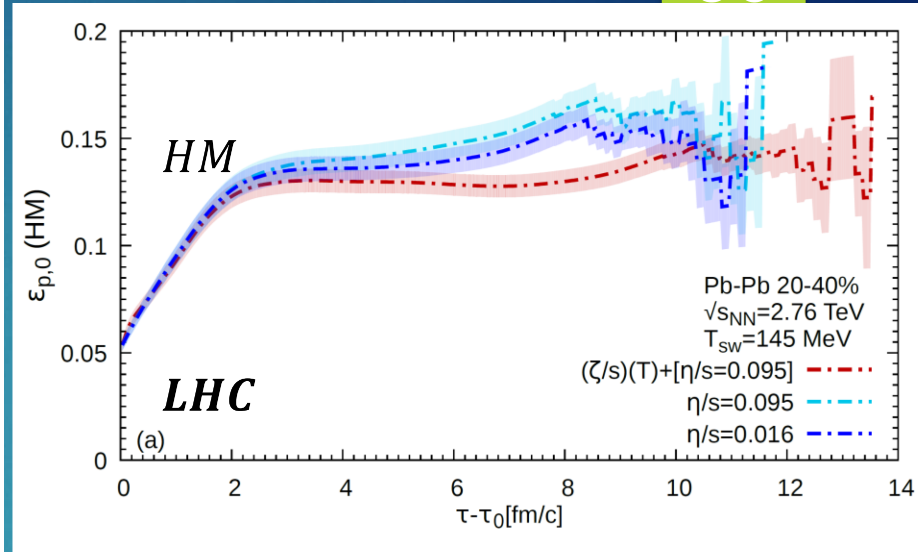


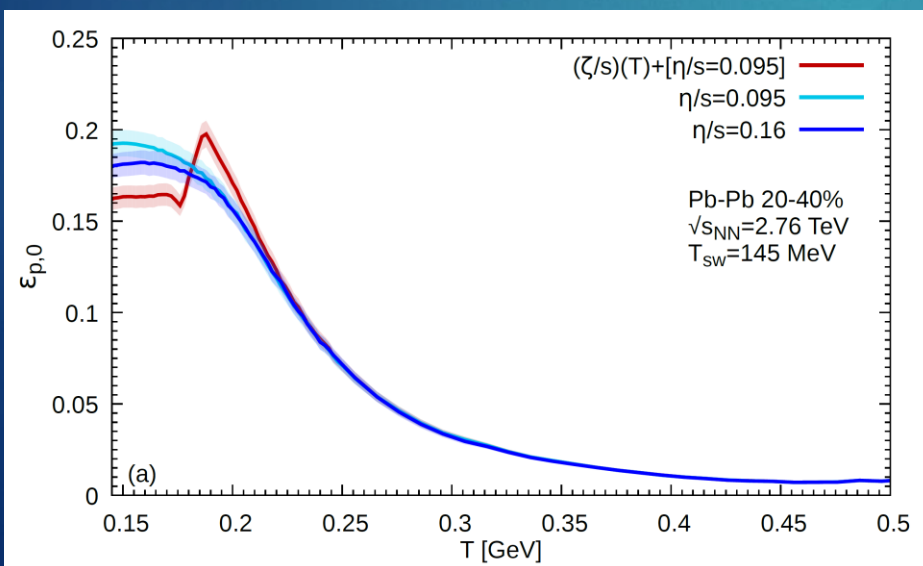


- In the HM sector: the dilepton v_2 at $M \sim 1$ GeV (emitted at early times) seem to be affected by $\uparrow \varepsilon_{p,0}(\tau - \tau_0)$.
- At later times, both dilepton v_2 and $\varepsilon_{p,0}$ are similar with and without bulk viscosity present in the medium.

Bulk viscosity and dileptons at LHC

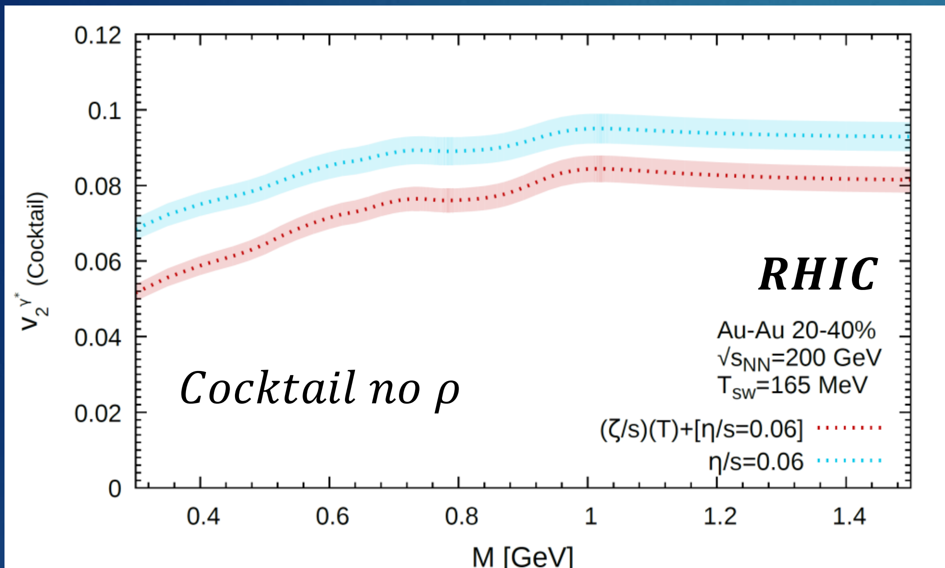


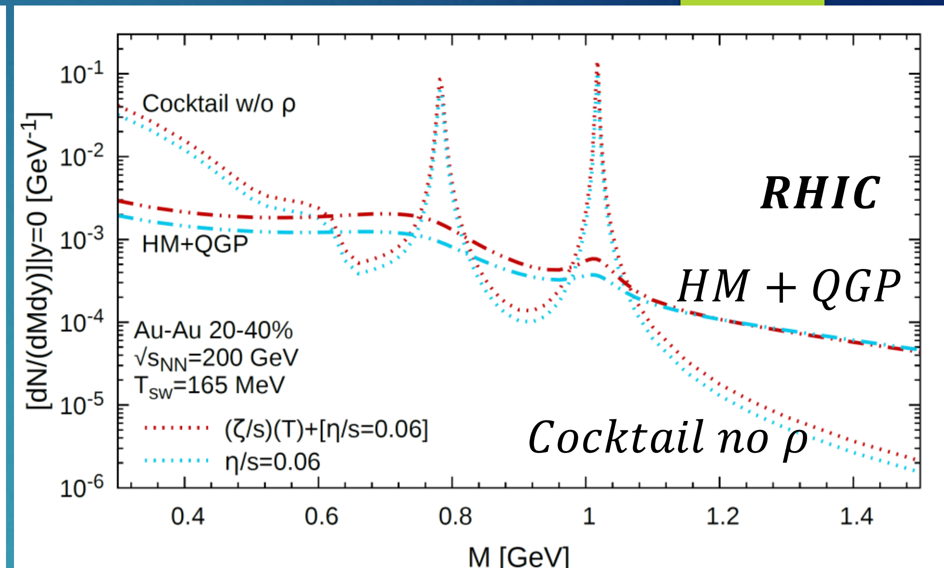


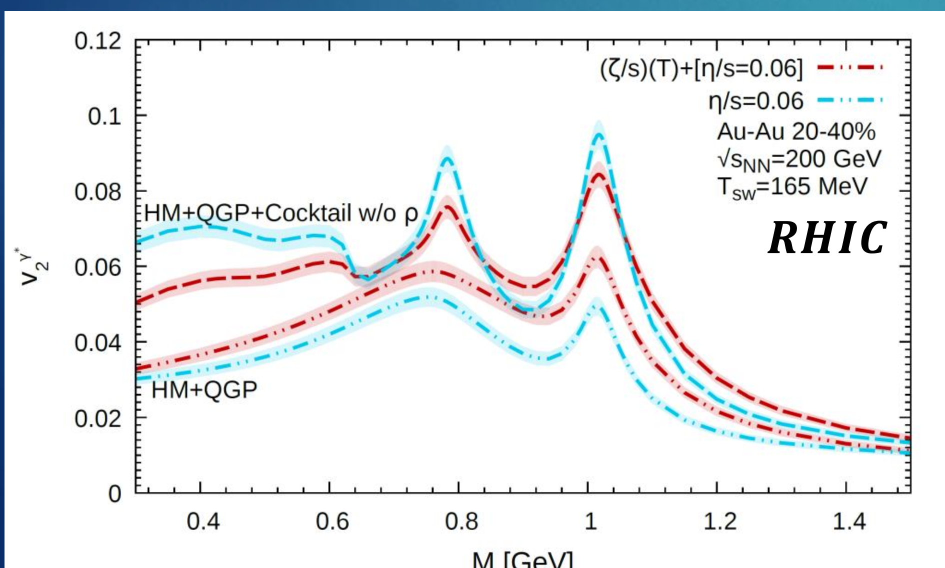


- At later times dilepton v_2 and $\varepsilon_{p,0}(\tau)$ are similar and reduced by bulk viscosity.
- The effects on $\varepsilon_{p,0}(T)$ are similar at RHIC vs LHC, but $T_{sw}^{LHC} < T_{sw}^{RHIC}$, hence more dynamics captured at lower T.

Bulk viscosity and dileptons at RHIC

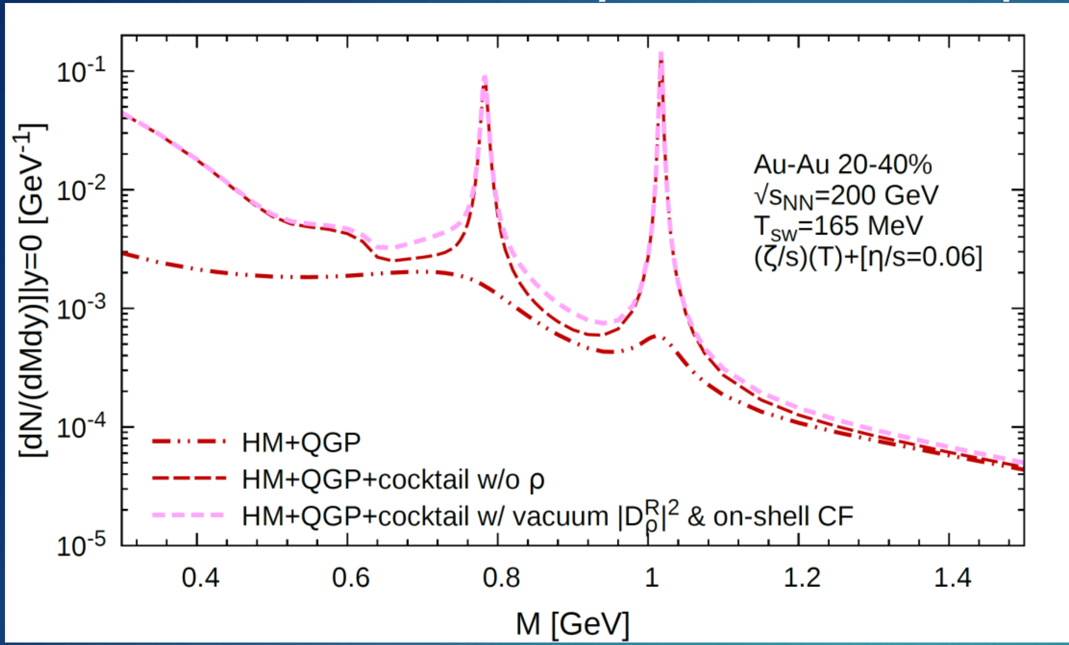






- The $v_2(M)$ of dileptons from the cocktail, which are emitted at late times, behaves similarly to the $v_2^{ch}\{2\}$ charged hadron.
- The interplay between the thermal and cocktail yields generates the final $v_2(M)$.

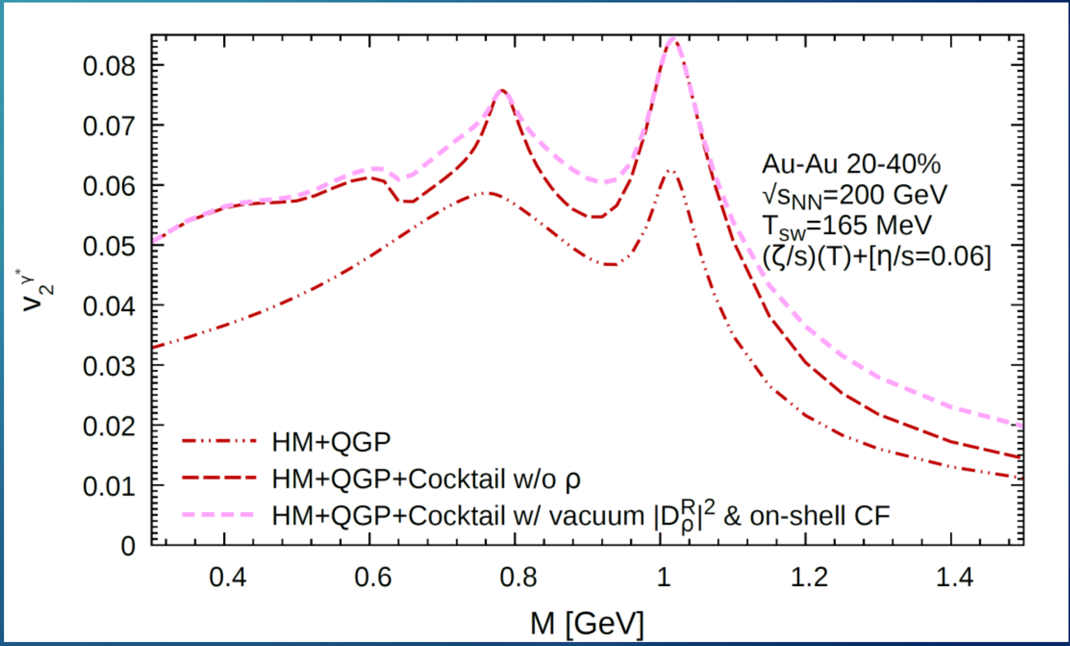
Bulk viscosity and dileptons at RHIC



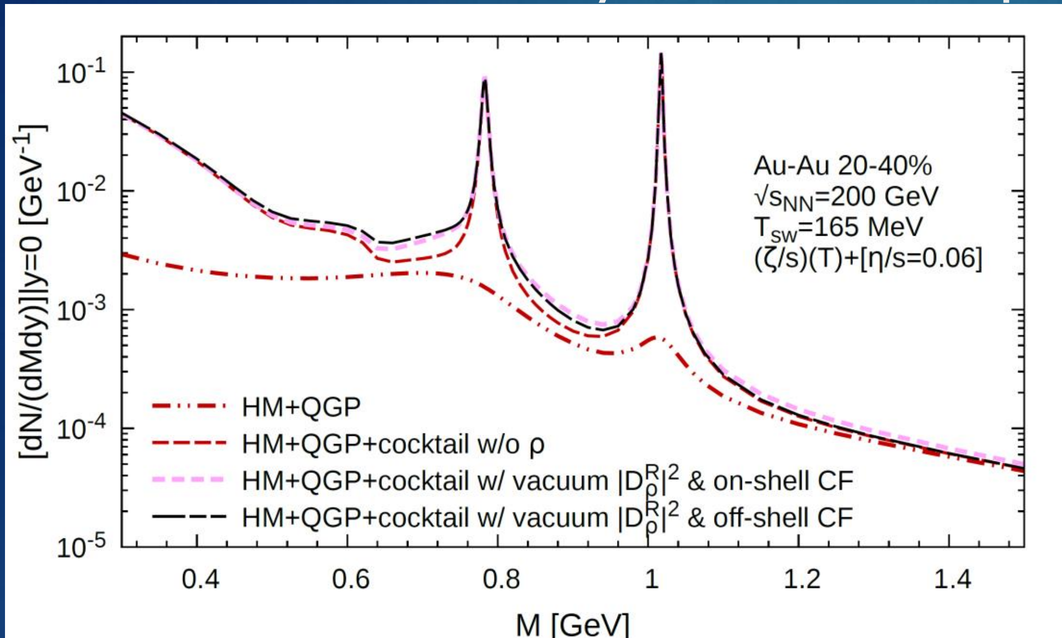
$$\frac{d^4 N_{\gamma^*}}{d^4 p} = \frac{\alpha_{EM}^2}{\pi^3} \frac{m_\rho^4}{g_\rho^2} \frac{L(M)}{M^2} \left| D_\rho^R(M, T=0) \right|^2 \times$$

$$\times \left[\begin{array}{c} \int d^3\Sigma_\mu p^\mu n_\rho (M = m_\rho) \\ NO\ res.decay \end{array} \right]$$

- Often, hydrodynamical calculations of hadron spectra assume hadrons are their mass on-shell.
- The ρ has a substantial contribution to both yield and v_2

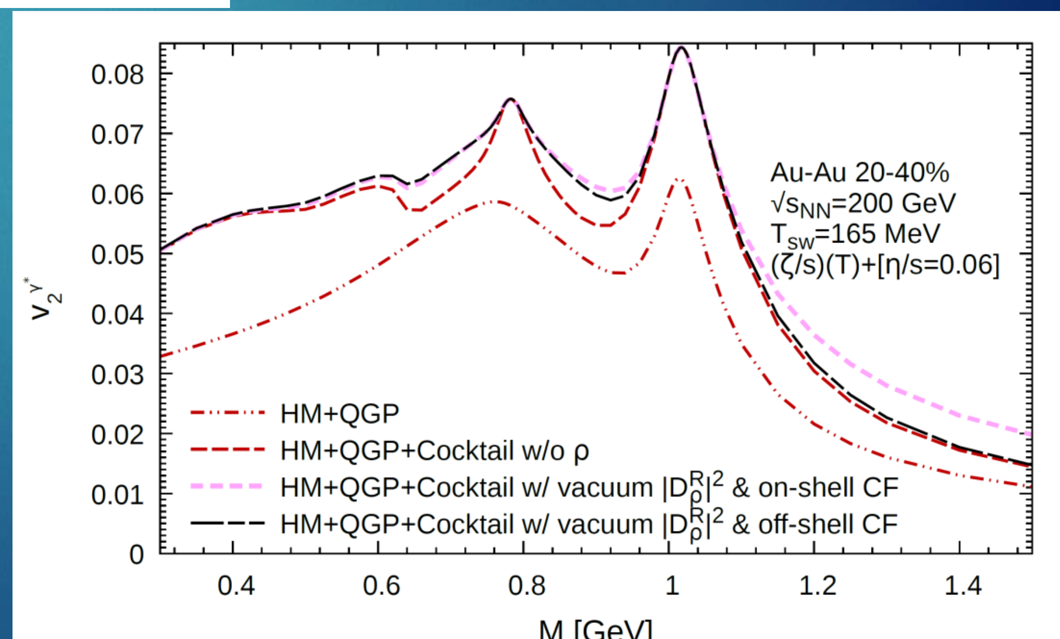


Bulk viscosity and dileptons at RHIC

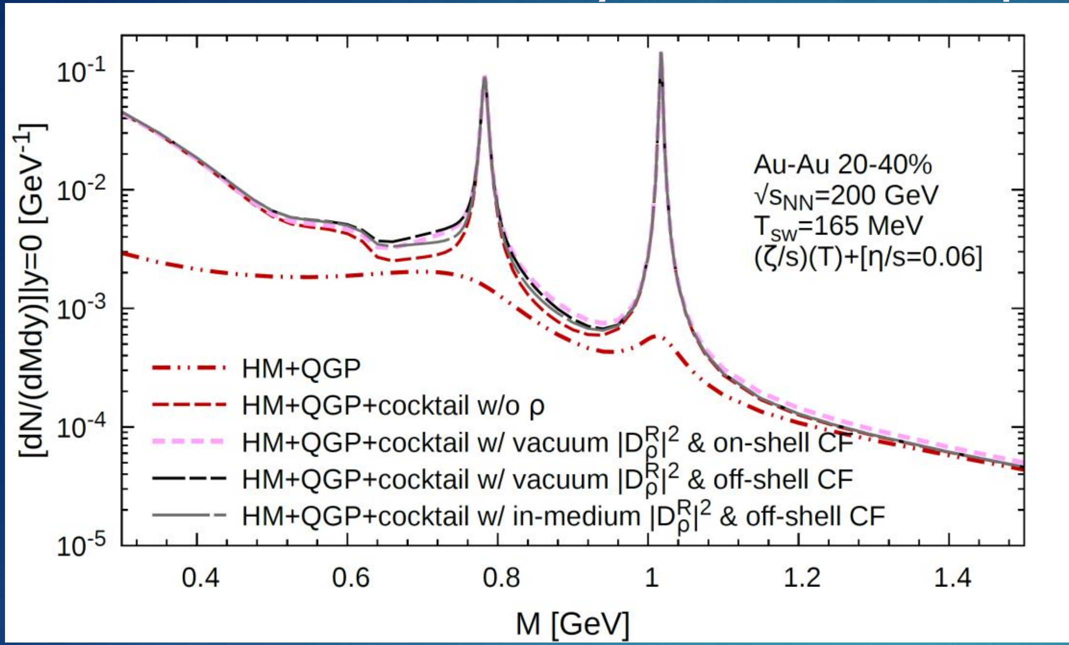


$$\frac{d^4N_{\gamma^*}}{d^4p} = \frac{\alpha_{EM}^2}{\pi^3}\frac{m_\rho^4}{g_\rho^2}\frac{L(M)}{M^2}\left|D_\rho^R(M,T=0)\right|^2 \times$$
$$\times\left[\begin{array}{c}\int d^3\Sigma_\mu p^\mu n_\rho(M)\\ NO\ res.decays\end{array}\right]$$

- The on-shell approximation must be relaxed if $\Gamma \sim m$.
- Including the vacuum width of the ρ, the dilepton yield spectrum is slightly modified, while v_2 is significantly changed especially for $M \gtrsim 1$ GeV.

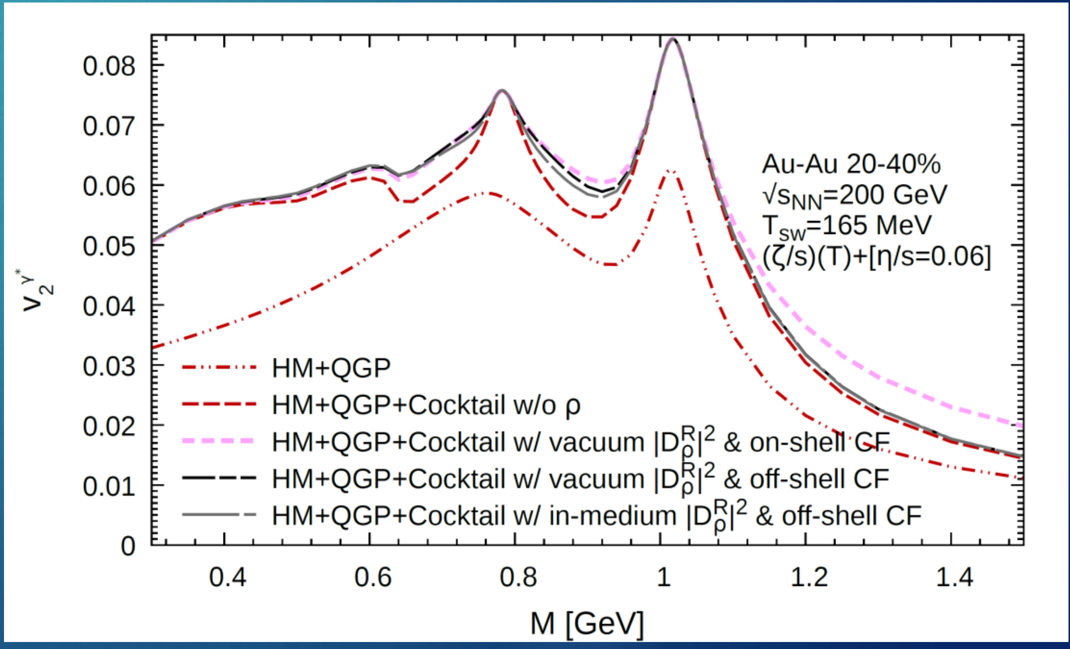


Bulk viscosity and dileptons at RHIC

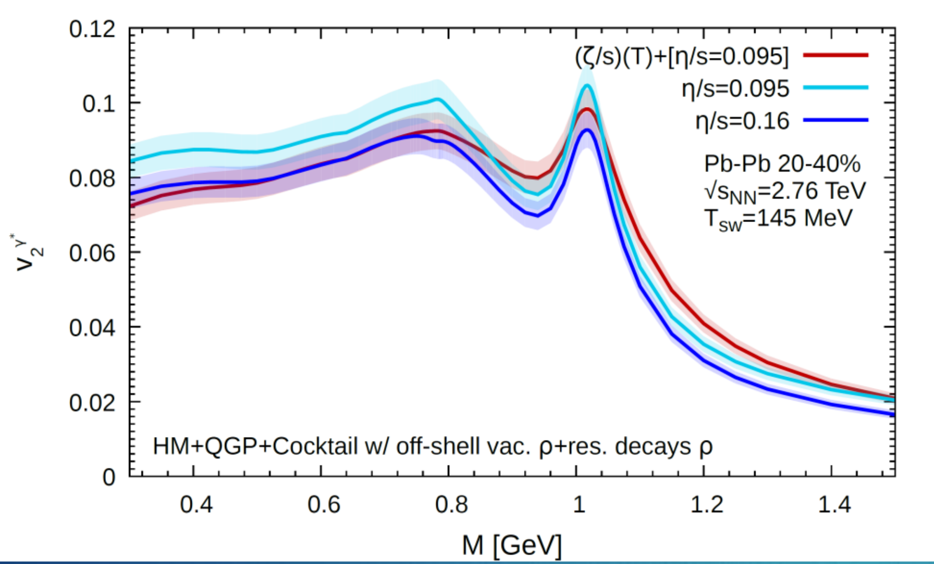


$$\frac{d^4N_{\gamma^*}}{d^4p} = \frac{\alpha_{EM}^2}{\pi^3}\frac{m_\rho^4}{g_\rho^2}\frac{L(M)}{M^2}\left|D_\rho^R(M, T = T_{sw})\right|^2 \times \left[\begin{array}{c}\int d^3\Sigma_\mu p^\mu n_\rho(M) \\ NO\ res.\ decays\end{array}\right]$$

- The lifetime of the ρ is comparable to the lifetime of the hydro simulation. Does $\Gamma_\rho^{\rm vac}(T=0)$ vs. $\Gamma_\rho^{\rm med}\,(T = T_{sw})$ matter?
- It really depends on the uncertainty of the measurement.



Bulk viscosity and dileptons at both RHIC and LHC



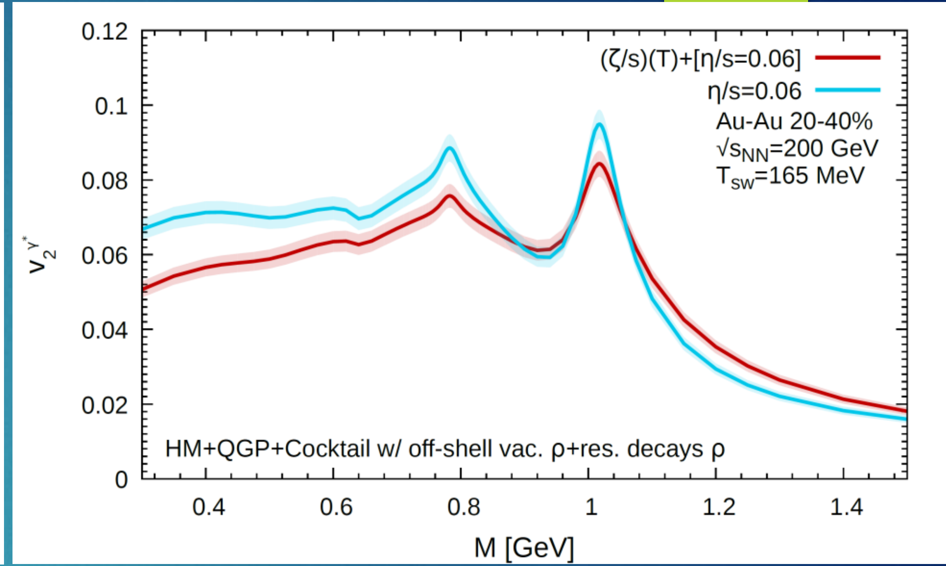


TABLE III: The $\frac{v_2(M=0.9\,\mathrm{GeV})}{v_2(M=0.3\,\mathrm{GeV})}$ ratio, including the cocktail ρ contribution, as a tool to measure the effects of bulk viscosity

LHC	$(\zeta/s)(T)+[\eta/s=0.095]$	$\eta/s=0.095$	$\eta/s=0.16$	RHIC	$(\zeta/s)(T)+[\eta/s=0.06]$	$\eta/s=0.06$
incl. off-shell vac. ρ	1.12	0.922	0.954	incl. off-shell vac. ρ	1.18	0.859
incl. off-shell vac. ρ & res. decay ρ	1.13	0.938	0.967	incl. off-shell vac. ρ & res. decay ρ	1.23	0.920

- These rather intricate v_2 curves are sensitive to effects of bulk viscosity, which can be highlighted via the ratio $\frac{v_2(M=0.9)}{v_2(M=0.3)}$ below.
- A measurement of $v_2(M)$ at several invariant masses would provide a similar constraint to ζ/s.

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, so measuring $v_2(M)$ at different M is needed.

Outlook

- Investigate the effects of open heavy-flavor semi-leptonic decays on dilepton yield and v_2.
- What are the prospects of removing the cocktail (e.g. NA60)?

Backup Slides

Modelling the thermal contribution

- In the non-rel. limit: $E_V = \frac{p^2}{2m_V} + U_{Va}^{Ret.}$
- The real part of the retarded optical potential $U_{Va}^{Ret.}$

$$Re\left[U_{Va}^{Ret.}\right] = \rho_a \int d^3x \, V_{Va}(\boldsymbol{x})$$

- V_{Va} 2-body potential for Va system
- Born approx., the Forward Scattering Amplitude (FSA)

$$Re[f_{Va}(\boldsymbol{k} = \boldsymbol{k}')] = -\frac{m_V}{2\pi} \int d^3x \, e^{i(\boldsymbol{0}\cdot\boldsymbol{x})} \, V_{Va}(\boldsymbol{x})$$
$$\Rightarrow Re\left[\Pi_{Va}^{Ret.}\right] \equiv 2m_V Re\left[U_{Va}^{Ret.}\right] = -4\pi\rho_a Re[f_{Va}]$$

- $Im[E_V] = \Gamma_V = \frac{u_{Va}}{\lambda_{Va}^{mfp}} = u_{Va}\rho_a\sigma_{Va}$
- The optical theorem: relates the $Im\left[U_{Va}^{Ret.}\right]$ to the FSA

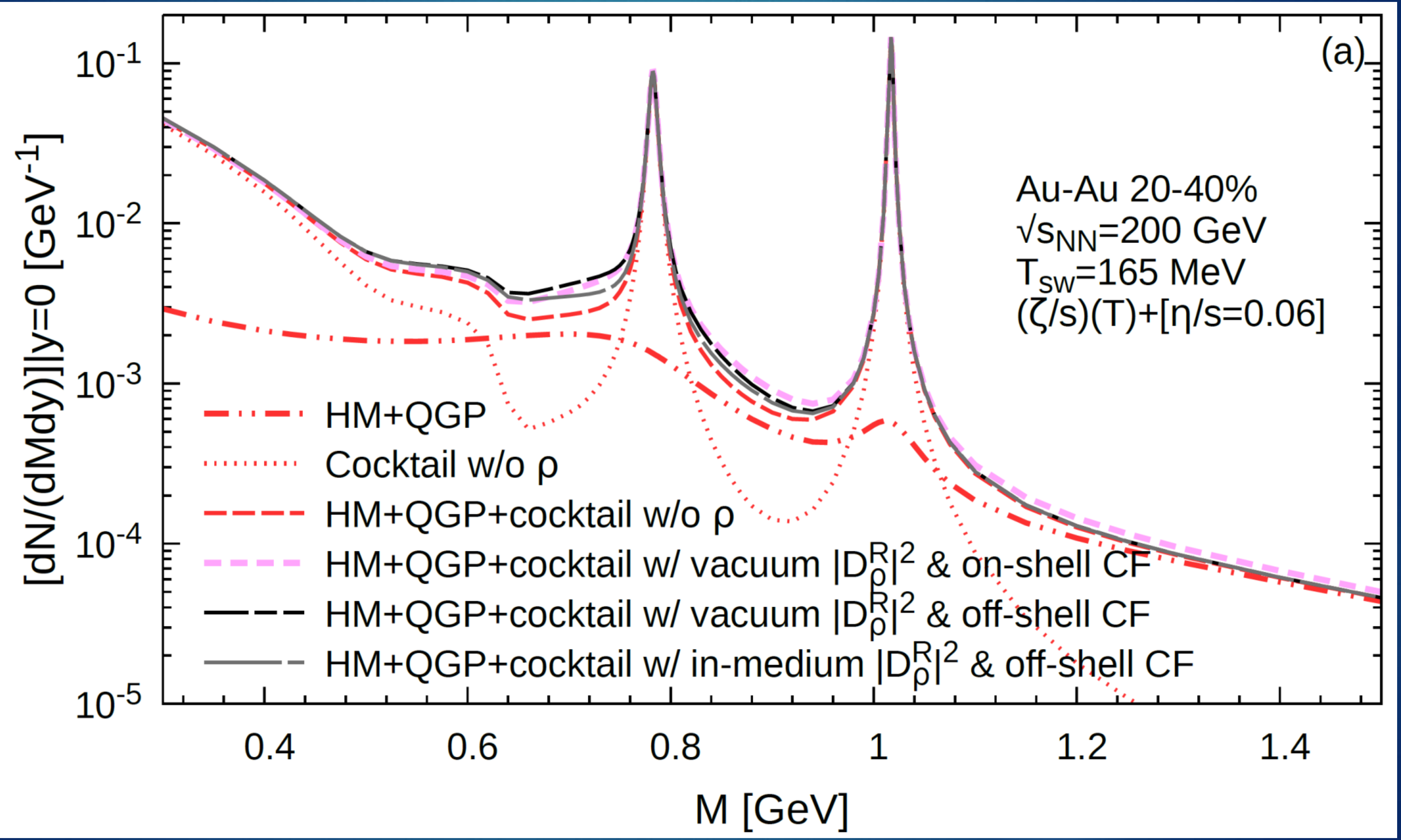
$$2m_V Im[U_{Va}] = -4\pi\rho_a Im[f_{Va}]$$

- Thus

$$Im\left[\Pi_{Va}^{Ret.}\right] = -4\pi\rho_a Im[f_{Va}] \Rightarrow \Pi_{Va} = -4\pi\rho_a f_{Va}$$

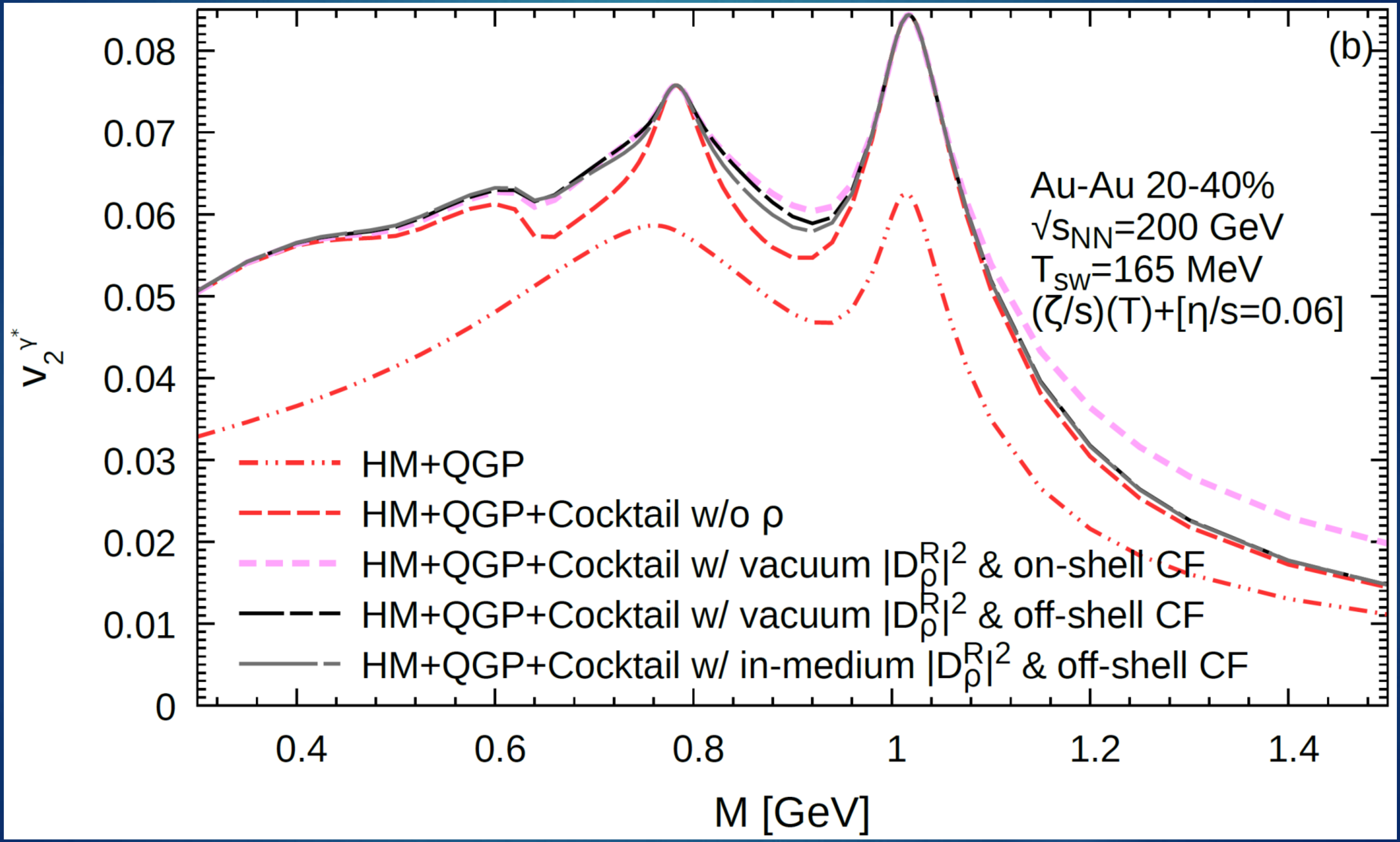
Cocktail dileptons from the ρ

- Effects on the yield

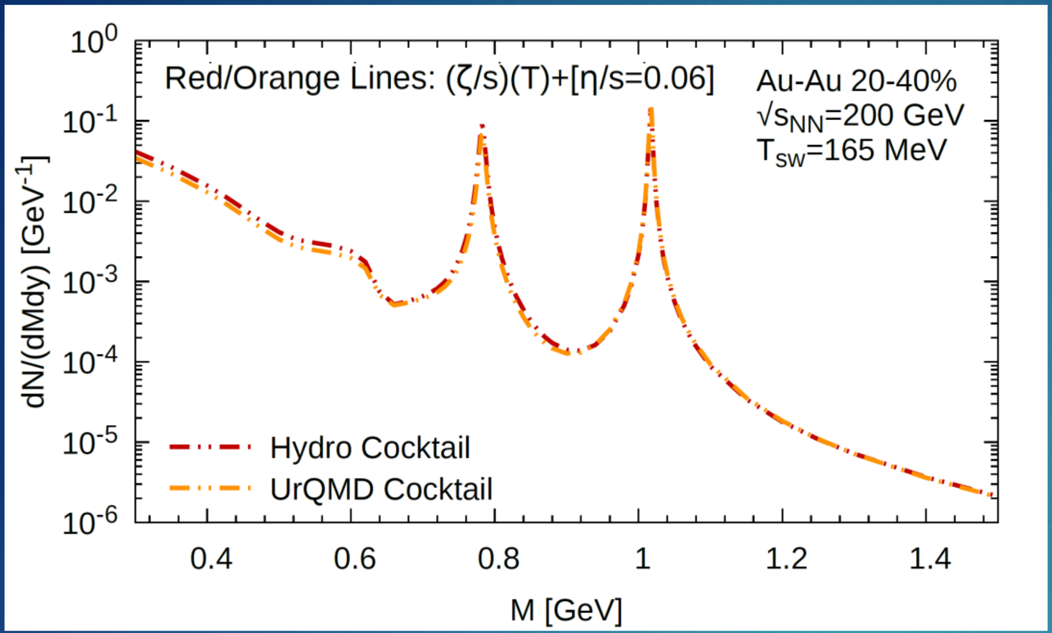


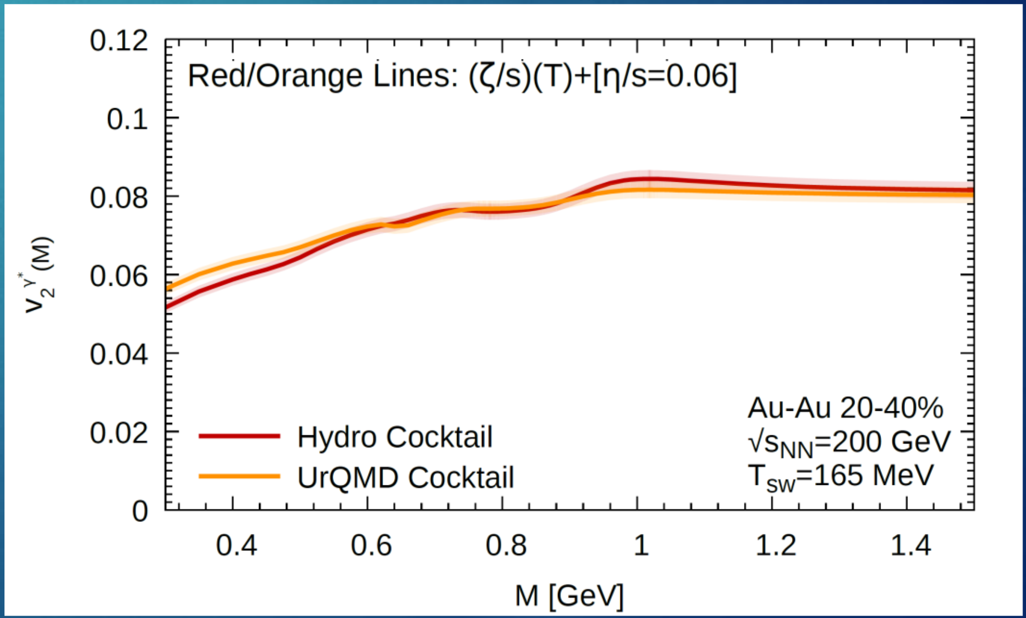
Cocktail dileptons from the ρ

- Effects on the $v_2(M)$

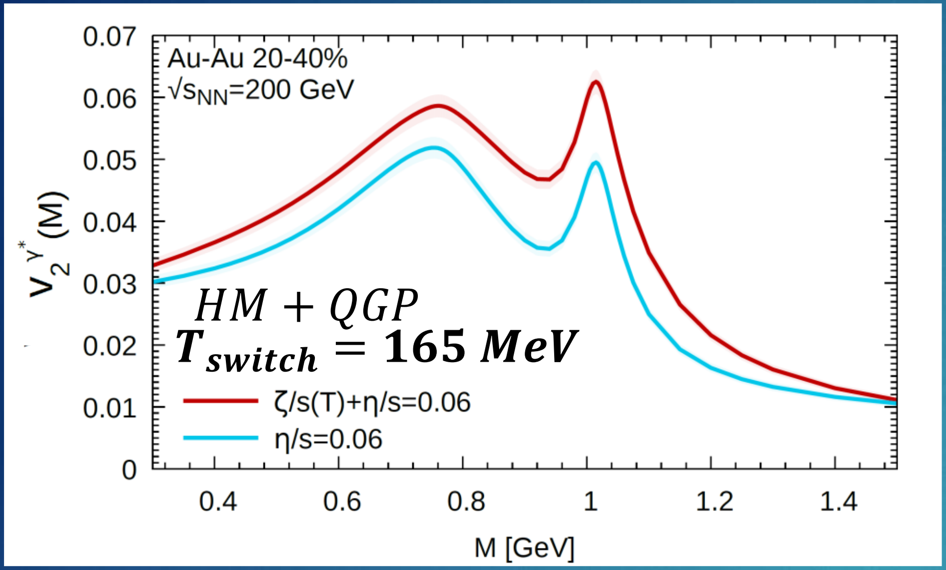


Cocktail: Hydro vs UrQMD at RHIC



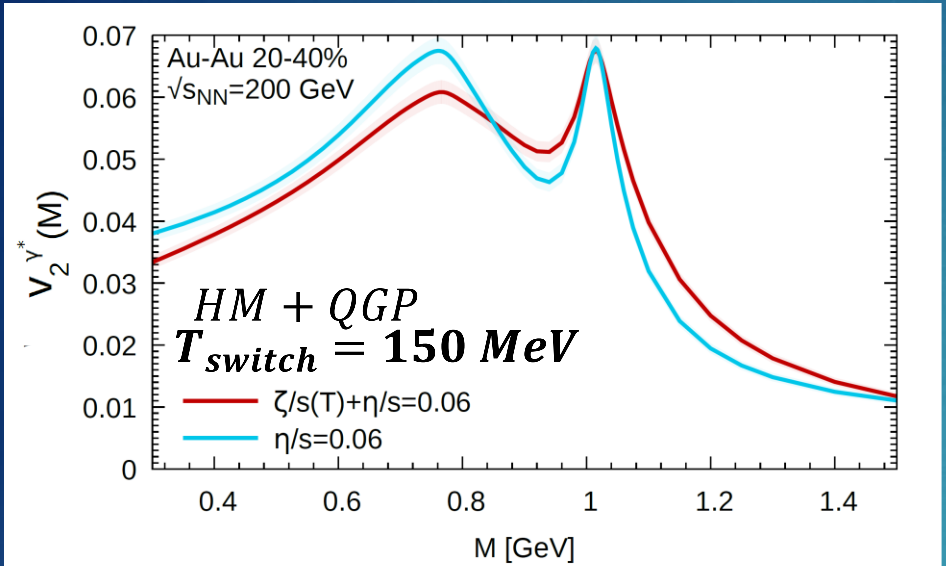


Bulk viscosity and dileptons at RHIC



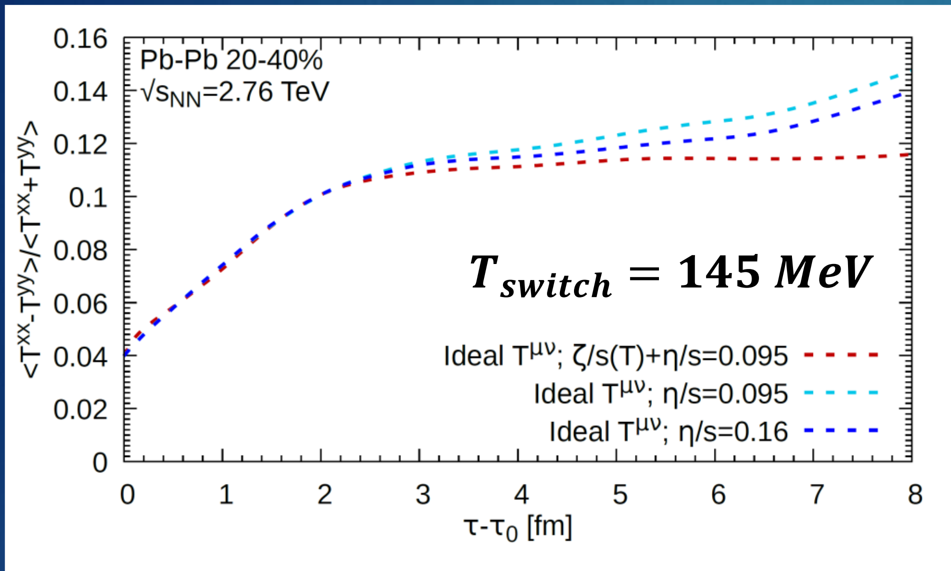
- As mentioned, the ↑ $v_2(M)$ with bulk viscosity is influenced by switching temperature.

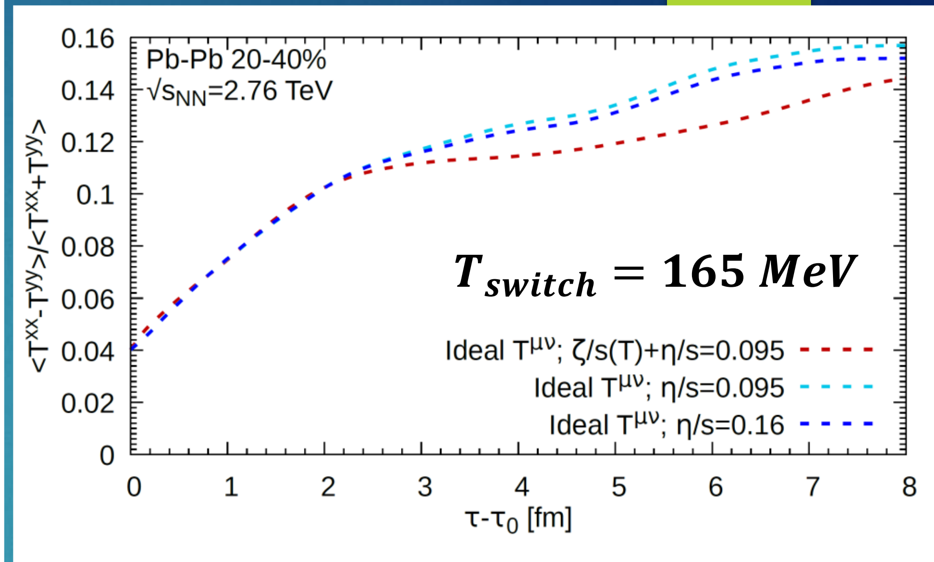
Bulk viscosity and dileptons at RHIC

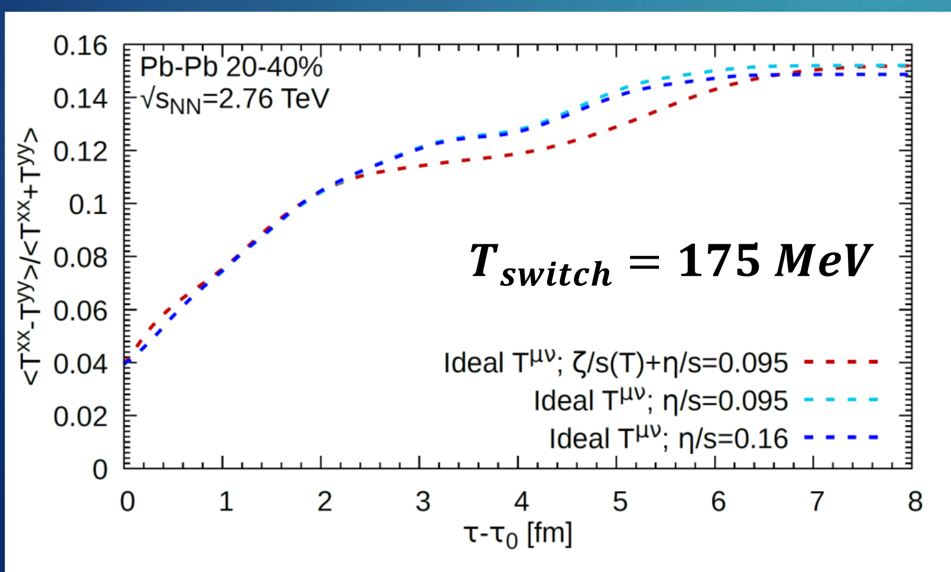


- As mentioned, the ↑ $v_2(M)$ with bulk viscosity is influenced by switching temperature.
- Indeed, running the hydrodynamical evolution until $\boldsymbol{T_{switch} = 150\ MeV}$, the effect is reduced, but is still present in the $M \sim 0.9\ GeV$ & $M > 1.1\ GeV$ regions.

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

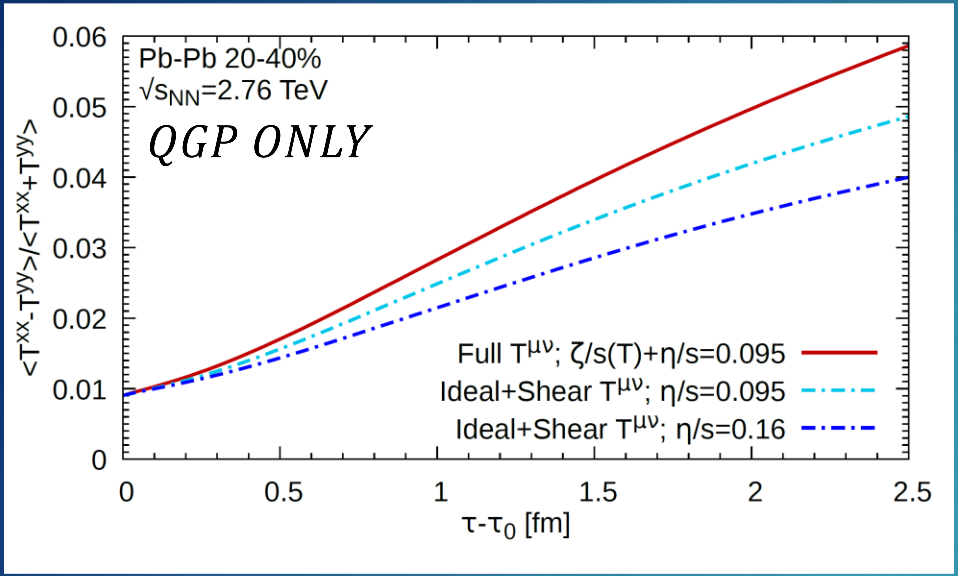






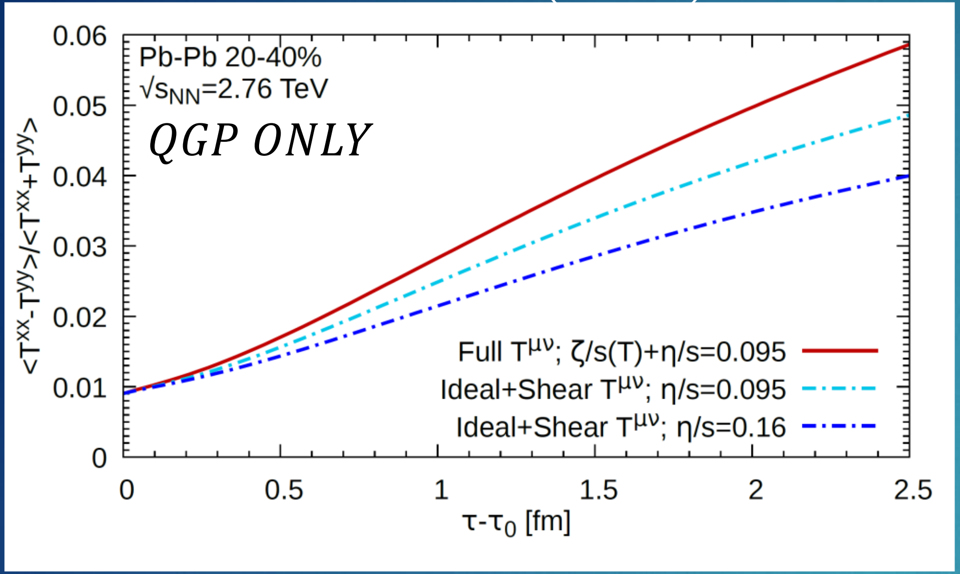
- $\frac{\langle T^{xx} - T^{yy}\rangle}{\langle T^{xx} + T^{yy}\rangle} \equiv \frac{\sum_i \int d^2x_\perp (T_i^{xx} - T_i^{yy})}{\sum_i \int d^2x_\perp (T_i^{xx} + T_i^{yy})}$ where the $\int d^2x_\perp$ integrates only the **HM** phase with $T > 145$ MeV, $T > 165$ MeV, and $T > 175$ MeV.

Bulk viscosity and QGP v_2 at LHC

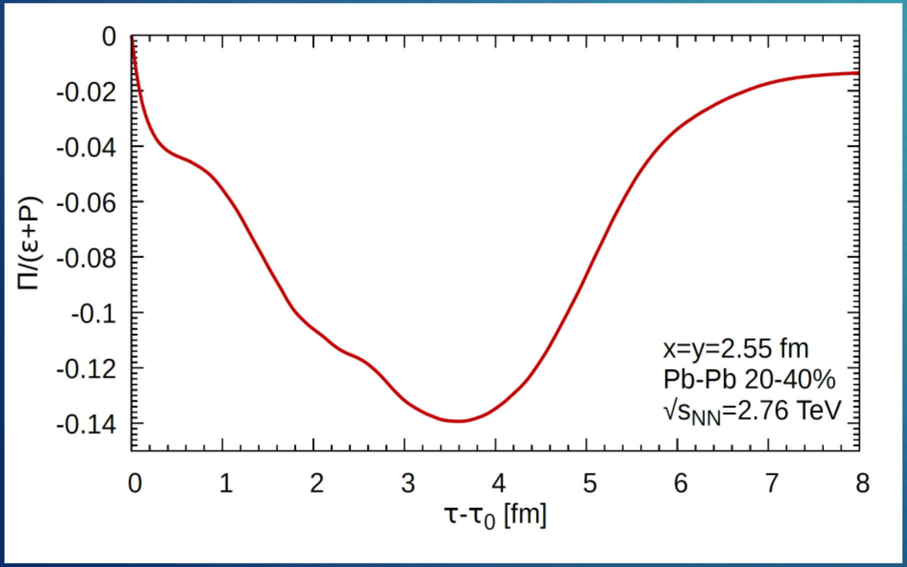


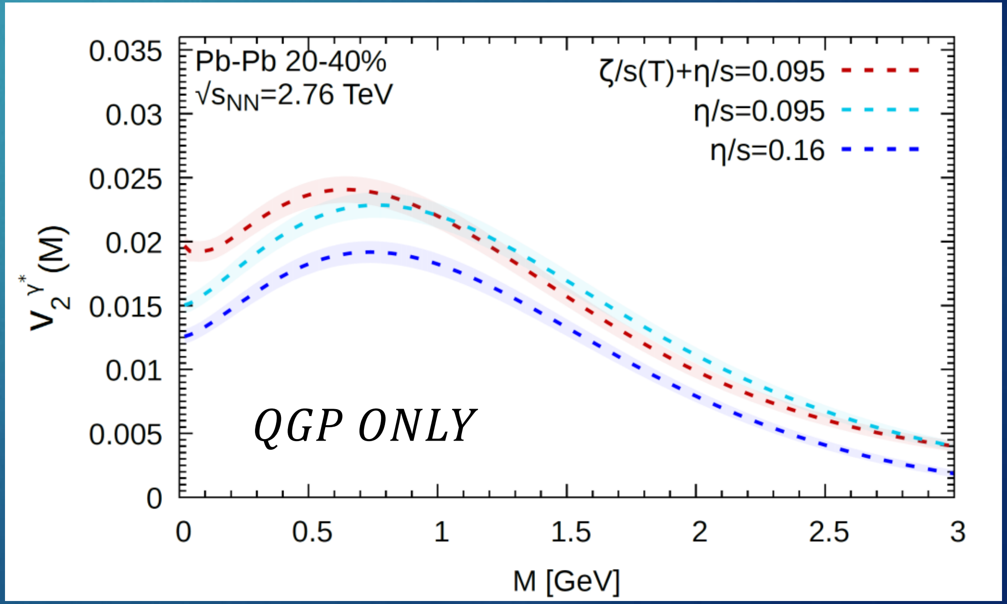
- $\langle T^{xx} \pm T^{yy} \rangle \equiv$
  $$\equiv \frac{1}{N_{events}} \sum_{i}^{N_{events}} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp (T_i^{xx} \pm T_i^{yy})$$
  where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ integrates only over the **QGP** phase.

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



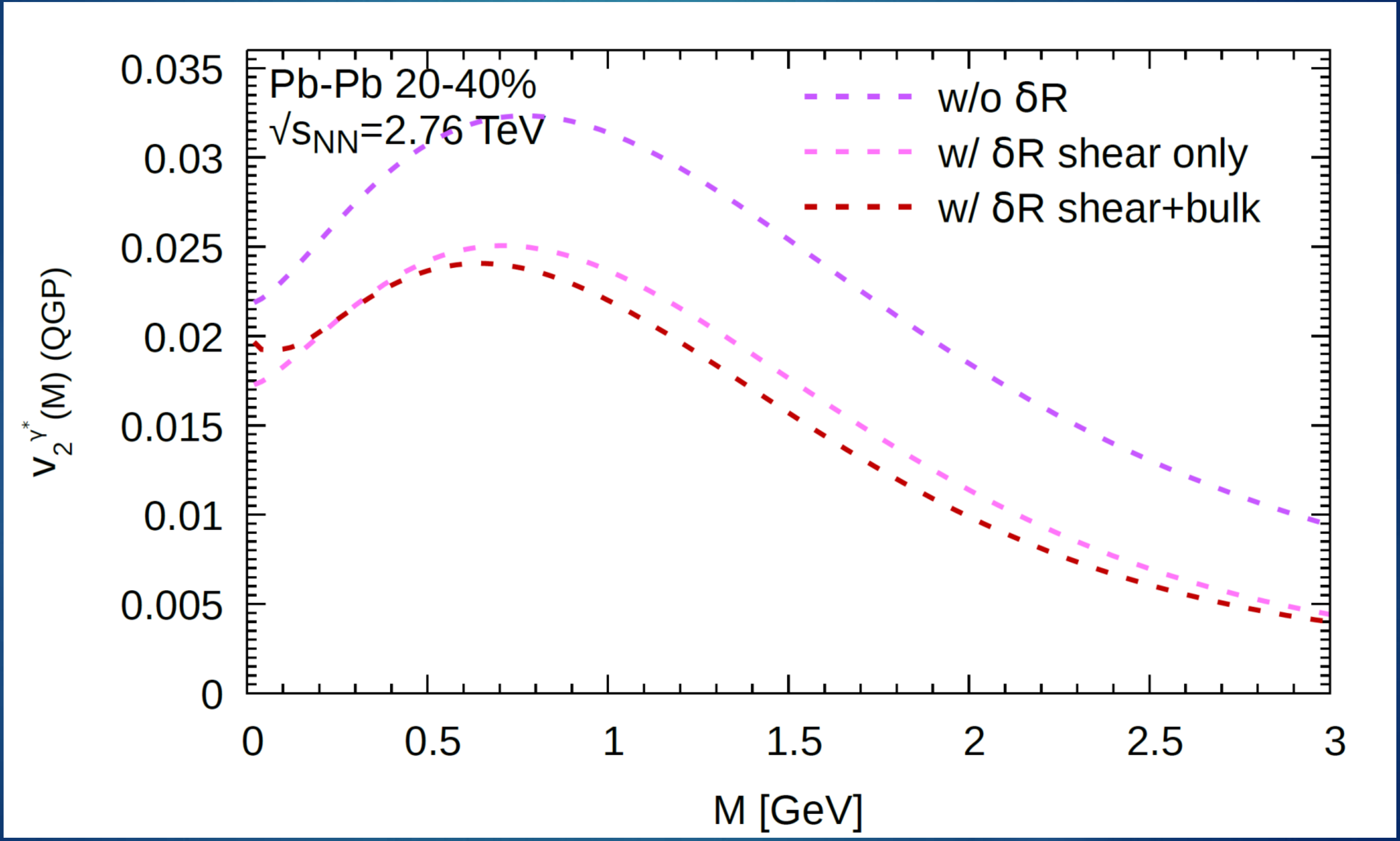
- $\delta n^{bulk} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP v_2, as $\frac{\Pi}{\varepsilon+P}$ doesn't change sign.



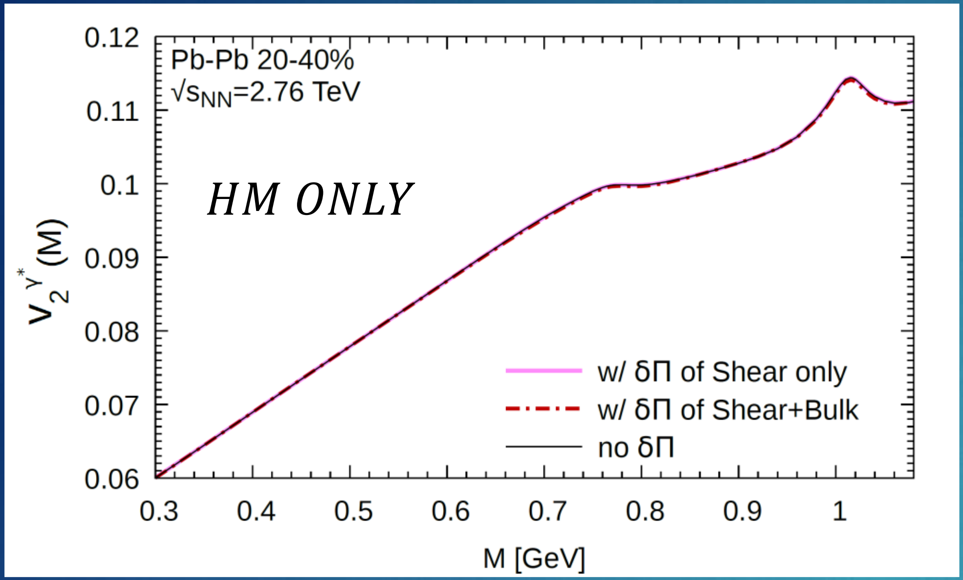


Viscous correction in the QGP

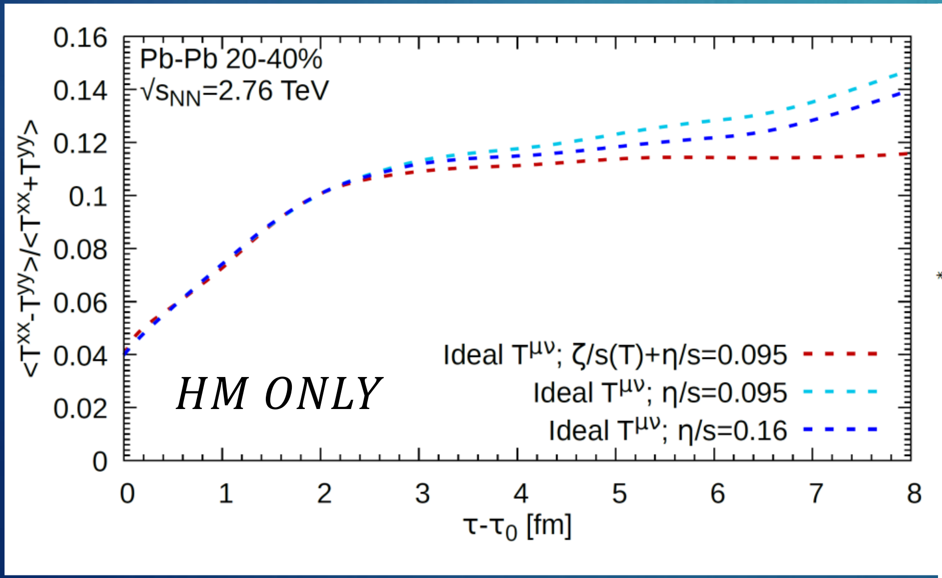
- Effects of viscous corrections on the QGP $v_2(M)$

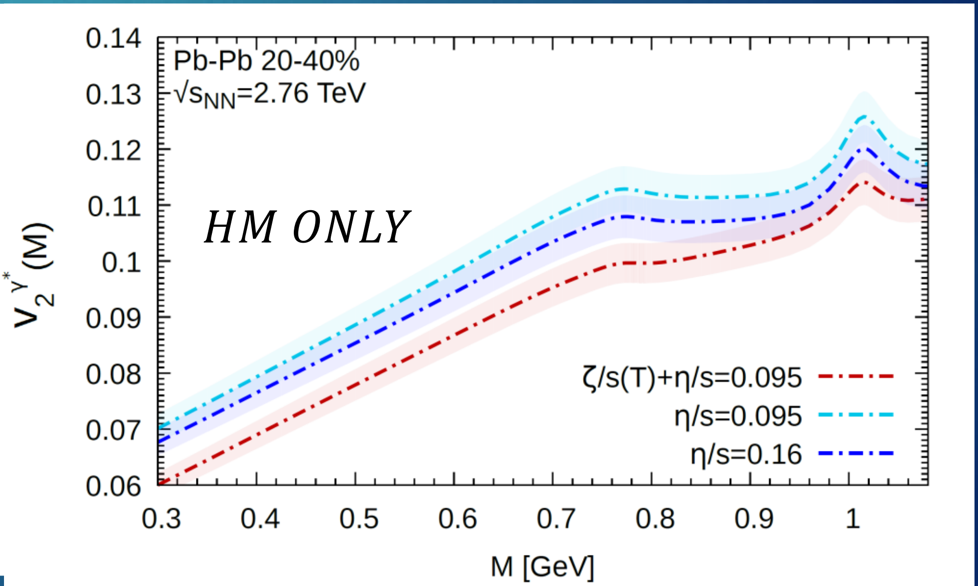


Bulk viscosity and HM v_2 at LHC

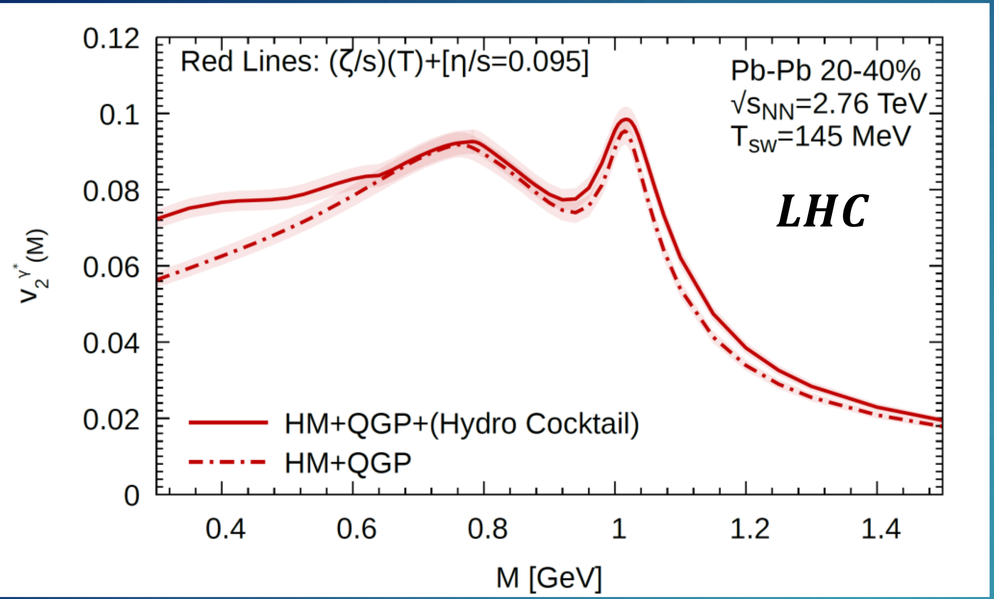


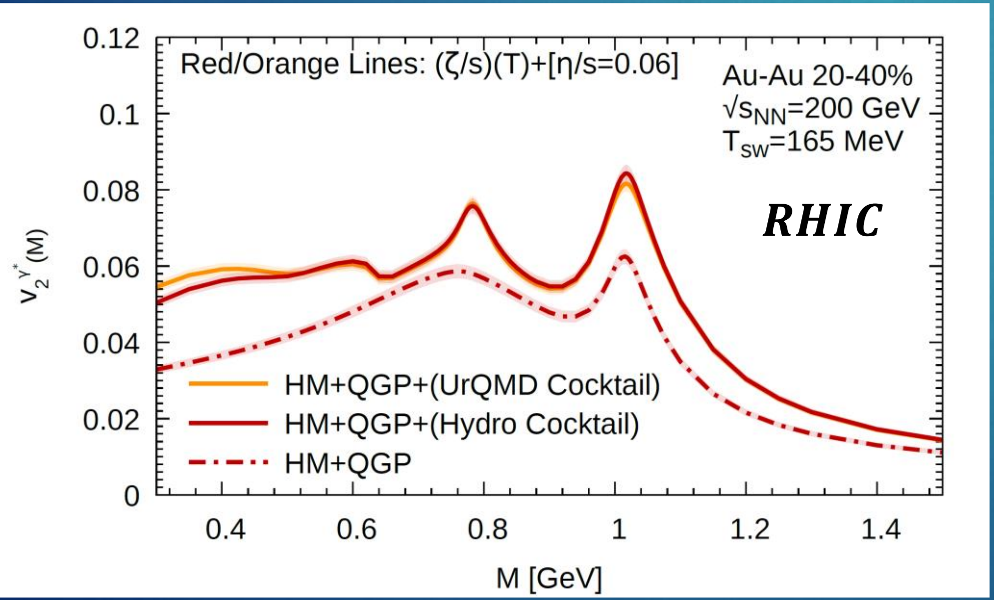
- However, HM dileptons are modestly affected by δn effects.
- v_2^{HM} is only affected by flow anisotropy.
- Where $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ in $\langle T^{xx} \pm T^{yy} \rangle$ integrates only over the **HM** region.





Thermal + Cocktail dileptons: LHC/RHIC

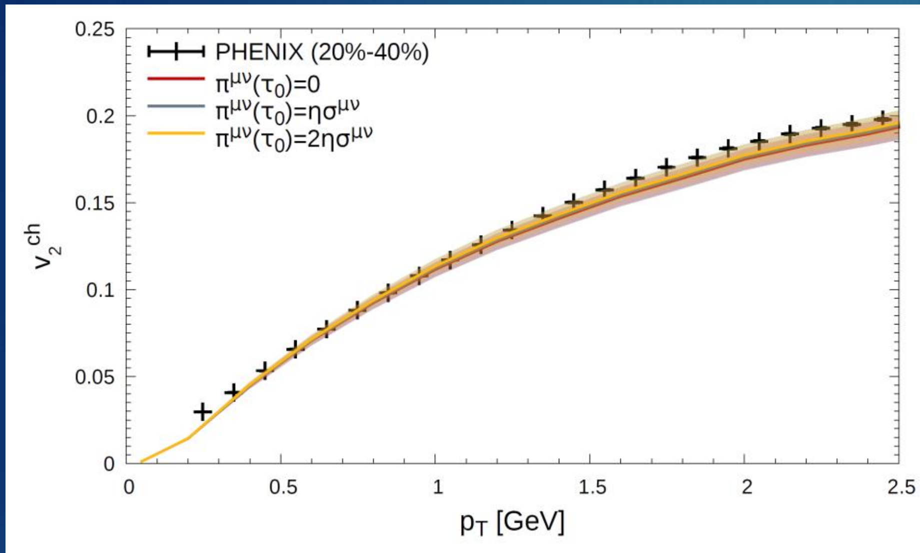


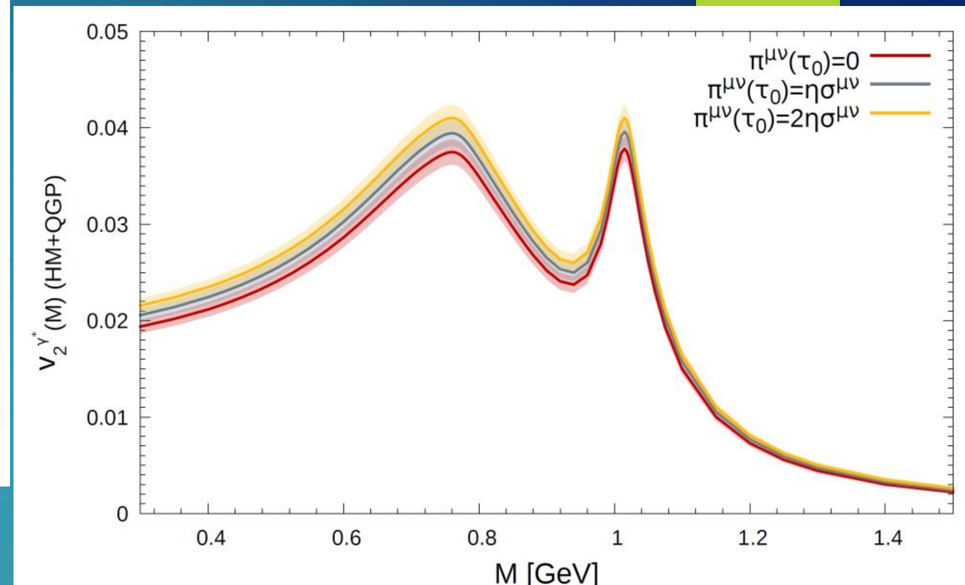


- At the LHC, as $T_{sw} = 145$ MeV, the contribution of the dilepton cocktail from a hydro simulation does not play a prominent role as far as the total $v_2(M)$, except in the region $M < 0.65\ GeV$.
- At RHIC, as $T_{sw} = 165$ MeV, the footprint of the dilepton cocktail left onto the total $v_2(M)$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

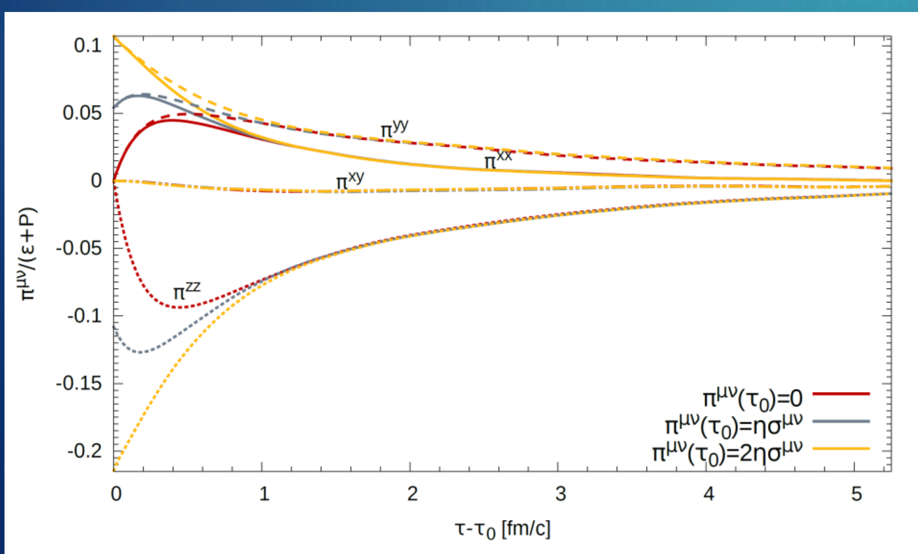
Why dileptons?

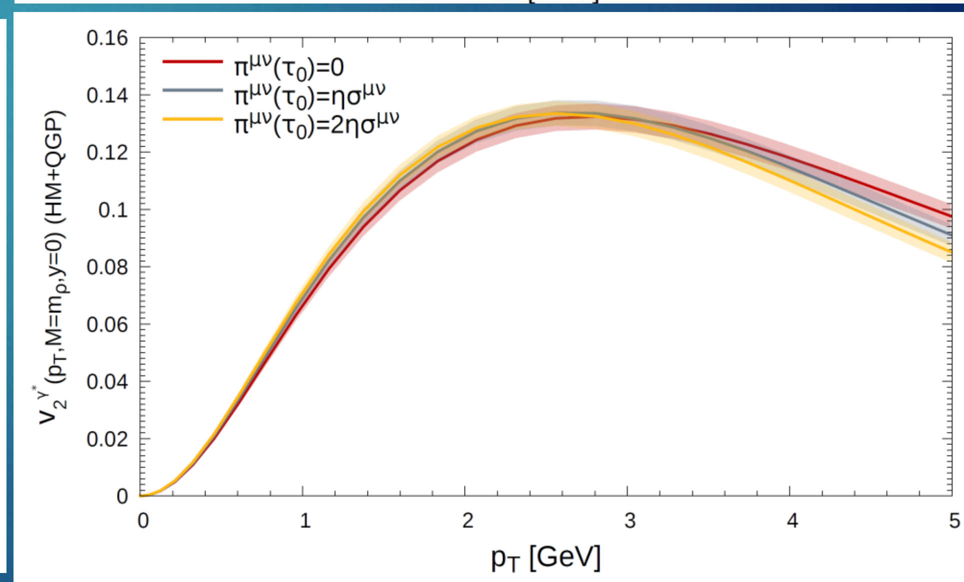
PRC 94, 014904, (2016)



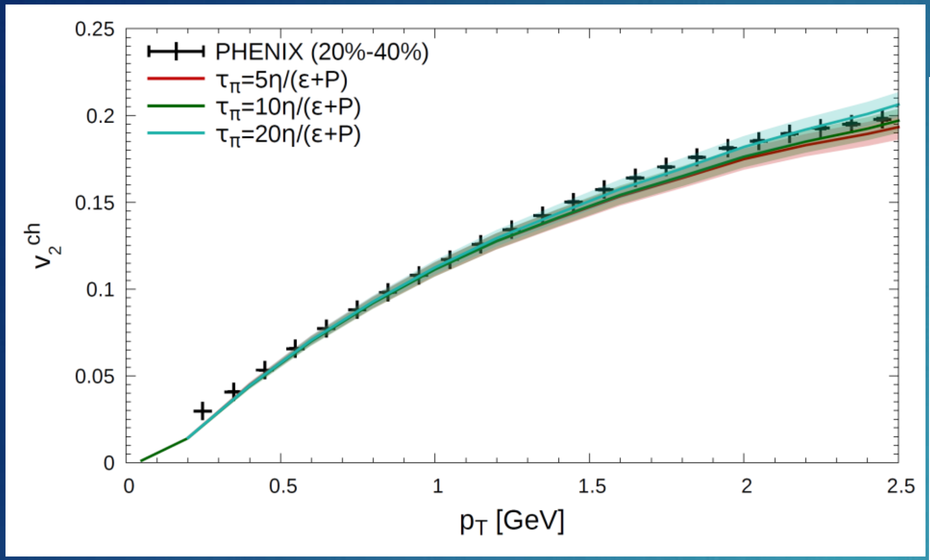


- Initial $\pi^{\mu\nu} = x\eta\sigma^{\mu\nu}$ with $x = 0{,}0.5{,}1$

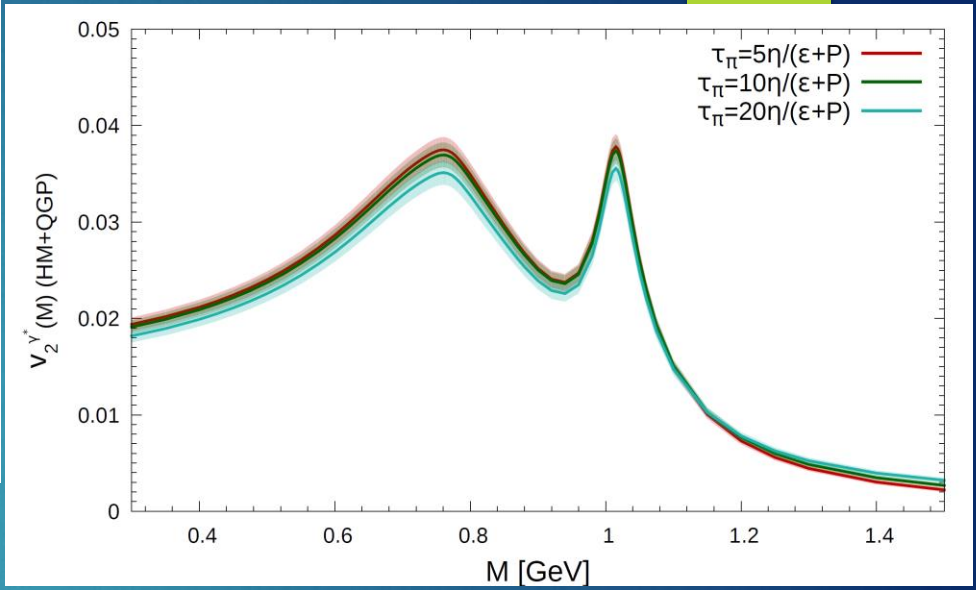




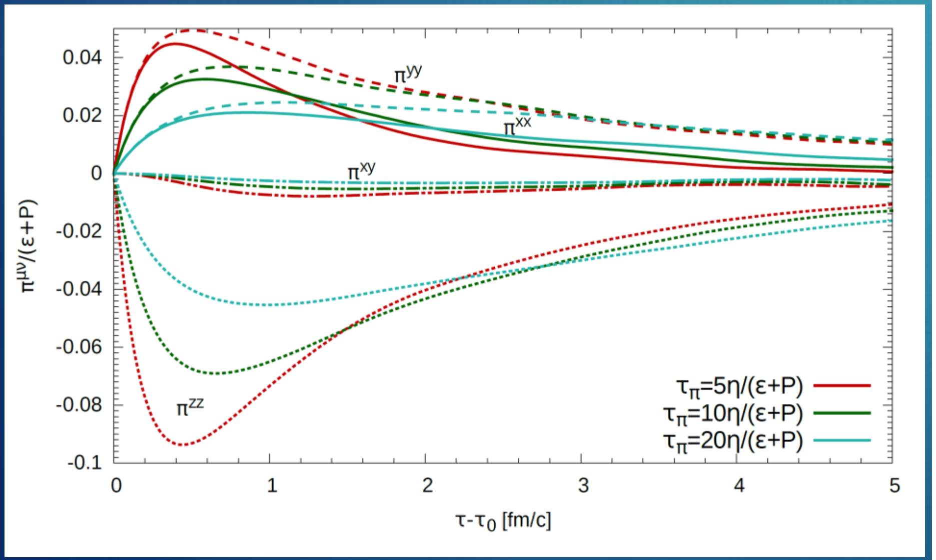
Why dileptons?

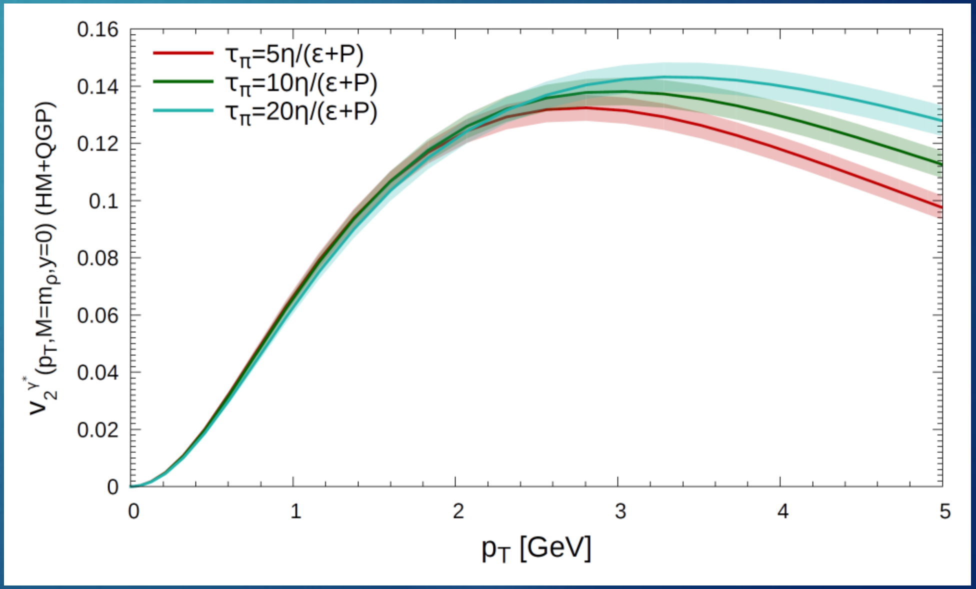


PRC 94, 014904, (2016)



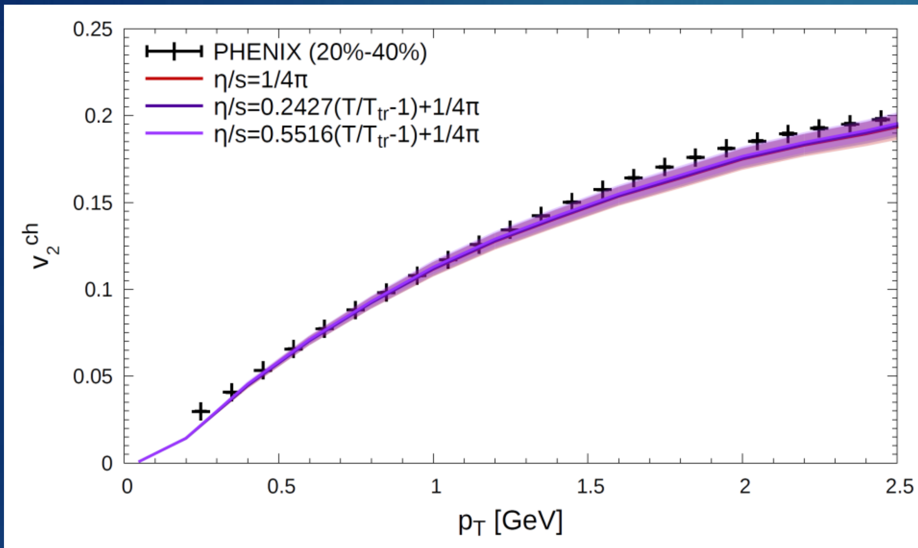
- $\tau_\pi = \mathrm{b}_\pi\, \eta/(\varepsilon + P)$ with $b_\pi = 5{,}10{,}20$

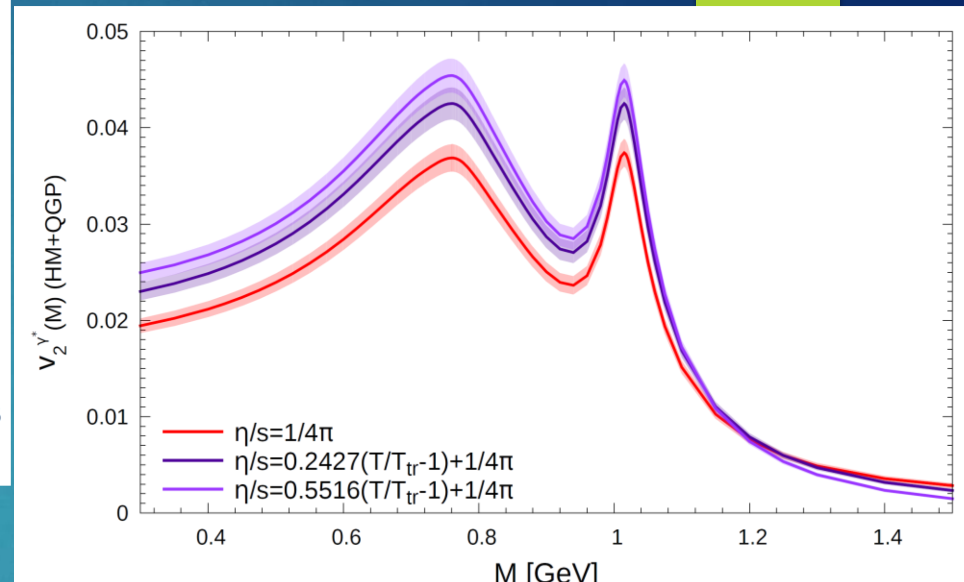




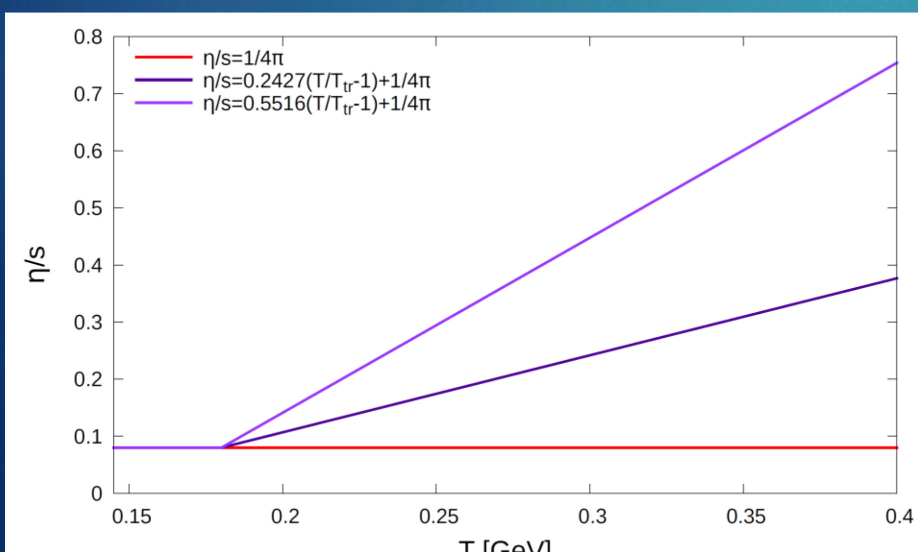
Why dileptons?

arXiv:1702.02941

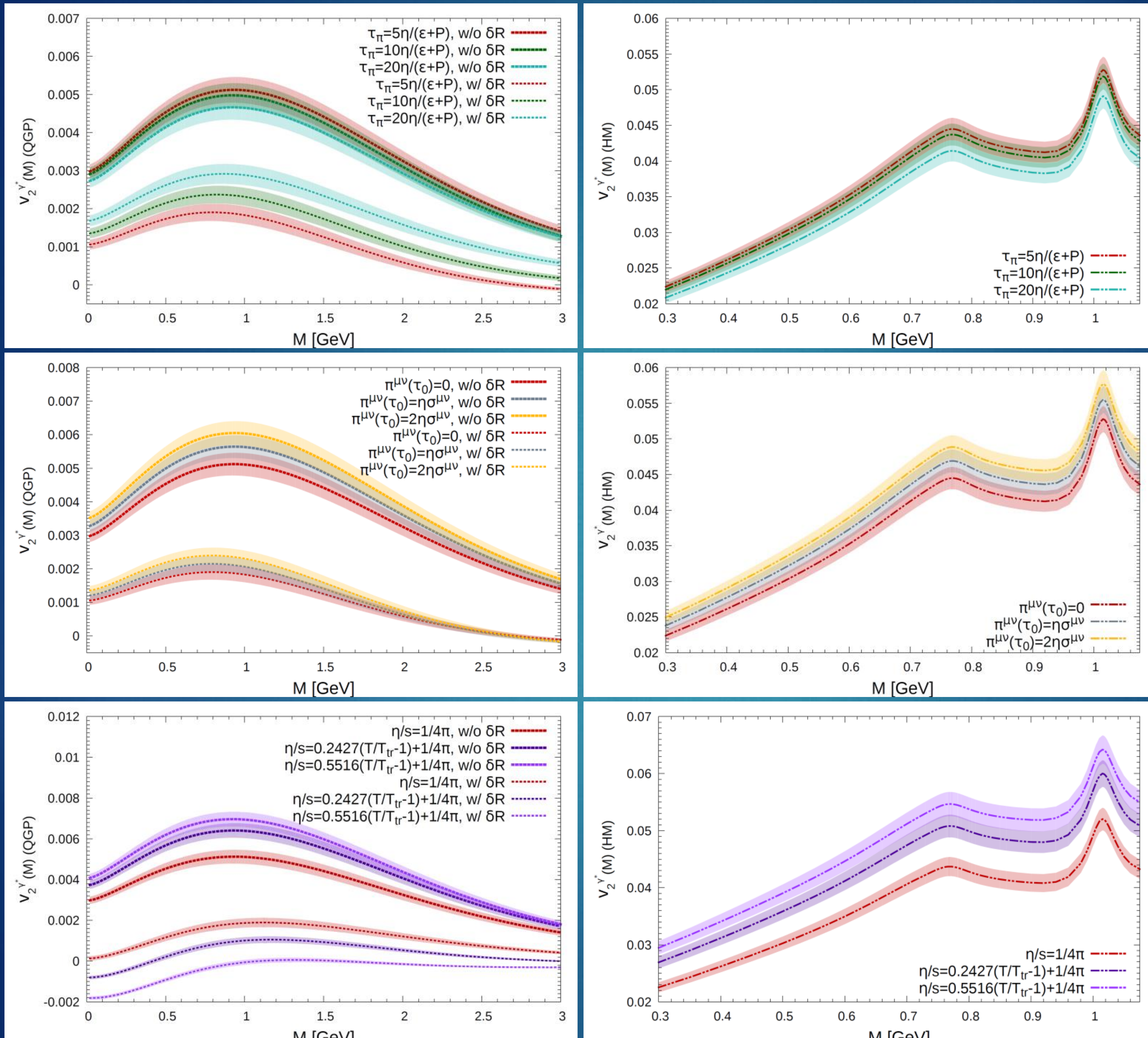




- Temperature-dependent $\frac{\eta}{s}$



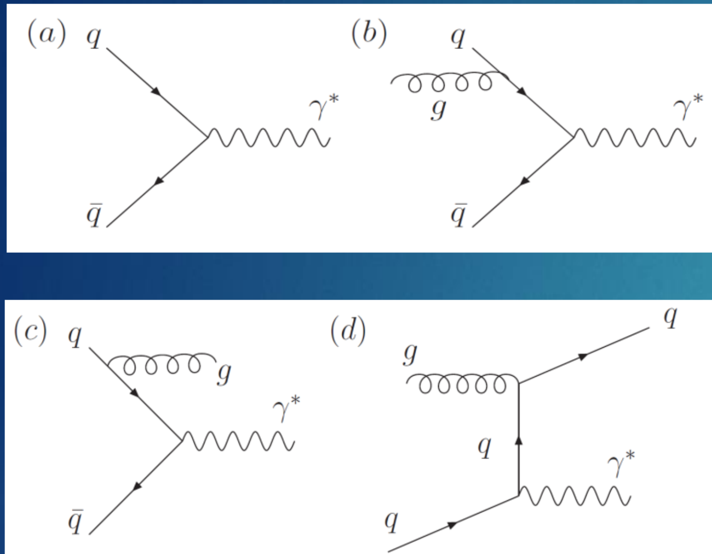
- Dileptons are more sensitive to initial conditions and transport coefficient of a QCD medium than hadrons

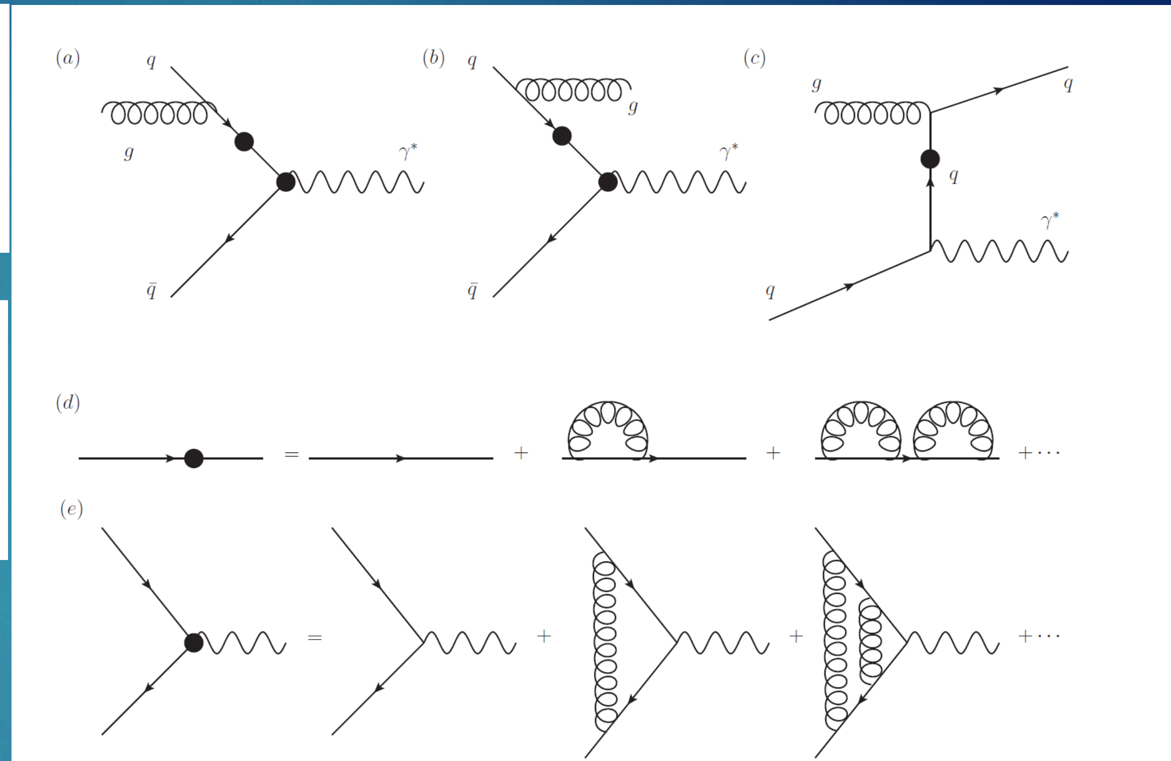


τπ=5η/(ε+P), w/o δR
τπ=10η/(ε+P), w/o δR
τπ=20η/(ε+P), w/o δR
τπ=5η/(ε+P), w/ δR
τπ=10η/(ε+P), w/ δR
τπ=20η/(ε+P), w/ δR
v2γ* (M) (QGP)
M [GeV]
τπ=5η/(ε+P)
τπ=10η/(ε+P)
τπ=20η/(ε+P)
v2γ* (M) (HM)
M [GeV]
πμν(τ0)=0, w/o δR
πμν(τ0)=ησμν, w/o δR
πμν(τ0)=2ησμν, w/o δR
πμν(τ0)=0, w/ δR
πμν(τ0)=ησμν, w/ δR
πμν(τ0)=2ησμν, w/ δR
v2γ* (M) (QGP)
M [GeV]
πμν(τ0)=0
πμν(τ0)=ησμν
πμν(τ0)=2ησμν
v2γ* (M) (HM)
M [GeV]
η/s=1/4π, w/o δR
η/s=0.2427(T/Ttr-1)+1/4π, w/o δR
η/s=0.5516(T/Ttr-1)+1/4π, w/o δR
η/s=1/4π, w/ δR
η/s=0.2427(T/Ttr-1)+1/4π, w/ δR
η/s=0.5516(T/Ttr-1)+1/4π, w/ δR
v2γ* (M) (QGP)
M [GeV]
η/s=1/4π
η/s=0.2427(T/Ttr-1)+1/4π
η/s=0.5516(T/Ttr-1)+1/4π
v2γ* (M) (HM)
M [GeV]

NLO QGP dilepton results

- Some diagrams contributing at LO & NLO



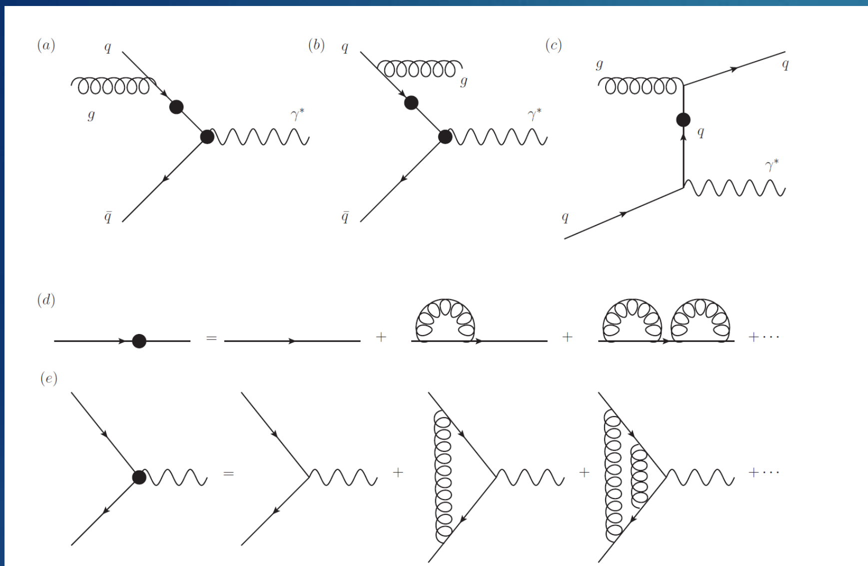


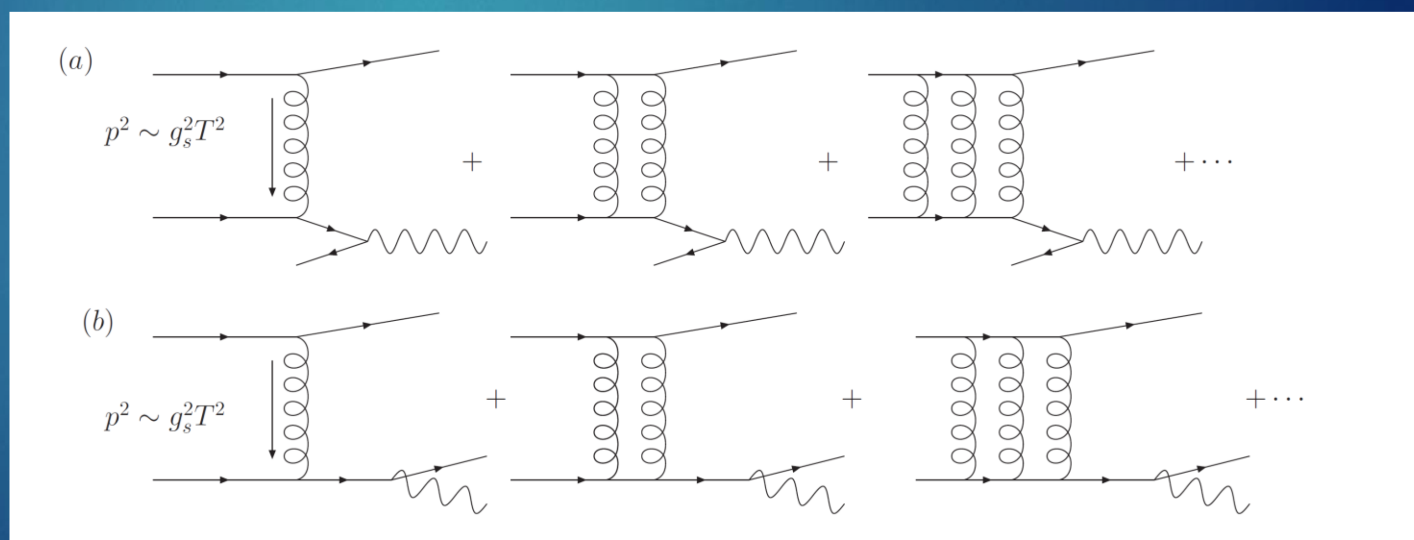
$$\frac{d^4R}{d^4q} = \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3} n_q(x) n_{\bar{q}}(x) \sigma v_{12} \delta^4(q - k_1 - k_2); \quad where\ \ x = \frac{u \cdot k}{T}$$

$$\sigma \; = \; \frac{16\pi\alpha_{\mathrm{EM}}^2 \left(\sum_{q'} e_{q'}^2\right) N_c}{3q^2}$$

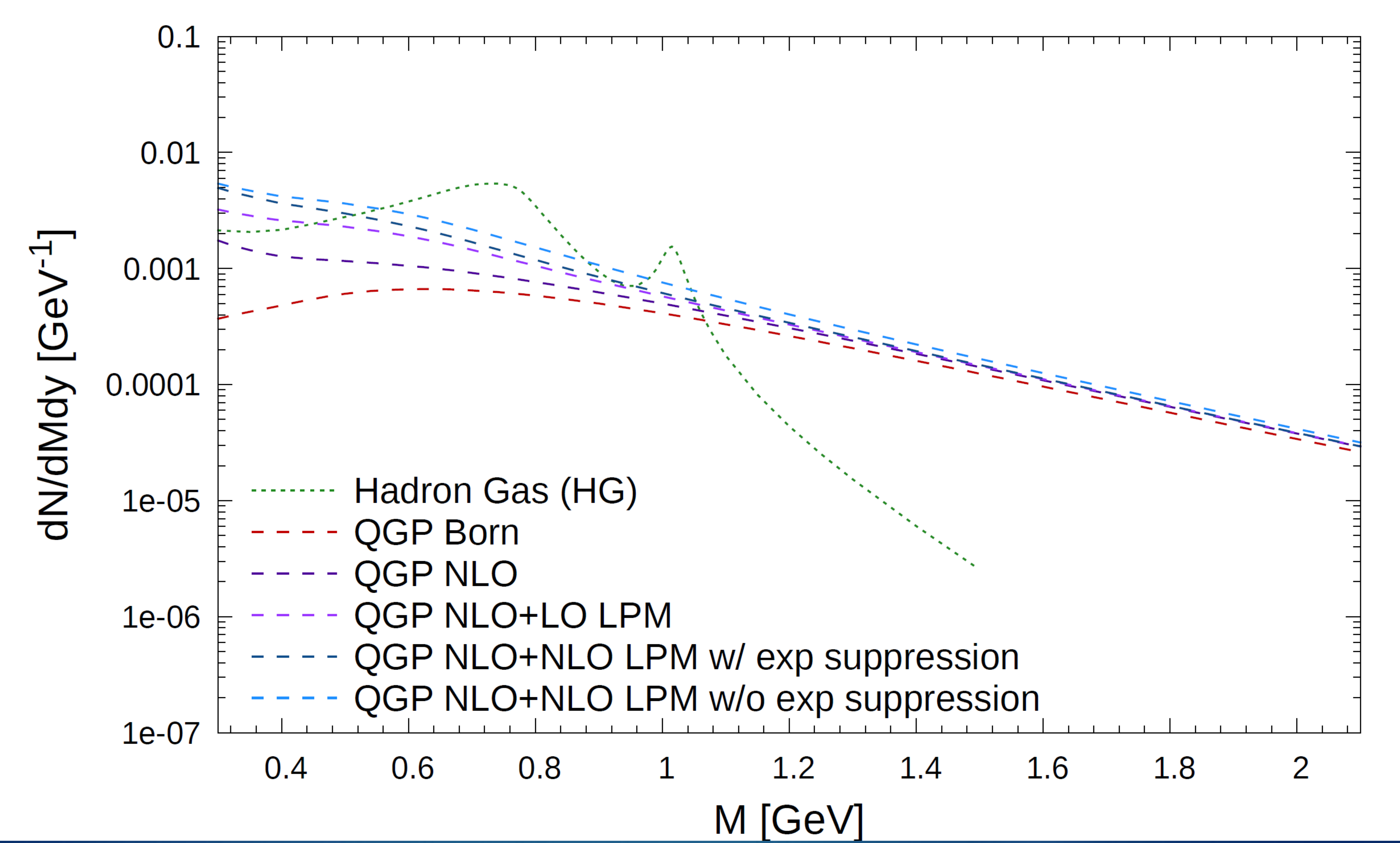
NLO QGP dilepton results

- Some diagrams contributing at LO & NLO



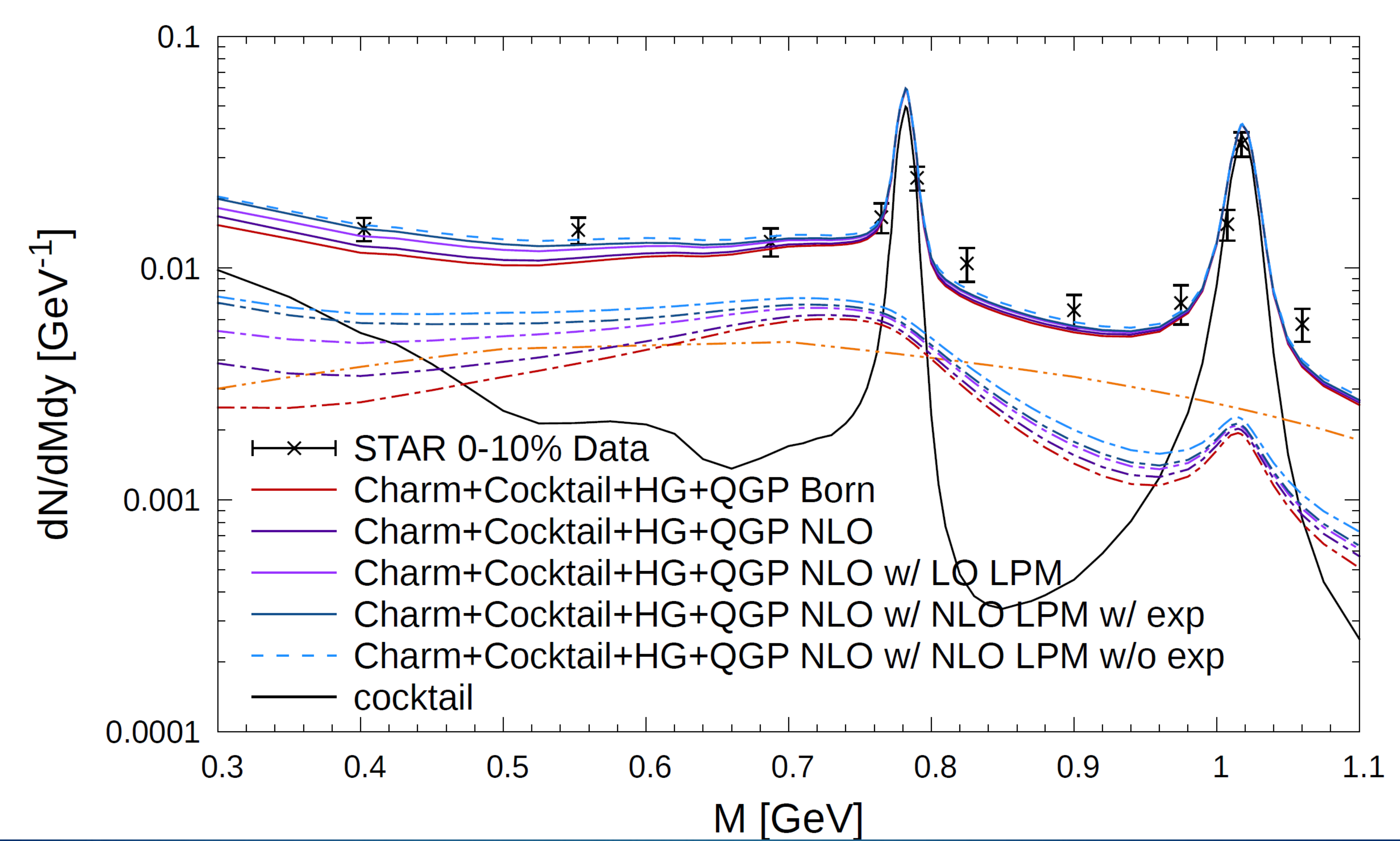


NLO QGP dilepton results



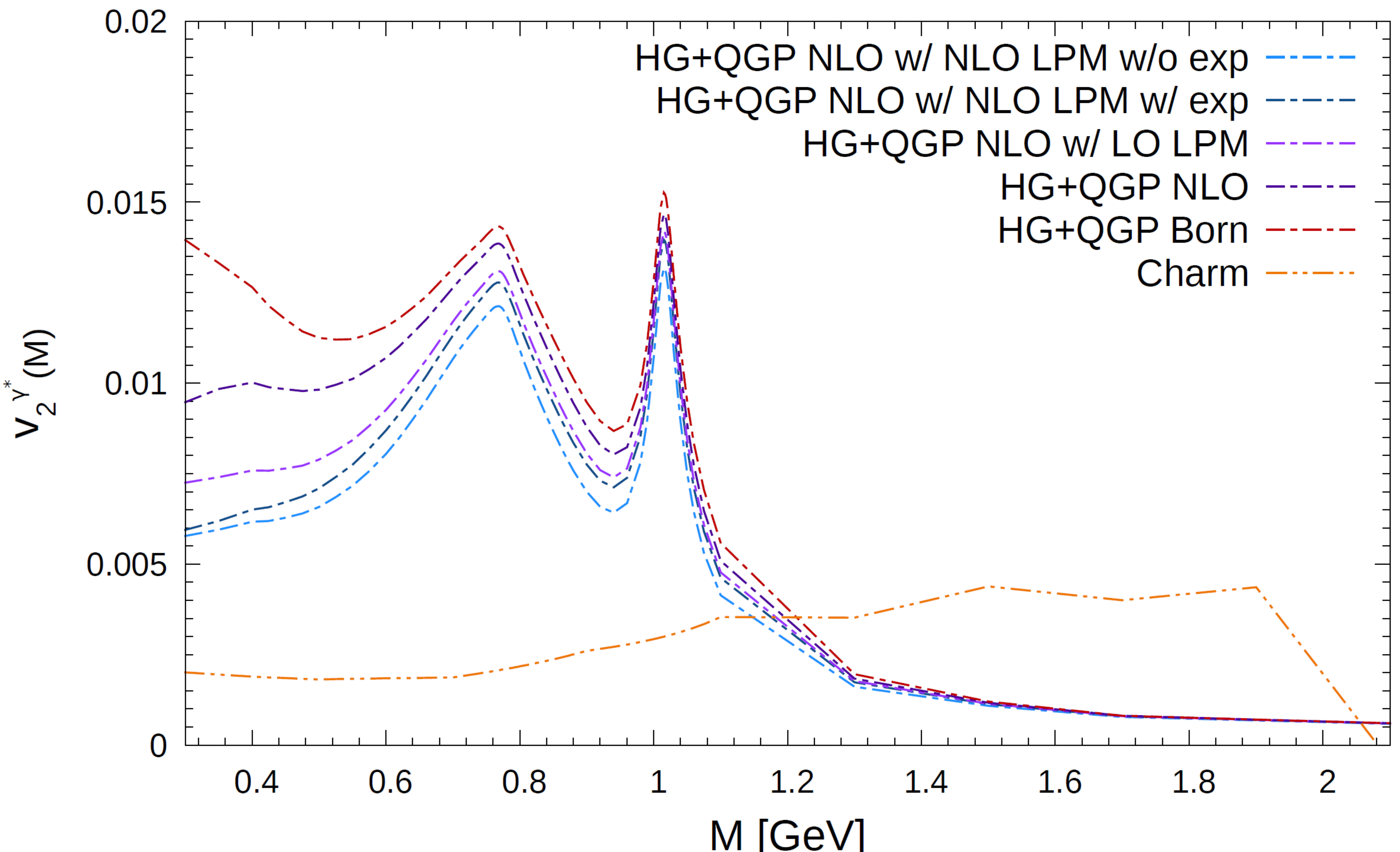
NLO QGP dilepton results

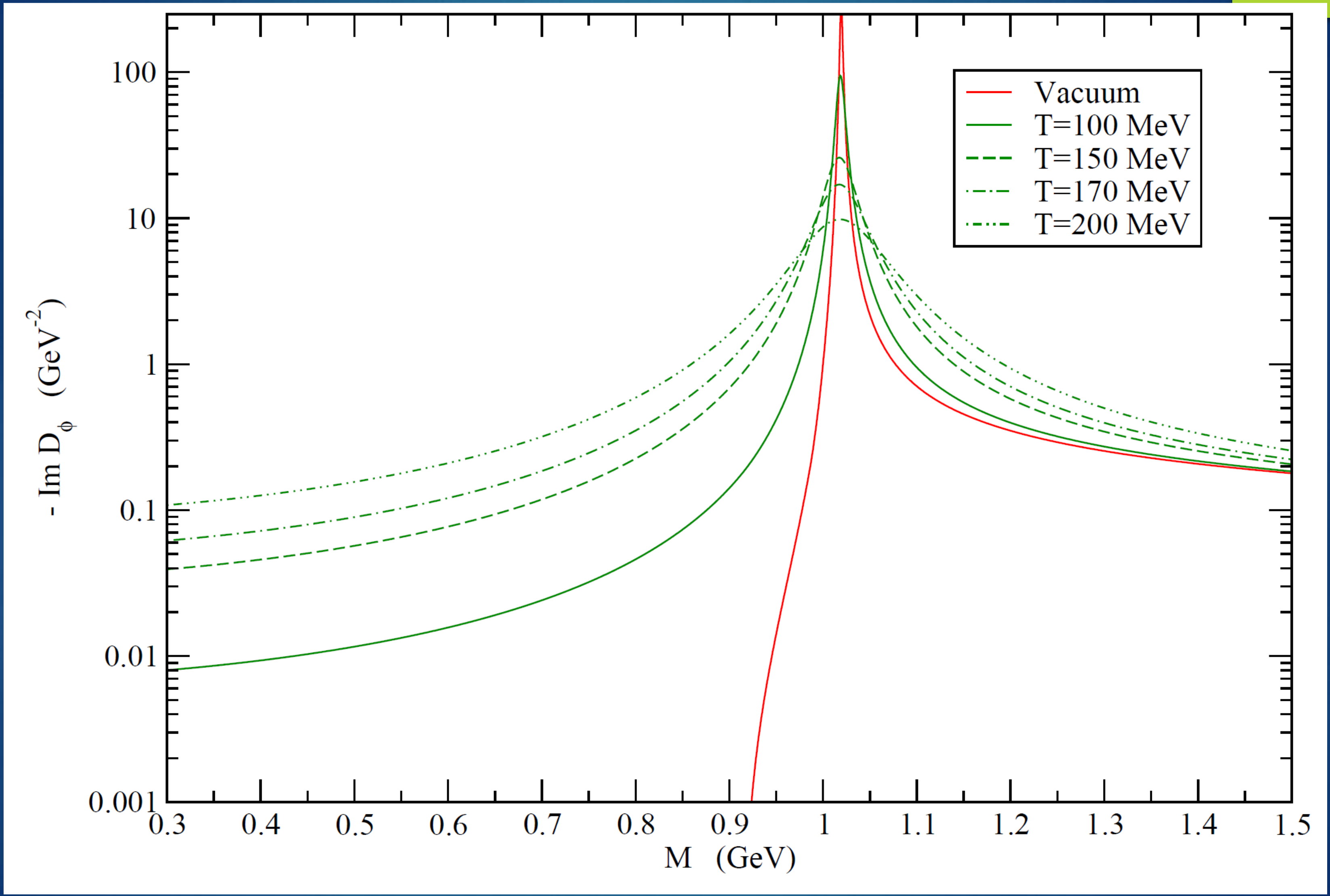
- Some diagrams contributing at LO & NLO



NLO QGP dilepton results

- Some diagrams contributing at LO & NLO




Vacuum
T=100 MeV
T=150 MeV
T=170 MeV
T=200 MeV
- Im D_ϕ (GeV^-2)
M (GeV)
100
10
1
0.1
0.01
0.001
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5