Dilepton radiation and dynamics of strongly interacting media

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Exploring the QCD Phase Diagram through Energy Scans

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BEST COLLABORATION

Outline

Part I: The high energy frontier from RHIC to LHC

- Viscous hydrodynamics with shear and bulk viscosity
- Dilepton Rates:
  1. Hadronic Medium Rates (w/ dissipative corrections)
  2. QGP Rate (w/ dissipative corrections)
- Effects of bulk viscous pressure on dilepton yield and v_n

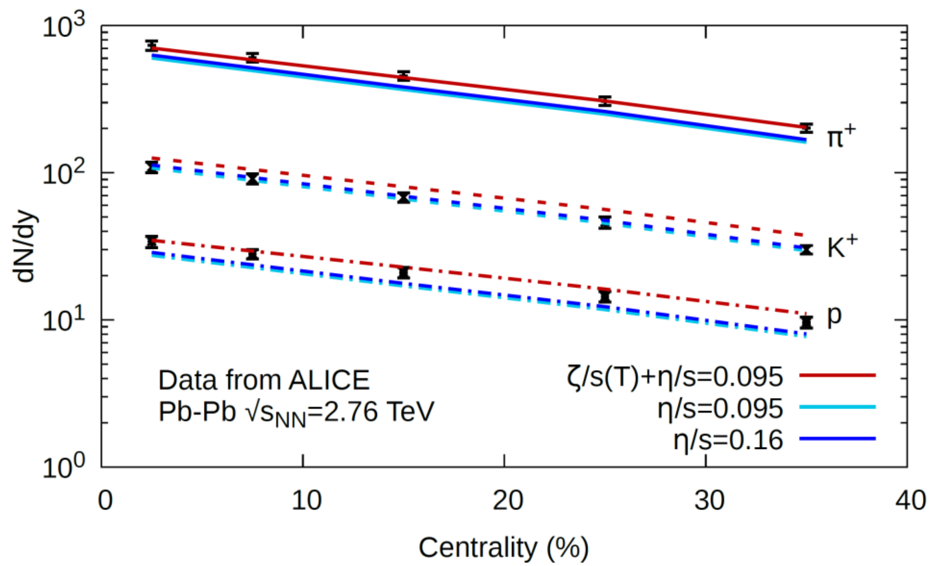
Part II: The Beam Energy Scan

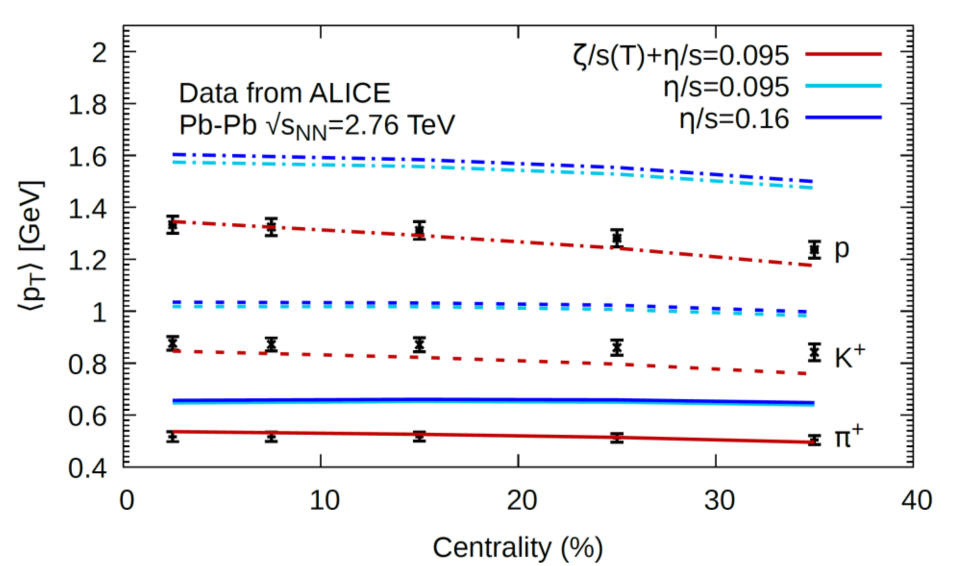
- Initial condition for baryon number
- Viscous hydrodynamics with shear and baryon diffusion
- Baryon diffusion correction to

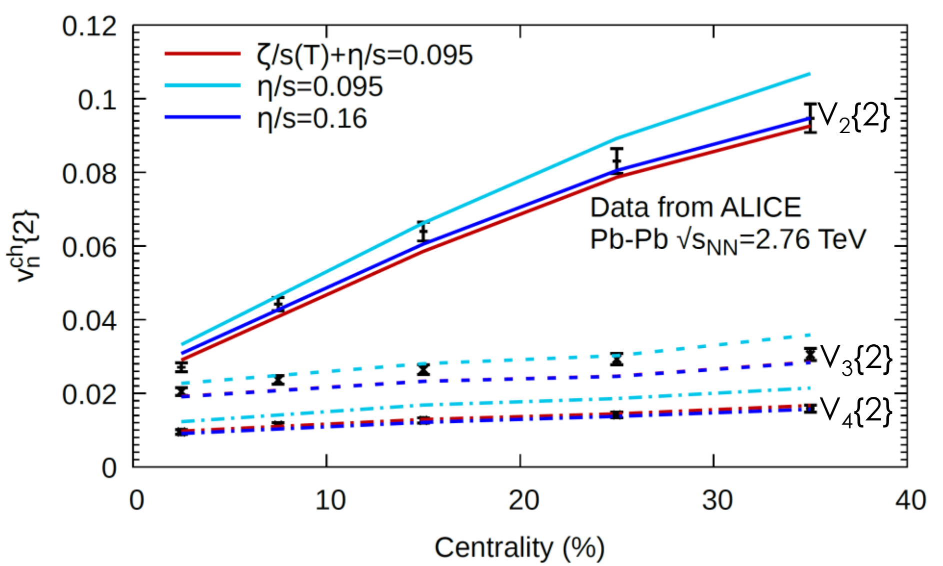
Part I: The high energy frontier from RHIC to LHC

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

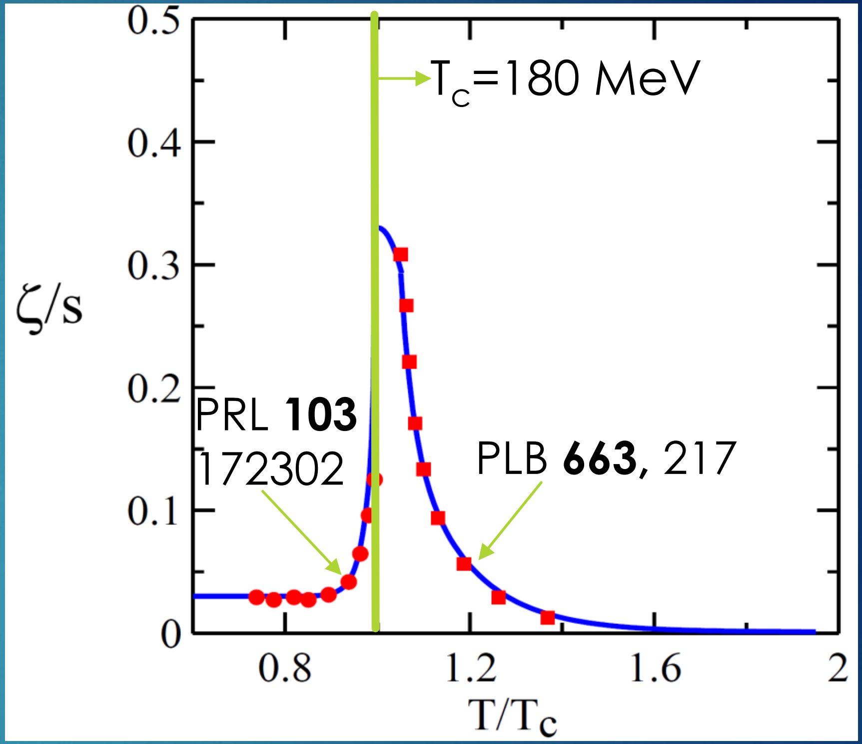
$$\partial_\mu T^{\mu\nu} = 0$$

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

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

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

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

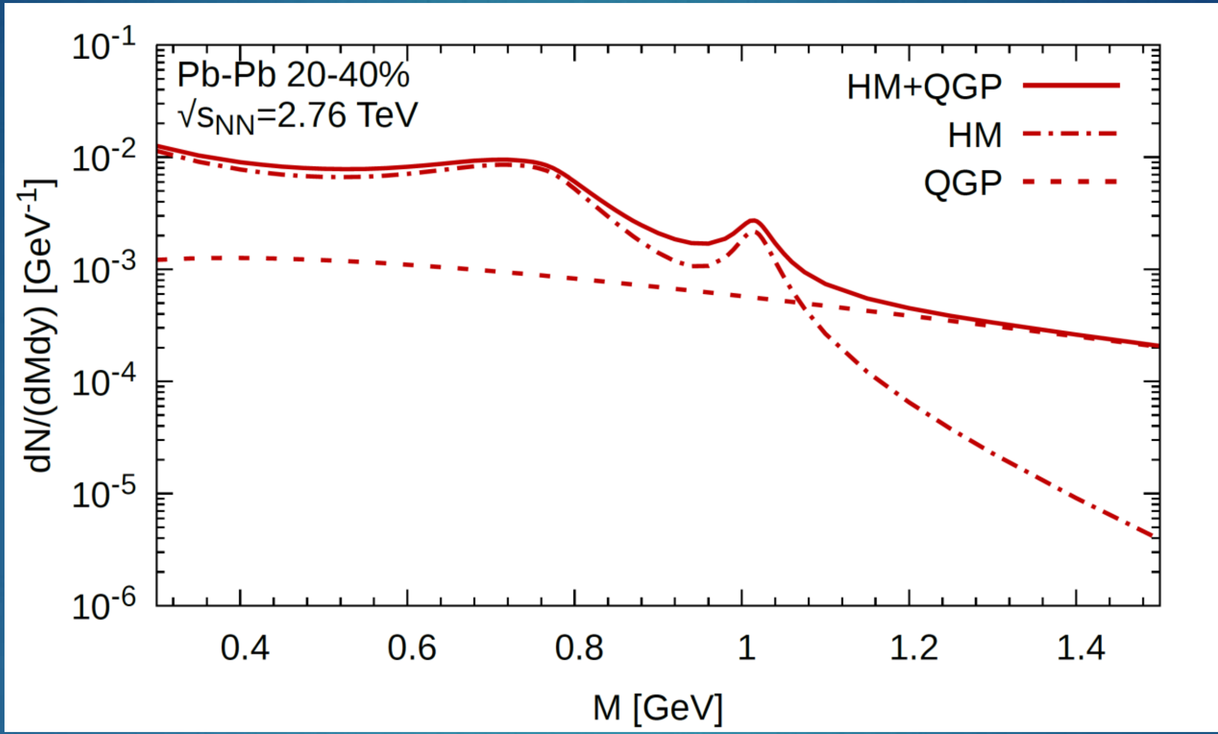


$\eta/s = constant$

- 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; no dileptons from initial dynamics and hadronic transport.

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

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

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

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

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:

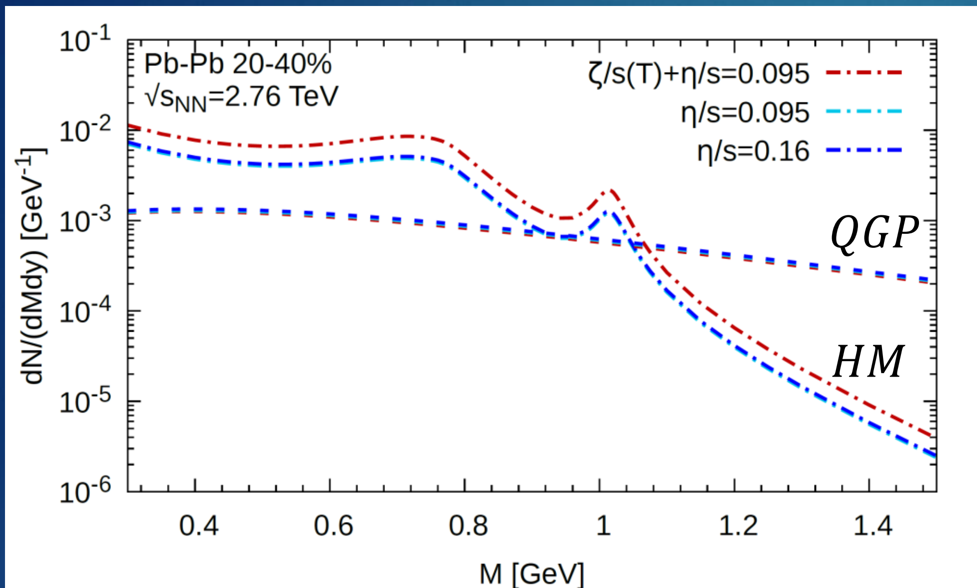
1. Within an event: v_n's are a yield weighted average of the different sources (e.g. HM, QGP, …).
2. The switch between HM and QGP rates we are using a linear interpolation, in the region $184\ MeV < T < 220 MeV$, given by the EoS [NPA **837**, 26]
3. Averaging over events: the flow coefficients (v_n)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

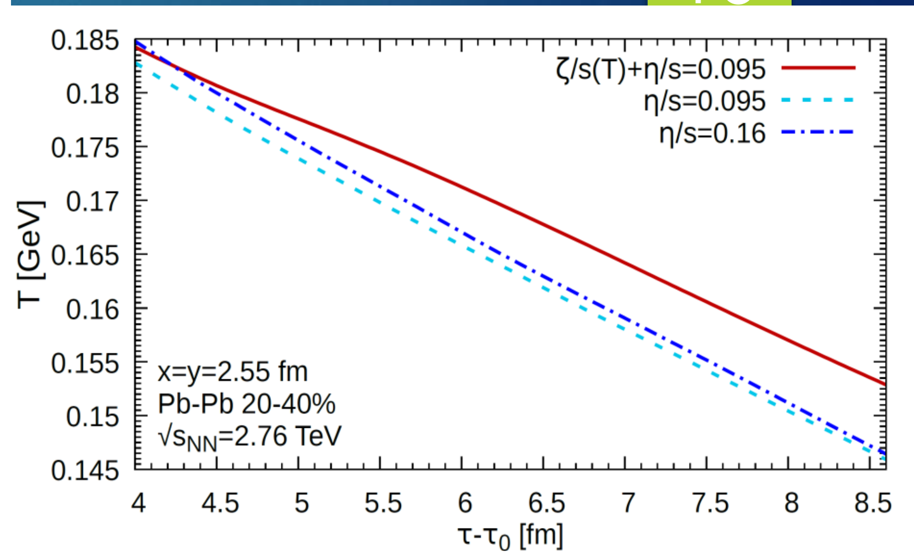
$$v_n\{SP\} = \frac{\left\langle v_n^{\gamma^*} v_n^h \cos\left[n\left(\Psi_n^{\gamma^*} - \Psi_n^h\right)\right]\right\rangle}{\left\langle \left(v_n^h\right)^2 \right\rangle^{1/2}}$$

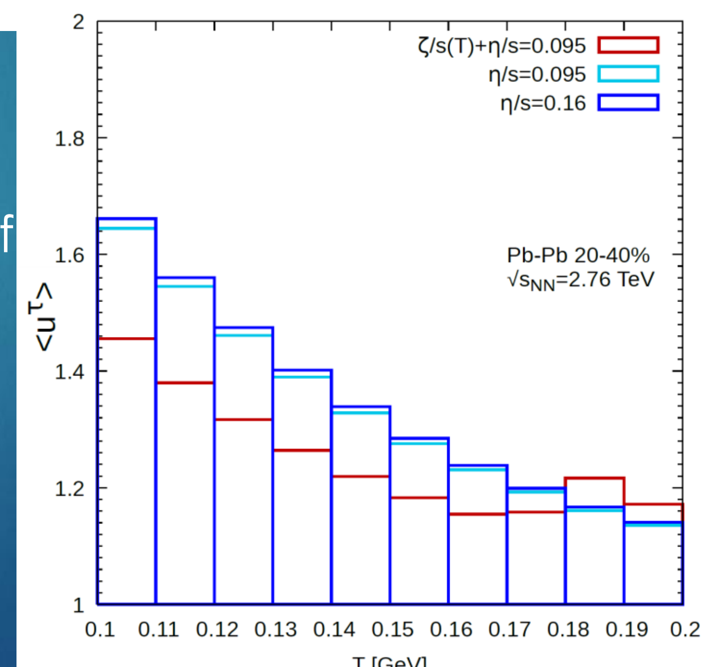
PRC **93**, 044906
PRC **94**, 014904

- 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

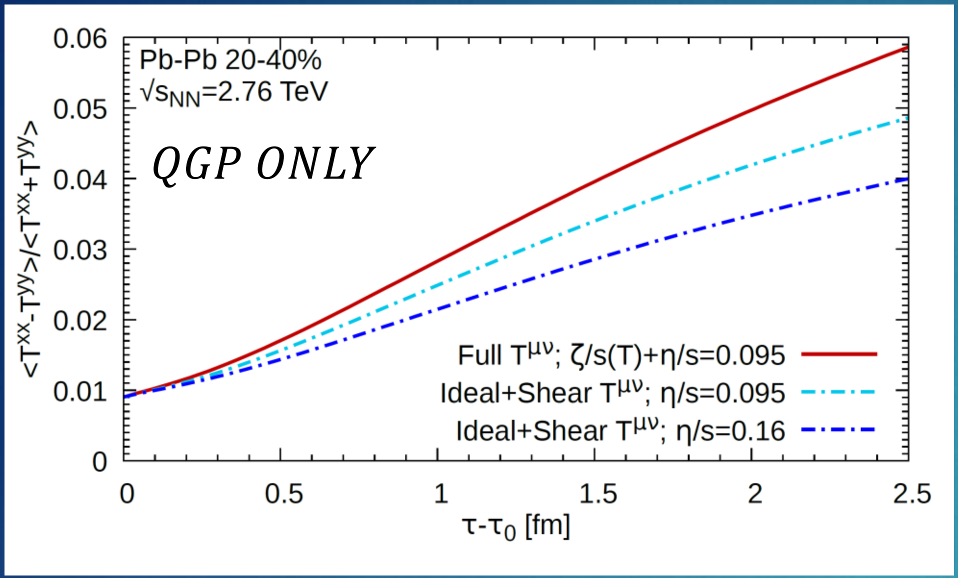






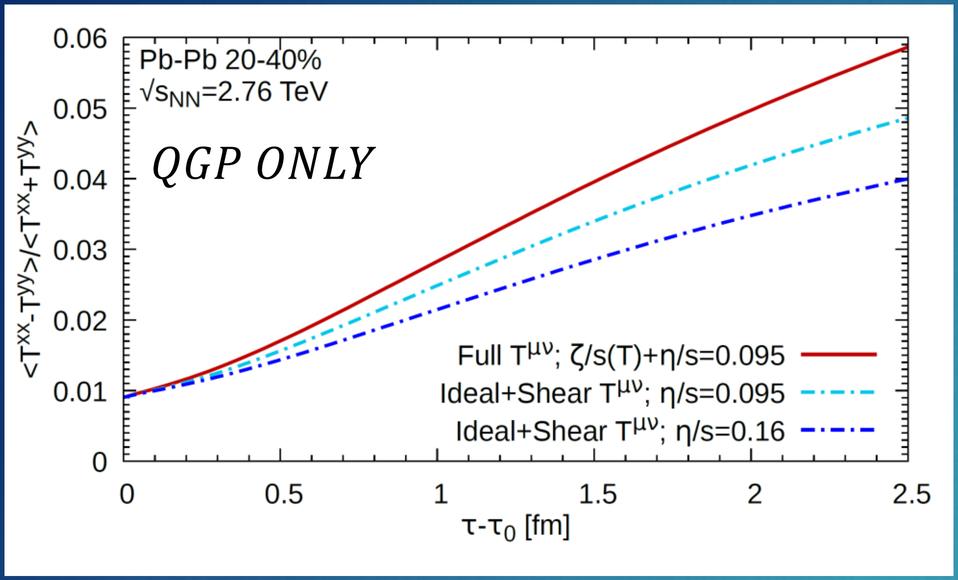
- $\frac{dN}{dMdy}$ is sensitive to the temperature profile.
- Bulk viscosity reduces the cooldown rate of the medium, by viscous heating and also via reduction of radial flow at late times.
- Dilepton yield is increased in the HM sector, since for $T < 184\, MeV$ purely HM rates are used.

Bulk viscosity and QGP v_2 at LHC

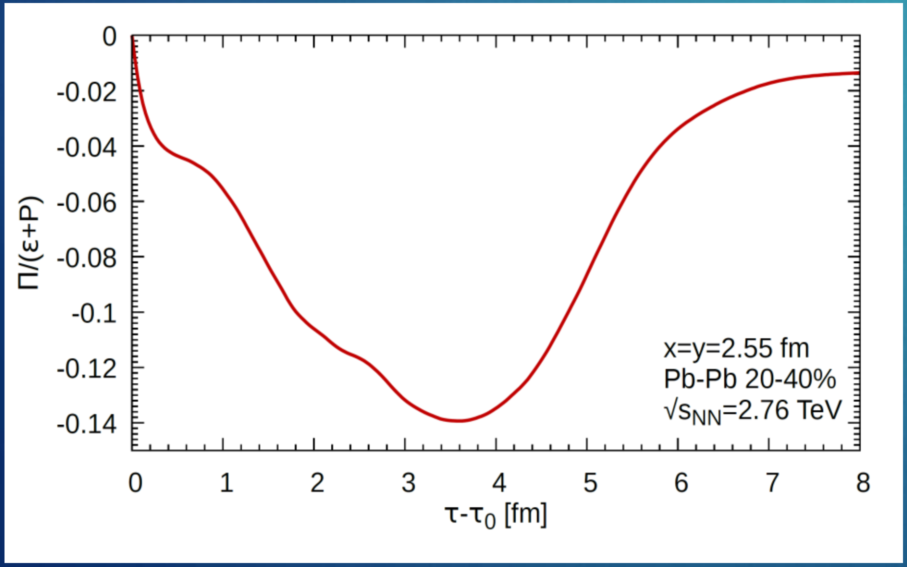


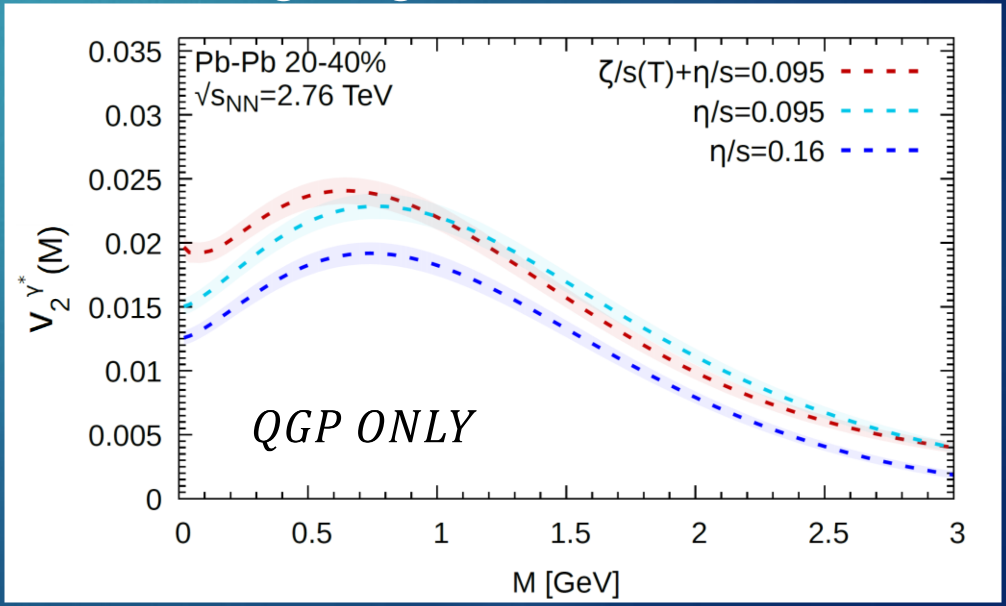
- $\langle T^{xx} \pm T^{yy} \rangle \equiv$
$$\equiv \frac{1}{N_{events}} \sum_{i}^{N_{events}} \int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp \left(T_i^{xx} \pm T_i^{yy}\right)$$
where the $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ integrates only over the **QGP** phase.

Bulk viscosity and QGP v_2 at LHC

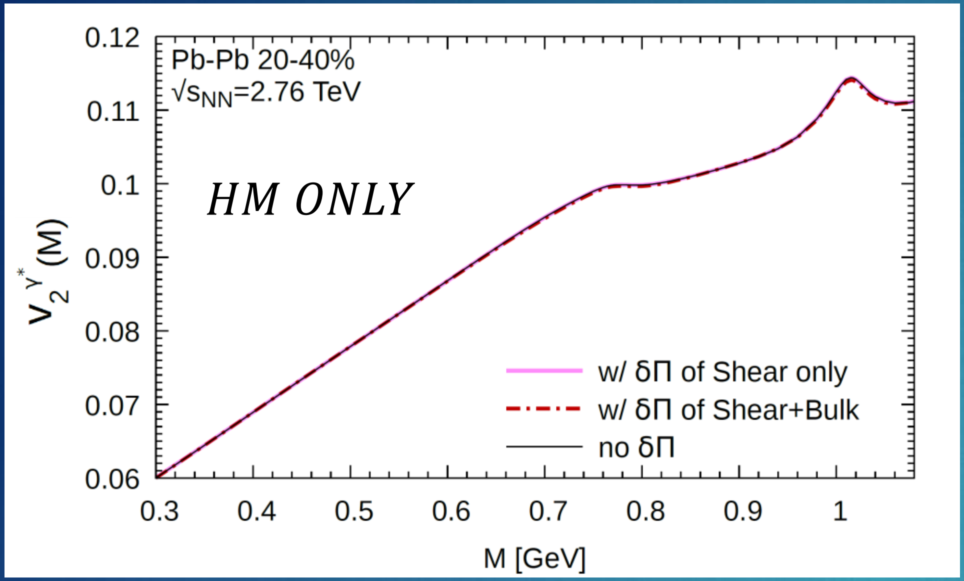


- At early times, hydrodynamic ($T^{\mu\nu}$) momentum anisotropy increases under the influence of bulk viscosity.
- $\delta n^{(bulk)} \propto \frac{T}{E} - \frac{E}{T}$ effects are responsible for the shape seen in QGP v_2, as $\frac{\Pi}{\varepsilon+P}$ doesn't change sign.

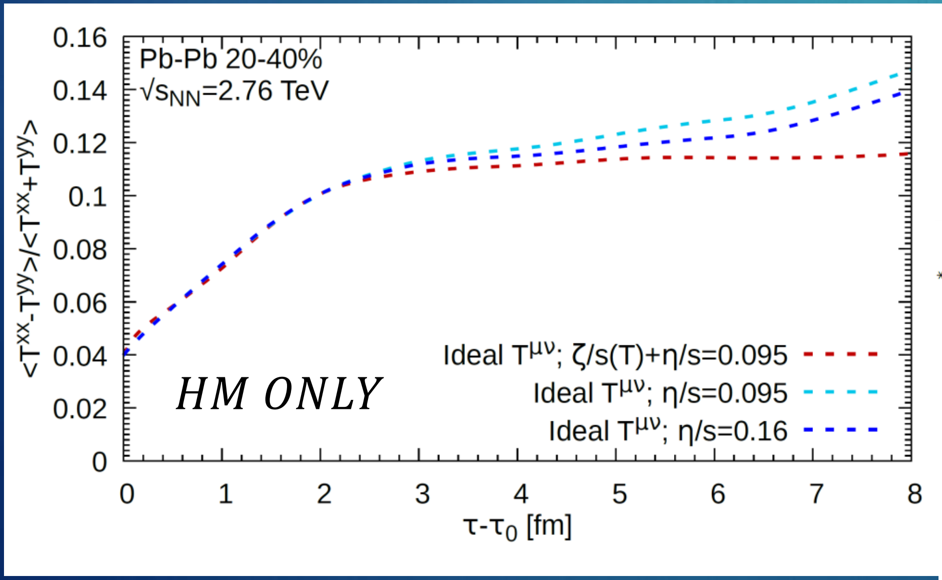


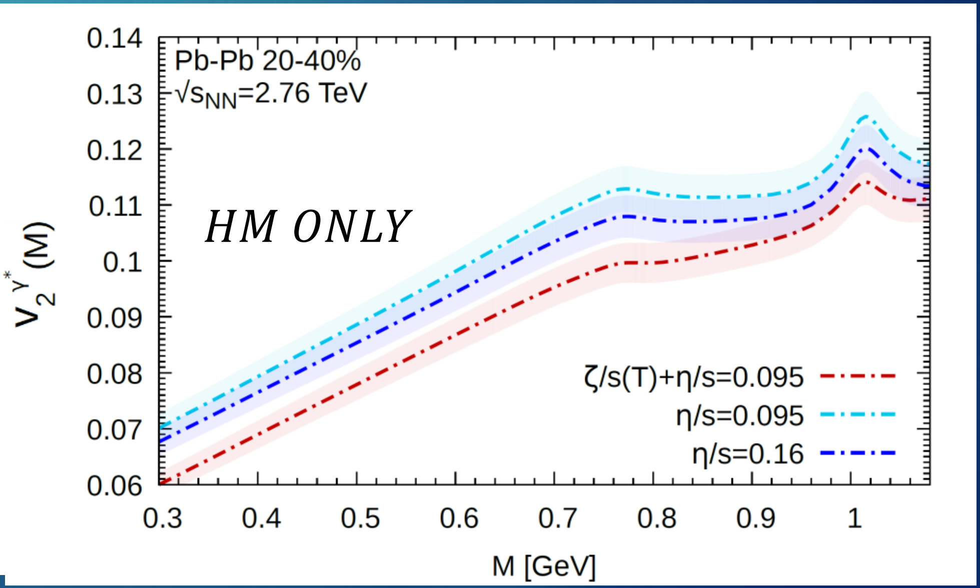


Bulk viscosity and HM v_2 at LHC

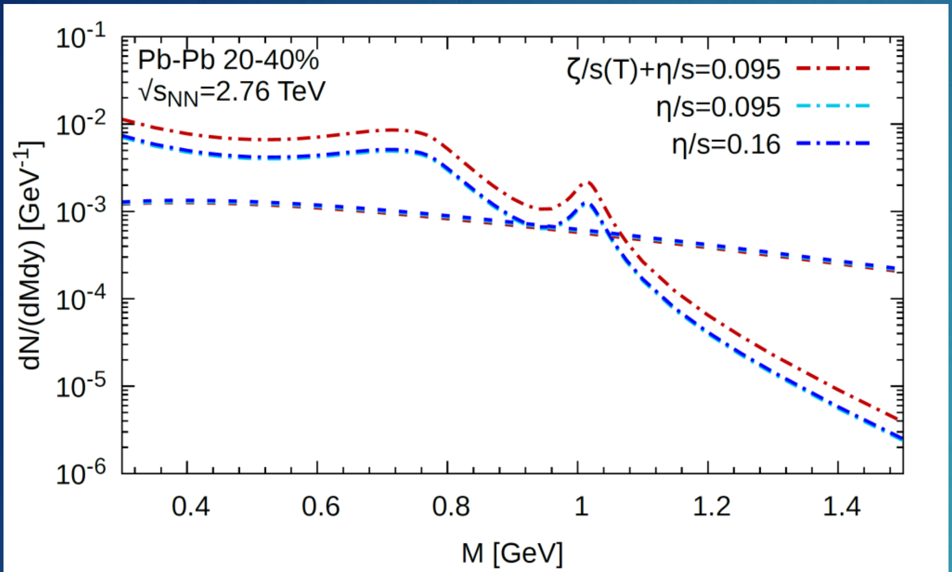


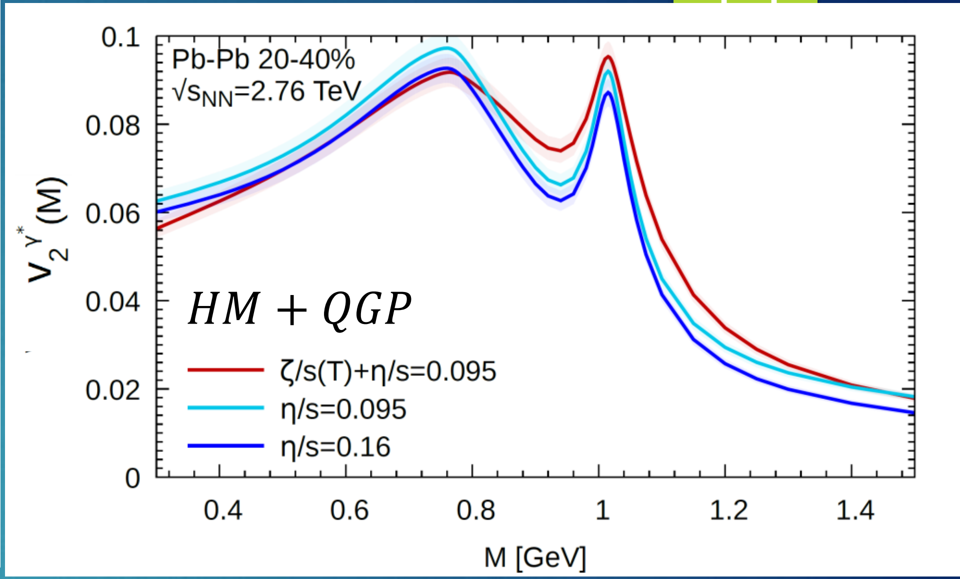
- However, HM dileptons are modestly affected by δn effects.
- v_2^{HM} is only affected by flow anisotropy.
- Where $\int_{\tau_0}^{\tau} \tau' d\tau' \int d^2 x_\perp$ in $\langle T^{xx} \pm T^{yy} \rangle$ integrates only over the **HM** region.

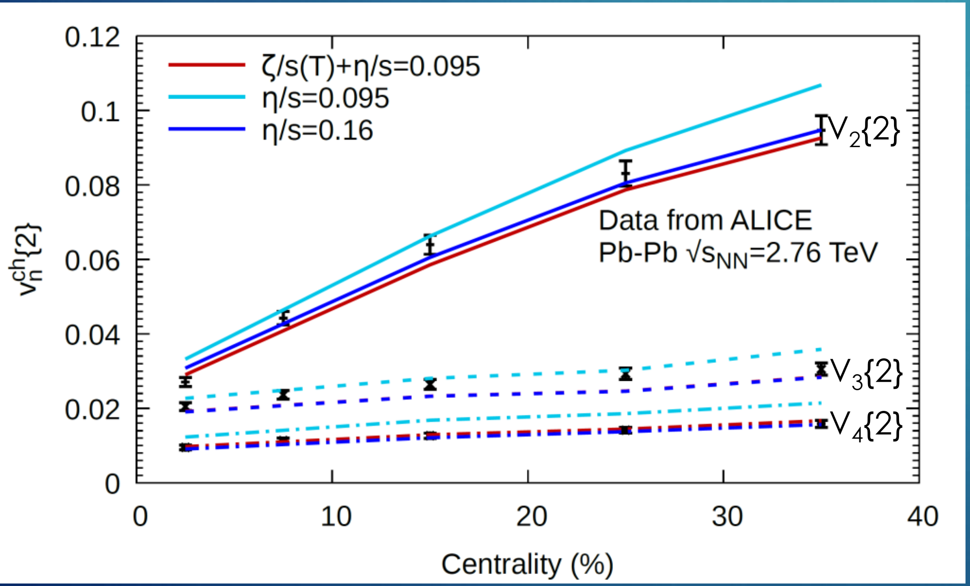




Bulk viscosity and dileptons at LHC

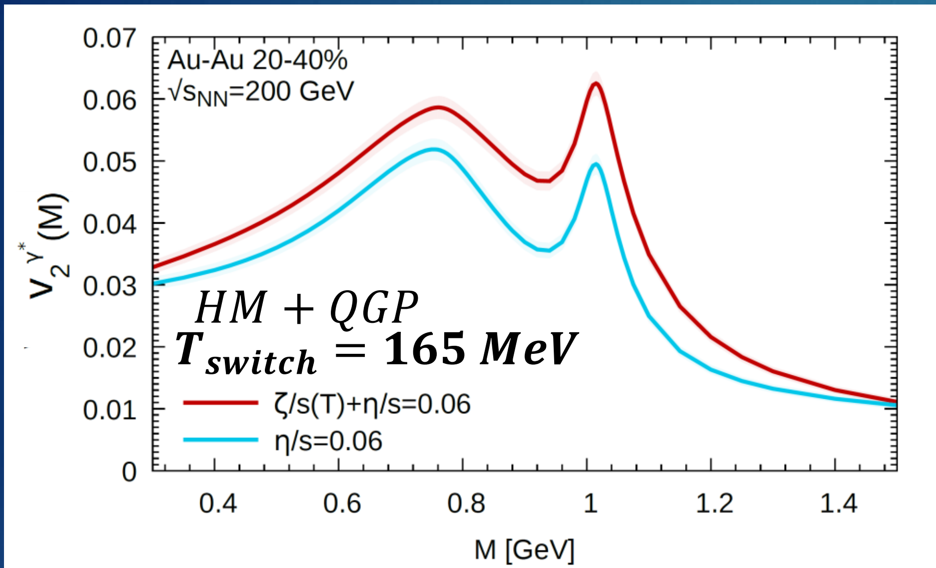


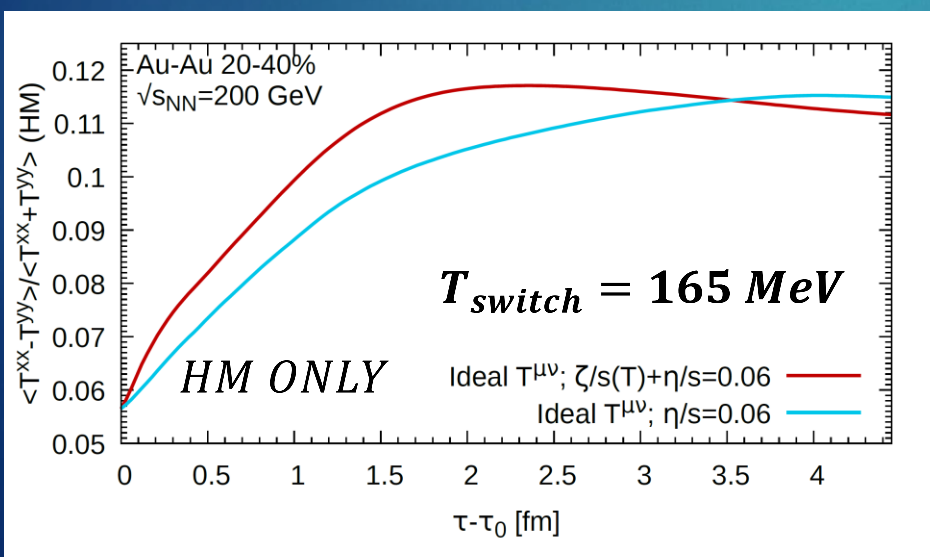




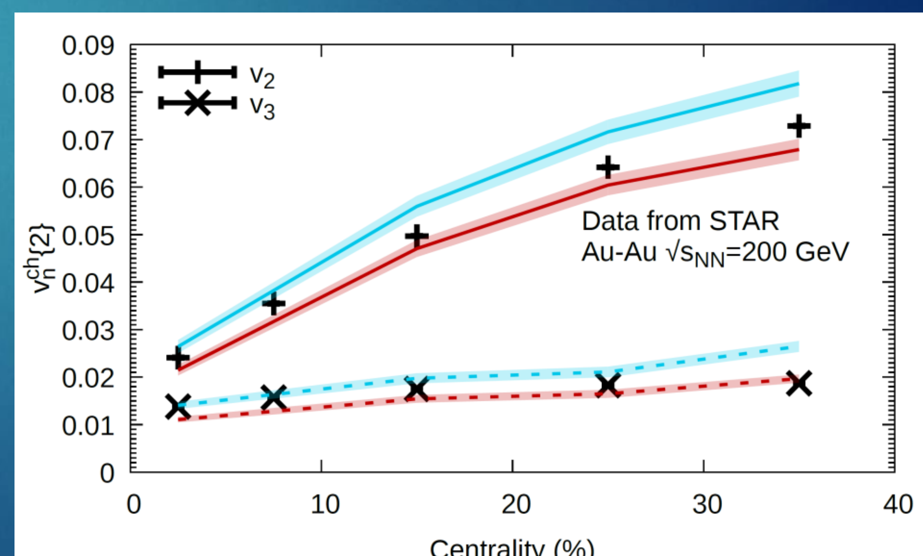
- Thermal $v_2(M)$ is a yield weighted average of HM and QGP contributions:
  - For $M < 0.8$ GeV $v_2(M)$ behaves same as charged hadrons.
  - For $M > 0.8$ GeV sector, $v_2(M) \uparrow$ because there is more weight in the HM sector.

Bulk viscosity and dileptons at RHIC

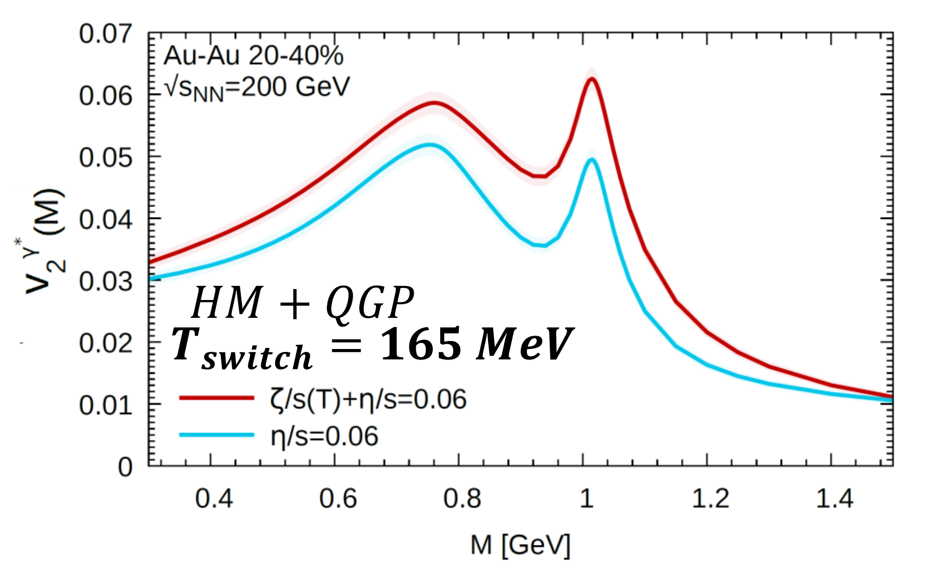


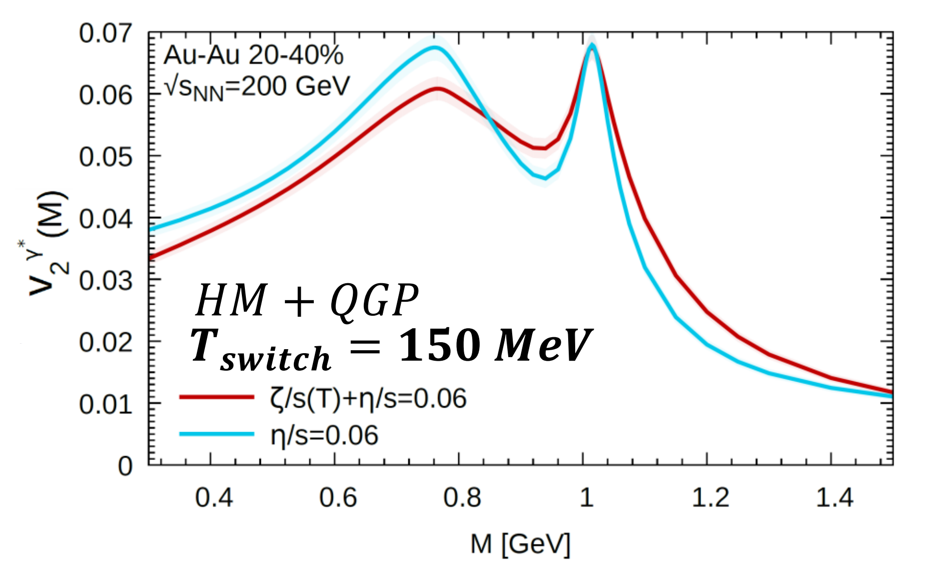


- Bulk viscosity causes an increase in anisotropic flow build-up in both the QGP and the hadronic sector which translates into an ↑ $v_2(M)$ of thermal dileptons.
- v_2^{ch} behaves in the opposite direction, as they are emitted at later times.
- This anti-correlation is a key feature of bulk viscosity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

Part I: Conclusions

- 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.

Part I: 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.

Part II: The Beam Energy Scan

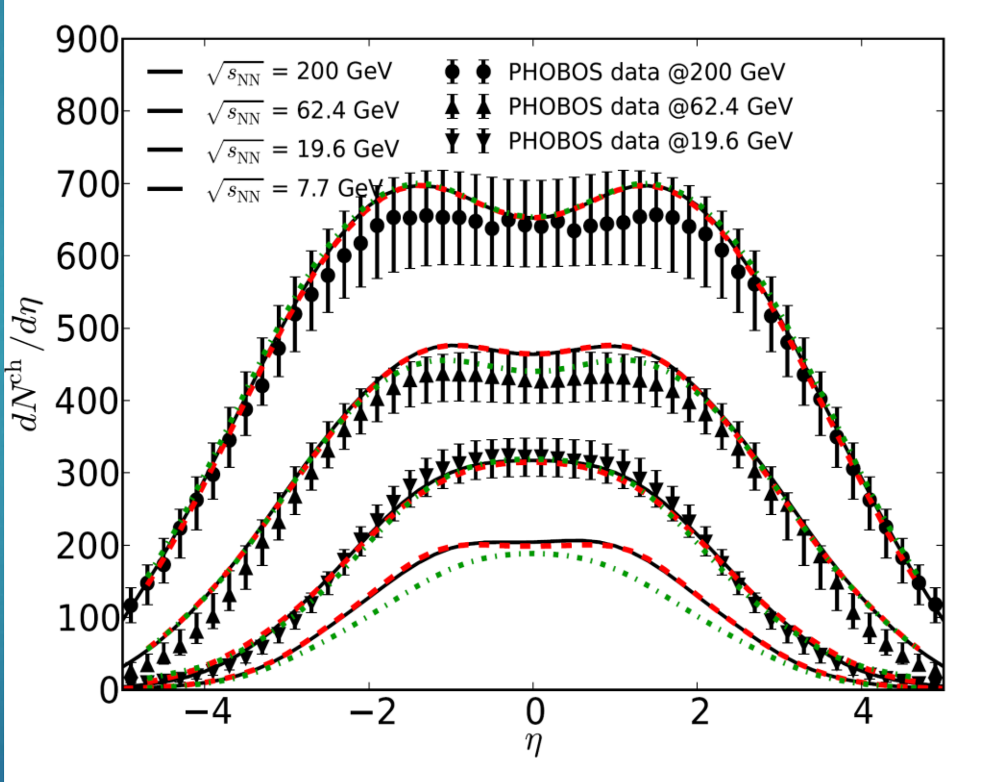
Initial Conditions

- Longitudinal direction: the spatial rapidity profile baryon density is

$$g_B(\eta_s) = N\Theta(|\eta_s| - \eta_{s,0}) \exp\left[-\frac{(|\eta_s| - \eta_{s,0})^2}{2\Delta\eta_{s,1}}\right] + N[1 - \Theta(|\eta_s| - \eta_{s,0})]\left[A + (1-A)\exp\left[-\frac{(|\eta_s| - \eta_{s,0})^2}{2\Delta\eta_{s,2}}\right]\right]$$

$$N = \left[\sqrt{2\pi}\Delta\eta_{s,1} + (1-A)\sqrt{2\pi}\Delta\eta_{s,2} + 2A\eta_{s,0}\right]^{-1}$$

- Parameters of $g_B(\eta_s)$ tuned to the measured charged hadron $dN^{ch}/d\eta$ spectrum extrapolated to $\sqrt{s_{NN}} = 7.7\ GeV$ using scaling from PRC **85**, 054902 (2012)



- $\varepsilon(\eta_s)$ same form as at high $\sqrt{s_{NN}}$

- In the transverse direction: averaged MC-Glauber initial condition with aligned event plane angles, yielding correct $\langle v_2 \rangle$ after averaging the MC-Glauber events.

Hydrodynamics at lower $\sqrt{s_{NN}}$

- Israel-Stewart dissipative hydrodynamics at lower beam energies:

$$\partial_\mu T^{\mu\nu} = 0$$
$$T^{\mu\nu} = T_0^{\mu\nu} + \pi^{\mu\nu}$$
$$T_0^{\mu\nu} = \varepsilon u^\mu u^\nu - P\Delta^{\mu\nu}$$
$$\tau_\pi \Delta^{\mu\nu}_{\alpha\beta} u^\sigma \partial_\sigma \pi^{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \delta_{\pi\pi}\pi^{\mu\nu}\theta$$
$$\tau_\pi = \frac{5\eta}{\varepsilon + P}; \quad \frac{\eta T}{\varepsilon + P} = \frac{1}{4\pi}; \quad \delta_{\pi\pi} = \frac{4}{3}\tau_\pi$$
$$2\eta\sigma^{\mu\nu} = 2\eta\left[\frac{\nabla^\mu u^\nu + \nabla^\nu u^\mu}{2} - \frac{1}{3}\Delta^{\mu\nu}\nabla^\alpha u_\alpha\right]$$

$$\partial_\mu \mathrm{J}^\mu_\mathrm{B} = 0$$
$$J_B^\mu = \rho_B u^\mu + V^\mu$$
$$\tau_V \Delta^\mu_\alpha u^\sigma \partial_\sigma V^\alpha + V^\mu = \kappa \nabla^\mu\left(\frac{\mu_B}{T}\right) - \tau_V V^\mu \theta - \lambda_{VV}\sigma^{\mu\nu}V_\nu$$
$$\tau_V = \frac{C}{T}; \quad \kappa = C\frac{\rho_B}{\mu_B}; \quad \lambda_{VV} = \frac{3}{5}\tau_V$$

RTA for massless particles and $\frac{\mu_B}{T} \lll 1$

$C = 0.2$ from PRD 77, 066014 (2008)

- Why no bulk? δn^{bulk} couples to baryon number. The effects of baryon number on δn^{bulk} are still being worked out.
- $P(\varepsilon, \mu_B)$: Lattice QCD at finite μ_B using Taylor expansion + Hadron Resonance Gas in chem. eq. [in collaboration with McGill University and Brookhaven National Laboratory].

Hydrodynamics at lower $\sqrt{s_{NN}}$ (cont'd)

- Starting from the same initial condition, while also keeping the same freeze-out energy density, investigate 3 hydrodynamical evolutions:

$$P = \begin{cases} P(\varepsilon) \\ P(\varepsilon, \mu_B) \end{cases}$$

$$V^\mu \rightarrow \begin{cases} 0 \\ \tau_V \Delta^\mu_\alpha u^\sigma \partial_\sigma V^\alpha + V^\mu = \kappa \nabla^\mu \left(\frac{\mu_B}{T}\right) - \tau_V V^\mu \theta - \lambda_{VV} \sigma^{\mu\nu} V_\nu \end{cases}$$

- Goals :
  - To investigate the influence of net baryon density ρ_B (or μ_B) and
  - Baryon diffusion V^μ on dilepton production, where the transport coefficient κ is governing the size of V^μ.

Diffusion corrections to the particle distribution function

- V^μ and $\pi^{\mu\nu}$ break spherical symmetry in the local rest frame of the medium.
- Matching fluid degrees of freedom to particles
  - using RTA approximation for V^μ

$$\rho_B u^\mu + V^\mu = \int \frac{d^3k}{(2\pi)^3 k^0} k^\mu \left[n_{a,0}(x) + \delta n_a^{(diff)}(x) \right]; x = \frac{k \cdot u}{T} - b_i \frac{\mu_B}{T}$$

$$\delta n_a^{(diff)}(x) = n_{a,0}(x)[1 \pm n_{a,0}(x)] \left[\frac{n_B T}{\varepsilon + P} - \frac{b_i}{u \cdot k/T} \right] \frac{k^\mu V_\mu}{T\, \kappa/\tau_V}$$

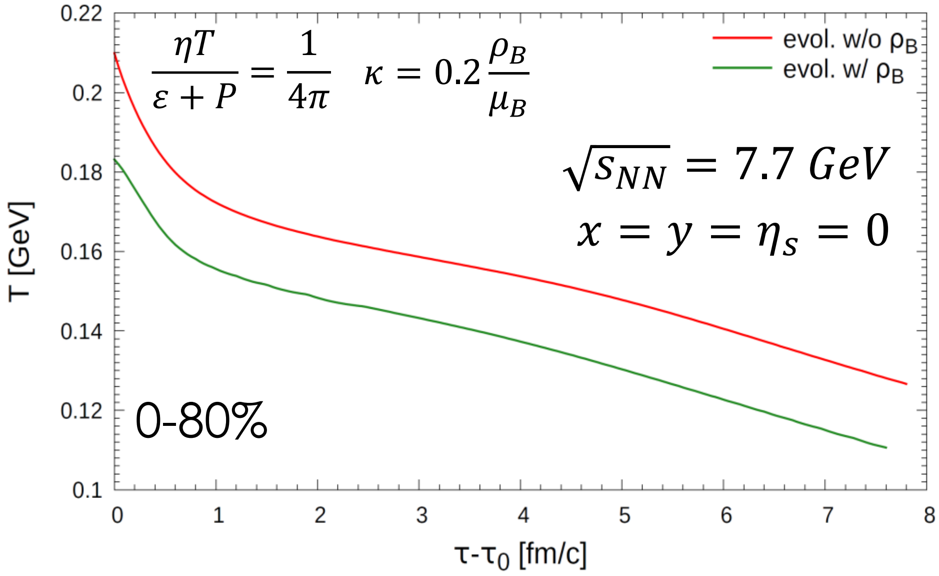
$$b_i = \begin{cases} -1 & for\ antibaryons \\ 0 & for\ mesons \\ 1 & for\ baryons \end{cases} \qquad b_i = \begin{cases} -1/3 & for\ antiquarks \\ 0 & for\ gluons \\ 1/3 & for\ quarks \end{cases}$$

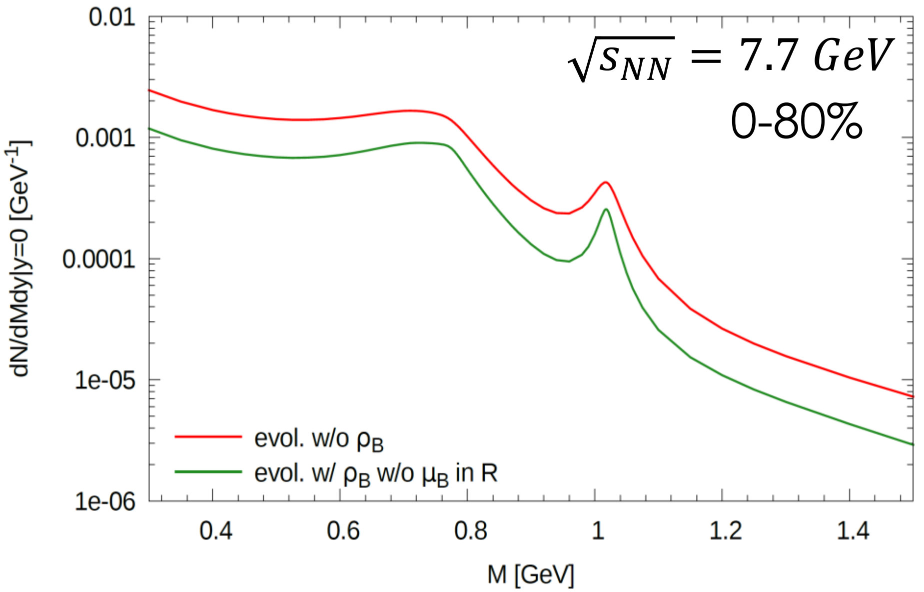
  - For $\pi^{\mu\nu}$, we use Israel-Stewart approximation

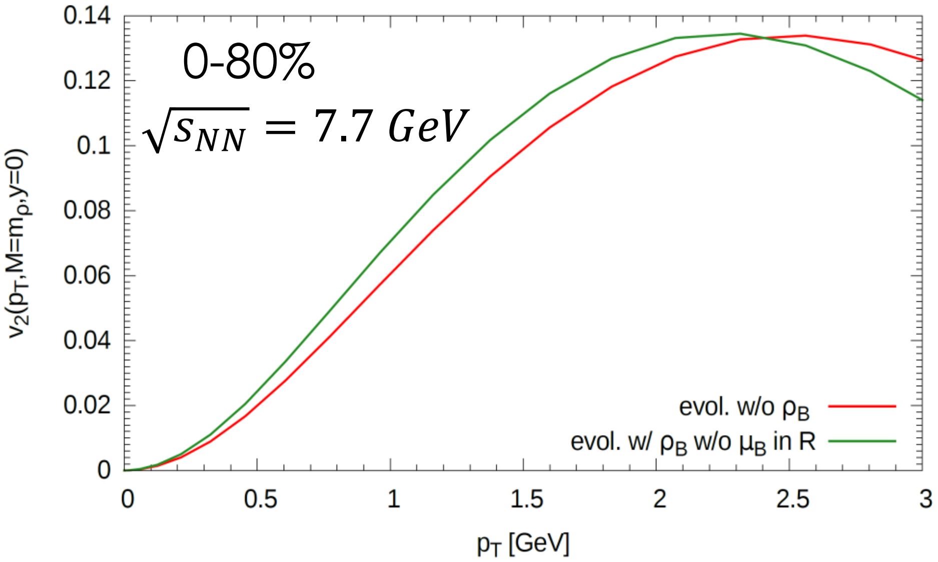
$$\delta n_a^{(shear)} = n_{a,0}(x)[1 \pm n_{a,0}(x)] \frac{k^\mu k^\nu \pi_{\mu\nu}}{2T^2(\varepsilon + P)}$$

- One needs to fold these distributions into the same dilepton rates as before, with the interpolation being now done in ε.

Dilepton yield and elliptic flow

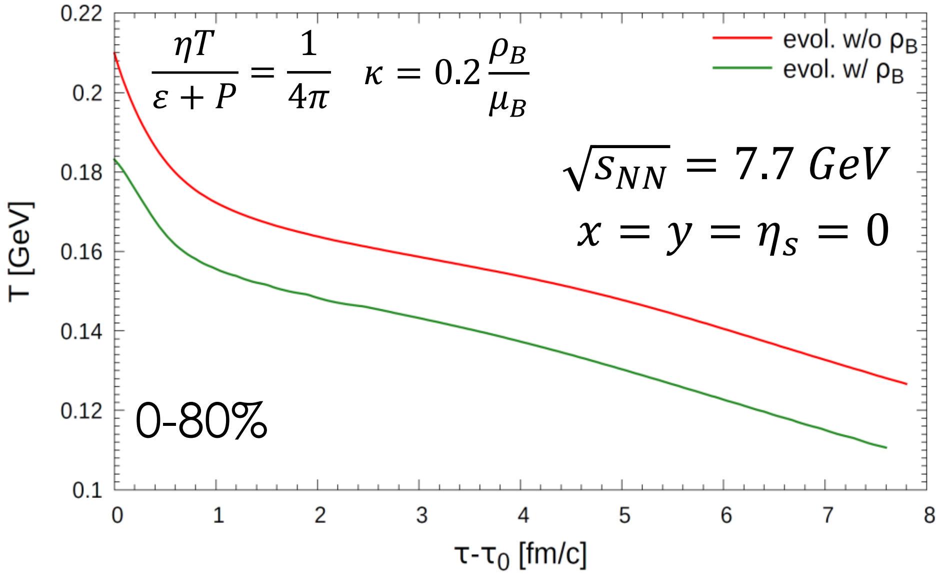


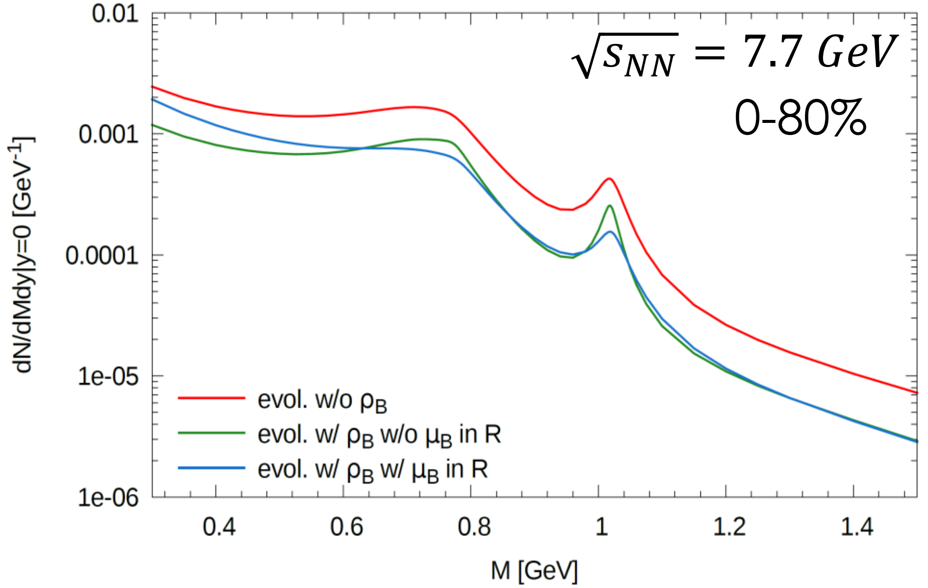


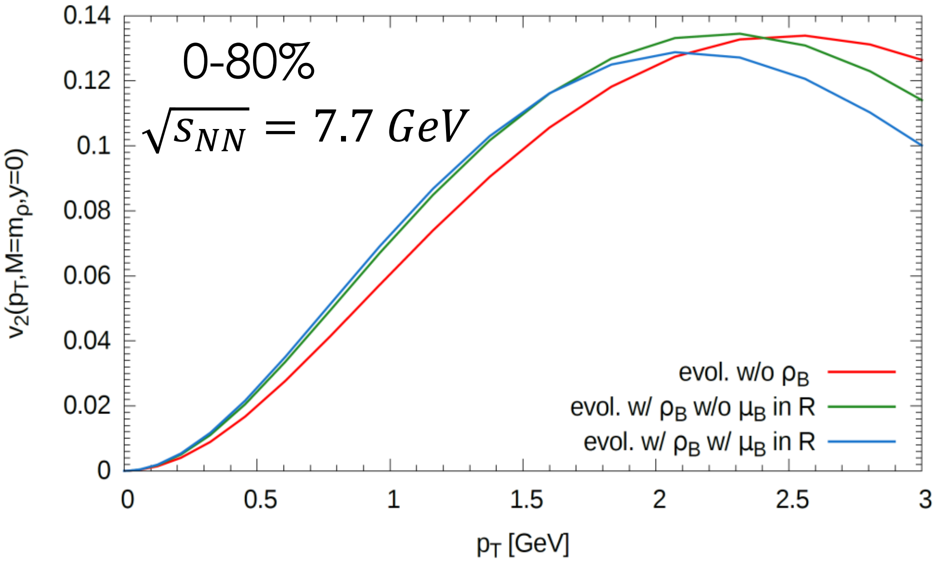


- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.

Dilepton yield and elliptic flow

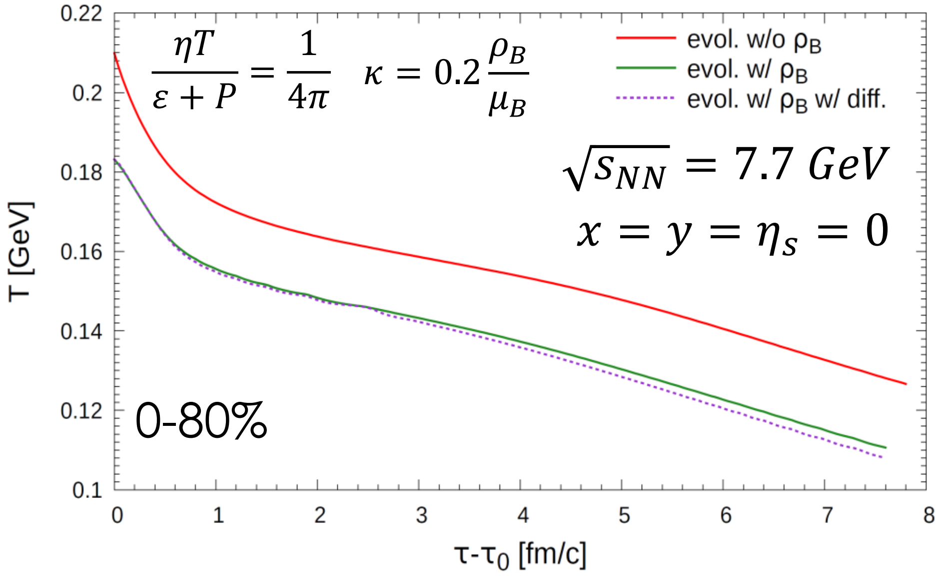


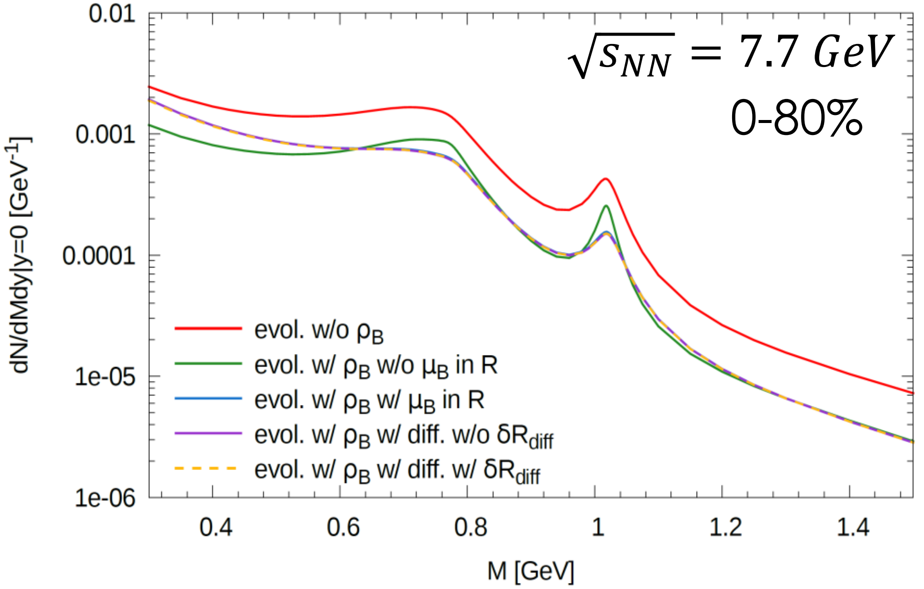


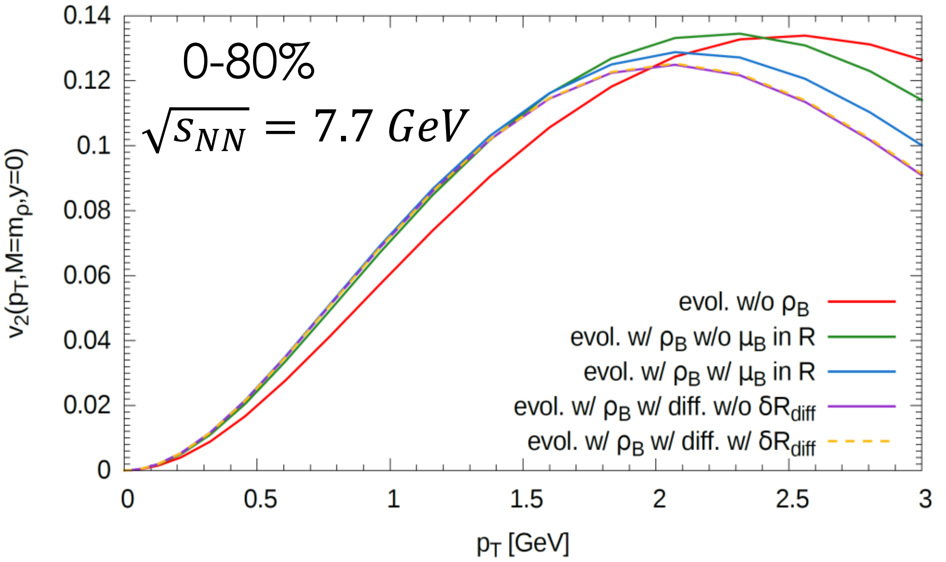


- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.
- Incl. μ_B in the dilepton rates ⇒ clear width broadening of vector mesons.

Dilepton yield and elliptic flow







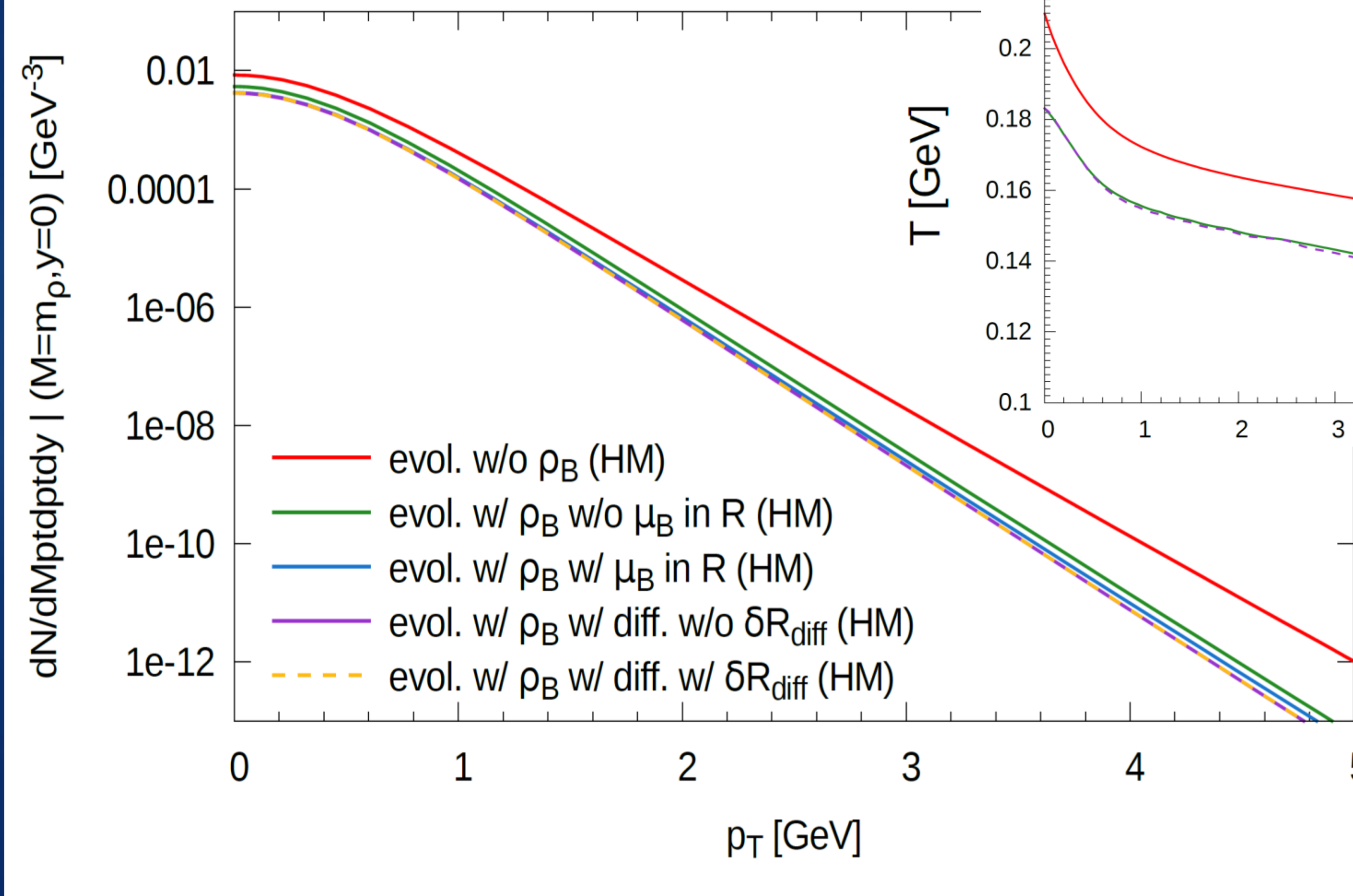
- Going from a medium w/o ρ_B to w/ ρ_B incurs a large change in dof. & ∴T ⇒ large effect on dilepton yield & v_2.
- Incl. μ_B in the dilepton rates ⇒ clear width broadening of vector mesons.
- The thermal $v_2(p_T)$ at fixed M is sizeable and sensitive to imprints left by baryon diffusion on the evolution.

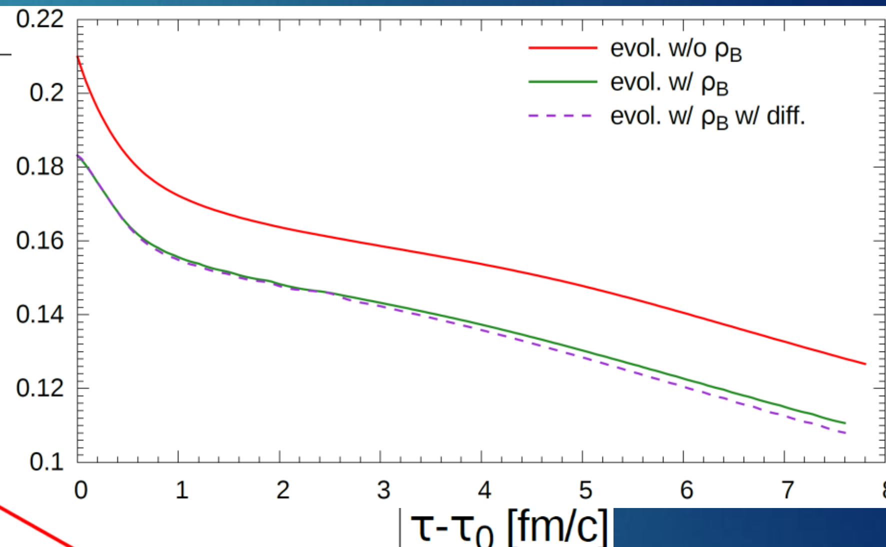
Why is total v_2 decreased with $\mu_B \& V^\mu$?

- Recall v_2^{total} is a yield weighted avg of HM's and QGP's v_2.
- v_2^{total} is reduced at high p_T because more weight is put on the QGP contribution of v_2, i.e. QGP yield remains the same while the HM yield is reduced.

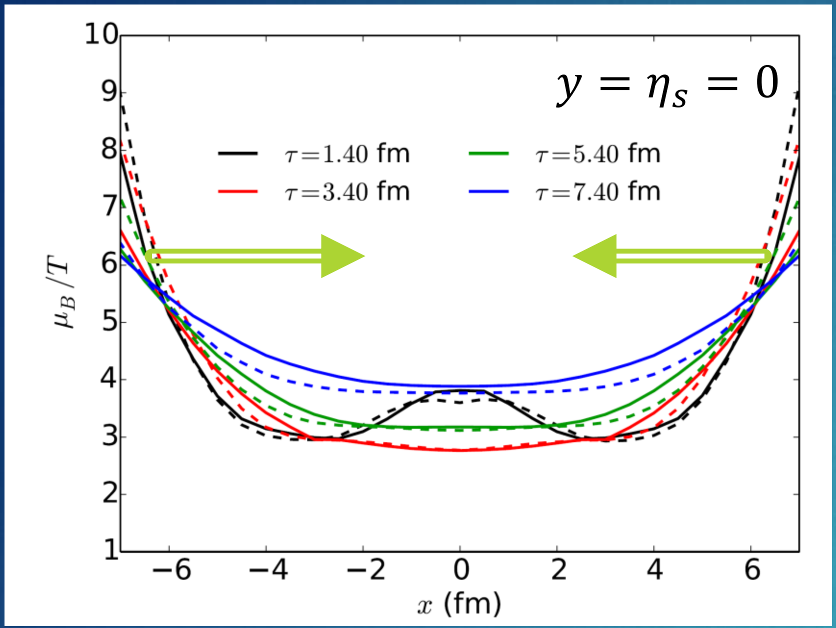
Why is total v_2 decreased with $\mu_B \& V^\mu$?

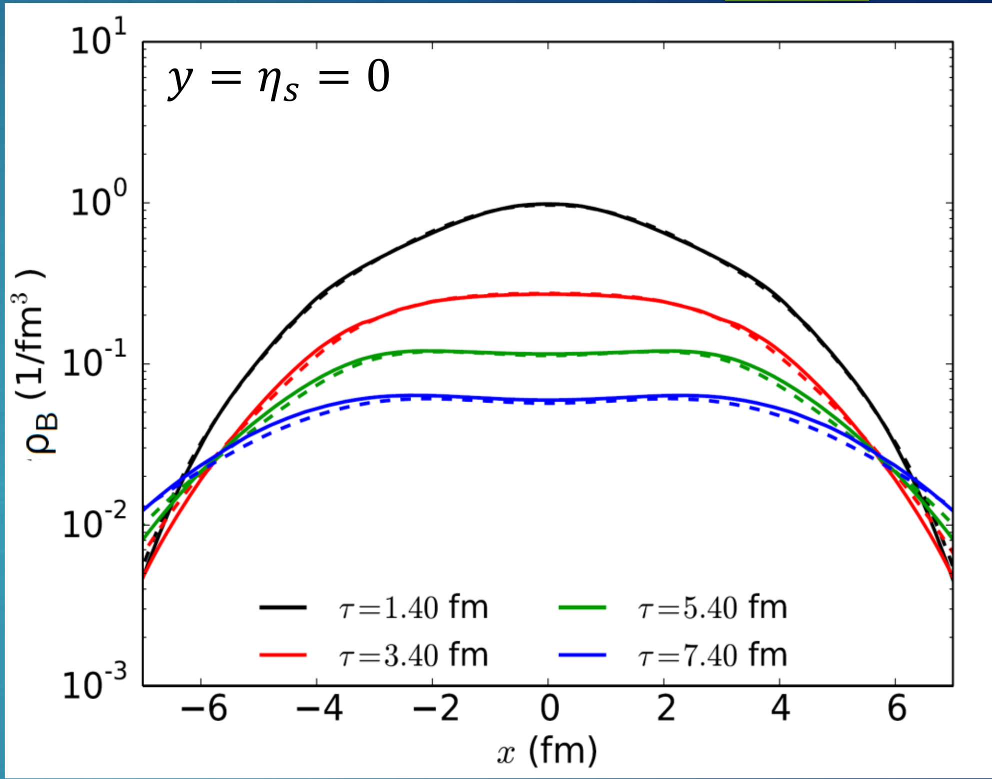
- Dilepton HM yield decreases via width broadening of vector mesons, and also because V^μ further slightly lowers the temperature of the medium in the hadronic sector, affecting dileptons at higher p_T.

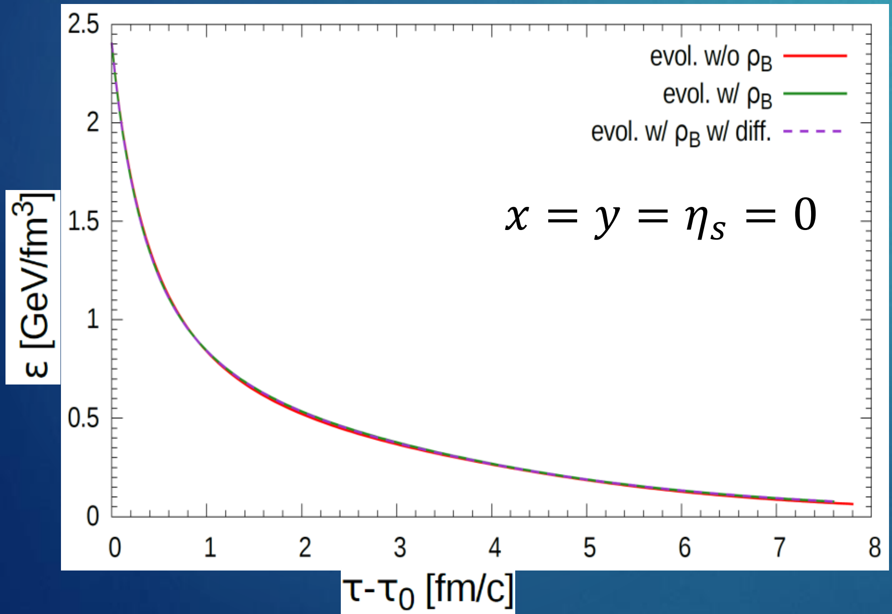




Why does V^μ change T?







- Recall diffusion equation:

$$\tau_V \Delta^\mu_\alpha u^\sigma \partial_\sigma V^\alpha + V^\mu = \kappa \nabla^\mu \left(\frac{\mu_B}{T}\right) - \tau_V V^\mu \theta - \lambda_{VV} \sigma^{\mu\nu} V_\nu$$

- Unlike heat diffusion, $V^\mu \propto \nabla^\mu \left(\frac{\mu_B}{T}\right)$ and not $\nabla^\mu \rho_B$.

Part II: Conclusions

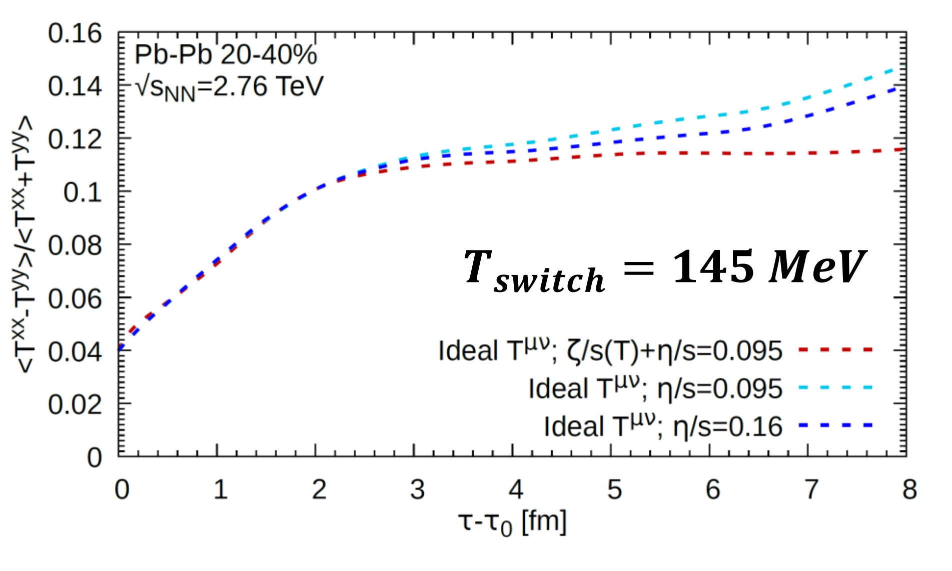
- A first (preliminary) dilepton calculation using dissipative hydrodynamical evolution, shows that:
  - Width broadening of vector mesons in the medium, as expected from a non-zero μ_B, is responsible for the main new features seen in dilepton yield and v_2, not present in the case of high energy HIC.
  - The dilepton $v_2(p_T)$ is sensitive to effects that baryon-number diffusion induces on the evolution of the medium, in the p_T region $1.5 \lesssim p_T \lesssim 3\ GeV$.
- All the ingredients are now in place to start studying the sensitivity of thermal dileptons to baryon diffusion, within a hydrodynamical context.

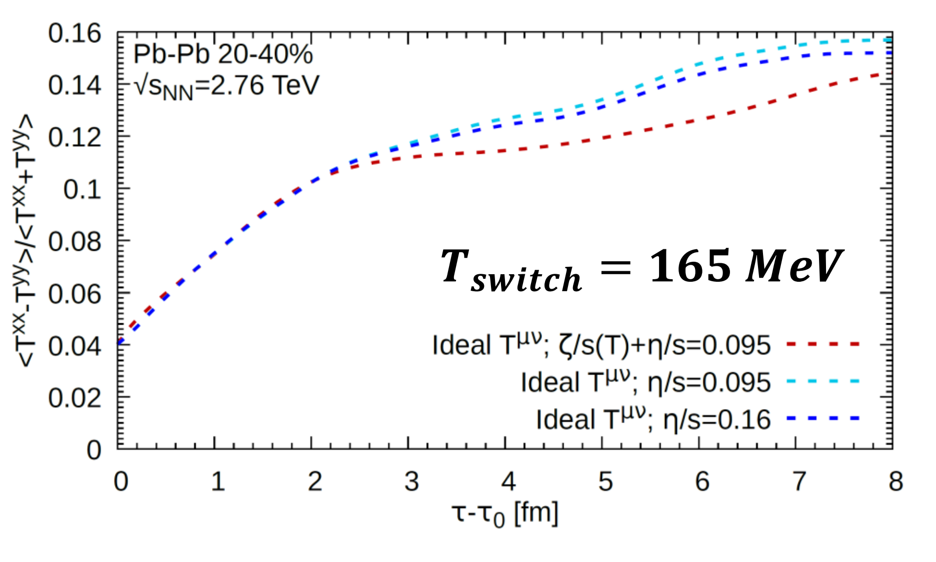
Part II: Outlook

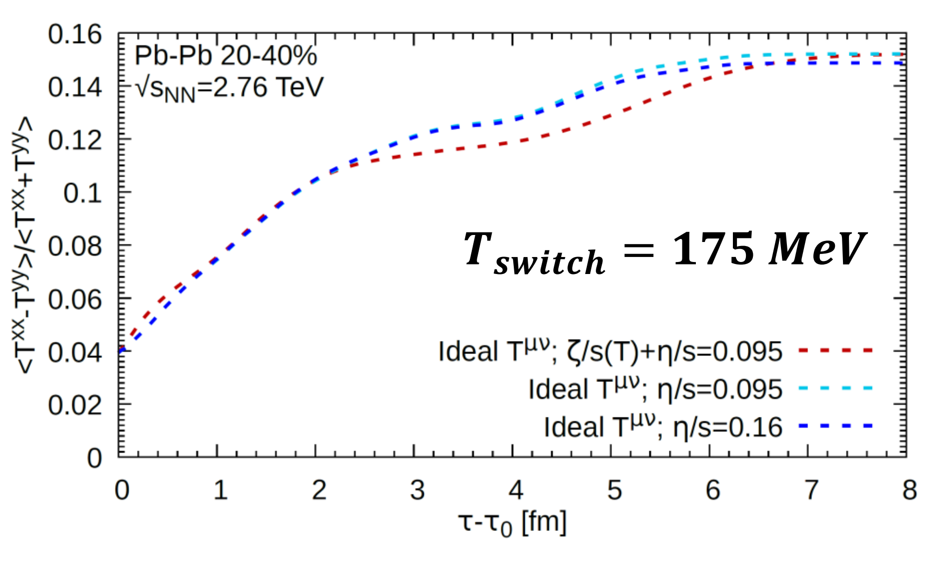
- Perform a dilepton calculation using an event-by-event hydrodynamical evolution from an improved initial condition model, for various parametrizations of κ, including a different temperature-dependence of κ, various initial values for V^{μ}, and different beam energies.
- Include the effects of other dissipative degrees of freedom (e.g. Π)
- Compute dilepton production from a hadronic transport model (e.g. SMASH), in order to have a more realistic account of the total number of dilepton produced in the context of BES.

Backup Slides

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



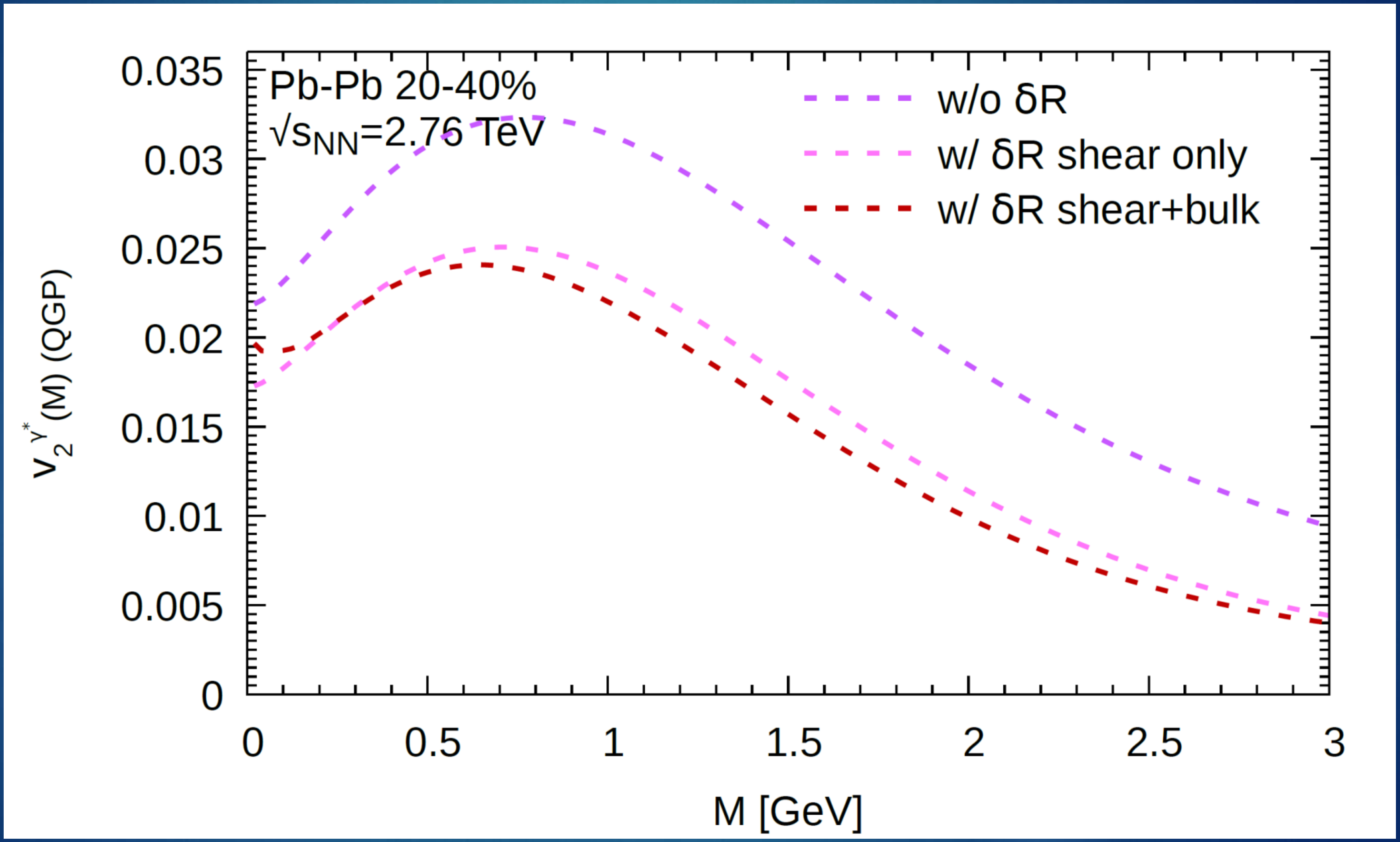




- $\frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} \equiv \frac{\sum_i \int d^2x_\perp (T_i^{xx} - T_i^{yy})}{\sum_i \int d^2x_\perp (T_i^{xx} + T_i^{yy})}$ where the $\int d^2x_\perp$ integrates only the **HM** phase with $T > 145$ MeV, $T > 165$ MeV, and $T > 175$ MeV.

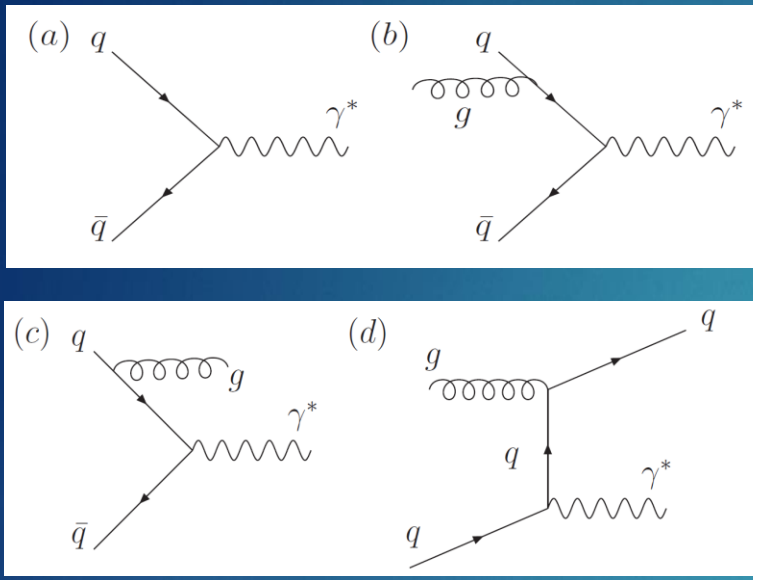
Viscous correction in the QGP

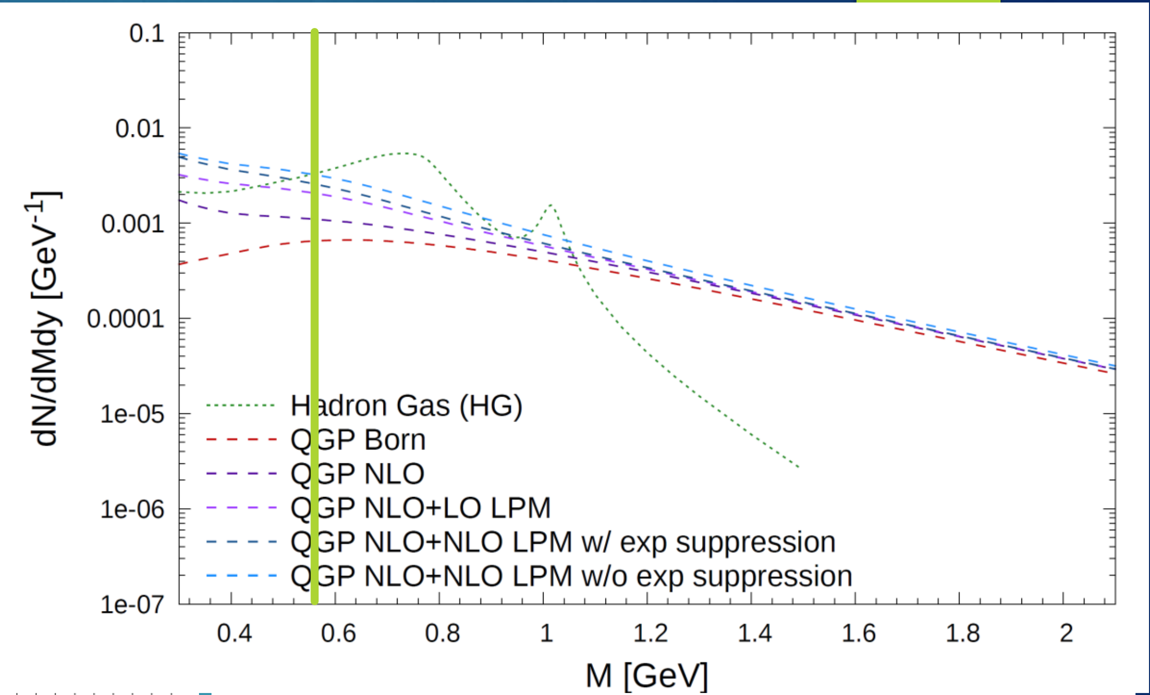
- Effects of viscous corrections on the QGP $v_2(M)$

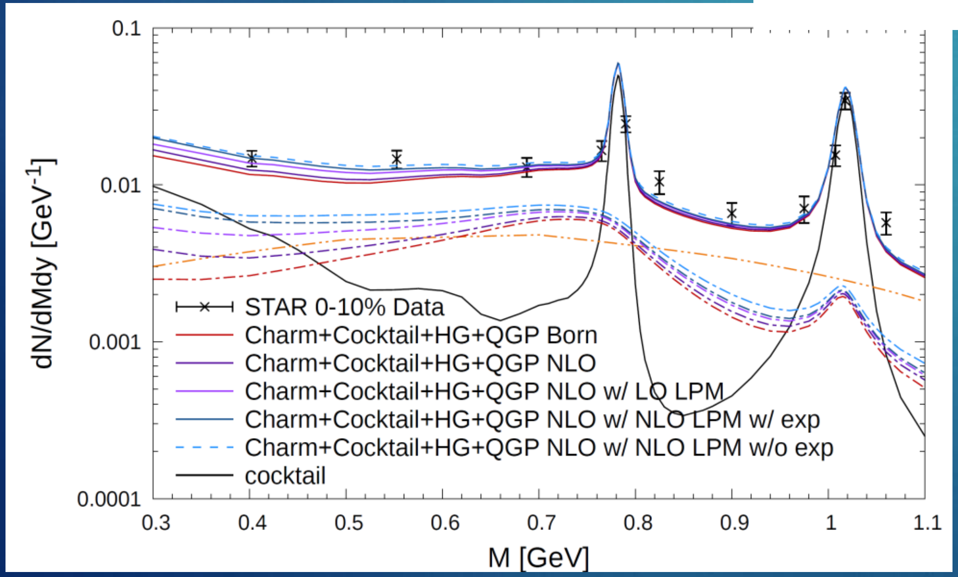


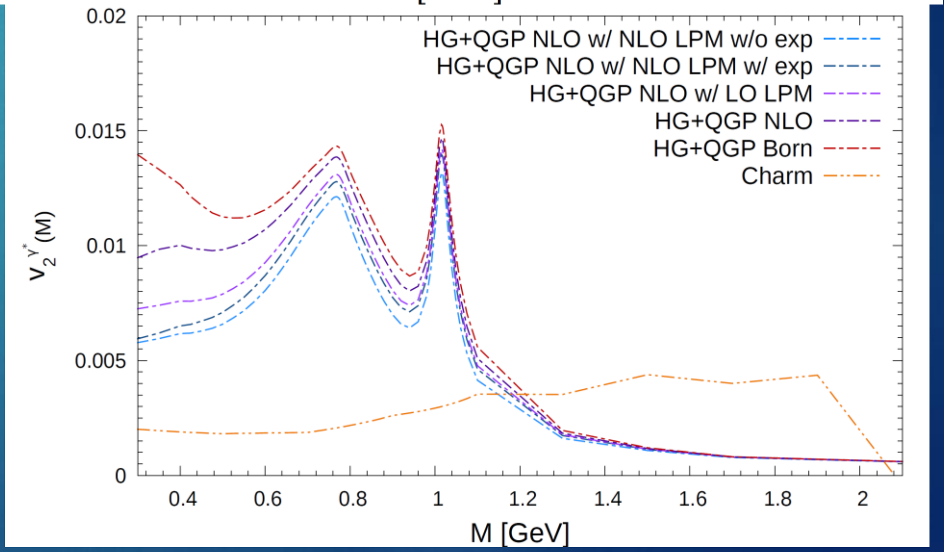
NLO QGP dilepton results

- Diagrams contributing at LO & NLO

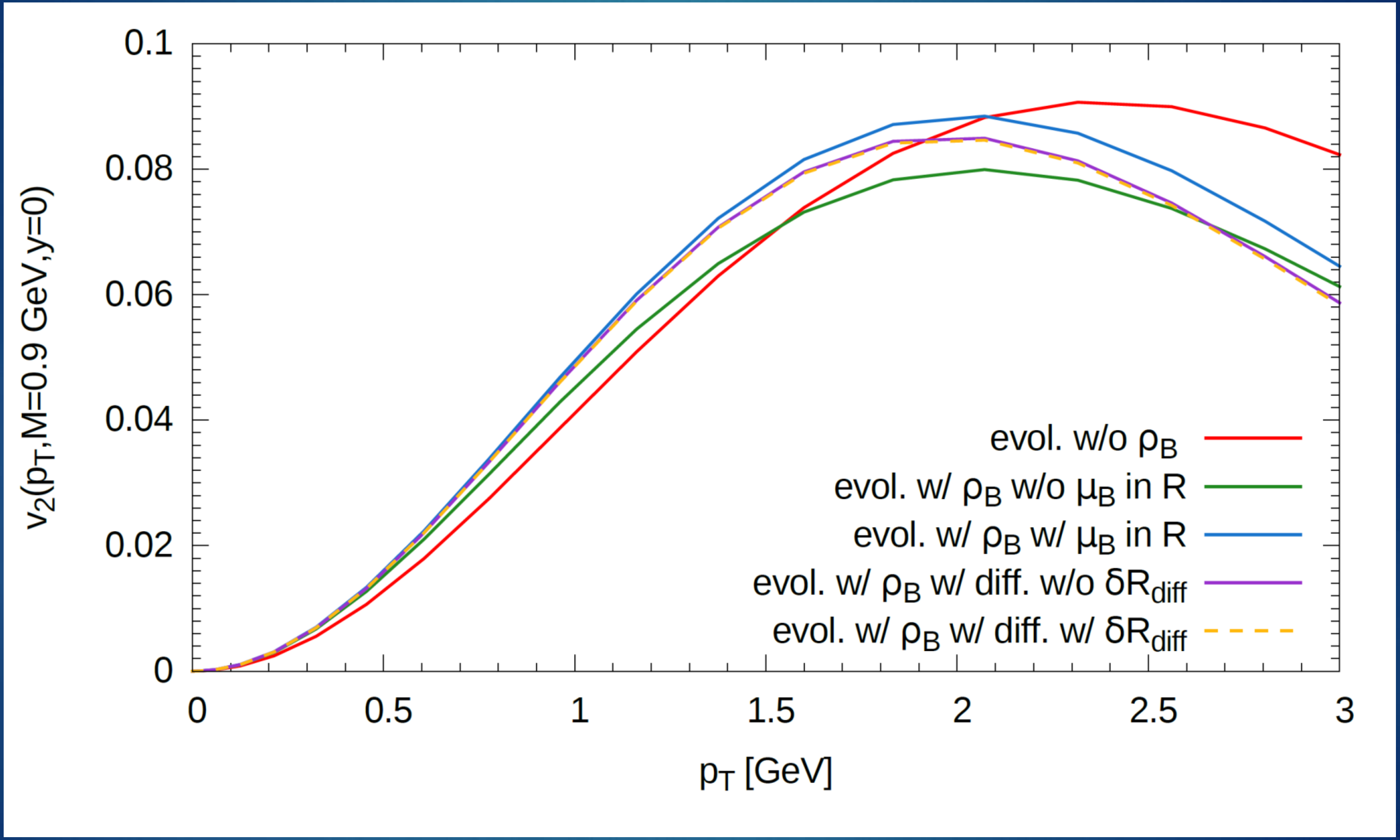




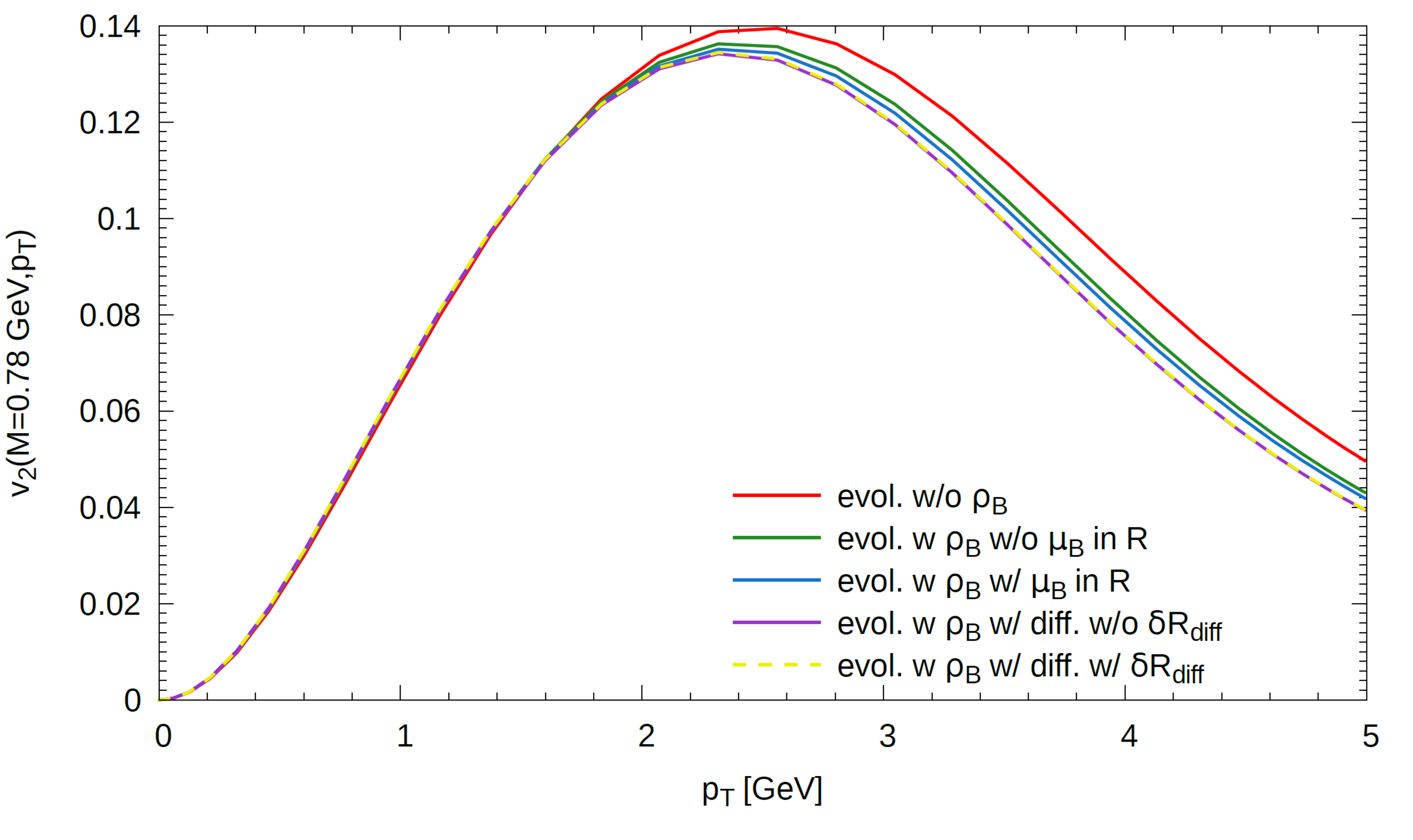




$v_2(p_T)$ for M=0.9 GeV

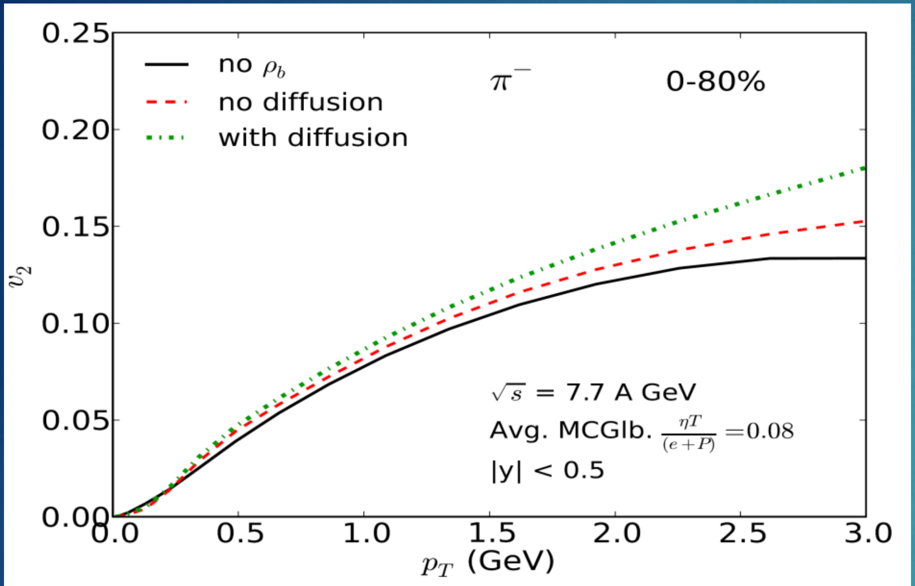


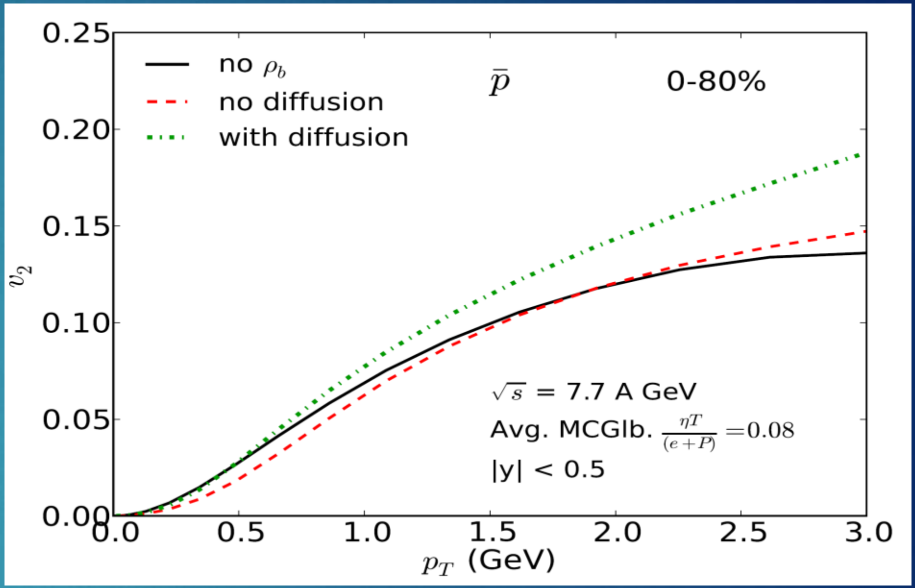
Variation of v_2 at $\sqrt{s_{NN}}$ =19.6 GeV

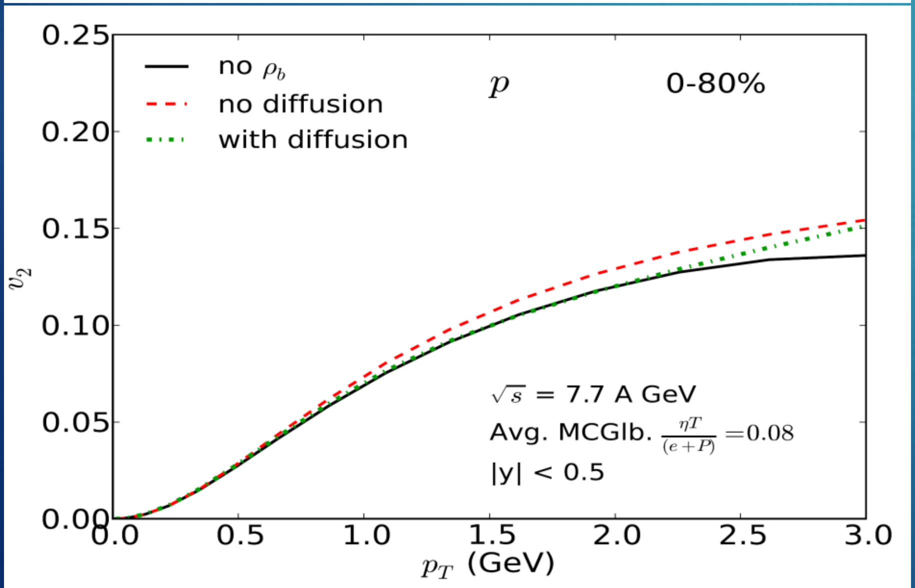


Motivation to study BES

- Sensitivity of hadronic observables to μ_B and V^μ







Interpolating between QGP and HM

- Unlike the case of high energy collisions (where T is used) to linear interpolation between HM and QGP, we now use ε

$$\frac{d^4R}{d^4q} = r_{QGP}\frac{d^4R_{QGP}}{d^4q} + (1 - r_{QGP})\frac{d^4R_{HM}}{d^4q}$$

$$r_{QGP} = \begin{cases} 1 & \varepsilon > \varepsilon_f \\ a\varepsilon + b & \varepsilon_i < \varepsilon < \varepsilon_f \\ 0 & \varepsilon < \varepsilon_i \end{cases} \qquad \begin{matrix} \varepsilon_f \sim 3.5\,\frac{GeV}{fm^3} \\ \varepsilon_i \sim 1\,\frac{GeV}{fm^3} \end{matrix}$$

The ε range over which this interpolation is done is an estimate, which will be improved upon very soon.